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

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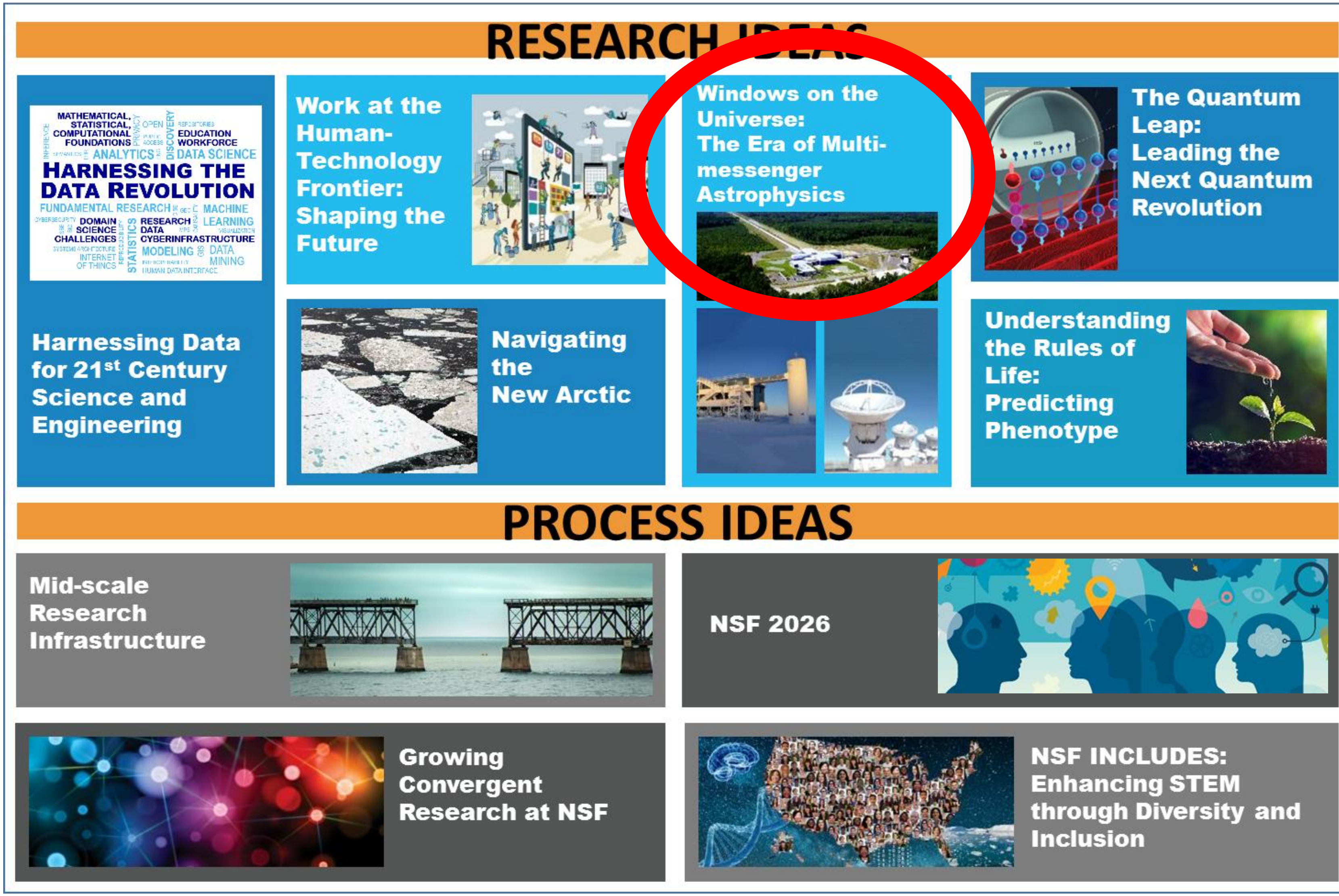
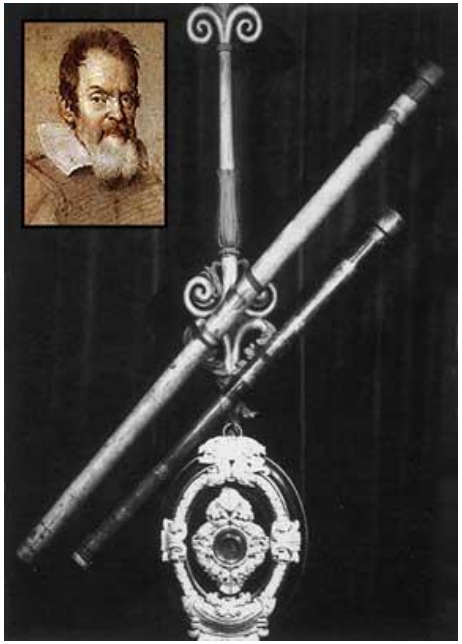
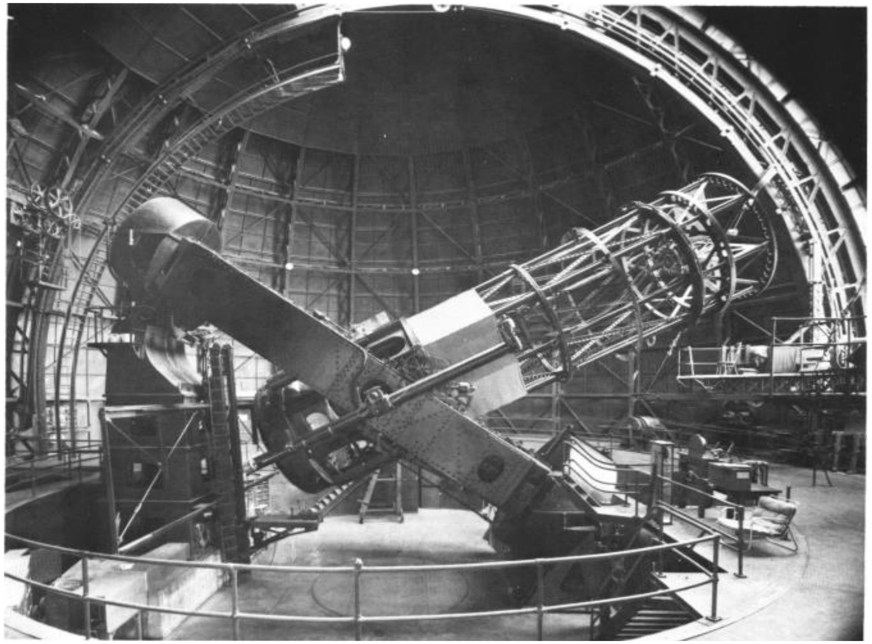
NSF's 10 "Big Ideas" for Future Investment



