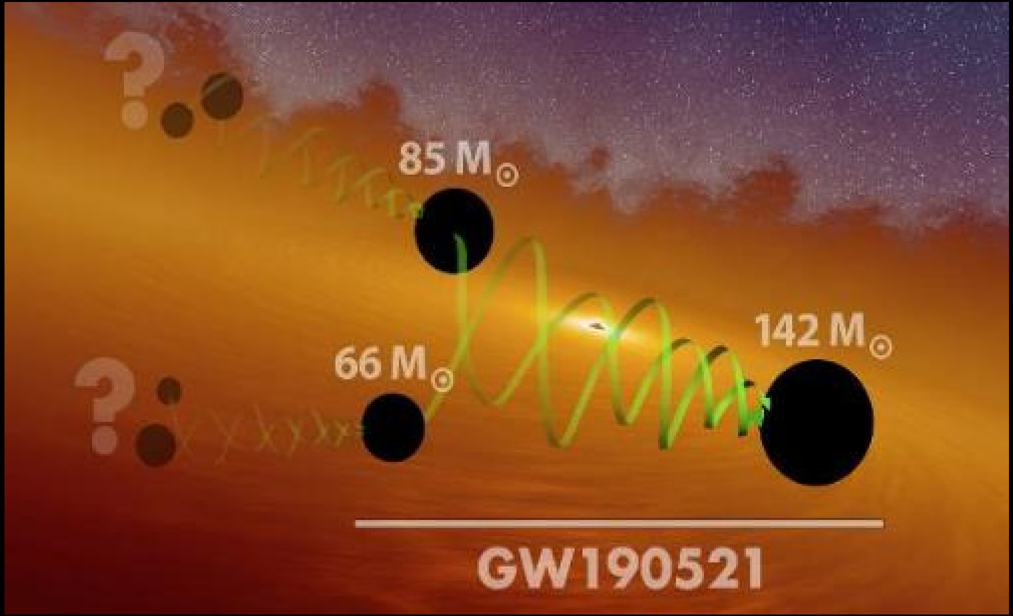
“Understanding our Universe with Gravitational Waves”



Barry C Barish

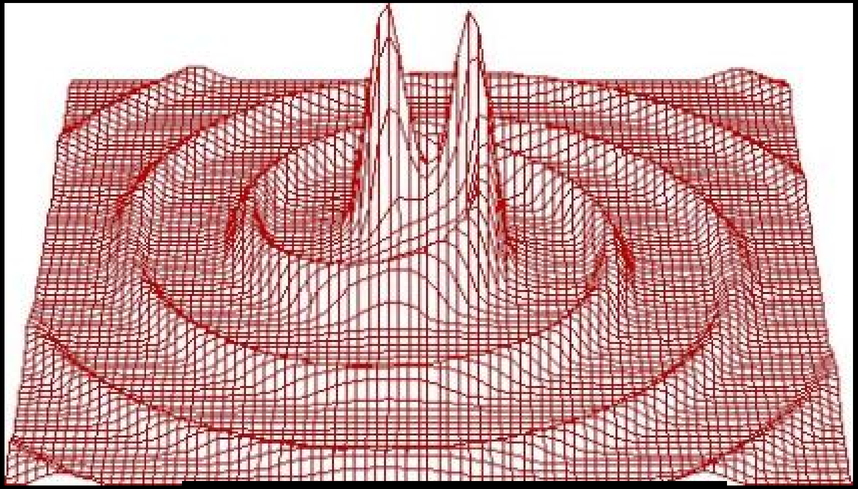
Caltech and UC Riverside

10-Feb-2021

Einstein's Theory Contains Gravitational Waves

A necessary consequence of Special Relativity with its finite speed for information transfer

Gravitational waves come from the acceleration of masses and propagate away from their sources as a space-time warpage at the speed of light



gravitational radiation
binary inspiral
of
compact objects

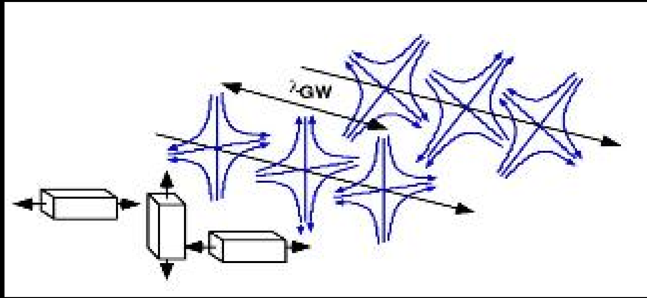
Einstein's Theory of Gravitation

Gravitational Waves

• Using Minkowski metric, the information about space-time curvature is contained in the metric as an added term, $h_{\mu\nu}$. In the weak field limit, the equation can be described with linear equations. If the choice of gauge is the *transverse traceless gauge* the formulation becomes a familiar wave equation

$$(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2})h_{\mu\nu} = 0$$

• The strain $h_{\mu\nu}$ takes the form of a plane wave propagating at the speed of light (c).



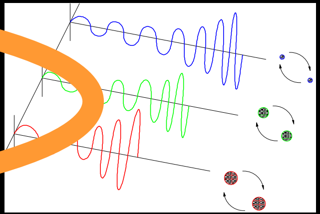
• Since gravity is spin 2, the waves have two components, but rotated by 45^0 instead of 90^0 from each other.

$$h_{\mu\nu} = h_+(t - z/c) + h_x(t - z/c)$$

Astrophysical Sources

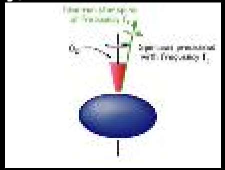
signatures

- Compact binary inspiral: *"chirps"*
  - NS-NS waveforms are well described
  - BH-BH need better waveforms
  - search technique: matched templates

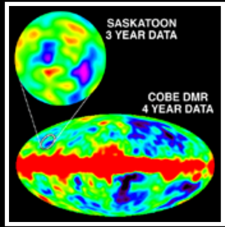


- Supernovae / GRBs: *"bursts"*
  - burst signals in coincidence with signals in electromagnetic radiation
  - prompt alarm (~ one hour) with neutrino detectors

- Pulsars in our galaxy: *"periodic"*
  - search for observed neutron stars (frequency, doppler shift)
  - all sky search (computing challenge)
  - r-modes

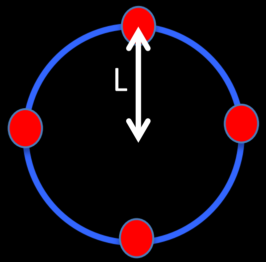


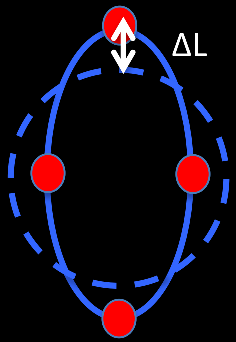
- Cosmological Signal *"stochastic background"*



Gravitational Waves

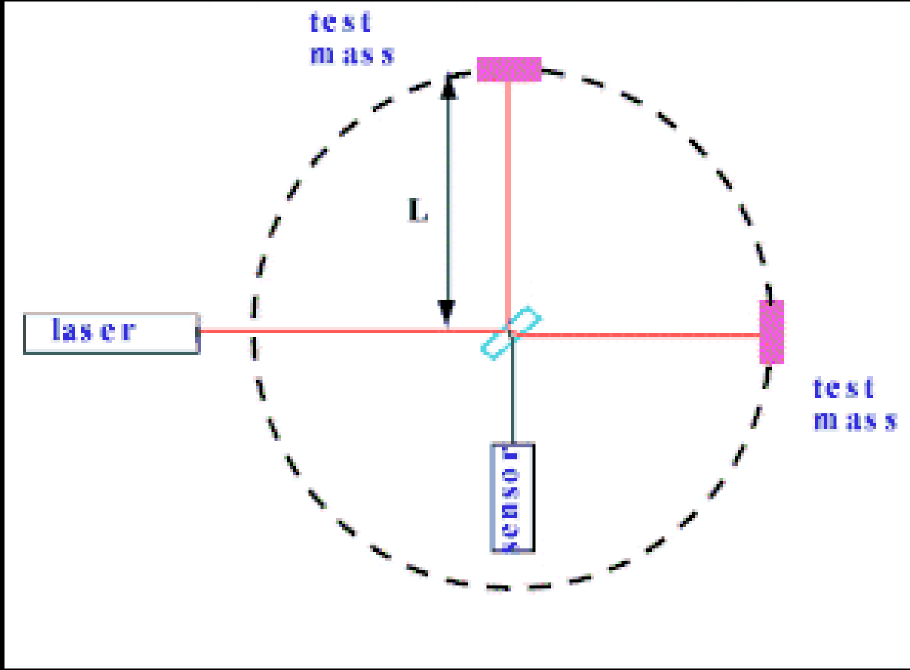
- Ripples of spacetime that stretch and compress spacetime itself
- The amplitude of the wave is $h \approx 10^{-21}$
- Change the distance between masses that are free to move by $\Delta L = h \times L$
- Spacetime is "stiff" so changes in distance are very small





$$\Delta L = h \times L = 10^{-21} \times 1\,\mathrm{m} = 10^{-21}\,\mathrm{m}$$

Suspended Mass Interferometry



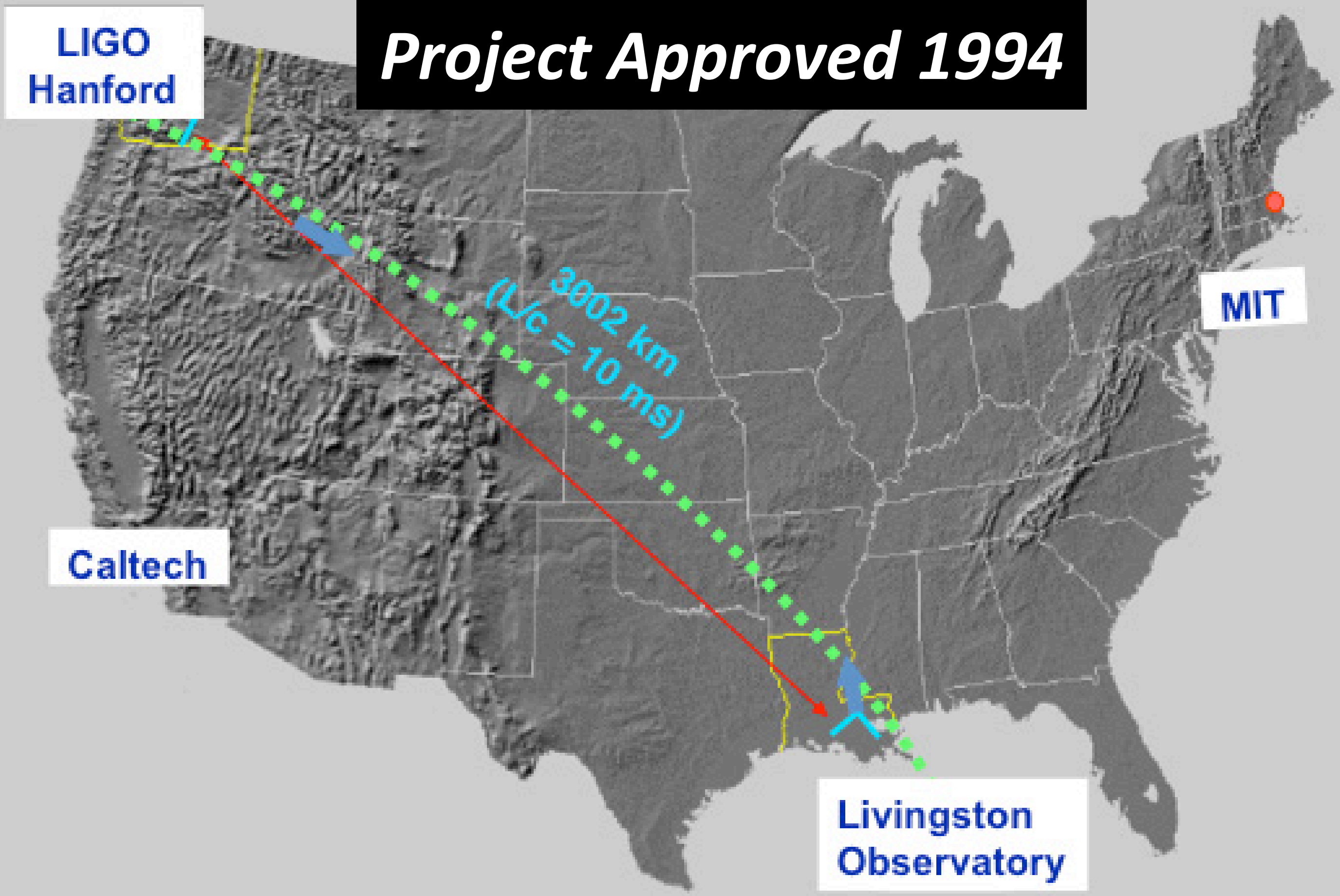
$$h = \frac{\Delta L}{L} \leq 10^{-21}$$

$$L = 4\,\text{km} \quad \Delta L \leq 4\text{x}10^{-18}\,\text{meters}$$

$\Delta L \sim 10^{-12}$ wavelength of light

$\Delta L \sim 10^{-12}$ vibrations at earth's surface

LIGO Sites
Project Approved 1994

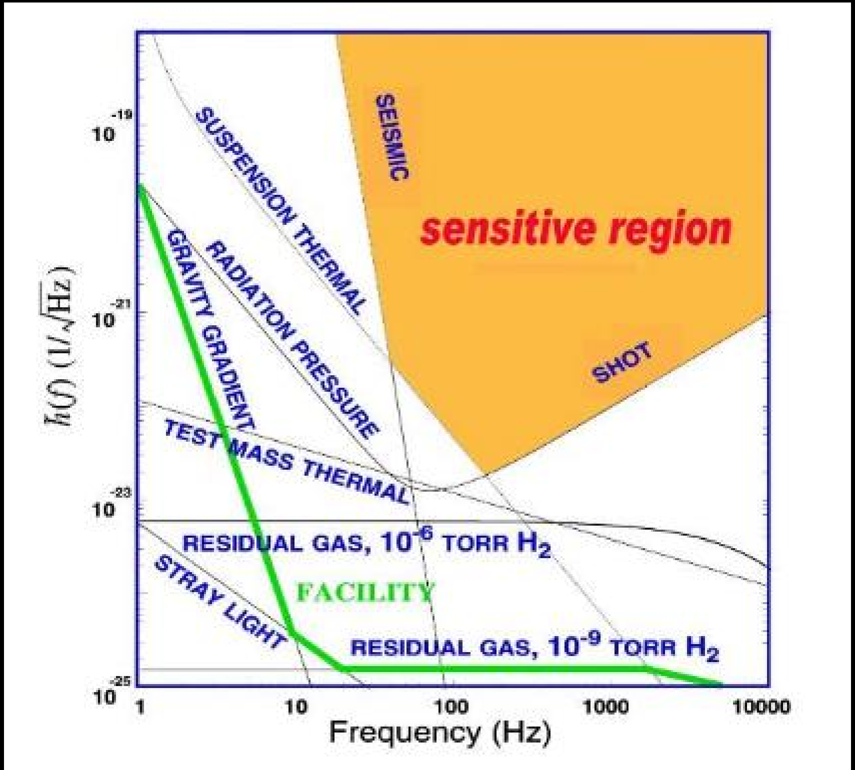


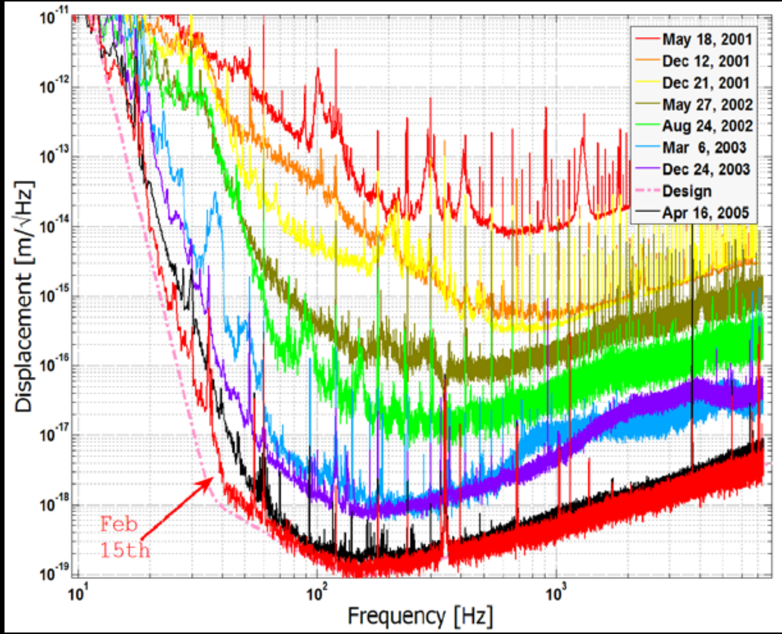
'Direct' Detection of Gravitational Waves
LIGO Interferometers

Hanford, WA

Livingston, LA

What Limits LIGO Sensitivity?





