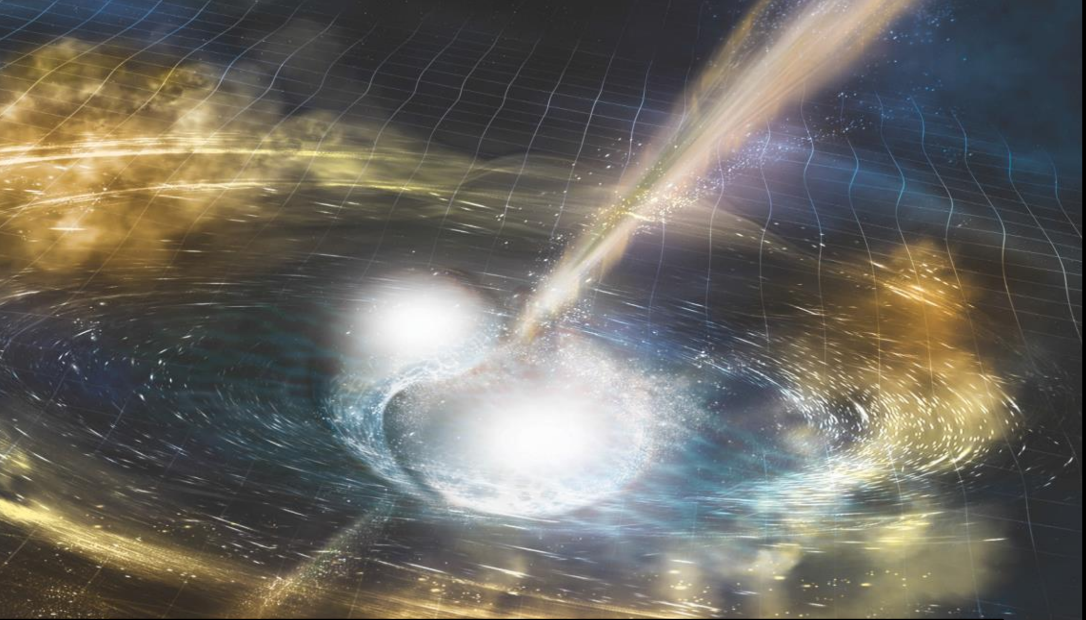
"Probing the Universe ~~for~~ Gravitational Waves"

11 Feb 2016



Artist's illustration: two merging neutron stars

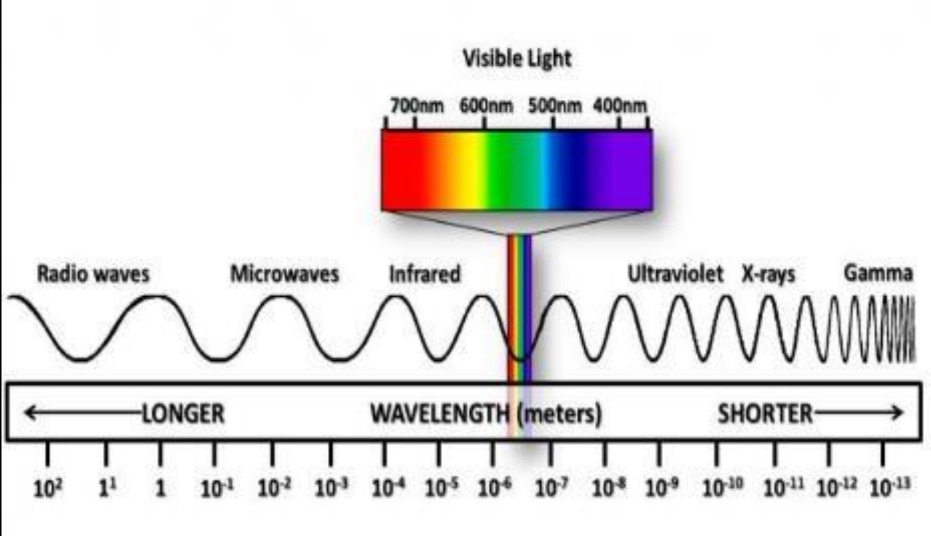
Barry C Barish

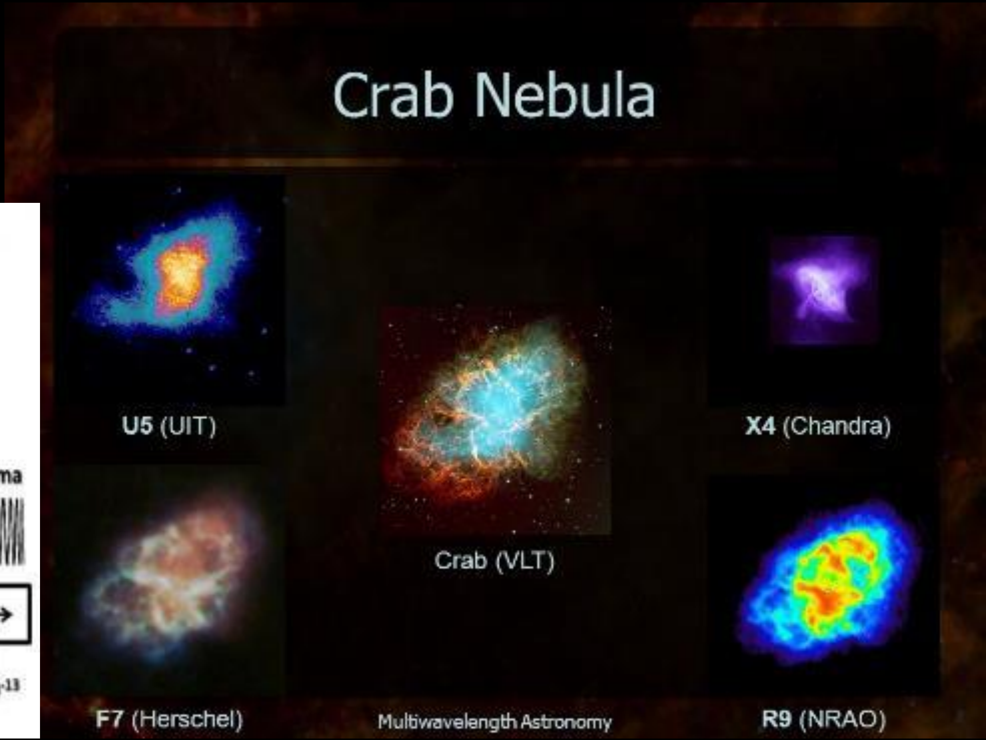
Caltech and UC Riverside

21-Nov-2019

20th Century : Multiwavelength Astronomy

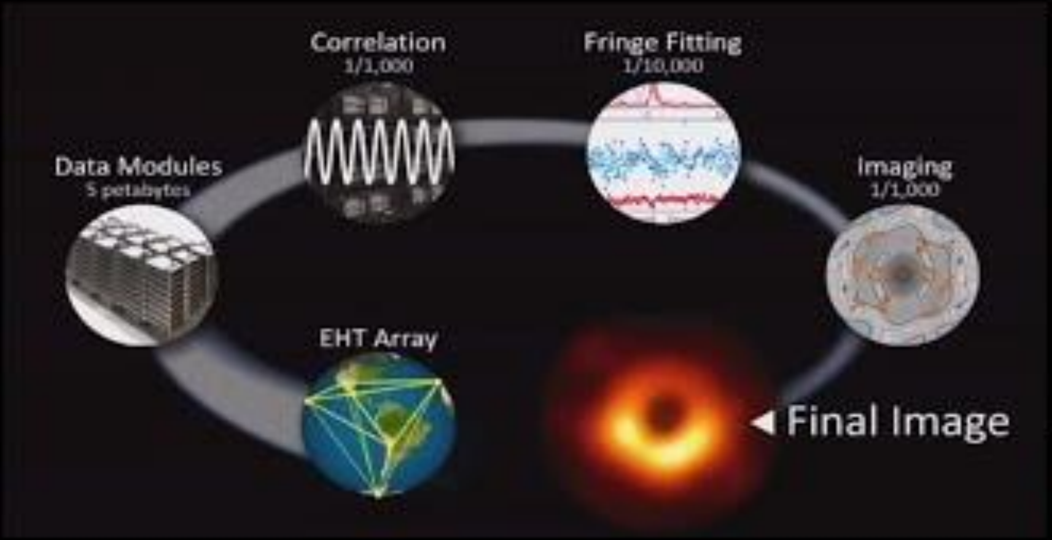
Electromagnetic Spectrum

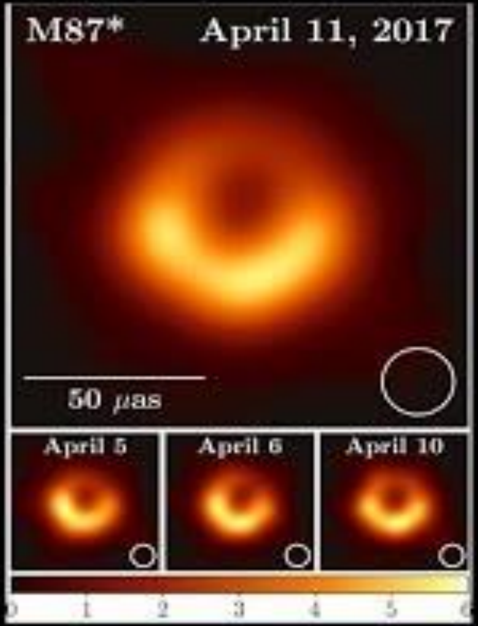




21st Century: "Combined Instrument"

Event Horizon Telescope Black Hole Image



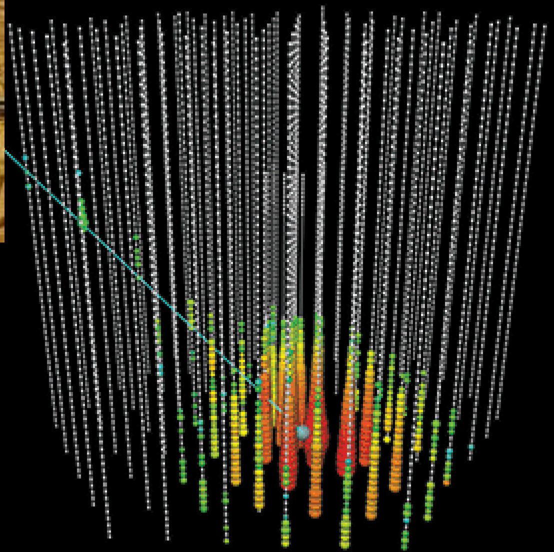


Next Frontier: Multimessenger Astronomy

Electromagnetic

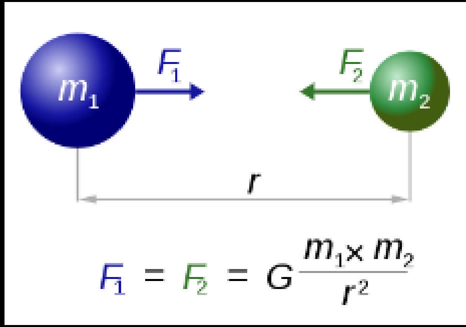
Gravitational Waves

Neutrinos

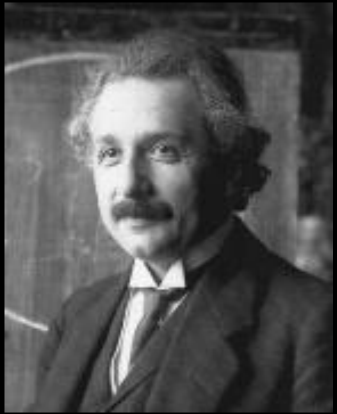


General Relativity and Gravitational Waves

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.

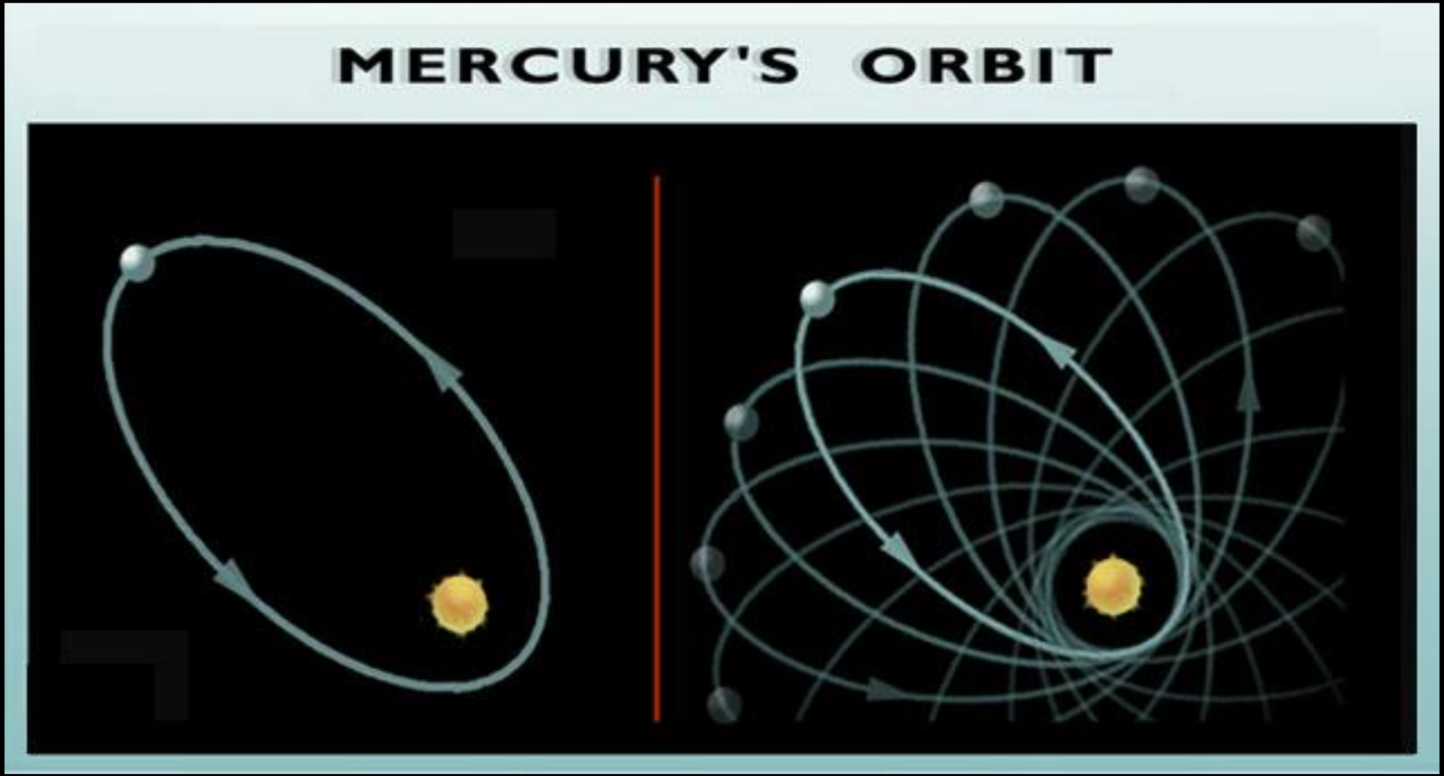


Einstein's Theory of Gravity (1915)

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

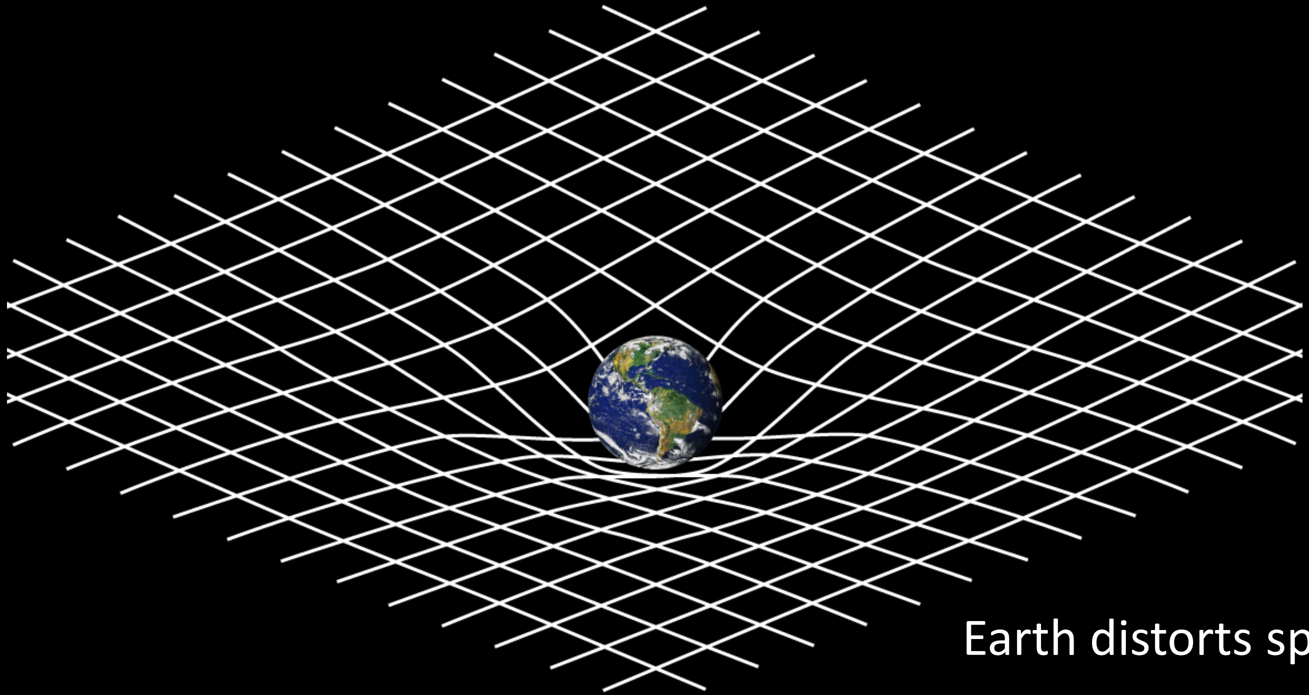
Space *and* Time are ***unified*** in a four dimensional

spacetime



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).

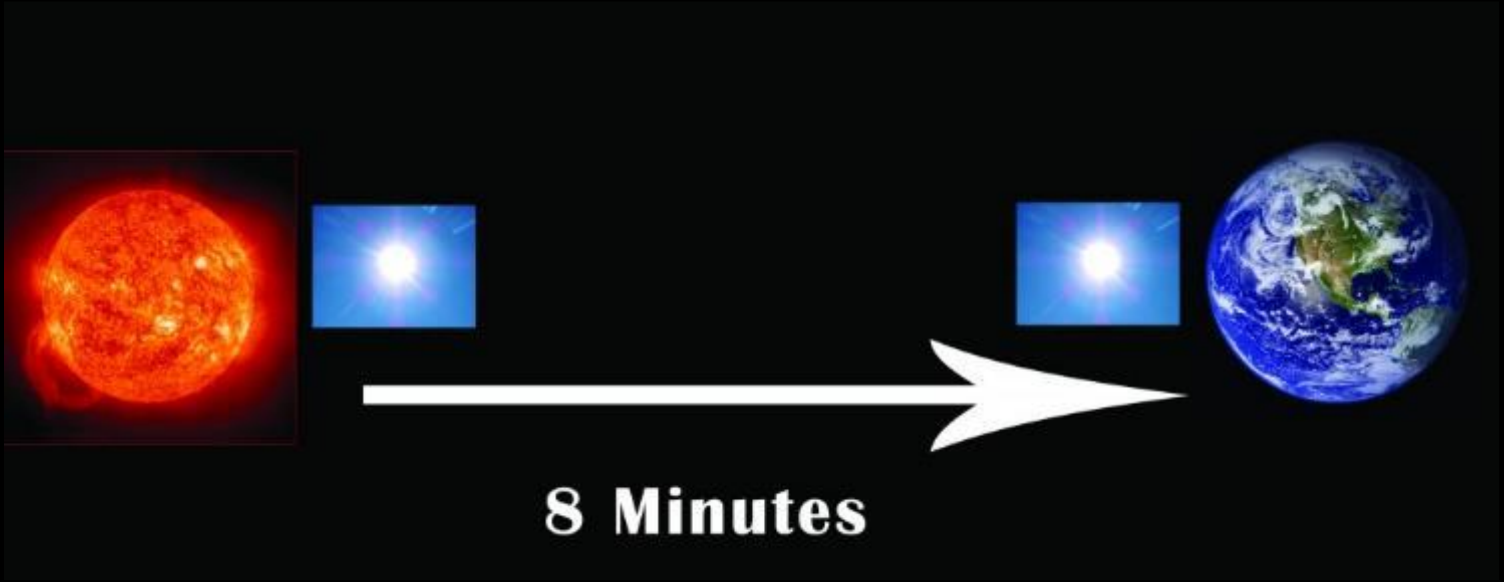
Einstein Explains WHY the apple falls!



