Report of the 2023 Committee of Visitors

Division of Physics

National Science Foundation

January 23-24, 2023

Submitted on behalf of the Committee by
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To
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I. Summary and Recommendations

The 2023 Committee of Visitors (COV) for the Physics Division (PHY) of the National Science Foundation (NSF) met in person on January 23-24, 2023.

The COV was charged to address and prepare a report on:

- the integrity and efficacy of processes used to solicit, review, recommend, and document proposal actions;
- the quality and significance of the results of the Division's programmatic investments;
- the relationship between award decisions, program goals, and Foundation-wide programs and strategic goals;
- the Division's balance, priorities, and future directions;
- the Division's response to the prior COV report of 2019; and
- any other issues that the COV feels are relevant to the review.

The Division also requested feedback on five additional questions.

- Does the new abbreviated Review Analysis provide appropriate and adequate information for understanding the recommendation?
- Are the programs achieving a reasonable and appropriate balance between award size, duration and success rate?
- Is the Division effectively participating in MPS- and NSF-wide activities (CAREER, MRI, MSRI-1, MSRI-2, ASCEND, LEAPS, QISE, AI, etc.) and utilizing them to best advantage?
- Are the Physics investments situated well within the context of investments made by other agencies, both national and international, in those areas in which the latter is significant?
- Based on what you have seen, is the Division well-positioned to respond to and address the priorities outlined by the NSF Director (i.e., the three pillars of "advancing the frontiers of research into the future", "ensuring accessibility and inclusivity", and "securing global leadership")?

The 2023 COV was organized around ten subcommittees representing the breadth of the Physics Division's portfolio. These were (individuals are identified in Appendix A):

- Atomic, Molecular and Optical Physics / Quantum Information Science
- Experimental Particle Physics / Large Hadron Collider
- Elementary Particle Physics / Cosmology Theory
- Gravitational Physics / LIGO
- Integrative Activities in Physics
- Nuclear Physics Theory and Experiment
- Particle Astrophysics / IceCube
- Physics of Living Systems
- Plasma Physics
- Physics Frontiers Centers / Partnerships in Research and Education Program

Special thanks go to Denise Caldwell, Jean Cottam Allen, and David Barley for their support and background materials as we prepared for the meeting, as well as the entire Physics Division administrative staff in helping to make our visit smooth. We also are very grateful to the Program Directors for all of the materials and context provided in advance of and during the meetings.

Below are observations, suggestions, and recommendations on topics identified by the subcommittees during the COV plenary sessions as well as on various topics extracted from the subcommittee reports. We list them here, although the context for each is provided in section II.

The individual subcommittee reports follow in section III. The COV's membership and subcommittees are listed in Appendix A. The COV's response to the standard NSF template is in Appendix B. Appendix C contains the meeting agenda.

As a preface to our report, we are reminded that the 2023 review encompassed a period of unique challenges for the science community, and indeed for the nation as a whole, as a result of the COVID-19 pandemic. The impact of COVID has been great, but also highly differential along many axes, including discipline, style of research activity, geographic location, stage of career, demographics of the affected community, and others. The Physics Division's approach to managing disruptions in research, education, and career development was to focus on mitigating the impact on junior members of the community, largely through supplementary funding for graduate students and postdocs when urgently needed. We found this to be an appropriate and strategic response. The tail of COVID's impact will be long, however, and we expect that attention to these concerns will be required for a number of years to come.

Summary of Findings

1: OBSERVATION: The Division benefits greatly from a strong and dedicated scientific staff who appropriately manage a diverse set of portfolios. The pairing of a permanent Program Director along with a rotator, when possible, enhances long-term stewardship as well as providing an avenue for fresh perspectives. The Division is also lucky to have a longstanding and experienced Division Director who has encouraged a spirit of flexibility, fairness, collaboration, and diversity of portfolio among the Program Directors.

2: SUGGESTION: As suggested by the 2019 COV, the Division leadership should continue to do what it can to make the Program Director positions as attractive as possible to recruit new talent, with the hope of providing continuity and mitigating gaps in transitions. The ability to offer flexibility in the mix of remote and in-person work is an important aspect, particularly for the rotational positions.

3: **RECOMMENDATION**: We recommend continued reinforcement of the intended broad meaning of "broader impacts" and of the importance of attention to it with the ad-hoc reviewers, in an appropriate balance with the reviews of intellectual merit.

4: **SUGGESTION:** We encourage the Division to consider options to document the practice of follow-up, particularly with declined proposals and first-time PIs, keeping in mind the impact of additional workload on the Program Directors.

5: SUGGESTION: The COV also discussed possible avenues for garnering wider input from the community on the review process, to augment the COV's review of eJackets, but did not come to consensus on an approach. We do not offer a specific solution, but suggest that this be considered at the Division leadership level for future COV reviews.

6: OBSERVATION: The COV's general sentiment was that we were not equipped, nor charged, to comment on the balance of the Division's portfolio across its program areas. We do, however, support the practice of ensuring that at least 50% of the Division's funding goes toward the research program (as opposed to facility operations and research infrastructure projects), as this largely supports the development of a strong scientific workforce at all levels.

7: SUGGESTION: In agreement with the 2019 COV recommendations, it is desirable for the different program areas to have some flexibility to adopt the length of cycle that best fits the proposal. If feasible, some language in the solicitation that informs the PI as to what's possible would be valuable.

8: SUGGESTION: We encourage the Division and Directorate leadership to continue to proactively foster opportunities for collaboration, for example through joint convenings of relevant Program Directors, to support sustainable partnerships that can outlast the efforts of individuals.

9: SUGGESTION: For large projects that cross agency boundaries, early adoption of inter-agency MOUs combined with jointly held operations reviews with agreed-upon metrics can both mitigate the effects of transitions, as well as help PIs navigate the process. We recognize that this is often a strategy but were unsure whether this is a formal practice.

10: SUGGESTION: As the Big Ideas Program reaches the end of its five-year window, we strongly encourage that every effort be made to minimize adverse impacts of its ending on projects and PIs that were initiated and supported through this initiative.

11: RECOMMENDATION: In alignment with NSF goal #2, we encourage the Division leadership to consider avenues for more coherence between IAP's portfolio and efforts within the science program areas to support the fostering of an inclusive community at all levels of participation, as well as to better align the language describing IAP with the initiatives it supports.

12: OBSERVATION: Towards the end of our meeting, we learned of the December 2022 "GRANTED" initiative. While it is too early for our COV to provide substantive comments, we view the strengthening of the research infrastructure, particularly among universities with emerging research aspirations, as an important support effort to lower barriers to participation, and we look forward to learning more about the initiative as it unfolds.

II. Division Level Comments

This section represents the COV perspectives that are at the level of the Physics Division as a whole. The ten subcommittee reports contain more detailed comments, research highlights, suggestions, and recommendations that should be especially useful to the individual programs.

A. SUMMARY OF THE WORK OF THE COV

Following the protocol from 2019, the COV began its work with a virtual opening session on December 16, 2022, consisting of an ethics briefing, a Division overview, and discussion of the charge elements. The ten subcommittees were then given access to a wide selection of eJackets over four funding years, which included both awards and declinations. In early January, they each met virtually with the relevant Program Director(s) to further understand the scope and specific processes of their assigned area. The subcommittees were charged with evaluating the questions identified above within the context of their program, from which common themes emerged for the Division-level evaluation. Most of the subcommittees had drafts of their program reports prior to the in-person convening. During the January 23-24 in-person meeting, time was spent in a mix of full committee convening, with and without NSF staff present, and additional discussions in breakout groups organized by the programs.

B. PROPOSAL REVIEW AND DECISION PROCESS

The Program Directors use a combination of ad-hoc reviews followed by a panel discussion for proposal evaluation, although specific processes for proposal review vary across the ten programs. In areas in which the proposals are almost exclusively individual investigator awards (such as in the theory areas), panel members may be asked to provide individual reviews along with the panel evaluation. In areas that involve large, long term, collaborative projects with cross-Divisional boundaries (such as in particle astrophysics), proposals may be viewed by more than one panel or organized by sub-program. Large collaborative proposals may involve a site visit (on-site or reverse) as additional input, and some long-term programs in this category benefit from special strategic reviews. Most importantly, the Program Directors are given the discretion to manage the combined review process as best fits their sub-discipline, and then use the collective input to make funding decisions within the boundaries of their respective budgets. The subcommittees all noted that the process within their area is managed well, while also recognizing the high workload of the Program Directors.

While the "Broader Impacts" element of proposals (of which broadening participation is one) seems to be considered in depth during panel reviews, some of the subcommittees noted that consideration of this element by the ad-hoc reviewers was not always consistent. Despite the Program Directors' efforts, consistent attention to this aspect of proposals is a longstanding issue which is very likely not unique to the Physics community of reviewers.

1: OBSERVATION: The Division benefits greatly from a strong and dedicated scientific staff who appropriately manage a diverse set of portfolios. The pairing of a permanent Program Director along with a rotator, when possible, enhances long-term stewardship as well as providing an avenue for fresh perspectives. The Division is also lucky to have a longstanding and experienced Division Director who has encouraged a spirit of flexibility, fairness, collaboration, and diversity of portfolio among the Program Directors.

2: SUGGESTION: As suggested by the 2019 COV, the Division leadership should continue to do what it can to make the Program Director positions as attractive as possible to recruit new talent, with the hope of providing continuity and mitigating gaps in transitions. The ability to offer flexibility in the mix of remote and in-person work is an important aspect, particularly for the rotational positions.

3: **RECOMMENDATION**: We recommend continued reinforcement of the intended broad meaning of “broader impacts” and of the importance of attention to it with the ad-hoc reviewers, in an appropriate balance with the reviews of intellectual merit.

C. DOCUMENTATION AND COMMUNICATION WITH PIs

In an effort to reduce duplication and lower the high workload, most of the Program Directors began, in 2022, to use a reduced length format for the Review Analyses, including only what is necessary to explain the decision. There was general agreement that this has been working well. Some Program Directors continue to write longer analyses and the flexibility is appreciated.

In cases in which the proposal is declined, the majority of the Program Directors either proactively contact the PI or offer to have a follow-up phone conversation to explain the decision and provide advice for future submissions. This information is not always in the eJackets so it was difficult for us to determine how uniformly this approach was used other than through conversation.

4: SUGGESTION: We encourage the Division to consider options to document the practice of follow-up, particularly with declined proposals and first-time PIs, keeping in mind the impact of additional workload on the Program Directors.

5: SUGGESTION: The COV also discussed possible avenues for garnering wider input from the community on the review process, to augment the COV’s review of eJackets, but did not come to consensus on an approach. We do not offer a specific solution, but suggest that this be considered at the Division leadership level for future COV reviews.

D. BALANCE OF THE PORTFOLIO

The Division’s portfolio is diverse, and has connections across program areas, connections with other Divisions (within and beyond the MPS Directorate) and with other agencies. In areas that cross traditional disciplinary boundaries, the Program Directors are empowered to foster partnerships and share in funding proposals. We view this as a healthy practice, often to the benefit of the Division, as a means to supporting emerging areas. Examples include the now well-established program in the Physics of Living Systems (PoLS) in collaboration with the Directorate for Biological Sciences, and the Plasma Physics program, through a longstanding partnership with the Department of Energy (DOE) as well as through the cross-directorate ECLIPSE initiative. Connections across program areas within the Division support scientific agendas that have broad common thrusts approached through differing techniques. The new emphasis on Precision Measurements, which connects program areas that address fundamental questions in elementary particle physics through a variety of techniques, is a recent example. Notable successes from both approaches are identified in the subcommittee reports.

6: OBSERVATION: The COV's general sentiment was that we were not equipped, nor charged, to comment on the balance of the Division's portfolio across its program areas. We do, however, support the practice of ensuring that at least 50% of the Division's funding goes toward the research program (as opposed to facility operations and research infrastructure projects), as this largely supports the development of a strong scientific workforce at all levels.

E. LENGTH OF AWARDS

We were asked to consider whether the Division should use a four-year cycle as the "standard" award length. Advantages include a reduction in the number of new proposals the Program Directors would have to manage in any given year. It would also provide those PIs who work on long-term projects with more continuity, as well as reduce the time spent by PIs on writing and processing grant proposals. Some of the advantages of the three-year cycle are more nimbleness in fields in which directions change on a rapid timescale, and somewhat less sensitivity to fluctuating budget cycles. Even in some cases, a two-year award may be more appropriate where the science case is strong but the project itself is short-term.

The subcommittees considered this within the context of their program areas, and there was not uniform consensus as to what should be the "standard", although the general consensus was to retain the three-year cycle with discretion for varying the length of the award. All agreed that flexibility is very helpful, depending on the type of research, the size and scope of the proposal, or the level of experience of the PI(s).

7: SUGGESTION: In agreement with the 2019 COV recommendations, it is desirable for the different program areas to have some flexibility to adopt the length of cycle that best fits the proposal. If feasible, some language in the solicitation that informs the PI as to what's possible would be valuable.

We also note a few challenges. Firstly, partnerships require a strong set of relationships and a common willingness to create meaningful and substantive collaborations. Successes are often the result of individual Program Directors looking for opportunities to share resources to fund a promising agenda.

8: SUGGESTION: We encourage the Division and Directorate leadership to continue to proactively foster opportunities for collaboration, for example through joint convenings of relevant Program Directors, to support sustainable partnerships that can outlast the efforts of individuals.

The Division uses a variety of community and stakeholder advisory groups and reports to inform, but not solely determine, funding decisions. These include input from the long-range planning of cross-agency advisory groups in particle (HEPAP/P5) and nuclear (NSAC) physics as well as proposals in plasma physics that are jointly reviewed by NSF, NNSA, NASA and AFOSR. They also include decadal and specialized National Academies reports such as the 2022 Physics of Life consensus study report. Given the diversity of the portfolio, we find the approach of using the community surveys as guiding principles but not rigid roadmaps to be strategic and appropriate. However, with long-duration projects that cross agencies, there are risks of gaps (of funding or of scope) when a PI moves, for example, from a university setting to a national laboratory or when responsibility for a specific portion of the project changes. Gaps may also occur when agency priorities shift, which can be disruptive without a formal transition plan. Successful transitions, such as the handoff of the NSF-funded National Superconducting Cyclotron Laboratory to the DOE-funded Facility for Rare Isotope Beams, were years in planning and benefited from a formal transition plan and a Joint Oversight Group. An issue raised by the 2019 COV that has yet to be resolved is the development of a joint NSF-DOE strategy for university-based education and training in accelerator research and development. This issue is discussed further in the Plasma Physics subcommittee report.

9: SUGGESTION: For large projects that cross agency boundaries, early adoption of inter-agency MOUs combined with jointly held operations reviews with agreed-upon metrics can both mitigate the effects of transitions, as well as help PIs navigate the process. We recognize that this is often a strategy but were unsure whether this is a formal practice.

F. PARTICIPATION in MPS- and NSF-WIDE INITIATIVES

The Division has very successfully participated in NSF-wide initiatives, frequently with the PHY Program Directors providing leadership. This has clearly enhanced the Division's effectiveness in advancing the science under its portfolio. The Major Research Instrumentation program has enabled PHY PIs to lead scientific instrumentation projects, often in areas in which the NSF is not the primary funder. Several of the "Big Ideas" areas have greatly enhanced the scientific impact of the Physics Division's investments, most notably, but not limited to, Quantum Leap, Understanding the Rules of Life, and Windows on the Universe. As already noted in the 2019 COV report, the Division has very successfully leveraged Windows on the Universe to support a number of its programmatic priorities, especially in particle astrophysics and LIGO but also in other areas such as plasma physics, nuclear physics, and cosmology. For example, LIGO's extraordinary recent discoveries have stimulated a growth in interest by young scientists in gravitational and multi-messenger astrophysics which has been supported in part through Windows on the Universe.

The intended five-year horizon of the Big Ideas initiative is approaching. There have been some straightforward transitions, such as Quantum Leap into Quantum Information Science and Engineering Research. As noted by the 2019 COV, the financial burden on the core programs would be too significant to sustain the momentum produced by the other Big Ideas initiatives if they were to be terminated abruptly.

10: SUGGESTION: As the Big Ideas program reaches the end of its five-year window, we strongly encourage that every effort be made to minimize adverse impacts of its ending on projects and PIs that were initiated and supported through this initiative.

G. ALIGNMENT WITH NSF-WIDE PRIORITIES

The COV's review of this charge element focused on the three pillars of the Director: "Advancing the Frontiers of Research into the Future", "Ensuring Accessibility and Inclusivity", and "Securing Global Leadership." Of these, the COV's discussions focused mostly on the second pillar and the Division's role in broadening participation and in fostering a culture of inclusion through its funding priorities.

There is no question that the Division's programmatic support has had a major impact on advancing scientific frontiers. The U.S. Physics community has a recognized position of global leadership in many areas, evidenced by the continued high demand for entry into U.S. graduate programs by international students. This is in no small part due to the excellent stewardship of the resources provided. Of particular importance is the Division's support in areas in which the NSF is the primary funder in the physics community, such as with LIGO. In areas in which the NSF is not the primary funder, the Division's approach has been to support research, projects, and PIs that would establish a well-defined and often leadership role.

Also in alignment with NSF-wide priorities, the Physics Division has provided leadership in supporting diversity, equity, and inclusion in the physics community, although the community as a whole has more progress to make. The Division's leadership has been, appropriately, through its funding priorities and collection of demographic information to the extent that privacy concerns allow. Examples include efforts to diversify the reviewer base and the makeup of review panels, and the creation of a local supplement program (PHY-GRS) that mirrors the NSF-wide AGEP-GRS program. As another example, the recent MPSAC review of the Physics Frontiers Centers identified the need for a more robust and coherent approach to addressing their collective diversity and outreach missions. The Division responded with higher expectations in the proposals, and with the establishment of the Partnerships for Research and Education in Physics (PREP) companion program. While it is too soon to know the impact of PREP, this initiative is well aligned with NSF-wide priorities. Program Directors in several of the other program areas have routinely supported efforts to bring the community of PIs along towards these goals, through funding for mentoring networks, undergraduate research, outreach activities, as well as community building in the professional societies (such as APS). Co-funding through the Integrative Activities Program has been important in stimulating these efforts. The IAP subcommittee has recommended that there be a clearer articulation of the intent of IAP, beyond the language that it is the home of proposals "that do not easily fall within any of the primary disciplinary areas". For example, IAP could be the central point of contact for curation of evidence-based best practices that can be implemented in physics and for identifying connections to relevant areas of research in the Education and Social and Behavioral Sciences.

11: RECOMMENDATION: In alignment with NSF goal #2, we encourage the Division leadership to consider avenues for more coherence between IAP's portfolio and efforts within the science program areas to support the fostering of an inclusive community at all levels of participation, as well as to better align the language describing IAP with the initiatives it supports.

12: OBSERVATION: Towards the end of our meeting, we learned of the December 2022 "GRANTED" initiative. While it is too early for our COV to provide substantive comments, we view the strengthening of the research infrastructure, particularly among universities with emerging research aspirations, as an important support effort to lower barriers to participation, and we look forward to learning more about the initiative as it unfolds.

H. COV PROCESS

The hybrid approach to the COV process, with virtual meetings prior to the in-person convening, was efficient and allowed time for thoughtful discussion and preparation for a Division-wide conversation. As noted above, the subcommittee reports contain a number of suggestions and recommendations the we hope will be useful to the Program Directors moving forward. We will have some minor process suggestions for the Division to consider for future COVs, and will convey them separately to the Division Director.

III. Reports of the Subcommittees

A. Atomic, Molecular and Optical Physics / Quantum Information Science

1. Introduction

The AMO/QIS Subcommittee of the 2023 Committee of Visitors reviewed three programs, as was the case in the previous (2019) report. These were: Experimental Atomic, Molecular, and Optical Physics (AMO-E), AMO theory (AMO-T), and Quantum Information Science (QIS). Currently this suite of PHY programs is overseen by two permanent and two IPA program directors. This group works as a highly effective team, each helping to oversee the *ad hoc/*panel review system for the programs, and recommending funding, but each is also heavily involved in numerous cross-cutting, division- and foundation-wide, as well as interagency initiatives that have important connections and implications for the three programs. Examples include staffing the FY21 panel for the MPS-LEAPS program, and the FY21 and FY22 interdisciplinary Precision Measurement panels. In terms of true FTE available to run the three programs themselves, we would argue that the current number of 'effective FTE' is substantially less than four. Staffing pressure concerns are further addressed below.

These three programs support an exciting and diverse portfolio of cutting-edge science, pushing the boundaries of knowledge, helping to develop new experimental and theoretical techniques, investing heavily in the research-training of the next generation of scientists, and working to promote diversity and broaden participation at all levels, from PIs to undergraduates.

In this report we briefly review the science and a few recent highlights covered by these programs, assess the proposal review process, and consider specific recommendations and comments made in previous reports, adding our own assessments and recommendations at the end. The work of the COV subcommittee so far has included the initial opening all-hands meeting in December, the subcommittee chair meeting (attended by Tiku Majumder), a long and productive meeting/discussion with the AMO/QIS programs staff, followed by extensive further discussion amongst the four members of our subcommittee. We have had the opportunity to read and study the previous COV report, 2019-2022 program updates, as well as a selection of proposals from each program available through eJacket, allowing us to trace the review process from the original submitted proposal to *ad hoc* reviews, to panel summaries, to review analyses by the program directors - all for a variety of proposal types, sizes, and outcomes. In addition to our discussion, we have read materials prepared by the division as well as the program staff within our subcommittee area.

Finally, we wish to point to two primary areas of focus for us during this COV cycle, which are expanded upon below. These are: (1) the opportunities and challenges for the PHY/QIS program as it navigates its future in the broader context of various division and foundation-wide initiatives in the general area of "Quantum Information Science and Engineering (QISE)" in the new landscape of the "National Quantum Initiative". These considerations have both funding and staffing implications; and also (2) the successful example provided by the recent Precision Measurement Dear Colleague Letter which identified a rapidly growing and highly interdisciplinary science objective, leveraging creative new ideas (at the PI/proposal level), and leveraging broad expertise in the form of a highly interdisciplinary panel, to evaluate, rank, and ultimately support a number of exciting new projects funded for both FY21 and FY22 which for budgetary and structural reasons may not have been able to be supported without the presence of this new initiative.

2. Highlights and Discussion of supported research, 2019-2022

COVID Statement. We wish to acknowledge the significant impact that COVID has in the form of research disruption, lab access restrictions, and health concerns. This has certainly negatively impacted research productivity during this COV review cycle, especially during FY21 and FY22. No doubt different sub-disciplines (*e.g.* theory vs. experiment) and different types of institutions (*e.g.* small colleges vs. R1 institutions) have experienced different types and degrees of challenges. Unsurprisingly, the programs discussed here experienced an overall reduction in new proposal submission during one or more of the fiscal years under review. Our group agrees that it makes no sense to extrapolate trends from a situation that (one hopes) has been uniquely disruptive, and we simply acknowledge the hard work of the foundation and its program staff to support the ongoing research of its PIs throughout this period.

2.1 Demographics of supported PIs and Institutions. Beyond the extensive overlap among the three programs discussed here, which routinely requires close collaboration and teamwork among the group of AMO/QIS program directors, there was significant participation in initiatives and programs that reached across programs and divisions. For example, with increased focus on DEI issues and representation in the list of NSF-supported scientists and institutions, the AMO/QIS programs participated in the PHY-GRS, AGEP-GRS, LEAPS, ASCEND, and ExpandQISE programs among others.

Collecting robust statistics regarding demographics of awards is always challenging, due in part to small numbers and the choice of some PIs not to self-declare racial/ethnic/gender status. Looking across the three programs, it appears that while the percentages of women and underrepresented minority PIs remains small, the funding rate for URM and female-identifying PIs is at or above those for the majority population.

Similarly, again using the AMO-E program within the 2019-2022 window as an example, while the number of proposals coming from minority serving institutions (MSI) and primarily undergraduate institutions (PUI) was small, the award rates were comparable to overall average rates in each case.

2.2 The CAREER program within AMO/QIS programs and the PHY division. The quality of the proposals to the CAREER Award program remains very high. In the NSF's own words this program is "a Foundation-wide activity that offers the National Science Foundation's most prestigious awards in support of early-career faculty". It is the consensus of our group that at the university/college level scientists and administrators alike broadly subscribe to this interpretation. Our sense is that the PHY division view – that CAREER is unique for its focus on educational components more than its intrinsic 'prestige' – is somewhat in tension with this broader view. We feel that the division should seek to reconcile these somewhat different interpretations. Overall, however, we applaud our program directors for their attention to supporting and funding young PIs through either CAREER or standard proposals.

Also, it is our sense that CAREER proposals are not routinely evaluated alongside standard proposals in review panels. In contrast, RUI proposals, which also come from a cross-cutting program and are at least somewhat distinct in their focus and evaluation, are routinely included in 'standard' panel evaluations. We wonder whether CAREER proposals in the relevant program areas covered here might benefit from panel consideration as well.

2.3 Precision Measurement Panels. As can be seen from the pie chart in Sec. 2.4 below (Fig. 1), Precision Measurement continues to be one of the most important components of the science supported by the AMO-E program (in fact the fraction of the 'pie' represented by these projects has increased from 21 to 27% in the time period since the last COV report). Historically these projects have contributed to important new results and insights into physics that are often far beyond the boundaries of atomic and molecular systems. Equally important, this work has produced a rich array of new techniques and technology in the realm of measurement science that have found applications very broadly in other science and engineering disciplines. Finally, these challenging experimental projects, which remain at the 'table-top' scale, require mastery of wide-ranging skills, including important aspects of theory and modeling, and have provided excellent research-training opportunities for large numbers of post-docs, graduate students and undergraduates over many years.

In September 2020, a division-wide Dear Colleague Letter (DCL) invited proposals focused on the experimental science at the intersection between AMO and EPP. The DCL was updated for the following fiscal year as well. The goal has been to "encourage interdisciplinary research across the domains of AMO and EPP physics aimed at developing new small-scale experiments and techniques that could complement large EPP facilities." More than 2/3 of the proposals submitted with the 'PM:' acronym came initially through AMO-E. The panels that have been assembled to read, evaluate, and rank these proposals in FY21 and FY22 were notably diverse, including both theorists and experimentalists, and AMO as well as elementary particle physicists.

The enthusiastic response to this DCL, the outstanding new scientific projects that have emerged from it, and the assembly of a highly diverse, interdisciplinary panel to review the proposed work all appear to represent a notable success. Furthermore, we feel that the thrust of this effort – to develop and carry out new experimental searches for physics beyond the Standard Model using table-top-scale techniques – will continue to produce important new experimental techniques and continue to constrain and guide models of beyond-standard model physics in the years ahead. Whether in its current annually updated 'DCL' form, or perhaps in the form of some more established entity with the physics division, we strongly recommend the continuation of this AMO/EPP intersectional effort. It should further be seen as a model of the very best kind of division-wide interdisciplinary activity, which we hope might encourage creative thought about similar endeavors in the future

2.4 Further details of AMO-Experiment program

2.4.1 General Comments

- We wish to note that John Gillaspy spent roughly 50% of his time during this cycle focused on activities outside of AMO-E program *per se*. These included QUANTUM LEAP working group, and the heavy AMO-E presence in the funding of several Physics Frontier Centers.

- The base budgets for the AMO-E program were relatively flat for the past four fiscal years. As noted, in FY21 and FY22 this was supplemented by the PM panel / DCL initiative which represented notable increases in the available budget to fund AMO-E proposals for those years.
- AMO-E traditionally supports work in five sub-fields: Precision Measurements (as discussed above), Cold Atoms and Molecules, Quantum Optics and Photonics, Ultrafast/Strong-field physics, and Structure/Collisions. Figure 1 shows the distribution of funded projects since the last COV. Since the 2019 report, the 'slices of the pie' from both Precision Measurements and Cold Atoms and Molecules have increased, while that from Quantum Optics has decreased (we note, of course, that this is only a partial picture as various interdisciplinary and cross-program/cross-division initiatives may well have drawn some AMO-E related proposals in other directions).

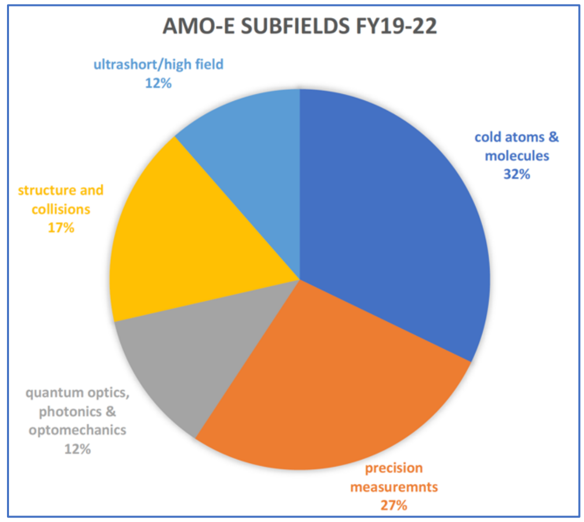

Fig. 1: distribution of funding to the five sub-fields of AMO-E over the past four fiscal years.

- Of the research programs currently funded through AMO-E, only a few are funded at a level greater than $300K/yr. The multi-institution ACME project, which continues to improve limits on the size of the electron's permanent electric dipole moment, and provide ever-tighter constraints on beyond-standard-model physics is notable for its large funding level, perhaps unique in the recent history of this program. We believe the expenditure is justified based on the productivity of the science, its intellectual merit, and its broader impacts (both impact across physics disciplines, and in terms of broadening participation and training). The great majority of funded proposals in AMO-E were supported at the $100K/yr to $200K/yr level. We feel that this balance and distribution is appropriate to support the breadth of excellent science and research-training that is happening throughout the AMO community.
- Another notable feature of the AMO-E/AMO-T programs is a long history of supporting research and research-training of undergraduates and small-college PIs, through the RUI cross-cutting program, a natural fit in many ways due the small physical scale and accessibility of the research. Of all RUI awards made in the 2019-2022 period throughout the Physics Division, more than 25% were made within these two programs alone (30 awards in all).

2.4.2 Examples of science supported by AMO-E program during this COV cycle.

We note that all of the examples shared here have in common that the reach and relevance of the work extends beyond the AMO regime to areas such as QIS, Chemical Physics, Nuclear Physics, and Particle Physics.

- The group of Dr. Gerald Gabrielse has recently reported a new measurement of the electron's g-factor which is a factor of two more precise and uses a newly constructed apparatus at Northwestern

Univ. [Phys. Rev. Lett. 130, 071801 (2023)]. The result agrees with theoretical predictions at the astonishing sub-part-per-trillion level, and when an ongoing discrepancy in the independently-measured fine structure constant is resolved, this g-factor measurement will be able to improve the test of the Standard Model and 'CPT' theorem by an order of magnitude. Such a result is particularly notable given the recent result from the nuclear physics community of the analogous anomalous g-factor value for the muon whose measured ratio to that of the electron differs significantly from theory.

- At Stanford, Dr. Monica Schleier-Smith's group is creating highly-entangled programmable networks of cold, interacting Rb atoms to create analogies to the kind of complex geometries that emerge from quantum gravity and space-time warping [Nature 600, 630-635 (2021)].
- Dr. Kang-Kuen Ni's group at Harvard has been involved in a series of pioneering experiments to produce ultracold arrays of molecules with applications ranging from ultracold chemistry to quantum simulations and quantum information processing. Recently Ni and her collaborators, including Norman Yao at Berkeley, published a paper describing an exciting scheme to "Enrich the quantum toolbox of ultracold molecules with Rydberg atoms" which would leverage the large transition dipole moments of Rydberg atoms to mediate qubits encoded in the molecules' coherent degrees of freedom [PRX Quantum 3, 303039 (2022)].
- Dr. Holger Mueller's group at UC Berkeley recently set a new 'world's record' demonstrating that a spatially separated atomic wavefunction that persisted for first 20 seconds [Science, 366, 746 (2019)], and then for one full minute [arXiv:2210.07289], making use of small-scale optical lattices for storage (in contrast to the traditional atomic fountain approach which limits coherence to a few seconds due to time of flight) (see Figure 2). The small scale of the apparatus makes it less sensitive to potential inhomogeneities in electromagnetic and gravitational fields, yielding the possibility of a new generation of precision measurement / quantum sensing experiments to study gravimetry, and beyond-standard-model (BSM) physics.
- The use of cold atom systems to simulate other systems of interest - quantum simulation - is a particular focus of AMO physics at present. The group of Dr. Randy Hulet at Rice University has created a 1D 'wire' of cold fermions (Li-6 atoms), realizing the predictions of the 60-yr-old Tomonaga-Luttinger (L-T) liquid theory, for the first time in a simple, well-characterized gas-phase system with tunable interactions [Science 366, 1305 (2022)]. An unusual prediction of this model is that the elementary excitations are collective charge and spin density fluctuations with bosonic character and which propagate at different velocities, leading to a separation of spin and charge. The work has allowed the nearly-exact L-T theory of this system to be compared to experimental results. A long-term goal of the group is to simulate a kind of 1D superconductor with these atoms that can support Majorana fermions, which, in turn, are a possible avenue to harnessing topological qubits for quantum computation.

2.5 Examples of science supported by AMO-Theory program during this COV cycle

The AMO Theory program supports research in five often interrelated subfields, Cold Atoms and Molecules, Precision Measurements, Ultrafast and Strong Field, Collisions and Spectra, and Quantum Optics and Photonics, along with an NSF Focused Research Hub in Theoretical Physics, ITAMP at Harvard. Work supported is often interdisciplinary and is connected to other programs, notably AMO Experiment, QIS, plasma science, astrophysics, and the NSF-wide priorities QISE and Quantum Leap.

Proposals considered and awarded span not only a wide range of phenomena and interconnections with applications but also an appropriately broad geographic and demographic range (e.g., institution type, PI diversity, and proposal area). Examples of this wide range of leading-edge research areas and project team demographics are the work of funded PIs Ana Asenjo-Garcia (Columbia University) and Kaden Hazzard (Rice University).

- Dr. Asenjo-Garcia's research group seeks to understand strongly interacting atoms and photons and to apply these phenomena in quantum information science, sensing, and metrology. In recent work supported by AMO-T a framework was developed allowing determination of the critical distance beyond which the emergence of macroscopic quantum coherence via correlated dissipation disappears [Physical Review Research 4, 023207 (2022); Nature Communications 13, 2285 (2022)]. Predictions from this framework can be tested experimentally using arrays of neutral atoms, molecules, or solid-state emitters and can lead to new understanding of the role of many-body physics in quantum simulation, metrology and lasing.
- Kaden Hazzard's research group studies ultracold atoms and their use in quantum simulation of condensed matter systems. As reported in Nature Physics [doi:10.1038/s41567-022-01725-6 (2022)], Dr. Hazzard and collaborators in the U.S. and Japan used ultracold atom simulations to treat an unexplored regime of quantum magnetism. In this study the comparison of theory and experiment inferred a record low temperature for such a cold-atom simulation. It led to a novel observation of antiferromagnetic correlations in an ultracold Hubbard model of a Mott insulator, a prototype condensed matter system with strongly correlated physics.

2.6 Further Details of the QIS program

2.6.1 General comments

Quantum information is an emerging, indeed disruptive field with a rapidly growing footprint both within and beyond physics during the review period. Truly addressing QISE is an endeavor bigger in scope than any program, division, or indeed directorate, and NSF is doing a good job of recognizing this in its programming. Federal funding for QISE encompasses a yet broader ecosystem, so a further important activity of NSF is to help ensure cross-agency synergy in alignment with the National Quantum Initiative (NQI). In this landscape of expanding activity and opportunity, the onus falls, in practice, onto program directors to handle a number of cross-cutting initiatives that are in their wheelhouse yet outside their bailiwick. The upcoming addition of the new TIP Directorate may add layers to this already complex picture.

Program directors in the AMO/QIS area have experienced a particularly high workload in this time period, when collaborators from other fields have often looked to AMO scientists as those with "longstanding" perspective on QISE. At least on the few-year time scale, this has created a situation in which the time spent by AMO PDs on cross-cutting QISE initiatives, such as the Quantum Leap Challenge Institutes, is outsized even compared to the fraction of the QISE funding that is going to research by the AMO community. At the same time, AMO-related advances continue to be essential drivers of innovation in quantum information technology and essential sources of basic science discovery in the field.

Within the growing ecosystem of federal and even NSF-specific funding for QISE, the QIS program itself continues to fill an important role in supporting current scientific advances as well as ensuring a stable platform for future growth through education and workforce development. As we note below, QIS funds science with direct application to developing capacity for quantum technology, as well as fundamental science whose near-term impacts lie primarily within physics (e.g., quantum simulation, quantum thermodynamics, fundamentals of entanglement). Relative to some of the other programs currently funding QISE within Physics, the QIS program also provides an important funding opportunity for single-investigator research projects.

