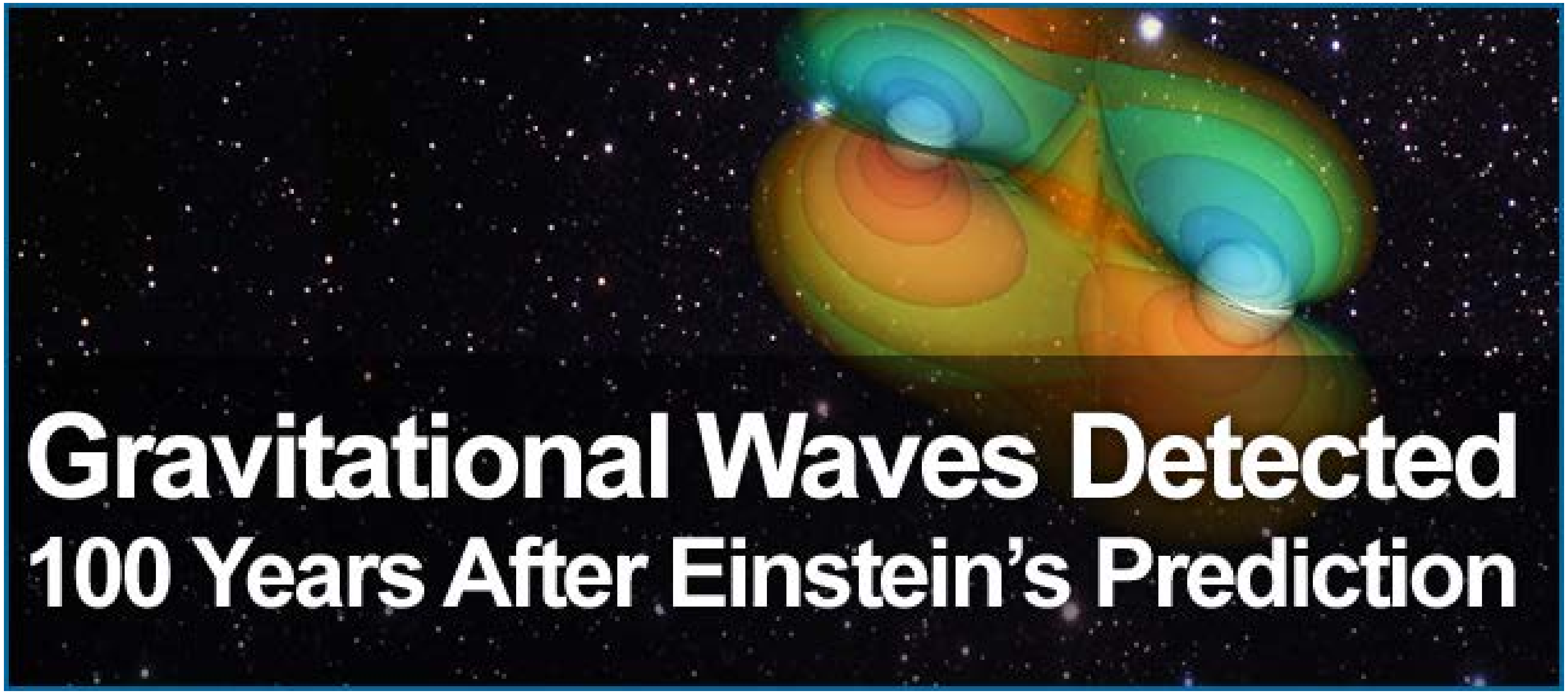


Thomas Corbitt
For the LIGO Scientific Collaboration and the Virgo Collaboration

LIGO

LIGO Scientific Collaboration

LSC

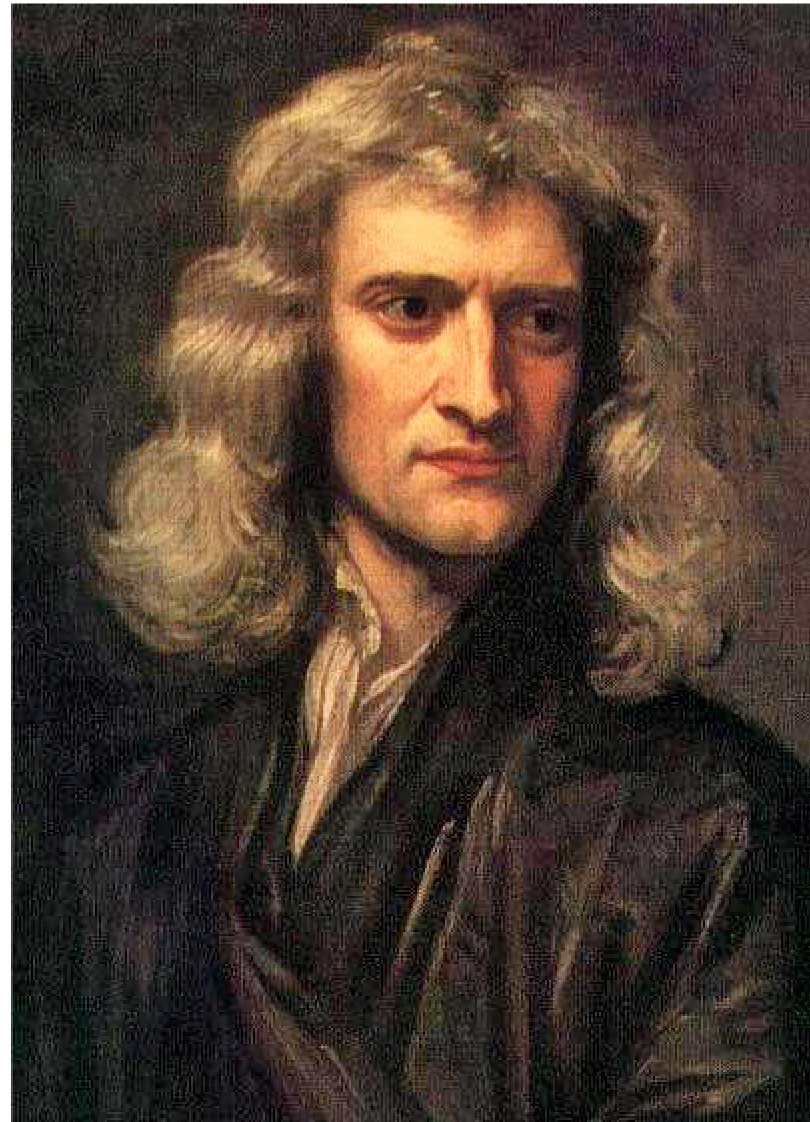
Trinity University
University of Maryland
Andrews University
Washington State University
California State University Fullerton
The University of Alabama in Huntsville
Whitman College
American University Washington, DC
Sonoma State University
indigo
Montclair State University
University of Glasgow
Australian National University
University of the West of Scotland UWS
Texas Tech University
清華大學 Tsinghua University
R·I·T
Max Planck Institute for Gravitational Physics Albert Einstein Institute
University of Strathclyde
Michigan
CITA ICAT
Università degli Studi del Sannio
NASA Goddard Space Flight Center
The University of Western Australia
University of Cambridge
ICTP SAIFR
Southern University Agricultural & Mechanical College
Columbia University in the City of New York
The University of Chicago
Montana State University
Caltech
University of Minnesota
The University of Mississippi
The University of Adelaide Australia
University of Birmingham
The University of Melbourne
Universitat de les Illes Balears
University of Washington
UTRGV
University of Wisconsin UW Milwaukee
Northwestern
Syracuse University
Cardiff University Prifysgol Caerdydd
Monash University
INPE
UF University of Florida
Georgia Institute of Technology
Korean Gravitational-Wave Group
LSU Louisiana State University
ACIGA
University of Southampton
Charles Sturt University
Embry-Riddle Aeronautical University
Leibniz Universität Hannover
Penn State
Science & Technology Facilities Council Rutherford Appleton Laboratory

What if you were there?

Newtonian Gravity

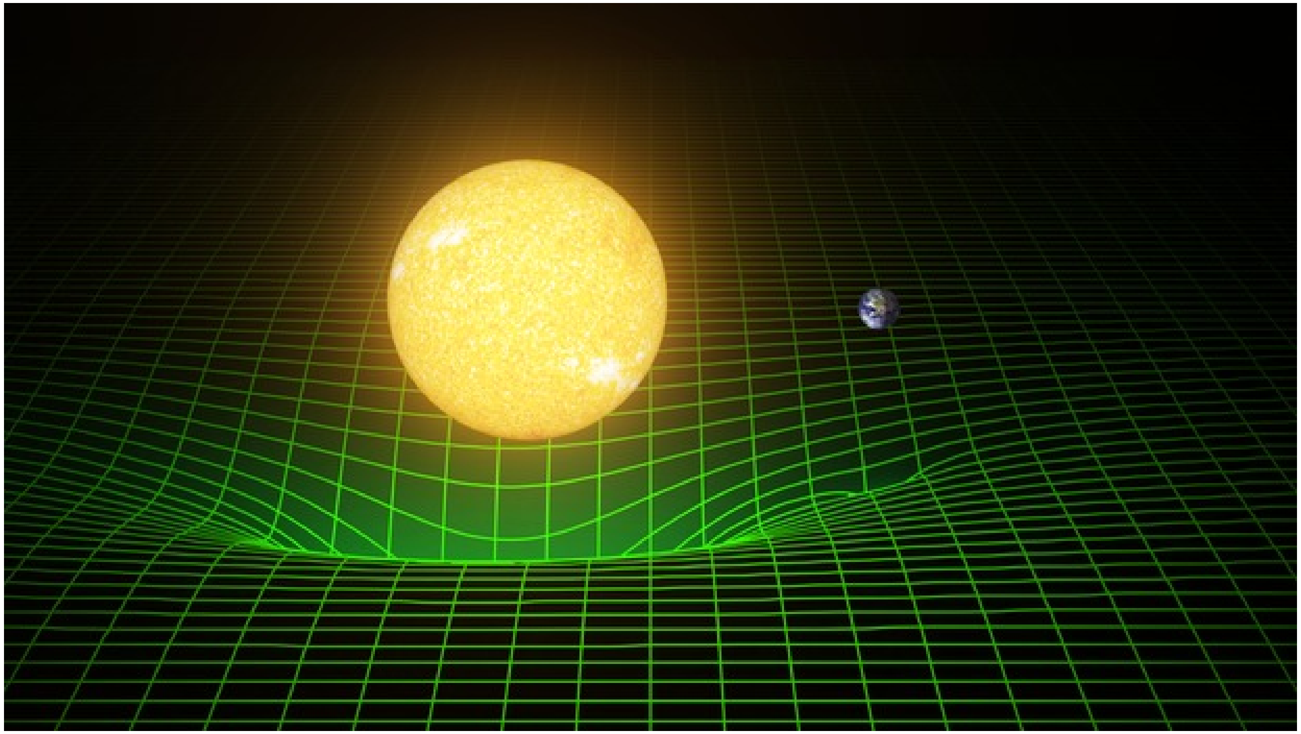
- Published in 1687
- Gravitational force is transmitted instantaneously

