ICTS at 10
January 7, 2018

Gravitational Wave Detections by LIGO and Virgo: The Birth of a Revolution in Astronomy

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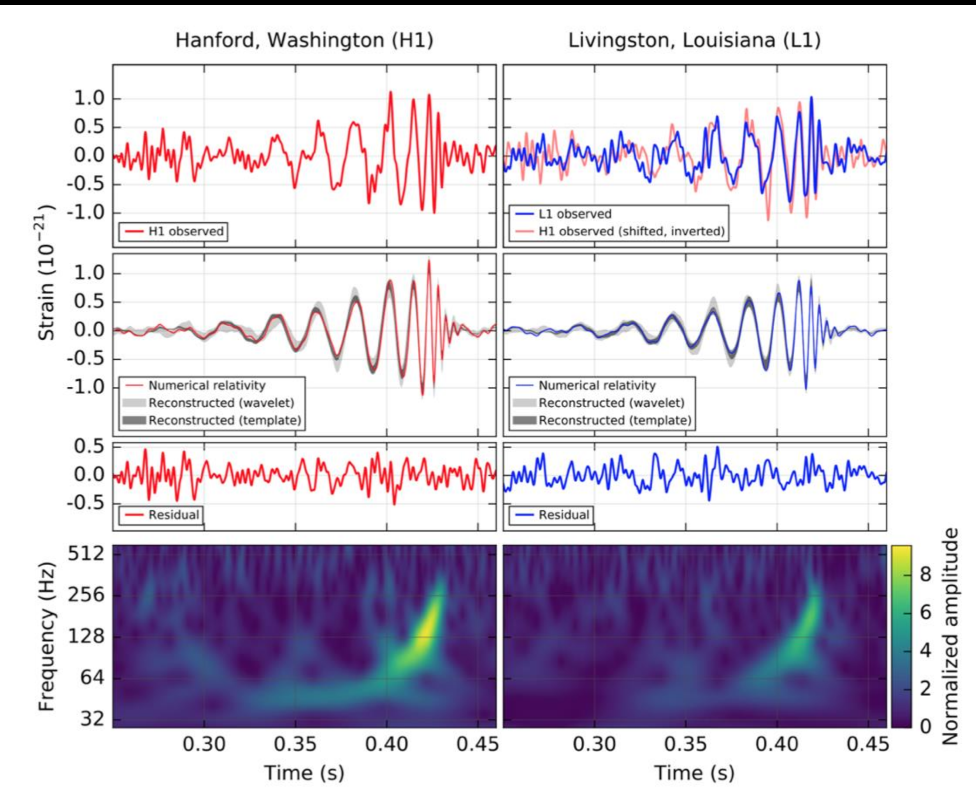
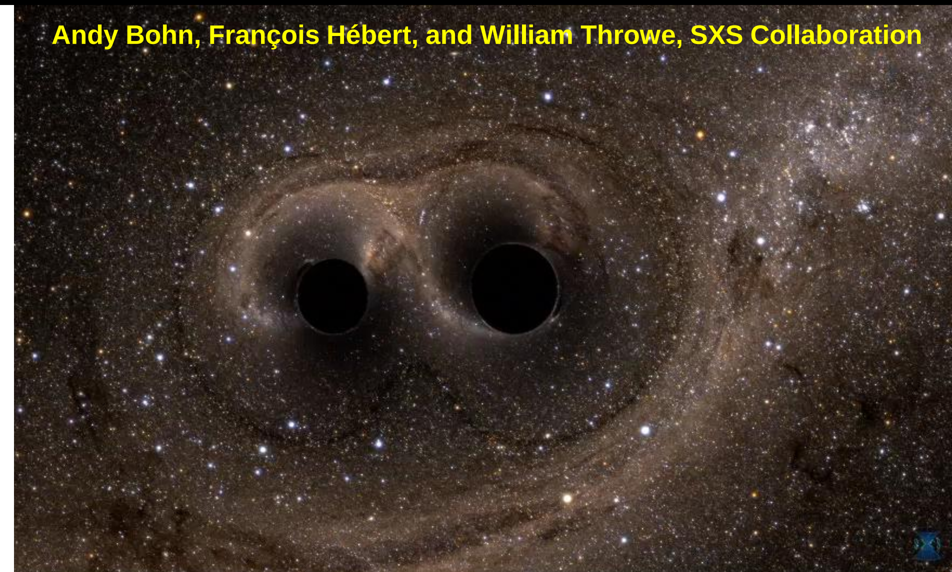
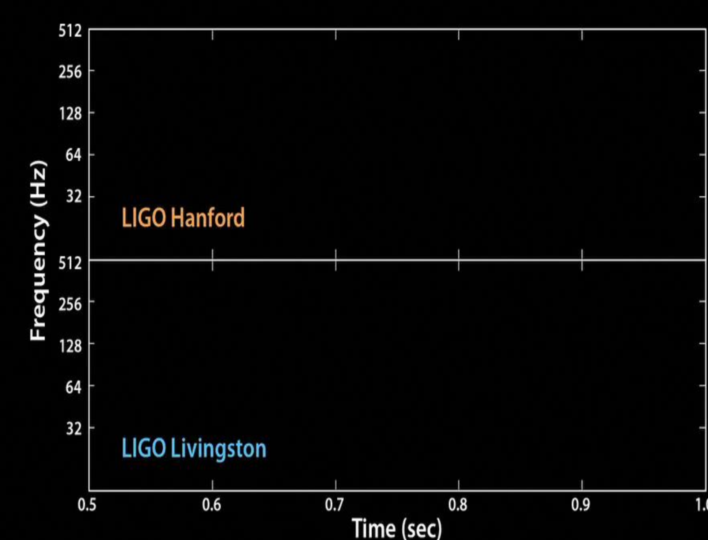
LIGO-G1702466-v1

GW150914: The First Binary Black Hole Merger







Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, “Observation of Gravitational Waves from a Binary Black Hole Merger” **Phys. Rev. Lett. 116, 061102 (2016)**

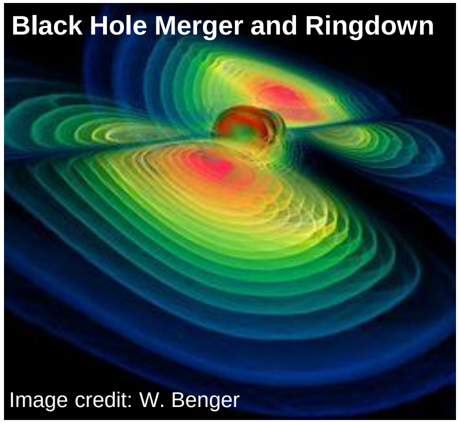
Outline

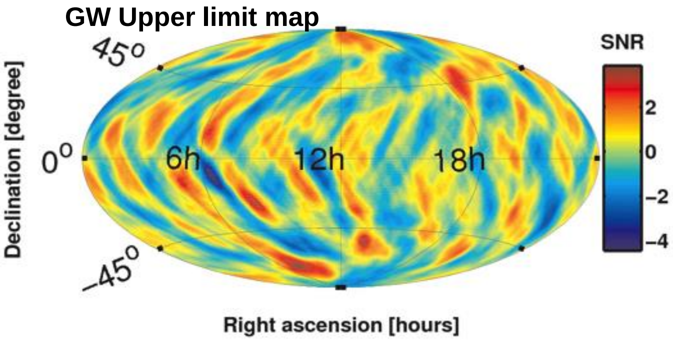
- *Motivations, Detectors*
- *Binary Black Hole Mergers*
- *The First Binary Neutron Merger → Dawn of Multi-messenger Astronomy with Gravitational Waves*
- *(A Few Slides About the Future)*

Some of the Questions That Gravitational Waves Can Answer

- **Outstanding Questions in Fundamental Physics**
  - *Is General Relativity the correct theory of gravity?*
  - *How does matter behave under extreme conditions?*
  - *No Hair Theorem: Are black holes truly bald?*

- **Outstanding Questions in Astrophysics, Astronomy, Cosmology**
  - *Do compact binary mergers cause GRBs?*
  - *What is the supernova mechanism in core-collapse of massive stars?*
  - *How many low mass black holes are there in the universe?*
  - *Do intermediate mass black holes exist?*
  - *How bumpy are neutron stars?*
  - *Can we observe populations of weak gravitational wave sources?*
  - *Can binary inspirals be used as “standard sirens” to measure the local Hubble parameter?*
  - *Are LIGO/Virgo’s binary black holes a component of Dark Matter?*
  - *Do Cosmic Strings Exist?*

