NASEM Board on Physics and Astronomy Fall Meeting, Irvine, CA, Nov 30, 2022

Update of the Status of LIGO And the Global Gravitational-Wave Network

Dave Reitze
LIGO Laboratory
Caltech

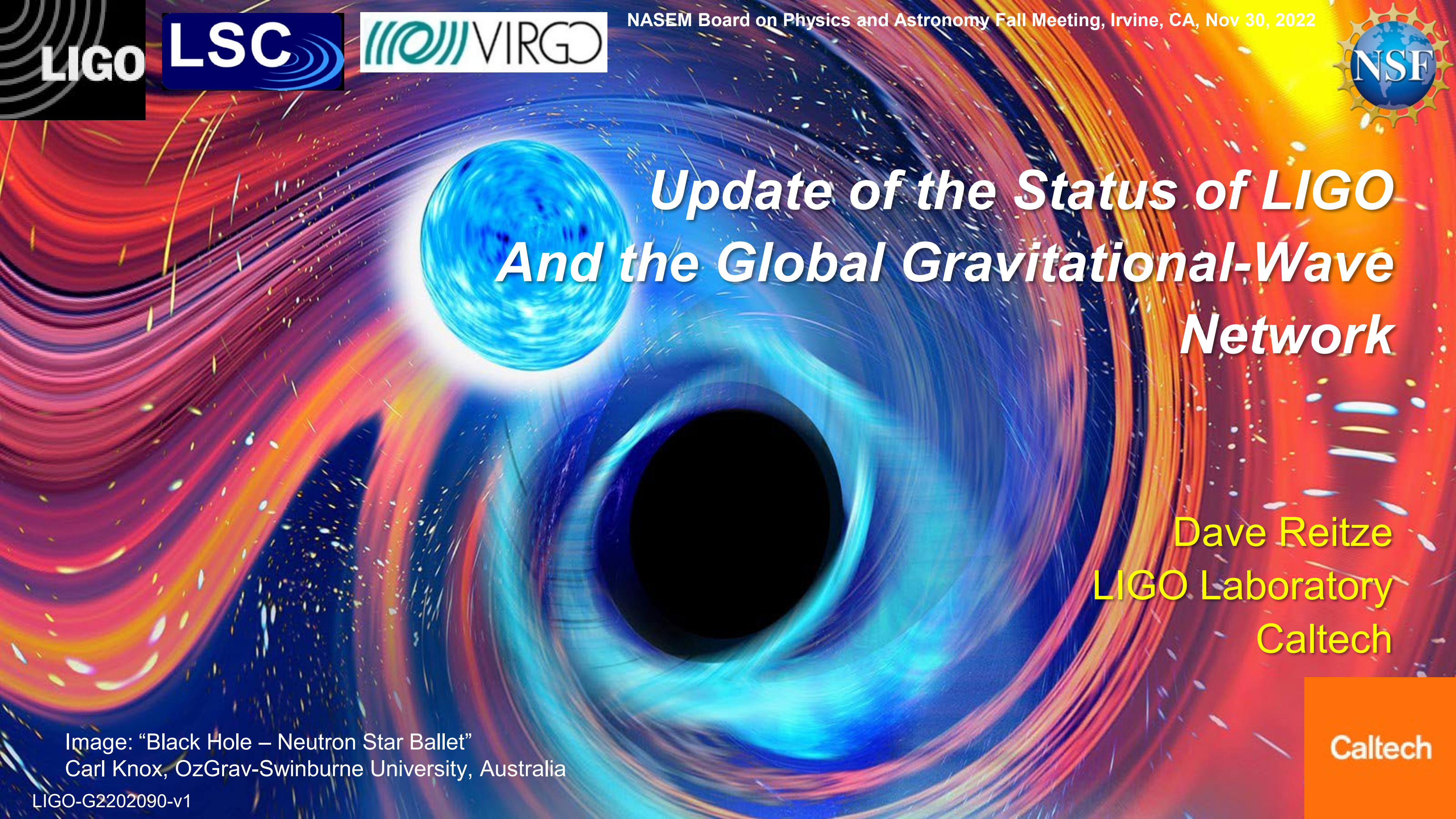


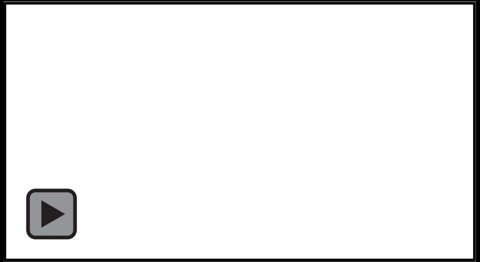
Image: "Black Hole – Neutron Star Ballet"
Carl Knox, OzGrav-Swinburne University, Australia

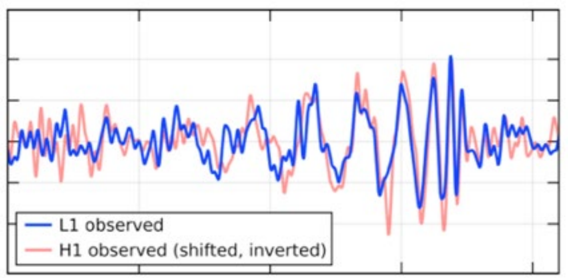
LIGO-G2202090-v1

Background: Gravitational Waves

- Gravitational waves are propagating dynamic fluctuations in the curvature of space-time ('ripples' in space-time)

- Gravitational waves are emitted when any object possessing mass accelerates
  - Sourced by the time-dependence of the quadrupole mass moment
  - Require very massive astrophysical objects moving at relativistic speeds to produce GWs that can be detected





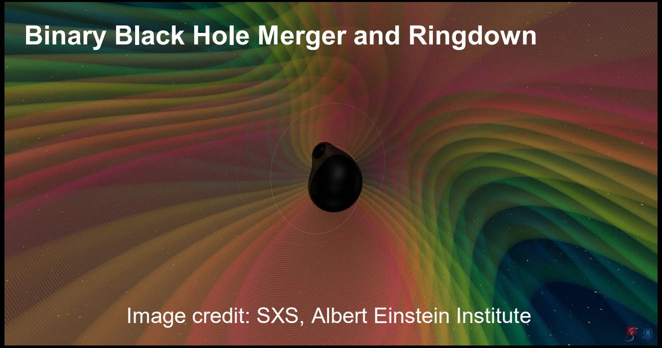
- *Physically, gravitational waves are strains.*

$\boxed{\textbf{Amplitude} = \Delta L/L \leq 10^{-21}}$ for GW sources in the near Universe

- *<u>… carrying unique information about the most violent events in the universe → a new and powerful probe of the high energy universe</u>*

Fundamental Questions That Gravitational Wave Observations Can Shed Light On

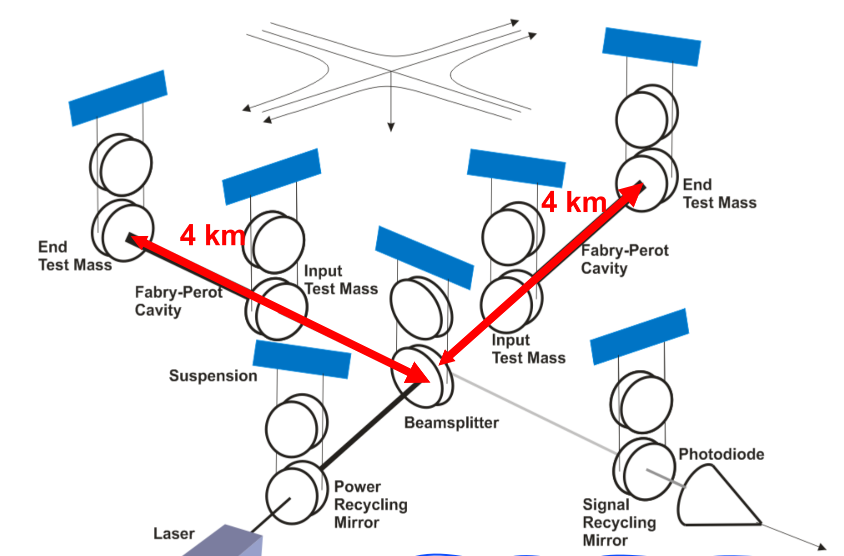
- **Outstanding Questions in Physics**
  - *Is General Relativity the correct theory of gravity? Where does it begin to break down?*
  - *Are black holes truly bald?*
  - *How are the heaviest elements in the Universe produced?*
- **Outstanding Questions in Astrophysics, Astronomy, Cosmology**
  - *How do binary neutron star mergers produce short hard gamma ray bursts (GRBs)?*
  - *How do massive stars explode?*
  - *How many low mass black holes are there in the universe? How do they form?*
  - *Do intermediate mass black holes exist? Do supermassive black holes grow from seeds?*
  - *What is the neutron star equation of state?*
  - *Can we observe populations of weak gravitational wave sources?*
  - *Can 'standard sirens' binary inspirals more accurately measure the local Hubble constant?*



