Quantum noise of ground base interferometer gravitational wave detector

June Gyu Park

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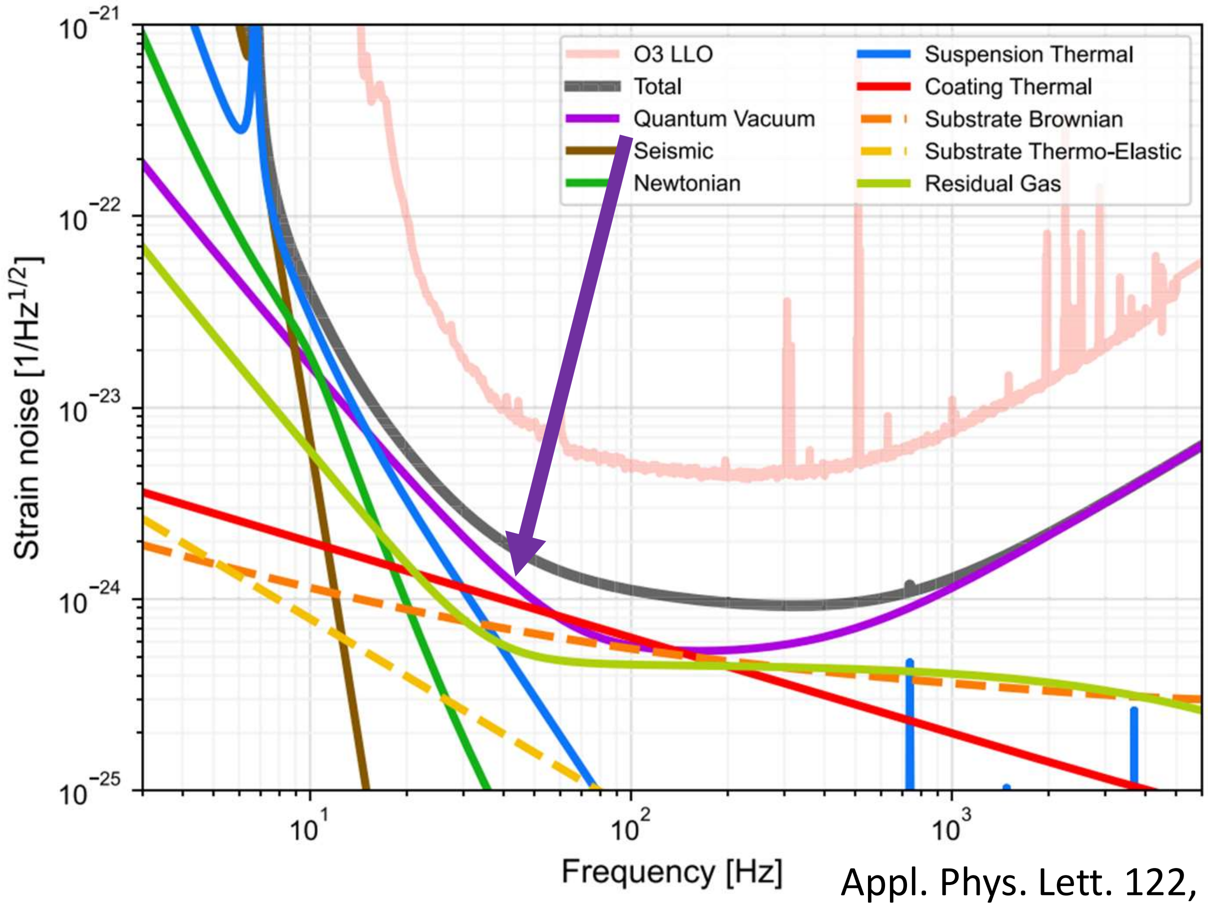
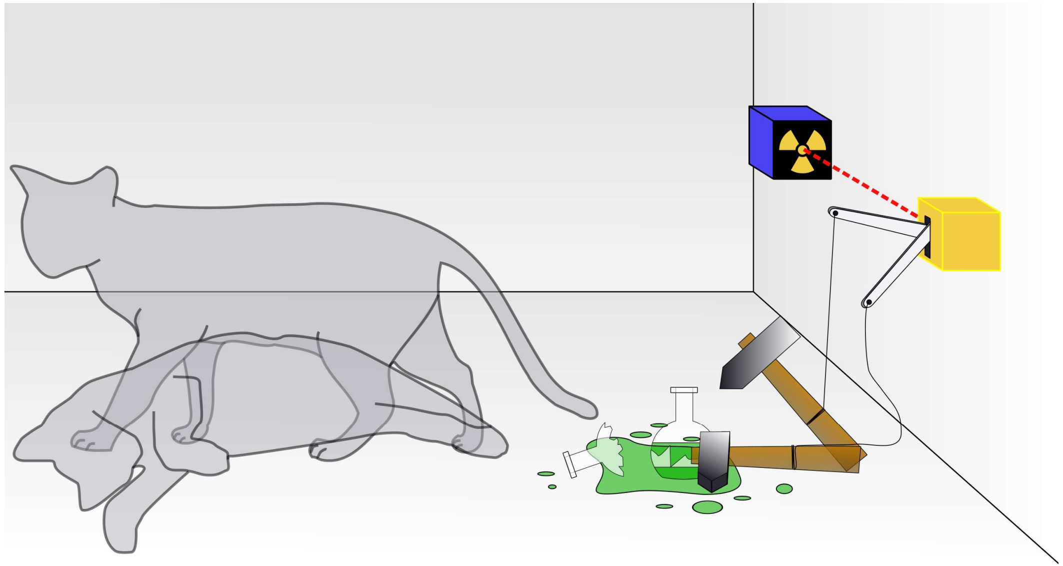
1. Standard quantum limit of gravitational wave detector

LIGO sensitivity

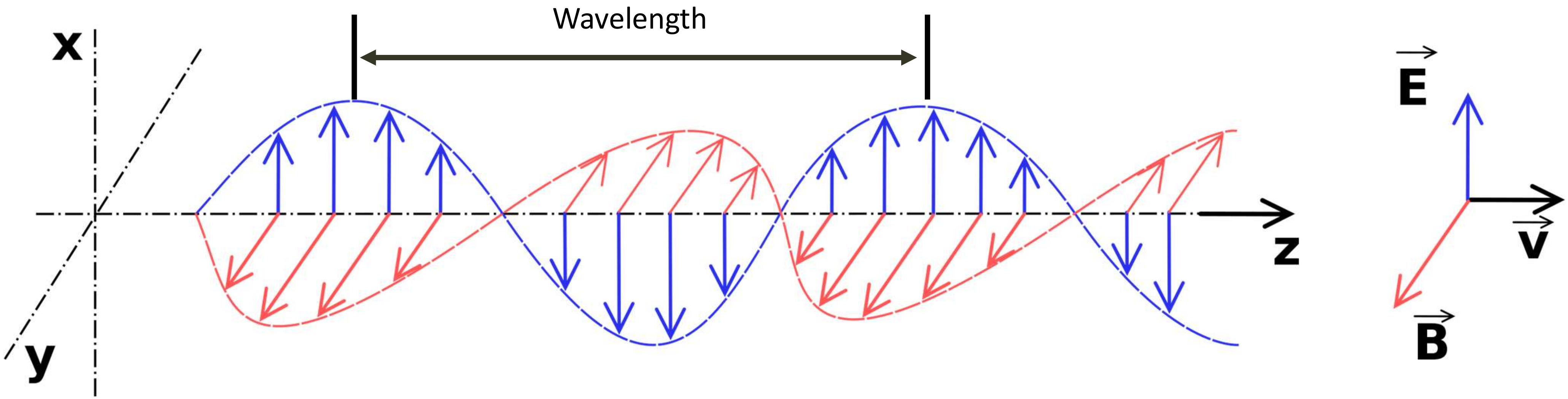


Appl. Phys. Lett. 122, 110502 (2023)

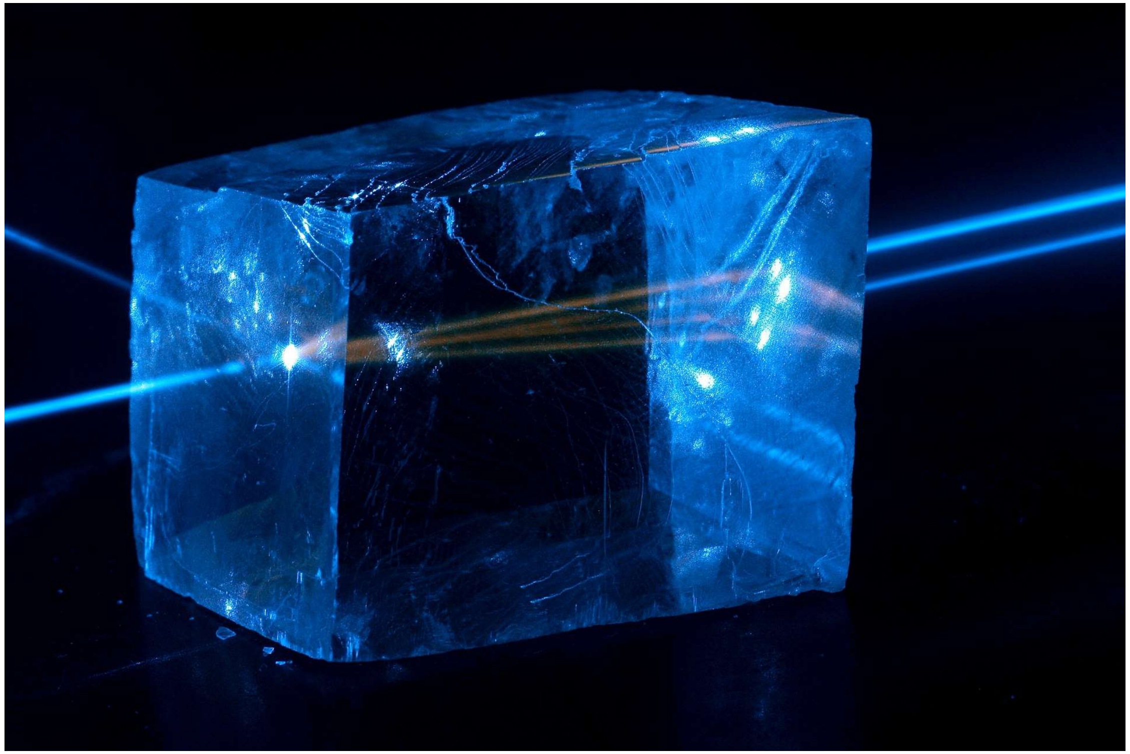
Quantum mechanics



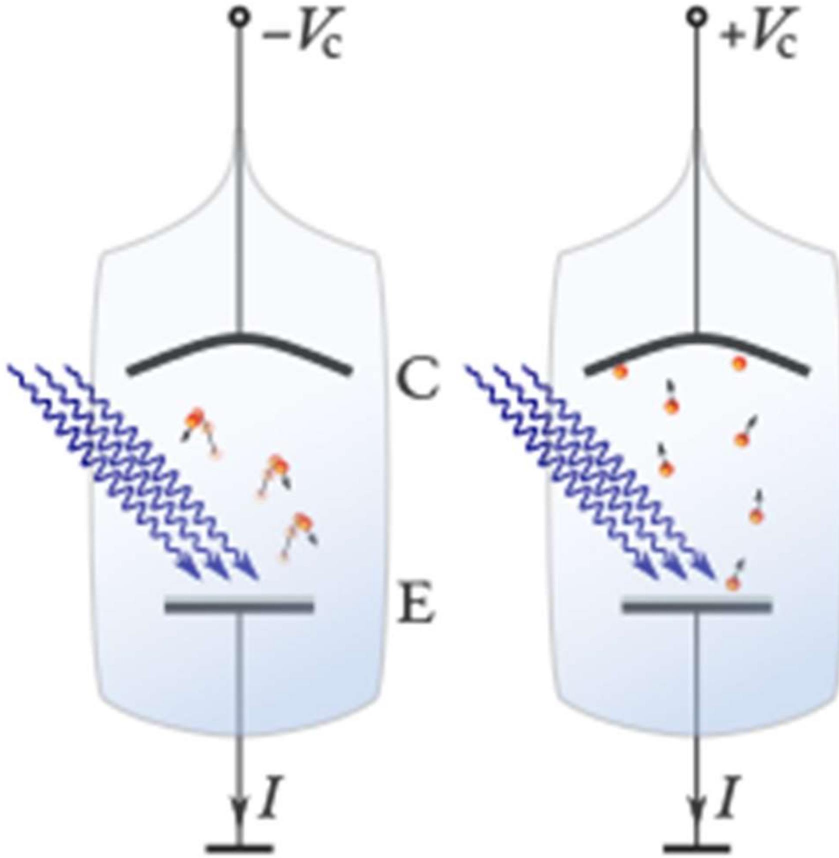
Light(Electromagnetic wave)



Wave-particle duality



Photoelectric effect



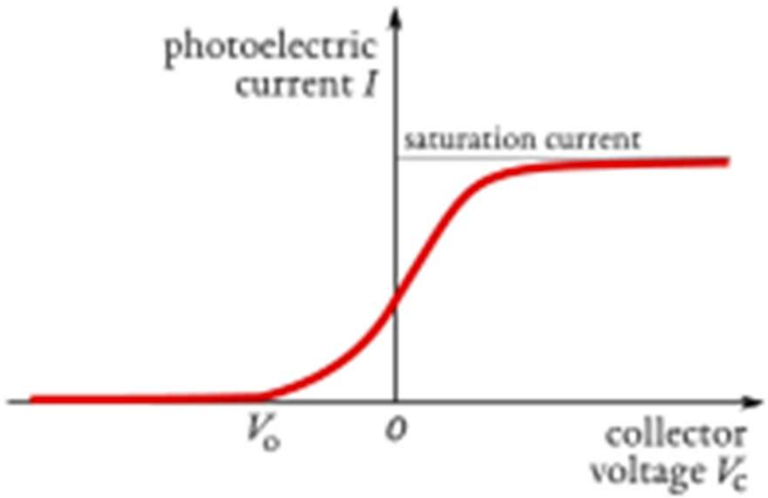
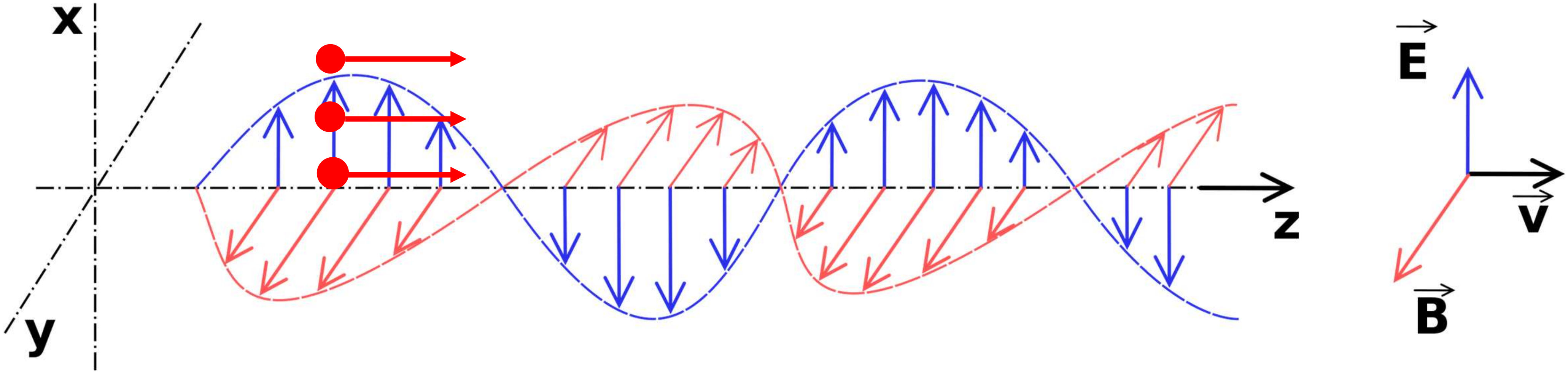


Photo detector

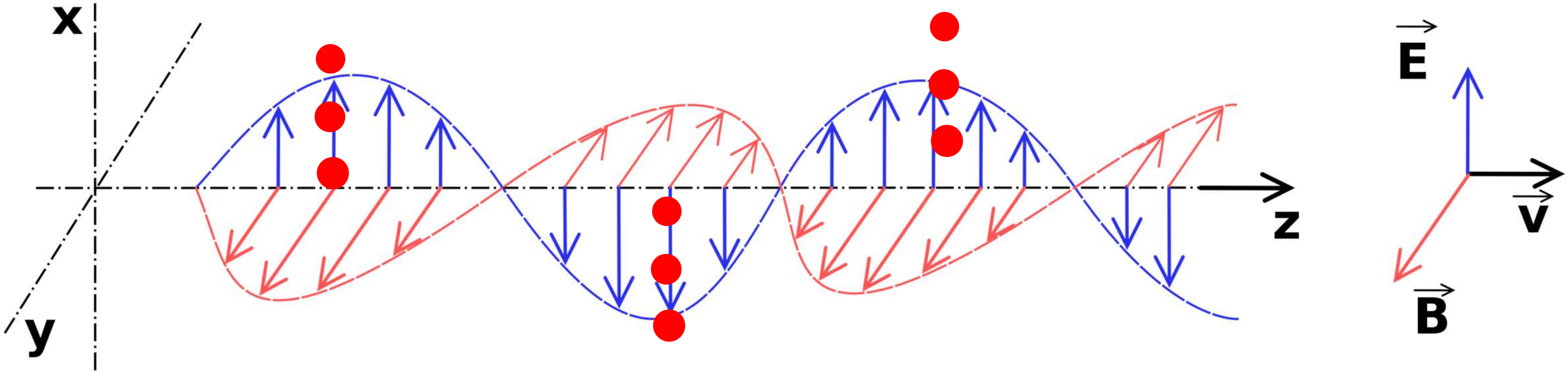
Amplitude of electricfield
$\propto \mathit{Number\ of\ photon}$

Measuring the intensity of light
= Counting the number of photon

Wave-particle duality

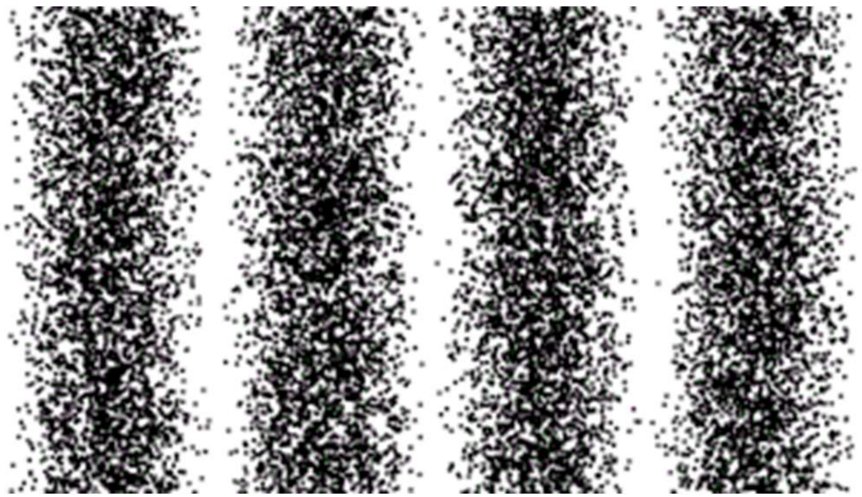


Wave-particle duality

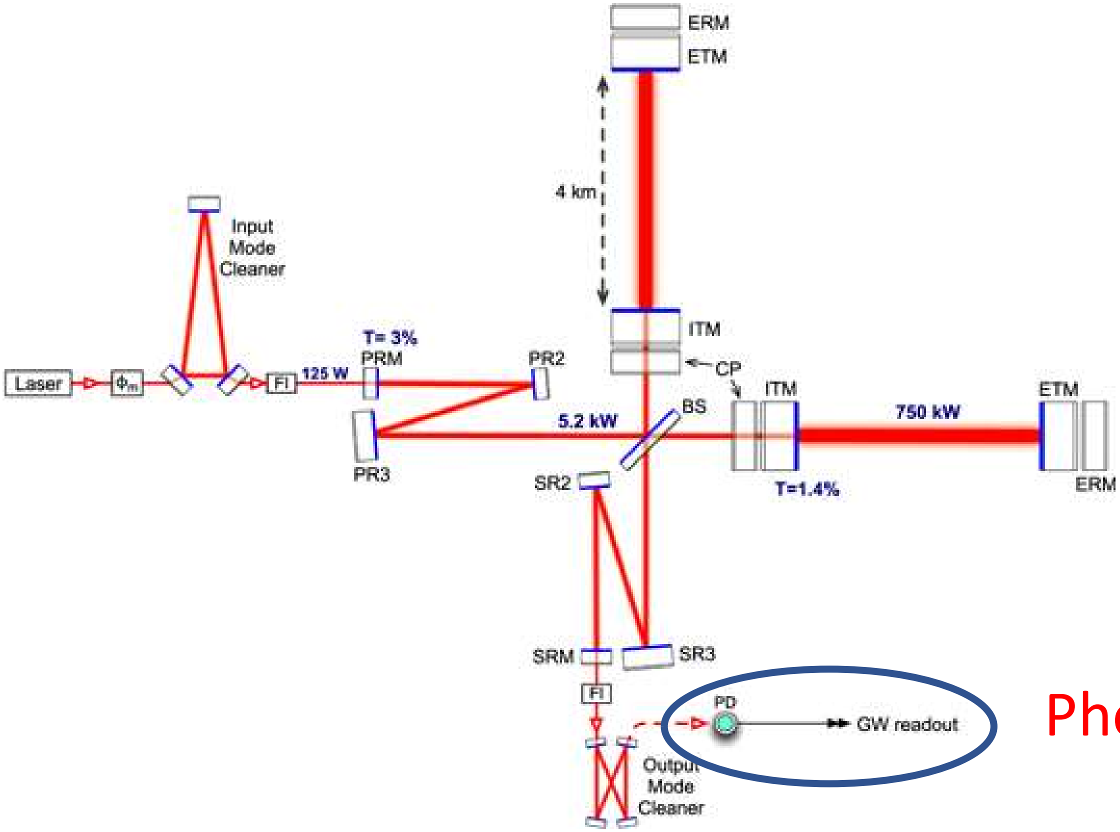


Number of observed photon is proportional to intensity of electric field

Double slit interference

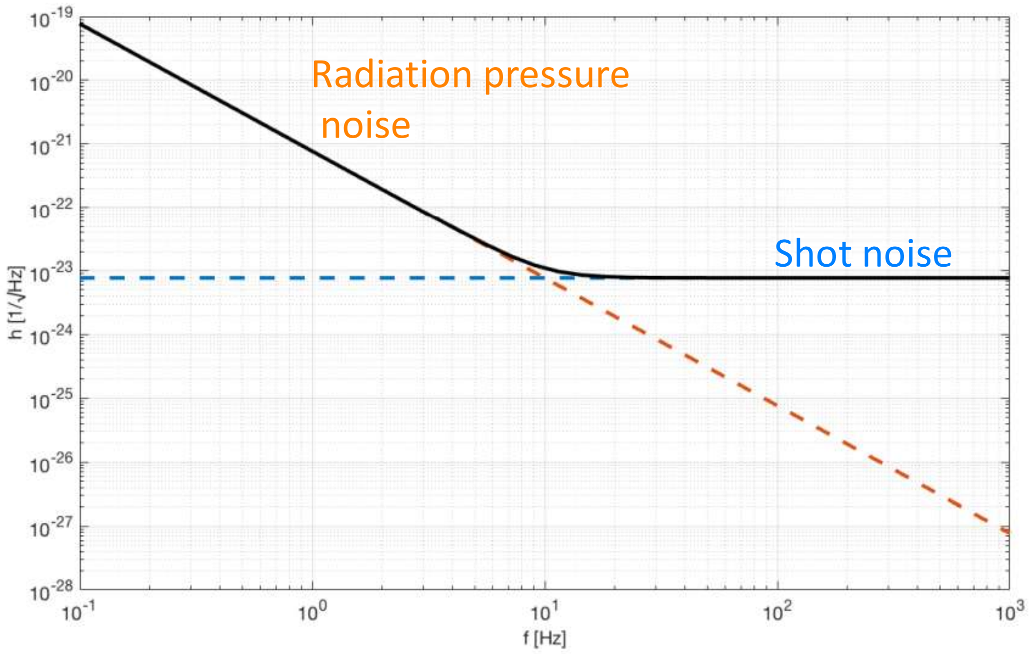


Gravitational wave detector



Photon counting

Standard quantum limit of GW detector



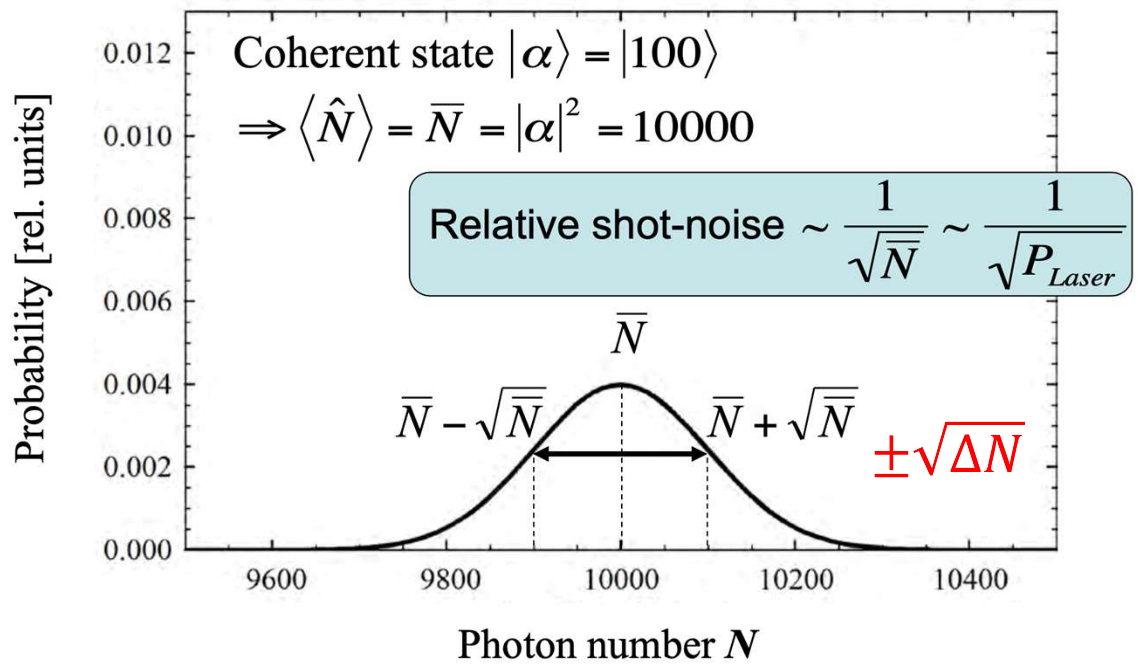
Standard quantum limit of gravitational wave detector
Shot noise + Radiation pressure noise