As noted elsewhere in this report, we recommend that NSF consider addressing this situation with additional staffing in the AMO/QIS programs and additional measures to ensure continuity in staffing. QISE programming at NSF would clearly benefit from an increased number of program directors beyond PHY and even beyond MPS who have interests and expertise in quantum information; though this recommendation may be beyond the specific purview of this COV, we feel such change could increase the effectiveness of partnerships in which the AMO/QIS program directors are involved.

Overall, we applaud the vision and dedication of the AMO/QIS staff to the intrinsically interdisciplinary nature of QISE, and their ongoing efforts to create robust structures within the Foundation to support the National Quantum Initiative.

2.6.2 Examples of science supported by the QIS program during this COV review cycle

The QIS program has funded a rich variety of research in the 2019-2022 review period. Funded research includes important progress in quantum computing on platforms that originate in both atomic and condensed matter physics (trapped ions, superconducting qubits, quantum dots, neutral atom arrays, color centers and other defects in solid state); fundamentals of quantum science including quantum resource theory, entanglement classification and measurement, quantum tomography, entanglement generation and entanglement swapping; advances in quantum error correction, algorithms, and gates; quantum optics and hybrid quantum systems for quantum information applications; quantum sensing, and much more. To name just a few examples:

- In a landmark result in quantum computing, PI Chris Monroe's group and collaborators demonstrated the first experimental demonstration of fault-tolerant control of an error-corrected qubit in the presence of native noise [Nature 598, 281 (2021)]. The notion of fault tolerance hinges on a physical qubit performance threshold, above which adding quantum error correction resources improves noise reduction whereas it only adds noise when below the fault tolerance threshold. The physical implementation of the logical qubits was done over 13 trapped-ion physical qubits. (NSF support for this work came through PFCQC:STAQ in the PIF program, exemplifying the breadth and connectivity of programmatic activity in this area.)

- PI Ana Maria Rey and her team demonstrated quantum-enhanced sensing of displacements and electric fields with two-dimensional trapped-ion crystals [Science 373, 673-678 (2021)]. The team, in collaboration with John Bollinger's group at NIST, realized a many-body quantum-enhanced sensor to detect displacements and electric fields using a crystal of 150 trapped ions. The center-of-mass vibrational mode of the crystal serves as a high-Q mechanical oscillator, and the collective electronic spin serves as the measurement device. High sensitivity is achieved by entangling the oscillator and collective spin and controlling the coherent dynamics via a many-body echo, while avoiding quantum back-action and thermal noise. This enhanced sensitivity may find applications in dark matter searches and gravitational wave detection.
- PI Marlan Scully and collaborators provided quantum optical explanations for acceleration radiation of an atom falling into a black hole, Bose-Einstein condensation, and entangled photon pairs in Unruh, Hawking, and Cherenkov radiation [Phys. Rev D 104, 084086 (2021), Physical Review Research 4, 033010 (2022), and J. Low Temp. Phys. 208, 160 (2022)]. They showed that uniformly accelerated atoms in Minkowski space, and atoms held above a black hole event horizon, will both emit entangled photon pairs in a squeezed state, providing new insight into the principle of equivalence between acceleration and gravity.
- PI Alicia Kollar investigated the impact of negative curvature on observables of a hybrid system consisting of qubits and photons on a hyperbolic lattice, and showed that interactions between qubits are mediated by photons propagating along geodesics [Phys. Rev. Lett. 128, 013601 (2022)]. Circuit QED is one of the most promising platforms for efficient quantum simulation and computation; this work may open the door to the possibility of engineering a quantum simulator of the AdS-CFT correspondence.
- PI Mark Saffman's team demonstrated multi-qubit entanglement and algorithms on a neutral-atom quantum computer [Nature 604, 457 (2022)]. To quote a popular press release by ColdQuanta, "The team is the first in the world to demonstrate quantum algorithms on a programmable gate model cold atom quantum computer. … These results highlight the highly scalable capability of cold atom qubit arrays for universal, programmable quantum computation, as well as preparation of non-classical states of use for quantum enhanced sensing."
- PIs Michael Raymer, Andrew Marcus, and Brian Smith demonstrated in a series of prototype experimental studies that entanglement of photons in the time-frequency domain provides a significant quantum advantage in newly proposed schemes in nonlinear spectroscopy and metrology. This research elucidates the conditions under which useful spectroscopic signals can be acquired using entangled-photon pairs, given the extremely small two-photon-absorption cross sections in typical molecules and the limited rates of delivering entangled-photon pairs into a sample. [Optica 8, 757 (2021); Optics Express 29, 20022 (2021); Phys. Rev. Research 3, 033154 (2021)].

These highlights illustrate the impact of QIS-funded science both in direct application to the quantum information industry and in connection to multiple areas of fundamental physics and other sciences.

The QIS program also supports two Focused Research Hubs in Theoretical Physics (FRHTP): the Center for Quantum Information and Computing (CQuIC) located at the University of New Mexico.

3. Comments on the Proposal Review Process and related matters

It is our strong consensus that the review process as currently operating in our programs adheres to the best practices of the Merit review process, and works effectively to rank and identify the strongest proposals based on both Intellectual Merit and Broader Impacts. Our sense that the overall process of several *ad hoc* reviews informing independent panel analysis and summary which in turn informs the program director's analysis and final funding decisions is working very well.

(i) ***Ad hoc* vs panel reviews.** The existing practice of utilizing both *ad hoc* reviews followed by panel review continues to yield a fair and thorough review of proposals and should be maintained. During this COV evaluation period, COVID disruptions no doubt provided challenges in obtaining as many ad hoc reviews as in past years. Nevertheless, even with the inclusion of two to three ad hoc reviews, sufficient and complementary expertise provided by panel members has allowed the overall process to remain robust and highly effective. Going forward, we would suggest working on strategies to insure a minimum of three ad hoc reviews prior to panel consideration. We feel that while occasional *ad hoc* reviews fall short of expectations in terms of number received, of depth of analysis, and/or explicit discussion of all of the review criteria, that between the sum of the *ad hoc* review and panel discussion and analysis there is appropriate attention and analysis of the proposals in the context of all review criteria. We felt that the review analysis (RA) narratives were informative, thorough, and appropriate. In 2022, upon adoption of the new, shorter RA form guidelines, we found those most recent RA's to be sufficiently detailed and often seemed indistinguishable from those from previous years in terms of length and depth. To the extent that is saving time, we support the continued use of the new form.

(ii) **Deadlines.** The existing procedure in which proposals to these programs are due upon an annual deadline, as opposed to being considered in "batches" throughout the year, has both relative strengths and weaknesses. For example, a weakness is that with a deadline there is pressure to complete a proposal with perhaps insufficient preliminary data or preparation. A strength is that all the proposals in a given cycle are reviewed at the same time by a single panel and therefore intercompared well. On balance, we recommend maintaining the procedure of review upon a single deadline. In this case, the staff might consider pushing the AMO deadlines into December to coincide with the current QIS deadline.

(iii) **Grant proposal length.** A discussion of whether to 'normalize' the length of grants in these programs to 5 years was documented in the previous COV report. The previous recommendation seems to support adopting 5 years as a default standard, but also recognized that the flexibility to entertain other durations should remain with the PDs of each program. We worry that transitioning suddenly to a 'new normal' will be difficult (as evidenced by the lack of longer proposals submitted in 2019-2022, even when this possibility was advertised) and may require a transitional period and more intentionality in making change happen.

Our consensus is that we do support the implementation of a longer 'standard' grant period both for scientific reasons (allowing PIs, especially in certain sub-fields, to pursue even more ambitious research goals…), but also because this would result in real workload reduction for the community of reviewers, panelists, and program directors.

At the same, we recognize the importance of flexibility. There may be excellent reasons why, for example, a precision measurements proposal might be ideally suited to a 4 or 5- year grant period, while other subfields and programs (for example, many AMO-T proposals) might appropriately remain at their now-typical 3-year length. Also, we acknowledge that for first-time grantees, there may be good reasons to maintain the heretofore 'standard' 3-year grant period (of course, this would not be relevant for early-career PIs who earn 5-year CAREER awards). For these younger PIs, in subsequent funding cycles, consideration could then be given to moving to a longer 'standard' grant cycle.

Ultimately, we recommend that the program directors pursue ideas that would help to normalize the longer grant period proposals within the communities, while retaining flexibility to encourage appropriate grant lengths for particular proposals or types of proposals. We feel this will require both a transitional period (for example with judicious use of supplements in the short term) and will certainly require better communication in solicitations to PIs and instructions to reviewers and panelists to help normalize the writing and reviewing process for grant requests of more than 3 years. The goal would be to ensure that fair and appropriate consideration be given to all proposals where a longer grant period request would not *per se* be seen as a negative factor in reviews. Having outlined a possible future goal of normalizing longer proposal periods in some cases, we leave it up to the Program Directors to explore the best possible path in this direction.

(iv) **Funding for success.** A question was raised about the current approach of 'funding for success', a policy to avoid trimming budgets to the point when the proposed science could no longer realistically be accomplished. We believe this is empowering, especially to junior PIs, and ought to be continued. This of course does not preclude budget reductions where the panel and program directors feel that only part of the proposed work is worthy of support, or if it is determined that the resources requested are greater than what is necessary to achieve the scientific goals.

4. Staffing pressures and concerns

In the absence of roles and assignments in other worthwhile NSF programs, staffing seems adequate, but given that these other roles and assignments take a very substantial fraction of their time, it is essential to provide additional support. Ideally this might be through the addition of permanent staff (which we understand is likely to remain a challenge given needs for additional permanent staff across NSF), or it might continue to be addressed through rotators and expert temporary staff. In any case, it is critically important to ensure continuity through the inevitable turn-over of all of these permanent and temporary staff positions.

This was noted in the previous COV report and was implicitly addressed through temporary positions. We strongly recommend that one additional rotator, primarily focused on work in the QIS program, be added to the staff. As noted elsewhere in this report, we feel that the particular challenges around involvement beyond the program in important division- and foundation-wide initiatives in this high-profile area make additional staffing here a key priority. Since the group of AMOE/AMOT/QIS staff work exceedingly well as a team, additional rotator staff would be very well positioned to share duties within the programs (as is traditionally expected, and justifiably so, of program managers in the Physics Division), but also provide important contributions to other extra-program initiatives, such as the aforementioned precision measurement DCL panel.

5. Responses to the 2019 AMO/QIS subcommittee recommendations

(i) **"QIS should integrate with Quantum Leap"** – there has been significant growth and reorganization of initiatives in this general area of science and engineering, requiring inter-program, inter-division, and even inter-agency consideration at the highest levels. As such a clear understanding as to how the PHY QIS program will fit into this landscape (as noted above) has yet to emerge.

(ii) "**Standard 5-year grants**" – addressed above in section 3.

(iii) **"Staffing levels for AMO/QIS programs"** – as discussed above the current status quo seems to be three permanent staff plus rotators and in some cases temporary appointment of experienced experts. Given the growing workload beyond management of the three programs, it seems that continued efforts should be made to pursue an additional permanent hire, or at a minimum temporary staff hired in a way that maximizes overlap and continuity.

6. Summary of 2023 recommendations

Each of the items listed below have been discussed in the text above. We reiterate the principal recommendations here:

R1. We strongly advocate for the addition of one new staff member to the AMO/QIS 'team' of permanent staff and rotators. We further suggest that the expertise and focus of the additional staff member be in the area of Quantum Information Science. Especially given the important role that Alex Cronin is playing in a number of broader working groups which are considering QISE-related initiatives, the additional support of an individual with QIS expertise (but who could also contribute at key moments to AMO-E and/or AMO-T program work) seems essential.

R2. We recommend restating and clarifying instructions regarding standard duration of grants, and communicating expectations and options more clearly with both PIs and reviewers, with the overall goal of normalizing the use of longer grant periods in these programs. For example, we suggest a plan in which each program should determine the standard duration but also be willing to consider other durations without bias in review, recognizing that some subfields would benefit, in terms of long-term science productivity, with a 4 or 5-year grant length. The precision measurement (PM) sub-field might be a particular example of this. We also recommend considering retaining the shorter 3-yr grant cycle length for first-time grantees.

R3. We recommend that the division more broadly consider the way in which the CAREER Award is viewed and assessed which strongly differs from the perception in other Directorates within the Foundation, and in higher-Ed institutions more broadly, where CAREER awards are seen as NSF's flagship early career award.

R4. We believe the success of the Precision Measurement DCL initiative can be a model for other interdisciplinary efforts with our (or other) PHY programs. Cross-cutting, interdisciplinary efforts such as this have long been an emphasis in the Foundation. Can new emerging scientific questions be identified that can expand from this successful example? Also, since we feel that the scientific questions, and cutting-edge experimental techniques at the core of the PM DCL are 'here to stay', we suggest that the programs involved with the PM initiative consider how to make this effort more permanent than simply annual calls for proposals through the DCL mechanism.

B. Experimental Particle Physics / Large Hadron Collider

Executive Summary

The Experimental Particle Physics (EPP) program supports experimental particle physics research that studies the properties and interactions of elementary particles, including searches for possible new particles and forces that would lead to breakthroughs not only in our understanding of particle physics, but also of cosmology, astrophysics and beyond. Progress in particle physics is closely coupled with advances in accelerator, computing, and detector technologies, and has driven important progress in those areas. The experiments and research groups supported by EPP have provided an excellent training ground for students and postdoctoral scientists, developing expertise in forefront technology and data analysis with many possible applications beyond particle physics, to the benefit of the society as a whole.

EPP has prioritized support for the Large Hadron Collider (LHC) program at the energy frontier including the research of university groups on the ATLAS, CMS, and LHCb experiments, as well as the operations and upgrades of these experiments including support of NSF MREFC of ATLAS and CMS High Luminosity LHC (HL-LHC) upgrades. Many properties of the Higgs boson, discovered only ten years ago, are now precisely known with even more accurate measurements expected. LHC measurements provide clues concerning where new particles and interactions might be found as well as precisely measure the properties of known elementary particles and their interactions.

EPP provides strong support to the U.S. neutrino program for the short-- and long--baseline programs, to perform precision measurements of the most elusive and least known elementary particle. The DUNE program holds the promise of making key measurements of the oscillation parameters associated with neutrino mixing and has the capability to perform a definitive search for charge-parity violation in the neutrino sector. In addition, the very large DUNE detectors will expand the sensitivity to supernova detection and proton decay.

EPP supports a modest, while very productive, suite of smaller experiments, including Belle II, which diversifies the portfolio and provides an opportunity for NSF PIs to participate in a wide range of activities in the field.

EPP is responsive in addressing national priorities, including AI/ML and quantum information science, as well as working to develop an inclusive and diverse scientific workforce of the future.

The COVID pandemic, over the past three years, provided major challenges to federally supported research programs, and the EPP program was not immune from such effects. EPP did their best to minimize impacts of the pandemic and preserve and develop exciting science programs.

With particle physics planning in the US for the next decade and beyond progressing, including P5 prioritization, the field is ripe for developing an exciting program and EPP is expected to play a major role in the future of the field.

I. Quality and Efficacy of the Proposal Review Process

1. Appropriateness of the Review Methods

An unbiased and thorough review of proposals for funding by the NSF is critical for the integrity of the program. Merit review of proposals take the form of ad-hoc reviews solicited from content-area experts, as well as reviews from a panel of peers gathered for the purpose of discussing both panel members' reviews and solicited ad-hoc reviews. Each of these elements is critical to the quality of the assessment of each proposal. As a panel of reviewers is necessarily limited in size, it is possible that specific expertise that would be helpful in evaluating a given proposal isn't found among the limited number of reviewers on the panel. Hence, ad-hoc reviews enable that additional expertise to be brought into the overall evaluation. The panel reviews and deliberations at the panel meetings bring the important element of comparative review and multiplicity of perspective that is essential for the overall process of evaluation of each proposal coming before the NSF.

With the wisdom gleaned from the panel and ad-hoc reviews, Program Directors (PDs) are then well equipped to carry out one of their principal responsibilities: allocation of program funds to those proposals deemed by the reviewers to be most worthy of funding. This deliberate, well-designed process has, in this four-year period under review, been undertaken with great care, transparency, and integrity.

2. Merit Review Criteria

Panel and ad-hoc reviewers are asked to evaluate proposals based on two major review criteria - Intellectual Merit and Broader Impacts. The definitions of these review criteria, and the five elements by which proposals are to be evaluated in terms of these criteria, are spelled out in documents such as the Proposal and Award Policies and Procedures Guide and provided on the NSF website. When reviewers are sought, and when panels are assembled for discussion, these review criteria and the evaluation elements are presented and discussed, reminding panelists and reviewers of their responsibility to undertake their work with these in the forefront of their minds.

The panel and ad-hoc reviews made a thorough assessment of both review criteria. In every case, most reviewers gave appropriate levels of detail in their reasoning for evaluating proposals. There were a few cases of reviews in which the reviewer failed to make separate evaluations of Intellectual Merit and Broader Impacts, but only gave a paragraph or two of summative comments. These seemed to be outliers, so we recommend no action for these few cases, while reaffirm the need for the reviewers to be strongly reminded of the requirements that they evaluate both review criteria and give substantive comments regarding each.

3. Comments from Individual Reviewers

As noted above, for the most part the ad-hoc reviews evaluated proposals in a substantive manner, and gave thorough descriptions of their assessment according to each of the review criteria. The recommendation that reviewers give, both summative and formative commentary in their reviews, is followed. It is important that the formative statements regarding potential improvements to the text of proposals continue to make their way into the panel summaries, to improve the experience of and success of PIs for both declined and awarded proposals.

4. Quality of Panel Summaries and Clarity of Consensus

Panel summaries are generally excellent summaries of the reviews and the subsequent discussions in the panel and reflect the consensus of the panel and reviewers well. The summaries are particularly useful for PIs when a panel summary includes specific recommendations or calls out commonly observed weaknesses or strengths in the proposal, and many summaries did include such advice or commentary.

In a few cases, the panel summary was brief, even if it did accurately reflect the comments made by individual reviewers. This is not particularly helpful to PIs, whether their proposals are funded. More details would help PIs to make sense of the evaluation of their proposals.

It is also important that the panel summary, since it is written at the end of the panel meeting when final rankings of proposals have been completed, be written in such a way as the PI can understand the consensus of the panel and make sense of the final evaluation of the panel's recommendation. This was not always the case, especially in those borderline cases where the panel recommendation is "Fund If Possible - Medium Priority" rather than "Fund If Possible". It would be helpful especially in these cases that panel summaries clarify the ranking choice.

PDs should redouble efforts in panel meetings to encourage strong, effective, and thorough panel summaries.

5. Documentation of the Rationale for Award Decisions in the eJacket

For the purpose of the review of the Merit Review process, the Program PD Review Analysis gave more insight than the individual reviews or the panel summaries. They reflect the thorough nature of the PDs decision making process, and these analyses were uniformly excellent. The PDs are to be commended for this, as these analyses reflect that the Merit Review Process has been undertaken with utmost concern for providing support to best PIs and their research groups in a process characterized by a superior degree of integrity.

One of the most useful components of the PDs review analysis is the narrative portions wherein the decisions of the panel are contextualized with information that the PD knows about the supported group, their collaborations, etc. When there are decisions to be made about reductions in budget in order to be able to fund a given proposal, when additional funds outside of EPP must be secured to support the proposal, or when a decision is made not to fund a proposal, remarks made in the review analysis are helpful in establishing the fulsome nature of the PDs concern for integrity of funding proposals at NSF.

6. Documentation of the Rationale for Award Decisions Sent to the PI

Given that the PDs review analysis is not what the PI receives directly, though PDs may pass on much of the review analysis during conversations with PI's whose proposals are not funded, the PI must rely on the panel summary and the individual reviews their proposals have received. It is thus paramount that the panel summaries and individual reviews be thorough and give the PI appropriate feedback about the result of panel deliberations, and the individual perspectives on the strengths and weaknesses of the proposal and how they are reflected in the final evaluation.

Some panel summaries do not fully flesh out these details - and therefore it is important that additional effort be devoted to making sure that summaries contain the relevant information to help PIs in their future proposals. This is not only the case for those proposals who fail to be awarded - but for those strong proposals which are funded. It is important for PIs who have authored those proposals to receive sufficient information to help them to understand why their proposals have been funded to develop strong proposals in the future.

7. Reviewer Selection

The panel and ad-hoc reviewers selected in the Merit Review Process are central to the entire review process, and they must be able to effectively review the proposals before them. It is paramount that the reviewers have the appropriate expertise to be able to assess the proposals, but also be able to provide a good variety of perspectives and come from a diversity of backgrounds to lend credibility to the review process. Finally, all potential conflicts of interest, and even the appearance of such, must be avoided if the review process is to be acceptable to all.

The reviewers selected in the sample eJackets provided to us have both the experience and expertise to be able to judge the scientific merits of the proposals before them. An excellent procedure is in place to avoid conflicts of interest, which includes the flexibility to flag potential conflicts of interest late in the review process. A good effort has been made to select reviewers which reflect an appropriate balance of such categories as geography, institution type, seniority, race and ethnicity, gender, etc. It is important that these categories reflect, at the very least, the distribution in the categories of the proposals received, and when possible, reviewers should be selected to over-represent historically under-represented groups. At the same time, it is important not to place undue burdens on reviewers from under-represented groups - this is a delicate balancing act.

From the annual reports, it is evident that geographic balance is well achieved, as is the institutional balance among R-1 institutions, and primarily undergraduate institutions. It is important to continue to seek out and obtain reviews from researchers at PUIs as they best understand the challenges and marks of success for proposals coming from PIs at such institutions. Thanks to the PDs for supplying information to our subpanel showing that the gender ratio for reviewers does exceed that for submitted proposals. On the other hand, it is unclear whether EPP has been successful in obtaining a sufficiently large number of reviewers to achieve balance in terms of race and ethnicity, or in terms of reviewers who serve at MSIs, given the incomplete nature of self-identification surveys.

Despite all the challenges we commend the EPP PDs for their efforts to provide PIs with a balanced portfolio of reviewers in all respects and urge them to continue to work hard on this important topic in the future.

8. Overall Program Management

This four-year period has been significantly impacted by the rise and continuation of the COVID-19 pandemic, and through it all we are impressed by the leadership shown and the service far beyond the call of duty of the EPP PDs.

The division of EPP into three different research areas of High Energy Physics (HEP, 1221), Precision Particle Physics (PPP, 156Y), and Tools for Particle Physics (TPP, 157Y) that has recently been implemented has been a welcome development, which helps to ensure the continued vitality of non-LHC experimental work by amplifying the presence of such efforts within the overall portfolio supported by EPP. In addition, the TPP area, because of the interdisciplinary nature of the work supported, enables the potential for pooling support with relevant domains such as AMO, QIS, and AI/ML. We recommend that EPP continue to seek diversification in the portfolio in these areas.

We commend EPP for continuing to support PIs from a wide variety of institutions, from large R1 universities through both large multi-PI and smaller single-PI grants, to PUIs that have good single-PI grants serving primarily undergraduate institutions. The diversity of the EPP portfolio and the extensive reach to supporting undergraduate students is important and must be maintained.

EPP has, during the four-year period under review, actively supported research groups who undertake research connected to one or more of the P5 panel science drivers. There is a healthy balance of PIs who lead groups which utilize the Higgs boson for investigation of new physics, study the neutrino mass and related problems, search for dark matter candidates by various techniques, and seek to expand our understanding of the physical universe in new and unexpected ways. Furthermore, EPP has established working relationships with several other programs both within the Physics Division and outside, among other groups within the MPS directorate and beyond. This healthy synergy is to be commended and should be continued vigorously, and expanded.

II. The quality and significance of the results of the EPP programmatic investments

1. Alignment with the field priorities

The High Energy Physics Advisory Panel (HEPAP) reports to both the Mathematical & Physical Sciences Directorate of the NSF and the Office of High Energy Physics at the DOE. HEPAP conducts periodic reviews of ongoing high energy physics programs, as well as reviews possible future high energy physics research directions. It is the physicists that discuss, formulate, and then pass on the recommendations for funding directions in the field via what is known as the Snowmass and P5 processes. This process has worked very well, and the NSF EPP funding priorities are aligned well with the field priorities.

2. Quality and significance of EPP investments

Quality and significance of EPP investments can be gauged by hundreds of high impact papers published in referenced journals by members of the activities supported by EPP. Among highlights over the review period are

- Papers by ATLAS and CMS collaborations about the studies of the Higgs boson obtained over ten years since its discovery at the LHC: from newly discovered particle to dozens of precision measurements of its properties is a major milestone for the field. Nature 607, 52–59 (2022). https://doi.org/10.1038/s41586-022-04893-w https://doi.org/10.1038/s41586-022-04892-x
- Unique experiment to search for magnetic monopoles using the MoEDAL detector at the LHC. Monopoles in the range of one to three base units of magnetic charge with mass lighter than approximately 75 times the mass of a proton have been excluded, providing invaluable input for the development of theoretical understanding of magnetic monopoles. https://www.nature.com/articles/s41586-021-04298-1
- The exciting discovery of the first open charm tetraquark by the LHCb experiment at the LHC, a new type of particle never seen before. https://home.cern/news/news/physics/lhcb-discovers-first-open-charm-tetraquark

III. Program balance, priorities, and future directions

1. Balance across disciplines and subdisciplines

The portfolio is balanced considering NSF/EPP priorities and P5 guidelines. Over the review period 65% of funding is allocated to ATLAS and CMS proposals, including where this funding is critical to the success of NSF MREFC project. 15% is allocated to the neutrino program with main support devoted to short and long-baseline oscillation experiments. 15% is allocated to the LHCb program where NSF is leading US participation in the experiment. The rest is allocated to precision physics and various detector R&D proposals.

2. Award size and duration

There is a wide range of award sizes and durations based on the proposals and programmatic priorities of the field and NSF. Typical award is about three years, while there are up to five years awards and some are short, for example, for student's support. Average award is about $200k per PI per year, while there is a wide distribution depending on the activity and award group size. Continuing with current practice is advisable so that EPP can be flexible and provide optimal funding for high quality and high priority proposals.

3. Awards to new and early-career investigators

EPP awarded the following number of CAREER awards during the last four fiscal years: 2019/0, 2020/3, 2021/3, 2022/0. The awards are highly competitive and progress through an in-depth review process. The current number of active awards is typical for the past decade. We expect EPP will continue to fund the best early career scientists via CAREER awards.

4. Geographical distribution of awards

EPP has a distribution of support from the east to the west coast of the United States with PIs from 32 states submitting applications over the review period. Areas which could use outreach include the southern states, particularly southeastern states, and the middle states and EPP is effectively using communication with EPSCOR funding in appropriate cases.

5. Awards to different types of institutions

EPP is actively engaged with promoting all types of institutions, including MSIs and PUIs, to participate in the development of proposals.

6. Innovative/potentially transformative projects, projects with elements of risk, inter- and multi-disciplinary projects

EPP handles many transformative proposals which could substantially modify our understanding of the most basic principles of nature and could revolutionize the future, including clean energy sources, medical, and multiple other applications. In many cases EPP attracted funding from other NSF programs to support strong proposals. For such proposals, including AI/ML and computing activities, the EPP program benefits strongly from contributions from various NSF organizations. Another excellent example is close cooperation with international funding agencies, including US-Israel Science Foundation, where joint efforts are providing strong mutual benefits. Joint activities with the DOE on LHC and DUNE are exemplary and indicate close and productive cooperation between two agencies.

7. Projects that integrate research and education, participation of groups that are under-represented in science and engineering

EPP-funded programs have a strong educational component for undergraduate and graduate students' participation in exciting scientific activities. Participation of MSI and PUI institutions is strongly encouraged and supported as are students and PIs from under-represented groups who are studying and working at other types of institutions. The fraction of women on the review committees exceeds the fraction of proposals submitted by women which serves to encourage women to apply.

8. Projects that are relevant to agency mission or national priorities

In the past, EPP has benefitted from NSF "Big Ideas", most notably "Windows on the Universe" and "Harnessing the Data Revolution". More recently, NSF has focused on two areas: Diversity, Equity and Inclusion (DEI) and bridging the gap from fundamental research to "use-inspired" research, "giving rise to new industries and engaging all Americans". The latter refers to the new NSF Directorate for Technology, Innovation and Partnerships, TIP. The EPP program has benefitted from these new initiatives, most notably in various DEI programs meant to expand the STEM workforce where EPP has obtained graduate student support supplements that support underrepresented minorities in STEM. We encourage strong partnership of EPP with TIP.

IV. Program response to the prior COV report of 2019

The response of the NSF EPP team to the 2019 COV report is reasonable and since FY19 substantial improvements along the recommendations have been achieved. There is openness to training sessions or additional materials to help prepare ad-hoc reviewers - we have included an additional suggestion in our panel recommendations. We also appreciate hearing the process the Program Directors use for communicating with PIs whose proposals were declined, and that the suggestion regarding multiple-PI awards was implemented accordingly. Finally, we appreciate the transparency with which the recommendation about proposals from large experiments was handled. Below are the recommendations from 2019 and our assessment of the response.

1) The subpanel recommends that the ad hoc reviews give sufficient detail so that the proponents can understand the basis for the rating they are given. The perceived strengths and deficiencies of the proposed program should be clearly stated by the reviewers so that PIs receive important feedback and so that the process is as transparent as possible.

We were assured that PI's have access to the ad-hoc reviews and the Panel Summary for their proposals, and they are typically contacted for more detailed discussion and to answer any questions.

2) The subpanel recommends that the EPP panel review reports are detailed enough to contain the elements that led to the final recommendation on the funding support and proposal ranking. From our readings, most proposals received sufficient feedback but we found some proposals with clear deficiencies.

Based on our review of the eJackets and discussions with the Program Directors, we believe that substantial progress since FY19 has been made in this regard, including for proposals with multiple PIs where the evaluations may vary significantly.

3) The subpanel recommends that the final information transmitted from the program directors to the PI's (e.g. regarding re---budgeting and individual PI feedback) is made available to ***all*** *PI's on a multi---PI or multi---institution grant, so that all proponents are given feedback that allows them to react and optimize any future submissions.*

The approach taken is to consider the PI as the contact person for the proposing team, who has responsibility for sharing/communicating the results of the merit review to the co-PIs. In most cases, the Program Directors meet with all of the investigators on a proposal by phone, except in cases that require special sensitivity. We believe this is a sensible approach.

4) The subpanel recommends that for large experiments such as the LHC, EPP should obtain ad hoc reviews from peers within the same experiment who don't have a conflict of interest. (This already occurs for the panels.) Such reviewers would be able to give better insight on the impact and importance of the current or proposed program as well as on the PI's contributions. These details can provide important input to the panel deliberations, but may not be available from a reviewer outside of the experiment.

In the cases reviewed by our team, we found that the Program Directors strive to follow the above recommendation, by consulting with the declared conflicts of interest in the single-copy documents submitted with the proposal in order to avoid persons so identified.

5) There was no written EPP response to the previous 2015 COV, even while most recommendations were addressed. It is recommended that EPP prepare a written response for this 2019 COV report that can be reviewed by the next COV as to what was planned and then implemented. This might also help with explaining the context of the requests and responses.

The COV was provided with the written response to the FY19 COV recommendations, and we expect such practice to continue.

V. Comments on any other issues the COV feels are relevant.

Impressive new discoveries, detectors, computing algorithm applications, and new approaches to research have resulted from the marvelous and impactful leadership in the MPS Directorate including EPP over many years. Skilled attention should be given to the successful role that EPP at the NSF has played in fostering diversity, equity, and inclusion in its program goals, and award decisions. This includes (again non-exhaustive)

(i) Inaugural NSF Physics Frontiers Centers included an MSI.

(ii) Supporting a Historically Black College or University in a major construction and physics research project at CERN that led to a Nobel Prize in Physics.

(iii) One of the first institutions to have a Cloud Computing site on its campus was an MSI.

A noticeable area that can be improved upon in DEI is the number of MSIs that send funding proposals to the NSF. The NSF EPP program has devoted substantial resources and effort to increasing participation in the field by individuals who come from historically underrepresented groups, and providing funding to universities that are under-represented in the field.

There are over 100 Historically Black Colleges and Universities (HBCUs), more than 270 Hispanic Serving Institutions, more than 30 Tribal Colleges and Universities, and a growing population of Asian American and Pacific Islander Serving Institutions in the United States, as reported by the U.S. Department of the Interior’s Office of Diversity, Inclusion and Civil Rights. Most of these institutions have a strong undergraduate focus. The pipeline which ultimately produces graduate students, postdoctoral associates, and faculty necessarily begins when people have their first encounter with research when they are undergraduates and are encouraged to pursue careers in physics. As a result, supporting HBCUs and other MSIs is of critical importance toward our goal of increasing diversity in physics.

Many of these MSIs may have opportunities and motivation to submit funding proposals to EPP. EPP supports large, successful, and exciting projects that usually require institutions associated with the project to have appropriate infrastructure at their sites to have a meaningful role to play in the project. That said, RUI proposals to EPP, which would be the appropriate funding vehicle for most HBCU/MSI, have been positively reviewed. Well-structured proposals with an appropriate scope can review well and have successful outcomes.

VI. 2023 EPP COV Recommendations

1. Consider the 2022 Snowmass report, coming 2023 P5 prioritization and 2024 National Academy of Sciences panel comments in setting EPP programmatic priorities for the coming decade and beyond.
2. Update NSF PIs about plans and priorities of EPP in advance of annual proposals submission. Continue NSF presentations at HEPAP meetings and other meetings of the US particle physics

community. Consider making abbreviated annual EPP end of the year summaries public to provide feedback and outline priorities to the PIs community.

3. Continue to provide detailed feedback about the reasons for the awards decisions to PIs of both awarded and declined proposals including consolidated panel reports.
4. In keeping with the excellent DEI work, including the supplements supporting graduate students who come from underrepresented backgrounds, consider new ways to increase the number of the proposals to EPP from PIs at HBCUs and other MSIs.

C. Elementary Particle Physics / Cosmology Theory (EPP Theory)

1. Introduction

The promotion of the progress of science and the advancement of the national health, prosperity, welfare, and security constitute the central mission of the National Science Foundation[1].

Theoretical physics research is essential to fulfilling these aspirations, and the elementary particle physics and cosmology theory programs ("EPP Theory" hereafter) contribute to these aims in significant and tangible ways, as detailed below.

Theoretical elementary particle physics explores the fundamental "building blocks" that make up the natural world. These consist of elementary particles that are the constituents of all matter and the forces that describe their interactions. In this way, one hopes to be able to expose the underlying laws of physics in their simplest forms. Theoretical particle astrophysics/cosmology attempts to understand the origin and evolution of the Universe from its earliest beginnings to the present time. Because the early Universe was extremely hot and energetic, the properties and subsequent development of the early Universe are directly governed by the properties of these fundamental forces and particles.

The pursuit of these two goals during the last century has resulted in remarkable progress, culminating in the formulation of the Standard Model of particle physics and the Standard Model of cosmology. The Standard Model of particle physics identifies elementary particles consisting of six "flavors" of quarks and leptons whose interactions are mediated by eight gluons (responsible for the strong nuclear interactions), one photon (responsible for the electromagnetic interaction) and the three weak bosons W+, W-, and Z (responsible for the weak nuclear interactions). One final key ingredient, the Higgs boson, necessary for the mathematical consistency of the theory, was discovered only recently in 2012 at the Large Hadron Collider operating at CERN, although it was predicted by theory nearly a half century earlier. The gravitational force remains separate from the Standard Model, and its ultimate incorporation remains a longstanding theoretical challenge.

Meanwhile, the development of the Standard Model of cosmology has been equally impressive. Due to remarkable experimental advances in astronomical observations over a wide range of wavelengths, we now know that the matter described by the Standard Model of particle physics constitutes only about 5% of the energy density of the Universe. The remaining 95% is dark: about 25% is attributed to "dark matter", whose interactions with Standard Model particles are either very weak to non-existent, and about 70% is attributed to "dark energy", an "entity" with negative pressure whose fundamental nature is presently unknown, although it seems consistent with the existence of a cosmological constant first proposed by Einstein shortly after formulating his theory of general relativity.

