Gravity, precision measurements and squeezed states of light.

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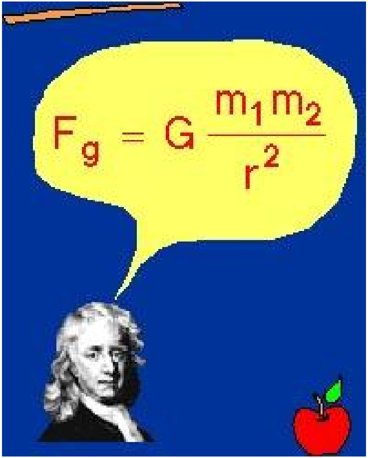
Outline

1. History of gravity
   - Newton's laws
   - Einstein's laws
   - A bit of astrophysics
2. Detectors
   - Gravitational wave interferometer
3. Quantum Optics
   - What is quantum optics
   - Squeezed states of light
   - Quadrature measurements with squeezed light
   - Tools for squeezing
4. Squeezing and interferometers
5. Squeezing experiments

Newton's laws



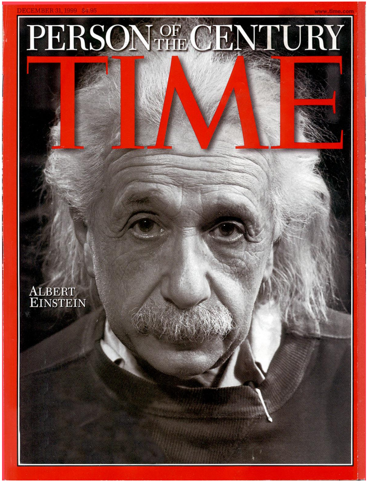
Laws of motion and law of gravitation solved problems of astronomy and terrestrial physics.

- 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

Einstein's laws

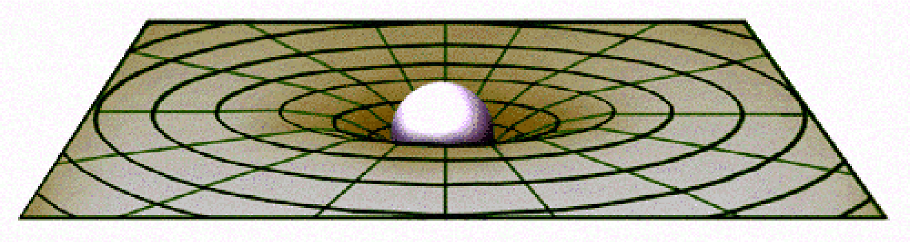


The General Theory of Relativity and theory of Gravity (1916)

- 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



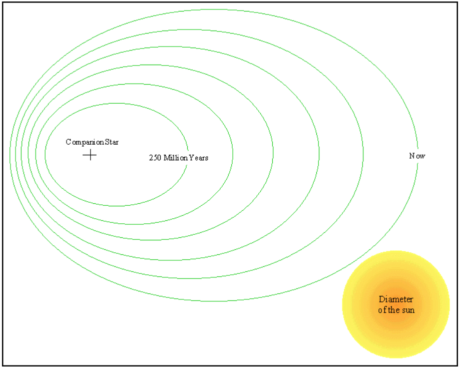
important predictions

- 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

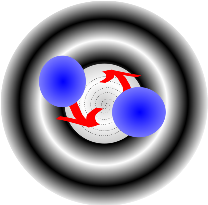
- orbital period decreased by 14 sec from 1975 to 1994
- measured to 50 msec accuracy
- deviation grows quadratically with time



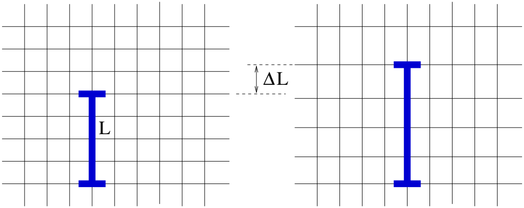
Nobel prize in 1997 Taylor and Hulse

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

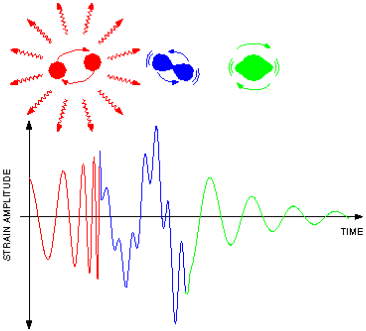
$$h = \frac{\Delta L}{L} \quad (1)$$

typical strain

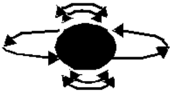
$$h \sim 10^{-21} \quad (2)$$

Astrophysical sources of GW

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

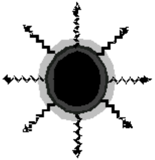


- Periodic sources
  - spinning neutron stars (pulsars)

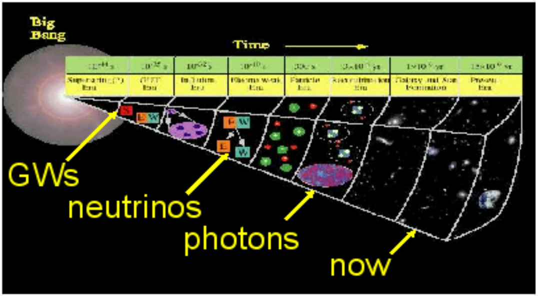


Astrophysical sources of GW (cont)

