Report of the MPSAC Subcommittee for the Review of the Physics Frontiers Centers Program of the National Science Foundation Directorate for Mathematical and Physical Sciences

6/28/2019

EXECUTIVE SUMMARY

A subcommittee of the National Science Foundation (NSF) Directorate of Mathematical and Physical Sciences (MPS) Advisory Committee (MPSAC) was charged to "*conduct an independent assessment*" of the Physics Frontiers Center (PFC) program with the following desired outcomes: "Rather than providing specific recommendations, the subcommittee should identify strengths and weaknesses of the PFC program and issues that the Division can address in developing and evolving the program."

The subcommittee was provided with the annual reports of each of the PFCs, their diversity plans, the reports of site-visit teams that visit at years 3 and 5 of the center's award, and the proposal solicitations. The subcommittee's evaluation of the relative success of the program is based on the subcommittee's holistic scientific expertise and judgment. Other sources of input were the PFCs themselves and the broader physics community.

STRENGTHS OF THE PFC PROGRAM

A. The PFC Environment

The subcommittee noted numerous advantages of the PFC program that contribute significantly to the goal of advancing the frontiers of physics. These advantages include:

- ***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 PFCs create a vibrant and collaborative environment for research and learning. A critical mass of investigators, post-docs, graduate students, and undergraduate researchers are brought into a large collective educational environment with regular seminars and career-building activities, wide-ranging interactions, and distributed mentoring.

B. Contributions to Major Scientific Breakthroughs

The subcommittee identified numerous examples of research breakthroughs that have emerged from the PFC program. Ten are identified in the report, but the number was only limited by a desire for brevity;

many more could have been listed. As compared to individual Principal investigator (PI) funding, these advances were judged to stem from:

- ***The greater freedom researchers have to pursue new ideas than they have via traditional funding mechanisms.***
- ***The greater opportunities researchers have to collaborate on interdisciplinary research.***
- ***The greater flexibility PFC funding affords to pursue truly exploratory science.***

C. Impacts on Physics or Related Fields

The PFCs have had tremendous impact in biophysics, atomic, molecular and optical physics including ultra-high intensity laser physics, quantum information science, gravitational wave physics, nuclear and particle astrophysics and cosmology.

D. Impacts on Education, Diversity, Public Outreach, and Infrastructure

- There is little doubt that ***Education and Public Outreach (EPO) activities at individual PFCs are valued by the leadership of the Centers*** and are guided by people with the passion to effect positive change locally. There is also little doubt that some promising strategies are being employed at individual Centers.

- A nearly universally reported strength of the PFC program is the ***strong support for training for the next generation of researchers***. The PFCs are seen as instrumental in fostering the development of unique research ecosystems within their larger fields.

- ***The public outreach efforts of most PFCs are quite impressive with a broad range of activities and scales***. The larger scale of a PFC enables substantially greater and more varied outreach activities. Many PFCs hire an education and public outreach (EPO) coordinator, giving them a significant advantage in coordinating outreach activities.

- ***Examples of exemplary activities abound***. For instance,

    - The NANOGrav PFC reports 35% of the Postdocs, 40% of the graduate students and 49% of the undergraduates are female, ***well above the national averages***.
    - The Center for the Origin and Structure of Matter (COSM) was established at three ***historically minority-serving institutions***. They tried to develop a broader network of such institutions with regular visits and opportunities for undergraduates to attend their summer school.
    - In 2016, the Joint Institute for Nuclear Astrophysics - Center for Evolution of the Elements (JINA-CEE) PFC developed and ratified a comprehensive diversity and inclusion Code of Conduct. Subsequent to the ratification, JINA-CEE management has embedded effective diversity and inclusion practices as a cultural change at the PFC, affecting all aspects of research, conference, educational and outreach activities. As a result, the representation of female faculty in JINA-CEE has doubled from 18% in 2016 to 37% in 2019.

  - The JILA Center's PISEC (Partnerships for Informal Science Education in the Community) has produced several ***physics education research papers establishing evidence-based methods for new approaches to teaching physics.***

- Some PFCs have increased and/or expanded the ***scientific research infrastructure***.

PFC PROGRAM WEAKNESSES AND ISSUES '

- ***The orientation toward Broader Impacts seems grounded in an enumeration approach***. For the PFC program to live up to its full potential, the EPO component of the PFCs has to go beyond high-quality (even exemplary) local activities and contribute to the research base of what works, for whom, and under which conditions. There is a need to study the effects of the PFC EPO activities with scholarly scrutiny, so that the whole field may learn from its evidence-based claims.

- ***There are few statistics available to evaluate the diversity of the people working for the different PFC initiatives***. This lack of quantitative information in itself is a problem.

- ***Diversity in most of the PFC groups is not significantly different than in physics in general***, which is highly unsatisfactory.

- ***The non-renewal of one PFC resulted in the immediate loss of the EPO coordinator and many of the PFC's outreach programs***. A small amount of additional close-out funding to keep the EPO activities going for a brief time would allow PFCs to seek alternative funding sources or allow a more gradual wind-down.

- ***There is a need to track networks of graduate students and postdoctoral researchers*** to better understand the longitudinal impacts of PFCs so that the field will understand better the value added by the PFCs.

- ***There is a need to prepare PFC junior researchers for their future roles as sophisticated physics educators*** who are familiar with physics education results so that physics departments can start building more rapidly on scholarly approaches to teaching.

- ***Ensuring that some of the educational legacies of a PFC persist beyond the existence of the PFC*** – for example, the summer/winter schools – ***is an issue***.

- ***There is a need to elucidate the relative priorities of the various aims in the PFC solicitation*** and/or the instructions given to reviewers so that Intellectual Merit and Broader Impacts are treated consistently.

- ***The current practice of having PFCs submit a proposal to be reviewed for a one-year extension in the fifth year for funding of the sixth year to match the cycle of a new solicitation every three years seems wasteful of effort for the PFCs, the NSF, and the reviewers.***

RISKS TO THE PFC PROGRAM

One risk is the potential for a PFC to be seen as a substitute for Regular PI funding. This risk may be mitigated by clearly articulating the PFCs' unique roles in NSF's research portfolio.

A second risk to the program arises from the perception that a significant fraction of the community views the program as helping "the rich get richer." We believe that if all the PFCs regularly committed to community-building activities, it would help allay this concern for the program.

CONCLUSIONS

We conclude that PFCS are producing major scientific breakthroughs and stimulating the development of interdisciplinary research communities. There is also the potential for the PFCs to make significant advances in their broader impacts.

I. Introduction

The Physics Frontiers Centers (PFC) program of the Physics Division of the National Science Foundation (NSF) Directorate of Mathematical and Physical Sciences (MPS) plays an important role in the physics investment portfolio of the National Science Foundation and the nation.

Quoting from the synopsis of the program from the 2016 Program Solicitation, "the Physics Frontiers Centers (PFC) program supports university-based centers where the collective efforts of a larger group of individuals can enable transformational advances in the most promising research areas. The program is designed to foster major breakthroughs at the intellectual frontiers of physics by providing needed resources such as combinations of talents, skills, disciplines, and/or specialized infrastructure, not usually available to individual investigators or small groups, in an environment in which the collective efforts of the larger group can be shown to be seminal to promoting significant progress in the science and education of students. Activities supported through the program are in all sub-fields of the physics within the purview of the Division of Physics: atomic, molecular, optical, plasma, elementary particle, nuclear, particle-astro, gravitational, and biological physics. Interdisciplinary projects at the interface between these physics areas and other disciplines may also be considered, although the bulk of the effort must fall within one of those areas within the purview of the Division of Physics. The successful PFC will demonstrate: (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 program began with the first centers being funded in 2001. Solicitations were issued in 2000, 2001, 2007, 2010, 2013 and 2016. In 2004 and 2005, three prototype PFCs (the Kavli Institute for Theoretical Physics, the Center for Ultracold Atoms and JILA), activities that were already part of the NSF portfolio, were phased in to be managed by the program with the understanding that they would compete for renewal in the next competition. Currently, centers are funded for five years (the maximum considered under current NSF policy) with the possibility of a one year extension to align with the current practice of a new solicitation every three years. Centers are reviewed in the third year of funding. A proposal and the fifth-year review provide the basis for the one year extension. In the sixth year, centers are free to submit new proposals in response to the solicitations. These new proposals are evaluated in direct competition with all new proposals received under the solicitation. There is no explicit limit to the number of times an institution or group of institutions can receive a PFC award. If a proposal from an existing center is not successful, phase out support may be provided for up to two years, generally to allow graduate students and post-docs to complete their terms. To date, 15 Physics Frontiers Centers have been funded. Table 1 lists each center and the award dates.

Scientific and co-funding partnerships with other divisions within MPS and in other Directorates have been essential to the success of the PFC program. Major partners include: MPS/Division of Materials Research, MPS/Division of Chemistry, MPS/Division of Astronomical Sciences, MPS/Office of Multidisciplinary Activities, BIO/Division of Molecular and Cellular Biosciences, BIO/Integrative Organismal Systems, CISE/Computing and Communication Foundations, GEO/Office of Polar Programs, and the Department of Energy/Office of Fusion Energy. Annual funding through the Physics Division is typically around $20M per year and partners typically contribute an aggregate of several million dollars per year. Originally university cost sharing was required. From 2007 on, it was not required and from 2010 it was prohibited following a National Science Board recommendation.

The PFC program is reviewed every three or four years by the Committee of Visitors (COV) of the Physics Division under its charge that includes addressing the integrity and efficacy of the processes used to solicit, review, recommend, and document proposal actions and the quality and significance of the results of the Division's investments. Recommendations of the 2015 COV relating to the PFC program were

- We recommend that the Physics Division charge an appropriate high-level body to conduct a retrospective review of the PFCs, outside of the context of a funding competition for renewal and new starts. This is a repeat recommendation from the last COV.
    - The charge should identify (i) the research breakthroughs that can be attributed to the Centers; (ii) the broader impacts of the Centers; and (iii) any other items that are clearly attributable to the structure and coherence of a PFC.
    - With the input from this retrospective review, the NSF should revisit the issue of the appropriate level of funding of the PFC program, being open to the possibility that the number might grow.
- We further suggest that the Physics Division use the PFCs as laboratories to explore the most effective ways to broaden participation and communicate effectively. The Division should continue to seek ways for the PFC directors to learn from each other, and at the same time, transmit that learning to the broader community.

In June 2018, the Physics Division charged a subcommittee of the MPS Advisory Committee (MPSAC) to review the Physics Frontiers Center program. The charge is given in Appendix A. The subcommittee membership was mutually agreed upon by the chair and Physics Division personnel in an attempt provide expertise in the diverse physics areas of the Physics Division and in education and outreach activities. The membership of the subcommittee is given in Appendix B.

The charge places significant requirements and boundaries on the activities of the subcommittee. The subcommittee is 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. In particular, the subcommittee should assess how well the PFC program is enabling advances in the following areas in ways that are distinct or best accomplished in a center structure:

Advancing the frontiers of Physics
a. ! How well is the PFC program contributing to major scientific breakthroughs?
b. ! Has the PFC program had significant impacts on Physics or related fields?

Enhancing education, diversity, public outreach, and broader impacts
a. ! In what ways is the program enabling unique or enhanced educational experiences for students and postdoctoral fellows?
b. ! In what ways is the program contributing significantly to broadening participation of traditionally underrepresented groups?
c. ! In what ways is the program enabling substantive outreach to the general public?
d. ! Are there other broader impacts of the PFC program?"

This report is organized around these elements of the charge. At the same time the charge requires the subcommittee to "conduct an independent assessment of the PFC program as a whole and not perform in-depth evaluations of each center. Rather than providing specific recommendations, the subcommittee should identify strengths and weaknesses of the PFC program and issues that the Division can address developing and evolving the program. The subcommittee will not review the PFC proposal review and selection process or the program funding levels which are regularly reviewed by the Division's Committee of Visitors."

The subcommittee was provided with the proposal solicitations, the annual reports of each of the PFCs, their diversity plans, and the reports of site-visit teams that typically visit at year 3 and 5 of a center's award. The subcommittee was not given copies of the original proposals and the proposal reviews. Therefore, the subcommittee cannot comment on whether the centers achieved their proposed goals. Since the committee does not have access to the proposals and reviews for the other programs in the Division including the individual investigator or facilities grants, the subcommittee's evaluation of the relative success of the program is based on the subcommittee's holistic scientific expertise and judgment. Other sources of input were the PFCs themselves and the broader physics community. Information gathering visits or video conferences were undertaken by 1-3 subcommittee members to all the individual centers. These were extremely helpful and the subcommittee was extremely appreciative of this input. Often discussions with university administrators gave a higher-level perspective on the importance of a PFC to their institutions. The subcommittee chair discussed the review with the MPSAC by video conference at their August meeting. He and Dave Kieda made a presentation about the review at the Midwest Physics Chair's Meeting in November 2018. The chair also attended the November (nominally annual) meeting of the PFC directors at the National Science Foundation. In order to obtain the broadest possible community input, a web site was set up at Auburn University to allow individuals to comment on the PFC program. Each of the Divisions of the American Physical Society was requested to send an announcement to their membership alerting them that this review was taking place and seeking input, either through the web site or directly to the subcommittee members. Most of the Divisions did this either directly through email or as an item in their division newsletters.

Table 1: List of the Physics Frontiers Centers !

Center	Location	1st Award	2nd Award	3rd Award	Ramp Down
Center for Gravitational Wave Physics (CGWP)	Penn State	2001-2005			2006-2007
Frontiers in Optical Coherence and Ultrafast Science (FOCUS)	Michigan	2001-2007			2008-2009
Kavli Institute for Cosmological Physics (KICP)	Chicago	2001-2005	2006-2010	2011-2016	2017-2018
Center for the Study of the Origin and Structure of Matter (COSM)	Hampton	2002-2007			2008-2009
Center for Theoretical Biological Physics (CTBP)	UCSD/Rice	2002-2007	2008-2013	2014-2019	
Center for Magnetic Self Organization (CMSO)	Wisconsin-Madison	2003-2007	2008-2013		2014-2015
Joint Institute for Nuclear Astrophysics (JINA)	Notre Dame/MSU	2003-2007	2008-2013	2014-2019	
JILA	Colorado	2006-2010	2011-2016	2017-2022	
Center for Ultracold Atoms (CUA)	Harvard/ M.I.T.	2006-2010	2011-2016	2017-2022	
Kavli Institute for Theoretical Physics (KITP)	UCSB	2007-2011	2012-2017		2018
PFC at the Joint Quantum Institute (PFC@JQI)	Maryland	2008-2013	2014-2019		
Center for the Physics of Living Cells (CPLC)	UIUC	2008-2013	2014-2019		
Institute for Quantum Information and Matter (IQIM)	CalTech	2011-2017	2018-2023		
North American Nanohertz Observatory for Gravitational Waves (NANOGrav)	Wisconsin-Milwaukee	2015-2020			
Center for the Physics of Biological Function (CPBF)	Princeton	2017-2022			

The subcommittee had three regular meetings: an organizational video conference on September 14, 2018; a video conference on January 22, 2019 to share the results of the information gathering visits and other input; and then a meeting at the National Science Foundation on February 22, 2019 to discuss issues and conclusions. The rest of the subcommittee business was conducted by email.

