National Science Foundation
Division of Physics Update

Board on Physics and Astronomy
April 27, 2021

Denise Caldwell
Division Director, Physics
Directorate for Mathematical and Physical Sciences

NSF 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 a diverse 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

Supports Experiment and Theory in Six Major Sub-Areas of Physics

Gravitational Physics (Includes LIGO Research Support)

Atomic, Molecular, and Optical Physics; Quantum Information Science and Revolutionary Computing

Nuclear Physics

Particle Physics (Elementary Particle Physics and Particle Astrophysics)

Physics of Living Systems

Plasma Physics

Integrative Activities in Physics (REU, Outreach, BP)

(Note that Condensed Matter Physics is **NOT** included – Housed in DMR)

Major Thrust – Fostering Connections

Focus on Science Question, not Discipline or Subarea

Partner with Others whenever Possible to Promote Science

Partnering within Division – AMO-Nuclear, AMO-Particle, AMO-Gravity, etc.

Partnering with other NSF divisions on individual awards and centers – MPS/AST,CHE,DMR,DMS; BIO/MCB,IOS,DBI; GEO/PLR,AGS; ENG/ECCS,CBET; CISE/CCF,OAC

Participation in NSF priority areas jointly with other Directorates/Divisions - e.g. Understanding the Brain, QIS, AI, etc.

Partnering with DOE/OS in Particle Physics, Nuclear Physics, Plasma Physics

Partnering with NASA in Gravitational Physics and Plasma Physics

Partnering with NNSA in Plasma Physics

Partnering with SU2C in PoLS and Gordon & Betty Moore Foundation in Gravity

Numerous international partnerships

PHY Funding Modalities

Individual Investigator Awards – Direct Research Support
Infrastructure Awards – Tools Needed for Research
Centers and Institutes – Large Groups of Investigators with Topic Focus

Individual Investigator Awards (www.nsf.gov award search)

Individuals or Small Groups (3-5 PI's) – The Major Component of PHY Funding (ca. 55%)
- Awards to Universities to Support Faculty-Directed Research Projects
- Awards selected based on peer review of submitted proposals

Infrastructure Awards (Facilities)

IceCube (Neutrino Detector at South Pole, funded jointly with Polar Programs in GEO)
Large Hadron Collider (Support for ATLAS and CMS M&O, funded jointly with DOE/HEP)
Laser Interferometer Gravitational Wave Observatory (LIGO)

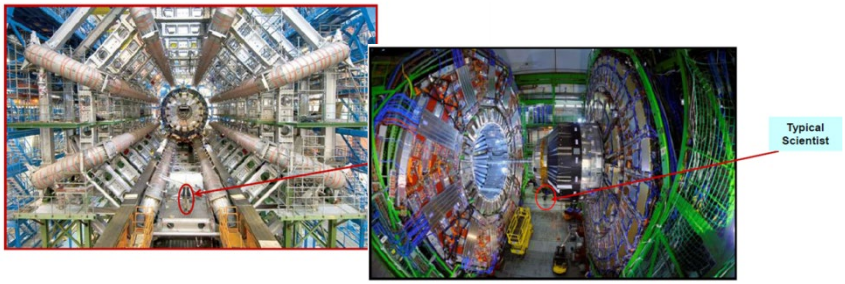
Infrastructure Awards (Mid-Scale)

Critical Instrumentation in the $4M - $30M TPC regime – Too large for program
- Proposals submitted to and reviewed in program
- Program provides operations support

Physics Frontiers Centers

Facilities in Physics Division

Laser Interferometer Gravitational Wave Observatory (LIGO)



ATLAS and CMS Detectors at Large Hadron Collider (LHC)