Despite the impressive successes of the Standard Models of particle physics and cosmology to explain a myriad of experimental observations, there are strong indications that key ingredients are missing. For example, the Standard Model of particle physics cannot explain the existence of nonzero neutrino masses (at least two of which, although much smaller than the masses of the quarks and charged leptons, are undoubtedly nonzero). Moreover, if dark matter consists of neutral weakly-interacting particles (perhaps the most likely explanation), then these particles must be new fundamental entities that lie

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[1] From the National Science Foundation Act of 1950 (P.L. 81-507).

outside the Standard Model. A third shortcoming of the Standard Model is that it provides no mechanism for the observed matter-antimatter asymmetry in the Universe. At a more fundamental level, the Standard Model is incapable of explaining the origin of many arbitrary parameters (e.g., masses and mixing angles of the fundamental particles), the origin of quark and lepton flavors, and the variety of strengths and ranges exhibited by the fundamental forces. Moreover, there is no clear path to incorporating gravity into the Standard Model.

As for the Standard Model of cosmology, the current paradigm cannot identify the nature of dark matter (beyond its gravitational properties), while the theory of dark energy, if associated with a cosmological constant, provides no explanation for the origin of its value. Another feature of the Universe that cries out for an explanation is the total energy density, which is observed to be equal (within statistical errors) to the so-called critical density, which is the dividing line between an open and closed Universe. The leading explanation for this observation invokes a very early inflationary epoch shortly after the Big Bang, in which the Universe expanded at an exponential rate. It is quite remarkable that the detailed observations of the cosmic background radiation can provide strong support for an inflationary epoch, and additional experiments now underway can provide significant constraints to specific inflationary models.

With numerous theoretical arguments to support the statement that the Standard Model is at best an effective field theory at the electroweak symmetry breaking scale (of order 100 GeV) that will be superseded at a higher energy scale, one of the main unanswered questions is at which energy scale will new physics beyond the Standard Model emerge. We currently live in the age of the Large Hadron Collider, which has begun to probe in detail energy scales of order 1 TeV and above. Thus, there is a significant potential for discovery of new fundamental physics phenomena that will signal the first departures from the Standard Model. Data from the LHC will be the driving force behind all of this, but only in the context of theory can it be properly interpreted and understood. A robust high energy theory program is therefore critical for the success of the LHC. Meanwhile, the next generation of neutrino experiments continue to explore the structure of the neutrino mass spectrum and its mixing while providing critical information on fundamental physics that lies beyond the Standard Model.

Astroparticle physics experiments continue to extend the scope in the search for dark matter. Initially, most dark matter detectors focused on a narrow range of masses and interaction strengths (known as the weakly-interacting massive particle or "WIMP" paradigm). More recently, it has been widely appreciated that the landscape of possible dark matter models is much larger and requires the development of new technologies to explore the entire parameter space. Interesting synergies arise that connect new models of dark matter with explanations of other features of fundamental particles and their interactions that cannot be addressed within the Standard Model.

Consequently, high energy theory spans many orders of magnitude in energy and runs the gamut from hard-core data-driven collider phenomenology to abstract model-building and considerations of the "ultimate theory", with an ever-increasing emphasis on interdisciplinary connections to particle astrophysics and cosmology.

2. Research Highlights

EPP Theory research includes the areas of particle physics phenomenology and model building, theoretical aspects of early Universe cosmology and topics in formal physics including string theory and gravity. Overall, we find that the program continues to correctly identify and therefore fund some of the most impactful research occurring in physics today. We list below a few examples of the important theoretical EPP research supported by NSF awards.

In the 1990s, data collected in high energy e+e- collisions at LEP and SLC (primarily through resonant production of the Z boson), provided the first stringent tests of the Standard Model of particle physics. Further observations at the Tevatron in the 2000s probed new electroweak observables which were included in the global electroweak fits. The march to precision continues at the Large Hadron Collider, starting with the discovery at CERN of the Higgs boson in 2012. All the evidence thus far suggests that this appears to be the Higgs boson as predicted by the Standard Model, although error bars on current LHC measurements are in the range of 5—20% (depending on the Higgs decay channel). As further data is collected, one expects to reach precisions of a few percent. Other electroweak processes will also provide useful constraints on the viability of the Standard Model. Tightly coupled with these experimental measurements are advances made by theorists in understanding critical aspects of collider signal detection. These include detailed theoretical NLO, NNLO, and N^3LO QCD calculations, combined with higher order electroweak predictions, which remain essential for understanding complicated experimental backgrounds and thereby extracting LHC physics. Along this avenue, the works of Ayres Freitas (Freitas/2112829; see work published in Journal of High Energy Physics 04 (2021) 179), Doreen Wackeroth (Wackeroth/2014021; see work published in Physical Review D 105 (2022) 9, 096009), and Ciaran Williams (Williams/1652066, CAREER award; see work published in Journal of High Energy Physics 06 (2019) 079) are particularly noteworthy. Along with collaborators, they have played a leading role in the exploration of electroweak precision physics and its value in constraining (with the possibility of eventually revealing) the existence of new physics phenomena beyond the Standard Model and in studying applications of precision calculations at the LHC and future e+e- colliders.

Beyond the LHC discovery of the Higgs boson, a second major "discovery" at the LHC to date is the apparent absence of supersymmetric (SUSY) particles or any other degrees of freedom from other Standard-Model extensions. This experimental situation has inspired many theorists to explore new directions for discovering new physics. It may turn out that the first evidence for physics beyond the Standard Model will be detected at energy scales that lie below the scale at which the degrees of freedom of the new physics are revealed. In this case, deviations from the Standard Model could first be associated with higher dimensional operators made up of Standard Model fields. One of the leading approaches employed for this purpose is the Standard Model Effective Field Theory (or SMEFT). The challenge of SMEFT is that in its full generality, one must allow for 2499 dimension-six operators. The precise counting of independent operators, depending on their dimensions, is based on very clever mathematics (the Hilbert series), which has been exploited to great success by Hitoshi Murayama and collaborators (Murayama/1915314 and 2210390; see work published in Journal of High Energy Physics 08 (2017) 016; 01 (2021) 142) and independently by Adam Martin and collaborators (Martin/2112540; see work published in Physical Review D 91 (2015) 105014). Martin has extended the SMEFT formalism with a geometric approach that has been influential in fits to data; see work published in Journal of High Energy Physics 03 (2020) 163.

Motivated by the results of collider searches for dark matter as well as the results of dark matter direct- and indirect-detection experiments, theorists are rapidly moving beyond the so-called WIMP paradigm and exploring non-traditional dark sectors. Indeed, it is now appreciated in the particle astrophysics community that one needs to be open to the possibility that possible dark matter candidates span masses from as low as 10^{-21} eV to masses as large as several hundred solar masses. For example, Tien-Tien Yu (Yu/1944826, CAREER award; see work published in Physical Review Letters 125 (2020) 17, 171802) has played a key role in a collaboration of theorists and experimentalists in the development of the Sub-Electron-Noise Skipper CCD Experimental Instrument (SENSEI), which uses recently developed Skipper-CCD technology to search for electron recoils from the interaction of sub-GeV dark matter particles with electrons in silicon.

One class of models that is receiving special attention are axion-like particles (or ALPs). Axions were originally conceived as a possible solution to the strong CP problem. For example, recent work by Anson Hook, Raman Sundrum, and collaborators at Maryland (Sundrum/2210361; see work published in Physical Review Letters 124 (2020) 22, 221801) argues that a theoretically robust model of the axion has a large and uncharted parameter space, which allows it to be probed at the LHC as a long-lived particle (LLP) — i.e., a particle with a macroscopic displaced vertex (whose decay would happen well beyond the traditional range of focus for the main LHC detectors). There exists a much broader class of ALPs with no direct connection to the strong CP problem, many of which can arise in models of new physics beyond the Standard Model. As an example, James Dent and collaborators (Dent/2112799; see work published in Physical Review D 104 (2021) 5, 055044) have advocated for the possibility of detecting photon signals arising from cosmic ray electron scattering on background ALPs.

In recent years there have been a variety of proposals for novel auxiliary detectors at the LHC to search for LLPs and study neutrinos. Prime examples along this avenue include the FASER and FASERν experiments, with Jonathan Feng (Tait/1915005; see work published in Physical Review D 97 (2018) 3, 035001 and in Journal of Physics G 50 (2023) 3, 030501) playing a leading role, along with Felix Kling and Sebastian Trojanowski who were postdocs at UC Irvine at the time of the initial ideas. Both experiments are now installed and currently collecting data during LHC Run 3, and FASERν has recently reported the detection of the first collider-produced neutrinos. Looking towards the future, there are ongoing discussions to build on these developments during the high-luminosity LHC era with a larger Forward Physics Facility, which would house several experiments studying a range of topics, including neutrinos, QCD, long-lived particles, and dark matter.

On the more formal side of theoretical particle physics, the AdS/CFT correspondence (first developed in the late 1990s) has led to new mathematical techniques for studying strongly interacting theories. Further continuing their studies of the AdS/CFT correspondence, string theorists have recently been focusing on various implications of holography as it relates to black-hole physics. Studies of quantum entanglement and the black-hole information paradox indicate that either the equivalence principle, unitarity, or quantum field theory must be abandoned. Those who give up the former argue that there must be a firewall at the event horizon, while others argue that wormholes can solve the problem. Work on understanding this paradox has continued with increasing intensity, with important results being obtained by Raphael Bousso and collaborators (Horava/2112880; see work published in Physical Review D 102 (2020) 10, 106019).

There has been a continuing interest in studies of the string landscape. The newest ingredient in this endeavor is the application of machine-learning, as exemplified by recent work by James Halverson (Halverson/1848089, CAREER award; see work published in Fortschritte der Physik 68 (2020) 5, 2000005). This has led to new interactions between string theorists, mathematicians, computer scientists, and private-sector computer professionals. On the more formal side of such landscape studies are new approaches towards determining the boundaries of the string landscape — i.e., in learning how to distinguish between the landscape (the space of self-consistent string vacua) and the so-called "swampland" (the space of theories which are self-consistent from a low-energy quantum field theory perspective, but which lack an ultraviolet string-theoretic realization). A key ingredient in this effort has been the development of a series of so-called swampland conjectures (such as the "de Sitter conjecture" and the "distance conjecture"), pioneered by Cumrun Vafa (Vafa/2013858; see work published in Journal of High Energy Physics 10 (2021) 070), who continues to be a leader in this area of study, with very interesting new developments by Benjamin Heidenreich (Heidenreich/1914934; see work published in JHEP 10 (2019) 055).

Continuing the line of research into using string theory to understand black-hole physics and information loss, very recent ideas have asserted that the interiors of different black holes are connected by wormholes, whereupon quantum entanglement leads to the proposition that part of the deep interior of a black hole — a so-called quantum extremal "island" proposed by Thomas Hartman and collaborators (Csaki/2014071; see work published in Journal of High Energy Physics 11 (2020) 111) — is secretly on the outside as far as Hawking-like entropy calculations are concerned. When these features are included in information-loss calculations, it appears that information is never lost after all. If true, this may represent a final resolution of the long-standing information-loss puzzle and demonstrate that wormholes play a significant role.

We note that many of the PIs listed in this section were non-tenured faculty members at the time of the NSF grants, demonstrating that the EPP Theory program has been successful in identifying emerging theoretical talent.

3. Challenges with Emerging New Opportunities, Responsiveness to Experimental Results, and Interdisciplinary Trends

While many of the central questions and physics drivers in theoretical particle physics and cosmology have remained steady over several decades, these fields are nonetheless extremely vibrant and fast-moving, with research trends changing from year-to-year in response to new experimental data or creative theoretical ideas. As certain subfields in EPP Theory have pivoted from one research avenue to another, the Program Director (PD) has consistently responded to these needs, e.g., by realigning funding priorities as appropriate. For example, at the onset of his tenure more than a decade ago, which corresponded to the beginning of the LHC era, he expanded the funding for research focused on collider phenomenology. This was a vital step which, along with other external efforts, has helped to maximize the physics deliverables of the LHC experiments.

There are several notable emerging interdisciplinary trends of relevance for EPP Theory. Like many fields, the artificial intelligence revolution has significantly influenced those areas of high energy theory research which involve the analysis and interpretation of large data sets. For instance, particle phenomenologists are developing state-of-the-art machine learning algorithms for a host of LHC analysis applications, while string theorists are employing such methods to explore the string landscape. In fact, these research activities have spurred new collaborations between particle theorists and data scientists from the private sector. EPP Theory is supporting several promising research efforts exploiting machine learning, in line with the NSF Big Idea *Harnessing the Data Revolution*.

In another emerging direction, particle theorists are applying methods from quantum information science (QIS) to address fundamental questions in particle physics and cosmology. This includes the development of new measurement techniques using novel quantum devices as well as leveraging insights from QIS to discern basic properties of gravitation and spacetime. The PD has been mindful of alternative (non-NSF) funding sources for interdisciplinary particle theory / QIS research (e.g., DOE-QIS) and has been taking steps aimed at increasing coordination and considering the potential need for realignment of funding priorities.

Likewise, there is growing interest in utilizing novel experimental techniques from Atomic/Molecular/Optical physics (AMO) to perform precision measurements and searches for new physics (e.g., dark matter). EPP Theory has begun co-reviewing and, in a few cases, co-funding proposals of this kind. Furthermore, to foster deeper connections between the high energy theory and experimental AMO communities, the program director, along with his NSF AMO counterpart, increased funding to the Aspen Center for Physics targeted at supporting new interdisciplinary programs on covering the overlapping interests of these fields.

4. Merit Review, Integrity, Efficiency of the Program Process

A. QUALITY AND EFFECTIVENESS OF THE PROGRAM'S USE OF THE MERIT REVIEW PROCESS

The PD employed a combination of mail reviews and panel reviews to assess the EPP Theory proposals. The mail reviewers are experts in the particular areas covered in the proposals. The PD also solicited formal reviews from the panel members. This change from entirely mail reviews had occurred at the time of the previous COV and was part of a division-wide effort to reduce the NSF administrative workload and that of the community of reviewers. This change to the review process appears to have worked well for EPP Theory. The PD's effort to ensure that all EPP Theory proposals are reviewed by experts in the field is to be commended, and the panel members and reviewers had the appropriate knowledge to make an informed judgment in the cases we reviewed. We found that the mail-in reviewers and the panels carefully considered the intellectual merit, along with the broader impacts of the proposed work in making their recommendations. In the vast majority of cases, reviewers provided detailed substantive remarks which elucidated their assessments of the proposals.

The review panels deliberated on the merits of each proposal and made comparative assessments between proposals. The panels served several functions. First, they reviewed the recommendations of the reviewers, both from external reviewers and the panel members, and second, the panels provided prioritizations of proposals across sub-areas. This prioritization is crucial, and we are impressed with the PD's diligence in forming a balanced program. We are convinced that the excellent and essential research needed for progress in the field was funded.

The panel subsequently provided recommended rankings of the proposals and prepared a Panel Summary for each proposal which encapsulated their deliberations and ranking. The Panel Summaries generally provided a careful and thorough description of the reasoning behind the final judgements rendered by the panel. Based on the external reviews, Panel Summaries and recommended rankings, programmatic considerations, NSF priorities, budgetary constraints, as well as his own assessments of the proposals, the PD then made final award/decline and funding level recommendations.

The PD's Review Analysis for each proposal provided a comprehensive summary of the essential considerations at various stages of the merit review process and a clear explanation of his rationale for the final funding recommendation. The PD has done an exceptional job of transparently communicating with PIs about the review process and the grounds for funding decisions, particularly when difficult decisions were necessary due to programmatic priorities or budget pressure. He also provided constructive feedback to PIs on how to improve their proposals, particularly when concerns are raised during the review process. The PD has been very responsive to queries from potential proposers and current NSF PIs. Likewise, the PD has strived to educate the broader community about opportunities available within the NSF along with challenges faced by the program.

We commend the PD for his detailed summaries of his thinking and justification for the decisions made and are impressed by his efforts to ensure fairness and transparency. He has gone to great lengths to communicate the rationales behind funding decisions with PIs, and we believe that this is a great strength of the PD.

The PD is a prominent theoretical physicist in his own right with broad expertise across formal field theory, particle phenomenology, and cosmology. The PD remains fully research active and maintains strong connections to the community through his collaborations, attendance at various conferences, and so on. This makes him extremely well-qualified to direct the EPP Theory program and informs his choices of reviewers and panelists. In summary, the PD has been highly successful in administering a merit review process of the utmost quality and effectiveness. The review methods and their implementation are thorough, rigorous, and fair.

Broader impacts on society forms an important part of NSF proposals. Typically, these include open houses, visits to local area schools, community lectures, and mentoring of women and minorities in STEM areas, among other things. Broader impact in the EPP Theory program takes many forms: research that has a lasting impact on the field; the science documentary *Particle Fever* produced by David E. Kaplan; the CAREER award to Joshua Ruderman mentoring NYU science journalism students; and TheoryNet, an outreach activity to high-school classrooms by university physics theorists working on elementary-particle physics, astrophysics and cosmology, are all examples of significant broader impacts of the program.

B. SELECTION OF REVIEWERS

The PD is to be commended on his judicious selection of well-qualified and unbiased reviewers with expertise that is well-matched to the proposals they are charged with reviewing. The collective scientific expertise of the Review Panels is chosen to squarely reflect the balance of research topics in the received proposals. Furthermore, he has consistently succeeded in composing panels that are diverse across many metrics, including, career stage, home-institutional profile, gender, and race/ethnicity, while being mindful that members from underrepresented groups are generally overburdened with service activities. The PD also takes great care to manage conflicts of interest as needed, including when he himself is conflicted on a particular proposal.

C. MANAGEMENT OF THE PROGRAM UNDER REVIEW

For more than a decade, the PD has provided sound and steady management of the EPP Theory program in the face of numerous and sometimes severe challenges. Under his stewardship, the program has been successfully guided from an initial state of unsustainable outyear commitment levels to its current state of relative financial stability. Along the way, with the support of NSF PHY management, the PD was able to deftly navigate several critical budgetary hurdles, including the dramatic FY13 Sequester cuts, the dissolution of the Mathematical Physics (Math Phys) program at the NSF at the end of FY14, and, in recent years, an increasing number of proposals to the EPP Theory program. With its current state of healthy outyear commitments, the PD has recently been able to respond to the emerging challenge of a dwindling number of postdoc positions in the U.S. through the creation of a new postdoctoral funding program. We also commend the PD for his responsiveness to a variety of challenges faced by PIs due to the COVID pandemic.

The current 3-year duration of the regular grants allows for responsiveness to new scientific opportunities as they arise and allows the PD to ensure that the program continues to be focused on cutting edge research. We support keeping 3 years as the norm for regular grants, while allowing flexibility for the PD in special cases.

D. PORTFOLIO

In reflecting the intellectual breadth and vibrancy of the fields of theoretical particle physics and cosmology, the PD has done an outstanding job in curating an especially rich and ever-evolving research portfolio. The program supports cutting-edge projects across several subdisciplines, including formal field theory and string theory to precision Standard Model calculations, beyond the Standard Model frameworks and phenomenology, and topics in astrophysics and cosmology. High-risk/high reward projects are balanced with necessary, solid research. There are a variety of projects of an interdisciplinary nature that are co-funded by EPP Theory with other NSF programs. Furthermore, the portfolio contains a healthy distribution of group and individual PI grants, as well as grants from research universities and primarily undergraduate institutions.

5. Diversity, Equity and Inclusion

The EPP Theory program shares the goals of MPS and the NSF to broaden participation among women and under-represented minority groups and the program director is actively involved in division-wide activities.

The representation of women and under-represented minority groups among PIs and Co-PIs is consistent with the pool of proposals submitted to the program.

Furthermore, the outreach aspects of EPP Theory proposals have an important component intended to include women and under-represented minorities in the scientific enterprise. We support the strong efforts of the EPP Theory program to continue and further enhance these outreach efforts.

As an example, the EPP Theory program initially supported a small effort at Sam Houston State University, a primarily undergraduate institution with a significant URM component. This seed has grown to support three theory PIs and has included students who are representatives of under-represented minority groups.

6. Responsiveness to the 2019 COV

The 2019 COV commended the PD for his efforts to ensure that the number of expert mail-in reviewers be more than the number of panel members serving as reviewers of a proposal, and the PD has made great efforts to ensure that this continues to be the case.

The CAREER program places strong emphasis on education and outreach, and the CAREER proposals supported by the theory program have gone to individuals who appear capable of managing strong programs in both research and outreach.

The 2019 COV also echoed a concern from the 2015 and 2012 COVs regarding the budgetary pressures on the EPP Theory program which prevent it from supporting graduate students adequately. This remains an important issue, especially in times of inadequate funding for the program as a whole. We encourage EPP Theory to continue its efforts to be able to meet emergency graduate student funding needs.

7. Changes in the Broader Funding Landscape

Funding opportunities for EPP Theory research primarily come from either the National Science Foundation or the Department of Energy. These funding sources are typically under severe financial stress. During the past decade, the funding levels from NSF have been remarkably stable, despite significant challenges due to the “sequester” cuts in 2013 and 2014 and the absorption of (a significant part of) the Mathematical Physics program. In contrast, the high energy theory support from the Department of Energy has been significantly cut during the past decade. This has further stressed the NSF program as more physicists previously supported by DOE have looked to NSF for funding opportunities.

One of the consequences of the large reduction in DOE funding has been a significant drop in the total funds available to support graduate student and postdoctoral researchers in theoretical high energy physics and cosmology resulting in a reduction in the number of postdoctoral positions in theoretical high energy physics across the US by approximately 1/3. Maintaining strong student and postdoc pipelines is critical not only for the research vitality of our entire community but also as a way of attracting and retaining the top talent in our field. Due to the reduction of postdoctoral support many promising junior physicists have been forced to leave the field.

In order to address the postdoctoral crisis described above, the EPP Theory program director created a new postdoctoral funding program, which aims to inject new postdoctoral positions in high energy particle physics and cosmology. In choosing the recipients of this new funding, the goal was to consider the postdoc perspective and create these positions where they would be most beneficial for the postdocs themselves in terms of professional development, variety of research opportunities, visibility, and career enhancement. This new program has been quite successful. Thus far, after three cycles, a total of seven additional postdoc positions were created at several large university groups at a cost of approximately $2 million. Looking to the future, it is expected that these opportunities will be extended more broadly, perhaps to smaller research groups and possibly Tier II institutions when warranted.

The continuing financial pressures on the EPP Theory program have not allowed sufficient funding for graduate students. The problem has persisted both at NSF and DOE for many decades and remains unresolved. It has historically been the case that the majority of EPP Theory graduate students are primarily supported through TA positions within their home departments throughout the bulk of their graduate-student careers. However, such service to the department significantly delays the research progress of the student. Nevertheless, this arrangement has permitted most grants within EPP Theory (both NSF and DOE) to provide only minimal graduate-student support (typically one graduate student per three senior faculty members for NSF).

Unfortunately, due to the budget cuts within the universities themselves, many universities have been forced to curtail the number of TA lines that are given to physics departments. This, in turn, has caused many departments to institute policies which restrict the length of time a graduate student may be supported through a TA, a policy which disproportionately hurts graduate students in EPP Theory. As a result, some graduate students have lost financial support prior to completing their Ph.D. To address this issue, it is critical to find ways to implement an increased level of graduate-student support throughout the EPP Theory program as a whole. The PD discussed this issue at great length with us and has provided emergency supplements to fund graduate students in cases of extreme hardships. It is clear that a more comprehensive solution cannot be found under current funding levels.

Another way to increase the effective funding level for EPP Theory is by developing increasingly robust connections to other sources of funding within NSF and beyond. Indeed, grants from private sources have been emerging (such as the Simons Foundation and the Templeton Foundation), although these sources of funds tend to target specific subfields within EPP Theory. Ideally, one would hope for better coordination of the respective funding priorities of the NSF and the private foundations so as to maximize the benefit to the EPP Theory research community at large. In practice, this has been difficult as the private foundations have different goals than the NSF. The PD is deeply aware of the issue and is working hard to increase communications.

8. Final Comments

The PD manages the program extremely well, choosing appropriate expert reviewers and making effective use of the panel reviews. The panel summaries provide a clear rationale into the deliberations, assessments, and proposal rankings. The PD’s recommendations are well documented in the review analyses and have led to an exciting and diverse EPP Theory program with support for new emerging areas of theory research. We applaud the influx of assistant professors into the funding stream and as reviewers and panelists. A continuing concern is adequate funding for graduate students and postdocs. The postdoctoral funding program instituted by the PD is a very positive first step. The relatively flat funding of the EPP Theory program over the last decade makes any solution for graduate student support extremely difficult to find.

D. Gravitational Physics / LIGO

Executive Summary

The Gravitational Physics Program is managed extremely well, supporting a good balance of theoretical and experimental proposals. However, we see a potential crisis on the horizon. The spectacular success of LIGO has led to a growth in the field and an increase in the number of proposals needing funding. So far, this has been managed by leveraging support from other areas in the NSF, mainly the Windows on the Universe program which might end soon. It is essential that a stable source of additional funds be identified to fully replace the Windows on the Universe program, if it is discontinued. Looking a little further ahead, it is important that a next generation gravitational wave detector be a high priority for the NSF.

1. Introduction:

The Gravitational Physics Program at the NSF oversees a broad range of research related to gravitational phenomena. A major focus is centered around the recent discovery of gravitational waves by LIGO, which are produced by the inspiral of binary black holes and neutron stars in our universe. We now have seen more than 90 examples of such inspirals and expect many more when the LIGO detectors turn on again later this year.

The Gravitational Physics Program supports LIGO data analysis, as well as research into next generation gravitational wave detectors (including mirror coating and seismic isolation), and gravitational-wave detection via pulsar timing (NANOGrav). It also supports a wide range of more theoretical topics including quantum gravity (other than string theory), numerical relativity, and other astrophysical phenomena involving strong gravity.

2. Management of the program:

This program is very well managed. The program director has divided the field into three main areas: Theory, LIGO Research Support, and Experiment and Data Analysis, and holds separate panels in each area. Since the last COV report, the number of LIGO data analysis proposals has grown substantially, and the number of non-LIGO experimental proposals has shrunk. As a result, the program director moved the data analysis proposals from LIGO Research Support to the recently renamed Experiment and Data Analysis. We support this change.

The reviewers chosen by the program director are well qualified and often produce substantial, thoughtful reports. The panels discuss the proposals and external reviews thoroughly and produce reasonable ranking of proposals. The program director usually follows the panel's recommendations (adjusting budgets when necessary), and in the few cases where he doesn't, he has well thought out arguments for his decision. We commend the program director for implementing a practice of awarding 1-year grants to those groups at risk of losing their current support. This provides these groups with an opportunity to overcome a weak proposal and/or variability in individual reviews.

A critical part of the gravitational physics mission is to balance the gravitational-wave and non-gravitational wave aspects of gravitational physics. This is essential since the NSF is the main source of funding in both of these areas. The program accomplishes this important goal by supporting a wide range of activities including short-range gravity experiments, non-string-theory-based approaches to quantum gravity, numerical relativity, classical and semiclassical gravity, work relating to relevant approximations to full general relativity, and astrophysics.

Following the initial success of LIGO, there was an increase in proposals of interest to both astronomy and gravitational physics. The program director wisely worked with the Astronomy Division to set up a joint panel called Multi-Messenger Astrophysics Theory. This is another panel (in addition to the three mentioned above) that reviews some proposals in gravitational physics. This structure is working well, and has been largely funded through the Windows on the Universe program.

Looking towards the future, the gravitational physics program faces a potential crisis. The spectacular successes of LIGO has led to tremendous interest and growth in the field. There are several new faculty positions in this area and the number of proposals has been increasing. Due to the natural time delay for young people to get faculty positions, the growth so far has not been overwhelming, and is being handled with the influx of new funds provided by the Windows on the Universe program. However, that program might end soon, and the growth in the field will continue. **It is essential that a stable source of additional funds be identified to fully replace the Windows on the Universe program, if it is discontinued.**

The program director has made an admirable effort to fund the new faculty entering the field. Each year about ten grants are made to PIs who have not previously had an NSF grant and are less than 10 years from their PhD. He has also made an effort to support minority physicists.

The program continues to support the proposal writing mentoring program, which makes the proposal-writing expertise of senior members of the gravitational physics community available to junior researchers and has helped increase the success rate of proposals submitted to the program.

Awards in gravitational physics are usually 3 years long. To ease the workload of PI's and the NSF, we recommend that the program director consider the possibility of offering 4-year grants to established groups with at least two renewals.

3. Response to previous COV recommendations

The previous COV recommended that, if new money was available, it should be used to fund more postdocs. The program director has indeed followed this recommendation, using funds provided by the Windows on the Universe program to almost double the number of gravitational physics postdocs from about 12 to 22 each year.

They also recommended continued stewardship of third generation gravitational wave detectors and putting together a "blue ribbon panel" to advise on the best organizational structure for the future of multi-messenger astronomy. A panel has indeed been formed recently by the NSF to study all aspects of the next generation gravitational wave detectors (see Section 5 below).

4. Celebrating and building on LIGO's success

We recognize with profound gratitude the support that the NSF has provided to the Laser Interferometer Gravitational-wave Observatory over many decades, making it possible to open a completely new window on the universe and ushering in a new era of multi-messenger astronomy. Going forward, we face new important challenges. The gravitational wave research effort has grown dramatically. As NSF manages the growth of the current gravitational wave effort, it also is looking forward to a next generation of gravitational wave detector(s). Specific features of that effort are discussed below.

The LIGO Laboratory continues to be well managed by the Gravitational Physics Program, and the cooperative agreement with NSF is up for a 5-year renewal this year.

5. Leadership in Gravitational Physics

We commend the program directors for their excellent leadership and stewardship of the Gravitational Physics Program and the field.

The Gravitational Physics Program has supported a critical upgrade to Advanced LIGO that will enhance its sensitivity; starting this year the upgrade will result in more and better-characterized gravitational-wave detections. It has also supported a new outreach center, the LIGO Exploration Center in Hanford, WA, similar to an existing center in Livingston, LA, which will dramatically increase the broader impacts of LIGO Laboratory work.

The program has also supported the Gravitational-Wave Open Science Center (GWOSC), which provides the public and the scientific community with gravitational-wave data as well as software tools to analyze that data. Data are available from all currently operational gravitational-wave observatories: LIGO, Virgo, KAGRA, and GEO600.

To ensure continued US leadership in the field for the next decade and beyond, the program is convening a panel to study the landscape of next-generation gravitational-wave observatories in the US. This panel will make recommendations for potential facilities as MREFC projects that consider the full portfolio of national and international gravitational-wave and other observatories.

The Gravitational Physics Program has grown collaborations with funding agencies from other countries (e.g. Germany and Canada) to facilitate collaborative proposals from US and international researchers. It has also continued to facilitate the Gravitational Wave Agencies Correspondents (GWAC), the idea for which originated in NSF Gravitational Physics. The purpose of GWAC is to establish a closer link between funding agencies from around the world to coordinate medium- and long-term planning, and leverage synergies between agency capabilities to galvanize the field. Current member agencies include ARC (Australia), BMBF (Germany), CFI (Canada), CNRS (France), CONACYT (Mexico), DFG (Germany), European Space Agency (ESA), DAE (India), DST (India), FWO (Belgium), INFN (Italy), NASA (US), NSF (US), NWO (Netherlands), STFC (UK).

6. Responding to challenging budgetary climate

The Gravitational Physics Program has had more or less flat base-budgets over the past decade. The resourcefulness of program director Pedro Marronetti in securing co-funding from other programs in NSF is commendable, and has allowed the program to grow dramatically over the past few years. This growth has been driven by ground-breaking discoveries in the field. In 2022 almost half of the funding awarded to Gravitational Physics PIs was obtained from outside the Gravitational Physics program. Sources of co-funding include Windows on the Universe, CSSI (OAC), AAG (Astronomy), PFC, MRI, PIF/CP, RAISE, and other agencies.

In light of the importance of co-funding for the strength of the program, the panel is concerned about continued support for these programs. For example, the creation of the Windows on the Universe program was predicated on the ground-breaking success of LIGO in detecting gravitational waves from binary black holes starting in 2015 and neutron star binaries in 2017. Indeed, the first binary neutron star merger detected was accompanied by emission across the electromagnetic spectrum and ushered in the era of multi-messenger astrophysics. The number of such important discoveries, and the work necessary to make the most of them scientifically, will only increase in the coming years. Therefore, continuing to fund Windows on the Universe or identifying equivalent additional support for this research in the Gravitational Physics program is essential.

The success rates of proposals in the Gravitational Physics Program are higher than the PHY and NSF averages. This is due to the co-funding efforts of the program director described above, the proposal mentoring program, and also the practice of funding as many high-quality proposals as possible by (sometimes significantly) reducing proposed budgets. This inclusive practice increases the PI diversity as well the institutional diversity of valuable contributors to Gravitational Physics, and the sub-committee believes it might benefit other programs at NSF.

7. The NSF's stewardship of next-generation gravitational-wave interferometers

The LIGO detectors have received support for an upgrade of the facilities to Advanced LIGO+ (A+), which via the so-called fifth observing run (O5) will deepen our view of the universe by increasing the detection rate to better than once per day. As new multi-messenger discoveries trickle in over the next three-five years, it is also key to enable multi-messenger astronomy to reach its longer-term full potential - a priority recognized also by the National Academies' 2020 Decadal Survey on Astronomy and Astrophysics. More specifically, while incremental LIGO upgrades will continue for years to come in the so-called post-O5 era, a qualitative leap in sensitivity requires new larger facilities, as highlighted in the NSF-funded "Cosmic Explorer Horizon Study" (successfully delivered recently by the NSF-funded Cosmic Explorer team).

Cosmic Explorer (CE) is a US concept for the next-generation observatories that will supersede the existing LIGO, with a factor of ten in sensitivity and reach, and hundreds of thousands to millions of gravitational wave detections per year. While the scientific payoff of a next generation of observatories is clear, the path to their funding in the US is currently not as clear. In this respect, the gravitational wave community is in great need of continued stewardship by the NSF. In addition to supporting the DAWN meetings and the GWAC, the program director Pedro Marronetti, directly responding to a recommendation of the 2019 COV, has put together a panel charged with making recommendations on potential candidates for next generation observatories as MREFC projects. This committee has been tasked to consider the existing gravitational wave detection network as well as all national and international observatories that could potentially be operational next decade. We commend the program director Pedro Marronetti for pushing forward this panel, and we look forward to its recommendations. We highlight the importance of a continued interaction between the panel and the broader multi-messenger community.

Going forward, we strongly recommend that the NSF's active stewardship of the next-generation gravitational wave detector effort, described above, remain a high priority. Pathways for funding of major gravitational wave detector upgrades must be identified swiftly and capitalizing on the amazing success of LIGO, so as to ensure that talent in the field continues to be developed, and relevant expertise isn't lost. We remark that both the funding level, and the timeline of the funding in relation to the development of the human capital, are critical in enabling the US to continue playing a leading role in ground-based gravitational wave detection over the next 10-20 years.

8. LIGO Scientific Collaboration

The LIGO Scientific Collaboration (LSC) is responsible for organizing, carrying out, and publishing the results of the analysis of LIGO data. As evident from publications such as those announcing the discovery of the black hole binary GW150914, the neutron star binary GW170817, the detection of several black hole - neutron star binary candidates, and the latest GWTC3 catalog reporting many more examples of LIGO detections, the LSC has made a tremendous impact on the field and continues to provide the collaborative environment needed for delivering timely results on an outstanding research portfolio, as well as for training the new generation of gravitational wave scientists. The LSC was responsible for organizing the research and the "visioning exercise" that led to the design of Advanced LIGO, the instrument that succeeded in discovering gravitational waves, and its "Aplus" improvements (O5 run). The LSC is also working to develop a vision for the post-O5 era. Hence, we strongly advocate for continued and increased support of LSC scientists and LSC efforts, via NSF individual grants.

The program director has been particularly mindful about making the gravity program accessible to new investigators located at a variety of institutions including minority-serving ones. We commend this aspect of the program. At the same time, the program director has recognized the value of independent investigations of LIGO data by non-LSC scientists: we believe this is fundamental to strengthen diversity and scientific progress (see also the considerations made about the LIGO open data).

As multi-messenger astronomy continues to make progress toward becoming a mature field, efforts by the LSC for engaging with other communities continue to grow, and we strongly emphasize the importance of their continued and strong support, for example via joint conferences and workshops. This is also relevant to ensure that a broad consensus is built within the scientific community for the next generation of gravitational wave detectors (see previous discussion) and, more generally, the future of this field.