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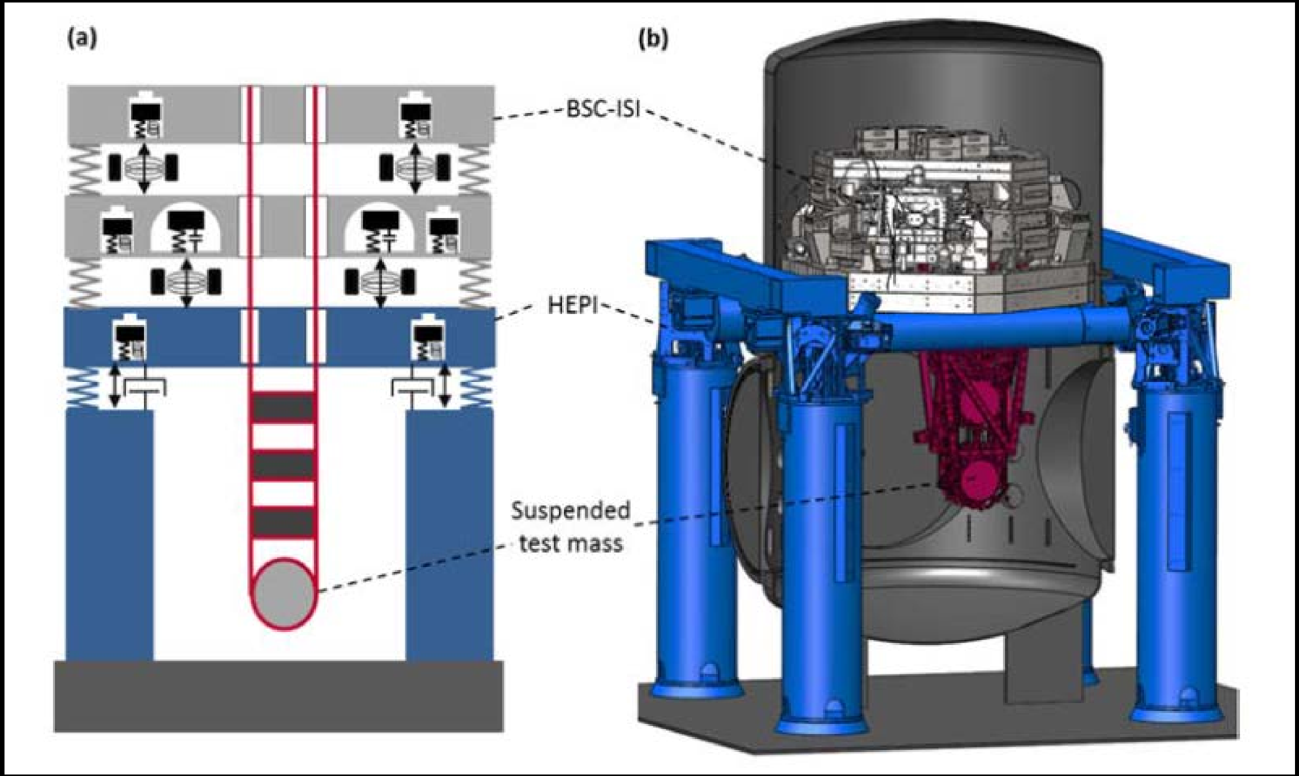
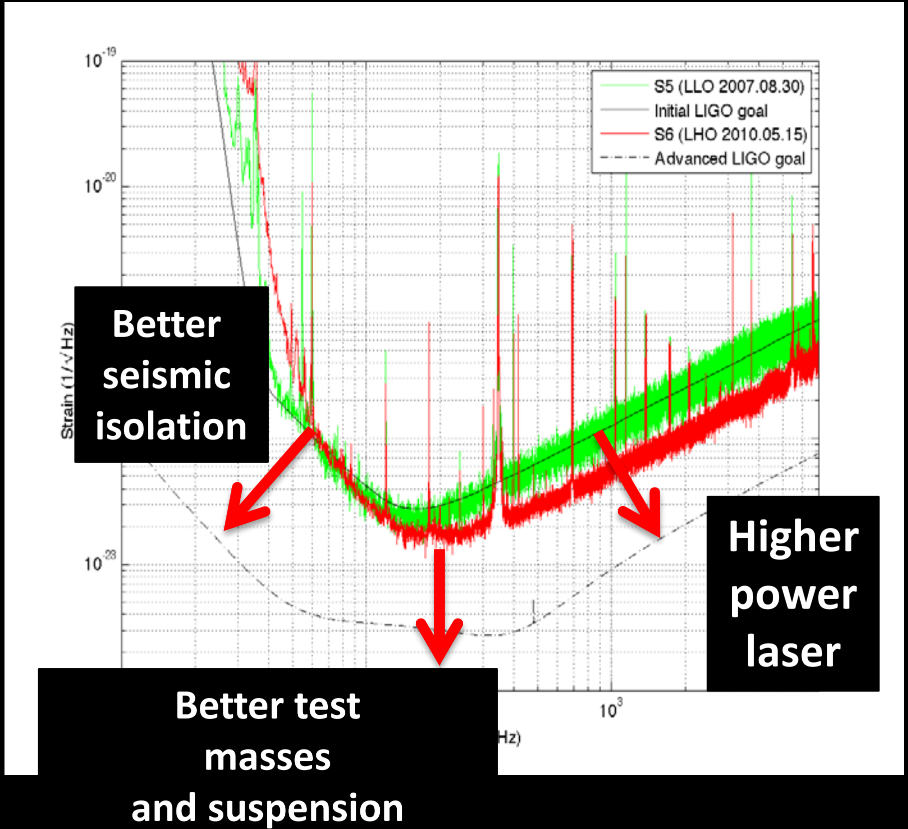
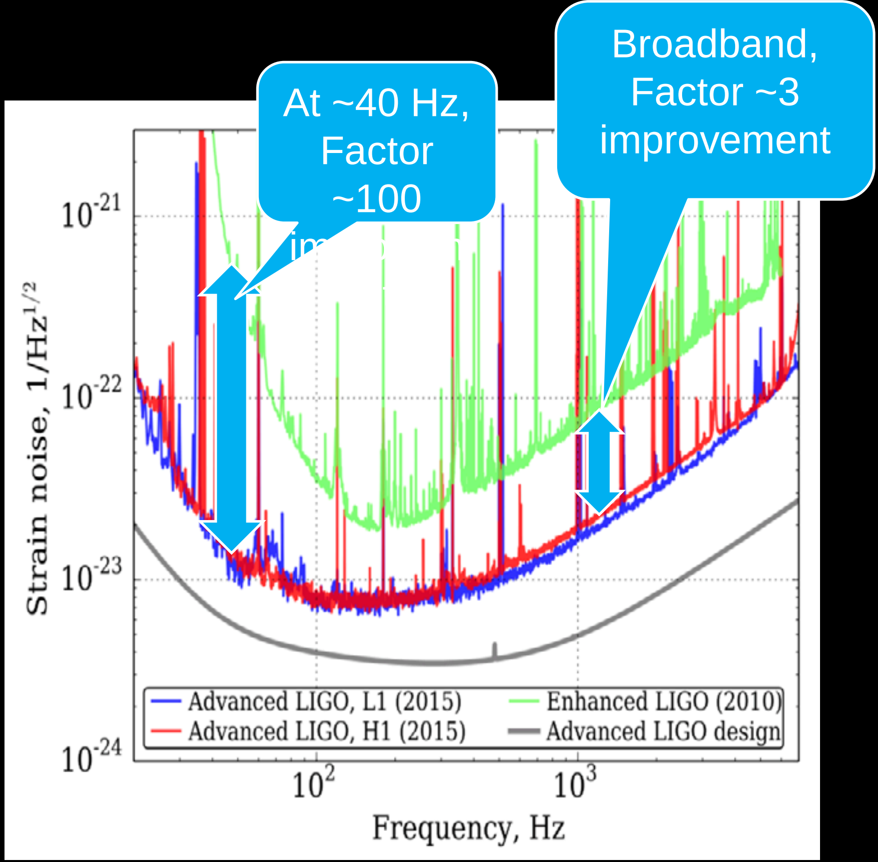
Passive / Active Multi-Stage Isolation

Advanced LIGO

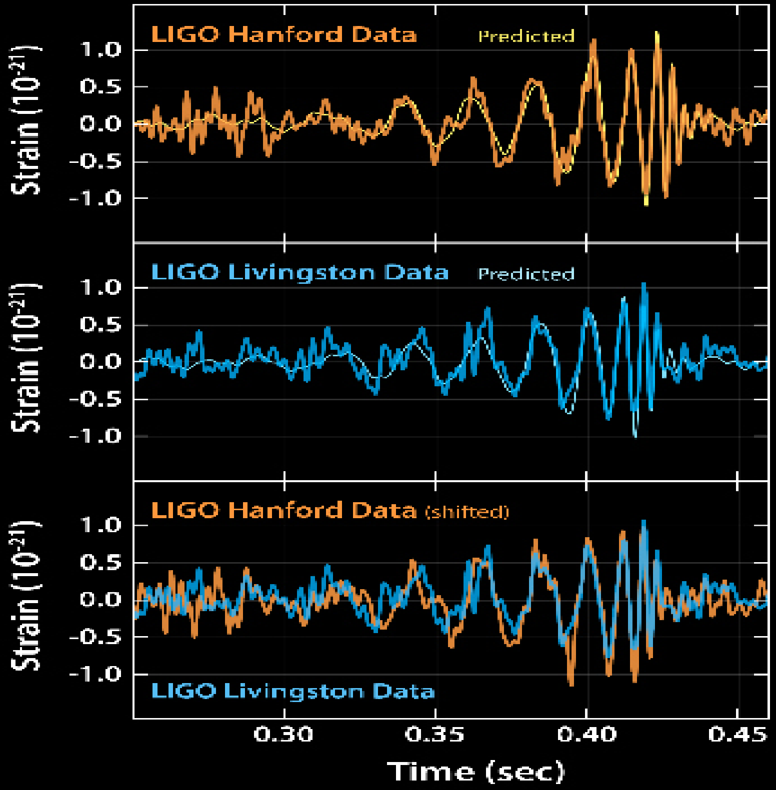


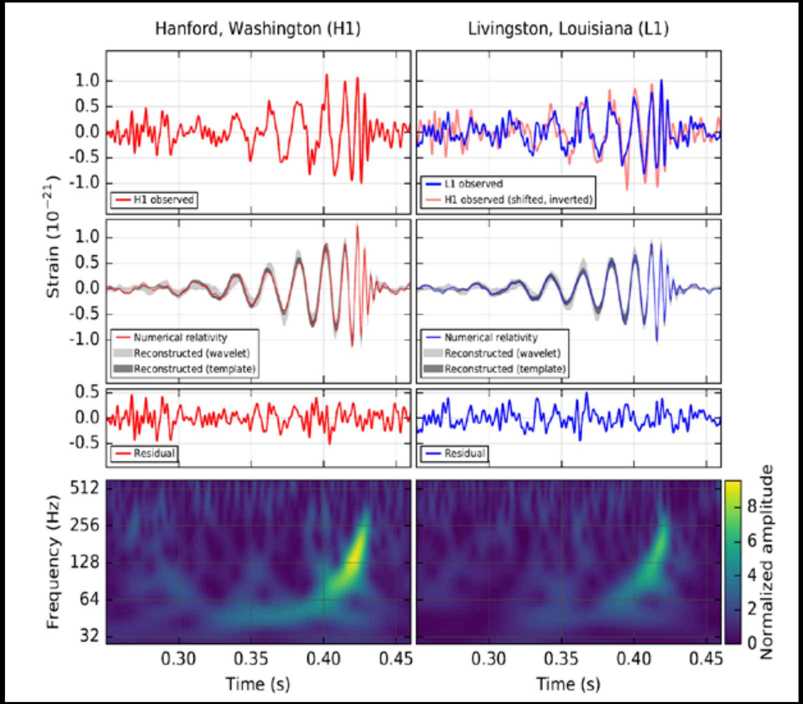
Advanced LIGO GOALS





Black Hole Merger: GW150914





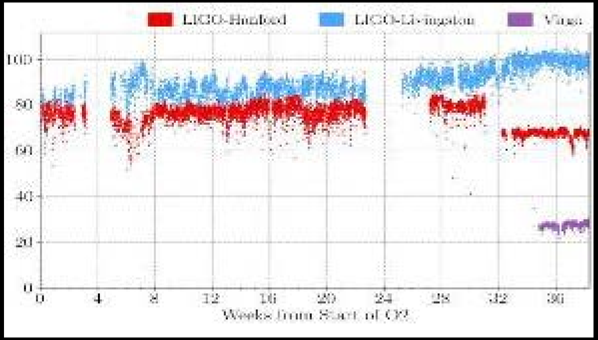
Measuring the parameters

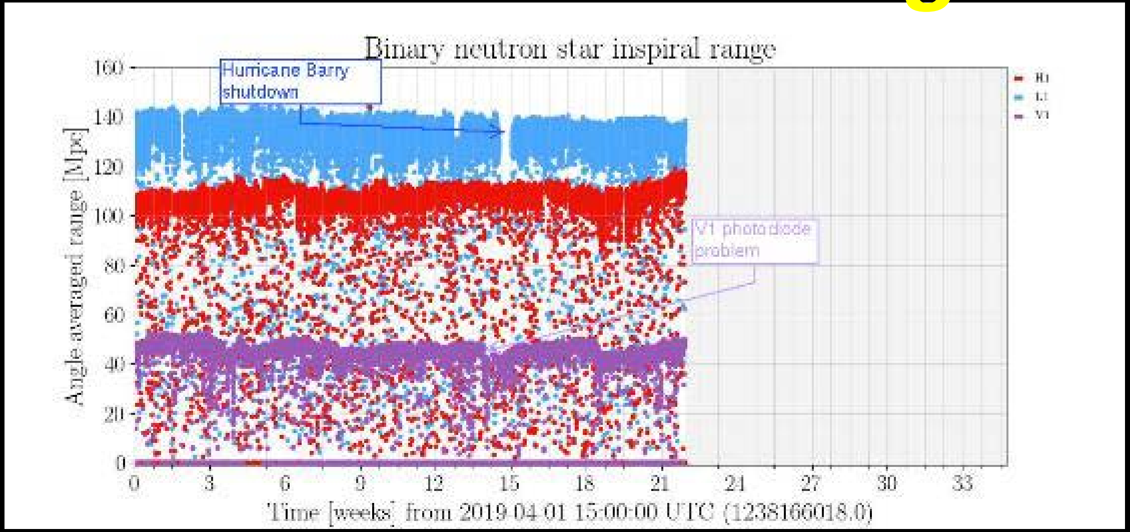
- Orbits decay due to emission of gravitational waves
  - **Leading order** determined by "chirp mass"

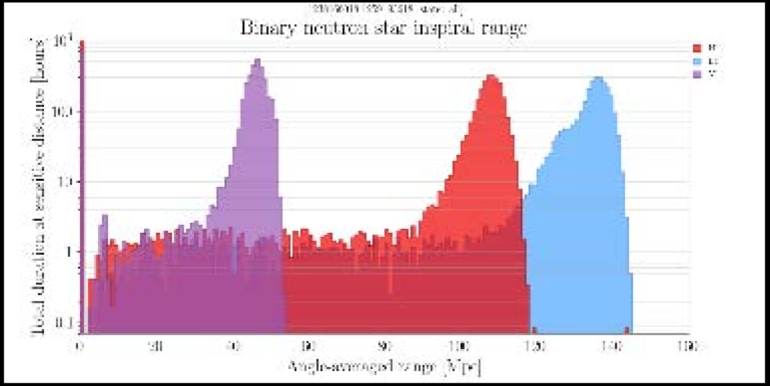
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{M^{1/5}} \simeq \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$