- Burst events
  - Supernovae with asymmetric collapse



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



Astrophysics with GWs vs. E&M

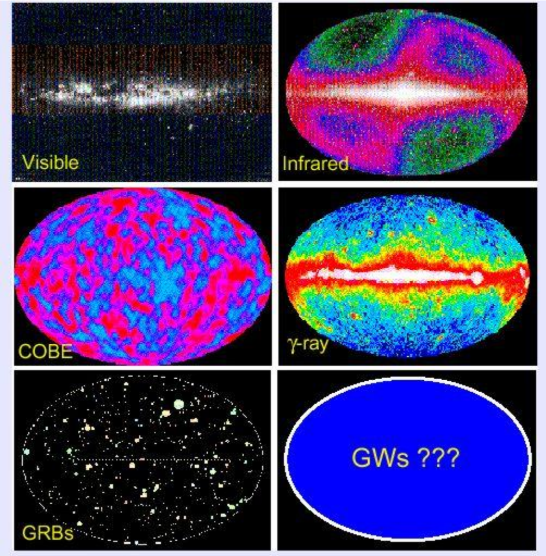
E&M (photons)

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

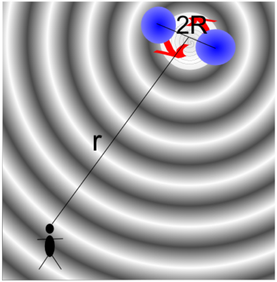
GW

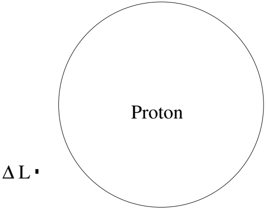
- Spacetime itself ripples
- Accelerating aspherical mass
- Very small interaction; matter is transparent
- 10 kHz and down
- Radiated by dark mass distributions

New view to the universe



Typical strain



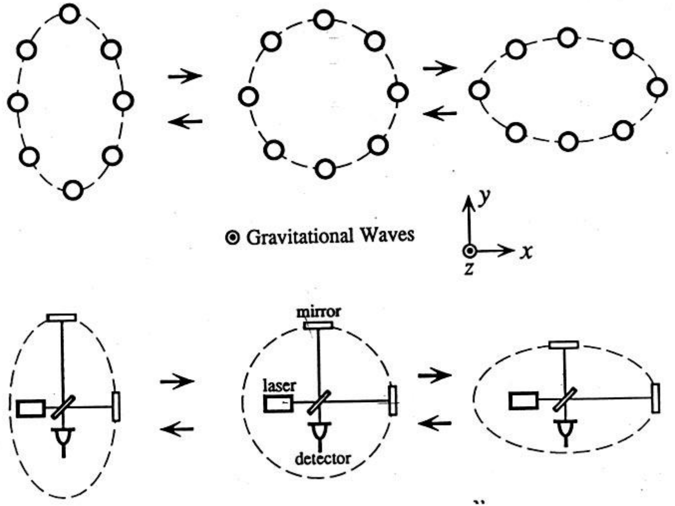


Two neutron star

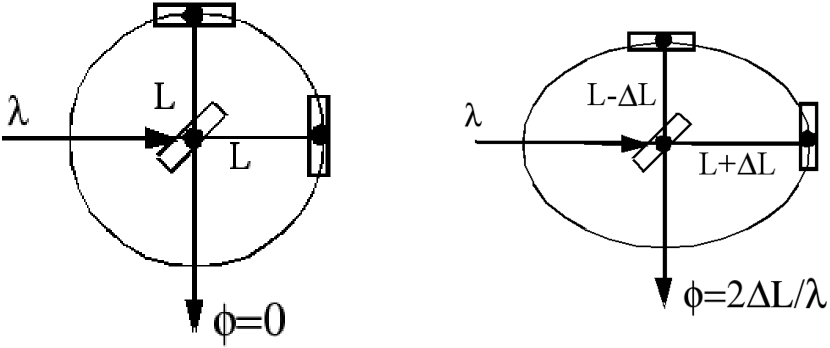
with a mass of 1.4 solar masses each
orbiting each other with a frequency $f = 400$ Hz
at a distance $2R = 20$ km
would generate strain $h \sim 10^{-21}$
at distance equal to 10^{23} m
(distance to the Virgo cluster)
For 4 km base line that would correspond to
ΔL thousand times smaller than size of proton.

Detection of GW is difficult problem

GW acting on matter



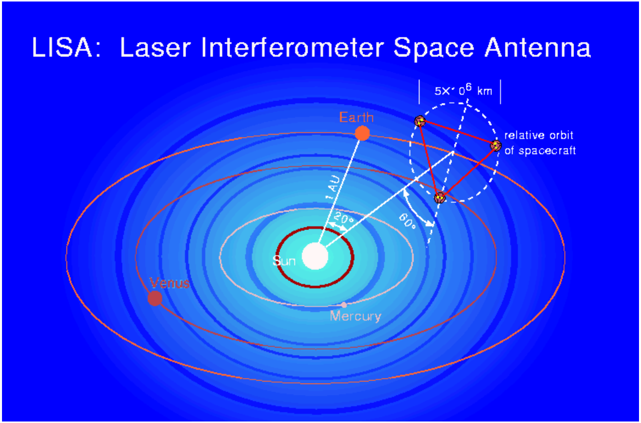
Interferometric Measurement



World wide network of detectors

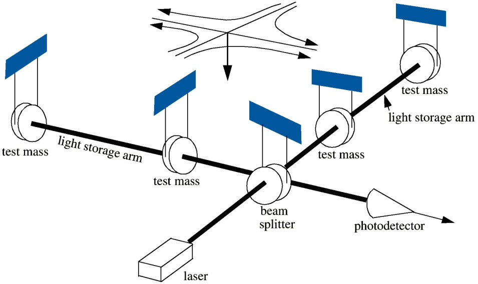
Laser Interferometer Space Antenna (LISA)

- Three spacecraft in triangular formation
- separated by 5 million km
- Formation trails Earth by 20°

