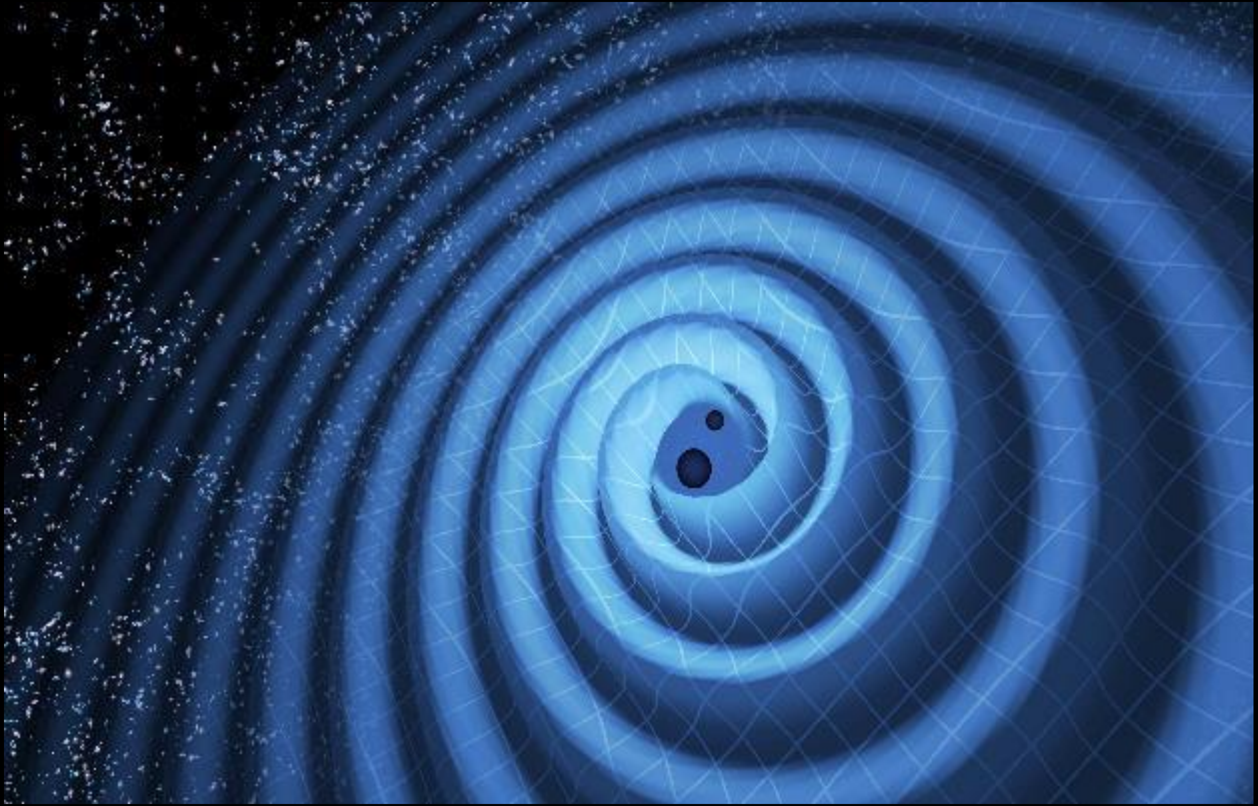
Gravitational Waves: From Einstein to a New Science



Barry C Barish

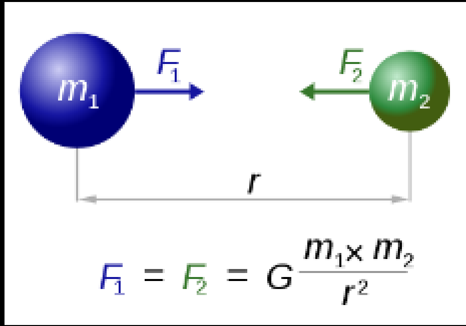
Caltech/UC Riverside

19-Feb-2023

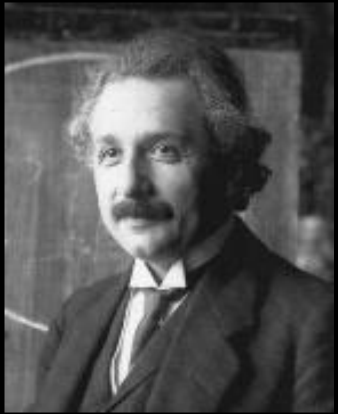
NICOLAUS COPERNICUS WORLD CONGRESS

General Relativity and Gravitational Waves

Newton's Theory of Gravity (1687)



<u>Universal Gravity</u>: force between massive objects is directly proportional to the product of their masses, and inversely proportional to the square of the distance between them.



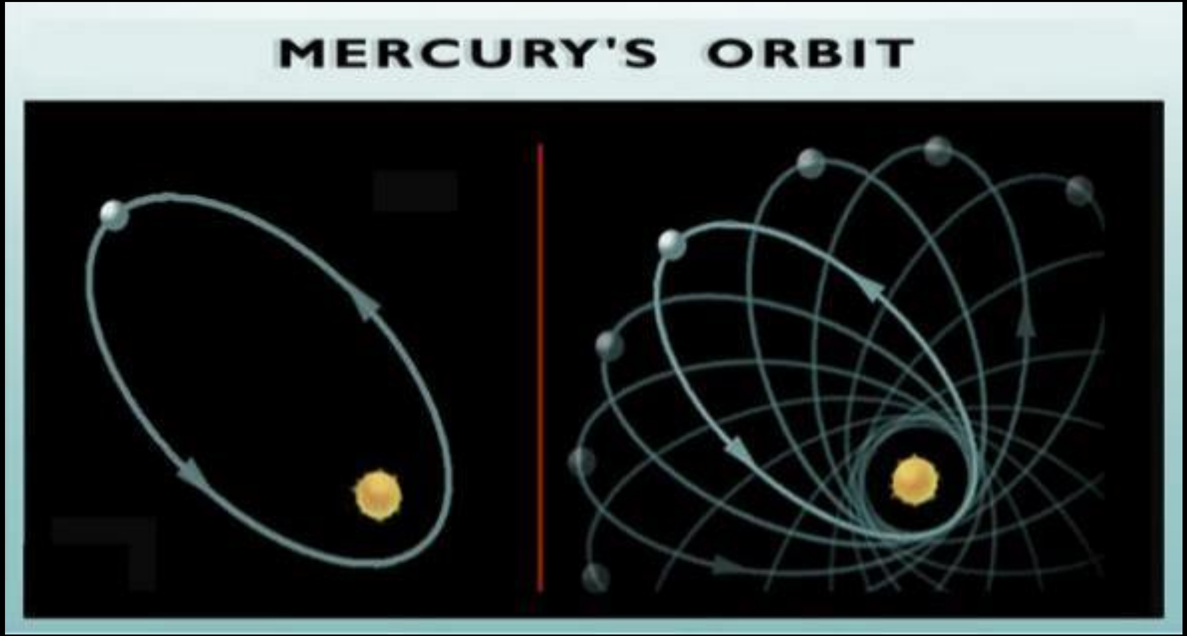
Einstein's Theory of Gravity (1915)

$$G_{ab} \equiv R_{ab} - \frac{1}{2}g_{ab}R = \frac{8\pi G}{c^4}T_{ab}$$

Space *and* Time are ***unified*** in a four dimensional

spacetime

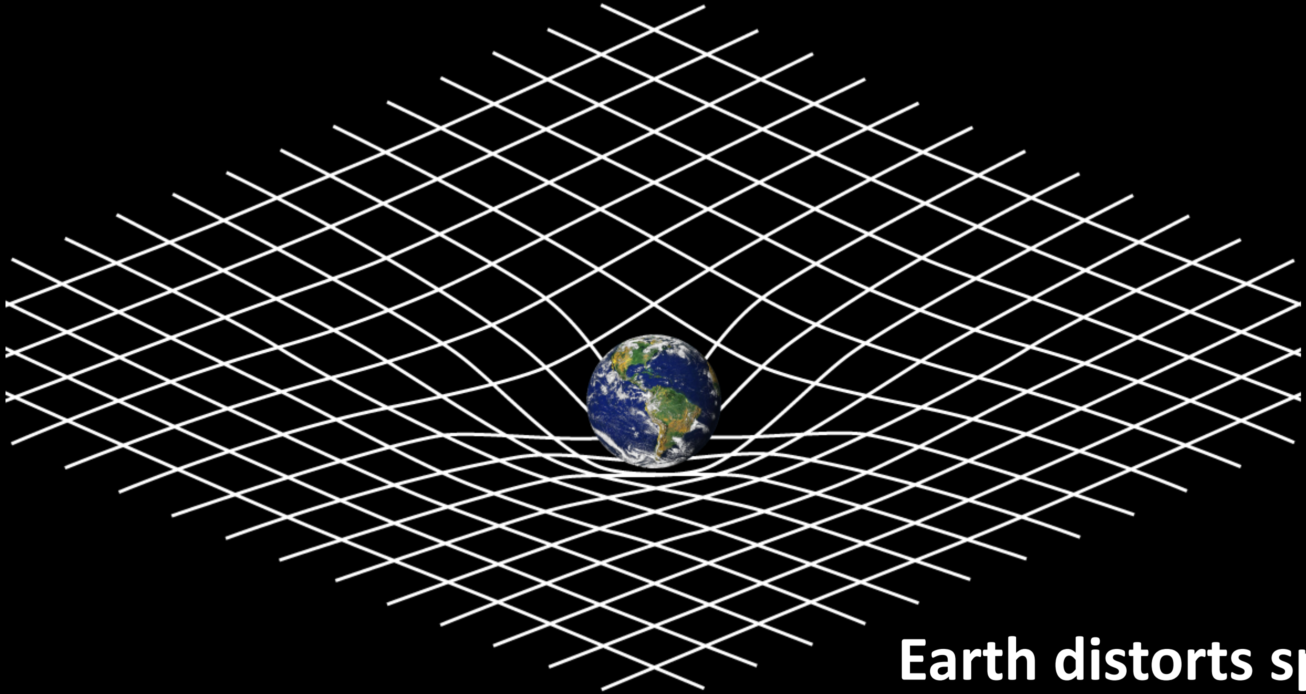
The Only <u>Observed</u> Problem with Newton's Gravity fixed in Einstein's Theory



Mercury's elliptical path around the Sun. Perihelion shifts forward with each pass. (Newton 532 arc-sec/century vs Observed 575 arc-sec/century)

(1 arc-sec = 1/3600 degree).

