LIGO and discovery of the gravitational waves

LIGO Scientific Collaboration

and

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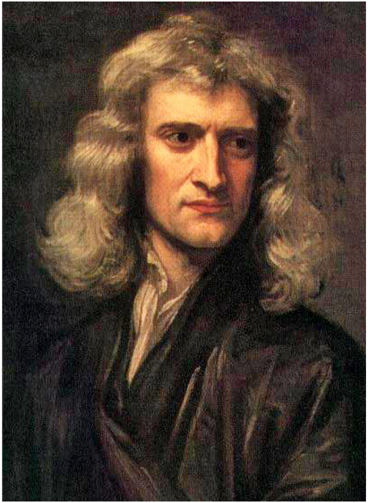
William & Mary
CHARTERED 1693

March 25th, 2017

LSC

LIGO Scientific Collaboration

Newton's laws 1686



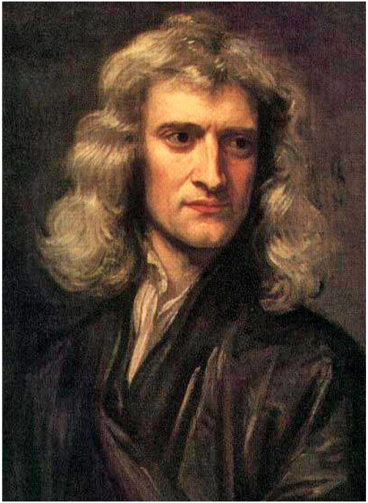
$$F_g = G\frac{m_1 m_2}{r^2}$$

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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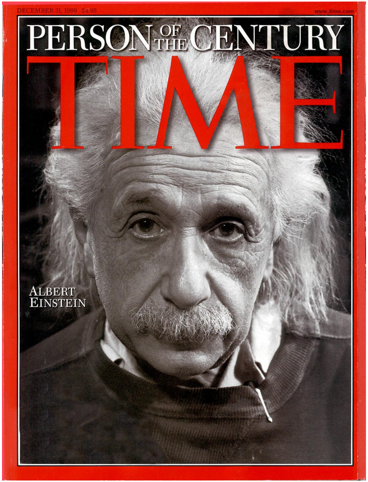
Unified the work of Galileo, Copernicus and Kepler.

Did not explained precession of Mercury orbit

Einstein’s laws 1915

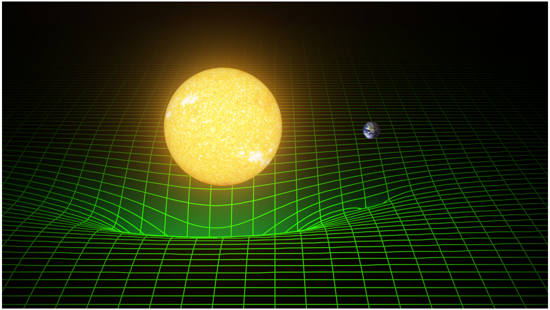


The General Theory of Relativity and theory of Gravity (1915)

- 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

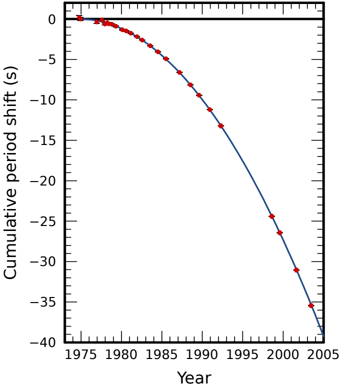
- Light path bends in vicinity of massive object $\rightarrow$ confirmed in 1919
- Gravitational radiation (waves) $\rightarrow$ confirmed indirectly in 1974

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

Astrophysics with GWs vs. E&M

E&M (photons)

