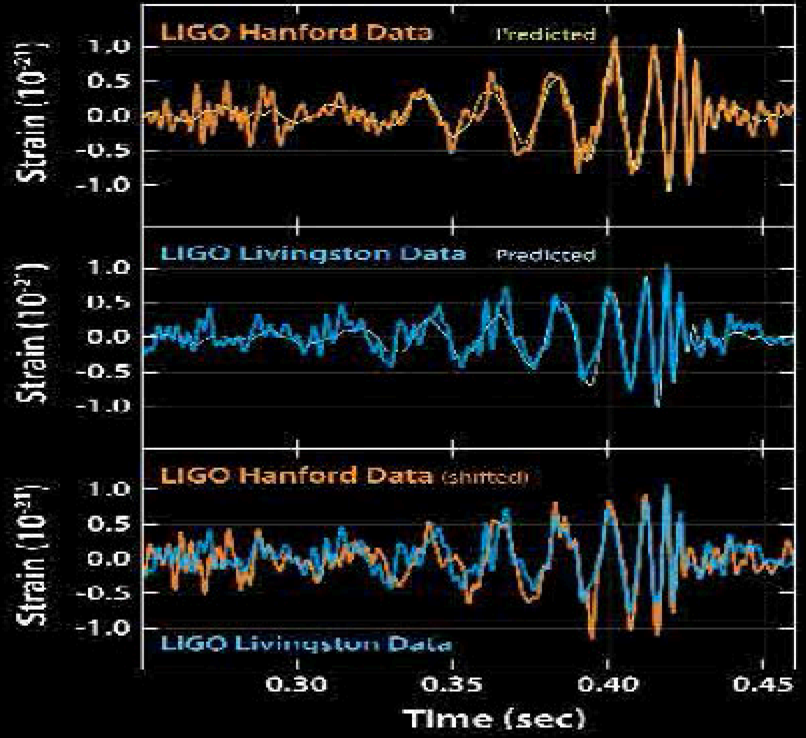
From Einstein to Gravitational Waves and Beyond ...



Barry C Barish

Caltech

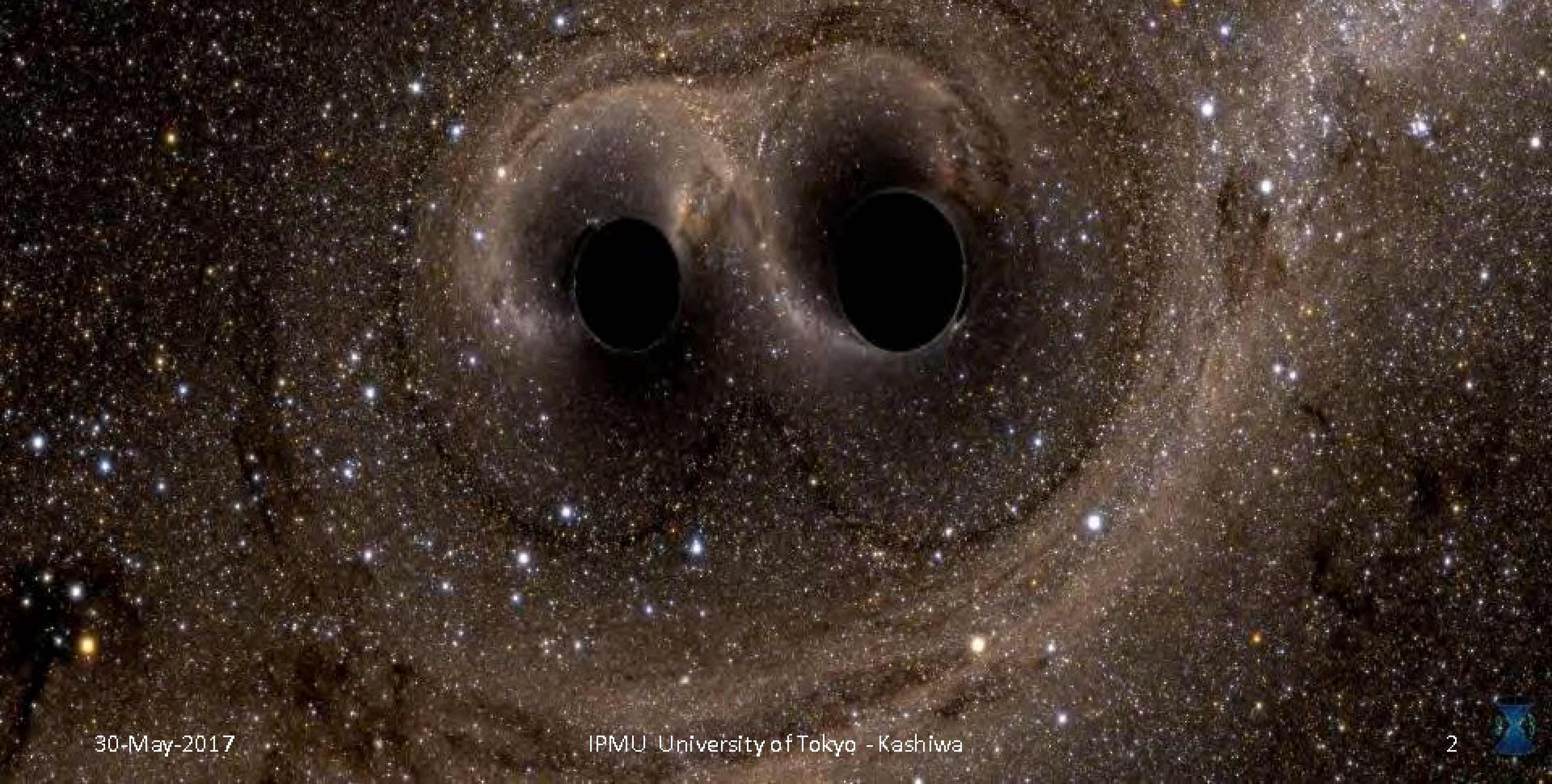
IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