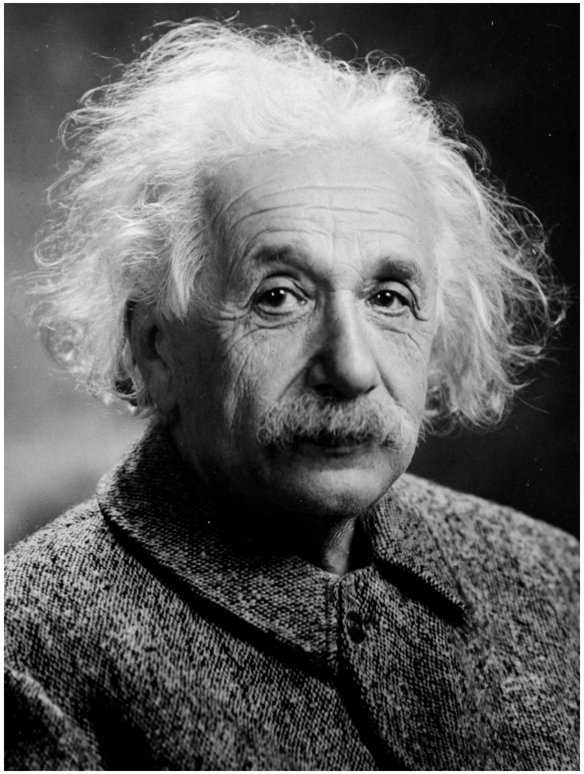
$$F = \frac{Gm_1m_2}{r^2}$$



Albert Einstein predicted the existence of gravitational waves in 1916, as part of the theory of General Relativity. In this theory, gravity is not just a force, but the curvature of space-time. Gravity also does not travel instantaneously, but at the speed of light.

Einstein thought that the waves would be too small to ever be detected – space is very stiff!

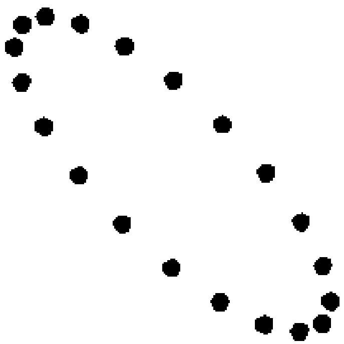


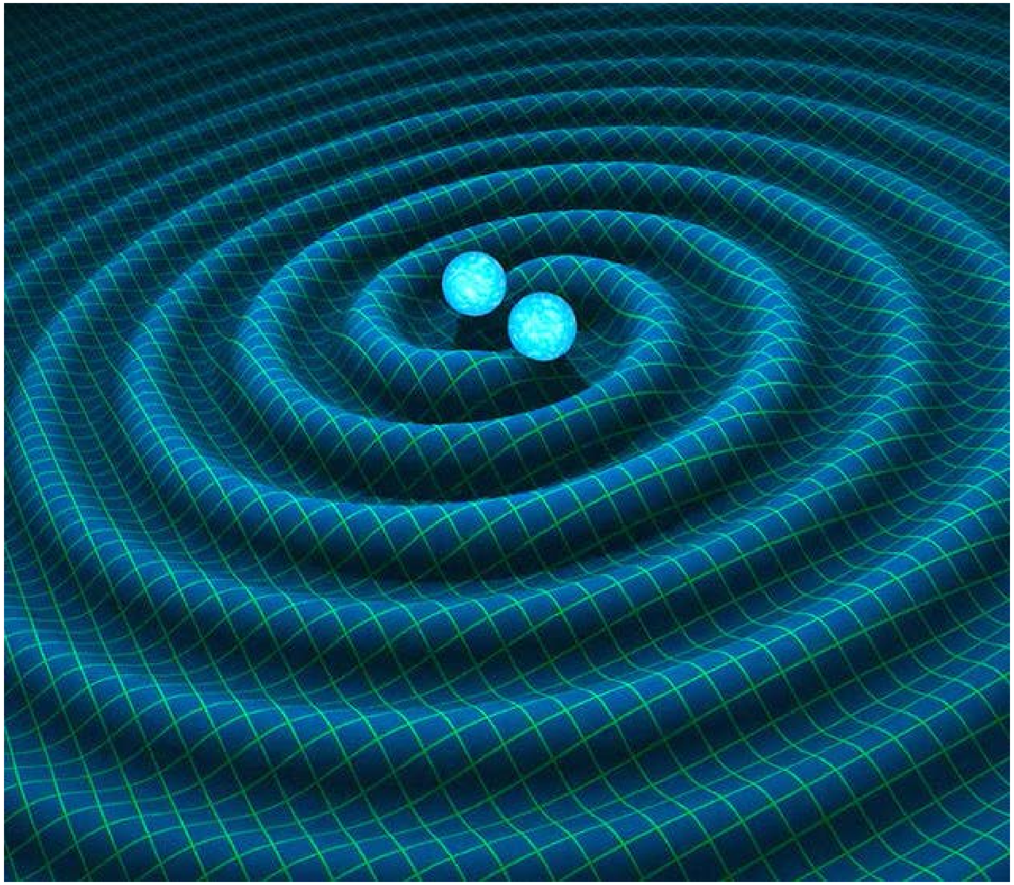


“Spacetime tells matter how to move; matter tells spacetime how to curve.” John Wheeler

Gravitational waves

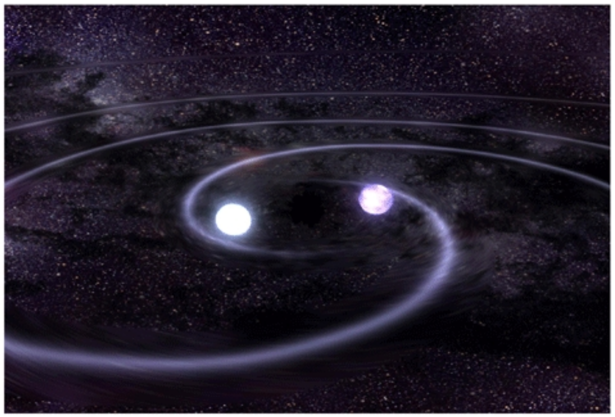
- Ripples in the fabric of spacetime
- Travel at the speed of light
- Stretch and squeeze space as they pass

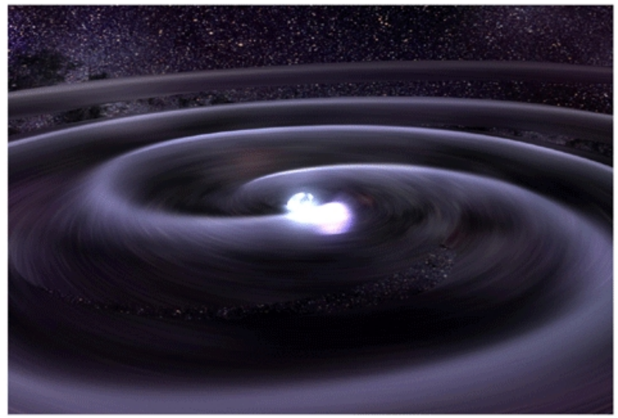


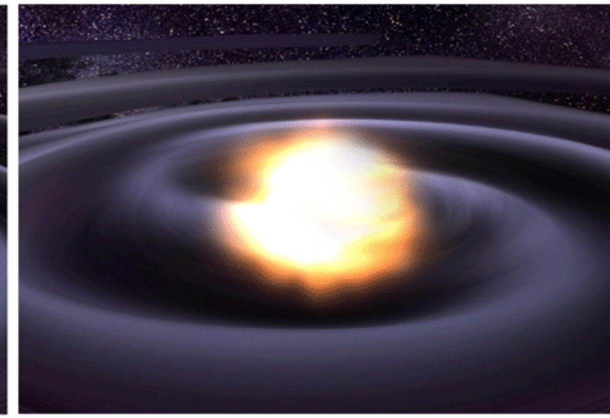


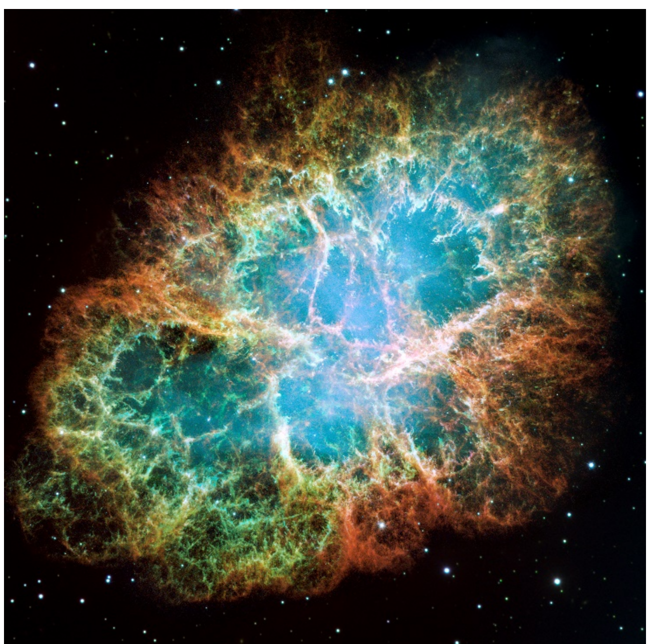
Gravitational wave sources

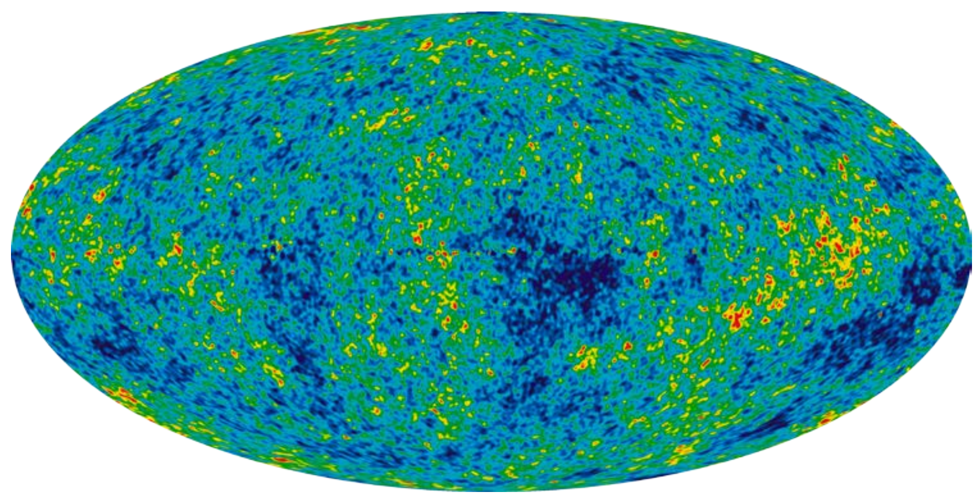
- Need large mass accelerating rapidly – compact binaries, supernova, big bang