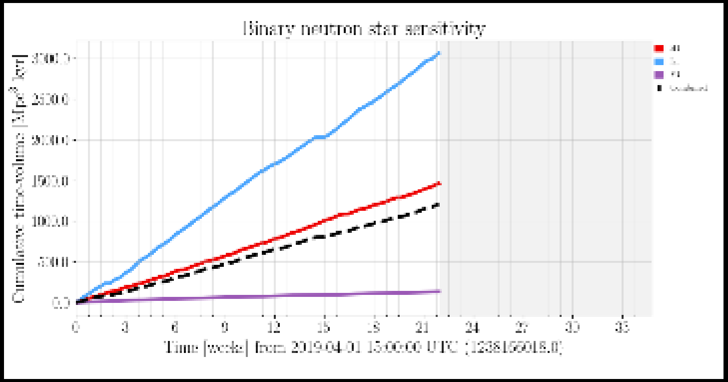
  - Next orders allow for measurement of mass ratio and spins
  - We directly measure the red-shifted masses (1+z) m
  - Amplitude inversely proportional to luminosity distance
- Orbital precession occurs when spins are misaligned with orbital angular momentum – no evidence for precession.
- Sky location, distance, binary orientation information extracted from time-delays and differences in observed amplitude and phase in the detectors

Detector Performance: BNS range



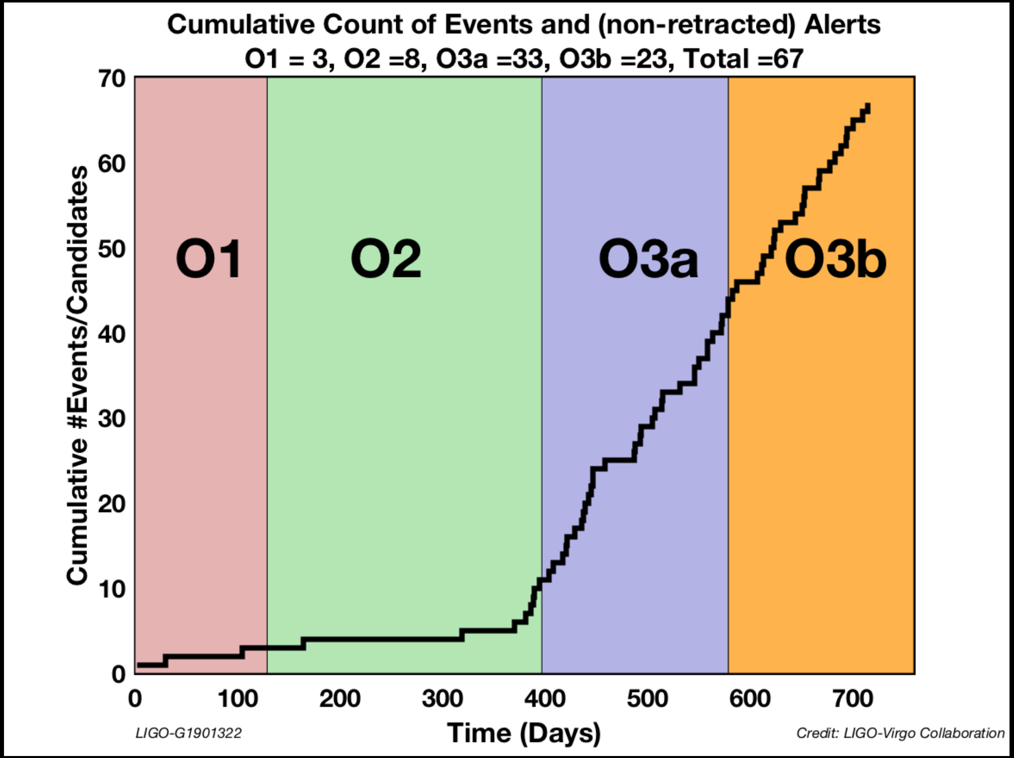


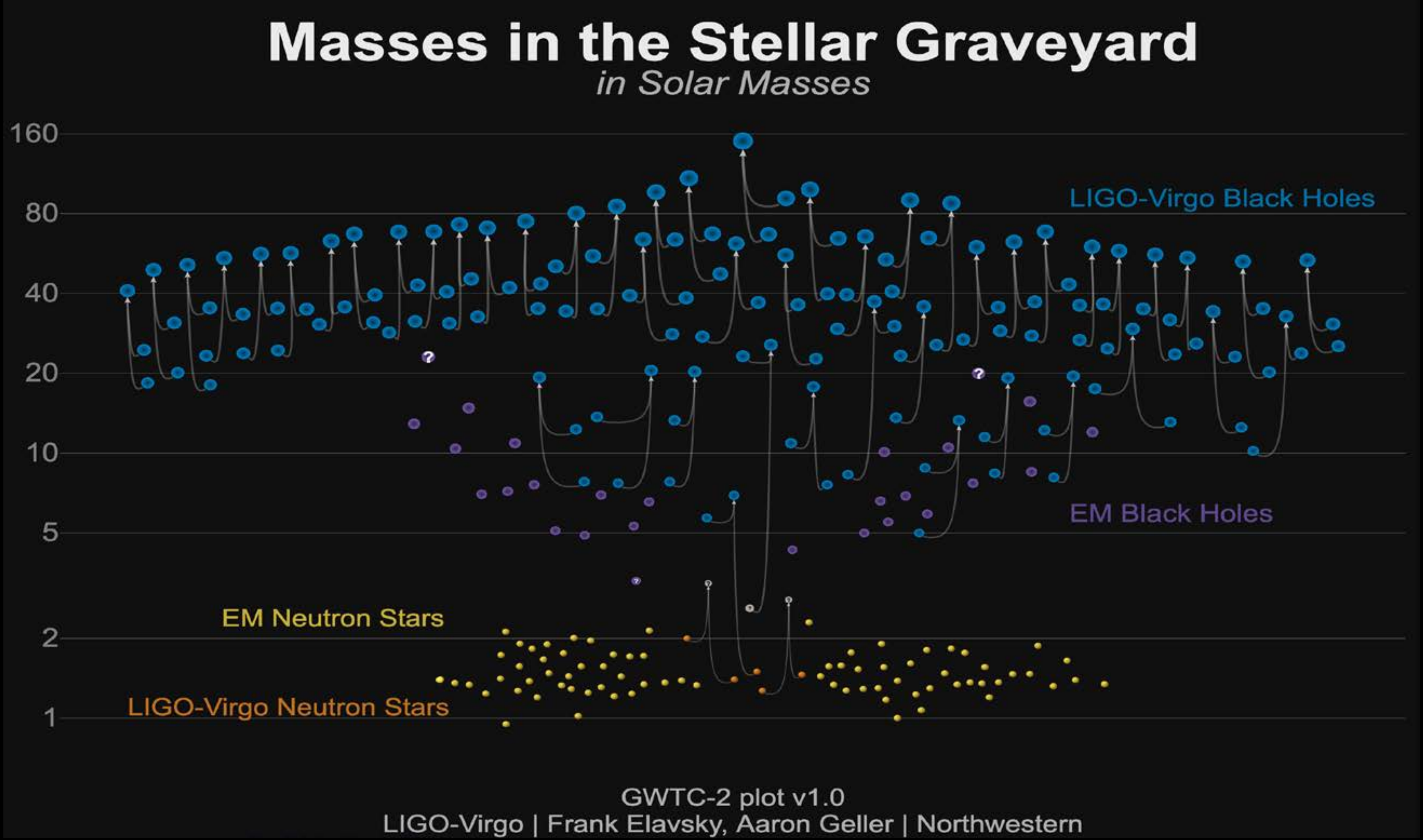




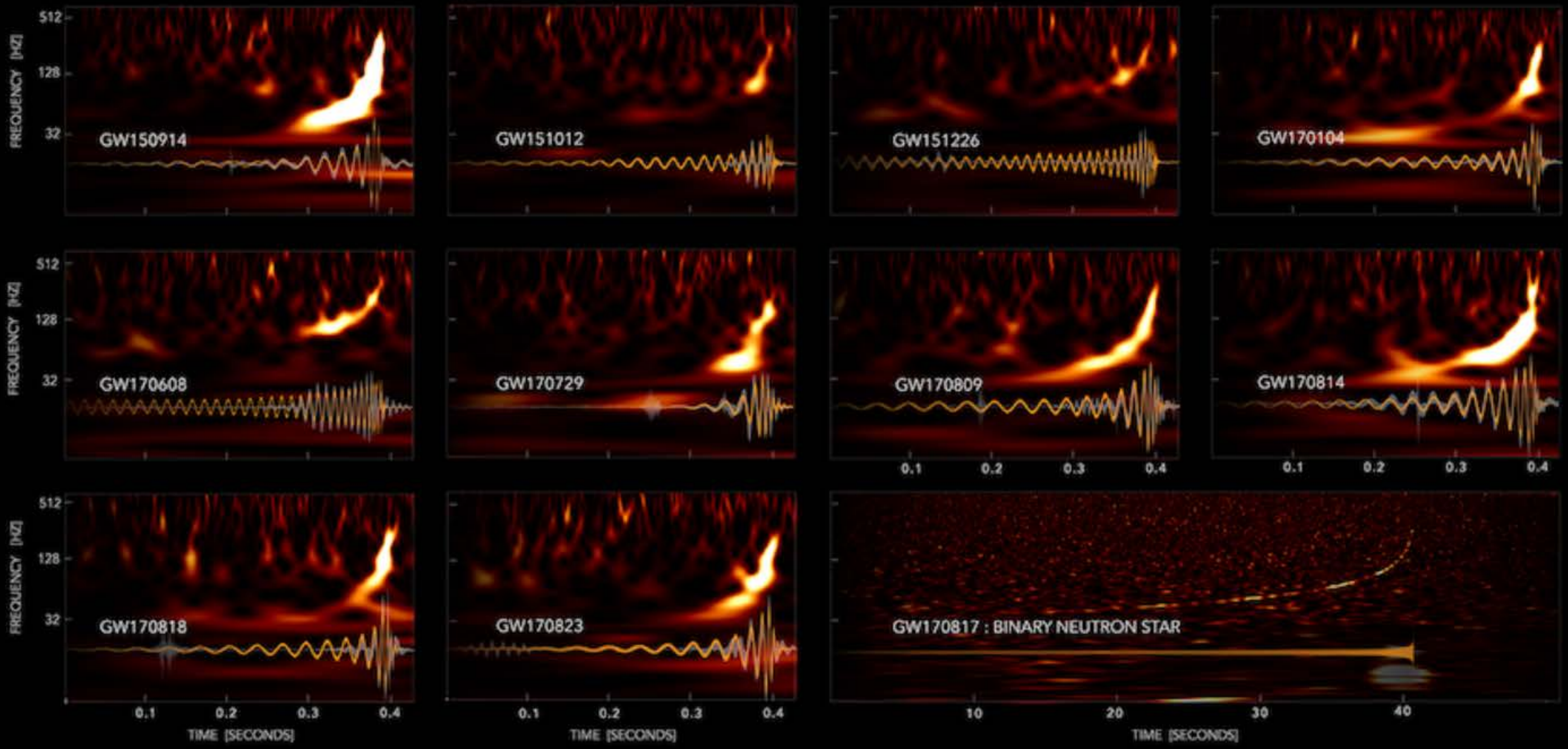
Observed Gravitational Wave Events

- 67 events total
- O1 3 events
- O2 8 events
- O3 56 events
- O4 next year → ~1 event/day




Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Observed Binary Mergers

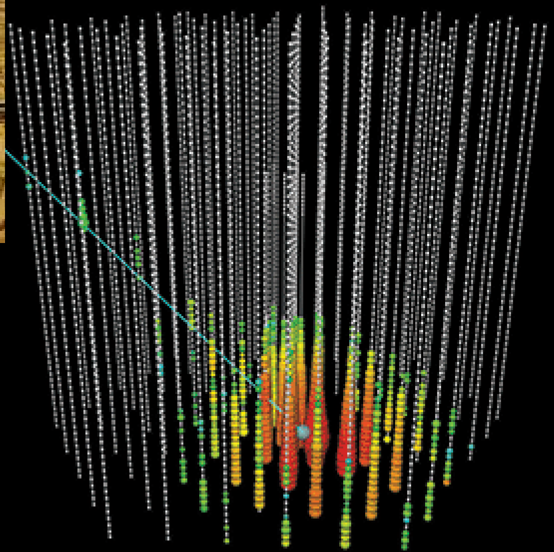


Next Frontier: Multimessenger Astronomy

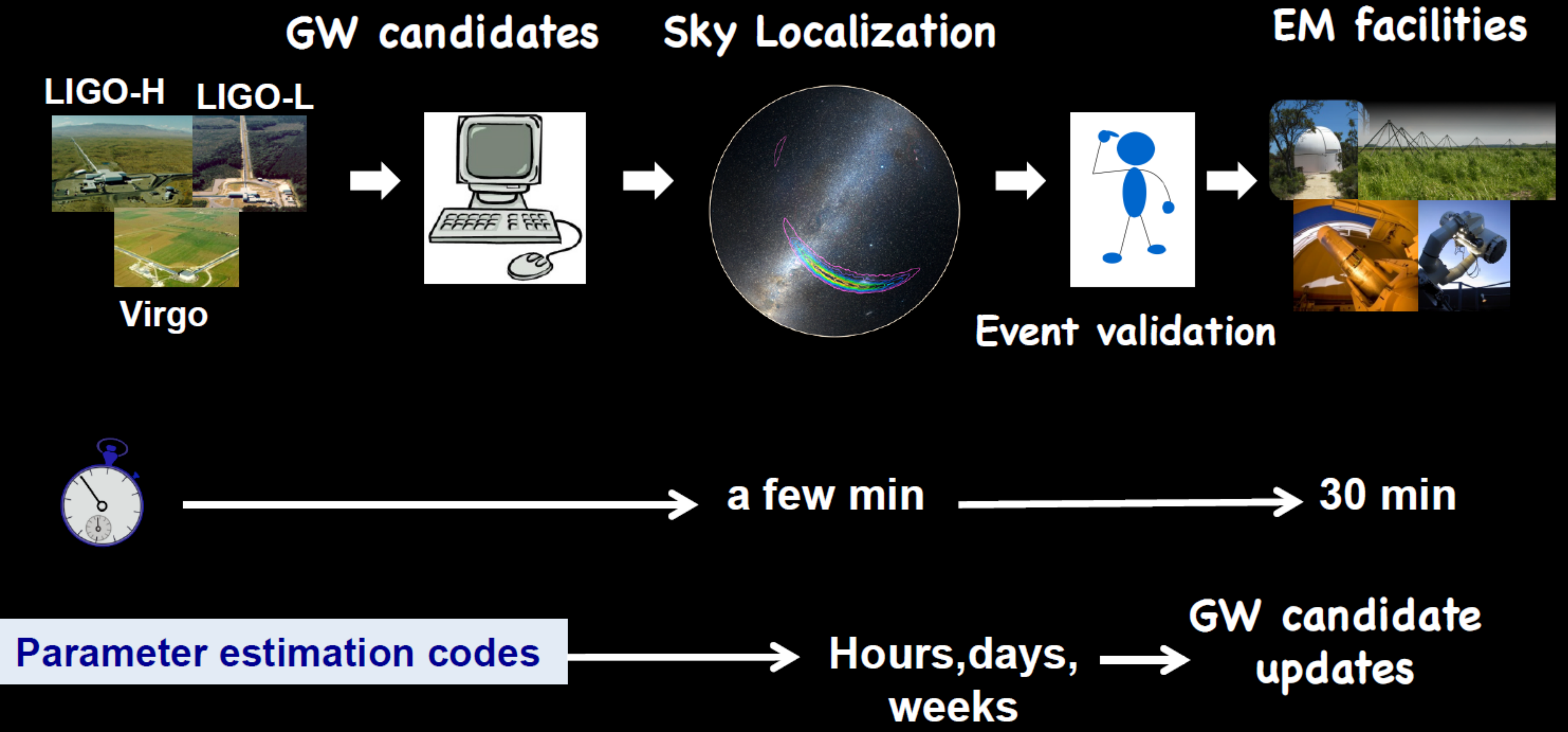
Gravitational Waves

Electromagnetic

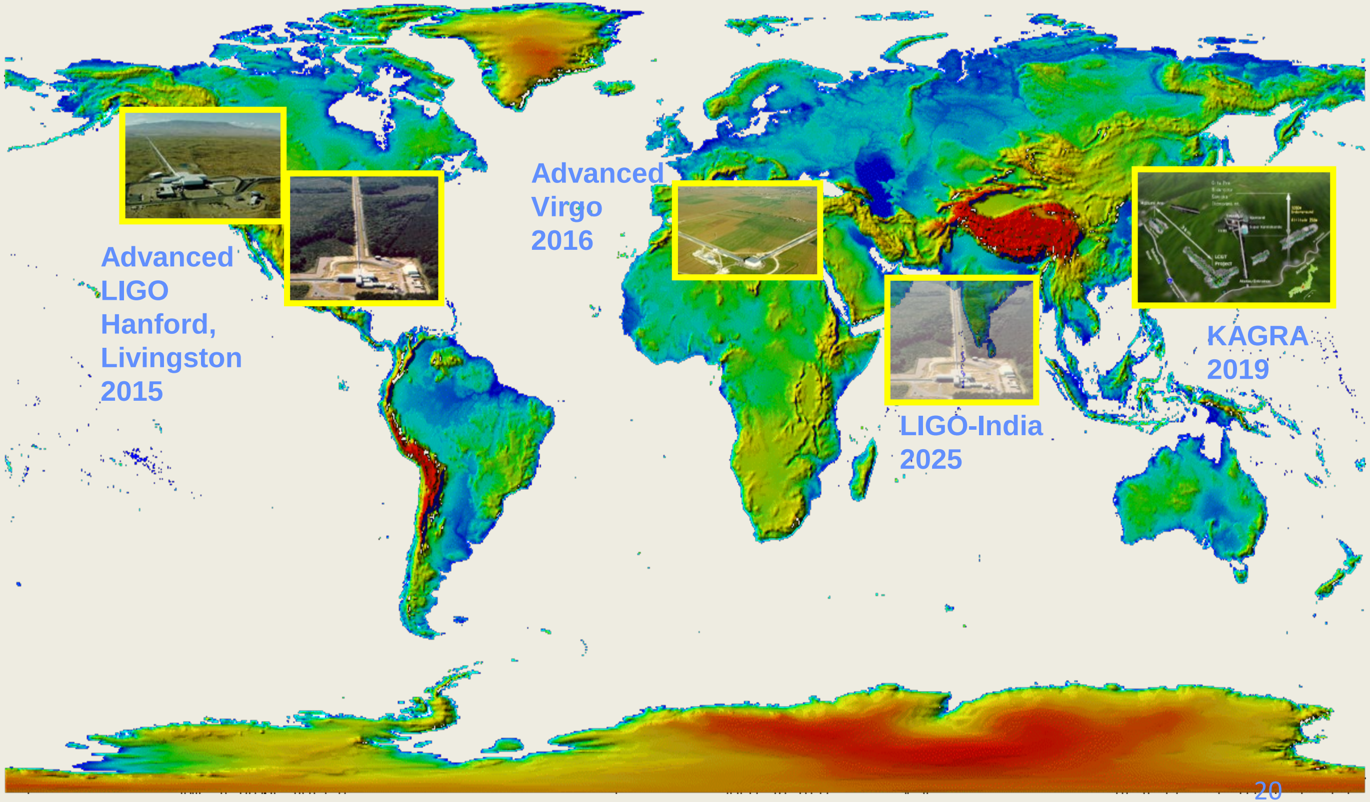
Neutrinos



Searching for Electromagnetic Counterparts



The Network in mid-2020’s



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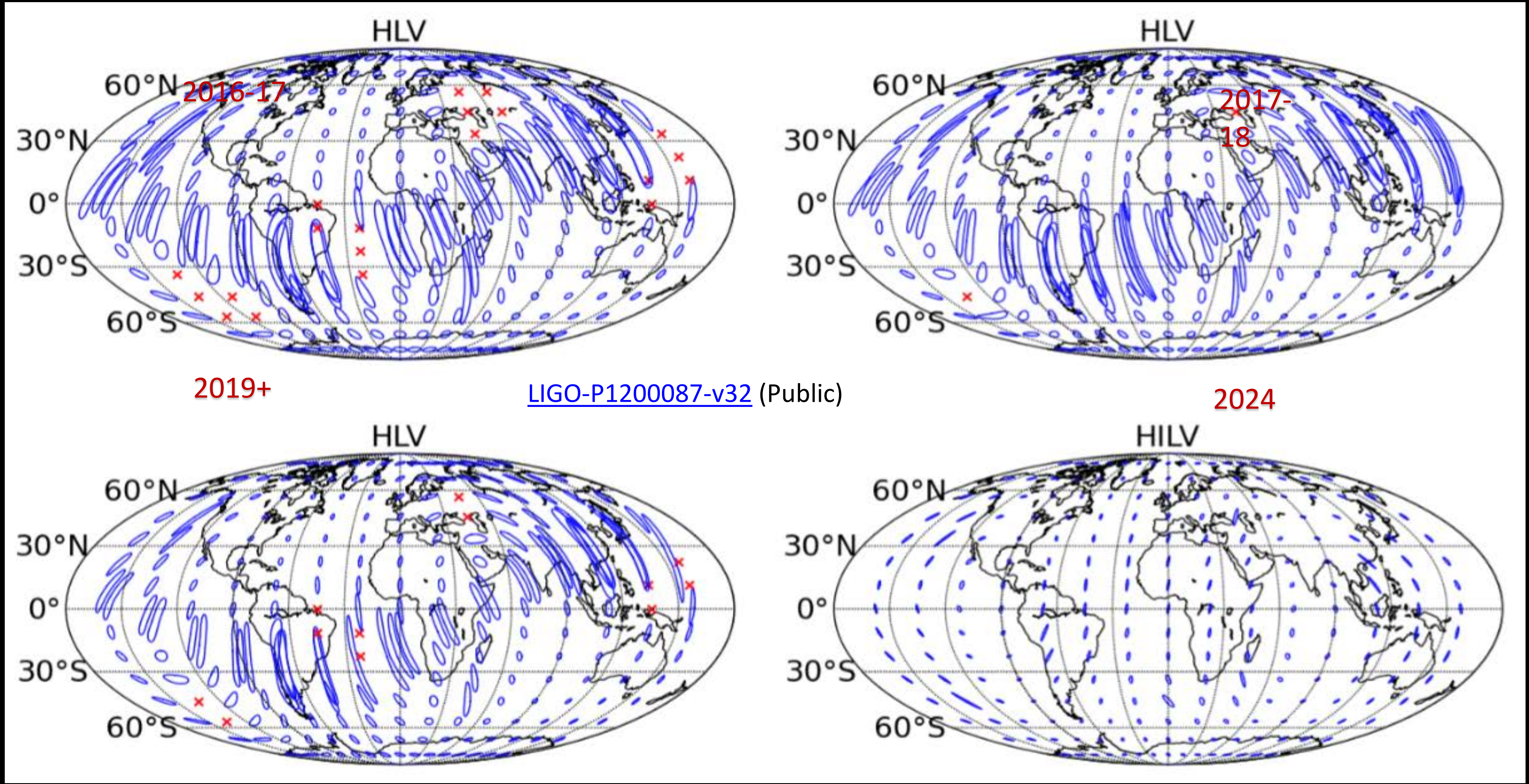
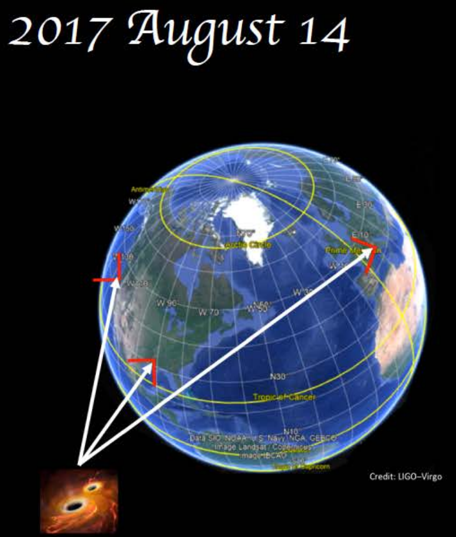
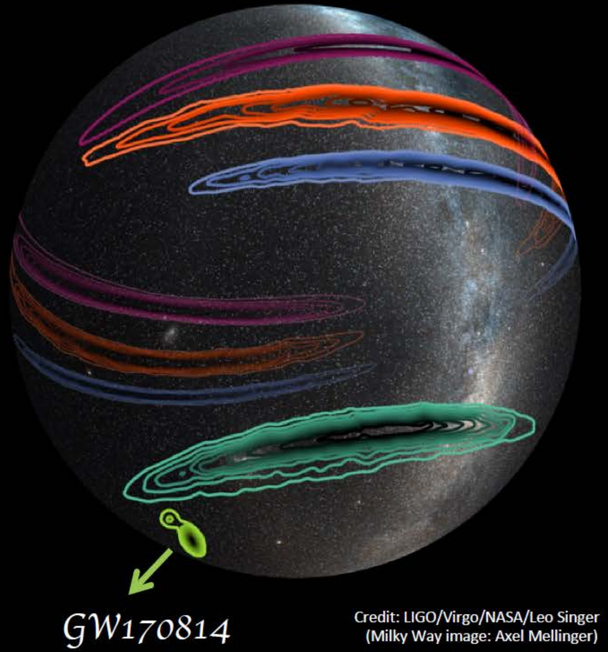
Improving Localization



Virgo Joins LIGO – August 14, 2017

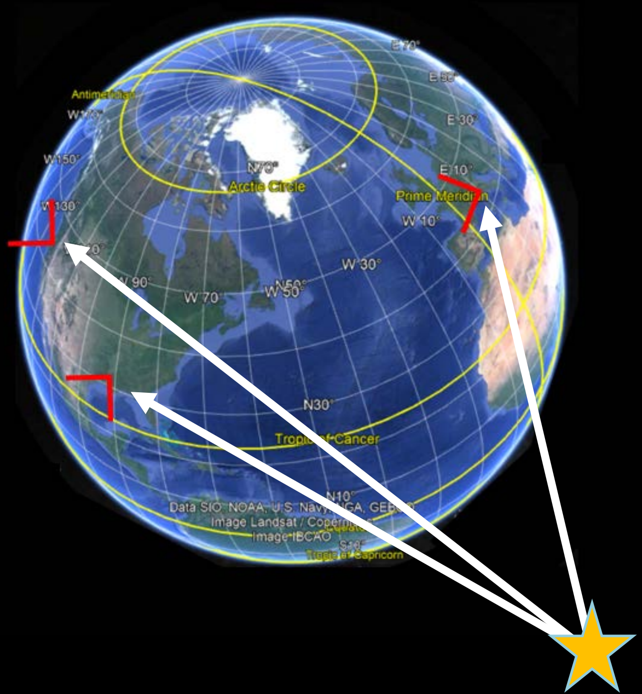




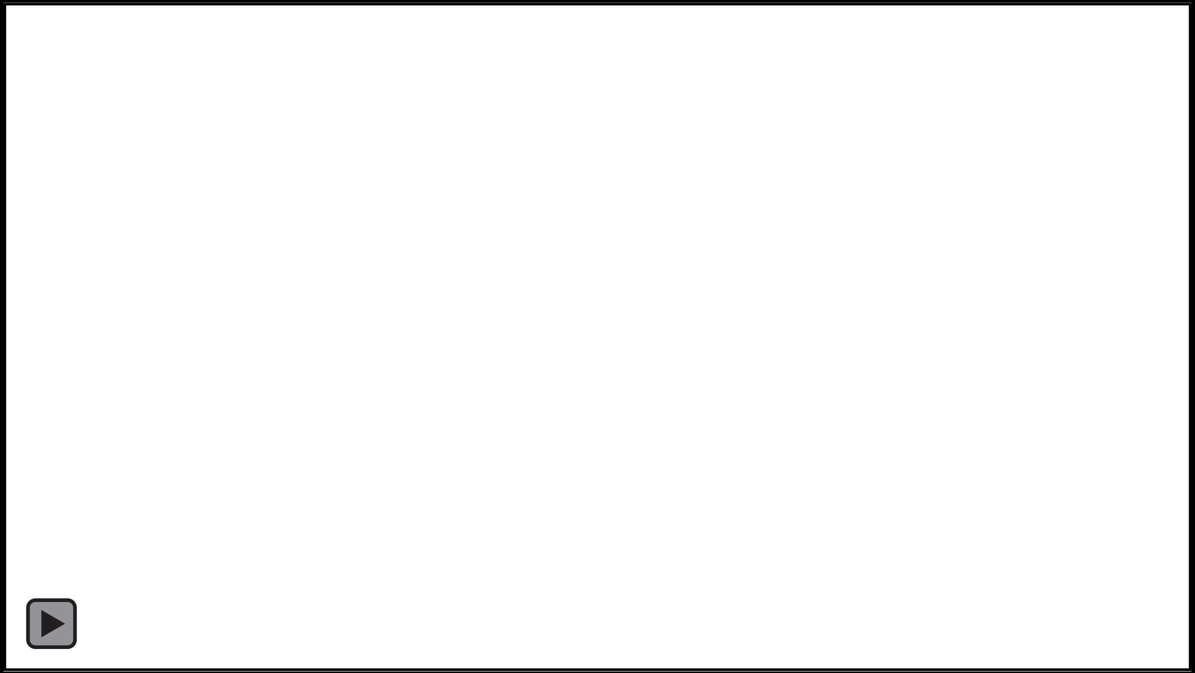
For all 10 reported Black Hole Binary Event NO Electromagnetic counterparts found !!

LH 1160 square degrees
LHV 60 square degrees

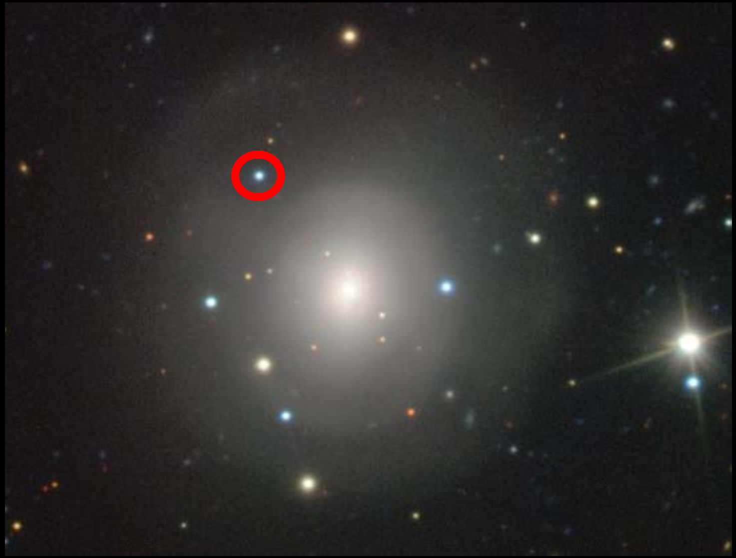
Localizing Gravitational-wave Events



By measuring the arrival time of the gravitational-wave at each observatory, it's possible to identify its location on the sky