University of Tokyo

Kashiwa Campus

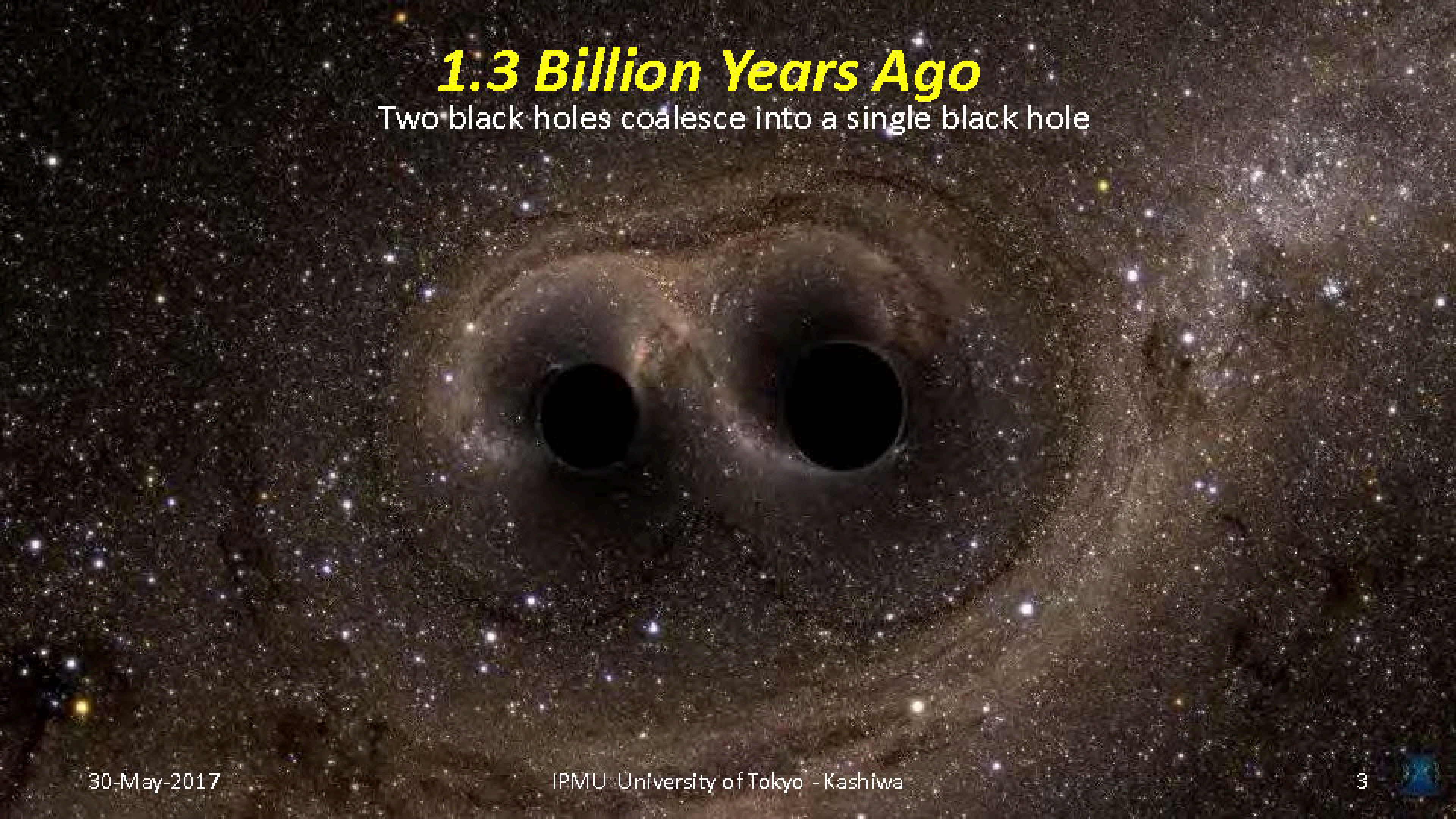
30-May-2017

1.3 Billion Years Ago

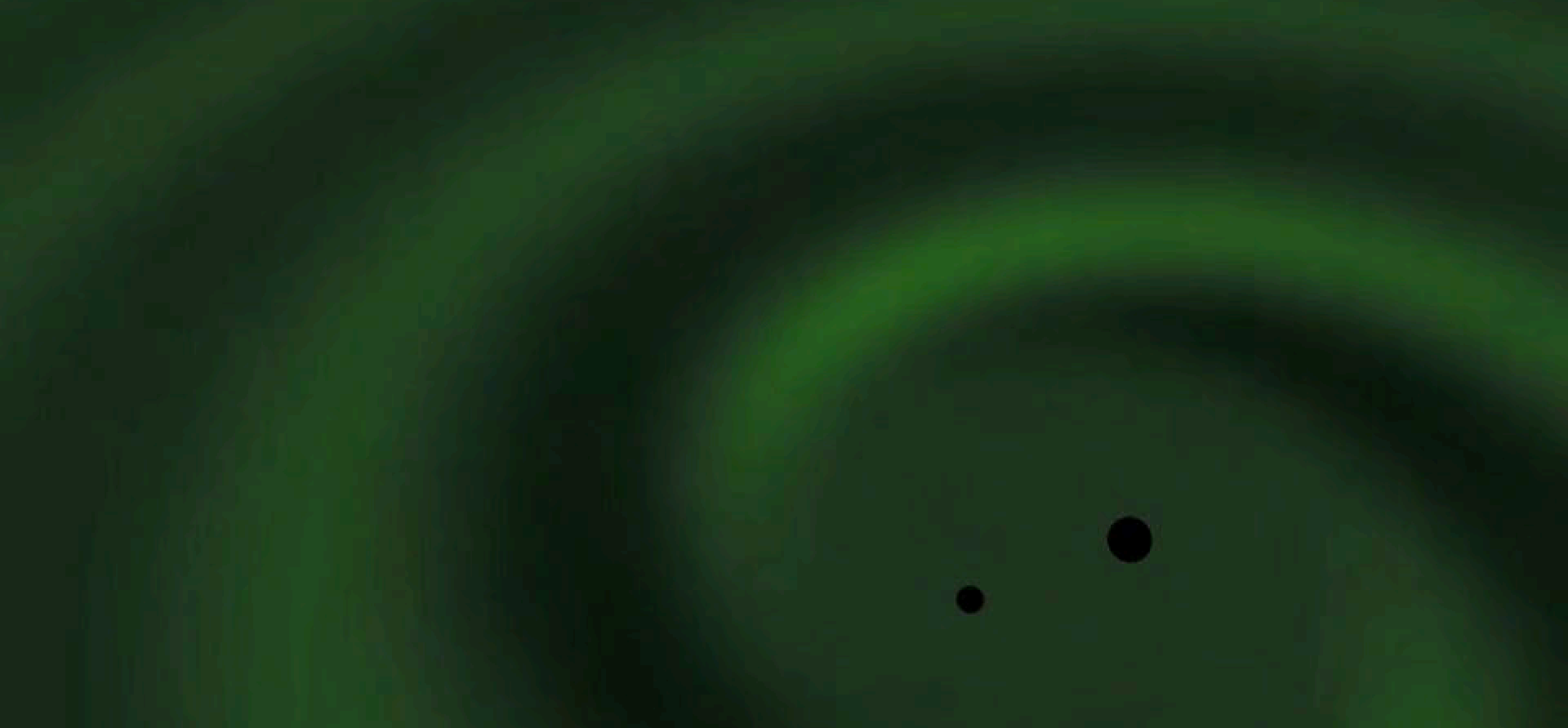


1.3 Billion Years Ago

Two black holes coalesce into a single black hole



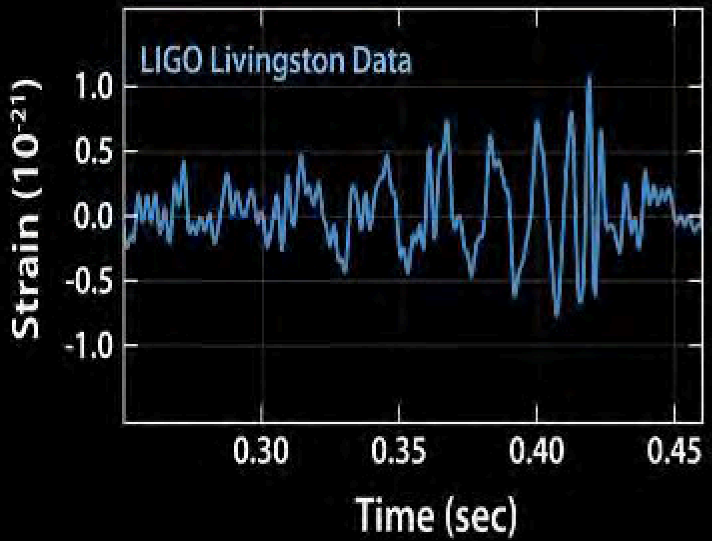
Gravitational Waves Travel to the Earth



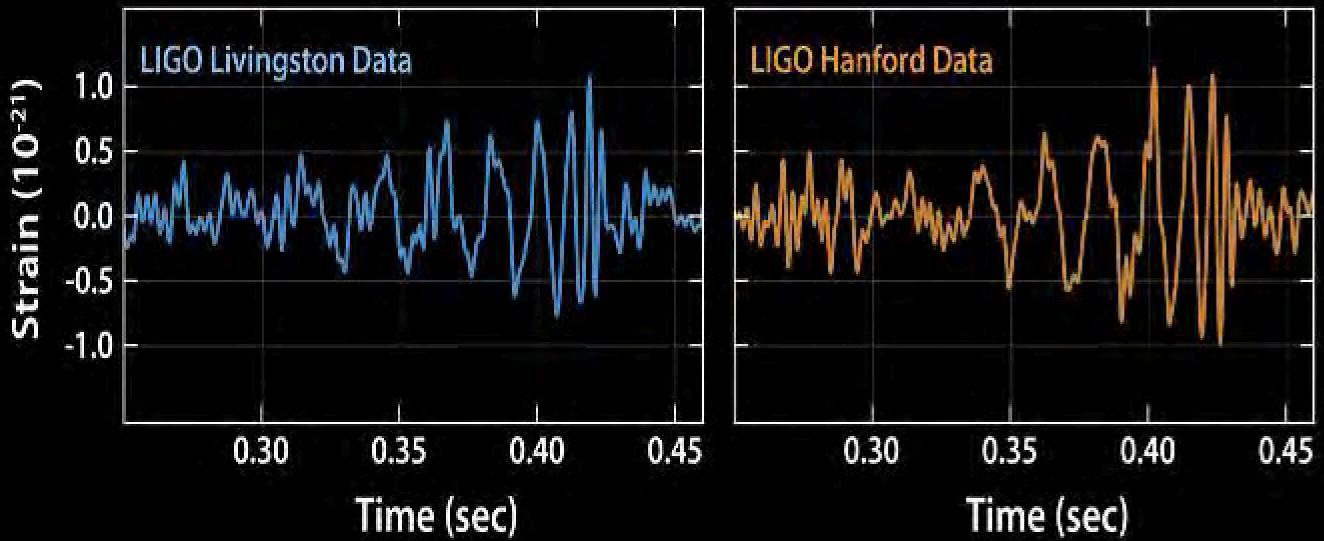
Sept 14, 2015

Coming up from
Southern Hemisphere

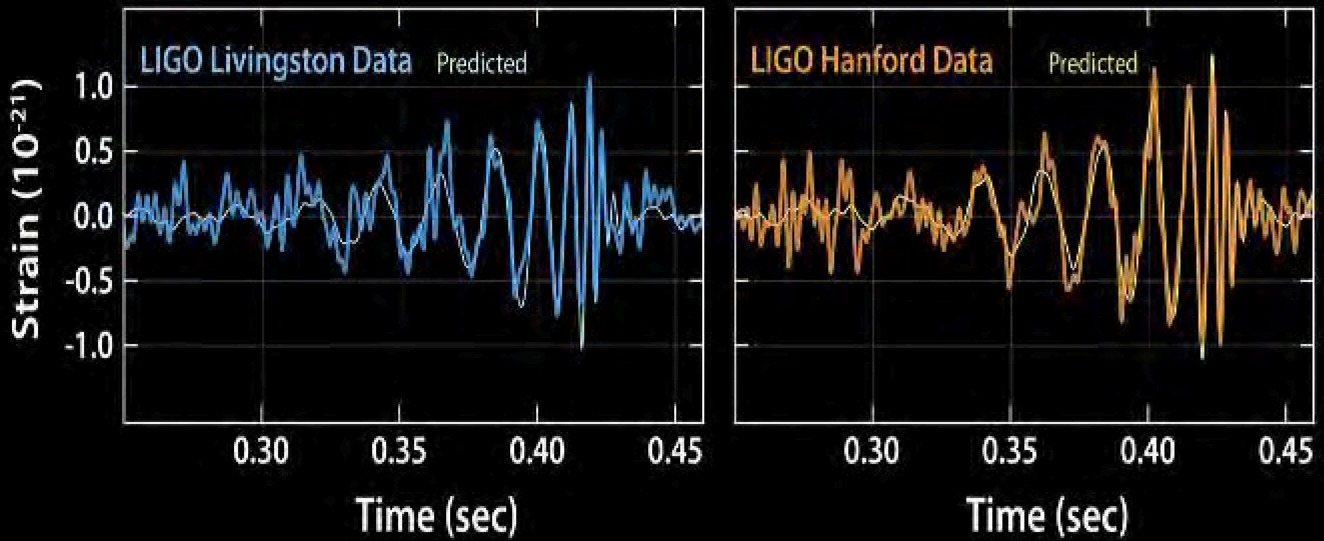
~ 20 msec later



After another 7 msec

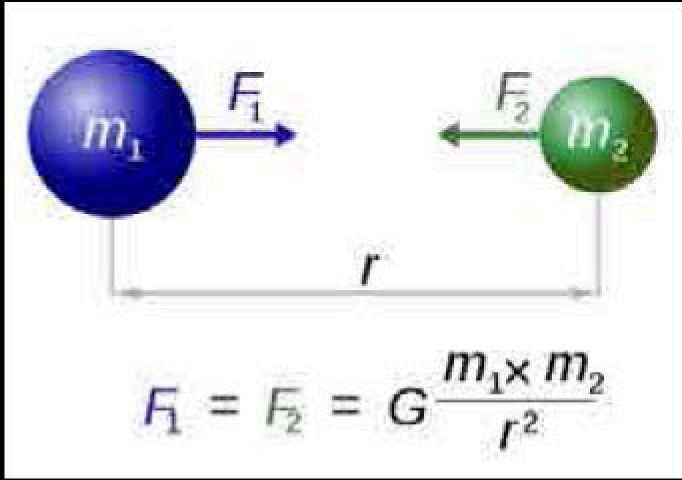


GR Prediction for BH merger

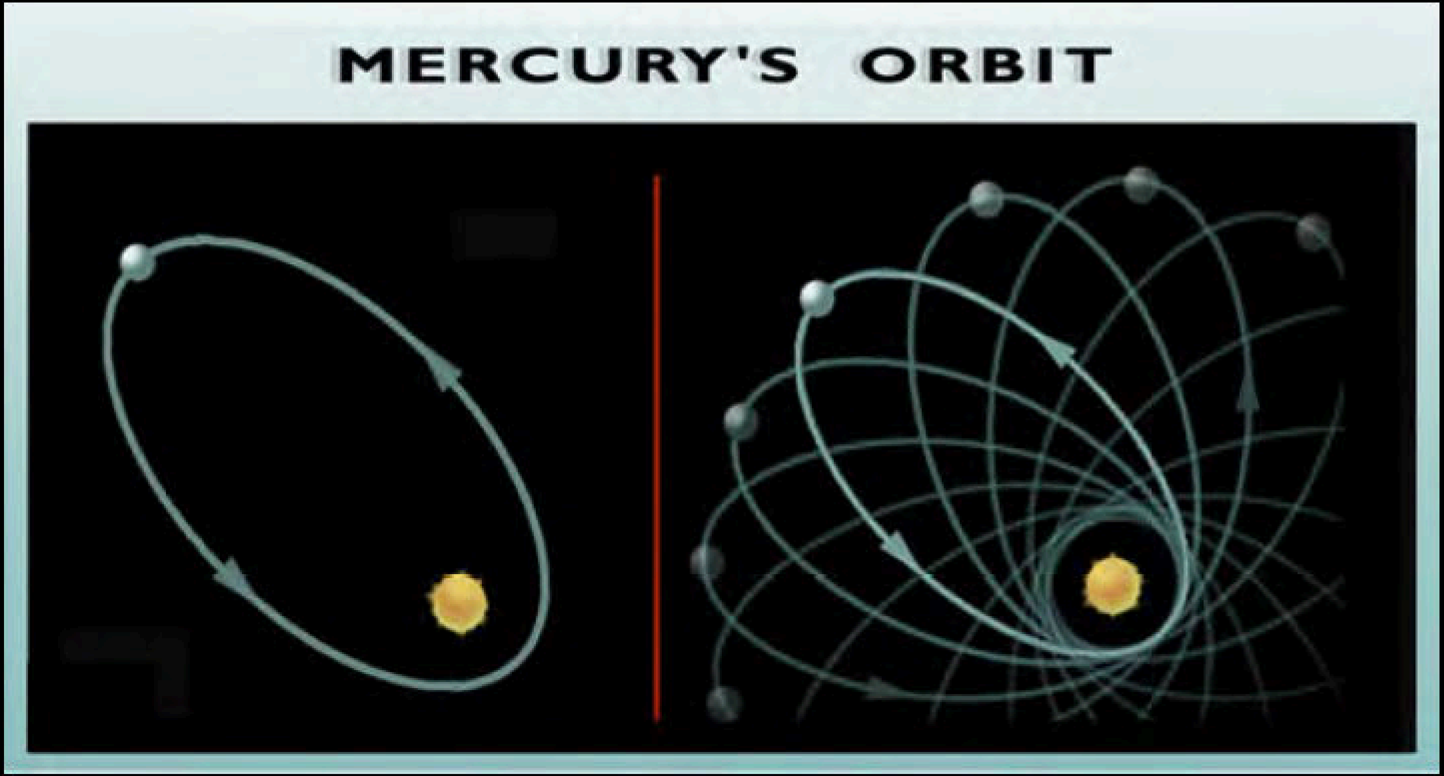


Newton's Theory of Gravity

1687



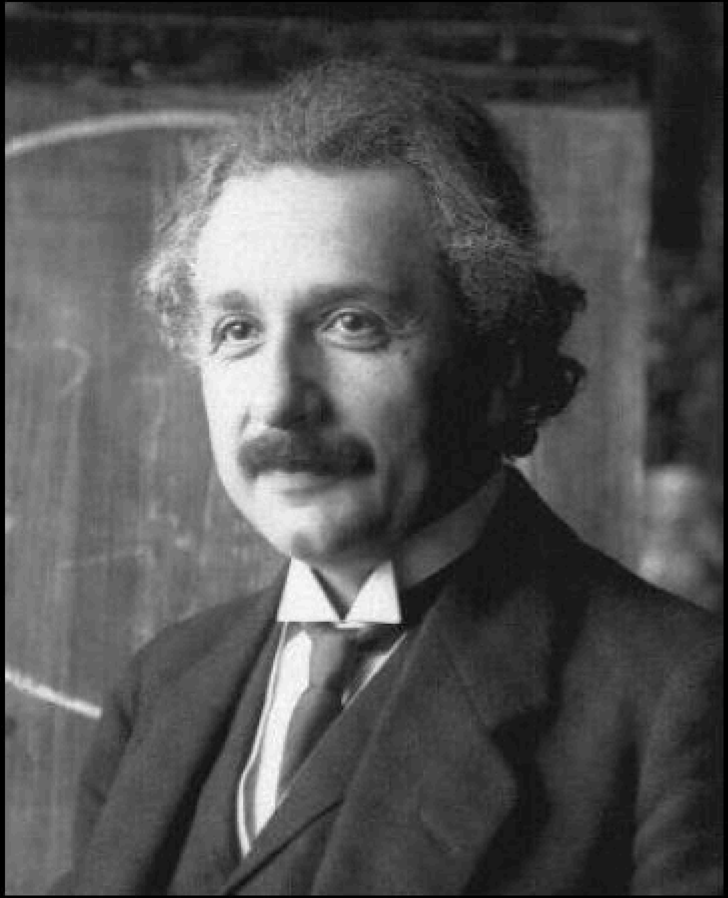
Universal Gravity: force between massive objects is directly proportional to the product of their masses, and inversely proportional to the square of the distance between them.



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

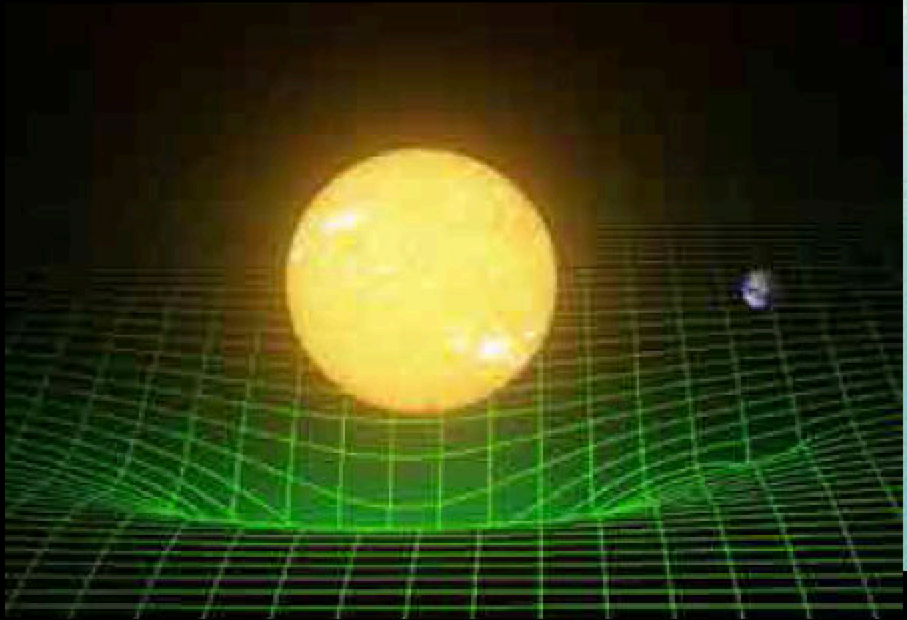


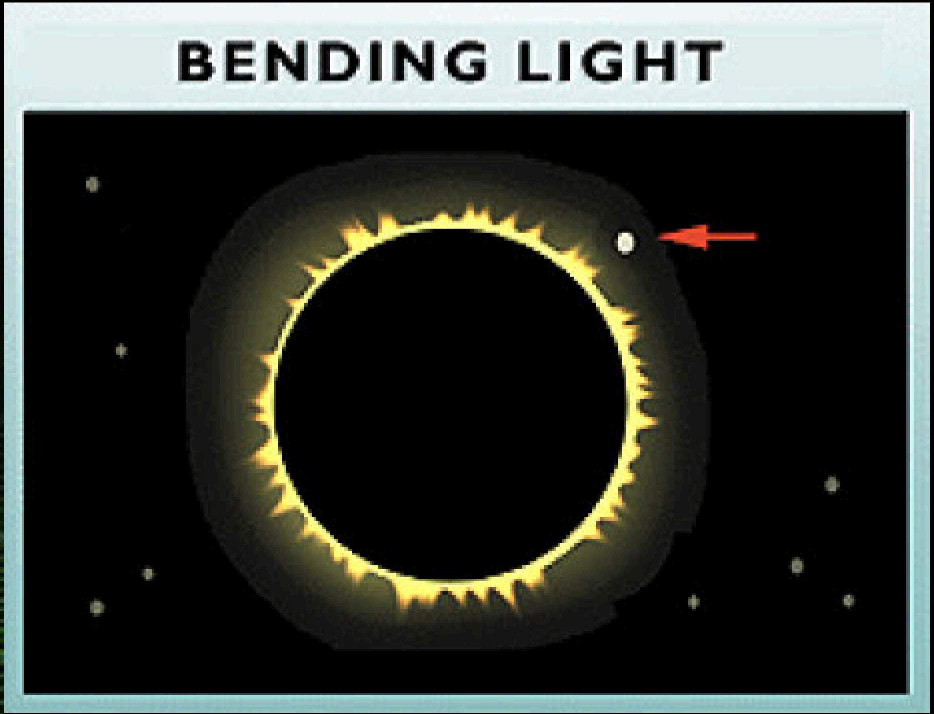
1915

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

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

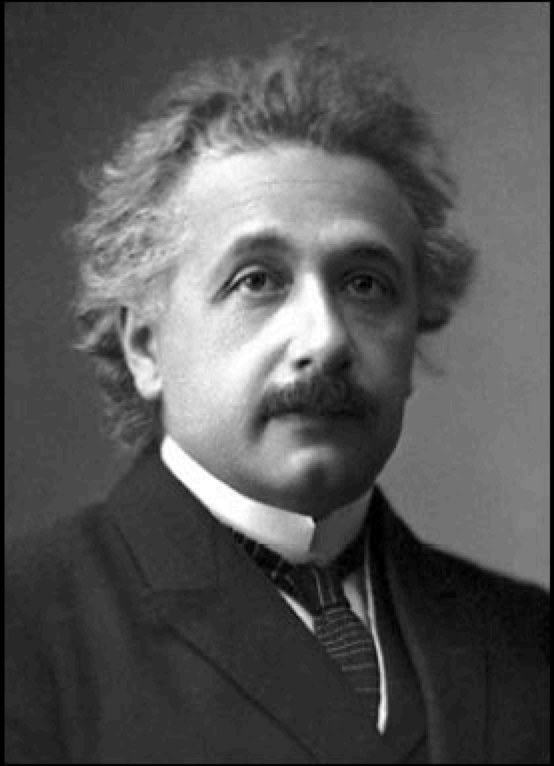
spacetime

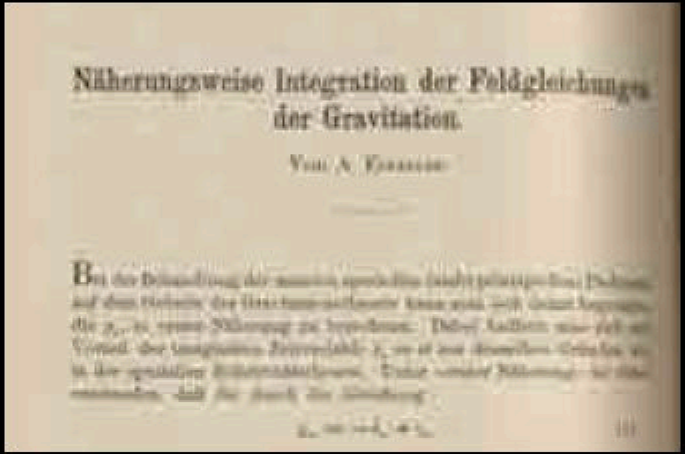




First observed during the solar eclipse of 1919 by Sir Arthur Eddington, when the Sun was silhouetted against the Hyades star cluster

Einstein Predicted Gravitational Waves in 1916





Näherungsweise Integration der Feldgleichungen der Gravitation.

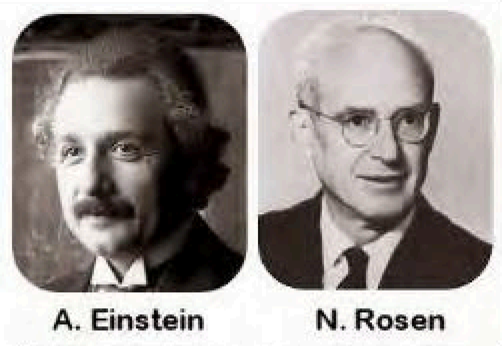
- 1st publication indicating the existence of gravitational waves by Einstein in 1916
  - Contained errors relating wave amplitude to source motions
- 1918 paper corrected earlier errors (factor of 2), and it contains the quadrupole formula for radiating source

Einstein vs Physical Review

1936

Einstein and Rosen Submited an article to Physical Review

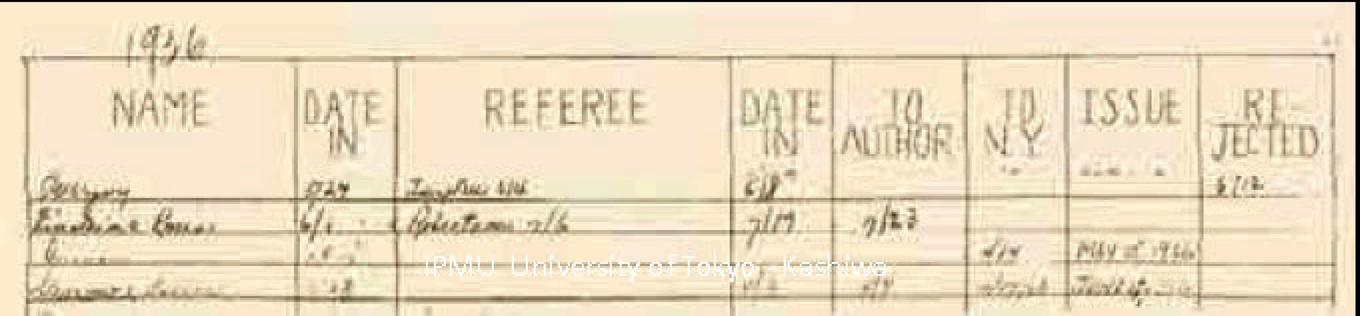
"Do Gravitational Waves Exist?"



John Tate sends the Paper for "Peer Review"

Howard Percy Robertson

- Einstein/Rosen used a single coordinate system to cover all of space-time and encountered a singularity.
- Robertson found the error and showed that casting metric in cylindrical coordinates removed the difficulty.
- Tate sent Einstein a mild letter stating "would be glad to have (Einstein's) reaction to referee comments and criticisms".



1936

NAME	DATE IN	REFEREE	DATE IN	TO AUTHOR	TO N.Y.	ISSUE	REJECTED
[illegible]	[illegible]	[illegible]	[illegible]				[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			
[illegible]	[illegible]				[illegible]	[illegible]	
[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	

All's well that ends well …

- Robertson returned from Caltech sabbatical a while later, struck up a friendship with Infeld. Robertson told Infeld he didn't believe Einstein's result, and went over Infeld's version of the argument. Robertson pointed out the error.

- Infeld reported to Einstein, and Einstein said he independently had found the error himself. He then completely modified the paper.

ON GRAVITATIONAL WAVES.

BY

A. EINSTEIN and N. ROSEN.

ABSTRACT.

The rigorous solution for cylindrical gravitational waves is given. For the convenience of the reader the theory of gravitational waves and their production, already known in principle, is given in the first part of this paper. After encountering relationships which cast doubt on the existence of rigorous solutions for undulatory gravitational fields, we investigate rigorously the case of cylindrical gravitational waves. It turns out that rigorous solutions exist and that the problem reduces to the usual cylindrical waves in euclidean space.

The Chapel Hill Conference

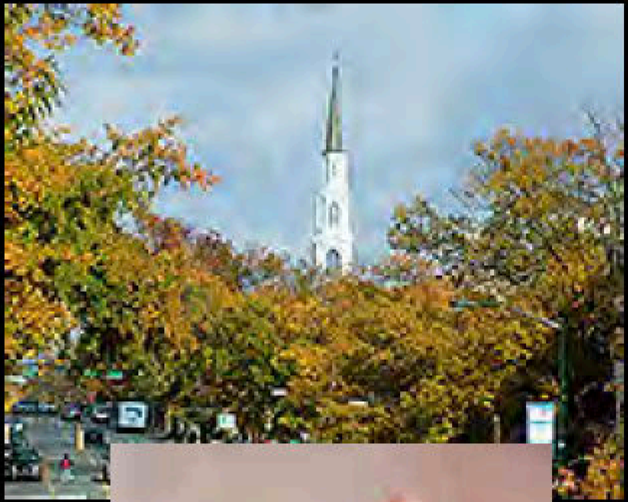
Could the waves be a coordinate effect only, with no physical reality? Einstein didn't live long enough to learn the answer.

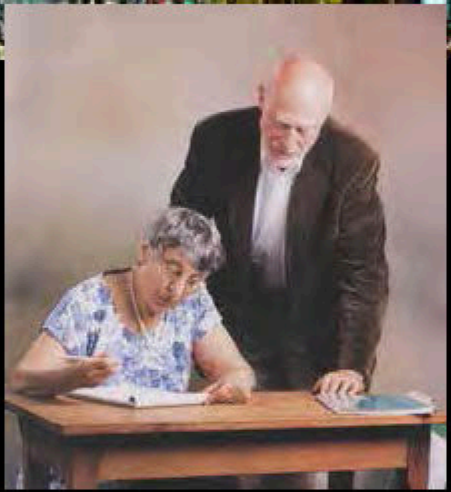
In January 1957, the U.S. Air Force sponsored the *Conference on the Role of Gravitation in Physics*, a.k.a. the Chapel Hill Conference, a.k.a. GR1.

