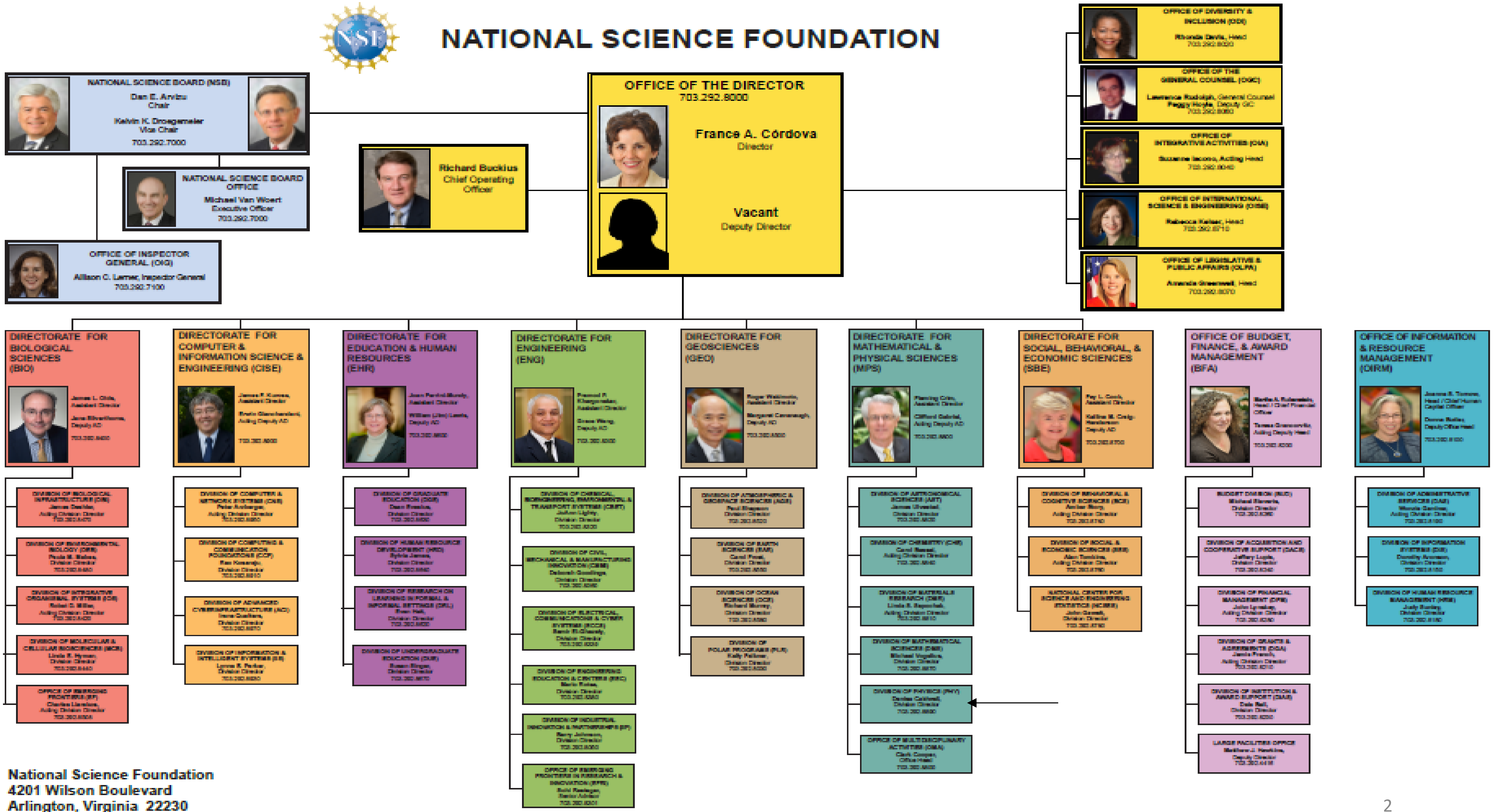
Astrophysics in the NSF Physics Division

C. Denise Caldwell
Division Director

With input from Jean Cottam, Jim Whitmore, Keith Dienes, Pedro Marronetti, Mark Coles, Allena Opper, and Slava Lukin

AAAC January 2016



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Division of Physics – 2017

Denise Caldwell, DD

Brad Keister, DDD

Atomic, Molecular, Optical & Plasma Physics
Gillaspy (F); Lukin (T); Cronin (I)

Interactive Activities in Physics
(REU Sites, MRI, CAREER, BP org) McCloud (F)

Elementary Particle Physics; LHC
Shank (I); Gonzalez (F); Ruchti (E); Coles (F)

Particle Astrophysics; IceCube
Whitmore (F); Cottam (F)

Physics at the Information Frontier
(QIS, Computational Physics, CDS&E)
Cronin (I); Mihaila (F)

Gravitational Physics; LIGO, AdvLIGO
Marronetti (F); Coles (F)