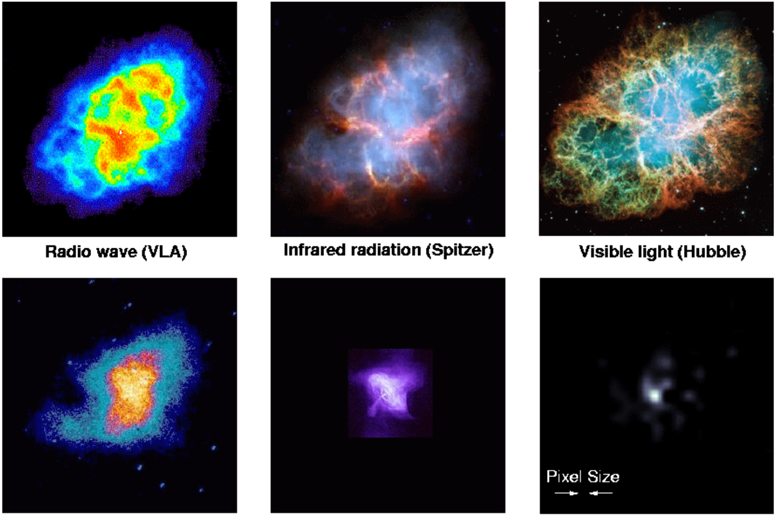
- Space as medium for field
- Accelerating charge
- Absorbed, scattered, dispersed by matter
- 10 MHz and up
- Light = not dark (but >95% of Universe is dark)

GW

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

New view to the universe

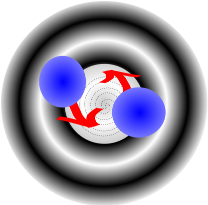
Crab Nebula: Remnant of an Exploded Star (Supernova)



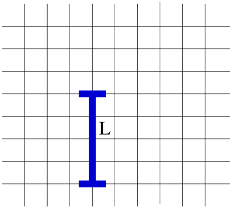
Radio wave (VLA) | Infrared radiation (Spitzer) | Visible light (Hubble)

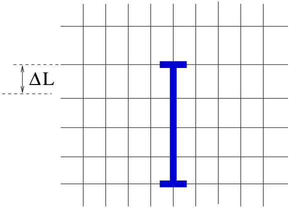
Ultraviolet radiation (Astro-1) | Low-energy X-ray (Chandra) | High-energy X-ray (HEFT)

- 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

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

Gravitational waves (GW)

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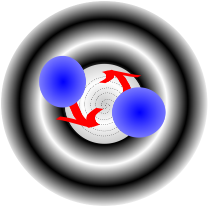
- Generated by aspherical mass distribution
- Induce space-time ripples which propagate with speed of light



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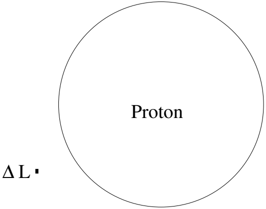

Strain - strength of GW

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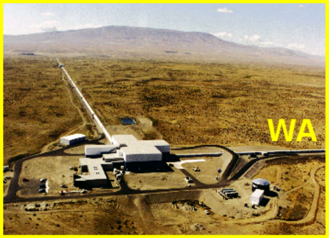
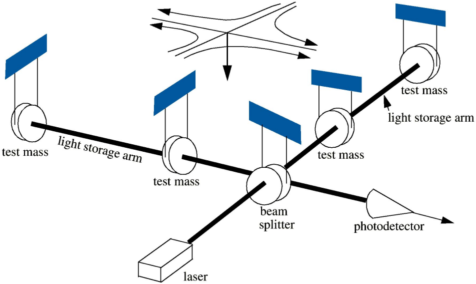
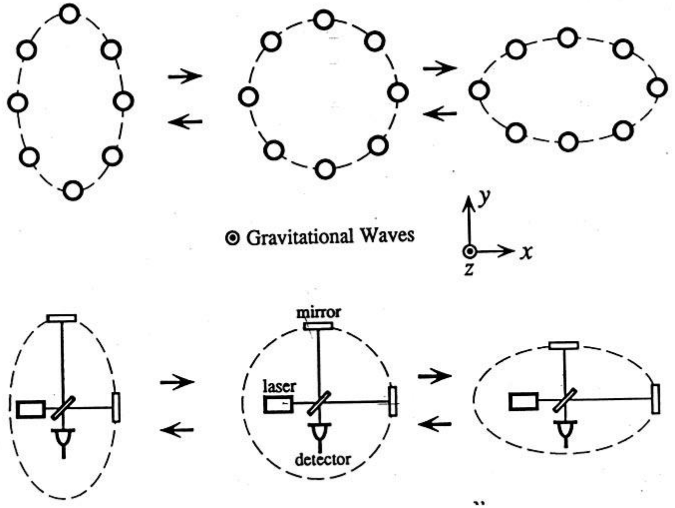
Laser Interferometer Gravitational-wave Observatory



