

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



and
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June 24th, 2016

Outline

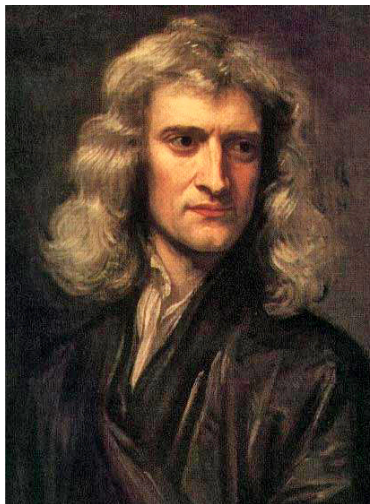
- 1 LSC
- 2 History of gravity
- 3 Detectors
- 4 Detection
- 5 Assorted LIGO pictures
- 6 Squeezing
- 7 Squeezing and atoms
- 8 Magnetometry with squeezing



LIGO Scientific Collaboration



Newton's laws 1686

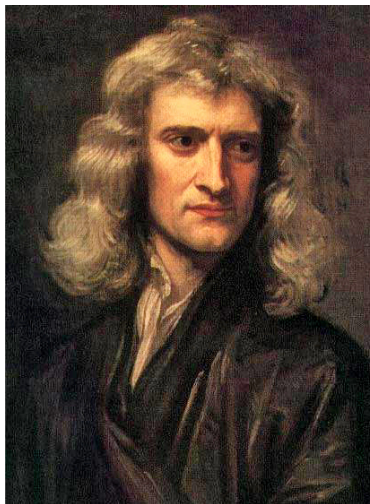


$$F_g = G \frac{m_1 m_2}{r^2}$$

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.



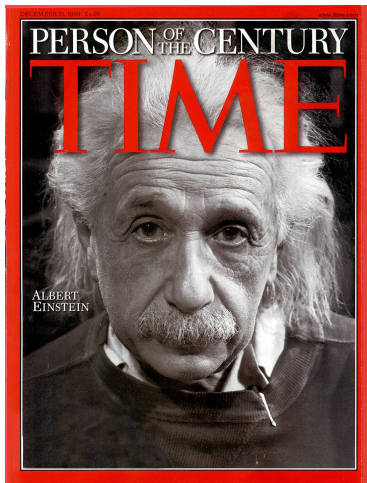
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Unified the work of Galileo, Copernicus and Kepler.

Did not explained precession of Mercury orbit

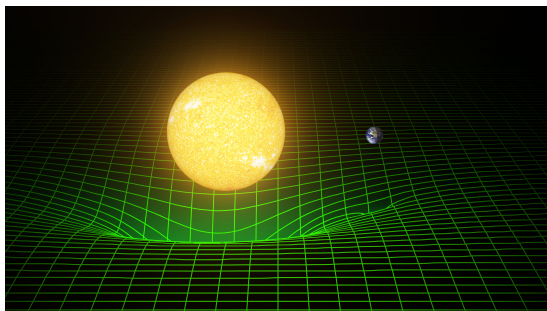


The General Theory of Relativity and theory of Gravity (1915)

- 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

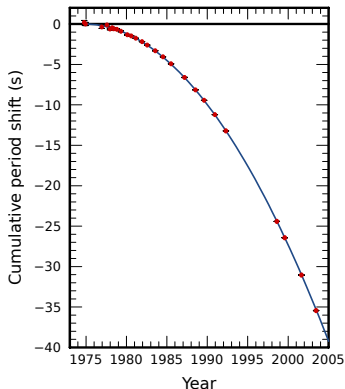
Indirect observation of gravitational wave

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.

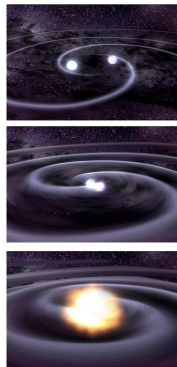
Nobel prize in 1993 to Hulse and Taylor



Astrophysical sources of GW

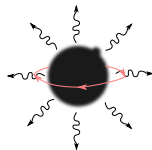
- Coalescing compact binaries

- objects: NS-NS, BH-NS, BH-BH
- physics regimes: Inspiral, merger, ringdown



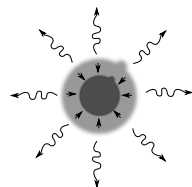
- Periodic sources

- spinning neutron stars (pulsars)

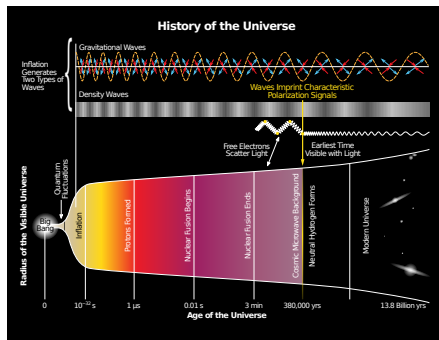


Astrophysical sources of GW (cont)

- Burst events
 - Supernovae with asymmetric collapse

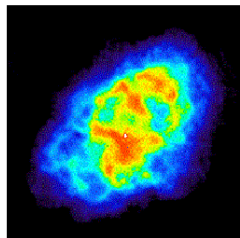


- Stochastic background
 - right after Big Bang ($t = 10^{-43}$ sec)
 - continuum of sources