Nuclear Physics; NSCL
Opper (F); Garcia (I)

Theoretical Physics
(AMO, Nuclear, EPP, AC)
Cavagnero (I); Mihaila (F); Dienes (V)

Physics of Living Systems
Blagoev (F)

Physics Frontiers Centers
Cottam (F); McCloud (F)

Accelerator Science
Shank (I); Gonzalez (F); Lukin (T)

Mid-Scale Instrumentation, Coles, Science Advisor

Physics Division Portfolio

The portfolio of awards made through the Physics Division has as primary goal “to promote the progress of science”, as expressed in the NSF act. Awards in the portfolio support the research needed to address a scientific question that is at the frontier of knowledge as it is currently known, while at the same time extending and redefining that frontier. Inherent in the implementation of this portfolio, which includes significant support for students and junior scientists, is the preparation of the next generation of the advanced high tech workforce and the development of innovative new technologies that arise in the quest to answer some of the hardest questions that Nature can pose.

Implementation:

Begin with new ideas generated by the physics community

Inform the process through workshops, input from advisory committees, proposal reviews, and the scientific expertise of the Program Directors

Five Perspectives on the Frontiers of Physics

Controlling the Quantum World– Electromagnetic radiation in the non-classical limit, Entanglement, Cavity QED, QIS, Optomechanics

Complex Systems and Collective Behavior – Living cells, biological systems, ultracold fermions and bosons, quark-gluon liquid

Neutrinos and Beyond the Higgs – Neutrino mass, new particles, unification of quantum mechanics and gravity, electron and neutron dipole moments

Origin and Structure of the Universe – Star formation and creation of the elements, dark matter and dark energy, modeling of black holes, gravitational waves

Strongly-Interacting Systems– QCD computations, quark structure of baryons, high-field laser-matter interactions, supernovae, strong gravity

Questions Cut Across Disciplinary Programs

Controlling the Quantum World: Optical Physics; Quantum Information Science

Complex Systems and Collective Behavior: Physics of Living Systems; Atomic and Molecular Dynamics; Nuclear Physics; Plasma Physics

Neutrinos and Beyond the Higgs: Particle Astrophysics; Gravitational Physics; Nuclear Physics; Precision Measurements; Elementary Particle Physics

Origin and Structure of the Universe: Gravitational Physics; Nuclear Physics; Particle Astrophysics; Plasma Physics

Strongly-Interacting Systems: Nuclear Physics; Gravitational Physics; Plasma Physics

Era of Gravitational Wave Astrophysics

Direct Detection of Gravitational Waves

Binary Black Hole – Black Hole mergers

<u>Event GW150914</u>

Original black holes:

29 and 36 solar masses ($M_{\odot}$).

Final black hole:

62 $M_{\odot}$ with dimensionless spin 0.67

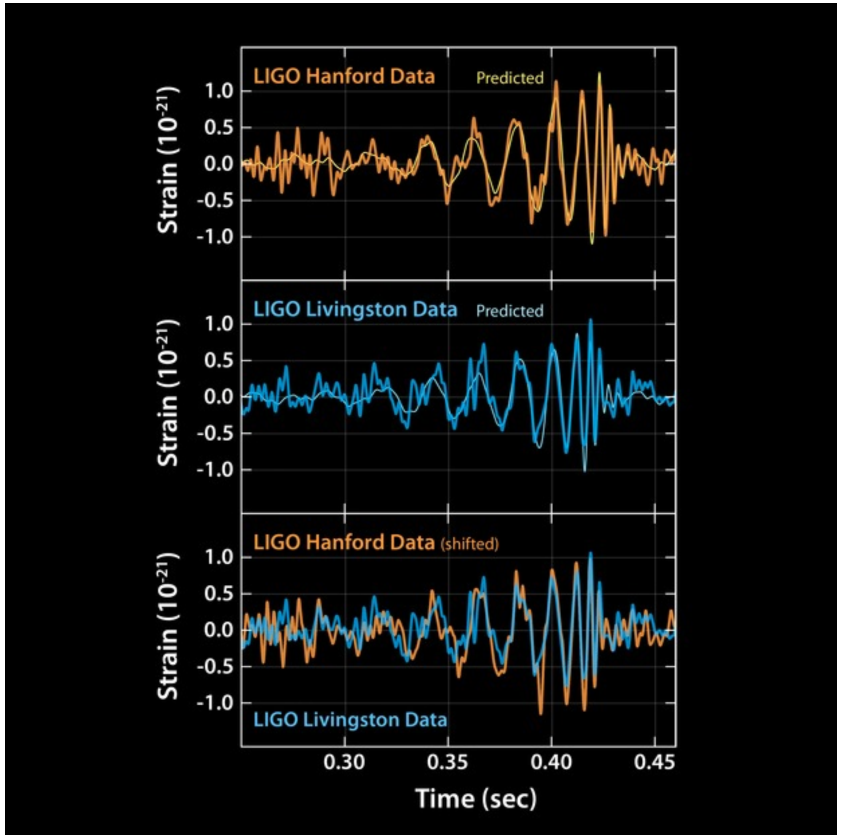
<u>Event GW151226</u>

Original black holes:

14 and 7.5 solar masses ($M_{\odot}$).