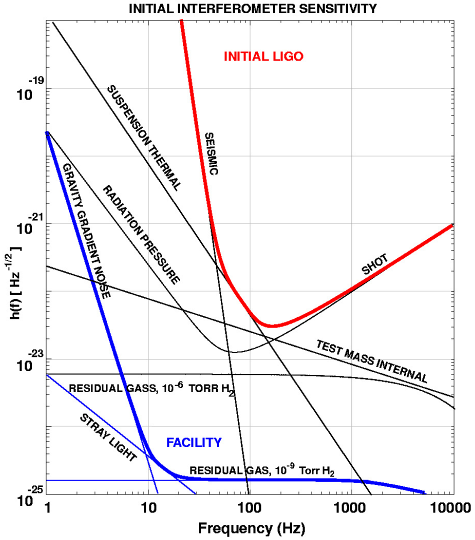


Laser Interferometer Gravitational-wave Observatory

- $L = 4$ km
- $h \sim 10^{-21}$
- $\Delta L \sim 10^{-18}$ m
- $\Delta\phi \sim 10^{-10}$ rad



LIGO sensitivity goal and noise budget



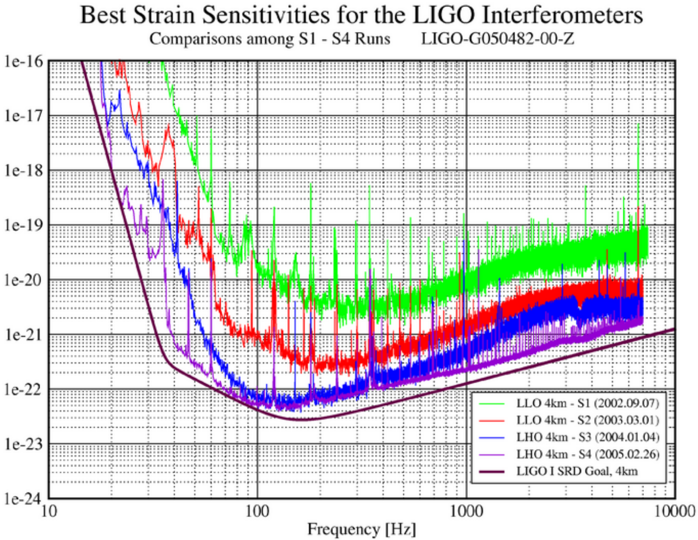
Displacement noise

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

Detection noise

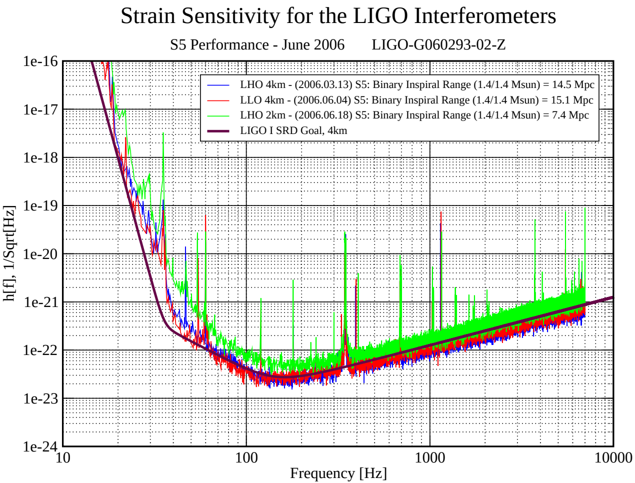
- electronics
- shot noise

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

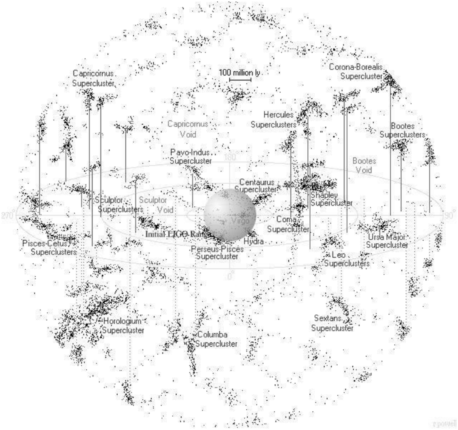
Upgrade

Goals

- Factor of 15 increase in sensitivity
- inspiral range from 20 Mpc to 350 Mpc
- Factor of 3000 in event rate
  One day > entire 2-year initial data run
- Quantum-noise-limited interferometer

How

- better seismic isolation
- decreasing thermal noise
- higher laser power



Limiting noise - Quantum Optical noise

Next generation of LIGO (advanced LIGO) will be quantum optical noise limited at almost all detection frequencies.

shot noise

Uncertainty in number of photons

$$h \sim \sqrt{\frac{1}{P}} \quad (3)$$

radiation pressure noise

Photons impart momentum to mirrors

$$h \sim \sqrt{\frac{P}{M^2 f^4}} \quad (4)$$

There is no optimal light power to suit all detection frequency.
Optimal power depends on desired detection frequency.

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What is quantum optics

Classical/Geometrical optics

- light is a ray
- which propagates straight
- cannot explain diffraction and interference

Semiclassical optics

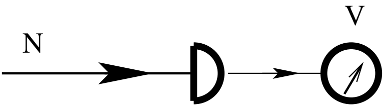
- light is a wave
- color (wavelength/frequency) is important
- amplitude (a) and phase are important, $E(t) = ae^{i(kz-\omega t)}$
- cannot explain residual measurements noise

Quantum optics

- light consists of photons: $N = a^\dagger a$
- detector measures quadratures: $X_1 = a^\dagger + a$ and $X_2 = i(a^\dagger - a)$
- amplitude and phase cannot be measured precisely: $\langle \Delta X_1^2 \rangle \langle \Delta X_2^2 \rangle \geq 1$

