LIGO, squeezed states of light, and nonlinear light-atom interactions.

LIGO Scientific Collaboration

and

Eugeniy E. Mikhailov

William & Mary
CHARTERED 1693

April 1st, 2016

Outline

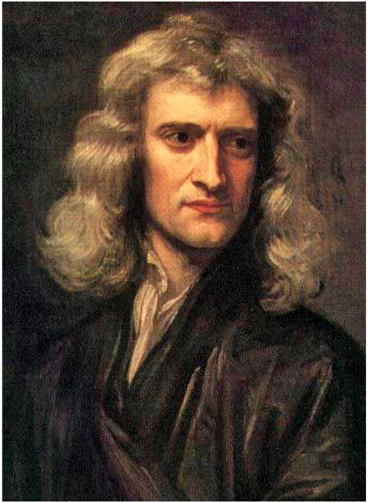
LIGO

LIGO Scientific Collaboration

LSC

Trinity University
University of Maryland
Andrews University
Washington State University
California State University Fullerton
The University of Alabama in Huntsville
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
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
ICTP SAIFR
The University of Western Australia
PAH
University of Cambridge
The University of Chicago
Montana State University
The University of Mississippi
The University of Adelaide Australia
Southern University Agricultural & Mechanical College
Columbia University in the City of New York
Caltech
University of Minnesota
University of Birmingham
The University of Melbourne
UIB Universitat de les Illes Balears
University of Washington
GEO 600
UTRGV
University of Wisconsin Milwaukee UWM
Northwestern
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
Penn State
Embry-Riddle Aeronautical University
Leibniz Universität Hannover
Science & Technology Facilities Council Rutherford Appleton Laboratory

Newton's laws 1686



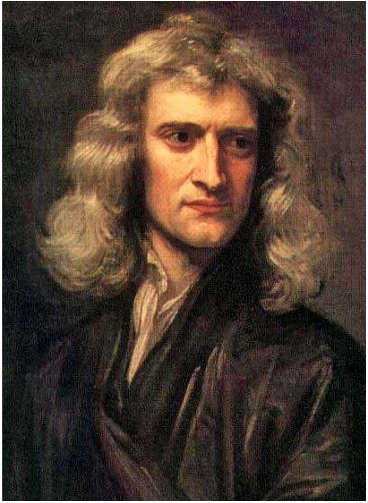
$$F_g = G\frac{m_1 m_2}{r^2}$$

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.

Did not explained precession of Mercury orbit



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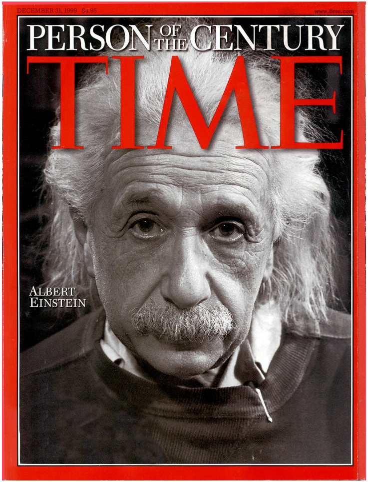
Einstein's laws 1915

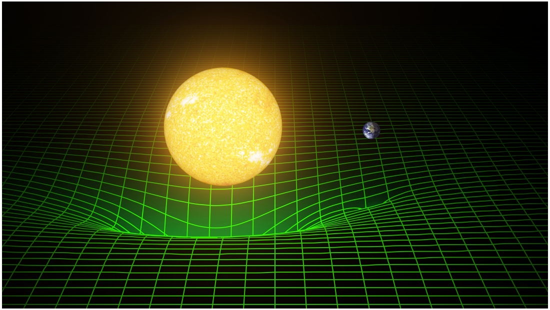


The General Theory of Relativity and theory of Gravity (1915)

- 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

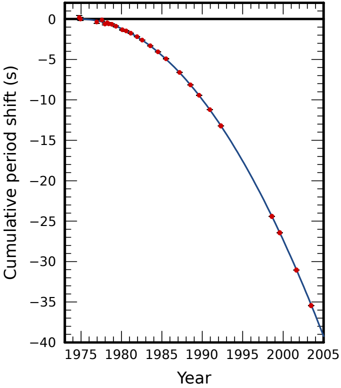
- Light path bends in vicinity of massive object $\rightarrow$ confirmed in 1919
- Gravitational radiation (waves) $\rightarrow$ confirmed indirectly in 1974

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

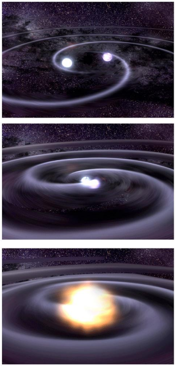
This can be explained by general relativistic effects: J.H. Taylor and J.M. Weisberg, Astrophysical Journal, Part 1, vol. 253, Feb. 15, 1982, p. 908-920.



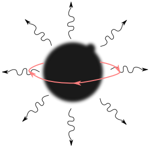
Nobel prize in 1993 to Hulse and Taylor

Astrophysical sources of GW

- Coalescing compact binaries
  - objects: NS-NS, BH-NS, BH-BH
  - physics regimes: Inspiral, merger, ringdown

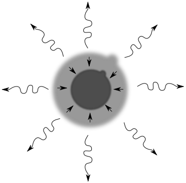


- Periodic sources
  - spinning neutron stars (pulsars)

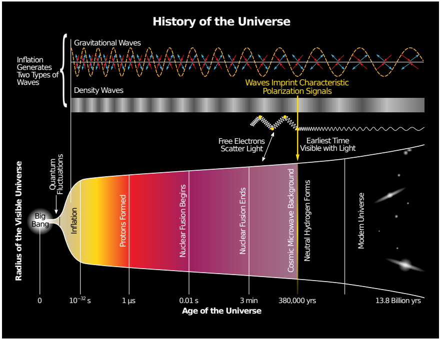


Astrophysical sources of GW (cont)