New view to the universe

Crab Nebula: Remnant of an Exploded Star (Supernova)



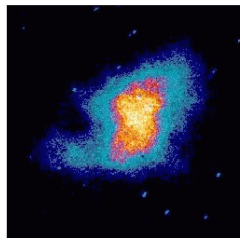
Radio wave (VLA)



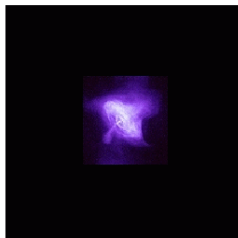
Infrared radiation (Spitzer)



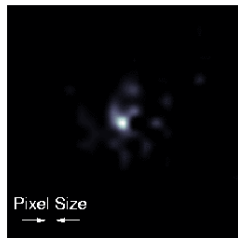
Visible light (Hubble)



Ultraviolet radiation (Astro-1)



Low-energy X-ray (Chandra)



High-energy X-ray (HEFT)

Astrophysics with GWs vs. E&M

E&M (photons)

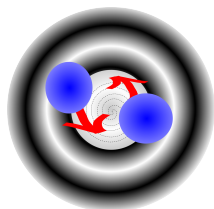
- Space as medium for field
- Accelerating charge
- Absorbed, scattered, dispersed by matter
- 10 MHz and up
- Light = not dark (but >95% of Universe is dark)

GW

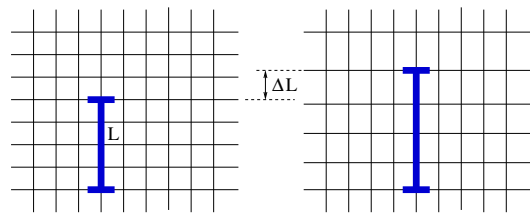
- Spacetime itself ripples
- Accelerating aspherical mass
- Very small interaction; matter is transparent
- 10 kHz and down
- Radiated by dark mass distributions

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
- New tool for astrophysics



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



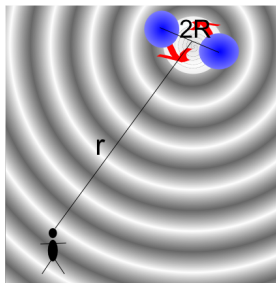
Strain - strength of GW

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

expected strain

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

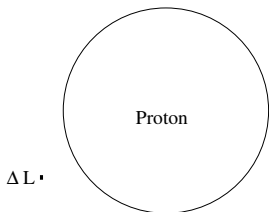
Typical strain



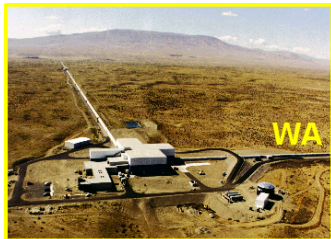
$$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$
$$h = 4 \frac{G}{c^2} \frac{M_c}{r} \left(\frac{G}{c^3} \pi f M_c \right)^{2/3}$$

Two neutron star

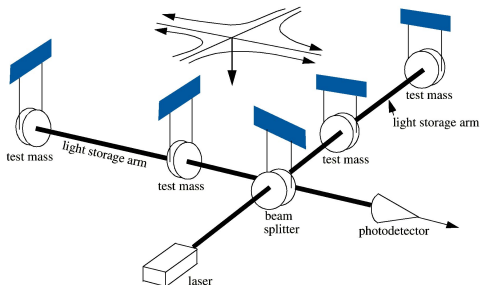
with a mass of 1.4 solar masses each
orbiting each other with a frequency $f = 400$ Hz
at a distance $2R = 20$ km
would generate strain $h \sim 10^{-21}$
at distance equal to 10^{23} m
(distance to the Virgo cluster)
For 4 km base line that would correspond to
 ΔL thousand times smaller than size of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



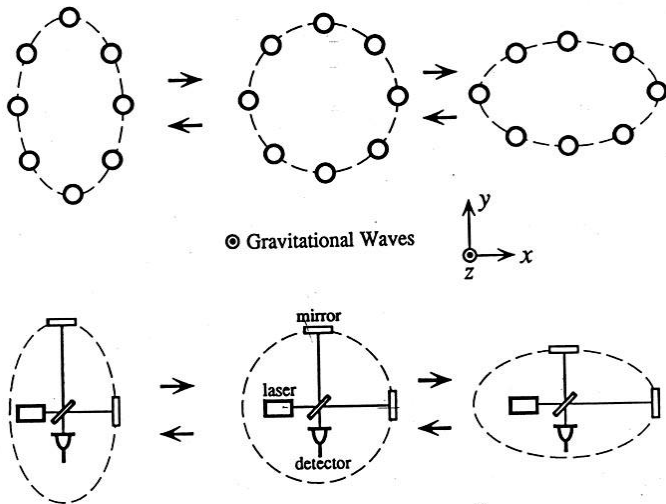
Laser Interferometer Gravitational-wave Observatory