Quantum noise

Simple photodetector



$$V \sim N$$

$$\Delta V \sim \sqrt{N}$$

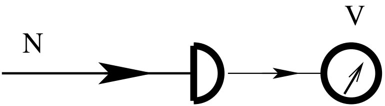
Balanced photodetector

$$V = 0$$

$$\Delta V \sim \sqrt{N}$$

Quantum noise

Simple photodetector



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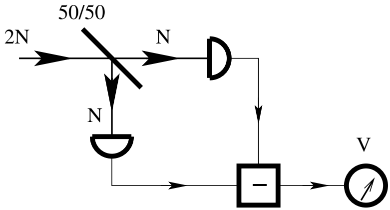

$$V = 0$$

$$\Delta V \sim \sqrt{N}$$

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

Optics equivalent strict definition

$\langle \Delta X_1^2 \rangle \langle \Delta X_2^2 \rangle \geq 1$

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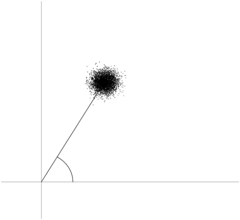
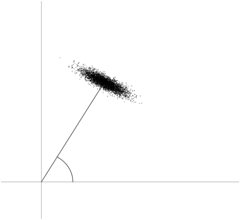
Squeezed states of light

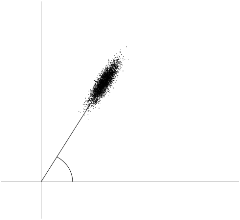
Unsqueezed state



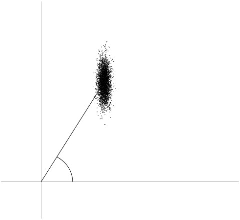
Amplitude squeezed state



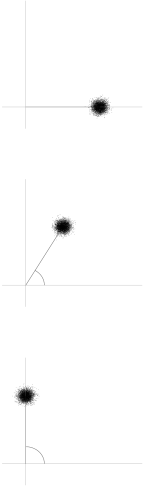
Phase squeezed state

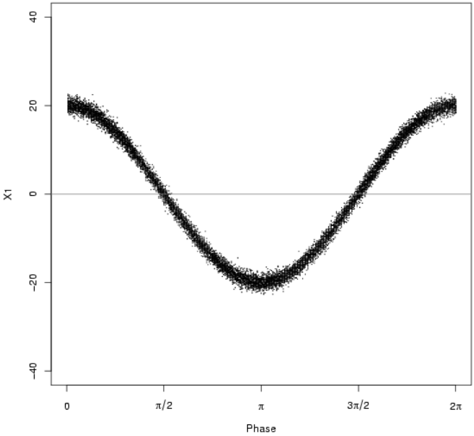


Squeezed state at $\pi/6$ angle

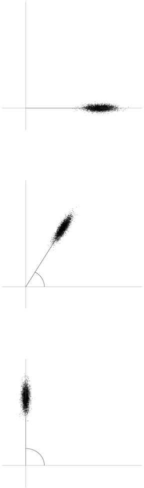


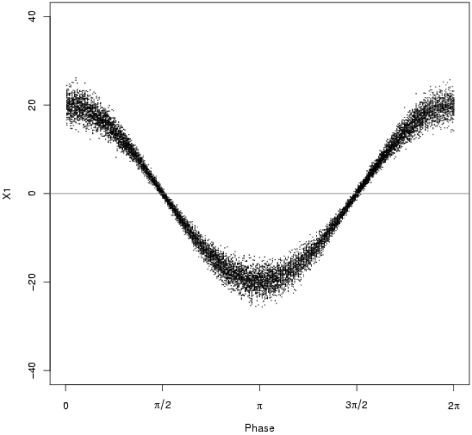
Quadrature measurements with unsqueezed light



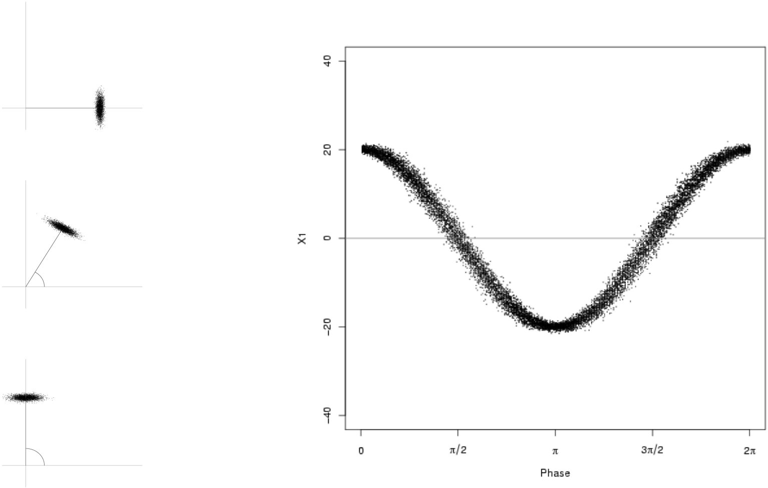


Quadrature measurements with phase squeezed light

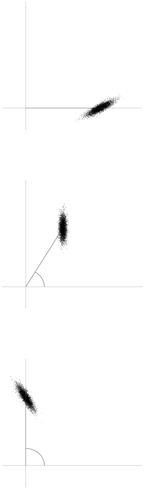


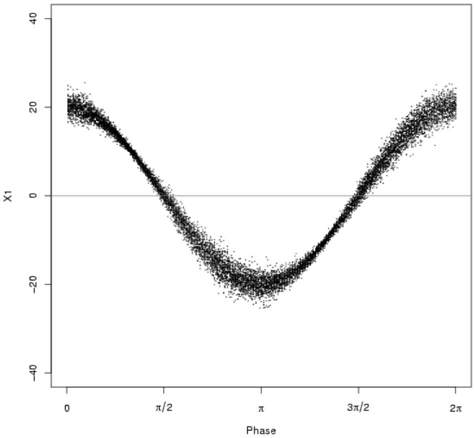


Quadrature measurements with amplitude squeezed light



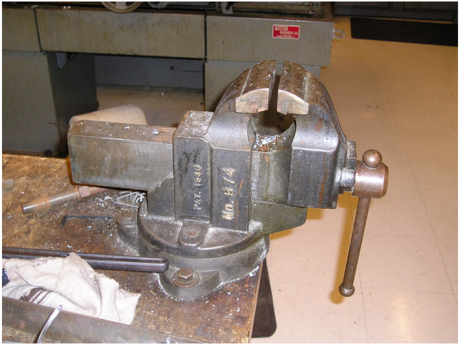
Quadrature measurements with light squeezed at $\pi/6$ angle





