



Exploiting the New Frontier of Gravitational-Wave Astronomy

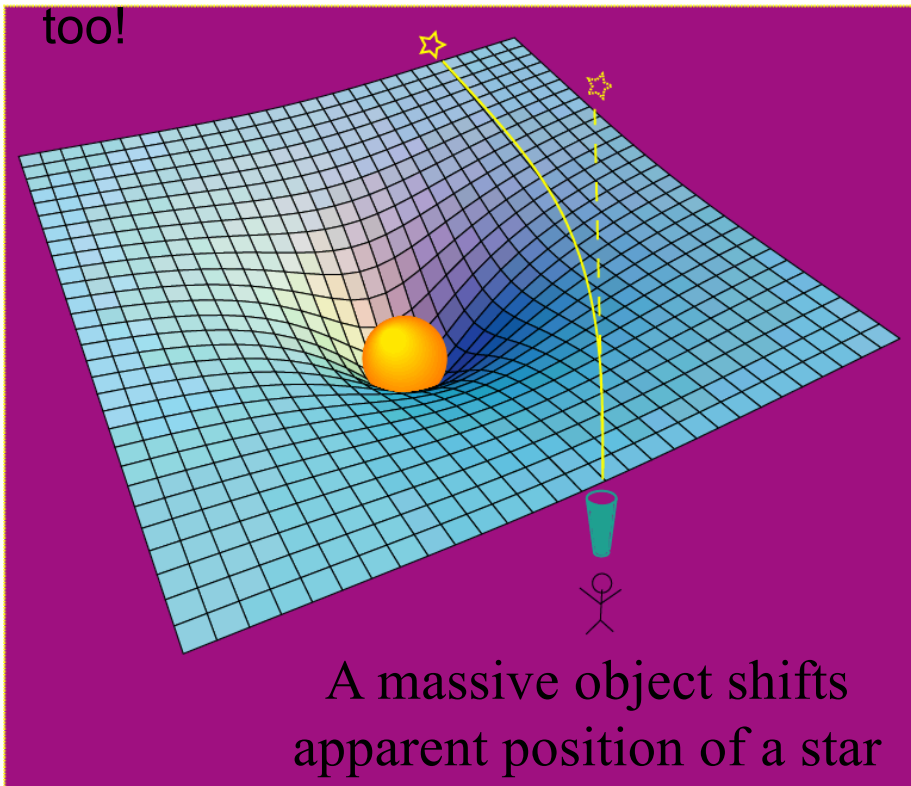
Fred Raab, for the LIGO
Scientific Collaboration and
the Virgo Collaboration



Basics of Gravitational-Waves

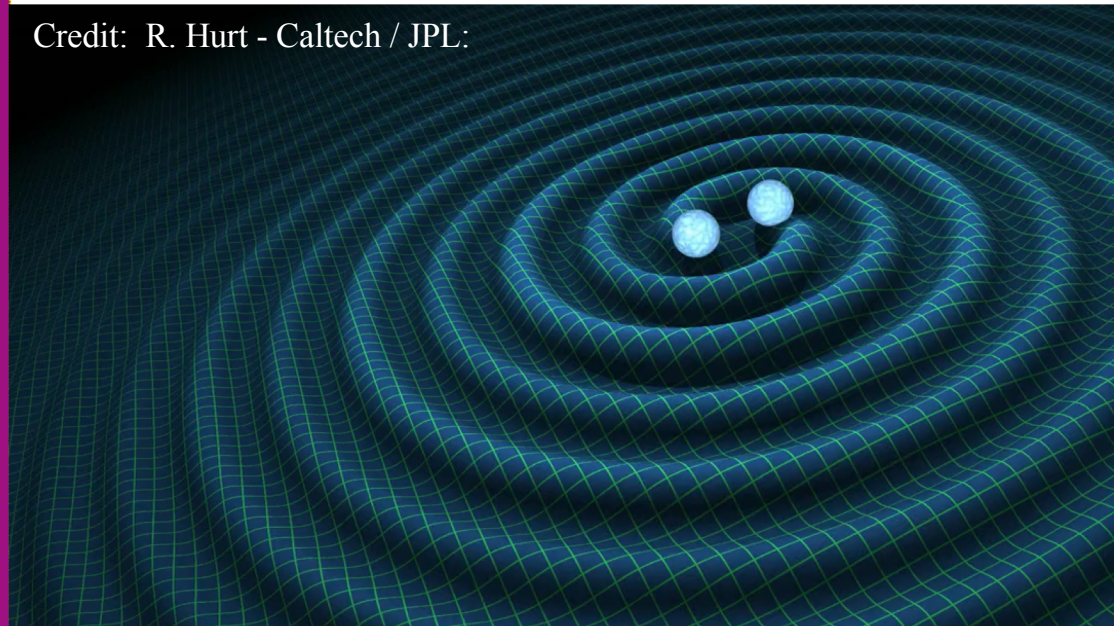
Einstein's General Relativity: gravity is a manifestation of space-time curvature

curved spacetime can bend light,
too!



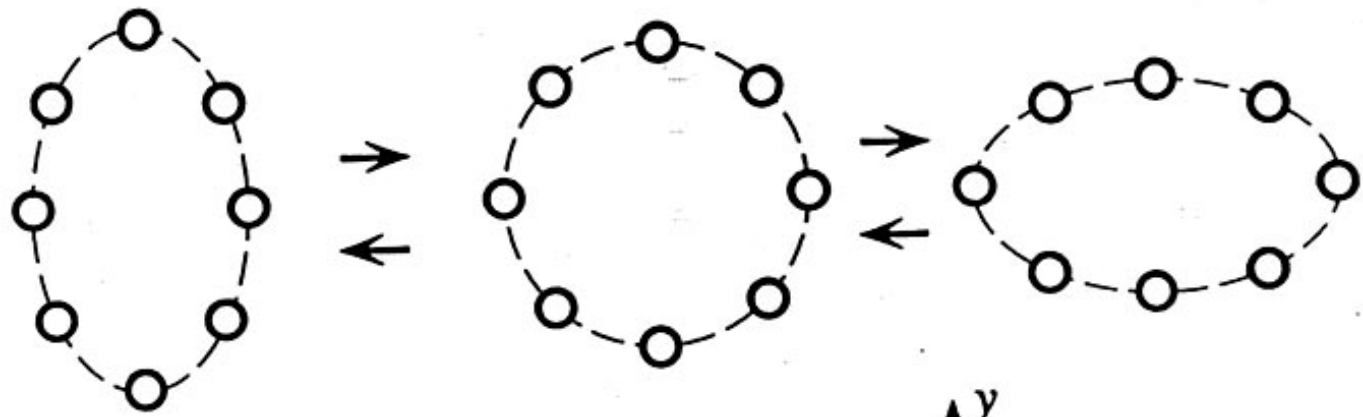
dynamic deformation of
spacetime

Credit: R. Hurt - Caltech / JPL:

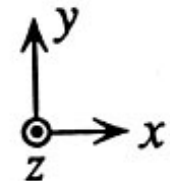


Space has a shape, a stiffness and a maximum speed for information transfer.