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

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

(Pirani, Feynman and Babson)

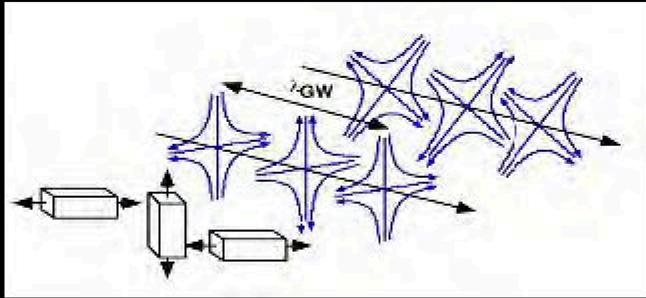




Einstein's Theory of Gravitation
Gravitational Waves

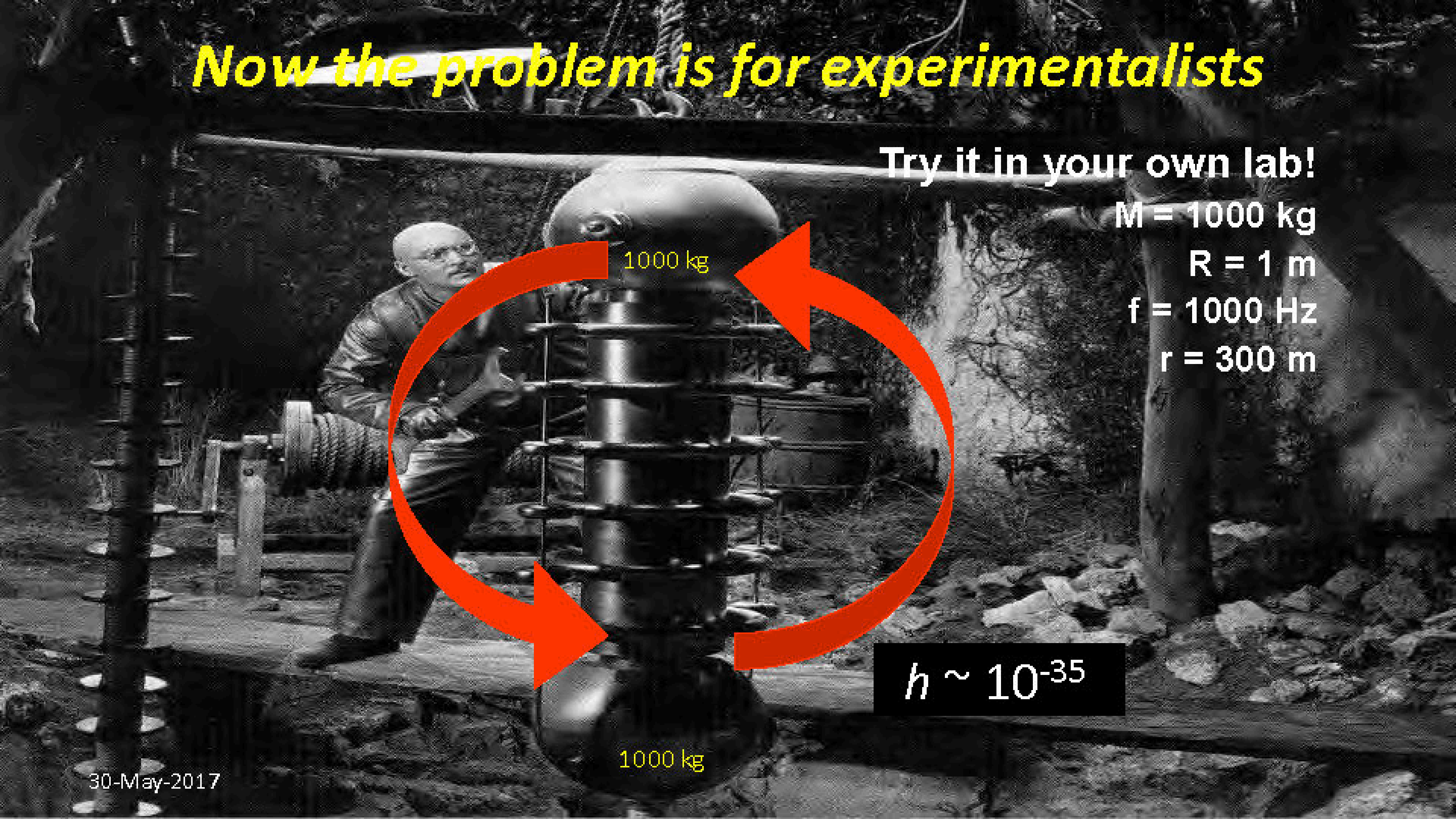
- Using Minkowski metric, the information about space-time curvature is contained in the metric as an added term, $h_{\mu\nu}$. In the weak field limit, the equation can be described with linear equations. If the choice of gauge is the *transverse traceless gauge* the formulation becomes a familiar wave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

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

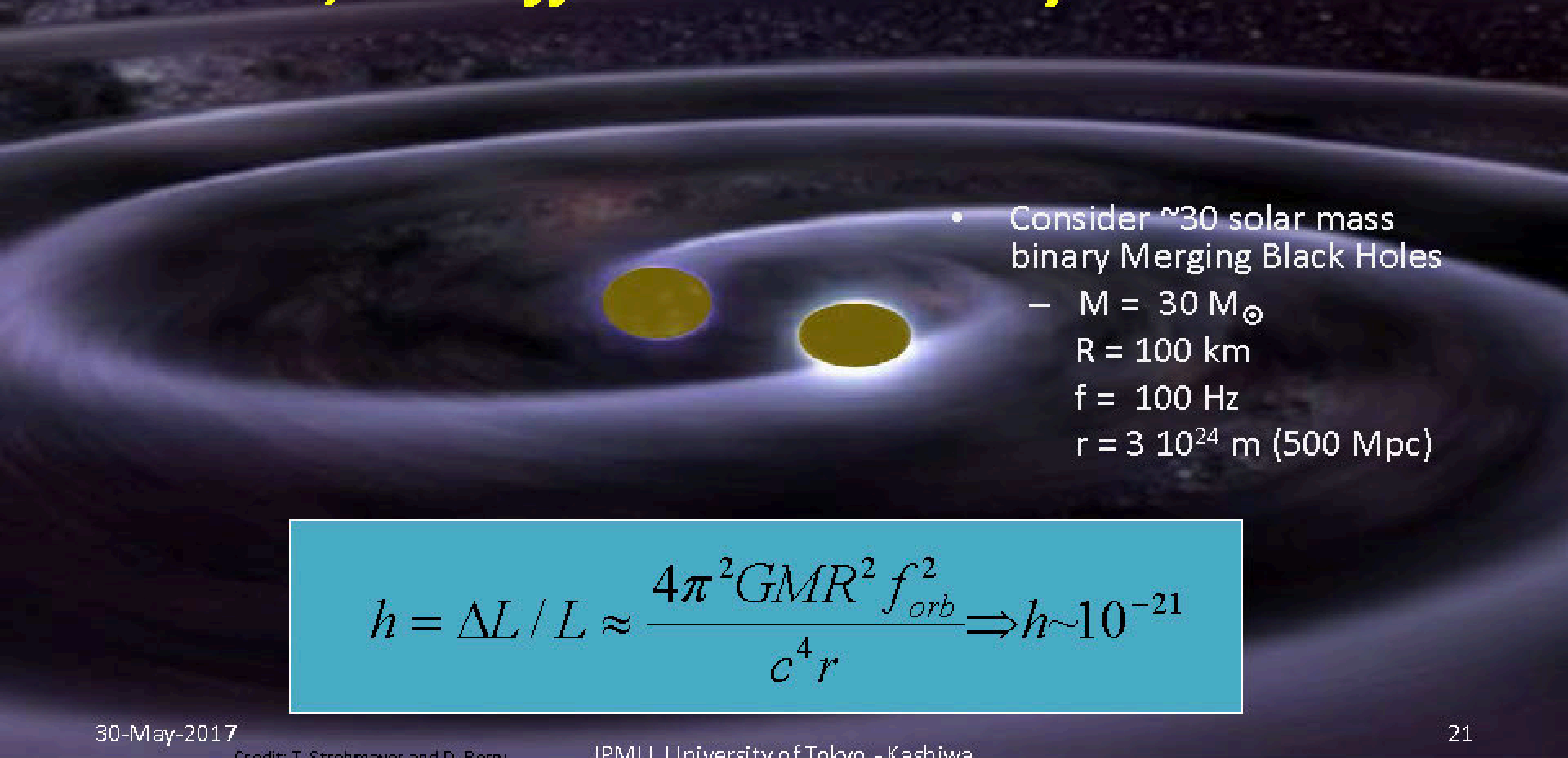


- The strain $h_{\mu\nu}$ takes the form of a plane wave propagating at the speed of light (c).
  - Since gravity is spin 2, the waves have two components, but rotated by 45^0 instead of 90^0 from each other.

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


Now the problem is for experimentalists
Try it in your own lab!
M = 1000 kg
R = 1 m
f = 1000 Hz
r = 300 m
1000 kg
1000 kg
$h \sim 10^{-35}$
30-May-2017

BUT, the effect is incredibly small



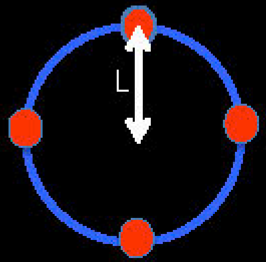
- Consider ~30 solar mass binary Merging Black Holes
  - $M = 30\ M_\odot$
    $R = 100$ km
    $f = 100$ Hz
    $r = 3\ 10^{24}$ m (500 Mpc)

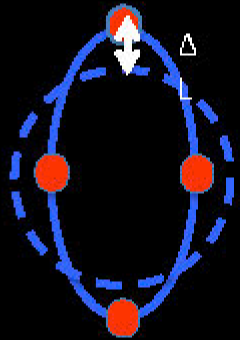
$$h = \Delta L / L \approx \frac{4\pi^2 GMR^2 f_{orb}^2}{c^4 r} \Rightarrow h \sim 10^{-21}$$

Credit: T. Strohmayer and D. Berry

Gravitational Waves

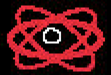
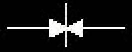
- Ripples of spacetime that stretch and compress spacetime itself
- The amplitude of the wave is h ≈ 10^{-21}
- Change the distance between masses that are free to move by $\Delta L = h \times L$
- Spacetime is "stiff" so changes in distance are very small



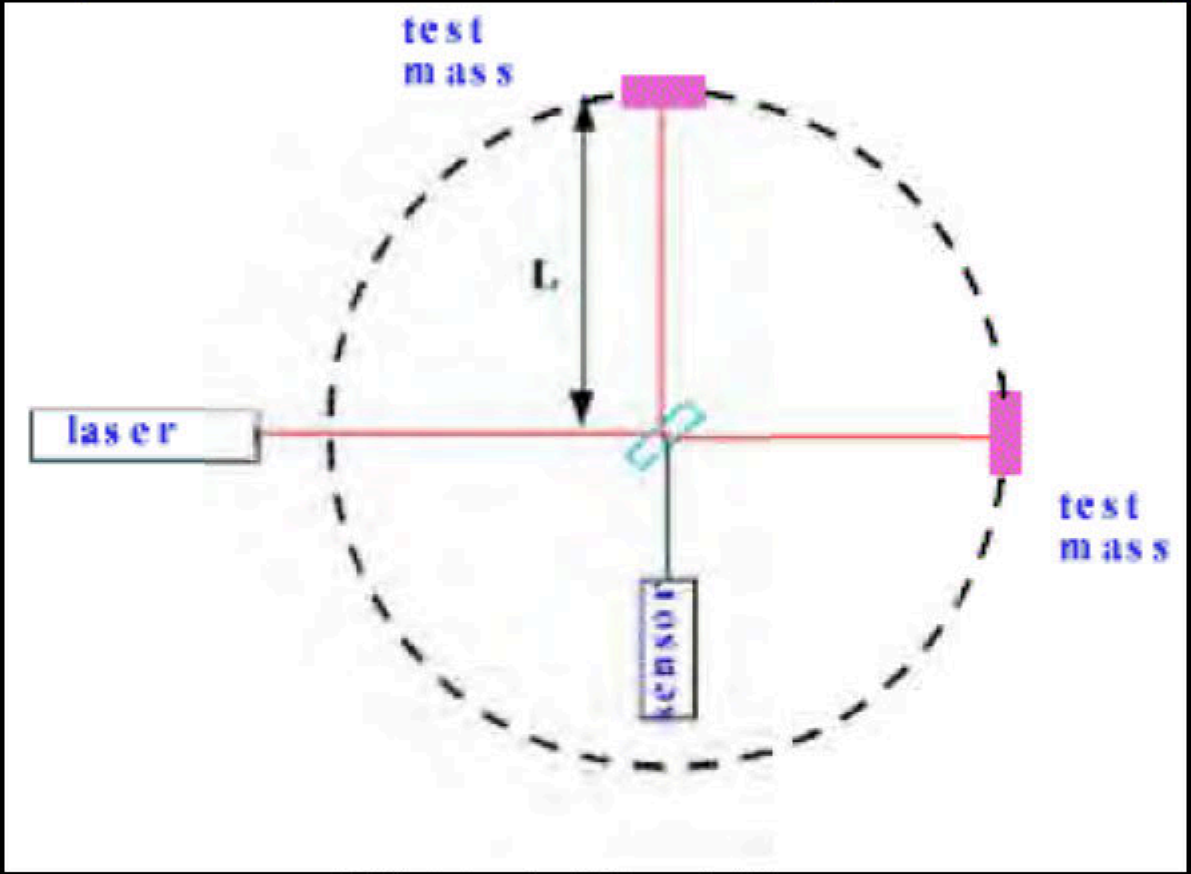


$$\Delta L = h \times L = 10^{-21} \times 1\,\mathrm{m} = 10^{-21}\,\mathrm{m}$$

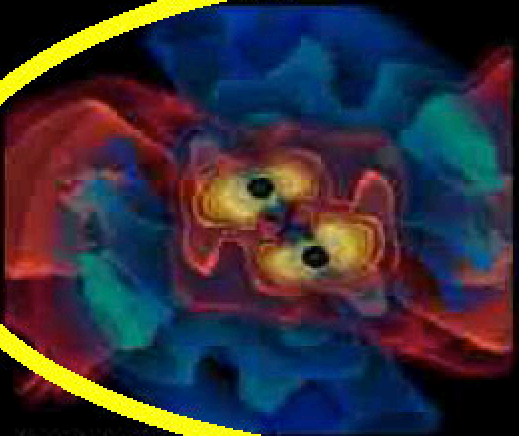
How Small is 10^{-18} Meter?

		One meter
÷10,000		Human hair, about 100 microns
÷100		Wavelength of light, about 1 micron
÷10,000		Atomic diameter, 10^{-10} meter
÷100,000		Proton diameter, 10^{-15} meter
÷1,000		LIGO sensitivity, 10^{-18} meter

Suspended Mass Interferometry



Astrophysical targets for ground-based detectors



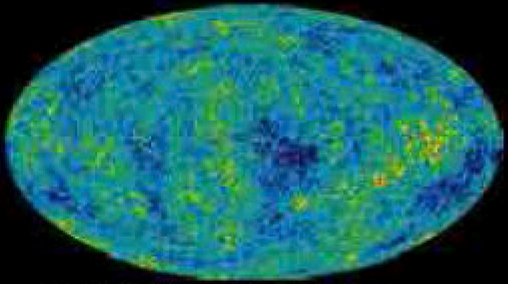
Credit: AEI, CCT,

Coalescing Binary Systems

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

'Bursts'

- galactic asymmetric core collapse supernovae
- cosmic strings
- ???



NASA/WMAP Science Team

Stochastic GWs

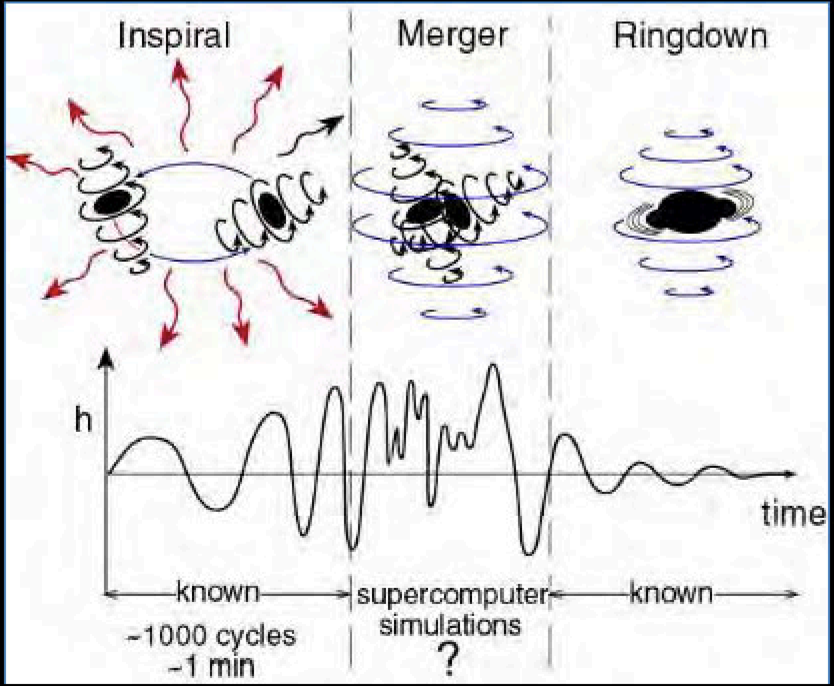
- Incoherent background from primordial GWs or an ensemble of unphased sources
- primordial GWs unlikely to detect, but can bound in the 10-10000 Hz range

Casey Reed, Penn State

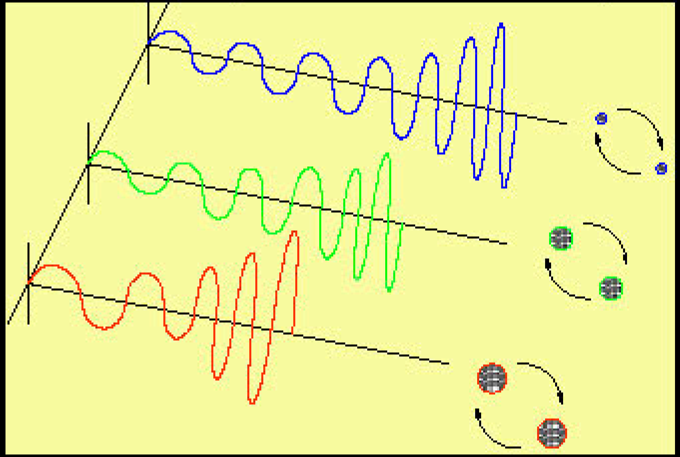
Continuous Sources

- Spinning neutron stars
- probe crustal deformations, 'EOS, quarkiness'

Compact Binary Collisions

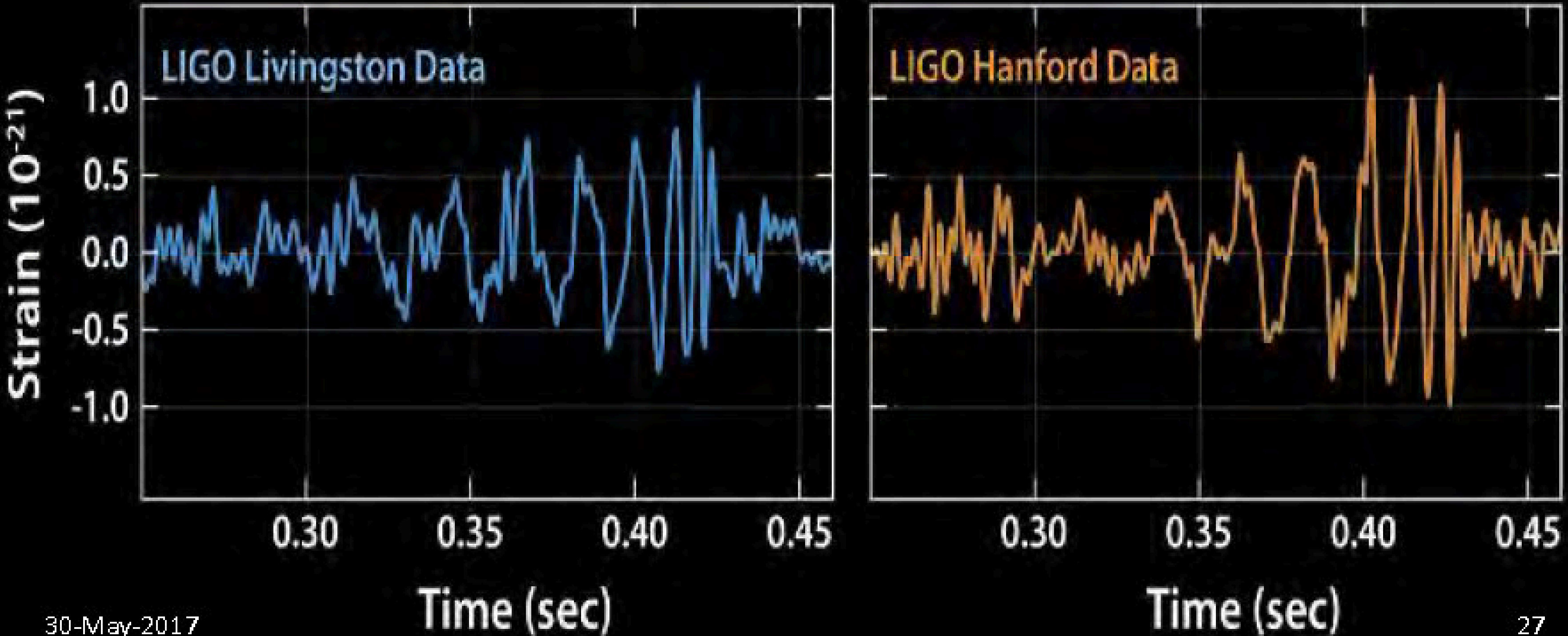


– Neutron Star – Neutron Star
  - **waveforms are well described**
– Black Hole – Black Hole
  - **Numerical Relativity waveforms**
– Search: *matched templates*