Gravitational Wave Interferometers: Advanced LIGO

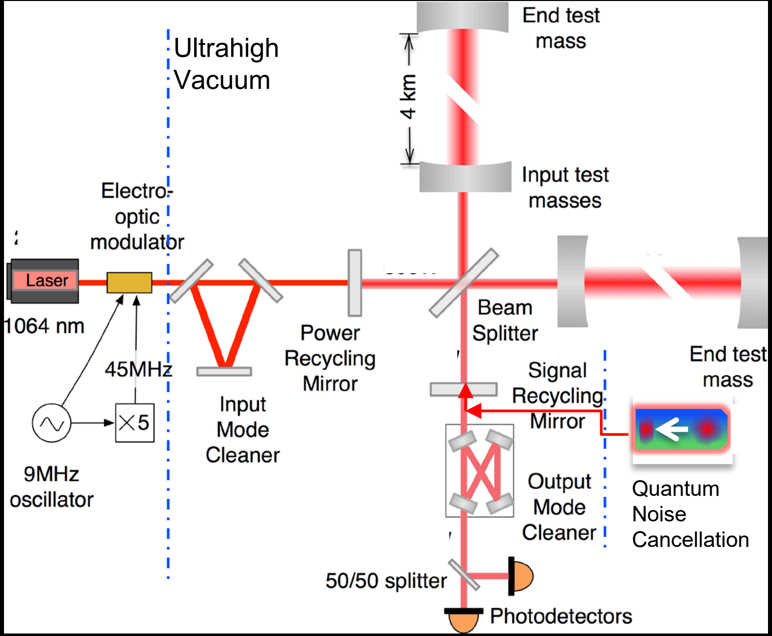
GW detectors use precision *interferometry* to detect displacements produced by passing gravitational waves

Concept



Gravitational wave signal $= \frac{\Delta L(t)}{L}$

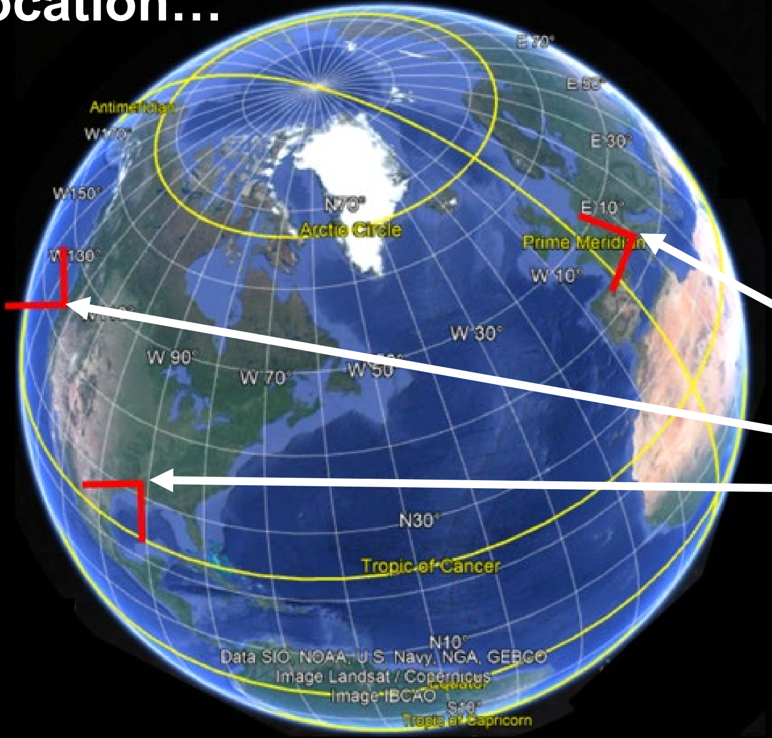
Implementation

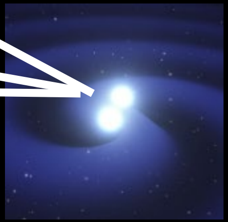



The Global Ground-based Gravitational-Wave Observatory Network
Virgo Observatory Italy
LIGO Hanford Observatory Washington, USA
LIGO Hanford 2001
LIGO Livingston 2001
GEO600 2001
VIRGO 2007
KAGRA 2019
LIGO India ~2030
Operational
Planned
Gravitational Wave Observatories
KAGRA Observatory (Japan)
LIGO Livingston Observatory Louisiana, USA

Gravitational-wave Networking

Location, location, location…





A single interferometer cannot localize a source. A network is needed.

LIGO-Virgo Detector Network Sensitivities during the Latest O3 Observing Run

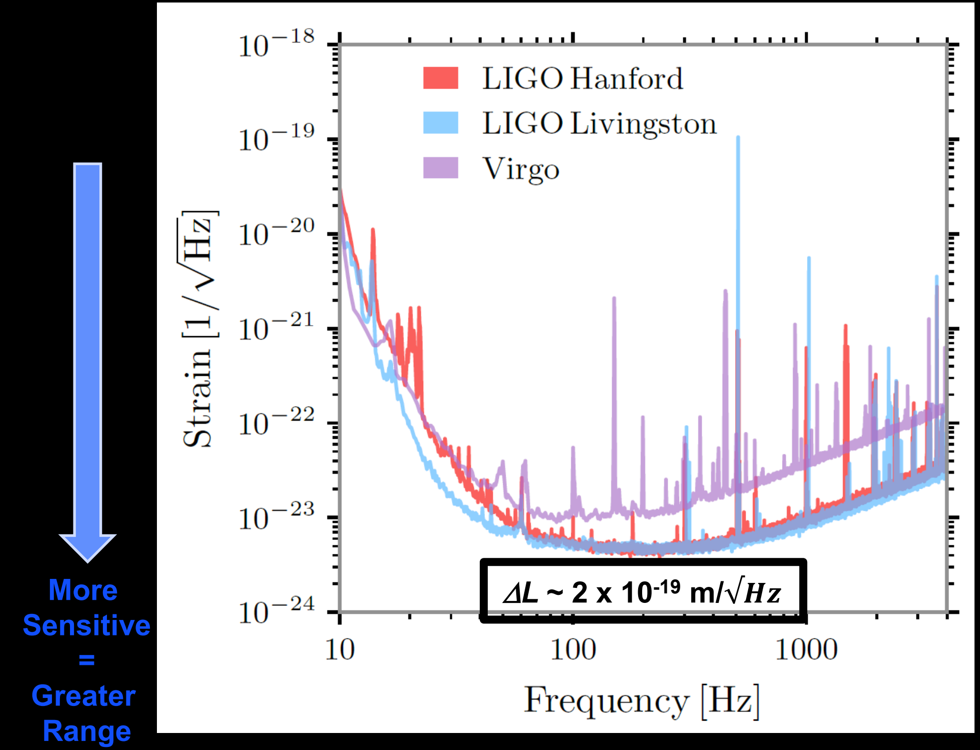


Figure of Merit: average range to detect a compact binary merger

- O1 Observing Run (Sept 12 2015 – Jan 19, 2016)
  - 1.4 M_{sun} – 1.4 M_{sun} BNS: ***68 Mpc***
  - 30 M_{sun} – 30 M_{sun} BBH: ***685 Mpc***
- O2 Observing Run (Nov 30 2016 – Aug 25, 2017)
  - 1.4 M_{sun} – 1.4 M_{sun} ***BNS: 68 Mpc***
  - 30 M_{sun} – 30 M_{sun} ***BBH: 908 Mpc***
- O3 Observing Run (Apr 1, 2019 – Mar 27, 2020)
  - 1.4 M_{sun} – 1.4 M_{sun} ***BNS: 128 Mpc***
  - 30 M_{sun} – 30 M_{sun} ***BBH: 1188 Mpc***

