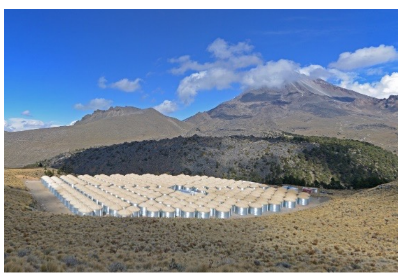
Astrophysics in the NSF Physics Division

A Snapshot

C. Denise Caldwell
Division Director

With input from Jean Cottam, Darren Grant, William Wester, Keith Dienes, Bogdan Mihaila, Pedro Marronetti, Mark Coles, Allena Opper, Alfredo Galindo-Uribarri, Slava Lukin, and Jose Lopez



Credit: HAWC

Credit: IceCube

Credit: LIGO Lab

AAAC January 2022

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)

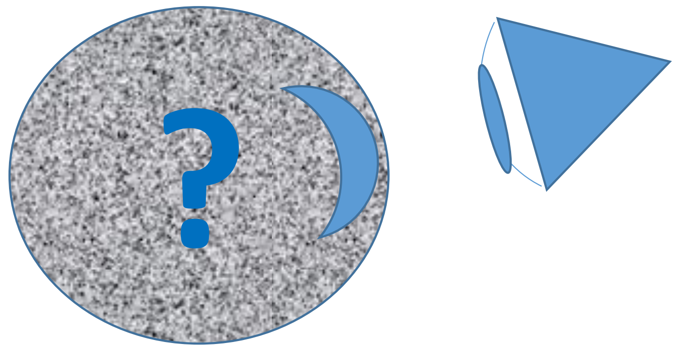
Neutrinos and Beyond the Higgs – Neutrino mass, new particles, unification of quantum mechanics and gravity, electron and neutron dipole moments (Particle Astrophysics; Gravitational Physics; Nuclear Physics; Precision Measurements; Elementary Particle Physics)

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, Cosmology; 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)

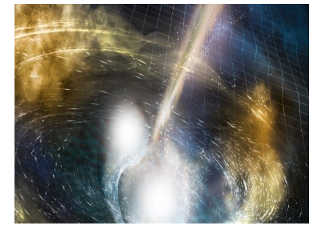
Support provided through disciplinary programs in theory and experiment, centers, and facilities

NSF/PHY Budget Status



FY 2021 Actual	Not Yet Released
FY 2022 Appropriation	Not Yet Voted On – Under CR
FY 2022 Current Plan	Needs Appropriation
FY 2023 Request	Under Development

WINDOWS ON THE UNIVERSE: THE ERA OF MULTI-MESSENGER ASTROPHYSICS (WoU-MMA)



Metaprogram PD 18-5115

The goals of WoU-MMA are to build the capabilities and accelerate the synergy and interoperability of the three messengers to realize integrated, multi-messenger astrophysical explorations of the Universe. It has three broad areas of emphasis:

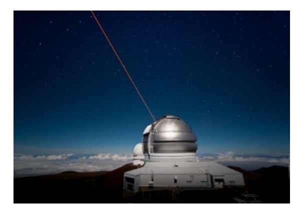
Enhancing and accelerating the theoretical, computational, and observational activities within the scientific community

Building dedicated midscale experiments and instrumentation

Exploiting current facilities and developing the next generation of observatories

