

LIGO and squeezed states of light



and
Eugeniy E. Mikhailov



W&M, May 01, 2025

2017/10/03 Nobel prize in Physics

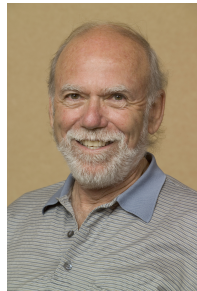
“for decisive contributions to the LIGO detector and the observation of gravitational waves”



Rainer Weiss



Kip S. Thorne



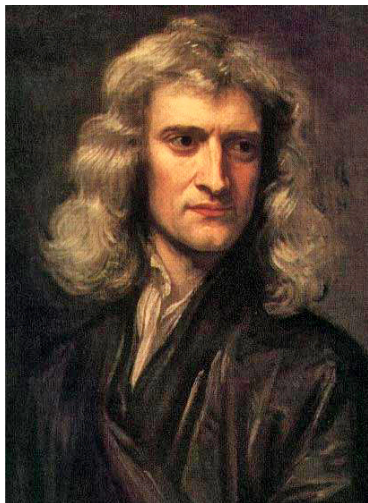
Barry C. Barish



LIGO Scientific Collaboration



Newton's laws 1686



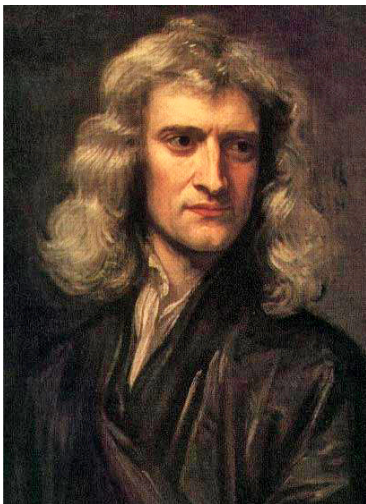
$$F_g = G \frac{m_1 m_2}{r^2}$$

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



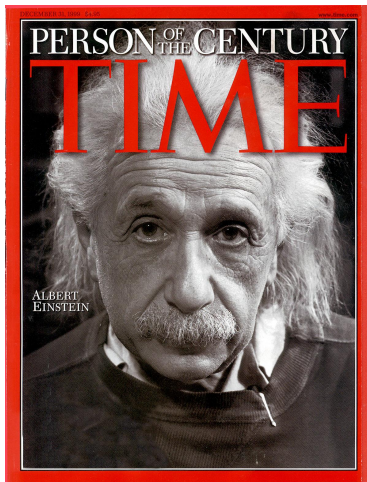
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Time is not in the formula

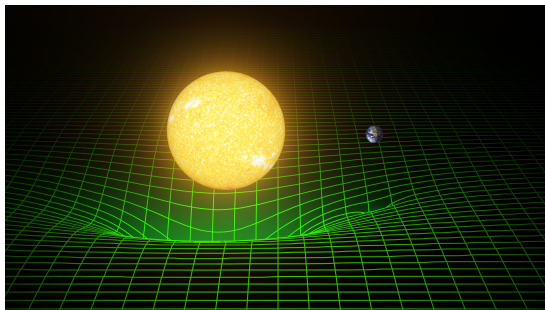


The General Theory of Relativity and theory of Gravity (1915)

- 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

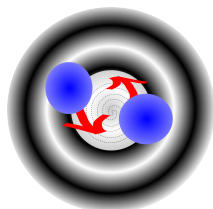


important predictions

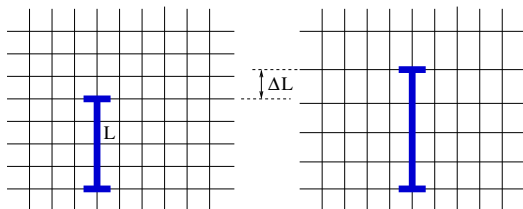
- Light path bends in vicinity of massive object → confirmed in 1919
- Gravitational radiation (waves) → confirmed **indirectly** in 1974

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

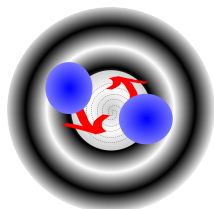
$$h = \frac{\Delta L}{L} \quad (1)$$

expected strain

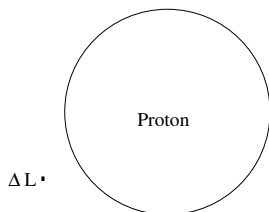
$$h \sim 10^{-21} \quad (2)$$

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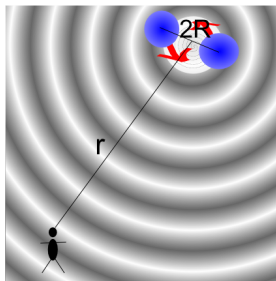
Strain - strength of GW