Shot noise

Shot noise of interferometer

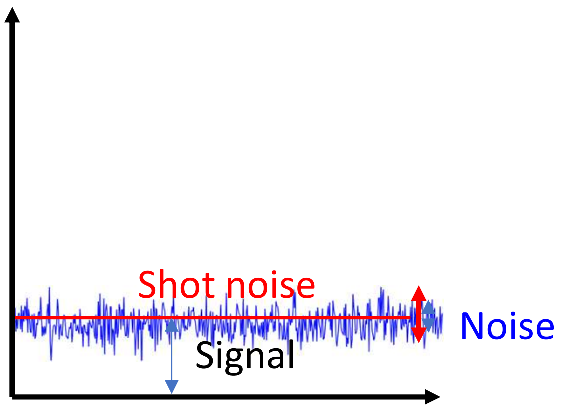
Photon Counting Statistics

h = 6.62607015×10^{-34} J·Hz^{-1}



Albert-Einstein-Institut | Leibniz Universität Hannover | Roman Schnabel, 17 / June/ 2013 | 4

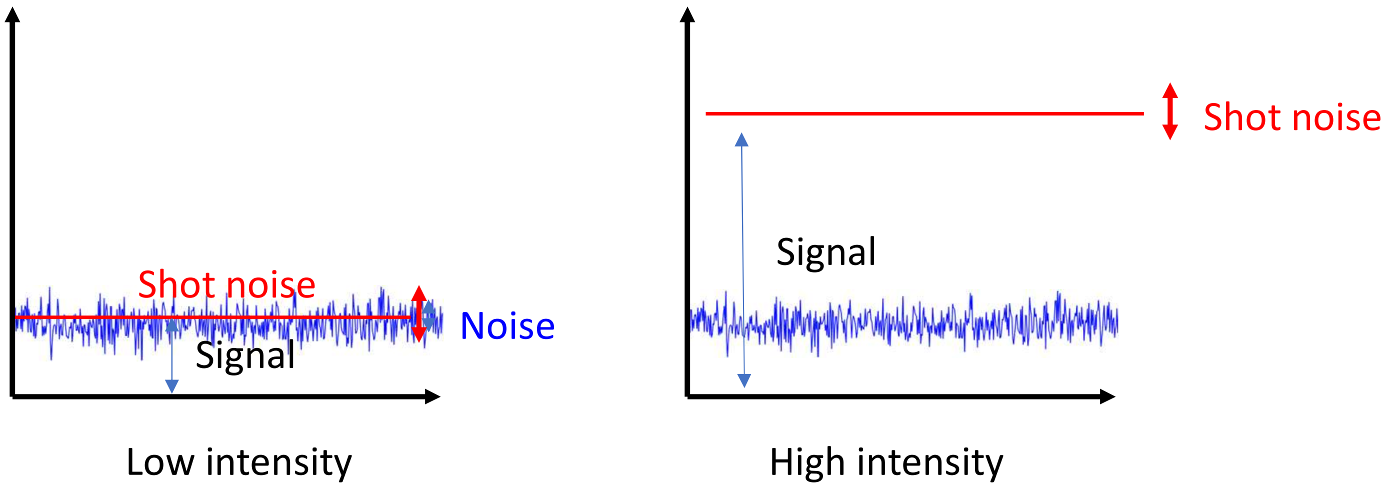
Shot noise of interferometer



Low intensity

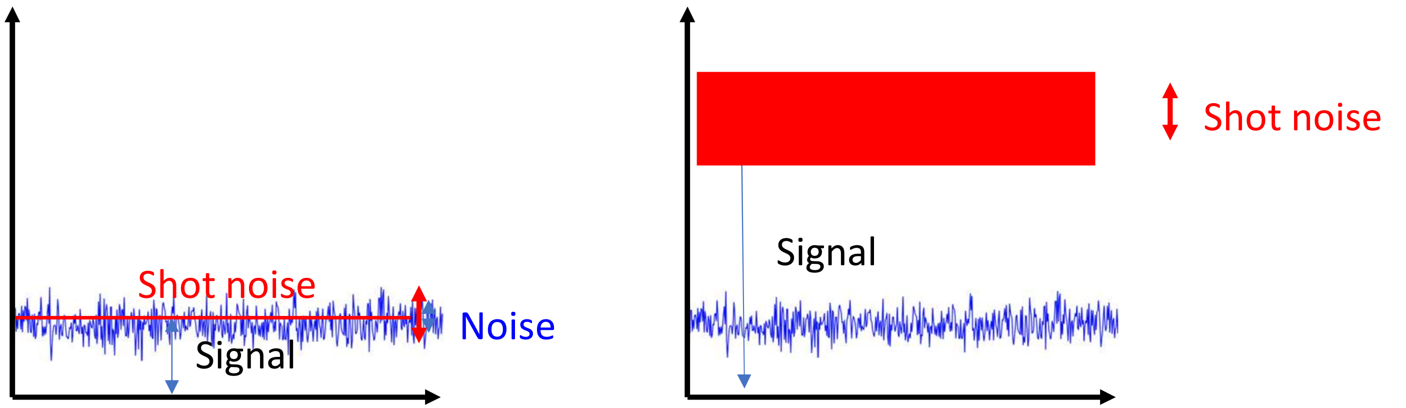
$$Signal\ to\ Noise\ ratio = \frac{N}{\sqrt{N}}$$

Shot noise of interferometer



$$Signal\ to\ Noise\ ratio = \frac{N}{\sqrt{N}}$$

Shot noise of interferometer



Low intensity

High intensity

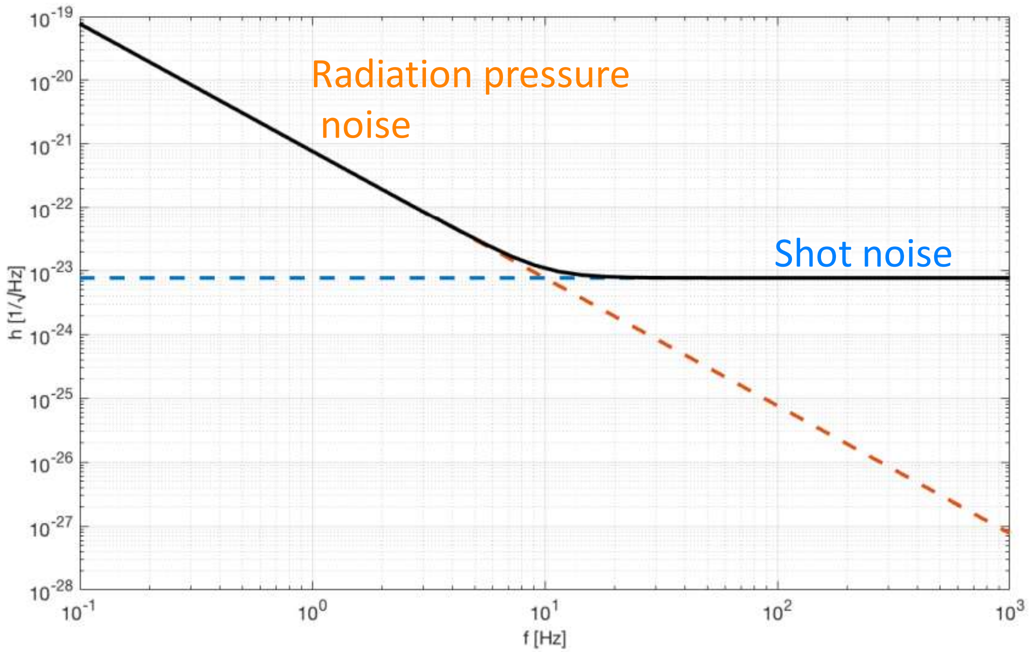
$$Signal\ to\ Noise\ ratio = \frac{N}{\sqrt{N}}$$

N=100 , SNR =10

N=10000 , SNR =100

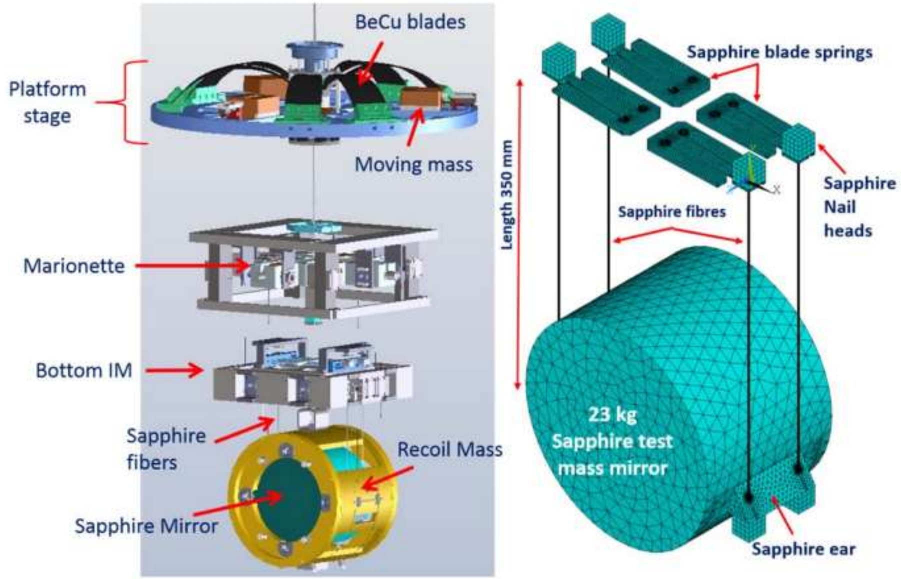
If Shot noise is relatively larger than other noise(Thermal, Electric.. etc)
We say that it has shot noise limit sensitivity

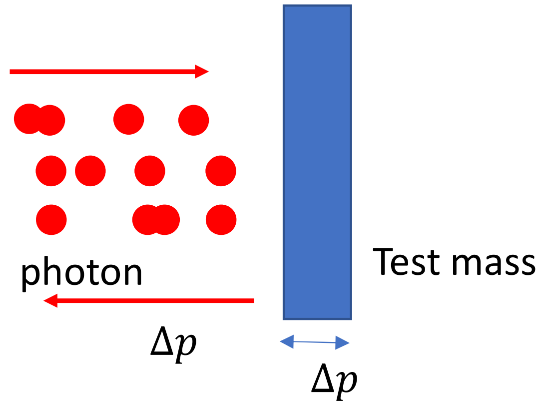
Standard quantum limit of GW detector



Standard quantum limit of gravitational wave detector
Shot noise + Radiation pressure noise

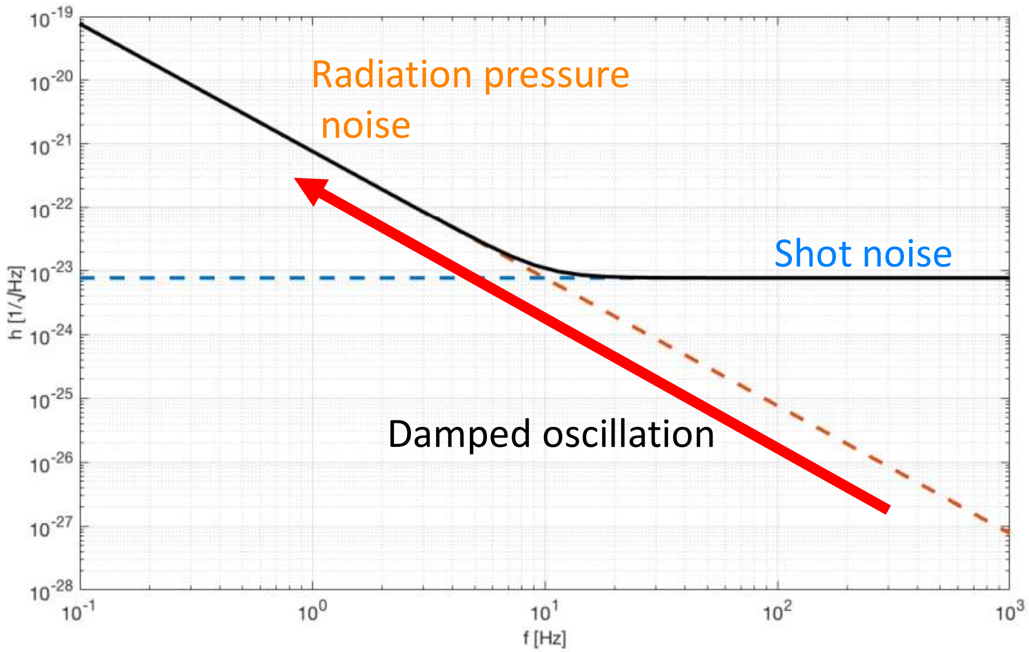
Radiation pressure noise





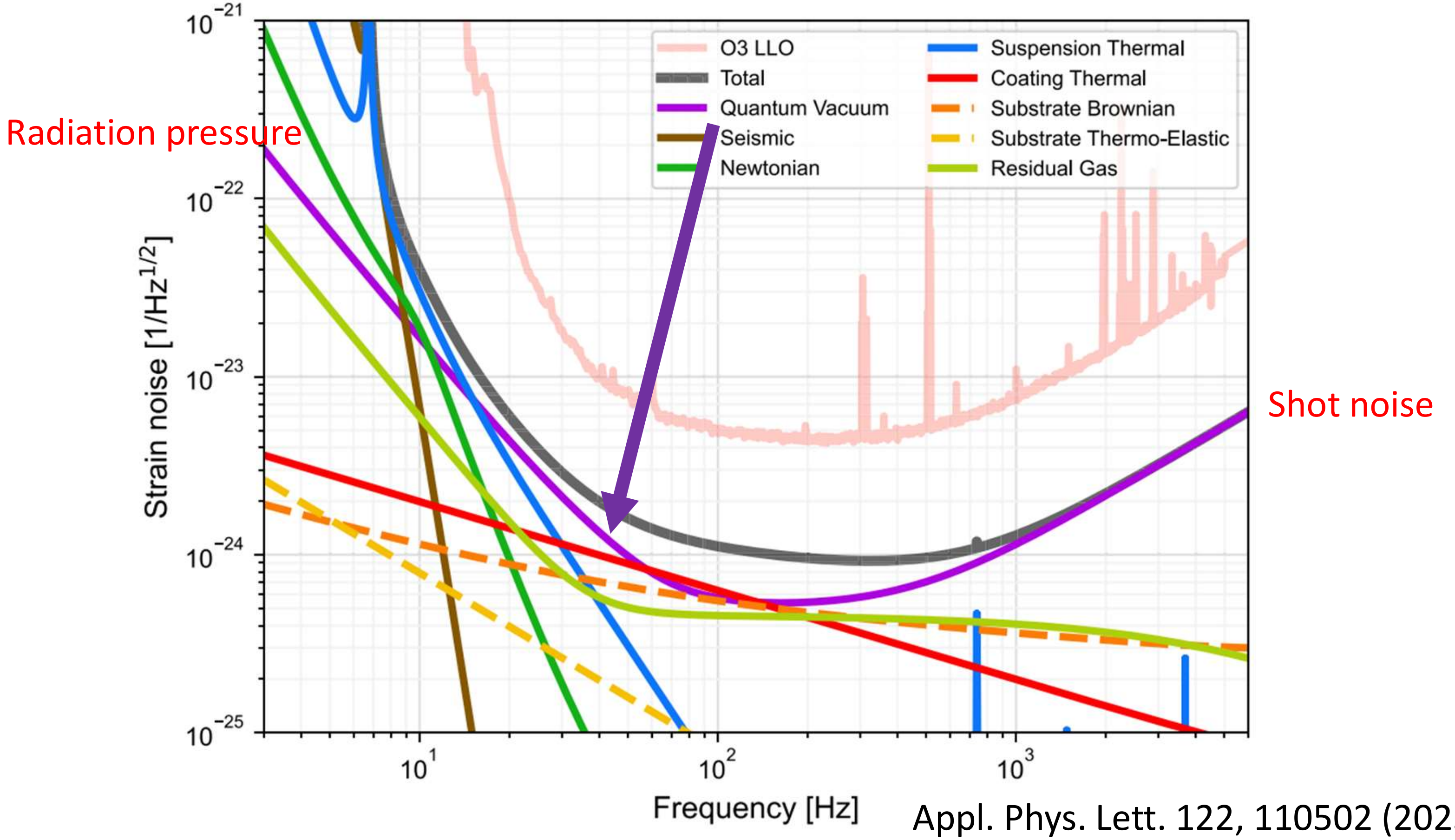
- Stored energy is very high (750 kW)
- Desired sensitivity is very high ($10^{-21} \sim 10^{-24}$)

Standard quantum limit of GW detector



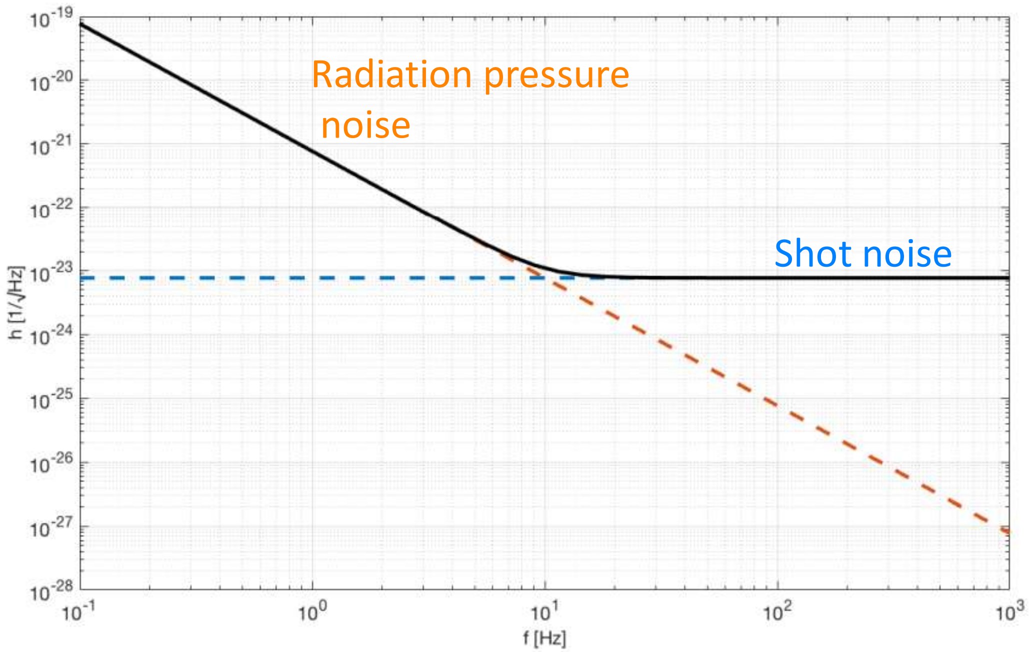
Standard quantum limit of gravitational wave detector
Shot noise + Radiation pressure noise

LIGO sensitivity



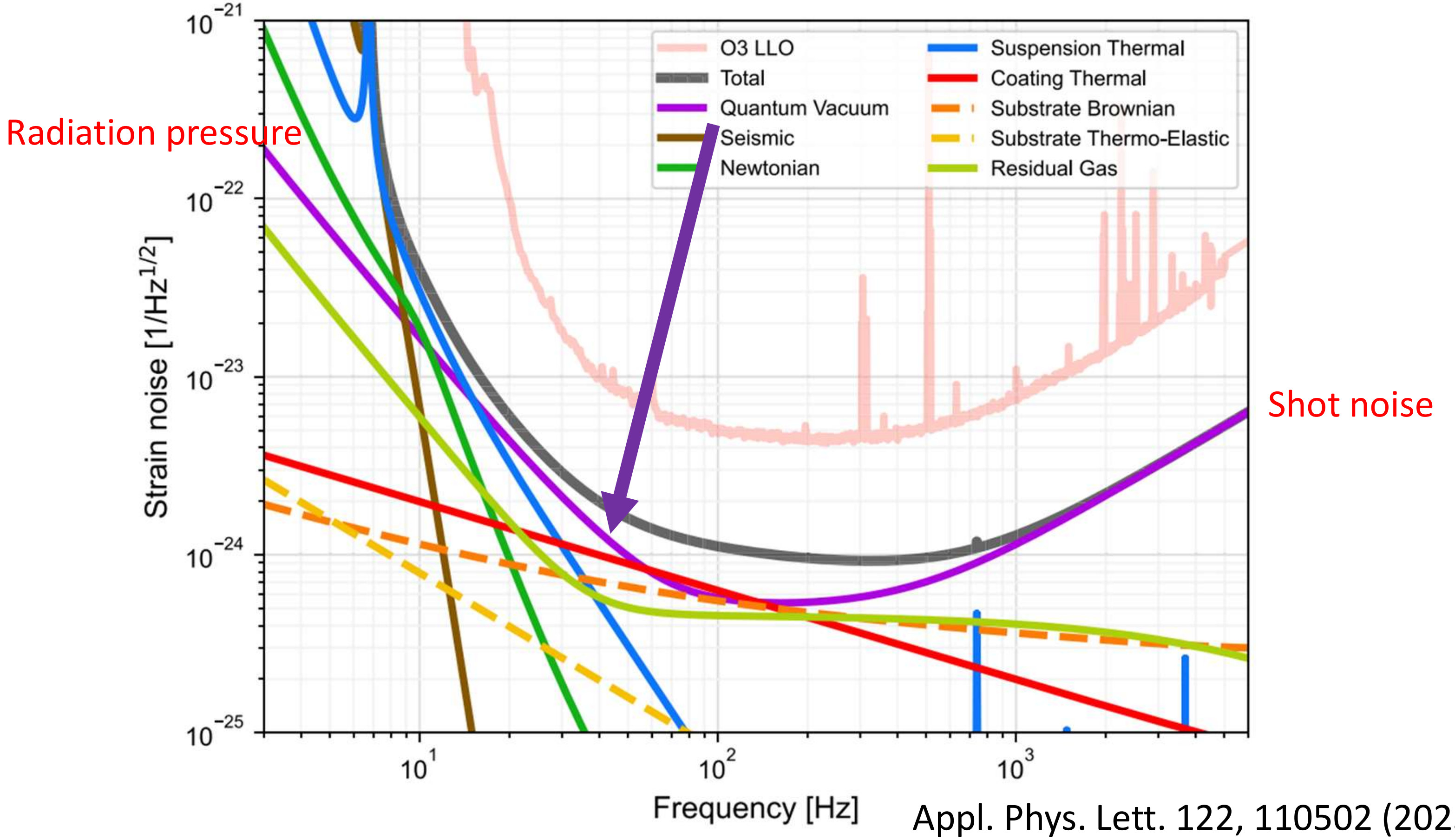
Appl. Phys. Lett. 122, 110502 (2023)

Standard quantum limit of GW detector



Standard quantum limit of gravitational wave detector
Shot noise + Radiation pressure noise

