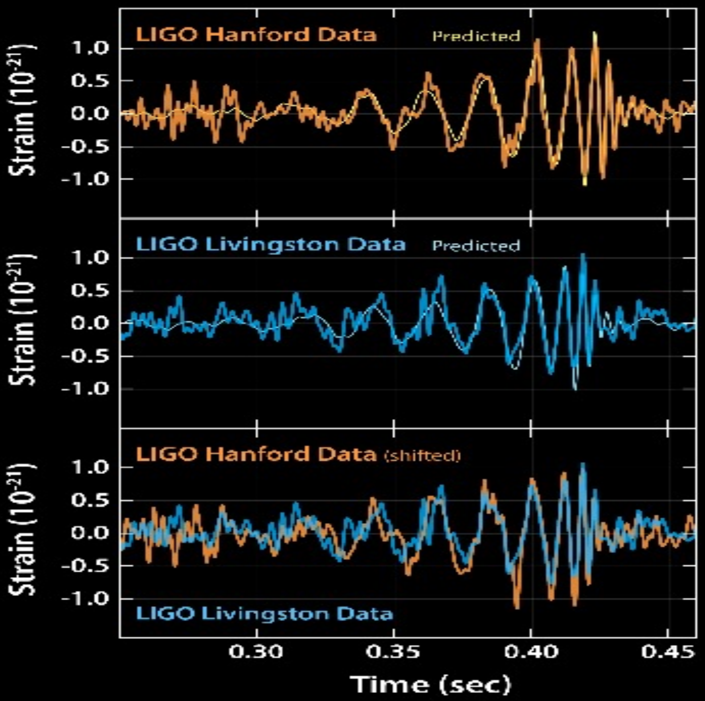
"The Onassis Foundation Science Lecture Series 2022 in Physics"

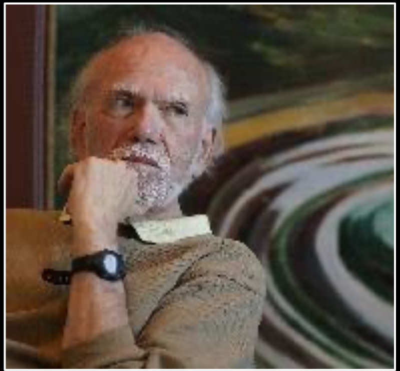
"Gravitational Waves"

Heraklion, Crete, July 25 - 29, 2022



Monday – July 25

09:15 - 10:00	Registration
10:00 - 10:15	Welcome
10:15 - 11:30	**“Intro to the School and Gravitational Waves”, by Barry Barish**
11:30 - 12:00	Break
12:00 - 13:15	**“Theory/Phenomenology of GW #1”, by Alessandra Buonanno**
13:15 - 14:30	Lunch Break
14:30 – 15:45	**“Theory/Phenomenology of GW #2”, by Alessandra Buonanno**



Alessandra Buonanno

- ***“Theory/Phenomenology of Gravitational Waves”***

1. Waveform models for inspiraling binary systems using post-Newtonian theory
2. Waveform models for coalescing binary systems (inspiral-merger-ringdown stages) using the effective-one-body formalism

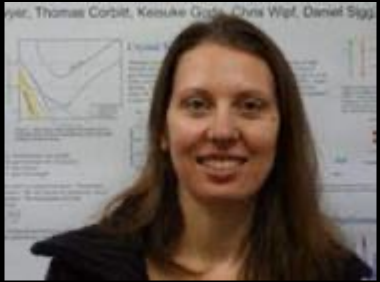
(other waveform models will also be mentioned)

3. Brief discussion of how those waveform models are used for searches and inference studies
4. A glimpse of results from gravitational-wave observations with LIGO and Virgo experiments

Point 3. and 4. may have some overlap with Patrick Sutton, but I will mentioned them briefly, mainly to motivate the importance of predicting the shape of gravitational waves from binary systems.

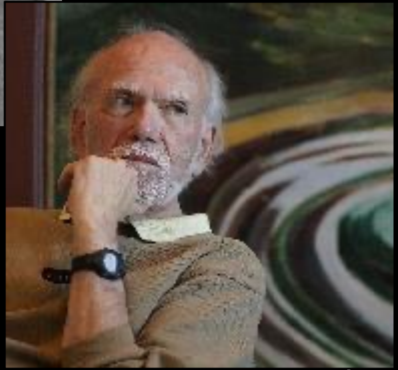
Tuesday – July 26

09:30 -10:45	**“LIGO/Virgo Detectors”, by Lisa Barsotti**
10:45 -11:15	B r e a k
11:15 -12:30	**“LIGO/Virgo Physics #1”, by Patrick Sutton**
12:30 -14:00	L u n c h B r e a k
14:00 – 15:15	**“LIGO/Virgo Data Analysis #1”, by Erik KatsErik Katsavounidisavounidis**



Wednesday – July 27

09:30 - 10:45	**"GW in Space", by Stefano Vitale**
10:45 - 11:15	Break
11:15 - 12:30	**"LIGO Virgo Data Analysis-Results#2" by Erik Katsavounidis**
12:30 – 14:00	Lunch Break
20:00	**"PUBLIC LECTURE" by Barry Barish (in English)**



Stefano Vitale

Gravitational Waves in Space

- Inaccessibility of low frequency from ground are the reason to go to space. Lower frequency: supermassive bodies and detached sources
- LISA science: Supermassive Black-hole binaries, EMRI, Galaxy (local group) binary survey and implications, Multi-band, Sirens and cosmology
- Detecting GW in space: the doppler link
  Basic principle: inertial masses, femtoWatt interferometry. Laser noise and time delay interferometry, Internal GPS and absolute timing. Orbits
- Acceleration noise and LISA Pathfinder: instrument, experiment, operations and results
  LISA current development status

Thursday – July 28

09:30 -10:45	**“The Virgo Detector”, by Jan Harms**
10:45 -11:15	B r e a k
11:15 -12:30	**“Einstein Telescope”, By Jan Harms**
12:30 – 14:00	Lunch Break
14:00 – 15:15	**“”””GW Astrophysics #1” by Marica Branchesi**

Jan Harms

The Virgo detector

The Virgo detector forms part of a global network together with the two LIGO detectors and the KAGRA detector. It has made important contributions to GW observation since 2017. In this lecture, I will discuss the current configuration of the Virgo detector and some of the implemented technologies in preparation of the upcoming observation run in 2023. I will explain how early decisions about detector infrastructure and technologies influence today's planning of the Virgo detector, and what the possible implications are for future upgrades and the development of the field in Europe.

Jan Harms

The Einstein Telescope

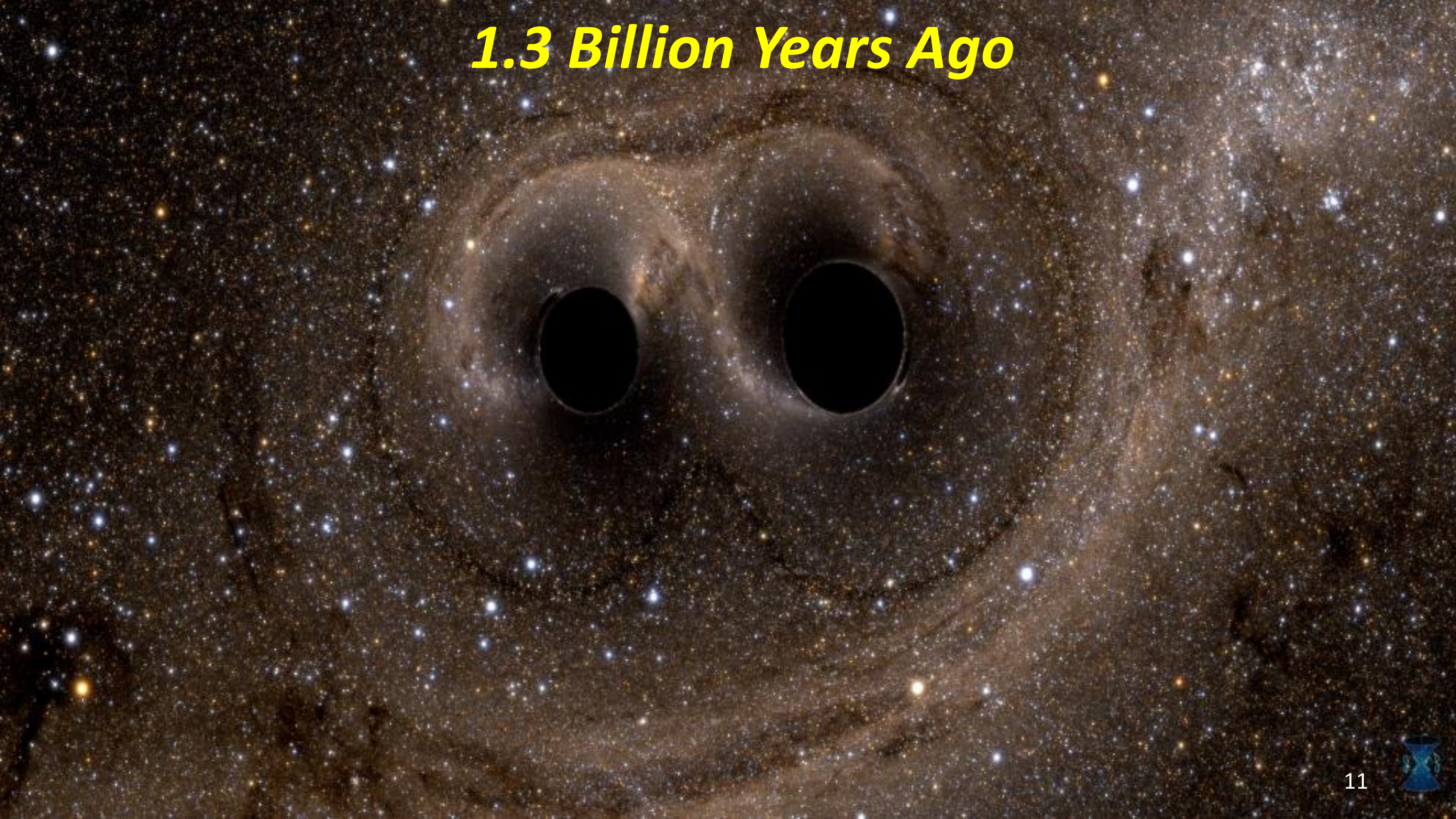
The Einstein Telescope is a proposed underground facility in Europe to host future generations of GW detectors starting operation in the mid 2030s. It takes a radical approach to extend the observation band of terrestrial detectors towards a few Hertz. Environmental noise is strongly reduced underground, and a so-called xylophone configuration is chosen to address the immense challenge of overcoming low-frequency sensitivity limitations of current GW detectors. As a consequence, the Einstein Telescope would be able to see mergers of black holes with masses up to several 1000 solar masses, or equivalently less massive systems at very high redshift. Low-frequency sensitivity also makes it possible to observe binary neutron stars for several hours to a day before they merge, which greatly helps with analyses of the source. In this lecture, I will review the concept, technologies, and science case of the Einstein Telescope.

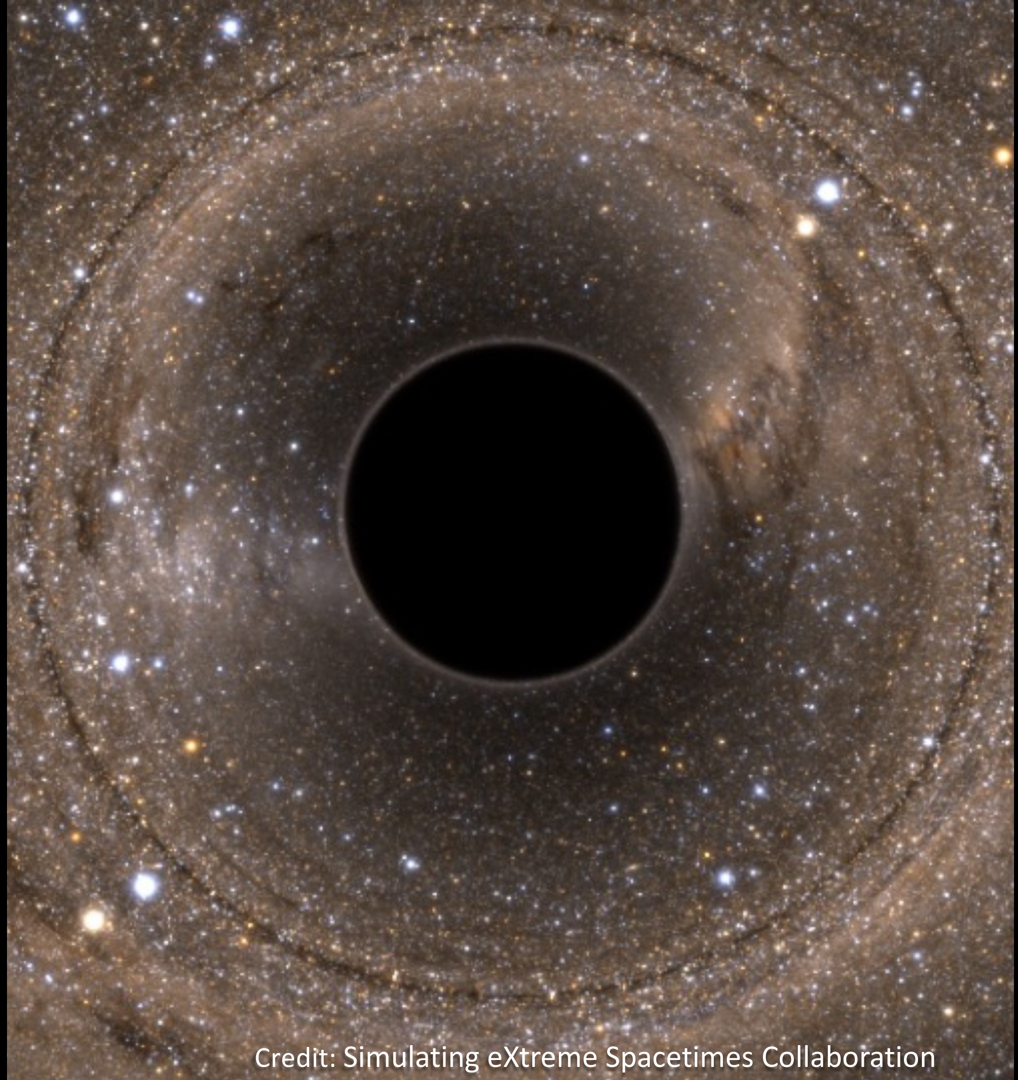
Friday – July 29

09:30 -10:45	**“Cosmic Explorer”, by Evans Matthew**
10:45 -11:15	B r e a k
11:15 -12:30	**“GW Astro Future #2”, by Branchesi Marica**
12:30 – 14:00	Lunch break
14:00 -15:15	**“GW Future Opportunities #2” , by Sutton Patrick**



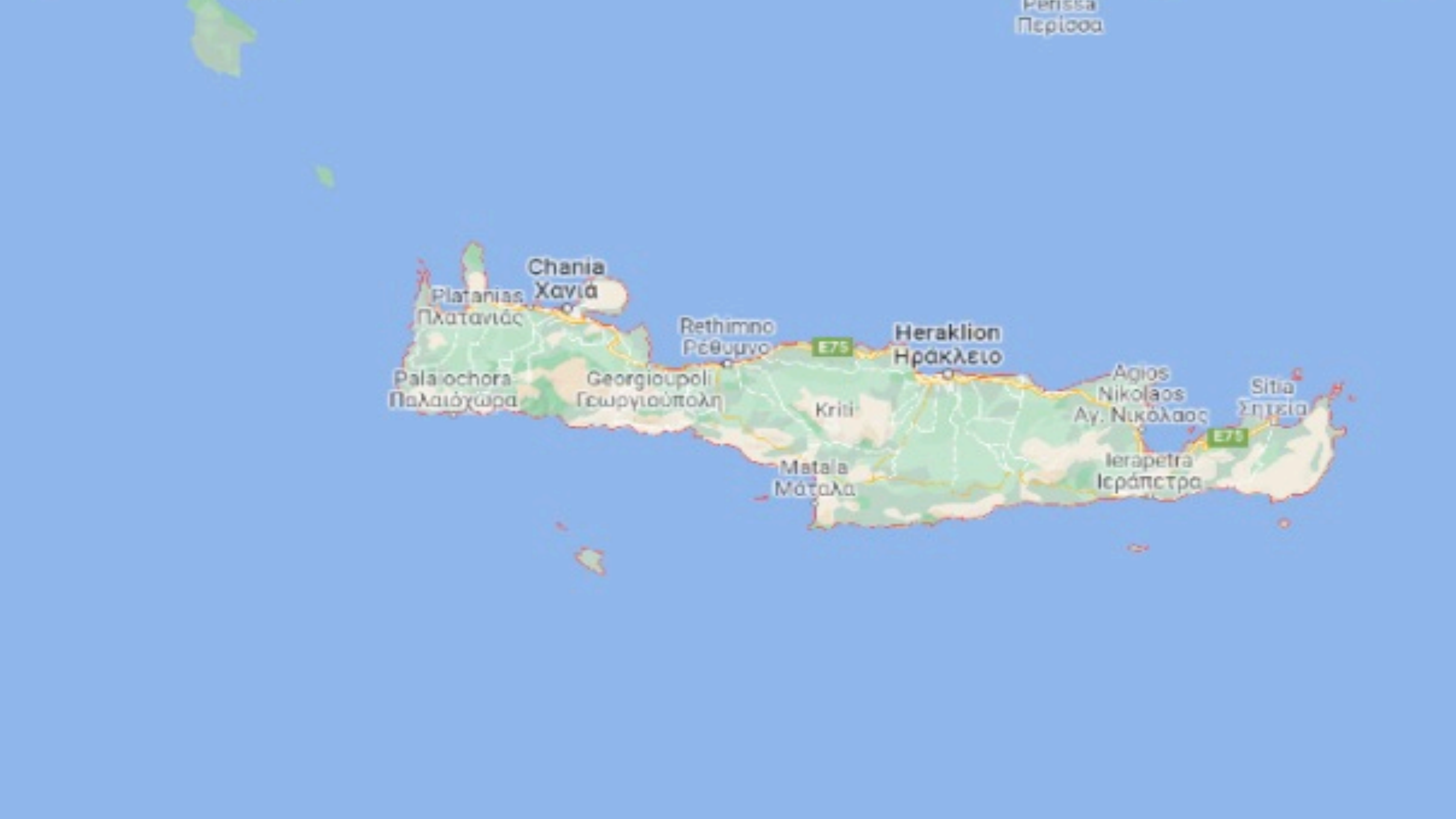
1.3 Billion Years Ago



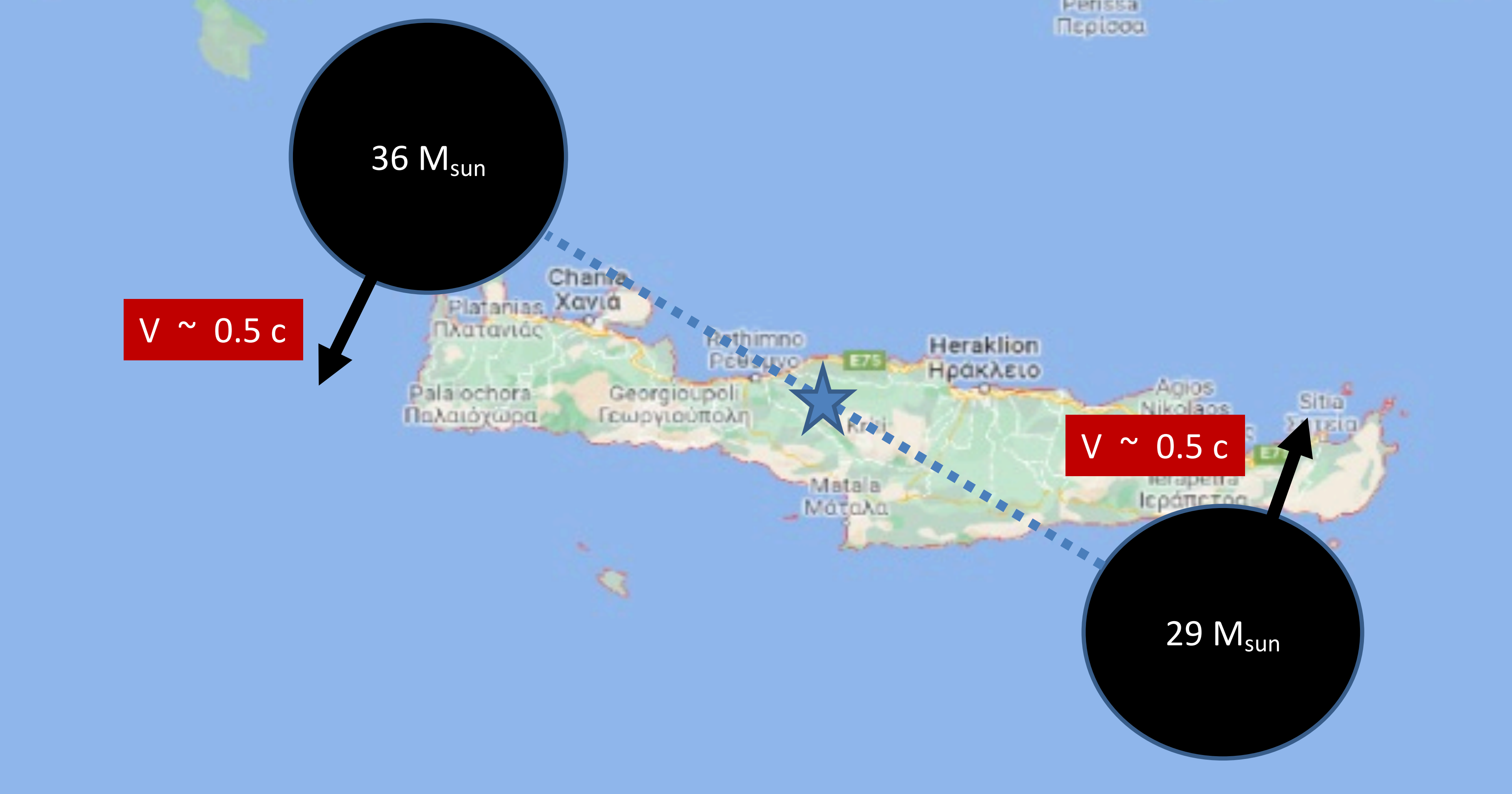


Black Holes

- Regions of space created by super dense matter from where nothing can escape due to the strength of gravity
- Some may form when very large stars collapse and die
- Expected to have masses from around 3 to 100s of times the mass of the Sun
- Others may have been created in the Big Bang



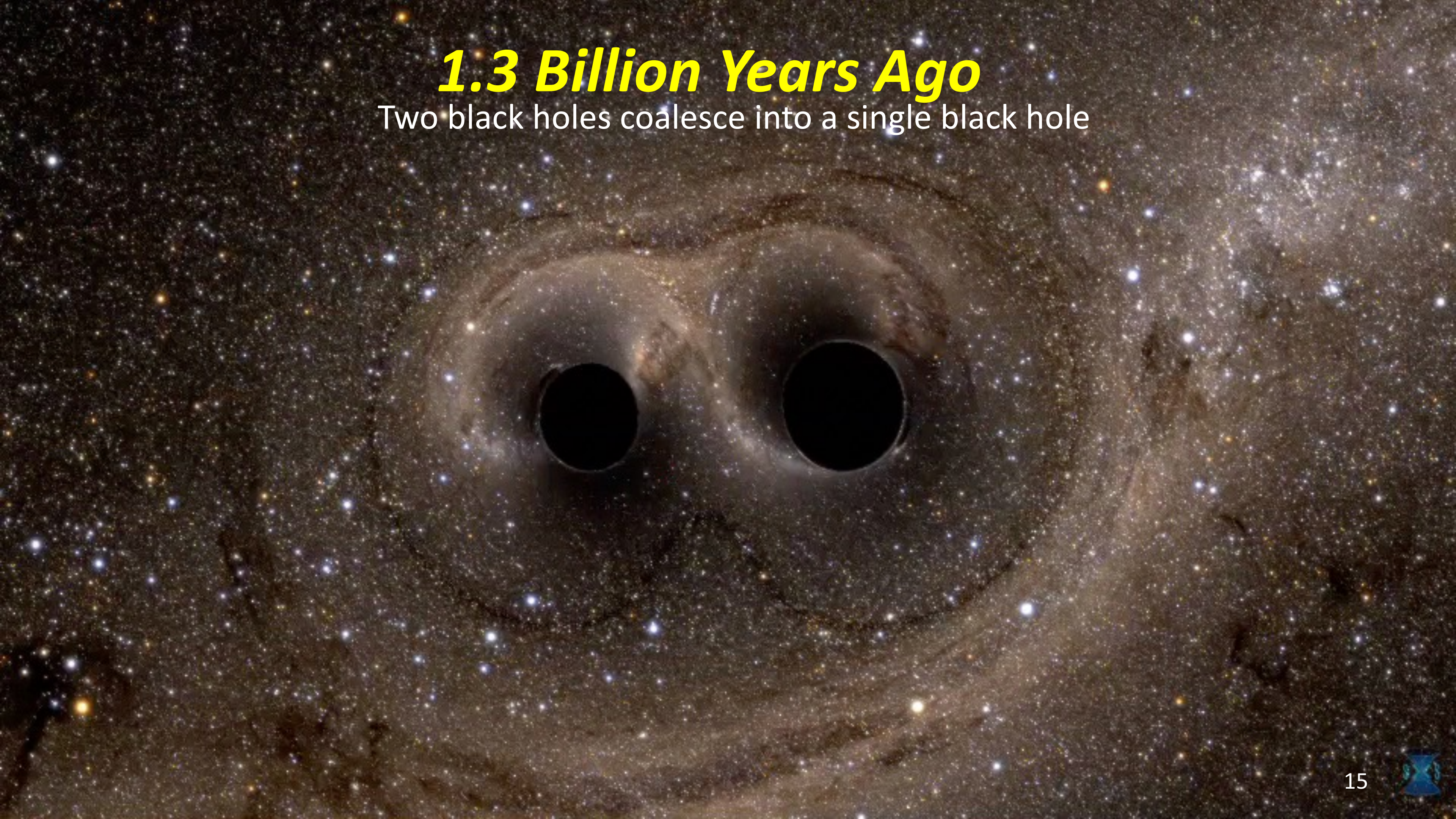
Perissa
Περίσσα
Chania
Χανιά
Platanias
Πλατανιάς
Rethimno
Ρέθυμνο
E75
Heraklion
Ηράκλειο
Palaiochora
Παλαιόχωρα
Georgioupoli
Γεωργιούπολη
Kriti
Agios
Nikolaos
Αγ. Νικόλαος
Sitia
Σητεία
E75
Ierapetra
Ιεράπετρα
Matala
Μάταλα