ATLAS

CMS

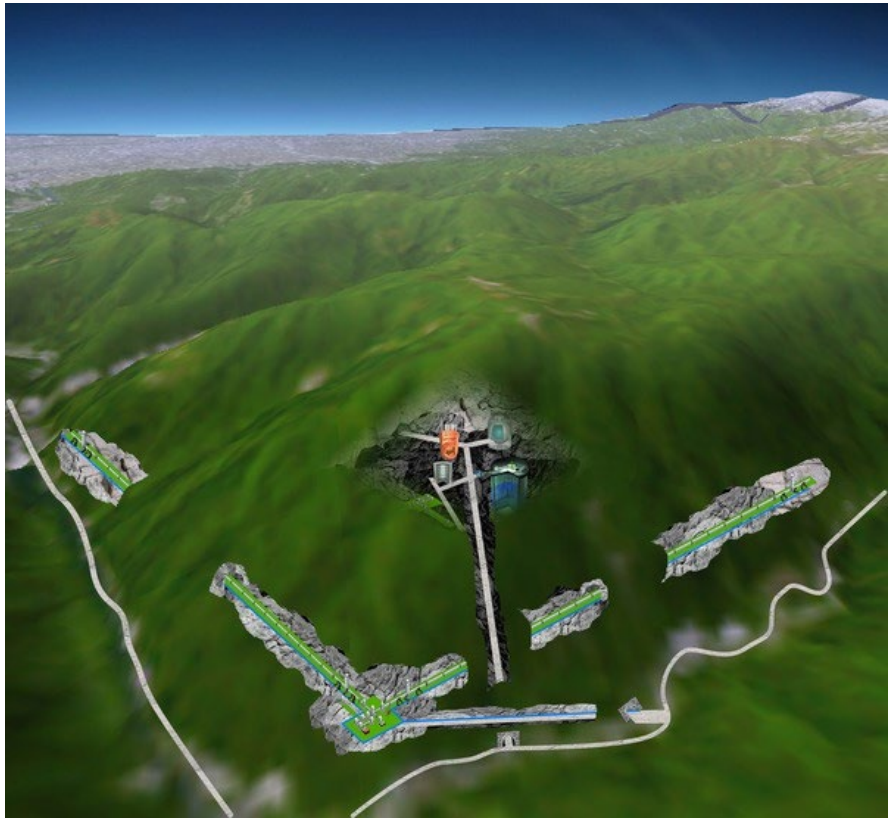
IceCube

NSCL is now

LIGO – Virgo News and Upgrades

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

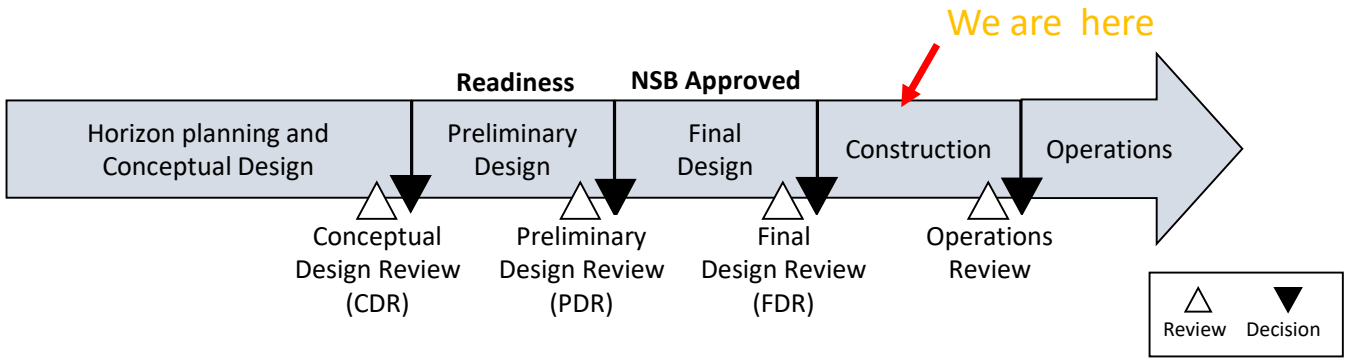
LIGO continues the development of the upgrade known as A+, funded by NSF, UKRI and ARC in 2018. A+ is expected to be fully operational by 2024, increasing Advanced LIGO sensitivity by 70%.