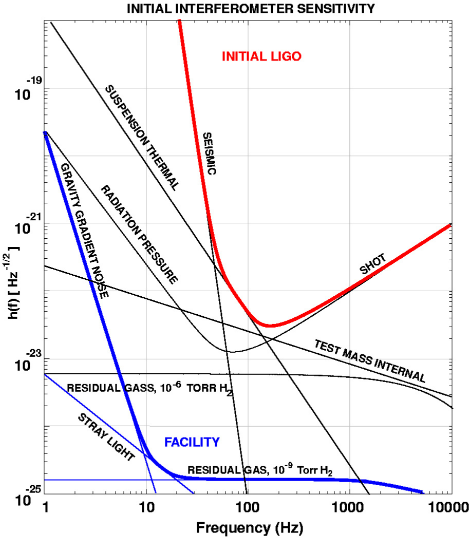
- $L = 4$ km
- $h \sim 10^{-23}$



GW acting on matter



Initial LIGO sensitivity goal and noise budget



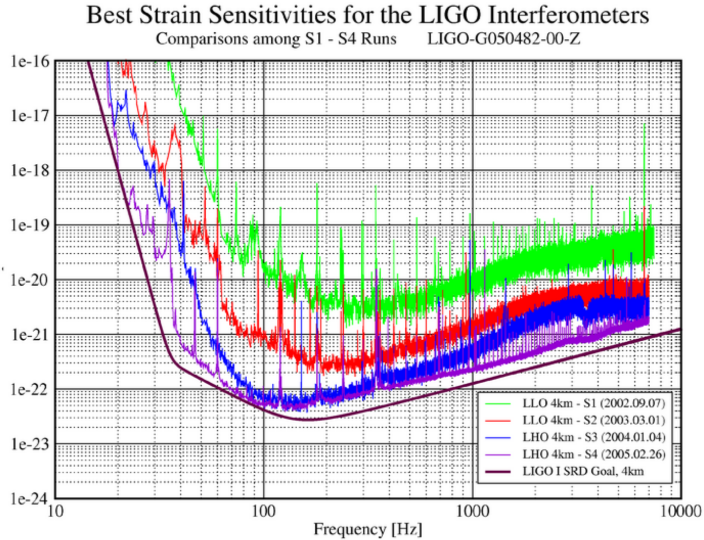
Displacement noise

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

Detection noise

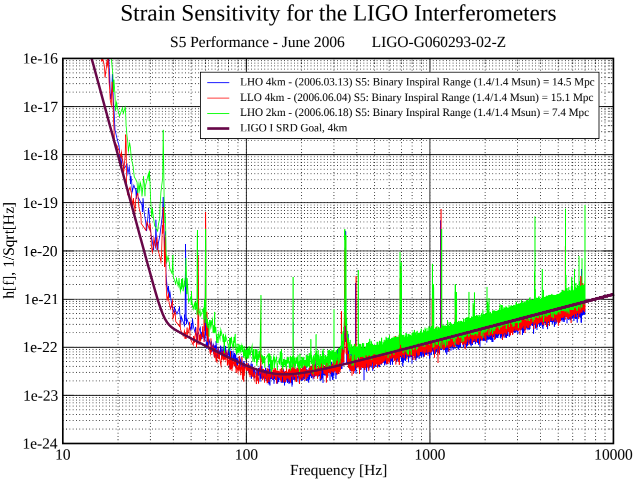
- electronics
- shot noise

LIGO sensitivity, S1-S4 runs



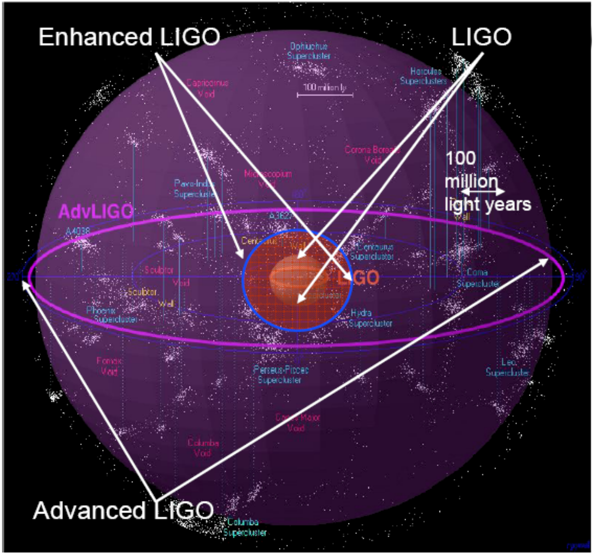
Inspiral search range during S4 was 8Mpc

