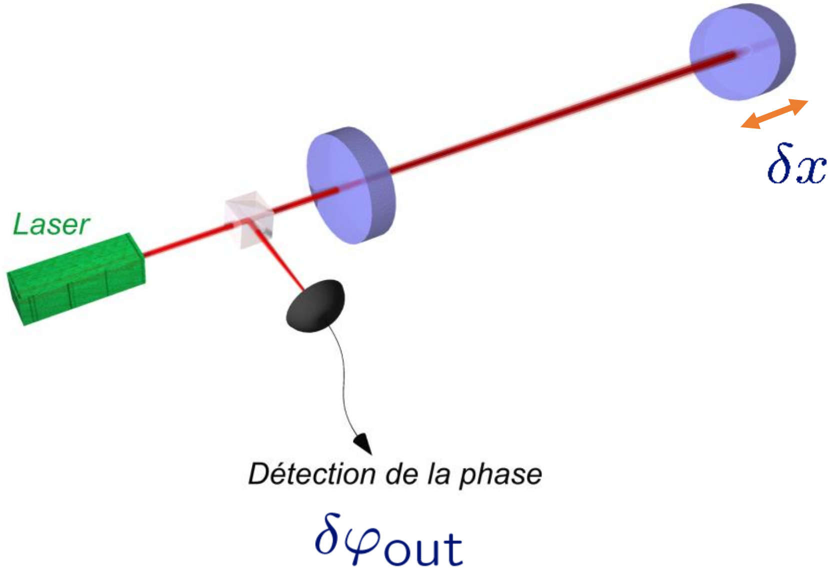
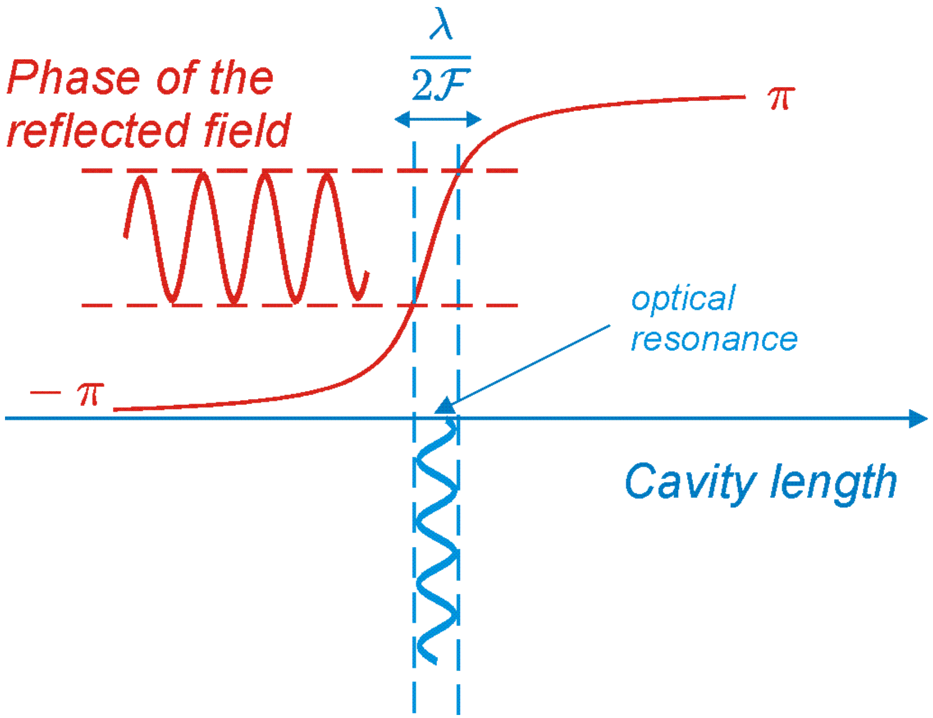
Interferometric measurements and quantum limits

$$\delta\varphi_{\text{out}} = \frac{8\mathcal{F}}{\lambda}\,\underbrace{\delta x}_{\text{signal}}$$





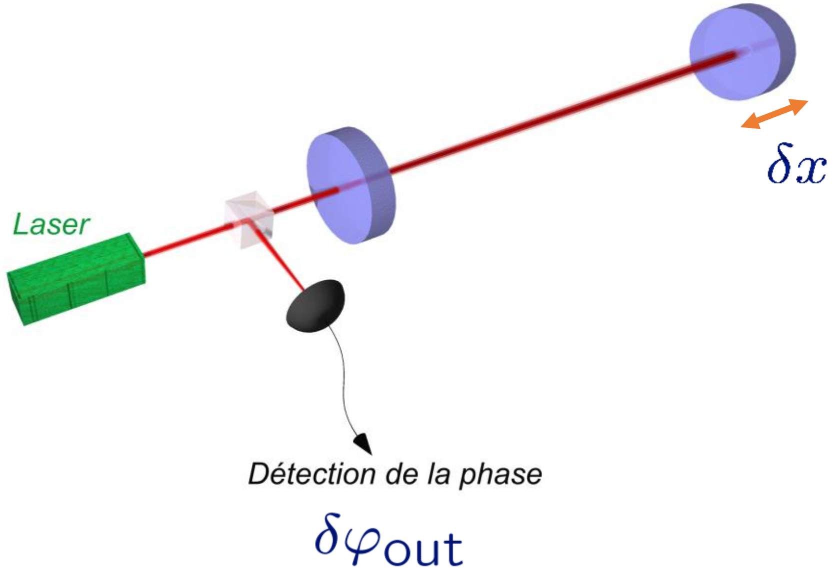
Interferometric measurements and quantum limits

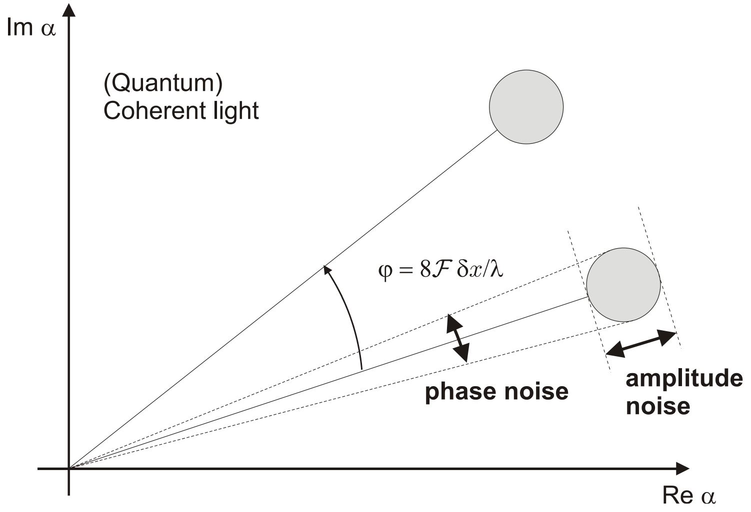
thermal noise

$$\delta\varphi\delta\varphi_{\mathrm{in}} + \frac{8\mathcal{F}}{\lambda}(\delta x + \delta x_{\mathrm{cl}})$$

phase noise

signal





Interferometric measurements and quantum limits

thermal noise

$$\delta\varphi_{\mathrm{out}} = \delta\varphi_{\mathrm{in}} + \frac{8\mathcal{F}}{\lambda}(\delta x + \delta x_{\mathrm{cl}})$$

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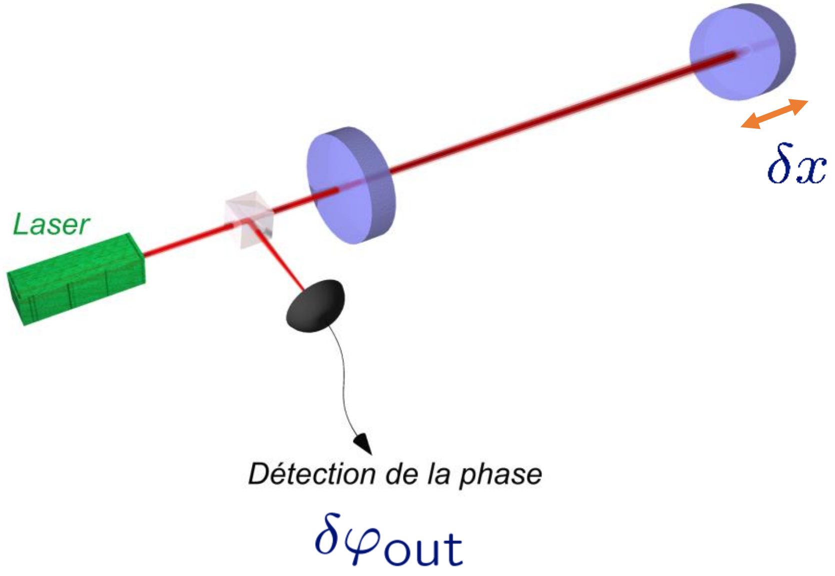
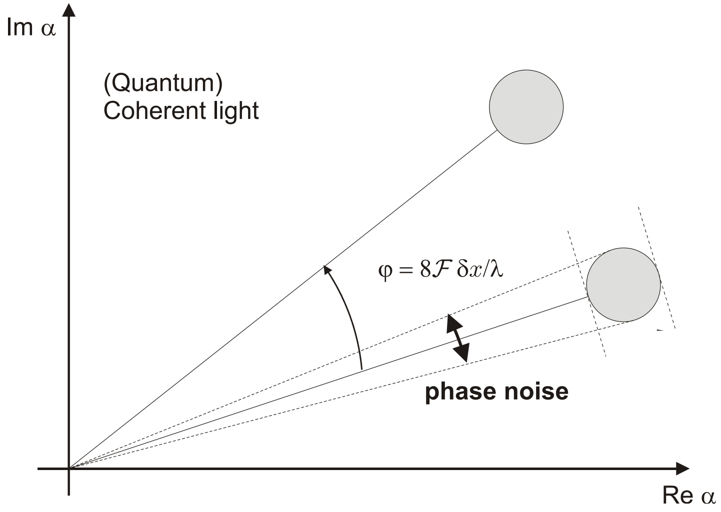




$$\delta x_{shot} = \frac{\lambda}{16\mathcal{F}}\frac{1}{\sqrt{I^{in}}}\sqrt{1+\left(\frac{\Omega}{\Omega_{cav}}\right)^2}$$

Quantum Noise and Measurement back-action

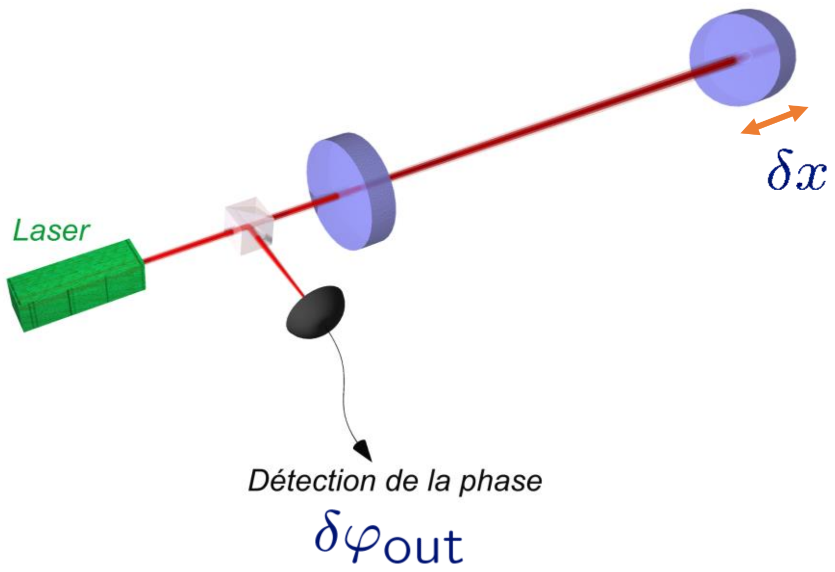
thermal noise

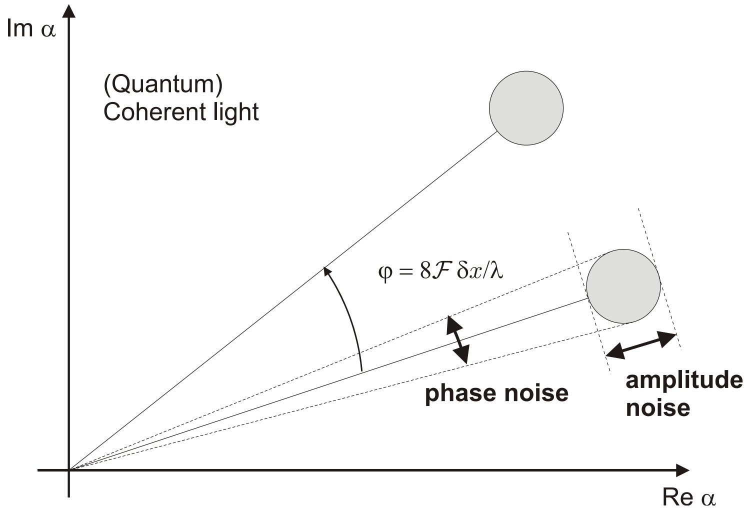
$$\delta\varphi_{\text{out}} = \delta\varphi_{\text{in}} + \frac{8\mathcal{F}}{\lambda}(\delta x + \delta x_{\text{cl}} + \delta x_{\text{rad}}$$