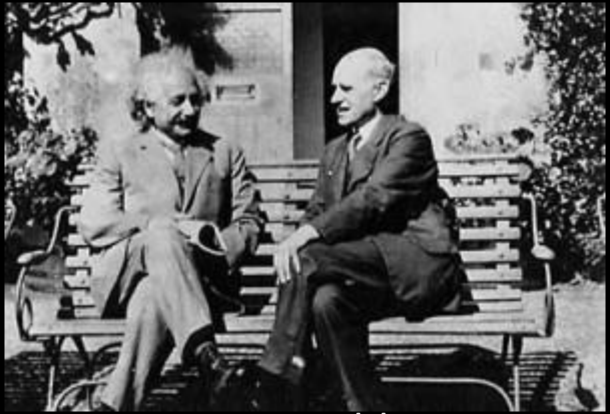
Earth distorts spacetime

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

"Instantaneous Action at a Distance"



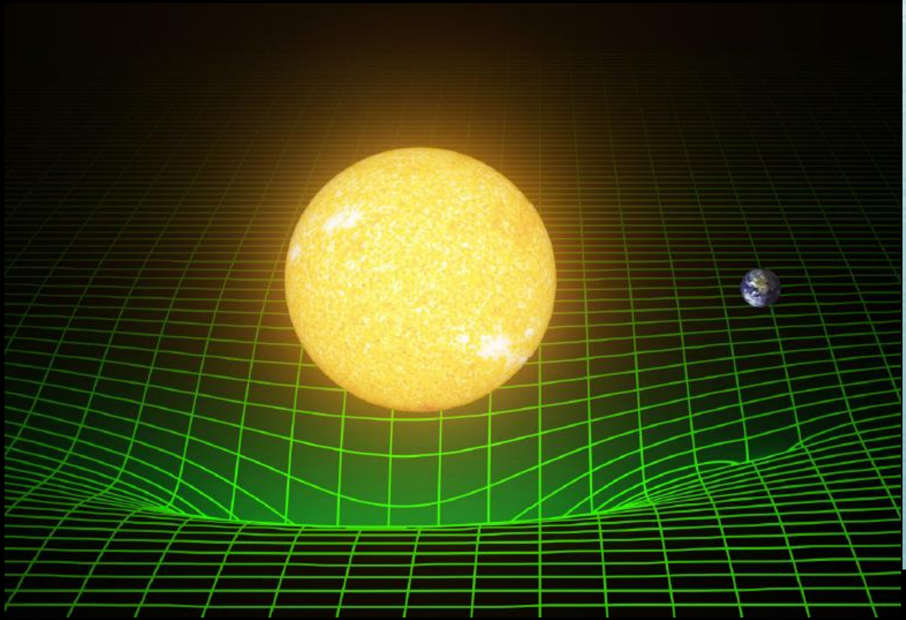
Einstein
Makes a 'New' Prediction

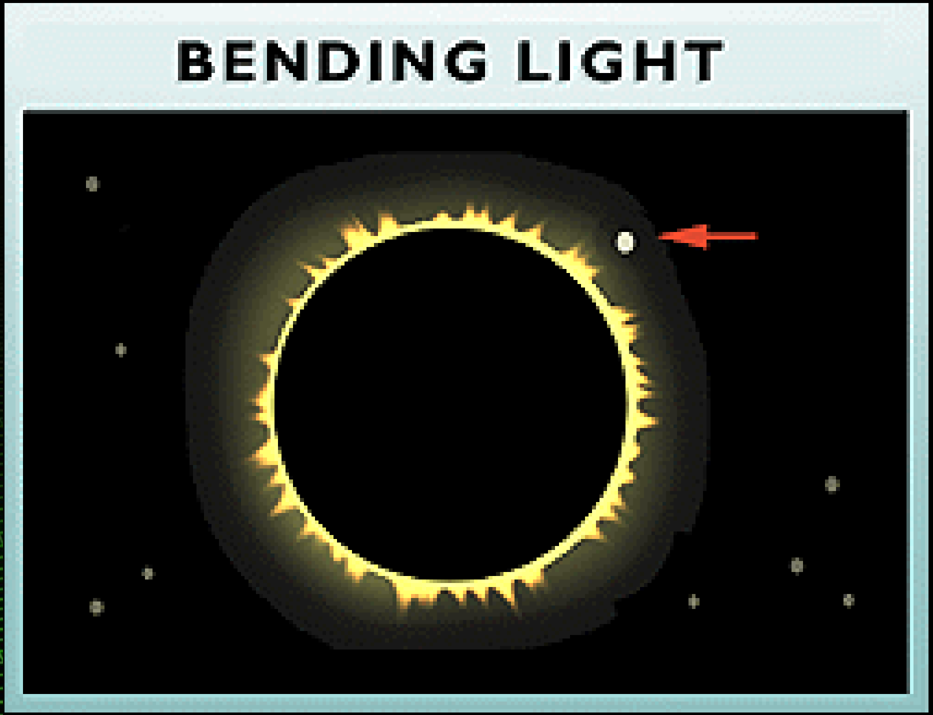


Einstein Eddington

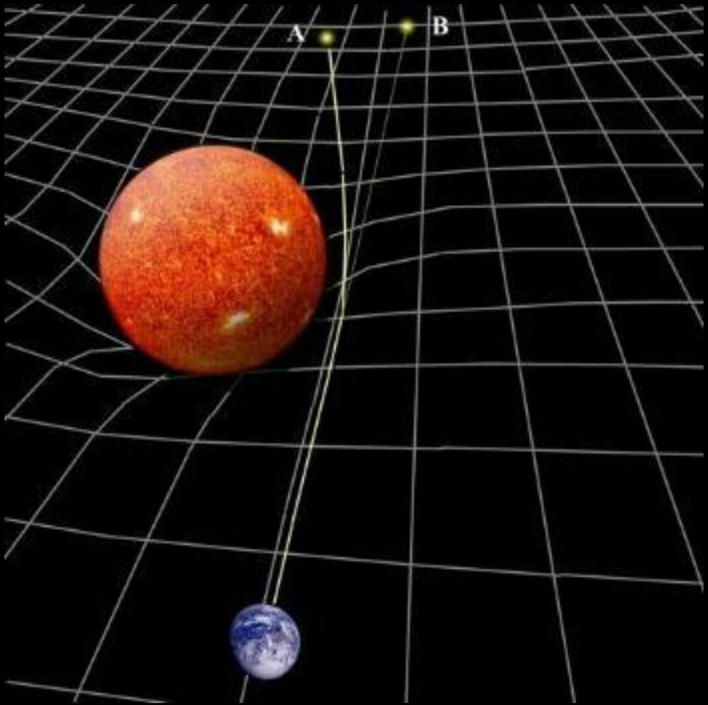
"Not only is the universe stranger than we imagine, it is stranger than we can imagine.

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.

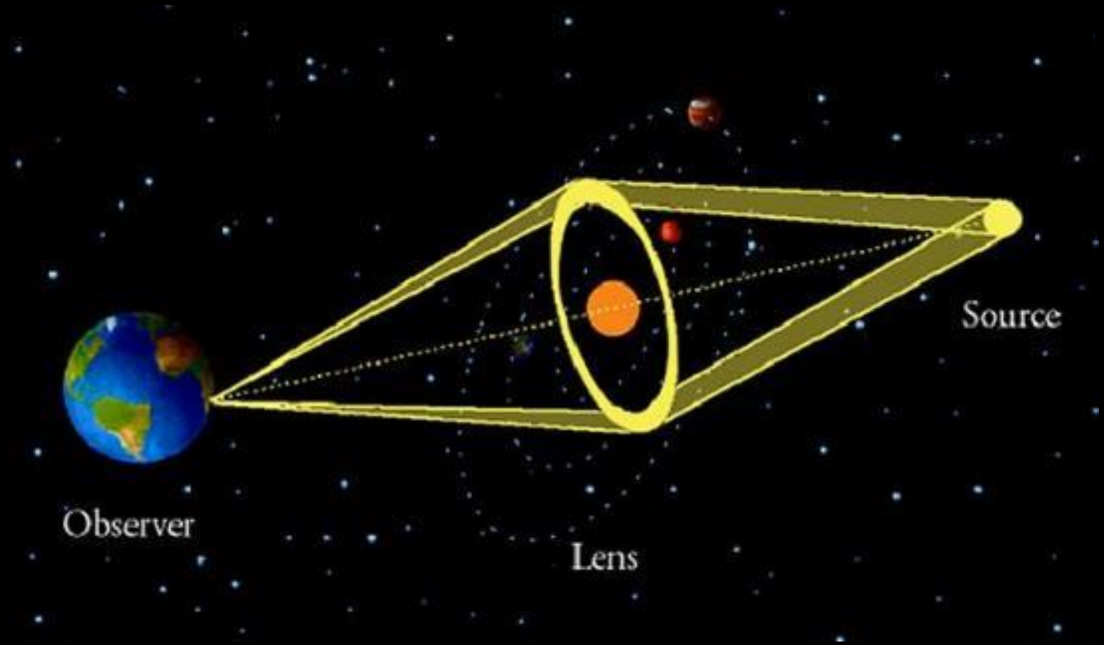
A BOOK FOR 12 WISE MEN

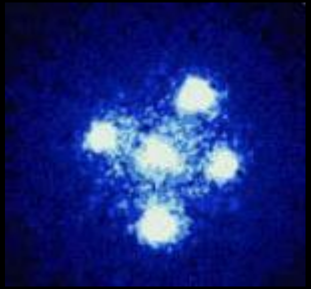
No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

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.

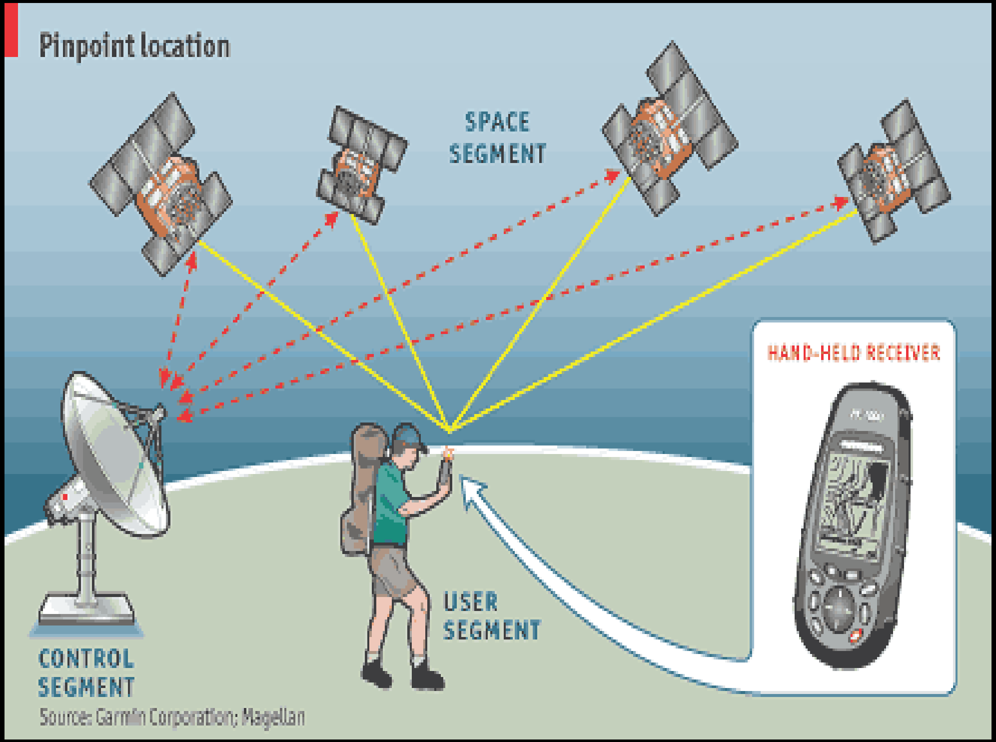
In Modern Astronomy: Gravitational Lensing





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

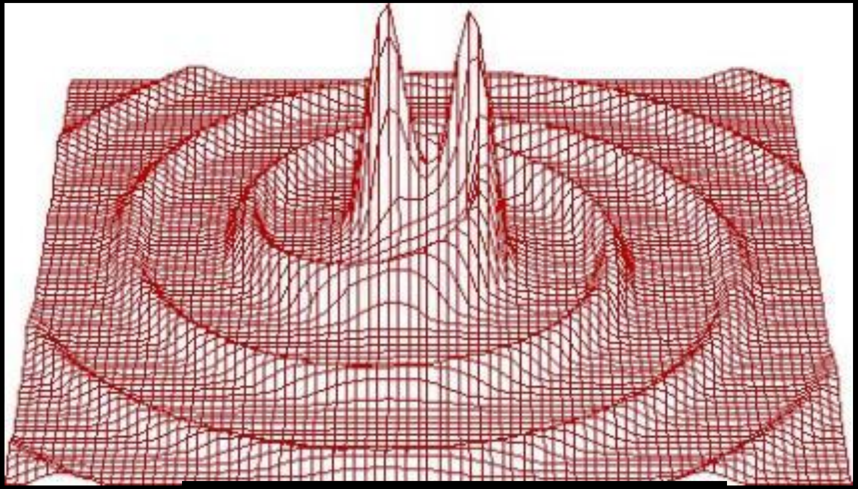
GPS Correction = + 38 microsec/day

(Accuracy required ~ 30 nanoseconds
to give 10 meter resolution

Einstein'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



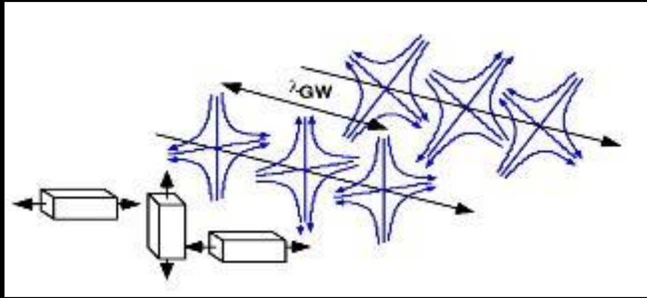
gravitational radiation
binary inspiral
of
compact objects

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).

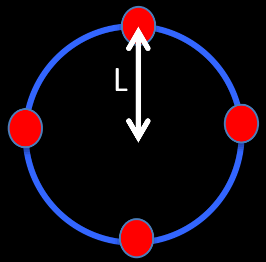
• Since gravity is spin 2, the waves have two components, but rotated by 45^0 instead of 90^0 from each other.

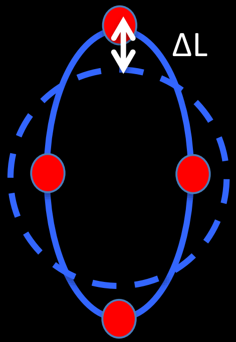
$$h_{\mu\nu} = h_+(t - z/c) + h_x(t - z/c)$$

Gravitational Waves

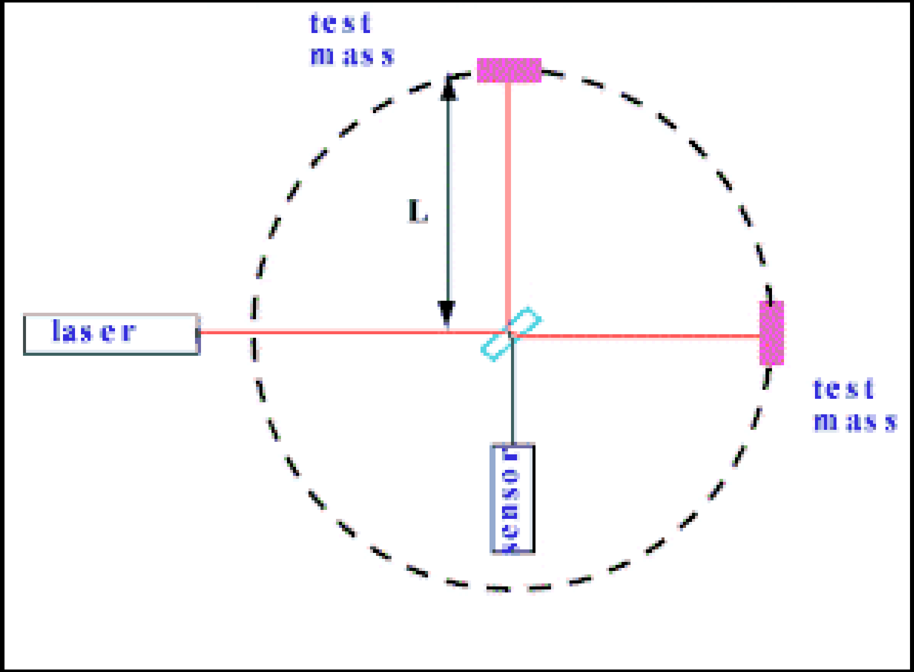
- Ripples of spacetime that stretch and compress spacetime itself
- The amplitude of the wave is h ≈ 10^{-21}
- Change the distance between masses that are free to move by $\Delta L = h \times L$
- Spacetime is "stiff" so changes in distance are very small

