Exploiting the New Frontier of Gravitational-Wave Astronomy

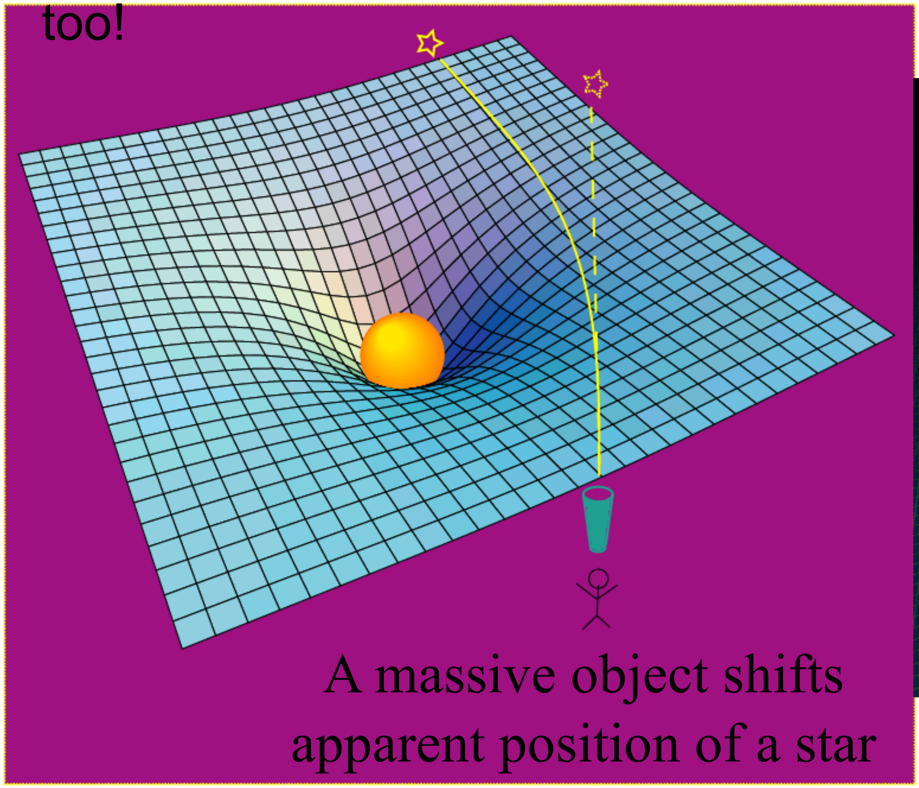
Fred Raab, for the LIGO
Scientific Collaboration and
the Virgo Collaboration

LIGO-G1801971

Basics of Gravitational-Waves

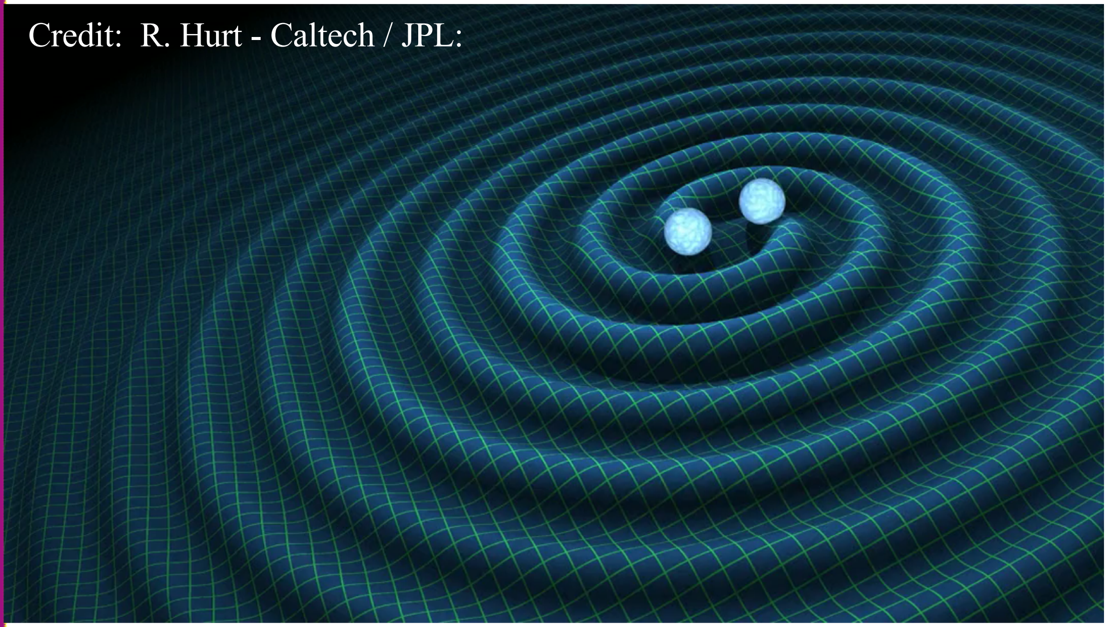
Einstein’s General Relativity: gravity is a manifestation of space-time curvature

curved spacetime can bend light, too!



A massive object shifts apparent position of a star

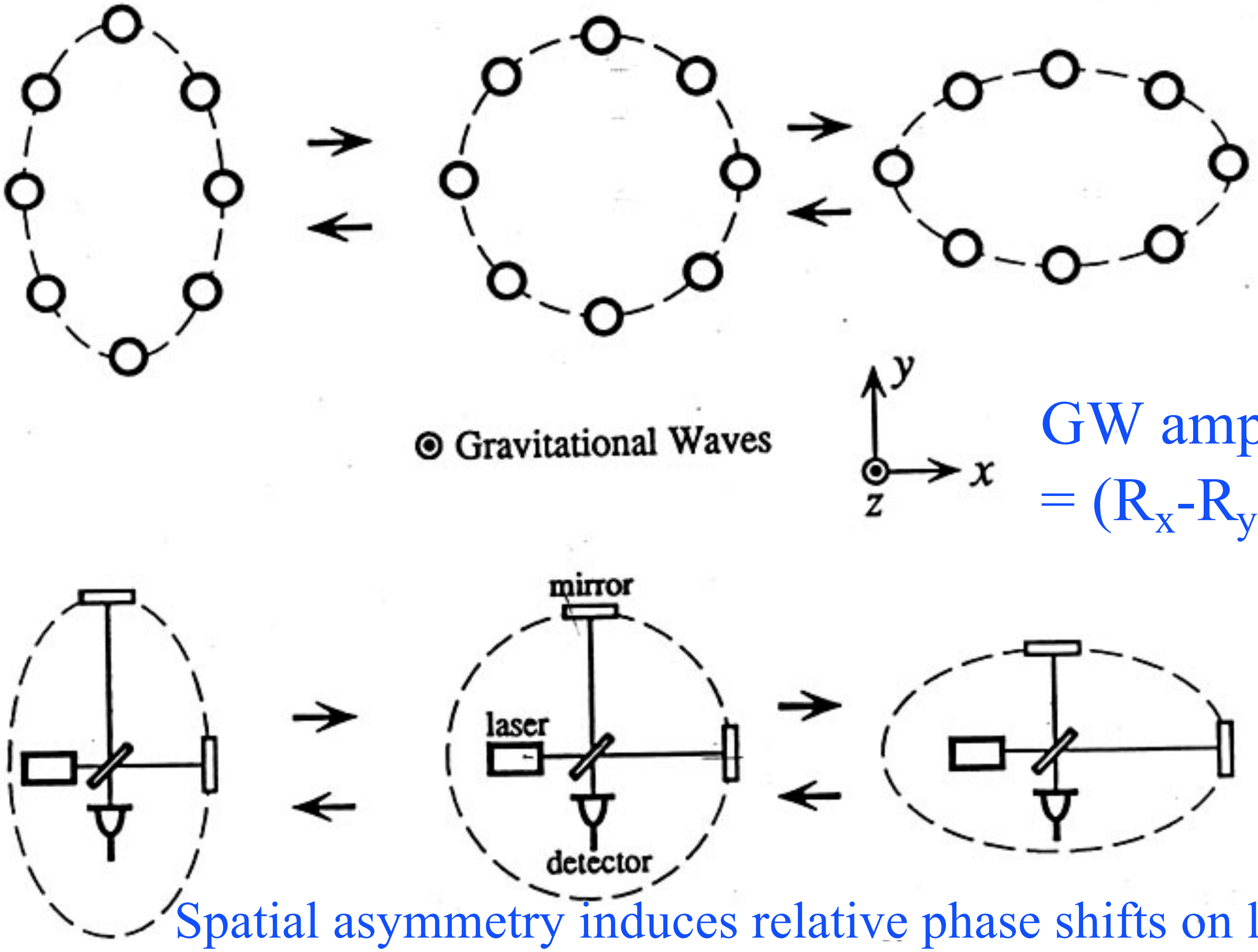
dynamic deformation of spacetime



Credit: R. Hurt - Caltech / JPL:

Space has a shape, a stiffness and a maximum speed for information transfer.

Basic idea for detection is simple



GW amplitude h = $(R_x - R_y)/R$

Spatial asymmetry induces relative phase shifts on light in arms

The Laser Interferometer Gravitational-wave Observatory

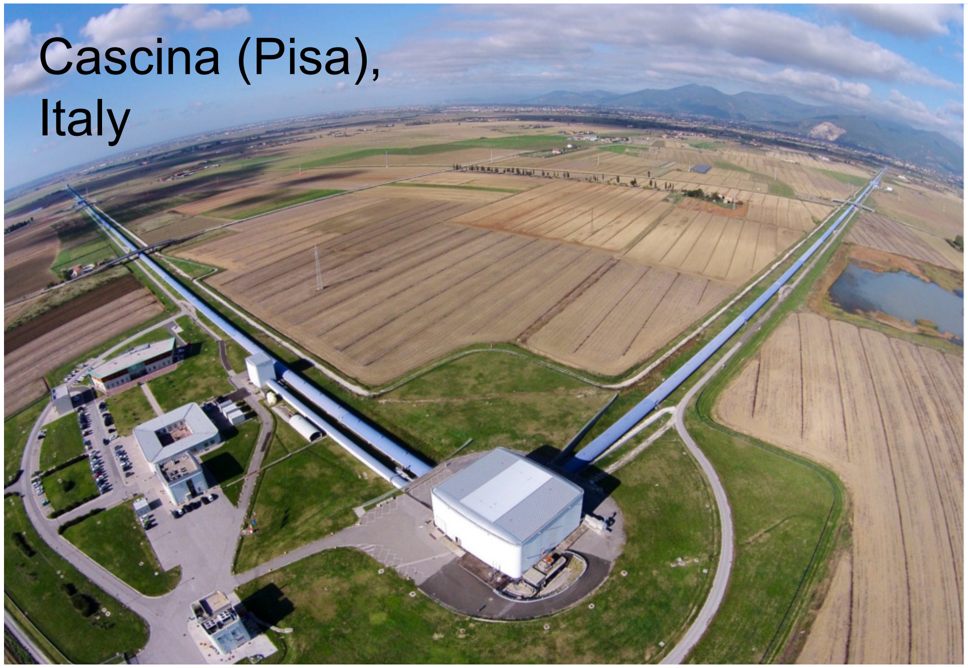
- Adapted from "The Blue Marble: Land Surface, Ocean Color
- NASA Goddard Space Flight Center Image by Reto Stöckli (land surface, shallow wa color, compositing, 3D globes, animation). Data and technical support: MODIS Land G Atmosphere Group; MODIS Ocean Group Additional data: USGS EROS Data Center (t Field Center (Antarctica); Defense Meteorological Satellite Program (city lights).