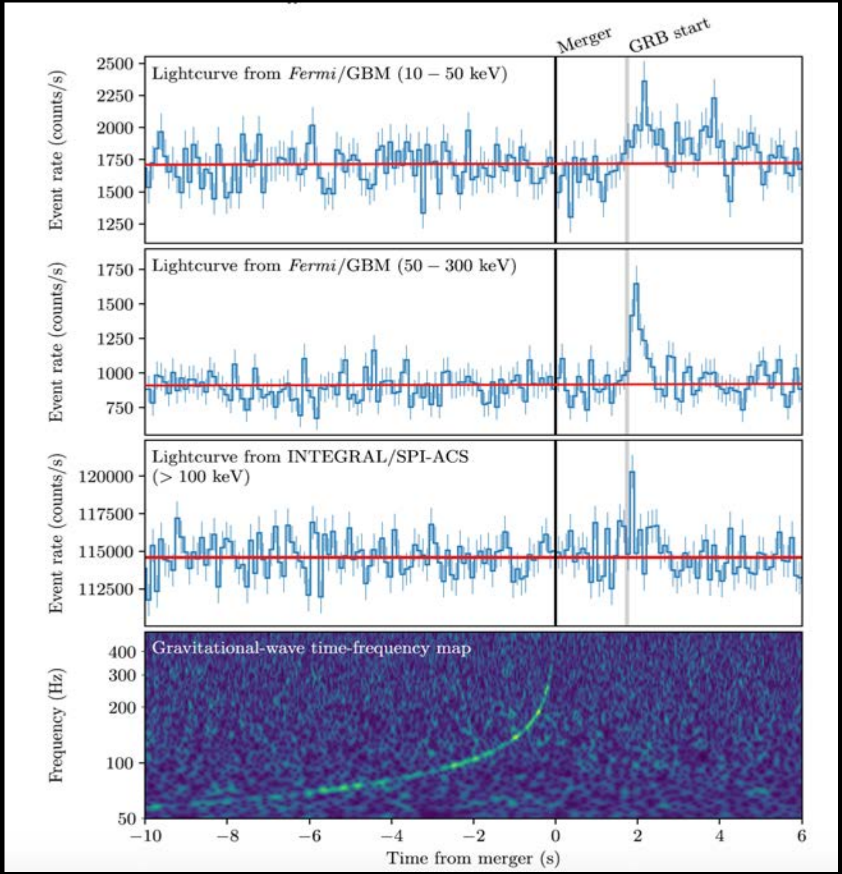


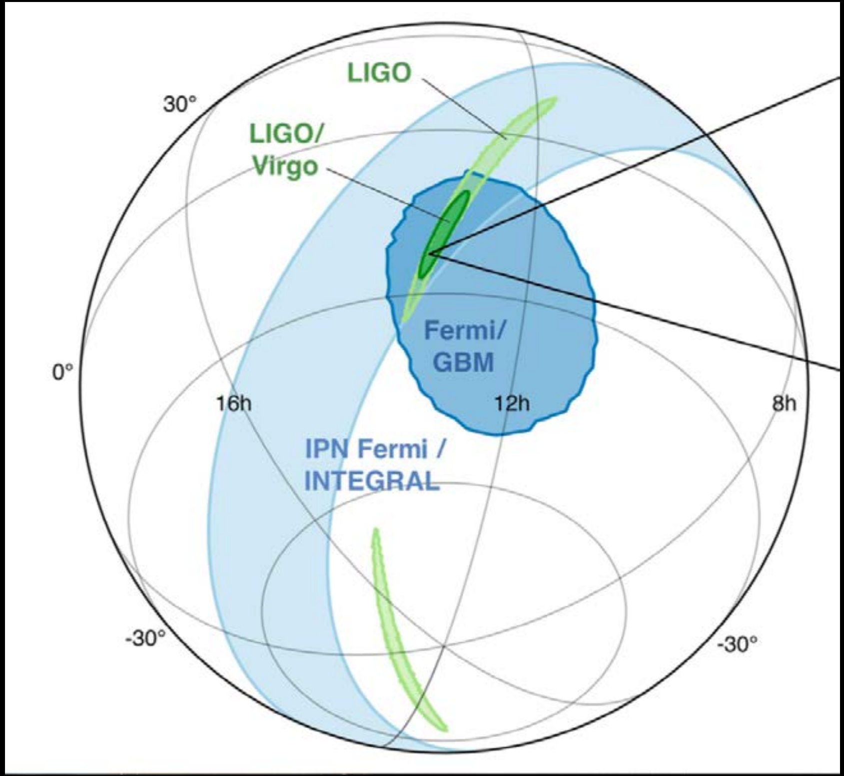
Credit: R. Hurt, Caltech IPAC



Galaxy NGC 4993

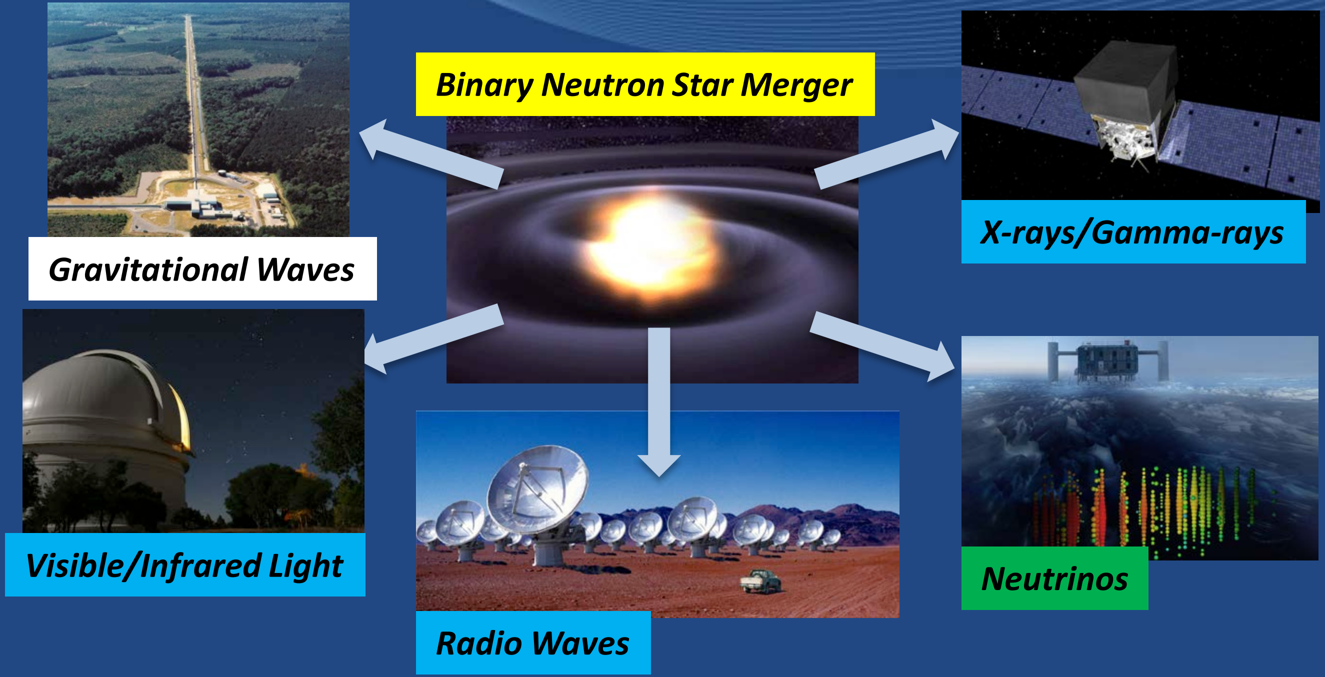
Fermi Satellite GRB detection 2 seconds later

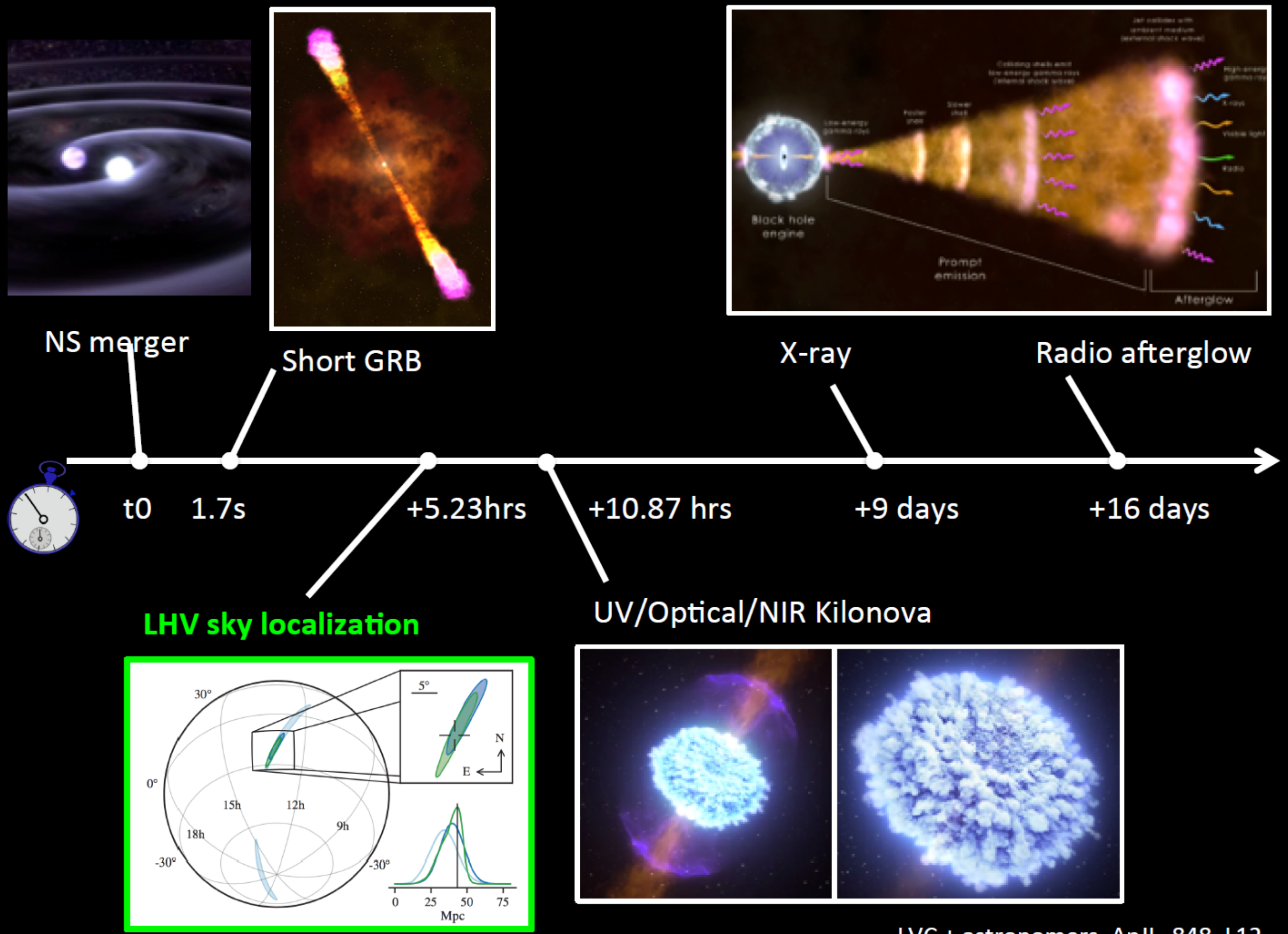




170817A" Astrophys. J. Lett., 848:L13, (2017)

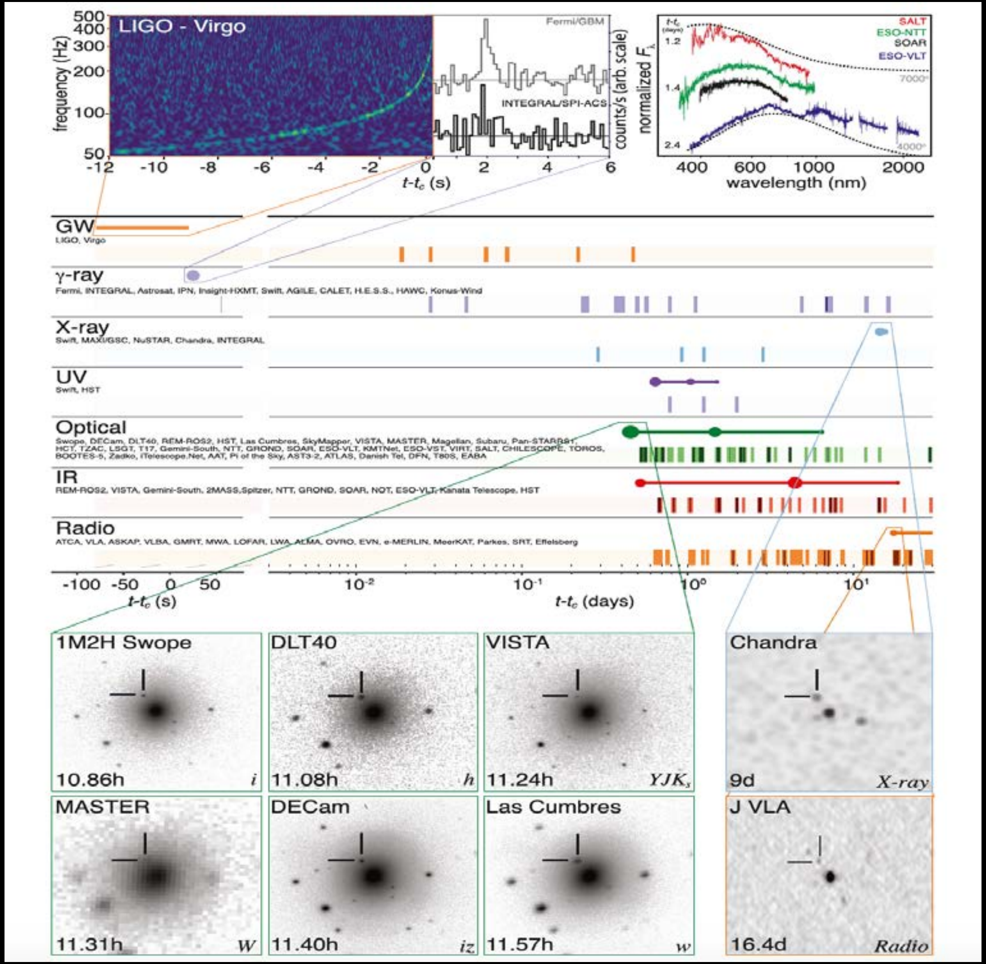
Multi-messenger Astronomy with Gravitational Waves

