Astrophysics in the NSF Physics Division

A Snapshot

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Division Director

With input from Jean Cottam, Jim Whitmore, Keith Dienes,
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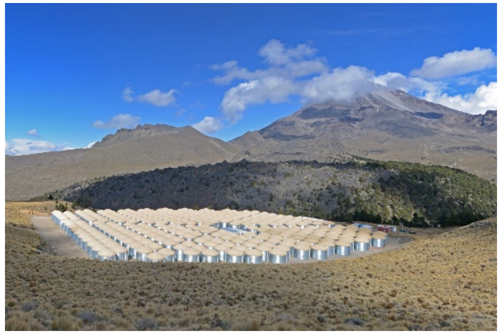


Credit: HAWC

Credit: IceCube

Credit: LIGO Lab

AAAC January 2021

Perspectives on the Frontiers of Physics

Controlling the Quantum World– Electromagnetic radiation in the non-classical limit, Entanglement, Cavity QED, QIS, Optomechanics (Optical Physics; Quantum Information Science)

Complex Systems and Collective Behavior – Living cells, biological systems, ultracold fermions and bosons, quark-gluon liquid (Physics of Living Systems; Atomic and Molecular Dynamics; Nuclear Physics; Plasma Physics)

Neutrinos and Beyond the Higgs – Neutrino mass, new particles, unification of quantum mechanics and gravity, electron and neutron dipole moments (Particle Astrophysics; Gravitational Physics; Nuclear Physics; Precision Measurements; Elementary Particle Physics)

Origin and Structure of the Universe – Star formation and creation of the elements, dark matter and dark energy, modeling of black holes, gravitational waves, magnetic fields (Gravitational Physics; Nuclear Physics; Particle Astrophysics; Plasma Physics)

Strongly-Interacting Systems– QCD computations, quark structure of baryons, high-field laser-matter interactions, supernovae, strong gravity (Nuclear Physics; Gravitational Physics; Plasma Physics)

PHY Budget Status

?

FY 2020 Actual	Not Yet Released
FY 2021 Current Plan	Under Development
FY 2022 Request	Under Development

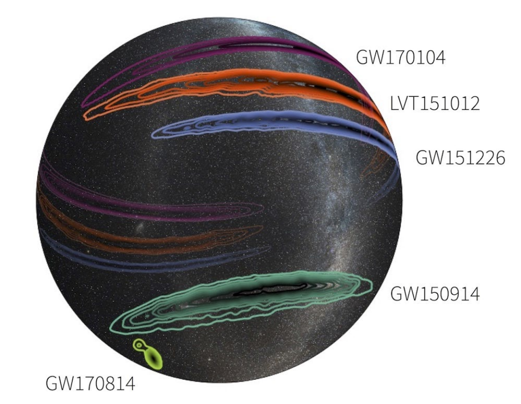
LIGO - Virgo Observation Run 3 (O3)

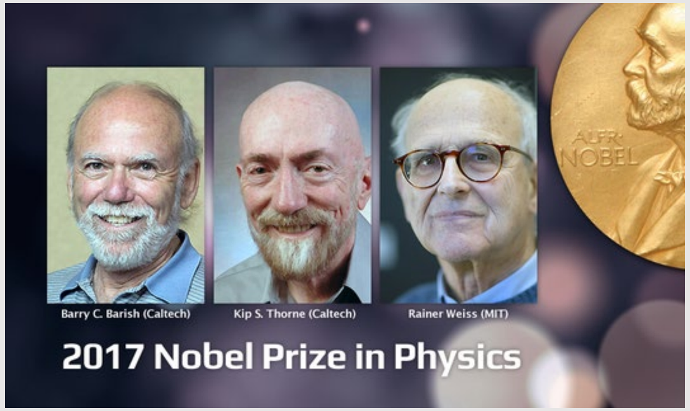
The 3rd Observational Run (O3) started in April 2019 and ended in March 27, 2020, a month shorter than planned due to the pandemic.

Its first part (O3a) ended at the end of September 2019 and, after a month-long break for maintenance and upgrades, the second part (O3b) started on November 1, 2019.

O3 produced 56 non-retracted public alerts (about a GW event per week).

No EM counterparts have been reported.



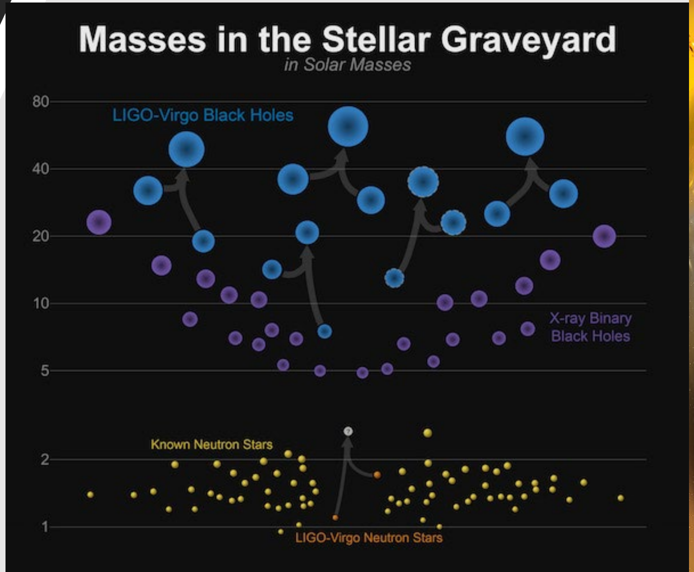


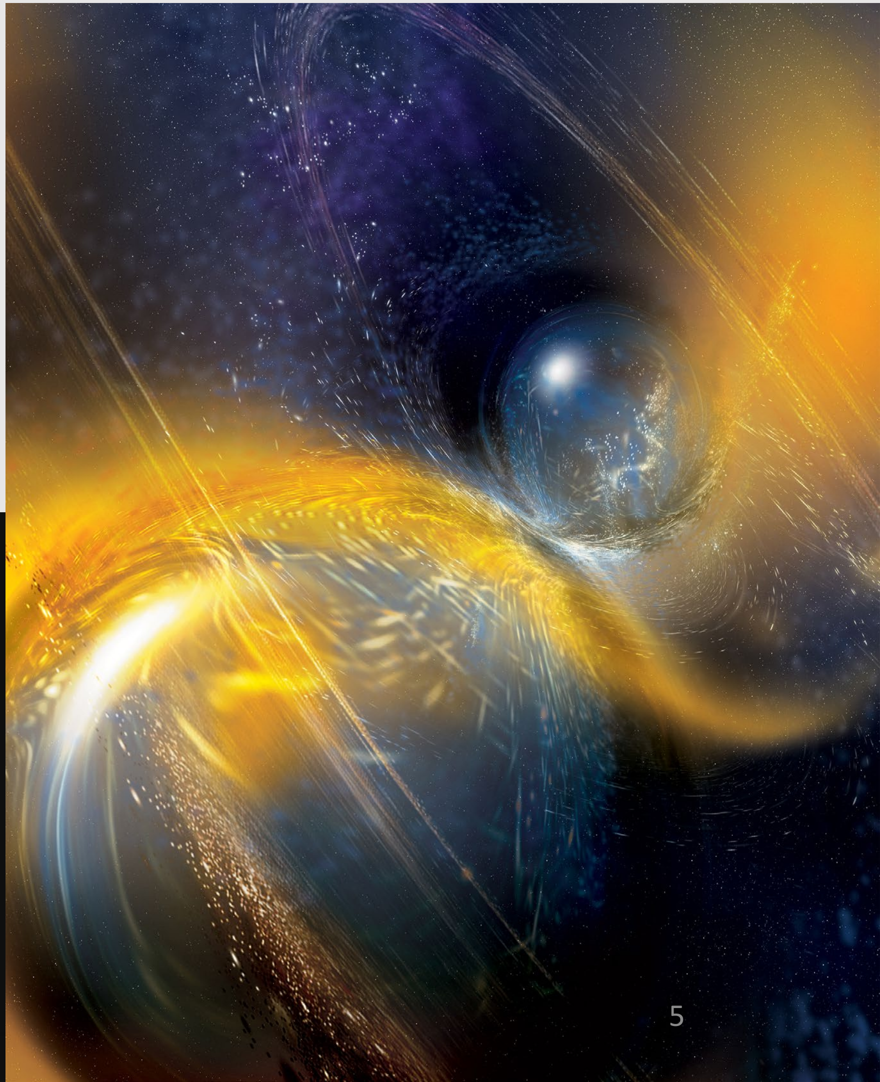
LIGO - Virgo O3 Highlights

Several "exceptional" GW events detected in O3a have been published:

2^{nd} Neutron Star Merger (GW190415, ApJL 892 (2020) L3)

- Very distant (500 Mly). No EM counterpart
- Total binary mass (3.4 $M_{\odot}$) larger than any known galactic NS binary (17 have been detected with a Maximum mass of 2.9 $M_{\odot}$)





LIGO - Virgo
O3 Highlights

The object in the "mass gap" (GW190814, *ApJL 896 (2020) L44)*

Binary with a 23 $M_{\odot}$ BH and a 2.6 $M_{\odot}$ object

The most extreme mass ratio (9!)

No EM counterpart

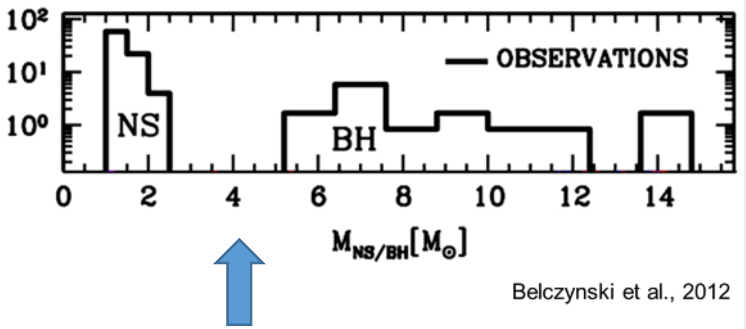
Not clear if the small object is a black hole or a neutron star

