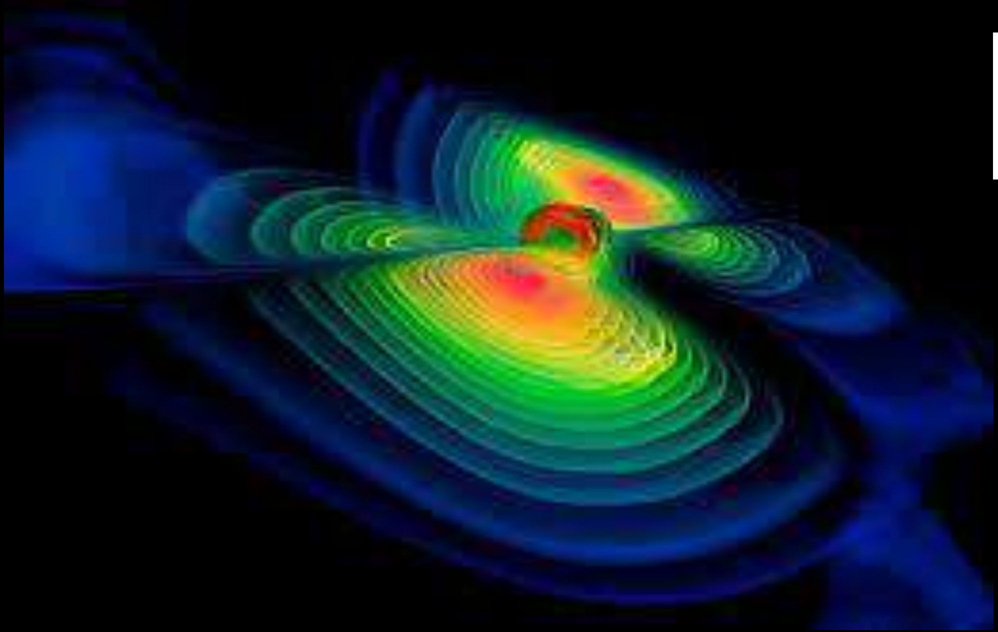
Probing the Universe with Gravitational Waves



Tohoku Forum for Creativity

Barry C Barish

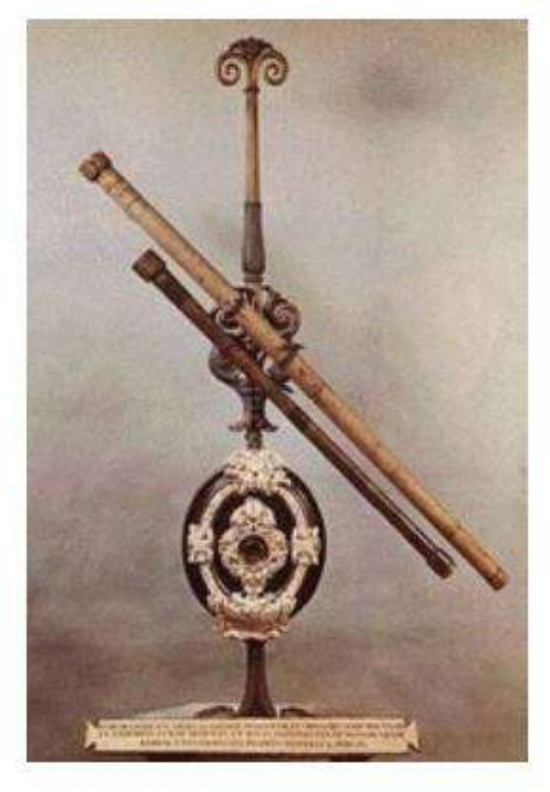
Caltech/UC Riverside

5-March-22

A Little History

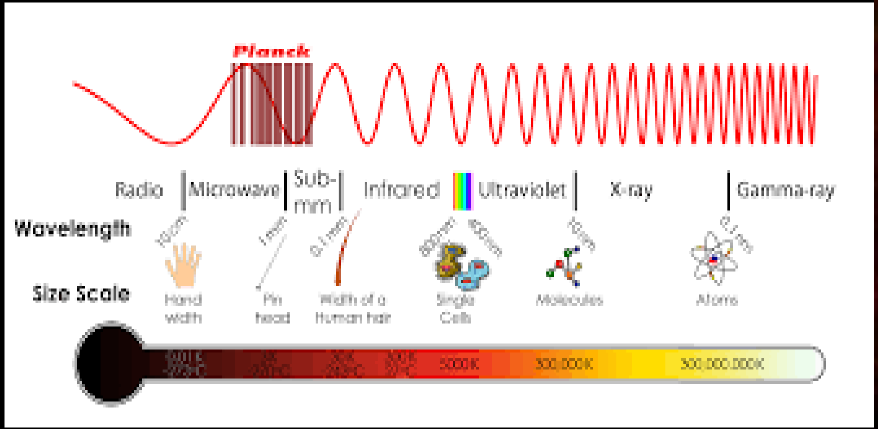
The Birth of Astronomy – January 1610

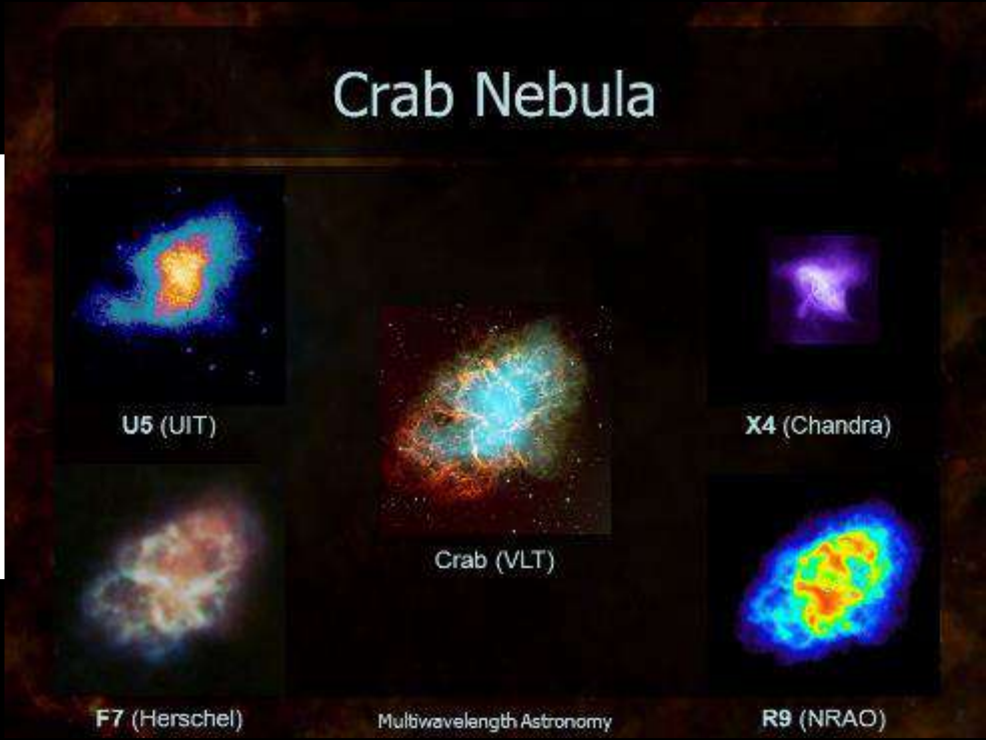
Galileo – Discovered four moon of Jupiter



20th Century : Multiwavelength Astronomy

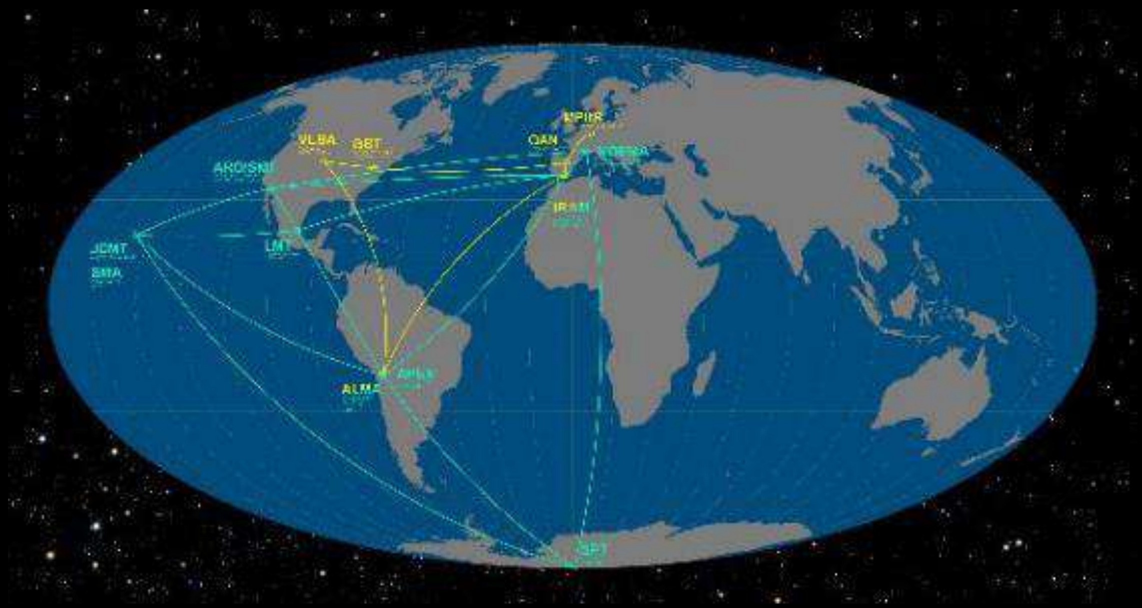
Electromagnetic Spectrum

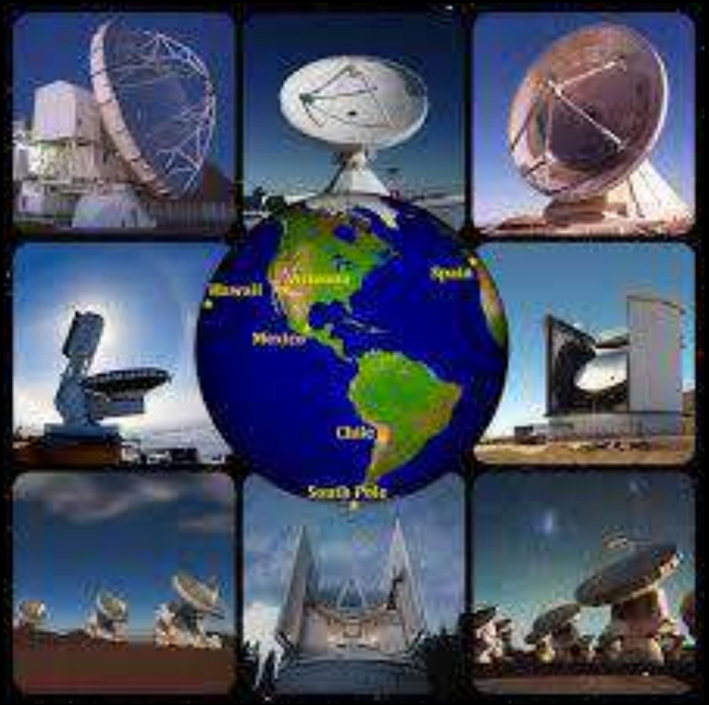




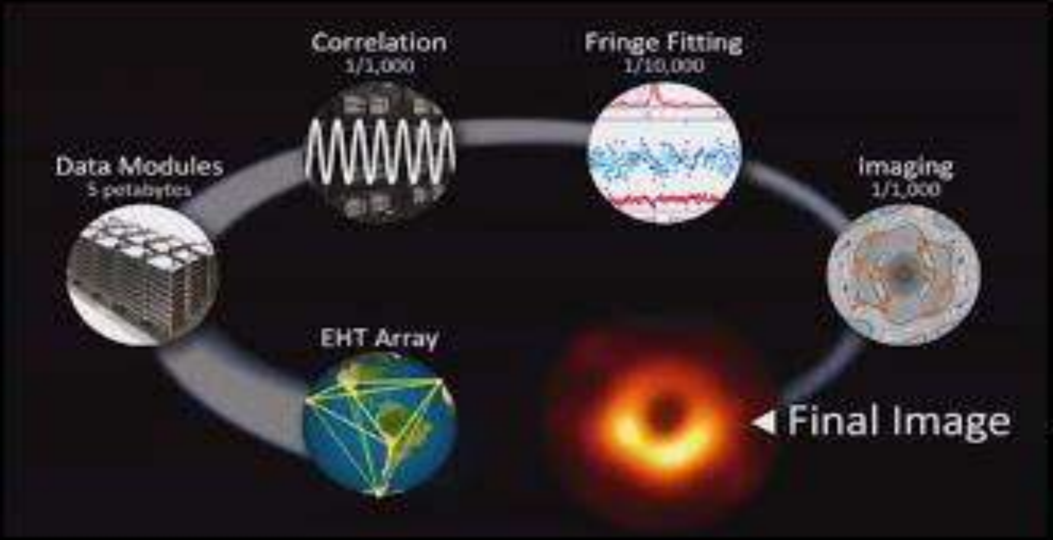
Observe Astronomical Phenomena at different wavelengths over the electromagnetic spectrum

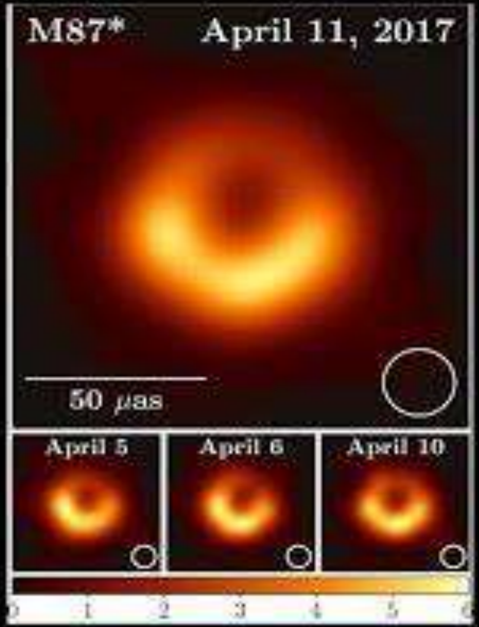
21st Century: “Combined Instruments”





Event Horizon Telescope: Black Hole Image



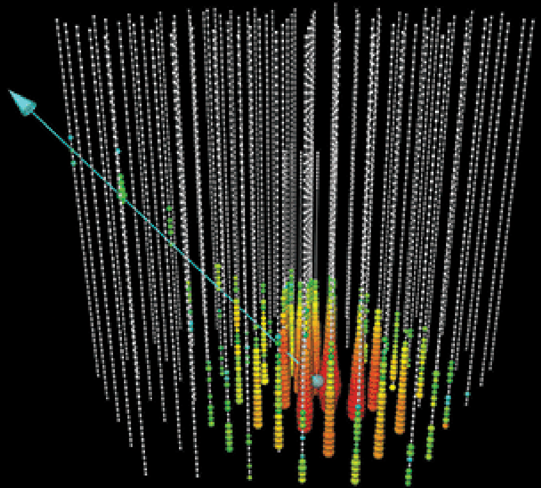


Next Frontier: Multimessenger Astronomy

Electromagnetic

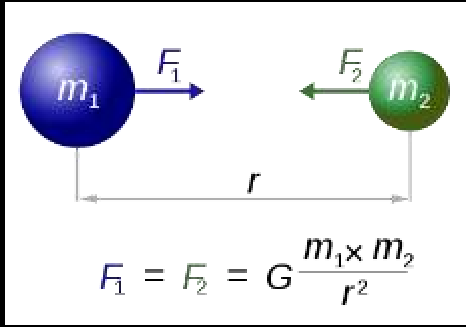
Gravitational Waves

Neutrinos

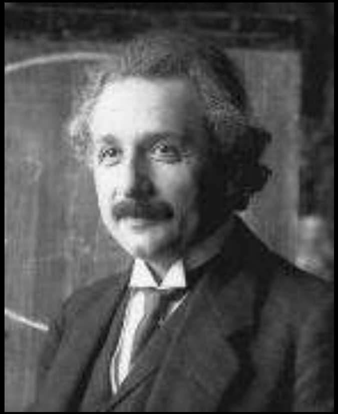


General Relativity and Gravitational Waves

Newton's Theory of Gravity (1687)