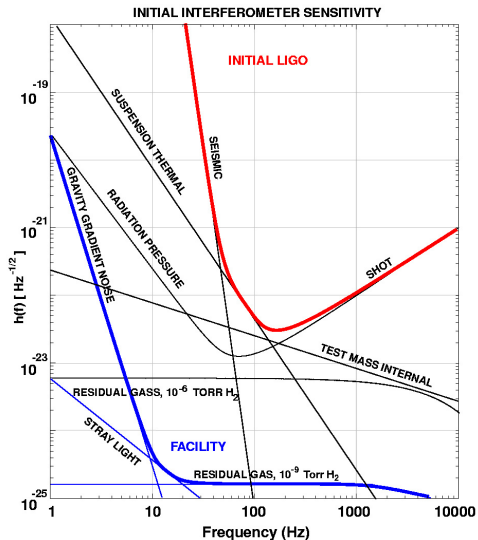
- $L = 4 \text{ km}$
- $h \sim 10^{-23}$



GW acting on matter



Initial LIGO sensitivity goal and noise budget



Displacement noise

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

Detection noise

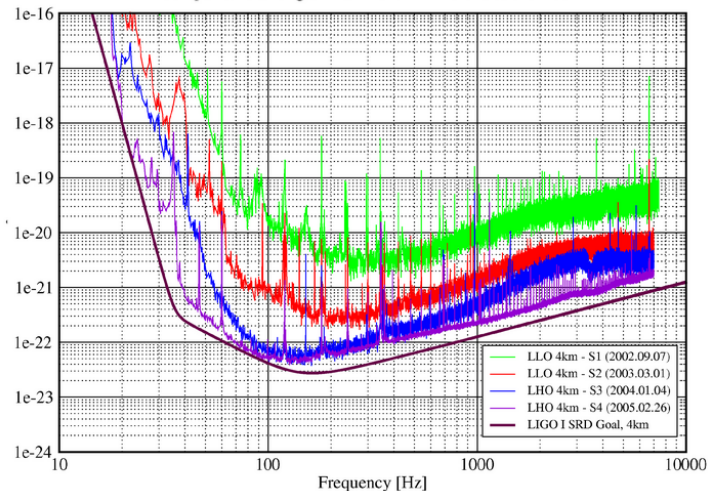
- electronics
- shot noise

LIGO sensitivity, S1-S4 runs

Best Strain Sensivities for the LIGO Interferometers

Comparisons among S1 - S4 Runs

LIGO-G050482-00-Z

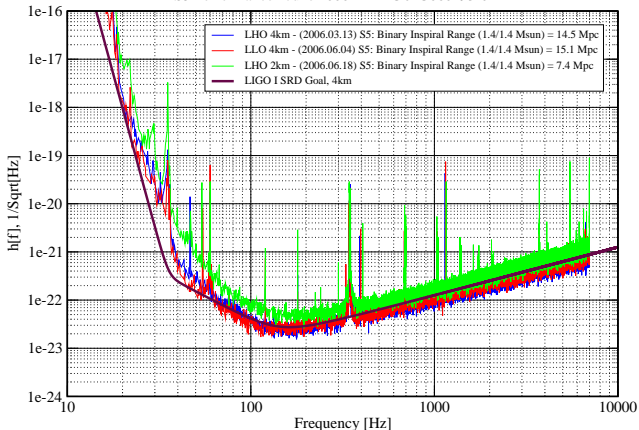


Inspiral search range during S4 was 8Mpc

LIGO sensitivity, S5 run, June 2006

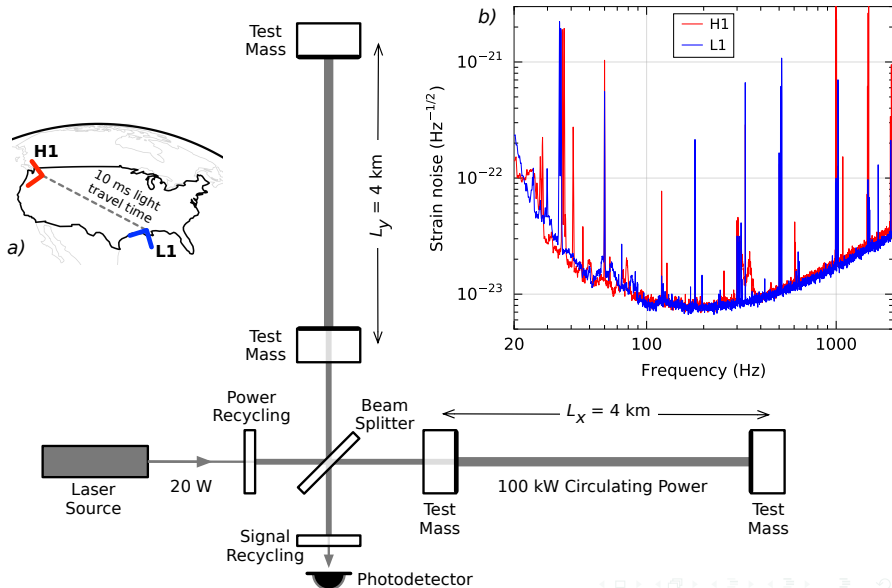
Strain Sensitivity for the LIGO Interferometers