Scientific Highlights from the O1, O2, and O3 Observing Runs

Observations

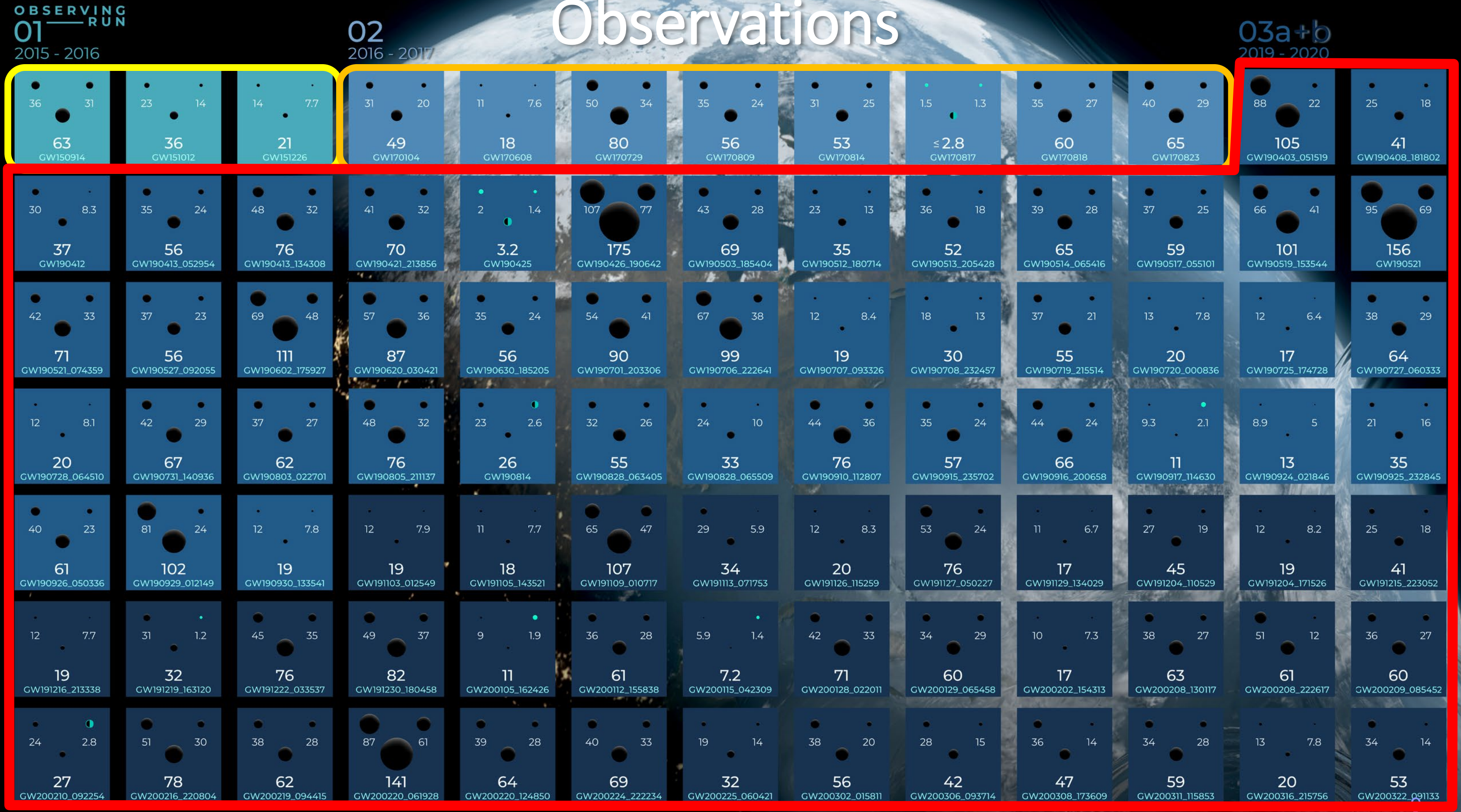
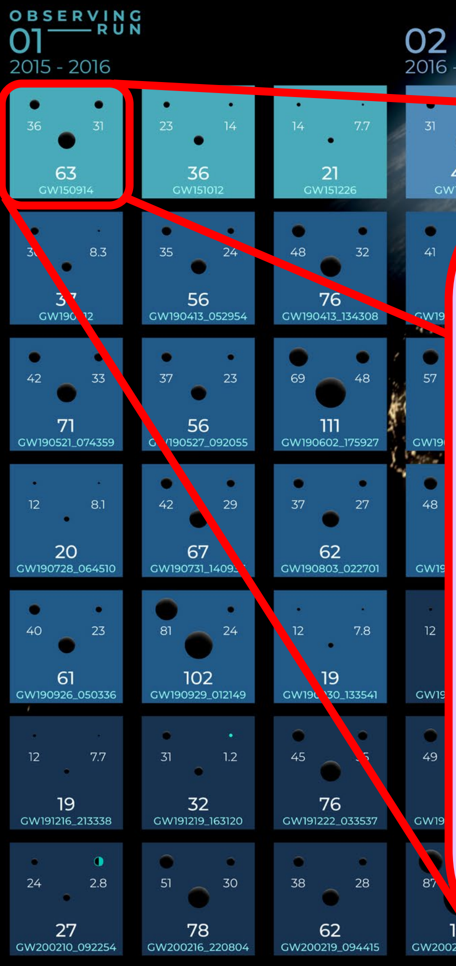
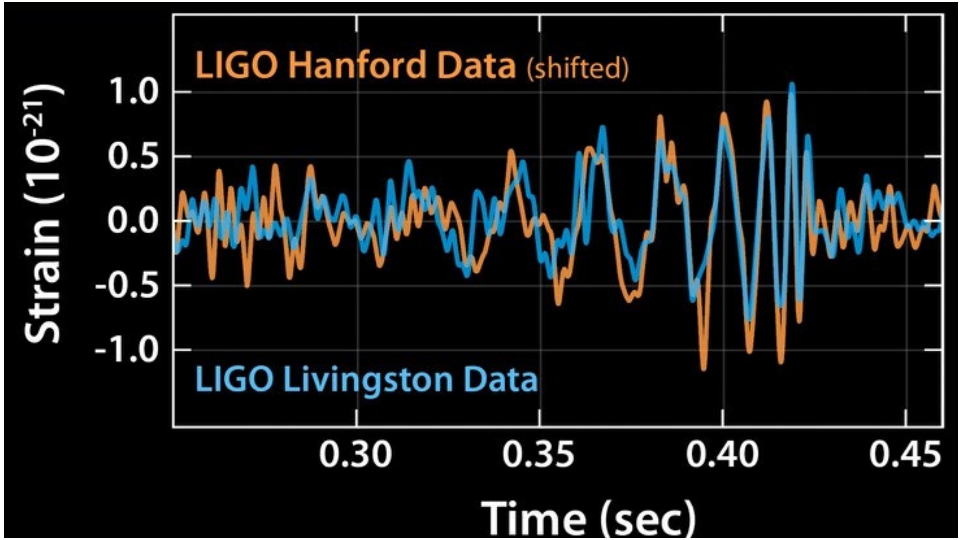


Image : Carl Knox (OzGrav, Swinburne University of Technology)