Tools for squeezing

Tools for squeezing



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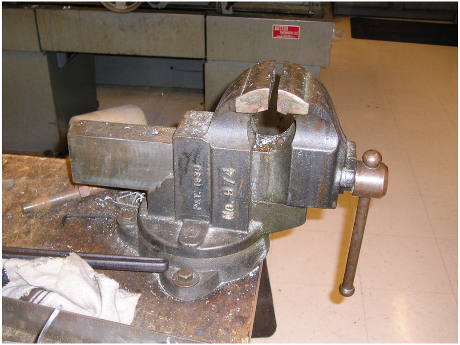
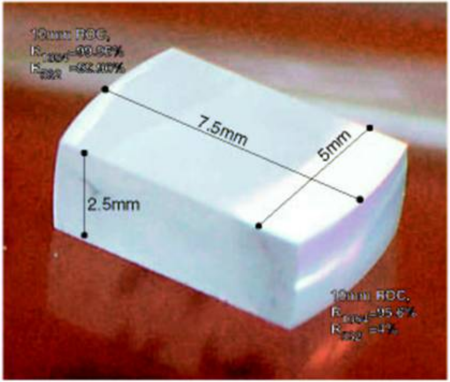
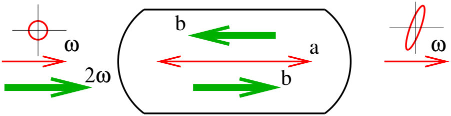
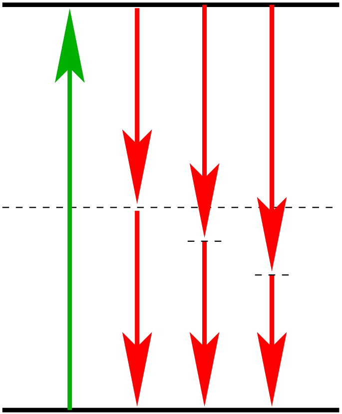






Two photon squeezing picture

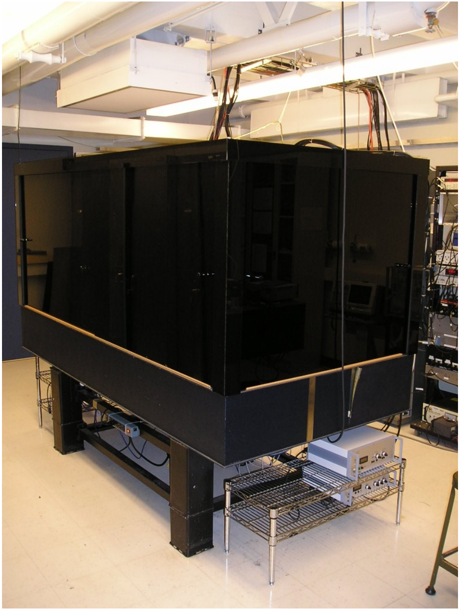


Squeezing

result of correlation of upper and lower sidebands

Squeezer appearance

Squeezer appearance



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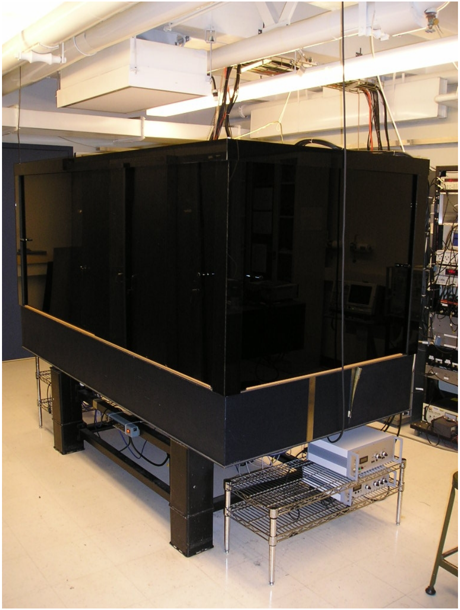
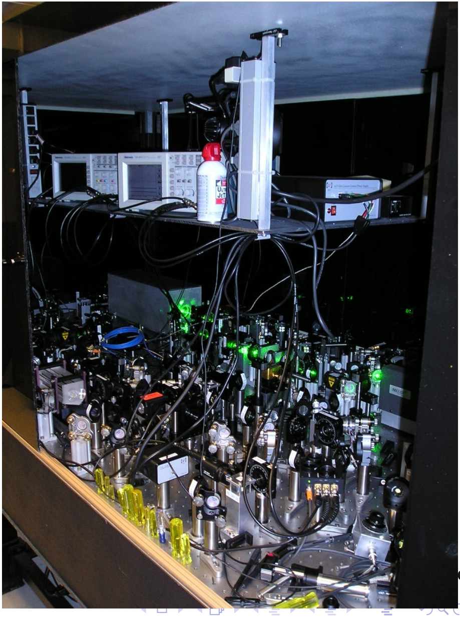
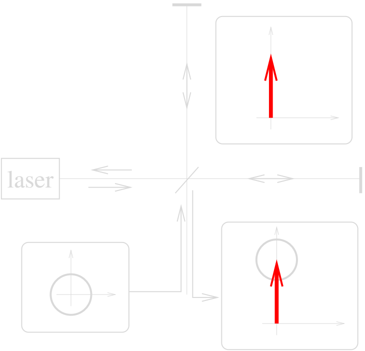