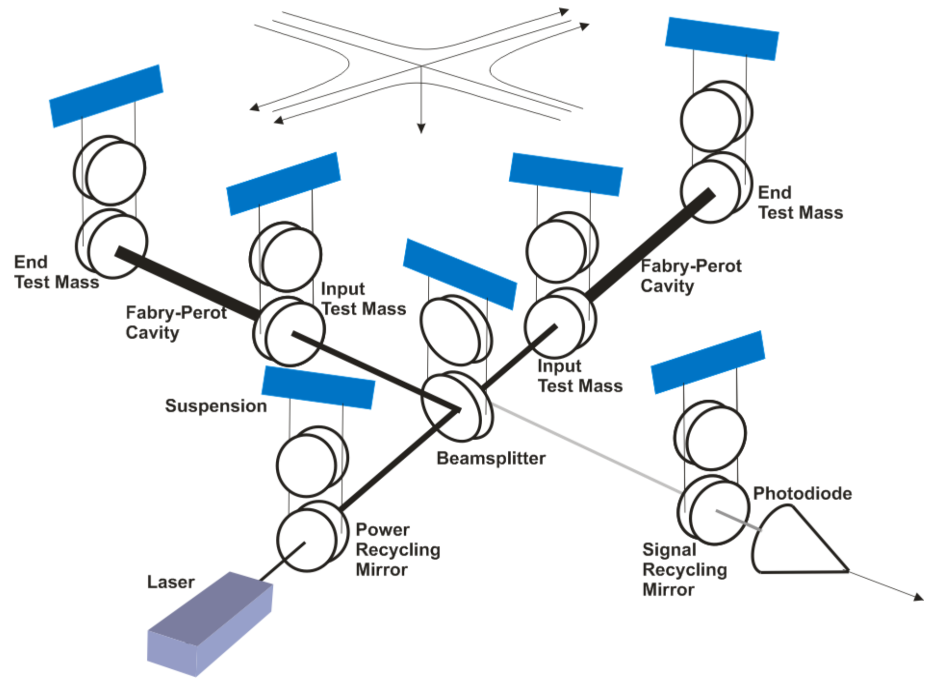


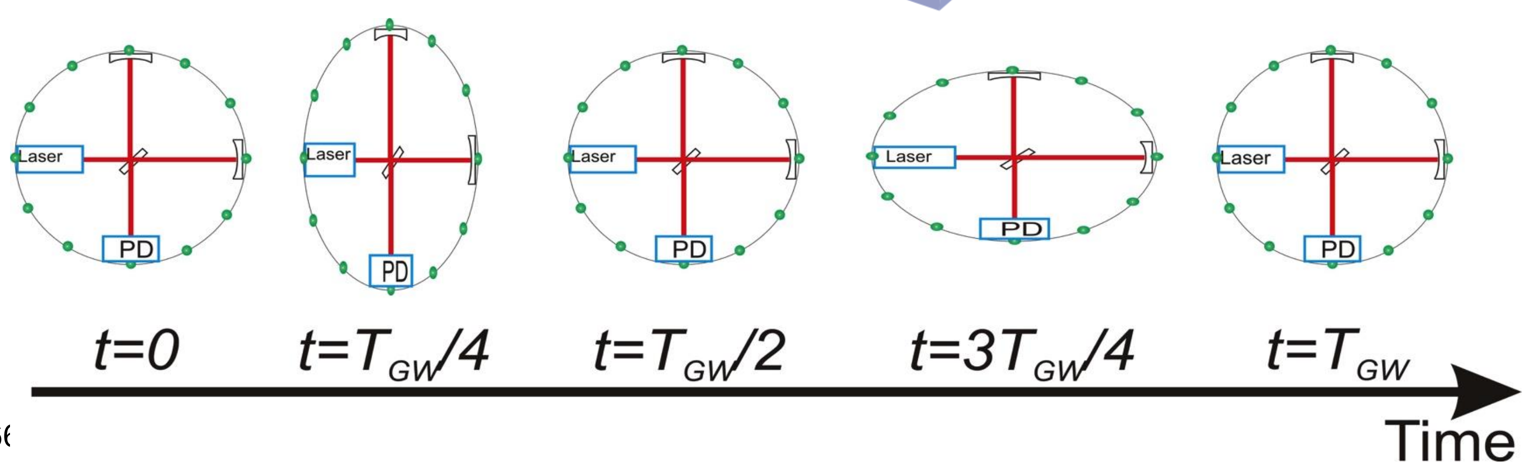


Gravitational-wave Interferometry

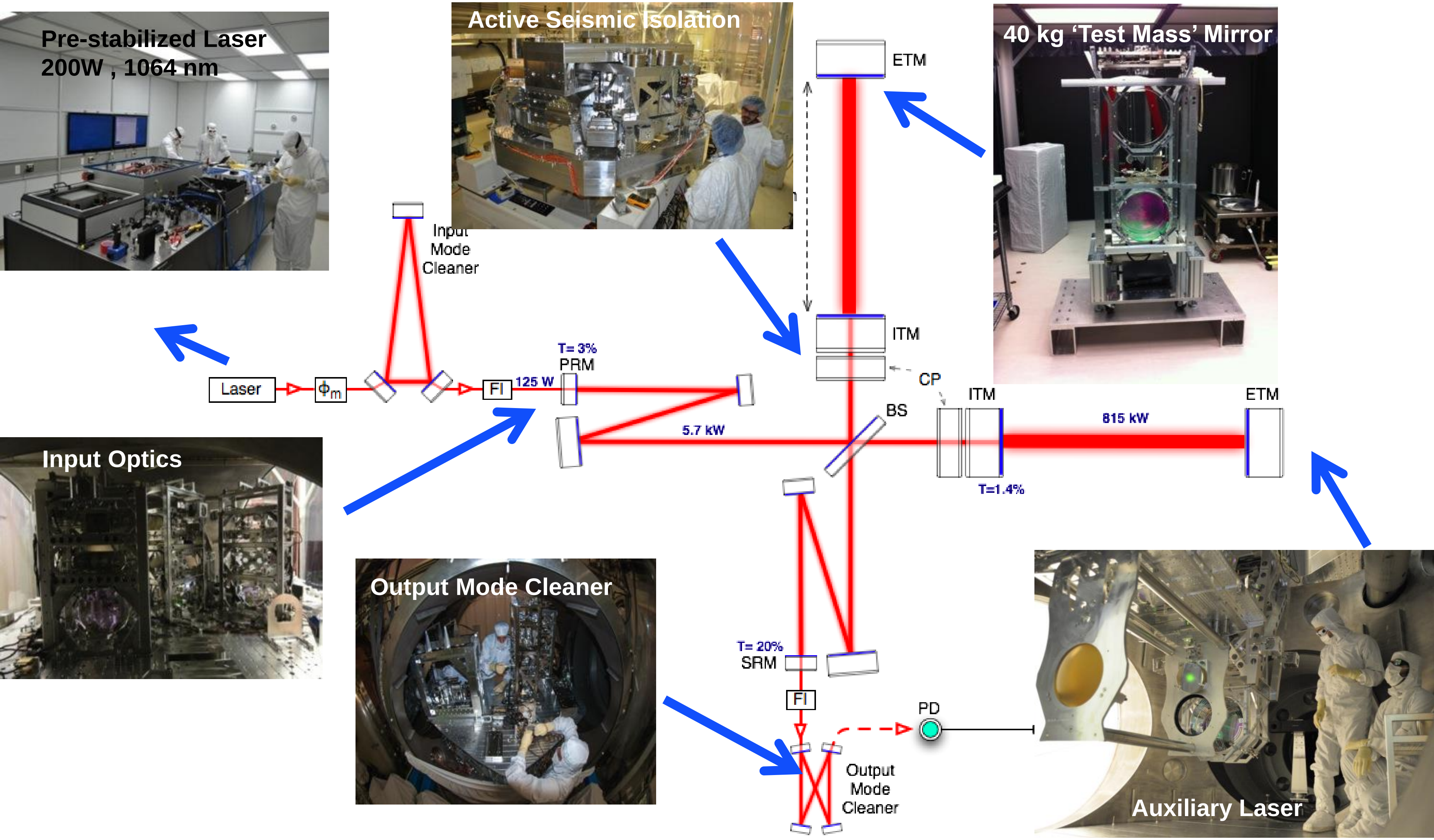
- Ground-based GW detectors uses enhanced Michelson interferometry
  - » With suspended ('freely falling') mirrors
- Passing GWs stretch and compress the distance between the end test mass and the beam splitter
- The interferometer acts as a transducer, turning GWs into photocurrent
  - » A coherent detector! 2X improvement in sensitivity == 8X increase in detection rate

Advanced LIGO

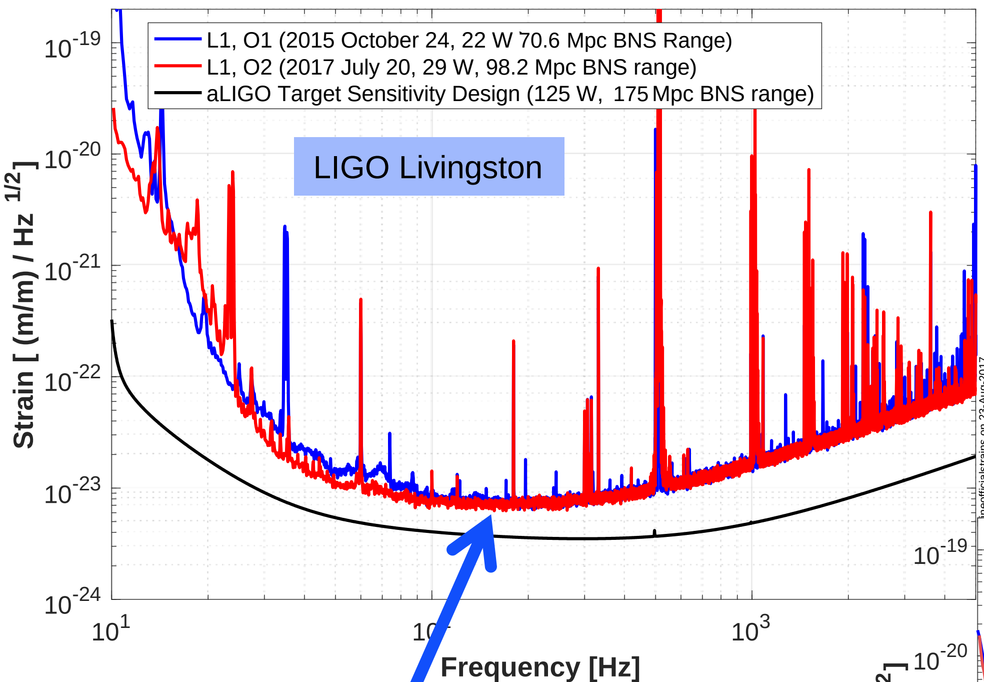




Advanced LIGO Interferometer

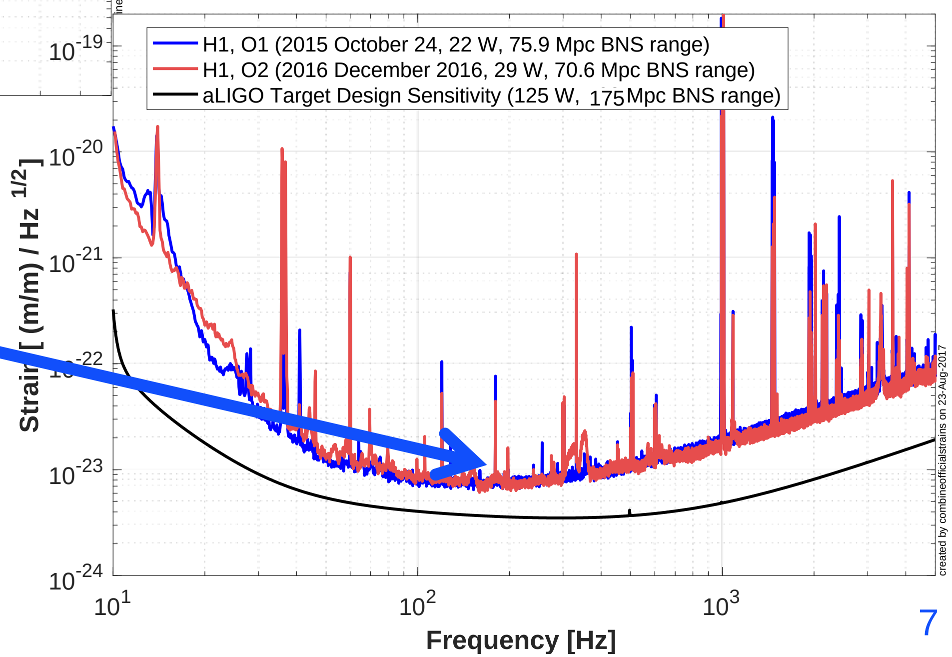


Advanced LIGO Sensitivity



BNS (binary neutron star) range - the 'average' distance to which an interferometer can detect a 1.4-1.4 $M_\odot$ BNS merger with an SNR of 8 (averaged over all sky positions and orbital inclinations)

$\Delta L \sim 3 \times 10^{-19}$ m




Virgo
Observatory
Italy

LIGO Hanford
Observatory
Washington, USA

LIGO Livingston
Observatory
Louisiana, USA

KAGRA
Observatory (2019)
Japan

LIGO-India (2025)

LIGO-India

- LIGO-India Project – a collaboration between India and the USA to build a LIGO interferometer in India.
  - Identical to the two USA LIGO detectors
  - India lead agencies: DAE&DST; US lead agency: NSF
- Good progress made in the past two years
  - Formal MOU between DAE and NSF in place
  - Site has been selected; land acquisition is proceeding
  - $23M (US equivalent) released to lead institutions for site acquisition, site studies and prep, vacuum prototyping, human resource development
  - A large of India institutions (including ICTS!) and researchers are joining the IndIGO collaboration
- Baseline LIGO-India Project schedule
  - Site preparation: 2018 – 2019
  - Observatory Construction: 2020-2022
  - Interferometer installation and commissioning: 2022-2024
  - **Observatory operations scheduled to begin in 2025**

LIGO-India Project

IndIGO - LSC

The First Gravitational Wave Detections: Binary Black Holes

Astrophysical Parameters of the Detected BBH Mergers

Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate FAR/yr^{-1}	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\,\sigma$	$> 5.3\,\sigma$	1.7σ
Primary mass $m_1^{\rm source}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\rm source}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathscr{M}^{\rm source}/\mathrm{M}_\odot$			
Total mass $M^{\rm source}/\mathrm{M}_\odot$			
Effective inspiral spin $\chi_{\rm eff}$			
Final mass $M_f^{\rm source}/\mathrm{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_f	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\rm rad}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\rm peak}/(\mathrm{erg\,s^{-1}})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance D_L/Mpc	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600

Radiated energy $E_{\rm rad}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\rm peak}/(\mathrm{erg\,s^{-1}})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$

GW170814

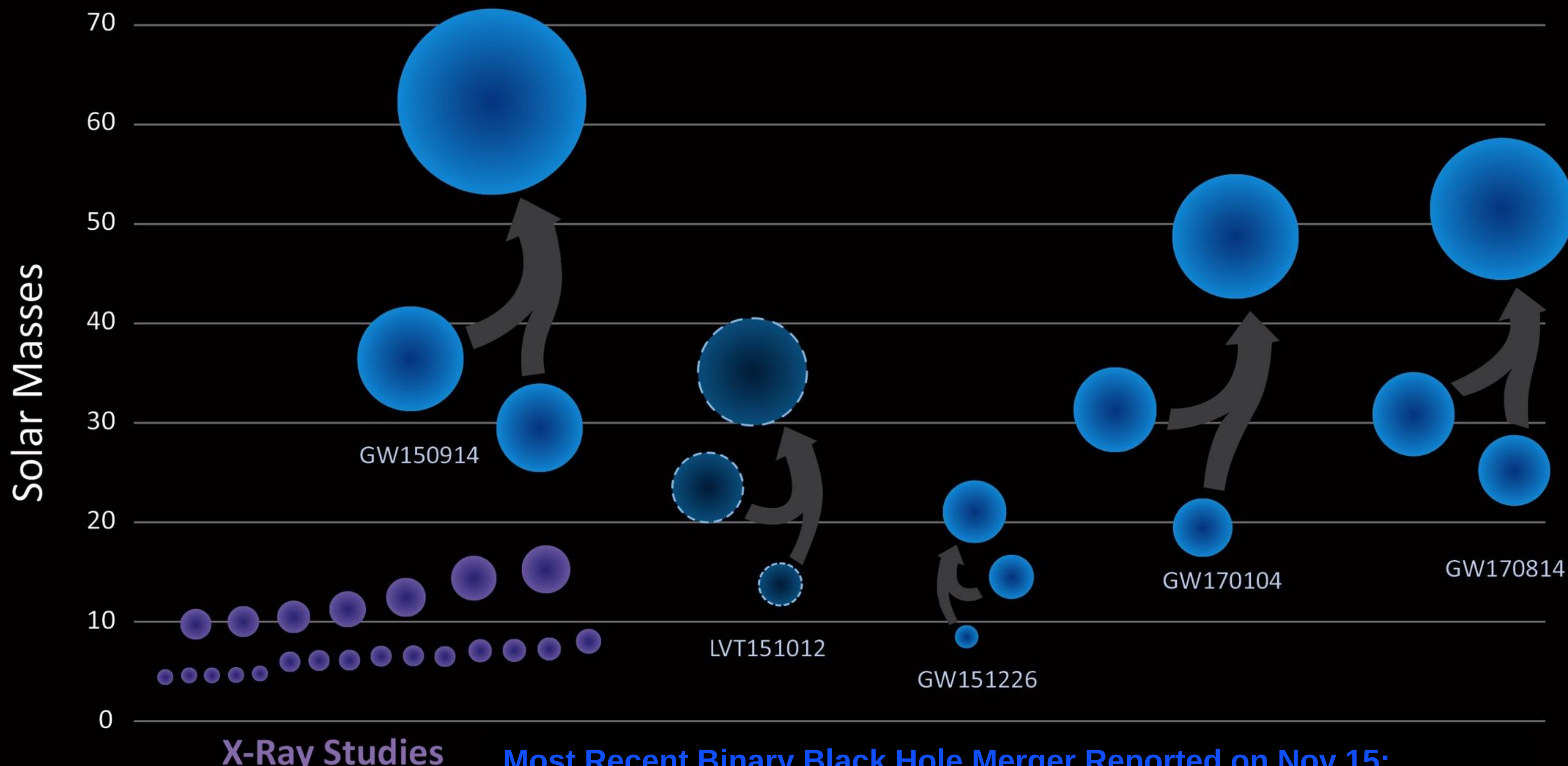
Primary black hole mass m_1	$30.5^{+5.7}_{-3.0}\ \mathrm{M}_\odot$
Secondary black hole mass m_2	$25.3^{+2.8}_{-4.2}\ \mathrm{M}_\odot$
Chirp mass $\mathcal{M}$	$24.1^{+1.4}_{-1.1}\ \mathrm{M}_\odot$
Total mass M	$55.9^{+3.4}_{-2.7}\ \mathrm{M}_\odot$
Final black hole mass $M_{\rm f}$	$53.2^{+3.2}_{-2.5}\ \mathrm{M}_\odot$
Radiated energy $E_{\rm rad}$	$2.7^{+0.4}_{-0.3}\ \mathrm{M}_\odot c^2$
Peak luminosity $\ell_{\rm peak}$	$3.7^{+0.5}_{-0.5} \times 10^{56}\ \mathrm{erg\,s^{-1}}$
Effective inspiral spin parameter $\chi_{\rm eff}$	$0.06^{+0.12}_{-0.12}$
Final black hole spin $a_{\rm f}$	$0.70^{+0.07}_{-0.05}$
Luminosity distance $D_{\rm L}$	540^{+130}_{-210} Mpc
Source redshift z	$0.11^{+0.03}_{-0.04}$