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

High Luminosity LHC MREFC

- NSF Contributions to HL LHC Detector Upgrades
- Made possible by:
  - 2013 Snowmass
  - 2014 P5 Plan
  - MPS Advisory Committee Report (Jan 2015)
  - U.S. CERN Agreement (May 2015)



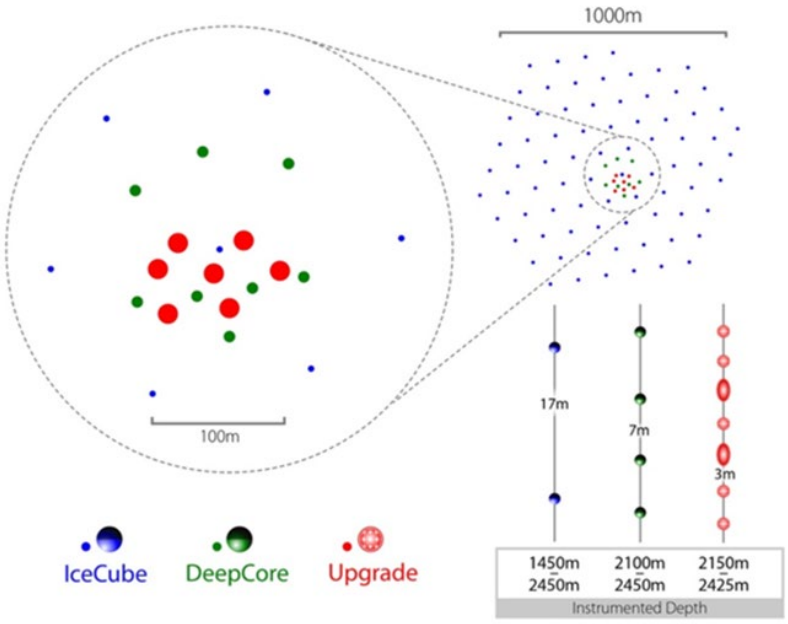
IceCube Upgrade

Funded in 2018 as a 5-year project to add seven additional strings of sensors with a greater density of instrumentation and to form an even tighter array of strings sensitive to lower energy neutrino interactions

Exciting science to connect with

- Lower energy cosmic neutrinos
- Fundamental neutrino properties
- Improved calibration to help with ten years of archival data

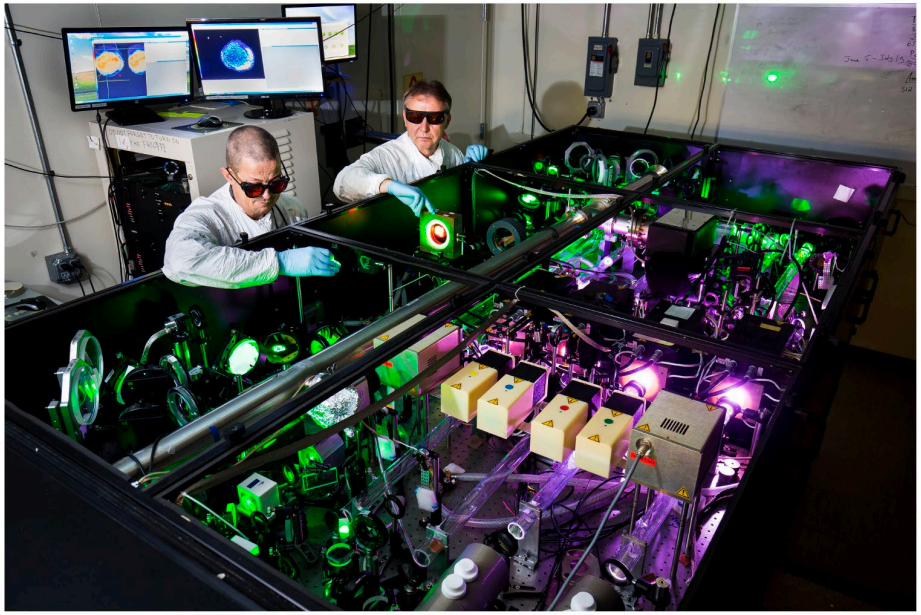
COVID impacts for work at the South Pole has added at least three years delay.