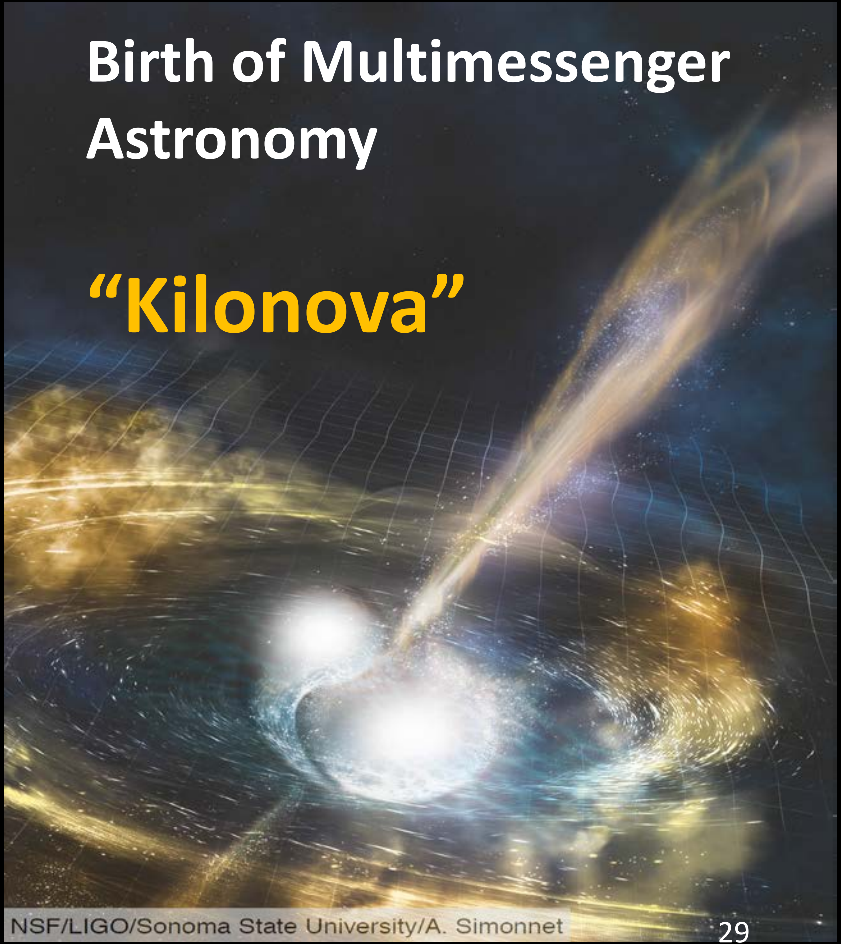




LVC + astronomers, ApJL, 848, L12

Observations Across the Electromagnetic Spectrum

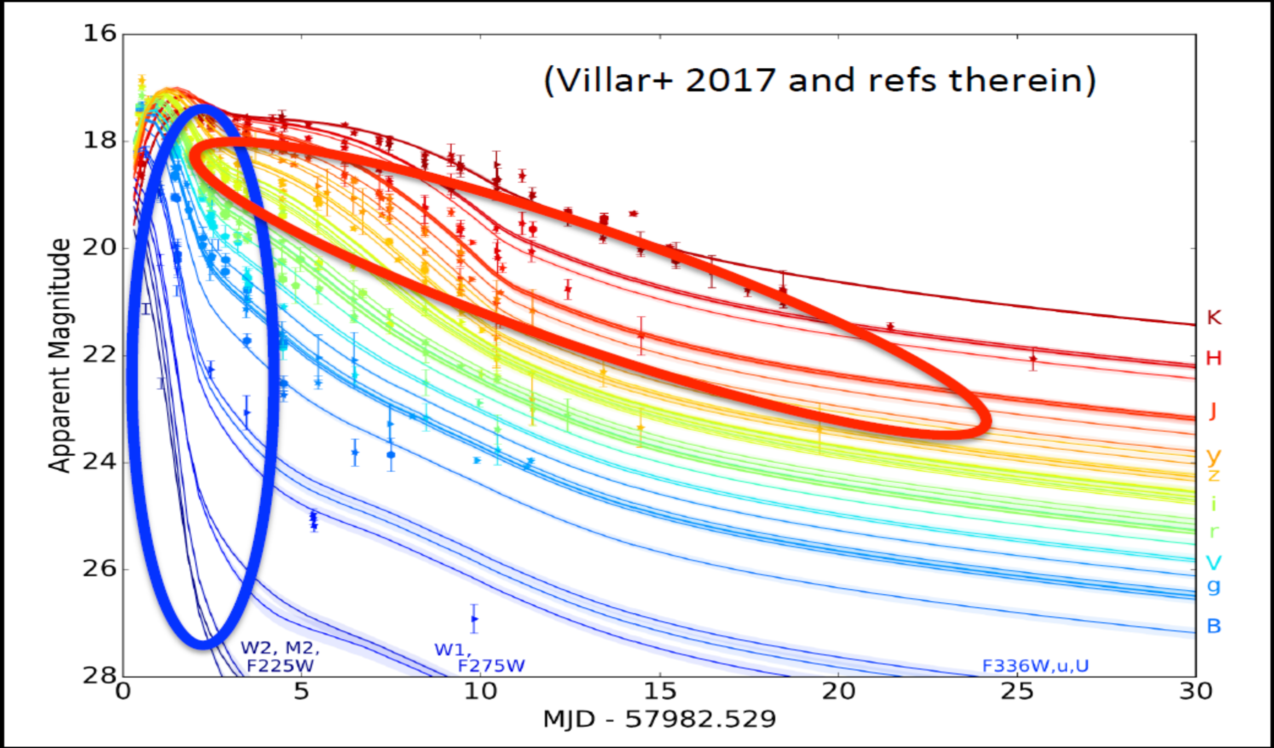




Birth of Multimessenger Astronomy

“Kilonova”

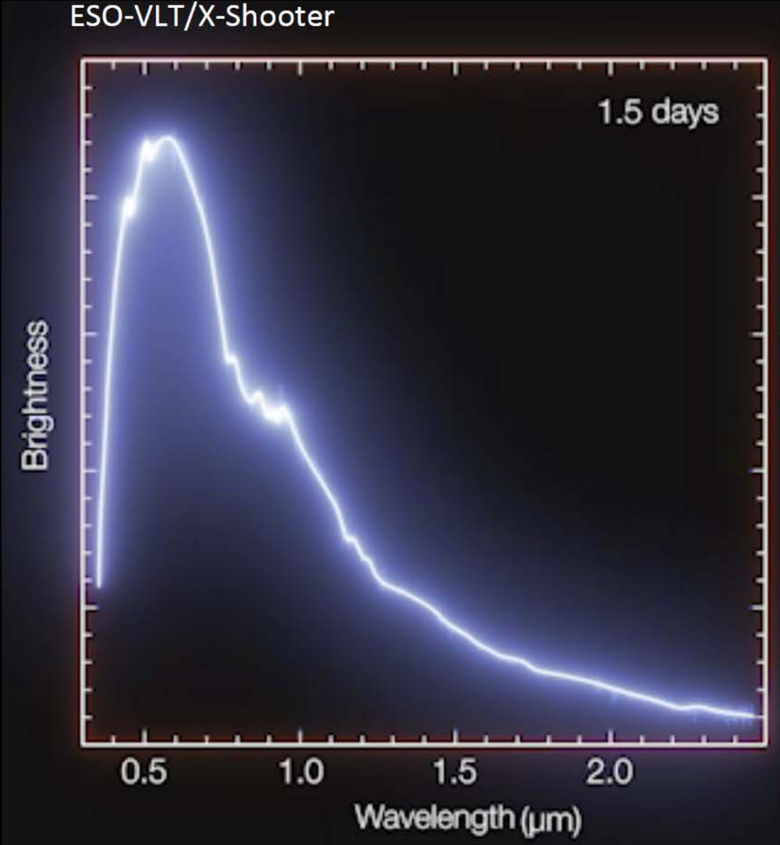
Light Curves



Extremely well characterized photometry of a Kilonova:

thermal emission by radiocative decay of heavy elements synthesized in multicomponent (2-3) ejecta!

Kilonova Emission



EJECTED MASS ~ 0.03 – 0.05 $M_\odot$

EXPANSION VELOCITY ~ 0.1 – 0.3 c

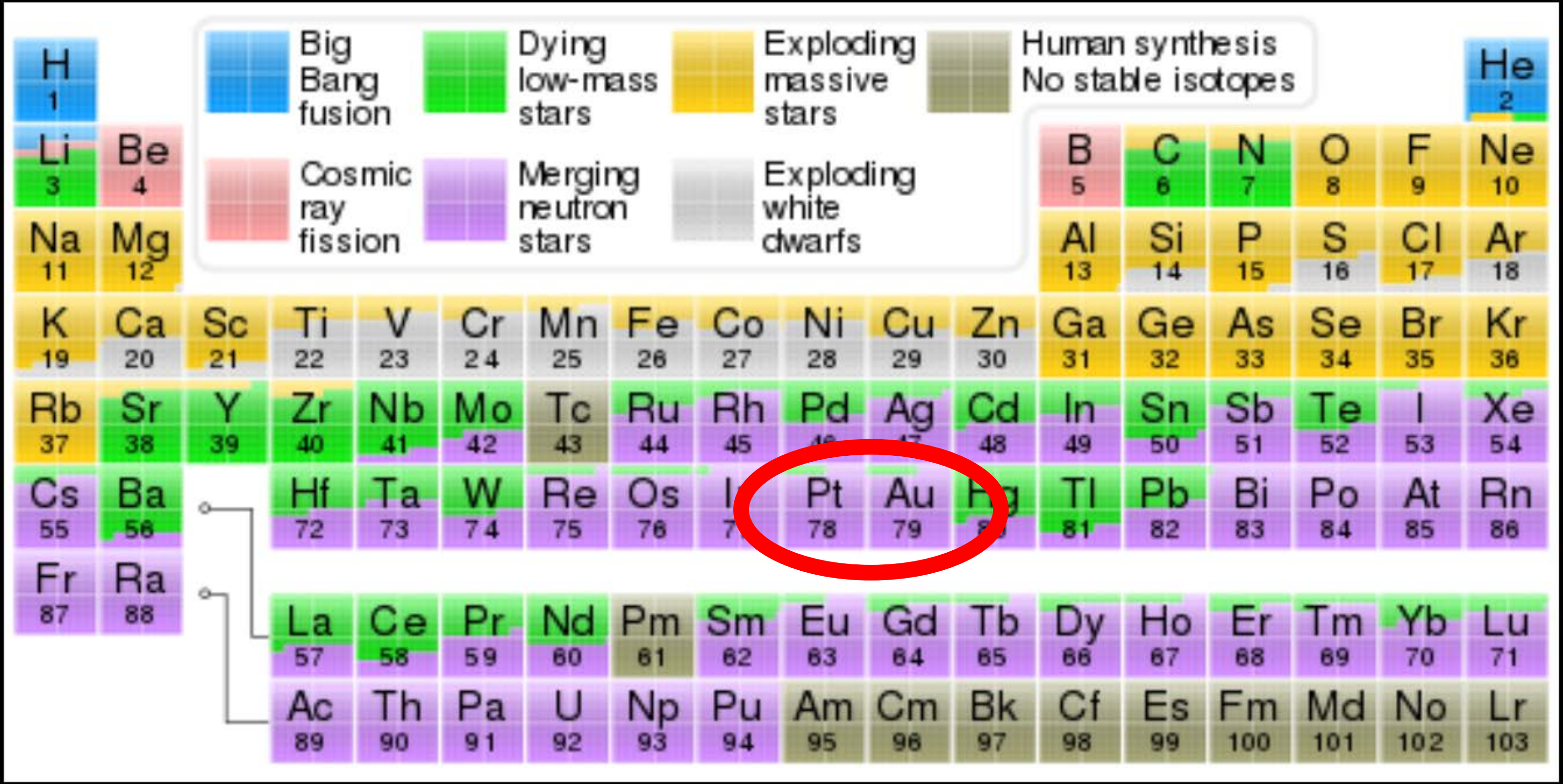
First spectral identification of the kilonova emission

- the data revealed signatures of the radioactive decay of **r-process nucleosynthesis**
  (Pian et al. 2017, Smartt et al. 2017)

- BNS merger **site for heavy element production in the Universe!**
  (Cote et al. 2018, Rosswog et al. 2017)

Credit: ESO/E. Pian et al./S. Smartt & ePESSTO/L. Calçada

Origin of the Heavy Elements

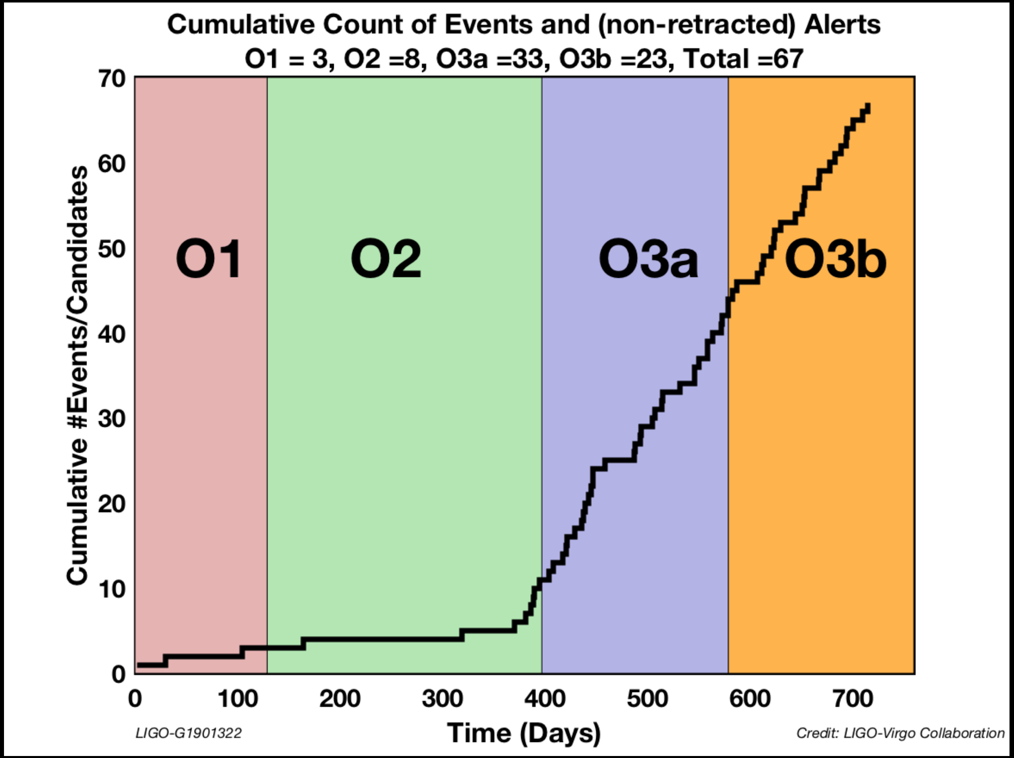


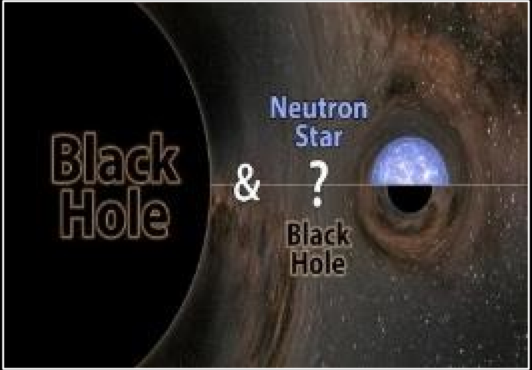
NS Mergers are Incredible Gold Factories

LIGO observed Neutron Star Merger produced ~ 100 Earth Masses of Gold

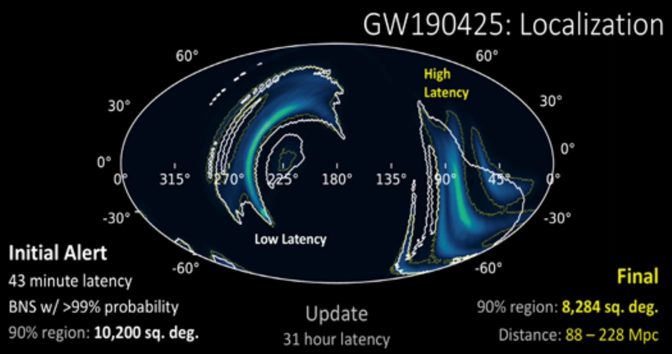
Observed Gravitational Wave Events

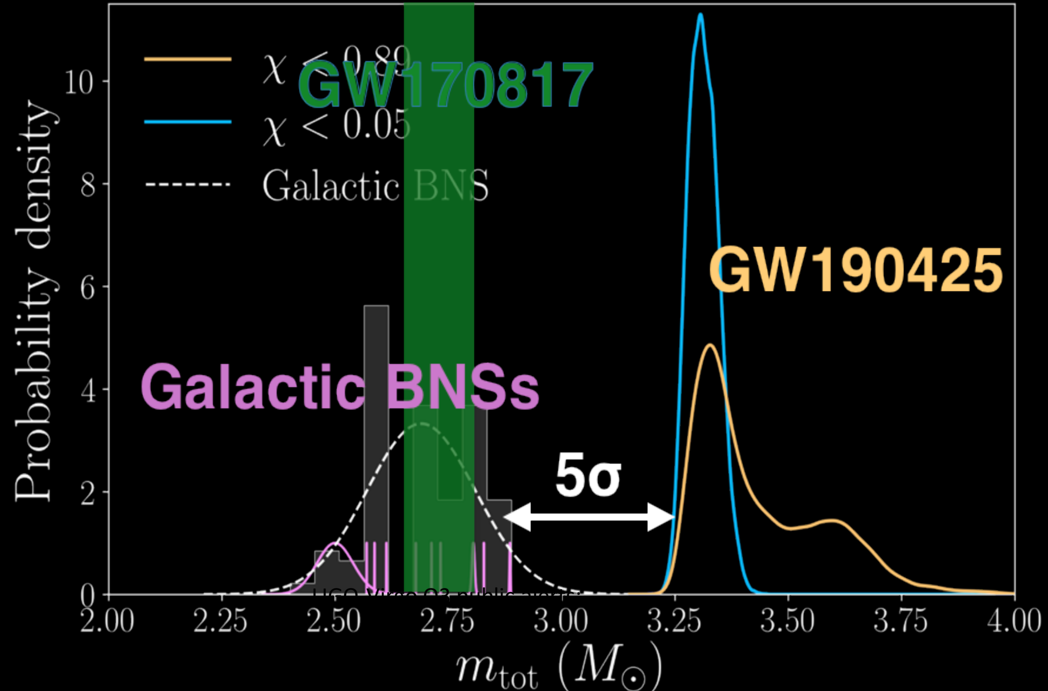
- 67 events total
- O1 3 events
- O2 8 events
- O3 56 events
- O4 next year → ~1 event/day