II. SUCCESS OF THE PFC PROGRAM IN ADVANCING THE FRONTIERS OF PHYSICS

Our committee's focus is on the effectiveness and level of success of the PFC program in advancing the frontiers of physics. We are aware that a widespread concern with the NSF PFC program, as with any similar program, is that funds are diverted from single investigator funding programs. However, a controlled study of physics advances achieved within the PFC program vis-à-vis those in single investigator programs is beyond the capability of this committee. Nevertheless, we have consciously compared the operations of the PFCs we visited with our individual experiences as single principal investigators (PIs) and have noted numerous advantages of the PFC program that contribute significantly to the goal of advancing the frontiers of physics. These advantages include:

- ***PFCs Foster Collaborations***

A clear-cut distinction of the PFC program is its focus on bringing together investigators with differing expertise to attack complex problems beyond the frontiers of known physics. While PIs who propose the establishment of a PFC think in advance about how they will collaborate, in our experience visiting existing PFCs, it seems a collaborative culture develops that makes new collaborations increasingly easy to form. These collaborations involve those between theorists and experimentalists as well as those involving PIs with expertise in different areas of physics. Even when PFCs are wound down, in many instances the collaborative culture remains. This is very different from the case in which individual PIs in the same general area of physics regard each other as competitors for funding from the same grant program.

- ***PFCs Enable Rapid Responses to Research Developments***

Many PFCs that we visited withheld a significant portion of their funding to enable rapid responses to both opportunities to pursue significant new research directions as well as to respond to urgent needs hindering research such as equipment breakdowns, etc. For example, at the JILA PFC, a graduate student informed us that he and his advisor attended a scientific conference and obtained a new idea for their own research. Upon return home, they asked for funds from the PFC management team to pursue their idea and were given sufficient funds to proceed. Such rapid responses to pursue new research directions or to obtain needed funds to repair necessary equipment could involve months or years of delays if pursued via single-investigator grant programs.

- ***PFCs Provide Local Oversight Over Research Progress***

A major advantage of the PFCs program is that the PFC management team is typically in regular communication with all PIs involved. Thus, shifts in funding from groups making slow progress to those making significant advances can and do occur on a timely basis. This flexibility is quite distinct from typical individual investigator programs in which researchers report progress only yearly and whose funding is often fixed for 3 years, even if successful and warranting additional funds.

- ***Postdoctoral Researchers Mature More Rapidly Within PFCs***

Postdoctoral researchers hired by PFCs are able to interact with the various groups within the PFC. They also contribute to discussions concerning research progress and ways to proceed. Furthermore, they are imbued in the PFC's collaborative environment. This is very different from the typical experience of postdocs hired by a single investigator to pursue research proposed in the PI's individual-investigator grant. Owing to their broader experience, greater scientific maturity, and involvement with collaborative research, postdoctoral researchers with experience in a PFC have an advantage over other candidates when applying for faculty positions. In this way the impact of PFCs on advancing the frontiers of physics extends to universities and other institutions not associated with a PFC.

- ***PFCs Offer Additional Unique Opportunities to Pursue Research***

PFC funding is longer term than typical individual PI funding (with a 6-year vs. 3-year funding cycle), owing generally to the larger, more complex problems that are studied. Notably, PFC researchers have access to shared research facilities and resources that cannot be afforded by individual PI grants. Thus, the PFC program should not be seen as competing with individual PI programs, but rather complementing them as a means for addressing larger-scale research problems.

- ***PFCs Enable the U.S.A. to Better Compete Globally***

In a global scientific context, PFCs enable the U.S.A. to compete with the leading research institutes abroad. These include the Max Planck Society institutes in Germany and the Chinese Academy of Sciences institutes in China, among others. Interest in pursuing research at the frontiers of physics exists in numerous countries. The PFC program assists the scientific community in the U.S.A. to compete in this global environment better than would reliance solely on single-investigator research funding programs.

In summary, based on our visits to the PFCs and reviewing the various center reports, the PFCs create a vibrant and collaborative environment for research and learning. By having a critical mass of investigators (even in the spatially delocalized centers), post-docs, graduate students, and undergraduate researchers are brought into a large collective educational environment with regular seminars and career-building activities, wide-ranging interactions, and distributed mentoring. Also, the educational and outreach opportunities are often greater within this environment, as discussed in Sec. III below. Collectively, the PFCs provide a high level of scientific training, which benefits other physics departments at institutions of higher education when hiring scientists trained at these centers, and benefits the nation by developing highly trained scientists who go on to work in industry or the national laboratories.

Another clear impact of the PFCs on physics is the high level of research undertaken at the PFCs. The volume of scientific papers published each year by PFC investigators, especially the number published in high-profile journals, is truly impressive. However, we cannot say whether this output level would occur without PFC funding: many of the PFC investigators are highly successful and may very well publish a similar number of research studies without the PFC. However, we found repeated instances where the flexibility of the PFC funding (usually as funds held by the center directors for new opportunities) allowed center investigators to jump on new opportunities and beat out competing groups around the globe. This gives these U.S. centers a competitive edge in physics and related disciplines.

Turning from these broad general findings concerning the PFC program, we focus now on specific instances of PFC program contributions to major scientific breakthroughs and to significant impacts on physics and related fields.

IIA. How Well is the PFC Program Contributing to Major Scientific Breakthroughs?

A key hypothesis of the PFC program is that this type of center funding fosters truly new scientific breakthroughs in ways that other funding mechanisms might not. This hypothesis is based on several perceptions about issues that inhibit innovation and collaboration in science:

- ***Perception 1: Standard funding mechanisms tend to favor more conservative advances in science***. Peer review is a powerful system, but given the competitive nature of funding, more well-established lines of scientific inquiry tend to be favored by reviewers.

- ***Perception 2: Standard funding mechanisms tend to favor disciplinary over broadly interdisciplinary science***. The size of individual NSF grants typically causes investigators to focus their efforts in a particular area, and while collaboration still happens, it is harder to establish entirely new, untried collaborations via that mechanism. A corollary is that breakthroughs often occur at the interface between very different disciplines.

- ***Perception 3: The nature of peer-review cycles slows the process of truly exploratory science***. The process of developing a new scientific concept, funding it through standard mechanisms and then testing it can easily take multiple years. In principle, a group of investigators having the resources to rapidly and flexibly provide funding for risky ideas that can be tested, succeed or fail, and move on could substantially accelerate the pace of new discovery.

The PFC program is designed to address these perceived issues by providing flexibility in what science is funded and when, putting much of the decision-making power in the hands of a highly capable set of investigators generally selected to cover multiple subdisciplines in physics. The best way to explore this is through examples. Below we describe briefly ten examples of significant results from the PFC centers that can be analyzed in terms of the three issues above.

These examples were taken from either committee member notes on PFC visits or from the document "*Physics Frontiers Centers, Program Highlights, 2018*" prepared by Jean Cottam Allen, Kathy McCloud and Michele Johnson.

- ***Scientific Breakthrough 1*: *Understanding the Physics of Magnetic Reconnection***
  [*PFC: Center for Magnetic Self-Organization (CMSO)*]

An improved understanding of how to control magnetic reconnection in the laboratory was obtained by a combination of laboratory experiment, theory, and simulation, in which predictions of two-fluid effects in reconnection were verified theoretically and validated experimentally. This work also led to complementary studies of the coupling between local and global reconnection physics and to a theory of reconnection in plasmas, such as stellar and accretion disk coronae. In order to build upon that work, it was critical to make a direct measurement of magnetic reconnection in the laboratory. The ultimate observational signature of magnetic reconnection in space and astrophysics is the energy released from the magnetic field to charged particles in plasma. Using the Magnetic Reconnection Experiment (MRX), the first such quantitative analyses were performed for laboratory reconnection in the case of anti-parallel reconnection [M. Yamada et al., "*Conversion of magnetic energy during magnetic reconnection in a laboratory plasma*," Nature Communications **5**, 4774 (2014)]. In this study, through the analysis of the Poynting vectors, enthalpy and energy flows, and heat flux in the ion diffusion region, a detailed breakdown of energy flow paths was completed and it was shown that more than half of the incoming magnetic energy is found to be converted to particle energies.

- ***Scientific Breakthrough 2: Evolution Under Constraint***
  [PFC: Center for the Physics of Living Cells (CPLC), UIUC]

In nature, organisms face many challenges, and species adapt to their environment by changing heritable traits over the course of many generations. How organisms adapt is often limited by trade-offs, in which improving one trait comes at the expense of another. Most experiments do not take into account that organisms in the wild face many pressures at the same time. Researchers in the Kuehn lab together with the Kuhlman group studied what happens when an organism's performance depends on two traits restricted by a trade-off [D.T. Fraebel *et al.*, "*Environment determines evolutionary trajectory in a constrained phenotypic space*," *eLife*, 2017]. Through experiments and mathematical modeling together with the Goldenfeld group [H.Y. Shih *et al.*, "*Biophysical constraints determine the selection of phenotypic fluctuations during directed evolution*," *Phys. Biol.* **15**(6), 065003 (2018)], the team found that the environment is crucial for determining how bacteria adapt when their swimming speed and population growth rate are restricted by a trade-off. When nutrients are plentiful, *E. coli* populations evolve to spread faster by swimming more quickly despite growing more slowly. In contrast, if nutrients are scarcer, the bacteria evolve to grow more quickly and swim more slowly. Next-generation sequencing identified single mutations that changed both swimming speed and growth rate by modifying negative regulatory activity in the cell.

- ***Scientific Breakthrough 3: Three Dimensional Architecture of the Human Genome***
  [PFC: Center for Theoretical Biophysics (CTBP), Rice]

The human genome is composed of 46 DNA molecules — the chromosomes — with a combined length of about 2 meters. Chromosomes are stored in the cell nucleus in a very organized fashion. This three-dimensional architecture is a key element of transcriptional regulation. CTBP scientists have developed a predictive theory of chromatin folding, the Minimal Chromatin Model [M. Di Pierro *et al*., "*Transferable model for chromosome architecture*," *PNAS* **113**(43), 12168 (2016)]. The model generates chromosome conformations by assuming there exist different structural types of chromatin. Interactions between these chromatin types are generated by the action of the proteome present in the nucleus and lead to phase separation. In this process, chromatin of different types form liquid droplets, which rearrange dynamically by splitting and fusing, thereby modulating DNA distal interactions and generating genomic compartments. Additionally, the theory accounts for the activity of molecular motors along the DNA polymer through a universal, translational-invariant effective potential. Subsequently, given immuno-precipitation data about modifications of histones, CTBP scientists were able to predict the chromatin types through a machine learning-based approach [M. Di Pierro *et al*., "*De novo prediction of human chromosome structures: Epigenetic marking patterns encode genome architecture*," *PNAS* **114**(46), 12126 (2017)]. The architecture of interphase chromosomes appears therefore to be encoded in the one-dimensional sequence of epigenetic markings, much as three-dimensional protein structures are determined by their one-dimensional sequence of amino acids. However, the sequence code provided by the epigenetic marks decorating the chromatin fiber is not fixed, but is dynamically rewritten during cell differentiation, modulating both the three-dimensional structure and gene expression in different cell types. The theory developed at CTBP generates structural ensembles that have been validated using Hi-C maps of multiple mammalian cell lines, as well as distances measured using 3D fluorescence in situ hybridization (FISH) experiments. Additionally, the very same interactions that account for genome architecture also predict the non-trivial dynamical behavior of chromosomes [M. Di Pierro *et al*., "*Anomalous diffusion, spatial coherence, and viscoelasticity from the energy landscape of human chromosomes*," *PNAS* **115**(30) 7753 (2018)]. The progress made in understanding the physical process of chromatin folding has enabled the development of computational tools that allow one to predict and study the spatial conformation of genomes with unprecedented accuracy and specificity, opening the way to the study of the functional aspects of genome architecture.

- ***Scientific Breakthrough 4: Rydberg Atom Tweezer Array***
  [PFC: Center for Ultracold Atoms (CUA), MIT/Harvard]

Controllable, coherent many-body systems can provide insights into the fundamental properties of quantum matter, enable the realization of new quantum phases, and might ultimately lead to computational systems that outperform existing computers based on classical approaches. In a joint effort, CUA PIs Greiner, Vuletic, and Lukin demonstrated a new method for creating controlled many-body quantum matter that combines deterministically prepared, reconfigurable arrays of individually-trapped cold atoms [M. Endres *et al*., "*Atom-by-atom assembly of defect-free one-dimensional cold atom arrays*," Science **354**, 1024 (2016)] with strong, coherent interactions enabled by excitation to Rydberg states [H. Bernien *et al*., "*Probing many-body dynamics on a 51-atom quantum simulator*," Nature **551**, 579 (2017)]. In this work, they realized a programmable Ising-type quantum spin model with tunable interactions and system sizes up to 51 qubits. This led to the discovery of a new class of quantum many-body states that challenge traditional understandings of thermalization in isolated quantum systems, and has triggered new theoretical investigations into these so-called "quantum many-body scars" [arXiv:1807.01815 (2018)]. Using the same platform and applying it to the study of condensed matter models, they observed quantum phase transitions into spatially ordered states that break discrete symmetries. This study of quantum critical dynamics offers the first experimental verification of the quantum Kibble-Zurek hypothesis, and showed its application to exotic, previously unexplored models such as the chiral clock model [arXiv:1809.05540 (2018)]. They have also prepared high-fidelity entanglement between two atoms, establishing neutral atoms as a competitive platform for quantum information processing [H. Levine *et al*., "*High-Fidelity Control and Entanglement of Rydberg-Atom Qubits*," PRL **121**, 123603 (2018)]. This degree of quantum control can be readily applied to quantum optimization of NP-complete problems, paving the way towards possibly the first demonstration of a quantum advantage [arXiv:1808.10816 (2018)].