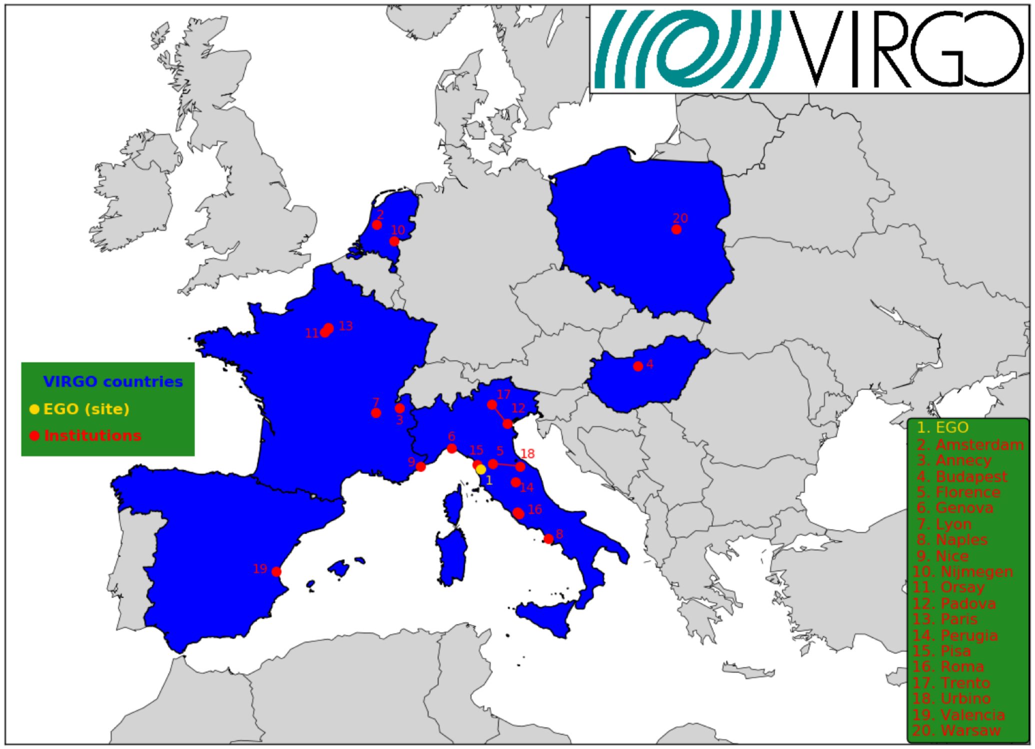
The Laser Interferometer Gravitational-wave Observatory

LSC Institutions

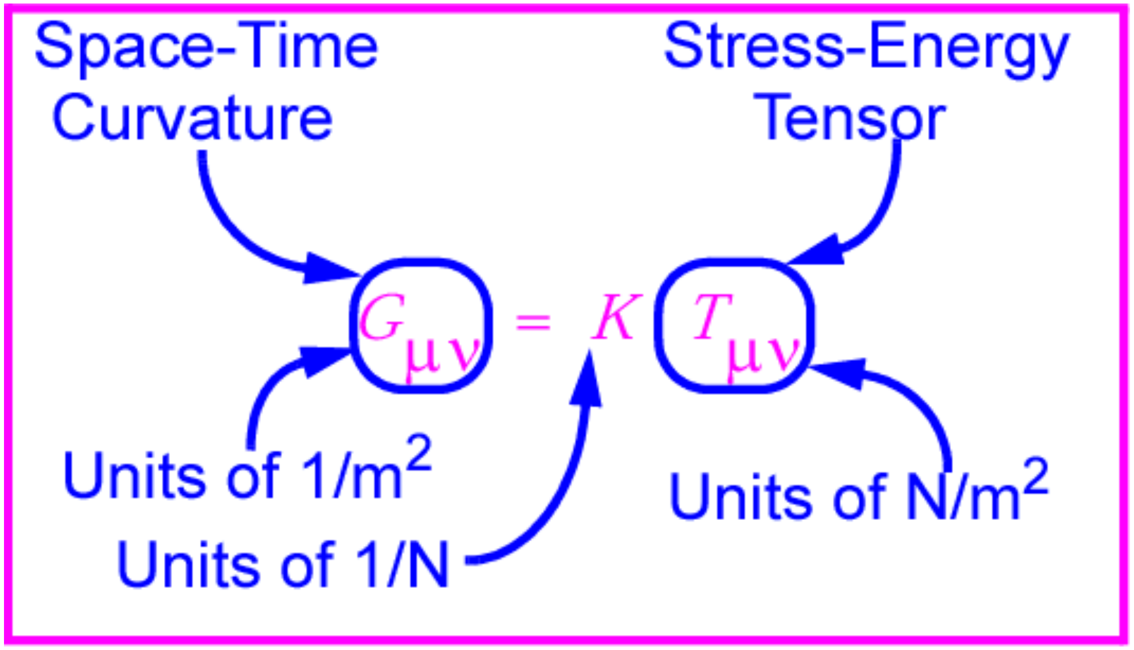
VIRGO

A collaboration made up of 20 laboratories in 6 european countries, involving more than 280 physicists and engineers


Cascina (Pisa), Italy



Gravitational waves: hard to find because space-time is stiff!



Following I.R. Kenyon, *General Relativity*

$K \sim [G/c^4]$ is combination of G and c with units of $1/N$

$$\mathbf{K \sim 10^{-44}\ N^{-1}}$$

⇒ Wave can carry huge energy with miniscule amplitude!

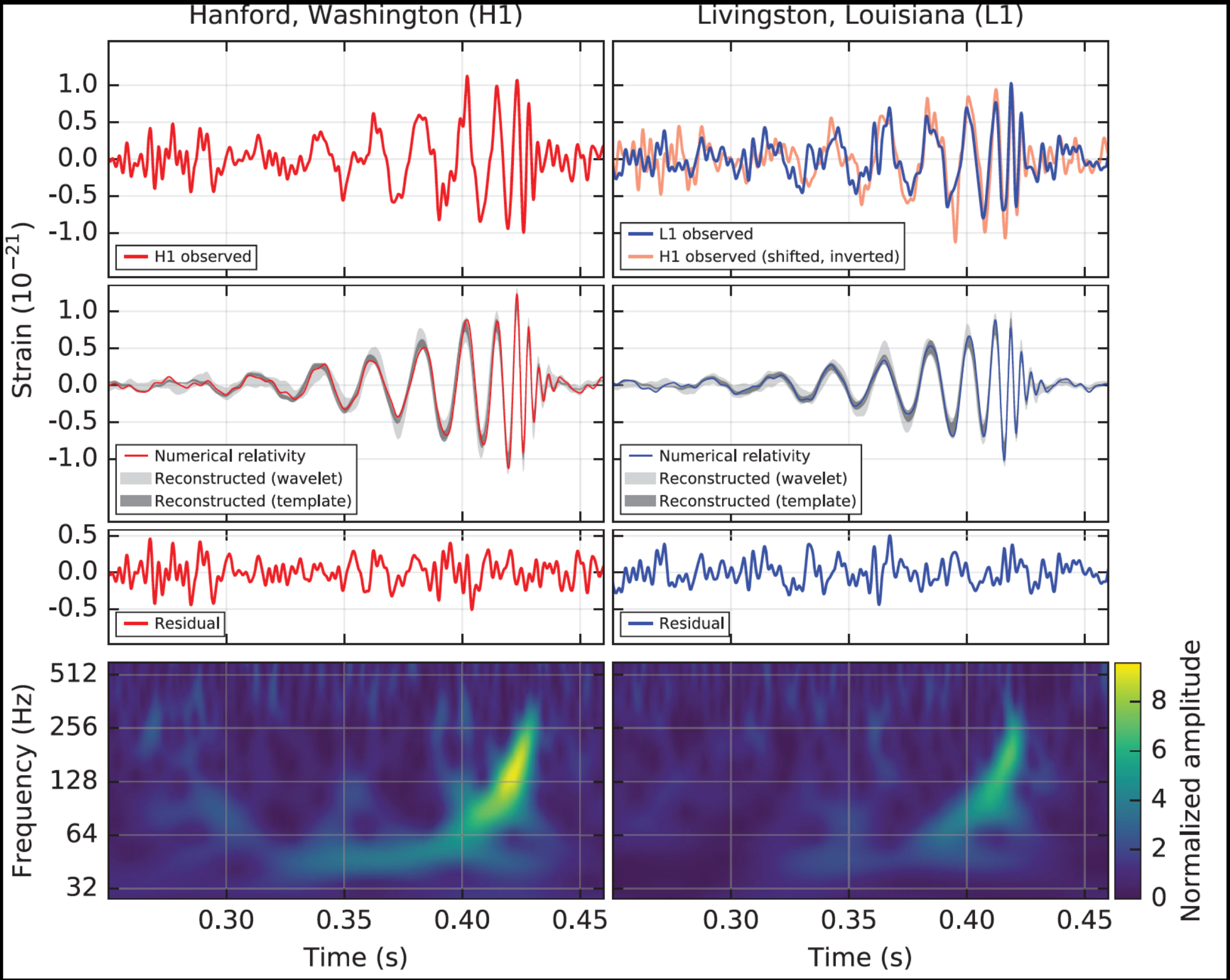
Expected strength

- Sense of scale: strain from a binary neutron star pair
  - » M = 1.4 M⊙,
  - » $r = 10^{23}$ m (15 Mpc, Virgo),
  - » R = 20 km
  - » f_{orb} = 400 Hz

$$h \sim \frac{G}{c^4} \cdot \frac{MR^2 f_{orbital}^2}{r}$$

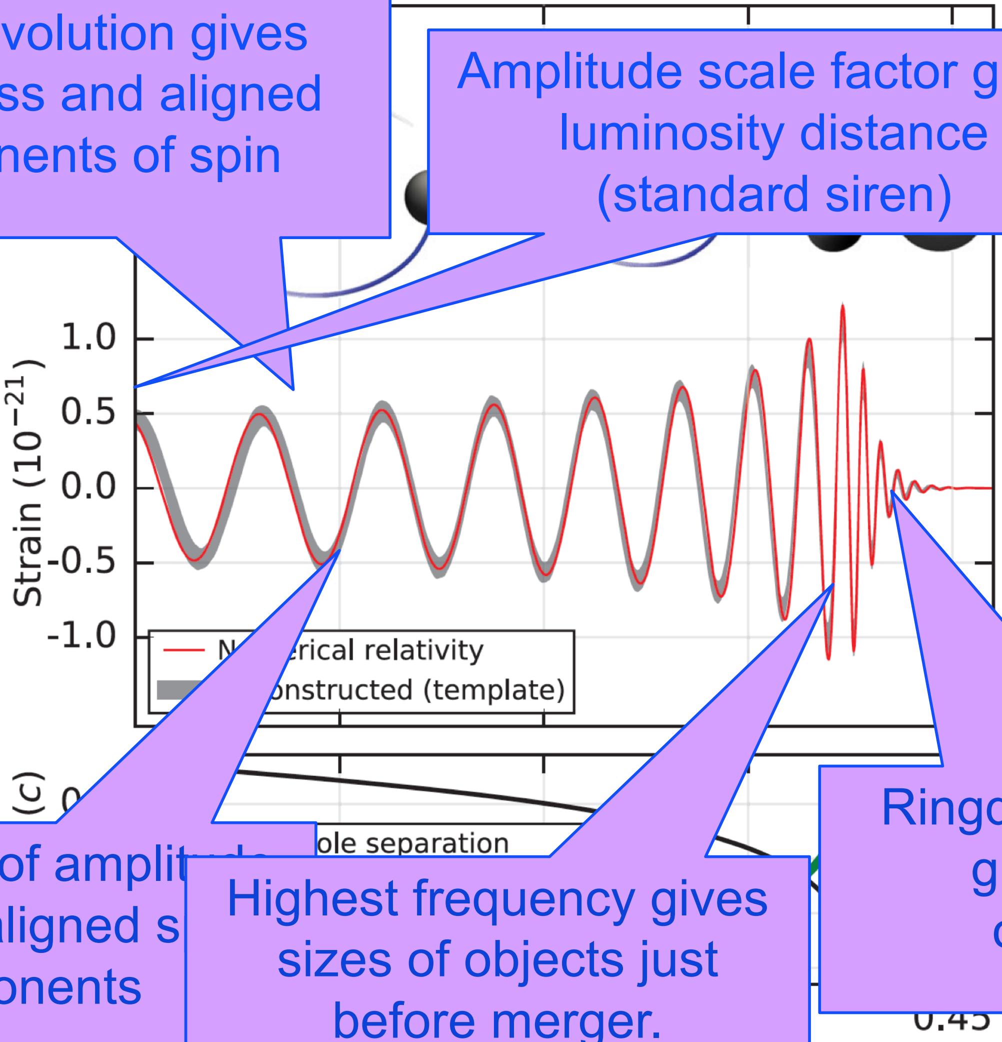
$$\boxed{h \sim 10^{-21}}$$

Breakthroughs



B. P. 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)

What can we learn from h(t)?