LIGO sensitivity



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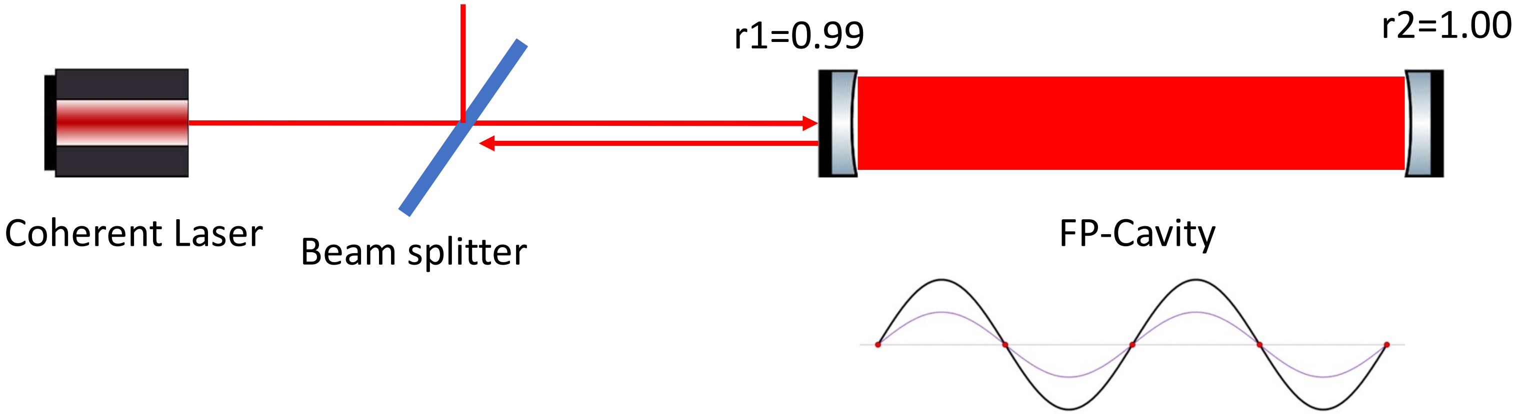
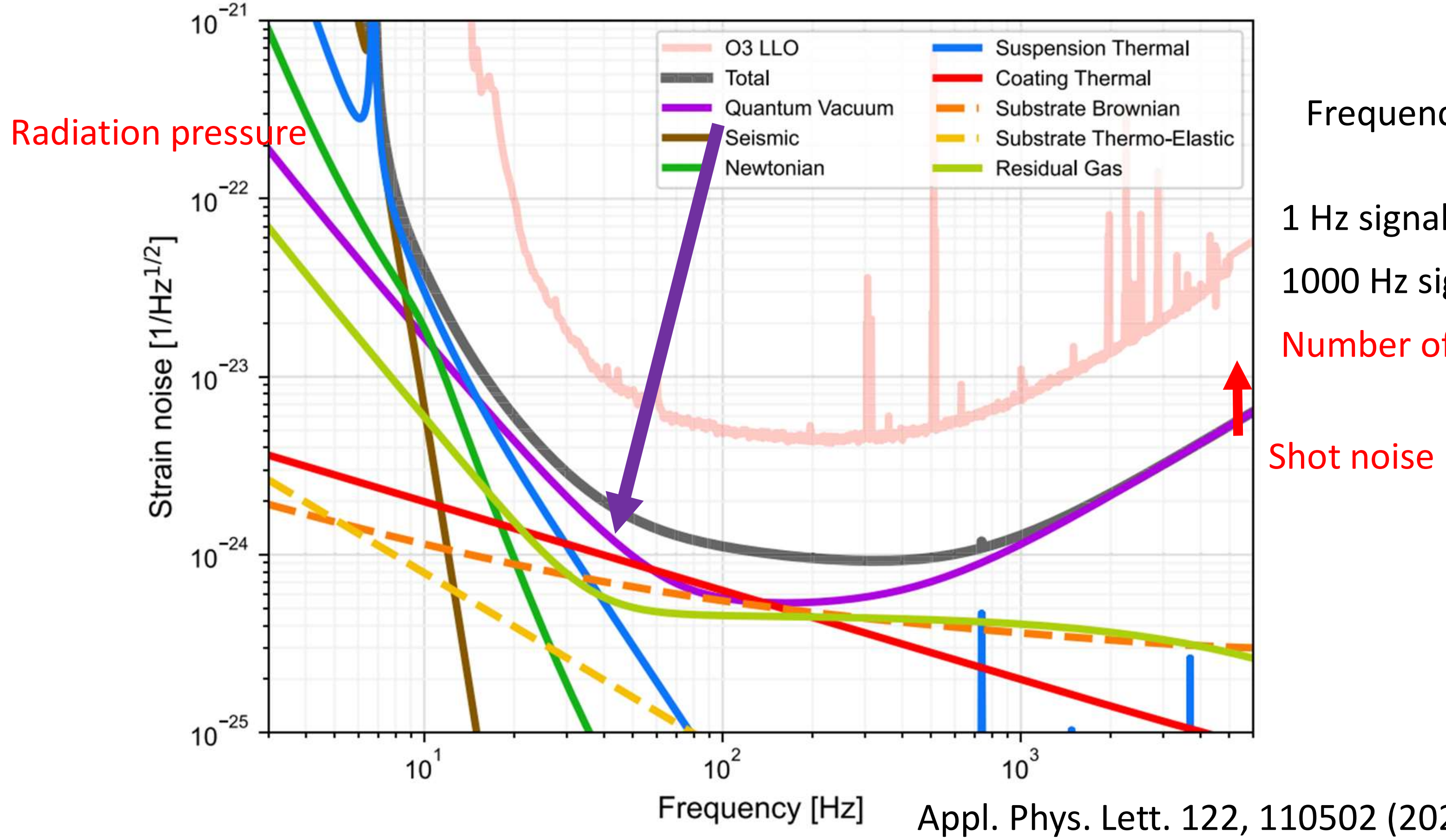
Fabry-perot cavity

Number of round trip > 250

4 km x 250 ~ 1000 km



LIGO sensitivity



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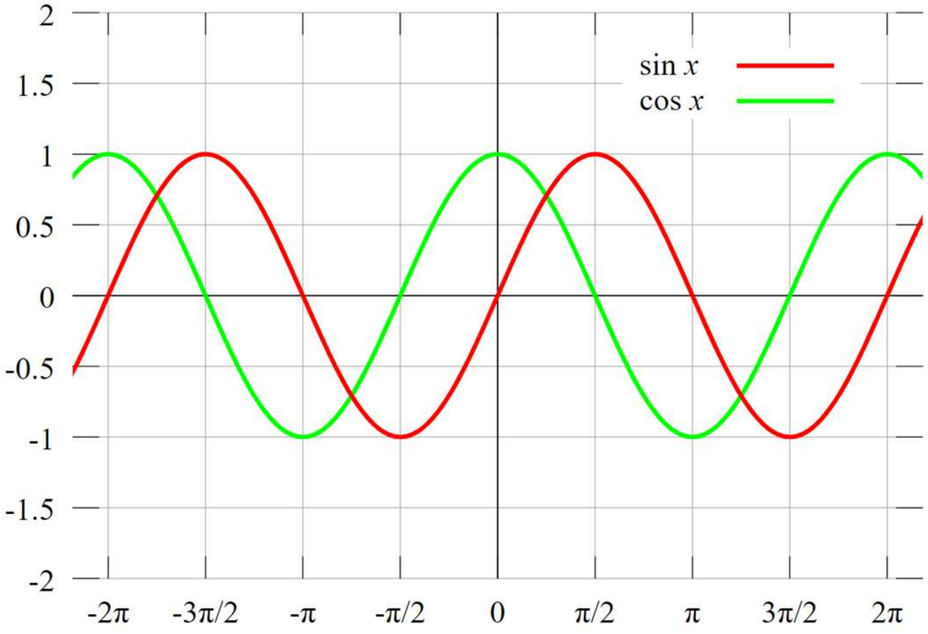
Frequency = 1/s (Hz)

1 Hz signal : 1 sec signal

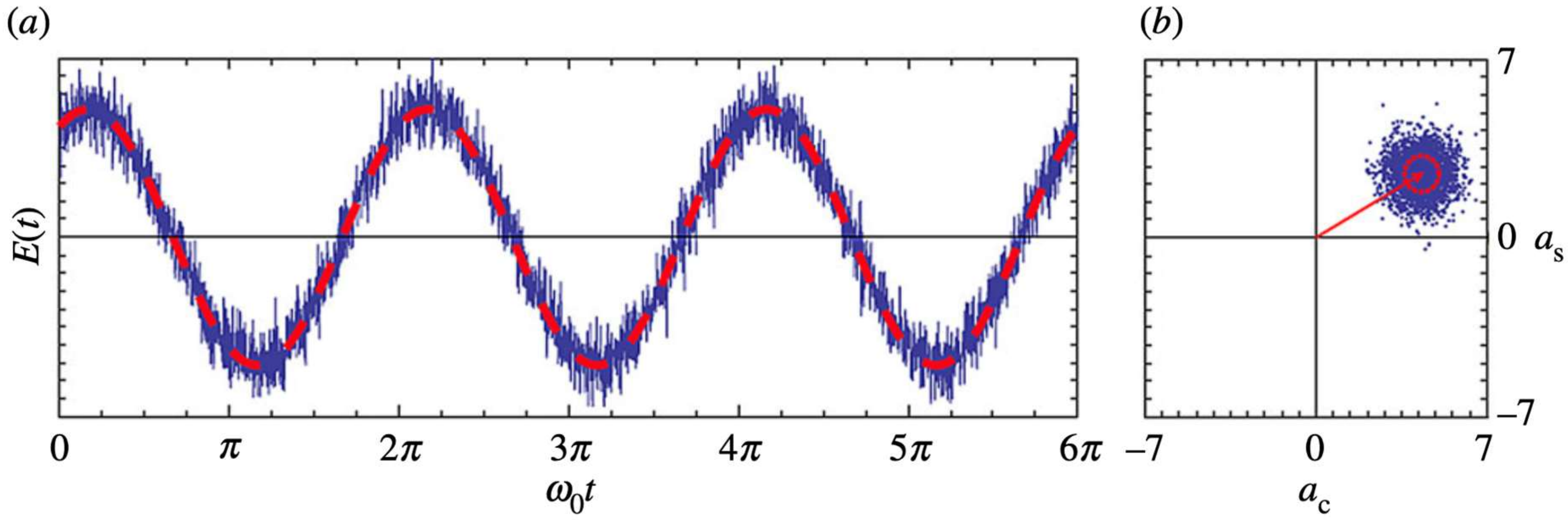
1000 Hz signal : 1/1000 sec signal

Number of round trip is different

Classical electromagnetic wave



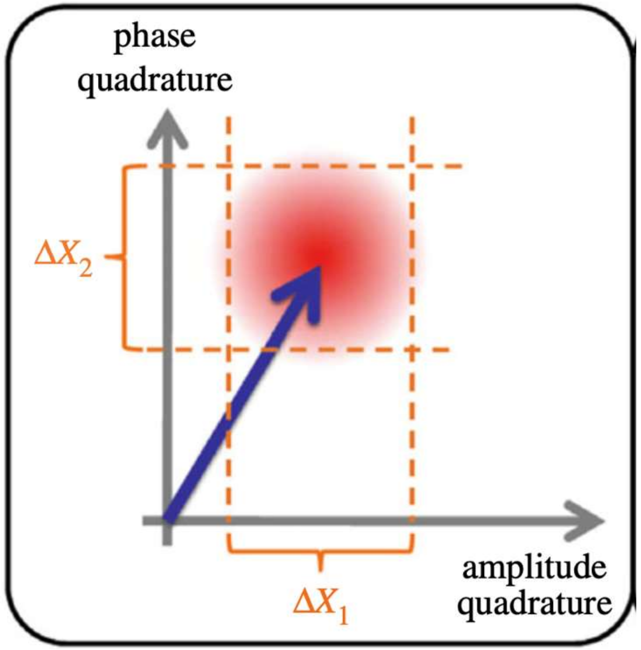
Quantum noise of coherent light



Heurs M. 2018 Gravitational wave detection using laser interferometry beyond the standard quantum limit.Phil. Trans. R. Soc. A 376: 20170289.

Phase and amplitude quadrature

(a) Shot noise



Radiation pressure noise

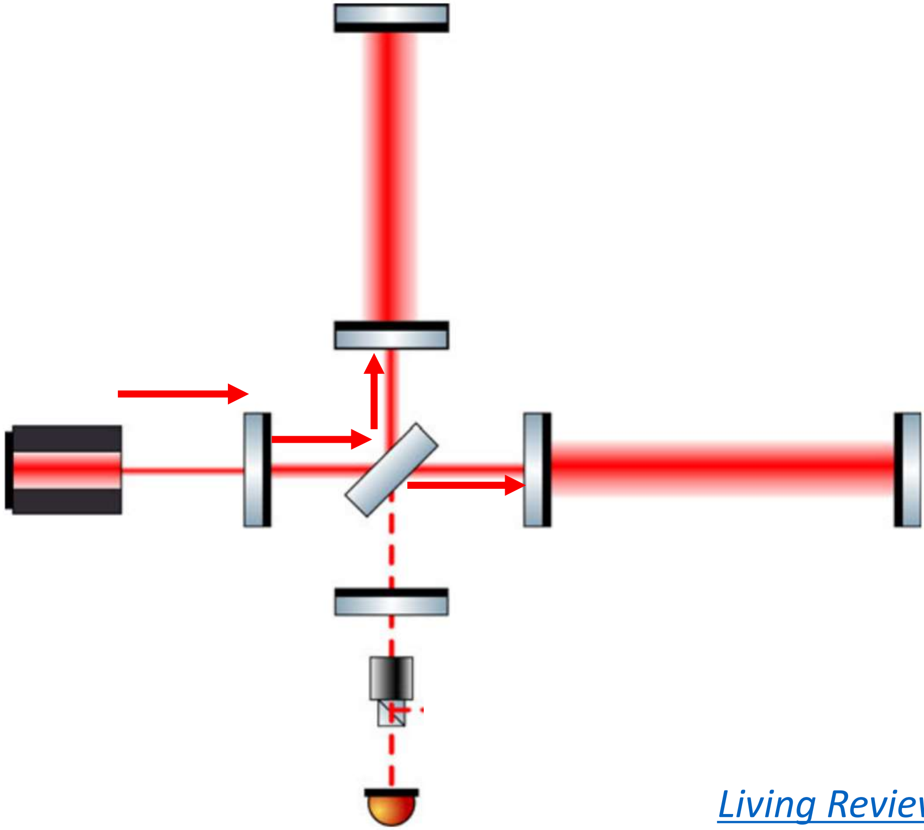
$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

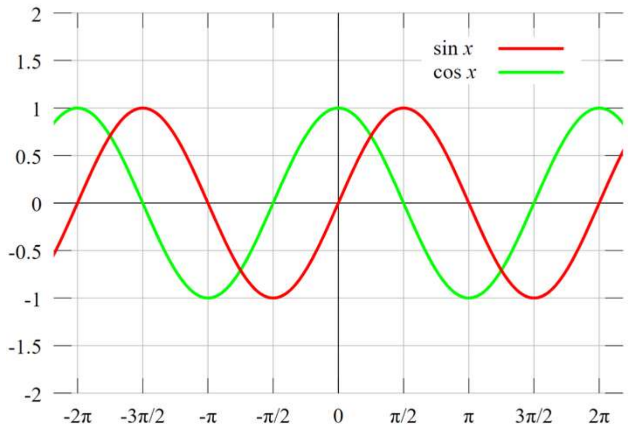
Uncertainty principle

Heurs M. 2018 Gravitational wave detection using laser interferometry beyond the standard quantum limit.Phil. Trans. R. Soc. A 376: 20170289.

2. Squeezed vacuum injection in gravitational wave detector

Gravitational wave detector





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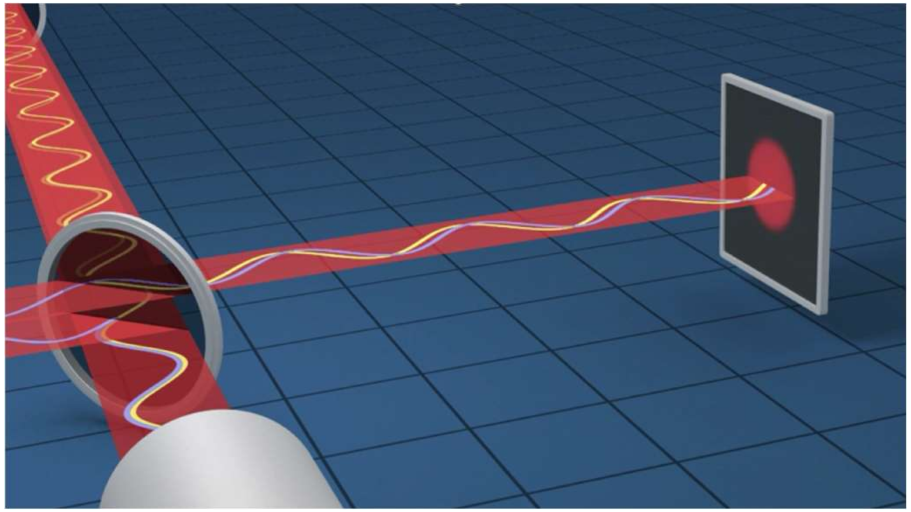
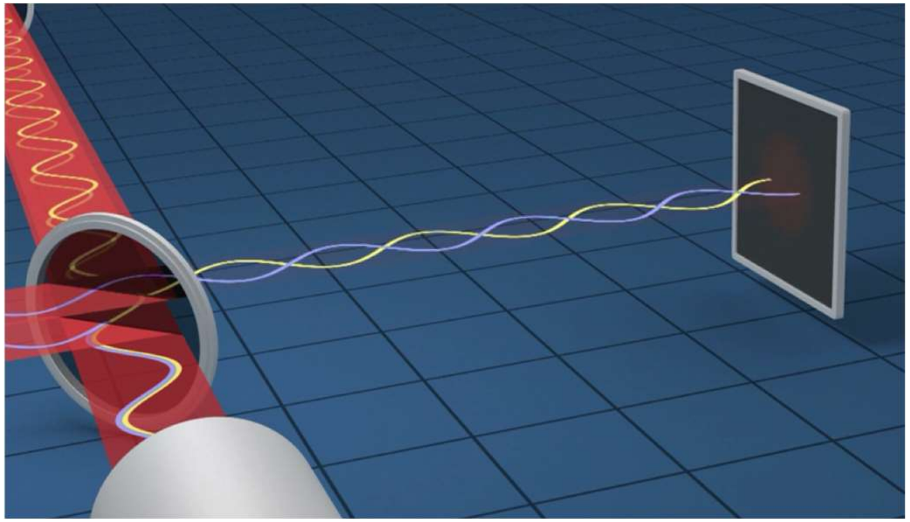
Article number: 2 (2019)

Bright port and dark port

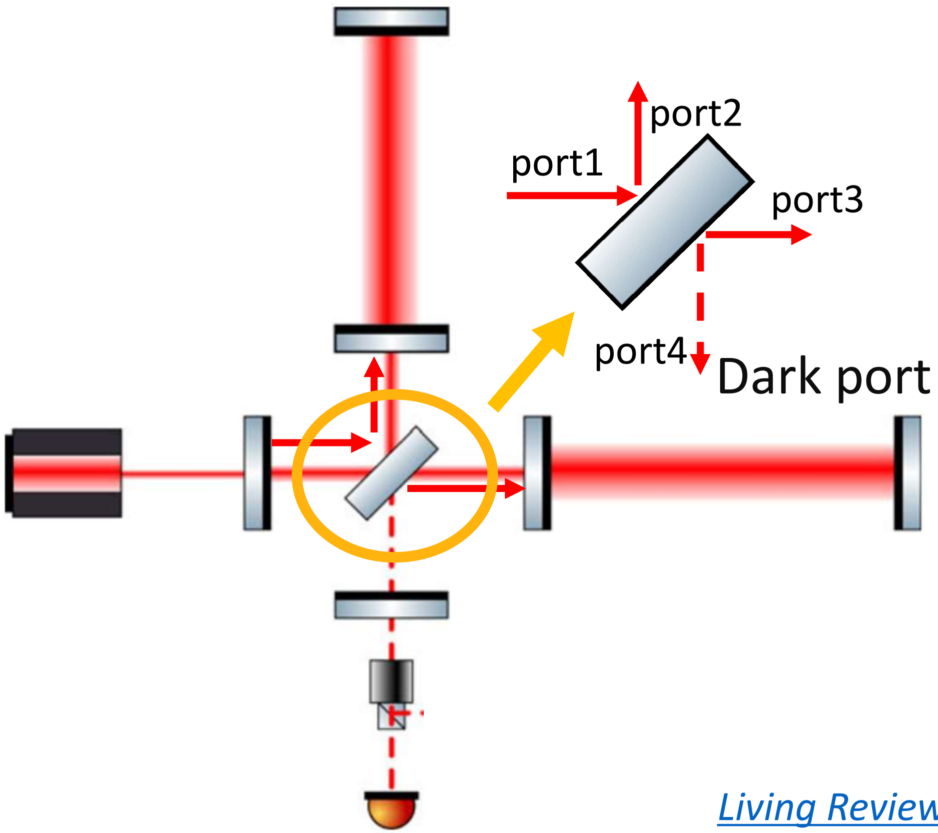


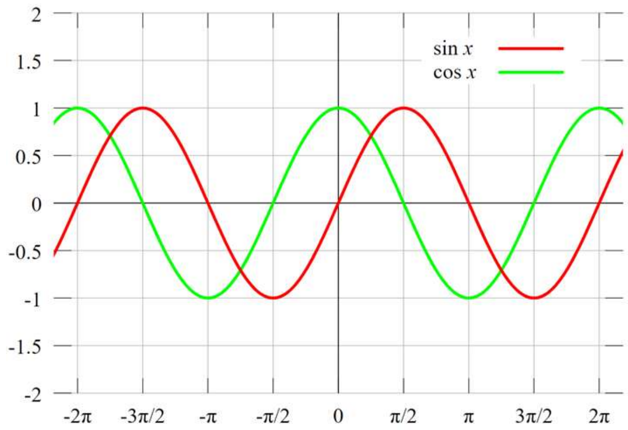
Bright



Dark

Gravitational wave detector





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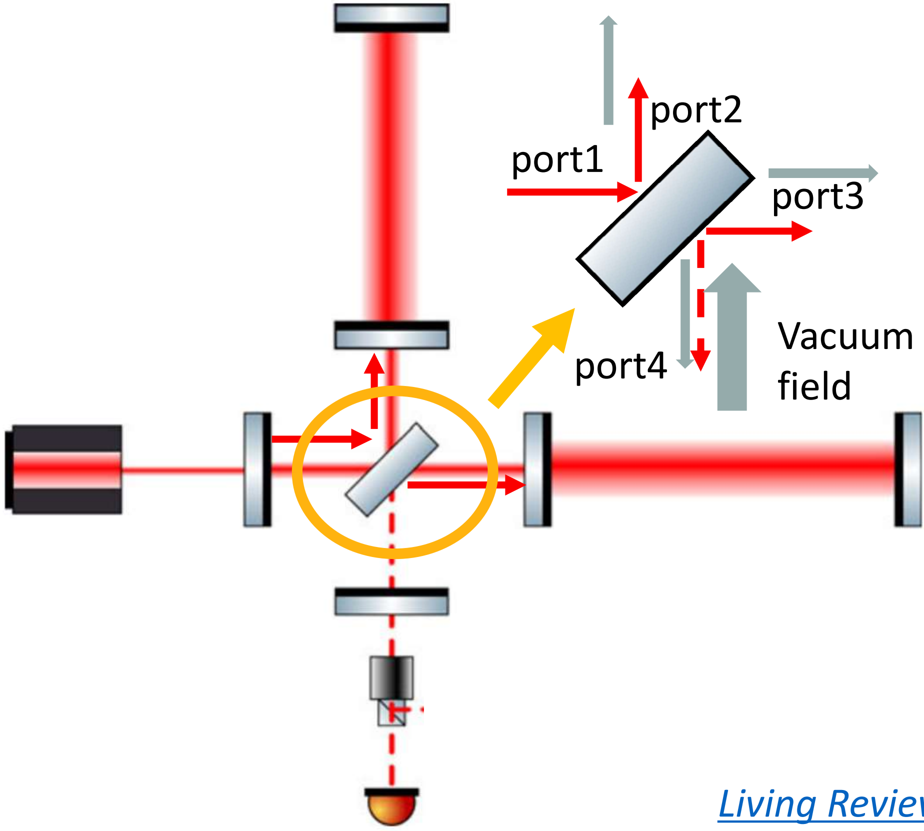
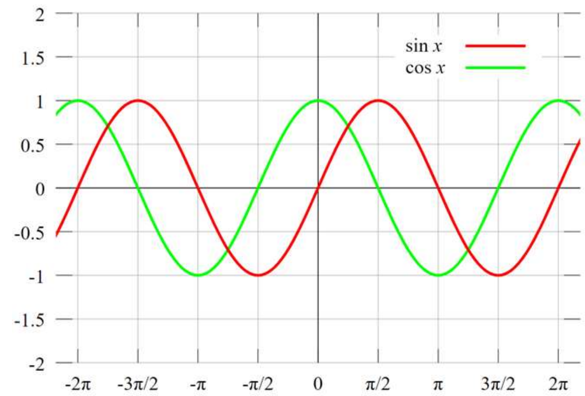
Quantum noise of gravitational wave detector





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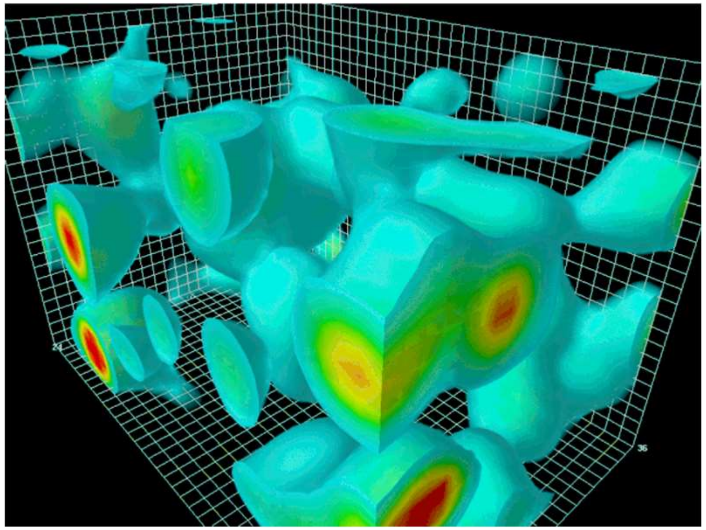
Quantum vacuum fluctuation

