LIGO and discovery of the gravitational waves

LIGO Scientific Collaboration
and
Eugeniy E. Mikhailov

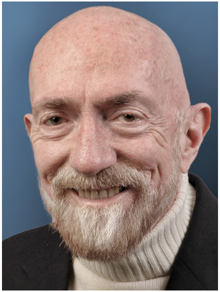
William & Mary
CHARTERED 1693

October 4th, 2017

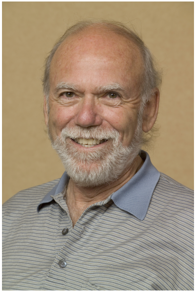
2017/10/03 Nobel prize in Physics

"for decisive contributions to the LIGO detector and the observation of gravitational waves"

Rainer Weiss



Kip S. Thorne



Barry C. Barish

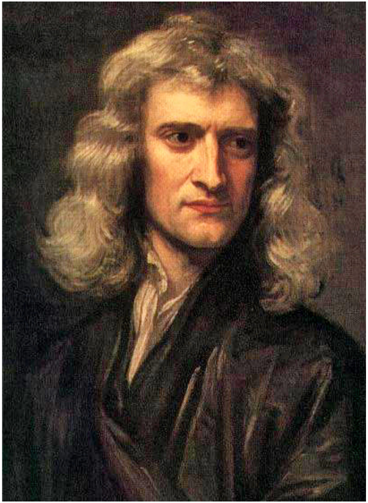
LIGO

LSC

LIGO Scientific Collaboration

TRINITY UNIVERSITY
UNIVERSITY OF MARYLAND
Andrews University
WASHINGTON STATE UNIVERSITY
CALIFORNIA STATE UNIVERSITY FULLERTON
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE
SONOMA STATE UNIVERSITY
indigo
MONTCLAIR STATE UNIVERSITY
University of Glasgow
Australian National University
WHITMAN COLLEGE
AMERICAN UNIVERSITY WASHINGTON, DC
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
Canadian Institute for Theoretical Astrophysics
L'institut Canadien d'astrophysique théorique
Università degli Studi del Sannio
GODDARD SPACE FLIGHT CENTER
NASA
ICTP SAIFR
THE UNIVERSITY OF WESTERN AUSTRALIA
UNIVERSITY OF CAMBRIDGE
THE UNIVERSITY OF CHICAGO
MONTANA STATE UNIVERSITY
SOUTHERN UNIVERSITY Agricultural & Mechanical College
COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK
Caltech
UNIVERSITY OF MINNESOTA
THE UNIVERSITY of MISSISSIPPI
THE UNIVERSITY OF ADELAIDE AUSTRALIA
UNIVERSITY OF BIRMINGHAM
THE UNIVERSITY OF MELBOURNE
GEO 600
UIB Universitat de les Illes Balears
UTRGV
UNIVERSITY OF WASHINGTON
UNIVERSITY of WISCONSIN UWMILWAUKEE
CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD
Northwestern
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
PENNSTATE
Science & Technology Facilities Council Rutherford Appleton Laboratory

Newton's laws 1686



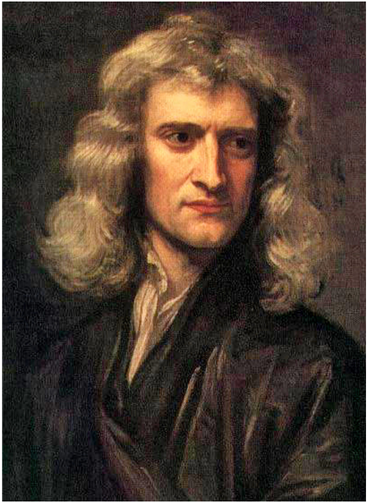
$$F_g = G\frac{m_1 m_2}{r^2}$$

Laws of motion and law of gravitation solved problems of astronomy and terrestrial physics.

- eccentric orbits
- tides
- perturbation of moon orbit due to sun

Unified the work of Galileo, Copernicus and Kepler.