Phase evolution gives chirp mass and aligned components of spin

Amplitude scale factor gives luminosity distance (standard siren)

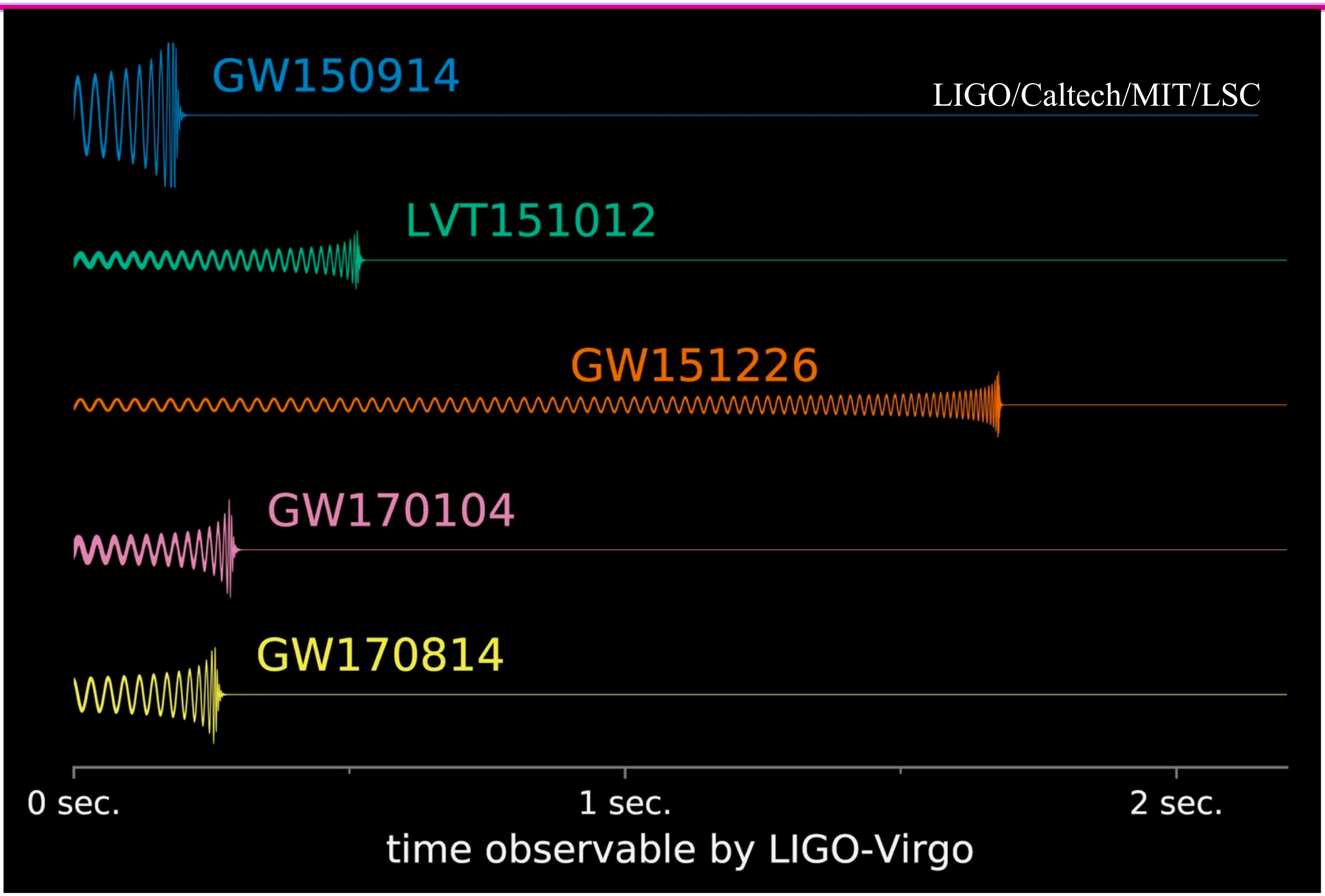
Modulation of amplit
gives nonaligned s
components

Highest frequency gives sizes of objects just before merger.

Ringdown frequency and Q give mass and spin of final black hole

B. P. 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)

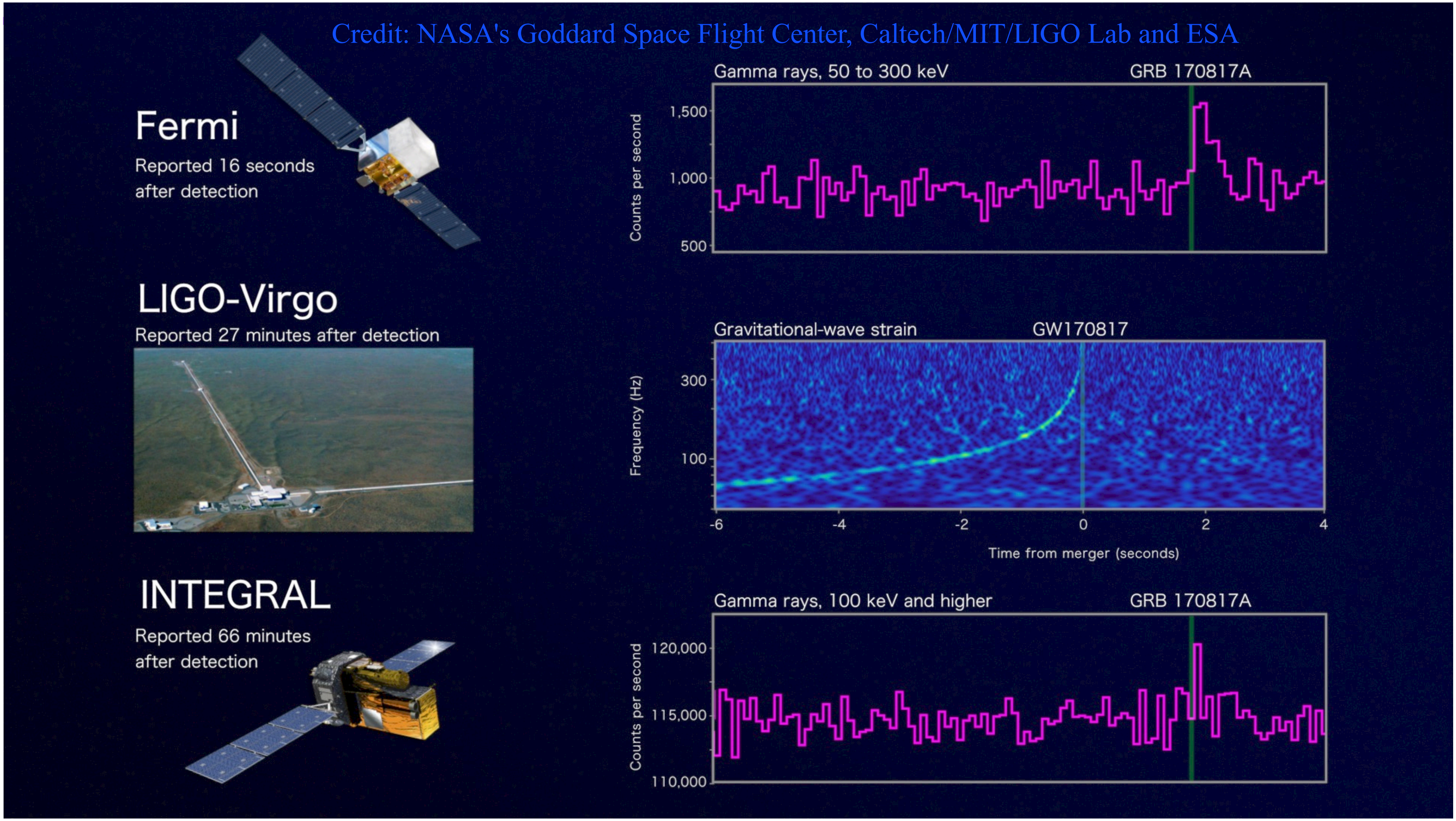
Comparison of GW Waveforms from BBHs (Sep 2017)



LIGO/Caltech/MIT/LSC

- These first observations of dynamic extreme spacetimes with BBHs show us that GR is reasonably accurate in this regime and can be used as a tool for examining and interpreting extreme states of matter.
- There are a rich collection of sources still to be examined!