Exceptional Events





The signal was detected by only the LIGO Livingston interferometer

The event has an estimated total mass of 3.4 M_{sun}

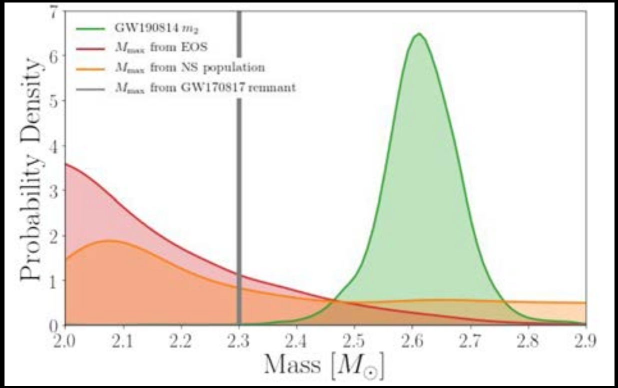
The combined mass of the neutron stars is greater than all known neutron star binaries (galactic, GW170817)

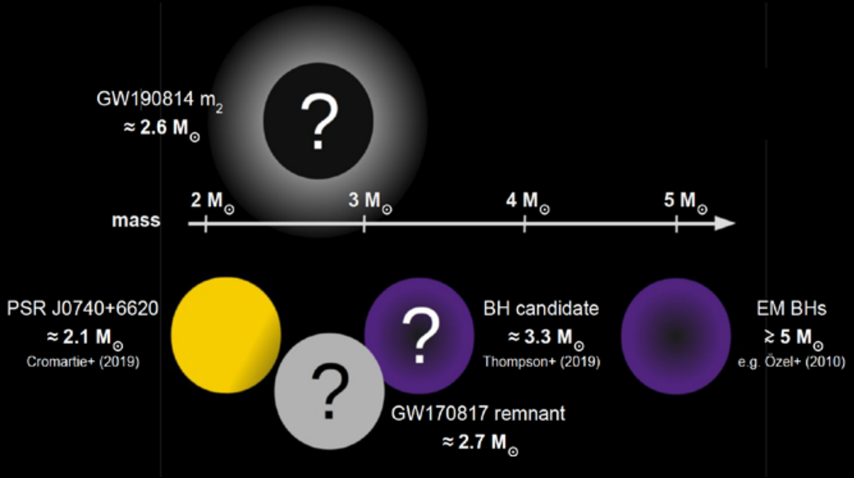
LIGO

Mystery Merger: GW190814

(Aug 14, 2018)

- The most asymmetric mass ratio merger ever observed, with a mass ratio $m_1/m_2 = 9$
- The secondary mass of 2.6 M_sun lies in a *'mass gap'*;
  - » it's greater than estimates the maximum possible NS mass and less than masses of the lightest black holes ever observed
  - » Comparable to the final merger product in GW170817, which was more likely a black hole.
- How did this system form? Like GW190425, this detection again challenges existing binary formation scenarios
  - » young dense star clusters and disks around active galactic nuclei are favored, but many other possibilities
- Many follow up observations by electromagnetic observatories, but no confirmed counterpart found

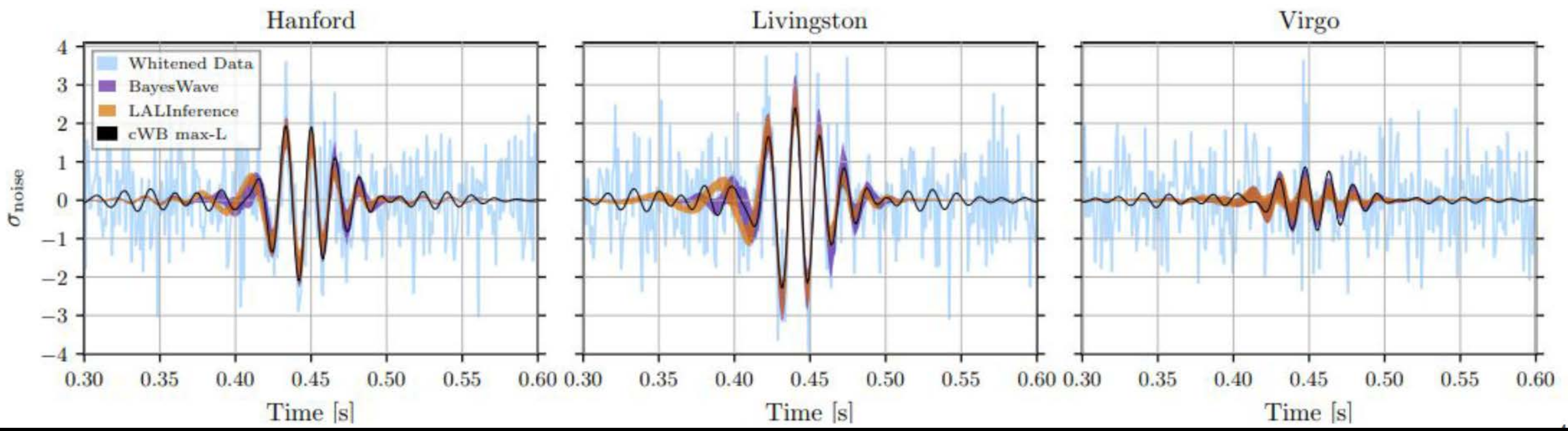


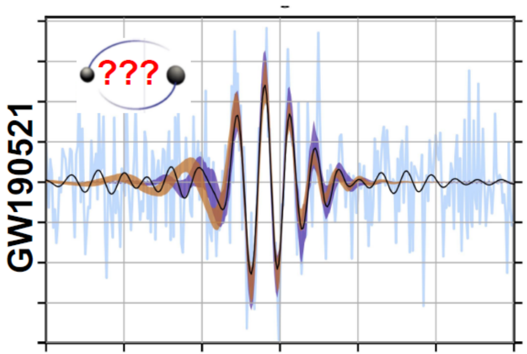


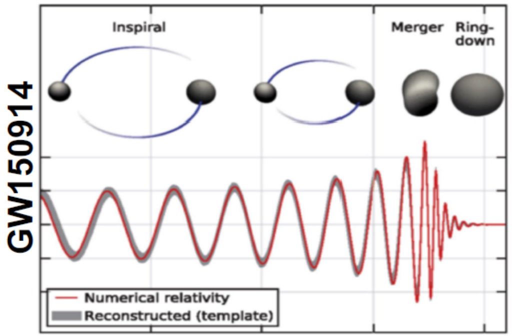
Exceptional Events

GW190521: Binary Black Hole Merger ? – Total Mass = 150 $M_\odot$

Properties and astrophysical implications of the 150 $M_\odot$ binary black hole merger GW190521







- Very short duration (~0.1 s)
- Low peak frequency (~60 Hz)

⇨ Massive source

- Standard scenario: quasi-circular BBH merger

  Very short inspiral signal

- Alternative scenarios may be explored:

  Eccentric Binary, Head-on merger

  Cosmic String

The Most Massive and Distant Black Hole Merger Yet: GW190521

(May 21, 2019)

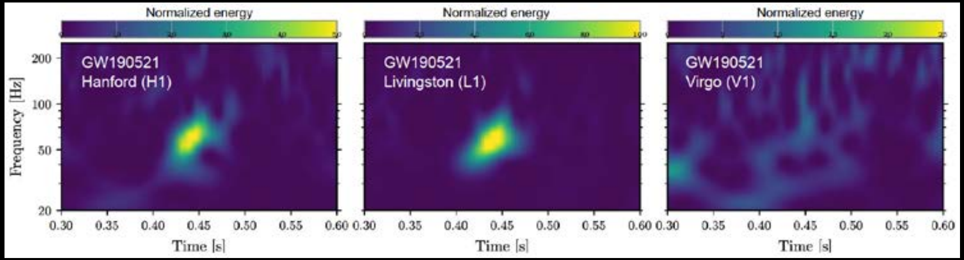
- The furthest GW event ever recorded: ~ 7 Glyr distant

- At least one of the progenitor black holes (85 M_{sun}) lies in the pair instability supernova gap
  - » Stars with helium cores in the mass range 64 - 135 M_{sun} undergo an instability and obliterate upon explosion

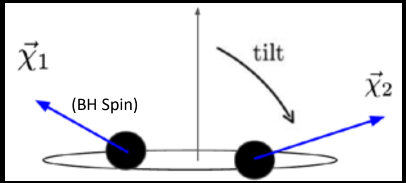
- The final black hole mass (85 M_{sun}) places it firmly in the intermediate mass category (between $10^2 – 10^5$ M_{sun}) → *the first ever observation of an intermediate mass black hole*

- Strong evident for spin precession; both progenitor black holes were spinning

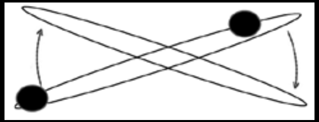
→ Implications for how these black holes formed

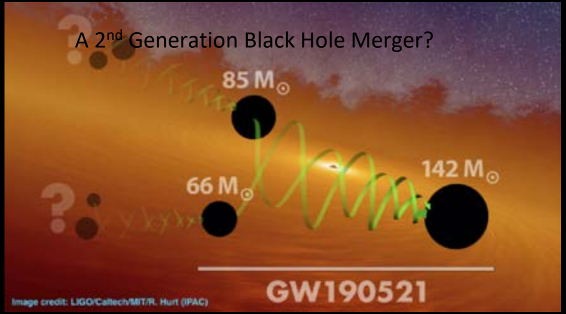


Orbital Angular Momentum



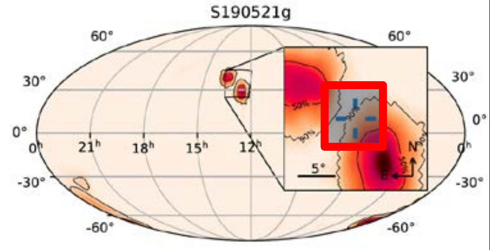
Orbital Plane Precession

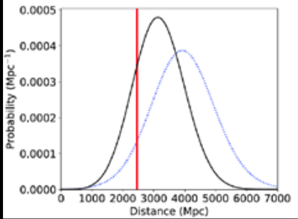


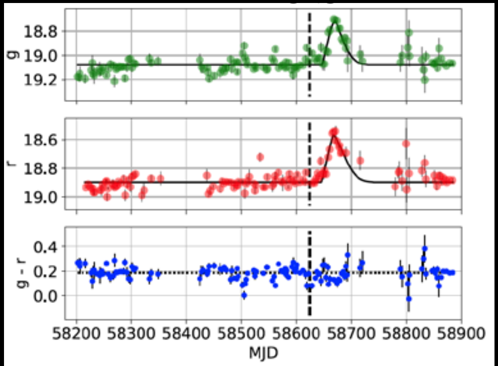


A Possible Electromagnetic Counterpart to GW1901521

- Zwicky Transient Facility surveyed 48% of the LIGO-Virgo 90% error box for GW190521
- An electromagnetic flare in the visible was found within the initial 90% LIGO-Virgo contour beginning ~ 25 days after GW190521, lasting for ~ 100 days
  - » Consistent with LIGO-Virgo initial distance estimates
  - » But less consistent with updated maps
- The EM flare is consistent with emission from gas in the accretion disk an active galactic nucleus (AGN) excited by the 'kicked' black hole passing through the AGN disk
- Graham, et al. estimate the final black hole mass to be ~ 100 M_{sun} with significant spin







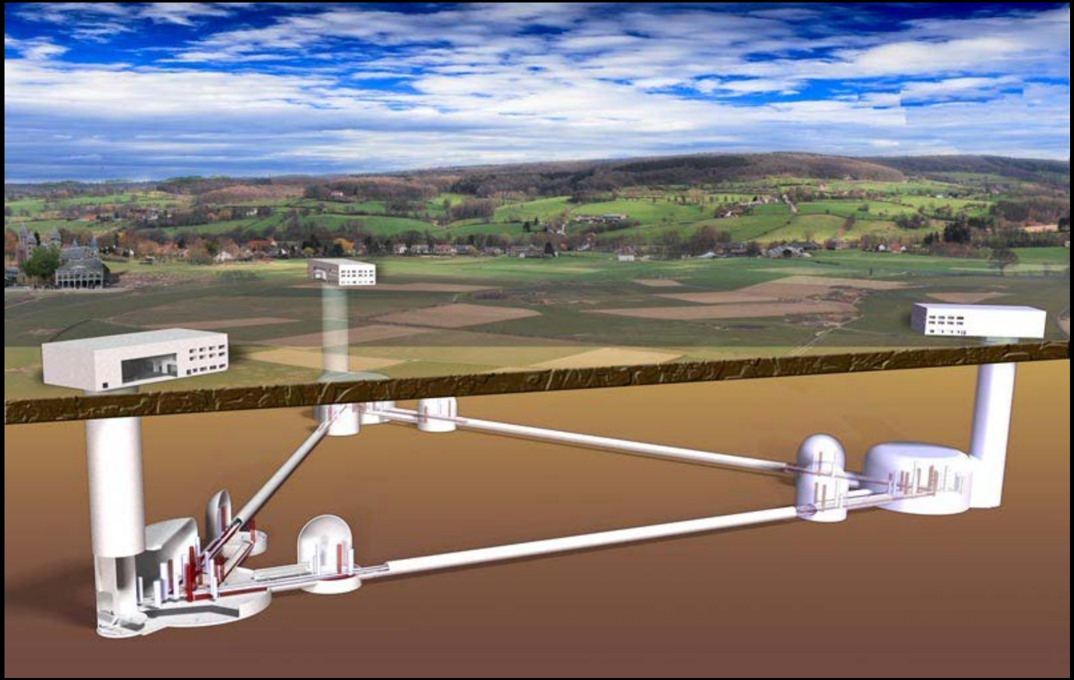
Graham, et al., "Candidate Electromagnetic Counterpart to the Binary Black Hole Merger Gravitational-Wave Event S190521g*, Phys. Rev. Lett. 124, 251102 (2020).

Proposed 3rd Generation Detectors

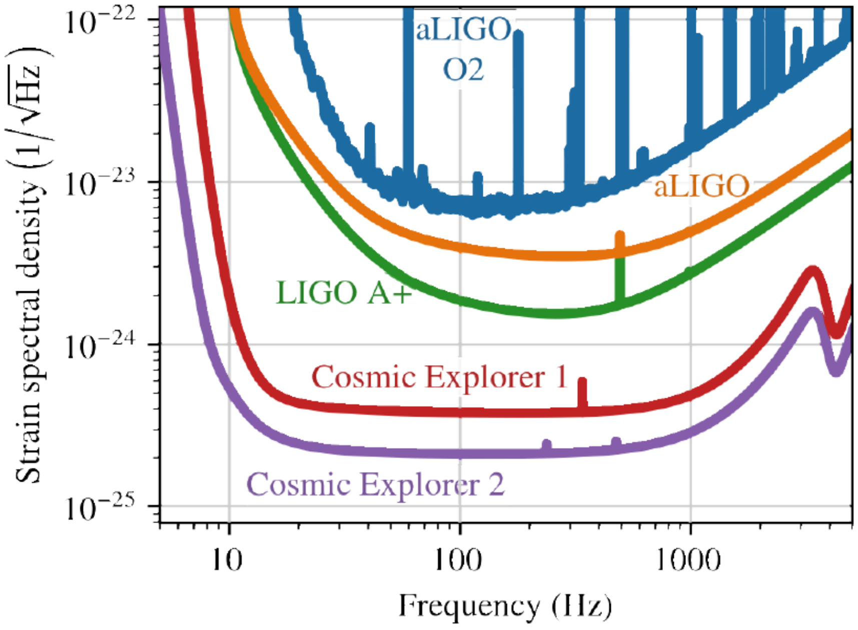
Einstein Telescope 10 km

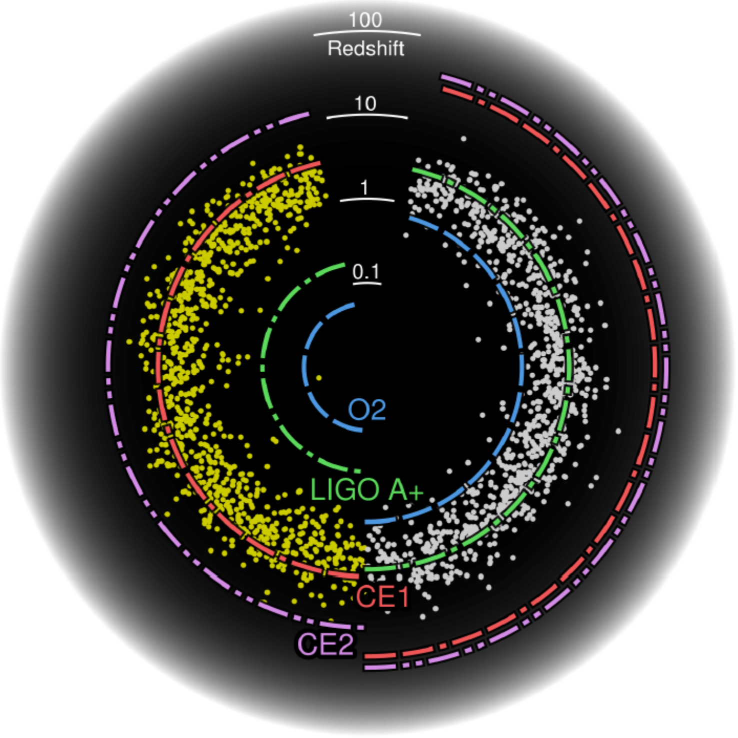
The Einstein Telescope: x10 aLIGO

- Deep Underground;
- 10 km arms
- Triangle (polarization)
- Cryogenic
- Low frequency configuration
- high frequency configuration