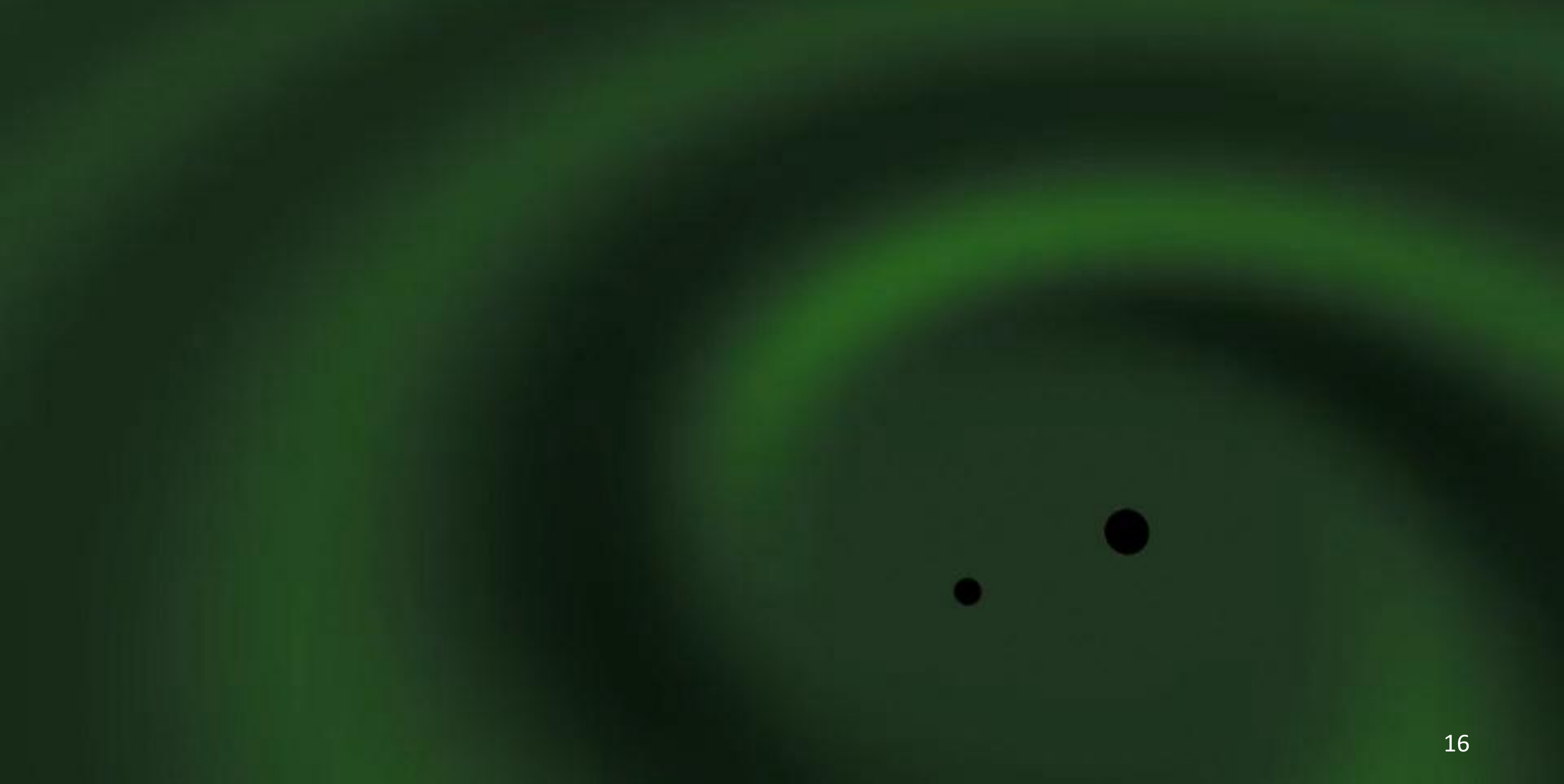
36 M_{sun}
V ~ 0.5 c
29 M_{sun}
V ~ 0.5 c
Chania
Χανιά
Platanias
Πλατανιάς
Palaiochora
Παλαιόχωρα
Georgioupoli
Rethimno
Heraklion
Ηράκλειο
Agios
Matala
Μάταλα
Sitia
Περισσα

1.3 Billion Years Ago

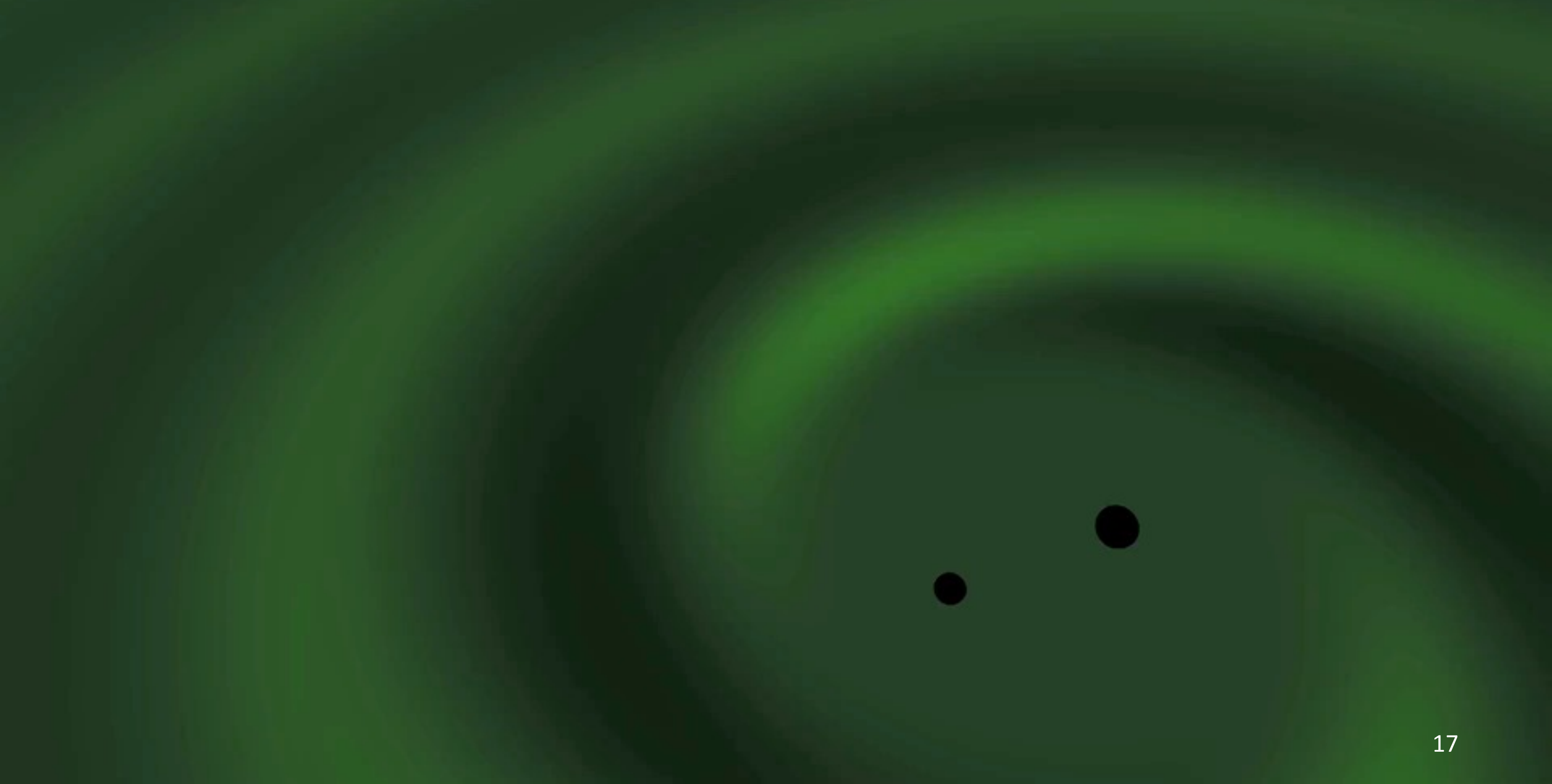
Two black holes coalesce into a single black hole



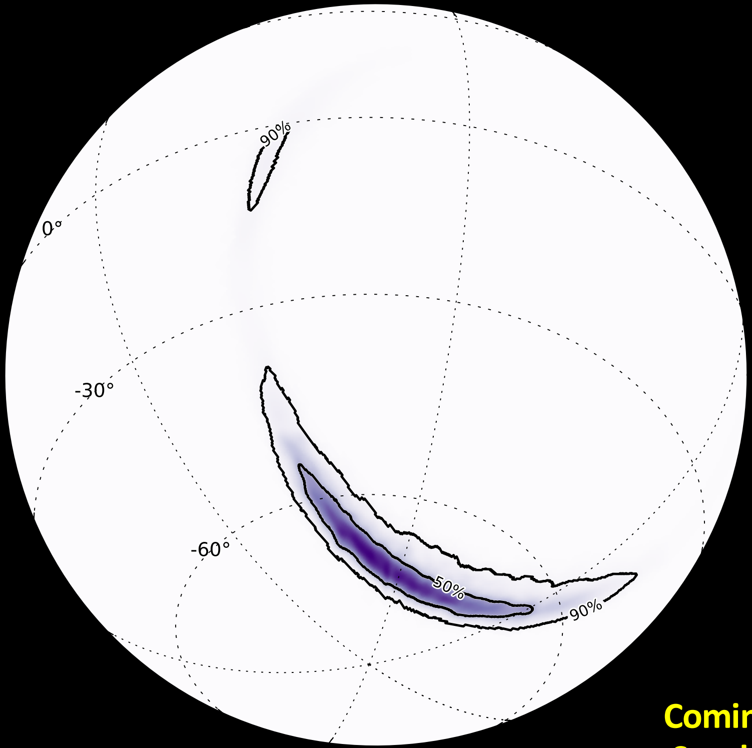
Gravitational Waves Travel to the Earth



Gravitational Waves Travel to the Earth

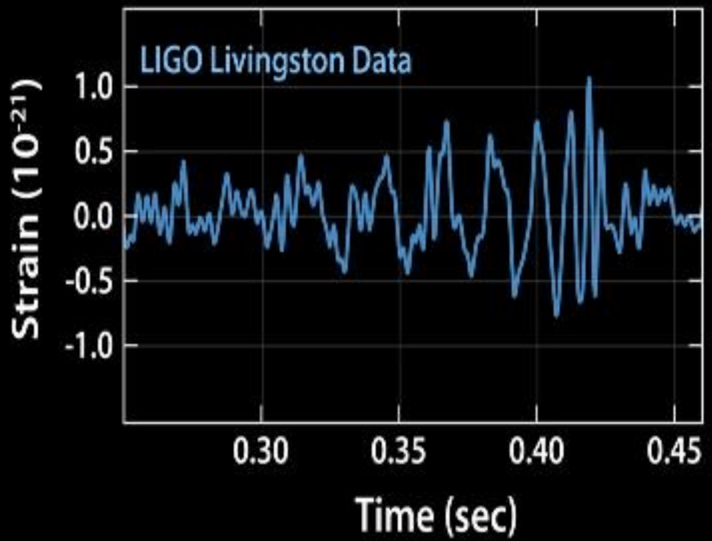


Sept 14, 2015

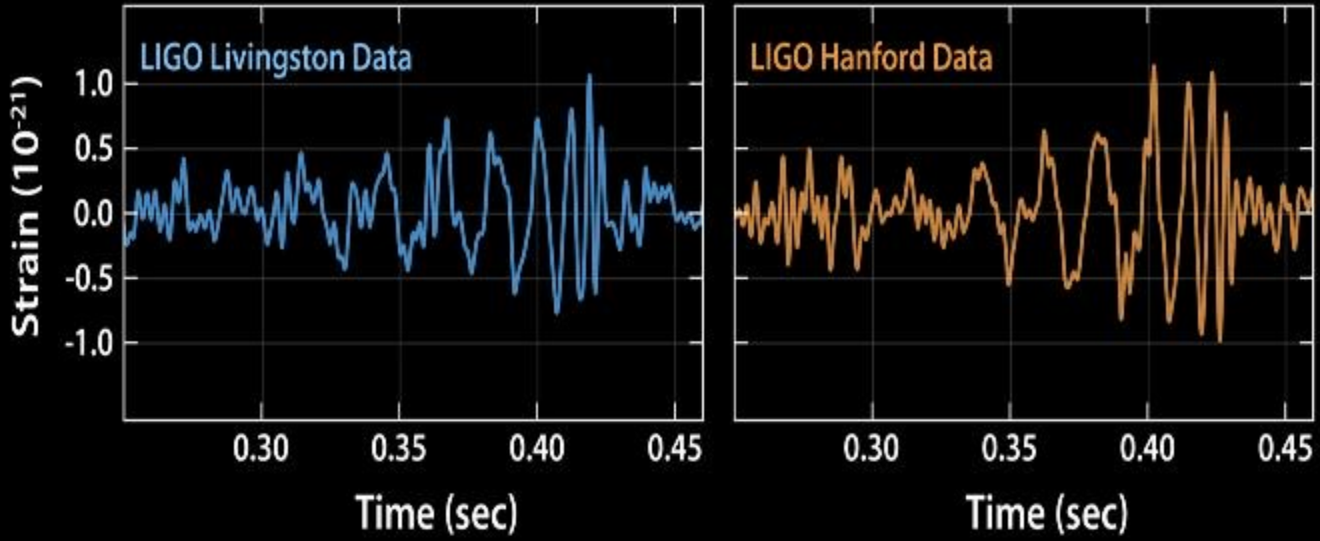


Coming up from
Southern Hemisphere

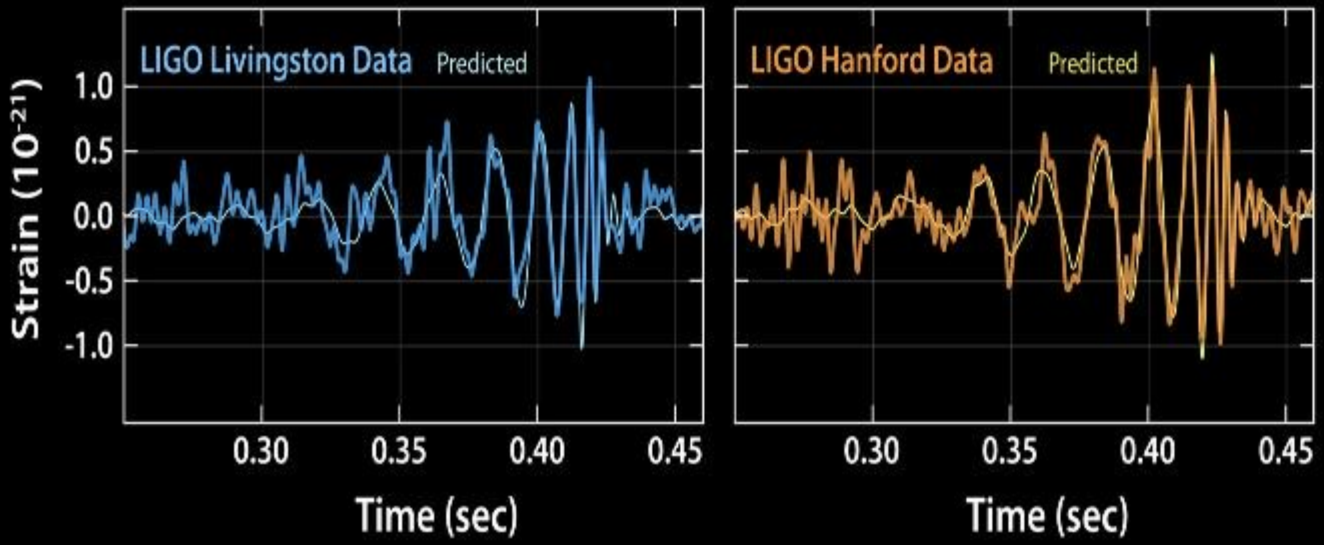
~ 20 msec later



After another 7 msec

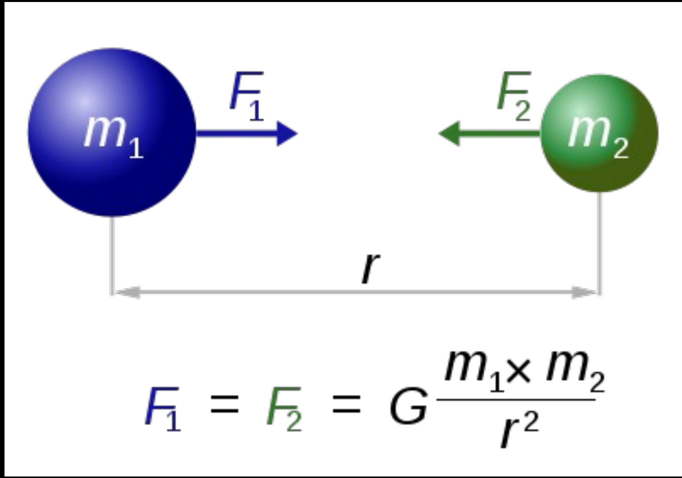


GR Prediction for BH merger

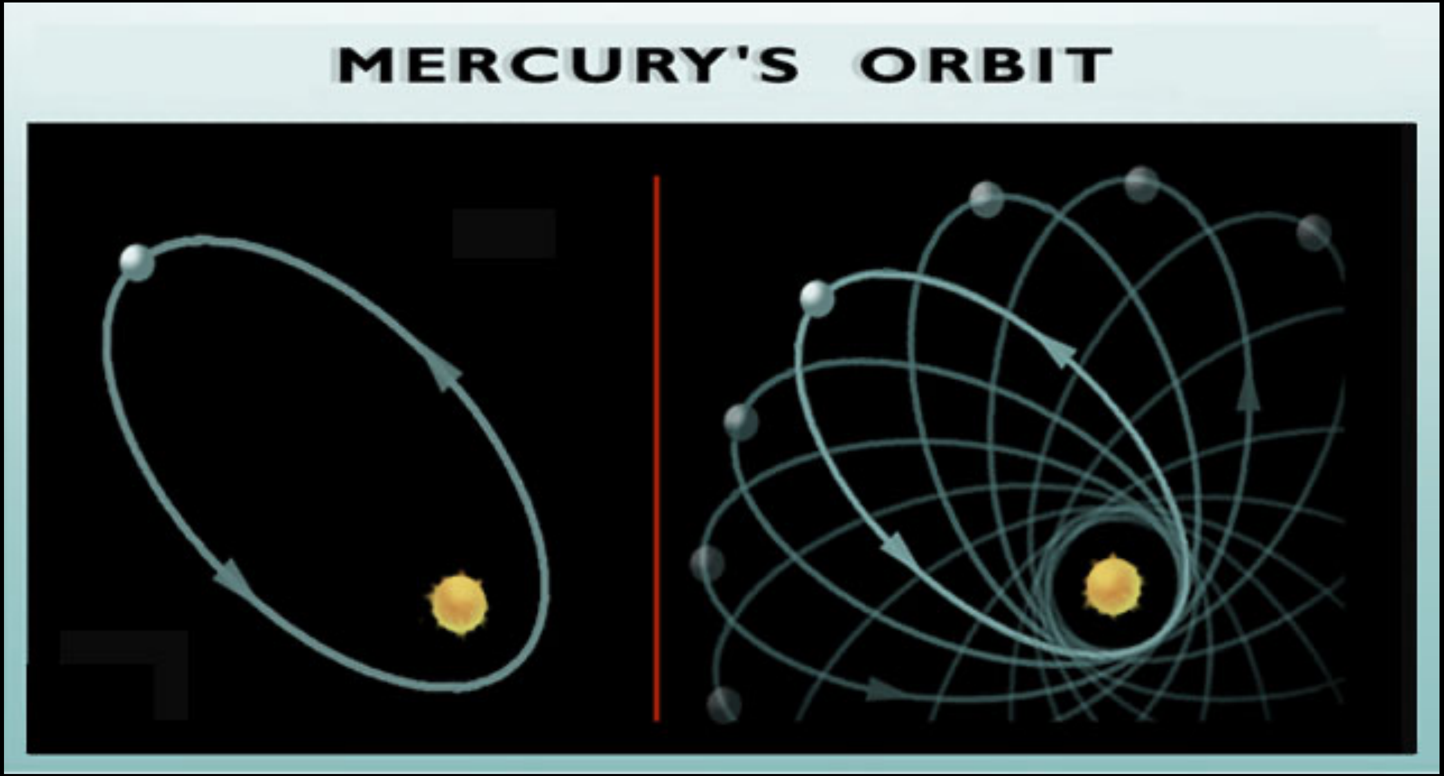


Newton's Theory of Gravity

1687



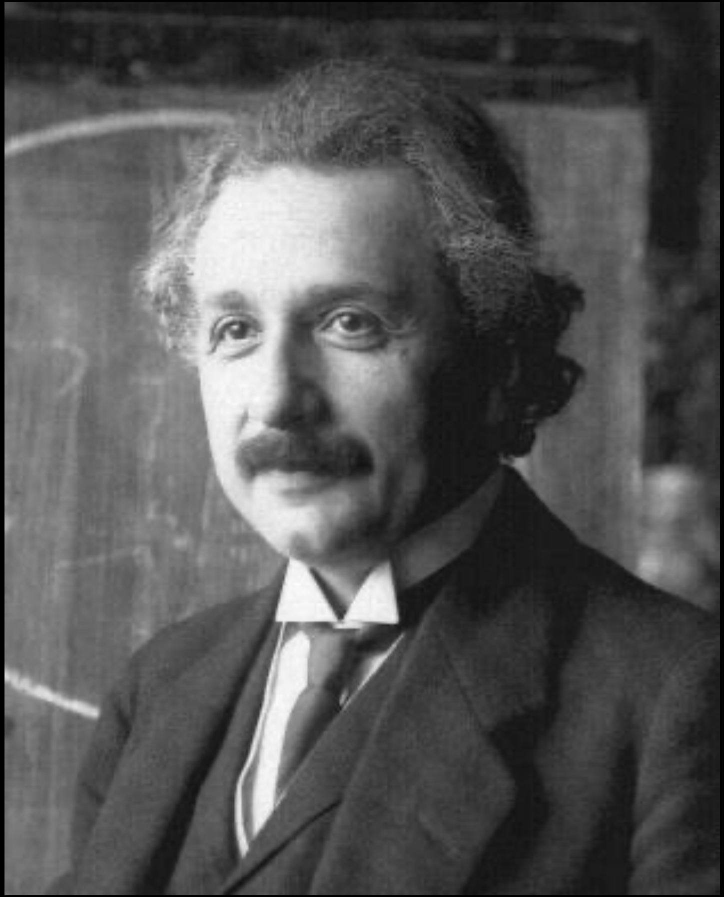
Universal Gravity: force between massive objects is directly proportional to the product of their masses, and inversely proportional to the square of the distance between them.