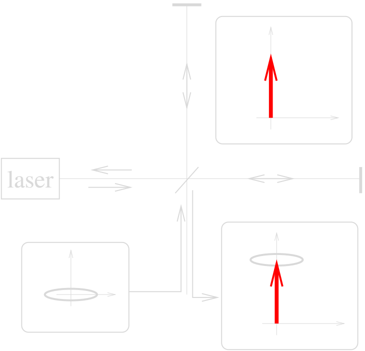


Squeezing and interferometer

Vacuum input



Squeezed input



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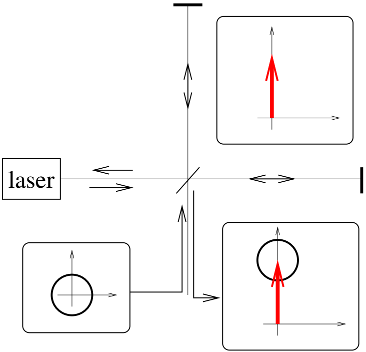
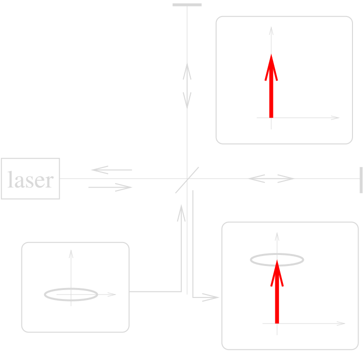


Squeezed input



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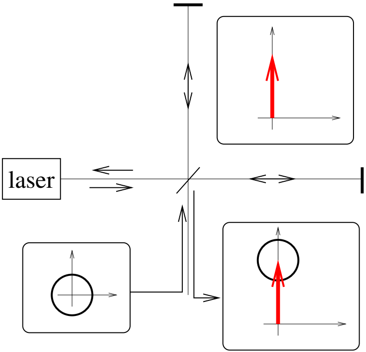

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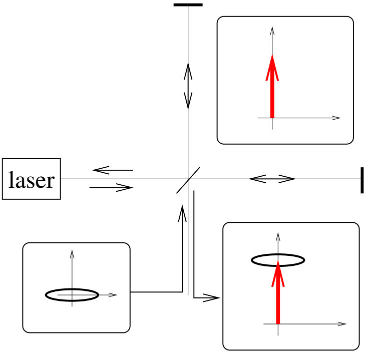
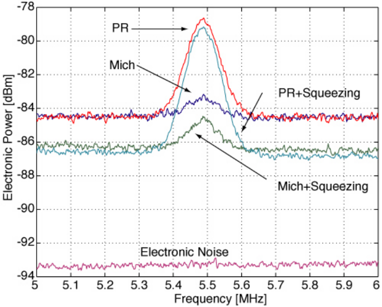


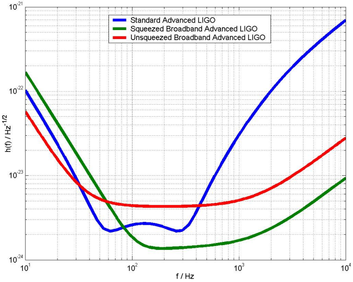
Interferometer sensitivity improvement with squeezing

Table top demonstration
Pioneered by M. Xiao, L. Wu, and H. J. Kimble
Phys. Rev. Lett. 59, 278-281 (1987)



Kirk McKenzie *et. al.*
Phys. Rev. Lett. 88, 231102 (2002)
The Australian National University

Projected advanced LIGO sensitivity



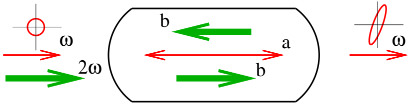
T. Corbitt *et.al.*
Phys. Rev. D 70, 022002 (2004) MIT

Requirements to squeezer

- squeezing at low frequency (10Hz - 10kHz)
- frequency dependent quadrature (angle) of squeezing
- stability (long time of operation)

Fundamental limits for squeezing in non-linear crystals

Optical parametric oscillator (OPO)



$$\delta\dot{a} = -(i\Delta_a + \gamma_a)\delta a + \varepsilon^* \bar{b}\delta a^\dagger + \delta N_a + \varepsilon^* \bar{a}\delta b - i\bar{a}\delta\Delta_a + \bar{a}^* \bar{b}\delta\varepsilon^* \quad (5)$$

Noise sources in nonlinear squeezing

Classical noise

- environment noise
  - seismic noise
  - acoustic noise
- electronics noise

Quantum noise

- seed noise δa
- losses δN_a
- pump noise δb
- photothermal noise
  - detuning noise $\delta\Delta_a$
  - phasematching noise

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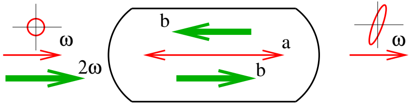

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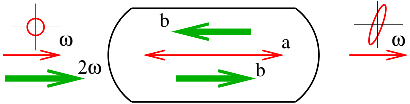

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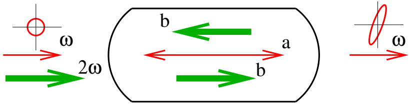

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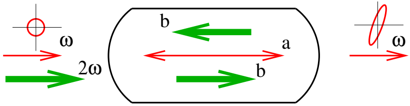

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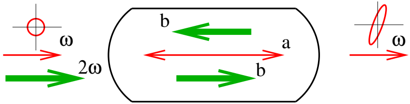