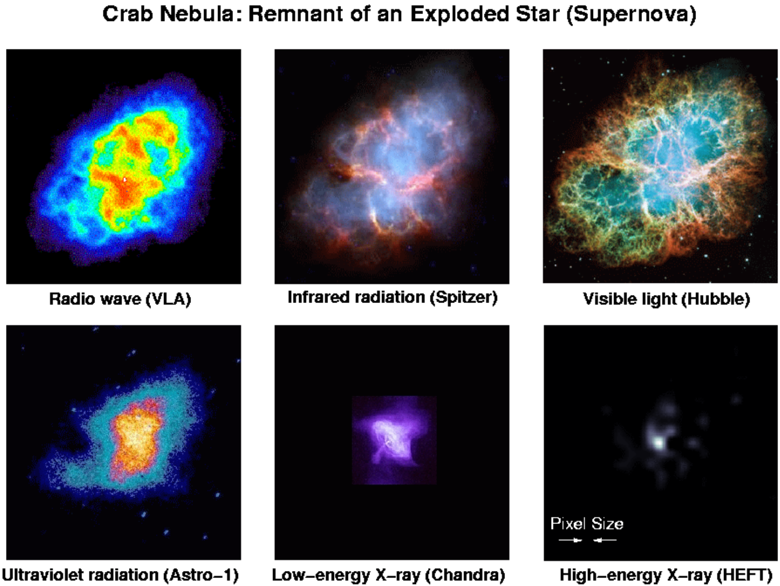
- Burst events
  - Supernovae with asymmetric collapse



- Stochastic background
  - right after Big Bang ($t = 10^{-43}$ sec)
  - continuum of sources



New view to the universe



Astrophysics with GWs vs. E&M

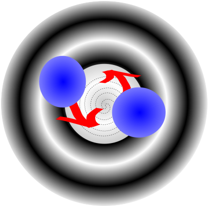
E&M (photons)

- 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)

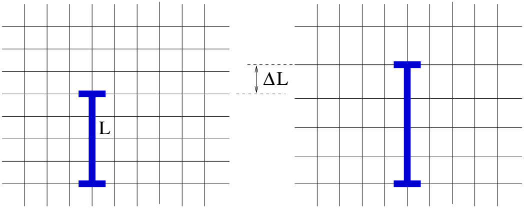
GW

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

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



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



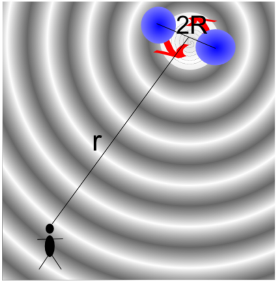
Strain - strength of GW

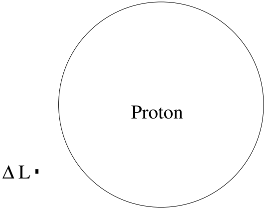
$$h = \frac{\Delta L}{L} \quad (1)$$

expected strain

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

Typical strain



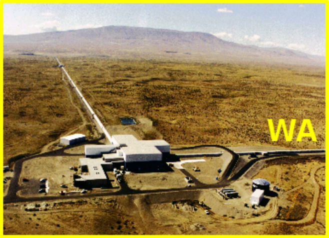


Two neutron star

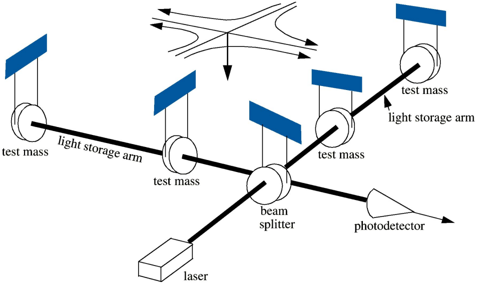
with a mass of 1.4 solar masses each
orbiting each other with a frequency $f = 400$ Hz
at a distance $2R = 20$ km
would generate strain $h \sim 10^{-21}$
at distance equal to 10^{23} m
(distance to the Virgo cluster)
For 4 km base line that would correspond to
ΔL thousand times smaller than size of proton.

Detection of GW is difficult problem

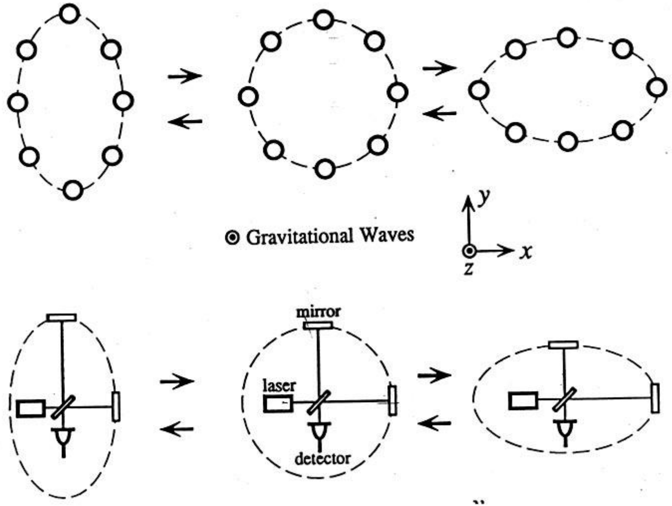
Laser Interferometer Gravitational-wave Observatory