- ***Scientific Breakthrough 5: Superconducting Metamaterials for Waveguide QED***
  [PFC: Institute for Quantum Information and Matter (IQIM), Cal Tech]

The way light propagates within materials can be strongly influenced not only by bulk material properties, but also by the arrangement and geometric structure of materials at the sub-wavelength scale. Such effects can be seen in the beautiful reflected color patterns of a peacock's feathers, and also show up in the design of lasers that power the backbone of the Internet. Sub-wavelength structured materials are called "metamaterials." This same concept applies not only to optical phenomena, but also to electromagnetic waves at other frequencies, including microwaves like those used by cell phones and wireless network routers. Oskar Painter's group has created metamaterials using microwave electrical circuits that look superficially like they could have been yanked from your cell phone [M. Mirhosseini, E. Kim, V. S. Ferreira, M. Kalaee, A. Sipahigil, A. J. Keller and O. Painter, "*Superconducting metamaterials for waveguide quantum electrodynamics,"* Nature Communications **9**, 3706 (2018)]. They stacked a series of tiny resonators composed of spiral inductors and finger capacitors, forming a compact microwave photonic bandgap waveguide with a deep sub-wavelength lattice constant. They studied the microwave emission of a superconducting qubit placed at one end of the waveguide, finding that the emission slows down significantly when the frequency of the excited qubit is tuned inside the waveguide's band gap. They also observed that the photon cloud attached to the qubit shrinks substantially when the qubit's emission frequency descends more deeply into the bandgap. Superconducting metamaterials like those devised by the Painter group may play an important role in future quantum computing technologies. With suitably engineered metamaterials, one can customize the spatial connectivity of qubits in a superconducting circuit, and also design the connectivity to occur only at certain desired frequencies. Thus, these structures provide a flexible and potentially scalable substrate on which to build complex topologies for circuits of interconnecting Josephson junction qubits, which might eventually make it possible to connect many qubits together on a chip while avoiding any unintended deleterious coupling to the external environment.

- ***Scientific Breakthrough 6: Twisting Atoms to Push Quantum Limits***
  [PFC: JILA Physics Frontier Center (JILA), U. of Colorado]

A collaboration between James Thompson's Lab and Ana Maria Rey's theory group is breaking through previous barriers of quantum precision defined by the Standard Quantum Limit. These advances may transform typical physics laboratories into probes for the most fundamental questions of our universe. The chaos within a black hole scrambles information. Gravity tugs on time in tiny, discrete steps. A phantom-like presence pervades our universe yet evades detection. These intangible phenomena may seem like mere conjectures of science fiction, but in reality, experimental comprehension is not far, neither in time nor in space. Advances in quantum sensors will likely be made within the decade, and the leading experiments for black holes, gravitons, and dark matter may not be viewed in space, but rather in basements – sitting on tables, in a black room lit only by lasers. These experiments--generally called quantum precision measurements--are at the forefront of our fundamental understanding of the universe. There's only one problem: we have already hit the limit of quantum precision known as the Standard Quantum Limit, or SQL for short. Inherent to quantum measurements, SQL defines the inevitable quantum noise that arises from wave function collapse. But unordinary quantum experiments could access precisions beyond the standard limit. Quantum noise can be evaded by harnessing quantum entanglement. Rey and Thompson have made strides in recent experiments to create and harness such quantum entanglement with gases of strontium atoms in an optical cavity. They have observed long-range exchange interactions mediated by an optical cavity, which manifest as tunable spin-spin interactions. This leads to dynamics known as one-axis twisting and the emergence of a many-body energy gap. Because the energy gap favors atoms maintaining their spins, both Rey and Thompson believe the gap could protect entangled states from becoming disentangled. [M.A. Norcia *et al.*, "*Cavity-mediated collective spin-exchange interactions in a strontium superradiant laser*," *Science* **361**, 259 (2018).]

- ***Scientific Breakthrough 7: First Stars in the Universe – What Were They Like?***
  [PFC: Joint Institute for Nuclear Astrophysics – Center for the Evolution of the Elements (JINA-CEE), Michigan State U.]

JINA-CEE research is providing a glimpse into the evolution of the first generation of massive stars in the universe, which burned using the primordial fuel of hydrogen, deuterium, and helium formed in the Big Bang and mark the beginning of stellar nucleosynthesis. How these stars burn hydrogen to stabilize against gravitational contraction has been a long-standing question as there is no primary carbon present to support a CNO cycle, the main hydrogen-burning mechanism in today's massive stars. New low-energy alpha-capture reaction measurements of Li and B isotopes performed by JINA-CEE researchers with accelerators at the Nuclear Science Laboratory at Notre Dame indicate that these reaction rates are considerably higher than previously thought. Coordinated NuGrid nucleosynthesis computer simulations by JINA-CEE theorists investigated how revised reaction rates alter the present paradigm on how the first stars produced carbon via several reaction sequences bridging the mass 5 and mass 8 gaps. More experimental work is needed to reduce uncertainties in these reactions. New experimental approaches such as the CASPAR underground accelerator have been developed within JINA-CEE. Advanced 3D high performance computer simulations of hydrogen and helium burning in the first stars are also underway to understand the evolution of the very first stars and the elements they created.

- ***Scientific Breakthrough 8: Discovery of a Merging Neutron Star Binary and the H_0 Controversy***
  [PFC: Kavli Institute for Cosmological Physics (KICP), U. of Chicago]

On Aug. 17, 2017 Reed Essick, a KICP Fellow and member of the U. of Chicago's LIGO group, received an alert about the first LIGO-Virgo detection of a neutron star coalescence. Essick quickly sent out a circular to astronomers around the globe announcing the event. Neutron star coalescences are expected to be very bright in the electromagnetic spectrum. In anticipation of exactly this sort of event, PFC members Daniel Holz and Josh Frieman had put together a collaboration to use the Dark Energy Camera on the 4-meter Blanco telescope at the Cerro Tololo Inter-American Observatory in Chile. As soon as the Sun set in Chile, the observations began. Within an hour, the first optical counterpart to a gravitational-wave source had been discovered. Holz had been waiting for the arrival of this type of event to make a very specific measurement. Over the past decade he has played a major role in developing the field of standard siren cosmology. Gravitational-wave detections of binary coalescences provide a clean measurement of cosmological distance. This single event could be used to measure the Hubble constant, H_0, the current rate of expansion of the universe. Traditional methods of determining H_0 currently give inconsistent results. This measurement fell right between the two conflicting values of H_0, but with large error bars encompassing both measured values. Future standard siren measurements are expected to lead to rapid convergence. The era of precision standard siren cosmology is rapidly approaching and a round of analyses can resolve the H_0 controversy.

- ***Scientific Breakthrough 9: Constraining Galaxy Evolution and Cosmology***
  [PFC: North American Nanohertz Observatory for Gravitational Waves (NANOGrav), U. Wisconsin-Milwaukee and W. Virginia U.]

NANOGrav periodically constructs a data release and carries out a suite of gravitational wave analyses to constrain the presence of different sources of gravitational waves (GWs) in the data. In spring 2018, it published its 11-year data release [Z. Arzoumanian *et al*., "*The NANOGrav 11-Year Data Set: High-precision Timing of 45 Millisecond Pulsars*," Astrophys. J. Suppl. **235**(2), 37 (2018)] and a corresponding limit on the GW stochastic background [Z. Arzoumanian *et al*., "*The NANOGrav 11-Year Data Set: Pulsar-timing Constraints on the Stochastic Gravitational-wave Background,"* Astrophys. J. **859**(1), 47 (2018)]. The new limit provides meaningful constraints on the processes through which galaxies merge. Specifically, we now know that either (i) the emission of gravitational waves is not the only process through which black holes at galactic cores are losing energy, i.e., they must also lose energy from scattering off stars in their cores or due to eccentric orbits; (ii) that mergers occur less frequently than was thought; or (iii) that black holes at the centers of galaxies are less massive than previously thought. This information will feed back into models for mergers, which can be compared with future, more sensitive limits and, ultimately, NANOGrav's detections. NANOGrav is already doing GW astrophysics, even before a detection! Published work [Astrophys. J. **859**(1), 47 (2018)] shows how one can simultaneously constrain the density of stars in galactic cores (r) and the eccentricity of binary black holes (*e0*) for three different mass-host galaxy mass relations in the literature through sophisticated simulations of binary populations and Bayesian parameter estimation techniques.

- ***Scientific Breakthrough 10: A 53-qubit Quantum Simulator***
  [PFC: Physics Frontier Center at the Joint Quantum Institute (PFC@JQI), U. Maryland]

Two independent teams of scientists, including one from the PFC@JQI and one from the CUA at Harvard and MIT, used more than 50 interacting atomic qubits to mimic magnetic quantum matter, blowing past the complexity of previous demonstrations. Such large quantum simulators are on the cusp of exploring physics that is likely unreachable by even the fastest modern supercomputers. The PFC@JQI team deployed up to 53 individual ytterbium ions—charged atoms trapped in place by gold-coated, razor-sharp electrodes. While modern, transistor-driven computers are great for crunching their way through many problems, they can struggle to deal with more than 20 interacting quantum objects. When these kinds of calculations hit a wall, a quantum simulator may help scientists push the envelope on difficult problems. This is a restricted type of quantum computer that uses qubits to mimic complex magnetic quantum matter. The ion-based quantum simulation begins with a laser pulse that places an array of qubits into the same state. Then, a second set of laser beams interacts with the qubits, forcing them to act like tiny magnets, each having a north and south pole. The team does this second step suddenly, which jars the qubits into action. They feel torn between two choices, or phases, of quantum matter. As magnets, they can either align their poles with their neighbors to form a ferromagnet or point in random directions yielding no magnetization. The physicists can change the relative strengths of the laser beams and observe which phase wins out under different laser conditions. The entire simulation takes only a few milliseconds. By repeating the process many times and measuring the resulting states at different times during the simulation, the team can see the process as it unfolds from start to finish. The researchers observe how the qubit magnets organize as different phases form, dynamics that the researchers say are nearly impossible to calculate using conventional means when there are so many interactions. [J. Zhang *et al*., "*Observation of a many-body dynamical phase transition with a 53-qubit quantum simulator*," *Nature* **551**, 601 (2017).]

Based upon the ten examples of PFC-generated scientific breakthroughs described above, as well as notes made in conversations of committee members with members of the PFC teams, we present below this committee's views on whether or not the PFC program overcomes perceived barriers to breakthrough research. Specifically, we address below the three perceptual issues concerning standard research funding mechanisms listed at the beginning of Sec. III.A above.

- ***Perception 1: Standard funding mechanisms tend to favor more conservative advances in science***.

Did the PFC funded research described above attempt less conservative science? While scientific breakthroughs 2 and 3 above both might have been funded by the right NSF panel provided preliminary results were presented, these are examples of situations where progress would have likely been delayed, possibly by years, while investigators increased the level of preliminary results. The concept of modeling evolution under multiple constraints is novel enough, and the physical mapping of the human chromosome risky enough, that it is likely that a panel would want to see significant evidence of feasibility prior to funding. In the case of AMO research, managers of the JILA PFC readily provide funding for even speculative new ideas so that researchers can prove their ideas and get a jump start in pursuing them or else fail early and move on. *We thus conclude that PFCs do allow researchers greater freedom to pursue new ideas than traditional funding mechanisms, even if --under the right circumstances-- similar proposed research might have been funded through standard funding mechanisms.*

- ***Perception 2: Standard funding mechanisms tend to favor disciplinary over broadly interdisciplinary science***.

Did the PFC-funded research favor science that merged disparate disciplines? This is an area where PFC funding seems to help, simply because there is an incentive for researchers who have not worked together to try things and because the centers foster interactions, not only between faculty, but also between postdocs and students, both of which foster inter-group collaborative research. Although it was not specifically in the cited breakthroughs listed above, the collaborations between the CTBP at Rice and the local Houston medical facilities was apparently greatly facilitated by the PFC funding. Similarly, at the CPLC, moving into the merger of cellular and intercellular experiment and theory (from an initially mostly molecular perspective) was spurred by the ability of groups to try experiments together requiring a small amount of funding. Comments on visits to the IQIM and JILA PFCs echoed some of the same themes. NANOGrav, in particular, further exemplified the benefits of bringing together not only researchers in different disciplines but also at different institutions. Committee visitors to the KITP PFC commented on the role of interdisciplinary seminars in fostering the development of new research collaborations. Several PFCs, including the PFC@JQI, funded postdocs to work with researchers in different labs and this also fostered collaboration. *We thus conclude that PFCs do allow researchers greater freedom to collaborate on interdisciplinary research*.

- ***Perception 3: The nature of peer-review cycles slows the process of truly exploratory science***.

Did the PFC-funded research described above appear to move faster because of the agility of funding? This is perhaps the most powerful argument we can confirm based on the results coming from researchers at the PFCs. In many of the site visits (JILA and CPLC are good examples), a common comment was how easily people were able to try a new idea, just to see if it was viable. A typical statement was “We went to a meeting and heard about XXX and realized this could be applied to what we are doing, so we came back, tried it, and it started a new research project.” This made it easy to “fail fast” and try something else or find new collaborative avenues quickly to explore. *We thus conclude that the flexibility of PFC funding allows managers to act as scientific venture capitalists and that this ability fosters truly exploratory science*.

II.B. Has the PFC program had significant impacts on Physics or related fields?

The PFCs have had a tremendous impact in the field of ***biophysics***. The last 20 years has seen a revolution in applying quantitative approaches from physics and chemistry to problems in biology. Biophysics is no longer a field of applying physical tools to biological problems, but exists right on the edge - pushing the frontiers of both biology and physics. The PFCs have been integral in driving this revolution. Consider the following impacts the PFCs have had:

- The CPLC PFC has become a national resource in single molecule biophysics, developing the instrumentation that has been adopted throughout the world, training many of today’s young leaders, and putting UIUC on the map in the field of biophysics. The impact of the center on the local community – an area not previously thought of as a top destination to train in the field – cannot be overstated.

