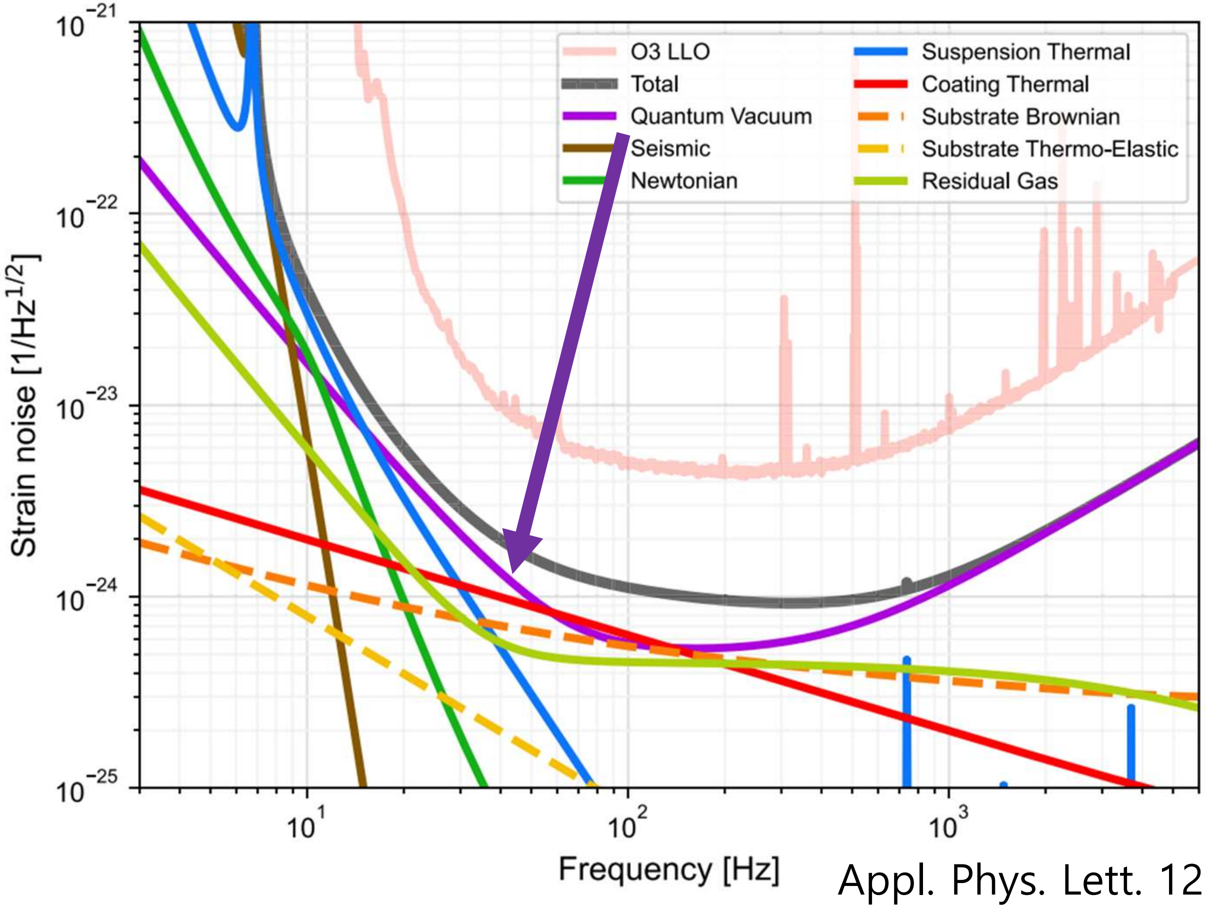
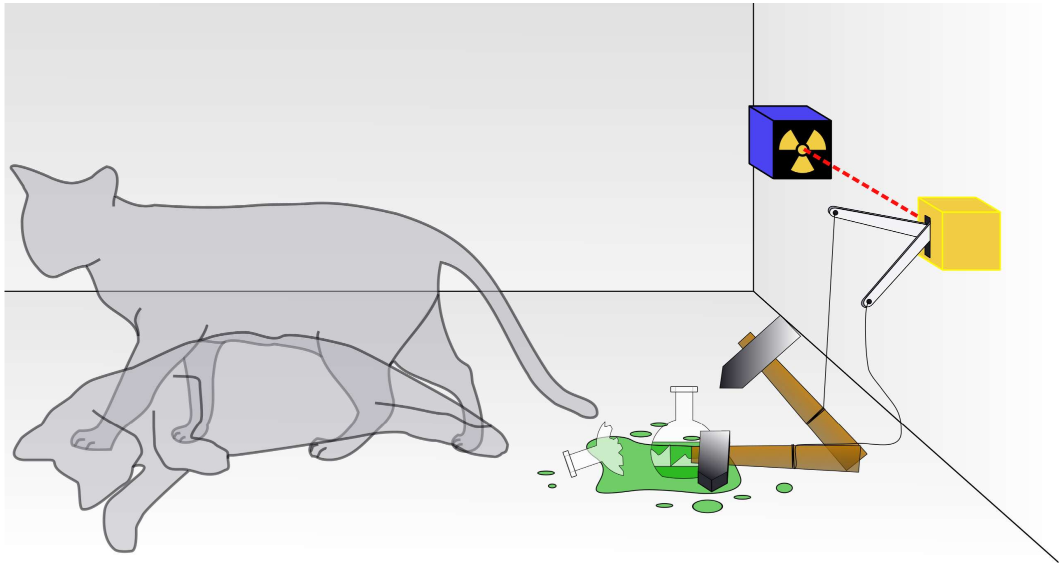
3. Quantum noise of gravitational wave detector

LIGO sensitivity

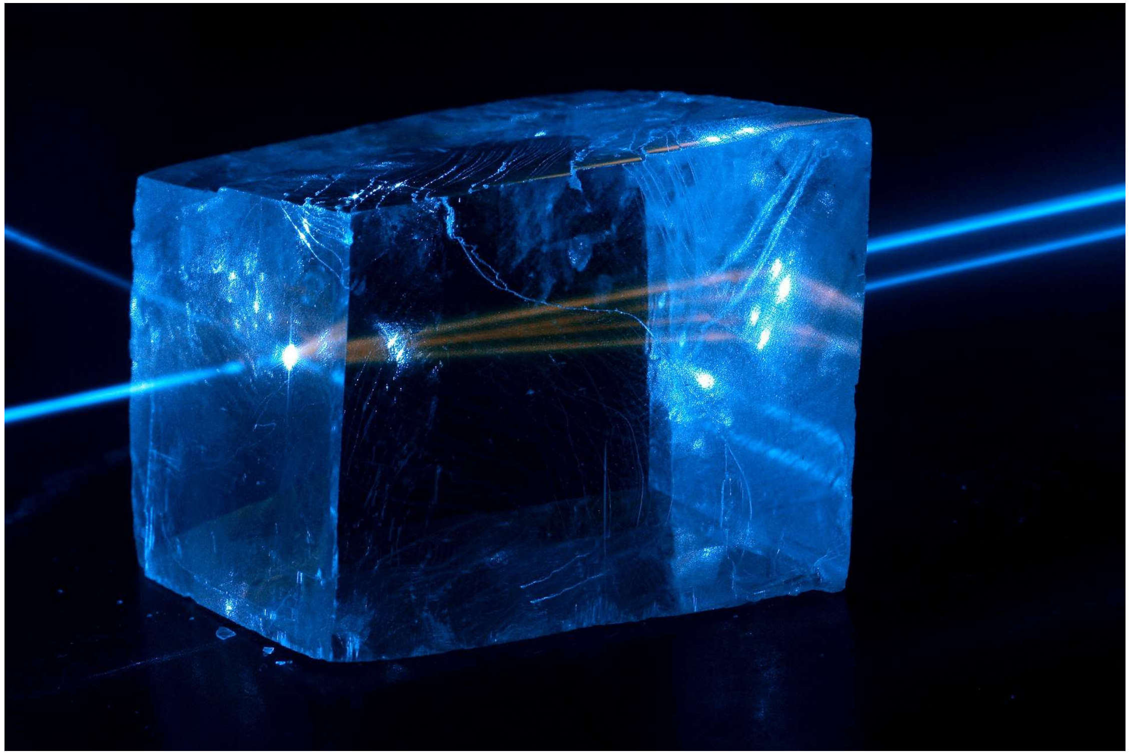


Appl. Phys. Lett. 122, 110502 (2023)

Quantum noise

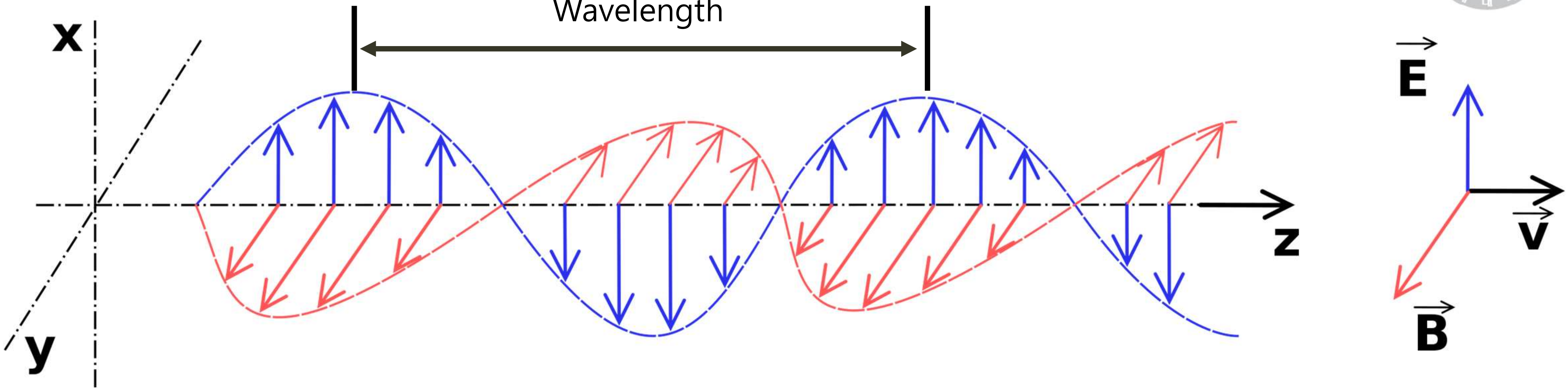


Wave-particle duality



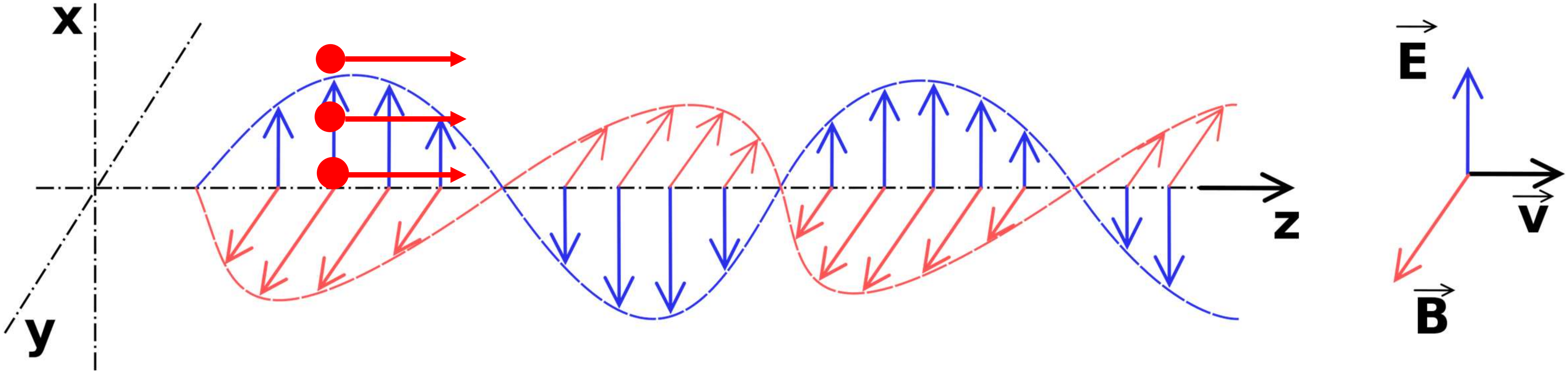
Wave-particle duality

Light(Electromagnetic wave)

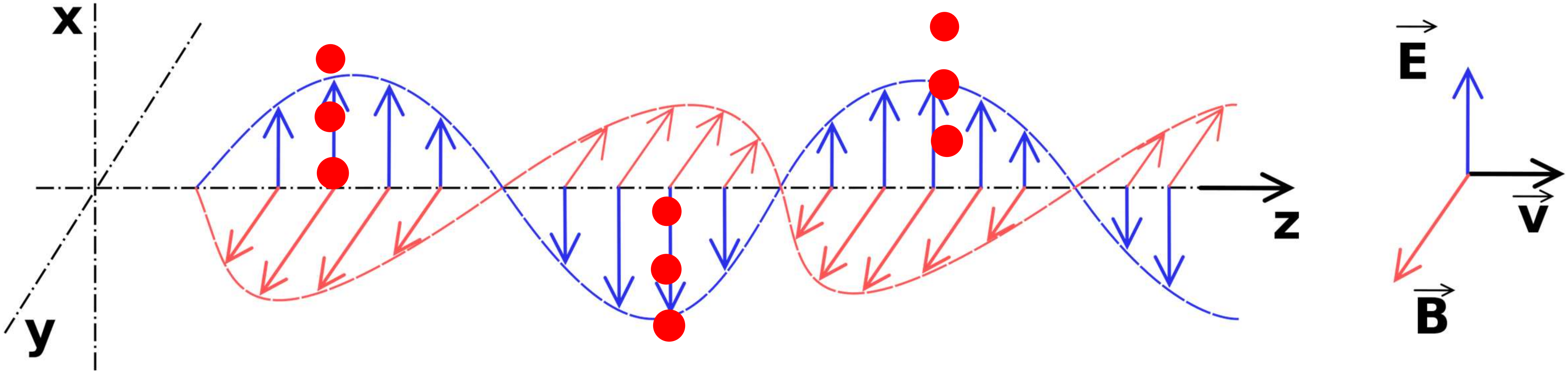


$$\left|\vec{E}\right| \propto Intensity\ of\ Light$$

Wave-particle duality

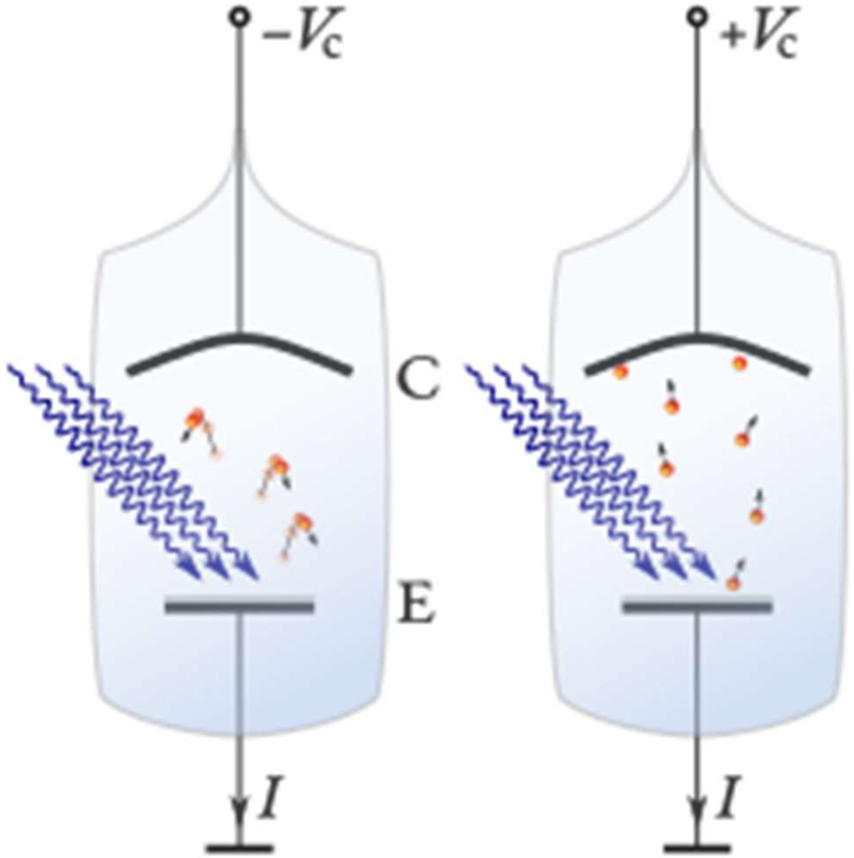


Wave-particle duality



Observed Photon

Photoelectric effect



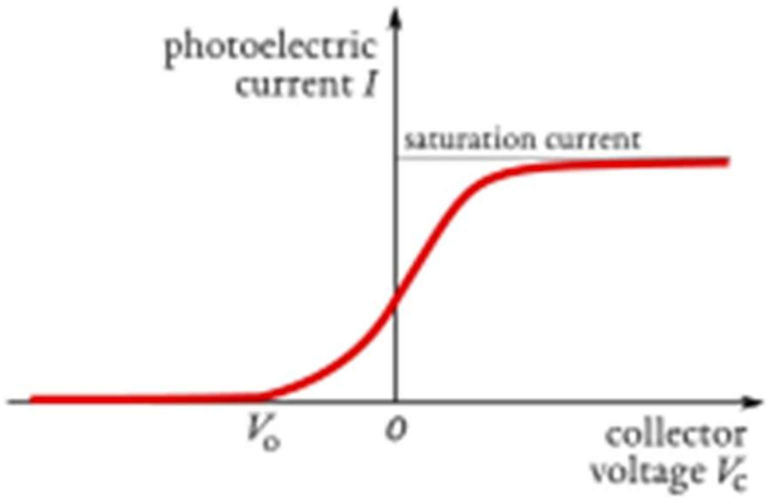
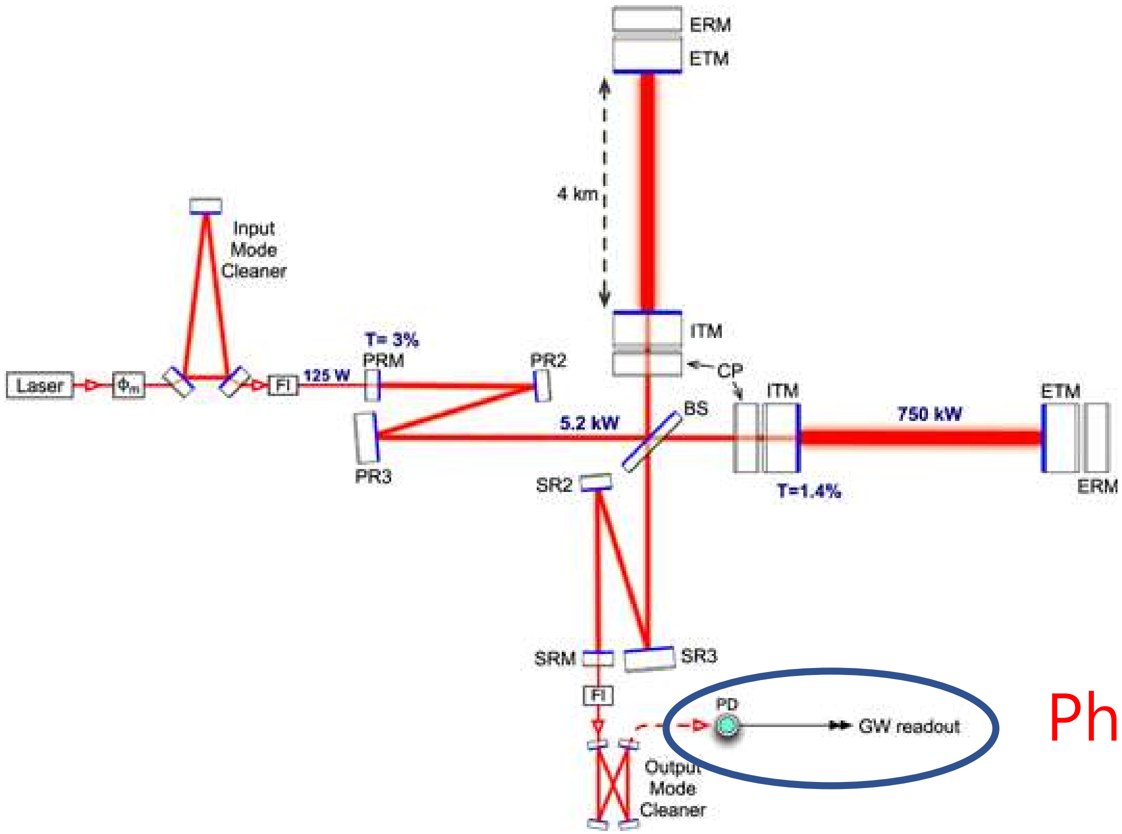


Photo detector

Amplitude of electricfield
$\propto Number\ of\ photon$

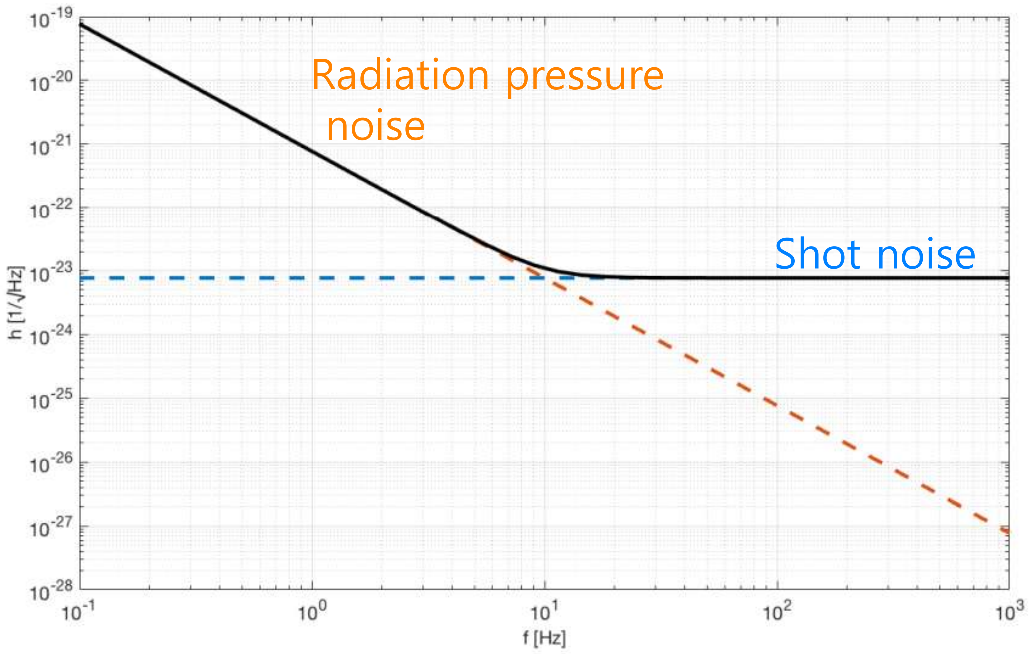
Measuring the intensity of light
= Counting the number of photon

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

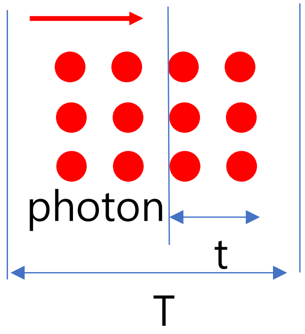
Shot noise of interferometer

$$E = h\nu$$

Photon energy

Laser power(W) = the number of photon(n) / time(s)

$nh\nu$ = / s



Shot noise

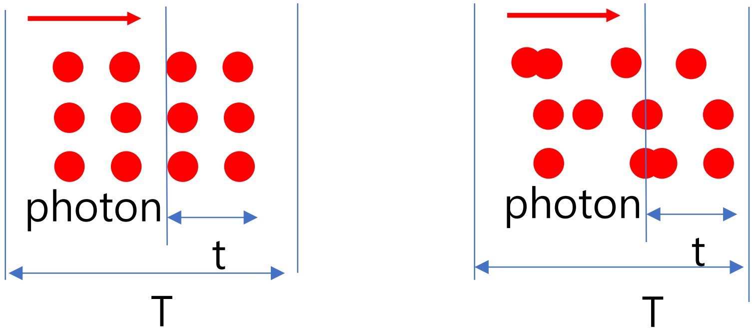
Shot noise of interferometer

$$E = h\nu$$

Photon energy

Laser power(W) = the number of photon(n) / time(s)