Vacuum ≠ empty

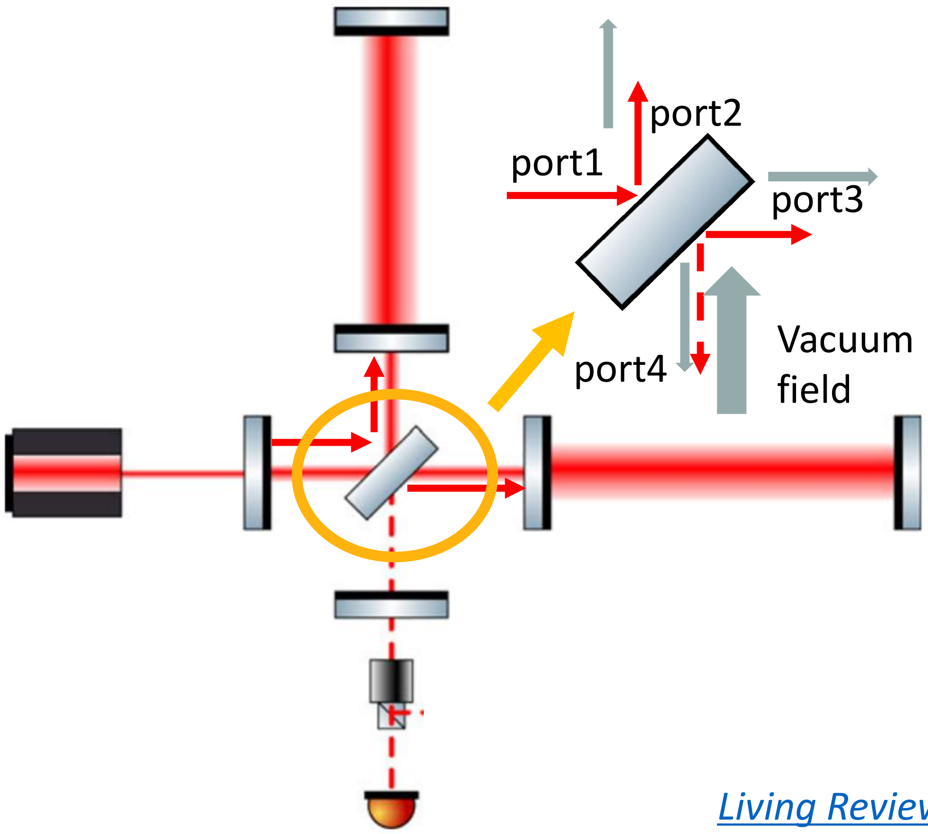
Vacuum

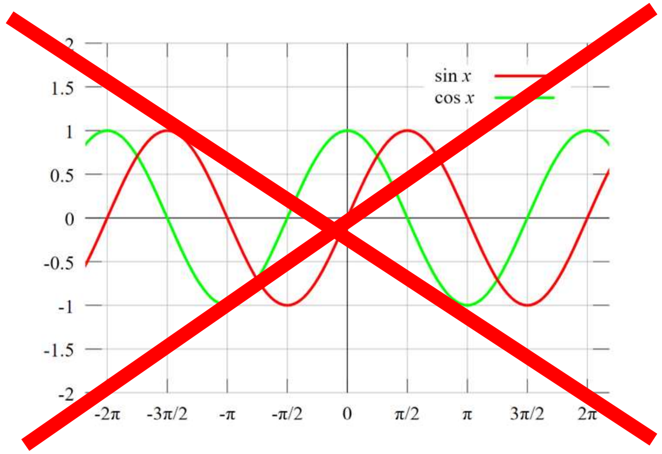
Transmission medium

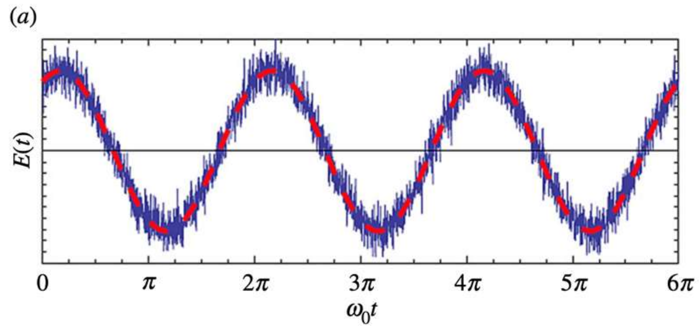


Average energy = zeropoint energy

Quantum noise of gravitational wave detector







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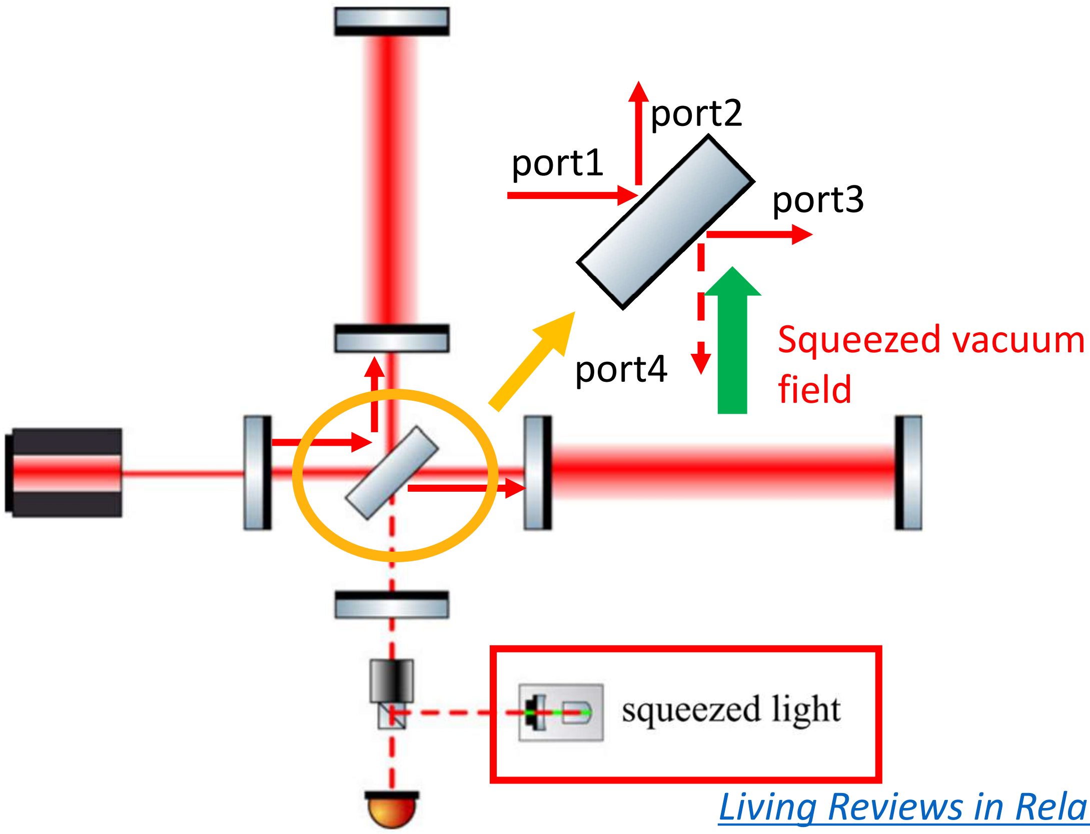
Gravitational wave detector



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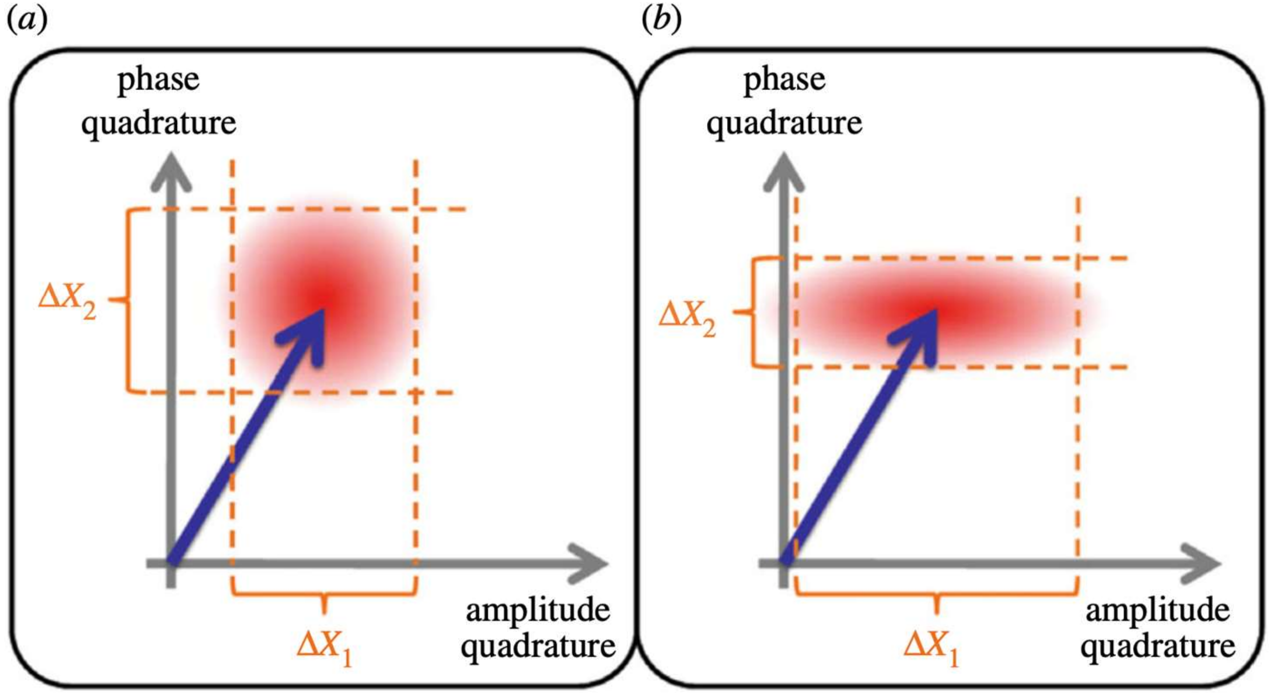
Squeezed light



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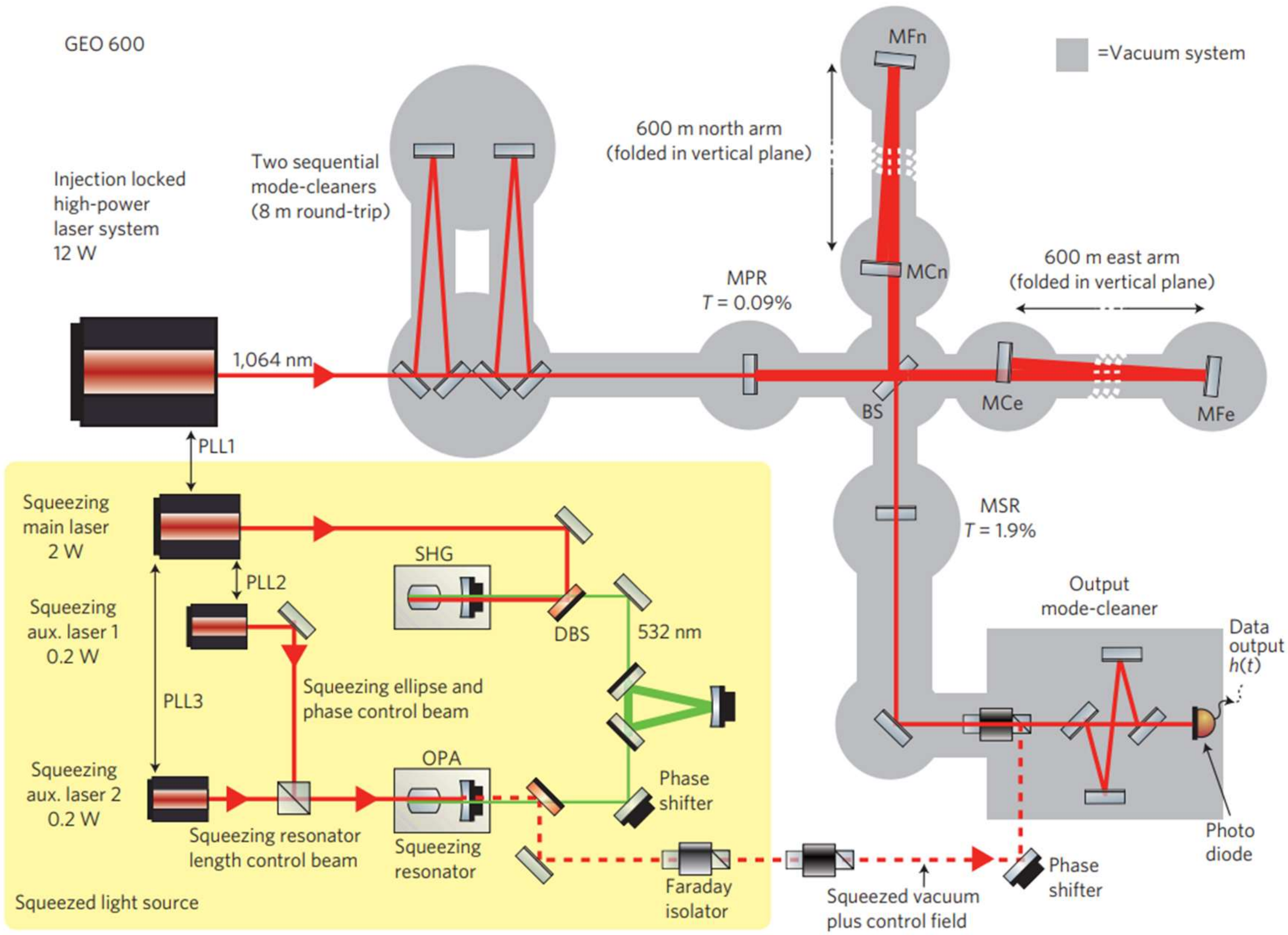
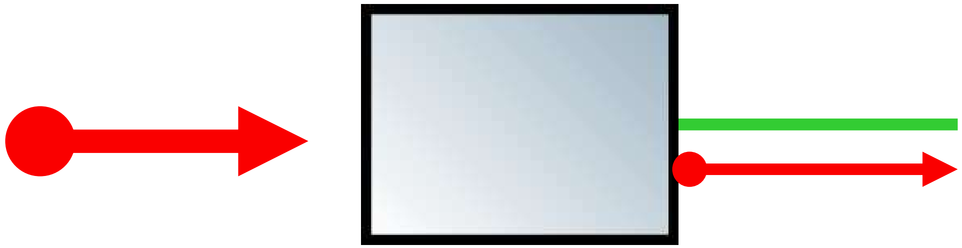
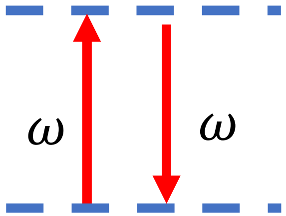

GEO 600
=Vacuum system
MFn
600 m north arm
(folded in vertical plane)
Injection locked
high-power
laser system
12 W
Two sequential
mode-cleaners
(8 m round-trip)
MCn
600 m east arm
(folded in vertical plane)
MPR
T = 0.09%
1,064 nm
BS
MCe
MFe
PLL1
Squeezing
main laser
2 W
MSR
T = 1.9%
SHG
PLL2
Output
mode-cleaner
Squeezing
aux. laser 1
0.2 W
DBS
532 nm
Data
output
h(t)
Squeezing ellipse and
phase control beam
PLL3
Squeezing
aux. laser 2
0.2 W
OPA
Phase
shifter
Squeezing resonator
length control beam
Squeezing
resonator
Photo
diode
Phase
shifter
Faraday
isolator
Squeezed vacuum
plus control field
Squeezed light source

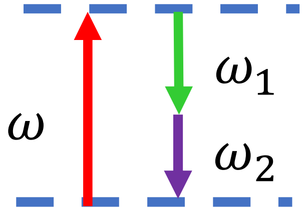
Non linear crystal



Non-linear crystal

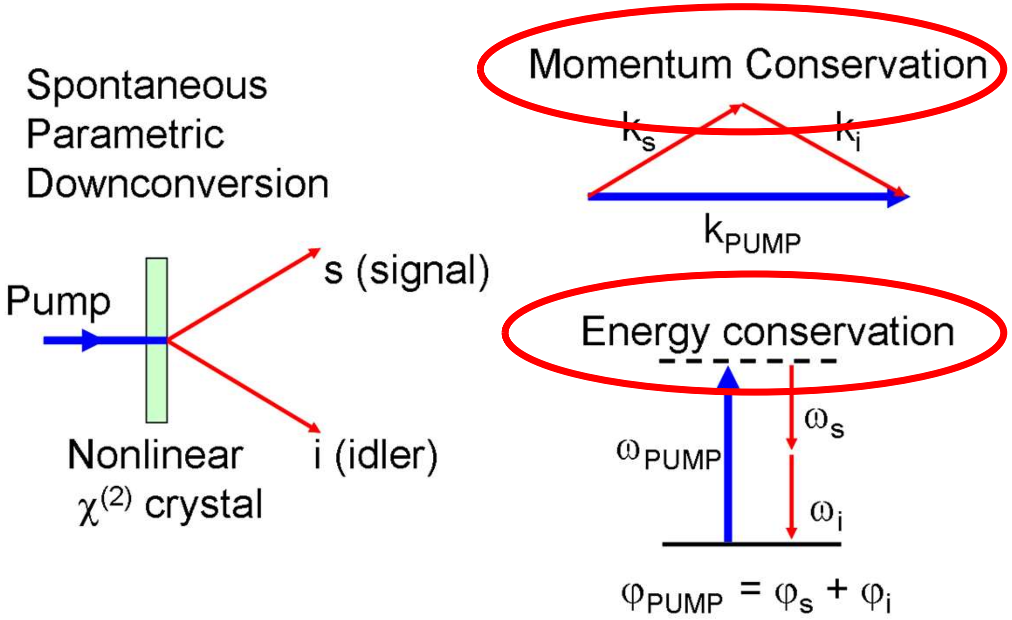


linear optics



Non linear optics

Parametric down conversion

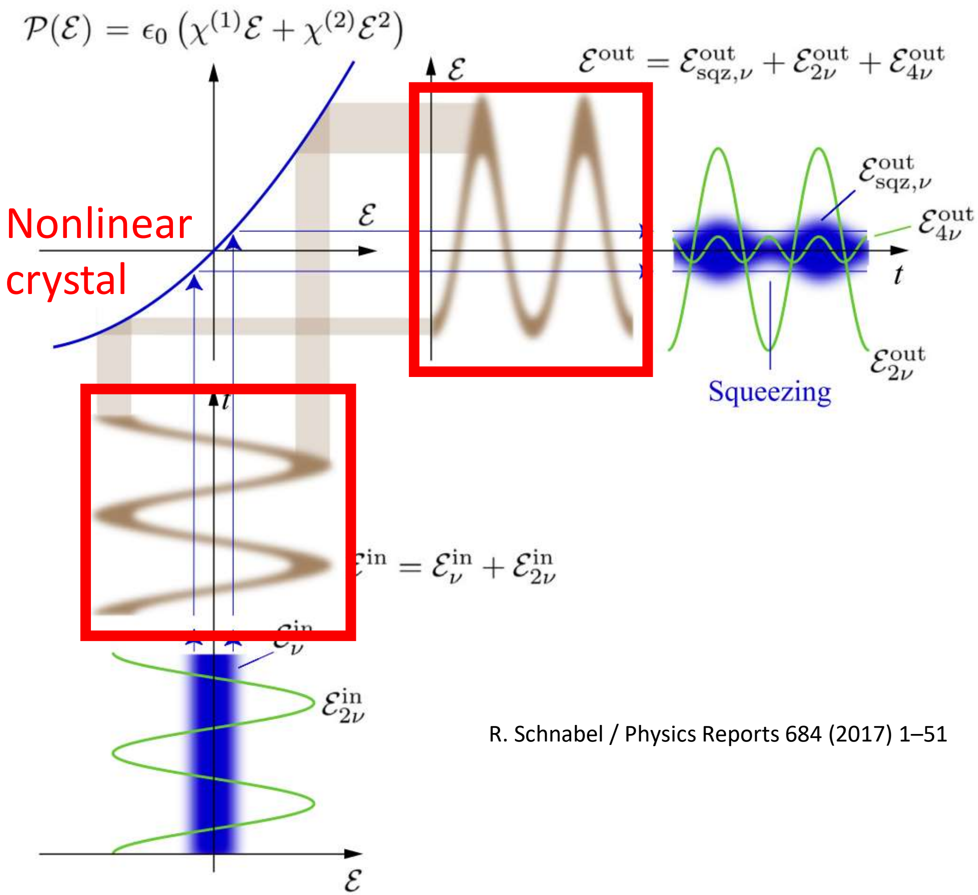


Every filed which are participated in
Non-linear conversion process,
Must obey energy, momentum conservation.

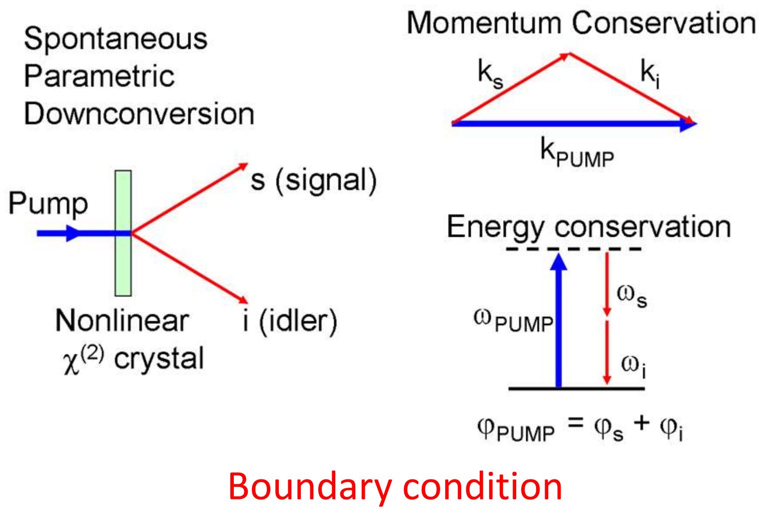
Even for vacuum field!!

J S Lundeen

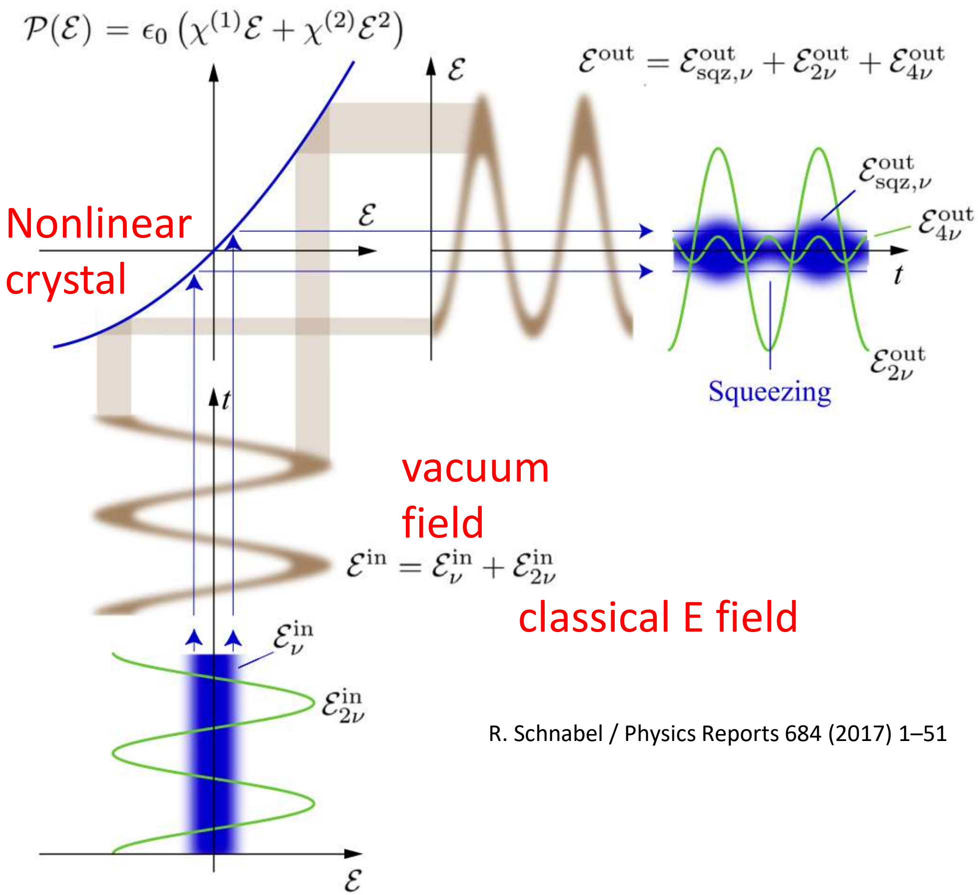
Parametric down conversion



R. Schnabel / Physics Reports 684 (2017) 1–51



Parametric down conversion



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State of vacuum is changed during conversion process
due to momentum and energy conservation