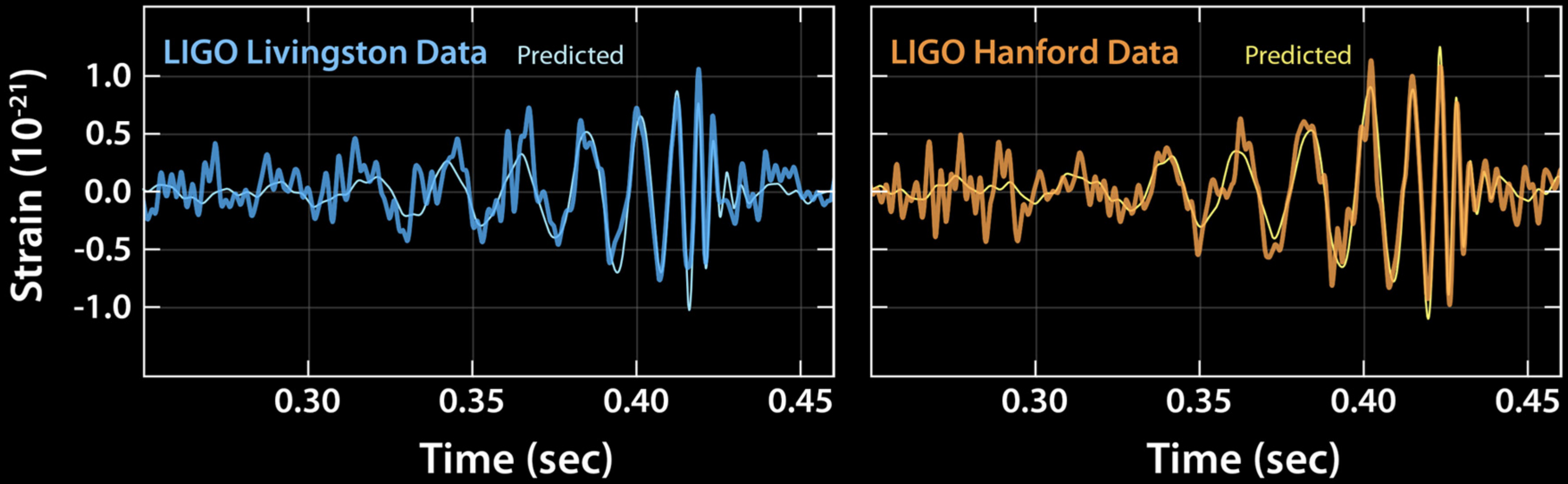
Gravitational waves

Animation created by R. Hurt, Caltech/MIT/LIGO Lab

The effect of gravitational waves

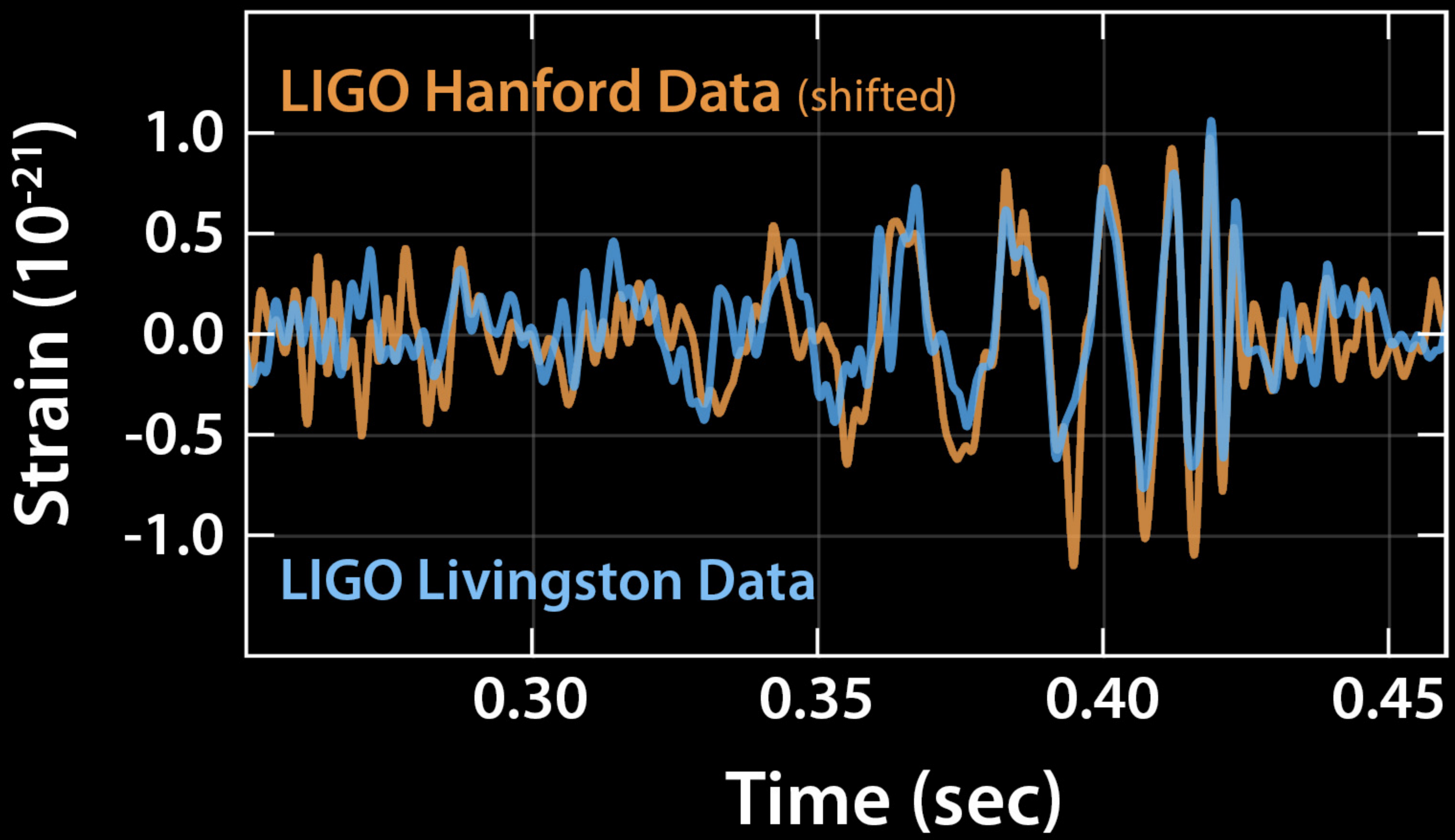
- As the gravitational waves pass the Earth, they alternately stretch and squeeze space. By how much?
- Measured in strain – $h = \frac{\Delta L}{L} \approx 10^{-21}$
- For a reasonable sized detector of 4 km, this leads to a distance of about 10^{-18} m, or about 1/1,000 the diameter of a proton.
- How small is 10^{-21}?
  - There are roughly 10^{21} grains of sand in all the beaches of the world.

What was observed?



B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) Phys. Rev. Lett. **116**, 061102

What was observed?



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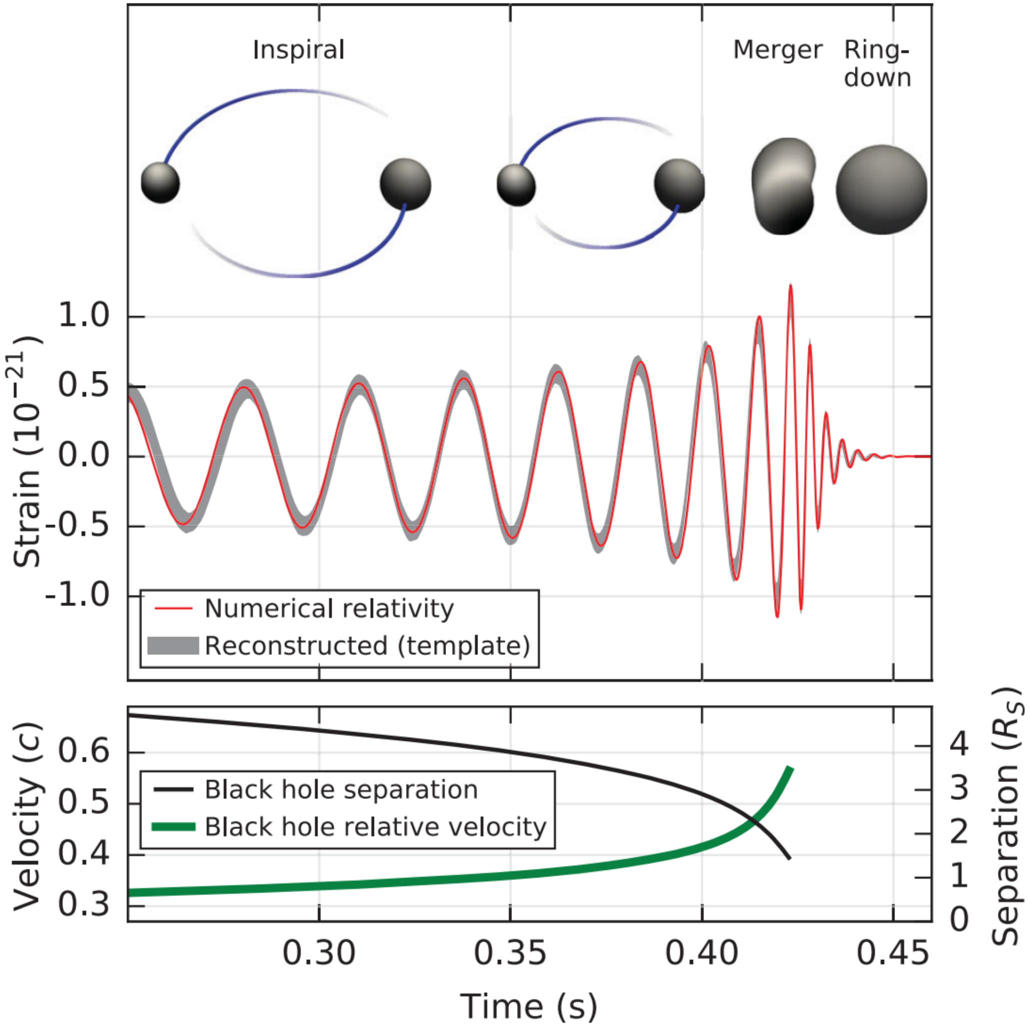
Waveform



