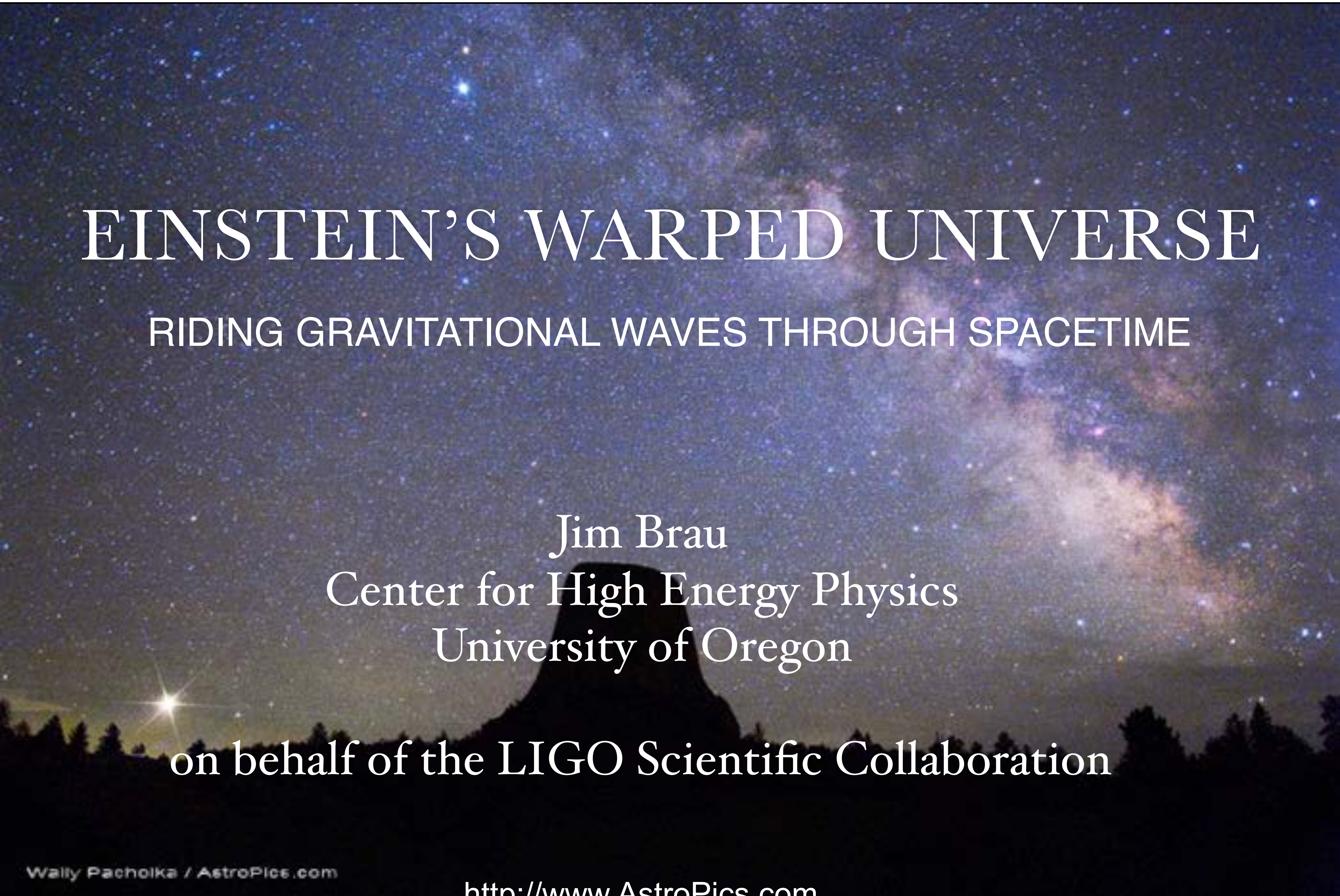


EINSTEIN'S WARPED UNIVERSE

RIDING GRAVITATIONAL WAVES THROUGH SPACETIME

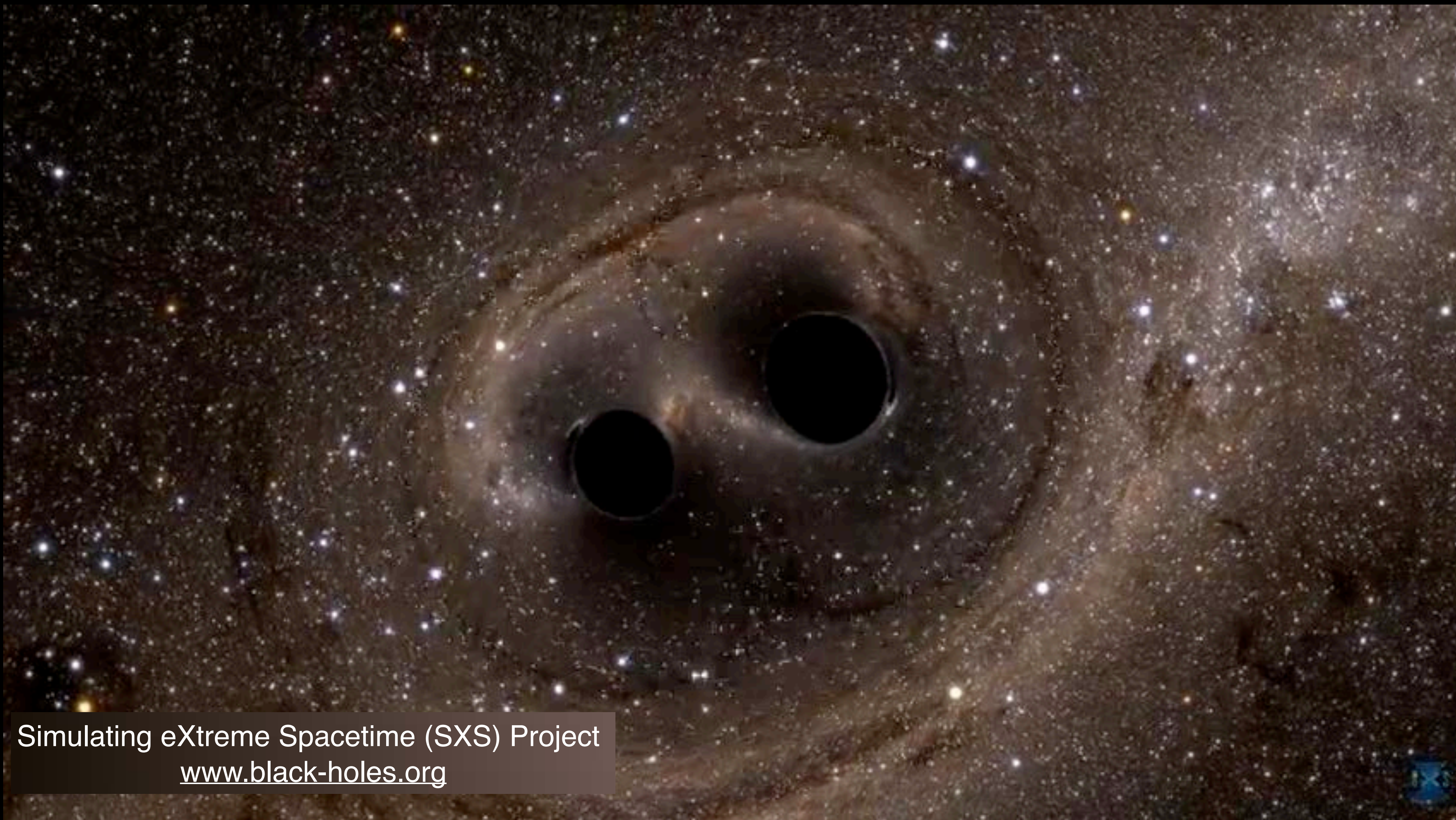
Jim Brau
Center for High Energy Physics
University of Oregon

on behalf of the LIGO Scientific Collaboration

http://www.AstroPics.com

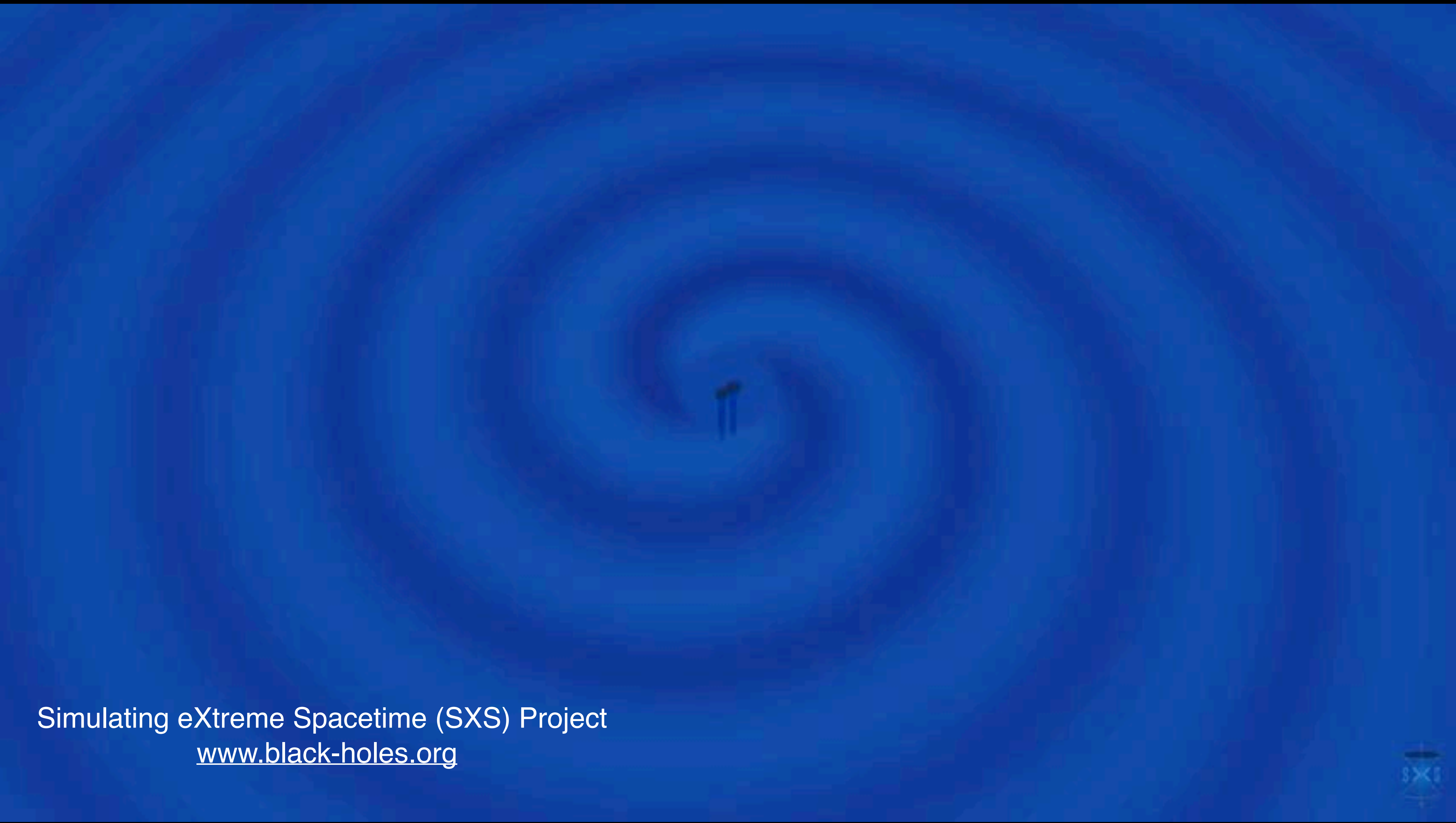
A long time ago in a galaxy far, far away

Two black holes, after millions or billions of years orbiting each other, coalesced into a single, larger black hole

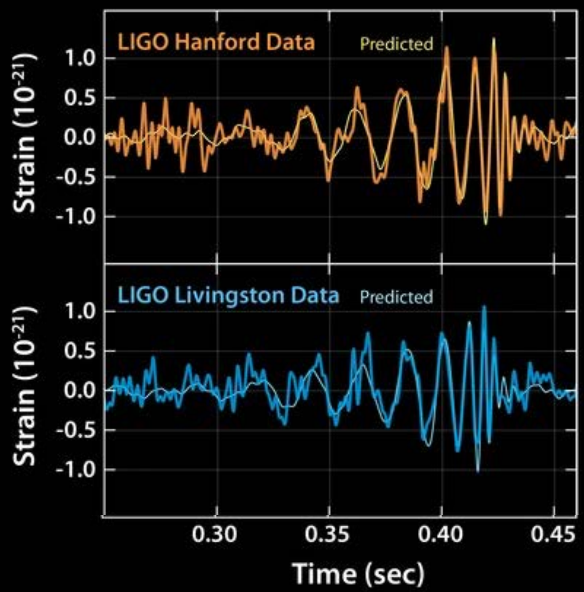


Simulating eXtreme Spacetime (SXS) Project
www.black-holes.org

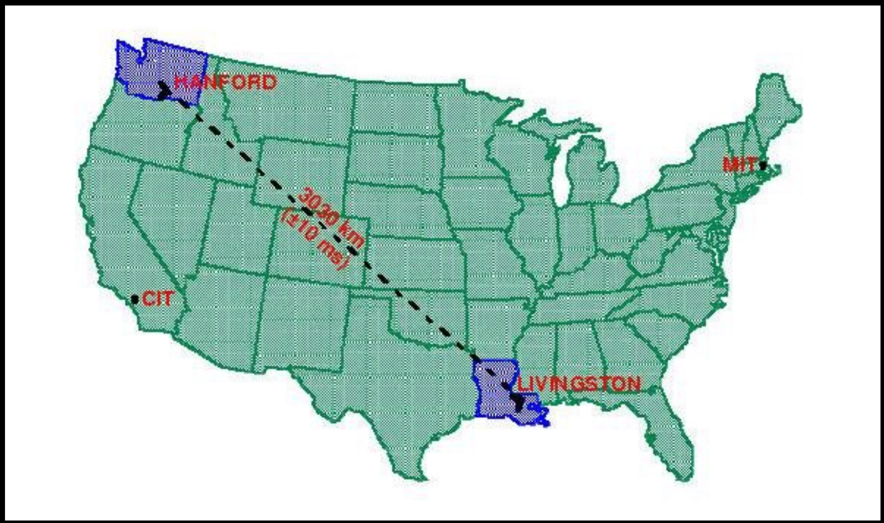
As they drew closer in orbit, they radiated enormous energy in gravitational waves



About one billion years later, on September 14, 2015, the LIGO detectors observed the waves



GW150914



LIGO Discovery of Gravitational Waves - announced Feb 11, 2016

National Press Club, Washington, DC

Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

LIGO Discovery of Gravitational Waves - announced Feb 11, 2016

National Press Club, Washington, DC

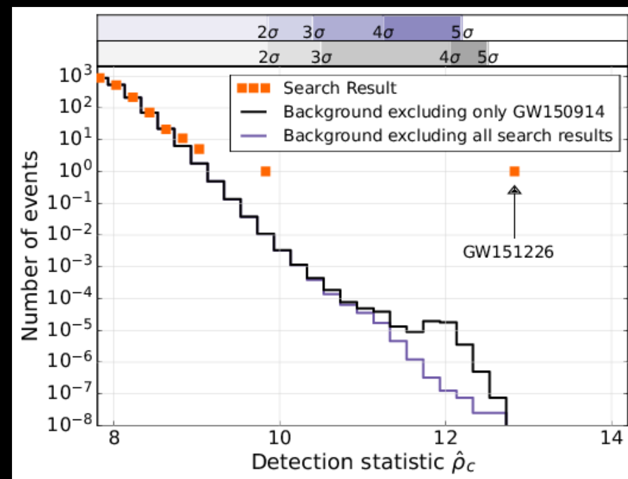
Rainer Weiss (MIT) invented the LIGO concept in 1972

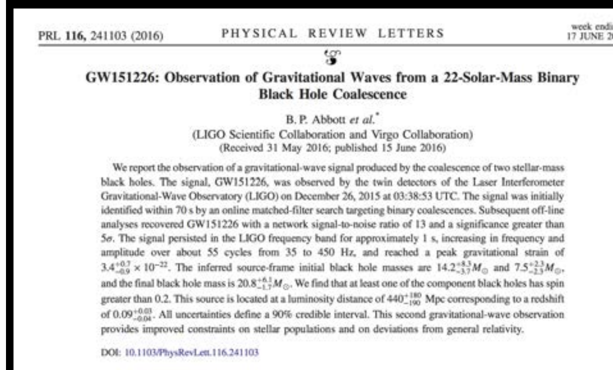
Second Direct Detection - announced June 15, 2016

AAS Meeting, San Diego, CA

December 26, 2015
at 03:38:53 UTC,
the “Boxing Day” event.

or **GW151226**





PRL **116,** 241103 (2016) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2016

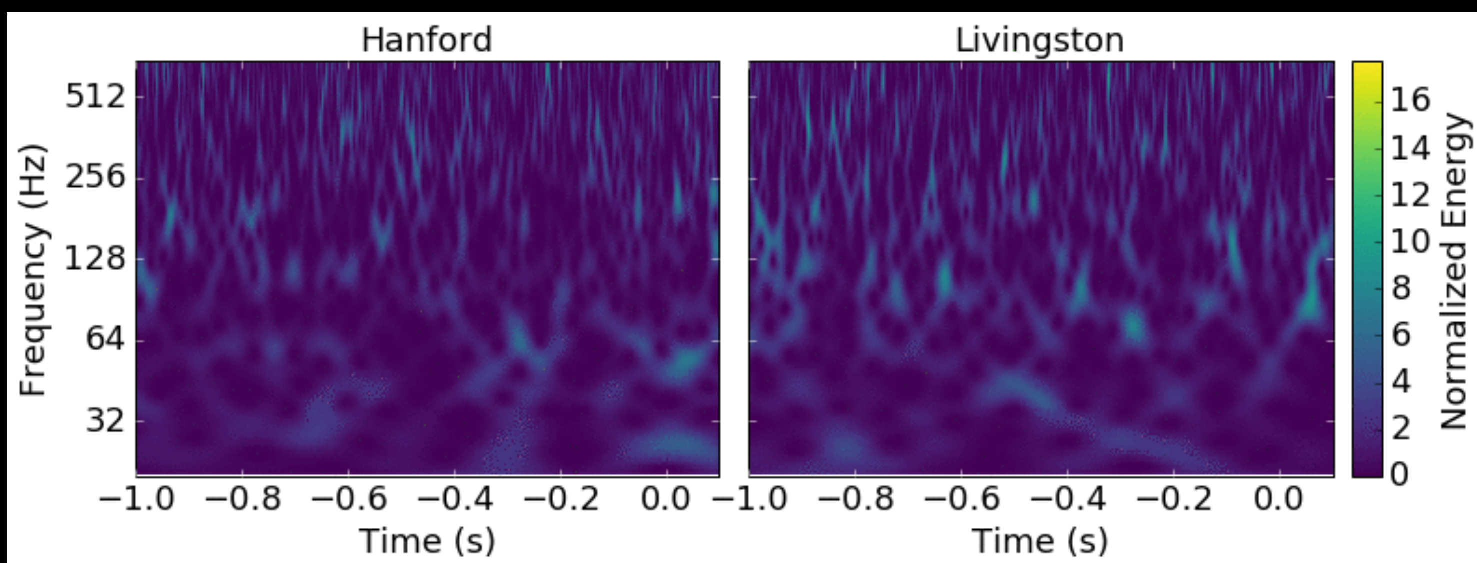
GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 31 May 2016; published 15 June 2016)

We report the observation of a gravitational-wave signal produced by the coalescence of two stellar-mass black holes. The signal, GW151226, was observed by the twin detectors of the Laser Interferometer Gravitational-Wave Observatory (LIGO) on December 26, 2015 at 03:38:53 UTC. The signal was initially identified within 70 s by an online matched-filter search targeting binary coalescences. Subsequent off-line analyses recovered GW151226 with a network signal-to-noise ratio of 13 and a significance greater than 5σ. The signal persisted in the LIGO frequency band for approximately 1 s, increasing in frequency and amplitude over about 55 cycles from 35 to 450 Hz, and reached a peak gravitational strain of $3.4^{+0.7}_{-0.9} \times 10^{-22}$. The inferred source-frame initial black hole masses are $14.2^{+8.3}_{-3.7} M_{\odot}$ and $7.5^{+2.3}_{-2.3} M_{\odot}$, and the final black hole mass is $20.8^{+6.1}_{-1.7} M_{\odot}$. We find that at least one of the component black holes has spin greater than 0.2. This source is located at a luminosity distance of 440^{+180}_{-190} Mpc corresponding to a redshift of $0.09^{+0.03}_{-0.04}$. All uncertainties define a 90% credible interval. This second gravitational-wave observation provides improved constraints on stellar populations and on deviations from general relativity.