Onto the study of the most extreme states of matter


Credit: NASA's Goddard Space Flight Center, Caltech/MIT/LIGO Lab and ESA

Fermi

Reported 16 seconds after detection

LIGO-Virgo

Reported 27 minutes after detection

INTEGRAL

Reported 66 minutes after detection

LIGO-Virgo network localization enables discovery of optical counterpart

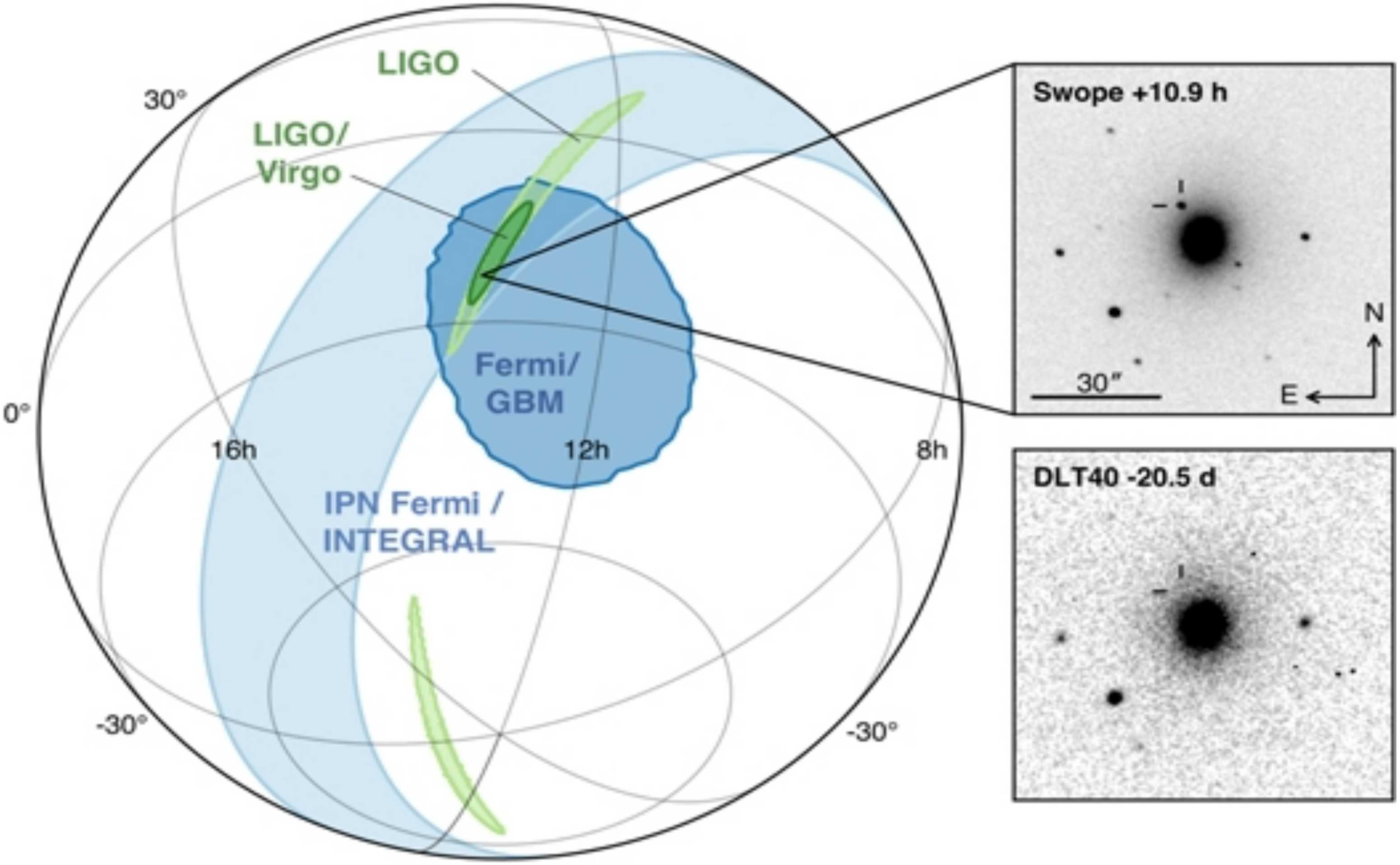


Figure 1 from Multi-messenger Observations of a Binary Neutron Star Merger
B. P. Abbott et al. 2017 ApJL 848 L12 doi:10.3847/2041-8213/aa91c9

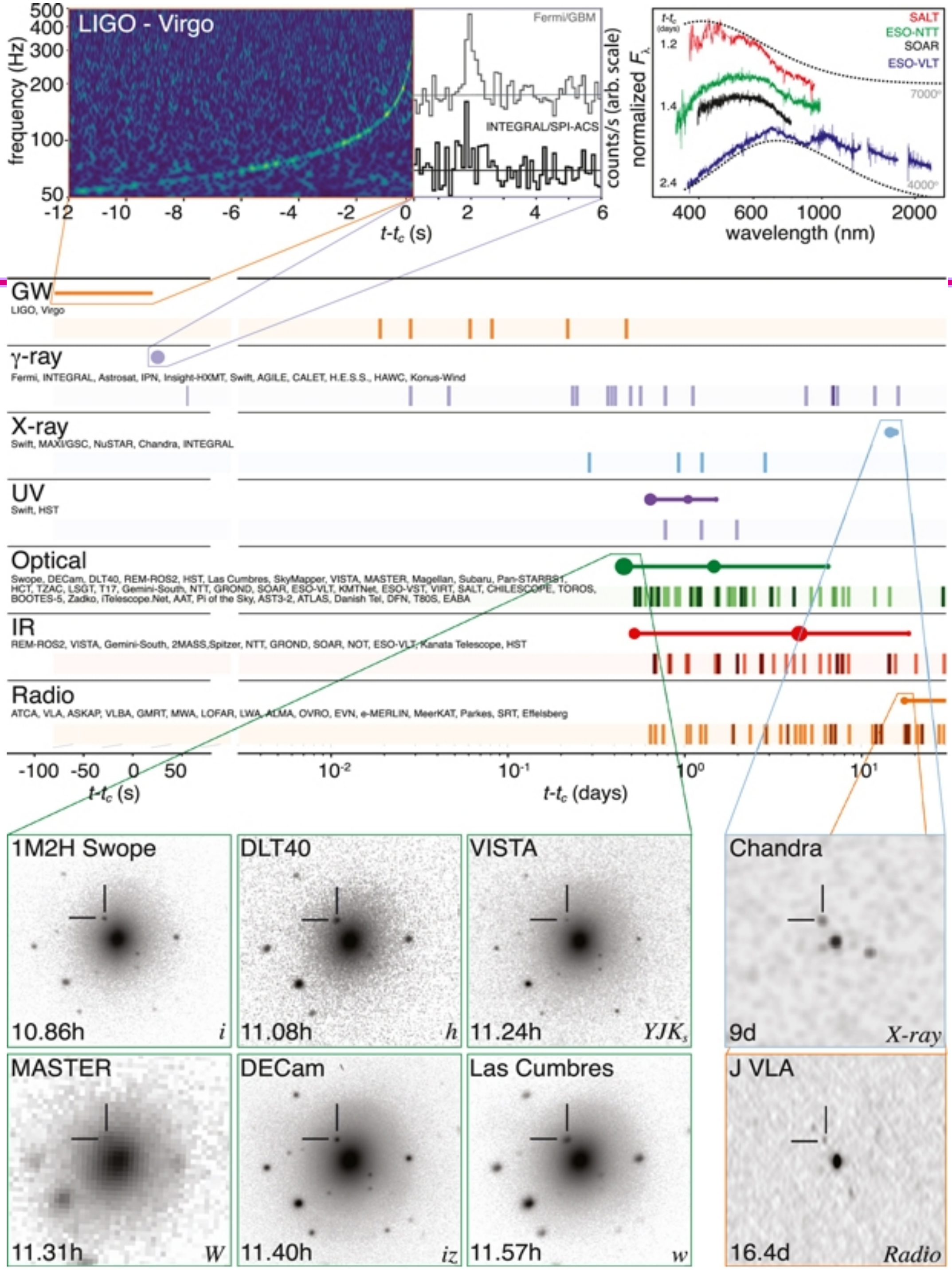
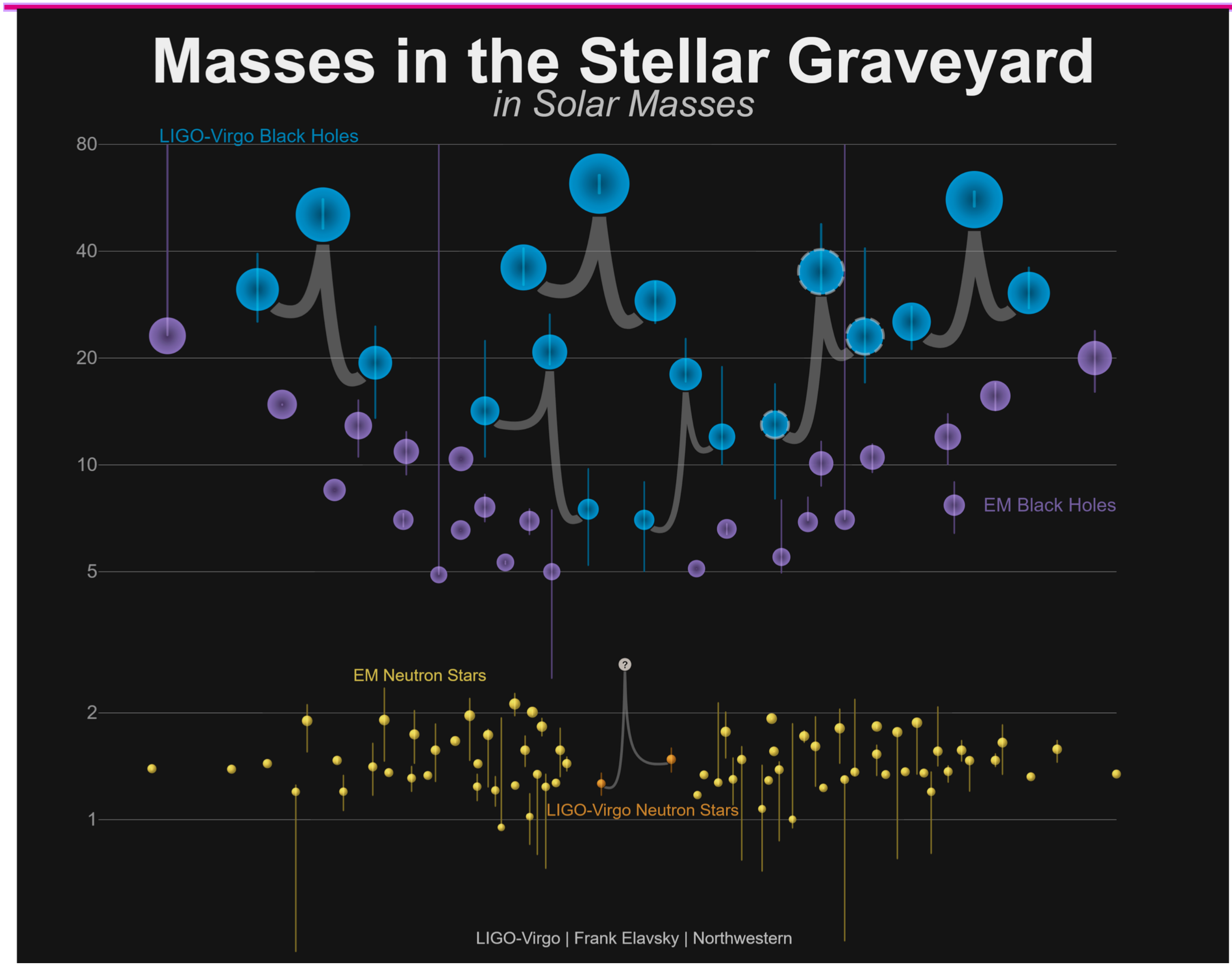


Figure 2 from Multi-messenger Observations of a Binary Neutron Star Merger
B. P. Abbott et al.
2017 ApJL 848 L12
doi:10.3847/2041-8213/aa91c9

Known Masses of Stellar Remnants – Dec 2017



LIGO-Virgo | Frank Elavsky | Northwestern

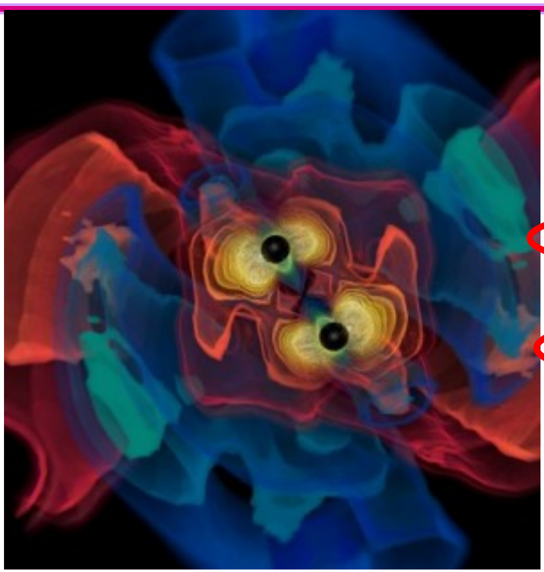
Non-LIGO Data Sources: Neutron Stars: http://xtreme.as.arizona.edu/NeutronStars/data/pulsar_masses.dat

