

Quantum enhanced measurements and LIGO

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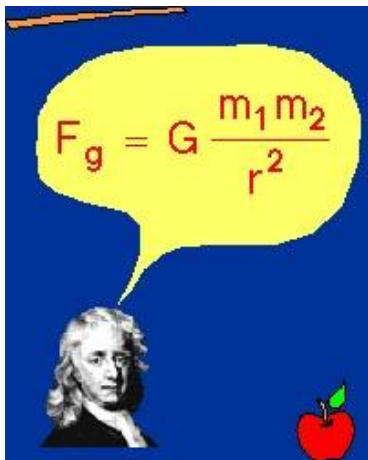
The College of William & Mary



July 25, 2014

- 1 History of gravity
 - Newton's laws
 - Einstein's laws
 - A bit of astrophysics
- 2 Detectors
 - Gravitational wave interferometer
- 3 Assorted LIGO pictures
- 4 Quantum optics
 - Classical field
 - Quantum field
- 5 Squeezing applications
 - Squeezing and interferometers
 - Squeezing enhanced magnetometry

Newton's laws 1687

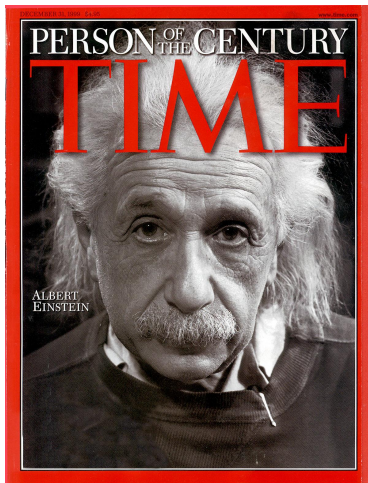


Laws of motion and law of gravitation solved problems of astronomy and terrestrial physics.

- 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

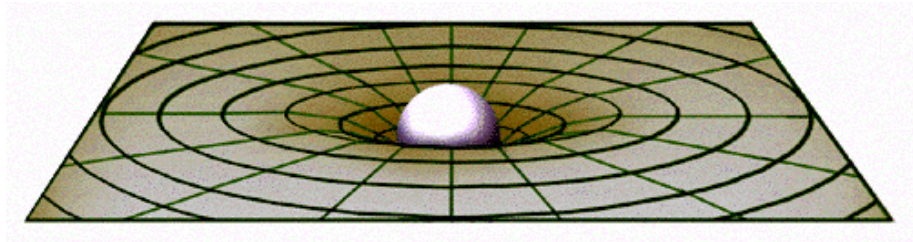


The General Theory of Relativity and theory of Gravity (1916)

- 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



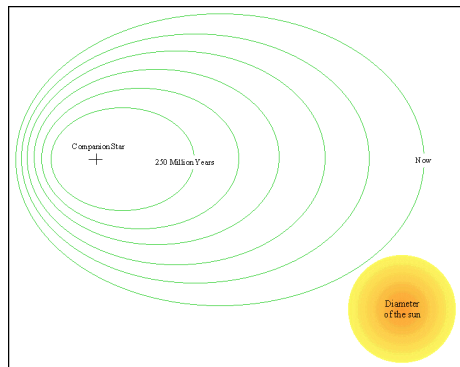
important predictions

- 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

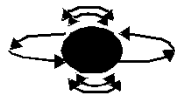
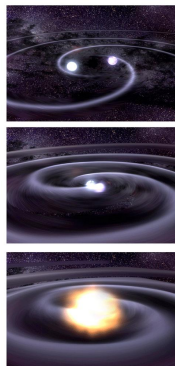


Nobel prize in 1997 Taylor and Hulse

Astrophysical sources of GW

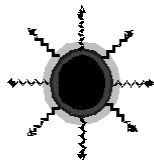
- Coalescing compact binaries
 - objects: NS-NS, BH-NS, BH-BH
 - physics regimes: Inspiral, merger, ringdown

- Periodic sources
 - spinning neutron stars (pulsars)

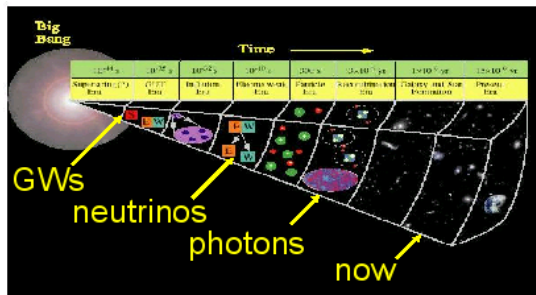


Astrophysical sources of GW (cont)

