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

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What Is MMA?

- Until mid 20th century, electromagnetic (EM) radiation (optical photons) was only messenger to study distant Universe; later, advanced technology allowed to span almost entire EM spectrum (radio to gamma rays).

- In recent decades, cosmic messengers from other three forces of Nature (gravity waves, neutrinos, and cosmic rays) began to be used in earnest.

- MMA is long-anticipated extension to traditional multi-wavelength astronomy; it recently emerged as distinct discipline providing unique and valuable insights into properties and processes of physical Universe.

- Now we are using complete set of forces of Nature to unravel its mysteries!

Key Insights from Recent Observations

- Diffuse backgrounds of high-energy neutrinos (HENs; energies > 10 TeV), ultra high-energy cosmic rays (UHECRs; energies > 10^{18} eV), and gamma-rays (energies from MeV to TeV) have been measured (via Cherenkov detectors, air-shower arrays, *etc.*).

- Sources of diffuse HENs and UHECRs remain unknown, although gamma-ray-flaring blazars (special type of AGNs) have been tentatively identified with observed HENs (30% of HEN background is due to blazars).

- First HEN detection used to locate blazar (3.7 Gly away) was achieved in Sep of 2017 thanks to IceCube Neutrino Observatory in Antarctica.

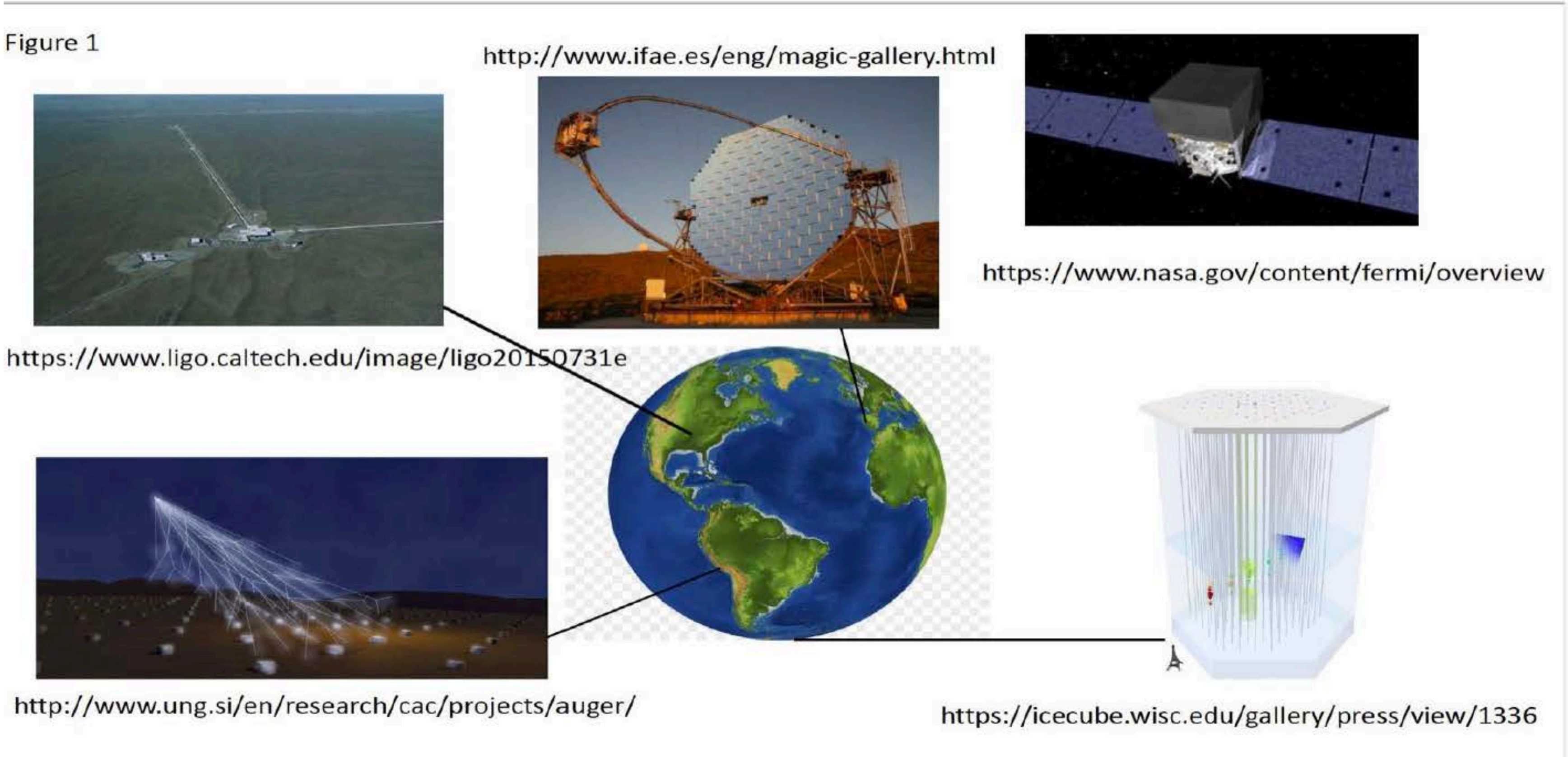
Key Insights from Recent Obs. (Cont.)

- Gravitational waves (GWs) from merging stellar-mass black hole (BH) and neutron star (NS) binaries have been detected by LIGO/Virgo (laser interferometers) in Apr of 2019.