Peak luminosity $\ell_{\rm peak}$	$3.4^{+0.5}_{-1.6} \times 10^{56}$ erg s^{-1}
Luminosity distance $D_{\rm L}$	340^{+140}_{-140} Mpc
Source redshift z	$0.07^{+0.03}_{-0.03}$

GW170104

Primary black hole mass m_1	$31.2^{+8.4}_{-6.0} M_\odot$
Secondary black hole mass m_2	$19.4^{+5.3}_{-5.9} M_\odot$
Chirp mass $\mathcal{M}$	$21.1^{+2.4}_{-2.7} M_\odot$
Total mass M	$50.7^{+5.9}_{-5.0} M_\odot$
Final black hole mass M_f	$48.7^{+5.7}_{-4.6} M_\odot$
Radiated energy $E_{\rm rad}$	$2.0^{+0.6}_{-0.7} M_\odot c^2$
Peak luminosity $\ell_{\rm peak}$	$3.1^{+0.7}_{-1.3} \times 10^{56}$erg s^{-1}
Effective inspiral spin parameter $\chi_{\rm eff}$	$-0.12^{+0.21}_{-0.30}$
Final black hole spin a_f	$0.64^{+0.09}_{-0.20}$
Luminosity distance D_L	880^{+450}_{-390} Mpc
Source redshift z	$0.18^{+0.08}_{-0.07}$

Black Holes of Known Mass



Most Recent Binary Black Hole Merger Reported on Nov 15: GW170608: Observation of a 19-solar-mass Binary Black Hole Coalescence, Astrophys. J. Lett 851:L35 (2017).

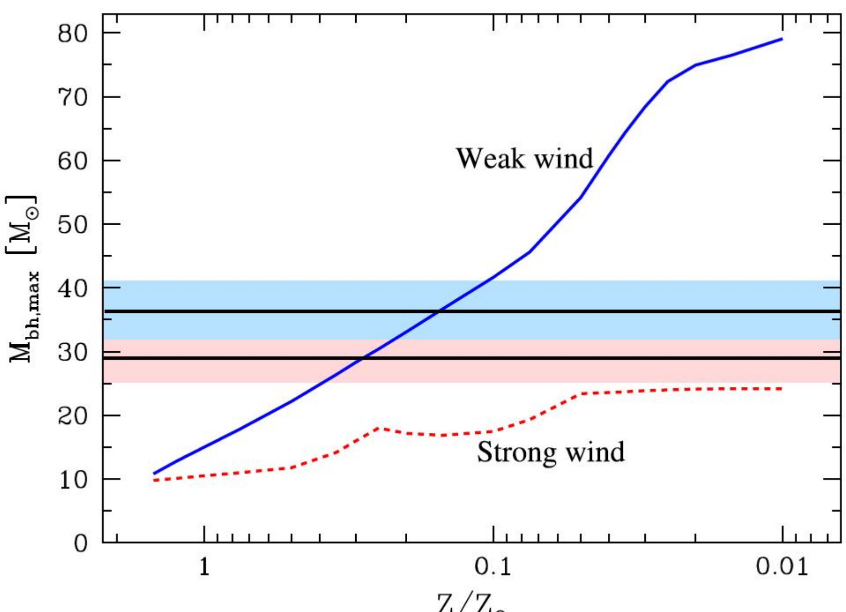
Astrophysical Implications of LIGO-Virgo Black Hole Mergers

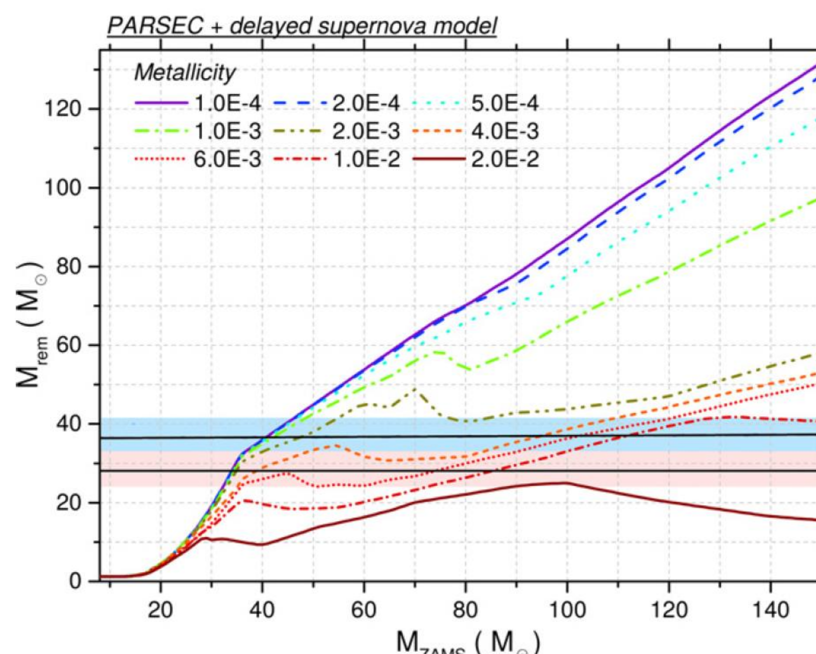
- Stellar mass binary black hole systems exist.
- Stellar mass binary black hole systems can merge in less than a Hubble time.
- ***First observation of 'heavy' stellar mass (> 25 $M_\odot$) black holes***
- Heavy mass BBH system most likely formed in a low-metallicity environment: < ½-¼ $Z_\odot$

What to expect in the future:

- Determination of mass and spin spectrum of black holes
  - » Confirm or rule out dark matter scenarios
- **Determine preferred formation channels: isolated binary evolution vs dynamical capture in dense stellar environments**

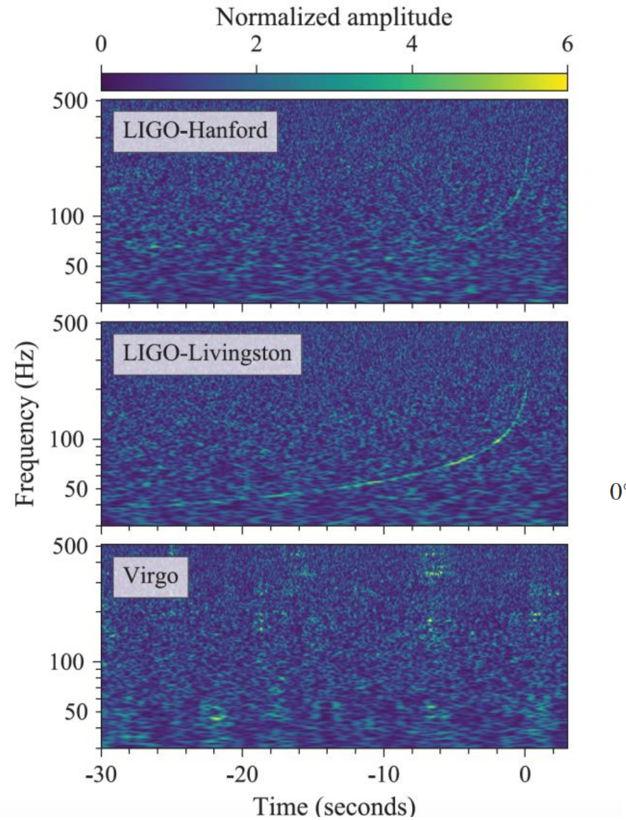
Abbott, et al., LIGO Scientific Collaboration and Virgo Collaboration, "Astrophysical Implications of the Binary Black Hole Merger GW150914" [Astrophys. J. Lett 818:L22 (2016)]