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's Theory of Gravity

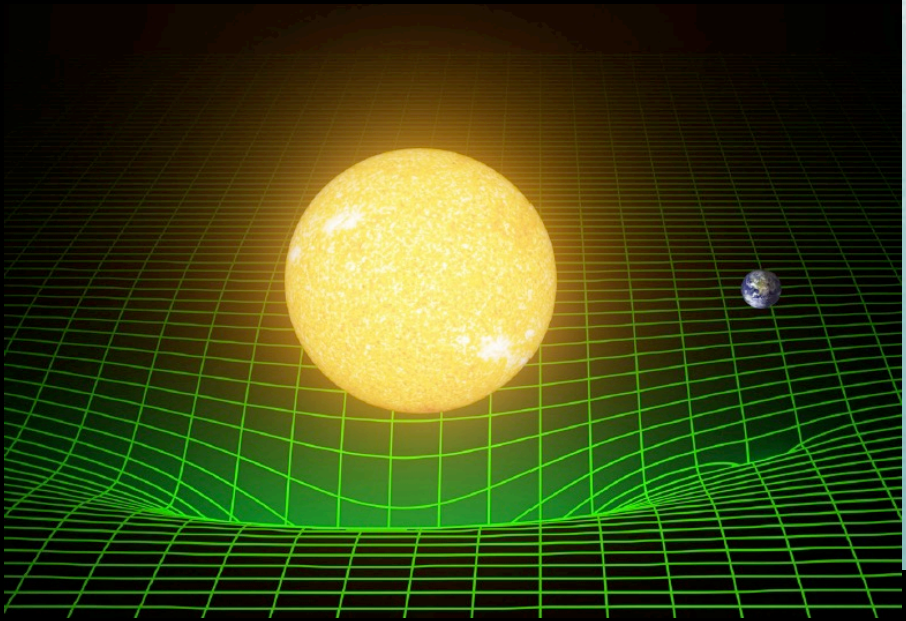


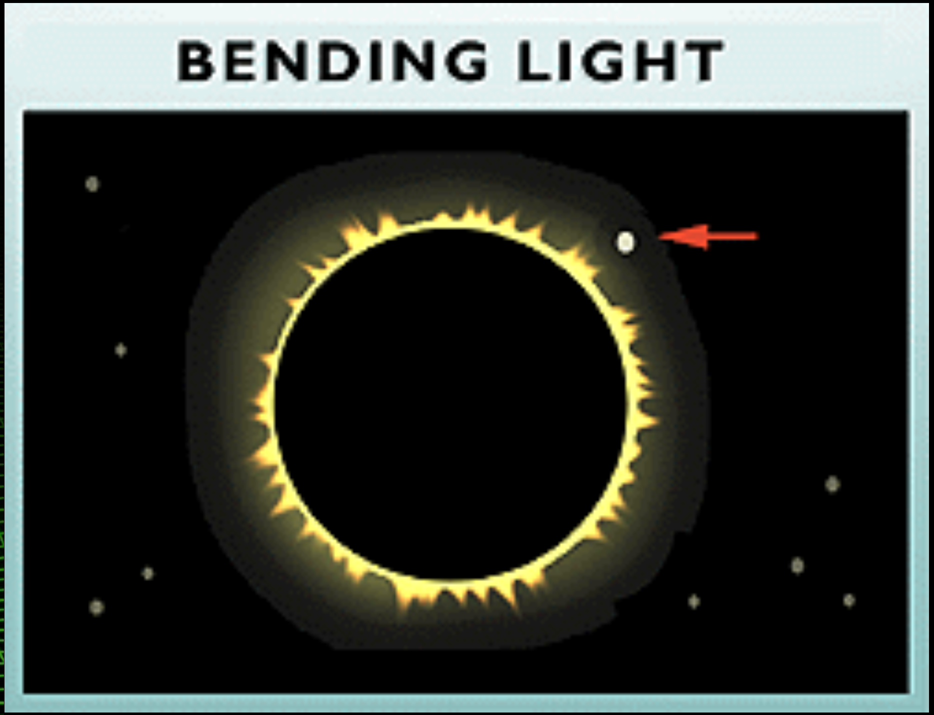
1915

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

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

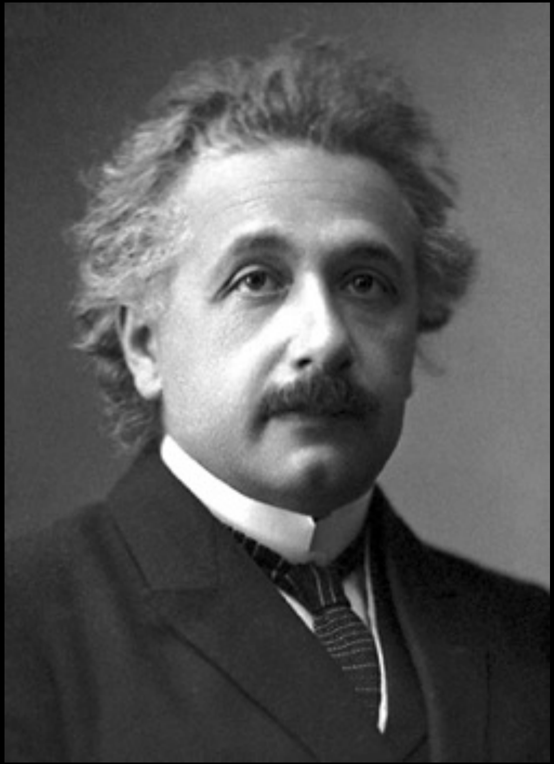
spacetime

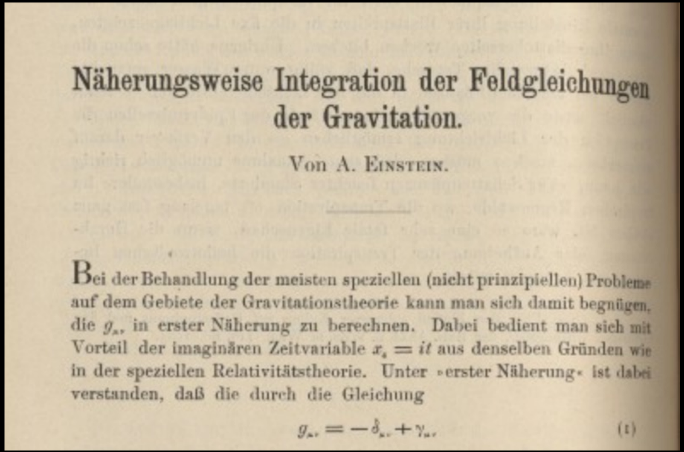




First observed during the solar eclipse of 1919 by Sir Arthur Eddington, when the Sun was silhouetted against the Hyades star cluster

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

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.

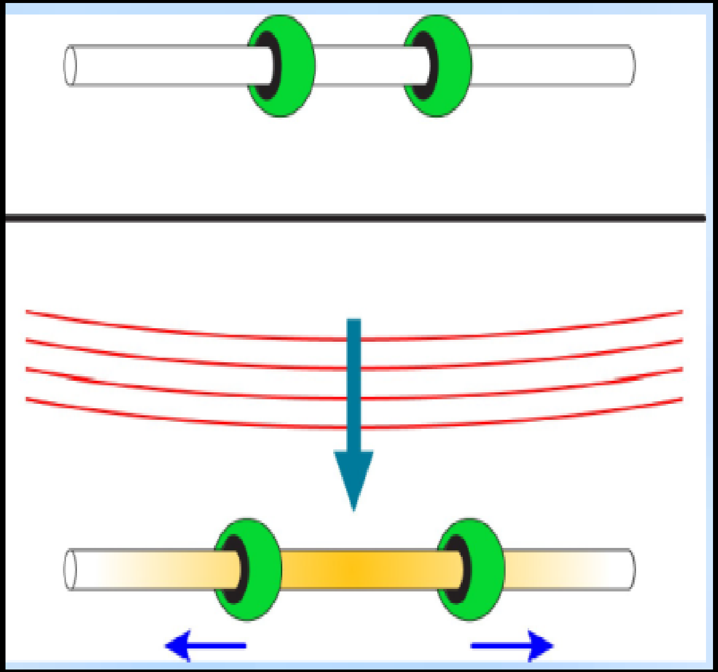
<ins>**The "gravitational wave problem" was solved there, and the quest to detect gravitational waves was born.**</ins>

(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.

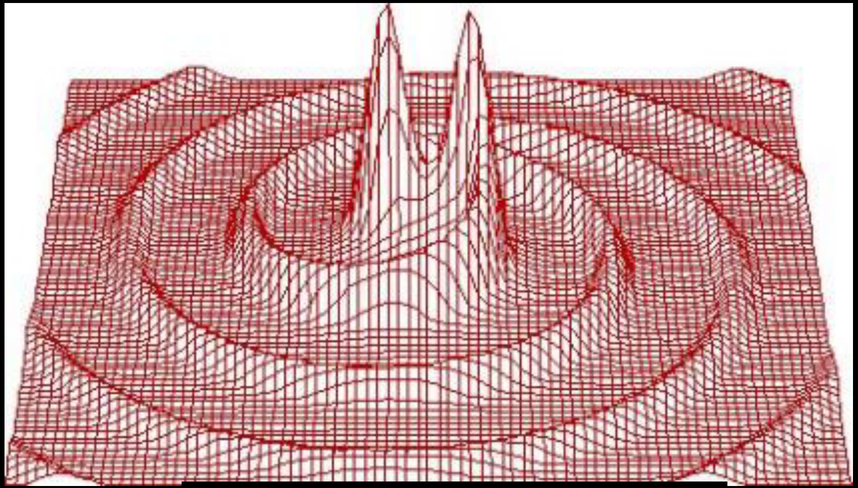
- Sticky bead argument (Feynman)
  - Gravitational waves can transfer energy?



Einstein's Theory of Gravitation

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



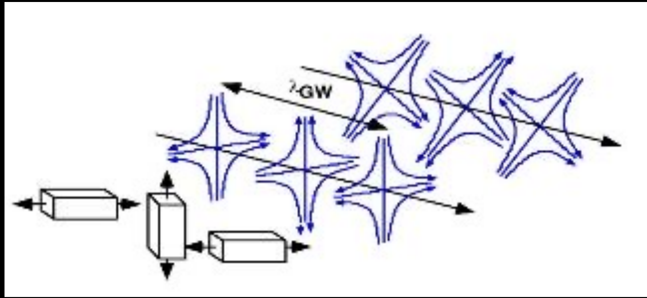
gravitational radiation
binary inspiral
of
compact objects

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.

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

Now the problem is for experimentalists

Try it in your own lab!

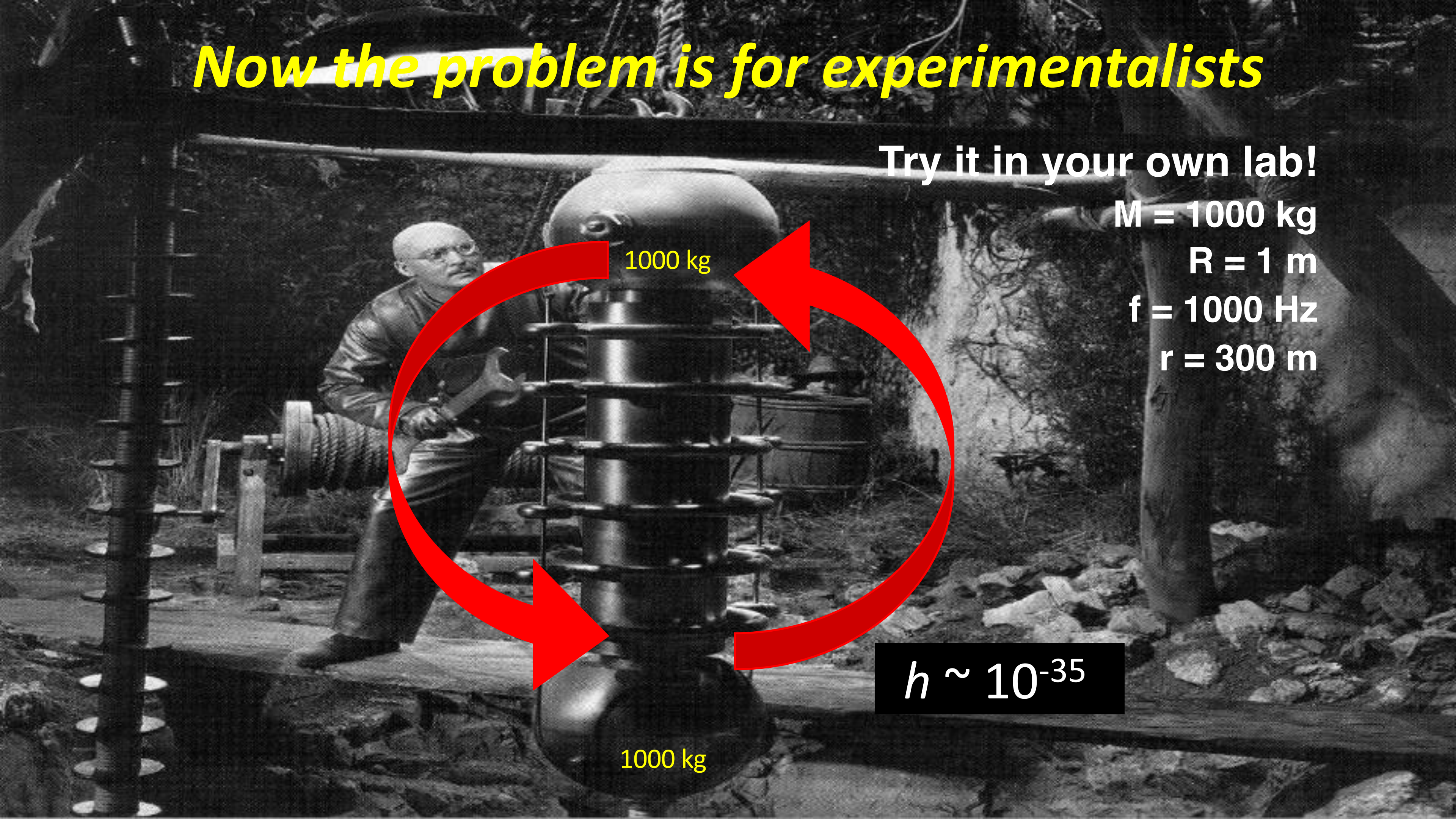
M = 1000 kg

R = 1 m

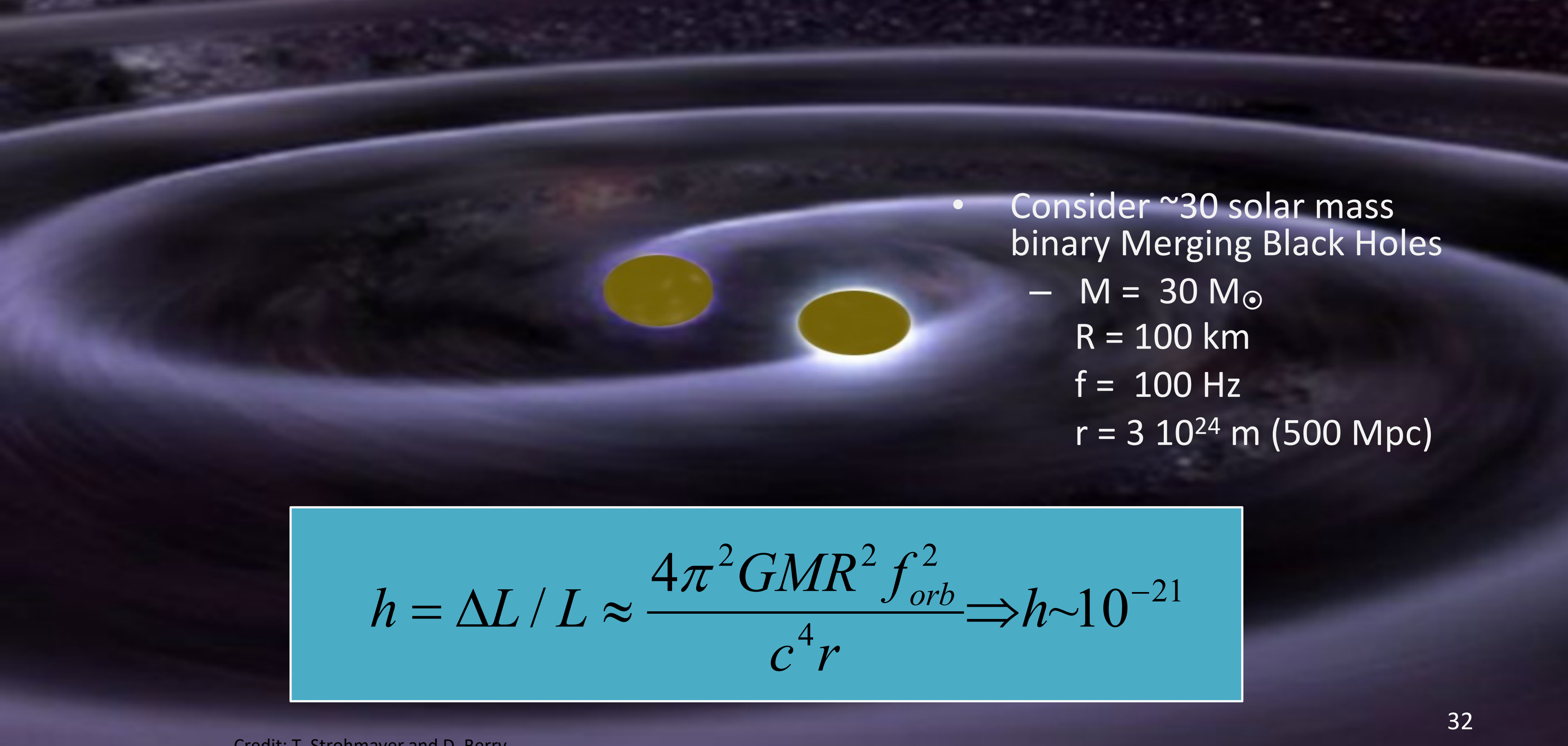
f = 1000 Hz

r = 300 m

$h \sim 10^{-35}$



BUT, the effect is incredibly small



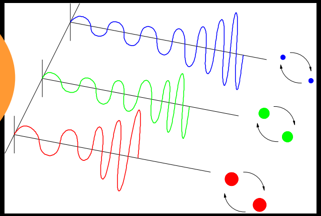
- Consider ~30 solar mass binary Merging Black Holes
  - M = 30 $M_\odot$
    R = 100 km
    f = 100 Hz
    r = 3 10^{24} m (500 Mpc)

$$h = \Delta L / L \approx \frac{4\pi^2 G M R^2 f_{orb}^2}{c^4 r} \Rightarrow h \sim 10^{-21}$$

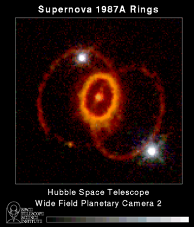
Credit: T. Strohmayer and D. Berry

Astrophysical Sources

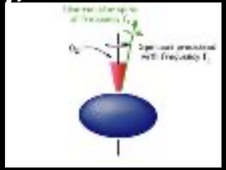
- Compact binary **inspiral:** ***"chirps"***
  - NS-NS waveforms are well described
  - BH-BH need better waveforms
  - search technique: matched templates



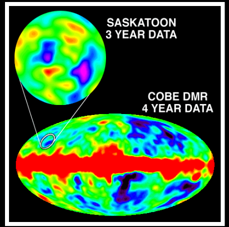
- Supernovae / GRBs: ***"bursts"***
  - burst signals in coincidence with signals in electromagnetic radiation
  - prompt alarm (~ one hour) with neutrino detectors



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

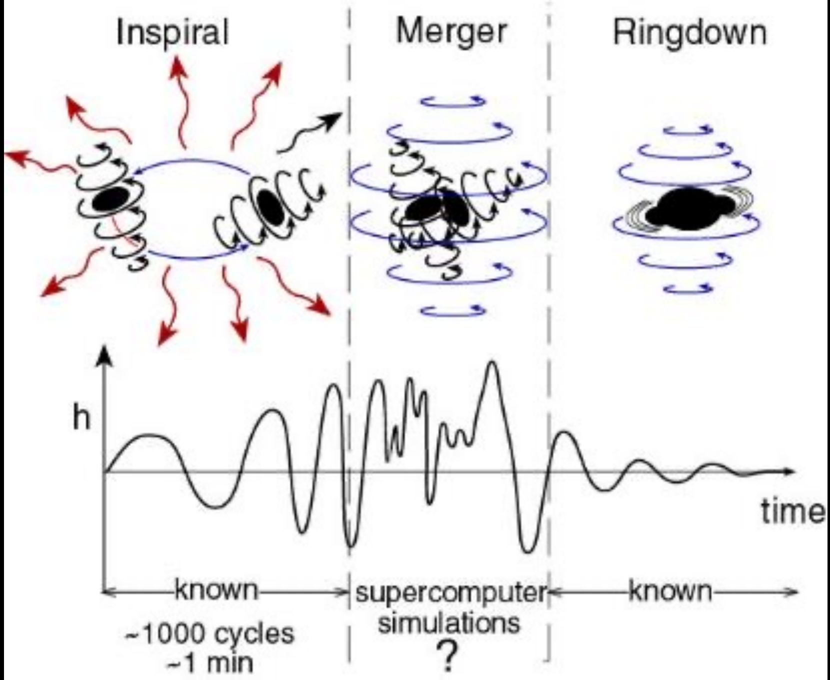


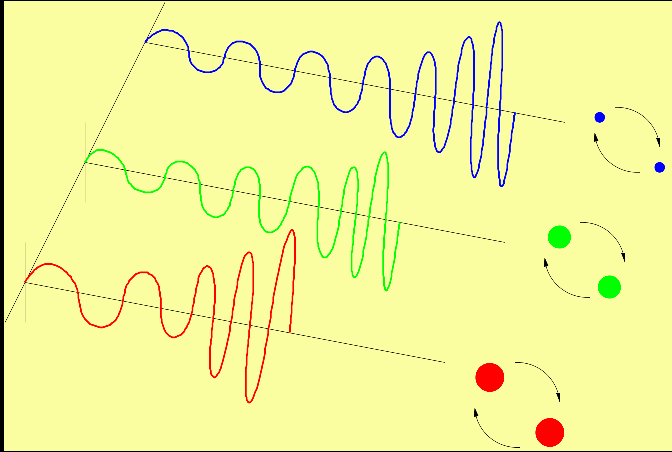
- Cosmological Signal ***"stochastic background"***



Compact Binary Collisions

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



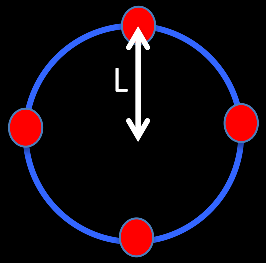


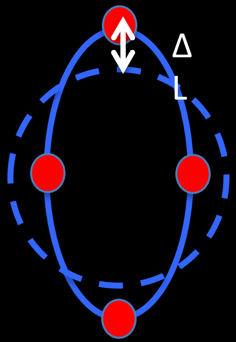
"chirps"

Gravitational Waves

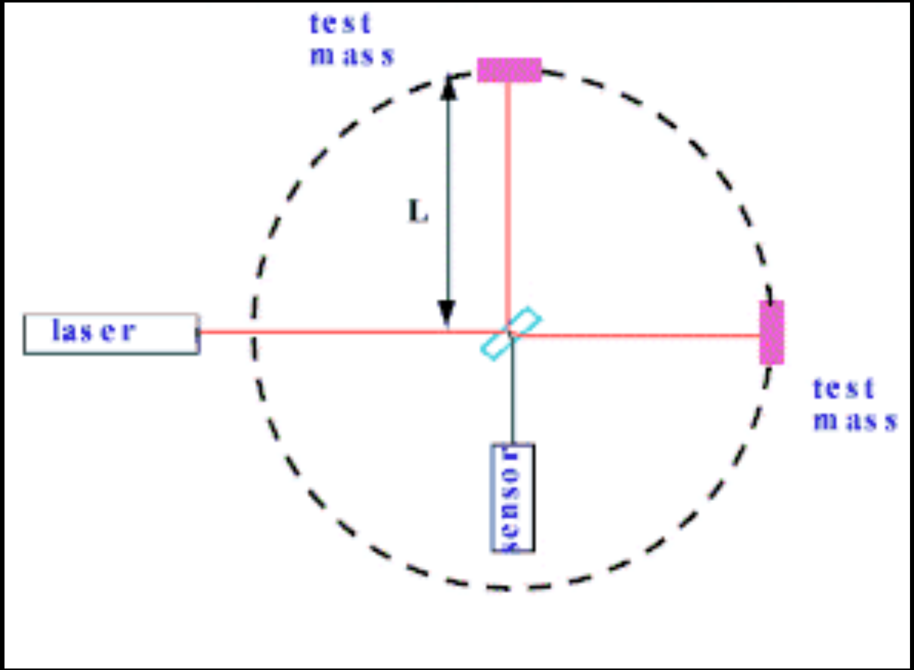
- Ripples of spacetime that stretch and compress spacetime itself
- The amplitude of the wave is h ≈ 10^{-21}
- Change the distance between masses that are free to move by $\Delta L = h \times L$
- Spacetime is “stiff” so changes in distance are very small

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





Suspended Mass Interferometry



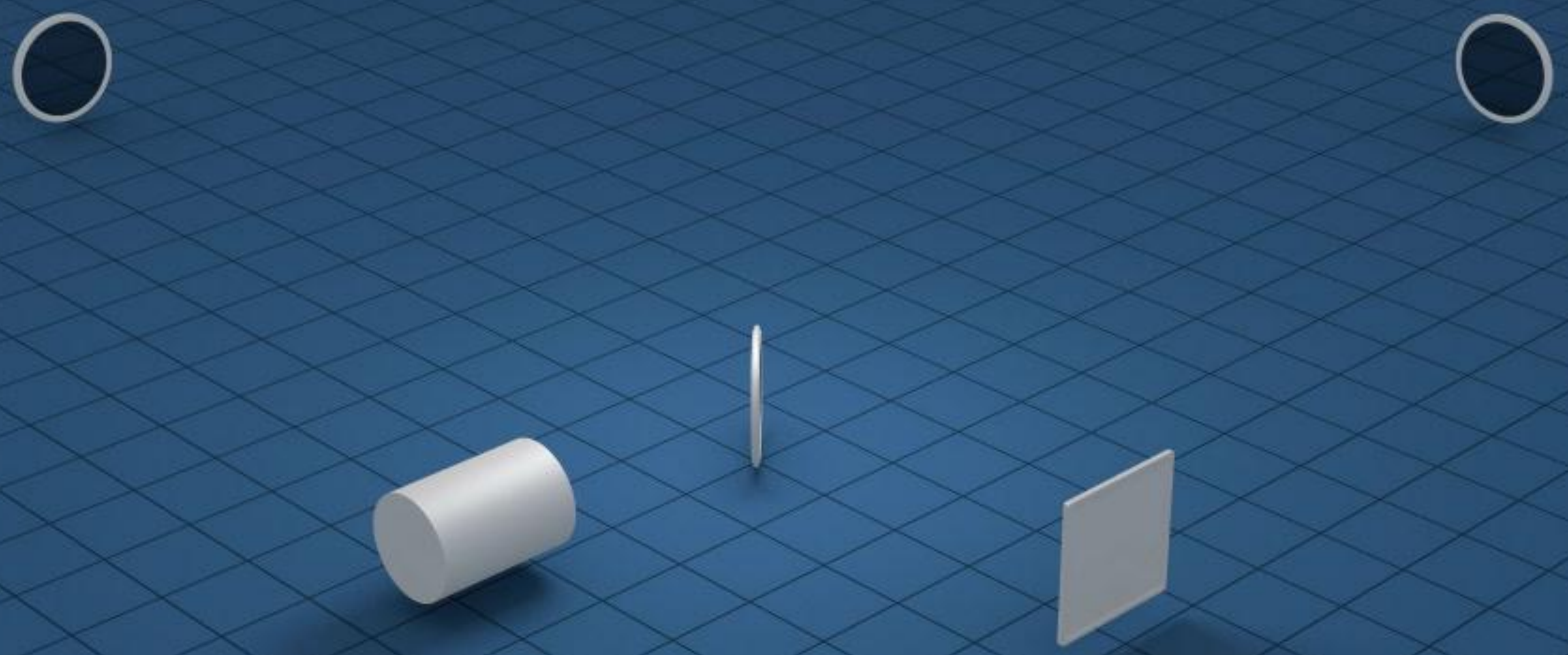
$$h = \frac{\Delta L}{L} \leq 10^{-21}$$