- 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

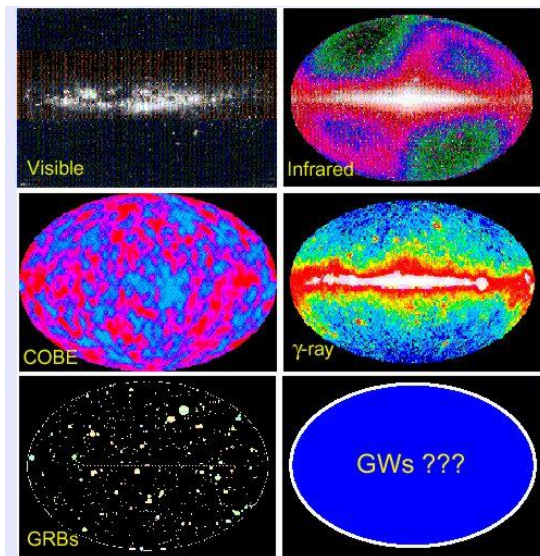
E&M (photons)

- 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

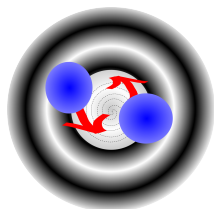
- Spacetime itself ripples
- Accelerating aspherical mass
- Very small interaction; matter is transparent
- 10 kHz and down
- Radiated by dark mass distributions

New view to the universe

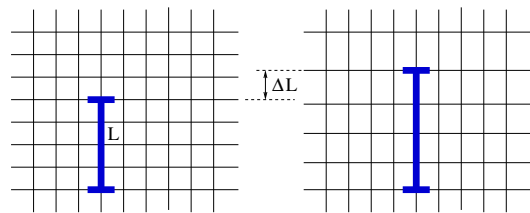


Gravitational waves (GW)

- 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



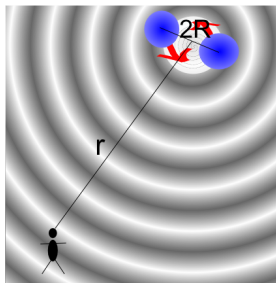
Strain - strength of GW

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

typical strain

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

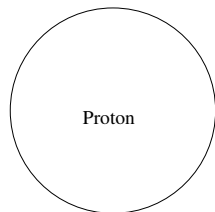
Typical strain



Two neutron star

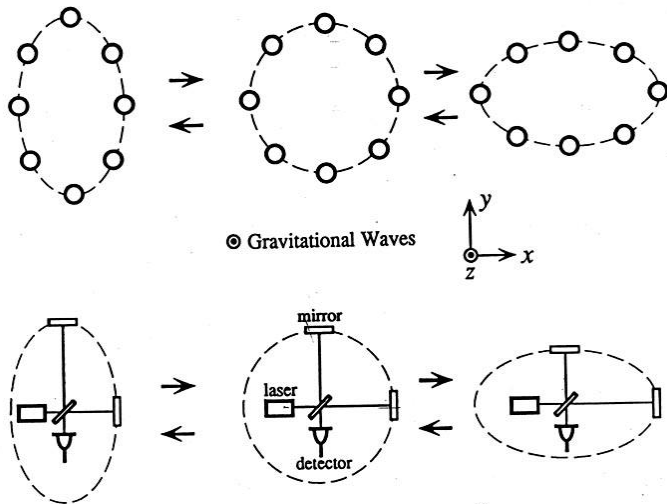
with a mass of 1.4 solar masses each
orbiting each other with a frequency $f = 400$ Hz
at a distance $2R = 20$ km
would generate strain $h \sim 10^{-21}$
at distance equal to 10^{23} m
(distance to the Virgo cluster)
For 4 km base line that would correspond to
 ΔL thousand times smaller than size of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

Detection of GW is difficult problem

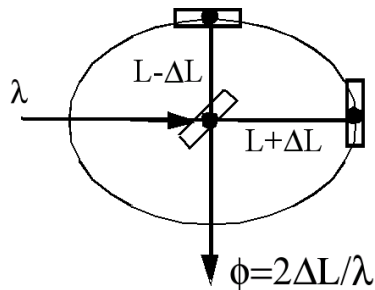
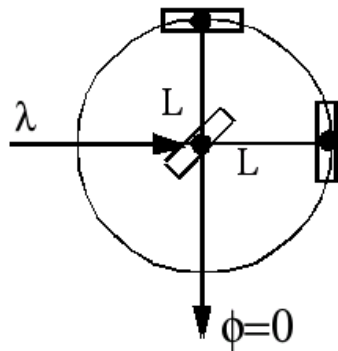