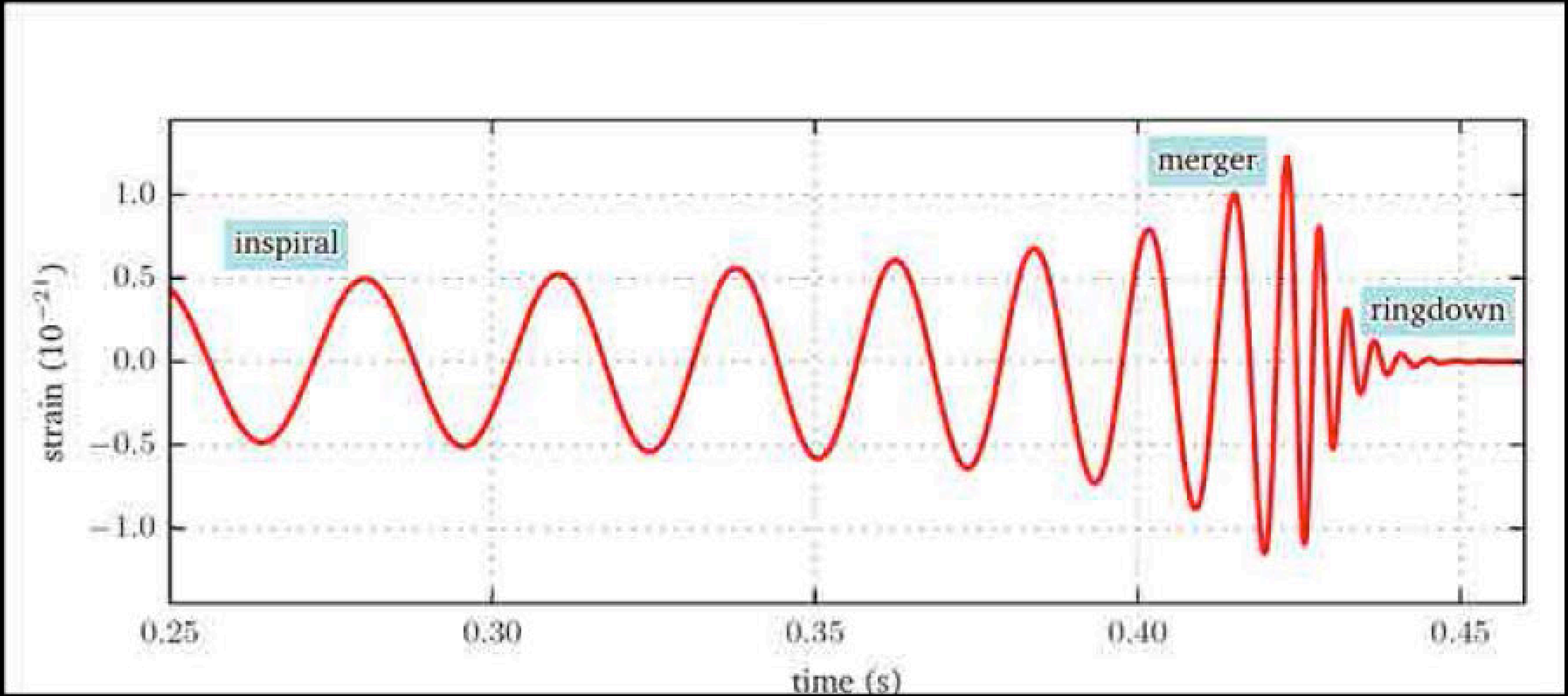


"chirps"

Observed Signals – Sept 14, 2015



Emission of Gravitational Waves



Einstein's Theory of Gravitation

Gravitational Waves

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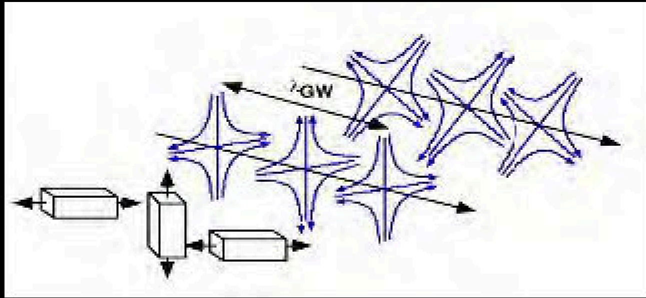


  - Since gravity is spin 2, the waves have two components, but rotated by 45^0 instead of 90^0 from each other.

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

LIGO Sites


LIGO
Hanford
3002 km
(L/c = 10 ms)
MIT
Caltech
Livingston
Observatory

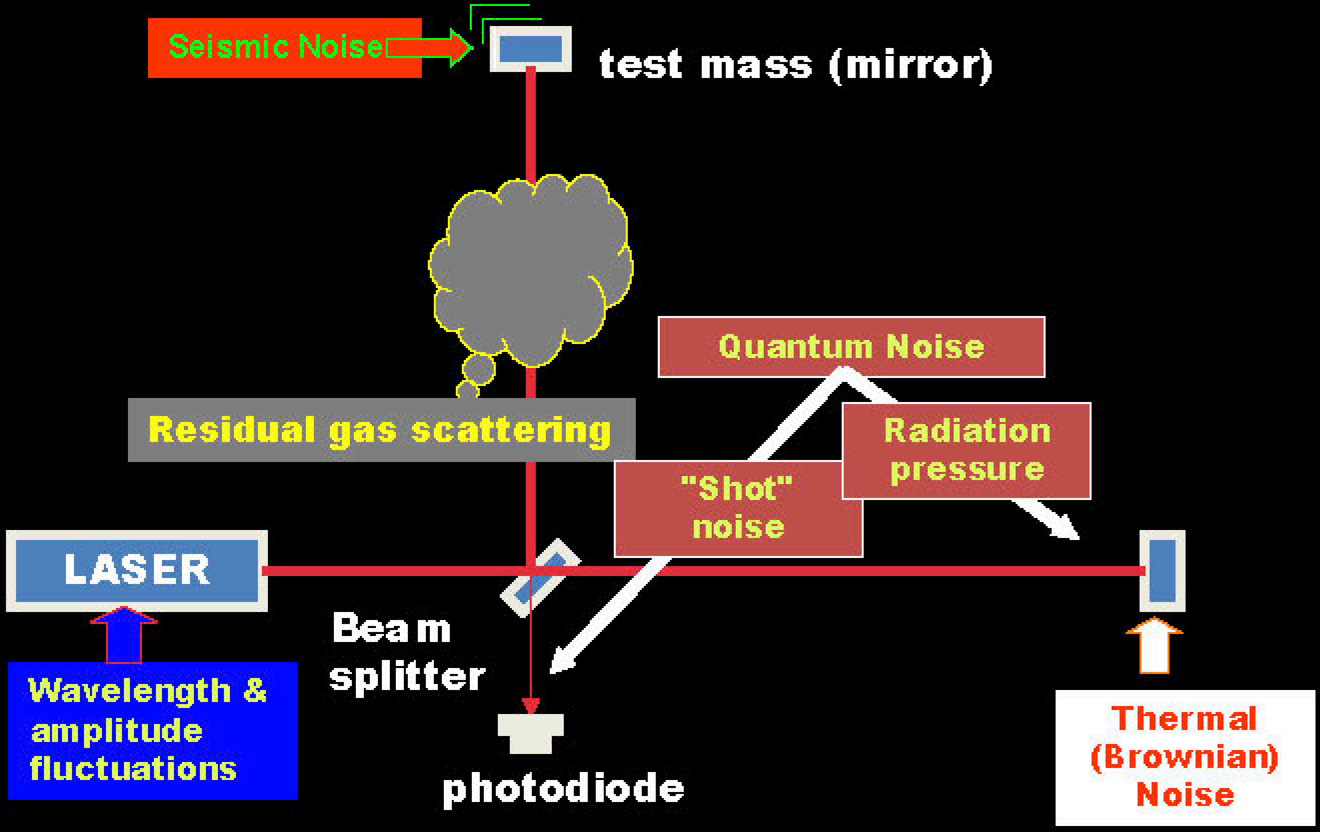
LIGO Interferometers

Hanford, WA

Livingston, LA

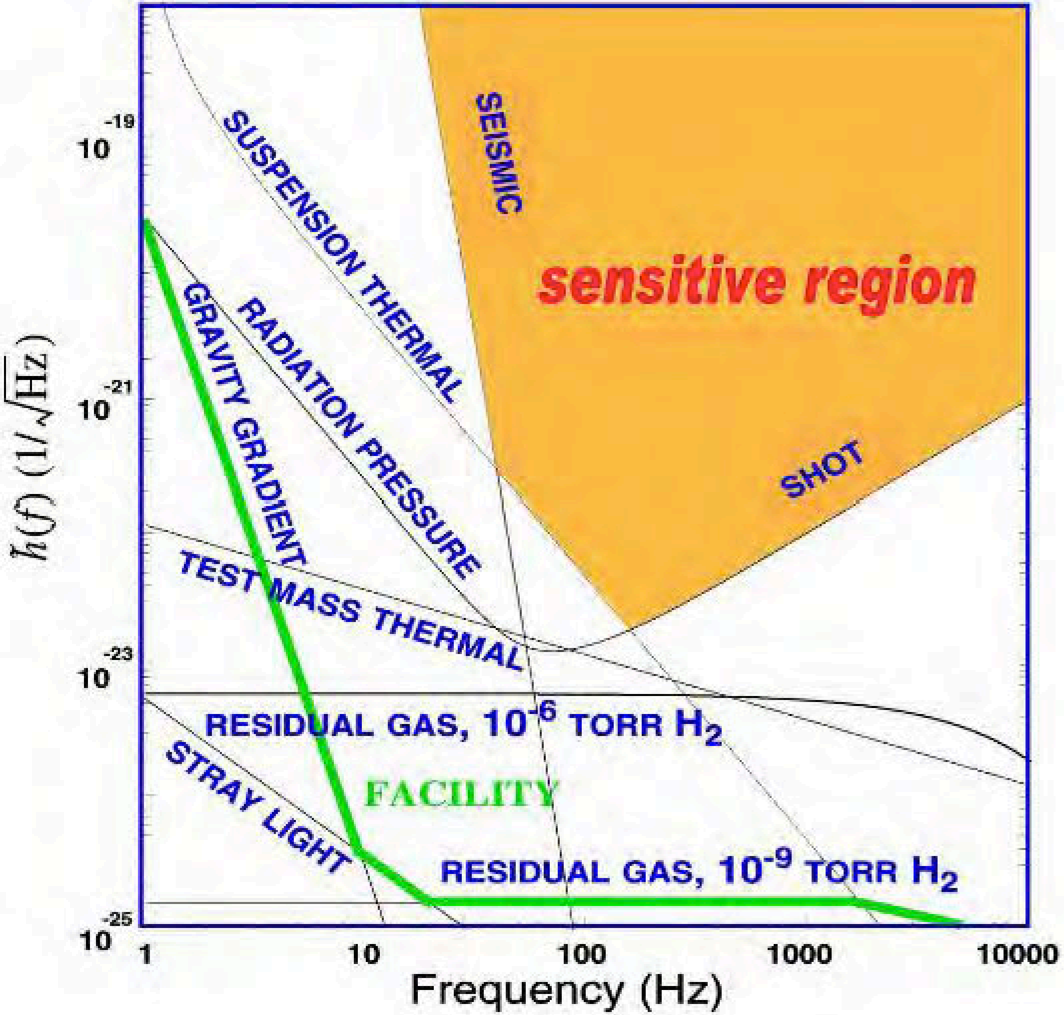

LIGO Interferometer Infrastructure

Interferometer Noise Limits

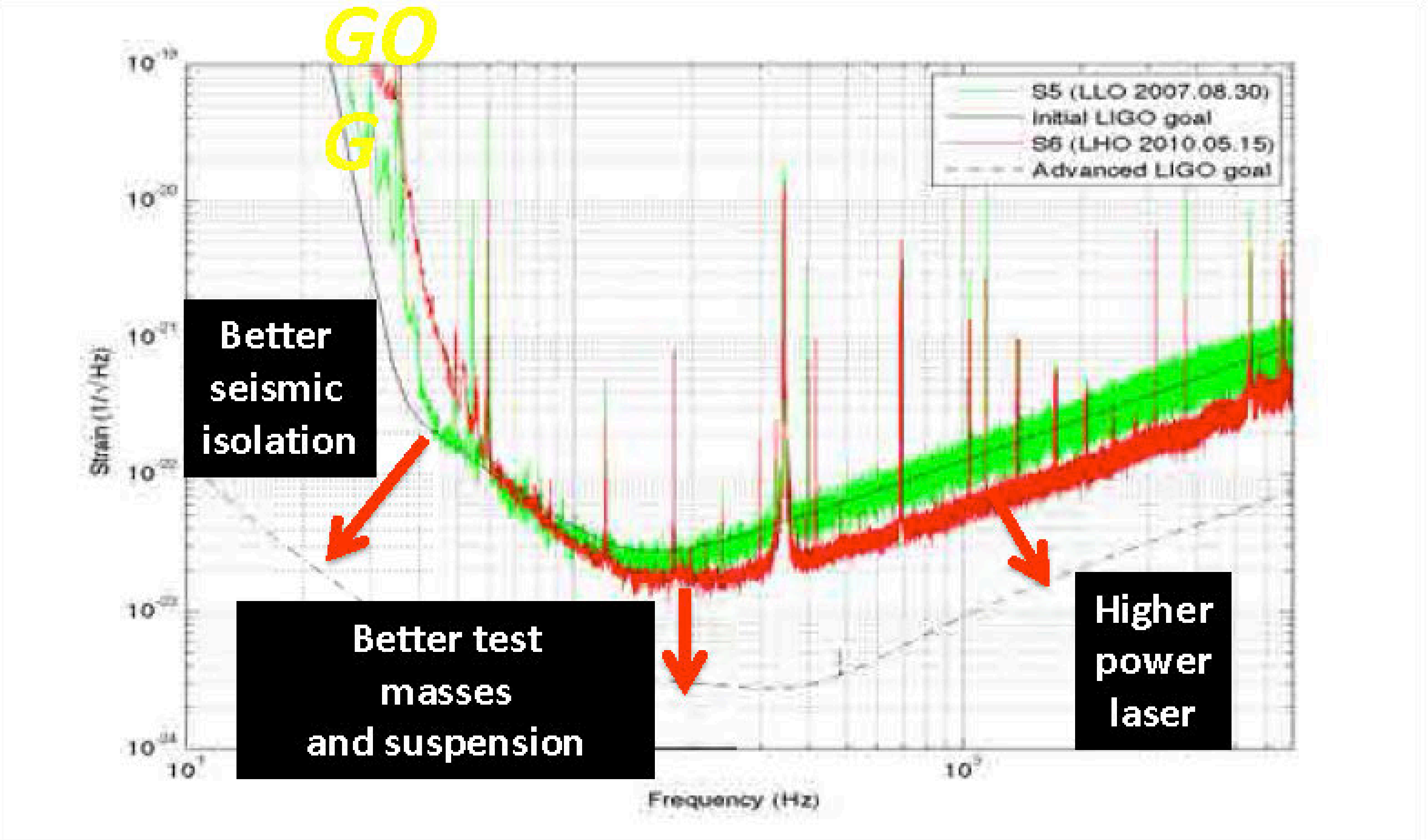


What Limits LIGO Sensitivity?

- 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



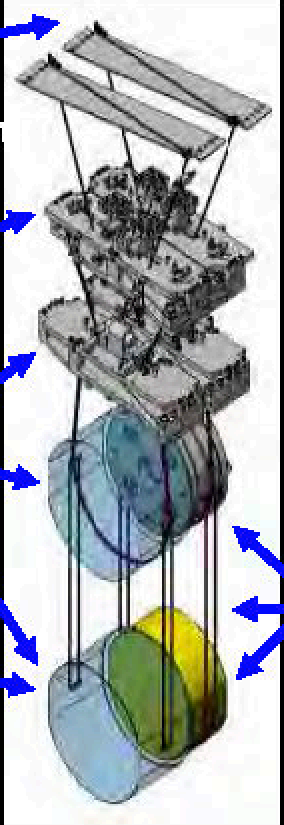
Test Mass
Quadruple Pendulum Suspension

Optics Table Interface (Seismic Isolation System)