- The CTBP PFC, now at Rice University, has led the way in bringing polymer physics and statistical mechanics to revolutionize the study of protein folding. The associated energy landscape view is a key concept in most of today's studies of protein dynamics, thereby influencing such distant fields as drug design and neurodegeneration. The CTBP PFC is having a similar impact in the field of genomics with its focus on the fundamental 4D-organization of DNA.

- KITP PFC funding has supported the growth of the "Santa Barbara Advanced School of Quantitative Biology" (QBio) program, held each year since 2013. It lasts 4-5 weeks and attracts graduate students and postdocs from all over the world. It runs in parallel with the KITP program on Biophysics, whose typical 2 lectures/day are open to the students and postdocs in the QBio summer program.

The current PFCs having a focus on ***atomic, molecular, and optical physics*** and on ***quantum information science*** include the Center for Ultracold Atoms (CUA, Harvard/MIT), the Institute for Quantum Information and Matter (IQIM, Caltech), JILA (U. Colorado), and the Physics Frontier Center at the Joint Quantum Institute (PFC@JQI, U. Maryland). One overlapping theme in these PFCs is the ability to control increasingly complicated quantum matter systems. This work is foundational for the relatively new field of quantum information science and the investigators in these centers have played a large role in establishing the new national initiative in this field, which has both impacts on the physics discipline and on the related fields of information theory, quantum sensing, and computer science. Consider also the following additional impacts of these four PFCs:

- At the CUA PFC, one recent development is on developing experimental methods for simulating the Fermi-Hubbard model using degenerate quantum gases. The Fermi-Hubbard model was constructed in the early 1960s to describe electrons in solid-state materials. Simulations using this model are significant for physics because they may shed light on the mechanisms for ***high-temperature superconductivity***. The model is also realized in optical lattices, which is the experimental cornerstone for simulating a wide range of other ***condensed-matter systems***.

- One recent result from the JILA PFC has an impact on the disciplines of both physics and ***precision measurement***. JILA researchers have reported on a unique atomic clock that uses a quantum degenerate gas and many-body effects to make the most precise frequency measurement to date. The increased precision is achieved by harnessing quantum many-body effects, rather than suppressing these effects, as was often done in prior approaches. This new result has an impact on tests of fundamental physics as well as on the establishment of new and improved optical frequency standards. In addition, JILA is very successful in spinning out companies based on the science and technologies developed within the PFC, thus having a substantial impact on the ***high-technology industries*** and ***economy*** in the Boulder/Denver area.

- At the PFC@JQI, one team recently demonstrated a very high level of control over a substantial number (53) of cooled and trapped ions, with various applications in ***non-equilibrium physics*** and ***quantum information science***. The experimental system was used as a small programmable quantum computer and was used to obtain some of the highest fidelity results for various standard quantum algorithms. Furthermore, PFC@JQI researchers are developing a variety of tools to make it easier to use the quantum processor. Recently, one PFC@JQI researcher co-founded a startup company in Maryland for developing trapped-ion-based quantum computers.

- One focus area of the IQIM PFC is the behavior of macroscopic mechanical systems in the quantum regime. IQIM researchers are now about to realize optomechanical systems that are in their quantum mechanical ground state and that strongly interact with single photons. These systems are used to study the fundamental physical properties of macroscopic quantum systems, such as entanglement with many particles, and as an interface interconverting quantum information between different bosonic modes. Such interfaces will be needed to realize distributed ***quantum sensing*** and computing.

Although the FOCUS PFC at the U. Michigan ended in 2009, we highlight the impacts of some of their results here. The FOCUS PFC had efforts in ultra-high-intensity lasers, use of ultrashort laser pulses to study ultrafast atomic and molecular processes, and quantum control of matter using a variety of laser techniques. In the area of ultra-high-intensity lasers, the center made great strides in ***laser wakefield acceleration*** in which ultra-high-intensity laser pulses are used to accelerate electron bunches in the laser-produced plasma. They observed ***hard x-ray production*** due to electron betatron motion, and they performed proof-of-concept ***x-ray diffractive imaging*** experiments, which have had implications for a wide variety of sciences including ***biology, materials science, and nanoscience***. Implications for physics include the possible development of a ***short-path front-end particle accelerator*** for injection into a larger particle accelerator.

The CMSO PFC at the University of Wisconsin ended in 2015, but it still has an important legacy in the field of ***plasma physics***. The work in CMSO brought together theoretical, laboratory, and observational investigations of magnetic field generation and magnetic reconnection in plasmas. The work in CMSO contributed to a greater acceptance and understanding of the role of magnetic fields in ***astrophysics***. Moreover, a lasting legacy of the CMSO is the development of next generation laboratory experiments to study plasma dynamos and magnetic reconnection – the “Big Red Ball” (BRB) device at the University of Wisconsin and the Facility for Laboratory Reconnection Experiments (FLARE) device at Princeton University. And, phenomena such as particle acceleration resulting from magnetic reconnections that were studied theoretically and experimentally in the CMSO PFC are contributing to the understanding of space missions such as the NASA Magnetospheric Multiscale Mission (MMS).

Both the Joint Institute for Nuclear Astrophysics – Center for the Evolution of the Elements (JINA-CEE) PFC and the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) PFC address fundamental questions in ***astrophysics*** based on a geographically distributed collaboration. Beyond the direct scientific goals, both centers seek to build strong national programs, together with international partners. Through regular team meetings, summer schools, and workshops, they successfully bring together a cohesive team that has exceled in its research, educational, and outreach goals. Consider the following impacts of these two PFCs:

- The primary goal of NANOGrav is to detect low-frequency gravity waves that will reveal the dynamics of the universe using a vastly different region of the gravity wave spectrum in comparison to LIGO. NANOGrav researchers predict the possibility of measuring stochastic gravitational waves due to the collection of orbiting black holes that are expected to form after a merger of galaxies. The detection mechanism relies on observing subtle variations in the timing of an array of cosmic clocks associated with millisecond-period pulsars. Already, analysis of the 11-year data set has placed constraints on the strength of the gravitational-wave stochastic background. These results require revisions of theories for galactic black holes relating to the distributions of their masses, the mechanisms for their energy losses, and the rate at which they are expected to merge. Another important aspect of the research generated by the NANOGrav PFC is that the collaboration widely disseminates the computer codes used to analyze the data, and publicly releases the full data set at regular intervals. This research has important implications for the field of ***astrophysics*** and provides a new path for multi-messenger astronomical observation if low-frequency gravitational waves are successfully observed.

- The JINA-CEE PFC focuses on determining how the elements are made in the cosmos and the properties of matter under extreme temperatures and pressures. Based on multi-messenger observation of a neutron star event detected by LIGO/VIRGO and the associated follow-up kilonova event, researchers can now make a complete prediction of the synthesis of heavy elements due to the so-called r-process. The conclusion is that the r-processes are rarer than previously thought, but that they are more productive than previously thought when they do happen. A large component of the PFC's research involves development of sophisticated nuclear physics computer codes to simulate stellar processes. As with NANOGrav, this PFC makes these codes and the related datasets available to the public. This research has important implications for the fields of ***astrophysics*** and ***nuclear physics***.

The KICP very effectively promoted the collaboration of particle physicists and astronomers, of theorists and observers/experimenters, and of experienced researchers and postdocs with an unusual degree of independence, to tackle problems in **particle-astrophysics** and **cosmology**.

- Since its inception, *the KICP has been a leader of research in the field of Cosmic Microwave Background (CMB) anisotropies*. In particular, the KICP has been highly impactful in the advancement of CMB polarization science. This is one of the forefronts of CMB cosmology and one that relies on tremendous interaction to make progress, due to the technological and astrophysical complications involved. The different types of polarization (E-mode and B-mode) come from different sources. E-mode CMB polarization was first detected by the Degree Angular Scale Interferometer (DASI) from the South Pole, a experiment with strong participation of the KICP (whose PI belonged to the KICP). B-modes provide a unique line-of-sight test of the structure in the universe arising from lensing, a prediction developed significantly by a KICP theorist, and may also provide a possible signal of primordial gravitational waves arising from inflation. The KICP led the South Pole Telescope (SPT) family of experiments, which provided the first measurement of B-mode polarization, and had active members in the BICEP/Keck collaboration that first detected B-modes at the degree scale (the appropriate scale to search for inflationary B-modes), although dust-contamination was later shown to be large enough that no claim of a primordial signal could be made. Key elements of SPT were seeded by the KICP. More recently, the KICP supported the workshop that initiated the CMB Stage 4 (CMB-S4) collaboration and began developing the science case for such an experiment. The KICP had a large impact in the organization, design and determination of the science possibilities for CMB-S4.

- *A crucial achievement of the KICP in the effort to determine the origin of the accelerated expansion of the Universe has been to use the combined data from SPT and the Dark Energy Survey (DES) to produce tomographic measurements of the growth of structure at different redshift slices*. This is a new direct way to measure the growth function, one of the key predictions of different dark energy models, which resulted from the strong interaction of theorists, observers and analysts at the Center. Such cross-correlation techniques marked the beginning of a new era in precision cosmology.

- *The KICP also strongly supported dark matter direct detection programs that operate at the frontier of the field, in part based on past and recent detector innovations made at the KICP*. As an example, CCD work for the DES project impacted the design of a new type of detector, the Dark Matter In CCDs (DAMIC) detector. The development of DAMIC, which uses thick CCDs with extremely good position resolution and very low energy threshold, was seeded with KICP funds and directly resulted from the unique synergy between particle physics experimentalists and astronomy observers at the KICP PFC .

As these examples make clear, each of the PFCs has made significant impacts on the physics areas in which it is focused as well as, in many cases, on other fields and technologies.

III. Enhancing education, diversity, public outreach, and broader impacts

As quoted in the Introduction, beyond the potential for a profound advance in physics a successful PFC is expected to propose and carry out creative, substantive activities aimed at enhancing education, diversity, and public outreach; have potential for broader impacts, e.g., impacts on other field(s) and benefits to society. This part of the report addresses these elements of a center’s responsibilities.

Our subcommittee notes that the PFC program has enabled the implementation of substantial education and outreach activities, which most likely would not have been possible—at least not to the current high degree—without the “Center-like approach” required of PFCs. Individual PFCs have fostered the scientific preparation of numerous graduate students and postdoctoral fellows, have engaged hundreds of undergraduates in top-notch research, have created a wide variety of outreach programs in which thousands of K-12 students and their teachers have participated, and have produced and disseminated a multitude of educational resources for specialists, non-specialists, and the general public.

There is little doubt that Education and Public Outreach (EPO) activities at individual PFCs are valued by the leadership of the Centers and are guided by people with the passion to effect positive change locally. There is also little doubt that some promising strategies are being employed at individual Centers. However, as evidenced by the annual reports of the PFCs, the orientation toward Broader Impacts is grounded in an *enumeration* approach to education and public outreach, in which the number of participants in a specific activity serves as a proxy for the intended ultimate outcome of said participation.

In Section III.A, we outline the experiences of students and postdoctoral fellows. In Section III.B, we describe the impact of the program on populations that are traditionally underrepresented in physics, including ethnic and racial minorities, as well as women. Section III.C summarizes ways in which the program enables substantive outreach to the general public, while Section III.D outlines other broader impacts of the program. Finally, in Section III.E, we discuss possible ways in which the program can be strengthened by infusing a more scholarly approach to Broader Impacts. This might seem like a category error, given that scholarship is typically associated with Intellectual Merit. However, we will argue that for the PFC program to live up to its full potential in broadening participation in physics, the EPO component of the PFCs has to go beyond high-quality (even exemplary) local activities and contribute to the research base of what works, for whom, and under which conditions. There is a need to study the effects of the PFC EPO activities and put them under scholarly scrutiny, so that the whole field may learn from its evidence-based claims. As a system, the PFC program has lived up to its promise by pushing the frontiers of physics research. It is high time it also pulled its weight in helping to change the face of physics for the whole nation and beyond.

III.A In what ways is the program enabling unique or enhanced educational experiences for students and postdoctoral fellows?

A nearly universally reported strength of the PFC program is the strong support for training for the next generation of researchers. All of the PFCs have provided direct support for graduate students and post-doctoral researchers; in fact, most of the PFCs reported that funding student and post-doc support was a much higher priority compared to direct funding of faculty. This focus on student and post-doc support is also evident in the close-out process of the PFCs, in which the NSF provides “soft landing” funds to ensure that students are able to complete their research projects. Because of this strong focus on research training, the PFCs have developed a variety of activities and experiences that have enhanced student training.

In terms of their overall impact on student training, the PFCs are seen as instrumental in fostering the development of unique research ecosystems within their larger fields. In this way, the PFCs create communities of researchers that are at the intersection between fields, providing opportunities for collaboration that may not have otherwise formed as easily without the PFC. This, in turn, provides opportunities for students and post-docs that are in a PFC to actively participate in the creation and growth of these new types of collaborations. This is seen as particularly valuable not only as a training activity, but also in creating the new types of partnerships that can expand the frontiers of physics.

Based upon the subcommittee’s discussions with the PFCs, there were several common themes that emerged related to student and post-doc training experiences. These are described below and will be followed by a few highlights from individual PFCs.

Recruiting: The presence of a PFC was seen an important tool for recruiting talented graduate students and post-docs to universities. Within a research community, the PFC program has become an important symbol that indicates that cutting-edge research is being performed at an academic institution. This message is being conveyed to students, who then seek out those programs. Even at the nation’s leading scientific institutions, the leaders of the various PFCs anecdotally report increases in the number and quality of students that apply. Uniformly, the PFC leaders said that they felt that a PFC helped them attract the “best and brightest” to their programs.

Academic training: Because of the interdisciplinary aspect of many of the PFCs, it is often necessary to use the PFCs as a catalyst to create the infrastructure for interdisciplinary courses, seminars, etc. to educate the students. In this way a PFC can serve as an important catalyst to bring together experts from these different fields. This has been particularly true at the biophysics-based PFCs. But other centers that link different areas of physics (e.g., atomic physics and condensed matter physics, plasma physics and astrophysics, etc.) have used the PFCs to create a similar academic infrastructure to ensure students have the necessary technical backgrounds to accomplish their studies.