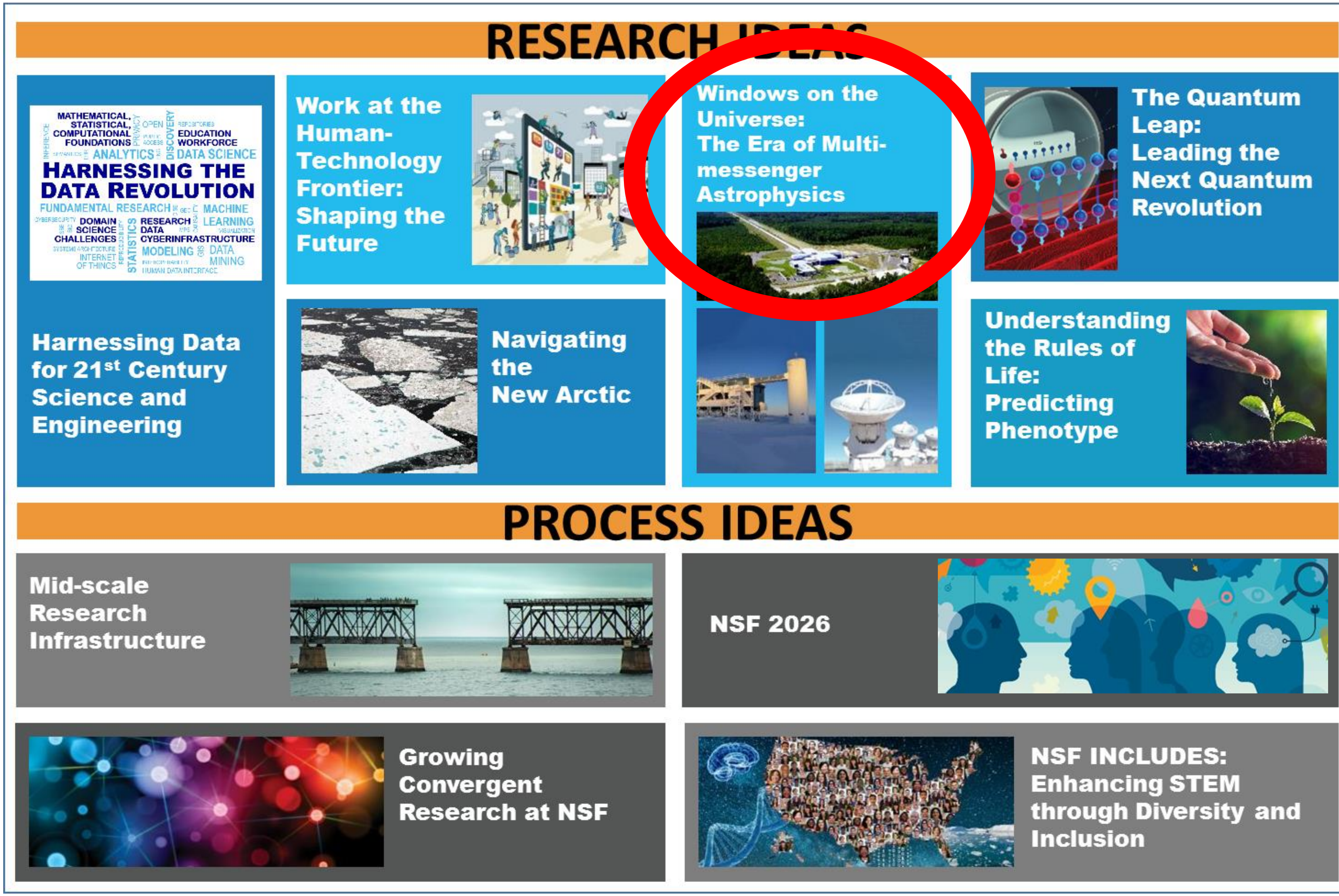
- Since 2015, advanced LIGO/Virgo observatories can detect tens of binary mergers (BH+BH, NS+NS, *etc.*) per run (O3 suspended) up to Gly distances; yet, EM counterpart searches are lagging due to premature aging detectors (*Swift*, *Fermi*, *etc.*).

- There is natural connection between UHECRs interactions and resulting HENs and gamma-rays, which needs to be fully exploited in order to better understand nature of its physical sources!