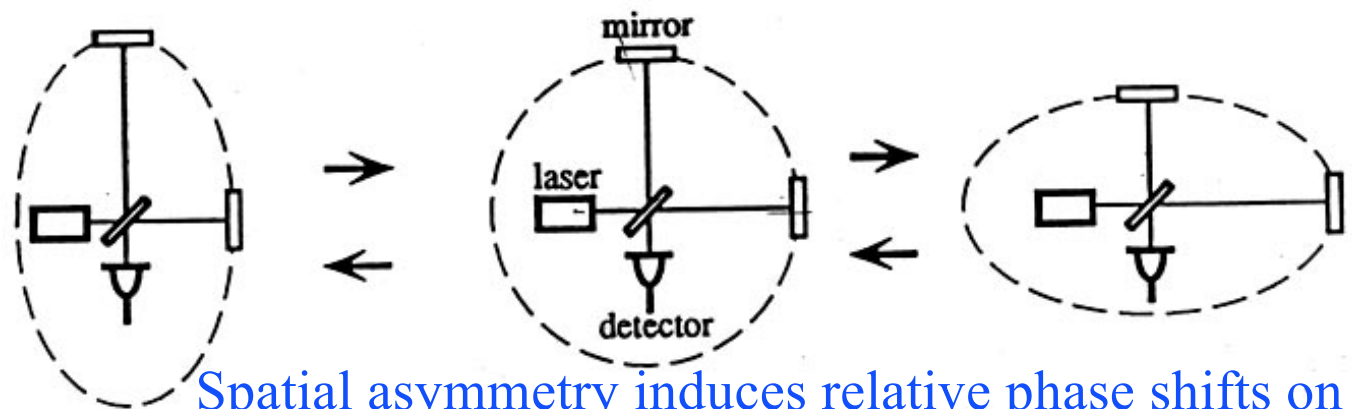
Basic idea for detection is simple



© Gravitational Waves



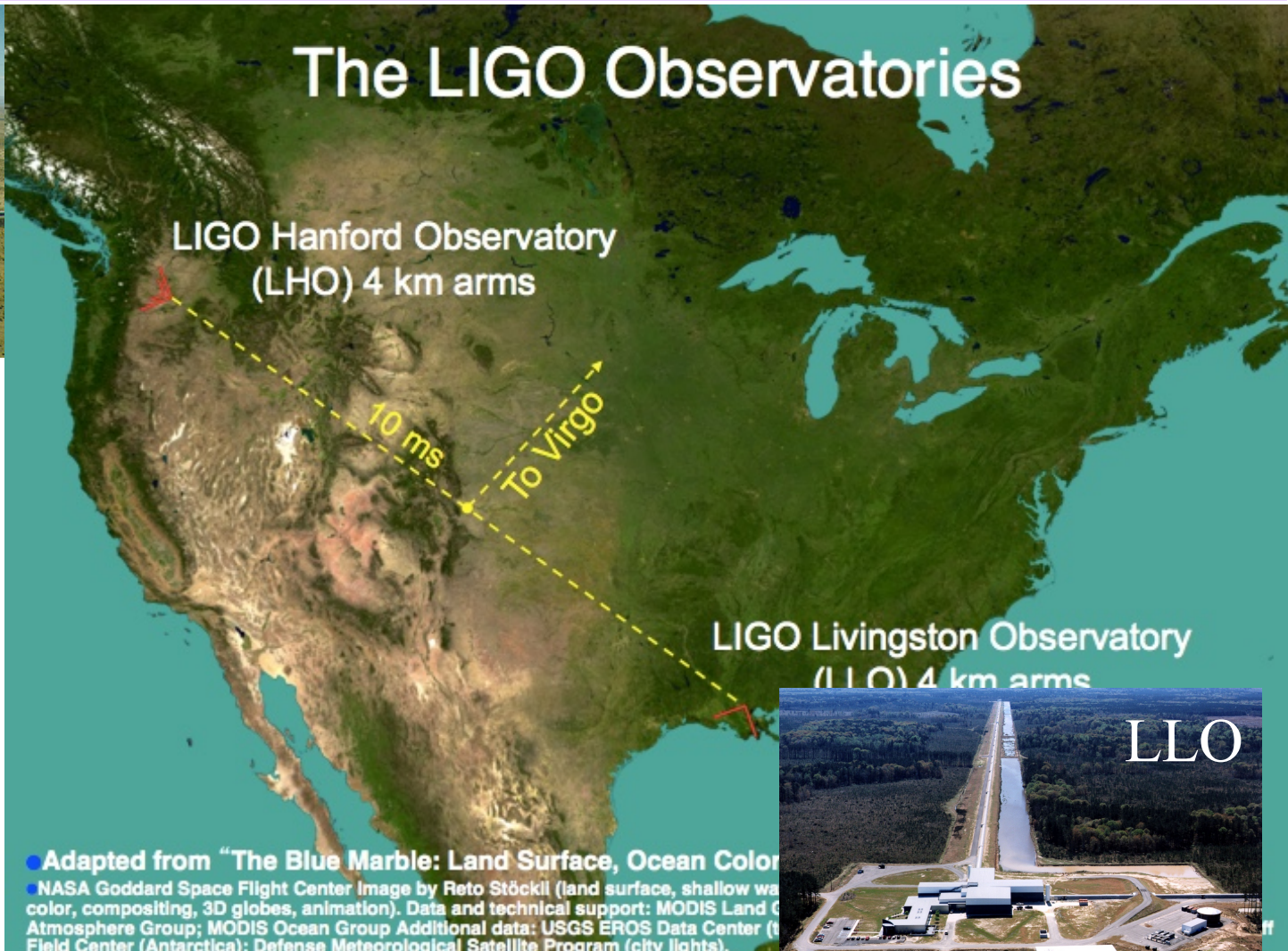
GW amplitude h
 $= (R_x - R_y) / R$



Spatial asymmetry induces relative phase shifts on light in arms



LIGO The Laser Interferometer Gravitational-wave Observatory



LIGO The Laser Interferometer Gravitational-wave Observatory

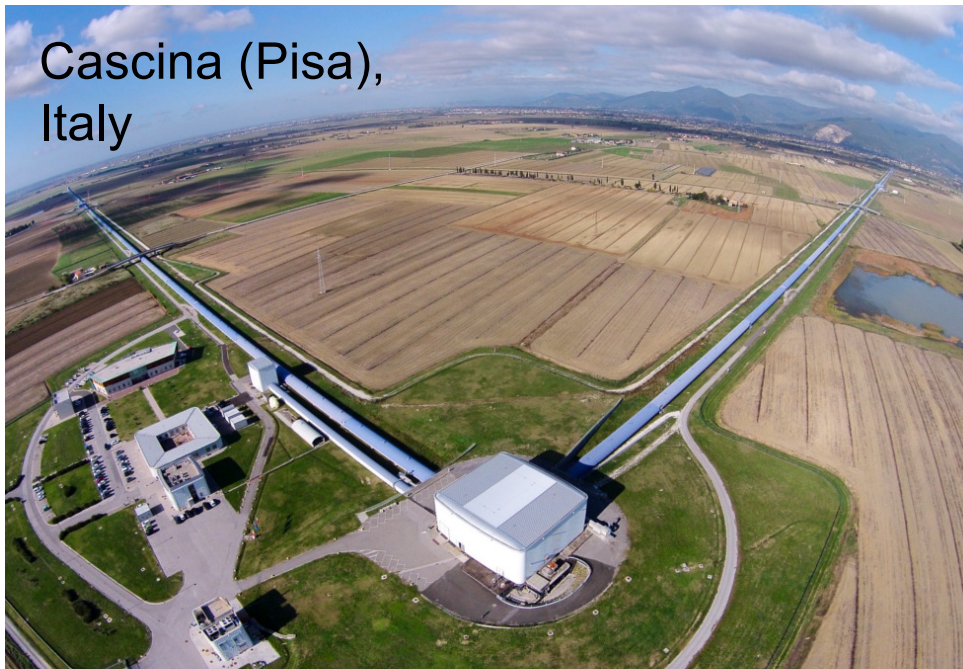




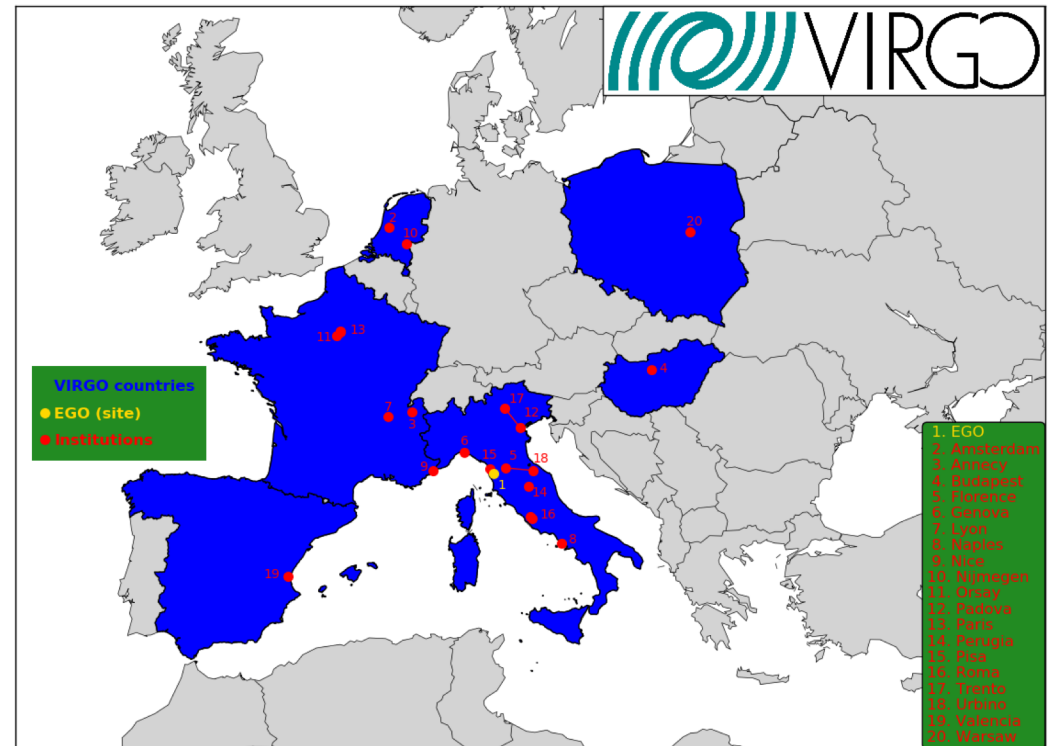
VIRGO



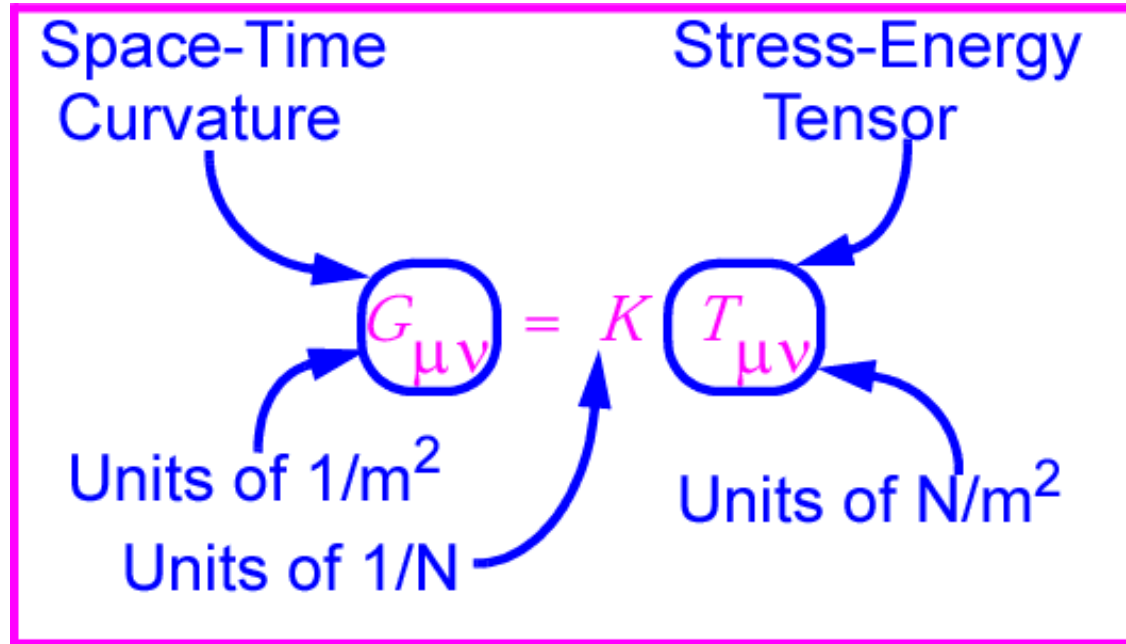
A collaboration made up of 20 laboratories in 6 european countries, involving more than 280 physicists and engineers



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 $1/N$

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

\Rightarrow Wave can carry huge energy with miniscule amplitude!