phase noise

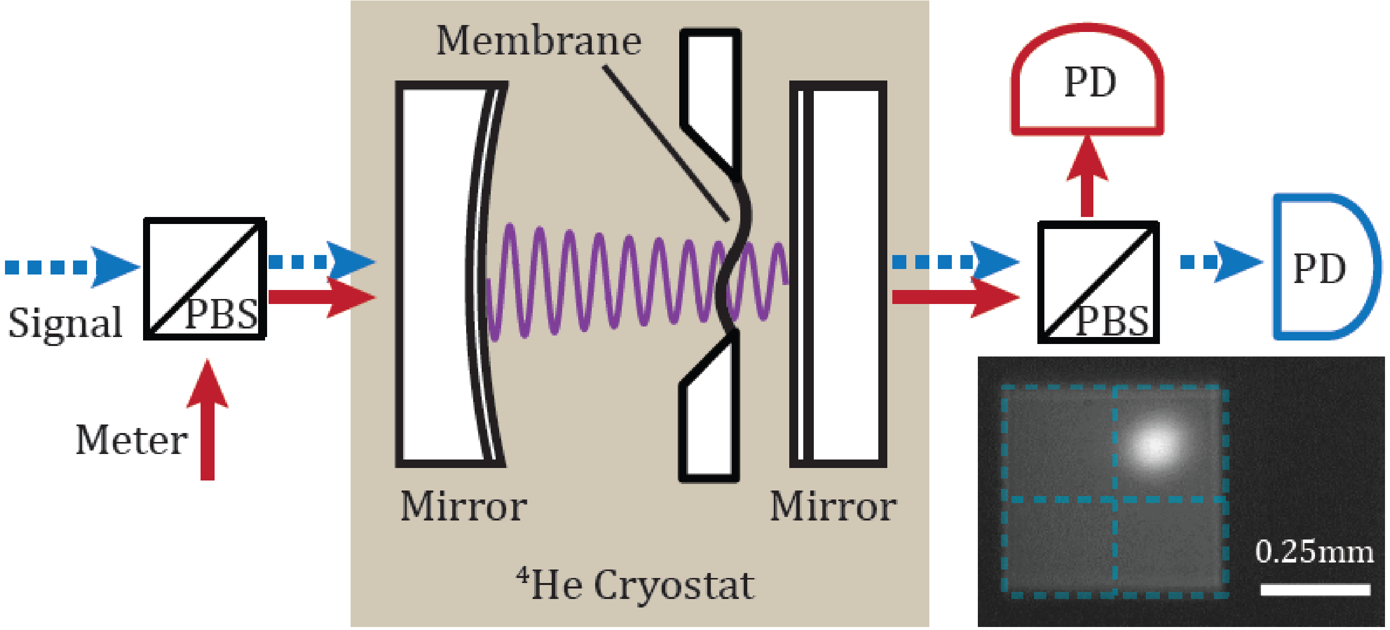
signal

radiation pressure noise

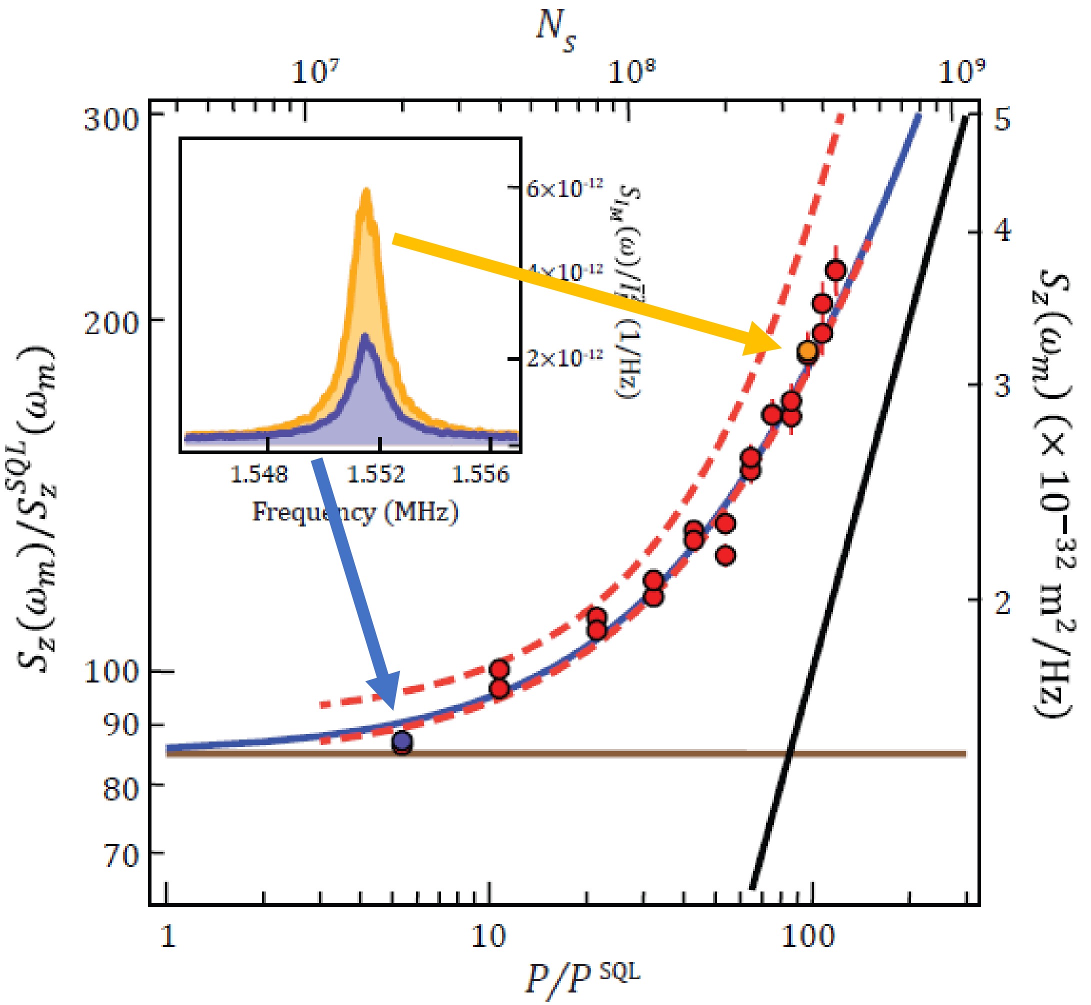




First QRPN demonstration

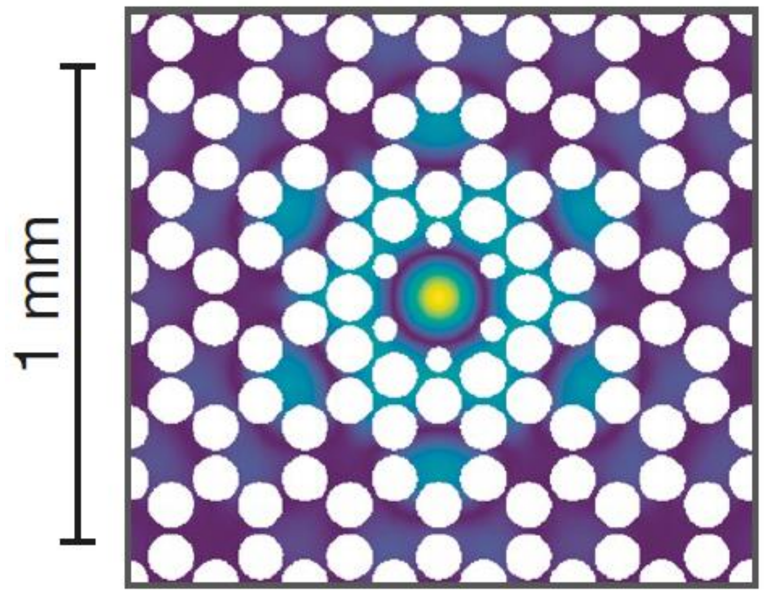


With a much lighter resonator:
SiN membrane
7 ng, ≈ 1.5 MHz, $Q \approx 10^6$
and T ≈ 2 mK (laser cooling)