Squeezed vacuum

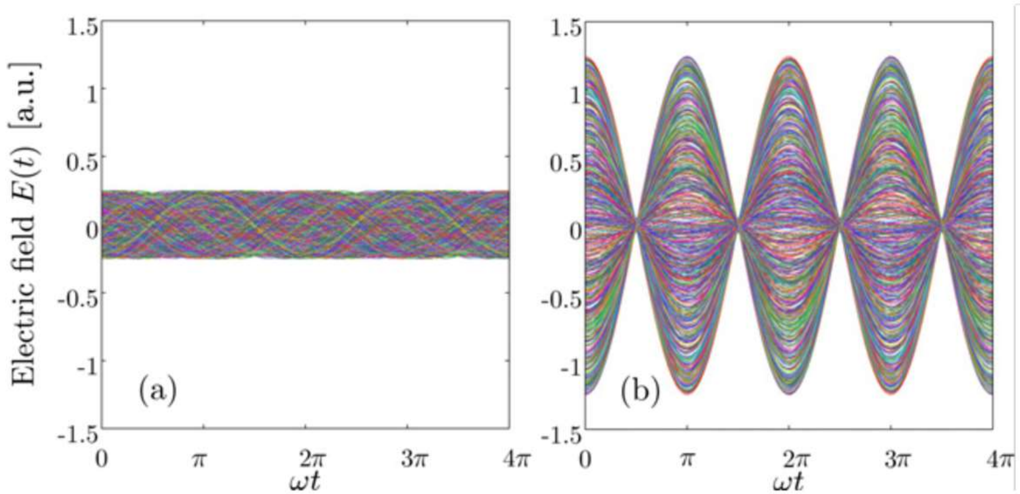
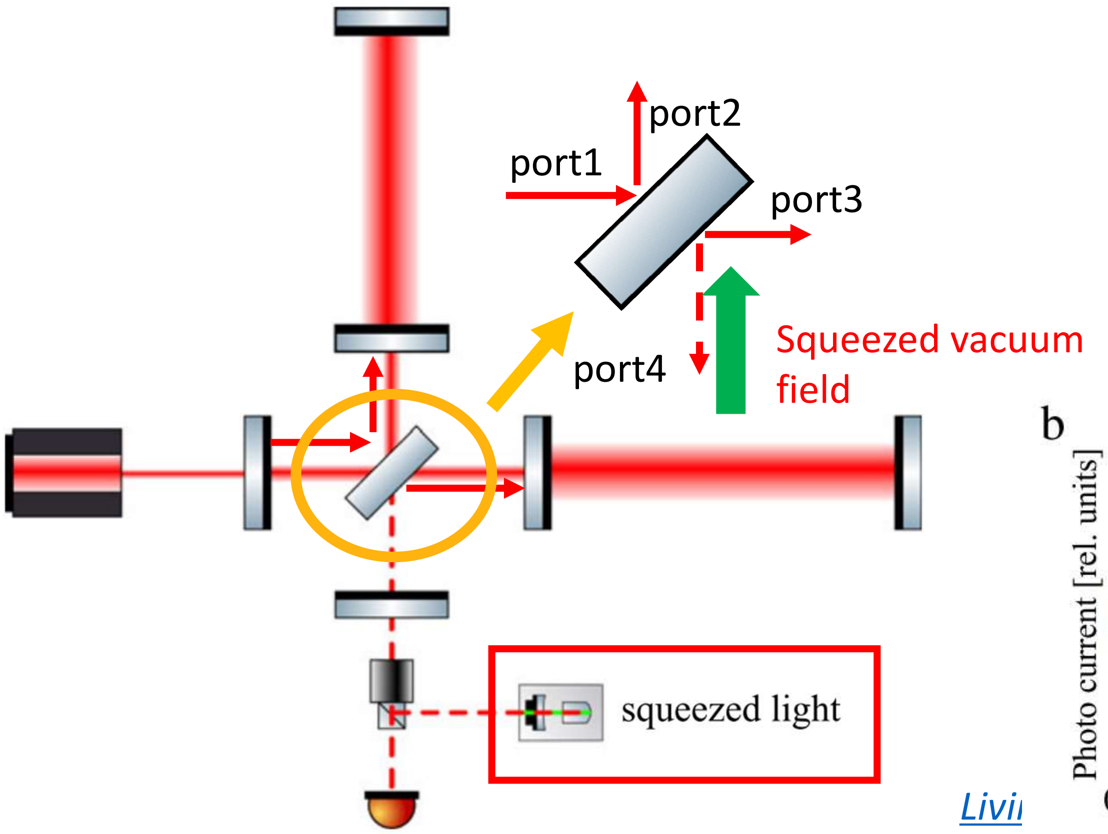
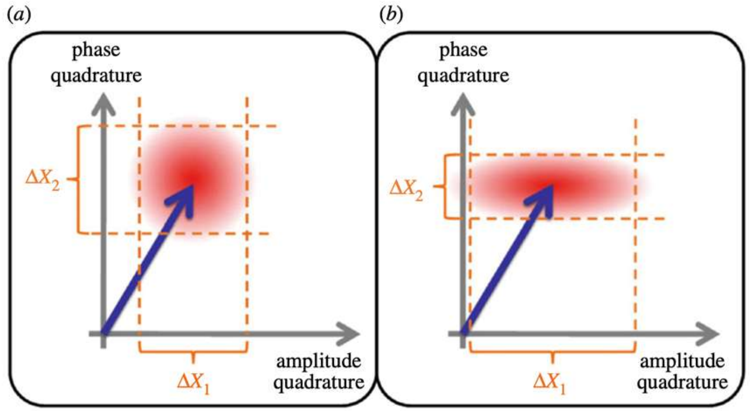
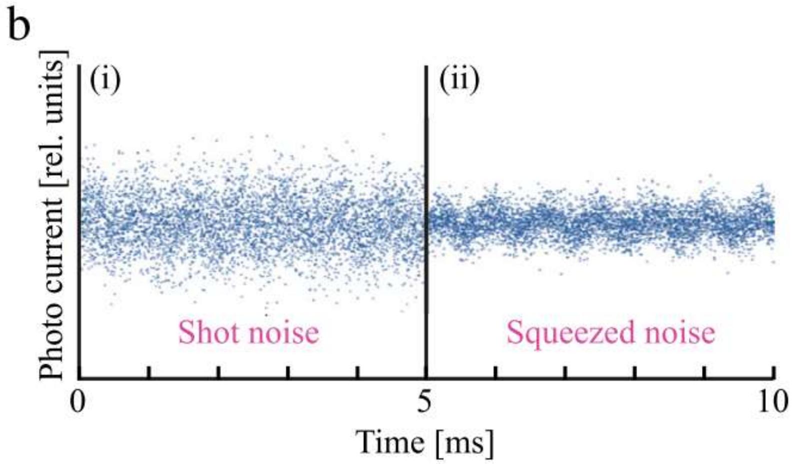


Figure 1.6: Simulation of electric field in time for (a) vacuum state and for (b) squeezed vacuum.

Gravitational wave detector

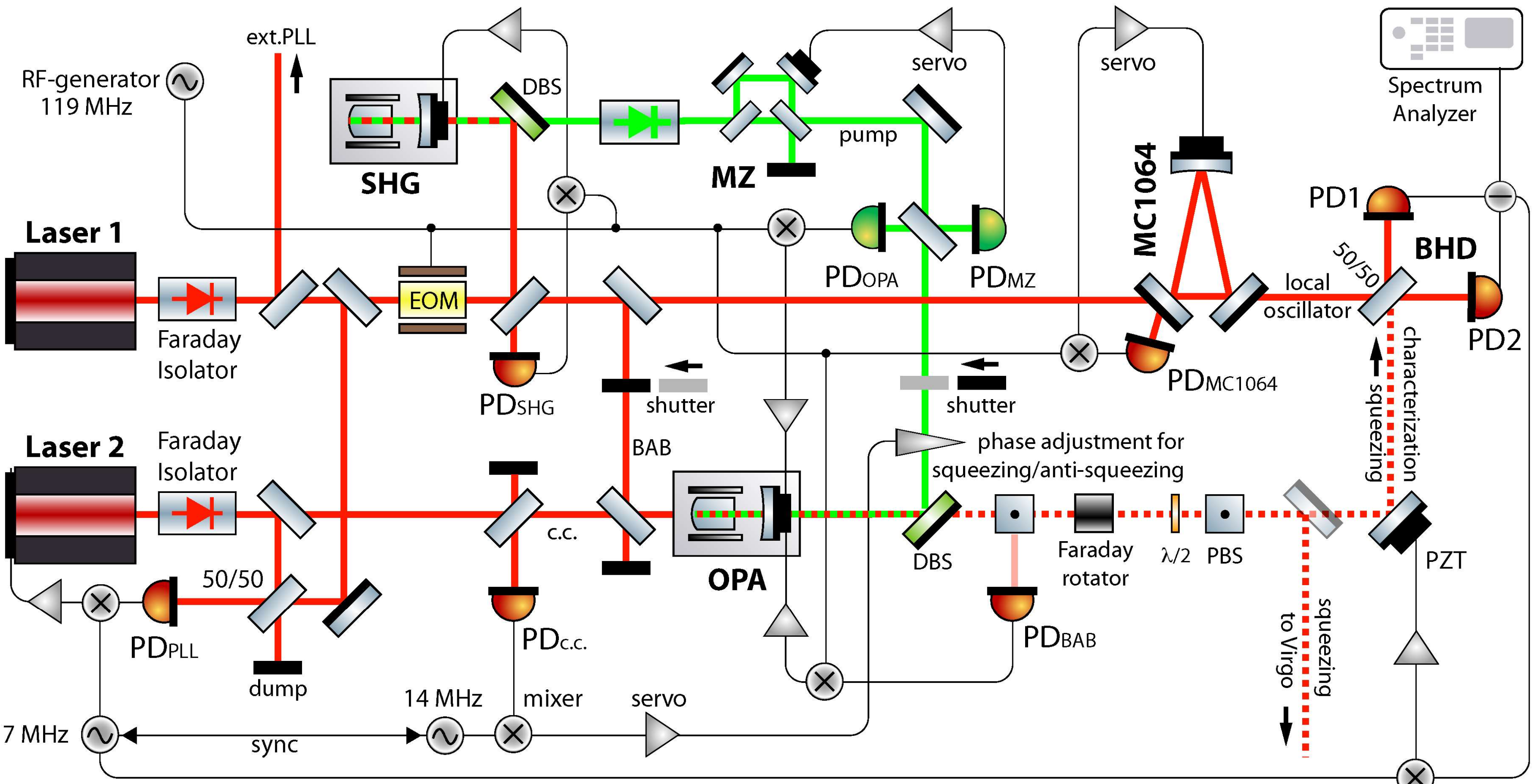


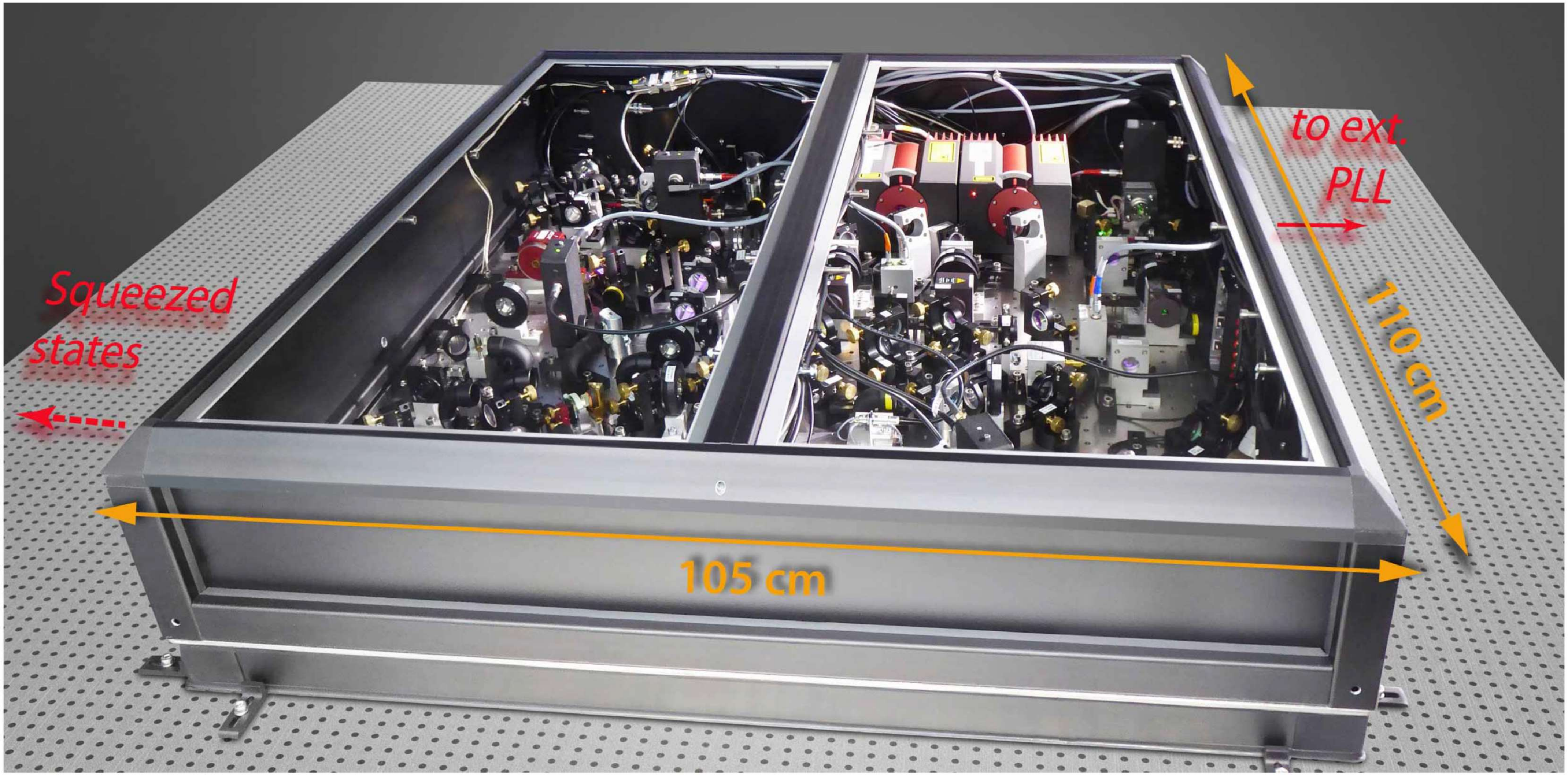




Livi

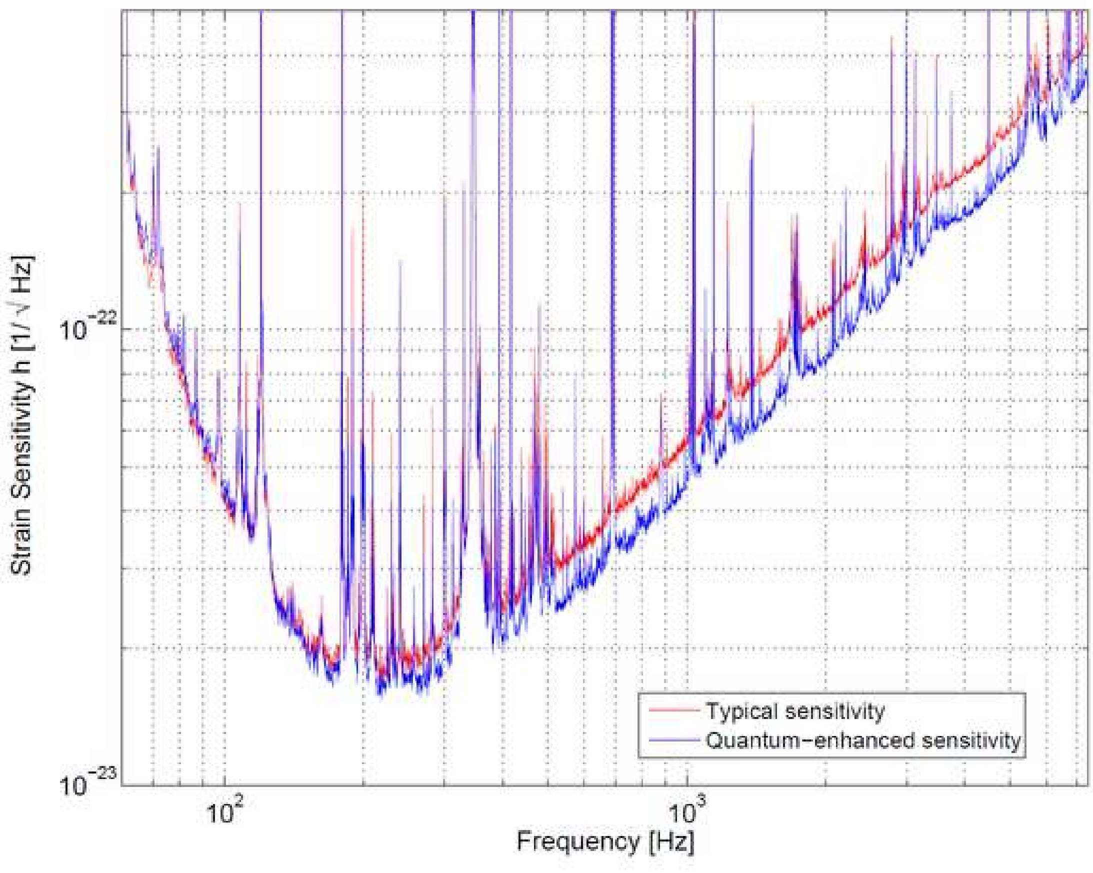
Arti


ext.PLL
RF-generator 119 MHz
SHG
DBS
MZ
servo
pump
servo
Spectrum Analyzer
MC1064
PD1
BHD
50/50
Laser 1
Faraday Isolator
EOM
PDOPA
PDMZ
local oscillator
PD2
PDSHG
shutter
shutter
PDMC1064
squeezing
characterization
Laser 2
Faraday Isolator
BAB
phase adjustment for squeezing/anti-squeezing
c.c.
OPA
DBS
Faraday rotator
λ/2
PBS
PZT
50/50
PDPLL
dump
PDc.c.
PDBAB
to Virgo
squeezing
14 MHz
mixer
servo
7 MHz
sync

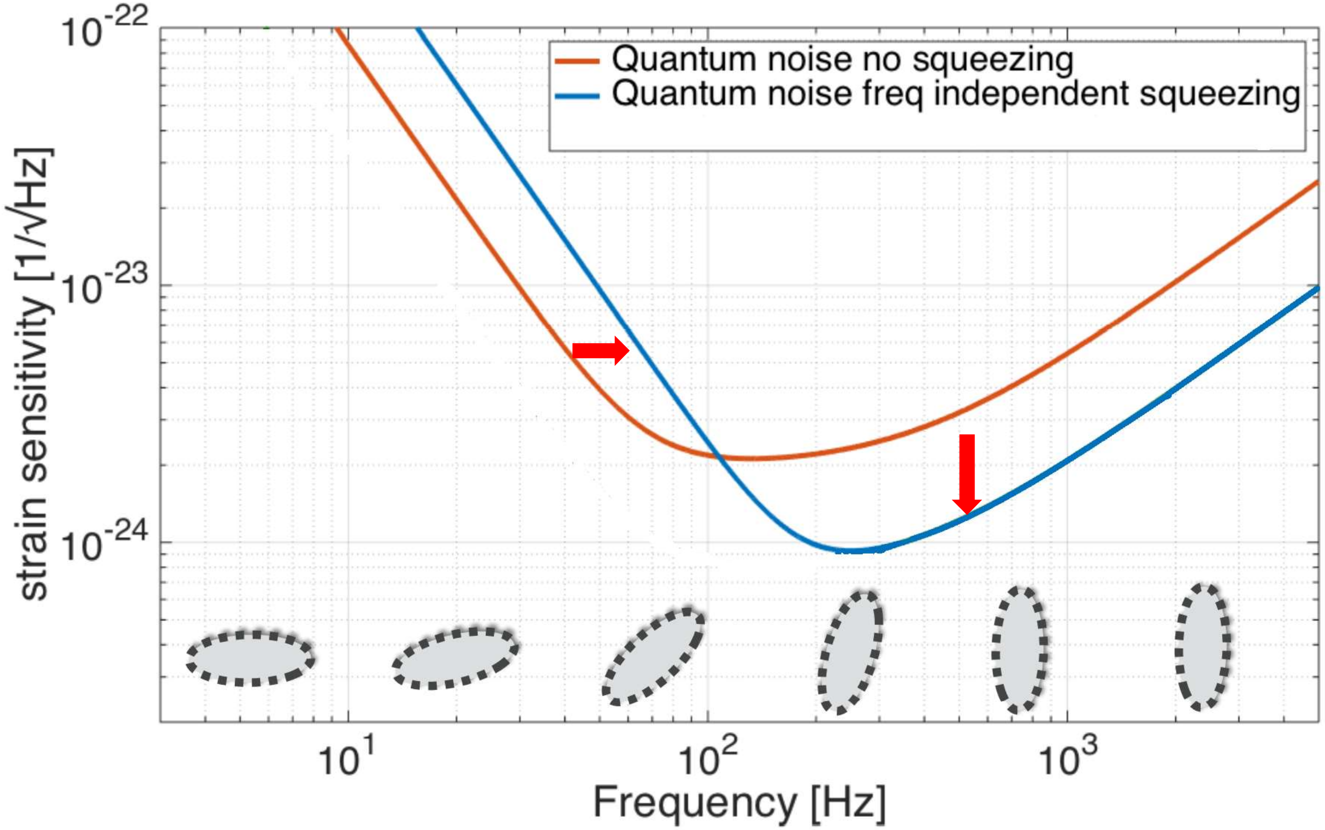


Squeezed
states
to ext.
PLL
110 cm
105 cm

Quantum noise enhancement of LIGO

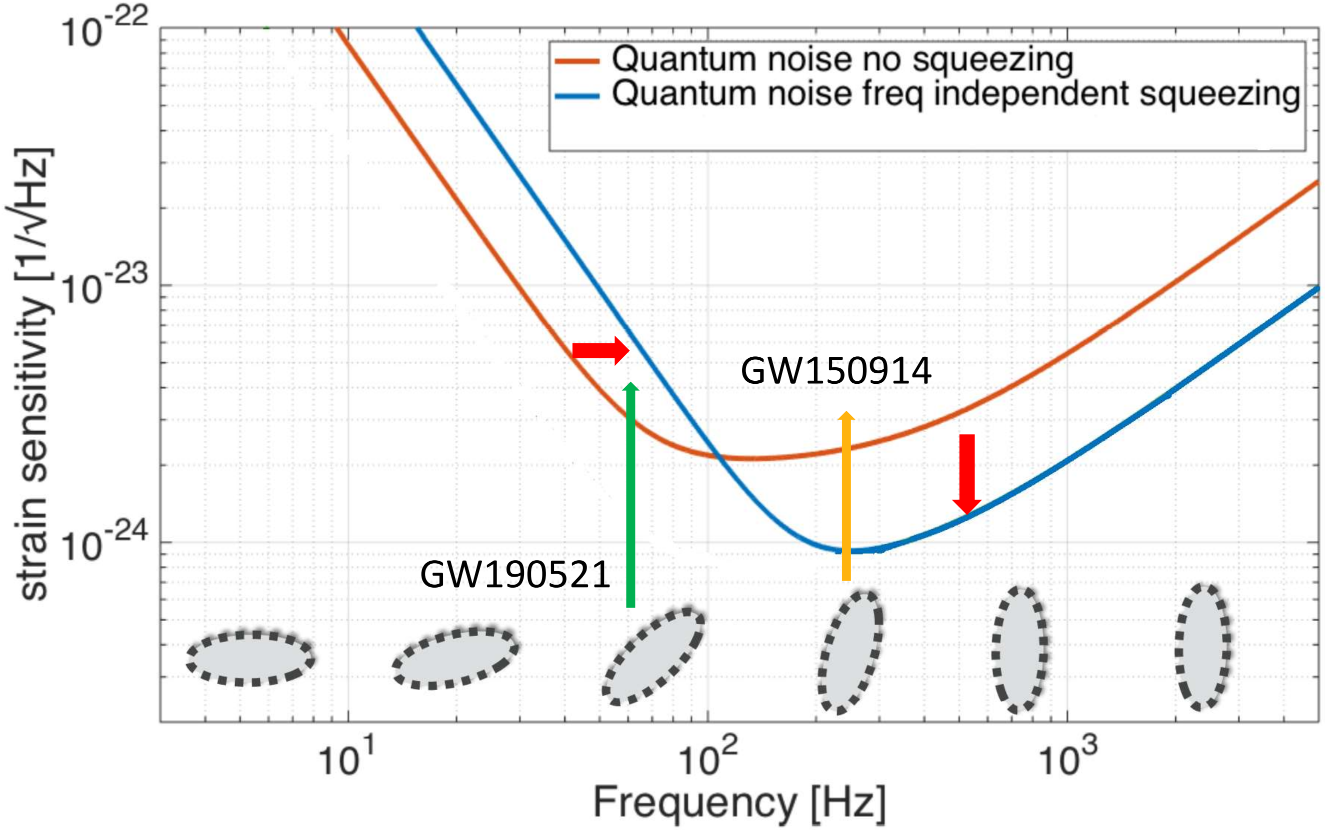


Frequency independent squeezing



Optical and noise studies for Advanced Virgo and filter cavities for quantum noise reduction
in gravitational-wave interferometric detectors, Eleonora Capocasa, UNIVERSITÉ PARIS DIDEROT (2017)

Frequency independent squeezing



Optical and noise studies for Advanced Virgo and filter cavities for quantum noise reduction
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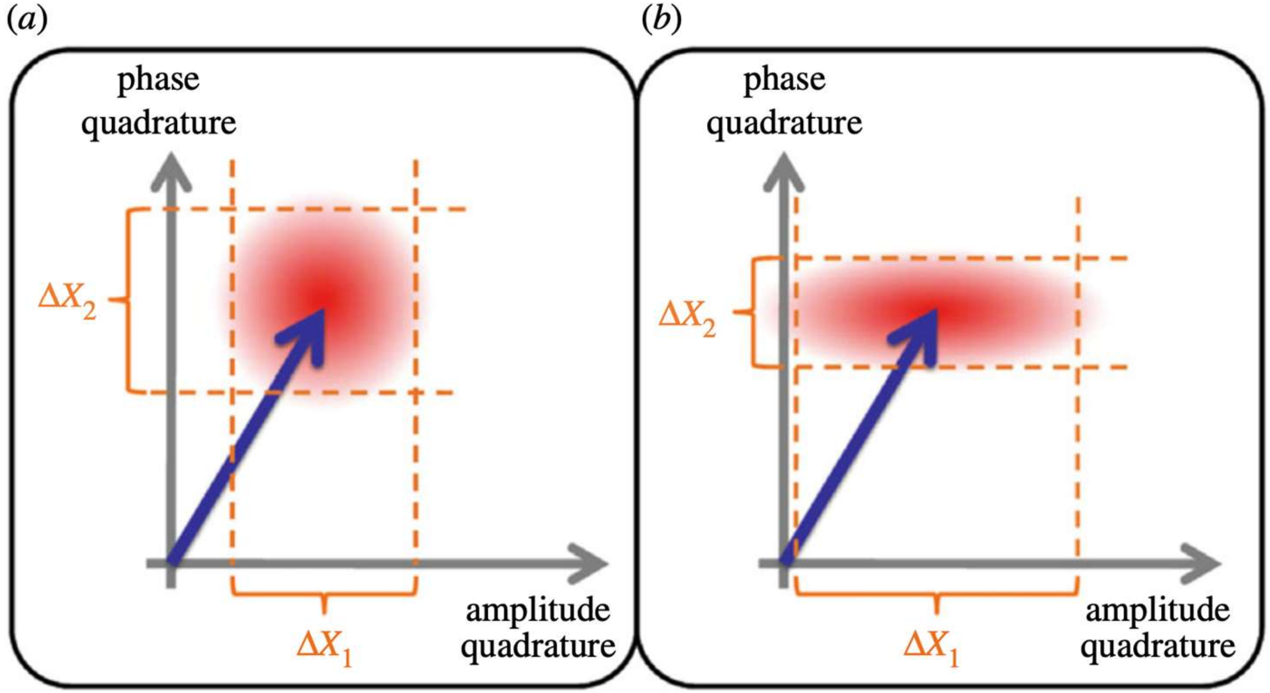
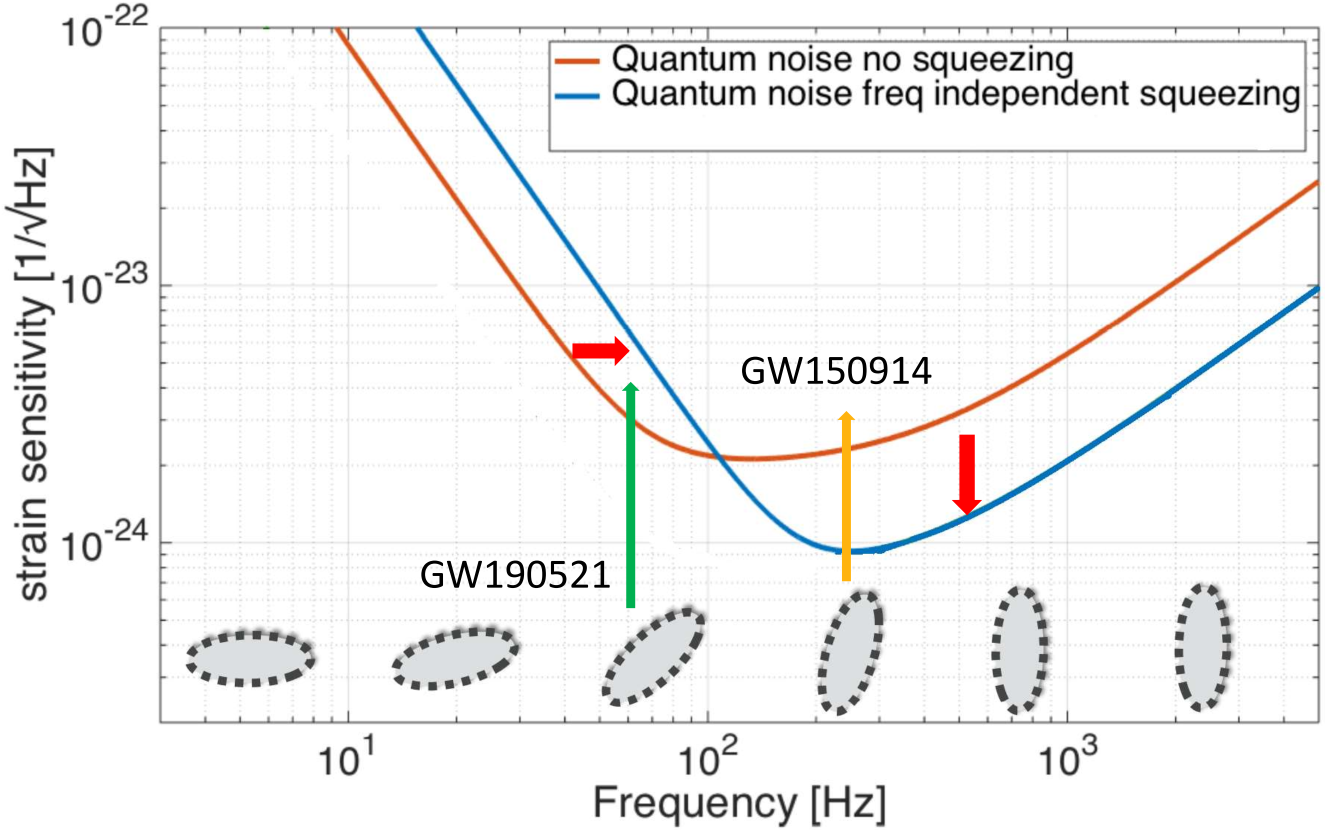
Squeezed light