B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) Phys. Rev. Lett. **116**, 061102

B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration)
Phys. Rev. Lett. **116**, 061102

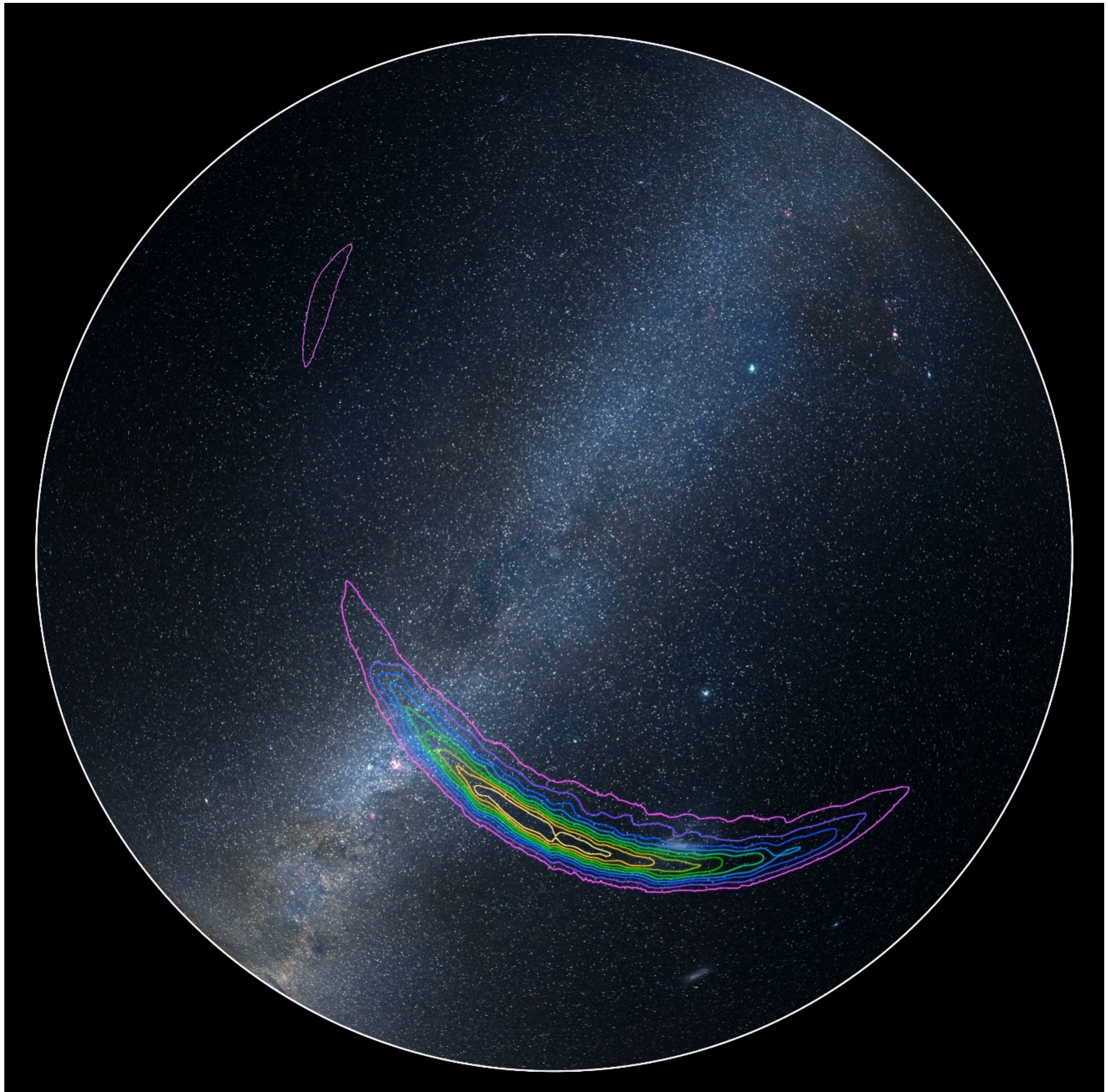
What do we know about the black holes?

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

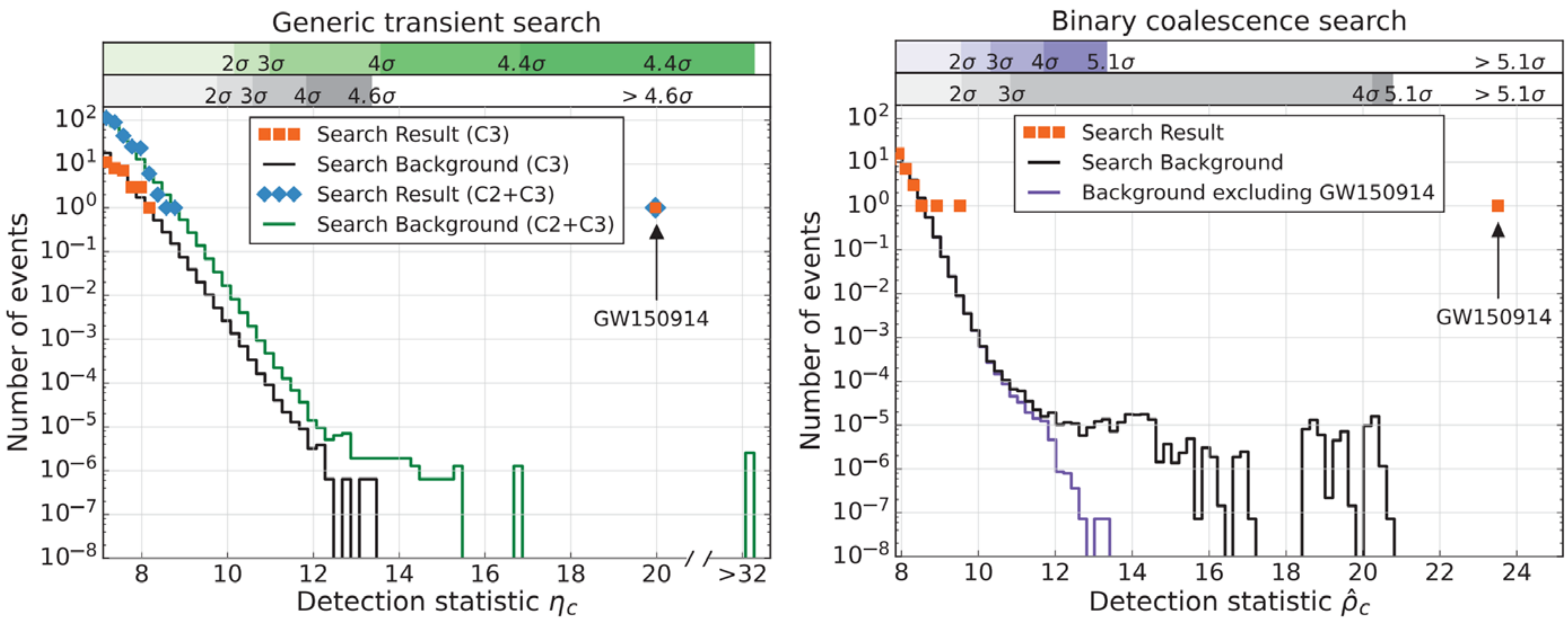
- About 3 times the mass of the sun was converted to gravitational waves. $E = mc^2$
- Over the sun's lifetime of about 10 billion years, it will only convert about 0.07% of its mass into energy – this event emitted over 1,000 times more energy in a fraction of a second.
- This event was outputting more power during its peak than all observable stars combined. By a factor of about 50.

B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) Phys. Rev. Lett. **116**, 061102

Where did the event occur?



Statistics



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Phys. Rev. Lett. **116**, 061102

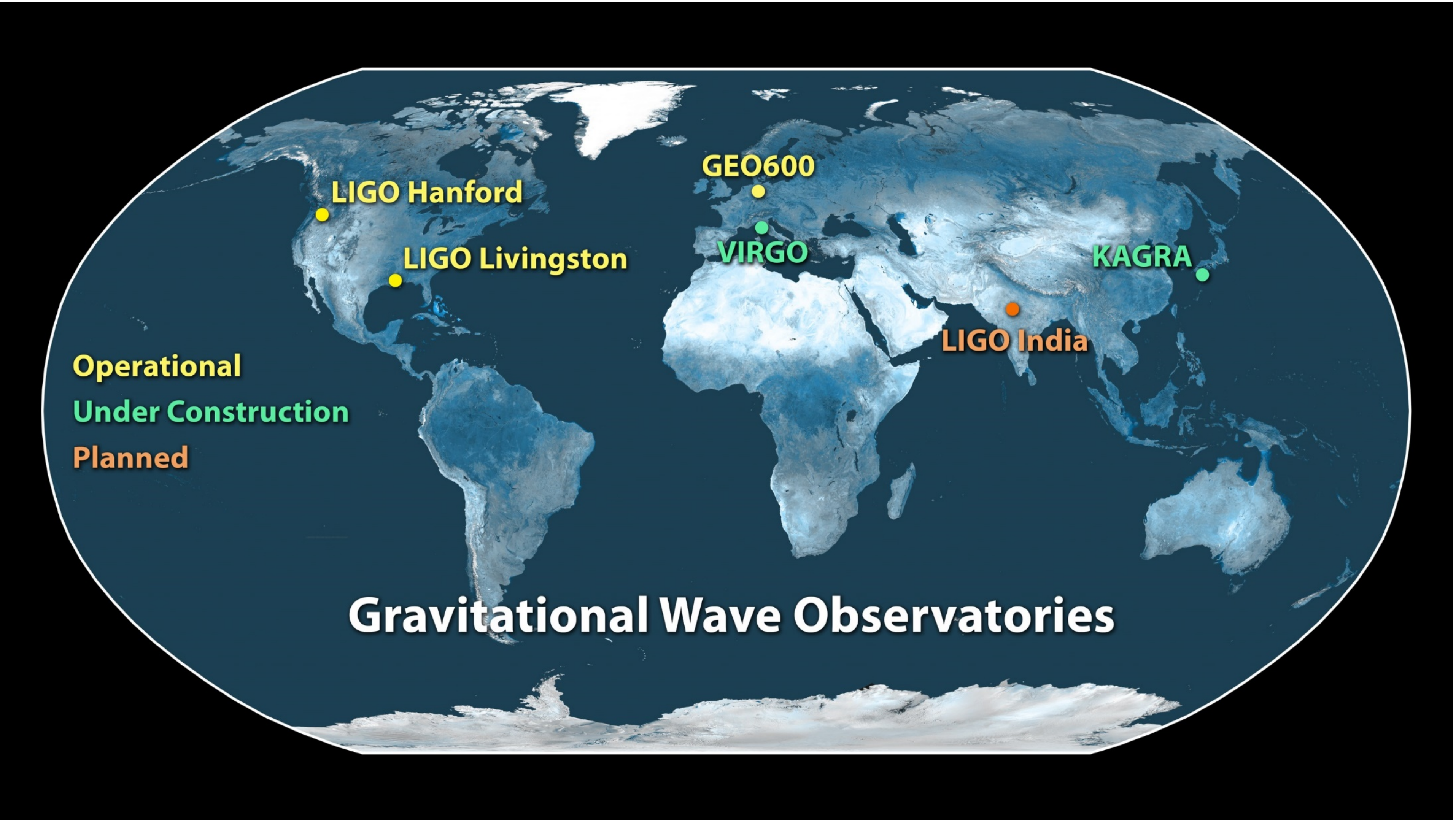
Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