S5 Performance - June 2006 LIGO-G060293-02-Z

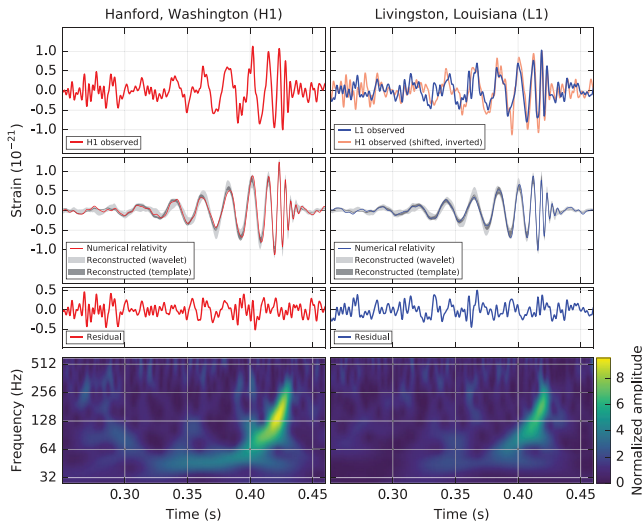


Inspirational search range during S5 is 14Mpc

advanced LIGO detector summary



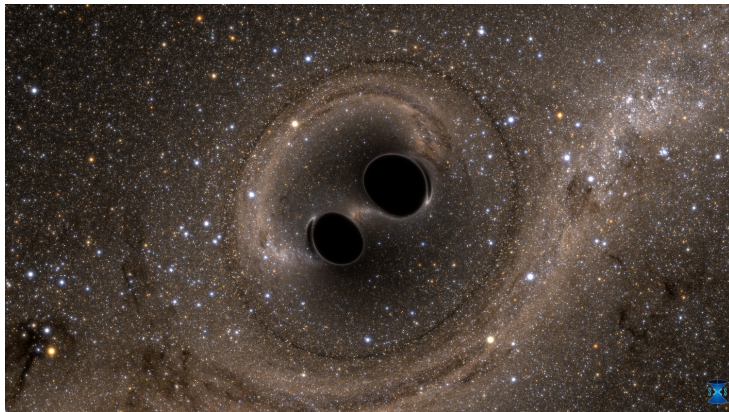
GW signal at 09:50:45 UTC on 14 September 2015



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

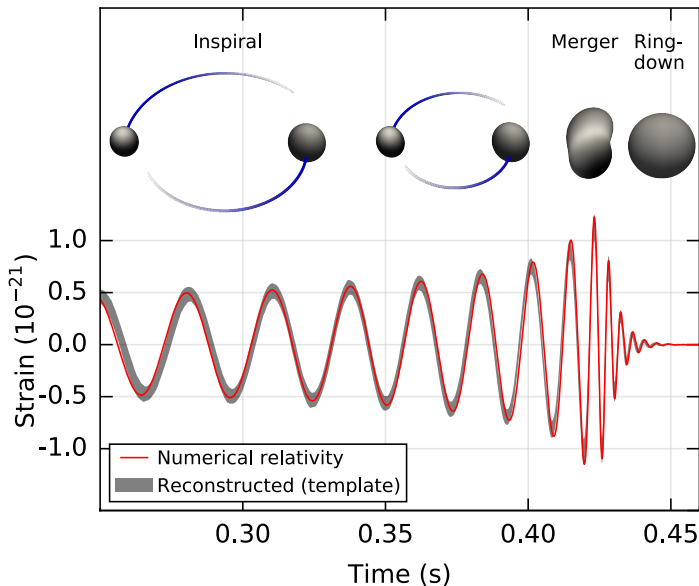
The sound of gravitational wave and simulated sky