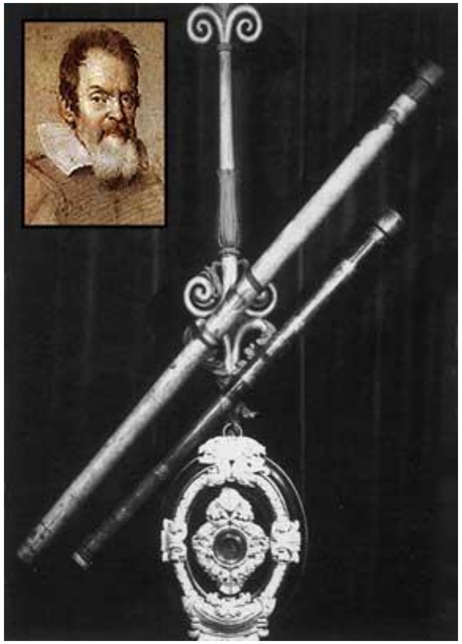
Current Fleet of Cosmic Messengers

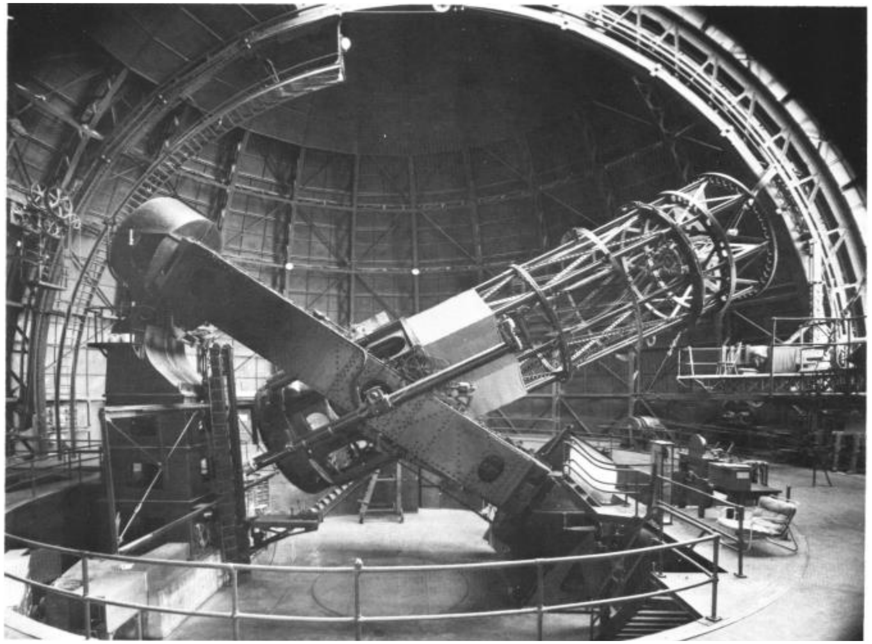


NSF's **10 Big Ideas** for Future Investment



First, There Was Optical Astronomy

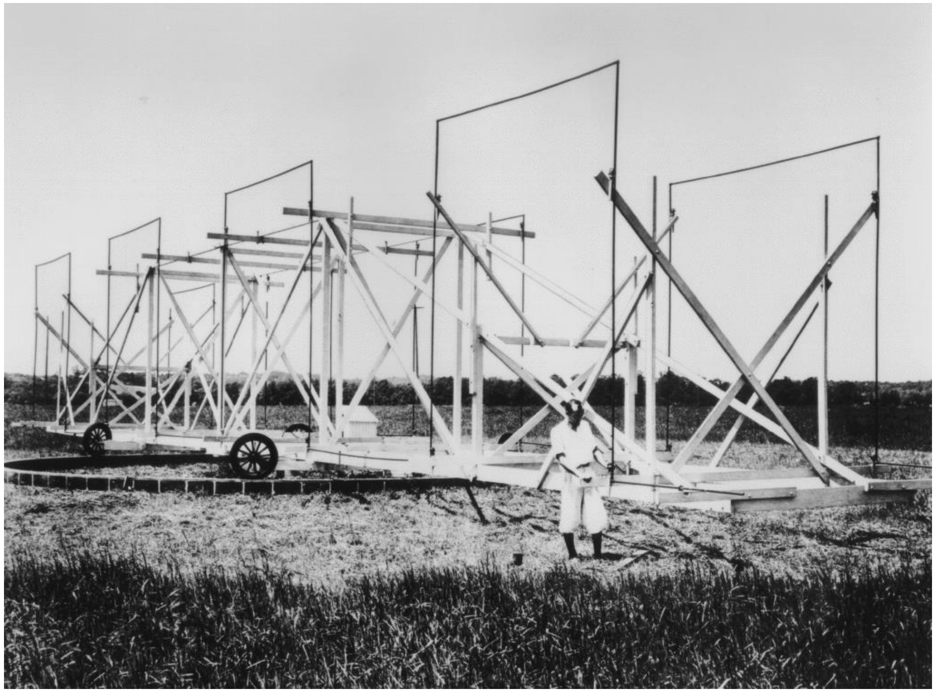




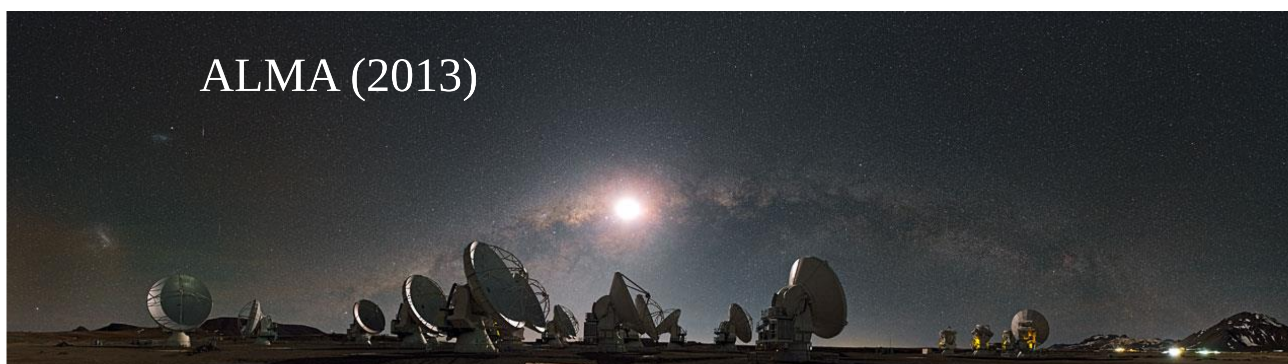
- Galileo (1609) → Mt. Wilson 100-inch (1917)