Credit: LIGO Laboratory

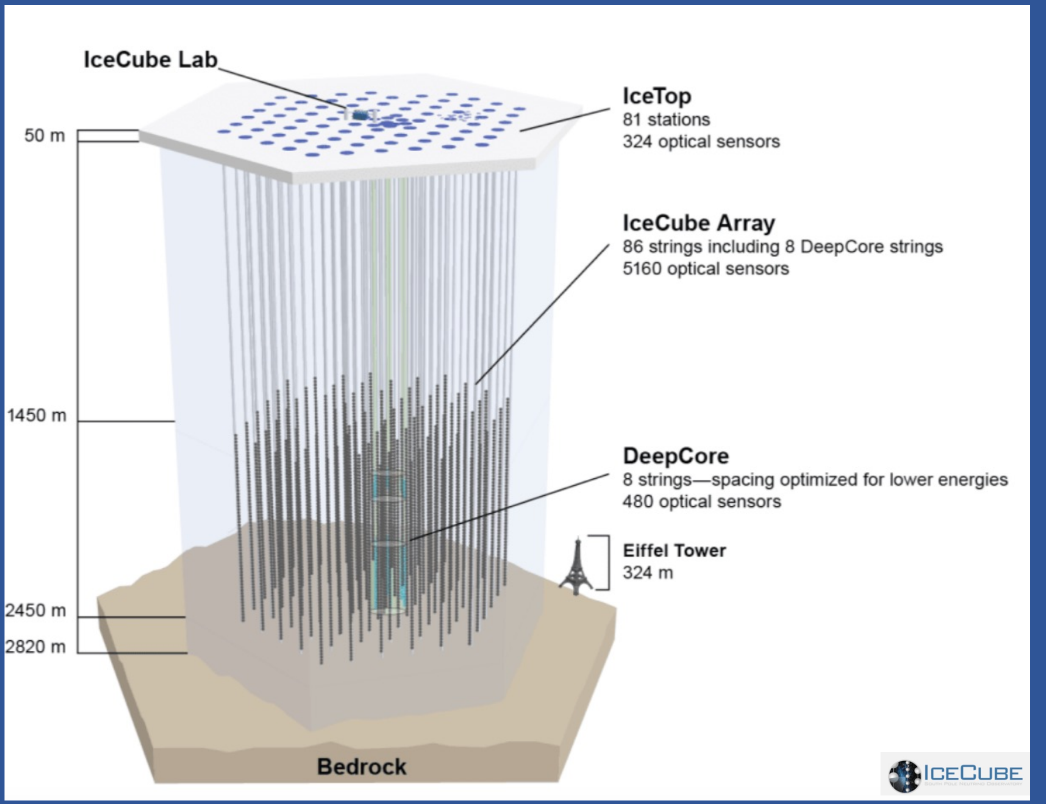
Credit: IceCube



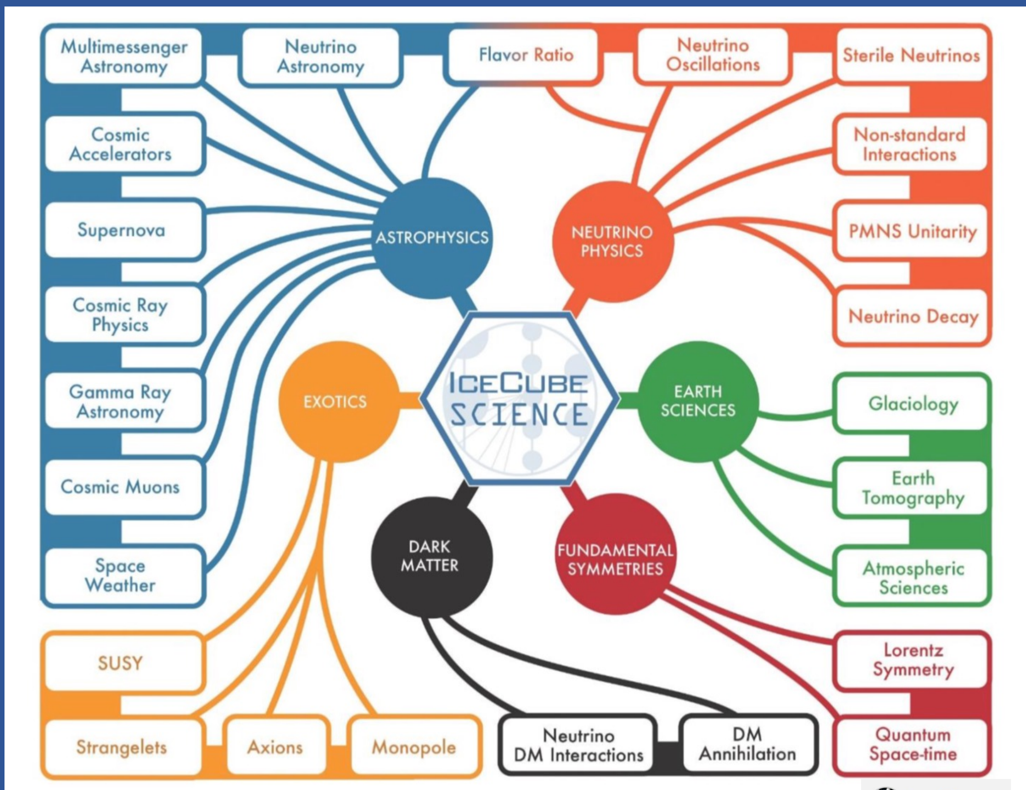
Credit: AURA

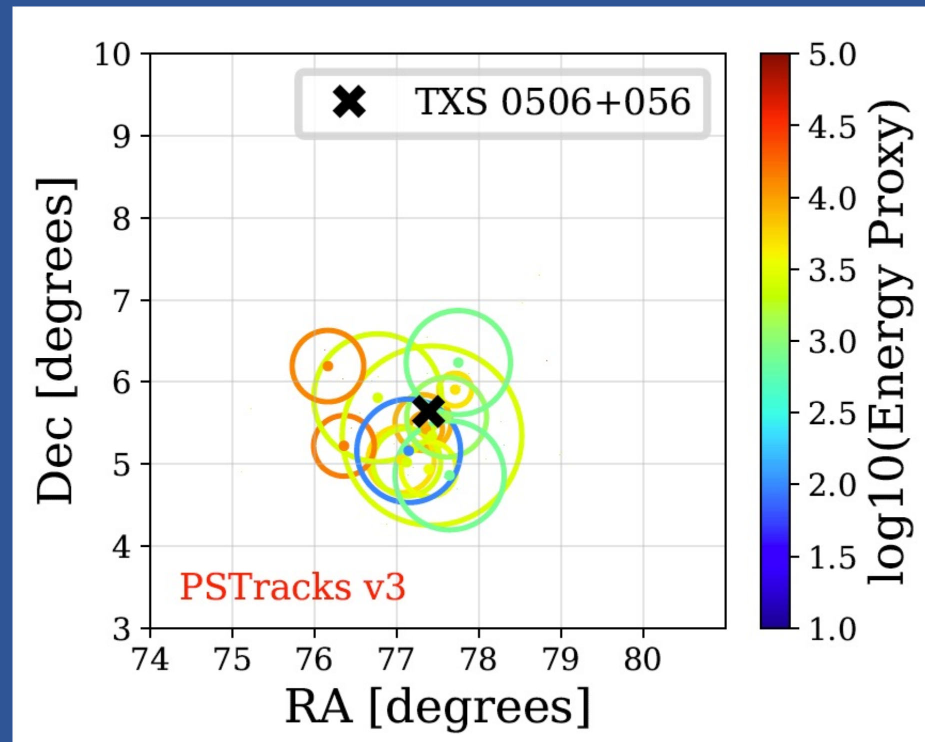
IceCube Neutrino Observatory

- 2011-2021: 10 years of IceCube
- 1 cubic kilometer of instrumented clear ice beneath the South Pole to capture the highest energy cosmic neutrino interactions
  - 86 strings of optical sensors
  - Additional stations with sensors
- International IceCube Collaboration
  - 320 Scientists, 28 U.S. institutions and 28 from other countries
  - In the U.S. / Non-U.S.
    - 47 / 45 faculty members
    - 45 / 33 postdocs / young scientists
    - 63 / 86 graduate students



IceCube Science Program

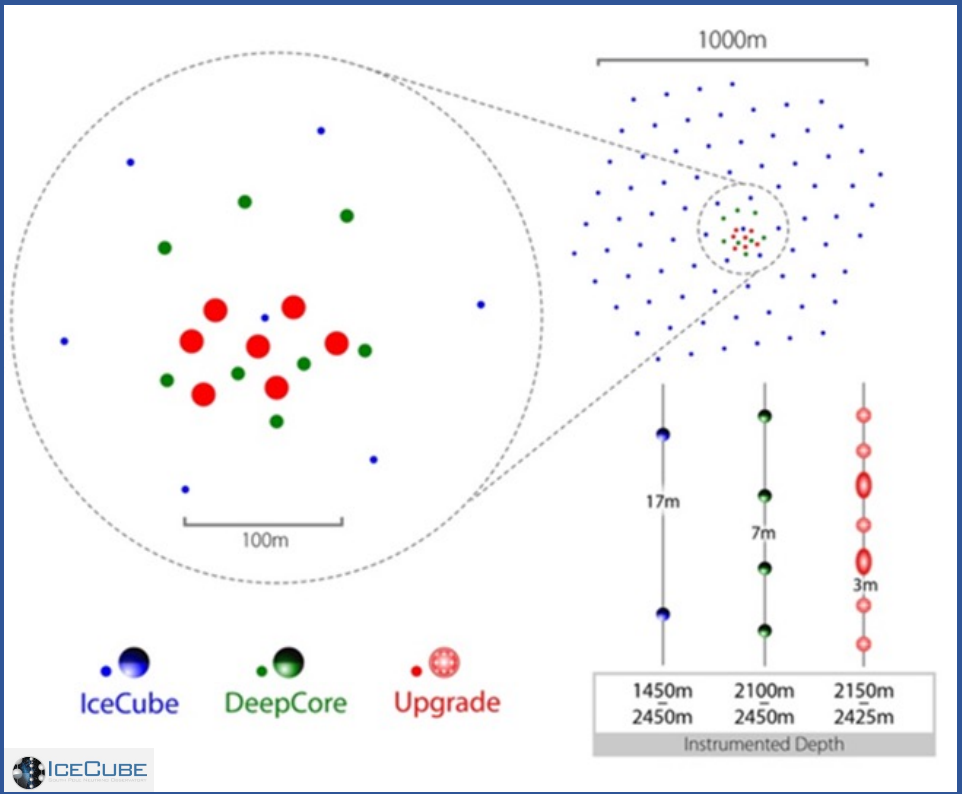




Each circle represents a neutrino pointing back to an astrophysical source which likely flared in 2014-15

IceCube upgrade

- Funded in 2018 as a 5-year project to add seven (7) 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 10+yrs of archival data
- COVID impacts for work at the South Pole has added at least 3 years delay and the project will be re-baselined

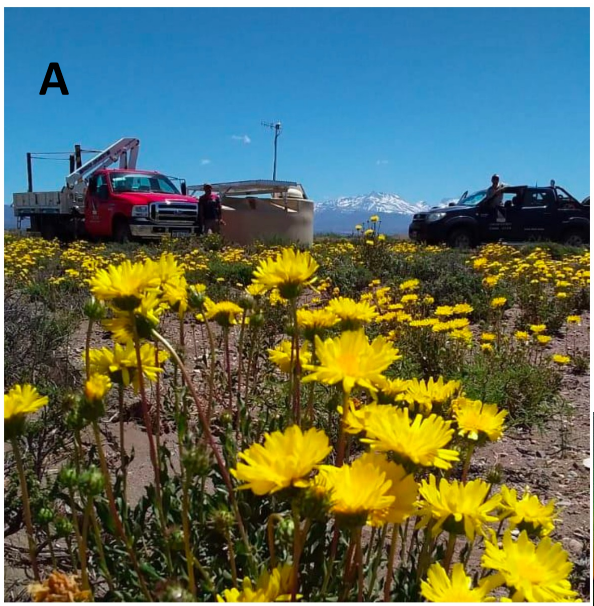


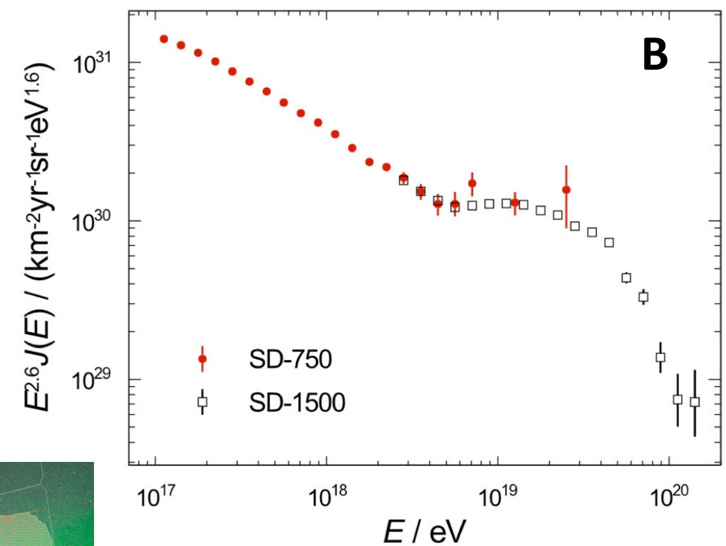
Particle Astrophysics – Cosmic Phenomena

Pierre Auger Observatory (PAO)

A: Assembly of the AugerPrime surface scintillator detector modules is completed with more than 90% deployed in the field.