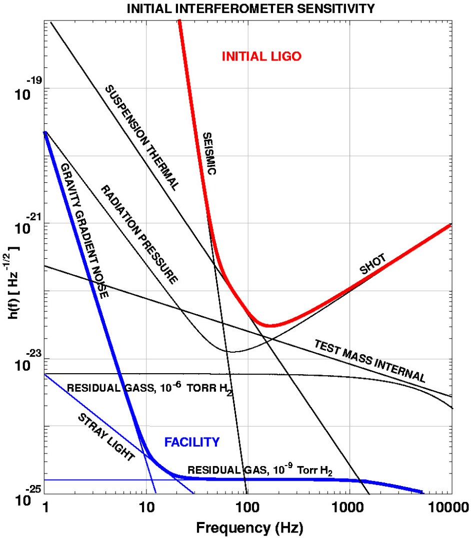
- $L = 4$ km
- $h \sim 10^{-23}$



GW acting on matter



Initial LIGO sensitivity goal and noise budget



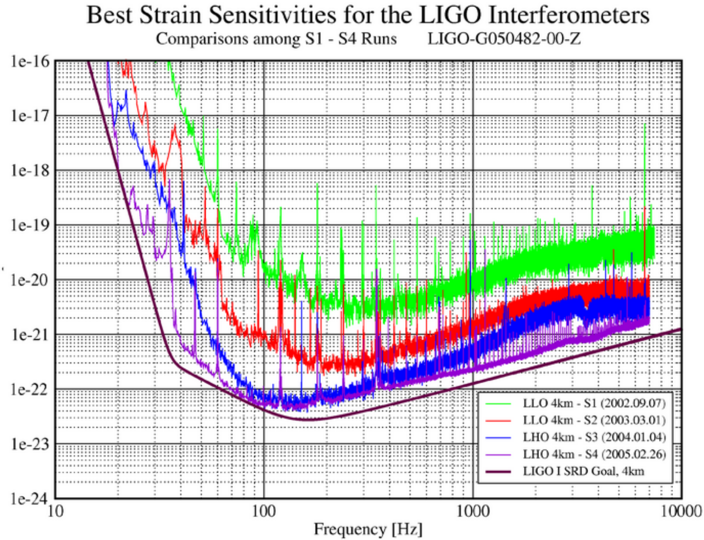
Displacement noise

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

Detection noise

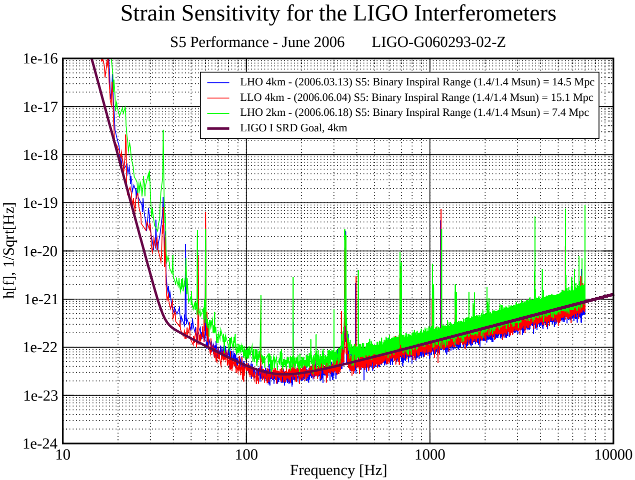
- electronics
- shot noise

LIGO sensitivity, S1-S4 runs



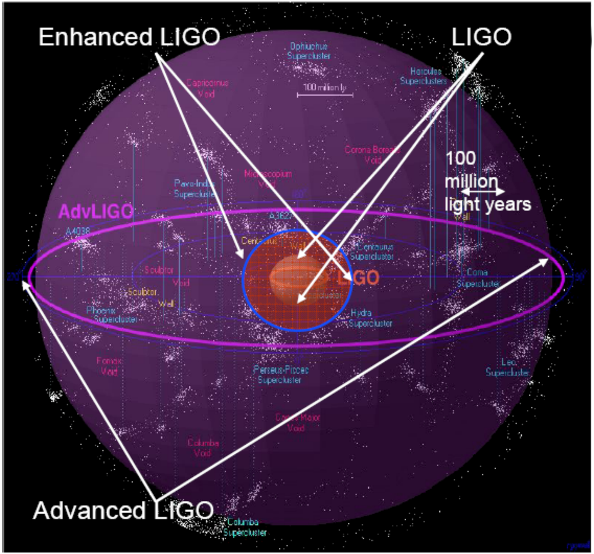
Inspiral search range during S4 was 8Mpc