E. Integrative Activities in Physics

1. Introduction

The Integrative Activities in Physics (IAP) Program is a comprehensive and holistic unit that plays a vital role in leading the Physics Division toward meaningfully contributing to the Director's strategic vision, which prioritizes three operational objectives: 1) advancing the frontiers of research, 2) ensuring inclusivity/accessibility, and 3) promoting global leadership. Given the diversity of its funding mechanisms and their reach across the entire field and community, the IAP program also plays a role in advancing the nation's agenda for broadening the participation of marginalized groups in physics and physics related fields. Together, the programmatic roles of the IAP – both within and beyond NSF – combine to position this unit as a critical resource for 1) continued cutting-edge discovery and innovation in physics, 2) cultivation of a competitively-trained, progressive, and forward-thinking workforce, and 3) promotion and promulgation of the voices of those with a sophisticated understanding of the physics and physics education enterprises into the public discourse. Therefore, the review of the IAP program portfolio by this subcommittee takes into consideration the criticality of this unit to the Division, NSF, and to the broader scientific community.

In this report, we make particular note of several overarching and recurring traditions, practices, and beliefs that are either facilitating or undermining the role of the IAP program and, ultimately, the capacity of the Division to address 21st century research questions. Collectively, these conditions have created a recurring mismatch between the Division's stated goal for research excellence and its positioning of integrative activities outside of the boundary definitions of excellence. For example, we call attention to the published and reappearing language that describes and positions the IAP program as the program that "*accepts proposals through the NSF-wide REU solicitation and through other solicitations that do not easily fall within any of the other primary disciplinary areas*." Identifying one of the Division's largest contributors to the NSF broadening participation agenda as something that "doesn't fall easily within any other primary area," undermines the Division's efforts to "promote the progress of science," minimizes the impact principal investigators (i.e., REU PIs) can have on their campuses and throughout the physics community, and potentially reduces enthusiasm for the IAP program. Separating the *scientific results* of physics from the *ways* in which physics is done (and *who* gets to do it), dangerously perpetuates the myth that physics is culture-free and seeks objective truth that is independent of the human experience. This leaves the NSF open to charges of lack of epistemological sophistication, as well as potentially subjugating the broader impacts criterion to the intellectual merit criterion while also inadvertently pushing away those who can, and want to, use the IAP program to achieve socially significant broader impacts. **It's not only that people need physics; physics also needs people.**

This subcommittee commends the IAP program for its deep commitment to, and overall success in, supporting a diverse awardee portfolio, while also balancing its budget allocations, and expanding its award mechanisms. In doing so, we draw a clear distinction between these *broadening participation* efforts and the other *broader impacts* efforts across the Division that, in and of themselves, do not necessarily lead to the kind of outcomes that are likely to advance the Director's objectives, or "three pillars." Indeed, without more of the intentionality toward accessibility and inclusion that has been demonstrated by the IAP program, the Division – and the NSF at large – is likely to fail in its reaching desired levels of global leadership in science and engineering. Indeed, after a long time of engaging in independent (and largely incoherent) attempts to decrease underrepresentation in physics, the field has not reached the desired outcomes. If the physics community continues to do what has been done in the past, logic and history suggest that it will continue to reproduce the status quo.

Overall, our recommendations are intended to call attention to potential organizational blind spots and ensure the next COV review can more deeply examine the organizational contexts that are influencing the IAP program and how it is positioned as a necessary and important feature of the Physics Division. We strongly believe that all PHY programs share in the responsibility and can contribute meaningfully to confronting the underrepresentation of historically marginalized groups, relying on the literature that details what works, for whom, and under which conditions it works best. Further, we posit that PHY, through the demonstrated success of the IAP program, is uniquely positioned to urge and support all PHY principal investigators to apply the same standards of excellence used in conducting physics research to the areas of their work that involve education, mentoring, and outreach.

2. Review of Proposals

The IAP program subcommittee is composed of three individuals with diverse disciplinary expertise and lived experiences. Collectively, the subcommittee reviewed electronic jackets dating between FY2019 and FY2022. Jackets reviewed were associated with several programs of the IAP program, with emphasis on the Research Experiences for Undergraduates (REU) program. In addition to electronic jackets, the subcommittee also reviewed extensive background information about the program and the division as a whole, including the Division Information and Statistics Report, 2019 COV Final Report, and other ancillary materials and relevant websites.

A series of two virtual meetings were held to make sense of materials provided, raise questions, and develop a cohesive report that details our findings and offers what we feel are important suggestions and recommendations for the Division to consider as the IAP program evolves and hopefully expands to embrace a diverse community of scholars and practitioners. Our major findings are related to various program areas.

Program Area 1: Alignment.

In its review, the subcommittee notes the very reasonable alignment of the Physics REU guidelines with the overall REU solicitation. However, we caution that the Division may miss the opportunity to solicit collaborative proposals for multi-REU site proposals – a distributed model that could be based on, and used to leverage, the strengths of several individual local sites. Already, there are successful models of this design for teacher research experiences, on which IAP can build.

Program Area 2: Diversity of Funding Streams.

The IAP program portfolio includes a “smorgasbord” of projects, all significant. We appreciate that large and unique projects such as the KITP are evaluated individually and not in direct comparison to smaller projects. We also highlight the indispensable role of IAP in funding physics-specific education research projects, which might otherwise be overlooked, deemed less significant, or over-generalized. Indeed, the particularities of the history of physics, the epistemology of physics, and the sociology of physics cannot be blended into an amorphous “science” without significant loss to physics. In particular, the educational challenges that the mathematization of physics brings to upper division and graduate-level physics students is, and should continue to be, a robust area in the IAP portfolio.

The subcommittee also notes that there is an emerging area of physics education in which the IAP program can play a stronger role, particularly basic research on the persistence of marginalized groups in physics, factors that negatively impact physics belongingness, and ways to overcome social threats to that sense of belonging. The importance of such research cannot be overstated, especially in view of the growing public response of some members of the physics community who have publicly denigrated ideas and views that suggest otherwise. **Physics needs more research, not less, in this area. Relegating this type of research to other NSF directorates is likely to dilute the distinctiveness of, and relevance to, the physics enterprise by incorporating it in a much larger, over-generalized STEM context.**

Program Area 3: Reviewers and the Review Process.

In all jackets to which the subcommittee had access to, the panelists had the requisite expertise and life experience to provide substantive feedback to the applicant and the program officer. Demographic data of reviewers for the REU program over the past three fiscal years revealed a noticeable increase in the percentage of women reviewers from approximately 22% to 44%. While this represents an important shift in ensuring that reviewers are diverse and representative of the entire audience that is capable of advancing the field, it should be noted that there were several instances where the diversity of reviewers was less than ideal. For example, for several non-panel proposals, the gender of all reviewers was the same. Also, for several panels, two panelists from the same institution were included. In many cases, it seems that women and men from racially minoritized backgrounds were represented at levels that are far below critical mass (approximately 30%). In order for the Division to ensure that the perspectives and views of diverse reviewers are meaningful to the review process – and that the review process itself is fair to them – keen attention and additional effort is needed to avoid including only one reviewer from any single group at one time. Rather, attention should be paid to optimizing the conditions whereby reviewers from diverse communities can participate in review panels without being the sole representative of their intersectional lived experiences. Indeed, the subcommittee recognizes that for panels reviewed as part of this COV review, some were managed by other program directors while Dr. McCloud was on detail; and that these panels were convened during the COVID-19 pandemic.

This subcommittee notes that the sophistication of panelist reviews can be improved. In many cases, there were weak reviews submitted by a few panelists on REU panels. In general, the weakest reviews were associated with proposals that were ultimately approved for funding, while more substantive reviews were submitted for proposals that were ultimately declined. While it is indeed the case that panel reviewers were likely responsible for completing more reviews than an ad hoc reviewer might, it was still disappointing to see several reviewers in the REU panel provide less informative reviews of which applicants who are declined would likely find little value. On the other hand, the panel summaries (for both the REU and PREP programs) were very informative for both the applicant and the program officer. The subcommittee also notes that the use of the same review team for proposals with similar topics was ideal for generating consistent feedback without the use of a panel.

Program Area 4. Attention to Broadening Participation.

Overall, we note that the efforts of IAP programs to broaden participation in physics are of unequal sophistication. We encourage the Division to empower funded PIs to go beyond counting numbers of participants who come from communities that have historically been excluded from the physics enterprise, writ large. Promoting PI collaboration with savvy, substantive, and evidence-based national physics education and outreach efforts implemented by experts is better for the field. In general, physics broader impacts can – and should – be multiplied beyond simple arithmetic targets to include generalizable knowledge on what works, for whom, and under which conditions.

3. Management of IAP Program

This subcommittee recognizes and acknowledges the efforts of the lead program officer, Dr. Kathy McCloud, in managing the IAP program with professionalism, unwavering commitment to broadening participation, and a mission of supporting excellence. Her thoroughness, priority setting, command of several bodies of literature from various disciplines, knowledge of and appreciation for the IAP community of scholars and practitioners, and effective discharge of her duties is exemplary. It is noted that PO McCloud's choice to prioritize and expand the role of REU proposals within the IAP program scope is consonant with the potential positive impact that the IAP program can have on the Division, at large.

Additionally, the service of other individuals who filled the program director position over various time frames during the program period under review is noted.

4. Recommendations

We argue that the significance of broadening participation, particularly for men and women of color, to both the Division and the field has been understated and the urgency for deep, systemic changes at the programmatic and Division levels intensified. Based on its review of the IAP program portfolio, the subcommittee offers the following recommendations:

- **Recommendation #1: Opportunities for Systemic Change.** Admittedly, there are no quick, one-and-done solutions that would ensure that the major tenets of the IAP program are well integrated throughout the entire Division. This is particularly true for IAP's efforts targeted toward broadening participation. As an important initial step, the Division is encouraged to identify suitable and appropriate language for the IAP program, naming and describing it and the new and emerging areas of physics that it funds in ways that are consistent with other research programs. The Division is encouraged to consider that such language is critical to its alignment with the NSF Director's "three pillars" and the Division's outreach efforts to audiences that have historically been marginalized from PHY's funding enterprise.

- **Recommendation #2: Promotion of the IAP program.** The subcommittee encourages the Division to seek additional and novel mechanisms for promoting the IAP program across its entire PI community and beyond. We note that addressing Recommendation #1 is integral to this effort. Additionally, the subcommittee sees the advantage of targeted Dear Colleague Letters in addressing this concern.

- **Recommendation #3a: Reviewer Proposal Load.** While proposal load is approximately 8 to 10 proposals per panelist at this time in the REU program, if the proposal pressure increases to pre-pandemic levels in the future, ensuring that the panelist and the program officer have the capacity to thoroughly review and thoughtfully discuss the full set of proposals is essential.
- **Recommendation #3b: Program Infrastructure.** The increasing need for cross-division collaboration has been met with a relatively modest investment in the program's infrastructure, to date. There is only one cognizant program officer. Yet, the PO workload has dramatically increased and expanded in recent years to include LEAPS, ASCEND, and PREP, in addition to IAP. While the goal should not be to relieve PO McCloud from any of these responsibilities because she possesses the institutional memory and skillset to ensure their continued success, there should be attention paid to increasing the human resources available for managing this critical suite of program activities. To that end, this subcommittee recommends the addition of at least one additional FTE, ideally an NSF rotator who would have the capacity to contribute to the intellectual rigor of integrative activities and the flexibility needed for conducting site visits and performing other duties as needed.
- **Recommendation #4: Resource Sharing.** It's a bit surprising that the REU panel feedback does not point applicants to the resources publicly shared by the Physics REU site directors on the NPRLG website when providing feedback on how to improve their proposals (whether they are recommended for funding or not). NPRLG itself, their conferences, and the resources they share are a valuable source of effective practices (many of which are evidence based). In addition, a funded analysis of longitudinal REU data collected by CIMER over the past several years is likely to have large enough sample sizes, individual item responses, and statistical power to guide the conceptualization and implementation of meaningful changes to REU programs. There is also an extant literature base on research experiences for students that PHY REUs can tap into and be guided by; PIs should be expected to build on that scholarship and ideally contribute to it.
- **Recommendation #5: The REU Program.** This subcommittee offers the following suggestions for modifying REU program guidelines and cultivating a robust community of practice among current and potential REU awardees. They are to:

  <u>Make funding parameters more transparent.</u> Currently, there is no formal mechanism for current or potential REU PIs to learn that 4- or 5- year site awards may be considered for experienced sites. Further, for new REU PIs, it should be made clear whether or not there is an expectation that new awards are funded at the 3-year level only, with potential for consideration of 4 or 5-year funding provided the award demonstrates success programmatically and fiscally. As appropriate, for PIs with 3-year awards, it should be explicitly stated that decisions for continued funding may, in part, depend on the quality of student experiences both in and outside of the laboratory.

  <u>Clarify vague language in the solicitation.</u> Currently, the solicitation limits REU proposers to 15 pages. This leads to proposals that fall short of fully describing either the scientific merit or coordination of student professional development within the 15-page limit. This dilemma could

potentially be overcome if the inclusive institutional practices aimed at student professional development activities or the description of the planned research could be included in a separate section of the proposal (i.e., the Facilities Section) or as a required addendum to the proposal. This will ensure that PIs understand the importance of both sections and reviewers are able to easily find these details; and these sections aren't competing with each other within the proposal.

Emphasize what is meant by inclusion. Too often, the Prior NSF Support section of the proposal requires applicants to include specific data tables of student demographics and lists of articles. However, these tables may not capture the full narrative of how broadening participation occurred as a result of prior NSF funding. This subcommittee encourages the IAP program to encourage applicants to complete these tables and also discuss, in narrative form, the impact of prior funding, including program evaluation results ad evidence of program effectiveness.

Underscore evaluation as a necessary component of all REU sites. Given the potential for evaluation to significantly improve and make sense of program outcomes, this subcommittee feels it is important to require all REU programs to utilize proven evaluation tools and instruments as a condition for continued or renewed funding. This will elevate the significant contributions of REU sites to the body of knowledge beyond mere anecdotes in annual reports about a small number of students at a single site to appropriate generalizations that can be made for the program, at large. relevant information about a program and that single site in the context of the program.

F. Nuclear Physics, Theory and Experiment

The NSF Nuclear Physics programs in Theory and Experiment fund a wide variety of research activities aligned with the strategic priorities of the field laid out in the 2015 Long Range Plan of the Nuclear Science Advisory Committee (NSAC). These include the properties and structure of nuclei, tested with various probes; nuclear reactions, ranging from single nucleon to heavy ion collisions; nuclear information for astrophysics; and tests of neutrinos, neutrons, and fundamental symmetries. Nuclear science connects directly to other fields like astrophysics, atomic physics, elementary particle physics, gravitational physics, quantum information science, and more. In the following, we report on our review of the NSF Nuclear Physics programs, covering both Theory and Experiment, as part of the 2023 Physics Committee of Visitors.

1. Summary of Findings and Recommendations

Observation: *The NSF Nuclear Physics programs fund outstanding research.*

Projects supported by NSF Nuclear Physics (NP) address fundamental topics in the nature of visible matter and its interactions. NSF identifies four broader areas, Nuclear Structure and Nuclear Astrophysics, Nuclear and Hadron QCD, Nuclear Precision Measurements and Nuclear Theory. Experimental Work is done at national accelerator facilities, underground laboratories, university facilities, and other government laboratories. All priority areas take advantage of new facilities and experiments, which are leading to scientific opportunities in the present or near future. NSF-funded research is positioned to provide scientific leadership in all these areas.
The new FRIB facility at MSU has begun operations in 2022, opening new discovery potential in Nuclear Structure, Nuclear Reactions, Nuclear Astrophysics and Nuclear Precision studies. Nuclear Structure research on the most exotic nuclei will elucidate the quantum many-body problem at the limit of binding through the strong force, challenging the most advanced theories of nuclei. Properties and reactions of the same exotic nuclei determine the pathways in which astrophysical events synthesize the elements, be it through Supernovae, neutron-star mergers or other cataclysmic events. FRIB promises to calibrate the nuclear physics needed to interpret the ever-more detailed and precise astronomical observations.
The NSF-supported NSCL facility has pioneered this field over the last two decades and laid the groundwork for the scientific program at FRIB. Although the facility funding has moved from NSF to DOE in 2021 when with the NSCL transformed to FRIB, NSF has maintained support for many of the leading groups working at FRIB, at MSU and other institutions, ensuring a continuing leadership role in this field. Simultaneously, the NSF-supported facilities at FSU and Notre Dame provide scientific and educational diversity, essential to the health of the field.

Research in Hadrons and QCD is focused on understanding how the properties of strongly interacting systems such as protons, neutrons, (light) nuclei and mesons arise from the interactions of quarks and gluons. The 12-GeV CEBAF facility creates new opportunities to investigate hadron structure at short and long distances, and detailed spectroscopy of excited QCD exotic states. The physics of QCD in hot-dense systems, has been pursued at the RHIC facility of Brookhaven National Lab (BNL) as well as the

LHC of CERN, investigating QCD matter at the highest energy and temperatures reached in the laboratory. BNL has begun its transition to build the next large (>$2bn) facility in nuclear science, the electron-ion collider (EIC). The EIC will be, worldwide, a unique accelerator facility which allows to explore fundamental science questions including the mass and spin decompositions of the proton in QCD, the multi-dimensional quark and gluon structure of hadrons, and a potential new state of strongly-interacting matter at very high gluon densities. The NSF already has visibility in the EIC science, which could further grow with targeted investments in experimental and theoretical activities.

Research in Nuclear Precision Measurements uses nuclei, neutrons, neutrinos, molecules, and nuclear-physics techniques designed to probe the foundations of the Standard Model of electroweak interactions and to search for new physics beyond the Standard Model (BSM). The NP program at NSF is very active in this area, with many exciting projects underway. Neutrinoless double beta decay experiments are making good strides toward understanding the nature of neutrinos, with the upcoming goal of reaching the ton-scale and potential discovery level results. Many other projects are probing different aspects of the standard model, searching for dark matter, probing sources of CP-violation, looking for new forces, and so on. Investments in upcoming larger-scale experiments such as those currently supported by ENP Midscale funding (LEGEND-200, nEDM@SNS, MOLLER@JLAB, MUSE, and BL3) will all provide important advances in these searches. Other new ideas, such as the use of polyatomic molecules in electric dipole moment (EDM) searches and other searches for Symmetry Violating Hadronic Physics represent new areas of growth and collaboration with other divisions in PHY.

Nuclear Theory addresses the structure and reactions of nuclei, and of hadrons in few-nucleon and nuclear environments, as well as the quark/gluon substructure expressed by QCD, with significant NSF-supported contributions over the last years. The work is closely related to astrophysical phenomena and to experimental programs at facilities such as FRIB, RHIC, the Jefferson Lab, and the future EIC. The field deals with new approaches for theoretical, computational, and experimental research that explore the fundamental laws of physics and the behavior of physical systems; formulating quantitative hypotheses; exploring and analyzing the implications of such hypotheses analytically and computationally; and interpreting the results of experiments. Additionally, there is significant overlap with quantum information science.
Work in Nuclear Theory is critical for the experimental efforts to fully reach their discovery potential. Also, theoretical studies are needed for identifying new areas and coming up with transformative ideas. The 2019 COV Report stated explicitly that the Nuclear Theory Program was undersized to maximize the benefits of the experimental program and recommended an increased budget. While Centers and collaborative grants have helped theory in specific areas, an overall problem remains with the small size of individual grants.

<u>Recommendation</u>: *In order to maintain NSF leadership in nuclear science, support for experimental and theoretical research in this area should be allowed to grow with the priorities guided by the NSAC Long Range Plan and new emerging opportunities.*

<u>Observation:</u> *Nuclear Physics provides outstanding opportunities for connections to other science areas, and NSF Nuclear Physics makes excellent use of cross-cutting funding initiatives*.

Many projects supported by Nuclear Physics address interdisciplinary topics. There are emerging new opportunities for cross-cutting science where nuclear physics expertise is critical. The NSF Nuclear Physics programs can contribute significantly to these forefront areas, through funding single investigators and small groups that can push transformative ideas and provide outstanding student and postdoc training. Theory is especially important for opening new areas and for connecting topics.

NSF Nuclear Physics has successfully contributed to and benefited from foundation-wide opportunities, like the Windows on The Universe (WOU) initiative, which is partially supporting several projects in the area of nuclear science helping interpret multi-messenger-astronomical observations.

Quantum information science (QIS) and artificial intelligence (AI) are rapidly developing fields. AI has the potential to provide new insights and even discoveries from nuclear physics data, including the correlation of experimental and computational data. There are also emerging opportunities for outstanding cross-cutting science where nuclear physics expertise is critical. The extensive expertise developed by nuclear physicists in shielding against cosmic rays and in the fabrication of radio-pure materials to suppress backgrounds can play an essential role in improving the coherence times of qubit-based systems. Quantum computing (QC) has the potential to revolutionize the study of strongly correlated many body systems.

The field of nuclear physics can highly benefit from understanding how AI and QIS can enhance discovery and boost NP goals. Continued support for interdisciplinary centers and consortia will ensure the full realization of NP contributions to QIS and AI, and vice versa, as well as close collaboration among national laboratories, universities, technology companies, and startups.

Suggestion: *Cross-cutting funding sources should be further strengthened, with a particular emphasis on the QIS and AI expertise in the Nuclear Physics workforce.*

Observation*: The NSF Nuclear Physics portfolio benefits from excellent management.*

Nuclear Physics Experiment and Theory each have permanent program directors. (Experiment also has a temporary staff rotator.) Generally, the main program directors serving for a longer term (as is currently the case) is beneficial for continuity and for finding new ways to support outstanding science. Rotators can bring in new ideas. Each proposal review was typically based on ad-hoc reviews, panel reviews, panel summary, and an excellent concise review analysis by the program director. In their decisions, the program directors carefully weighed the intellectual merit and broader impacts of a proposal, by taking into account the reviews and the outcome of the panel discussions, general Foundation policies, and the need to maintain appropriate balance among subfields. This was done by paying close attention to the recommendations of the NSAC Long Range Plan. Overall, the COV finds that the current program directors are considerate and efficient managers who have consistently shown outstanding judgment, and as such served the nuclear physics community in the best way possible.

Recommendation*: Maintaining the processes in NSF Nuclear Physics with longer-term and devoted program directors, supplemented by temporary rotators, is critical for the quality of its portfolio.*

Observation: *NSF NP recognizes the importance of Broadening Participation and is working to support that goal in the NP community.*

Significant effort has been placed to increase underrepresented minority (URM) groups' representation in the program's portfolio. These efforts include support for research activities at minority-serving institutions (MSIs), including collaborations such as the HBCU Collider Collaboration and the LEAPS program. DEI activities are also highly encouraged to be included as part of the research awards, including outreach events and training and mentoring of students from URMs.

Nonetheless, MSI awards are often made to R1 universities, with few awards made to non-R1, primarily undergraduate institutions which could benefit from the support to build the infrastructure and expertise needed to submit a competitive proposal.

We observed that program managers put special effort into ensuring that the diversity in the panel reviewers reflected the statistics in the APS DNP unit membership.

Recommendation: *Continued support for DEI and activities that broaden the participation of URMs in the field of nuclear physics is vital for ensuring a diverse pipeline for the next generation of scientists. Nonetheless, special attention should be placed on ensuring that small universities not currently part of the NP portfolio have access to NSF.*

Observation: MRI grants have been a very useful tool in broadening research opportunities to smaller groups and provide education opportunities in hands-on instrument development, but overall budgets have stagnated or shrunk over the last decade.

Recommendation: *We encourage strengthening the MRI program Foundation wide.*

2. Description of COV Review Process

The Nuclear Physics COV review process followed the procedures and rules of the general Physics COV review process, as described in the overall report. The Physics Division supplied substantial information on its operations over the past four years, as well as the 2019, and prior Physics COV reports and responses. We also reviewed the response of Nuclear Physics to the recommendations of the 2019 COV subcommittee. For Nuclear Physics specifically, we were provided additional information by the program directors Bogdan Mihaila (Theory; he also covers Physics at the Information Frontier) and Allena Opper and Alfredo Galindo-Uribarri (Experiment). We were also given access to many proposals and associated documents through the eJacket system, where these proposals were selected by the program directors to provide a representative sampling. Each jacket was assigned to one of our four-person subcommittee as primary reader. Careful attention was paid to managing conflicts of interest. In addition to email discussions, our subcommittee held three video conferences (including the program directors for parts of these meetings) prior to our in-person meeting in Washington in January 2023. The program directors were extraordinarily helpful and forthcoming at providing factual information and explaining their perspectives. All decisions of our subcommittee, and the text of this report, reflect our consensus opinions.

3. Merit Review Process

The review process has three parts. First are individual reviews, which are written by ad hoc reviewers (typically 1-4 per proposal) as well as by panel members – most proposals have 2 panelists who write individual reviews, while the larger ones have 3. For the ad hoc reviews, the response rate is around 80 %, which suggests good community support. While the NSF requirement is for 3 independent reviewers, having a larger number of reviewers, as is typical in nuclear physics, is beneficial to the quality of the review process. In particular the role of the ad-hoc reviewers is very important and should be maintained or increased. The reviewers are selected according to the required expertise and generally provide substantive and meaningful comments. The quality of the individual reviews is generally very good, with some being excellent, and a few rather lacking. The larger number of individual reviews means that even if one review is short or lacking in substance, the other reviews easily make up the slack.

Certain large proposals may also have a site visit by a panel charged by NSF to closely review the group and submit a written report; those that we reviewed were thorough and well considered. The use of site visits seems to be appropriate.

The second part of the review process is the panel reviews, with 10-12 members for Theory and 16-20 members for Experiment. Again, this relatively large number is crucially important to the quality of the process as it provides both a sufficient range of expertise and enough opinions to draw a clear consensus. The experimental panels included theorists and vice versa, which is good practice. The composition of the panels was fitting for reviewing the suites of proposals. The panel reviews explain the rationale for the rating in detail. In cases where there was significant variation across individual review ratings, the panel summaries explain how the panel weighed the various reviews in reaching consensus. High-quality summaries were written by the panel for every proposal reviewed by the COV.

The final part of the review process is the assessment by the program directors. The review analyses prepared by the program directors are of high quality. They summarize and reflect on the input from the previous steps as well as provide insight that places the proposal in the larger context of the program, and its strategic priorities and goals. They give the appropriate rationale for funding decisions. This summary information is valuable for the program, for communicating with PIs, for helping new program directors understand the history and scope of the program and other aspects.

In 2022, the Physics Division switched to an abbreviated review analysis format. This abbreviated review analysis works well. It includes all of the necessary information, includes summaries of the reviews and panel; still includes the program manger's own opinions where relevant, and includes details that deviate somewhat from the panel (such as identifying the strategic importance of a particular proposal to the NP program). It also gives more consistency between program managers, which is a benefit.

We observed that across the full range of the review process, both intellectual merit and broader impacts criteria were addressed and considered appropriately, and were used appropriately in the proposal ranking and funding decisions. However, we found that there was significant variation in the quality of the individual reviews (both ad hoc and panelists) of the broader impacts criteria. Reviewers are given examples of what qualifies as broader impacts, and what the criteria are, although not everyone paid careful attention to that information. The panelists are given additional instruction by program directors, particularly on the need for a broader impacts discussion – to have a plan and success metrics, not just general statements. These instructions seem to improve the overall discussion of broader impacts by the panel as expressed in the panel summaries. Perhaps, there is a way to more effectively communicate the necessary elements of broader impacts with the PIs and to the individual reviewers in a similar manner.

While the ad-hoc reviews generally reach consistent conclusions about the overall merit of a proposal, this is not always the case and there appears to be more of a range of opinion in the Theory proposals. Because the panel reviews are comparative in nature and consensus-driven, they can make clear recommendations, even when the ad-hoc reviews do not. Further, in cases where the panel's ranking does not appear to agree with the ad-hoc reviews, the reasoning is clearly described and well-considered. The independent assessment by the program director provides an additional layer of context and provides the rationale for the funding decision.

The program directors put significant effort into managing conflicts of interest. Selecting (ad-hoc) reviewers with the proper expertise, which at the same time have no conflict of interest, can be difficult and requires a good knowledge of the community. Some conflicts of interest among panelists are difficult to avoid. The program directors properly handled such cases, with conflicted reviewers having no access to those proposals and not participating in the discussion of them.

The program directors paid a lot of attention to selecting panels that are diverse in various respects, including but not limited to area of expertise, level of seniority, gender, race/ethnicity, type of institution, and geographic location. Diverse panels are needed for an in-depth and objective review process. Regarding broadening the participation, the panels had fractions of women ranging from 20% to 40%, as compared to about 18% in the APS DNP. Up to about 15% of the panel members were from under-represented minorities. We also observed an appropriate rotation of both ad-hoc reviewers and panel members to ensure mixed perspectives and to avoid overburdening certain individuals, especially those from underrepresented groups. This rotation also helps to inform the entire community on how the proposal review process works, an experience that is particularly valuable to early career scientists in helping them to craft better proposals themselves.

We observe that the nuclear physics program makes diligent use of the information obtained in the various layers of the merit review process. Judging from the examples reviewed by the COV, the decisions are made in a well-designed and well-executed process. The individual reviewers, the panel, and the program directors take the job seriously and produce substantive and well-reasoned documents. High priority and high-quality research are being identified and funded. While there is some minor room for improvement, overall, the review process in nuclear physics (both experiment and theory) is excellent.

Other Aspects of the Review Process

Sometimes proposals are co-reviewed, which is important for building interdisciplinary science, as new topics emerge at the boundaries of traditional disciplines. Although co-review may be requested by the proposer, this decision is typically made by the program directors, which is preferred, because the program directors are better informed of opportunities and which proposals might be competitive for them. Co-review can occur with other programs in Physics or with other divisions within the MPS Directorate. We saw a few such examples of co-review in the jackets we reviewed.

The nuclear physics program directors take good advantage of co-funding opportunities that further NSF goals and increase the impact of awards. These other avenues include the Integrative Activities in Physics and the Physics at the Information Frontier programs in Physics, the Office of Multidisciplinary Activities in MPS, the Office of Advanced Cyberinfrastructure in CISE and the WOU-MMA initiative. Co-funding is typically decided by the cognizant program directors.

Once grants are funded, they are subject to annual review by the program directors. We found that, although there was considerable variation in the responses, the annual reports submitted by the PIs were generally substantive and informative. In the cases we reviewed, we believe the program directors made appropriate choices in the continuation of funding.

Communicating Reviews to Proposers

After the review process is completed and concurred by Division management, PIs are informed of the decision by the program managers. The PIs are notified via a letter from the division that includes a context statement on that year's funding and review information as well as the text (minus any necessary redactions) of the individual reviews and the panel summary. The information supplied is detailed and can help the PIs develop better proposals. In addition, the program directors are available to give additional feedback, if and as requested, to the PIs, typically via phone calls. This additional availability and discussion are very important in helping the PIs to develop better proposals.

4. Management of the Program

The nuclear physics programs in experiment and theory are run by two program directors with the support of one temporary rotator. The Experimental program is subdivided into Nucleon and Hadron QCD, Nuclear Astrophysics, Structure, and Reactions (including accelerator facilities at Florida State University and the University of Notre Dame), Nuclear Precision Measurements, and the National Superconducting Cyclotron Laboratory (NSCL). Experiment and Theory are separate programs but managed in coordination and with very similar procedures.

The long-term priorities of the field in Nuclear Science are set through a community-driven process administered through the Nuclear Science Advisory Committee (NSAC), appointed jointly between the DOE Office of Science and NSF Nuclear Physics. The last long-range plan was published in 2015, and a new long-range plan process is currently ongoing, with a new document expected in 2023. NSF NP aligns its science portfolio to the priorities identified in the long-range plan and is well positioned to support leadership science in emerging areas of nuclear research.

While the Department of Energy's Office of Nuclear Physics supports the majority of the national research program in nuclear physics, NSF is a critical partner through its investment in individual investigators, university groups, instrumentation, and university- based laboratories. The PIs supported by the Nuclear Physics programs are scientific leaders in their respective areas, and their programs provide a significant and fertile training ground for the next generation. As noted in the 2015 Long Range Plan, the two programs work in partnership "to maximize the scientific and societal impact of federal spending" in the field, guided by the community-driven planning process.

Over the years under review, the budget of NP Physics has undergone a significant restructuring, driven by the transfer of operations funding for the National Superconducting Cyclotron (NSCL) to the FRIB facility, which is now being supported by the DOE at the same location. While the NSCL operations budget dropped to zero over the course of 2020-2022, some of the funds were recovered into the research budgets, allowing reallocation into other parts of the portfolio. As an example of successful longer-term management of the NP program, a significant fraction of the scientists previously supported by the NSCL grant were brought into the NSF portfolio as smaller groups and in a staged approach. This allowed NSF-supported scientists to maintain continued leadership at FRIB.

The nuclear physics programs made good use of the NSF "Big Ideas" initiatives "Windows on the Universe" and "Harnessing the Data Revolution", which are represented in the current Nuclear Physics portfolio. Especially the "Windows on the Universe" has spawned many fruitful projects connecting NP with Astrophysics and the program would continue to have a significant continued impact if it is continued. NSF nuclear physics has also found opportunities for Mid-Scale instrumentation, supporting five such projects at present. Although not part of the proposals reviewed here, a new Focused Research Hub in theoretical Physics "Nuclear Physics from Multi-Messenger Mergers" was started in FY21, pursuing a research opportunity arising from the astronomical observation of neutron-star mergers. This center also exemplifies the continued leading role of NSF-supported scientists in nuclear astrophysics.

The COVID epidemic led to delays and disruptions in the progress of many projects. NSF NP was able to mitigate some of the worst effects on the careers of postdocs and graduate students by dedicated grant extensions and supplements.

The NP COV subcommittee discussed whether the three-year grant length is optimal for the NSF-funded grants, which was seen as a trade-off between greater efficiency for PI and PD in the administration of longer-period grants on one hand and greater flexibility to react to scientific opportunities and funding fluctuations for shorter-period grants on the other. Flexibility in the funding length would give PD the opportunity to optimize this balance depending on the nature of the grant in question.

Broadening Participation in Nuclear Physics

The NSF NP program directors are committed to the goal of broadening participation, as we observed in multiple aspects. We commented on the diversity of the review panels in the previous section. Proposals from PIs in underrepresented groups are successful at the same or at higher rates than average, a sign that the DEI aspects of the review process are well managed. The program directors have been actively promoting programs aimed at increasing participation of underrepresented groups at APS / DNP meetings and in other venues and encourage pre-application communication in order to remove thresholds. Special attention should be placed on ensuring that small universities not currently part of the NP portfolio have access to NSF funding.

Implementation of Recommendations from the 2019 COV Report

The NSF NP program seems to have taken actions to address the major points of the previous report.

<u>2019 NP-specific Recommendation 1)</u> *The NSF Nuclear Physics programs have outstanding new scientific opportunities that could be realized with new investments, especially in Theory. An upcoming*

transition in the NSCL stewardship associated with as increased DOE role is planned to have an associated transition of funds and PIs to the Experiment program, which we endorse. This could also provide critical opportunity to benefit the Theory program, which we strongly encourage.

2019 General Recommendation 6) *We suggest that the Physics Division examine the priority that is placed on postdoctoral support in grants, although we are not suggesting that there is an easy solution.*

In response to these recommendations, we noticed that some of the funds freed at the NSF by the transition from NSCL to FRIB were used to increase support in research funding, partially by supporting the previously NSCL-funded proposals as grants, but also by supporting other research grants. The observation of the 2019 report that Theory support is undersized to maximize the scientific impact of experiments, however, remains true. While additional funding in the form of Centers for specific areas has helped providing more support for postdocs, the size of individual grants is still on average at a critically low level. The Theory program director showed excellent judgment under these conditions, by not allowing the number of NSF-supported PIs to be reduced. In conclusion, while progress has been made, we repeat that especially the Theory Program remains undersized.

2019 General Recommendation 4) *Improvements should be made to the processes of collecting data on the diversity of proposers and their groups.*

The NP program provided the COV with meaningful statistics on the demographic information obtained from PI's. Collecting should be encouraged with annual reports. It appears that the comment has been addressed.

5. Resulting Portfolio of Awards

During the period of FY 2019 to 2022, the budget of both experimental and theory programs had a steady increase. The Theory program supported numerous individual investigators and several awards under the "Focused Research Hubs in Theoretical Physics" (FRHTP) solicitation. The Experiment program funded investigator awards as well as the support and maintenance of the National Superconducting Cyclotron Laboratory (NSCL). The Physics division recognizes the importance of supporting a diverse physics community that is inclusive of all groups. The NP program directors have consistently ensured that URMs are represented in the portfolio of opportunities, and this is reflected in the success rates of proposals by female PIs, which is well above the average in the experimental and the theory programs. Also, for PIs who identify as members of URMs, the success rate is high in both programs. These observations are evidence that such proposals are generally very competitive in the review process. Overall, we found that the resulting NP portfolio generally reflects the diversity of the field. For the PIs of awarded proposals, the fraction of women PI is about 18% for Experiment and 16% for Theory (averaged over four years). This is comparable to the fraction of women faculty in physics departments nationally. (For comparison, the fraction of women in the APS Division of Nuclear Physics membership is about 18%).