First, there was Optical Astronomy

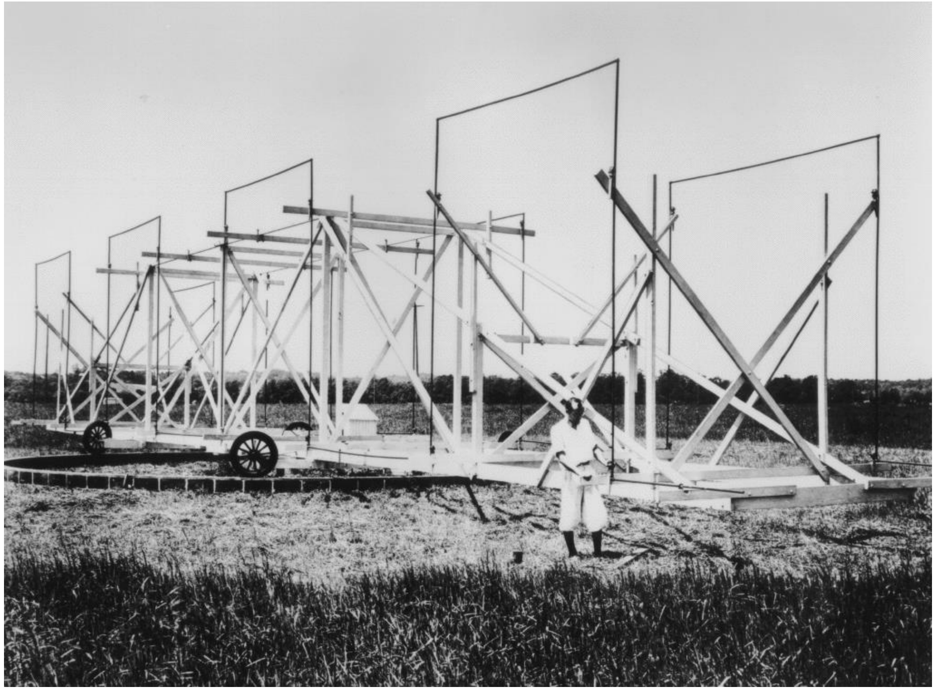




- Galileo (1609) → Mt. Wilson 100-inch (1917)