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

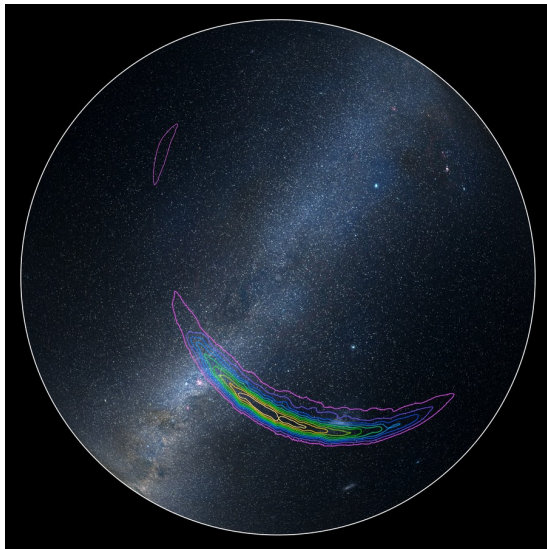


Two black holes with 29 and 36 solar masses merged about 1.3 billion years ago

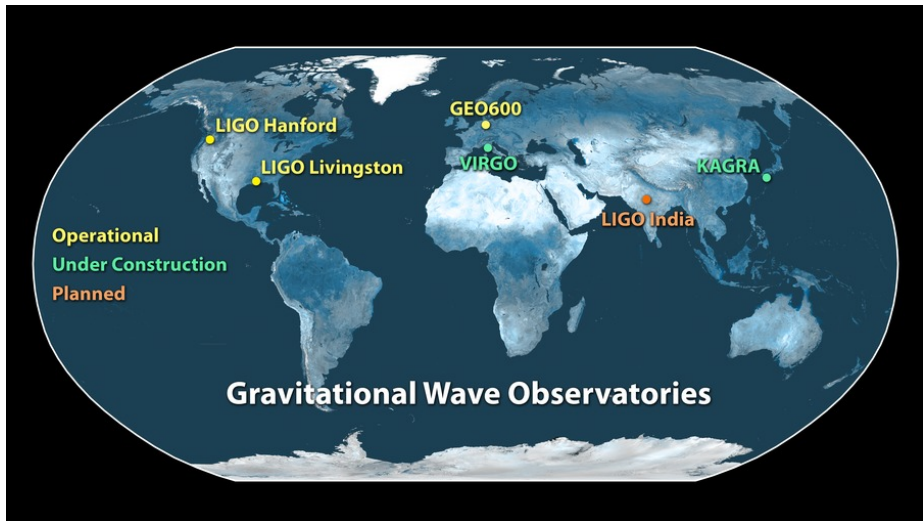
Reconstructed signal



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

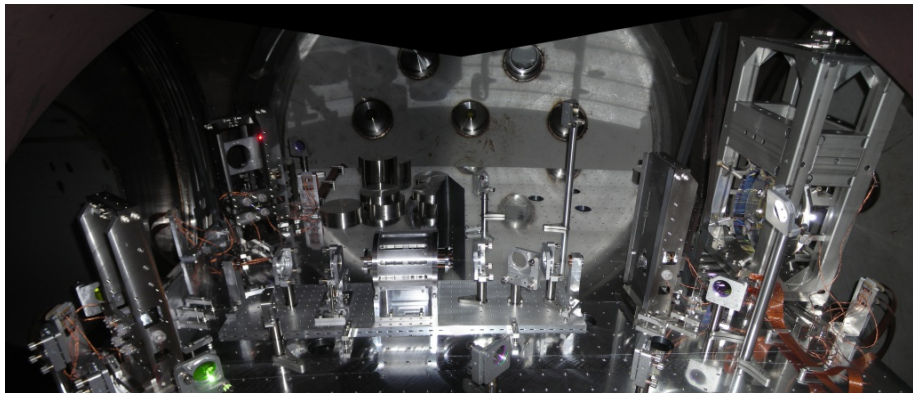


Photo from LIGO Magazine <http://www.ligo.org/magazine/>

Mirror

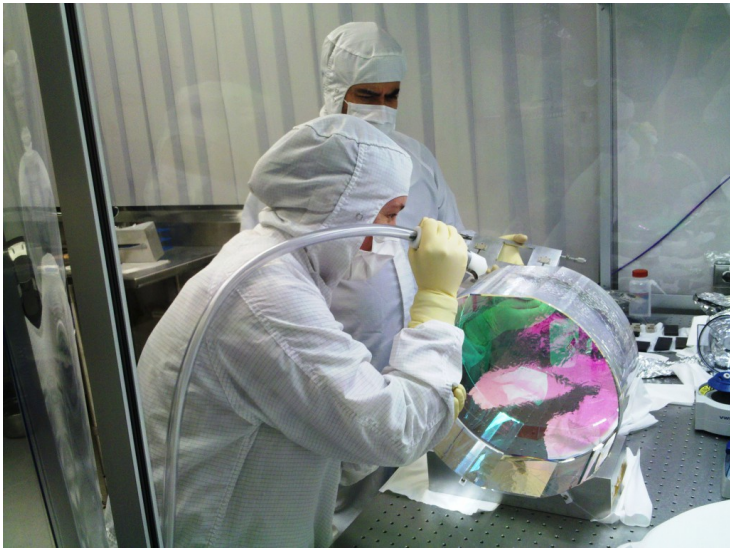


Photo from LIGO Magazine <http://www.ligo.org/magazine/>

Inner test mass

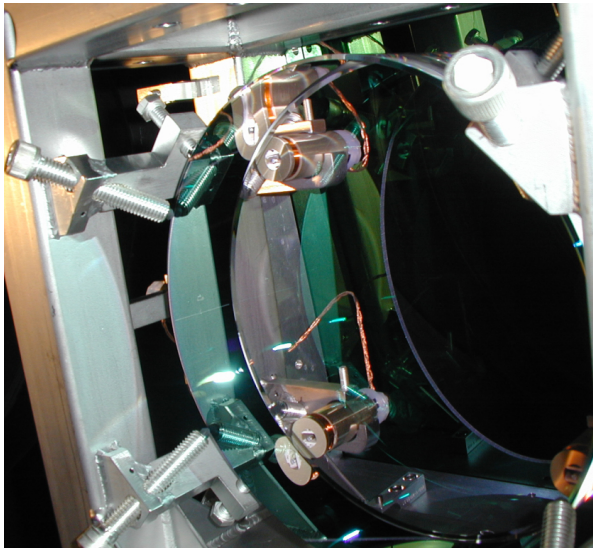


Photo from LIGO Magazine <http://www.ligo.org/magazine/>

We can detect stars collisions and ...