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



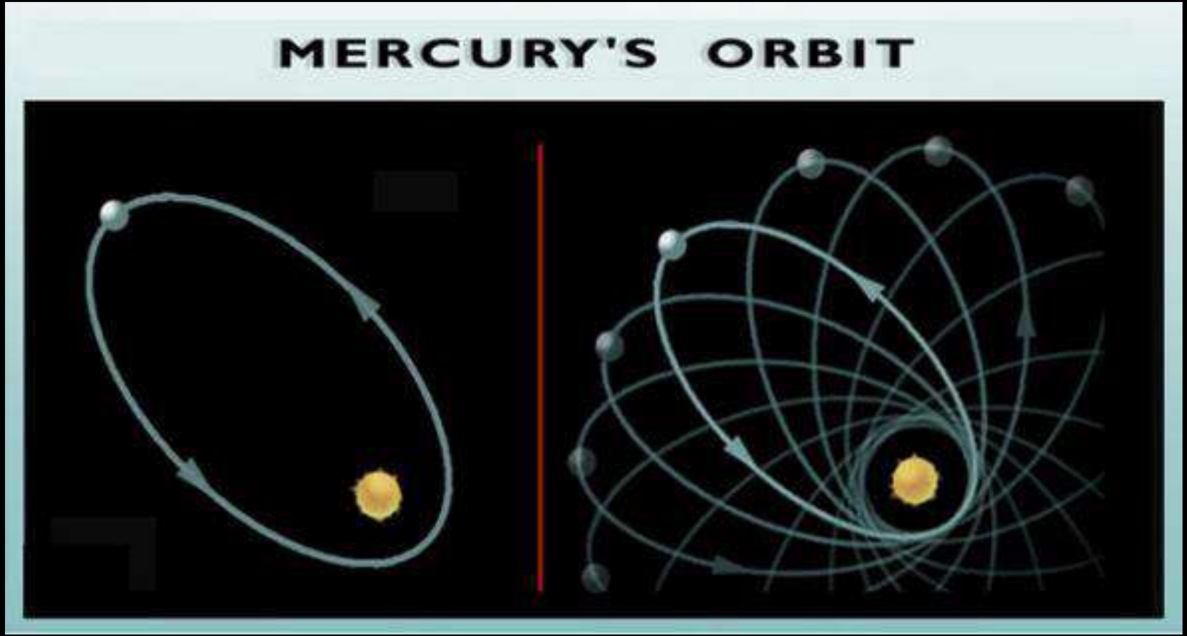
Einstein's Theory of Gravity (1915)

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

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

spacetime

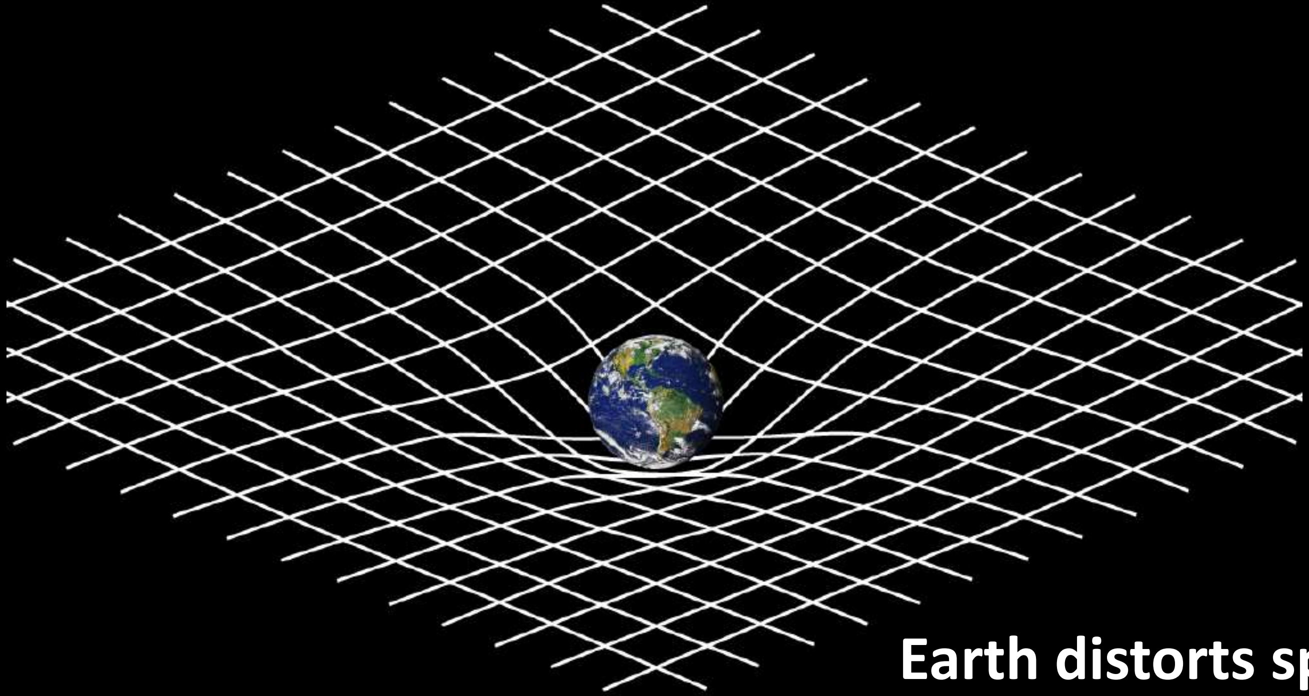
Only Observed Problem with Newton's Gravity fixed in Einstein's Theory



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).

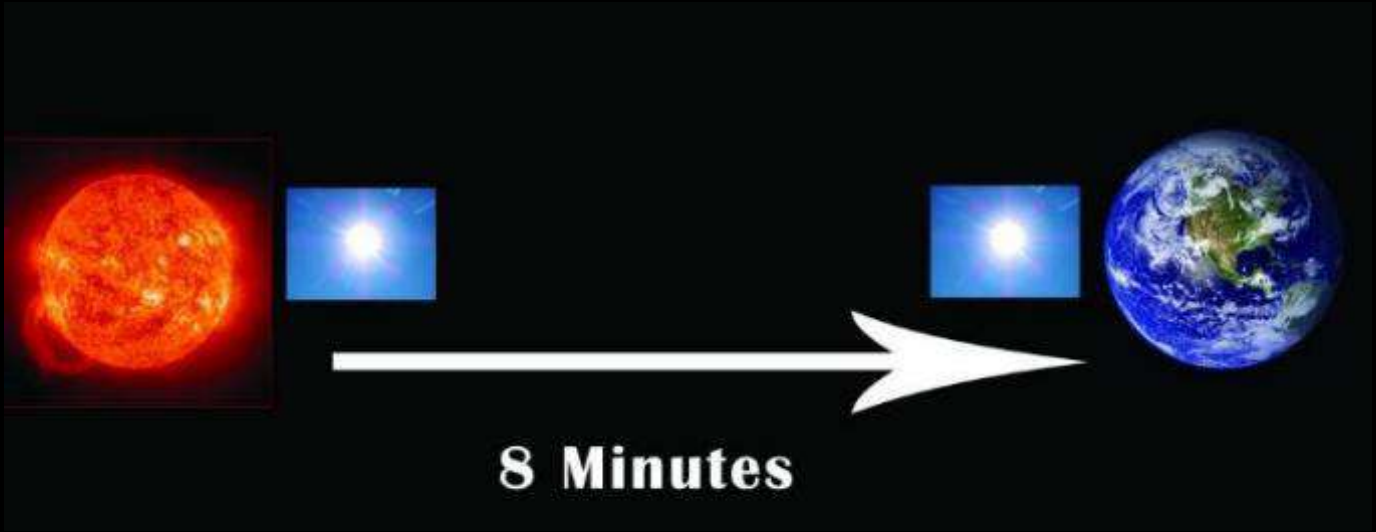
Einstein Explains WHY the apple falls!



Earth distorts spacetime

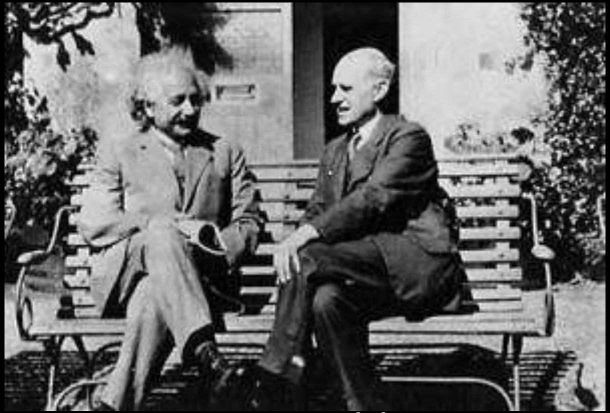
Einstein Solves a Conceptual Problem with Newton's Theory of Gravity

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



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

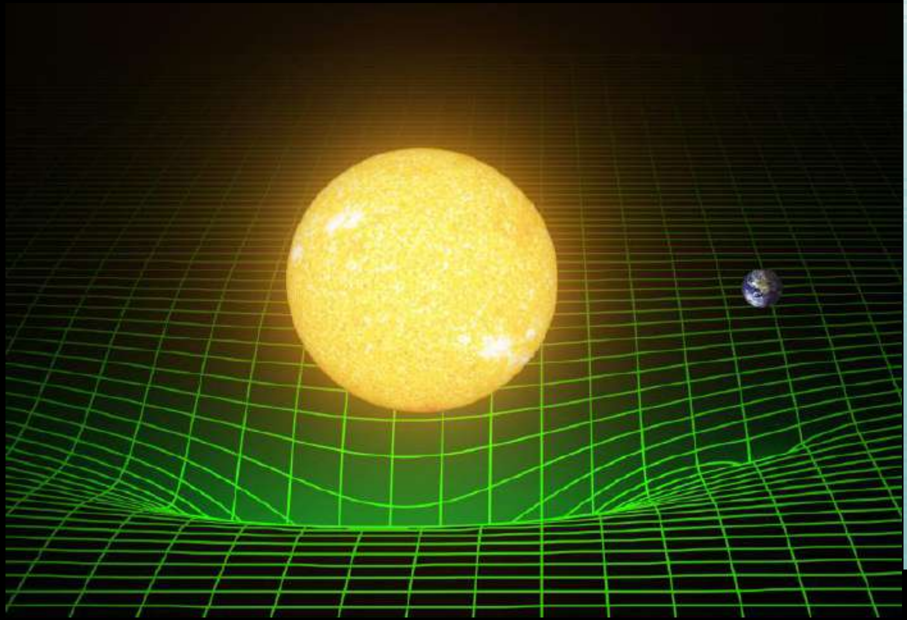
Einstein Theory
Makes a ‘New’ Prediction

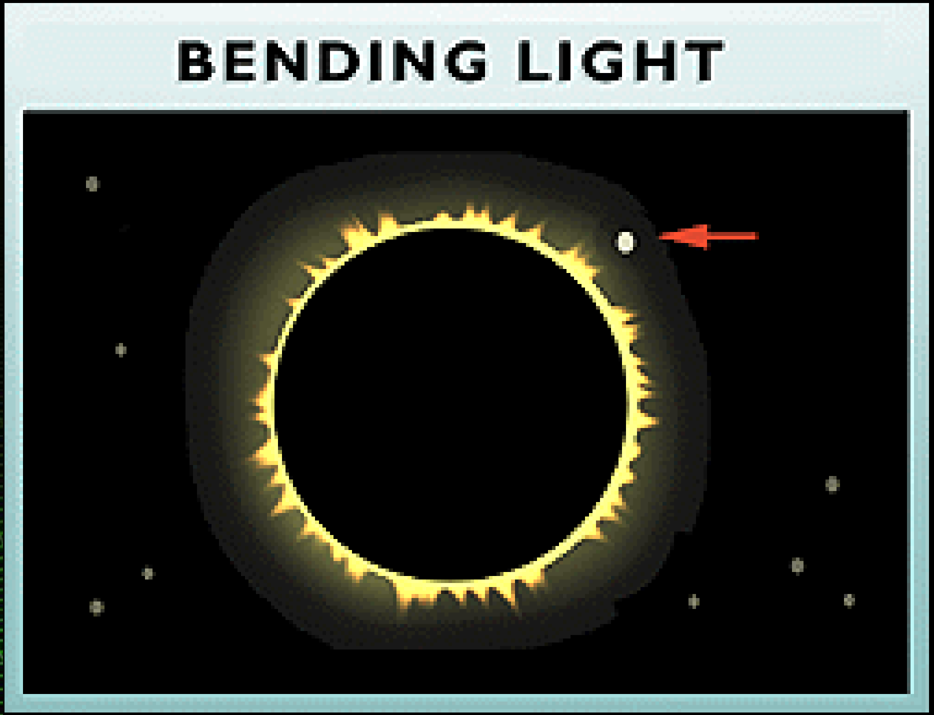


Einstein Eddington

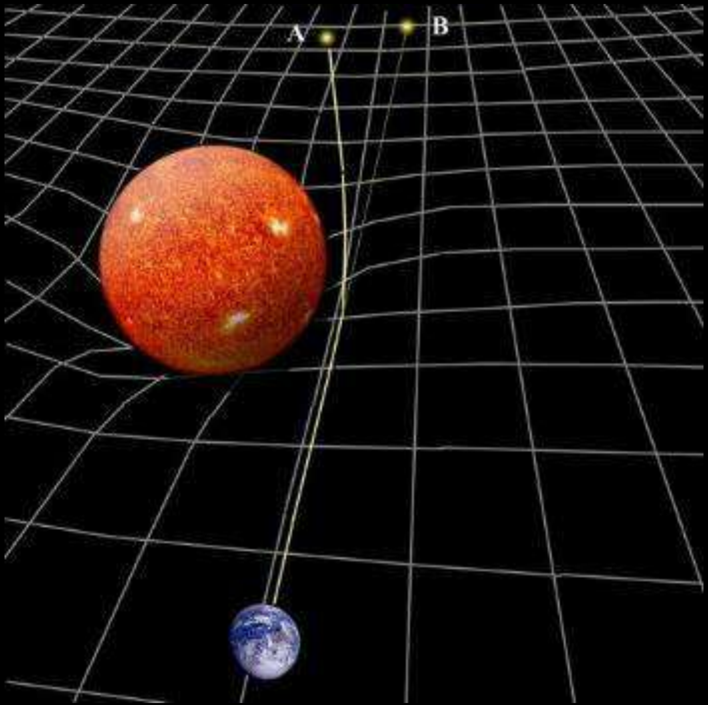
"Not only is the universe stranger than we imagine, it is stranger than we can imagine.

Sir Arthur Eddington





First observed during the solar eclipse of 1919 by Sir Arthur Eddington, when the Sun was silhouetted against the Hyades star cluster



The New York Times.

LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

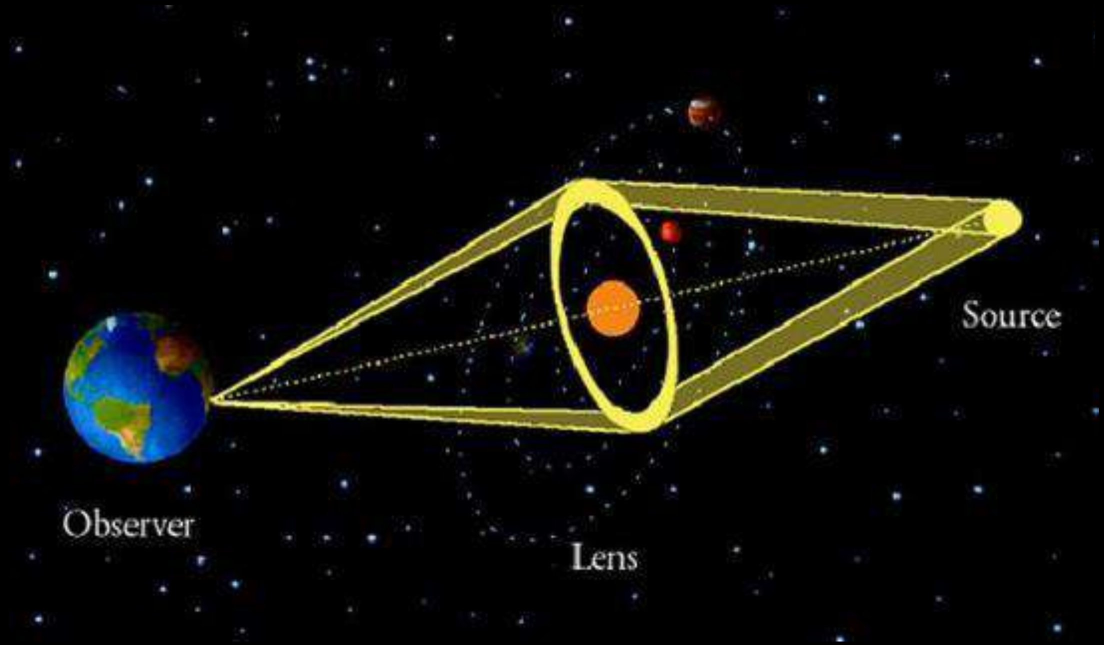
A BOOK FOR 12 WISE MEN

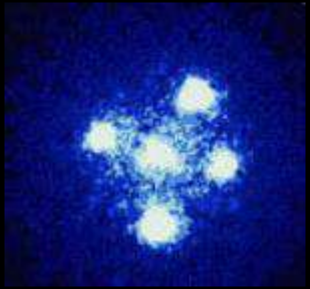
No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

Thompson states that the difference between theories of Newton and those of Einstein are infinitesimal in a popular sense, and as they are purely mathematical and can only be expressed in strictly scientific terms it is useless to endeavor to detail them for the man in the street.