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





Suspended Mass Interferometry



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

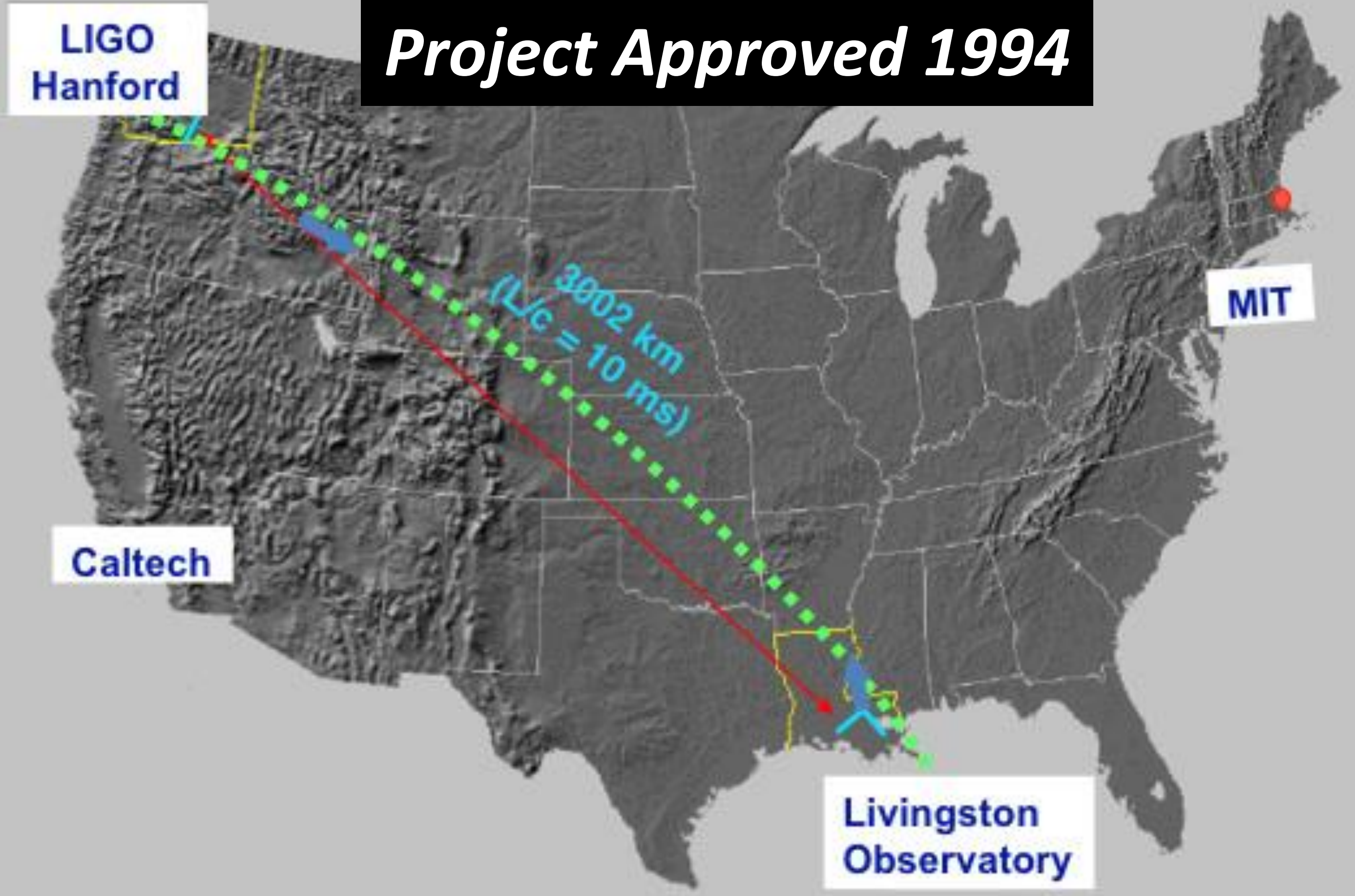
$$L = 4\text{km} \quad DL \le 4\text{x}10^{-18}\text{ meters}$$

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

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

LIGO Sites

Project Approved 1994

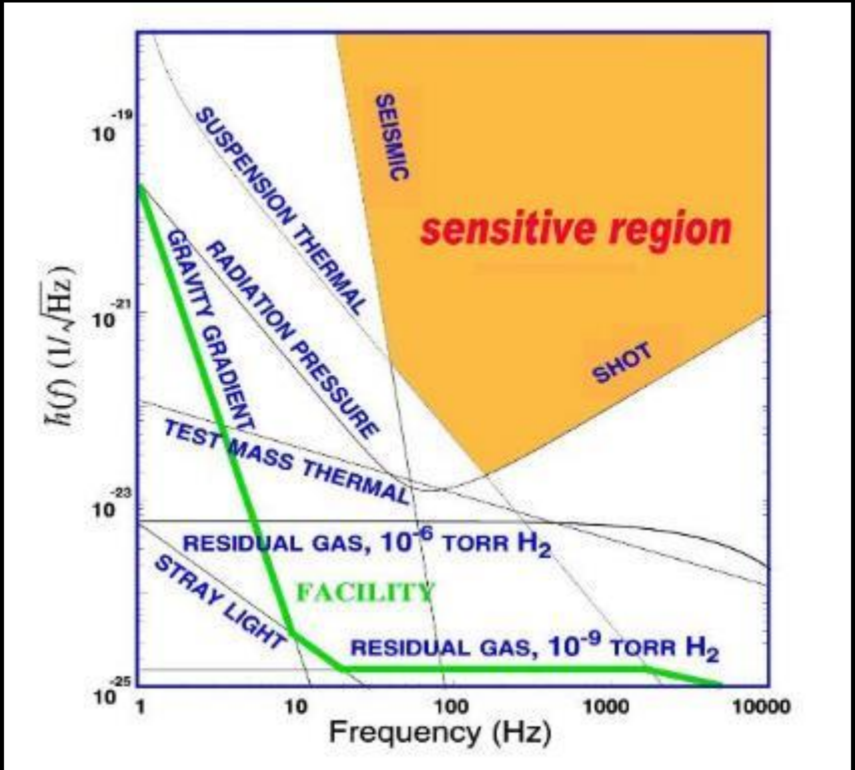


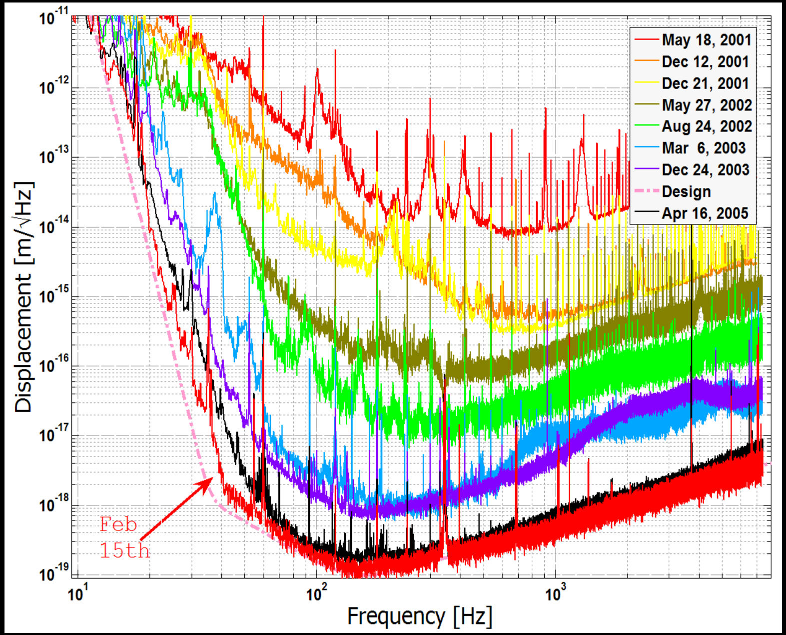
'Direct' Detection of Gravitational Waves
LIGO Interferometers

Hanford, WA

Livingston, LA

What Limits LIGO Sensitivity?





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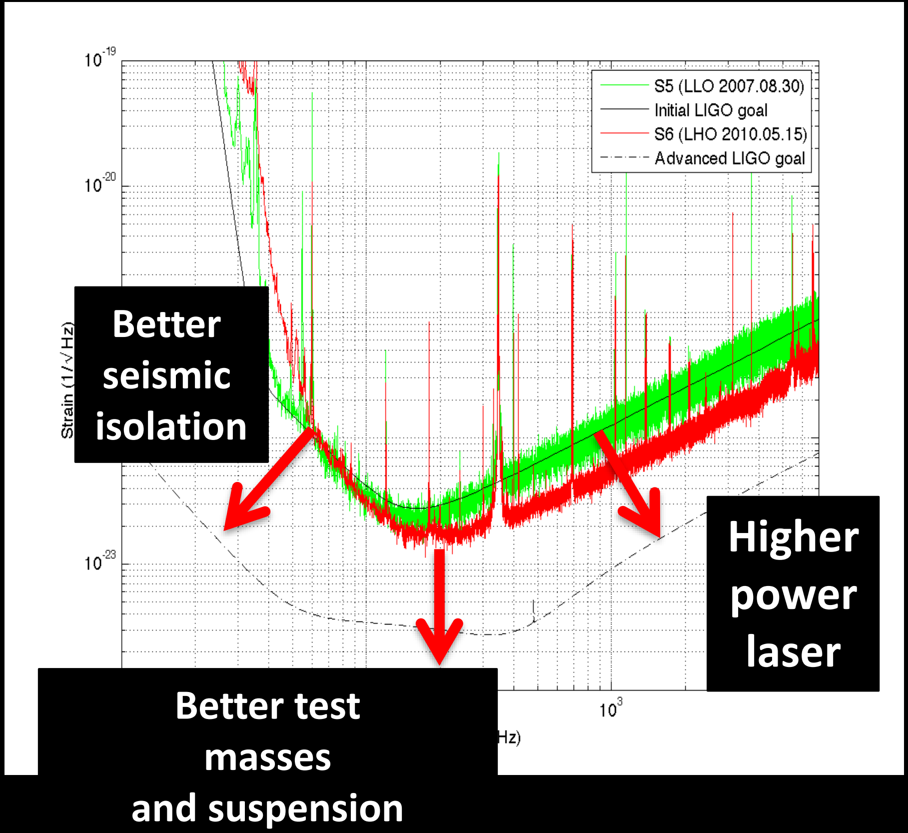
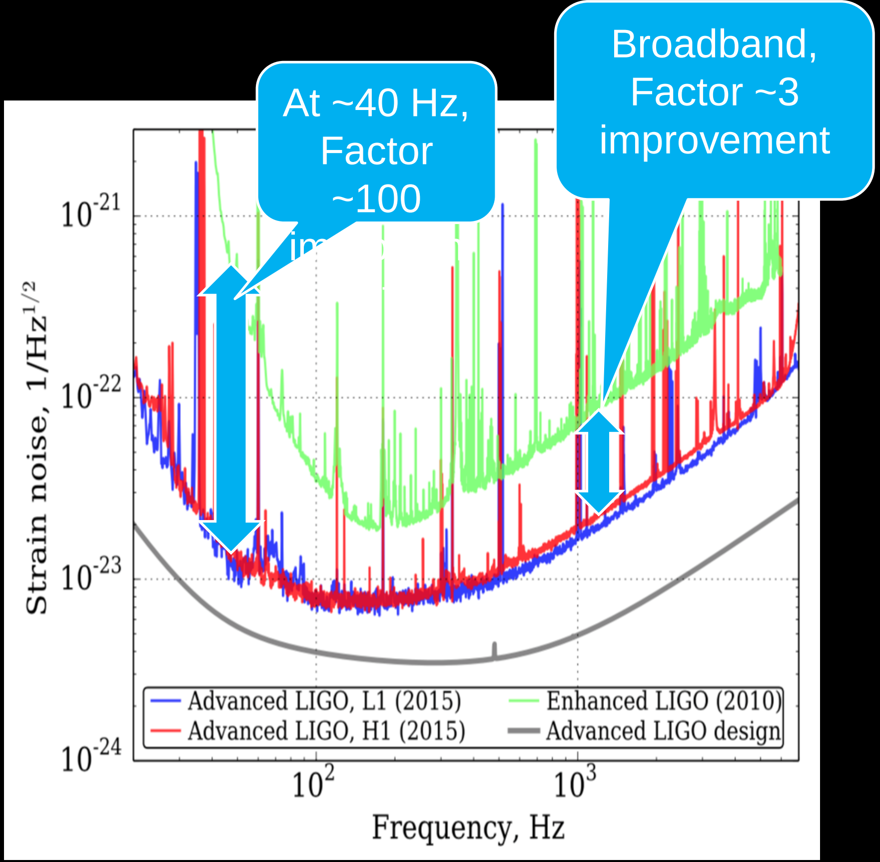
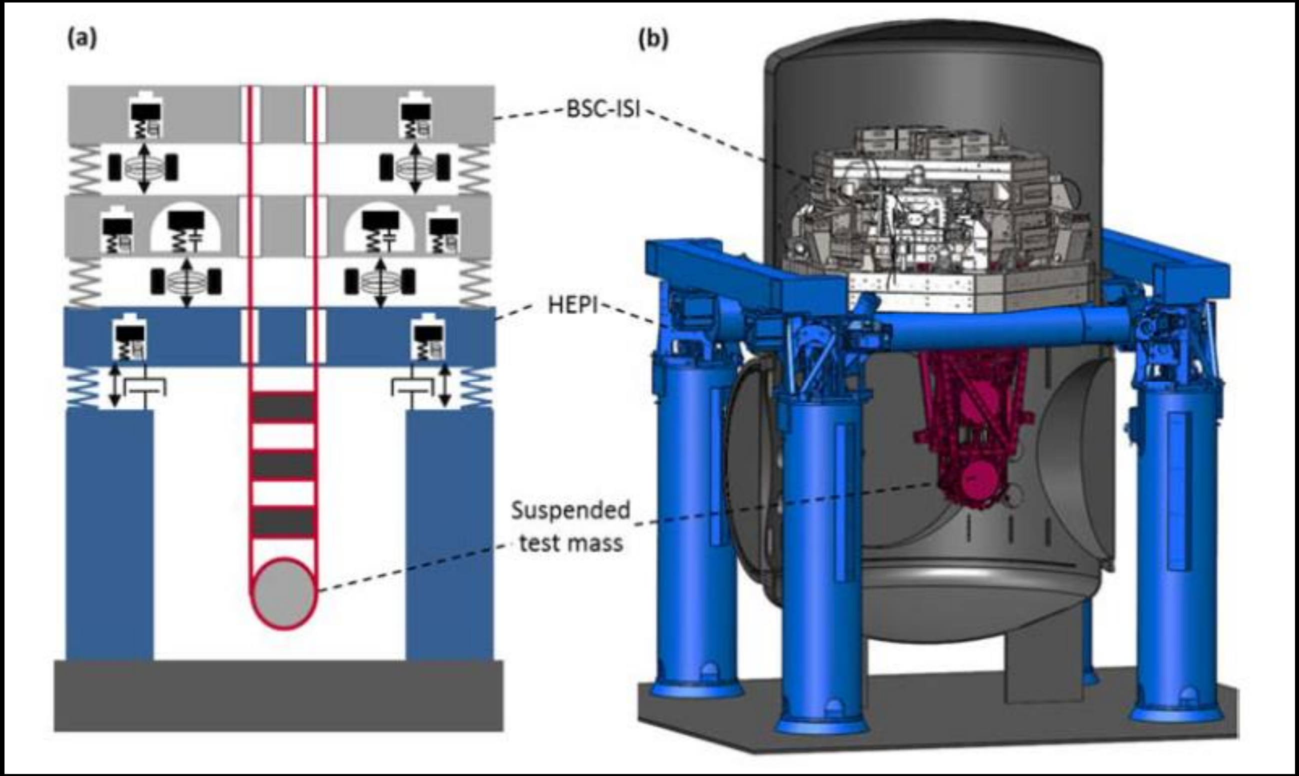
Advanced LIGO GOALS



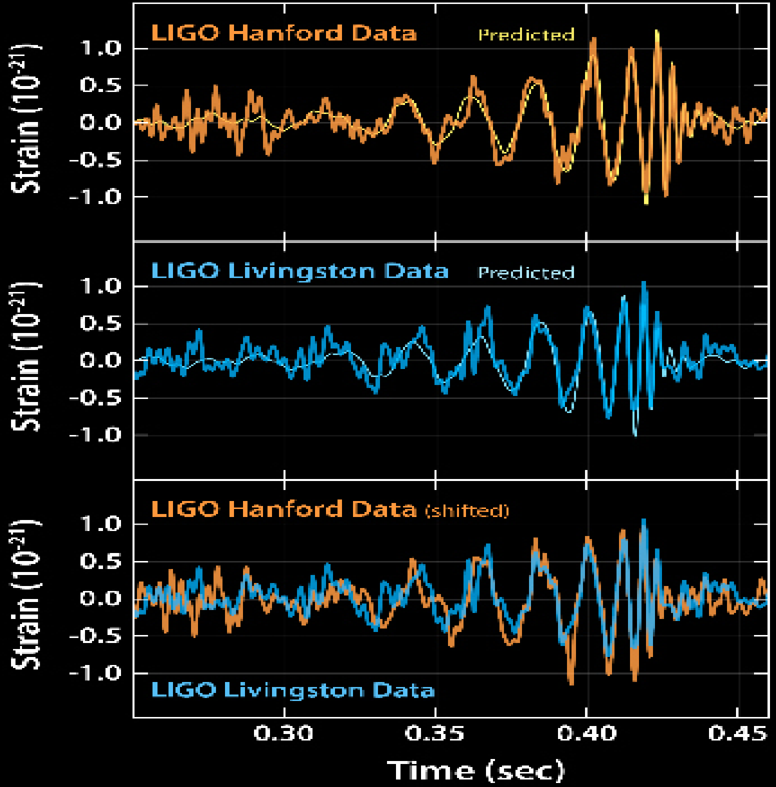


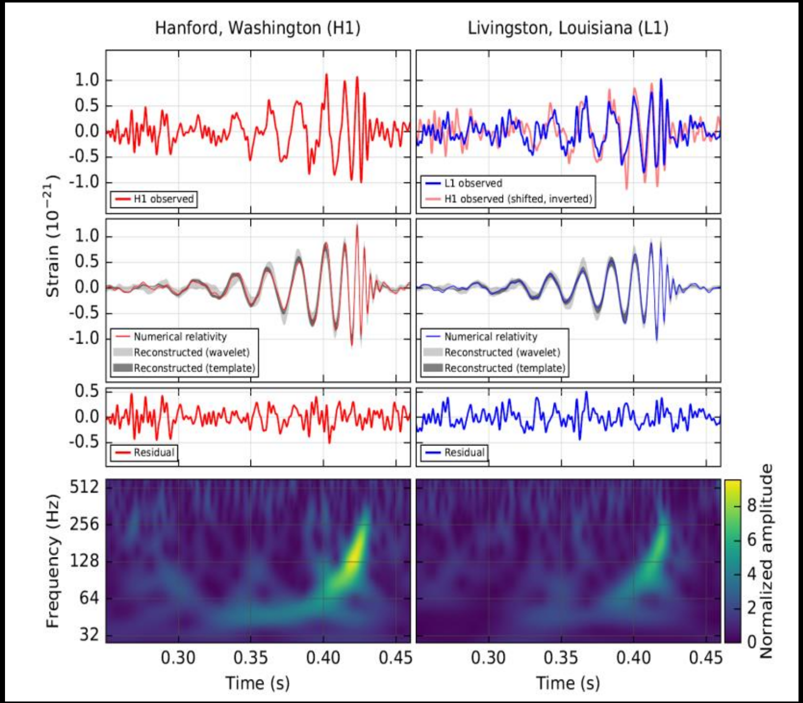
Passive / Active Multi-Stage Isolation

Advanced LIGO



Black Hole Merger: GW150914





Measuring the parameters

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

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

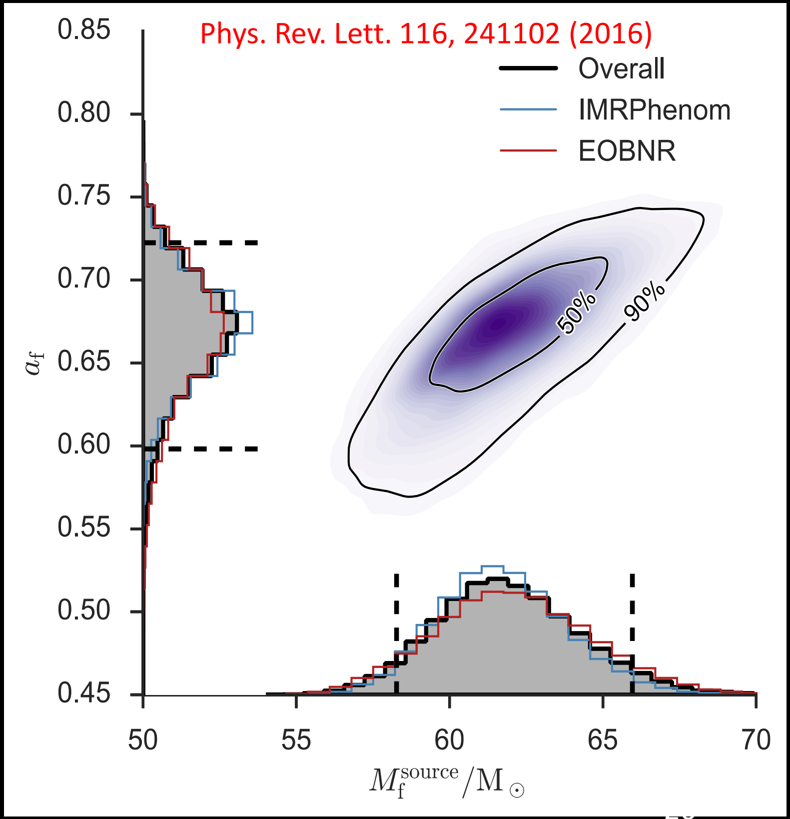
  - Next orders allow for measurement of mass ratio and spins
  - We directly measure the red-shifted masses (1+z) m
  - Amplitude inversely proportional to luminosity distance
- Orbital precession occurs when spins are misaligned with orbital angular momentum – no evidence for precession.
- Sky location,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