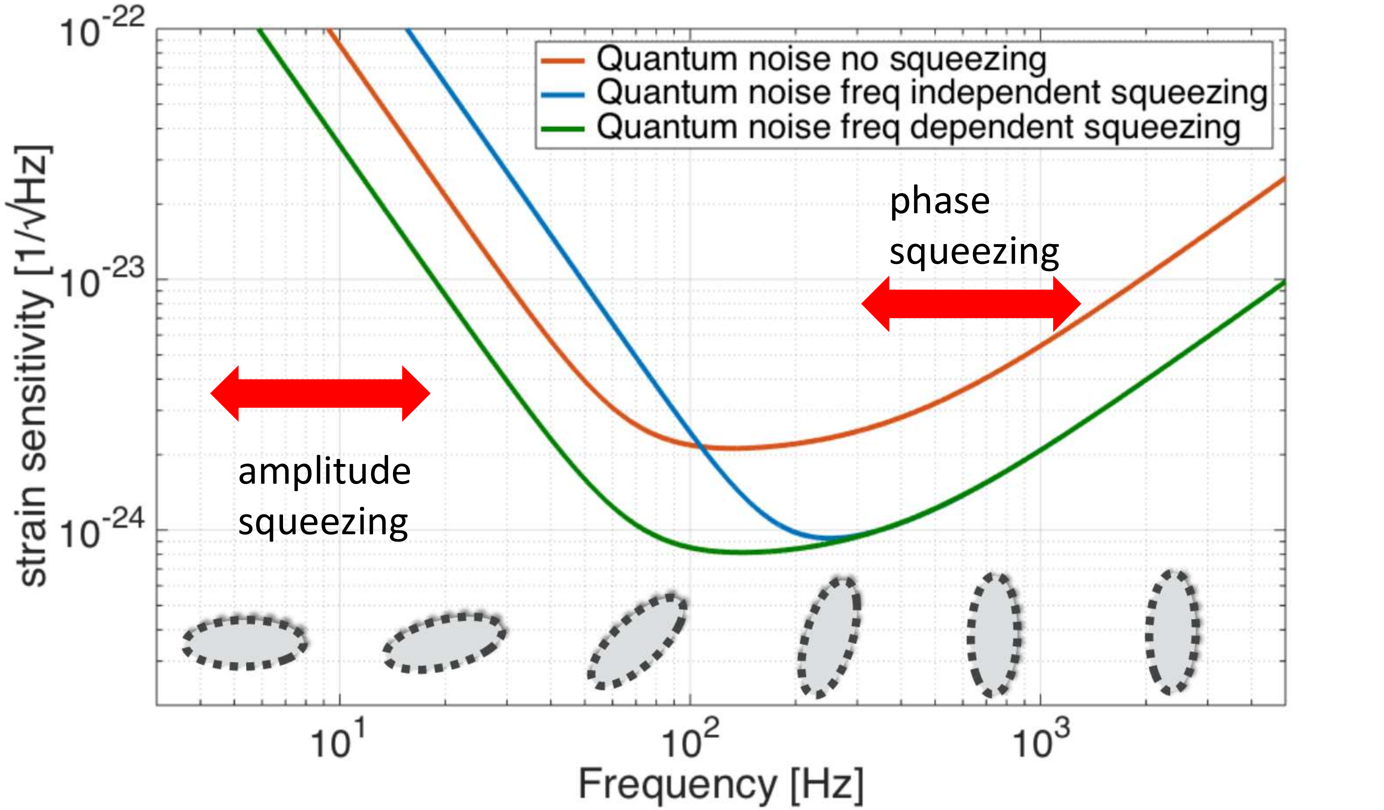
Heurs M. 2018 Gravitational wave detection using laser interferometry beyond the standard quantum limit.Phil. Trans. R. Soc. A 376: 20170289.

Frequency independent squeezing



Optical and noise studies for Advanced Virgo and filter cavities for quantum noise reduction in gravitational-wave interferometric detectors, Eleonora Capocasa, UNIVERSITÉ PARIS DIDEROT (2017)

Frequency dependent squeezing(FDS)



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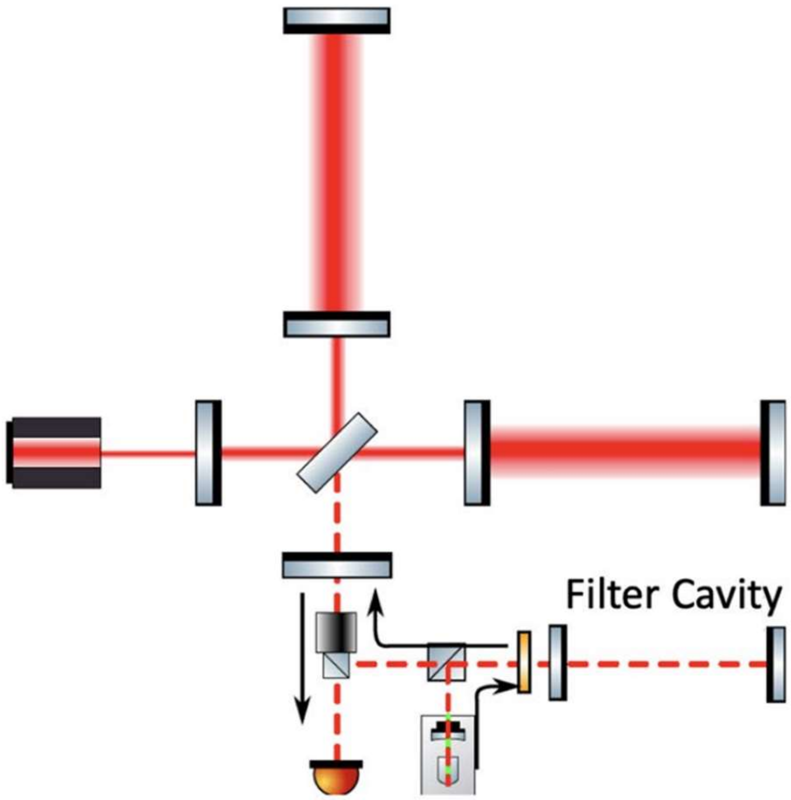
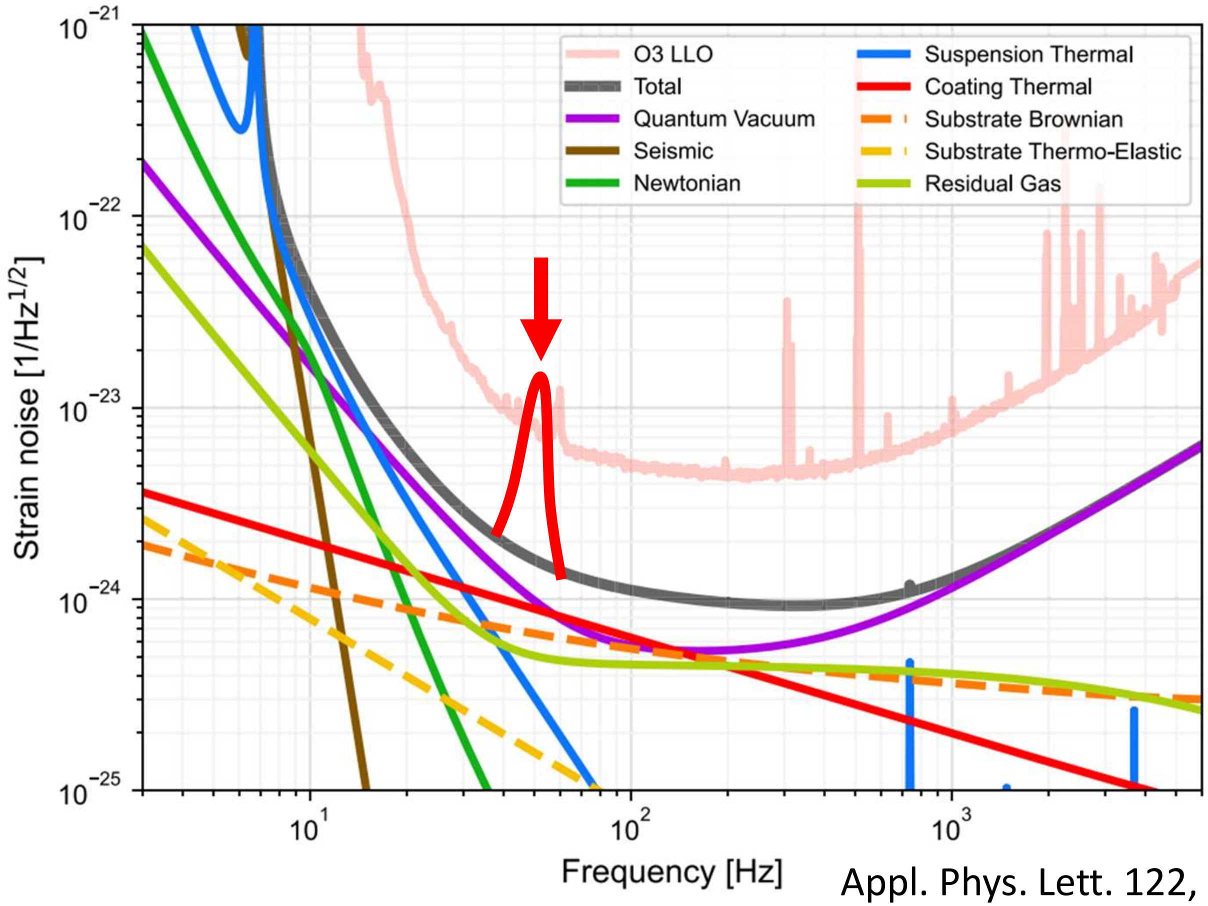
Frequency dependent squeezing using filter cavity

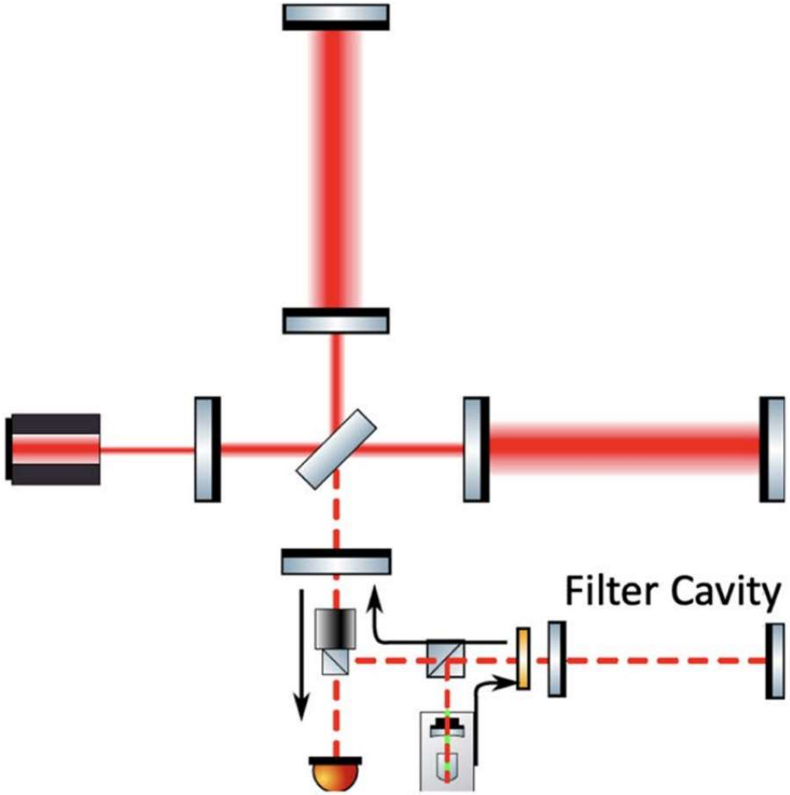


LIGO sensitivity



Appl. Phys. Lett. 122, 110502 (2023)

Frequency dependent squeezing using filter cavity



$$E^{(+)}(t) = \int_0^\infty E(\omega) e^{-i\omega t} \frac{d\omega}{2\pi}$$

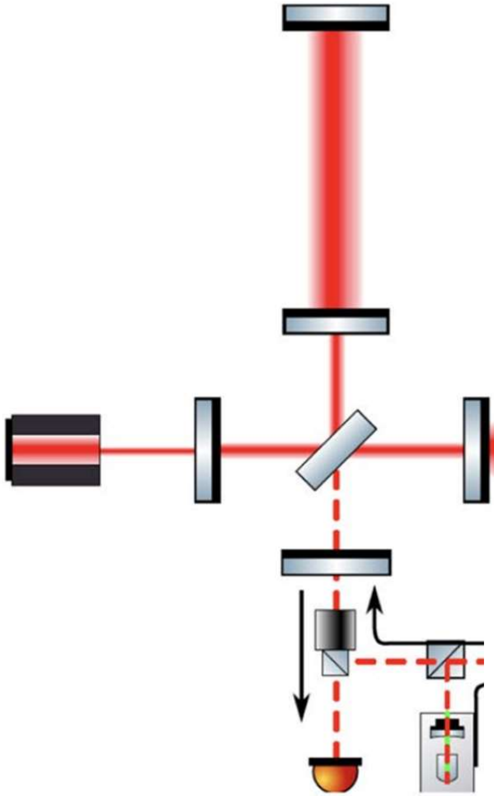
$$E^{(+)}(t) = e^{-i\omega_0 t} \int_0^\infty \left(E(\Omega) e^{-i\Omega t} + E(-\Omega) e^{+i\Omega t} \right) \frac{d\Omega}{2\pi}$$

$$\omega = \omega_0 + \Omega$$

Laser frequency

GW signal frequency

Frequency dependent squeezing using filter cavity



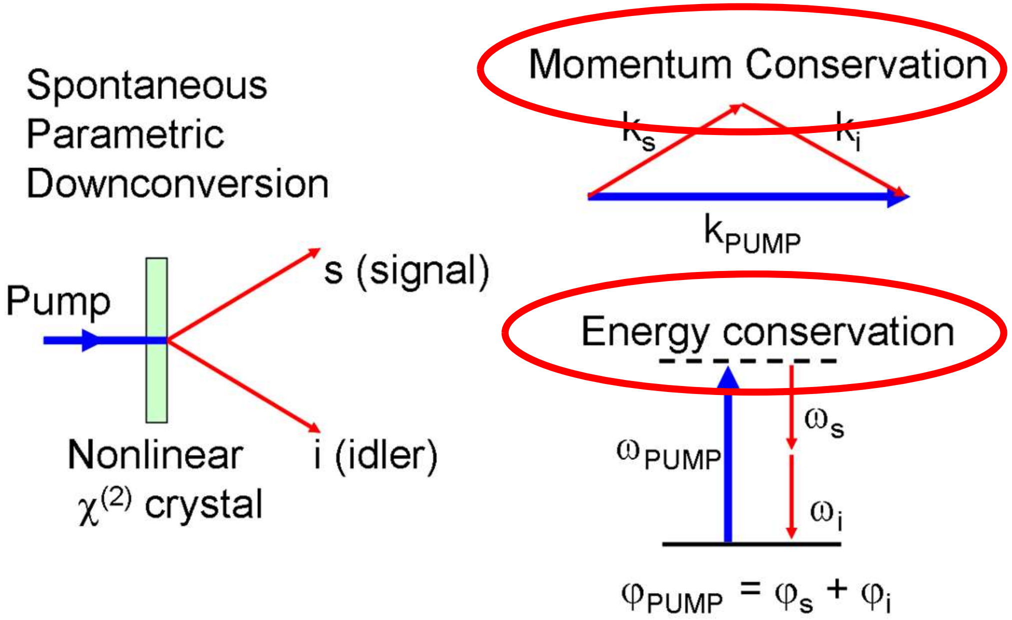
$$E(t) = \sqrt{\frac{4\pi\hbar\omega_0}{Ac}}\left[a_1(t)\cos(\omega_0 t) + a_2(t)\sin(\omega_0 t)\right]$$

$$\textbf{Amplitude Quadrature}: \; a_1(t) = \frac{a(t) + a^\dagger(t)}{\sqrt{2}}$$

$$\textbf{Phase Quadrature}: \; a_2(t) = \frac{a(t) - a^\dagger(t)}{i\sqrt{2}}$$

$$E(t) = \sqrt{\frac{4\pi\hbar\omega_0}{Ac}}\Bigg[\cos(\omega_0 t)\int_0^\infty (a_1(\Omega)e^{-i\Omega t} + a_1^\dagger(\Omega)e^{+i\Omega t})\frac{d\Omega}{2\pi} + \sin(\omega_0 t)\int_0^\infty (a_2(\Omega)e^{-i\Omega t} + a_2^\dagger(\Omega)e^{+i\Omega t})\frac{d\Omega}{2\pi}\Bigg]$$

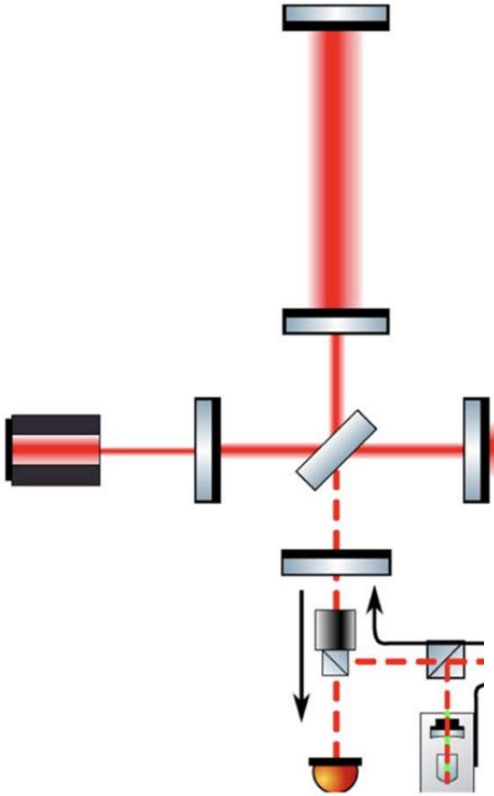
Parametric down conversion



J S Lundeen

Every filed which are participated in
Non-linear conversion process,
Must obey energy, momentum conservation.

Frequency dependent squeezing using filter cavity



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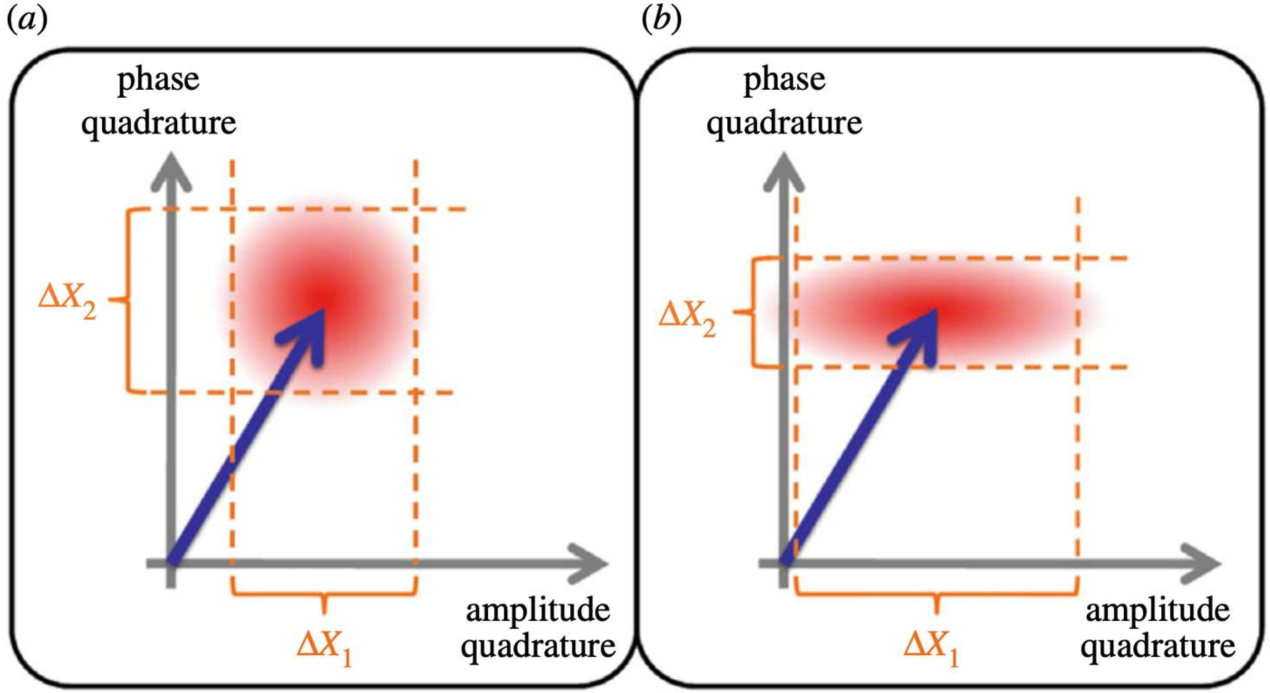
$$E(t) = \sqrt{\frac{4\pi\hbar\omega_0}{Ac}}\Bigg[\cos(\omega_0 t)\int_0^\infty \left(a_1(\Omega)e^{-i\Omega t} + a_1^\dagger(\Omega)e^{+i\Omega t}\right)\frac{d\Omega}{2\pi} + \sin(\omega_0 t)\int_0^\infty \left(a_2(\Omega)e^{-i\Omega t} + a_2^\dagger(\Omega)e^{+i\Omega t}\right)\frac{d\Omega}{2\pi}\Bigg]$$