ΔL

GW acting on matter



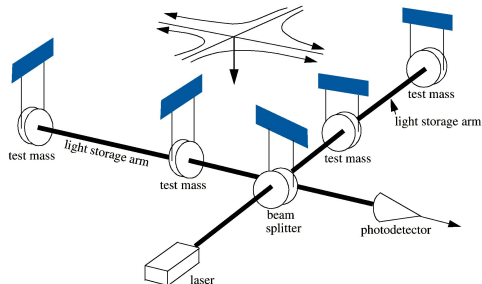
Interferometric Measurement



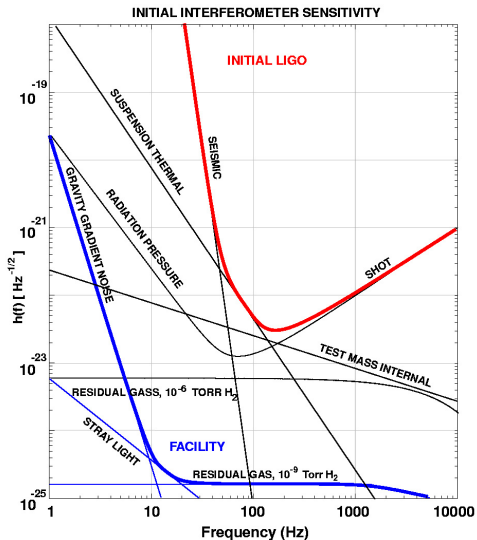
Laser Interferometer Gravitational-wave Observatory