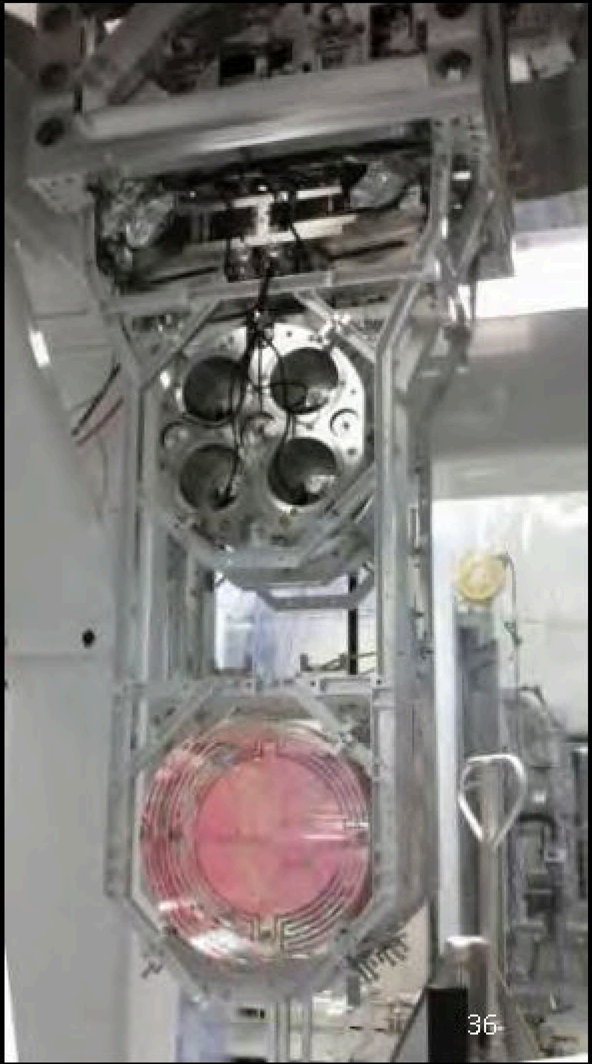
Damping Controls

Hierarchical Global Controls

Electrostatic Actuation

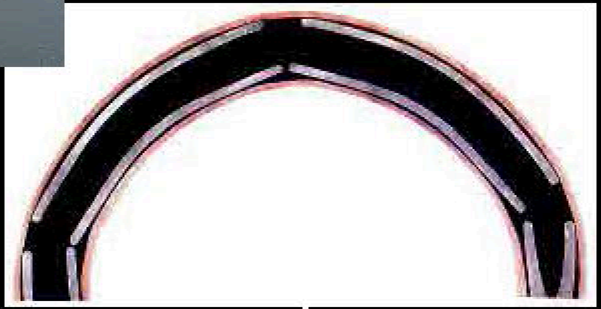


Final elements
All Fused silica



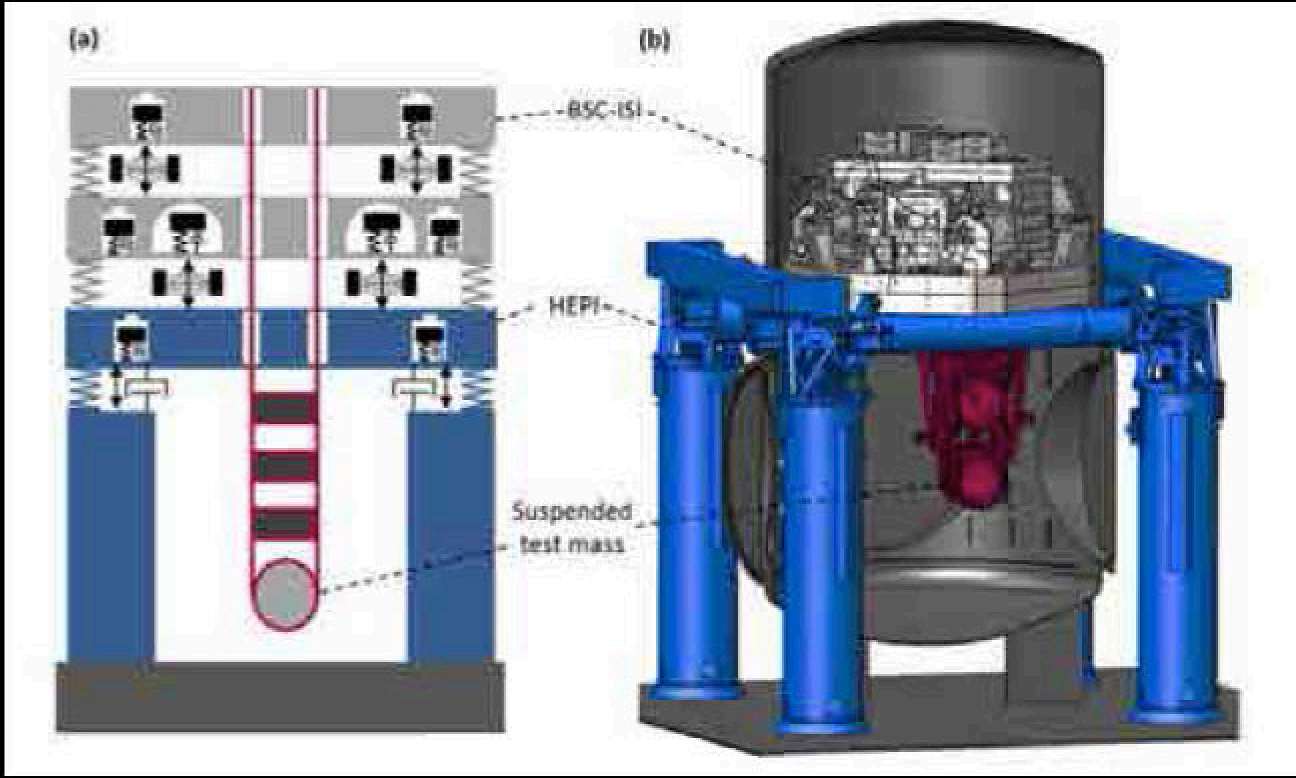
Passive Seismic Isolation

Initial ILIGO

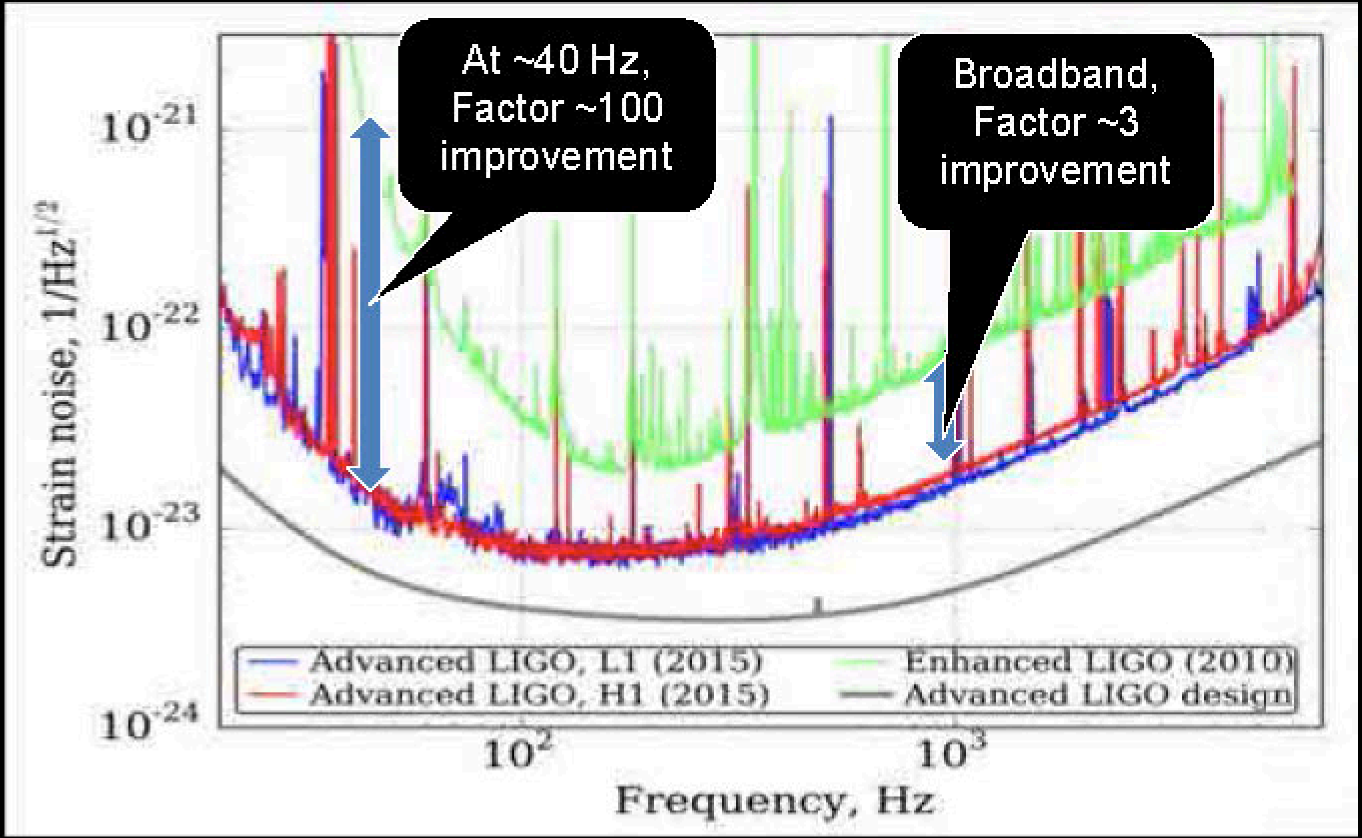


damped spring

Seismic Isolation
Passive / Active Multi-Stage



Sensitivity for first Observing run



Initial LIGO

O1 aLIGO

Design aLIGO

Phys. Rev. D 93, 112004 (2016

Gravitational Wave Event

GW150914

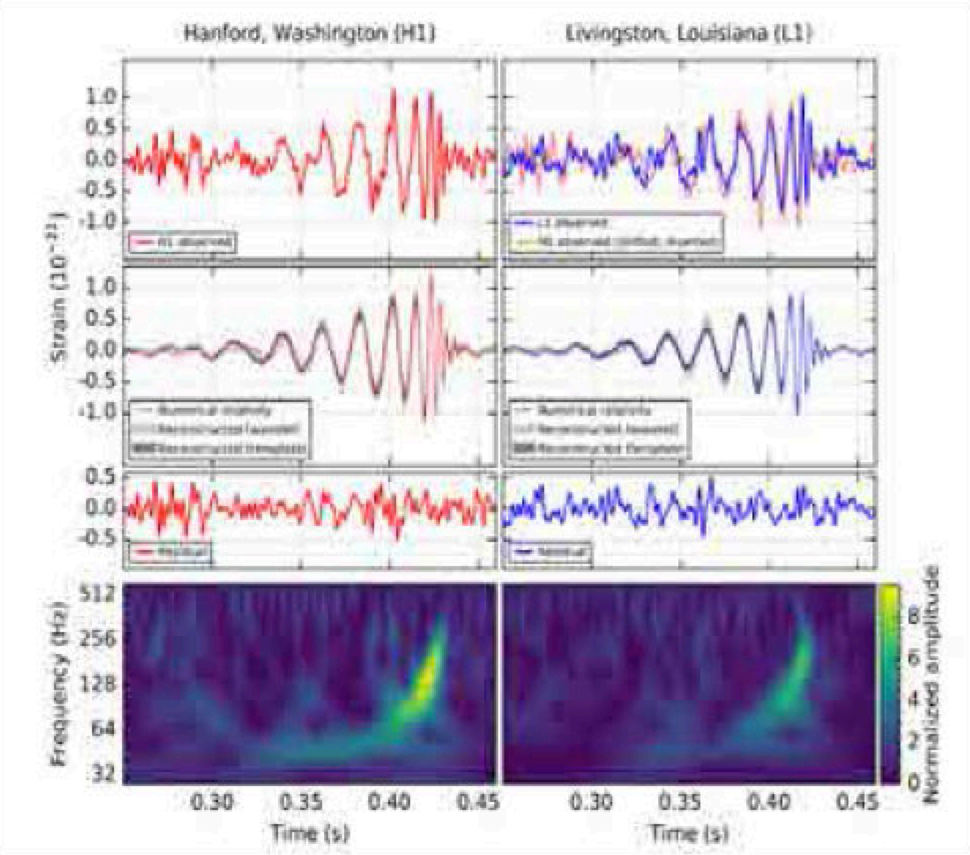
Data bandpass filtered between 35 Hz and 350 Hz

Time difference 6.9 ms with Livingston first

Second row – calculated GW strain using Numerical Relativity Waveforms for quoted parameters compared to reconstructed waveforms (Shaded)

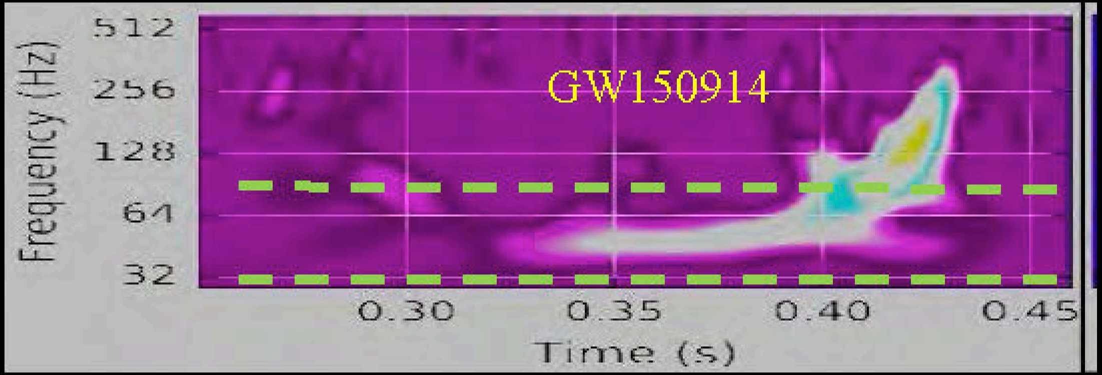
Third Row –residuals

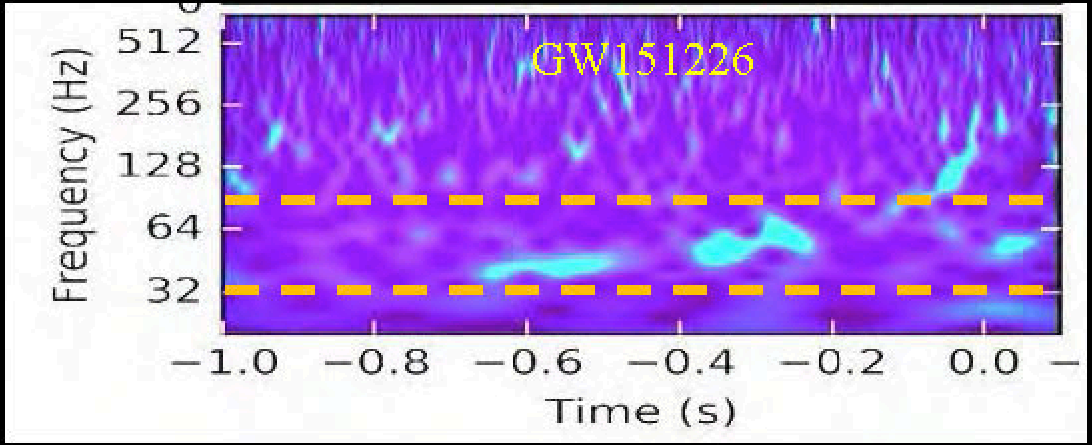
bottom row – time frequency plot showing frequency increases with time (chirp)



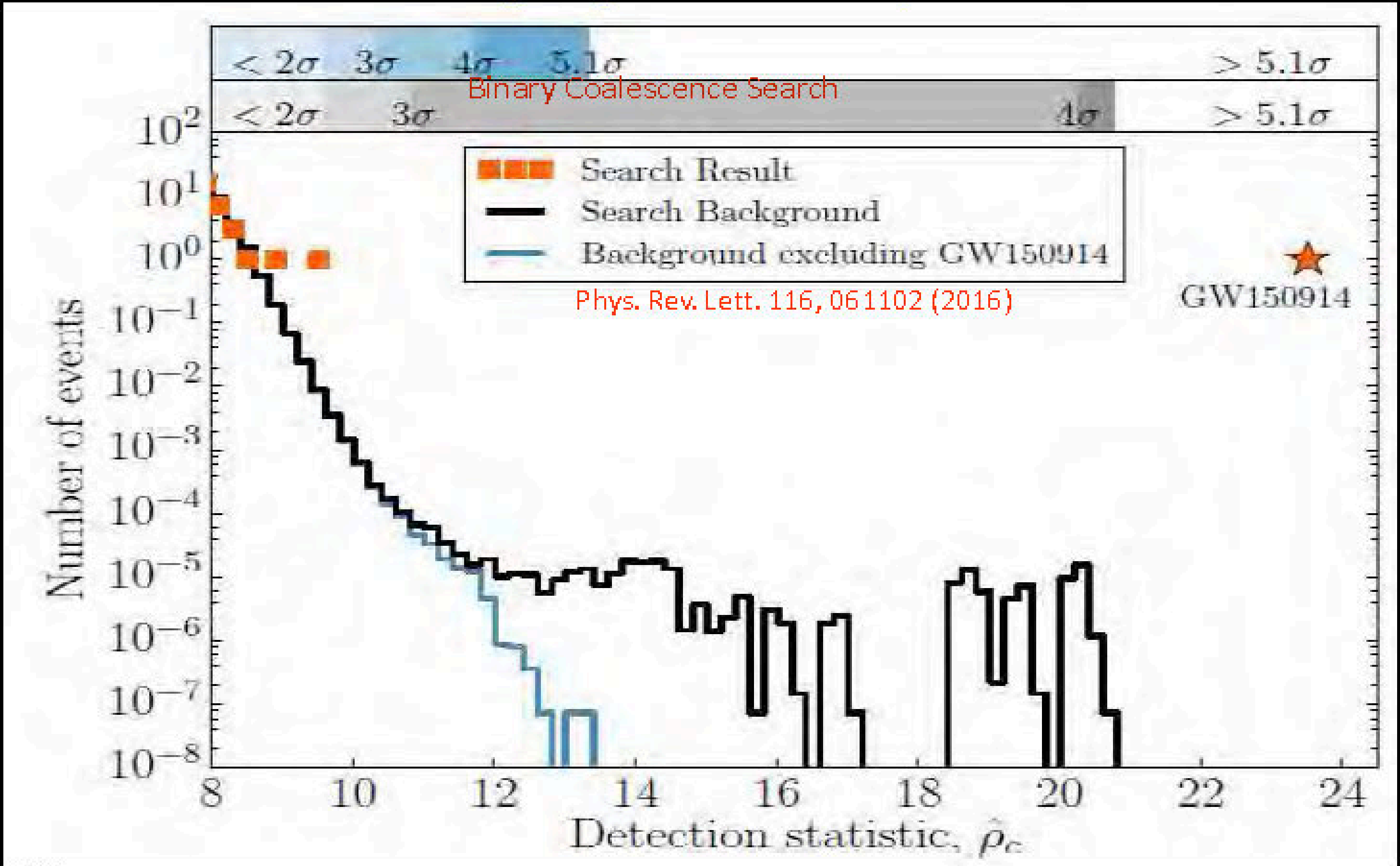
Phys. Rev. Lett. 116, 061102 (2016)

Black Hole Merger Events and Low Frequency Sensitivity





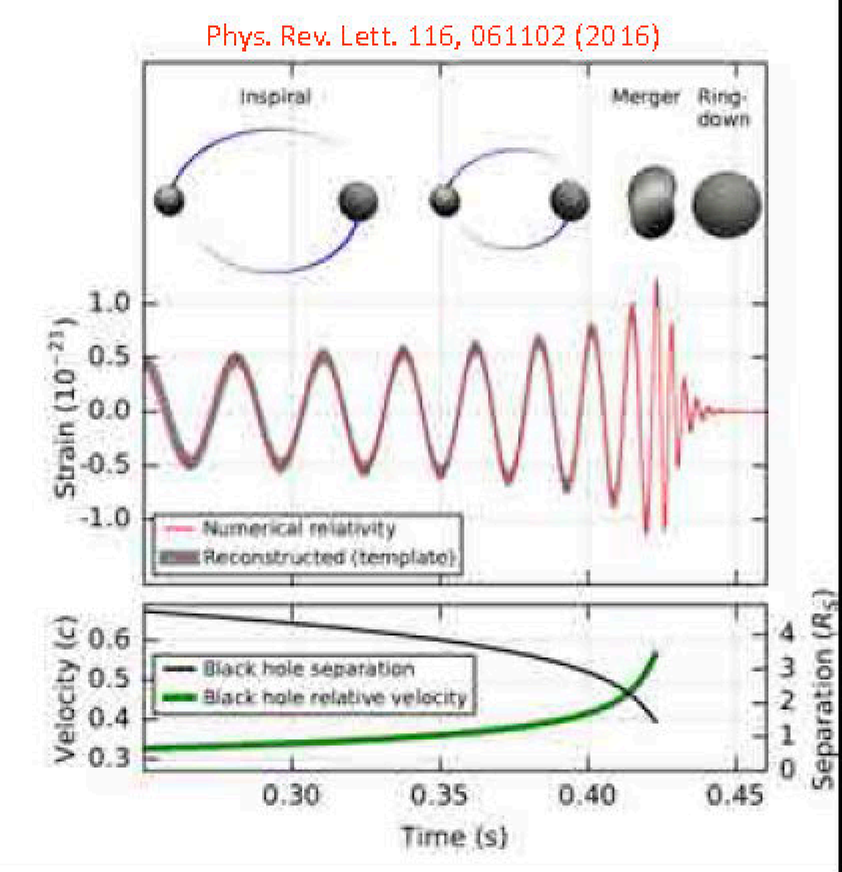
Statistical Significance of GW150914



Black Hole Merger: GW150914

Full bandwidth waveforms without filtering. Numerical relativity models of black hole horizons during coalescence

Effective black hole separation in units of Schwarzschild radius ($R_s = 2GM_f / c^2$); and effective relative velocities given by post-Newtonian parameter $v/c = (GM_f \pi f/c^3)^{1/3}$