New Laboratory Astrophysics Capability:

ZEUS -- NSF Mid-Scale Laser User Facility

Most powerful laser in the US to be built at U-M



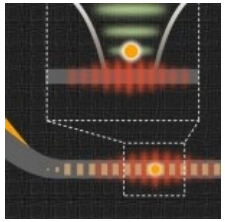
Anatoly Maksimchuk, EECS Research Scientist, and John Nees, EECS Associate Research Scientist, demonstrate use of the HERCULES 300 TW laser. Image credit: Joseph Xu, College of Engineering

https://news.umich.edu/most-powerful-laser-in-the-us-to-be-built-at-u-m/

https://zeus.engin.umich.edu/

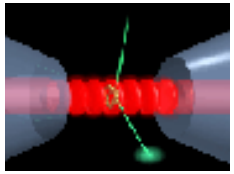
- Builds on prior NSF investments, including a Science and Technology Center led by 2018 Nobel Prize winner Prof. Gerard Mourou.
- Intended to be supported by NSF for operations as a User Facility.
- Will enable better understanding of the physics of high energy astrophysical systems and phenomena, from astrophysical jets and black holes to cosmic rays.

Physics Frontiers Centers



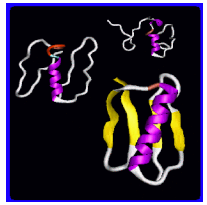
Center for Ultracold Atoms – MIT/Harvard – Ketterle
(With CISE/CCF)

PFC@JILA – Colorado – Cornell



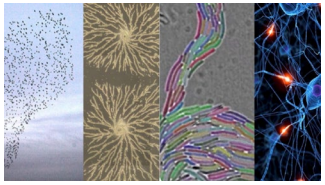
Institute for Quantum Information and Matter – Caltech
- Preskill (With CISE/CCF)

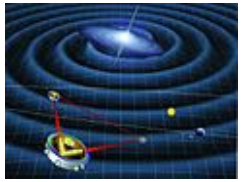
Center for Theoretical Biological Physics – Rice – Onuchic
(Jointly between MPS/PHY/CHE/DMR and BIO/MCB)



Physics Frontiers Centers (Cont'd)

Center for the Physics of Biological Function - CUNY/Princeton – Bialek
(Jointly between MPS/PHY/CHE and BIO/MCB/IOS)





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

The Network in Neutrinos, Nuclear Astrophysics and Symmetries (N3AS) – UC Berkeley - Haxton

N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

MAP

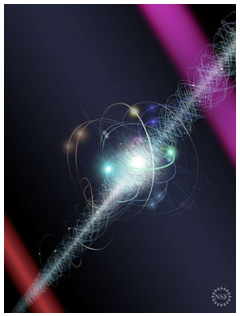
The Center for Matter at Atomic Pressures (CMAP) – U Rochester - Collins

Windows on the Universe: The Era of Multi-Messenger Astrophysics PD 18-5115

- Proposals submitted to participating programs in MPS/AST, MPS/PHY and GEO/OPP.
- Proposals funded through central allocation as well as existing programs.
- Criteria: any area of research supported through the participating divisions that address at least one of the following:
  - *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.

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

Precision Matters

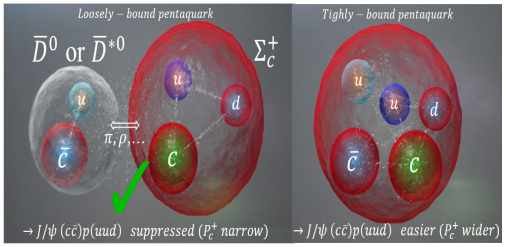


Credit: Nicolle R. Fuller/NSF

ACME: [Extremely close look at electron advances frontiers in particle physics | NSF - National Science Foundation]

LHCb: [Intriguing new result from the LHCb experiment at CERN | CERN (home.cern)]

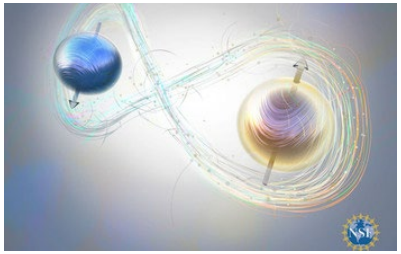
Muon g-2: [First results from Fermilab's Muon g-2 experiment strengthen evidence of new physics | NSF - National Science Foundation]



[T. Skwarnicki, Moriond QCD, 2019]