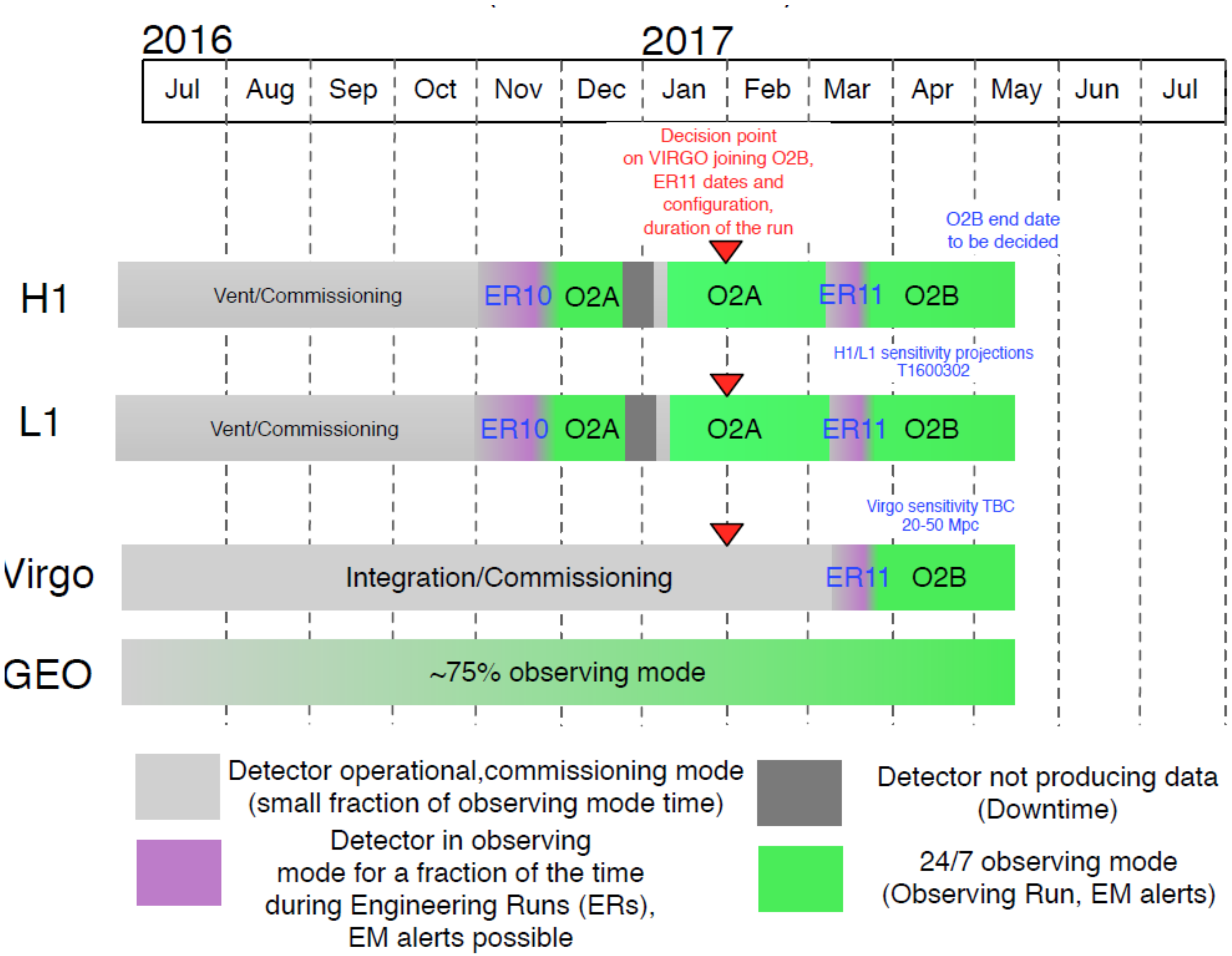
Final black hole:

20.8 $M_{\odot}$ with one component spin >0.2



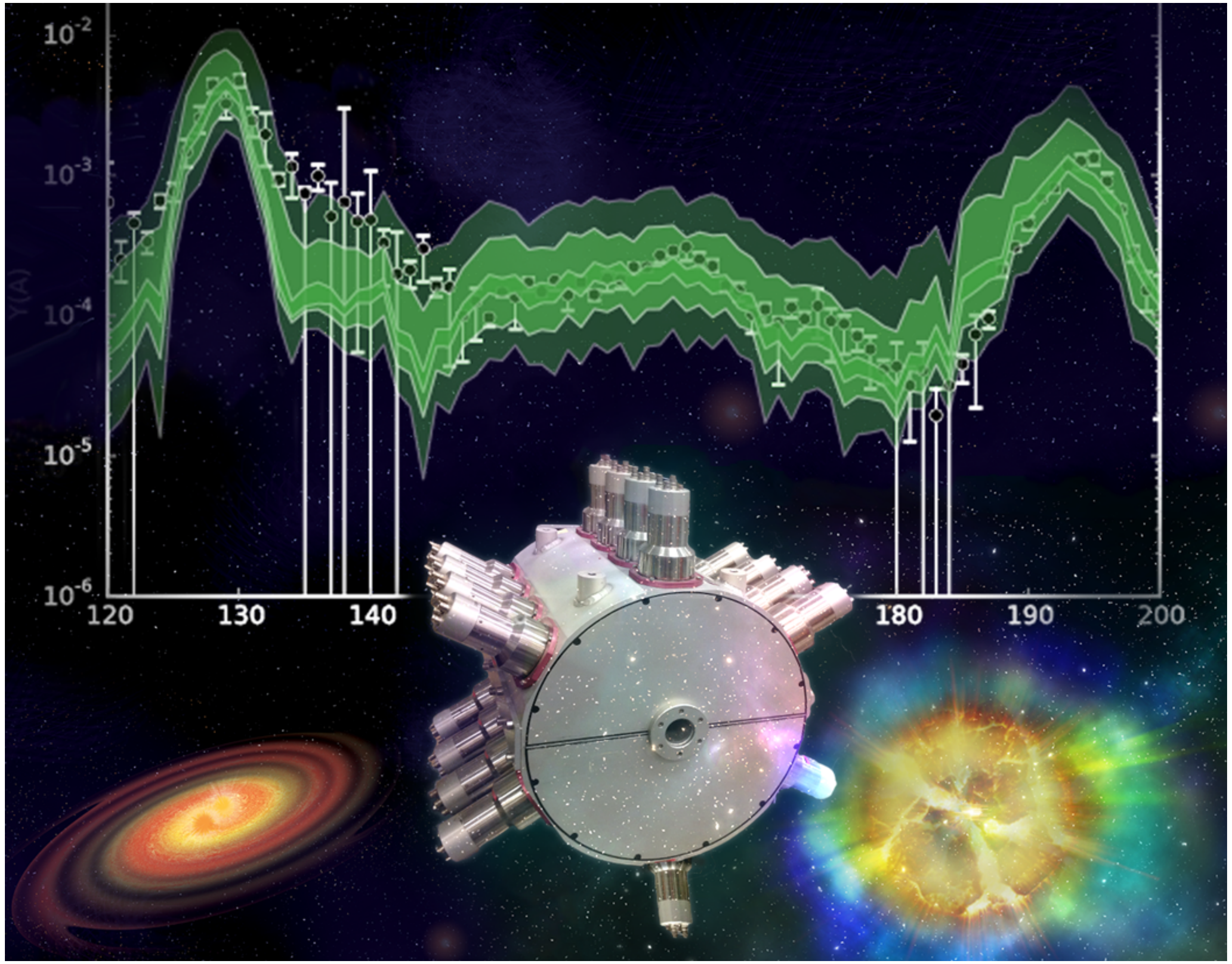
LIGO is preparing for the second scientific observation run after Advanced LIGO upgrade (O2)

- O2 begins first week of December 2016
- After a holiday break, O2 continues during spring 2017
- LIGO sensitivity is expected to be 10% to 30% greater than first run (1.3 to 2.2 increase in event rate)
- Virgo operation planned to overlap with LIGO in spring 2017. Virgo sensitivity TBD



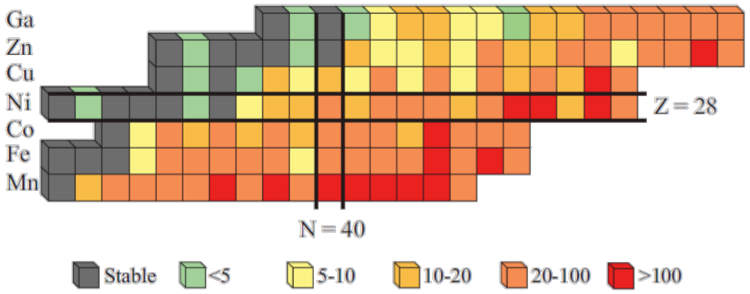
Credit: LIGO Lab

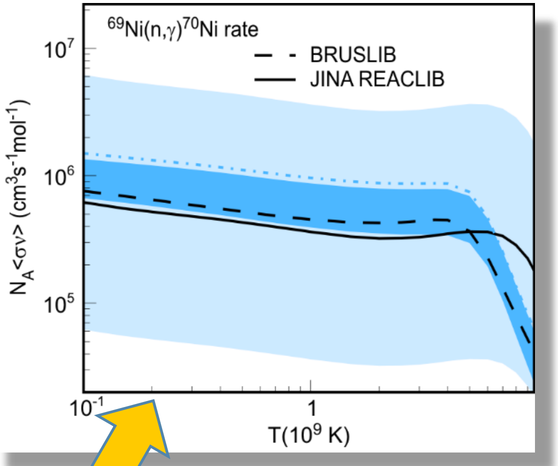
Connecting astrophysics and low-energy nuclear physics