DOI: 10.1103/PhysRevLett.116.241103



Gravitational Waves

- What are gravitational waves?
- Indirect evidence (Hulse-Taylor)
- What are the detectable natural sources?
- How are they detected?
- Future?

Einstein's Theory of Gravitation

General Relativity

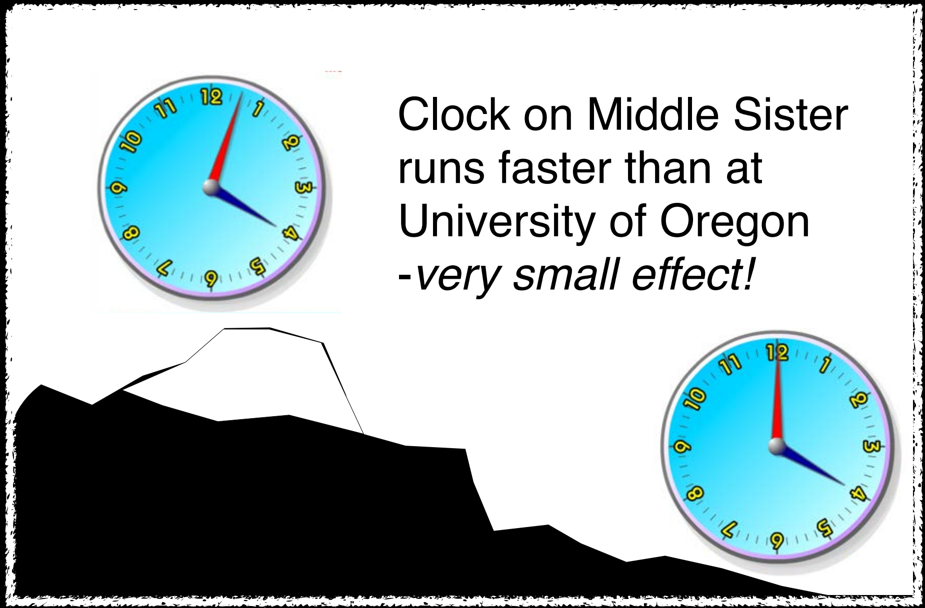
$$\mathbf{G} + \Lambda g = 8\pi\,(G_N/c^4)\,\mathrm{T}$$

G is the curvature tensor
T is the stress-energy tensor

This equation says space-time curvature is a result of the existence of matter and energy and space is stiff ($G_N/c^4 = 8.2\ \ 10^{-45}\ \mathrm{s^2/kg\text{-}m}$)

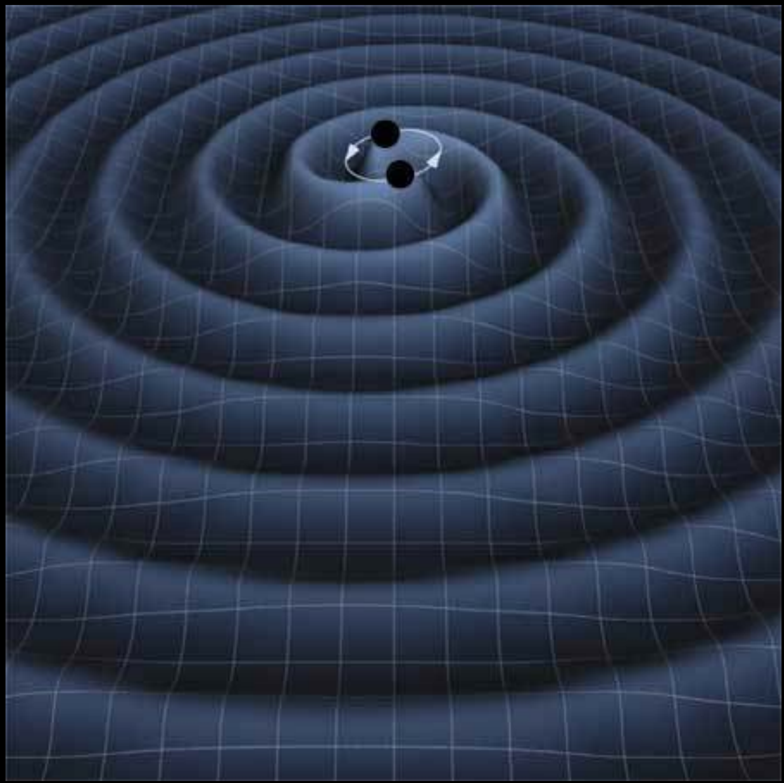
Experimental Evidence for General Relativity

- Bending of starlight
- Time slows down in a gravitational field



Experimental Evidence for General Relativity

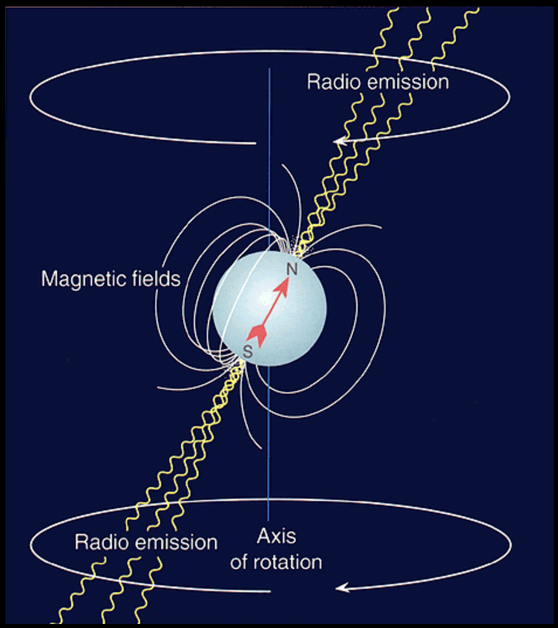
- Bending of starlight
- Time slows down in a gravitational field
- Orbit of Mercury
  - precession
- Binary neutron star pulsar
  - orbit speeding up
  - due to emission of **gravitational radiation** (waves)



Neutron star binary system

PSR 1913 + 16

- Neutron star (Pulsar) observed through radio wave emission
  - rotation rate = 17/second



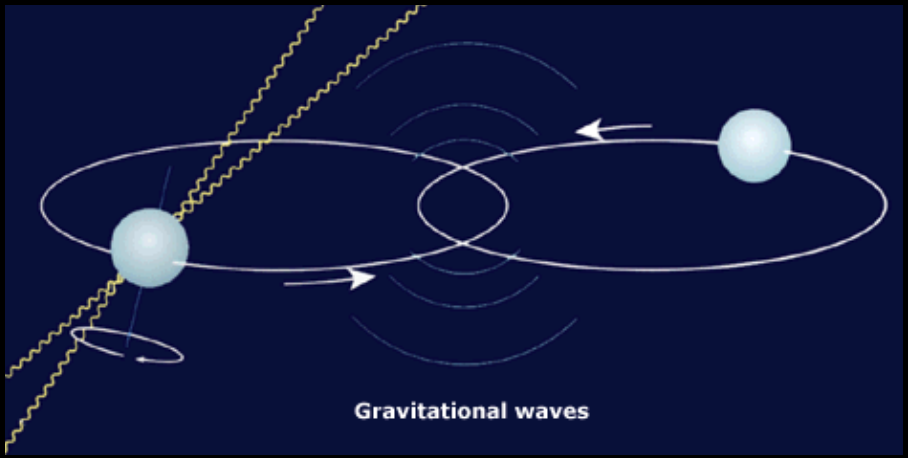
credit: nobelprize.org

Neutron star binary system

PSR 1913 + 16

- Neutron star (Pulsar) observed through radio wave emission
  - rotation rate = 17/second

- Two neutron stars orbiting every 8 hours

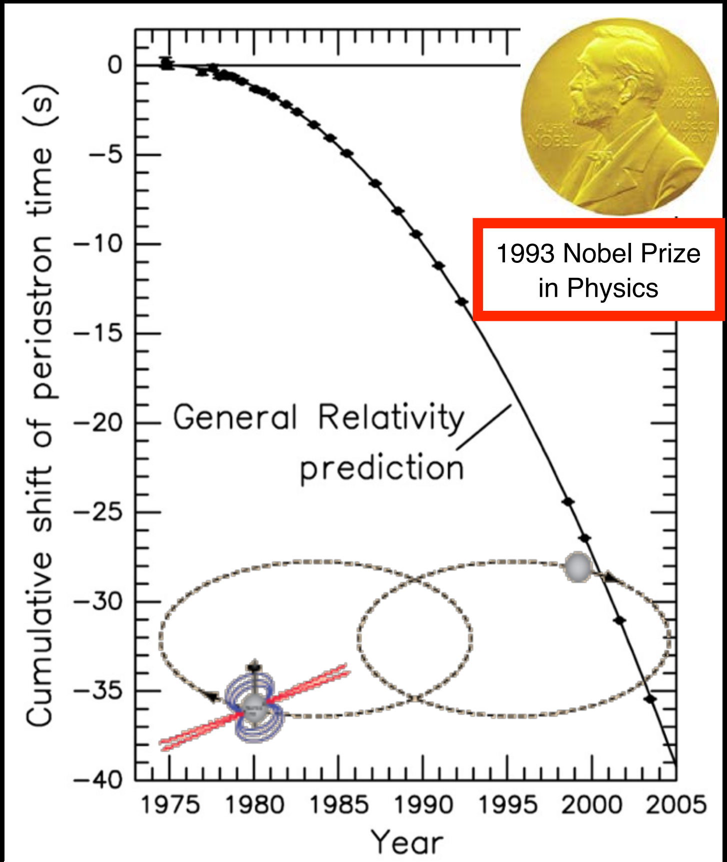


credit: nobelprize.org

Hulse & Taylor measurements of PSR 1913 + 16

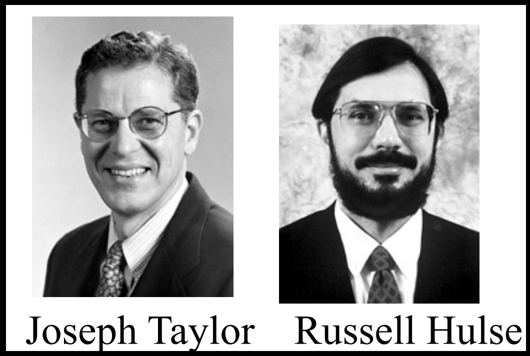
Joseph Taylor   Russell Hulse

- Gravitational waves emitted leading to loss of orbital energy
- Consequently, period of orbit decreases by 35 seconds from 1975 to 2003
- Agrees with predicted rate of emission of gravitational waves by General Relativity
- Gravitational waves exist, but can they be directly detected?



Astrophys.J.722:1030-1034,2010

Hulse & Taylor measurements of PSR 1913 + 16



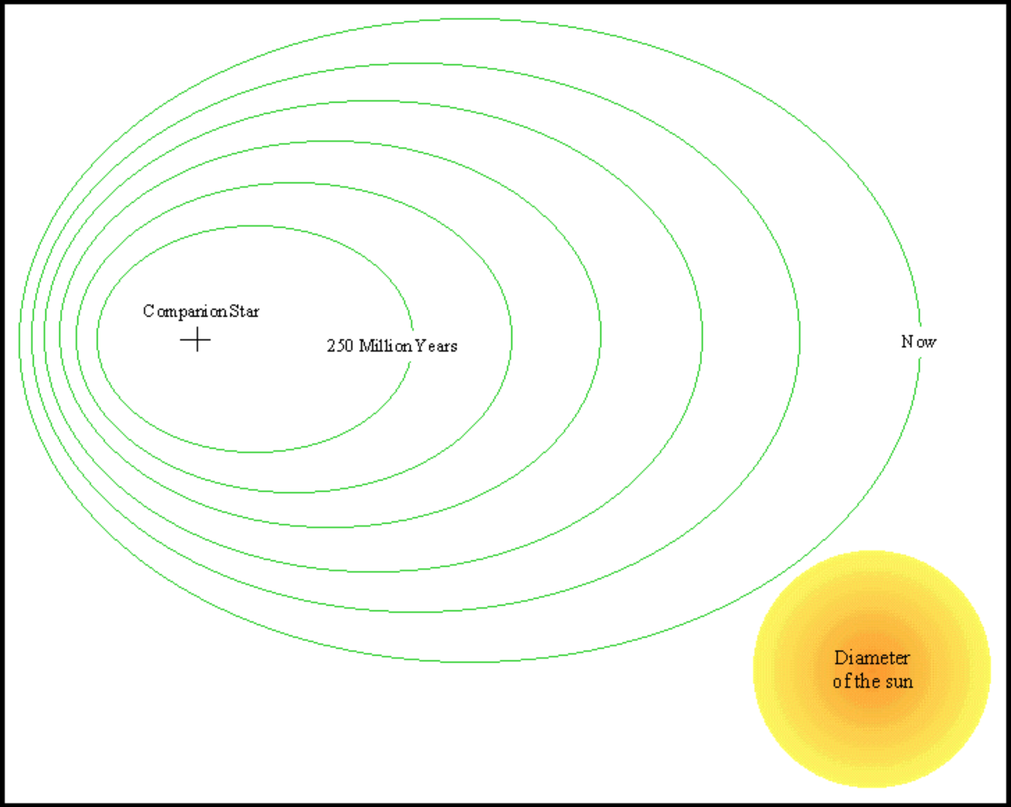
- Radiating energy

$$\frac{dE}{dt} = \frac{32GI^2w^6}{5c^5}$$

- Not much today

- In 300,000,000 years coalesce with a burst of gravitational radiation

- We can't wait for this one



Space-time Geometry

The local geometry is defined by the curvature metric (G), a function of the local space-time metric (g)

$$ds^2 = dx^2 + dy^2 + dz^2 - c^2\, dt^2$$

$$ds^2 = g_{\mu\nu}\, dx^\mu\, dx^\nu$$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \quad (h << 1, \text{weak-field limit})$$

η is the flat space metric

$$\eta = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Space-time Geometry

In the weak-field limit (h << 1), linearize equation in "transverse-traceless gauge" and arrive at wave equation for h

$$\nabla^2 h - \frac{\partial^2 h}{c^2 \partial t^2} = \frac{16\pi G_N}{c^4} T$$

<u>Quadrupole radiation</u>

- monopole radiation forbidden by Energy conserv.
- dipole radiation forbidden by momentum conserv.

There are two polarizations

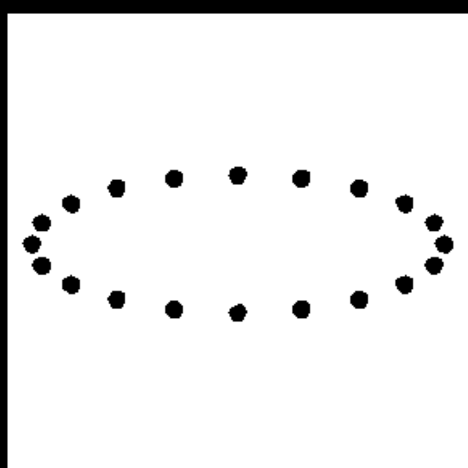
plus (+) and cross (×)

Two polarizations

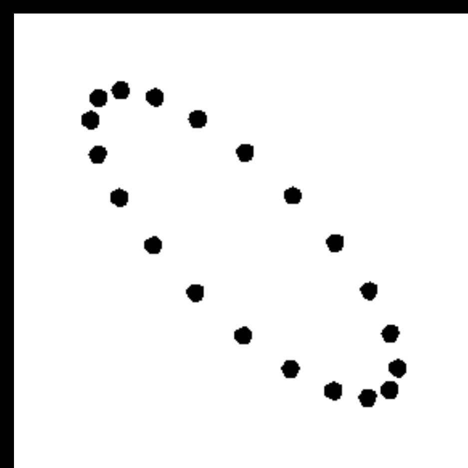
- Wave will distort a ring of test masses like tidal deformation

- Specific movement of the test masses during one period of the wave depends on polarization

+



×



Generation of gravitational radiation

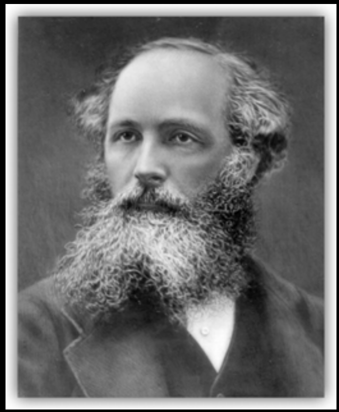
- Quadrupole radiation, requires quadrupole source
- Accelerating mass generates wave, much as accelerating charge generates EM radiation

$$h_{\mu\nu} = \frac{2G}{c^4 r}\ddot{I}_{\mu\nu}$$

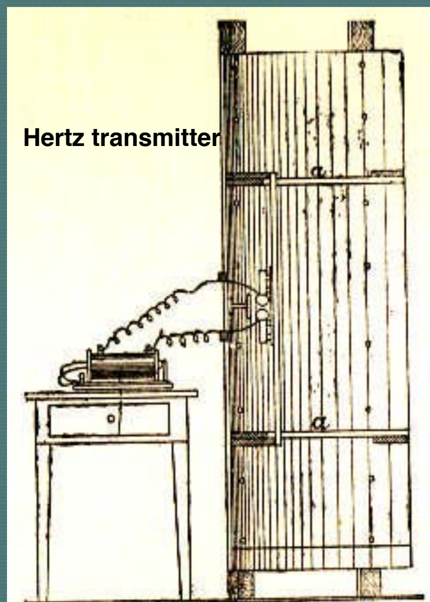
Recall
$G_N/c^4 = 8.2\ \ 10^{-45}\ s^2/kg\text{-}m$,
very small

Direct Detection of Gravitational Waves

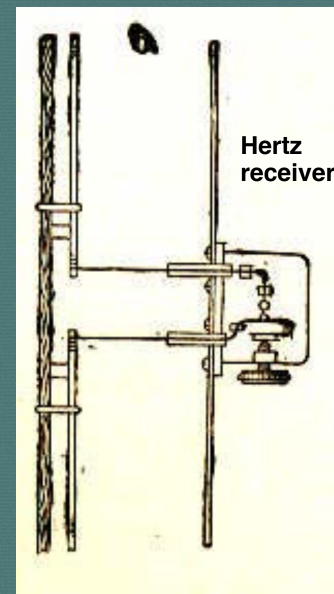
- Maybe the history of the discovery of electromagnetic waves is useful
  - 1864 Maxwell predicted existence of electromagnetic waves
  - 1879 Prussian Academy of Science offered a prize for experimental proof of Maxwell's theory



Direct Detection of Gravitational Waves



Source of images:
http://www.newscotland1398.net/nfld1901/marconi-nfld.html



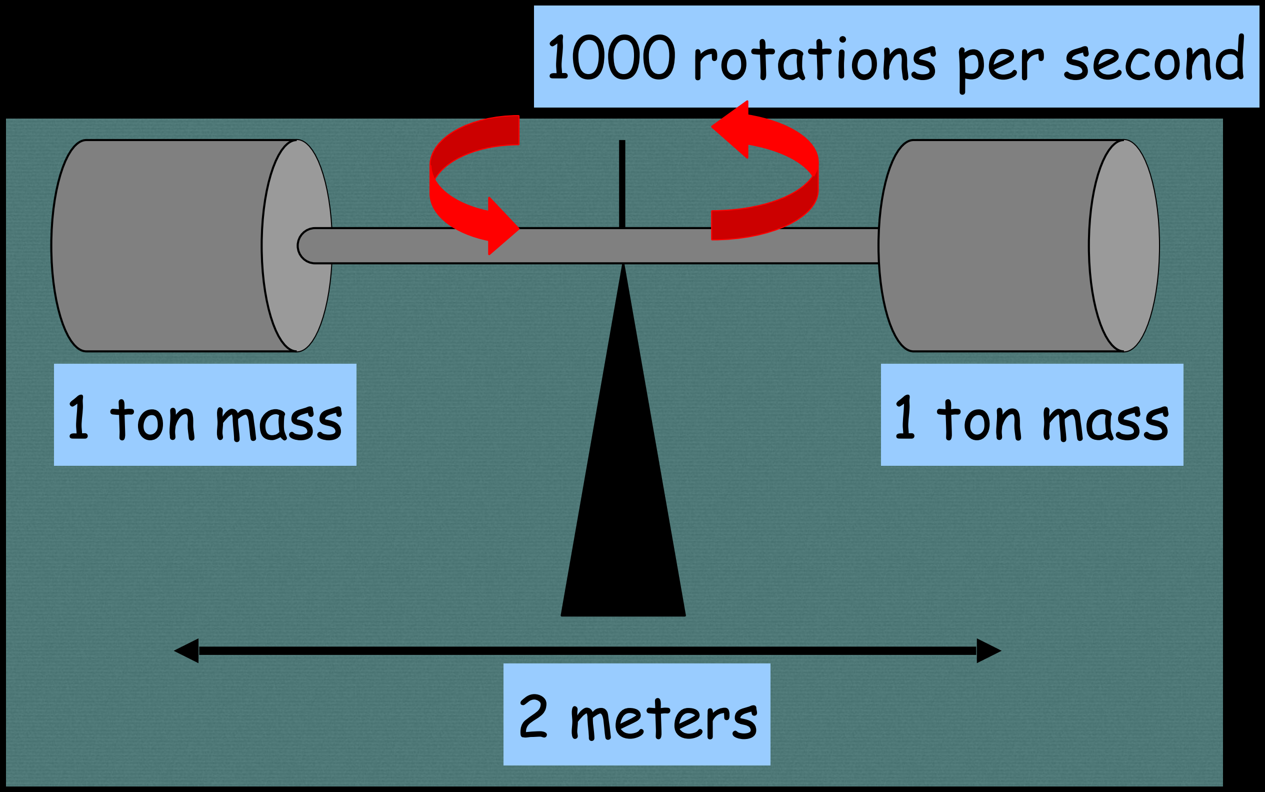
– 1886 Hertz created primitive transmitter and receiver; he produced and directly detected the electromagnetic waves

- Can we envision a similar laboratory demonstration of gravitational waves?