Additional links



**LIGO
Scientific
Collaboration**

www.ligo.org

Couple movies

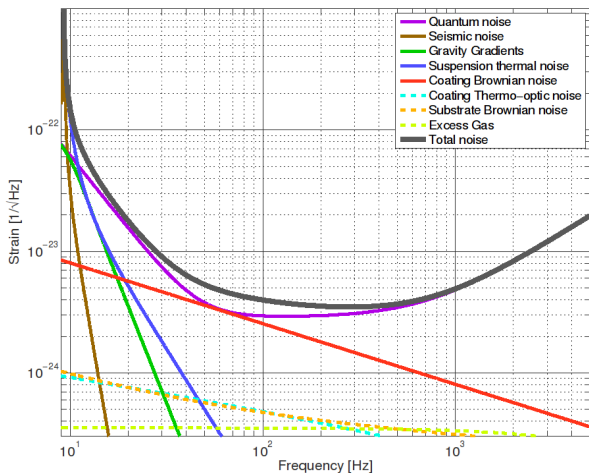
- LIGO Generations <http://www.space.com/28409-ligo-generations-the-film-hd-video.html>
- LIGO: A Passion for Understanding <http://www.space.com/25455-ligo-documentary-film-complete-coverage.html>

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



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

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

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

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Optics equivalent

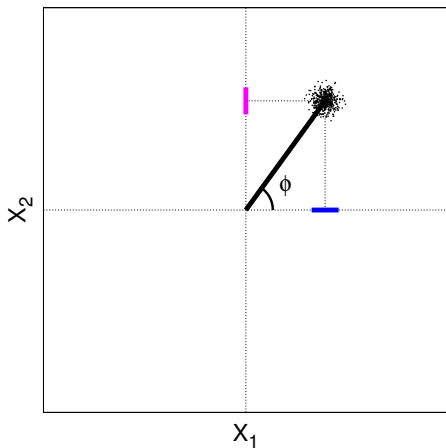
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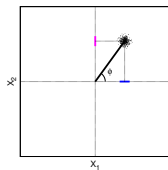
Optics equivalent strict definition