Credits: APS, NPS, Caltech, AURA

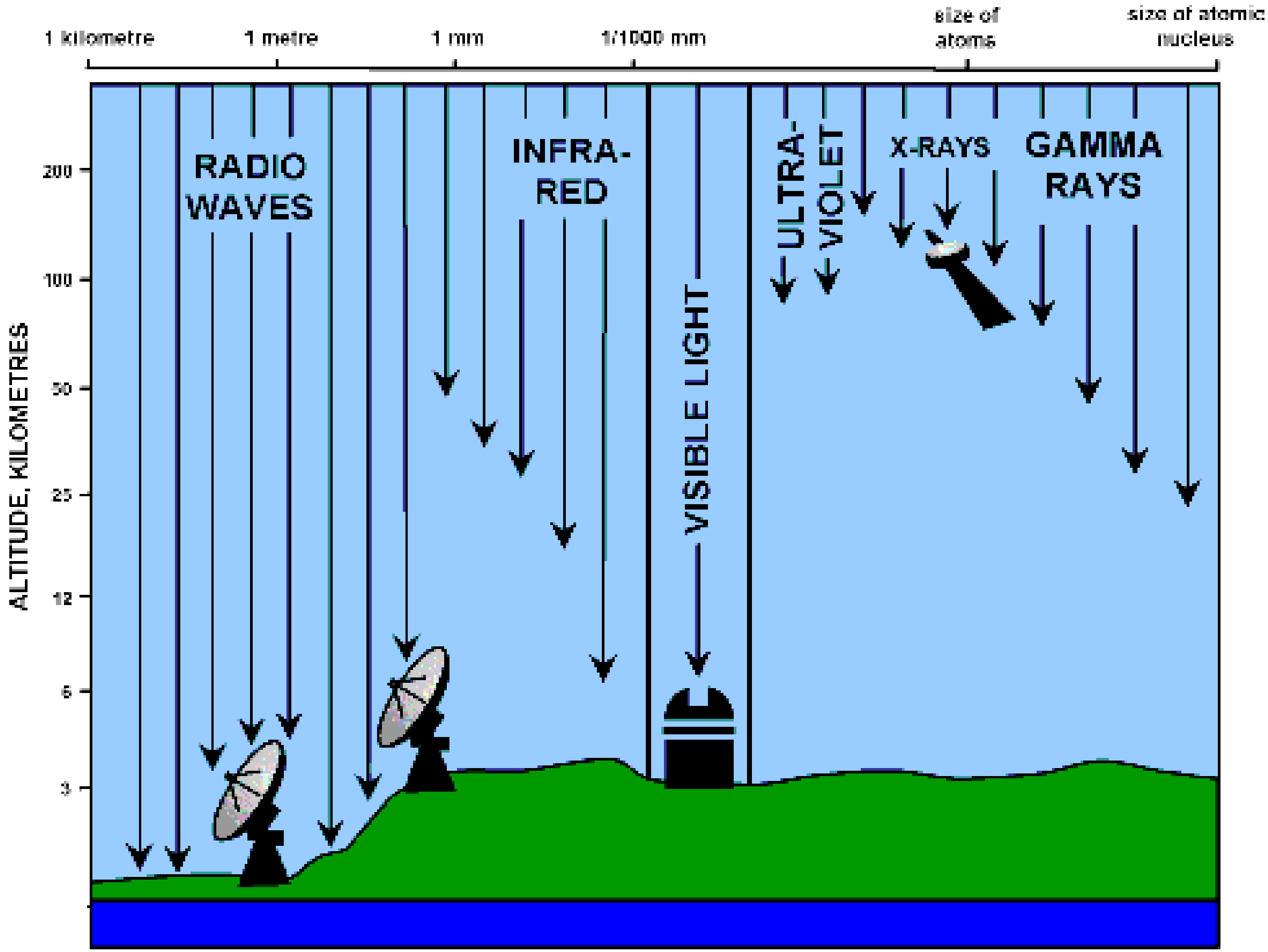
Then, There Was Radio Astronomy



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

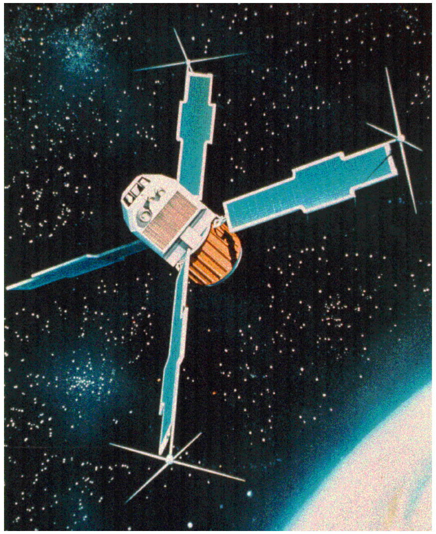


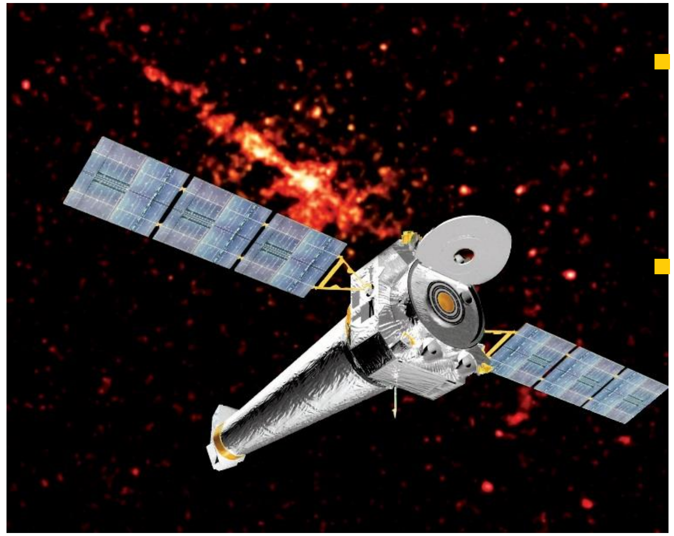
Atmospheric Transparency



Credit: CSIRO/ATNF

Space-Based Detectors



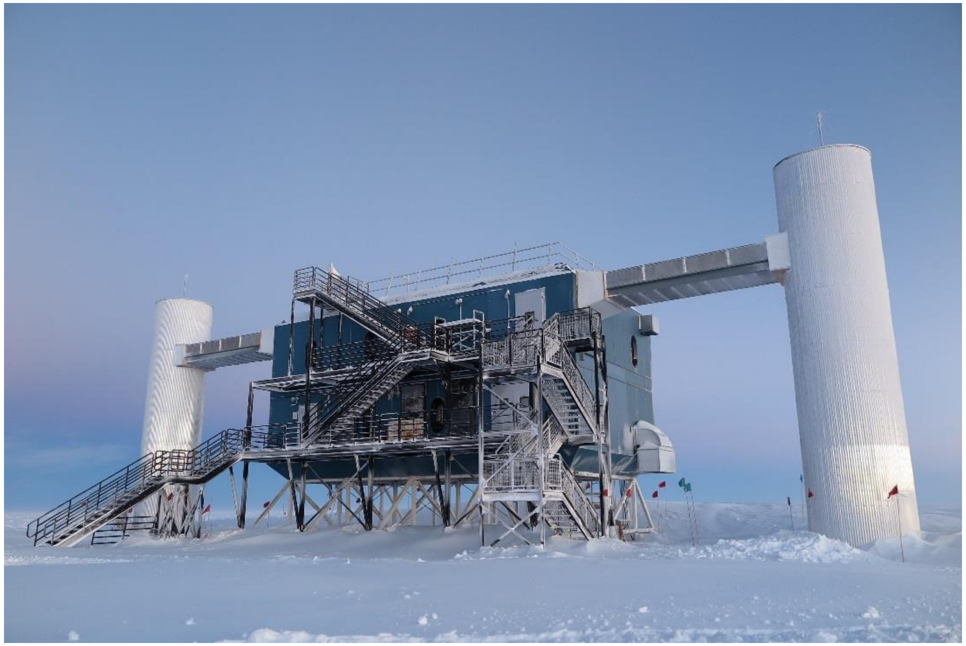


- γ-ray: Compton (1991)→
- Fermi (2008)

- X-ray: Uhuru (1970)→Chandra (1999)
- Infrared; IRAS (1983)→Spitzer (2003)→James Webb Space Telescope (2021)

Credits: Harvard, NASA, GSFC, Caltech/JPL

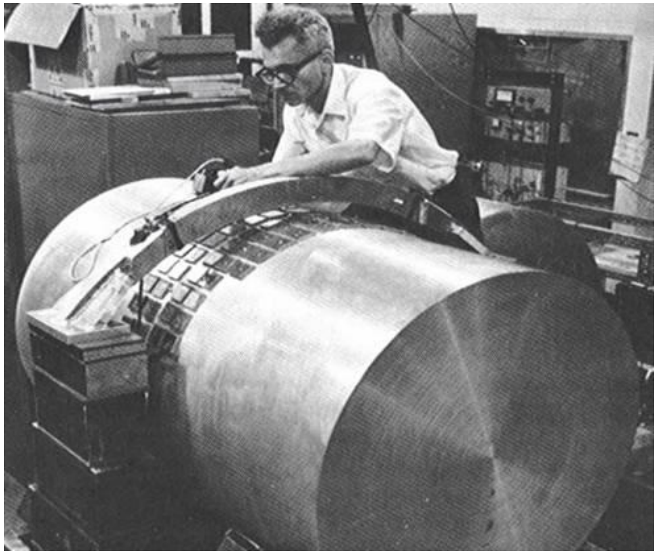
Neutrino Detectors



- 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

NSF's Science Vision

The goal of "Windows on the Universe" is to bring electromagnetic (EM) waves, high-energy particles (UHECRs and HENs), and gravitational waves (GWs) together to study Universe and probe events in real time in way that was previously impossible.