Newton's laws 1686



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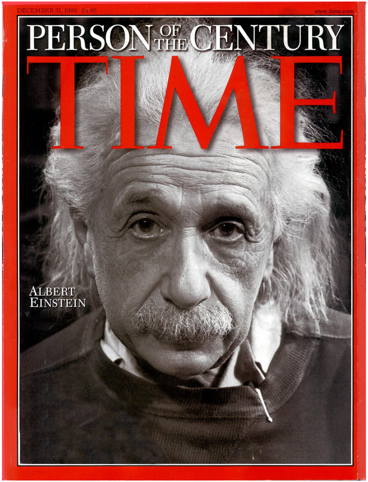
Did not explained precession of Mercury orbit

Einstein's laws 1915

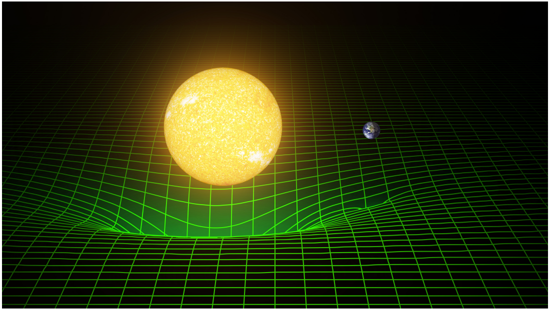


The General Theory of Relativity and theory of Gravity (1915)

- No absolute motion
  thus only relative motion
- Space and time are not separate
  thus four dimensional space-time
- Gravity is not a force acting at a distance
  thus warpage of space-time

General relativity

- A geometric theory connecting matter to spacetime
- Matter tells spacetime how to curve
- Spacetime tells matter how to move



important predictions

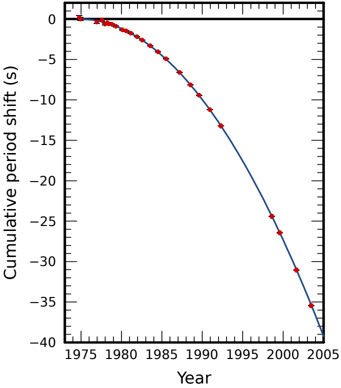
- Light path bends in vicinity of massive object → confirmed in 1919
- Gravitational radiation (waves) → confirmed indirectly in 1974

Indirect observation of gravitational wave

Emission of gravitational radiation from pulsar PSR1913+16 leads to loss of orbital energy.

- orbital period decreased by 36 sec from 1975 to 2005
- measured to 50 ms accuracy
- deviation grows quadratically with time

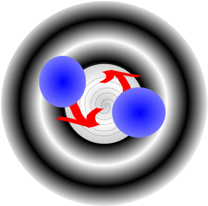
This can be explained by general relativistic effects: J.H. Taylor and J.M. Weisberg, Astrophysical Journal, Part 1, vol. 253, Feb. 15, 1982, p. 908-920.



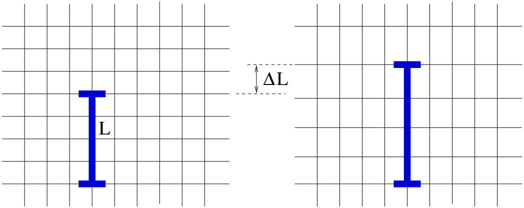
Nobel prize in 1993 to Hulse and Taylor

Gravitational waves (GW)

- Predicted by the General Theory of Relativity
- Generated by aspherical mass distribution
- Induce space-time ripples which propagate with speed of light



GW stretch and squeeze space-time thus move freely floating objects



Strain - strength of GW

$$h = \frac{\Delta L}{L} \quad (1)$$

expected strain

$$h \sim 10^{-21} \quad (2)$$

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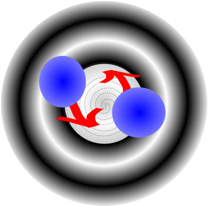

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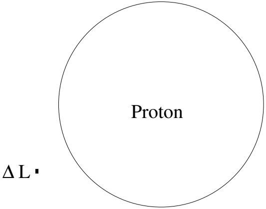