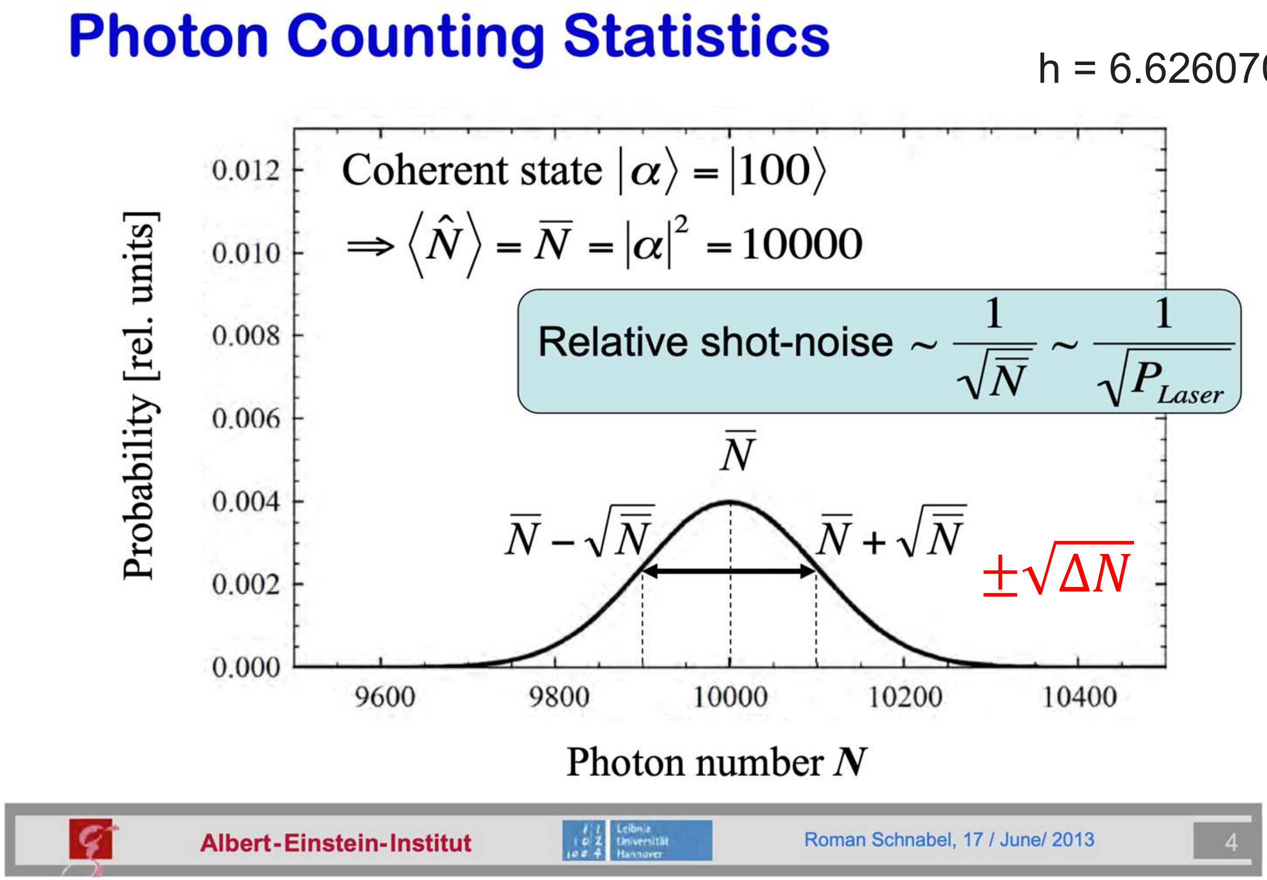
$nh\nu$ = / s



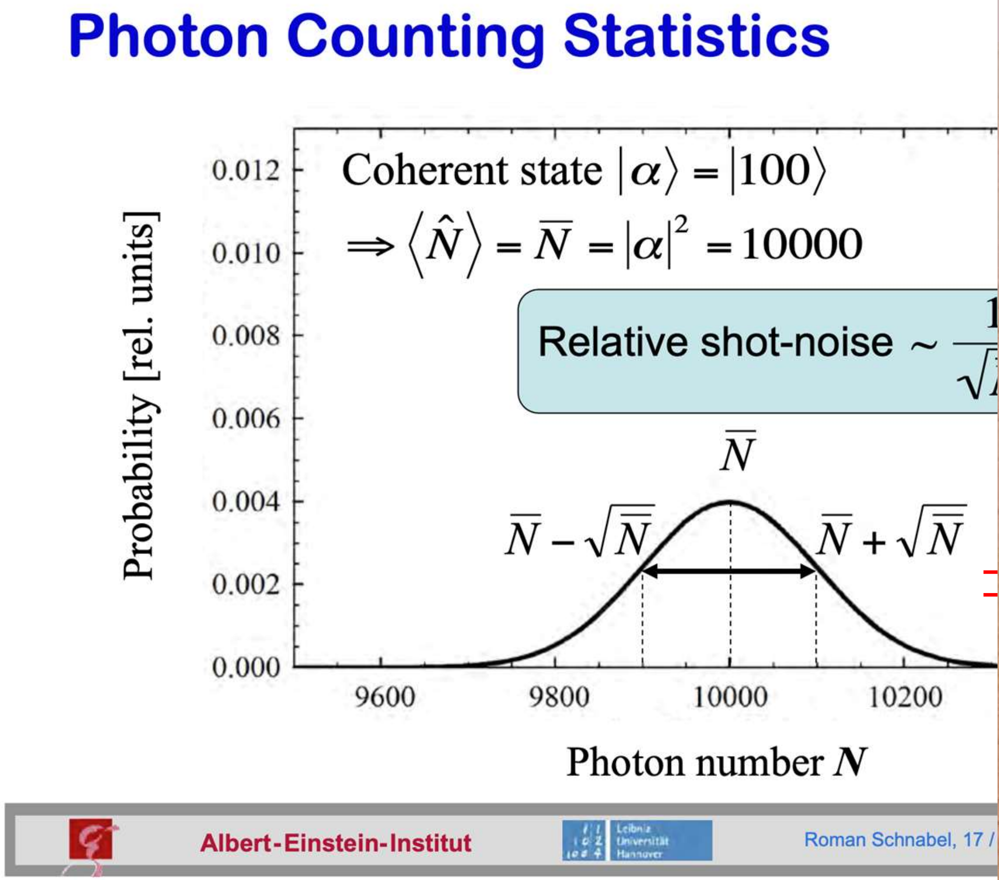
Shot noise

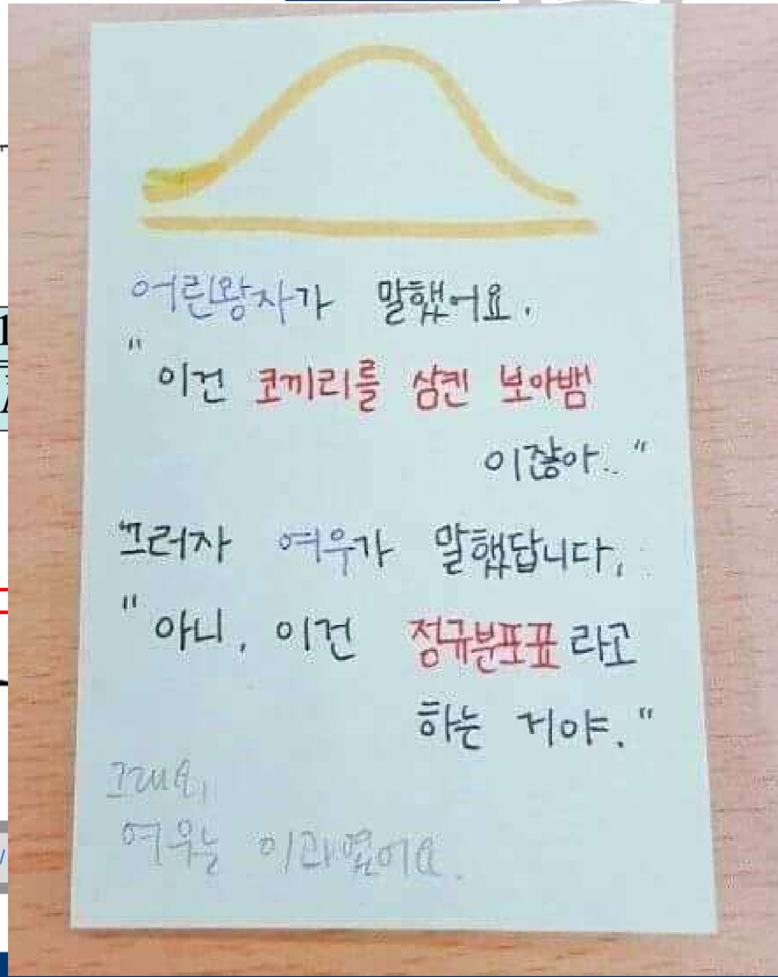
Shot noise of interferometer

$h = 6.62607015 \times 10^{-34}$ J·Hz^{-1}

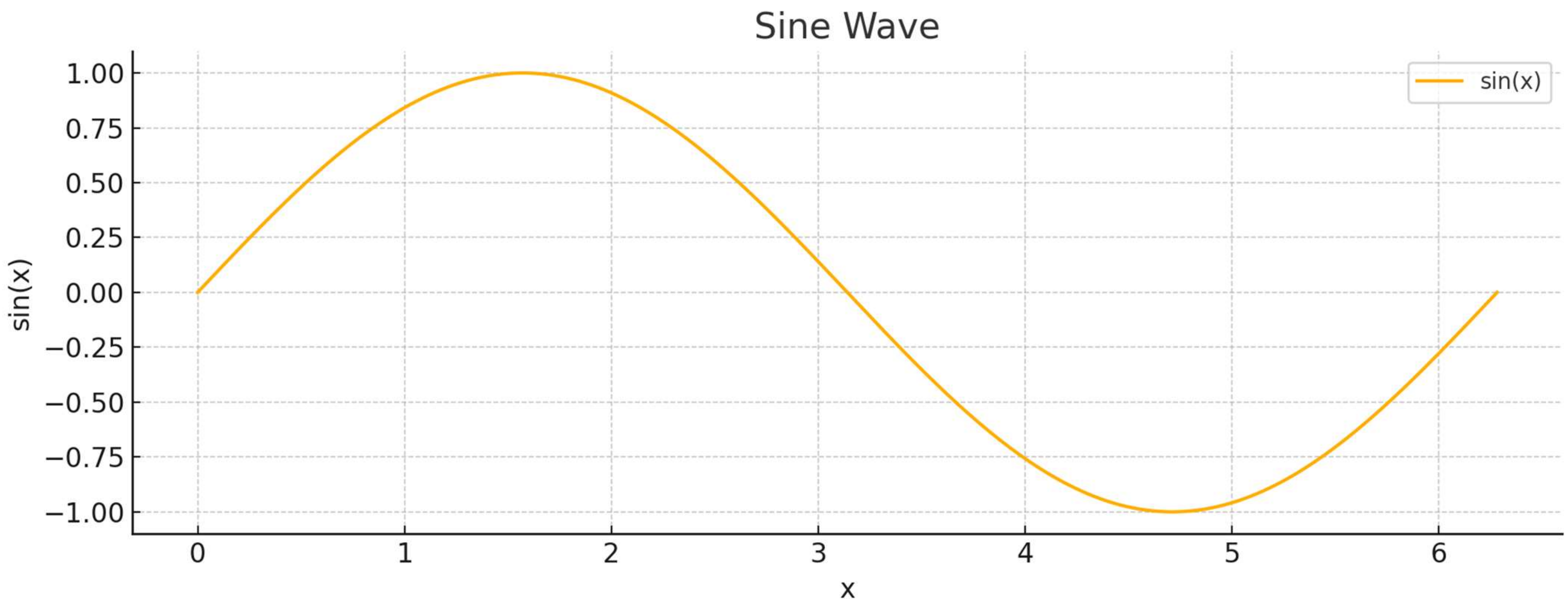


Shot noise of interferometer



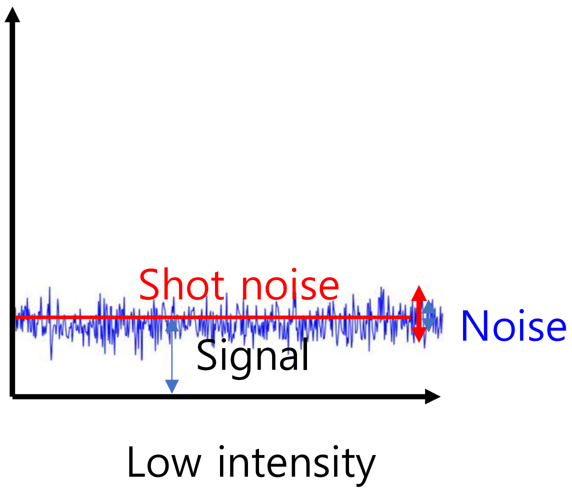


Sine wave



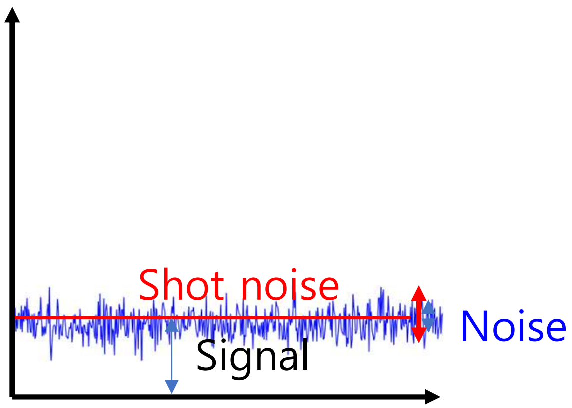
Sine Wave
sin(x)
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
0
1
2
3
4
5
6
x
sin(x)

Shot noise of interferometer

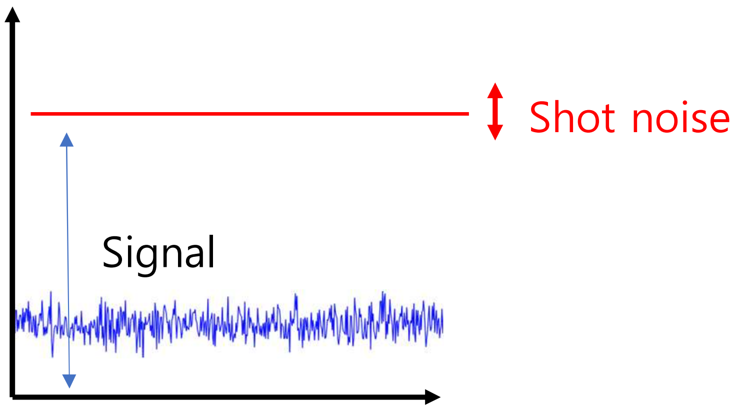


$$Signal\ to\ Noise\ ratio = \frac{N}{\sqrt{N}}$$

Shot noise of interferometer



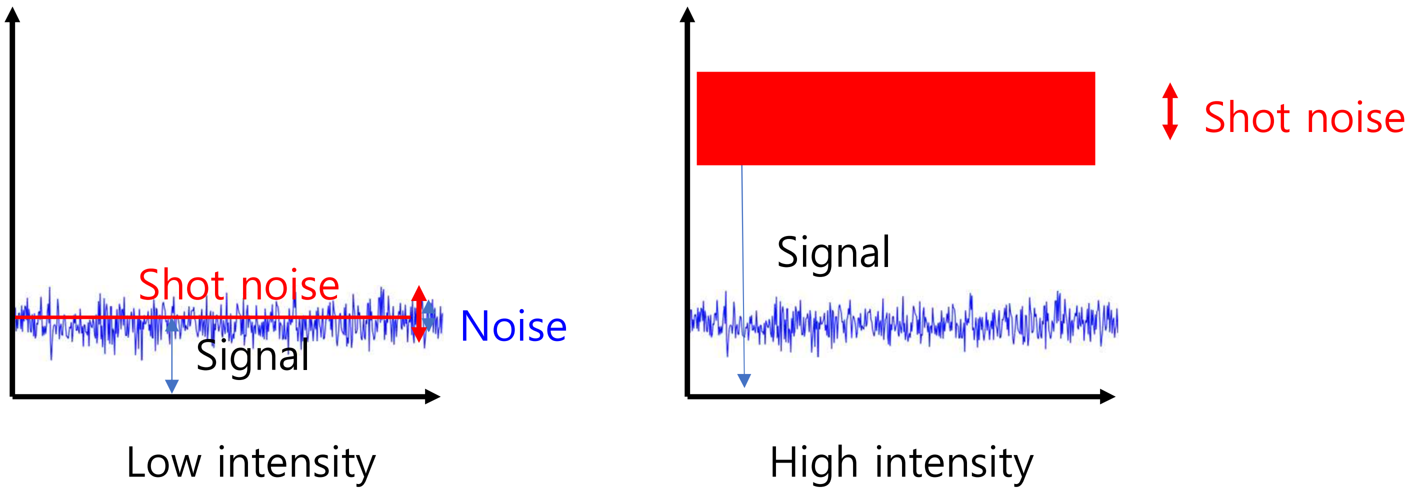
Low intensity



High intensity

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

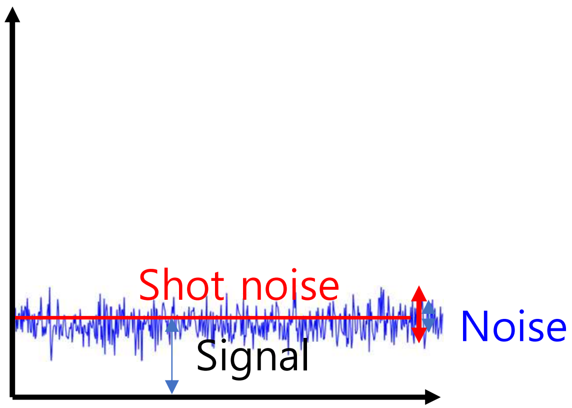
Shot noise of interferometer

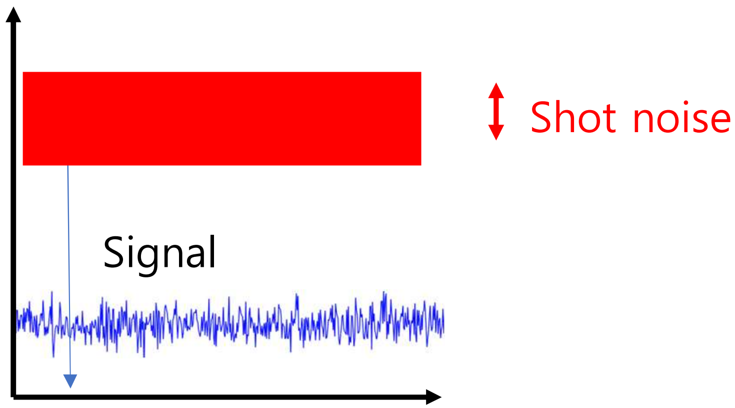


$$Signal\ to\ Noise\ ratio = \frac{N}{\sqrt{N}}$$

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

Shot noise of interferometer



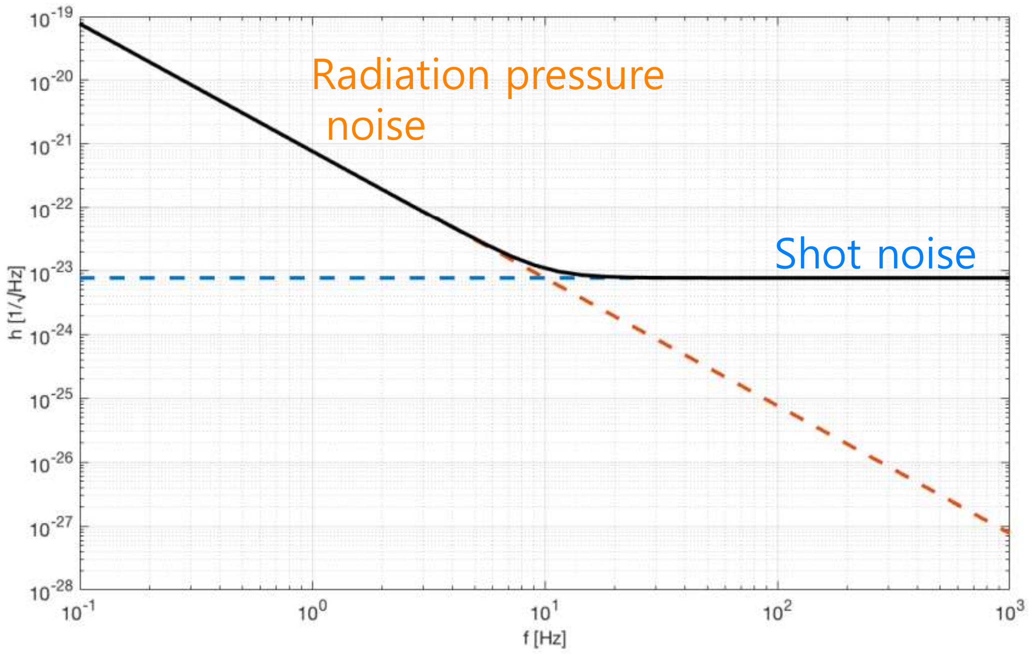


$$Signal\ to\ Noise\ ratio = \frac{N}{\sqrt{N}}$$

N=100 , SNR =10
N=10000 , SNR =100

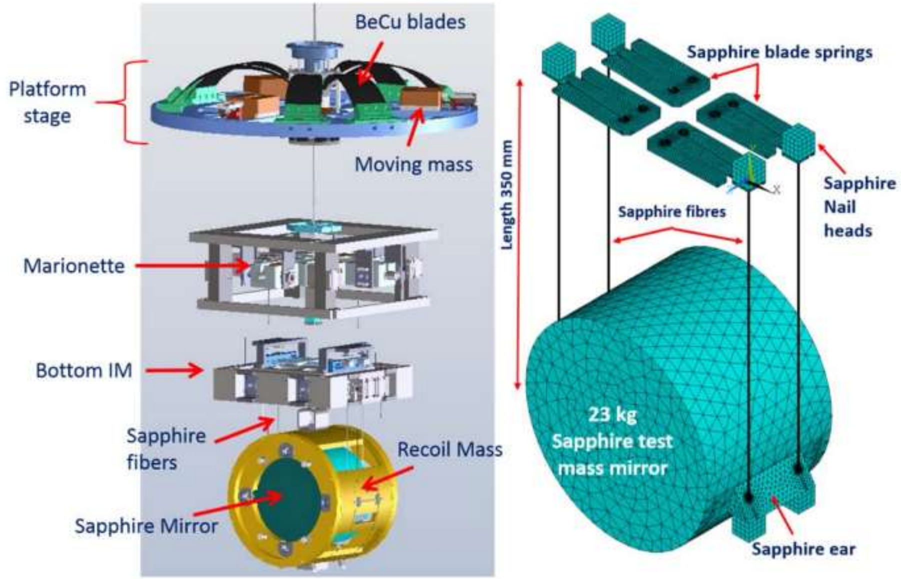
If Shot noise is relatively larger than other noise(Thermal, Electric.. etc)
We say that it has shot noise limit sensitivity

Standard quantum limit of GW detector

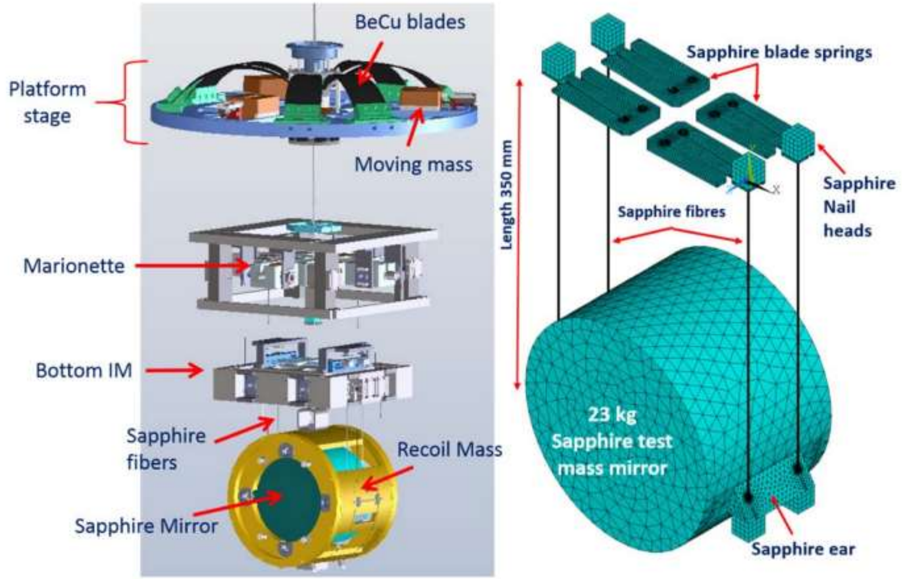


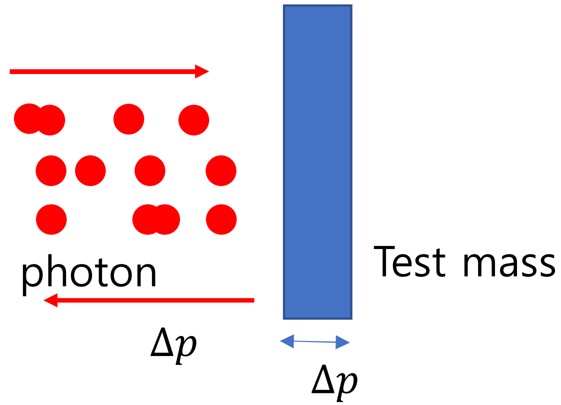
Standard quantum limit of gravitational wave detector
Shot noise + Radiation pressure noise

Radiation pressure noise



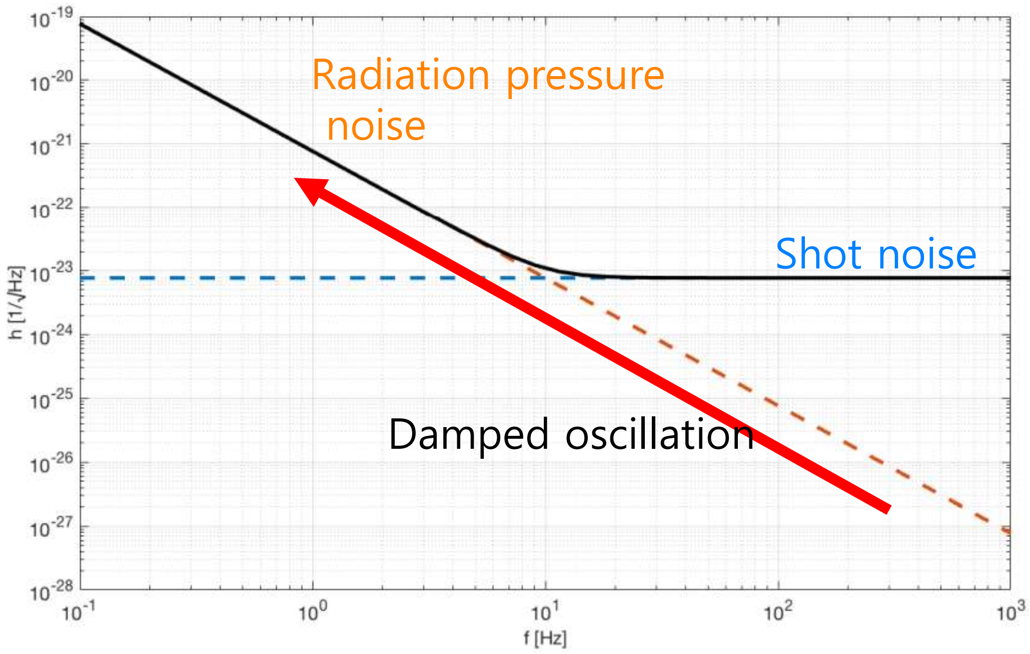
Radiation pressure noise





- 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

Radiation pressure noise
- Photon pressure fluctuation at **mirror**

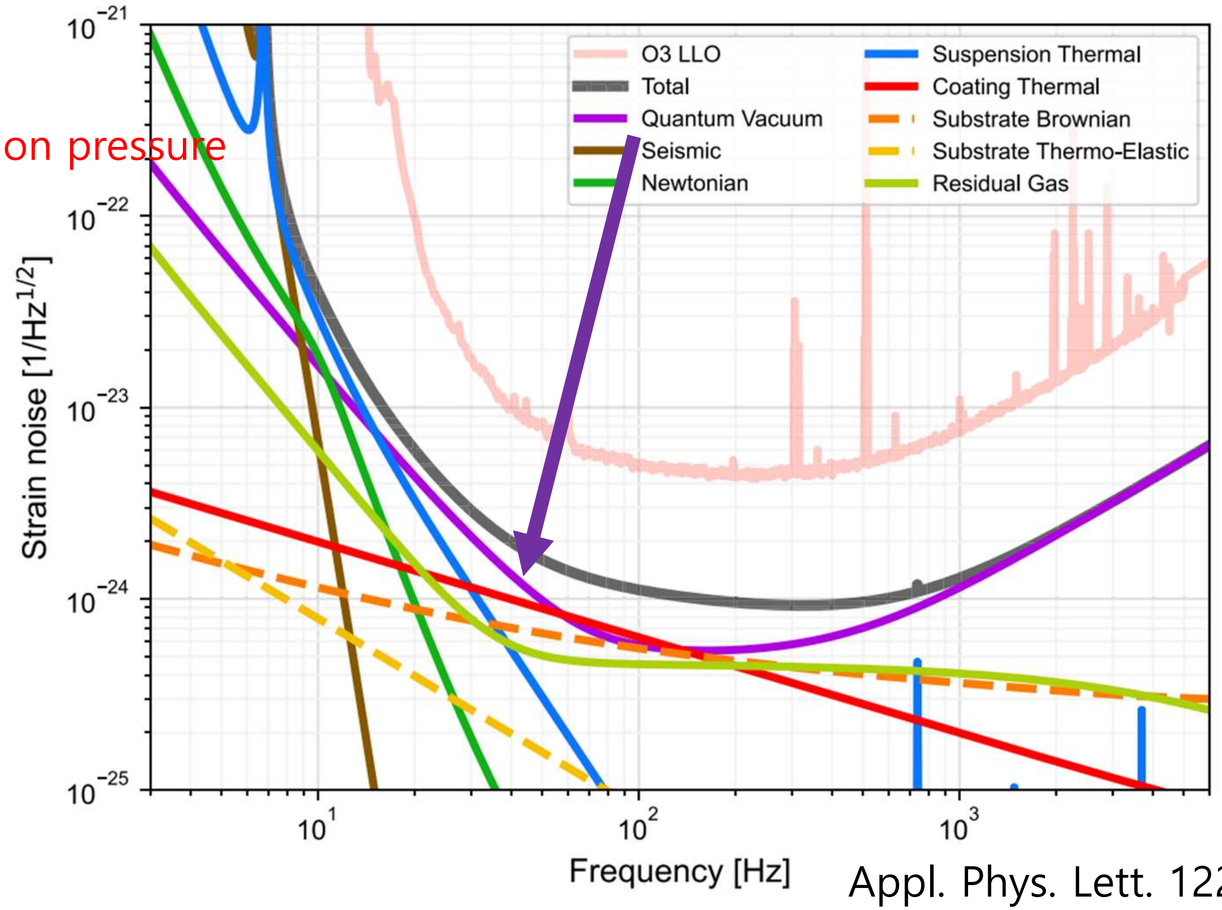
-> Intensity noise

Shot noise
- Photon number fluctuation at **PD**

-> Phase noise

LIGO sensitivity

Radiation pressure



Shot noise

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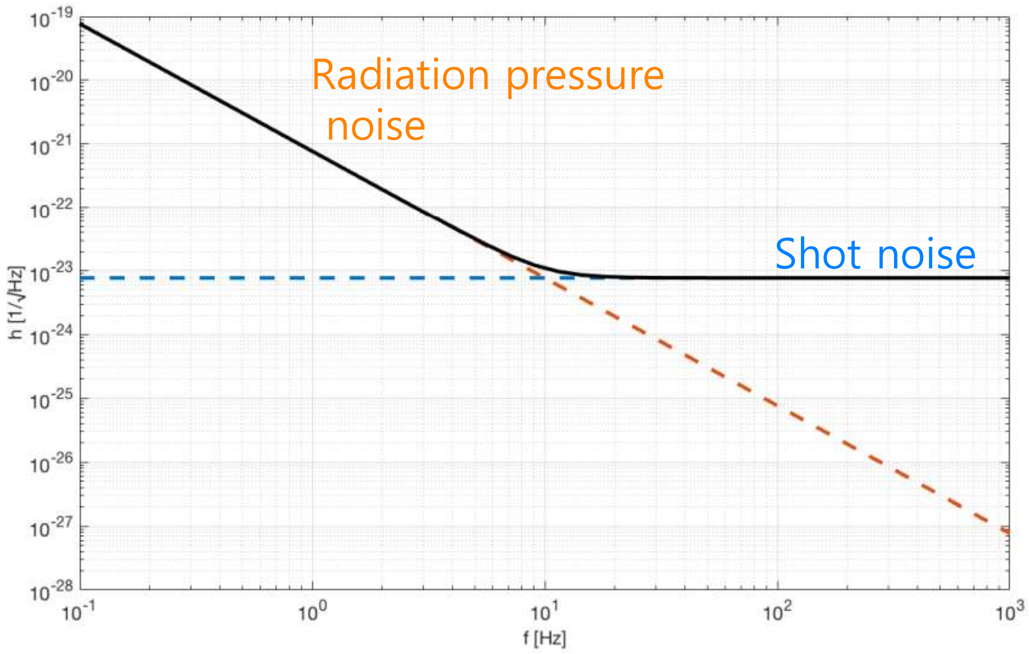
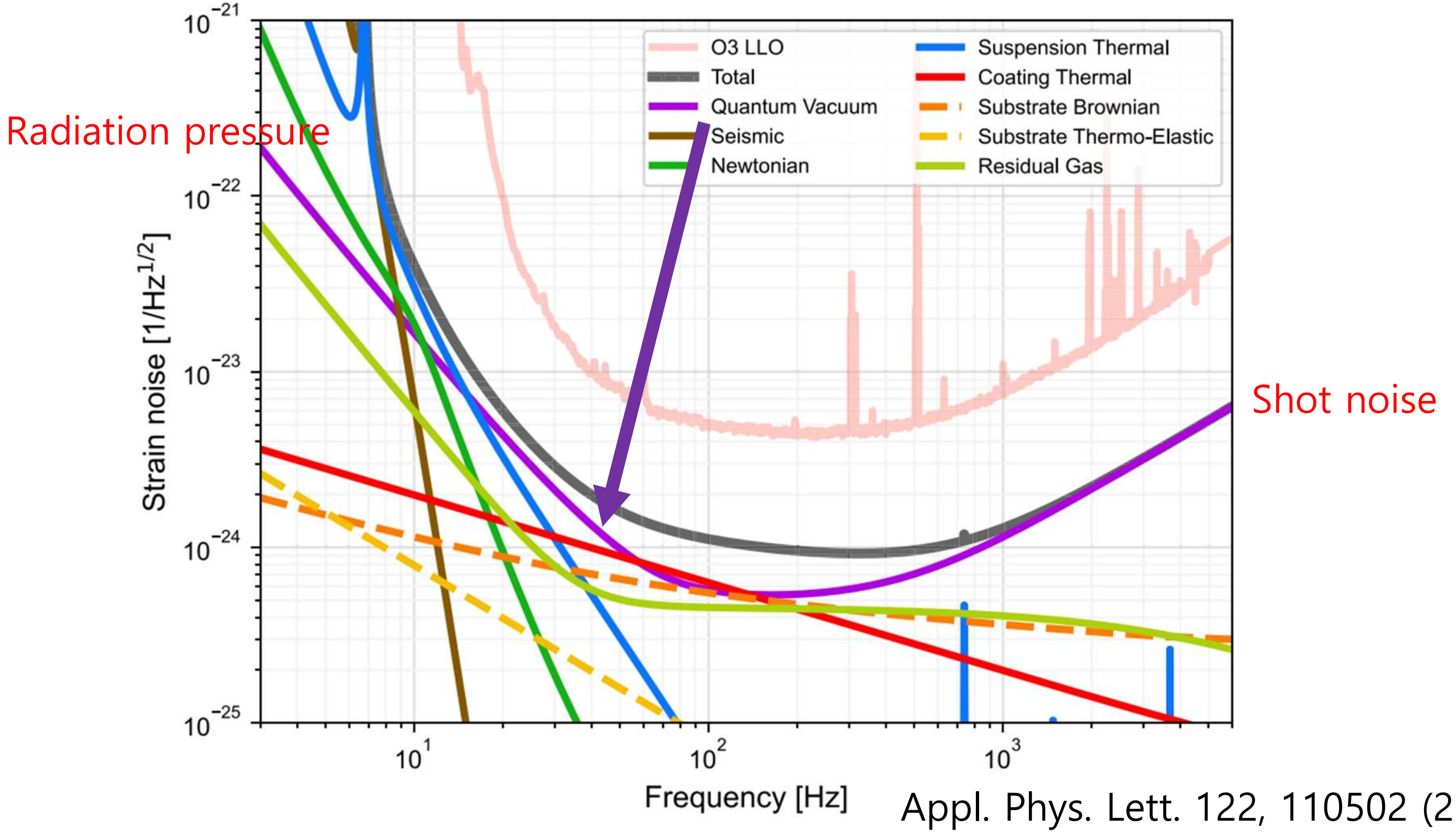
Standard quantum limit of GW detector



