# Frequency dependent squeezing for quantum noise reduction in second generation Gravitational Wave detectors

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Journée des doctorants

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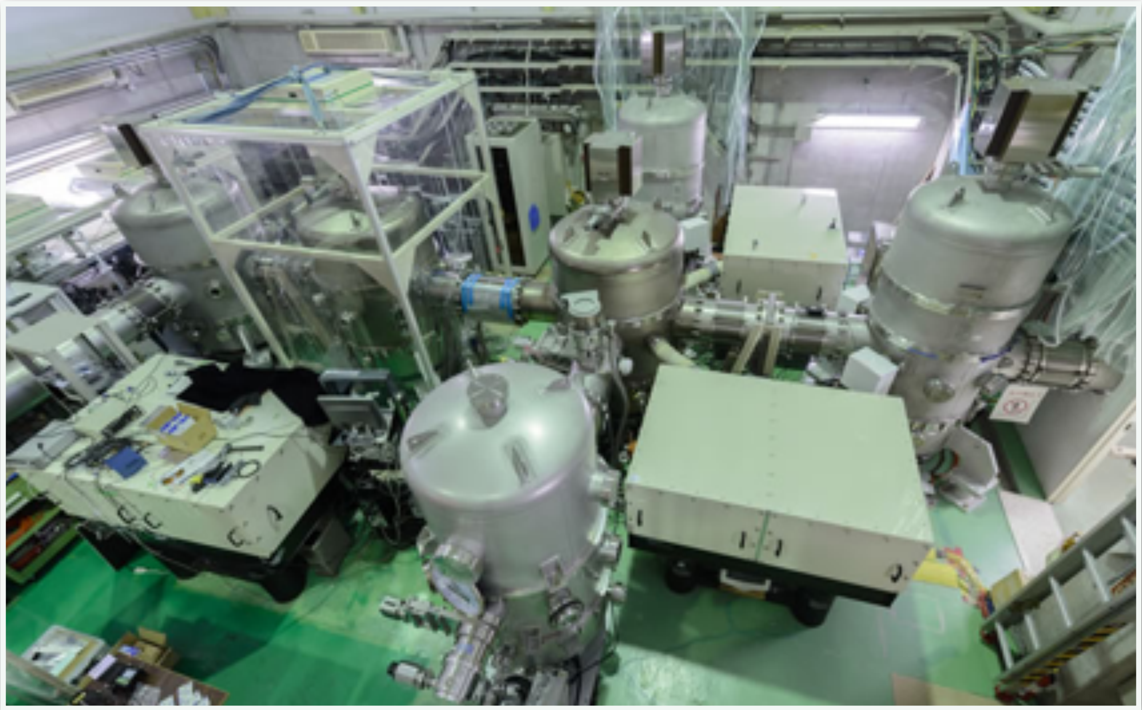
PARIS DIDEROT PARIS 7

# My thesis work is dived into two parts:

Participation in the Virgo commissioning activity



Development of techniques for the reduction of quantum noise in second generation GW detectors

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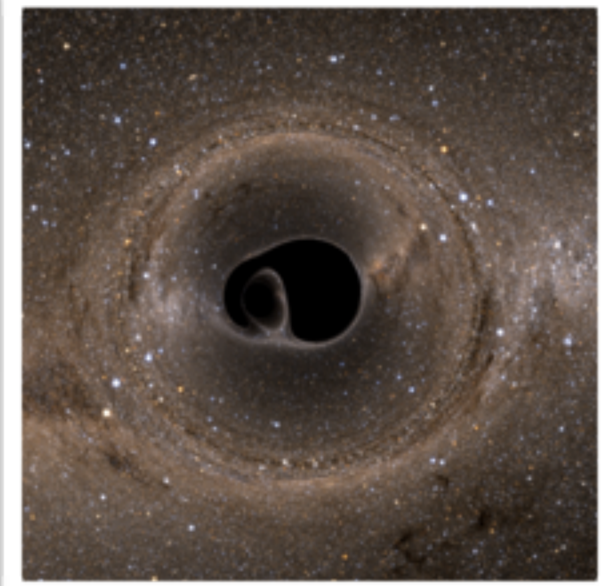
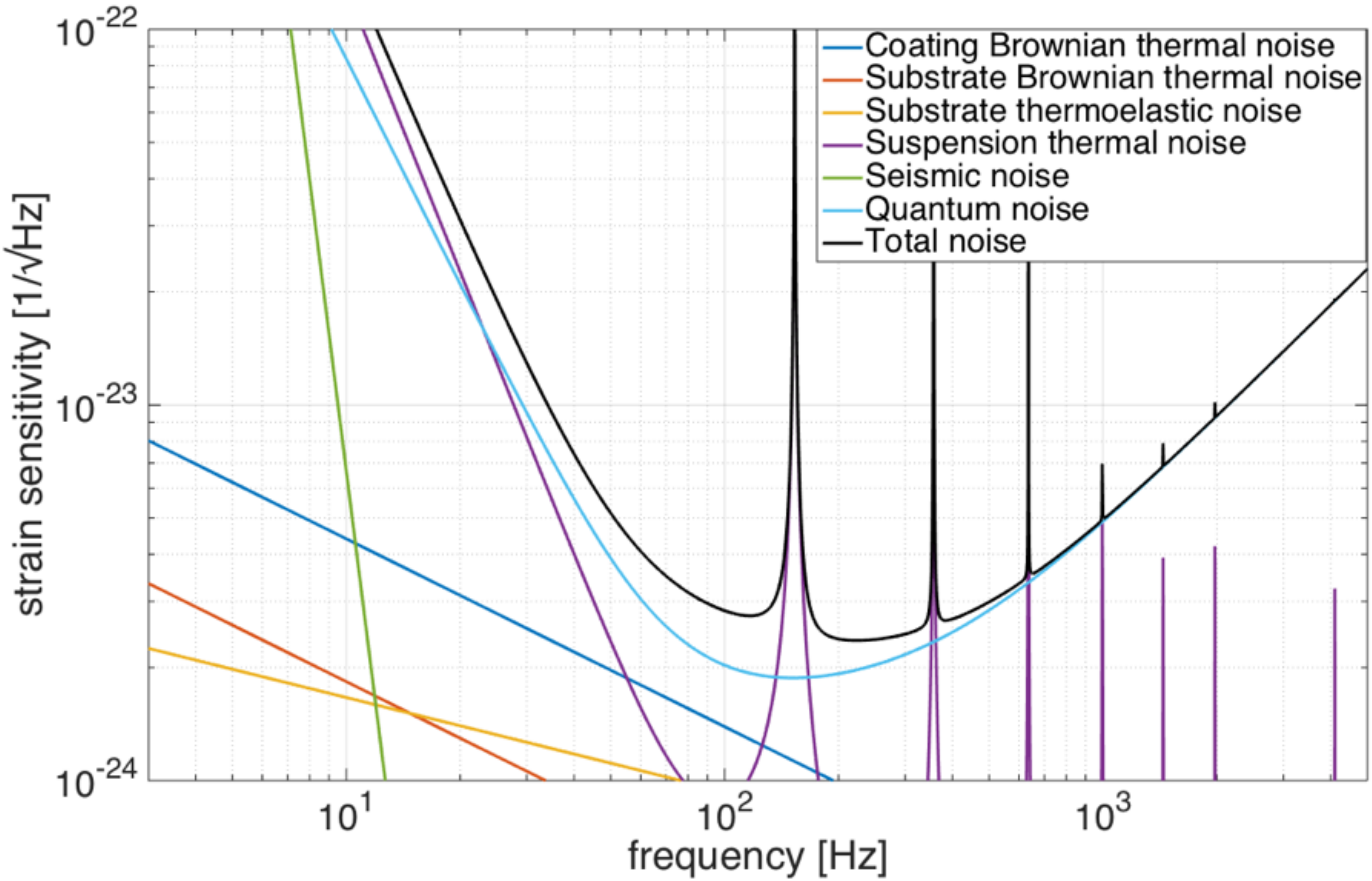
Development of techniques for the reduction of quantum noise in second generation GW detectors

# Why to increase detectors' sensitivity?
# Physics, astrophysics and cosmology with GW

- Tests of general relativity
- Astrophysics mechanisms acting in supernovae, neutron stars, black holes.
- Multimessenger astronomy
- Origin of gamma ray burst
- Physics of the early universe from the stochastic background

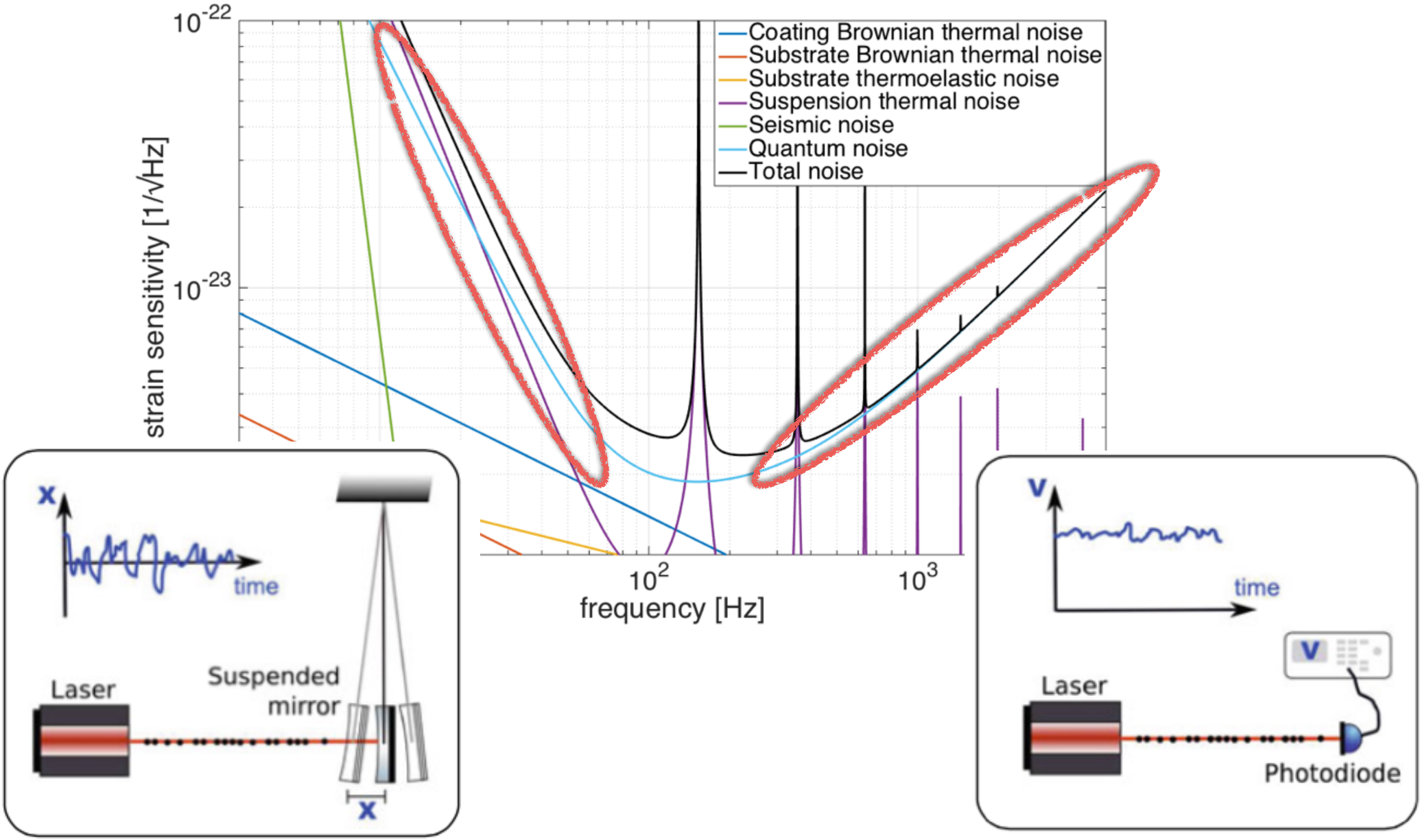


# Quantum noise limits the sensitivity of GW detectors




KAGRA detector

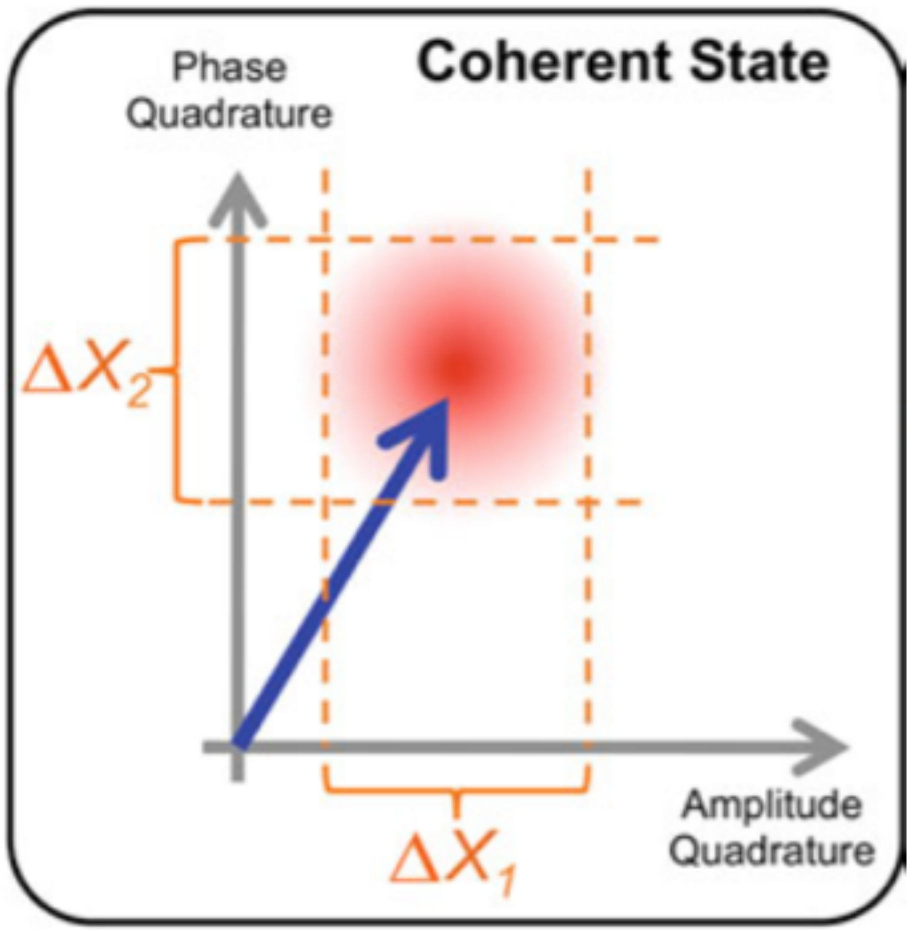
# Quantum noise components




Radiation pressure noise

Shot noise

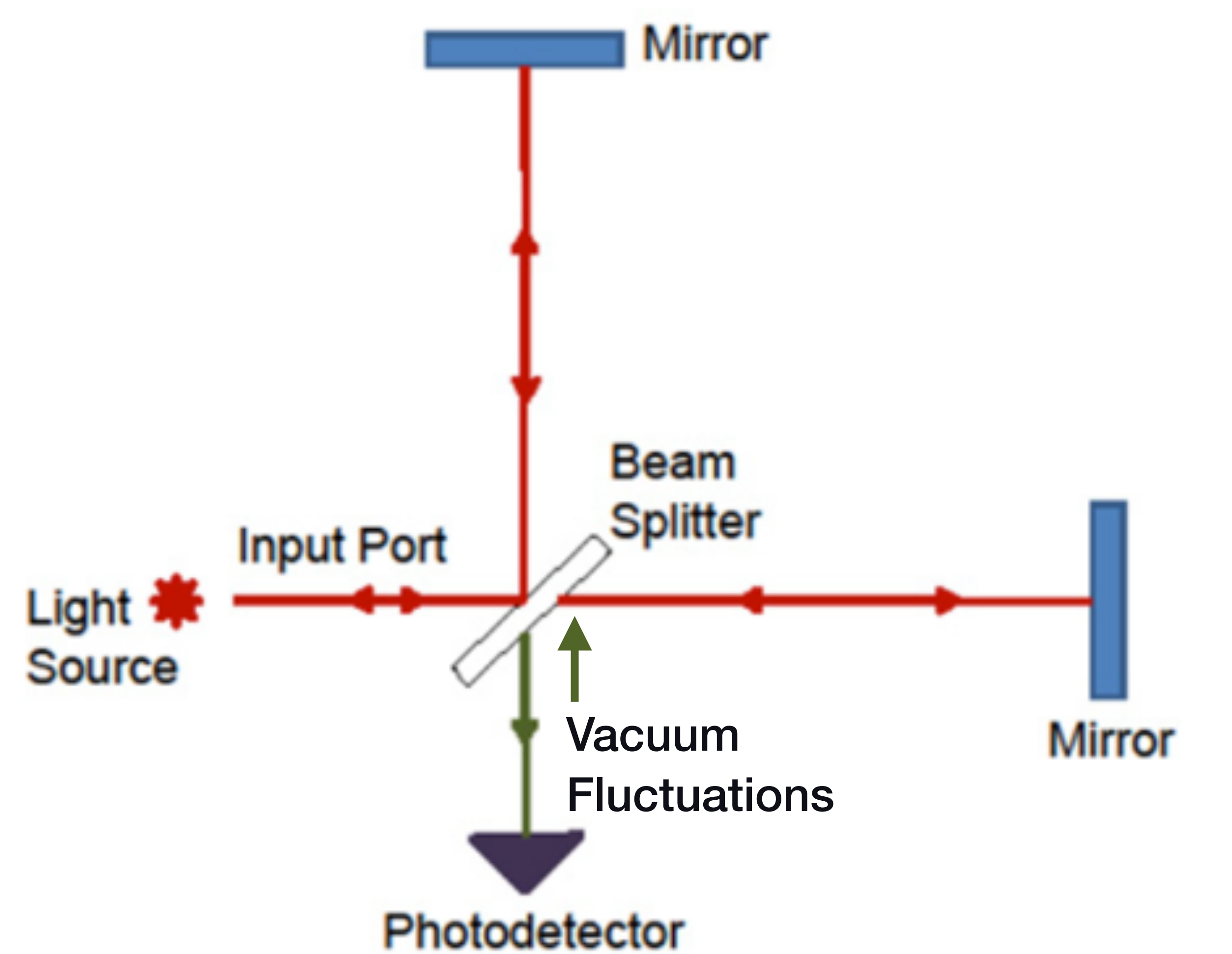
# Quantum representation of a light state: quadrature picture

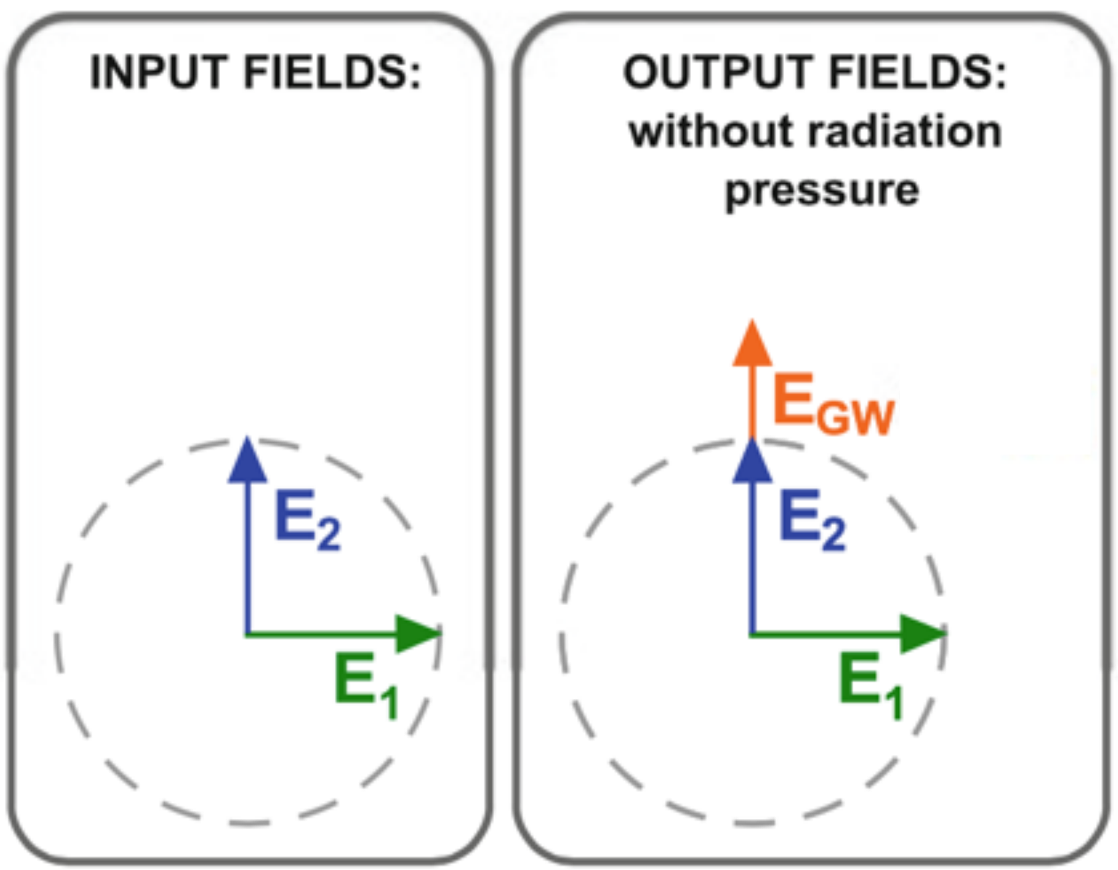



- Amplitude and phase fluctuations equally distributed and uncorrelated
- According to Heisenberg principle their product cannot be reduced

# Quantum noise in GW interferometers

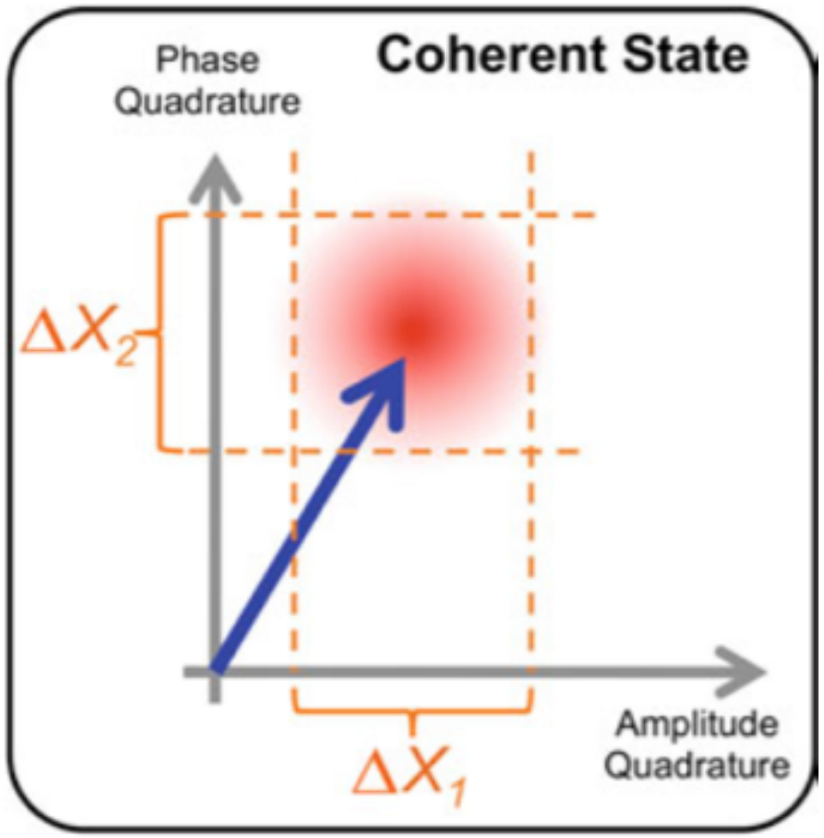
- Strangely enough, if the cavities are symmetric only vacuum fluctuations are responsible for quantum noise

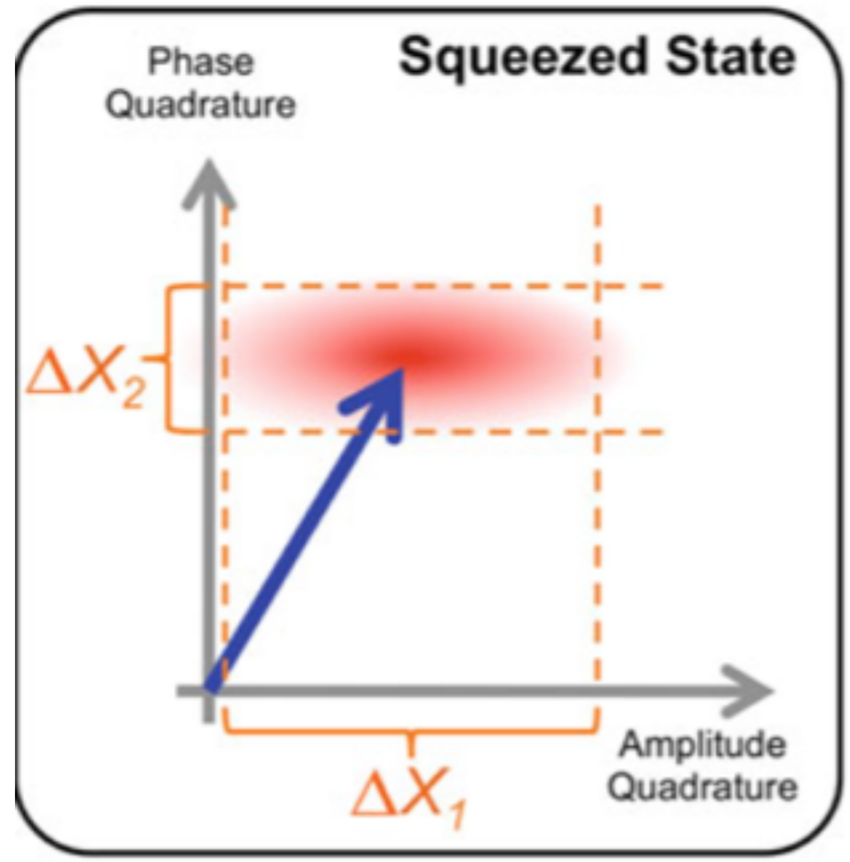



C.Caves “Quantum-mechanical noise in an interferometer” Phys. Rev. D 23 (1981)

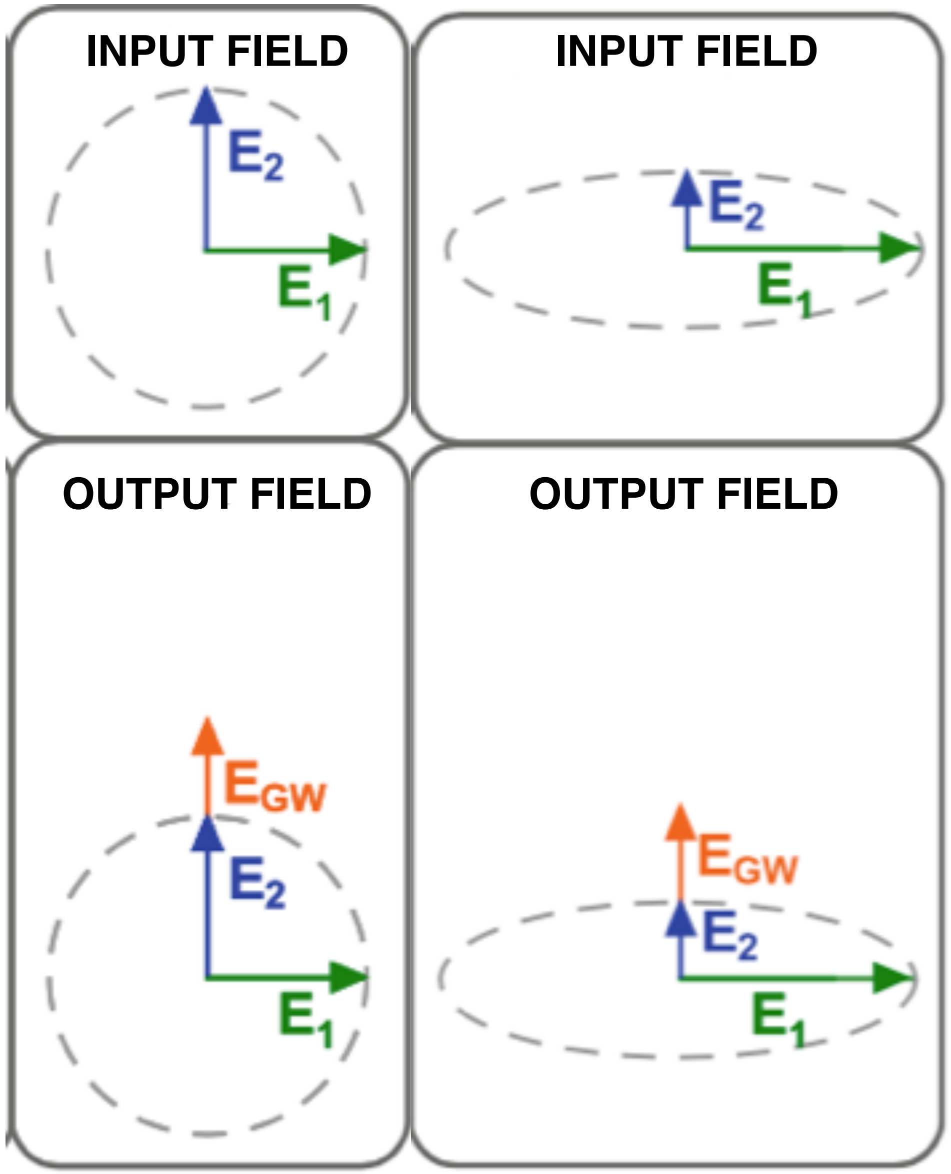
# Squeezed state

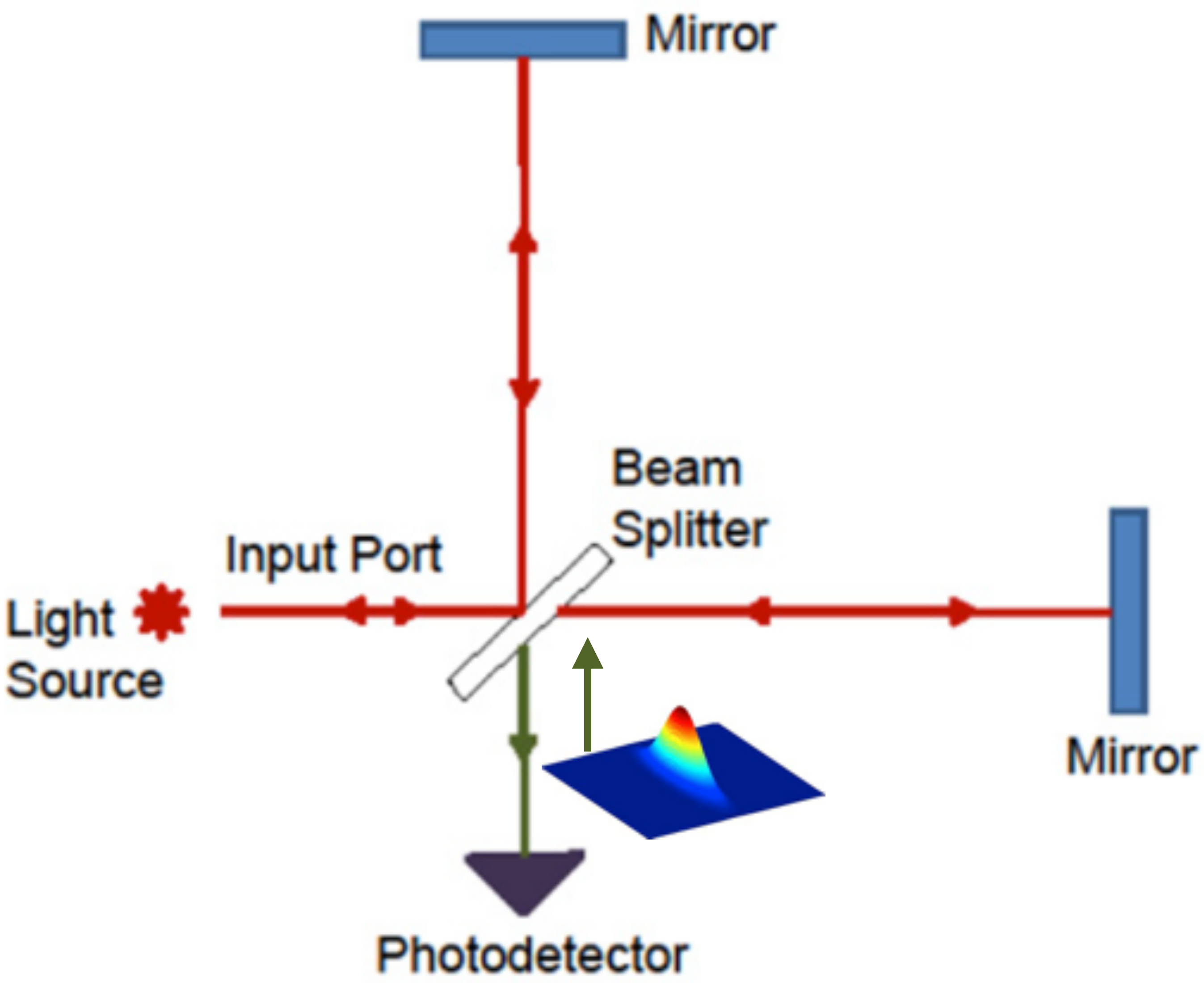


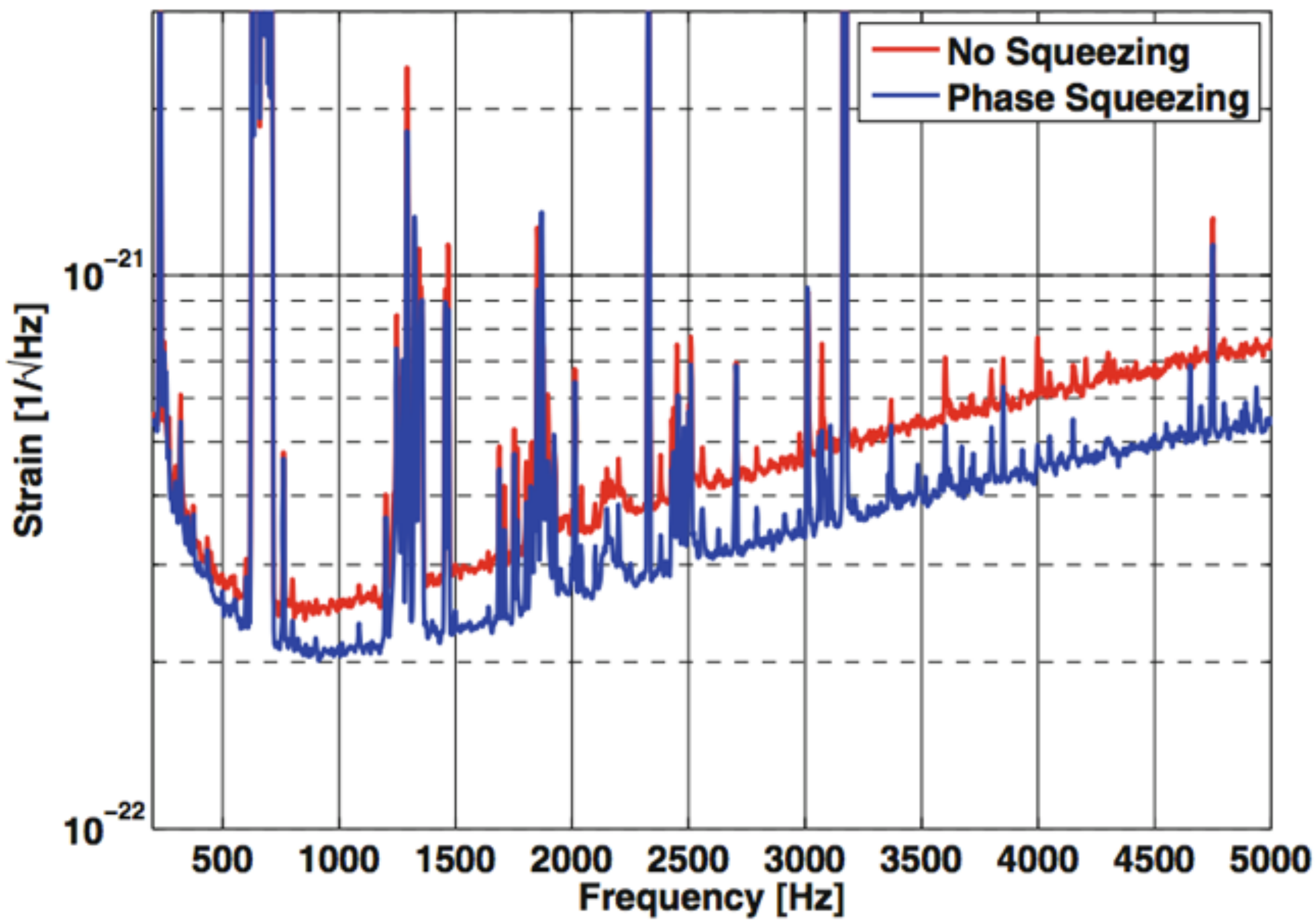

- Noise in one quadrature is reduced with respect to that of a coherent state
- Because of Heisenberg principle the noise in the other quadrature increases

# Quantum noise reduction using squeezed light



# Quantum noise reduction using squeezing

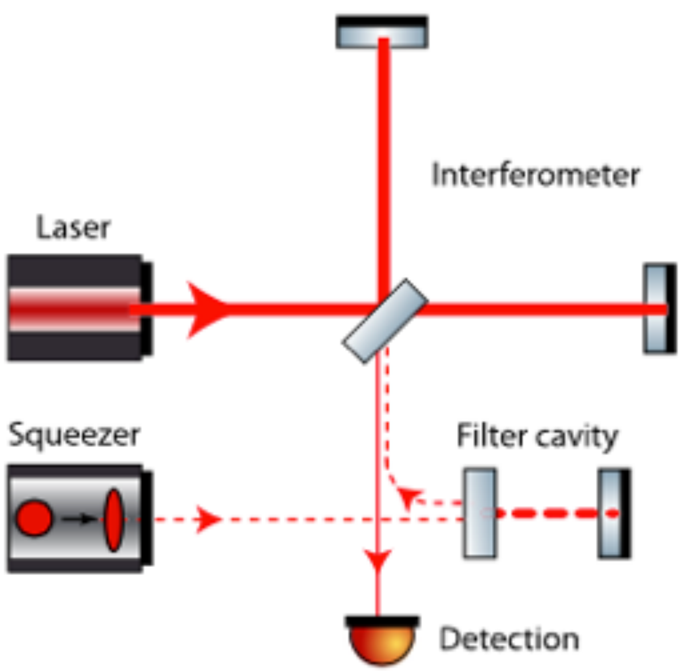


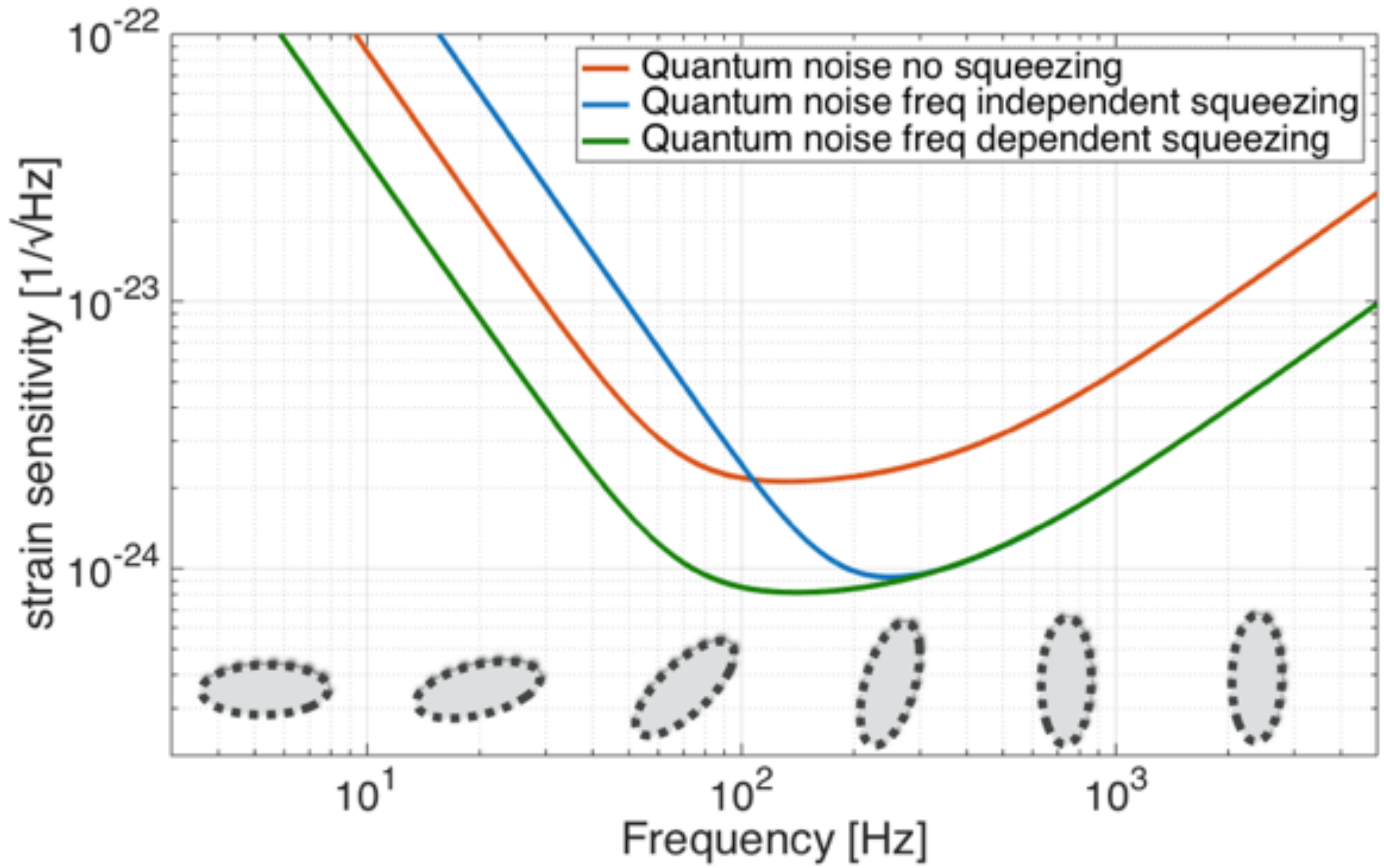

GEO

[1]H. Grote et al. "First Long-Term Application of Squeezed States of Light in a Gravitational-Wave Observatory" Phys. Rev. Lett. 110, 181101 (2013)

# Frequency dependent squeezing improves noise at all frequencies

- Squeezing ellipse undergoes a rotation inside the interferometer
- Squeezing angle should change with the frequency for optimal noise reduction

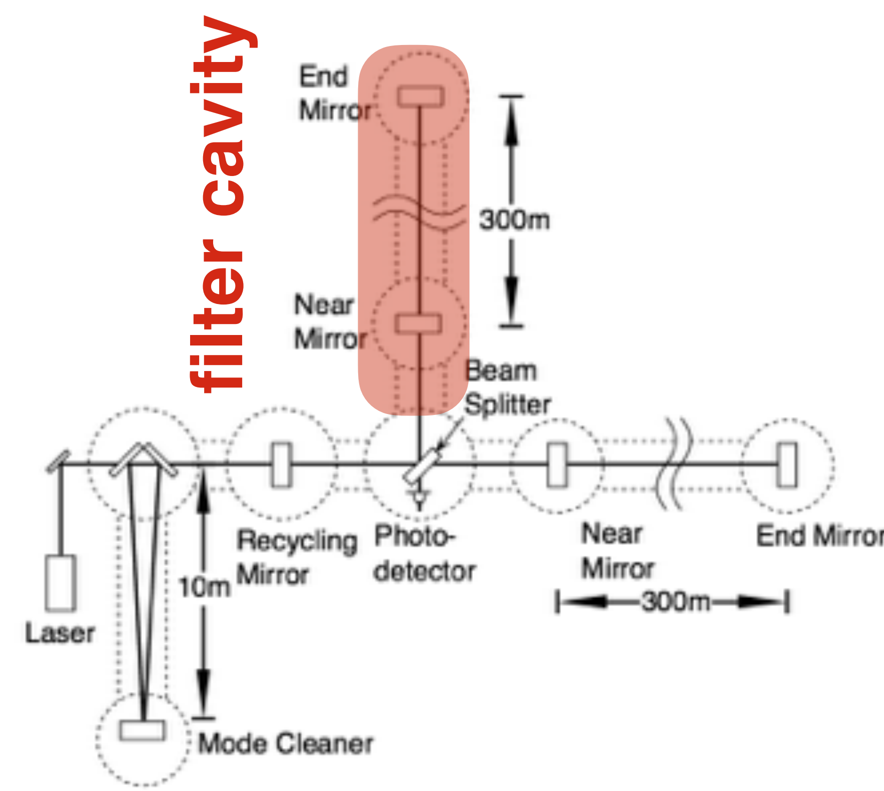


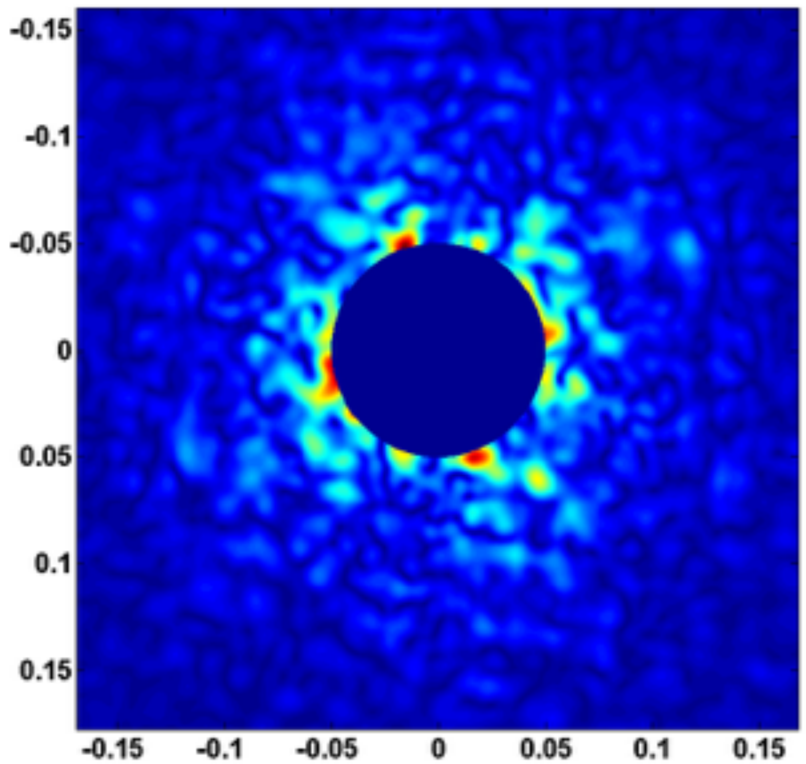

- Frequency dependence is obtained by reflecting off frequency independent squeezing by a Fabry-Pérot cavity

# A 300 meter filter cavity is being installed in TAMA



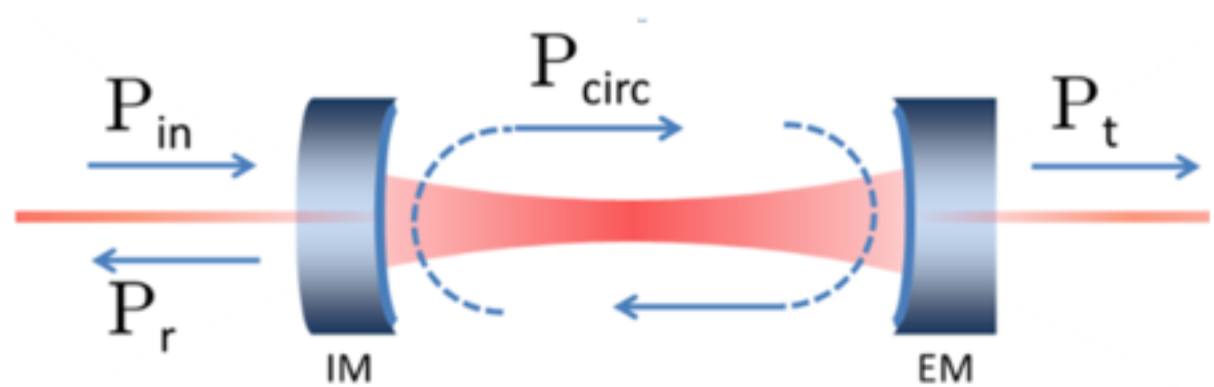


# My first task: cavity optical design and loss estimation

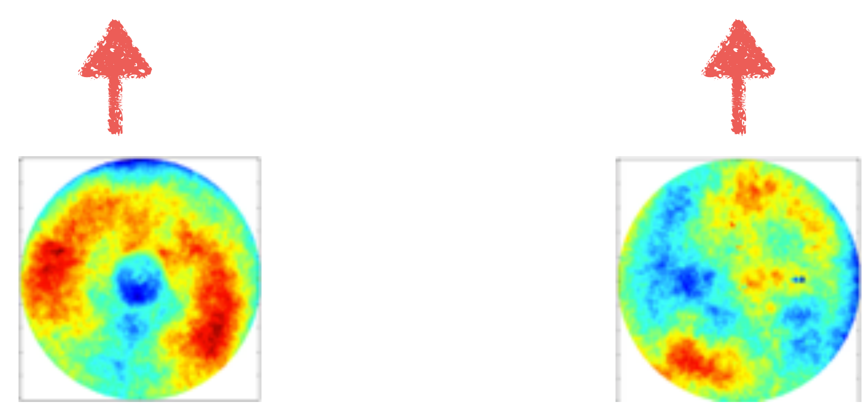



Losses mainly from mirror imperfection degrade squeezing

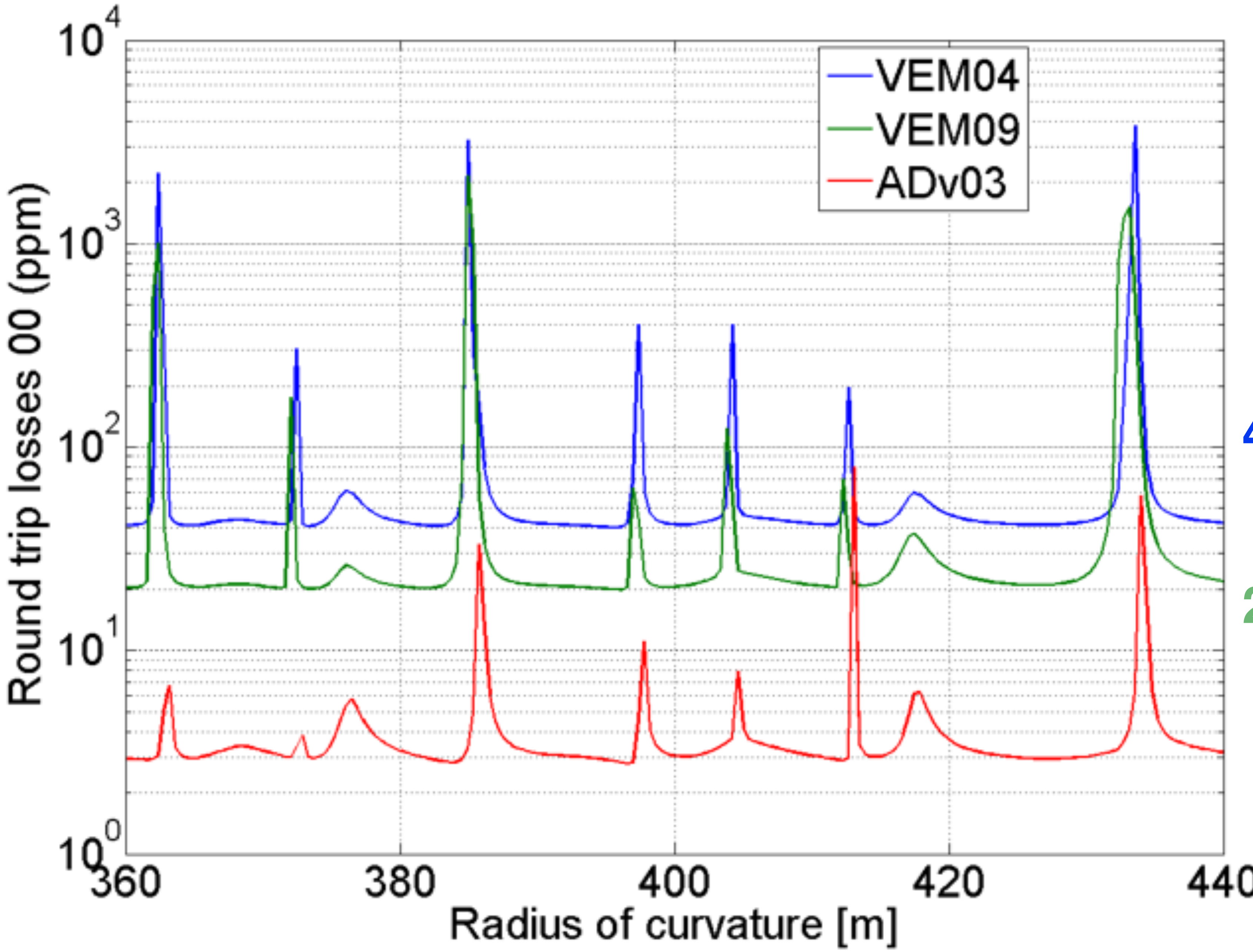
How good mirrors should be?




I simulate the cavity applying realistic mirror maps



# Losses and mirror quality comparison




**41 ppm**

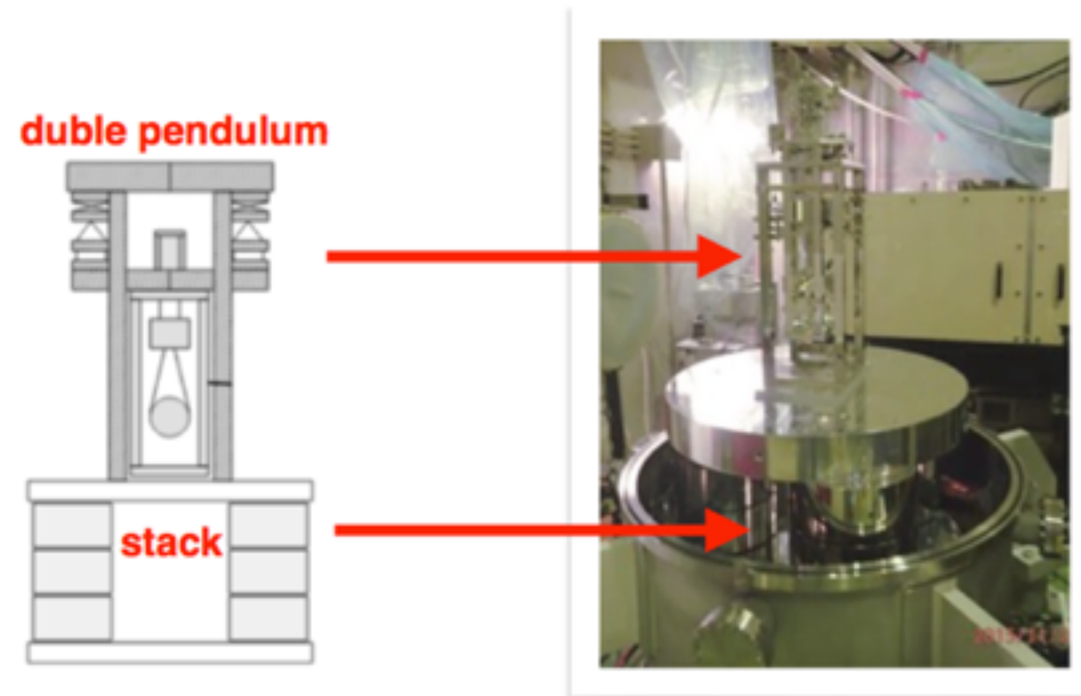
**21 ppm**

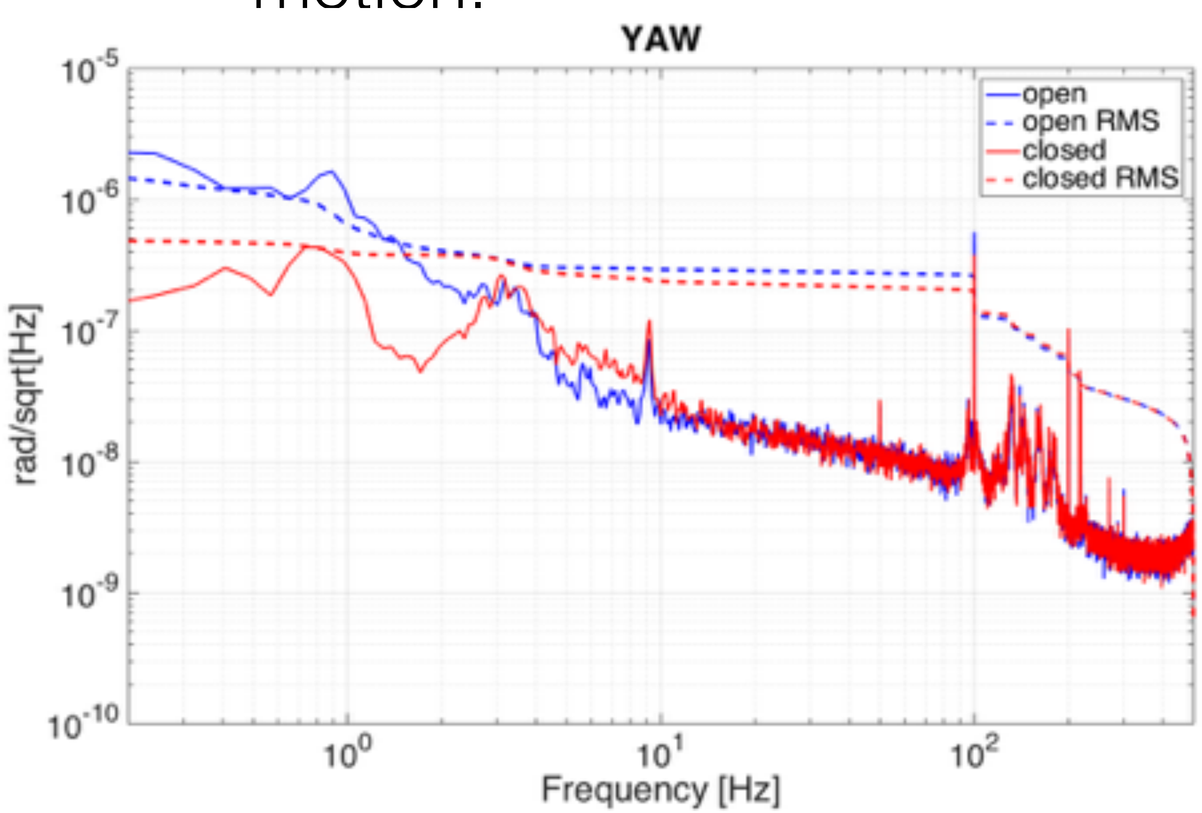
**3 ppm**

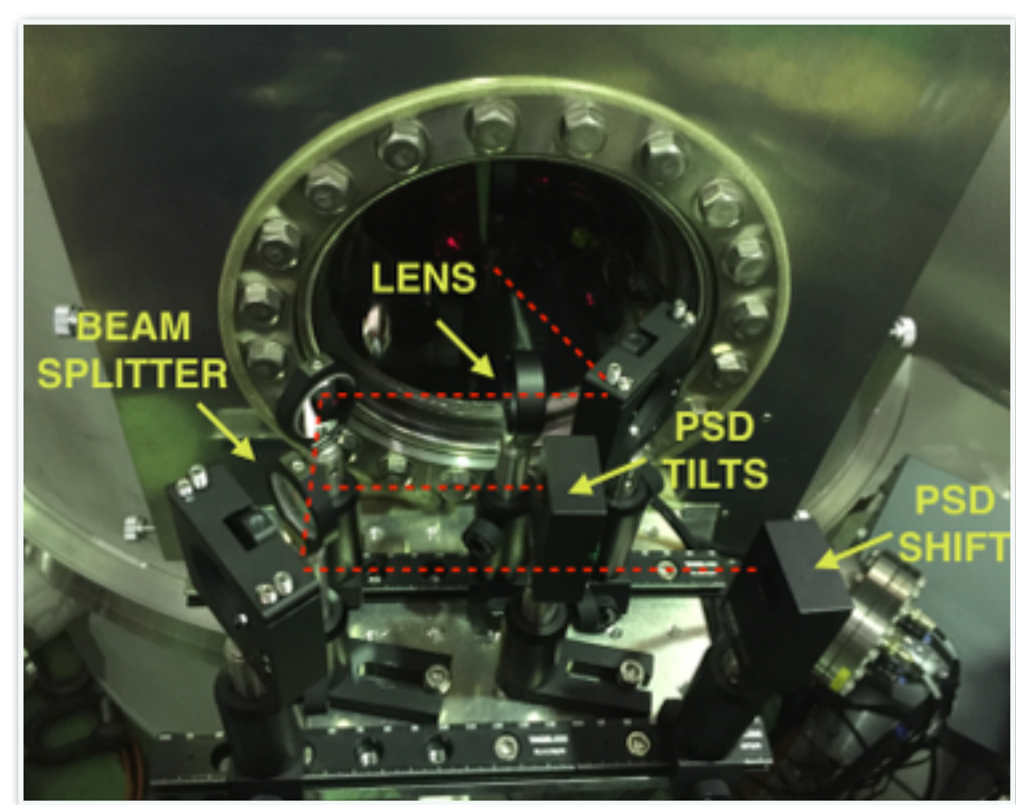
| | diameter[m] | |
|---|---|---|
| | 0.05 | 0.01 |
| RMS [nm] | 1.23 | 0.81 |
| RMS [nm] | 1.36 | 0.53 |
| RMS [nm] | 0.27 | 0.18 |

# My second task: control the suspended mirrors to reduce its low frequency motion

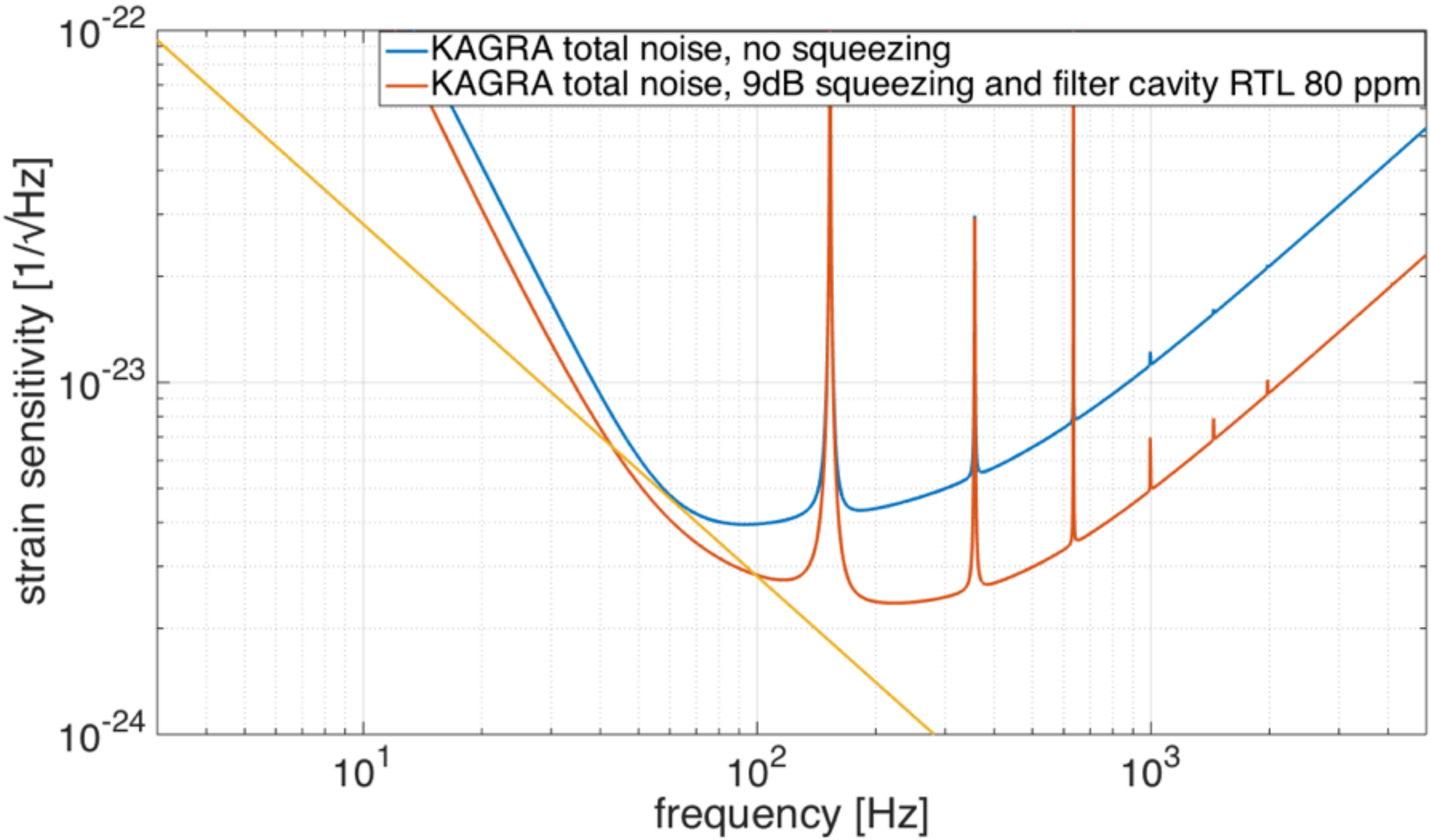
- Sense the mirror displacement and generate an error signal.
- Process the error signal to produce a correction.
- Apply the correction to the mirror to reduce its motion.



# Sensitivity improvement in KAGRA



# Summary

- A lot of science can be done with more sensitive GW detectors
- Our goal: reduce quantum noise (one of the limiting noise in GW detectors)
- How? Using frequency dependent squeezing produced with filter cavities
- (a part of) my thesis work: development of a full scale filter cavity prototipe in TAMA

# Summary

- A lot of science can be done with more sensitive GW detectors
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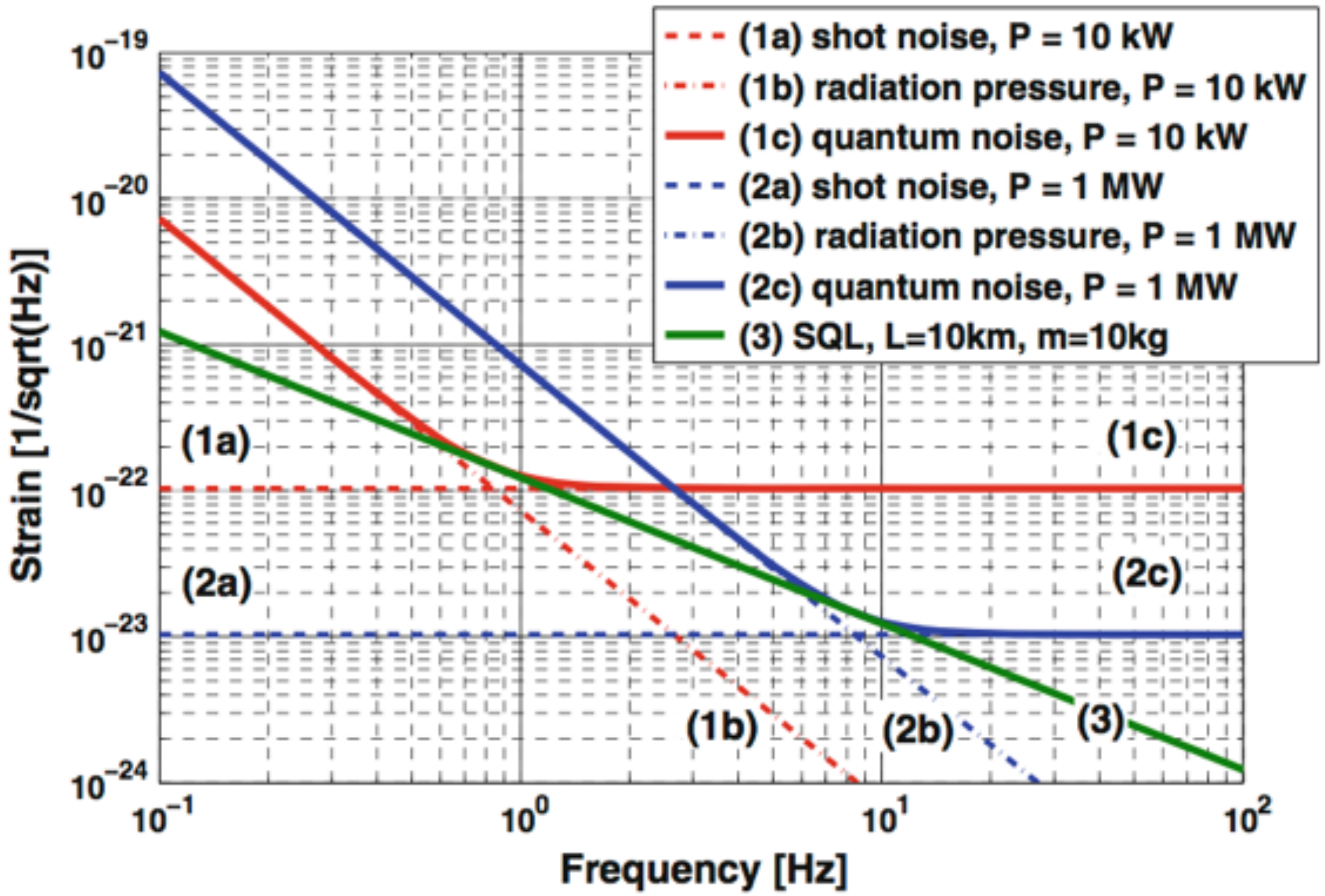
# BACK-UP SLIDES

# The standard quantum limit (SQL)




$S_{SQL} = 8\hbar/(m\Omega^2L^2)$

- It comes from Heisenberg uncertainty principle
- It is not a fundamental limit for our measurements

- Quantum mechanics of the test mass wave function

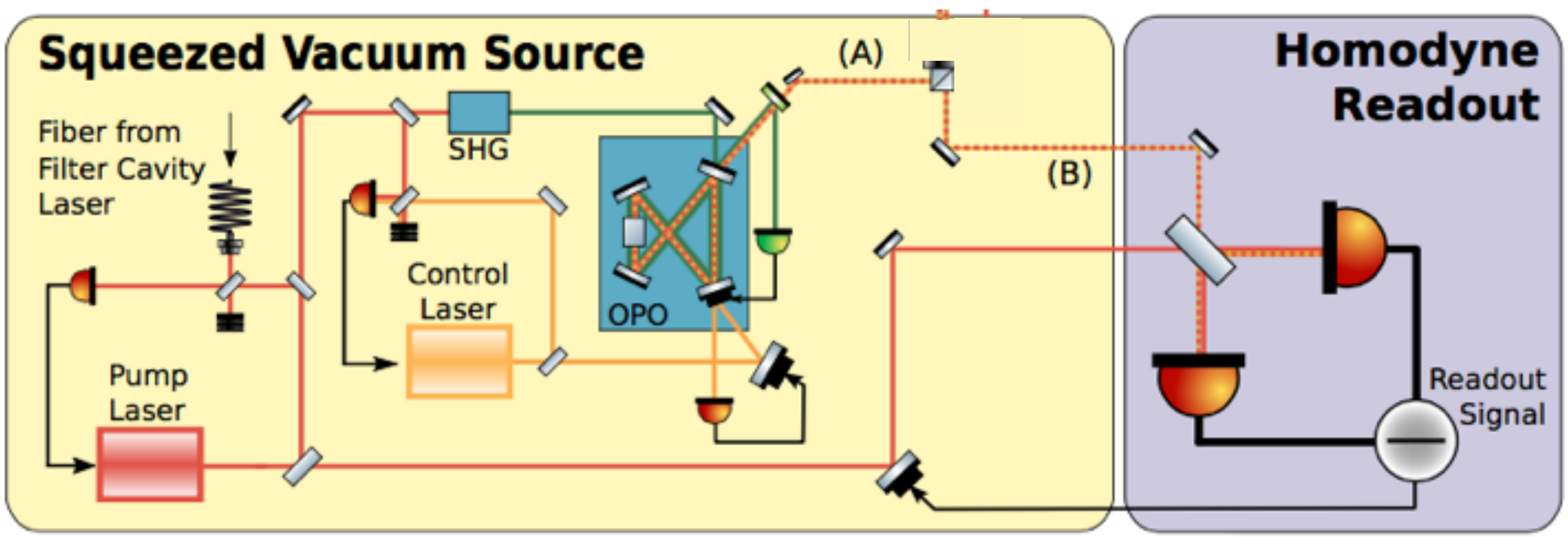
  turns out to be irrelevant since we measure classical forces[1]

- Quantum mechanics of the laser light used for the measurement wave function

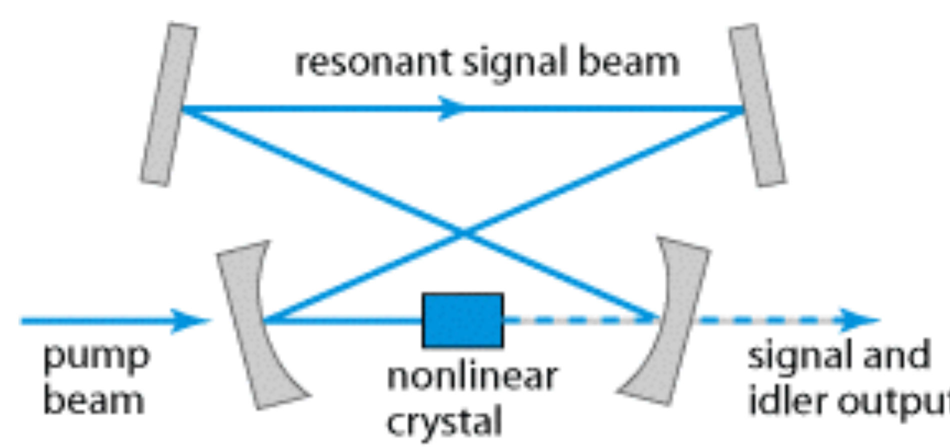
  can be circumvent using “special” states of light

[1]Braginsky, Khalili, “Quantum measurement” (1992)

# What's squeezed vacuum? How is it produced?

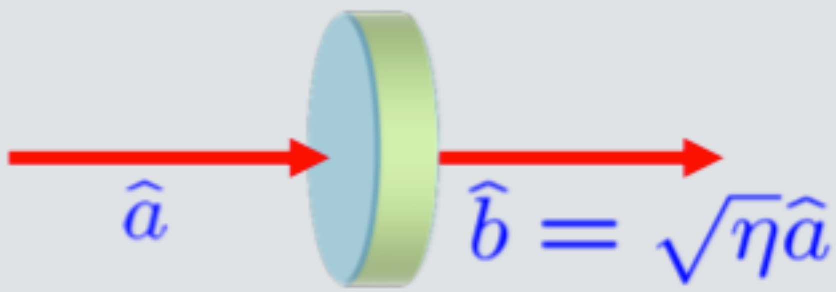



- Squeezing is produced inducing correlation between quantum fluctuations
- The most effective way to generate correlation is a optical parametric oscillator (OPO)
- OPO uses non linear crystal to create correlation between quadratures



# Optical losses degrade squeezing

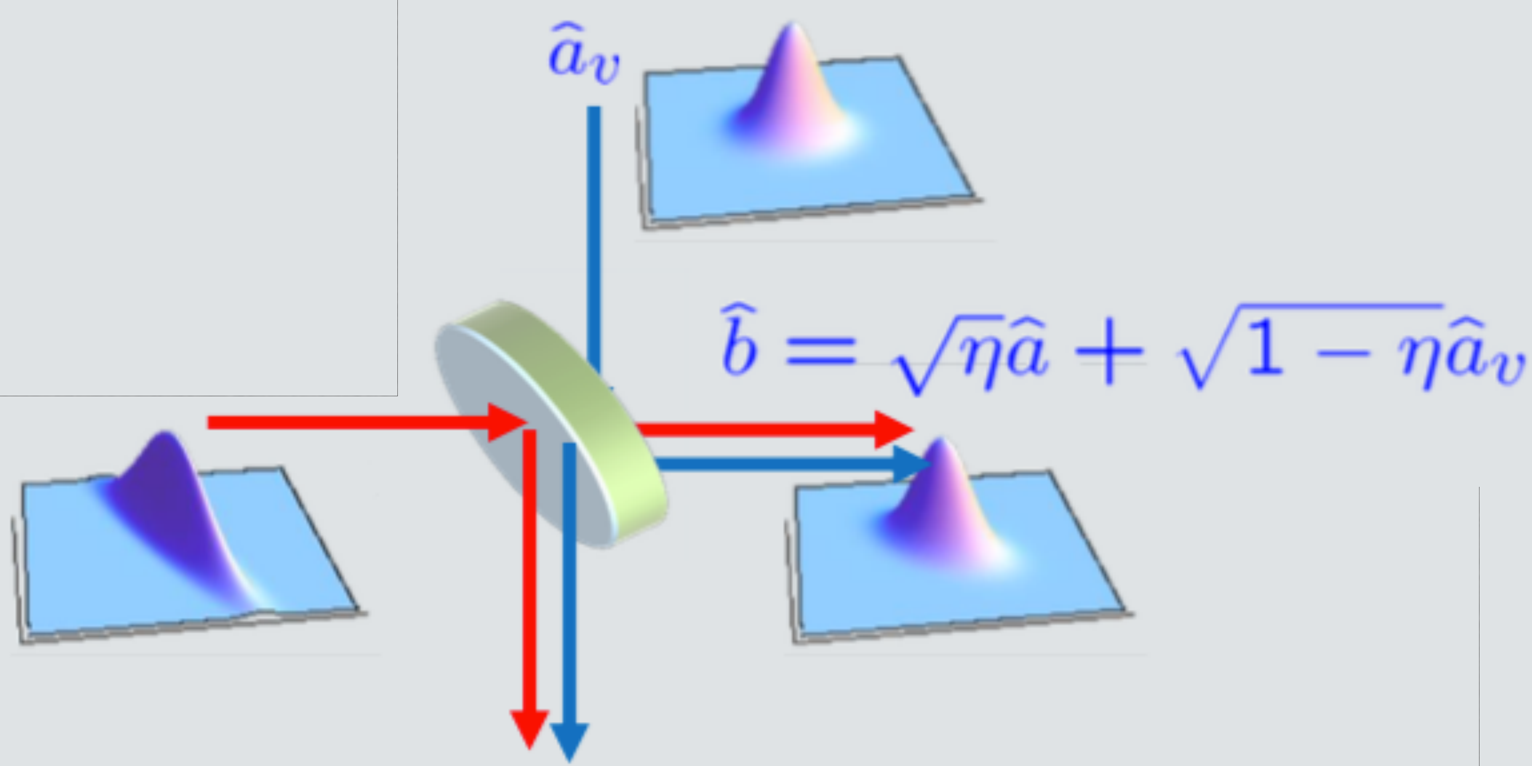
- Naive model




$$[\hat{a}, \hat{a}^{+}] = 1$$

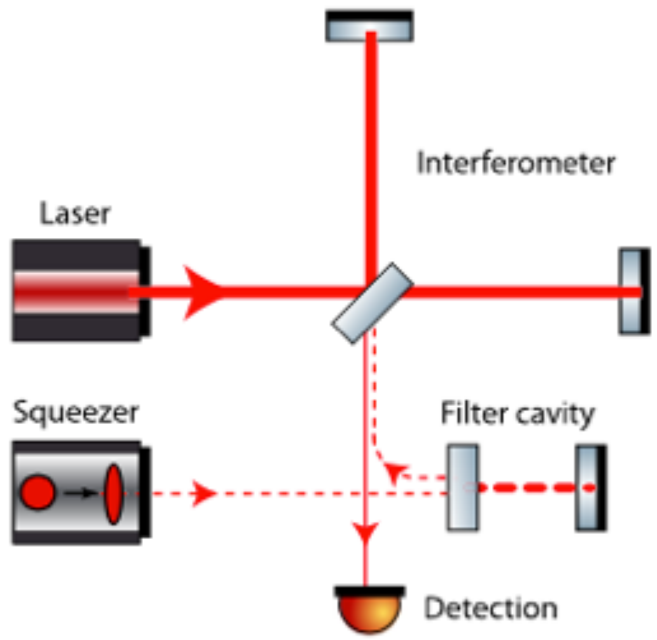
$$[\hat{b}, \hat{b}^{+}] = \eta \neq 1$$