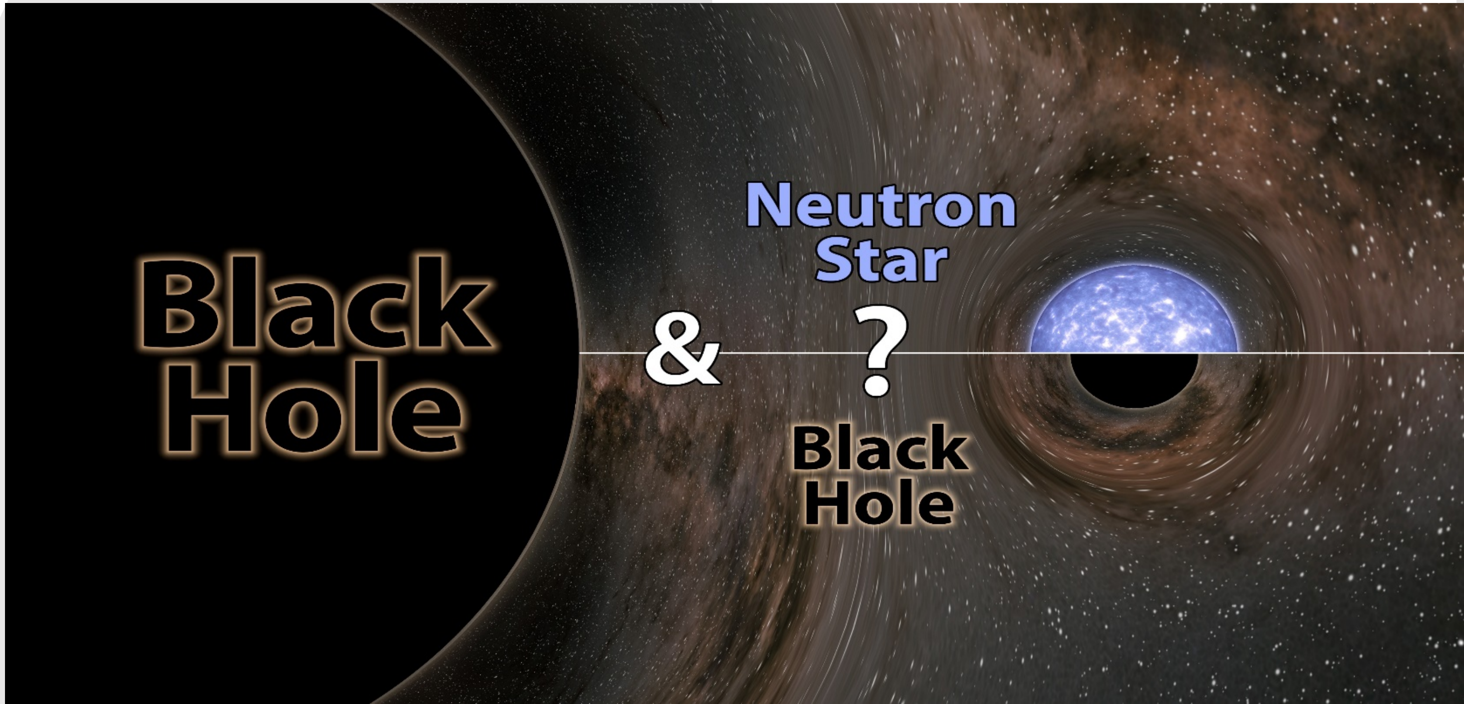
If NS: First BH/NS detected and

Heaviest NS ever observed

If BH: Lightest BH ever observed

Low mass gap:
~2.5 to 5 $M_{\odot}$



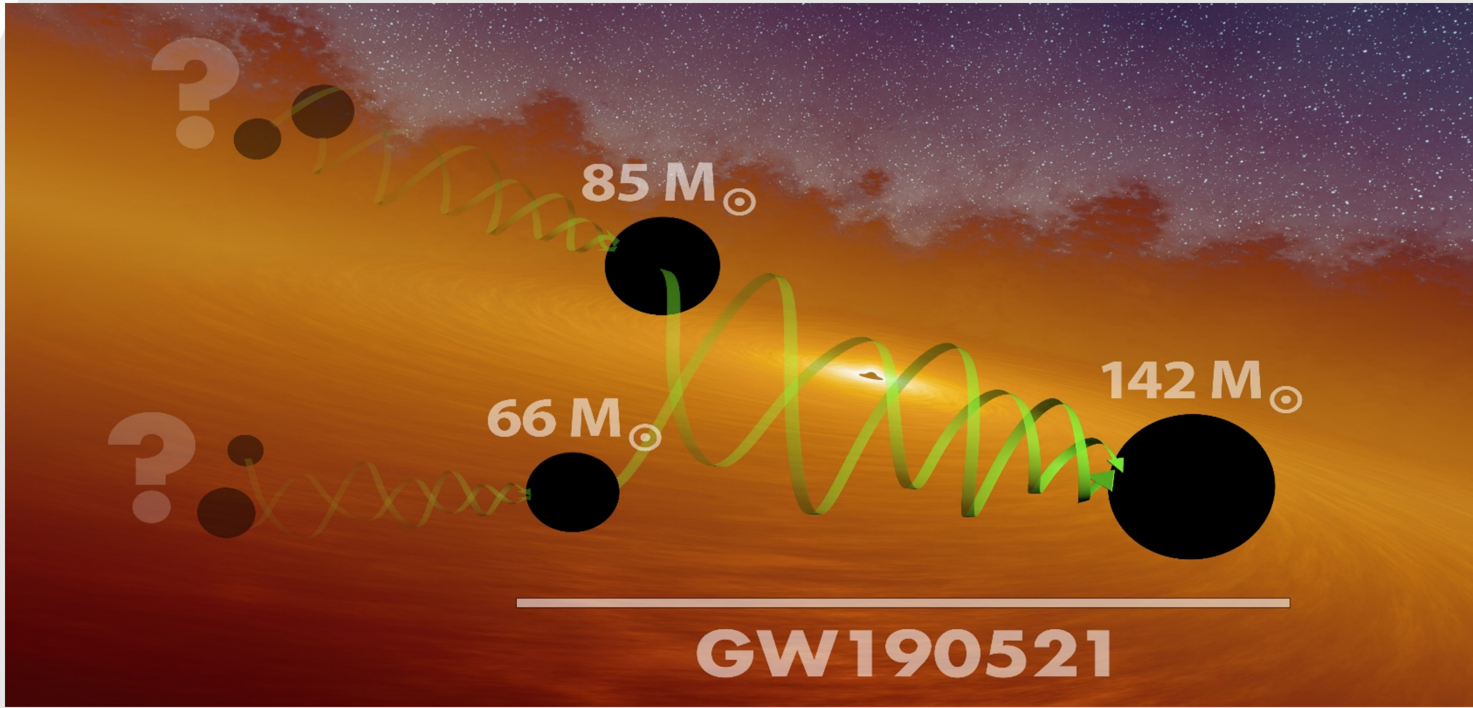


LIGO - Virgo O3 Highlights

The most massive BH binary yet (GW190521, *PRD 125 (2020) 101102)*

- Binary with a 66 $M_\odot$ BH and a 85 $M_\odot$ BH merge to create a 142 $M_\odot$ monster
- One (or two) BH found in the high mass gap
- The heaviest BH (not counting the supermassive BH at galactic centers)
- The merger created the first intermediate mass BH ever observed
- The most powerful explosion detected since the Big Bang: 8 $M_\odot$!

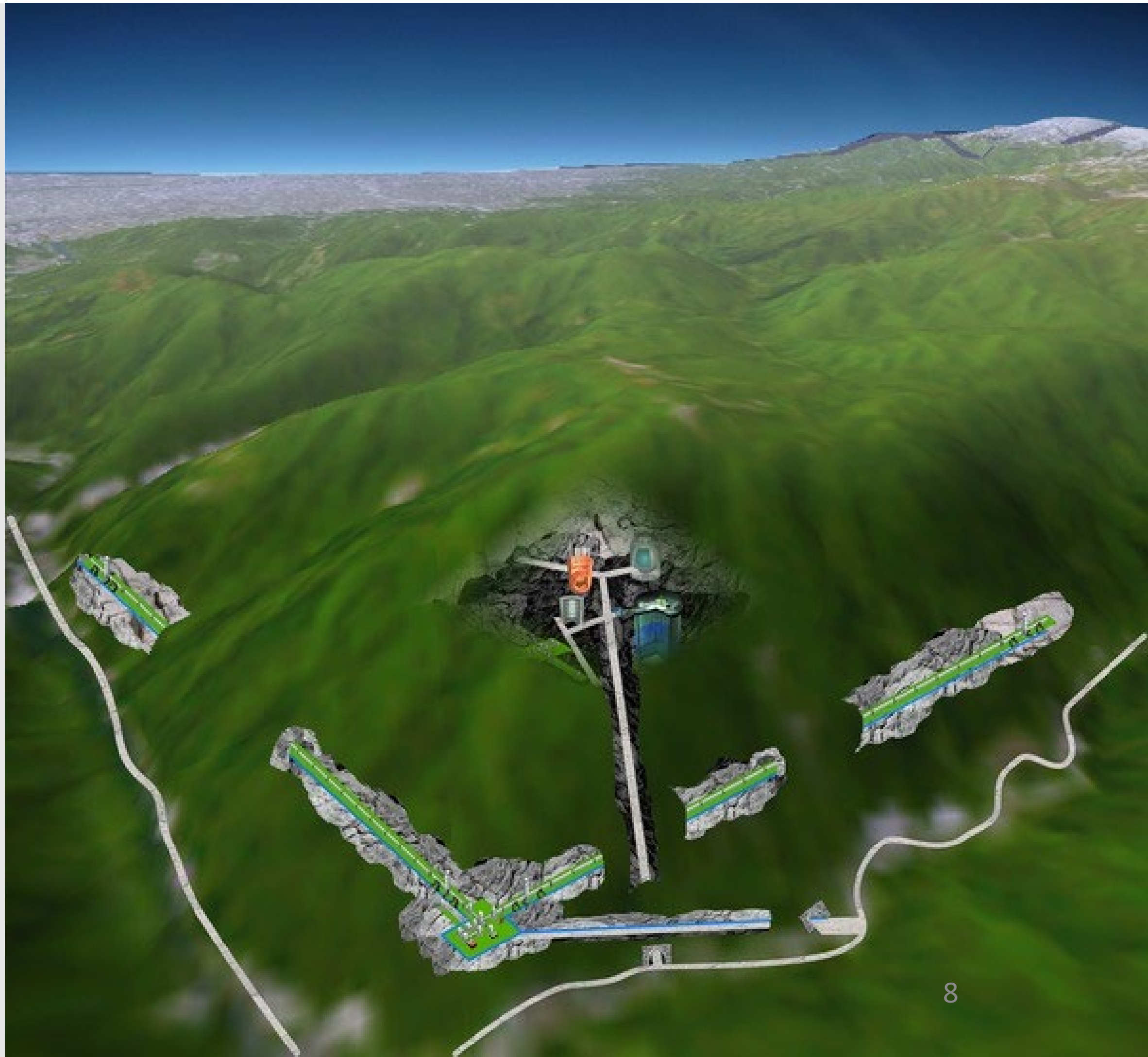
High mass gap: ~65 to 120 $M_\odot$



LIGO – Virgo News and Upgrades

LIGO is now preparing for a fourth observing run, possibly as early as June 2022, depending on COVID impacts on the schedule. Detector improvements now being implemented are expected to improve sensitivity by at least 25%.

LIGO continues the development of the upgrade known as A+, funded by NSF, UKRI and ARC in 2018. A+ is expected to be fully operational by 2024, increasing Advanced LIGO sensitivity by 70%.

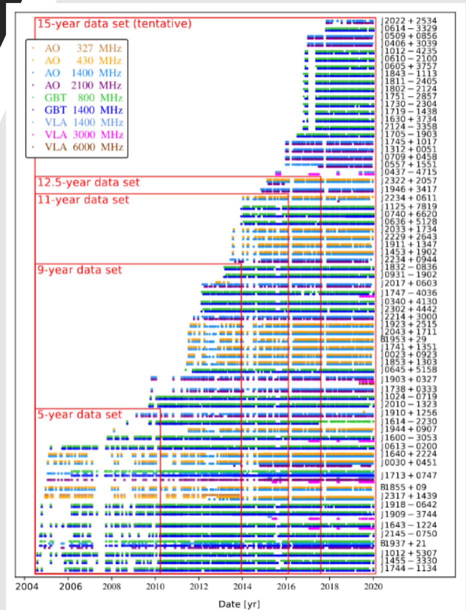


An illustration of the underground KAGRA gravitational-wave detector in Japan. [Image credit: ICRR, Univ. of Tokyo.]