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

LIGO sensitivity



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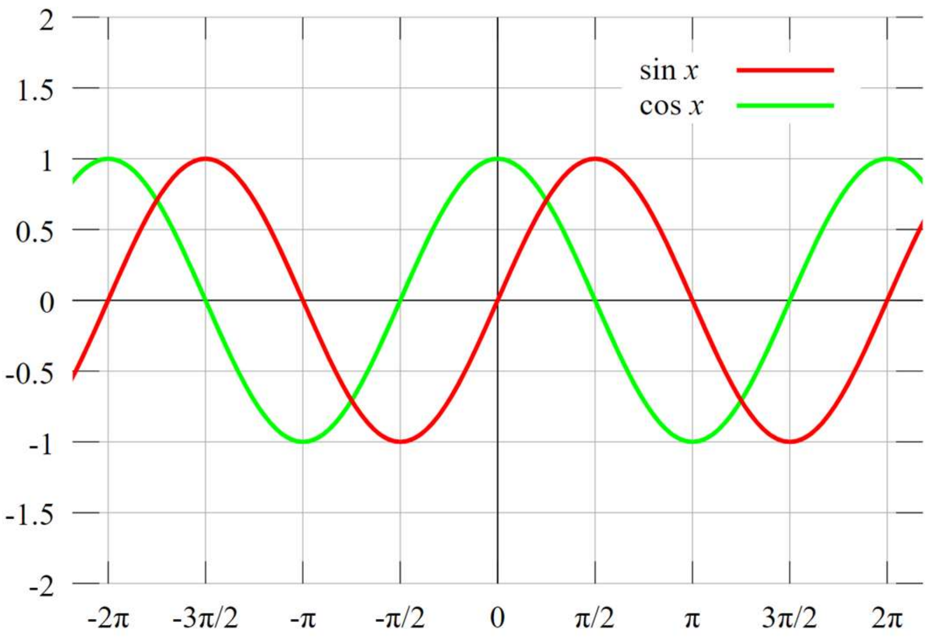
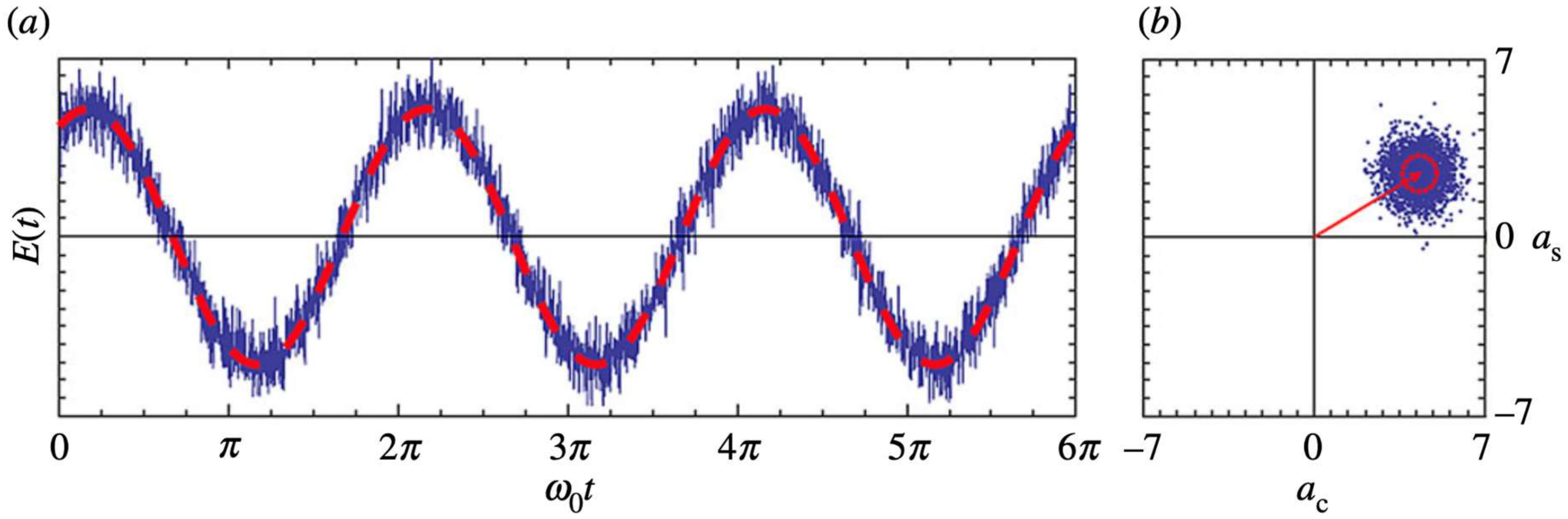
Classical electromagnetic wave

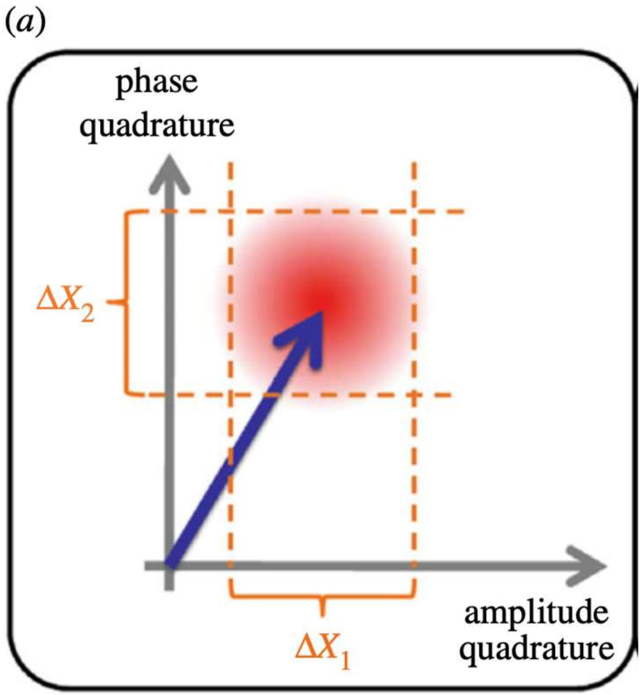


Quantum noise of coherent light



Heurs M. 2018 Gravitational wave detection u
sing laser interferometry beyond the standard
quantum limit.Phil. Trans. R. Soc. A 376: 20170
289.

Phase and amplitude quadrature



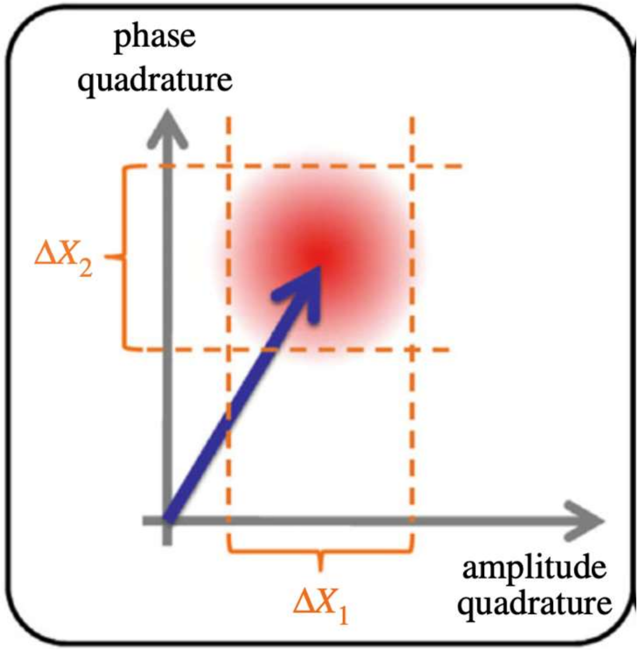
$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

Uncertainty principle

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

Phase and amplitude quadrature

(a) Shot noise



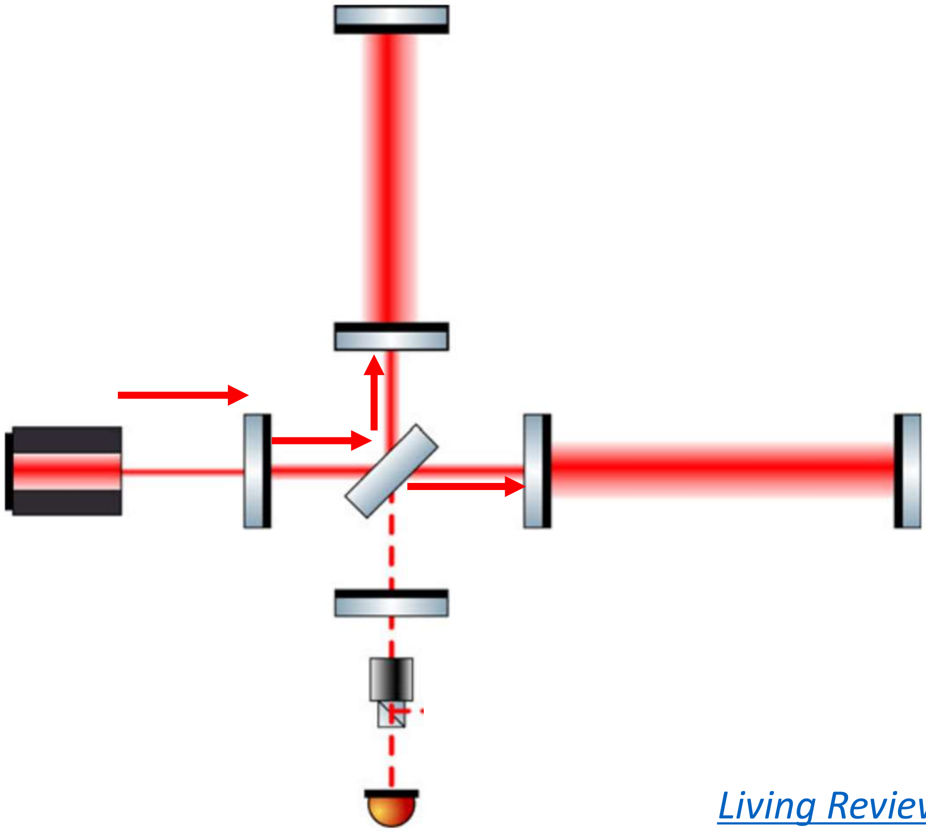
Radiation pressure noise

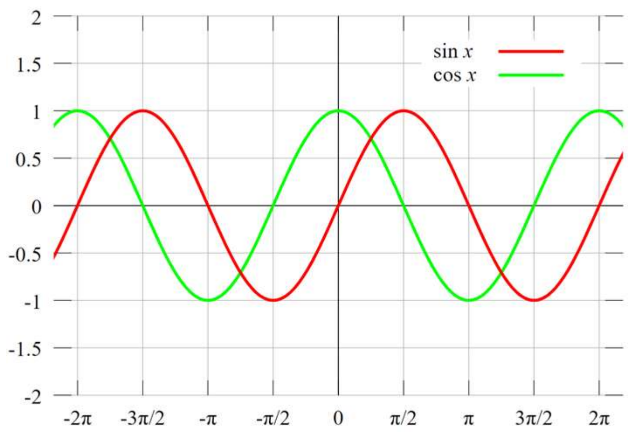
$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

Uncertainty principle

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

Gravitational wave detector





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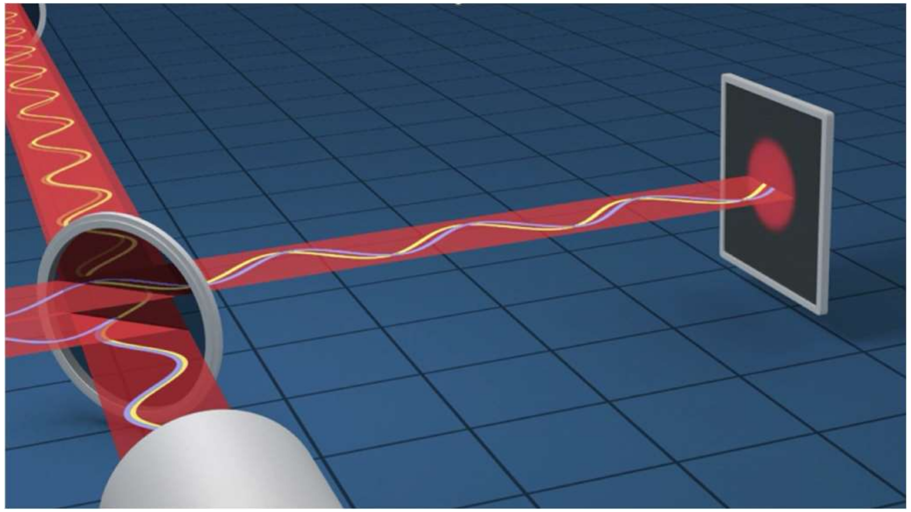
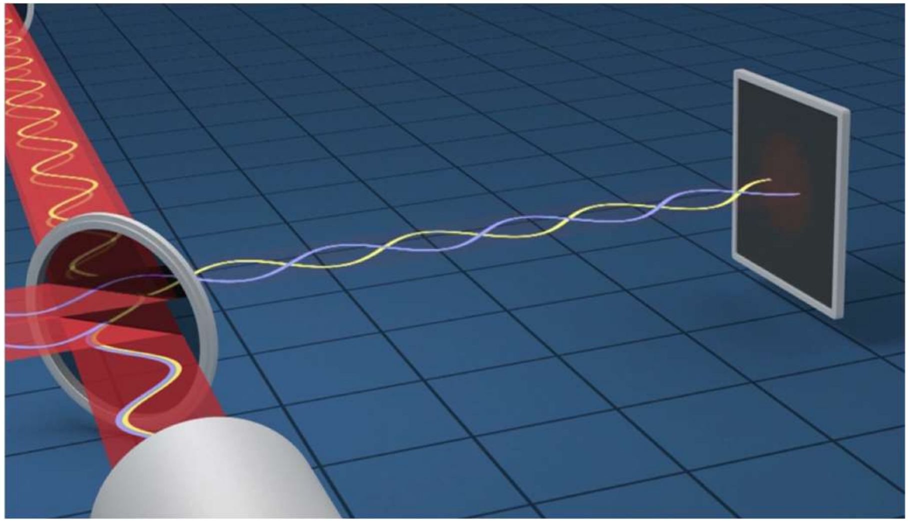
Bright port and dark port

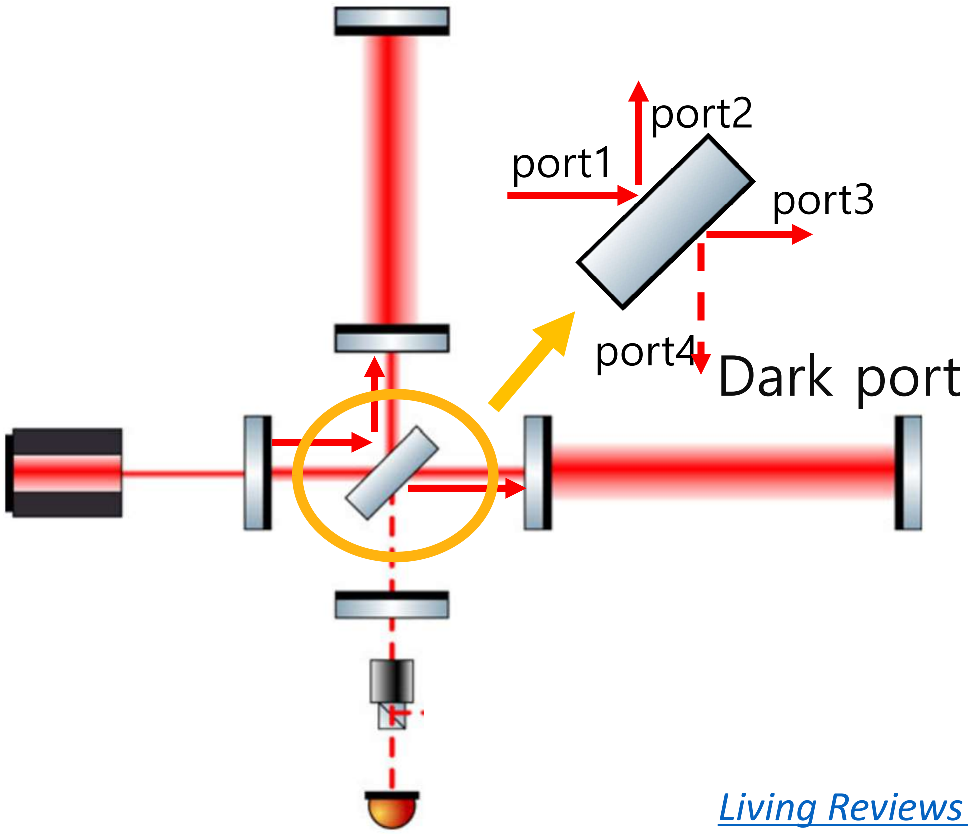


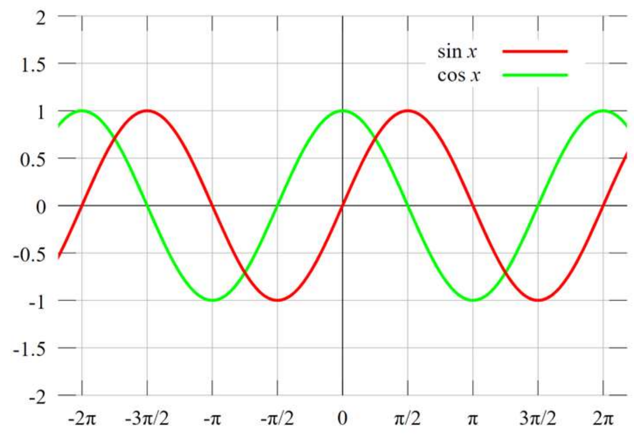
Bright



Dark

Gravitational wave detector





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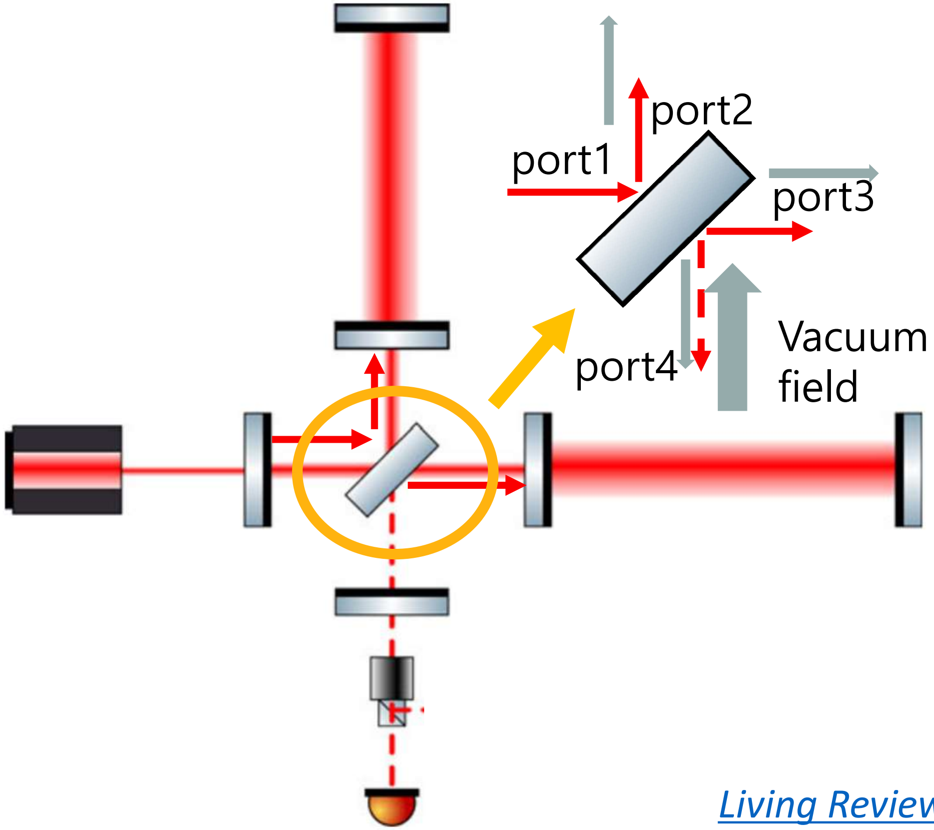
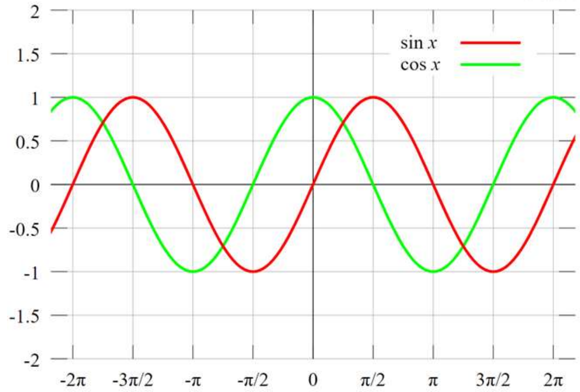
Quantum noise of gravitational wave detector





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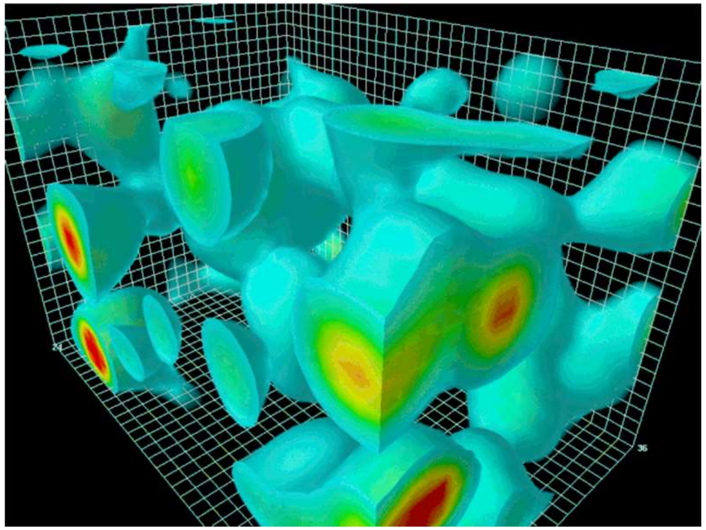
Quantum vacuum fluctuation

Vacuum ≠ empty

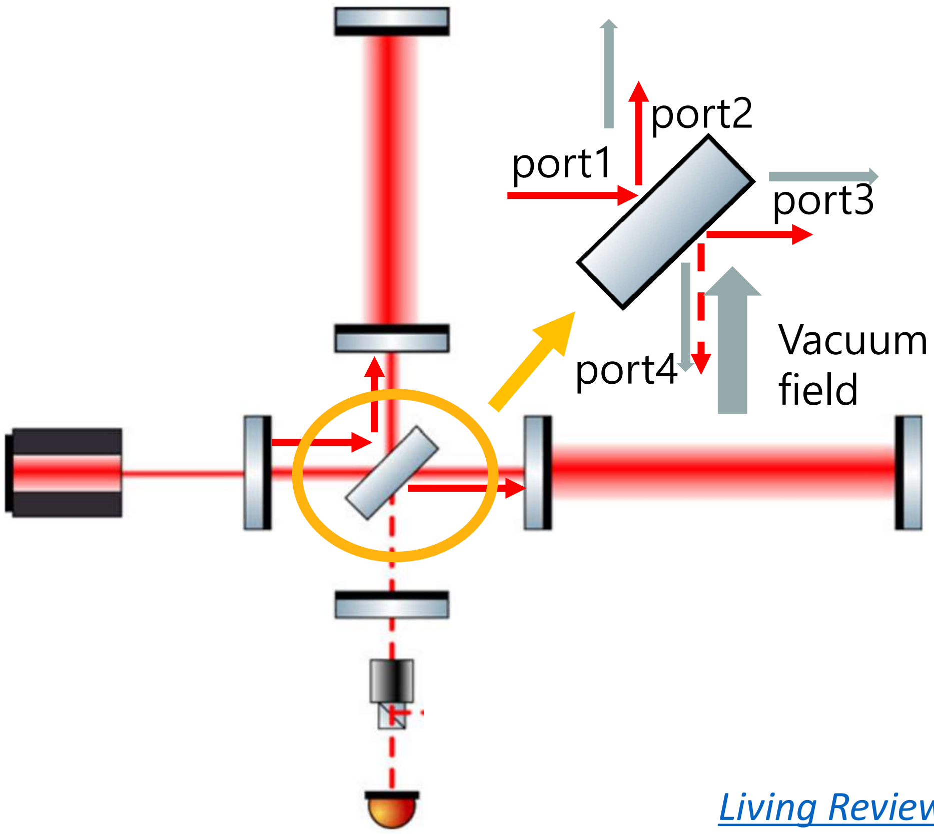
Vacuum

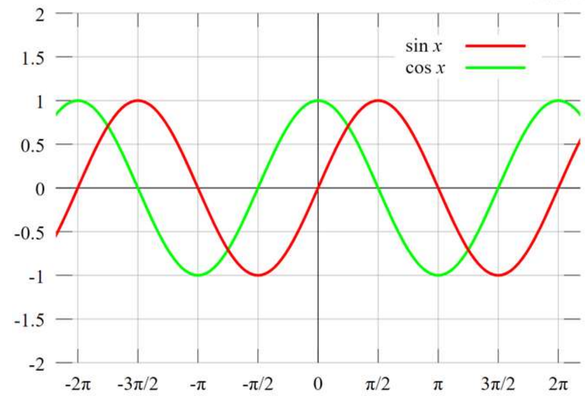
Transmission medium



Average energy = zeropoint energy

Quantum noise of gravitational wave detector





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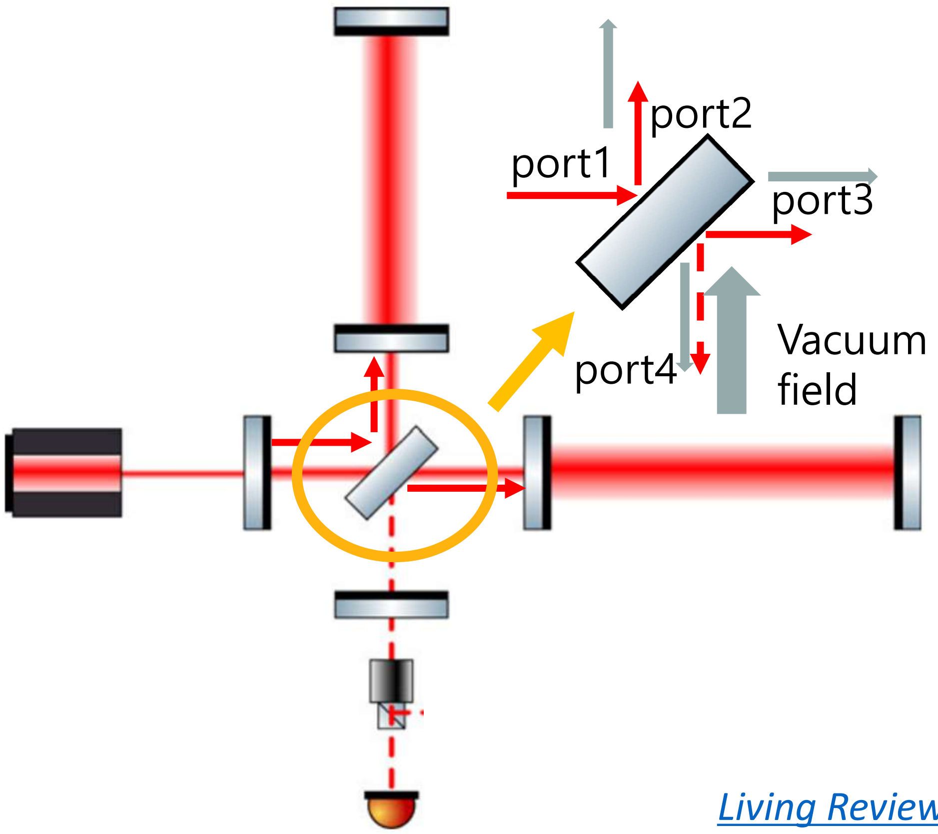
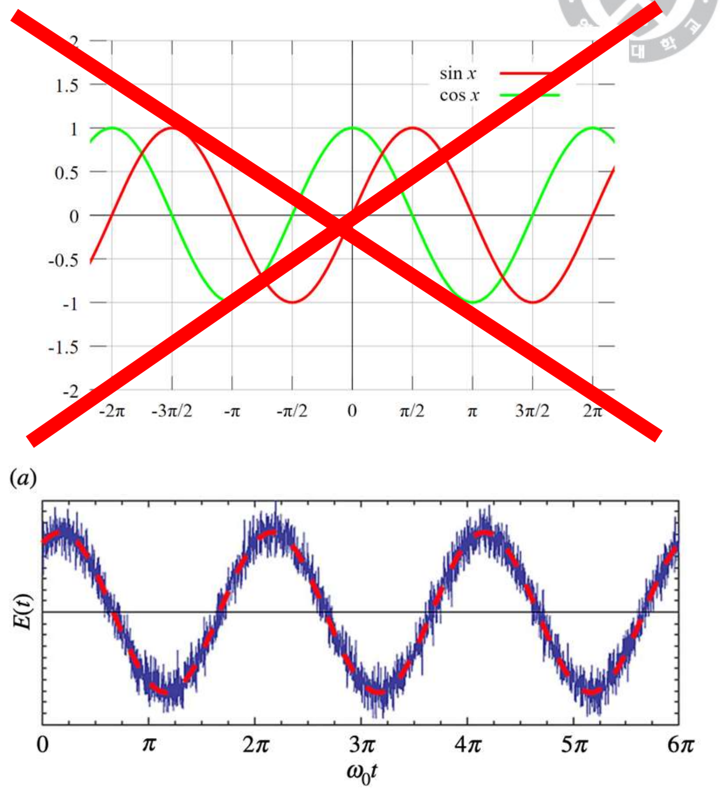
Quantum noise of gravitational wave detector