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



LIGO sensitivity goal and noise budget



Displacement noise

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

Detection noise

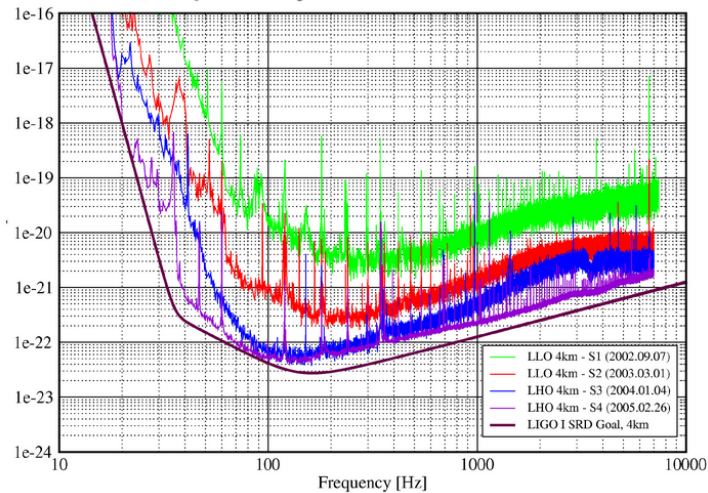
- electronics
- shot noise

LIGO sensitivity, S1-S4 runs

Best Strain Sensivities for the LIGO Interferometers

Comparisons among S1 - S4 Runs

LIGO-G050482-00-Z

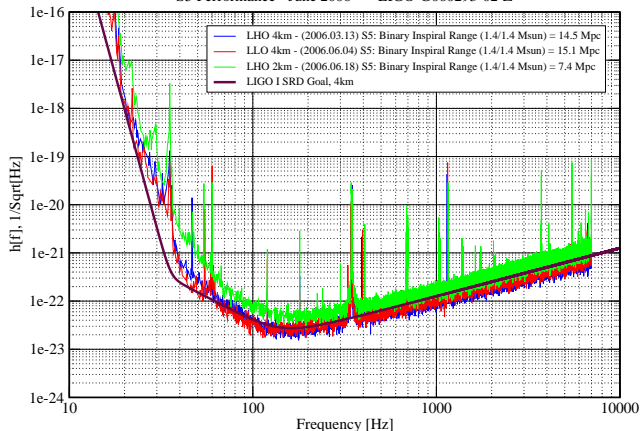


Inspiral search range during S4 was 8Mpc

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

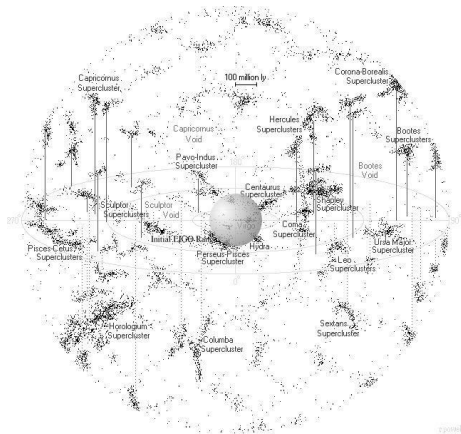
Upgrade

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



Seismic isolation



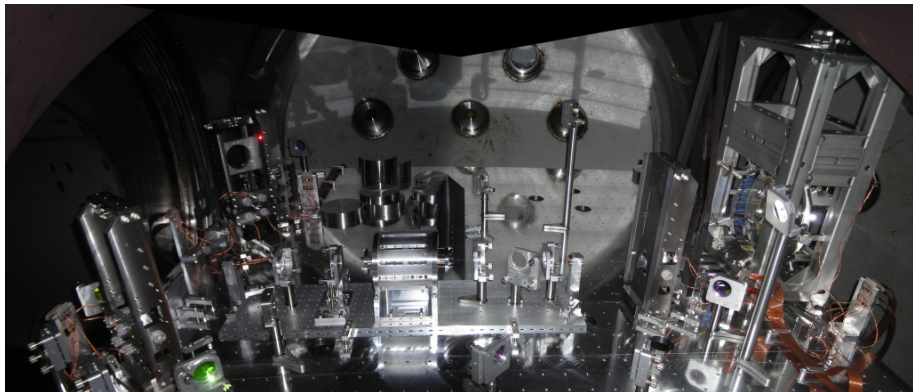
Part of large system



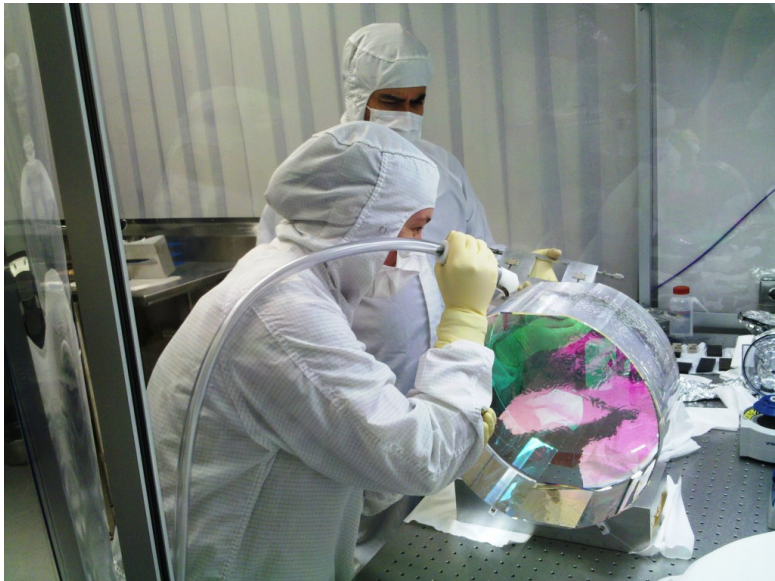
Work in chamber



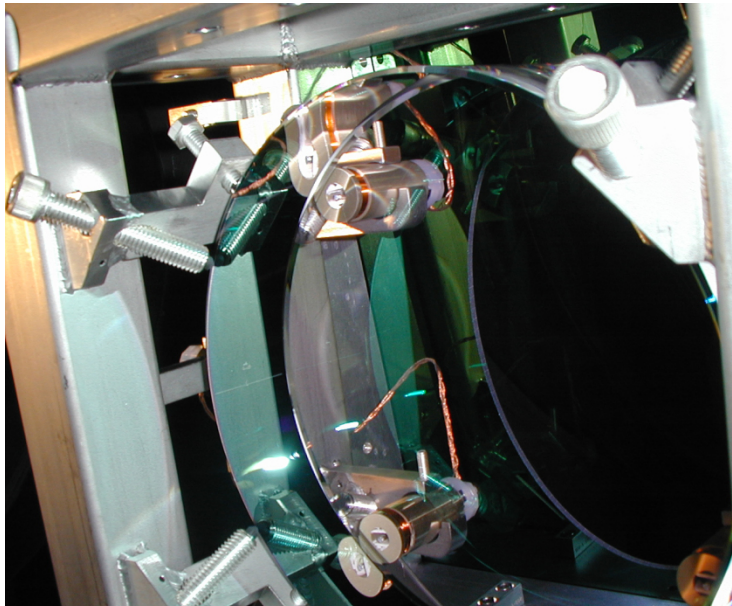
Inside vacuum chamber



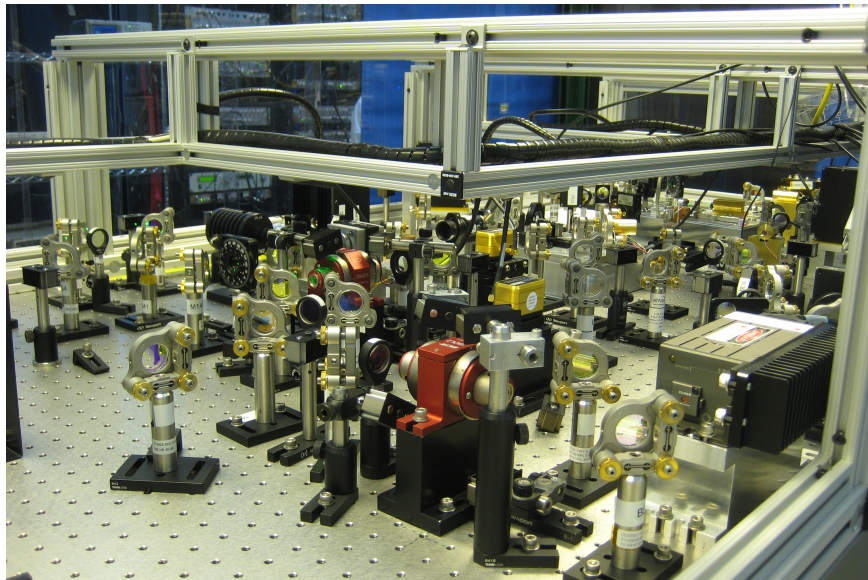
Mirror



Inner test mass



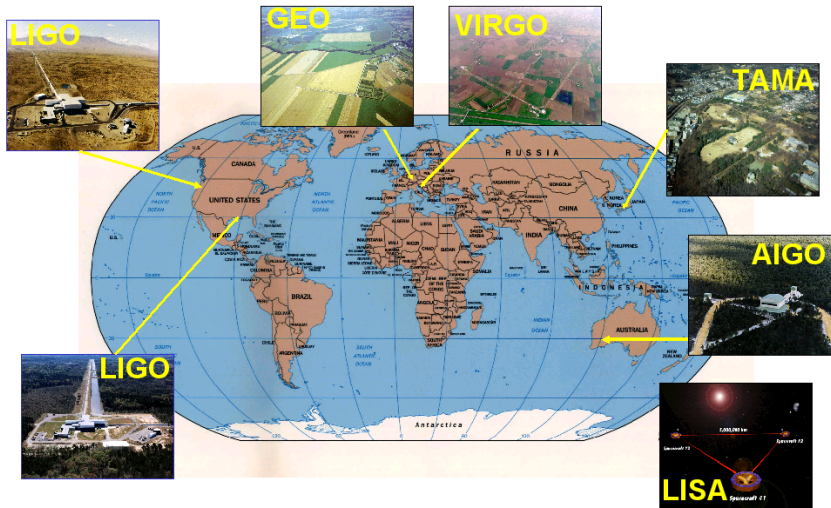
Squeezer optical table



We all hope to catch GW but ...



World wide network of detectors



Additional links

www.ligo.org



You can help to detect a gravitational wave