LIGO sensitivity, S5 run, June 2006

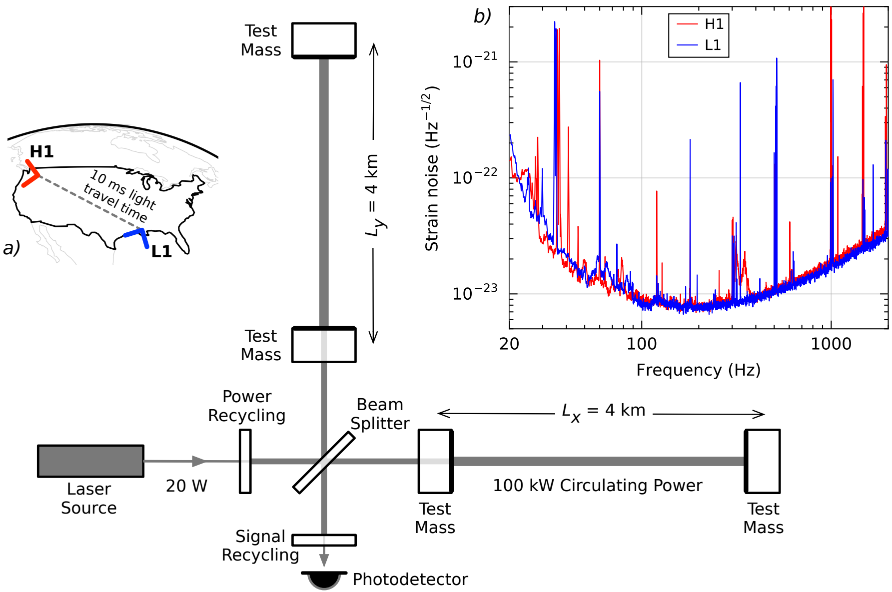


Inspiral search range during S5 is 14Mpc

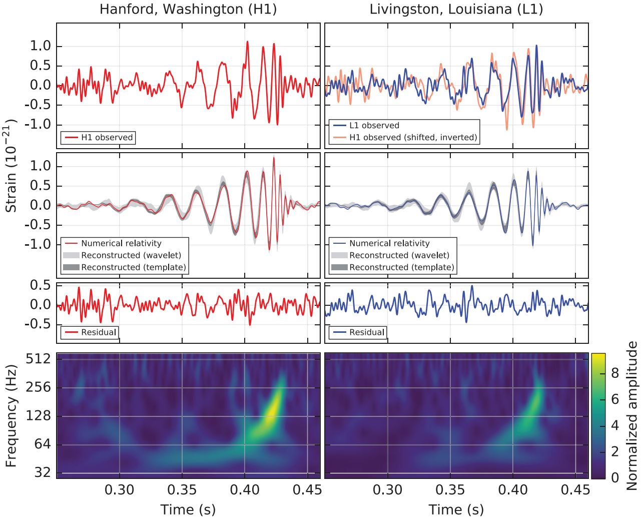
From LIGO to advanced LIGO



advanced LIGO detector summary



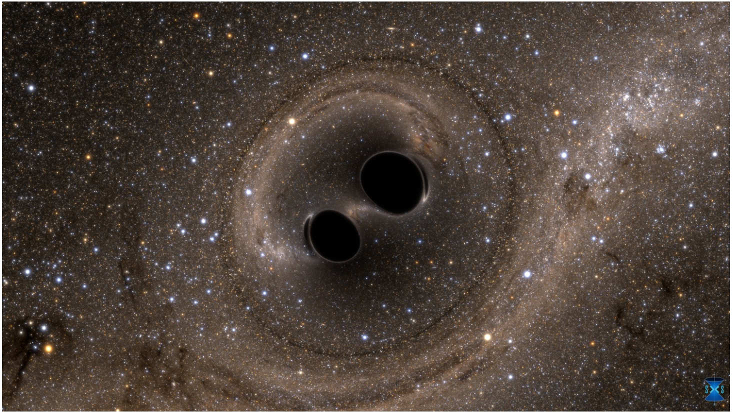
GW signal at 09:50:45 UTC on 14 September 2015