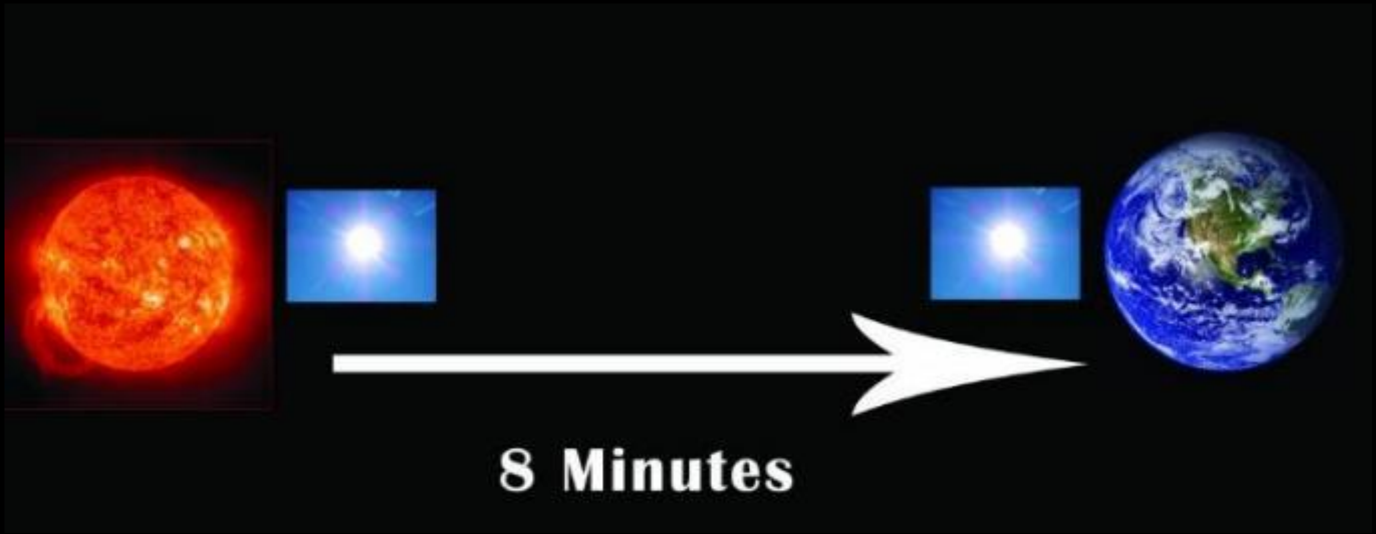
Einstein Explains <u>WHY</u> the apple falls!



Earth distorts spacetime

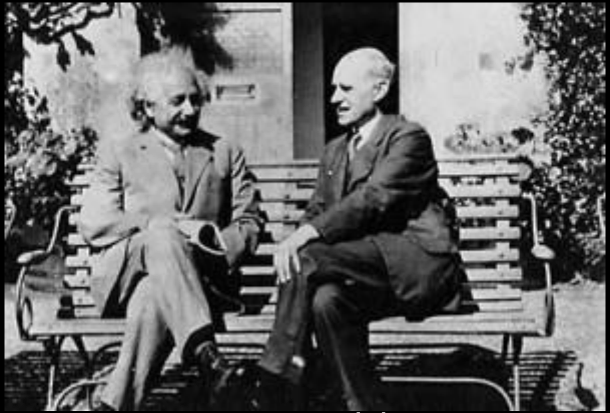
Einstein Solves a Conceptual Problem with Newton's Theory of Gravity

In Newton's Theory: "Instantaneous Action at a Distance"

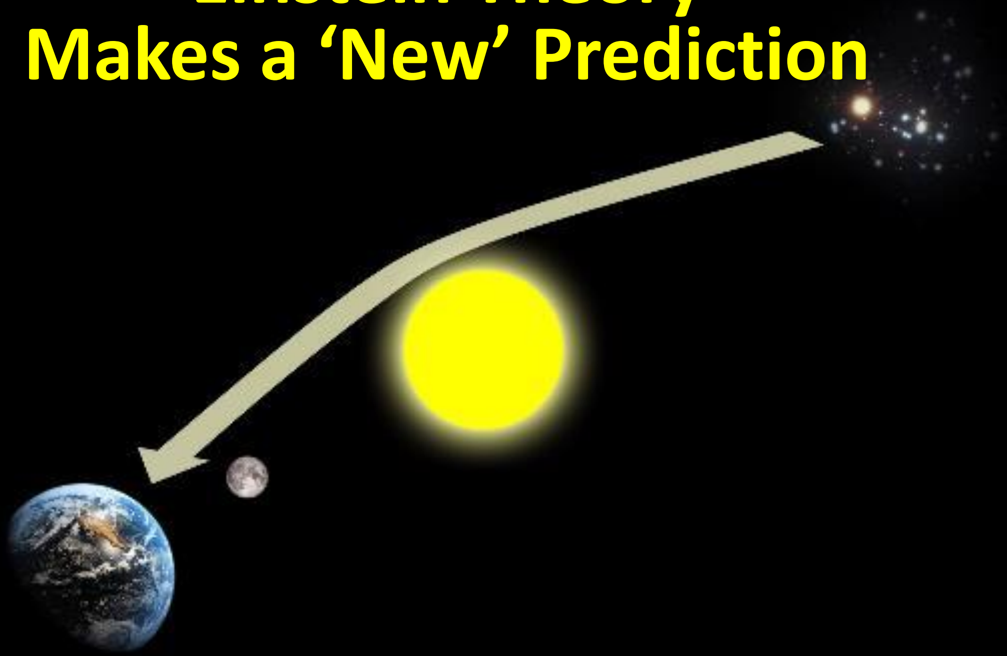


It takes finite time for information to travel from the sun to the earth

Einstein Theory
Makes a 'New' Prediction



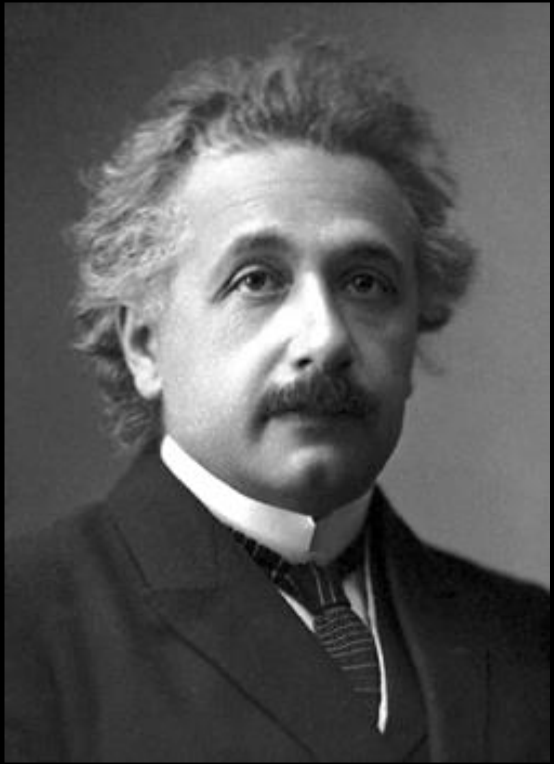
Einstein   Eddington

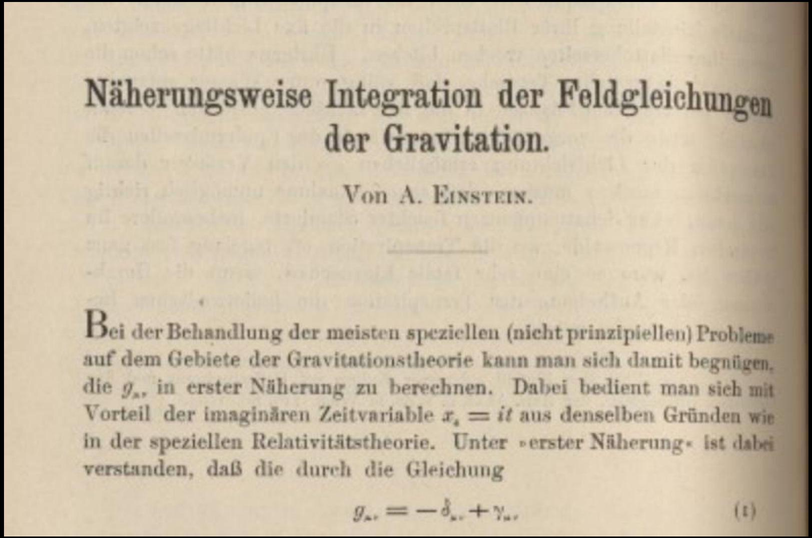


"Not only is the universe stranger than we imagine, it is stranger than we can imagine.

Sir Arthur Eddington

Einstein Predicted Gravitational Waves in 1916





Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

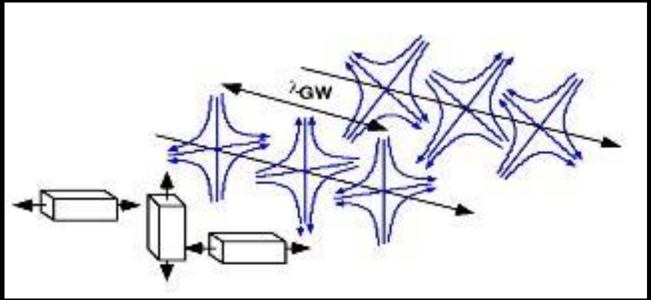
- 1st publication indicating the existence of gravitational waves by Einstein in 1916
    - Contained errors relating wave amplitude to source motions
- 1918 paper corrected earlier errors (factor of 2), and it contains the quadrupole formula for radiating source

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

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



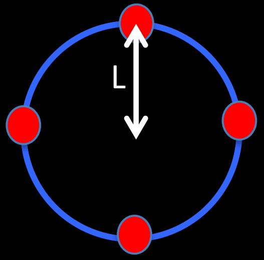
• The strain $h_{\mu\nu}$ takes the form of a plane wave propagating at the speed of light (c).

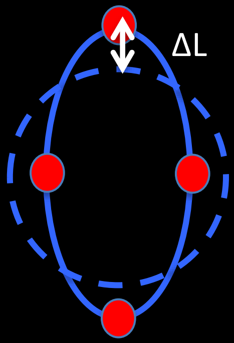
• Since gravity is spin 2, the waves have two components, but rotated by 45^0 instead of 90^0 from each other.