Black Holes: https://stellarcollapse.org/sites/default/files/table.pdf |

LIGO-Virgo Data: https://losc.ligo.org/events/

The full range of expected sources

Astrophysical Sources of Gravitational Waves



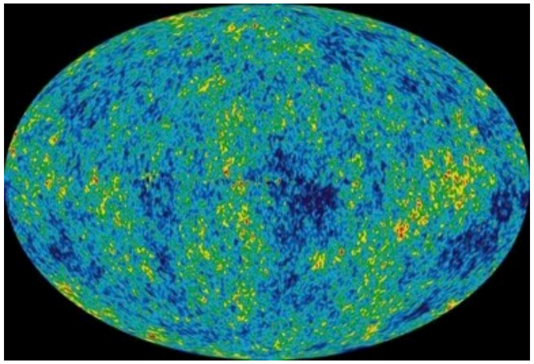
Credit: AEI, CCT, LSU

Coalescing Compact Binary Systems:

Neutron Star-NS, ✓
Black Hole-NS,
BH-BH ✓

- Strong emitters, well-modeled,

- (effectively) transient

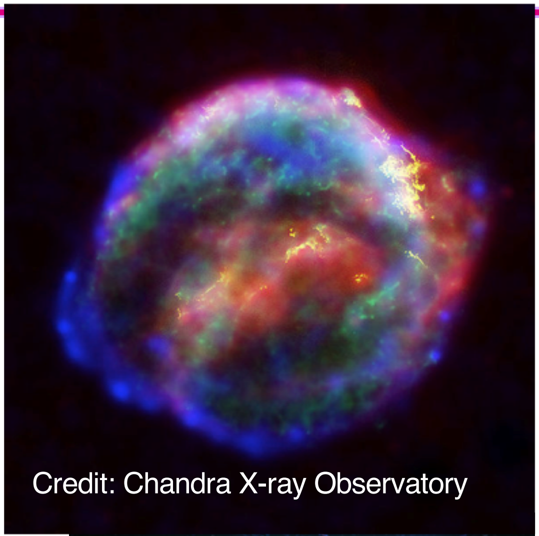


NASA/WMAP Science Team

Cosmic Gravitational-wave Background

- Residue of the Big Bang

- Long duration, stochastic background

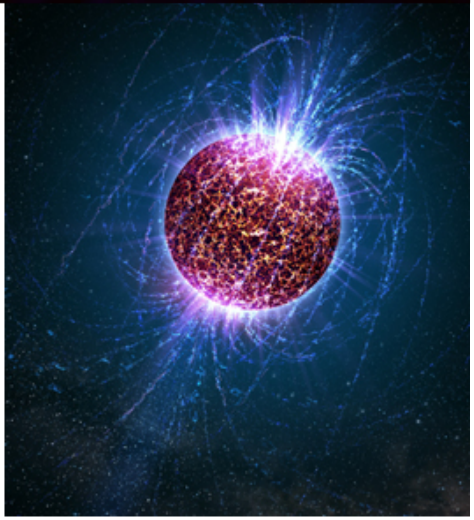


Credit: Chandra X-ray Observatory

Asymmetric Core Collapse Supernovae

- Weak emitters, not well-modeled

(‘bursts’), transient



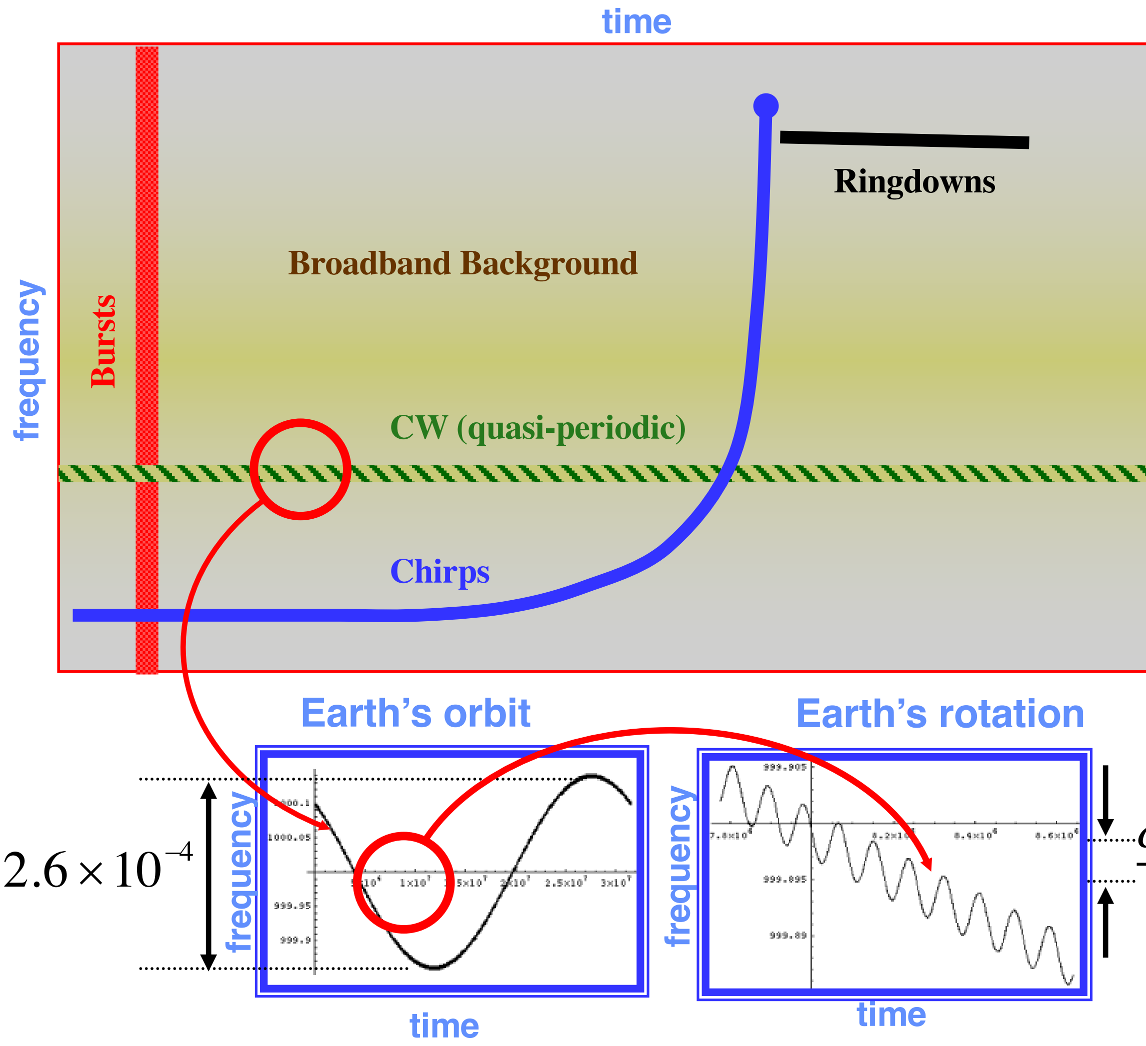
Casey Reed, Penn State

Spinning neutron stars

- (nearly) monotonic waveform

- Long duration