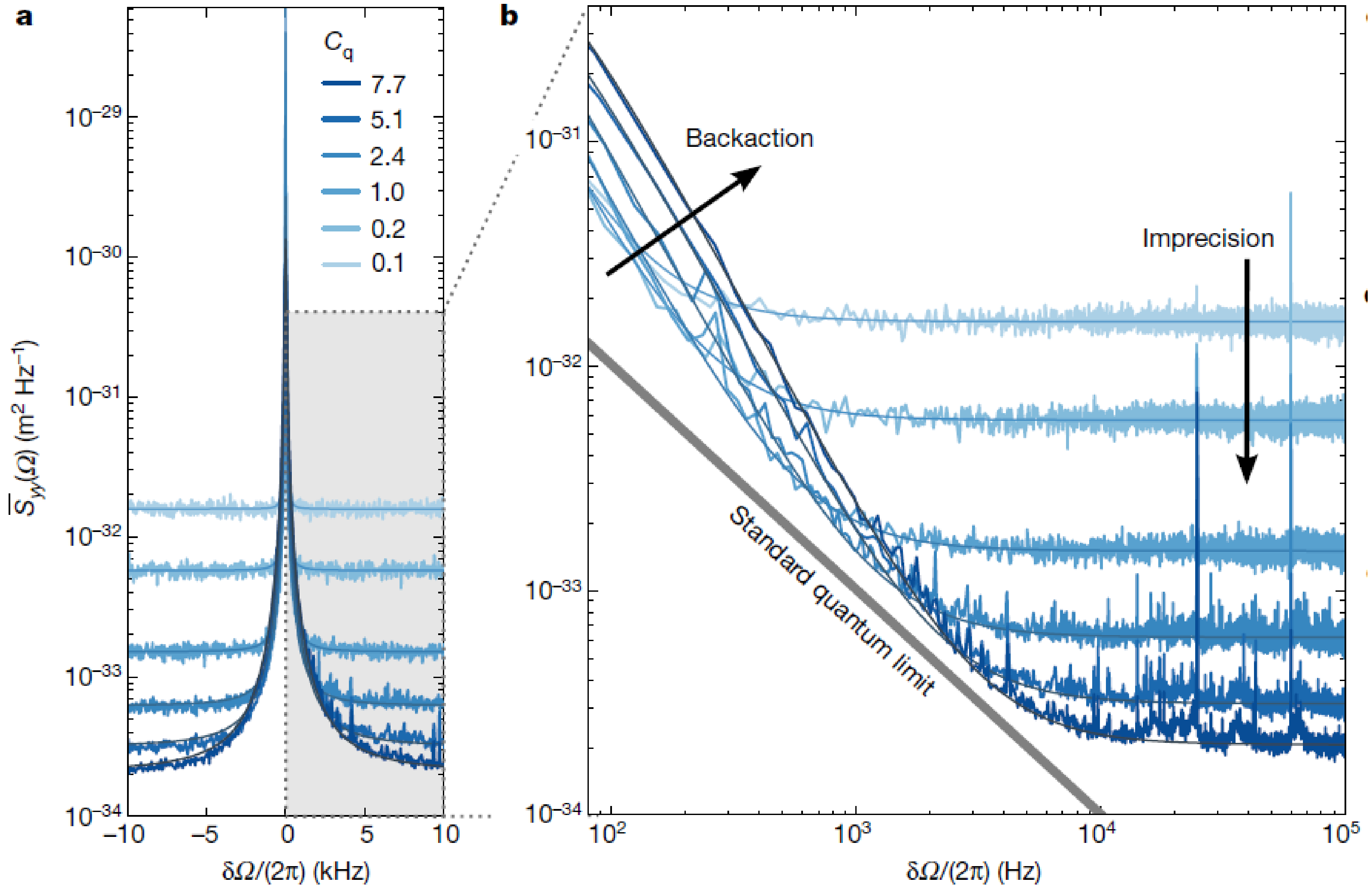


C. Regal, JILA Boulder
Science 2013

QRPN and the SQL with an optomechanical membrane

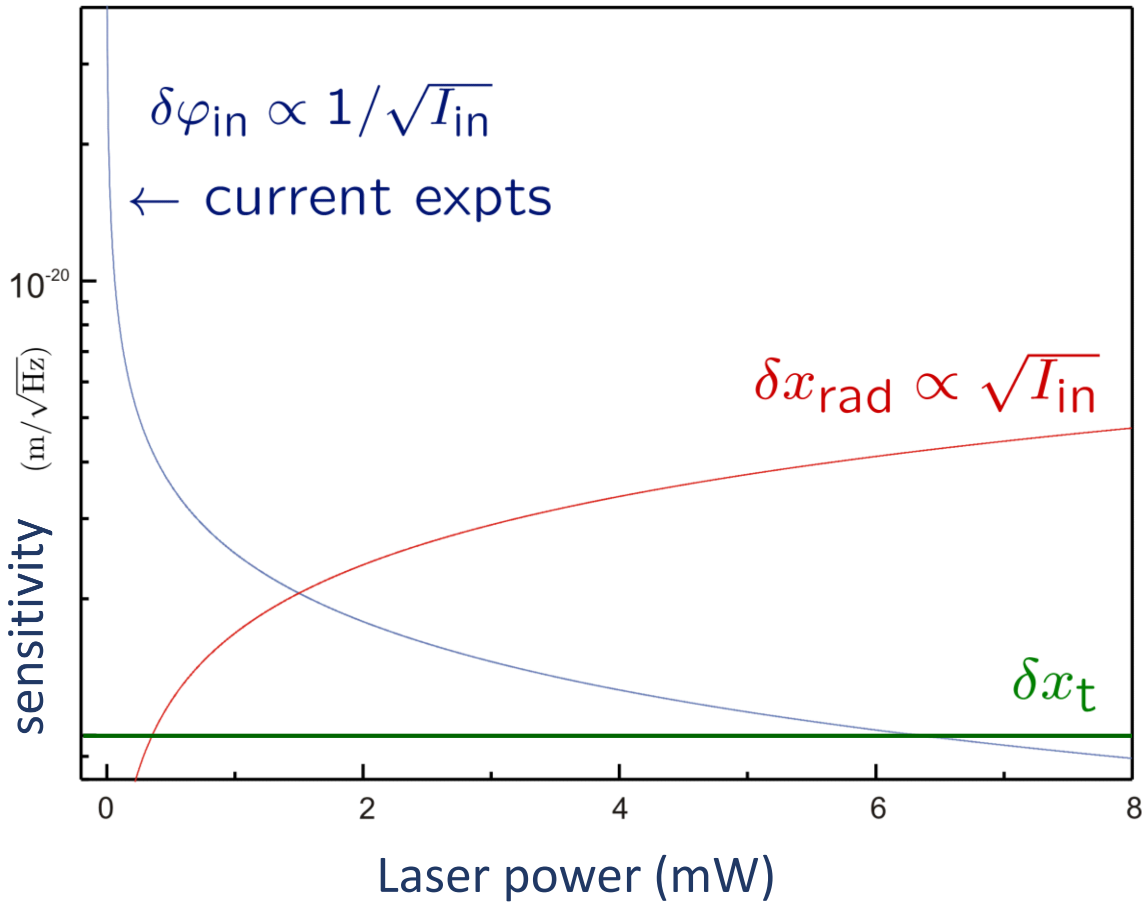


20-nm thick phononic-crystal SiN membrane
≈ 1.5 MHz, Q ≈ 10^9
and T ≈ 10 K



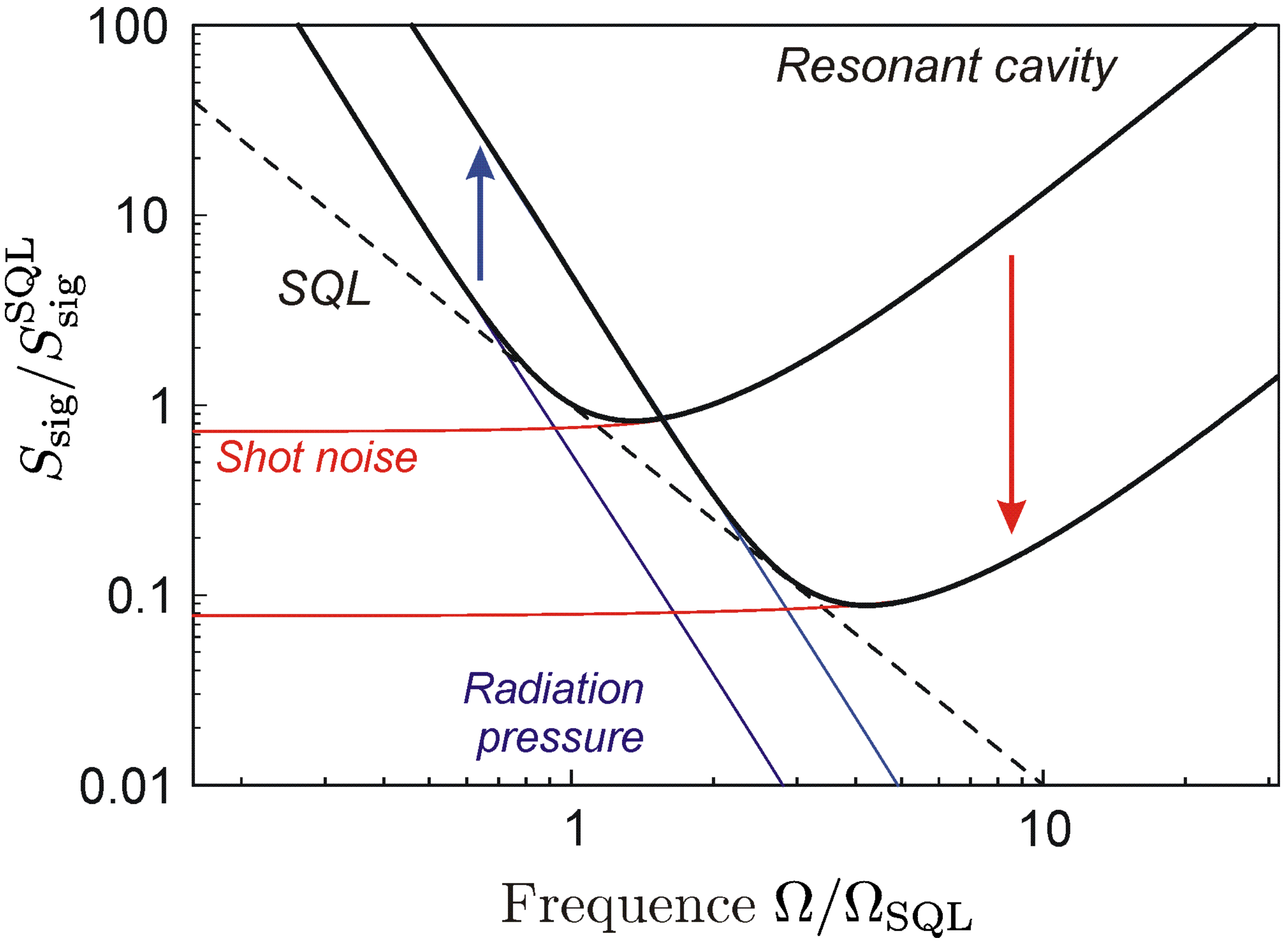
Rossi,… Schliesser, Nature **563**, 503 (2018)

The Standard Quantum Limit



$M = 100\,\mu\mathrm{g}$
$\Omega_{\mathrm{m}}/2\pi = 1\,\mathrm{MHz}$
$Q = 10^6$
$T = 1\mathrm{K}$
$\mathcal{F} = 100\,000$
(computed for $\Omega \ll \Omega_{\mathrm{m}}$)

SQL for a GW interferometer



Computed for a free mass (GWI case):
$\chi(\Omega) = 1/M\Omega^2$
Changing the laser power increases QRPN while decreasing phase noise: compromise leads to an optimal power at every frequency

How to beat Quantum Noise and the Standard Quantum Limit

For a coherent input beam, uncorrelated noises lead to the SQL

Different ideas to lower QN level and go beyond the SQL:

- **Reduce the QN** level by injecting light with correlations
  Frequency-independent squeezing (O3, 2019-2020)
  Frequency-dependent squeezing (O4, 2023-2024)
- Create correlations inside the (detuned) ITF
- **Use correlations** in the detected signal (Variational Readout)
- **Use correlated beams** (EPR entanglement)

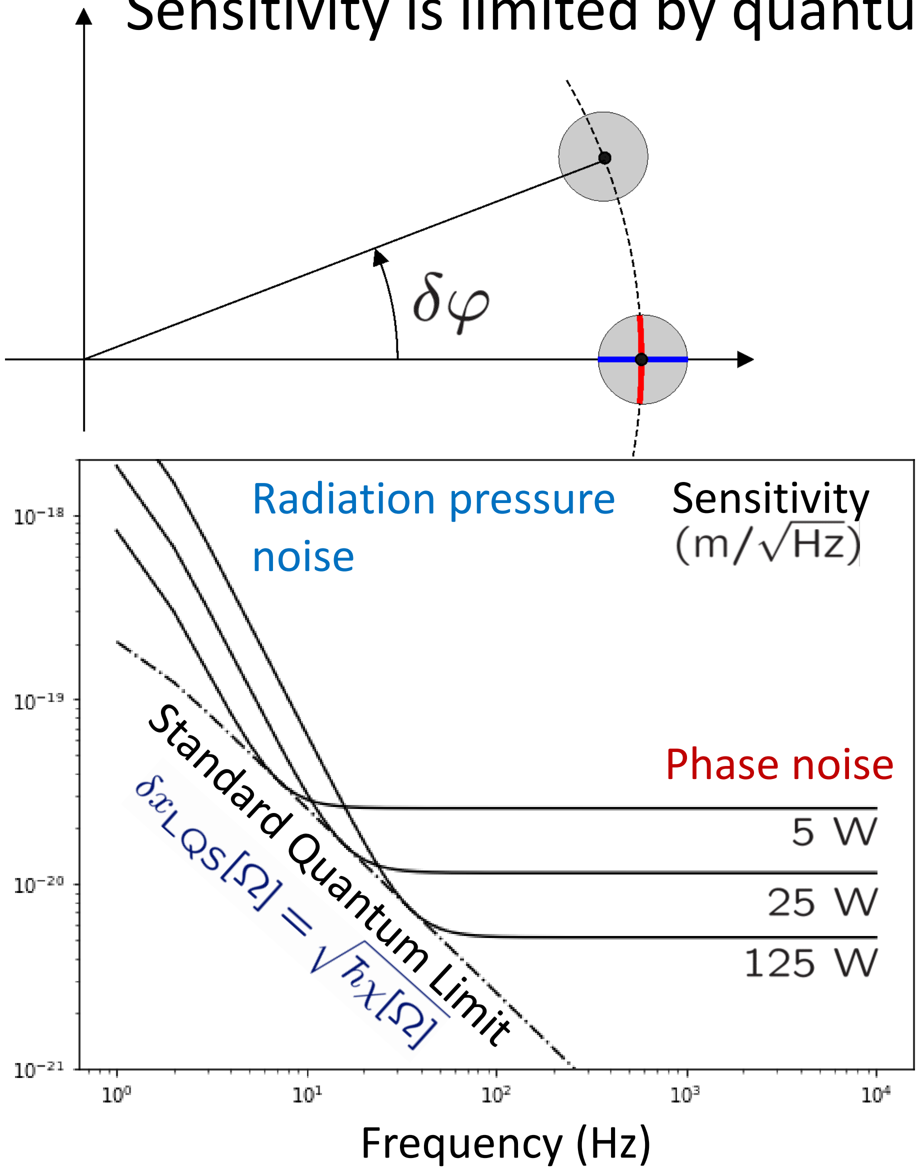
Quantum noise

- Sensitivity is limited by quantum noise: phase noise and radiation-pressure noise

$$\delta\varphi_{\text{out}} = \delta\varphi_{\text{in}} + \frac{8\mathcal{F}}{\lambda}(\delta x + \delta x_{\text{rad}})$$

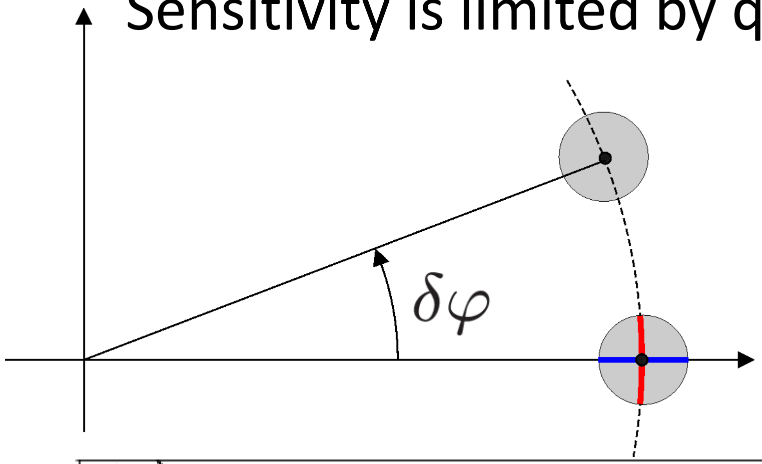
$$\delta x_{\text{rad}} = \chi(\Omega)\,\delta I[\Omega]$$

$\chi(\Omega)$: Mechanical response



Quantum noise and Squeezing

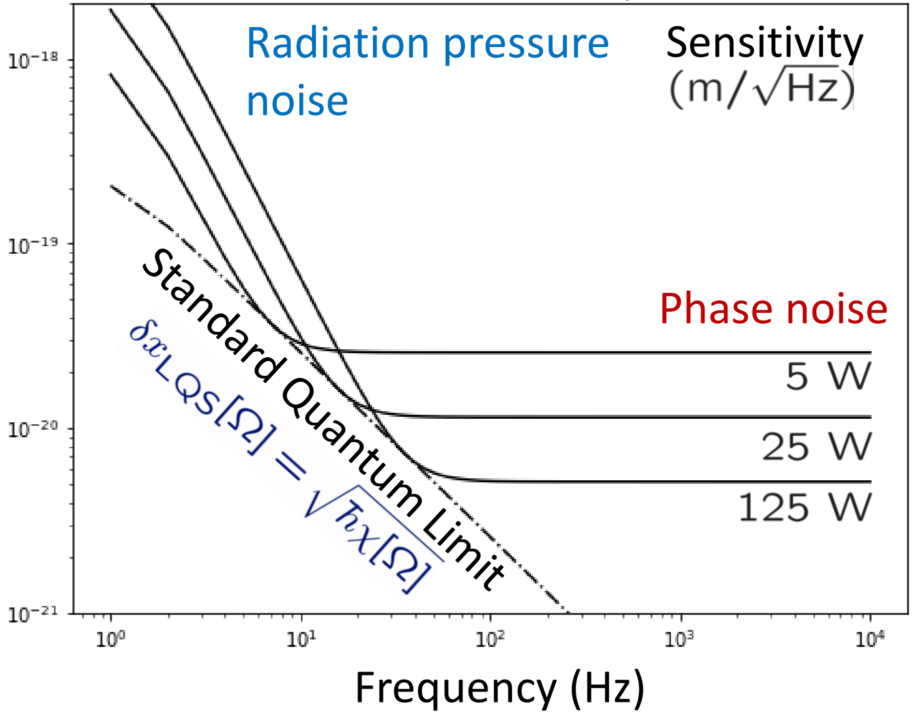
Sensitivity is limited by quantum noise: phase noise and radiation-pressure noise

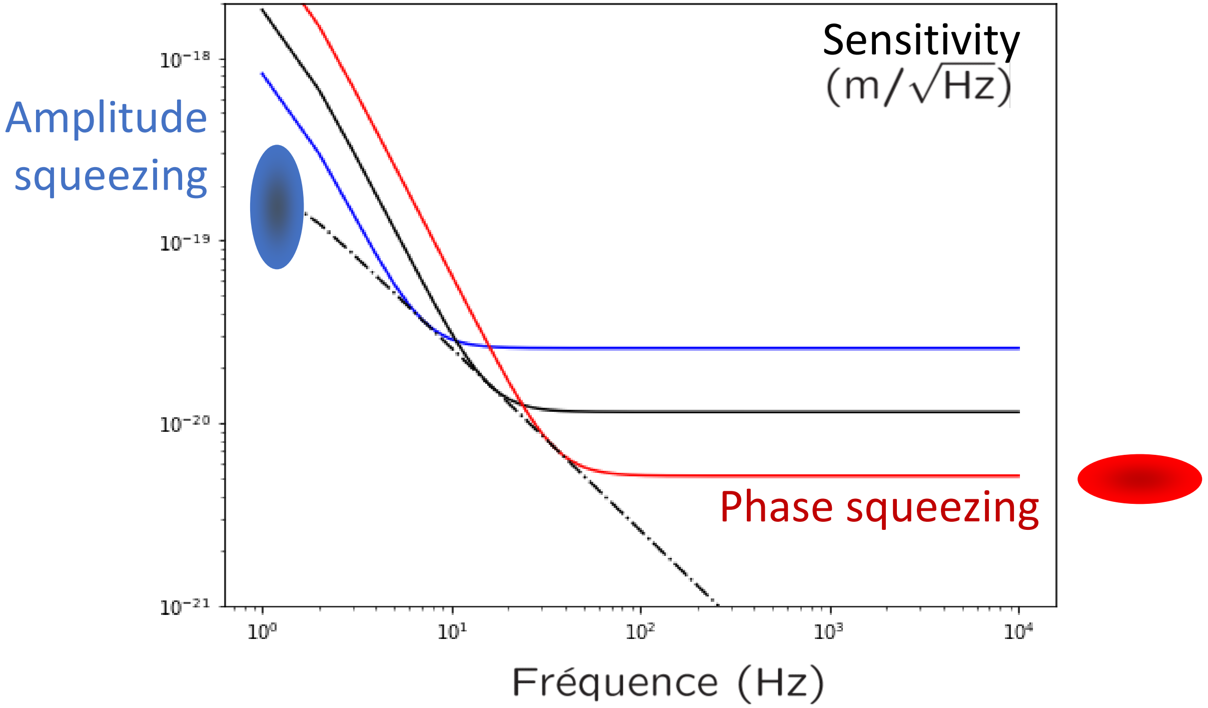


$$\delta\varphi_{\text{out}} = \delta\varphi_{\text{in}} + \frac{8\mathcal{F}}{\lambda}\left(\delta x + \delta x_{\text{rad}}\right)$$

$$\delta x_{\text{rad}} = \chi(\Omega)\,\delta I[\Omega]$$

$\chi(\Omega)$: Mechanical response

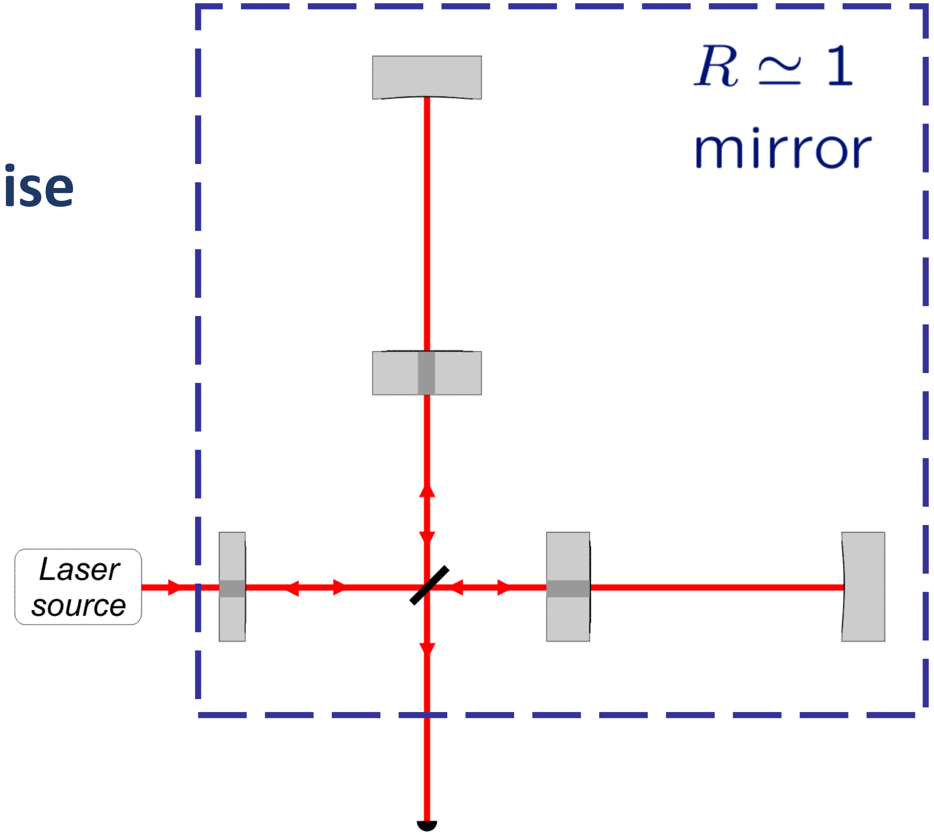




Why vacuum squeezing?

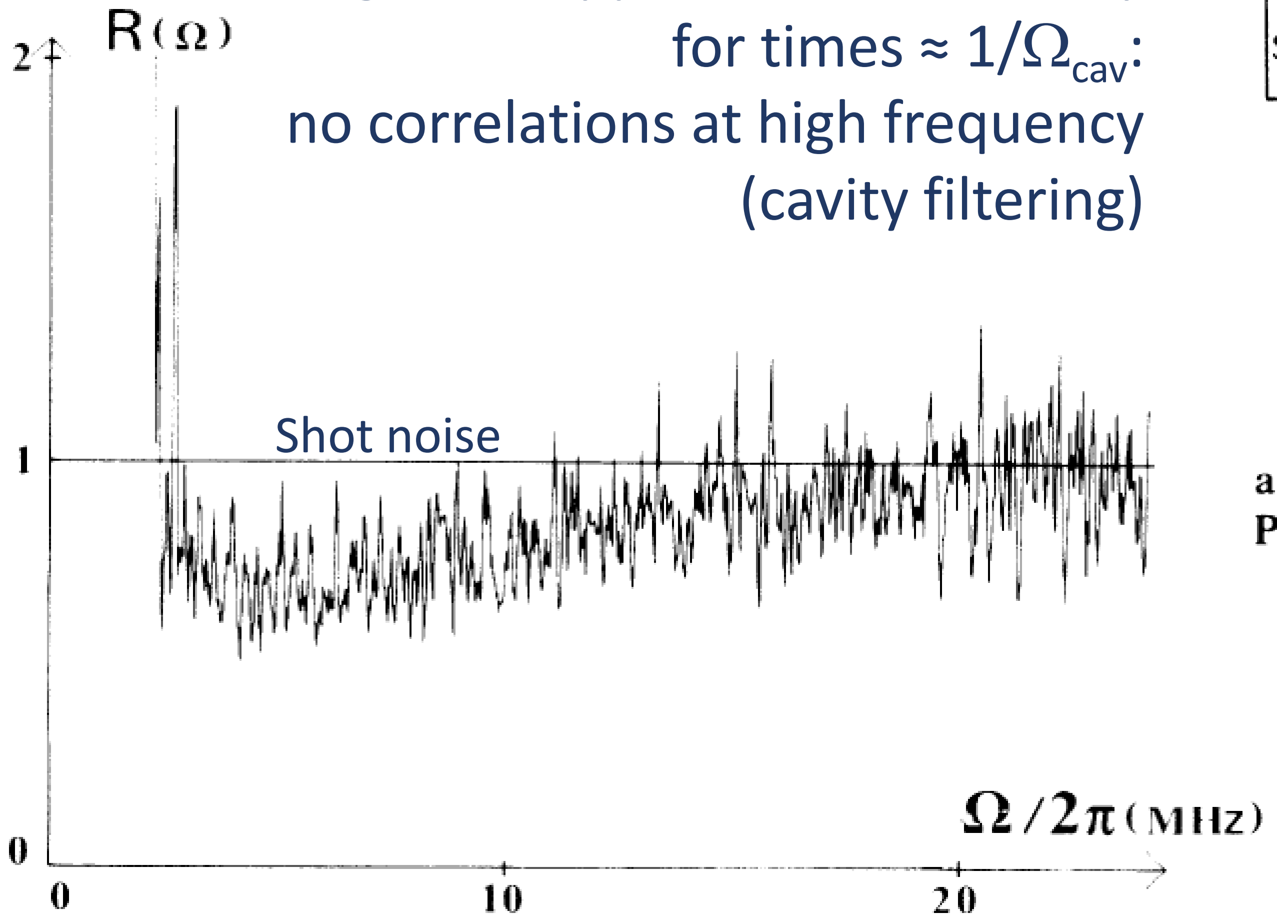
GWI on a dark fringe

$\rightarrow$ Sensitive to vacuum noise



Twin beams

Light is trapped inside the cavity
for times ≈ $1/\Omega_{cav}$:
no correlations at high frequency
(cavity filtering)