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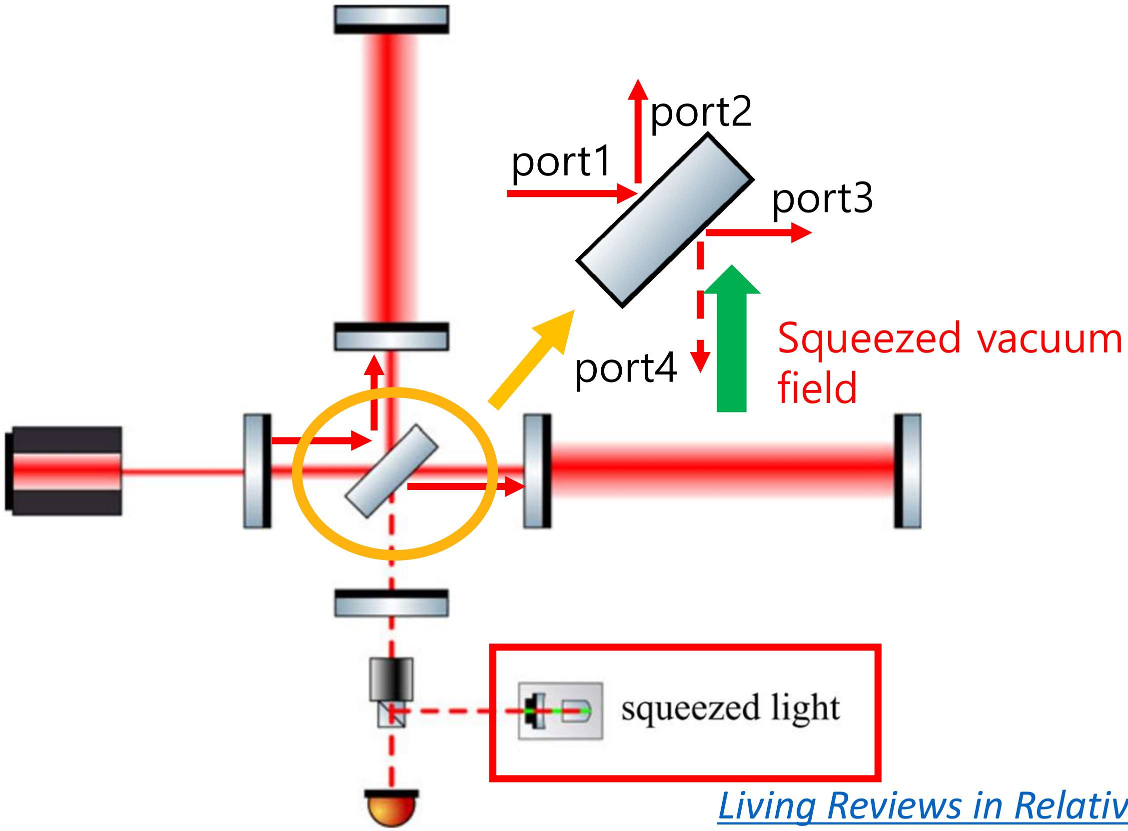
Gravitational wave detector



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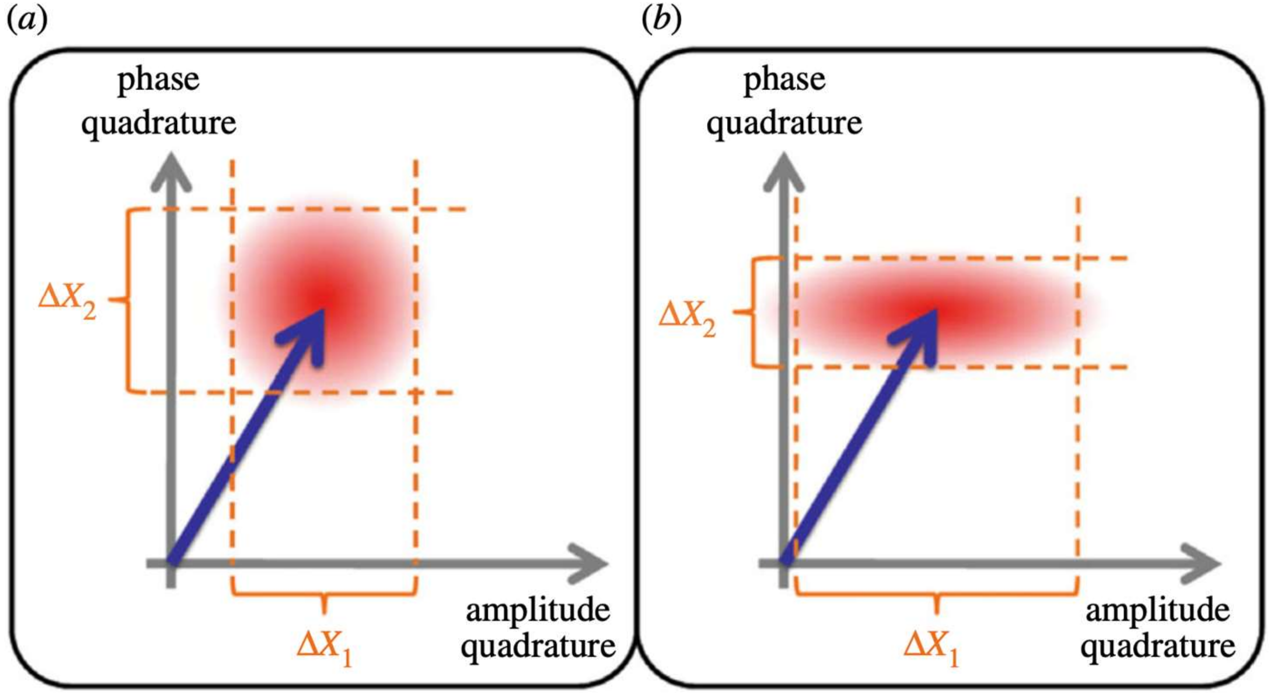
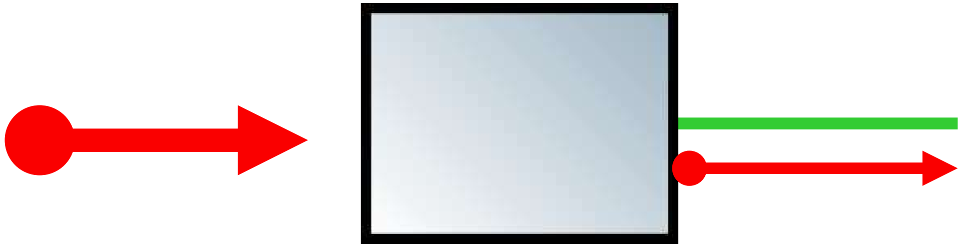
Squeezed light

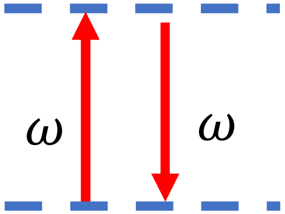


Heurs M. 2018 Gravitational wave detection using laser interferometry beyond the standard quantum limit.Phil. Trans. R. Soc. A 376: 20170289.

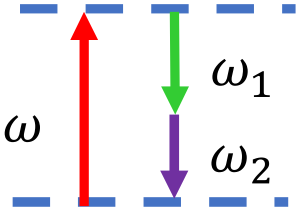
Non linear crystal



Non-linear crystal

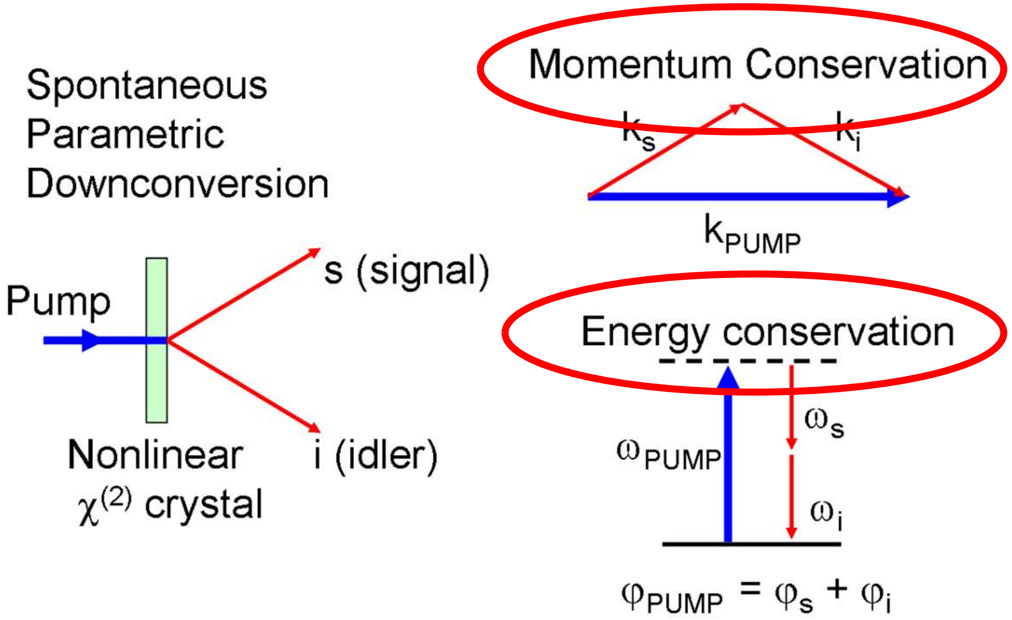


linear optics



Non linear optics

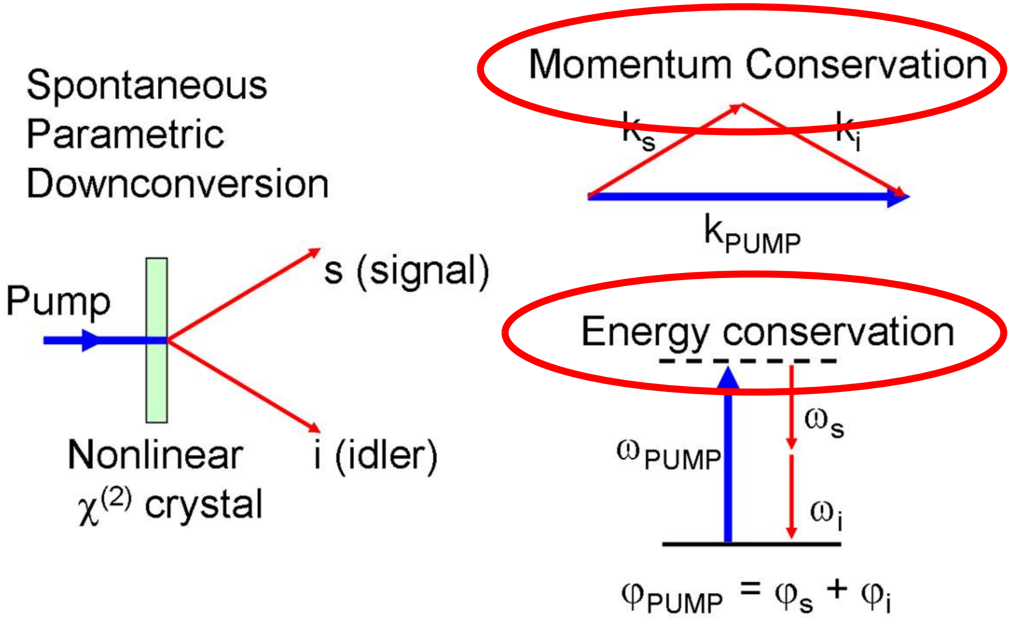
Parametric down conversion



J S Lundeen

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

Parametric down conversion

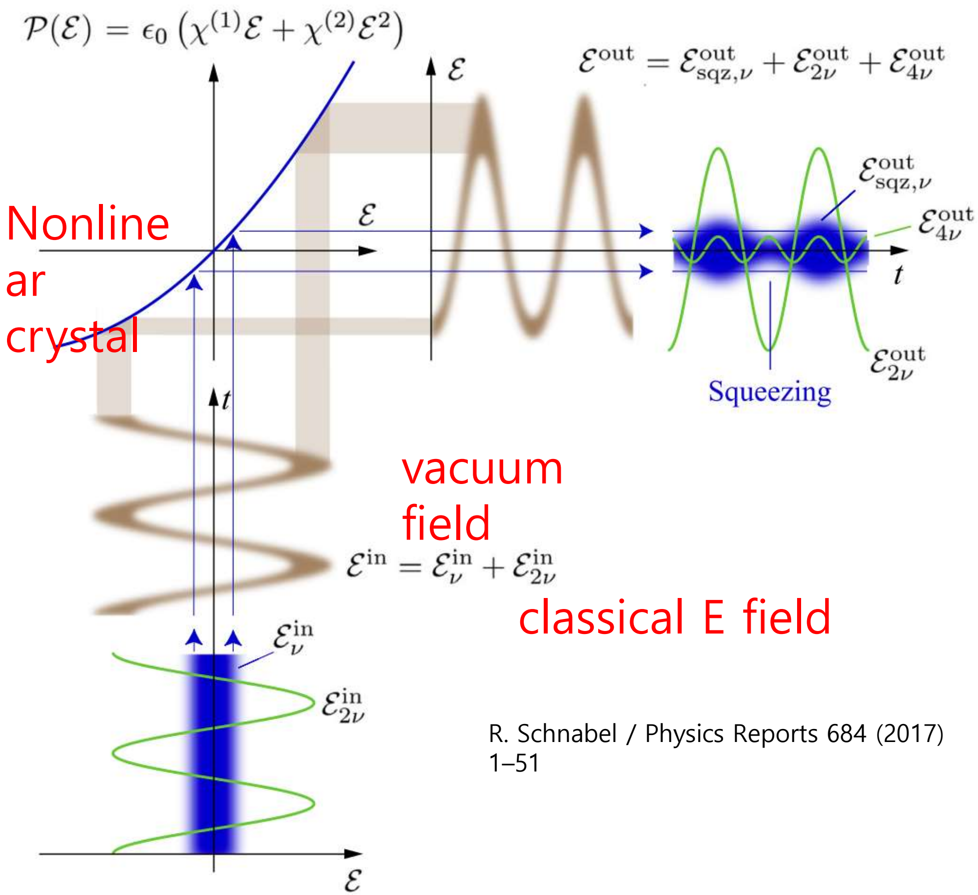


Every filed which are participated in
Non-linear conversion process,
Must obey energy, momentum conservation.

Even for vacuum field!!

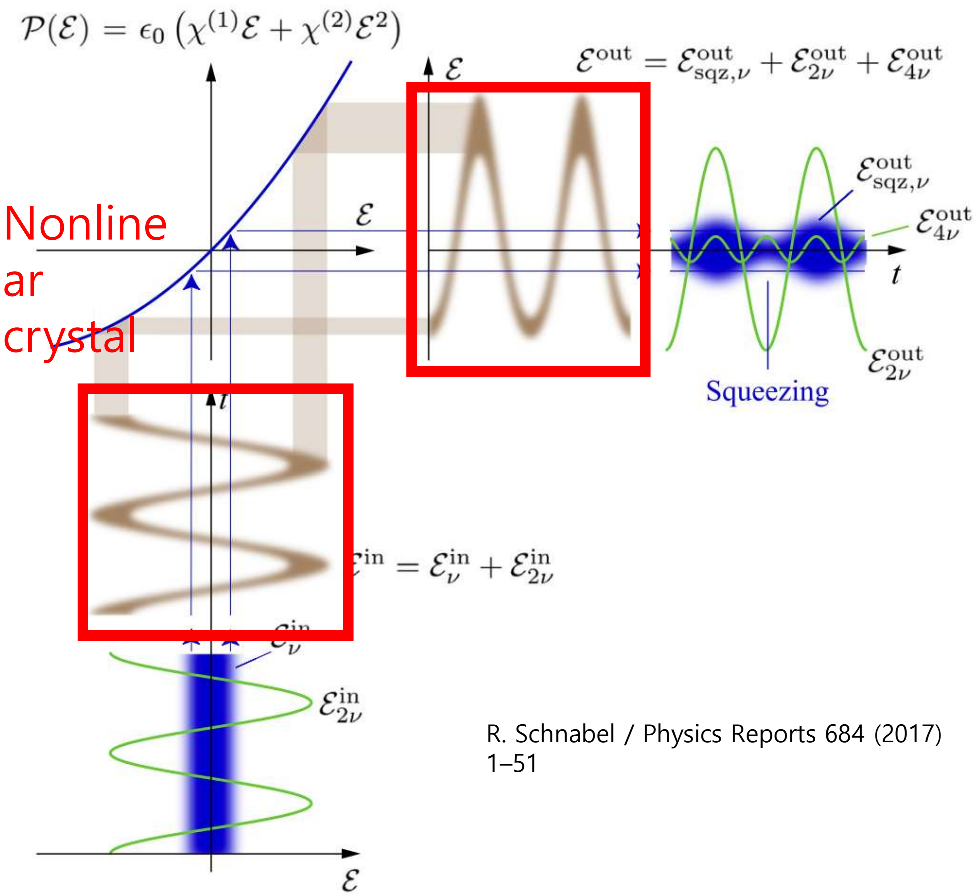
J S Lundeen

Parametric down conversion

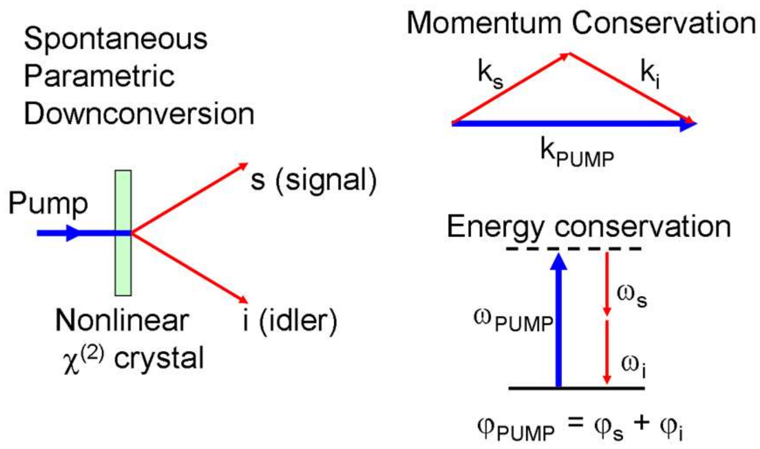


R. Schnabel / Physics Reports 684 (2017) 1–51

Parametric down conversion

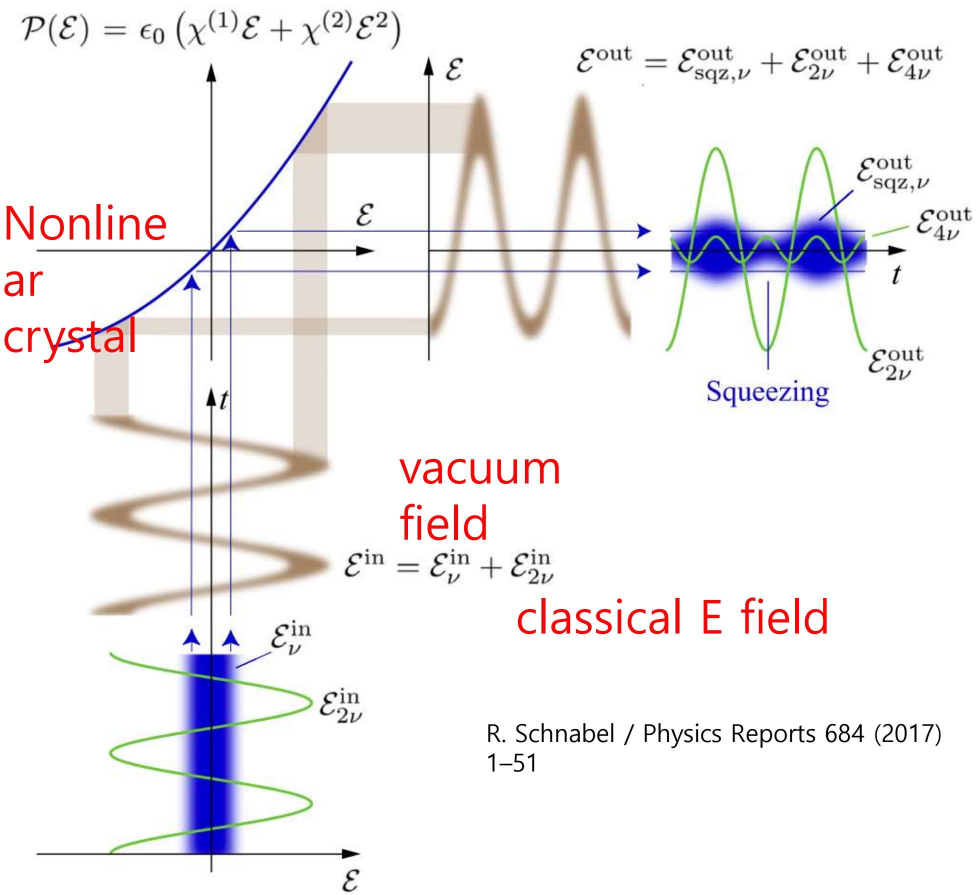


R. Schnabel / Physics Reports 684 (2017) 1–51



Boundary condition

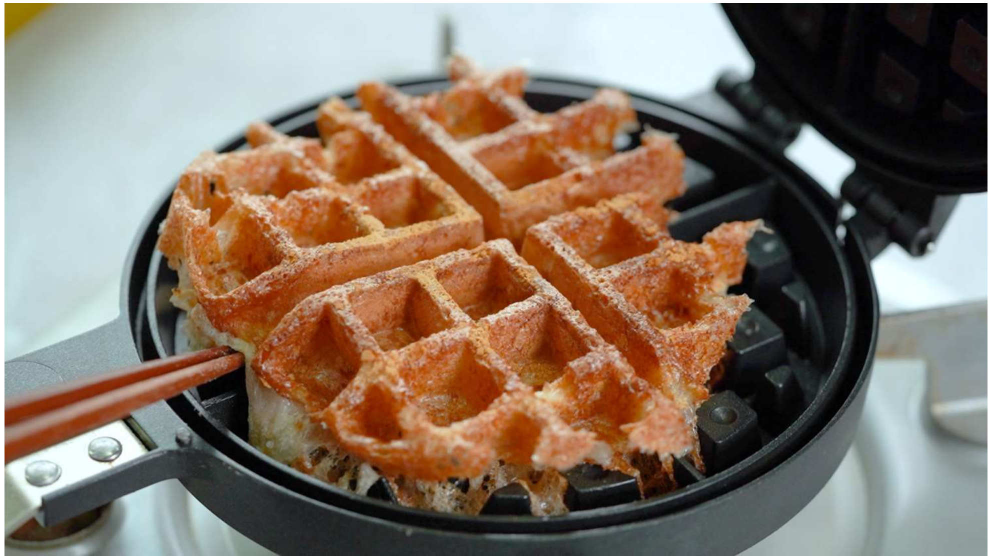
Parametric down conversion



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

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

Boundary condition



Squeezed vacuum

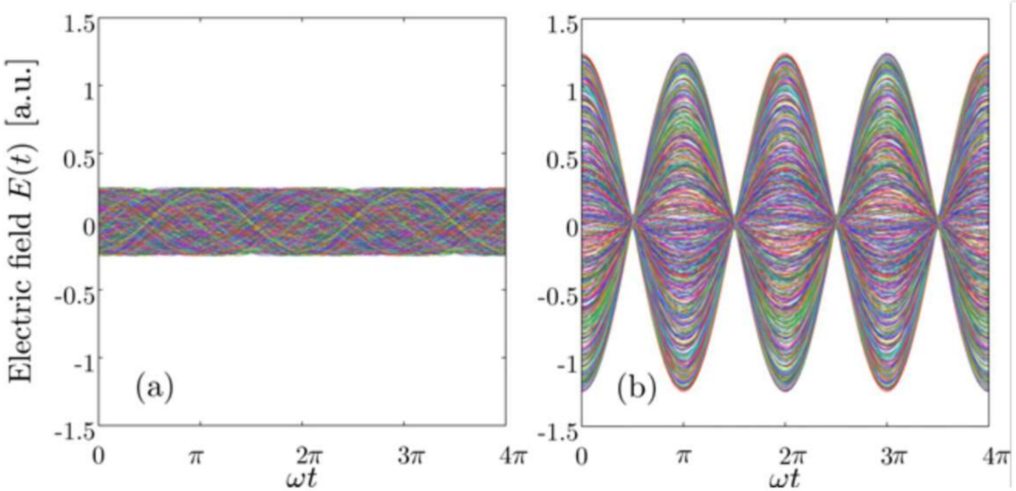
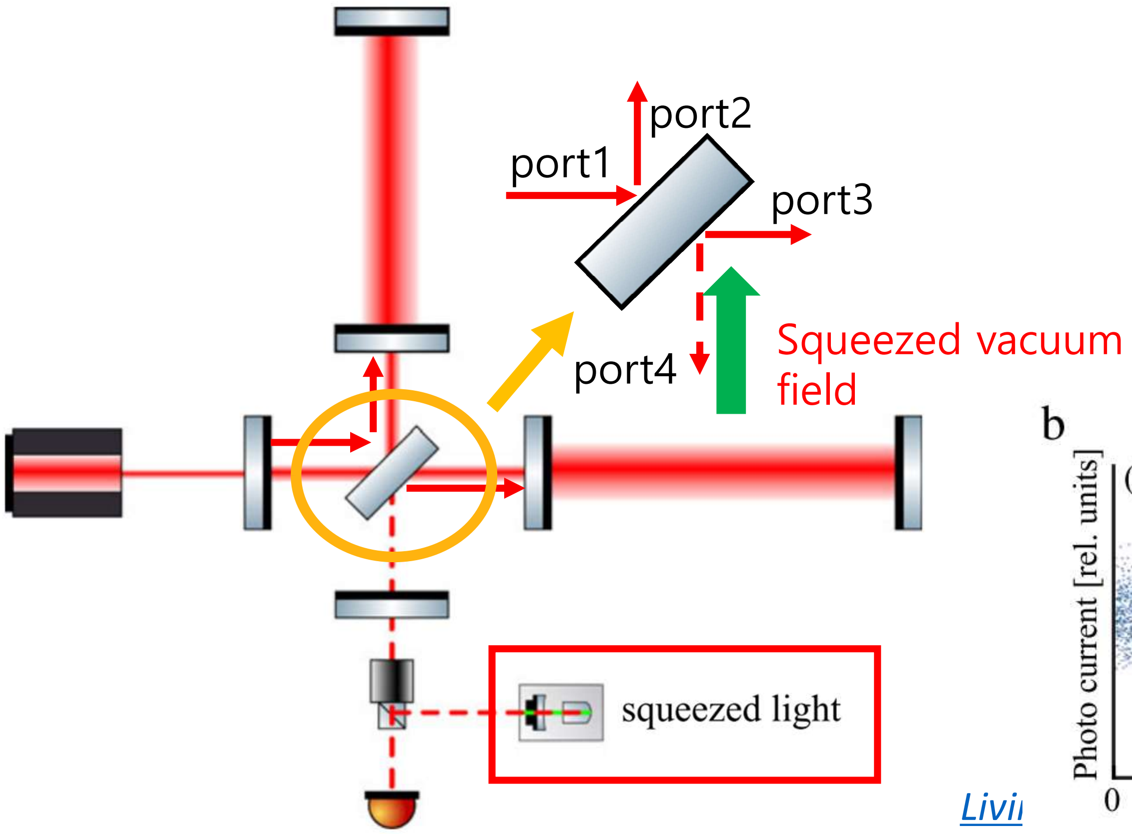
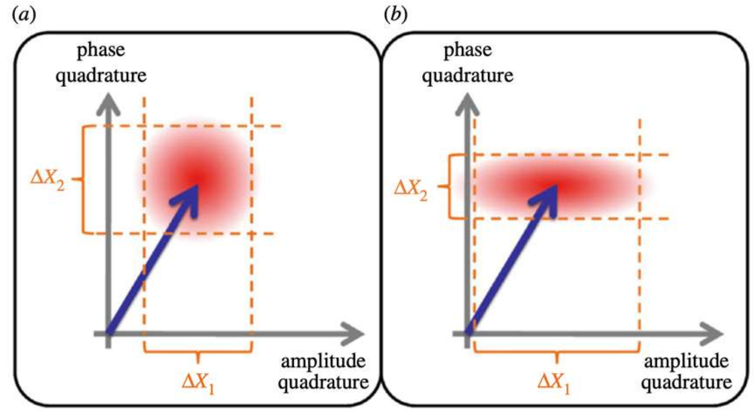
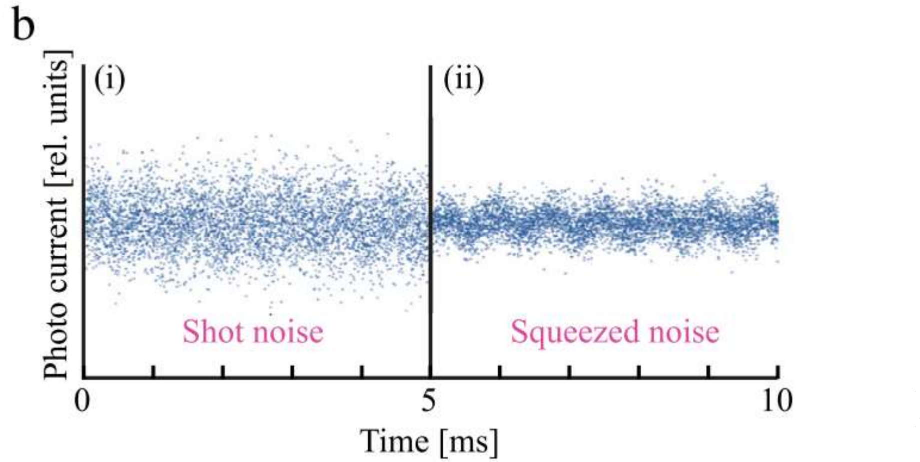


Figure 1.6: Simulation of electric field in time for (a) vacuum state and for (b) squeezed vacuum.