www.einsteinathome.org



From ray optics to semiclassical optics

Classical/Geometrical optics

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



From ray optics to semiclassical optics

Classical/Geometrical optics

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



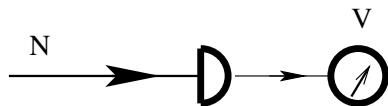
Semiclassical optics

- 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



Detector quantum noise

Simple photodetector

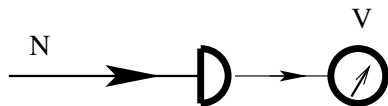


$$V \sim N$$

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

Detector quantum noise

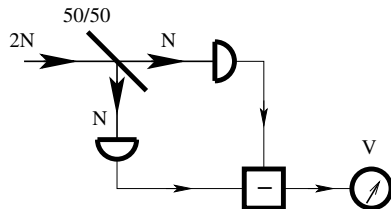
Simple photodetector



$$V \sim N$$

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

Balanced photodetector



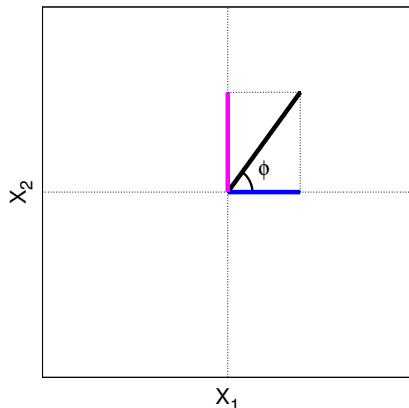
$$V = 0$$

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

Classical field

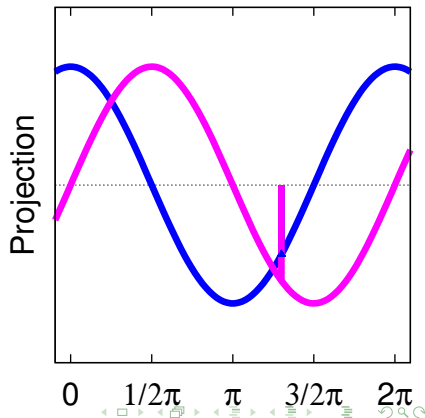
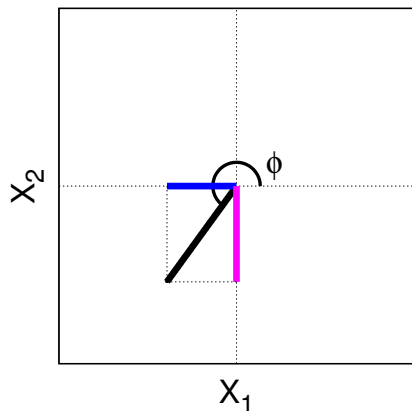
$$E(\phi) = |a|e^{-i\phi} = |a|\cos(\phi) + i|a|\sin(\phi) = X_1 + iX_2, \quad \phi = \omega t - kz$$

Detectors sense the **real** part of the field (X_1) but there is a way to see X_2 as well