The award data for the Nuclear Physics programs for PIs at MSIs indicated that the number of awards to PIs at MSIs increased from two to five from 2019 to 2022 in the Experimental program and the same group had a high success rate in the Theory program. We concluded that the program directors have been proactive in taking advantage of programs from within and outside the Physics Division to support NSF's overall goal of increasing participation from under-represented groups. We also considered the distribution of awards in other aspects, including the proposer's professional seniority, level and type of research activity, type of institution and geographic location, and others. In general, new PIs have a slightly lower success rate than that of more experienced PIs, but the reasons for award declination are well described in the review summary. Overall, we found these additional aspects to be well balanced.

The theory hubs are a very important part of the Nuclear Physics program. They are designed to enhance significant breakthroughs at an intellectual frontier of physics by providing resources beyond those available to individual investigators. They have also been an effective instrument for postdoc support. During the period covered by this report, the "Network in Neutrinos, Nuclear Astrophysics and Symmetries" (N3AS) collaboration was successful in competing for a Physics Frontier Center award. The current FRHTP support is for the newly established "Nuclear Physics from Multi-Messenger Mergers" (NP3M). We also commend three new cross-cutting collaborative projects in Nuclear Theory: "X-Ion Collisions with a Statistically and Computationally Advanced Program Envelope" (X-SCAPE), "Modular Unified Solver of the Equation of State" (MUSES), and "Bayesian Analysis of Nuclear Dynamics" (BAND). They all address forefront scientific areas which are well aligned with the overall mission of the NSF.

Mid-scale Instrumentation

The nature of nuclear physics experiments makes them particularly well suited for the mid-scale funds made available at the division level. This creates an avenue for NSF PIs to have a strong, and often leadership, role in some of the most exciting projects that require a higher level of technical or instrumentation support than would normally fit within an investigator award. The projects that have been funded have been well vetted both for scientific merit and technical readiness and have strong management plans. The experiments funded under the PHY Midscale funding program includes BL3, MOLLER@JLAB, MUSE, LEGEND-200, and nEDM@SNS.

Major Research Instrumentation (MRI) Grants

Nuclear Physics has historically benefitted strongly from MRI grants, which allows for the development of innovative research instruments by a variety of university groups, used at a variety of experimental facilities. Over the course of the four years under review, funding for MRI in nuclear physics has been significantly lower than in previous periods. Maintaining a balance in funding between these smaller instrumentation projects and the mid-scale awards seems important to maintain a diversity of approaches in nuclear physics.

Cross Disciplinary Activities

As noted in the 2019 COV Report, the Division has been using the frame of an overall science portfolio rather than a series of individual programs. The Nuclear Physics program directors have been able to leverage this philosophy by co-funding proposals with other programs within Physics and with other divisions such as Chemistry and Astronomy, or with funds from the MPS Office of Multidisciplinary Activities or Integrative Activities in Physics.

6. Program Highlights

Nuclear Structure, Reactions and Nuclear Astrophysics:

NSF-funded research has maintained a leadership role in Nuclear Astrophysics, through the support of groups at the NSCL- now FRIB -, at Notre Dame and Florida State University as well as through the JINA Physics Frontier Center, connecting nuclear experiment and theory to Astrophysics and Astronomy.

Experimental work with radioactive isotopes, performed at the NSCL, FSU and Notre Dame laboratories is used to calibrate the pathways of explosive nucleosynthesis, which connect to astronomical observations of cataclysmic events. As an example, a collaboration of scientists from the National Superconducting Cyclotron Laboratory (NSCL) performed detailed spectroscopy of proton-resonances in S-31, populated by beta-decay (Phys. Rev. Lett 128, 182701 (2022)). The proton-capture reaction on the radioisotope P-30 is a "bottleneck" in the nuclear reactions driving classical Nova explosions. The experiment with the specialized GADGET detector system allowed the group to identify the dominant resonance by-passing this bottleneck, and thus to calibrate the thermal reaction rate. This work improves the precision of nuclear thermometers by a factor of four, where the abundance ratios of Aluminum, Sulfur and Phosphorus observed in Nova explosions are used to extract information on the temperature profile of the explosion.

The calibration of nuclear reactions occurring in the steady-state burning of stars require very different specialized laboratories, to measure the relevant miniscule nuclear cross sections at the lowest energies. With NSF support, the Notre Dame group has installed a dedicated small accelerator called CASPAR at the Sanford Underground Research Facility, 4850-foot underground. The low background of natural radiation allowed the group to measure the miniscule cross section of the $^{18}O(\alpha,\gamma)^{22}Ne$ reaction, which is an essential part of a reaction chain that produces the $^{22}Ne(\alpha,n)^{25}Mg$ neutron source for both the weak and main components of the slow neutron-capture process in stars. The experiment with the γ-summing High EffiCiency TOtal absorption spectrometeR (HECTOR) showed a decrease of the reaction rate compared to previous works, by as much as ≈46+6−11% in the relevant temperature range of stellar helium burning (Phys. Rev. Lett. 128, 162701 (2022)).

Hadrons and QCD (Experiment):

One of the most important topics in hadronic physics over the last decade has been the charge radius of the proton. The value obtained from spectroscopic muonic-hydrogen experiments is significantly smaller than that determined from early measurements of elastic electron-proton scattering. Later measurements of the latter provided split results. The NSF supported the PRad Experiment in Hall B at the Jefferson Laboratory, which also used electron-proton scattering but with the detection of the outgoing proton, rather than the electron, allowing to scan a range of distance scales in one setting. The final PRad result (r_p = 0.831 ± 0.014 femtometer) has been published (W. Xiong et al, Nature 575 (2019) 7781), and agrees within errors with the outcome from the spectroscopic experiments. Most of the community considers now the question about the proton charge radius as settled.

Another experimental highlight with NSF support concerns the asymmetry of antimatter in the proton. The strong interaction as described by QCD allows the creation of matter-antimatter quark pairs inside the proton that only exist for a very short time. Their fleeting existence makes the antimatter quarks difficult to study experimentally, but they are discernible in reactions where a matter-antimatter quark pair annihilates. The SeaQuest Experiment at the Fermi National Laboratory, through di-muon production, measured the distributions of the up and down antimatter quarks, finding more abundant down antimatter quarks than up antimatter quarks over a wide range of momentum (J. Dove et al, Nature 590 (2021) 561). These pioneering results revived the interest in several proposed mechanisms as the origin of this antimatter asymmetry in the proton.

Nuclear Precision Measurements:

One important highlight in nuclear precision measurements is the anomalous magnetic moment of the muon. A long-standing disagreement between theory and experiment could be an indication of new physics beyond the standard model, and the Fermi National Accelerator Lab (FNAL) muon g-2 experiment aims to confirm that discrepancy and improve the experimental precision beyond the 5 standard deviations discovery level. This experiment has been running for a number of years, and the first results have recently been published (B. Abi et al. (Muon g−2 Collaboration) Phys. Rev. Lett. 126, 141801), confirming the longstanding experimental result from the Brookhaven National Lab experiment and increasing the tension with theory to 4.2 standard deviations. The experiment continues to operate, with additional results expected in the coming years.

Another important experimental highlight from recent years is the improved measurement of the free neutron lifetime from the UCNtau experiment with 0.039 % precision (F. M. Gonzalez et al. (UCNτ Collaboration) Phys. Rev. Lett. 127, 162501). This is the most precise determination of the free neutron lifetime and sets up the possibility to competitively probe current tensions in first-row CKM unitarity when combined with upcoming experimental and/or lattice QCD determinations of the axial coupling constant. Such a test of CKM unitarity would avoid the nuclear structure corrections that are necessary for superallowed nuclear decays.

Finally, one exciting new area of development in nuclear precision measurements is in the use of polyatomic molecules in the search for Beyond Standard Model physics (Anderegg, Loïc, et al. arXiv preprint arXiv:2301.08656 (2023); Jadbabaie, Arian, et al. arXiv preprint arXiv:2301.04124 (2023)). This intersection between traditionally AMO techniques and nuclear physics questions looks poised to make many new contributions in the coming years, and is a good example of the kinds of interdisciplinary research that PHY and NP are doing a great job identifying and supporting.

Theory:

We repeat that the NSF Focused Theory Research Hubs are a success of the Nuclear Theory Program. The aforementioned NP3M Theory Hub, led by the University of Tennessee, systematically investigates the properties of hot and dense strongly interacting matter with multi-messenger observations of neutron stars. The NP3M Hub is an interdisciplinary collaboration across nuclear physics, astrophysics, and gravitational-wave physics. This network involves 21 faculty at 15 institutions. The funds are used to support early-career scientists. This hub is a very important development for Theory in terms of both science and training.

Many key results in NSF-supported Nuclear Theory have been reported over the last years. One example are new insights into tidal disruption events, where a star is torn apart by the tidal forces of a supermassive black hole. While such events had early been proposed as sources of high-energy cosmic rays and neutrinos, experiments so far suggested that their contribution to the diffuse extragalactic neutrino flux should be low. However, a recent association of a track-like astrophysical neutrino observed by the IceCube Experiment with a tidal disruption event indicated that some such events might well be a promising class of neutrino emitters. A pioneering model calculation (W. Winter, C. Lunardini, Nature Astronomy 5 (2021) 472) provided support to such a scenario. These developments may change significantly how one should think about cosmic rays.

Another NSF-supported highlight concerns the neutron-matter equation of state at the densities inside neutron stars. Bayesian machine learning techniques allowed, for the first time, to efficiently quantify and propagate theoretical uncertainties of the equation of state (C. Drischler et al, Physical Review Letters 125 (2020) 202702), providing robust error estimates for key quantities of neutron stars. First theoretical predictions were found to be consistent with experimental constraints.

The tensor charge is a fundamental property of the proton, equally important as, for instance, its axial charge. A recent work discusses the extraction of the tensor charge from a global data analysis of spin asymmetries in high-energy electron-positron, lepton-proton, and proton-proton collisions (J. Cammarota et al, Physical Review D 102 (2020) 054002). In particular, compatibility was found with results for the tensor charge from lattice QCD, leading to a coherent picture. This study, which has been widely recognized by the community and represents the state of the art, was made possible by NSF RUI awards.

A highlight regarding low-energy nuclear theory and nuclear astrophysics was published by a collaboration centered at Louisiana State who performed calculations using an ab-initio symmetry-adapted no-core shell model, which showed an unexpected symplectic symmetry in nuclei up through the intermediate-mass region (Phys. Rev. Lett. 124,042501 (2020)). The same approach also allowed to calculate clustering and alpha-capture reactions or astrophysical interest (Phys. Rev. C 102, 044608 (2020)). This work may have potential impacts, in general, to studies of strongly interacting quantum systems, e.g., incorporating emergent symmetries into tensor network quantum states.

G. Particle Astrophysics and IceCube

1. Introduction and COV Process

The Particle Astrophysics (PA) Program administers proposals in three sub-areas called Cosmic Phenomena (CP), Underground Physics (UG) and research pertaining to the IceCube neutrino detector in Antarctica (IC). Astrophysical sources of neutrinos, cosmic rays, and gamma-rays observed using particle physics techniques are covered under CP, while experiments requiring low-background environments are covered under UG (including terrestrial dark matter searches, neutrino experiments that rely on reactor, solar, or atmospheric neutrinos, and neutrino mass measurements). The boundaries are somewhat overlapping and the program directors have discretion to sort incoming proposals as needed. Currently, research which uses data from existing CMB experiments are welcomed, but Stage-4 CMB project funding is primarily covered by NSF Divisions of Astronomical Sciences and the Polar Program, as well as DOE Cosmic Frontier.

To evaluate the program, the COV subpanel was provided with a report of the particle astrophysics program over the years 2019 – 2022. On January 11, 2023, the COV subpanel held a virtual meeting to discuss the particle astrophysics program. The PA program directors presented summary slides and reminded the sub-panel of their charge, after which the sub-panel developed a work plan for the review report. The panel reviewed a wide variety of proposal jackets that represented the breadth of the program portfolio, including a selection of large and small proposals.

The Review Summaries were very helpful and the material was synthesized appropriately in all cases we reviewed. We appreciated the more succinct, but still informative, "short form" of the review analysis. A number of questions arose during e-Jacket review and these were collated during two additional virtual meetings, followed by a third meeting with the PA program directors to answer them. The PA Program Directors were very helpful and forthright in their answers. Division-wide discussion and report-writing was carried out during a final 2-day in-person meeting at NSF headquarters on January 23-24.

2. Program Strengths and Staffing

It became clear that one of the strengths of the NSF MPS/PHY division is the experience and high quality of its program directors, who tirelessly deliver great science by choosing reviewers, engaging panels, and finding ways to fund as many excellent proposals as possible. We especially commend the excellent communication between programs and the flexibility to re-home proposals if necessary. The Particle Astrophysics program especially made efficient use of the WoU-MMA fund, by identifying appropriate proposals for co-funding. More explicit use of the Quantum Leap program might have been useful for HAYSTAC. The PA program has also had proposals reviewed by more than one program and/or division panel, when appropriate. This supervisory, hands-on role is extremely important as it ensures that proposals which cross a boundary can be properly reviewed and that proposers are not responsible for optimizing to which program they should submit. Examples include co-reviews with the Precision Measurement Panel or with the Experimental Nuclear Physics Panel. Especially in neutrino physics, the boundary between nuclear and particle physics has multiple overlaps and requires active engagement by program directors, as is evidently the case and working well.

When PA leadership changes, it is important to plan the transition with sufficient time and overlap to transfer knowledge of current practices and to continue the strong culture of cooperative partnership that has been established. Currently, with two rotators and no permanent staff member, we have concerns about sustainability. We recommend moving back to the pre-COVID model with at least one permanent staff member. With the growth of PA and its diversity, two rotators and one permanent member would be optimum.

Both staffing transitions, as well as the strong engagement in coordination and communication required for partnering with other programs and divisions is fostered by face-to-face meetings and the informal interactions that occur when there is a greater on-site presence. This has to be balanced with hiring new staff, which is often improved by the flexibility offered by remote work. As we move out of COVID, attention needs to be directed toward developing a hybrid model which optimizes these competing trends. It is especially important to schedule regular times when program directors and leadership overlap in person.

3. Quality and Significance of the Research

The success of a program is measured by the quality of the research that follows, as well as a much harder-to-define metric of minimizing lost scientific opportunities - which is addressed by fairness in evaluation, pro-active and institutionalized encouragement of new ideas and diverse perspectives, and a balance of large and small projects. We start by reviewing the many successes which have been possible because of the PA program and follow with paragraphs concerning the integrity of the process, issues related to long-duration projects, and broader impacts.

PA supports experiments and individual research that engage in multi-messenger astrophysics (MMA) and time-domain astronomy (TDA), relevant to key scientific questions identified by the most recent National Academies Decadal Survey on Astronomy and Astrophysics (Astro 2020). The funding opportunities available through PA and through NSF-wide opportunities like MRI and WoU have enabled participation in strategic science through individual investigator research as well as facilities operations and instrumental development.

Highlights in PA-CP

NSF PA supported projects under Cosmic Phenomena that explore physics through the application of particle techniques to astrophysical observations. Funded awards supported research across a range of investigations that develop, apply, and interpret gamma-ray, cosmic-ray and neutrino observations. The PA-CP portfolio from 2019 to 2022 included support for researchers in a very wide range of projects including ARA, ARIANNA, BEACON, Cherenkov Telescope Array (CTA), HAWC, IceCube, Pierre Auger Observatory (PAO), Radio Neutrino Observatory, Telescope Array (TA), TRINITY, and VERITAS. Large investments in operating HAWC, PAO, TA and VERITAS generated unique and valuable data sets. Modest investments supported development activities working toward next generation observatories capable of advancing beyond the current state of the art in maturing and emerging disciplines.

The diversity of the portfolio contributed to exciting highlight results from the CP program. Technical advances have been made using astroparticle radio-detection techniques. HAWC observations provided mapping of the >10 TeV sky and insight into some of the highest energy accelerators in the Galaxy, including evidence for the acceleration of protons above 100 TeV in the Cygnus Cocoon region (A.U.Abeysekara, A.Albert, R.Alfaro et al. 2021, Nature Astronomy, 5, 465). VERITAS also reported evidence for proton acceleration to TeV energies in the supernova remnant Cassiopeia A (A.U.Abeysekara, A.Archer, W.Benbow et al. 2020, Ap.J. 894, 51) The combination of observations from PAO and TA have allowed a full-sky map of ultra-high-energy cosmic rays to be correlated with a full-sky map of high-energy neutrinos from IceCube and ANTARES (A.Albert, S.Alves, M.Andre et al. 2022, Ap.J. 934, 164). This is the first time such a comprehensive analysis could be accomplished between these two astrophysical messengers to directly probe the origins of the highest energy astroparticles.

Highlights in PA-UG

The UG-supported projects and related research were originally united under the need for low background environments achieved by being sited underground. They are more properly understood as those experiments that search for rare events using particle physics techniques. Under direct searches for dark matter, NSF funded projects include SuperCDMS SNOLAB looking for low-mass particle dark matter, XENON and DarkSide exploring WIMP-like particle dark matter using noble liquids. Wave-like dark matter is supported under the HAYSTAC program. Participation in DAMIC, PICO, COSINE and SABRE are also supported at a lower level.

SuperCDMS has shipped the initial payload of 4 towers of 24 silicon and germanium solid state detectors to SNOLAB. World-leading results are expected in the next year from operating one tower in a co-located test cryostat in parallel with commissioning the main cryostat. The parameter space accessible to both athermal phonon and CCD-based devices like DAMIC, has been mapped out in the recent Snowmass strategy white paper by SuperCDMS (https://arxiv.org/abs/2203.08463 (2022)), demonstrating that both these technologies can test a wide range of dark sector candidates without needing additional background reduction.

Last summer, XENONnT published its first science run results (E. Aprile et al., 2022,Phys. Rev. Lett. 129, 161805), showing that they do not observe the excess of low-energy electronic recoil events seen by XENON1T. This success is due to a factor of 10 times lower background and sets the stage for continued exploration of both nuclear and electron recoiling dark matter, as well as solar neutrinos and axions. DarkSide deploys liquid argon as its target material. DarkSide-50 is decommissioned and the collaboration is in the midst of constructing the larger DarkSide-20K experiment. The NSF-funded site infrastructure for the Urania project is under construction in Colorado to extract low-radioactivity argon Ar-40 from deep underground, which will be used in DarkSide-20K.

Recent progress in developing squeezed state receivers has allowed HAYSTAC to reduce noise levels below the standard quantum limit, resulting in a factor of two scan rate enhancement. This quantum-enhanced search extended the scanned region to axions with masses between 18.45-18.69 μeV (M.J.Jewell et al., arXiv:2301.09721 [hep-ex])

The Underground Physics program supports research using several detectors studying neutrino properties and astrophysics and doing beyond-the-Standard-Model physics searches using reactor, solar, supernova, atmospheric and other astrophysical neutrinos; currently and previously funded experiments include Super-K, JUNO and Borexino. The IsoDAR program aims to develop new isotope decay-at-rest 8-Li beta decay source for deployment in conjunction with an underground detector with the primary aim of sterile neutrino searches. A recent highlight of this program is the tour-de-force measurement of the CNO cycle neutrinos with the Borexino detector. (Nature 587, 577–582 (2020)).

Highlights in PA-IC

IceCube, an NSF-led facility with a large international collaboration, is a cubic-kilometer-scale under-ice detector located at the South Pole with a broad physics and astrophysics program including searches for cosmic neutrino sources up to EeV energies via targeted source class searches, all-sky searches and multi-messenger follow-up searches; neutrino oscillations with atmospheric neutrinos; supernova burst neutrino detection; cosmic ray studies; and new physics searches via multiple approaches. IceCube is currently pursuing an upgrade with deployment of new strings and upgraded photosensors, and the collaboration is also pursuing a longer-term, larger-scale upgrade with a larger optical array along with surface air shower and radio array components called IceCube-Gen2. Research that specifically uses data from IceCube is considered under the PA-IC program. Exciting recent IceCube highlights include the first observation of a 6-PeV Glashow resonance event (Nature 591(2021), 220–224), and very recently, the first identification of a neutrino excess from the NGC1068 active galactic nucleus source (Science 378 (2022) 6619, 538-543).

Participation in NSF Big Ideas: Windows of the Universe

The program has made strong connections to the "Windows of the Universe: the era of Multimessenger Astrophysics (WoU-MMA)" program, which is entirely appropriate given the high degree of alignment of many of the science goals for all PA subareas with the "Big Ideas" of the WoU-MMA metaprogram. These awards make up the majority of the Co-Review and Co-Funding actions for PA-CP. We consider this a joint success of PA and WoU-MMA.

4. Integrity of the Process

A deep dive into the reviews of the e-Jackets revealed a mix of ad hoc reviews, panel summaries and reviews of projects via strategy panels. A standard review process included several ad hoc written reviews which were then input to a comparative panel, which was able to rank the proposals. These proposal processes are all well-documented and the correlation between merit review and award determination is clear and fair. Choosing the reviewers is the most time-consuming part of the process since it requires overlapping expertise, balances in review experience and demographics. Based on the e-Jackets reviewed, the COV believes that the quality of the reviewers chosen is excellent and that a good balance has been achieved. The standard review process is equitable. It encourages new ideas and properly rewards innovation.

We noticed that PA has migrated from criteria based on funding (fund, fund if possible, do not fund) to a purely merit-based (excellent, very good, good, etc.) in order to allow the program directors to adjust the funding line based on budget realities without reference to a language that already implies a funding decision. This is a good choice. It also enables the program directors to move funds between the sub-programs and determine their best balance between long-duration projects that should be maintained at critical size and smaller research projects for whom the same funding decrement would eliminate the small research group altogether.

Structure of large and "long-duration" project awards

PA has experienced growth and consolidation over the last two decades of its existence. Over the last 4 years, approximately 80% of its funding is allocated for research associated with large and "long-duration" projects in both PA-CP and PA-UG (PA-IC is entirely associated with a large project). This is a natural evolution as the field matures and people join larger collaborations. Support for activities within "long-duration" projects, defined as those with lifetimes that extend beyond a standard award duration, is handled with special procedures and consideration.   Proposals for work on these projects by either individuals or groups are evaluated in the context of the overall performance goals and schedule for these projects. The project evaluations are conducted separately, sometimes by "strategic reviews", potentially involving site visits.

Many of these projects include multiple agencies and international collaborations. The details of the organization and award structure are fairly heterogeneous among them.

PA-CP Large Project Award Structure

The larger operating projects supported by PA-CP follow a distributed structure for supporting awards. Operations are frequently supported through a dedicated grant, with separate grants supporting data analysis. In the case of externally-led international projects, this supports US fair-share contributions to the operation of the experiment. Additional individual investigator grants support research efforts at collaborating institutions. There are some differences among the operating needs and organizational structures for the large operating projects. Auger is a large international facility with NSF support for a fair-share contribution. The HAWC observatory is sited in Mexico and operated in partnership with Mexico. VERITAS and TA are both based in the US with NSF leading those operations. The procedures followed by the program allow for flexibility in review and support to accommodate structural differences.

IceCube Award Structure

IceCube, an NSF-led facility, is a special case due to its large scale and long duration, meriting its own dedicated research support area. IceCube is jointly funded by the Office of Polar Programs in the GEO NSF directorate, and about 50% of the operations and science funding comes from international sources. There is oversight from an International Oversight and Finance Group.   IceCube funding is under the control of the PI of a large collaborative grant; the contributions of all individual researchers are reviewed as part of the collaborative proposal review, but funding is allocated by the PI of the primary grant in the original proposal and reviewed when the award is made. Individual researchers can request supplements, which are subject to the 20% rule. New IceCube researchers are encouraged to apply for their own grants to start out, but may then be folded into the larger one. This configuration is efficient given NSF program management resources, and it does seem to be working well, but it potentially has the drawback that NSF loses fine-grained control of disbursement of funds and cannot respond on short timescales if there are issues with accountability for deliverables.

PA-UG Large Project Award Structure

DarkSide and XENON, both large projects with significant international partners, have similar NSF collaborative research configurations in which a multi-institution award is controlled by a single PI. In FY2020, a $3M award was made for the DarkSide project to support the Urania purification plant. DarkSide-20K construction has been funded via the Physics Division mid-scale funding program in FY22. Separating operations review panels from science reviews has benefitted running experiments, such as SuperCDMS. Another improvement has been increased use of the CERN model (infrastructure funding is linked to the number of NSF-funded PhD scientists on the project).

Strategic Support for large and "long-duration" projects

In response to the saturation of the program by large collaborations, the program directors have paid increasing attention to whether this balance is optimum. Without careful management of the long-duration projects, this balance could easily trend toward 100%. Once a large project is approved, funds must be allocated over the duration of the project. Project oversight and progress is tracked through periodic reports and budgets can be adjusted as necessary. If the project is in partnership with another agency, such as the DOE or an international entity, NSF often participates in a Joint Oversight Group in order to manage any shifting financial commitments. PA is a young and growing program, evolving from smaller, exploratory experiments into larger collaborations. They have recently negotiated a number of large projects in both CP and UG sub-fields, as described above. In order to evaluate the relative merits and optimum lifetime of long-duration projects within a sub-field, PA has initiated the use of a periodic strategy review.

PA-CP employed a strategic review in 2019 to make recommendations on the merits and duration of continued support for VERITAS, HAWC, TA and PAO, with the intent to set long-term scientific priorities. After evaluation, the panel provided a written report based on presentations from the projects on their scientific accomplishments, goals and plans, and operations efficiency. The strategic review of PA-CP facilities provided useful recommendations about goals for continued support and the rationale for when and why projects should be assessed and potentially closed out. These reports were used effectively to set the context for following panel reviews that have revisited the recommendations and updated them where merited. We anticipate (and recommend) another CP strategy panel in the near future (2023) to account for changes in the experiments and the field.

This approach emphasizes NSF's science-driven approach to achieving high-impact results and developing innovative advancements. It provides flexibility for updates to timelines for new facilities and allows planned transitions for experiments. Having a clear and transparent process for this is important for maintaining a vigorous research community. That practice is commendable and can account for changes to schedules and new scientific developments.

There was no NSF-initiated strategic review for the large dark matter projects (DarkSide, SuperCDMS and XENON) although aspects are reviewed jointly with other agencies. Although we do not see any specific issues with these programs, which overall seem to be managed very well, a comprehensive NSF strategic plan for experimental dark matter projects could potentially be useful for consistent evaluation of these projects moving forward, as well as any new initiatives that might be proposed. Neutrino-related projects supported by PA (IceCube, radio detection, IsoDAR, as well as smaller contributions to other projects such as JUNO and new ideas) are on diverse scales and topics, but NSF could also consider a strategic review for all or a subset of these.

Large projects with inter-agency funding can find it challenging to navigate differing approaches to project planning (e.g. mission-driven DOE vs proposal-driven NSF), especially when funding expectations are not met. Successful inter-agency partnerships have been those that have clear deliverables associated with NSF. On the other hand, when conditions have shifted (collaborators moving from Universities to National Labs, or deliverables changing hands), there have been deleterious funding gaps or other disruptions due to loss of the NSF scope. A remedy might be the early adoption of clear and binding inter-agency MOUs combined with operations reviews held jointly with the other custodial agencies. Guidance from the joint reviews should be part of the e-Jacket and considered as primary, rather than superseded by NSF-only review panels.

Other successful Operations models are allied to experiments which are largely NSF-funded. As appropriate, PA has instituted dedicated Operations panels which streamlines the process and makes it possible to honor commitments to investments already made. Finally, support for infrastructure and operations in some (mostly very large) experiments avoids the need to identify (and then react to changes) of NSF-specific contributions by using fair-share models which exact a tax proportional to the number of NSF-supported PhD scientists.

NSF exists within the larger physics ecosystem, and PA in particular is aligned with high energy physics goals within the cosmic frontier. Community planning exercises like Snowmass determine the high-impact research that is endorsed by the particle physics community as a whole. This provides input to P5, which then prioritizes the projects which can accomplish these physics goals. While DOE has a formal budgetary process governed by P5, PA is not bound by the recommendations, although it certainly uses them as input. While NSF Astronomical Sciences continually measures itself against the goals of the National Academy of Sciences Astrophysics Decadal survey, PA does not follow the same strict yardstick. In a proposal-driven agency, this leaves open the possibility that a small subset of the community can redirect research via reviewer bias. Strategic reviews provide a measure of correction since they depend on identifying the high priority science goals within the field. In addition, better integration of PA within the AAAC would enable better cross-division and cross-agency inclusion of the PA goals and research program within the larger long-range planning landscape.

5. Broader Impact and DEI

While broader impact has always been a core NSF review criterion, the attention it receives by reviewers has been increasing over time. The willingness of reviewers to give poor marks to a proposal based on a wishy-washy broader impact statement has, in turn, improved both proposals and NSF's response. Education of core scientists continues, but growing recognition of the need for proactive recruitment of under-represented groups has resulted in the following efforts in PA:

- *PHY Supplements: Growing a Strong, Diverse Workforce* (NSF 21-0654) and the AGEP-GRS program provided supplemental student support for 18 PA awards.
- Statistics on women and Hispanic reviewers, as well as PIs from under-represented groups were collected and presented. With low statistics, no obvious trends in 4 years can be seen, but data now exist.
- Supported PA research proposals show a substantial engagement in public outreach, which includes but is not limited to public talks, involvement in large-scale science festivals, project visitor centers, and Citizen Science programs including Zooniverse.org.
- Large projects supported by PA all include a dedicated outreach program and many have instituted Codes of Conduct, Ombuds officers, and specific diversity and inclusion strategies.
- Panels made detailed assessments of the broader impacts and paid close attention to training plans and best practices to support diversity, equity and inclusion and generate useful feedback for proposers. The program acted in response to cases where panels found that renewal proposals did not demonstrate satisfactory response to prior feedback.

6. Suggestions and Recommendations

The following suggestions and recommendations have been extracted and summarized based on the observations above.

Suggestions

- Given that an increasing number of funded projects in the Underground Physics research sub-program are not located underground, consider a better-aligned name (e.g. "Low background experiments and rare event searches"). This may also provide the flexibility needed to redraw boundaries among the three sub-programs. It would provide clarity to proposers and possibly encourage a more diverse pool of submissions.
- PA has accumulated experience managing long-duration projects under a variety of operations models. Some models have been more successful than others. Are there any lessons to be learned from the variety of approaches used? Can operations management principles, adjusted appropriately to the scale and NSF-investment in each project, be developed now to guide future, larger projects when they require long-term investment by the program? We suggest an internal study of these questions.
- For PA science, research timescales can vary considerably from small-scale exploratory projects or short-term, well-defined collaboration tasks, to very long-term experiments. We do not see any reason to settle on a single standard award length and recommend flexibility for the Program Directors to define appropriate award lengths from several years for individual researchers to five years for long-duration projects.

- Many programs within the Physics Division are wrestling with the appropriate balance between large and small projects. The COV can make comments with respect to their individual programs, but NSF could consider calling a task force with a limited charge to study this balance in detail for all the programs (while taking into account the specific needs of the individual programs). Data-driven criteria could be developed that compare science lost in unfunded individual proposals measured against science gained in the project (often also by individual researchers).

Recommendations

- The workload is increasing as the rapidly-evolving field of Particle Astrophysics grows, but PA used to have two permanent staff and now has two rotators. To guarantee sustainability and improve continuity, while keeping up with the current portfolio, we recommend the addition of a permanent staff member to PA in addition to the two rotators. The breadth of the field argues for complementary strengths in the three program directors.
- A hybrid work plan should be developed as soon as possible to optimize overlap of personnel when on site. The mix of remote and in-person work should be adjusted based on a well-formulated plan that accounts for the unique strengths of on-site work and the flexibility of remote work.
- We recommend that PA-UG conduct a strategic review (similar to that undertaken by PA-CP for HAWC, VERITAS, TA, and PAO) covering their Dark Matter Program and to *consider* whether such a strategic review might also be appropriate for some or all of neutrino experiments in their portfolio. It may be preferable to hold these strategic reviews *after* the P5 report has been delivered.
- In light of the new Snowmass Report, along with the new NAS HEP Survey, Astro2020, and the pending P5 recommendations, PA should evaluate the relative importance of individual panel recommendations versus community priorities in long-term funding strategies. The Strategic Reviews provide a tool for this, as would tighter integration with the AAAC.

H. Physics of Living Systems

I. Overview

1. Nature of the field and program

The "Physics of Living Systems" program (PoLS) funds a broad range of research that collectively integrates theoretical and experimental approaches from physics to explore the most fundamental aspects of living systems. This spans from how biological functions are performed in dynamic and diverse environments bridging molecular, cellular, and organismic levels, to the behavior of populations and ecology. Projects that endeavor to understand evolution on short and long time scales, as well as the exploration of artificial life forms and how life began, are also funded. The PoLS program primarily supports individual investigators, although collaborative proposals between physicists and biologists are welcome. Proposals that use physics equipment only as a tool to study biological questions, ones that could readily be funded by Biology programs, or ones that focus on "biologically-inspired physics" with little biological relevance, are of very low priority.

The future of science lies in using all available tools and concepts to understand the complexity of biology, rather than being limited by questions such as "Is it physics?" The first National Academies' Decadal Report on the "Physics of Life" (2022) argues forcefully that the physics of living systems is an integral part of physics. Many universities are establishing interdisciplinary programs to bridge the gaps between the physical/mathematical and life sciences, but many others, including top physics departments, lag far behind. PoLS, which provided funding for the Decadal Report, has played an important role in the development of the field and has outpaced much of the physics community in the inclusion of the physics of living systems under the physics umbrella. The PoLS program and the PHY Division should be commended for their important role.

Physics approaches to systems at multiple levels have been very successful in understanding inanimate systems. Their potential to enable a deep understanding of living, replicating systems, through testable phenomenological theories, is rapidly advancing. PoLS encourages research that emphasizes the physical principles of biological functions – the crucial special features of biology. Many of these involve, in essential ways, collective phenomena for which physics approaches are crucial. Questions addressed in proposals must be important for advancing our understanding of the living world in a quantitative way. The emphasis is on the overall quality of science and the nature of the approaches, rather than whether the questions asked are physical. But taken together, the research PoLS supports expands the intellectual range of physics.

The PoLS program is highly interdisciplinary, and partnerships with other areas of the NSF are vital. From early on PoLS has had a close partnership with the Molecular and Cellular Biology (MCB) program in the BIO Division, and more recently also with the Integrated and Organismal Systems program. These partnerships led to the co-funding of multiple individual research awards and three Physics Frontiers Centers by MCB. PoLS also has partnerships with programs in the Division of Mathematical Sciences (DMS), the Division of Material Sciences (DMR), and the Division of Chemistry (CHE).

Broader impacts of PoLS include, in addition to activities under individual grants, several initiatives with various community-building foci: the International Physics of Living Systems Graduate Research Network (iPOLS), which includes multiple US and international institutions; a network of hundreds of high school physics teachers (PoLS-T); and the "Cancer-Convergence" education network which develops links between physicist and clinical oncology trainees and is jointly funded by Stand Up To Cancer (SU2C) Foundation. At the individual investigator level, proposals with potential societal impact such as renewable energy, human health, and education are of interest to the program.

2. Spectrum of research funded

Awards cover a broad spectrum of biological phenomena and a broad spectrum of approaches influenced by physics, including, in particular, theory which is all-too-often less appreciated and less funded by conventional life sciences programs than merited.

Building up from single molecule biophysics, currently supported research includes switches made of RNA, genome organization and dynamics, and coupling between proteins and membrane dynamics. Cellular-level processes are a major focus of PoLS awards. These span compartmental structure, cytoskeletal mechanics and dynamics, transport processes, regulation by proteins and genes, intra- and extra-cellular sensing and signaling, photosynthesis, and cell motility. Much of the remarkable advances in molecular biology have come from essentially static experiments, especially gene knockouts from which the molecular players and some of their roles are inferred. But many cellular functions are intrinsically dynamical, with multiple time scales, collective effects, and often novel physics including feedback and control. Because of these complexities, for probing and developing an understanding of such functions, physics approaches are invaluable. The development and use of new ways of measuring and manipulating cells and intra-cellular processes, with a close interplay between theory and experiment, are a key part of many of the projects funded by PoLS.