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

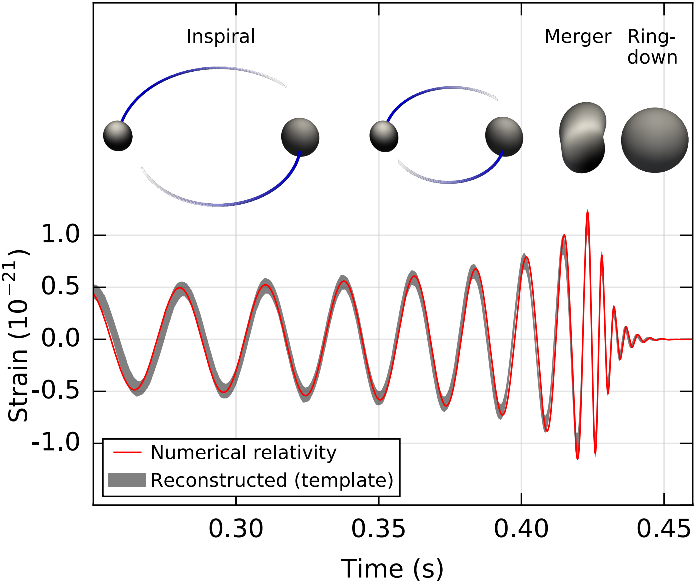
The sound of gravitational wave and simulated sky

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

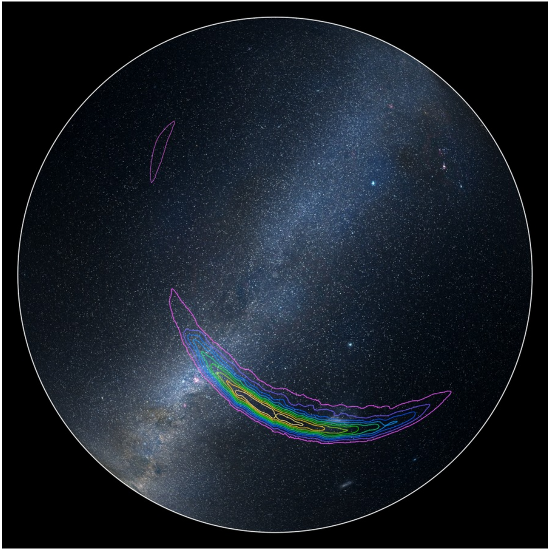


Two black holes with 29 and 36 solar masses merged about 1.3 billion years ago

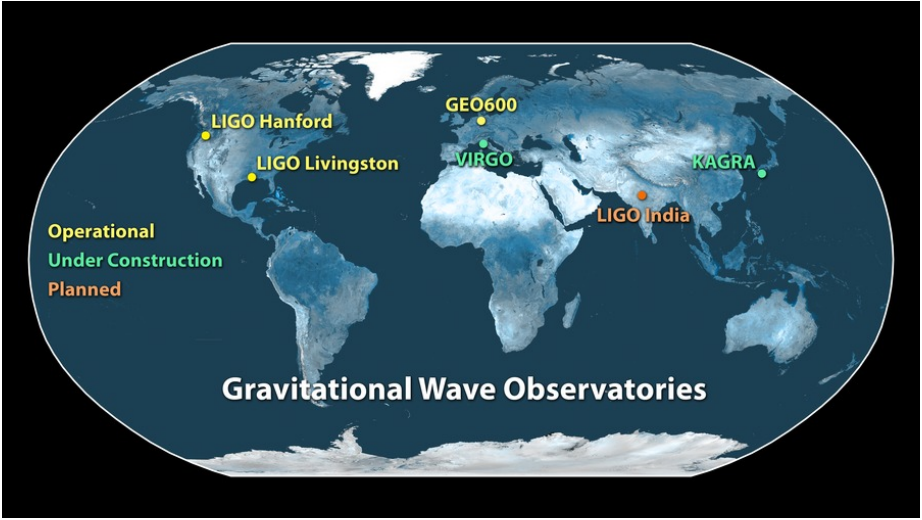
Reconstructed signal



GW source location at the southern hemisphere sky



World wide network of detectors



Confirmed GW detections

Event name	GW150914	GW151226
Mass 1	36 $M_\odot$	14.2 $M_\odot$
Mass 2	29 $M_\odot$	7.5 $M_\odot$
Final mass	62 $M_\odot$	20.8 $M_\odot$

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

"GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence", Phys. Rev. Lett., 116, 241103, (2016).