NANOGrav (Physics Frontier Center)

The Nanohertz Observatory for Gravitational Waves (NANOGrav) presented results from the analysis of the 12.5-year catalog.

These show “first hints” of low-frequency gravitational wave background (ApJ Suppl. 252, 5 (2021)) obtained from the analysis of 47 millisecond pulsars data.



Physics Frontiers Centers (PFC)

Supports university-based centers and institutes where the collective efforts of a larger group of individuals can enable transformational advances in the most promising research areas.

Designed to foster major breakthroughs at the intellectual frontiers of physics by providing needed resources 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.

Supports all sub-fields of physics within the purview of the Division of Physics as well as interdisciplinary projects when the bulk of the effort falls within one of those areas within the purview of the Division of Physics.

The successful PFC activity 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.

See US NSF - MPS - PHY - Physics Frontiers Centers (PFC)

Physics Frontiers Centers – New in FY 2020

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

University of California Berkeley

This PFC, based at UC Berkeley, is a collaboration of theorists who utilize astrophysical observations to answer some of the most important open questions in physics and multi-messenger astrophysics. The Center has the potential to influence the future directions of nuclear, particle, and astrophysics. The new generation of postdoctoral researchers that N3AS-PFC is training and the diverse group of students it recruits and engages through a new program for transfer students from local community colleges will be crucial to both current research and the development of the STEM workforce.

The Center for Matter at Atomic Pressures (CMAP)

University of Rochester

This University of Rochester based center brings together a diverse team, spanning disciplines from plasma physics, condensed matter, and atomic physics, to astrophysics and planetary science to study matter under extreme conditions and address critical gaps in our understanding of most of the atomic and chemical constituents of the Universe. CMAP's research, education and outreach programs aim to bring a new understanding of the universe to the public and inspire and engage a new generation of scientists of all ages and backgrounds.

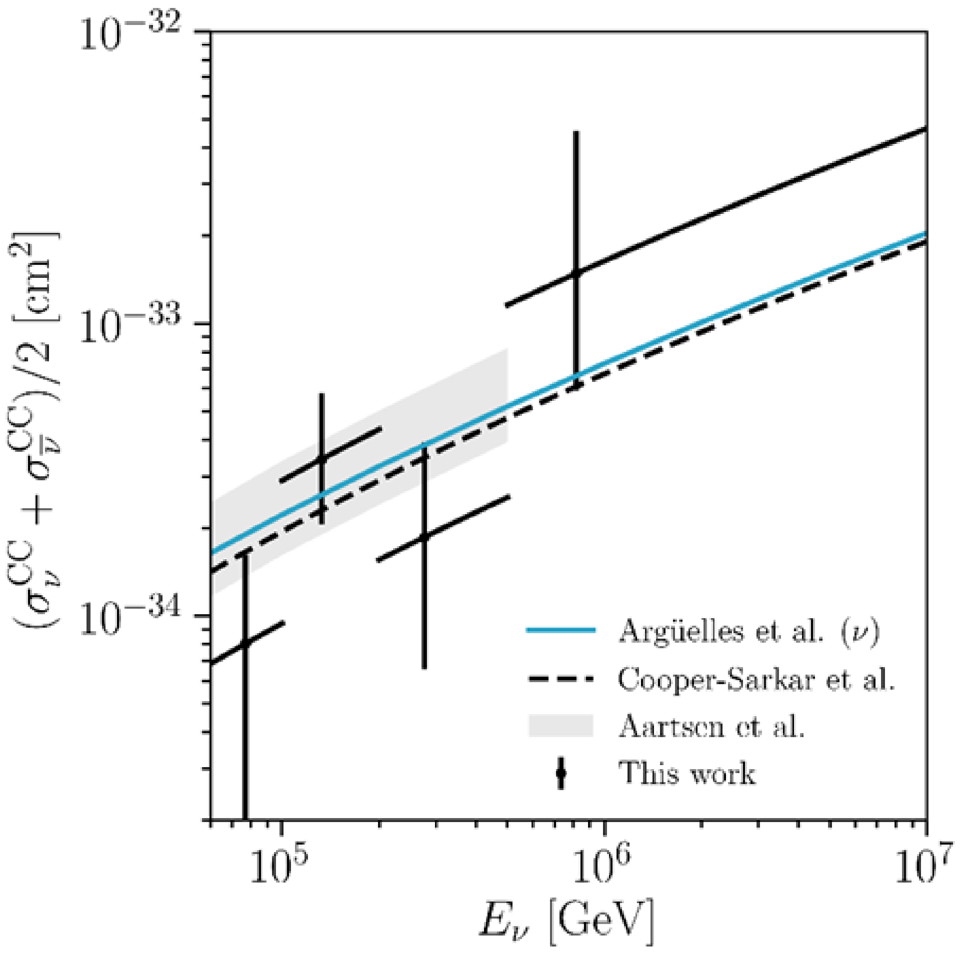
An IceCube Result

IceCube performs new measurement of all-flavor neutrino cross section

Based on 7.5 years of data from high-energy neutrinos that originated in the IceCube detector.

Reported the neutrino Deep Inelastic Scattering cross section that combines information from all three neutrino flavors for the first time.

Consistent with the Standard Model cross section predictions even with large uncertainties



An IceCube Result

IceCube Collaboration awarded 2021 Rossi Prize

Named after Italian experimental physicist Bruno Rossi, the Rossi Prize is awarded "for a significant contribution to High Energy Astrophysics, with particular emphasis on recent, original work."

The 2021 Bruno Rossi Prize was awarded to Francis Halzen and the IceCube Collaboration "for the discovery of a high-energy neutrino flux of astrophysical origin."

In September 2017 IceCube detected a high-energy neutrino from the direction of a blazar called TXS 0506+056—the first-ever evidence of a source of high-energy cosmic rays.

Blazar, designated by astronomers as TXS 0506+056.

Triumph of multi-messenger astrophysics

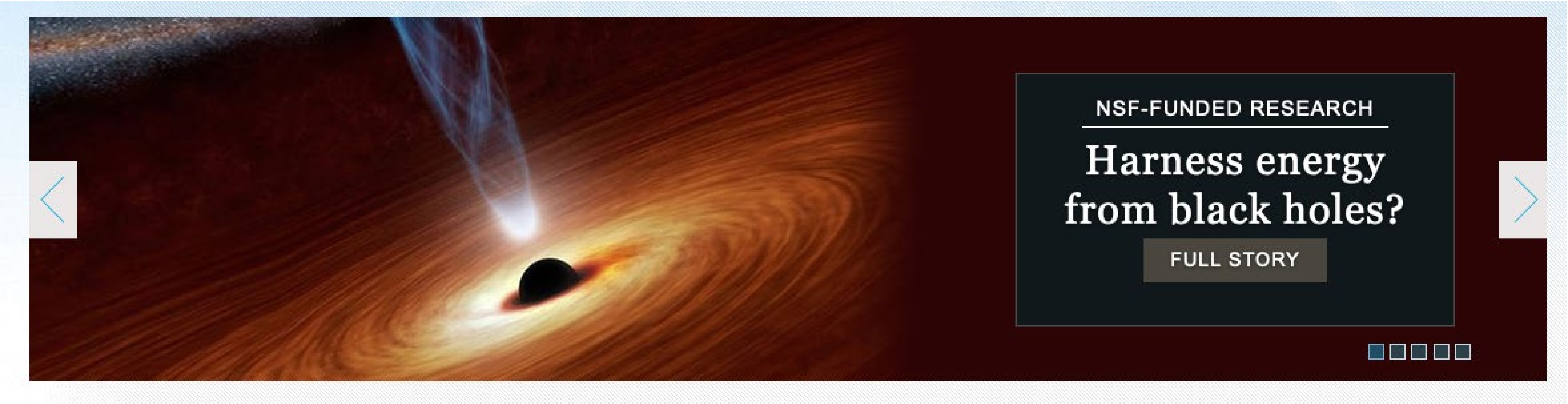
PD 18-5115

Program Description: Windows on the Universe: The Era of Multi-Messenger Astrophysics