Measuring the parameters

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

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

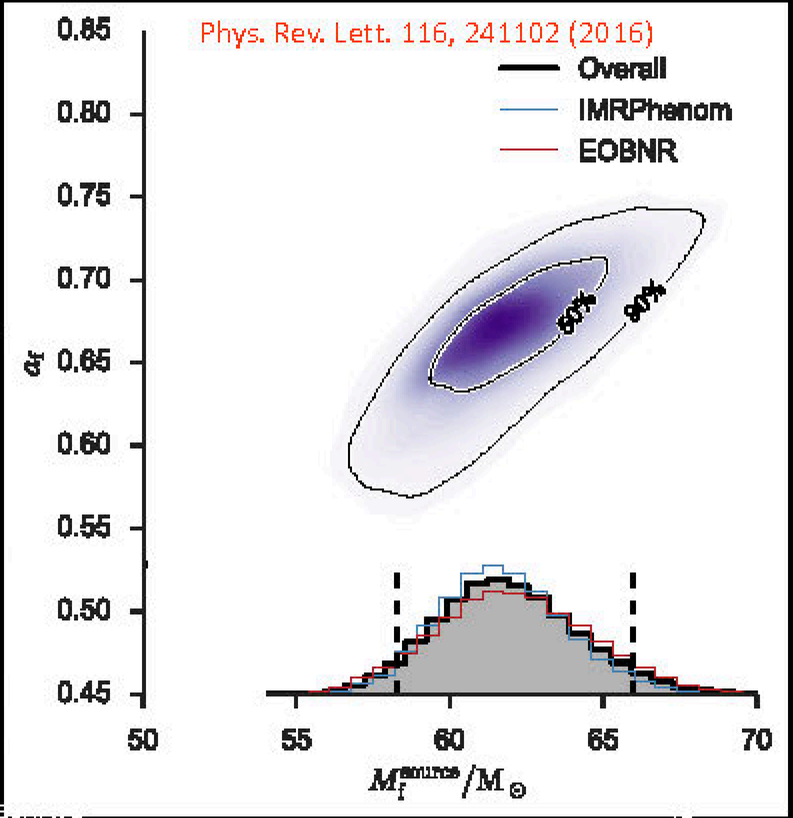
  - Next orders allow for measurement of mass ratio and spins
  - We directly measure the red-shifted masses (1+z) m
  - Amplitude inversely proportional to luminosity distance
- Orbital precession occurs when spins are misaligned with orbital angular momentum – no evidence for precession.
- Sky location, 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 $M_0 c^2$. 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)



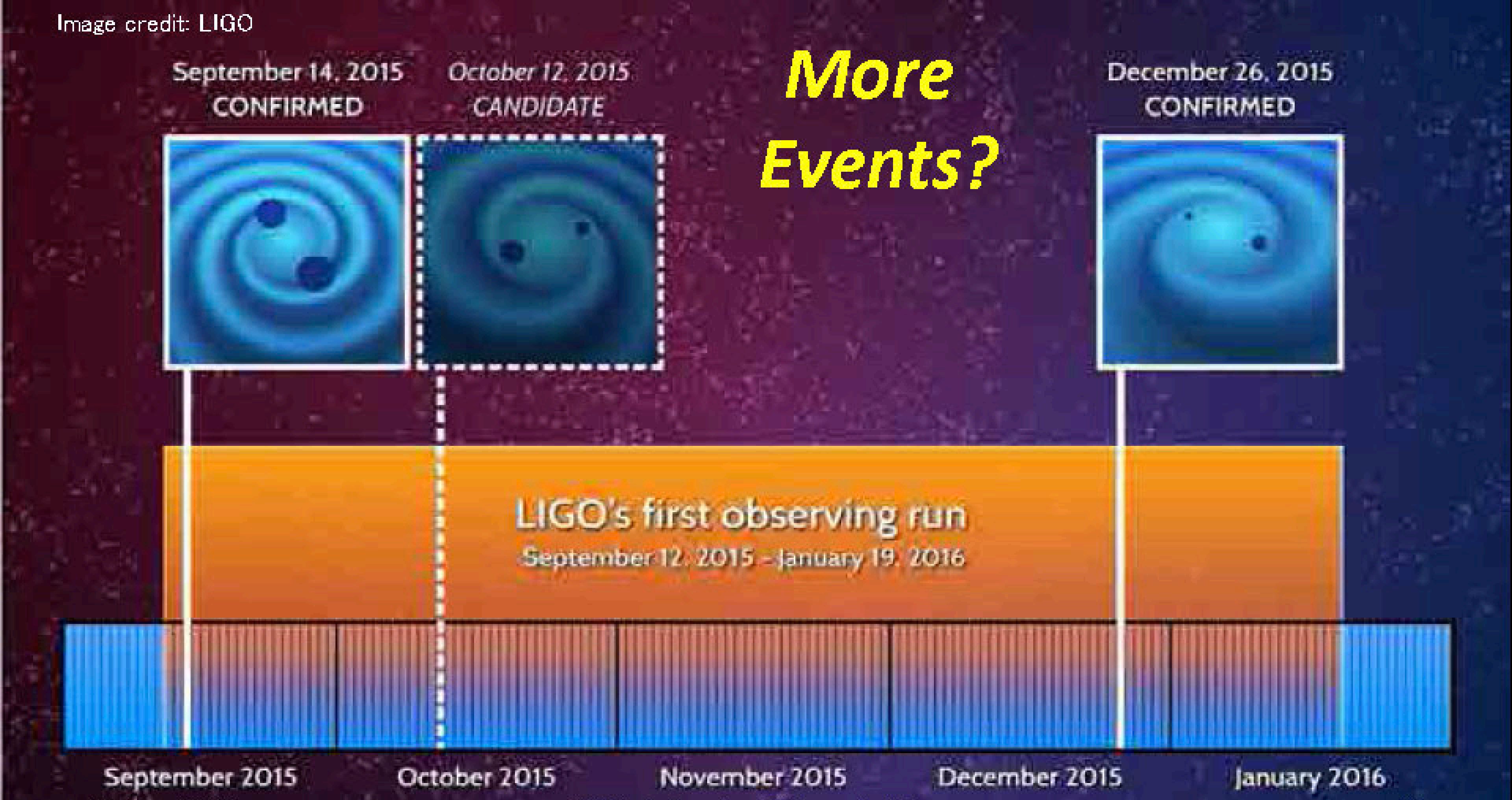
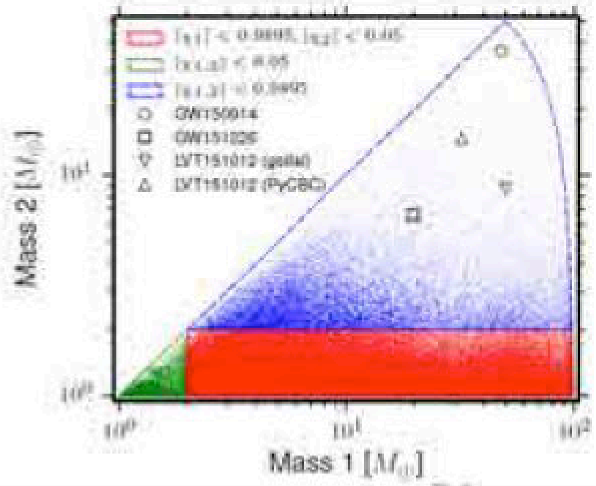


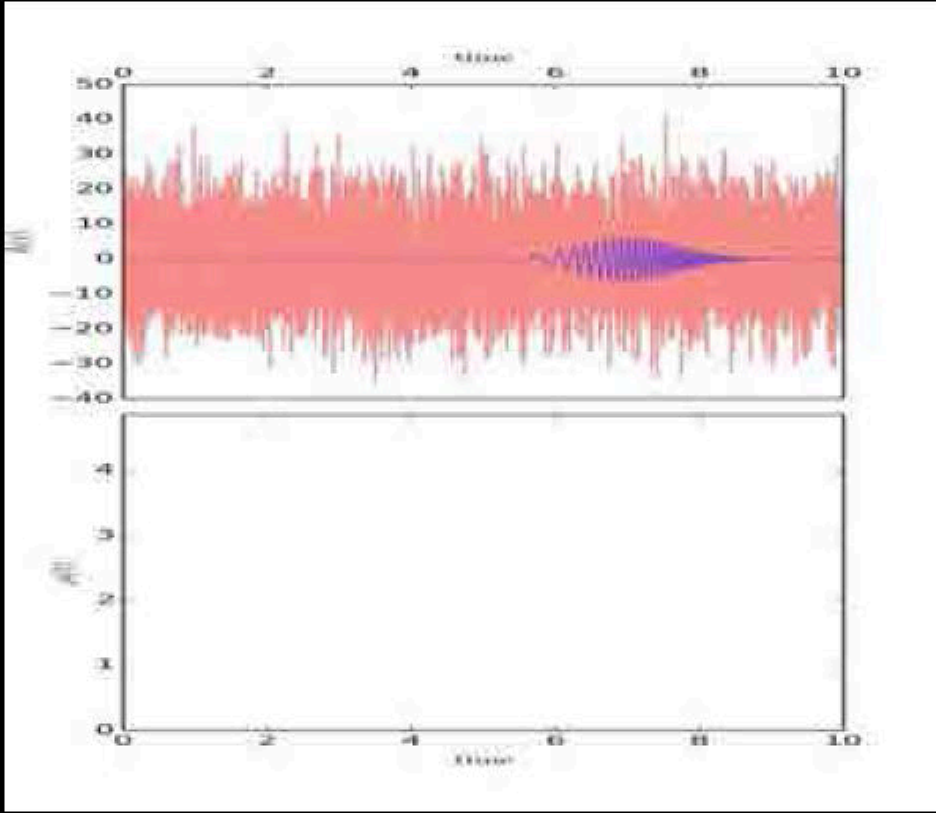
Image credit: LIGO
September 14, 2015
CONFIRMED
October 12, 2015
CANDIDATE
More
Events?
December 26, 2015
CONFIRMED
LIGO's first observing run
September 12, 2015 - January 19, 2016
September 2015
October 2015
November 2015
December 2015
January 2016

Finding a weak signal in noise

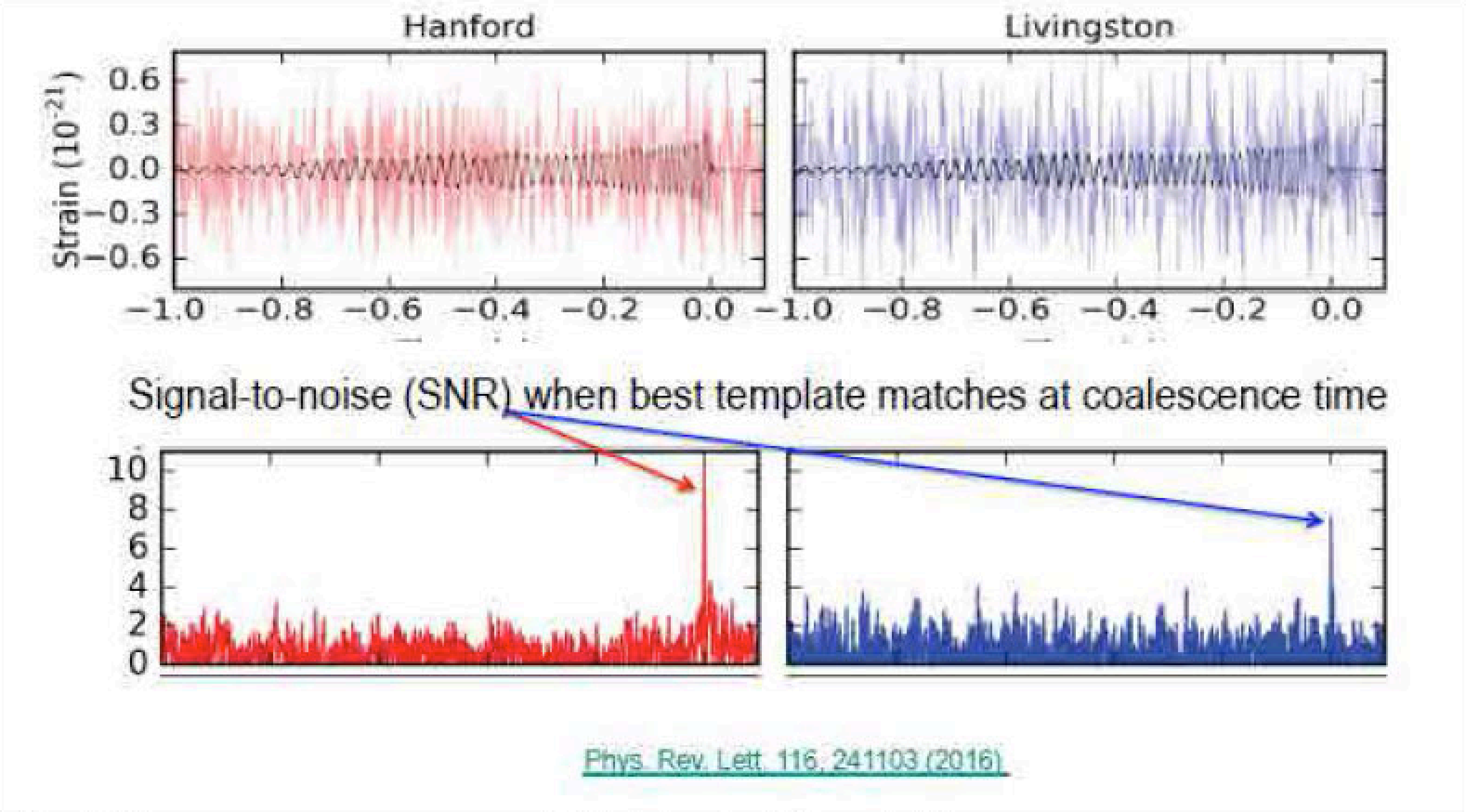
- "Matched filtering" lets us find a weak signal submerged in noise.
- For calculated signal waveforms, multiply the waveform by the data
- Find signal from cumulative signal/noise

PHYS. REV. X 6,041015 (2016)