At the multi-cellular organismic level, PoLS projects range from development in plants and animals, for which the interplay between active mechanico-dynamical processes, signaling, feedback, and control are essential, to insect respiration, magnetic sensing, ultrasound generation by bats, and hair cells crucial for hearing. Grants on neural processes include the connections between neural anatomy and activity, population-coding from collections of neurons, and performance of functions such as navigation and flight control. Supported research on the collective behavior of communities ranges from social bacteria and nematodes, to schools of fish, and honey bee colonies.

The underlying process that shapes biology, evolution, is being studied in various contexts. For microbial evolution, this includes highly quantitative laboratory experiments and modeling evolutionary and ecological dynamics on a spectrum of time-scales, as well as, on the longest time-scales, prebiotic chemical evolution. Evolutionary processes that cause human diseases and our responses to them – cancer, evolving pathogens, and the adaptive immune system's responses – are each topics of small numbers of PoLS grants. PoLS should be commended for responding rapidly to the COVID pandemic by supporting a number of projects on the epidemiology, the immune response, and other aspects of interactions between the SARS-COV-2 virus and its human hosts.

II. Integrity and Efficiency of the Process and Management of the Program

1. Effectiveness of the Review Process

The Physics of Living Systems (PoLS) program supports a research portfolio where physics-based approaches study the biology of living organisms. The program encourages projects that require the skills and training of physicists and that can often be carried out within physics departments, but, at the same time, have strong biological relevance. PoLS extensively collaborates with the MCB/BIO and IOS/BIO divisions of the NSF to identify grants that can be jointly considered and/or supported.

The PoLS program typically runs two panels to review individual proposals. This was the case in 2019 and 2020. However, in 2021 and 2022 only one panel was convened since the number of proposals was slightly reduced. During those years, the CAREER proposals were reviewed with individual (ad hoc) reviewers. Each panel is composed of 12-15 members. When two panels are used, one panel focuses on molecular-to-cellular phenomena, topics related to the MCB/BIO division of the NSF. The other panel focuses on larger-scale systems, organisms, and collective phenomena, which are topics related to IOS/BIO. For funding by POLS, proposals must shed light on the unique physical properties of living systems, and not on properties shared by the living and nonliving matter (e.g., elasticity, viscosity), an area that might be studied as Materials Science or Soft Condensed Matter.

Reviewers are asked to consider both the intellectual merit and broader impacts in detail. Most of the community now understands the role and expectations associated with NSF reviews in this regard, though there are differing opinions about the appropriate balance between the criteria. For the most part, individuals, panels, and program officers all recognize the value of a balanced proposal, and in the proposals included in our packet, both criteria were directly assessed.

Normally, ad hoc external reviews are not solicited for single investigator grants. Instead, each grant is reviewed in detail by 2-3 panelists and then discussed broadly by the entire panel at the panel meeting. A diversity of panelists is selected from a range of backgrounds in relevant areas. A mix is sought of young investigators as well as more experienced members to achieve viewpoint diversity. POLS constituted a new Panel every time to balance fresh perspectives with experienced evaluation. About half of panelists have served before (to maintain some experience in conducting a panel), while others are added to bring new people, a broader range of expertise, and diversity to the panel. The results of panel discussions are shared with Program Directors from the BIO divisions to better understand differences of opinion and to better understand how the PHY and BIO divisions can work together to encourage and fund the best science.

CAREER proposals remain one important avenue for young investigators to initiate NSF funding in Physics, though they can also apply for normal awards. As mentioned above, in 2019 and 2020, CAREER proposals were considered in regular panels while in 2021 and 2022 external Ad Hoc reviewers were used. In either case, Program Directors from MCB/BIO and IOS/BIO were consulted, though funding decisions are made within PoLS.

The iPoLS Graduate Student Network grants span all levels of biology, and each proposal is reviewed by both PoLS panels. The activities of the existing 2 PoLS Graduate Student Networks are jointly funded by MCB/BIO and regularly reviewed by Program Directors from the BIO divisions. These programs are considered to be very effective at enhancing graduate student activities. Currently, however, iPoLS funding cannot be used for funding graduate student stipends. Thus, it would in principle be possible to expand the network considerably at the current funding level by simply including students from a larger number of different universities in the network activities.

The panel review system used by PoLS and described above allows a diversity of opinions to be expressed and the ability for robust discussion. Site visits are used for larger programs where "place" is a key factor in evaluation and success. This said, there are no perfect proposal evaluation mechanisms. Social dynamics can bias interactions on panels, ad hoc reviews lack the benefit of group consideration, and video interaction is different from in-person panel discussions, but from the sample proposals studied, we conclude that the program directors generally do a good job of encouraging a balanced view. While it is understood that developing a diverse representation of reviewers on panels in all respects is difficult, POLS has taken this seriously and should continue to strive to increase the number of reviewers from less represented states (defined by EPSCoR) and non-academic settings (Natl Labs, Industry).

One issue for consideration is that all of the representative jackets made available to the COV had between two and three written reviews by panel members, and in most cases, there were only two reviews per proposal. While it is understood that the panel as a whole considers each proposal, what normally happens is that the tenor of the discussion is very strongly influenced by panelists that actually read the proposal in detail (based on our own panel experiences). The COV recommends that obtaining three reviews per proposal would provide more balance, particularly in cases where there are substantial differences in opinion. For large proposals, (e.g., iPOLS network), more than three reviews should be considered.

One of the most important aspects of a panel-based evaluation is the fact that the discussion includes the entire panel. This generally proceeds via a brief description of the proposal by one of the reviewers that read it in detail followed by the personal evaluation of the 2-3 detailed reviewers. After this the panel considers the points made by the detailed reviews and discusses them as a group, culminating in a final classification into one of four categories: high priority, medium priority, low priority, and non-competitive. The decision to place a proposal into high priority is arrived only after all the proposals are thoroughly discussed.

Invariably, the level of care taken and detail provided by reviewers is rather heterogeneous. About one-third of the reviews we looked at were terse to the point of being of little value to the PI. This was normally balanced, however, by one or more thoughtful and detailed reviews. Whether or not proposals are funded, the individual reviews and panel summaries constitute critical feedback for applicants. In the examples provided to us, the summaries were not always entirely consistent with individual reviews. However, there may be a good reason for this; the purpose of the panel discussion is to allow all viewpoints to be considered and to converge to the extent possible. In this regard, discussion with the program director is still an essential aspect of helping to inform the PI.

The Program Director synthesizes review materials and factors that contribute to the final decision into a summary document. This is not released to the PIs, but the Program Director uses it as a basis for discussion with the PI, often by phone, and provides the applicant with additional feedback useful in deciding whether to resubmit the proposal and what to modify. There was some variability in the review analyses provided. There were a couple of cases in which the review analysis seemed rather incongruous with regard to rather mixed reviews and panel summaries but resulting in a positive funding decision. It is reasonable and appropriate for the PM to sometimes recommend proposals for funding that the panel may have not been the most excited about. However, the reasoning in some analyses for moving such a proposal into the funded category was not always clear when this happened.

Little explanation was provided to the PI about the funding decision in the proposal cases we studied. The panel recommendation (non-competitive or low/medium/high priority) should be consistently included in the Panel Summary. In addition, it would be useful to have someone to do a thorough check (for example, an AAAS science fellow) for completeness (i.e., data management, postdoctoral plan) as well as details about the discussion's most relevant comments, final ranking by the panel, etc. if any, in the Panel summary before releasing the reviews to the PIs.

2. Broader Impacts

This is a major strength of the program. Its research portfolio has broadened as the range of biological areas in which physicists' work has broadened. Particularly the MCB shows interest in co-sponsoring projects involving molecular evolution with POLS.

The CAREER investigators demonstrate a particularly rich diversity of creative and far-reaching outreach activities that will broaden the participation of diverse groups at all levels. All single investigator grants have some elements of outreach and education, as well as the Physics Frontiers Centers that connect to biology. A highlight (although not part of the PoLS program) is the PFC at Rice University of Houston (an MSI) and Texas Southern University (an HBCU) with a biological focus. This PFC makes an explicit link between an elite private university, a minority-serving institution, and an HBCU that broadens the participation of faculty and students from historically marginalized groups in STEM. This type of sharing and collaboration is important to build a broad and deep research community across the USA, exposing NSF-funded research and opportunities to socio-economically diverse communities.

POLS has participated in PHY Division's research projects through three Physics Frontier Centers. The portfolio succeeds in achieving the geographical diversity of funded projects and spans states and institutions in the Northeast, mid-Atlantic, South, Midwest, and West. Naturally, it is impossible to cover all states evenly, but the effort to obtain a geographical distribution is clear and successful. The PoLS program and the Physics Division sponsored the National Academies of Sciences, Engineering, and Medicine First Decadal Survey of Biological Physics/the Physics of Living Systems (BPPLS). The study assessed the progress and developments in BPPLS over the past decade and explored promising new directions for the period 2020-2030. The report by the Academies was released in 2022. A key outcome of this report is that Biological Physics and the Physics of Living Systems are now recognized as a field of physics.

The subcommittee observed that several programs within the portfolio in POLS make an effort to create collaborative networks for graduate students across geographical areas. A mix of public and private research universities and collaborative networks that connect institutions promotes the dissemination of ideas and sharing of tools and technologies to unravel the mysteries of living dynamics across the USA. The iPoLS *"Collaborative Research: International Physics of Living Systems Graduate Research Network"* is in its 11th year, with over 200 graduate students from the US and international nodes (France and German) attending its yearly meeting. More networks were funded to sponsor a cohort with focused projects, such as *"The High Flux Student Research Network (HF-SRN)"*, and *"The NSF-SU2C-Cancer Convergence Education Network"*. The latter is a network of graduate students, post-doctoral researchers, and clinical fellow trainees, both during and following their participation in research grants in cancer biology. Most funding appears to have successfully fostered collaborations between labs at individual R1, and elite universities and involved collaboration with international partners.

In response to the COVID pandemic, PoLS was the first program to support COVID research. It funded 6 RAPID (Grants for Rapid Response Research (RAPID)) to study the impact of federal investments in science and technology programs and to advance the scientific understanding of science policy. These proposals dealt with different aspects related to the COVID-19 pathogenesis, immunogenicity, epidemiological modeling, ventilators, and survival of the SARS-COV2 virus outside a host.

In response to the need for remote teaching of high school physics in a virtual setting during the pandemic, POLS sponsored the workshop "Building a Network to Support and Improve High-School Education", organized by Eric Mazur at Harvard (with EAGER). The POLS-T network launched during the pandemic to reach out to over 600 physics teachers who were impacted by the need for virtual learning across the nation. Grassroots activities of teachers from POLS-T drive the discussion about the current state of high school physics teaching and explore ways to improve as well as address how to build capacity.

PoLS is a forefront program to support societal issues bringing equity and inclusion to historically marginalized groups in STEM. POLS supported the *Physics of Living Systems Education Meeting* to learn more about how we can better support Black scientists in the field. The meeting ***"****2021 iPoLS Education Meeting: Black in iPoLS*" (Virtual) was organized by Rice University and held during March 12-21, 2021. This meeting brought together leaders in academia and industry to highlight best practices in improving research climate, culture, and opportunities for Black scientists in interdisciplinary scientific research. Faculty, postdocs, graduate students, undergrads, and K-12 educators were encouraged to attend. Mentoring workshops for students were organized to discuss topics such as, ***"****Becoming an Effective Mentor: Strategies, Skills, and Conversations",* and ***"****Networking Strategies for Building a Mentor Team Tailored to Your Identities and Interests".*

The subcommittee encourages the POLS program to further broaden its impact by growing access to these collaborative networks to faculty and graduate students from emerging research institutions that typically offer large classes of introductory physics courses. These introductory physics courses have been typical "gateway" courses since most students have to pass through them to claim STEM majors, disproportionately impacting undergrads from socio-economically diverse backgrounds. Finally, the subcommittee recommended growing the ecosystem of physics by sharing and implementing best practices for PoLS network member nodes to overcome systemic barriers to inclusion, equity, and diversity that exist in STEM fields at all education and career levels, and identify methods to create equitable paths towards rewarding science careers, particularly in biological physics.

3. Portfolio of Awards and Management

The intersection between the physical and life sciences is broad and occurs at all levels from molecular to cellular to systems to the behavior of individuals and collectives. It is impressive that this breadth is reflected in the funding portfolio without apparent compromise of quality in any area. Most funded grants received robust support from the individual reviews of competent panelists and in the panel summaries. In addition, the portfolio shows a diversity of theoretical and experimental approaches, an essential quality of the "physics" of living systems as opposed to more conventional biological approaches. The portfolio also has a distribution of scientists at all levels from early career scientists to senior investigators.

PoLS has very strong and effective connections with MCB/Bio and IOS/Bio and some also with other areas of BIO and other programs, to the credit of the PMs. But it would further strengthen the program to develop connections also with programs in other areas, such as evolution and ecology (in DEB/BIO) in which PoLS funds research. By encouraging and funding the best proposals across the physical and life sciences, the team of program directors across disciplines enhances the quality and amount of NSF-funded science. Sharing support of single investigator projects that cut across the physical and life sciences has become a standard and admirable practice. Another impactful activity is an explicit collaboration between PoLS and MCB/Bio in reviewing and funding the three PFCs that connect to different areas of the life sciences. This exemplifies the collaboration between different NSF divisions.

III. **Summary, Comments, and Recommendations**

The program fits the mission of the NSF in identifying and supporting our national priorities to innovate in cross-cutting research that will best serve the training needs of future generations.

1. The number of grants, success rate, and typical grant size have been roughly constant over the last decade. The quality of funded research and investigators has been consistently high. Several funded researchers have become leaders in their fields. However, the costs of research have significantly risen whereas the amount of funding has not. Graduate student and postdoctoral salaries have increased substantially, and the costs of many experimental programs have increased with technology. Consequently, the impact of each award is diminished. Funding awards should, at the very least, keep up with inflation. Individual investigator PoLS awards typically fund at most one student and one month of PI summer salary. For groups that have several potential sources of funds, such small grants can discourage proposals, although the policy that the duration of PoLS awards is often five years, does slightly alleviate this. For theorists, for whom PoLS may be a primary source of research support, awards do not fund even a minimal group.

   The Committee strongly urges PHY to endeavor to increase the PoLS budget so as to increase the size of awards so that they can typically support two graduate students or a postdoc. As emphasized in the NAS Decadal Study, the physics of living systems is growing steadily and increasingly becoming a part of mainstream physics. We hope that this can be supported by substantially expanding the size of the PoLS program.

2. One way to alleviate the funding gap for postdocs is to grow the opportunity of independent funding mechanisms or to leverage NSF-wide mechanisms, which might have special relevance for the Physics of Living Systems. Individuals with PhDs in the physical sciences who want to switch to the life sciences will have difficulty getting postdoctoral fellowships from the NIH or other funding mechanisms that require substantial prior research experience in any subdiscipline. A robust program to fund postdocs, and even investigators at later stages of their careers, who want time and

flexibility to pioneer new directions in the physics of living systems, would fill an important gap. We do not recommend reducing the size of any of the current programs to fund postdocs. We strongly recommend budget increases to allow the inclusion of such an NSF-wide funding program as Mathematical and Physical Sciences Ascending Postdoctoral Research Fellowships (ASCEND) to establish ~3 PoLS PD fellowships.

3. The PoLS Graduate Student Networks have been established with nodes at several major research universities. Initially, these networks funded graduate student stipends, but not anymore: The funding now primarily supports conferences and travel of trainees. Yet their budget is a substantial part of PoLS. The program managers should consider increasing the number of graduate students and institutions that participate in the PoLS networks' activities while decreasing or keeping flat their overall budget. And the processes for institutions becoming involved should be made more transparent. Comparisons with the operations of the NSF-funded Research Collaboration Networks from other divisions that cost less than POLS' (e.g., the Protein Folding Network; the Extreme Biology Network"), might serve as examples.
4. PoLS has developed strong connections and collaborations with MCB/BIO and IOS/BIO. The program directors have made efforts to also establish collaborations with other BIO areas, for example the Division of Environmental Biology (DEB/BIO). We strongly encourage these efforts to increase the range of BIO (and other) programs with which joint reviewing and joint funding is done, and PHY Division leadership to proactively foster these efforts. These would substantially enhance the total impact of PoLS and physics of living systems more broadly.
5. We commended the success of POLS-T, spearheaded by Eric Mazur (Harvard), in establishing a broad community to foster a future workforce by connecting high school physics teachers nationwide. The subcommittee encourages the POLS program to further broaden the impact of POLS-T, or via other means, to narrow the gap between high-school physics and college physics for young people by including more faculty from diverse institutions that offer large classes of introductory physics courses and get more biological physics into physics curricula. Such efforts resonate with the NAS Decadal report on the impact of biological physics which broadens access and exposure to the exciting forefronts in the physics of living systems at all stages of scientific training.
6. We recognize that the PoLS program has developed tremendous fundamental intellectual assets and networks which could be of great value to organizations beyond PoLS and, importantly, beyond NSF. Leveraging these capabilities to form mutually beneficial relationships with industry, foundations and other government agencies (NIH, DoE, DoD) would serve multiple purposes. First, it will bring additional avenues of translation, accelerating the impact and prominence of the excellent work being done. Second, it provides valuable exposure for our students, many of whom will work in applied or mission-oriented environments. Third, it directly engages the broader community in NSF research, increasing awareness of the tremendous value of this resource. Finally, it represents a leveraging opportunity financially. PoLS assets, and NSF assets more broadly, have great value and provide key capabilities these other organizations lack. Working to design mechanisms in which funding feeds back into NSF's research environment from this larger community while serving the needs of that community could allow further leveraging of NSF research funds.

7. Krastan Blagoev has been a highly effective and energetic program director for many years. Currently, Angel Garcia has joined as a rotator and we have been impressed with the role he has played in helping to bring new perspectives to PoLS. We recommend that the practice of having a rotator be continued. This has particular value in PoLS where there are so many interactions with other research areas within NSF. Having rotators with differing backgrounds move through the program can help further facilitate those interactions as well as generally broaden the network of input from the community.

I. Plasma Physics

1. Introduction

The Plasma Physics Subcommittee of the 2023 COV reviewed the experimental, theoretical, and computational components of the plasma physics program. The program has been overseen by Vyacheslav Lukin (NSF) and Jose Lopez (IPA). The plasma physics portfolio spans an incredibly broad range of physical conditions: intense laser-matter interactions; heavy ions in ultrastrong magnetic fields; low density plasmas used for plasma processing of materials; low-temperature plasma-matter interactions in biological systems; and fundamental studies of turbulence and self-organization. The plasma physics program has a significant applied physics component which directly addresses major societal and national needs, e.g., green manufacturing, energy storage, clean chemistry, semiconductor manufacturing, and environmental restoration.

The specific NSF plasma program description reads "*Plasma Physics is a study of matter and physical systems whose intrinsic properties are governed by collective interactions of large ensembles of free charged particles. ... The Plasma Physics program supports research that can be categorized by several broad, sometimes overlapping, sub-areas of the discipline, including: magnetized plasmas in the laboratory, space, and astrophysical environments; high energy density plasmas; low temperature plasmas; dusty, ultra-cold, and otherwise strongly coupled plasmas; non-neutral plasmas; and intense field-matter interaction in plasmas. The focus of the Plasma Physics program is to generate an understanding of the fundamental principles governing the physical behavior of a plasma via collective interactions of large ensembles of free charged particles, as well as to improve the basic understanding of the plasma state as needed for other areas of science and engineering.*" It is important to note that "*Principal Investigators (PIs) are encouraged to consider including specific efforts to increase diversity of the plasma physics community and broaden participation of under-represented groups in Science, Technology, Engineering, and Mathematics (STEM) as Broader Impacts of proposed work. Development of new undergraduate and graduate plasma physics curricula, or curricula enhancement to include plasma physics topics in other courses, at institutions lacking such coursework is similarly encouraged.*"

Over the period FY19-FY22, the Plasma Program has had remarkable success in adding to its base funding through interactions with other programs, divisions, and directorates within NSF and with external agencies. Key to program success has been a full-time program director with specific responsibility for Plasma Physics. Other important developments over the review period include the establishment of the NSF-wide ECLIPSE program (ECosystem for Leading Innovation in Plasma Science and Engineering), the successful initiation of a major new mid-scale experimental laser facility (ZEUS) at the University of Michigan, and the establishment of new collaborative agreements with NASA, AFOSR, and the NNSA that have led to joint support of new projects.

Here we highlight some of the recent research successes of the program, discuss budget and funding rates, assess the proposal review process, and consider the relationship of the plasma physics program within NSF with external agencies such as the Department of Energy (DoE), the National Nuclear Security Administration (NNSA), NASA, and the Air Force Office of Scientific Research (AFOSR). Finally, we make recommendations which we believe to be important for the future success of the plasma physics program.

2. Research Program Highlights

Research supported by the plasma physics program spans an enormous range of physical systems – from studies of galactic turbulence to the purification of water by plasmas; from theoretical studies of the acceleration of charged particles in intense laser fields to the melting of dust crystals in a zero-G environment – the range of topical areas is extensive. Some highlights are given below.

2.A Laser-Matter Interactions to Study Astrophysical Turbulence

The matter in galaxy clusters is mostly tenuous ionized gas (plasma) with magnetic fields in a turbulent state. Researchers at the University of Rochester and other institutions created a replica of the plasma conditions expected to occur in galaxy clusters [*J. Meinecke, et al.*, "Strong suppression of heat conduction in a laboratory replica of galaxy-cluster turbulent plasmas," Sci. Adv. **8**, eabj6799 (2022): doi.org/10.1126/sciadv.abj6799]. The team used laser beams to vaporize plastic foils and generate turbulent and magnetized plasma, demonstrating the turbulent dynamo mechanism that results in magnetic field amplification in a lab environment for the first time. This work provides a new, experimental path to addressing a long-standing astrophysical question: Why are the cores of galaxy clusters so hot, despite the copious amounts of radiation they emit. Understanding the energy budget is critical to understanding how galaxy clusters evolve and how their large-scale structure develops. The experiments conducted at the National Ignition Facility and the associated simulations demonstrate how laboratory explorations can help the understanding of astrophysical systems, plasma physics, and the behavior of magnetized and turbulent plasma.

Astronomers find hot, turbulent plasma at the center of galaxy clusters. Credit: Giannandrea Inchingolo

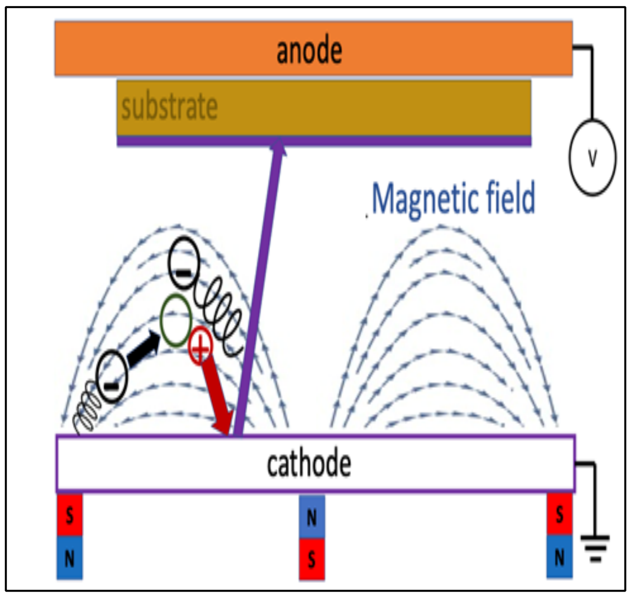
2.B Alfvén Wave Electron Acceleration

We have known that electrons and other energized particles, which emanate from the sun as part of the "solar wind," speed down Earth's magnetic field lines and reach the upper atmosphere. There they collide with oxygen and nitrogen molecules, kicking them into an excited state. These molecules then relax by emitting light, producing the beautiful green and other hues of the aurora. What has not been well understood is precisely how groups of electrons accelerate through the magnetic field on the last leg of their journey, reaching speeds of up to 45 million mph. A popular theory has been that electrons hitch a ride on Alfvén waves -- electromagnetic waves that spacecraft have frequently identified traveling toward Earth along magnetic field lines above auroras. While space-based research has provided strong support for the theory, limitations inherent to spacecraft measurements have prevented a definitive test. In a study published in Nature Communications in 2021, physicists conducted laboratory experiments at UCLA's Basic Plasma Science Facility, supported by the U.S. National Science Foundation and the U.S. Department of Energy. The research is the first direct test showing that Alfvén waves can produce accelerated electrons [*Schroeder, et al.* "Laboratory measurements of the physics of auroral electron acceleration by Alfvén waves," *Nat Commun* **12**, 3103 (2021): https://doi.org/10.1038/s41467-021-23377-5]. This work was picked up by the popular press and was featured on major media outlets around the world.

The aurora borealis swirling curtains of green light, captured in Alaska. Credit: Jean Beaufort

2.C Low Temperature Plasmas

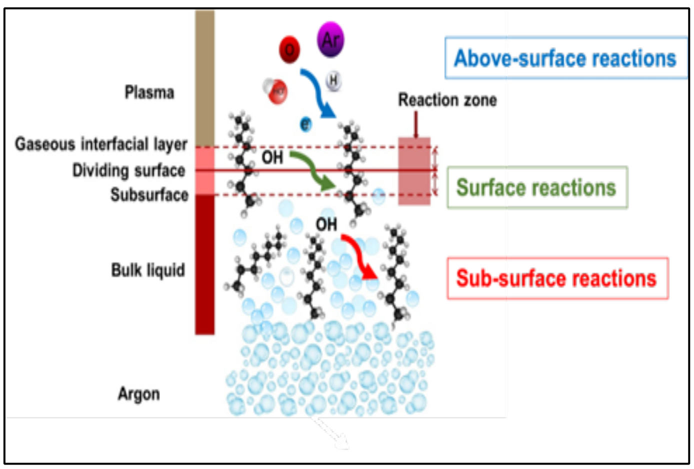
Magnetron sputtering is a primary method used in solar cells manufacturing and the coating industry (reduced friction surfaces, insulating windows – all of which are key for clean energy progress). A new project at CU Boulder funded through the ECLIPSE program (Award PHY-2206904) is "ECLIPSE: Multiscale modeling of crossed-field discharges with speed-limited particle-in-cell simulation." The project aims for a 10-fold decrease in computing time for producing optimal designs of magnetron sputtering systems. The new algorithms and modeling tools to be developed will also enable more efficient modeling of many other plasma systems for fundamental and applied plasma physics research.



Sketch of a sputtering magnetron, in which material is sputtered off the cathode to be deposited on the substrate. Credit: Greg Werner and John Cary, U. Colorado

2.D Plasma Chemistry

PFAS (per- and polyfluoroalkyl substances) are chemicals that persist in the environment for extremely long times and are a significant source of groundwater contamination. Fundamental plasma research supported by the plasma physics program predicted and then demonstrated a method of eliminating PFAS from water [*Nzeribe et al*., "Physico-Chemical Processes for the Treatment of Per- And Polyfluoroalkyl Substances (PFAS): A review, Critical Reviews in Environmental Science and Technology," **49:10**, 866-915, (2019): DOI: 10.1080/10643389.2018.1542916]. The scientific results have led to the formation of a company that is piloting this method on an industrial scale. The specific proposal, PHY-1617822: Interdisciplinary Study of Chemical and Transport Processes at a Plasma-Liquid Interface (co-funded with CBET) with Prof. Selma Mededovic Thagard at Clarkson University began with a theoretical study that developed a general mechanistic model for predicting the compound's reactivity/treatability based on its molecular structure. Then an enhanced contact plasma reactor was developed for the treatment of perfluorinated compounds and the industrial scale system is now in demonstration trials. This particular research project is just one example of the strong interconnections between the Plasma Physics program and programs in other Directorates (CBET in this case).



General mechanistic model for predicting compound's reactivity/treatability based on its molecular structure.

Enhanced contact plasma reactor developed for the treatment of perfluorinated compounds

Large volume perfluorinated substance (PFAS) treatment

3. Budgets and Funding Rates

Over the years FY19-FY22, there has been considerable change in interconnectedness of the plasma physics program with other programs within NSF and external to NSF. Plasma physics appears in a wide range of NSF Programs, Divisions, and Directorates. Over FY19-FY22, the Plasma Physics program made a concerted effort to redirect other programs' submissions that do not fit within the scope of the Plasma Physics program and to use the new ECLIPSE program to fund plasma research across the agency. During FY19-FY20, all proposals to the Plasma Physics Program were submitted through the NSF-DOE Partnership in Basic Plasma Science and Engineering. In FY21 and FY22, proposals were submitted through the Partnership and through the Division-wide, Division of Physics: Investigator-Initiated Research Projects solicitation. The base budget of the Plasma Program has remained flat over the past three fiscal years. The strength of the proposal pool and its responsiveness to NSF priorities has enabled the program to add additional funds to the portfolio within Physics. Within the Foundation, the impact of the Plasma Physics program is further enhanced by partnering with other NSF programs to co-fund research awards. Through these efforts, the Physics Division funding of research projects managed by the plasma physics program grew more than 50% from FY19 to FY22. The Plasma Physics program has an even larger footprint when the funding provided by other agencies through the coordinated review processes is included in the overall program impact.

The NSF-DOE Partnership excluded research directly related to fusion energy production. Both the NSF and DOE contribute to support operations at the Basic Plasma Science collaborative user facility at UCLA (BaPSF) and the DOE supports operations at other collaborative plasma user facilities: the Magnetized Dusty Plasma Experiment (MDPX) at Auburn University, the Wisconsin Plasma Physics Laboratory (WiPPL), and the Low Temperature Research Facility at Princeton Plasma Physics Laboratory. Construction of BAPSF, WiPPL, and MDPX was supported with funding from the NSF Major Research Instrumentation (MRI) program managed by the Plasma Physics program and researchers supported by the Plasma Physics program (and other NSF programs) routinely access those facilities for fundamental plasma and materials research.

According to the NSF Division of Physics reports made available to the COV, only Quantum Information Science and Physics at the Information Frontier have smaller annual budgets than Plasma Physics. However, according to the same report, the Plasma Physics program has one of the largest number of proposals submitted over FY19-FY22 and therefore the plasma physics program has a lower funding rate than all other programs within the Physics Division.

Over the years FY19-FY22, the NSF plasma physics program has also proactively partnered with other agencies, NNSA, NASA, and AFOSR to jointly review and fund proposals. A key recommendation of the Plasma 2010 Decadal Study was the need for a federal agency to take "ownership" of plasma physics within the USA. Since its inception, the NSF/DOE Partnership has played a major role in coordinating basic plasma physics research in the USA. This was particularly important when plasma physics was intertwined with other programs, e.g., AMO and Accelerator Science, within NSF. With the establishment of an independent plasma physics program within NSF PHY and installation of a full-time program director, the NSF has assumed a more well-defined leadership role for fundamental plasma physics in the USA. Coordination with other programs within NSF and external agencies that fund plasma physics research is an ongoing and vital role for the plasma physics program.

A significant element of additional recent NSF funding managed by the Plasma Physics program is the construction of the mid-scale new facility at the University of Michigan, the ZEUS (Zettawatt Equivalent Ultrashort pulse laser System) high intensity, short pulse laser. This new user facility was motivated, in part, by a Plasma Physics program sponsored workshop in 2019 on Opportunities, Challenges, and Best Practices for Basic Plasma Science User Facilities. The ZEUS laser system will be a premier user facility for studying relativistic plasma physics. An additional $670K on top of the original $16M construction budget was needed to resolve pandemic related cost increases. The first experiments began on ZEUS in 2022 (funding awarded in October of 2019). Full power operation is nearly on schedule and constructing and commissioning ZEUS during the pandemic is a remarkable achievement by the Plasma Physics program. The COV also notes the importance of the operations funding ($18.5M over 5 years) now allocated to ZEUS which enables the facility to operate as an open user facility.

3.B.1 Relationship to other Physics Programs

Although the recently developed, stand-alone plasma physics program at NSF has provided a focal point for plasma physics research within the Physics Division, the list of projects supported entirely or partially by the Plasma Physics program (or transferred to other programs) shows ongoing overlap with other programs within the division. These overlaps include some traditional areas of plasma physics:

Atomic, Molecular, and Optical Physics: Cold atoms

Nuclear Physics: Nuclear matter

Physics of Living Systems: Interaction of reactive species with living systems

DMR: Condensed Matter Physics: Materials growth and modification

In addition to these traditional areas of overlap, new applications of plasma-physics inspired research in collective phenomena and nonlinear self-organization of quantum, classical and living systems is now appearing in a variety of other Physics programs. For example, in the Gravitational Physics program (understanding and modeling non-linear wave-matter interactions), in the Cosmology program (understanding potential collective effects in dark matter), in the Elementary Particle Physics program (plasma-based particle acceleration), and in the AMO program (creation and control of antihydrogen for precision measurements). The widespread use of high intensity lasers in fundamental plasma physics studies (whether as diagnostic tools or as the driver of novel light-matter interactions) leads to continuing overlap with AMO supported projects.

During the period of this review, FY19 – FY22, plasma physics projects also received support from the Physics at the Information Frontiers (PIF) program, which "*supports the development of enabling capabilities through computational advances that are required to address compelling scientific goals relevant to disciplines within the purview of the Physics Division*," in cooperation with the Cyberinfrastructure for Sustained Scientific Innovation (CSSI) program managed by CISE/OAC. These programs provided some support for the computational plasma physics community by supporting the PlasmaPy project in FY19 and the Gkeyll-based effort to create “a software ecosystem for plasma science and space weather applications” initiated in FY22.

3.B.2. Relationship to other NSF Divisions

A large part of the funds expended by the Plasma Physics program in FY19-FY22, between 63% and 70% each year, were awarded to proposals submitted to the NSF/DOE Partnership in Basic Plasma Science and Engineering, which besides NSF/MPS/PHY and DOE/SC/FES, included three other NSF Divisions: MPS/AST, GEO/AGS, and ENG/CBET. Many of the awards were co-funded between the Plasma Physics program and these other NSF programs. Some NSF/DOE Plasma Partnership awards were made entirely by other NSF Divisions. More recently, the plasma physics program led the establishment of multiple new NSF-wide solicitations and programs that formalize and even expand these types of interactions.

Following recommendations of the 2020 Decadal Assessment of Plasma Science by the National Academies, “Plasma Science: Enabling Technology, Sustainability, Security, and Exploration,” the Plasma Physics program led establishment of a new cross-NSF meta-program, ECosystem for Leading Innovation in Plasma Science and Engineering (ECLIPSE). The ECLIPSE meta-program was established in September of 2021 and includes participation from ENG/(CBET, CMMI, ECCS) and GEO/AGS.

In FY19-FY20, the Plasma Physics program led development and implementation of a pilot cross-NSF solicitation, Next Generation Software for Data-driven Models of Space Weather with Quantified Uncertainties (SWQU), which included participation of MPS/(AST,DMS), CISE/OAC, and GEO/AGS, as well as NASA/SMD/Heliophysics.

Throughout the FY19-FY22 period, the Plasma Physics program was an active participant in several other cross-NSF meta-programs, such as Computational and Data-enabled Science and Engineering (CDS&E) and Windows on the Universe: The Era of Multi-Messenger Astrophysics (WoU-MMA), which has enabled further cooperation, proposal co-review and co-funding with other programs outside of Physics. The net result of these collaborative activities is the co-review and co-funding of proposals between Plasma Physics and CISE/OAC, ENG/CBET, ENG/CMMI, ENG/ECCS, GEO/AGS, MPS/AST, MPS/DMR, and MPS/DMS.

3.B.3. Impact of NSF “Big Ideas” and other initiatives on the Plasma Physics Program

The WoU-MMA “big idea” has had the greatest impact on the Plasma Physics program at the individual investigator award level. From information provided by the Plasma Physics program leadership to the COV, the additional resources provided within NSF’s WoU-MMA budget allocation contributed significant additional funding to individual investigator awards managed by the Plasma Physics program over FY19-FY22. The Growing Convergence Research and NSF 2026 “big ideas” had limited impact on the Plasma Physics program and community, each only contributing to one project managed by the program. EPSCoR co-funding of Plasma Physics program-managed awards, typically for awards to new PIs in EPSCoR-designated states, contributed modestly to the program’s portfolio and the large EPSCoR Track-1 (RII Track-1) award to the state of Alabama (~$4M/year) provides direct funding to multiple research groups in the plasma science and engineering. The MRI program funded a single, “large” (over

$1M) plasma award to the University of Maryland-College Park in FY22. The MPS-wide Launching Early-Career Academic Pathways in the Mathematical and Physical Sciences (LEAPS-MPS) program funded a single proposal within the scope of the Plasma Physics program while the agency-wide CAREER program funded ten awards in plasma physics over FY19-FY22, 50% of which went to women and investigators from historically underrepresented populations.