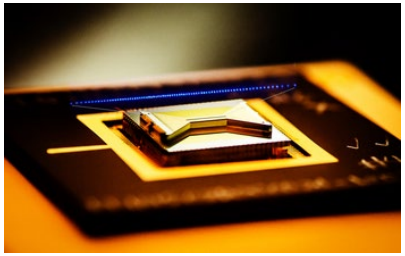
[nsf20127 Dear Colleague Letter: Searching for New Physics Beyond the Standard Model of Particle Physics Using Precision Atomic, Molecular, and Optical Techniques | NSF - National Science Foundation]

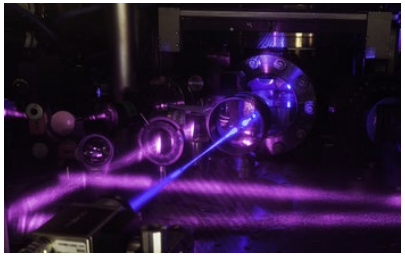
NSF and the National Quantum Initiative (NQI)



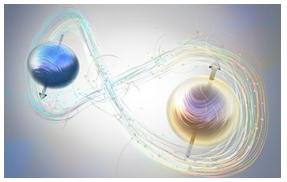
Sec. 301: The Director of the National Science Foundation shall carry out a basic research and education program on quantum information science and engineering, including the competitive award of grants to institutions of higher education or eligible nonprofit organizations (or consortia thereof).

Sec. 302: The Director of the National Science Foundation, in consultation with other Federal departments and agencies, as appropriate, shall award grants to institutions of higher education or eligible nonprofit organizations (or consortia thereof) to establish at least 2, but not more than 5, Multidisciplinary Centers for Quantum Research and Education (referred to in this section as ‘‘Centers’’).





Quantum Information Science and Engineering at NSF – Summary of Investments



Strong disciplinary programs in MPS/CHE,DMR,DMS,PHY; CISE/CCF; ENG/ECCS + **Centers** (PFC, STC, MRSEC)

Quantum Leap Challenge Institutes: 5 awards; cover four subareas of QIS plus one in BIO

Quantum Foundries: 2 Q-AMASE-I awards; UC Santa Barbara and Montana State/U Arkansas

Transformational Advances in Quantum Systems (TAQS) Series: QII-TAQS 19 awards; QuIC-TAQS 10 awards

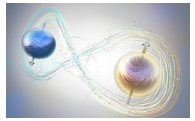
Quantum Computing Focus: 2 awards; PFCQC: STAQ, Duke U (Ken Brown); EPiQC, U Chicago (Fred Chong)

Quantum Networking Focus: Engineering Research Center for Quantum Networks; U Arizona

Convergence Accelerator: Track C; Quantum Technology: 4 phase-II awards

Workforce: Triplets; Faculty Fellowships; Q-12 Education Partnership; NRT; GRFP

Infrastructure: Facilities and Shared Laboratories (NNCI, MIP, CHESS, HRNS, NHMFL)



Ideas Lab: Practical Fully-Connected Quantum Computer (PFCQC)

Brings together physicists, computer scientists, and engineers to construct a quantum computer capable of showing an advantage over current computer technology.

NSF Award 1818914 PFCQC: STAQ: Software-Tailored Architecture for Quantum co-design

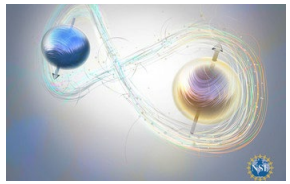
$15 million grant for a multi-institution quantum research collaboration.

Trapped ions (superimposed) above a fabricated trap to capture and control ion qubits (quantum bits).

Image Credit: *K. Hudek, Ion Q&E / E. Edwards, JQI*

NSF 17-548

Expanding Capacity in Quantum Information Science and Engineering (ExpandQISE) NSF 22-561



Two Tracks:

Track 1: Institutions with minimal current focus on research

- Target individual PIs initiating planning for research program
- Provide opportunity for institution to establish research-support infrastructure if needed
- Support engagement with existing centers to build up expertise

Track 2: Institutions with strong research activity but no substantial investment in QISE

- Target faculty heavily engaged in research but not in QISE
- Focus on small teams of 2-3 investigators to build strong competitive program
- Provide larger-scale resources to enable development of competitive research program in QISE
- Support engagement with existing centers to build up expertise and get quick access to infrastructure