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

Gravitational Waves

- Ripples of spacetime that stretch and compress spacetime itself
- The amplitude of the wave is h ≈ 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

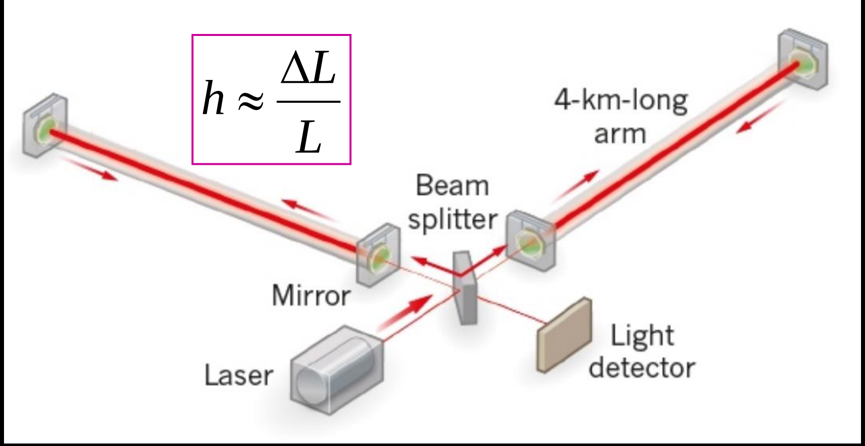




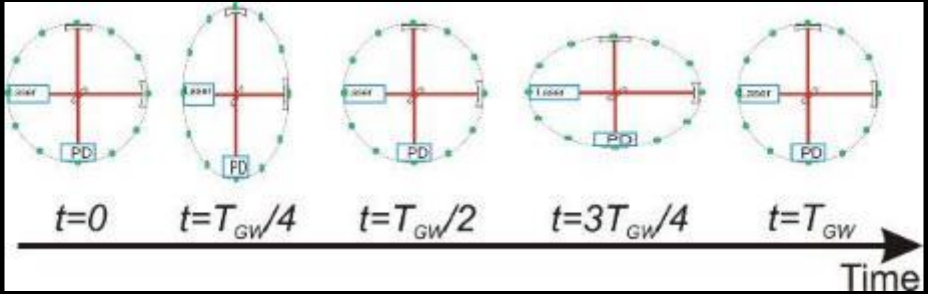
$$\Delta L = h \times L = 10^{-21} \times 1\,\mathrm{m} = 10^{-21}\,\mathrm{m}$$

LIGO: Measurement Scheme

- Enhanced **Michelson interferometers**
- GWs modulate the distance between the end test mass and the beam splitter
- The interferometer acts as a transducer, turning GWs into photocurrent proportional to the strain amplitude
- Arms are short compared to our GW wavelengths, so longer arms make bigger signals
  → multi-km installations
-

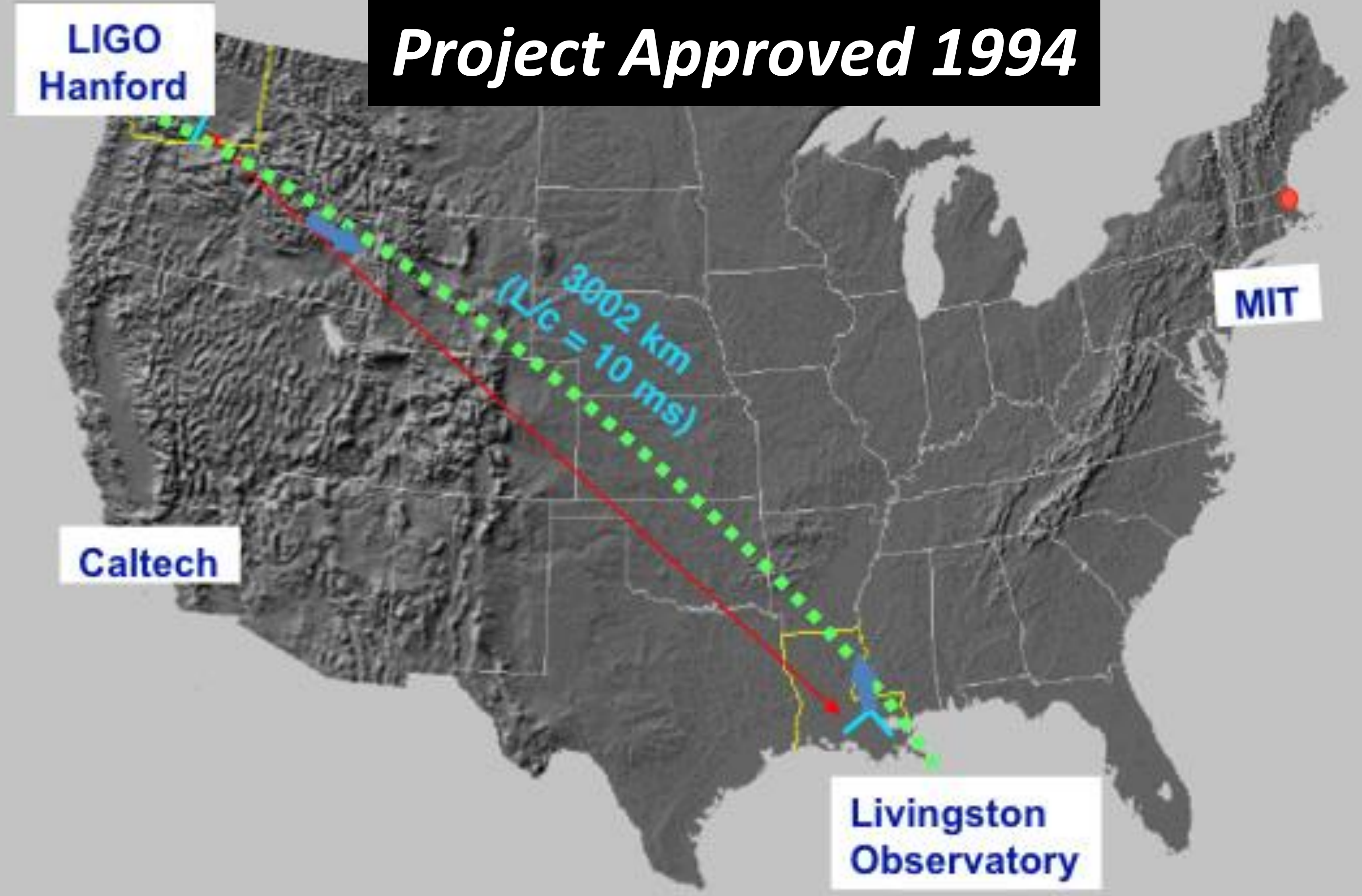


Magnitude of h at Earth: Detectable signals h ~ 10^{-21}
For L = 4km, **ΔL= 4x10^{-18} m**



LIGO Sites

Project Approved 1994

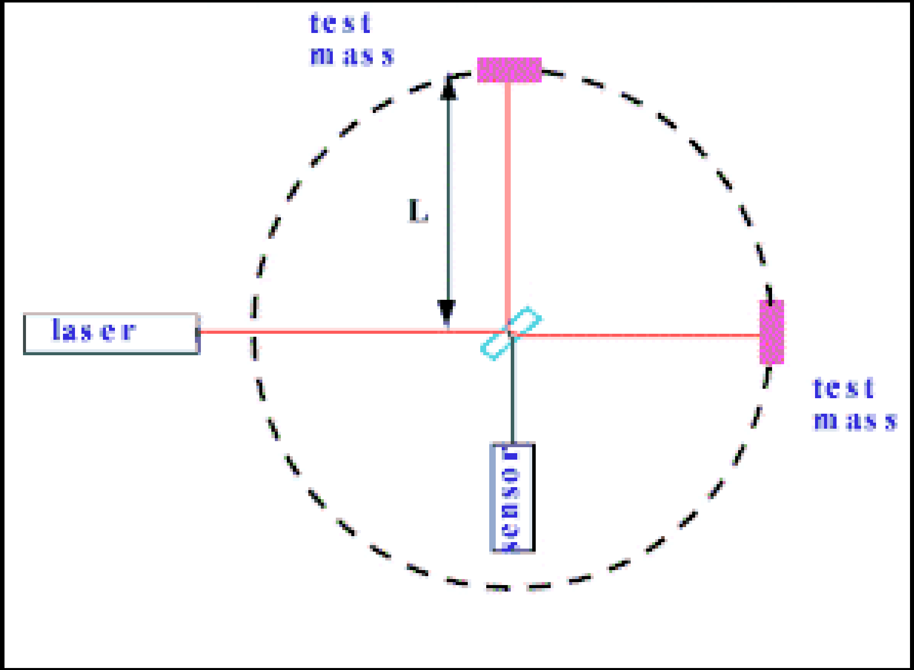


LIGO Interferometers

Hanford, WA

Livingston, LA

Suspended Mass Interferometry



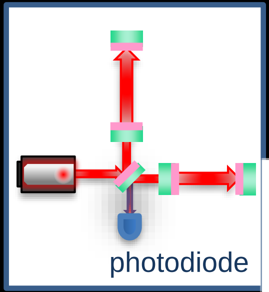
$$h = \frac{\Delta L}{L} \approx 10^{-21}$$

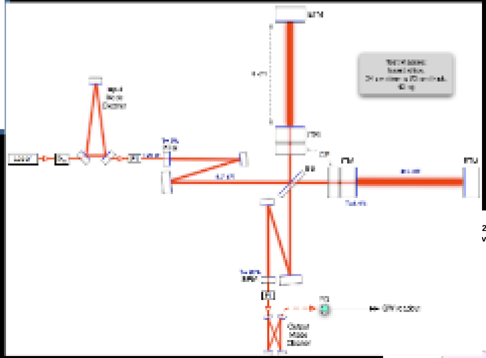
$$L = 4\mathrm{km} \quad \Delta L \approx 4\mathrm{x}10^{-18}\ \mathrm{meters}$$

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

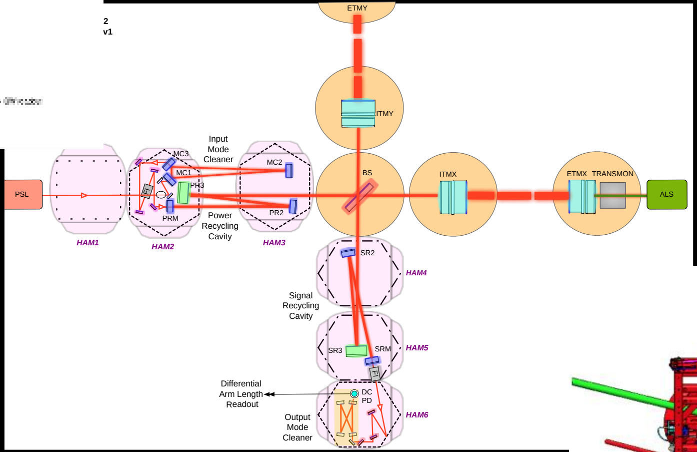
$$\Delta L \sim 10^{-12}\ \text{vibrations at earth's surface}$$