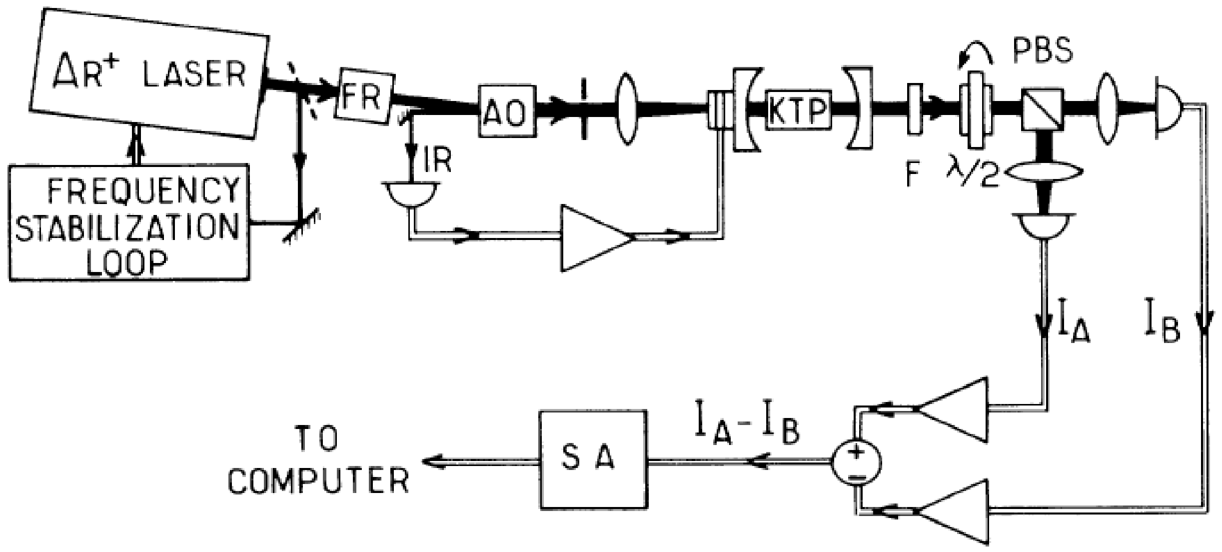
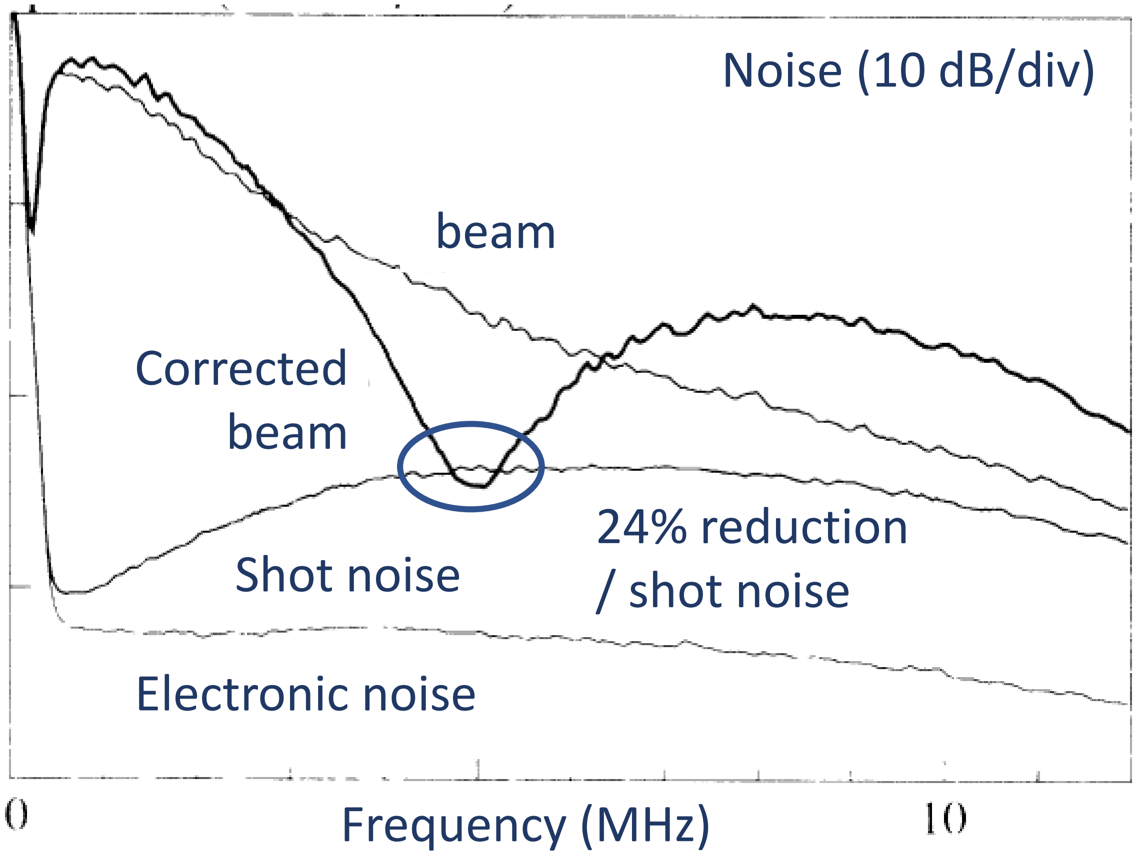


FIG. 1. Experimental setup, FR, Faraday rotator; AO, acousto-optic modulator; F, green filter; $\lambda/2$, half-wave plate; PBS, polarizing beamsplitter; SA, spectrum analyzer.

A. Heidmann *et al., Phys. Rev. Lett.* ***59**, 2555 (1987)*

Twin beams and intensity squeezing



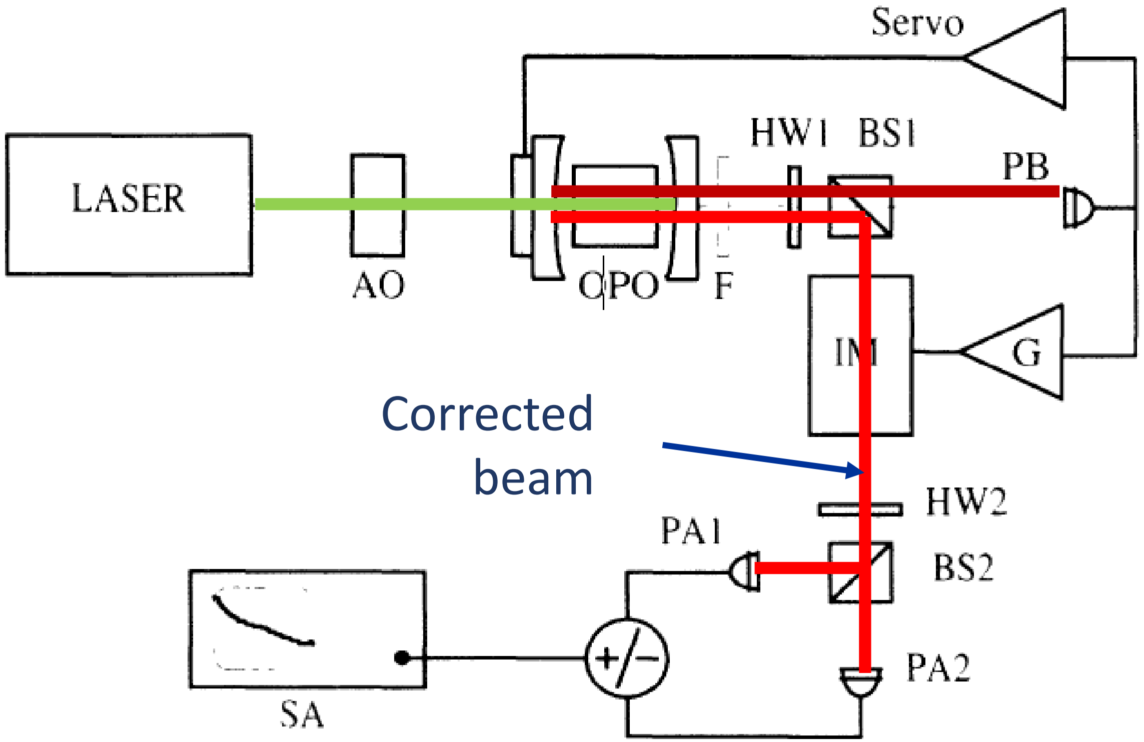
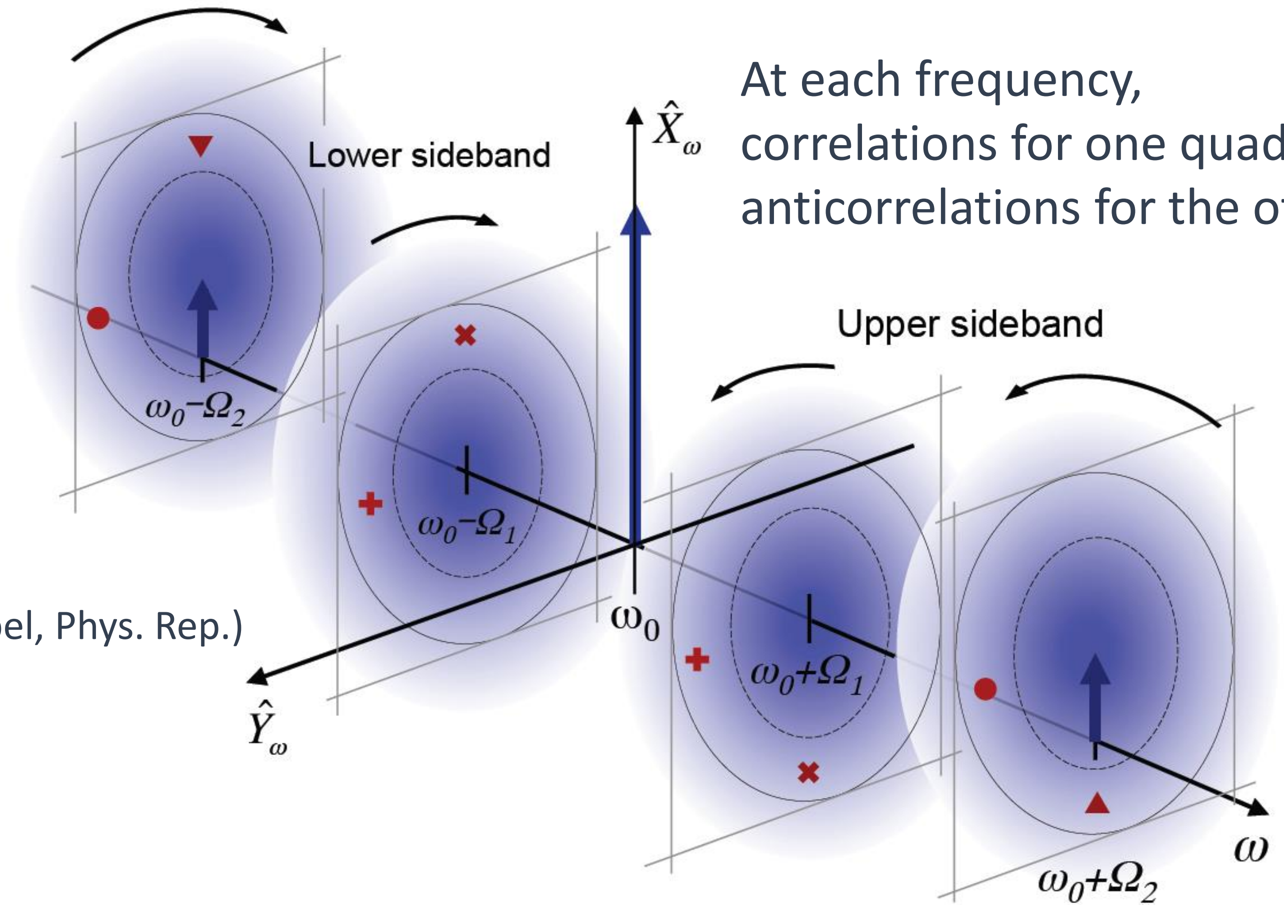


FIG. 1. Experimental setup. AO: acousto-optic modulator; F: dichroic filter; HW1,HW2: half-wave plates; BS1,BS2: polarizing beam splitters; IM: intensity modulator; PA1, PA2,PB: photodetectors; SA: spectrum analyzer.

J. Mertz *et al.*, *Phys. Rev. Lett.* ***64,*** *2897 (1990)*

Squeezing as correlations between upper and lower sidebands



At each frequency,
correlations for one quadrature,
anticorrelations for the other

(Schnabel, Phys. Rep.)