Expected strength

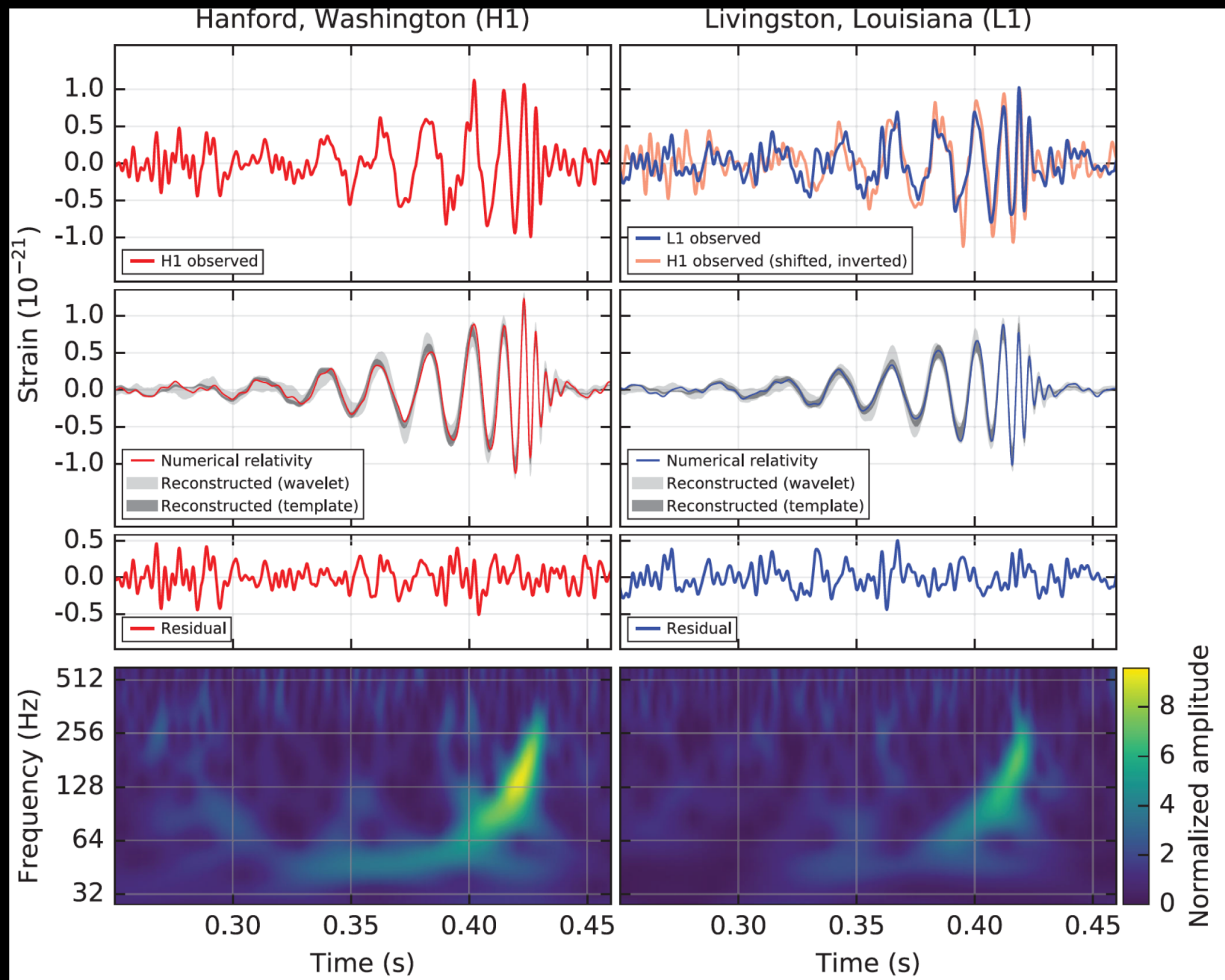
- Sense of scale: strain from a binary neutron star pair
 - » $M = 1.4 M_{\odot}$,
 - » $r = 10^{23}$ m (15 Mpc, Virgo),
 - » $R = 20$ km
 - » $f_{orb} = 400$ Hz

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

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



Breakthroughs

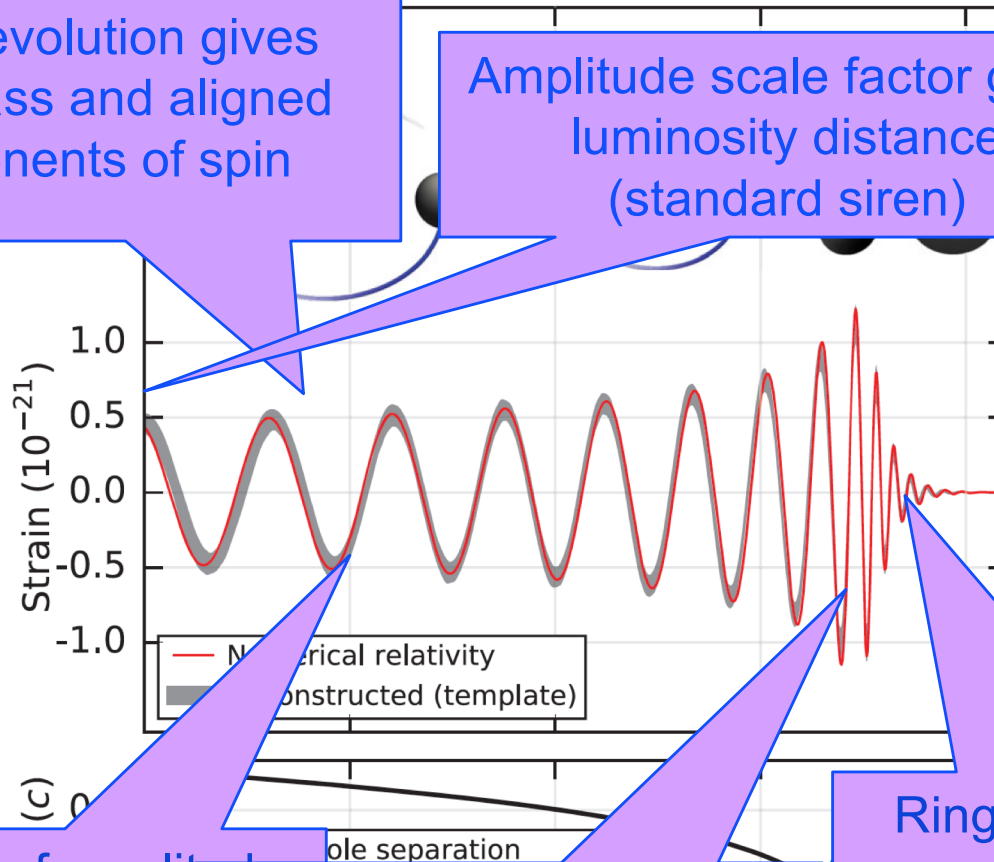


B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), *Observation of Gravitational Waves from a Binary Black Hole Merger*, Phys. Rev. Lett. 116, 061102 (2016)

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)



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)

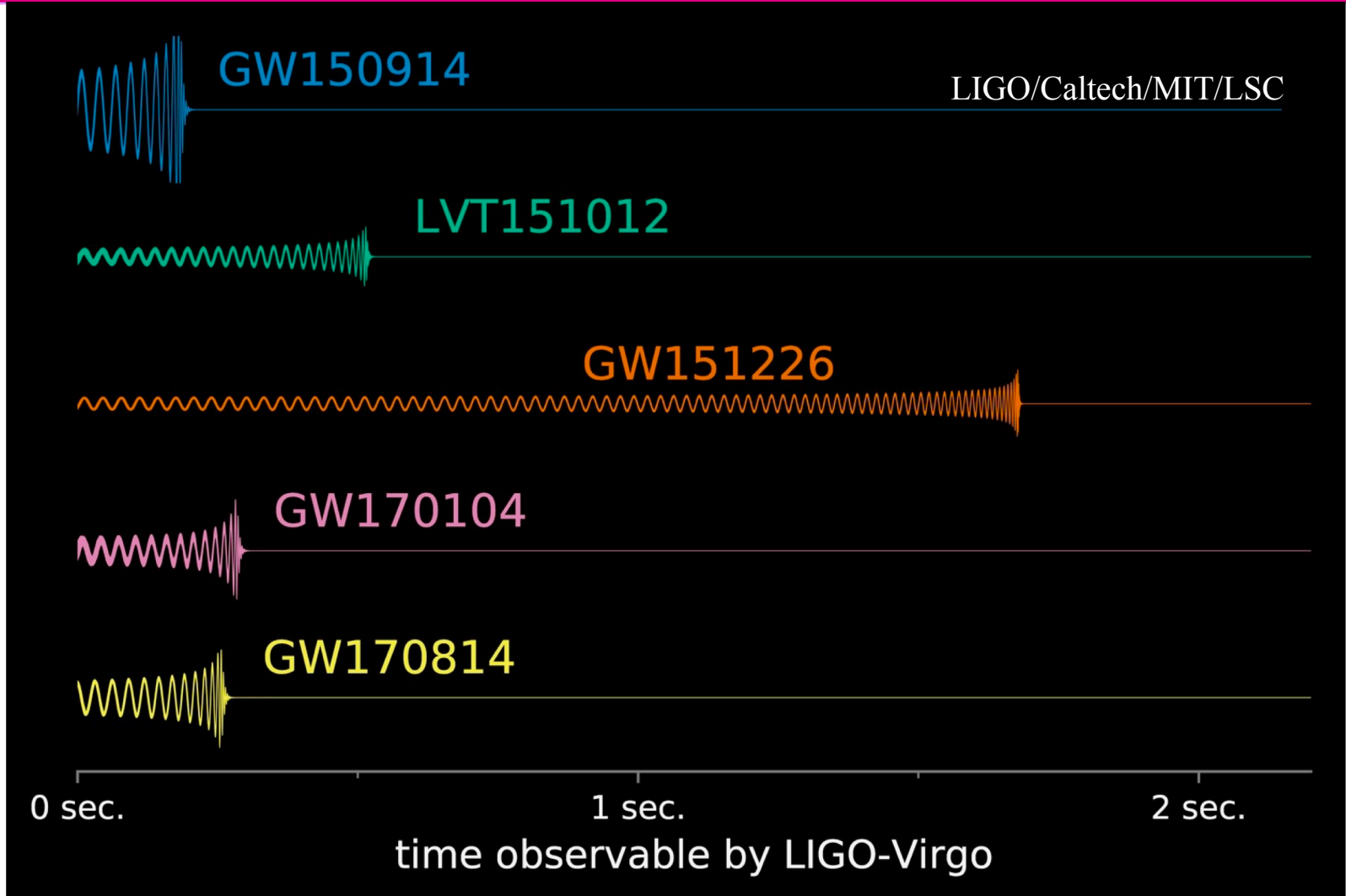
Modulation of amplitude gives nonaligned spin components

Highest frequency gives sizes of objects just before merger.

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



LIGO Comparison of GW Waveforms from BBHs (Sep 2017)



-
- 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!