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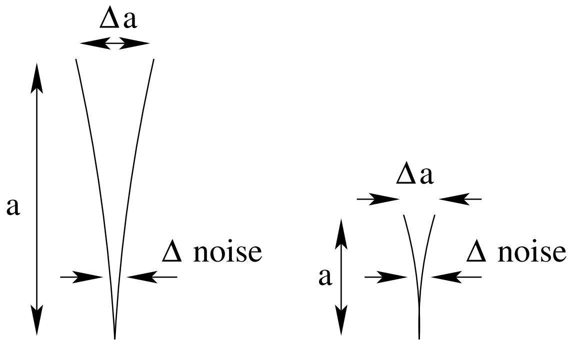
Squeezed vacuum vs squeezed light pro and contra

squeezed vacuum: $a \to 0$



Pro

- minimal possible seed noise
- decoupled from pump noise angle

Contra

- no coherent amplitude
- hard to lock

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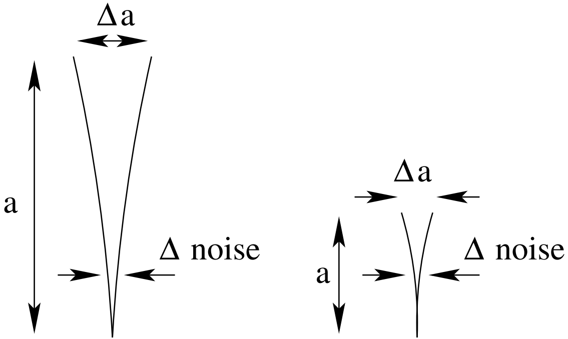

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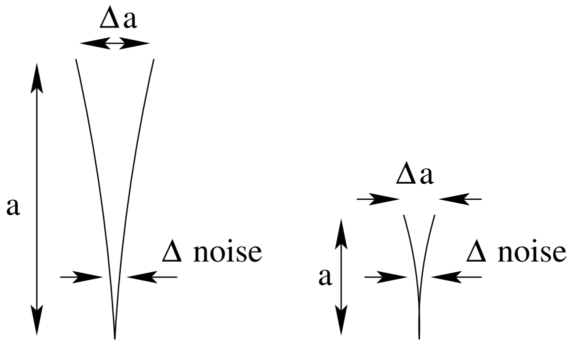

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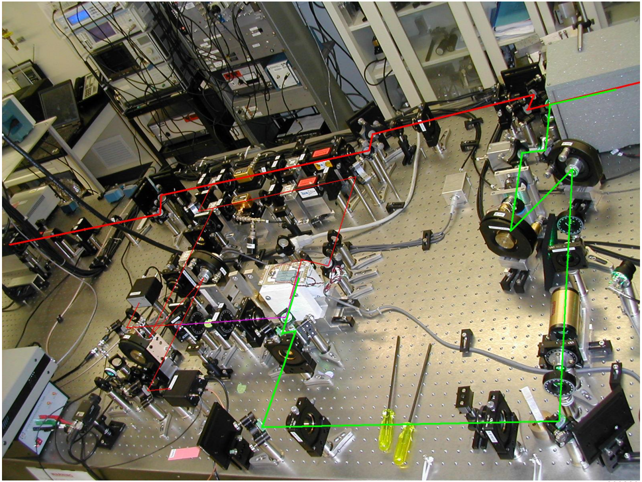
Setup photo