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

expected strain

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

Typical strain



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

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

Assuming $m_1 = m_2 = m$ and recalling that

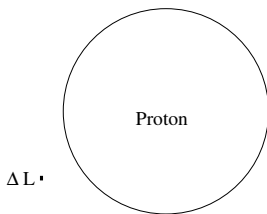
$$f^2 \sim Gm/R^3$$

we obtain

$$h \sim \frac{G^2 m^2}{r R c^4} \sim \frac{R_s^2}{R r}$$

Where R_s is Schwarzschild radius of the mass m

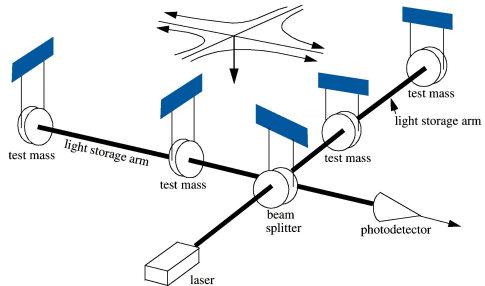
$$R_s = \frac{2Gm}{c^2}$$



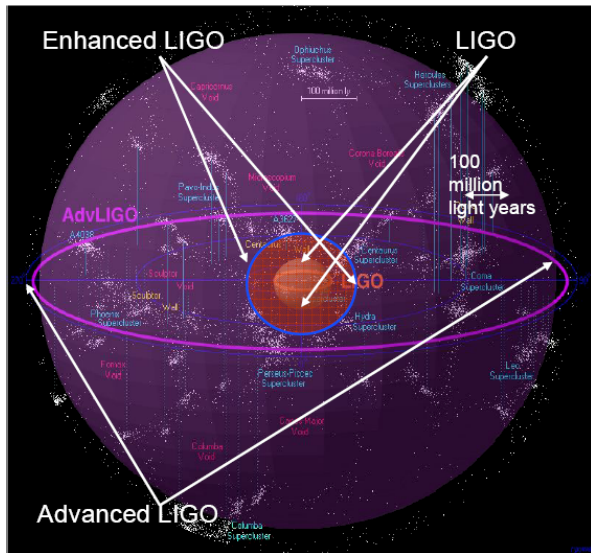
Laser Interferometer Gravitational-wave Observatory



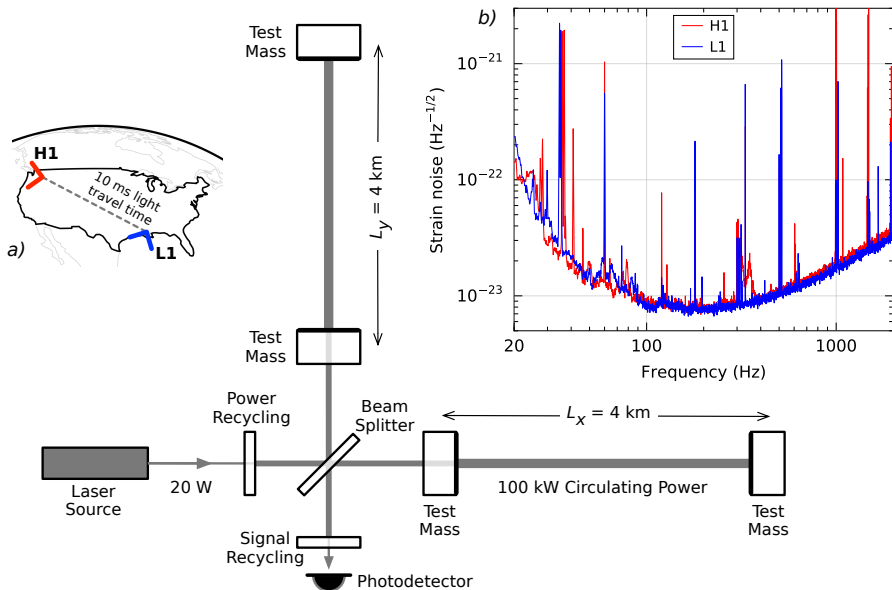
- $L = 4 \text{ km}$
- $h \sim 10^{-23}$



From LIGO to advanced LIGO

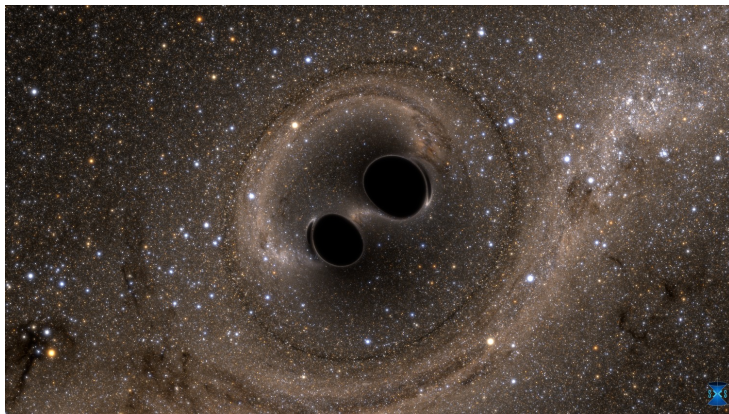


advanced LIGO detector summary



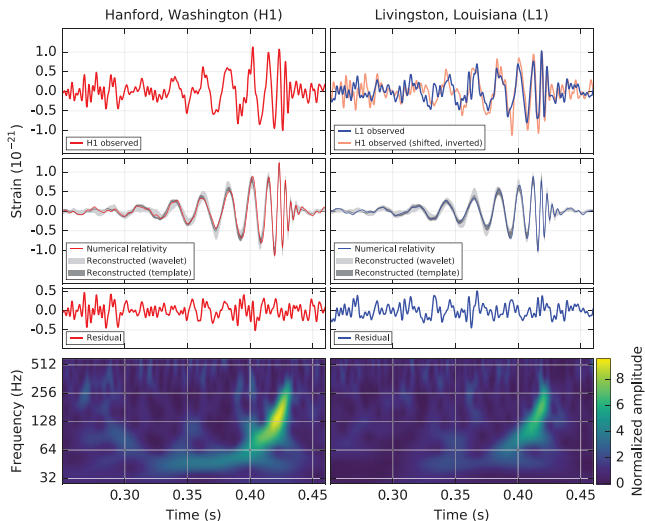
The sound of gravitational wave and simulated sky

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



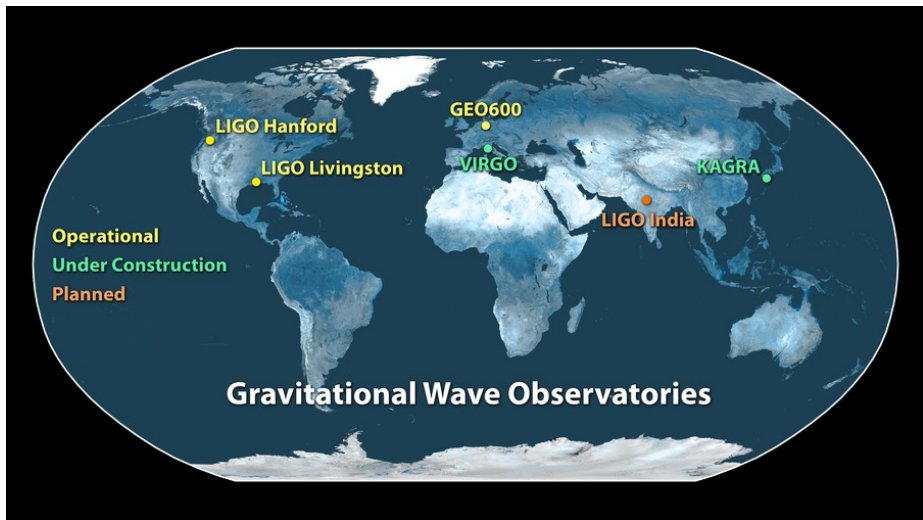
Two black holes with 29 and 36 solar masses merged about 1.3 billion years ago