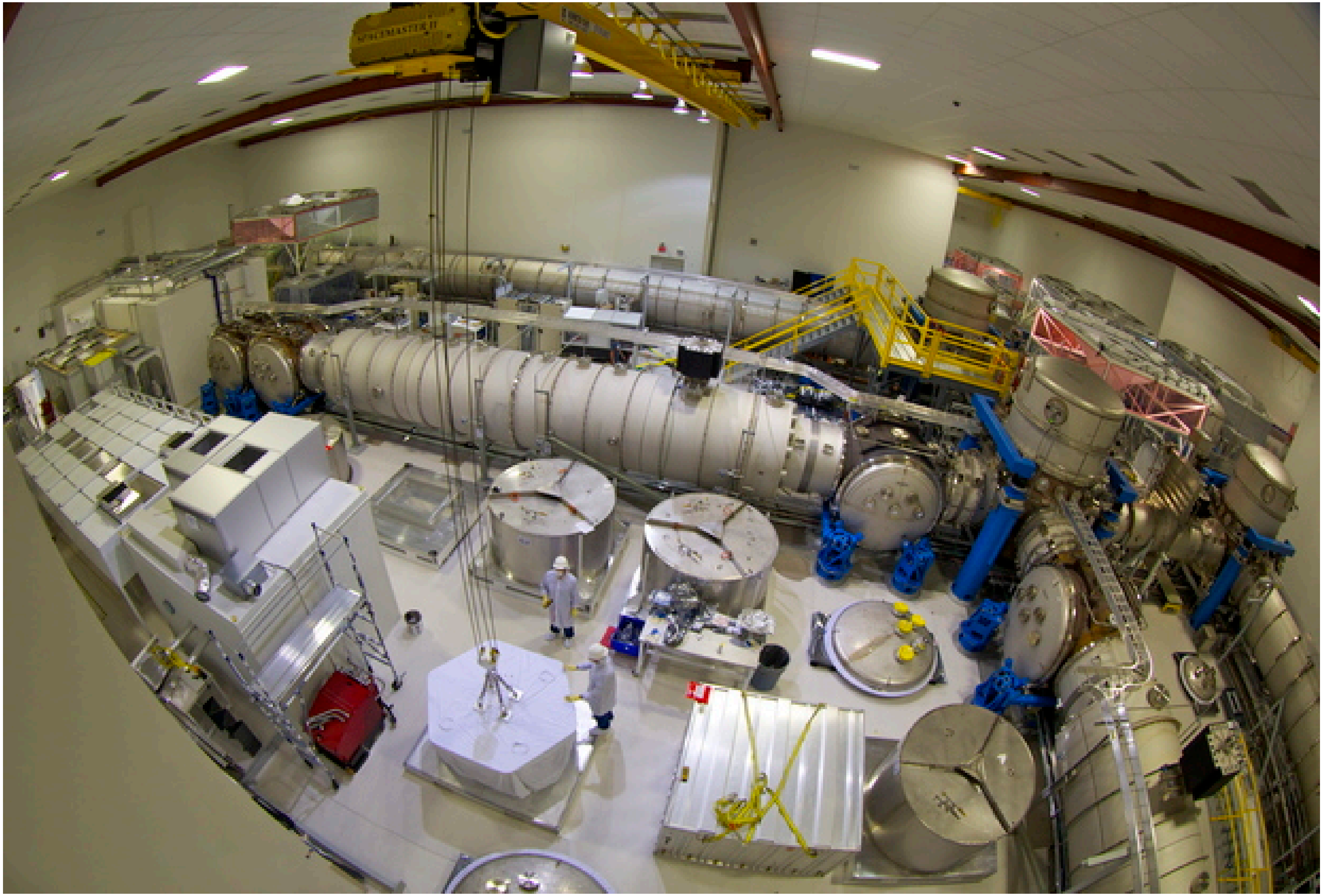
On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches 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.

B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration)
Phys. Rev. Lett. **116**, 061102