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	$0.09^{+0.03}_{-0.04}$

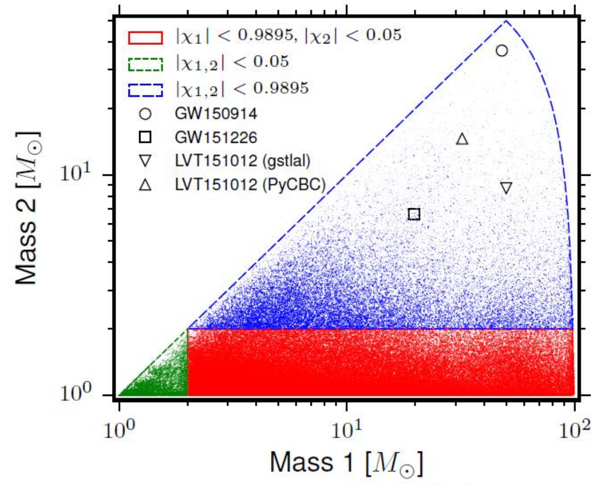
Phys. Rev. Lett. 116, 061102 (2016)

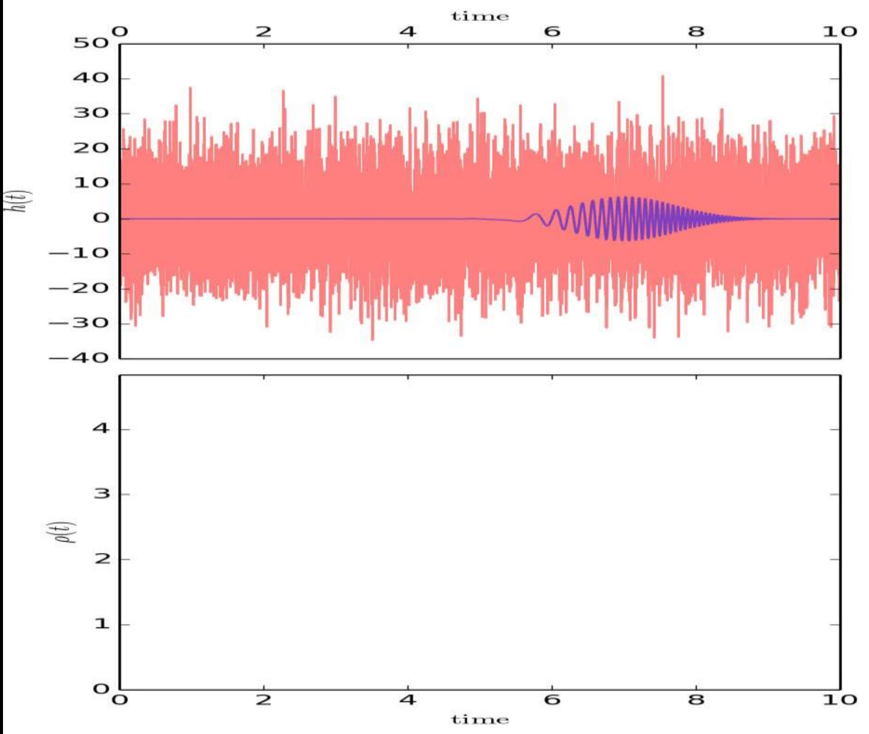


Finding a weak signal in noise

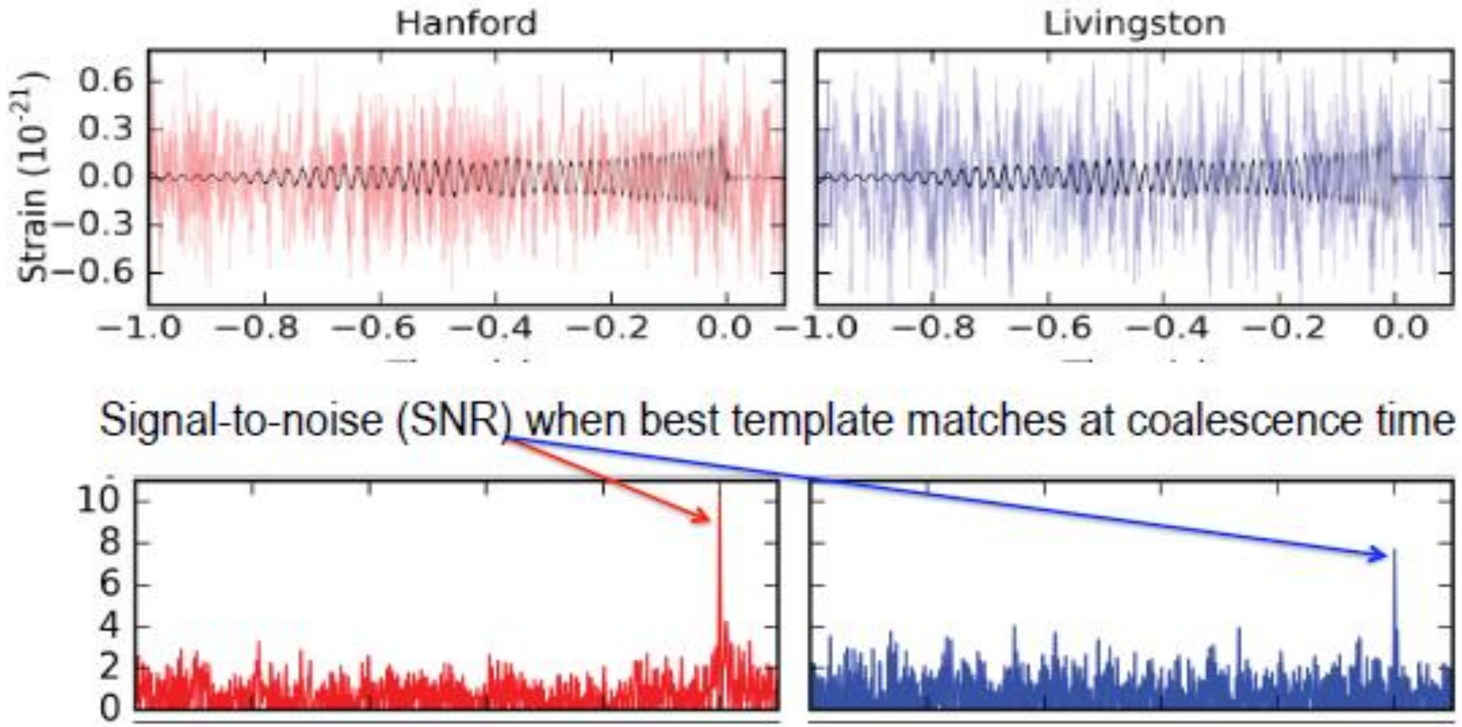
- "Matched filtering" lets us find a weak signal submerged in noise.
- For calculated signal waveforms, multiply the waveform by the data
- Find signal from cumulative signal/noise

PHYS. REV. X 6,041015 (2016)



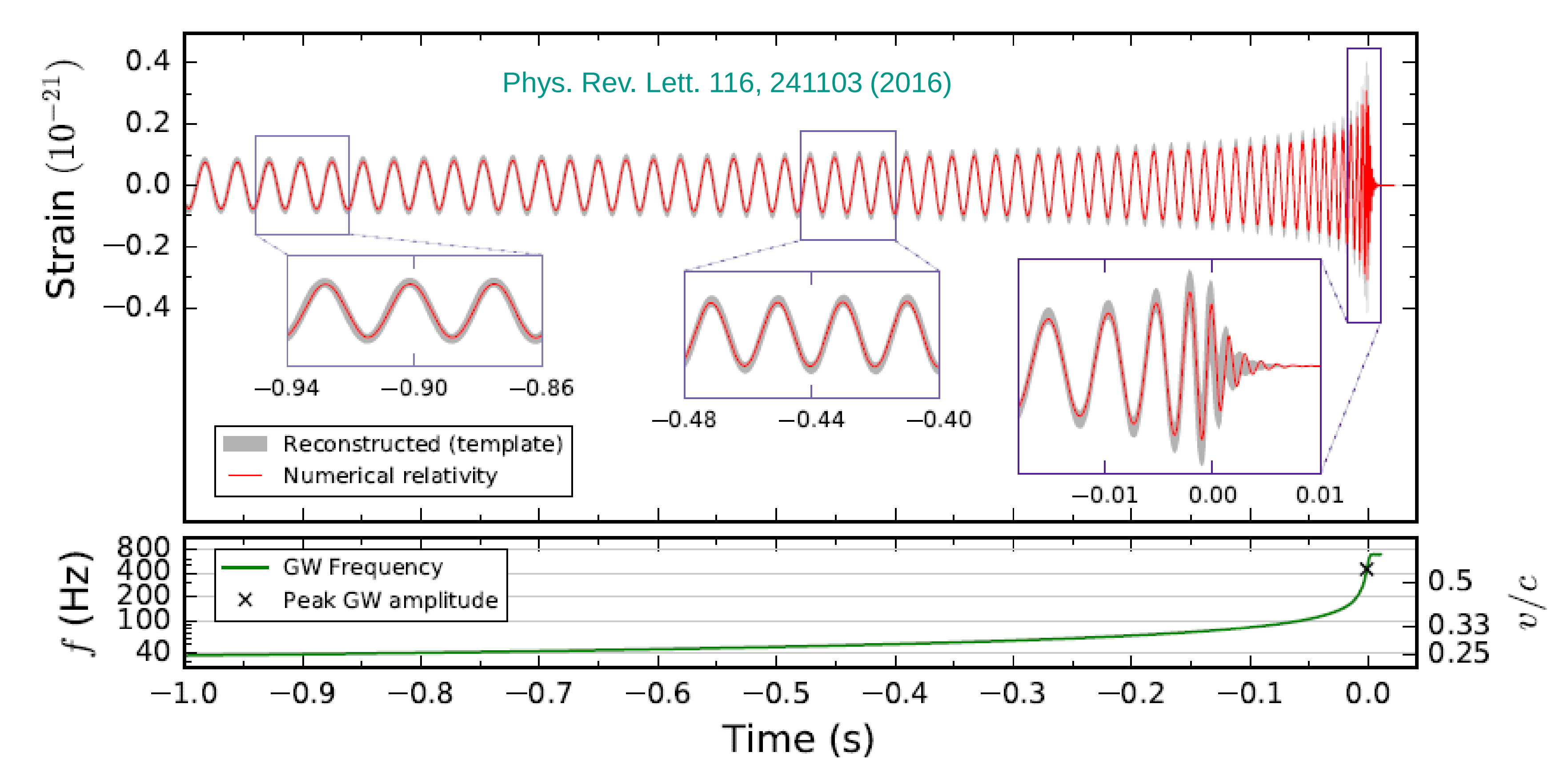


GW151226 – Matched Filter



Phys. Rev. Lett. 116, 241103 (2016)

"Second Event" Inspiral and Merger GW151226



Testing General Relativity – Dispersion Term?

- In GR, there is no dispersion!

Add dispersion term of form

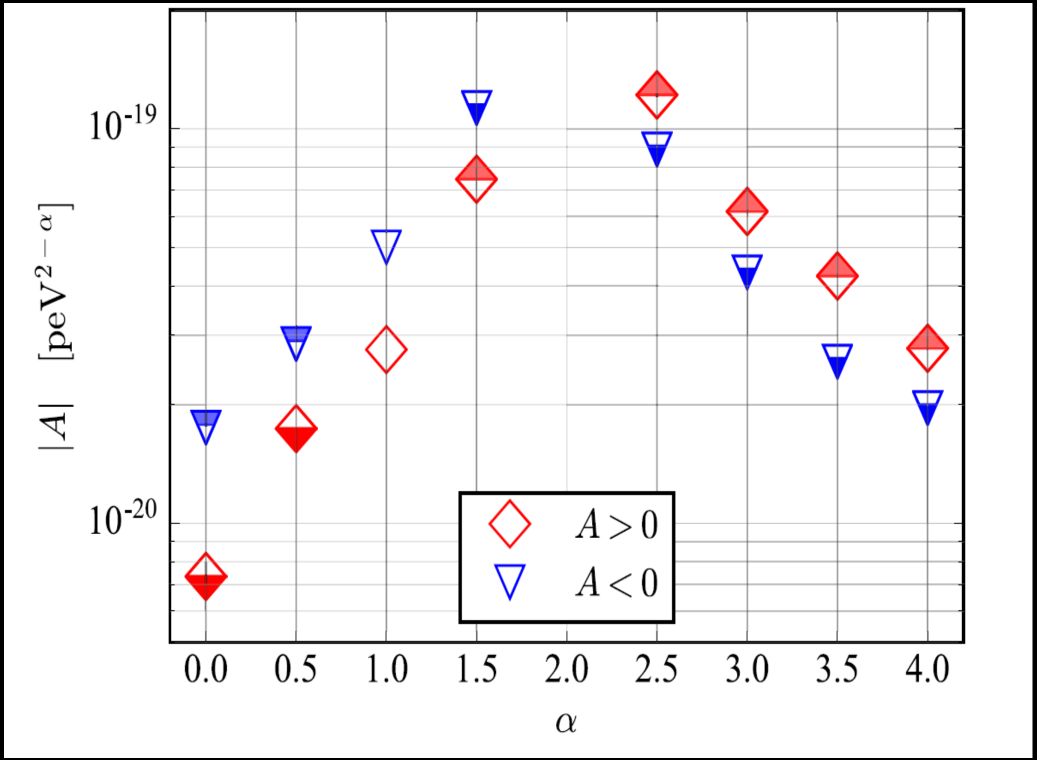
$$E^2 = p^2c^2 + Ap^{\alpha}c^{\alpha}, \quad \alpha \geq 0$$

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

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

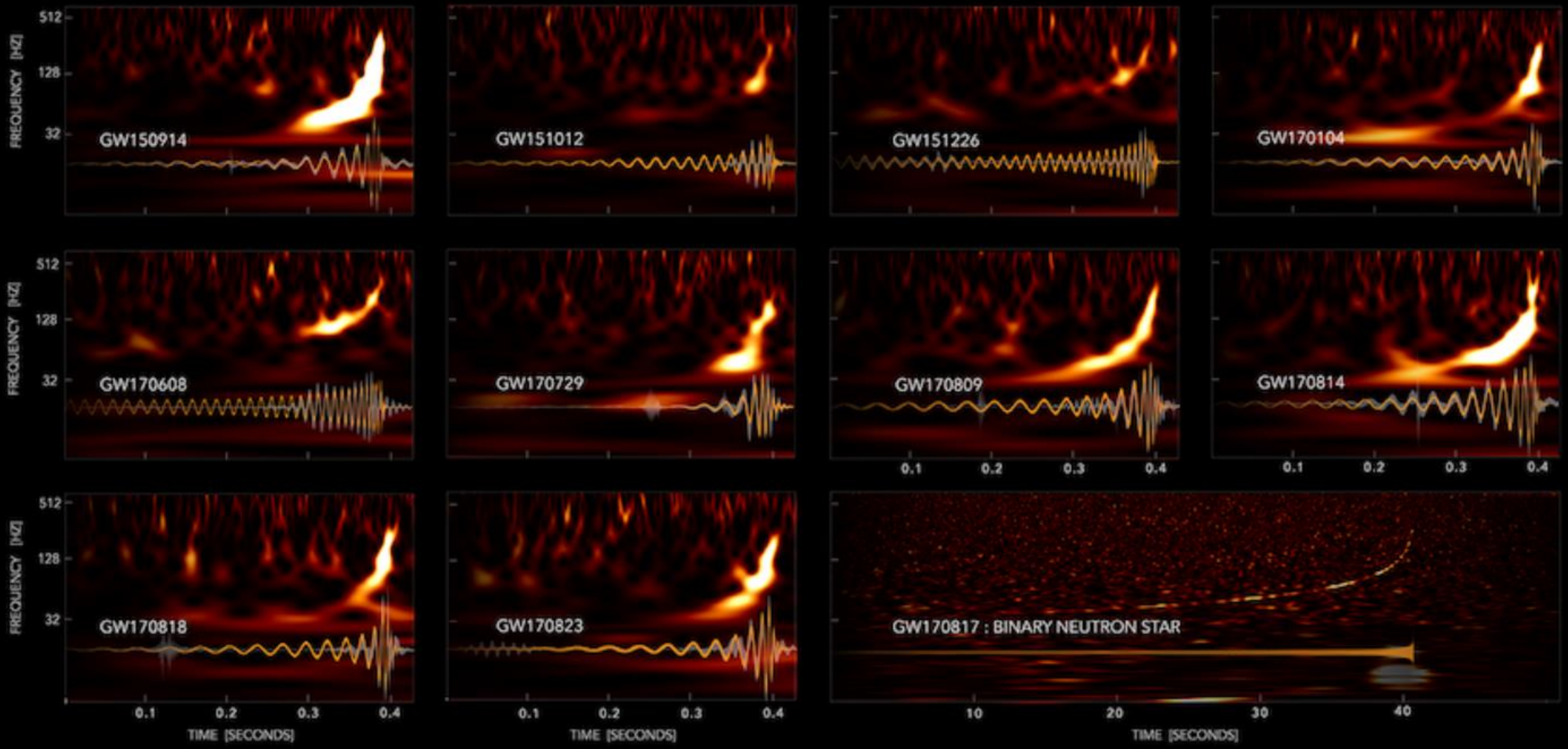
$$M_g \leq 7.7 \times 10^{-23}\ \mathrm{eV}/c^2$$

- Null tests to quantify generic deviations from GR



PhysRevLett.118.221101

Observed Binary Mergers to Date



New Astrophysics

- Stellar binary black holes exist
- They form into binary pairs
- They merge within the lifetime of the universe
- The masses ($M > 20\ M_{\odot}$) are much larger than what was known about stellar mass Black Holes.