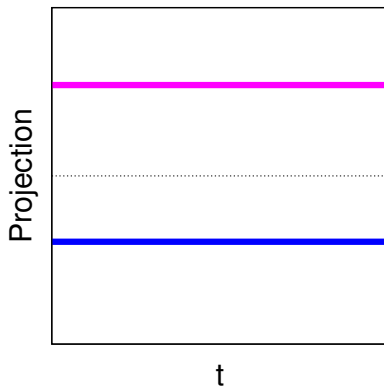
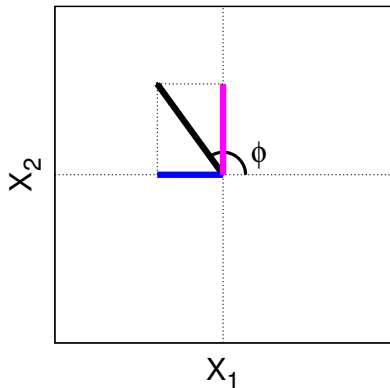
Classical field

$$E(\phi) = |a|e^{-i\phi} = |a|\cos(\phi) + i|a|\sin(\phi) = X_1 + iX_2, \quad \phi = \omega t - kz$$



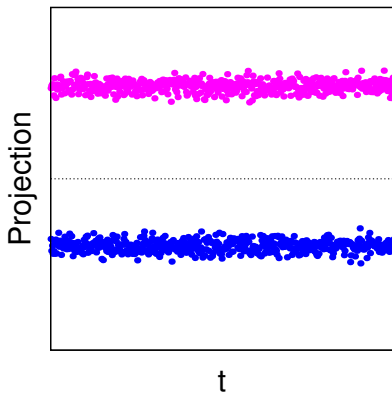
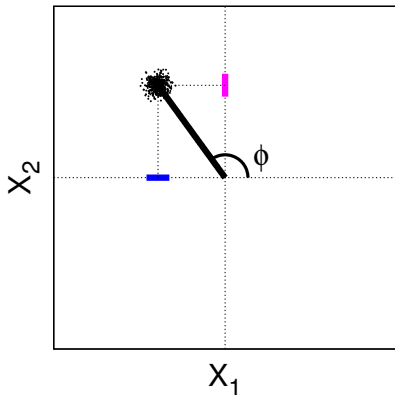
Classical quadratures vs time in a rotating frame

$$E(\phi) = |a|e^{-i\phi} = |a|\cos(\phi) + i|a|\sin(\phi) = X_1 + iX_2, \quad \phi = \omega t - kz$$



Reality check quadratures vs time

$$E(\phi) = |a|e^{-i\phi} = |a|\cos(\phi) + i|a|\sin(\phi) = X_1 + iX_2, \quad \phi = \omega t - kz$$

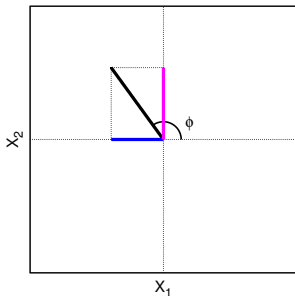


Transition from classical to quantum field

Classical analog

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

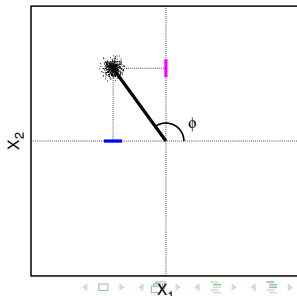
$$E(\phi) = |a|e^{-i\phi} = X_1 + iX_2$$