During the review period, Plasma Physics was well represented in projects reviewed by the Mid-Scale program. Part of the reason for the strong participation in the Mid-Scale program by plasma physics researchers employing ultrafast lasers was the 2017 National Academies report, “Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light” and follow-on workshops supported by the program and other federal agencies. As noted above, one proposal was successfully funded in FY19 to construct the mid-scale NSF ZEUS Laser facility at the University of Michigan – Ann Arbor. The $16M for construction came from a combination of NSF Mid-scale funds, MPS/OMA funds, additional WoU-MMA funds, and Physics division internal mid-scale funds. ZEUS is NSF’s single biggest plasma physics infrastructure investment to date. In FY21, Physics funded a 5-year ZEUS Operations award of $18.5M, ramping up operations support for ZEUS as an open user facility to $5.5M/year by the last year of the award.

While the WoU-MMA, EPSCoR, MPS-LEAPS, and Mid-scale programs are the types of programs in which Physics programs are typically involved, it is important to note that the plasma physics program has a unique potential to contribute to the new (in FY21-22) Critical Aspects of Sustainability (CAS) initiative – particularly the Critical Aspects of Sustainability (CAS): Innovative Solutions to Sustainable Chemistry (CAS-SC) program. Just one plasma proposal was funded through this initiative in FY22 and the Plasma Physics program leadership is actively encouraging a wider community response.

3.B.4. Relationship with other Federal Agencies

NSF is one of the federal agencies that fund plasma science and engineering in the USA. Since FY97, the joint NSF/DoE Partnership in Basic Plasma Science and Engineering has served as one of the main sources of support for and has widely been considered as the home of basic plasma physics in the USA. The Partnership Solicitation has been governed by an MOU on plasma physics between NSF and DoE that was last renewed in November of 2015 through December of 2021, and then amended to be extended for one year through December of 2022. All plasma proposals submitted to NSF were considered under the Partnership solicitation in FY19 and FY20. Since then, plasma physics proposals submitted to NSF were submitted through either the Partnership or through the regular Physics solicitation. While the Partnership is not yet renewed, a healthy and collaborative future relationship between NSF Division of Physics and DoE Fusion Energy Sciences will continue to play an important role in the plasma physics research community.

The Plasma Physics program has made significant progress in coordinating support for plasma physics across multiple federal agencies by developing cooperative proposal review agreements with NNSA, AFOSR, and by developing joint research funding programs with NASA. These agreements enable multiple federal agencies to access proposals submitted to NSF that would be more appropriate for their research program interests.

4. Analysis of the Program, its Management, and the Review Process

Overall, the program seems very well managed. The Program Director has organized the program in such a way that it interfaces well with other plasma funding organizations without significantly creating redundancy, is cognizant of diversity issues, and has structured a fair reviewing system to encourage creative ideas that would not fit nicely into other organizations.

The presence of a permanent, full-time Director in Plasma Physics has had a significant impact in the profile and impact of the program, through engagement of the plasma physics community, year-to-year continuity and the opportunity to develop and execute a long-term vision that enriches plasma physics efforts through connections within the Physics Division, across NSF divisions and with other funding agencies.

4.A The Review Process

The proposal review processes in Plasma Physics were extremely thorough and effective. This is due in large measure to the integrity and hard work of the PDs who oversee the review process. Detailed written summaries are prepared by the Program Directors, which not only report but also analyze the information collected by the review, often adding additional important ancillary information such as the history of the PI's work, important career milestones such as tenure, and the context of other programs such as EPSCOR.

Review Methods

Among the proposal eJackets reviewed by the subcommittee, in most cases, a review panel was employed but no site visit was conducted. For each proposal reviewed by a panel, the panelists considered typically 3-6 written individual reviews, contributed by a mix of panel members and ad hoc reviews contributed by other experts not part of the panel process. Individual reviewers provided a rating of each proposal reviewed, as well as written evaluations of the proposal intellectual merit and broader impacts, and a summary statement. The panel discussion of the proposal and individual reviews formed the basis of a consensus rating for each proposal and a written panel summary.

The review analyses further described the review methods, including examples where site visits or reverse site visits were appropriately conducted for the base program. The review analyses also described instances where the Plasma Physics program participated in cross-cutting programs such as Science and Technology Center (STC) proposal reviews.

The reviewers selected contributed expertise very well suited to the proposals to which they were assigned. Written reviews for many proposals were provided by well-known and highly respected for their expertise in areas relevant to the proposal. Panel members were generally all knowledgeable in plasma physics, and panels were constructed to provide overall appropriate expertise for the range of topics addressed in the proposals they were assigned.

The depth of analysis in the individual reviews varied, from fairly superficial to extremely detailed and specific, reflecting to some extent the degree of "impedance match" between reviewer expertise and proposal topic. In one example of the former, a reviewer who specializes in theory gave an "excellent" rating to an experimental proposal due to the appeal of the innovative proposal concept, while other reviewers with considerable relevant expertise provided compelling questions about feasibility and gave ratings of “fair” and “poor.” (On the other hand, the value of the theorist’s input should not be discounted just because they lacked expertise to evaluate the feasibility of the experiment. The theorist’s enthusiasm for the proposal concept is a valuable data point, showing that if the experimental challenges can be overcome, the project results will be appreciated as contributions to the larger plasma physics knowledge base.)

Reviews: Consideration of Merit Criteria

In most of the eJackets read by the COV Plasma Physics Subcommittee, reviewers, panels, and the program officer all carefully considered both the Intellectual Merit and the Broader Impacts of the proposed work. In a few of the eJackets examined by the subcommittee, ad hoc reviewers included a review of the Intellectual Merit and either omitted a review of the Broader Impacts or gave it a very cursory treatment. However, for each proposal reviewed by a panel, the panel summary addresses both Intellectual Merit and Broader Impacts. In every case the Program Officer performed a detailed analysis based on the review(s), except for those in which the proposal was funded through a different NSF program or by another federal agency. For those cases, the Program Officer analysis was not included in the eJacket viewed by the Plasma Physics COV subcommittee, but presumably an analysis was made and documented by the program officer for the program that ultimately made the award.

Individual reviews: quality and effectiveness

Many written reviews provided substantial technical detail, clearly separately highlighting the strengths and weaknesses of both the Intellectual Merit and the Broader Impacts. Overall, the level of thoughtful effort to clearly articulate the bases for the assessments was quite impressive. In a subset of reviews, one individual reviewer provided a rather short and superficial review. However, this was the exception rather than the rule. All proposals had at least one detailed written review (and the other referees wrote reports that were consistent in their assessment of strengths and weaknesses with the more detailed reports, although there was a significant spread in individual reviewer ratings (E, V, G, F & P) for some proposals).

Panel reviews: quality and effectiveness

Generally, the panel summaries were thorough and clear in describing the analyses that led to the panel rating. Particularly notable were cases where there was significant spread in the ratings submitted by individual reviewers - the panel summaries reflected considerable effort to analyze and weigh the factors contributing to the spread, resulting in both positive and negative outcomes for specific proposals that were logically justified.

Among the eJackets reviewed by the subcommittee, a consensus was reached by the panel for every proposal that underwent a panel review, including proposals for which there was significant variance in the ratings given by individual reviews. The panel summaries were written in such a fashion that the PI should have a clear understanding of the funding decision.

Jackets: rationale of funding award/decline

The full set of eJacket materials were complete and thorough, and provided a very well documented case for each decision made for proposals that were fully reviewed within the Plasma Physics program. In a small number of cases, the panel “triaged” proposals, i.e., made a decision not to have a full panel review due to the weaknesses identified in the individual reviews. In those cases, no panel summary was produced. For NSF/DOE Partnership proposals that were ultimately funded by DOE (and other cases where awards were ultimately made by other programs or agencies), the NSF Program Officer appropriately did not provide an analysis.

Selection of Reviewers

Generally, each proposal received 3-6 individual reviews and a panel summary, and the selected reviewers typically had technical expertise appropriate for the proposal. The individual reviews were conducted by a mix of panel members and ad hoc reviewers, and the subcommittee was favorably impressed by their overall qualifications and expertise specific to the topic of the proposal.

Because of the breadth of proposal topics considered by the panels, the panels necessarily included a sufficiently broad cross section of experts for the topics within the panel. Between the overall expertise of the panels and the thoughtful analyses provided by the individual reviews and panel lead reviewers, the subcommittee did not find any cases in which a proposal did not receive fair consideration. This subcommittee conclusion is also reflected in the panel summaries which detail the factors considered and clearly articulate the logic behind the panel's assessment.

The Review Record document in each eJacket appears to give a full listing of ad hoc reviewers and panelists, with an indication of those panelists who did not review due to a conflict of interest. The processes by which the conflicts were identified were not explicitly stated, but based on the evidence available it appears that conflicts of interest were identified and handled appropriately. The reviewer lists reflect an ongoing commitment to achieve demographic (gender and race/ethnicity) balance to the extent possible given the available reviewer pool with suitable expertise. There were isolated examples of proposals where the group of reviewers lacked diversity, thereby increasing the possibility of bias/stereotypes interfering with a process intended to emphasize the merit criteria.

4.B Diversity and balance of the portfolio

The scientific diversity and balance of the Plasma Physics portfolios is impressively broad, and we appreciate the work and care that goes into maintaining this. Demographic diversity is an ongoing challenge for the plasma physics community. The American Physical Society maintains gender statistics on the membership of its divisions. The Division of Plasma Physics historically has the lowest representation of women among the divisions. The DPP membership was 11.6% in January of 2022. Notably, the 11.6% figure represents a steady increase in recent years, but is still the lowest of the APS divisions.

The Plasma Physics program has demonstrated leadership in its efforts to broaden participation. It was the first NSF program to add guidance encouraging PIs to include actions with the goal of broadening participation in the Broader Impacts component of their proposals. It has actively mentored early career PIs from underrepresented groups in preparation of competitive proposals for submission to the Plasma Physics program and has promoted opportunities through the MPS ASCEND and LEAPS programs. The program has constructed diverse review panels during FY19-FY22, a strategy shown to reduce bias in the review process. The program staff have also encouraged all PIs to take advantage of award Supplement opportunities to pursue broadening participation goals.

These efforts are reflected in recent proposal statistics; the agency-wide CAREER program funded ten awards in plasma physics over FY19-FY22, 50% of which went to women and investigators from historically underrepresented populations, while overall, women were PIs or co-PIs of 13.5% of plasma physics awards during this period. Accelerating progress toward a diverse and inclusive plasma physics community will depend on the sustained efforts of the Plasma Physics program as well as parallel efforts at other agencies that support plasma research.

5. Standard length of grants.

Currently, the standard length of grants in the plasma physics program is 3 years. The 3-year interval gives the program considerable flexibility given tight budgets and avoids long term commitments of funds. However, the 3-year interval is historical and dates back to an era when it was common for graduate students to complete their PhD degrees in 3-4 years. In a program with a healthy proposal success rate, a funded PI has a reasonable chance of success with a follow-on proposal that could support a student beyond the 3-year interval. As long as the Plasma Physics program proposal success rate remains at the healthy proposal success rate, we do not see any reason to recommend a change in the length of proposals. When a PI is unsuccessful with a subsequent proposal, the plasma program could remind the PI that supplements specifically to support a graduate student for an additional year (when less than 20% of the total grant cost) are possible. Such support would be consistent with NSF's mission of developing the plasma physics workforce.

6. Program Staffing Levels

As noted elsewhere, the introduction of a full time Program Director and a rotator position for Plasma Physics has had a profound impact on the health of the Plasma Physics program. There is now enough staff to manage the substantial number of proposals submitted each year while still leaving time for the program leadership to develop new initiatives with partners within and external to NSF.

7. Other Topics

While this COV was specifically tasked with reviewing the Plasma Physics program, one of our charges was to examine the response of the Plasma Physics program to the recommendations of the last COV. The last COV report covered both plasma physics and accelerator science and one of their recommendations was for the Physics Division to work in collaboration with the DoE to develop a partnership targeted at supporting fundamental accelerator science beyond the plasma physics - centric efforts that are continuing to be supported by the Plasma Physics program, e.g., plasma wakefield accelerator science. The specific recommendation for Accelerator Science in the previous COV report was:

> "Since the technological limits of traditional particle accelerators are in plain sight, the development of advanced plasma-based accelerators is a crucial component of the NSF research portfolio in Plasma Physics. Although it is a cutting-edge physics field on its own, plasma-based accelerators have applications (novel light sources, colliders) of tremendous benefit for many other disciplines (material science, high energy density science, high energy physics, medical imaging and diagnostics, non-destructive imaging, homeland security). In view of the overlaps with several DOE/SC offices (HEP for plasma-based acceleration, including laser and dielectric acceleration, and BES for new electron sources for applications such as light sources), the subpanel recommends that a new partnership between NSF/PHY and DOE/SC/HEP be explored for the Accelerator Science program. This would allow coverage of all areas of accelerator science (conventional

sources and advanced concepts), and a strong connection between national lab programs and universities. "

According to the NSF leadership, discussions with the Office of Accelerator Research & Development and Production within the DoE Office of Science are ongoing and intended to address this recommendation. The Plasma Physics COV highlights this issue here as a task still to be resolved by the Physics Division. Within the Plasma Physics program, considerable advanced accelerator concept research is still being supported through basic research proposals.

8. Program Response to 2019 Recommendations

There were 5 specific Plasma Physics Recommendations by the previous Plasma Physics COV.

A. *The presence of a permanent Program Director for the Plasma Physics program provides great stability and a long-term vision to the program. The subpanel strongly recommends that the presence of a permanent Program Director for Plasma Physics be maintained.*

The program has responded appropriately by appointing a permanent full-time Program Director for Plasma Physics. As a result, the program has thrived and a central vision has been clearly formulated. While the Plasma Physics program has developed a very diverse plasma portfolio, it has maintained the common thread of studying collections of charged particles to improve the understanding of the plasma state. The Program Director is commended for developing a diverse portfolio derived from this vision.

Additionally, the appointment of a full-time plasma director has led to better coordination with other physics categories within the NSF and non-NSF organizations currently funding plasma physics. Where there is overlap, the Plasma Physics director has partnered with the other funding organization. For example, the Plasma Physics director successfully arranged for joint awards between NSF/Plasma Physics and DOE/FES while maintaining a unique posture between the two organizations. Having a permanent Program Director provides a central figure to propose (and possibly negotiate) collaborations between the various plasma physics funding organizations. This can (and probably should) be the blue-print for future cooperation between the various funding organizations.

B. *The low averaged funding rates in Plasma Physics provides ample evidence of the rigorous standards applied by the program director. The subpanel recommends that the high reviewing standards applied by the program director be maintained.*

The previous COV acknowledged the high standards of the Plasma Physics program illustrated by the fair but competitive funding rate. The subpanel suggested maintaining a funding rate that was consistent with this competitive funding rate. The Plasma Physics program has performed well in responding to this request and has continued to fund proposals at a rate that is competitive while ensuring high quality proposals submitted are not overlooked.

C. *The subpanel was encouraged to see that the NSF funding contributions to the NSF/DOE Partnership in Basic Plasma Science and Engineering appear to be increasing relative to the DOE/SC/FES contribution, which speaks to the continued interest from the plasma physics community in carrying research activities that focus on high-quality research in fundamental theoretical, computational, and experimental plasma physics. The subpanel recommends that the NSF PHY division continue its vigorous support of Plasma Physics.*

The Plasma Physics program has maintained a Partnership with the DOE/SC/FES through 2022. The working agreement has been governed by a MOU between NSF and DOE/FES which was first signed 1996. The Partnership was a focal point for basic plasma physics in the US. Since 1996 the MOU has been renewed several times through 2022. However, it is noted that the MOU expired December 2022. While it is unclear how this process will continue going forward, the COV encourages continued coordination between NSF/Plasma Physics and DOE/FES.

The Plasma Physics program appears in the list of NSF programs connected with the Windows on the Universe (WoU) Big Idea program, which involves the Astronomical Sciences and Physics divisions (within the MPS Directorate) and the Office of Polar Programs (within the GEO Directorate). The COV recommends that the participation of Plasma Physics in the WoU program be supported aggressively by promoting it within the plasma physics community.

The Plasma Physics program has taken the advice of the 2019 COV in supporting the Windows of the Universe (WoU) Big Idea program. In particular, the Plasma Physics program has supported the WoU: The Era of Multi-Messenger Astrophysics meta-program. Since 2019, the Plasma Physics program has co-funded $0.83 M (co-funded 3 awards in 2020), $1.01M (co-funded 4 awards in 2021), and $1.83M (co-funded 5 awards in 2022) for a total of $3.67M, demonstrating an understanding of the importance of supporting the WoU program. The COV commends the NSF/Plasma Physics for its strong interaction with the WoU Big Idea program. The COV recommends a continued support of the WoU program going forward.

D. Among the strategic opportunities associated with the Harnessing the Data Revolution (HDR) Big Idea program, two topics intimately connected to the Plasma Physics program (matter at the high energy and intensity frontier, and space weather prediction) are cited as topics that will advance as a result of harnessing the data revolution. Plasma Physics continues to play a pioneering role in contributing to the development of high-performance computational methods and advanced diagnostics in physical space and higher-dimensional phase space. The subpanel recommends that the NSF Plasma Physics program seek ways to become an integral part of the HDR Big Idea program.

While the previous COV suggested the Plasma Physics program take advantage of strategic opportunities associated with HDR (specifically in the areas of matter at high energy and intensity and space weather predictions), the HDR program no longer exists within NSF. New initiatives at NSF, such as in Artificial Intelligence, could be a new opportunity for engagement by the Plasma Physics program.

E. *The subpanel recommends that the NSF Plasma Physics program continue its support and promotion of the NSF Mid-Scale Research Infrastructure program within the plasma physics community.*

   The program followed the suggestion of the 2019 NSF COV suggestion of supporting and promoting the NSF Mid-Scale Research Infrastructure program. The program followed up the initial infrastructure investment of $16M in the high intensity, ultrashort pulse laser project ZEUS with up to an additional $5.5M/yr funding (over 5 years) to support operations (total $18.5M). The program also participated in the NSF-wide Mid-scale Research Infrastructure-2 initiative.

9. Recommendations

The 2020 Plasma Decadal Report contained over 30 NSF relevant recommendations. Many of those recommendations encouraged more coordination within NSF for Plasma Physics in specific research areas. The ECLIPSE program and other initiatives led by the Plasma Physics program have already directly addressed many of these recommendations. Improved coordination between NSF and other agencies on plasma physics has also been addressed by the new MOUs and joint programs with NASA, NNSA, AFSOR, and DoE. Recommendations in the Decadal to better coordinate experimental plasma facilities and develop networks of users to better utilize those facilities have also been addressed by the NSF Plasma Physics through sponsorship of a number of workshops over the past four years specifically targeted at these issues. Many of the other recommendations from the Decadal are consistent with the recommendations we provide below.

The increased federal emphasis on re-invigorating the domestic semiconductor manufacturing industry, national security needs for plasma science trained personnel, recent high-visibility successes in inertial confinement fusion, the explosive growth in private fusion companies, expansion of humanity and human technology into space, and the societal need to develop less environmentally damaging methods of chemical synthesis are tremendous opportunities for plasma science and have also placed significant pressure on the plasma physics workforce. Fundamental plasma science research supported by the NSF plasma physics program at universities plays a critical role in developing the domestic plasma physics workforce and is also consistent with the Foundation's vision for the agency (the Director's Pillars). To address national workforce needs and to be responsive to the Director's vision for the Foundation, we recommend that

1. The Division of Physics continues to support an independent Plasma Physics program with a full-time program director and at least one rotator staff position.
2. The Division of Physics addresses the imbalance in base levels of individual investigator funding

within the Division given the large number of high-quality Plasma Physics proposals available for support.

3. The Division of Physics considers creating a faculty development program modeled on the Faculty Development in the Space Sciences program (NSF 19-558) created by the Geospace Section of the Division of Atmospheric and Geospace Sciences. Not only would such a program provide an immediate boost in the number of new plasma faculty positions in physics, it would also demonstrate to universities at all levels that there is a national need and support for developing new plasma physics faculty positions.
4. The Division of Physics continues to negotiate with the DoE Office of Fusion Energy Science to develop a new model of collaboration for Plasma Physics that results in a bilateral relationship which facilitates joint review of proposals between these agencies. The DoE-NSF relationship in plasma physics has been foundational to the health of the plasma physics research ecosystem in the United States and it is critical that such a relationship continue.
5. The Division of Physics supports efforts by the Plasma Physics program to coordinate with other programs (within Directorates and cross-cutting programs such as the Precision Measurement program) and other agencies on the development of critical physical data needed for high energy density plasma physics and low temperature plasmas, e.g., collision cross sections, and atomic, ionic, and molecular structure data.
6. The Plasma Physics program facilitates workshops and similar programs to bring together researchers in AMO, Quantum Systems, and plasma physics, to share insights into the development of new measurement techniques based on recent advances in all these areas of physics.
7. The Plasma Physics program regularly communicates to the plasma physics research community specifics about existing cross cutting programs (such as ECLIPSE, Major Research Instrumentation, and Mid-Scale programs) and new programs, such as the Directorate for Technology, Innovation and Partnerships to encourage plasma community participation.
8. The Plasma Physics program prioritizes continuing current efforts to broaden participation by groups currently underrepresented in plasma physics, as well as by adopting new approaches as opportunities arise.
9. The Plasma Physics program promotes access to plasma user facilities by educational institutions with an undergraduate focus, possibly with special funding solicitations. This could become an important strategy for addressing high workforce needs and for broadening participation in plasma physics through increased exposure to plasma physics among the undergraduate physics population (the new GRANTED program could play a role in this).
10. The COV recommends maintaining and enhancing (as funds are available) international collaborations that employ plasma user facilities. A good example is the new international collaboration developed between ZEUS and the European facility ELI. That collaborative activity will increase exposure of the U.S. effort in high intensity laser-matter interactions and will help draw international scientists and students to the facility.

J. Physics Frontiers Centers and Partnerships for Research and Education in Physics

1. Introduction

The Physics Frontiers Centers (PFC) program funds large group efforts (centers and institutes) at universities that advance the frontiers of physics research; strengthen physics education, diversity, and outreach; and have high potential for broad impact. The salient feature of a PFC is that the center structure must enable synergy, such that center activities surpass what is possible through single-investigator or small-group grants. The PFC program is unique within the Division of Physics in this respect, and importantly, single-investigator funds are not used to support PFCs. Investigators in any subfield covered by the Division of Physics (atomic/molecular/optical physics, elementary particle/nuclear/particle astrophysics, gravitational physics, quantum information science, plasma physics, and physics of living systems) may propose a PFC. Interdisciplinary centers are also supported, provided that most of the effort is within these areas, and such centers are co-reviewed and possibly co-funded by relevant programs in other divisions. The new and closely related Partnerships for Research and Education in Physics (PREP) program, described in more detail below, enables and nurtures partnerships between PFCs and minority-serving institutions.

The earliest PFC competition dates back to FY2001, resulting in four PFC awards. Competitions are now held every three years, with the most recent competition (and the only PFC competition in the scope of this COV) having been held in FY2020. In this most recent competition, three existing centers were phased out, two new centers were awarded, two existing centers were renewed (while four other continuing centers, funded in FY2017, did not compete in this competition).

PFC awards were made for five years, with an option for a sixth-year supplement after a successful fifth-year review, keeping the awards aligned with the competition cycles. In the ongoing FY2023 competition, successful awards will be for a full six years, eliminating the one-year extension. This policy change was a response to a suggestion of the 2019 MPSAC report, described in more detail below. There are no limits on how many times a funded center may recompete for funding, but there is also no expectation that a funded center will continue—it competes on equal footing with new center proposals. Unsuccessful renewal proposals may receive phase-out support for up to two years under the current award, and they may seek alternate sources of funding.

This COV, echoing the sentiments of prior COVs, finds the management of the PFC program by the Program Directors to be superb. The Program Directors have successfully maintained and overseen a portfolio of program activities of impressive quality, novelty, and breadth. As also noted by prior COVs in 2015 and 2019, the Program Directors have been notably successful at securing co-funding from other divisions across NSF for the PFC awards. This cooperation from other divisions attests to the importance of the PFC program within NSF, as does the high quality of the PFC activities.

2. PFC Program General Overview

The PFC program currently (FY2022) funds 8 centers, listed below.

Started or renewed in FY2020 or FY2021:

- The Center for Matter at Atomic Pressures (CMAP), University of Rochester
- Center for Theoretical Biological Physics (CTBP), Rice University
- The Network in Neutrinos, Nuclear Astrophysics and Symmetries (N3AS), University of California Berkeley
- North American Nanohertz Observatory for Gravitational Waves (NANOGrav), Oregon State University

Started or renewed in FY2017 or FY2018:

- Institute for Quantum Information and Matter (IQIM), Caltech
- JILA Physics Frontier Center, University of Colorado, Boulder/NIST
- Center for Ultracold Atoms (CUA), Harvard/MIT
- Center for the Physics of Biological Function (CPBF), Princeton University

In addition, three centers were recently phased out, all receiving phase-out funds in FY2020 and FY2021:

- Joint Institute for Nuclear Astrophysics - Center for the Evolution of the Elements (JINA-CEE), Michigan State University
- Physics Frontier Center at the Joint Quantum Institute (PFC@JQI), University of Maryland, College Park
- Center for the Physics of Living Cells (CPLC), University of Illinois at Urbana-Champaign

The PFC awards represent significant financial commitments on the part of the Division of Physics, which is commensurate with the scale and impact of the program. The total PFC annual budget has been in the range of $20-25M over the past few years, with the average award size of around $2.4M/year. This budget includes funds from a variety of partner programs: Mid-scale Innovations Program in Astronomical Sciences (AST/MSIP), Office of Multidisciplinary Activities (OMA), Earth Sciences (EAR), Division of Molecular and Cellular Biosciences (MCB), Division of Integrative Organismal Systems (IOS), Division of Materials Research (DMR), Division of Computing and Communication Foundations (CCF), and Chemistry of Life Processes (CHE/CLP). Nearly a quarter of the PFC budget has come from the funding partners. The range of partners and magnitude of the co-funding for the PFCs is an impressive accomplishment by the Program Directors.

The funding level of the PFC program amounts to roughly 7-8% of the Division of Physics budget from FY2019-22. This level was a subject of some discussion among prior COVs. The 2015 and 2019 COVs noted budget amounts in a similar range, and prior COVs had suggested that the PFC's budget fraction be kept at less than 10%. The 2019 COV expressed some disappointment at a reduction in the PFC's budget. Noting that the large scale of the awards is important in attracting top-quality people and proposals, the 2019 COV suggested that as a coping strategy, reducing the number of awards is preferable to reducing their size. Indeed, the Program Directors have reduced the number of supported centers from 9 in the 2019 COV report to 8 in this report, in order to keep the size of the awards approximately the same. This COV concurs that this is a good funding strategy for the program. The Program Directors noted that inflation is still a challenge, with funding requests bigger than what the program can accommodate, reflecting a larger issue in scientific funding.

3. PREP Program

The PREP program was recently created to enable and grow partnerships between minority serving institutions (MSIs) and Physics Frontiers Centers (PFCs). Its aims are to develop true partnership between PFCs and MSIs; increase the participation of underrepresented groups in physics; and develop research infrastructure at the MSIs.

The PREP program supports experimental and theoretical research partnerships between MSIs and PFCs. It has had one competition so far (FY2022), where the typical award was ~$300K/year for 3 years. Physics departments at MSIs are underfunded and underequipped. This program offers investigators at MSIs the opportunity to strengthen research capabilities at their home institutions, as well as to advance their professional development. Through the PFCs, they gain access to cutting edge science infrastructure while improving their own infrastructure. There is therefore an increased potential for creating a pipeline for PFCs to attract and recruit students from a broader, more diverse pool of students, including those from underrepresented populations.

The PREP program currently funds six partnerships:

- CUNY City College and CUA
- Florida International University and JILA PFC
- The University Corporation, Northridge, and IQIM
- University of Puerto Rico Mayaguez and NANOGrav
- Texas Southern University and CTBP
- Southern University and CMAP

4. Review Process

The only PFC competition within the scope of this COV review occurred in FY2020. Preliminary proposals for PFCs were reviewed by a panel who recommended whether the groups should be invited to submit a full proposal. Three members of each panel provided individual, written reviews of each proposal in advance of the panel meeting, and the proposals were then discussed in a panel meeting. Program Directors within the Physics Division and those from interested programs outside the Division discussed the recommendations. They concurred with the panel's recommendations for proposals to invite, but they also invited an additional four proposals not recommended by the panel. As two of these additional four were ultimately funded, the COV views this leadership by the Program Directors positively. In the individual reviews and panel discussion, panelists were instructed to review according to the PFC requirements from the solicitation: (1) the potential for a profound advance in physics; (2) creative, substantive activities aimed at enhancing education, diversity, and public outreach; (3) potential for broader impacts, e.g., impacts on other field(s) and benefits to society; (4) a synergy or value-added rationale that justifies a center- or institute-like approach.

The successful preliminary proposals were then invited to submit detailed full proposals. The full proposals were sent out for ad hoc reviews by scientific experts. Reviewers were selected for their scientific and technical expertise and their ability to thoroughly address part or all of the science in a given proposal. At least eight reviewers were contacted to review each proposal. The review process for this competition played out as the COVID-19 pandemic was ramping up in the United States. A major challenge was that a number of ad hoc reviewers were unable to complete their promised reviews on time, while they were adapting to university closures and classes moving online. All proposals ultimately had at least 5 ad hoc reviews except for 1, which had 4 reviews. Aside from this, the review process seemed to proceed remarkably smoothly given the circumstances, and the Program Directors performed well in a difficult time. Following this review, decisions on whether or not to invite PIs to the final stage of review were based on the ad hoc reviews and the input from Program Directors in related fields.

The final stage of the competition was a reverse site visit, where PIs presented to a panel consisting of scientific experts covering all the fields represented in the proposals under consideration. Prior to the panel meeting, the PI of each invited proposal was sent anonymized versions of the ad hoc reviews of their proposal. The PIs were able to address the reviews in a written response, which was provided to the panelists in advance of the reverse site visit.

Because of the wide-ranging scale of the proposed PFC activities, a major challenge for the Program Directors is to identify panelists and ad hoc reviewers who are free from conflicts of interest. Potential conflicts of interest are managed carefully and in consultation with general counsel when they are not clearly problematic. Despite these difficulties, the Program Directors seem to have done well in recruiting the large pool of competent reviewers required for the program.

PREP proposals are reviewed in a more straightforward process. At least two ad hoc reviewers provided written reviews for each proposal, and a panel then discussed the proposals and ad hoc reviews, and made recommendations on whether or not each proposal should be funded. Based on this information the Program Director then recommended the best proposals for funding. The COV reviewed 3 representative eJackets in detail, which were reasonably straightforward cases. The COV agrees that this process is effective in selecting PREP awards.

The funded PFCs are carefully overseen through in-depth site-visit reviews. These included mid-cycle reviews and reviews for one-year funding extensions at the end of a 5-year award, to bridge center support until the next competition. Going forward, and in partial response to the MPSAC subcommittee report described below, awards are changing to full 6-year awards by default. A review by NSF-only personnel will take place in the second year of the award, and a site-visit panel will conduct a review early in the fourth year of the award. This structure helps to address a concern mentioned by the Program Directors that fifth-year reviews could confer unintended competitive advantages to existing PFCs in the next competition (renewal proposals are supposed to compete on equal footing with proposals for new centers). The COV agrees that the new oversight process is reasonable and likely an improvement over the former process.

The COV recognizes the enormous workload, borne by both reviewers and the Program Directors, involved in these thorough review and oversight processes. Considering the large financial investment represented by PFC awards, this COV feels that this process is worth the hard work, and is effective in selecting the best proposals. The COV also supports the tradition of carefully considering panel recommendations, other reviews, and input from partner Program Directors, but ultimately using their experience and perspective to arrive at independent funding decisions and oversight decisions regarding continuing funding.

In terms of the PREP program, the COV encourages a continued focus on building infrastructure at MSIs. As much as possible, PREP should seek to enhance research interaction between individual faculty at MSIs and at PFCs based on mutual research interests. The involvement of undergraduate students, graduate students, and postdocs in both directions should continue to be a main point of focus.

Intellectual Merit

The PFC centers have distinct advantages over other grant programs within the Physics Division. Specifically, they foster collaboration among groups located at different types of universities and in different parts of the country. They enable rapid response to new developments in research. They create environments in which students and postdocs can grow and thrive intellectually. They have the research focus, the critical mass, and the diversity in expertise to compete globally with similar efforts being undertaken at the national level in other countries.

Among the currently funded centers there is a wide range of science across physics and surrounding areas such as astrophysics and biophysics:

The Center for Matter at Atomic Pressures (CMAP)

CMAP involves physicists, astrophysicists, and planetary scientists studying matter at high enough pressures to disrupt the structure of individual atoms. Topics of inquiry include atoms and molecules at atomic pressure, transport properties in high-energy-density matter, dense hydrogen and helium, and quantum matter in gaseous planets.

Center for Theoretical Biological Physics (CTBP)

Major science directions at CTBP are in areas including physics of the genome, biological functionality including biomolecular physics and cellular function, regulatory control of active processes in living cells.

Center for Ultracold Atoms (CUA)

The CUA studies physics in the areas of quantum gases of atoms and molecules, atoms and photons, and atom-like and hybrid systems, with connections to condensed matter physics and quantum information science. Recent highlights include the demonstration of quantum entanglement between polar molecules in an optical tweezer array, and the experimental observation of a quantum spin liquid using neutral atoms on frustrated lattices.

Center for the Physics of Biological Function (CPBF)

CPBF researchers are making progress on current mysteries in animal behavior searching both for universal dynamics at long time scales and for the origin of individuality; the emergence of collective phenomena or states in groups of molecules, genes, neurons, and organisms; information transfer in genetic code, neural circuits, cellular sensors; and the integration of biochemical networks for specific functions, and mechanism of adaptive immunity.

Institute for Quantum Information and Matter (IQIM)

Research in the IQIM focuses on the areas of quantum information physics, topological quantum physics, and quantum dynamics. Highlights include the fabrication of mechanical resonators with phonon lifetimes exceeding 1 second (with potential applications as quantum memory elements and to testing quantum collapse models), and the development of the "classical shadow," which is a succinct, efficiently generated classical description of a many-body quantum state.

JILA Physics Frontier Center

JILA explores quantum matter from fundamental constituents, quantum correlated states, and out of equilibrium dynamics of quantum systems. As examples, JILA researchers have recently used delocalized, entangled quantum states to measure accelerations below the standard quantum limit, and have also demonstrated layer-resolved imaging of 2D layers of ultracold molecules using them to study spin exchange and chemical reactions.

The Network in Neutrinos, Nuclear Astrophysics and Symmetries (N3AS)

N3AS studies neutrino physics, nucleosynthesis, dense matter in compact astrophysical objects such as neutron stars, dark matter, and performs astrophysical simulations.

North American Nanohertz Observatory for Gravitational Waves (NANOGrav)

The NANOGrav collaboration is a partnership dedicated to measuring low-frequency gravitational waves using radio pulsar timing data. The center has interdisciplinary activities in astronomy, engineering, and computer science.

Each of the PFCs has web site with a prominent acknowledgement of the major funding support that comes from NSF.

Broader Impacts

NSF has very high expectations from its PFC and PREP awardees in the area of broader impacts. Among proposed broader impact activities are: public lectures and events, workshops and summer schools, symposium series, visitor programs, ideas incubators, interdisciplinary studies and interdisciplinary research programs, workforce training, and technology development. Some examples of outreach and education activities in the existing PFCs include the Quantum Chess game and an impressive collection of science YouTube videos for a non-technical audience from IQIM, and a Bootcamp at CMAP for students to learn the fundamentals of effective science communication.

Through broader impacts activities, PFCs reach both the current/next generation of researchers and the general public. They therefore have the potential for effecting positive change on the representation and status of underrepresented groups in the physical sciences. The overall quality of the programs is high.

Successful efforts in these areas generally build upon existing infrastructure at the PFC partner institutions. Among the non-awarded proposals, broader-impact criticisms appeared to center on a narrow definition of broader impacts as activities that impact underrepresented groups. Certain reviewers expected nearly exclusive focus on education, outreach, and improving diversity, with professional efforts in this arena, and metrics of success that are well-defined and proposed to be measured and assessed. Some reviewers even questioned the dedication of PIs to their proposed broader impacts activities.