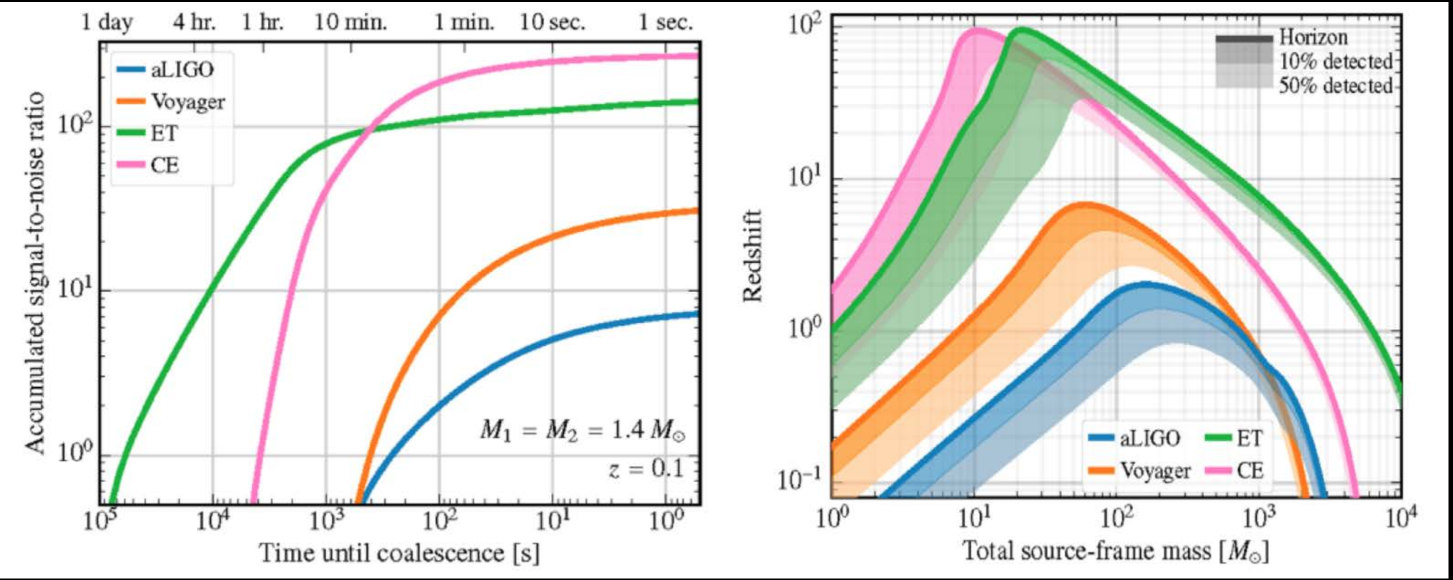


Exploring Binary Systems with Increased Sensitivity

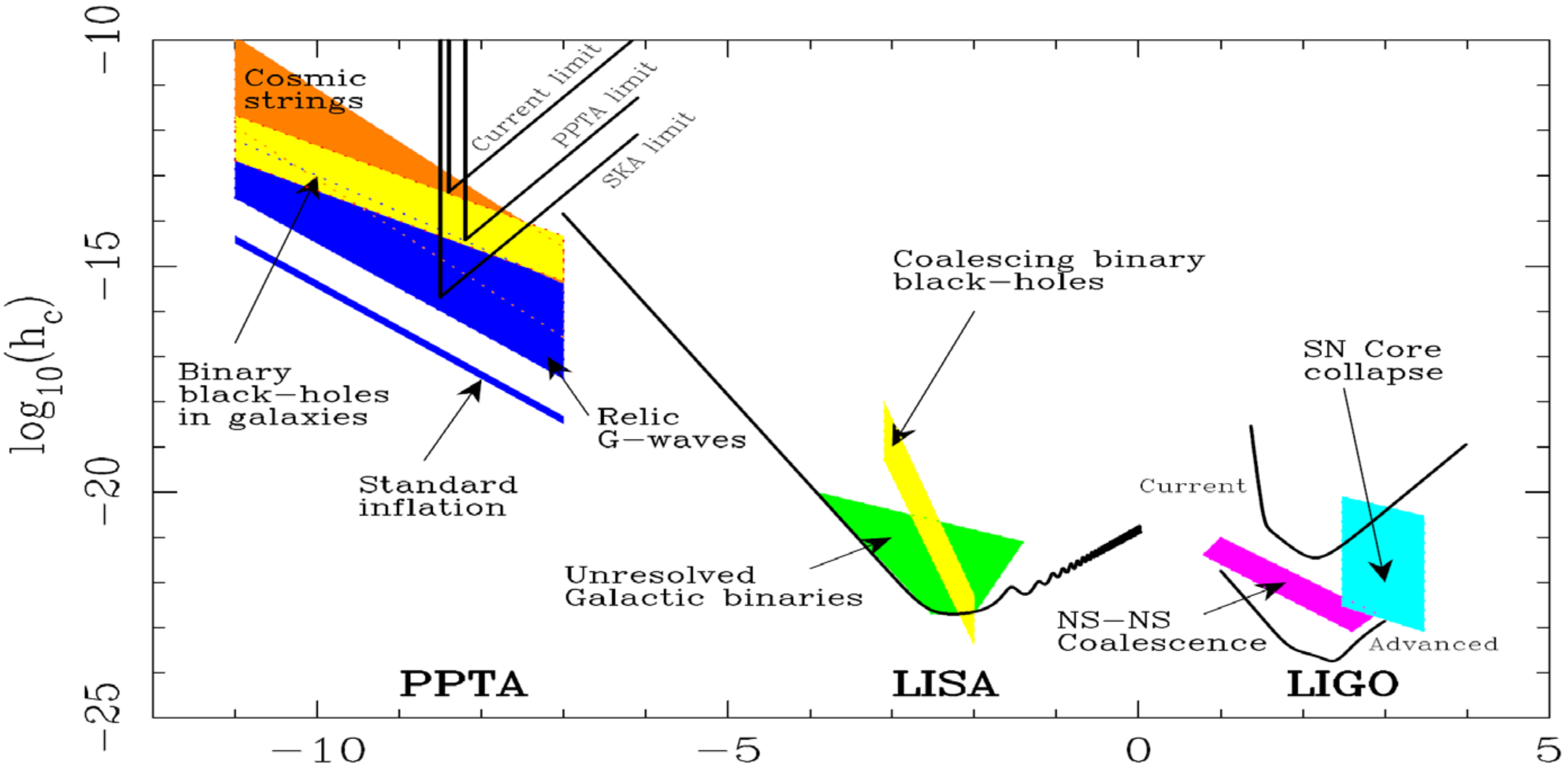




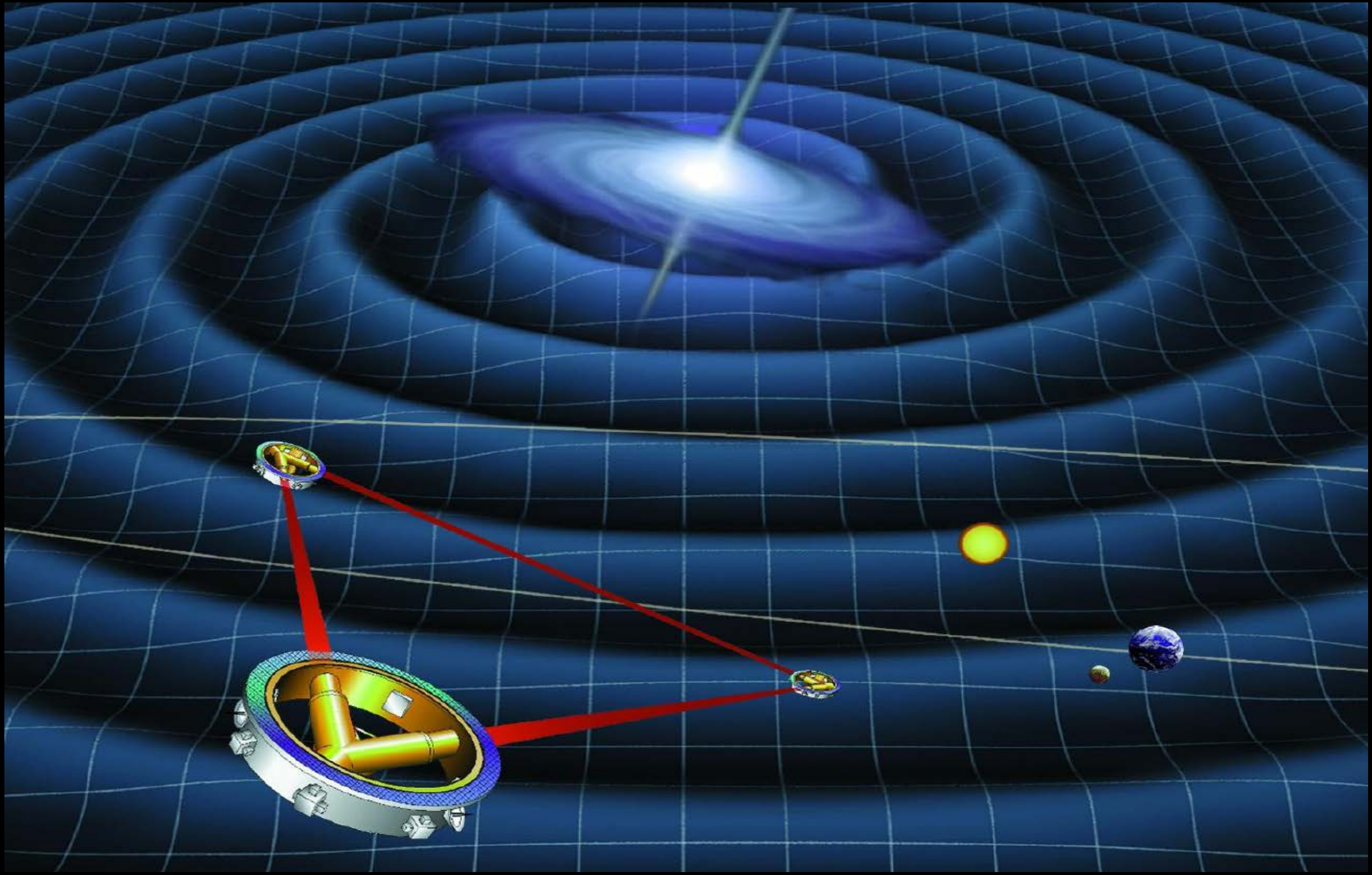
Cosmology with Gravitational Waves



Gravitational Wave Frequency Coverage



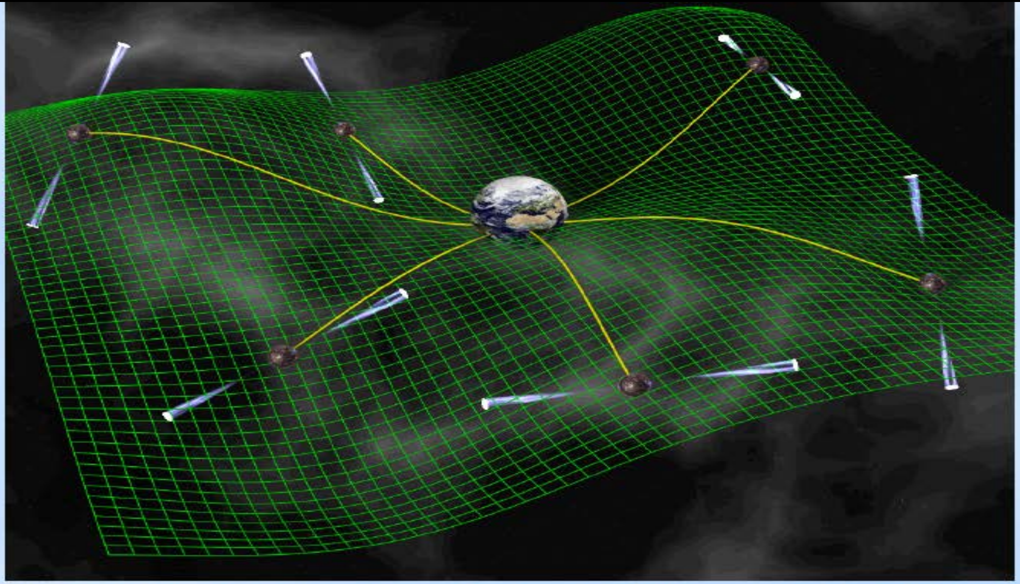
LISA: Laser Interferometer Space Array



Three Interferometers

2.5 10^6 km arms

Pulsar Timing Arrays



Distant pulsars send regular radio pulses – highly accurate clocks.
A passing gravitational wave would change the arrival time of the pulse.

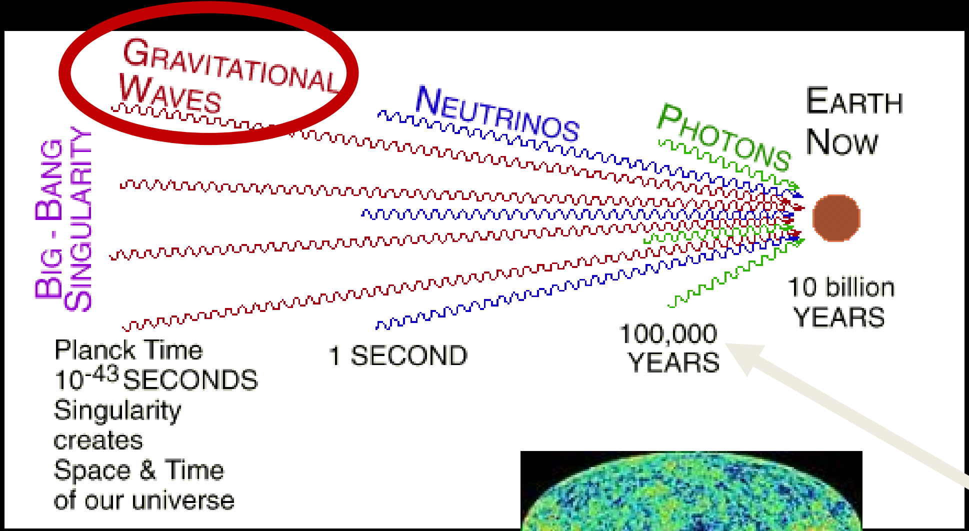
Numerous collaborations around the world. Interesting upper limits and likely detections in the near future.

66

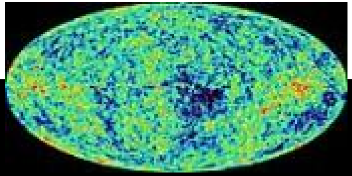
arXiv:1211.4590

Signals from the Early Universe

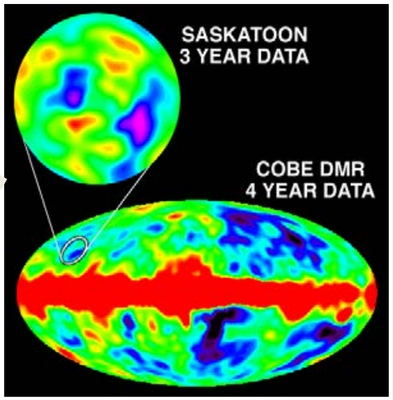
stochastic background



Cosmic Microwave background



WMAP



Thanks !