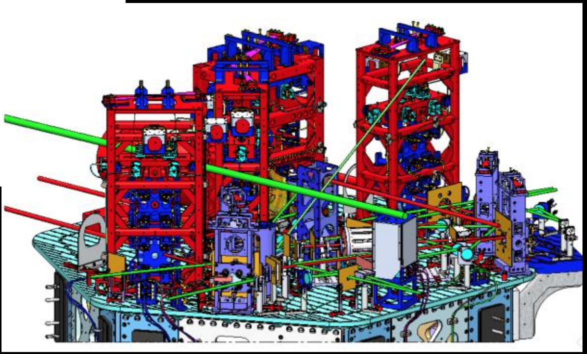
LIGO: Interferometry





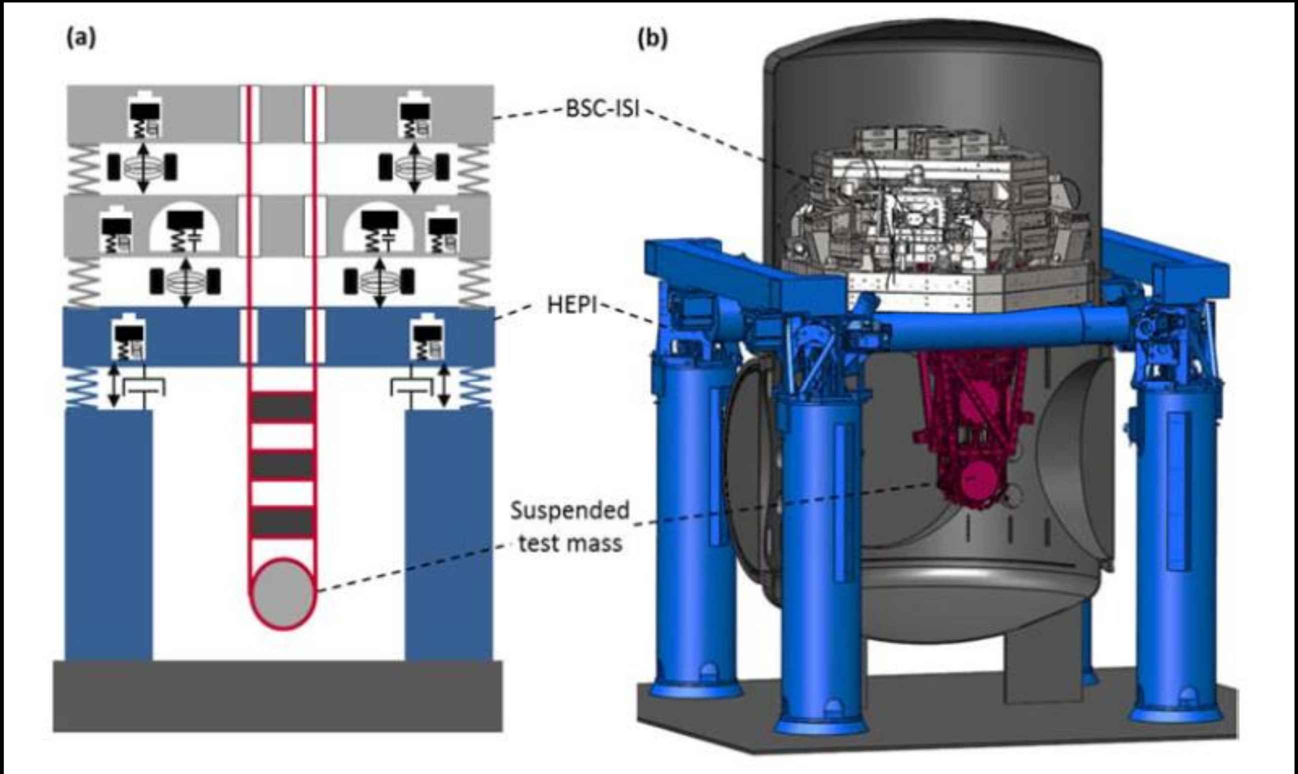
Many innovations to make the instrument so sensitive



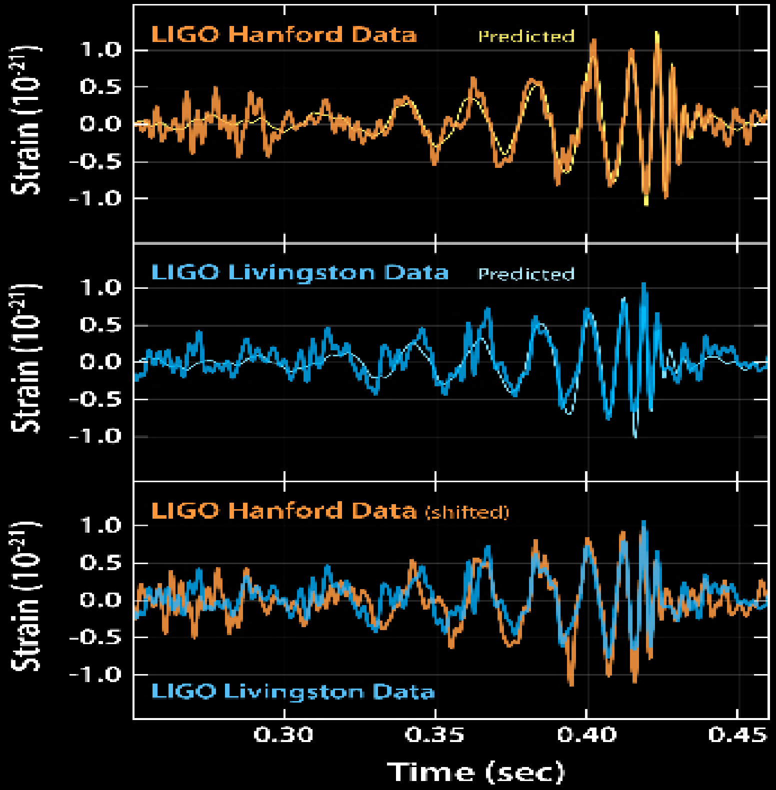


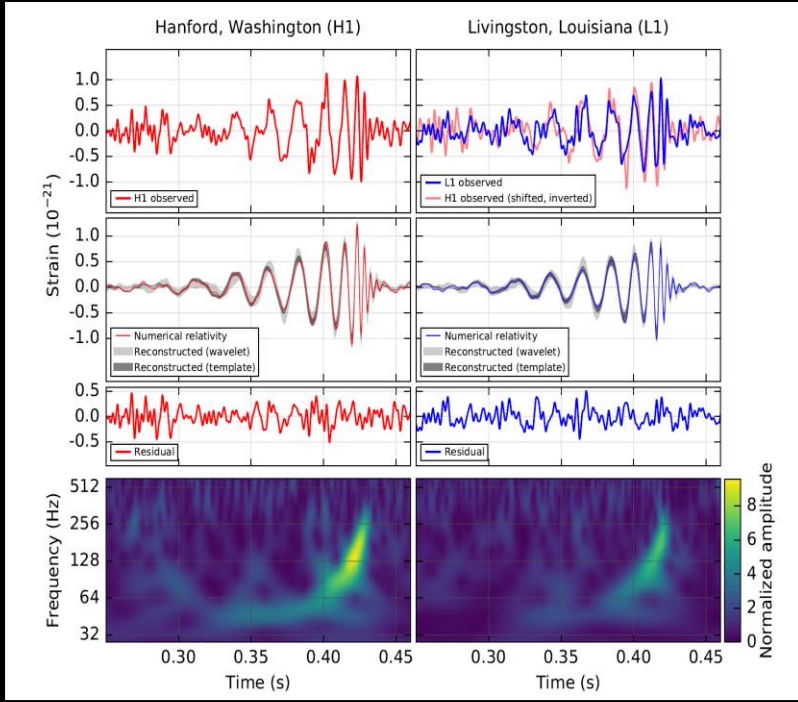
Passive / Active Multi-Stage Isolation

Advanced LIGO

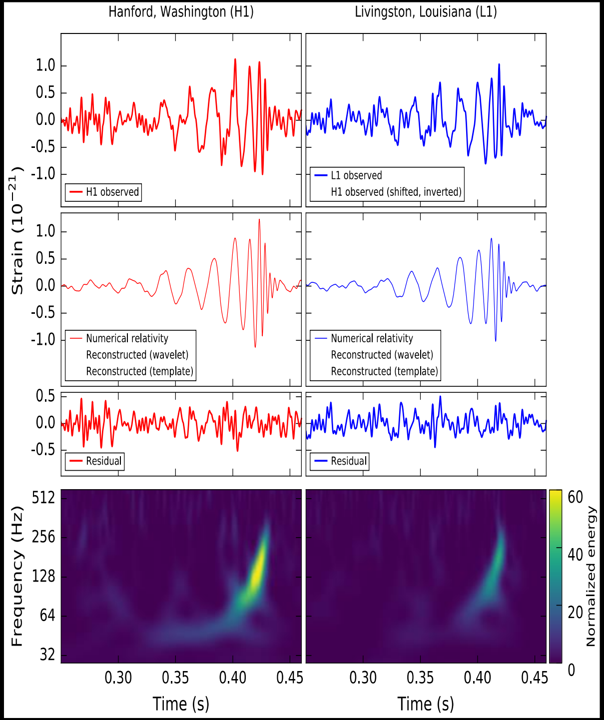


Black Hole Merger: GW150914





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

Testing General Relativity – Dispersion Term?

- In GR, there is no dispersion!