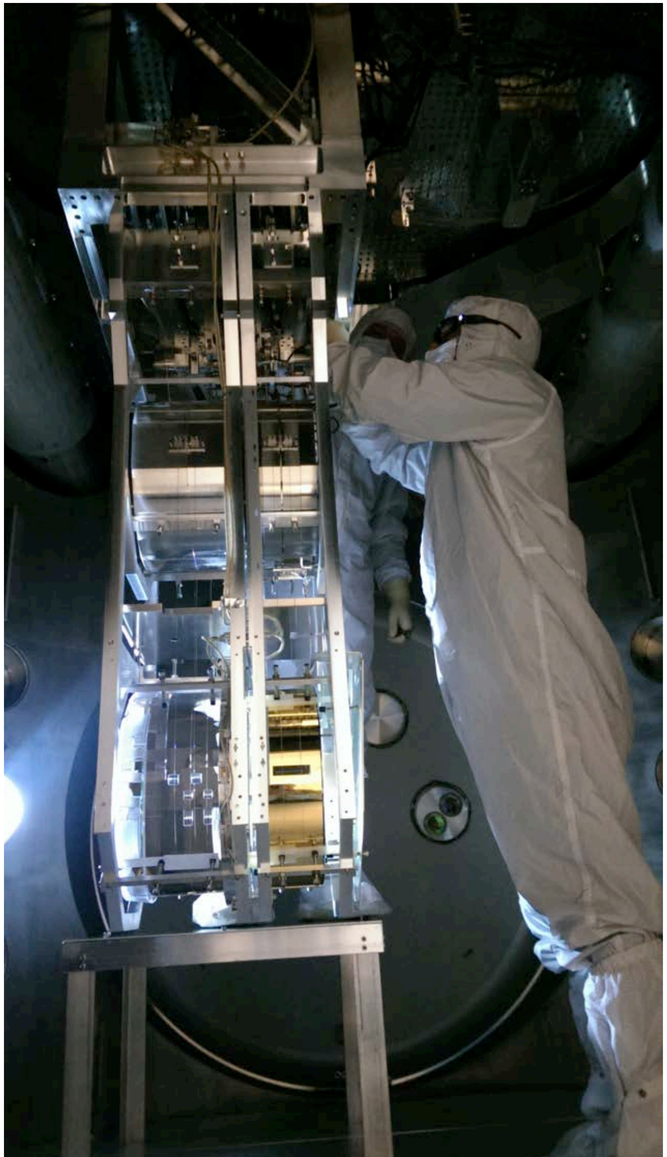
International network of detectors

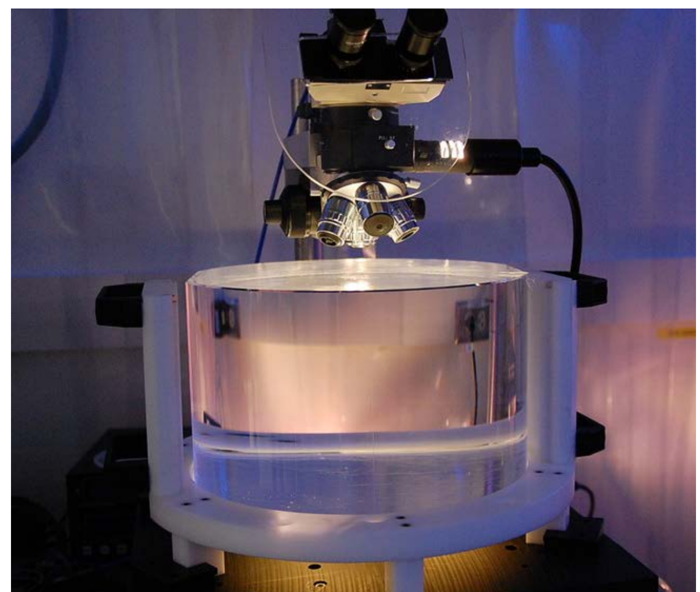



LIGO
Livingston Observatory



LIGO.org





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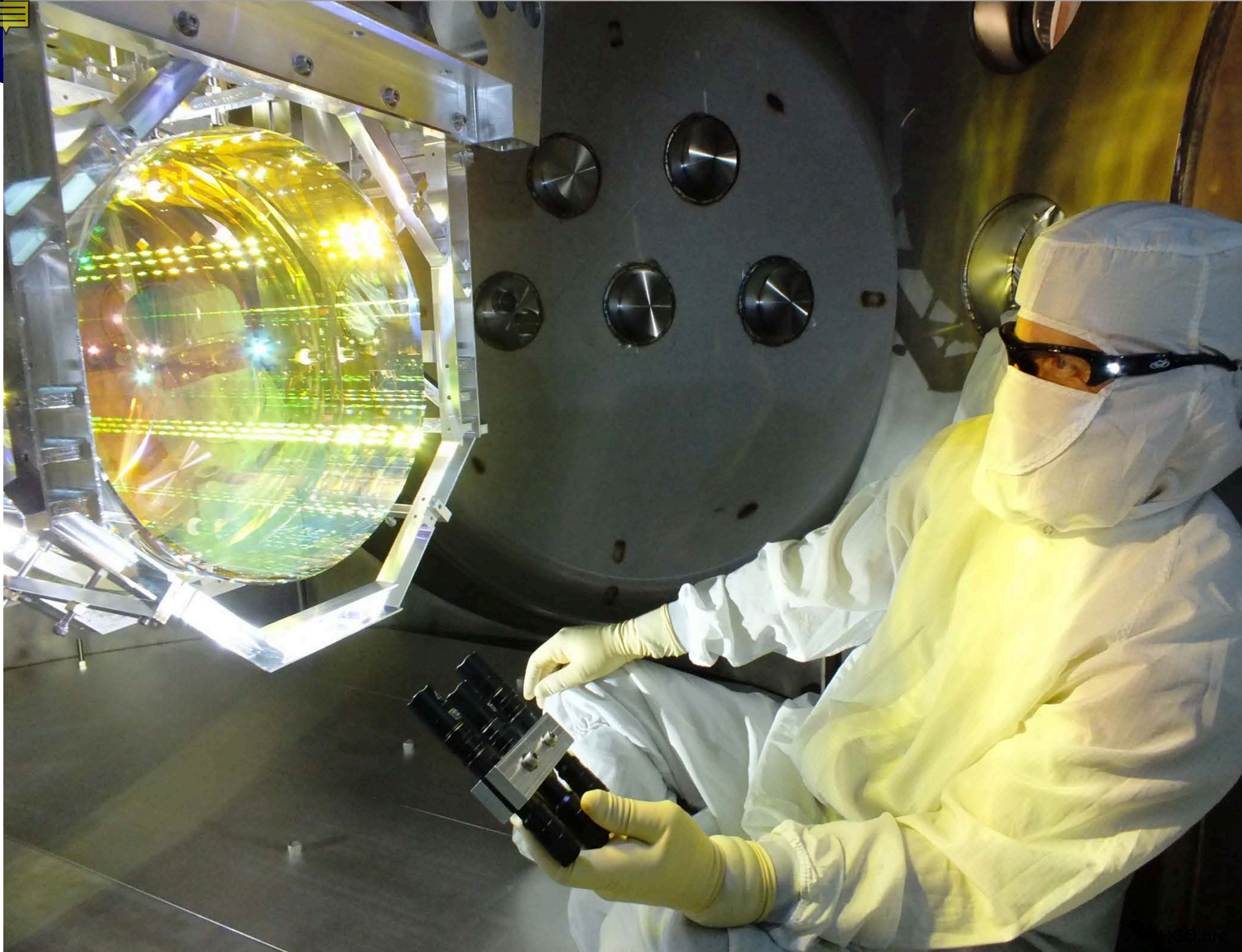
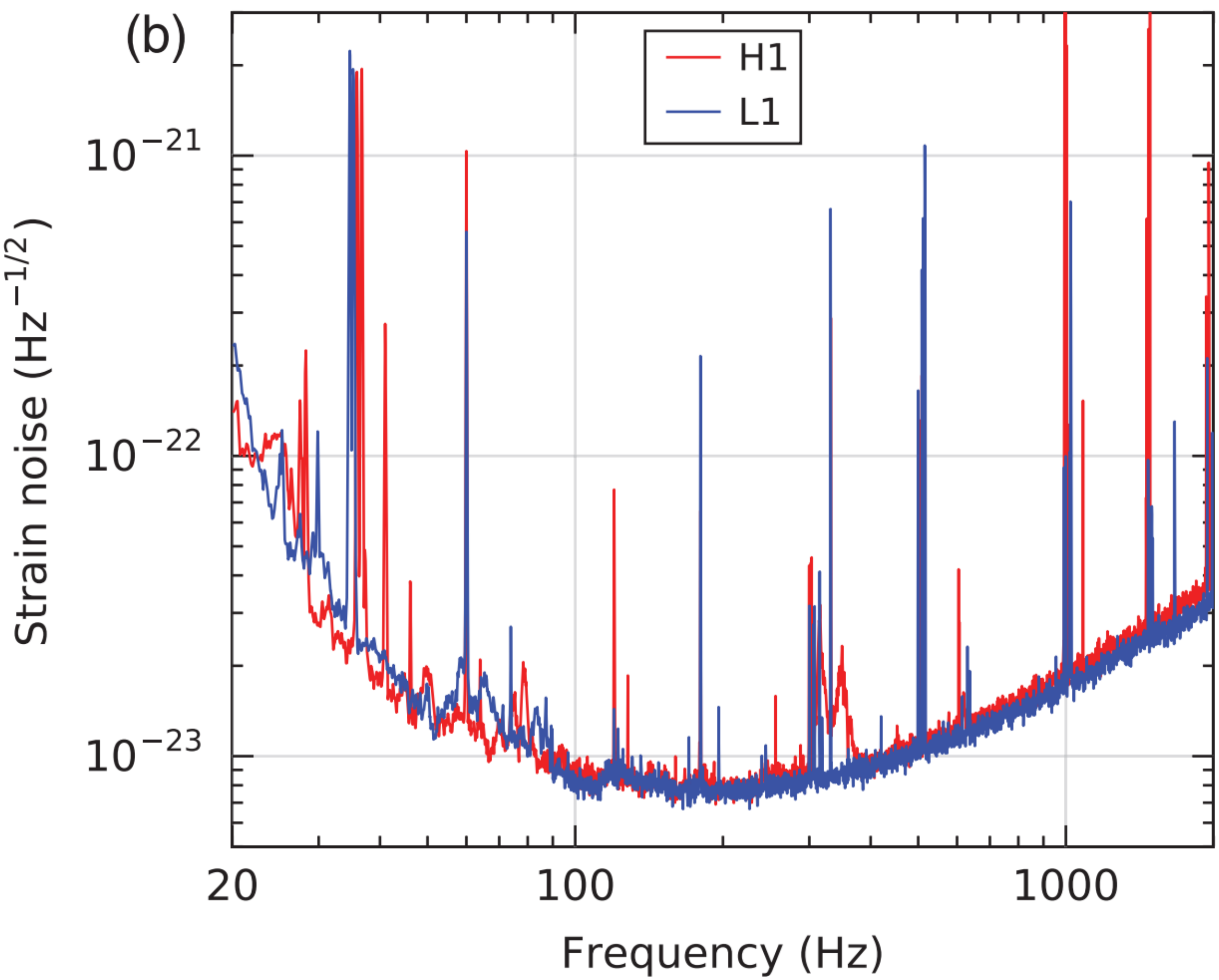


LIGO.org

Sensitivity



Why does this matter?

Hevelius

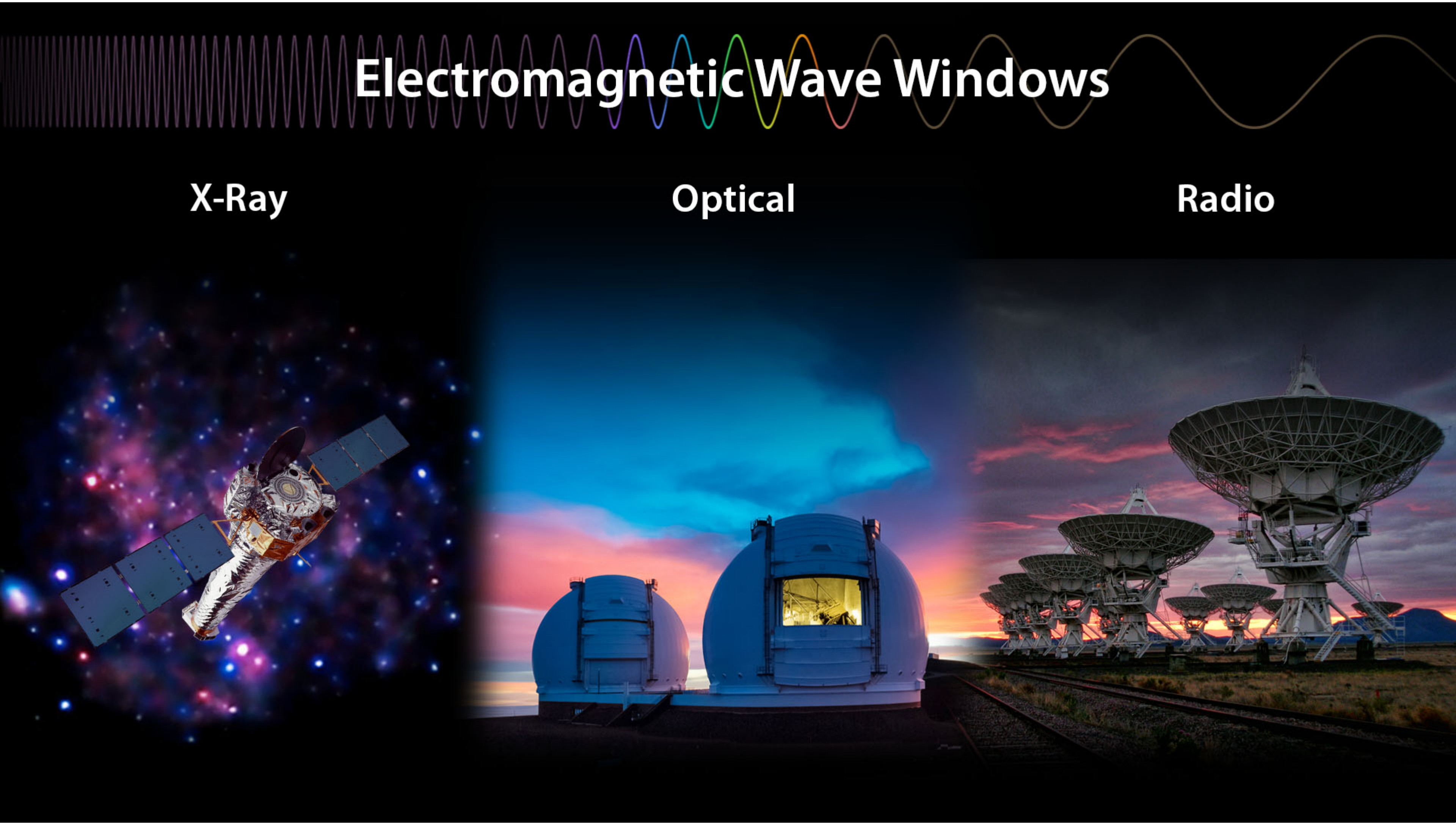
400 years ago, Galileo used the first telescope to discover the moons of Jupiter