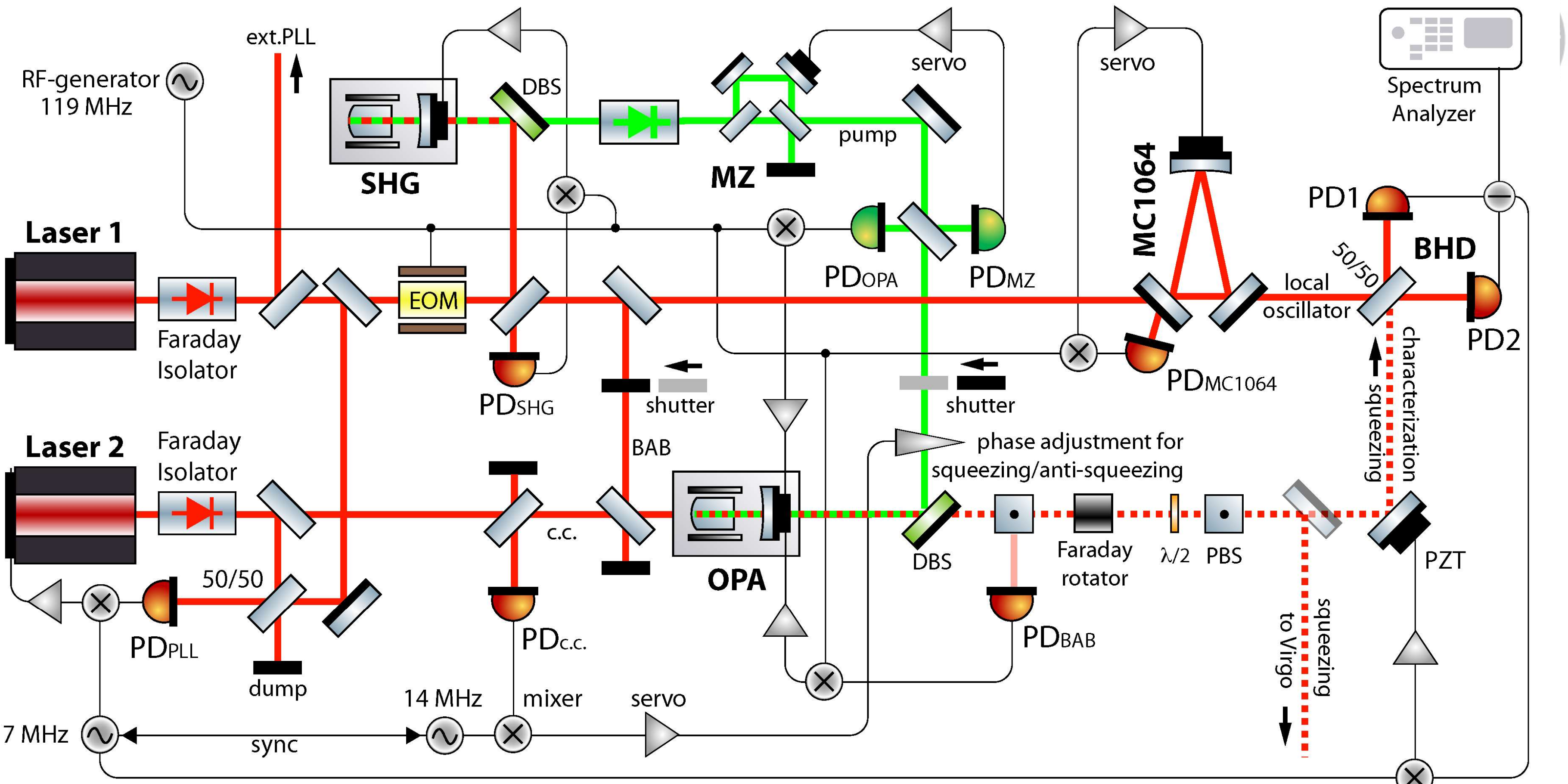
Gravitational wave detector





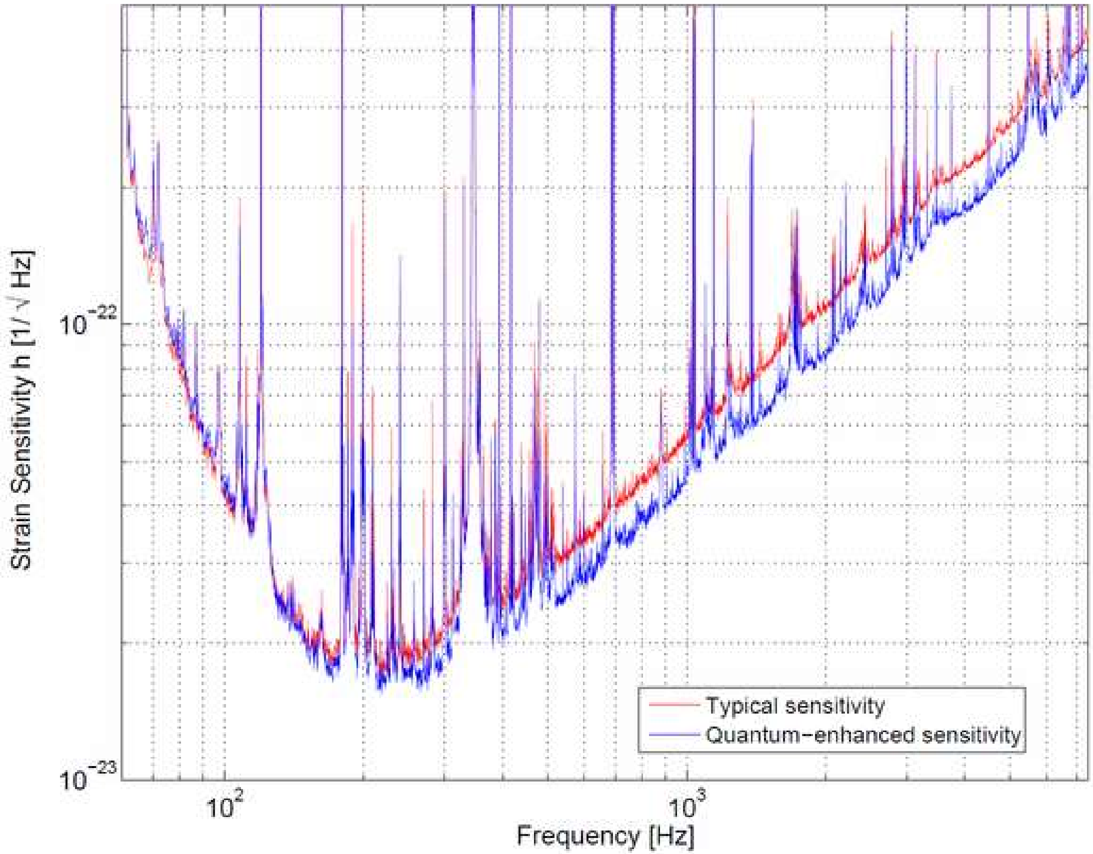


Livi 2019)



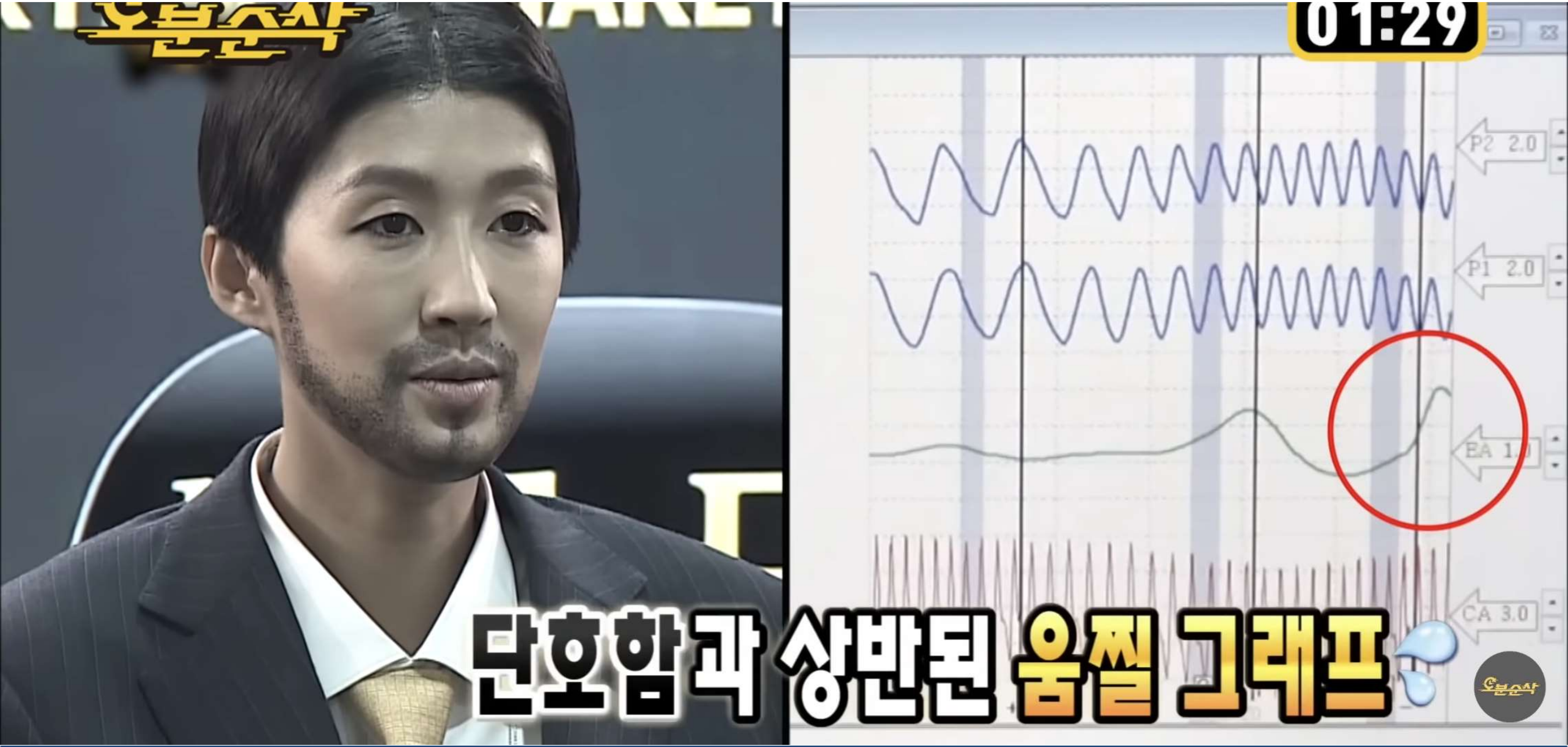
ext.PLL
RF-generator
119 MHz
SHG
DBS
MZ
servo
pump
servo
MC1064
Spectrum
Analyzer
PD1
BHD
Laser 1
Faraday
Isolator
EOM
PDOPA
PDMZ
local
oscillator
50/50
PD2
PDSHG
shutter
shutter
PDMC1064
Laser 2
Faraday
Isolator
BAB
phase adjustment for
squeezing/anti-squeezing
squeezing
characterization
c.c.
OPA
DBS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

Quantum noise enhancement of LIGO




오분순삭
01:37
Q 지금 지쳤나요?
오분순삭


01:35
아니요
Q 지금 지쳤나요?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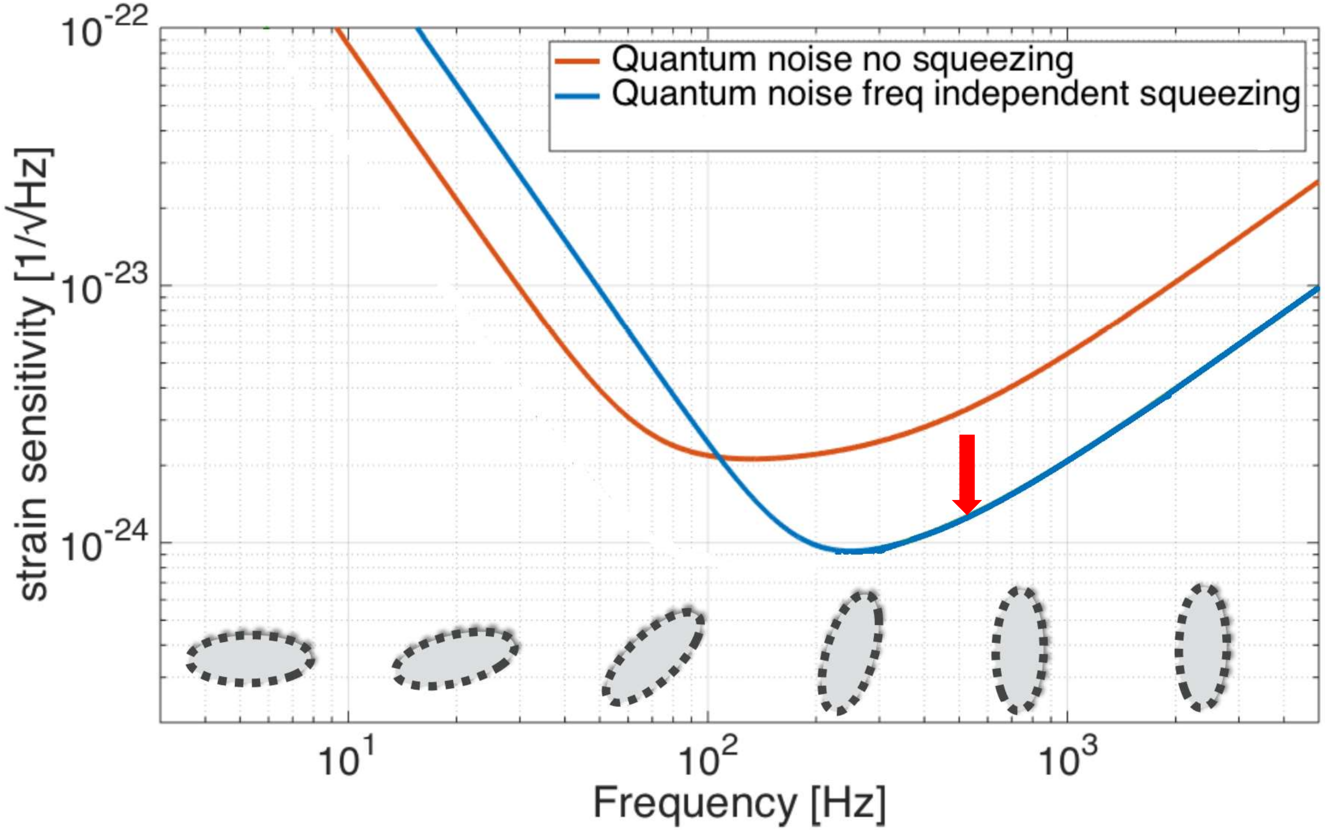
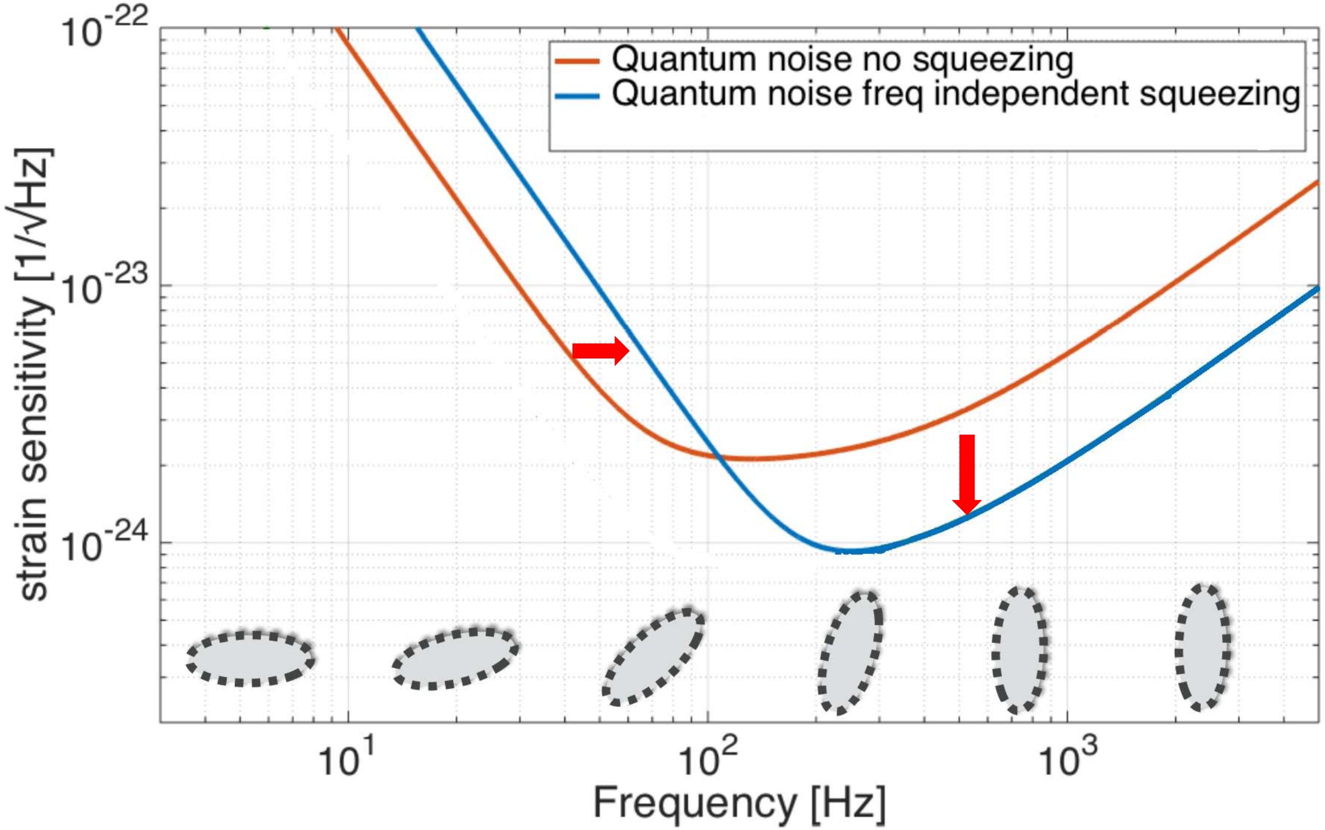
01:29
P2 2.0
P1 2.0
CA 3.0
단호함과 상반된 움찔 그래프
오분순삭

Frequency independent squeezing



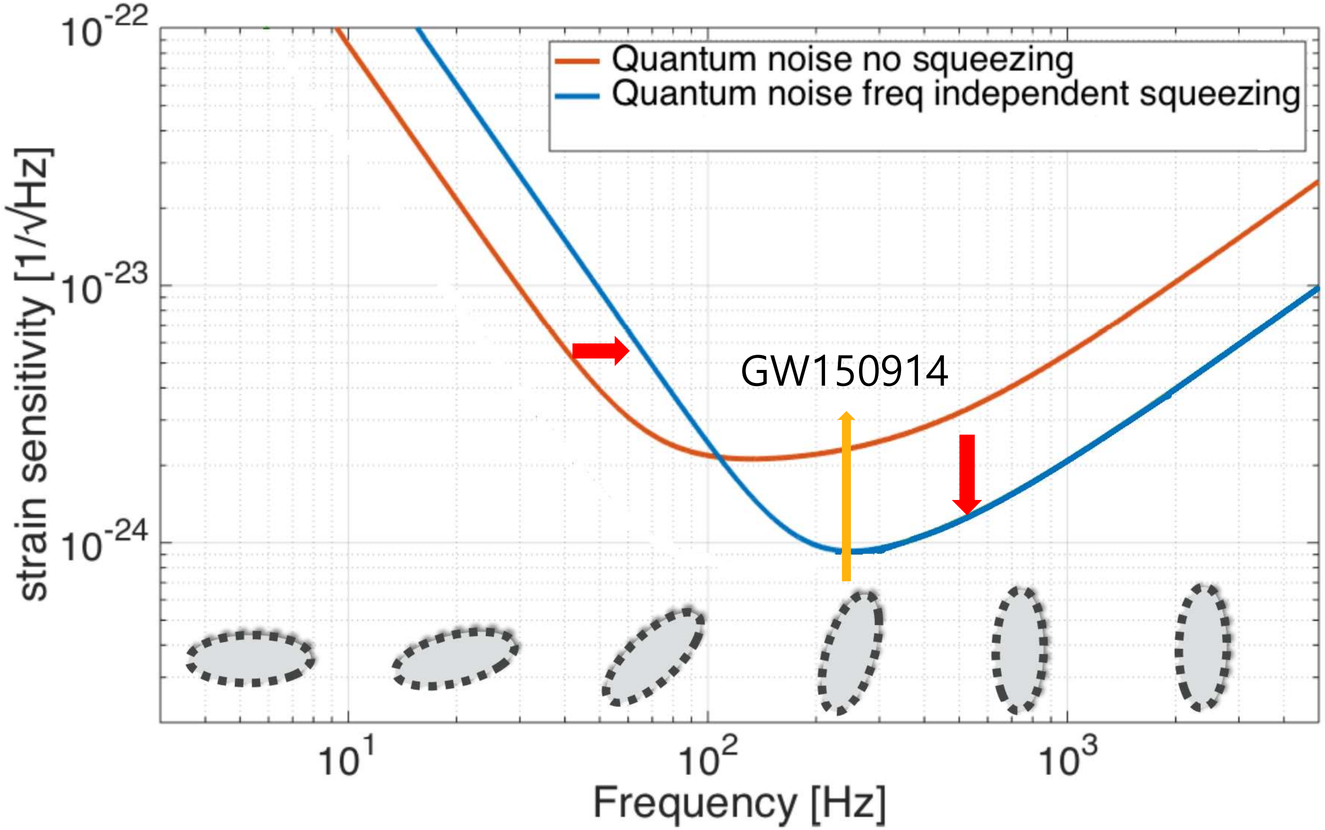
Optical and noise studies for Advanced Virgo and filter cavities for quantum noise reduction in gravitational-wave interferometric detectors, Eleonora Capocasa, UNIVERSITÉ PARIS DIDEROT (2017)

Frequency independent squeezing



Optical and noise studies for Advanced Virgo and filter cavities for quantum noise reduction 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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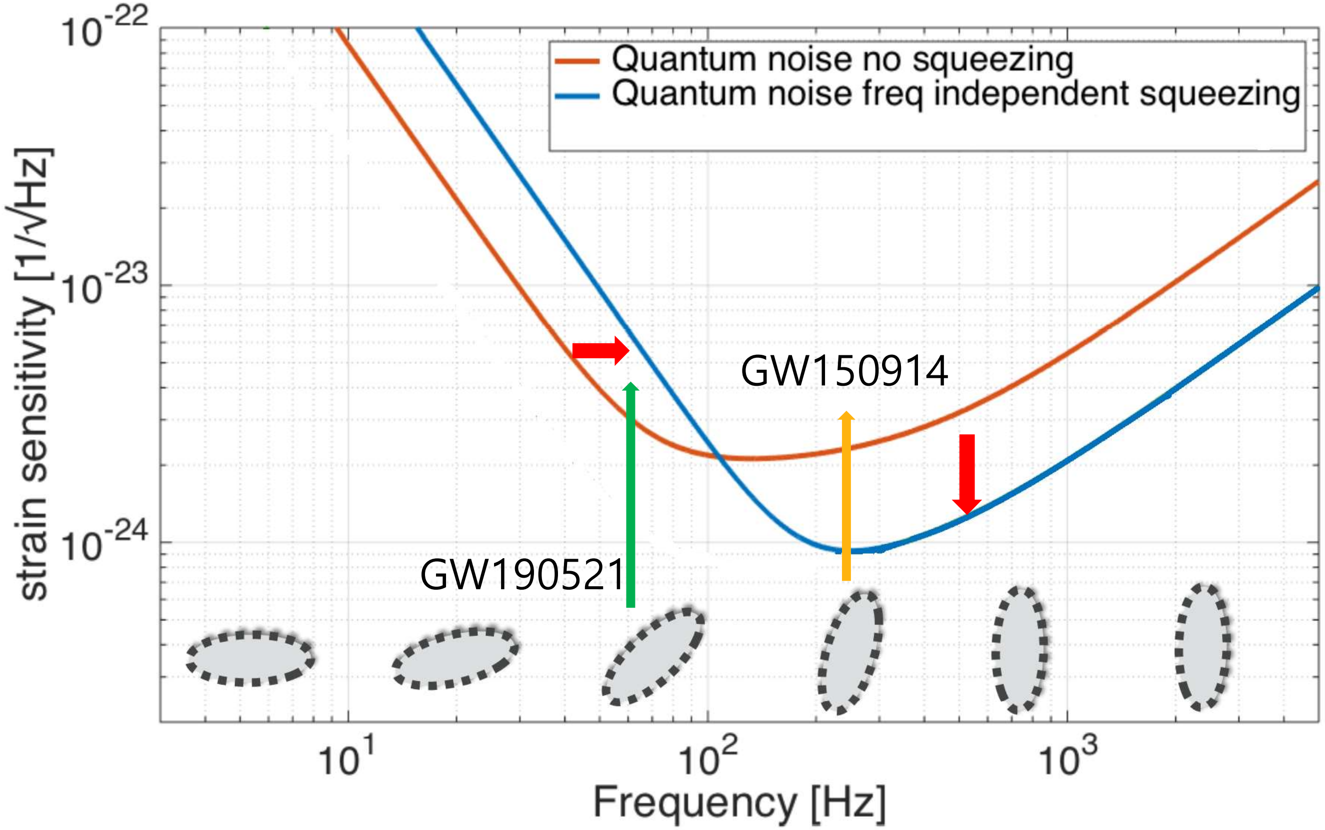
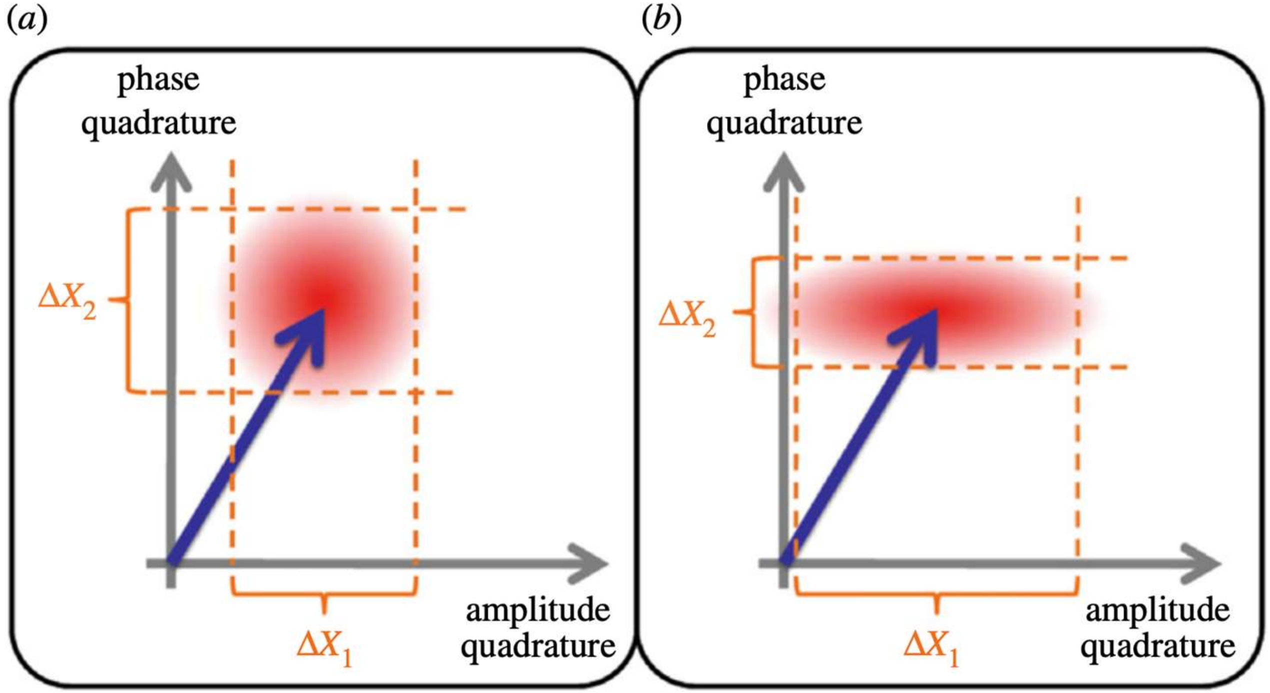
Frequency independent squeezing