Credits: APS, NPS, Caltech, AURA

Then, there was Radio Astronomy

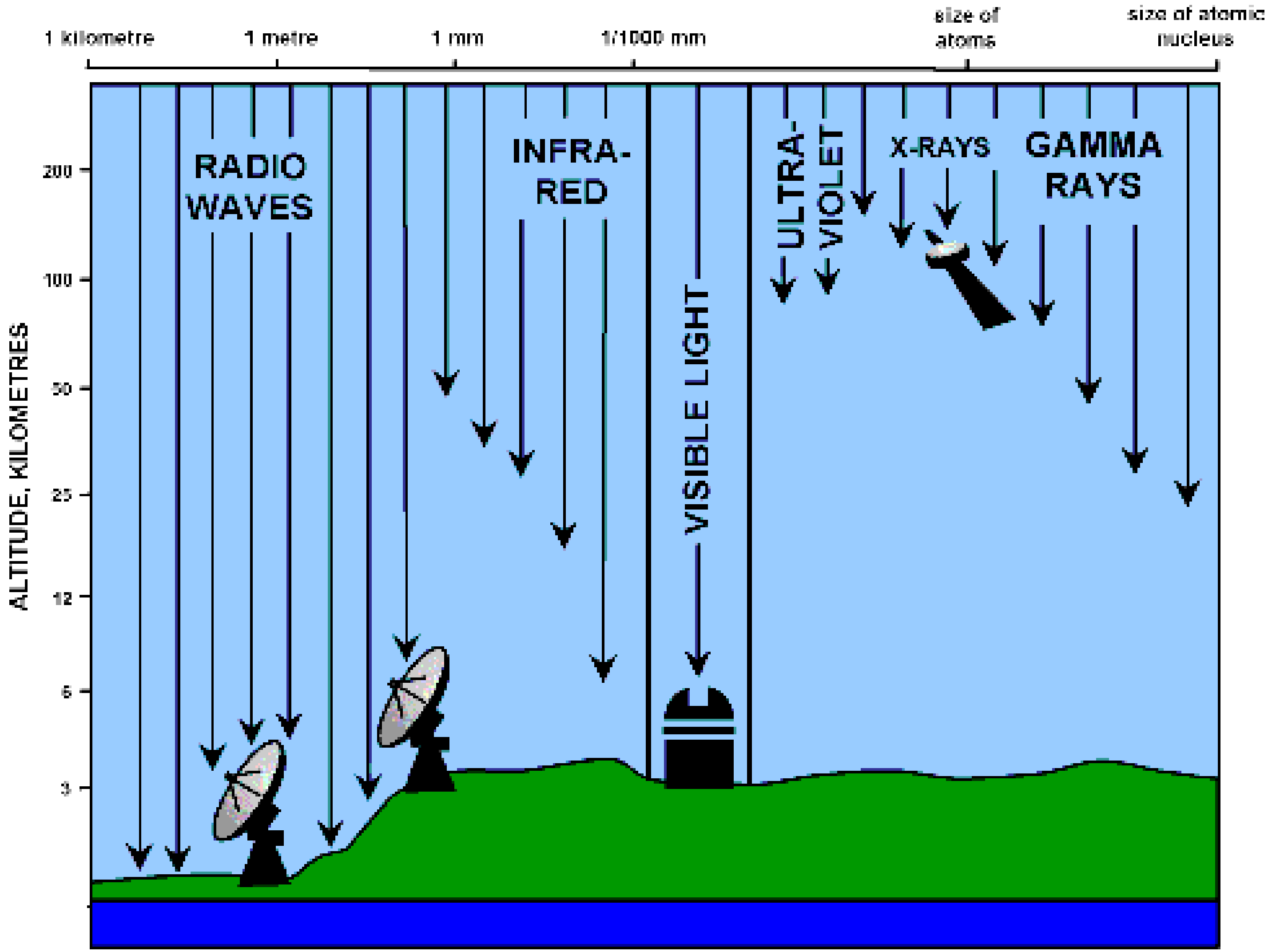


- Karl Jansky Radio Telescope (1933) → Karl G. Jansky Very Large Array (1980)

ALMA (2013)