https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505593

- Proposals submitted to participating programs in MPS/AST, MPS/PHY and GEO/OPP.
- Proposals funded through "Big Idea" allocation as well as existing programs.
- Criteria: <u>any area of research supported through the participating divisions that address at least one of the following:</u>
  - *Coordination:* Hardware, software, or other infrastructure to coordinate observations involving more than one messenger.
  - *Observations:* Observations of astrophysical objects or phenomena that are potentially sources of more than one messenger, including the use of existing observatories, experiments, and data archives, as well as the development and construction of new capabilities for advancing multi-messenger astrophysics.
  - *Interpretation:* Theory, simulations and other activities to understand or interpret observations of astrophysical objects that are sources of more than one messenger.

Plasma Astrophysics of Black Holes



Work supported by the *Windows on the Universe: The Era of Multi-messenger Astrophysics* program

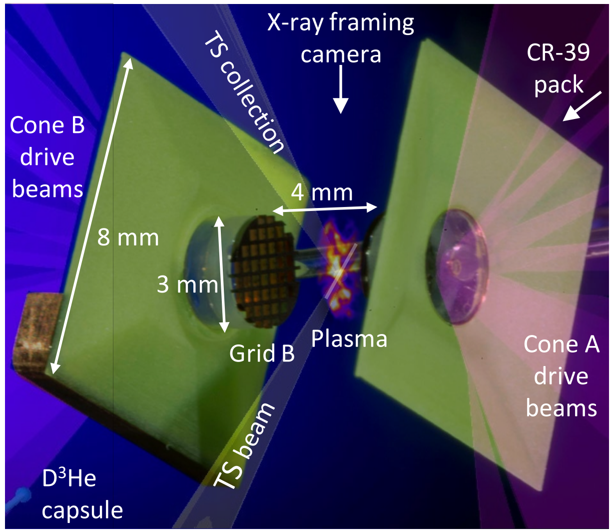
- *A new way to extract energy from black holes by breaking and rejoining magnetic field lines near the event horizon, the point at which nothing, not even light, can escape a black hole's gravitational pull.*
- *The theory shows that when magnetic field lines disconnect and reconnect in just the right way, they can accelerate plasma particles to negative energies, and large amounts of black hole energy can be extracted.*
- *The U.S. National Science Foundation-funded research results could allow astronomers to better estimate the spin of black holes and possibly discover a source of energy for the needs of an advanced civilization*

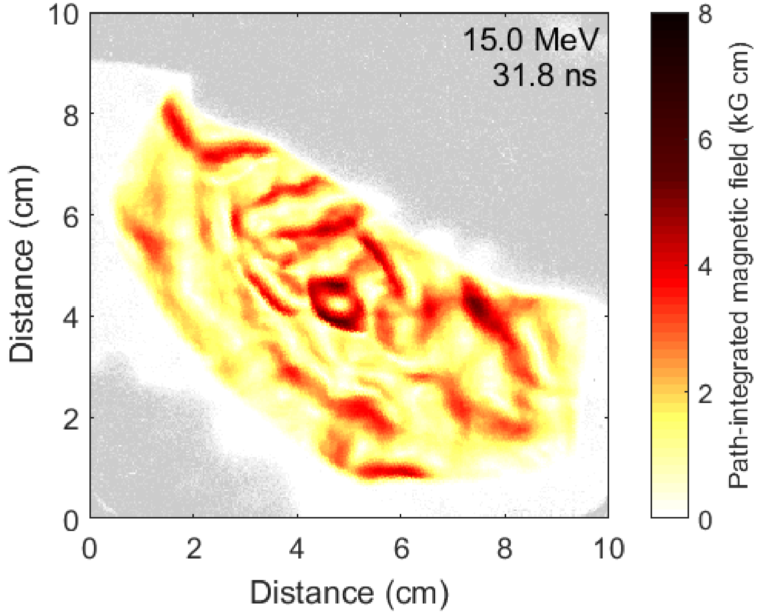
Comisso & Asenjo, Phys. Rev. D, https://doi.org/10.1103/PhysRevD.103.023014

https://www.nsf.gov/discoveries/disc_summ.jsp?cntn_id=301953

Astrophysical Plasma Turbulence in a Lab

Omega Experimental Setup





Dynamo-generated Magnetic Field

Time-resolved characterization of fluctuation dynamo with laser-driven experiments at Omega

- *Experimentally observed efficient amplification of large-scale magnetic fields could explain the* <u>*origin of large-scale fields observed in turbulent astrophysical plasmas*</u>*, not predicted by idealized studies of fluctuation dynamo.*
- *High-fidelity FLASH simulations used to design and interpret laser-driven experiment at the* ***Omega Laser Facility****, which created for the first time a* <u>*laboratory plasma dynamo at order-unity Prandtl number*</u>*.*
- *Time-resolved evolution of the magnetic field amplification showed that plasma turbulence by strong shear can generate fields more efficiently than anticipated by idealized MHD simulations of nonhelical fluctuation dynamo*

Bott, Tzeferacos, *et al.*, PNAS, *in press*, https://arxiv.org/abs/2007.12837

Space Weather with Quantified Uncertainties

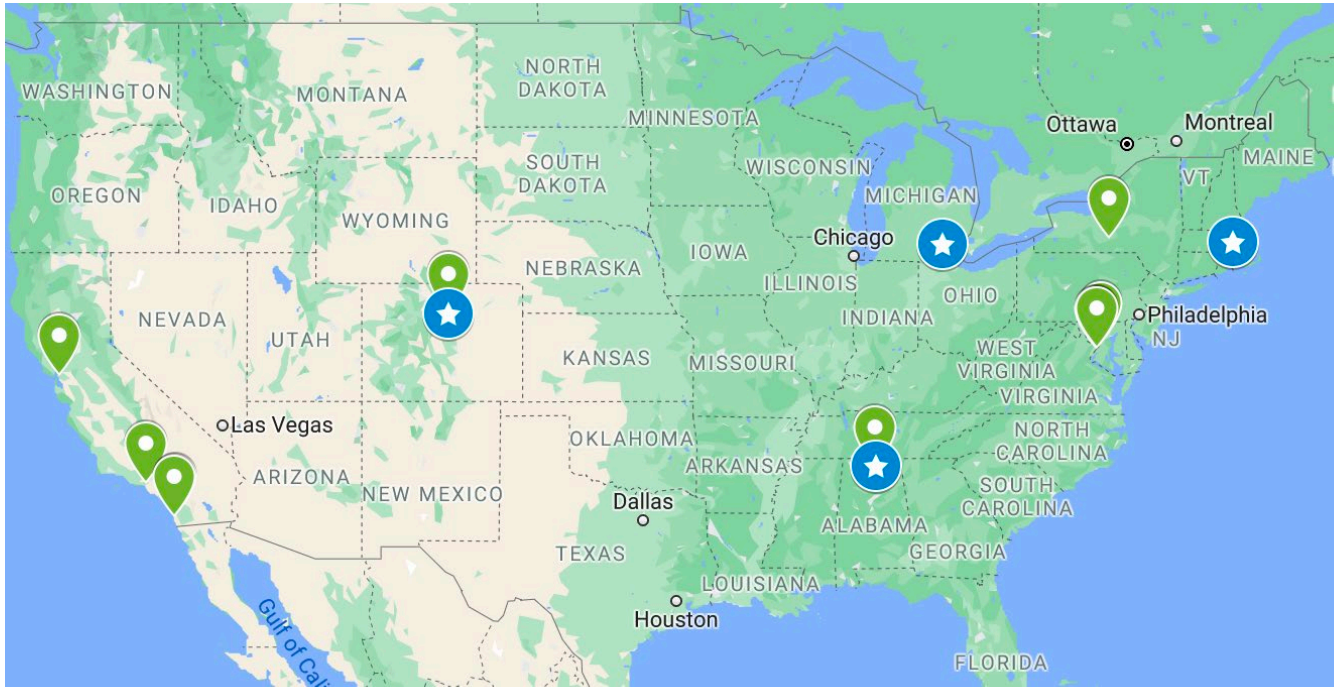
Motivation:

- Understand the necessary and sufficient requirements of model complexity, computational performance, and observational inputs for practical development of predictive space weather modeling
- *National Space Weather Strategy and Action Plan* and the *National Strategic Computing Initiative*

Funding partners:

NSF: MPS, GEO, CISE

NASA: SMD

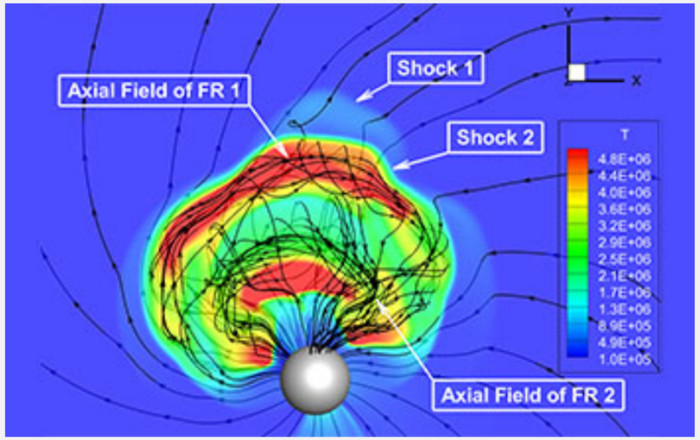


- *Kick-off meeting held in September, 2020*
- Collaborations among multiple universities, national labs, and private companies
- Builds connections with other federal agencies and international partners
- Joint management of the SWQU award portfolio by NSF/MPS, NSF/GEO, and NASA/SMD promises to maintain and build on this collaborative effort

Space Weather with Quantified Uncertainties

NSF and NASA partner to address space weather research and forecasting

https://www.nsf.gov/news/special_reports/announcements/090120.01.jsp



Solar activity simulation: Interaction of two coronal mass ejections in the inner heliosphere. The distribution of plasma temperature and magnetic field lines.
Credit: Talwinder Singh, Tae Kim, and Nikolai Pogorelov, University of Alabama in Huntsville; Charles N. Arge, NASA Goddard Space Flight Center

September 01, 2020

Space weather — solar wind, coronal mass ejections, magnetic storms, upper atmosphere disturbances — can damage infrastructure from electrical power supplies and computer networks to satellite and radio communications — and can even threaten astronauts' health. Accurate forecasting of energetic events on the sun and in the near-Earth space environment is critical for national security and the wellbeing of society. To address this need, the U.S. National Science Foundation and NASA have partnered in funding six projects that will lay the groundwork for faster and more robust space weather forecasting capabilities.

"Together, NSF and NASA are investing over $17 million into six, three-year awards, each of which contributes to key research that can expand the nation's space weather prediction capabilities."

https://news.mit.edu/2020/mit-led-team-will-develop-software-forecast-space-storms-0910

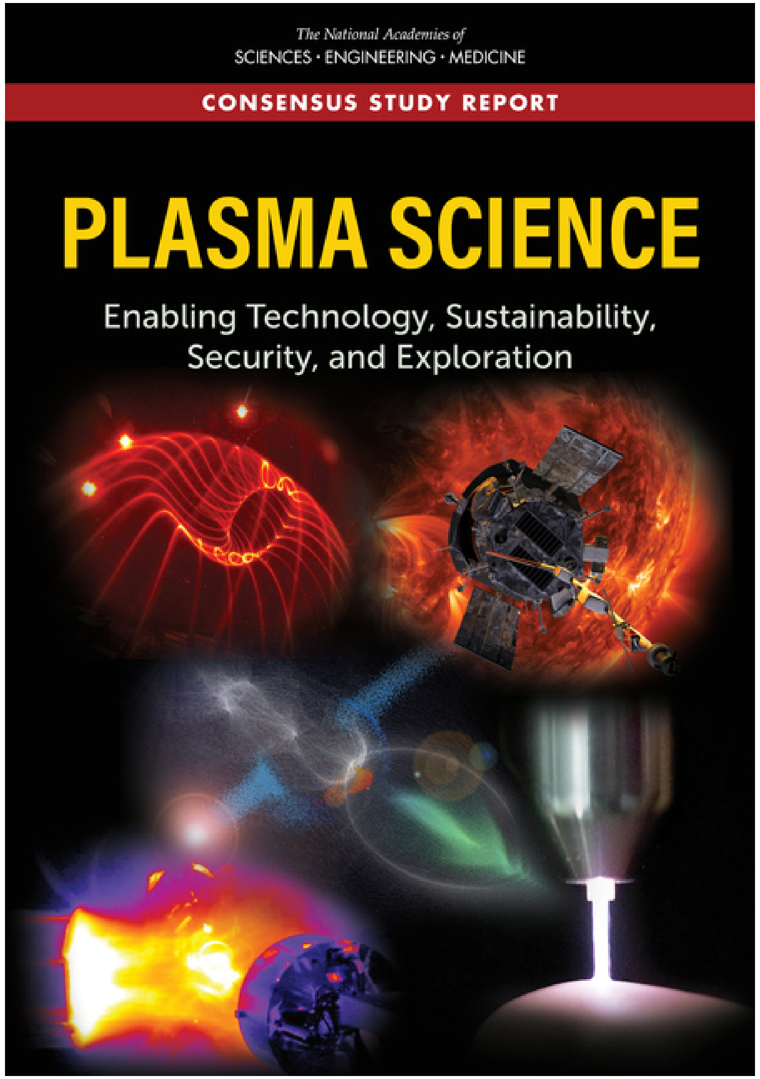
https://news.engin.umich.edu/2020/09/more-than-5m-to-improve-solar-storm-forecasts/

https://cires.colorado.edu/news/cires-scientists-awarded-53m-space-weather-research

https://www.uah.edu/news/news/uah-leads-3-2-million-solar-software-model-effort-to-aid-in-space-weather-predictions