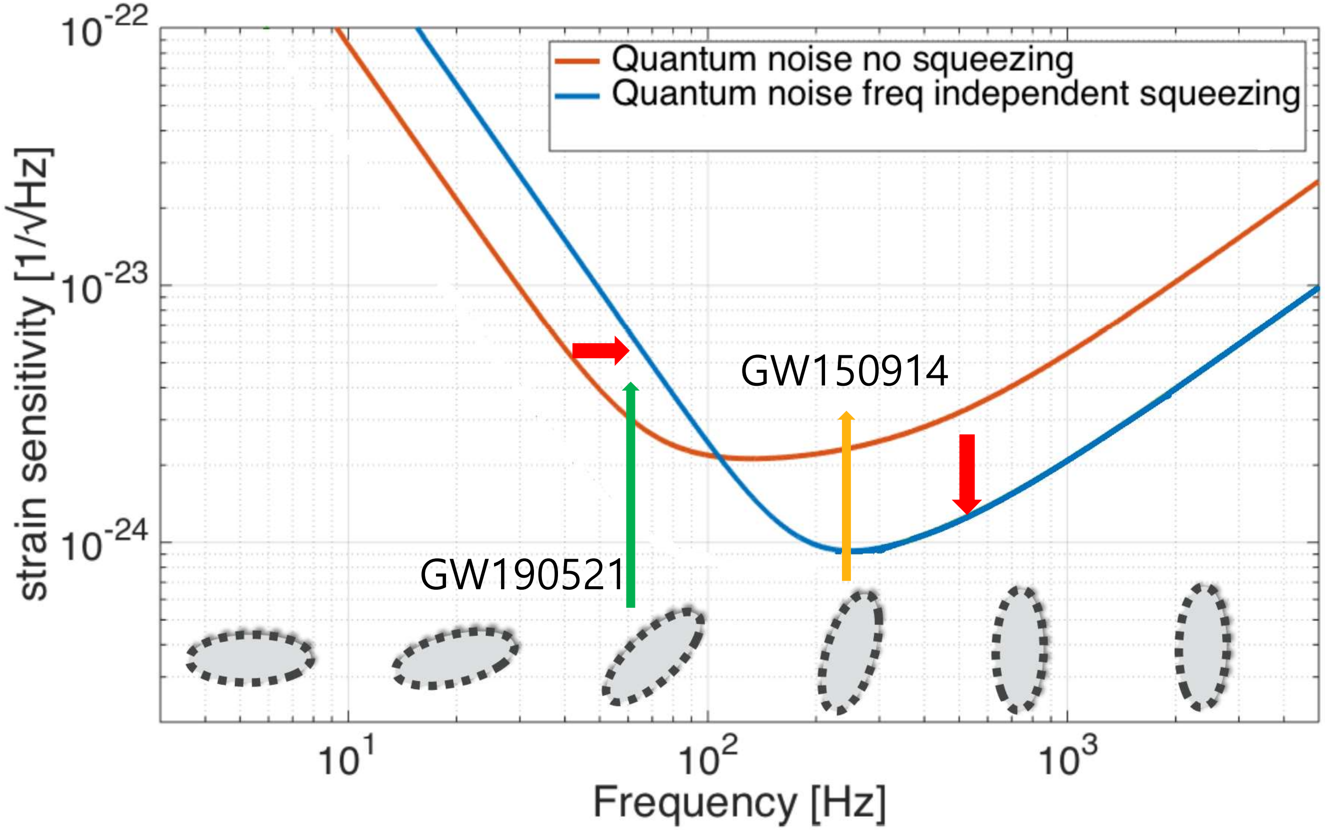
Optical and noise studies for Advanced Virgo and filter cavities for quantum noise reduction
in gravitational-wave interferometric detectors, Eleonora Capocasa, UNIVERSITÉ PARIS DIDEROT (2017)

Squeezed light



Heurs M. 2018 Gravitational wave detection u
sing laser interferometry beyond the standard
quantum limit.Phil. Trans. R. Soc. A 376: 20170
289.

Frequency independent squeezing



Optical and noise studies for Advanced Virgo and filter cavities for quantum noise reduction
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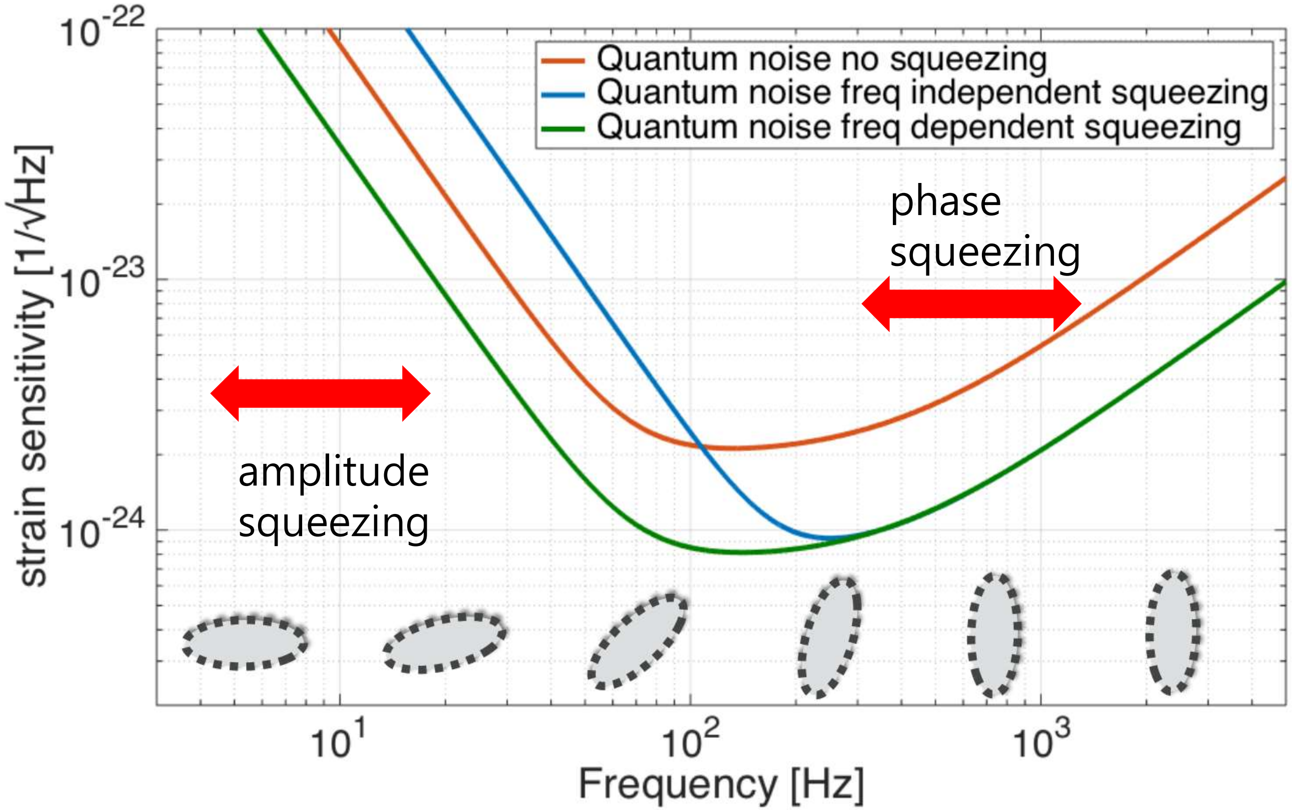
Frequency dependent squeezing(FDS)



Optical and noise studies for Advanced Virgo and filter cavities for quantum noise reduction
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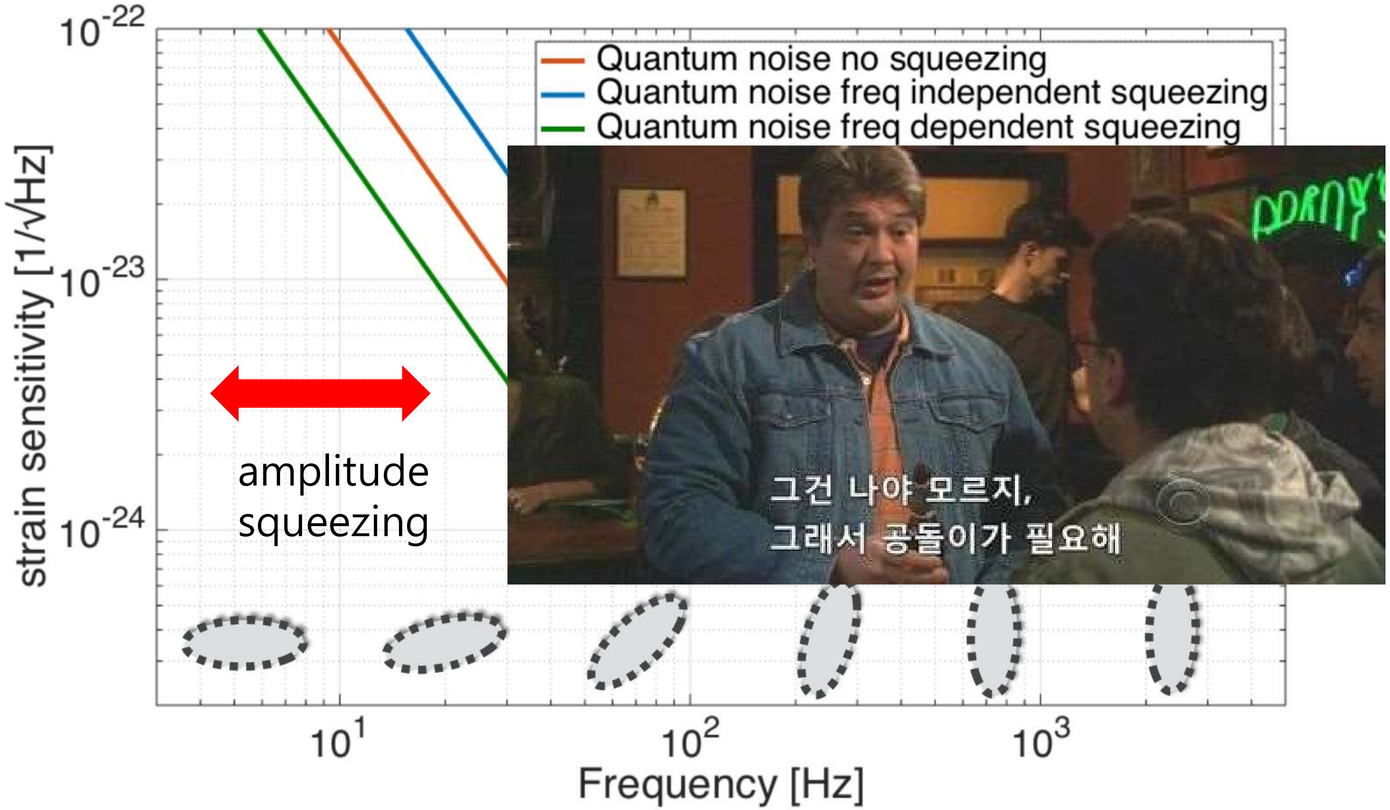
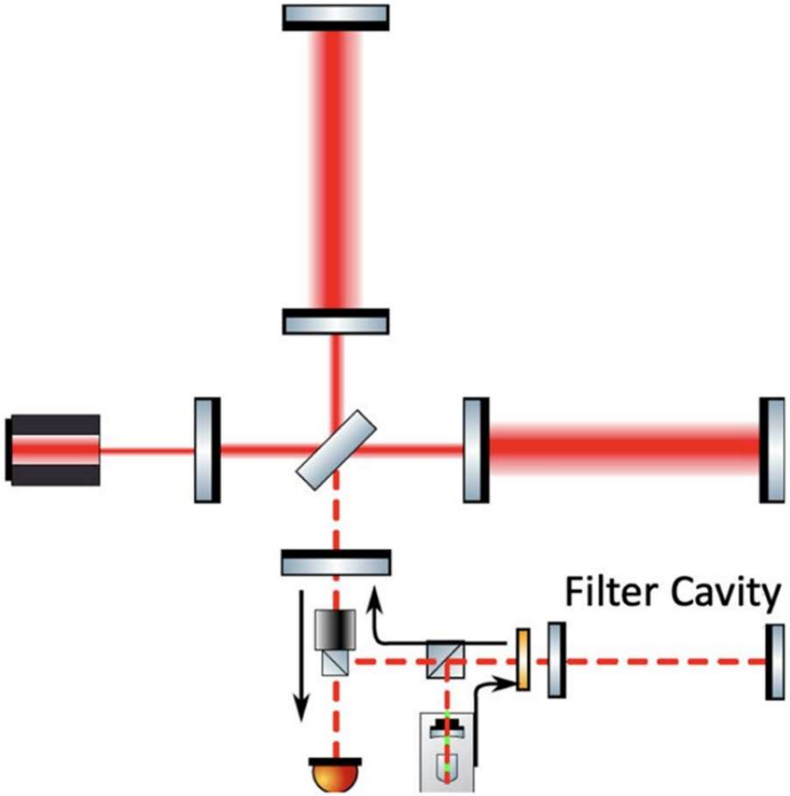
Frequency dependent squeezing(FDS)

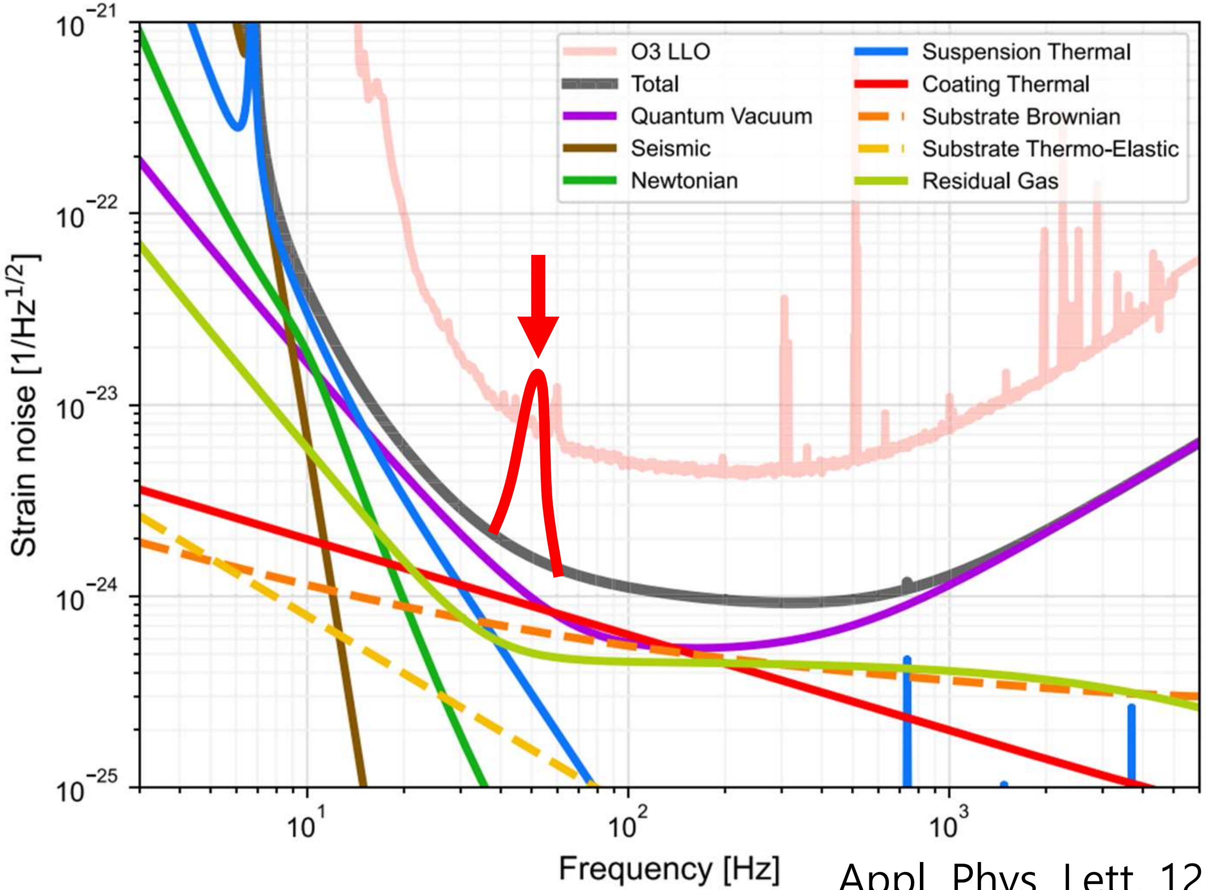


Optical and noise studies for Advanced Virgo and filter cavities for quantum noise reduction
in gravitational-wave interferometric detectors, Eleonora Capocasa, UNIVERSITÉ PARIS DIDEROT (2017)

Frequency dependent squeezing using filter cavity

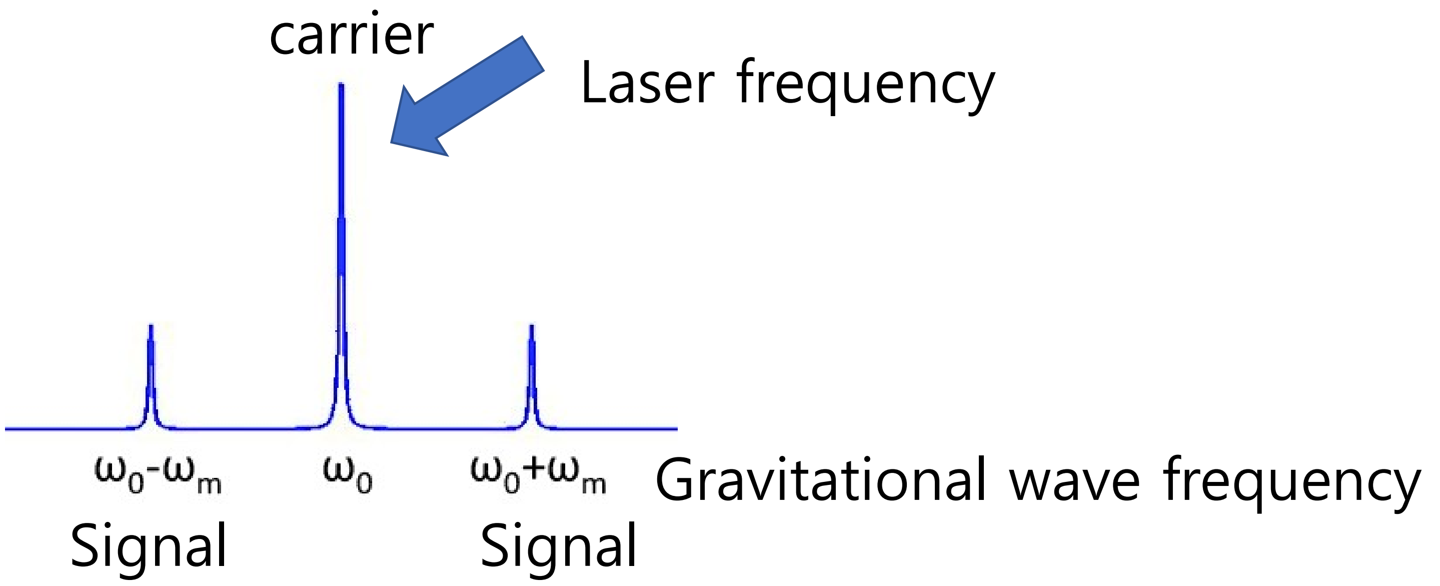


LIGO sensitivity

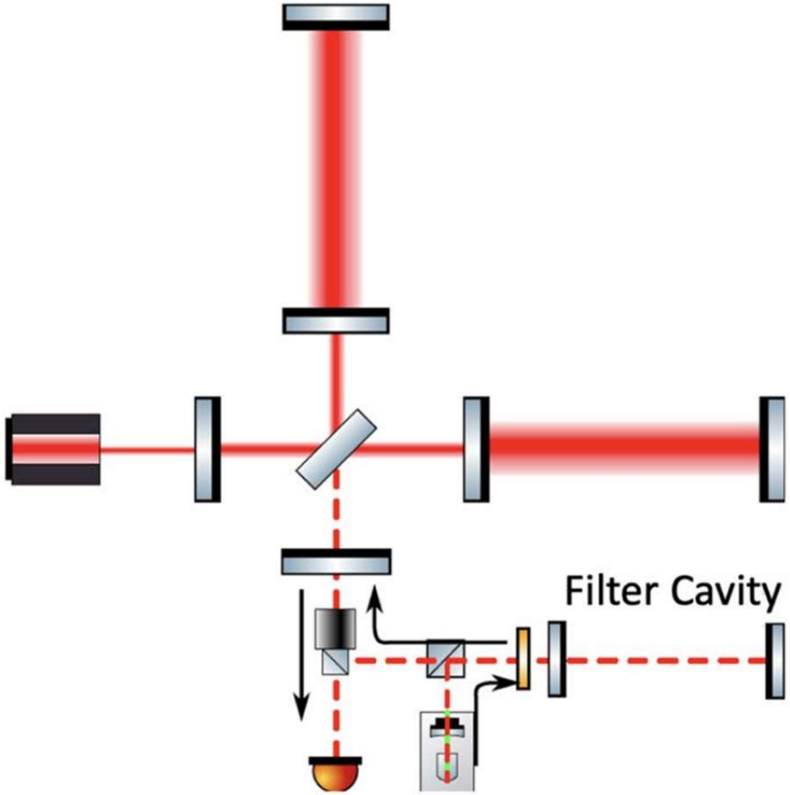


Appl. Phys. Lett. 122, 110502 (2023)

Side band figure

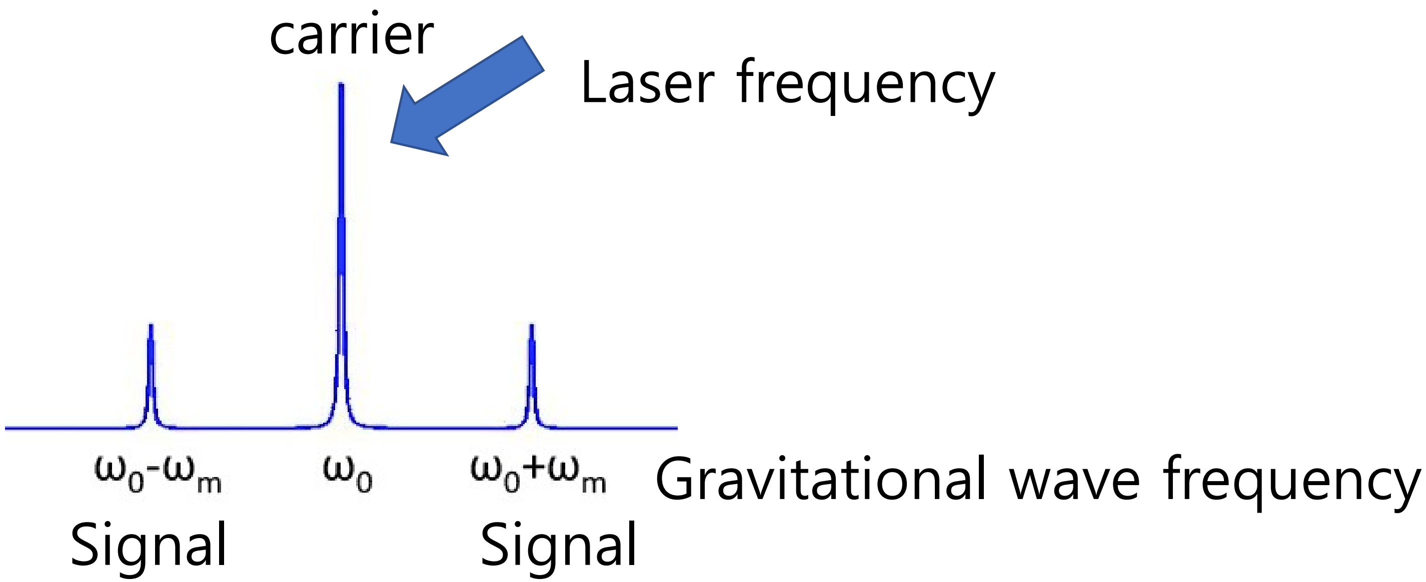


Frequency dependent squeezing using filter cavity

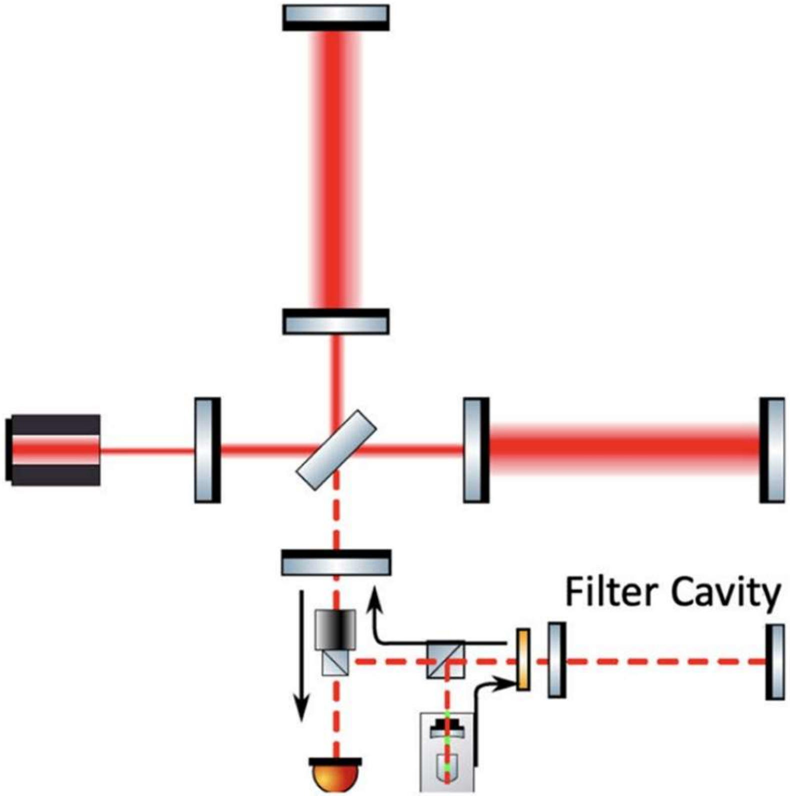


$$E^{(+)}(t) = \int_0^\infty E(\omega) e^{-i\omega t} \frac{d\omega}{2\pi}$$

Side band figure



Frequency dependent squeezing using filter cavity



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

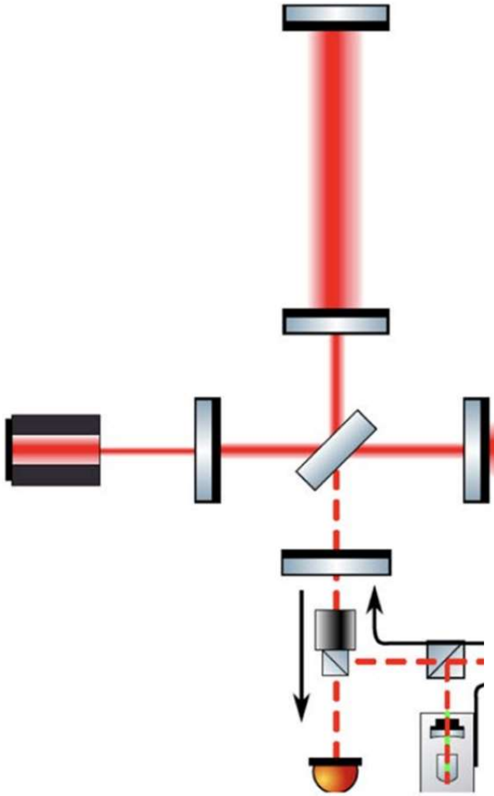
$$E^{(+)}(t) = e^{-i\omega_0 t} \int_0^\infty \left(E(\Omega) e^{-i\Omega t} + E(-\Omega) e^{+i\Omega t} \right) \frac{d\Omega}{2\pi}$$

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

Laser frequency

GW signal frequency

Frequency dependent squeezing using filter cavity



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

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

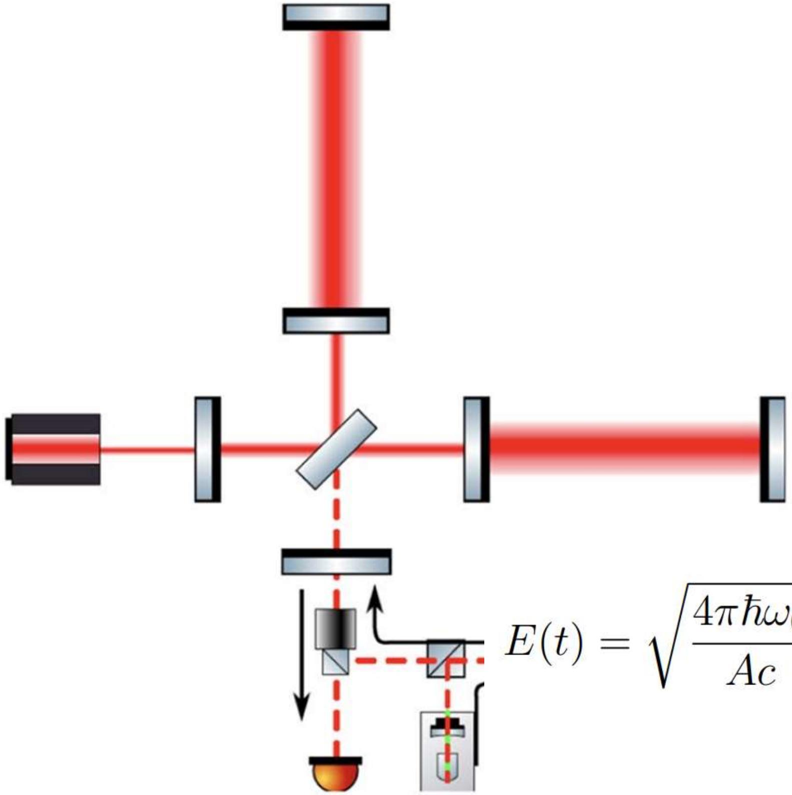
$$\textbf{Phase Quadrature}: \; a_2(t) = \frac{a(t) - a^\dagger(t)}{i\sqrt{2}}$$

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


오분순삭
01:21
아니요
Q
집에 가고 싶으세요?