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

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

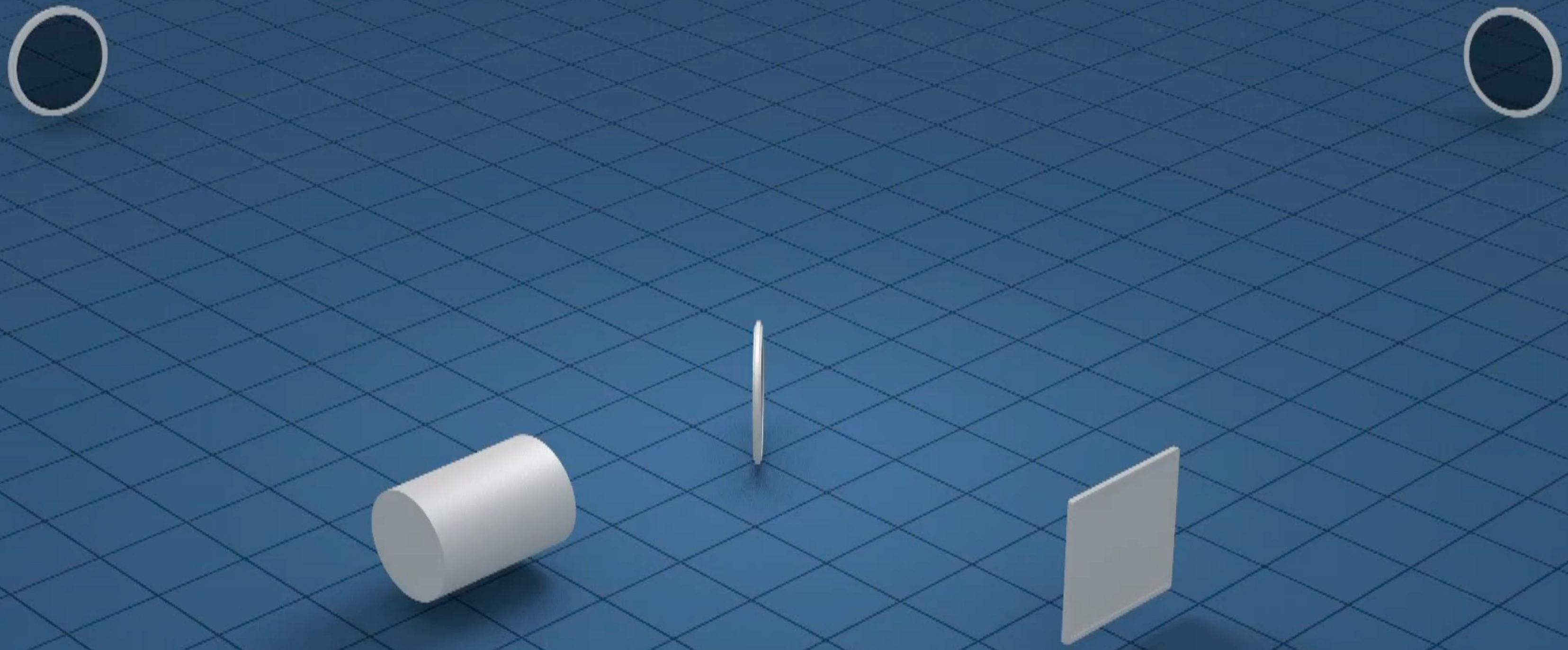
$\Delta L \sim 10^{-12}$ vibrations at earth's surface

Interferometry – The scheme

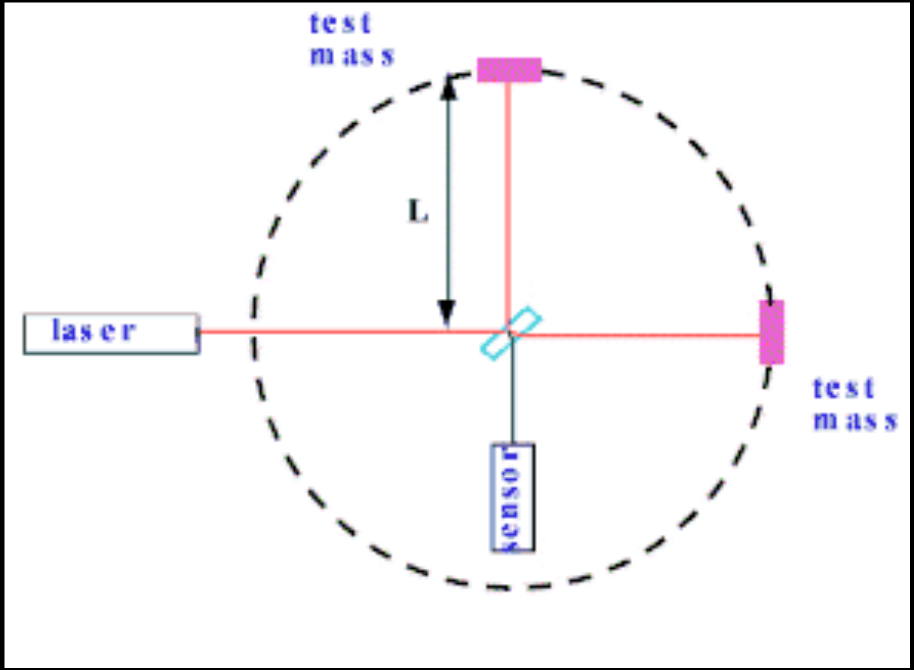


Credit: LIGO/T. Pyle

Interferometry – The scheme



Suspended Mass Interferometry



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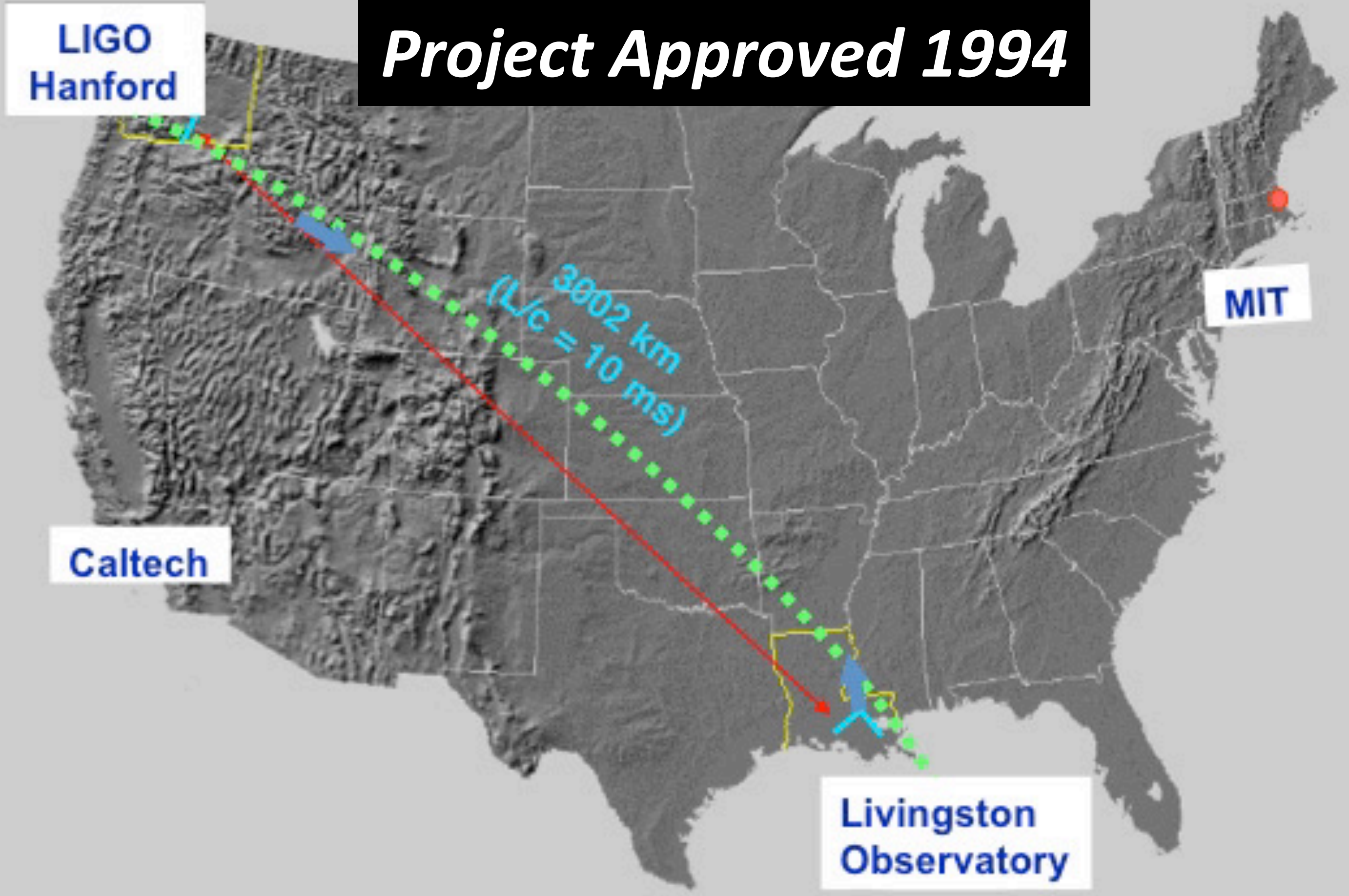
$\Delta L \sim 10^{-12}$ wavelength of light

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

LIGO Sites
Project Approved 1994




LIGO Construction Began in 1994
Evolution over 22 years to Advanced LIGO

LIGO Infrastructure beam tube

LIGO Interferometers

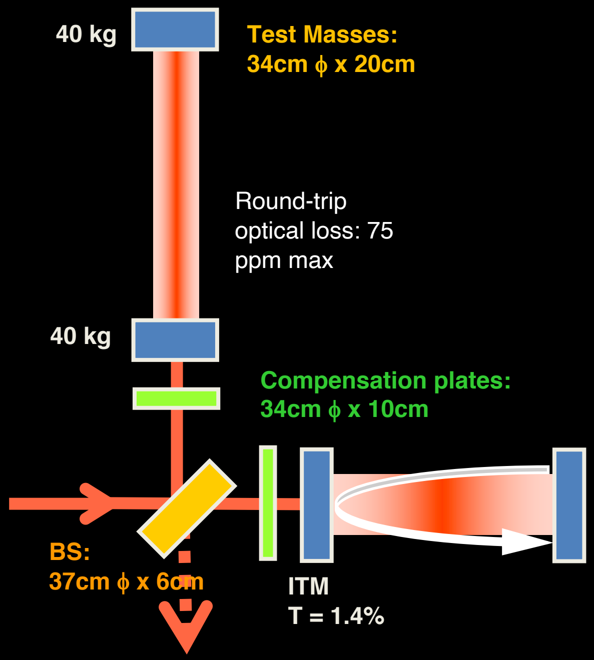
Hanford, WA

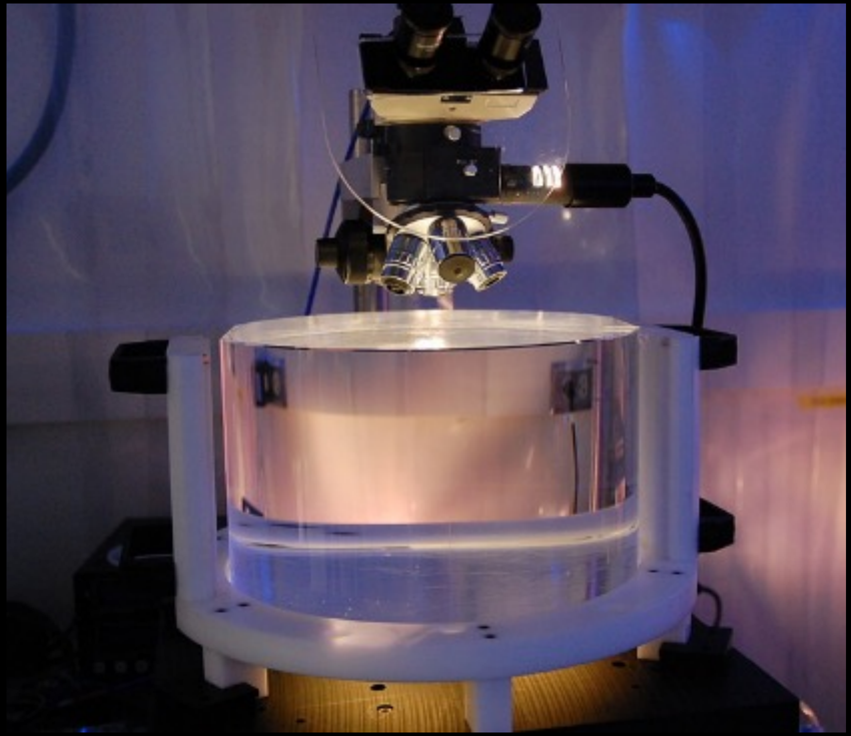
Livingston, LA

LIGO Interferometer Infrastructure

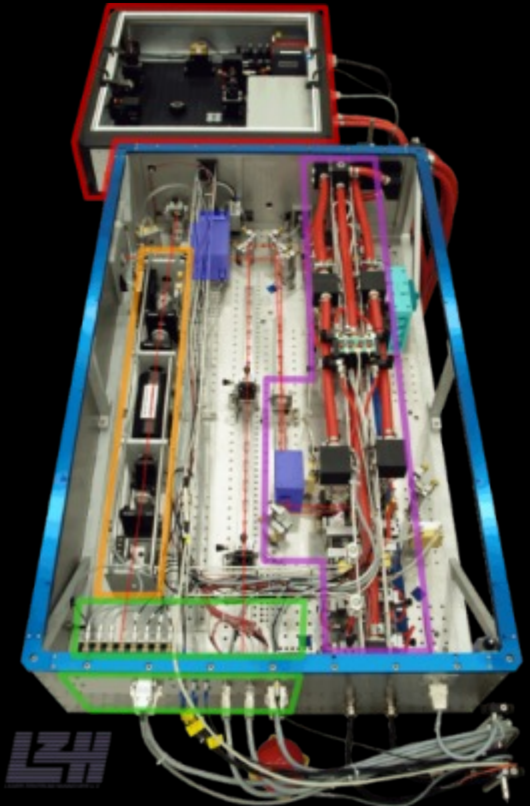
Mirror / Test Masses

- Mechanical requirements: bulk and coating thermal noise, high resonant frequency
- Optical requirements: figure, scatter, homogeneity, bulk and coating absorption





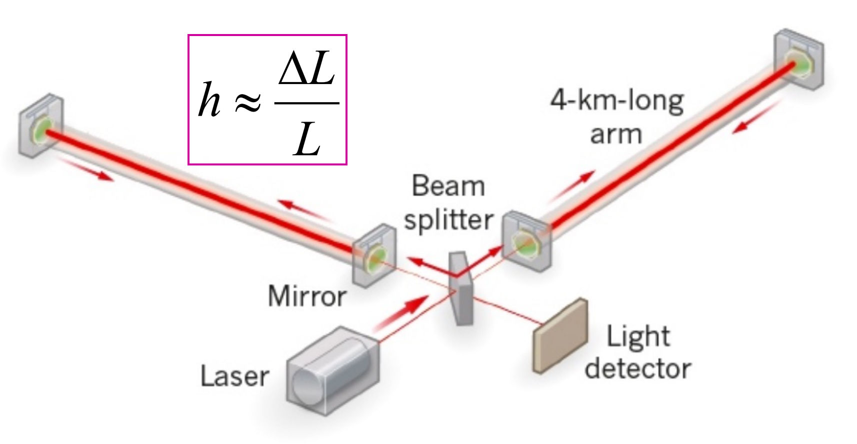
Nd:YAG Laser



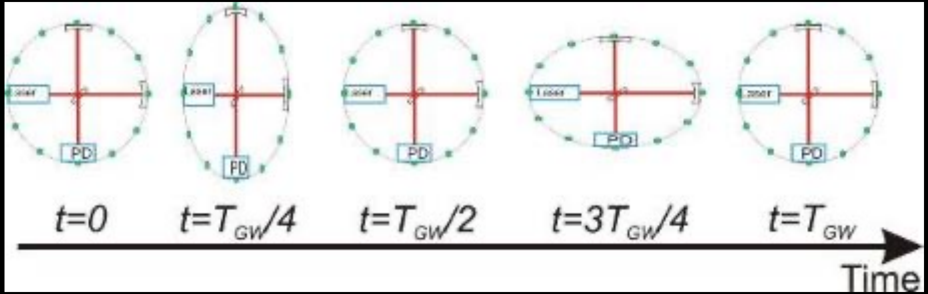
- Stabilized in power and frequency
- Uses a monolithic master oscillator followed by injection-locked rod amplifier

LIGO: Measurement Scheme

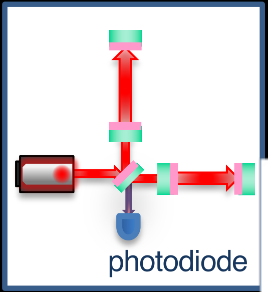
- Enhanced **Michelson interferometers**
- GWs modulate the distance between the end test mass and the beam splitter
- The interferometer acts as a transducer, turning GWs into photocurrent proportional to the strain amplitude
- Arms are short compared to our GW wavelengths, so longer arms make bigger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



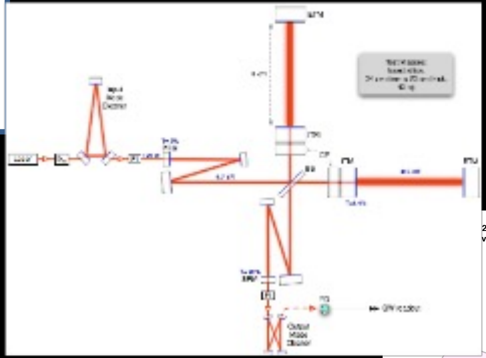
Magnitude of h at Earth: Detectable signals h ~ 10^{-21}
For L = 4km, **ΔL= 4×10^{-18} m**

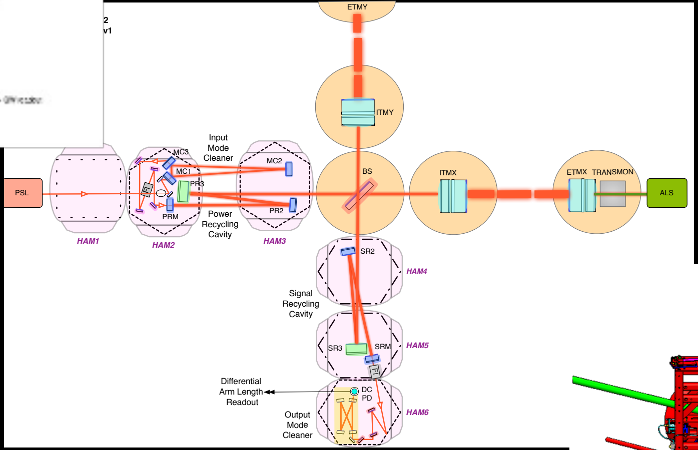


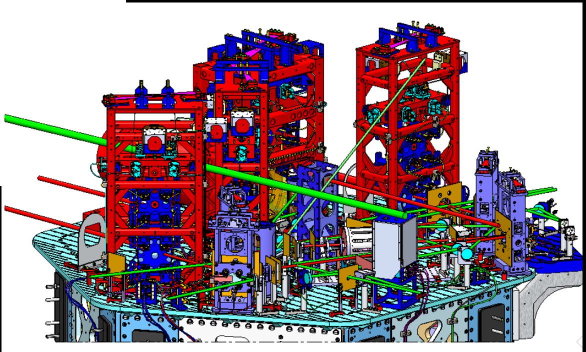
LIGO: Interferometry



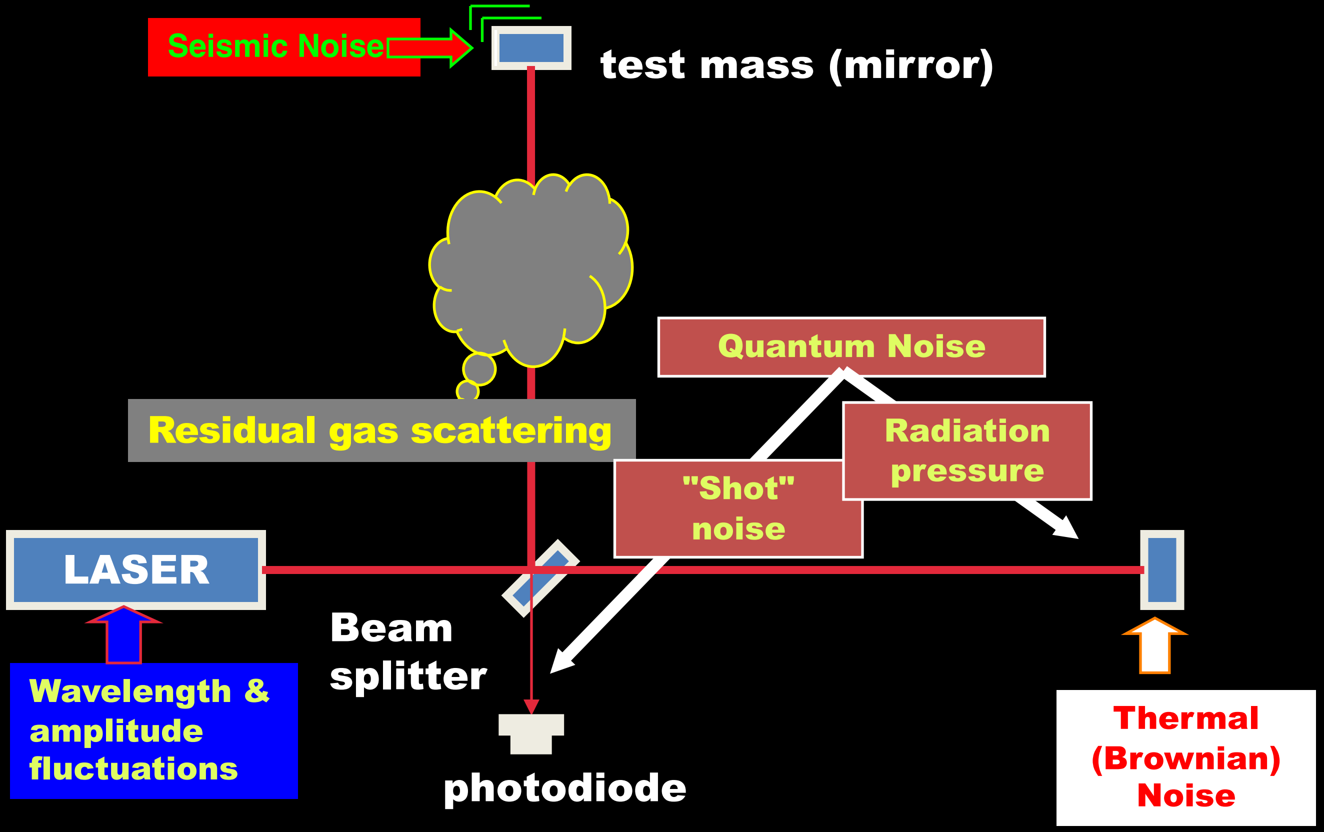
Many innovations to make the instrument so sensitive