Inter-agency and cross-NSF effort initiated and led by NSF/PHY

Plasma 2020: Released in May, 2020

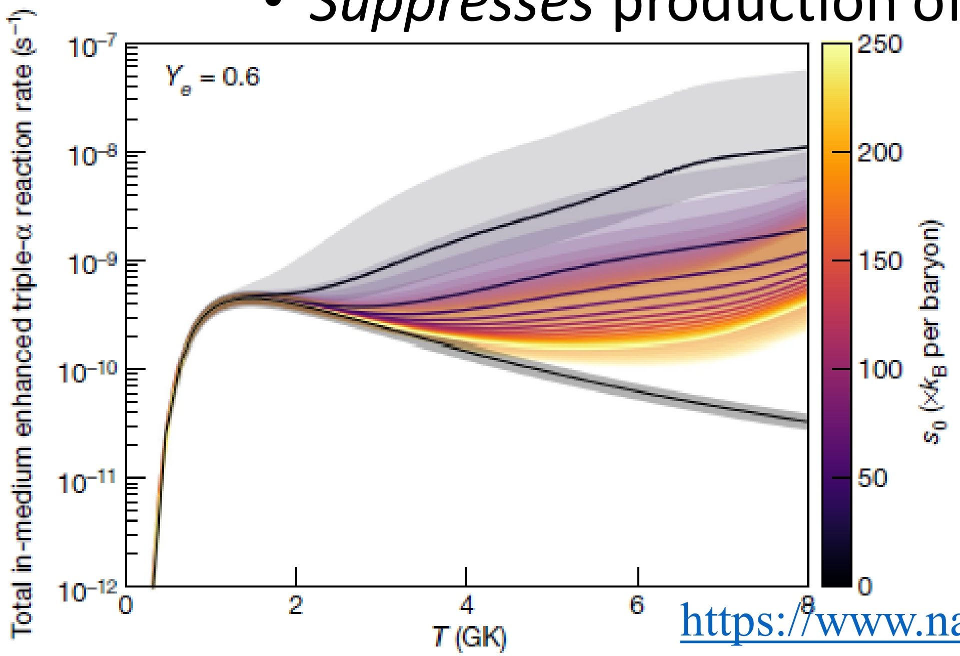


- Presented to this committee by Gary Zank at the September, 2020 meeting
- Executive level vision for plasma science & engineering, with plasma physics at its core, in the US for the next decade.
- Primary focus on increased and better coordinated multi-agency cooperation at multiple levels
  - Includes recommendations for improved tri-lateral coordination between NSF, DOE and NASA on plasma space and astrophysics topics
- Many tasks for NSF, along with other agencies, including to help address DEI and workforce pipeline issues
- NSF is considering possible implementation strategies. Initial steps include:
  - PHY/Plasma Physics Program Description now explicitly encourages DEI efforts
  - NSF/MPS and DOE/NNSA have signed an MOU for cooperation in the area of high energy density science

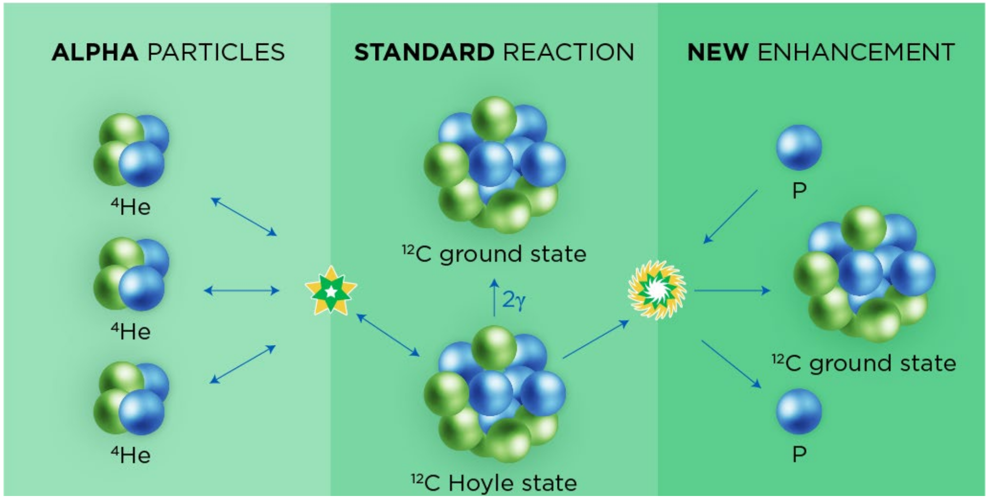
https://www.nationalacademies.org/our-work/a-decadal-assessment-of-plasma-science

Enhanced triple-α reaction reduces p-rich nucleosynthesis in supernovae

- Long been thought that νp processes dominated production of ground state ^{12}C in $3\alpha \rightarrow {}^{12}C^* \rightarrow {}^{12}C_{gs} \rightarrow$ … heavy elements
  - including anomalously high abundances of $^{92,94}Mo$ and $^{96,98}Ru$ and Ga-Cd in spectra of ancient metal-poor stars
- Adding p- and n-scattering to grid of p-rich supernovae nucleosynthesis models
  - *Enhances* $3\alpha \rightarrow {}^{12}C^* \rightarrow {}^{12}C_{gs}$ by order of magnitude
  - *Suppresses* production of heavy isotopes through νp processes