"What is easily understandable," he continued, "is that Einstein predicted the deflection of the starlight when it passed the sun, and the recent eclipse has provided a demonstration of the correctness of the prediction.

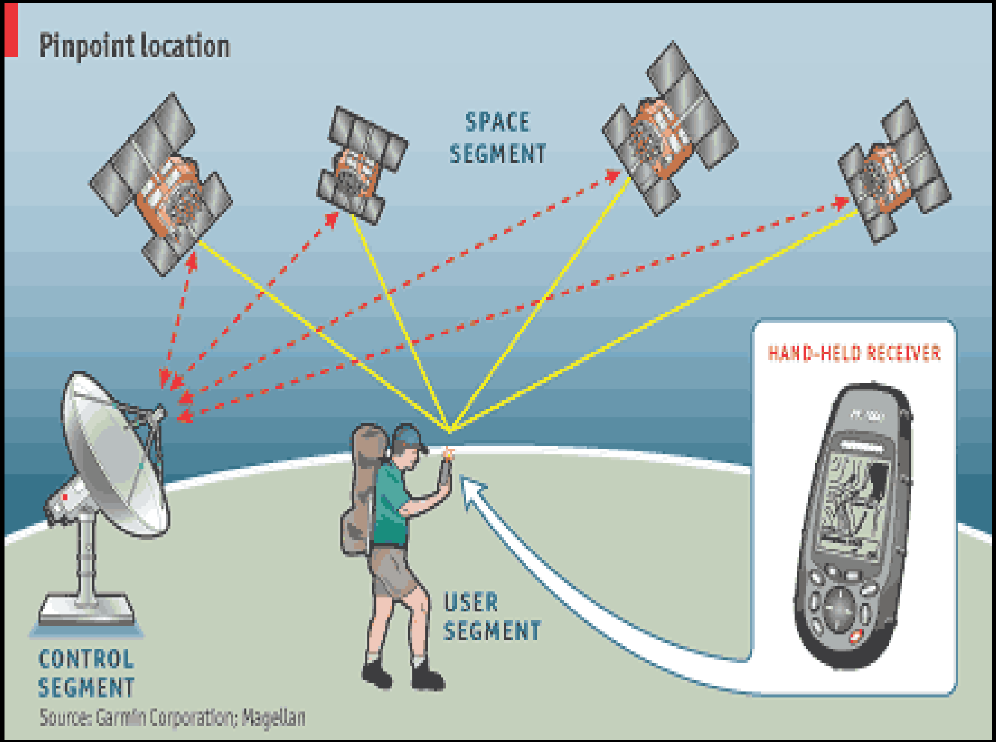
In Modern Astronomy: Gravitational Lensing





Einstein Cross

GPS: General Relativity in Everyday Life



Special Relativity

(Satellites v = 14,000 km/hour

"moving clocks tick more slowly"

Correction = - 7 microsec/day

General Relativity

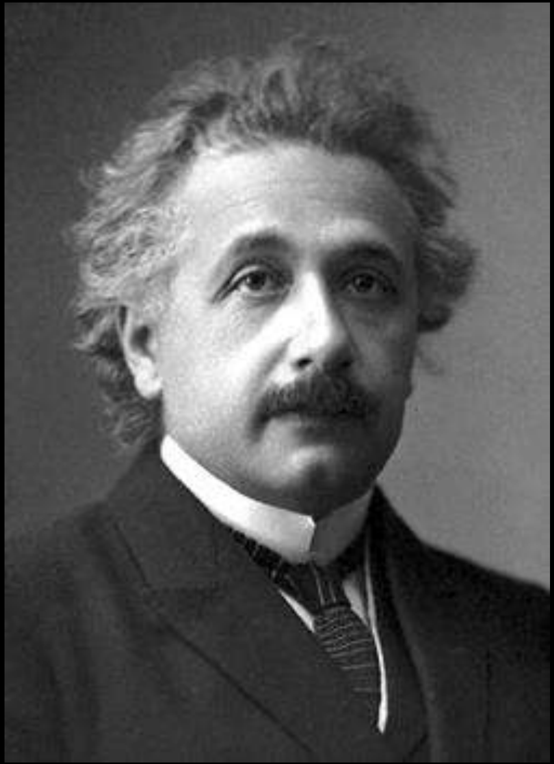
Gravity: Satellites = 1/4 x Earth

Clocks faster = + 45 microsec/day

GPS Correction = + 38 microsec/day

(Accuracy required ~ 30 nanoseconds to give 10 meter resolution

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

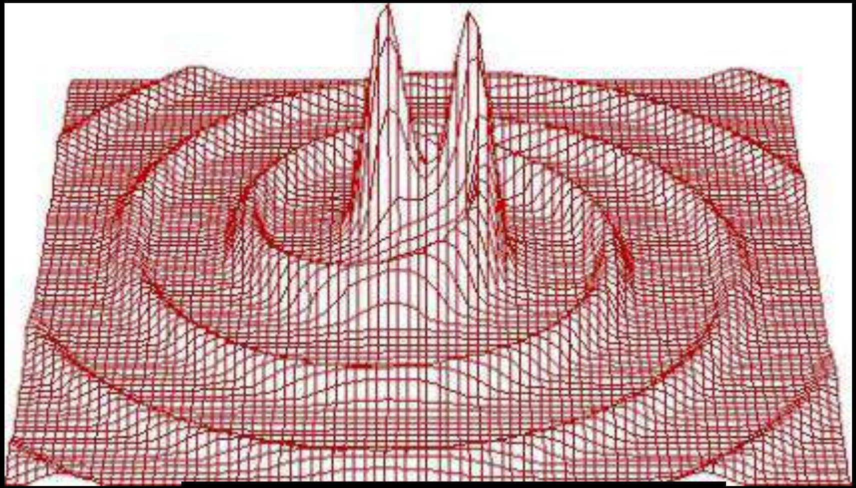
$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

- 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 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

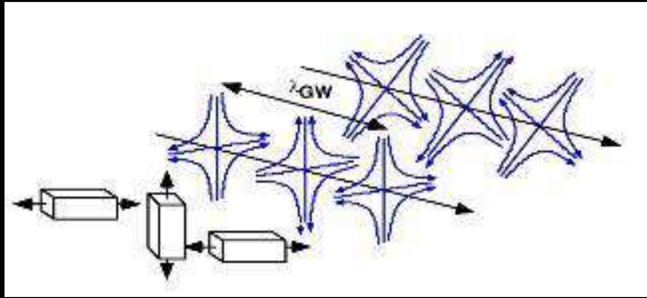
Einstein's Theory of Gravitation

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.

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

The Chapel Hill Conference

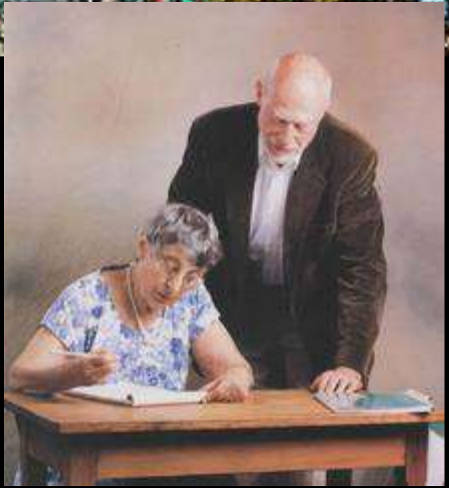
Could the waves be a coordinate effect only, with no physical reality? Einstein didn't live long enough to learn the answer.

In January 1957, the U.S. Air Force sponsored the *Conference on the Role of Gravitation in Physics*, a.k.a. the Chapel Hill Conference, a.k.a. GR1.

The organizers were Bryce and Cecile DeWitt. 44 of the world's leading relativists attended.

The "gravitational wave problem" was solved there, and the quest to detect gravitational waves was born.

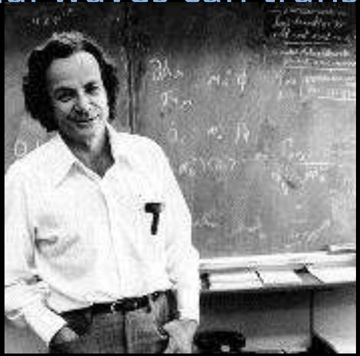
(Pirani, Feynman and Babson)

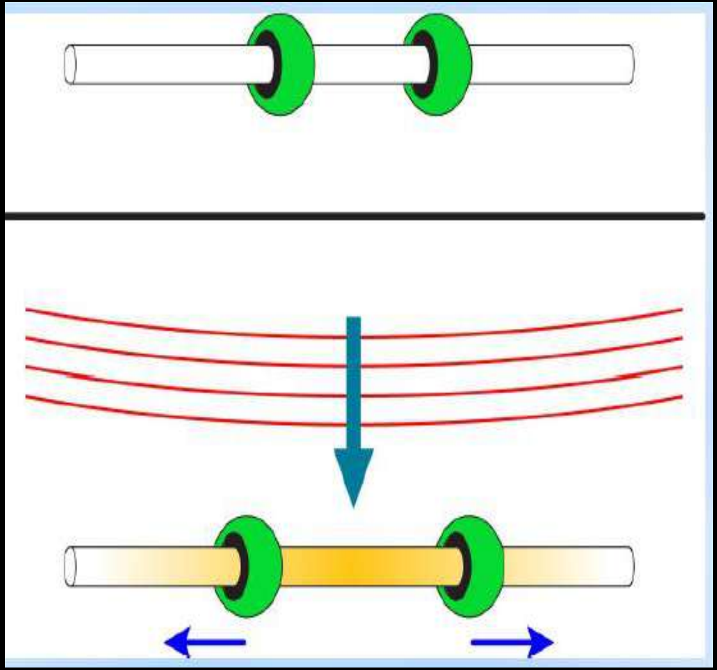


Agreement: Gravitational Waves are Real

- Felix Pirani presentation: relative acceleraton of particle pairs can be associated with the Riemann tensor. The interpretation of the attendees was that non-zero components of the Riemann tensor were due to gravitational waves.

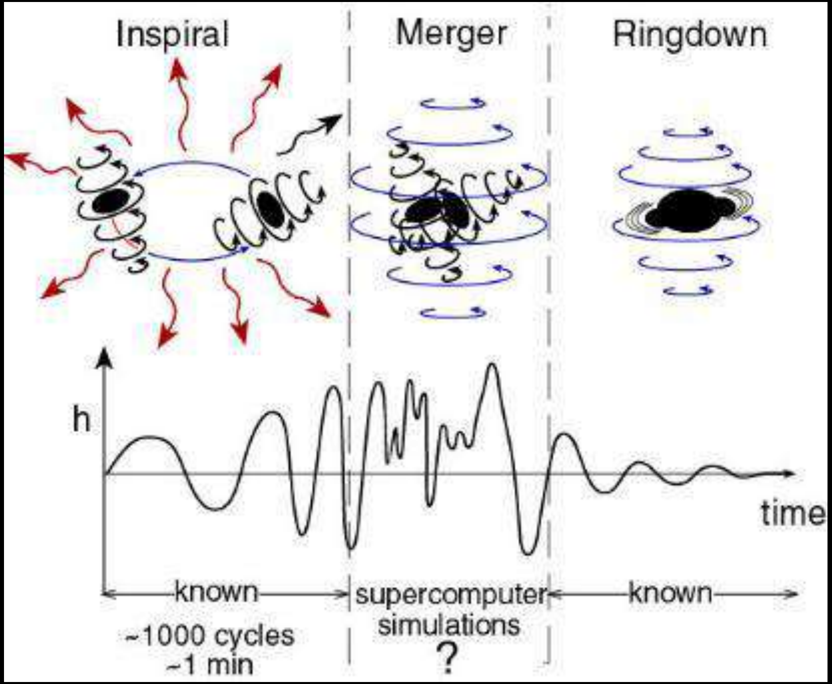
- Sticky bead argument (Feynman)
  - Gravitational waves can transfer energy?



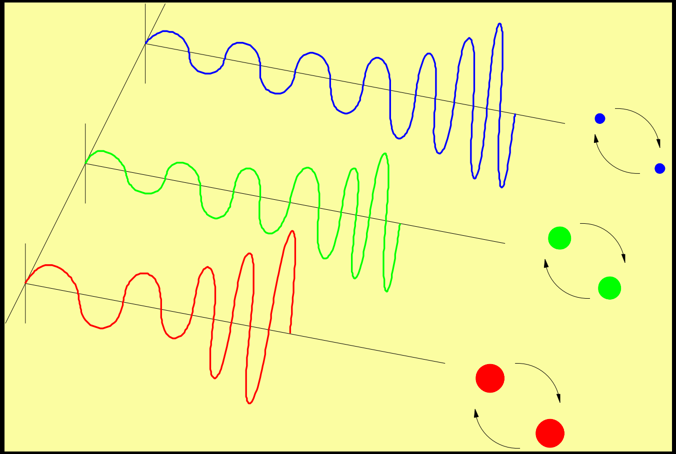


How to Detect Gravitational Waves

Compact Binary Collisions



- Neutron Star – Neutron Star
  - **waveforms are well described**
- Black Hole – Black Hole
  - **Numerical Relativity waveforms**
- Search: *matched templates*

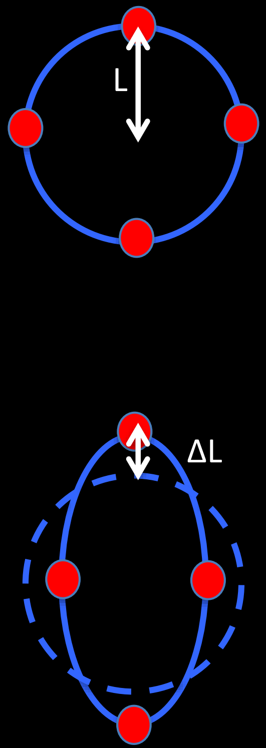


“chirps”

Gravitational Waves

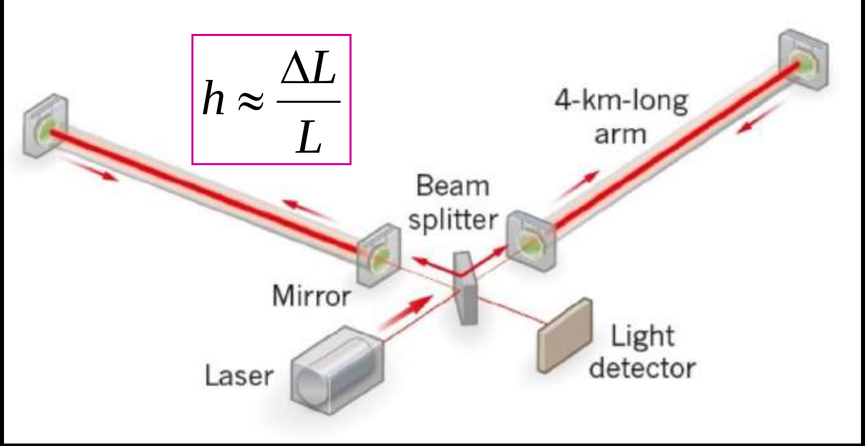
- Ripples of spacetime that stretch and compress spacetime itself
- The amplitude of the wave is h ≈ 10^{-21}
- Change the distance between masses that are free to move by $\Delta L = h \times L$
- Spacetime is "stiff" so changes in distance are very small