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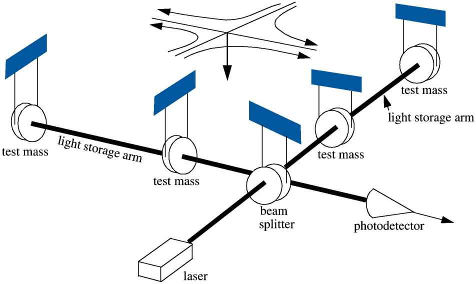
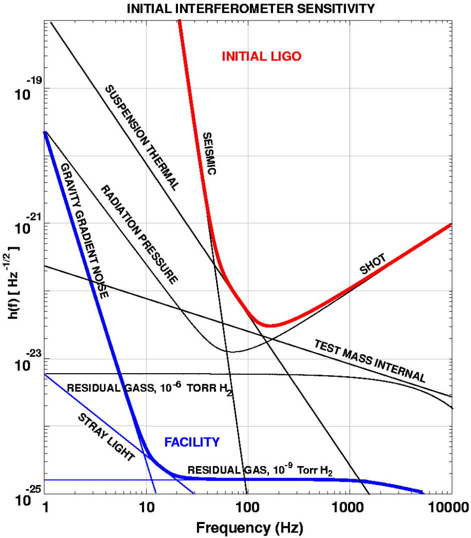
Laser Interferometer Gravitational-wave Observatory