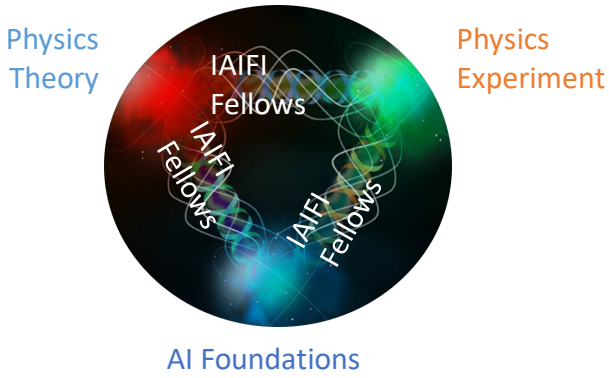
Recent PHY investment in AI

- AI Institute: **AI Institute for Artificial Intelligence and Fundamental Interactions (**IAIFI) Award: 2019786
- AI Planning award: Dodelson (CMU)
  - https://www.cmu.edu/ai-physics-institute/people/index.html
- New OAC award in HDR: (OAC-2117997)
  - HDR Institute: Accelerated AI Algorithms for Data-Driven Discovery
  - U Washington, Seattle
  - A3D3.ai

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



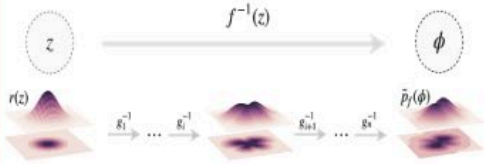
Build strong multidisciplinary collaborations
Advocacy for shared solutions across subfields
Training, education & outreach at Physics/AI intersection
Cultivate early-career talent (e.g. IAIFI Fellows)
Foster connections to physics facilities and industry


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

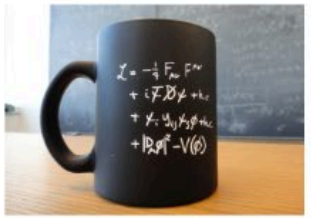
Can a Computer Devise a Theory of Everything?

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

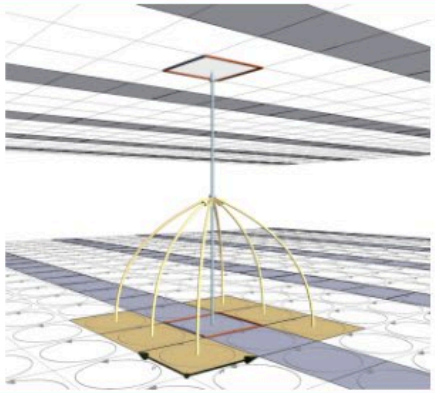
NSF AI Institute for Artificial Intelligence & Fundamental Interactions



Generative models based on normalizing flows



Symmetry structure of the Standard Model of particle physics



Development of machine learning frameworks for efficient sampling in lattice quantum field theory

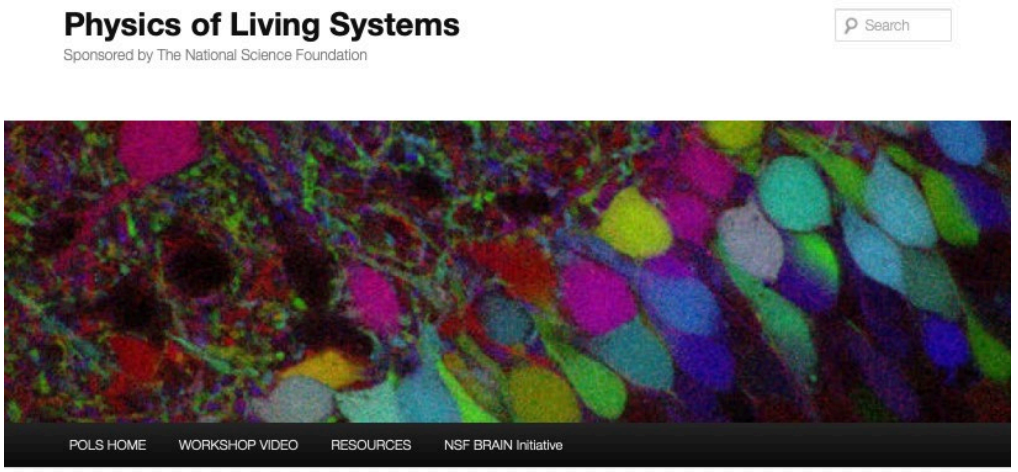
- Series of papers developing generative flow models on compact domains, and on U(n) and SU(n) Lie group variables
- Proof-of-principle demonstration of orders-of-magnitude acceleration over traditional sampling approaches
- Roadmap to QCD for state-of-the-art nuclear/particle physics studies
  - ☑ Architectures for compact variables
  - ☑ Incorporation of gauge symmetry
  - ☑ Non-Abelian groups
  - ☑ Fermions
  - ☐ Scaling to state-of-the-art, exascale hardware