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

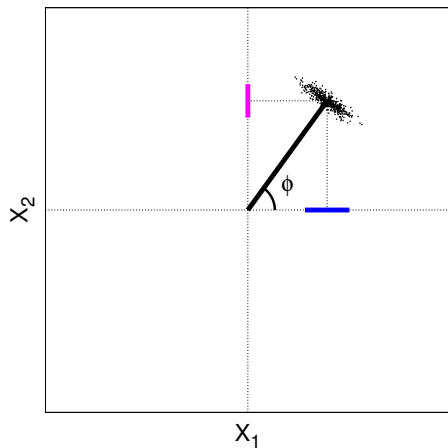
Squeezed quantum states zoo



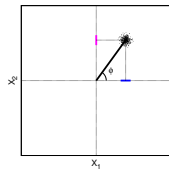
Unsqueezed
coherent



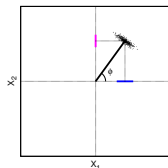
Squeezed quantum states zoo



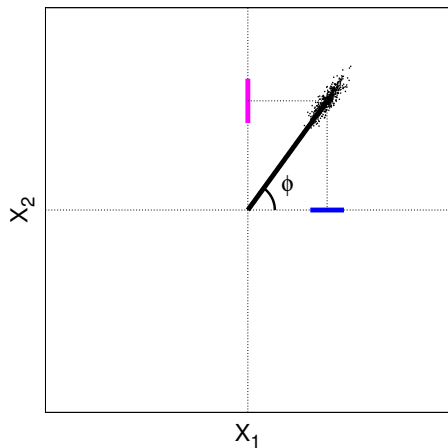
Unsqueezed
coherent



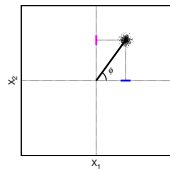
Amplitude
squeezed



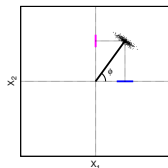
Squeezed quantum states zoo



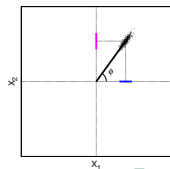
Unsqueezed
coherent



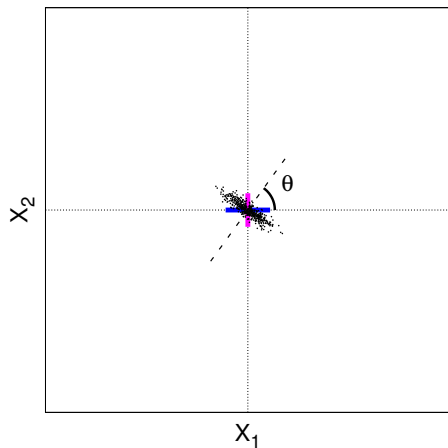
Amplitude
squeezed



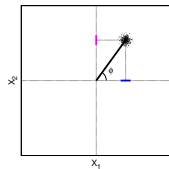
Phase
squeezed



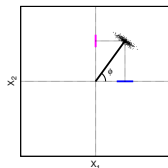
Squeezed quantum states zoo



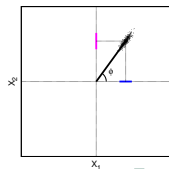
Unsqueezed
coherent



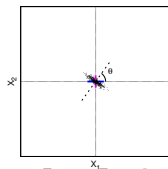
Amplitude
squeezed



Phase
squeezed



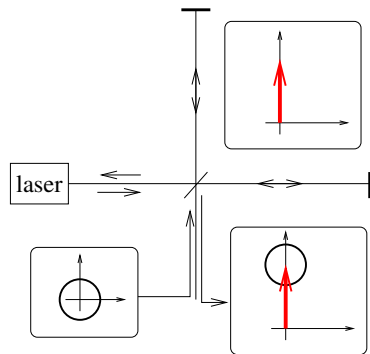
Vacuum
squeezed



Squeezing and interferometer

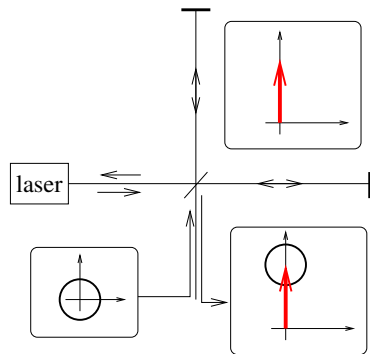
Squeezing and interferometer

Vacuum input

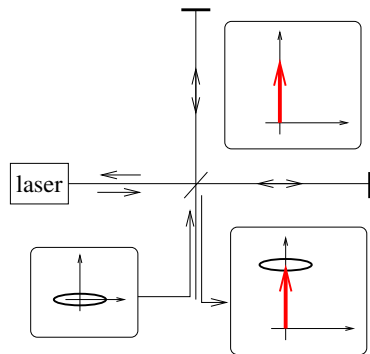


Squeezing and interferometer

Vacuum input



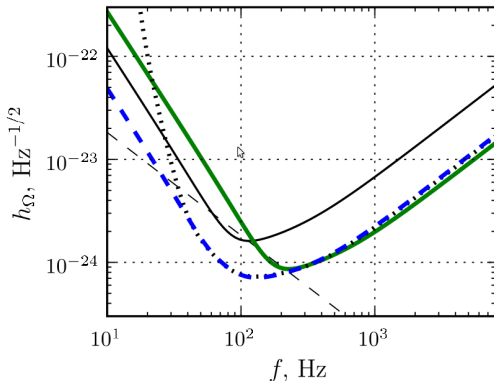
Squeezed input



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)

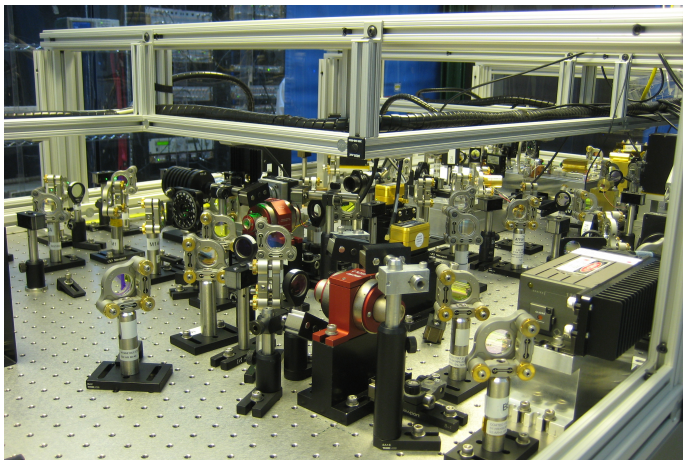
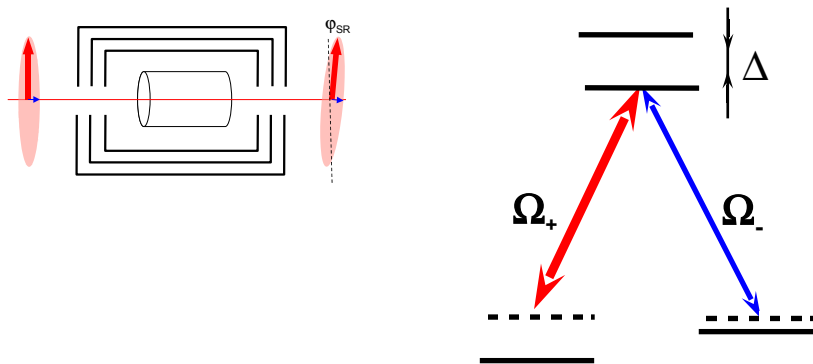


Photo of Squeezer, LIGO Magazine <http://www.ligo.org/magazine/>

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



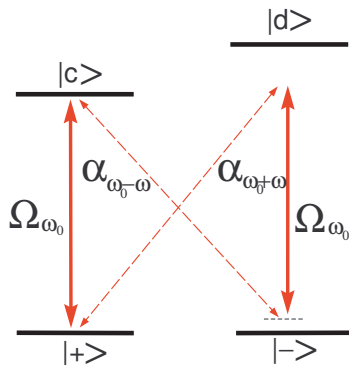
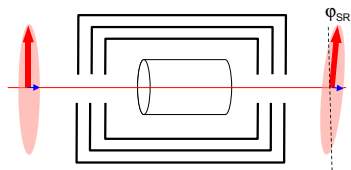
Self-rotation of elliptical polarization in atomic medium



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

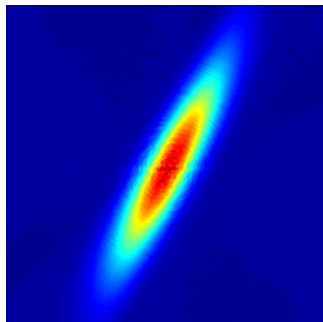
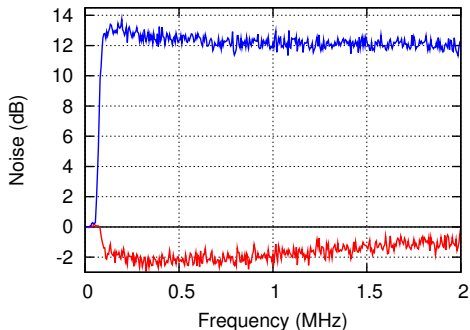