Mobile graduate students: At many of the PFCs, there is a multi-PI approach to graduate student education. This allows the graduate students to not only gain experiences in both experimental and theoretical physics, but also to move around to different laboratories – which allows them to learn a broad range of scientific techniques. At some of the geographically distributed PFCs, there was also support for graduate students to participate in research projects at partner institutions. While this kind of opportunity is not unique to the PFCs, it is an important feature of the graduate student training that is provided by the PFCs. Among the PFC participants that spoke with the committee, this multi-PI / multi-lab training is highly valued by students and faculty alike.

Flexible post-docs: Similar to the graduate student training, the post-doctoral researchers in many of the PFCs had opportunities to gain flexible training experiences. In several of the PFCs, this was done in the form of a "PFC post-doc" appointment rather than an appointment to a specific person or project within the PFC. The post-docs were then actively encouraged to identify several projects that caught their interest and pursue them. This not only allowed multiple PIs to gain access to and benefit from the expertise brought to the PFCs by the post-docs, but it also enabled a direct cross-fertilization of ideas across different components of a Center. As was noted in one PFC report, "when postdocs were in a collaborative environment, they matured much more rapidly as scientists because they often played as great a role in the research as did the PIs involved." A number of the PFC post-doc participants who met with the subcommittee noted that the "center structure allowed them to explore new directions and move out of their comfort zone." We believe that this is truly the unique scientific training opportunity that is afforded by the PFC.

Summer/Winter Schools: A particularly compelling component of student training that not only benefitted the students and post-docs at the PFC, but the entire research community served by the PFC was the creation of Summer and Winter schools. These were universally viewed as one of the most positive features of the support provided by the PFCs as they provided a strong service to the broader research community. When these Schools were targeted to the students and post-docs, they were seen as particularly effective. In fact, because of the perceived value of these programs, one major concern that was raised by several of the closed PFCs was finding a mechanism to continue the Schools during the "wind down" phase of a PFC.

Young Scholar programs: Beyond their scientific training, many of the post-docs were also given their first opportunities to gain experience in leadership activities in the PFCs. Some examples of this include serving as mentors to graduate students and post-docs, organizing sessions at Center annual meetings, and even serving as members of the Center management team.

Undergraduate student training: While the PFCs are largely focused on graduate student and post-doc training, several of the PFCs have also engaged in active programs to train undergraduate students. Often, this takes the form of supporting Research Experiences for Undergraduates (REU) programs at the PFC. However, some centers also have programs that reach out to local and regional undergraduate institutions and provide extensive hands-on training for students, often using Center graduate students and post-docs as mentors.

Some specific highlights of training activities:

- COSM, centered at an HBCU, was a unique opportunity to target the training of an under-represented group.
- CGWP, CMSO, CPLC, JILA and COSM are among the PFC examples where summer/winter schools were created.
- KICP post-doctoral fellows are not assigned to a single project, but allowed 3 years to move between theory/experiment projects allowing them to sample and contribute to a variety of scientific problems.

- KITP "Graduate Student Fellow" program allowed six graduate students per semester to reside at the KITP for 6 months.
- CTBP and NanoGrav are examples of two PFCs that are particularly heavily involved in undergraduate student training.

Challenges to be addressed:

- Inclusion – attracting the "best and brightest" is an important goal; but this should extend to the full spectrum of physics majors. Could the PFCs play a bigger role by recruiting talented students from a broader range of universities, e.g., more minority-serving institutions, a broader range of primarily undergraduate institutions, etc.?
- Has the existence of the PFC led to the formation of new types of research connections among students/post-docs/faculty that are long lasting – what type of assessment could be done to confirm this?
- What can be done to ensure that some of the educational legacy of PFCs persists beyond the existence of the Center – notably the summer/winter schools? Also, can the NSF do more to encourage partnerships among PFCs with similar themes to leverage their expertise in creating and running these summer/winter schools?

III.B. In what ways is the program contributing significantly to broadening participation of traditionally underrepresented groups?

According to the AIP, the fraction of bachelor's degrees awarded to women and African-American students has remained stable for the last 10 years at 20% and 3-4%, respectively, compared with 50% and 12% in the general population (fractions of PhDs and faculty members are lower). The fraction of Hispanic-American bachelor's degrees in physics has been growing, close to 8% in 2016, but still lower than the (also growing) 12% in the general population [https://www.aip.org/statistics/data-graphics/proportion-physics-bachelors-degrees-awarded-african-americans-and-hispanic, https://www.aip.org/statistics/data-graphics/percent-physics-bachelors-and-phds-earned-women-classes-1975-through-2016]. Increasing the representation of women and minorities in physics is an important goal of the scientific community and of the NSF in particular.

Unfortunately, there are few statistics available to evaluate the diversity of the people working for the different PFC initiatives. This lack of quantitative information in itself is a problem, highlighted by NSF: the response to voluntary demographic information is lower than 5%, not enough for considering it representative (this is true for grant-supported people in general, and for PFC personnel in particular).

As one example of a success story, the NANOGrav center reports 35% of the Postdocs, 40% of the graduate students and 49% of the undergraduates are female, which are levels well above the national averages. In the proposal they had set a goal to increase female plus underrepresented minority undergraduate participation to 50% and they have already exceeded that figure. NANOGrav has a clear diversity policy, holds yearly diversity trainings at their Fall and Spring meetings, and has a Climate and Equity Committee to look at systemic climate and other issues with NANOGrav. There is a formal procedure to distribute speaking opportunities among junior personnel and a code of conduct during meetings. They actively work to recruit female undergraduate and graduate student participation as well as Hispanic and African American students and focus on retention of these groups.

The Center for the Origin and Structure of Matter (COSM) was established at three historically minority-serving institutions. They tried to develop a broader network of such institutions with regular visits and opportunities for undergraduates to attend their summer school.

In 2016, the Joint Institute for Nuclear Astrophysics - Center for Evolution of the Elements (JINA-CEE) PFC developed and ratified a comprehensive diversity and inclusion Code of Conduct. Subsequent to the ratification, JINA-CEE management has embedded effective diversity and inclusion practices as a cultural change at the PFC, affecting all aspects of research, conference, educational and outreach activities. As a result, the representation of female faculty in JINA-CEE has doubled from 18% in 2016 to 37% in 2019. The striking success of the JINA-CEE Code of Conduct is now leading to a pending adoption of a similar comprehensive Code of Conduct across the full research lab, and across Michigan State University.

However, in general, there is enough anecdotal experience and self-reported data to conclude that: (i) Diversity in most of the PFC groups is not significantly different than in physics in general, which is highly unsatisfactory; and (ii) Some PFCs have been more successful in recruiting and retaining minorities among their members. The subcommittee understands this is a difficult and very important issue.

III.C. In what ways is the program enabling substantive outreach to the general public?

The public outreach efforts of most PFCs are quite impressive. Several hold summer schools and summer camps for local middle and high school students as well as learning workshops for schoolteachers. There are science fairs, public talks by postdocs and faculty, radio and YouTube presentations as well as outreach to HBCUs.

Most regular NSF grants also have a public outreach component, and the question arises as to the added benefit of a PFC, versus an equivalent investment in regular grants. There are several areas in which the larger scale of a PFC enables substantially greater and more varied outreach activities.

Many PFCs can hire an education and public outreach (EPO) coordinator. With one person dedicated to EPO, much more can be done. At the IQIM, for example, the EPO coordinator arranges activities geared to public, K-12 and schoolteachers, enriching the sense of community in the area. The EPO coordinator at the PFC@JQI organizes science fairs, sending undergraduates to local-area schools, *etc.* These activities would be difficult without the large scale of a PFC. In many cases, the EPO is done by enthusiastic postdocs, graduate students as well as PIs. This not only is valuable to the public but is an excellent training and mentoring experience.

Some PFCs have summer science camps and various summer programs. Again, these would be impossible with individual or small-scale grants. At JILA, the "Partnerships for Informal Science Education in the Community" serves 250-300 students a year, enables minority students to explore science in after-school programs and is now beginning to work with high school students. NANOGrav is a widely distributed center with an extraordinary EPO program, including a broad outreach program with a special emphasis on K-12 programs. It is especially effective at engaging high school students through its Pulsar Search Collaboratory (with 500 students and 58 teachers from 56 schools around the country). There are special NANOGrav groups dedicated to outreach, including the Space Public Outreach team, which coordinates K-12 activities. While the NANOGrav EPO programs have been led by postdocs or junior faculty, they are now looking for a full-time coordinator.

A concern arises when centers are closed. In several cases, the non-renewal of a PFC resulted in the immediate loss of the EPO coordinator and many of the outreach programs, with the close-out funding usually given to postdocs and graduate students. A small amount of additional close-out funding to keep the EPO activities going for a brief time would allow the PFC leadership to look for alternative sources or allow a more gradual wind-down.

III.D Other Broader Impacts of the PFC Program

The two previous sections have detailed the PFC program's role in increasing participation of underrepresented groups (Section III.B), and in enabling substantive outreach to the general public (Section III.C). Here we focus on other criteria identified in the NSF's Dear Colleague Letter on Broader Impacts (https://www.nsf.gov/pubs/2007/nsf07046/nsf07046.jsp) such as enhanced research infrastructure and benefit to society.

In some cases, "benefit to society" was readily identifiable, such as the Joint Quantum Institute, which provided summer research opportunities to students from Historically Black Colleges and Universities (HBCUs) at the University of Maryland, or the Center for the Origin and Structure of Matter, which engaged HBCU students in the research efforts at Jefferson Lab and the international laboratory CERN. The Kavli Institute for Theoretical Physics, through its practice of video-recording all talks at its various workshops, provides access to this cutting-edge material for students and researchers around the world, averaging 240 viewing hours per day. Both NANOGrav and JINA-CEE have provided top-tier research opportunities for undergraduates studying in small four-year liberal arts colleges. The JILA Center's PISEC (Partnerships for Informal Science Education in the Community) has produced a number of physics education research papers establishing evidence-based methods for new approaches to teaching physics. [For example:doi:10.1119/perc.2017.pr.008;
https://www.per-central.org/items/detail.cfm?ID=14784]

Other centers increased and/or expanded the research infrastructure. For example, the Center for Magnetic Self-Organization increased ties between academic researchers and three national laboratories (LANL, LLNL and PPPL), and also positively influenced NASA efforts such as its four-satellite Magnetospheric Multiscale Mission. Both the Center for the Physics of Living Cells and the KITP have established summer schools that have introduced students and postdocs from across the country (and beyond) to the rapidly developing interface between physics and biology. The Center for Theoretical Biophysics, co-located with a prominent medical school, has introduced medical trainees to this same methodology.

More generally, we can categorize the societal benefits of the PFP program into three broad themes:

1. **The Physics of the Universe (CMSO, CGP, JINA-CEE, KICP, KITP, NANOGrav)**

   The public has a broad interest in the structure of the universe, the origin of the elements, black holes, etc. These centers address those questions and engage the public through both their discoveries and their outreach programs.

2. **The Physics/Biology interface (CPBF, CPLC, CTB, KITP)**

   The future health of humans as individuals, societies, and as a species depends on quantitative understanding and mathematical modeling of biological systems. These are true multi-scale problems, requiring breadth and understanding ranging from molecular dynamics to humans and the environment. Insights derived from physicists' approaches to biological problems are likely to greatly improve our understanding of biological systems by having quantitative methods for predicting behavior. Techniques derived from physics allowing the manipulation of single molecules have the potential for new methods to modify the machinery within cells with potential application to agriculture, pharmaceuticals, and human health.

3. **The Quantum Frontier (CUA, FOCUS, IQIM, JILA, PFC@JQI)**

   Much of the work at these centers is devoted to having exquisite control over increasingly complicated quantum systems. This is leading to a better understanding of condensed matter systems, which eventually may lead to discovery of new materials. In addition, each of these centers has a footprint in quantum information science, and a plausible case can be made that many of the researchers in these centers were responsible for propelling this field into the national spotlight via the recently signed National Quantum Initiative Act. A new computing paradigm based on manipulation of quantum states will have an enormous impact on society and on our national security. The research in these centers also focuses on precision measurement, including new ways to measure time, gravity, frequency, etc. We already have numerous examples of ways in which these technologies have made their way into systems that are important to society. At least one of these centers has spun off multiple high-tech start-up companies, enabling the transfer of quantum technologies to the private sector.

We note that our subcommittee was not able to determine if the PFC program provides the *optimal* way to deliver these benefits to society. Nonetheless, we observe that the program has been *effective* in doing so.

III.E. Achieving Even Broader Impacts

In the previous sections, we have presented plenty of examples of high-quality efforts in education and public outreach associated with PFCs. We note, however, that the examples collected from annual reports, diversity statements, or our visits are vignettes; they are anecdotal in their very nature. And the plural of anecdote is not data. There is a lost opportunity here: If the PFCs were to take better advantage of discipline-based education research or even science education research in formal and informal settings, the Broader Impacts would most likely have broader impact and inform—through scholarship—the experience of people (K-12 students, teachers, the general public, but also undergraduate and graduate students and postdocs in physics settings) who do not have the benefit of having direct contact with the Centers' programs. Below are four examples:

1) ! Postdoctoral researchers and graduate students associated with PFCs receive excellent scientific preparation in the PFC program. Anecdotes suggest that some such researchers become leaders in the field. There is currently no mechanism for the field to track systematically the subsequent professional trajectory of students and scholars who are prepared at PFCs.

> *There is a need to track networks of graduate students and postdoctoral researchers to better understand the longitudinal impacts of PFCs so that the field will understand better the value added by these Centers and more broadly by any NSF Center.*

2) ! Unlike the scientific preparation of junior researchers, which is typically top notch, we did not encounter programs that systematically acquaint—let alone professionally prepare—future faculty for their roles as physics educators who are at least aware of results of research on the learning and teaching of physics. We recognize that such an expectation has never been articulated by the program and, therefore, no single PFC should be held to such a standard. We want to be clear that this is not a criticism of any Center. It is rather a missed opportunity for the physics community.

> *There is a need to prepare PFC junior researchers for their future roles as sophisticated physics educators who are familiar with physics education research results so that physics departments can start building more rapidly on scholarly approaches to teaching.*

3) ! In a similar vein, although outreach programs associated with specific centers are vibrant in terms of numbers of participants or passion of program designers, the field at large learns little about what works, for whom, and under which conditions. This again speaks to an emphasis on body count as opposed to a scholarly approach to understanding the strengths and limitations of different interventions in a way that stands up to scholarly scrutiny and can serve as a template for large-scale replicability of successful programs. To be sure, there are powerful counter examples, such as the outreach program at JILA, which regularly contributes to the knowledge base through peer reviewed publications.