LIGO

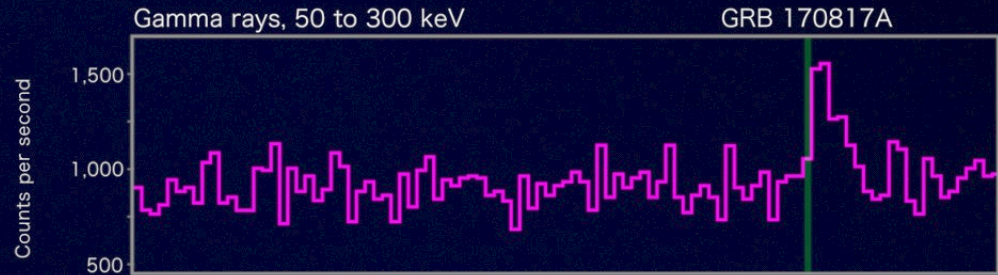
Onto the study of the most extreme states of matter



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

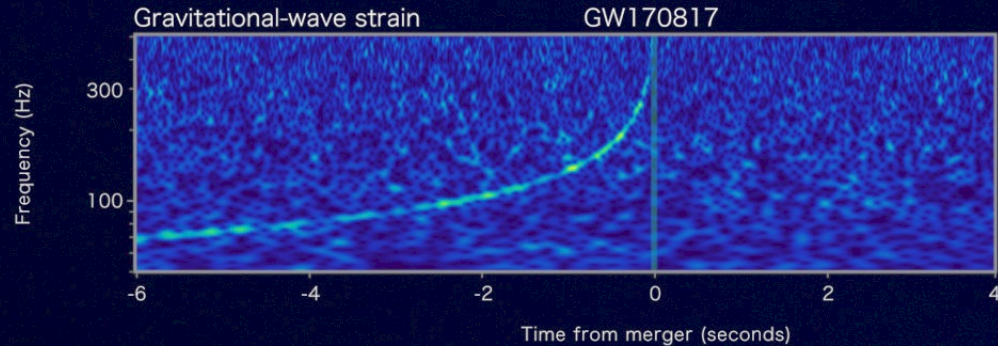
Fermi

Reported 16 seconds after detection



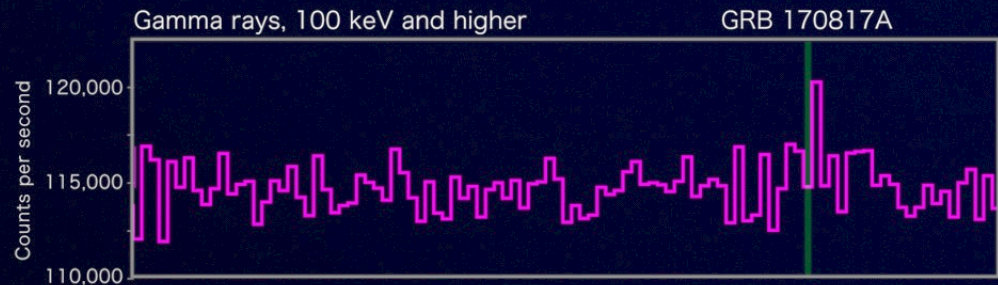
LIGO-Virgo

Reported 27 minutes after detection



INTEGRAL

Reported 66 minutes after detection



LIGO-Virgo network localization enables discovery of optical counterpart

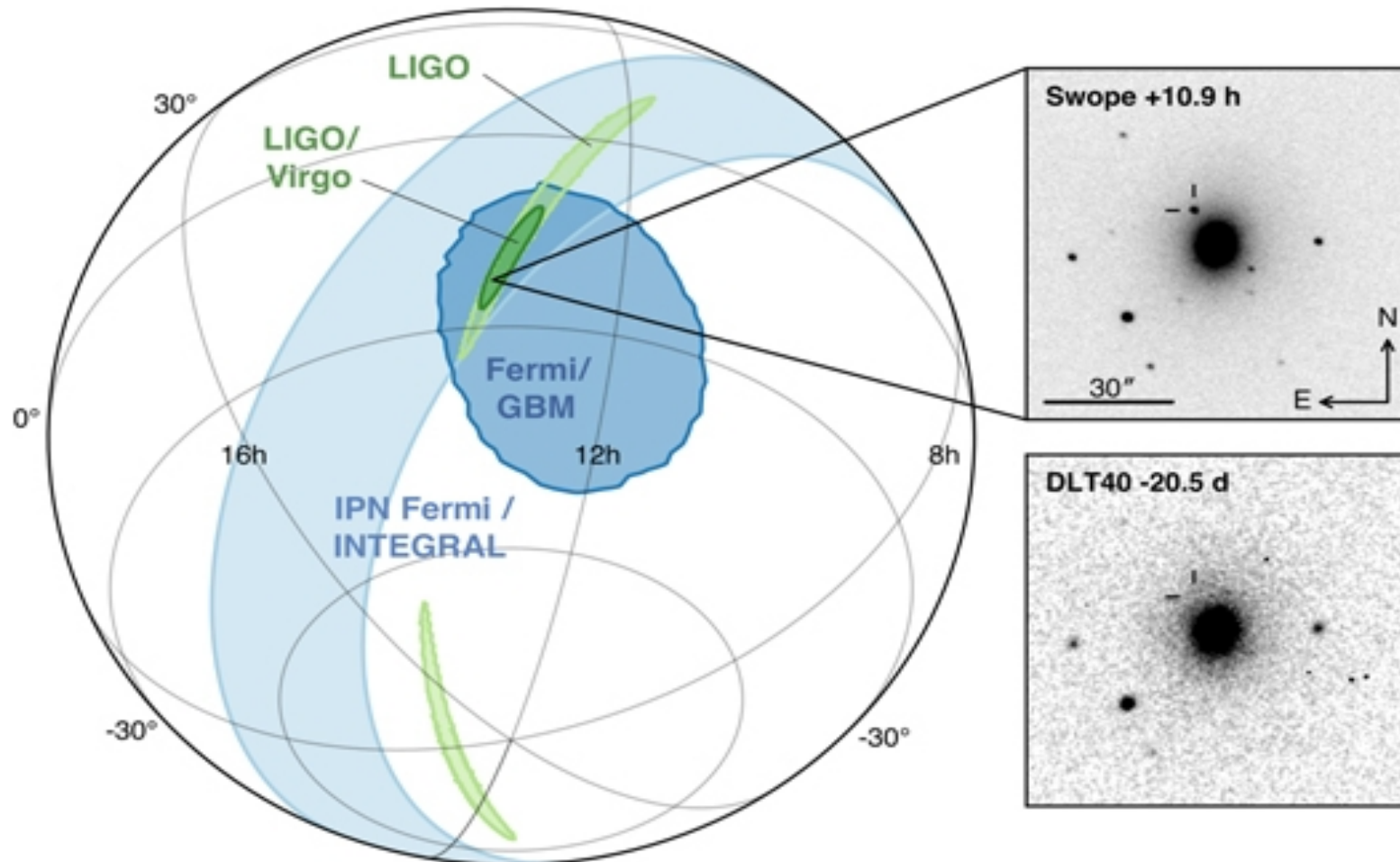


Figure 1 from Multi-messenger Observations of a Binary Neutron Star Merger
B. P. Abbott et al. 2017 ApJL 848 L12 doi:10.3847/2041-8213/aa91c9