오분순삭
01:19
P2 2.0
P1 2.0
CA 3.0
집에 몹시
가고 싶음...

Frequency dependent squeezing using filter cavity



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

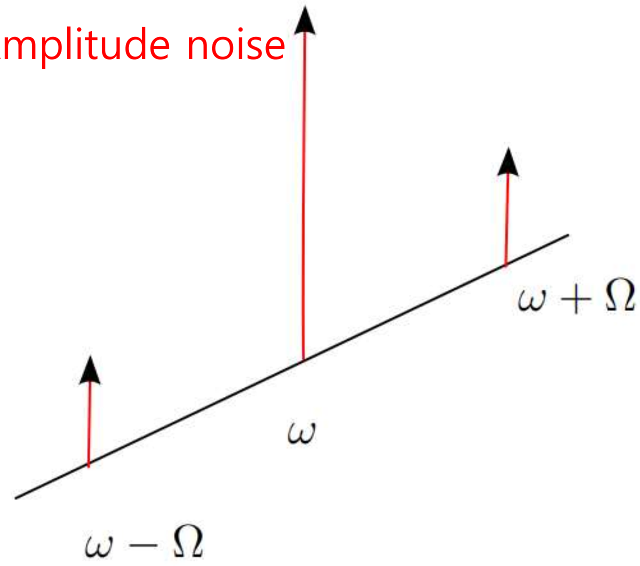
$$\textbf{Amplitude Quadrature}: \; a_1(t) = \frac{a(t) + a^\dagger(t)}{\sqrt{2}}$$

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

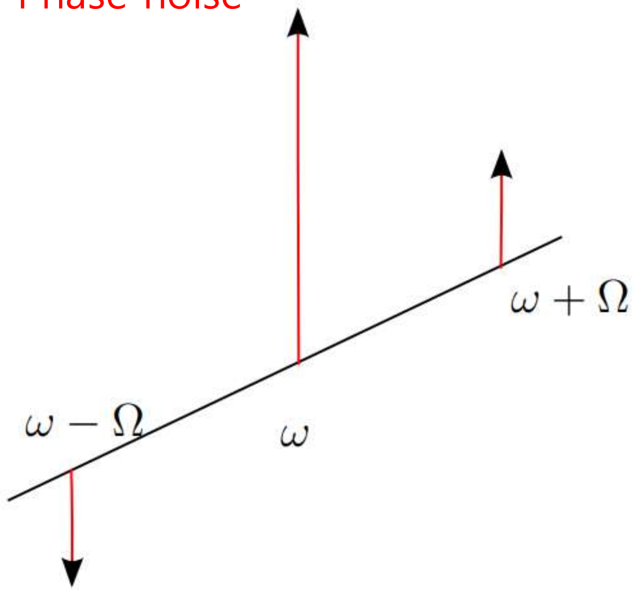
$$E(t) = \sqrt{\frac{4\pi\hbar\omega_0}{Ac}}\Bigg[\cos(\omega_0 t)\int_0^\infty \left(a_1(\Omega)e^{-i\Omega t} + a_1^\dagger(\Omega)e^{+i\Omega t}\right)\frac{d\Omega}{2\pi} + \sin(\omega_0 t)\int_0^\infty \left(a_2(\Omega)e^{-i\Omega t} + a_2^\dagger(\Omega)e^{+i\Omega t}\right)\frac{d\Omega}{2\pi}\Bigg]$$

Quantum noise side band figure

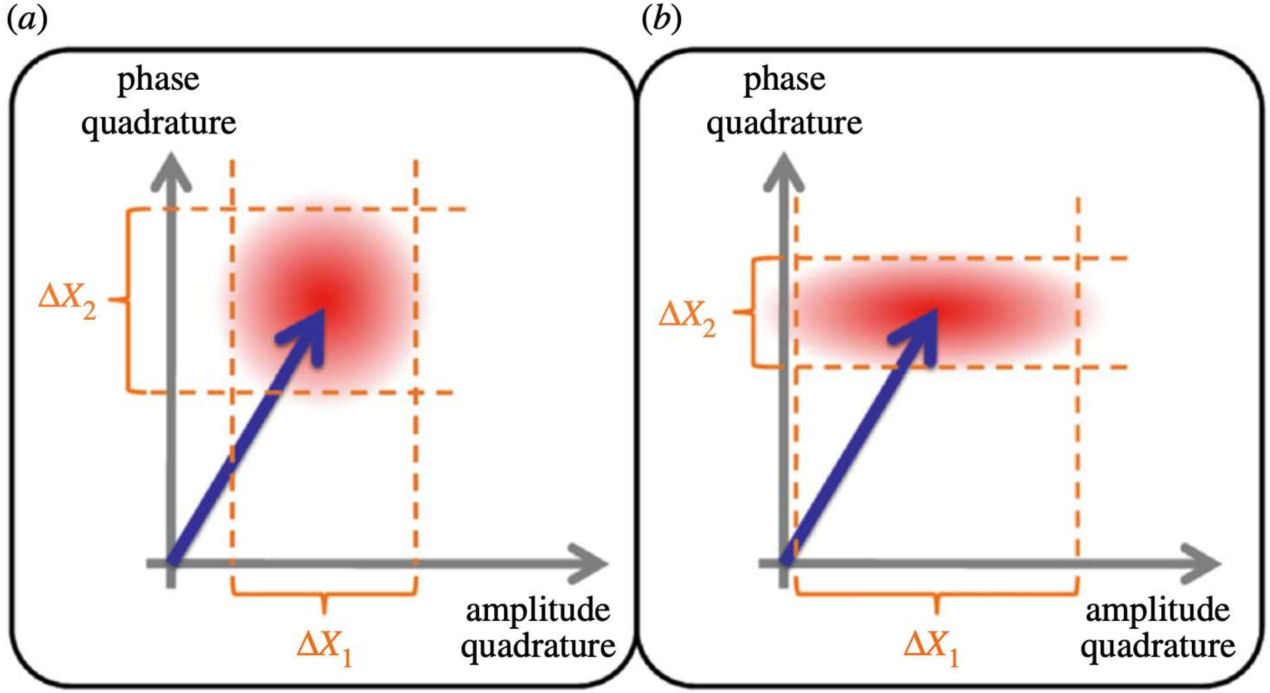
Amplitude noise



Phase noise

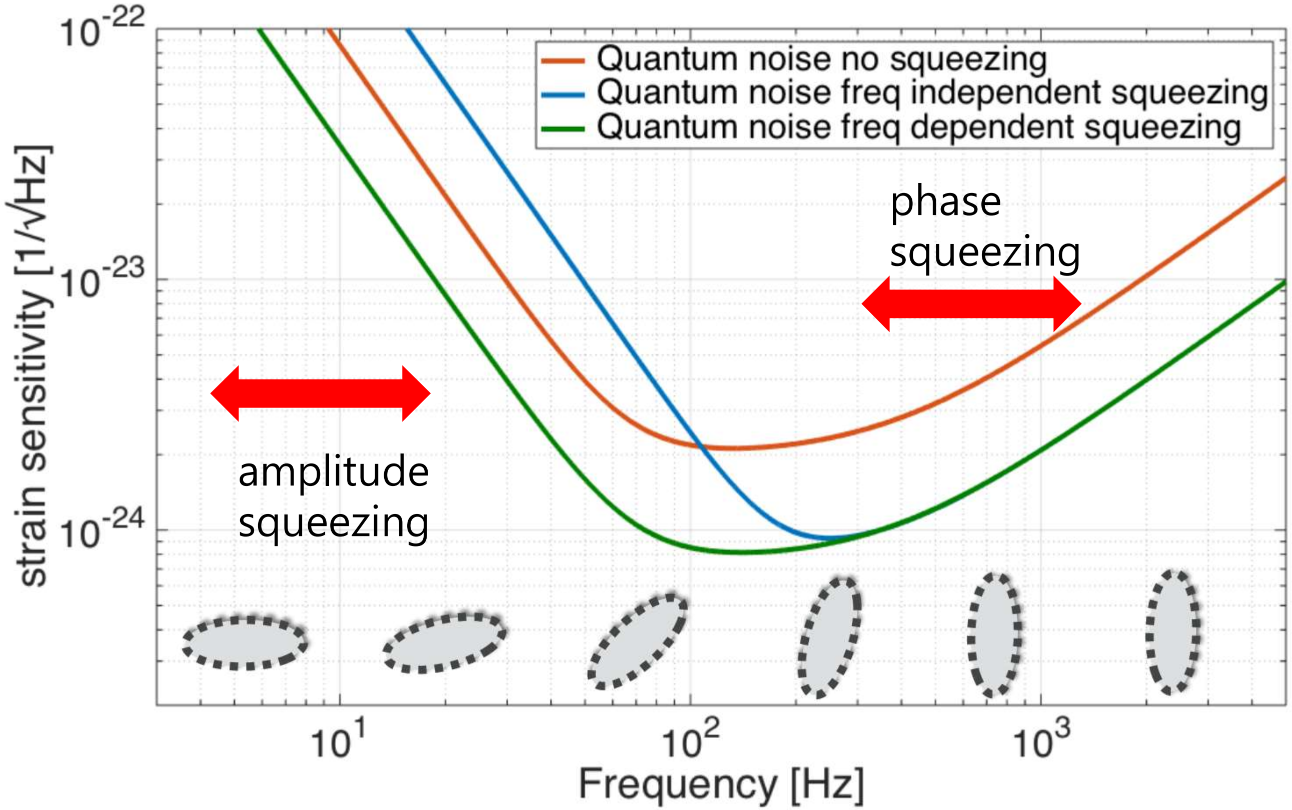


Squeezed light



Heurs M. 2018 Gravitational wave detection u sing laser interferometry beyond the standard quantum limit.Phil. Trans. R. Soc. A 376: 20170 289.

Frequency dependent squeezing(FDS)



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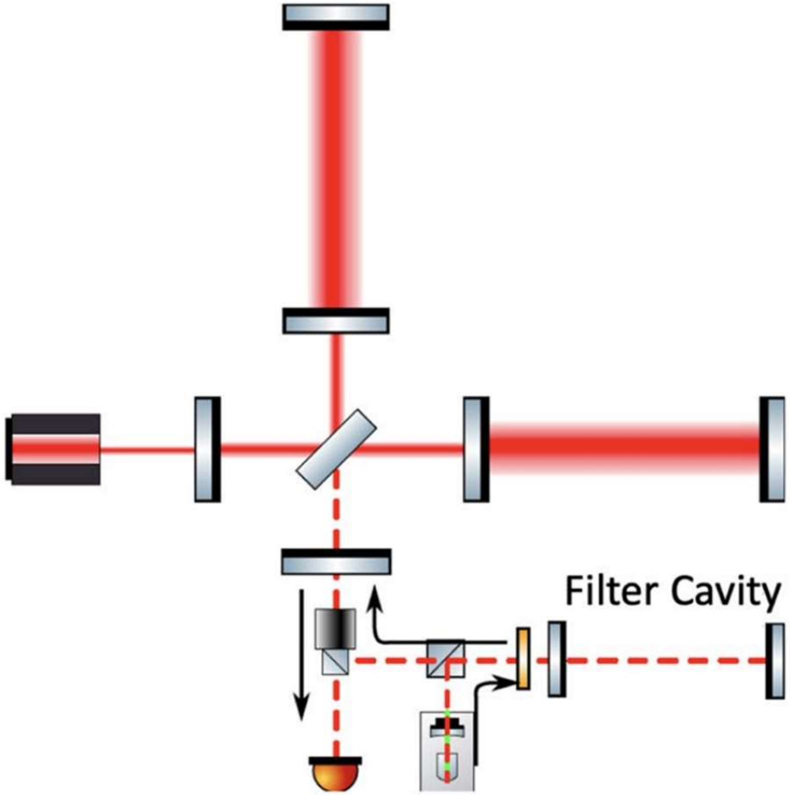
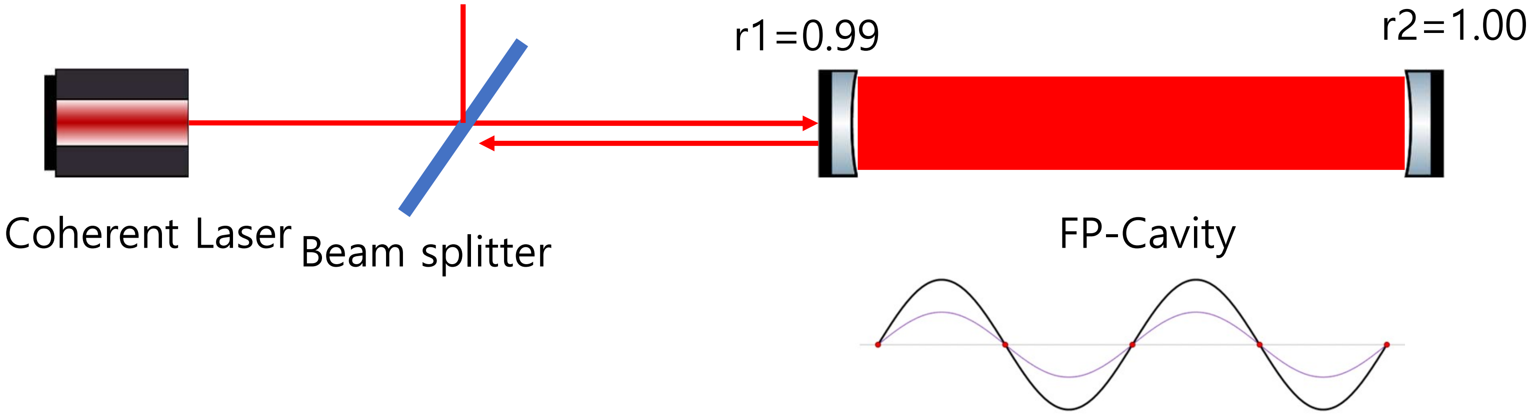
Frequency dependent squeezing using filter cavity



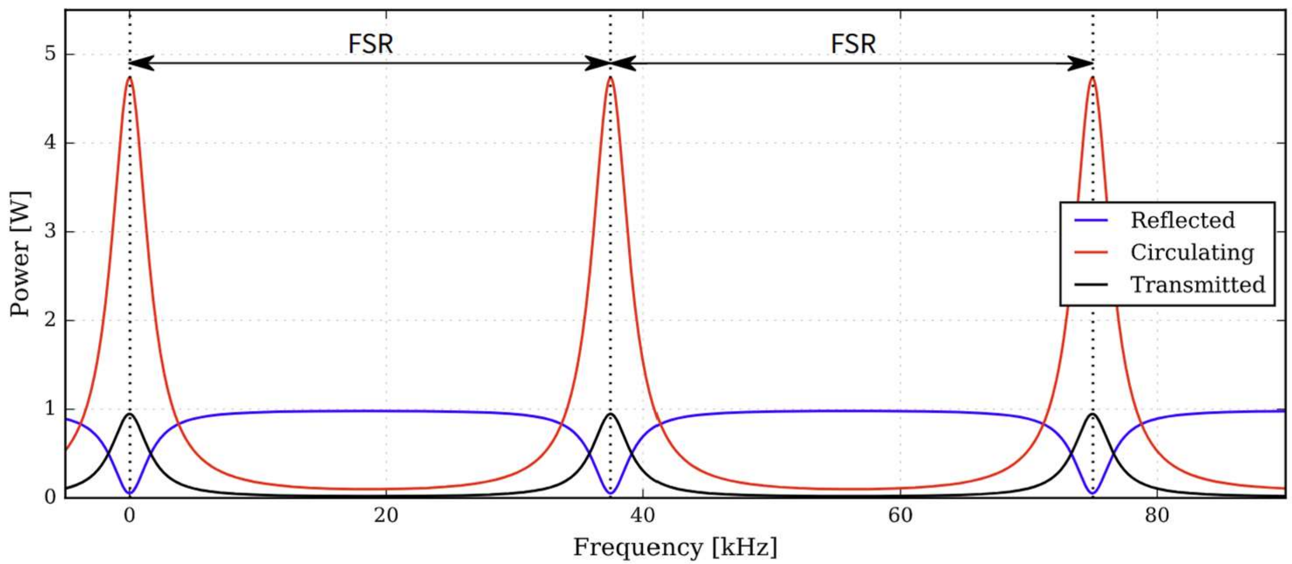
Fabry-perot cavity

Number of round trip > 250

4 km x 250 ~ 1000 km



Free spectral range of cavity



Detuned cavity

Simple picture

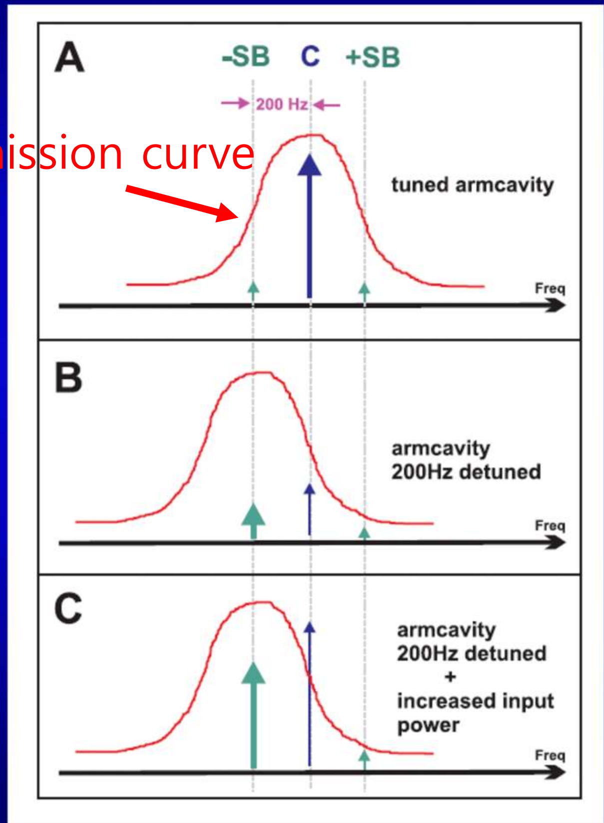
Stefan Hild et al, “Detuned arm cavities”, 3rd GEO simulation workshop, Hannover, June 2007

B:
• less carrier light in cavity => less GW sidebands are produced.
• Since one GW sideband is resonant, it gets enhanced.

=> Smaller GW signal

C:
• optical power is restored in the cavity by larger PR-gain.
• Same amount of GW sidebands are produced.
• Since one GW sideband is resonant, it gets enhanced.
Overall we win GW signal.

=> Larger GW signal



Quantum noise side band figure

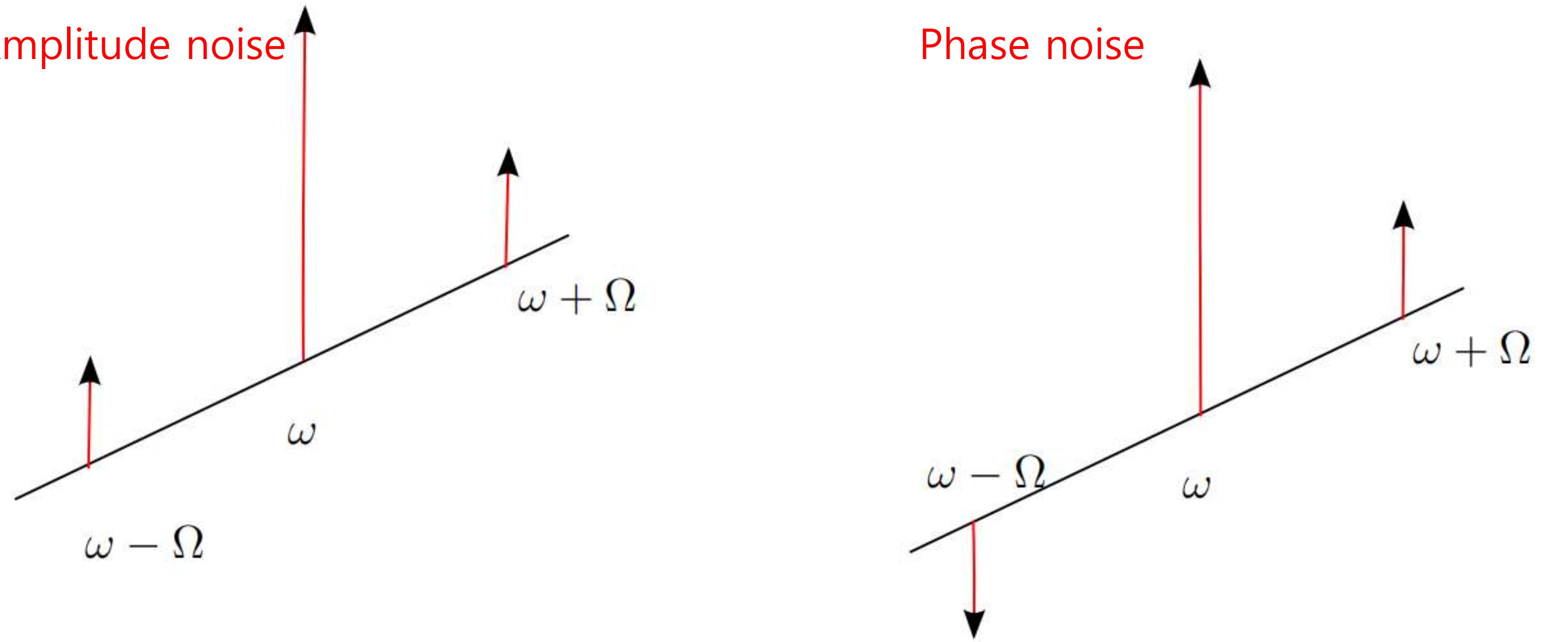
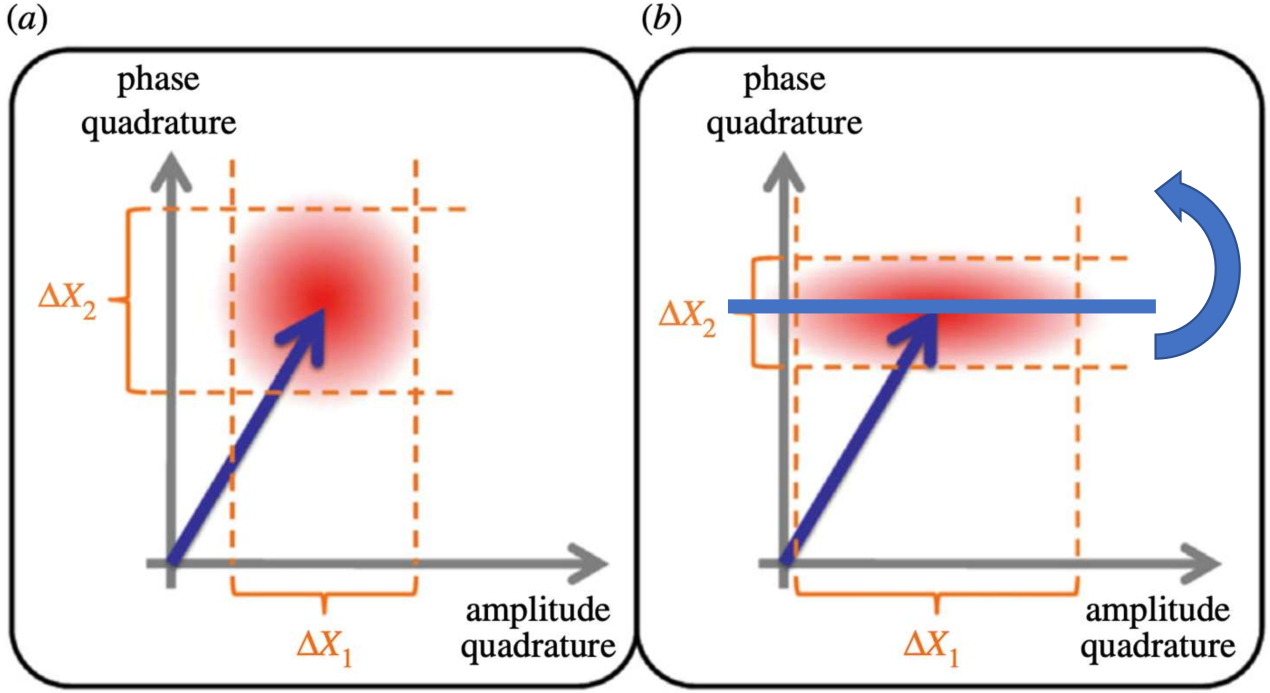


Figure 1-2: Phasors of amplitude noise (left) and phase noise (right) in the sideband picture. In the frame rotating at the carrier frequency ω the carrier is still in these diagrams while the sidebands rotate at Ω, the signal at $\omega + \Omega$ rotating clockwise while the idler at $\omega - \Omega$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