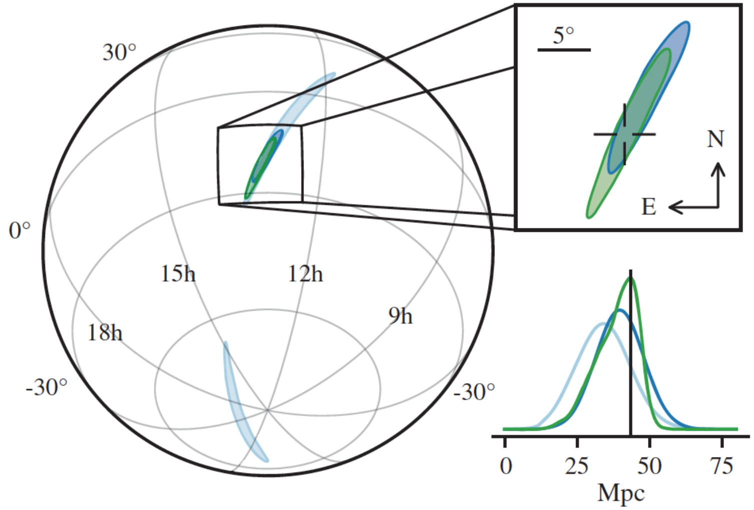


The Newest Detection:
A Binary Neutron Star Merger

GW170817: The First Detected Binary Neutron Star Merger

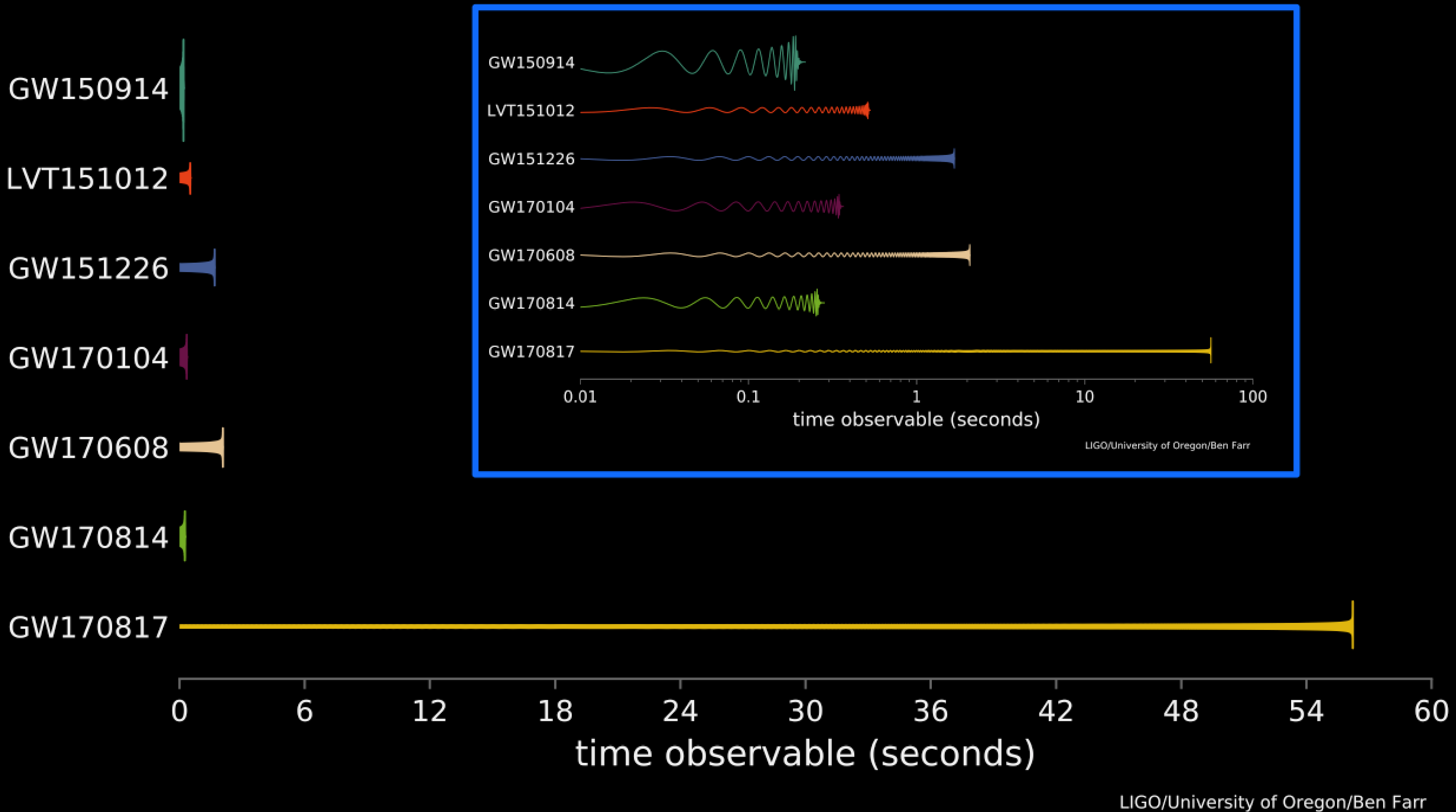


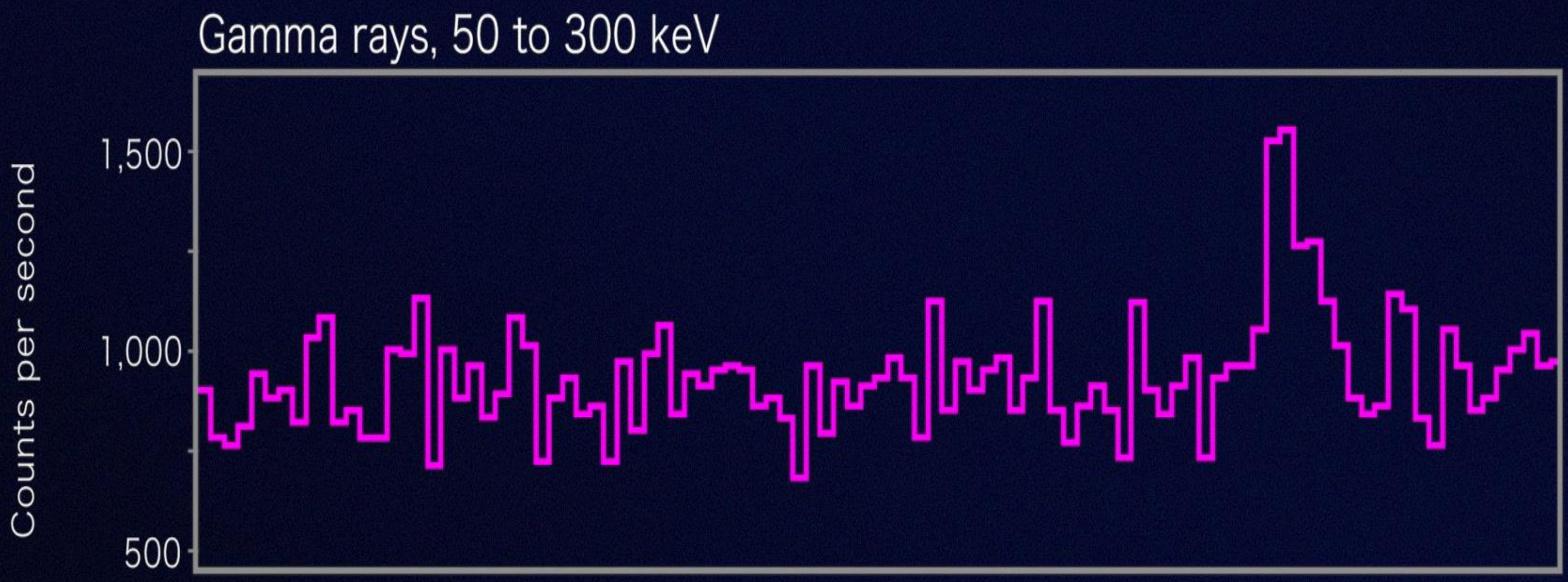
Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, “GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral” Phys. Rev. Lett. 161101 (2017)



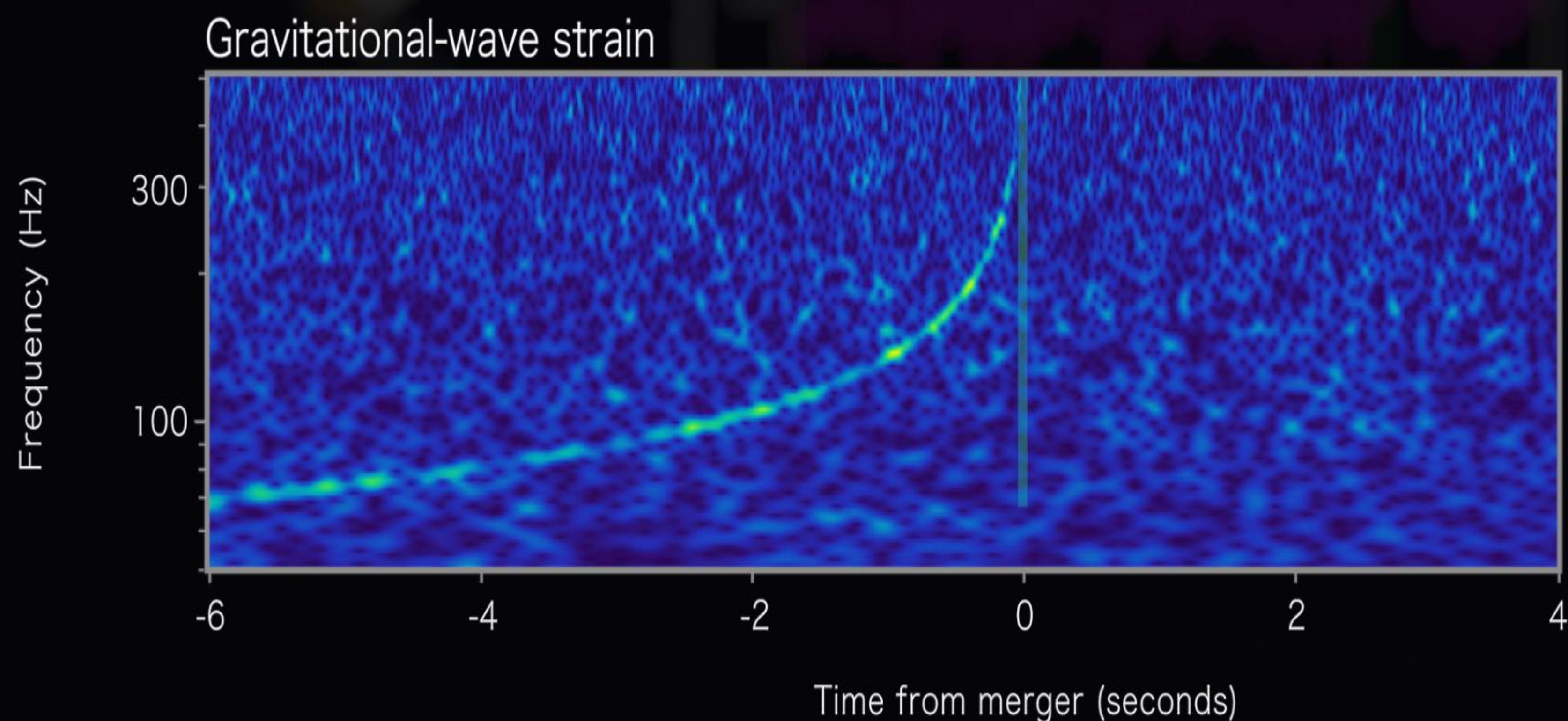
	Low-spin priors ($\|\chi\| \leq 0.05$)	High-spin priors ($\|\chi\| \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

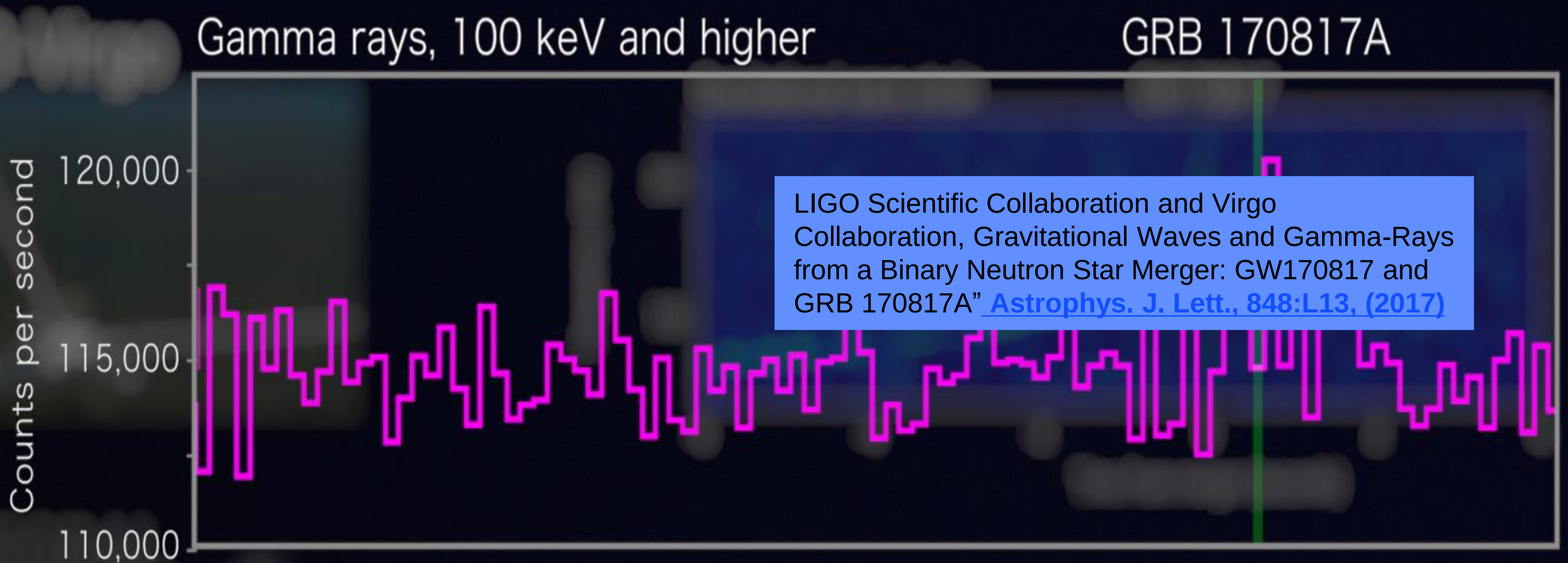
Comparison of the Gravitational Waveforms





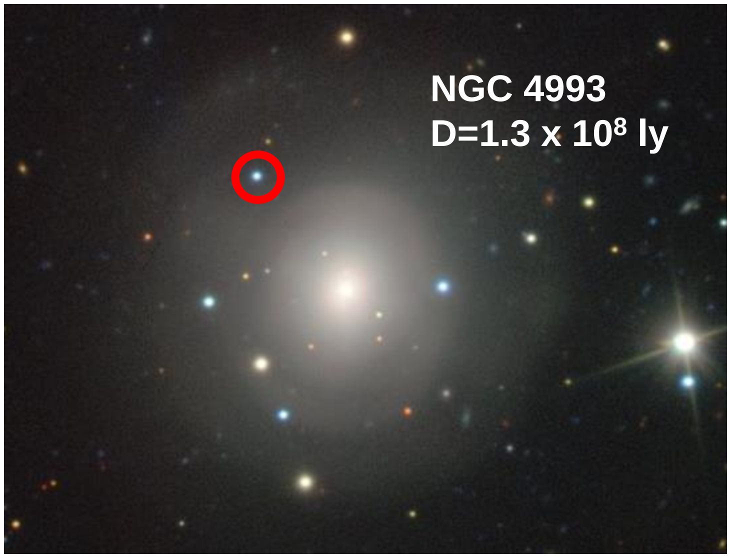
Gamma rays, 50 to 300 keV
Counts per second
1,500
1,000
500


Gravitational-wave strain
Frequency (Hz)
300
100
-6
-4
-2
0
2
4
Time from merger (seconds)

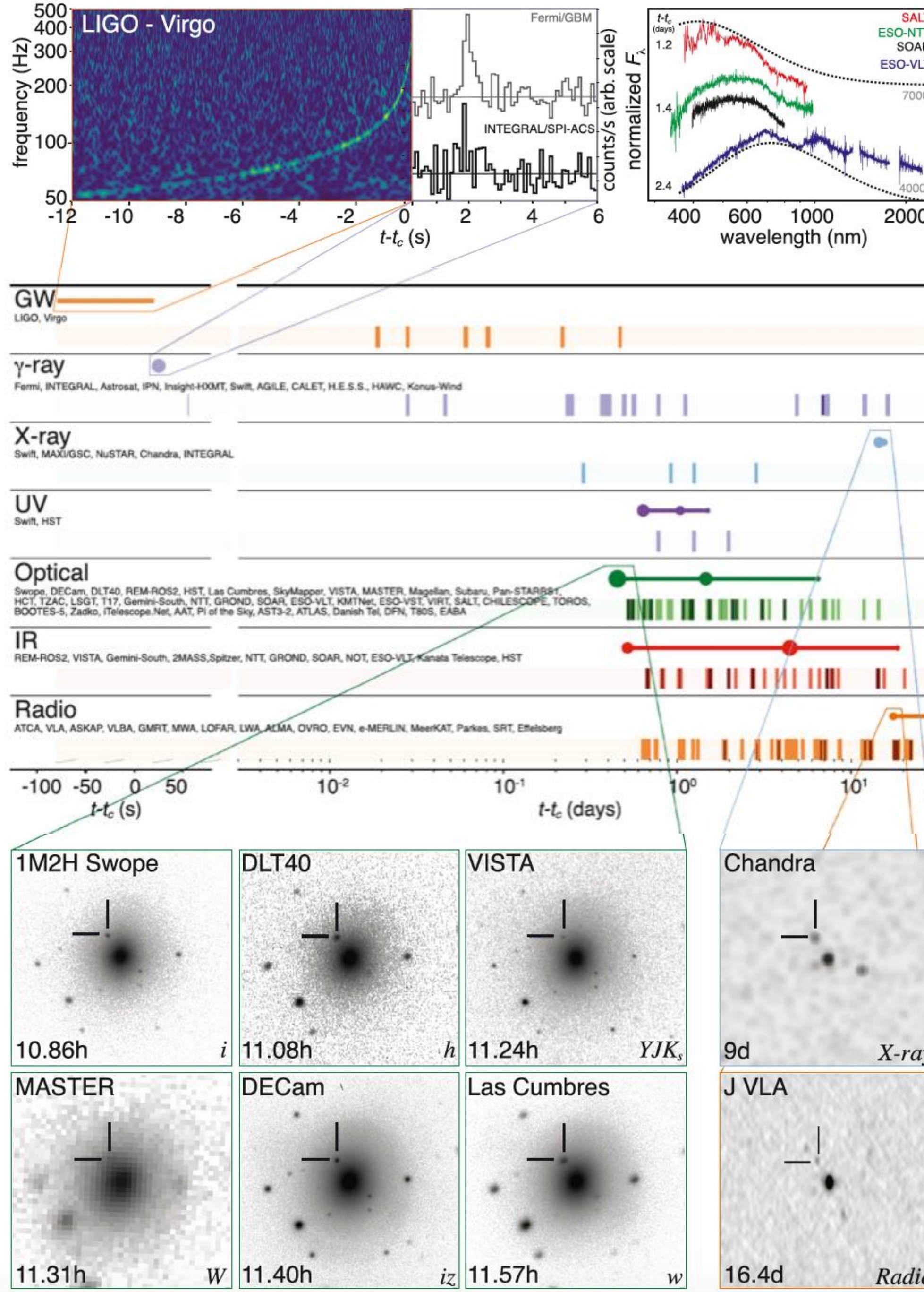


LIGO Scientific Collaboration and Virgo Collaboration, Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A” [Astrophys. J. Lett., 848:L13, (2017)]

Observations Across the Electromagnetic Spectrum



Credit: European Southern Observatory
Very Large Telescope



Abbott, et al. ‚LIGO Scientific Collaboration and Virgo Collaboration, “Multi-messenger Observations of a Binary Neutron Star Merger” [Astrophys. J. Lett., 848:L12, (2017)]

Are Gravitons Massless?