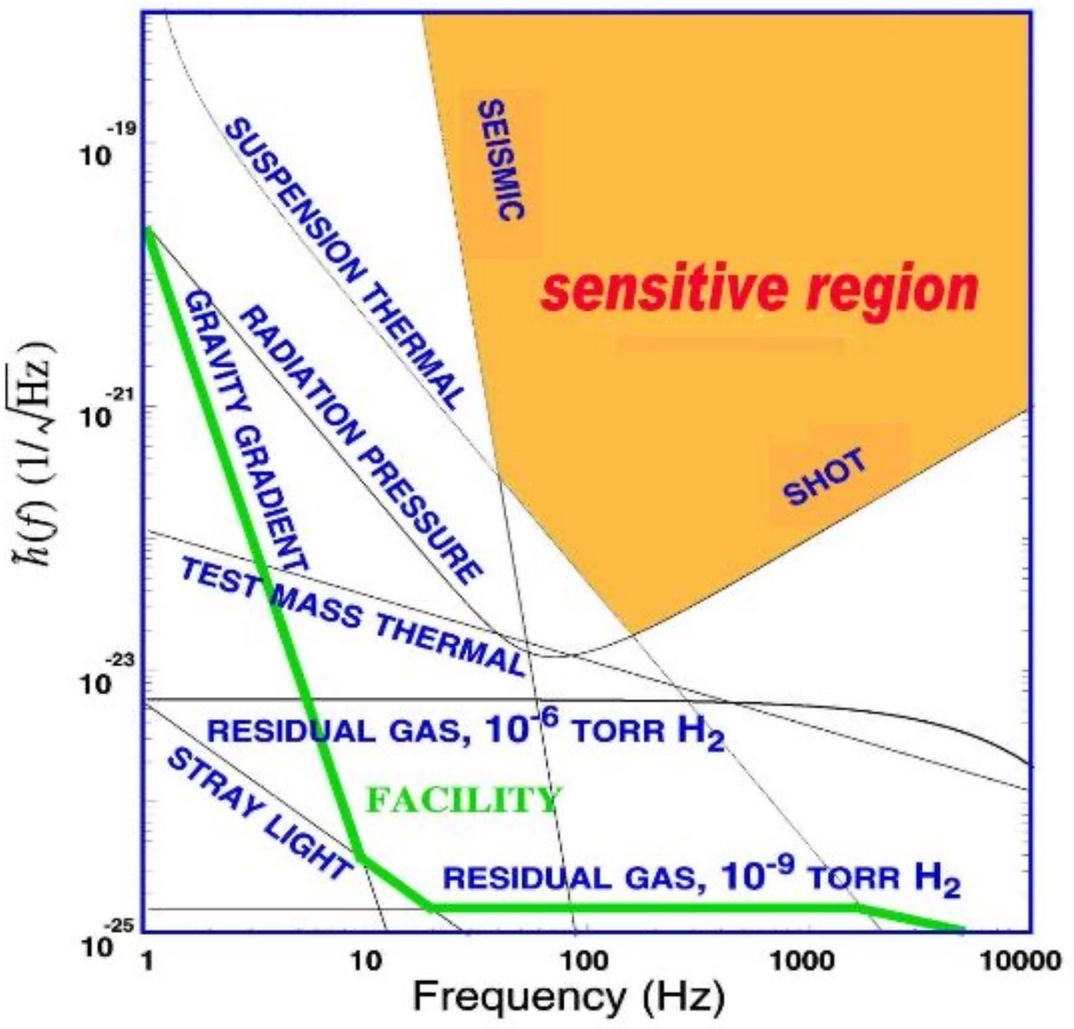


Interferometer Noise Limits

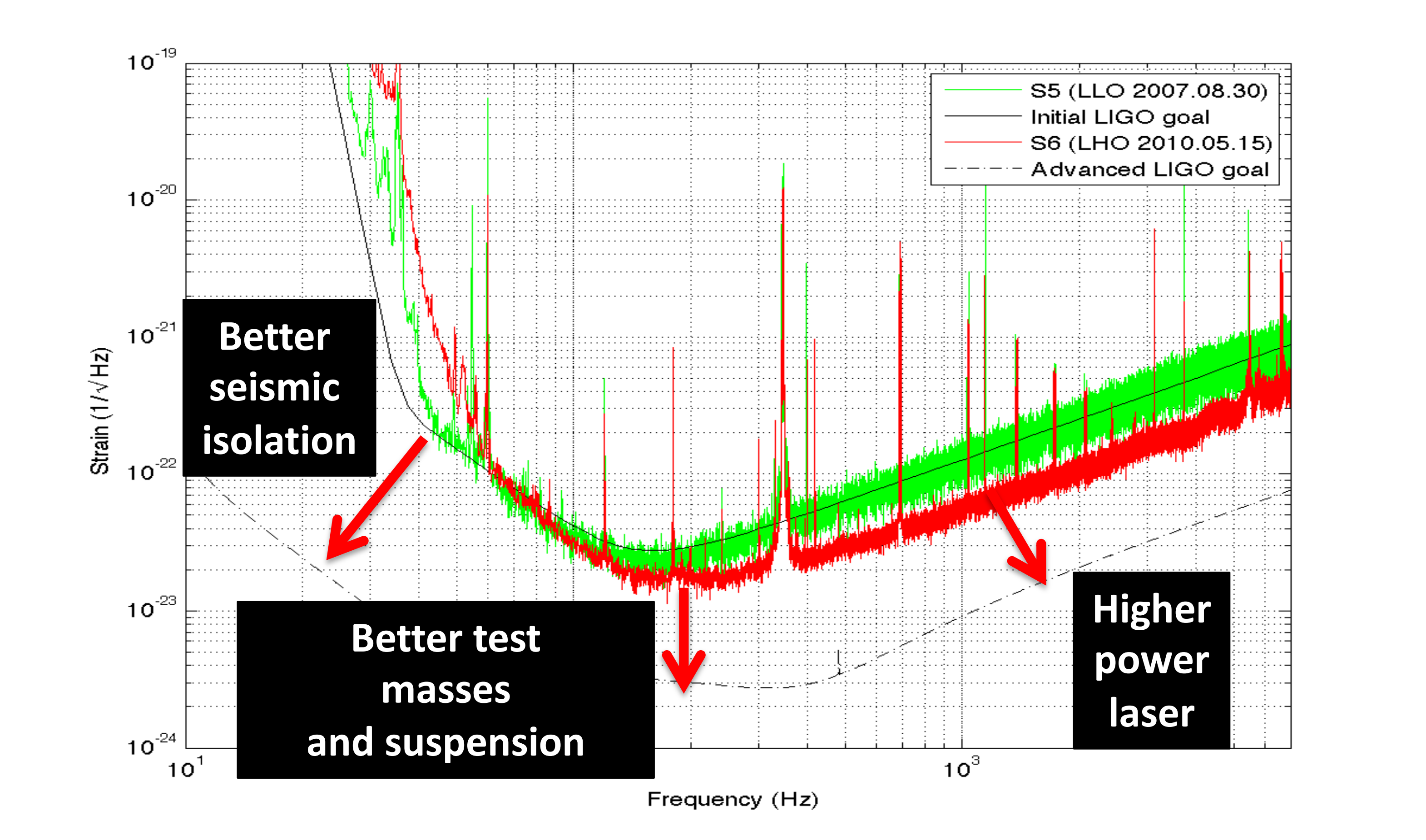


What Limits LIGO Sensitivity?

- Seismic noise limits low frequencies
- Thermal Noise limits middle frequencies
- Quantum nature of light (Shot Noise) limits high frequencies
- Technical issues - alignment, electronics, acoustics, etc limit us before we reach these design goals

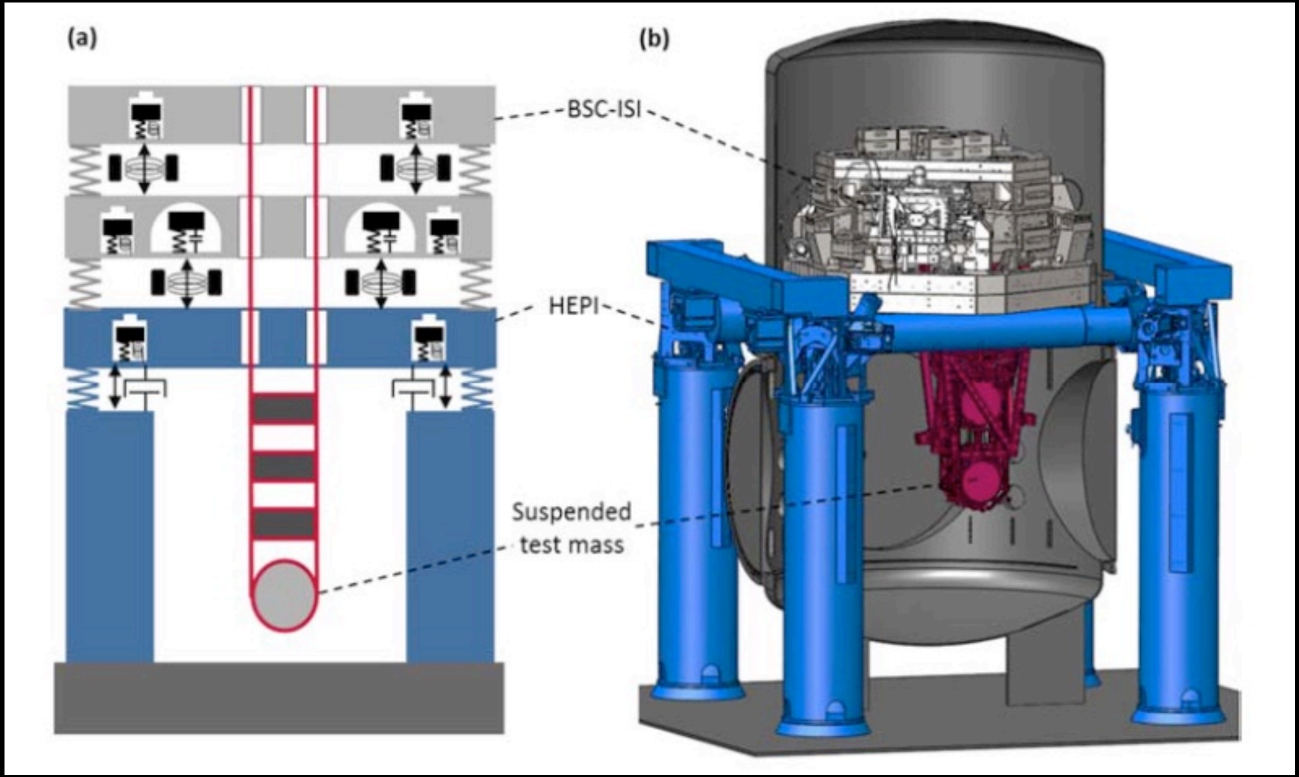


Advanced LIGO GOALS

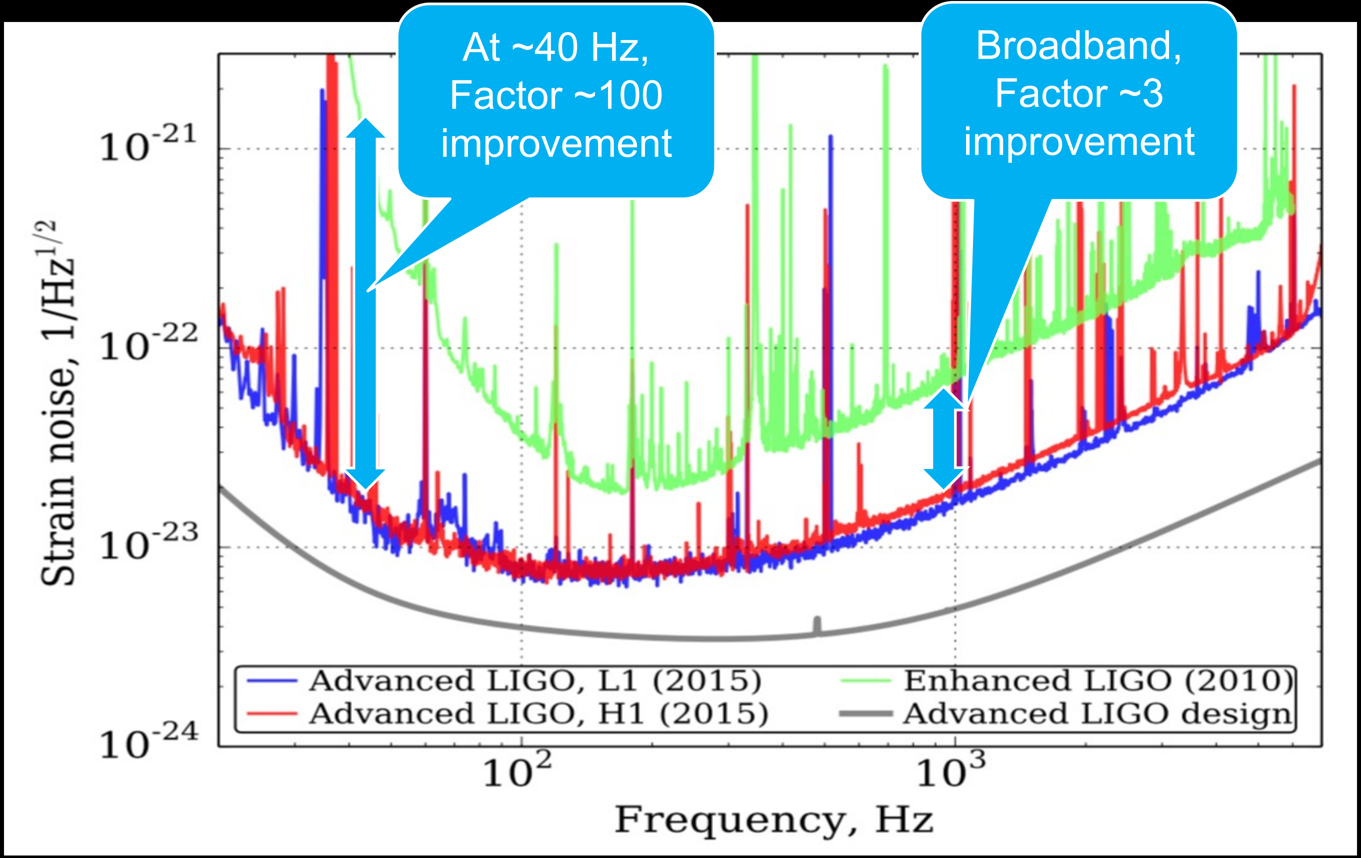


Passive / Active Multi-Stage Isolation

Advanced LIGO



Sensitivity for Advanced LIGO

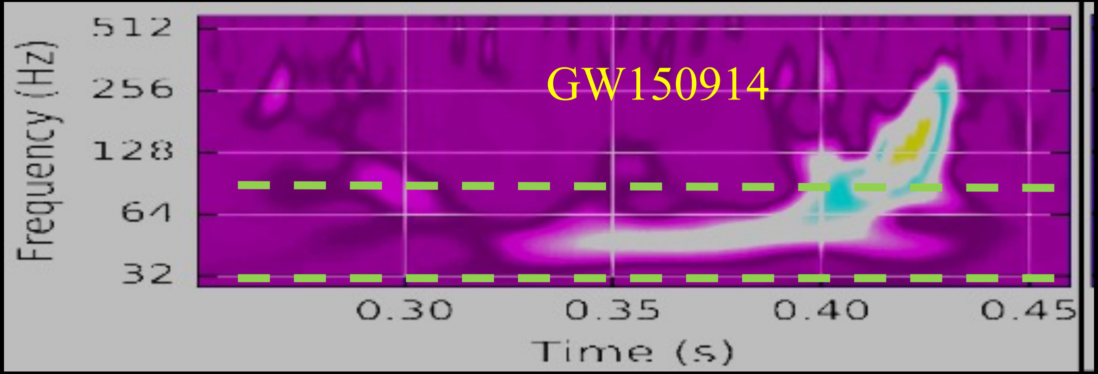


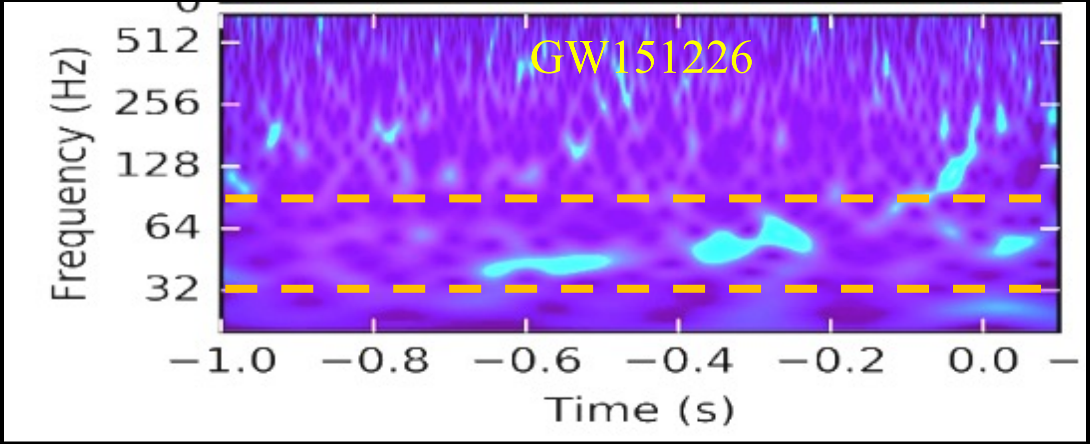
Initial LIGO

O1 aLIGO

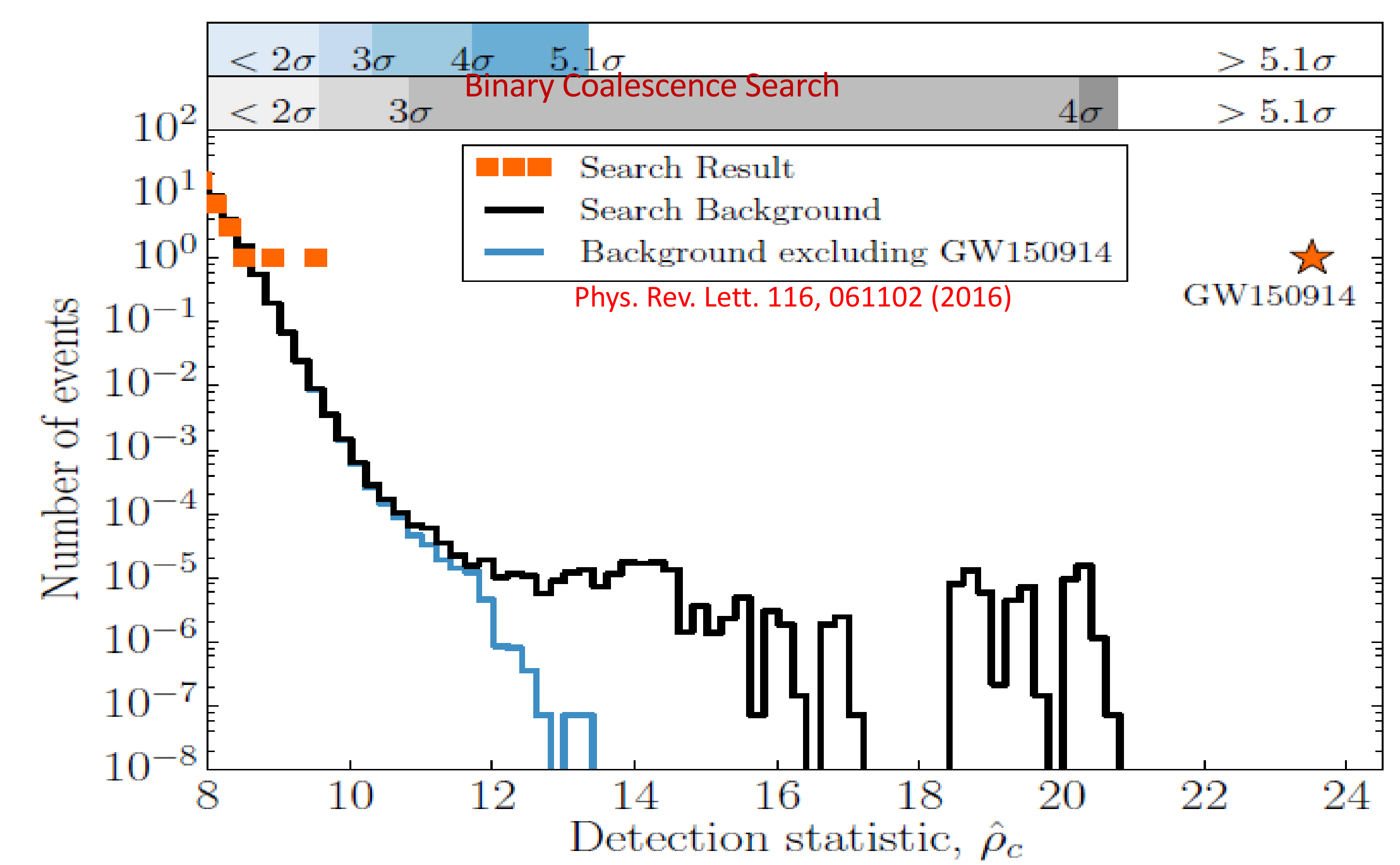
Design aLIGO

Black Hole Merger Events and Low Frequency Sensitivity





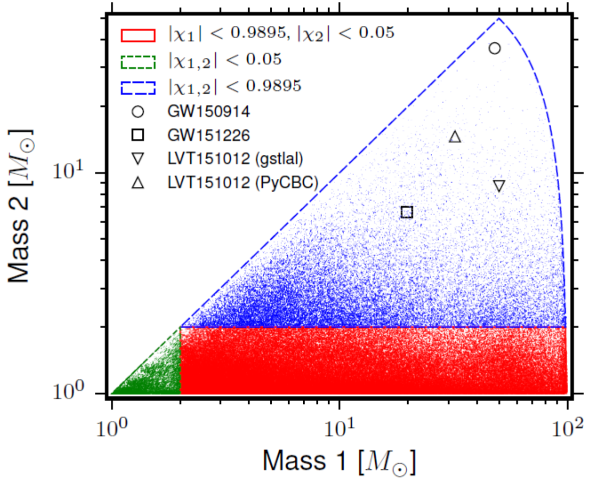
Statistical Significance of GW150914

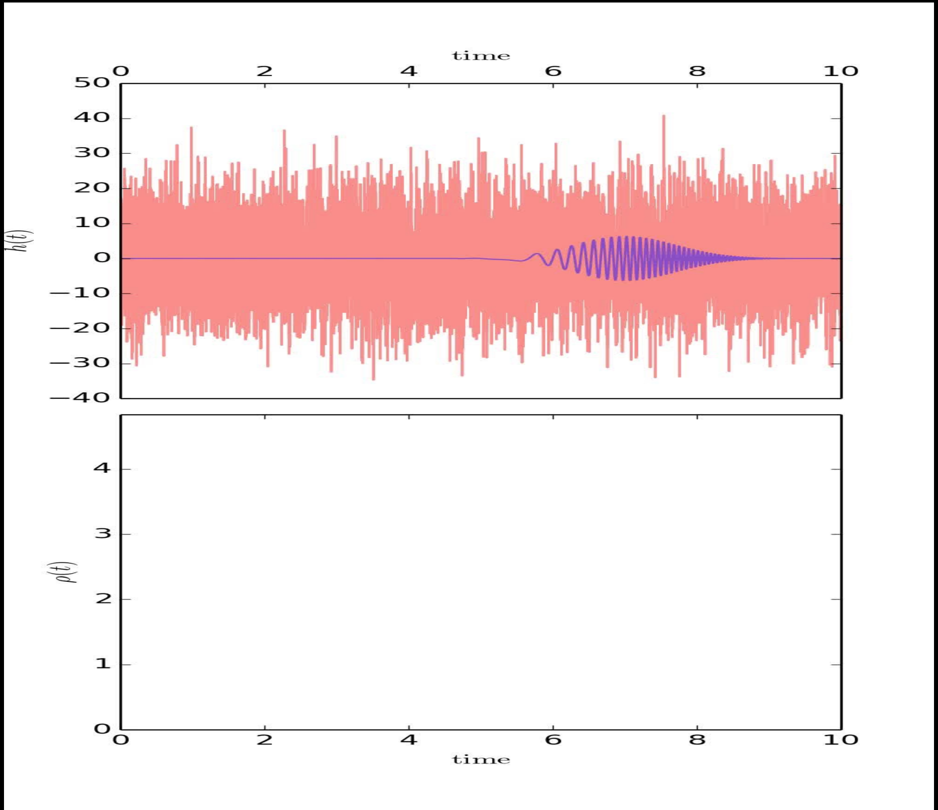


Finding a weak signal in noise

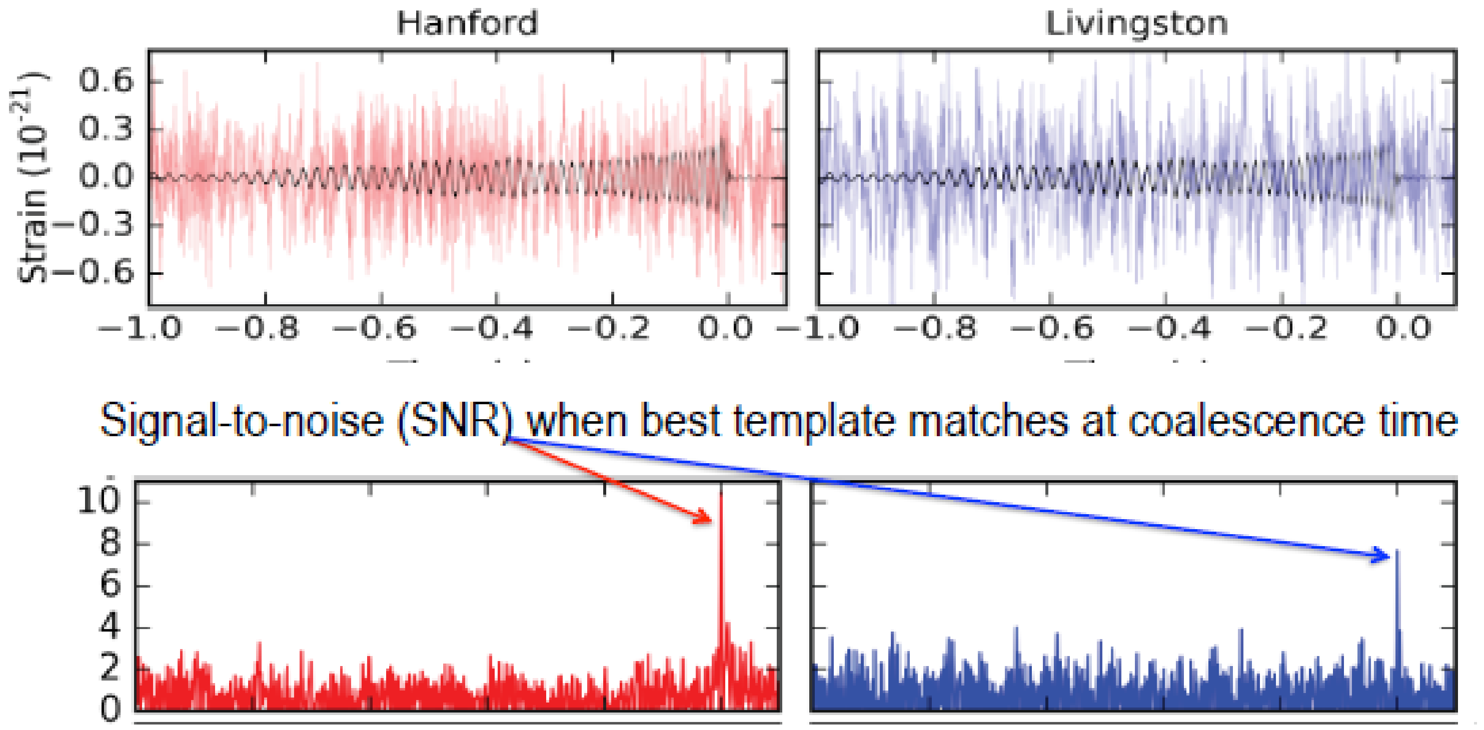
- "Matched filtering" lets us find a weak signal submerged in noise.
- For calculated signal waveforms, multiply the waveform by the data
- Find signal from cumulative signal/noise