Add dispersion term of form

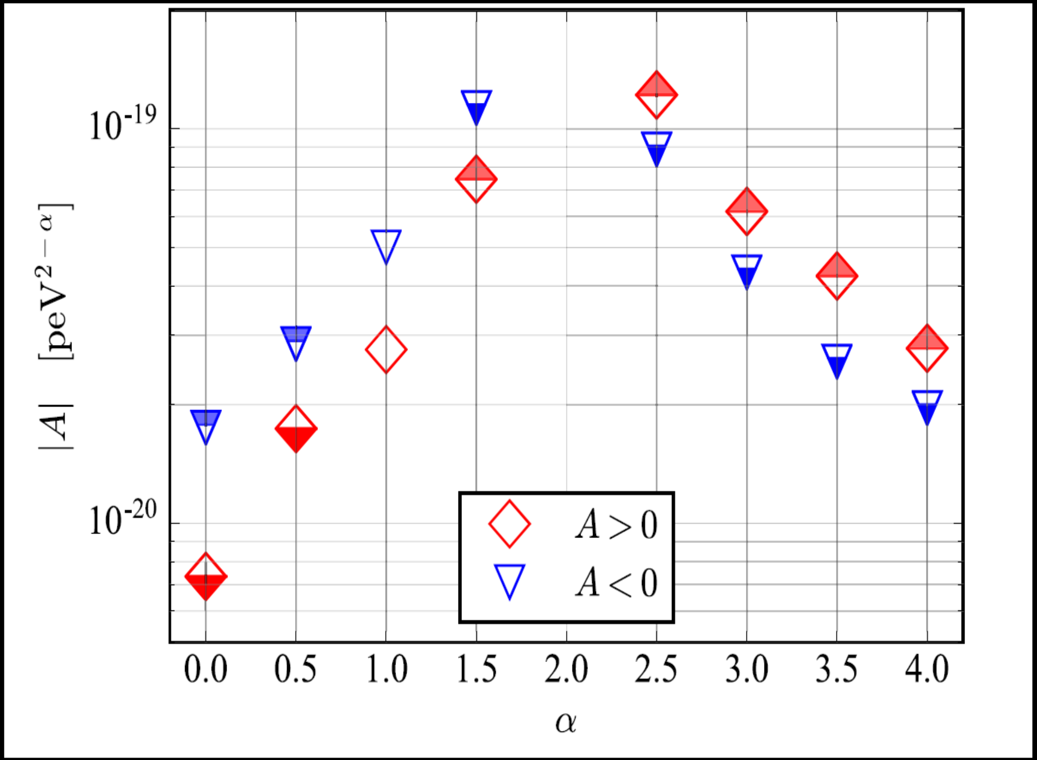
$$E^2 = p^2c^2 + Ap^{\alpha}c^{\alpha}, \quad \alpha \geq 0$$

(E, p are energy, momenturm of GW, A is amplitude of dispersion)

- Plot shows 90% upper bounds
- Limit on graviton mass

$$M_g \leq 7.7 \times 10^{-23}\ \text{eV}/c^2$$

- Null tests to quantify generic deviations from GR

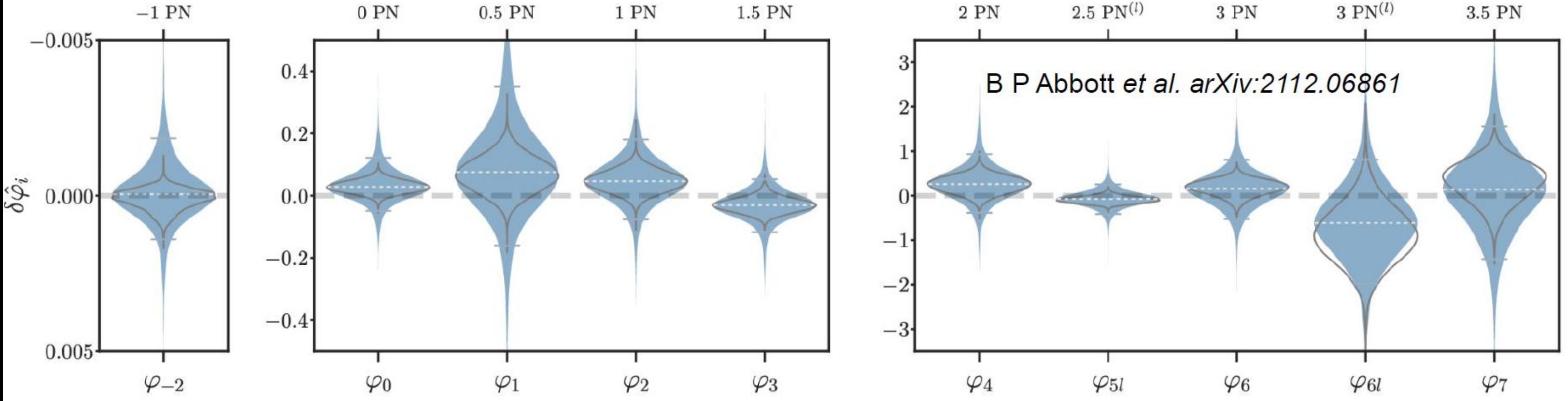


PhysRevLett.118.221101

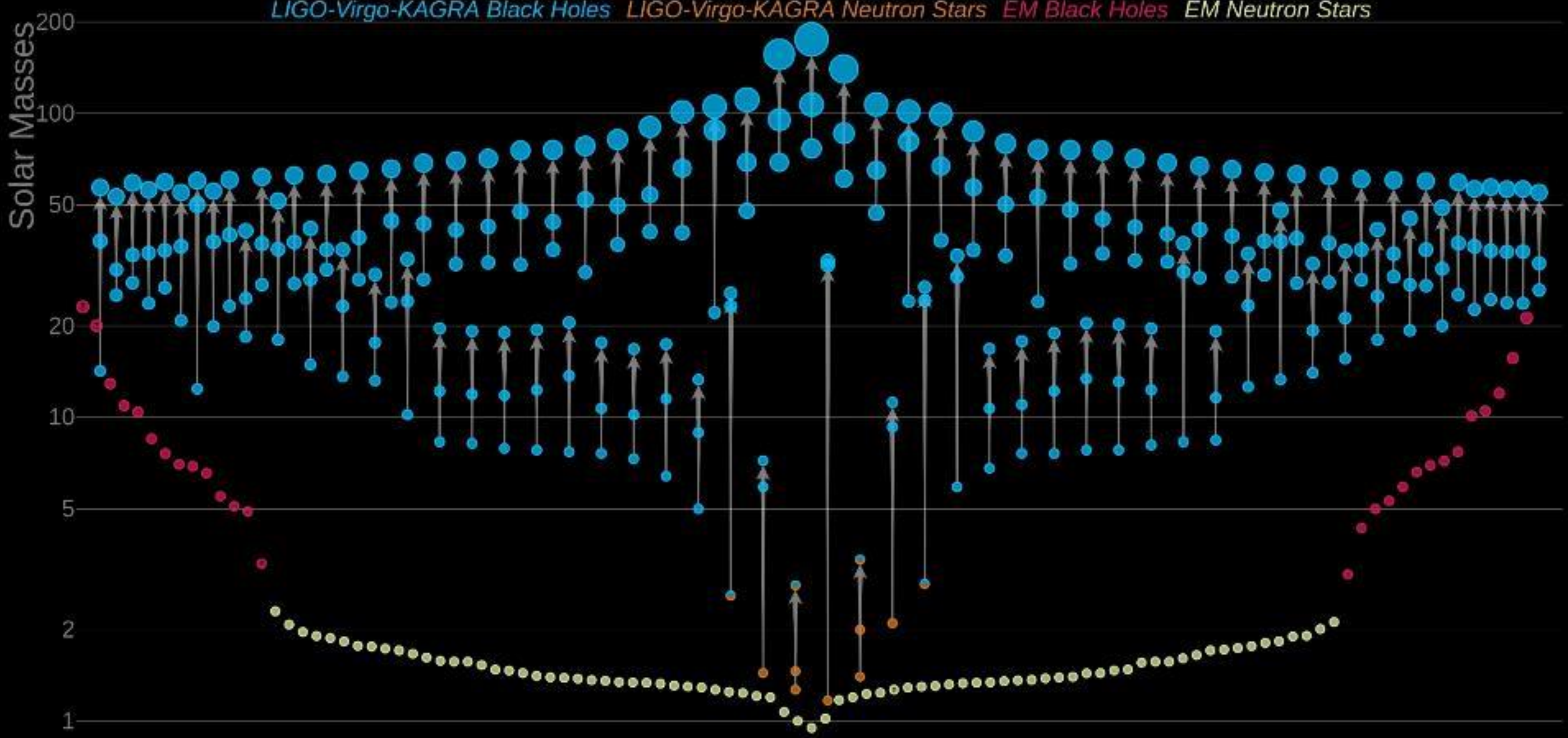
Testing GW generation with BBH

- Look for deviations in the phasing coefficients of a 3.5PN TaylorF2 phase:

$$\varphi_{\mathrm{PN}}(f) = 2\pi f t_{\mathrm{c}} - \varphi_{\mathrm{c}} - \frac{\pi}{4} + \frac{3}{128\eta}\left(\pi\tilde{f}\right)^{-5/3}\sum_{i=0}^{7}\left[\varphi_i + \varphi_{i\,l}\log(\pi\tilde{f})\right]\left(\pi\tilde{f}\right)^{i/3}$$