Laser

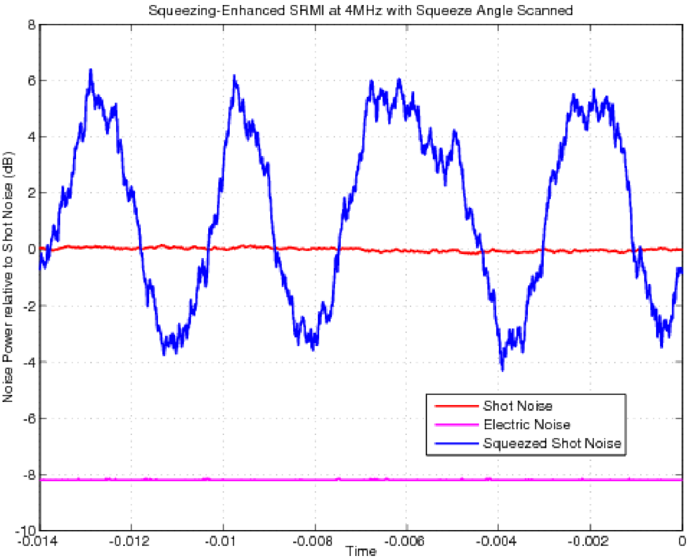
- $\lambda = 1064$ nm
- power 700 mW

Green pump

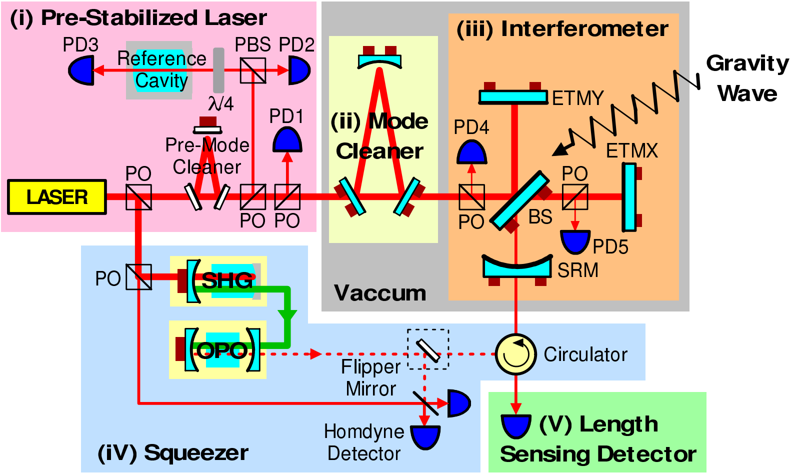
- power 200 mW



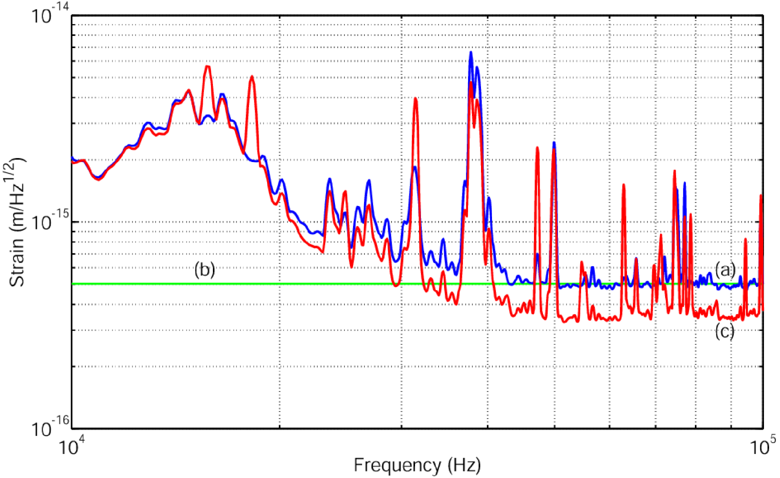
Squeezing level vs time (unlocked)



GW 40m detector and squeezer

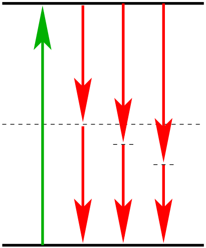


GW 40m detector with 4dB of squeezed vacuum



Signal to noise improvement by factor of 1.43

Cavity parameters with squeezing



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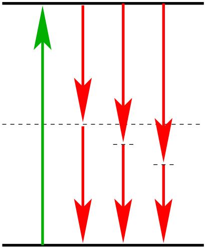

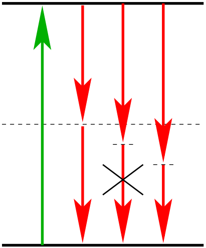

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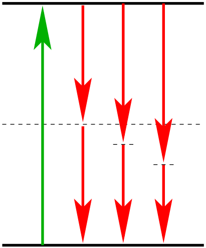

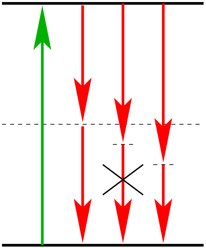

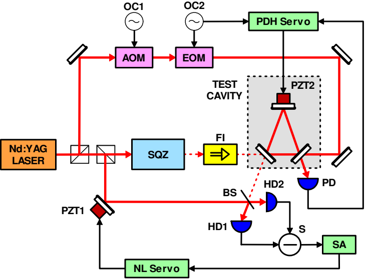

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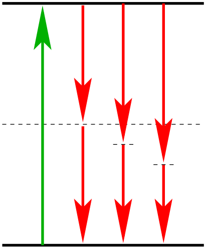
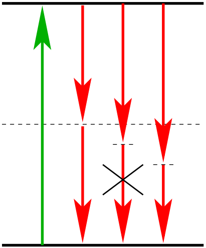
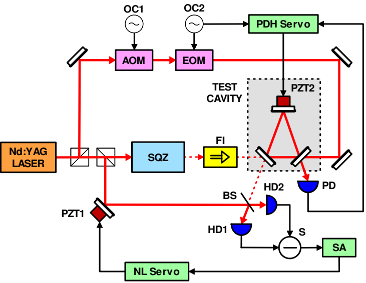
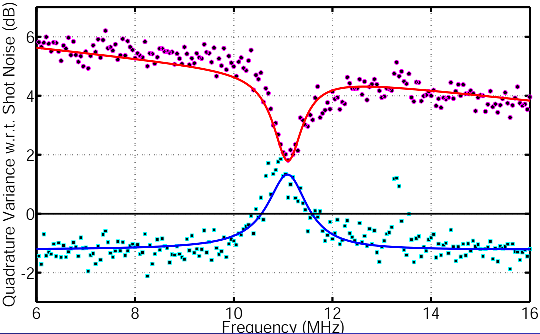
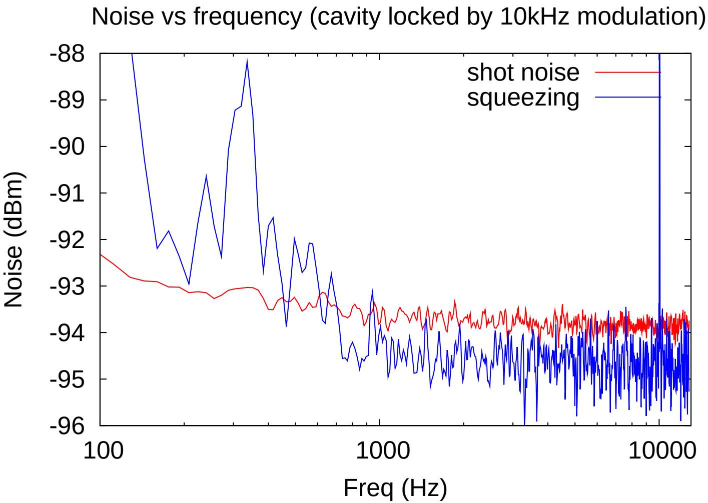








Low frequency squeezing with light free noise lock



MIT, 2006

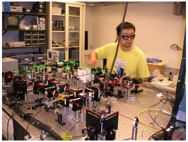
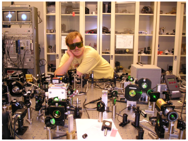
People

LIGO team

40m Interferometer team

- Osamu Miyakawa

Quantum measurements group in MIT

- Nergis Mavalvala (group leader) 
- Crystal squeezers
  - Keisuke Goda (graduate student) 
  -  Eugeniy Mikhailov

Summary

- Gravitational waves are a purely classical effect
- Their detection requires precise measurements at the sub-quantum level
- Use of quantum optics is the way to reach sub-quantum sensitivities