- $L = 4$ km
- $h \sim 10^{-23}$



Initial LIGO sensitivity goal and noise budget



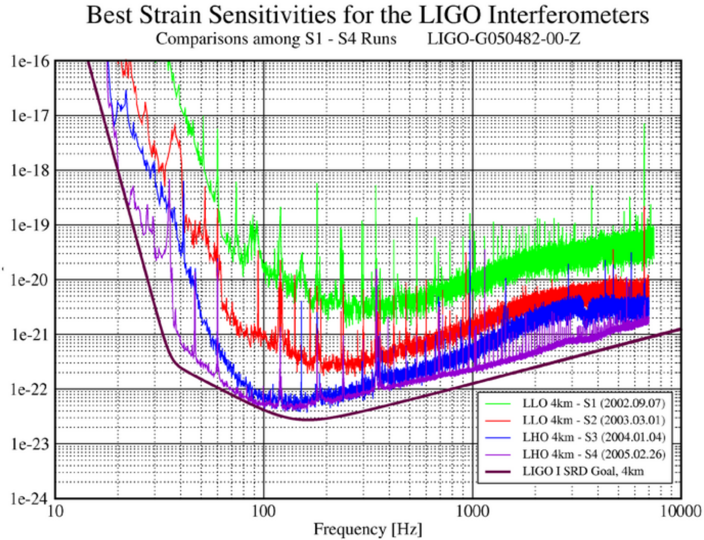
Displacement noise

- seismic
- thermal suspension
- thermal Brownian
- radiation pressure noise

Detection noise

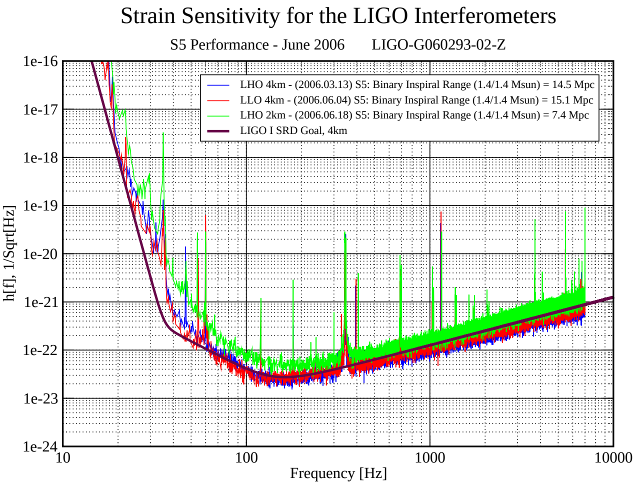
- electronics
- shot noise

LIGO sensitivity, S1-S4 runs

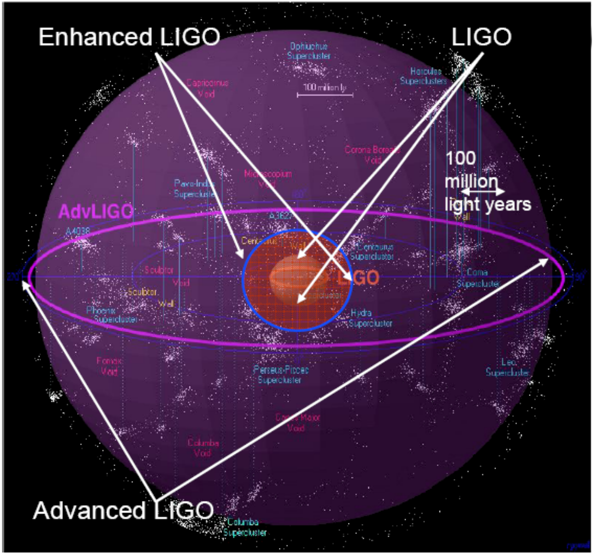


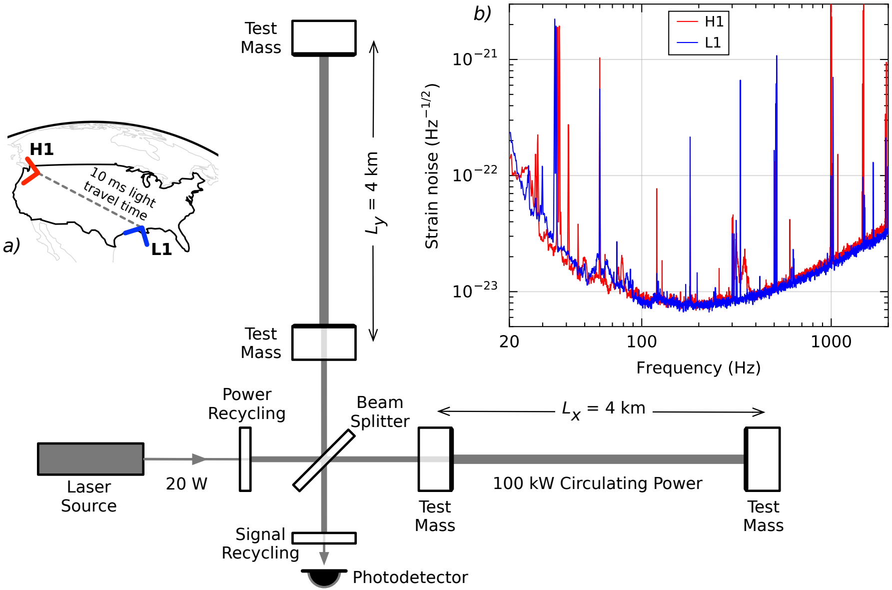
Inspiral search range during S4 was 8Mpc

LIGO sensitivity, S5 run, June 2006



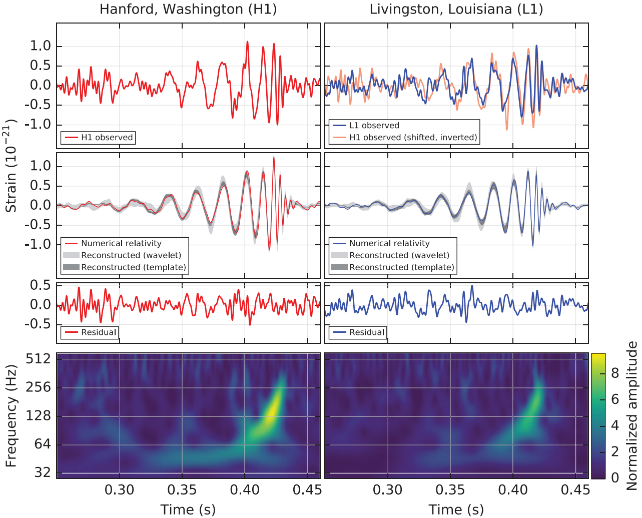
Inspiral search range during S5 is 14Mpc


Enhanced LIGO
LIGO
100 million light years
AdvLIGO
LIGO
Advanced LIGO
Ophiuchus Supercluster
Hercules Superclusters
Capricornus Void
100 million ly
Corona Borealis Void
Pavo-Indus Supercluster
Centaurus Supercluster
Coma Supercluster
Hydra Supercluster
Phoenix Supercluster
Sculptor Void
Sculptor Wall
Fornax Void
Perseus-Pisces Supercluster
Leo Supercluster
Columba Void
Columba Supercluster
A4038
A3627