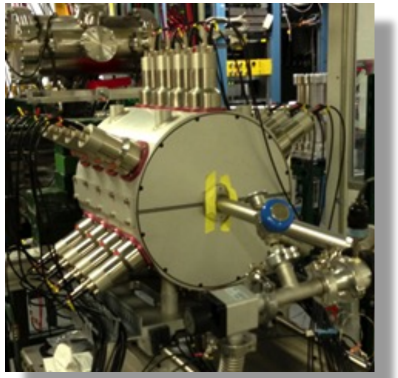


New work at NSCL: constrains neutron capture rates – key to modeling stellar explosions

- The abundance pattern from stellar events encodes the underlying physics.
- Nuclear reaction rates needed to test r-process models against observations
- Color = uncertainty of neutron-capture rates. Most key reactions are far from stability

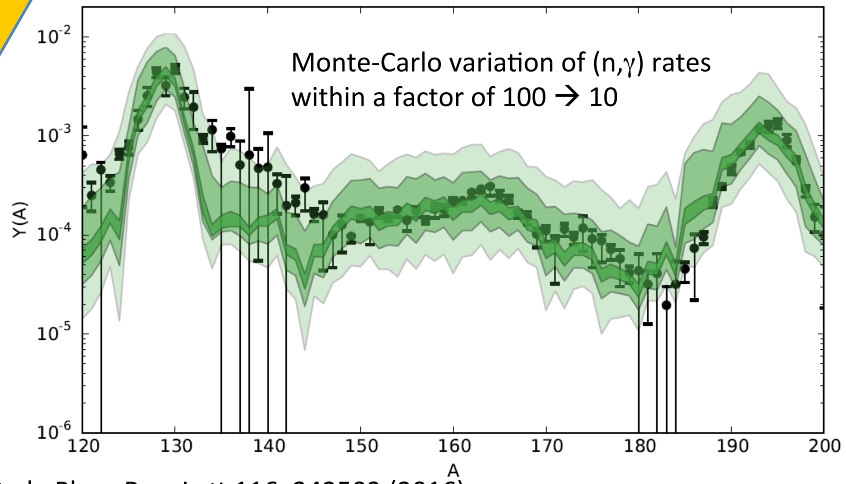






SuN detector at NSCL

- New technique using γ-ray calorimetry developed by MSU and Univ of Oslo using SuN detector at NSCL used to extract ^{69}Ni(n,γ)^{70}Ni.
- Uncertainty now approximately 2-3 (dark blue band) – achievable for rare isotopes far from stable
- Accurate rates allow model comparisons. With error of 2-3 dark green band is possible

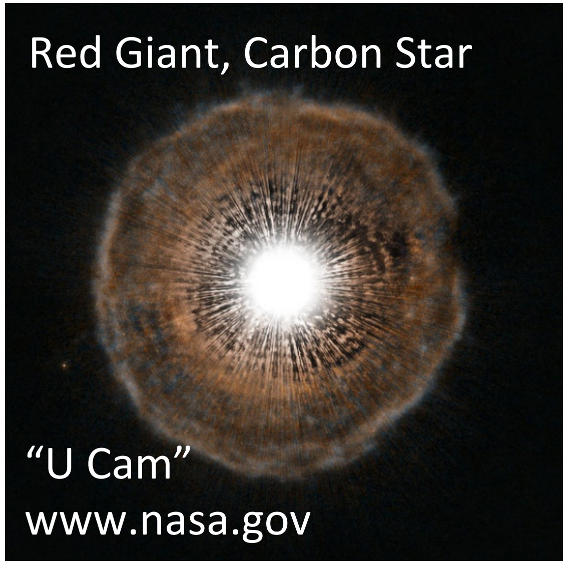


S.N. Liddick, A. Spyrou et al., Phys. Rev. Lett 116, 242502 (2016)