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

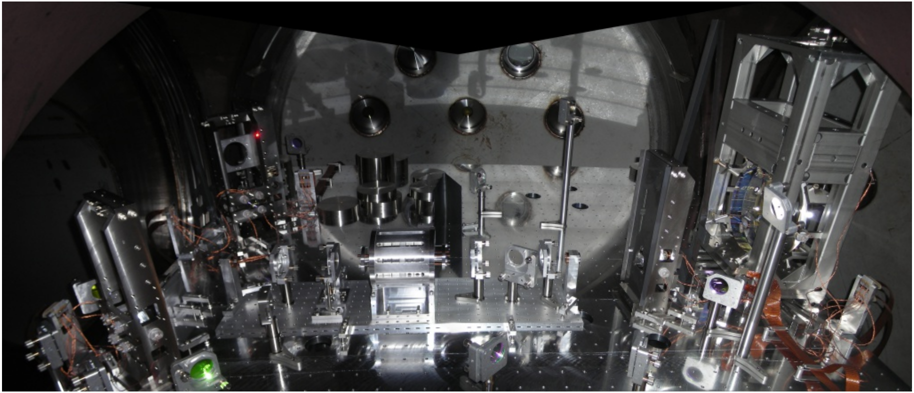


Photo from LIGO Magazine http://www.ligo.org/magazine/

Mirror

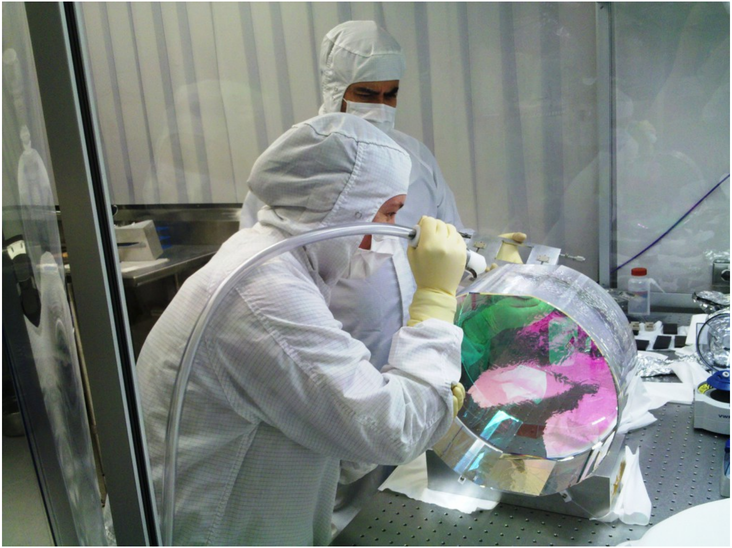


Photo from LIGO Magazine `http://www.ligo.org/magazine/`

Inner test mass

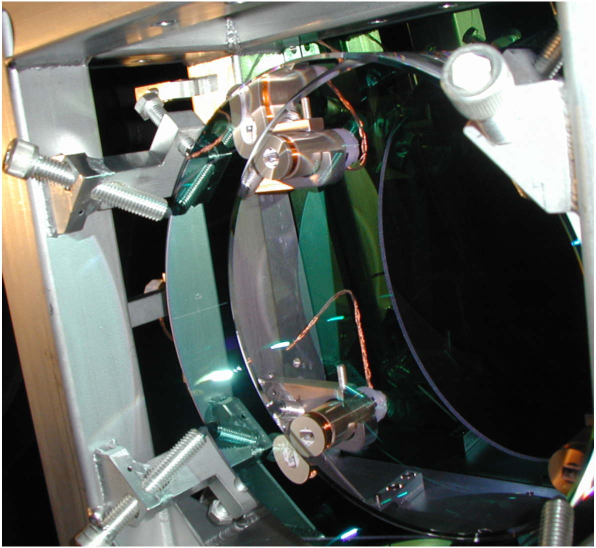


Photo from LIGO Magazine `http://www.ligo.org/magazine/`

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