H1
10 ms light travel time
L1
a)
Test Mass
Test Mass
L_y = 4 km
Power Recycling
Beam Splitter
L_x = 4 km
Laser Source
20 W
Test Mass
100 kW Circulating Power
Test Mass
Signal Recycling
Photodetector
b)
H1
L1
Strain noise (Hz$^{-1/2}$)
10^{-21}
10^{-22}
10^{-23}
20
100
1000
Frequency (Hz)

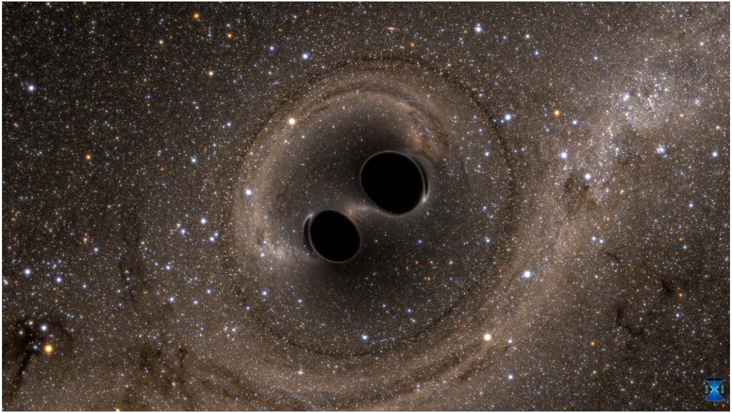
GW signal at 09:50:45 UTC on 14 September 2015



LIGO Scientific Collaboration, "Observation of Gravitational Waves from a Binary Black Hole Merger", Phys. Rev. Lett., 116, 061102, (2016).

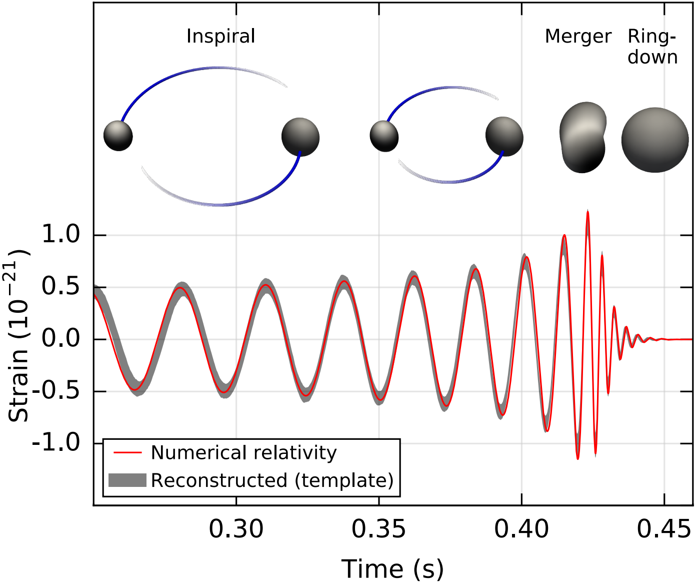
The sound of gravitational wave and simulated sky