Laboratory Demonstration

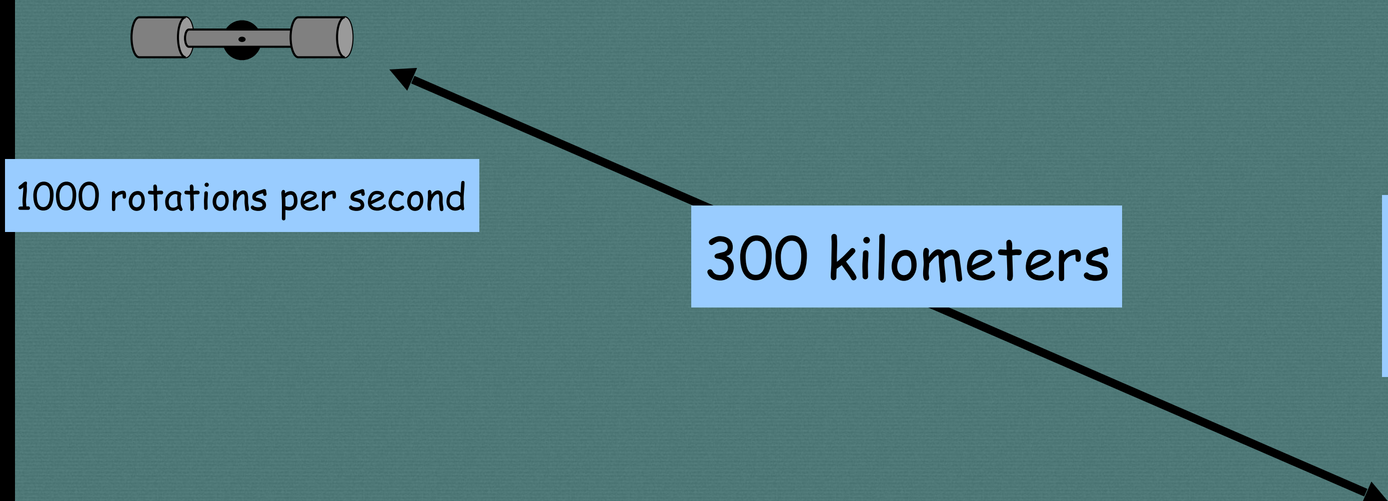
- Gravitational waves generated by time dependent quadrupole moment of masses, as electromagnetic waves are generated by accelerating charges

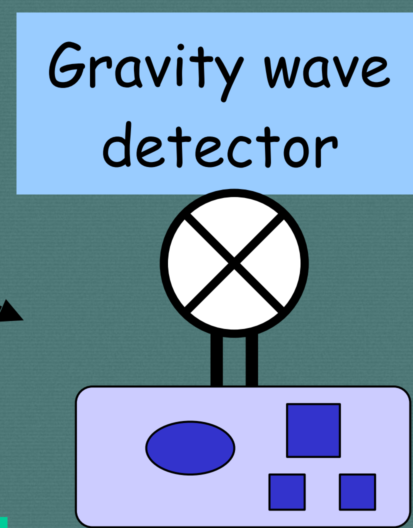
Side view



Laboratory Demonstration

- Now look for waves from this source





- ΔL at 300 kilometers is 3×10^{-33} meters, far too small to be detectable

$$h = \Delta L / L \approx 3 \times 10^{-33}\ \mathrm{m} / 3 \times 10^{5}\ \mathrm{m} \approx 10^{-38}$$

- This system would only create a **strain** ($h = \Delta L / L$) of 10^{-38}

Astrophysical Source:
Coalescing neutron stars or black holes

Source of Detectable GWs

- Laboratory
  - mass = 1 ton
  - radius = 1 m
  - freq. = 1000 Hz
  - distance = 300 km
- **strain** ≈ 10^{-38}
  NOT DETECTABLE

- Astrophysical
  - binary compact stars (NSs or BHs)
  - mass = 1.4 $M_\odot$
  - radius = 20 km
  - freq. = 400 Hz
  - distance = 5×10^{23} m = 15 Mpc
- **strain** ≈ 10^{-21}
  POSSIBLY DETECTABLE

How small is strain of 10^{-21}?

- size of basketball over scale of Milky Way Galaxy

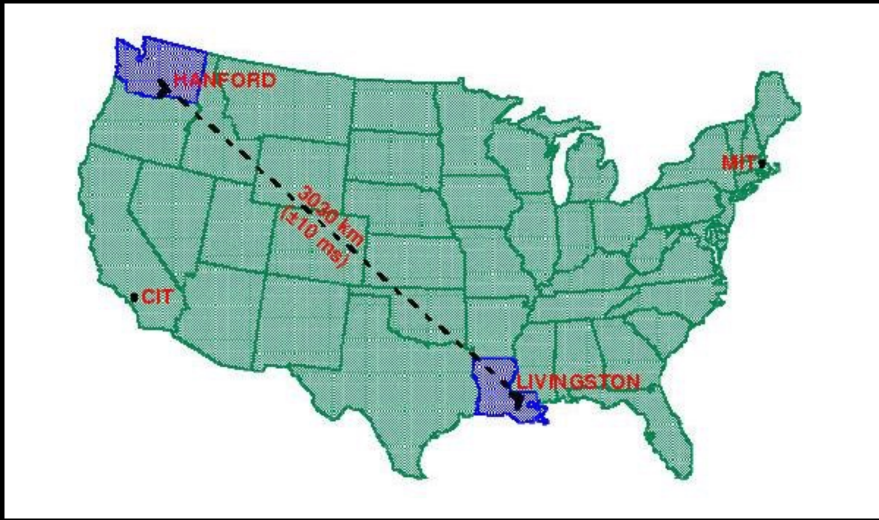
- fraction of the size of a human hair over distance to nearest star beyond the sun (Proxima Centauri)
- 10^{-8} size of atom over LIGO arm length
- 10^{-3} size of proton over LIGO arm length
  - VERY CHALLENGING!

Joseph Weber and the Bar Antenna

- Massive aluminum cylinders
  - Vibrated at a resonance frequency of 1660 hertz
  - Designed to be set in motion by gravitational waves
  - Since waves were expected to be very weak, the cylinders were massive with very sensitive piezoelectric sensors, capable of detecting a change in the cylinders' lengths by about 10^{-16} meters

Laser Interferometer Gravitational-wave Observatory (LIGO)

- Created to directly detect gravitational waves for the first time



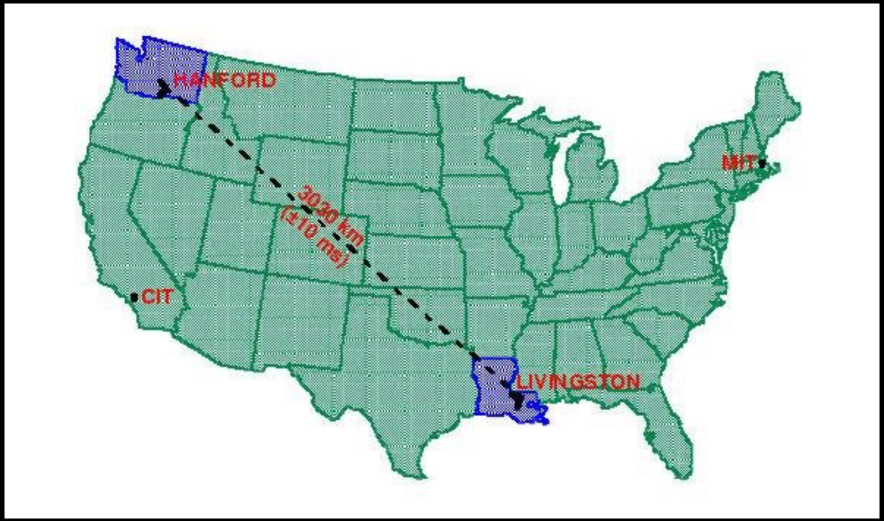
Laser Interferometer Gravitational-wave Observatory (LIGO)

1992-cofounded by Kip Thorne & Ronald Drever (Caltech) & Rainer Weiss (MIT)

1997-LIGO Scientific Collaboration formed including Univ. of Oregon

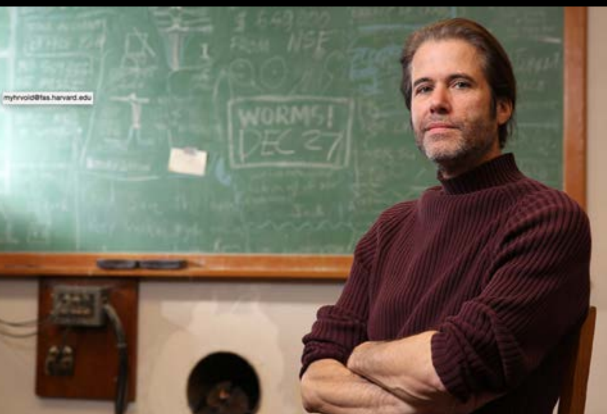
2002- LIGO initial operations

2015-Advanced LIGO began operations



LIGO Scientific Collaboration

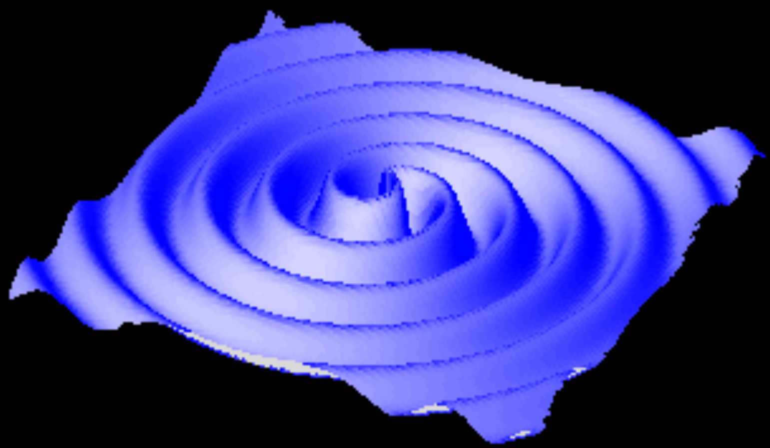
Oregon LIGO Researchers

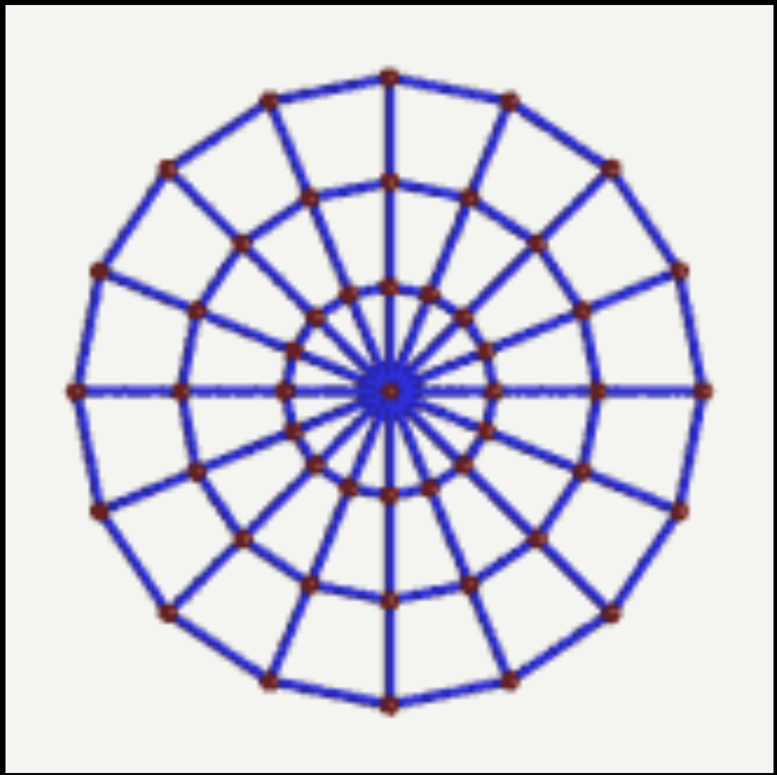


- Ray Frey & Jim Brau - faculty
- Robert Schofield - research professor
- Dipongkar Talukder - postdoctoral researcher
- Sudarshan Karki, Jordan Palamos, Vincent Roma, Paul Schale, Ryan Quitzow-James - grad students

- Former UO LIGO members - David Strom, Isabel Leonor, Anatoli Arodzero, Masahiro Ito, Rauha Rahkola, Emelie Harstad

Effect of Gravitational Waves



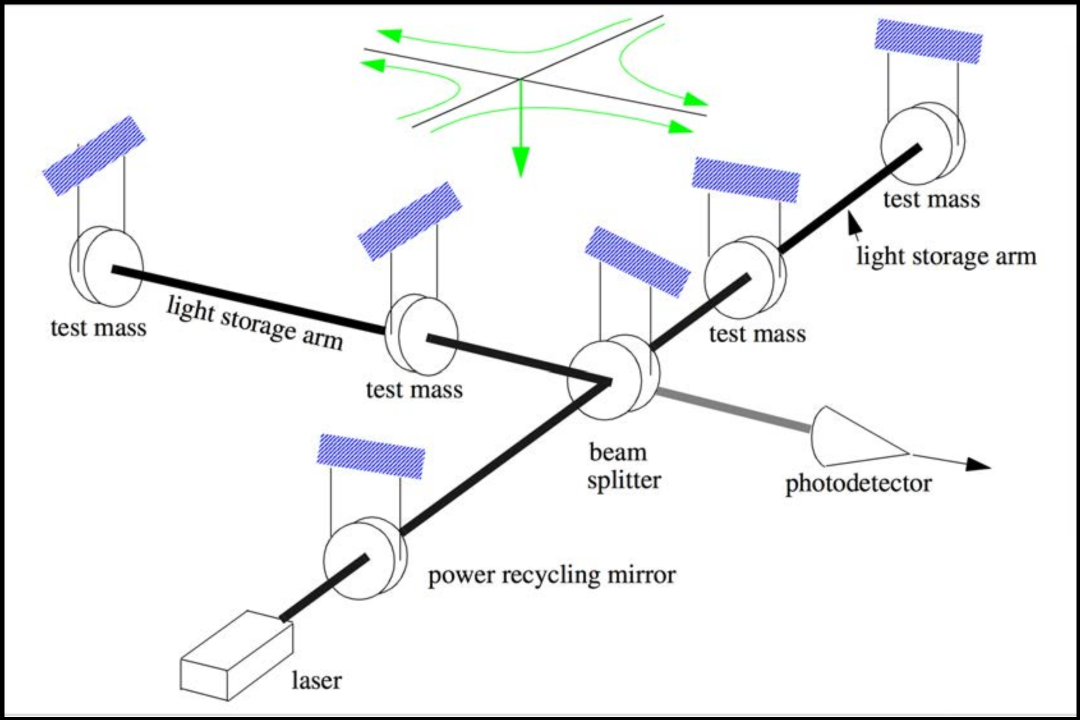


Space will stretch and squash in perpendicular directions at the frequency of the gravitational waves

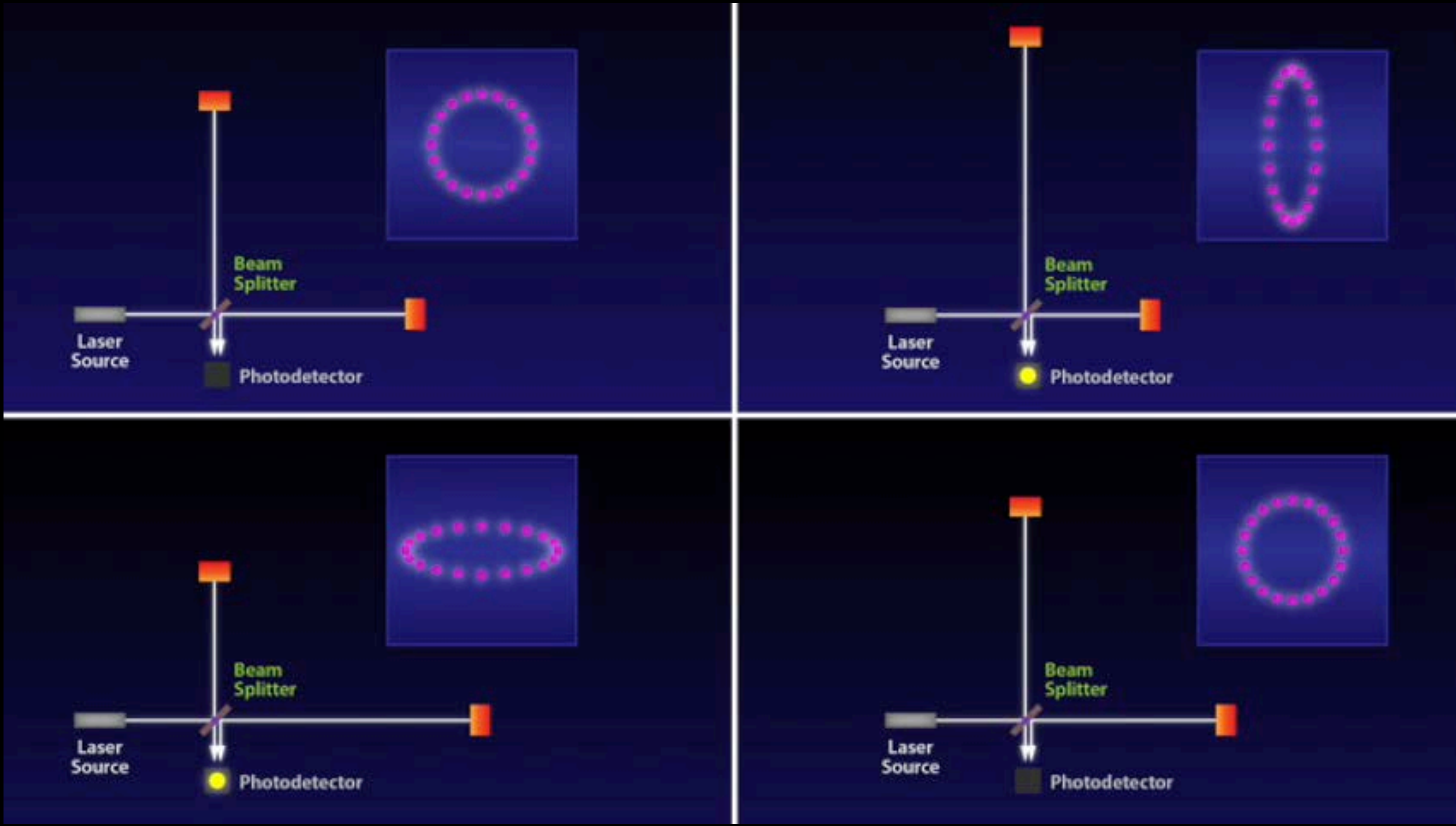
But effect is very small - distance of a kilometer may change by only 10^{-18} meters

<u>Strain</u> = change/distance ≈ 10^{-18} m / 10^{3} m = 10^{-21}

LIGO Detector Concept



- Compare the time it takes light to travel in two orthogonal directions transverse to the gravitational waves.
- The gravitational wave causes the time difference to vary by stretching one arm and compressing the other.
- An interference pattern is measured to one part in 10^{10}, to obtain required sensitivity.