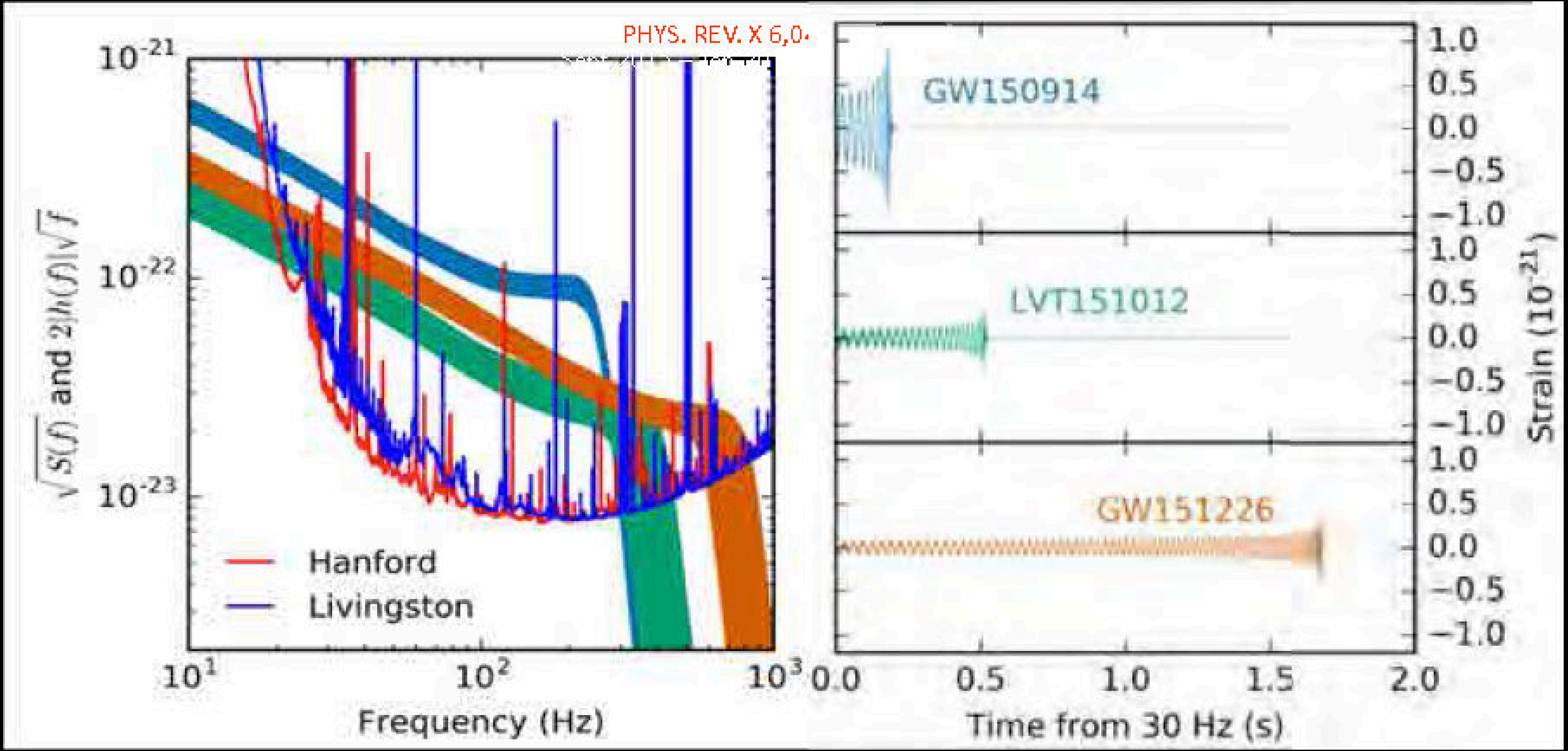




GW151226 – Matched Filter



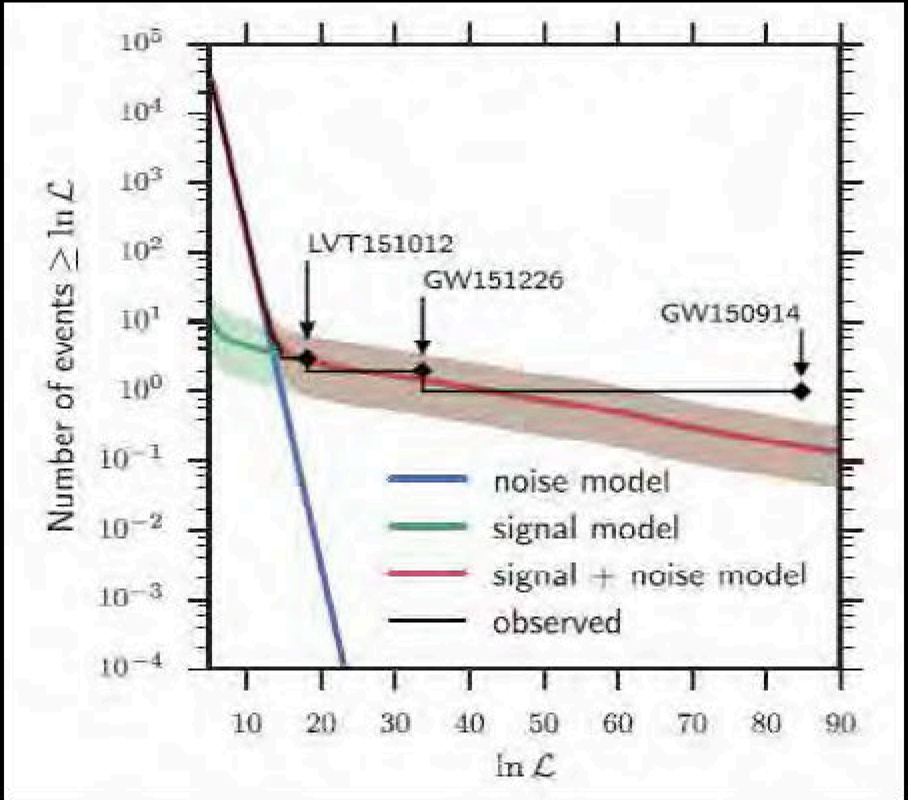
Second Event, Plus another Candidate



Sensitivity

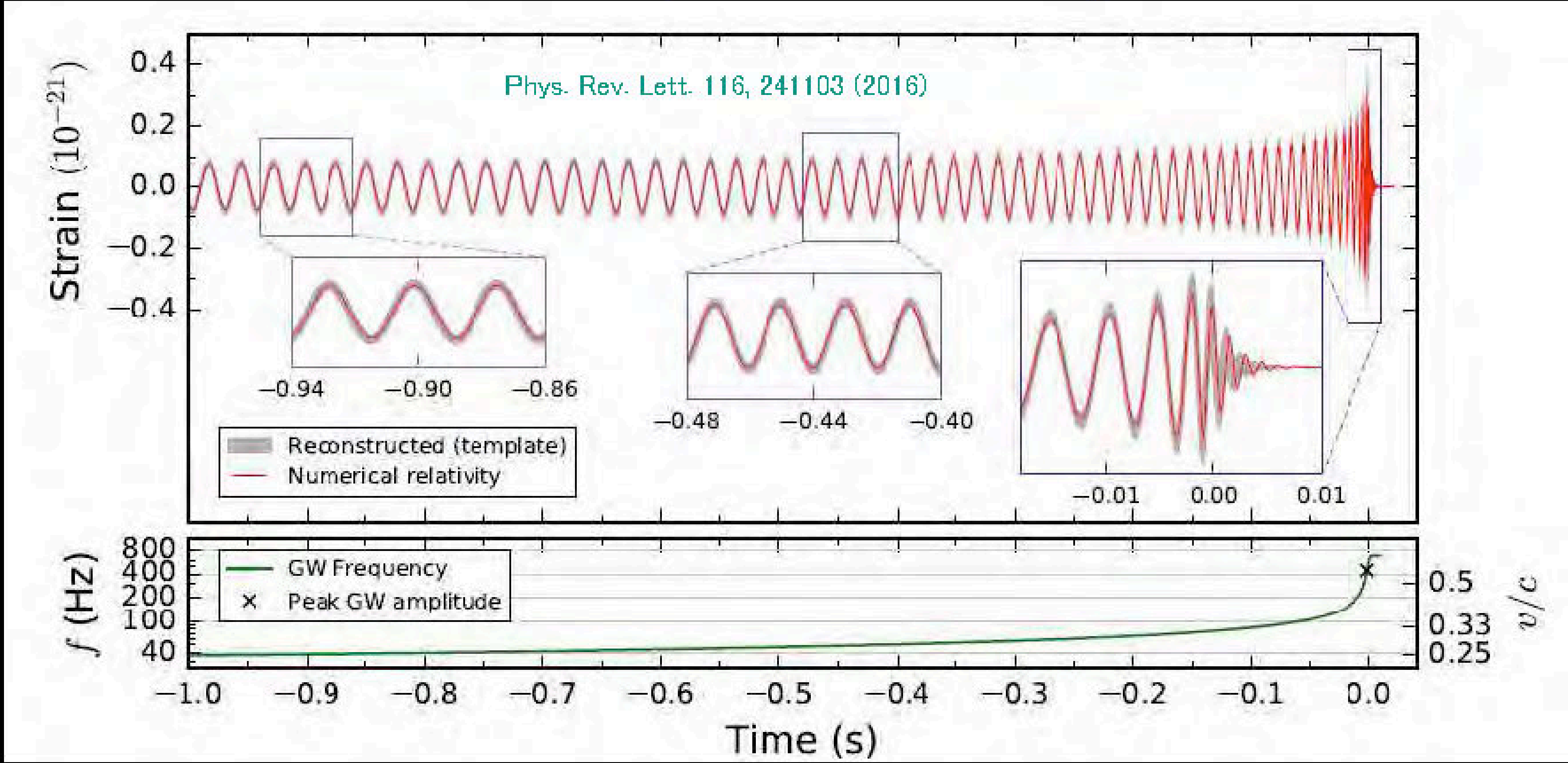
Lessons from LIGO O1

- 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

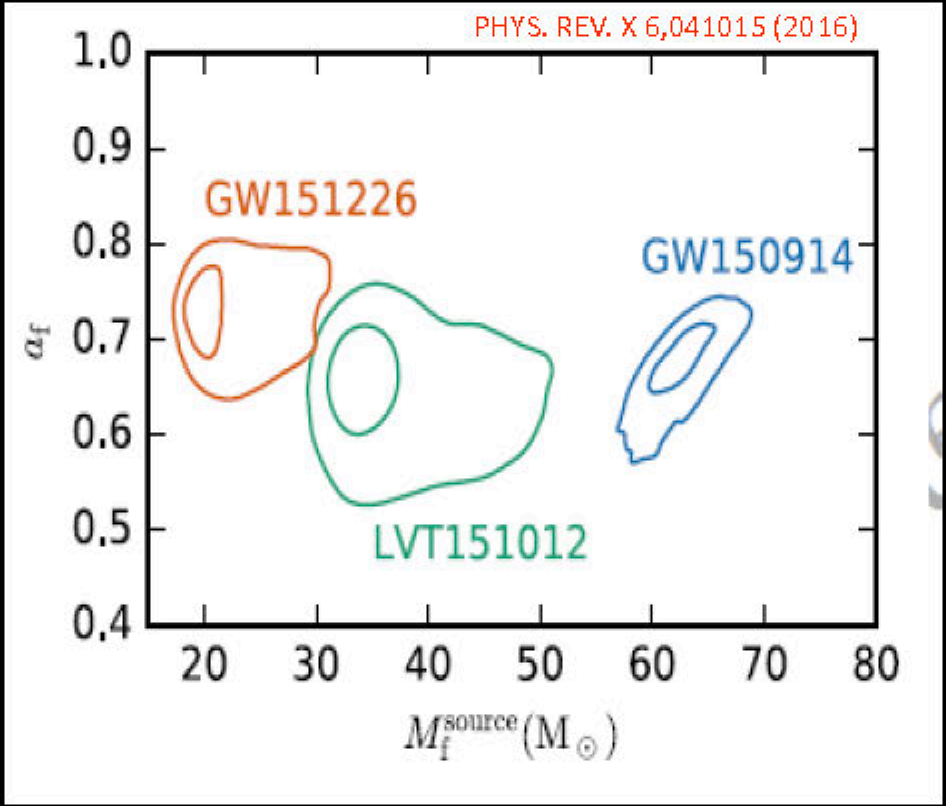


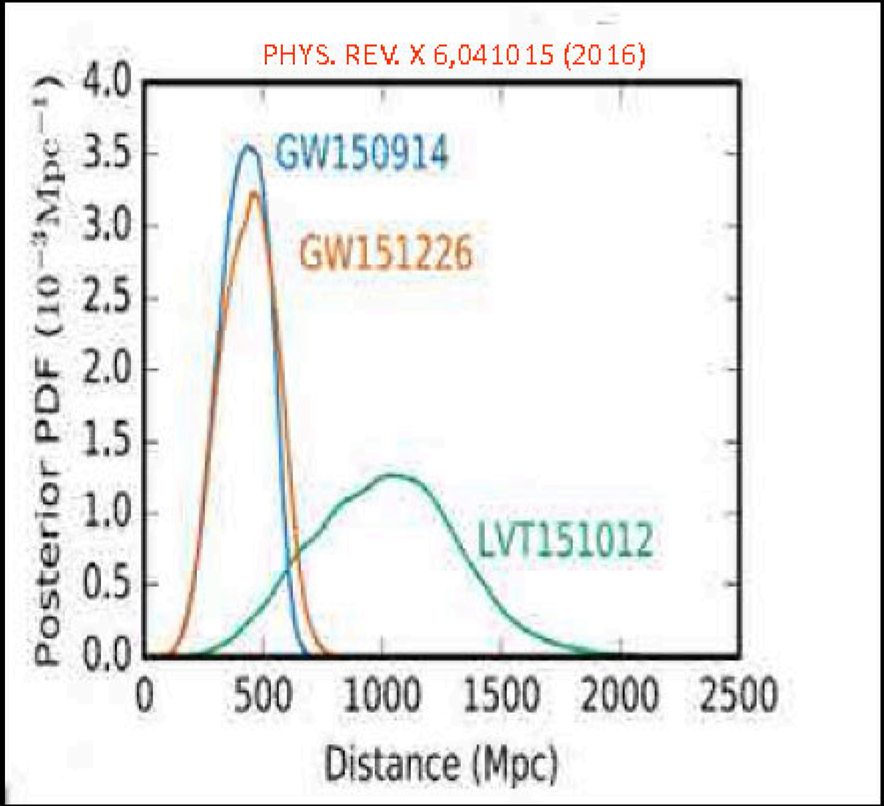
O1 BBH Search

"Second Event" Inspiral and Merger GW151226



Final Black Hole Masses, Spins and Distance





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.

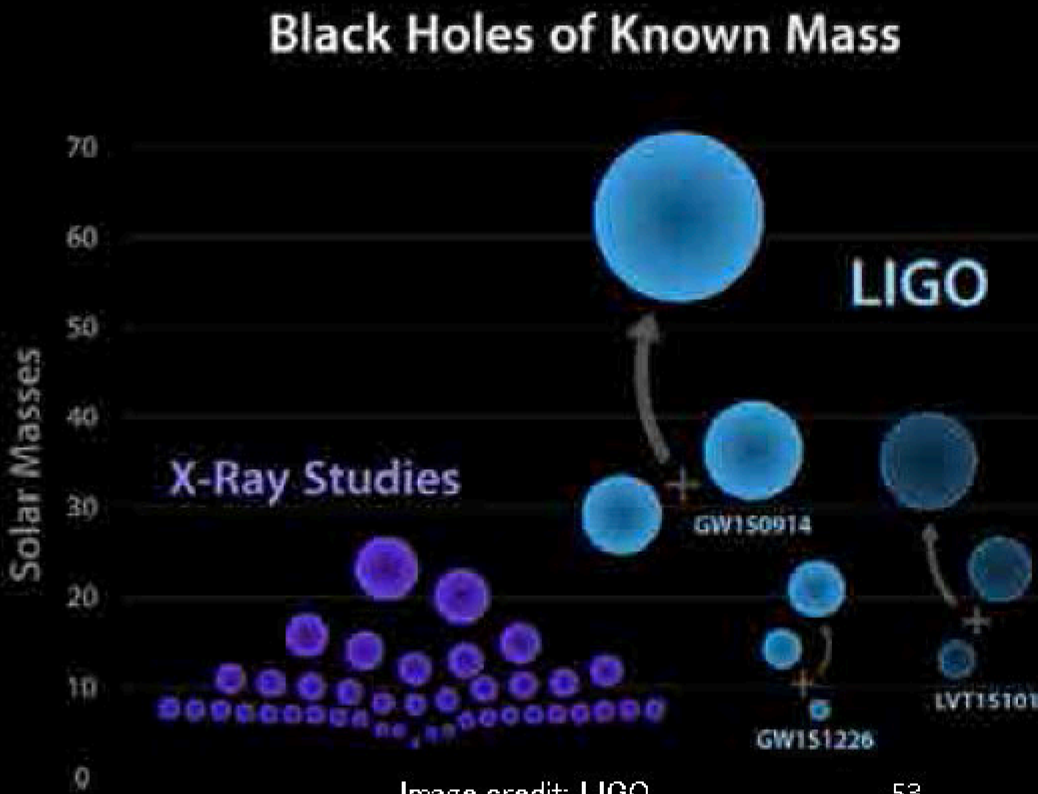
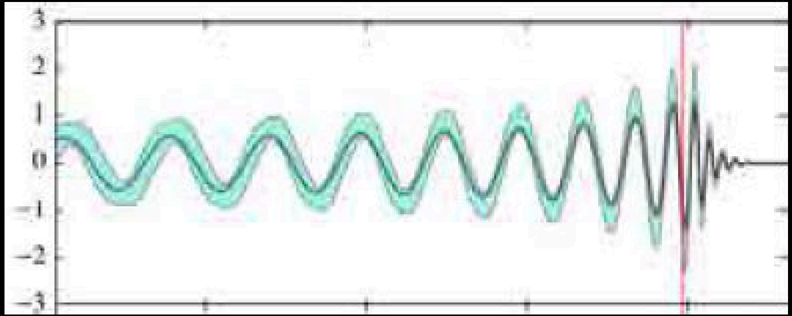
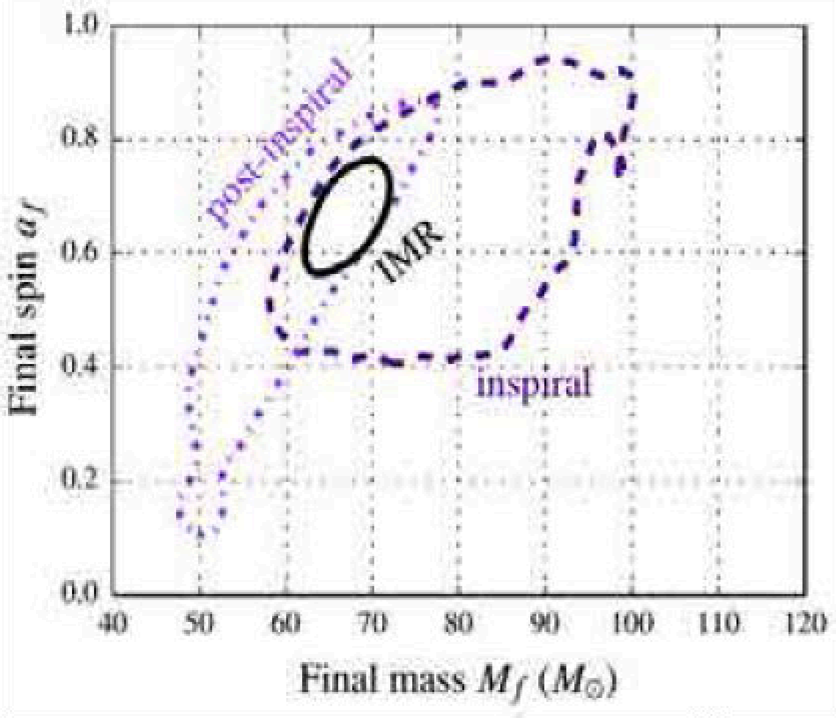


Image credit: LIGO

Testing General Relativity

- We examined the detailed waveform of GW150914 in several ways to see whether there is any deviation from the GR predictions
  - Known through post-Newtonian (analytical expansion)and numerical relativity
- Inspiral / merger / ringdown consistency test
  - Compare estimates of mass and spin from before vs. after merger

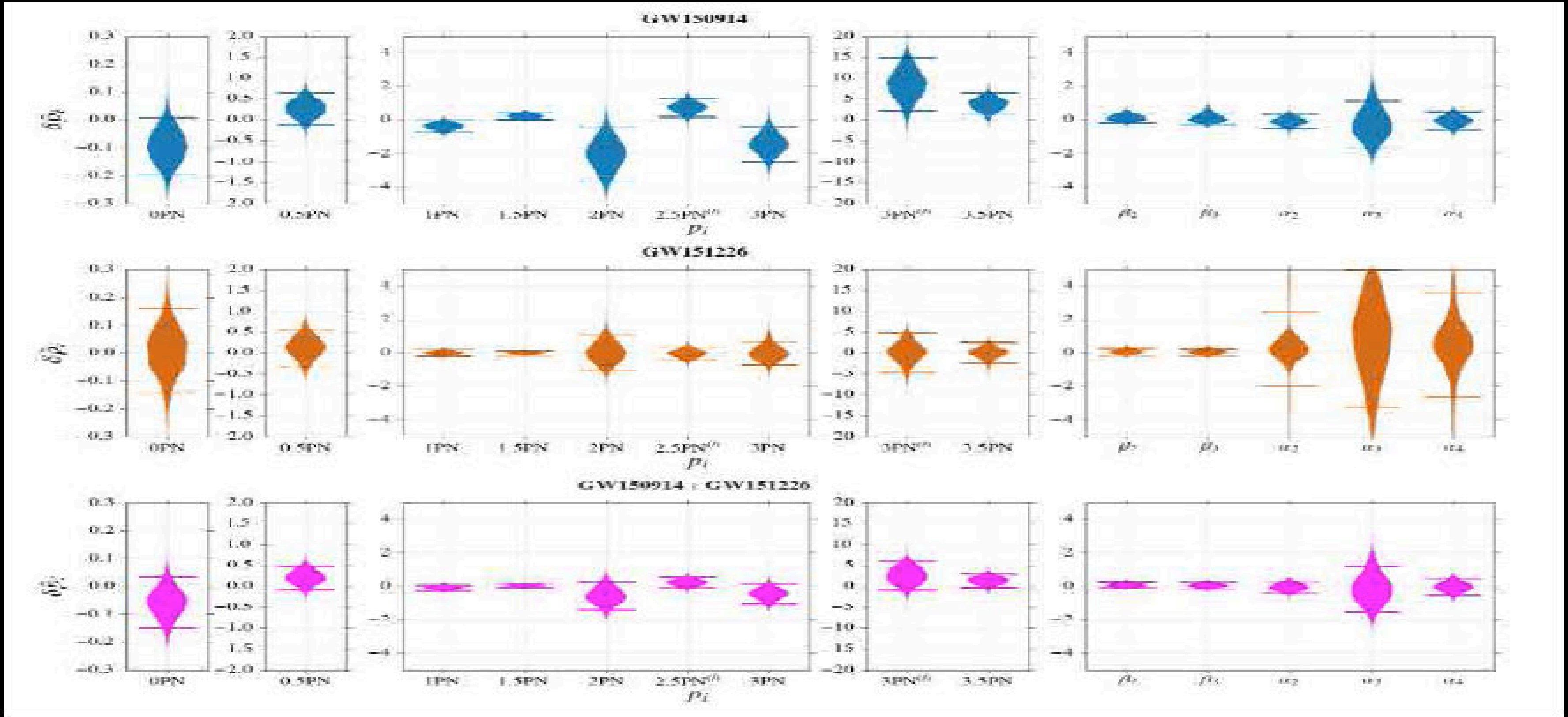




- Pure ringdown of final BH?
  - Not clear in data, but consistent

PRL 116, 221101 (2016)

Testing General Relativity – Both Events

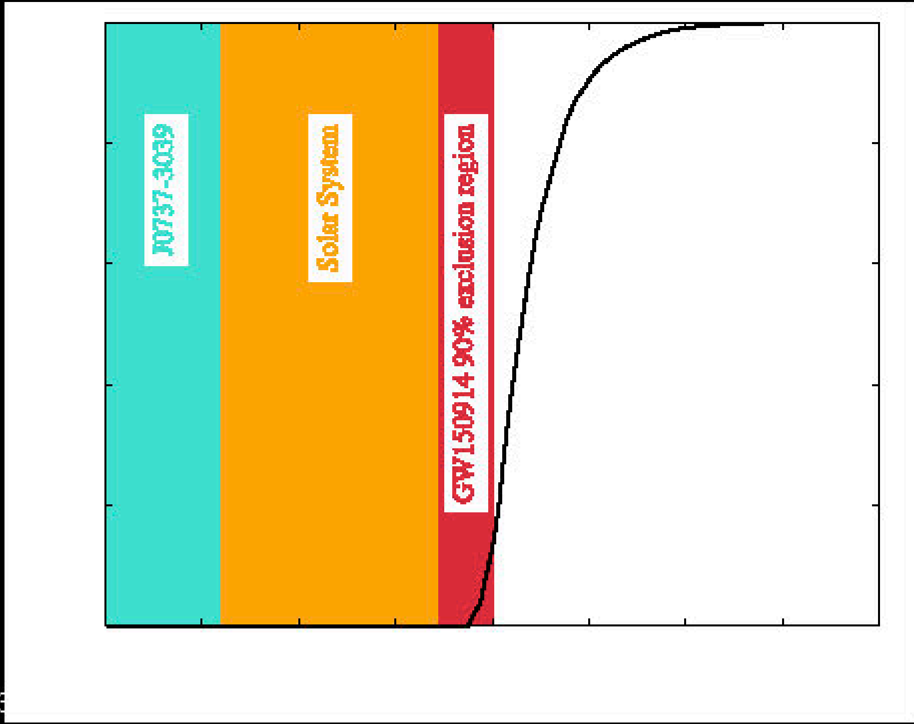


PHYS. REV. X 6, 041015 (2016)

Testing General Relativity

graviton mass

If $v_{GW} < c$, gravitational waves then have a modified dispersion relation. There is no evidence of a modified inspiral