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

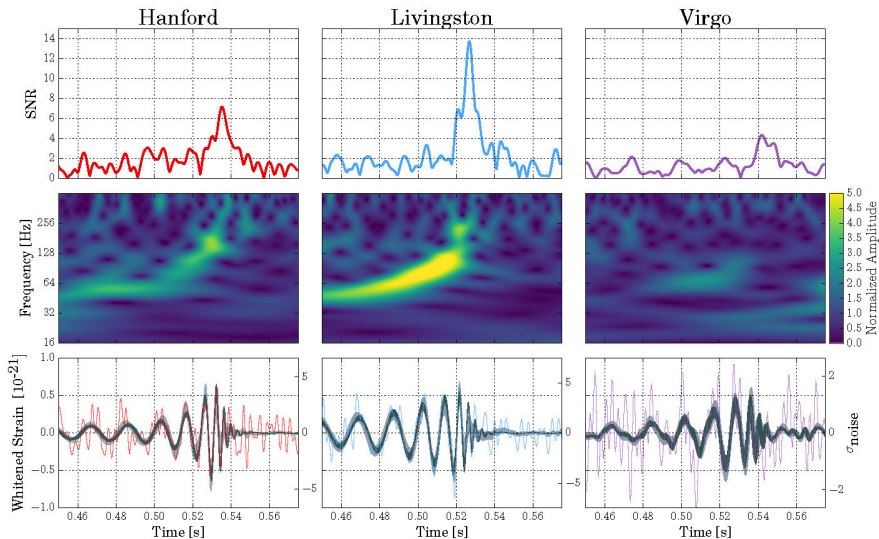


LIGO Scientific Collaboration, "Observation of Gravitational Waves from a Binary Black Hole Merger", Phys. Rev. Lett., 116, 061102, (2016).

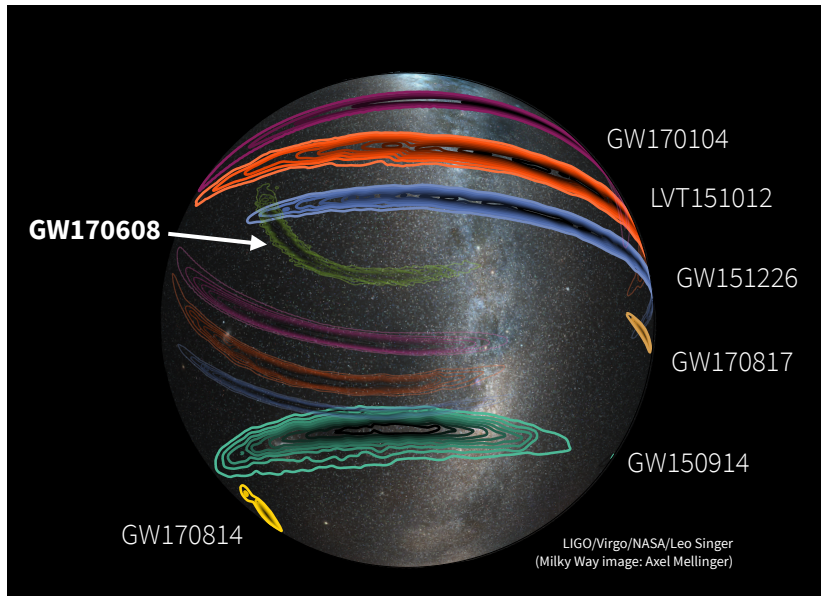
World wide network of detectors



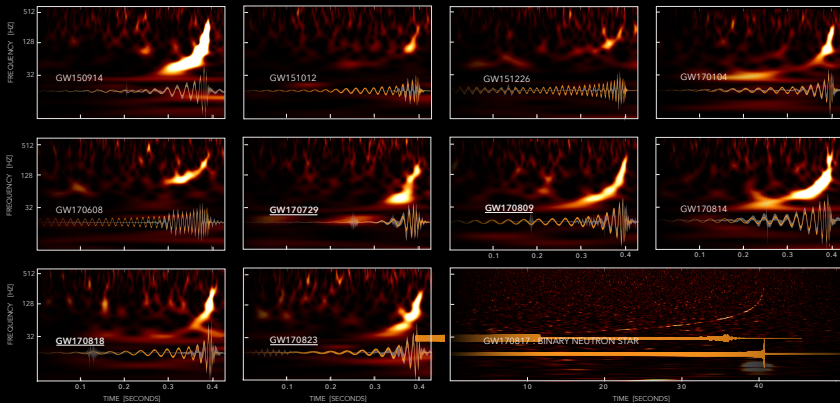
GW170814 triple detection



Sky maps



GRAVITATIONAL-WAVE TRANSIENT CATALOG-1



LIGO-VIRGO DATA: [HTTPS://DOI.ORG/10.7935/82H3-HH23](https://doi.org/10.7935/82H3-HH23)

WAVELET (UNMODELED)