Beam
Splitter
Laser
Source
Photodetector
Beam
Splitter
Laser
Source
Photodetector
Beam
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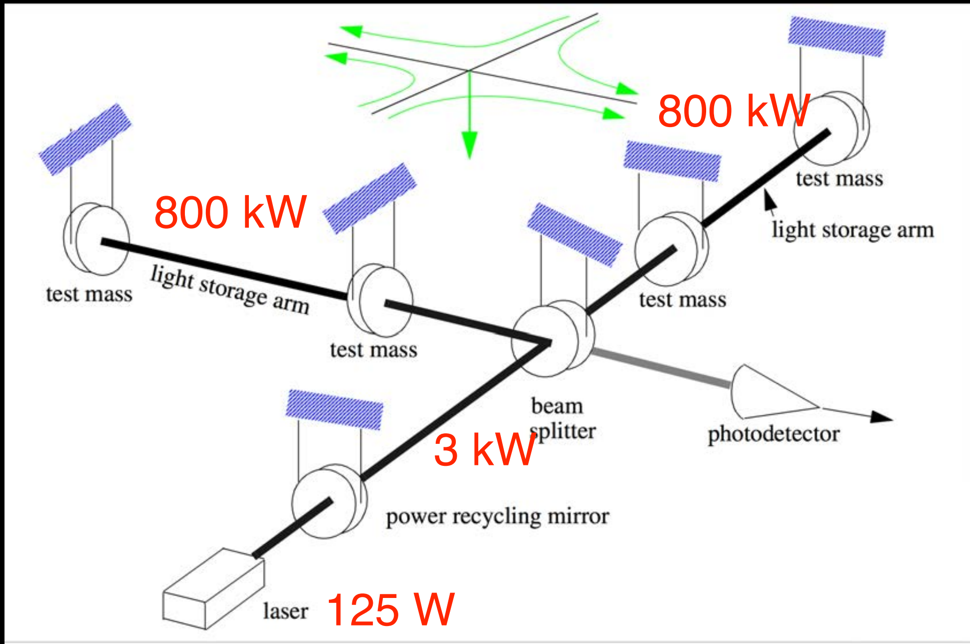
Beam
Splitter
Laser
Source
Photodetector

How to achieve precision

- $\Delta\phi = B \frac{\Delta L}{\lambda} = B \frac{hL}{\lambda}$ - B = number of laser bounces in arm
- $\Delta\phi_{LIM} \approx 1/\sqrt{N}$ - N = number of photons - shot noise
- $h_{min} \approx \frac{\lambda}{L}\frac{1}{B}\frac{1}{\sqrt{N}}$ BL < 1/2 grav. wavelength

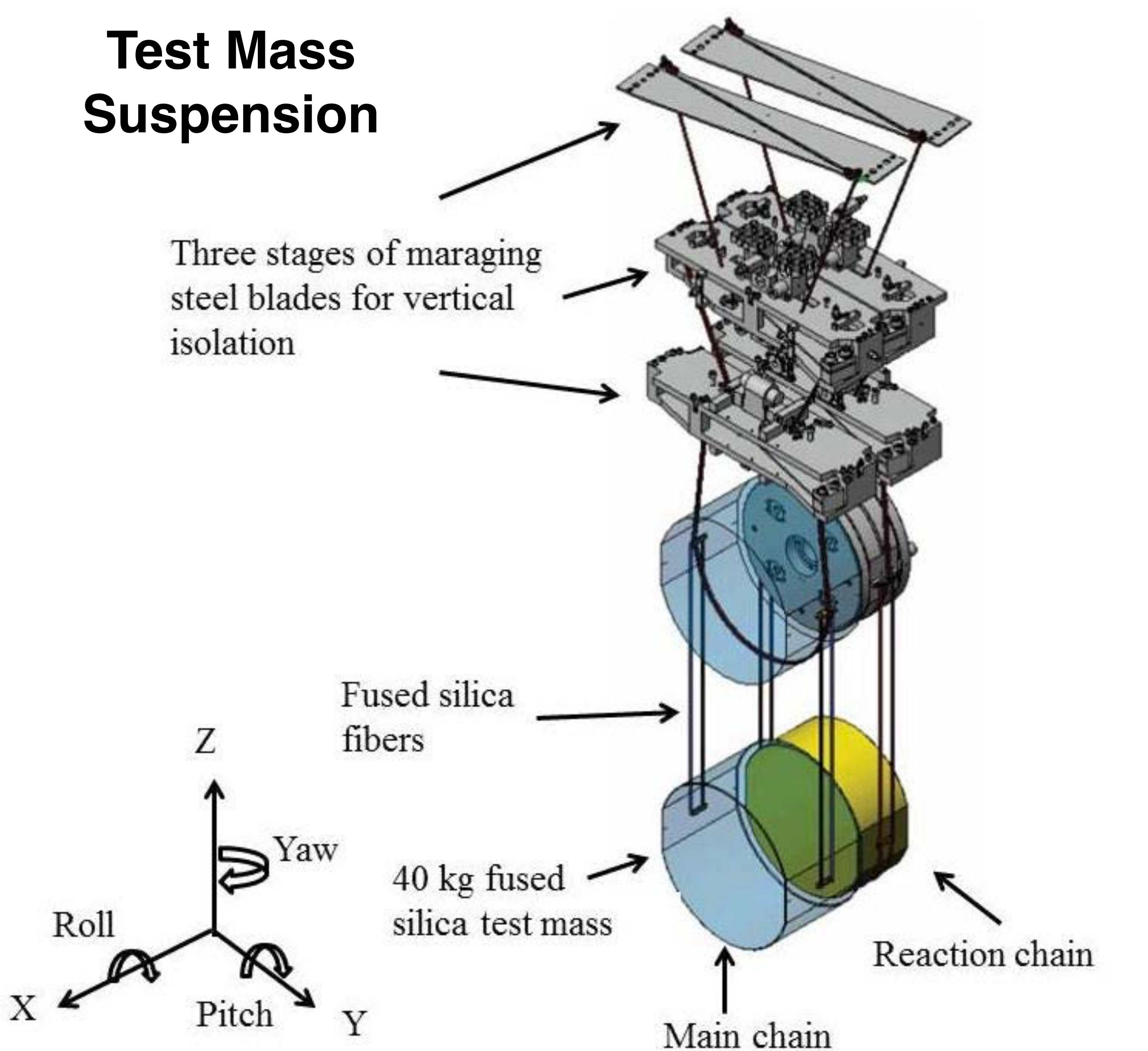
aLIGO, λ = 1.064 μm,
N > 10^{20} (125 W), B ≈ 300,
L = 4000 m

- $h_{min} < 10^{-22}$



A. Abramovici et al., Science 256, 325 (1992)

Test Mass Suspension



Advanced LIGO Noise Budget

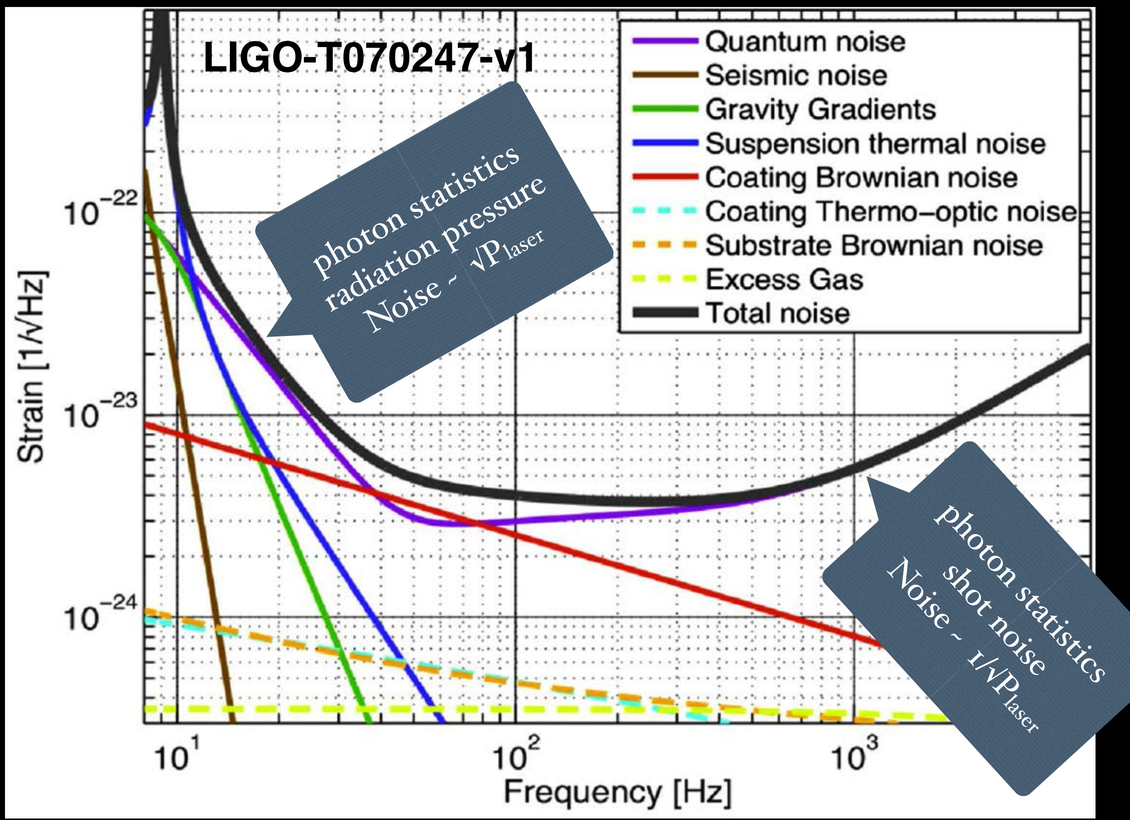
- Fundamental noise sources

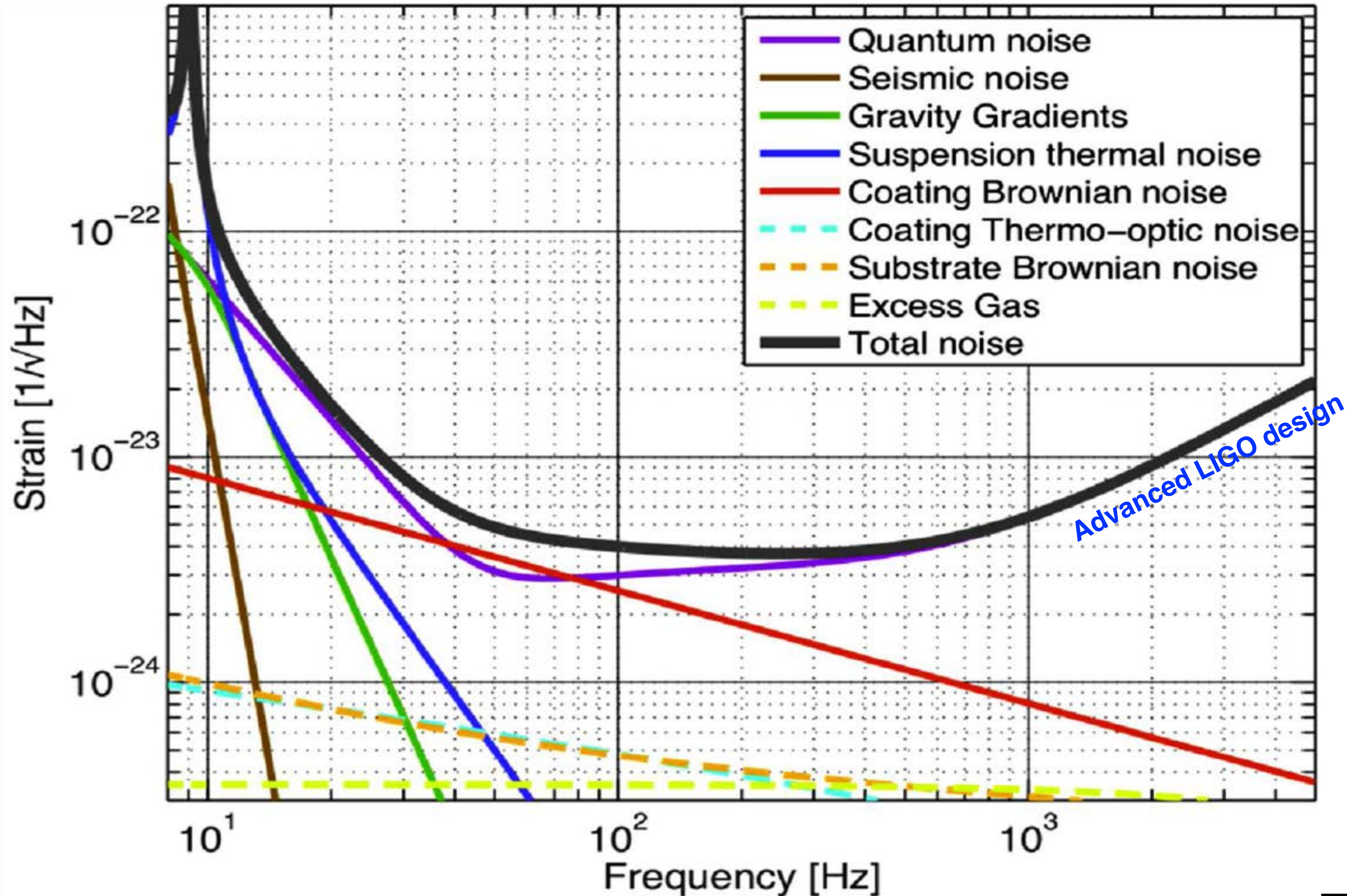
  Displacement noise {ΔL}

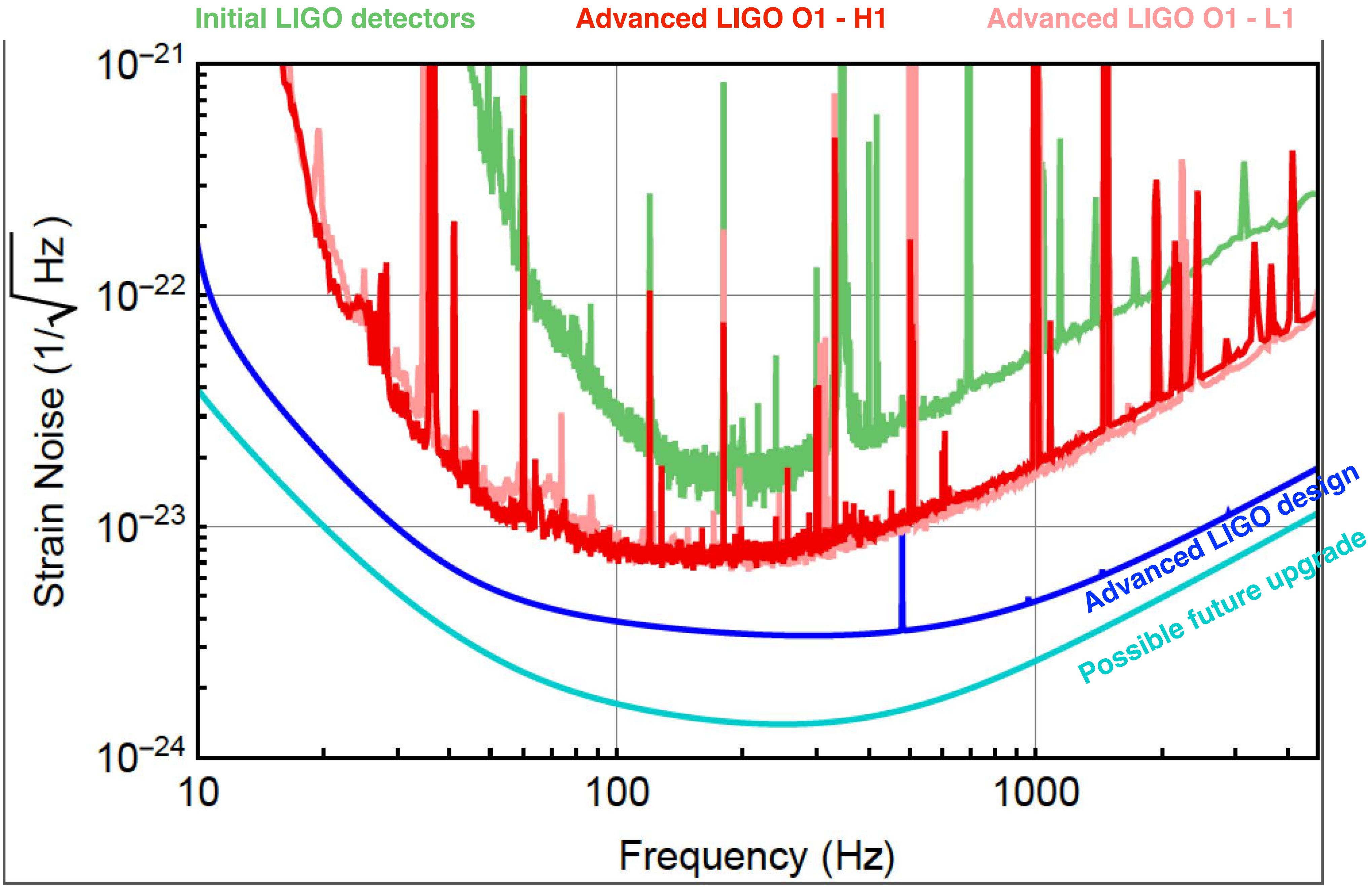
  - Seismic noise
  - Radiation pressure
  - Thermal noise
    - Suspensions
    - Optics

  Sensing noise {Δt_{photon} (f)}

  - Shot noise
  - Residual gas




Quantum noise
Seismic noise
Gravity Gradients
Suspension thermal noise
Coating Brownian noise
Coating Thermo–optic noise
Substrate Brownian noise
Excess Gas
Total noise
Advanced LIGO design
Strain [1/√Hz]
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}
Frequency [Hz]

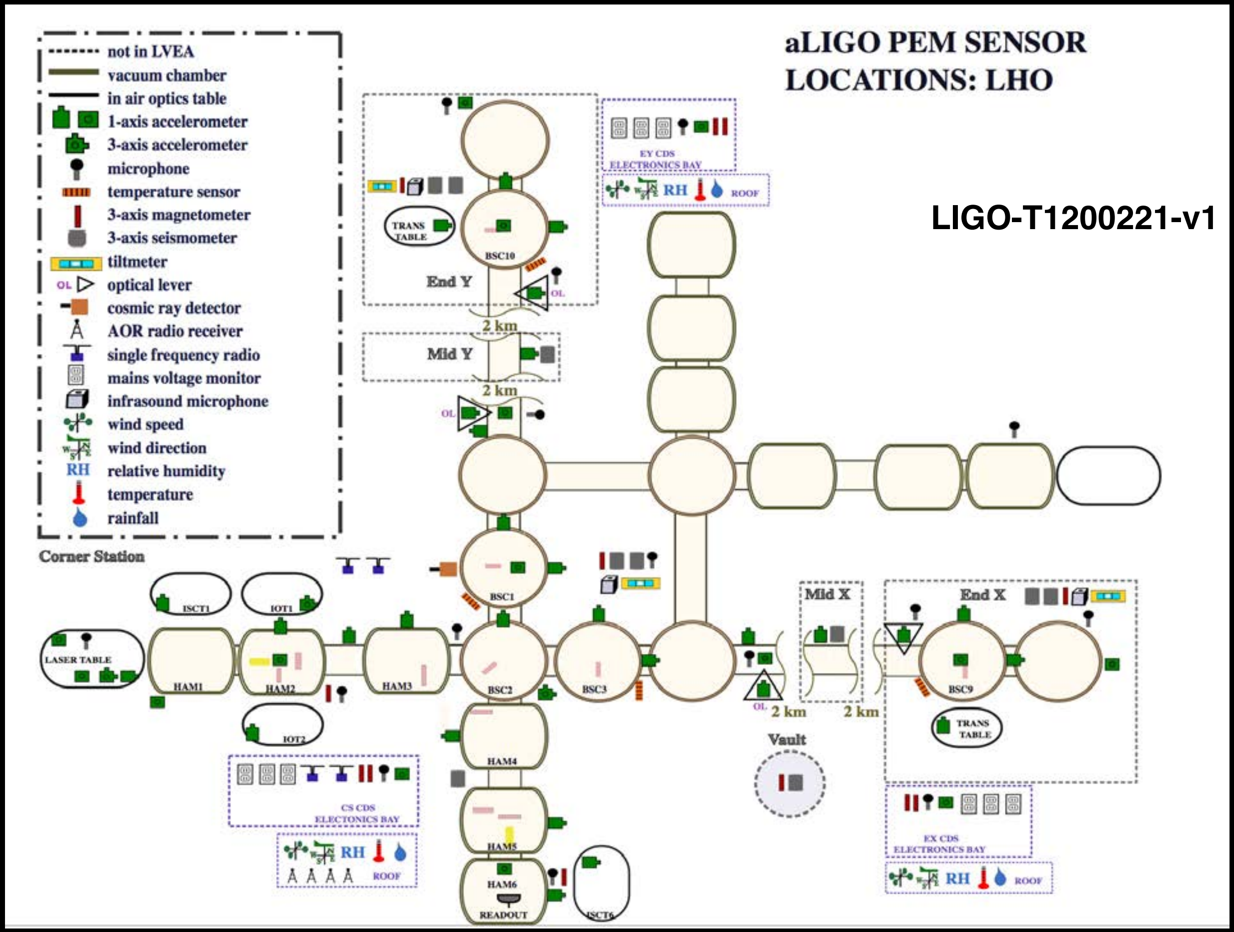


LIGO-P1500237-v10

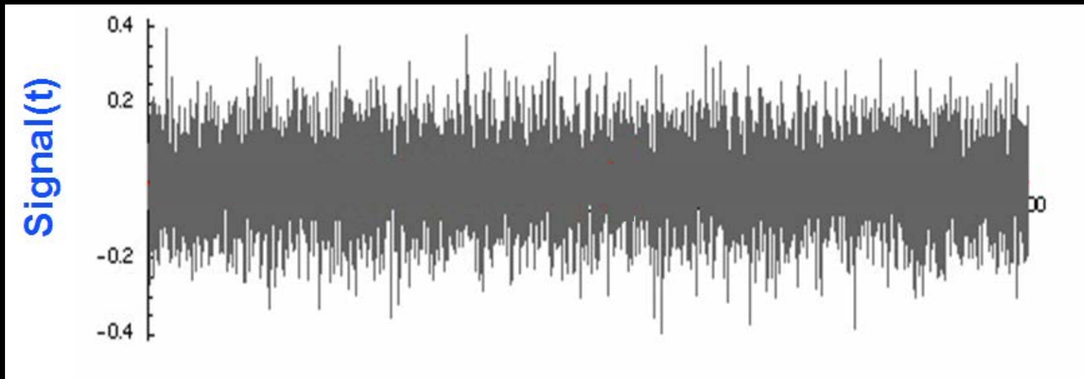
Physics Environment Monitoring

- LIGO-Hanford
  173 sensors
- LIGO-Livingston
  130 sensors

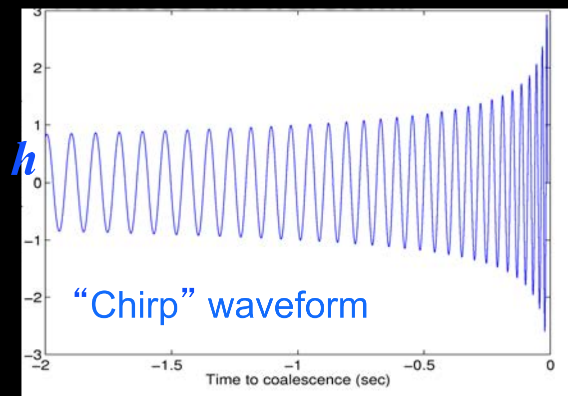
- seismometers and ground tilt sensors
- audio frequency microphones
- power voltage monitors
- fluxgate magnetometers
- accelerometers
- radio frequency receivers
- wind speed sensors
- cosmic ray detector