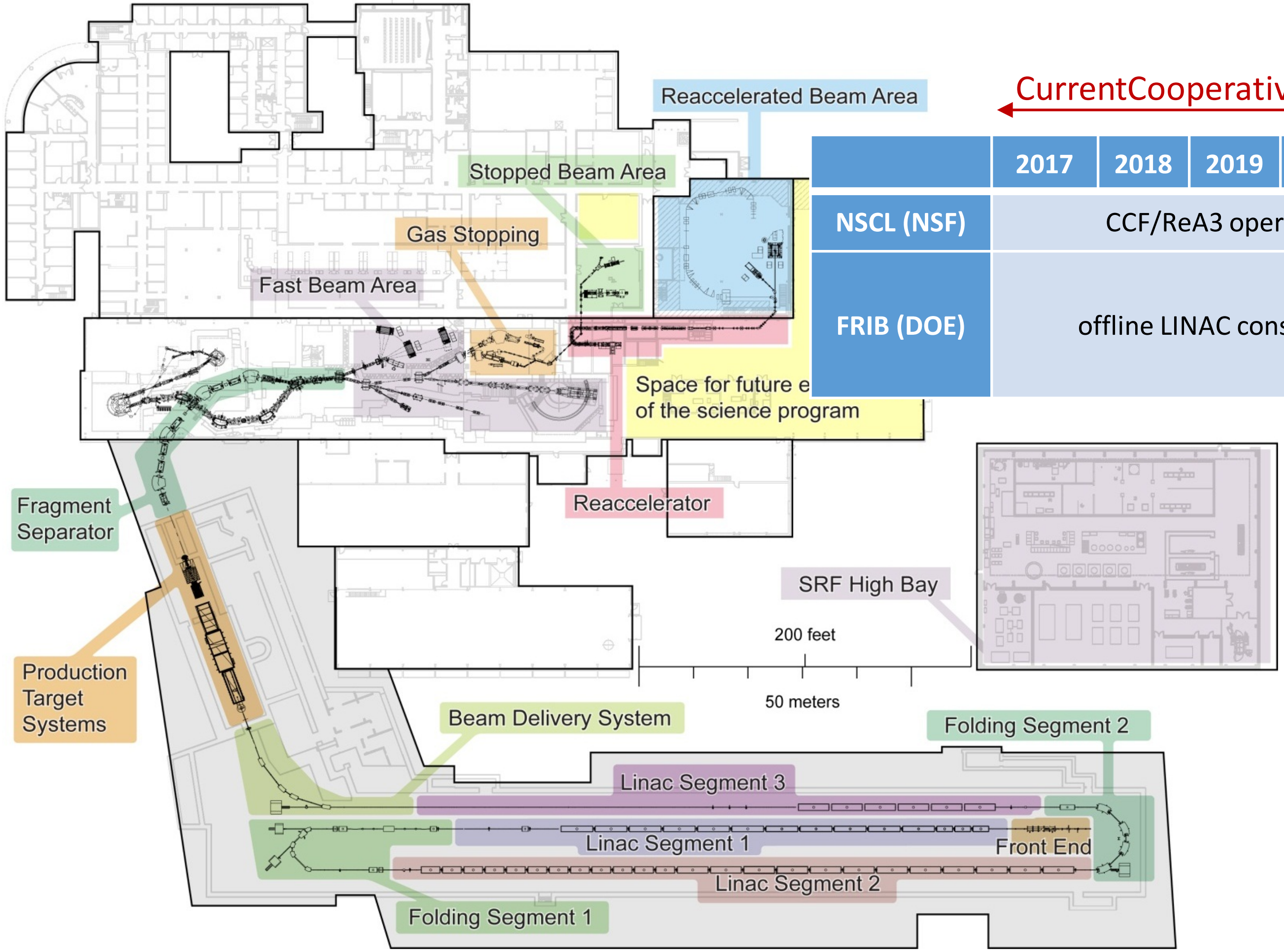


So, where do the high abundances of $^{92,94}Mo$ and $^{96,98}Ru$ come from?



https://www.nature.com/articles/s41586-020-2948-7

MSU Lab: NSF-NSCL → DOE-FRIB Transition



CurrentCooperative Agreement (2017–2021)

	2017	2018	2019	2020	2021	2022	2023
NSCL (NSF)	CCF/ReA3 operations					no NSF operations support	
FRIB (DOE)	offline LINAC construction					connect FRIB LINAC commissioning & operations	FRIB operations

- NSF/DOE Joint Oversight Group working since 2010
- NSF-NSCL → DOE-FRIB Transition MOU

The NSF National AI Research Institutes

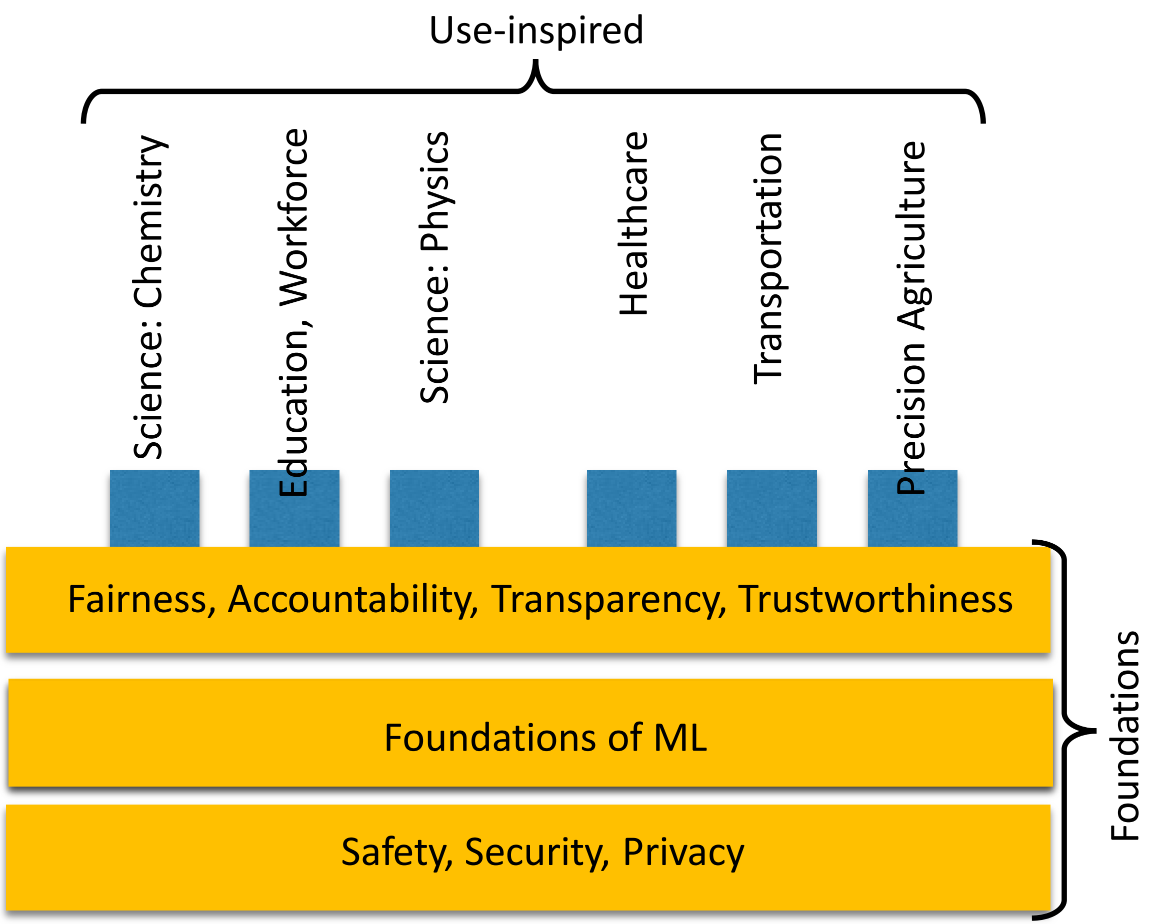
National nexus points for universities, federal agencies, industry and nonprofits to **advance AI research and education**

In FY 2020 (NSF 20-503):

- Issued planning grants for future Institutes
- Launched seven multidisciplinary, multi-institutional research Institutes

Investment: $200M over six years

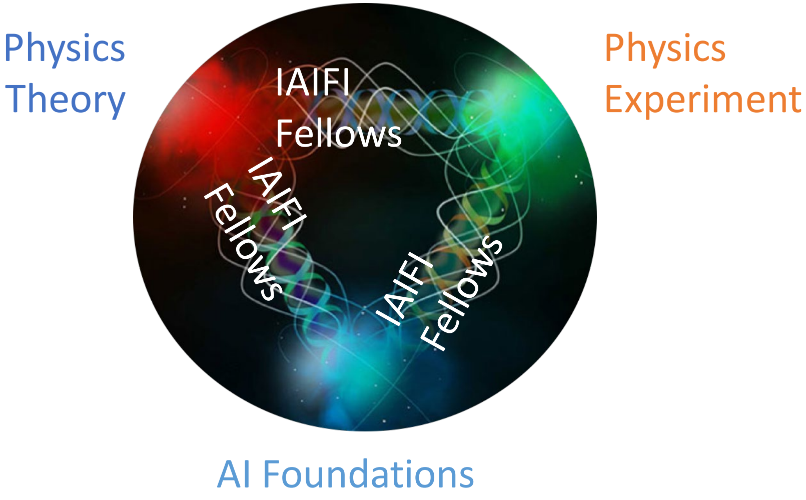
FY 2021 (NSF 20-604): Ongoing



The NSF AI Institute for Artificial Intelligence and Fundamental Interactions (IAIFI)

"eye-phi"

Advance physics knowledge — from the smallest building blocks of nature to the largest structures in the universe — and galvanize AI research innovation



Build strong multidisciplinary collaborations
Advocacy for shared solutions across subfields
Training, education & outreach at Physics/AI intersection
Cultivate early-career talent (e.g. IAIFI Fellows)
Foster connections to physics facilities and industry


The New York Times — By Dennis Overbye — Nov. 23, 2020

Can a Computer Devise a Theory of Everything?

$20 million over 5 years – cofunding from MPS/PHY, CISE/IIS, and MPS/AST