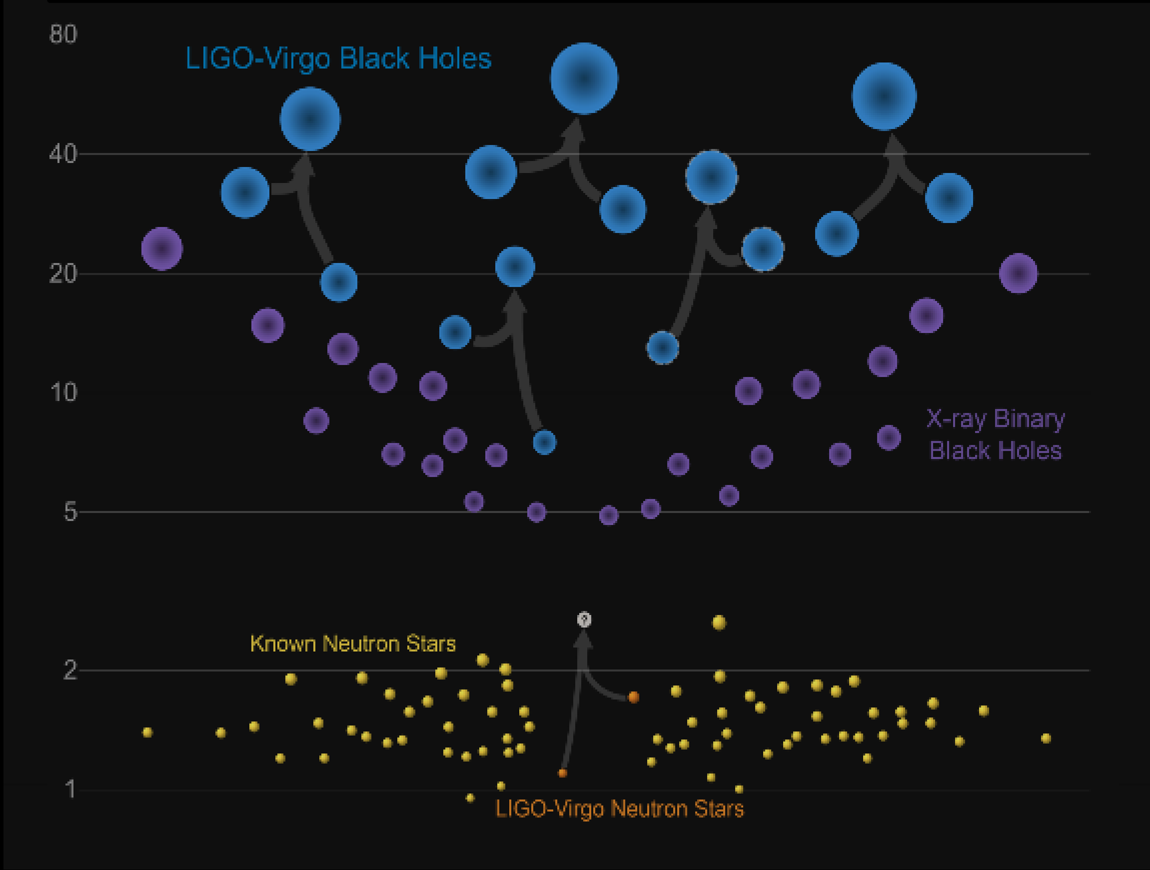


Image credit: LIGO

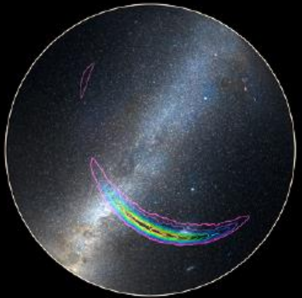
Searching for Electromagnetic Counterparts

LIGO-H LIGO-L

Virgo

GW candidates

Sky Localization



Event validation

EM facilities

→ a few min → 30 min

Parameter estimation codes → Hours, days, weeks → GW candidate updates

Sky Localization for only LIGO

Sky localizations

90% credible areas of about

1200 deg² GW170104

230 deg² GW150914

1600 deg² LVT15012

850 deg² GW151226

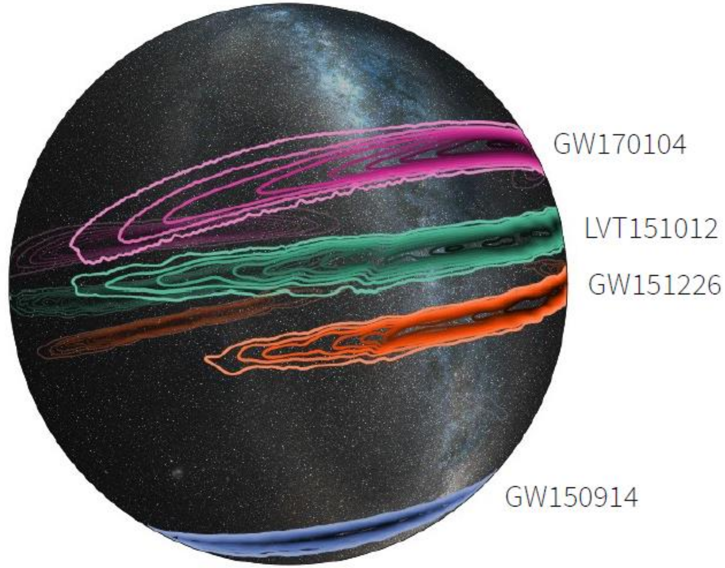
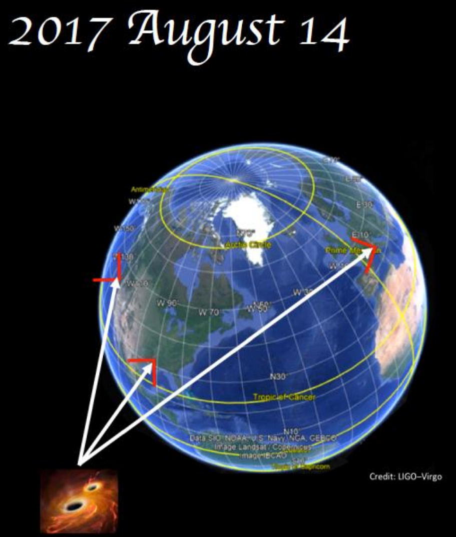
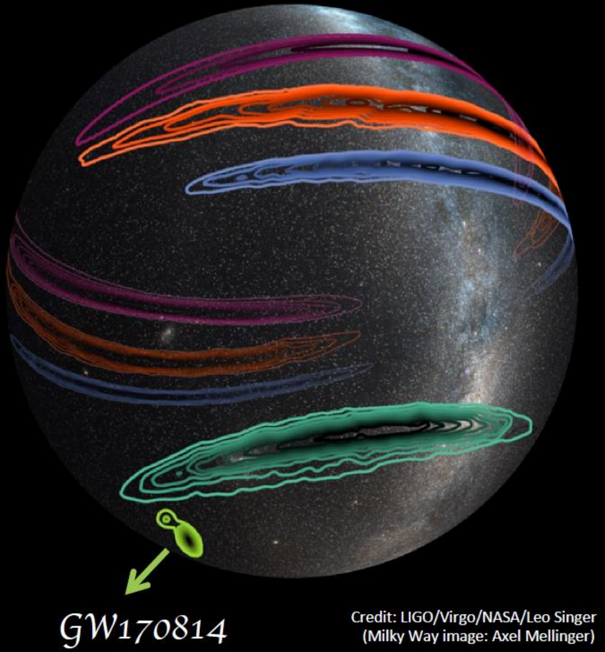


Image credit: LIGO/L. Singer/A. Mellinger

In the volume of the Universe corresponding to GW150914, LVT151012, GW151226 there are 10^5-10^6 galaxies

Virgo Joins LIGO – August 14, 2017



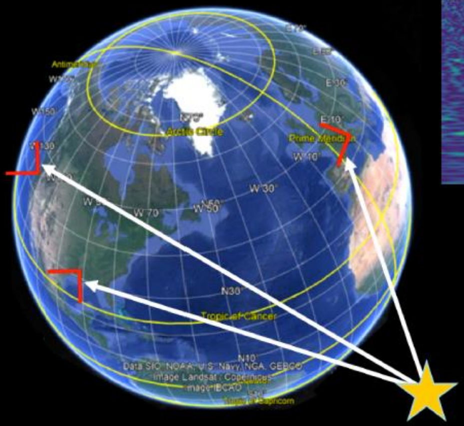


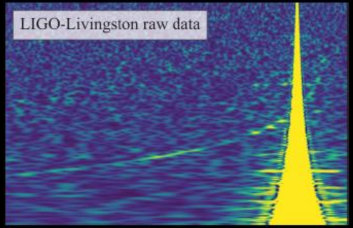
For all 10 reported Black Hole Binary Event NO Electromagnetic counterparts found !!

LH 1160 square degrees
LHV 60 square degrees

And, on August 17

17 August 2017, 12:41:04 UT



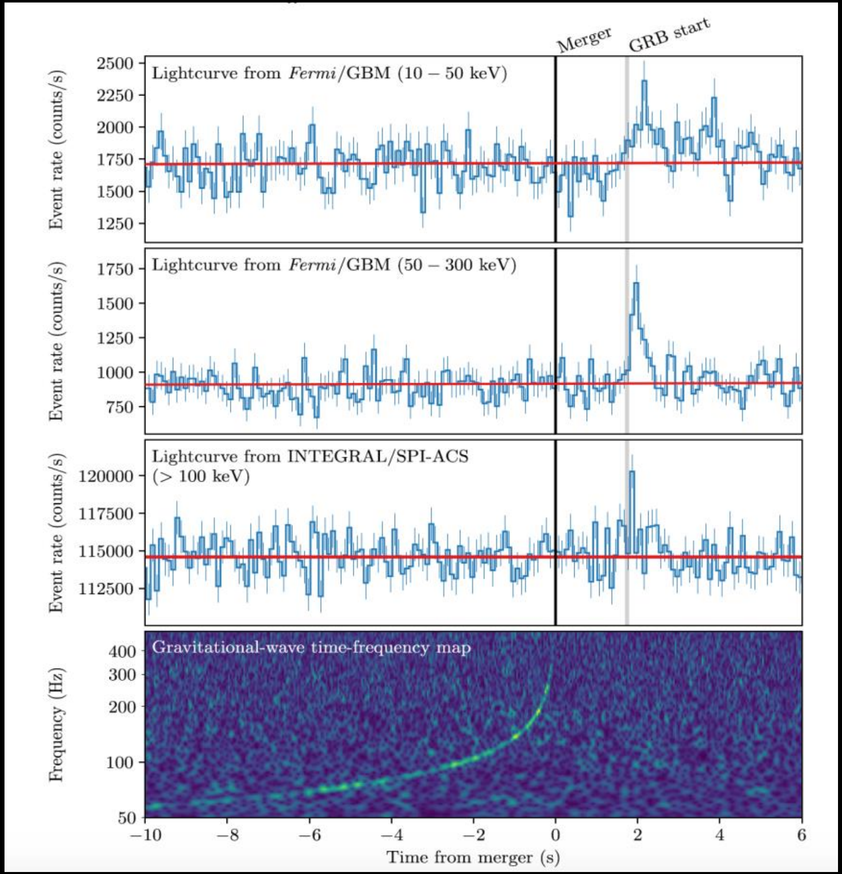


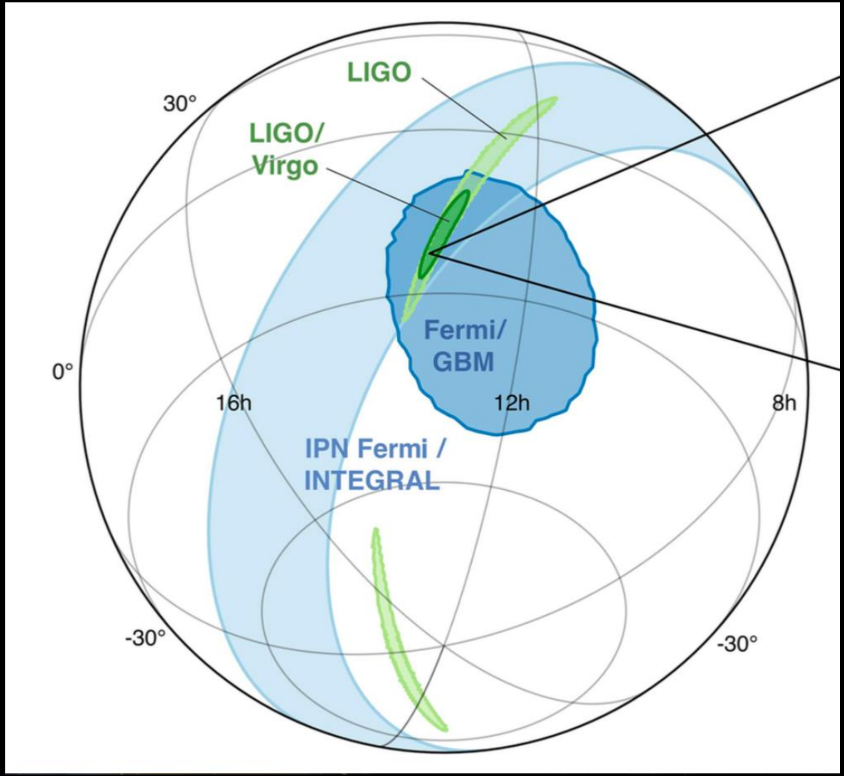
→ 17:54:51

Sky localization 31 deg^2
Distance is 40 +/- 8 Mpc

Credit: LIGO/Virgo/NASA/Leo Singer

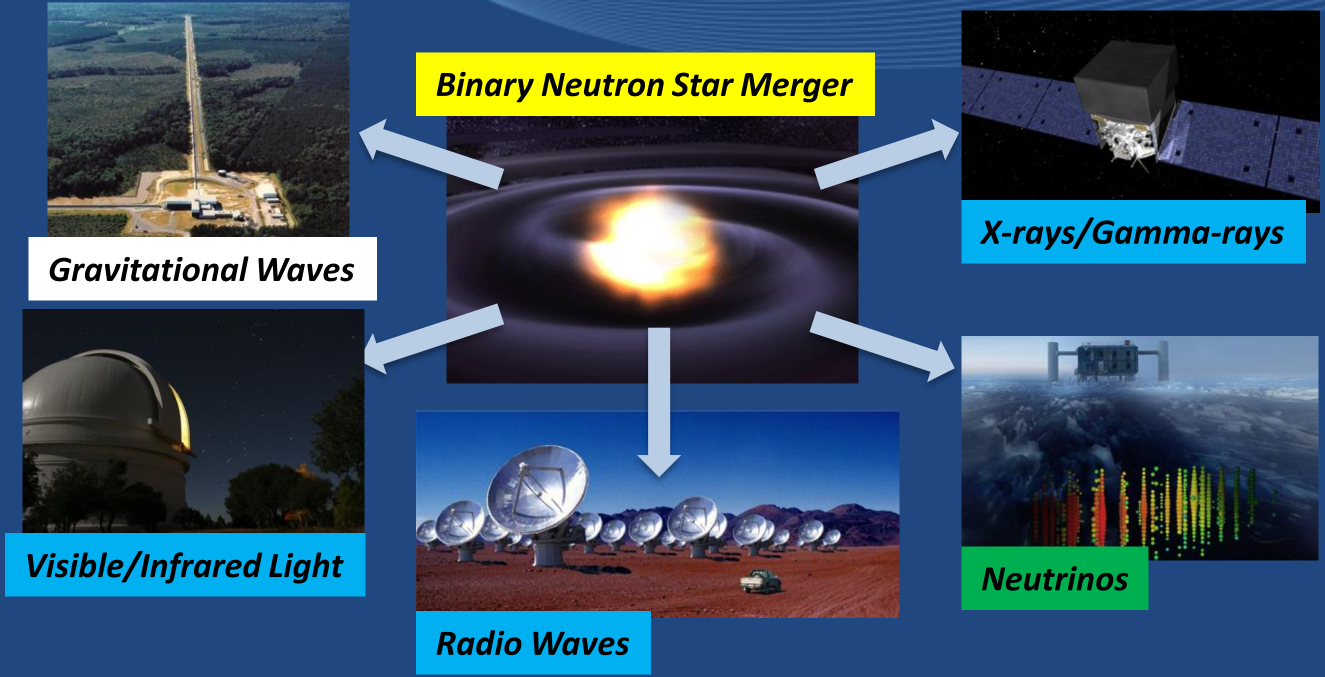
Fermi Satellite GRB detection 2 seconds later

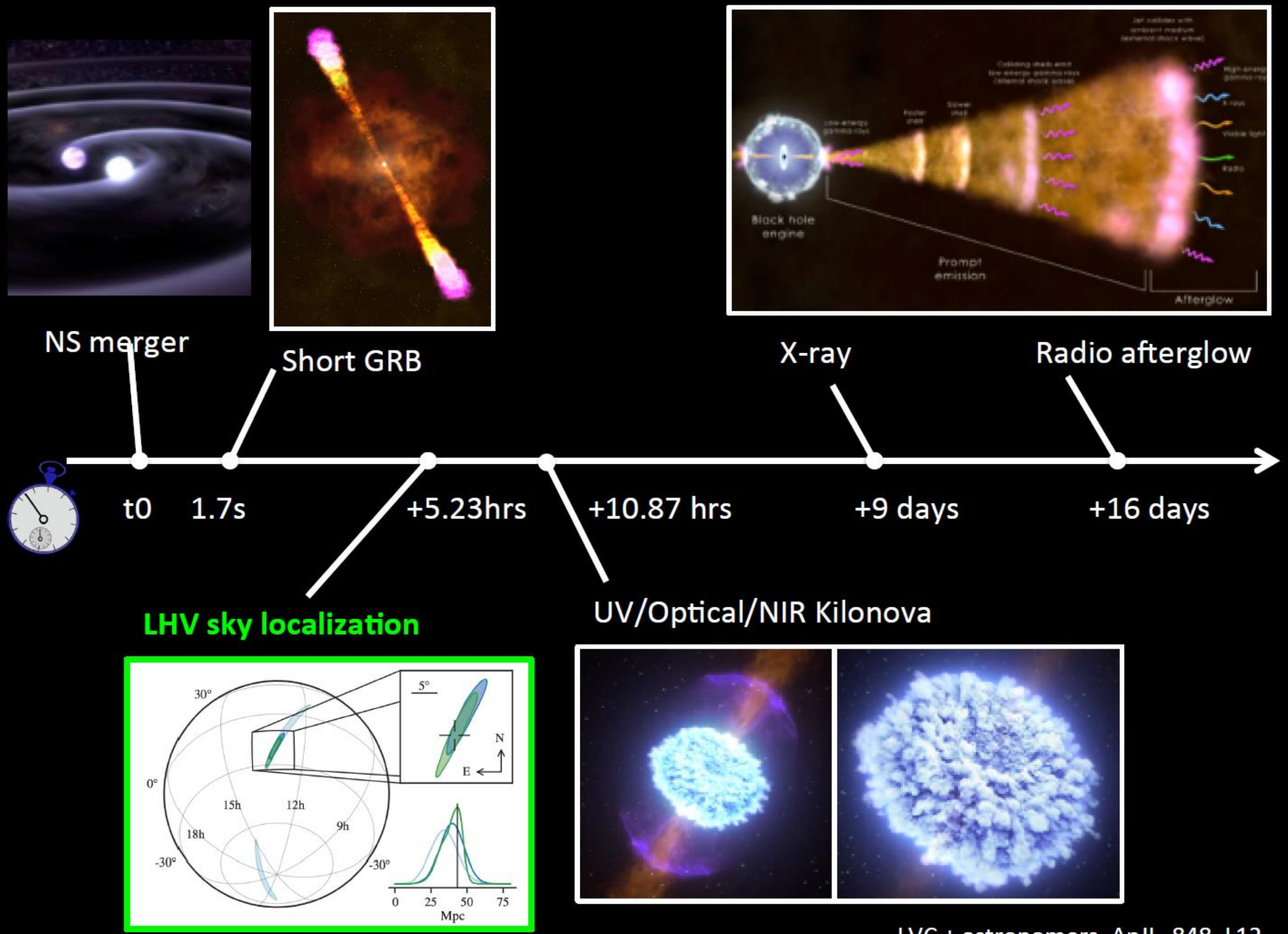




170817A" Astrophys. J. Lett., 848:L13, (2017)