Frequency-Time Characteristics of GW Sources

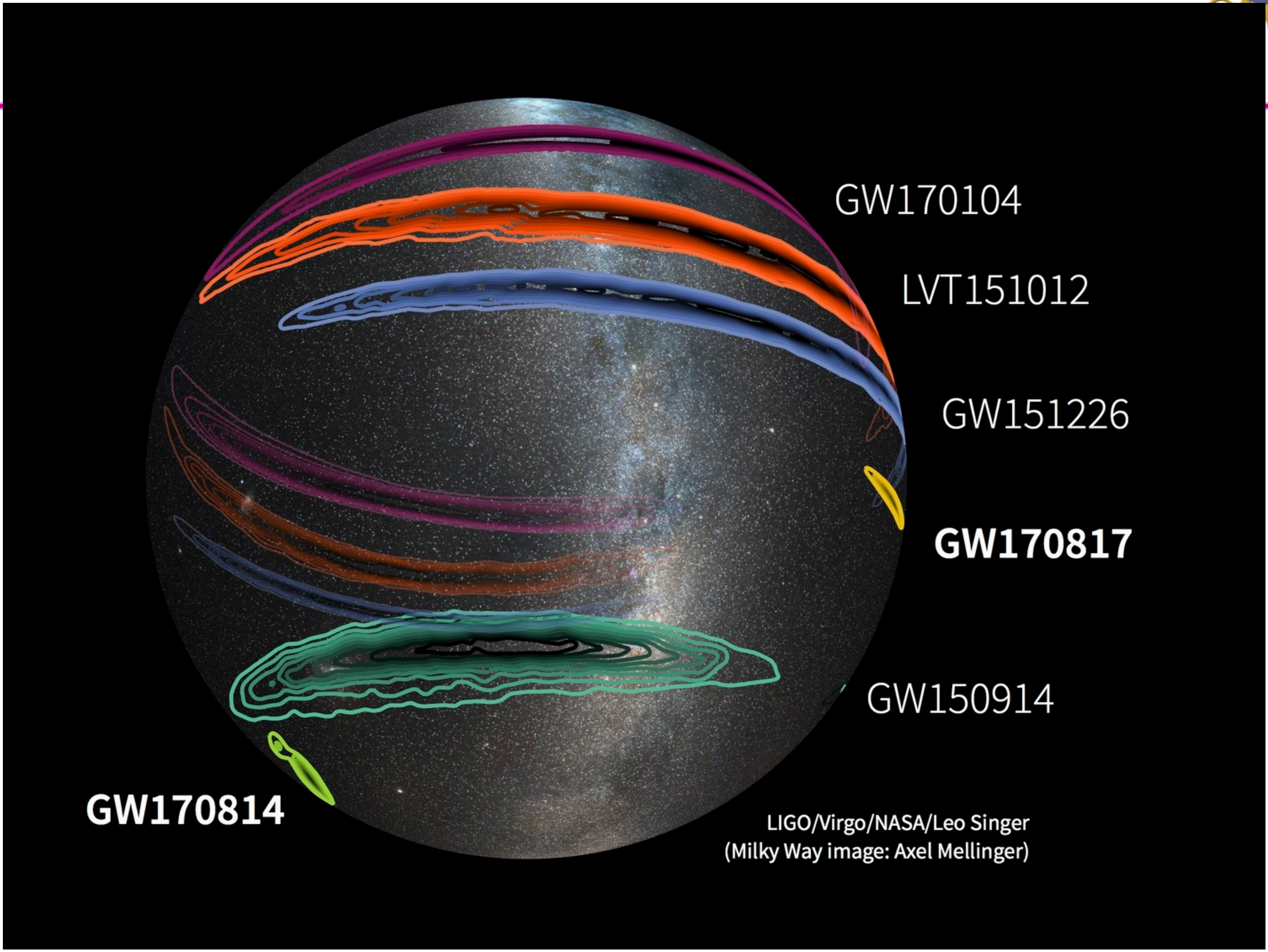


$$\frac{\delta f}{f} \approx 2.6 \times 10^{-4}$$

$$\frac{\delta f}{f} \approx 4 \times 10^{-6}$$

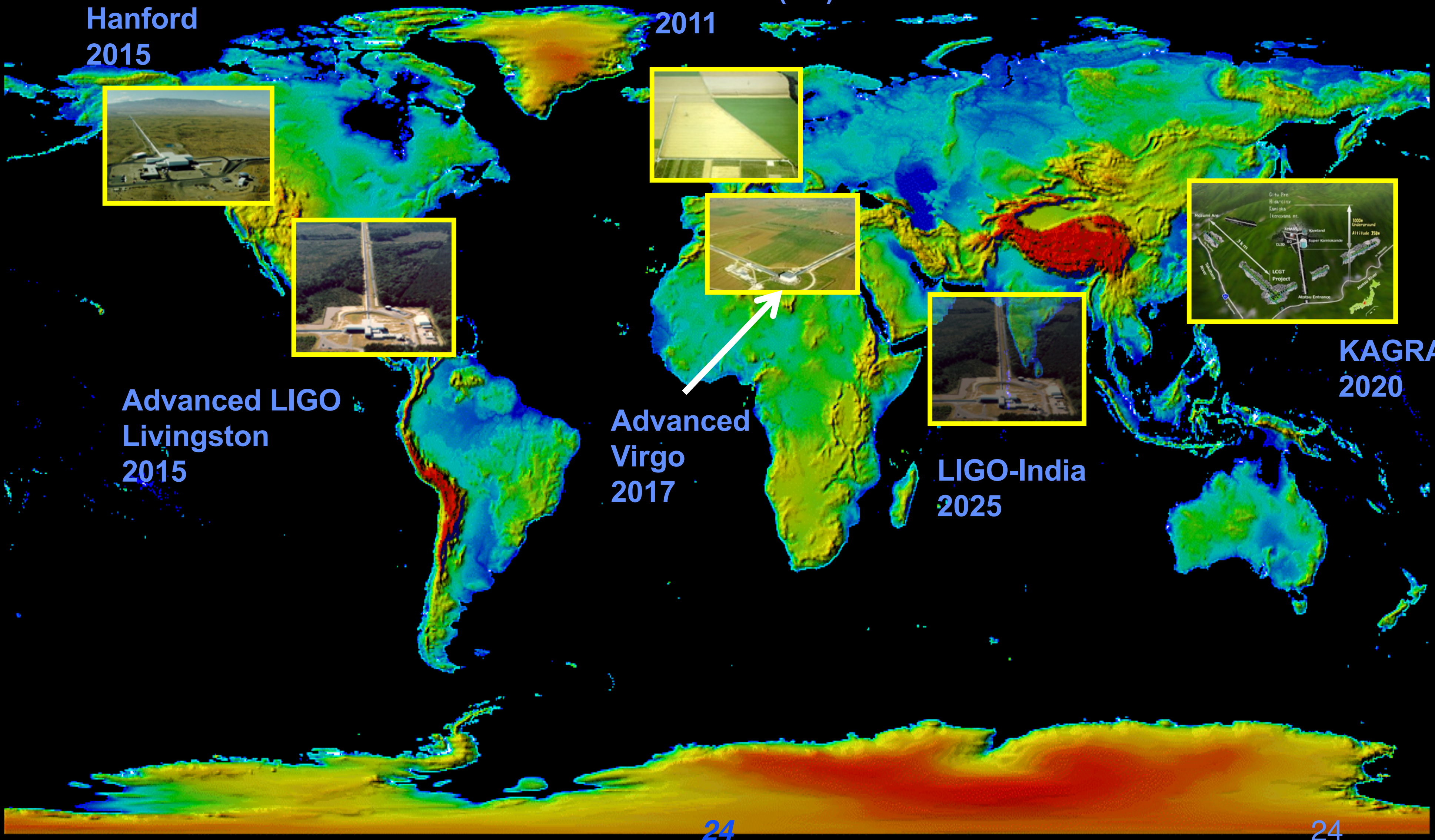
Building Out the Terrestrial Gravitational-Wave Network

Localization for events - Oct 2017



LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

The advanced GW detector network: 2015-2025



Advanced LIGO
Hanford
2015

GEO600 (HF)
2011

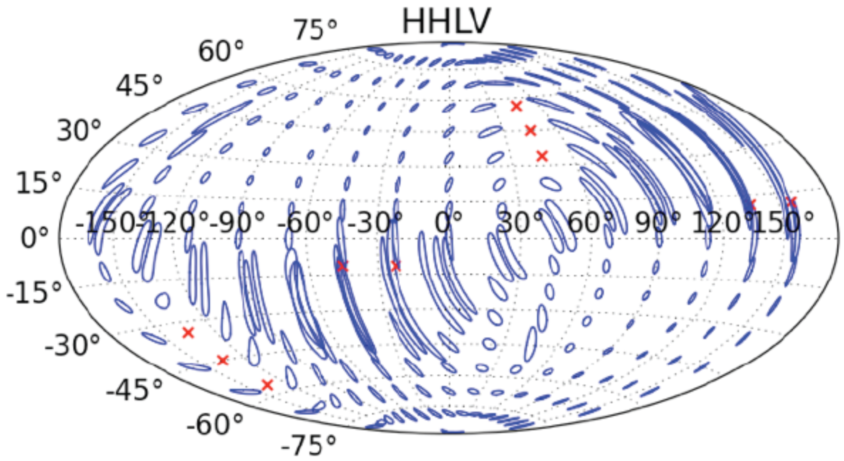
Advanced LIGO
Livingston
2015

Advanced
Virgo
2017

LIGO-India
2025

KAGRA
2020

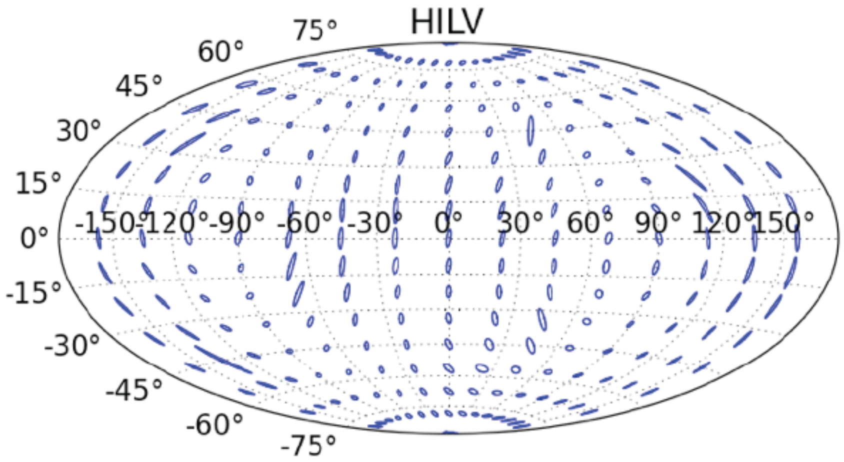
Effect of Adding LIGO-India to the LIGO+Virgo Network



Fairhurst 2011

Red crosses denote regions where the network has blind spots

LIGO+Virgo only



Fairhurst 2011

With LIGO-India

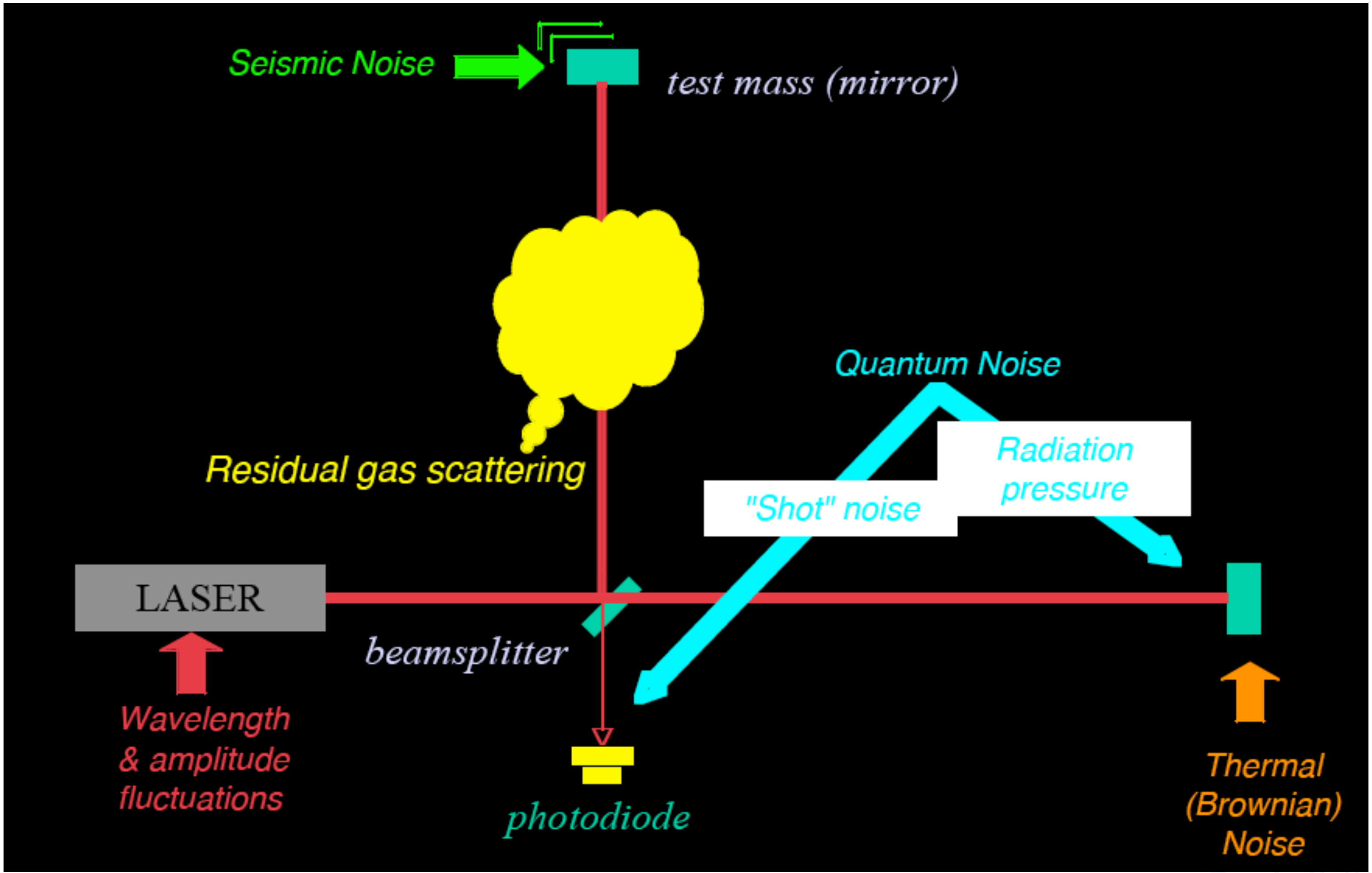
GW170817 Landed in a Good Region of Sky When 3 Detectors Were Up