In a few cases the broader impacts focused on technology development, and this is also a reasonable and in-scope interpretation of the broader impacts criterion. NSF/MPS/PHY should instruct its panels appropriately on the viability of different avenues of satisfying the broader impacts requirements. Research scientists at the frontier may or may not also be the best at public outreach and diversity efforts, and their existing talents and time should be leveraged as much as possible concerning use of NSF funding.

5. Recommendations of Prior COVs

The 2019 COV report made these recommendations regarding the PFC program:

> The PFC program is an excellent, tremendously successful, and well-run program; thus, the COV is not recommending major changes. It is clear that the PFCs consistently produce groundbreaking scientific discoveries, and they are phenomenal in terms of broader impact.
>
> Although we will not be able to comment on the MPSAC subcommittee's review of the program, we think that idea of the review is a good one, and suggest that the PFC program conduct this review again at some time in the future.
>
> We also reiterate that the reduction in funding level for the PFC that began in FY2018 is a disappointing development. We suggest maintaining the size of PFC awards, even though this will translate into a reduction in the number of awards. As a minor mitigation, the PFC PDs may consider limiting even further the number proposals that move on beyond the preliminary stage.
>
> The 2015 COV commented that "It is important for the Division to remain vigilant so that the Centers do not become entitlements, unfairly leveraging their history and momentum in competitions." We believe that the PFC program's selection process has been successful in this regard, and we encourage the Division's continued vigilance.

<u>NSF response to the 2019 COV</u>

Since the last COV, three PFCs have been phased out (JINA, PFC@JQI and CPLC), two have been renewed (CTBP, NANOGrav), and two new ones have been launched (N3AS and CMAP). This evolution reduced the number of PFCs from nine to eight. Thus, while the total funding has declined about 6% from the last COV period (2015-18) to this one (2019-22), the average funding per center has held constant at ~$2.4M/year. Preservation of the average funding level and the competitive renewal process align fully with the advice of the 2019 COV.

The review of the 2019 MPSAC subcommittee is discussed in the next section. NSF has not yet responded to the 2019 COV advice that "the PFC program conduct this review again at some time in the future." Given the substantial effort involved, this committee suggests planning for the next review in ~2029, that is, after a decade-long interval.

6. MPSAC Subcommittee Report

Following advice from the 2012 and 2015 COVs, MPSAC in 2018 charged a subcommittee to conduct an independent assessment of the PFC program. Specifically, the subcommittee was asked to "assess how well the PFC program is addressing its goals of fostering profound advances in physics, enhancing education, diversity, and public outreach, and addressing broader impacts through center or institute awards." Rather than seeking recommendations, the charge called for the subcommittee to "identify strengths and weaknesses of the PFC program and issues that the Division can address in developing and evolving the program." The subcommittee, which was chaired by Donald Geesaman (Argonne National Lab), submitted its report in June 2019.

The MPSAC Subcommittee noted numerous strengths of the PFCs:

- PFCs foster collaborations
- PFCs enable rapid responses to research developments
- PFCs provide local oversight over research progress
- Postdoctoral researchers mature more rapidly within PFCs
- PFCs offer additional unique opportunities to pursue research
- PFCs enable the U.S.A. to better compete globally

The subcommittee identified weaknesses and issues in the areas of diversity and workforce development, including the lack of coherent tracking of diversity statistics and outcomes for students and postdocs; diversity statistics no better than in physics as a whole; and the sudden demise of educational activities and programs when PFCs close. The summary observes:

> This needs a change in culture. The subcommittee recognizes the difficulty, cost and privacy issues in tracking participation and outcomes, but without better tracking of the students, post-docs, and other participants, the education, outreach and diversity efforts will not be a data driven scholarly endeavor. There needs to be more sharing of the results in the science education literature. The position of education and outreach coordinator often needs to be more valued and, in some cases, more professional. The subcommittee would suggest that when a center is closed, ramp-down funds need to be available to responsibly complete these education and outreach activities. We also suggest that these efforts would benefit from more regular networking among the centers by the education and outreach coordinators.

Elsewhere in the report, the committee pointed out "a need to elucidate the priorities of the various aims of the programs." In addition, the subcommittee found

> The current practice of having PFCs submit a proposal for a one-year extension in the fifth year for funding of the sixth year, a proposal that must be reviewed, and then a new proposal in the sixth year that goes in a different scientific direction in response to the next program solicitation is very wasteful of effort at the PFC, at the NSF and for the reviewers. NSF should develop a strategy to fix this.
>
> At the bottom line, the subcommittee understands the community perception that the PFC program may appear to favor the "rich." We do not see that as an inherent bias in the goals and solicitation for the program. It can only be addressed by careful choices of the selection panels and clear delineation of NSF expectations. Since this goes to the heart of the proposal review process, it is beyond our charge.

<u>NSF Response to the MPSAC Subcommittee Report</u>

In response to the concerns related to diversity, NSF established the PREP program, which partners the PFCs with minority-serving institutions as described above. This is an important initiative that brings best practices to the PFCs. It is too soon, however, to assess the impact of PREP or to measure any resulting increase in the diversity of the PFCs.

To address other concerns related to diversity and workforce development, the 2022 PFC proposal solicitation (22-592) adds two pages to the proposal length to expand the Education, Human Resources, Diversity, and Outreach Section, add a section on Broader Impacts, and accommodate a newly required "plan to sustain the Education, Outreach, and Diversity activities beyond the lifespan of the center." The COV applauds these changes, which better capture the importance of these PFC activities.

The tracking of students, postdocs and other center participants and their outcomes continues to be spotty, and the lack of tracking is exacerbated by inconsistency among centers in the definition of a participant. These conditions continue to hinder assessments of program impact as well as center diversity. This committee hopes that this tracking may be facilitated in the future through more explicit requests for compiled information in annual reports and site-visit reviews.

Solicitation 22-592 also states that "Physics Frontiers Centers funded through this solicitation will be funded for six years instead of the previous five years." This change eliminates the proposals for one-year extensions, as advised by the MPSAC Subcommittee.

The success of NSF in the "careful choices of the selection panels and clear delineation of NSF expectations" is addressed in the Review Process and Broader Impacts sections of this subcommittee's report.

7. Summary Recommendations

The PFC program enables research that is collaborative, agile, can afford to take risks, and often reaches across disciplinary boundaries. Overall this is an excellent, successful, and well-run program, and the Program Directors are to be commended for doing great work.

The COV welcomes the addition of the PREP program and its emphasis on involving faculty from MSI institutions in PFC research, which has the potential to both enhance the research of the PFCs and build the strength of the research programs at MSIs. Impact will become clearer by the time of the next COV.

The PFC proposal review process is thorough and multi-staged. Program officers work hard to find reviewers with the needed expertise, in spite of the elimination of many potential reviewers due to the conflict-of-interest constraints that are inevitable for a large center proposal.

PFCs take a variety of approaches to funding allocation, increasing diversity, and building the cohesiveness of their teams. The COV encourages NSF to develop means for sharing experience and best practices among centers. In the past, annual meetings of the leadership teams fostered cross-center communication about these topics and others. The COV encourages NSF to resume these meetings and to share best practices.

The MPSAC review provided a useful assessment of PFC value. It also highlighted the shortcomings—and opportunities—for the PFCs to develop and share best practices for workforce development and diversity, resulting in the PREP program. Given this very positive outcome, this COV suggests that NSF plan for a similar review in the future. Given the long timescales required for increasing diversity and thus to assess the impact of PREP and other changes, together with the considerable effort involved in an MPSAC review, the COV suggests holding MPSAC subcommittee reviews at roughly decade-long intervals.

In order to foster effective programs in diversity, equity and inclusion, the COV encourages NSF to provide more explicit guidance in the proposal call regarding expectations in these areas based on proven models.

Appendix A: 2023 COV Membership and Subcommittees

Subcommittee chair is indicated by *

PHY 2023 COV Member	Institution	email address
COV CHAIR		
Elizabeth (Betsy) Beise	University of Maryland	beise@umd.edu
Atomic, Molecular, and Optical Physics / Quantum Information Science		
Protik (Tiku) Majumder *	Williams College	pmajumde@williams.edu
Theresa Lynn	Harvey Mudd College	lynn@g.hmc.edu
Olivier Pfister	University of Virginia	opfister@virginia.edu
David Schultz	Universities Research Association (Sandia Site Office)	DSchultz@ura-hq.org
Elementary Particle Physics Experiment / Large Hadron Collider		
Dmitri Denisov *	Brookhaven National Laboratory	denisovd@bnl.gov
Oliver (Keith) Baker	Yale University	oliver.baker@yale.edu
Todd Pedlar	Luther College	todd.pedlar@luther.edu
Elementary Particle Physics / Cosmology Theory		
Sally Dawson *	Brookhaven National Laboratory	sdawson@bnl.gov
Brian Batell	University of Pittsburgh	batell@pitt.edu
Howard Haber	University of California - Santa Cruz	haber@scipp.ucsc.edu
Gravitational Physics / LIGO		
Gary Horowitz *	University of California - Santa Barbara	horowitz@ucsb.edu
Alessandra Corsi	Texas Tech	Alessandra.Corsi@ttu.edu
Xavier Siemens	Oregon State University	xavier.siemens@oregonstate.edu
Integrative Activities in Physics		
Kelly Mack *	Project Kaleidoscope at AAC&U	mack@aacu.org
Catherine Mader	Moore Foundation (formally APS)	catherine.mader@moore.org
Stamatis Vokos	California Polytechnic State University	svokos@calpoly.edu
Nuclear Physics Theory & Experiment		
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Andrea Delgado	Oak Ridge National Laboratory	delgadoa@ornl.gov
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Andreas Metz	Temple University	andreas.metz@temple.edu
Particle Astrophysics / IceCube		
Priscilla (Prisca) Cushman *	University of Minnesota	cushman@umn.edu
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Kate Scholberg	Duke University	kate.scholberg@duke.edu

PHY 2023 COV Member	Institution	email address
Physics of Living Systems		
Margaret Cheung *	University of Washington	mscheung@uw.edu
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Physics Frontiers Centers / Partnerships for Research & Education in Physics		
Daniel Steck *	University of Oregon	dsteck@uoregon.edu
Lynne Hillenbrand	California Institute of Technology	lah@astro.caltech.edu
J. Ritchie Patterson	Cornell University	jrp3@cornell.edu
Anderson Sunda-Meya	Xavier University of Louisiana	asundame@xula.edu

APPENDIX B: Template Response

(Table 2 can be found in Appendix A)

Table 1 - Summary Information

Summary Information
Date of COV: Asynchronous subgroup meetings: January 3 – 13, 2023 In-person meetings: January 23 – 24, 2023
Program/Cluster/Section: All programs in the Division
Division: Division of Physics (PHY)
Directorate: Directorate for Mathematical and Physical Sciences (MPS)
Number of actions reviewed: 336 **Awards:** 209 **Declinations:** 111 **Other:** 16
Total number of actions within Program/Cluster/Division during period under review: 3,095 **Awards:** 1,314 **Declinations:** 1,618 **Other:** 163
Manner in which reviewed actions were selected: The PHY proposal samples provided to the COV were chosen to provide a balanced and representative selection of awards, declinations, and other actions from each of the subprograms over the four years under review. PHY also provided the committee with the complete list of all actions taken during this period.

INTEGRITY AND EFFICIENCY OF THE PROGRAM'S PROCESSES AND MANAGEMENT

Briefly discuss and provide comments for *each* relevant aspect of the program's review process and management. Comments should be based on a review of proposal actions (awards, declinations, returns without review, and withdrawals) that were *completed within the past four fiscal years*. Provide comments for *each* program being reviewed and for those questions that are relevant to the program(s) under review. Quantitative information may be required for some questions. Constructive comments noting areas in need of improvement are encouraged.

I. Questions about the quality and effectiveness of the program's use of merit review process. Please answer the following questions about the effectiveness of the merit review process and provide comments or concerns in the space below the question**.**

Table 2 - Quality and Effectiveness of the Merit Review Process

QUALITY AND EFFECTIVENESS OF MERIT REVIEW PROCESS	**YES, NO, DATA NOT AVAILABLE, or NOT APPLICABLE**
1. Are the review methods (for example, panel, ad hoc, site visits) appropriate? The use of both panels and ad hoc reviews allows for a diversity of opinions and the ability for robust discussion. Site visits (either on-site or reverse) are critical for the larger proposals, as are some specialized strategic reviews for long-term projects.	YES

QUALITY AND EFFECTIVENESS OF MERIT REVIEW PROCESS	YES, NO, DATA NOT AVAILABLE, or NOT APPLICABLE
2. Are both merit review criteria addressed a) In individual reviews? b) In panel summaries? c) In Program Officer review analyses? There is a fairly wide variance in the level of detail and substantive nature of the comments, but given the portfolio of ad hoc reviews, there is ample substantive assessment. Among the ad-hoc reviewers there continues to be variation in the level of attention paid to “broader impacts”, but the panel reviews add substantive evaluation in this area. We recommend continued reinforcement of the intended broad meaning of “broader impacts”, and of the importance of attention to it in the ad-hoc reviews. The COV generally agreed that the abbreviated Review Analyses implemented in 2022 provide sufficient justification for the decisions made.	YES
3. Do the individual reviewers giving written reviews provide substantive comments to explain their assessment of the proposals? The comments of individual reviewers vary widely in their length and detail, but with multiple reviews there is generally enough information to understand the assessments.	YES
4. Do the panel summaries provide the rationale for the panel consensus (or reasons consensus was not reached)? While the panel consensus is not always consistent with the individual reviews, the panel discussions allow more viewpoints to be considered. The panel summaries are particularly useful in understanding the rationale behind the panel consensus. In many cases, they were more reliable than the individual reviews.	YES

QUALITY AND EFFECTIVENESS OF MERIT REVIEW PROCESS	YES, NO, DATA NOT AVAILABLE, or NOT APPLICABLE
5. Does the documentation in the jacket provide the rationale for the award/decline decision? The COV was generally of the opinion that the abbreviated Review Analysis process used beginning in 2022 provided sufficient justification for the decisions made by the Program Directors. Some PDs prefer to write lengthier analyses and the COV subcommittee reviewing these jackets expressed that the PDs should have the flexibility to do so, as appropriate.	YES
6. Does the documentation to the PI provide the rationale for the award/decline decision? During the COV discussions, we learned that the general practice among the PDs is to either proactively follow-up with the PI or to offer a verbal conversation, in the case of declines, and especially among first-time proposers. COV members were not always able to verify how widespread this practice is solely from the e-Jackets.	YES /DATA NOT ALWAYS AVAILABLE
7. Additional comments on the quality and effectiveness of the program's use of merit review process: Program Directors were consistently thoughtful and fair in analyzing recommendations from ad hoc reviews, panels, and other program directors, particularly in cases of conflicting guidance.	

II. Questions concerning the selection of reviewers. Please answer the following questions about the selection of reviewers and provide comments or concerns in the space below the question**.**

Table 3 - Selection of Reviewers

SELECTION OF REVIEWERS	**YES, NO, DATA NOT AVAILABLE, or NOT APPLICABLE**
1. Did the program make use of reviewers having appropriate expertise and/or qualifications? Reviewer choices are appropriate, and often quite complementary. When aspects of the proposal are farther away from the reviewer expertise, the reviewer generally notes such, allowing the panel to evaluate and supplement the ad hoc content.	YES
2. Did the program recognize and resolve conflicts of interest when appropriate? Most conflicts are identified by the Program Director in advance of the review process. Conflicts can be very challenging to avoid in some of the larger projects, particularly in the assembly of panels with adequate diversity of expertise. Conflicted panelists (or the Program Director) would simply identify their conflict and be recused from the discussion.	YES
3. Additional comments on reviewer selection: Data on the demographic diversity of the reviewers are collected. For some program areas, data by institution type (large/small/R1/R2/MSI/public/private) could also be valuable for the COV to understand the diversity of the reviewer pool. Some subcommittees suggested that there be an effort to increase the number of reviewers from less represented states and from non-academic settings.	

III. Questions concerning the management of the program under review. Please comment on the following:

Table 4 - Management of the Program Under Review

MANAGEMENT OF THE PROGRAM UNDER REVIEW
1. Management of the program. All subcommittees indicated that the programs are consistently managed well. Several subcommittees felt that the program directors have a significant workload and could be more effective with additional staffing, particularly in responding to the growing number of multi-divisional and NSF-wide initiatives. The strategy of pairing a permanent Program Director with a rotator, when feasible, has been very effective in providing both stewardship and fresh perspectives.
2. Responsiveness of the program to emerging research and education opportunities. Most programs have participated in several of the NSF-wide “Big Ideas” initiatives, focused on emerging areas, often through proactive outreach by the Program Directors. An excellent example of a Division-level response to emerging research is the Dear Colleague Letter on Precision Measurements, which supports a diversity of techniques to address a big question.
3. Program planning and prioritization process (internal and external) that guided the development of the portfolio. The Division uses a variety of community and stakeholder advisory groups and reports to inform, but not solely determine, funding decisions. These include national advisory committees and National Academies reports, among others. Given the diversity of the portfolio, we find this approach to be strategic and appropriate.
4. Responsiveness of program to previous COV comments and recommendations. The COV as a whole, and the subcommittees individually, found that the Division and the Program Directors responded to the majority of the 2019 suggestions and recommendations, when feasible.

IV. Questions about Portfolio. Please answer the following about the portfolio of awards made by the program under review.

Programs should provide materials to the COV regarding portfolio goals and can insert specific targeted questions about their portfolios. *(Some dimensions of portfolio balance to consider include: balance across disciplines and sub-disciplines, award size and duration, awards to new and early-career investigators, geographical distribution of awards, awards to different types of institutions, innovative/potentially transformative projects, projects with elements of risk, inter- and multi-disciplinary projects, projects that integrate research and education, participation of groups that are under-represented in science and engineering, and projects that are relevant to agency mission or national priorities).*

Detailed comments on the portfolio can be found in the main body of the report, most specifically throughout the subcommittee reports.

OTHER TOPICS

1. Please comment on any program areas in need of improvement or gaps (if any) within program areas.

Various program specific comments are in the subcommittee reports. Two general areas identified that could be opportunities for growth are: a) proactive support by the Division and MPS-level leadership to cultivate sustained interdisciplinary partnerships; and b) Division-level support for addressing a coherent strategy towards broadening participation, perhaps building upon the existing IAP program area.

2. Please provide comments as appropriate on the program's performance in meeting program-specific goals and objectives that are not covered by the above questions.

The Division leadership and Program Directors are performing at an exemplary level in meeting their goals and objectives and the expectations of the community, within the boundaries of their budget and staffing levels.

3. Please identify agency-wide issues that should be addressed by NSF to help improve the program's performance.

With the increasing number of agency-wide initiatives, the workload on program directors continues to increase. Additional staffing to support new NSF-wide initiatives should be considered when budgeting for them.

4. Please provide comments on any other issues the COV feels are relevant.

5. NSF would appreciate your comments on how to improve the COV review process, format and report template.

While we don't offer an implementation strategy, some COV members felt that some community input would help inform the COV further about the wider perception of the Division's processes and practices. We recognize that this may be challenging to implement in an unbiased fashion. And given the Agency-level pillar of "Accessibility and Inclusivity", some specific questions might be directed towards the next COV as to what extent the Division's goals of broadening participation are being met. Generally, the process of virtual meetings in advance of the two-day in-person convening went well, although the timing of the meeting falling so close to the December holiday period was challenging. The COV chair will convey some specific suggestions on the agenda to the Division Director for consideration by the next COV chair for future meetings.

SIGNATURE BLOCK:

____
For the 2023 Physics Division Committee of Visitors
Elizabeth Beise, University of Maryland (Chair)

APPENDIX C: 2023 PHY COV Meeting Agenda

Virtual: December 16, 2022, January 3 – 13, 2023
In-Person: January 23 – 24, 2023
2415 Eisenhower Avenue, Alexandria, VA 22314

Friday, December 16 – Opening Session -- Virtual (Zoom)
(Note: This session officially opens the CoV meetings)

2:00 Introduction to COV Process, Ethics Briefing
Dr. Jean Cottam, Deputy Director, Division of Physics

2:30 Overview of PHY Division
Dr. Denise Caldwell, Director, Division of Physics

3:15 Initial Instructions to COV
Dr. Betsy Beise, Chair, COV

3:30 Demonstration of eJacket Module
Mr. David Barley, Program Support Manager, Division of Physics

January 3 – January 13 – Program Sessions -- Virtual (Zoom)

60’ PHY Program Director Presentations on Individual Programs

90’ Discussion of NSF COV Template items I, II, III, IV covering charge elements:

- Integrity and Efficacy of Program Processes for Proposal Actions
- Quality and Significance of Program Investments
- Relationship to Foundation-wide Programs and Strategic Goals

Discussion of *Additional PHY Topics* as related to individual programs:

- Balance between award size and success rate per program
- Engagement in cross-cutting programs (PHY Midscale, PIF, LEAPS)

60’ Executive Session for Program Subcommittee / Formulation of Additional Questions to Program

(Program chairs collect input to Template Items I, II, III, IV and draft program reports.)

30’ Discussion of Additional Questions with Program Directors

Monday, January 23 – NSF

8:00	Refreshments
8:30	Welcome and Charge to Committee of Visitors (COV) Dr. Sean L. Jones, Assistant Director, Directorate for Mathematical and Physical Sciences (MPS)
8:50	Introductory Remarks Dr. Betsy Beise, Chair, COV
9:15	Introduction to Division-Level Review and Full Panel Discussion Denise Caldwell, Director, Division of Physics Dr. Betsy Beise, Chair, COV
10:55	Instructions for Breakout Sessions Dr. Betsy Beise, Chair, COV
11:00	BREAK
11:15	Breakout: Individual Program Group Discussions of Division-Level Questions
12:30	WORKING LUNCH
13:30	Breakout: Executive Session of Program Groups to Consolidate Input
14:30	Executive Session of Full COV Panel Dr. Betsy Beise, Chair, COV
15:30	BREAK
15:45	Breakout: Preparation of Program Reports
17:00	Executive Session [If necessary, formulate additional questions to Division Leadership] Dr. Betsy Beise, Chair, COV
18:00	Adjourn

Tuesday, January 24 – NSF

Combined meetings of COV will take place in Room 2020/2030
Zoom link and room assignments for breakout meetings are listed below

8:00	COFFEE
8:30	Presentation of Preliminary Program Reports by Program Chairs
10:30	[If necessary] PHY answers to previous evening questions Dr. Denise Caldwell, Director, Division of Physics
11:00	Breakout: Complete drafts of Program Reports
12:00	WORKING LUNCH
13:00	Discussion of Overall Report Dr. Betsy Beise, Chair, COV
14:00	Complete Draft of Overall Report
15:00	Closeout Session with AD/MPS and PHY Staff
15:30	Adjourn

APPENDIX D: Division of Physics – Charge to 2023 Committee of Visitors (COV)

By NSF policy, each program that awards grants and cooperative agreements must be reviewed at four-year intervals by a COV comprised of qualified external experts. NSF relies on their judgment to maintain high standards of program management, to provide advice for continuous improvement of NSF performance, and to ensure openness to the research and education community served by the Foundation. Reports generated by COVs are used in assessing agency progress in order to meet government-wide performance reporting requirements and are made available to the public.

Decisions to award or decline proposals are ultimately based on the informed judgment of NSF staff, based on evaluations by qualified reviewers who reflect the breadth and diversity of the proposed activities and the community. Systematic examination by the COV of a wide range of funding decisions provides an independent mechanism for monitoring and evaluating the overall quality of the Division's decisions on proposals, program management and processes, and results.

The FY 2023 Division of Physics (PHY) COV is charged to address and prepare a report on:

- the integrity and efficacy of the program's processes and management including those used to solicit, review, recommend, and document proposal actions;
- the quality and significance of the results of the Division's programmatic investments;
- the relationship between award decisions, program goals, and Foundation-wide programs and strategic goals;
- the Division's balance, priorities, and future directions;
- the Division's response to the prior COV report of 2019; and
- any other issues that the COV feels are relevant to the review.

The COV report is made available to the public to ensure openness to the research and education community served by the Foundation.

The review will assess operations of individual programs in PHY as well as the Division as a whole for four fiscal years: FY 2019, FY 2020, FY 2021, and FY 2022. The PHY programs under review include:

- Atomic, Molecular and Optical Physics
- Elementary Particle Physics
- Gravitational Physics
- Integrative Activities in Physics
- Midscale Infrastructure (Division-wide)
- Nuclear Physics
- Particle Astrophysics
- Plasma Physics
- Quantum Information Science
- Physics at the Information Frontier
- Physics Frontiers Centers
- Physics of Living System

Where appropriate these include both experimental and theoretical research programs.

APPENDIX E: Acronyms

AAAC	Astronomy and Astrophysics Advisory Committee
AAAS	American Association for the Advancement of Science
ACME	Advanced Cold Molecule Electron Electric DIpole Moment Search
AdS	Anti-de-Sitter
AdS-CFT	Anti-de Sitter/Conformal Field Theory
AFOSR	Air Force Office of Scientific Research
AGEP	Alliances for Graduate Education and the Professoriate
AGEP-GRS	Alliances for Graduate Education and the Professoriate – Graduate Research Supplements
AGS	NSF Division of Atmospheric and Geospace Sciences
AI	Artificial Intelligence
ALPs	Axion-Like Particles
AMO	Atomic Molecular and Optical Physics
AMOE/AMO-E	PHY Atomic Molecular and Optical Experimental Physics program
AMOT/AMO-T	PHY Atomic Molecular and Optical Theoretical Physics program
APS	American Physical Society
ARA	Askaryan Radio Array
ARC	Australian Research Council
ARIANNA	Antarctic Ross Ice Shelf Antenna Neutrino Array
Ascend	Mathematical and Physical Sciences - Ascending Postdoctoral Research Fellowships
ATLAS	A Toroidal LHC Apparatus
BAND	Bayesian Analysis of Nuclear Dynamics
BaPSF	Basic Plasma Science Facility
BEACON	Beam forming Elevated Array for COsmic Neutrinos
BIO	NSF Directorate for Biological Sciences
BL3	Beam-method (neutron) Lifetime 3rd Generation
BMBF	Bundesministerium fur Bildung und Forschung (German Ministry for Education and Research)
BNL	DOE Brookhaven National Laboratory
BSM	Beyond the Standard Model
CAREER	NSF Faculty Early Career Development Program
CAS	NSF Critical Aspects of Sustainability program
CAS-SC	NSF Critical Aspects of Sustainability for innovative solutions to Sustainable Chemistry program
CBET	NSF Division of Chemical, Bioengineering, Environmental and Transport Systems
CCF	NSF Division of Computing and Communications Foundations

CE	Cosmic Explorer
CEBAF	Continuous Electron Beam Accelerator Facility
CERN	Conseil Européen pour la Recherche Nucléaire (European Laboratory for Particle Physics)
CFI	Canada Foundation for Innovation
CFT	Conformal Field Theory
CHE	NSF Division of Chemistry
CIMER	Center for the Improvement of Mentored Experiences in Research
Circuit QED	Circuit Quantum Electrodynamics
CISE	NSF Directorate for Computer and Information Science and Engineering
CKM	Cabibbo-Kobayahi-Miskawa
CLP	NSF Chemistry of Life Processes program
CMAP	Center for Matter at Atomic Pressures
CMB	Cosmic Microwave Background
CMMI	NSF Division of Civil, Mechanical and Manufacturing Innovation
CMS	Compact Muon Solenoid
CNO	Carbon Nitrogen Oxygen cycle
CNRS	Centre National de la Recherche Scientifique (French National Center for Scientific Research)
CONACYT	Consejo Nacional de Ciencia y Tecnología (Mexican Council for Science and Technology)
COV	Committee of Visitors
CP	Charge-Parity
CP	Cosmic Phenomena
CPBF	Center for the Physics of Biological Function
CPLC	Center for the Physics of Living Cells
CQUIC	Center for Quantum Information and Control
CTA	Cherenkov Telescope Array
CTBP	Center for Theoretical Biological Physics
CUA	Center for Ultracold Atoms
DAE	Indian Department of Atomic Energy
DAMIC	DArk Matter in Charged Coupled Devices
DEB	NSF Division of Environmental Biology
DEI	Diversity, Equity and Inclusion
DFG	Deutsche Forschungsgemeinschat (German Research Foundation)
DMR	NSF Division of Material Sciences
DMS	NSF Division of Mathematical Sciences
DNP	APS Division of Nuclear Physics
DoD	Department of Defense

DOE	Department of Energy
DPP	APS Division of Plasma Physics
DST	Indian Department of Science and Technology
DUNE	Deep Underground Neutrino Experiment
EAR	NSF Division of Earth Sciences
ECCS	NSF Division of Electrical, Communications and Cyber Systems
ECLIPSE	NSF ECosystem for Leading Innovation in Plasma Science and Engineering
EDM	Electric Dipole Moment
EeV	Exa electron volts
EIC	Electron-Ion Collider
ELI	Extreme Light Infrastructure laser user facility
ENP	PHY Nuclear Physics - Experiment program
EPP	PHY Experimental Elementary Particle Physics program
EPSCoR	Established Program to Stimulate Competitive Research
ExpandQISE	NSF Expanding Capacity in Quantum Information Science and Engineering
FASER	ForwArd Search ExpeRiment
FLARE	Facility for Laboratory Reconnection Experiments
FNAL/Fermilab	DOE Fermi National Accelerator Laboratory
FRHTP	Focused Research Hubs in Theoretical Physics
FRIB	Facility for Rare Isotope Beams
FSU	Florida State University
FTE	Full Time Employee
FWO	Fonds Wetenschappelijk Onderzoek – Vlaanderen (Belgian Research Foundation)
FY	Fiscal Year
GADGET	GAseous Detectpr with Germanium Tagging
GEO	NSF Directorate for Geosciences
GeV	Giga electron volts
GRANTED	Growing Research Access for Nationally Transformative Equity and Diversity
GWAC	Gravitational Waves Agencies Correspondents
GWOSC	Gravitational-Wave Open Science Center
HAWC	High-Altitude Water Cherenkov Observatory
HAYSTAC	Haloscope At Yale Sensitive to Axion Cold dark matter
HBCU	Historically Black Colleges or Universities
HECTOR	High EffiCiency TOtal absorption spectrometeR
HEP	PHY High Energy Physics subprogram
HEPAP	High Energy Physics Advisory Panel
HF-SRN	The High Flux Student Research Network
HL-LHC	High Luminosity - Large Hadron Collider

IAP	PHY Integrative Activities in Physics program
IC	PHY IceCube Research Support subprogram
INFN	Istituto Nazionale di Fisica Nucleare (Italian Institute for Nuclear Physics)
IOS	NSF Division of Integrative and Organismal Systems
iPOLS	International Physics of Living Systems Graduate Research Network
IQIM	Institute for Quantum Information and Matter
IsoDAR	ISOtope Decay-At-Rest experiment
ITAMP	Institute for Theoretical Atomic and Molecular Physics
JILA PFC	Physics Frontiers Center at JILA
JINA-CEE	Joint Institute for Nuclear Astrophysics - Center for the Evolution of the Elements
JUNO	Jiangmen Underground Neutrino Observatory
KEK	Kō Enerugī Kasokuki Kenkyū Kikō (Japanese High Energy Accelerator Research Organization)
KITP	Kavli Institute for Theoretical Physics
LBNF	Long Baseline Neutrino Facility
LEAPS	NSF Launching Early-Career Academic Pathways in the Mathematical and Physical Sciences program
LEGEND	Large Enriched Germanium Experiment for Neutrinoless ββ Decay
LHC	Large Hadron Collider
LHCb	LHC-Beauty
LIGO	Laser Interferometric Gravitational-Wave Observatory
LLP	Long-Lived Particle
LSC	LIGO Scientific Collaboration
MCB	NSF Division of Molecular and Cellular Biosciences
MDPX	Magnetized Dusty Plasma Experiment
ML	Machine Learning
MMA	Multi-Messenger Astrophysics
MOLLER	Measurement of a Lepton-Lepton Electroweak Reaction
MOU	Memorandum of Understanding
MPS	NSF Directorate for Mathematical and Physical Sciences
MPSAC	MPS Advisory Committee
MRI	NSF Major Research Instrumentation program
MSI	Minority Serving Institution
MSIP	NSF Mid-scale Innovations Program in Astronomical Sciences program
MSRI	NSF Midscale Research Infrastructure Program
MSU	Michigan State University
MUSE	MUon proton Scattering Experiment
MUSES	Modular Unified Solver of the Equation of Sate
N^3LO	Next-to-Next-to-Next-to-Leading-Order

N3AS	Network in Neutrinos, Nuclear Astrophysics and Symmetries
NANOGrav	North American Nanohertz Observatory for Gravitational Waves
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
nEDM@SNS	Neutron Electric Dipole Moment at the Spallation Neutron Source
NIF	DOE National Ignition Facility
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NLO	Next-to-Leading-Order
NNLO	Next-to-Next-to-Leading-Order
NNSA	National Nuclear Security Administration
NOW	Nederlandse Organisatie voor Wetenschappelijk Onderzoek (Dutch Research Council)
NP	Nuclear Physics
NP3M	Nuclear Physics from Multi-Messenger Mergers
NPRLG	NSF Physics REU Leadership Group
NQI	National Quantum Initiative
NSAC	Nuclear Science Advisory Committee
NSCL	National Superconducting Cyclotron Laboratory
NSF	National Science Foundation
OMA	NSF Office of Multidisciplinary Activities
OPP	NSF Office of Polar Programs
P5	Particle Physics Project Prioritization Panel
PA	PHY Particle Astrophysics program
PA-CP	PHY Particle-Astrophysics - Cosmic Phenomena subprogram
PA-IC	PHY Particle Astrophysics - IceCube Research Support subprogram
PA-UG	PHY Particle Astrophysics - Underground Physics subprogram
PAO	Pierre Auger Observatory
PD	Program Director
PeV	Pico electron volts
PFAS	Per-and Polyfluoroalkyl Substances
PFC	Physics Frontiers Center
PFC at JQI	Physics Frontier Center at the Joint Quantum Institute
PHY	NSF Division of Physics
PHY-GRS	PHY – Graduate Research Supplements
PI	Principal Investigator
PICO	Merger of the PICASSO and COUPP collaborations
PIF	PHY Physics at the Information Frontier program

PM	Precision Measurement
PoLS	PHY Physics of Living Systems program
PoLS-T	Physics of Living Systems Teaching Network
PPP	PHY Precision Particle Physics subprogram
PPPL	DOE Princeton Plasma Physics Laboratory at Princeton University
PRad Experiment	Proton Radius Experiment
PREP	PHY Partnerships for Research and Education in Physics program
PUI	Primarily Undergraduate Institution
QC	Quantum Computing
QCD	Quantum Chromodynamics
QIS	PHY Quantum Information Science program
QIS	Quantum Information Science
QISE	Quantum Information Science and Engineering
R1	"Doctoral Universities – Very high research" in Carnegie classification system
REU	Research Experiences for Undergraduates
RHIC	Relativistic Heavy Ion Collider
RNA	Ribonucleic Acid
RNO	Radio Neutrino Observatory
RNO-G	Radio Neutrino Observatory-Greenland
RUI	Research in Undergraduate Institutions
SABRE	Sodium Iodide with Active Background Rejection Experiment
SARS-COV-2	Severe acute respiratory syndrome coronavirus 2
SENSEI	Sub-Electron-Noise Skipper-CCD Experimental Instrument
SMEFT	Standard Model Effective Field Theory
SNOLAB	Sudbury Neutrino Observatory Laboratory
STC	Science and Technology Center
STEM	Science, Technology, Engineering and Mathematics
STFC	UK Science and Technology Facilities Council
SU2C	Stand Up to Cancer
Super-K	Super-Kamiokande – Super-Kamioka Neutrino Detection Experiment
SuperCDMS	Super Cryogenic Dark Matter Search
SURF	Sanford Underground Research Facility
SUSY	Supersymmetry
SWQU	Space Weather with Quantified Uncertainties
TA	Telescope Array
TDA	Time-Domain Astronomy
TeV	Tera electron volts
TPP	PHY Tools for Particle Physics subprogram

UCNtau/UCNt	Ultra Cold Neutron Lifetime experiment
URM	Underrepresented minority
VERITAS	Very Energetic Radiation Imaging Telescope Array System
WIMP	Weakly Interacting Massive Particle
WiPPL	Wisconsin Plasma Physics Laboratory
WoU	NSF Windows on the Universe
WoU-MMA	NSF Windows on the Universe – the Era of Multi-messenger Astrophysics
X-SCAPE	X-Ion Collisions with a Statistically and Computationally Advanced Program Envelope
ZEUS	Zettawatt-Equivalent Ultrashort pulse laser System