Why Now? What Is Needed?

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

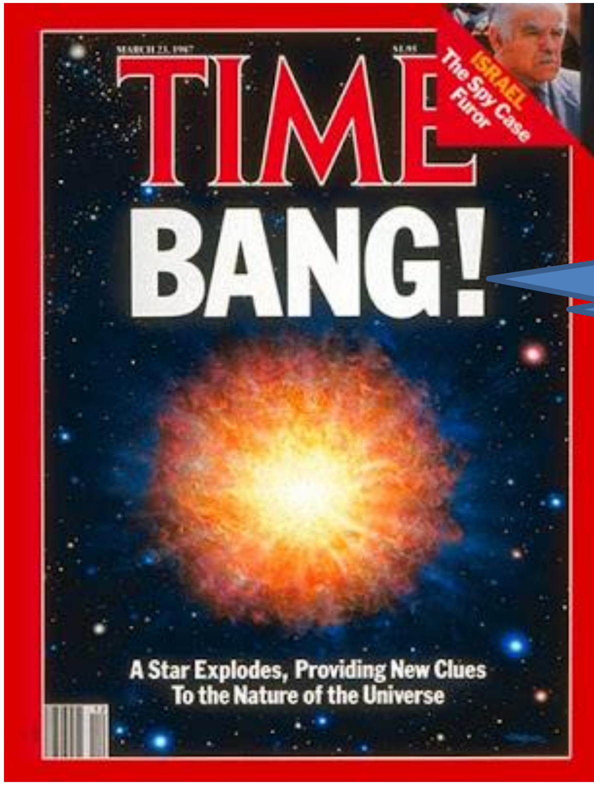
Windows on the Universe: Science Questions

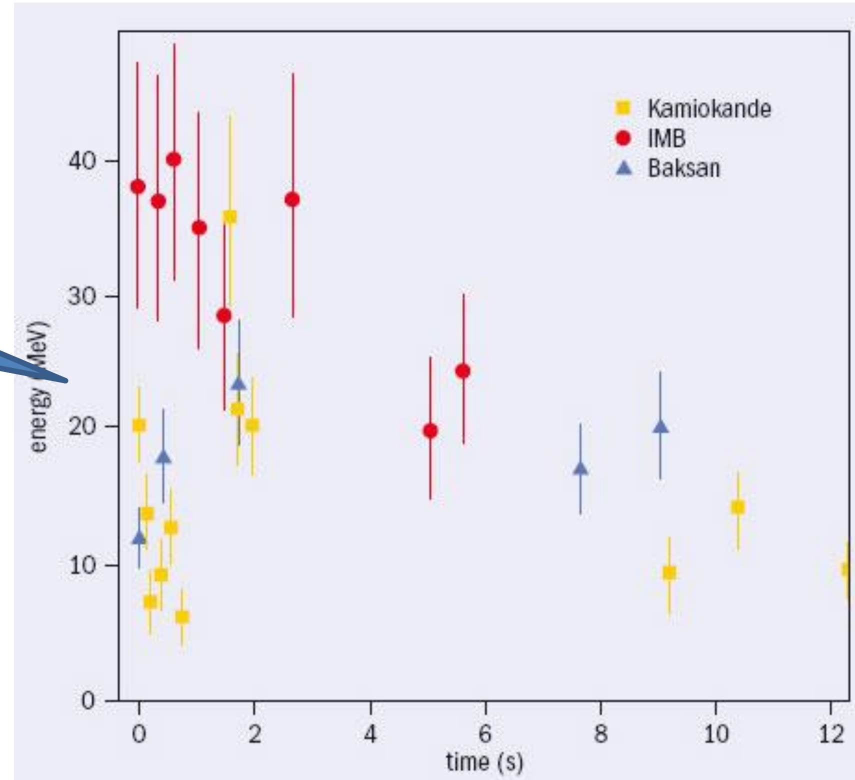
- How did the Universe begin?
- Why is the Universe accelerating?
- What is the unseen matter that constitutes much of the Universe?
- How does gravity work under the most extreme conditions?
- What are the properties of the most exotic objects in the Universe?
- How do matter and energy evolve to produce the Universe around us?
- Not all of astrophysics! (*e.g.*, heliophysics, exoplanets, *etc.*)

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 ^8B decay).
  - Detection of neutrinos: Nobel Prize to Davis & Koshiba in 2002
  - Discovery of neutrino oscillations and neutrino state mixing: Nobel Prize to Kajita & McDonald in 2015

Supernova 1987A (EM+particle)

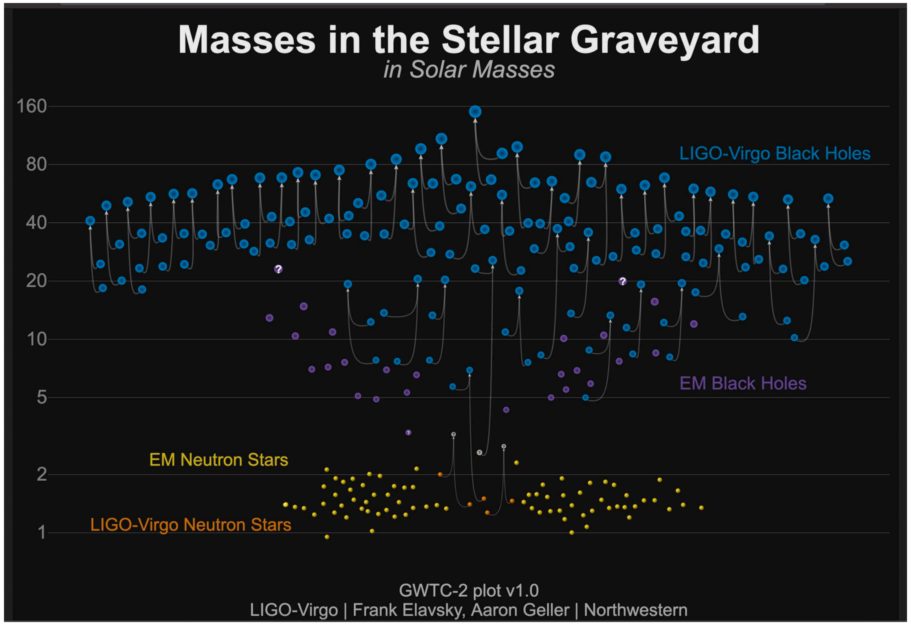




Credit: CERN/IOP

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

LIGO/Virgo Detections (GW+EM)



<u>50 Confirmed LIGO/Virgo Detections</u>

The binary black hole mergers have detectable signals for up to two seconds, while the neutron star merger signal lasted for over a minute