PHYS. REV. X 6,041015 (2016)



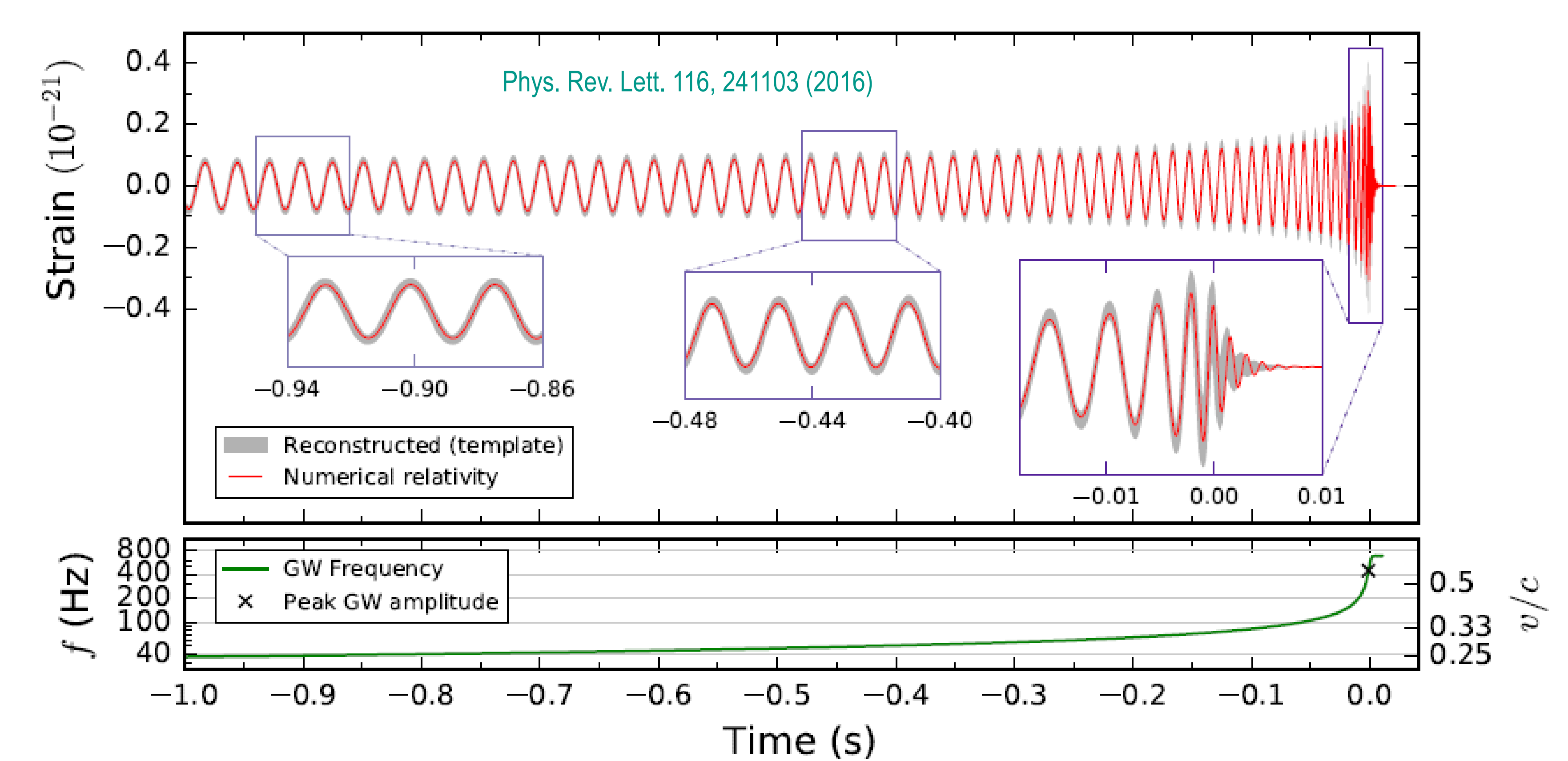


GW151226 – Matched Filter

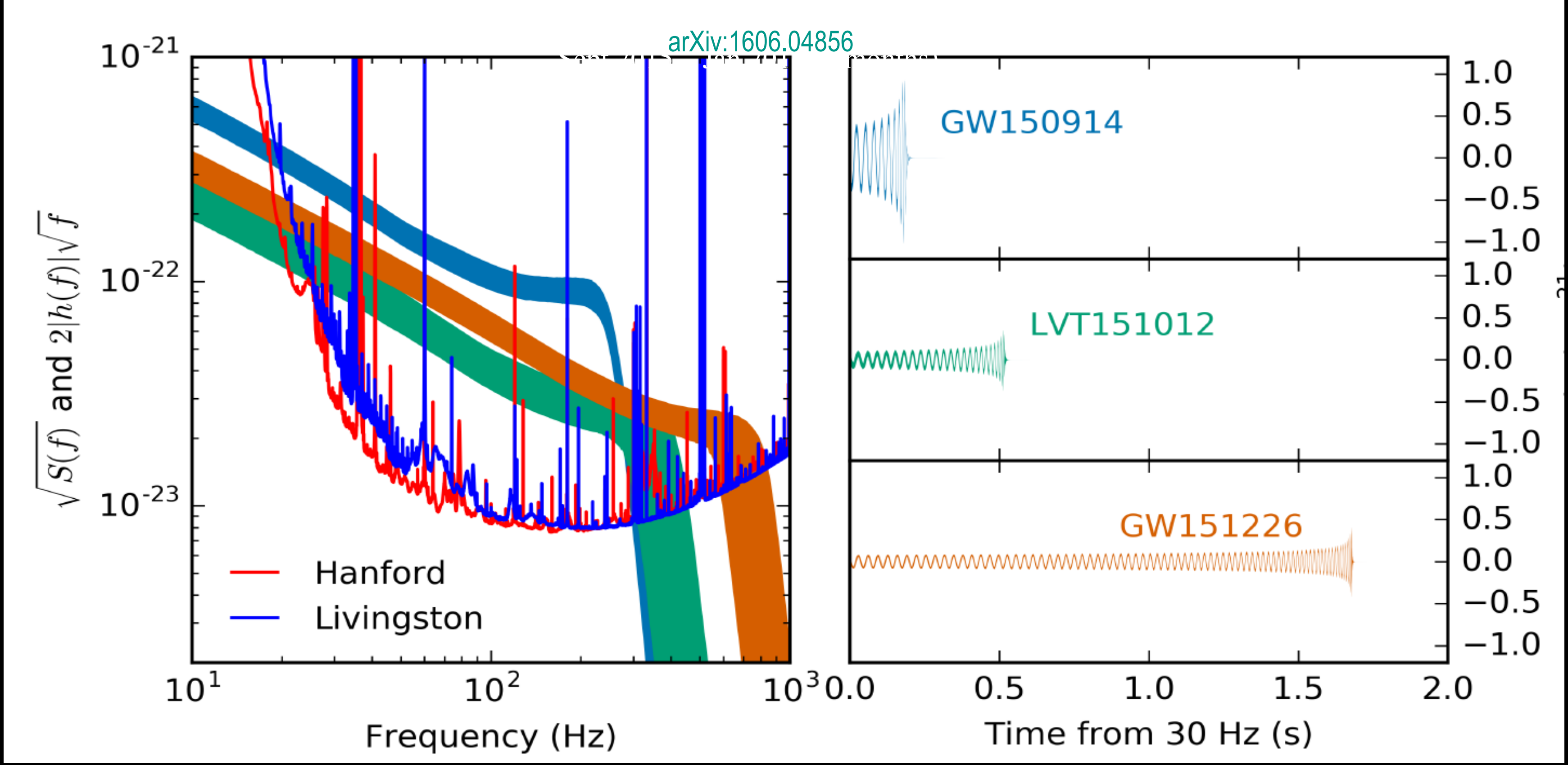


Phys. Rev. Lett. 116, 241103 (2016)

“Second Event” Inspiral and Merger GW151226



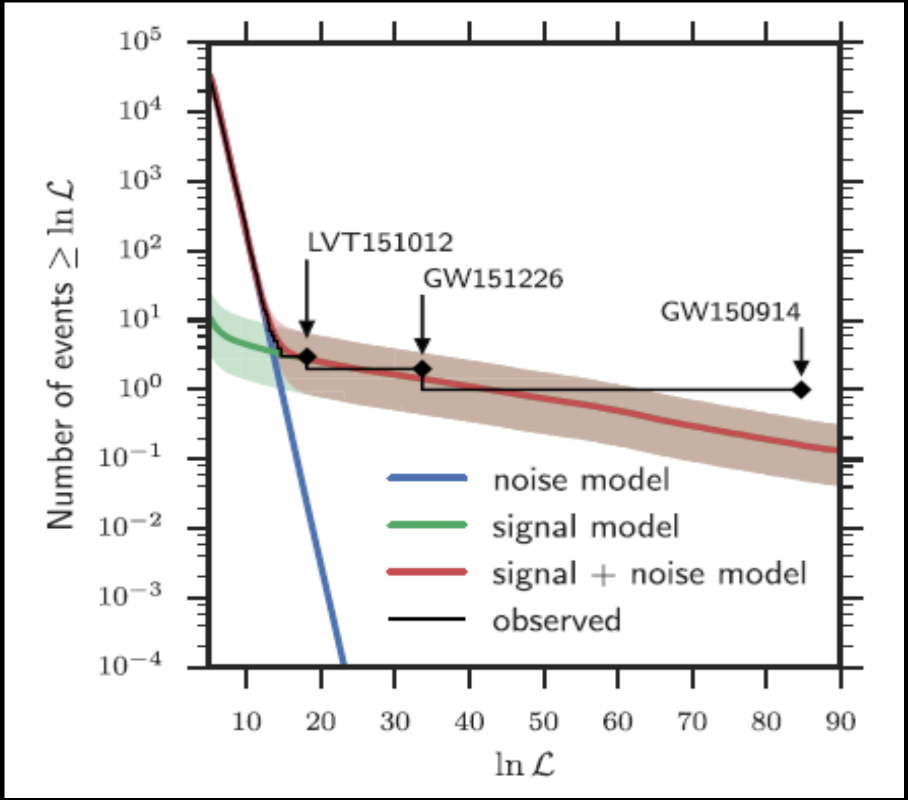
Second Event, Plus another Candidate



Sensitivity

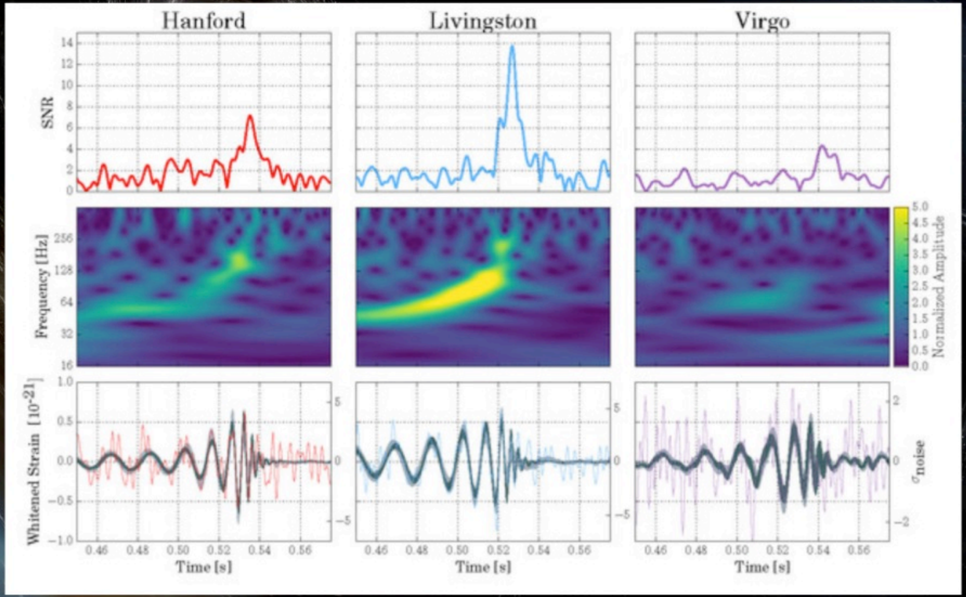
Lessons from LIGO O1

- Steep drop in false alarm rate versus size means edge of observable space is very sharp
  - » Very far out on tail of noise due to need to overcome trials factor

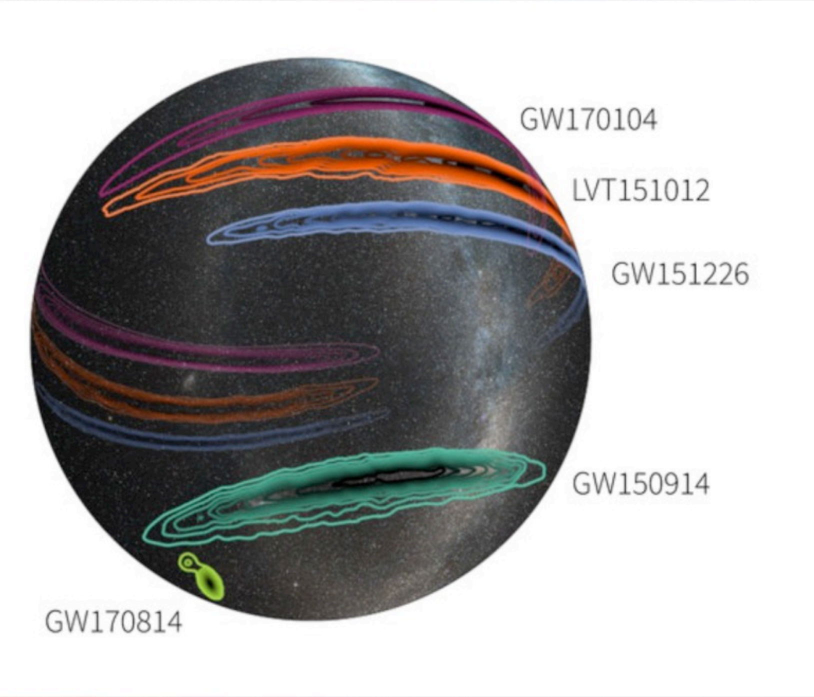


O1 BBH Search

Three detectors: GW170814



A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence
2017, Phys. Rev. Lett., 119, 141101



[redacted]

Reported Black Holes Mergers

Testing General Relativity – Dispersion Term?

- In GR, there is no dispersion!

Add dispersion term of form

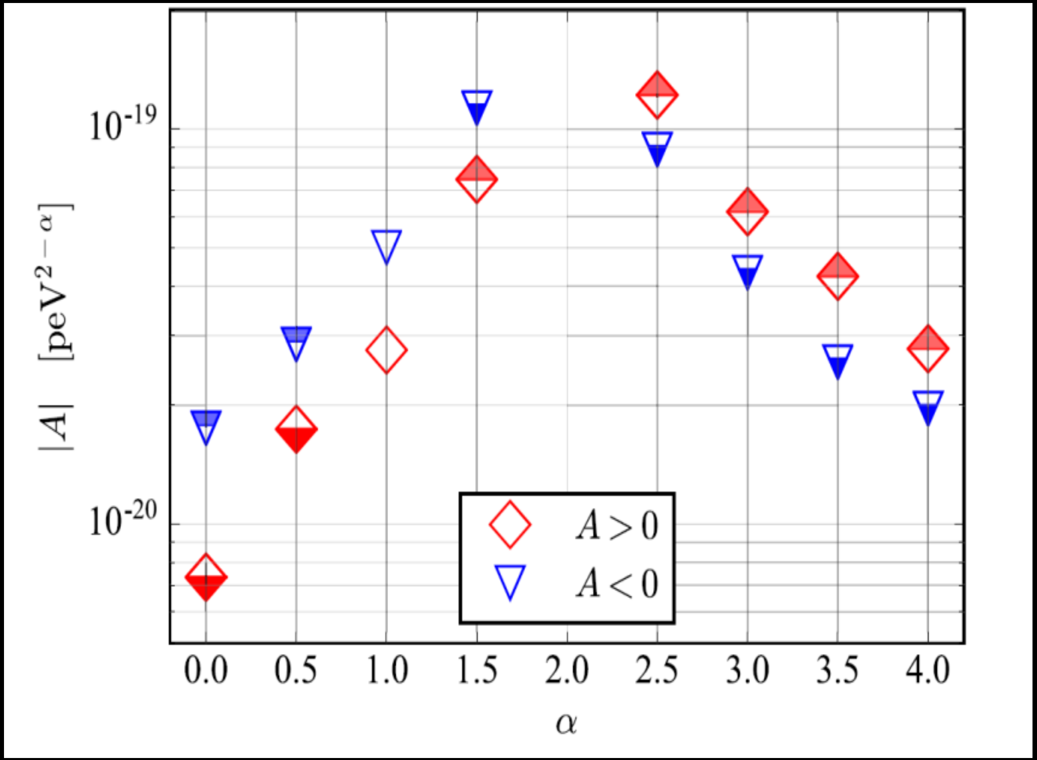
$$E^2 = p^2c^2 + Ap^\alpha c^\alpha, \quad \alpha \geq 0$$

(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

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.

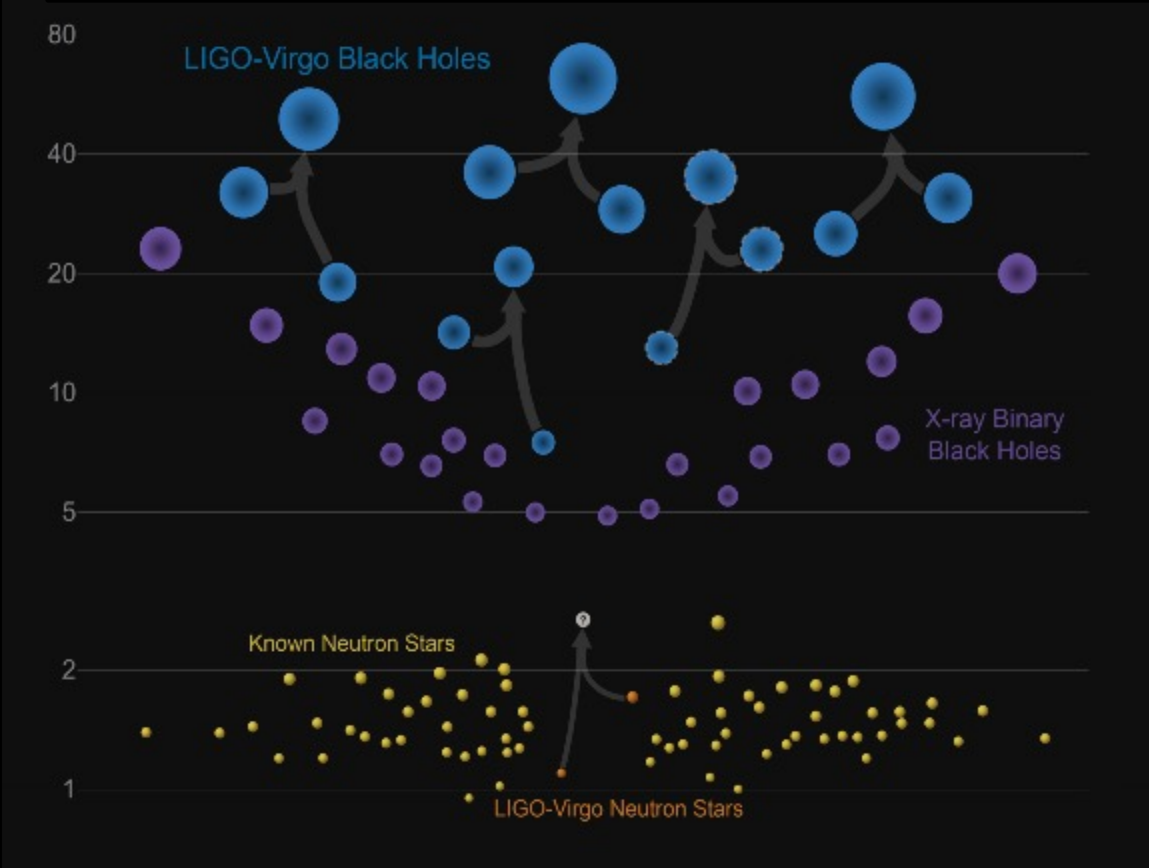
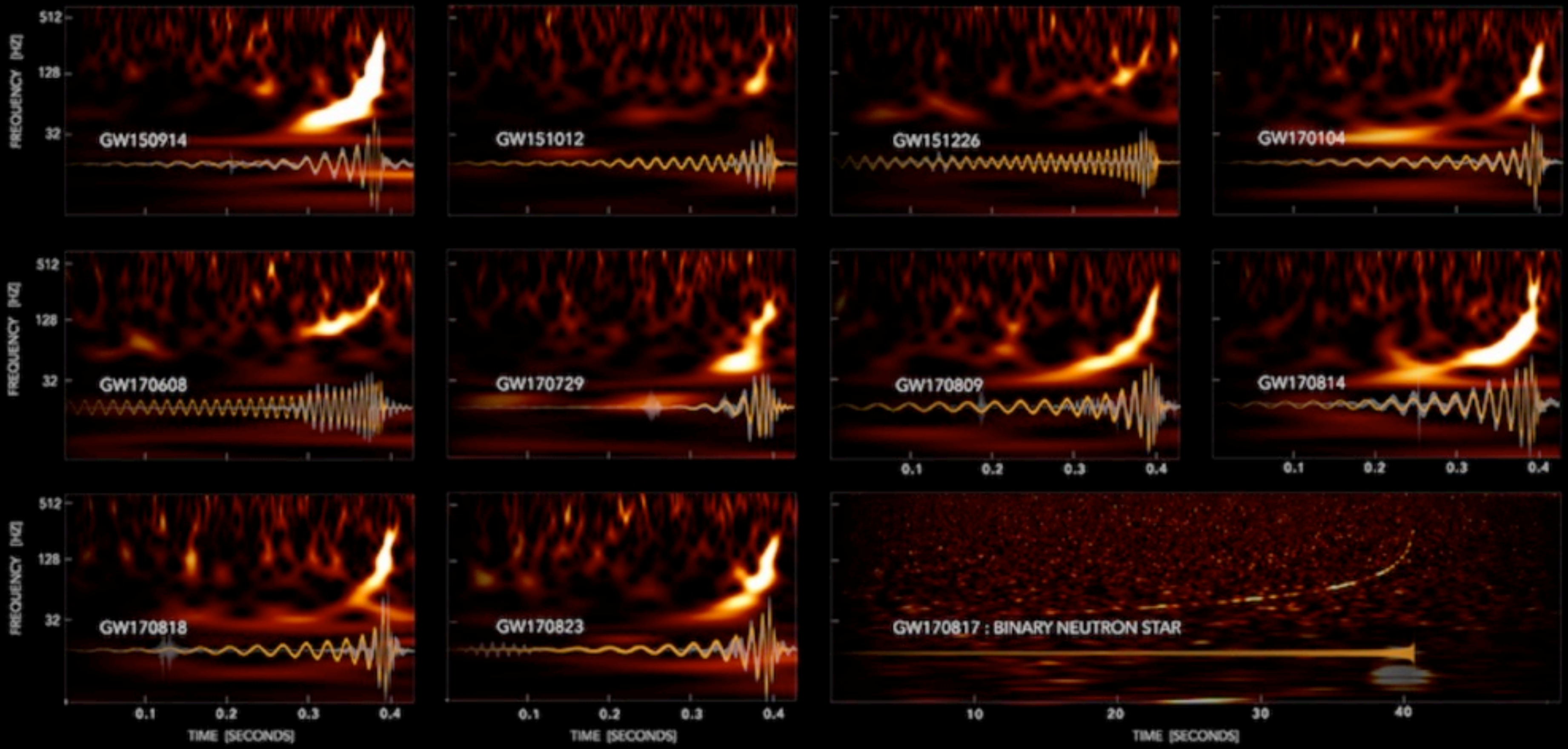


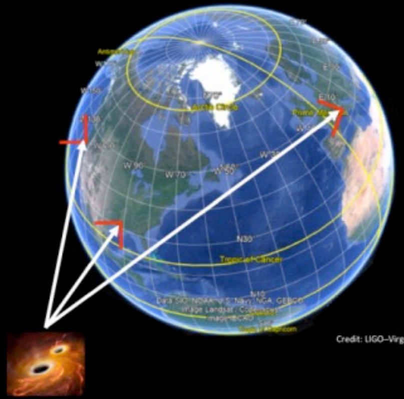
Image credit: LIGO

Observed Binary Mergers to Date

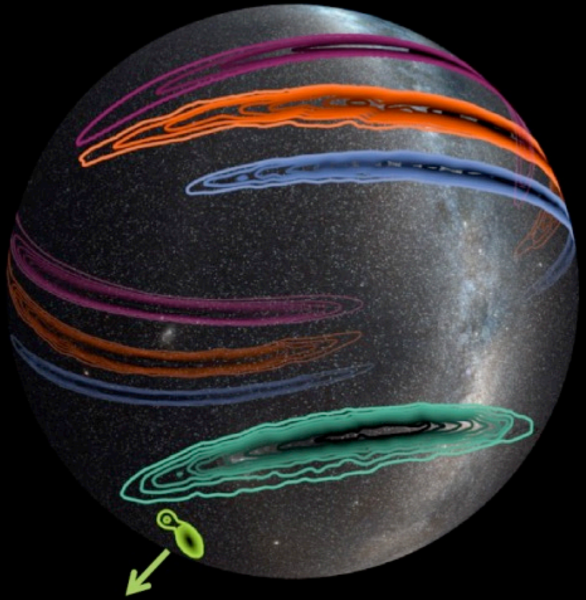


Virgo Joins LIGO – August 14, 2017

2017 August 14



Credit: LIGO–Virgo



GW170814

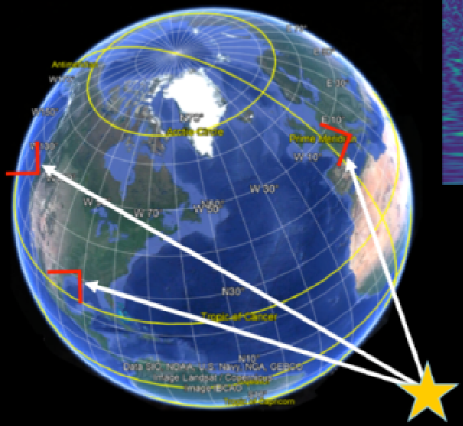
Credit: LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

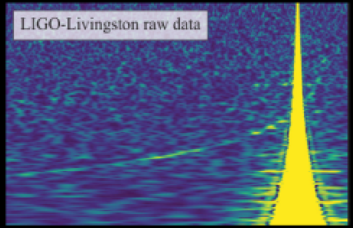
For all 10 reported
Black Hole Binary Event
NO Electromagnetic
counterparts found !!