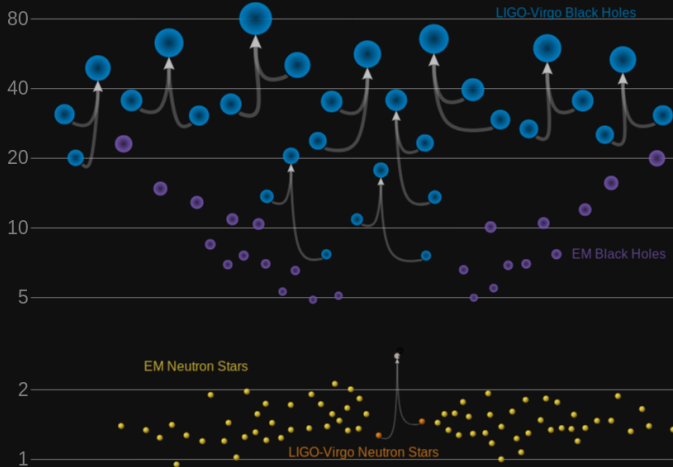
EINSTEIN'S THEORY

IMAGE CREDIT: S. GHONGE, K. JANI | GEORGIA TECH

2018/12/01

Masses in the Stellar Graveyard

in Solar Masses

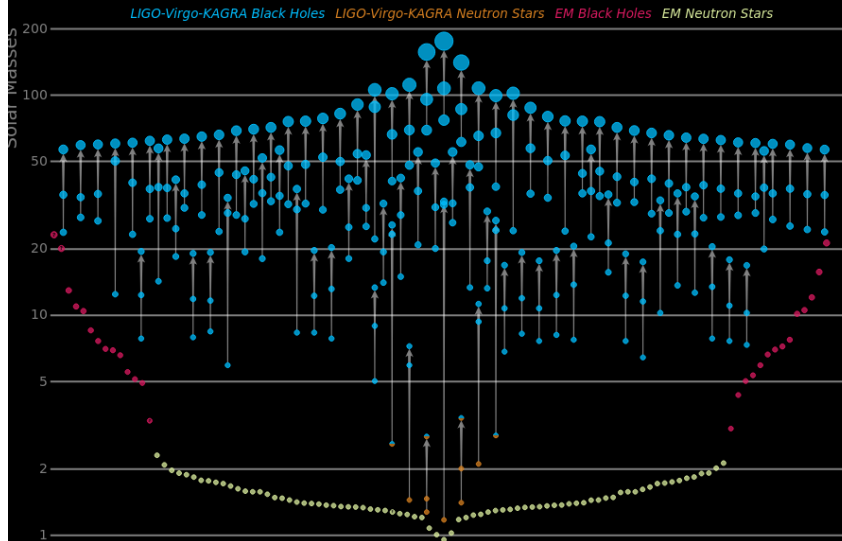


Updated 2018-12-01
LIGO-Virgo | Frank Elavsky | Northwestern

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

2022/02/21

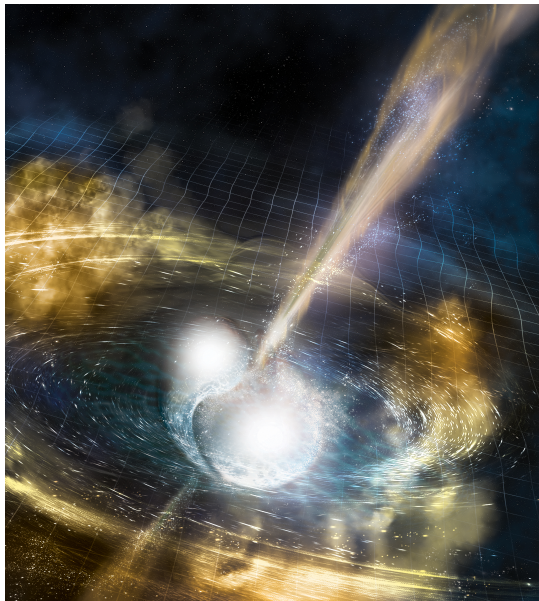
Masses in the Stellar Graveyard



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

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

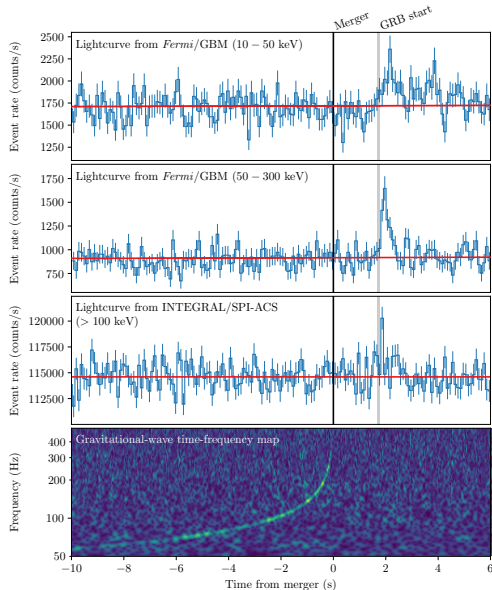
GW170817-kilonova artistic depiction



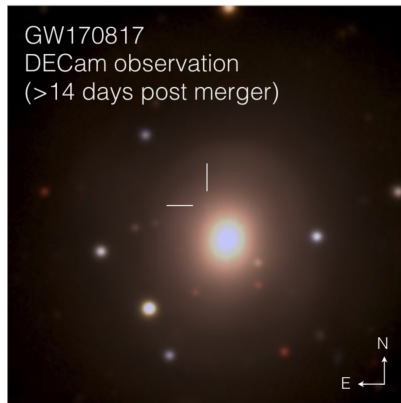
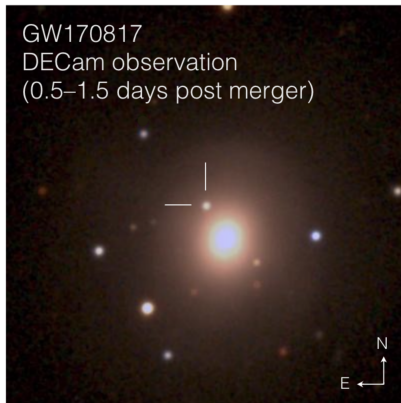
Simulation movie