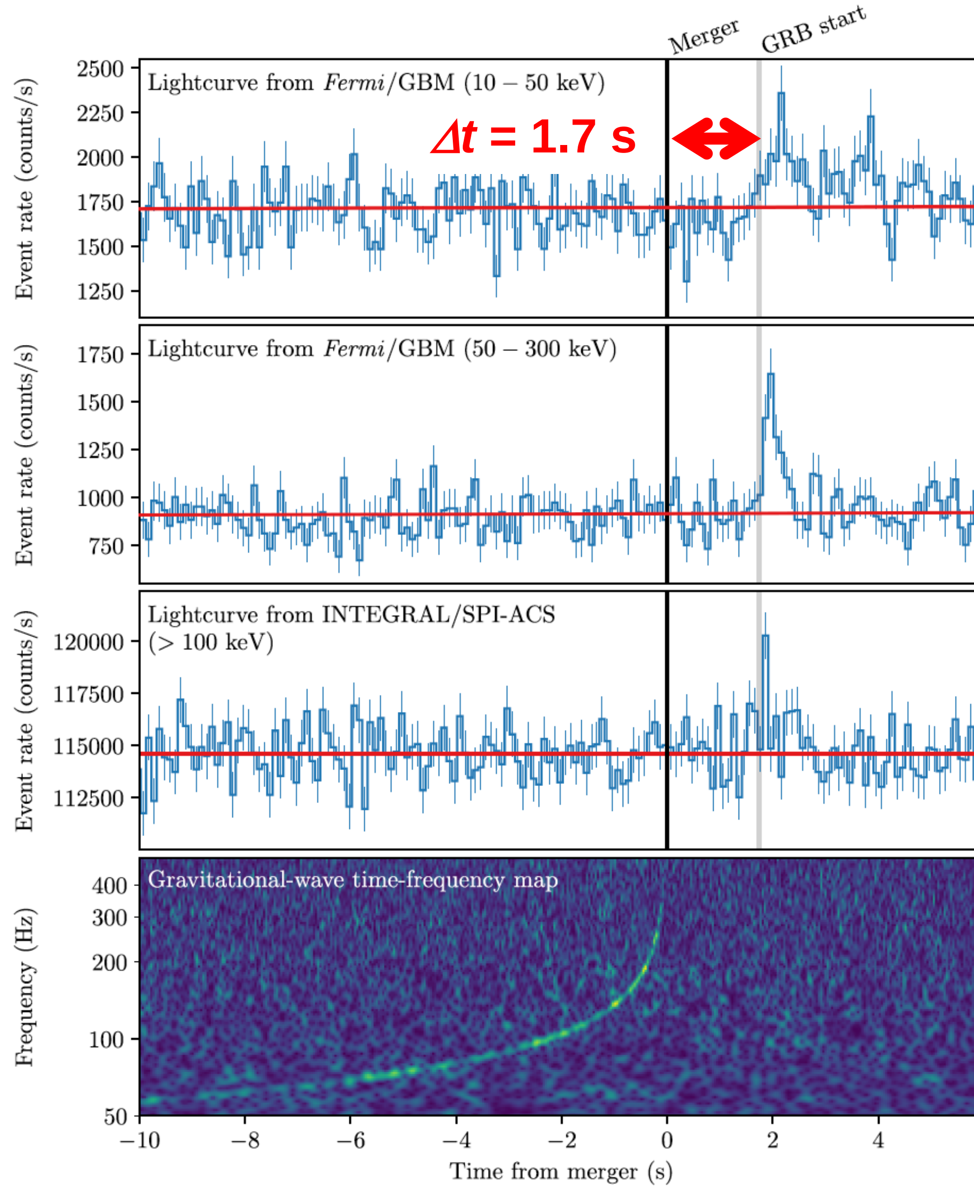
- GW170817 provides a stringent test of the speed of gravitational waves

$$\frac{v_{GW} - c}{c} \approx \frac{c\Delta t}{D}$$

- Δt =1.74 +/- 0.05 s
- $D \approx$ 26 Mpc
  - Conservative limit – use 90% confidence level lower limit on GW source from parameter estimation

$$\boxed{-3 \times 10^{-16} \leq \frac{v_{GW} - c}{c} \leq +7 \times 10^{-16}}$$

- GW170814 also puts limits on violations of Lorentz Invariance and Equivalence Principle

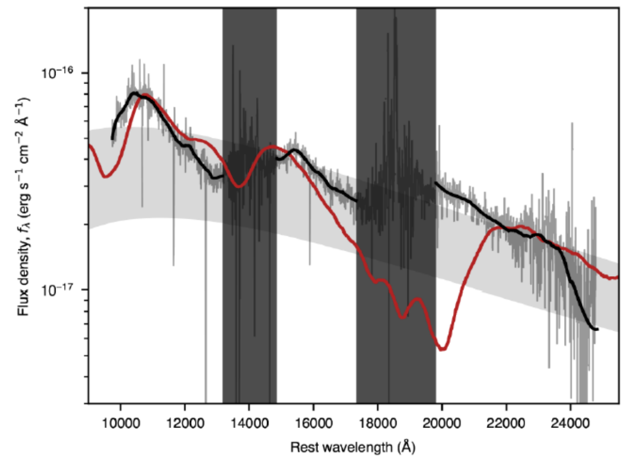


LIGO Scientific Collaboration and Virgo Collaboration, Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A" Astrophys. J. Lett., 848:L13, (2017)

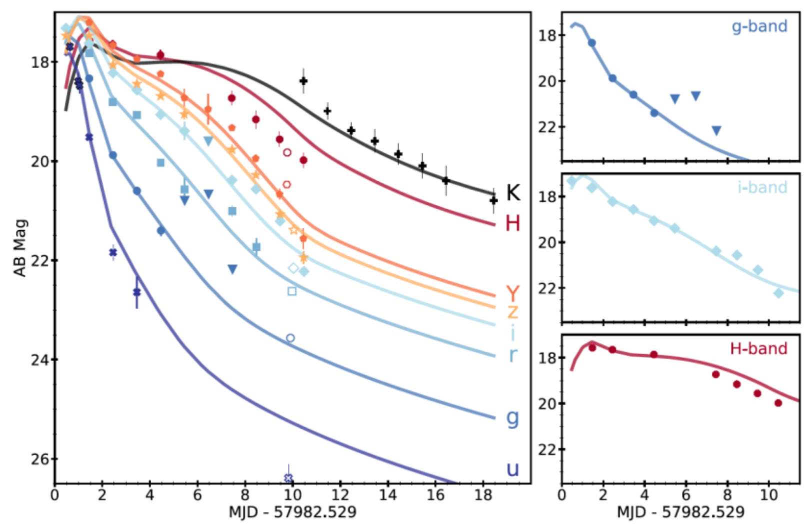
Binary Neutron Star Mergers Produce Kilonovae

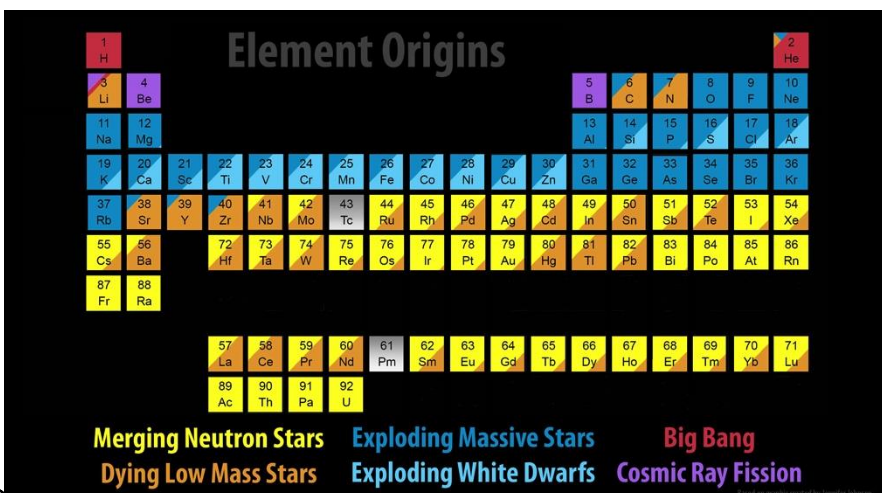
- Electromagnetic follow-up of GW170817 provides strong evidence for kilonova model
  - » kilonova - isotropic thermal emission produced by radioactive decay of rapid neutron capture (‘r-process’) elements synthesized in the merger ejecta
- Spectra taken over 2 week period across all electromagnetic bands consistent with kilonova models
  - » “Blue” early emission dominated by Fe-group and light r-process formation; later “red” emission dominated by heavy element (lanthanide) formation
- Recent radio data prefers ‘cocoon’ model to classical short-hard GRB production!

Kasliwal et al. 2017,
Science, DOI: https://doi.org/10.1126/science.aap9455



Cowpersthwaite, et al. 2017,
Ap. J. Lett. DOI: https://doi.org/10.3847/2041-8213/aa8fc7



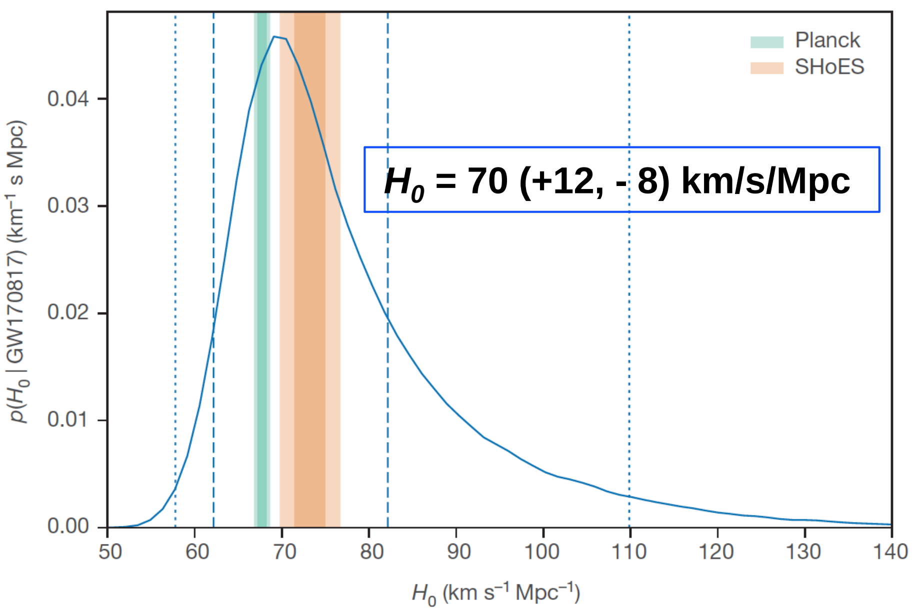


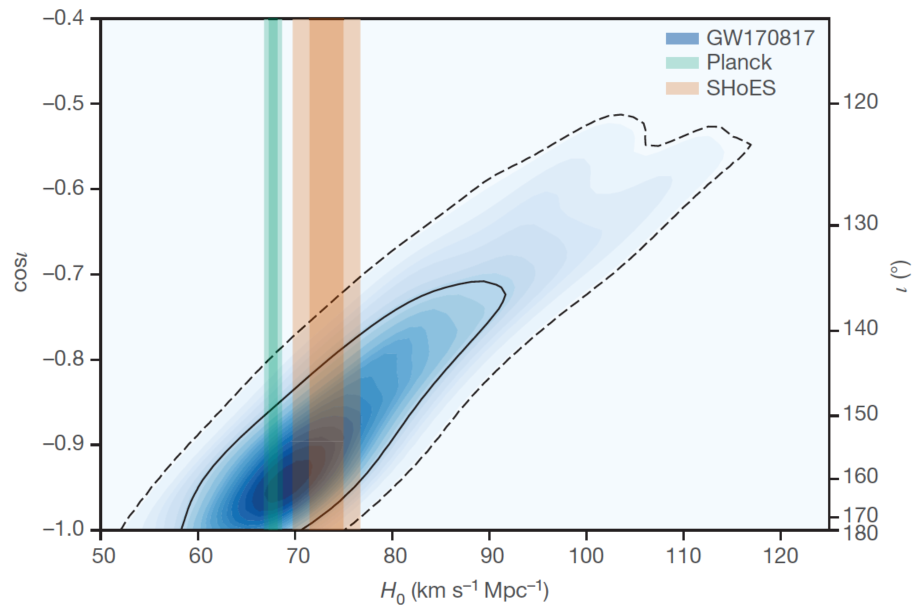
A gravitational-wave standard siren measurement of the Hubble constant

- Gravitational waves are ‘standard sirens’, providing absolute measure of luminosity distance d_L
- can be used to determine H_0 directly if red shift is known:

$$c\,z = H_0\,d_L$$

- … without the need for a cosmic distance ladder!