LIGO sensitivity, S5 run, June 2006

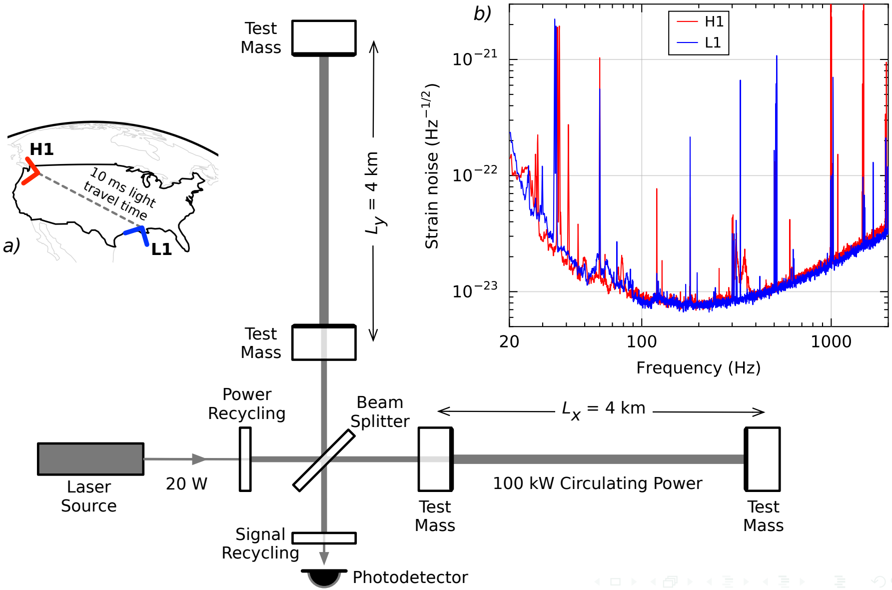


Inspiral search range during S5 is 14Mpc

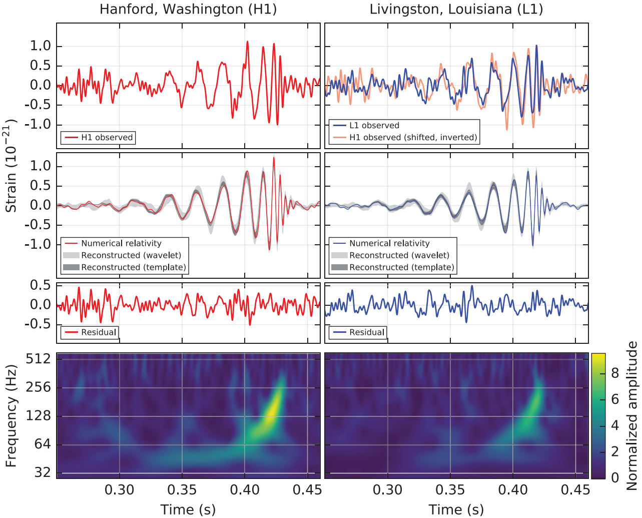
From LIGO to advanced LIGO



advanced LIGO detector summary



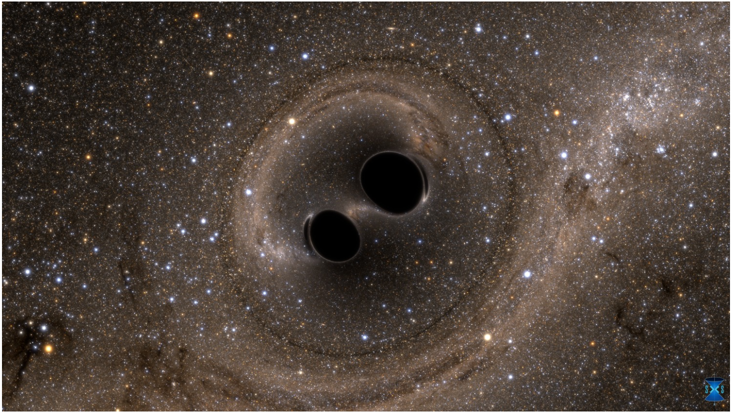
GW signal at 09:50:45 UTC on 14 September 2015



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

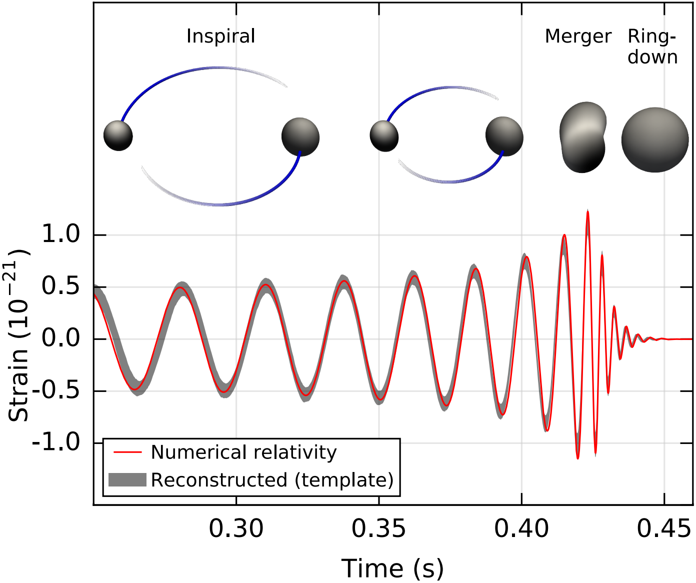
The sound of gravitational wave and simulated sky