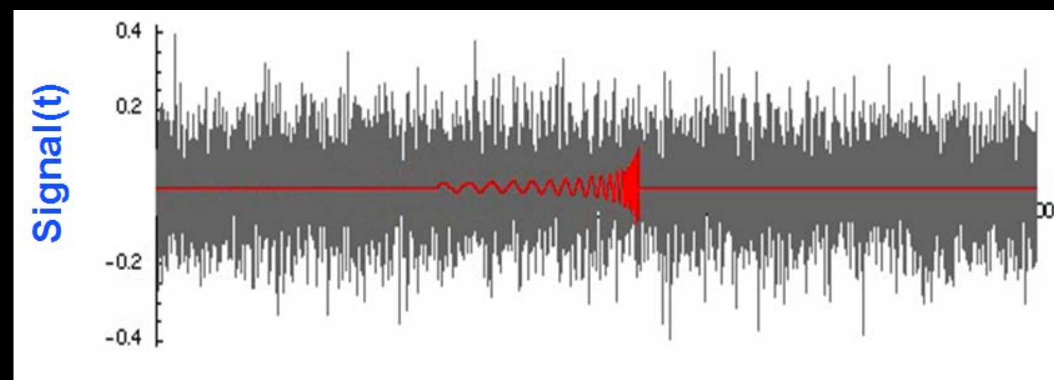


Finding signal in noise dominated data

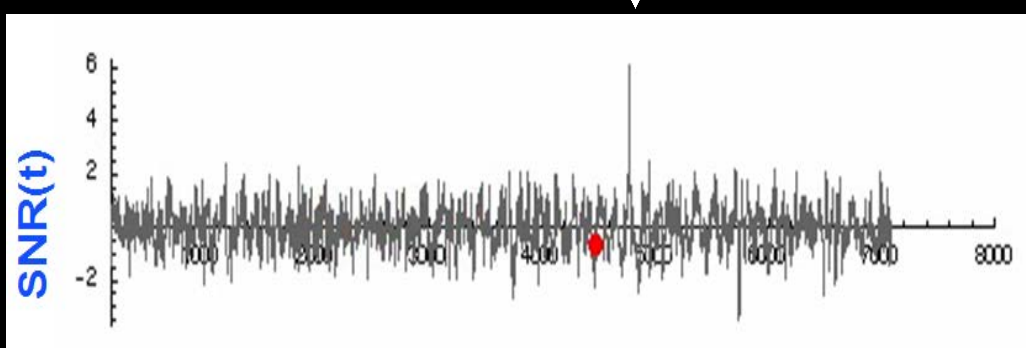


Templates for each candidate signal





Matched filters to pull signal from noise



September 14, 2015 signal

Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

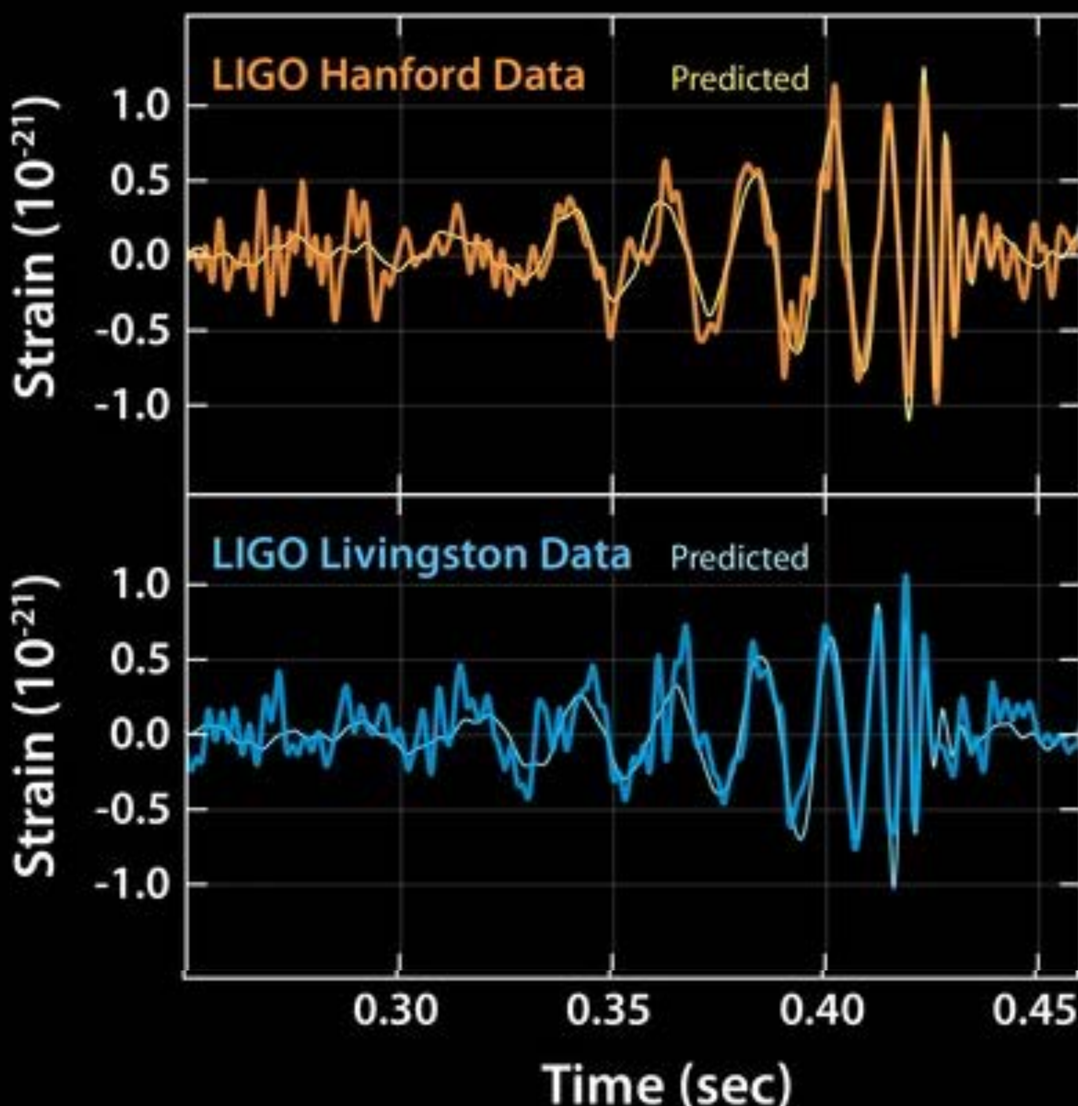
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

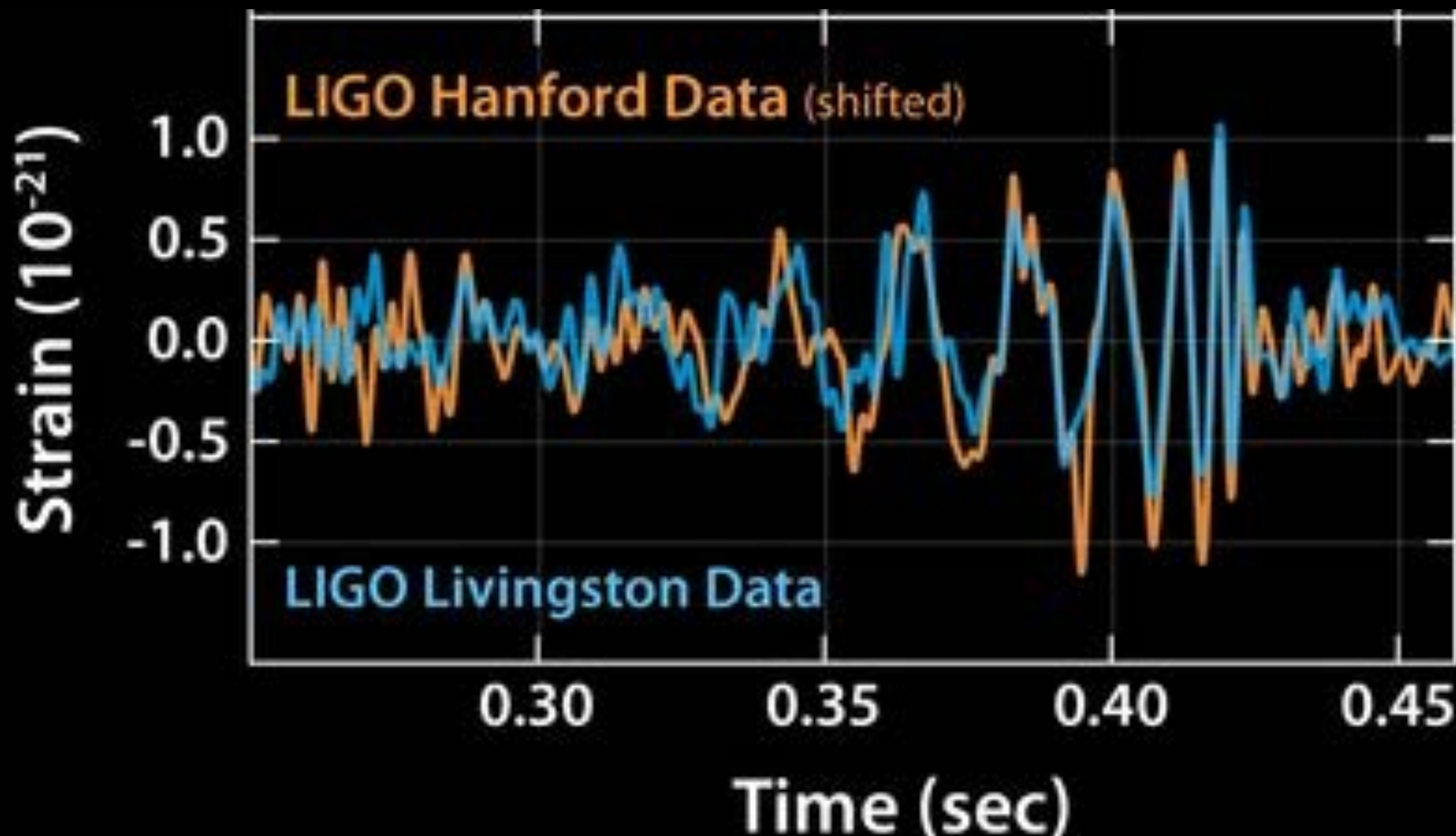
September 14, 2015 signal



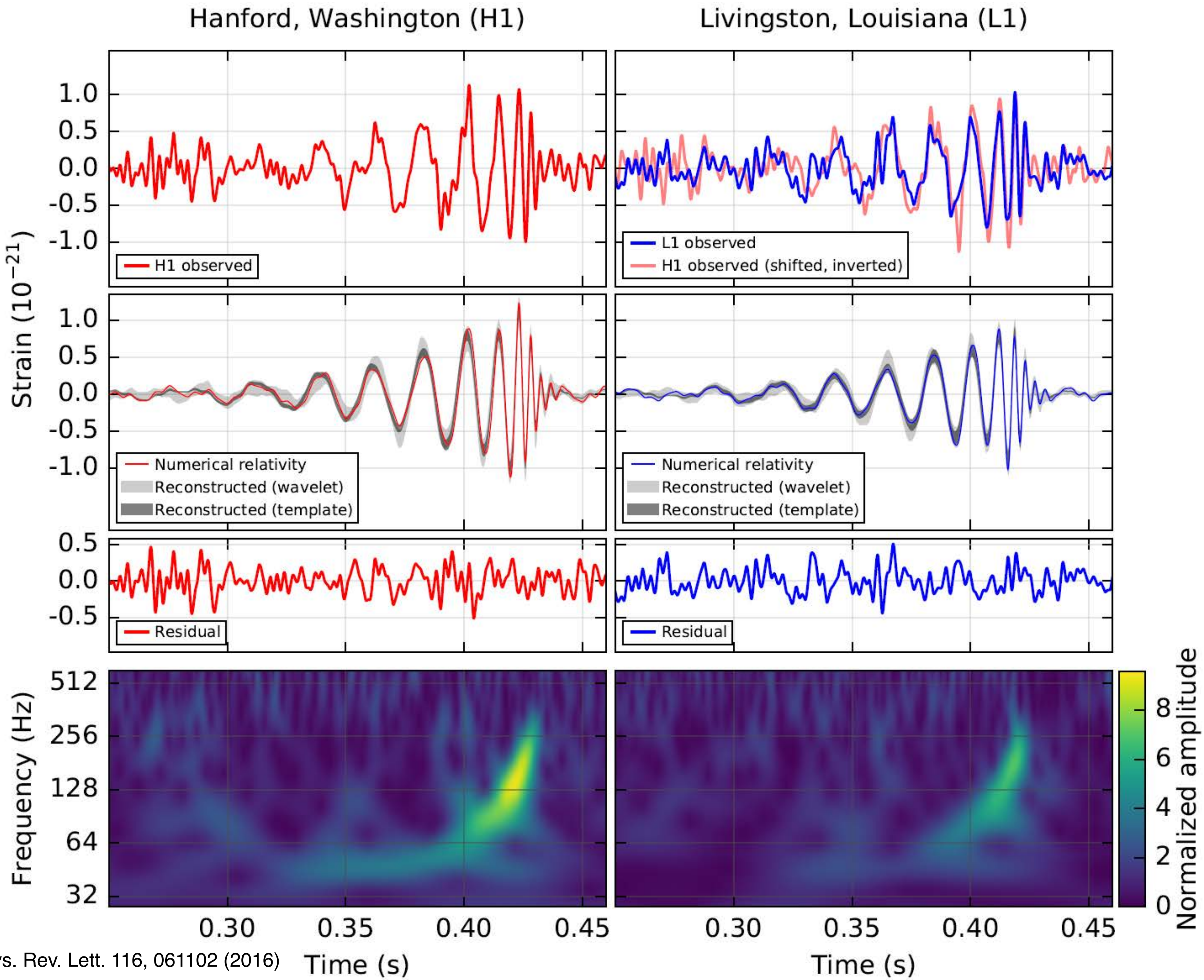
time series filtered with
35–350 Hz band-pass filter and
band-reject filters to remove
strong instrumental spectral lines

September 14, 2015 at 2:51 a.m. Pacific Daylight Time (09:51 UTC)

September 14, 2015 signal

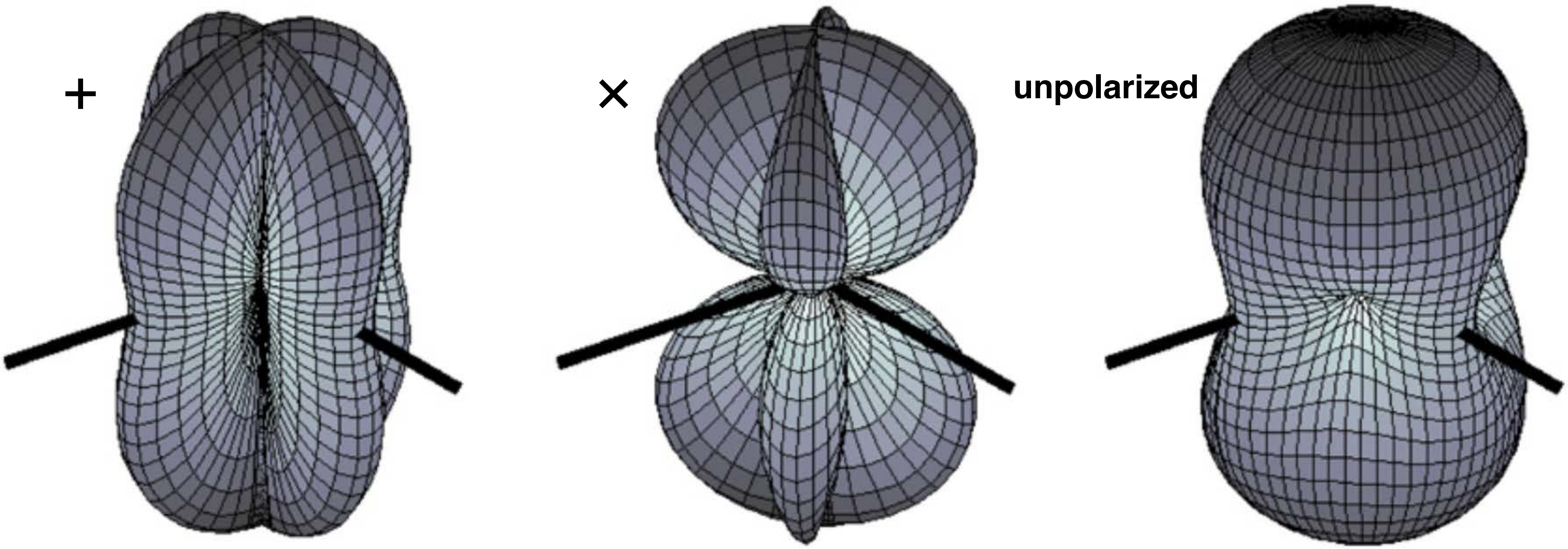


September 14, 2015 at 2:51 a.m. Pacific Daylight Time (09:51 UTC)