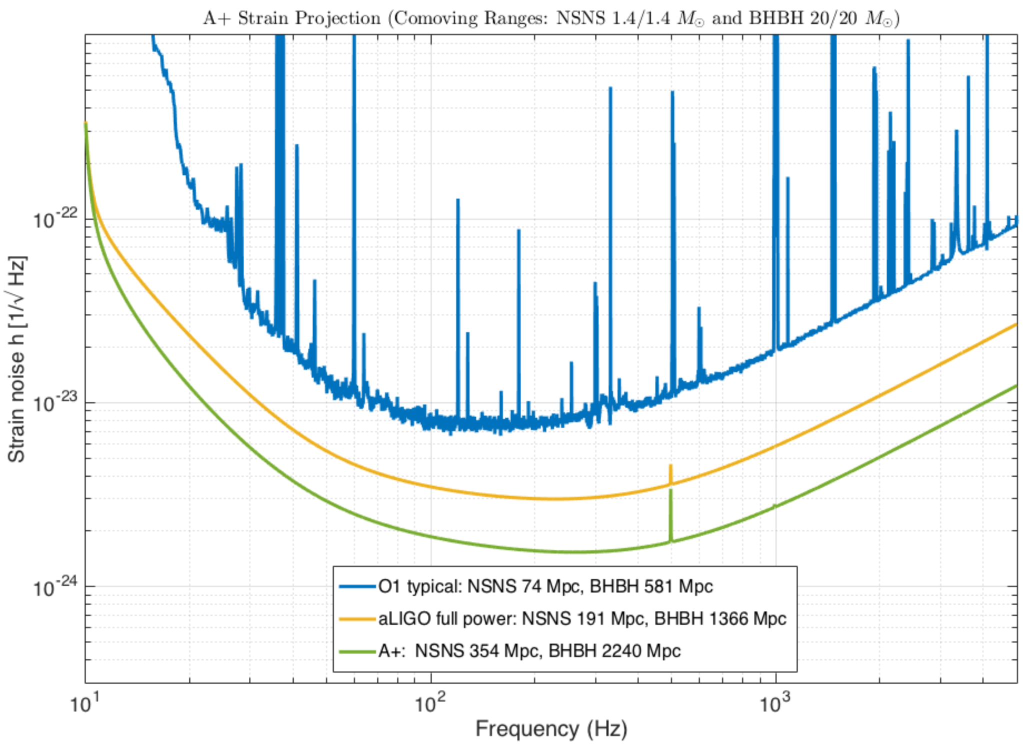


Abbott, et al., LIGO-Virgo Collaboration, 1M2H, DeCAM GW-EM & DES, DLT40, Las Cumbres Observatory, VINRO UGE, MASTER Collaborations, A gravitational-wave standard siren measurement of the Hubble constant”, *Nature* **551**, 85–88 (2017).

The Future of GW Astrophysics: Beyond Advanced LIGO

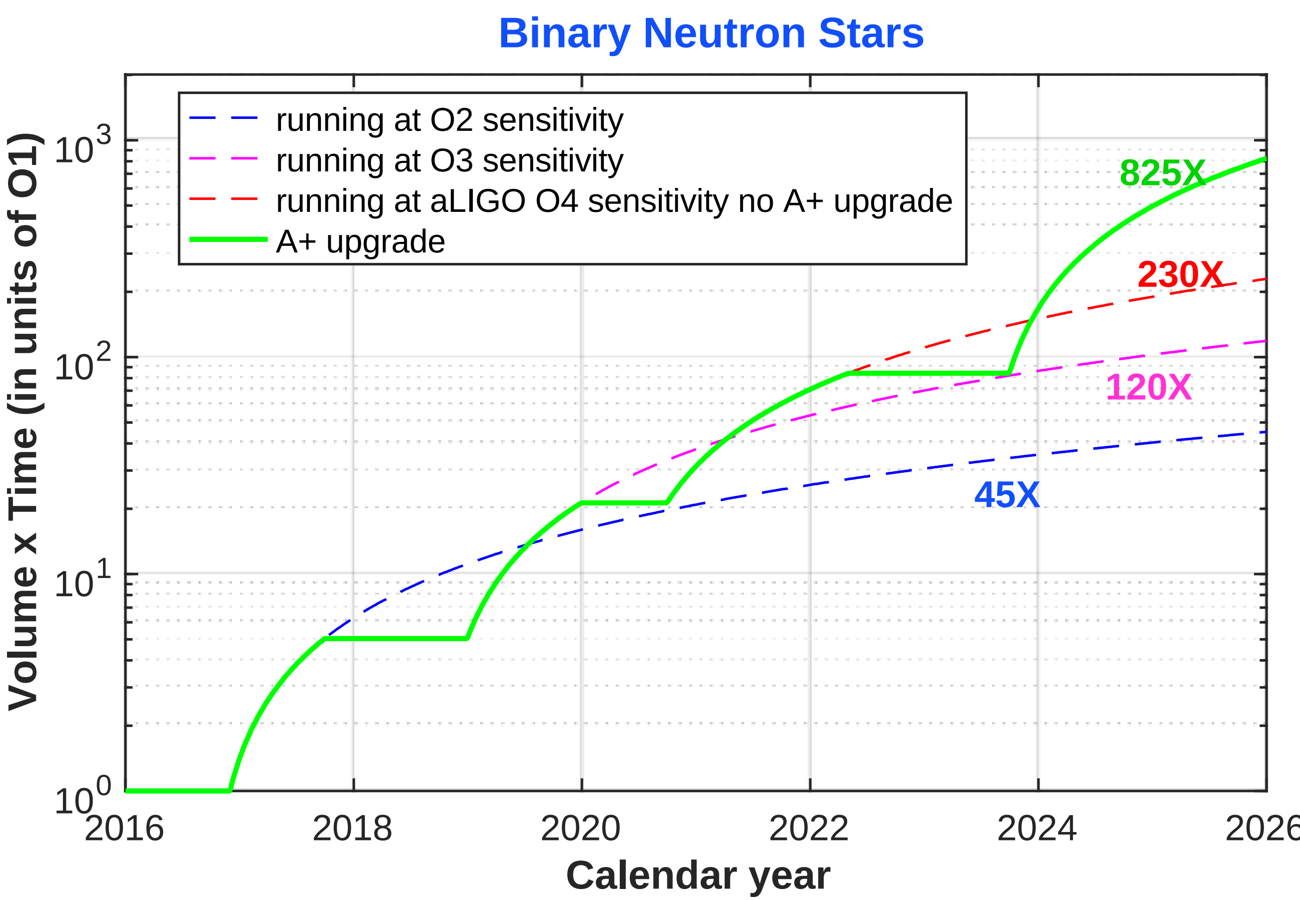
‘A+’ Advanced LIGO Mid-scale Upgrade

- An upgrade to aLIGO that leverages existing technology and infrastructure, with minimal new investment and moderate risk
- Target: average 1.7 increase in range over aLIGO
- ➔ ***~ 5 greater event rate than Advanced LIGO; ~ 40 times better than current Advanced LIGO sensitivity***
- A+ is a stepping stone to future detector technologies
- ***Timescale – begin upgrade in 2021; back online in 2023***
  - » Assumes funding begins in 2019
- LIGO-India is planned to come online in the A+ configuration



A+ key parameters:
12dB injected squeezing
15% readout loss
100 m filter cavity (FC)
20 ppm round trip FC loss
Coating Thermal Noise half of aLIGO

LIGO Science is Sensitivity Driven



1) Rates

$N_{events} = \langle R \rangle VT$

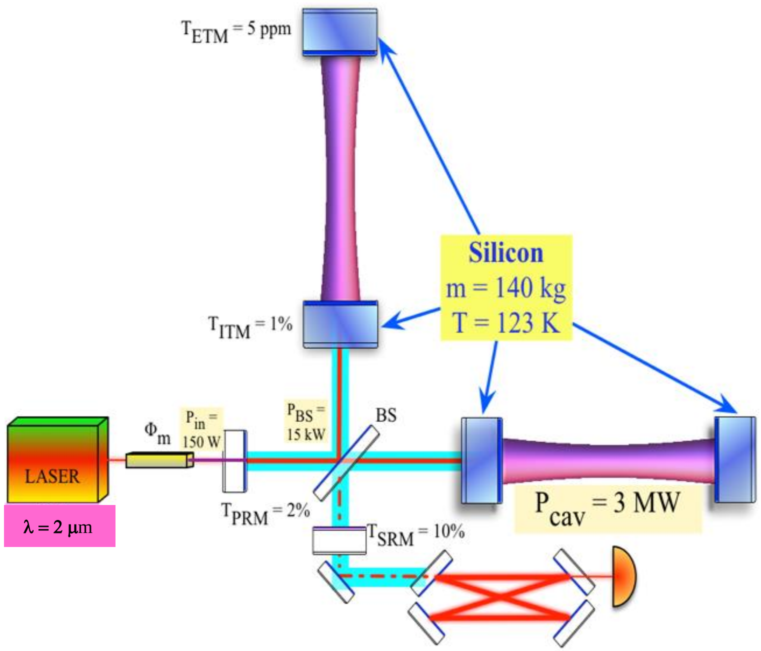
<R>: average astrophysical rate
V: volume of the universe probed → $(Range)^3$
T: coincident observing time

2) *Many sources require higher SNR to uncover new astrophysics*

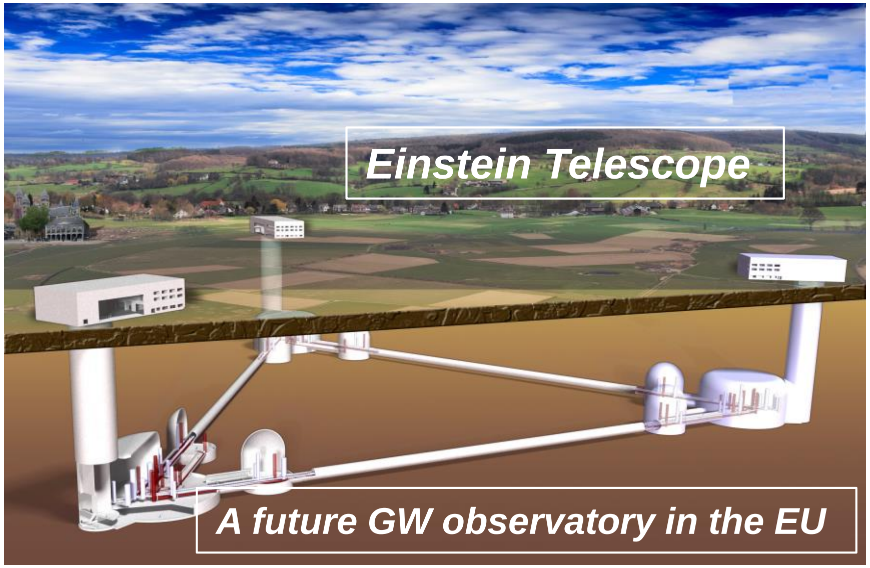
- tidal disruption in BNS mergers
- tests of alternative theories of gravity
- Black hole ringdowns
- Stochastic background
- Isolated neutron stars
- Galactic supernova
- ....

Further on: Voyager, Einstein Telescope, Cosmic Explorer

LIGO Voyager – exploiting the LIGO Observatory facility limits

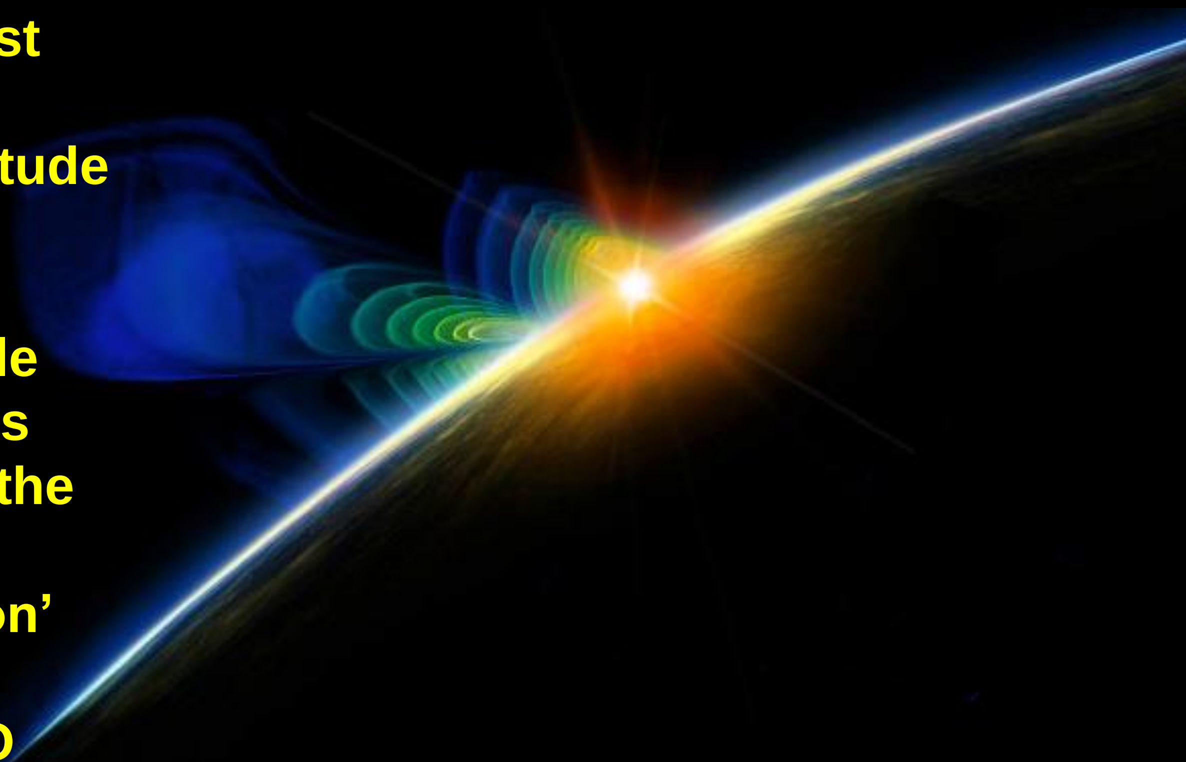


New Facilities:
Longer Arm Length Interferometers



Advanced LIGO and the Dawn of Gravitational-waves Physics and Astronomy

- **LIGO-Virgo has made first measurements of gravitational wave amplitude and phase**
- **Merging binary black hole and neutron star systems have been observed for the first time!**
  - **'a scientific revolution'**
- **Future increases in LIGO sensitivity will increase the rate of detections**
  - **Daily Binary Black Hole Mergers, weekly binary neutron star mergers**