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

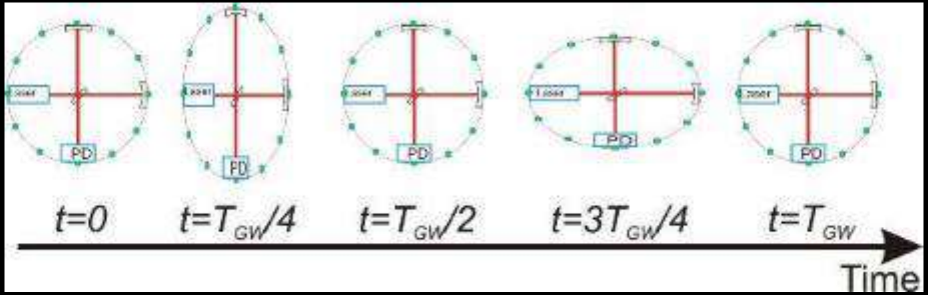


LIGO: Measurement Scheme

- 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
-

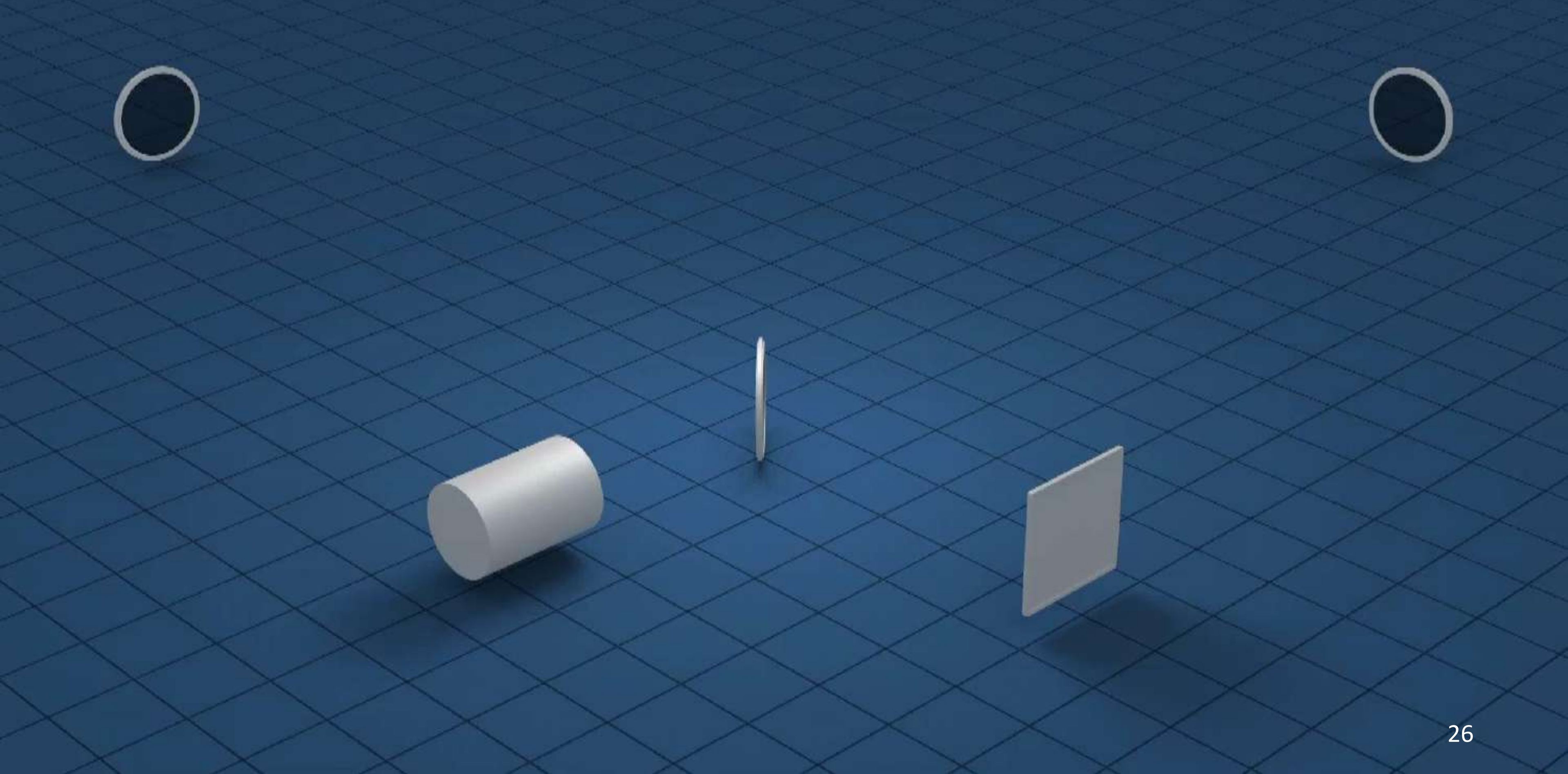


Magnitude of h at Earth: Detectable signals h ~ 10^{-21}
For L = 4km, **ΔL= 4x10^{-18} m**



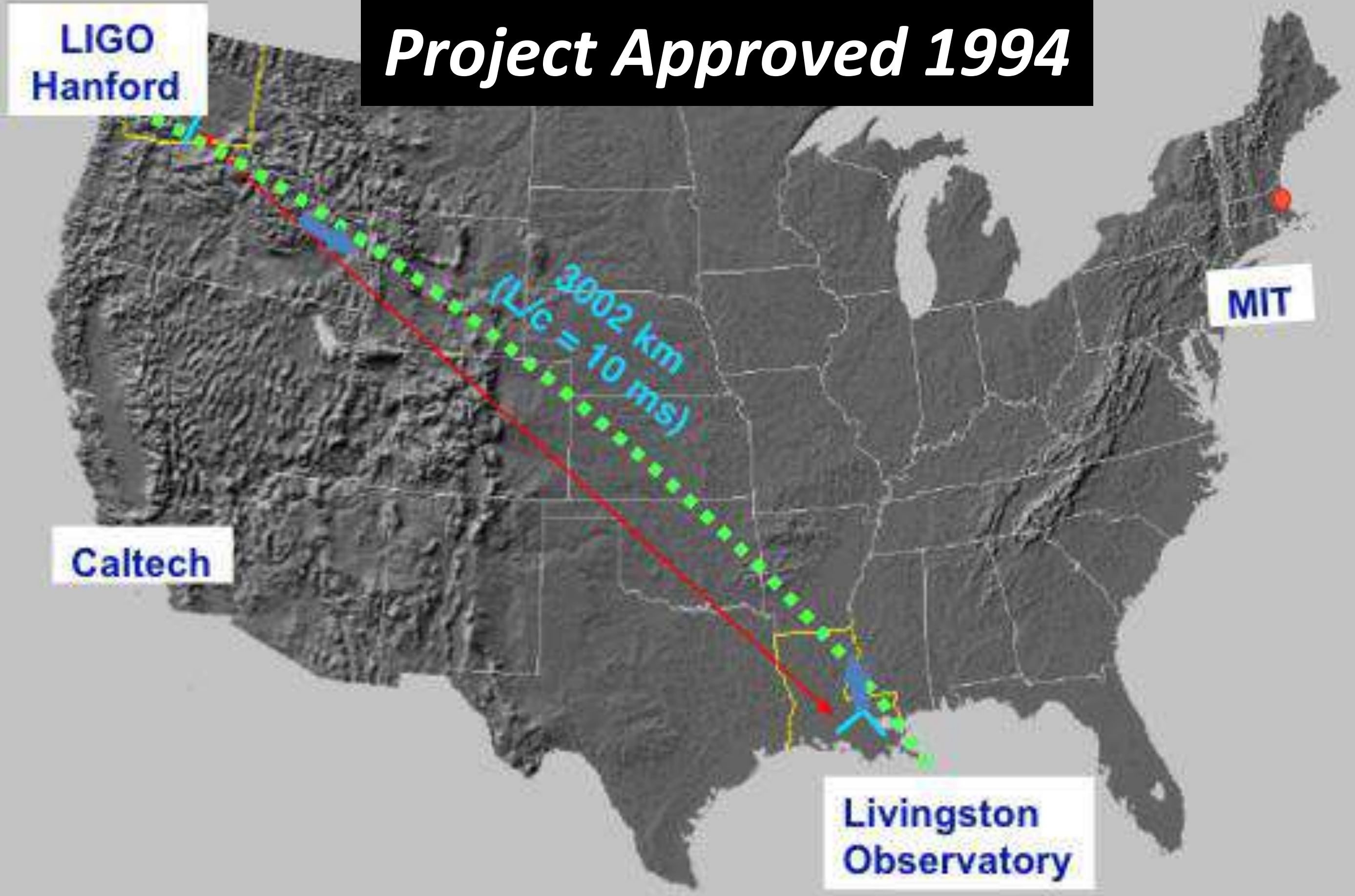
Credit: LIGO/T. Pyle

Interferometry – The scheme



LIGO Sites

Project Approved 1994

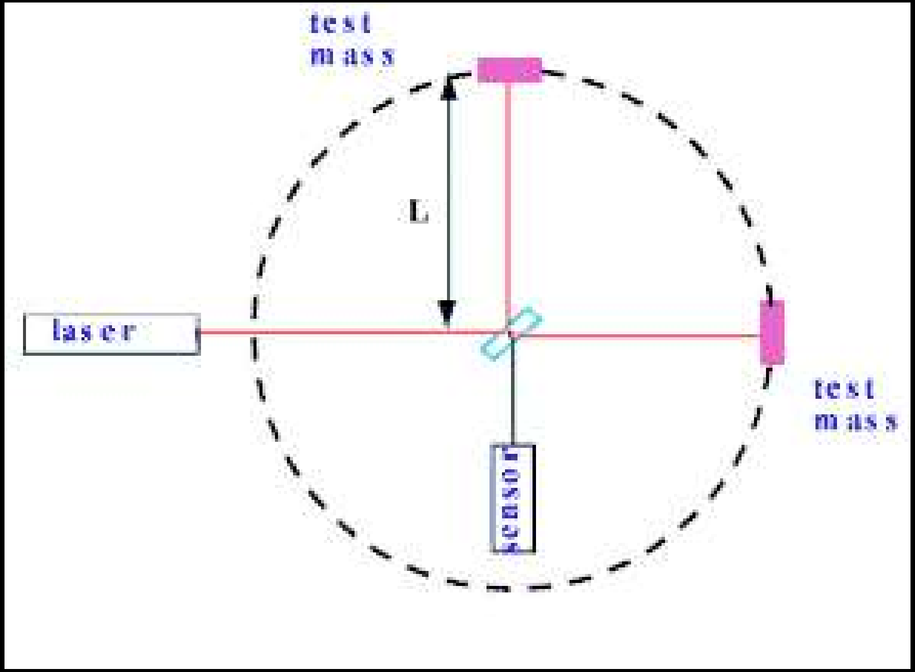


LIGO Interferometers

Hanford, WA

Livingston, LA

Suspended Mass Interferometry



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

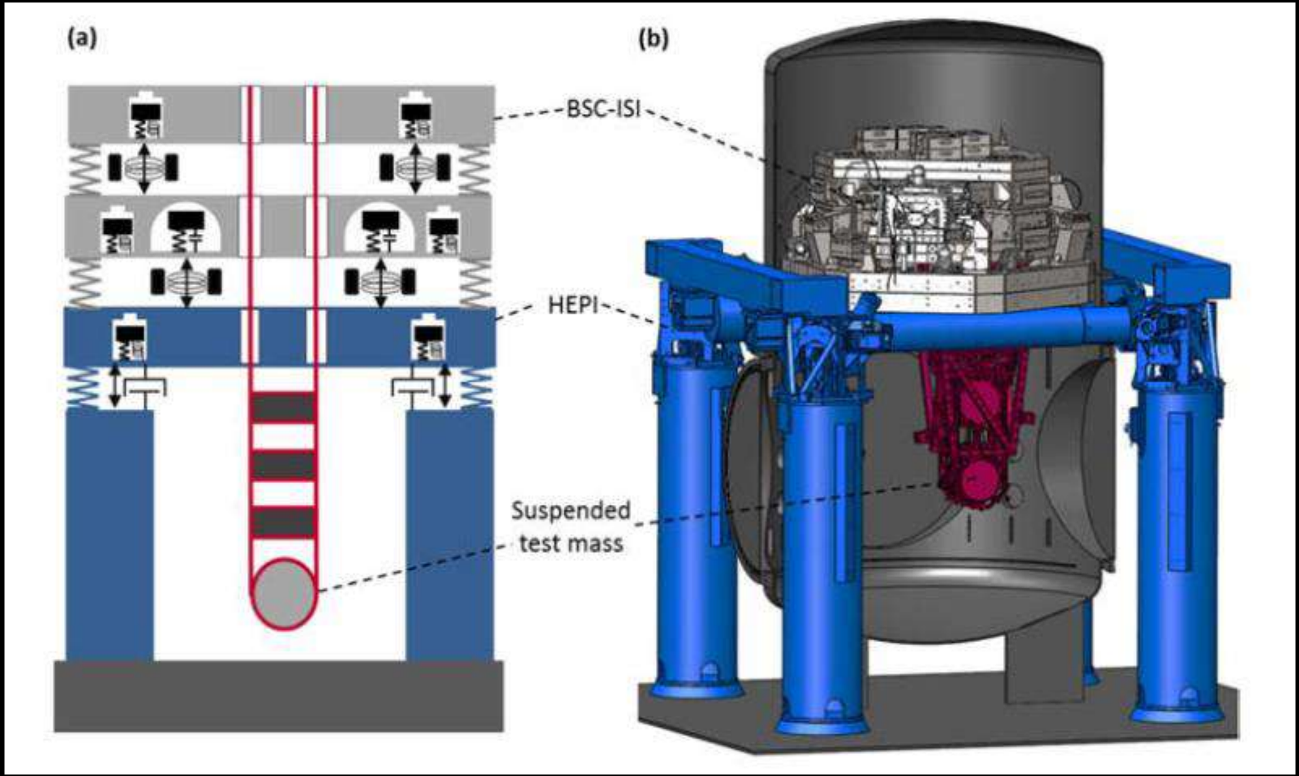
$$L = 4km \quad DL \leq 4x10^{-18} \text{meters}$$