[PRD 103, 074504 (2020), PRL 125, 121601 (2020), ICML, PMLR 8083-8092 (2020), 2107.00734 (2021) 2106.05934 (2021), 2101.08176 (2021)]

Shanahan group (MIT)
+ Industry Partners (Google DeepMind)

Upcoming Workshop: 23-24 June

Still in planning stage—Web page: http://wp.me/P3qDa4-QP



Foundations of Machine Learning and its Applications for Scientific Discovery in Physical and Biological Systems Workshop

JUNE 23 – 24, 2022 | DC METRO AREA, USA

Growing a Strong, Diverse Workforce
Physics Supplements

- Dear Colleague Letter NSF 21-065
- Undergraduate Students:
  - Supported through REU supplements
  - Students must be U.S. citizens, U.S. nationals, or permanent residents of the U.S.
  - PIs strongly encouraged to support students who are members of underrepresented groups
- Graduate Students:
  - Supplement to a current MPS/PHY research award for one additional graduate student
  - Not limited to AGEP institutions
  - Intended to improve diversity and retention at the doctoral level within Physics

Partnerships for Research and Education in Physics (PREP)

- Increase the participation of members of underrepresented groups through excellent research and education endeavors.
- Awards to Minority Serving Institutions to partner with Division-supported Physics Frontiers Centers.
- Full intellectual engagement on both sides: partners are more than a source of students.
- Solicitation 21-610: Deadline Jan 21, 2022

MPS-Wide Programs

Launching Early-Career Academic Pathways in the Mathematical and Physical Sciences (LEAPS-MPS) PROGRAM SOLICITATION NSF 22-503

Designed to launch the careers of pre-tenure faculty in Mathematical and Physical Sciences (MPS) fields at minority-serving institutions (MSIs), predominantly undergraduate institutions (PUIs), and Carnegie Research 2 (R2) universities, and with the goal of achieving excellence through diversity

MPS-Ascend

Mathematical and Physical Sciences Ascending Postdoctoral Research Fellowships | NSF - National Science Foundation NSF 22-501

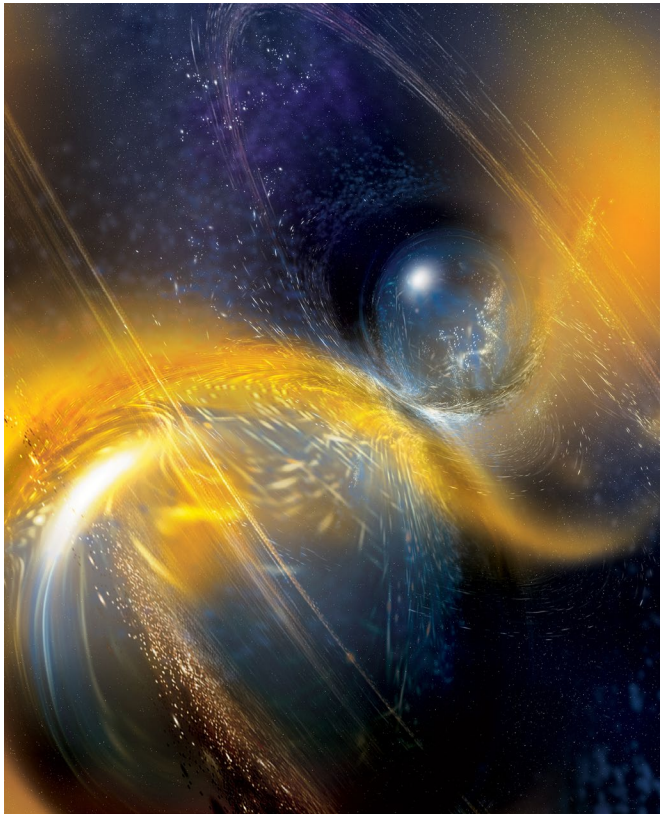
Designed to support postdoctoral Fellows who will broaden the participation of groups that are underrepresented in MPS fields in the U.S., including Blacks or African Americans, Hispanics, Latinos, and Native Americans, as future leaders in MPS fields.