Stay Tuned…

LIGO

LSC

LIGO Scientific Collaboration

Trinity University

University of Maryland

Andrews University

Washington State University

California State University Fullerton

The University of Alabama in Huntsville

Whitman College

American University Washington, DC

Sonoma State University

indigo

Montclair State University

University of Glasgow

Australian National University

University of the West of Scotland UWS

Texas Tech University

清華大學 Tsinghua University

R·I·T

University of Strathclyde

Max Planck Institute for Gravitational Physics Albert Einstein Institute

Michigan

CITA ICAT

Università degli Studi del Sannio

NASA Goddard Space Flight Center

ICTP SAIFR

The University of Western Australia

University of Cambridge

Montana State University

The University of Chicago

Southern University Agricultural & Mechanical College

Columbia University in the City of New York

Caltech

University of Minnesota

The University of Mississippi

The University of Adelaide Australia

University of Birmingham

The University of Melbourne

UIB Universitat de les Illes Balears

University of Washington

GEO 600

UTRGV

University of Wisconsin Milwaukee

Cardiff University Prifysgol Caerdydd

Northwestern

Monash University

INPE

UF University of Florida

Georgia Institute of Technology

Korean Gravitational-Wave Group

LSU Louisiana State University

ACIGA

University of Southampton

Charles Sturt University

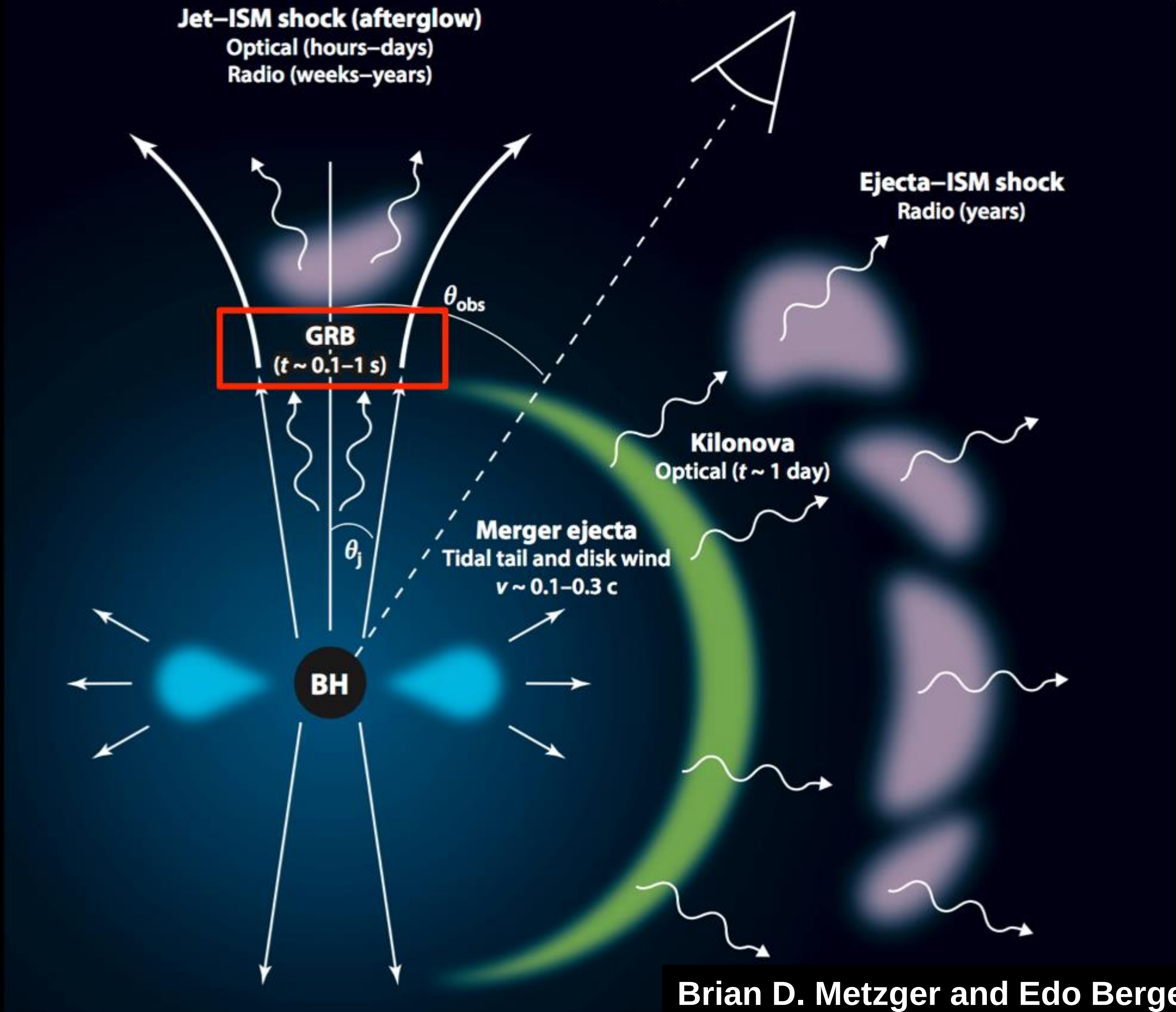
Embry-Riddle Aeronautical University

Leibniz Universität Hannover

PennState

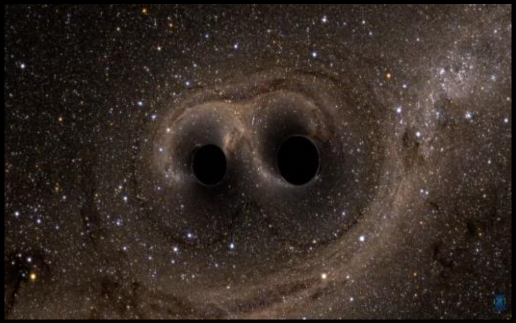
Science & Technology Facilities Council Rutherford Appleton Laboratory

Electromagnetic Counterparts of NS Mergers



Brian D. Metzger and Edo Berger, 2012

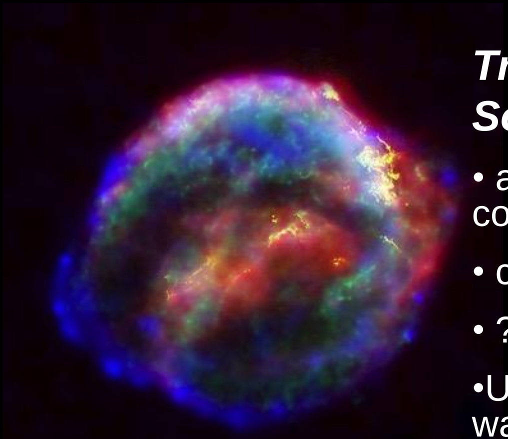
The Astrophysical Gravitational-Wave Source Catalog



Credit: Bohn, Hébert, Throwe, SXS

Coalescing Binary Systems

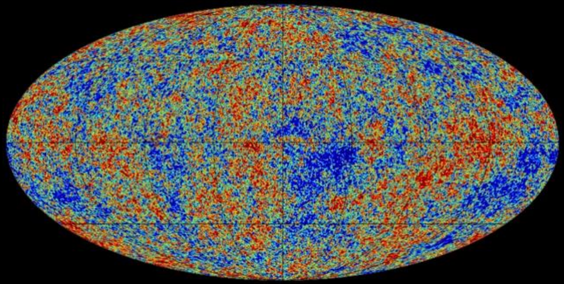
- Black hole – black hole
- Black hole – neutron star
- Neutron star – neutron star
- modeled waveform



Credit: Chandra X-ray Observatory

Transient 'Burst' Sources

- asymmetric core collapse supernovae
- cosmic strings
- ???
- Unmodeled waveform



Credit: Planck Collaboration

Cosmic GW Background

- residue of the Big Bang
- probes back to < 10^{-15} s
- stochastic, incoherent background
- Difficult (impossible?) for LIGO-Virgo to detect

Credit: Casey Reed, Penn State

Continuous Sources

- Spinning neutron stars
- monotone waveform

A Revolution in Astronomy

- “The reported observations, connecting GWs to both gamma-ray bursts (GRBs) and a long-theorized—but hitherto undetected—short-lived EM transient represents a watershed moment in astrophysics.”
  - Josh Bloom and Steinn Sigurdsson, *Science*, Oct 16
- “The modern era has brought us a plethora of great wonders. In doing so, however, it might have eroded the sense of awe that wonder can inspire. Stories like this one ought to help restore it. The sheer scale of this discovery is awesome — from the distance (130 million light years) to the density of neutron stars (one teaspoon of neutron-star material would weigh a billion tons).”

  \- *Richmond Times-Dispatch* Editorial, Oct 17
- “The last two years of gravitational waves astronomy have brought us an immense wealth: the dream of being able of studying the universe with a battery of simultaneous probes (the so-called "multi-messenger astrophysics") has become true. Whoever says this is not a scientific revolution has not grasped the implications, or is just envious for not being involved.”

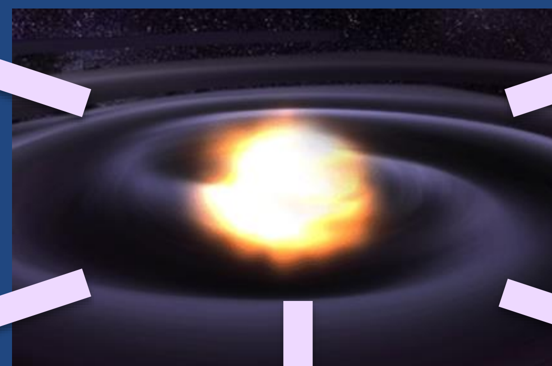
  \- Tommaso Dorigo, Science 2.0, Oct 17
- "This is the future of gravitational wave detection, which is a new astronomy that has been opened. It's a new window on the universe that has been anticipated for decades, and it's an amazing coming-to-fruition of the ambitions of thousands of scientists, technologists, that actually accomplished what many people thought they could not."

  \- Adam Burrows, Phys.org, Nov 2

Multi-messenger Astronomy with Gravitational Waves

Gravitational Waves

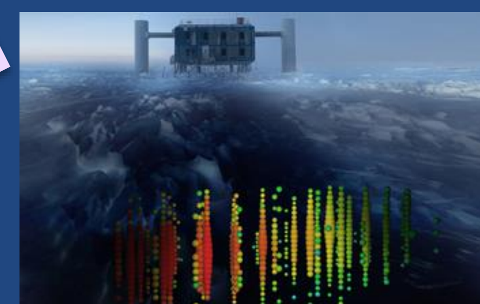
Binary Neutron Star Merger



X-rays/Gamma-rays

Visible/Infrared Light

Radio Waves

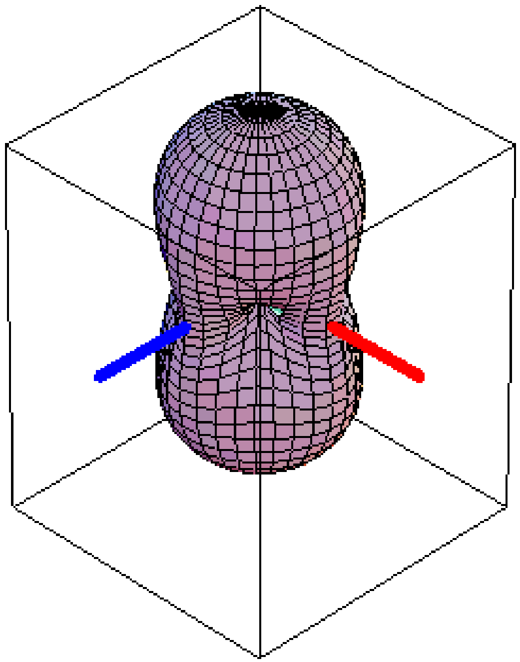


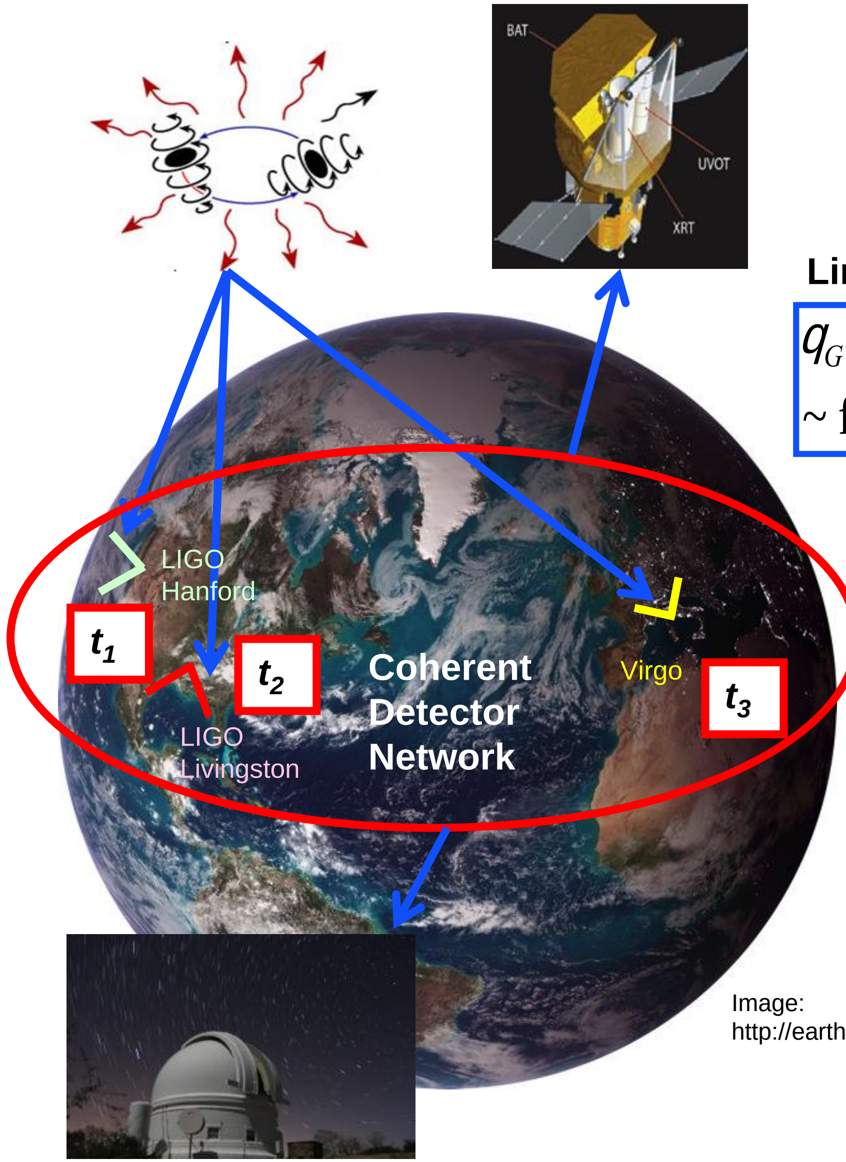
Neutrinos

Enabling multi-messenger astronomy with gravitational waves

Interferometers are ‘omni-directional microphones’!!