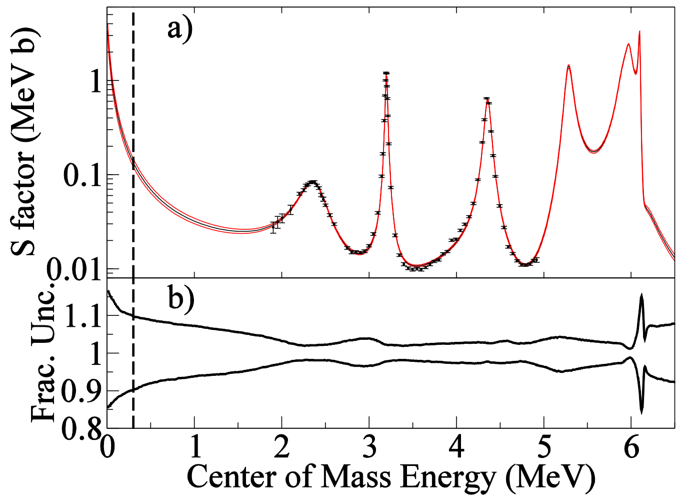
http://physics.aps.org/synopsis-for/10.1103/PhysRevLett.116.242502

The $^{12}C(\alpha, \gamma)^{16}O$ reaction and stellar helium burning

- $^{12}C(\alpha, \gamma)^{16}O$ reaction determines ^{12}C:^{16}O in the universe
  - building blocks of organic life and the fuels for stars in the later stages of their evolution
- Comprehensive *R*-matrix analysis to fit an unprecedented amount of experimental nuclear physics data →
  - constrain the $^{12}C(\alpha, \gamma)^{16}O$ cross section
  - investigate uncertainties stemming from data and model



Monte Carlo Uncertainty analysis



R.J. deBoer *et al.*, RMP (submitted to journal)

Experimental Particle Astrophysics (PA)

Particle Astrophysics – Cosmic Phenomena:

This area supports university research that uses astrophysical sources and particle physics techniques to study fundamental physics. This includes the study of ultra-high energy particles reaching Earth from beyond our atmosphere (cosmic-rays, gamma-rays, and neutrinos with the exception of IceCube); searches for supernova neutrinos; and studies of the Cosmic Microwave Background (CMB) and Dark Energy.

Particle Astrophysics – Underground Physics:

This area supports university research that generally locates experiments in low background environments. Currently supported activities include: studies of solar, underground and reactor neutrinos; neutrino mass measurements; and searches for the direct detection of Dark Matter.

Particle Astrophysics – IceCube Research Support:

This area supports university research that utilizes the facilities of IceCube at the South Pole. Currently supported activities include: searches for ultra-high energy neutrinos and studies of the properties of neutrinos.

Also Strong Theoretical Program in Theoretical Astrophysics and Cosmology

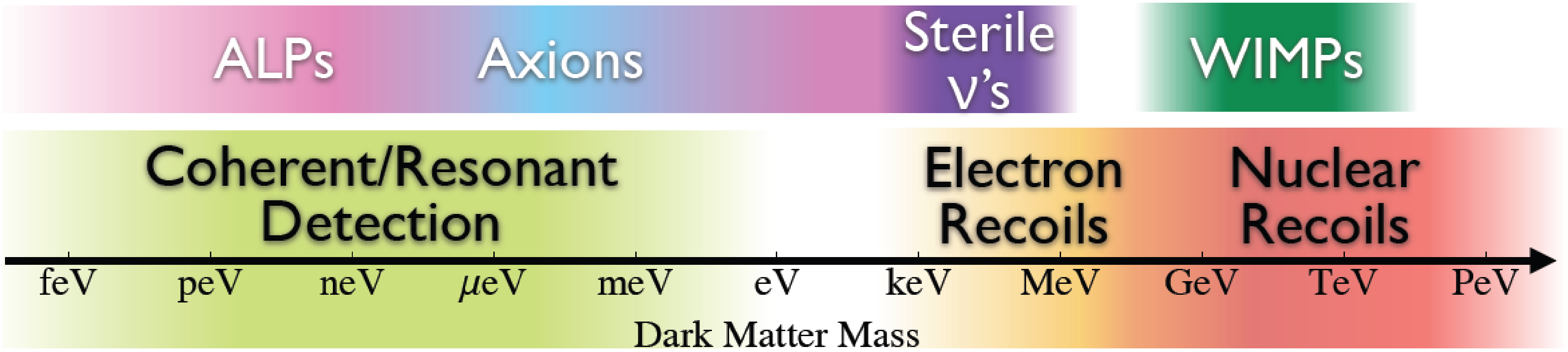
PA Program Scope & Currently Supported Projects

- Direct Dark Matter Detection – WIMP and non-WIMP experiments
  SuperCDMS at SNOLAB, XENON100/1T, LUX, DArkSide, PICO, DRIFT, DM-Ice, SABRE, DAMIC, ADMX-HF, ALPS2 and DM-GPS
- Indirect Dark Matter Detection
  VERITAS, HAWC, IceCube
- Cosmic Ray, Gamma Ray, and UHE Neutrino Observatories
  IceCube, VERITAS, HAWC, Auger, Telescope Array, ARA, ARIANNA
- Cosmic Microwave Background
  SPT, ACT-Pol (w/ Gravity)
- Neutrino Properties
  Double Chooz, Daya Bay, Project 8, IceCube, IsoDAR
- Solar, Geo- and SuperNova Neutrinos
  Borexino, SNEWS
- Planck Scale Physics
  Holometer
- Detector R&D
  NaI/CsI, LiSc/QD