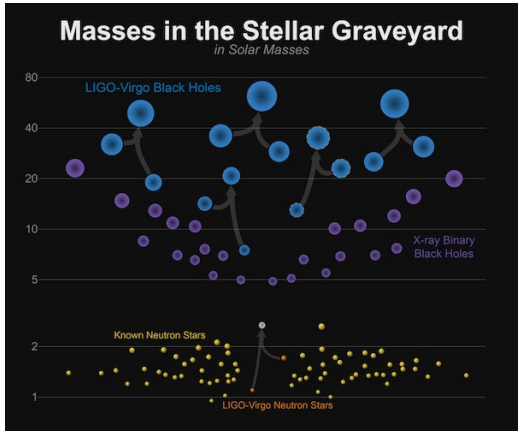
LIGO – Virgo
O3 Highlights

Several “exceptional” GW events detected in O3a have been published:

2nd 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)*

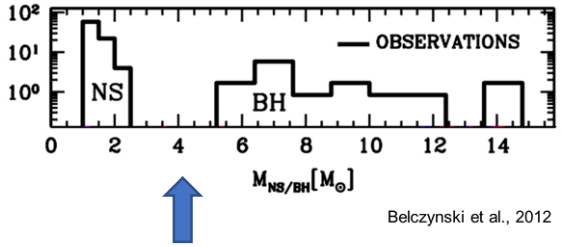
Binary with a 23 $M_\odot$ BH and a 2.6 $M_\odot$ object

The most extreme mass ratio (9!)

No EM counterpart

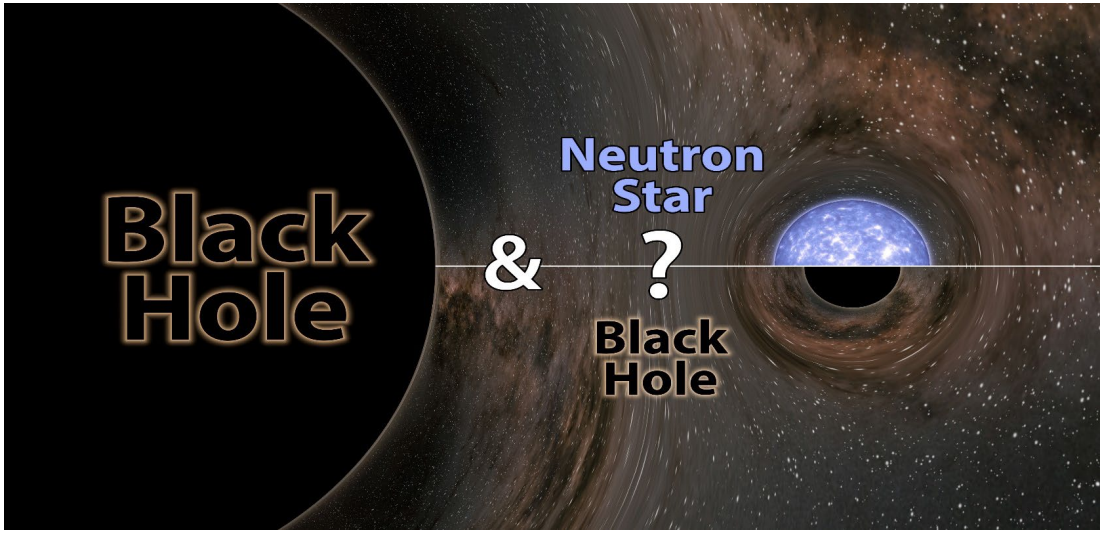
Not clear if the small object is a black hole or a neutron star

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



If NS: First BH/NS detected and
Heaviest NS ever observed

If BH: Lightest BH ever observed



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

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

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 $M_\odot$!