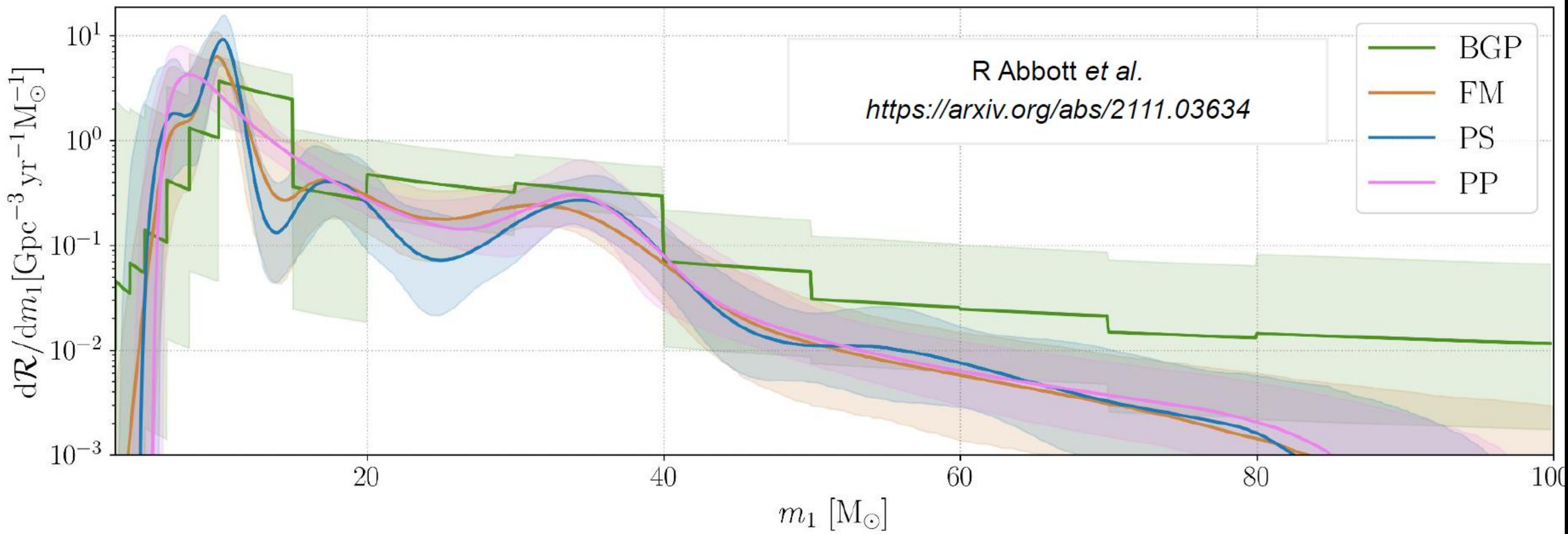


Masses in the Stellar Graveyard



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

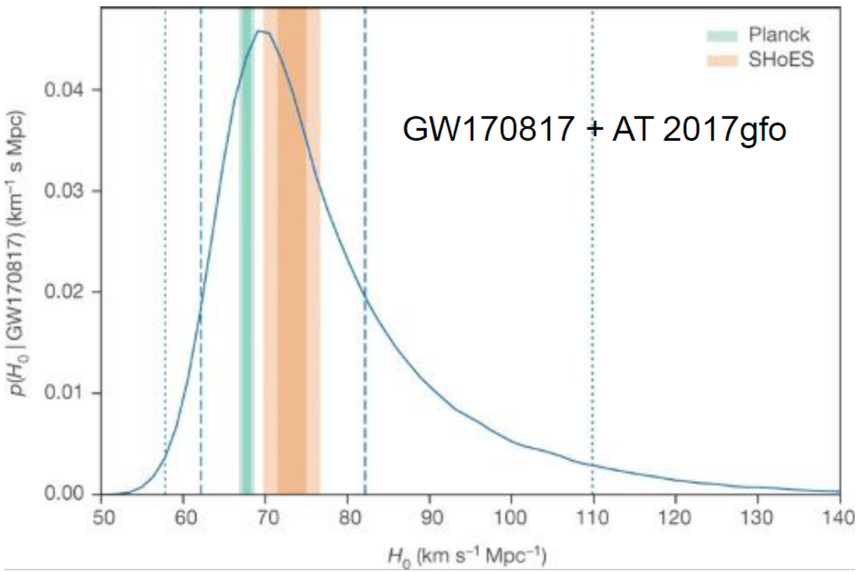
Origin of Black Holes – Distributions



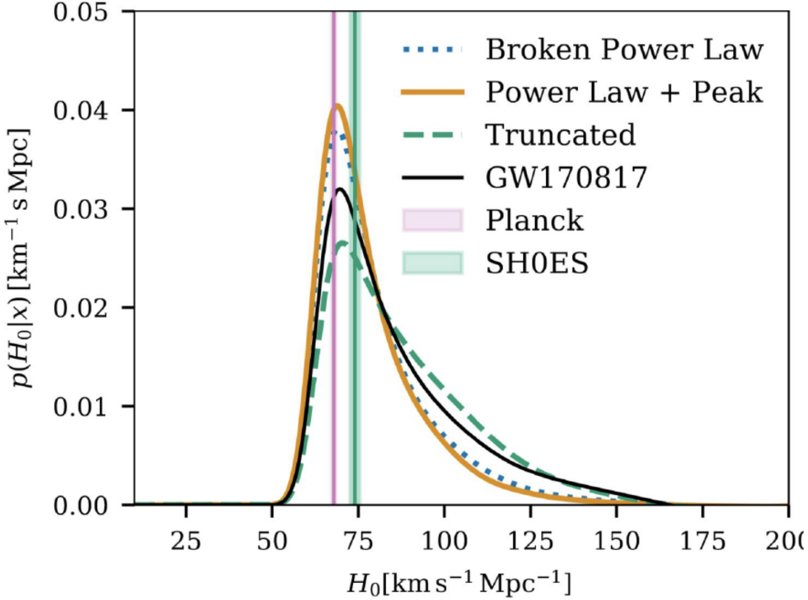
Merger rate density as a function of primary mass using 3 non-parametric models compared to the power-law+peak (pp) model.

Hubble Constant - Expansion Rate of the Universe

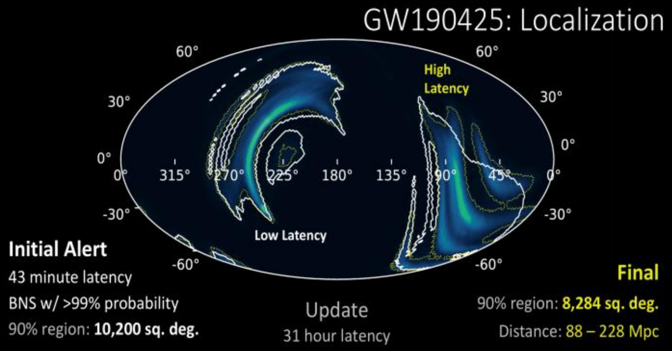
B P Abbott *et al. Nature* **551**, 85–88 (2017) doi:10.1038/nature24471

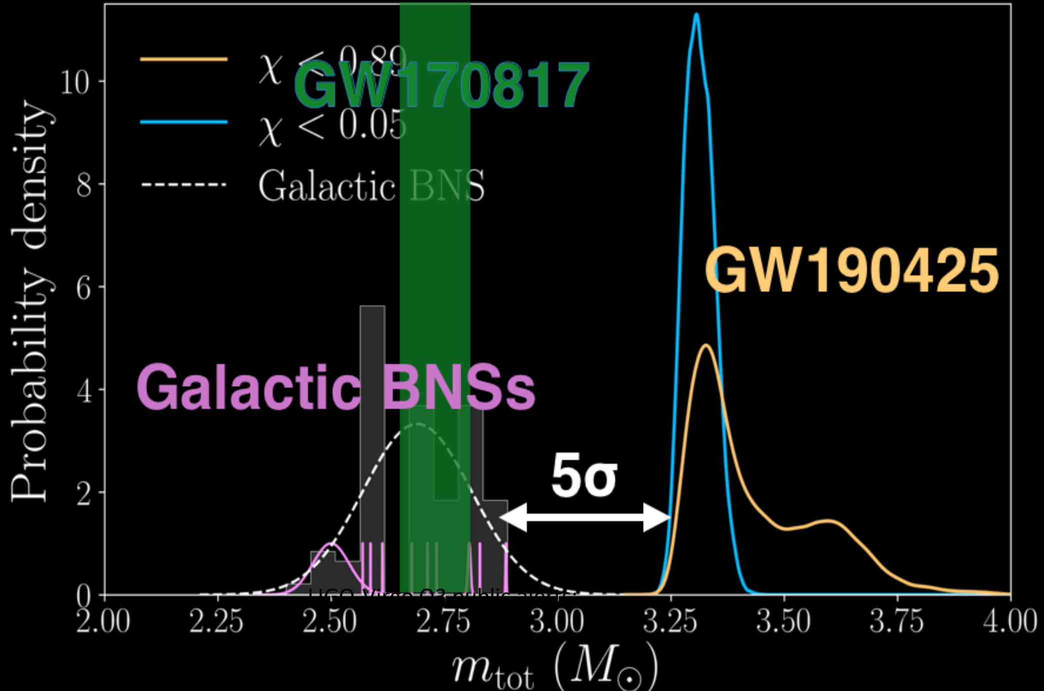


R Abbott *et al. arXiv:2111.03604 (2021)*



Exceptional Events





The signal was detected by only the LIGO Livingston interferometer

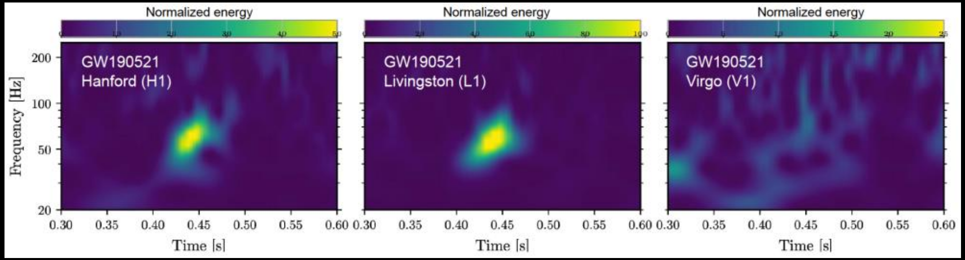
The event has an estimated total mass of 3.4 M_{sun}

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

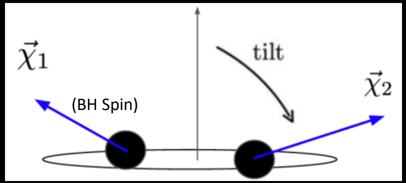
The Most Massive and Distant Black Hole Merger Yet: GW190521

- 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

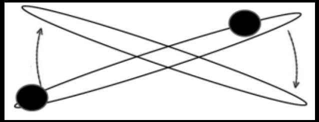
→ Implications for how these black holes formed