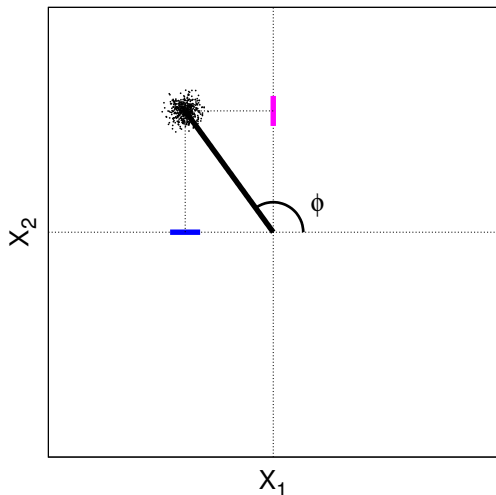
Quantum approach

- 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 \hat{X}_1 and \hat{X}_2

Uncertainty relationship

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

Heisenberg uncertainty principle and its optics equivalent



Heisenberg uncertainty principle

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

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

Heisenberg uncertainty principle and its optics equivalent



Heisenberg uncertainty principle

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

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

Optics equivalent

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

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

Heisenberg uncertainty principle and its optics equivalent



Heisenberg uncertainty principle

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

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

Optics equivalent

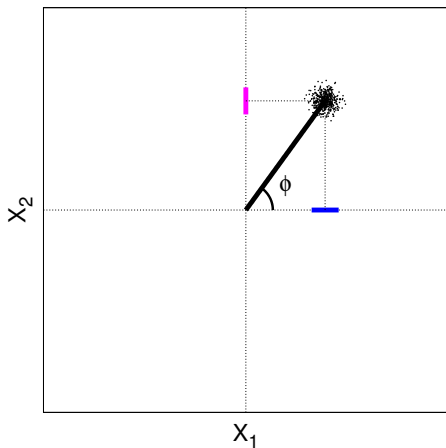
$$\Delta \phi \Delta N \geq 1$$

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

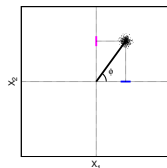
Optics equivalent strict definition

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

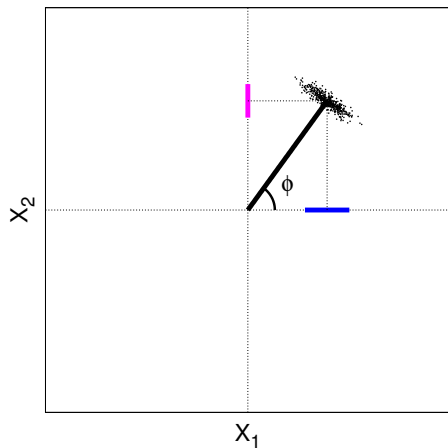
Squeezed quantum states zoo



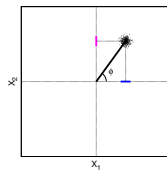
Unsqueezed
coherent



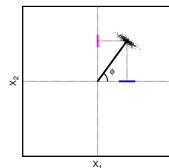
Squeezed quantum states zoo



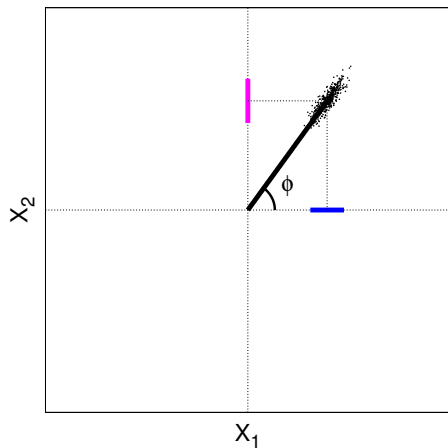
Unsqueezed
coherent



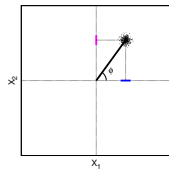
Amplitude
squeezed



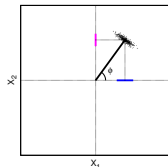
Squeezed quantum states zoo



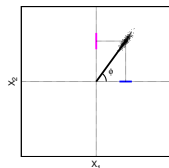
Unsqueezed
coherent



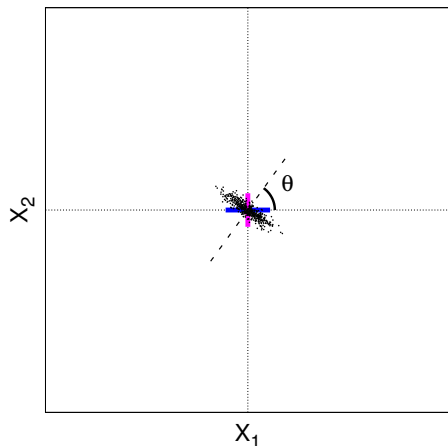
Amplitude
squeezed



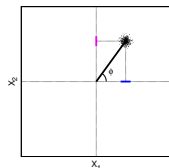
Phase
squeezed



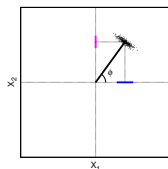
Squeezed quantum states zoo



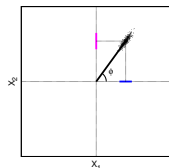
Unsqueezed
coherent



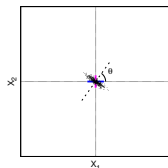
Amplitude
squeezed



Phase
squeezed



Vacuum
squeezed

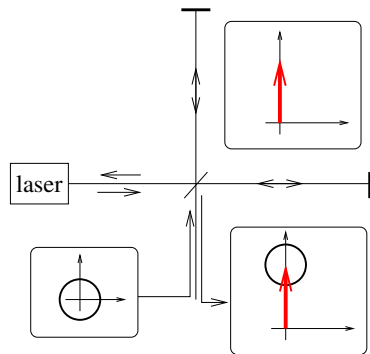


Possible squeezing applications

- improvements any shot noise limited optical sensors
- noiseless signal amplification
- photon pair generation, entanglement, true single photon sources
- interferometers sensitivity boost (for example gravitational wave antennas)
- light free measurements
- quantum memory probe and information carrier