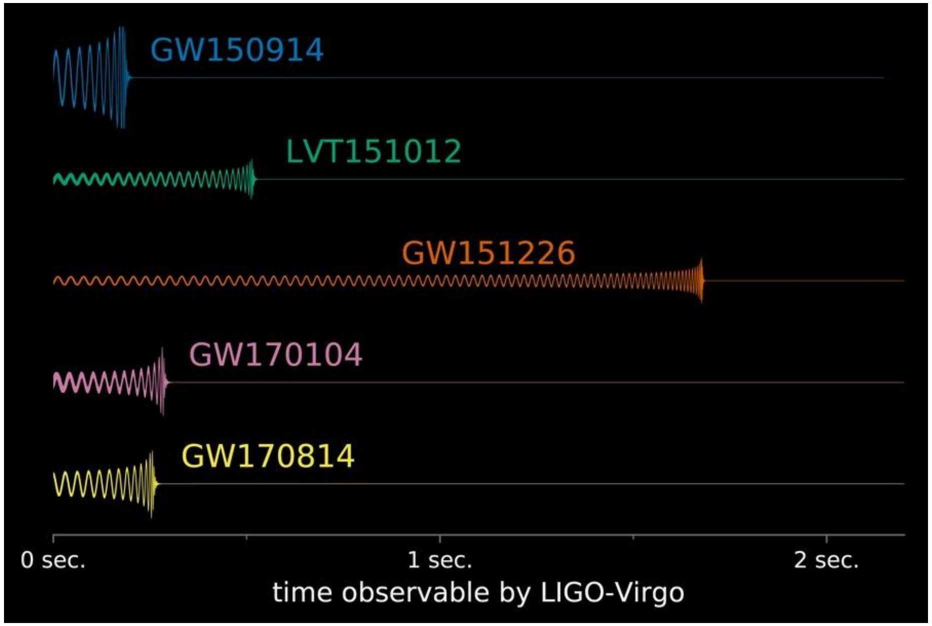
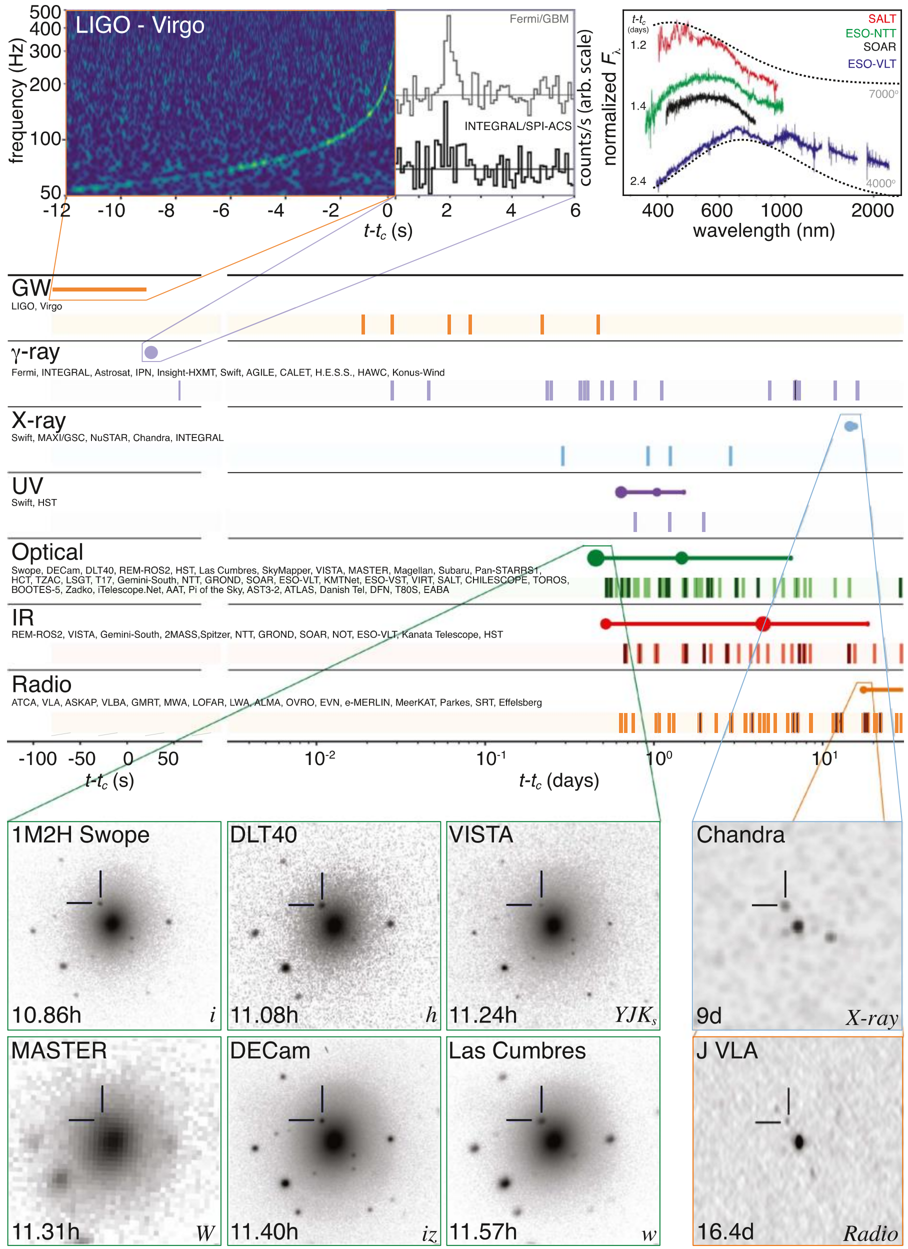