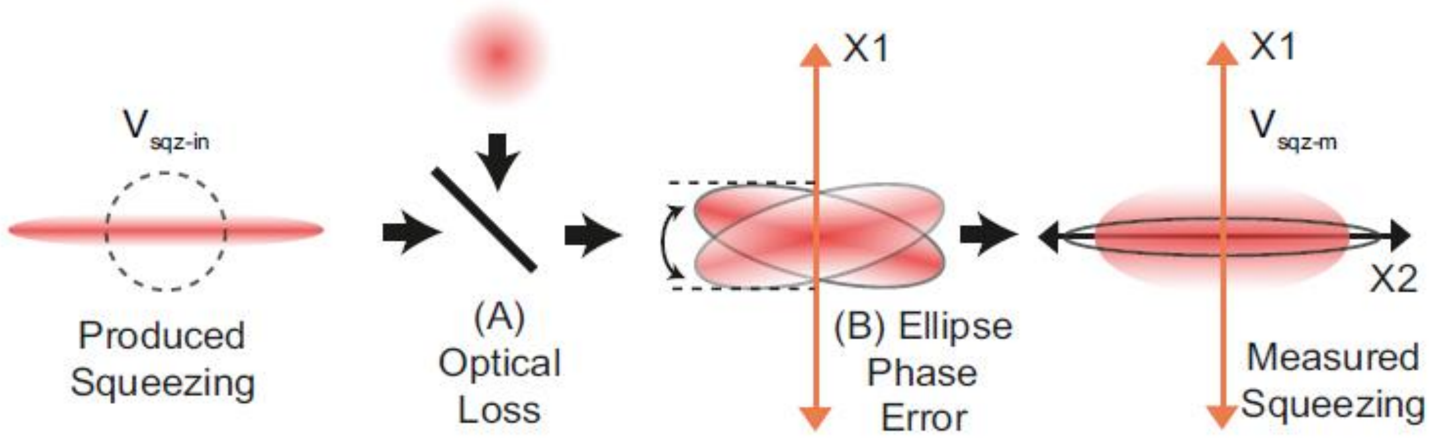
Anticorrelations along the mean field
(carrier at ω_0)
⇔ **Amplitude squeezing**

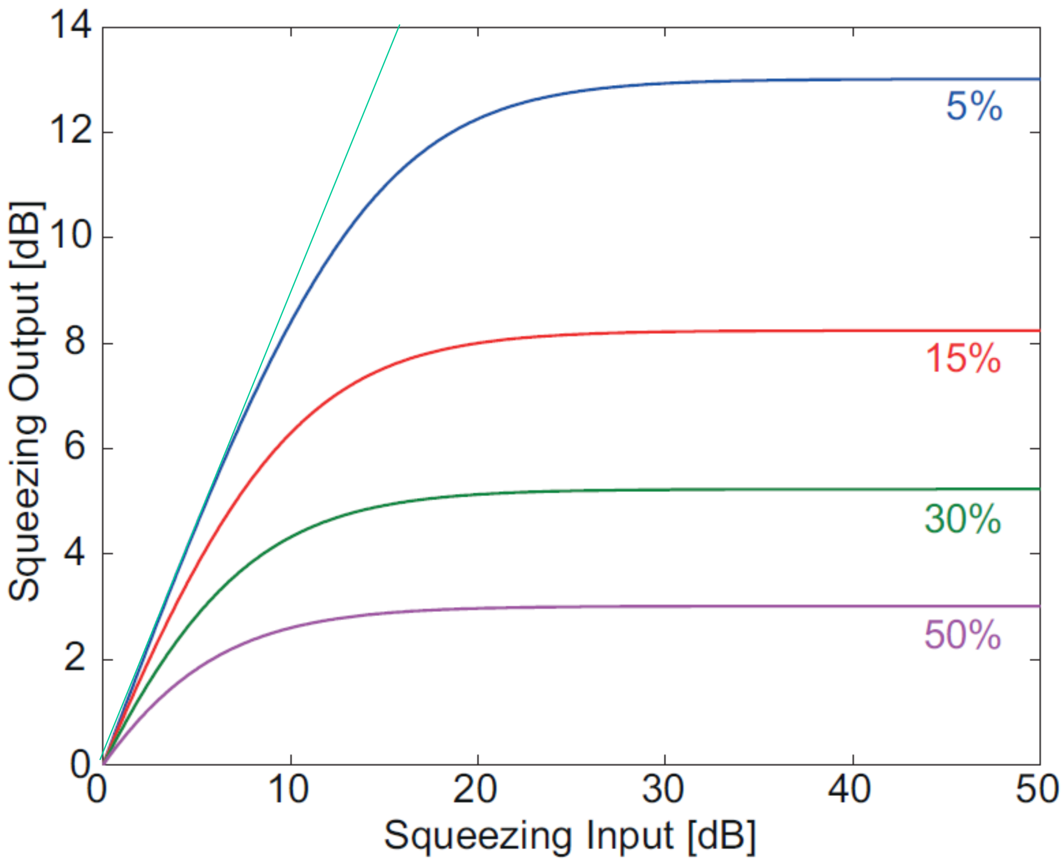
Here, (anti)correlations
do not depend on frequency
⇔ **frequency-independent** squeezing

Influences of losses on detected squeezing level

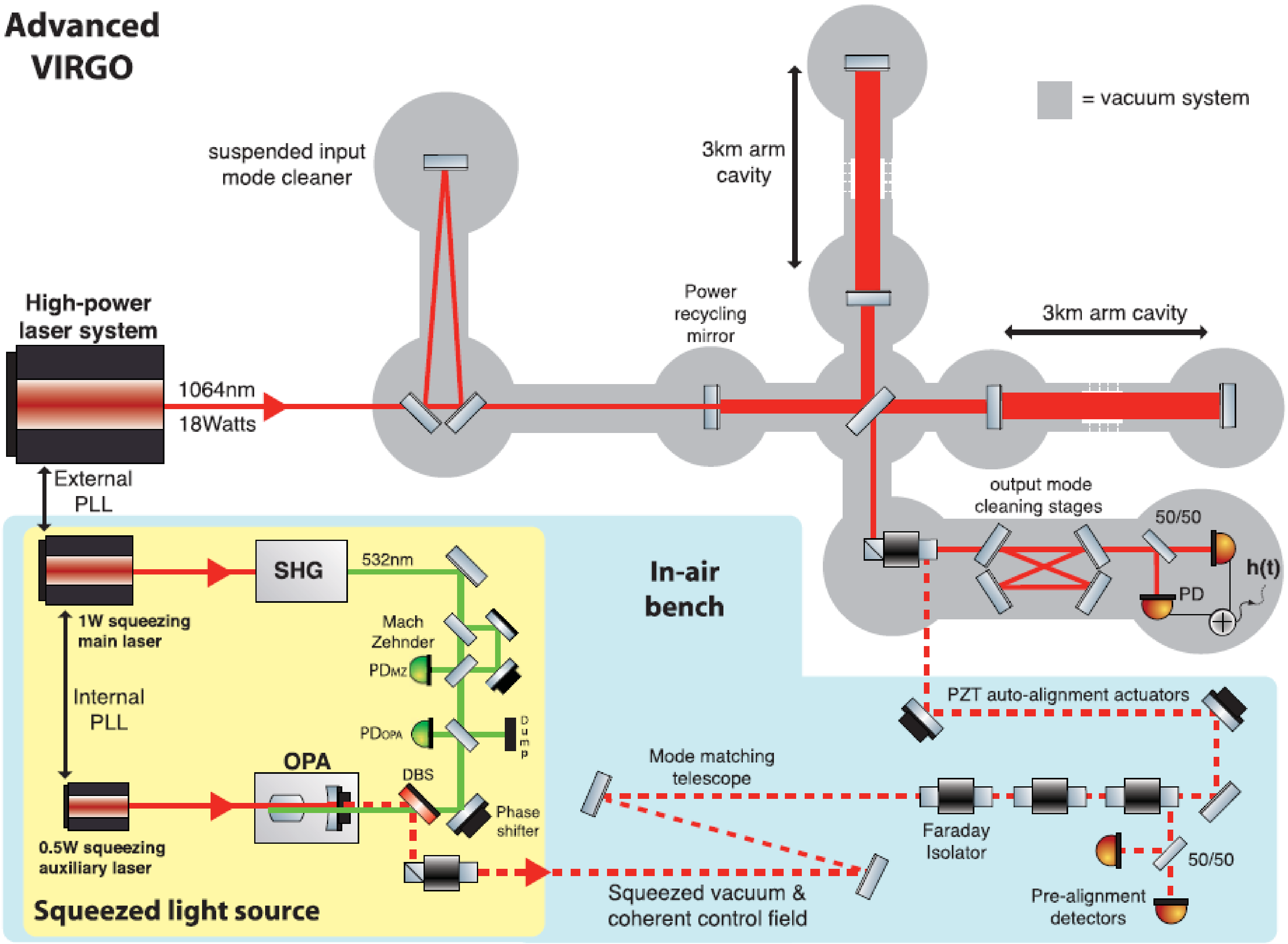
Optical losses are an important factor to take into account for gravitational-wave interferometers: detection efficiency, insertion losses, Faraday, mode-matching....

The higher the squeezing level, the more important it is to detect the good quadrature



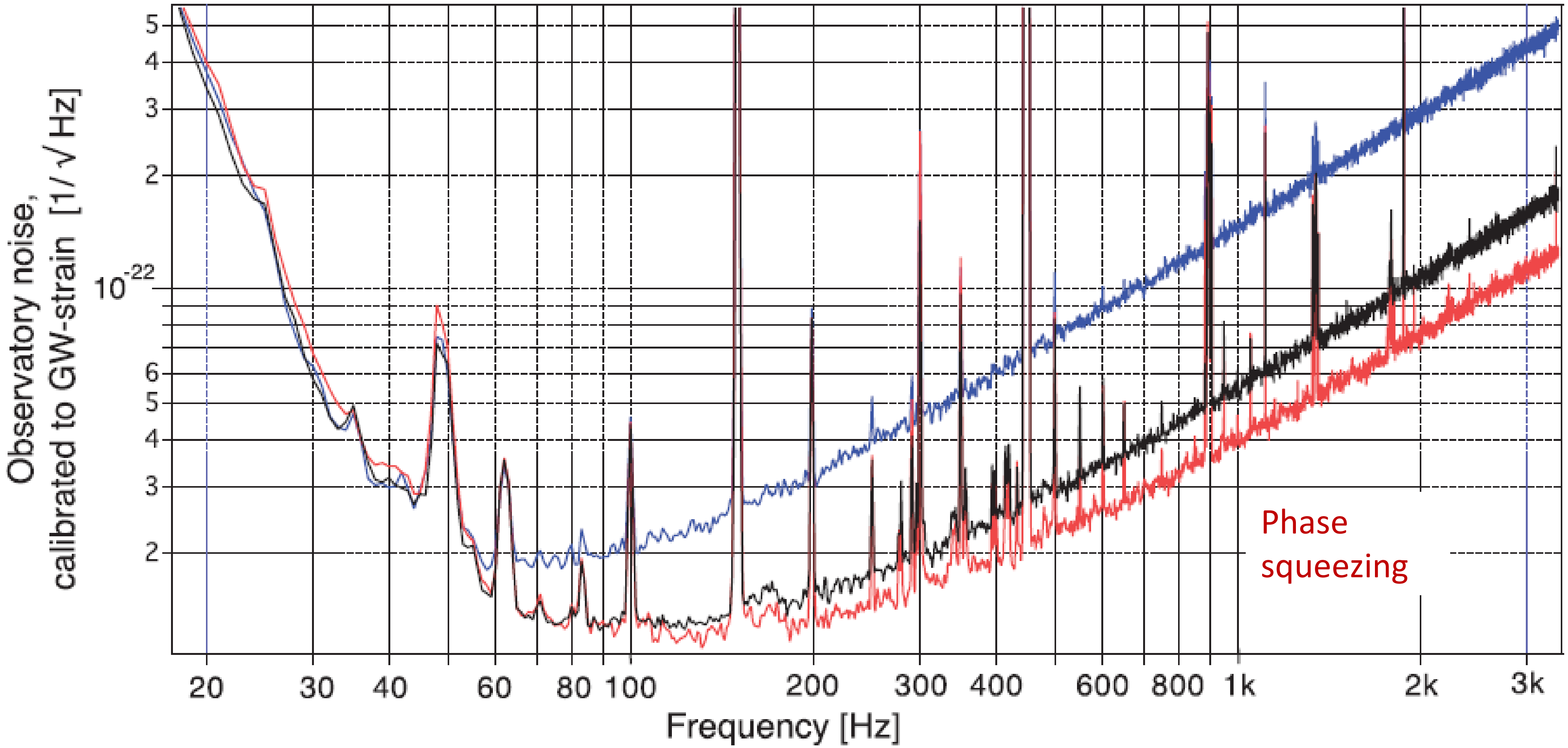


Frequency-independent squeezing in Advanced Virgo



Phys. Rev. Lett. **123**, 231108 (2019)