26 years ago, NASA launched the Hubble Telescope

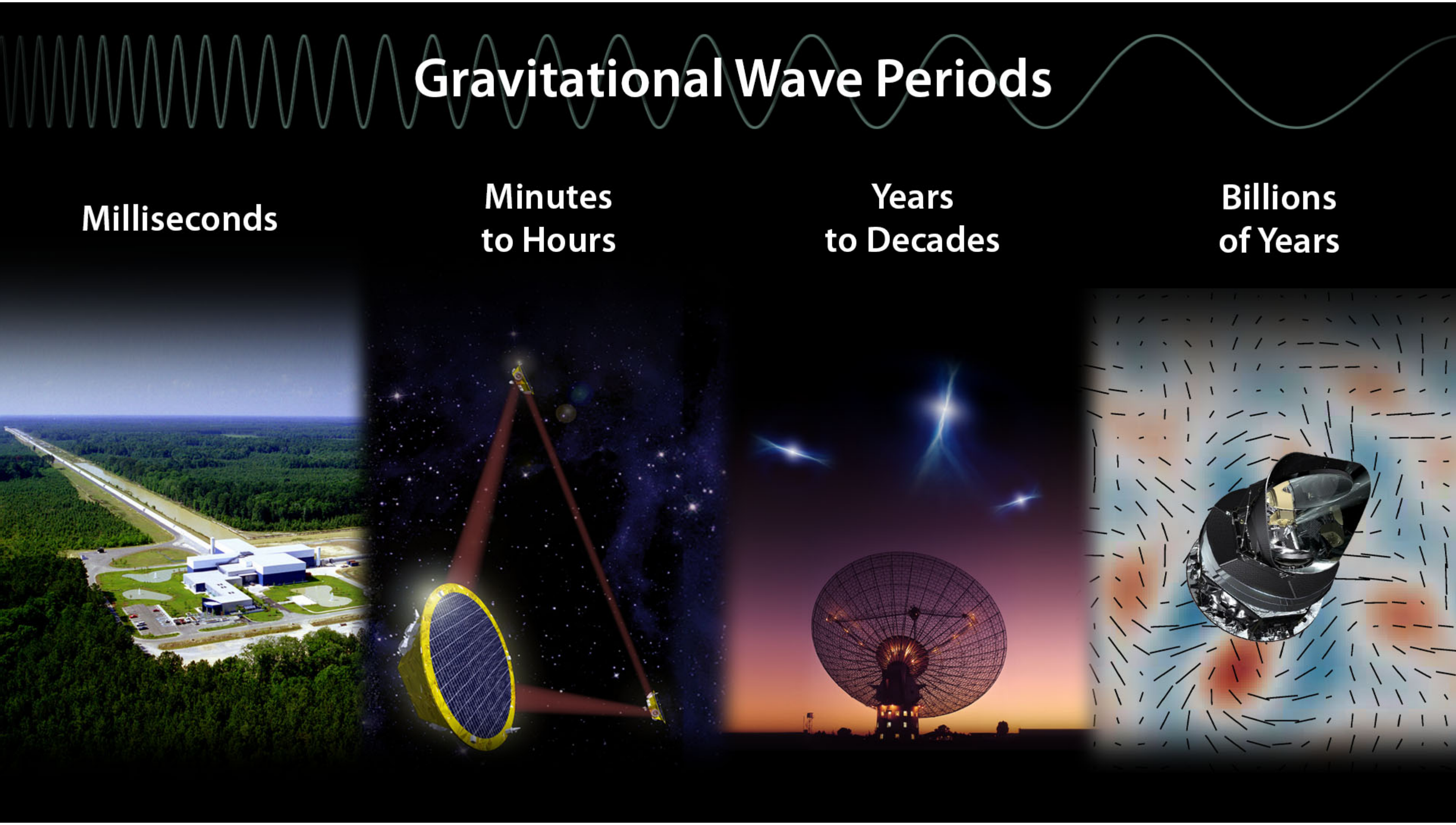
Today, we know the age of the universe, that it is expanding, and more about the starts and galaxies that fill it

Why does this matter?

- First direct detection of gravitational waves, confirming a prediction from GR
- First observation of a binary black hole merger
- Opens a new window on how we see, or listen to the universe
- There are many mysteries still out there


Electromagnetic Wave Windows
X-Ray
Optical
Radio

A New Window

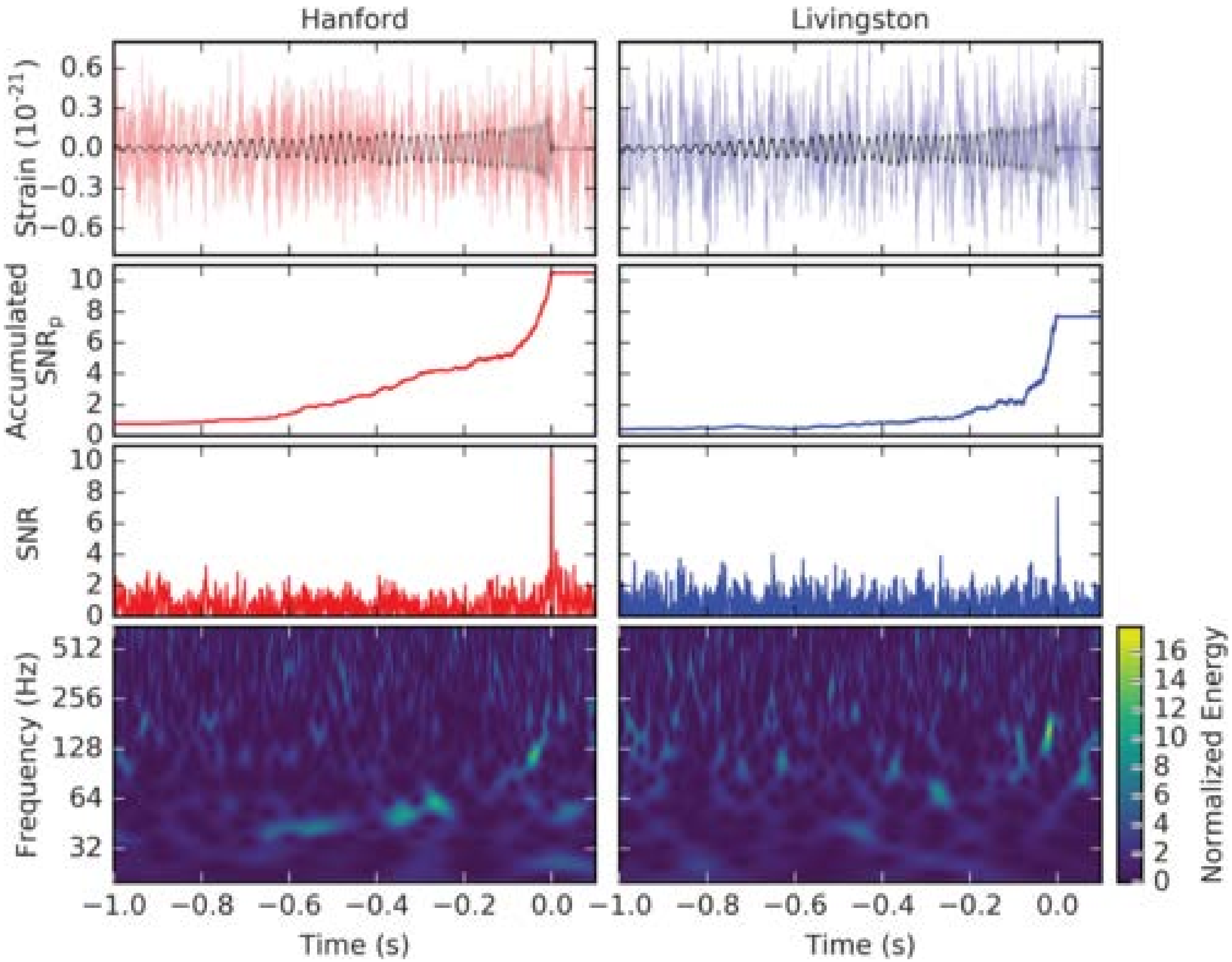

Gravitational Wave Periods
Milliseconds
Minutes
to Hours
Years
to Decades
Billions
of Years

LIGO Team members at the Congressional hearing on Feb 24, 2016. Left to right: Assistant Director of the NSF's Directorate of Mathematical and Physical Sciences Dr. Fleming Crim, LIGO Lab Director Dr. David Reitze, LSC Spokesperson Dr. Gabriela Gonzalez, LIGO MIT Director Dr. David Shoemaker.