AST

Polar Programs

Dark Matter Candidates



ARIADNE

ADMX-HF

←--- ALPS-IIc ----→

IsoDAR

XENON-100/1T

DArkSide-50

Super-CDMS@SNOLab

SABRE

COSINE-100

Dark Matter

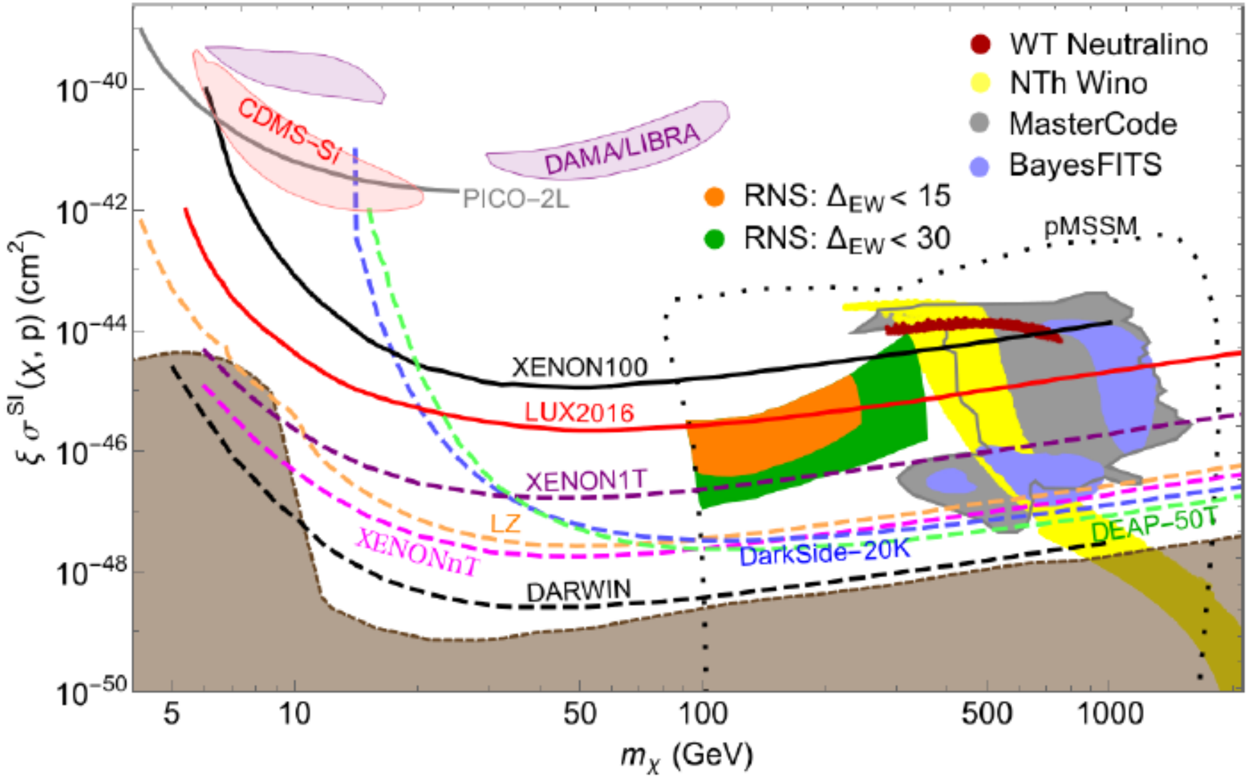


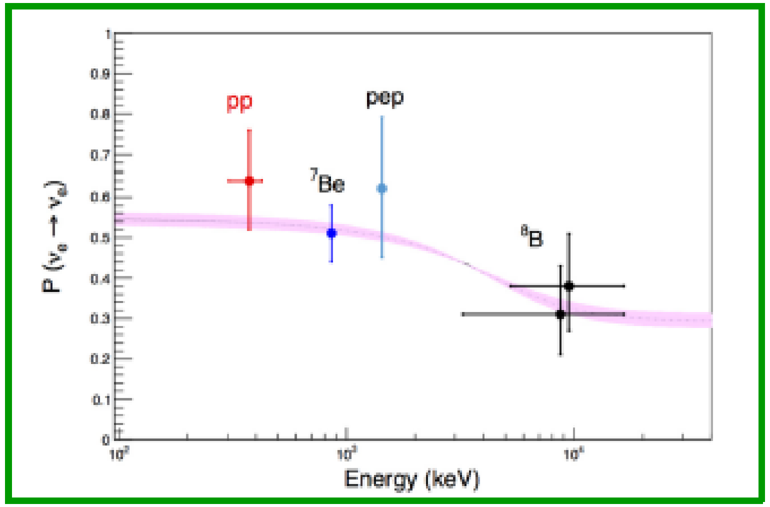
Figure 1: Plot of rescaled spin-independent WIMP detection rate $\xi\sigma^{SI}(\chi, p)$ versus m_χ from several published results versus current and future reach (dashed) of direct WIMP detection experiments. $\xi = 1$ for all models except RNS and pMSSM.