B: Highest precision measurement of the cosmic ray spectrum over three orders of magnitude above 1e17 eV utilizing the infill (750 m spacing) array.



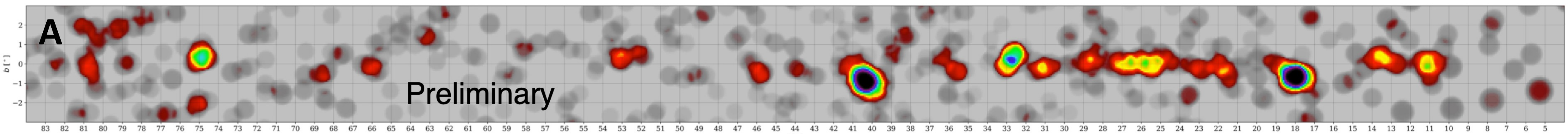


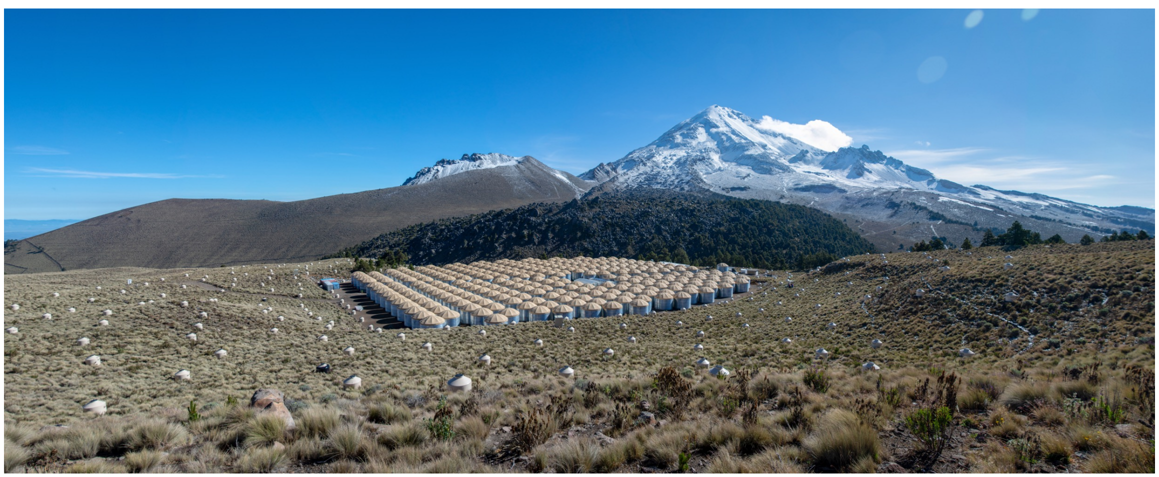
Particle Astrophysics – Cosmic Phenomena

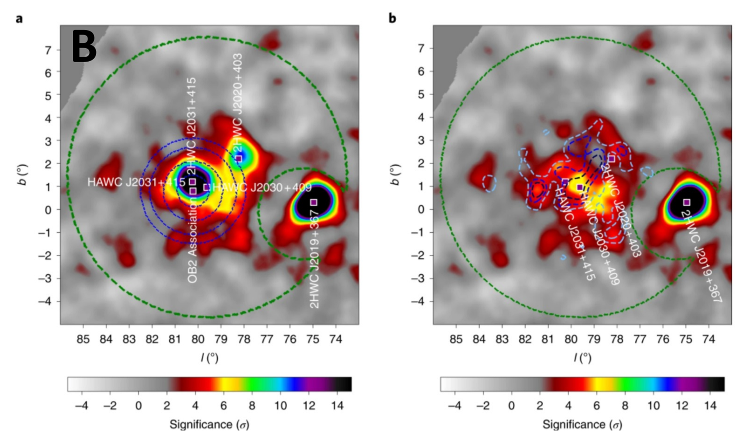
High-Altitude Water Cherenkov Observatory (HAWC)

A: First evidence of the highest energy gamma-ray galactic sources measured to date; 9 sources with spectrum extending beyond 100 TeV

B: First observation of gamma-rays up to 100 TeV in the "Cygnus Cocoon," a superbubble surrounding a massive star formation region. New evidence these regions are producing PeV-scale cosmic rays.







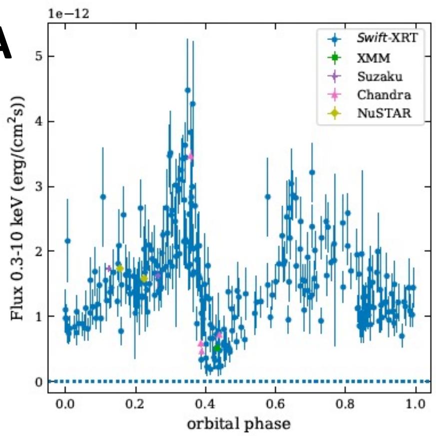
Particle Astrophysics – Cosmic Phenomena

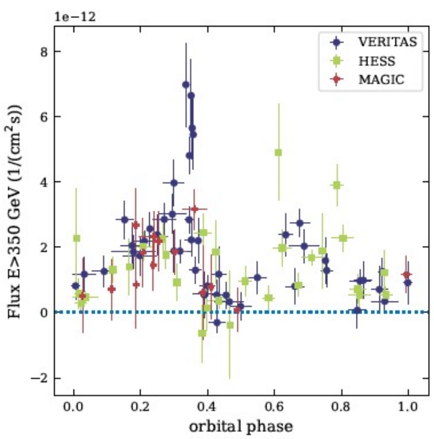
Very Energetic Radiation Imaging Telescope Array System (VERITAS)

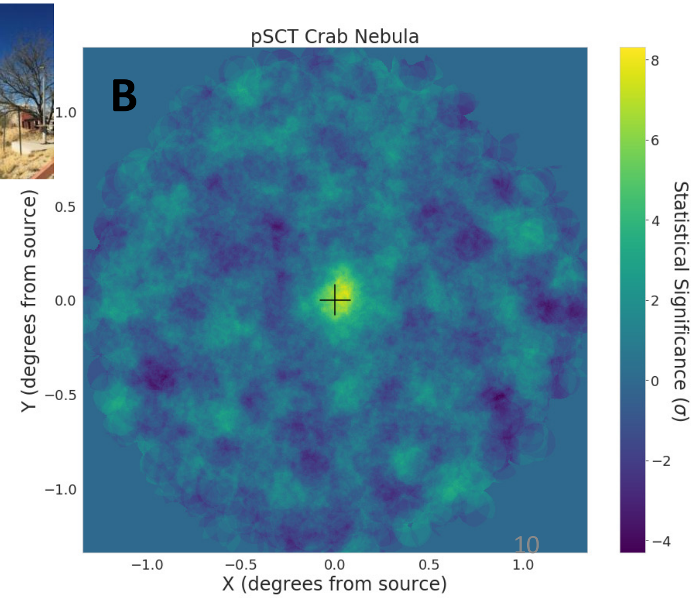
A: Long-term observations of the binary system HESS J0632+057 (massive star + compact object) shows strong correlation between X-ray and gamma-ray behavior suggesting a single population is responsible for both

B: First very-high energy gamma-ray observations of the Crab Nebula with the Cherenkov Telescope Array prototype Schwarzschild-Couder Telescope.