LH 1160 square degrees
LHV 60 square degrees

And, on August 17

17 August 2017, 12:41:04 UT



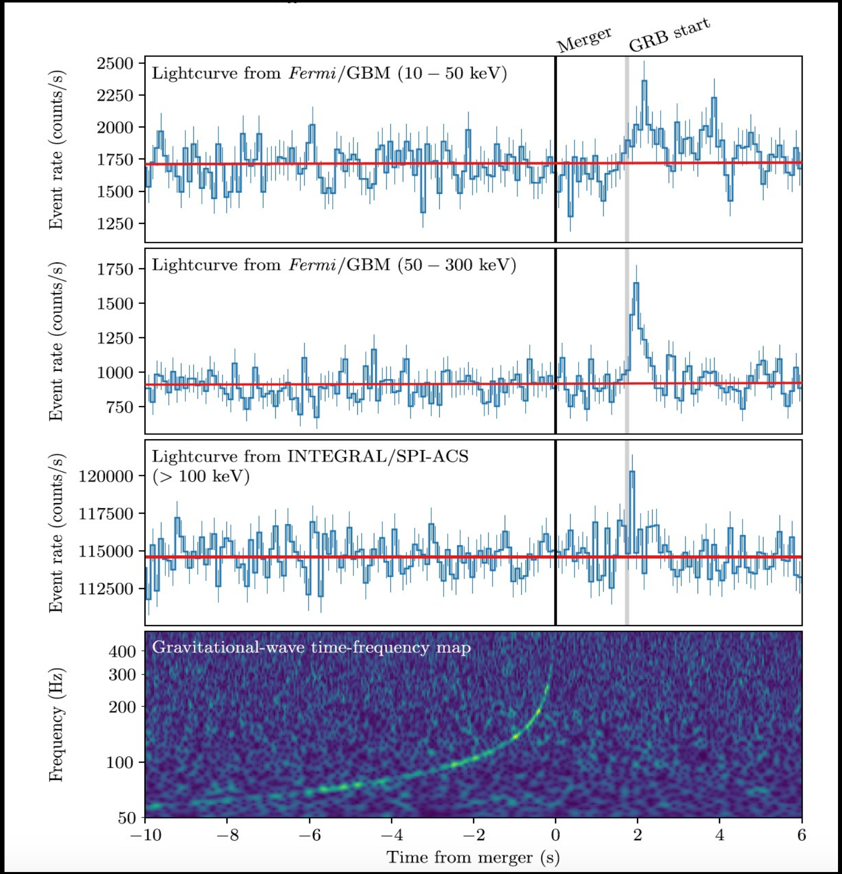


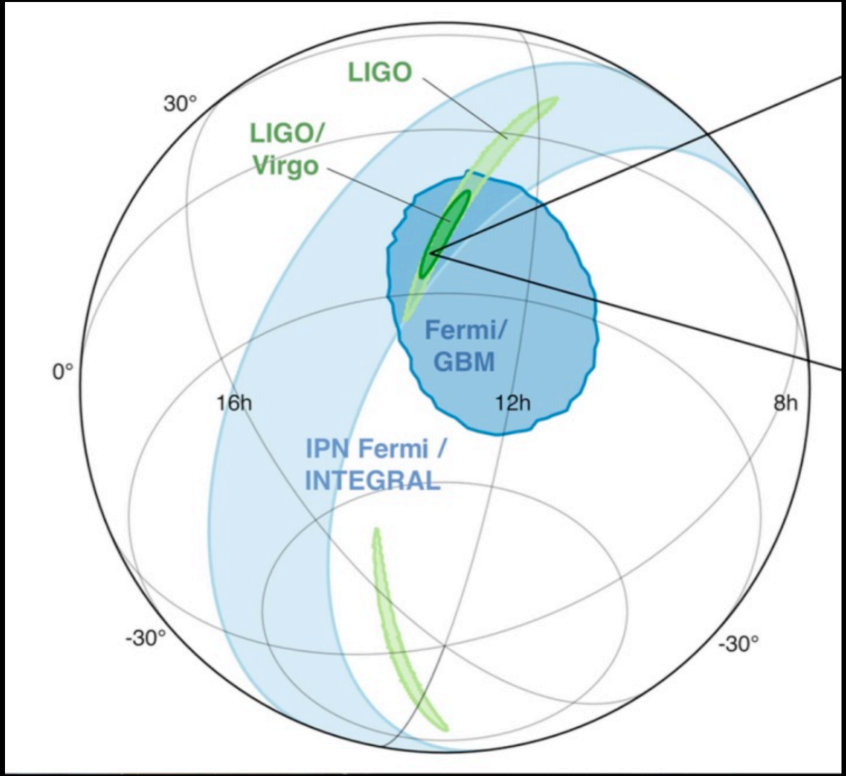
→ 17:54:51

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)

Searching for Electromagnetic Counterparts

GW candidates

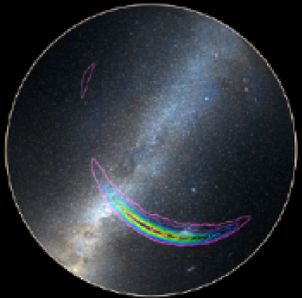
Sky Localization

EM facilities

LIGO-H

LIGO-L

Virgo



Event validation

a few min

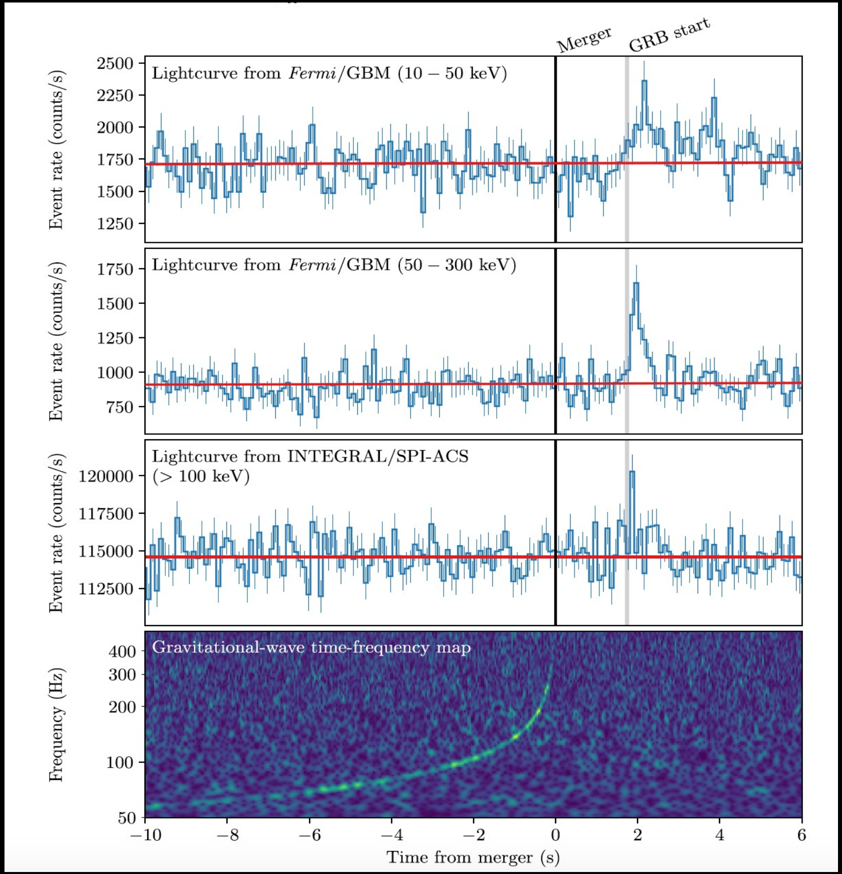
30 min

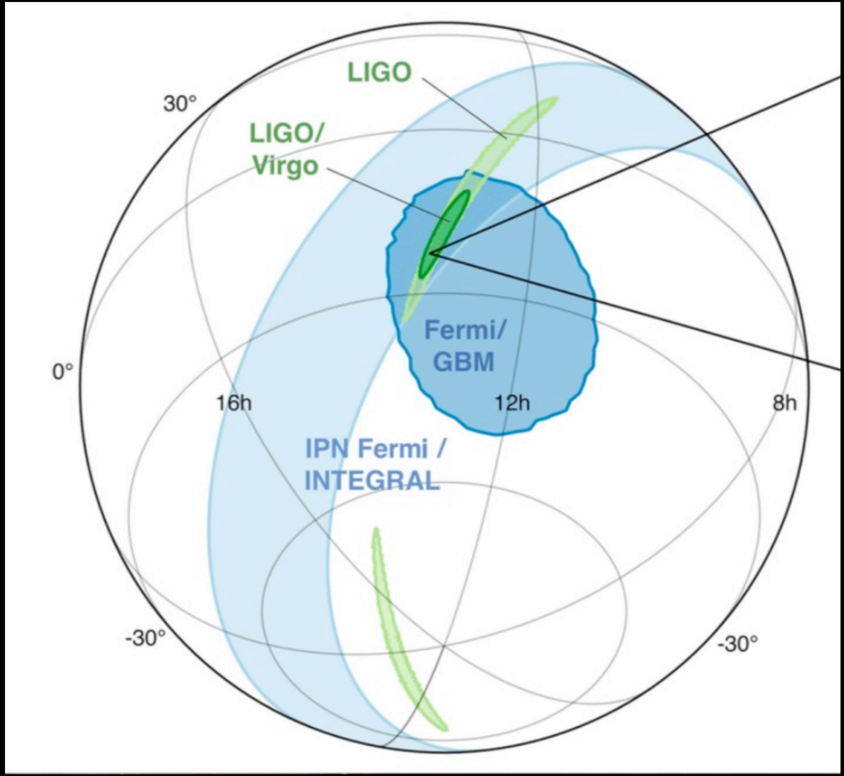
Parameter estimation codes

Hours,days, weeks

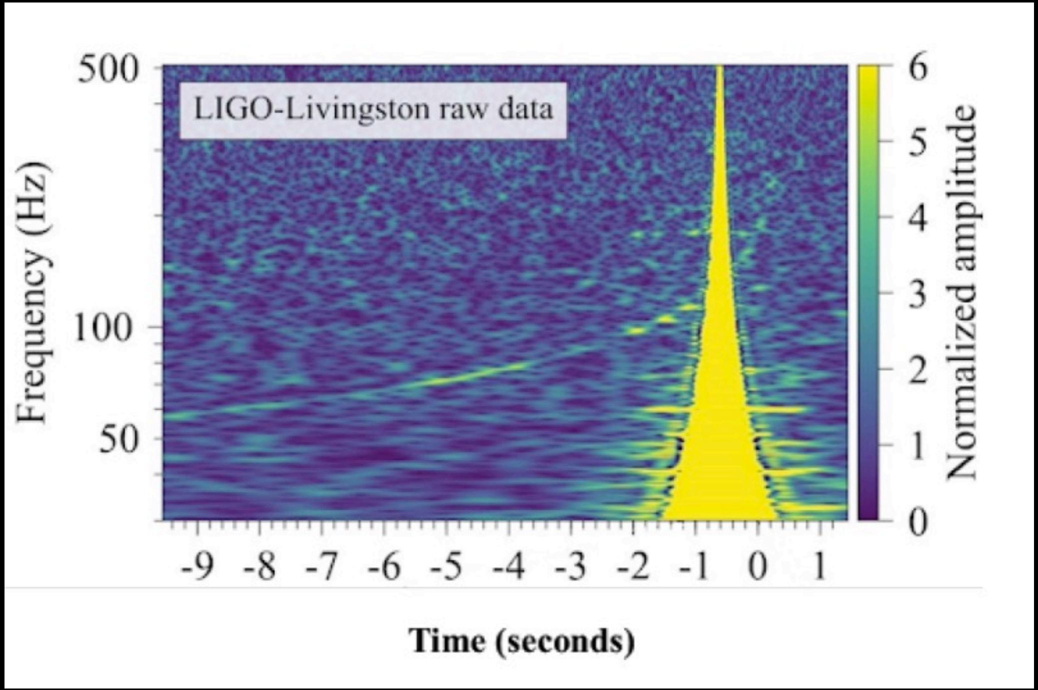
GW candidate updates

Fermi Satellite GRB detection 2 seconds later



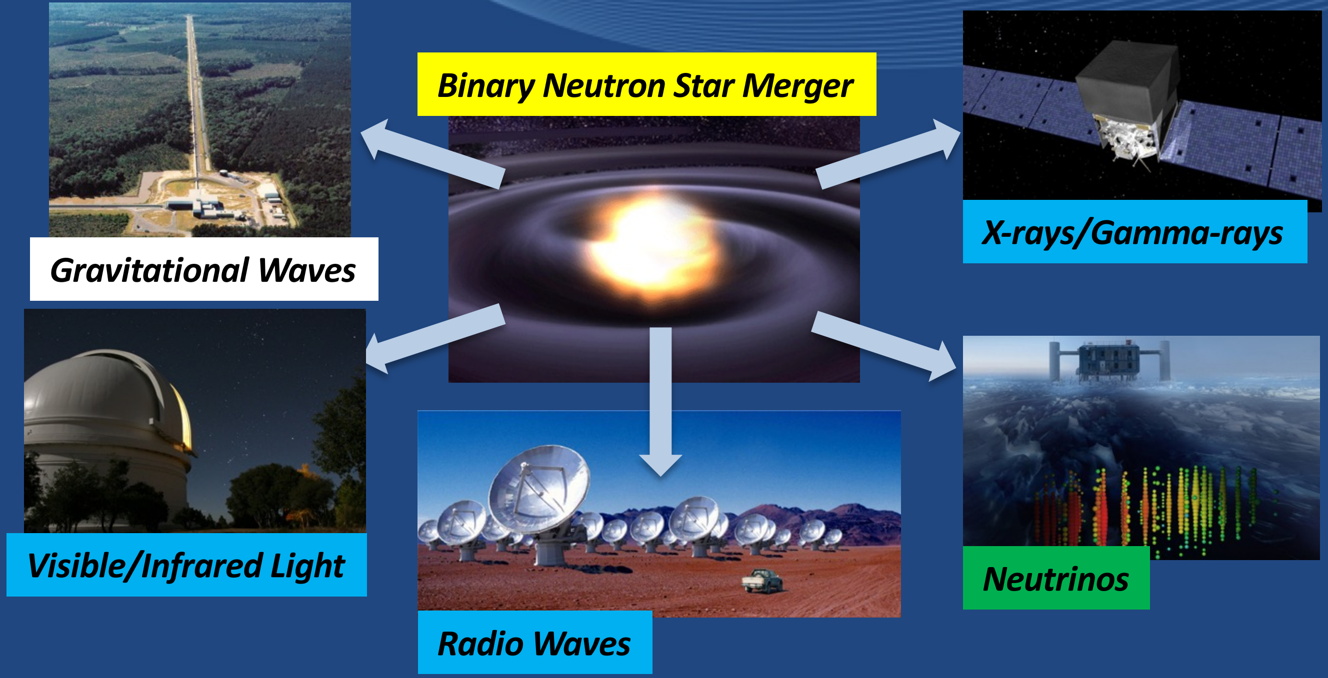


170817A" Astrophys. J. Lett., 848:L13, (2017)

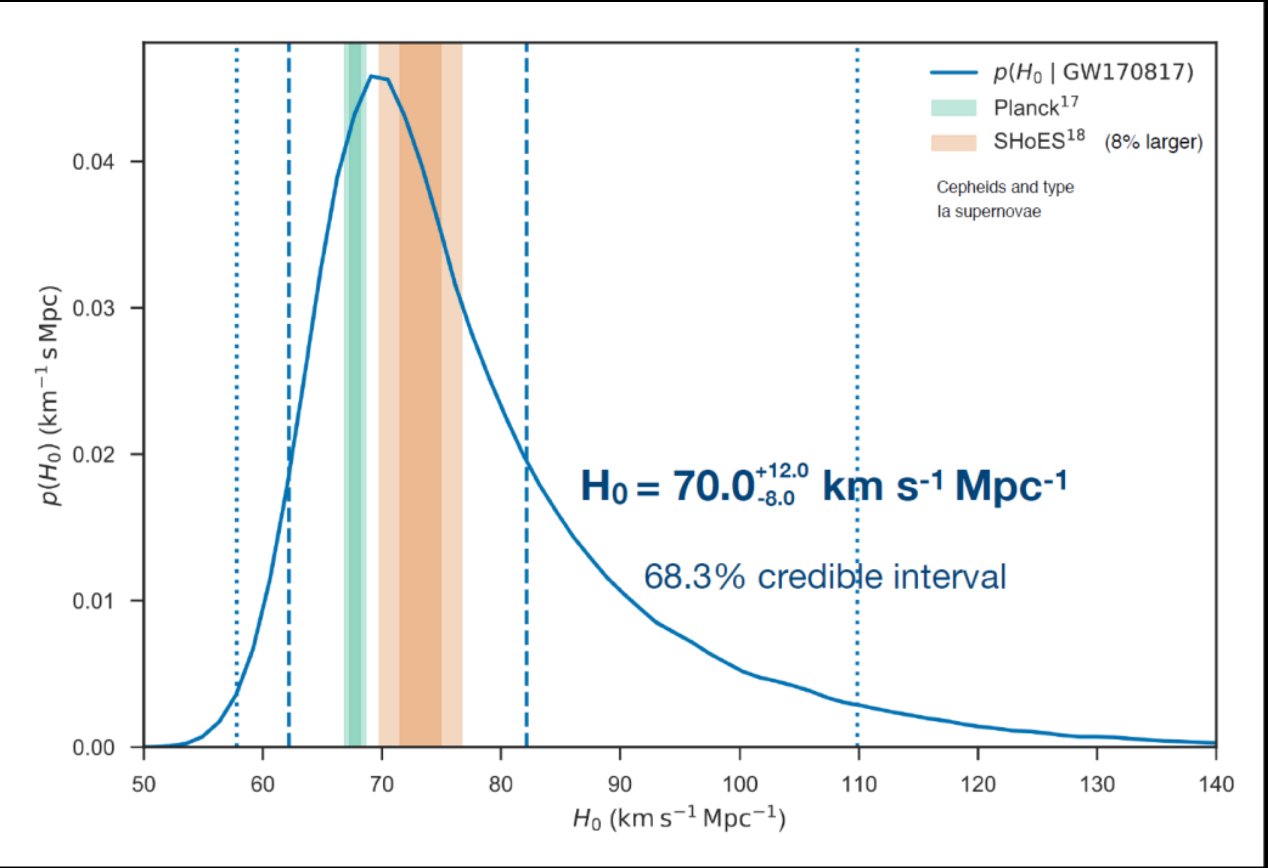


Time-frequency representation of the gravitational-wave event GW170817, as observed by the LIGO Livingston detector. Moments before merger, a noise glitch 1,000 times louder than the gravitational-wave signal occurred.

Multi-messenger Astronomy with Gravitational Waves



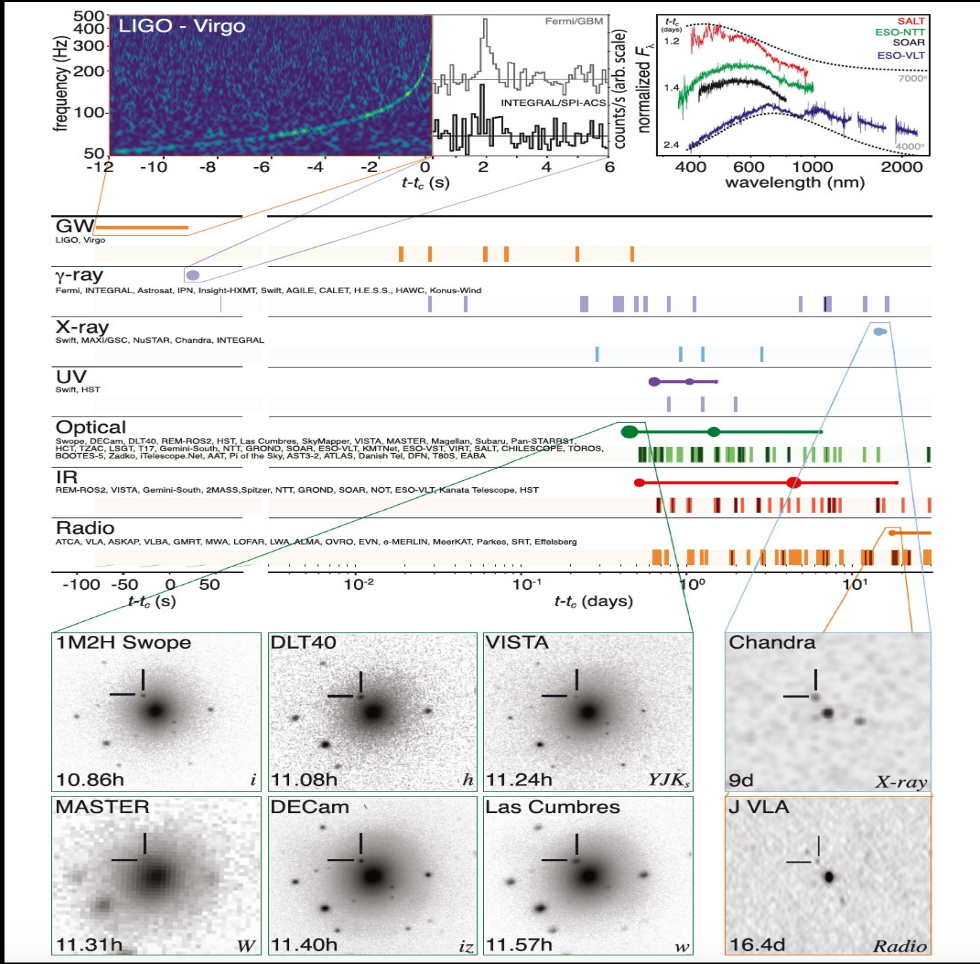
Hubble Constant – Expansion of the Universe