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

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

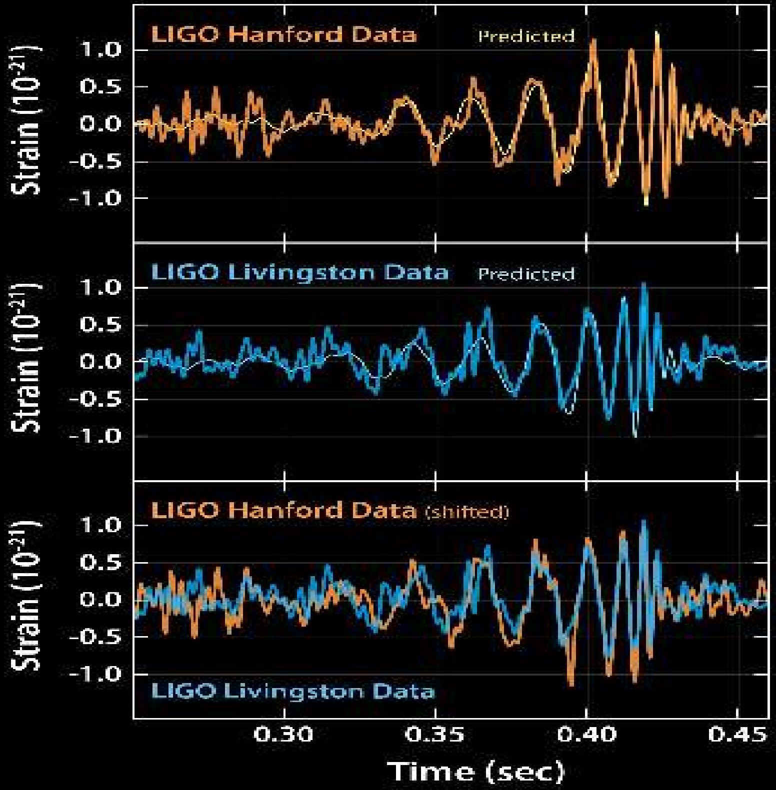
Passive / Active Multi-Stage Isolation

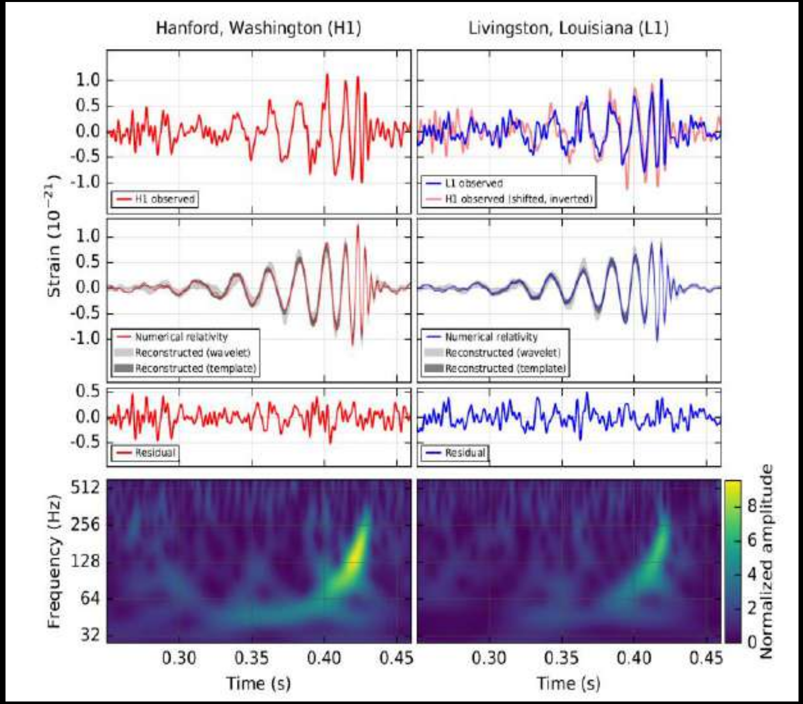
Advanced LIGO



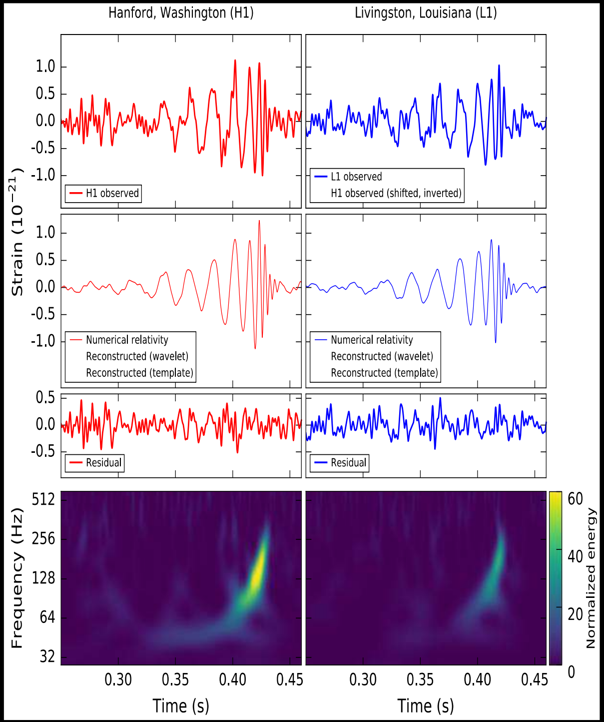
Gravitational Wave Detections

Black Hole Merger: GW150914





Measuring the parameters



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

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

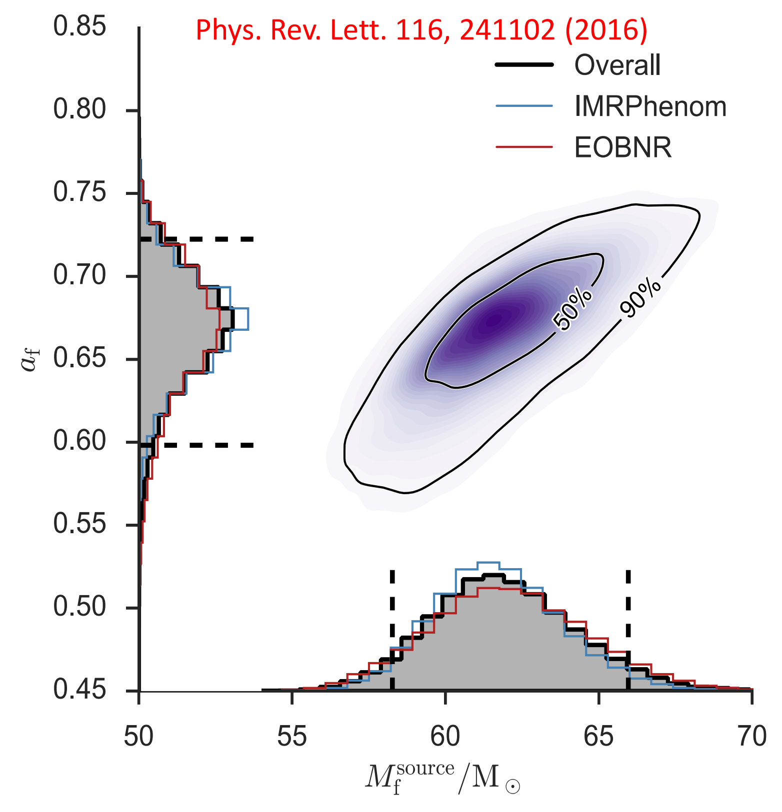
  - Next orders allow for measurement of mass ratio and spins
  - We directly measure the red-shifted masses (1+z) m
  - Amplitude inversely proportional to luminosity distance
- Orbital precession occurs when spins are misaligned with orbital angular momentum – no evidence for precession.
- Sky location,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

Black Hole Merger Parameters for GW150914

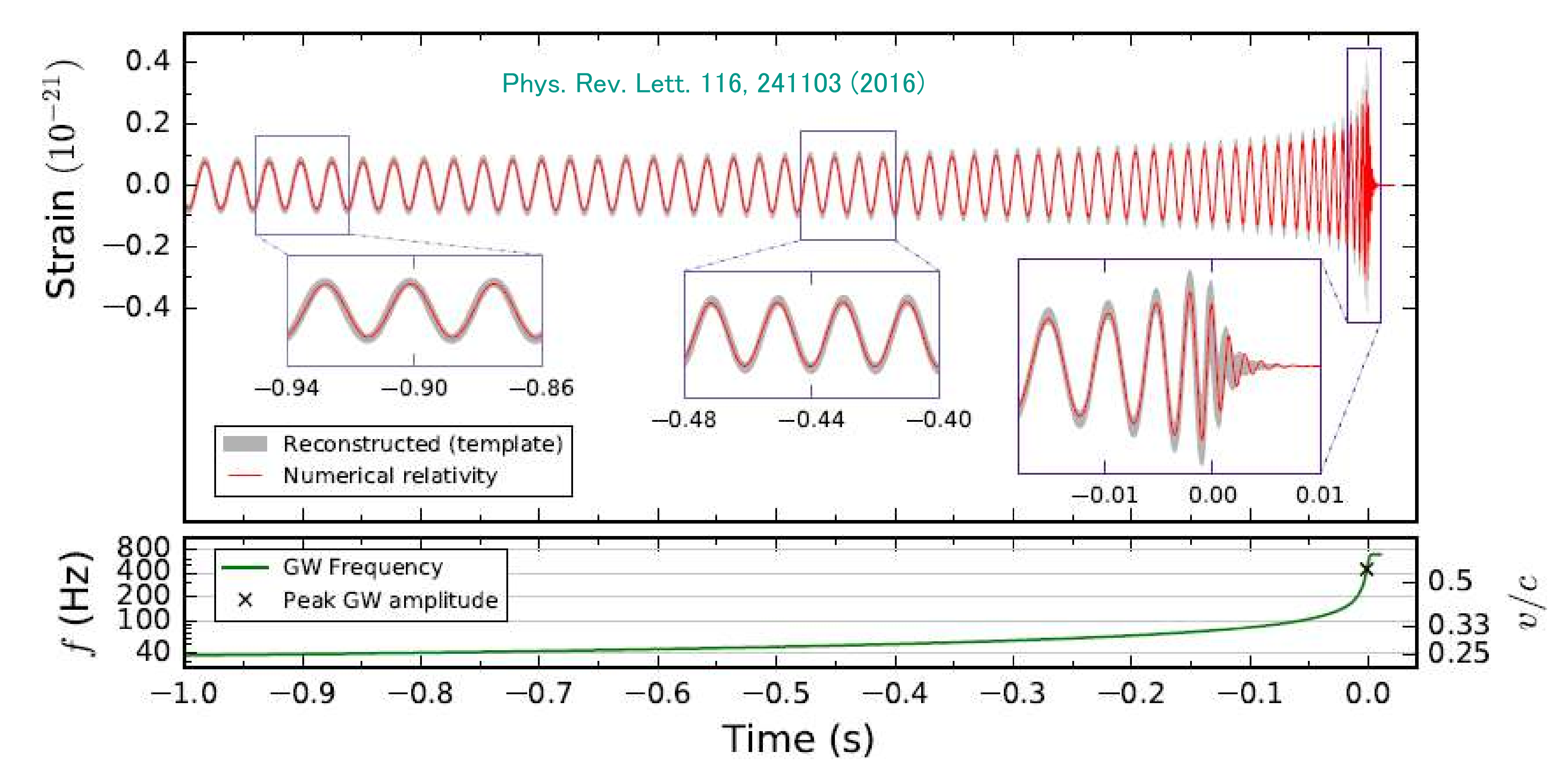
- Use numerical simulations fits of black hole merger to determine parameters; determine total energy radiated in gravitational waves is 3.0±0.5 $M_o c^2$. The system reached a peak ~3.6 x10^{56} ergs, and the spin of the final black hole < 0.7 (not maximal spin)

Primary black hole mass	$36^{+5}_{-4}\ M_\odot$
Secondary black hole mass	$29^{+4}_{-4}\ M_\odot$
Final black hole mass	$62^{+4}_{-4}\ M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift, z	$0.09^{+0.03}_{-0.04}$

Phys. Rev. Lett. 116, 061102 (2016)



“Second Event” Inspiral and Merger GW151226



Testing General Relativity – Dispersion Term?

- In GR, there is no dispersion!

Add dispersion term of form

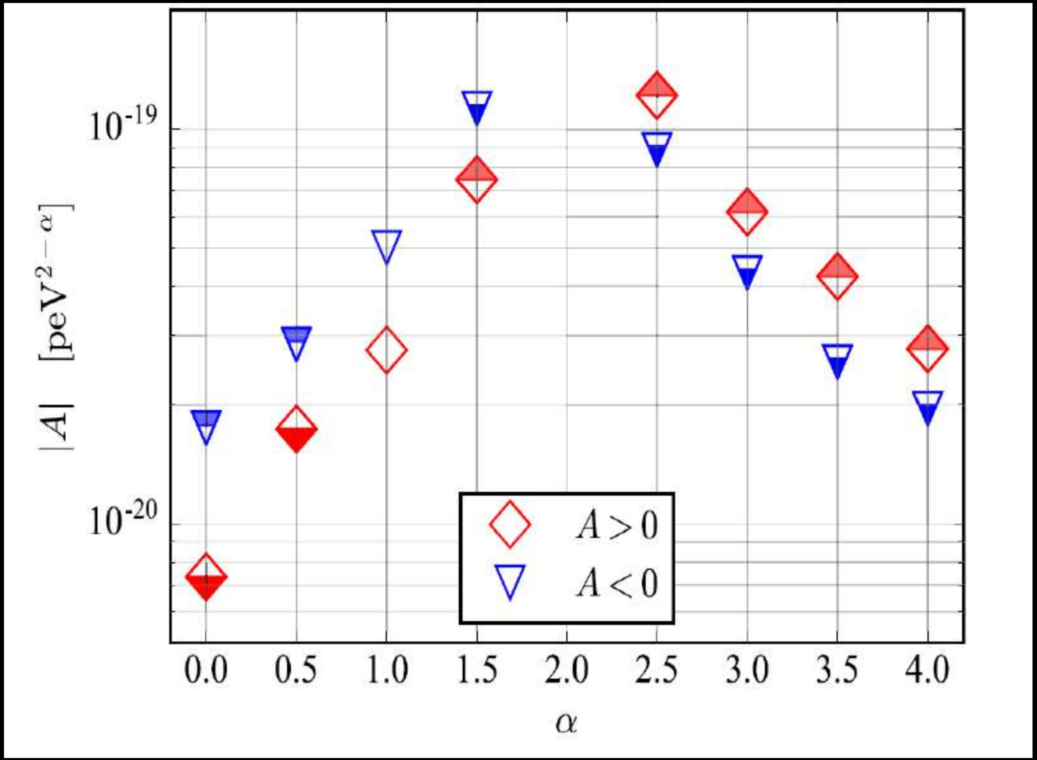
$$E^2 = p^2c^2 + Ap^{\alpha}c^{\alpha}, \quad \alpha \geq 0$$

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

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

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

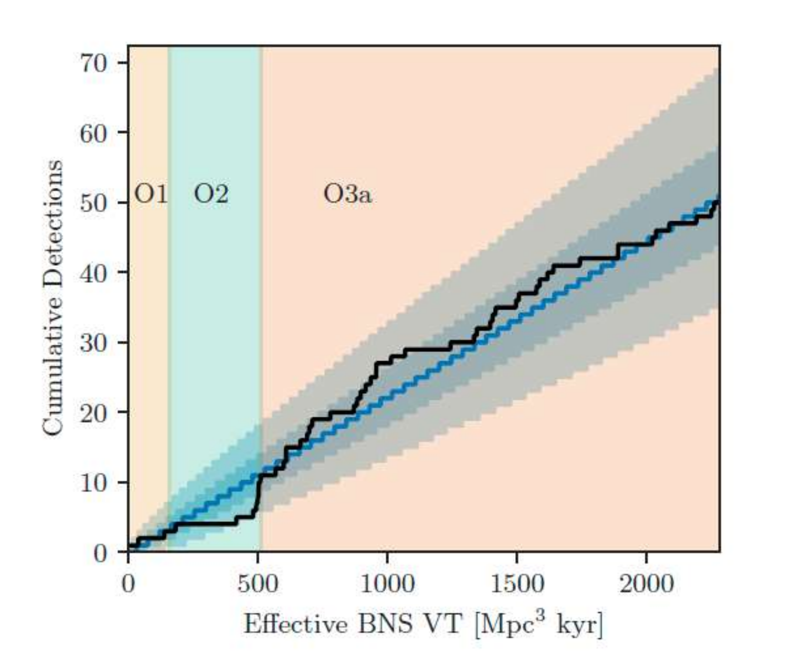
- Null tests to quantify generic deviations from GR

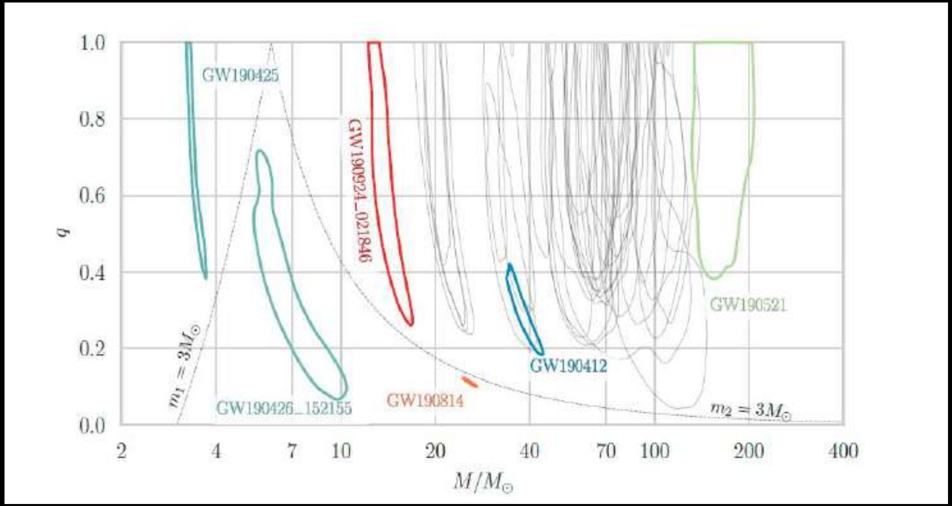


PhysRevLett.118.221101

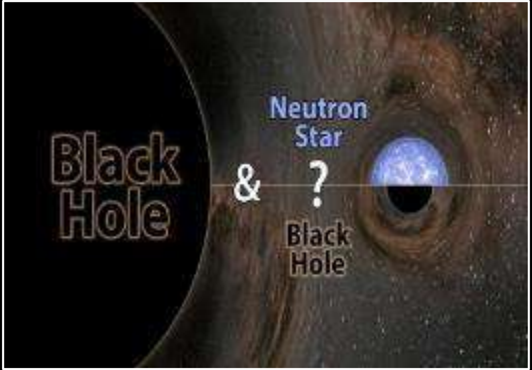
~14 $M_\odot$ for GW190924_021846 to ~150 $M_\odot$ for GW190521

Distributions of BH-BH events

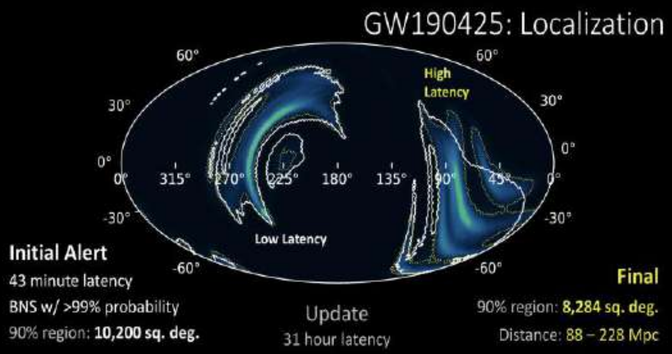


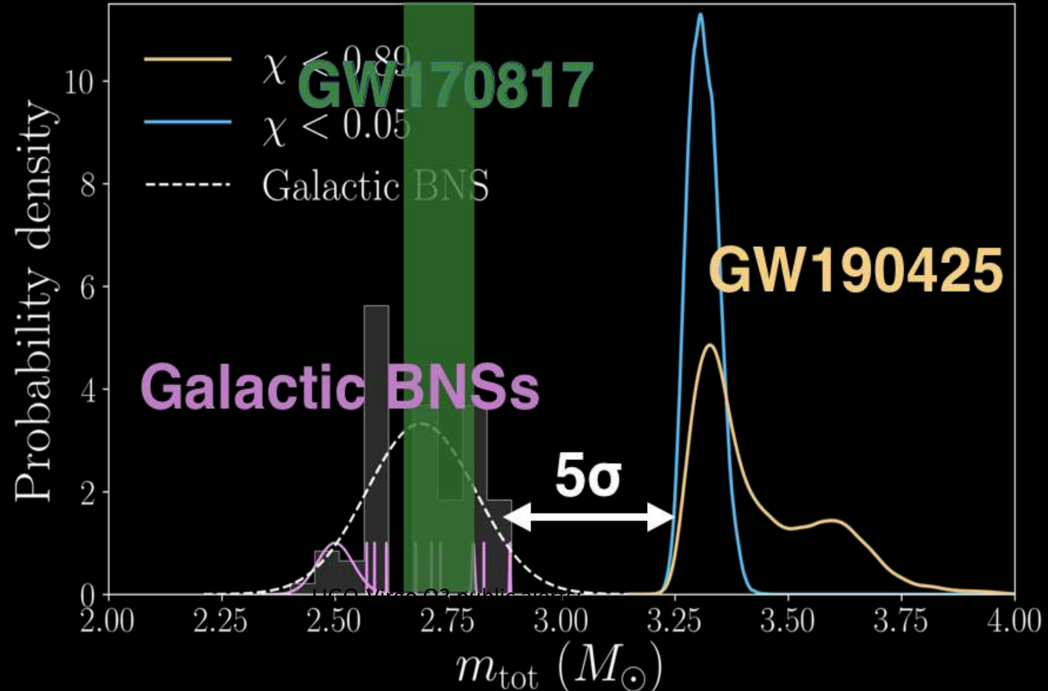


- **Total Masses** from 14 solar masses to 150 solar masses



Exceptional Events





The signal was detected by only the LIGO Livingston interferometer

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

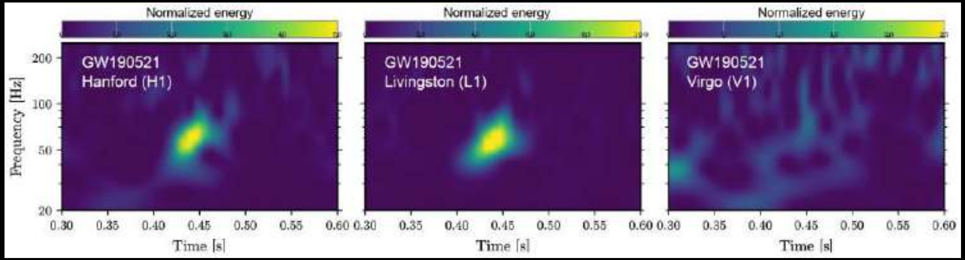
The combined mass of the neutron stars is greater than all known neutron star binaries (galactic, GW170817)