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

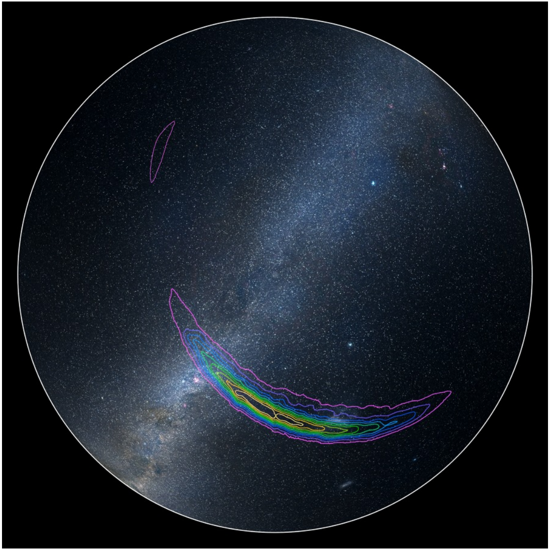


Two black holes with 29 and 36 solar masses merged about 1.3 billion years ago

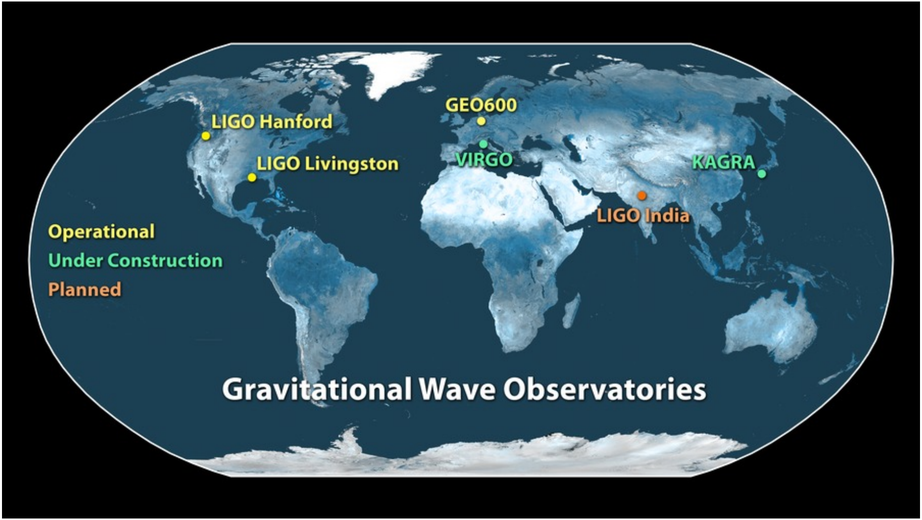
Reconstructed signal



GW source location at the southern hemisphere sky



World wide network of detectors



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

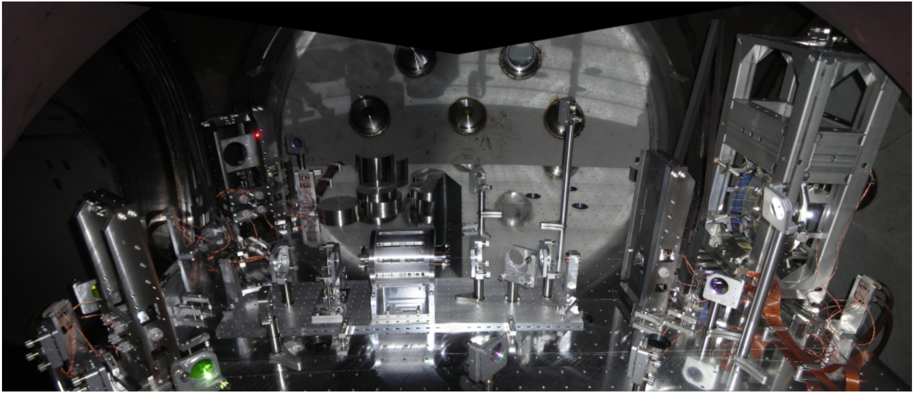


Photo from LIGO Magazine `http://www.ligo.org/magazine/`

Mirror

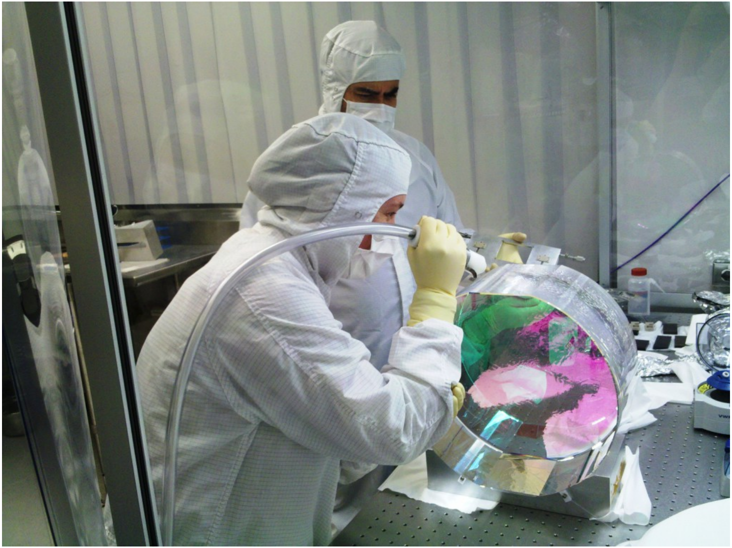


Photo from LIGO Magazine http://www.ligo.org/magazine/

Inner test mass

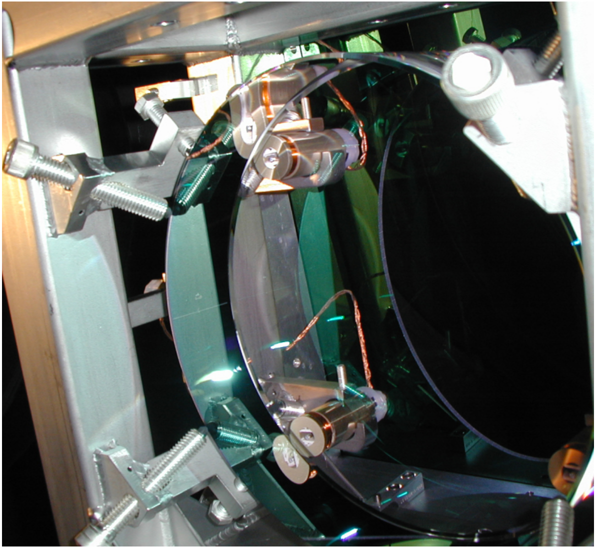


Photo from LIGO Magazine http://www.ligo.org/magazine/

We can detect stars collisions and ...

Additional links

LIGO Scientific Collaboration

www.ligo.org

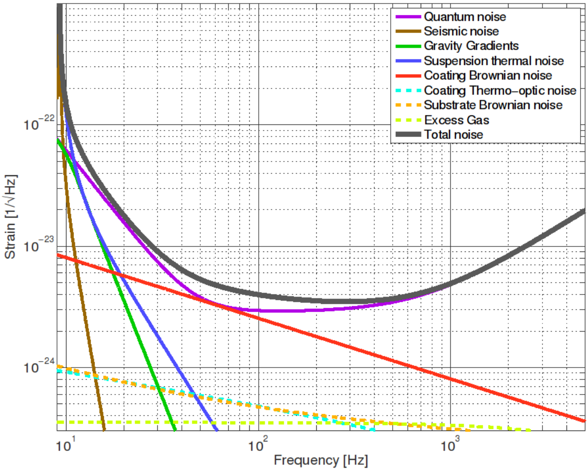
Couple movies

- LIGO Generations http://www.space.com/28409-ligo-generations-the-film-hd-video.html
- LIGO: A Passion for Understanding http://www.space.com/25455-ligo-documentary-film-complete-coverage.html