<https://youtu.be/V6cm-0bwJ98>

GW170817-kilonova: two neutron stars collision

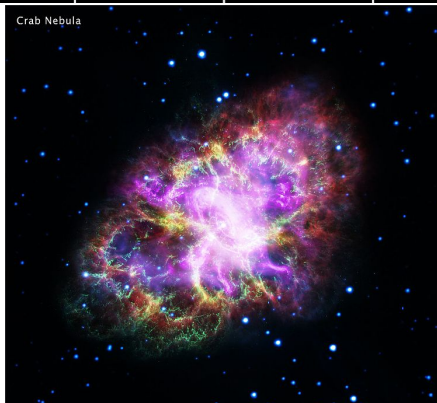
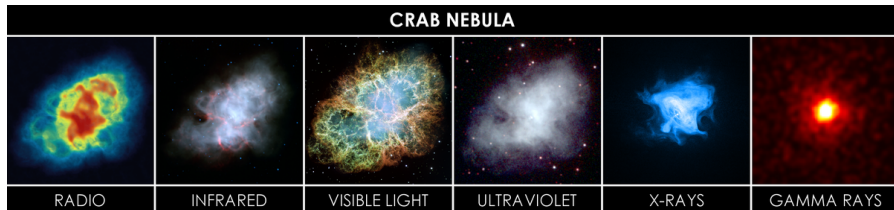


GW170817-kilonova: two neutron stars collision

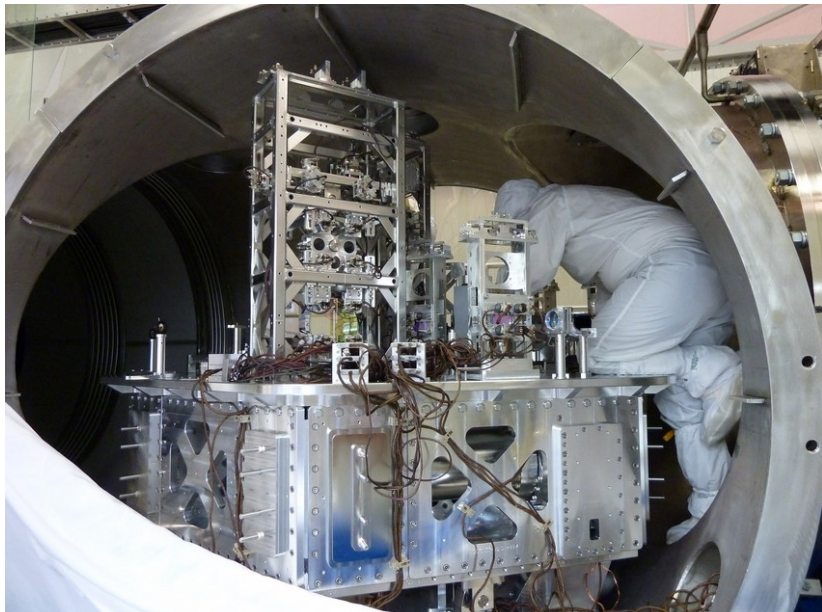


- GW170817: Coherent Spectrogram and Audio <https://dcc.ligo.org/LIGO-G1701924>
- GW170817: Fermi and LIGO signals https://wiki.ligo.org/pub/EPO/GW170817/GBM_GW170817_small.mov

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 Measuring 1000 kg / squeezing 1000 kg