Frequency-independent squeezing in Advanced Virgo

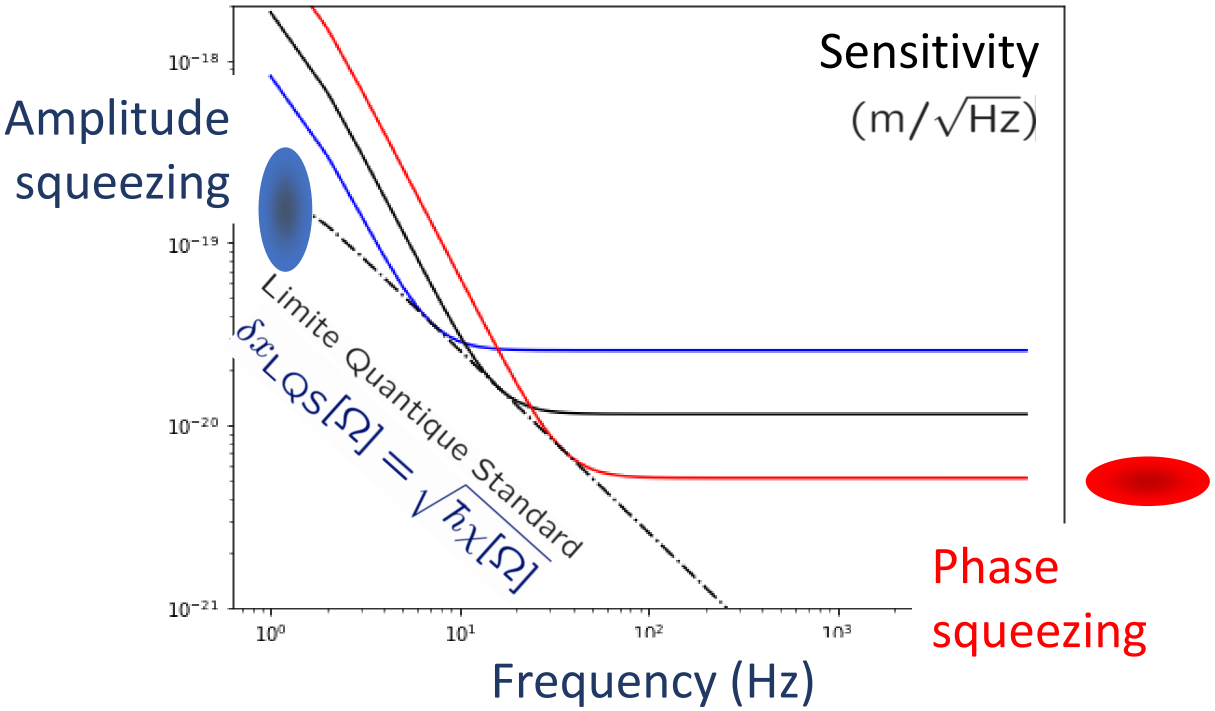


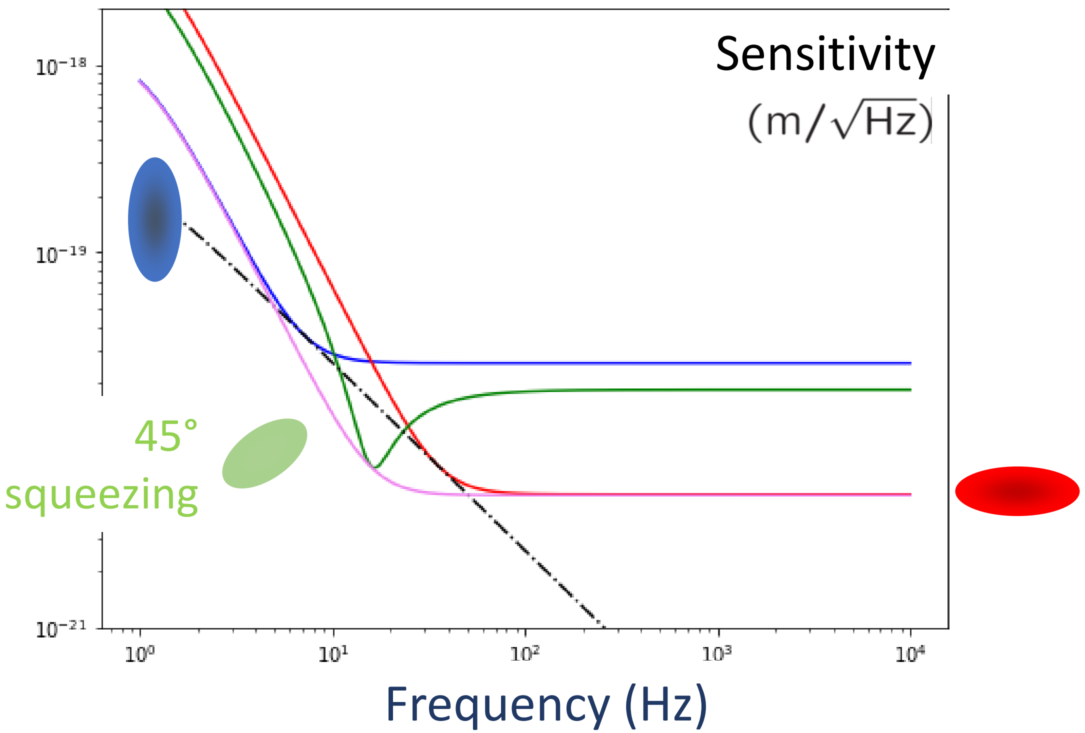
Phase squeezing increases the sensitivity by **3 dB** at **high frequency**

Sensitivity increase limited by optical losses (between 30 and 40%)

Phys. Rev. Lett. **123**, 231108 (2019)

Standard Quantum Limit and squeezing

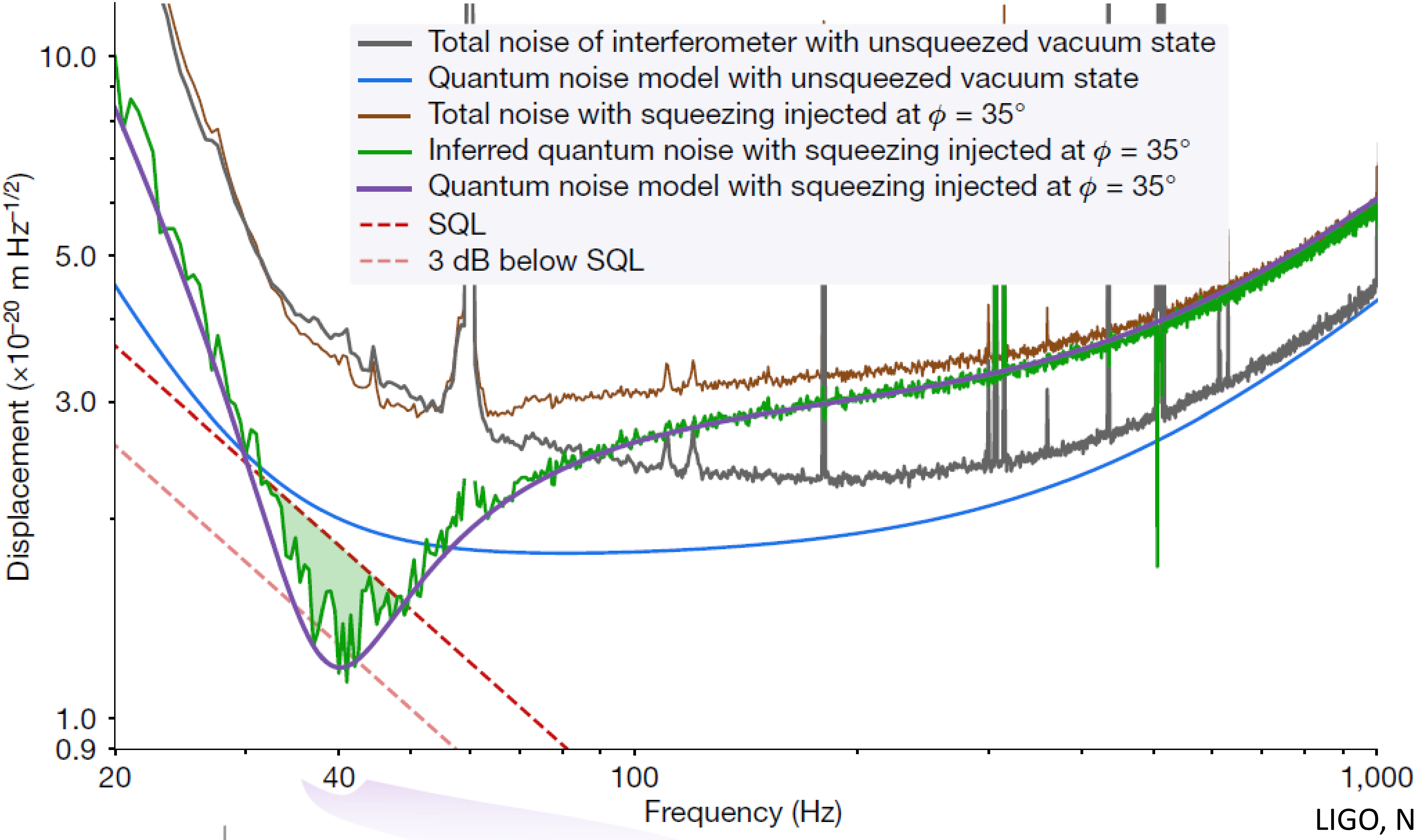




To go beyond the SQL, one needs:

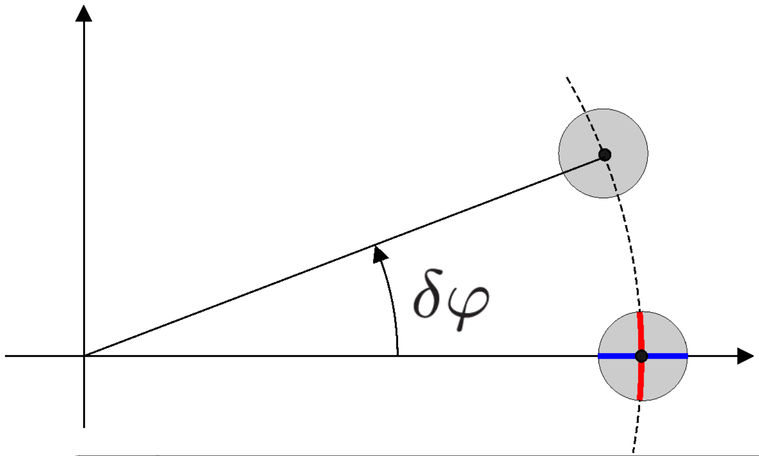
- phase – amplitude correlations
- (ideally on a frequency-dependent quadrature)