There is a need to approach outreach activities from a scholarly perspective so that new NSF PIs will have a literature—as opposed to personal opinion—on which to ground their EPO efforts. We recognize that this requires specialized expertise. All science requires specialized expertise. PIs construct fabulous collaborations to push science forward; here we invite them to do the same for the sake of broader Broader Impacts.

4) ! The subcommittee saw evidence of personal passion among Center personnel for broadening participation in the programs of the PFCs. To be sure, some PFCs have had significant local successes. Looking at the *national* demographics of physics, however, one cannot claim that the PFC program has played a major role in broadening participation in physics. One wonders about what the outcome would be should the PFCs attempt to connect local efforts with national initiatives, such as the APS Bridge Program and the STEP UP 4 Women project of APS, AAPT, and Florida International University, and incorporate learnings from the literature on equity and inclusion in STEM, and more recently physics. In the same way that the PFC program is premised on the conviction that cutting-edge physics is enhanced through synergies among a community of well-informed researchers working together, the serious challenges associated with the lack of demographic diversity in physics cannot be tackled without systemic efforts of a whole community.

There is a need to participate in and contribute to national initiatives addressing demographic diversity in physics so the PFCs might play a role in this area analogous to the one they play in the scientific area.

5) ! The production of cutting-edge physics results is clearly an indispensable goal of the PFC program. Another important goal needs to be elevated and clarified, namely community-building efforts by the center, some of the outcomes of which are harder to associate uniquely with a specific center activity.

There is a need to elucidate in the PFC solicitation and/or the instructions given to reviewers the relative priorities of these efforts so that (a) Intellectual Merit and Broader Impacts are treated consistently and (b) the efforts of individual PFCs to promote tighter connections among members of the physics community are recognized.

IV. What Happens when Centers Close

Successful PFCs develop substantial integrative activities, centered around shared postdocs (not assigned to a specific single PI project), meetings and other programs, as well as shared EPO efforts. The issue we address here is how to either help to continue some of these activities (with NSF or other sources of funding) or else to phase them out. Several distinct ideas came about while talking with PFCs that have been closed and these were discussed in our subpanel. We discuss them in turn.

- ***A better prior understanding of the amount and possible uses of NSF's temporary ramp-down funds***

Some PFCs were caught off guard when they were terminated, without a clear understanding of the support NSF would provide for the close-out and without having made concrete plans to terminate, phase out in an orderly fashion, and/or preserve their many activities. At the time of the termination, the PFC and its host institution had generally made substantial commitments and the administration had put aside funds for the case of a non-successful renewal, however they did not have a clear plan on how to move ahead. This meant considerable anxiety among postdocs and students until their situation was clarified, as well as the abrupt termination of the full time EPO coordinator (with immediate disruption of EPO efforts).

A sentence about support for postdocs and students after termination is already contained in the PFC solicitation, and it clearly is the responsibility of the particular PFC administration to be ready for a potential termination. However, the question arose of a mechanism for NSF to help a PFC to be more aware and prepared for a potential termination. This could be done through a conversation of the NSF monitor with the PFC director a year before the present support expires or a more formal requirement for the director to propose a short termination plan in writing (before and after the outcome of the final proposal is known). Another possibly useful modification to current NSF practice could be to allow a PFC to use ramp-down NSF funds not only for postdocs and students but also for the EPO coordinator. This would provide continuity and stability to EPO efforts. A termination of a PFC often results in outreach programs being suddenly halted; with some ramp-down NSF support, there would be time for either other sources to be found to continue this position or else a more orderly phase out.

- ***Make available NSF group grants for integrative activities, separate from individual PI research grants, for which ex-members of a PFC (but not exclusively) could compete***

The future of groups that have been successful in a PFC could use additional consideration. If synergy is the main characteristic of a PFC, the ability to compete for group grants for integrative activities could maintain these already established efforts after the PFC is closed. These could be grants that fund exclusively shared postdocs, following the example of the network postdocs of N3AS in Nuclear Theory.

- ***Consider a sunset provision for PFCs after a certain number of potential "renewals"***

There was substantial discussion in some of the PFC site visits and in the subcommittee concerning the possibility of a sunset provision. Although the majority of the subcommittee was opposed to this possibility, we are including here the arguments that were presented because they may be useful to others evaluating the PFC program in the future.

The type of sunset provision we considered is one in which PFCs would not continue beyond two or three "renewals" (we use the word "renewal" when a current PFC applies for a new award; we understand that all applications are ab initio). This would limit the lifetime of a PFC to 12-18 years. The subcommittee did not reach a consensus on the question, although a majority opposed such a provision.

The arguments in favor of such a provision are as follows:
--in 2014, for example, there were five awards, but only one was to a new center. There was also only one award to a new center in 2017. While the NSF does not make public the number of applications that respond to the program solicitation, it is clear that the competition is intense. With recently only one new center funded per cycle, there is a sense in the community that the PFC program is pretty "locked-in," thus discouraging new applications.
--PFCs are to study "emerging frontiers." After over a decade, either a frontier has already emerged or it has not. In either case, it is no longer an "emerging frontier." Yes, PFCs are supposed to reinvent themselves for each cycle, but it isn't clear to what extent they do so.
--Current PFCs, due to their experience and many years of operations, have a big advantage in every new cycle of proposals. The obvious equilibrium configuration would be a completely locked-in and static program.
--With a known end-date, PFCs could plan without being forced to suddenly find their funding being phased out with, in some cases, little warning.

The arguments against such a provision are as follows:
--It is true that in 2014, four of the five awards were to current PFCs, but those were the strongest proposals. If the NSF is to support the best science, funding should go to the best proposals without arbitrary time limits. Shutting down a Center which might be the best in the country due to an arbitrary time limit is contrary to the mission of supporting the best science.
--Centers do have to reinvent themselves, to establish that they are still doing research at the "Frontier."   If they don't, that is an issue that should be dealt with in the review process.
--The fact that the KITP and KICP were not funded in the last cycle shows to the community that the PFC program is not "locked-in."
--If a PFC knew that they were going to be closed, the science that they perform in the last few years would not be as robust, and new initiatives and ideas would be less likely to occur. The process of an application for a current PFC stimulates new ideas and proposals (as every grant-writer knows).

After a substantial discussion in the subcommittee, a majority of its members felt that a sunset provision was not warranted.

The possible transition to a more permanent structure of successful PFCs was also discussed. The KITP is a prime example of a long-lived entity within NSF, as are a number of facilities. This would require a new type of structure to be created which does not exist within NSF at the moment. It would still require a regular review protocol. There are no permanent structures supported by NSF. The only other NSF center for which a PFC could compete is a Science and Technology Center, which has a maximal duration of 10 years. In the end the subcommittee did not see particular advantages of creating such a new structure.

V. Opportunities and Threats

The Competing Requirements of Frontier Research

The primary motivation for the PFC program is to accelerate research discovery at the frontiers of our knowledge. The definition of the frontiers of research may take on two different aspects:

1) ! Research that explores completely new or previously undiscovered physical regimes, concepts or paradigms, where the validity of the approach needs verification, and the implications of the idea are not clearly understood.

2) ! Research that provides transformational progress in the reliability and/or precision of our current understanding of a physical phenomenon, especially where the improved progress may provide a critical measurement that changes our current understanding of the physical world.

As evidenced in the previous sections, the PFC program has been successful in providing funding opportunities for both aspects of frontier research.

The first frontier aspect includes the development of new ideas that establish links between multiple fields or ideas that were previously thought to be unconnected. The first frontier aspect explores whether the new concepts may be valid, and whether the new approach or paradigm might lead to a larger framework or capability that can provide a deeper understanding of previously unconnected ideas. This exploratory work in the initial stages of research is a high-risk, high-reward enterprise. The appropriate type of funding requires nimble seed funding of small teams of researchers who freely explore the new/novel concepts and ideas on short time scales, and explore the basic feasibility of the idea. Ideas that survive the basic feasibility review can then effectively pursue larger research funding that can provide the more in-depth, longer-term research funding that can refine the understanding and implications of the idea, moving the nascent concept into mainstream research.

The latter frontier research aspect supports transformational research in long-established fields. In many complex fields, such as nuclear astrophysics, progress is accomplished through a long-term, comprehensive approach that requires a sequence of carefully designed research orchestrated over an extended duration to provide the high precision, legacy research results necessary for confirming or extending the frontiers of knowledge. These legacy-size efforts require a substantial investment of research, often including the use of national facilities. The large cost associated with this type of research requires a conservative, longer-term approach to eliminate the unacceptable risk of failure.

PFC and the Research Funding Scaffold

A robust and effective research funding portfolio in physics will provide a scaffold of funding opportunities. The funding scaffold should be designed to respond to a wide range of needs according to the maturity of the field of investigation, and the scale of resources and personnel required to make substantial progress. Critical factors that influence the success of the research portfolio include the speed required for a funding decision, the required duration of support, and the ability of the funding opportunity to address the perceived risk and rewards of a particular research project. The NSF Physics division, through various funding opportunities [Standard PI grants, Early-Concept Grants for Exploratory Research (EAGER), Grants for Rapid Response Research (RAPID), PFC], and using support through NSF-wide Major Facility funding [Major Research Instrumentation (MRI), Mid-scale Research Infrastructure (MS RI), Major Research Equipment and Facilities Construction (MREFC)] has developed a strategy that provides a scaffolded set of funding opportunities that supports the logical progression of research activity from infancy through mature phases.

Figure 1 Illustrates various funding opportunities that have been available to researchers since the inception of the PFC program. The grant sizes, durations, and funding response times shown these figures should be viewed as notional and can be larger or smaller in specific cases. The standard PI support grant program (light blue) forms the core of the available research support to Physics investigators. These are typically three years in duration though they may extend up to five (as represented by the fading out of the color in years four and five). This program was supplemented by the RAPID and EAGER programs to provide scaffolding for new ideas and fast time scales that were outside the scope of the standard PI research grant program. The Institutional seed funding (red) is not an NSF program, but it is illustrative of the typical support available to researchers at universities and national laboratories. These funds are provided as a scaffold into both RAPID and EAGER, or to the PI grant program, and are designed to provide the recipient with modest funds over a short period to answer basic feasibility questions that are critical for successful federal funding.

The dark blue funding opportunities indicate the various NSF research infrastructure programs, extending from the NSF-MRI program to the large MREFC, with the recent MS RI program providing a bridge in funding level between MRI and MREFC. The PFC program (green) provides funding opportunities at both short and long funding durations that substantially extend the research scaffold. Somewhat arbitrarily, we illustrated the grant size as a range for a five-year grant but we have illustrated the length of the PFC awards as extending from one to two successful awards (6 to 12 years followed by funding ramping down), recognizing that proposals from existing PFCs have a high probability of being successful, but that the research goals evolve so a typical research topic would not be continued into a third award. Existing PFC awards have built-in programs for modest seed funding opportunities to explore various new ideas over short time scales; if these initial projects are successful, the researchers have subsequently sought (and received) second-stage funding through the middle rungs of the research funding scaffold. This type of support is highly responsive to the needs of the *high-risk, high reward* aspect of the frontiers of physics, as previously discussed. At the same time, the typical extended duration of the PFC awards has enabled the support of the *low-risk, high reward, longer-term* aspect of research at the frontiers of physics. There is no other NSF funding mechanism that supports both requirements for research at the frontiers of physics.

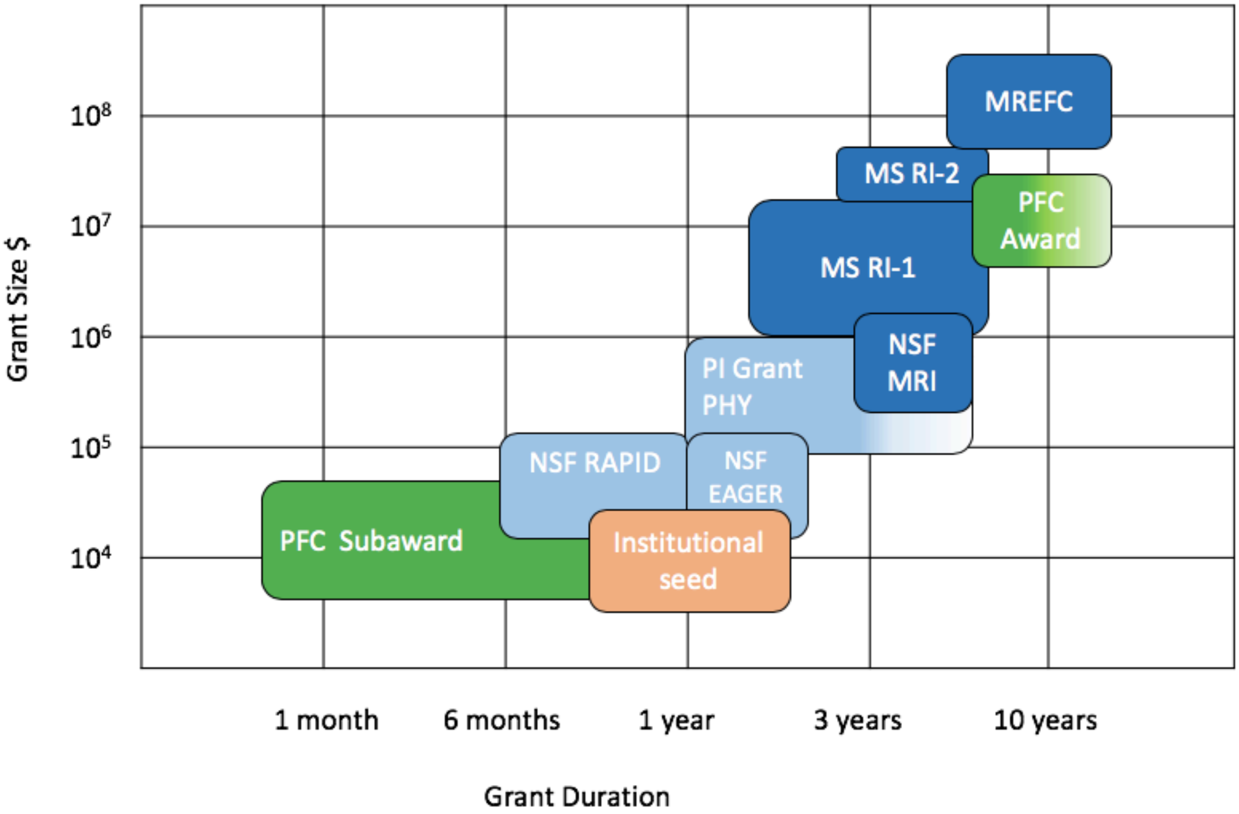

Figure 1: Approximate range of Grant size ($US) as a function of grant duration for various NSF and institutional funding programs. Light Blue: standard PHY PI grants. Dark Blue: NSF-wide major research infrastructure and instrumentation investments. Red: Typical Institutional seed funding programs. Green: PFC Award program and typical PFC sub-awards administered by individual PFCs.