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

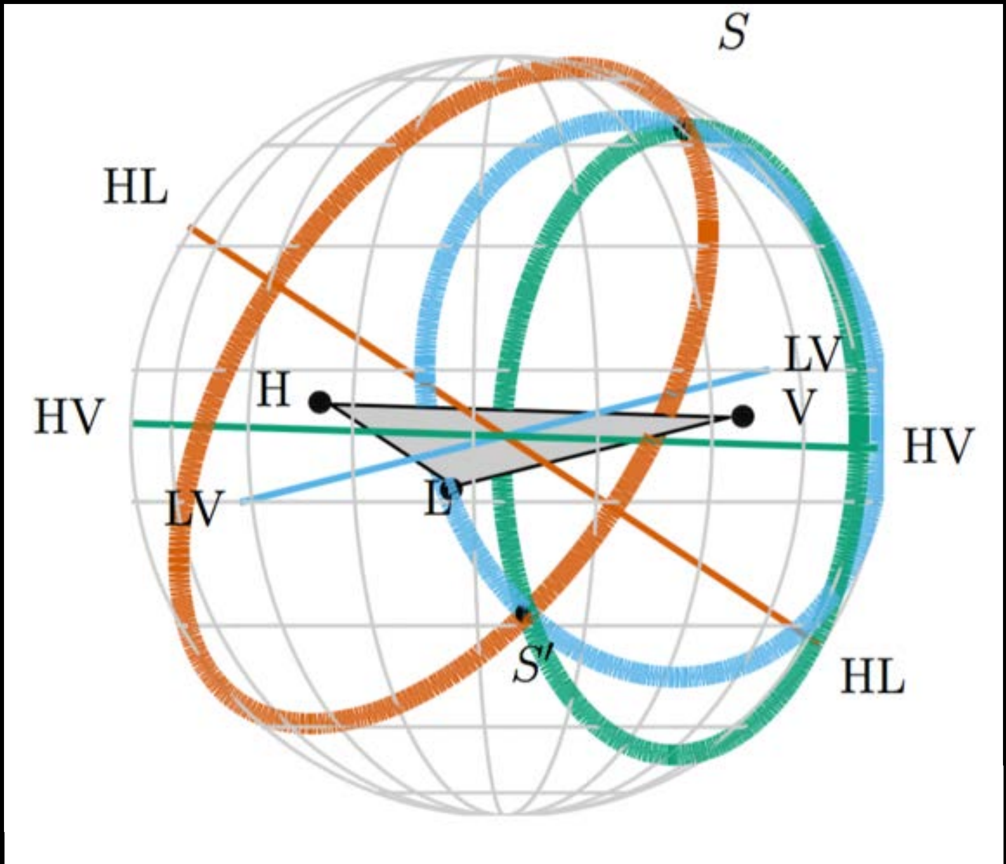
Antenna pattern
- each interferometer



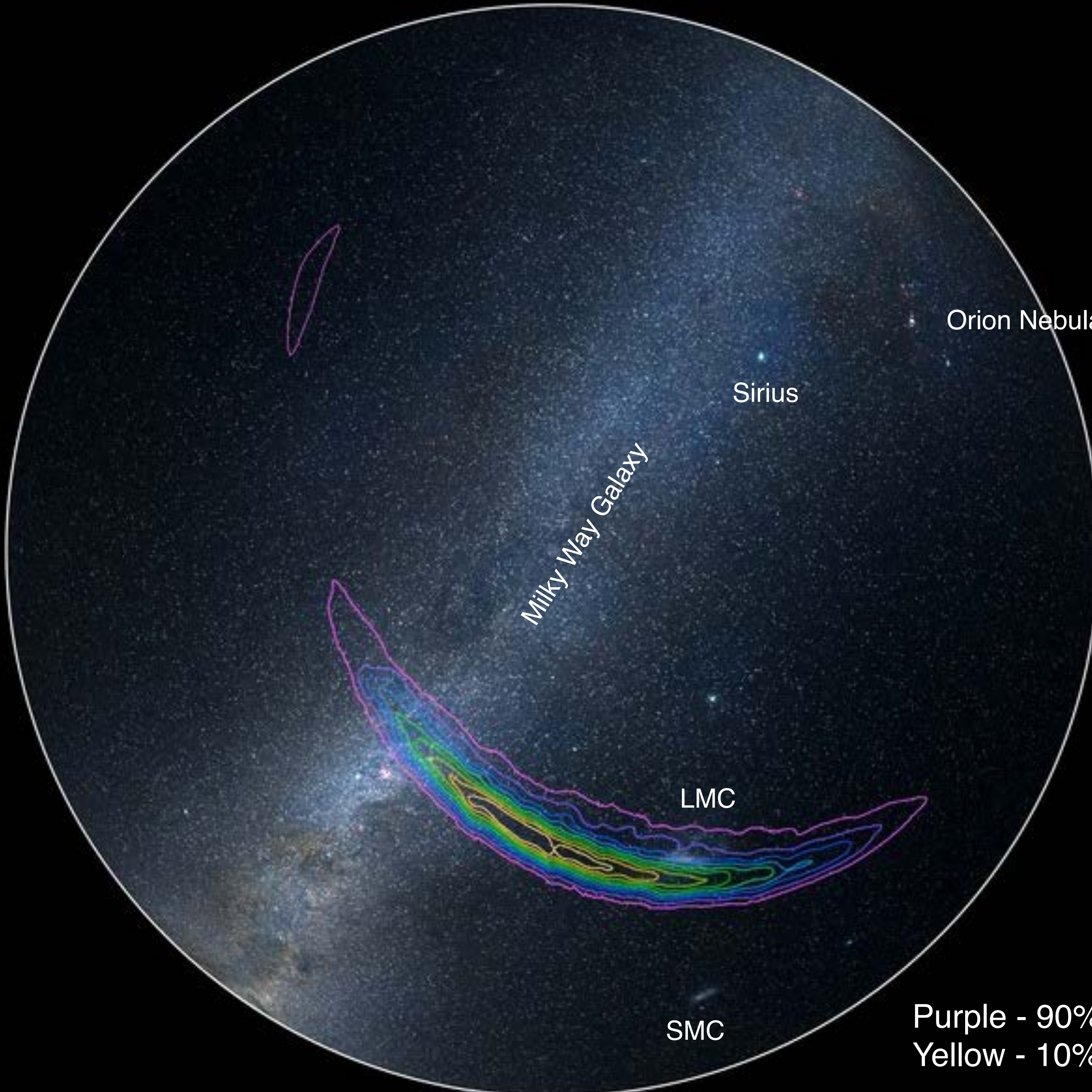
Rep. Prog. Phys. 72 (2009) 076901

Two interferometer localization

- Localization primarily from timing
- Two interferometers produces approximately a ring of possible origins
- A third interferometer (VIRGO in Italy) will sharpen the localization



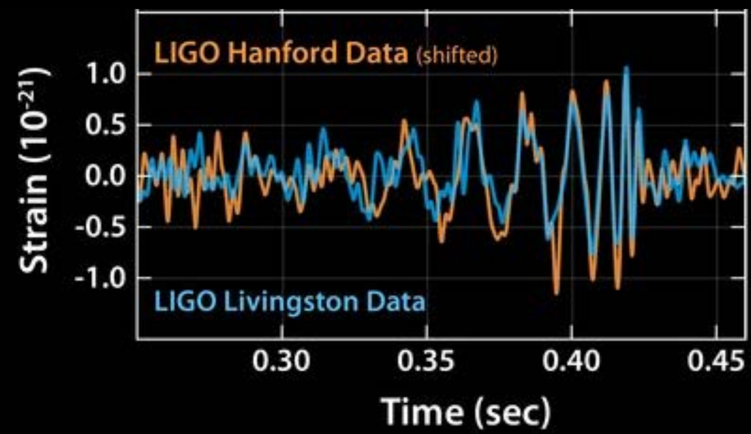
arXiv:1304.0670v3 [gr-qc]



Purple - 90% confidence
Yellow - 10% confidence

What caused GW150914 ?

Over 0.2 s (about 8 cycles) the signal frequency and amplitude increases from **35** to **150** Hz.



Most plausible explanation is the inspiral of two orbiting masses, **m**1 and **m**2, due to gravitational-wave emission.

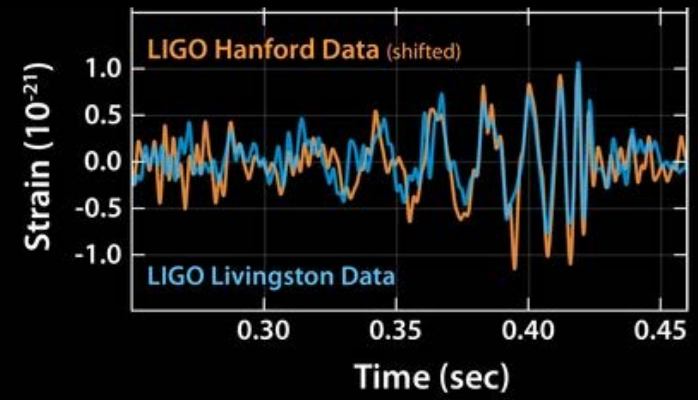
At the lower frequencies, such evolution is characterized by chirp mass:

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

Estimating f and $\dot{f}$ from the data yields a chirp mass of 30 $M_\odot$, implying total mass $M = m_1 + m_2$ is > 70 $M_\odot$ in the detector rest frame.

Only pair that satisfies constraints on waveform is black hole pair.

What caused GW150914 ?



Binary Massive Black Hole Merger

m1 = $36^{+5}_{-4}\,\mathrm{M}_{\odot}$

m2 = $29^{+4}_{-4}\,\mathrm{M}_{\odot}$

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

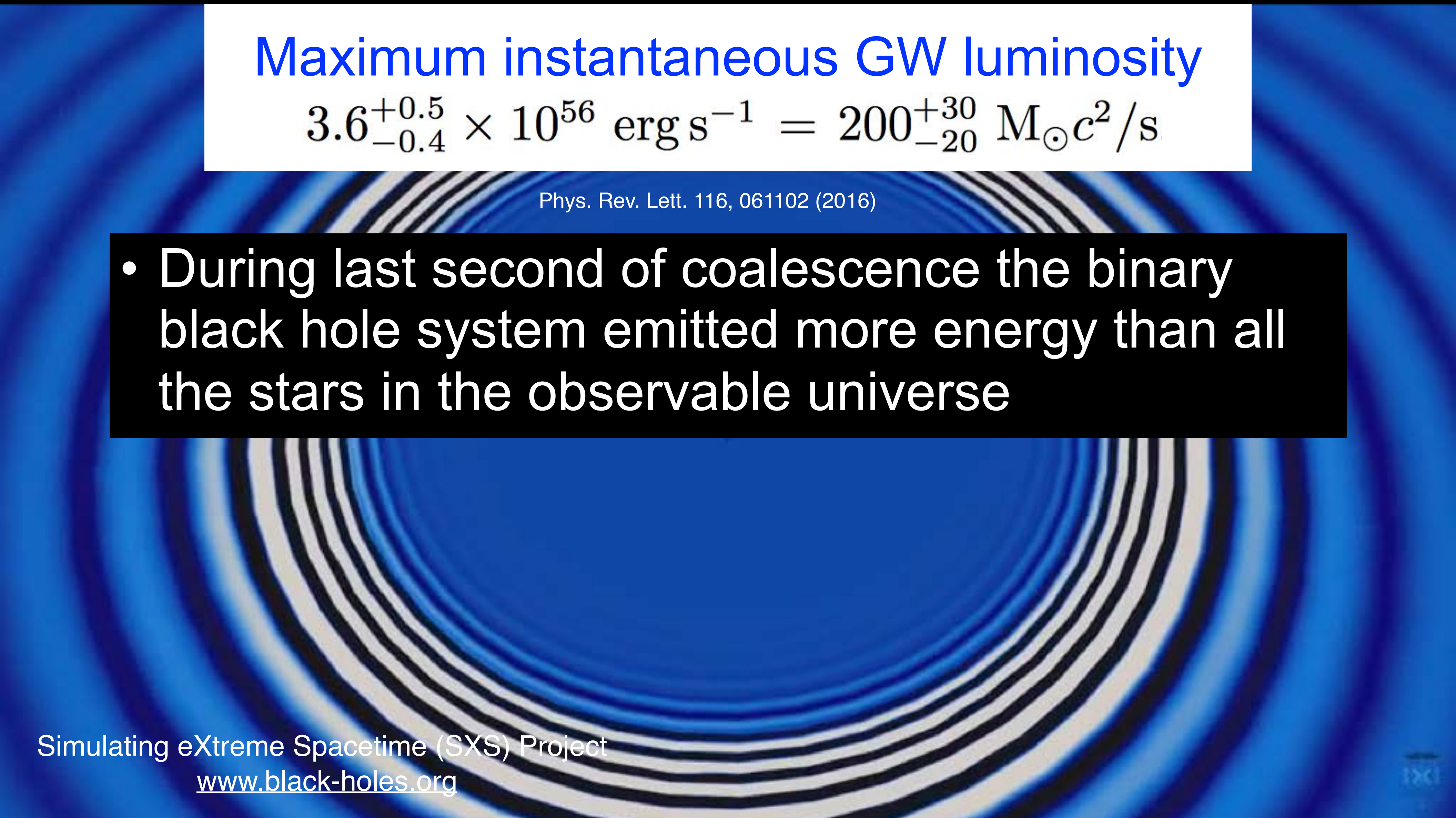
5% of the black hole mass-energy

$$3.0^{+0.5}_{-0.5}\ \mathrm{M}_{\odot}c^{2}$$

converted into gravitational waves

Simulating eXtreme Spacetime (SXS) Project
www.black-holes.org

Enormous output of energy



Maximum instantaneous GW luminosity

$$3.6^{+0.5}_{-0.4} \times 10^{56}\ \mathrm{erg\,s^{-1}} = 200^{+30}_{-20}\ \mathrm{M_{\odot}}c^2/\mathrm{s}$$

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

- During last second of coalescence the binary black hole system emitted more energy than all the stars in the observable universe

Simulating eXtreme Spacetime (SXS) Project
www.black-holes.org

Enormous output of energy

Maximum instantaneous GW luminosity

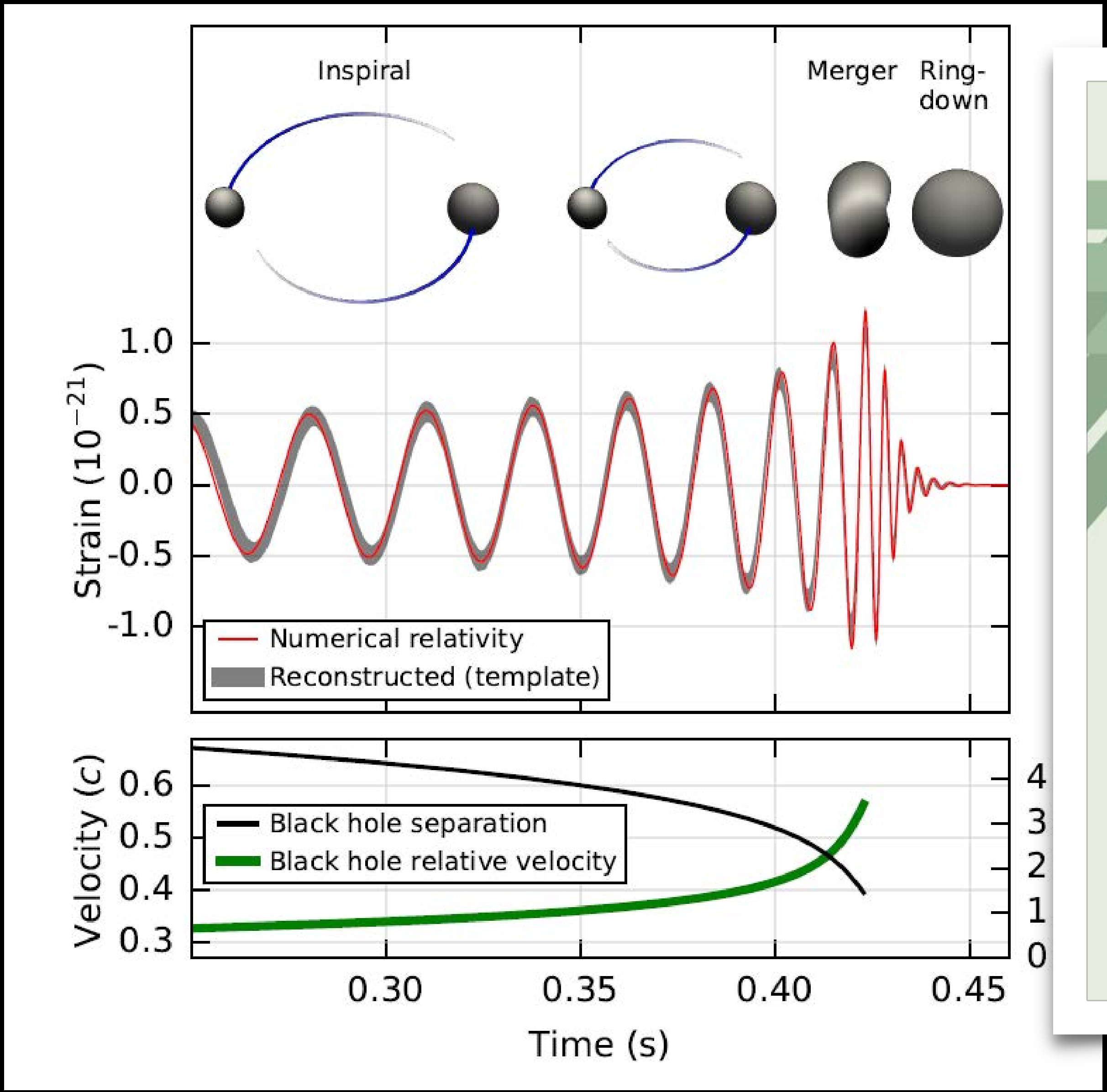
$$3.6^{+0.5}_{-0.4} \times 10^{56}\ \mathrm{erg\,s^{-1}} = 200^{+30}_{-20}\ \mathrm{M_{\odot}}c^2/\mathrm{s}$$

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

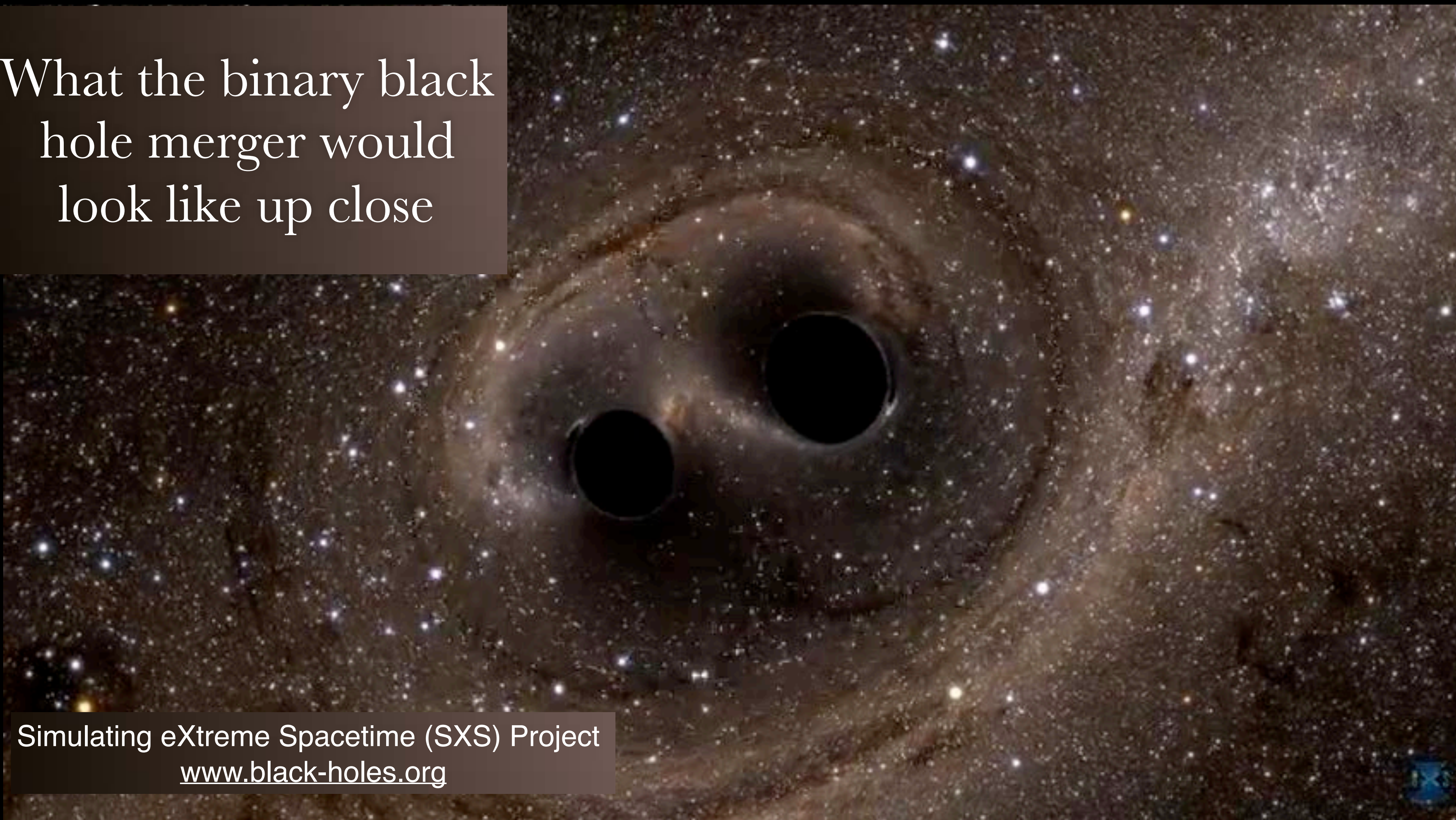
- The flux of energy passing through Earth during the last second (1.5 μW/cm^2) was
  - about a hundred times brighter than the full Moon (20 nW/cm^2)
  - approximately equivalent to the flux of radiation from a cell phone at 1 meter

Simulating eXtreme Spacetime (SXS) Project
www.black-holes.org

What caused GW150914 ?