Slide: S. Fairhurst



GW150914: First Detection

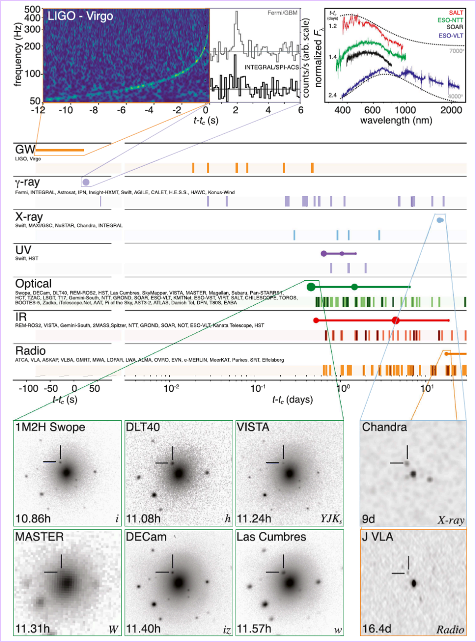


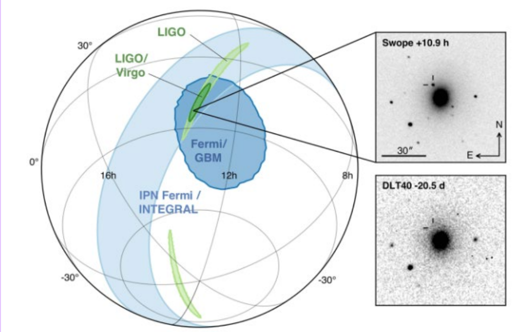
Abbott et al, “Observation of Gravitational Waves from a Binary Black Hole Merger”, 2016

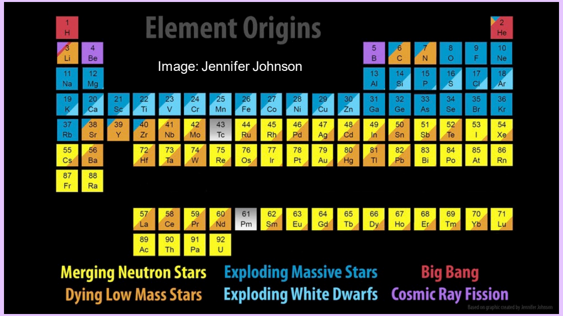
Image : Carl Knox (OzGrav, Swinburne Univers

S. Fairhurst

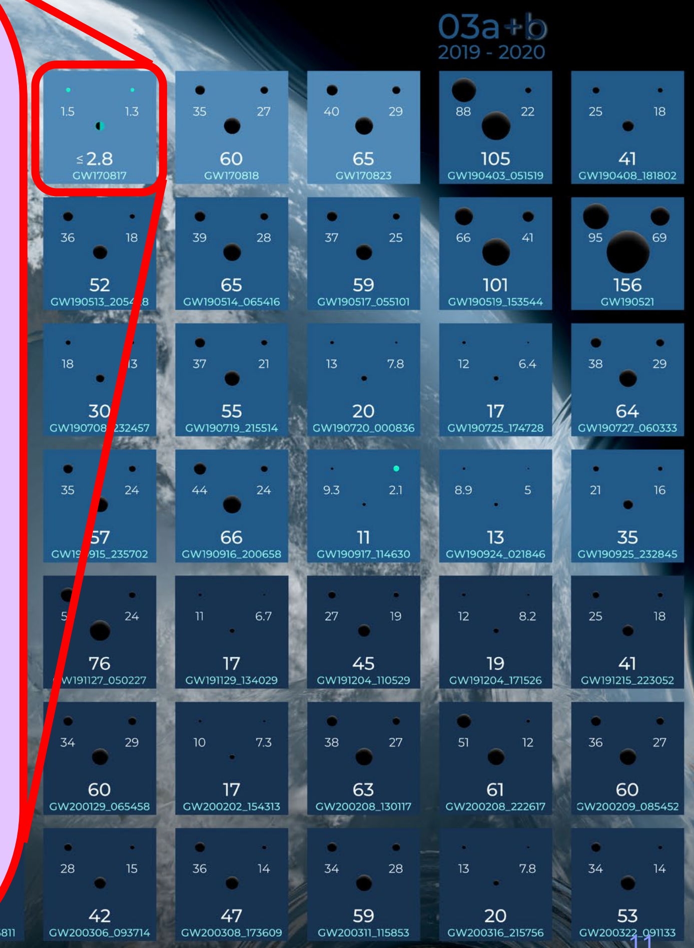
GW170817: Binary Neutron Star Multi-messenger Observation





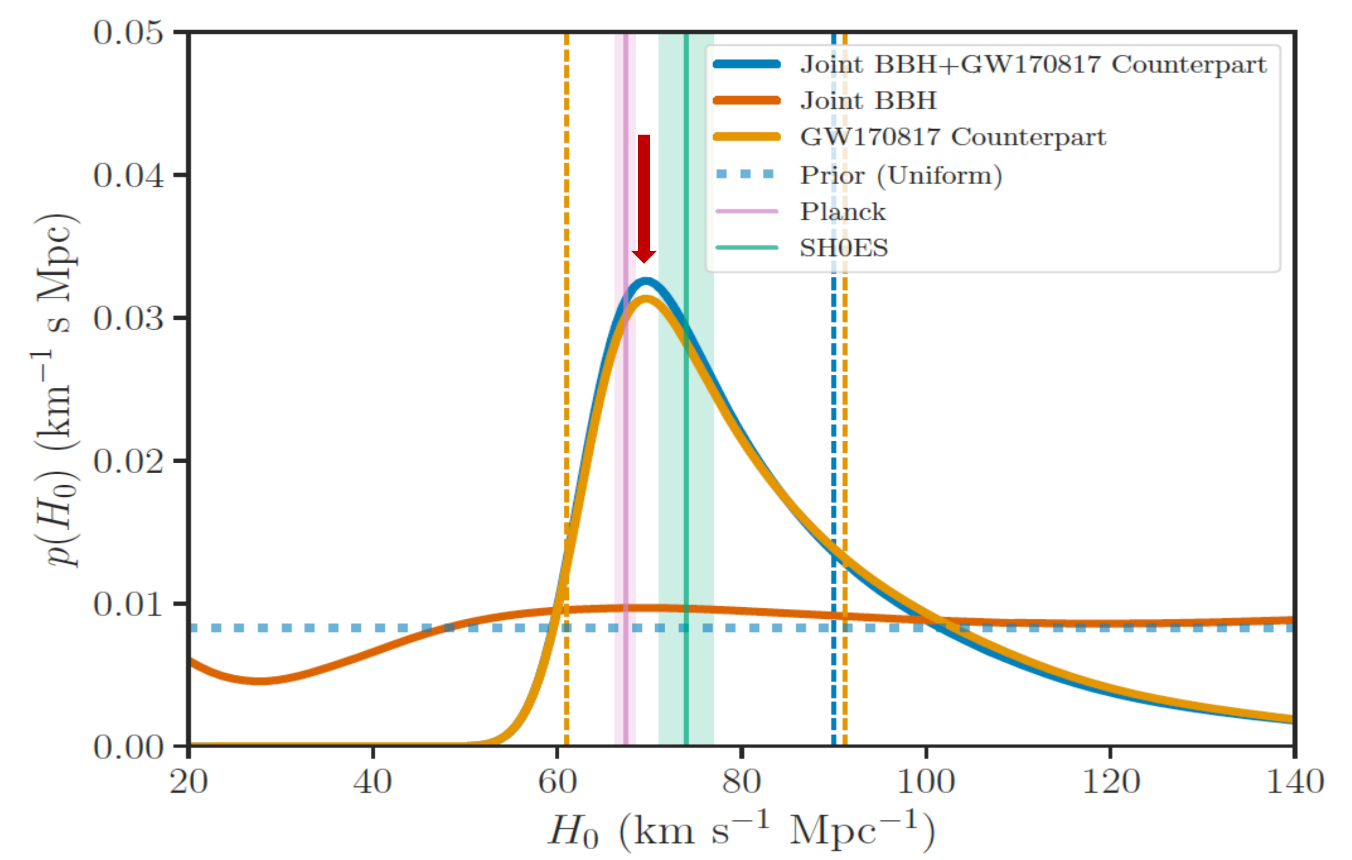


From Abbott et al, “Multi-Messenger Observations of a Binary Neutron Star Merger ”, 2017



Slide: S. Fairhurst

Measuring the Hubble Constant Using Gravitational-wave 'Standard Sirens'



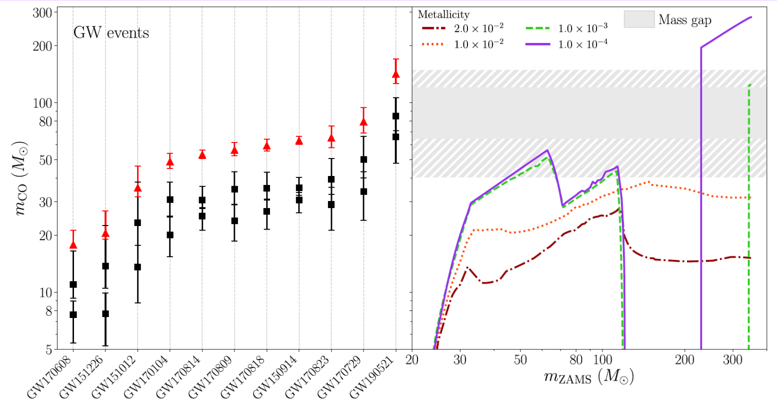
B. F. Schutz, "Determining the Hubble Constant from Gravitational Wave Observations", Nature 323, 310–311 (1986).