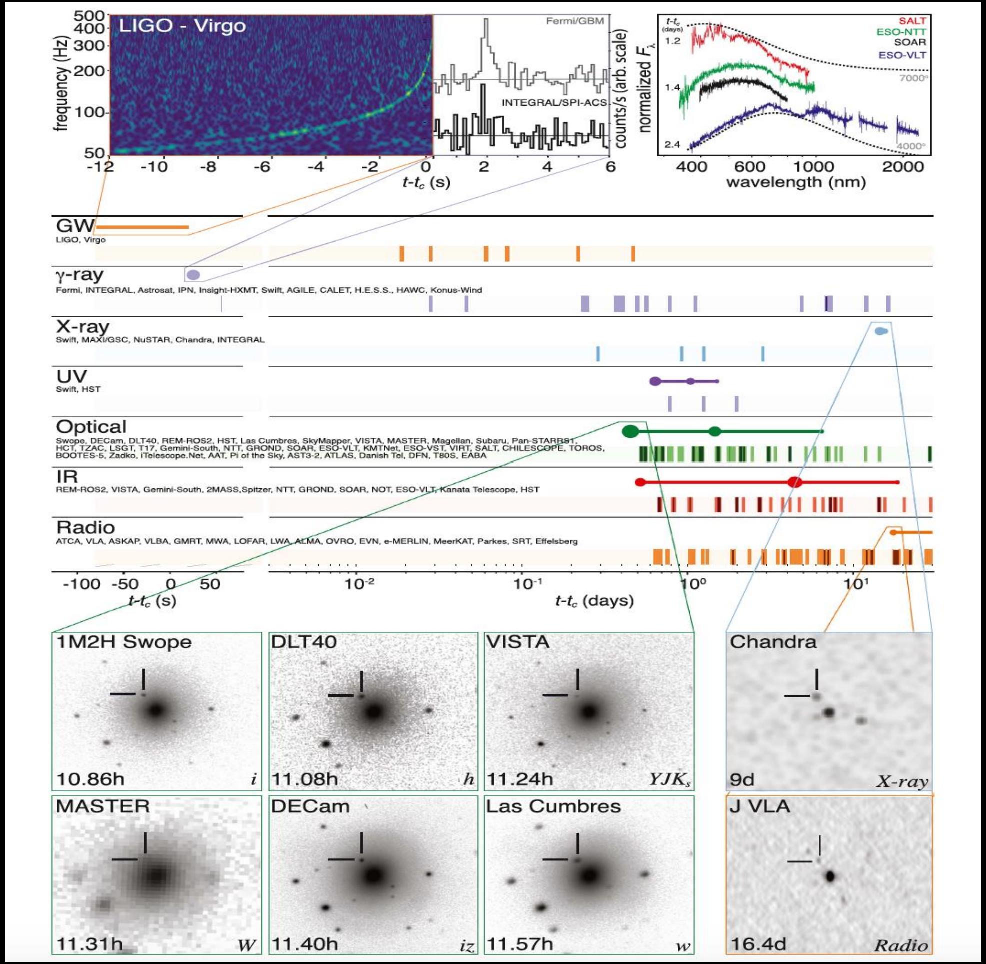
Multi-messenger Astronomy with Gravitational Waves

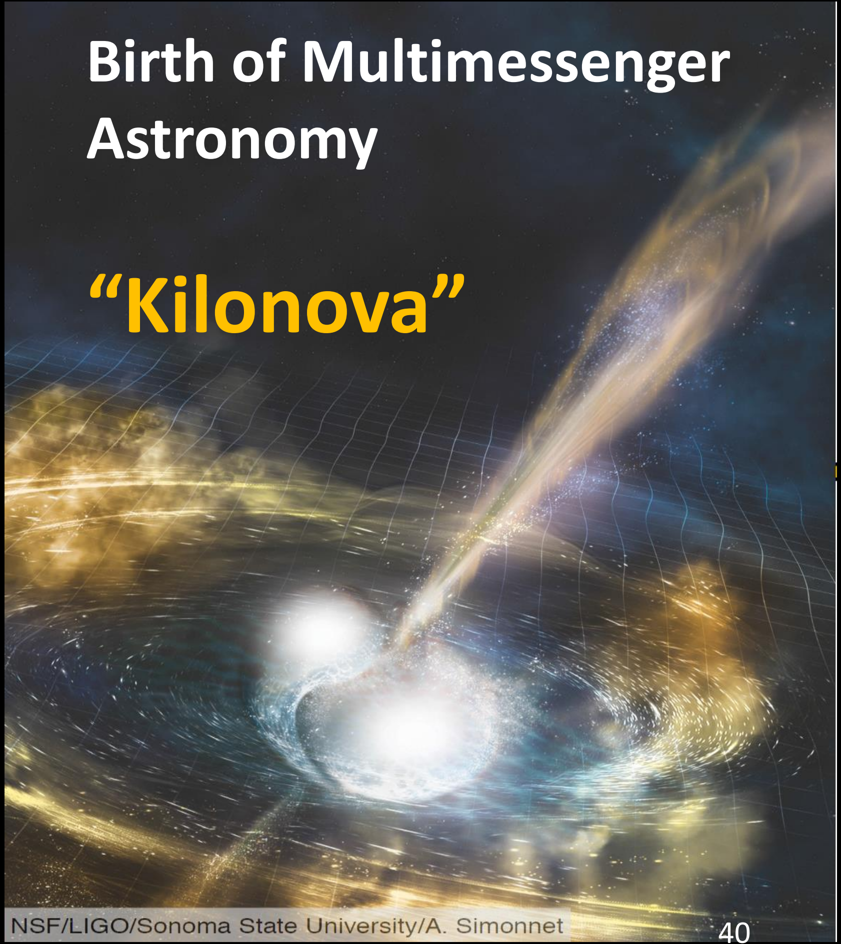




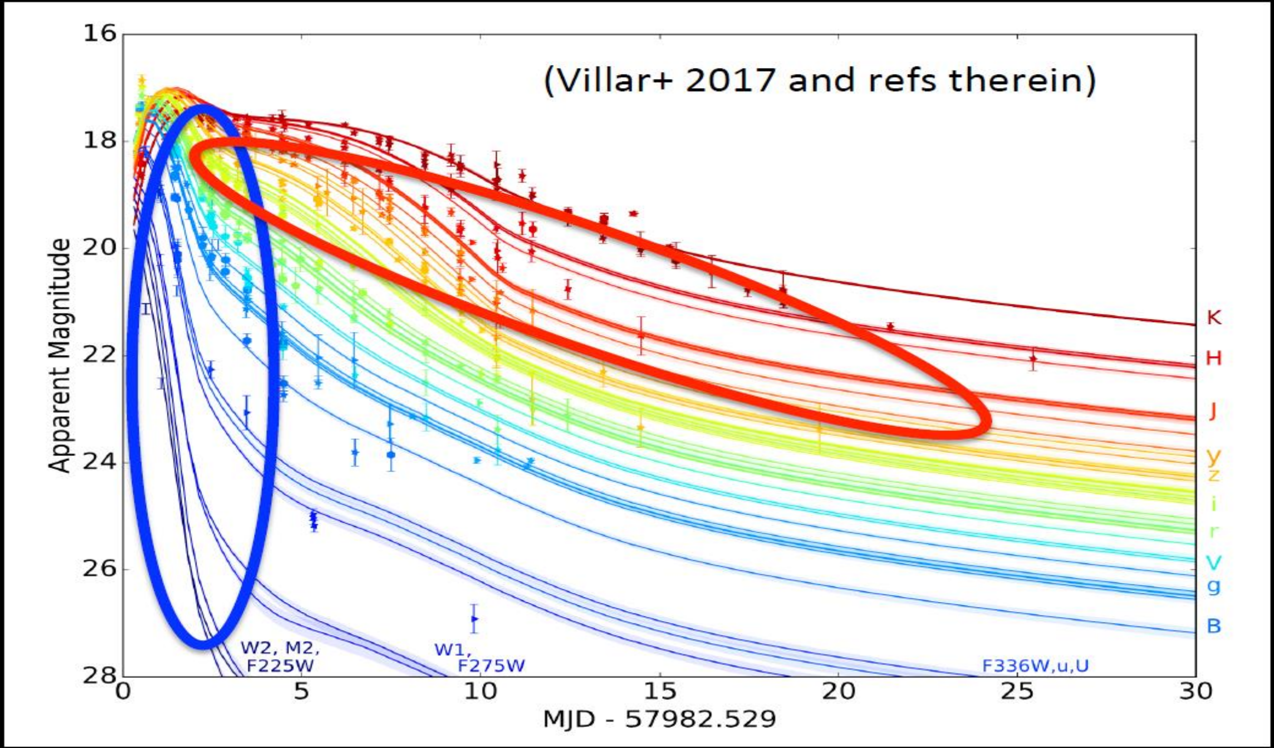
LVC + astronomers, ApJL, 848, L12

Observations Across the Electromagnetic Spectrum



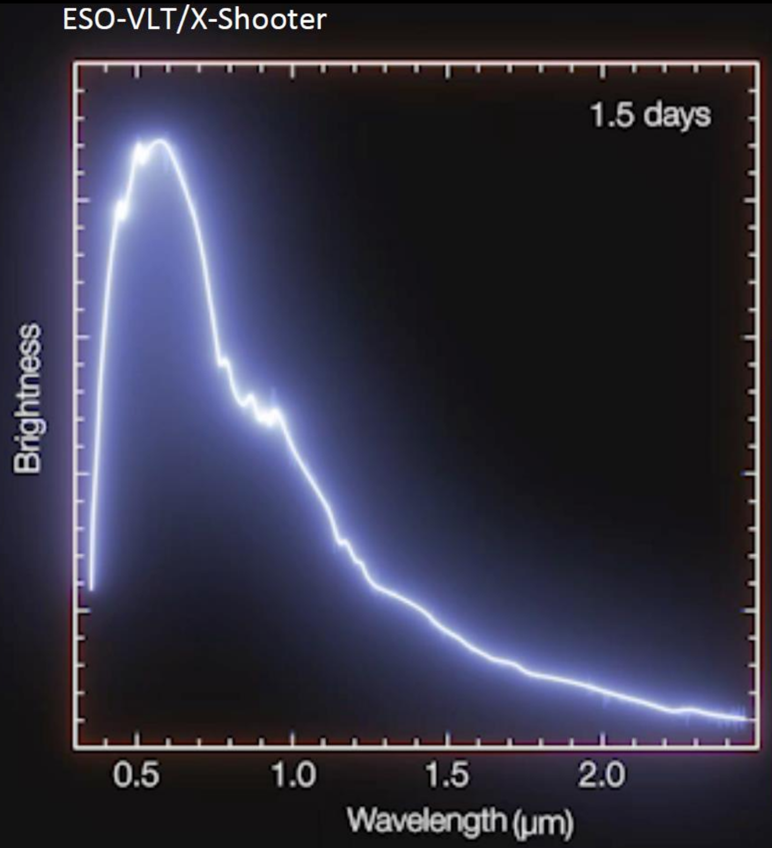


Light Curves



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

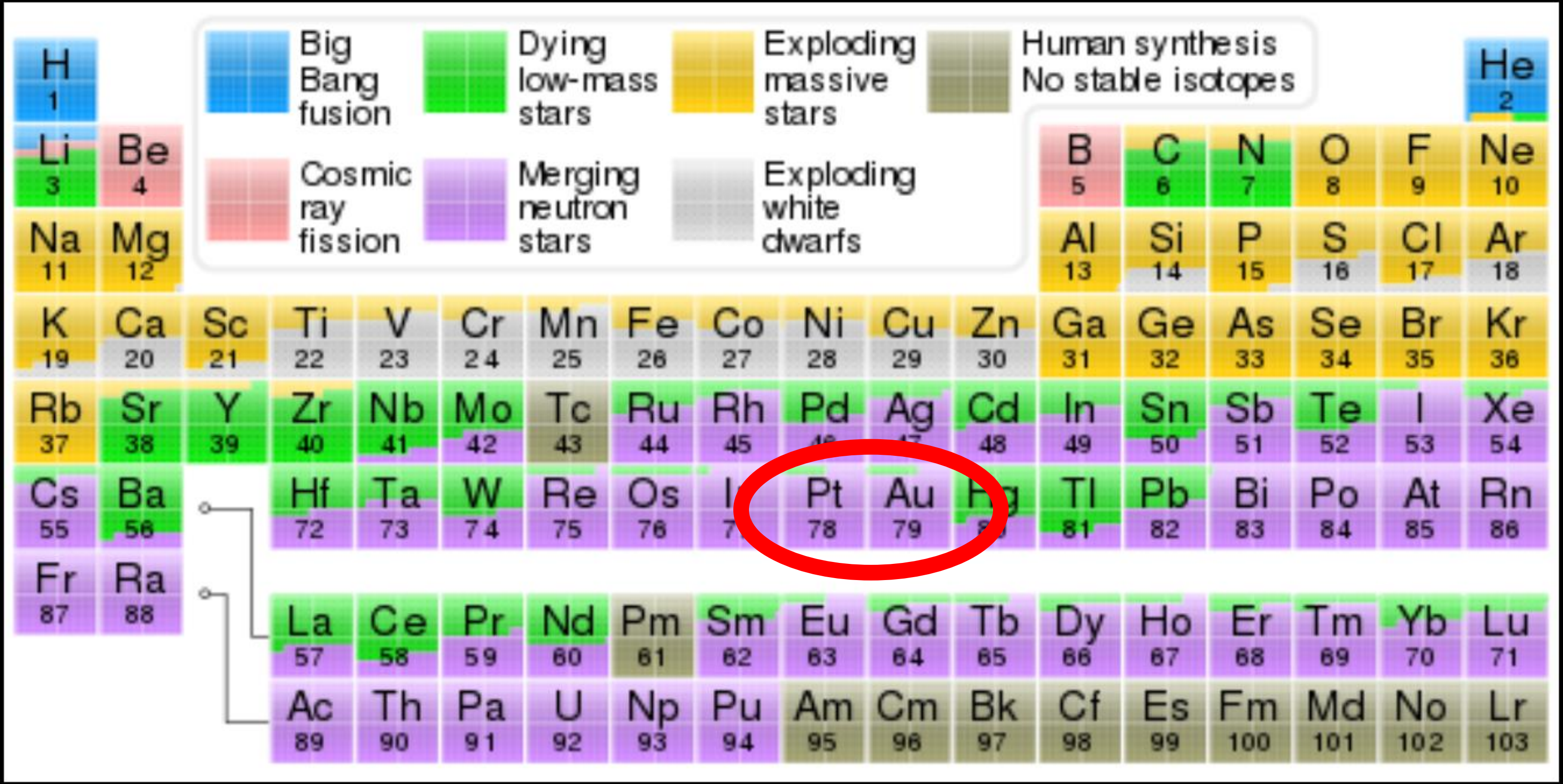
First spectral identification of the kilonova emission

- 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

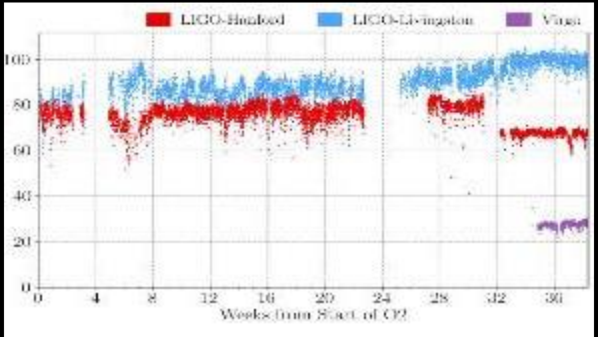
Origin of the Heavy Elements

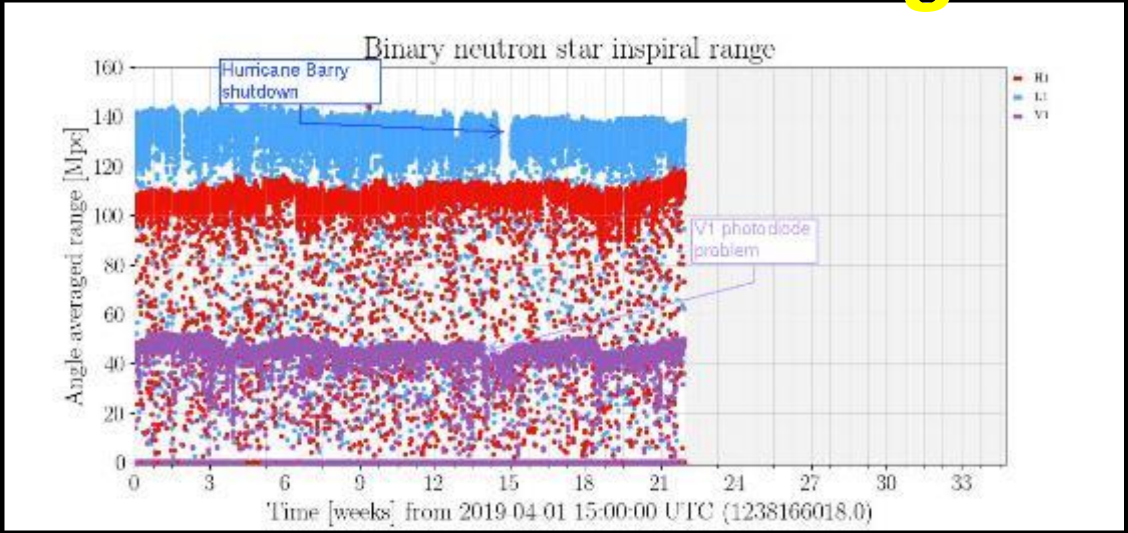


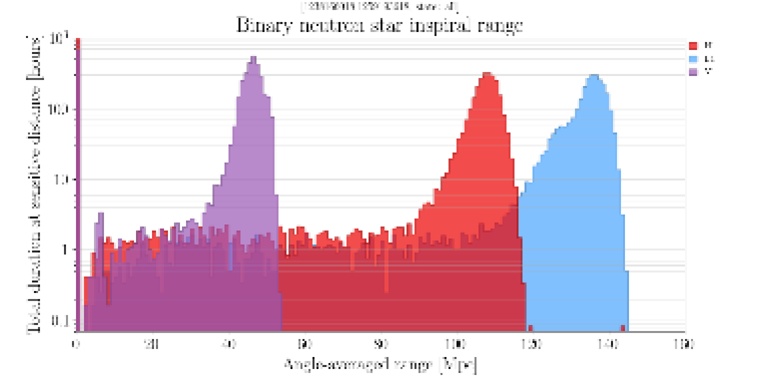
NS Mergers are Incredible Gold Factories