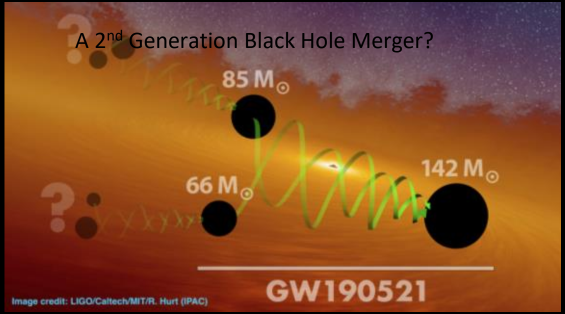


Orbital Angular Momentum



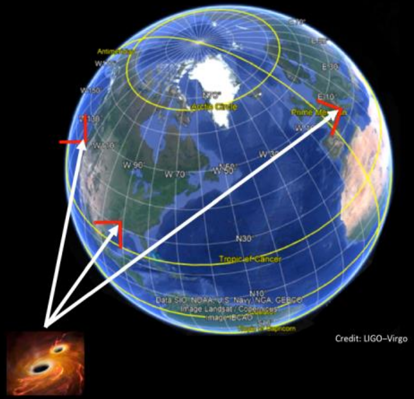
Orbital Plane Precession

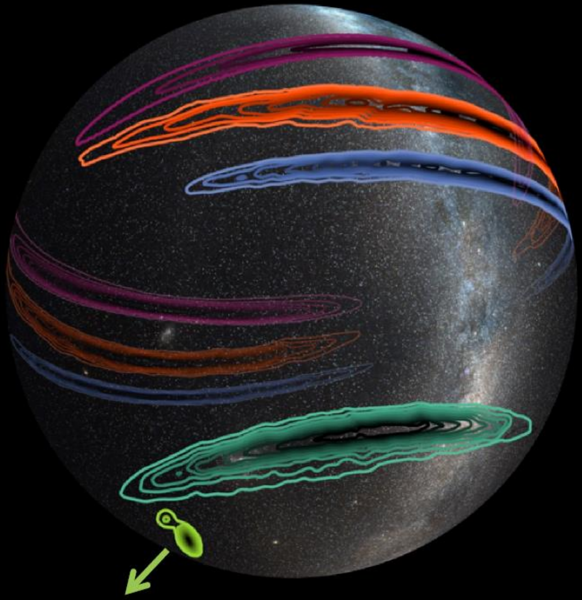




Virgo Joins LIGO – August 14, 2017

2017 August 14





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

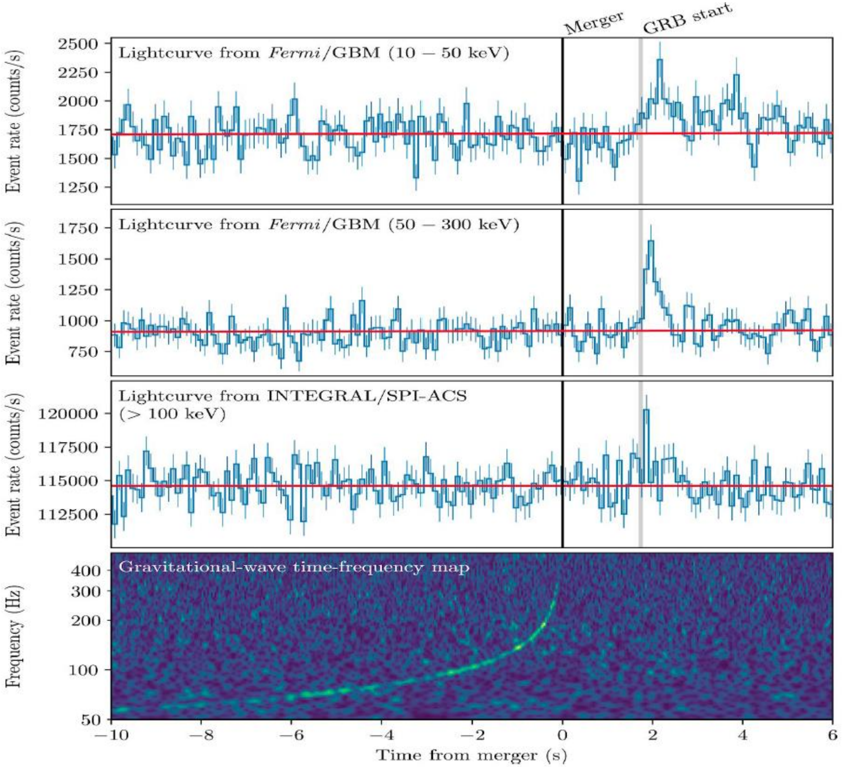
For all reported Black Hole Binary Events, **NO** Electromagnetic counterparts found !!

LH 1160 square degrees
LHV 60 square degrees

Binary Neutron Star Merger

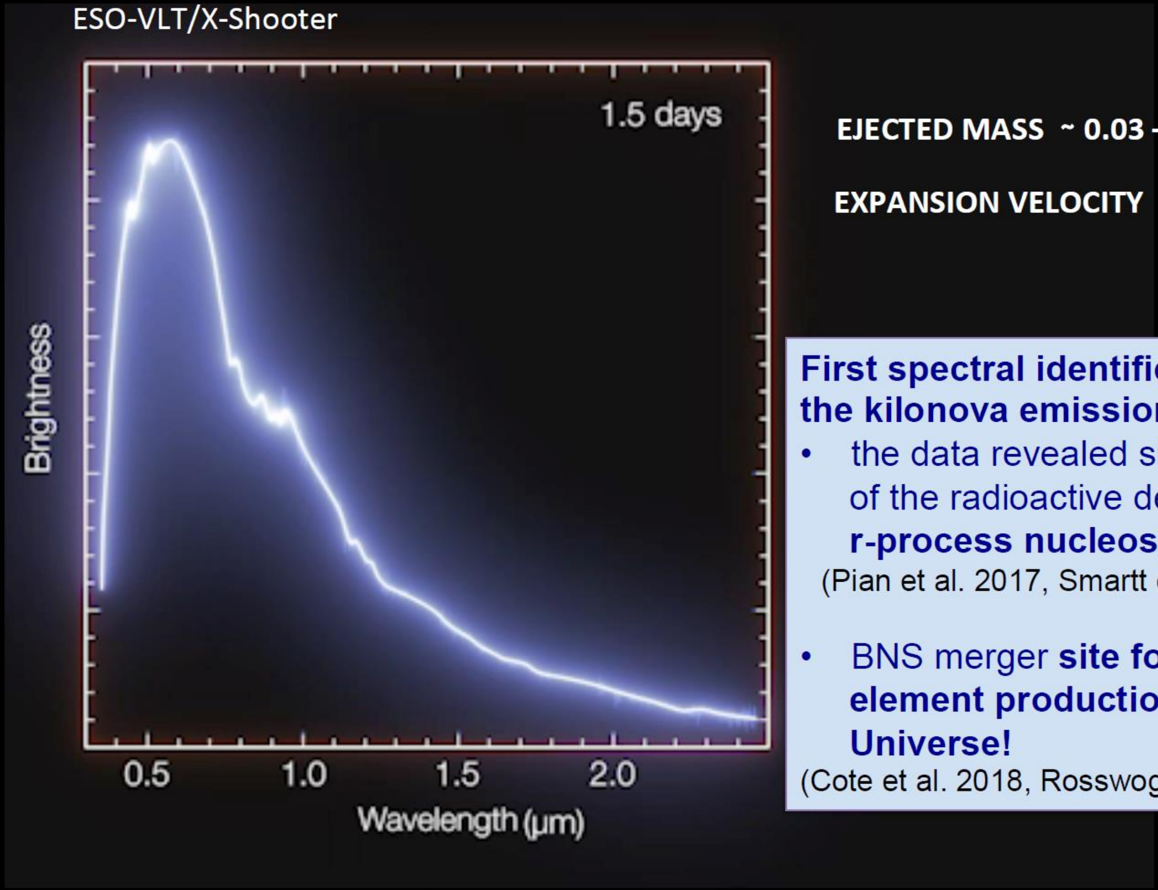
First BNS-GRB association ….

B. P. Abbott et al 2017 ApJL 848 L13



- GW170817
  - Binary neutron star (BNS) merger waves
- GW170817 & GRB 170817A
  - Fractional difference in speed of gravity and the speed of light is between -3 x 10^{-15} and 7 x 10^{-16}
- GW170817 & AT 2017gfo
  - Binary neutron star mergers produce kilonova explosions that generate heavy elements

Kilonova Emission



EJECTED MASS ~ 0.03 – 0.05 $M_\odot$

EXPANSION VELOCITY ~ 0.1 – 0.3 c

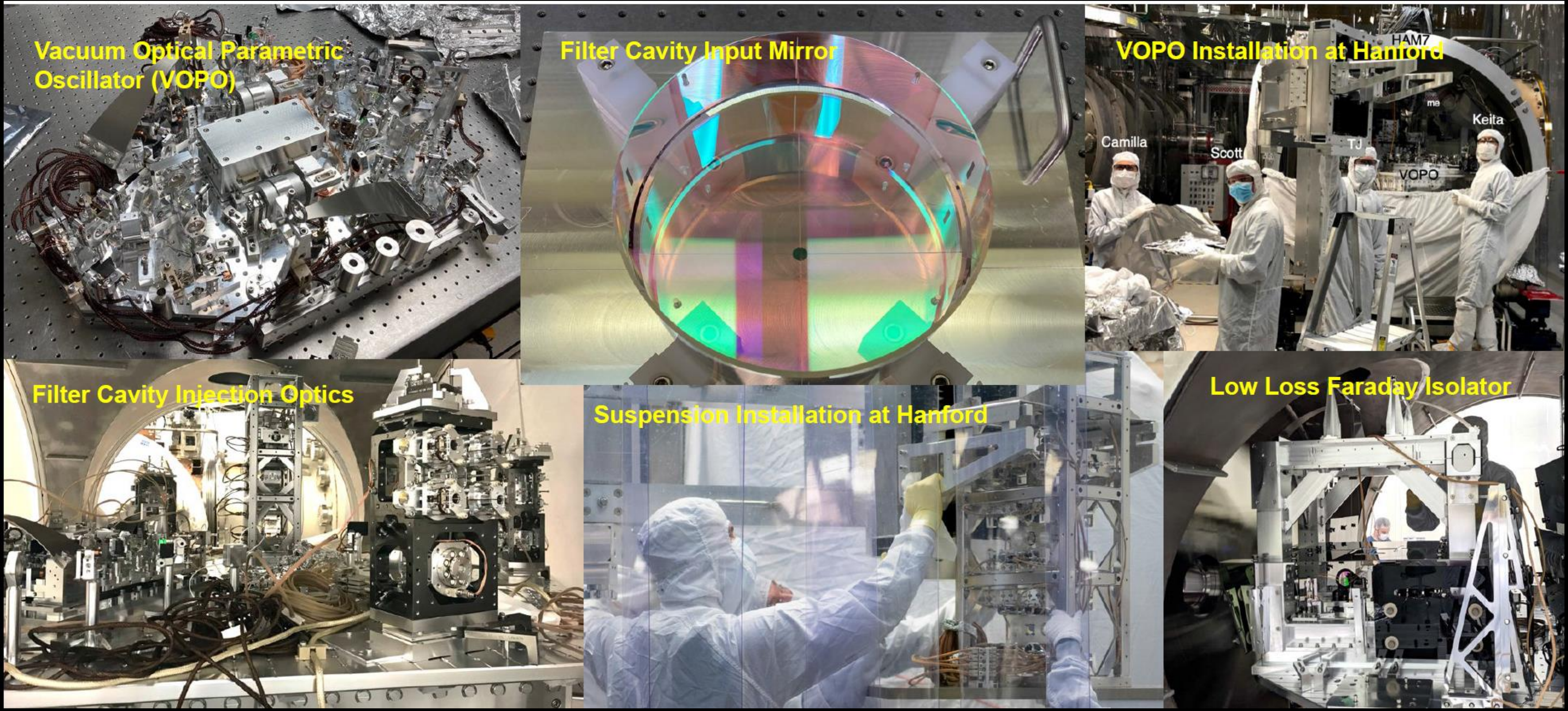
First spectral identification of the kilonova emission

- 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

The Pandemic Pause



O4 Run and Upgrade Plans

LIGO and Virgo are currently engaged in an extended upgrade period in advance of the next O4 observing run

- Advanced LIGO 'A+' and Advanced Virgo + upgrade program will implement frequency-dependent squeezing to reduce low frequency noise
- Also, LIGO will replace many of the primary 'test mass mirrors

O4 will include the two LIGO Observatories, the Virgo Observatory, and the KAGRA Observatory