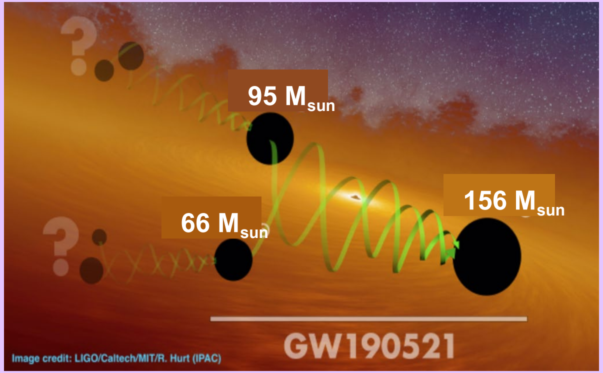
B. P. Abbott, et al., "A gravitational-wave standard siren measurement of the Hubble constant", Nature 551, 85-88 (2017).

Observations

OBSERVING RUN 01 2015 - 2016 | 02 2016 - 2017 | O3a+b 2019 - 2020

GW190521: A Black Hole in the Pair Instability Mass Gap





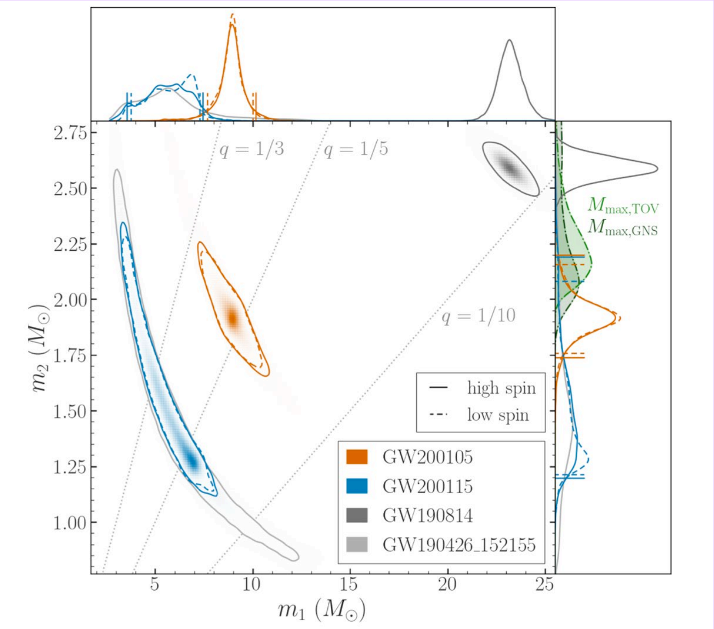
Evidence for a hierarchical merger? Or perhaps dynamical capture?

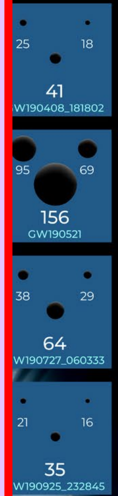
Image : Carl Knox (OzGrav, Swinburne University of Technology)

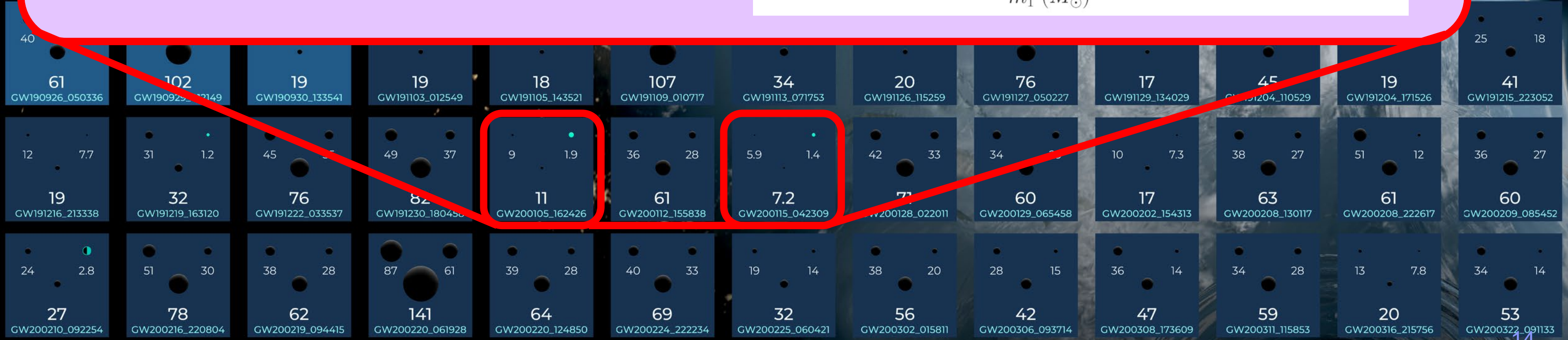
Slide: S. Fairhurst

GW200105 and GW200115: Observation of Neutron Star Black Hole Mergers

First unambiguous observation of NS-BH systems







Slide: S. Fairhurst

Roadmap Through 2030

Astro2020 and Snowmass 2021

The discovery of gravitational waves from merging black holes in 2015 propelled LIGO to its current essential position as a premier observatory for understanding the demographics and astrophysical implications of black holes, and for identifying the sources of heavy elements in the universe. These are among the most rapidly advancing areas in modern astrophysics, and future discoveries are likely to bring additional surprises. Therefore, the future of gravitational wave detection is central to progress in astronomy and astrophysics, and to this report.

– from "Pathways to Discovery in Astronomy and Astrophysics for the 2020s"

The detection of gravitational waves from merging binary neutron stars and black holes by the LIGO and Virgo Collaborations was a watershed moment for cosmic science. This new observational tool will be important for many areas of particle astrophysics and cosmology including measurements of cosmic acceleration at high redshift, searches for dark matter, and detection of relic gravitational wave radiation from early universe phase transitions.

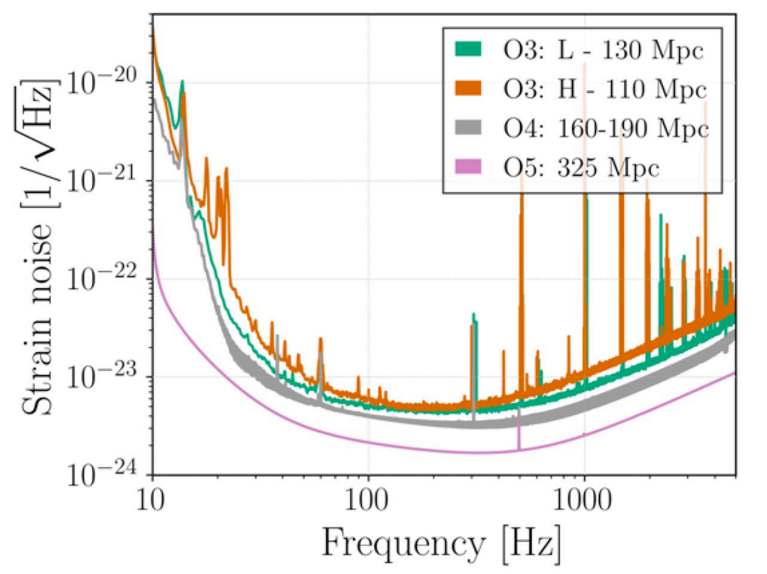
– from "The Future of US Particle Physics, Report of the 2021 Snowmass Community Study Chapter 5: Cosmic Frontier"

Near Term Upgrade and Observing Plans

- The LIGO detectors are undergoing a mid-scale upgrade 'A+' program
  - Supported by the NSF, the UK Science and Technologies Facility Council, and the Australian Research Council
  - The goal: *to substantially improve sensitivities over the O3 run.*
  - Two upgrade stages are planned: higher laser power, reduction of quantum noises (shot noise and photon radiation pressure noise), mirrors with improved coatings (higher damage thresholds, lower thermal noise)

- Scientific rationale for the LIGO A+ upgrade: interferometers are coherent (amplitude) detectors.
  - *A factor of 2 improvement in sensitivity for a given source provides a factor of 2 in range, and thus a factor of 8 in volume*
    - And an increase in signal to noise for a given source at a given distance

- The upcoming O4 and O5 runs will be carried out jointly by LIGO, Virgo, and KAGRA.