Inside vacuum chamber

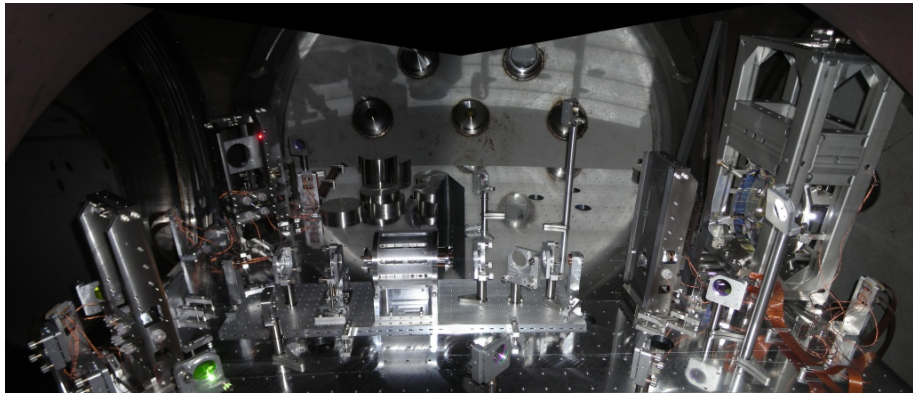


Photo from LIGO Magazine <http://www.ligo.org/magazine/>

Mode cleaner optics



Large optics suspension



Mirror

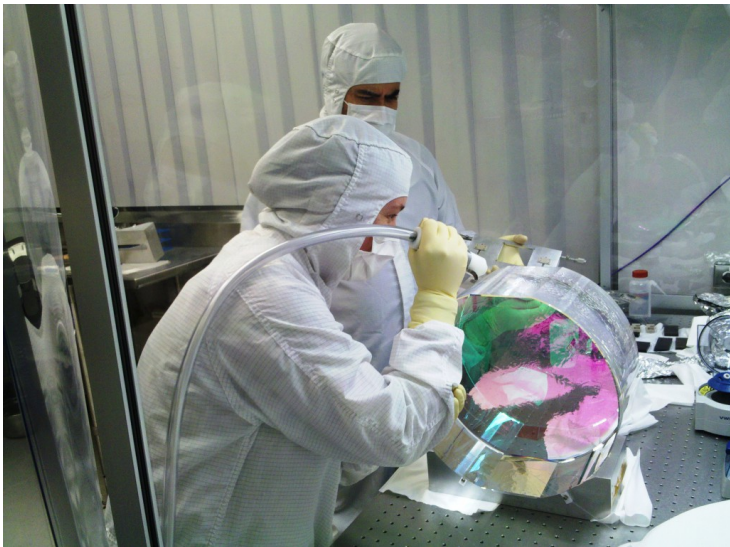


Photo from LIGO Magazine <http://www.ligo.org/magazine/>

Inner test mass

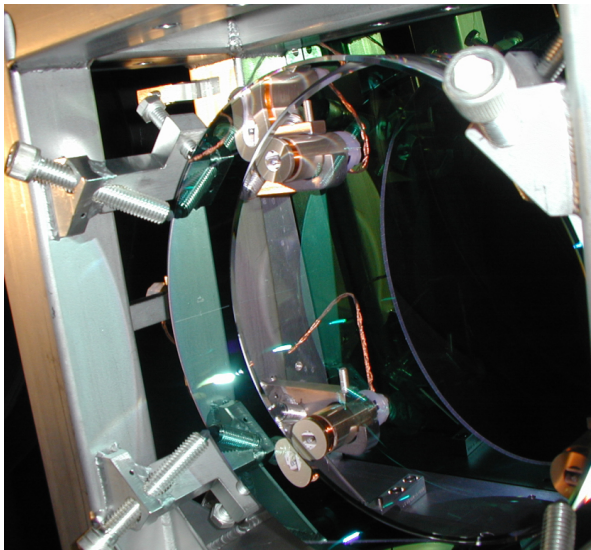


Photo from LIGO Magazine <http://www.ligo.org/magazine/>

Baffle

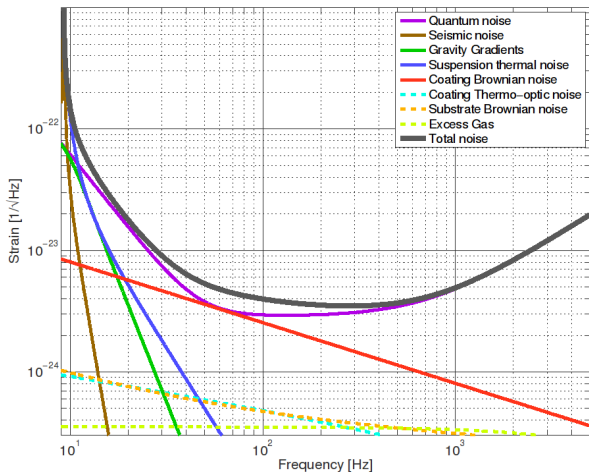


Photo from LIGO Magazine <http://www.ligo.org/magazine/>

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

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

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



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Optics equivalent strict definition

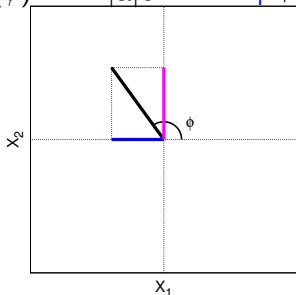
$$\Delta X_1 \Delta X_2 \geq 1/4$$

Transition from classical to quantum field

Classical analog

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

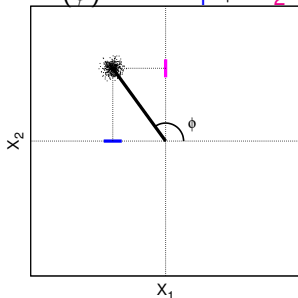
$$E(\phi) = |a|e^{-i\phi} = X_1 + iX_2$$