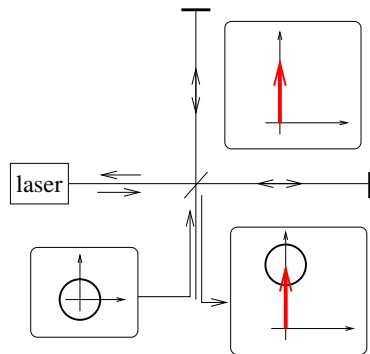
Squeezing and interferometer

Vacuum input

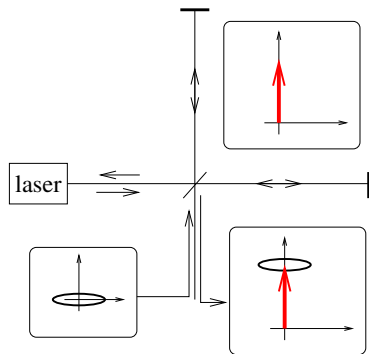


Squeezing and interferometer

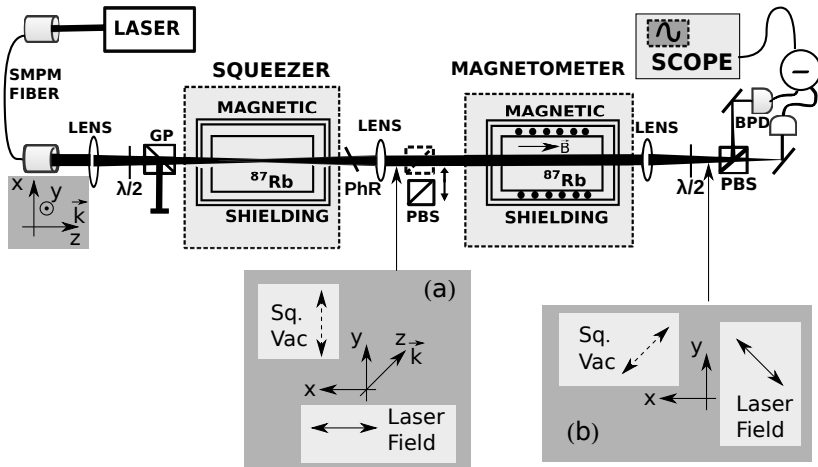
Vacuum input



Squeezed input

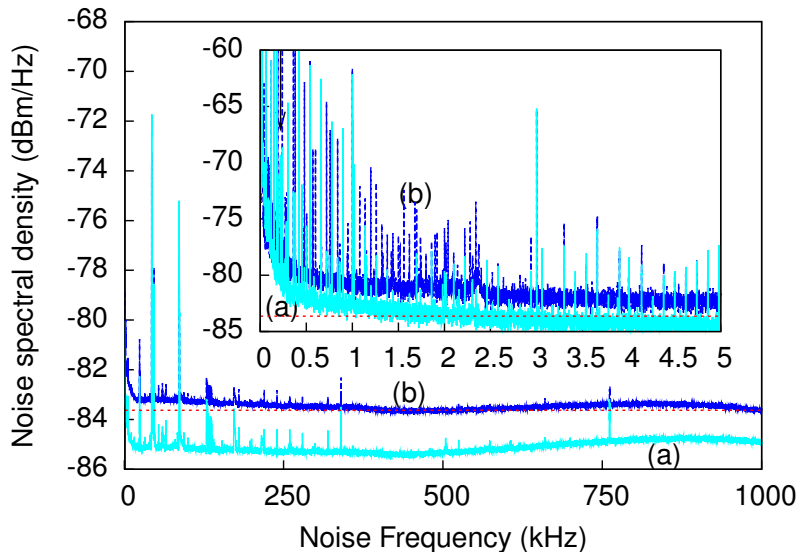


Squeezed enhanced magnetometer setup

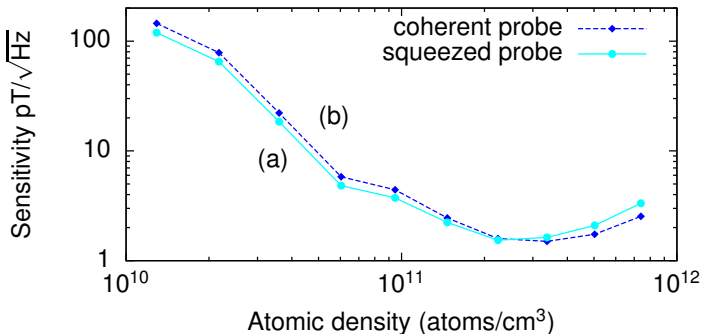
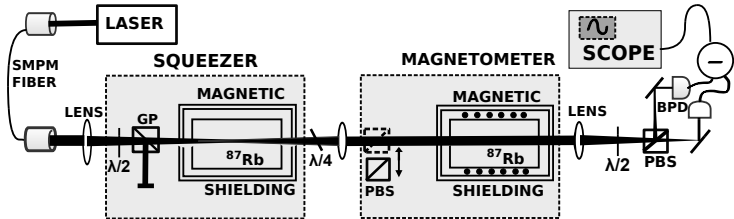


Note: Squeezed enhanced magnetometer was first demonstrated by Wolfgramm *et. al*/ Phys. Rev. Lett, **105**, 053601, 2010.

Magnetometer noise floor improvements



Magnetometer with squeezing enhancement



- The future is in quantum noise suppression :)