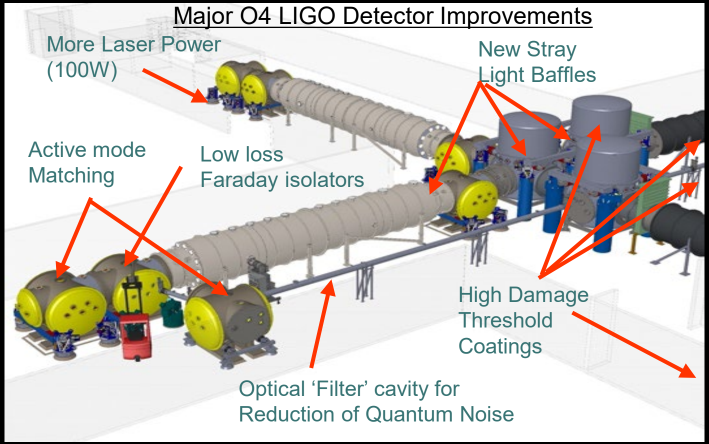


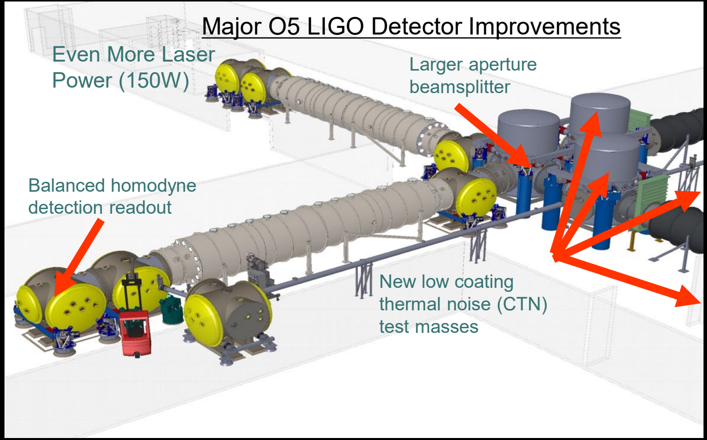
LIGO O4 and O5 Upgrades

- LIGO-Virgo-KAGRA Fourth Observing Run 'O4'
  - *Planned start in the Spring of 2023*, currently scheduled to be a one year long run
  - Original planned start date of January 2022 delayed due to the pandemic.
  - Compact binary mergers observable one every 2 to 3 days*

- LIGO-Virgo-KAGRA Fifth Observing Run 'O5'
  - Planned start in early 2026, a three year long run
  - Compact binary mergers expected a few times per day*

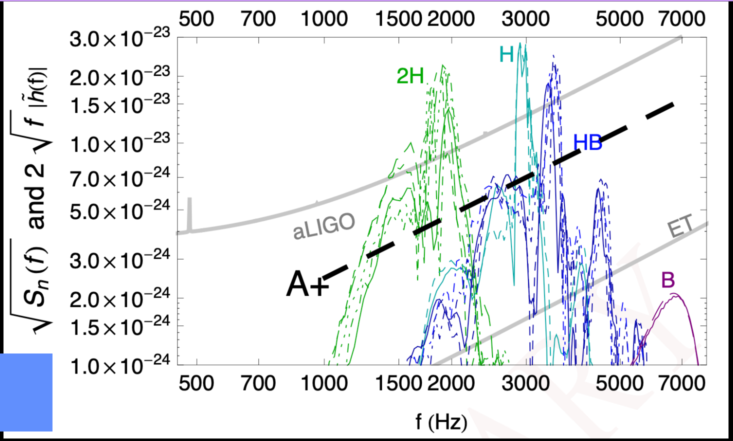
* Based on current measured mean rates for binary black hole, black hole – neutron star, and binary neutron star mergers





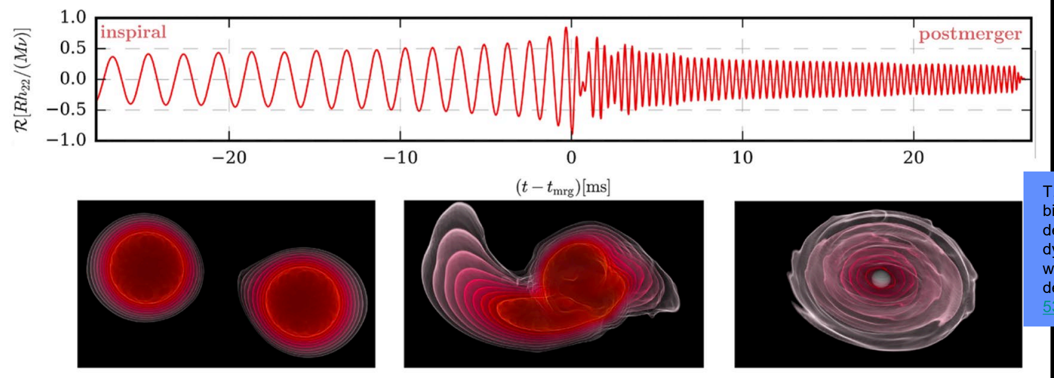
Science Target: Binary Neutron Stars

- Probe properties of matter super-nuclear densities:
  - » For sufficiently nearby BNS events, A+ should allow for the direct measurement of detailed waveform deviations that are expected from tidal disruption before coalescence.



J. S. Read, et al., "Matter effects on binary neutron star waveforms." Phys. Rev. D 88, 044042 (2013).

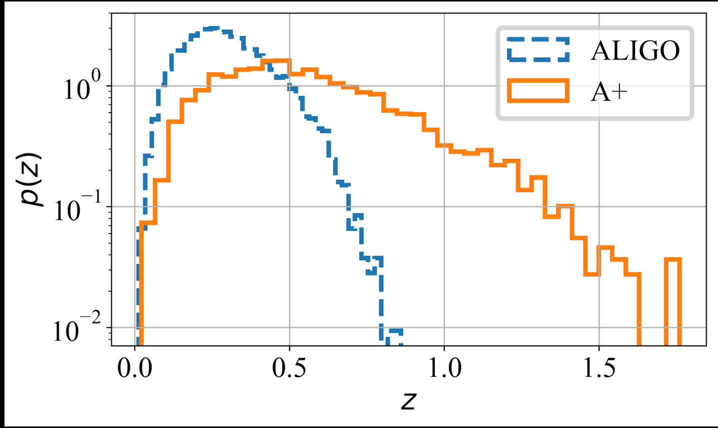
- And:
  - » Joint GW-EM investigations of kilonovae
  - » Joint observations of short GRBs and gravitational waves
  - » Precision Tests of General Relativity
    - – Speed of Gravity
  - » 'Bright' siren cosmology



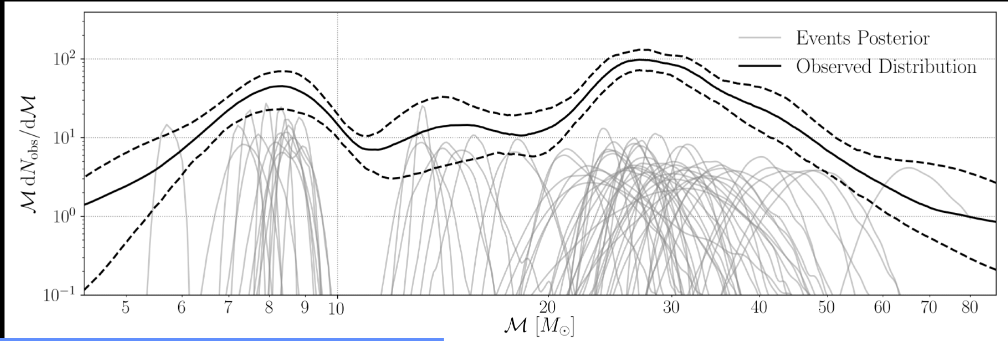
T. Dietrich, et al., "Interpreting binary neutron star mergers: describing the binary neutron star dynamics, modelling gravitational waveforms, and analyzing detections", Gen. Relativ. Gravit. 53, 27 (2021).