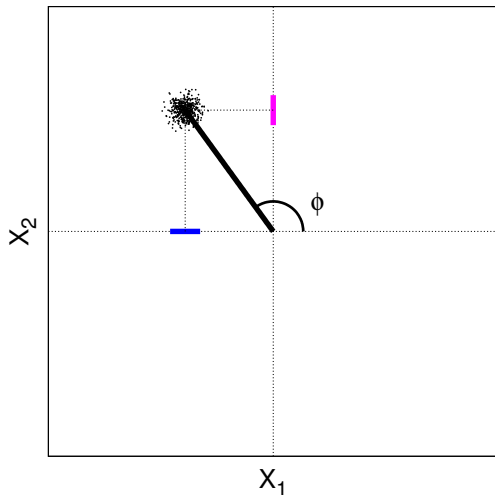
Quantum approach

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

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



Quantum optics summary



Light consist of photons

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

Commutator relationship

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

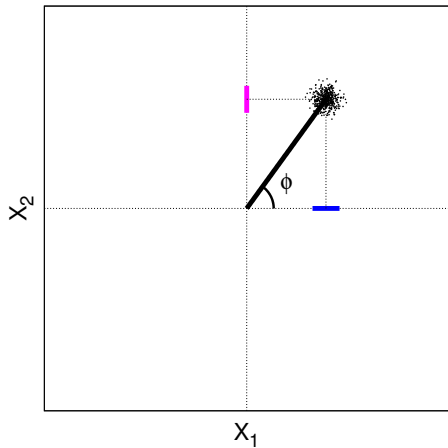
Detectors measure

- number of photons \hat{N}
- Quadratures X_1 and X_2

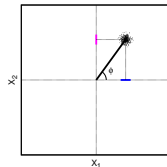
Uncertainty relationship

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

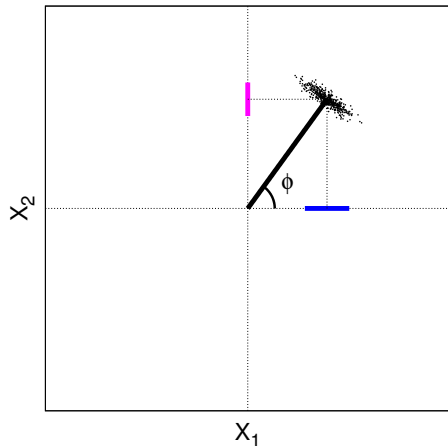
Squeezed quantum states zoo



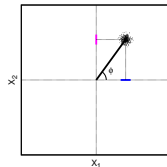
Unsqueezed
coherent



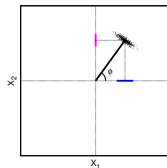
Squeezed quantum states zoo



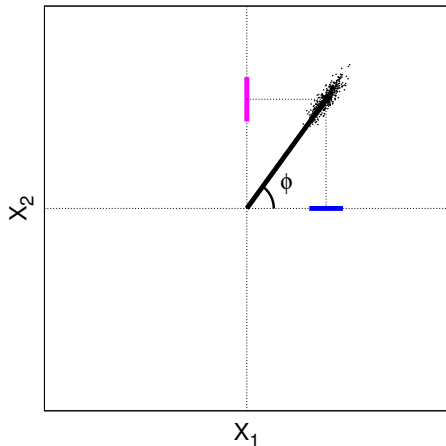
Unsqueezed
coherent



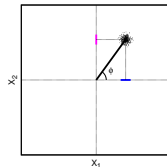
Amplitude
squeezed



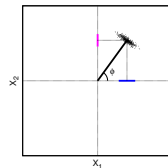
Squeezed quantum states zoo



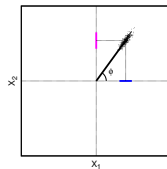
Unsqueezed
coherent



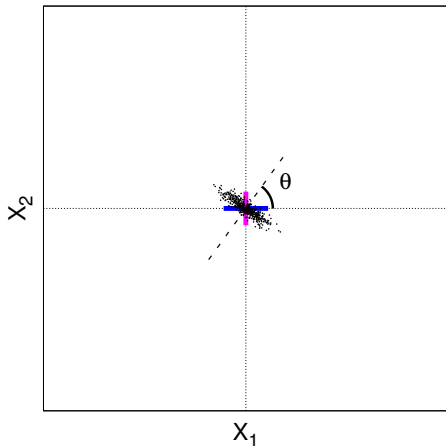
Amplitude
squeezed



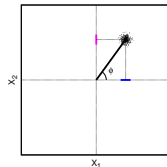
Phase
squeezed



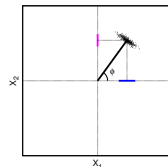
Squeezed quantum states zoo



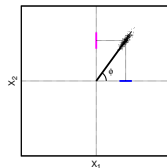
Unsqueezed
coherent



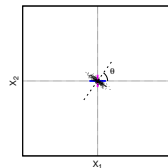
Amplitude
squeezed



Phase
squeezed

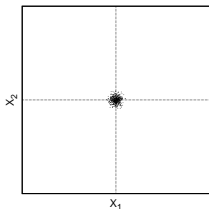


Vacuum
squeezed



Squeezed field generation recipe

Take a vacuum
state $|0\rangle$

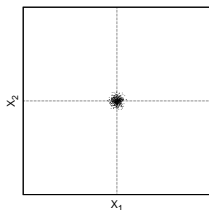


$$H = \frac{1}{2}$$

Squeezed field generation recipe

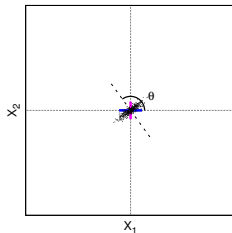
Take a vacuum state $|0\rangle$

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



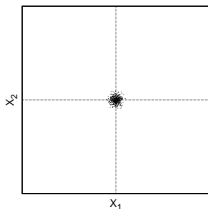
$$H = \frac{1}{2}$$

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



Squeezed field generation recipe

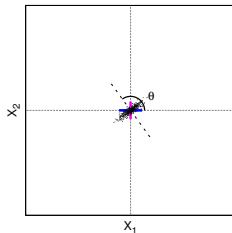
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$$H = \frac{1}{2}$$

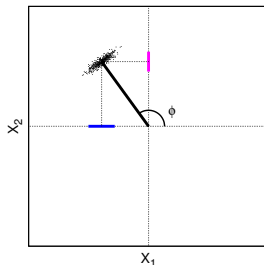
Apply squeezing operator $|\xi\rangle = \hat{S}(\xi)|0\rangle$

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



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

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

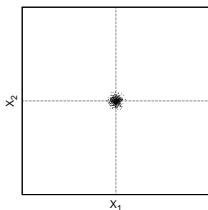


$$\langle \alpha, \xi | X_1 | \alpha, \xi \rangle = \text{Re}(\alpha),$$

$$\langle \alpha, \xi | X_2 | \alpha, \xi \rangle = \text{Im}(\alpha)$$

Squeezed field generation recipe

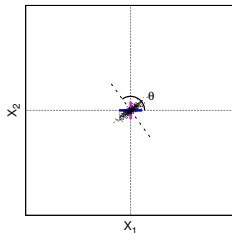
Take a vacuum state $|0\rangle$



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

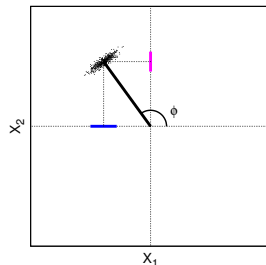
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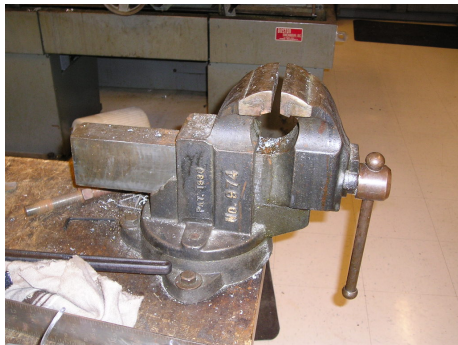
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$$\langle \alpha, \xi | X_2 | \alpha, \xi \rangle = \text{Im}(\alpha)$$