A





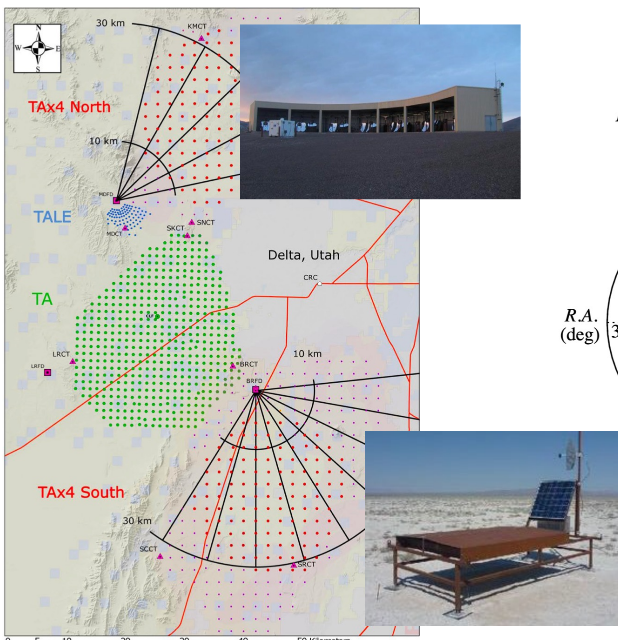


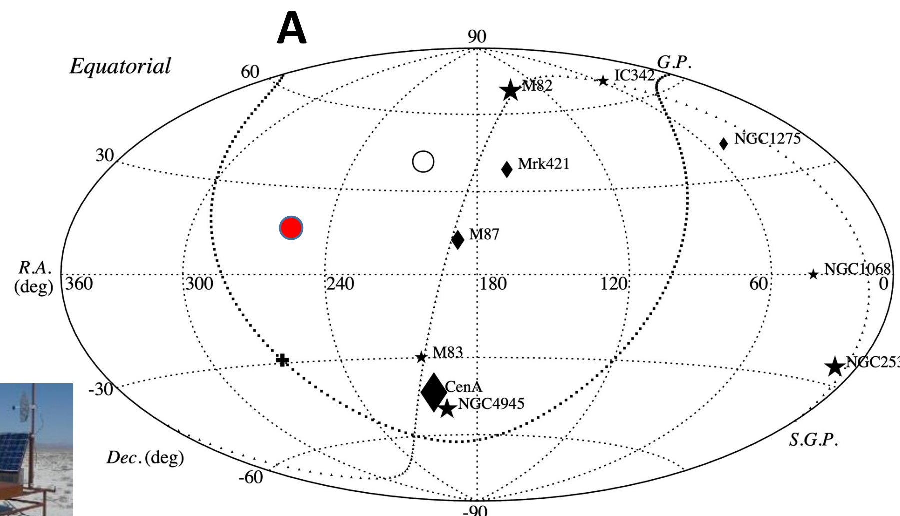
Particle Astrophysics – Cosmic Phenomena

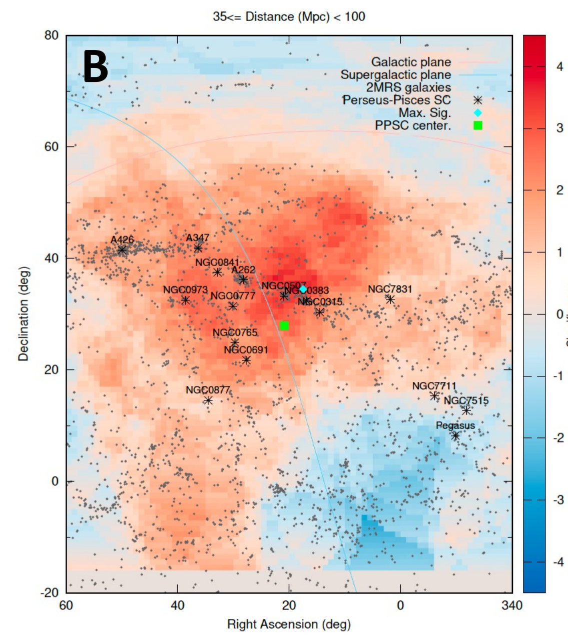
Telescope Array Observatory (TA)

A: Detection of the highest energy cosmic ray event to date with TA @ 243.6 EeV (preliminary); approaching the energy-scale of the Fly's Eye OMG! particle

B: Lower energy (>40 EeV) excess of cosmic ray events observed in the direction of the Perseus-Pisces supercluster. Expected significance between 3 and 5 sigma.







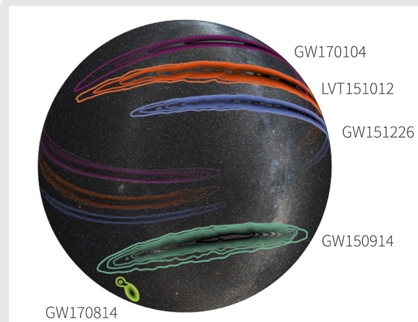
LIGO Update

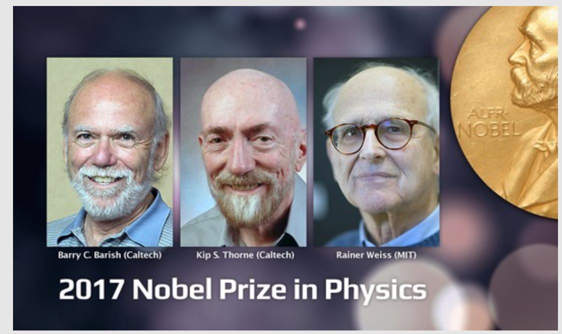
LIGO, Virgo and KAGRA continue the upgrades to ready the observatories for the next observational run (O4).

O4 will start on Dec 15, 2022, bt it may be adjusted. O4 will last one full year (though it could be extended) in 6-month blocks with one-month long break in between.

LIGO's sensitivity for O4 is expected to be 160-190 Mpc (a potential increase of -25-45%),

detecting in average an event every two days.