Squeezed light



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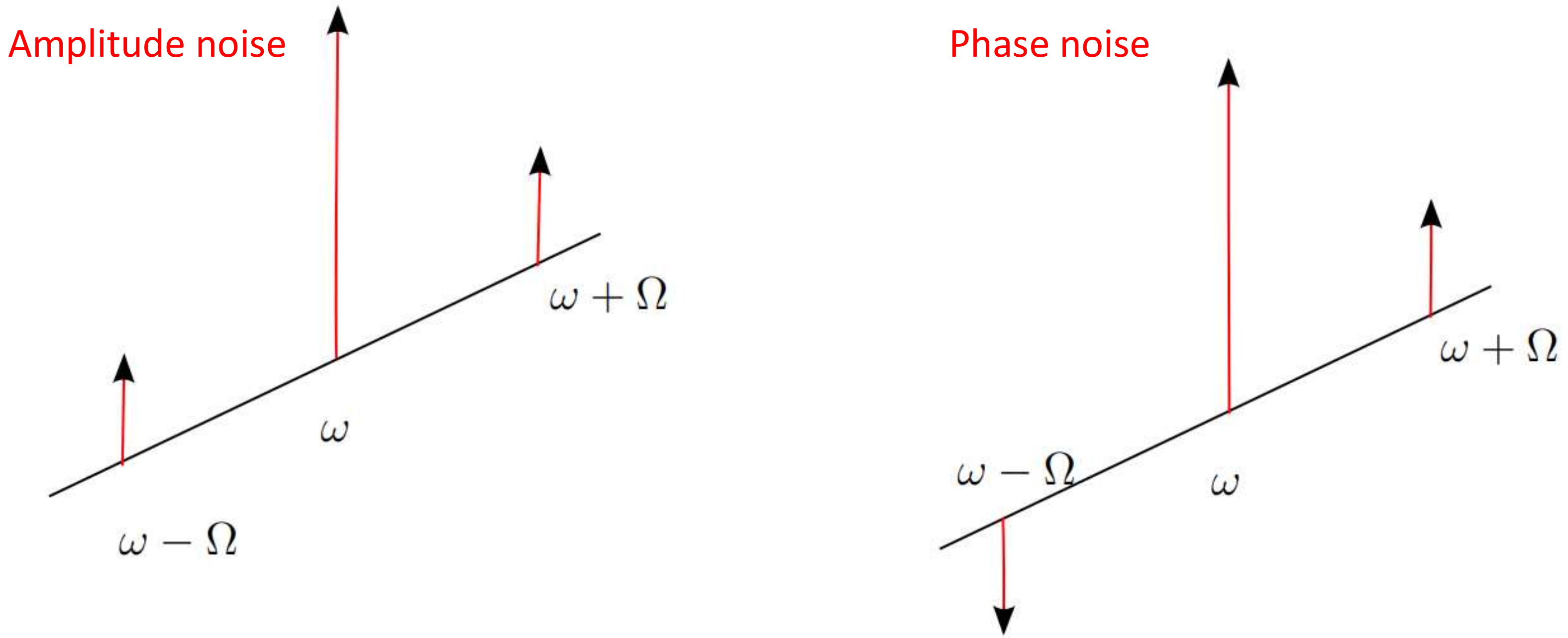
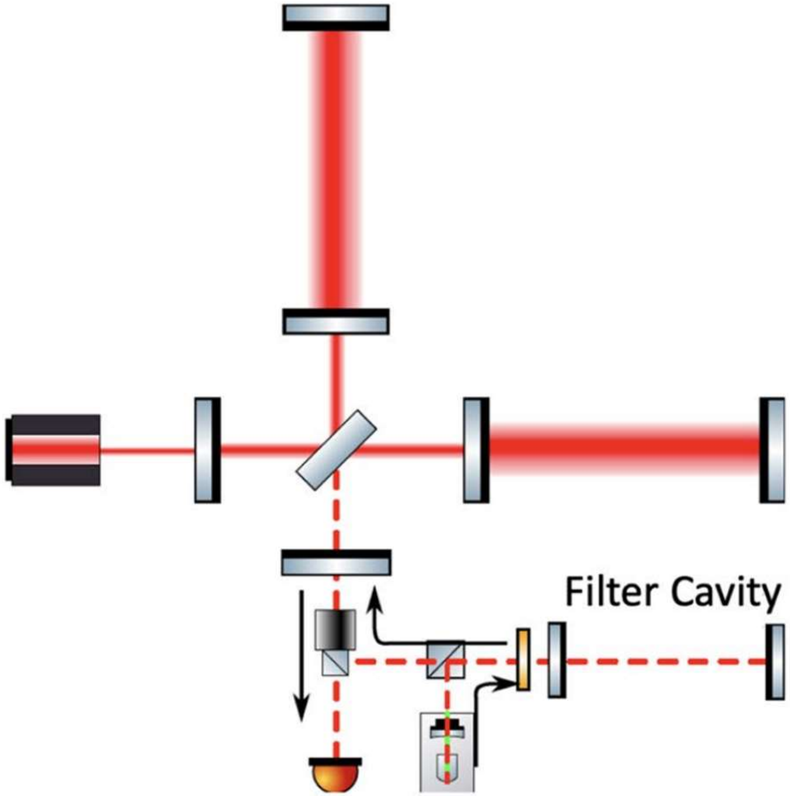
Quantum noise side band figure



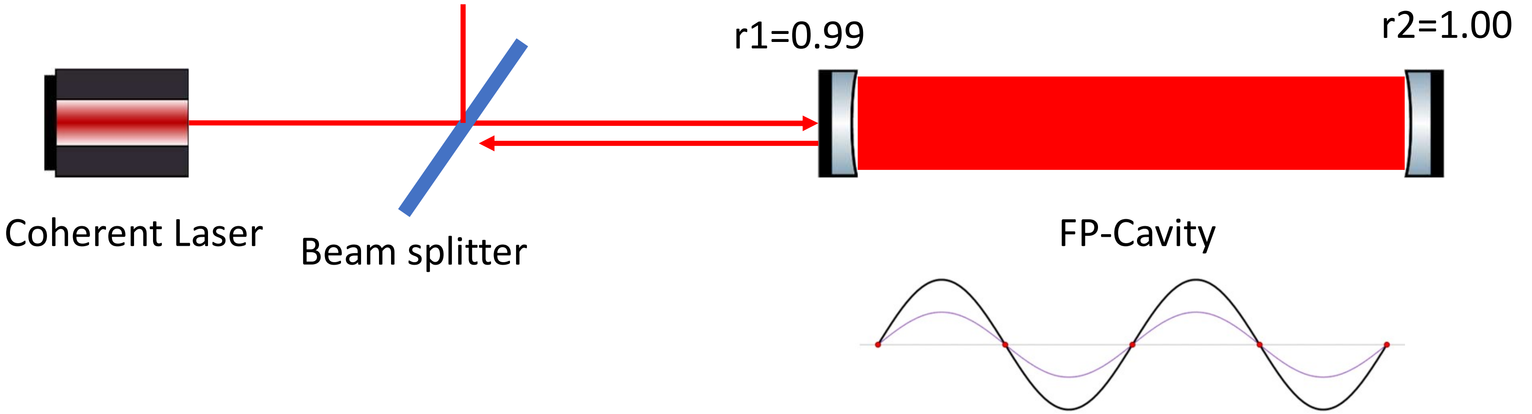
Frequency dependent squeezing using filter cavity



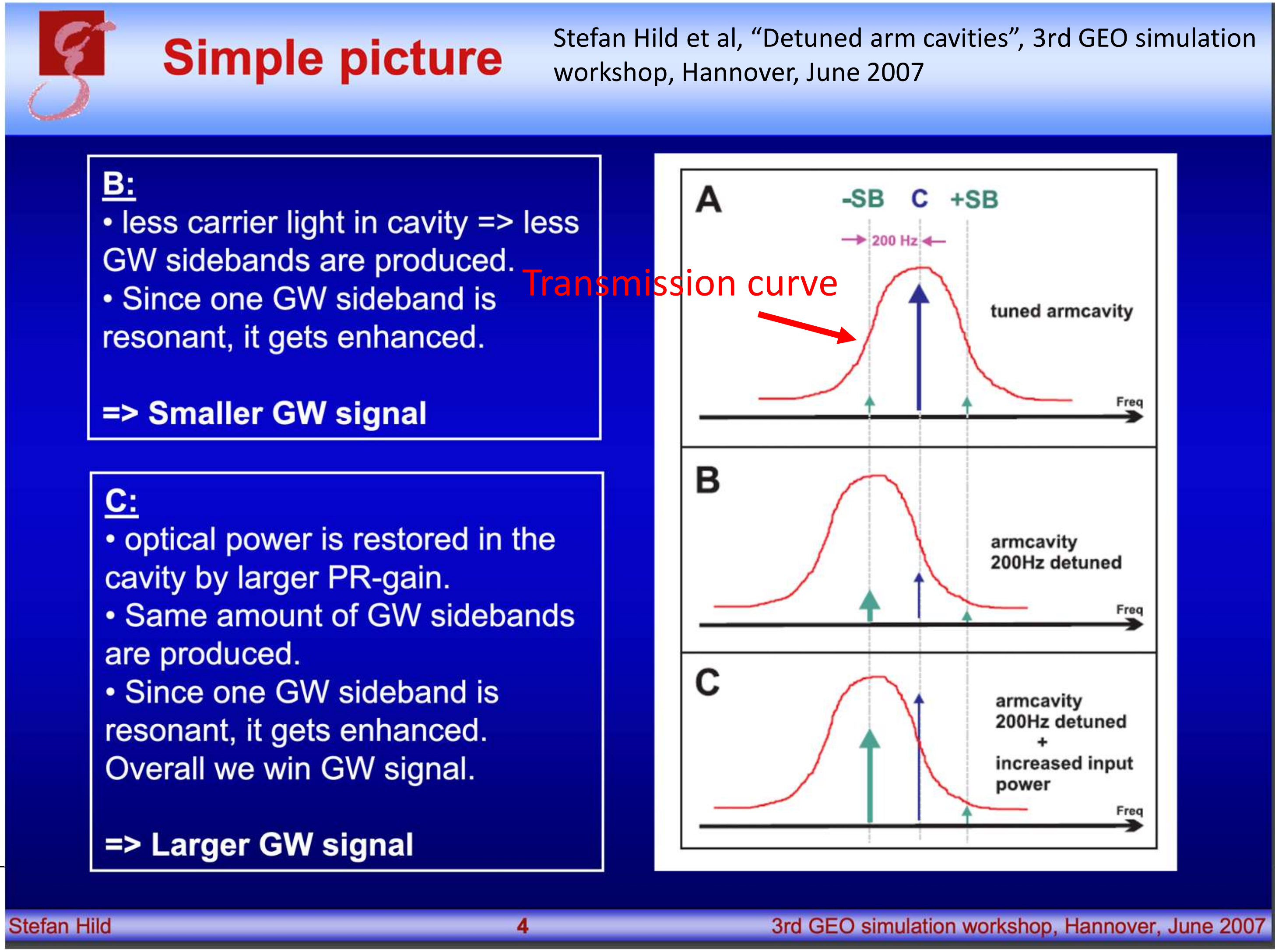
Fabry-perot cavity

Number of round trip > 250

4 km x 250 ~ 1000 km



Detuned cavity



Quantum noise side band figure

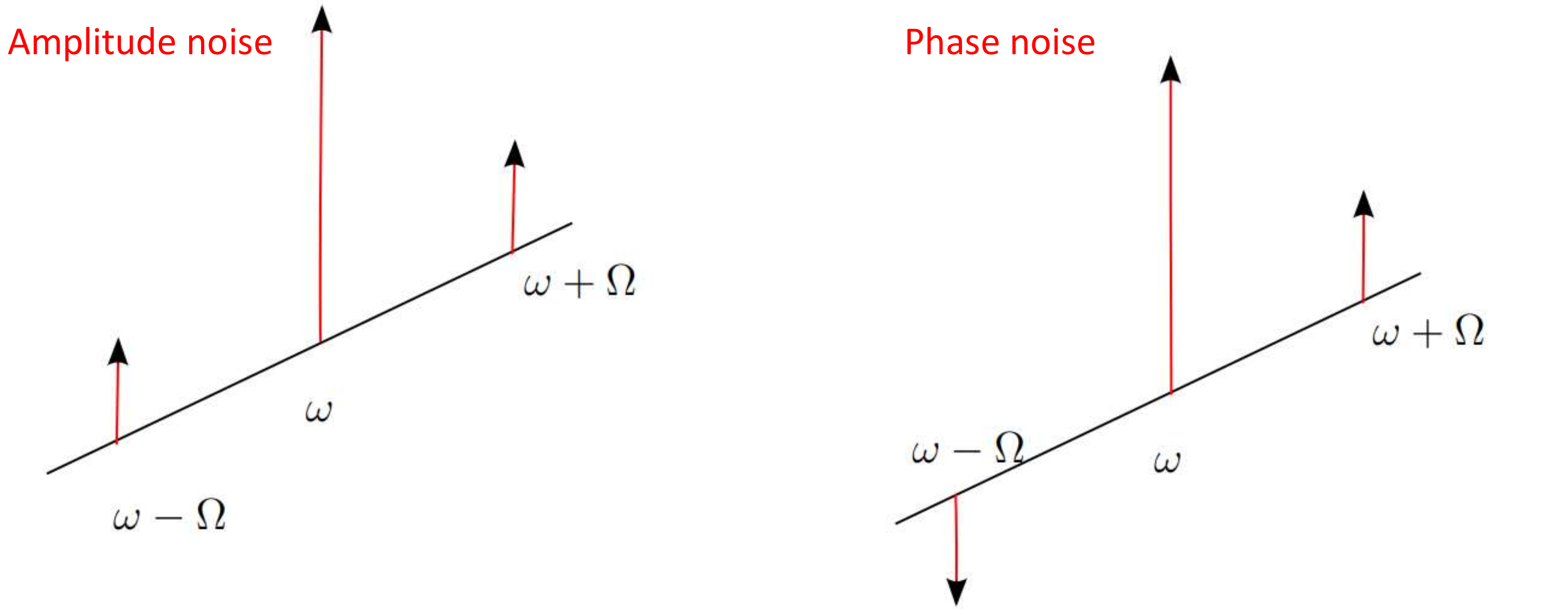
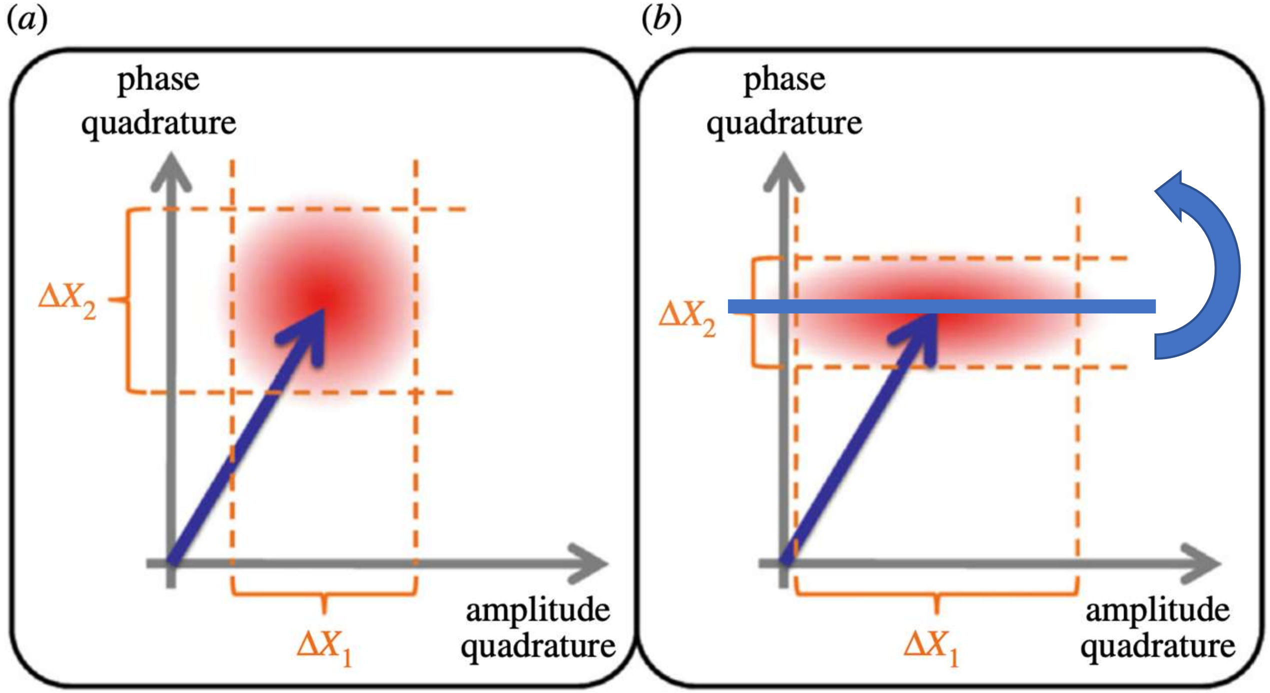


Figure 1-2: Phasors of amplitude noise (left) and phase noise (right) in the sideband picture. In the frame rotating at the carrier frequency ω the carrier is still in these diagrams while the sidebands rotate at Ω, the signal at $\omega + \Omega$ rotating clockwise while the idler at $\omega - \Omega$ rotates counter clockwise. (Sidebands have equal amplitudes)

Squeezed light



Squeeze angle rotation

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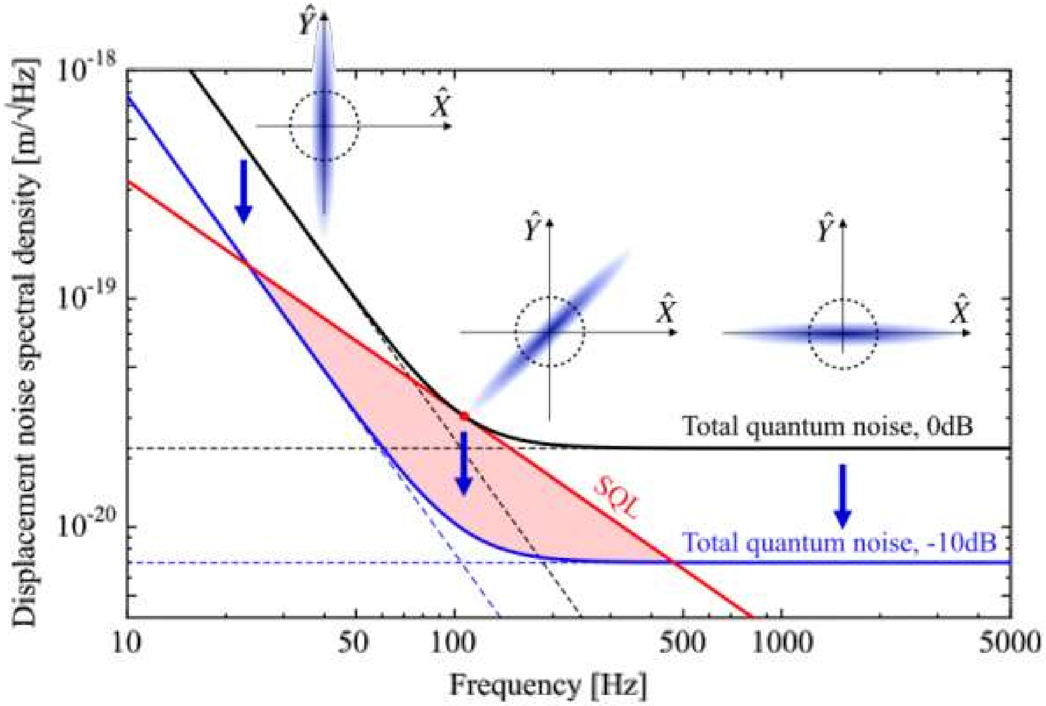
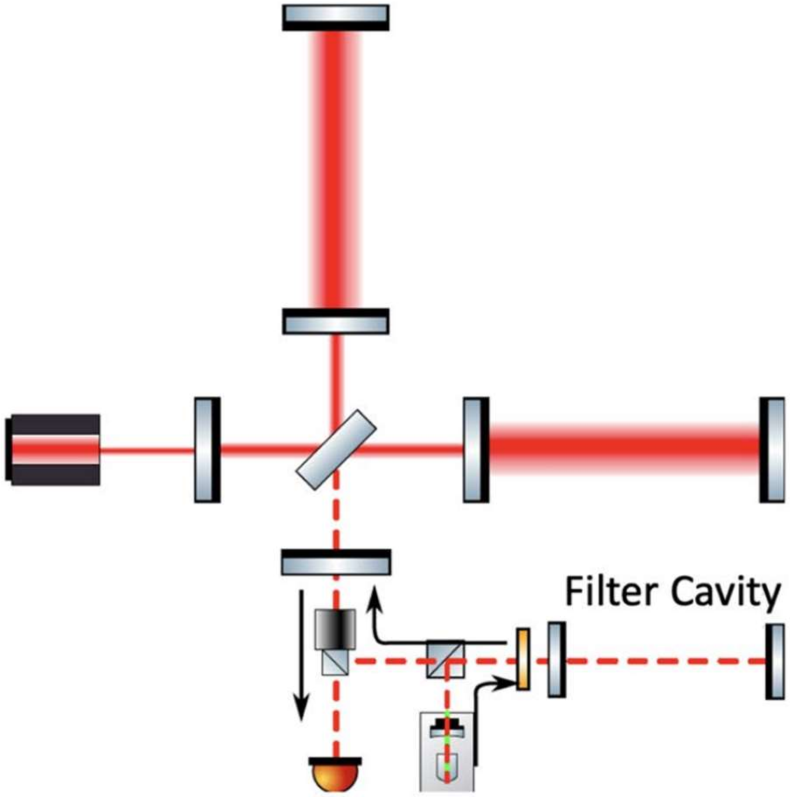
Squeeze angle rotation



$$\alpha_p = \arctan\left(\frac{2\gamma_{\rm fc}\Delta\omega_{\rm fc}}{\gamma_{\rm fc}^2 - \Delta\omega_{\rm fc}^2 + \Omega^2}\right)$$

$$t_{\rm st} = \frac{1}{\gamma_{\rm fc}} = \frac{\sqrt{2}}{\Omega_{\rm SQL}} \simeq 3\,{\rm ms}$$

Frequency dependent squeezing using filter cavity



Frequency dependent squeezing – KAGRA

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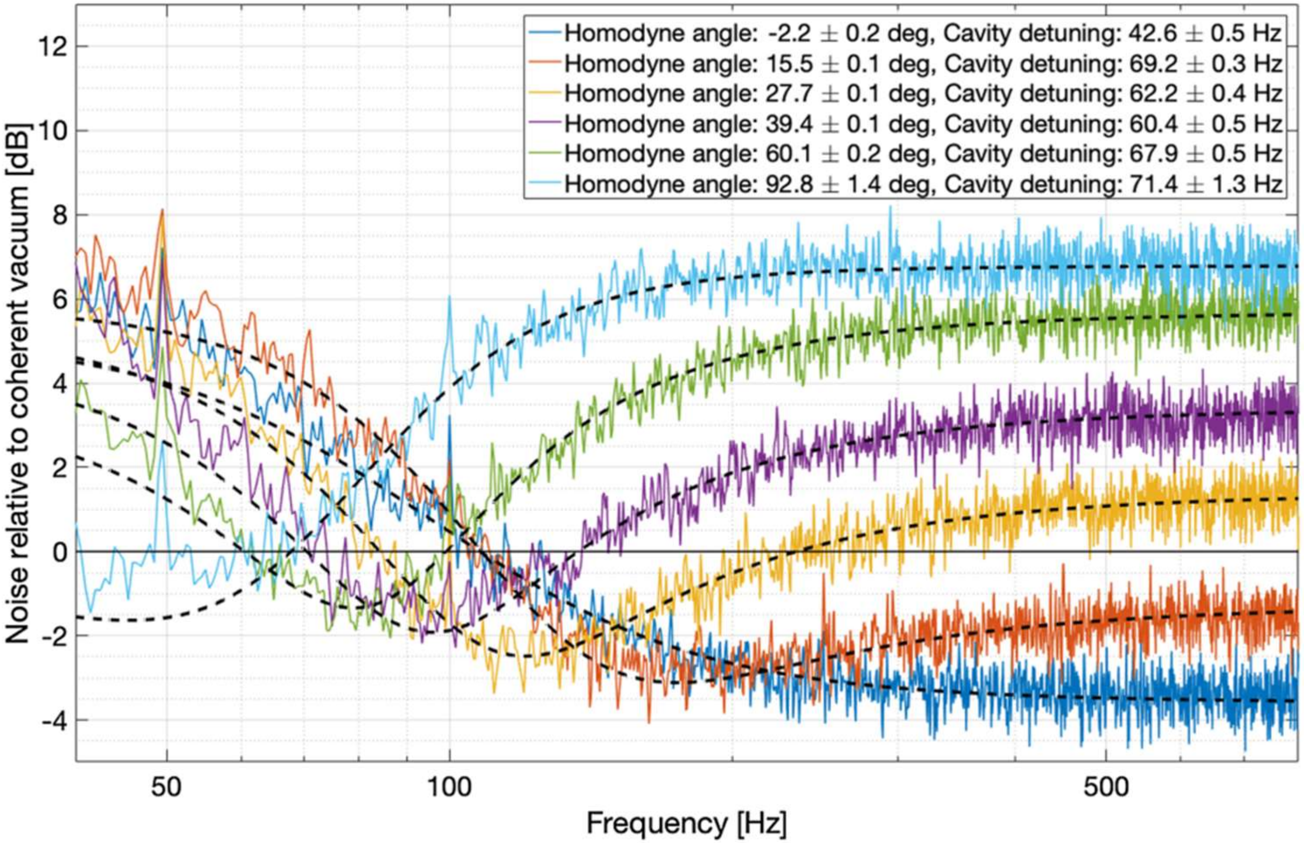
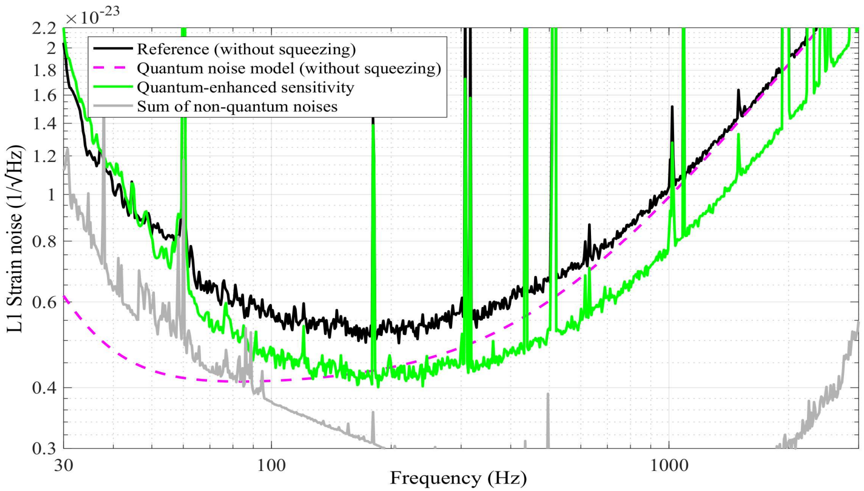
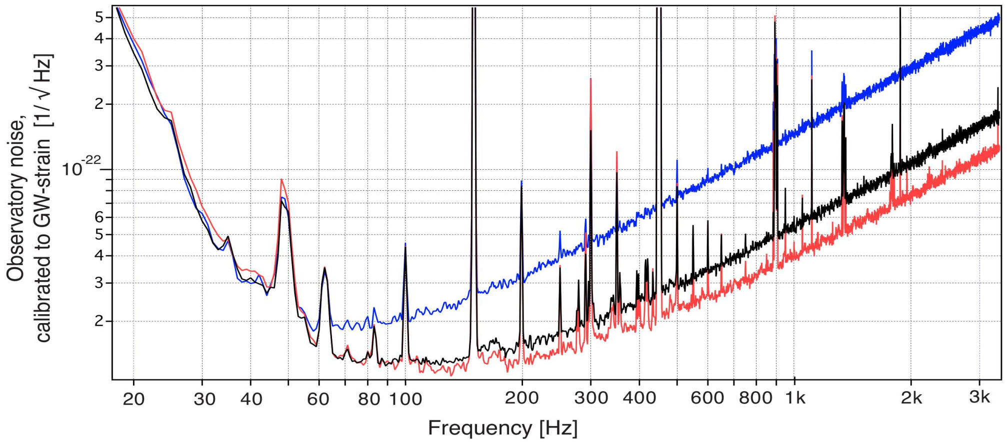
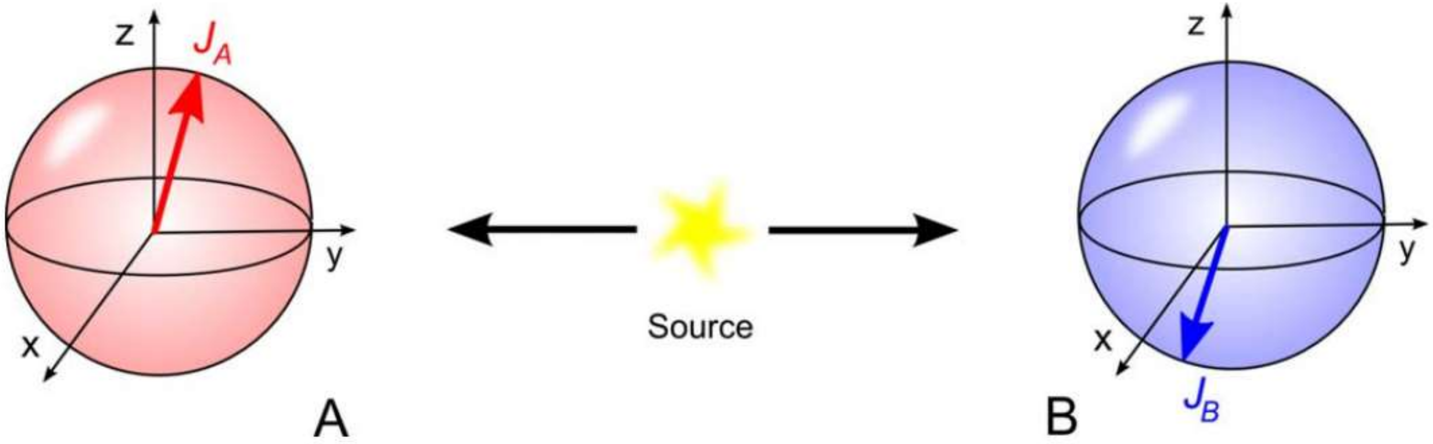