You can help to detect a gravitational wave

www.einsteinathome.org

Advanced LIGO sensitivity goal and noise budget



Displacement noise

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

Detection noise

- electronics
- shot noise

"Advanced LIGO", Class. Quantum Grav., 32, 074001 (2015)

Heisenberg uncertainty principle and its optics equivalent

Heisenberg uncertainty principle

$\Delta p \Delta x \geq \hbar/2$

The more precisely the POSITION is determined, the less precisely the MOMENTUM is known, and vice versa

Heisenberg uncertainty principle and its optics equivalent

Heisenberg uncertainty principle

$\Delta p \Delta x \geq \hbar/2$

The more precisely the POSITION is determined, the less precisely the MOMENTUM is known, and vice versa

Optics equivalent

$\Delta \phi \Delta N \geq 1$

The more precisely the PHASE is determined, the less precisely the AMPLITUDE is known, and vice versa

Heisenberg uncertainty principle and its optics equivalent

Heisenberg uncertainty principle

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Optics equivalent

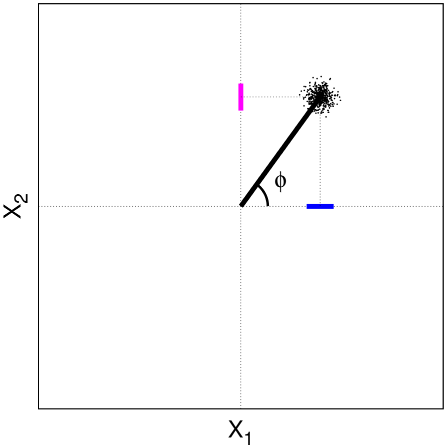
$\Delta\phi \Delta N \geq 1$

The more precisely the PHASE is determined, the less precisely the AMPLITUDE is known, and vice versa