→ ***the first LIGO-Virgo-KAGRA 4-detector run***

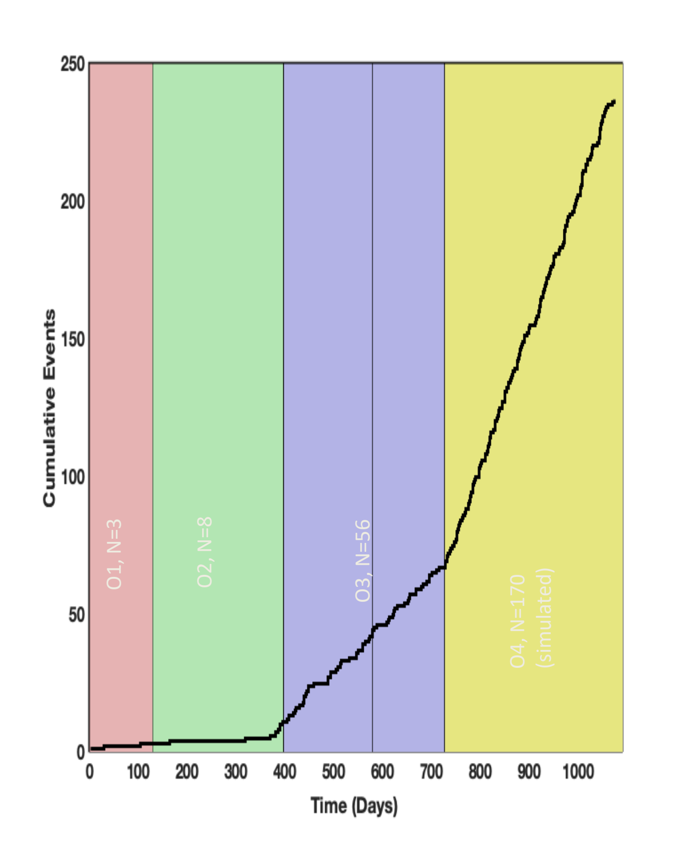
Target sensitivities (binary neutron star inspiral range):

- LIGO: 160-190 Mpc (520 - 620 Mly)
- Virgo: 90 MPc (200 Mly)
- KAGRA: 25 - 130 MPc (80 - 425 Mly)

→***A 2X to 3X increase in GW event rate***

O4 will start no earlier than March 2023

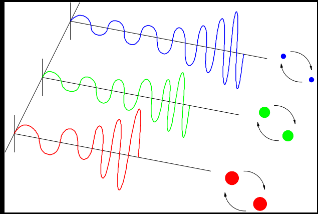
O4 run duration is still not set, but likely somewhere in the 12 – 18 month range



Astrophysical Sources

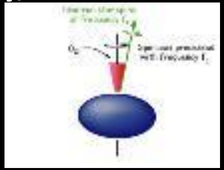
signatures

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

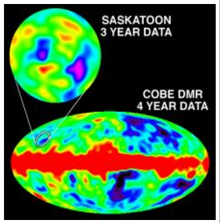


- Supernovae / GRBs: *"bursts"*
  - burst signals in coincidence with signals in electromagnetic radiation
  - prompt alarm (~ one hour) with neutrino detectors

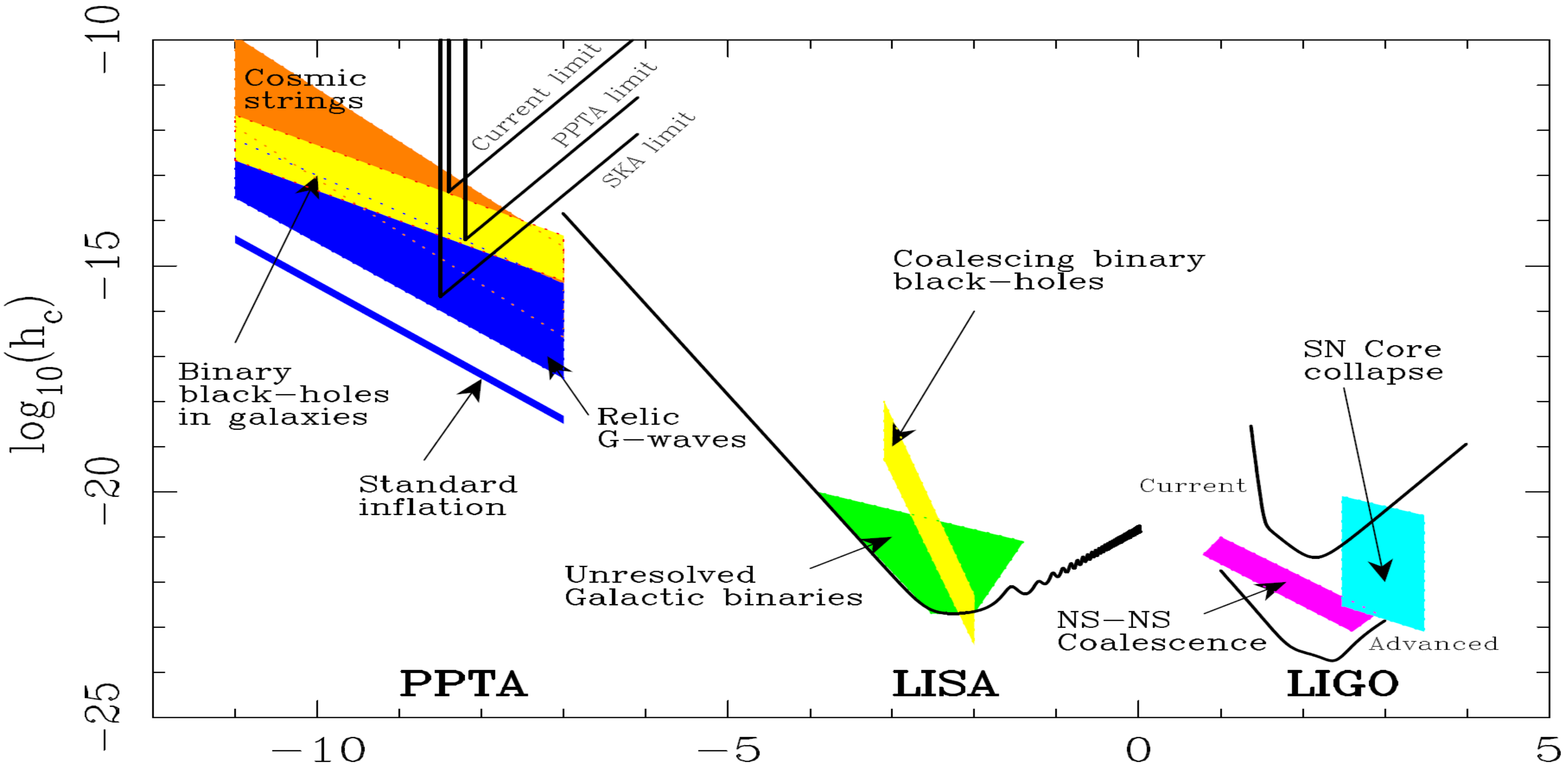
- Pulsars in our galaxy: *"periodic"*
  - search for observed neutron stars (frequency, doppler shift)
  - all sky search (computing challenge)
  - r-modes

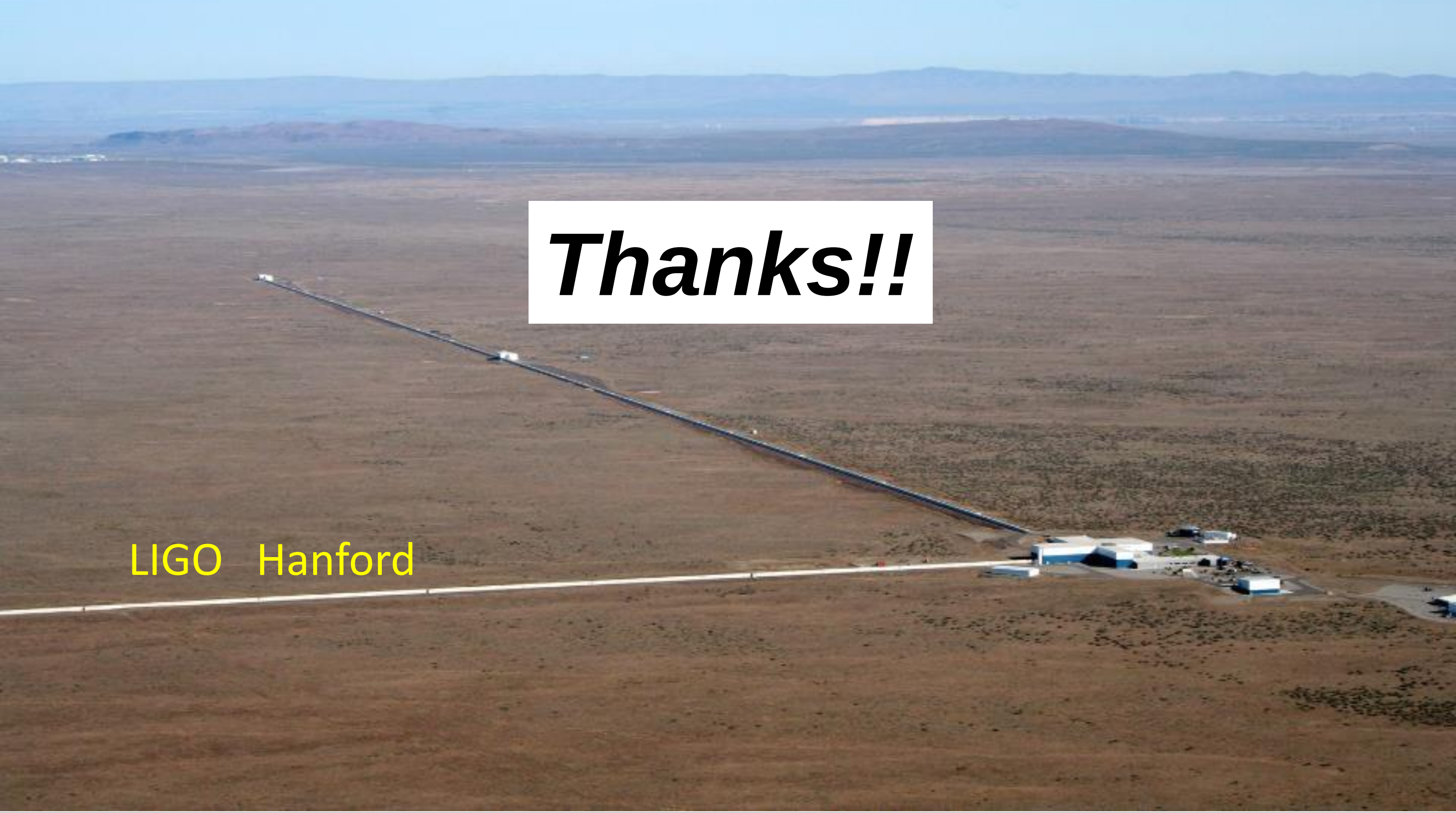


- Cosmological Signal *"stochastic background"*



Gravitational Wave Frequency Coverage




Thanks!!
LIGO Hanford