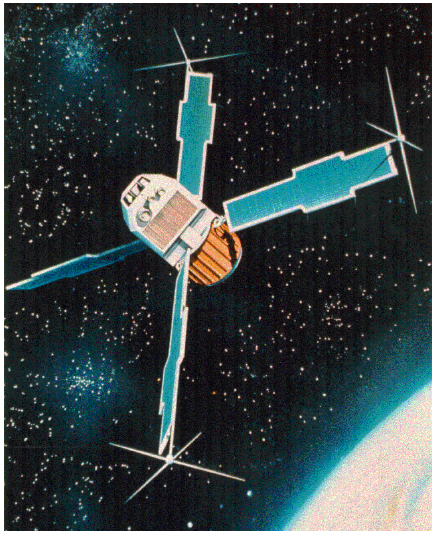
Credits: AUI/NRAO

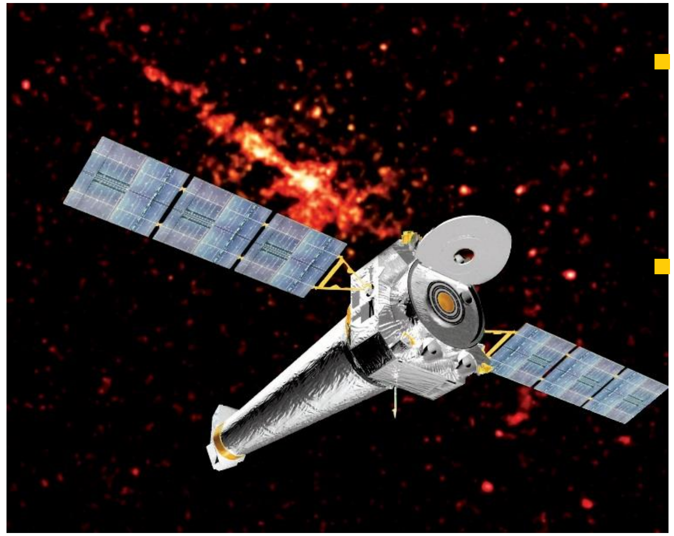
Atmospheric Transparency



Credit: CSIRO/ATNF

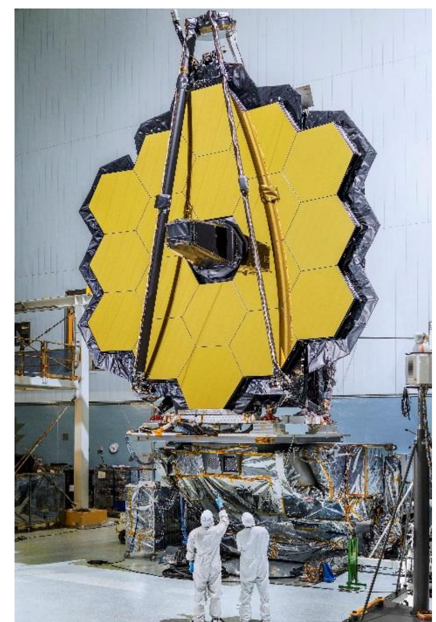
Space-based Detectors





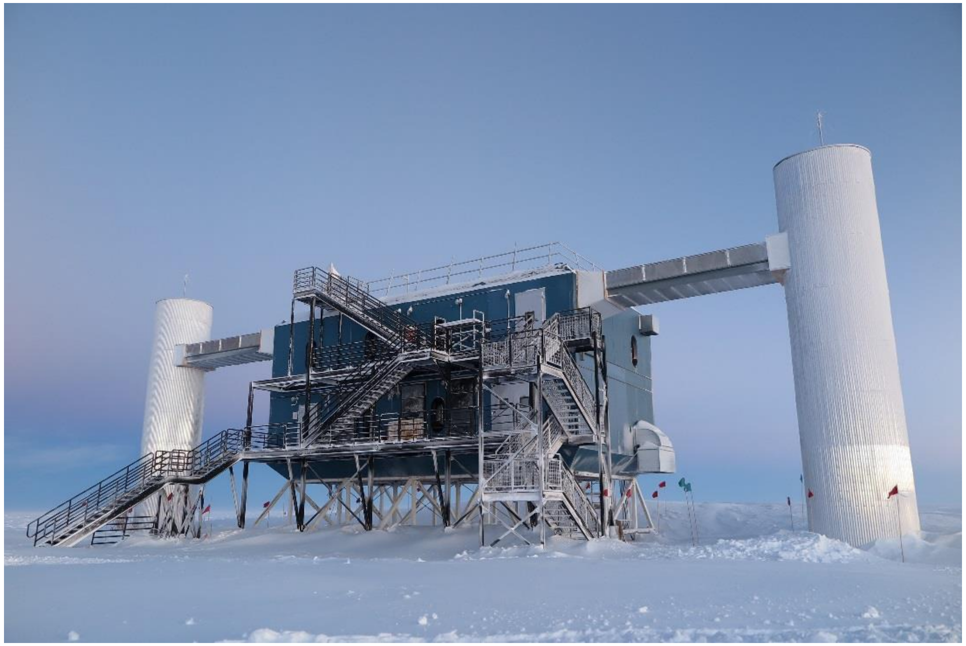
- γ-ray: Compton (1991)→
- Fermi (2008)

- X-ray: Uhuru (1970)→Chandra (1999)
- Infrared; IRAS (1983)→Spitzer (2003)→James Webb Space Telescope (2019)



Credits: Harvard, NASA, GSFC, Caltech/JPL

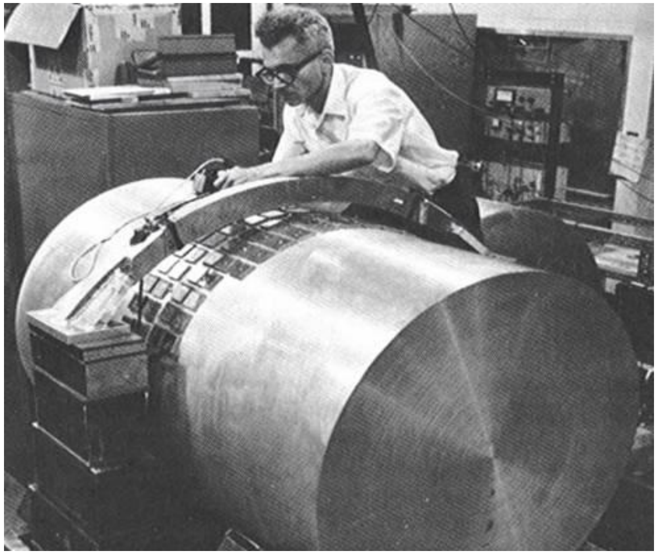
Neutrino Detectors



- Homestake Mine (1960s) → IceCube (2010s)

Credits: Brookhaven National Lab, Erik Beiser, IceCube/NSF

Gravitational Wave Detectors



- Weber Bar (1966) → LIGO (2017)

Credits: UMd, Caltech/MIT/LIGO Laboratory

Science Vision

- The goal of “Windows on the Universe” is to bring electromagnetic waves, high-energy particles, and gravitational waves together to study the universe and probe events in real time in a way that was previously impossible.

Why Now? What's Needed?

- We are at the cusp of a new era where we can finally utilize all three "windows" to study the universe and address long-standing questions
- NSF is uniquely positioned as the only agency engaged in all three windows
  - Interagency collaboration has important role to play
- We are currently supporting efforts in all three windows, but scope has been limited to opening or maintaining this windows, not to expanding them
- New resources needed to make the connections among the different messengers, simultaneously utilize different windows, and fully exploit the scientific opportunities

Windows on the Universe—Science Questions

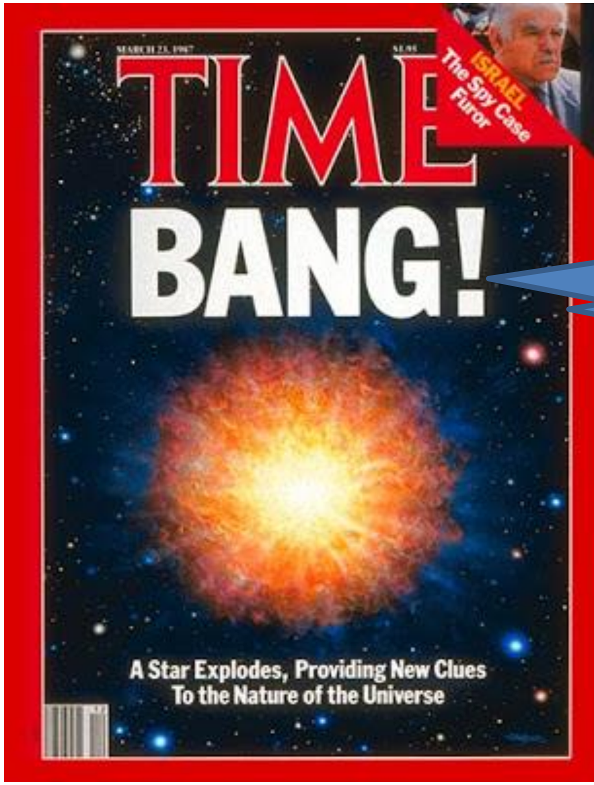
- How did the universe begin?
- Why is the universe accelerating?
- What is the unseen matter that constitutes much of the universe?
- How does gravity work under the most extreme conditions?
- What are the properties of the most exotic objects in the universe?
- How do matter and energy evolve to produce the universe around us?