- The Sound of Two Black Holes Colliding
- Two Black Holes Merge into One

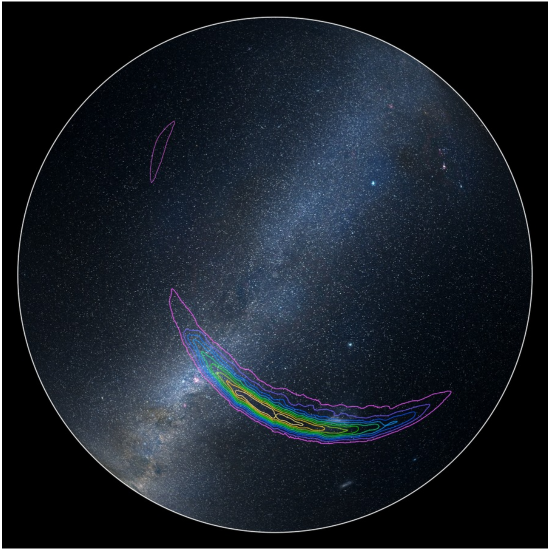


Two black holes with 29 and 36 solar masses merged about 1.3 billion years ago

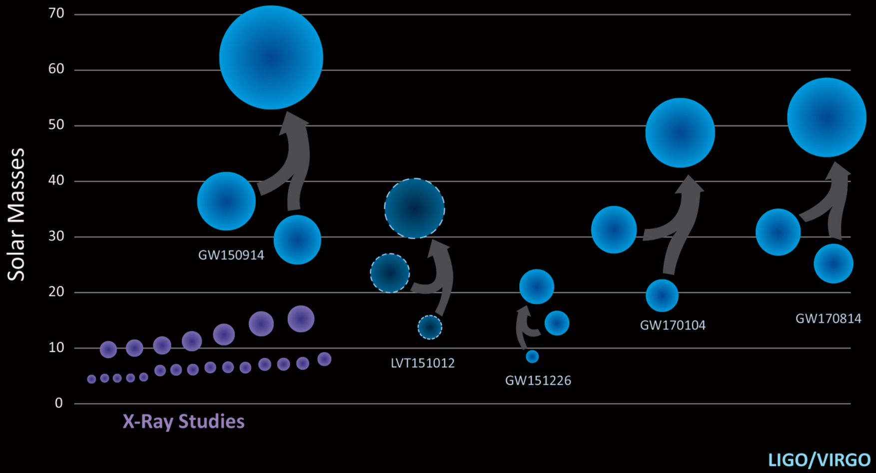
Reconstructed signal



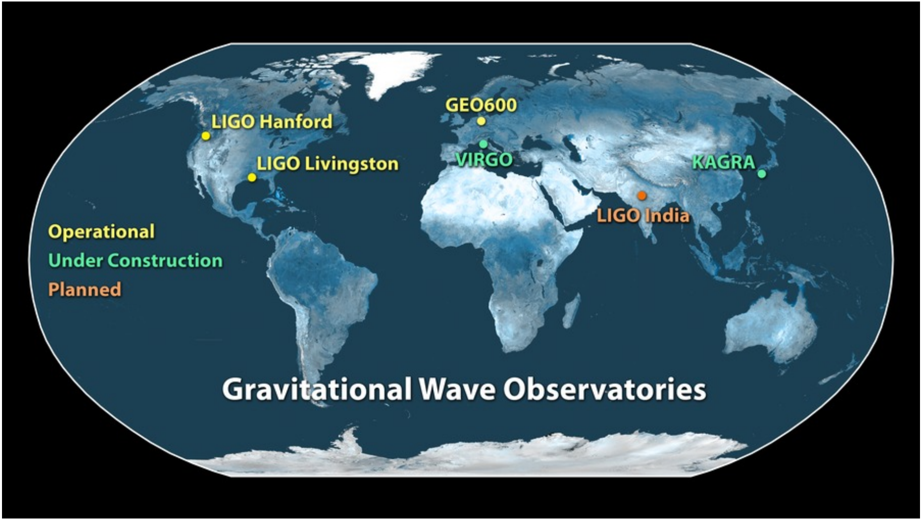
GW source location at the southern hemisphere sky