Science Target: Black Hole Populations and Rates

- Origins of the invisible stellar mass black hole population
  - A number of possible formation scenarios exist for these types of system: isolated binary (common envelope, dynamical friction or hierarchical merger)
  - Measurements of masses, mass ratios, component spins and redshift dependent rates can provide insights into formation channels and dynamics



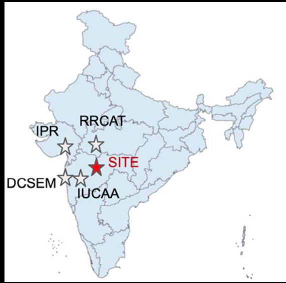
- And:
  - Delineation of upper (65 – 130 M_{sun}) and lower (2 – 3 M_{sun}) mass gaps
  - Precision Tests of General Relativity
    - 'No hair' theorem
    - black hole thermodynamics
  - 'Dark' siren cosmology



R. Abbott, et al, "The population of merging compact binaries inferred using gravitational waves through GWTC-3", https://arxiv.org/abs/2111.03634

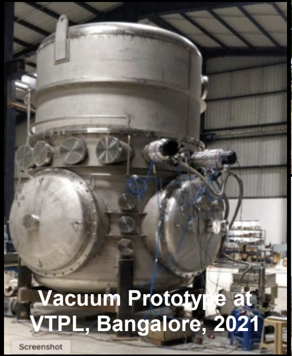
Later this Decade: LIGO India

- An India-US partnership to construct a third LIGO observatory in India
  - » LIGO detector components already in possession
- Science case: significantly improved localization of gravitational wave events
- NSF-DAE-DST MOU signed in 2016
  - » "…the LIGO-India project will be a partnership among NSF, DAE, and DST, through their respective awardee institutions and participating laboratories, to provide such a capability, to operate it for a period of at least ten years, and to pursue a program of gravitational-wave science."
- Status:
  - » LIGO India Observatory in final design phase
  - » Site acquired; construction has begun
  - » Vacuum system prototyping program underway
  - » LIGO India Testing and Training Facility completed
  - » Awaiting final approval from Government of India




LIGO-India Design Concept

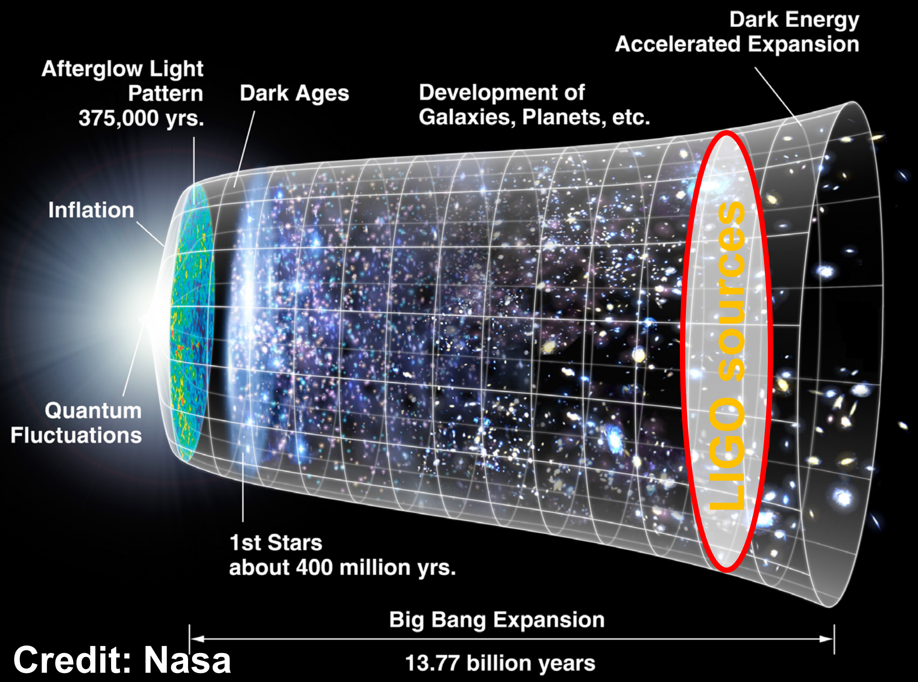

LIGO-India Testing and Training Facility
Raju Ramanna Centre for Advanced Technology, 2022


Vacuum Prototype at VTPL, Bangalore, 2021

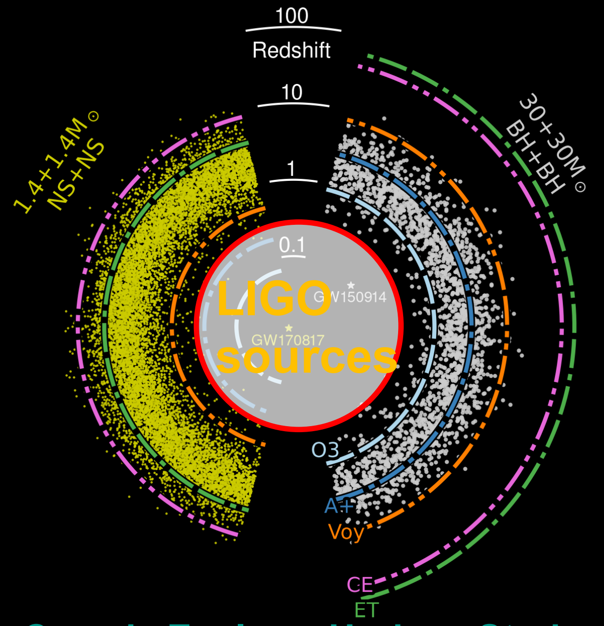

LIGO-India Site Construction, 2022

The 2030s and 2040s: New Detectors, New Horizons

Ground-based GW Detector 'Reach'



Credit: Nasa



Cosmic Explorer Horizon Study

Slide: S. Ballmer

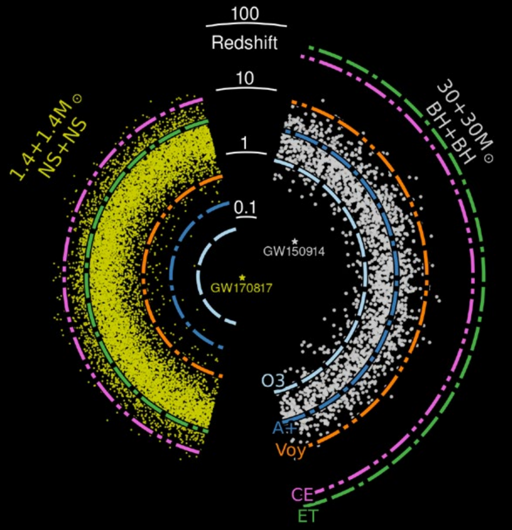
Gravitational-Wave International Committee

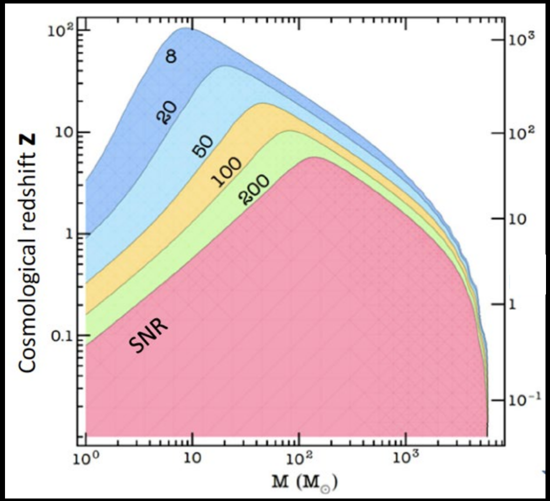
- GWIC Mission: *facilitate international collaboration and cooperation in the construction, operation and use of the major gravitational wave detection facilities world-wide*