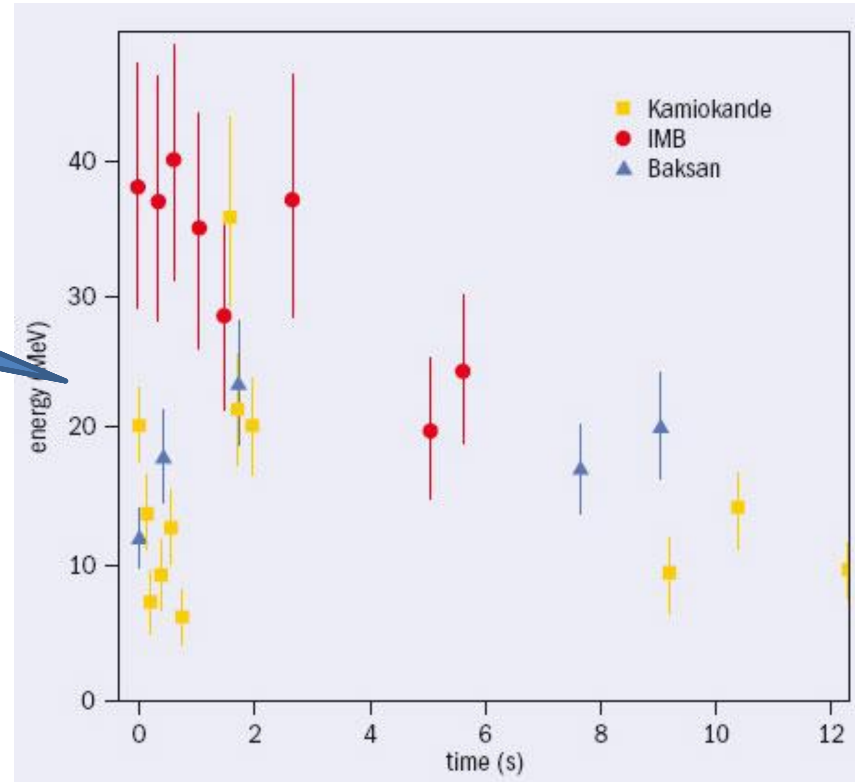
- Not all of astrophysics! (e.g., life beyond Earth)

Solar Neutrinos (EM+particle)

- Visible brightness of Sun provides constraint on modeling of Sun's interior, and rate of production of neutrinos
- Long-time deficit in apparent flux of solar electron neutrinos (from ^{8}B decay)
  - Detection of neutrinos: Nobel prize to Davis and Koshiba in 2002
  - Discovery of neutrino oscillations and neutrino state mixing: Nobel prize to Kajita and McDonald in 2015

Supernova 1987A (EM+particle)

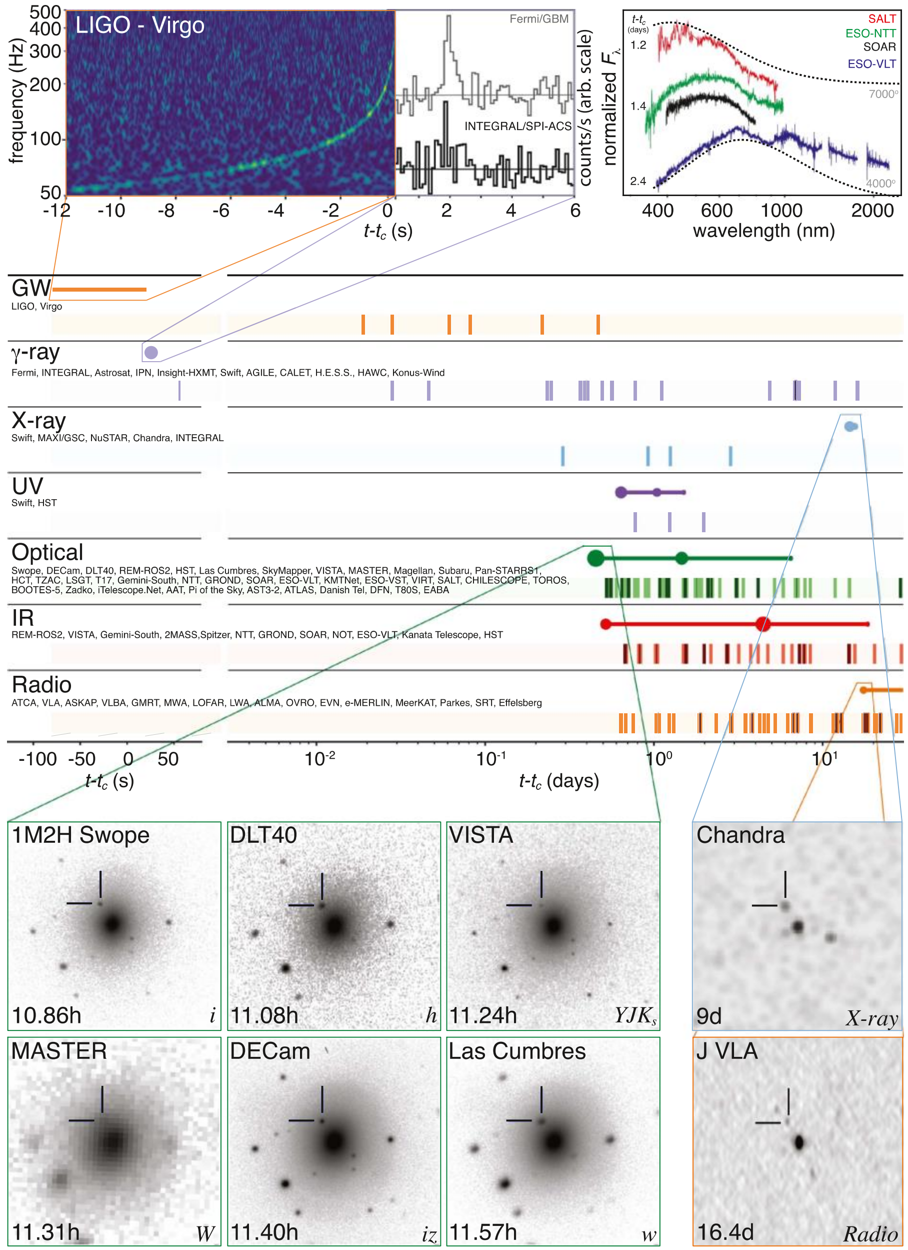




Credit: CERN/IOP

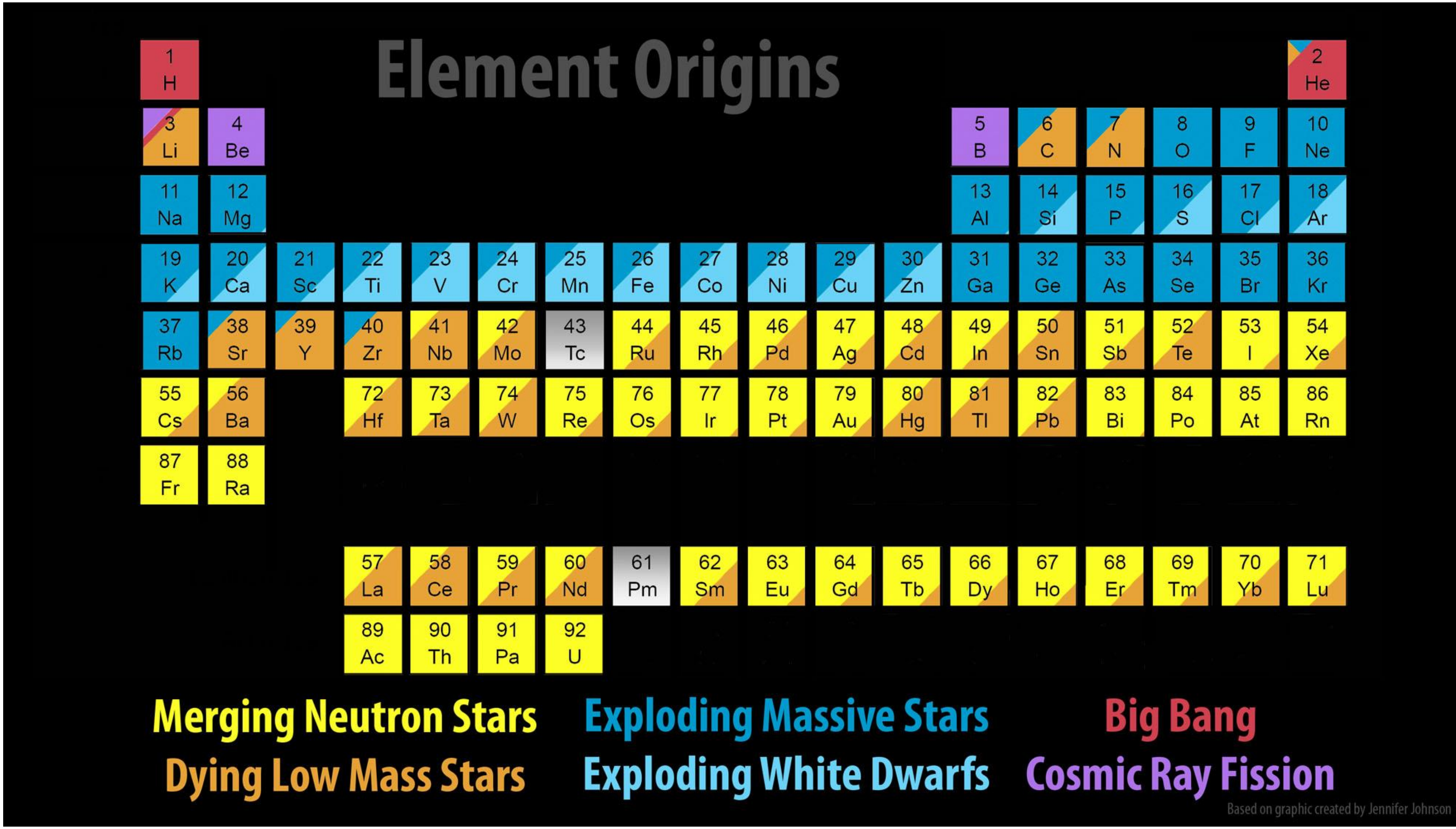
- Detection of anti-neutrinos preceded the visible light by several hours

Binary Neutron Star Merger (Grav. Wave + EM)



