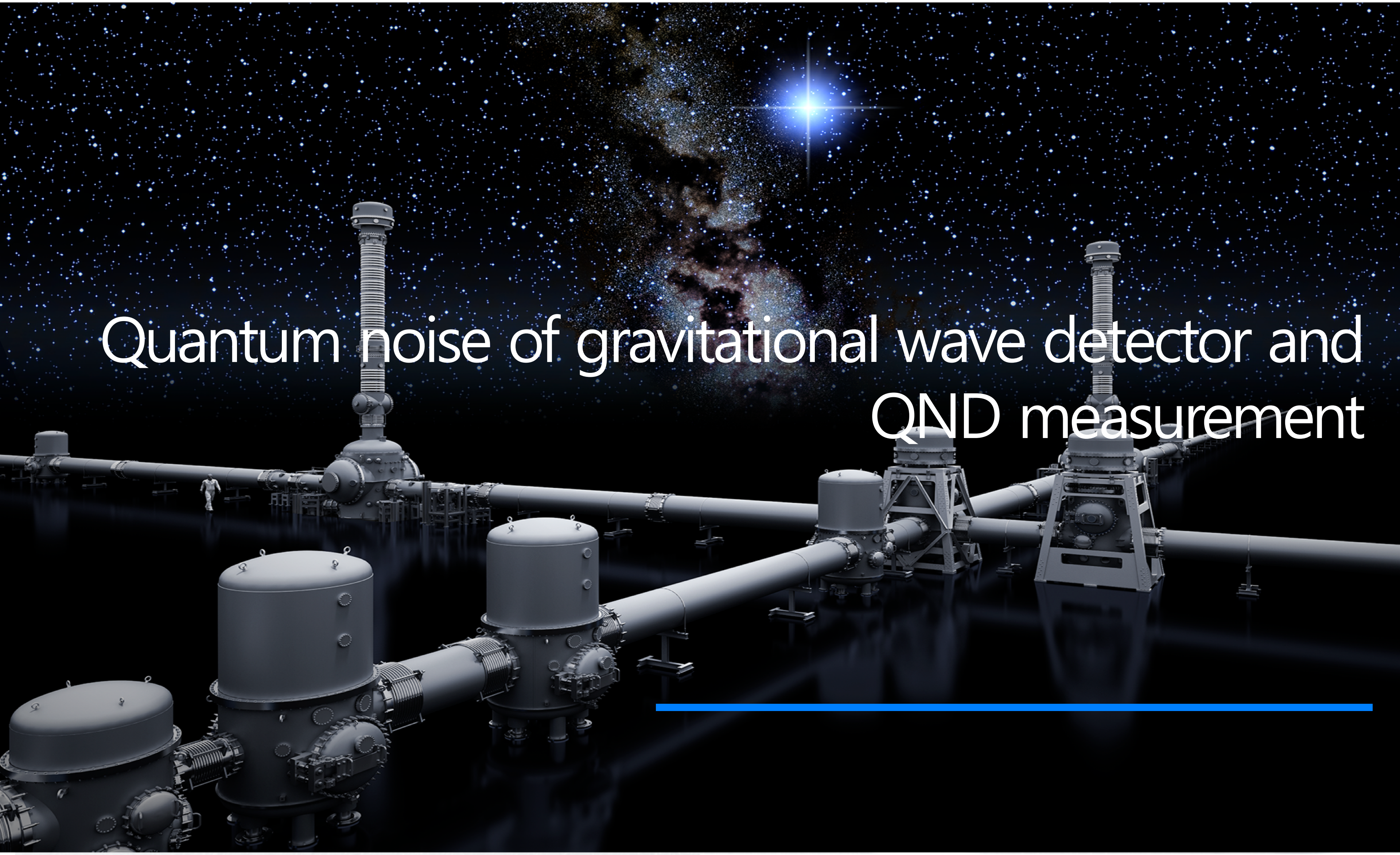
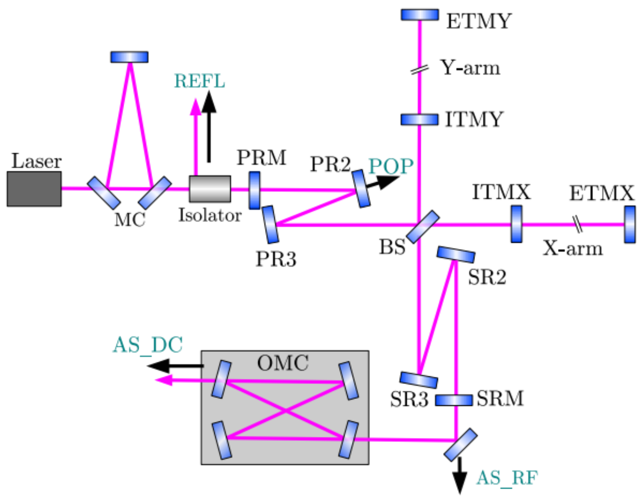
Quantum noise of gravitational wave detector and QND measurement



KASI
Korea Astronomy and
Space Science Institute

Quantum noise of GW detector

Interferometer of GW detector

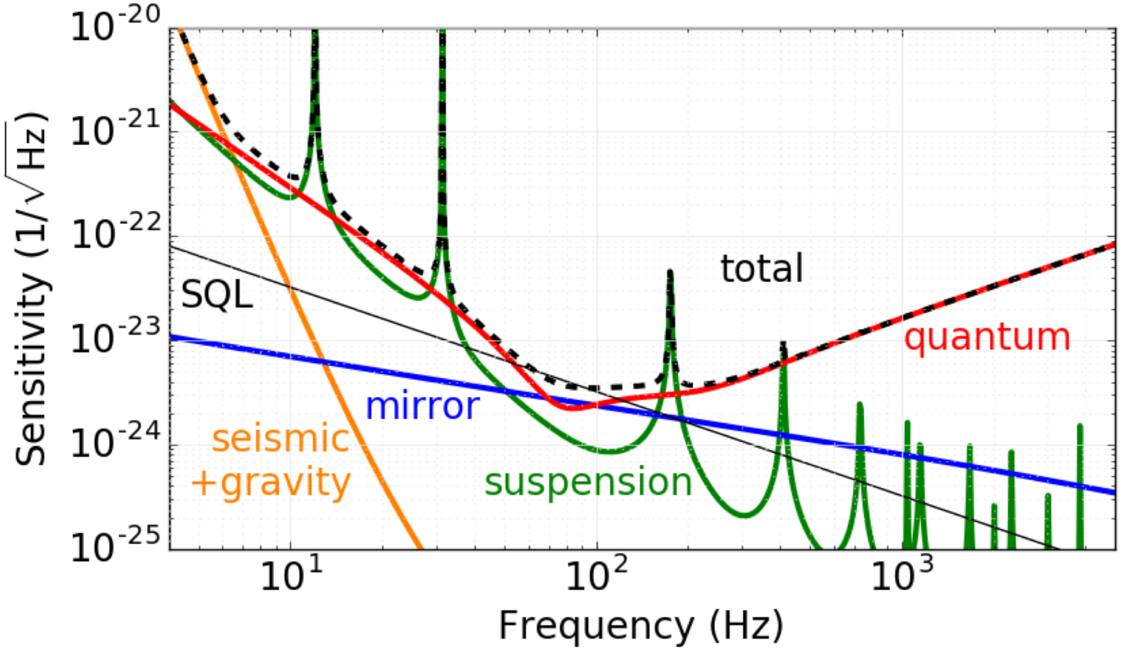


MC : Mode Cleaner
ITMX : Input Test Mass X
ITMY : Input Test Mass Y
REFL : Reflection Port
PRM : Power Recycling Mirror
OMC : Output Mode Cleaner
AS_DC : Anti Symmetric DC
SRM : Signal Recycling Mirror
POP : Pick-off-in-the-PRC
ETMX : End Test Mass X
ETMY : End Test Mass Y
AS_RF : Anti Symmetric RF

Y. Aso et al. (KAGRA Collaboration), Phys.Rev. D88, 043007 (2013)

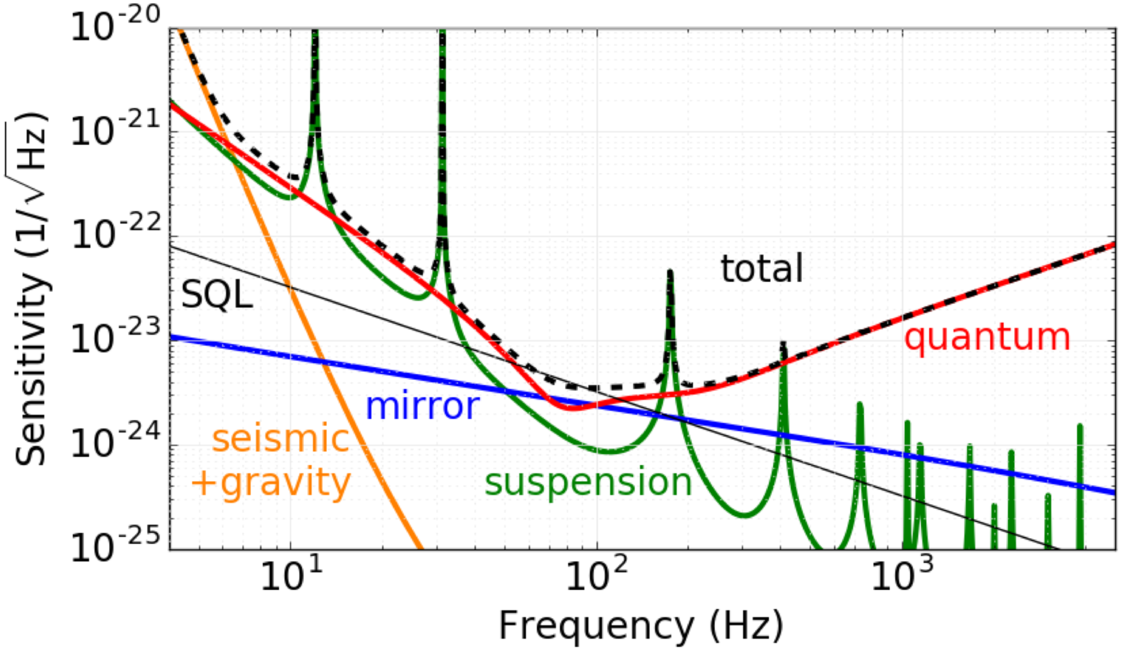
Interferometer of KAGRA
(gravitational wave detector)

Target sensitivity of KAGRA

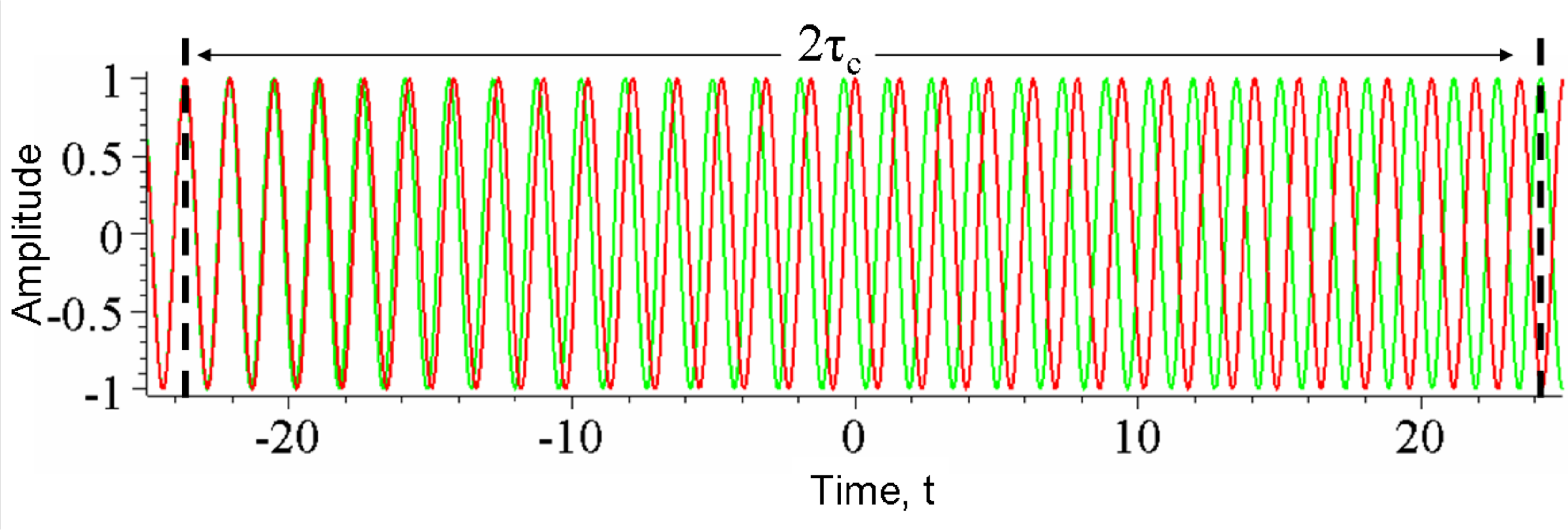


VIRGO detector

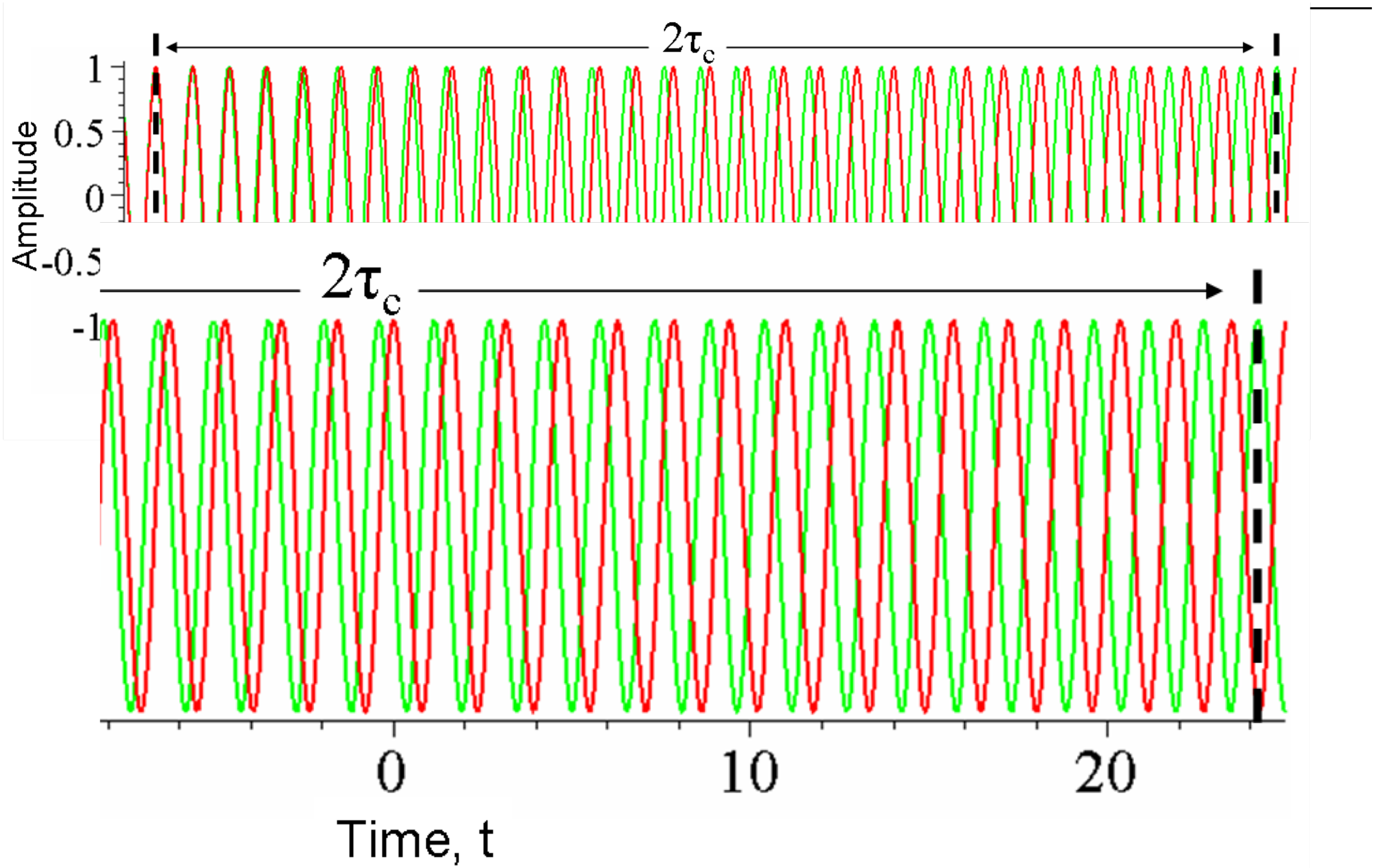
Target sensitivity of KAGRA



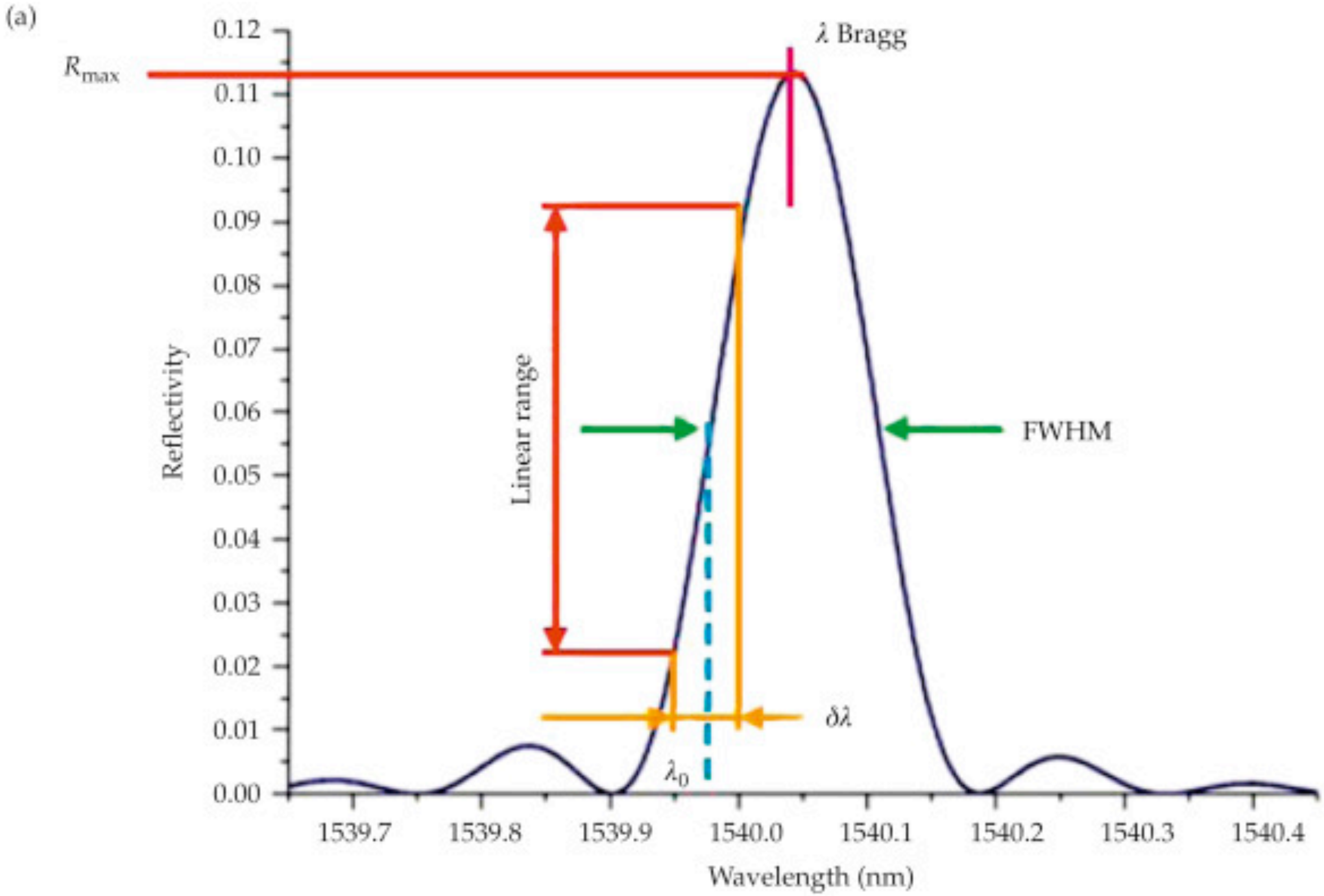
Coherence



Coherence



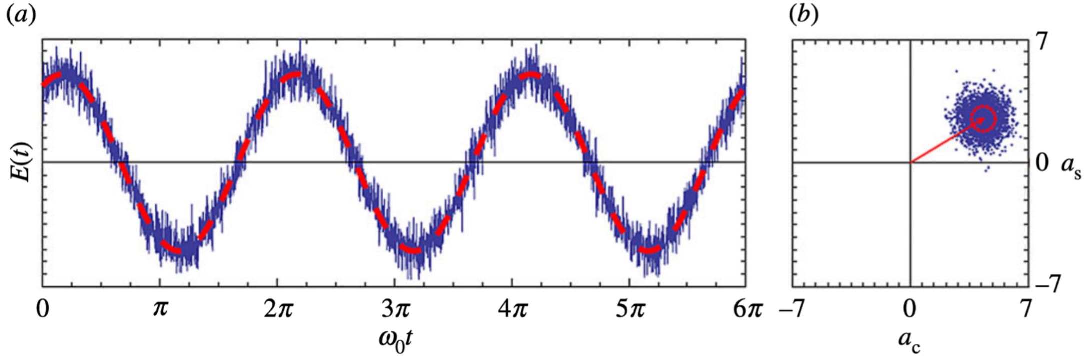
Linewidth of laser



Transmitter and Receiver Design for Amplified Lightwave Systems

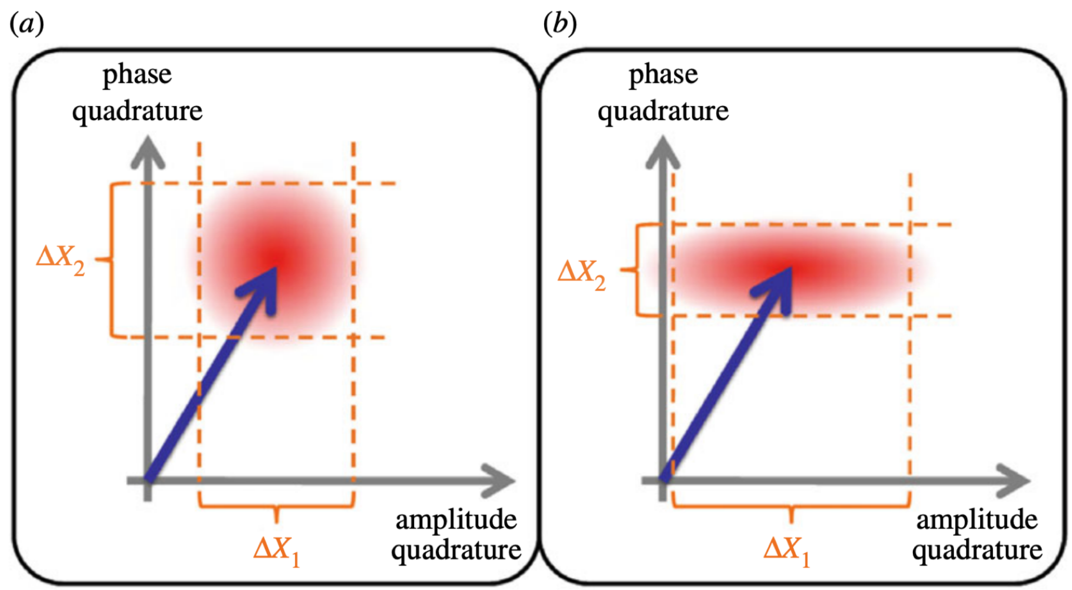
Daniel A. Fishman, B. Scott Jackson, in Optical Fiber Telecommunications (Third Edition), Volume B, 1997

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.

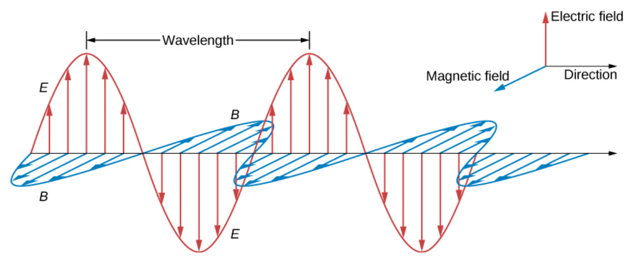
Phase and amplitude noise of light



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

Amplitude

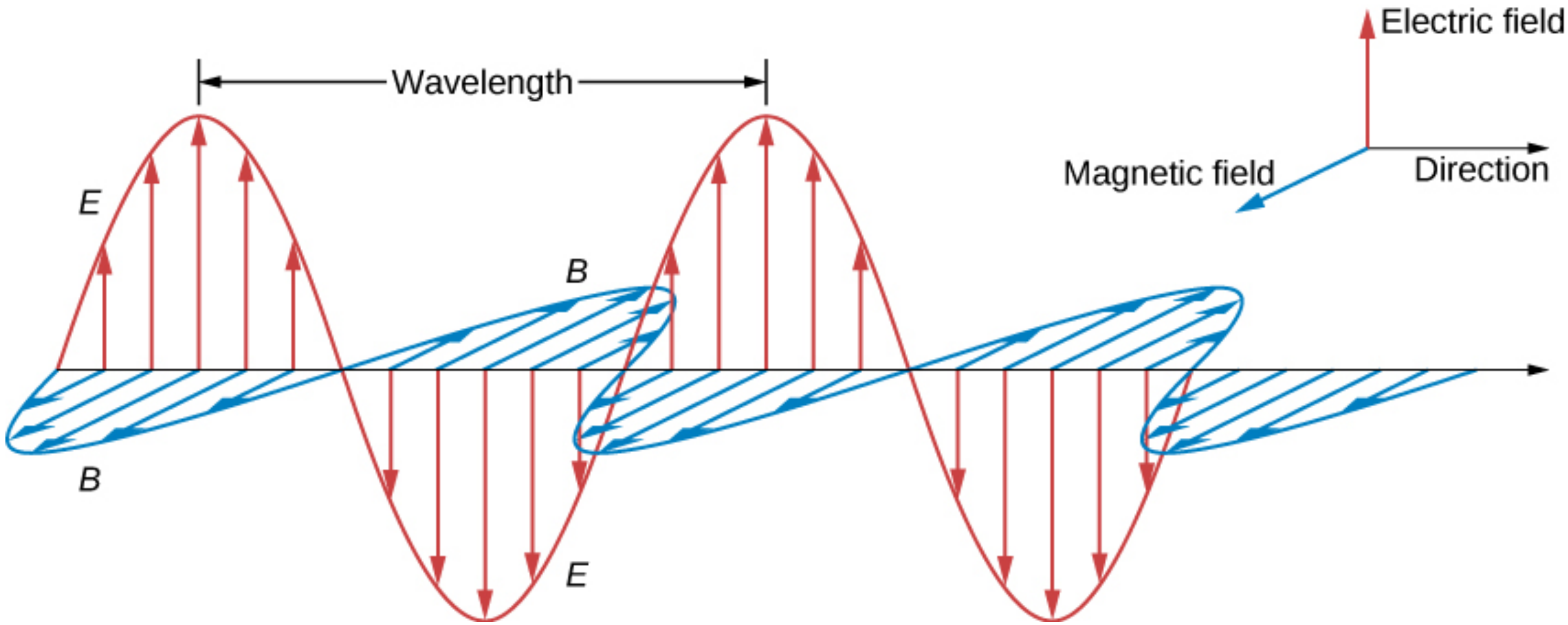
$$Itensity \rightarrow \left|\vec{E}\right|^2 \rightarrow (W/m^2) \propto (Number\ of\ photon)$$



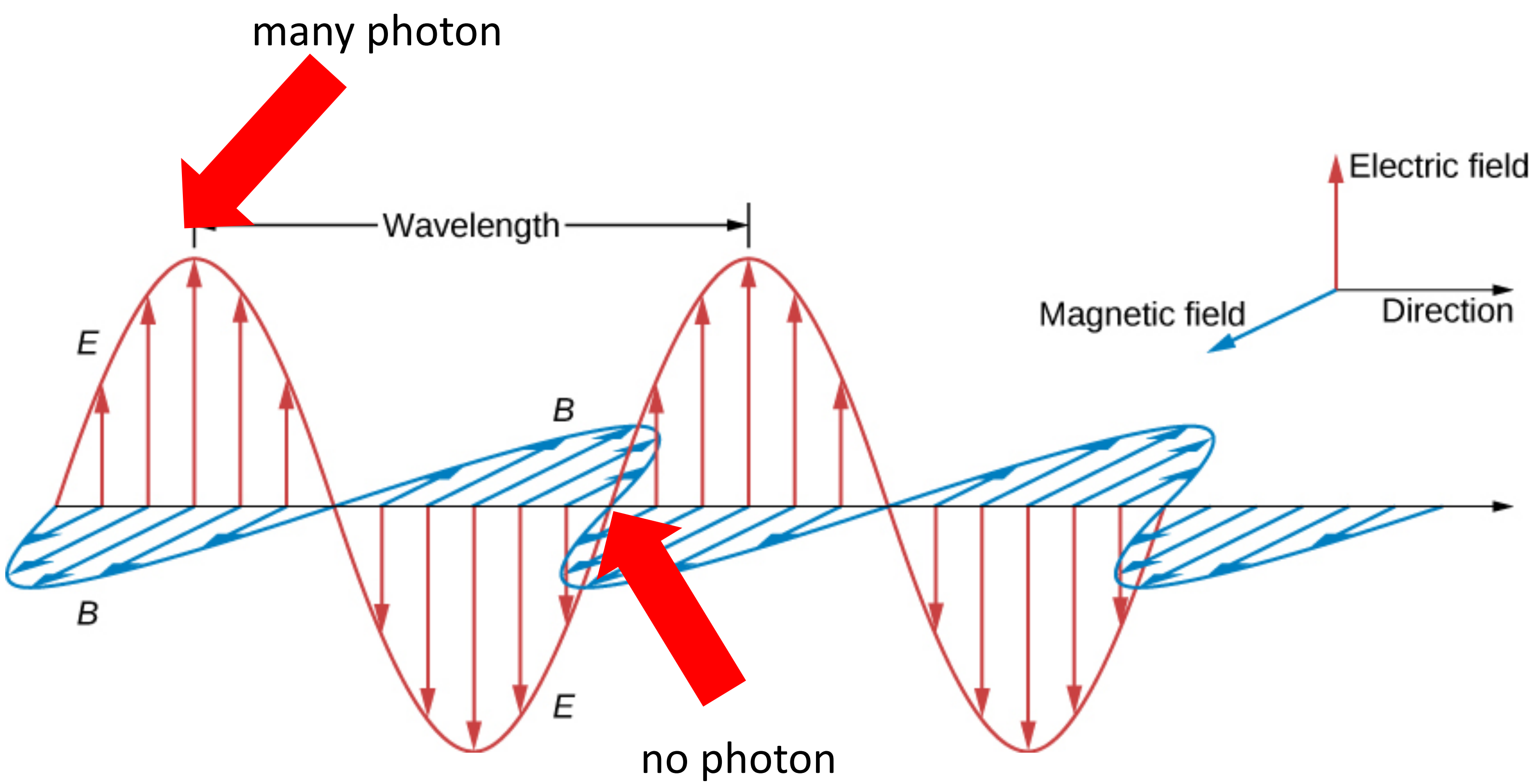
$$Photo\ dioe\ current\ (I) \propto Intensity \propto (Number\ of\ photon)$$

Momentum

Phase



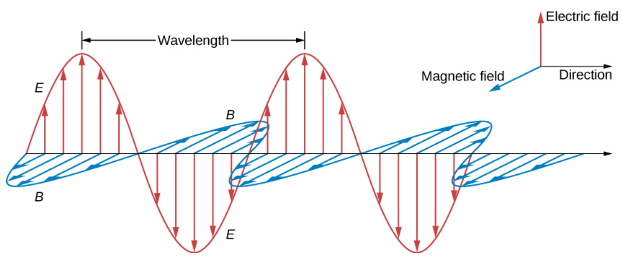
Phase



Position

Classical light

$$Itensity \rightarrow \left|\vec{E}\right|^2 \rightarrow (W/m^2) \propto (Number\ of\ photon)$$

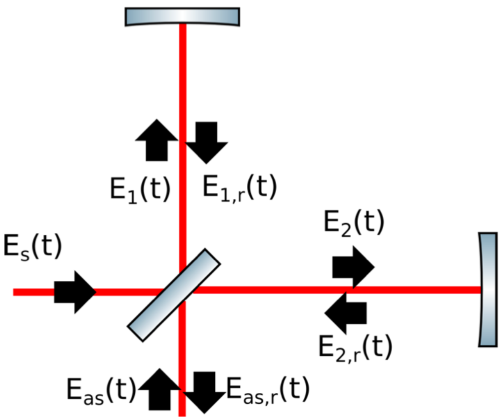


$$Photo\ dioe\ current\ (I) \propto Intensity \propto (Number\ of\ photon)$$

$$E_{1,r}(t) \approx \frac{1}{\sqrt{2}}[E_0\cos(\omega_0 t) - E_0\sin(\omega_0 t)\frac{2\omega_0 x_1(t)}{c} + E_{as}(t)]$$

$$E_{2,r}(t) \approx \frac{1}{\sqrt{2}}[E_0\cos(\omega_0 t) - E_0\sin(\omega_0 t)\frac{2\omega_0 x_2(t)}{c} - E_{as}(t)]$$

Quantum noise of interferometer



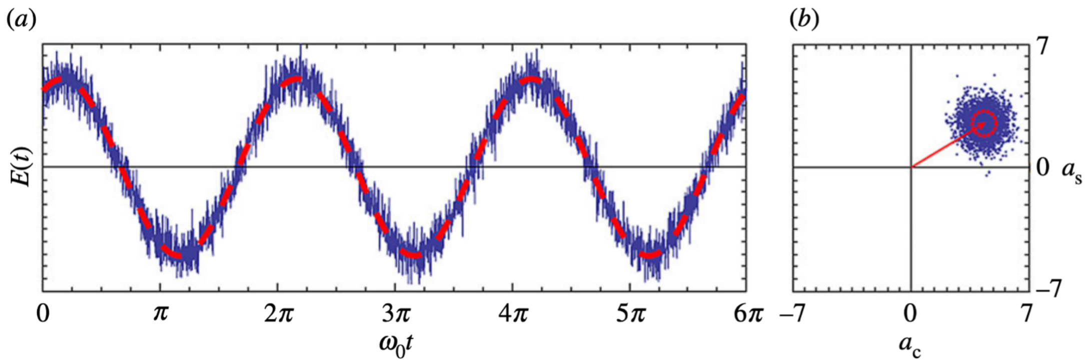
Assume anti-symmetric port is dark port

$$E_1(t) = \frac{1}{\sqrt{2}}[E_s(t) + E_{as}(t)]$$
$$E_2(t) = \frac{1}{\sqrt{2}}[E_s(t) - E_{as}(t)]$$

'as' is vacuum field

Squeezed States for Advanced Gravitational Wave Detectors, B.A., University of California Berkeley, Eric Oelker (2009)

Quantum noise of coherent light

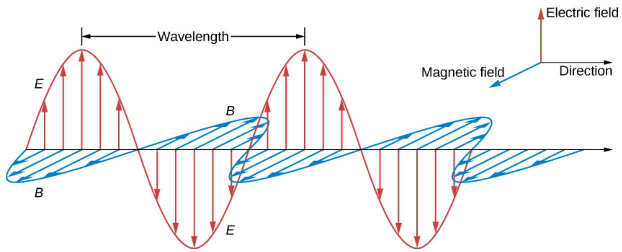


Heurs M. 2018 Gravitational wave detection using laser interferometry beyond the standard quantum limit.Phil. Trans. R. Soc. A 376: 20170289.

Quantum shot noise

Quantum Shot noise
-> Noise induced by photon fluctuation

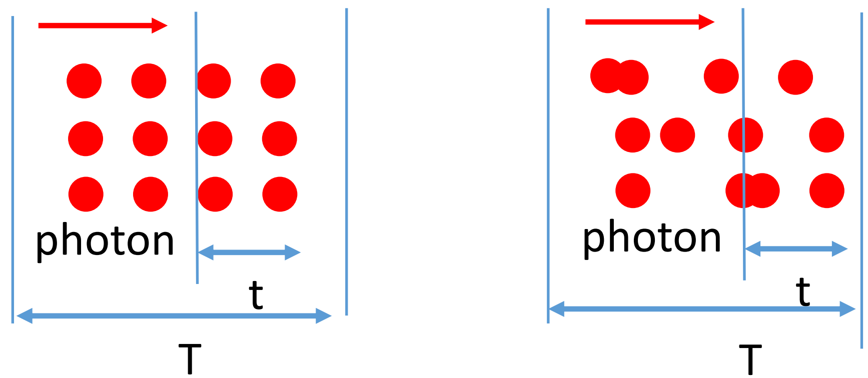
$$Itensity \rightarrow \left|\vec{E}\right|^2 \rightarrow (W/m^2) \propto (Number\ of\ photon)$$



$$Photo\ dioe\ current\ (I) \propto Intensity \propto (Number\ of\ photon)$$

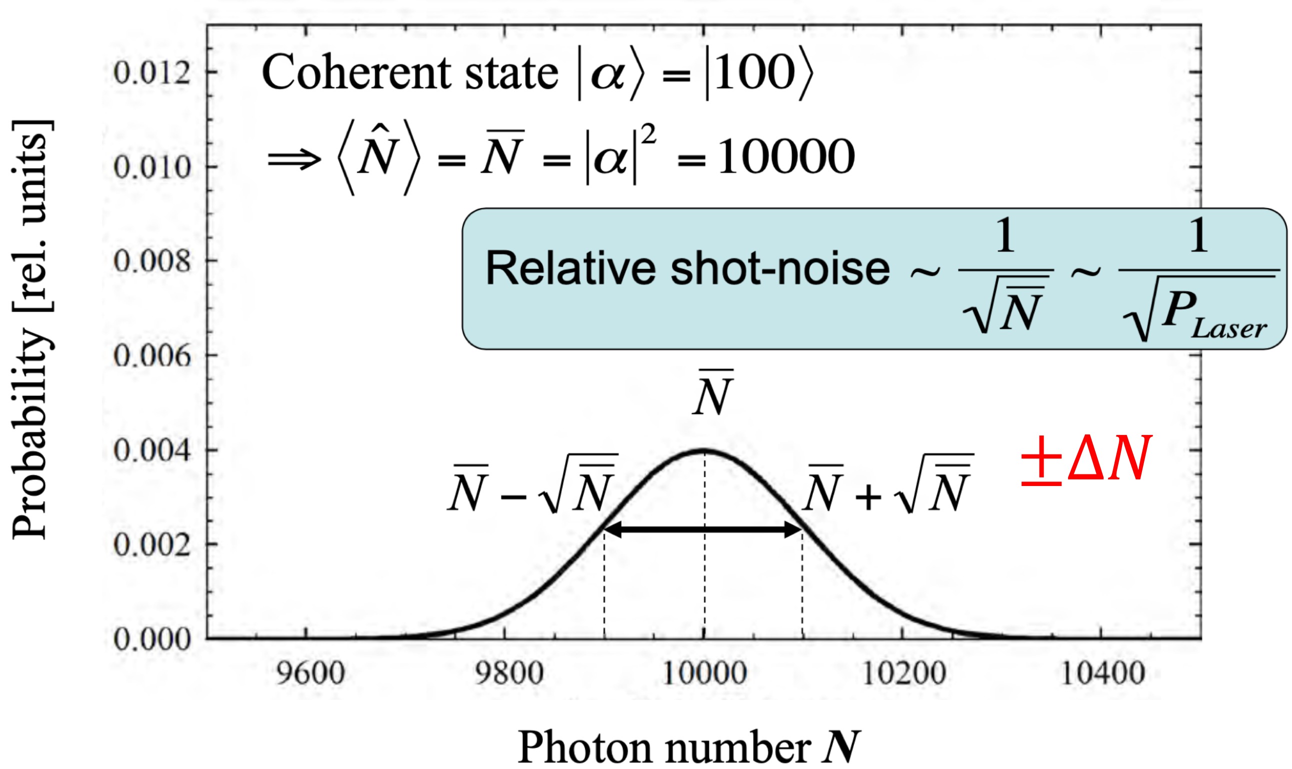
Shot noise of interferometer

Laser power = the number of photon / time

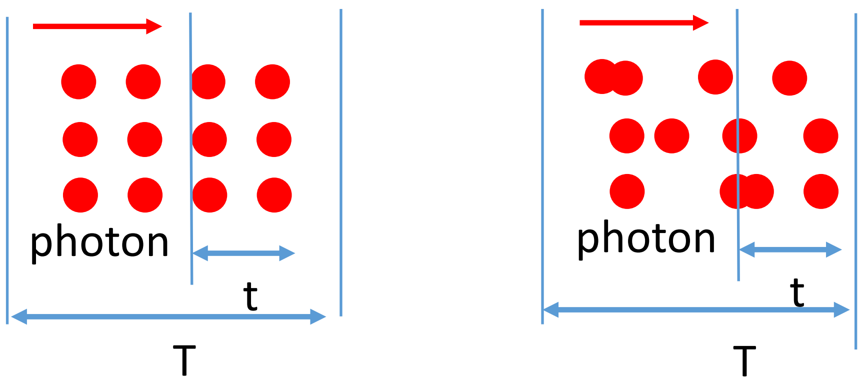


Shot noise

Photon Counting Statistics



Shot noise of interferometer

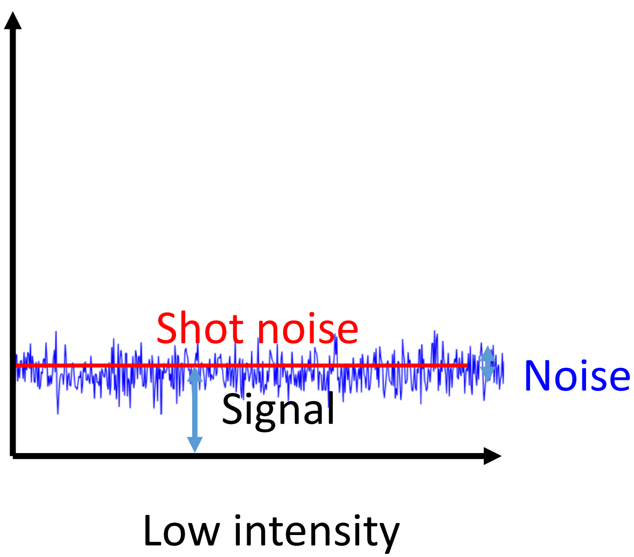


When we have coherent laser source

$$Signal \propto (Number\ of\ photon)$$

$$Shot\ Noise \propto \sqrt{Number\ of\ Photon}$$

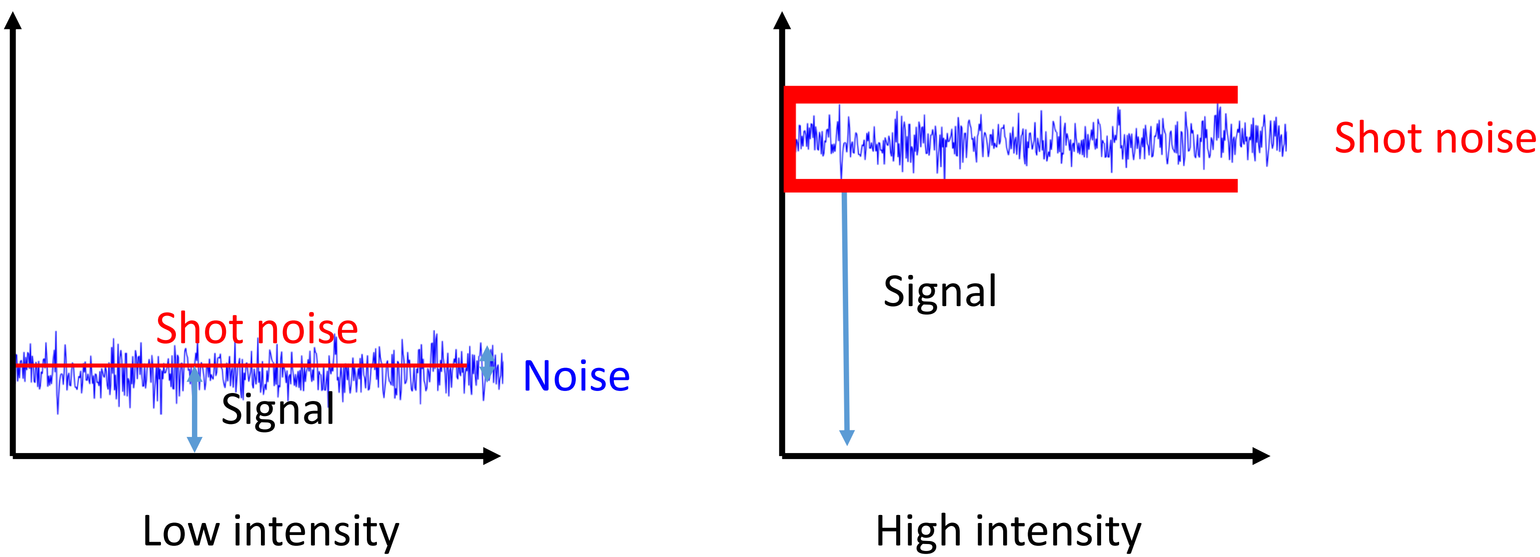
Shot noise of interferometer



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

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



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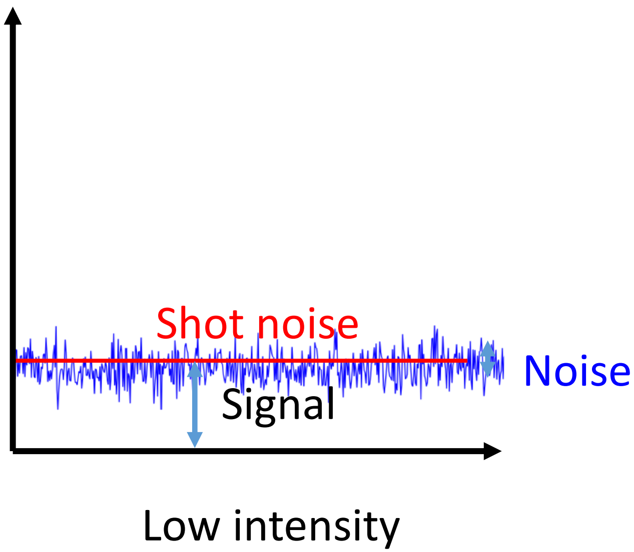
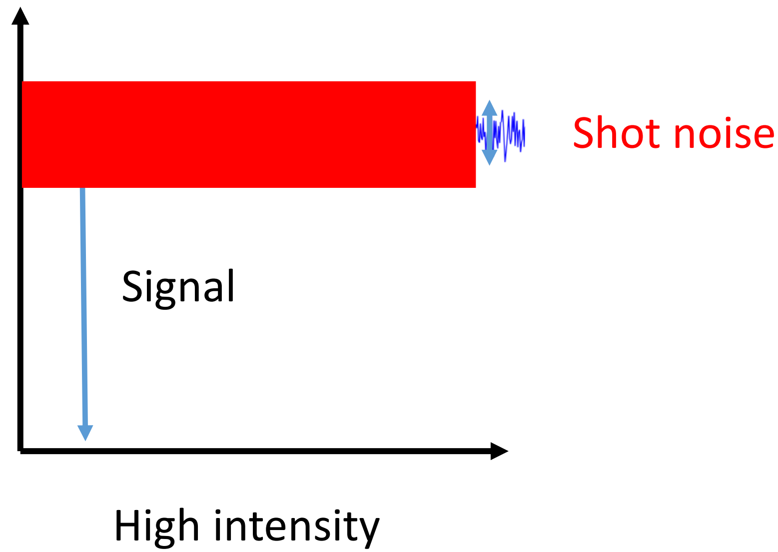
Shot noise of interferometer

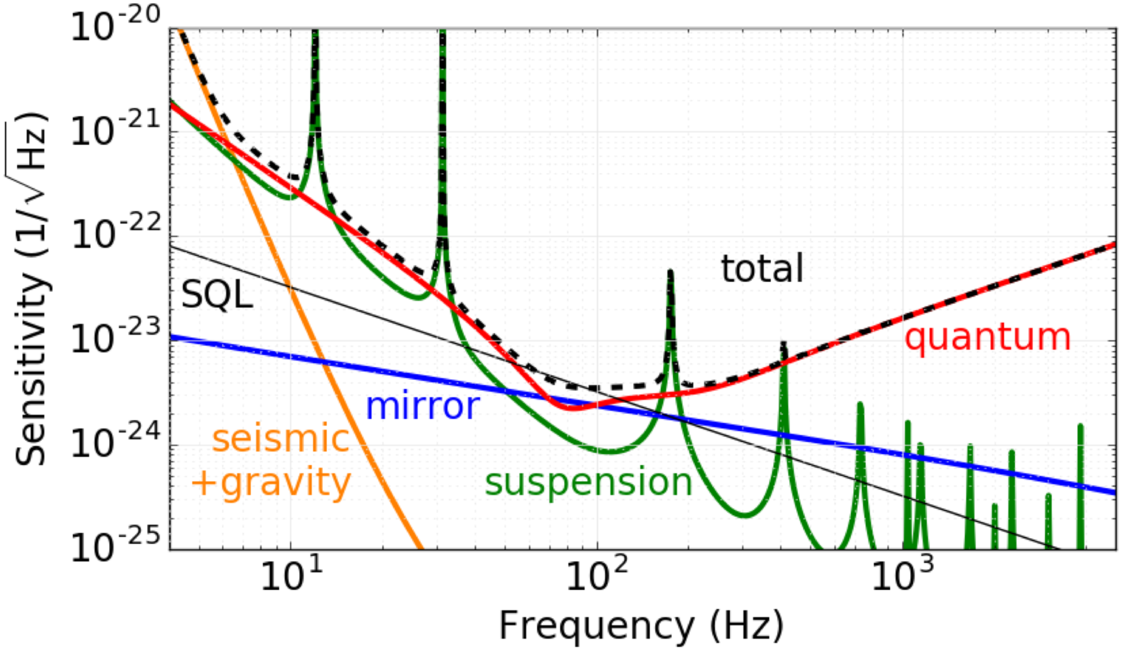




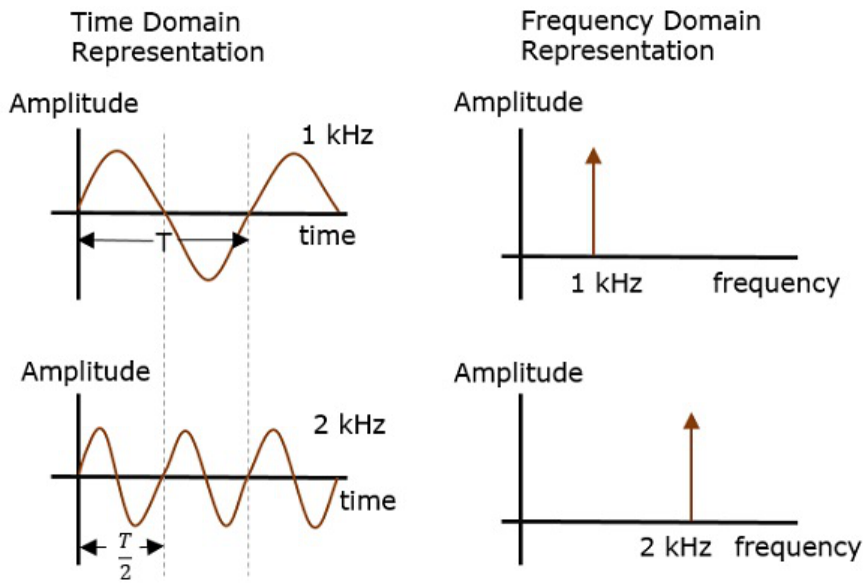
$$Signal\ to\ Noise\ ratio = \frac{N}{\sqrt{N}}$$

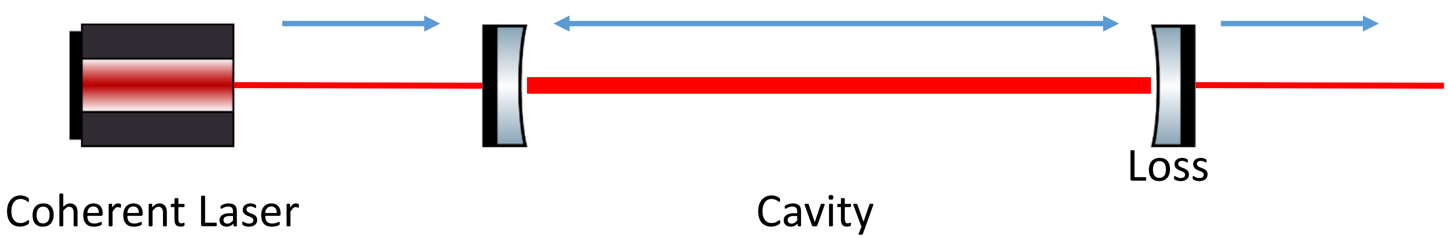
If Shot noise is relatively larger than other noise(Thermal, Electric.. etc)
We say that it has shot noise limit sensitivity

Target sensitivity of KAGRA



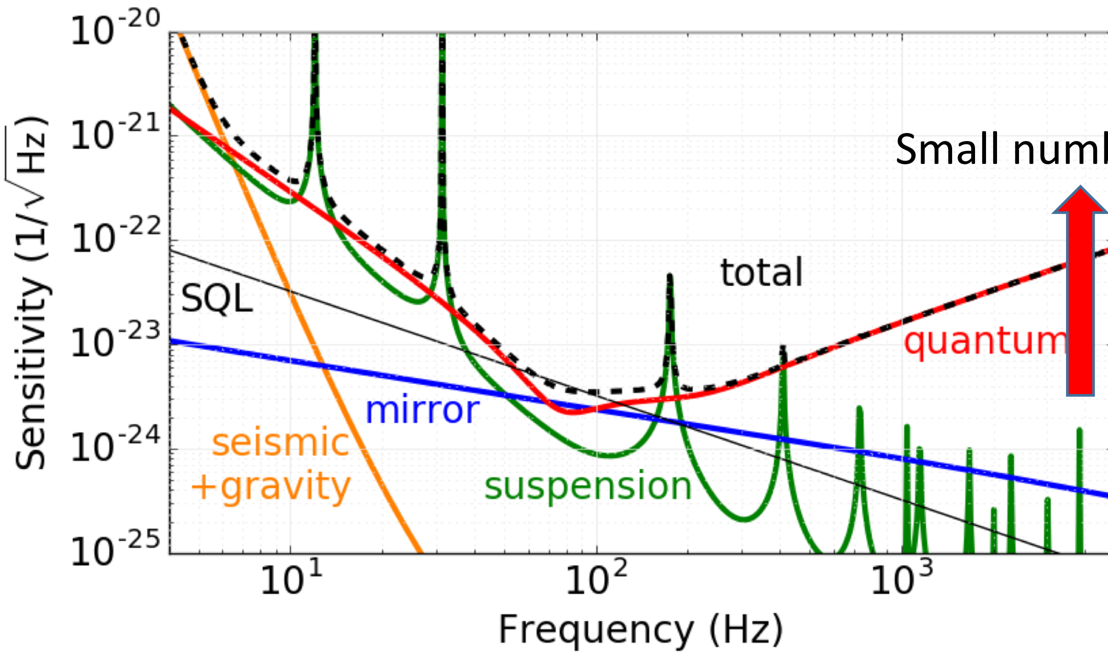
Shot noise curve of GW detector





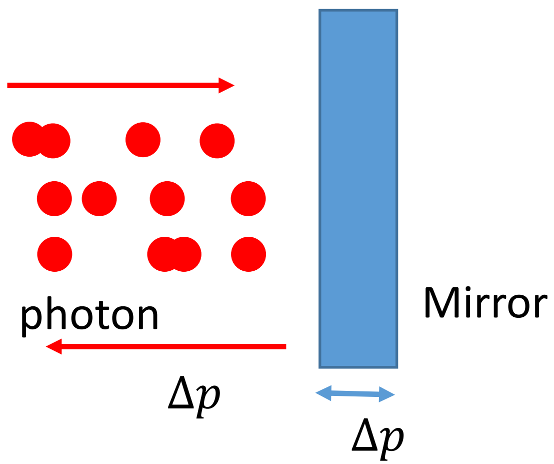
Interaction length ~ Number of round trip x Length

Target sensitivity of KAGRA



Small number of round trip

Radiation pressure noise



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

Radiation pressure noise in GW detector

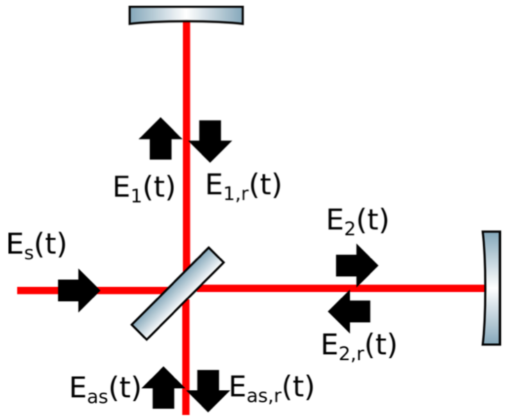


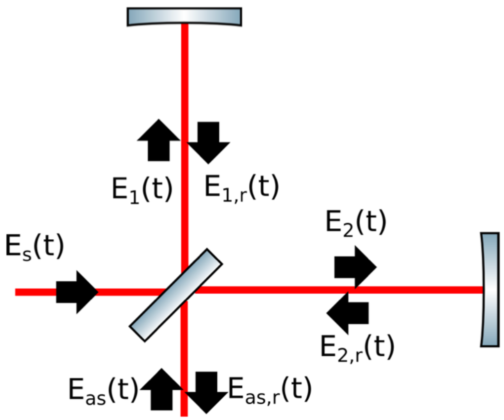
Figure 1-3: Schematic of a Michelson interferometer. A classical carrier field $E_s(t)$ enters from the interferometer symmetric port while a vacuum fluctuations represented by $E_{as}(t)$ enter from the anti-symmetric port. The quantum noise level at the readout is contained in the AC component of the field exiting the interferometer $E_{as,r}(t)$

$$E_s(t) = E_0 \cos(\omega_0 t) + \underline{\delta E_s(t)}$$

Noise term

Squeezed States for Advanced Gravitational Wave Detectors, B.A., University of California Berkeley, Eric Oelker (2009)

Radiation pressure noise in GW detector



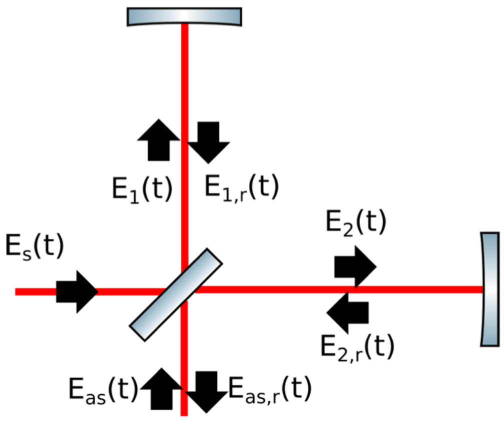
Assume anti-symmetric port is dark port

$$E_1(t) = \frac{1}{\sqrt{2}}[E_s(t) + E_{as}(t)]$$
$$E_2(t) = \frac{1}{\sqrt{2}}[E_s(t) - E_{as}(t)]$$

'as' is vacuum field

Squeezed States for Advanced Gravitational Wave Detectors, B.A., University of California Berkeley, Eric Oelker (2009)

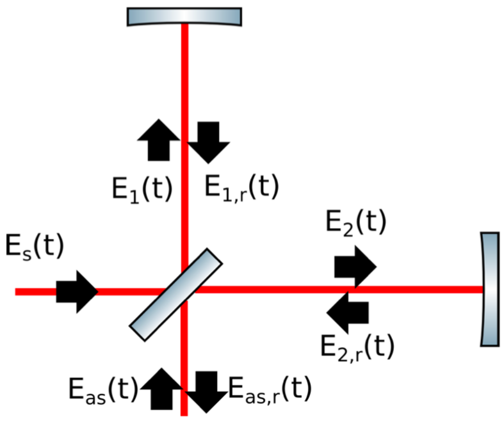
Radiation pressure noise in GW detector



$$E_{as,r}(t) = E_{as} + E_0 \frac{\omega_0 [x_2(t) - x_1(t)]}{c} \sin(\omega_0 t)$$

Squeezed States for Advanced Gravitational Wave Detectors, B.A., University of California Berkeley, Eric Oelker (2009)

Radiation pressure noise in GW detector

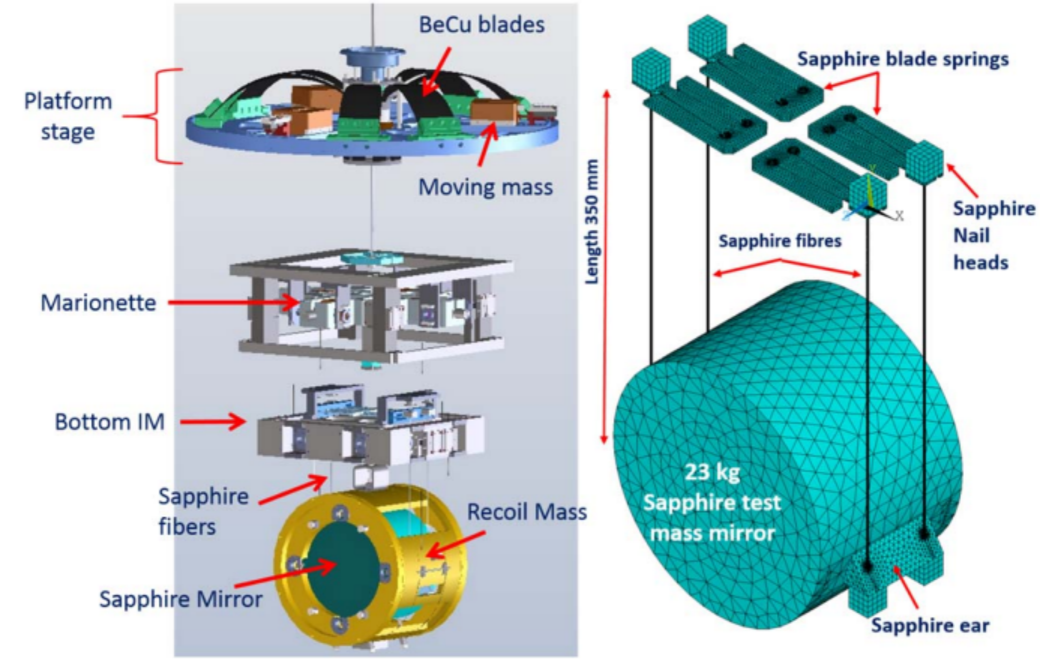


$$x_1(t) - x_2(t) = \underline{x_{cl,1}(t) - x_{cl,2}(t)} + \underline{\delta\hat{x}_1(t) - \delta\hat{x}_2(t)} + \underline{Lh(t)}$$

Thermal, seismic   Radiation pressure   GW source

Squeezed States for Advanced Gravitational Wave Detectors, B.A., University of California Berkeley, Eric Oelker (2009)

Test mass of KAGRA



Standard quantum limit of GW detector

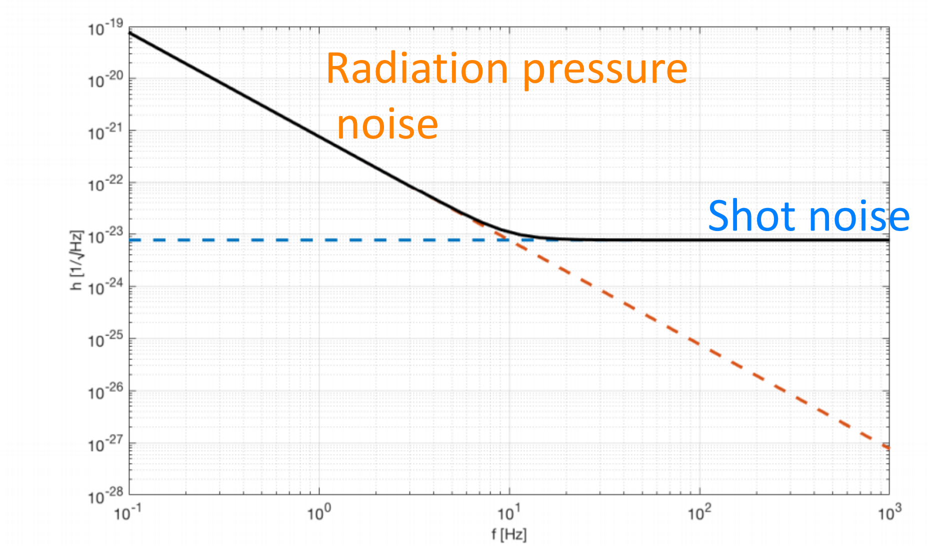
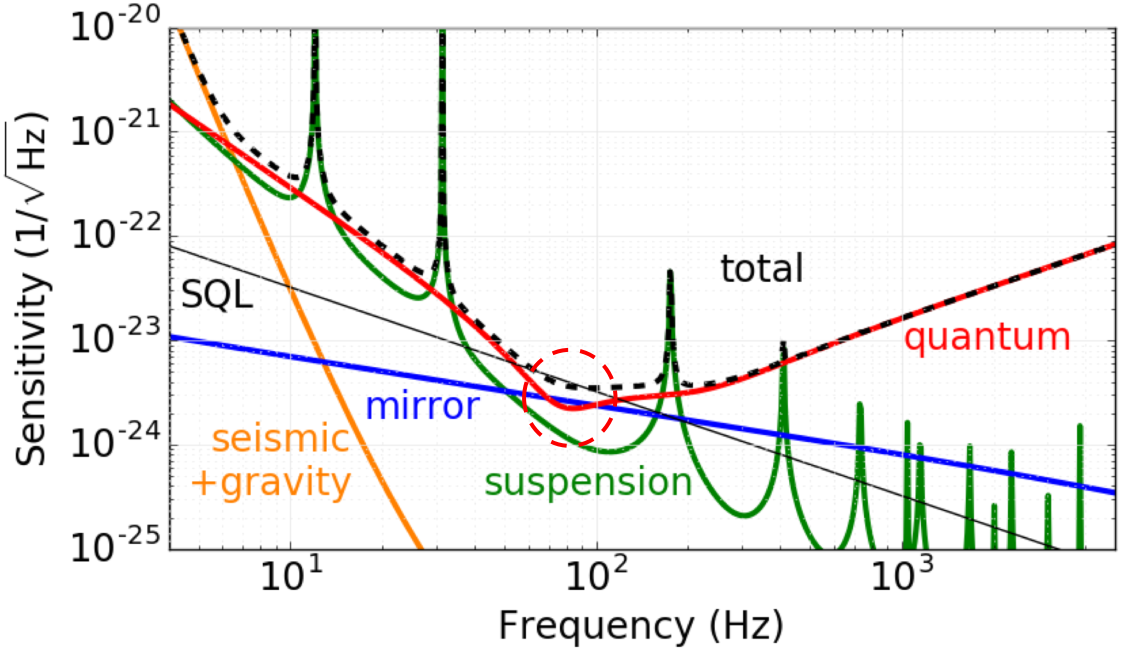


Figure 2.3: The strain equivalent quantum noise is plotted for an interferometer with M = 50 kg, L = 3 km, P = 10 MW. The two contribution of radiation pressure noise and shot noise are shown in blue and red respectively.

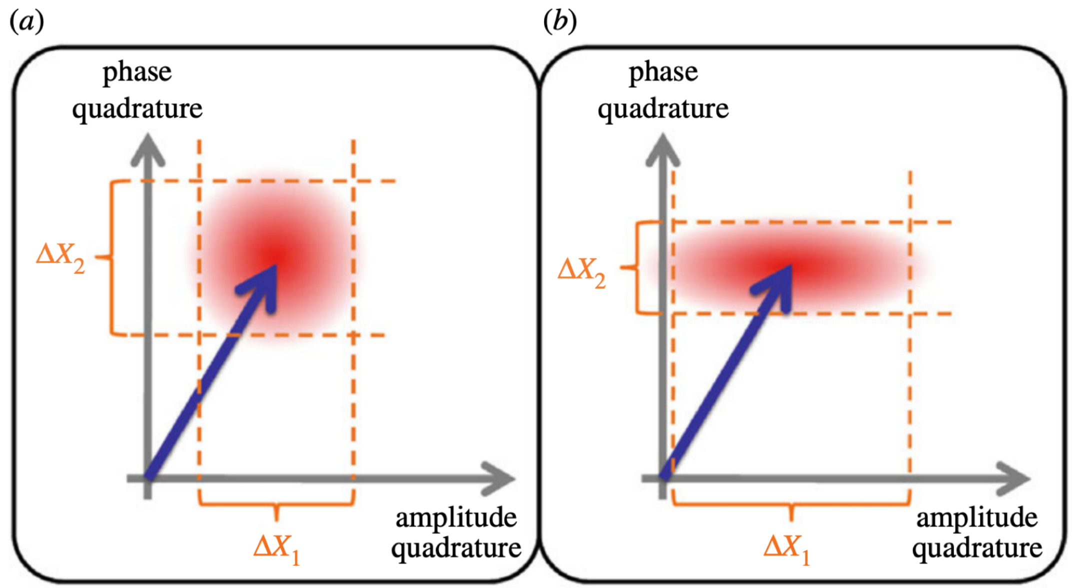
Standard quantum limit of gravitational wave detector
Shot noise + Radiation pressure noise

Target sensitivity of KAGRA



Squeezed vacuum injection in GW detector

Phase and amplitude noise of light



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

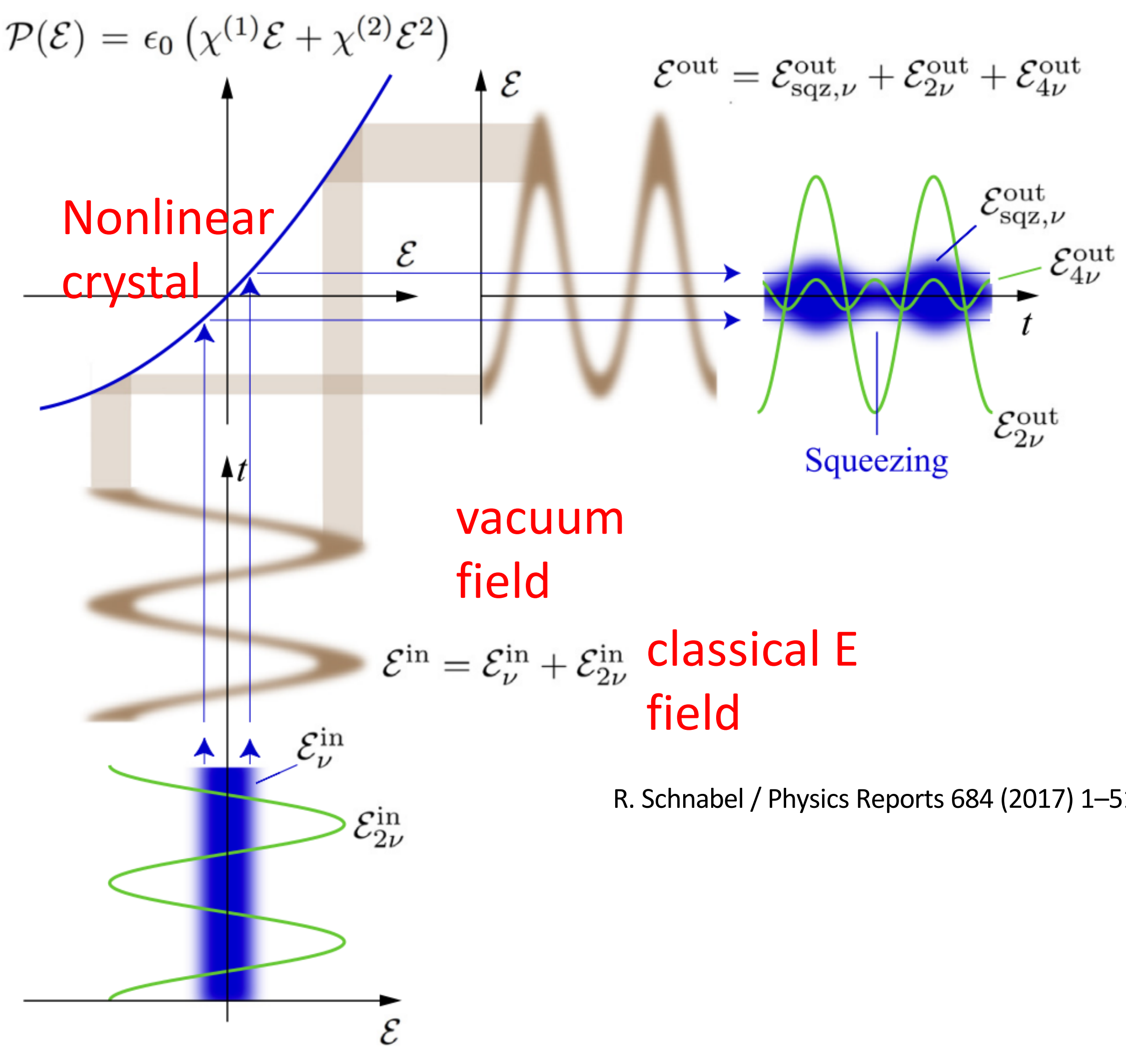
Non linear crystal

Non-linear crystal

linear optics

Non linear optics

Parametric down conversion process

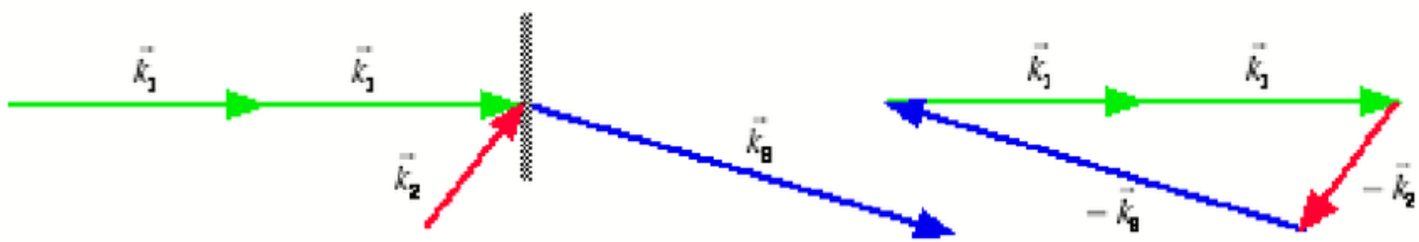


R. Schnabel / Physics Reports 684 (2017) 1–51

Phase matching condition

$\omega_3 = \omega_1 + \omega_2 - \omega_2$

$\Delta\vec{k} = \vec{k}_1 + \vec{k}_2 - \vec{k}_2 - \vec{k}_3 = 0$



$\omega_3 = 2\omega_1 - \omega_2$

$\Delta\vec{k} = 2\vec{k}_1 - \vec{k}_2 - \vec{k}_3 = 0$

Parametric down conversion process

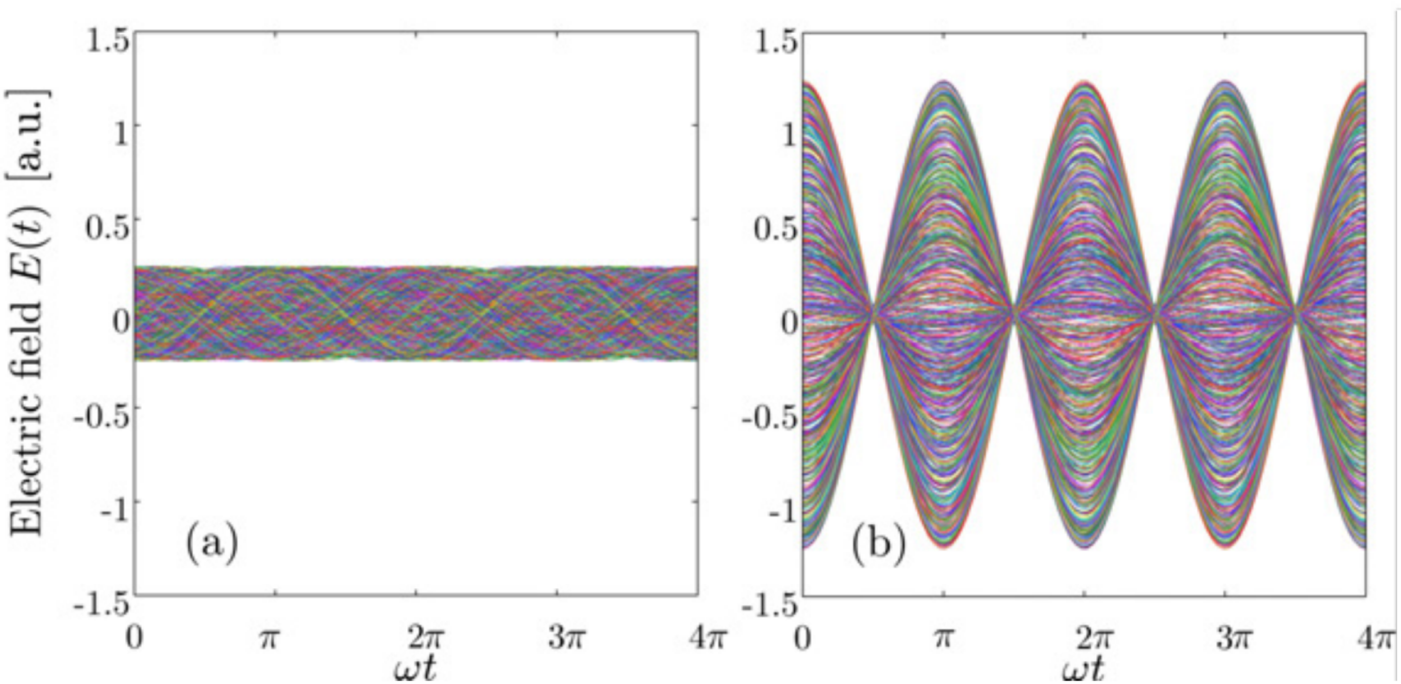
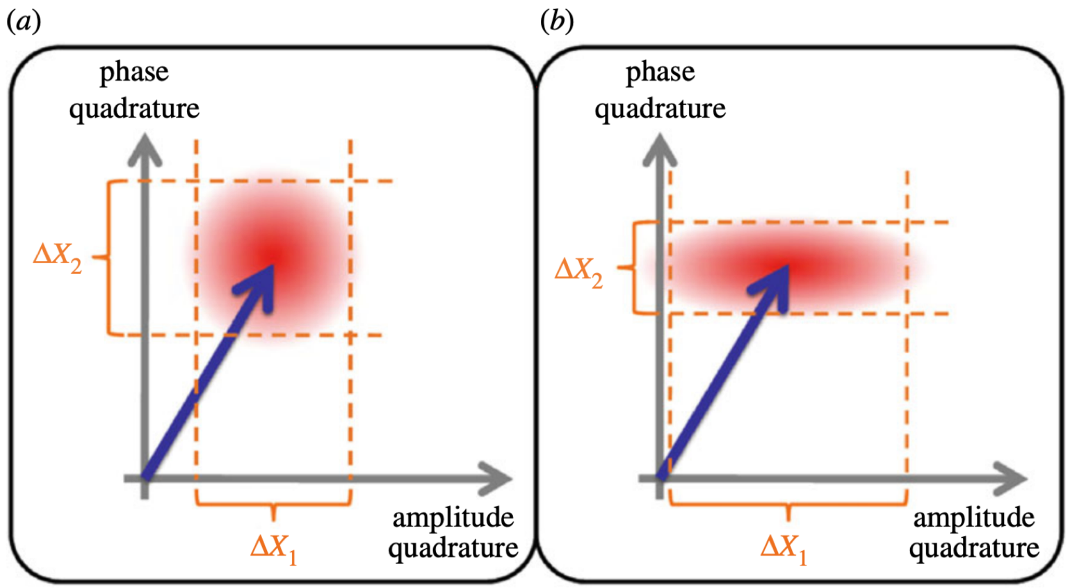


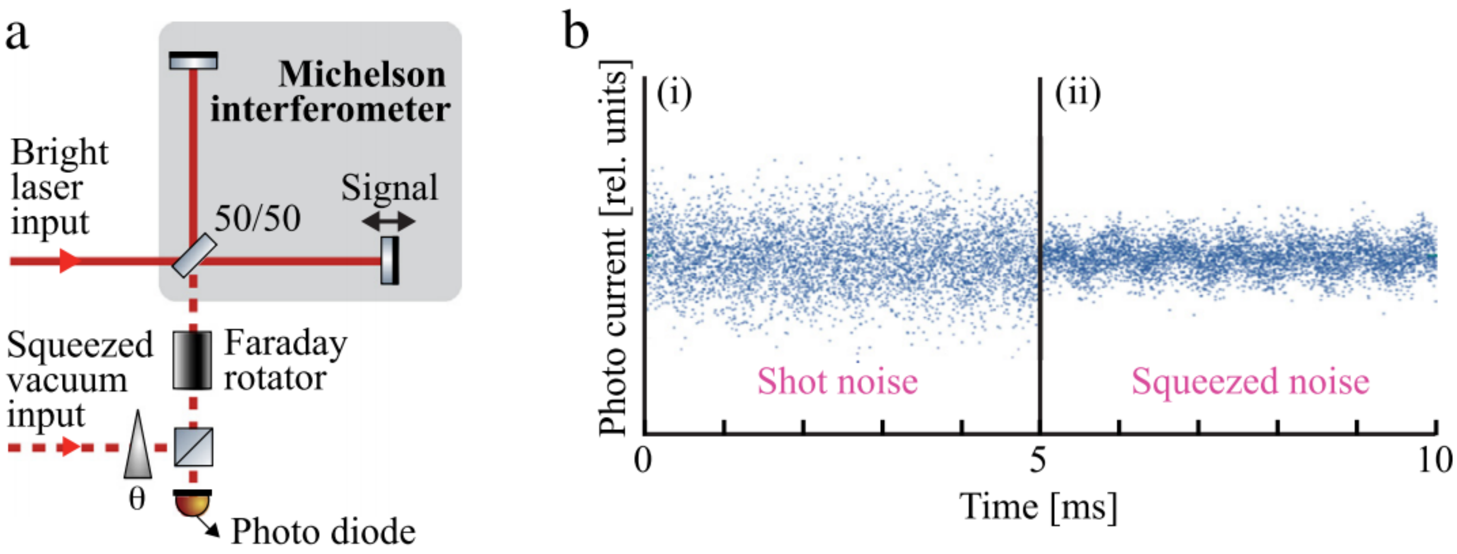
Figure 1.6: Simulation of electric field in time for (a) vacuum state and for (b) squeezed vacuum.

Phase and amplitude noise of light



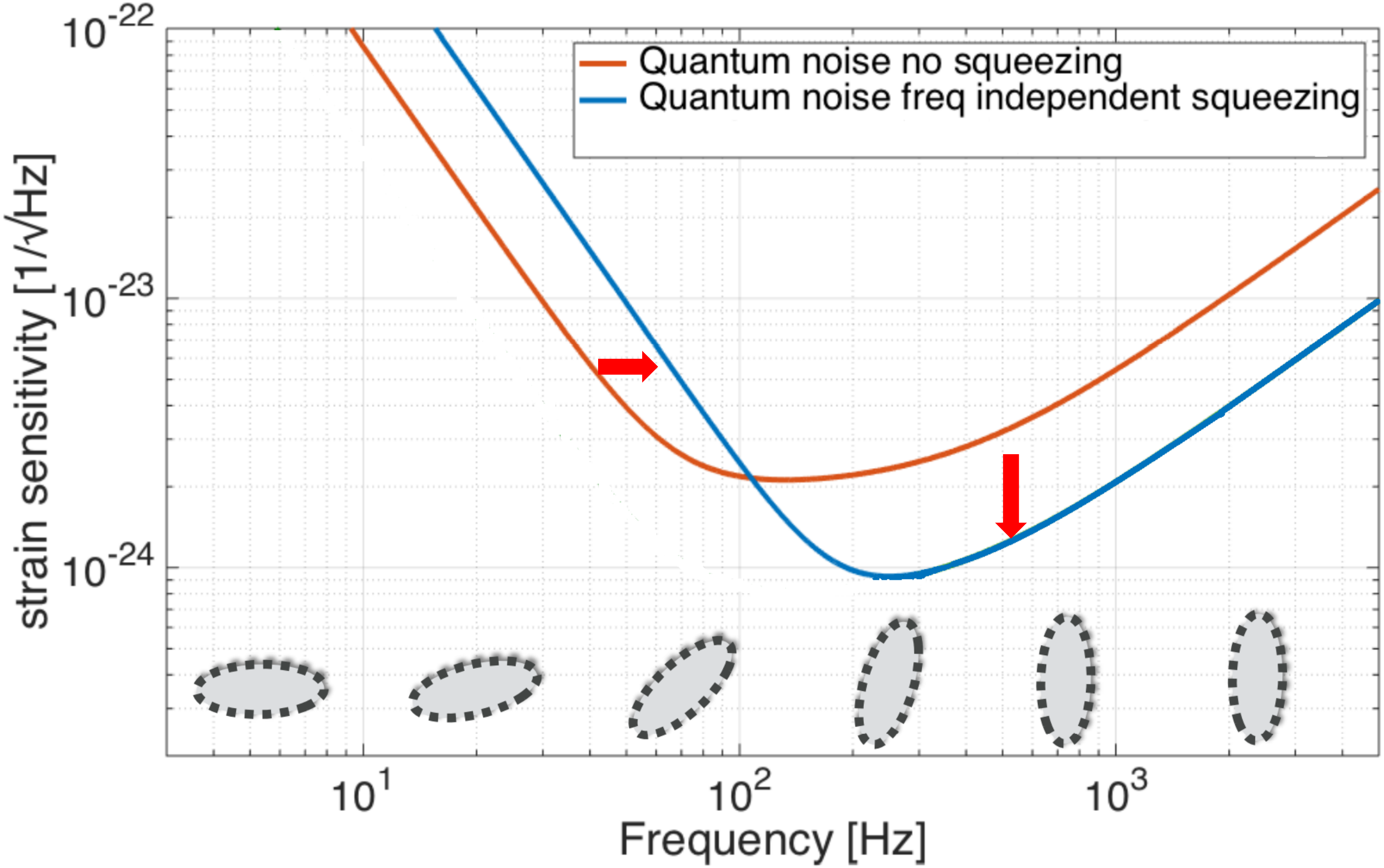
Heurs M. 2018 Gravitational wave detection using laser interferometry beyond the standard quantum limit.Phil. Trans. R. Soc. A 376: 20170289.

Squeezed state of light



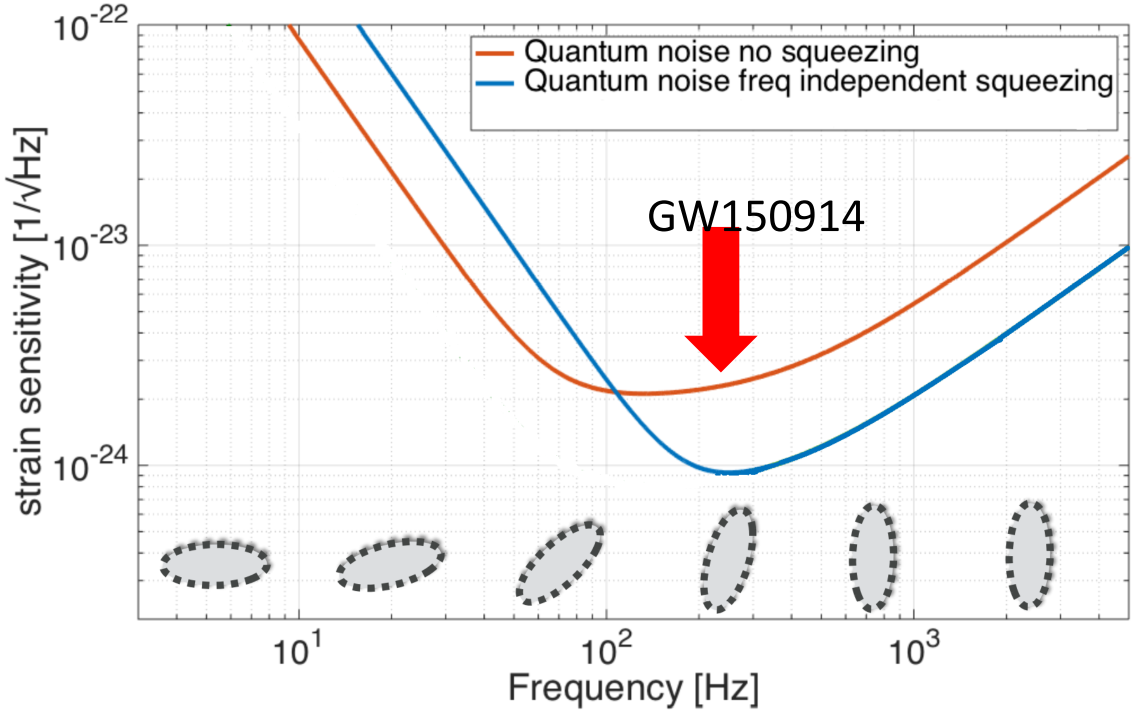
R. Schnabel / Physics Reports 684 (2017) 1–51

Frequency independent squeezing



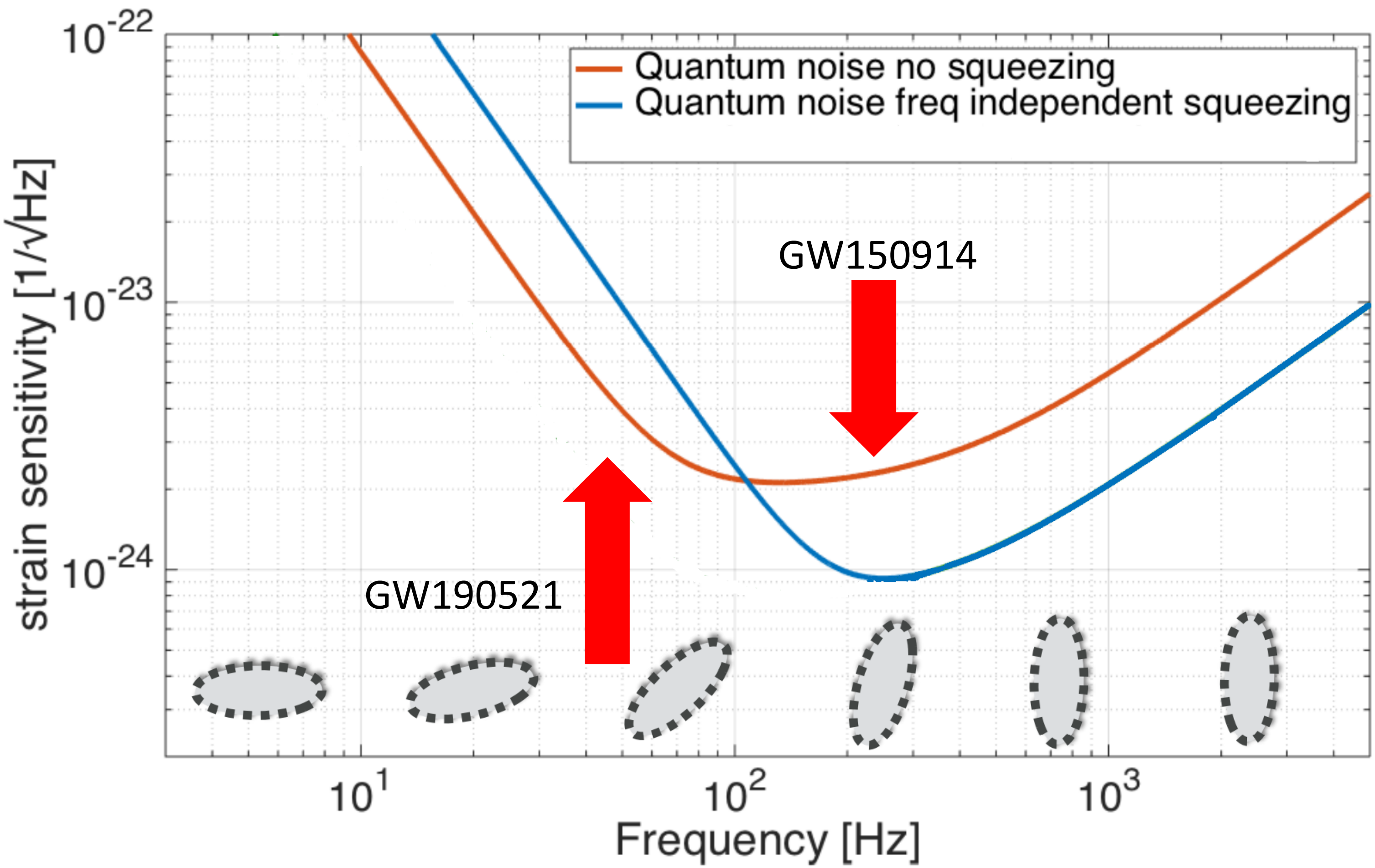
Optical and noise studies for Advanced Virgo and filter cavities for quantum noise reduction in gravitational-wave interferometric detectors, Eleonora Capocasa, UNIVERSITÉ PARIS DIDEROT (2017)

Frequency independent squeezing



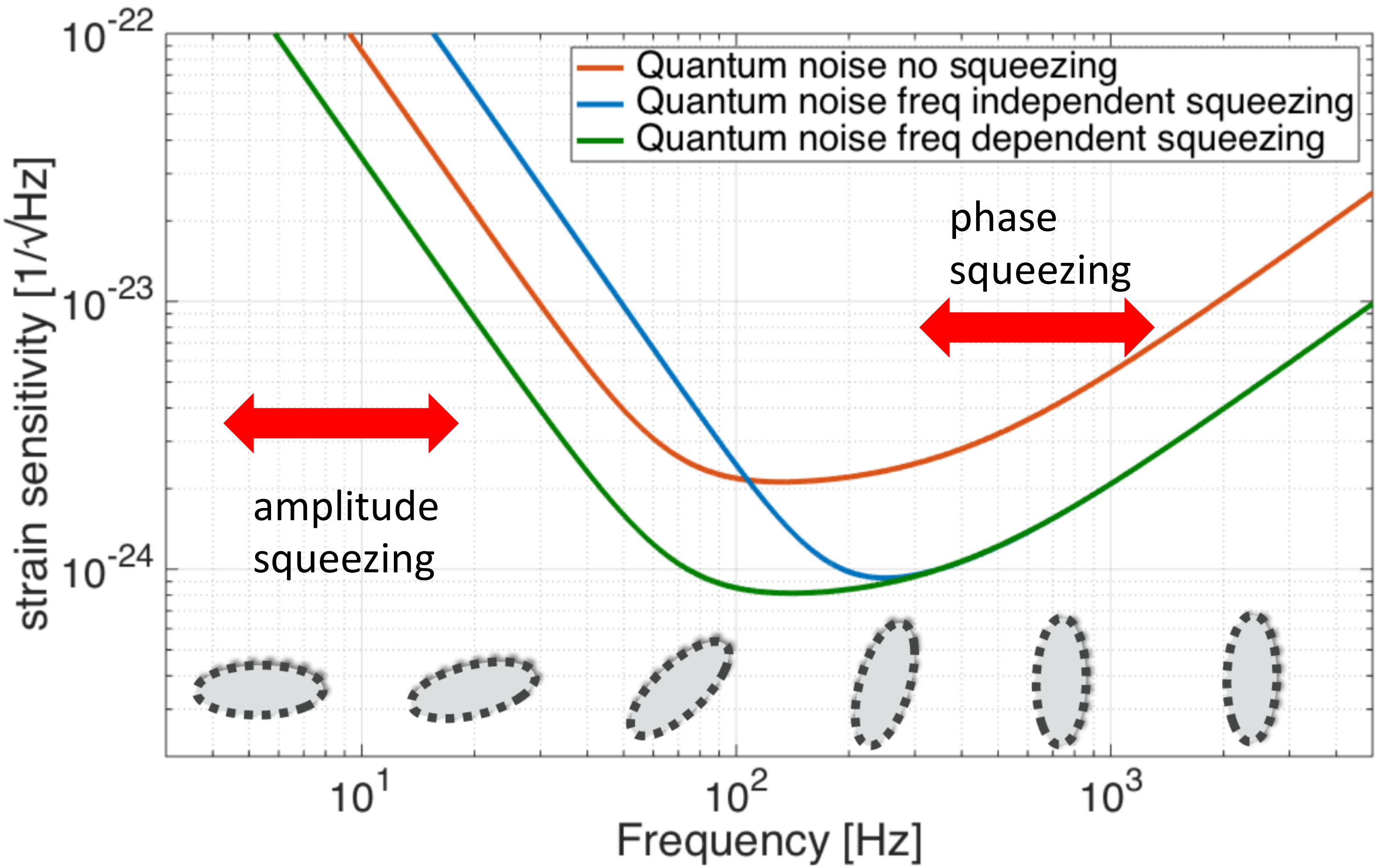
Optical and noise studies for Advanced Virgo and filter cavities for quantum noise reduction in gravitational-wave interferometric detectors, Eleonora Capocasa, UNIVERSITÉ PARIS DIDEROT (2017)

Frequency independent squeezing



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

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)

4. Frequency dependent squeezing in GW detector

First suggestion of filter cavity in FD squeezing

Conversion of conventional gravitational-wave interferometers into quantum nondemolition interferometers by modifying their input and/or output optics

H. J. Kimble,[1] Yuri Levin,[2,*] Andrey B. Matsko,[3] Kip S. Thorne,[2] and Sergey P. Vyatchanin[4]
[1]*Norman Bridge Laboratory of Physics 12-33, California Institute of Technology, Pasadena, California 91125*
[2]*Theoretical Astrophysics, California Institute of Technology, Pasadena, California 91125*
[3]*Department of Physics, Texas A&M University, College Station, Texas 77843-4242*
[4]*Physics Faculty, Moscow State University, Moscow, 119899, Russia*

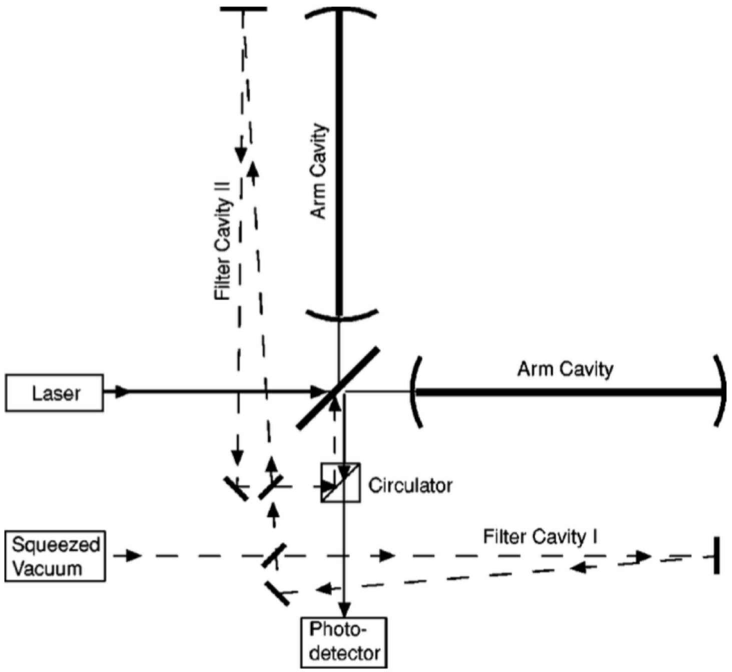
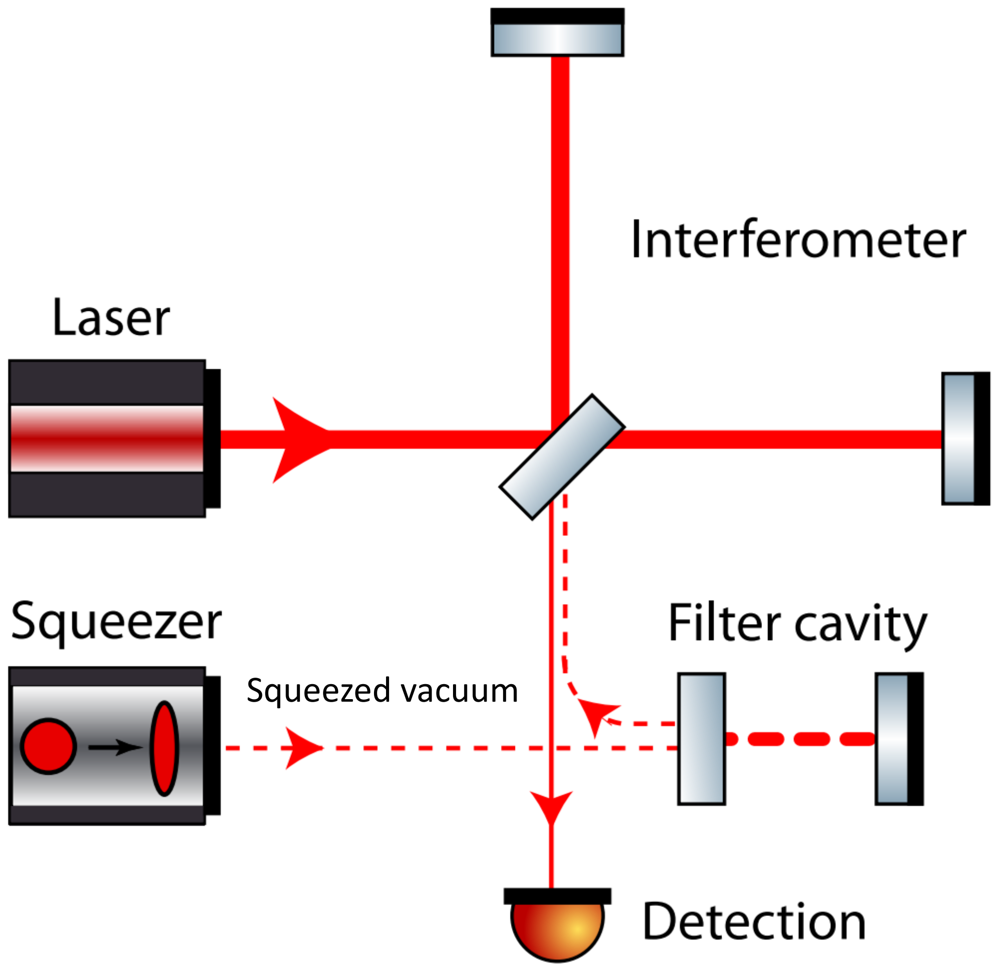


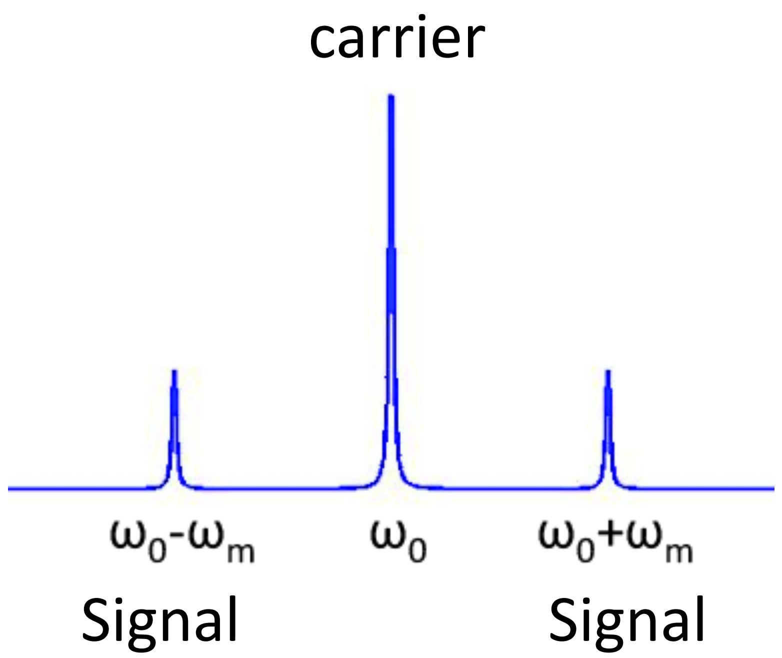
FIG. 1. Schematic diagram of a squeezed-input interferometer.

Squeezed vacuum injection with filter cavity



M. Evans, L. Barsotti, P. Kwee, J. Harms, and H. Miao
Phys. Rev. D **88**, 022002 – Published 29 July 2013

Side band figure



Detuned cavity

Simple picture

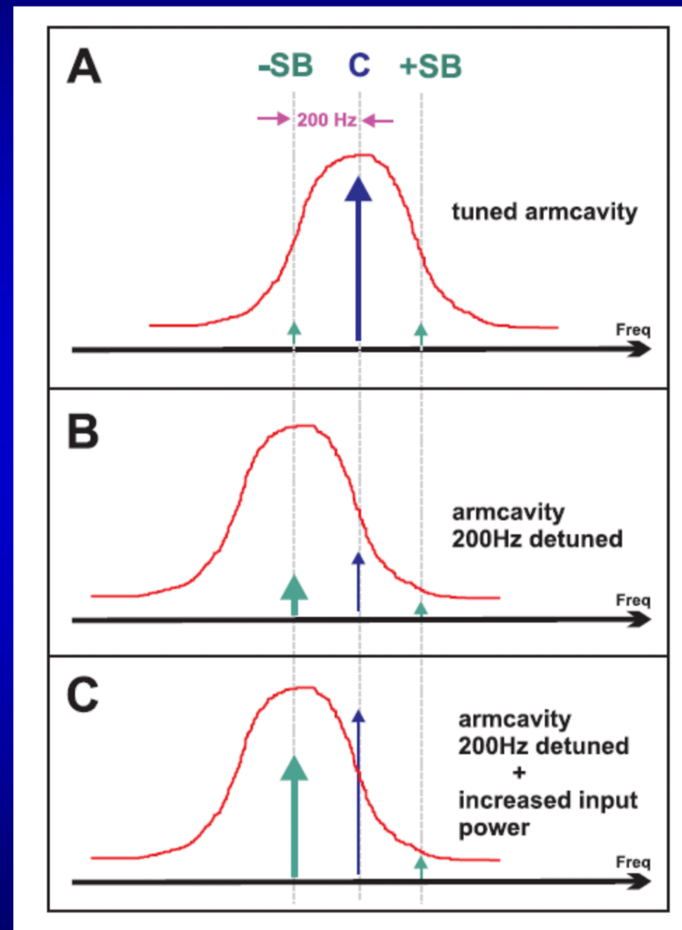
Stefan Hild et al, "Detuned arm cavities", 3rd GEO simulation workshop, Hannover, June 2007

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

=> Smaller GW signal

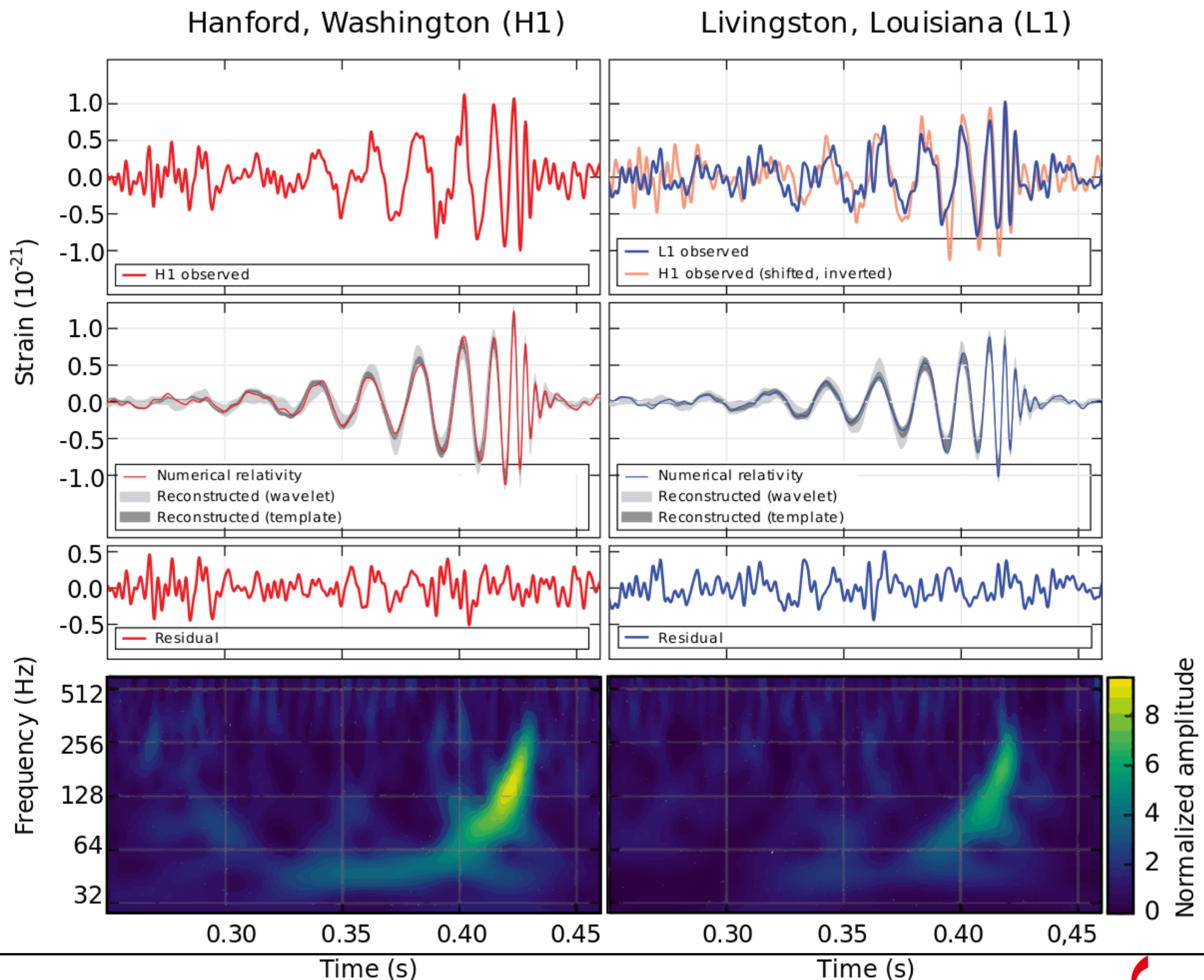
C:
• optical power is restored in the cavity by larger PR-gain.
• Same amount of GW sidebands are produced.
• Since one GW sideband is resonant, it gets enhanced.
Overall we win GW signal.

=> Larger GW signal



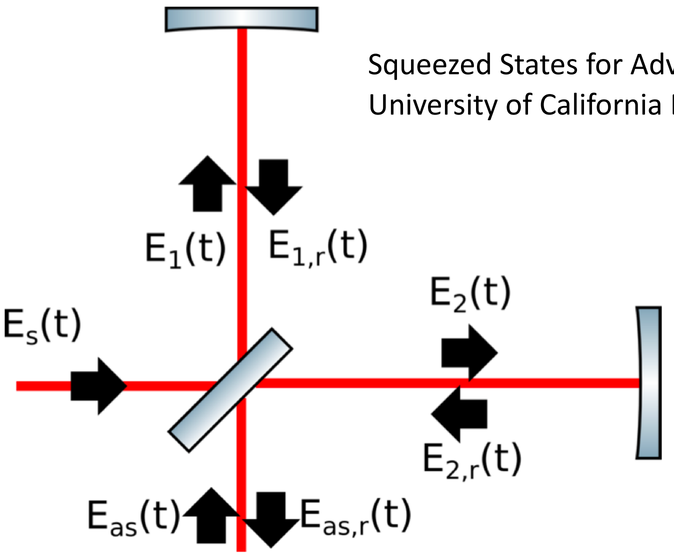
and
itute

Gravitational wave signal



Korea Astronomy and Space Science Institute

Electric field in simple Michelson interferometer



Squeezed States for Advanced Gravitational Wave Detectors, B.A., University of California Berkeley, Eric Oelker (2009)

Assume anti-symmetric port is dark port

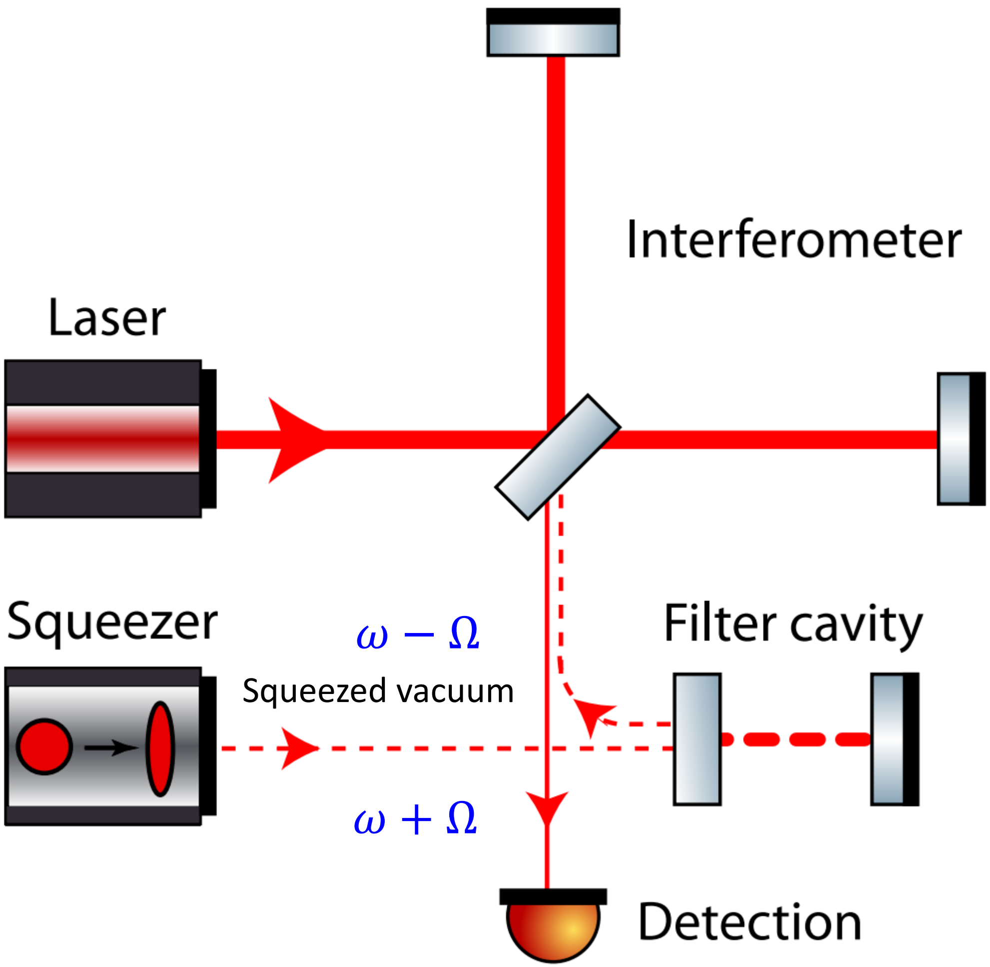
$$E_1(t) = \frac{1}{\sqrt{2}}[E_s(t) + E_{as}(t)]$$

$$E_2(t) = \frac{1}{\sqrt{2}}[E_s(t) - E_{as}(t)]$$

'as' is vacuum field

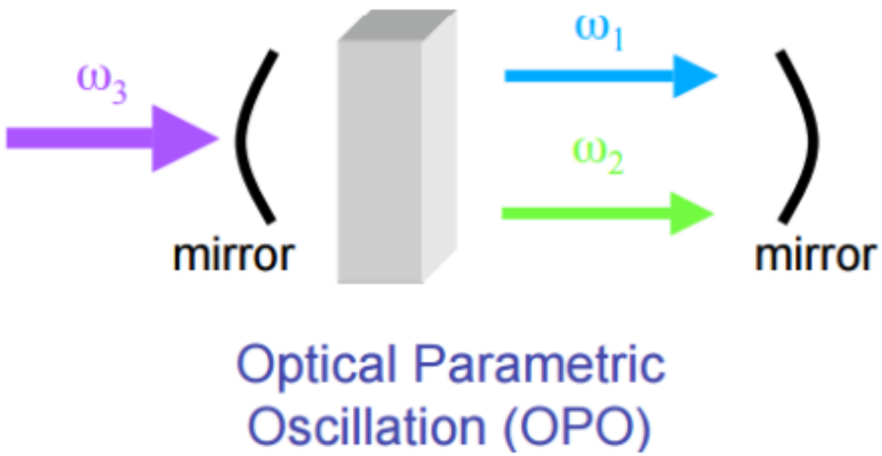
Squeezed States for Advanced Gravitational Wave Detectors, B.A., University of California Berkeley, Eric Oelker (2009)

Squeezed vacuum injection with filter cavity



M. Evans, L. Barsotti, P. Kwee, J. Harms, and H. Miao
Phys. Rev. D **88**, 022002 – Published 29 July 2013

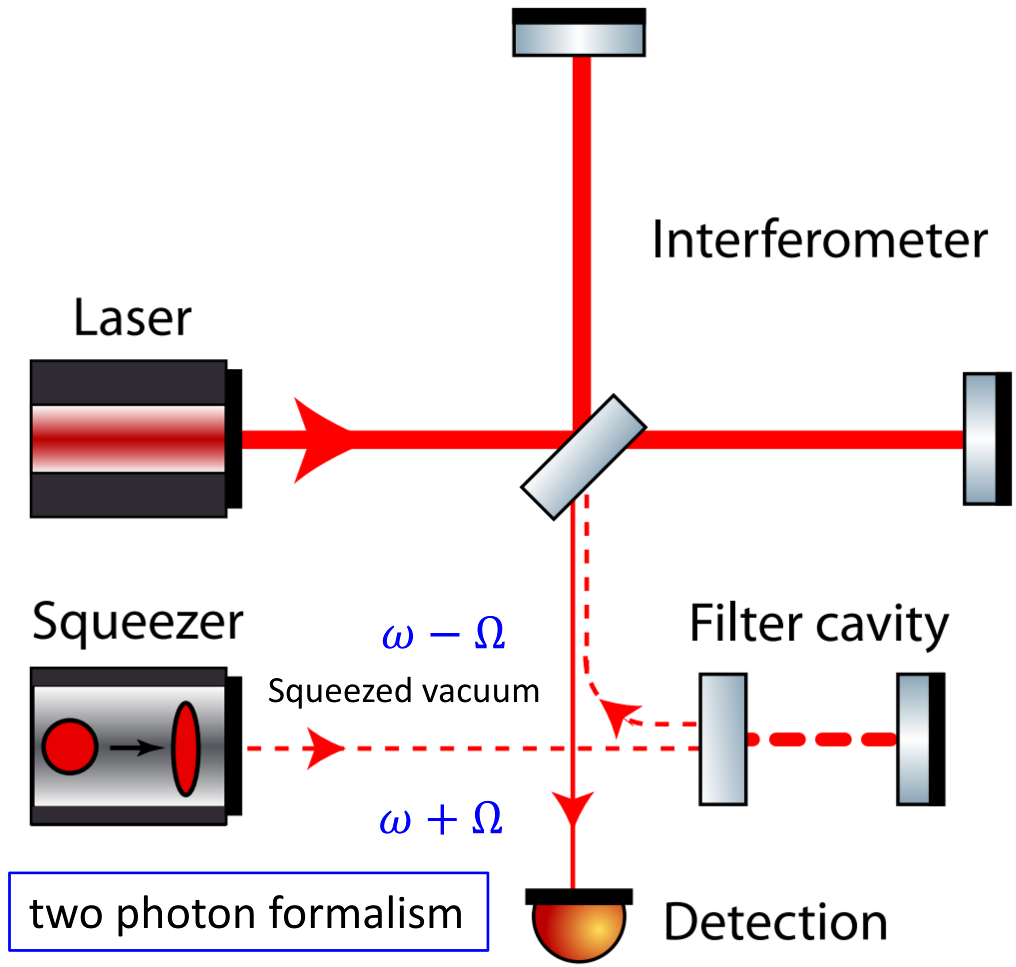
Optical parametric oscillator



$$\omega_1 = \omega_2 : degenrated\ OPO$$

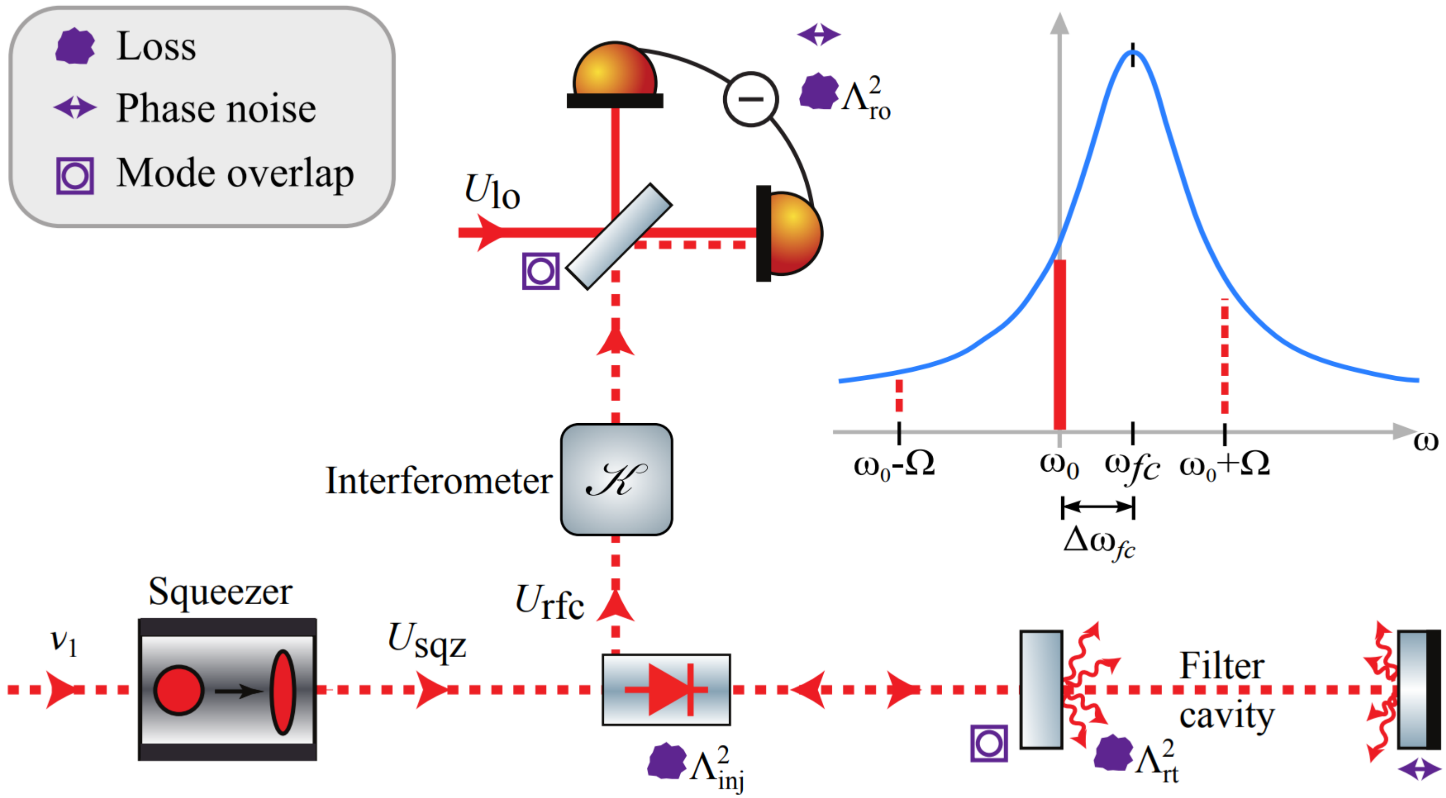
All-Optical Electron Acceleration with Ultrafast THz Pulses, Wenqian Ronny Huang, MIT(2017)

Squeezed vacuum injection with filter cavity



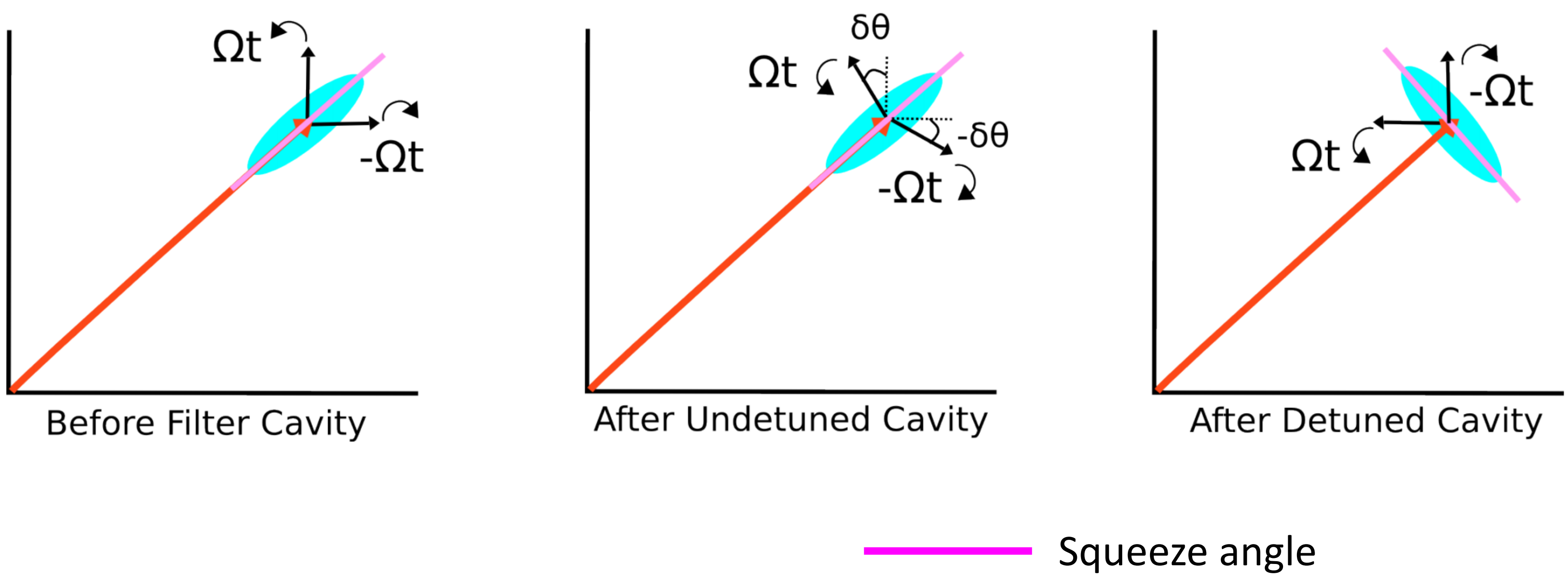
M. Evans, L. Barsotti, P. Kwee, J. Harms, and H. Miao
Phys. Rev. D **88**, 022002 – Published 29 July 2013

Detuned filter cavity



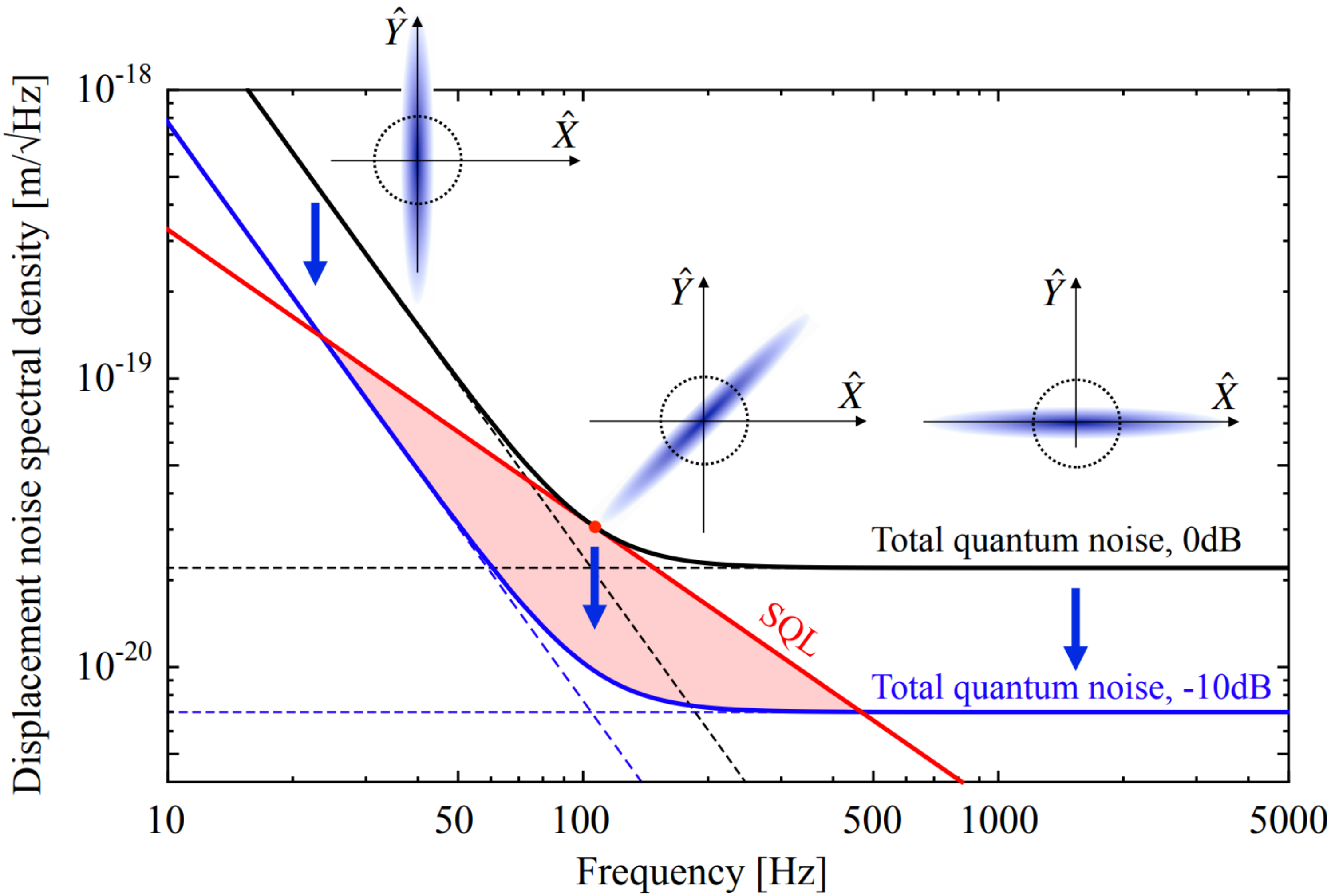
P. Kwee, J. Miller, T. Isogai, L. Barsotti, and M. Evans
Phys. Rev. D 90, 062006 – Published 5 September 2014

Squeeze angle



M. Evans, L. Barsotti, P. Kwee, J. Harms, and H. Miao
Phys. Rev. D **88**, 022002 – Published 29 July 2013

Squeeze angle rotation



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

Squeeze angle rotation

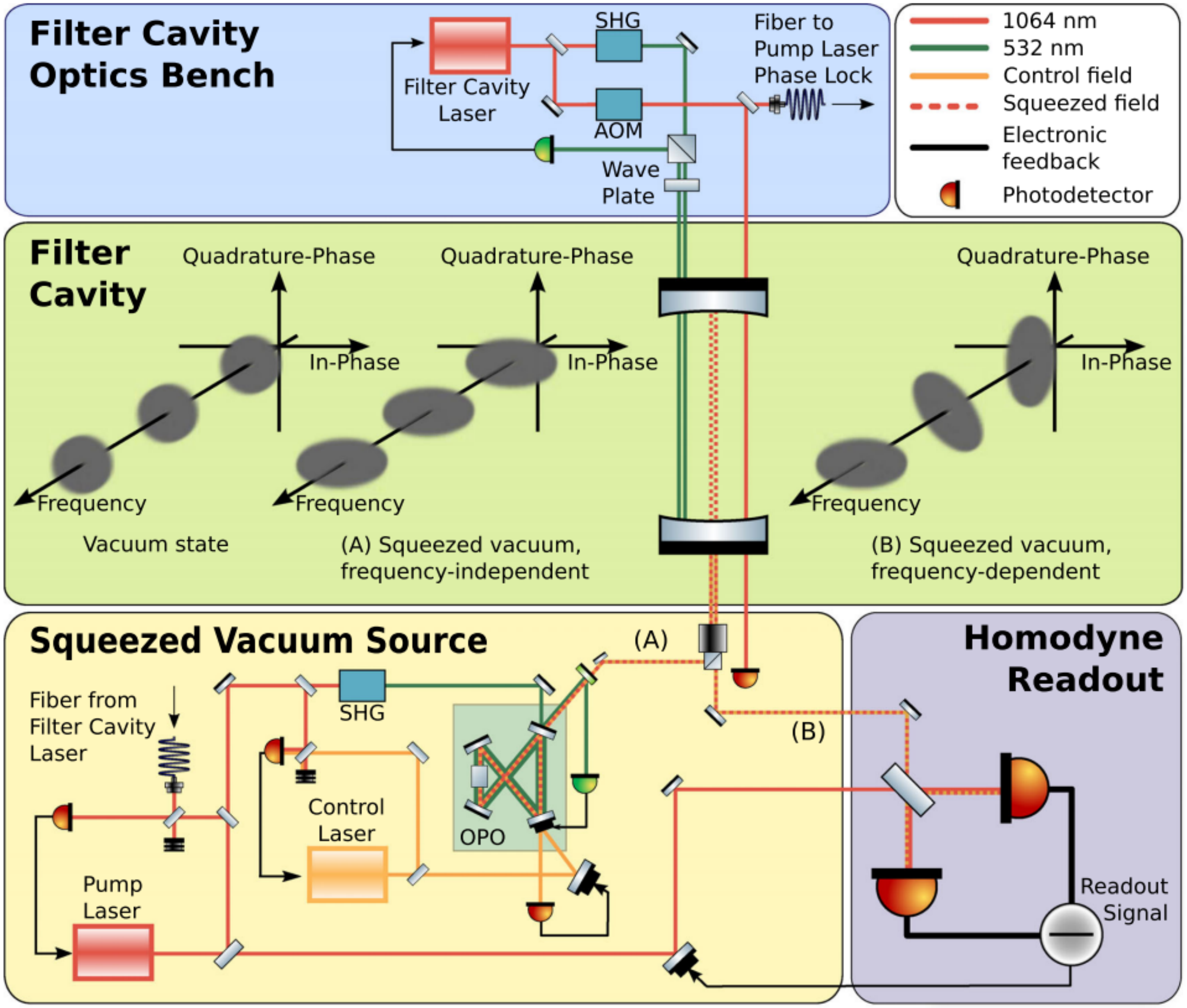
$$\alpha_p = \arctan\left(\frac{2\gamma_{\rm fc}\Delta\omega_{\rm fc}}{\gamma_{\rm fc}^2 - \Delta\omega_{\rm fc}^2 + \Omega^2}\right)$$

$\gamma = loss\ of\ filter\ cavity$
$\omega_{fc} = detuned\ frequency$

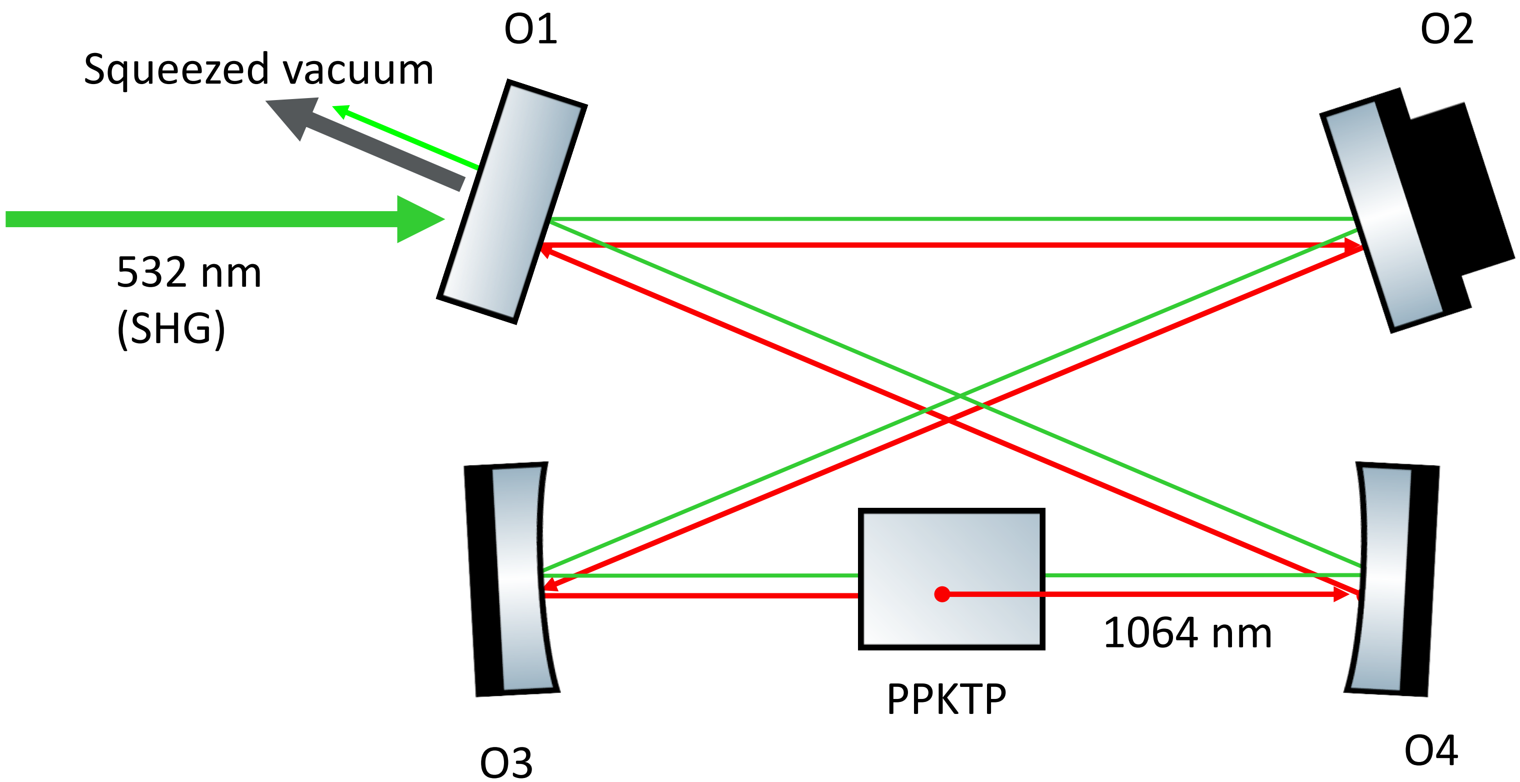
$$t_{\rm st} = \frac{1}{\gamma_{\rm fc}} = \frac{\sqrt{2}}{\Omega_{\rm SQL}} \simeq 3\,{\rm ms}$$

LIGO filter cavity

PRL 116, 041102 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

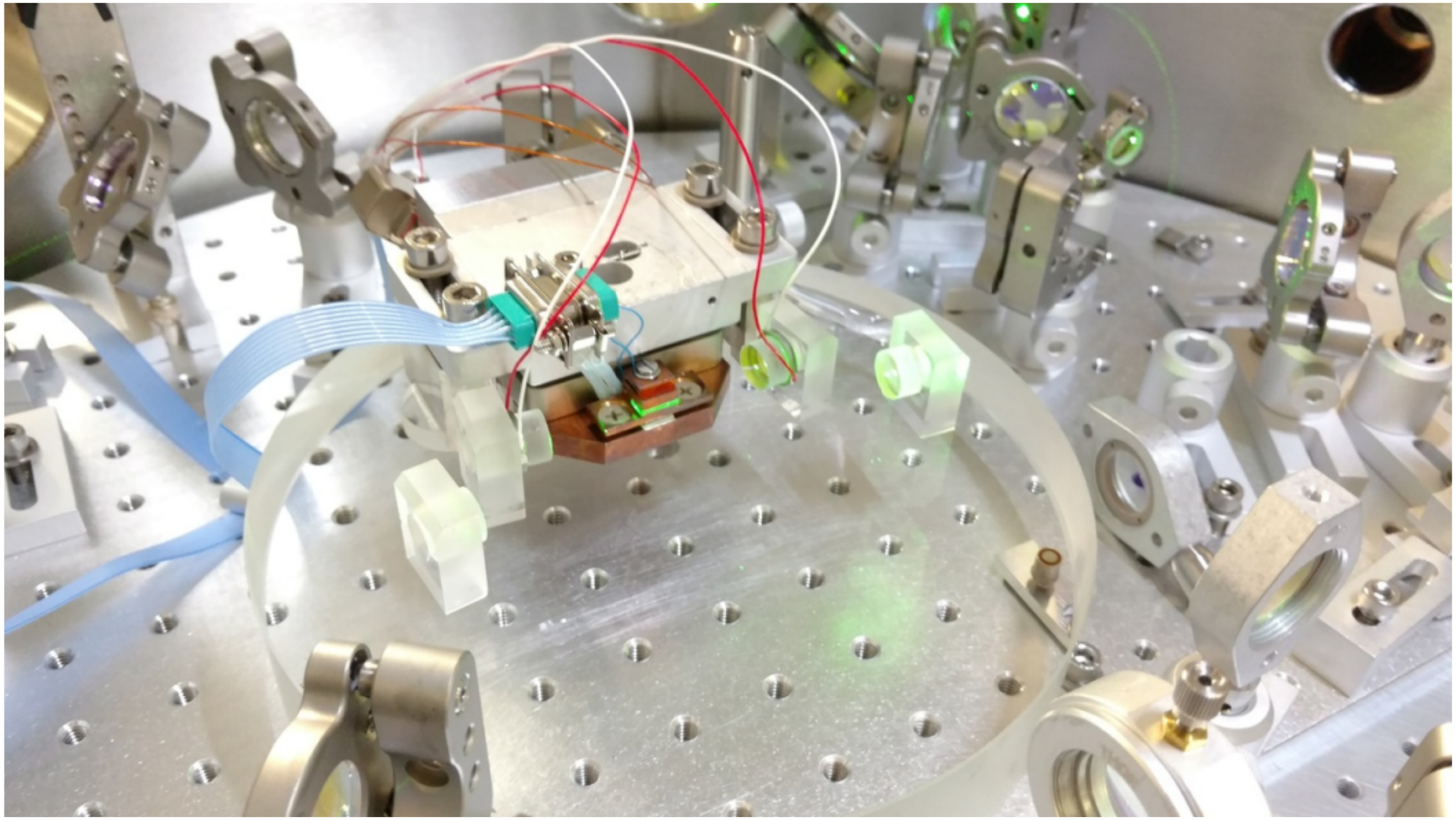


OPO of LIGO squeezer



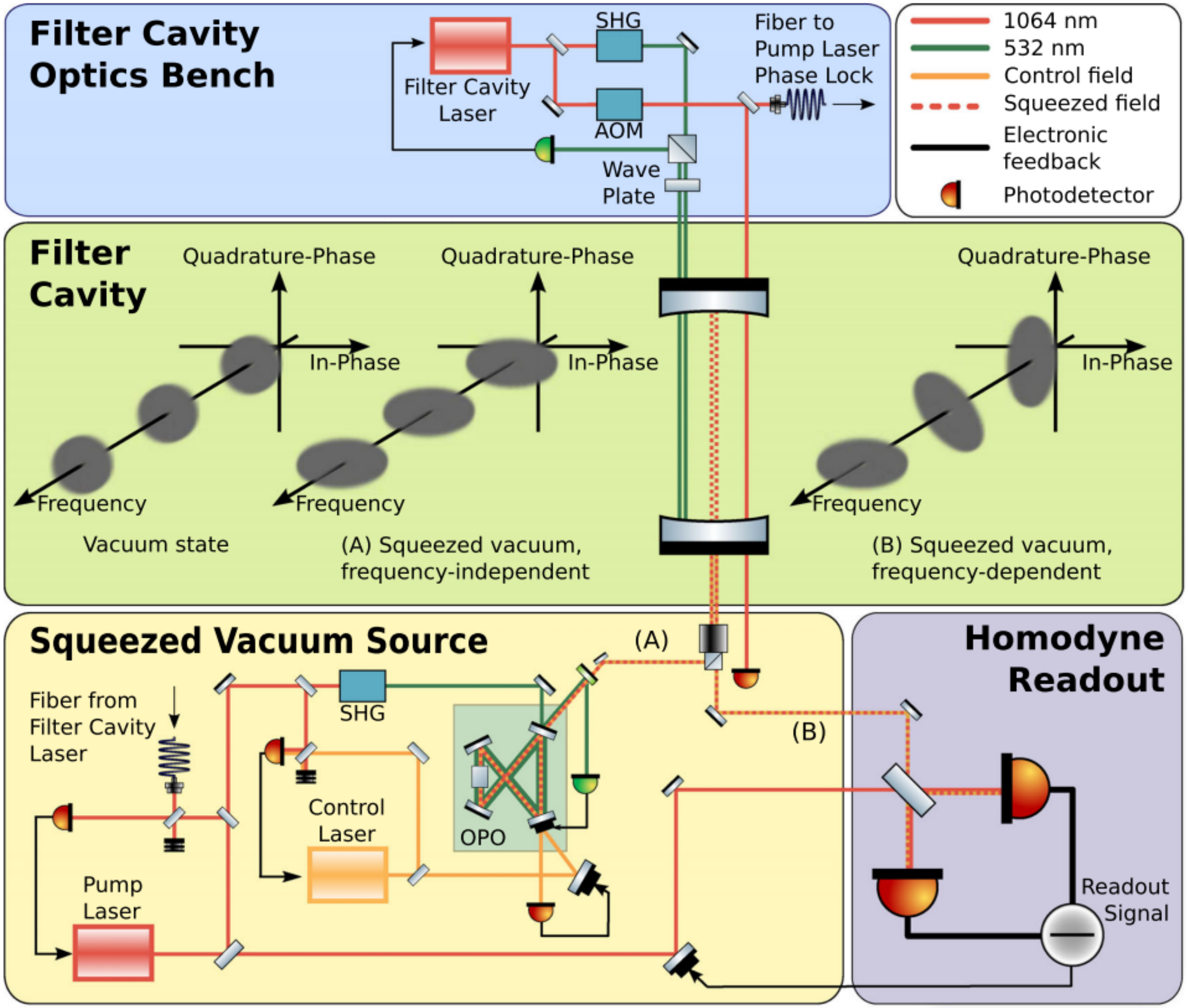
Under threshold operation

LIGO OPO



LIGO filter cavity

PRL 116, 041102 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016



ALS with green laser

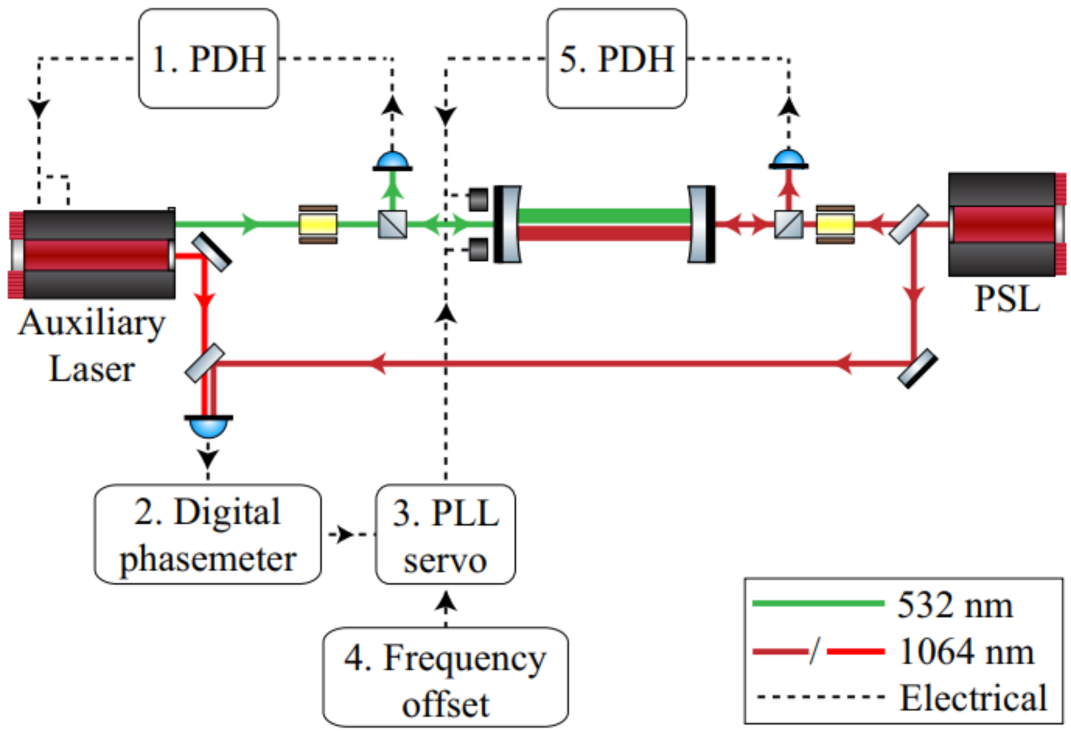
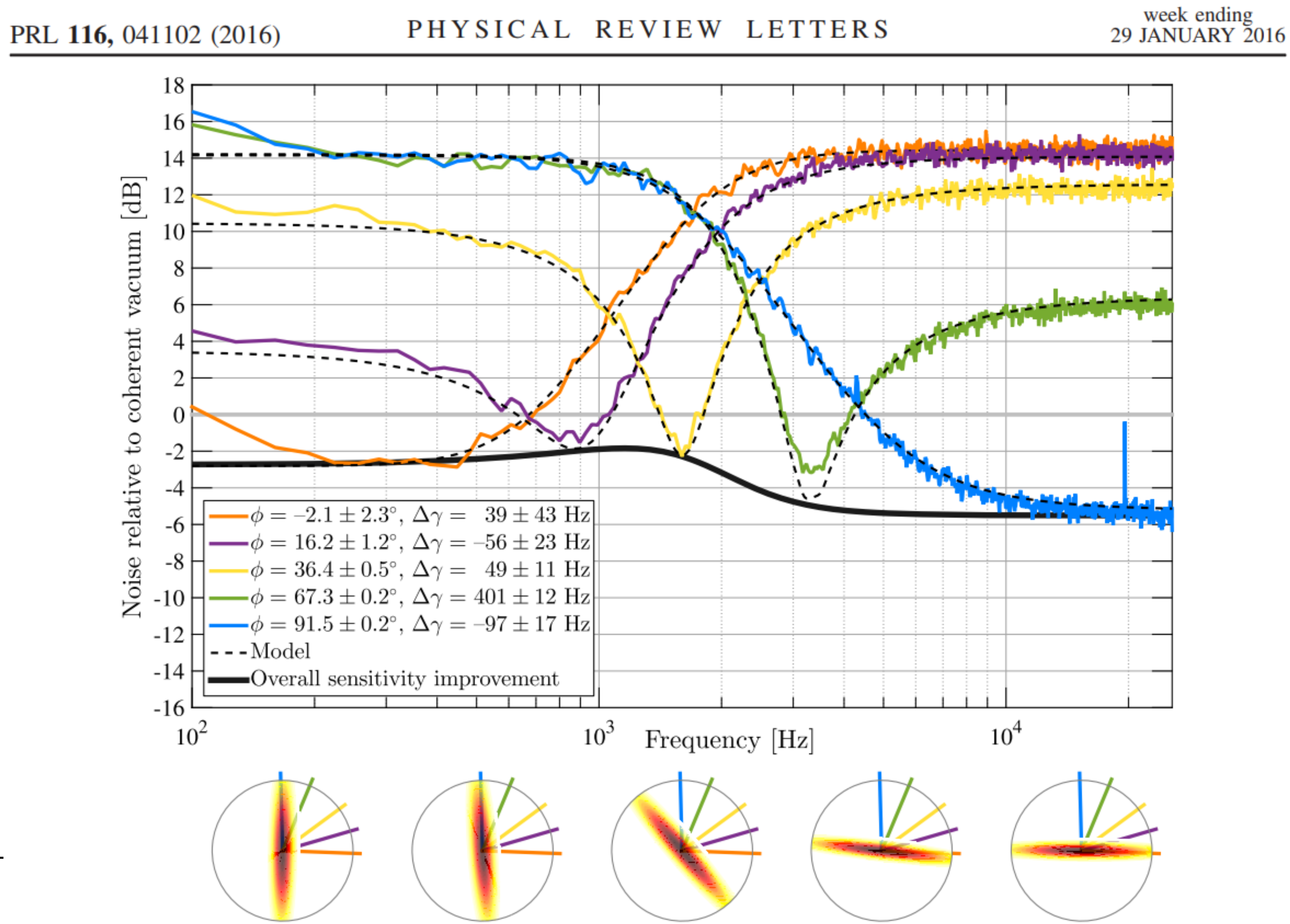


Fig. 2. (Color online) Schematic of the arm-length stabilisation system. The numbering indicates the flow of the lock acquisition process and corresponds to the enumerated list below.

LIGO filter cavity



5. Frequency dependent squeezing using EPR entanglement

EPR paradox

Albert Einstein   Boris Podolsky   Nathan Rosen

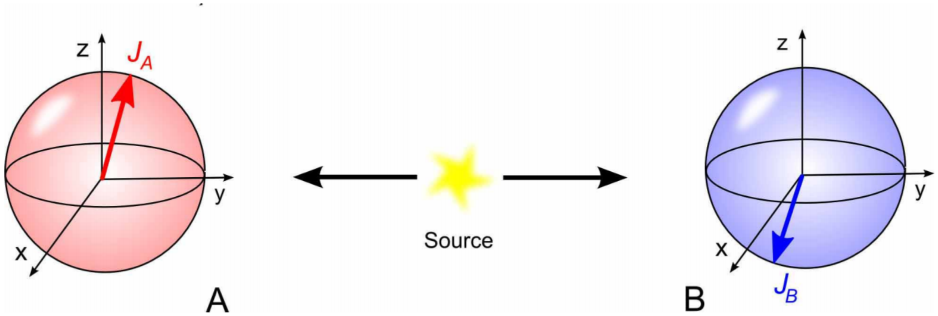
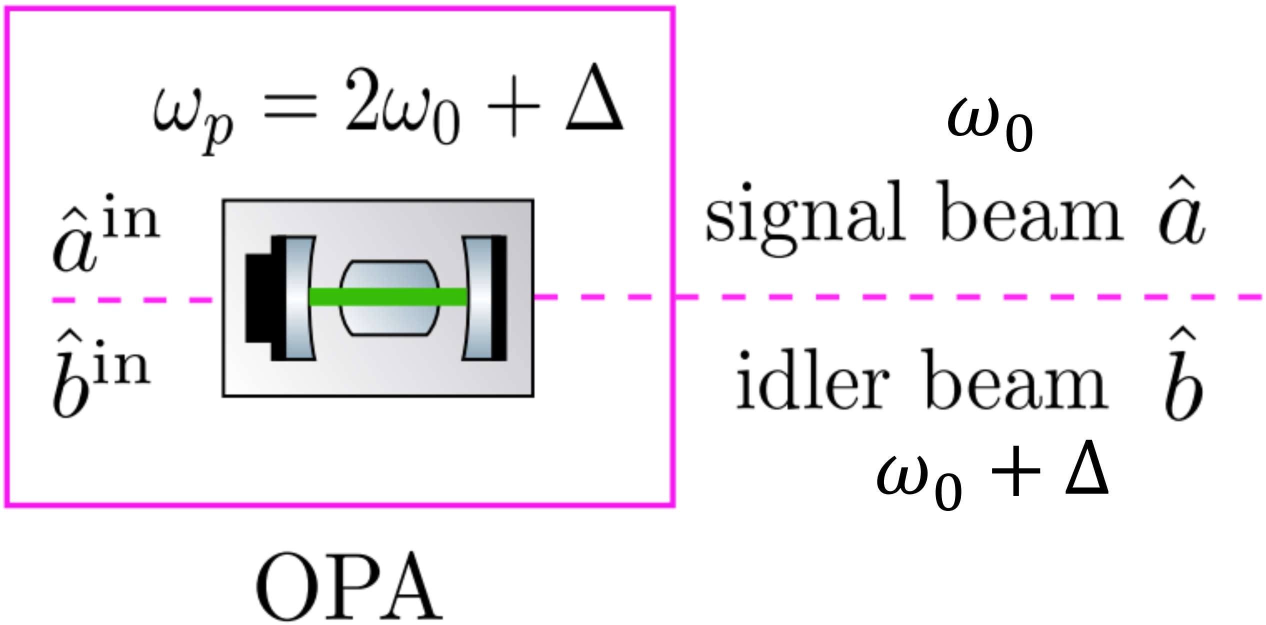


Fig. 1. Schematic diagram of Bohm's EPR experiment with correlated spins at spatially-separated locations A and B.

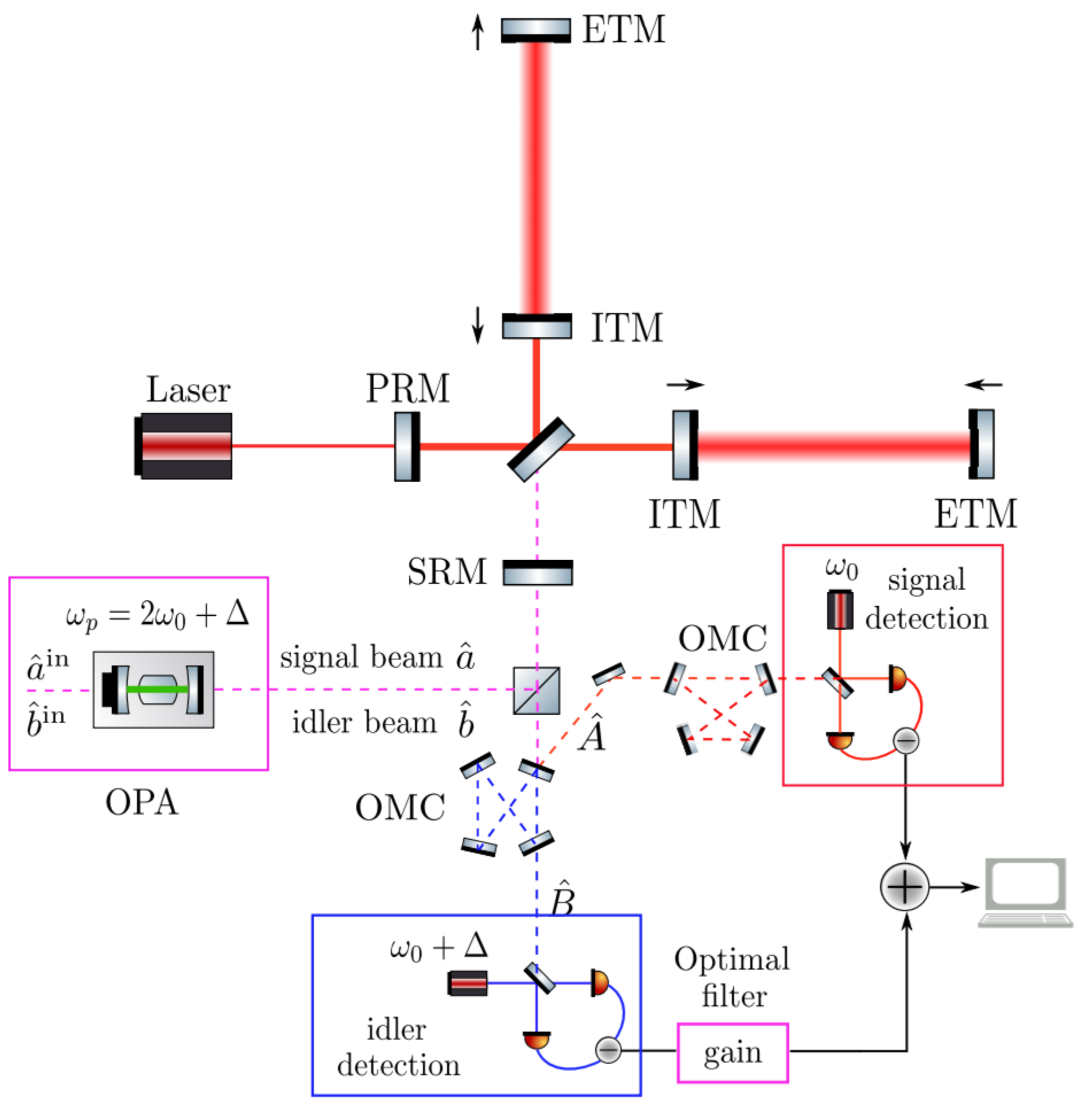
E. G. Cavalcanti, P. D. Drummond, H. A. Bachor, and M. D. Reid, "Spin entanglement, decoherence and Bohm's EPR paradox," Opt. Express 17, 18693-18702 (2009)

Non-degenerated PDC

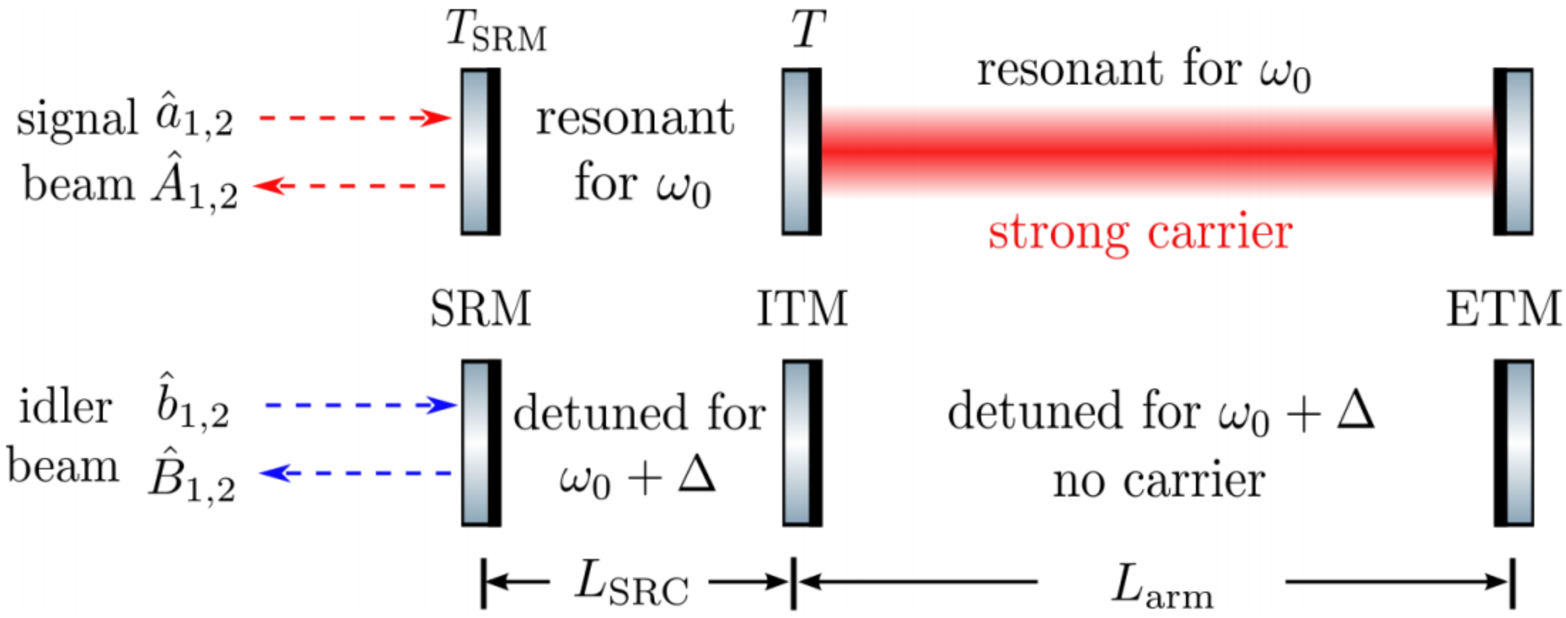


Ma, Y., Miao, H., Pang, B. *et al.* Proposal for gravitational-wave detection beyond the standard quantum limit through EPR entanglement. *Nature Phys* **13,** 776–780 (2017)

FDS using EPR squeezing



FDS using EPR squeezing



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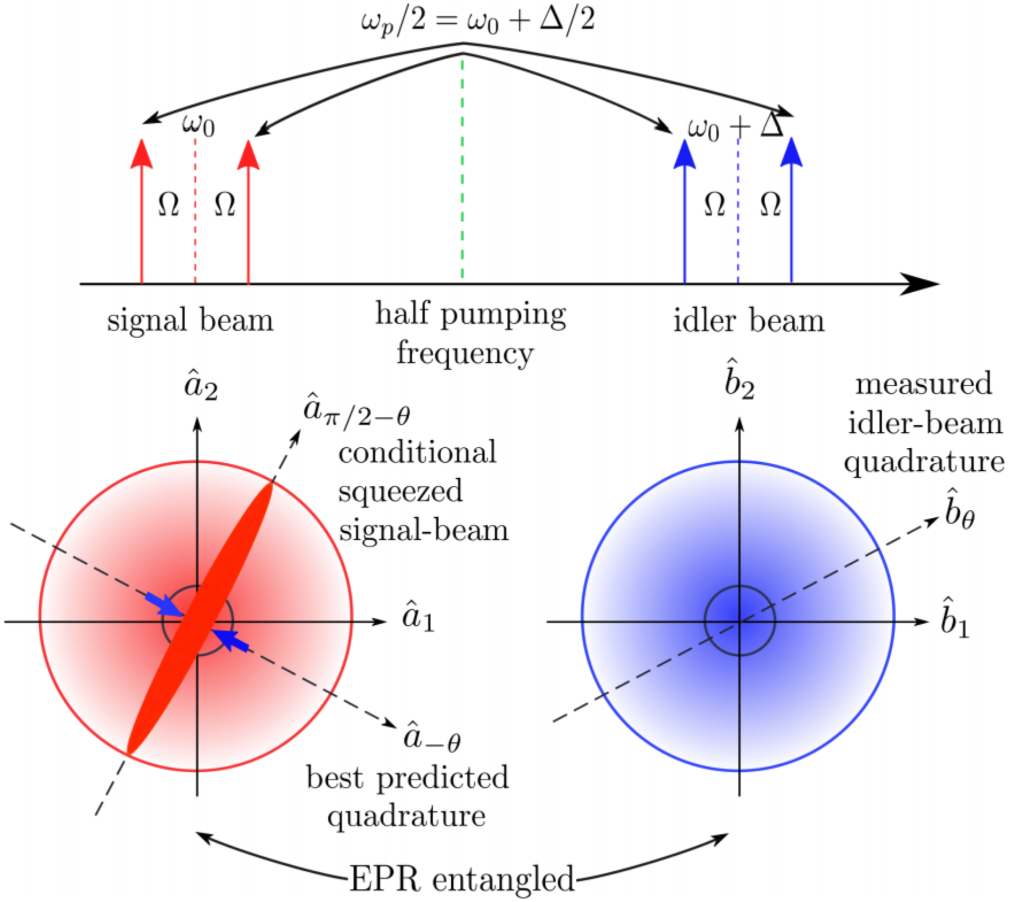

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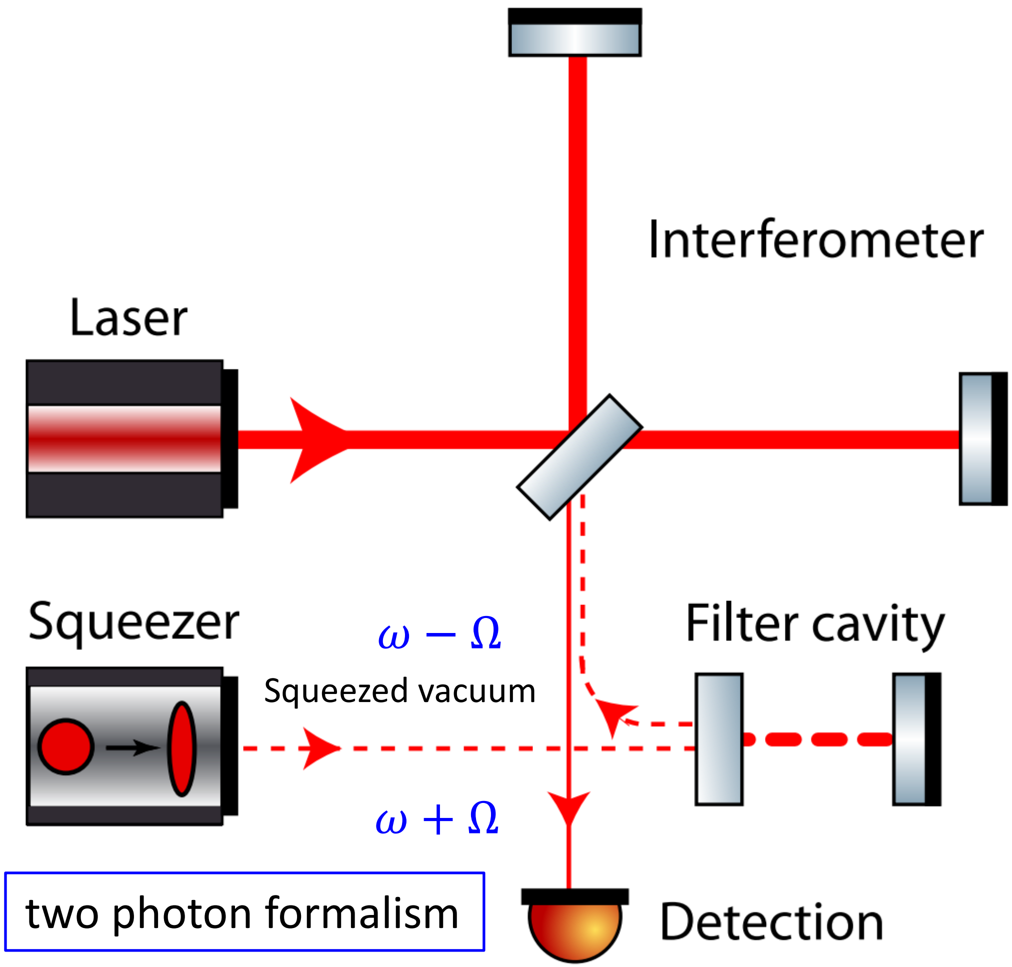
Squeezed vacuum injection with filter cavity



two photon formalism

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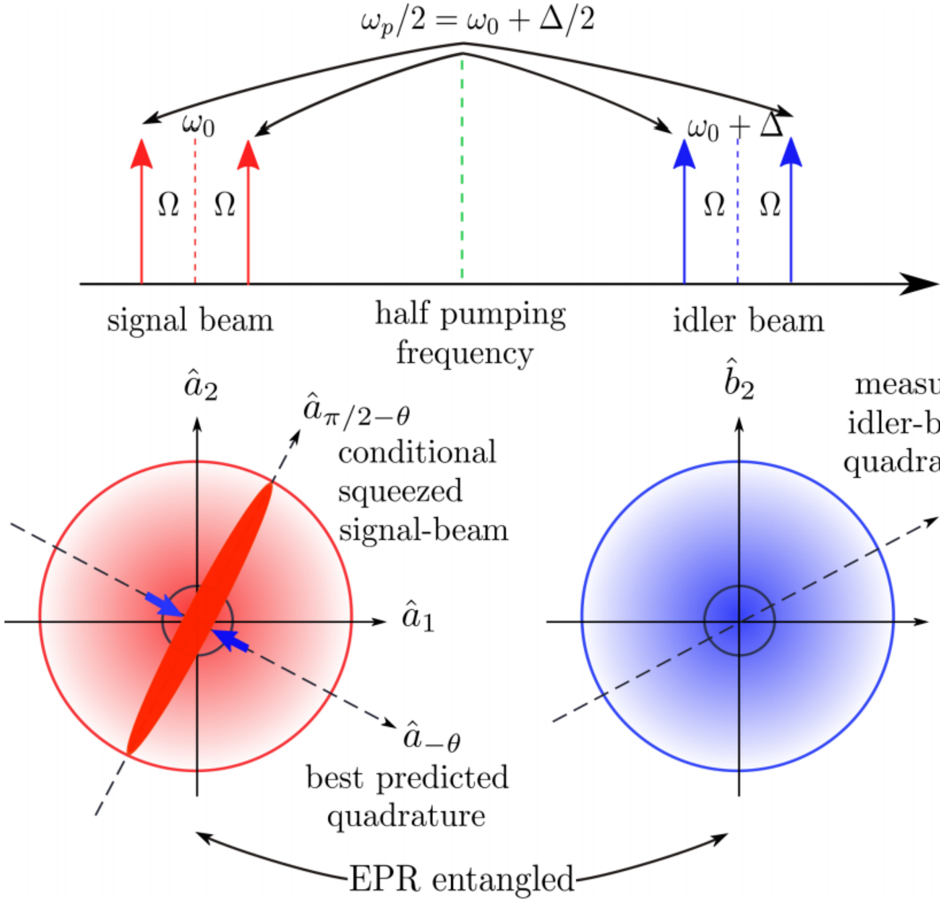
FDS using EPR squeezing



Ma, Y., Miao, H., Pang, B. *et al.* Proposal for gravitational-wave detection beyond the standard quantum limit through EPR entanglement. *Nature Phys* **13,** 776–780 (2017)

Thank you