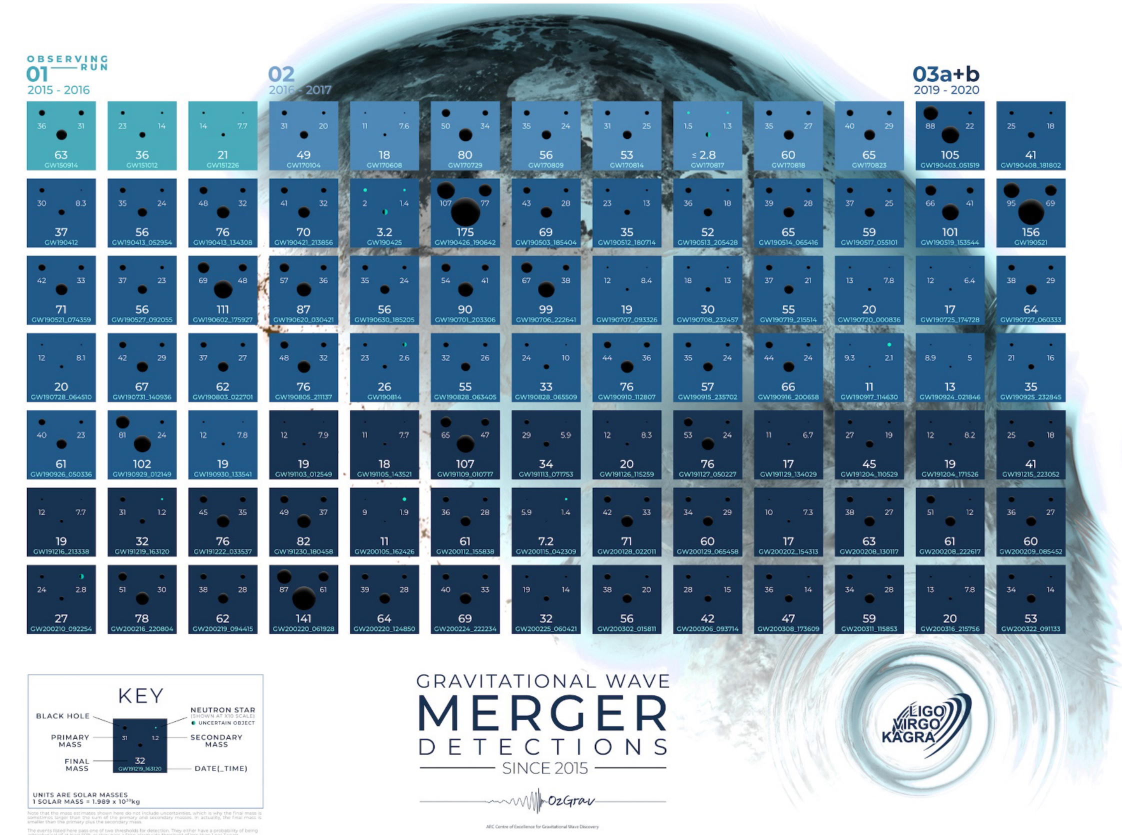
LIGO – Virgo - KAGRA
2021 Highlights

GWTC-3 Catalog
(arXiv: 2111.03606)

On November 7, 2021, LIGO-Virgo-KAGRA released the results of the 2nd half of O3.

The release announced 35 new GW events, bringing to 90 the total number of detections to date:

- 2 neutron star mergers
- 4 black hole – neutron star mergers
- 2 black hole – uncertain objects (either BH or NS)
- 82 black hole mergers



LIGO – Virgo - KAGRA
2021 Highlights

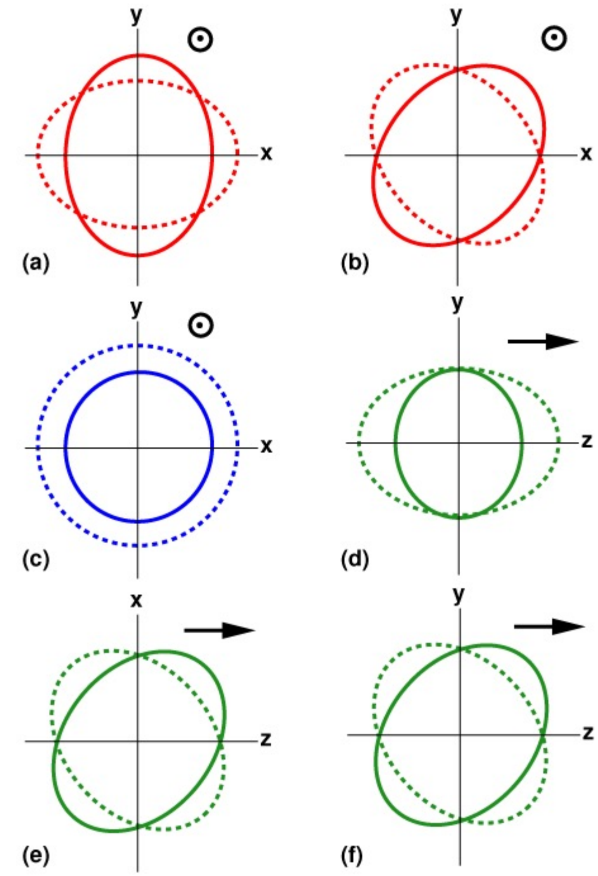
Testing GR with the GWTC-3 catalog
(arXiv 2112.06861)

On December 14, 2021, LVK released the collaboration's most comprehensive tests of GR to date

Nine different tests were conducted, looking for deviations from GR

GR passed all the tests within the detectors' noise uncertainty

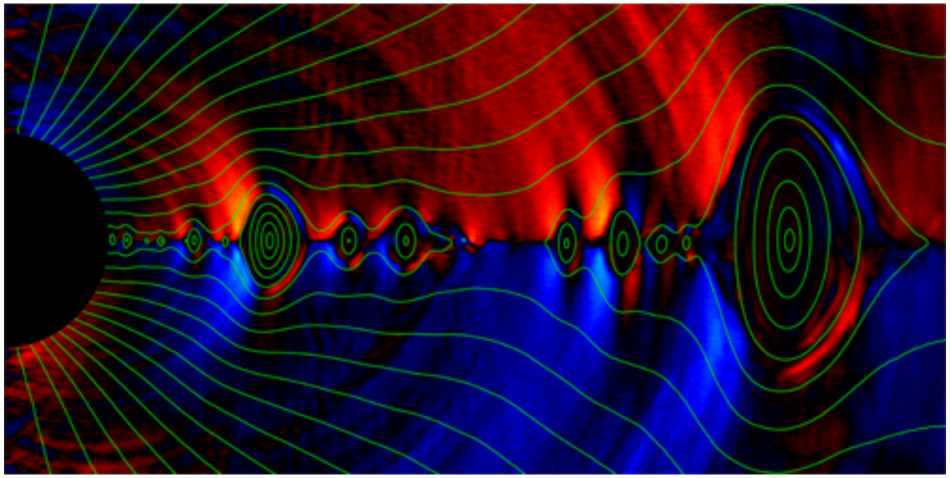
Six polarization modes allowed in a general gravity theory. The first three correspond to the situation when the direction of propagation of the wave is into the plane of the screen (transverse) and in the last three the arrow denotes the direction of propagation of the wave. **The first two, in the top row, are the only modes allowed by GR** referred to as `+' and `x'. (Figure credit: : Clifford Will, Living Reviews in Relativity)



Plasma Astrophysics

Understanding of compact objects and their environments advanced using theory and computational efforts in plasma astrophysics

- E.g., from APS Physics Synopsis*:* Balding Black Holes Lose Their Magnetic Hair: *First-principles plasma simulations show that black holes can't keep their magnetic fields.*



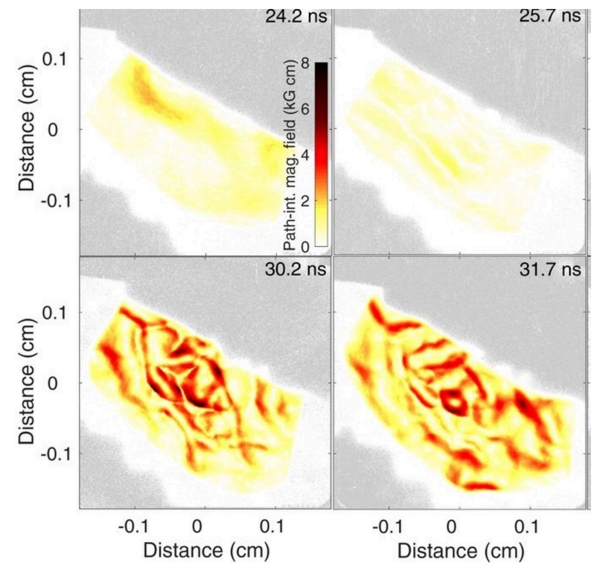
Bransgrove *et al.*, "Magnetic hair and reconnection in black hole magnetospheres," Phys. Rev. Lett. **127**, 055101 (2021).]