Detection rate improves as sensitivity cubed

Sensitivity of Detectors is Determined by Noise and Background

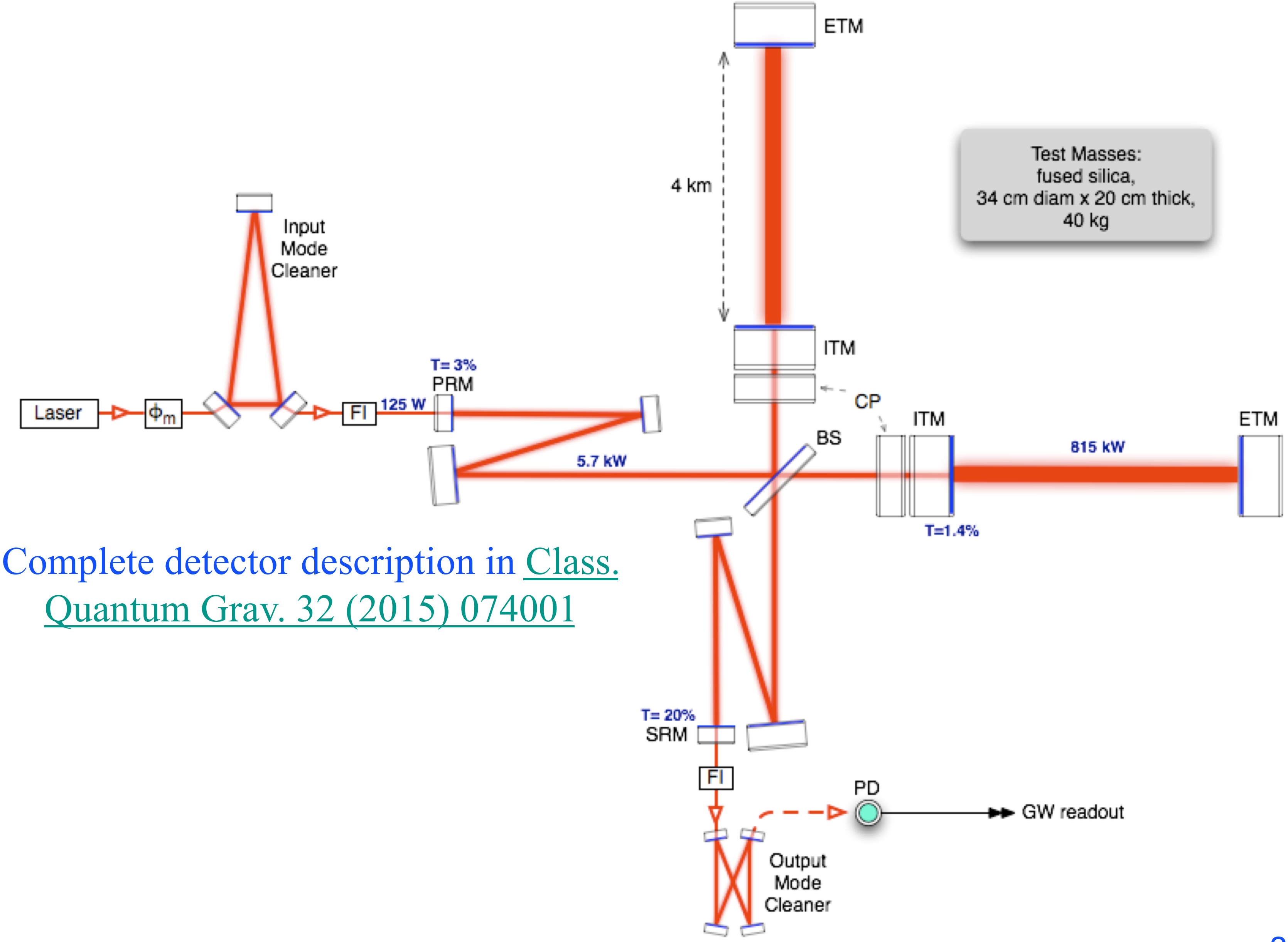
- The key to improving detectors is sensitivity which is improved by reducing noise and background.
- Range is proportional to sensitivity.
- Event rate is proportional to volume, which is proportional to range cubed.
- Thus a factor of 2 in sensitivity gives a factor of 8 in event rate (nearly an order of magnitude).

Noise and background cartoon



R. Adhikari

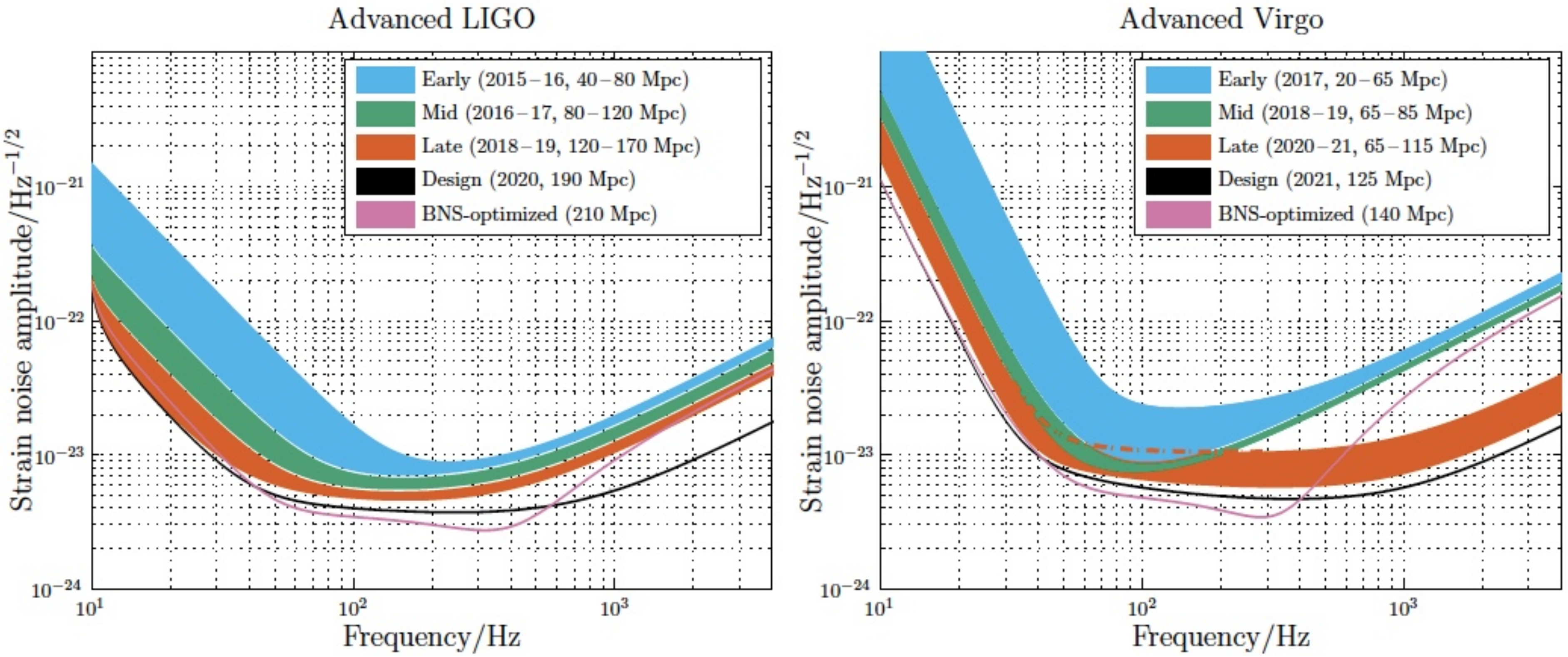
Optical configuration



Complete detector description in Class. Quantum Grav. 32 (2015) 074001

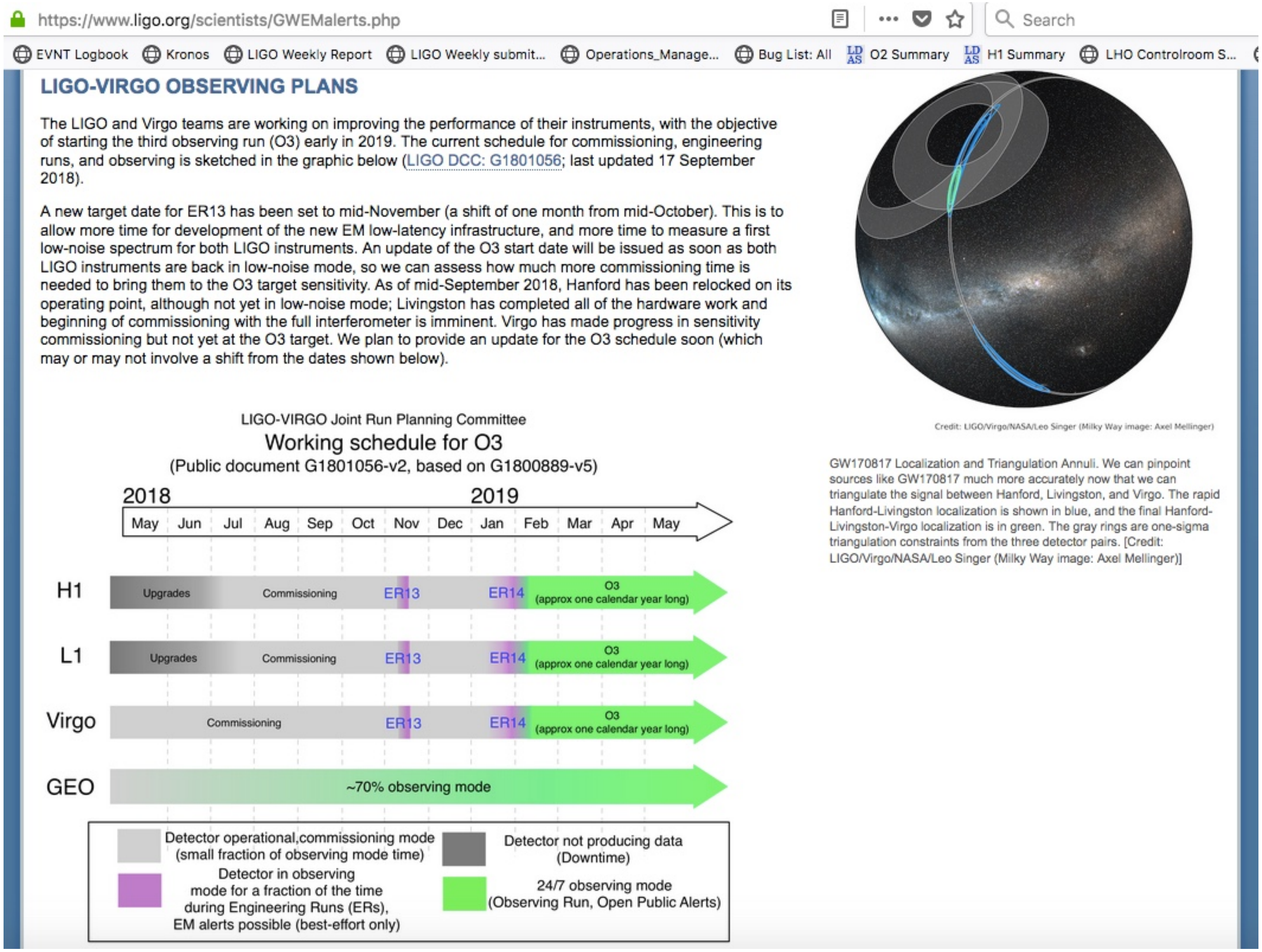
The next step: O3

LIGO-Virgo Observing Scenario (arXiv:1304.0670)



Journal reference: Living Reviews in Relativity; 21:3; 2018
DOI: 10.1007/s41114-018-0012-9

Working schedule for next observing run (O3)



LIGO-VIRGO OBSERVING PLANS

The LIGO and Virgo teams are working on improving the performance of their instruments, with the objective of starting the third observing run (O3) early in 2019. The current schedule for commissioning, engineering runs, and observing is sketched in the graphic below (LIGO DCC: G1801056; last updated 17 September 2018).