The Most Massive and Distant Black Hole Merger Yet: GW190521

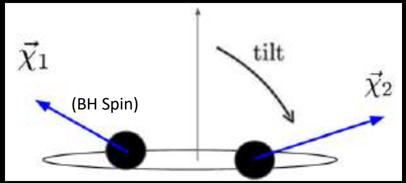
(May 21, 2019)

- 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

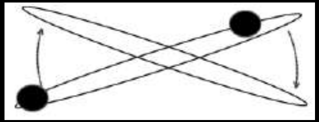
→ Implications for how these black holes formed

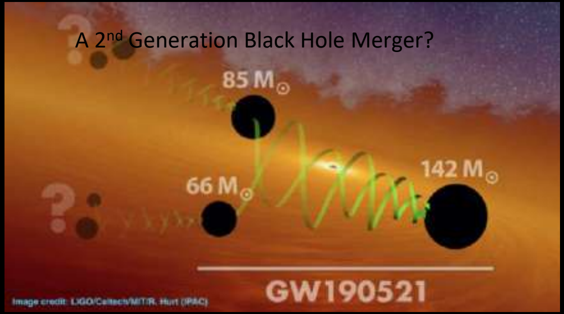


Orbital Angular Momentum

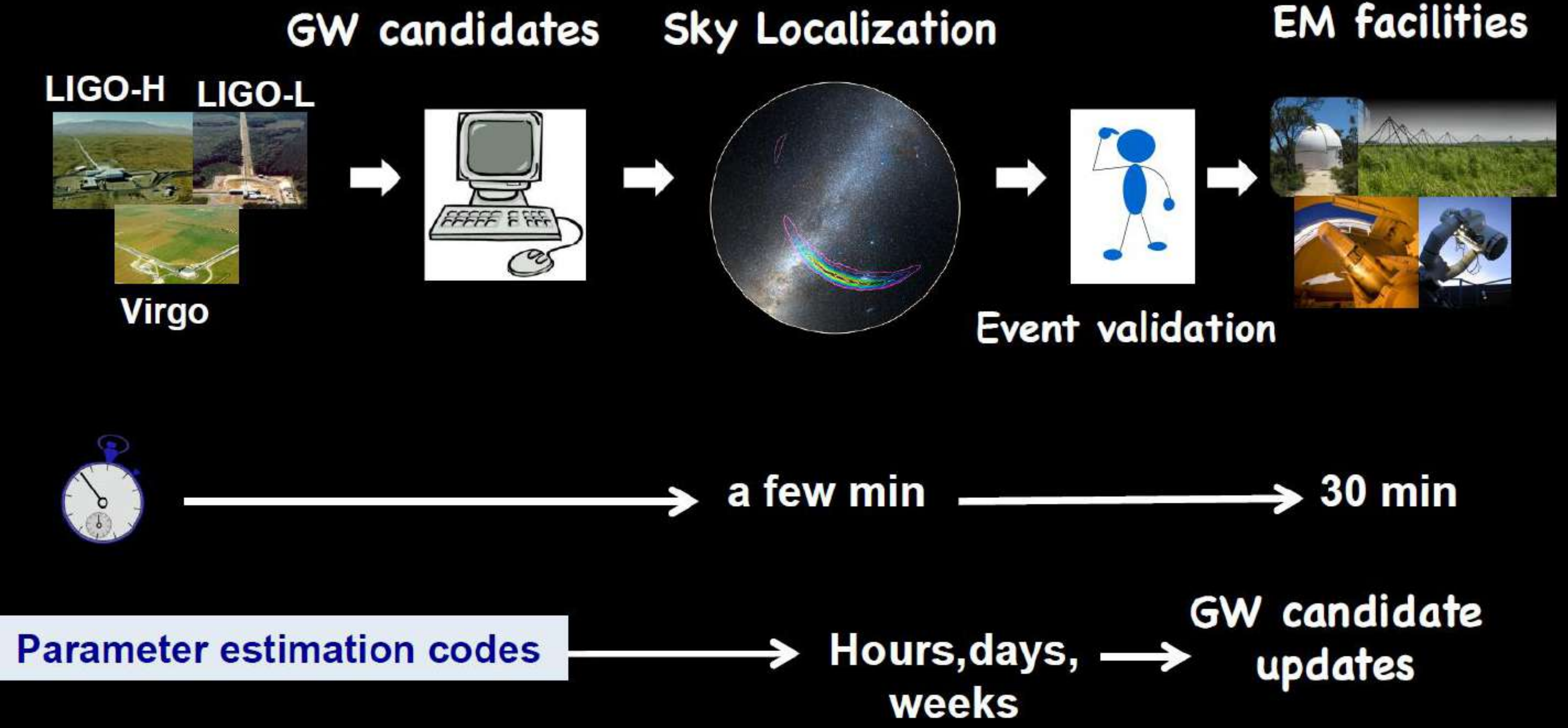


Orbital Plane Precession

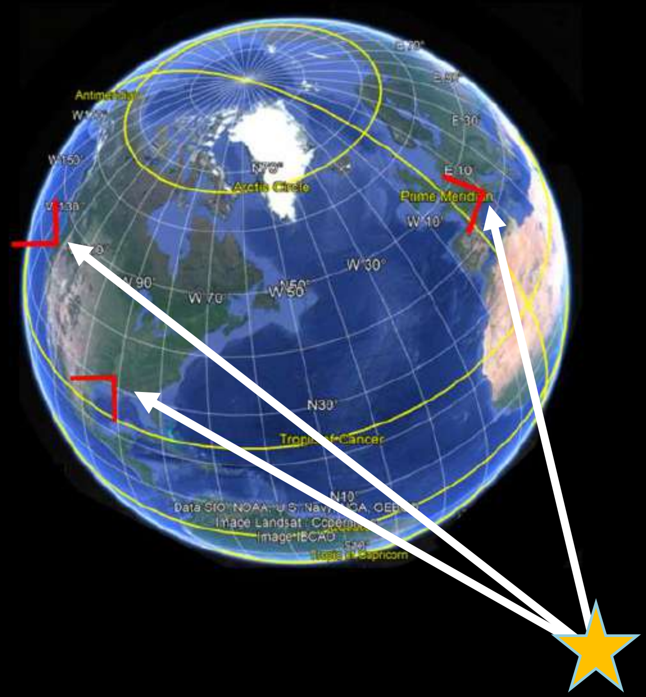




Searching for Electromagnetic Counterparts

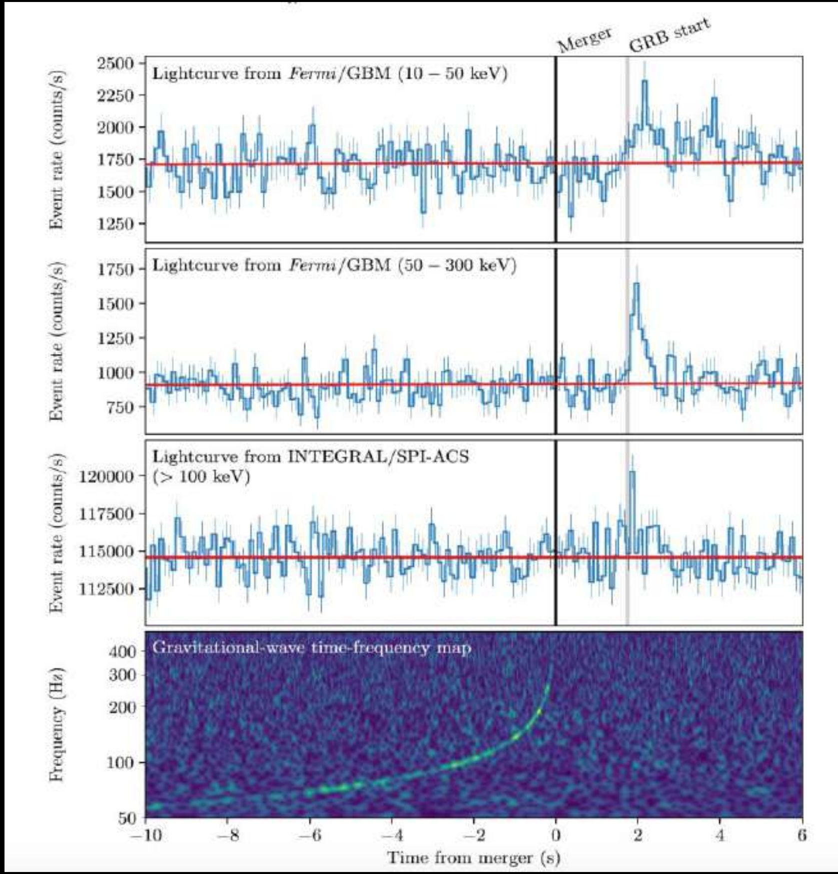


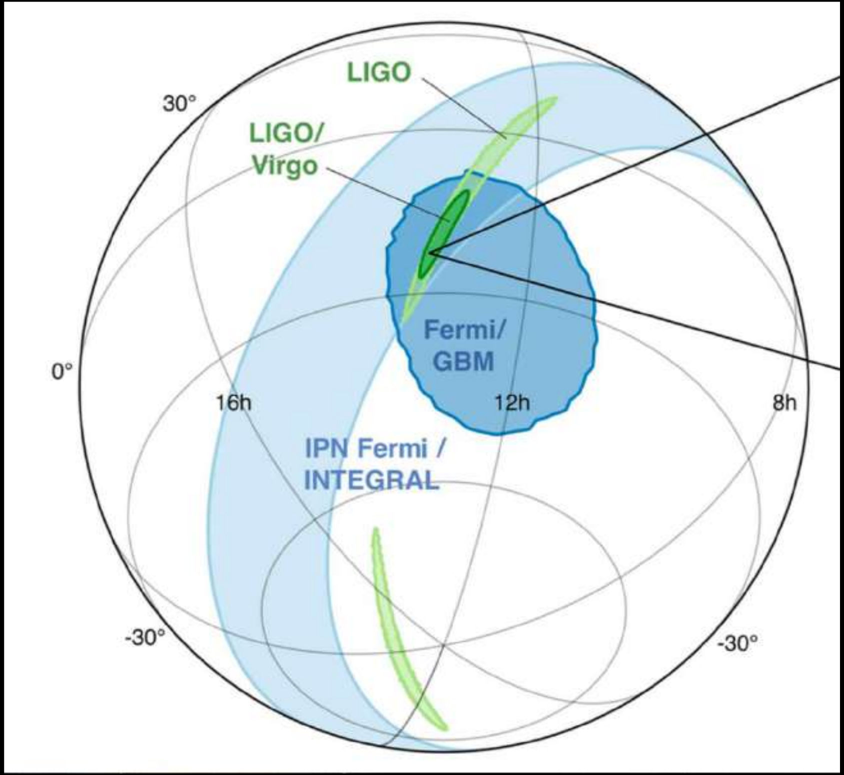
Localizing Gravitational-wave Events



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

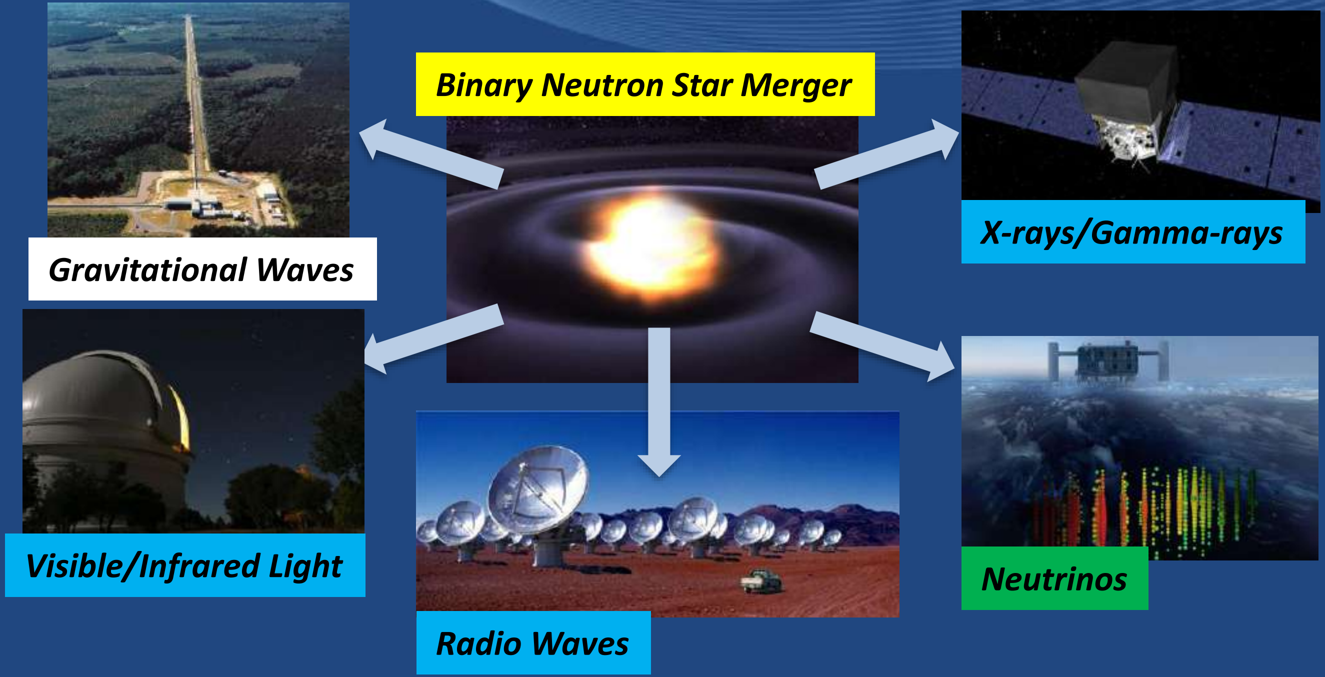
Fermi Satellite GRB detection 1.7 seconds later