This Figure also illustrates several other important aspects of the PFC program. The location of the PFC award funding opportunity adjacent to the Major Research infrastructure opportunities (dark) blue makes the case that the PFC program is also a major research investment in researchers and students, not physical facilities or instrumentation. The extended duration of the PFC and the size of the award, however, are well matched to the Major Research Instrumentation Program, and therefore there is a natural affinity for PFC programs that take advantage of this synergy. Figure 2 illustrates the ability of the various opportunities in the research portfolio to respond to a research funding need. It is clear that individual PFC programs developed internal funding mechanisms that can rapidly respond with seed funding on short time scales, thereby accelerating the process of innovation and discovery. The time required to develop and fund a new PFC award is substantially longer than the standard PI grant program but is in the middle of the range of Major Research Infrastructure timescales. It is also constrained by the practice of having a solicitation every third year.

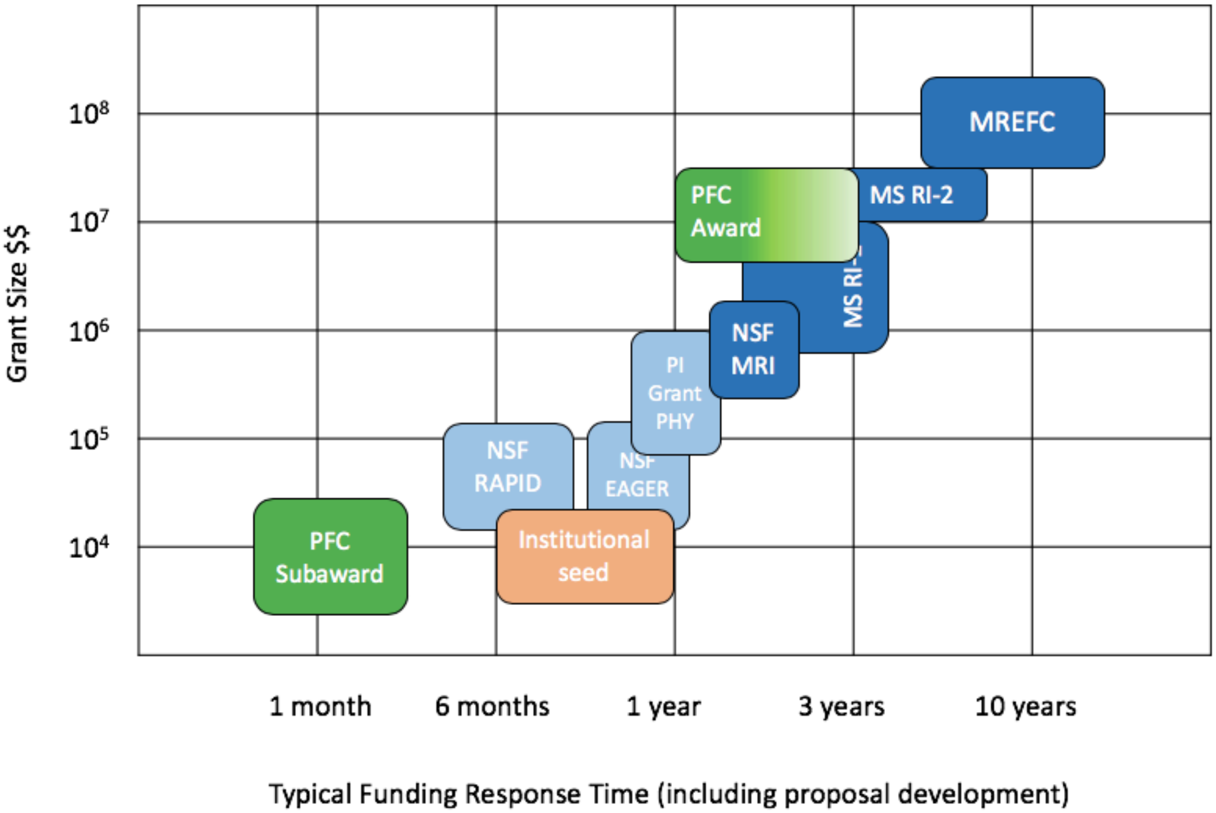

Figure 2: Approximate range of Grant size ($US) as a function of time to receive a grant for various NSF and institutional funding programs. Light Blue: standard PHY PI grants. Dark Blue: NSF-wide major research infrastructure and instrumentation investments. Red: Typical Institutional seed funding programs. Green: PFC Award program and typical PFC sub-awards administered by individual PFCs.

Figure 3 illustrates the personnel (FTE) that are typically funded by the various funding mechanisms. The PFC awards support a modest number of researchers over extended periods in support of a legacy research project; this capability is not matched in other parts of the research portfolio (except for MREFC, which is focused mostly on infrastructure acquisition). PFCs have provided fractional FTE support over short periods to support novel investigations and ideas. These durations are often too short to justify the investment in writing a formal proposal to the RAPID, EAGER, or institutional funds programs.

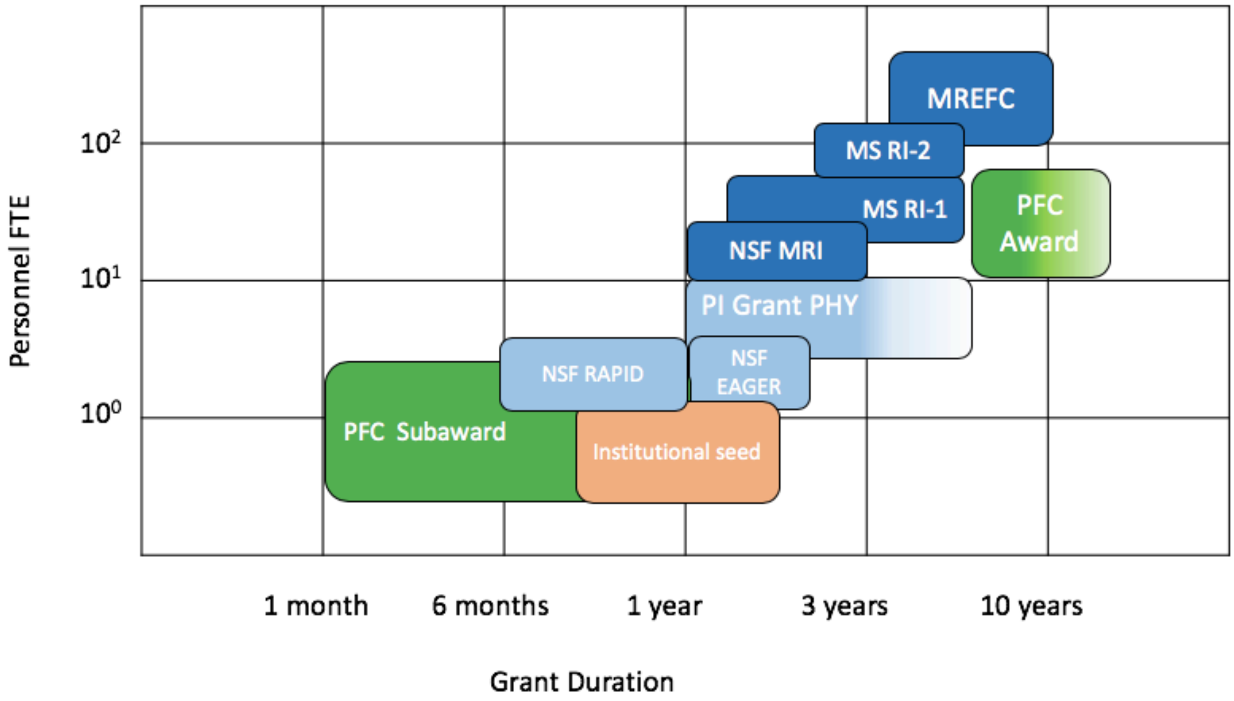

Figure 3: Approximate range of grant-supported FTE as a function of grant duration for various NSF and institutional funding programs. Light Blue: standard PHY PI grants. Dark Blue: NSF-wide major research infrastructure and instrumentation investments. Red: Typical Institutional seed funding programs. Green: PFC Award program and typical PFC sub-awards administered by individual PFCs.

Broader Impacts Funding Scaffold

Figures 4 and 5 illustrate the range of typical funding opportunities available for broader impact activities within NSF. In the case of education and public outreach, each PI grant dedicates a small fraction of its grant funds towards education and public outreach activities. More comprehensive funding of education and public outreach can be received through formal research proposals to the NSF Directorate for Education and Human Resources, such as the PI grant program or the Advancing Informal Stem Learning (AISL) program. It is important to note that the success of many broader impact activities, such as outreach to local museums and K-12 institutions, are built upon long-term relationships between individuals that have been established over several years. At the same time, there are occasional one-time, short-term, high-impact opportunities which may arise in a community, and it may be difficult to anticipate the need for this funding in a time frame that could allow funding by other mechanisms (i.e., institutional or NSF-PI programs). PFC programs have provided modest funding for both short-term, exploratory initiatives as well as multi-year, legacy initiatives. The funding characteristics of the PFC program provide additional opportunities for broader impacts that are not easily achieved through other funding mechanisms.

Opportunities presented by the PFC Program

Five+One Year x N renewable funding

The PFC program can allow for sustained funding of a major initiative over timescales that are 2-5 times the duration of typical PI Grants. This opportunity allows the establishment of longer-term, comprehensive research planning to enable concentrated research efforts that cannot be addressed in the standard PI program. Advantages of this extended funding profile include the ability to engage in solutions involving more complex, difficult research investigations, and the provision of an extended framework for development and refinement of long-term initiatives in Broader Impacts.

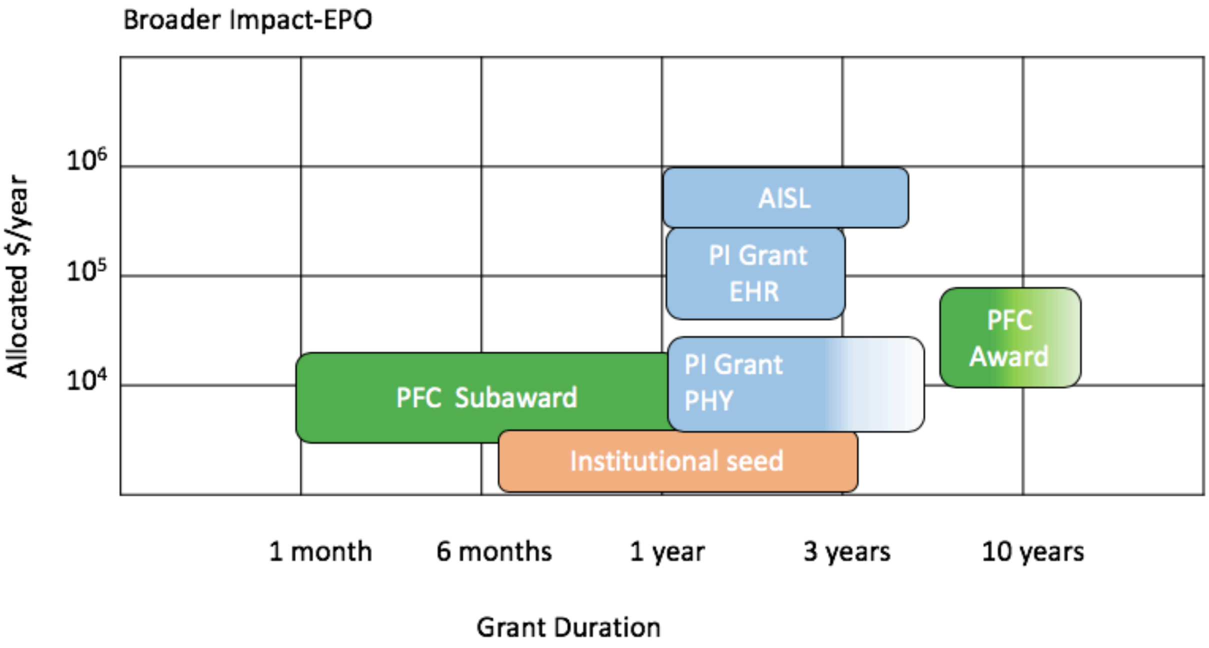

Figure 4: Approximate range of grant support ($US) as a function of grant duration for various NSF and institutional funding programs for Broader Impacts/EP&O. Light Blue: Standard PHY PI grants. Red: Typical Institutional seed funding programs. Green: PFC Award program and typical PFC sub-awards administered by individual PFCs.

The extended funding period for broader impacts provides the opportunity to develop and nurture long term, transformational projects with community partners that may extend beyond the duration of the PFC. Institutional HR pilot initiatives for developing a diverse workforce can be anchored over a longer period, thereby providing stability and best practices that can grow to serve the larger institution, as well as other institutions across the nation. The longer-term broader impact programs also allow for an extended period of direct assessment of impact, thereby improving the value of the research to the larger community. There is a strong opportunity to disseminate the results of PFC broader impact research through a common forum. This type of initiative could return stronger investment to the community in the development and testing of effective practices for Broader Impacts

Engagement of a wider group of investigators

The PFC program provides the opportunity to engage a larger group of investigators onto a problem of high scientific impact, thereby enabling new cross-disciplinary approaches that may spark unanticipated innovations. Many PFC programs can develop and provide shared access to research facilities/databases/resources that cannot practically be accessed or managed by a single PI grant. A wider group of investigators allows different viewpoints to explore the implications and the development of frontier physics research. It has been observed that the PFC has effectively developed a community approach/joint commitment for education and human resources development and broader impacts. By engaging the wider group of investigators into common expectations and responsibility for broader impact activities, the successes of these programs are improved, and the longevity of the broader impacts can extend beyond the lifetime of an individual PFC.