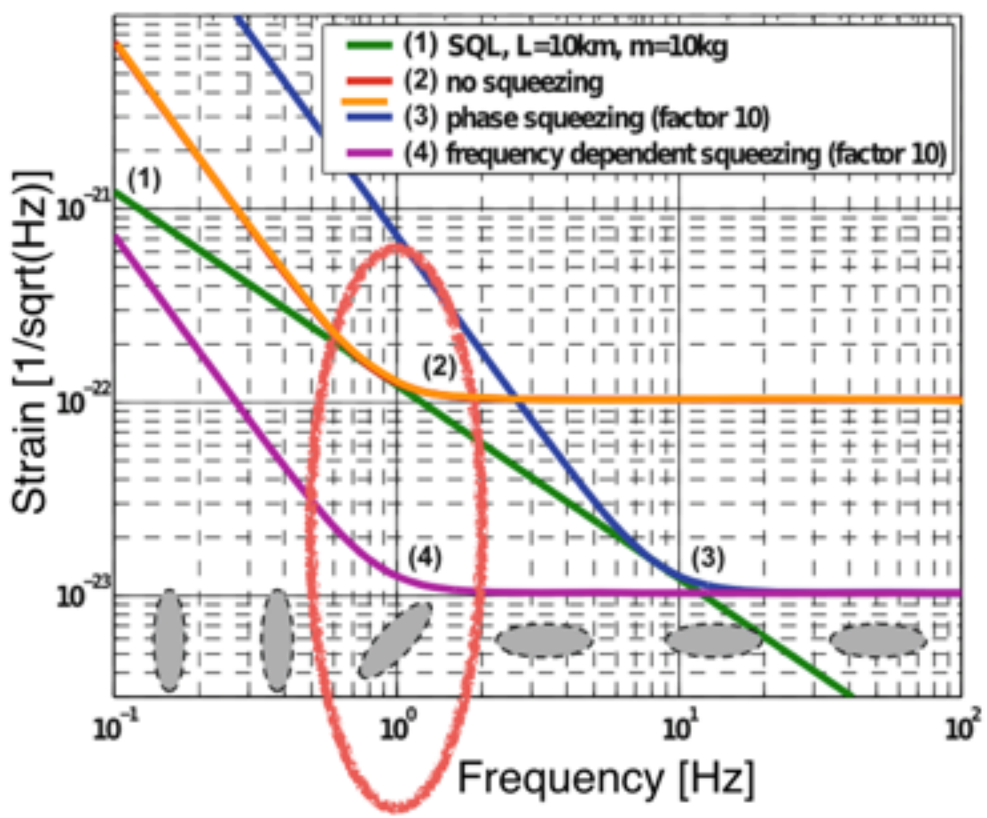
- Consistent model




Squeezing deteriorated because of its recombination with non squeezed vacuum

# How to produce frequency dependent squeezing?




Optimal squeezing rotation in correspondence of $\Omega_{\mathrm{SQL}}$

- Reflect frequency independent squeezing of a Fabry-Pérot cavity

- Rotation angle depends on cavity detuning and finesse

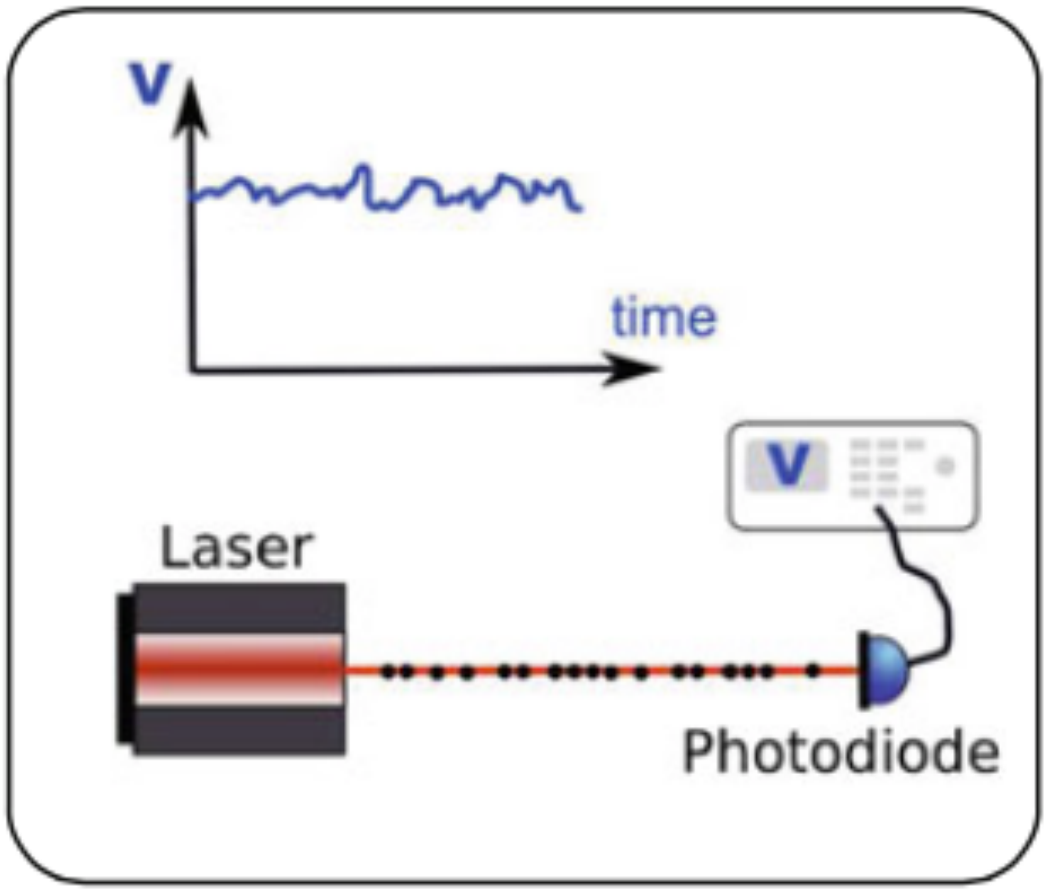
$$\alpha_p = \mathrm{atan}\left(\frac{2\gamma_{\mathrm{fc}}\Delta\omega_{\mathrm{fc}}}{\gamma_{\mathrm{fc}}{}^2 - \Delta\omega_{\mathrm{fc}}{}^2 + \Omega^2}\right)$$

- Many technical issues

  High storage time
  Low losses

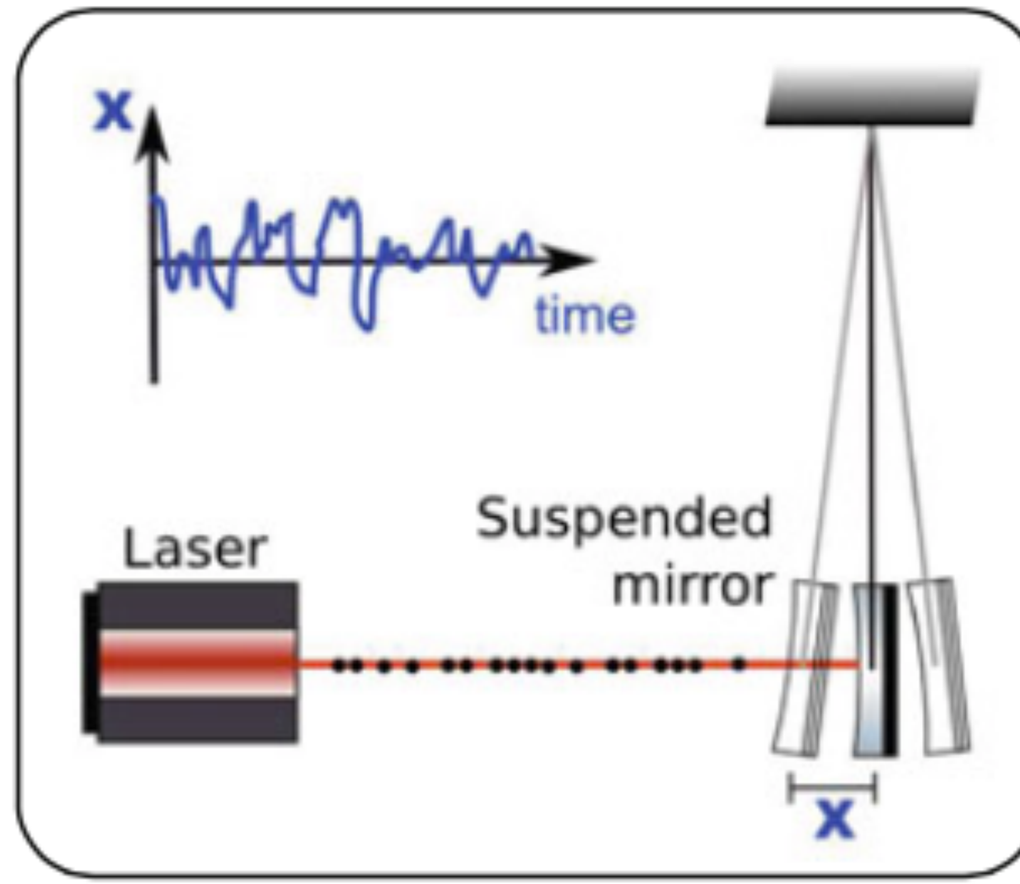
# Quantum noise in a semiclassical picture

## Shot noise



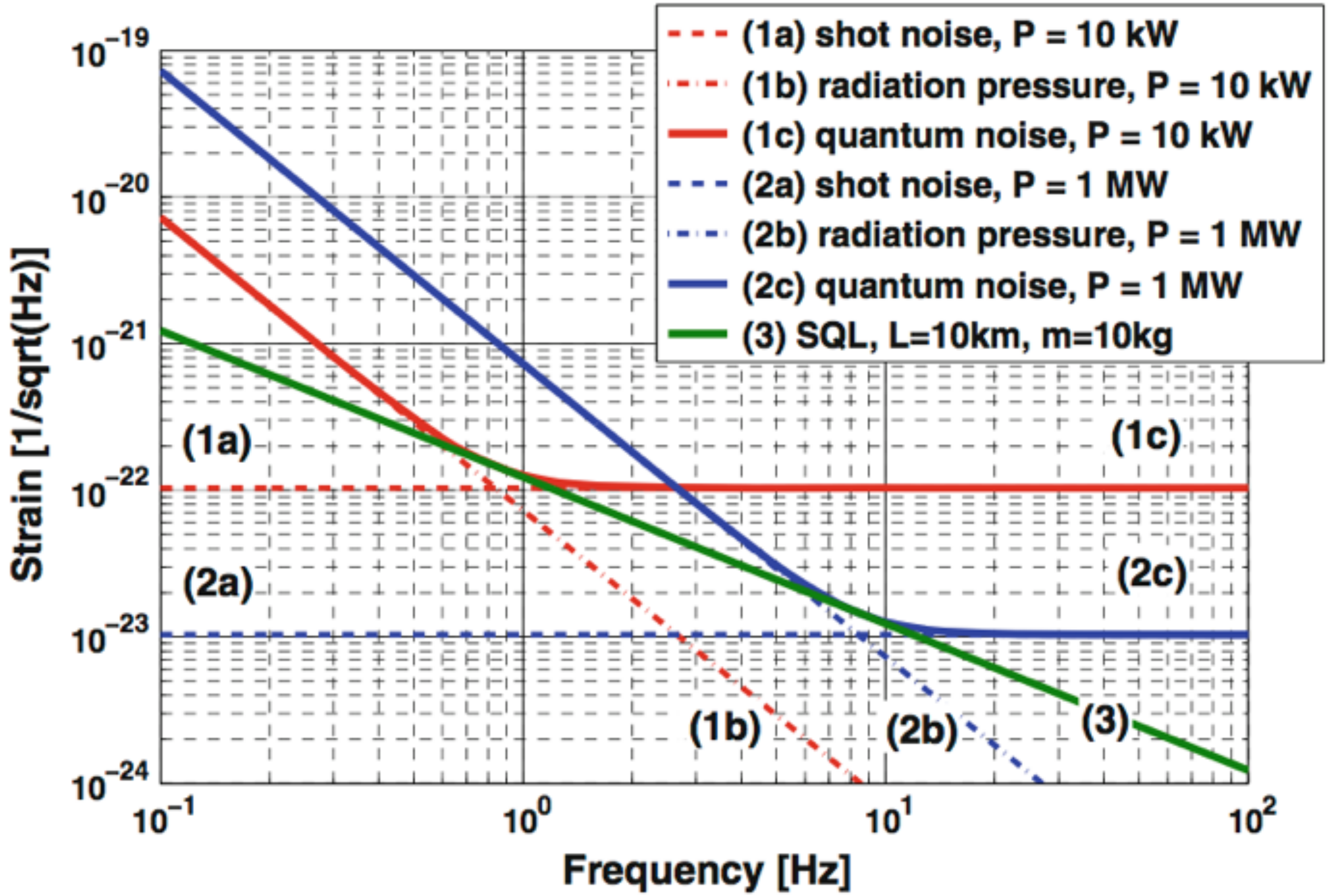

- Poissonian statistics on the photon arrival time

## Radiation pressure noise




- Fluctuation in the momentum transferred to the mirror

# Quantum noise in a semiclassical picture



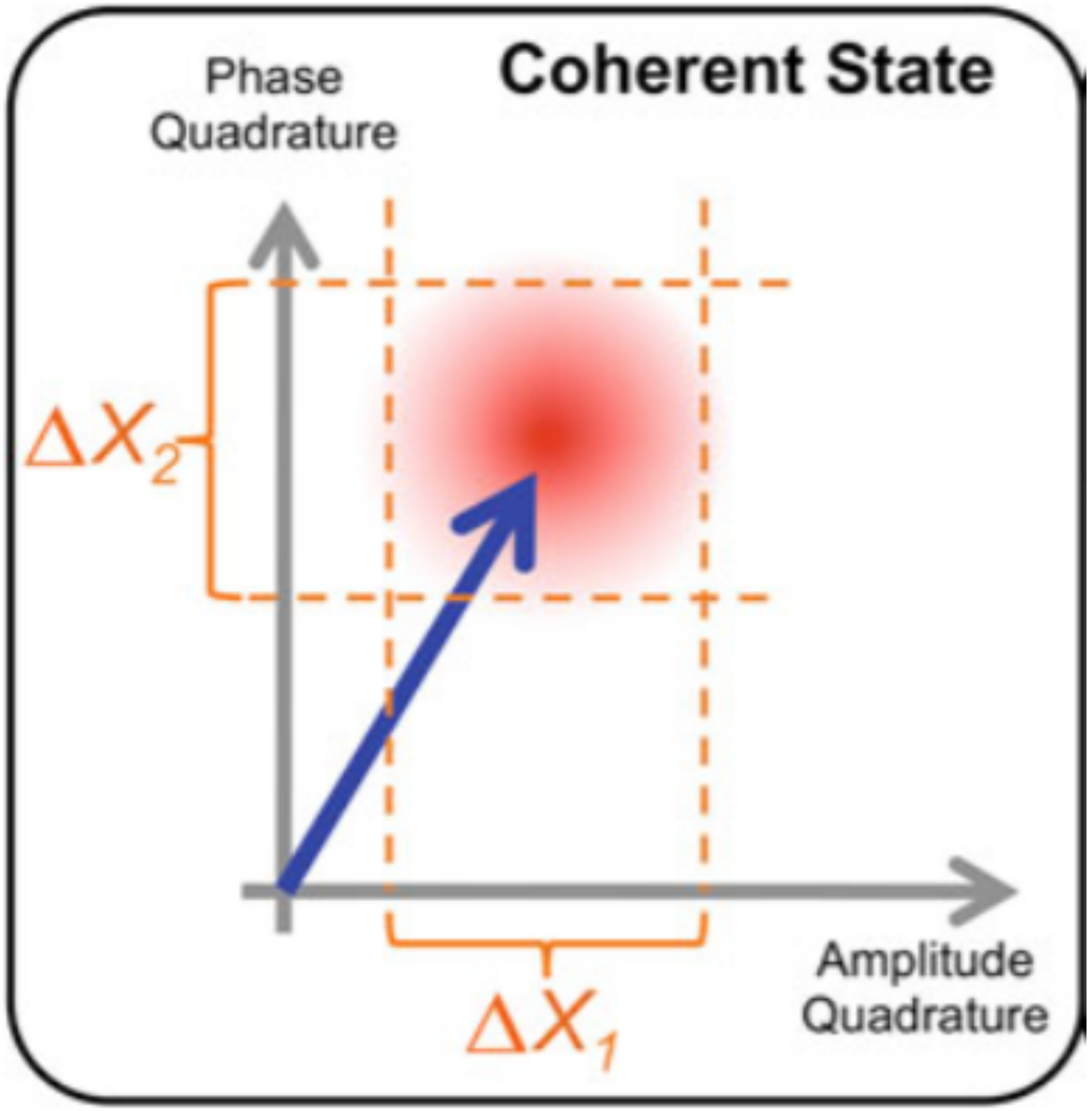

Radiation pressure noise

$$h_{\rm rp}(f) = \frac{1}{m f^2 L}\sqrt{\frac{\hbar P}{2\pi^3 c\lambda}}$$

Shot noise

$$h_{\rm sn}(f) = \frac{1}{L}\sqrt{\frac{\hbar c\lambda}{2\pi P}}$$

# Quantum representation: coherent state

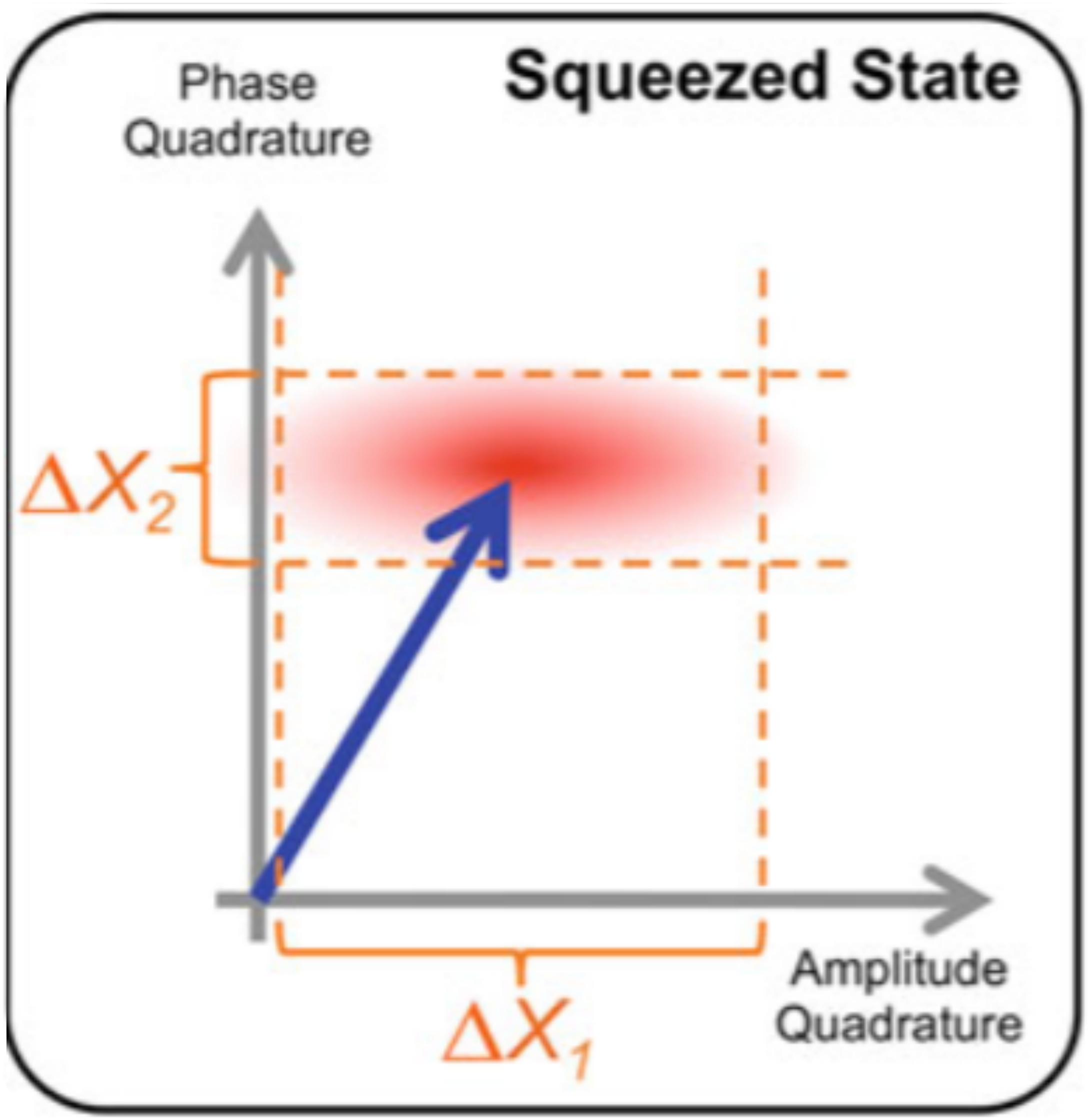



- Quantization of the EM filed
- Amplitude and phase fluctuations are equally distributed and uncorrelated
- In frequency domain is described by two quantum operators accounting for quantum fluctuation in each quadrature

$$\hat{E}(t) = \left[E_0 + \hat{E}_1(t)\right] \cos \omega_0 t + \hat{E}_2(t) \sin \omega_0 t$$

$$\vec{a}(\Omega) = \begin{pmatrix} a_1(\Omega) \\ a_2(\Omega) \end{pmatrix}$$

# Quantum representation: coherent state

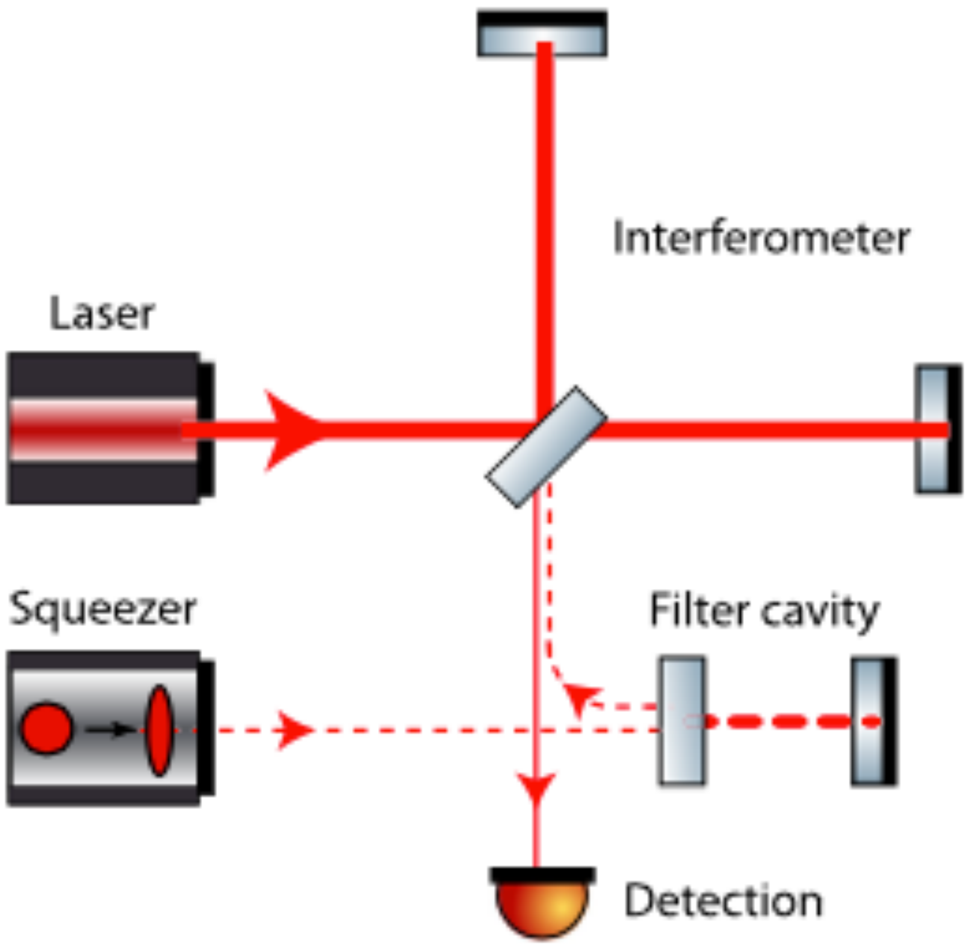


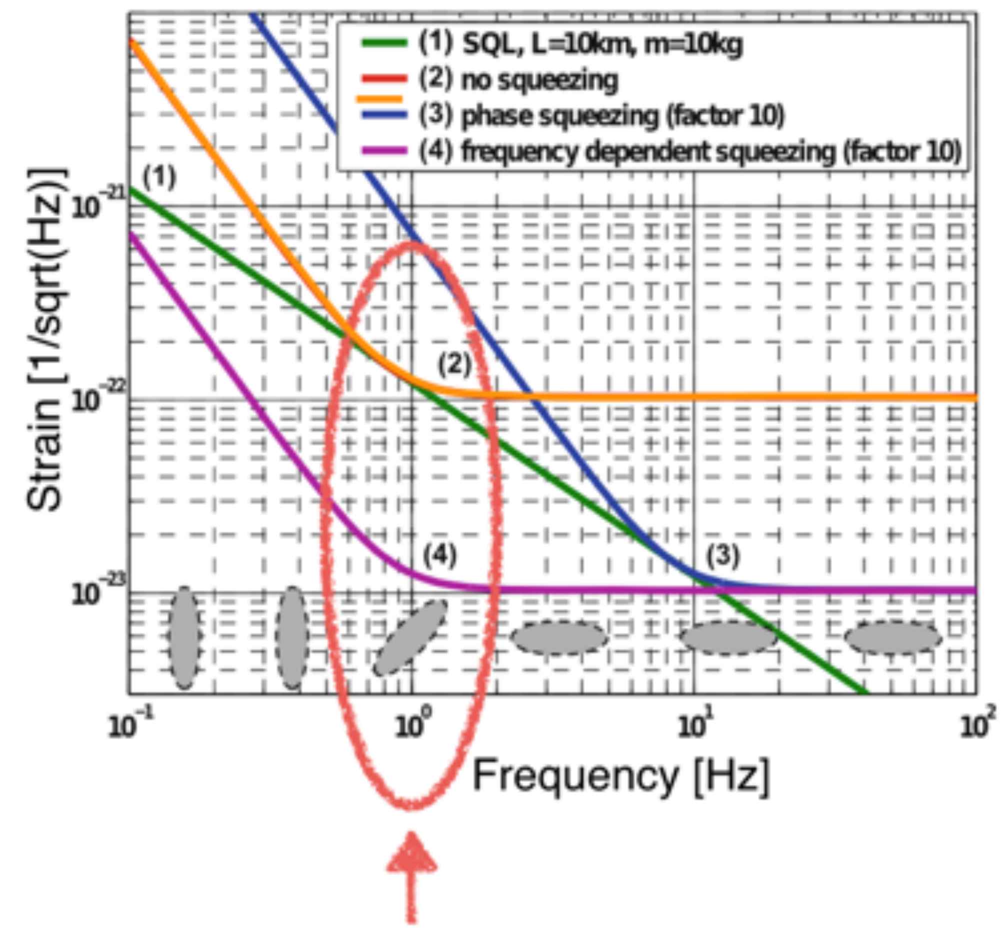

- Non classical light state
- Noise in one quadrature is reduced with respect to the one of a coherent state
- Correlations are introduced between amplitude and phase fluctuations

Each state is characterized by

- Squeezing factor (magnitude of the squeezing)
- Squeezing angle (orientation of the ellipse)

# How to produce frequency dependent squeezing?

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