Image Credits: LIGO.org

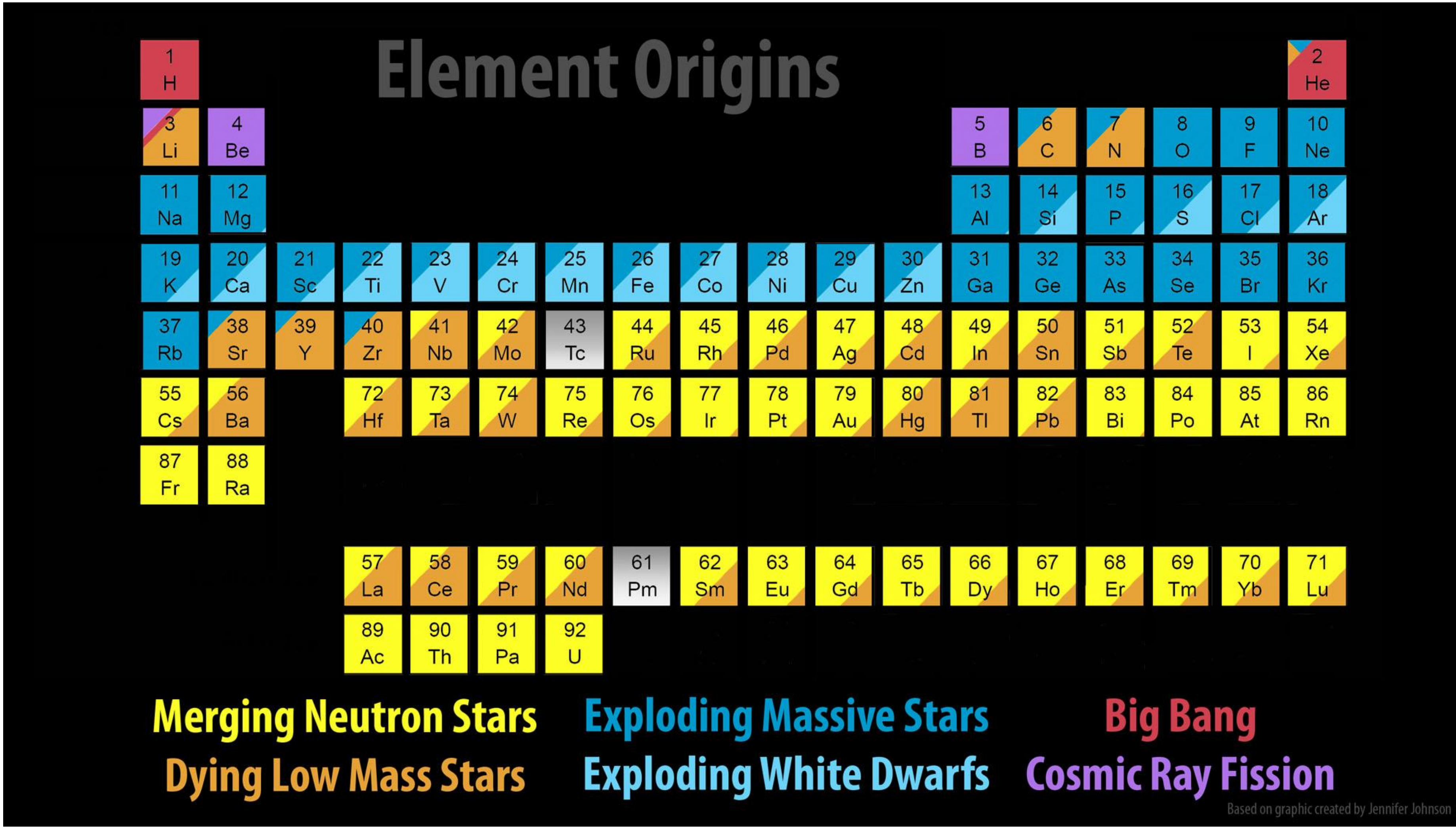
Black-hole mergers result in final black holes with masses 20-60 times the mass of the sun. The binary neutron star merger involved the merger of two objects with masses of 1.1 and 1.6 times the mass of the sun, with the resulting object being either a low-mass black hole or a massive neutron star.

Binary Neutron Star Merger (GW+EM)



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

Products of Neutron Star Merger



Credit: Jennifer Johnson/SDSS

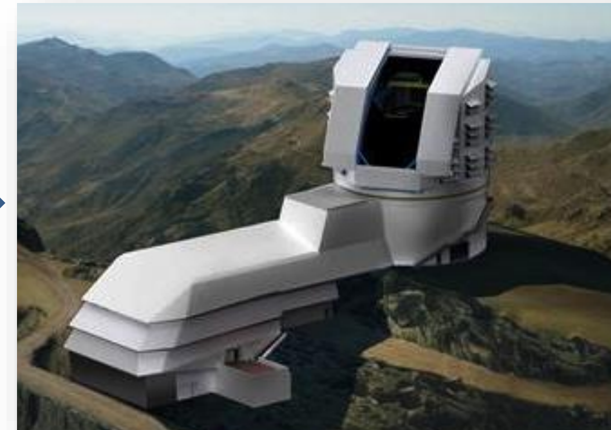
Windows of Universe Implementation

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

- These are all closely related to the **Big Idea** on *Harnessing the Data Revolution*.
- New projects tend to fall in "large mid-scale" research facility class.

Who Does Multi-Messenger Astronomy?

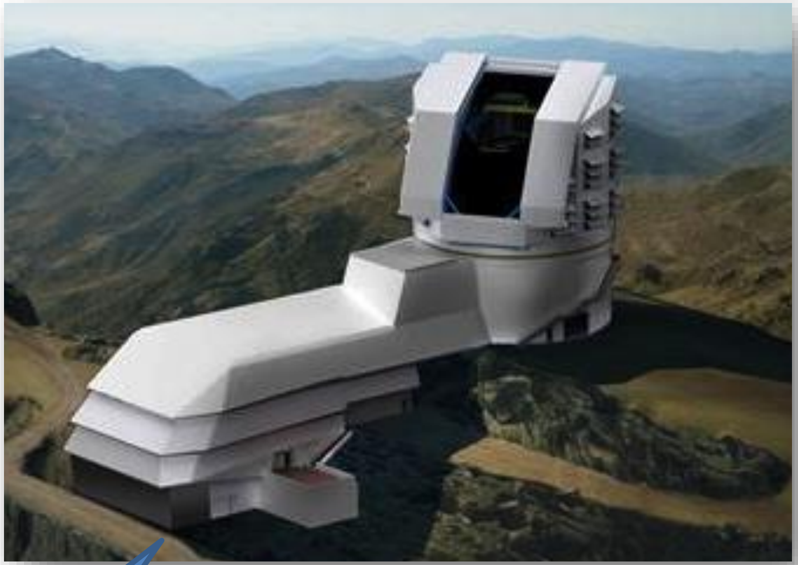
Example 1: Large Synoptic Survey Telescope (LSST)



- LSST will complete 10-year survey to begin 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

Large Synoptic Survey Telescope (LSST)



- 10 million alerts per night

Example 2: Cosmic Microwave Background (CMB)

- CMB Stage 4 (CMB-S4) Goals: measure polarization imprinted by gravitational waves at epoch of inflation (also neutrino masses).
- Two sites: South Pole and Atacama desert.
- 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 factor of ~1.7 over design sensitivity of current LIGO, resulting in 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.