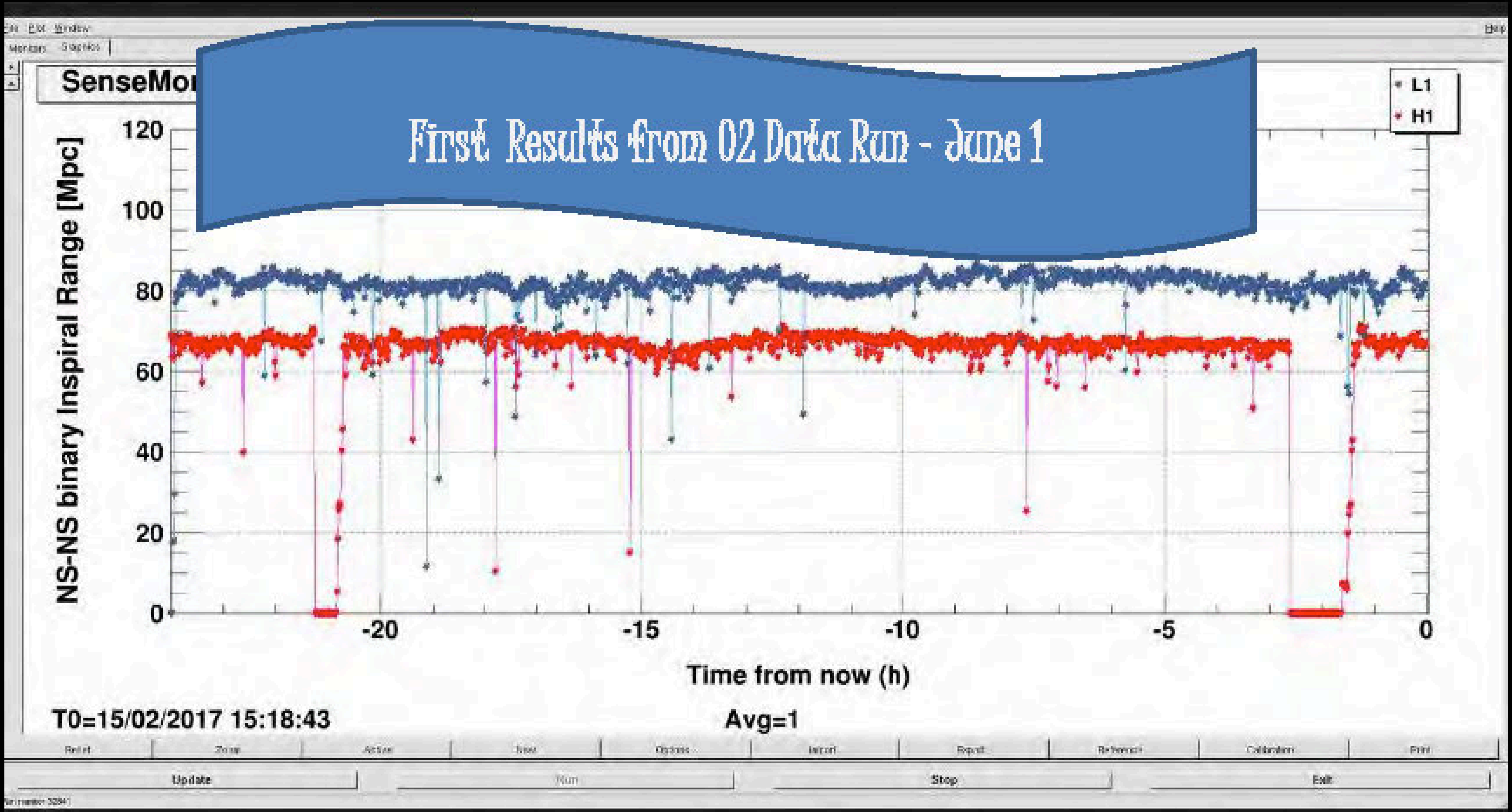
$$\lambda_g > 10^{13}\ \text{km}$$

$$m_g < 1.2 \times 10^{-22}\ \text{eV}/c^2$$

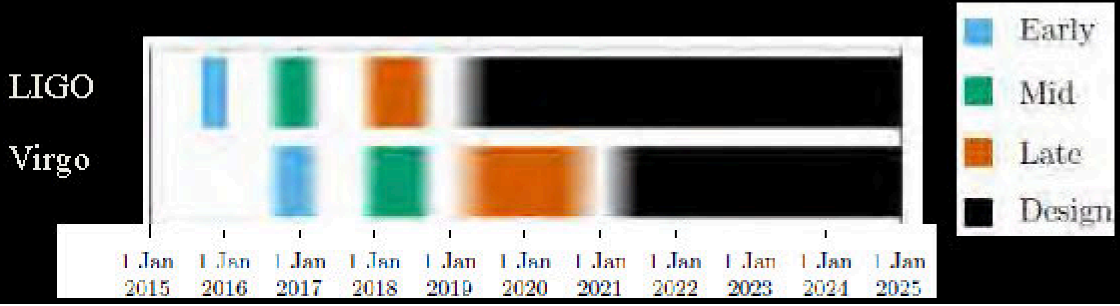
LIMIT 90% Confidence

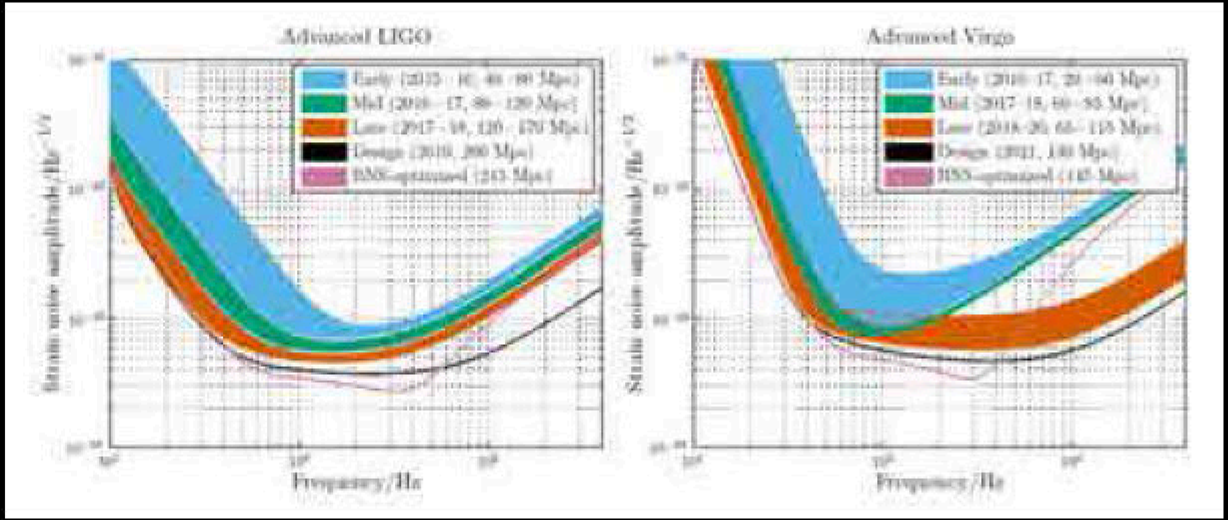
Phys. Rev. Lett. 116, 221102 (2016)

LIGO O2 Observational Run Underway



LIGO-Virgo Observing Plans





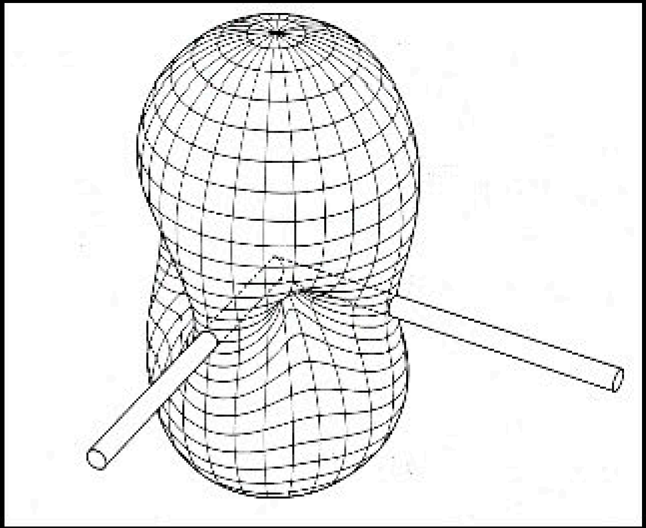
Living Rev. Relativity 19 (2016), 1

The Future for Ground-based Gravitational Waves

Coalescing Binary Systems

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

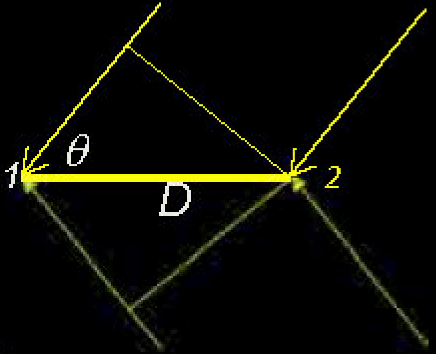
Source Localization Using Time-of-flight



- LIGO detectors are nearly omni-directional
  - Individually they provide almost no directional information
- Array working together can determine source location
  - Analogous to “aperture synthesis” in radio astronomy

- Accuracy tied to diffraction limit

$$\Delta t = (D \cos\,\theta)/c$$



Comparing time of arrival and amplitude

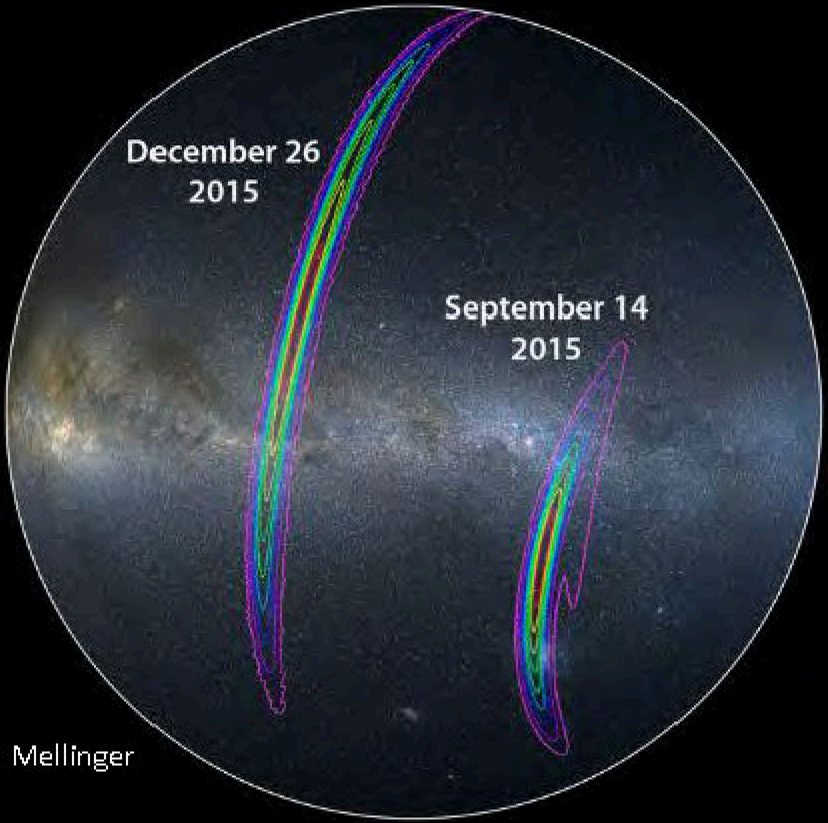
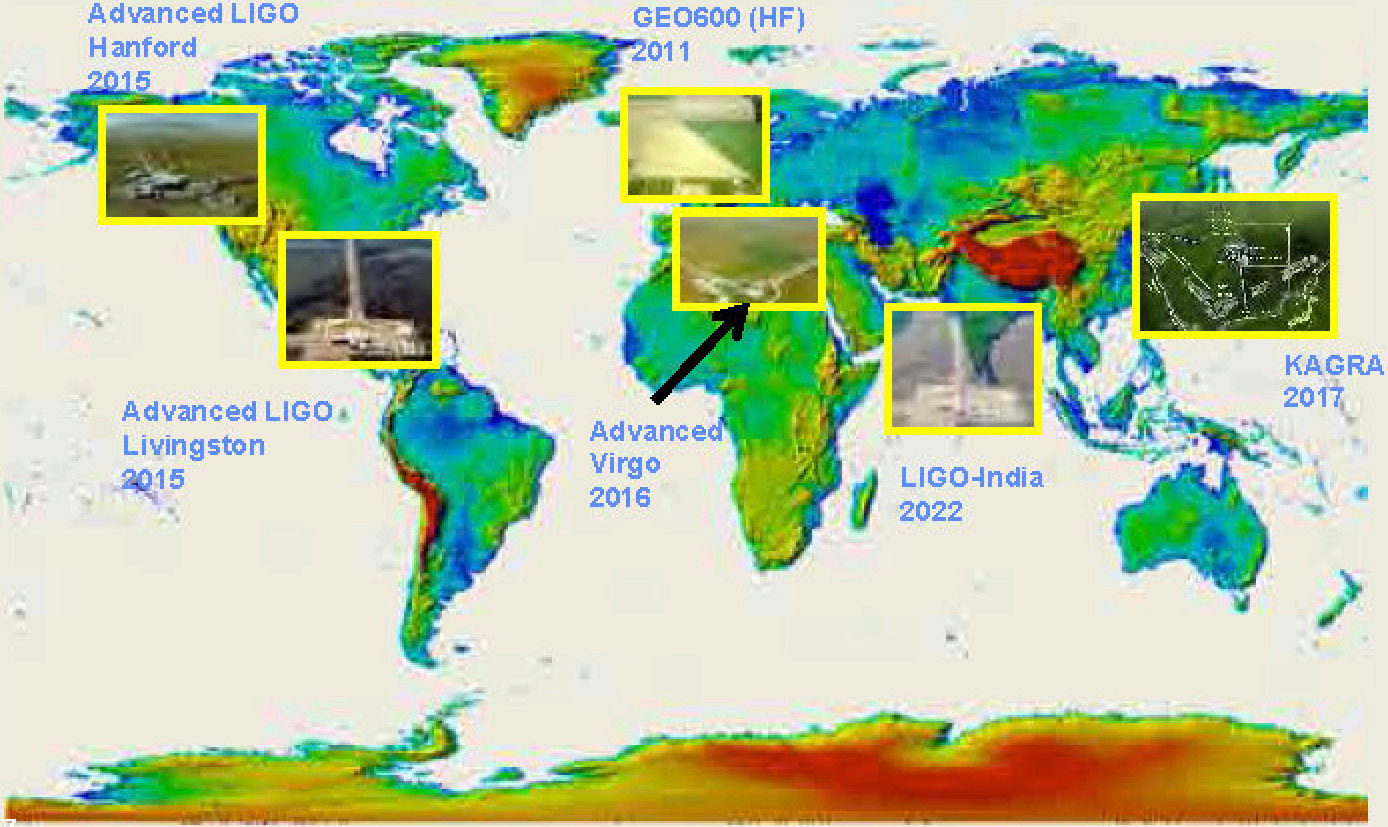


Image credit: LIGO/Axel Mellinger

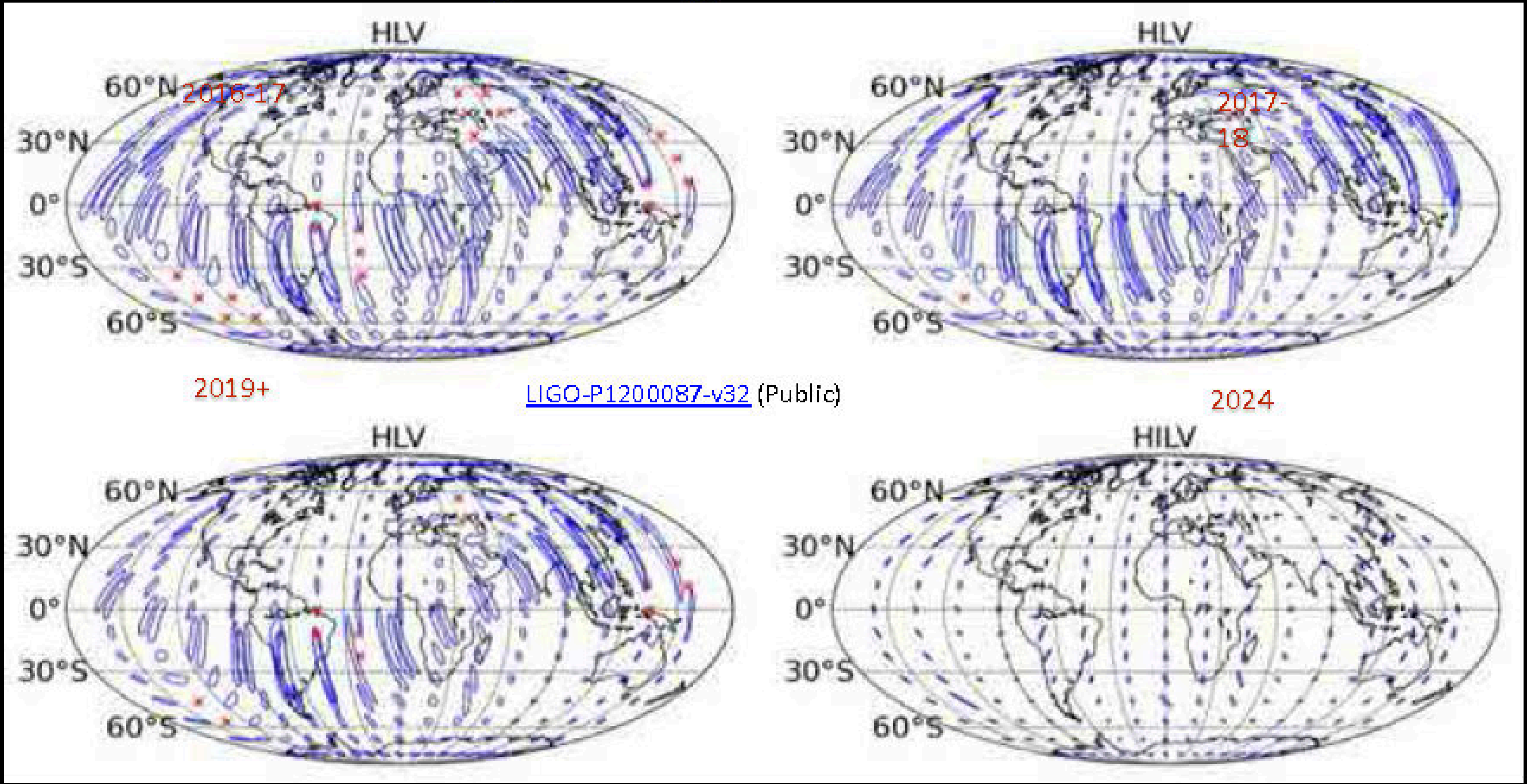
GW150914: Signal arrived 6.9 milliseconds earlier in LIGO Livingston, LA than LIGO Hanford, WA

GW detector network: 2015-2025




KAGRA
Kamioka Mine
Cryogenic Mirror
Underground
Technologies crucial for next-generation detectors;
KAGRA can be regarded as a 2.5-generation detector.

Improving Localization

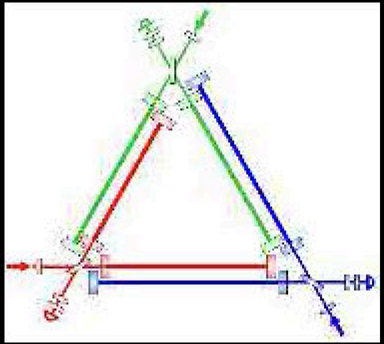


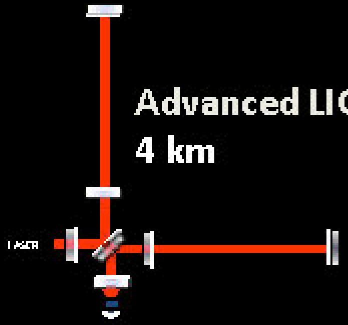
ASPERA: Proposed 3rd Generation Detector

The Einstein Telescope: x10 aLIGO

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

Einstein Telescope 10 km





Advanced LIGO
4 km

The Future for Gravitational Wave Astronomy

Milliseconds

Thanks!