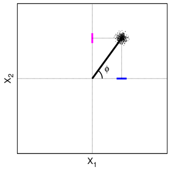
Optics equivalent strict definition

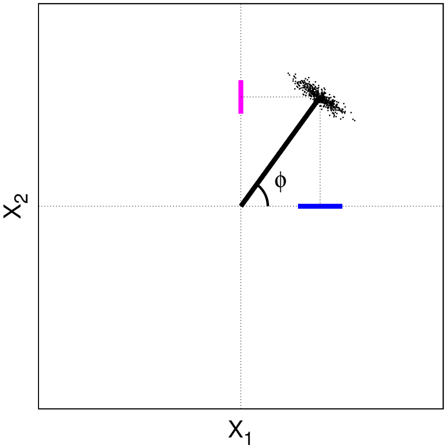
$\Delta X_1 \Delta X_2 \geq 1/4$

Squeezed quantum states zoo

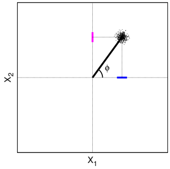


Unsqueezed coherent

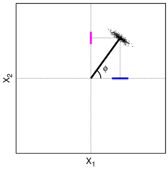


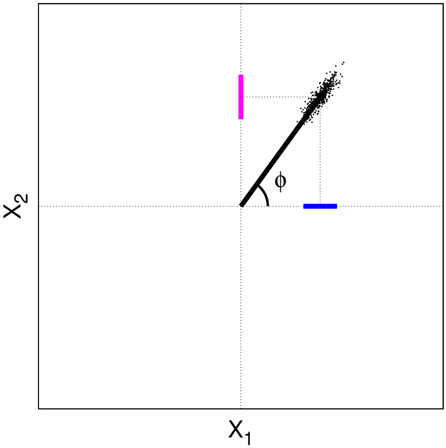


Unsqueezed coherent

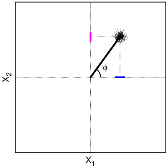


Amplitude squeezed

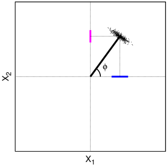




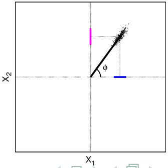
Unsqueezed coherent



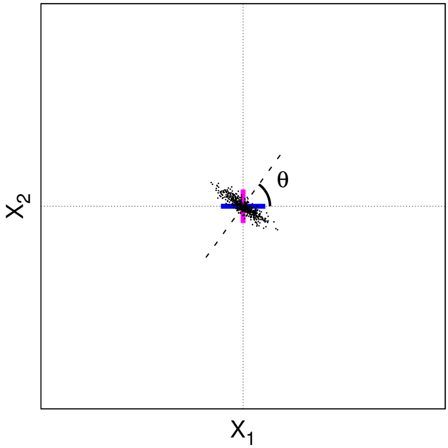
Amplitude squeezed



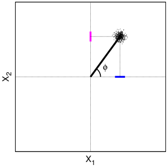
Phase squeezed



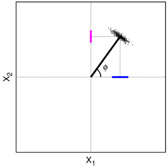
Squeezed quantum states zoo



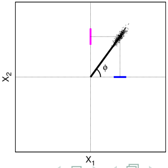
Unsqueezed coherent



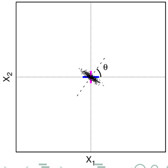
Amplitude squeezed



Phase squeezed

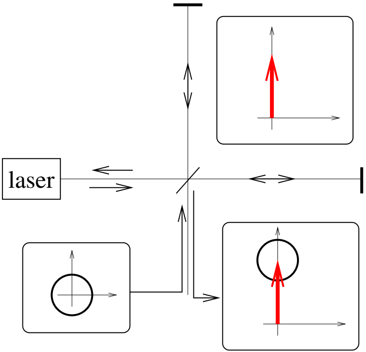


Vacuum squeezed



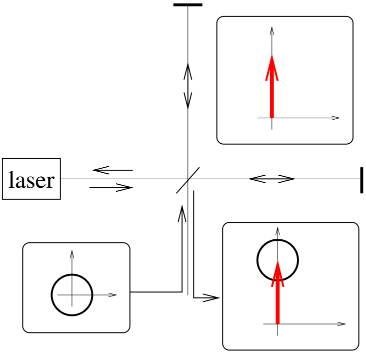
Squeezing and interferometer

Vacuum input

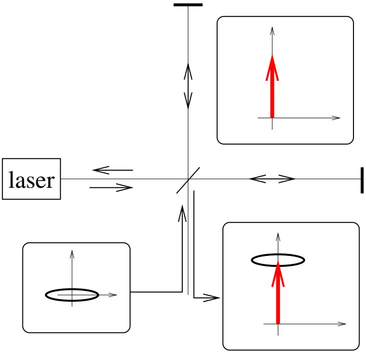


Squeezing and interferometer

Vacuum input

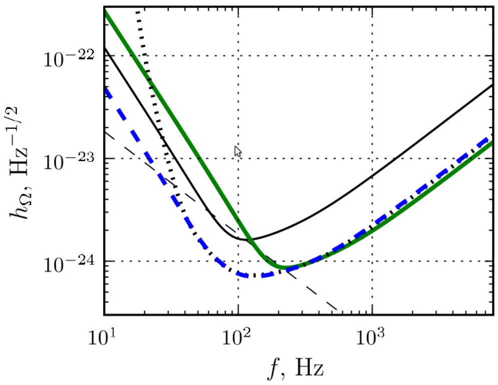


Squeezed input



Interferometer sensitivity improvement with squeezing

F. Ya. Khalili Phys. Rev. D 81, 122002 (2010)
Projected advanced LIGO sensitivity



Demonstrations of quantum enhancement of LIGO

Keisuke Goda, et al., Nature Physics, **4**, 472-476, (2008)
Ligo Scientific Collaboration, Nature Photonics **7**, 613-619 (2013)

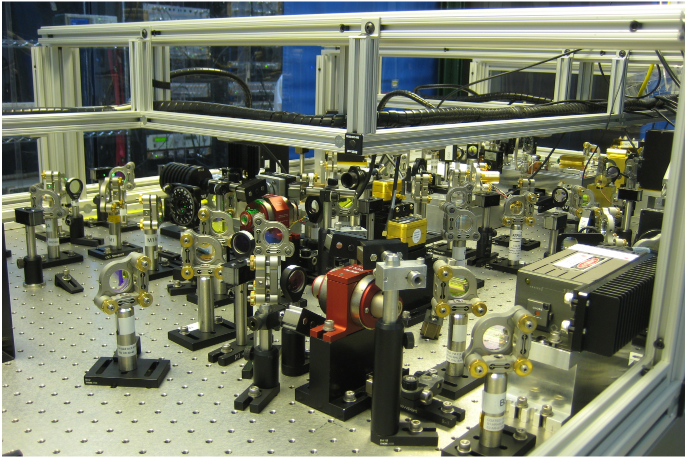
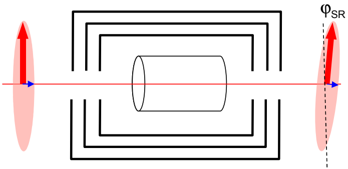
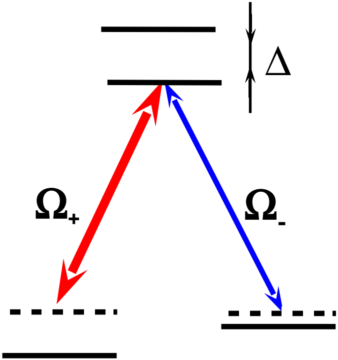


Photo of Squeezer, LIGO Magazine `http://www.ligo.org/magazine/`

We are changing gears!
From LSC results to studies at W&M.

Self-rotation of elliptical polarization in atomic medium

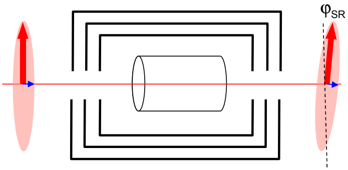


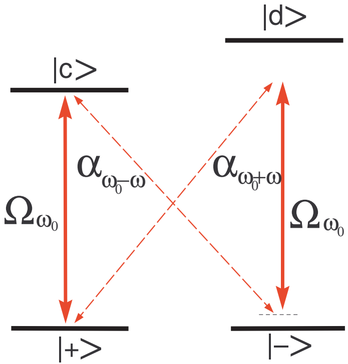


A.B. Matsko et al., PRA 66, 043815 (2002): theoretically prediction of 4-6 dB noise suppression

$$a_{out} = a_{in} + \frac{igL}{2}(a_{in}^{\dagger} - a_{in})$$

Self-rotation of elliptical polarization in atomic medium



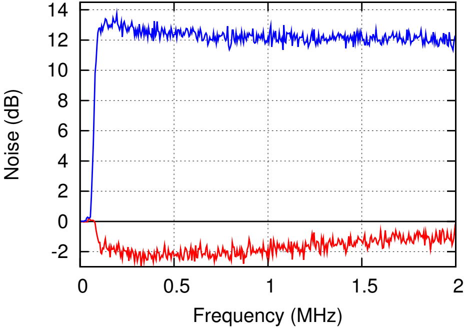


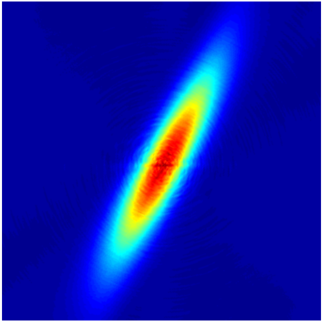
A.B. Matsko et al., PRA 66, 043815 (2002): theoretically prediction of 4-6 dB noise suppression