Polarization-averaged antenna pattern for an interferometer





Limit:

$$\theta_{GW} \sim \lambda_{GW} / d_{earth}$$

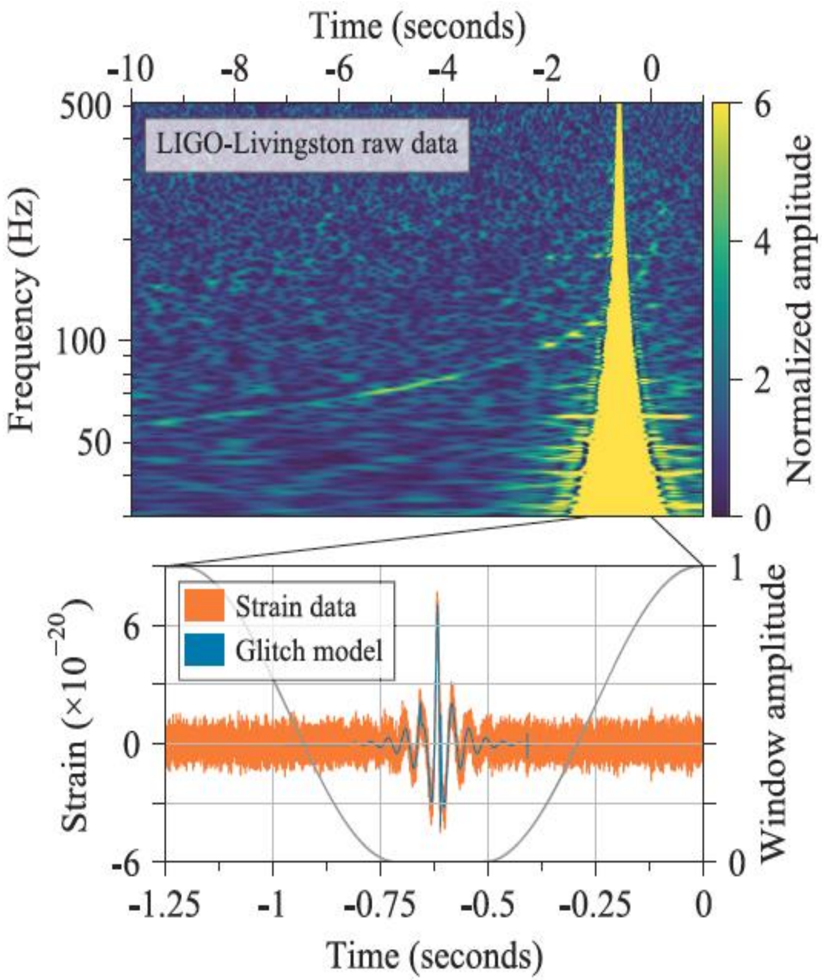
$\sim$ few degrees

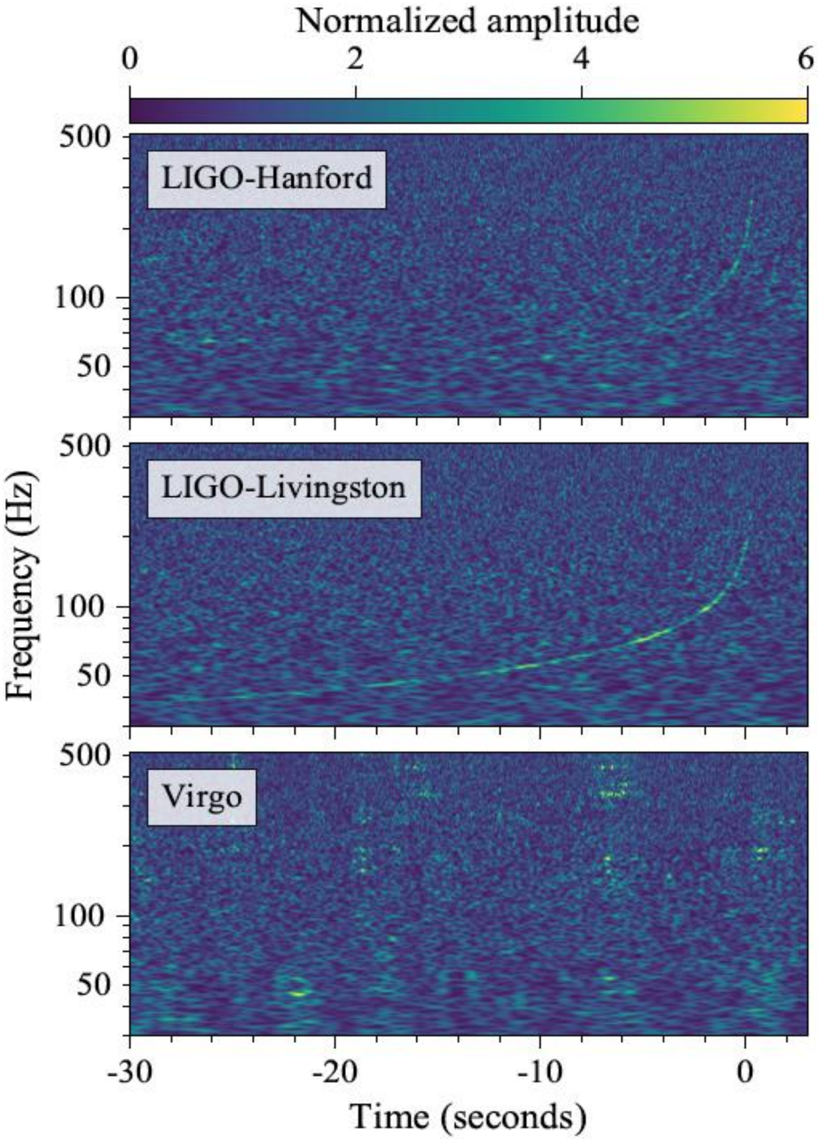
Image: http://earthobservatory.nasa.gov/

Abadie, et al, (LSC & Virgo Collaborations) Astron. Astrophys. **541** (2012) A155.

GW170817: The First Binary Neutron Star Merger

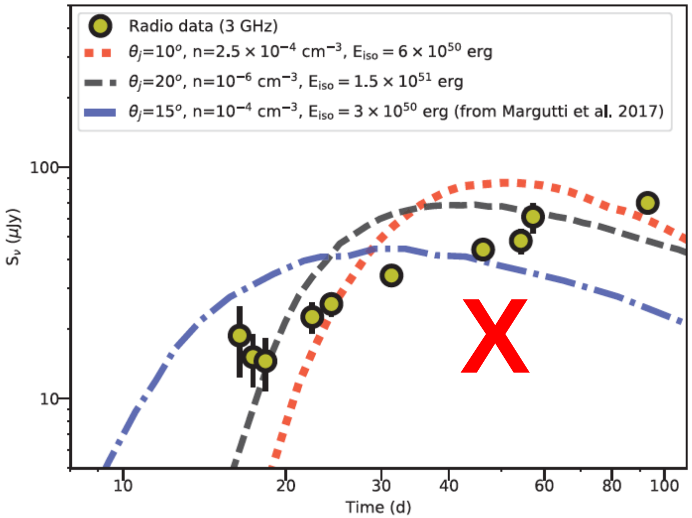
Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral" Phys. Rev. Lett. 161101 (2017)



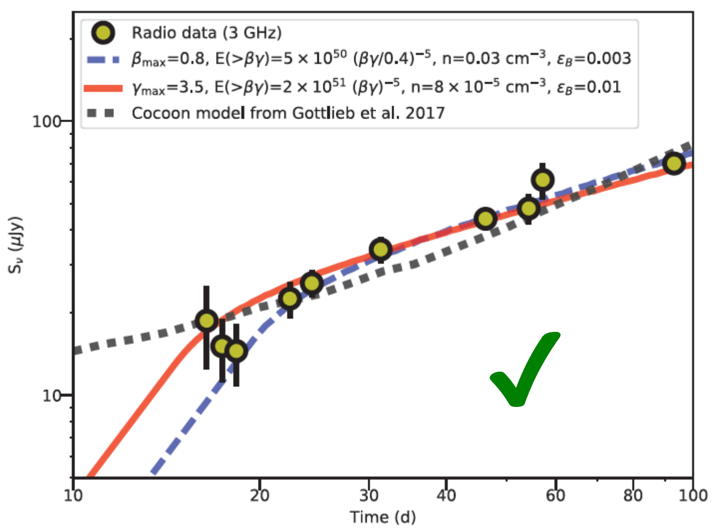


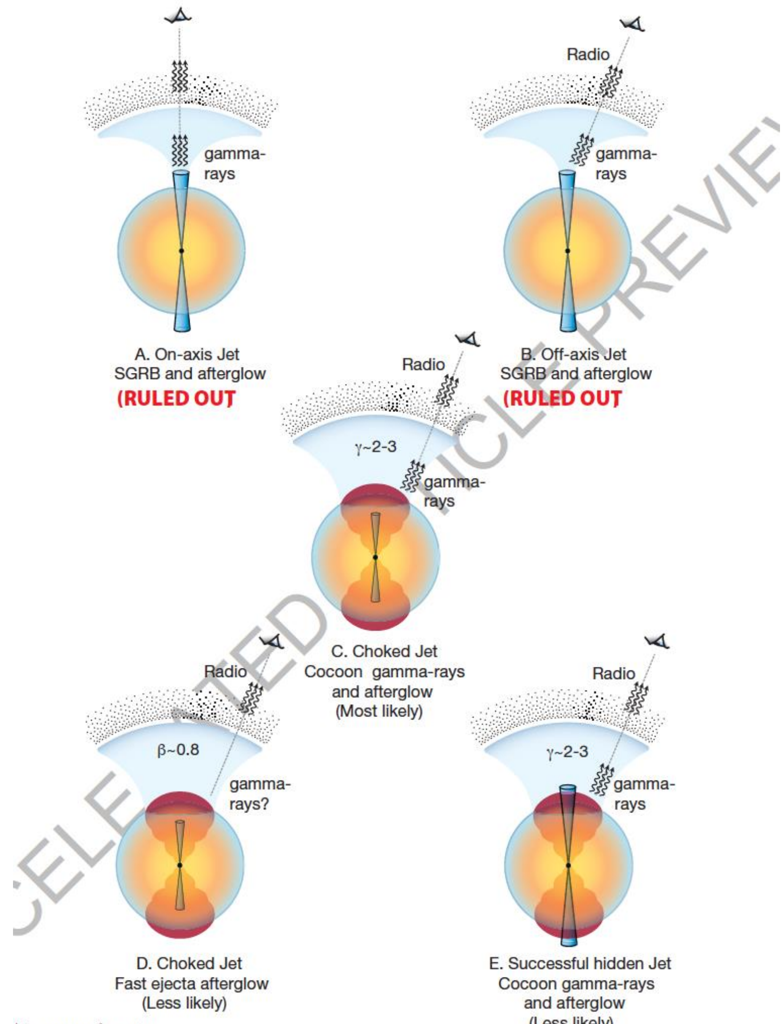
Cocoon Model

Off Axis Jet Model



Cocoon Model





| See next page for caption.

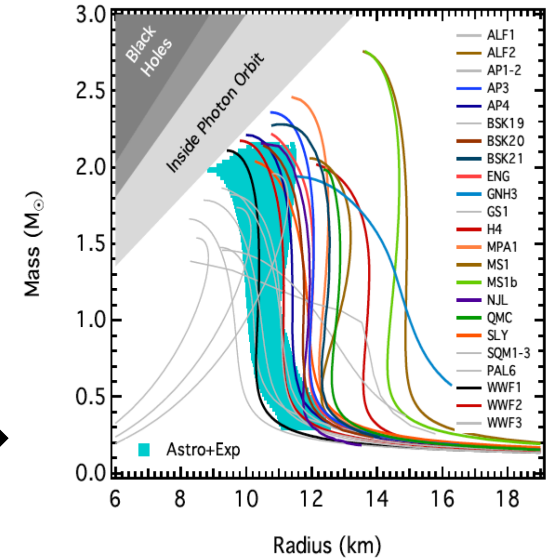
Mooley et al., “A mildly relativistic wide-angle outflow in the neutron-star merger event GW170817”, Nature http://dx.doi.org/10.1038/nature25452 (2017)

Constraining the Neutron Star Equation of State with GW170817

- Gravitational waveforms contain information about NS tidal deformations → allows us to constrain NS equations of state (EOS)
- Tidal deformability parameter:

$$\Lambda = \frac{2}{3} k_2 \left(\frac{R}{M} \right)^5$$

- GW170817 data consistent with softer EOS → more compact NS



Ozel and Friere (2016)

Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral" Phys. Rev. Lett. 161101 (2017)