A.B. Matsko et al., PRA 66, 043815 (2002): theoretically prediction of 4-6 dB noise suppression

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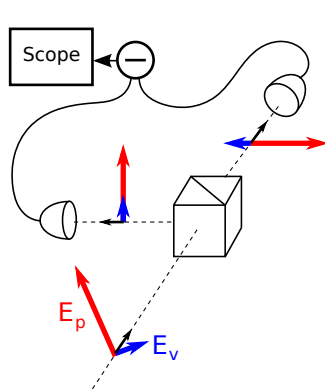
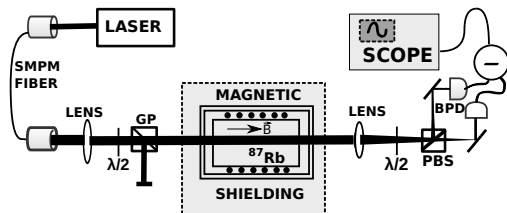
Typical squeezed spectrum with ^{87}Rb

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



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

Shot noise limit of the magnetometer

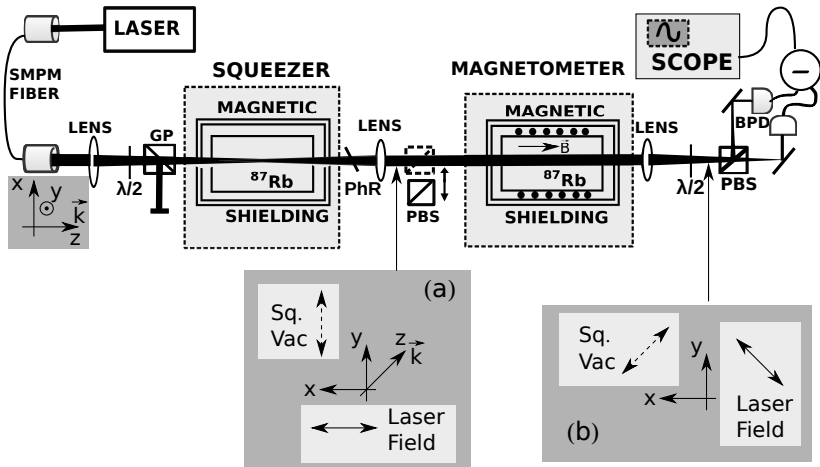


$$S = |E_p + E_v|^2 - |E_p - E_v|^2$$

$$S = 4E_p E_v$$

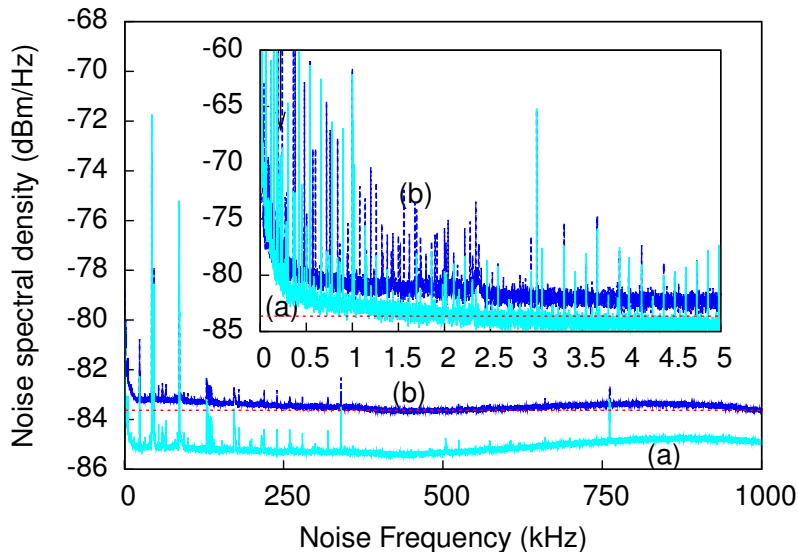
$$\langle \Delta S \rangle \sim E_p \langle \Delta E_v \rangle$$

Squeezed enhanced magnetometer setup

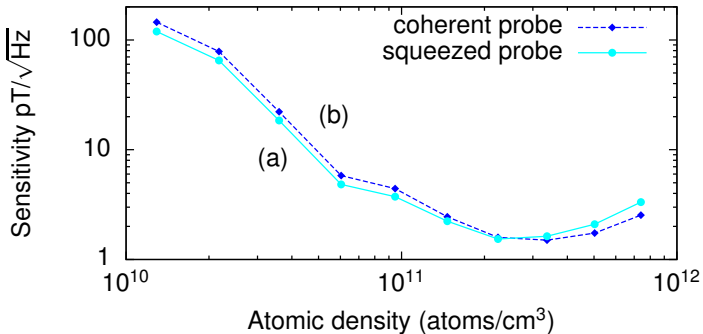
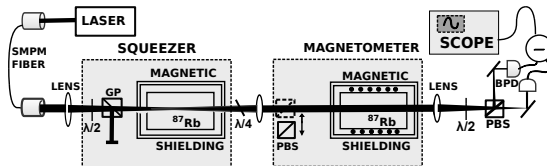


Note: Squeezed enhanced magnetometer was first demonstrated by Wolfgramm *et. al*/ Phys. Rev. Lett, **105**, 053601, 2010.

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