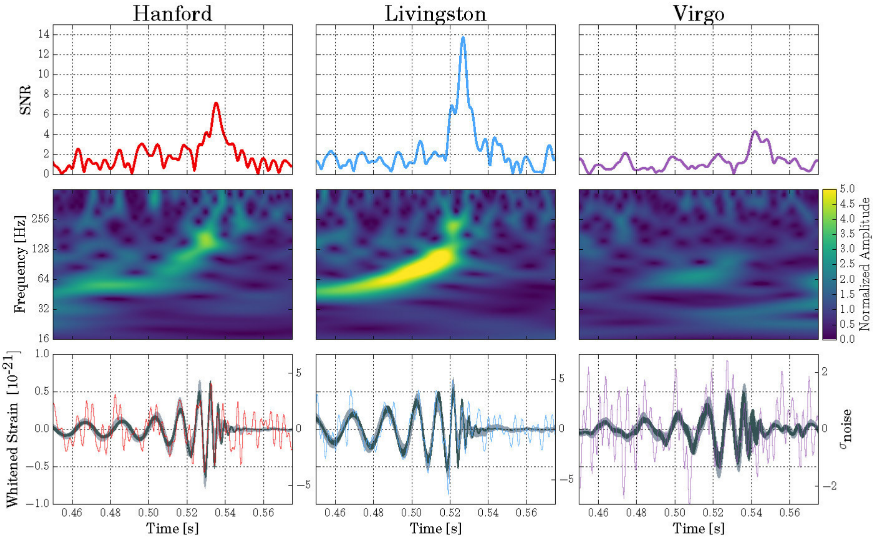
Black Holes of Known Mass



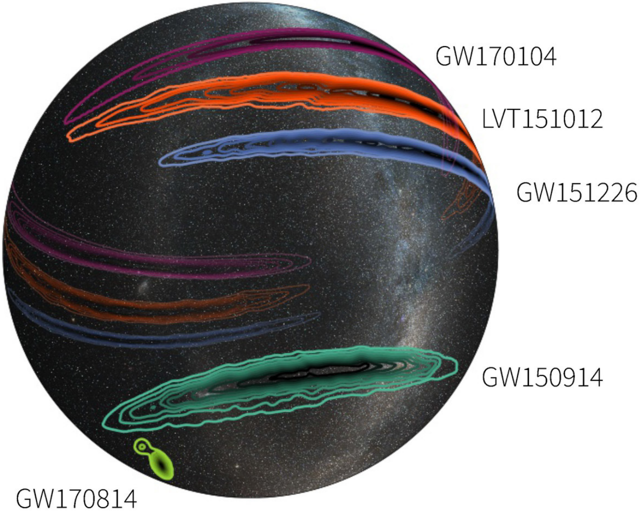
World wide network of detectors



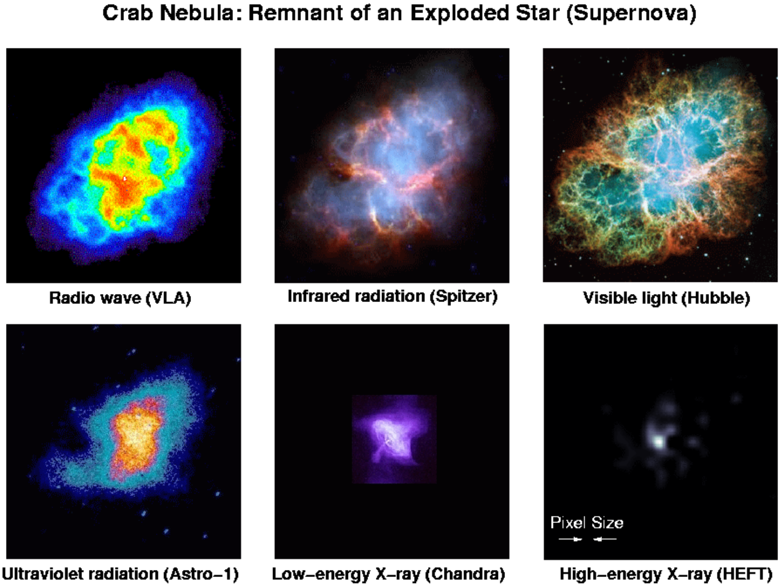
GW170814 triple detection



Sky maps



New view to the universe



Astrophysics with GWs vs. E&M

E&M (photons)

- Space as medium for field
- Accelerating charge
- Absorbed, scattered, dispersed by matter
- 10 MHz and up
- Light = not dark (but >95% of Universe is dark)

GW

- Spacetime itself ripples
- Accelerating aspherical mass
- Very small interaction; matter is transparent
- 10 kHz and down
- Radiated by dark mass distributions