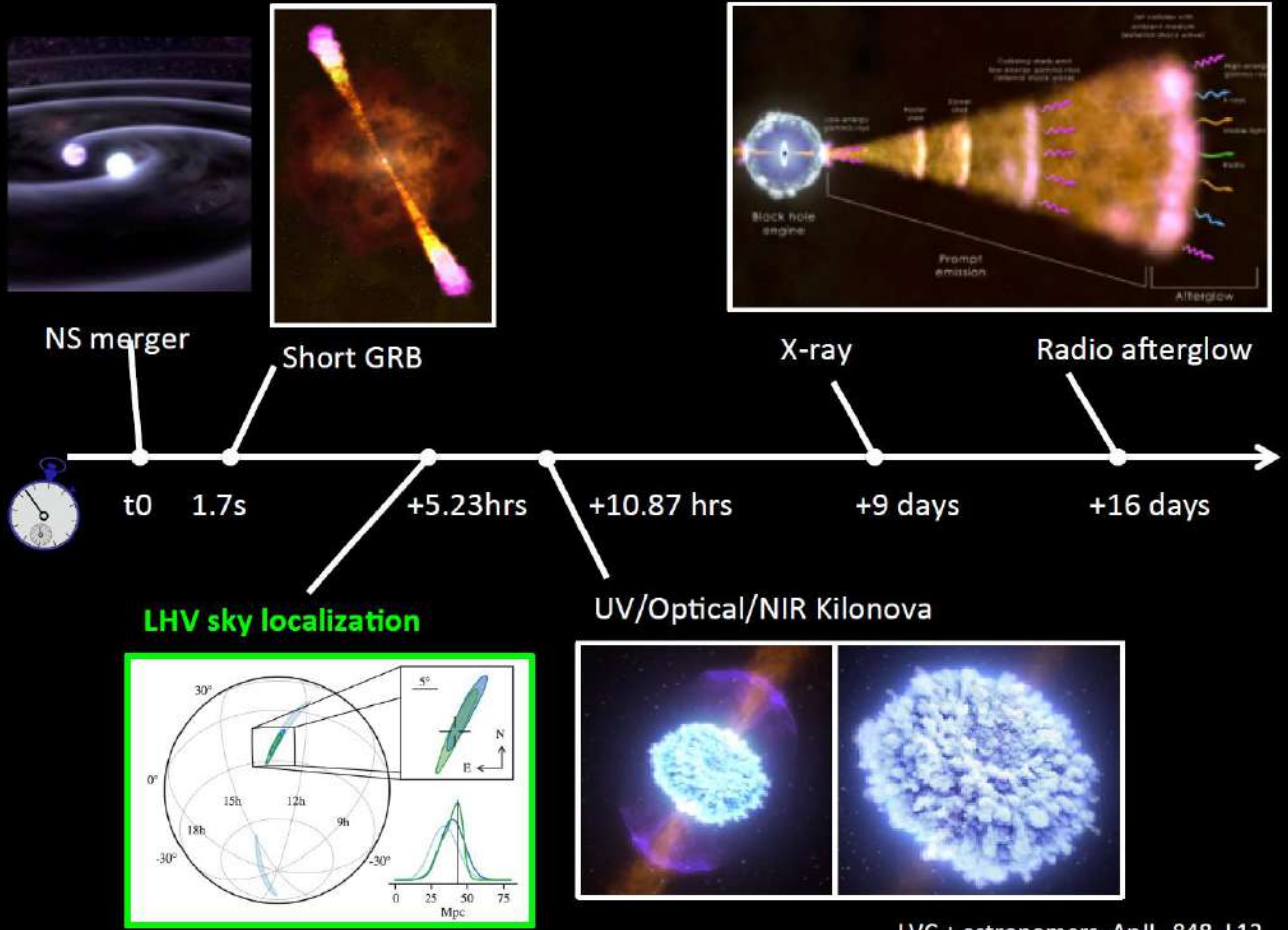




170817A" Astrophys. J. Lett., 848:L13, (2017)

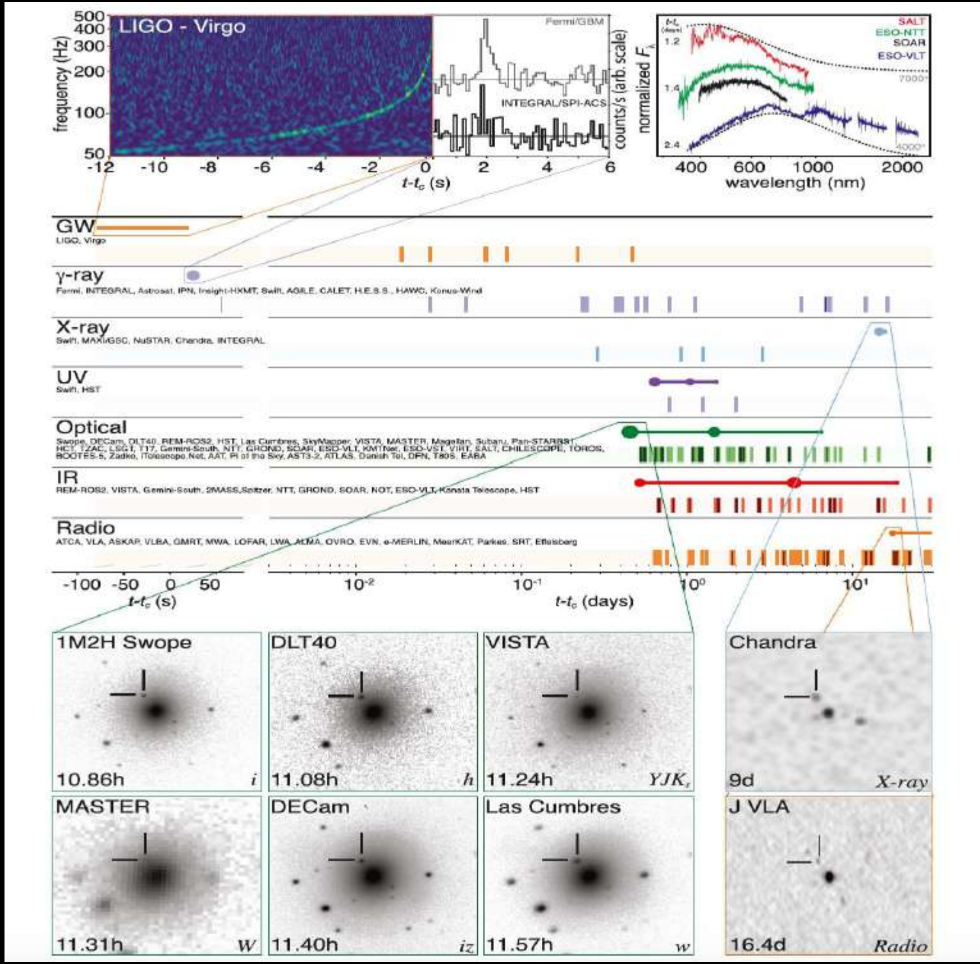
Multi-messenger Astronomy with Gravitational Waves





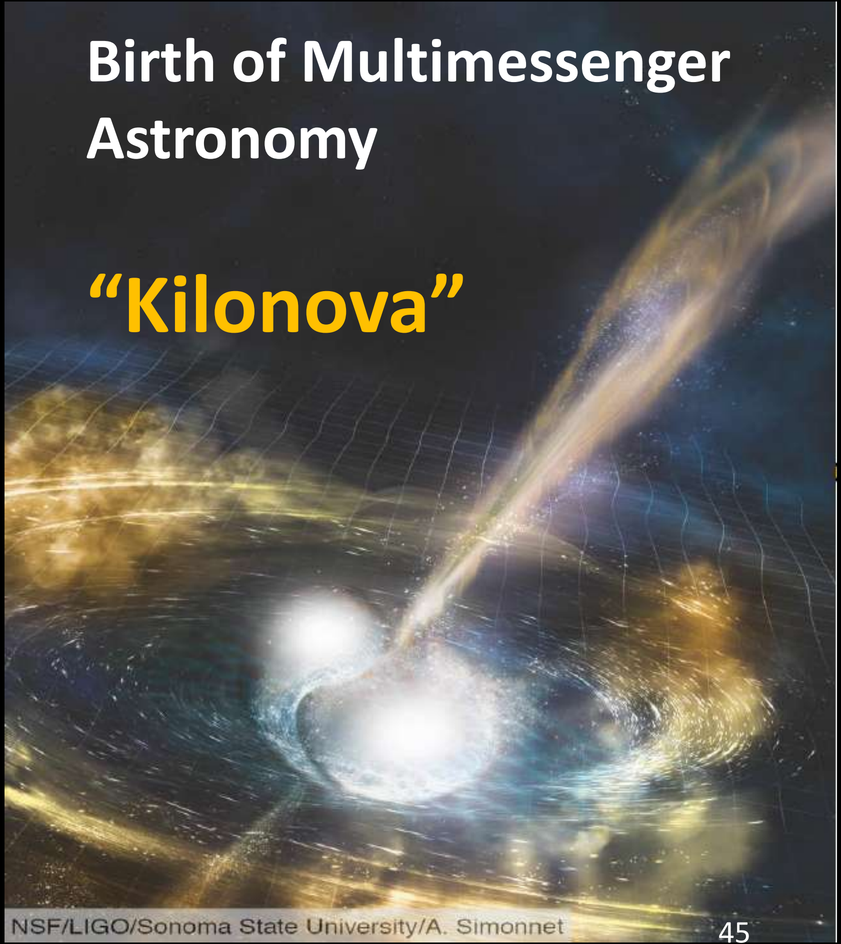
LVC + astronomers, ApJL, 848, L12

Observations Across the Electromagnetic Spectrum

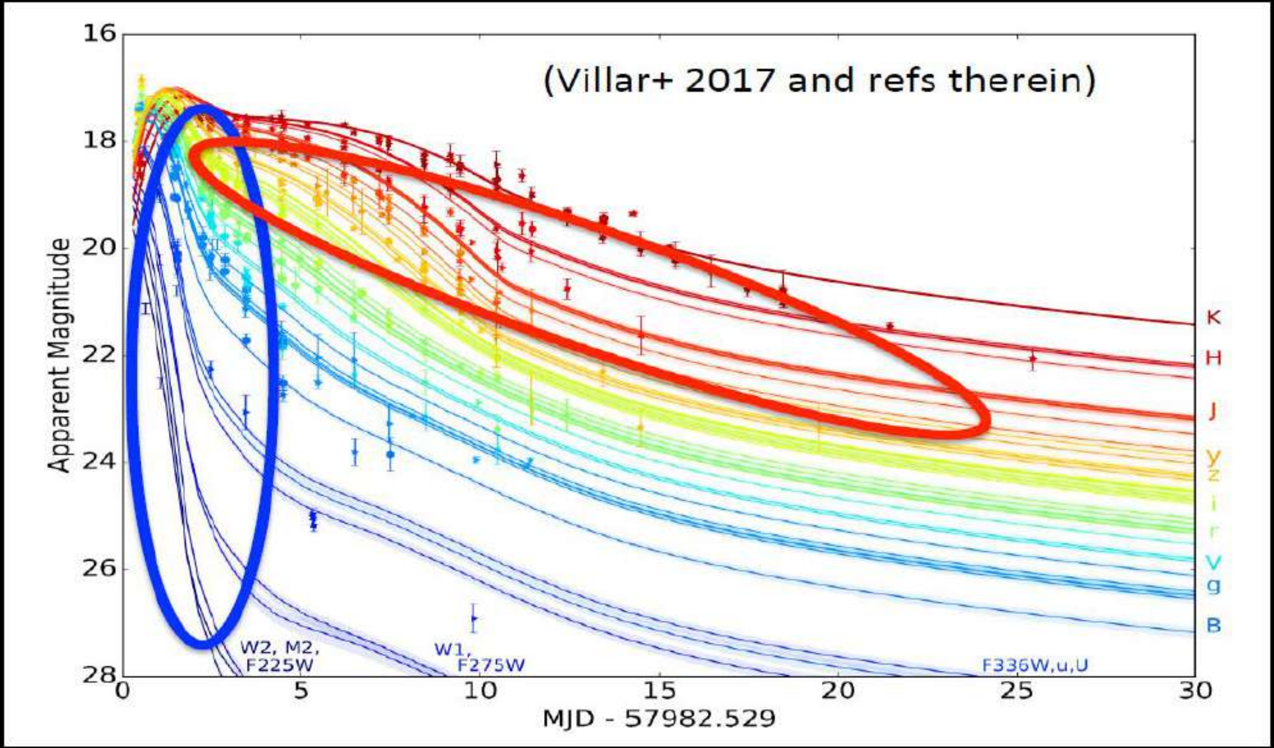


Birth of Multimessenger Astronomy

"Kilonova"



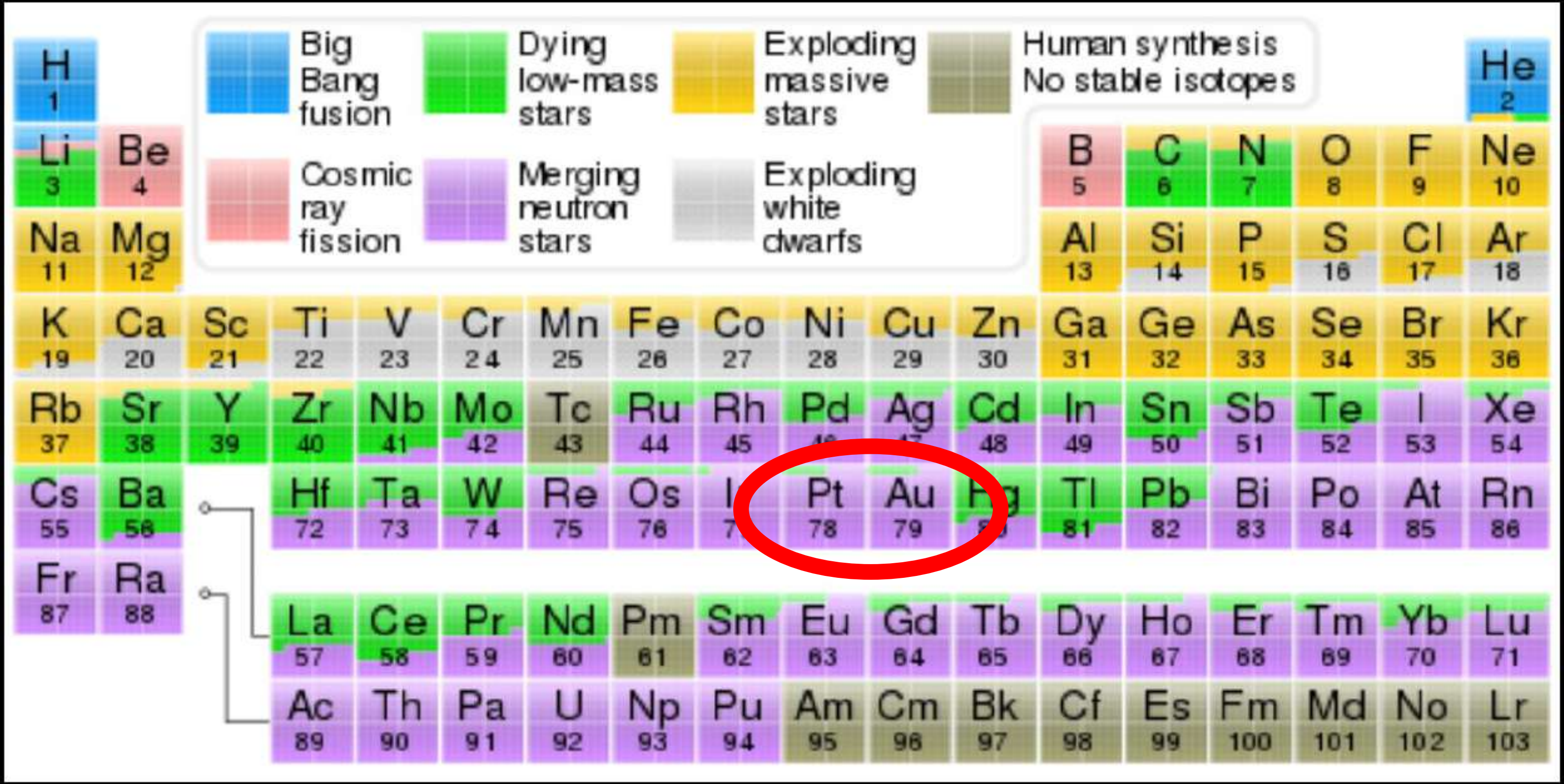
Light Curves



Extremely well characterized photometry of a Kilonova:

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

Origin of the Heavy Elements



NS Mergers are Incredible Gold Factories

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

What the Future Holds

Future 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***

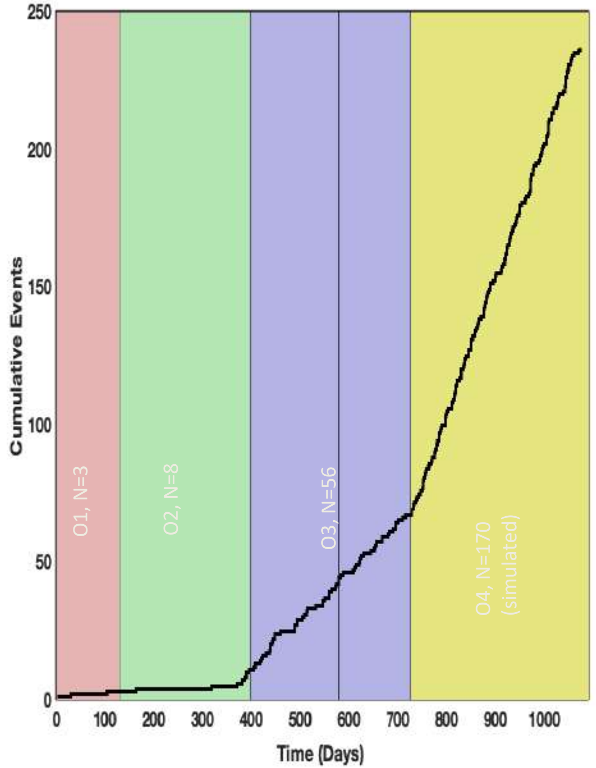
Target sensitivities (binary neutron star inspiral range):