Credit: Abbott et al., 2017. ApJL, 848, L12, IOP/AAS

Products of Neutron Star Merger



Credit: Jennifer Johnson/SDSS

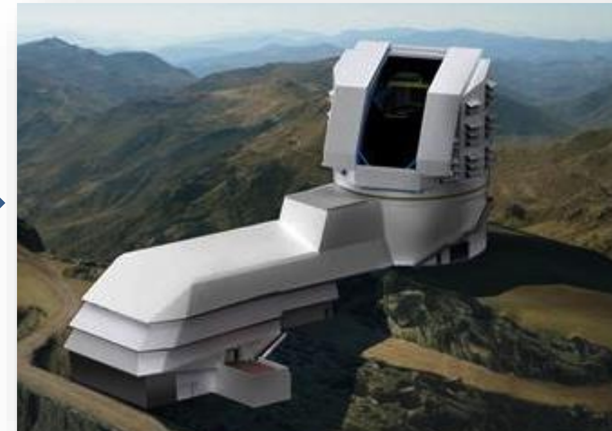
Windows Implementation

- Enhanced support for growing community of individuals and groups needed to fully enable the multi-messenger paradigm
- Enhanced support for existing facilities including computational and data activities to provide broad access to data in a heterogeneous environment
- Development and construction of instrumentation and new projects that enhance the role of the existing large facilities

- These are all closely related to the Big Idea on Harnessing the Data Revolution
- New projects tend to fall in the “large mid-scale” class

Who Does Multi-Messenger Astronomy?

Example 1: Large Synoptic Survey Telescope (LSST)



- LSST 10-year survey to start in FY 2023
- Wide field of view, high sensitivity, and rapid observing cadence are ideal for identifying gravitational-wave counterparts and sources of particle events
- At 10 million events per night, infrastructure and algorithms will be critical to proper identification
- LSST addresses acceleration of universe in multiple ways

Credit: LSST Project/NSF/AURA

Example 2: Cosmic Microwave Background (CMB)

- CMB Stage 4 goals: measure polarization imprinted by gravitational waves at epoch of inflation (also neutrino masses)
- Two sites: South Pole and Atacama
- Fourteen small (0.5m) telescopes and three large (6m) telescopes, with 512K total detectors

Credits: U. Chicago, U. Penn

Some Other Examples

- Example 3: LIGO A+ Upgrade
  - Use squeezed light and new coatings to increase sensitivity by a factor of ~1.7 over design sensitivity of current LIGO, resulting in a 5-fold increase in detections of neutron-star mergers
- Example 4: TRIPODS + X
  - Transdisciplinary Research In Principles Of Data Science (mathematics, computer science, statistics) joined with domain scientists to use data science to solve specific domain-science problems

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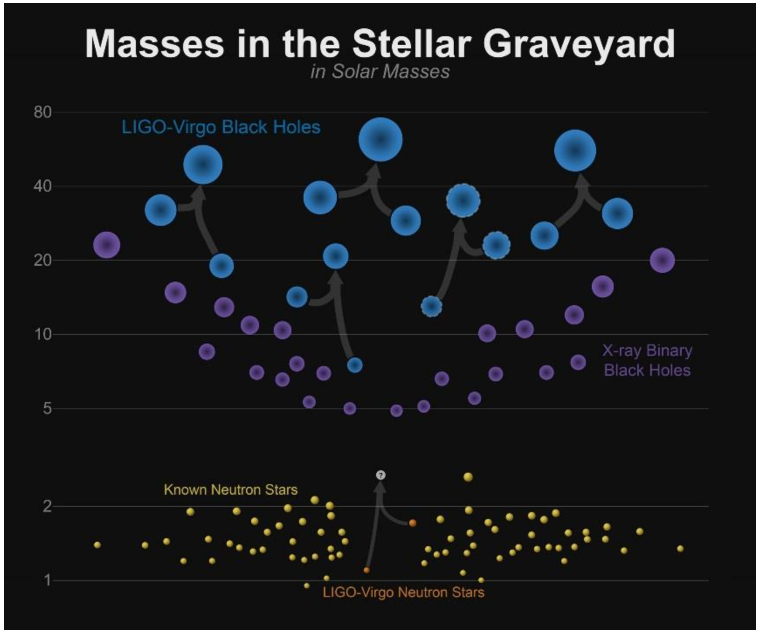
Backup Slides Follow

LIGO Detections (Grav. Waves + EM)



Five Confirmed LIGO Detections

Four mergers of binary black holes, and one merger of a binary neutron star pair. The binary black hole mergers have detectable signals for up to two seconds, while the neutron star merger signal lasted for over a minute