Seismic isolation

Photo from LIGO Magazine `http://www.ligo.org/magazine/`

Part of large system

Photo from LIGO Magazine http://www.ligo.org/magazine/

Work in chamber

Inside vacuum chamber

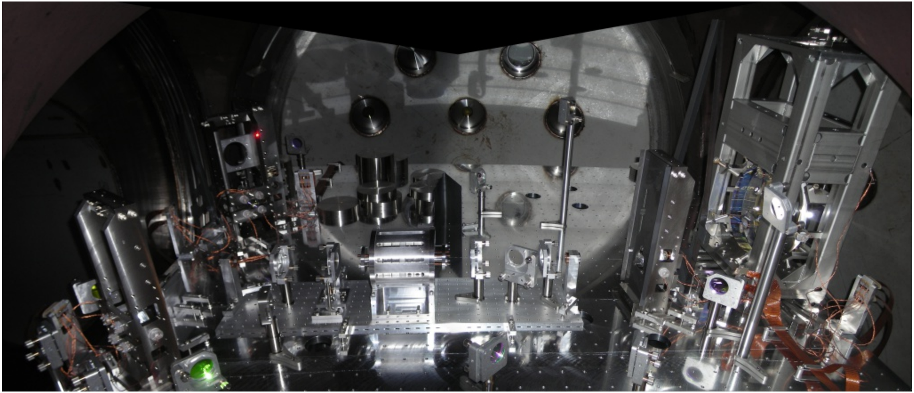


Photo from LIGO Magazine http://www.ligo.org/magazine/

Mirror

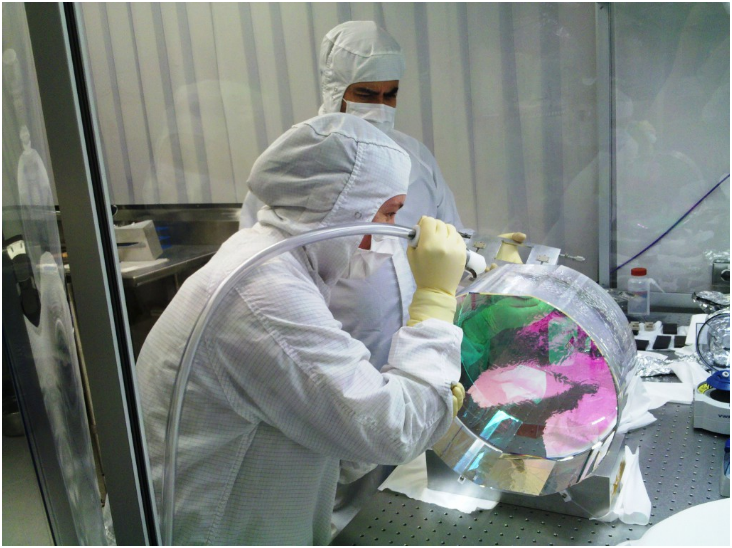


Photo from LIGO Magazine http://www.ligo.org/magazine/

Inner test mass

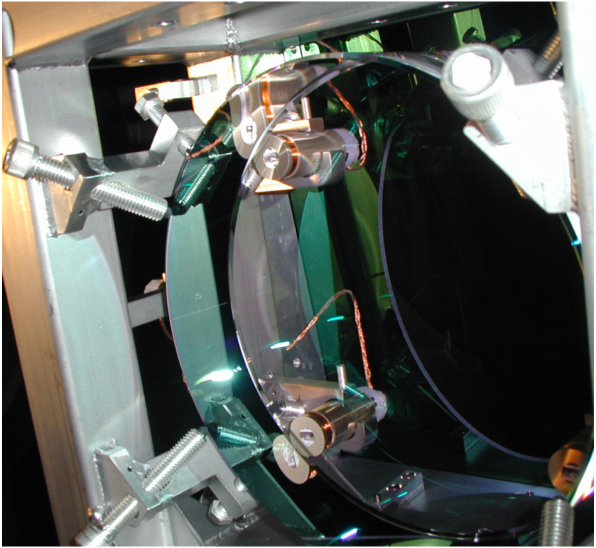


Photo from LIGO Magazine http://www.ligo.org/magazine/

We can detect stars collisions and ...

Summary

- Gravitational waves exist and they are detected
- Moreover we can learn from them and do GW astronomy
- The future is in quantum noise suppression