A new target date for ER13 has been set to mid-November (a shift of one month from mid-October). This is to allow more time for development of the new EM low-latency infrastructure, and more time to measure a first low-noise spectrum for both LIGO instruments. An update of the O3 start date will be issued as soon as both LIGO instruments are back in low-noise mode, so we can assess how much more commissioning time is needed to bring them to the O3 target sensitivity. As of mid-September 2018, Hanford has been relocked on its operating point, although not yet in low-noise mode; Livingston has completed all of the hardware work and beginning of commissioning with the full interferometer is imminent. Virgo has made progress in sensitivity commissioning but not yet at the O3 target. We plan to provide an update for the O3 schedule soon (which may or may not involve a shift from the dates shown below).

LIGO-VIRGO Joint Run Planning Committee

Working schedule for O3

(Public document G1801056-v2, based on G1800889-v5)

Detector operational,commissioning mode (small fraction of observing mode time)

Detector not producing data (Downtime)

Detector in observing mode for a fraction of the time during Engineering Runs (ERs), EM alerts possible (best-effort only)

24/7 observing mode (Observing Run, Open Public Alerts)

Credit: LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)

GW170817 Localization and Triangulation Annuli. We can pinpoint sources like GW170817 much more accurately now that we can triangulate the signal between Hanford, Livingston, and Virgo. The rapid Hanford-Livingston localization is shown in blue, and the final Hanford-Livingston-Virgo localization is in green. The gray rings are one-sigma triangulation constraints from the three detector pairs. [Credit: LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)]

Open Public Alerts (OPAs) begin in O3

- Starting with O3 (late 2018) the LIGO and Virgo Collaborations will release open public alerts (OPAs) for all transient event candidates in which we have reasonable confidence and we consider likely to be real
- For compact binary coalescences we aim an overall astrophysical purity of 90% which will translate to a false alarm rate threshold of 1/month – 1/year. For unmodeled transient events, this threshold will probably be in the 1/10years – 1/100years range
- We aim to have preliminary, fully automated alerts (not vetted by humans) sent out within 5min from data collection via GCN Notices
- Human vetting is expected to take place within 4 hours from data collection, following which another GCN Notice and Circular will be issued; depending on the human vetting, such GCN Notice/Circular may be a retraction one
- Event profile/information will be very much like the one during O2: search and source type (unmodeled, BNS, NSBH, BBH), significance (false alarm rate), 3D localization (with added error ellipses and multi-resolution option), “EM bright” classification, p_astro estimation

The longer term

Science drives Requirements

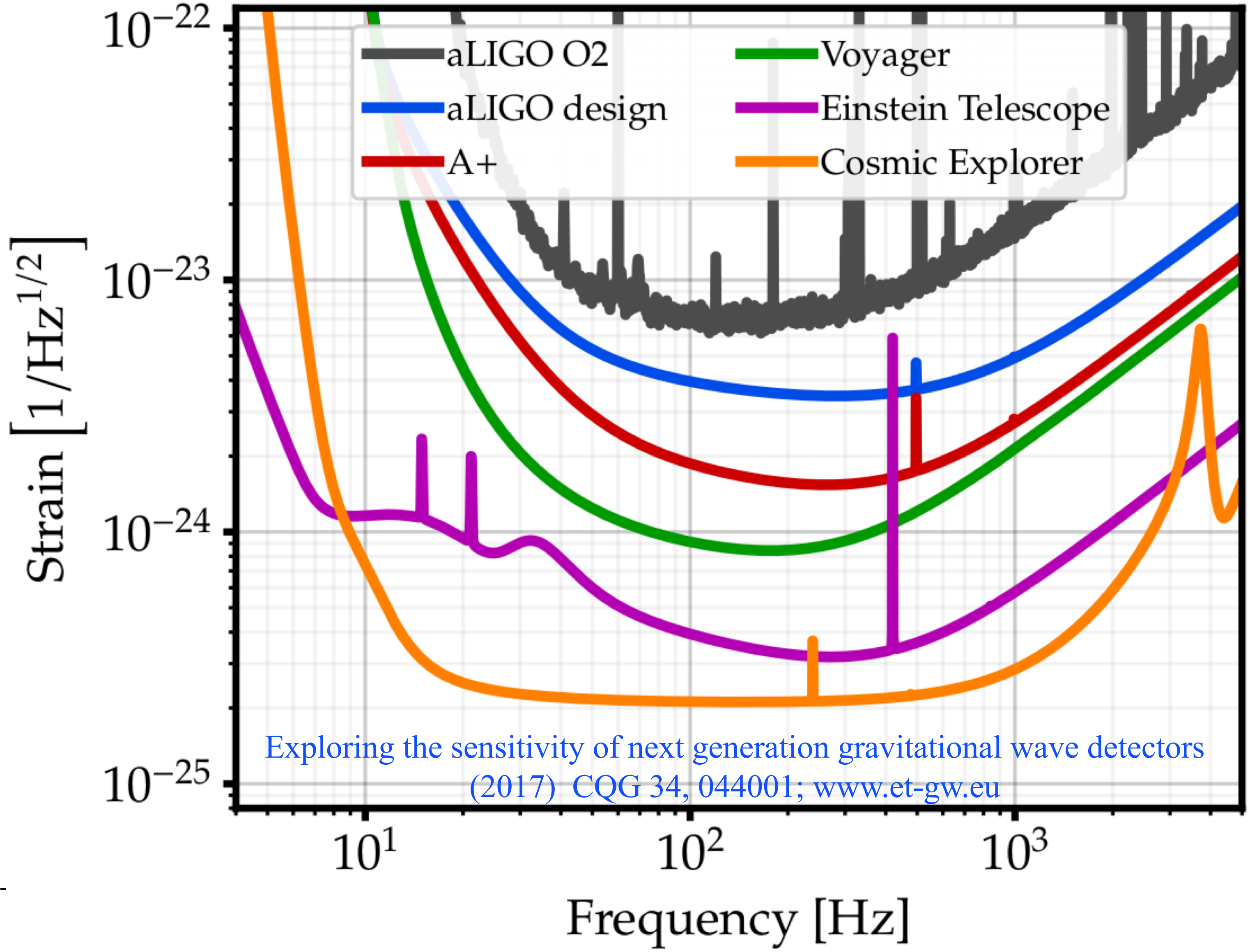
- **Stellar Evolution at High Red-Shift: Black Holes from the first stars (Population III)**
  - Reach z > ~10
  - At least moderate GW luminosity distance precision
- **Independent Cosmology and the Dark Energy Equation of State**
  - Needs precision GW luminosity distance and localization for EM follow-ups (for redshift)
- **Checking GR in extreme regime**
  - High SNR needed
  - GW luminosity distance and localization not essential

Advanced LIGO upgrade path

- Advanced LIGO is limited by quantum noise & coating thermal noise

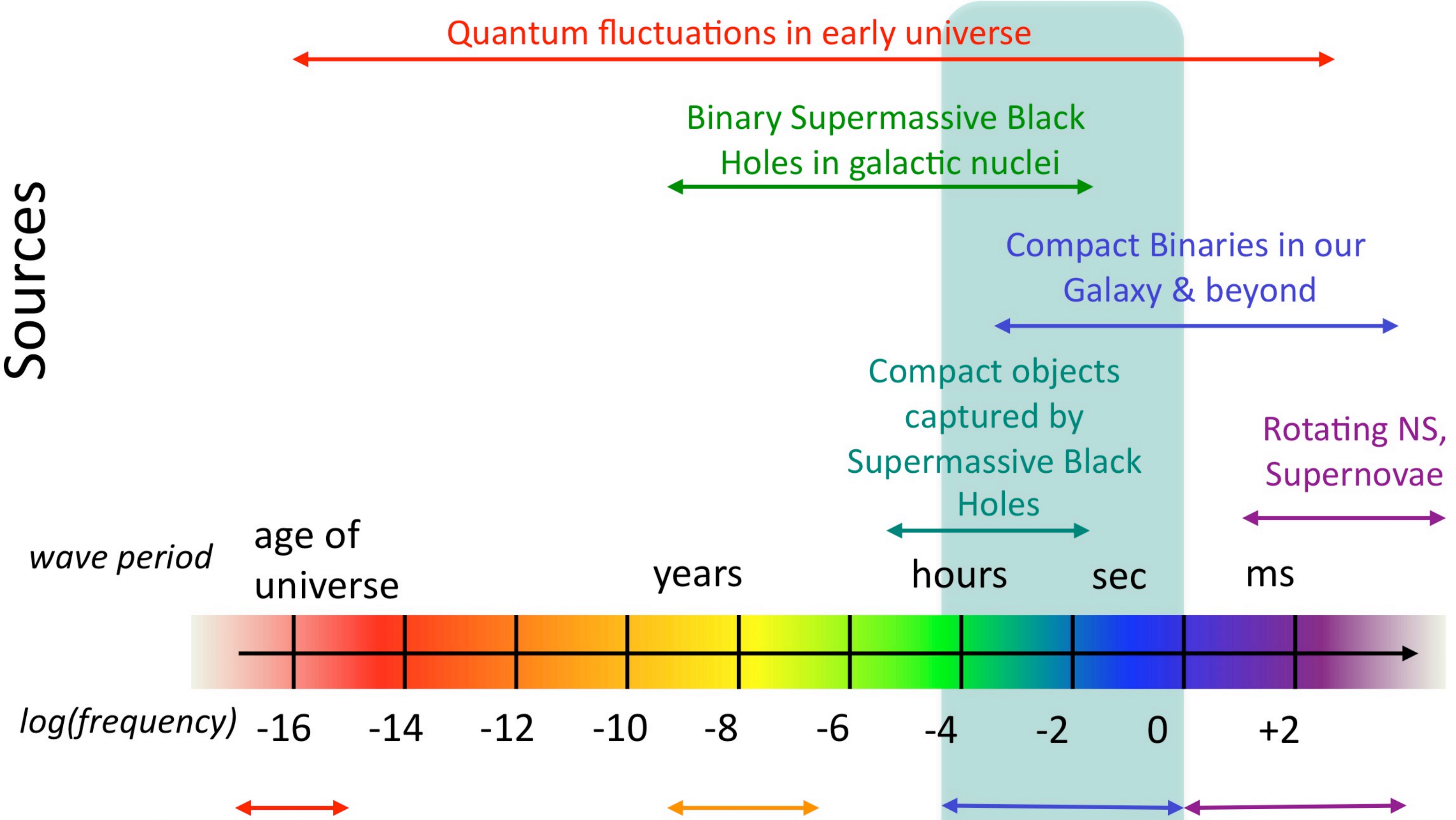
- Squeezed vacuum can reduce quantum noise
- Options for thermal noise:
  - » Better coatings
  - » Cryogenic operation
  - » Longer arms (new facility)

Upgrade possibilities



Exploring the sensitivity of next generation gravitational wave detectors (2017) CQG 34, 044001; www.et-gw.eu

The Gravitational Wave Spectrum



Sources

Quantum fluctuations in early universe

Binary Supermassive Black Holes in galactic nuclei

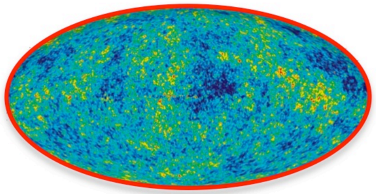
Compact Binaries in our Galaxy & beyond

Compact objects captured by Supermassive Black Holes

Rotating NS, Supernovae

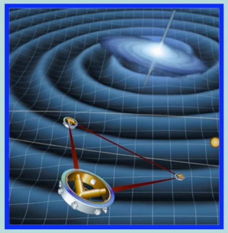
Detectors

Cosmic microwave background polarization



Pulsar Timing

Space Interferometers



Terrestrial interferometers

Credit: NASA