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

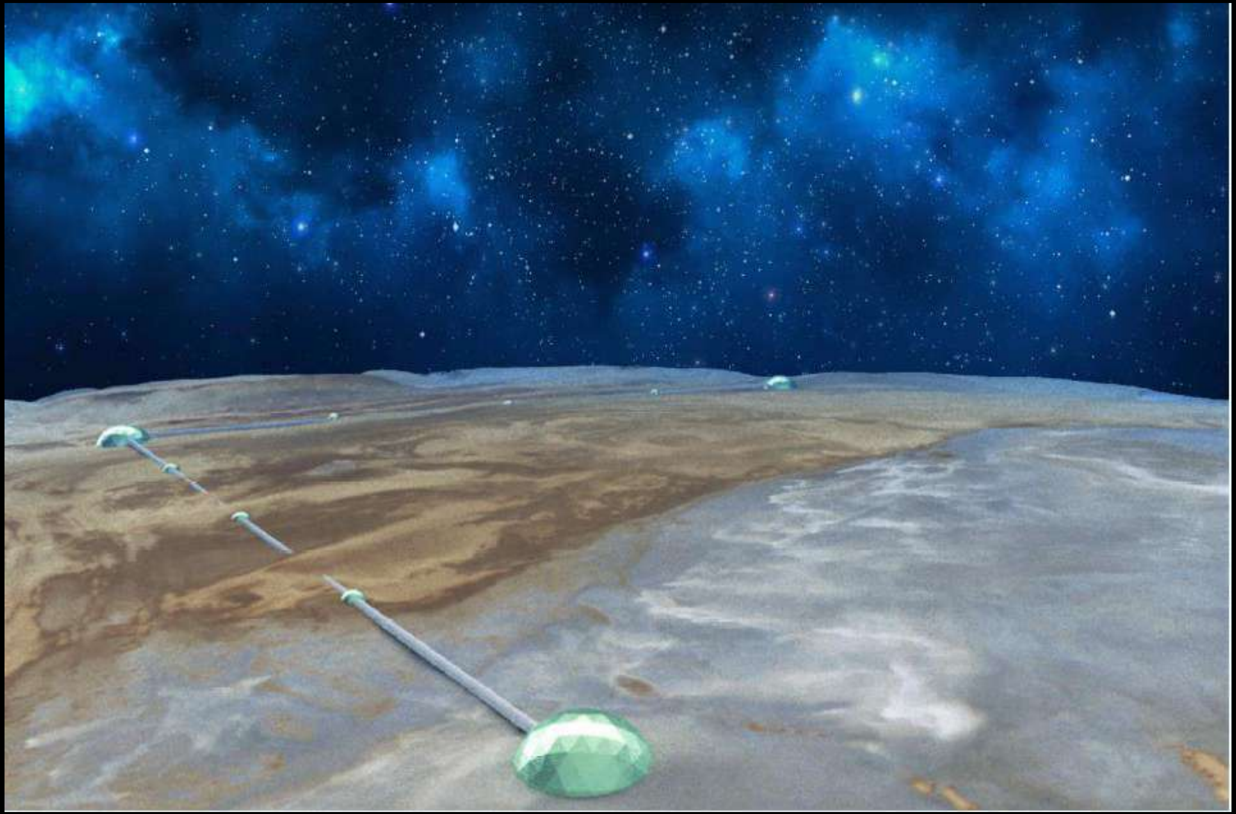
→***A 2X to 3X increase in GW event rate***

O4 will start no earlier than June 2022

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



Proposed 3rd Generation Detectors

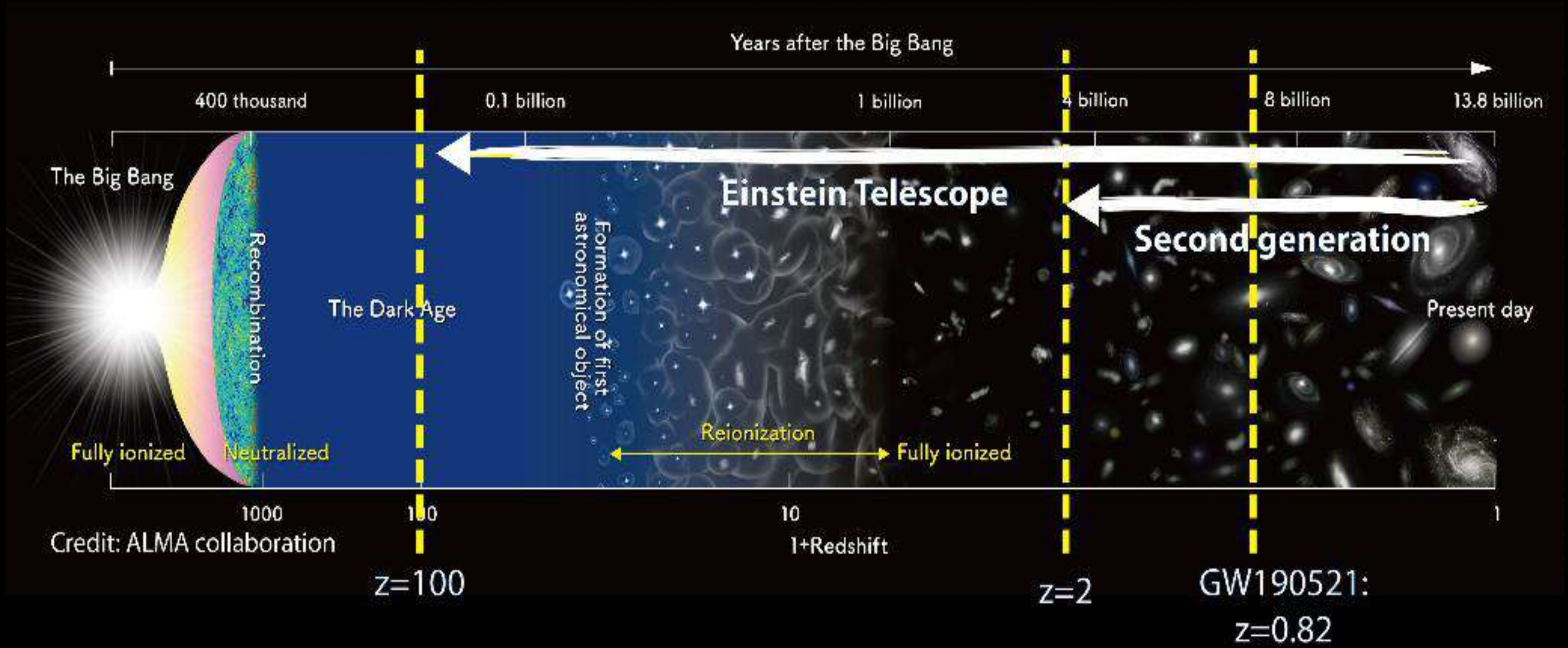


Cosmic Explorer 40 km

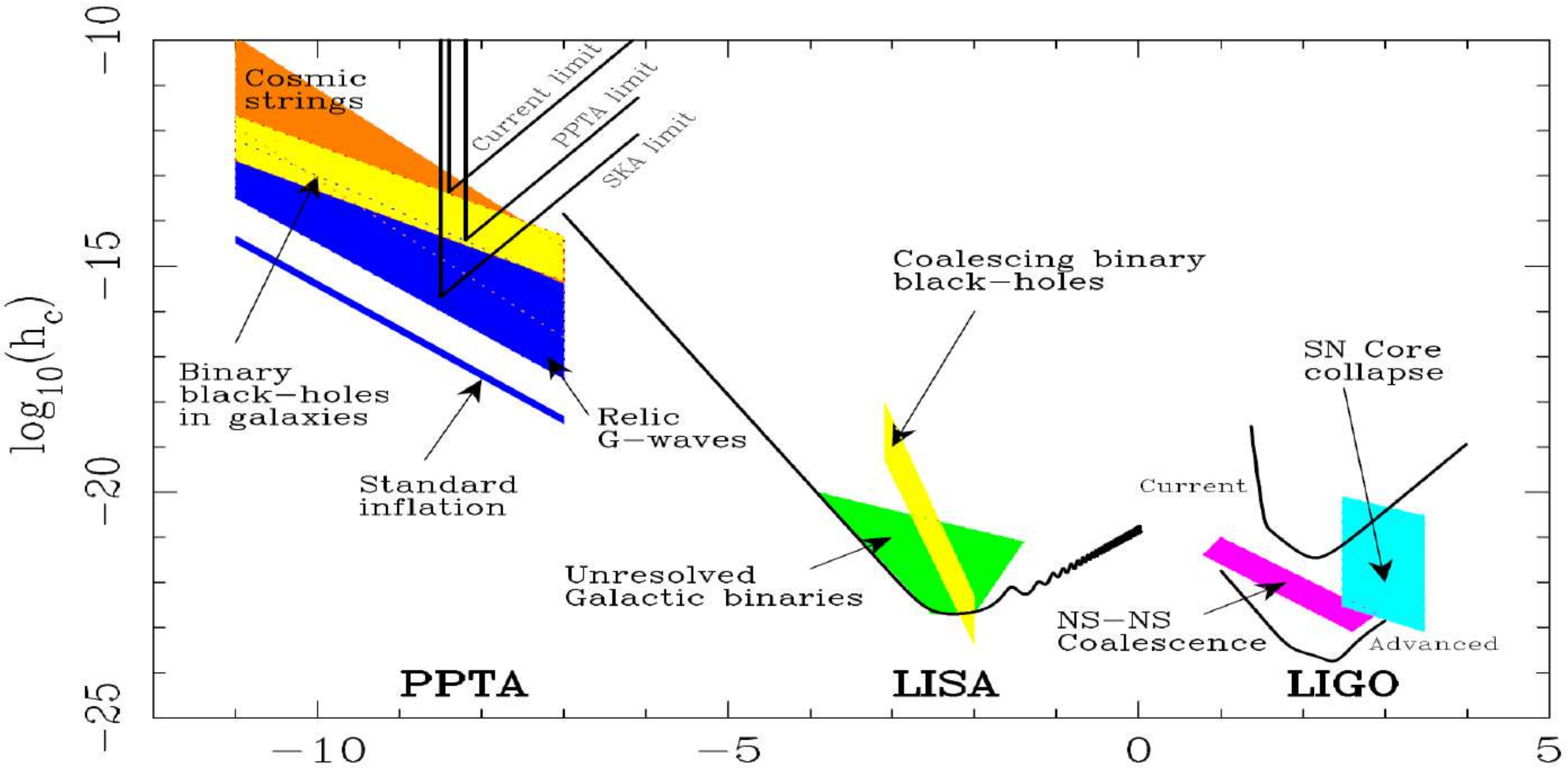
The Einstein Telescope: x40 aLIGO

- On the Earth's Surface
- 40 km arms
- L - shape
- Cryogenic (2nd generation)
- Multiple Detectors for Multi-messenger Astronomy

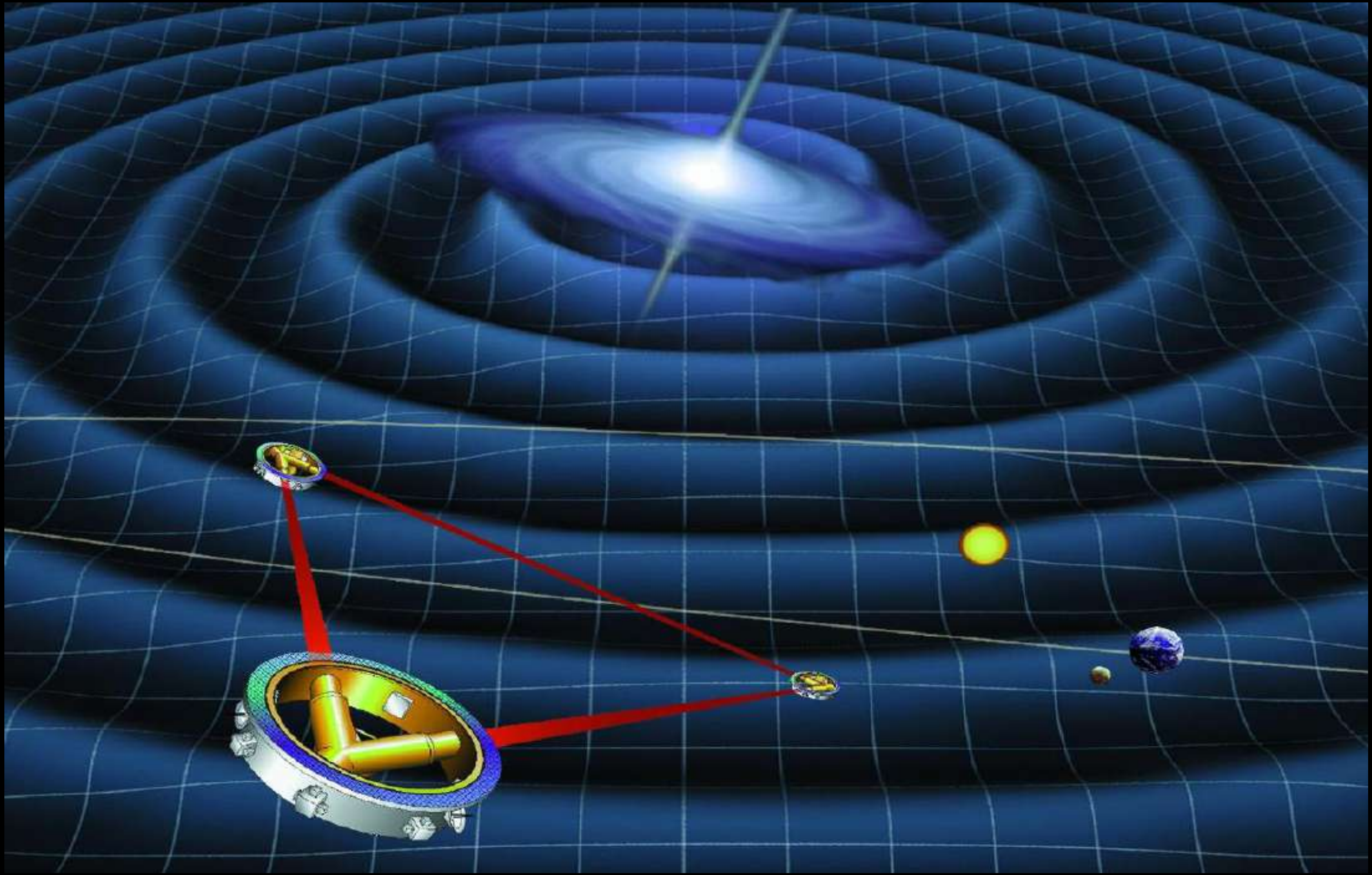
Detection horizon for black-hole binaries



Gravitational Wave Frequency Coverage



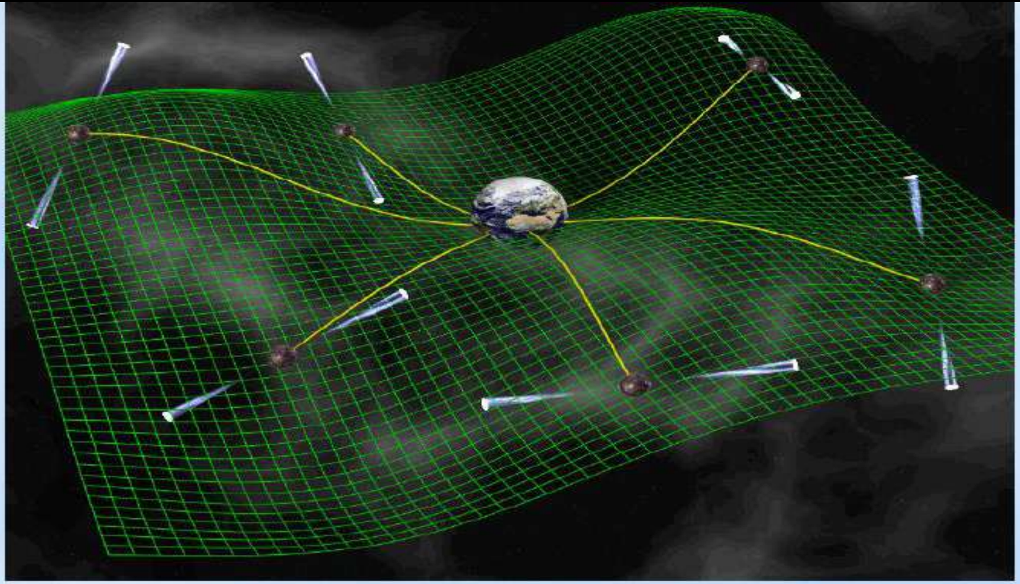
LISA: Laser Interferometer Space Array



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

Gravitational Waves: A New Frontier