"Projections from ton-scale noble liquid detectors should discover or rule out WIMPs from the remaining parameter space of these surviving models." Baer et al., arXiv:1609.06735v2, Sept 2016

BOREXINO

Solar Neutrino: Published Results

Species	Rate [cpd/100t]	Flux [$cm^{-2}s^{-1}$]
^{7}Be (863 keV)	$46.0 \pm 1.5 ^{+1.5}_{-1.6}$	$3.1 \pm 0.15 \times 10^{9}$
pep	$3.1 \pm 0.6 \pm 0.3$	$1.6 \pm 0.6 \times 10^{8}$
CNO	< 7.9 (95% CL)	7.7×10^{8}
^{8}B(> 3 MeV)	$0.22 \pm 0.04 \pm 0.01$	$2.4 \pm 0.4 \pm 0.1 \times 10^{6}$
pp	$144 \pm 13 \pm 10$	$6.6 \pm 0.7 \times 10^{10}$



P_{ee} survival probability in the MSW-LMA scenario with Borexino data only!

Plasma Astrophysics

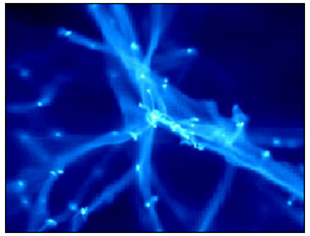
- 99.9% of the visible Universe consists of fully or partially ionized plasmas. Plasma physics processes are known or conjectured to be responsible for:
  - Magnetization from cosmic to planetary scales
  - Cosmic rays and solar energetic particles
  - Extragalactic gamma ray bursts, stellar and solar flares
  - Etc, etc…

- In cooperation with NSF/AST, NSF/AGS and DOE/SC/FES, PHY has provided continuous support for synergetic observation, theory, modeling and laboratory experiments in the area of plasma astrophysics:
  - NSF/DOE Partnership for Basic Plasma Science and Engineering [Workshop to celebrate 20 years of the Partnership in January, 2017]
  - Center for Magnetic Self-Organization (Physics Frontier Center: 2005-2016) [PI: Ellen Zweibel (U. Wisconsin)]
  - Max-Planck-Princeton Center for Fusion and Astro Plasma Physics (2012-*present*) [PI: Jim Stone (Princeton U.)]
  - Several MRI awards to enable laboratory plasma astrophysics research

Plasma Astrophysics

- There is also ongoing formal and informal cooperation with various parts of NASA:
  - IAA between NSF and NASA/HEOMD regarding cooperation in support of dusty plasma research on the Plasma Krystal – 4 (PK-4) facility on board the International Space Station signed in January, 2016; joint NASA/NSF solicitation issued in May, 2016 with proposals submitted in August, 2016 currently under review;
  - Due to significant grey area of overlapping scope [particularly in theory and modeling] between work supported by the NSF/DOE Plasma Partnership and the NASA/Heliophysics & NASA/Astrophysics, frequent communication and cooperation between NSF and NASA is necessary for proper stewardship of the field. At this time, there is no formal mechanism for such cooperation.
  - In response to the OSTP's two recent initiatives: the National Strategic Computing Initiative (July, 2015) and the National Space Weather Strategy & Action Plan (October, 2015), there is an ongoing conversation about closer cooperation between NSF/MPS, NSF/CISE, NSF/GEO and NASA/SMD.

Physics Frontiers Centers



Kavli Institute for Cosmological Physics – Chicago - Turner (PHY/OPP)

Joint Institute for Nuclear Astrophysics – Center for the Evolution of the Elements – Michigan State/Notre Dame - Schatz

North American Nanohertz Observatory for Gravitational Waves – U Wisconsin/Milwaukee – Siemens – (PHY/AST)

Kavli Institute for Theoretical Physics – UCSB – Bildsten (Joint MPS/PHY/AST/DMR and BIO/MCB)

Partnerships

Premium on Partnerships driven by Strong Intellectual Overlap

NSF Facilities: IceCube (GEO/PLR;MPS/PHY)

NSF Physics Frontiers Centers: NanoGrav (MPS/PHY/AST); KICP (MPS/PHY;GEO/PLR);
KITP (MPS/PHY/AST/DMR;BIO/MCB)

NSF Large Experiments: SPT, ACT, CMB, etc.

DOE: LHC, SuperCDMS, HAWC, Plasma Partnership, etc.

International: LHC, XENON1T, VIRGO, IceCube, etc.

Part of "Windows on the Universe" Big Idea

Invest when PHY funds have significant impact