$$a_{out} = a_{in} + \frac{igL}{2}(a_{in}^{\dagger} - a_{in})$$

Typical squeezed spectrum with ^{87}Rb

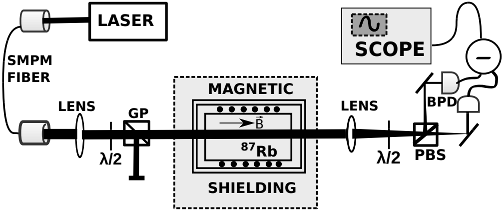
W&M team. ^{87}Rb $F_g = 2 \to F_e = 2$, laser power 7 mW, T=65° C

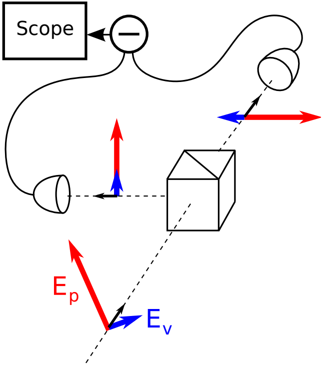




Lezama et.al report 3 dB squeezing in similar setup
Phys. Rev. A 84, 033851 (2011)

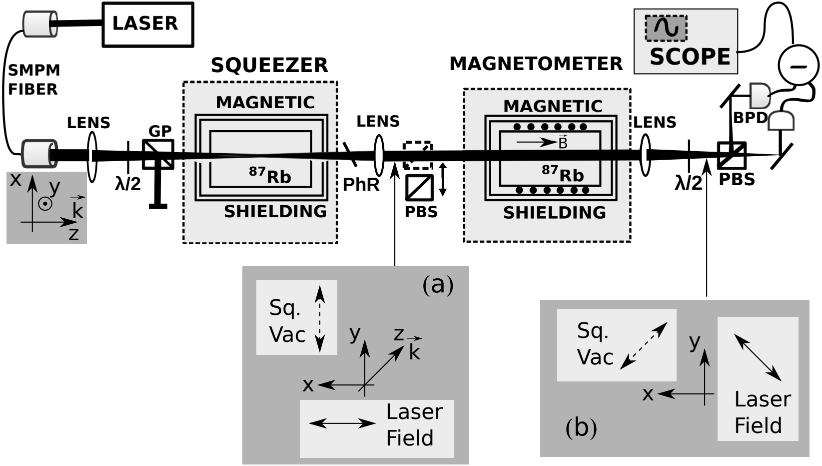
Shot noise limit of the magnetometer





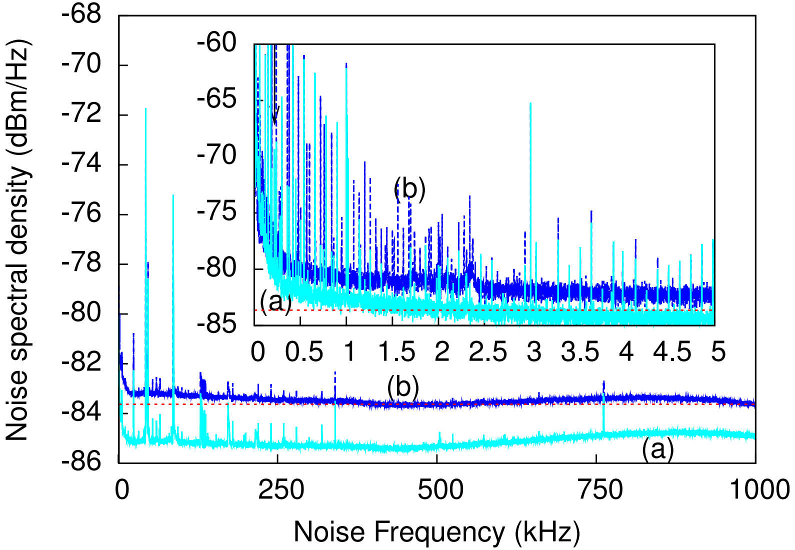
$$S = |E_p + E_v|^2 - |E_p - E_v|^2$$
$$S = 4 E_p E_v$$
$$< \Delta S > \sim E_p < \Delta E_v >$$

Squeezed enhanced magnetometer setup

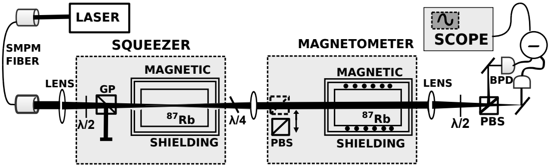


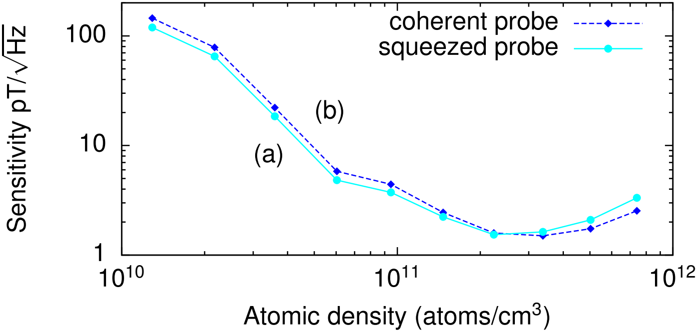
Note: Squeezed enhanced magnetometer was first demonstrated by Wolfgramm *et. al* Phys. Rev. Lett, **105**, 053601, 2010.

Magnetometer noise floor improvements



Magnetometer with squeezing enhancement





T. Horrom, et al. **PRA**, 86, 023803, (2012).

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