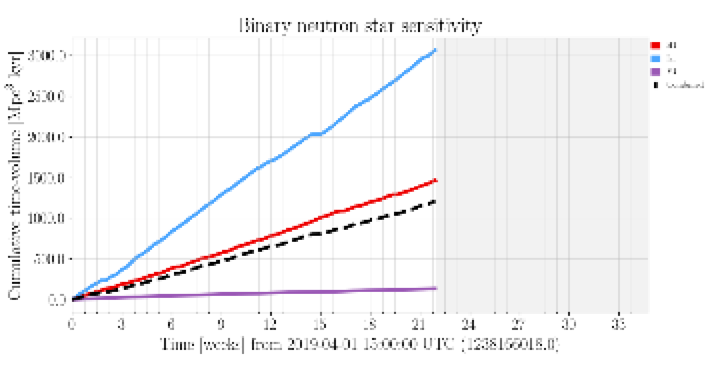
LIGO observed Neutron Star Merger produced ~ 100 Earth Masses of Gold

Detector Performance: BNS range



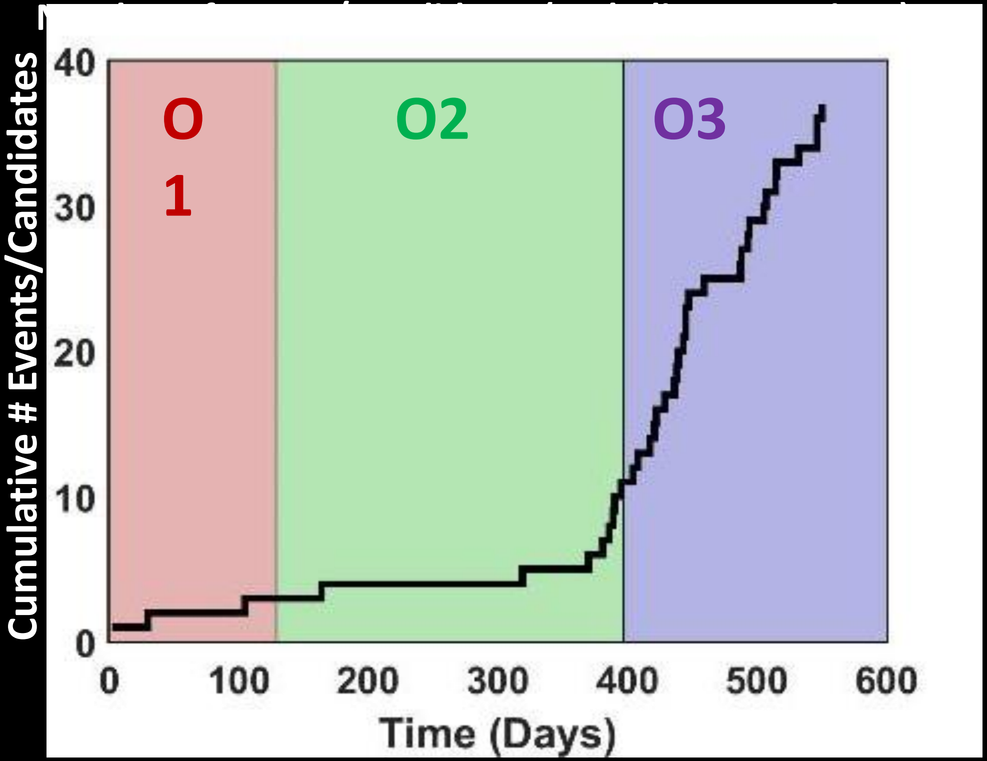


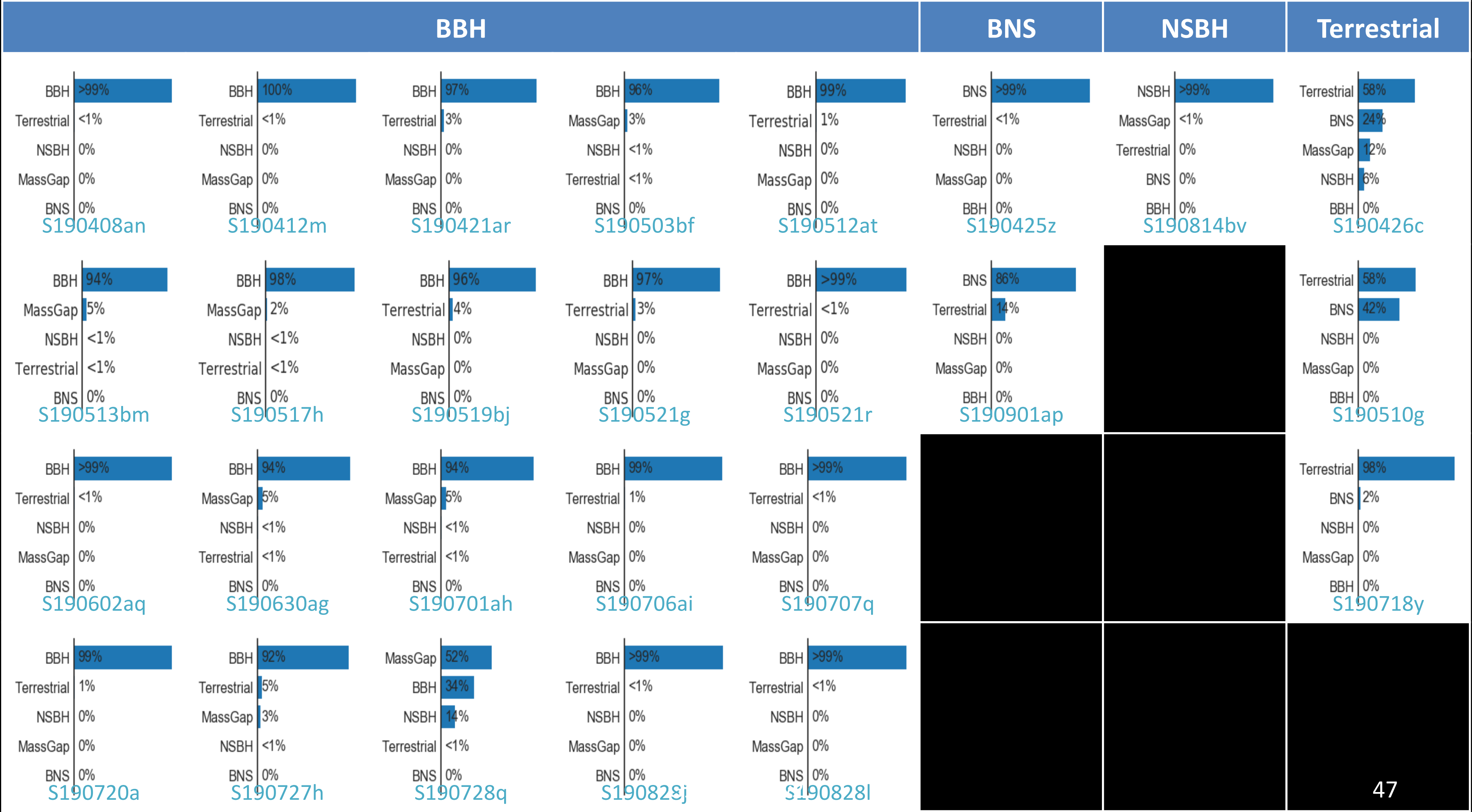




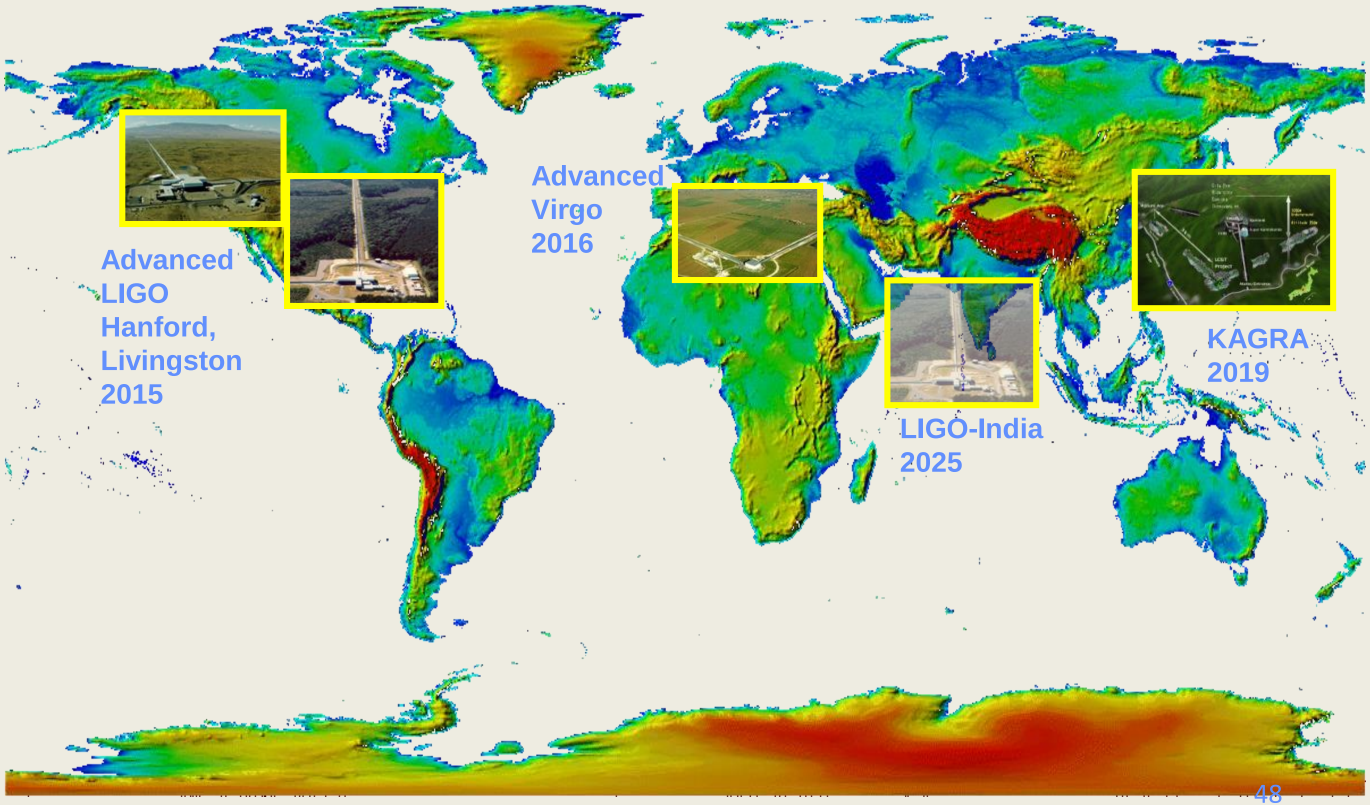
O3 Detection Candidates to September

- 5 months of observing
- 33 LVC public alerts
  - Of those, 7 retracted
- 1 FermiGBM-LVC public alert for subthreshold candidate




BBH
BNS
NSBH
Terrestrial
BBH >99% Terrestrial <1% NSBH 0% MassGap 0% BNS 0%
S190408an
BBH 100% Terrestrial <1% NSBH 0% MassGap 0% BNS 0%
S190412m
BBH 97% Terrestrial 3% NSBH 0% MassGap 0% BNS 0%
S190421ar
BBH 96% MassGap 3% NSBH <1% Terrestrial <1% BNS 0%
S190503bf
BBH 99% Terrestrial 1% NSBH 0% MassGap 0% BNS 0%
S190512at
BNS >99% Terrestrial <1% NSBH 0% MassGap 0% BBH 0%
S190425z
NSBH >99% MassGap <1% Terrestrial 0% BNS 0% BBH 0%
S190814bv
Terrestrial 58% BNS 24% MassGap 12% NSBH 6% BBH 0%
S190426c
BBH 94% MassGap 5% NSBH <1% Terrestrial <1% BNS 0%
S190513bm
BBH 98% MassGap 2% NSBH <1% Terrestrial <1% BNS 0%
S190517h
BBH 96% Terrestrial 4% NSBH 0% MassGap 0% BNS 0%
S190519bj
BBH 97% Terrestrial 3% NSBH 0% MassGap 0% BNS 0%
S190521g
BBH >99% Terrestrial <1% NSBH 0% MassGap 0% BNS 0%
S190521r
BNS 86% Terrestrial 14% NSBH 0% MassGap 0% BBH 0%
S190901ap
Terrestrial 58% BNS 42% NSBH 0% MassGap 0% BBH 0%
S190510g
BBH >99% Terrestrial <1% NSBH 0% MassGap 0% BNS 0%
S190602aq
BBH 94% MassGap 5% NSBH <1% Terrestrial <1% BNS 0%
S190630ag
BBH 94% MassGap 5% NSBH <1% Terrestrial <1% BNS 0%
S190701ah
BBH 99% Terrestrial 1% NSBH 0% MassGap 0% BNS 0%
S190706ai
BBH >99% Terrestrial <1% NSBH 0% MassGap 0% BNS 0%
S190707q
Terrestrial 98% BNS 2% NSBH 0% MassGap 0% BBH 0%
S190718y
BBH 99% Terrestrial 1% NSBH 0% MassGap 0% BNS 0%
S190720a
BBH 92% Terrestrial 5% MassGap 3% NSBH <1% BNS 0%
S190727h
MassGap 52% BBH 34% NSBH 14% Terrestrial <1% BNS 0%
S190728q
BBH >99% Terrestrial <1% NSBH 0% MassGap 0% BNS 0%
S190828j
BBH >99% Terrestrial <1% NSBH 0% MassGap 0% BNS 0%
S190828l

The Network in mid-2020's



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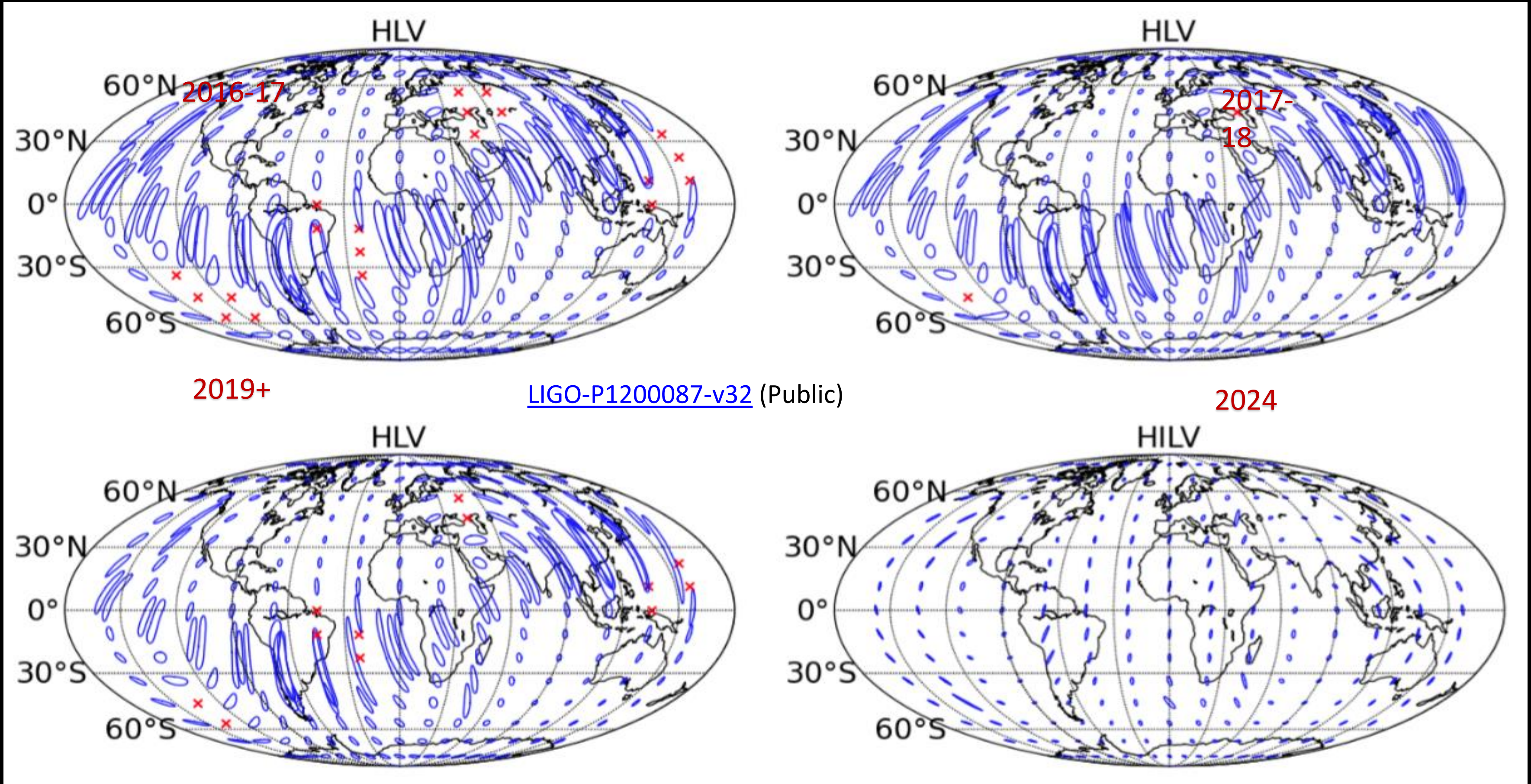
Improving Localization

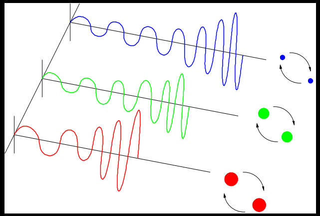


LIGO-P1200087-v32 (Public)

Astrophysical Sources

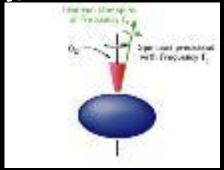
signatures

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

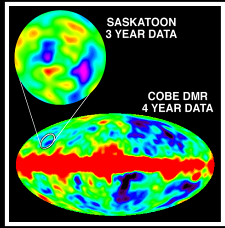


- Supernovae / GRBs: ***"bursts"***
  - burst signals in coincidence with signals in electromagnetic radiation
  - prompt alarm (~ one hour) with neutrino detectors