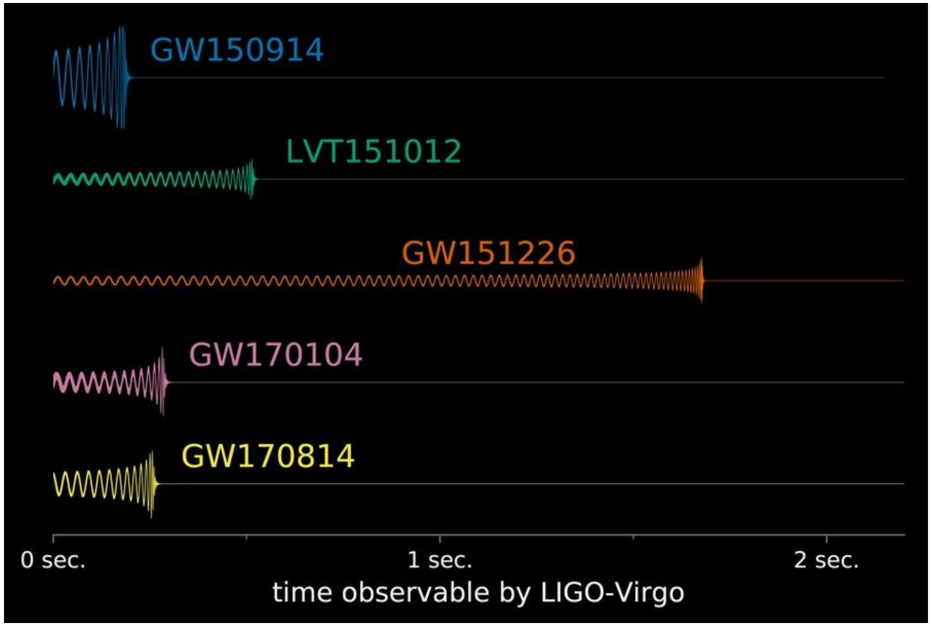


Image Credits: LIGO.org

Black-hole mergers result in final black holes with masses 20-60 times the mass of the sun. The binary neutron star merger involved the merger of two objects with masses of 1.1 and 1.6 times the mass of the sun, with the resulting object being either a low-mass black hole or a massive neutron star.

2002 Connecting Quarks with the Cosmos - 1

- What is dark matter?
- What is the nature of dark energy?
- How did the universe begin?
- Did Einstein have the last word on gravity?
- What are the masses of the neutrinos, and how have they shaped the evolution of the universe?
- How do cosmic accelerators work and what are they accelerating?

2002 Connecting Quarks with the Cosmos - 2

- Are protons unstable?
- What are the new states of matter at exceedingly high density and temperature?
- Are there additional space-time dimensions?
- How were the elements from iron to uranium made?
- Is a new theory of matter and light needed at the highest energies?

2010 Astronomy & Astrophysics Decadal Survey

- Frontiers of Knowledge:
  - Why is the universe accelerating?
  - What is dark matter?
  - What are the properties of neutrinos?
  - What controls the mass, radius, and spin of compact stellar remnants?
- Understanding the Cosmic Order
  - What controls mass-energy-chemical cycles in galaxies?
  - How do black holes grow, radiate, and influence their surroundings?
  - How do the lives of massive stars end?
- Discovery
  - Gravitational-wave & time-domain astronomy

2014 Particle Physics Project Prioritization Panel (P5)

- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with the neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles

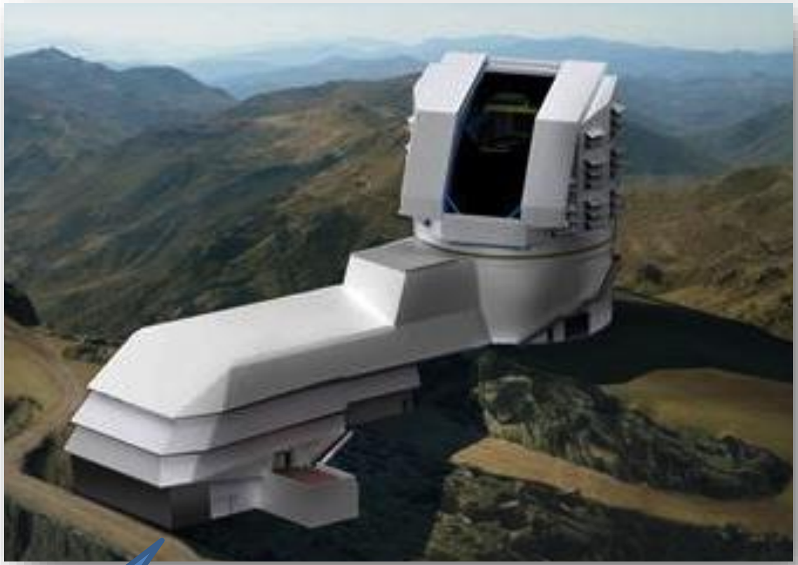
2015 Nuclear Science Advisory Committee Long Range Plan

- Where do nuclei and elements come from?
- How does structure (stars, galaxies, galaxy clusters, and supermassive black holes) arise in the universe and how is this related to the emergence of the elements in stars and explosive processes?
- What is the nature of matter at extreme temperatures and densities?
- How do neutrinos and neutrino masses affect element synthesis and structure creation?

Electromagnetic Radiation

- Investigators and Groups: Grow the multi-messenger community; support computational and theoretical networks; data-science initiatives
- Facility Operations and R&D: Data brokering for Large Synoptic Survey Telescope (LSST); new software, algorithms, and data structures
- Equipment Construction: New instruments for 8-m class optical telescopes; next-generation gamma-ray experiments
- Interagency collaboration: (LSST + WFIRST, CMB-S4)

Large Synoptic Survey Telescope (LSST)



- 10 million alerts per night

Gravitational Waves

- Investigators and Groups: LIGO has created a new field of astrophysics—this field will grow rapidly, and needs increased support

- Facility Operations and R&D: Development of new mirror coatings; design studies for third generation of detectors

- Equipment Construction: Advanced LIGO Plus (A+), could increase LIGO's range by a factor of 1.7 (five-fold increase in event rate) over current design sensitivity by 2023.

- When LIGO detects neutron-star mergers on a regular basis, how will the EM community respond?

High-Energy Particles

- Investigators and Groups: IceCube is spurring growth of particle astrophysics, and Windows on the Universe needs to draw on this community

- Facility Operations and R&D: Development of two potential enhancements to IceCube, one small-scale and one MREFC-scale, and next-generation cosmic-ray facilities

- Equipment Construction: radio-frequency radiation from neutrino-ice interaction; expand low-energy limit of IceCube; increase sensitive IceCube volume from 1 km^3 to 10 km^3