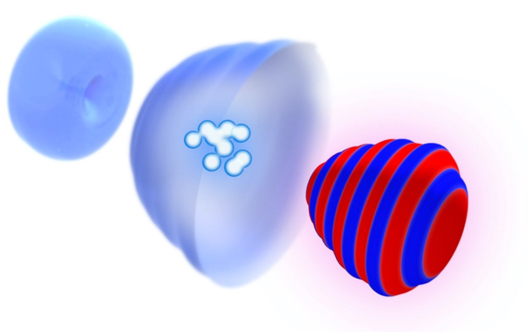
Plasma Astrophysics

Fundamental astrophysical processes are being explored in laser-driven laboratory studies

- Magnetogenesis (from U. Chicago News): Using powerful lasers, scientists recreate how magnetic fields grow in clusters of galaxies: *Pioneering experiments capture how physical process called turbulent dynamo grows these fields* [Bott *et al.*, **"**Time-resolved turbulent dynamo in a laser plasma,**"** PNAS March 16, 2021 118 (11) e2015729118]

Dynamo-generated magnetic field





ZEUS's full-power 3 petawatt laser pulses will be used to generate a 10 billion electron volt electron beam. Image credit: Steve Alvey/University of Michigan Engineering, Communications & Marketing.

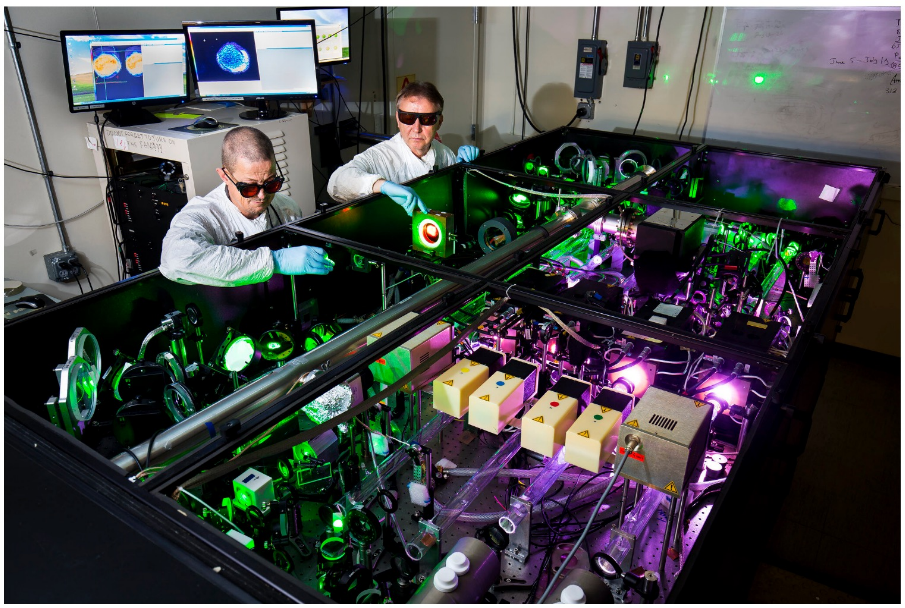
- "Extreme" plasmas (from U. Michigan News): Most powerful laser in the US to begin operations soon, supported by $18.5M from the NSF**:** *Experiments at the ZEUS facility are expected to contribute to the understanding of how the universe operates at the subatomic level and how astrophysical phenomena such as jets can be produced by black holes*. [Also, see NSF News item: Even COVID Can't Stop ZEUS]

New Laboratory Astrophysics Capability:

ZEUS -- NSF Mid-Scale Laser User Facility

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

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



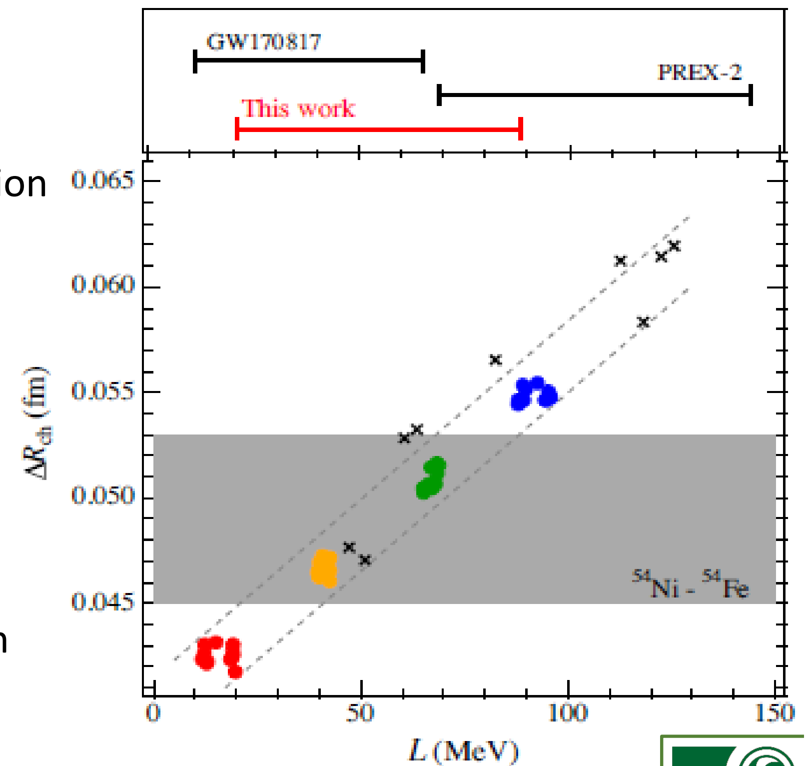
Anatoly Maksimchuk, EECS Research Scientist, and John Nees, EECS Associate Research Scientist, demonstrate use of the HERCULES 300 TW laser. Image credit: Joseph Xu, College of Engineering

- 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.

Operations beginning

EOS Symmetry Energy:
Neutron Stars, Parity Violation, Mirror Pair Charge Radii

- Nuclear Matter EOS → nuclei structure & stability, nucleosynthesis, NS structure
- For ∞ NM, EOS = $\frac{E}{A} - M = \mathcal{E}_{SNM}(\rho) + \alpha^2 S(\rho)$
  - $S(\rho)$ = "symmetry energy", with ρ dependence = L
- Pressure of n matter → neutrons outward against surface tension
  - Affects NS Radius: NICER + LIGO → 10 <~ L ~< 55 MeV
  - n-skin ($R_n - R_p$) of nuclei (see below)
- PREX @ JLab: elastic e + ^{208}Pb → A_{PV} → R_w → ΔR_{np} → L
- $\Delta R_{np} = R_{ch}(^A{}_Z X_N) - R_{ch}(^A{}_N Y_Z) = \Delta R_{ch} \sim |N - Z| \times L$
  - BECOLA @ NSCL:
    ^{54}Ni beam cooled, trapped, co-linear spectroscopy
    → $R_{ch}(^{54}Ni)$ [Z = 28, N = 26]
  - Compare w/$R_{ch}(^{54}Fe)$ [Z = 26, N = 28] → ΔR_{ch} = 0.049(4) fm
  - 21 < L < 88 MeV; somewhat softer than PREX

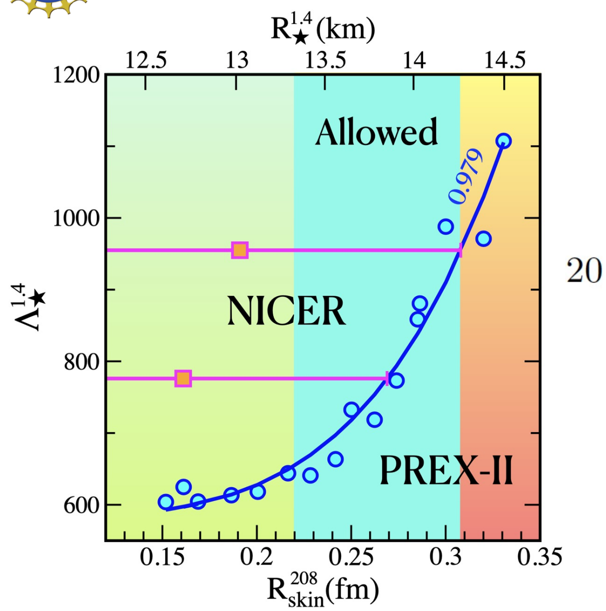


D. Adhikari, et al., Phys Rev Lett, **126**, 172502 (2021)

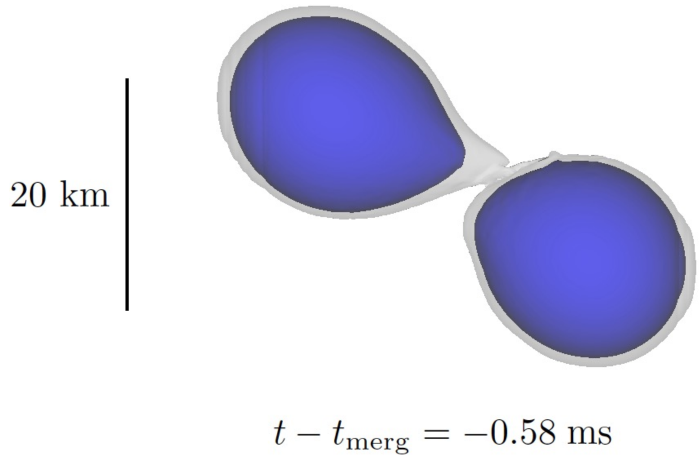
B.T. Reed, et al., Phys Rev Lett, **126**, 172503 (2021)