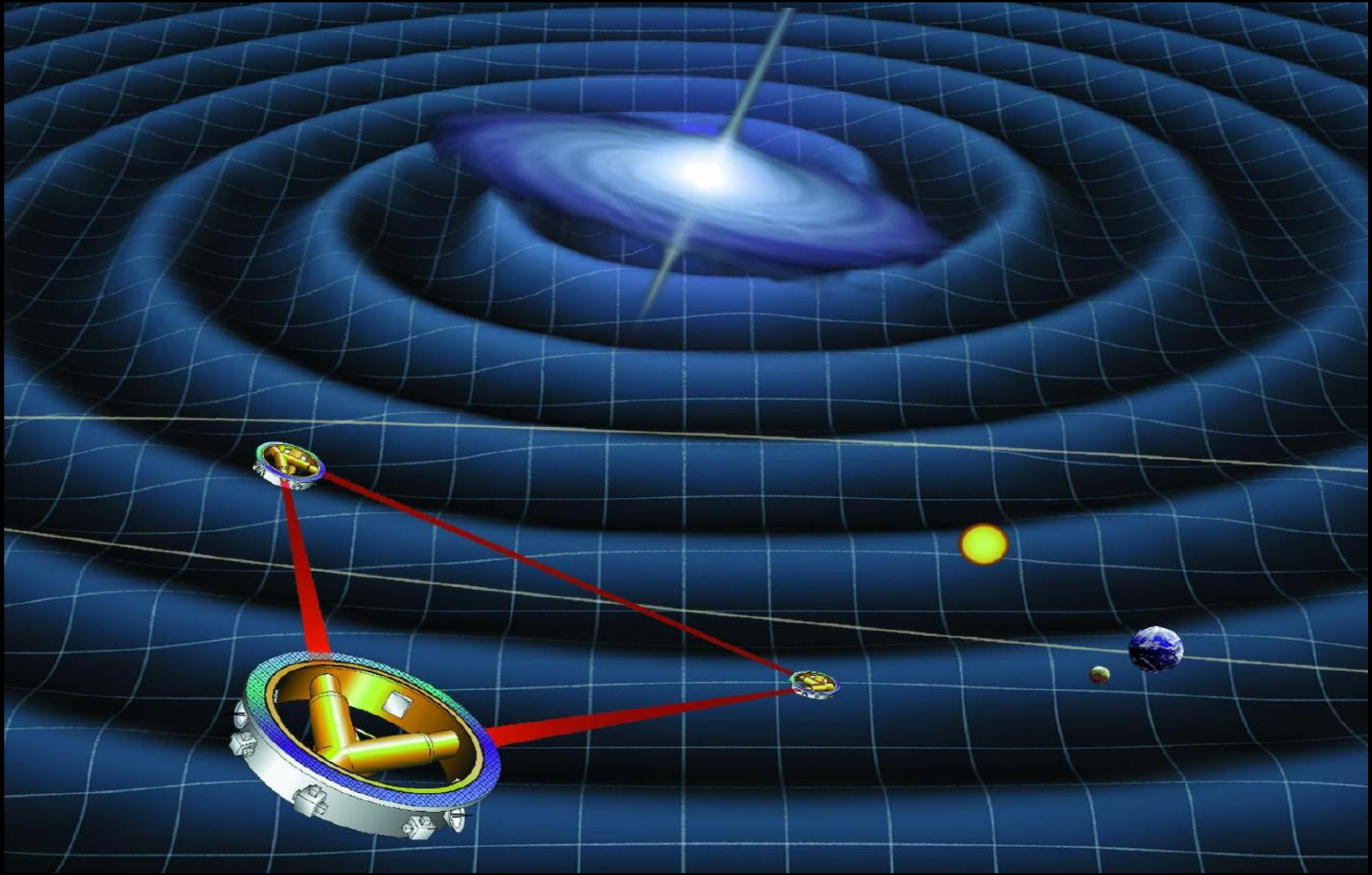
- Pulsars in our galaxy: ***"periodic"***
  - search for observed neutron stars (frequency, doppler shift)
  - all sky search (computing challenge)
  - r-modes



- Cosmological Signal ***"stochastic background"***



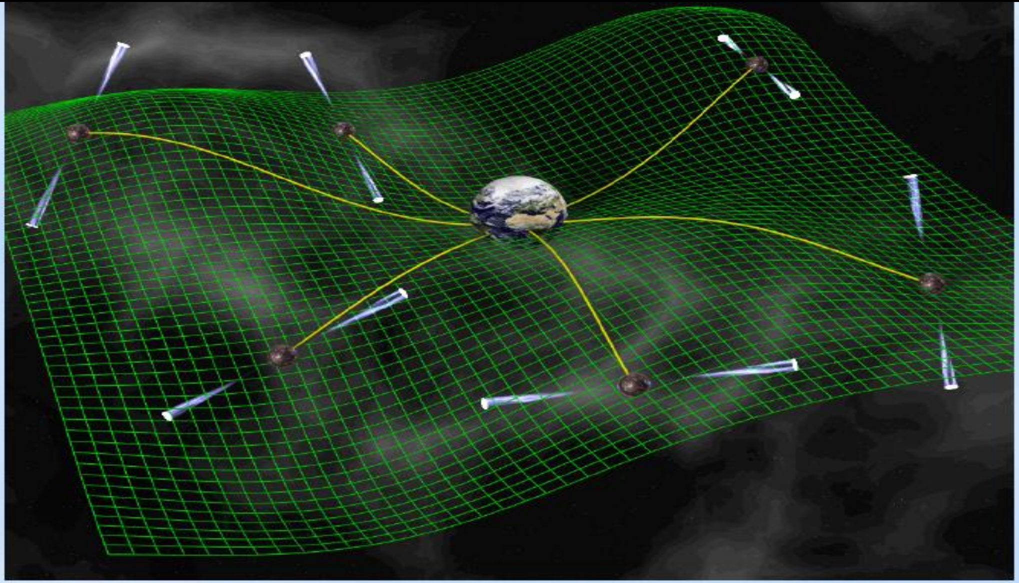
LISA: Laser Interferometer Space Array



Three
Interferometers

2.5 10^6 km arms

Pulsar Timing Arrays

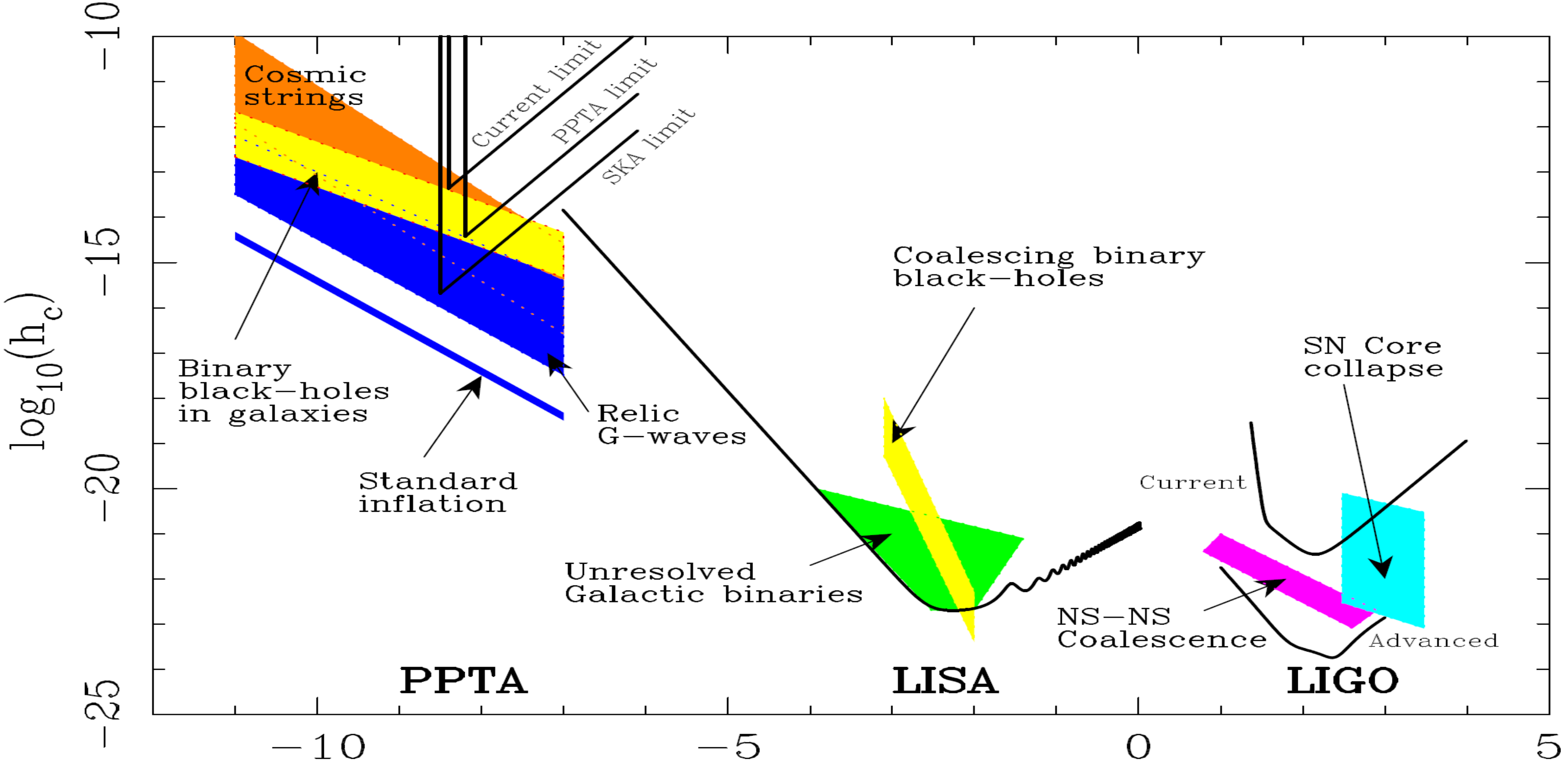


Distant pulsars send regular radio pulses – highly accurate clocks.
A passing gravitational wave would change the arrival time of the pulse.

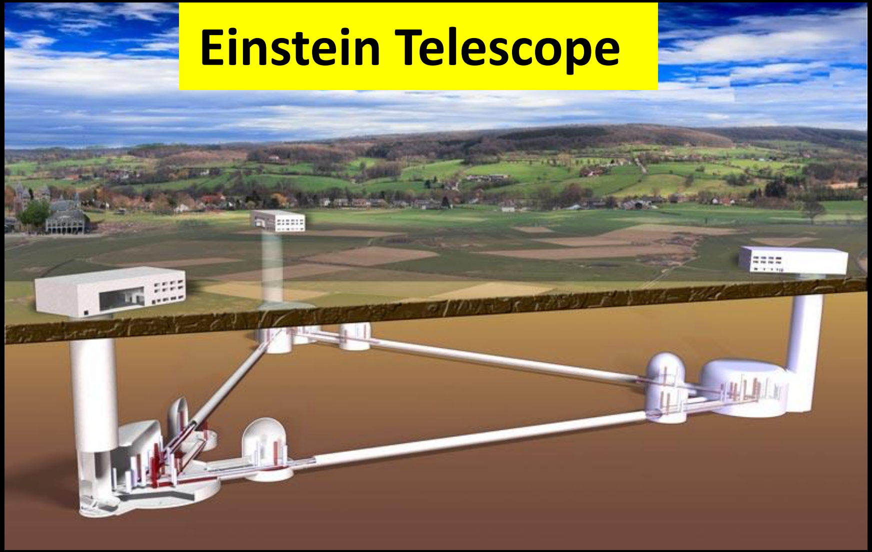
Numerous collaborations around the world. Interesting upper limits and likely detections in the near future. 66

arXiv:1211.4590

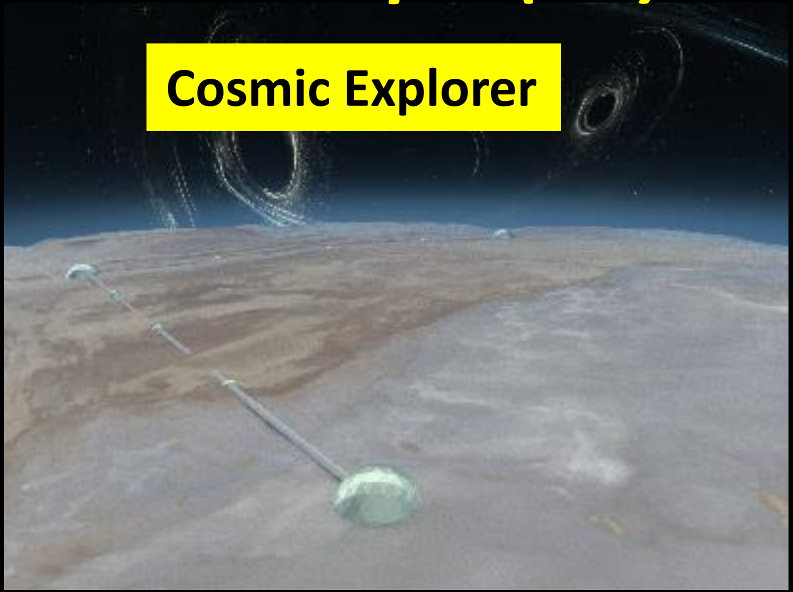
Gravitational Wave Frequency Coverage



Proposed 3rd Generation Concepts (3G)

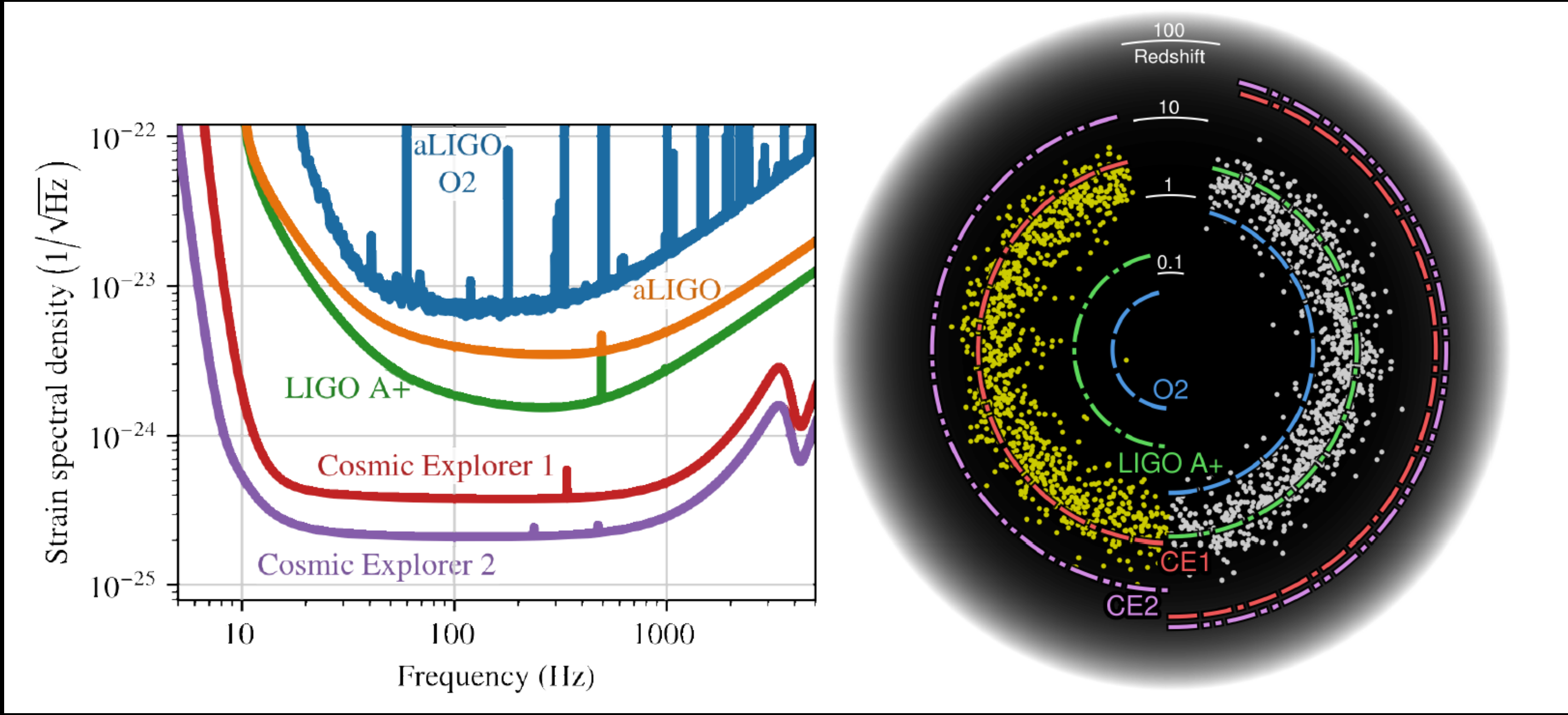


- Deep Underground;
- 10 km arms
- Triangle (polarization)
- Cryogenic
- Low frequency configuration
- high frequency configuration



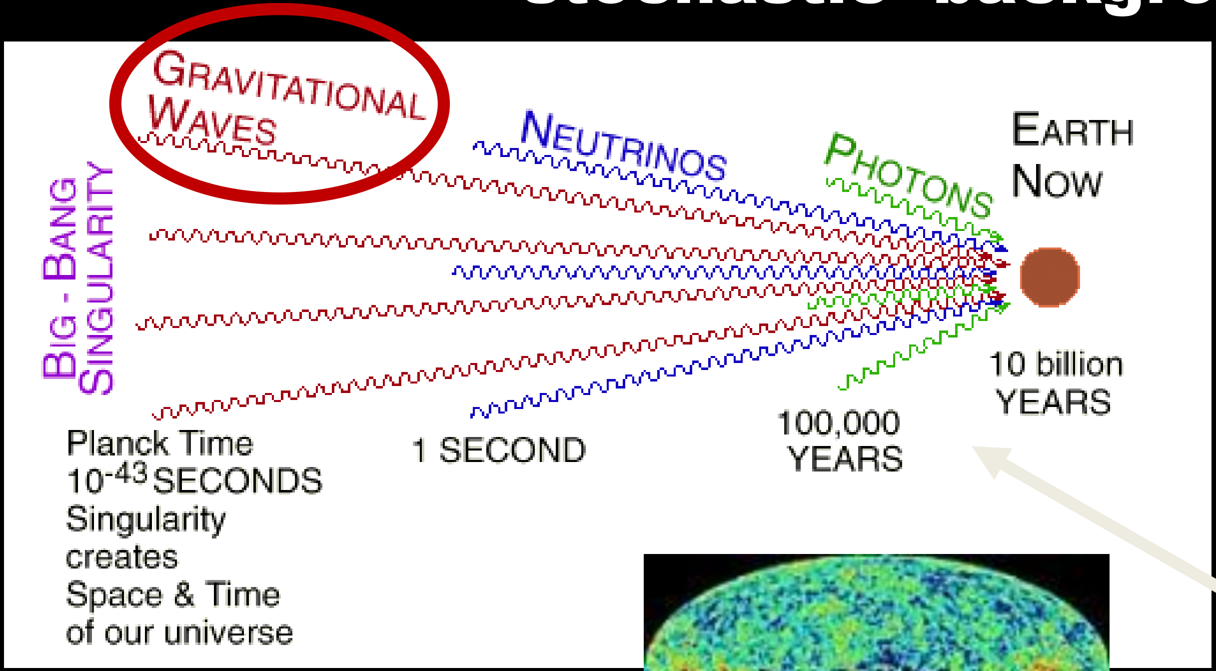
- Earth's surface
- 40 km arms
- L - shaped
- Cryogenic
- Multiple Sites for pointing

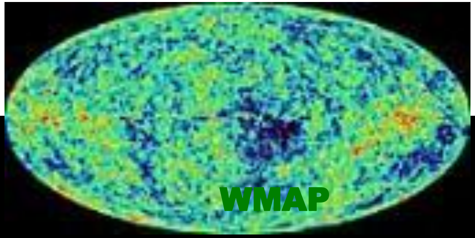
Exploring Binary Systems with Increased Sensitivity



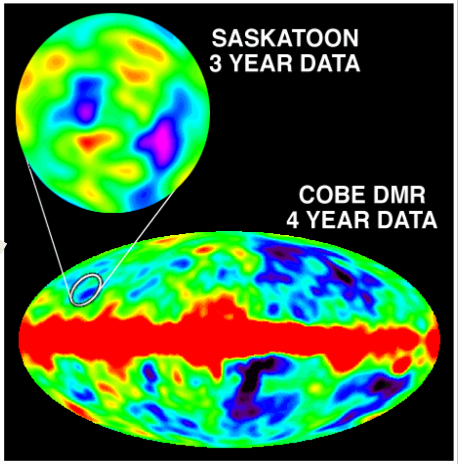
Signals from the Early Universe

stochastic background





Cosmic Microwave background



“Probing the Universe with Gravitational Waves”

The Birth of Multimessenger Astronomy