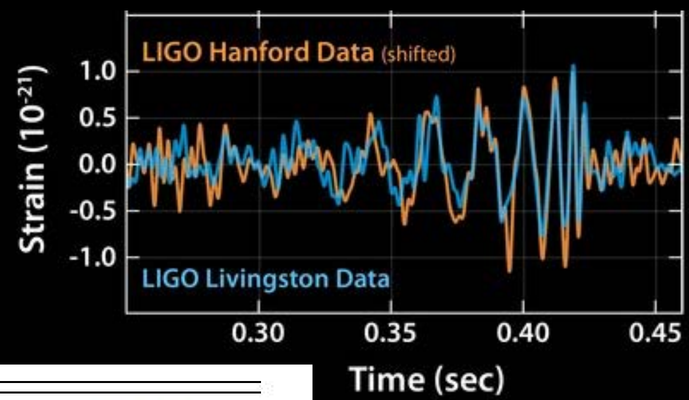
What caused GW150914 ?



What the binary black hole merger would look like up close

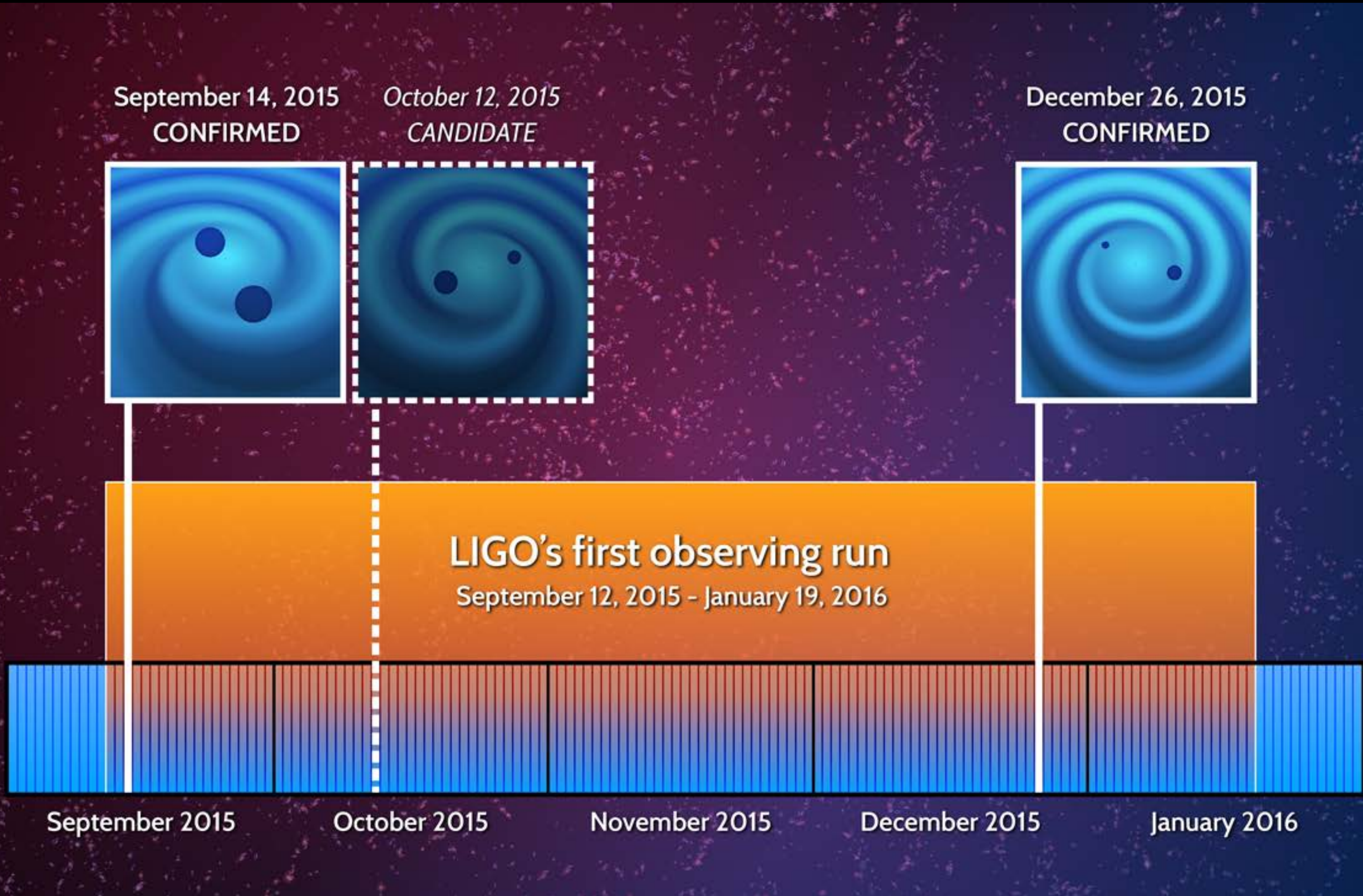
Simulating eXtreme Spacetime (SXS) Project
www.black-holes.org

What caused GW150914 ?



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 = 1.3 billion light-years
Source redshift, z	$0.09^{+0.03}_{-0.04}$

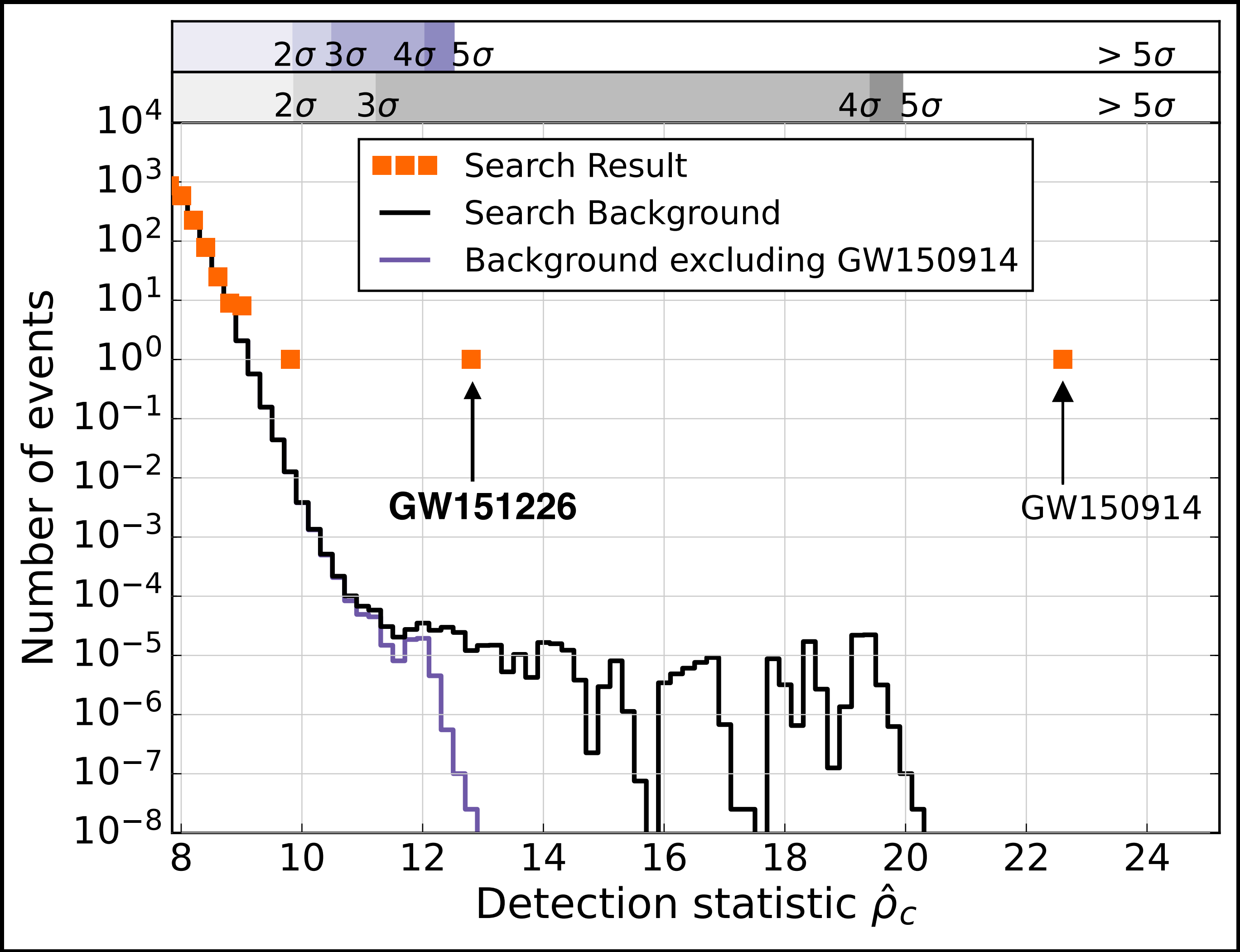
Phys. Rev. Lett. 116, 061102 (2016)

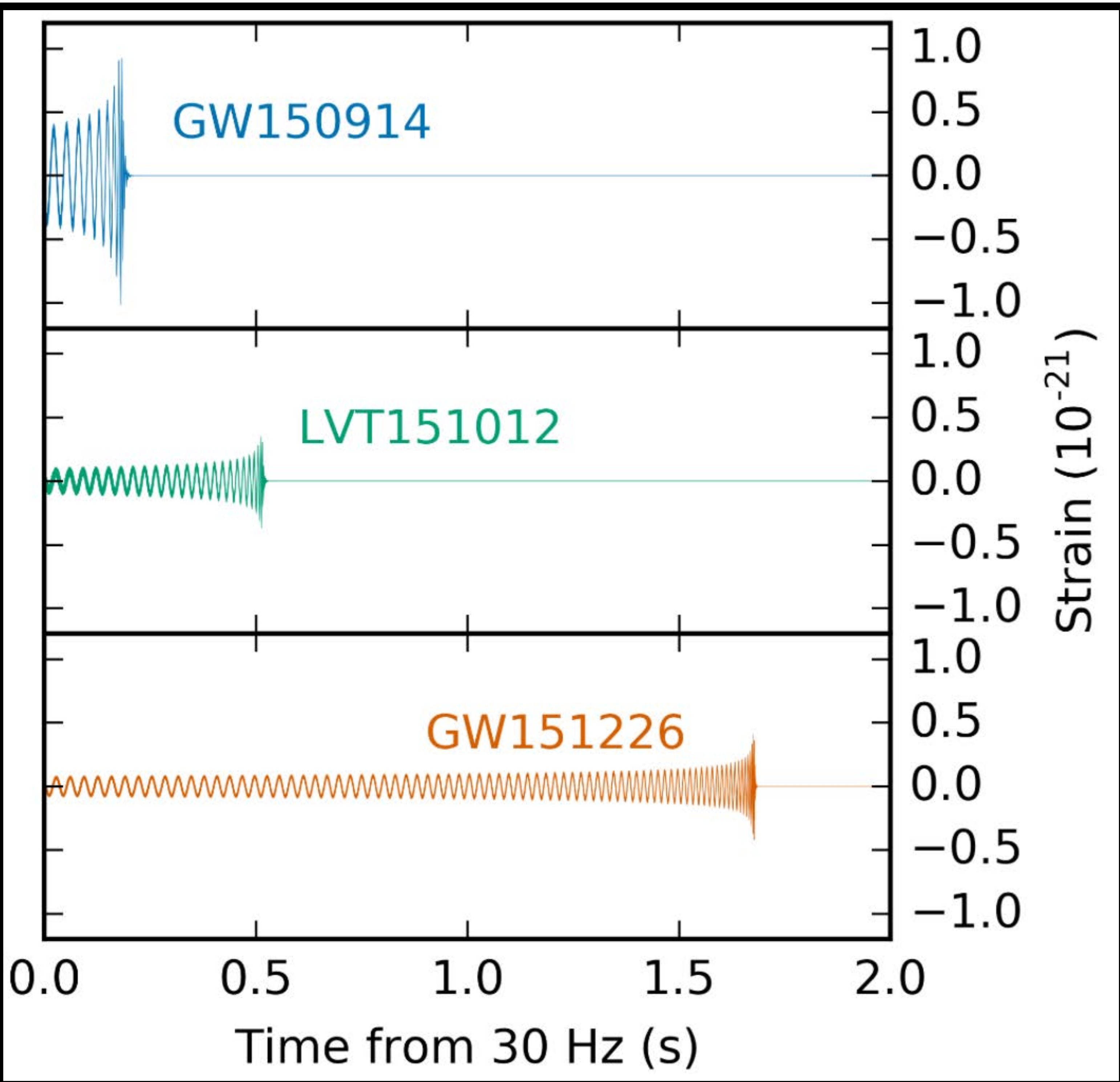

September 14, 2015
CONFIRMED
October 12, 2015
CANDIDATE
December 26, 2015
CONFIRMED
LIGO's first observing run
September 12, 2015 - January 19, 2016
September 2015
October 2015
November 2015
December 2015
January 2016

Search for binary black holes systems

O1 (Sep 12, 2015-Jan 19, 2016, ~48 days of coincident data)

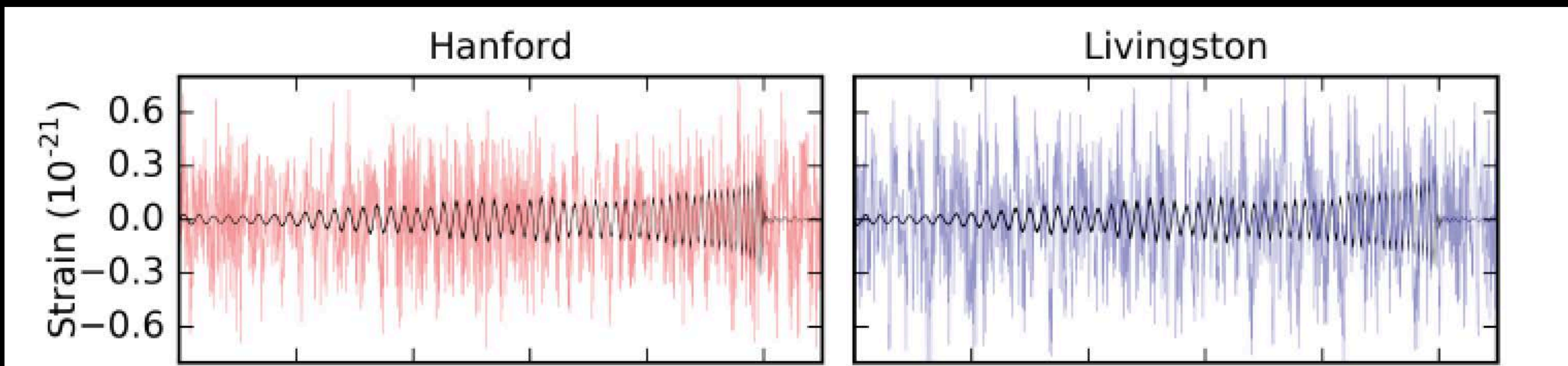
Selection: black hole mass > 2 $M_\odot$ and total mass < 100 $M_\odot$



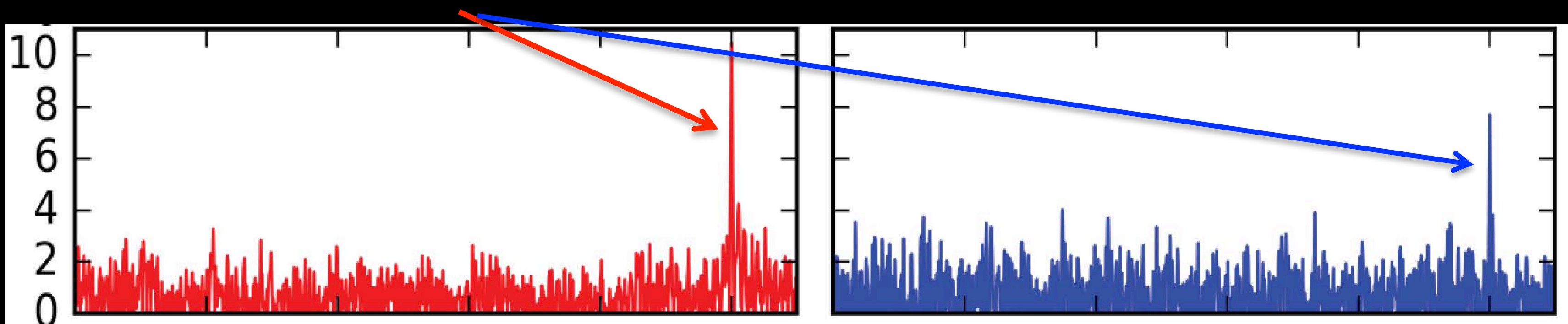

GW150914
LVT151012
GW151226
1.0
0.5
0.0
−0.5
−1.0
Strain (10^{-21})
0.0
0.5
1.0
1.5
2.0
Time from 30 Hz (s)

GW151226

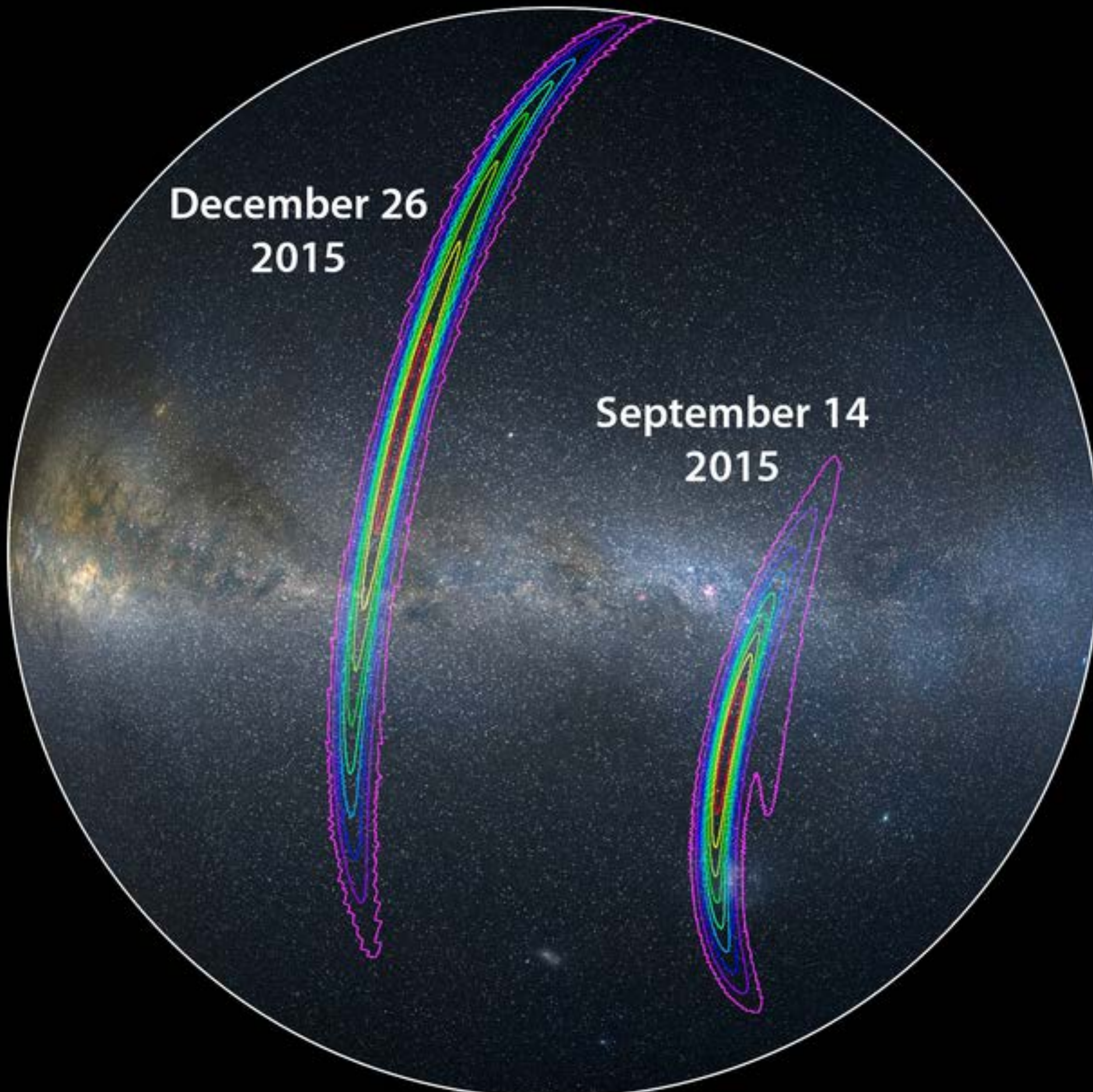
Filtered detector output and filtered best matching waveform



Signal-to-noise (SNR) when best template matches at coalescence time



PRL 116, 241103 (2016)