S.V. Pineda, et al., Phys Rev Lett, **127**, 1825013 (2021)

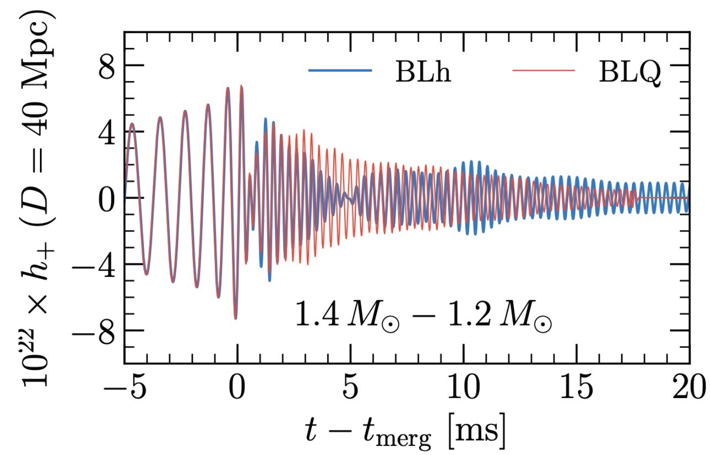
Nuclear Physics from Multi-Messenger Mergers (NP3M)



Nuclear physics of dense matter connected to neutron star observations



Simulations of NS mergers and kilonovae



Connections to multi-messenger observations

- NP3M Focused Research Hub in Theoretical Physics. Nuclear Physics. Supports 6 postdoc FTEs over 5 years, schools, workshops
- Goal: Advance nuclear theory and generate microphysics input for simulations and comparisons with multi-messenger observations
- Involves theorists and observers from the astronomy community

Theoretical Particle Astrophysics and Cosmology at NSF ---

deeply connected to HEP Theory program, reflecting the close synergies between these two fields --- even reviewed and funded together!

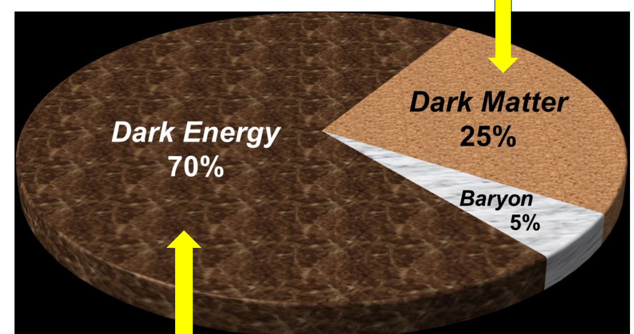
Broad Spectrum of Funded Research

- RUI: The Non-Linear Universe: Precision Numerical Cosmology and Fundamental Physics
- Investigating Fundamental Physics with Cosmological Probes
- Probing Dark Matter Physics throughout Cosmic History
- Observational Signatures of Cosmic Strings
- Testing SIDM (Self-Interacting Dark Matter) with Realistic Galaxy Formation Simulations
- Imprints of New Physics on Cosmological Observations
- RUI: Precision Cosmological Tests of Varying Fundamental Constants
- Fundamental Physics and Cosmology
- Novel Astrophysical Probes of Exotic Dark Matter
- CAREER: New Dimensions in Particle Dark Matter and Physics Pedagogy
- Dark Matter: Fundamental Processes and Quantum Information Aspects
- Dark Matter, Dark Energy, and New Physics
- RUI: Exploring Asymmetric Dark Universes
- Initial Perturbations on Ultra-Small Scales and Primordial Black Holes
- Cosmological and Astrophysical Signatures of Axions
- CAREER: Illuminating the Early Universe with Dark Matter
- CAREER: Searching for Dark Sectors from Earth to Sky
- Investigating the Nature of Dark Matter throughout Cosmological History

Major theme of current research!

- Not just WIMPS!
- Axions?
- Primordial Black Holes?
- Cosmic strings?
- Basic properties: Self-interactions? Decays? Couplings to visible sector?

Funded research pushes the boundaries on all parts of the cosmic pie…



Major theme of current research!

- New Inflationary paradigms and tests
- New methods of reheating
- Studies of structure formation
- Alternate cosmological timelines --- not just standard thermal history
- Hubble tension, other anomalies

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.

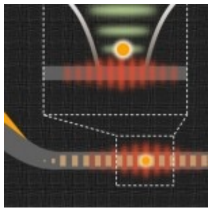
Designed to foster major breakthroughs at the intellectual frontiers of physics by providing needed resources not usually available to individual investigators or small groups, in an environment in which the collective efforts of the larger group can be shown to be seminal to promoting significant progress 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.

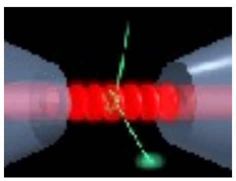
See US NSF - MPS - PHY - Physics Frontiers Centers (PFC)

Physics Frontiers Centers



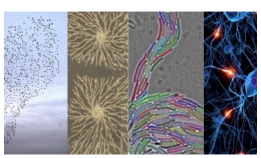
Center for Ultracold Atoms – MIT/Harvard – Ketterle
(With CISE/CCF)

PFC@JILA – Colorado – Cornell



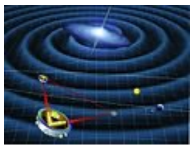
Institute for Quantum Information and Matter – Caltech
- Preskill (With CISE/CCF)

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



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

Physics Frontiers Centers (Cont'd)



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

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

The Center for Matter at Atomic Pressures (CMAP) –
U Rochester – Collins (GEO/EAR)

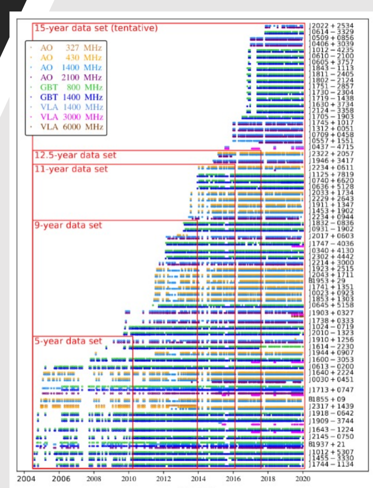
New Competition in FY 2023; opens August 2022

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

The results of analysis of the 14-year catalog, expected in 2022, could confirm the first detection of GW not using laser interferometry.