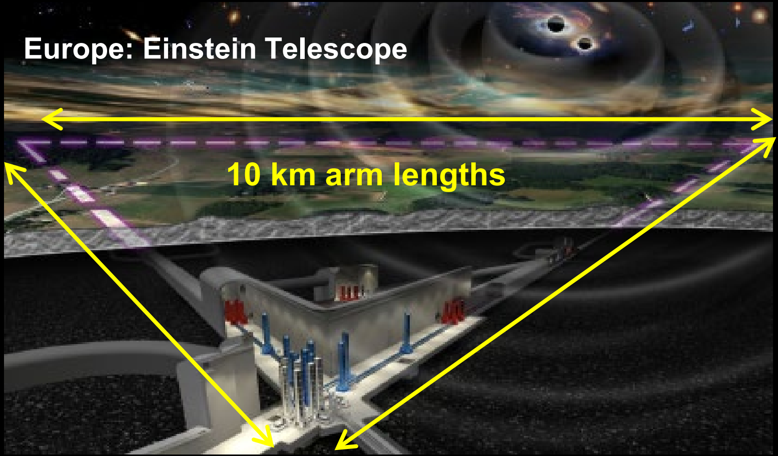
https://gwic.ligo.org

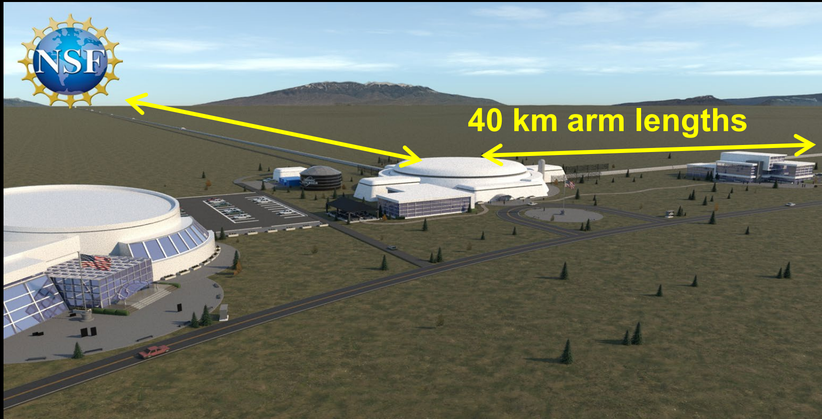
Gravitational Wave Observatories in the 2030s & 2040s: Detector Networks that See the Entire Stellar Universe

- Next Generation GW Observatory Projects in Europe and the US are under development
  - Einstein Telescope (ET) in Europe
  - Cosmic Explorer (CE) in the US
- ***ET and CE will observe compact GW events to the edge of the star-forming universe as a global network***



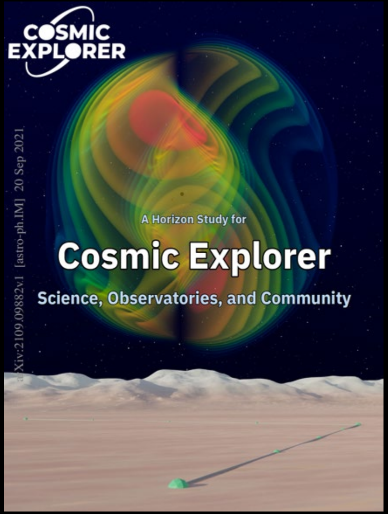


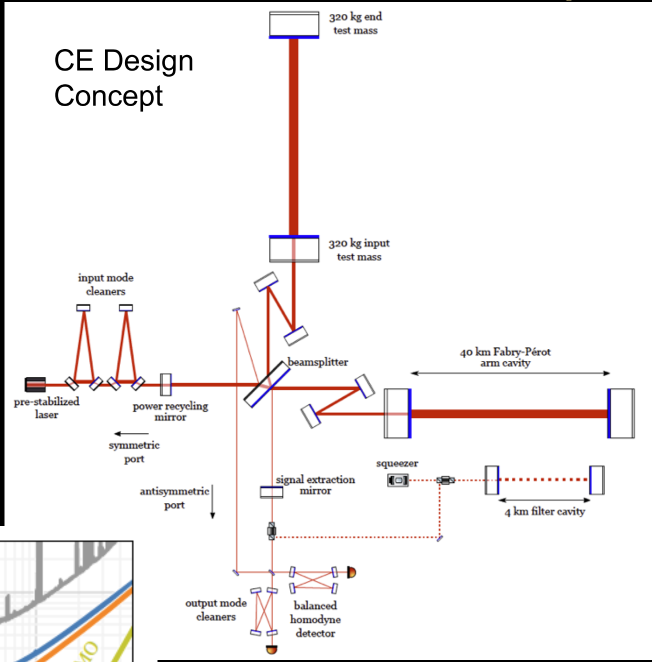


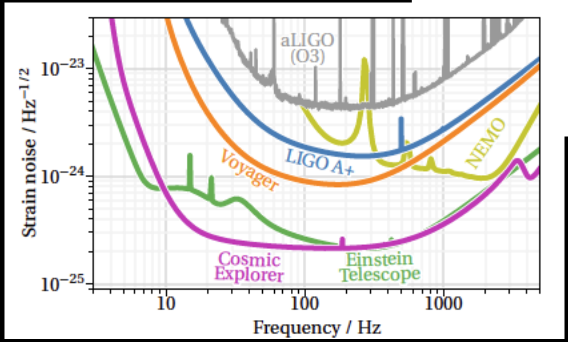


US Cosmic Explorer Observatory

- Detector Concept: one 40 km and one 20 km L-shaped surface observatories
  - Detector technology based on scaling up existing LIGO interferometer technology
- Possible sites:
  - No specific sites identified, however a trade study has identified several candidate sites in NW and SW United States
- Envisioned timeframe:
  - Construction to begin in 2029
  - Science operations to begin in ~ 2035 - 2037
- Status:
  - CE Horizon Study released in October 2022
  - NSF Math and Physical Science MPSAC subcommittee forming with the charge: to *assess and recommend configurations for a U.S. GW detector network that can operate at approximately an order of magnitude the sensitivity of LIGO A+ by the middle of the next decade*.

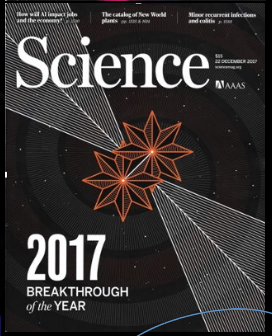






Conclusions

- Over the past 7 years, ground-based gravitational-wave observatories have opened a new window on the Universe
- What have we learned? A lot!
  - Astrophysics:
    - Binary black hole (BBH) systems exist.
    - Binary neutron stars (BNS) are progenitors of short gamma ray bursts.
    - BNS mergers produce kilonovae, which are foundries for heavy elements.
    - Black hole – neutron star binary systems exist.
    - Compact objects exist in the 2 – 3 $M_{\odot}$ mass range. We don't know what they are!!
    - Black holes with masses in the pair instability gap between ~60 – 135 $M_{\odot}$ exist.
  - General Relativity:
    - Astrophysical black holes are Kerr black holes as predicted by GR.
    - The speed of gravitational waves equals the speed of light.
    - GR is valid in the high curvature, high field regime.
  - Cosmology:
    - The Hubble constant can be measured using EM-bright GW 'sirens' (neutron star mergers) and even using dark GW 'sirens' (black hole mergers)
- Upcoming O4 and O5 Observing Runs beginning next year promise to yield new discoveries into the nature of neutron stars, black holes, and possibly other high energy astrophysical phenomena.
- New gravitational-wave observatories such as Cosmic Explorer will 'see' out to the beginning of star formation



Acknowledgments: