LIGO and squeezed states of light

LIGO Scientific Collaboration
and
Eugeniy E. Mikhailov

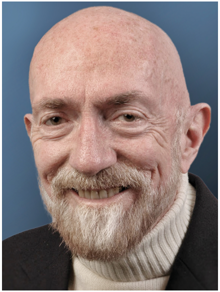
William & Mary
CHARTERED 1693

W&M, May 02, 2024

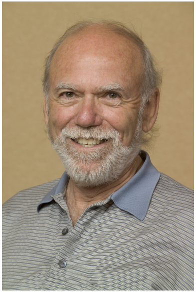
2017/10/03 Nobel prize in Physics

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

Rainer Weiss



Kip S. Thorne



Barry C. Barish

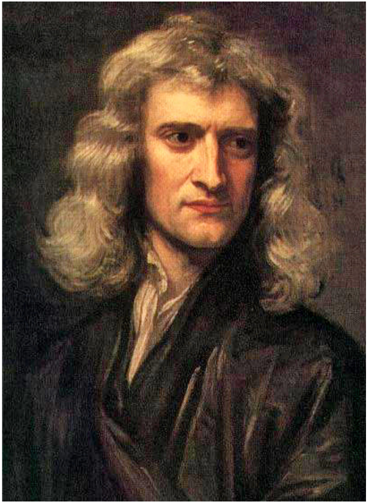
LIGO

LSC

LIGO Scientific Collaboration

Trinity University
University of Maryland
Andrews University
Washington State University
California State University Fullerton
The University of Alabama in Huntsville
Whitman College
American University
Sonoma State University
indigo
Montclair State University
University of Glasgow
Australian National University
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
Università degli Studi del Sannio
CITA ICAT
Goddard Space Flight Center
ICTP SAIFR
The University of Western Australia
University of Cambridge
Monash University
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
UIB Universitat de les Illes Balears
University of Washington
University of Wisconsin UW Milwaukee
UTRGV
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
Embry-Riddle Aeronautical University
Leibniz Universität Hannover
PennState
Science & Technology Facilities Council Rutherford Appleton Laboratory

Newton's laws 1686



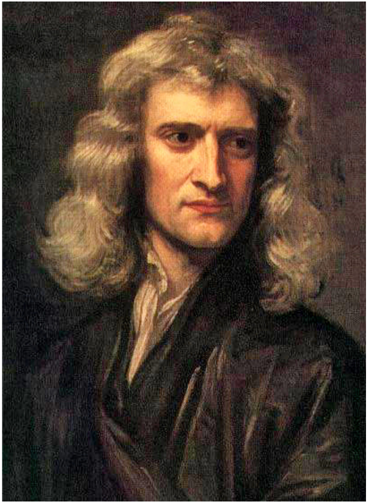
$$F_g = G\frac{m_1 m_2}{r^2}$$

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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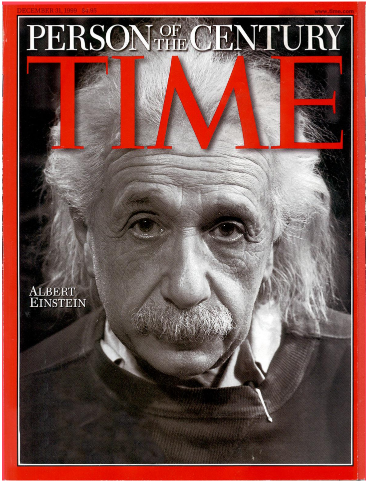
Time is not in the formula

Einstein's laws 1915

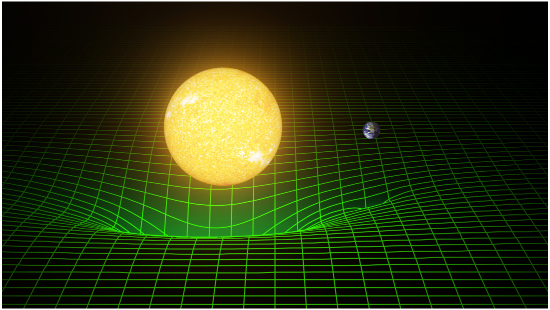


The General Theory of Relativity and theory of Gravity (1915)

- 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

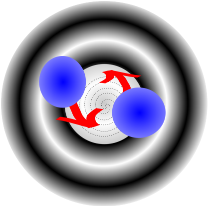


important predictions

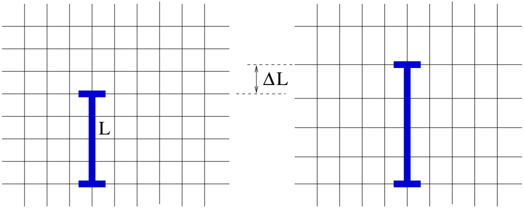
- Light path bends in vicinity of massive object → confirmed in 1919
- Gravitational radiation (waves) → confirmed indirectly in 1974

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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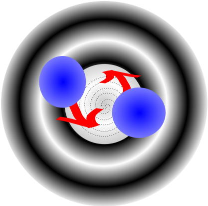

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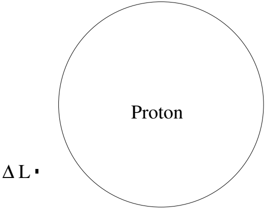

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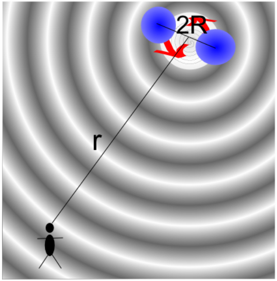


$$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

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

Assuming $m_1 = m_2 = m$ and recalling that

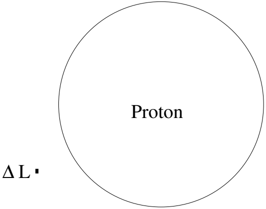
$$f^2 \sim Gm/R^3$$

we obtain

$$h \sim \frac{G^2 m^2}{rRc^4} \sim \frac{R_s^2}{Rr}$$

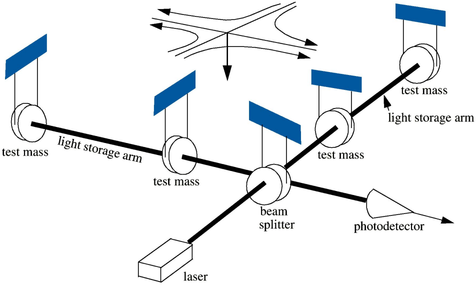
Where R_s is Schwarzschild radius of the mass m

$$R_s = \frac{2Gm}{c^2}$$

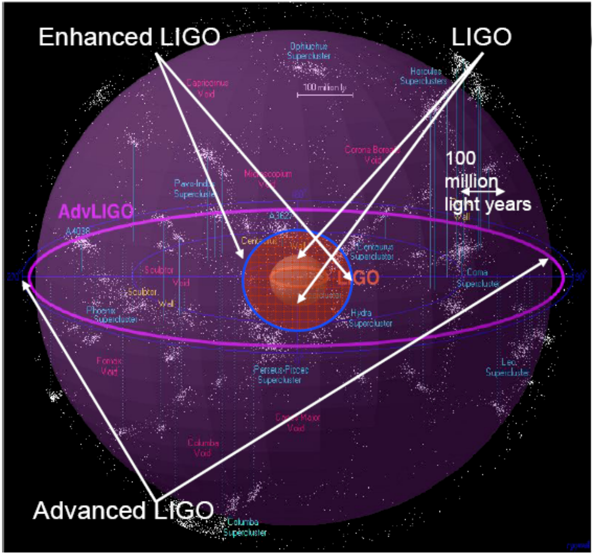


Laser Interferometer Gravitational-wave Observatory

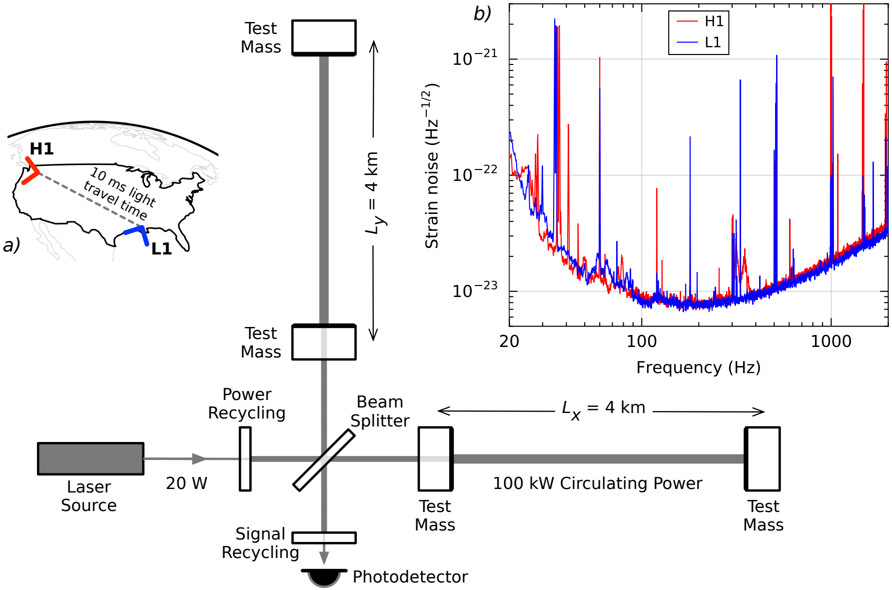
- $L = 4$ km
- $h \sim 10^{-23}$



From LIGO to advanced LIGO

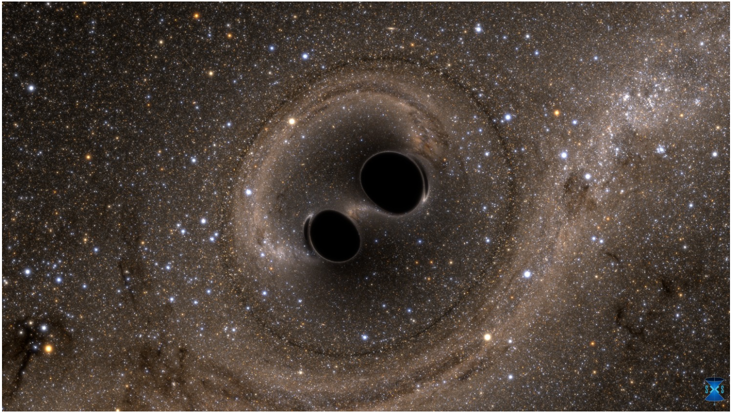


advanced LIGO detector summary



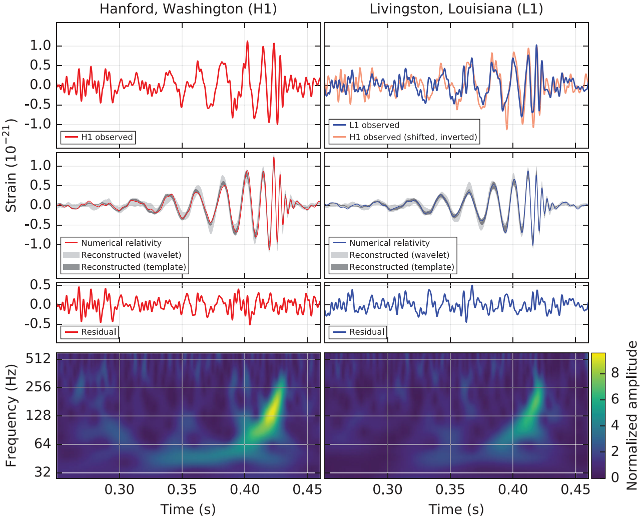
The sound of gravitational wave and simulated sky

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



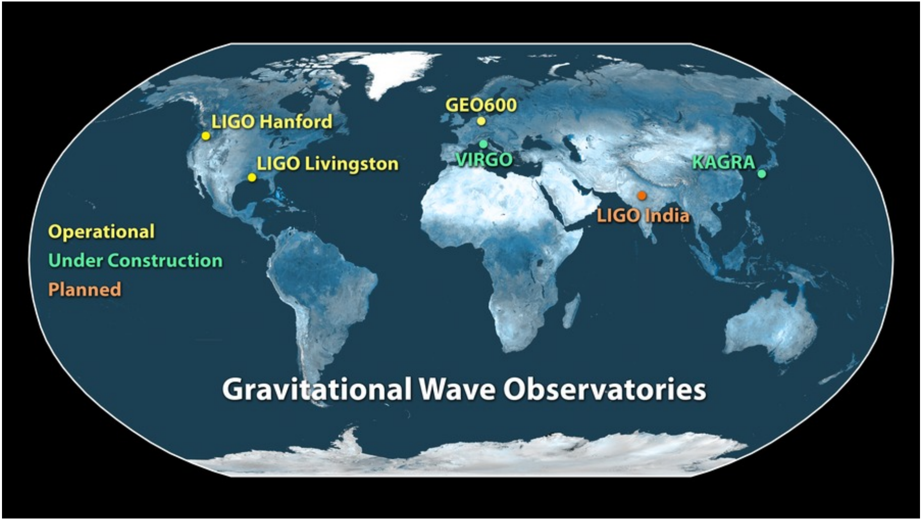
Two black holes with 29 and 36 solar masses merged about 1.3 billion years ago

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

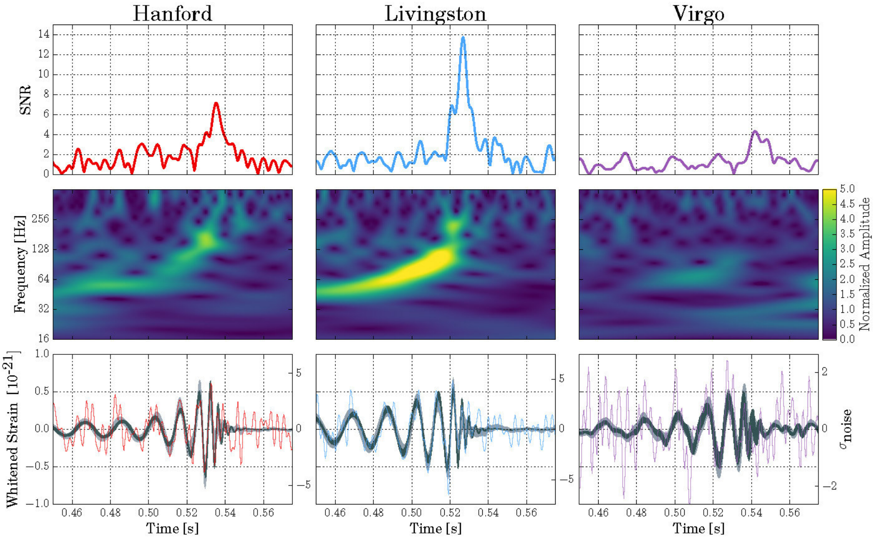


LIGO Scientific Collaboration, "Observation of Gravitational Waves from a Binary Black Hole Merger", Phys. Rev. Lett., 116, 061102, (2016).

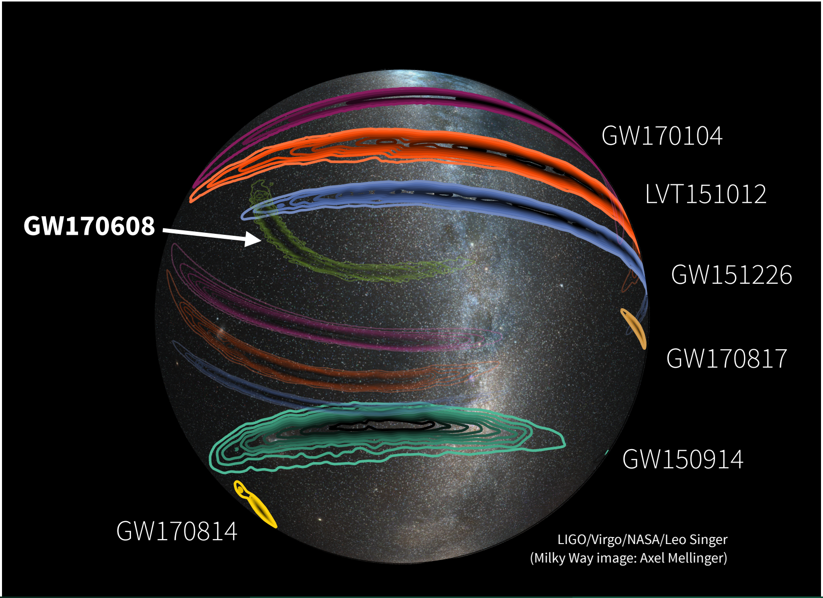
World wide network of detectors

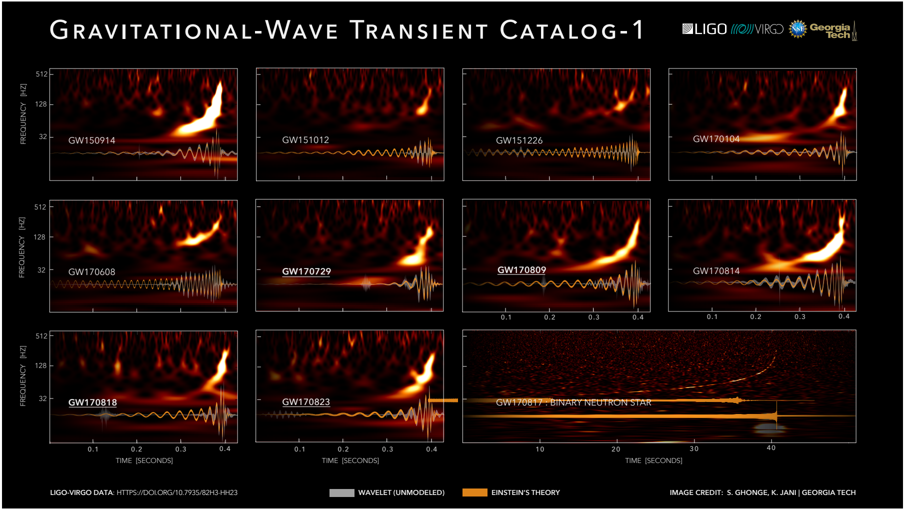


GW170814 triple detection



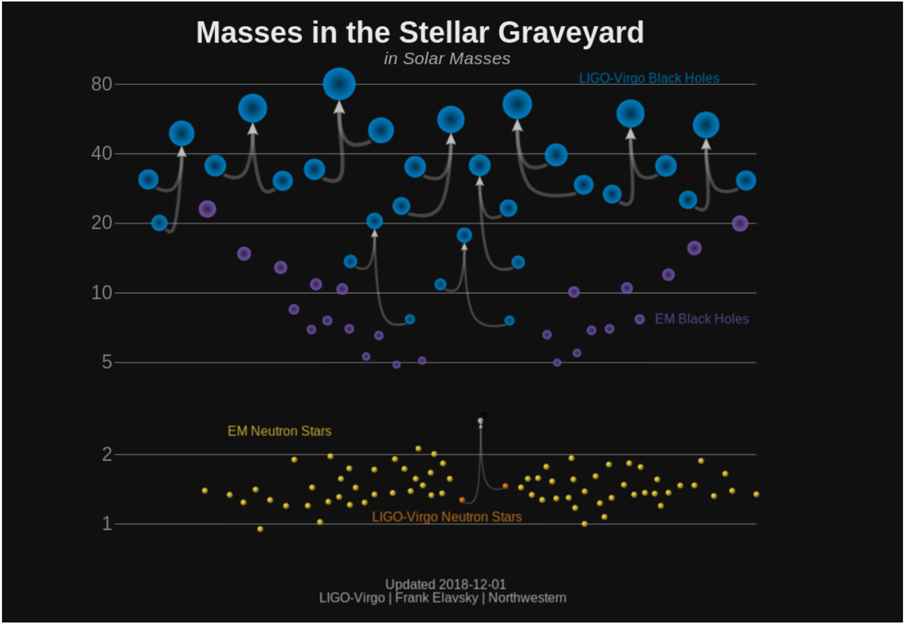
Sky maps


GW170104
LVT151012
GW170608
GW151226
GW170817
GW150914
GW170814
LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)



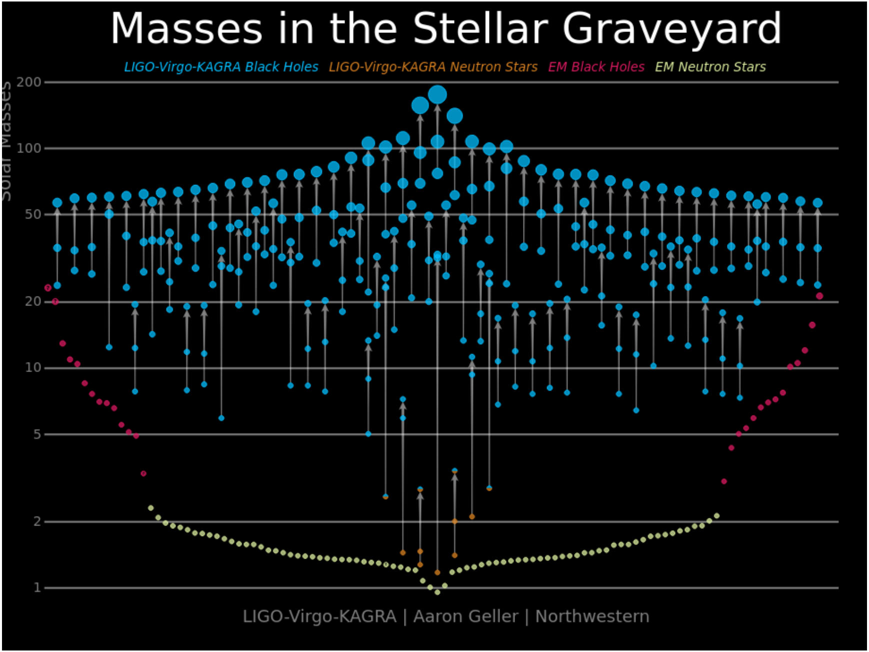
GRAVITATIONAL-WAVE TRANSIENT CATALOG-1
LIGO
VIRGO
NSF
Georgia Tech
FREQUENCY [HZ]
512
128
32
GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823
GW170817 : BINARY NEUTRON STAR
0.1
0.2
0.3
0.4
10
20
30
40
TIME [SECONDS]
LIGO-VIRGO DATA: HTTPS://DOI.ORG/10.7935/82H3-HH23
WAVELET (UNMODELED)
EINSTEIN'S THEORY
IMAGE CREDIT: S. GHONGE, K. JANI | GEORGIA TECH

2018/12/01



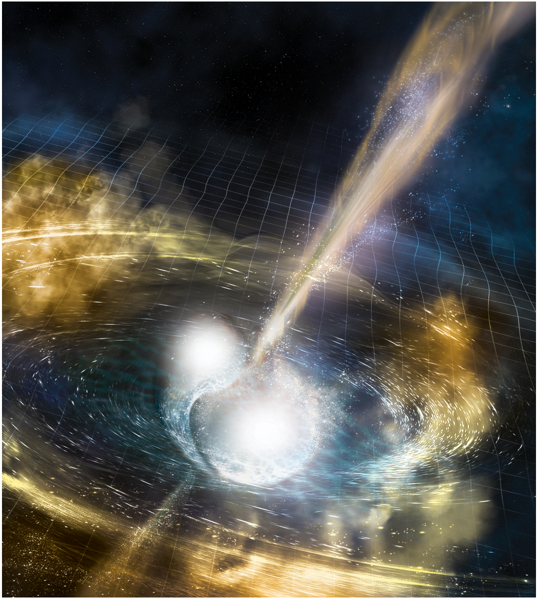
https://media.ligo.northwestern.edu/gallery/mass-plot

2022/02/21



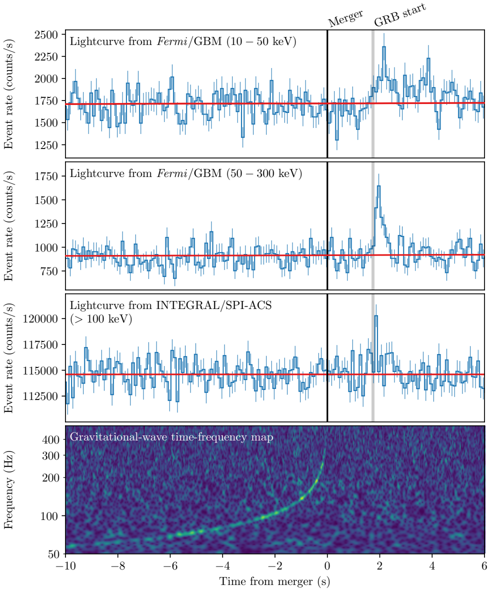
https://media.ligo.northwestern.edu/gallery/mass-plot

GW170817-kilonova artistic depiction



Simulation movie
https://youtu.be/V6cm-0bwJ98

GW170817-kilonova: two neutron stars collision



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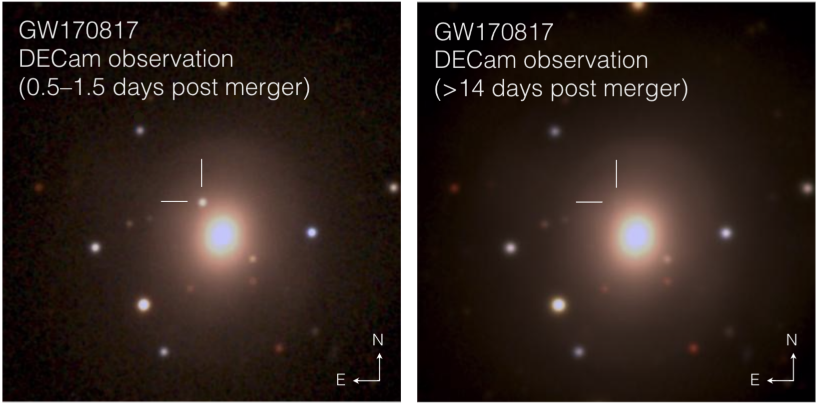
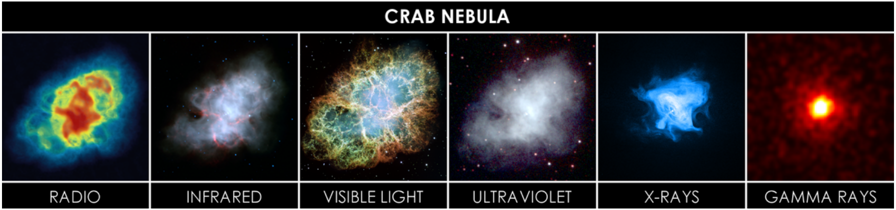
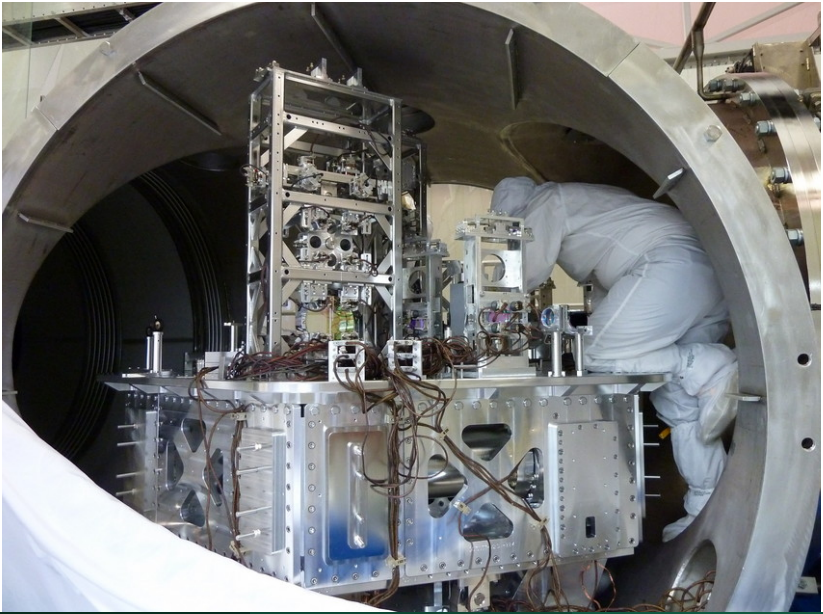


- GW170817: Coherent Spectrogram and Audio https://dcc.ligo.org/LIGO-G1701924
- GW170817: Fermi and LIGO signals https://wiki.ligo.org/pub/EPO/GW170817/GBM_GW170817_small.mov

Crab nebula, supernova 1054 remnants



Inside the tube



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

Photo from LIGO Magazine

Inside vacuum chamber

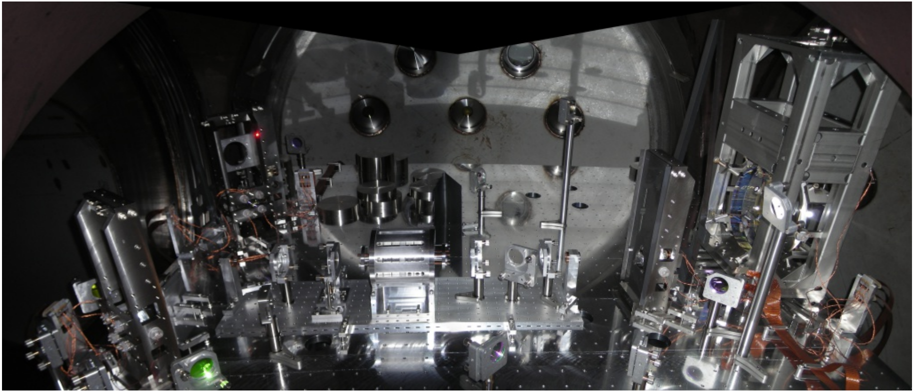
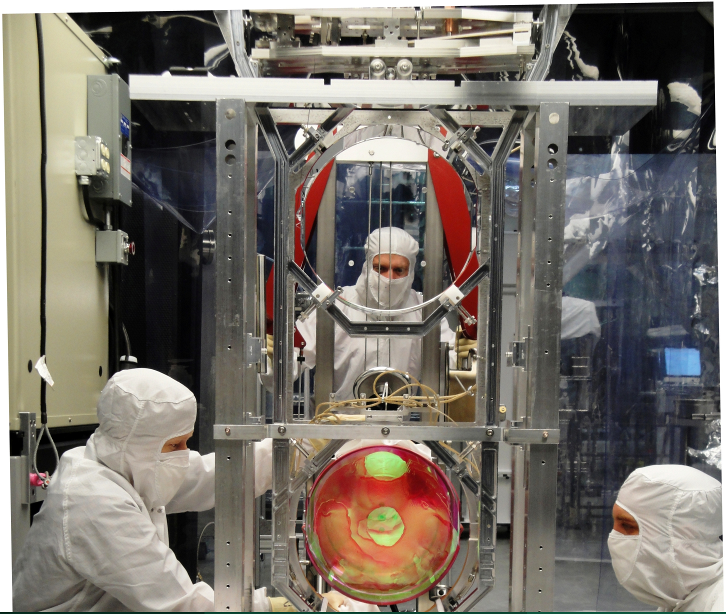


Photo from LIGO Magazine http://www.ligo.org/magazine/

Mode cleaner optics

Large optics suspension



Mirror

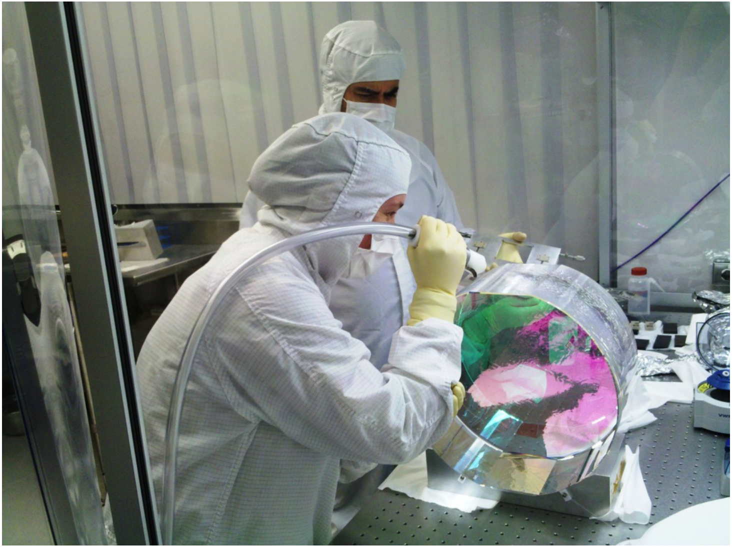


Photo from LIGO Magazine http://www.ligo.org/magazine/

Inner test mass

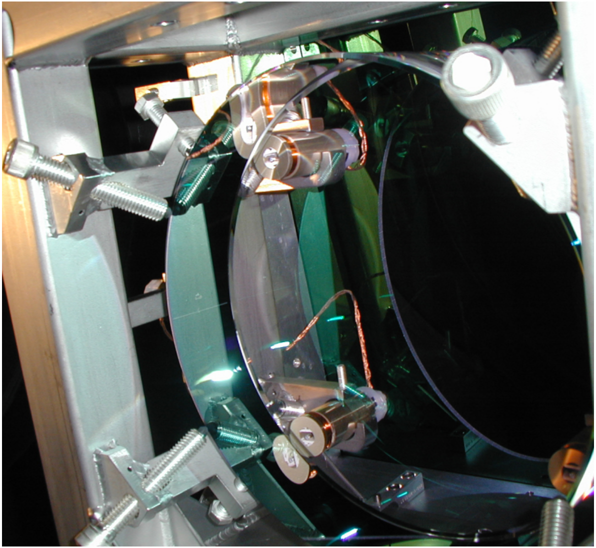


Photo from LIGO Magazine `http://www.ligo.org/magazine/`

Baffle

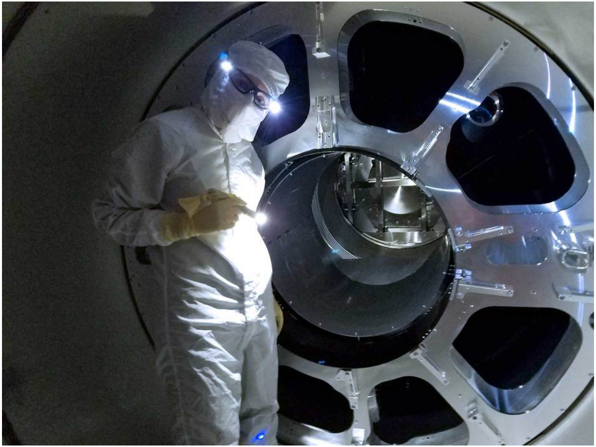
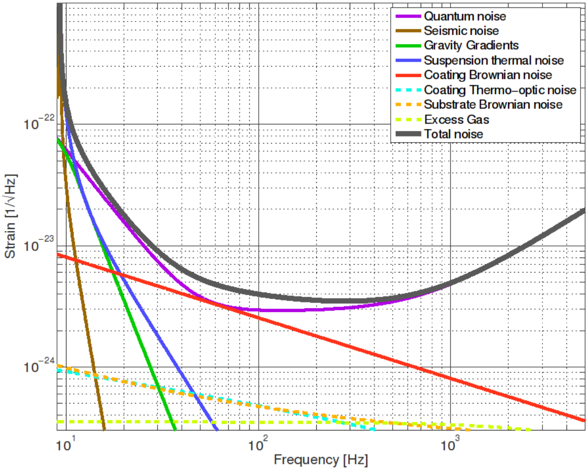


Photo from LIGO Magazine http://www.ligo.org/magazine/

We can detect stars collisions and ...

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

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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

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Optics equivalent strict definition

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

Transition from classical to quantum field

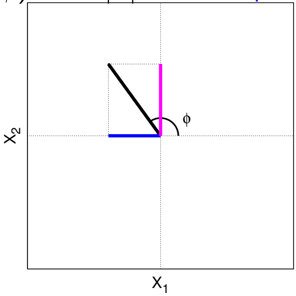
Classical analog

- Field amplitude a
- Field real part $X_1 = (a^* + a)/2$
- Field imaginary part $X_2 = i(a^* - a)/2$

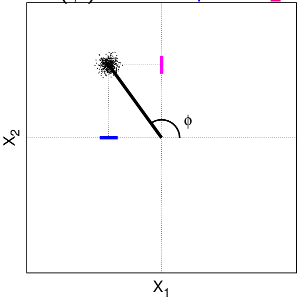
Quantum approach

- Field operator $\hat{a}$
- Amplitude quadrature $\hat{X}_1 = (\hat{a}^\dagger + \hat{a})/2$
- Phase quadrature $\hat{X}_2 = i(\hat{a}^\dagger - \hat{a})/2$

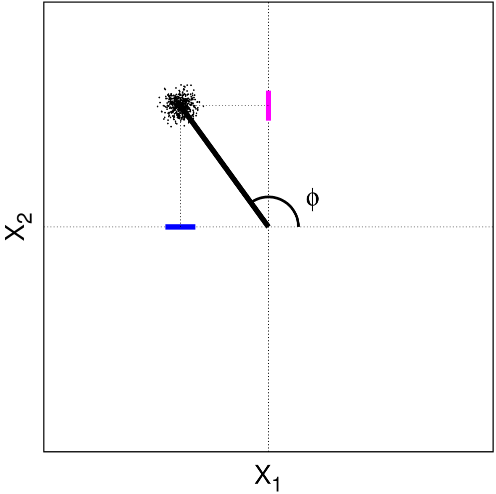
$$E(\phi) = |a|e^{-i\phi} = X_1 + iX_2$$



$$\hat{E}(\phi) = \hat{X}_1 + i\hat{X}_2$$



Quantum optics summary



Light consist of photons

- $\hat{N} = a^\dagger a$

Commutator relationship

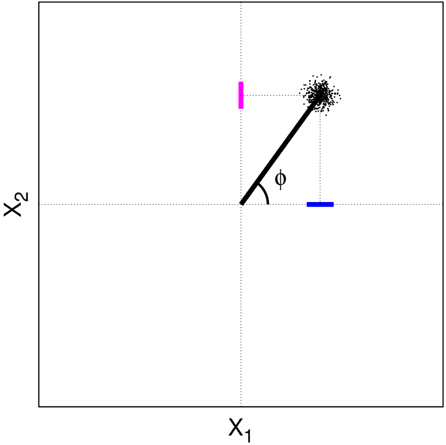
- $[a, a^\dagger] = 1$
- $[X_1, X_2] = i/2$

Detectors measure

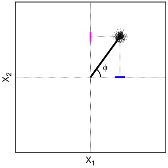
- number of photons $\hat{N}$
- Quadratures $\hat{X}_1$ and $\hat{X}_2$

Uncertainty relationship

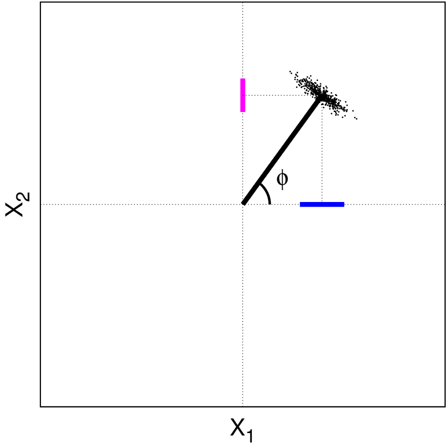
- $\Delta X_1 \Delta X_2 \geq 1/4$



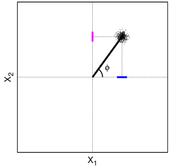
Unsqueezed coherent



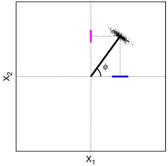
Squeezed quantum states zoo



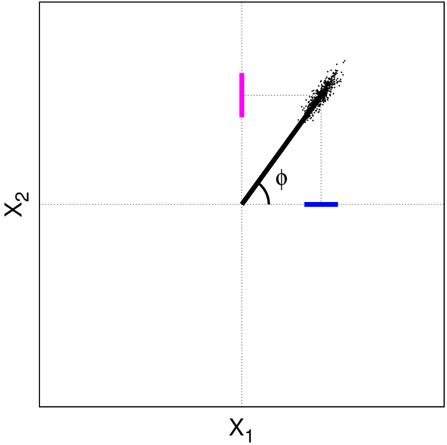
Unsqueezed coherent



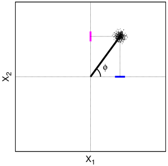
Amplitude squeezed



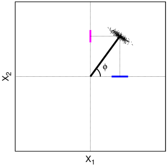
Squeezed quantum states zoo



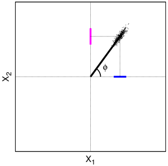
Unsqueezed coherent



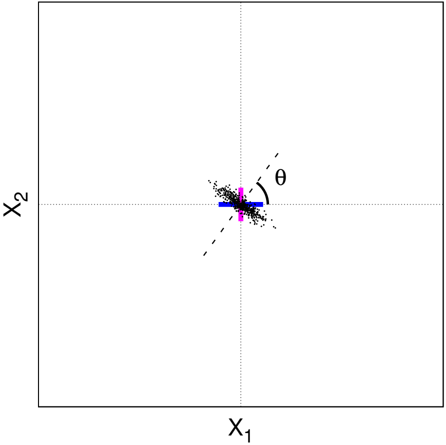
Amplitude squeezed



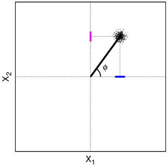
Phase squeezed



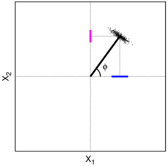
Squeezed quantum states zoo



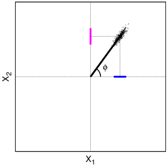
Unsqueezed coherent



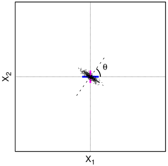
Amplitude squeezed



Phase squeezed

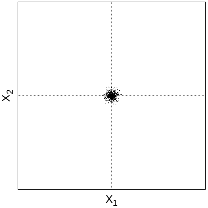


Vacuum squeezed



Squeezed field generation recipe

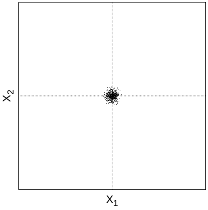
Take a vacuum state $|0>$



$$H = \frac{1}{2}$$

Squeezed field generation recipe

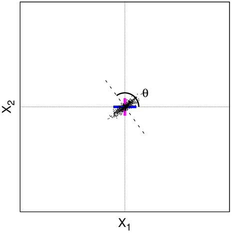
Take a vacuum state $|0>$



$$H = \frac{1}{2}$$

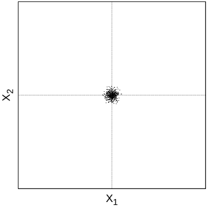
Apply squeezing operator $|\xi >= \hat{S}(\xi)|0>$

$$\hat{S}(\xi) = e^{\frac{1}{2}\xi^* a^2 - \frac{1}{2}\xi a^{\dagger 2}}$$



Squeezed field generation recipe

Take a vacuum state $|0>$



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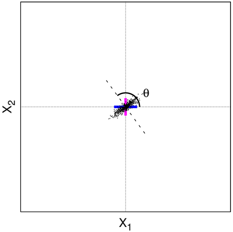
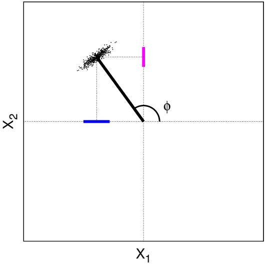


Apply displacement operator $|\alpha, \xi >= \hat{D}(\alpha)|s >$

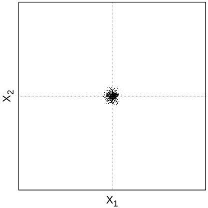
$$\hat{D}(\alpha) = e^{\alpha a^\dagger - \alpha^* a}$$



$$\begin{aligned} < \alpha, \xi | X_1 | \alpha, \xi > &= Re(\alpha), \\ < \alpha, \xi | X_2 | \alpha, \xi > &= Im(\alpha) \end{aligned}$$

Squeezed field generation recipe

Take a vacuum state $|0>$

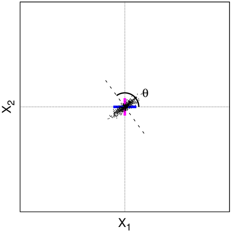


$$H = \frac{1}{2}$$

Notice $\Delta X_1 \Delta X_2 = \frac{1}{4}$

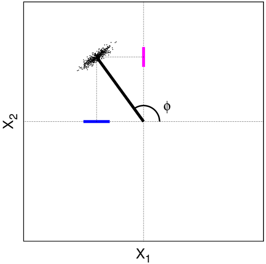
Apply squeezing operator $|\xi >= \hat{S}(\xi)|0>$

$$\hat{S}(\xi) = e^{\frac{1}{2}\xi^* a^2 - \frac{1}{2}\xi a^{\dagger 2}}$$



Apply displacement operator $|\alpha, \xi >= \hat{D}(\alpha)|s>$

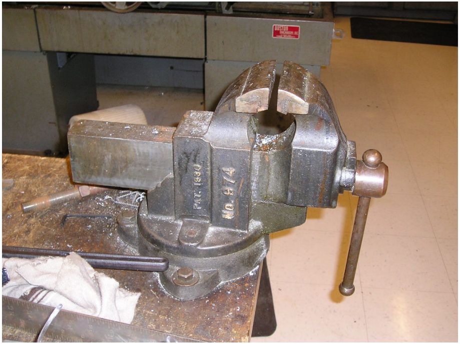
$$\hat{D}(\alpha) = e^{\alpha a^\dagger - \alpha^* a}$$



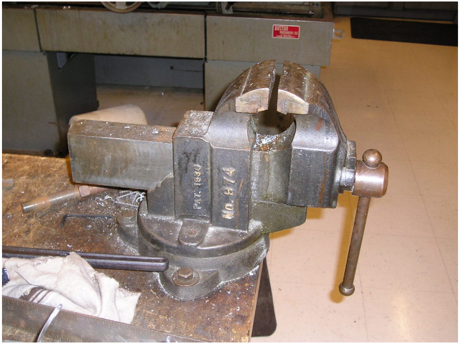
$$< \alpha, \xi | X_1 | \alpha, \xi > = Re(\alpha),$$
$$< \alpha, \xi | X_2 | \alpha, \xi > = Im(\alpha)$$

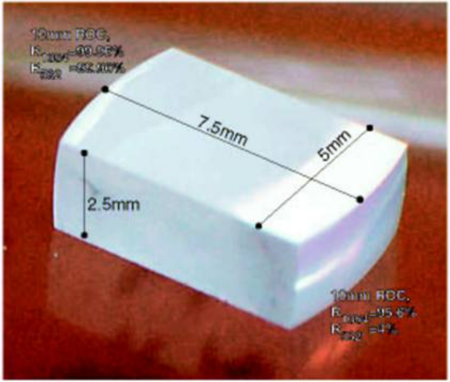
Tools for squeezing

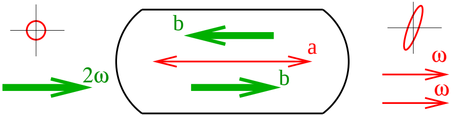
Tools for squeezing



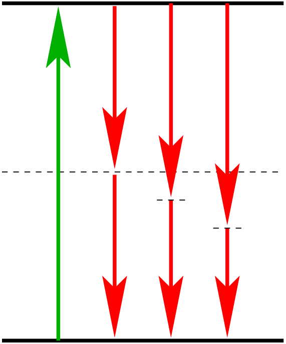
Tools for squeezing







Two photon squeezing picture

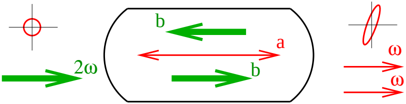


Squeezing operator

$$\hat{S}(\xi) = e^{\frac{1}{2}\xi^* a^2 - \frac{1}{2}\xi a^{\dagger 2}}$$

Parametric down-conversion in crystal

$$\hat{H} = i\hbar\chi^{(2)}(a^2 b^\dagger - a^{\dagger 2} b)$$

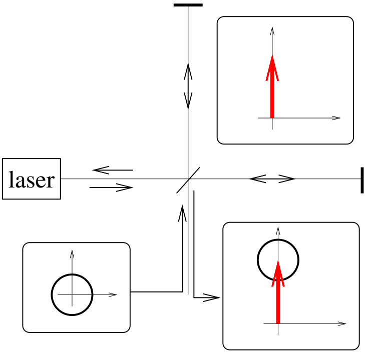


Squeezing

maximum squeezing value detected 15 dB at 1064 nm
Henning Vahlbruch, Moritz Mehmet, Karsten Danzmann, and Roman Schnabel Phys. Rev. Lett **117**, 110801 (2016)

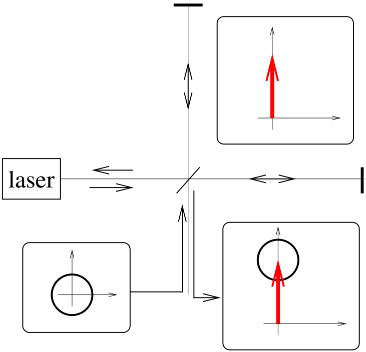
Squeezing and interferometer

Vacuum input

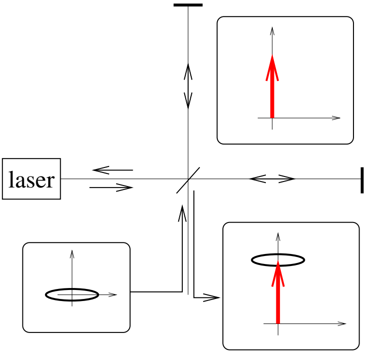


Squeezing and interferometer

Vacuum input

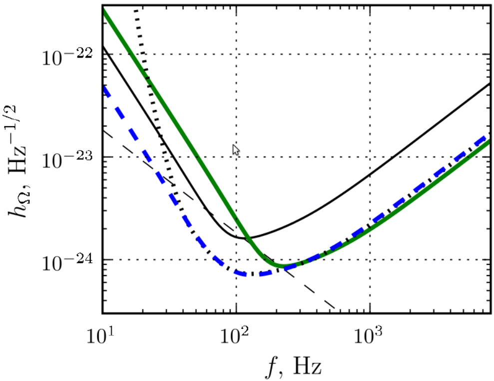


Squeezed input



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)

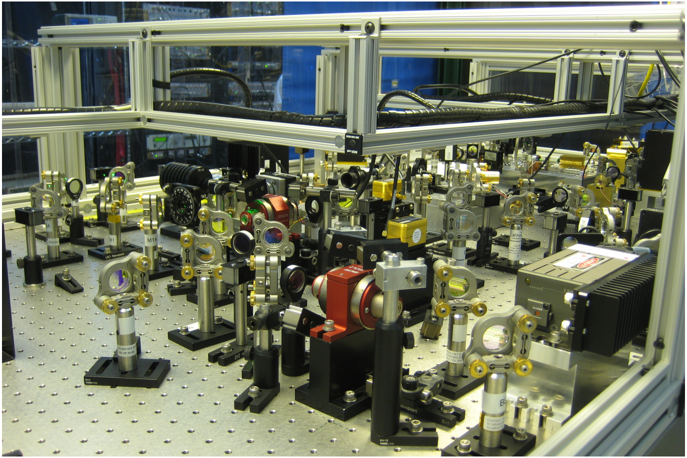
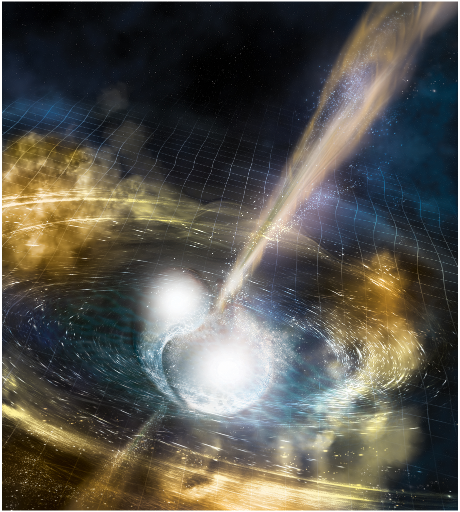


Photo of Squeezer, LIGO Magazine `http://www.ligo.org/magazine/`

Summary



- In 2015 we detected the first Gravitational Wave
- Now we are talking about GW astronomy