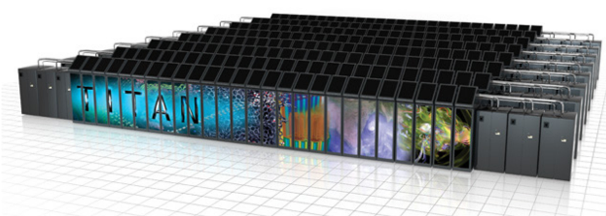
Network for Neutrinos, Nuclear Astrophysics and Symmetries (N3AS)

– a Physics Frontier Center (PFC), NSF-2020275

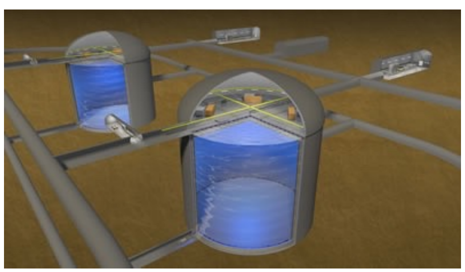
- *Connecting Quarks to the Cosmos*
- Multi-disciplinary, *national* theory collaboration to support multi-messenger astrophyisics
- UC Berkeley leads a 12-institution collaboration & DoE National Laboratory (LANL)
- International partners: RIKEN, CNRS

LIGO/Virgo/KAGRA

James Webb Telescope

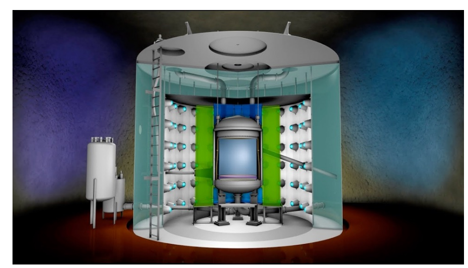


Exascale simulations



DUNE and Hyper-Kamiokande

Simons Observatory, CMB S4, …



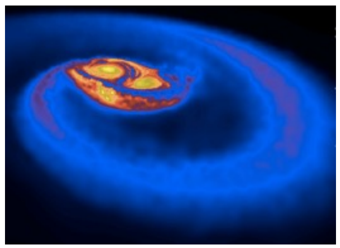
Dark Matter (LZ)

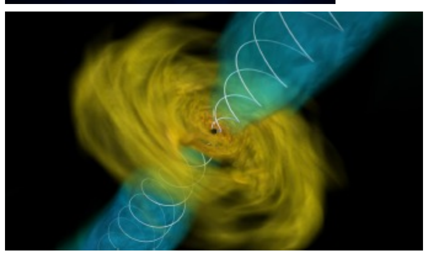
Network for Neutrinos, Nuclear Astrophysics and Symmetries (N3AS)

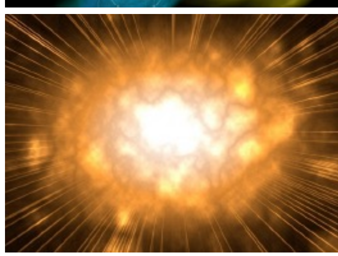
– a Physics Frontier Center (PFC), NSF-2020275

MA5: State-of-the-art HPC modeling critical to N3AS goals

Neutron Star Merger (e.g. GW170817)



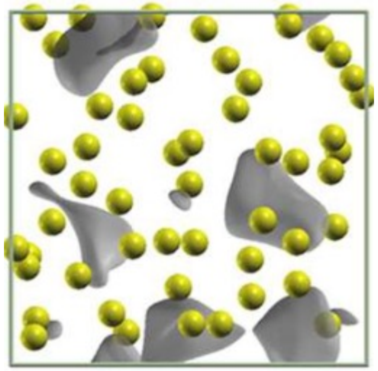


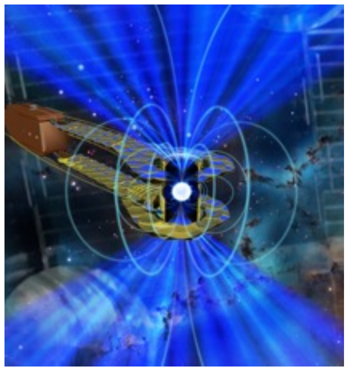


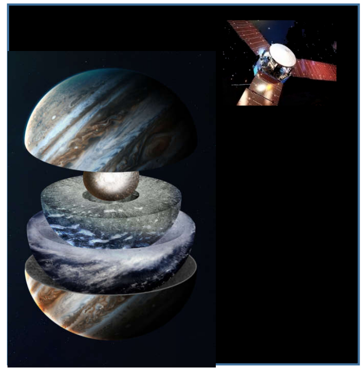
Epoch	*Physics*
Merger (milliseconds)	***Gravitational Waves***
NSs are deformed, disrupted, and expel matter as they coalesce	Wave form constrains masses, spins, and EoS of the NSs
Disk Accretion (seconds)	***Winds and Relativistic Jets***
Neutrino-irradiated disk material both accelerated and blown off star by jets, winds	Observations of gamma ray/x-ray/radio emission constrain the relativistic outflows
Aftermath (weeks)	***Kilonova***
Cloud of ejected neutron-rich material, radioactively powered, expanding and cooling, radiating	Matter re-assembles into heavy unstable nuclei via the r-process, impacting optical/infrared signatures

NSF Physics Frontiers Center

Center for Matter at Atomic Pressures (CMAP)







Emerging experimental and computational capabilities enable the exploration of atomic pressure matter to understand astrophysical observations

CMAP invites today's and tomorrow's leaders to explore the nature of planets and stars throughout the universe, as well as the potential for revolutionary states of matter here on Earth: **https://www.rochester.edu/cmap/**

CMAP includes a summer internship program for high schoolers, an undergraduate summer school, and a communications bootcamp

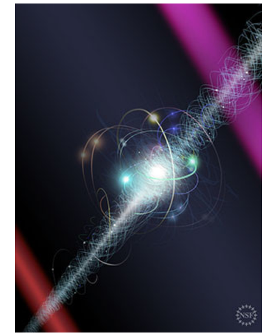
Future physicists experience research firsthand during internship at Rochester

October 31, 2021

East High School student Six Williams focuses a camera to take emission measurements on a spectrometer. (Photo credit: Imani West-Abdallah)

CMAP | Massachusetts Institute of Technology | Princeton University | University at Buffalo | UC Davis | Berkeley University of California | University of Rochester | NSF

Precision Matters

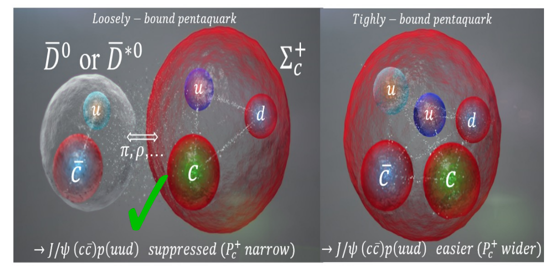


Credit: Nicolle R. Fuller/NSF

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

Partnerships for Research and Education in Physics (PREP)

Goals:

- Enable and grow partnerships between minority-serving institutions and Division-supported Physics Frontiers Centers
- Increase the participation of members of underrepresented groups in physics through excellent research and education endeavors
- Full intellectual engagement on both sides

Status:

- Solicitation 21-610
- First deadline Jan 21, 2022

The Center for Matter at Atomic Pressures (CMAP)
University of Rochester

North American Nanohertz Observatory for Gravitational Waves
University of Wisconsin - Milwaukee

Center for the Physics of Biological Function
Princeton University

JILA Physics Frontiers Center
University of Colorado, NIST

Center for Theoretical Biological Physics
Rice University

Center for Ultracold Atoms
Massachusetts Institute of Technology

Institute for Quantum Information and Matter
California Institute of Technology

The Network in Neutrinos, Nuclear Astrophysics and Symmetries
University of California Berkeley

Diversity and Inclusion

Updated Physics Division Diversity Plan and Activities

US NSF - MPS - PHY - Broadening Participation Resources

Links provide a sampling of information that may help Principal Investigators and others in broadening participation in their activities. The list is not meant to be exhaustive or to imply any special endorsement by PHY (or NSF).

nsf21065 Dear Colleague Letter: PHY Supplements: Growing a Strong, Diverse Workforce | NSF - National Science Foundation

Encourages meaningful actions that increase the awareness and participation by historically underrepresented groups in all fields of research supported by the Division of Physics.

Division also participates in MPS-wide AGEP, LEAPS and ASCEND programs