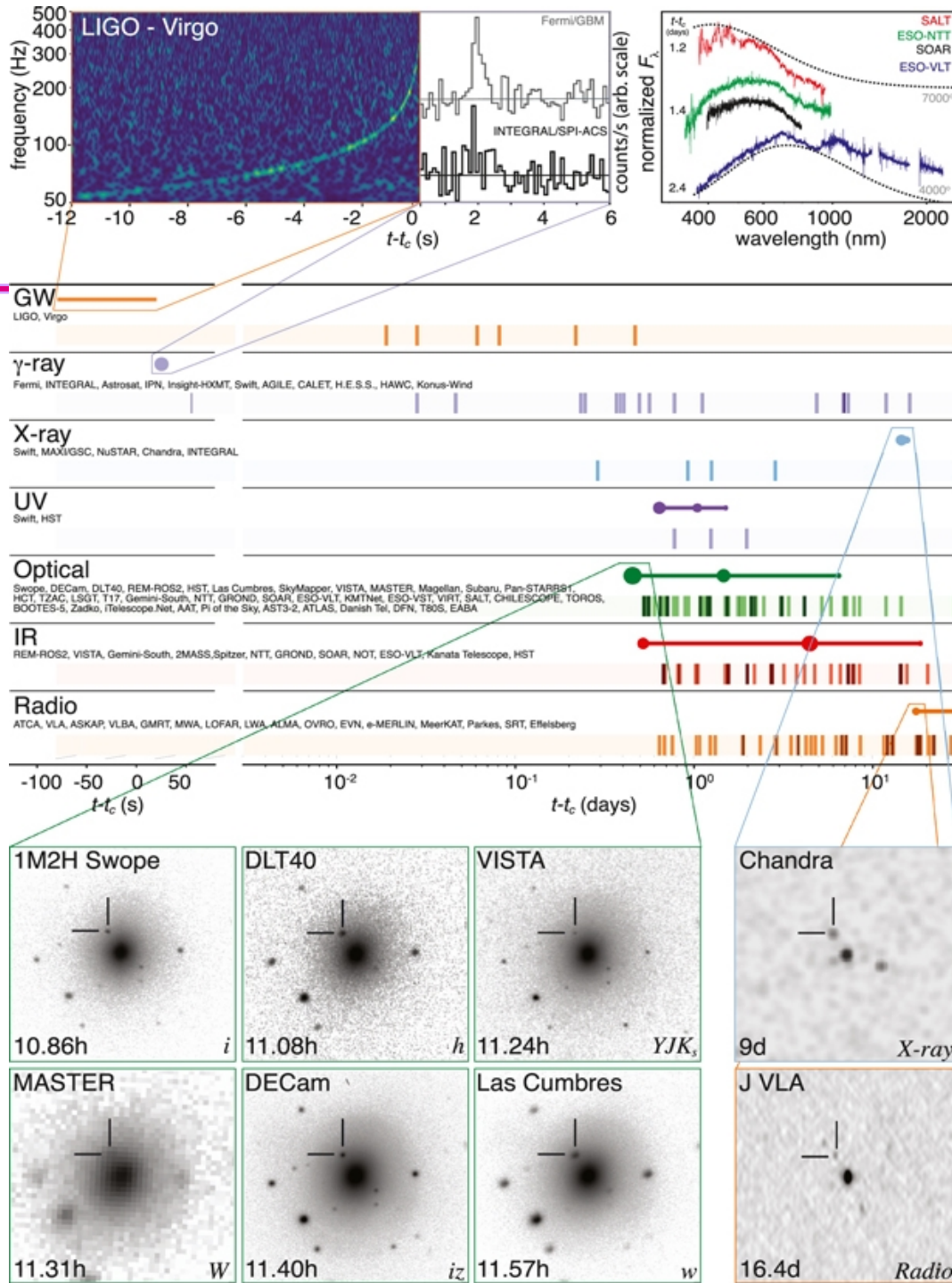


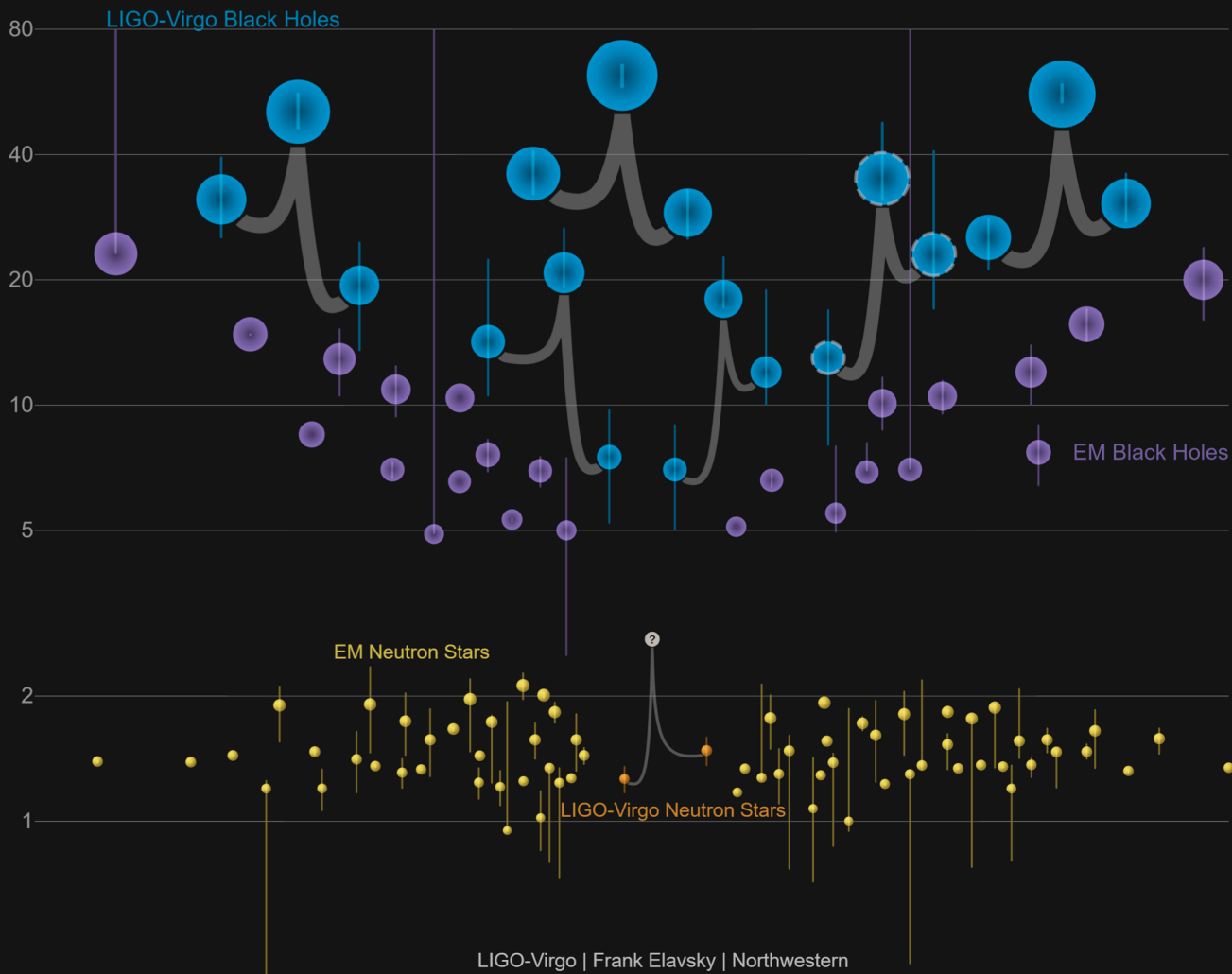
Figure 2 from Multi-messenger Observations of a Binary Neutron Star Merger
 B. P. Abbott et al.
 2017 ApJL 848 L12
 doi:10.3847/2041-8213/aa91c9



Known Masses of Stellar Remnants – Dec 2017



Masses in the Stellar Graveyard *in Solar Masses*



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>

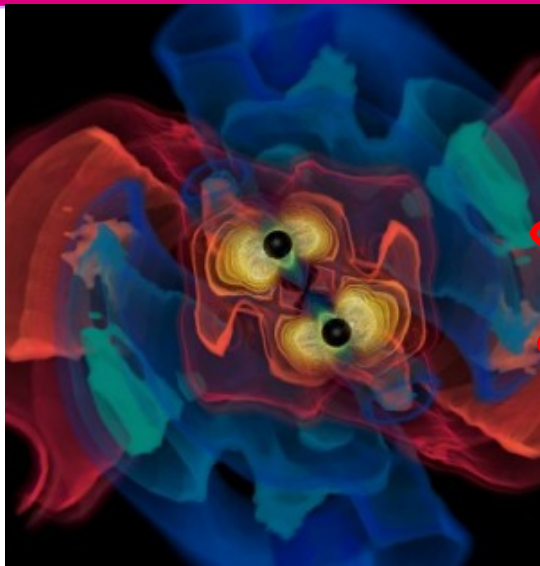
LIGO-Virgo Data:

<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

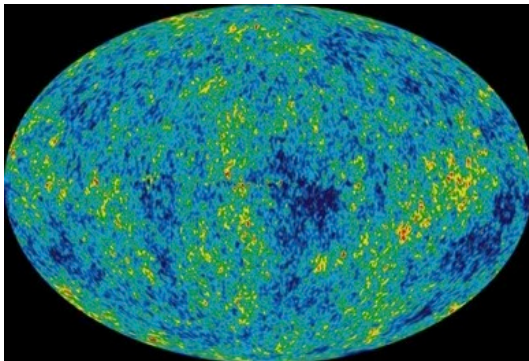
- Strong emitters, well-modeled,

- (effectively) transient

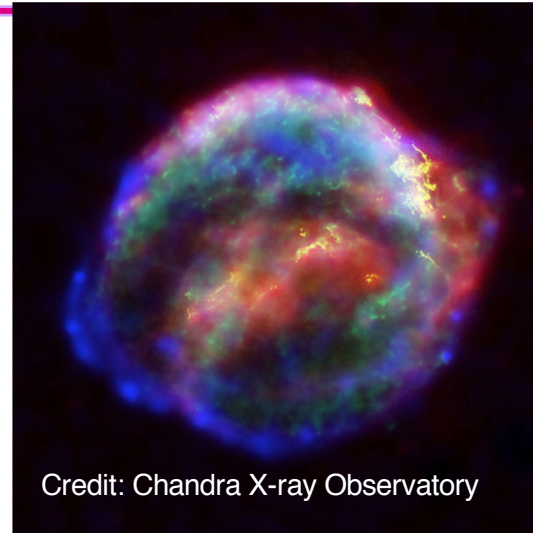
Cosmic Gravitational-wave Background

- Residue of the Big Bang

- Long duration, stochastic background



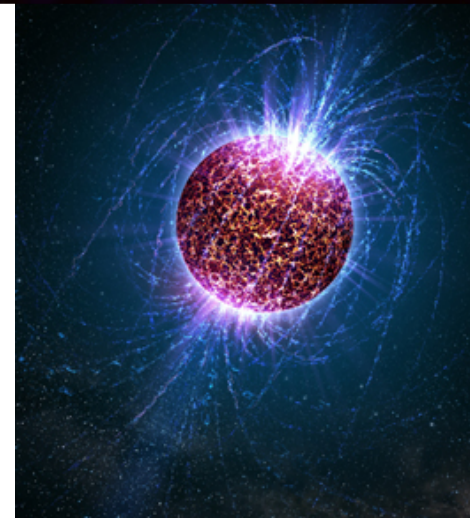
NASA/WMAP Science Team



Credit: Chandra X-ray Observatory

Asymmetric Core Collapse Supernovae

- Weak emitters, not well-modeled ('bursts'), transient



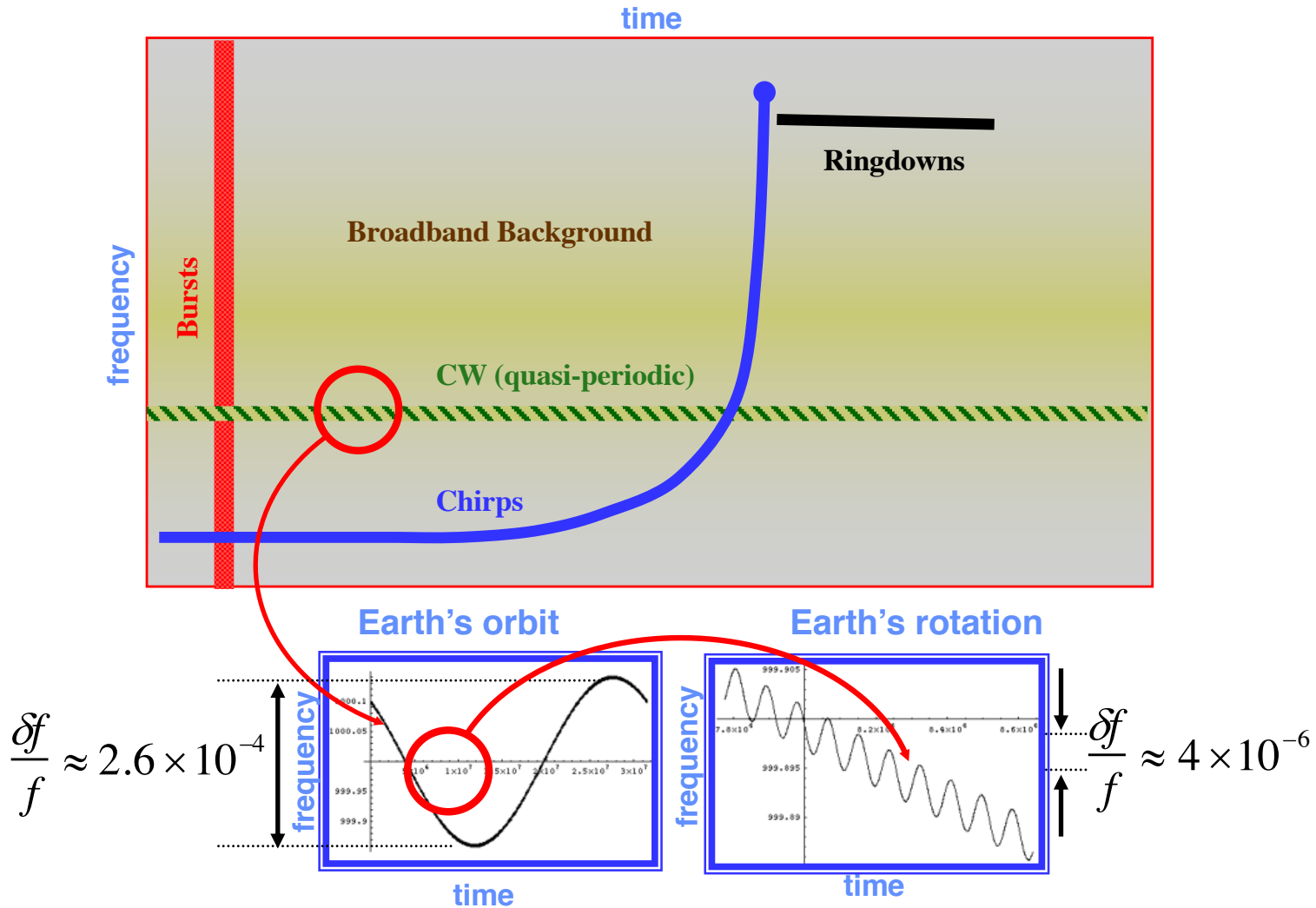
Casey Reed, Penn State

Spinning neutron stars

- (nearly) monotonic waveform

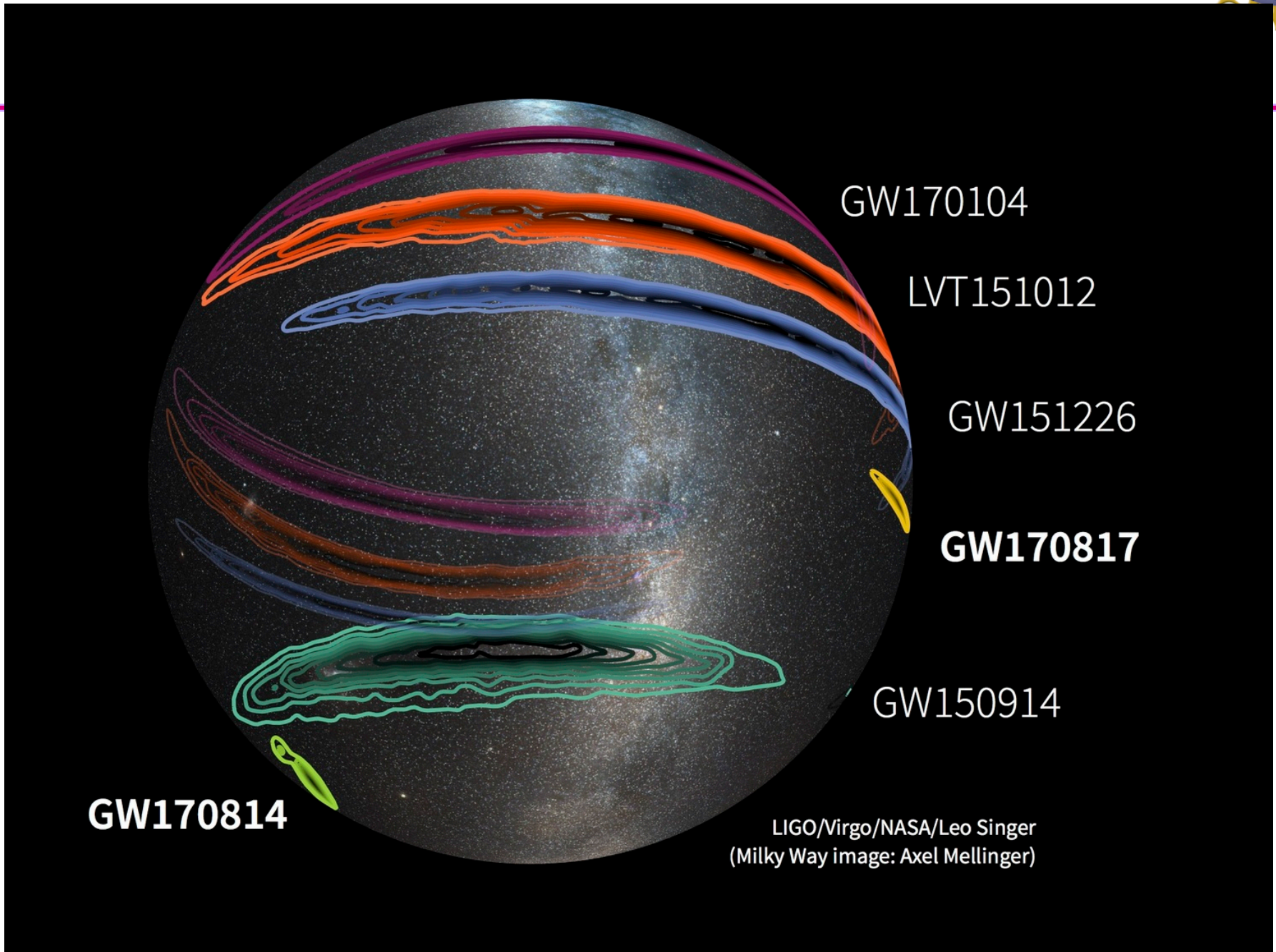
- Long duration

Frequency-Time Characteristics of GW Sources





Building Out the Terrestrial Gravitational-Wave Network



LIGO

The advanced GW detector network: 2015-2025

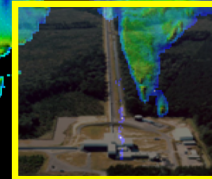
Advanced LIGO
Hanford
2015



GEO600 (HF)
2011



Advanced
Virgo
2017



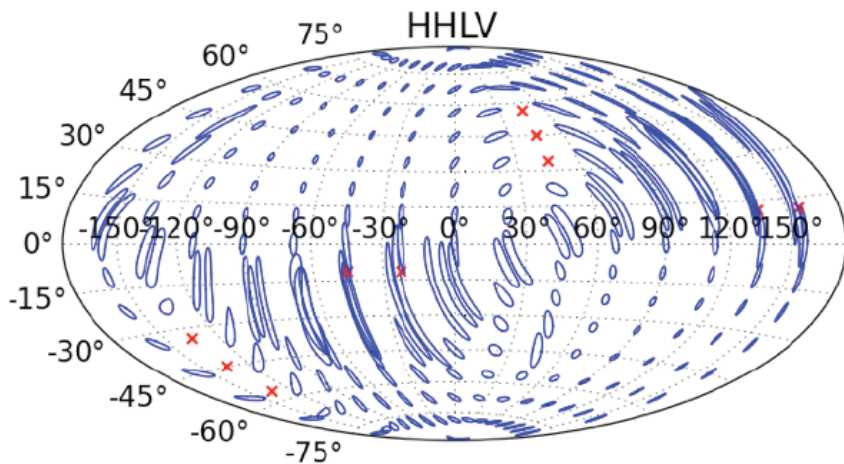
LIGO-India
2025



KAGRA
2020

Advanced LIGO
Livingston
2015

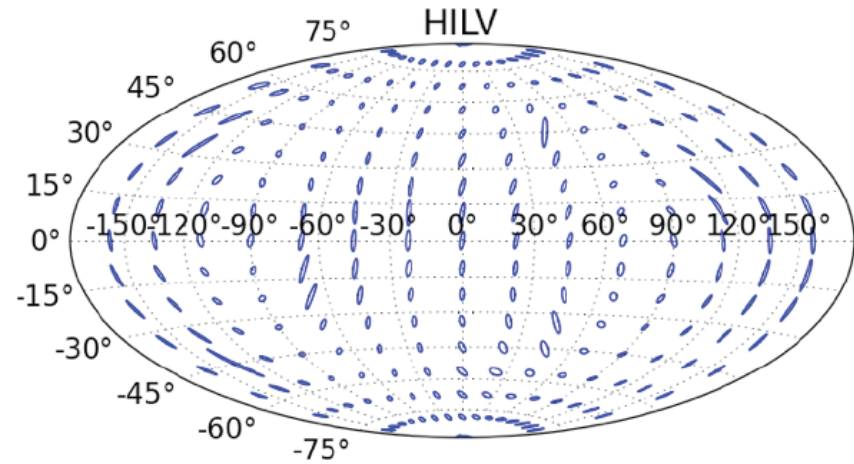
LIGO Effect of Adding LIGO-India to the LIGO+Virgo Network



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

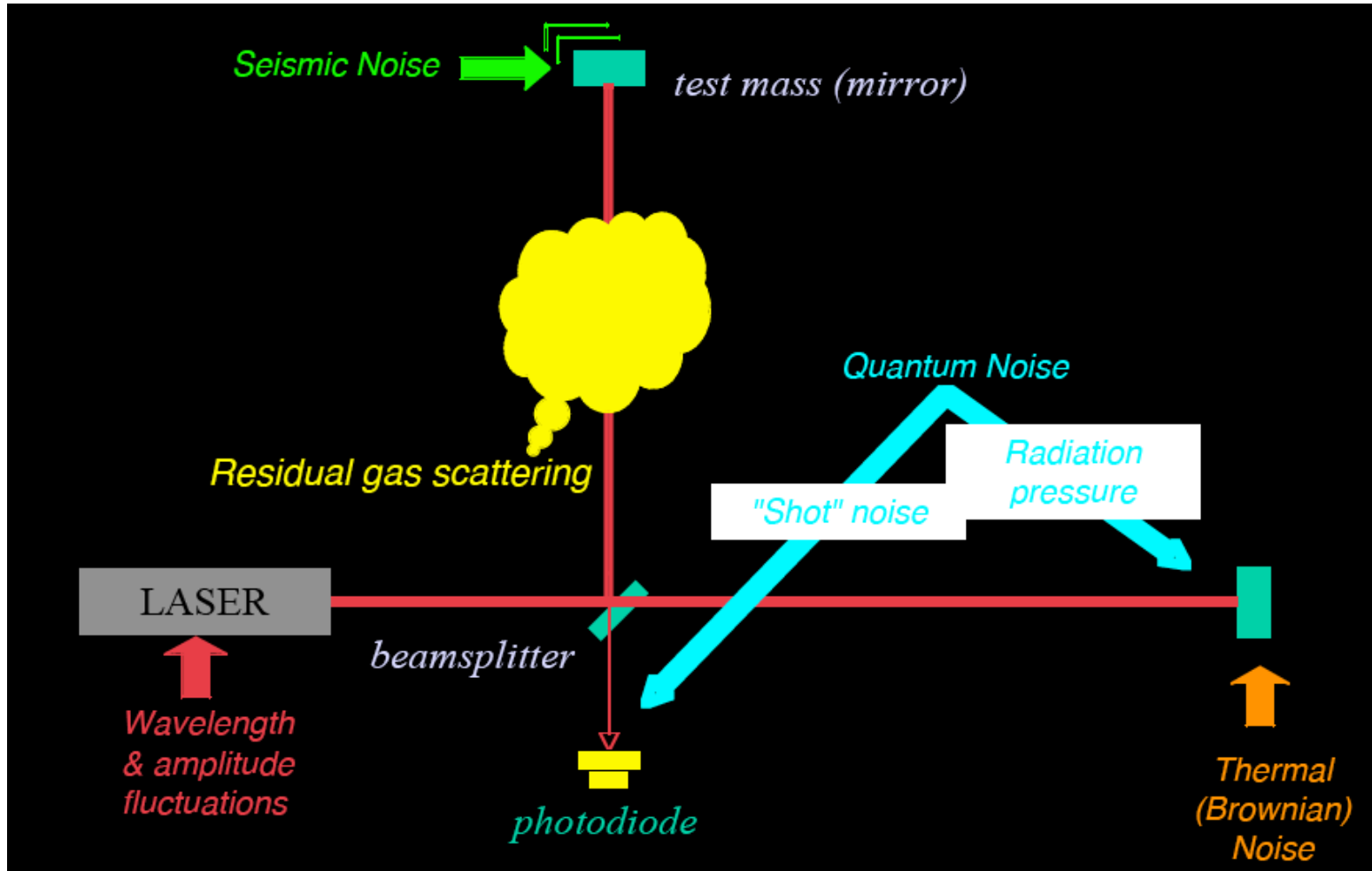


Sensitivity of Detectors is Determined by Noise and Background

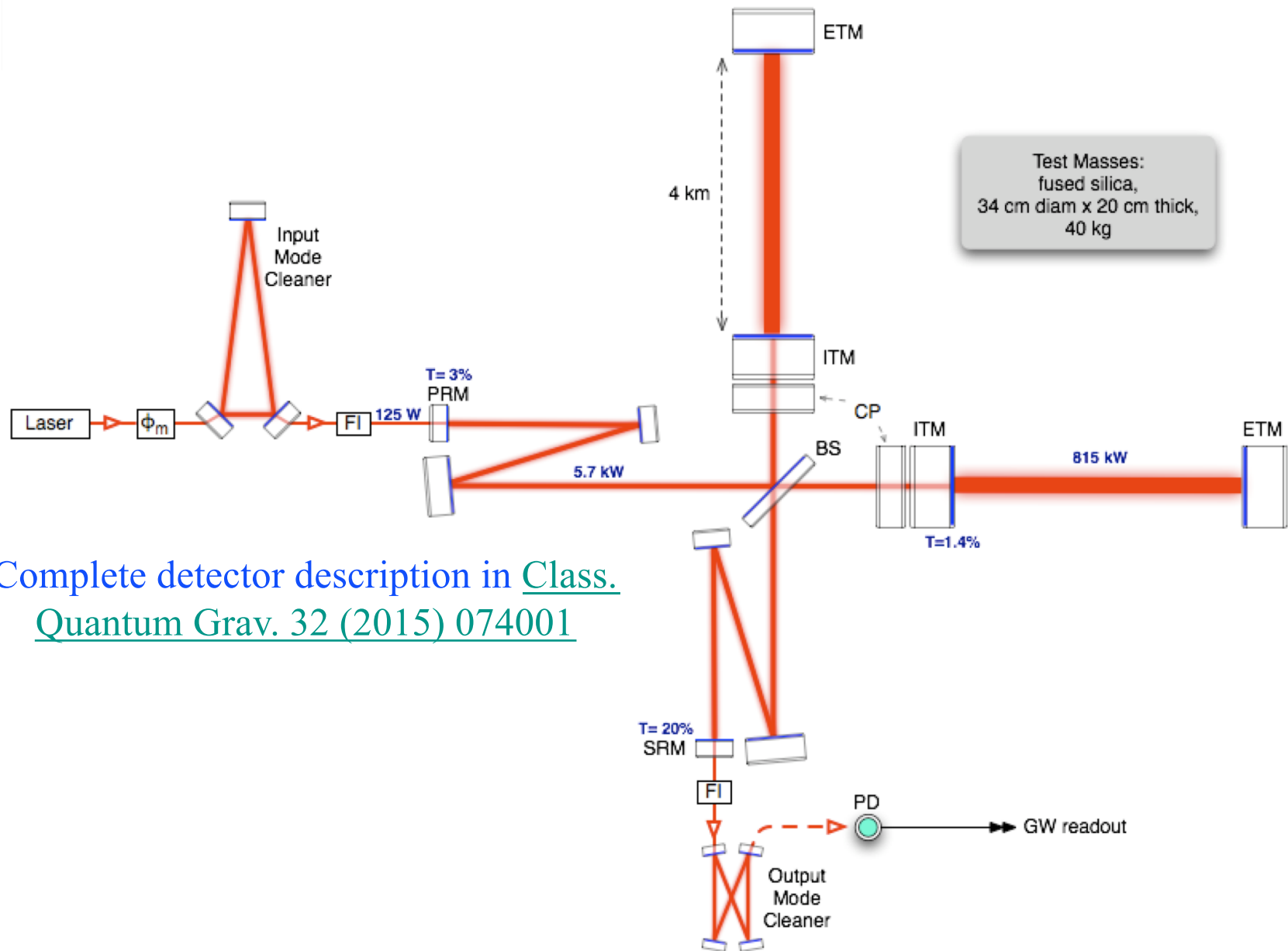


- The key to improving detectors is sensitivity which is improved by reducing noise and background.
- Range is proportional to sensitivity.
- Event rate is proportional to volume, which is proportional to range cubed.
- Thus a factor of 2 in sensitivity gives a factor of 8 in event rate (nearly an order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

Noise and background cartoon



R. Adhikari



Complete detector description in [Class. Quantum Grav. 32 \(2015\) 074001](#)

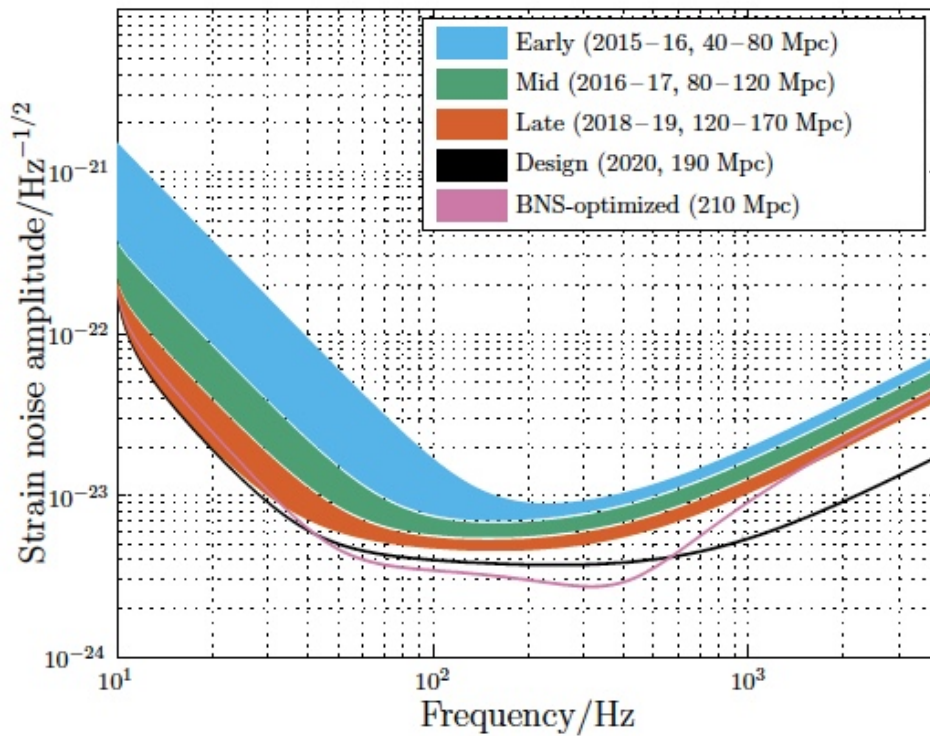


The next step: O3

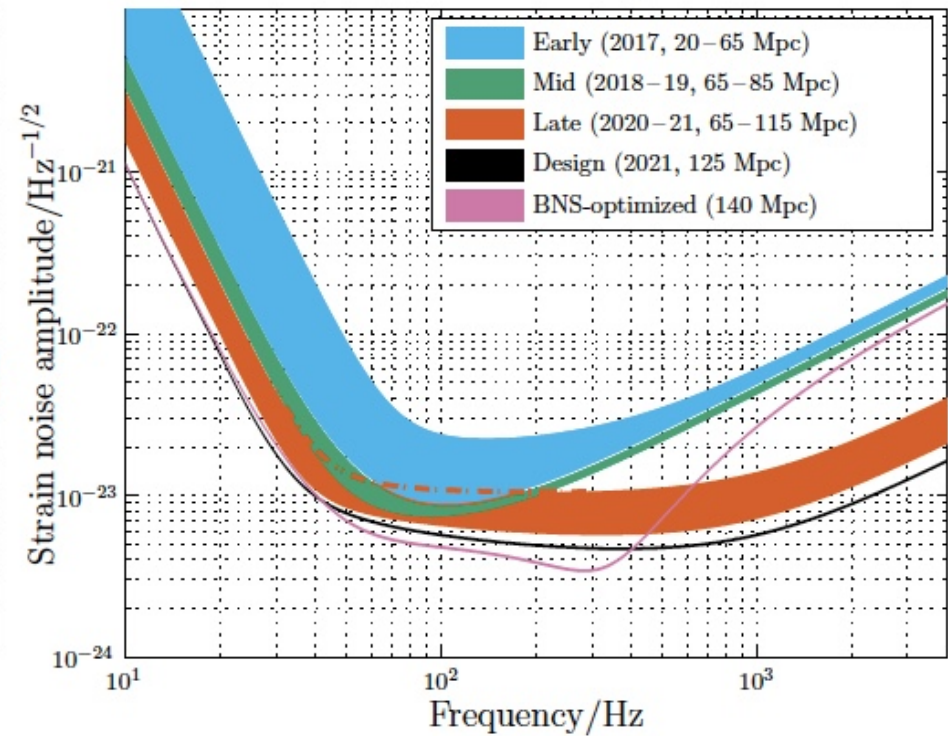
LIGO-Virgo Observing Scenario

([arXiv:1304.0670](https://arxiv.org/abs/1304.0670))

Advanced LIGO



Advanced Virgo



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

Working schedule for next observing run (O3)

<https://www.ligo.org/scientists/GWEMalerts.php>

[EVNT Logbook](#)
[Kronos](#)
[LIGO Weekly Report](#)
[LIGO Weekly submit...](#)
[Operations_Manage...](#)
[Bug List: All](#)
[LD AS O2 Summary](#)
[LD AS H1 Summary](#)
[LHO Controlroom S...](#)

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	Phase	Start	End	Notes
H1	Upgrades	May 2018	Aug 2018	Detector operational, commissioning mode (small fraction of observing mode time)
	Commissioning	Aug 2018	Nov 2018	Detector in observing mode for a fraction of the time during Engineering Runs (ERs), EM alerts possible (best-effort only)
L1	Upgrades	May 2018	Aug 2018	Detector operational, commissioning mode (small fraction of observing mode time)
	Commissioning	Aug 2018	Nov 2018	Detector in observing mode for a fraction of the time during Engineering Runs (ERs), EM alerts possible (best-effort only)
Virgo	Commissioning	Aug 2018	Nov 2018	Detector in observing mode for a fraction of the time during Engineering Runs (ERs), EM alerts possible (best-effort only)
	O3	Jan 2019	May 2019	24/7 observing mode (Observing Run, Open Public Alerts)
GEO	O3	May 2018	May 2019	~70% observing mode

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

GW170817 Localization and Triangulation Annull. 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 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



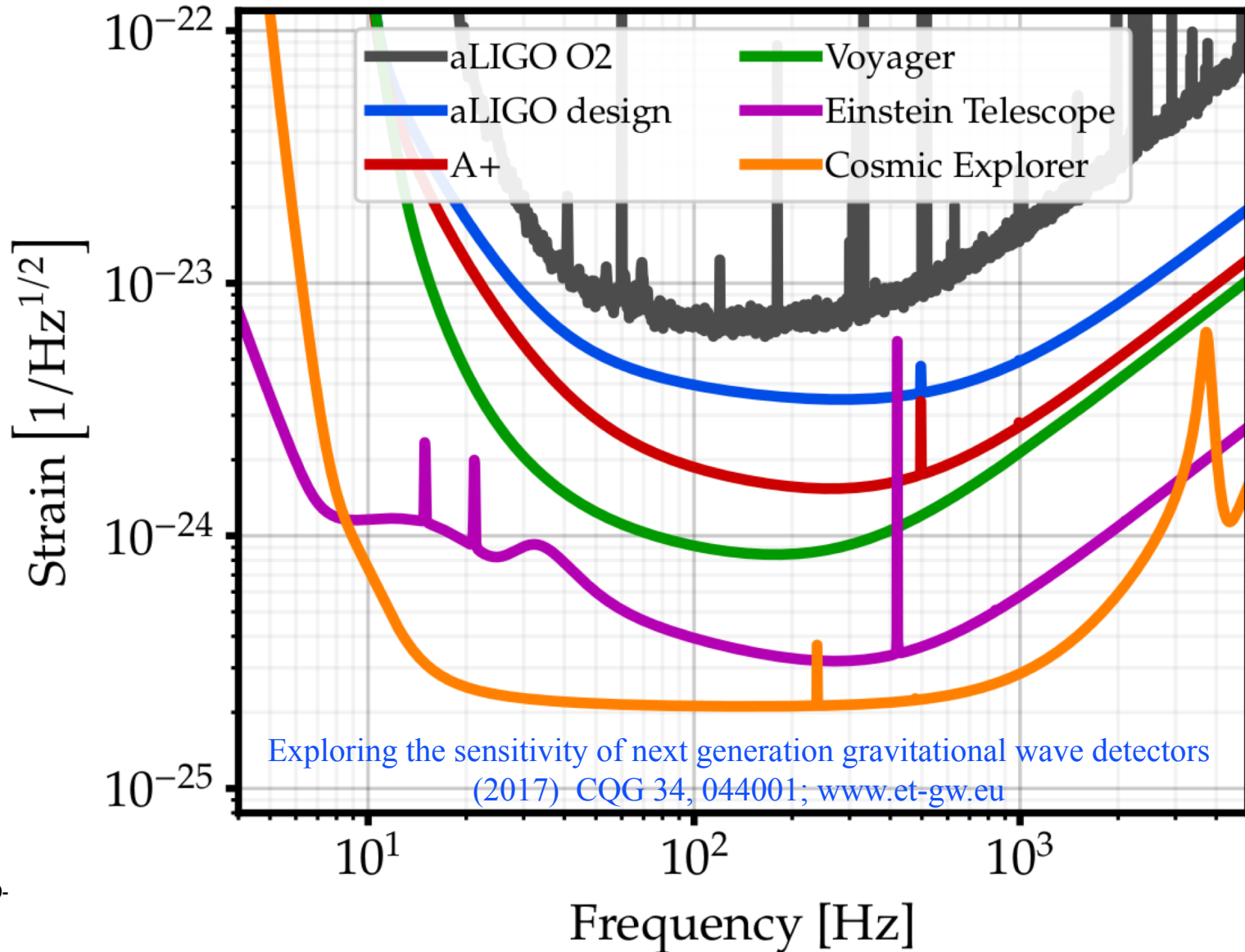
- **Stellar Evolution at High Red-Shift: Black Holes from the first stars (Population III)**
 - » Reach $z > \sim 10$
 - » At least moderate GW luminosity distance precision
- **Independent Cosmology and the Dark Energy Equation of State**
 - » Needs precision GW luminosity distance and localization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



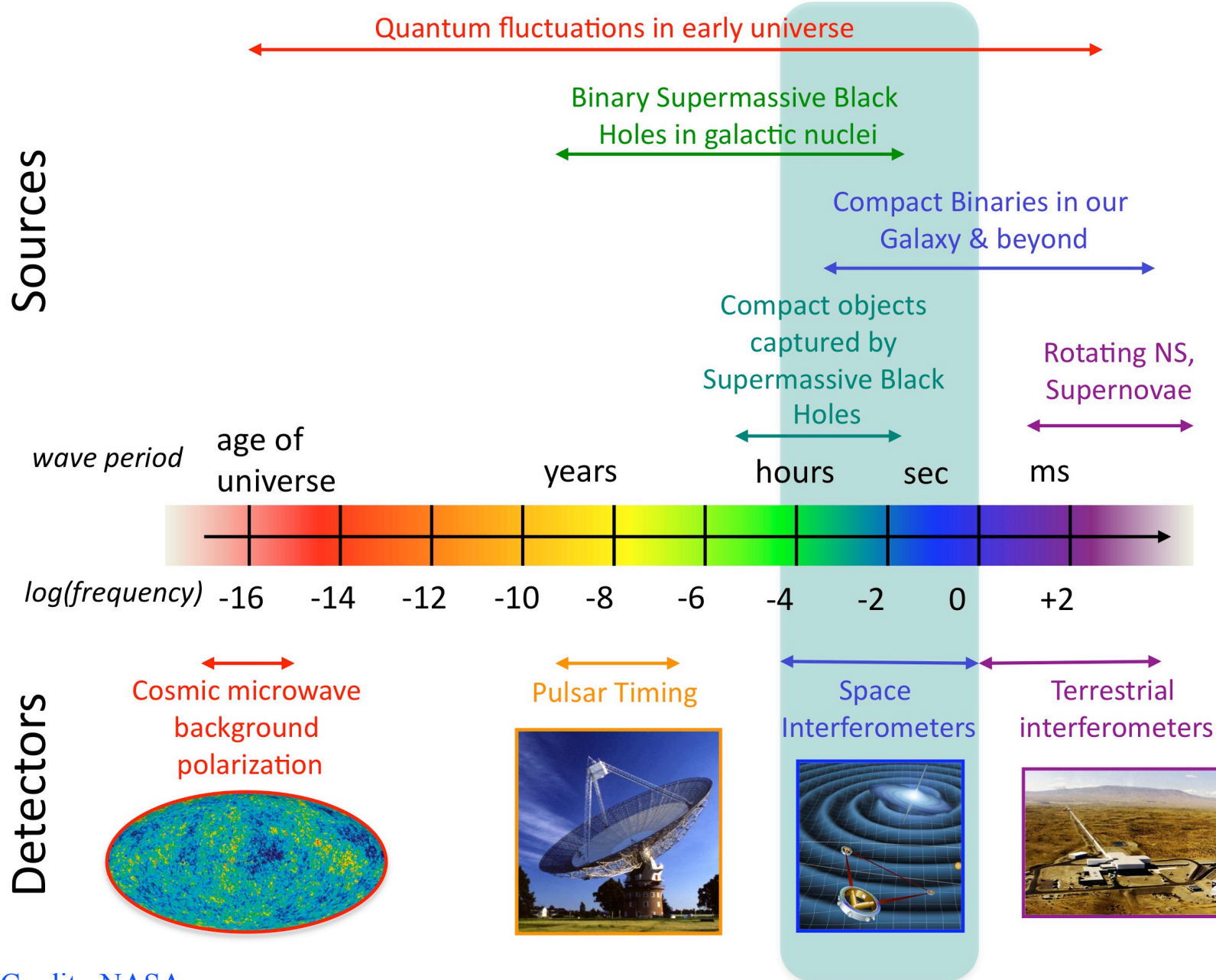
Advanced LIGO upgrade path



- 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)



The Gravitational Wave Spectrum



Credit: NASA