December 26
2015
September 14
2015

	GW150914	GW151226	LVT151012
Primary mass $m_1^{\text{source}}/\text{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\text{source}}/\text{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Final mass $M_f^{\text{source}}/\text{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Radiated energy $E_{\text{rad}}/(\text{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\text{peak}}/(\text{erg}\,\text{s}^{-1})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance D_L/Mpc	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$

	GW150914	GW151226	LVT151012
Primary mass $m_1^{\text{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
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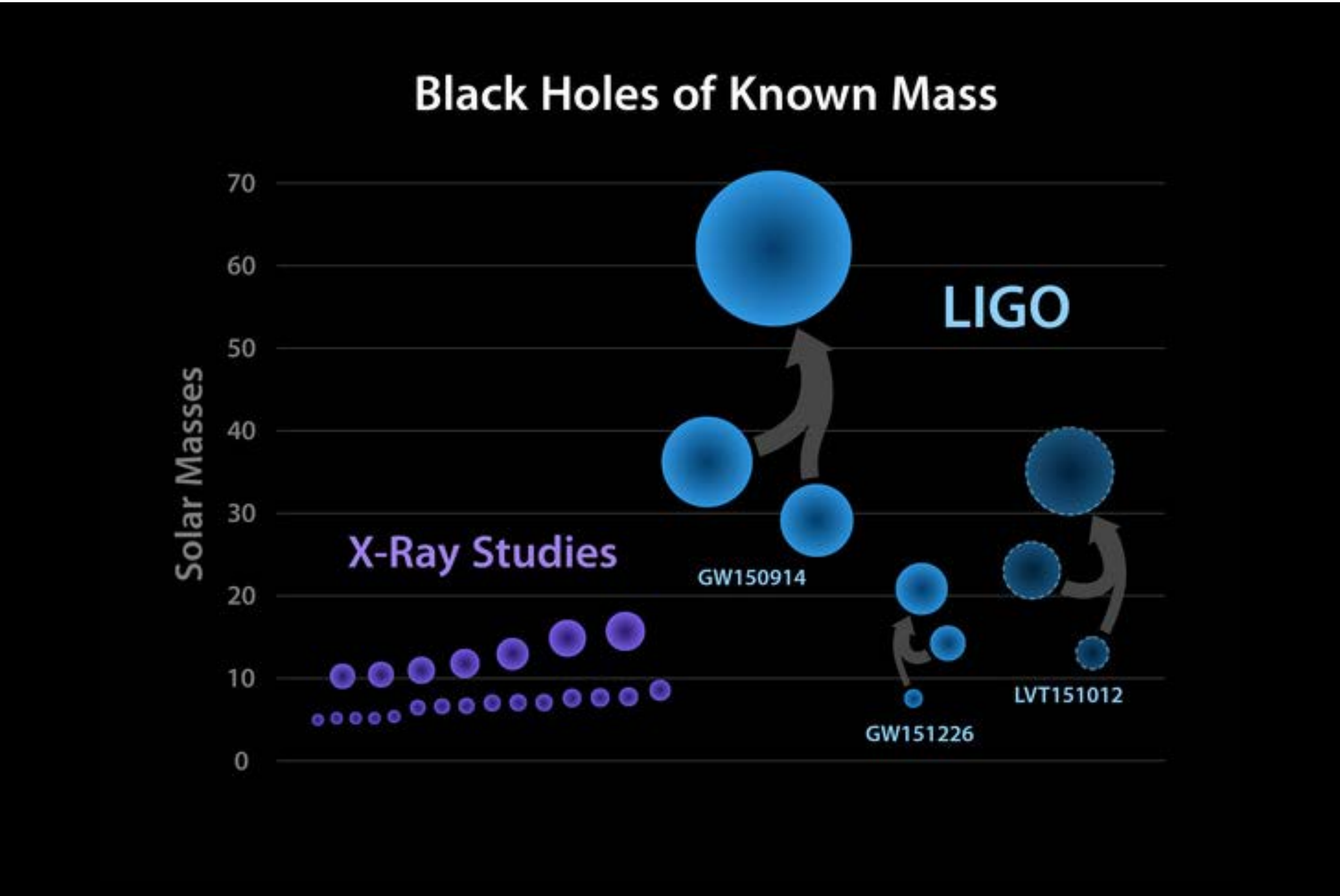
Luminosity distance D_L/Mpc	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Luminosity distance D_L/Giga -light-yrs	**1.4**	**1.4**	**3.3**

Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate $\mathrm{FAR}/\mathrm{yr}^{-1}$	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\,\sigma$	$> 5.3\,\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathscr{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_{\mathrm{f}}^{\mathrm{source}}/\mathrm{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_{f}	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s^{-1}})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600

, 2016

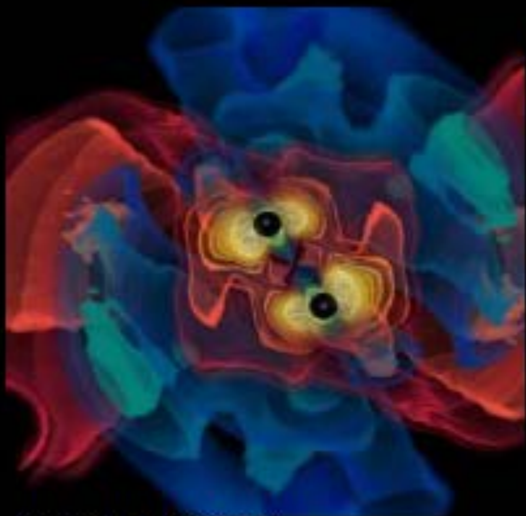

Black Holes of Known Mass
70
60
50
40
30
20
10
0
Solar Masses
X-Ray Studies
LIGO
GW150914
GW151226
LVT151012

Electromagnetic Follow up on GW150914

arXiv:1602.08492

- LIGO/Virgo is trying to capture and identify an EM counterpart to a GW event (as well as neutrino source counterparts)
- More than 70 groups have signed MOUs with LIGO+Virgo
- Most interesting report for GW150914:
  - Fermi GBM weak transient 0.4 s later, ~1 s long
    - arXiv:1602.03920 [astro-ph.HE]
  - False alarm probability estimated to be 0.0022 ⇒ inconclusive
  - Poorly localized, but consistent with GW150914 skymap
  - Appears to have a hard spectrum within GBM band, at least
  - Controversial; e.g., ACS instrument on INTEGRAL saw nothing

Ground-based GW astronomy



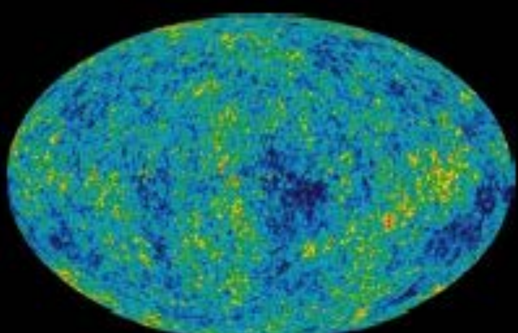
Credit: AEI, CCT, LSU

Coalescing Binary Systems

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

'Bursts'

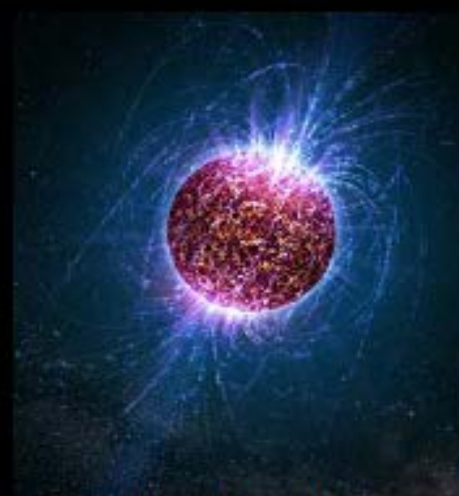
- galactic asymmetric core collapse supernovae
- cosmic strings
- ???



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

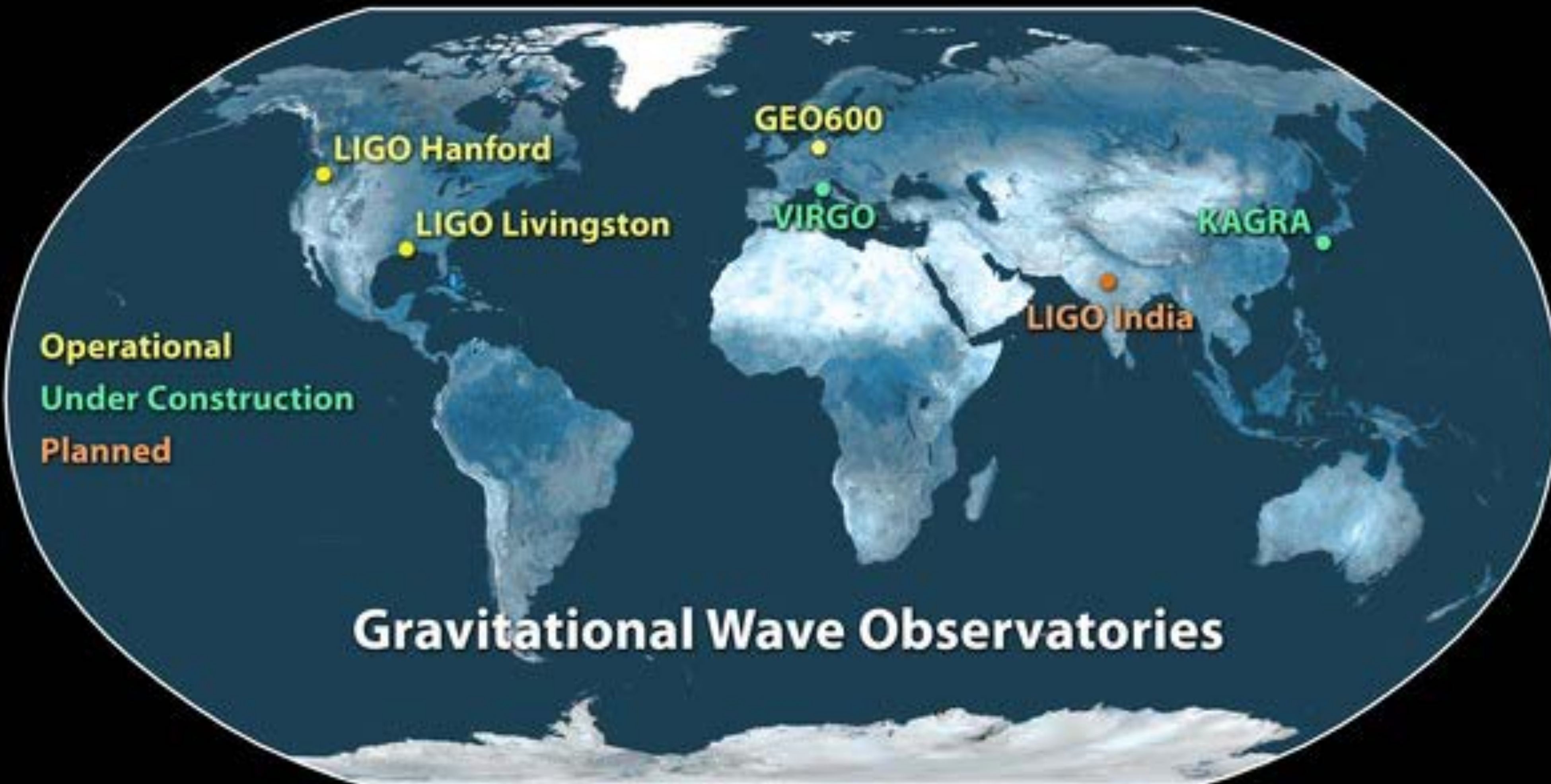


Casey Reed, Penn State

Continuous Sources

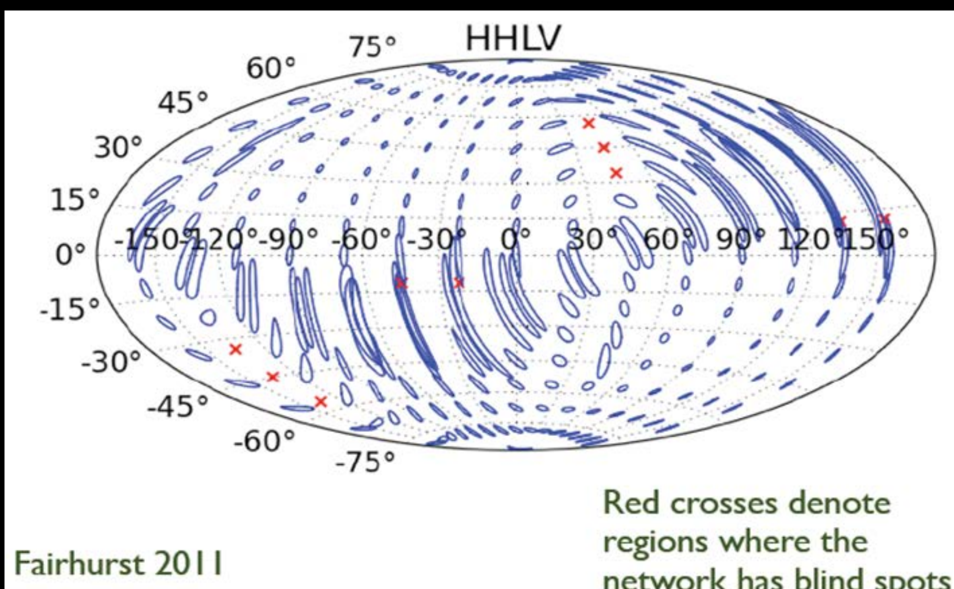
- Spinning neutron stars
- probe crustal deformations, 'EOS, quarki-ness'

Future of Earth-based GWs

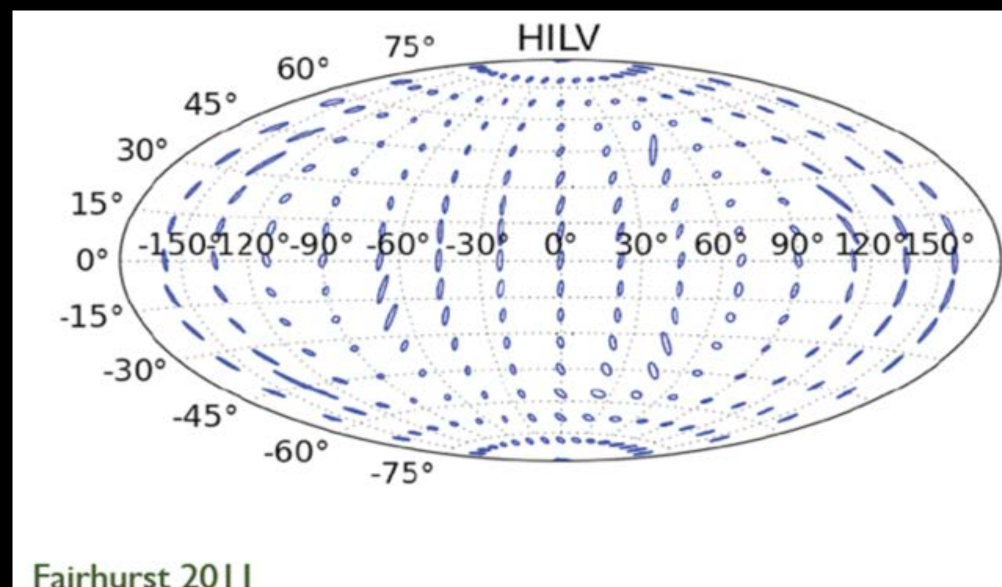


Localization with Global Network

- Source localization with LIGO and VIRGO
  - three interferometers



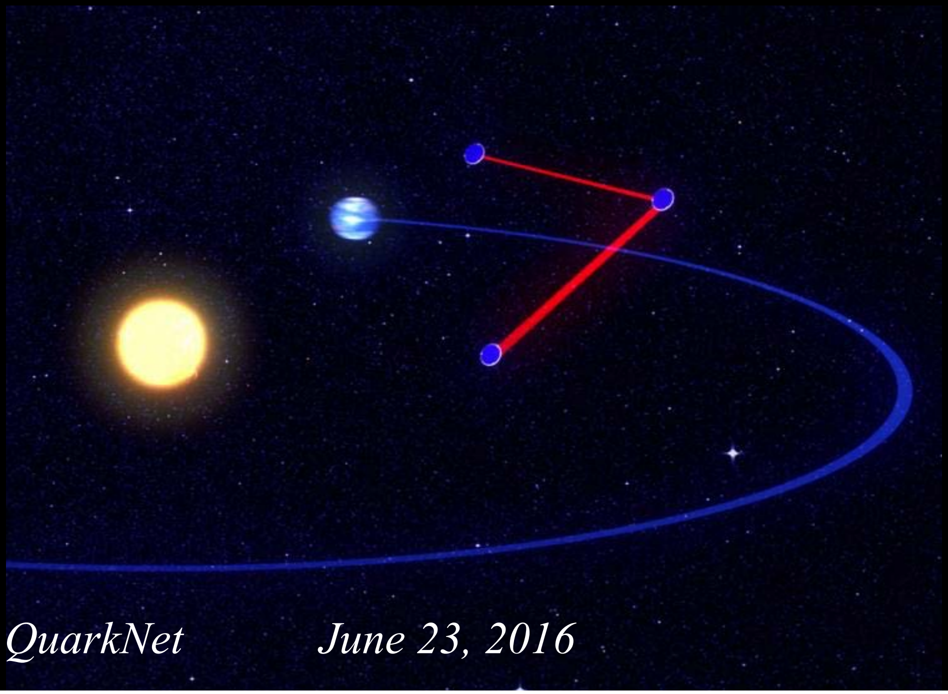
- Source localization with LIGO, VIRGO +India
  - four interferometers



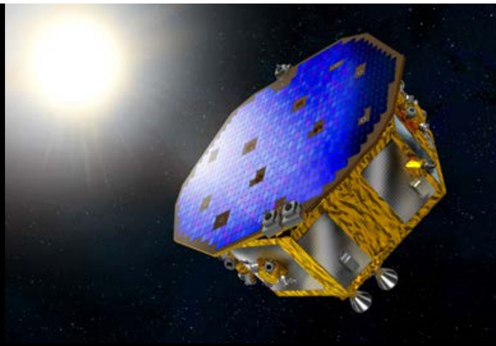
Credit: Stephen Fairhurst, "Improved source localization with LIGO India"

Future for Gravitational Waves in Space?

- eLISA (evolved Laser Interferometer Space Antenna)
  - one “Mother” and two “Daughter” spacecraft orbiting the Sun in a triangular configuration, connected by the two arms of a laser interferometer
  - three satellites, separated by one million kilometers
  - Earth’s orbit around sun, trailing by 20 degrees
  - Sensitive to low frequency (0.1 mHz to 1 Hz) early phase of inspiral



LISA Pathfinder



Test key technologies needed for space-based gravitational wave detector.

Launched December 3, 2015.

FIRST RESULTS: PRL 116, 231101 (2016)

First two months of science operation showed technology exceeding expectations.

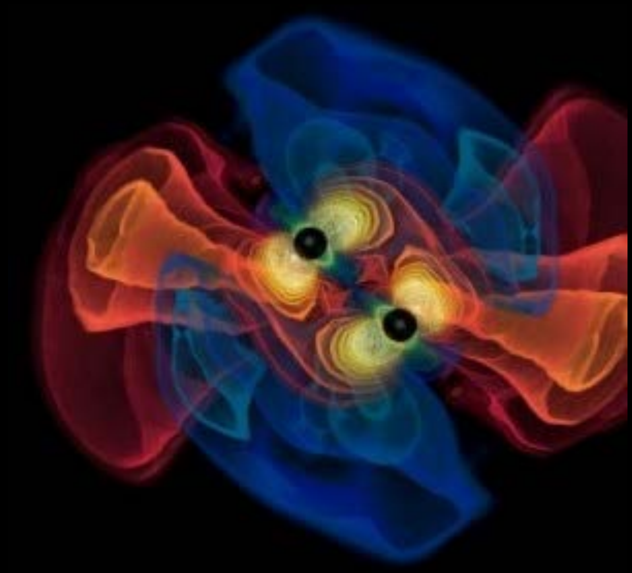
The two freely falling cubes,

unperturbed by other external forces 5 times better than required.

Performance allows for a space-based gravitational wave observatory with sensitivity close to what was originally foreseen for LISA.

Gravitational Wave Astronomy Has Begun!

- Ground-based observations will continue to improve sensitivity and expand with more observing sites
- Space-based systems are being developed



Colliding black holes (Max Planck Institute for Gravitational Physics)

Summary:

Gravitational Waves

- First direct detection (September 14, 2015) achieved by large, international collaboration (LIGO Scientific Collaboration)
- Second significant event discovered December 26, 2015.
- LIGO and other instruments are now using gravitational waves for a new astronomy.
- Finding phenomena invisible to other means of observation!