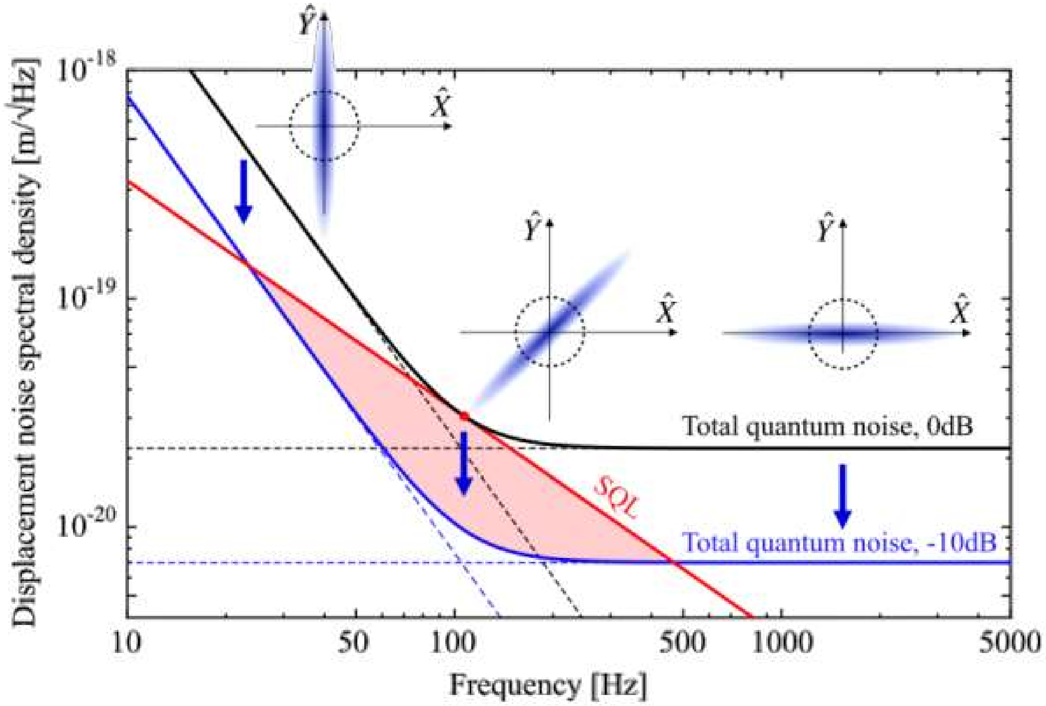
Squeezed light



Squeeze angle rotation

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

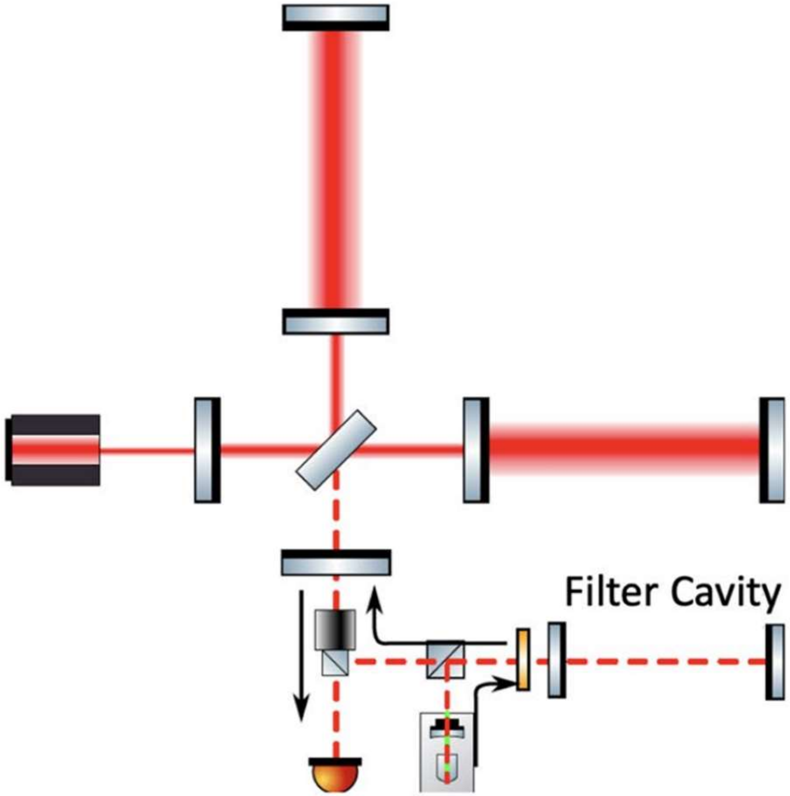
Squeeze angle rotation



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

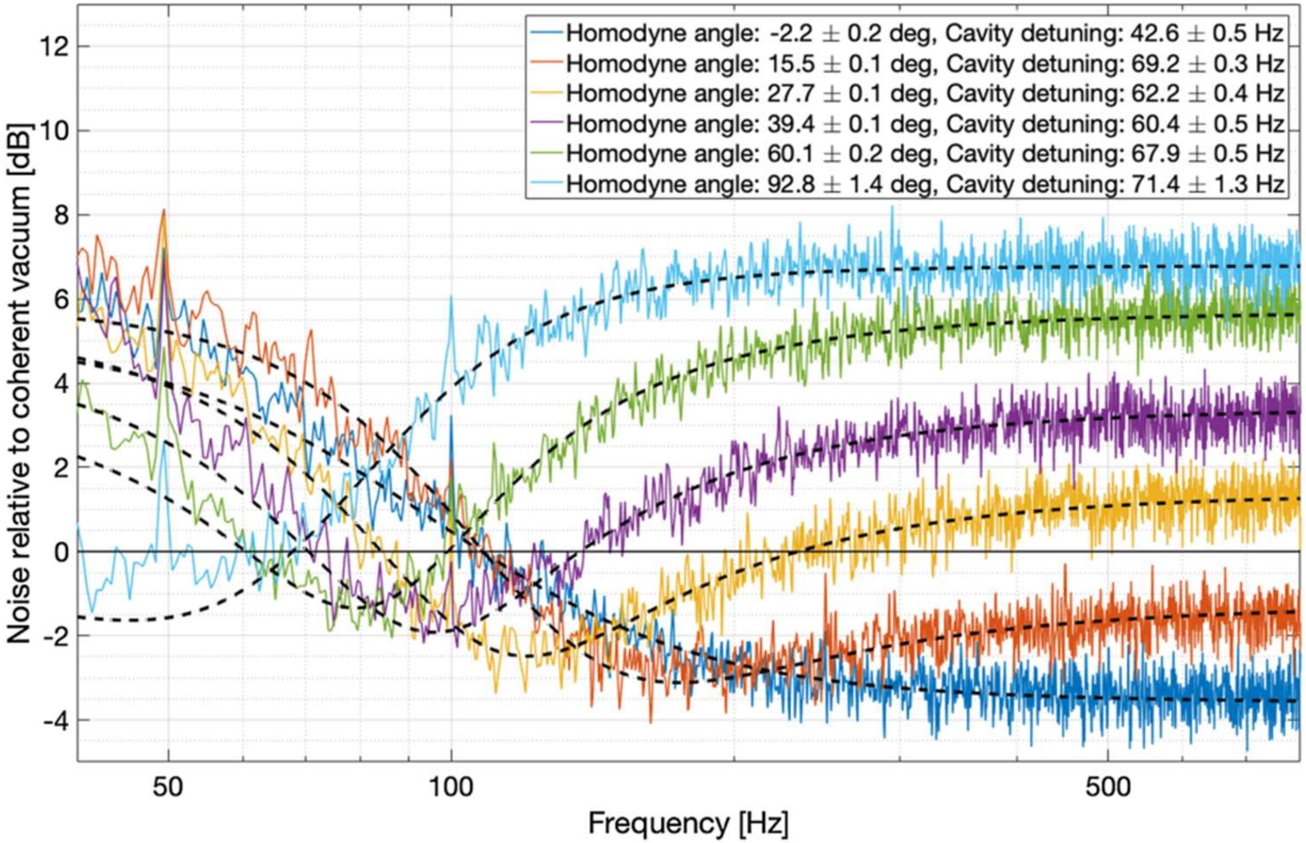
$$t_{\rm st} = \frac{1}{\gamma_{\rm fc}} = \frac{\sqrt{2}}{\Omega_{\rm SQL}} \simeq 3\,{\rm ms}$$

Frequency dependent squeezing using filter cavity

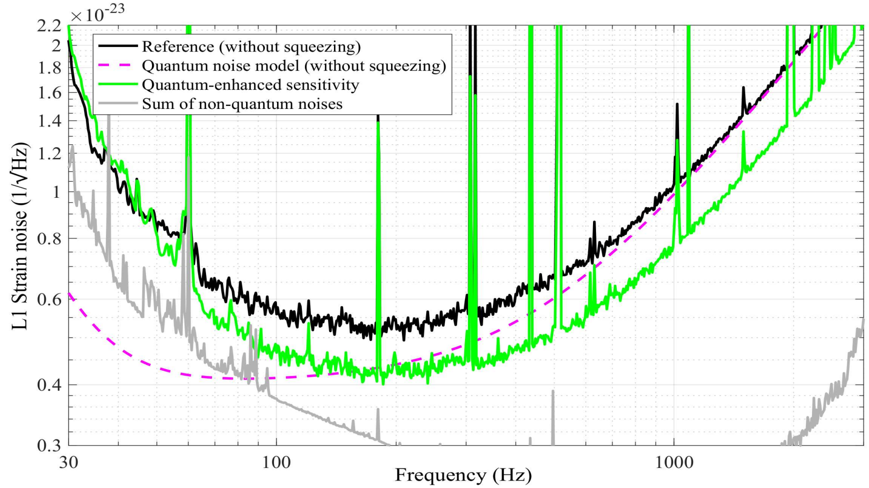


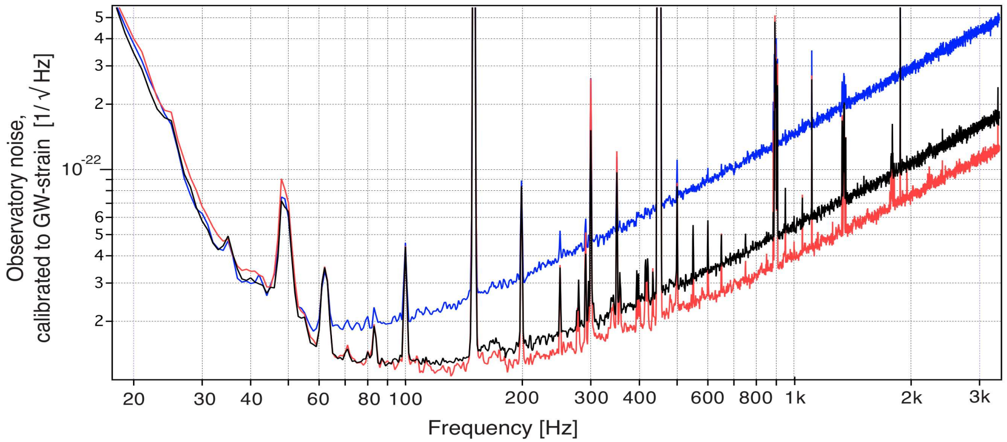
Frequency dependent squeezing - KAGRA

PHYSICAL REVIEW LETTERS **124,** 171101 (2020)

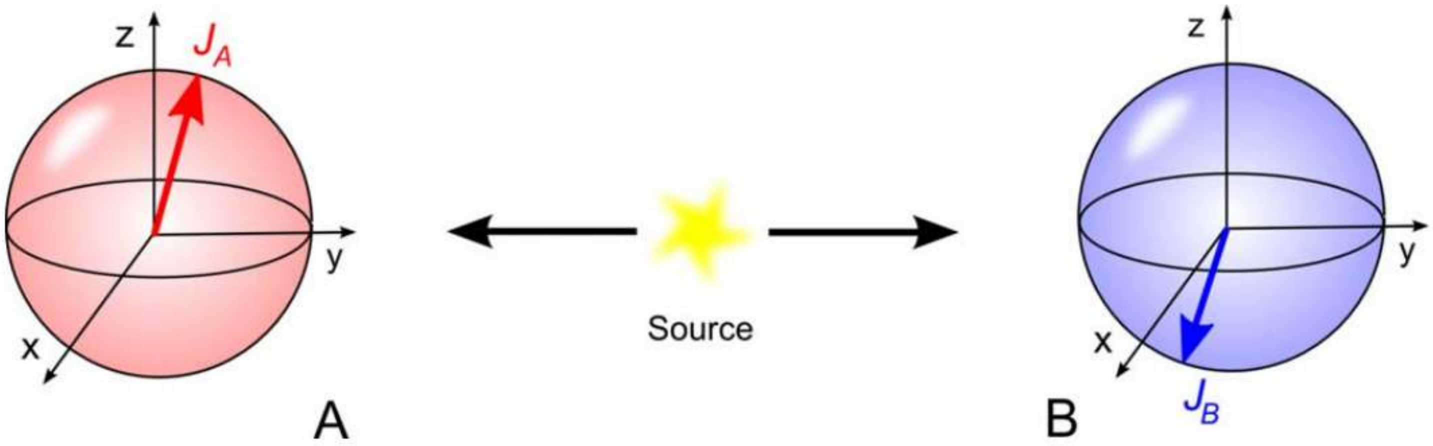


Quantum noise of gravitational wave detector

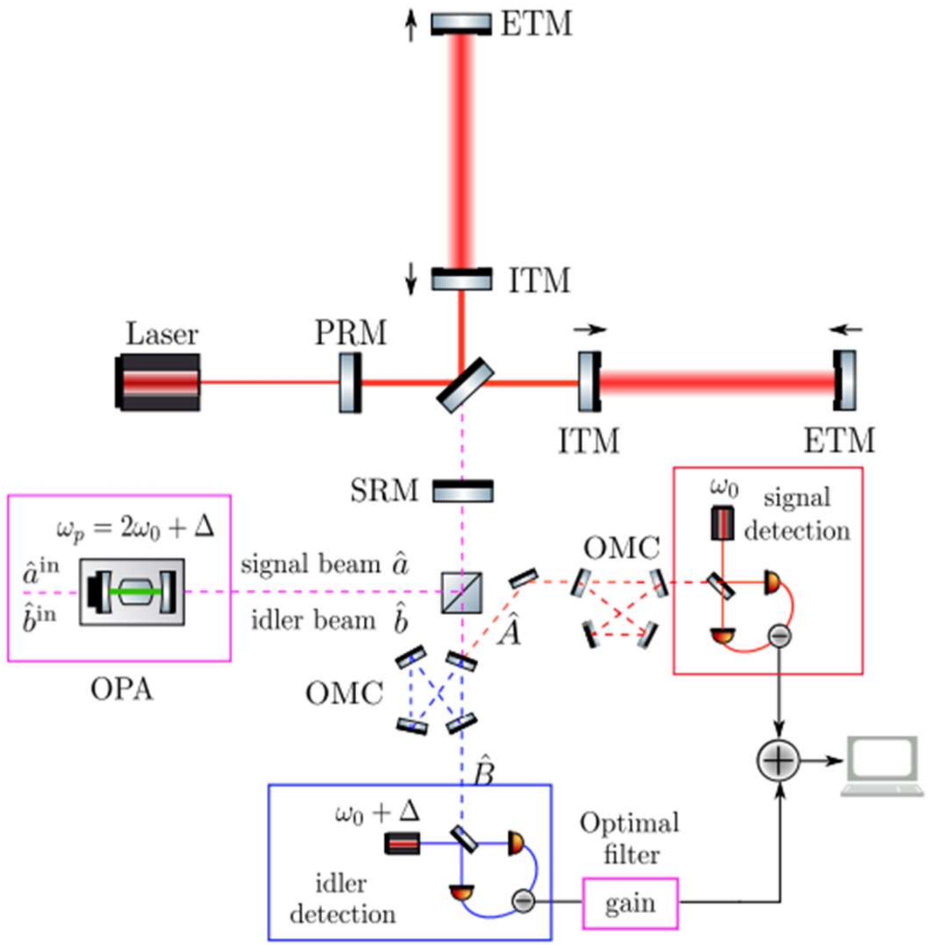


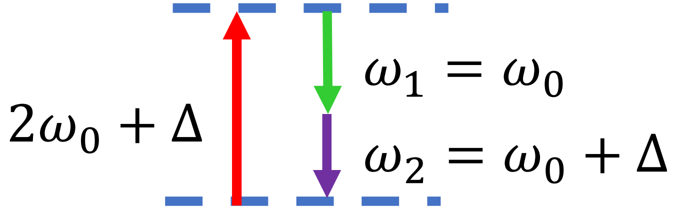


Einstein-Podolsky-Rosen paradox



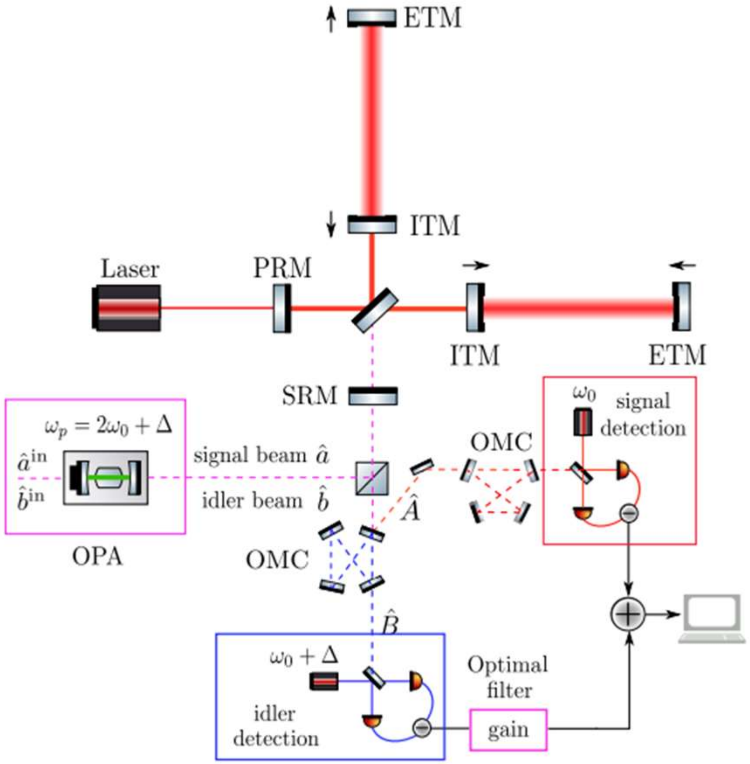
EPR squeezing for gravitational wave detector

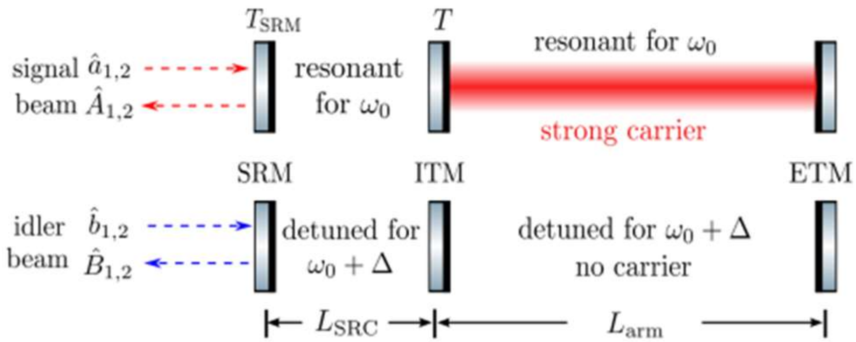


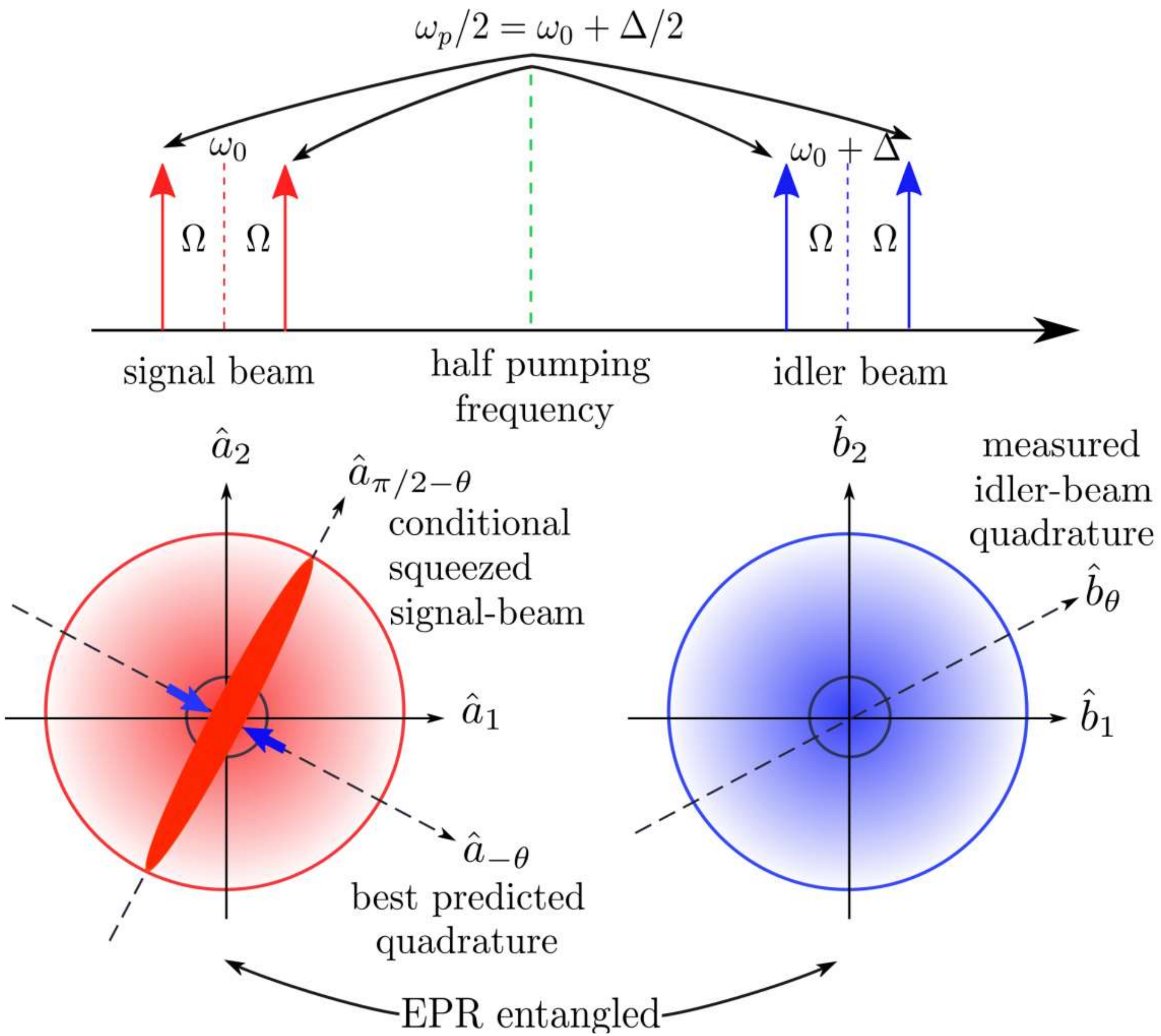


Non linear optics

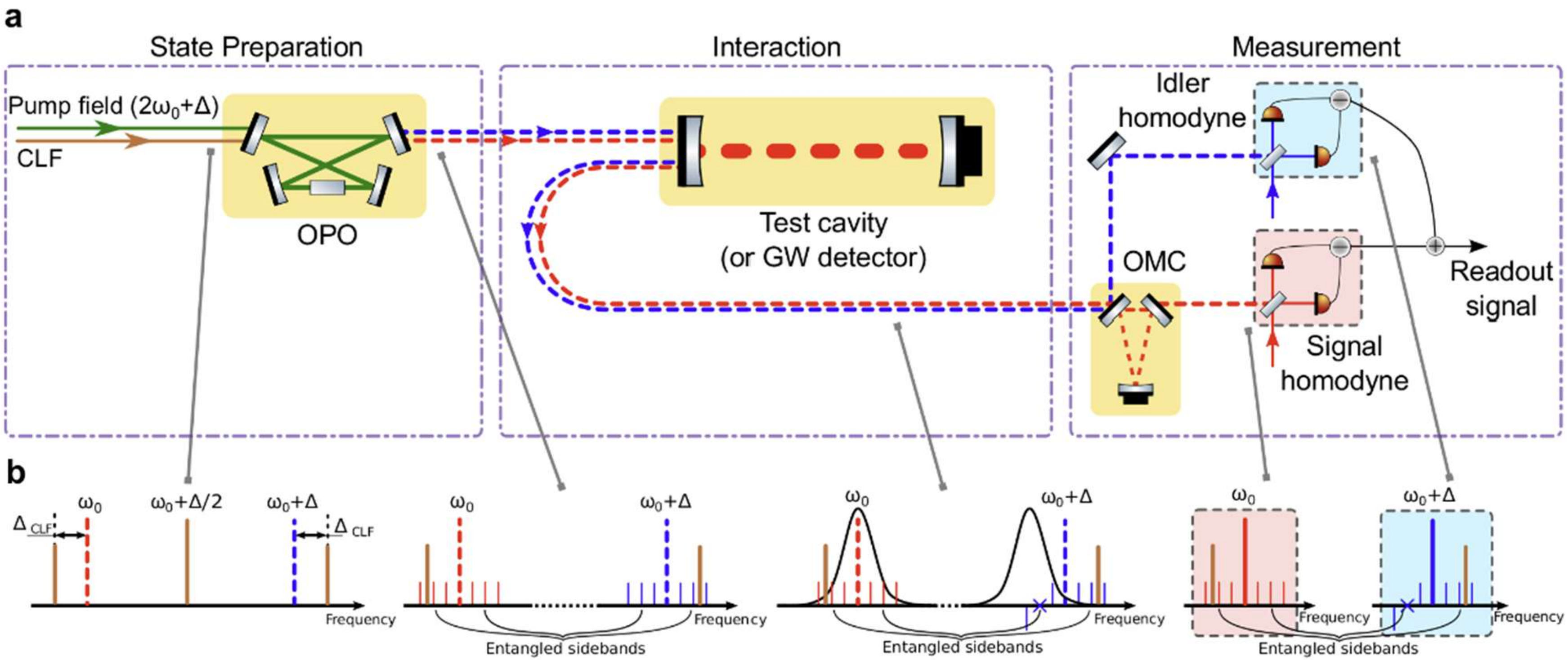
EPR squeezing for gravitational wave detector





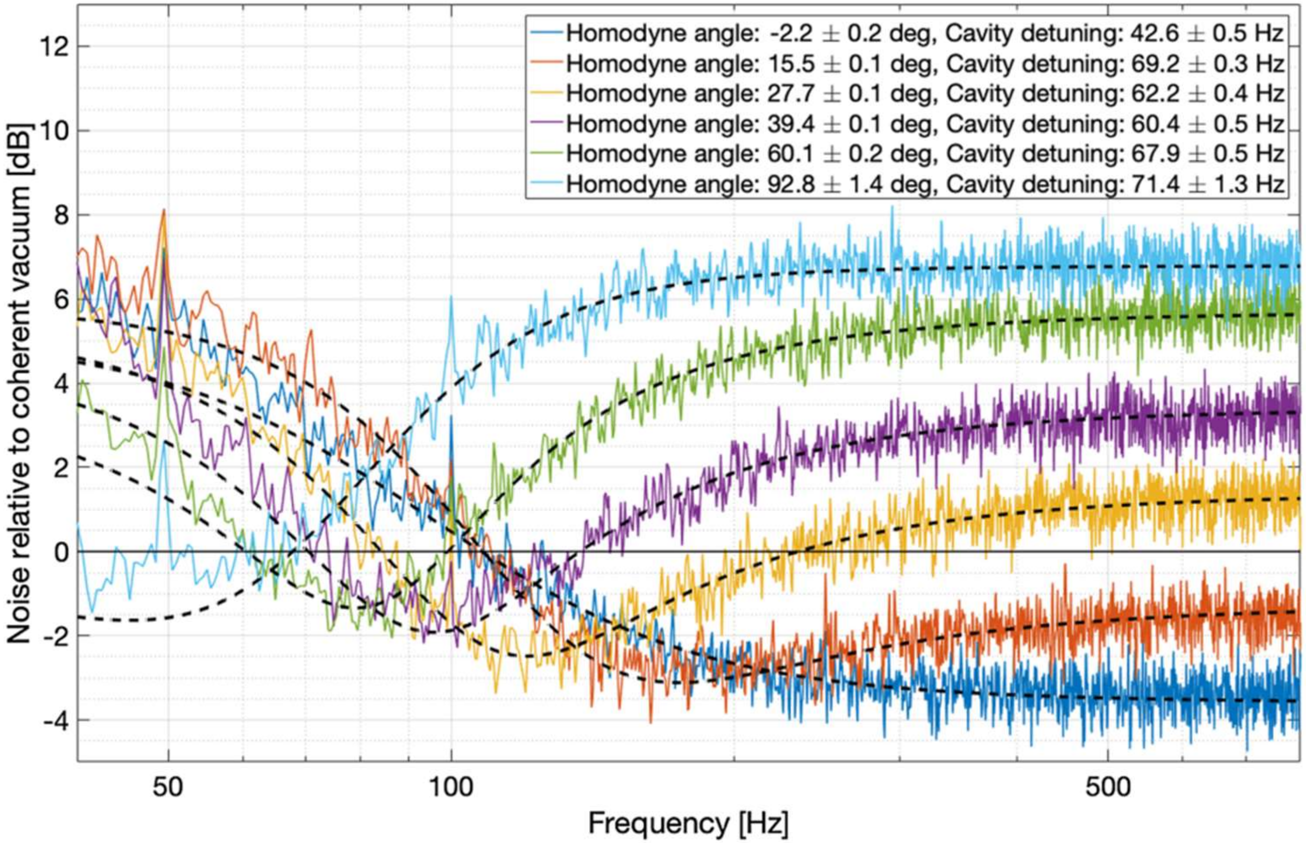

$\omega_p/2 = \omega_0 + \Delta/2$
ω_0
$\omega_0 + \Delta$
Ω
Ω
Ω
Ω
signal beam
half pumping frequency
idler beam
$\hat{a}_2$
$\hat{a}_{\pi/2-\theta}$
conditional squeezed signal-beam
$\hat{a}_1$
$\hat{a}_{-\theta}$
best predicted quadrature
$\hat{b}_2$
measured idler-beam quadrature
$\hat{b}_\theta$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

Generation and control of frequency dependent squeezing via EPR entanglement

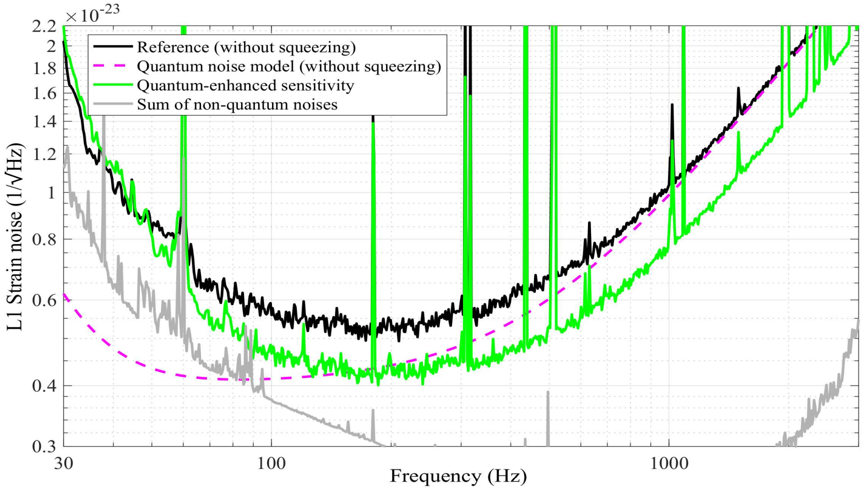


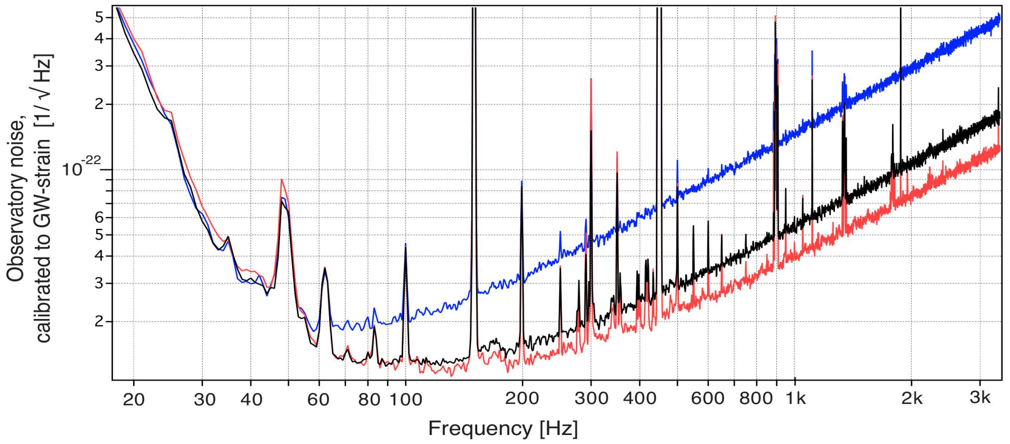
Frequency dependent squeezing - KAGRA

PHYSICAL REVIEW LETTERS **124,** 171101 (2020)



Quantum noise of gravitational wave detector






오분순삭
01:06
꾸욱~


오분순삭
01:01
P2 2.0
P1 2.0
EA 1.0
CA 3.0
C6
복잡한 심경 대변(?)
잔뜩 뒤엉킨 그래프