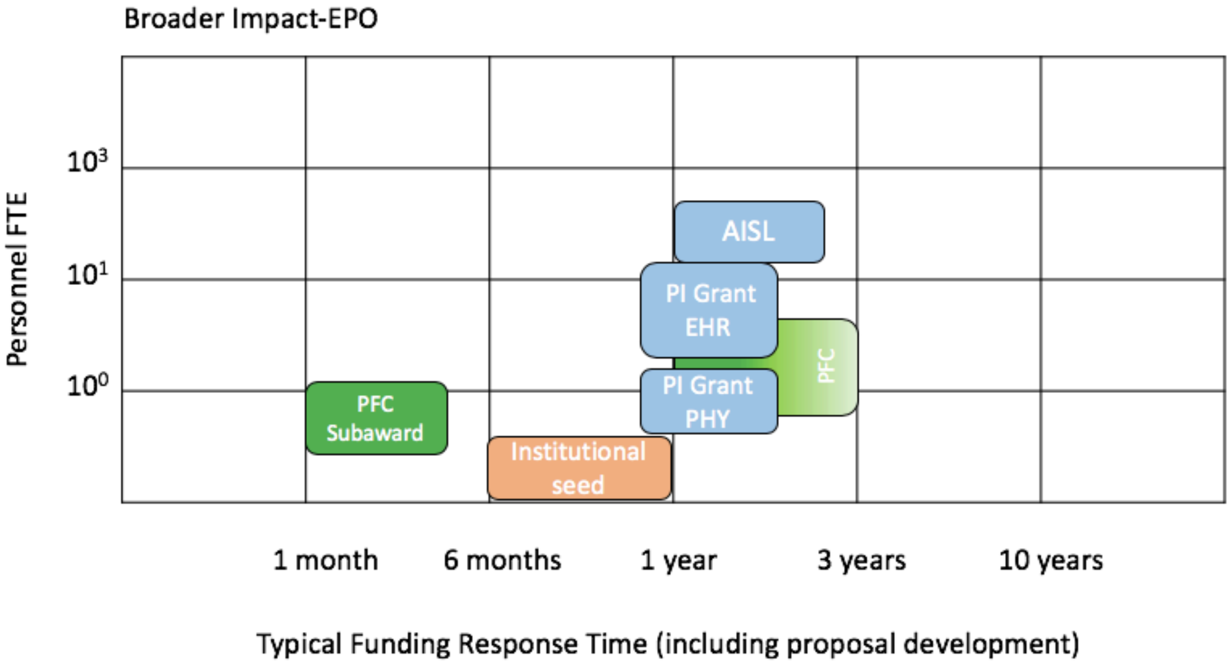

Figure 5: Approximate range of Personnel supported (FTE) as a function of funding response time for various NSF and institutional funding programs for Broader Impacts/EP&O. Light Blue: Standard PHY PI grants. Red: Typical Institutional seed funding programs. Green: PFC Award program and typical PFC sub-awards administered by individual PFCs.

Rapid response to new ideas/discoveries

The PFCs have demonstrated the advantages of providing local control of some resources to quickly invest in recent discoveries. These nimble initiatives provide the ability to form small teams to explore high-risk, high-return opportunities without the burden and time delay of writing a formal proposal. Research has demonstrated [L. Wu, D. Wang and J. A. Evans, "*Large teams develop and small teams disrupt science and technology,*" Nature **566**, 378 (2019)] that small research teams generate more impactful, innovative science than large research teams.

The key opportunities inherent in the PFC approach

The PFC program has a fundamental tension between the goal of supporting larger teams to build upon/develop/evolve existing paradigms, and the goal of supporting smaller teams that will lead to fundamental disruptions to the existing paradigms. Properly balanced, this tension is one of the major strengths of a PFC award. It is critical that PFCs retain the ability (and are encouraged) to simultaneously focus on the pursuit of disruptive research discoveries as well as the deep exploration of difficult, long-term questions that challenge fundamental paradigms in physics.

The PFC program provides important scaffolding into the Standard PI Grant program, as well as a linkage from success in the PI grant program to the larger scope of a longer-term, major national initiative in the Frontiers of Physics. The PFC thereby leverages existing programs and provides the opportunity to improve the quality of research proposals submitted to regular PI grant programs, and major research infrastructure investments.

The PFC program acts as a major research investment in personnel, science, education, and human resources mirroring the NSF programs for major investments in infrastructure and instrumentation.

Potential Risks to be managed by the PFC program

There is a potential for a Physics Frontiers Center to be seen as a substitute for Regular PI funding (ongoing group funding). It is critical that the centers retain the unique character of the Physics Frontiers Centers. This program has a different purpose and focus than the PI grant program. It has a synergistic/complementary role, and it is important that the community understand this role. If the PFC program becomes viewed as elitist (the rich get richer), there may be a groundswell of opinion to redirect PFC funds back to the PI grant program. As discussed above, such a change would hurt the entire NSF funding scaffold, including the PI grant program.

This risk may be mitigated by clearly articulating the PFCs' unique roles in a transparent manner. The PFC solicitation, proposal review process, and management must reflect the unique roles of the PFCs in the portfolio of PHY funding opportunities. The PFC solicitation should encourage proposals that enable engagement in the PFC science and activities in the broader community so that the researchers from institutions with varied levels of research engagement will not perceive barriers to participation in the goals of the PFC.

A second risk to the program is the perception that a significant fraction of the community views the program as helping "the rich get richer." This issue was raised in much of the input to the subcommittee from the community, for example at the Midwest Physics Chairs meeting and in the contributions to the web site set up for community input. Many of the centers are at top-ranked research universities, though one can point to counterexamples. Similarly, the probability that a funded center secures another round of funding in later solicitations is over 70% over the lifetime of the program and there has been only one new center from each of the FY11, FY14 and FY17 solicitations.

Of course, this is a chicken or the egg situation. Top research universities attract top research talent and the research funding to realize opportunities at the frontier. Selection panels have more confidence that a proven researcher can achieve challenging research goals than a less proven researcher. Existing PFCs can build a record of activities in education, outreach and diversity and broader support of community building initiatives. We heard much less of this criticism for the centers that are actively involved in community building. Examples of this type of success have occurred at JINA, CGWP, and NANOGrav. FOCUS had an active visitor program to involve the wider community. The subcommittee sees the value for NSF to create a separate program to encourage and fund visitors to PFCs, but concluded a recommendation to do this would be micromanaging the program. We do believe if all the centers regularly committed to community building activities, it would allay some of this concern for the PFC program.

There is a risk that other NSF-wide programs may supplant the PFCs' unique roles and uproot the underlying need for the PFC program. This is low risk, as there appears to be strong NSF-wide coordination in the design of research funding portfolio opportunities.

VI. Summary

While it is indeed difficult to trace the origins of scientific breakthroughs, the overall conclusion of the subcommittee was that the Physics Frontiers Centers are indeed contributing to major scientific breakthroughs at the frontiers of physics. Section II gave only a small sample of these transformational developments. We noted several advantages of the center format in Section II:

- PFCs Foster Collaborations.
- PFCs enable rapid responses to research developments.
- PFCs provide local oversight over research programs.
- 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 current portfolio of PFCs has a heavy emphasis on quantum computing. Given the current national priority for quantum information science, the National Science Foundation was visionary in its support of this science. A second heavy emphasis is on biophysics. The PFCs have a natural place here with their focus on breaking down barriers to interdisciplinary activities.

Several of the centers have had a major impact in building research communities. These efforts require center-like resources and have paid off handsomely. Examples include the bridges established between the nuclear science, astrophysics and astronomy communities at JINA, the growth of quantitative biology supported by KITP, and the gravitational wave community nurtured by CGWP and NANOGrav. It is essential that the value and appropriate weight be given to these community-building activities in the center selection process.

It is also clear that the centers value their educational, diversity and public outreach activities and are trying to effect positive change. Their hearts are in the right place. However, the subcommittee concludes that the PFCs have not reached their potential in these latter areas. There is a need to approach these from a scholarly perspective and the PFCs would appear to have the resources (that individual investigator grants usually do not) to do this. After 18 years of effort, can we and NSF point to what has been learned?

A large part of the difficulty here lies in the relative weighting by NSF selection panels of the two criteria for NSF proposals, intellectual merit and broader impacts. NSF program officers are reluctant to provide a weighting. They ask the panels to bring their own perspective to this. But if NSF wants the PFC program to be transformational in education, outreach and diversity efforts, this expectation needs to be made clear.

The subcommittee echoes the recommendation of the Committee of Visitors that the PFCs should be laboratories to explore the most effective ways to broaden participation and communicate effectively, but we emphasize the importance of sharing the results.

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.

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.

In conclusion, this report has attempted to emphasize the unique role of the Physics Frontiers Centers in the physics investment portfolio of the nation. The physics return has been outstanding. We believe that the program has the potential to do much more in the areas of enhancing education, diversity, public outreach, and broader impacts, in such a way that lessons learned are communicated to the research and educational communities. With the advantages and the potential of the center concept, we encourage all eligible researchers to consider proposing new centers in response to the solicitations. Yes, the competition is fierce. Yes, one must identify a new, cutting-edge project and assemble a strong collaboration. Yes, one has to present a plan where the community can truly learn from the efforts in broader impacts. All of this takes tremendous effort.

We conclude that these centers are producing major scientific breakthroughs and are stimulating the development of interdisciplinary communities. There is the potential for the PFCs to make significant advances in broader impacts. We expect that the Physics Frontiers Centers program is primed to produce new success stories in the future.

Appendix A: Charge '

National Science Foundation
Directorate for Mathematical and Physical Sciences
Charge to: MPSAC Subcommittee for the Review of the Physics Frontiers Centers Program

The NSF Physics Division's Physics Frontiers Centers (PFC) program is designed to foster major breakthroughs at the intellectual frontiers of physics by providing needed resources such as combinations of talents, skills, disciplines, and/or specialized infrastructure, not usually available to individual investigators or small groups, in an environment in which the collective efforts of the larger group can be shown to be seminal to promoting significant progress in the science and the education of students. PFCs are expected to demonstrate potential for profound advances in physics; creative and substantive activities aimed at enhancing education, diversity, and public outreach; potential for broader impacts, e.g., impacts on other fields and benefits to society; and a synergy or value-added that justifies a center- or institute-like approach.

The PFC program was initiated in 2001. Over its 17-year history, 15 centers or institutes have been awarded PFC funding and, of these, 6 have been phased out. Since 2008 open competitions for new and renewing centers have been held every three years. The PFC program is open to any subfield of physics within the purview of the NSF Physics Division and PFCs have been awarded in almost all subfields: atomic, molecular, optical, plasma, elementary particle, nuclear, astro-, gravitational, and biological physics. As the PFCs address frontier science, their scope often extends beyond the programmatic boundaries of the Division and significant partnerships with other divisions have been established to support these centers.

The Physics Division's Committees of Visitors have recommended a review of the program: "We believe that the Center program would benefit from a dedicated comprehensive review by a high-level body with the time, access and expertise to evaluate the PFC program. One would like independent confirmation that the PFCs add value in a way that individual investigator grants do not." After nearly 2 decades of PFCs, the Physics Division agrees that this is an excellent time to evaluate the impacts and effectiveness of the program.

This MPS subcommittee is 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. In particular, the subcommittee should assess how well the PFC program is enabling advances in the following areas in ways that are distinct or best accomplished in a center structure:

Advancing the frontiers of Physics

- a. How well is the PFC program contributing to major scientific breakthroughs?
- b. Has the PFC program had significant impacts on Physics or related fields?

Enhancing education, diversity, public outreach, and broader impacts

a. In what ways is the program enabling unique or enhanced educational experiences for students and postdoctoral fellows?
b. In what ways is the program contributing significantly to broadening participation of traditionally underrepresented groups?
c. In what ways is the program enabling substantive outreach to the general public?
d. Are there other broader impacts of the PFC program?

The subcommittee should conduct an independent assessment of the PFC program as a whole and not perform in-depth evaluations of each center. Rather than providing specific recommendations, the subcommittee should identify strengths and weaknesses of the PFC program and issues that the Division can address in developing and evolving the program. The subcommittee will not review the PFC proposal review and selection process or the program funding levels, which are regularly reviewed by the Division's Committee of Visitors.

Timeline: Charge Delivered to MPSAC: May 2018
Interim Report Due to MPSAC: April 2019
Final Report Due to MPSAC: June 2019

We would appreciate an interim report from the Subcommittee to the MPSAC in April of 2019, and a final report delivered to the MPSAC in June of 2019. The interim report will detail progress and interim (draft) findings. The final written report will be due no later than June 30, 2019. The Chair of the subcommittee should coordinate delivery of materials with the MPSAC Chair in advance of scheduled MPSAC meetings. Presentations to the MPSAC may be delivered remotely or in person and will be coordinated by the MPSAC.

The Subcommittee will terminate once MPSAC as accepted the final report and determined that no further edits or substantive changes need to be made by the subcommittee.

Resources

NSF will arrange for and host in-person or virtual meetings of the subcommittee as required by the Chair.

Appendix B: Membership of the Subcommittee '

Name	Institution	Primary Area of Expertise
Dan Gauthier	Ohio State University	Quantum Information Systems
Donald Geesaman (Chair)	Argonne National Laboratory	Nuclear Physics
Graciela Gelmini	University of California -Los Angeles	Particle Astrophysics/Cosmology
Gabriela Gonzalez	Louisiana State University	Gravitational Physics
David Kieda	University of Utah	Particle Astrophysics
Susan Marqusee	University of California - Berkeley	Biophysics
Patricia McBride	Fermi National Accelerator Laboratory	Particle Physics
Mark Saffman	University of Wisconsin - Madison	Atomic, Molecular and Optical Physics/Quantum Information Systems
Marc Sher	College of William and Mary	Particle Physics
Anthony Starace	University of Nebraska - Lincoln	Atomic, Molecular and Optical Physics
Edward Thomas	Auburn University	Plasma Physics
Stamatis Vokos	CalPoly – San Luis Obispo	Physics Education
Neal Woodbury	Arizona State University	Biophysics
William Zajc (member of MPSAC)	Columbia University	Nuclear Physics

Susan Seestrom of Sandia National Laboratory was an original member of the subcommittee but had to resign over the course of the subcommittee deliberations.