LIGO Members Testify at US Congress on Gravitational Wave Discovery

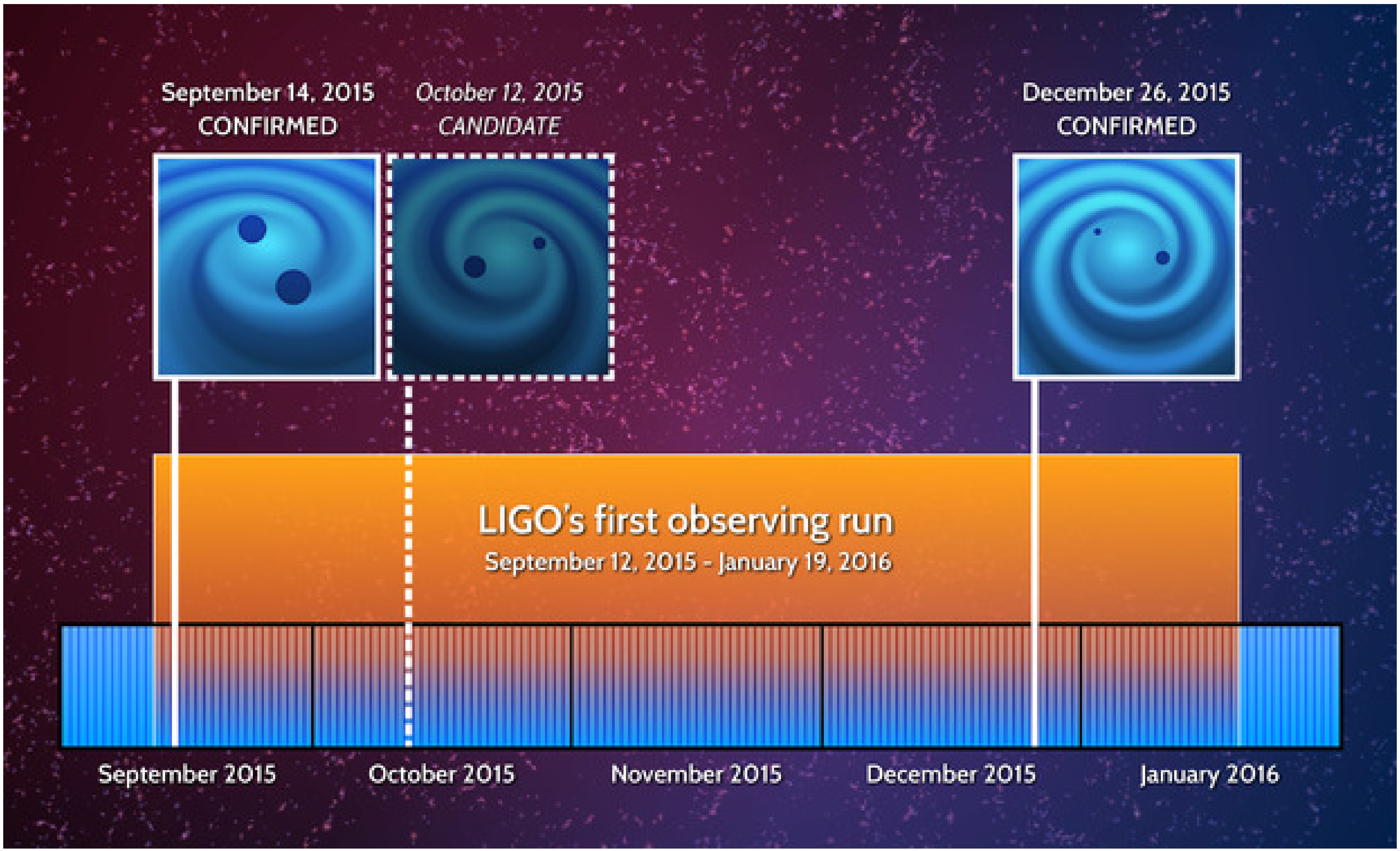
News Release • February 18, 2016

A second detection: GW151226

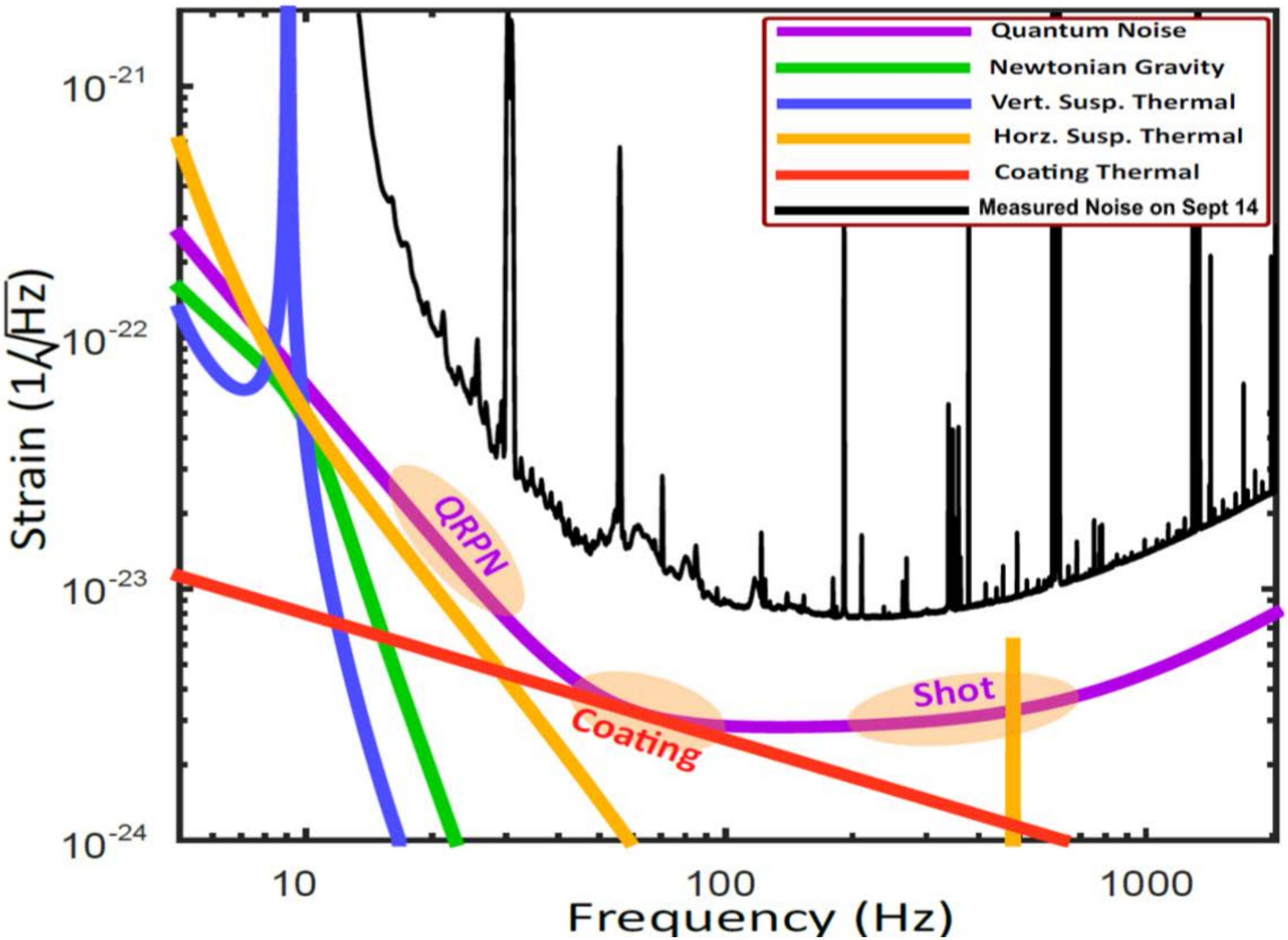


B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration)
Phys. Rev. Lett. 116, 241103

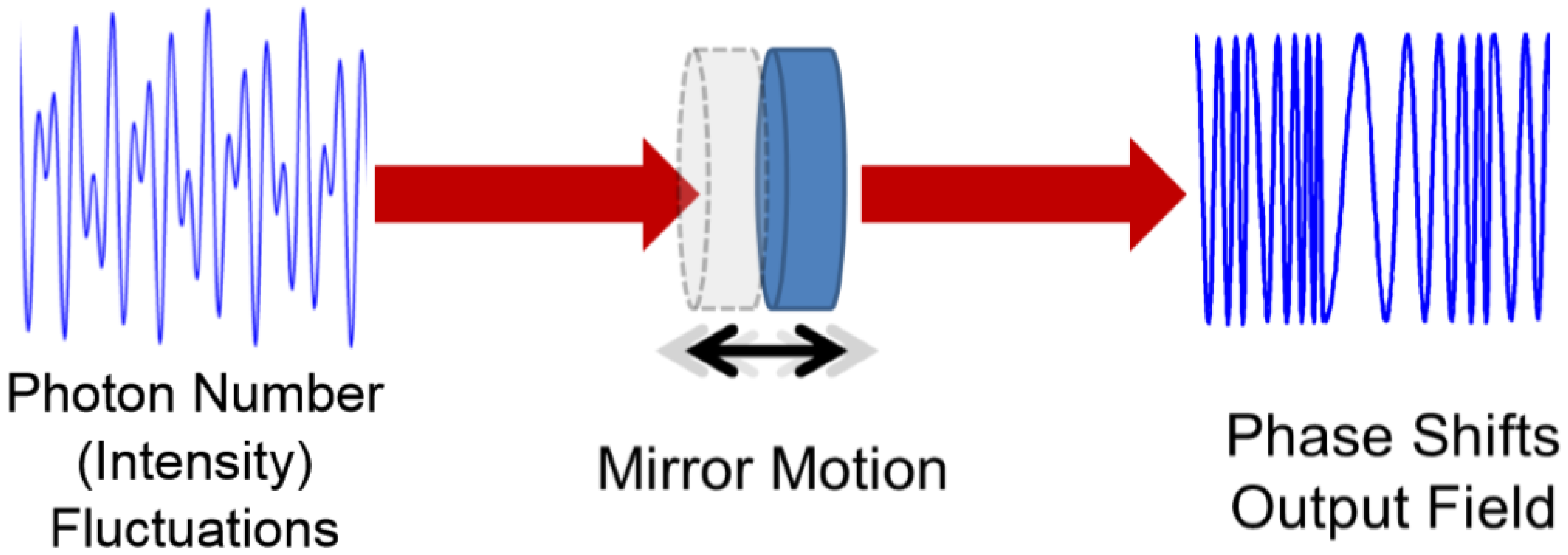
LIGO’s First Observing Run



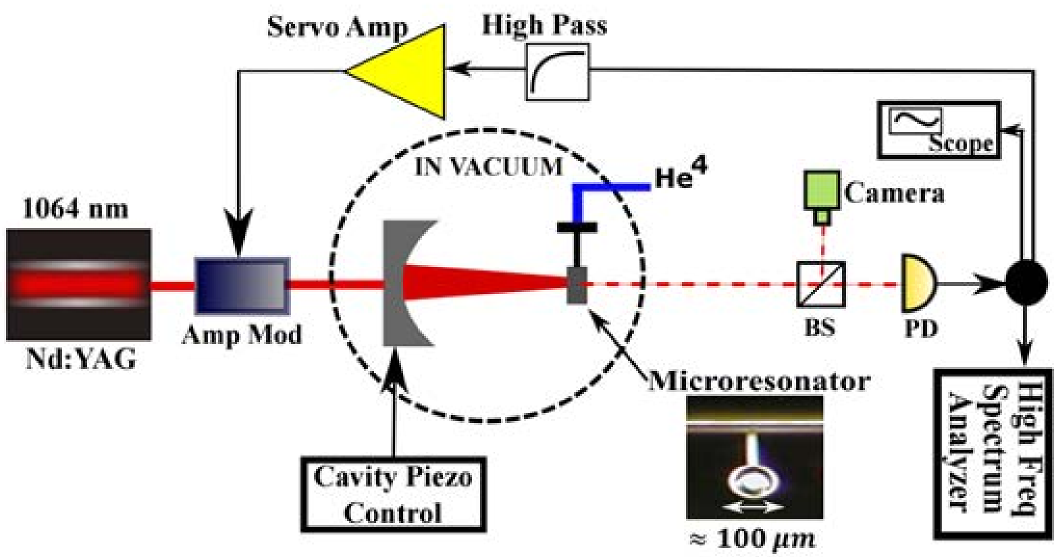
Looking ahead



Quantum noise



Prototypes


Servo Amp
High Pass
Scope
IN VACUUM
He^4
Camera
1064 nm
Nd:YAG
Amp Mod
BS
PD
Microresonator
High Freq
Spectrum
Analyzer
Cavity Piezo
Control
≈ 100 μm

Thank you!