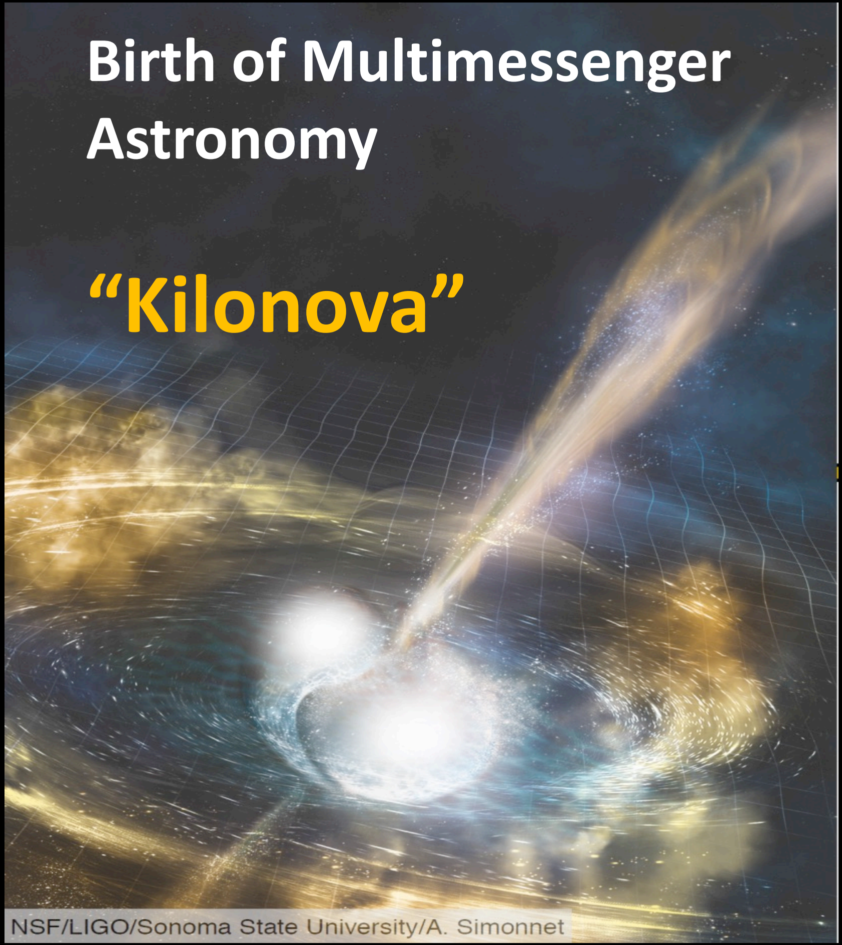


$$v_H = H_0 d$$

- v_D = local "Hubble flow" velocity of the source
- Optical identification of the host galaxy NGC 4993
- D = distance to the source

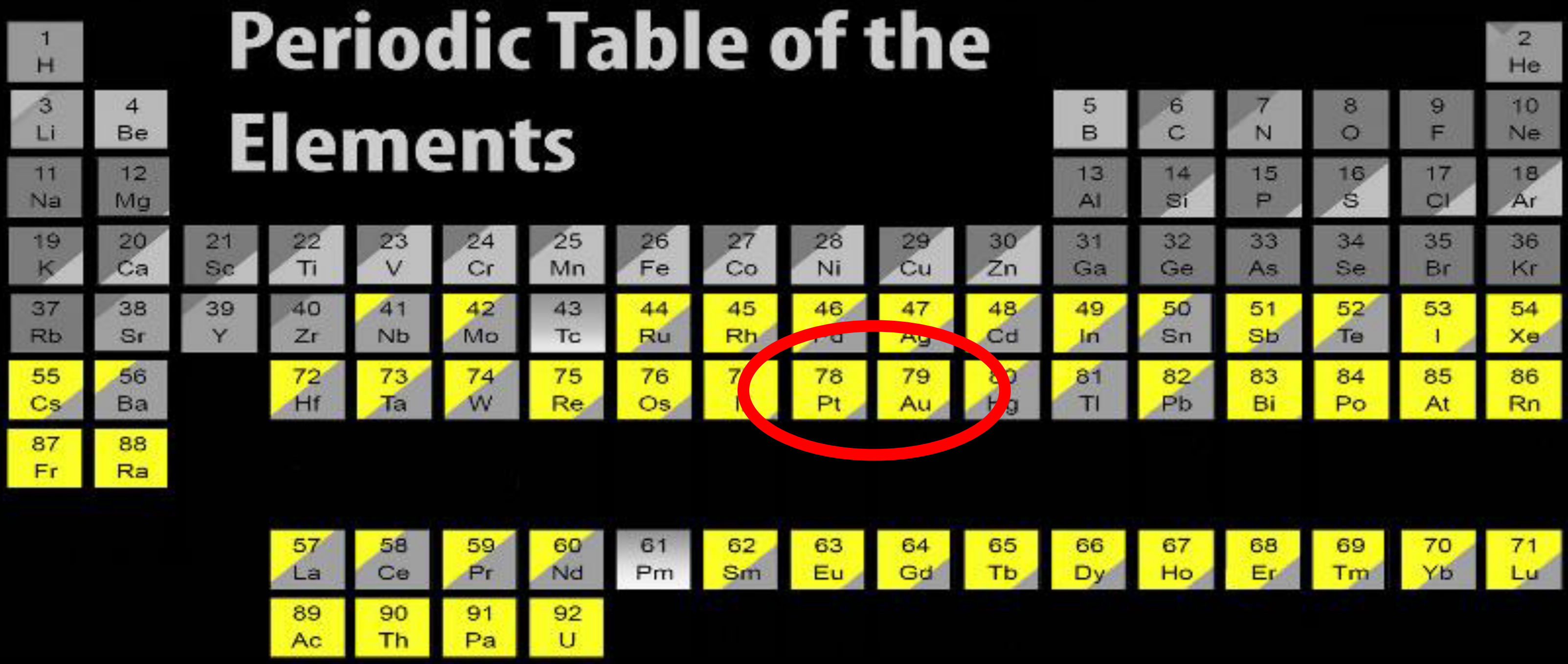
Observations Across the Electromagnetic Spectrum





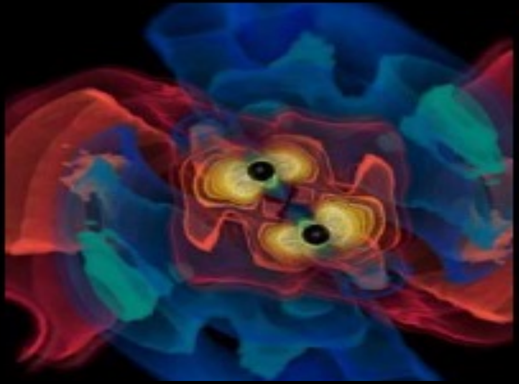
The Origin of Heavy Elements

Gold Factory in the Sky



Yellow: Formed by Merging Neutron Stars

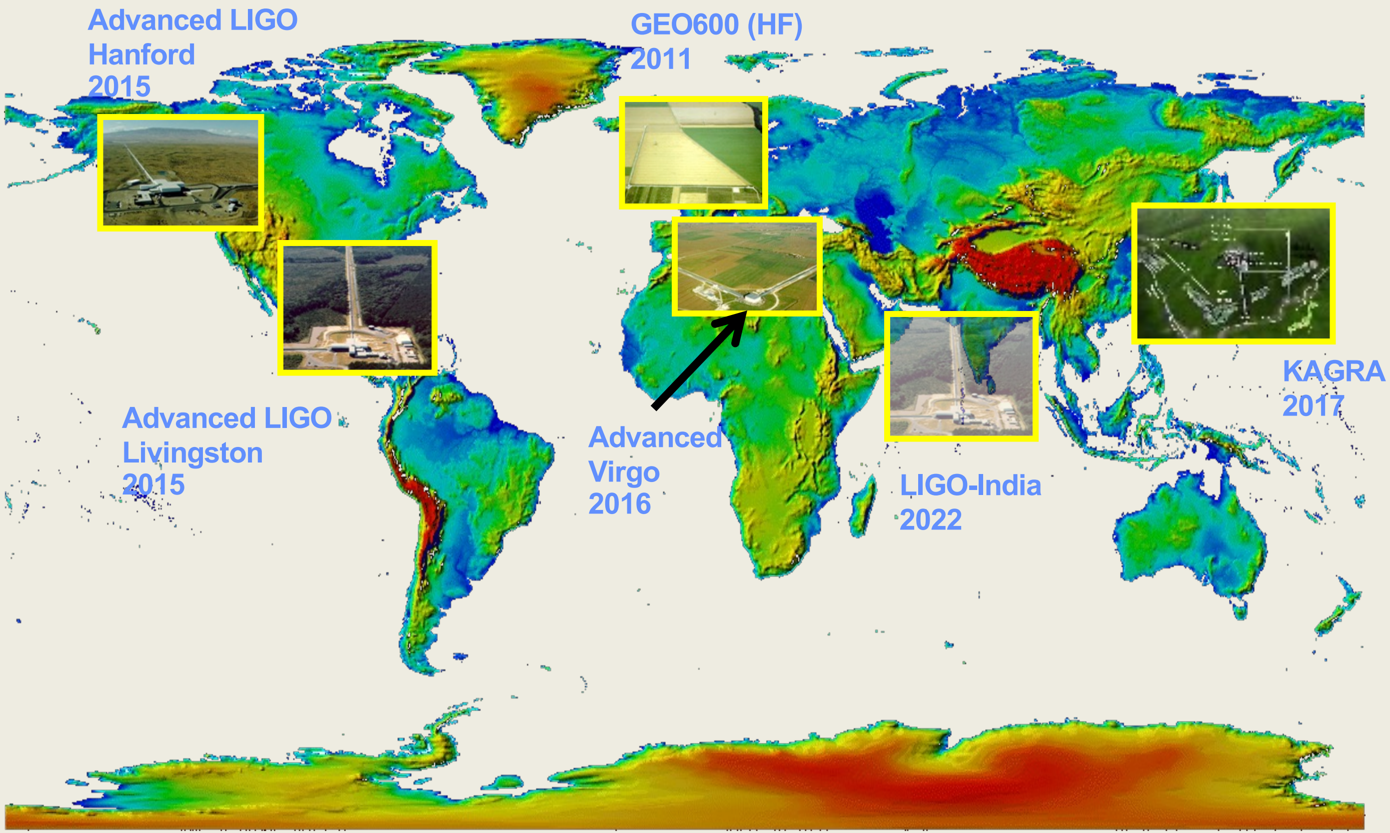
The Future for LIGO



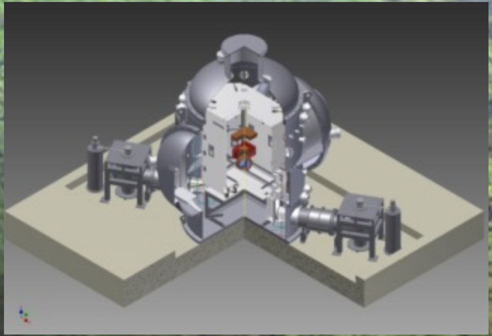
Coalescing Binary Systems

• Neutron stars, low mass black holes, and NS/BS systems

GW detector network: 2015-2025



Cryogenic Mirror

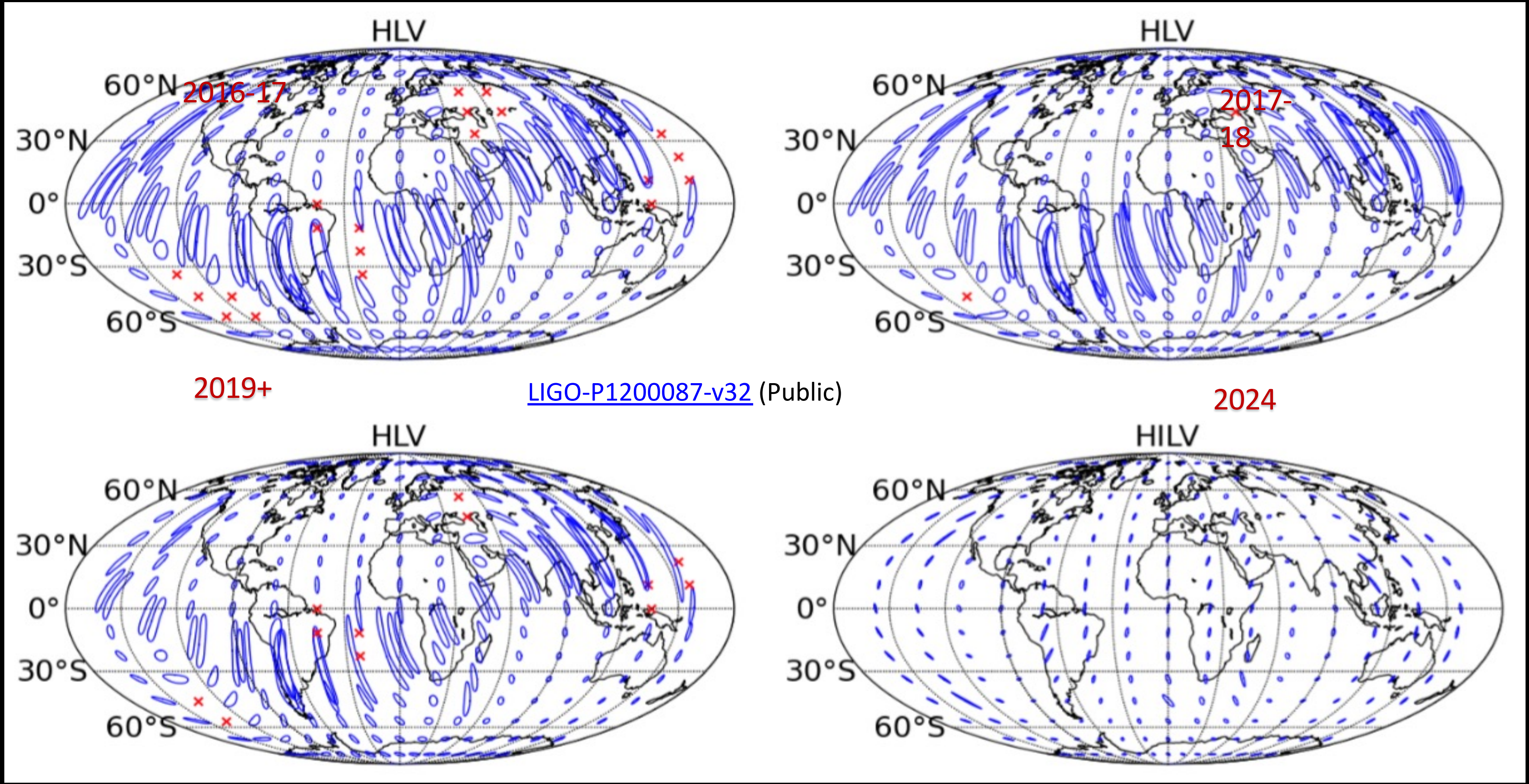


KAGRA

Kamioka Mine

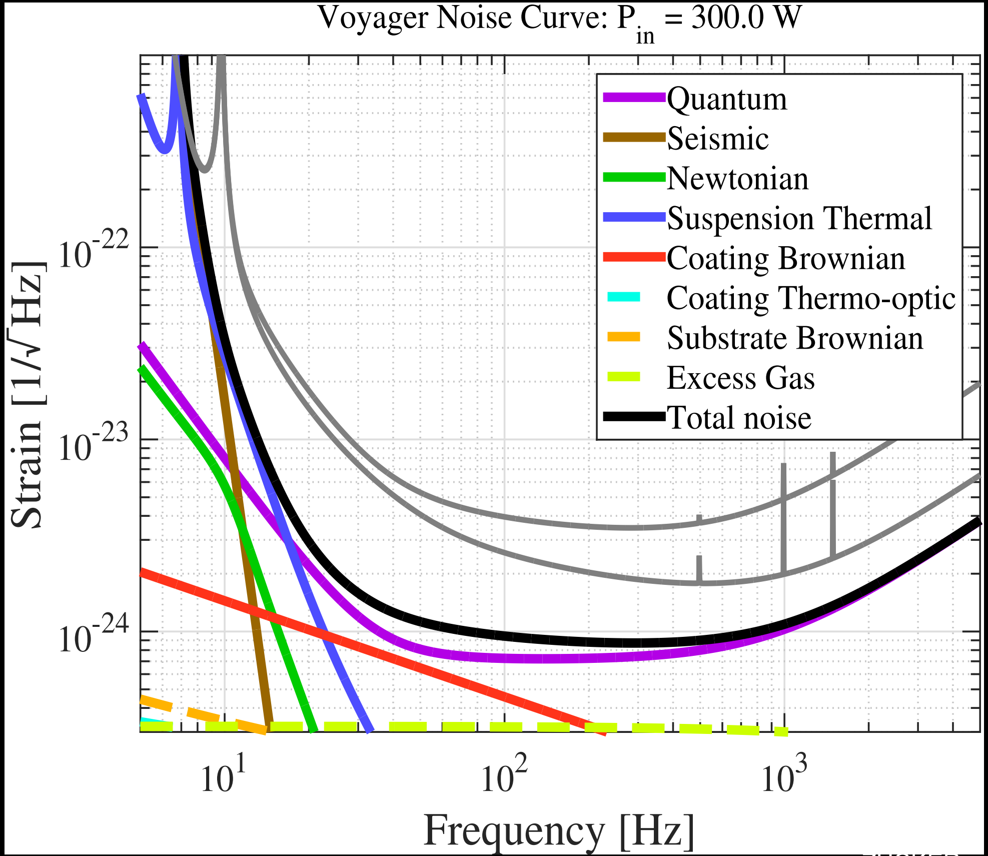
Underground

Improving Localization



LIGO-P1200087-v32 (Public)

Voyager: Concept to fully exploit LIGO sites



ZUCKER

Technological Improvements

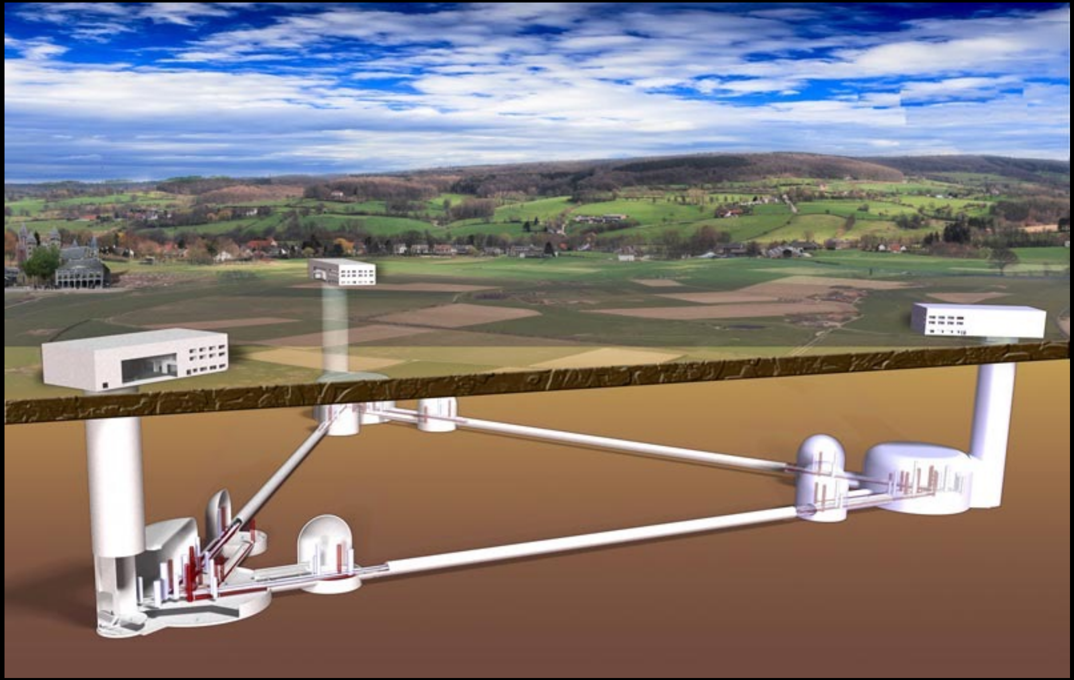
- Large 100 kg Test Masses
- Silicon
- Lower Temperature
- Improved Coatings
- ~300 W Laser (2 μm)

Science Potential

- More cosmological reach
- Improved Signal/Noise events
- aLIGO event rate x 10

Proposed 3rd Generation Detectors

Einstein Telescope 10 km



The Einstein Telescope: x10 aLIGO

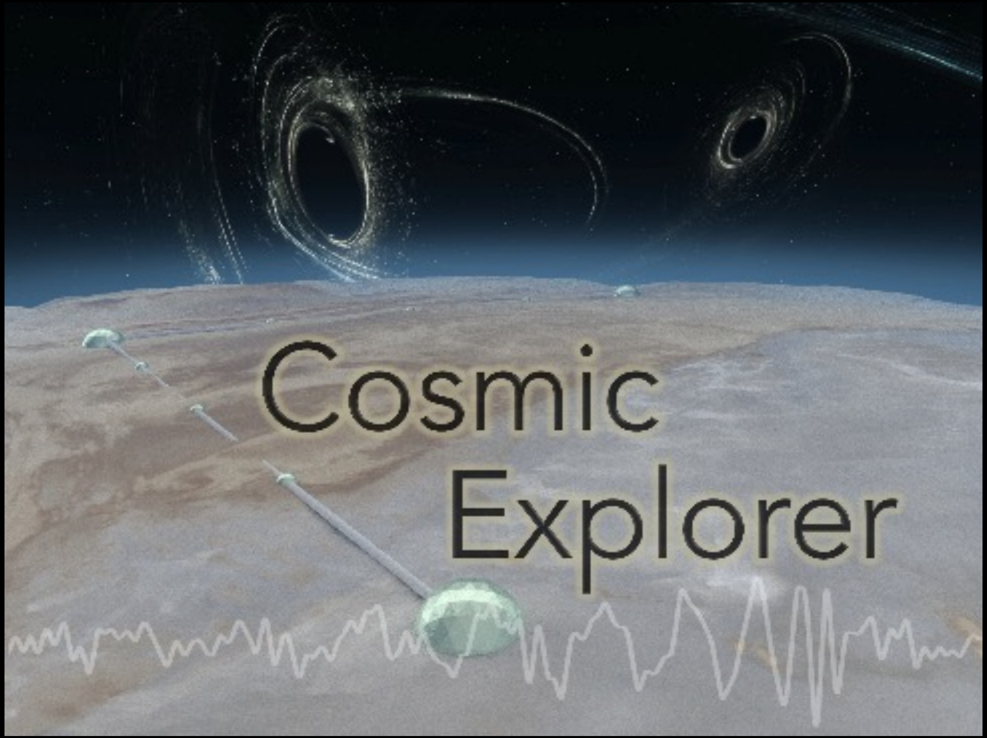
- Deep Underground;
- 10 km arms
- Triangle (polarization)
- Cryogenic
- Low frequency configuration
- high frequency configuration

Proposed 3rd Generation Detectors

Cosmic Explorer 40 km

The Cosmic: x10 Voyager

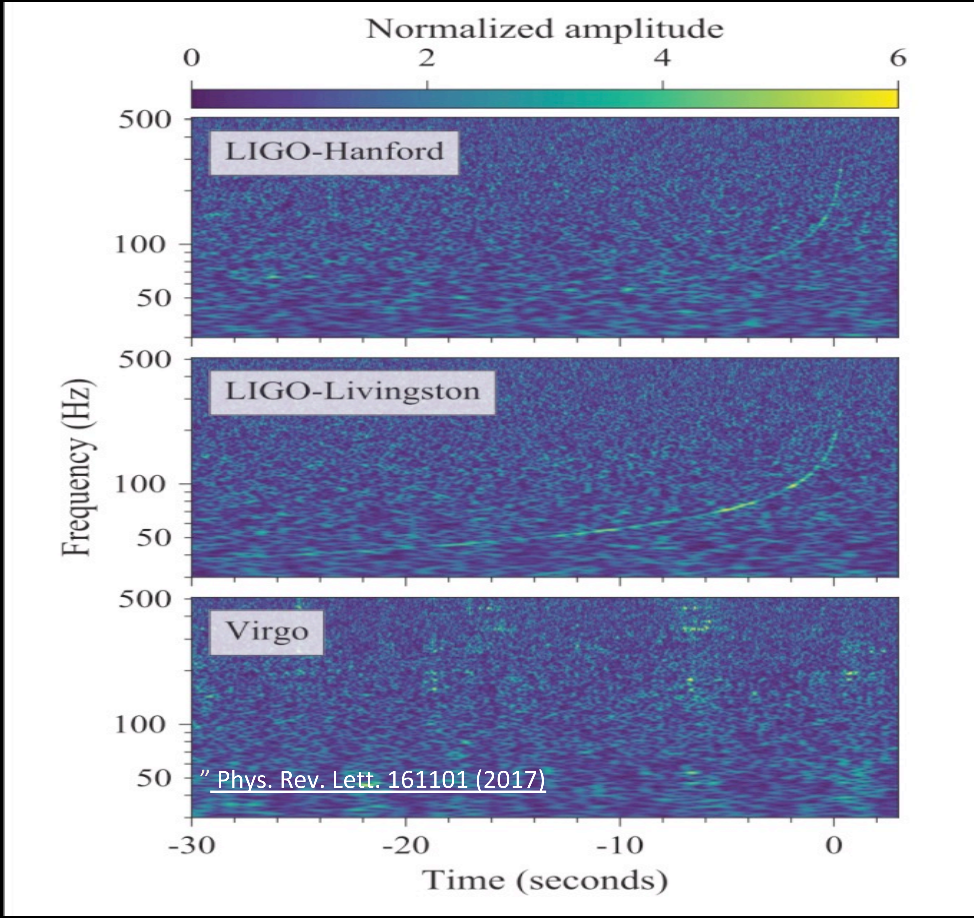
- Earths surface;
- 40 km arms
- Low frequency configuration
- high frequency configuration



The Future for Gravitational Wave Astronomy

Thanks!

First Binary Neutron Star Merger



	Low-spin priors $(|\chi| \leq 0.05)$
Primary mass m_1	1.36–1.60 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$

	High-spin priors $(|\chi| \leq 0.89)$
Primary mass m_1	1.36–2.26 $M_\odot$
Secondary mass m_2	0.86–1.36 $M_\odot$