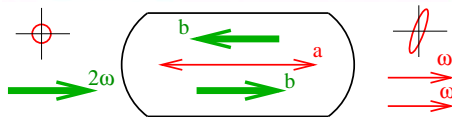
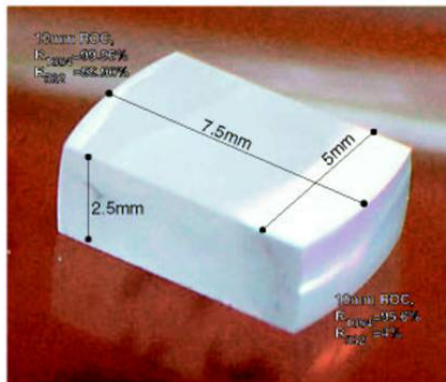
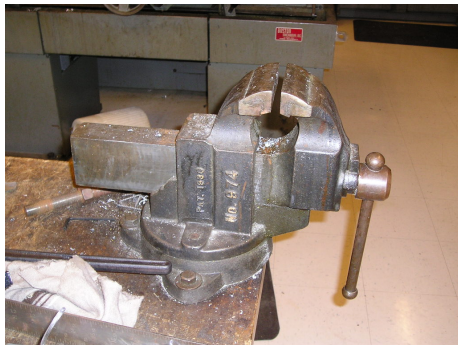
Notice $\Delta X_1 \Delta X_2 = \frac{1}{4}$

Tools for squeezing

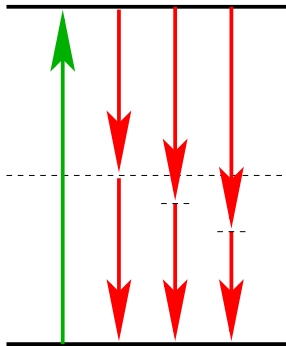
Tools for squeezing



Tools for squeezing



Two photon squeezing picture

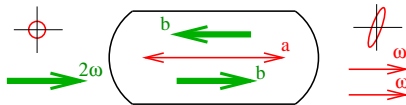


Squeezing operator

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

Parametric down-conversion in crystal

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



Squeezing

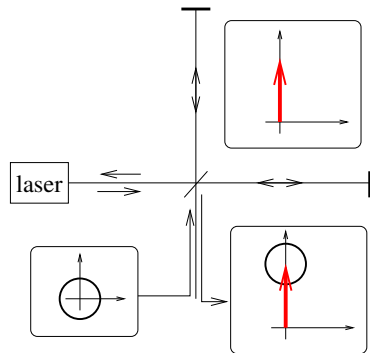
maximum squeezing value detected **15 dB at 1064 nm**

Henning Vahlbruch, Moritz Mehmet, Karsten Danzmann, and Roman Schnabel Phys. Rev. Lett **117**, 110801 (2016)

Squeezing and interferometer

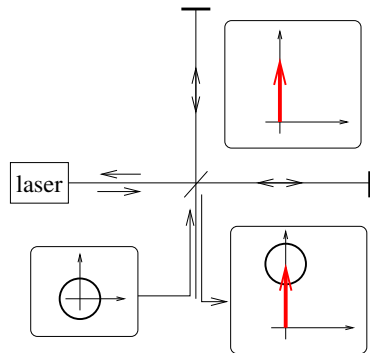
Squeezing and interferometer

Vacuum input

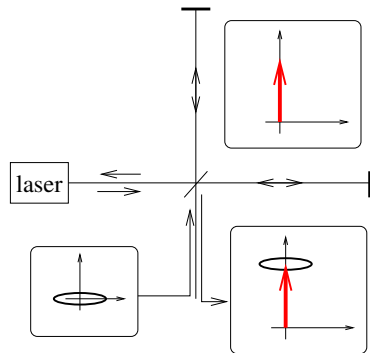


Squeezing and interferometer

Vacuum input



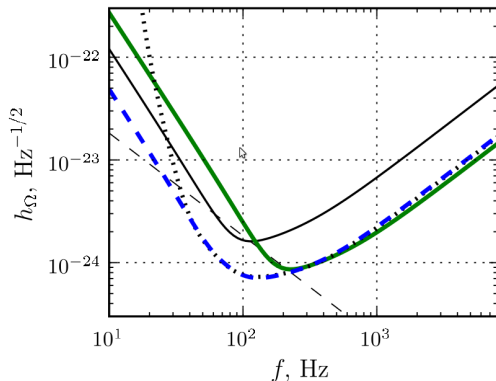
Squeezed input



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)

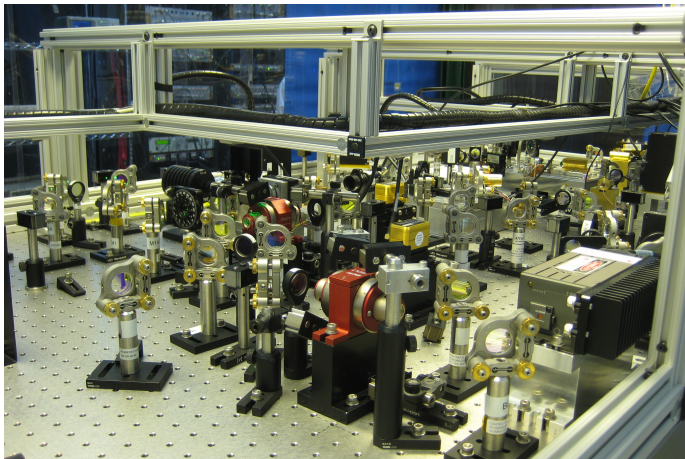
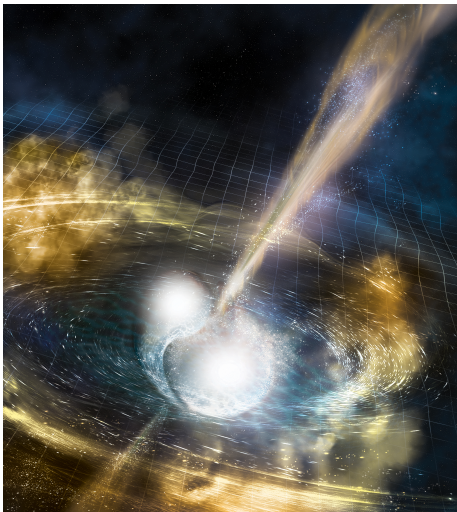


Photo of Squeezer, LIGO Magazine <http://www.ligo.org/magazine/>

Summary



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