Quantum noise of gravitational wave detector

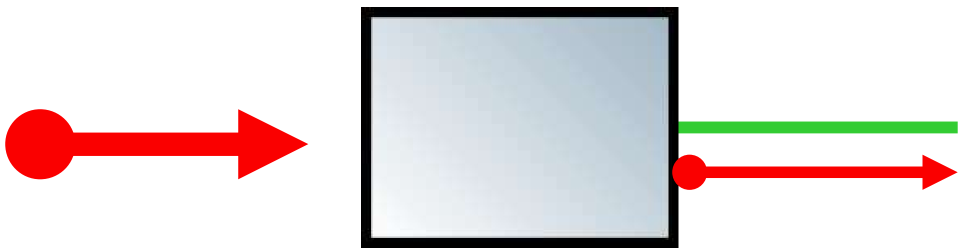




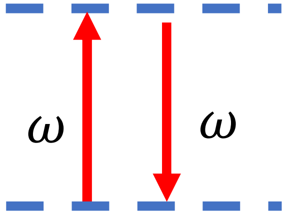
Einstein-Podolsky-Rosen paradox



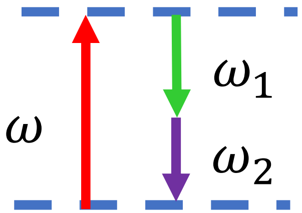
Non linear crystal



Non-linear crystal

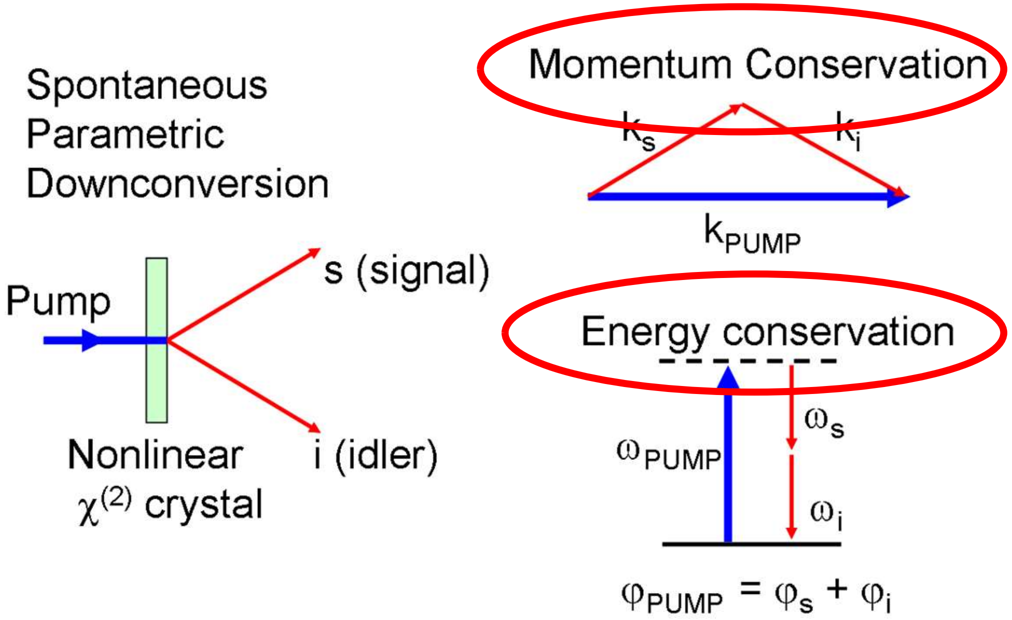


linear optics



Non linear optics

Parametric down conversion



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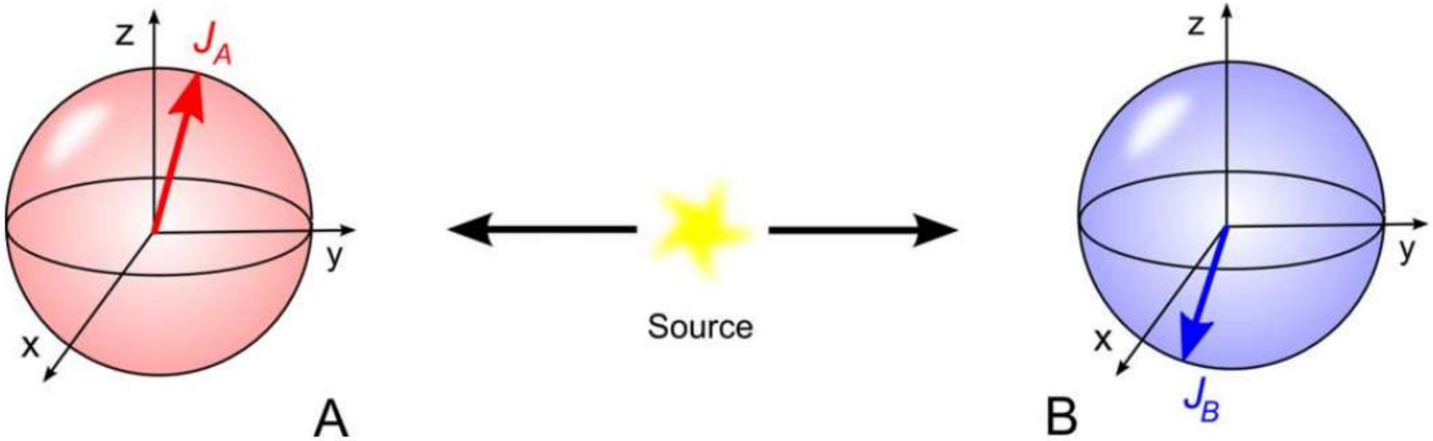

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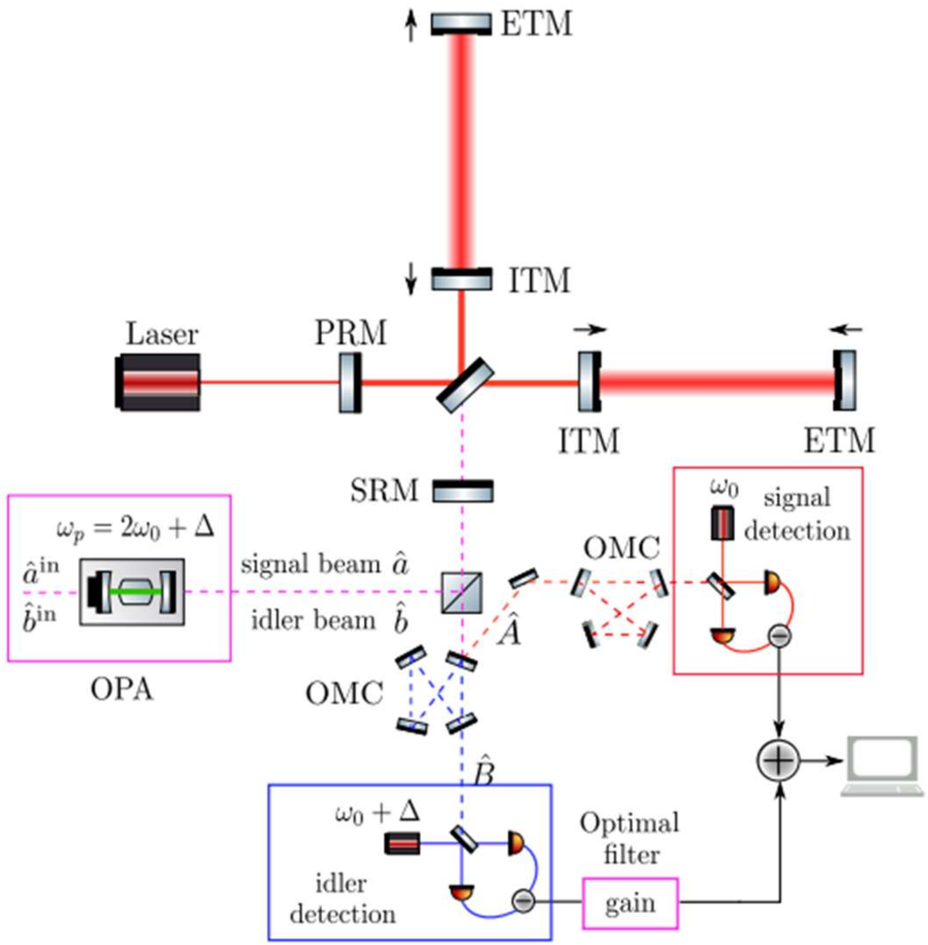
EPR squeezing for gravitational wave detector



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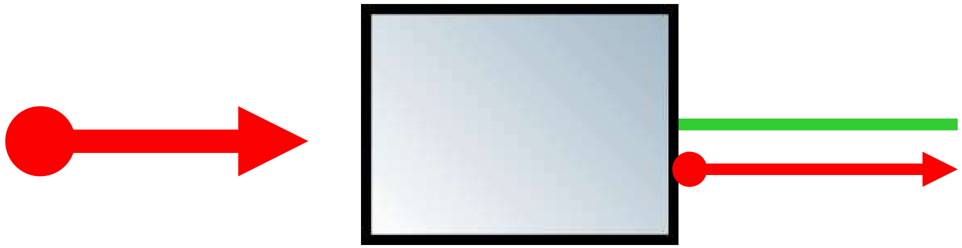

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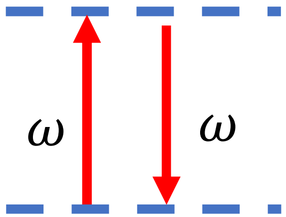
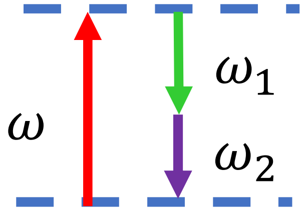


linear optics



Non linear optics

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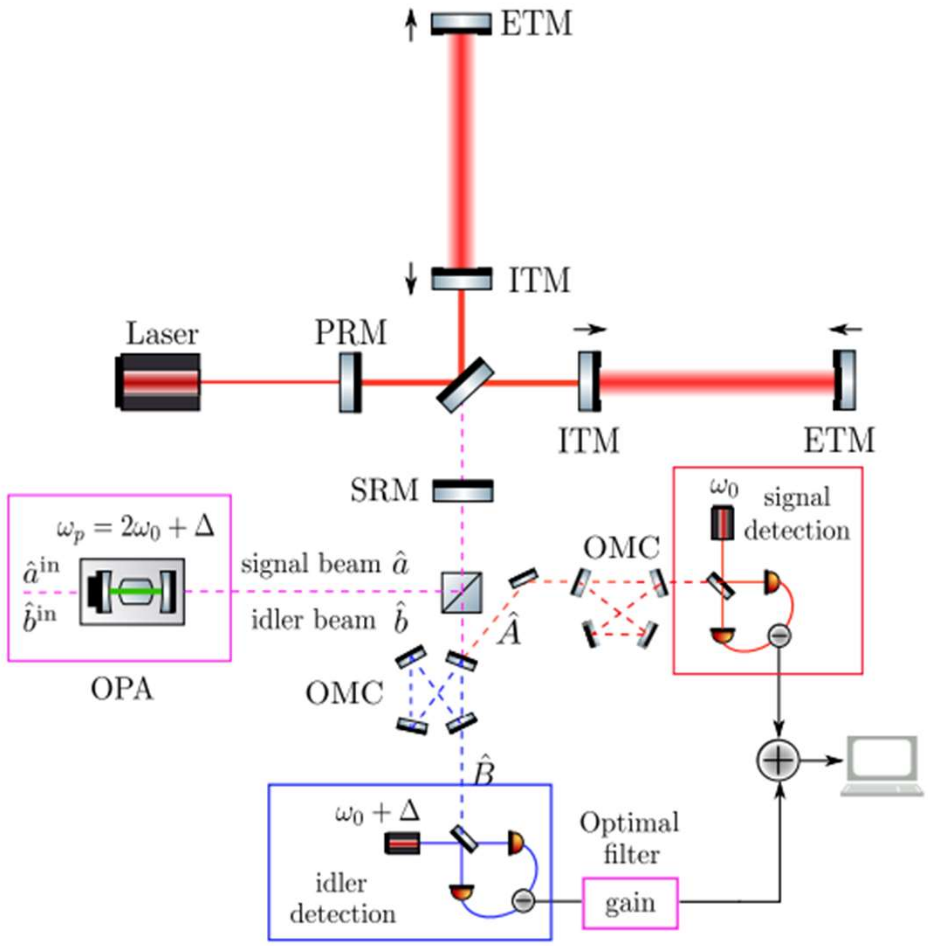

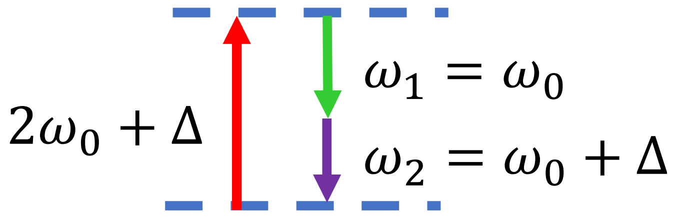

Non linear optics

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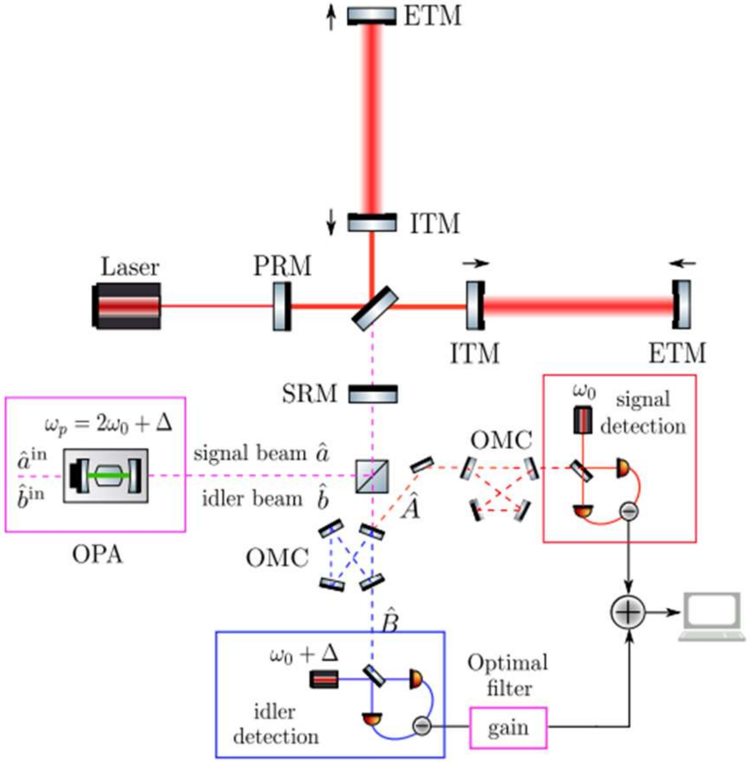
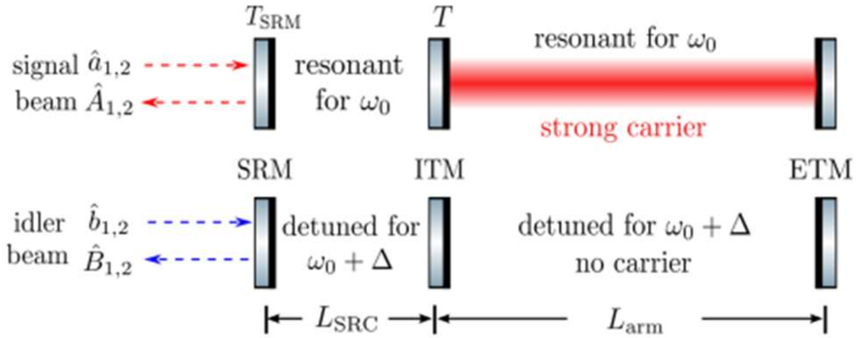
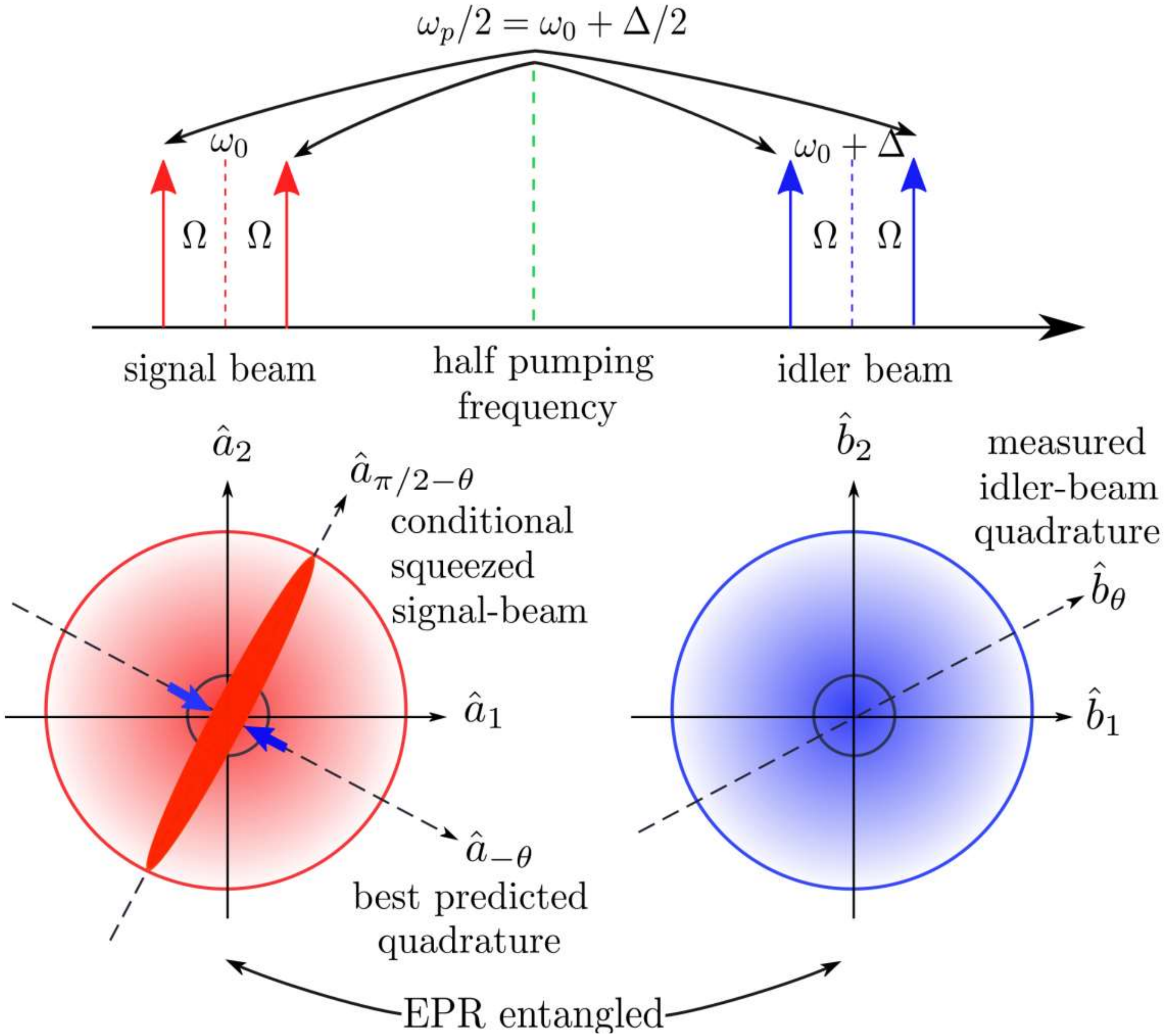
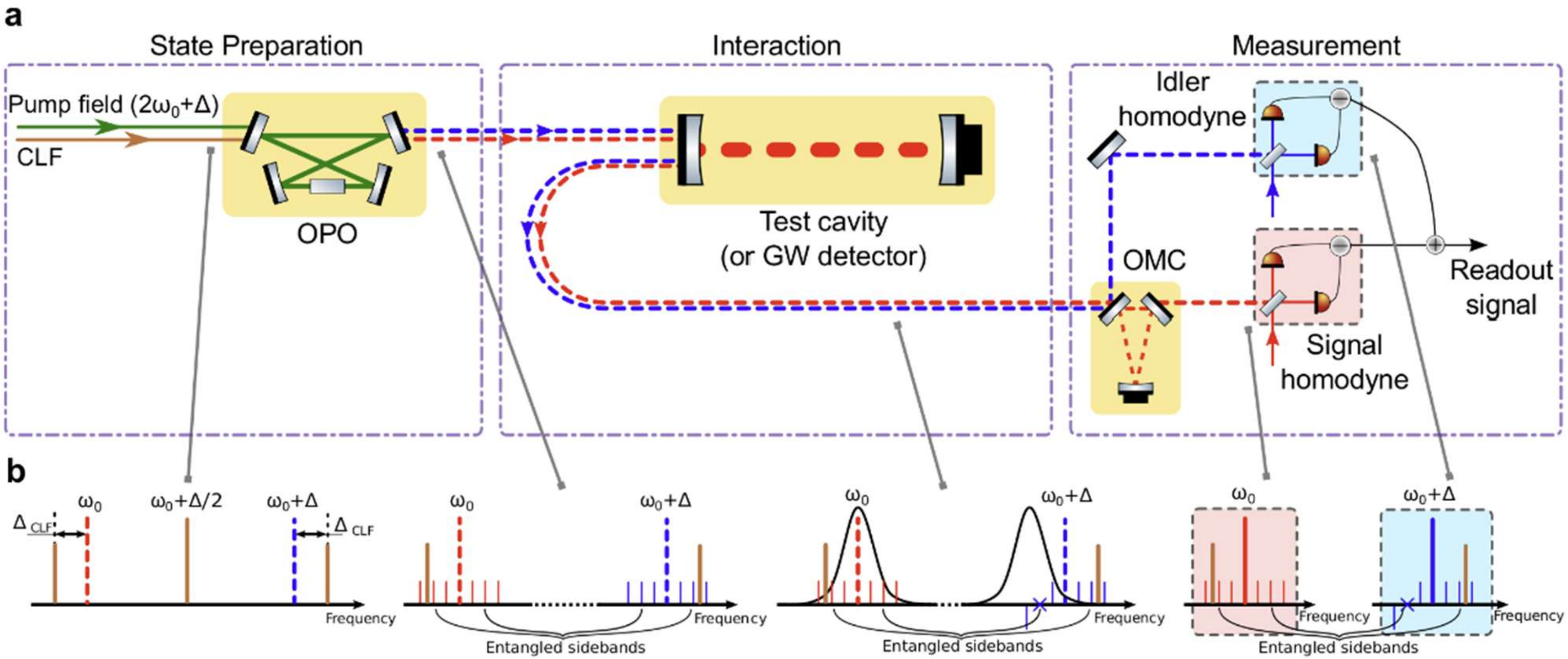






$\omega_p/2 = \omega_0 + \Delta/2$
ω_0
$\omega_0 + \Delta$
Ω
Ω
Ω
Ω
signal beam
half pumping frequency
idler beam
$\hat{a}_2$
$\hat{a}_{\pi/2-\theta}$
conditional squeezed signal-beam
$\hat{a}_1$
$\hat{a}_{-\theta}$
best predicted quadrature
$\hat{b}_2$
measured idler-beam quadrature
$\hat{b}_\theta$
$\hat{b}_1$
EPR entangled

Generation and control of frequency dependent squeezing via EPR entanglement



Thank you