Advancement of Solar Observations

Major Milestones in NSF-Funded Solar Astronomy

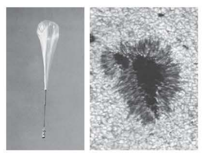
NSF has long supported solar astronomy research. This science has helped inform what we know about the sun, other stars and the plasma state of matter (like the sun's corona). This fundamental knowledge is at the crux of space weather, which impacts communication networks and power grids on our own planet. NSF's newest investment, the Daniel K. Inouye Solar Telescope, is poised to collect unprecedented images and data about the sun when it becomes fully operational in 2020.

1953-1954

NSF awards its first grants for solar research.

1958

American scientists with NSF funding observe sun continuously for 12 months for first time in history as part of International Geophysical Year scientific program.

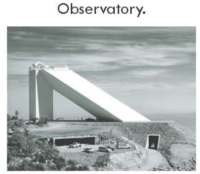


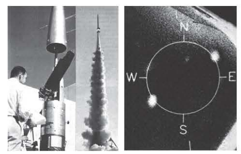
1959-1960

Balloon-mounted solar telescope captures historic photos of sunspots.

November 2, 1962

NSF dedicates McMath Solar Telescope at Kitt Peak National Observatory.



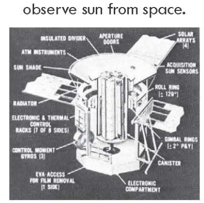


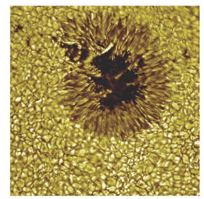
1965

NSF's Kitt Peak National Observatory assists Aerobee rocket launch to capture X-ray images of the sun. Also, NSF coordinates U.S. federal research participation in "International Year of the Quiet Sun" to study sun's corona.

1973

NSF funds the National Center for Atmospheric Research's High Altitude Observatory to develop a coronagraph for Skylab to observe sun from space.



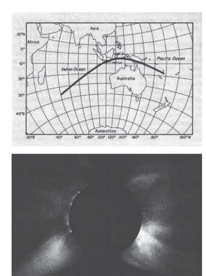


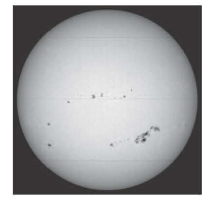
1975

Franz Deubner, using the NSF Dunn Solar Telescope at Sacramento Peak, demonstrates how solar five-minute oscillations are trapped inside the sun, leading to helioseismology.

1983

NSF sends scientific expedition to Indonesia to observe total solar eclipse, including a newly developed special camera to capture the interplay between solar magnetic fields and corona.



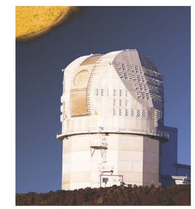


1995

NSF funds a Global Oscillation Network Group (GONG) to observe sun continuously as possible and provide space weather data.

2003

Synoptic Optical Long-term Investigations of the Sun (SOLIS) instrumentation is deployed at NSF's Kitt Peak National Observatory to map sun's magnetic field in photosphere and chromosphere daily.



2012

Site construction begins on NSF's 4-meter Daniel K. Inouye Solar Telescope. The world's most powerful solar telescope, it released its first images of the sun's surface in 2020.

August 21, 2017

NSF funds projects to obtain uninterrupted observation of total solar eclipse as it traverses U.S.; NCAR and Smithsonian Astrophysical Observatory flies along path of totality and NSO leads nationwide citzen science observation project, Citizen Cate.

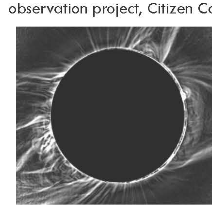


Image credits:
Top row: US Navy; NASA; NSF (2); NSO/AURA/NSF (2)
Bottom row: NOAO/AURA/NSF; NASA; NSF; NSO/AURA/NSF

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Multi-Messinger Heliophysics

2020:

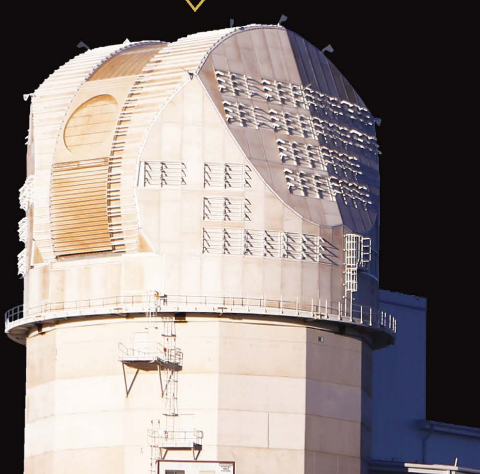
A NEW ERA OF SOLAR ASTRONOMY

Working together to study the Sun

A new era for solar astronomy is dawning, specifically because of three separate observation initiatives. Each is equipped with the necessary tools and located where they can best achieve those goals. Ultimately, because of their different, yet complementary approaches to studying the sun, these efforts led by the National Science Foundation, NASA and the European Space Agency, will augment what each can do, making robust scientific endeavors even better. Together, they create a comprehensive understanding of our sun.

	NSF's Daniel K. Inouye Solar Telescope	ESA/NASA Solar Orbiter	NASA Parker Solar Probe
Mission	Ground-based remote observation and mapping	Space-based measurements	Space-based measurements
Research goals	Map Sun's surface & its atmospheric magnetic fields, especially the inner corona, where solar storms begin	Make detailed measurements of the solar wind, which is responsible for sending problematic radiation towards Earth	Probing the Sun's outer corona (part of its atmosphere) to understand origins of the solar wind
Closeness to Sun	91 million miles (Earth)	35 million miles (similar to distance of Mercury)	4 million miles (nearest to Sun)
Length of Mission	50 years	7 years	7 years
Telescope Size	4m	12.5cm (equivalent to 50cm telescope on Earth)	No telescope observing Sun's surface
Image resolution	Can clearly resolve solar features the size of 330 football fields	Can clearly resolve solar features the size of 2,200 football fields	n/a

NSF's Daniel K. Inouye Solar Telescope



ESA/NASA Solar Orbiter

NASA Parker Solar Probe

National Science Foundation

Summary

- We can finally utilize all three "windows" (EM + GW + Particle) to study Universe and address long-standing questions.
- NSF is uniquely positioned as only funding agency in USA engaged in all three windows.
- New resources needed to make connections among different messengers, simultaneously utilize different windows, and fully exploit scientific opportunities.

NSF's **10 Big Ideas** for Future Investment

Questions?

Thank you!