Beyond the Standard Quantum Limit

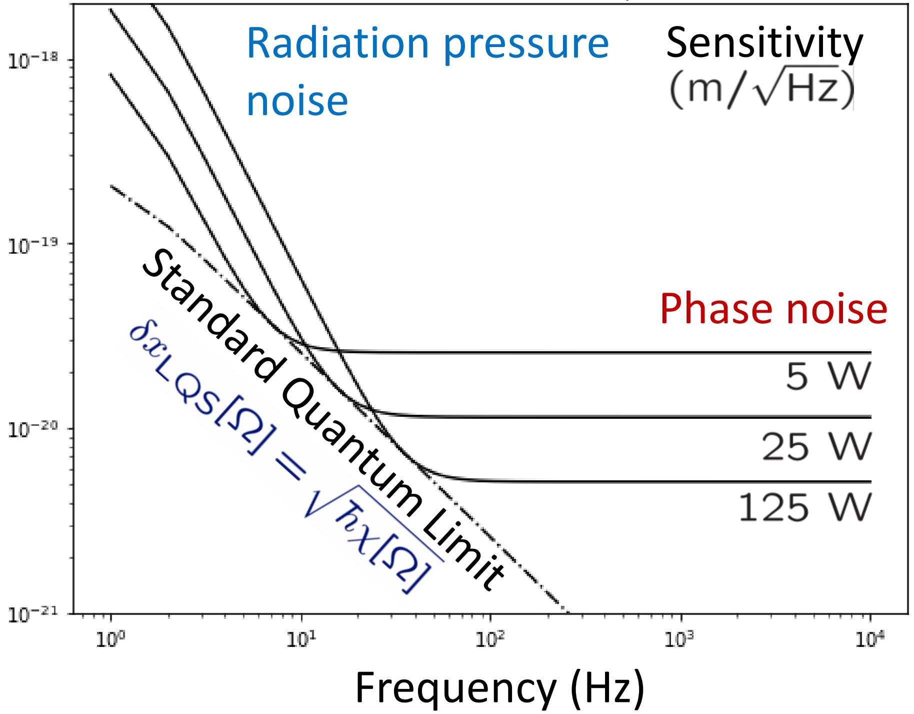


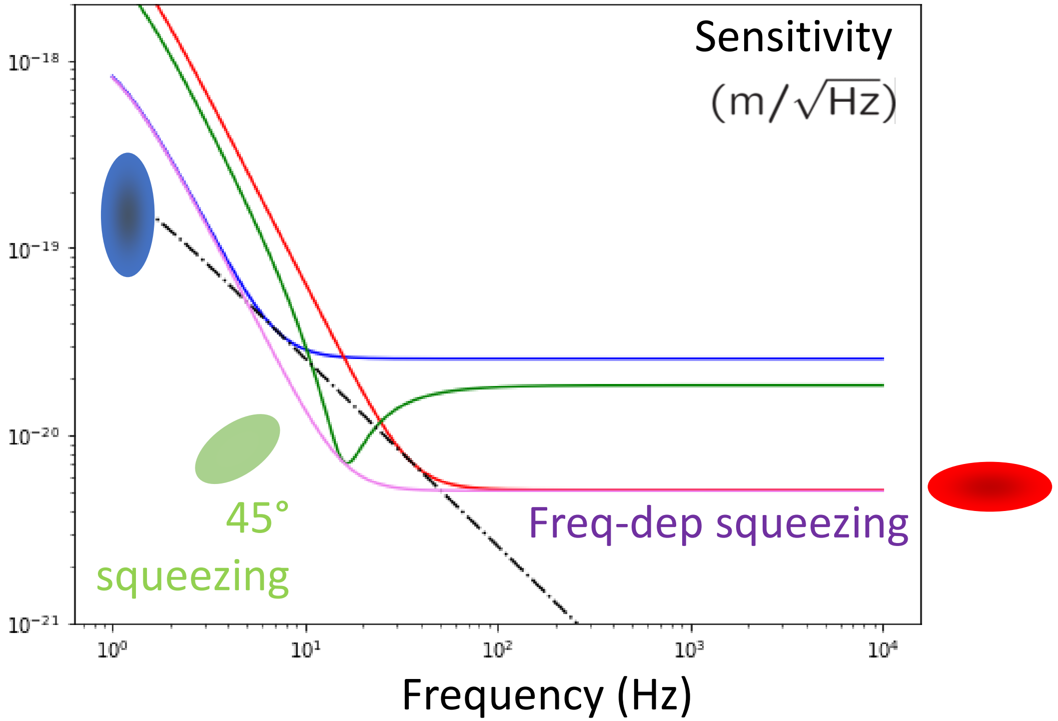
LIGO, Nature 2020

Beyond the SQL with frequency-dependent squeezing

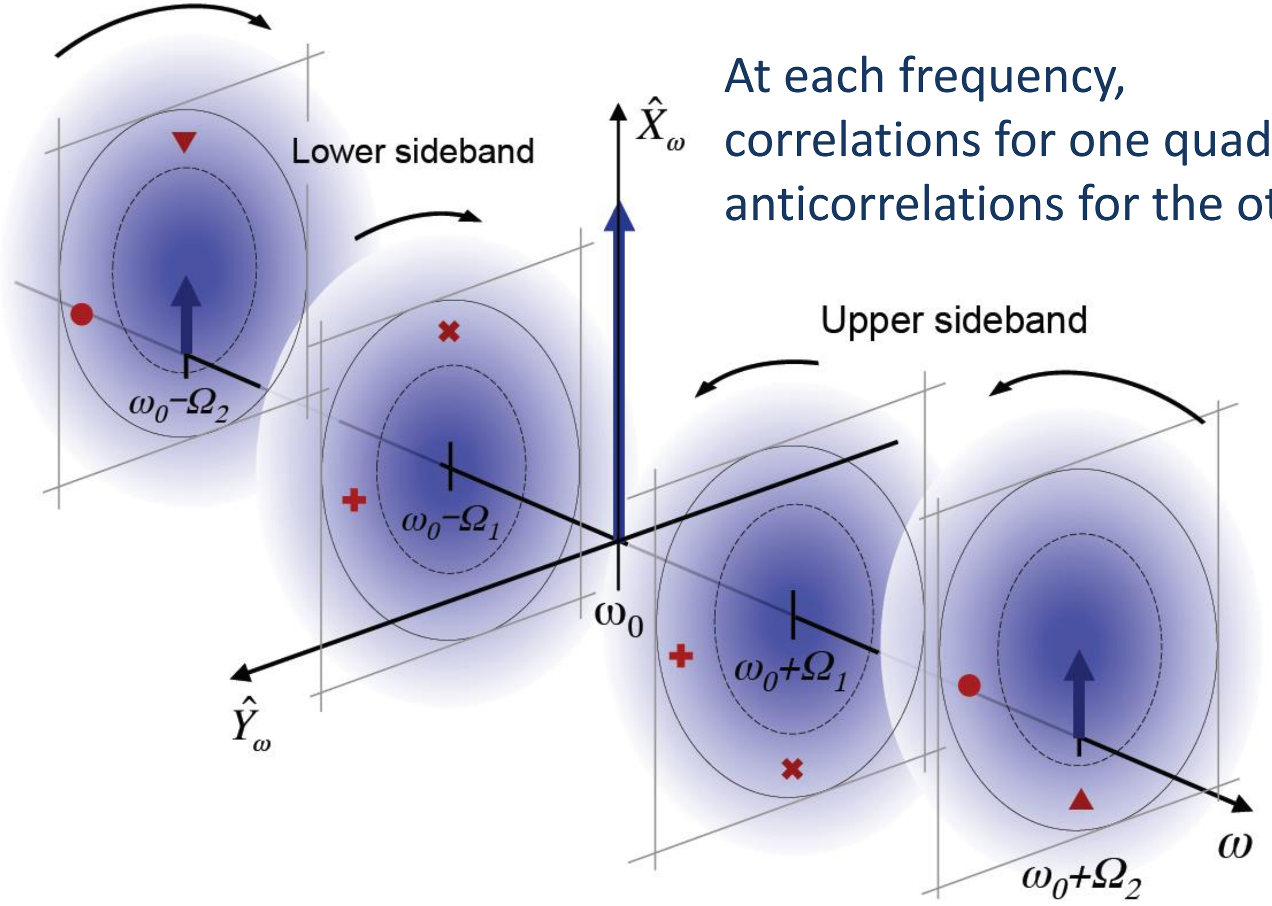


$$\delta\varphi_{\text{out}} = \delta\varphi_{\text{in}} + \frac{8\mathcal{F}}{\lambda}(\delta x + \delta x_{\text{rad}})$$





Generating frequency-dependent squeezing



At each frequency,
correlations for one quadrature,
anticorrelations for the other

Anticorrelations along the mean field
(carrier at ω_0)
⇔ Amplitude squeezing

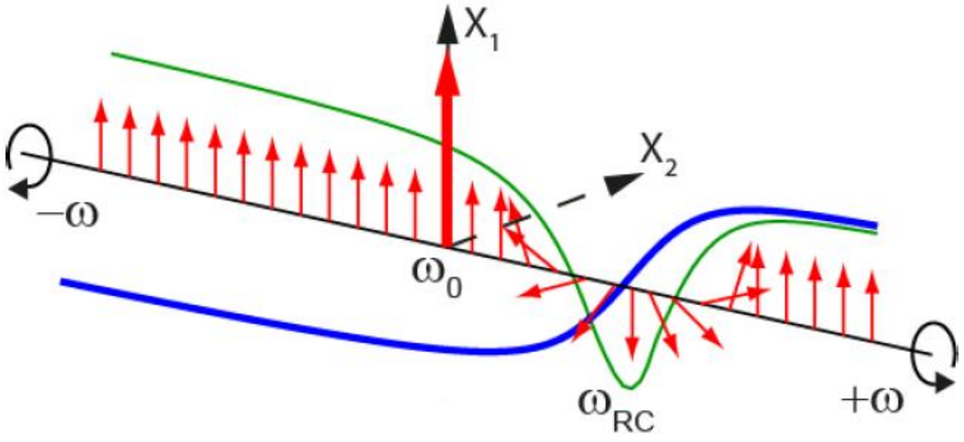
Here, (anti)correlations
do not depend on frequency
⇔ frequency-independent squeezing

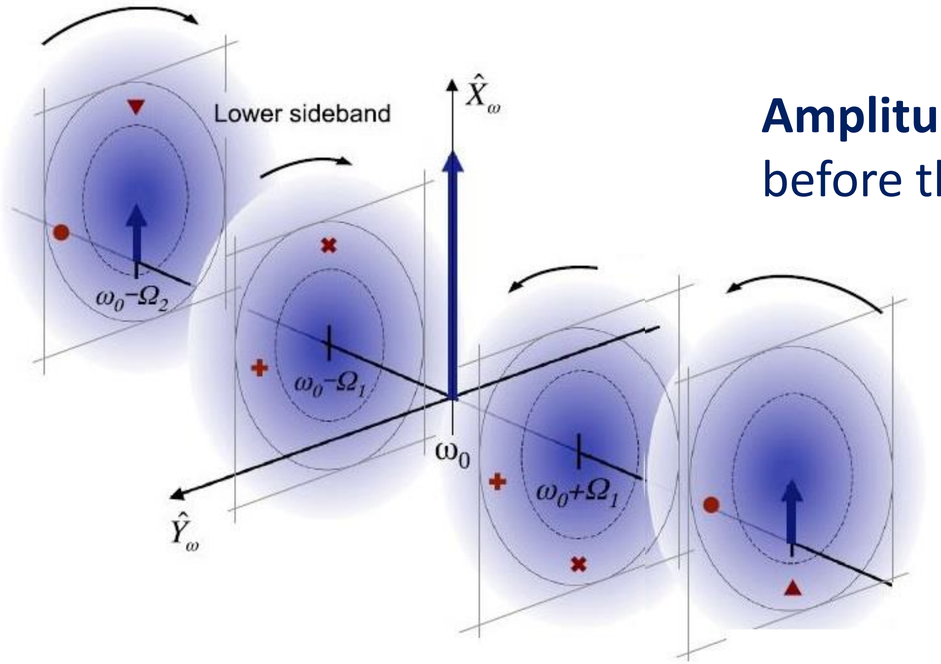
Schnabel, Phys. Rep.

Quadrature flipping by cavity reflection

Simple idea to generate frequency-dependent squeezing:

- Start with (efficient) FIS generated by an OPO
- Use a **single-ended cavity** as an optical filter
  to create the required frequency dependence



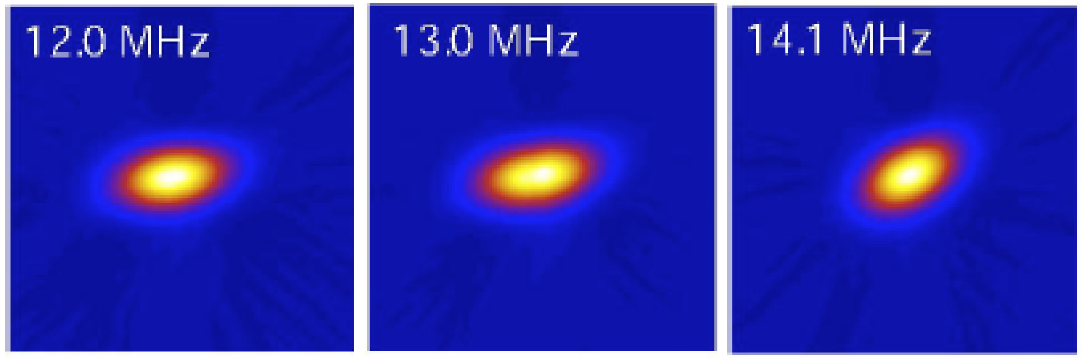


Amplitude squeezing
before the filter

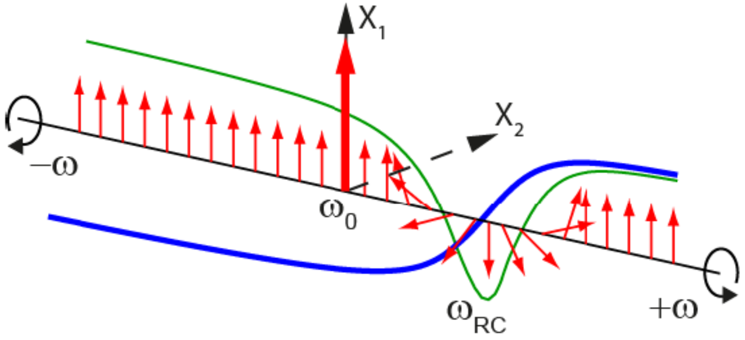
Phase squeezing at Ω_2
after the filter

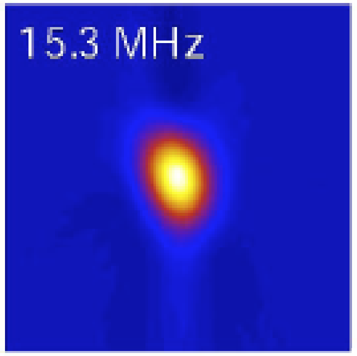
Quadrature flipping by cavity reflection

Phase squeezing

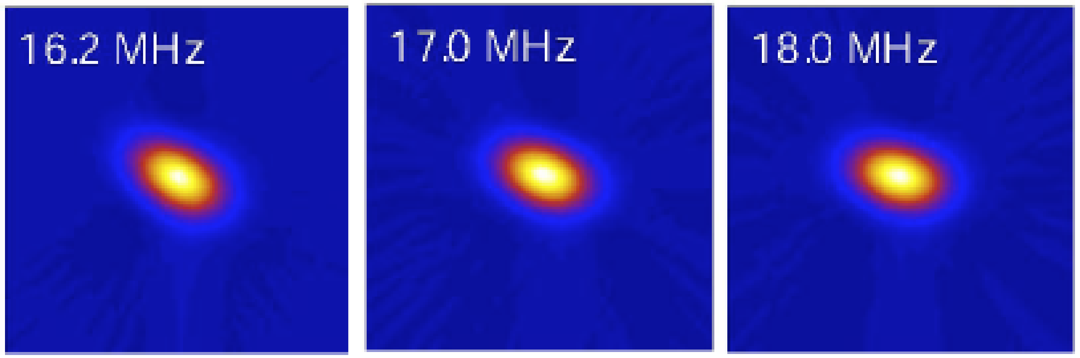


45° squeezing





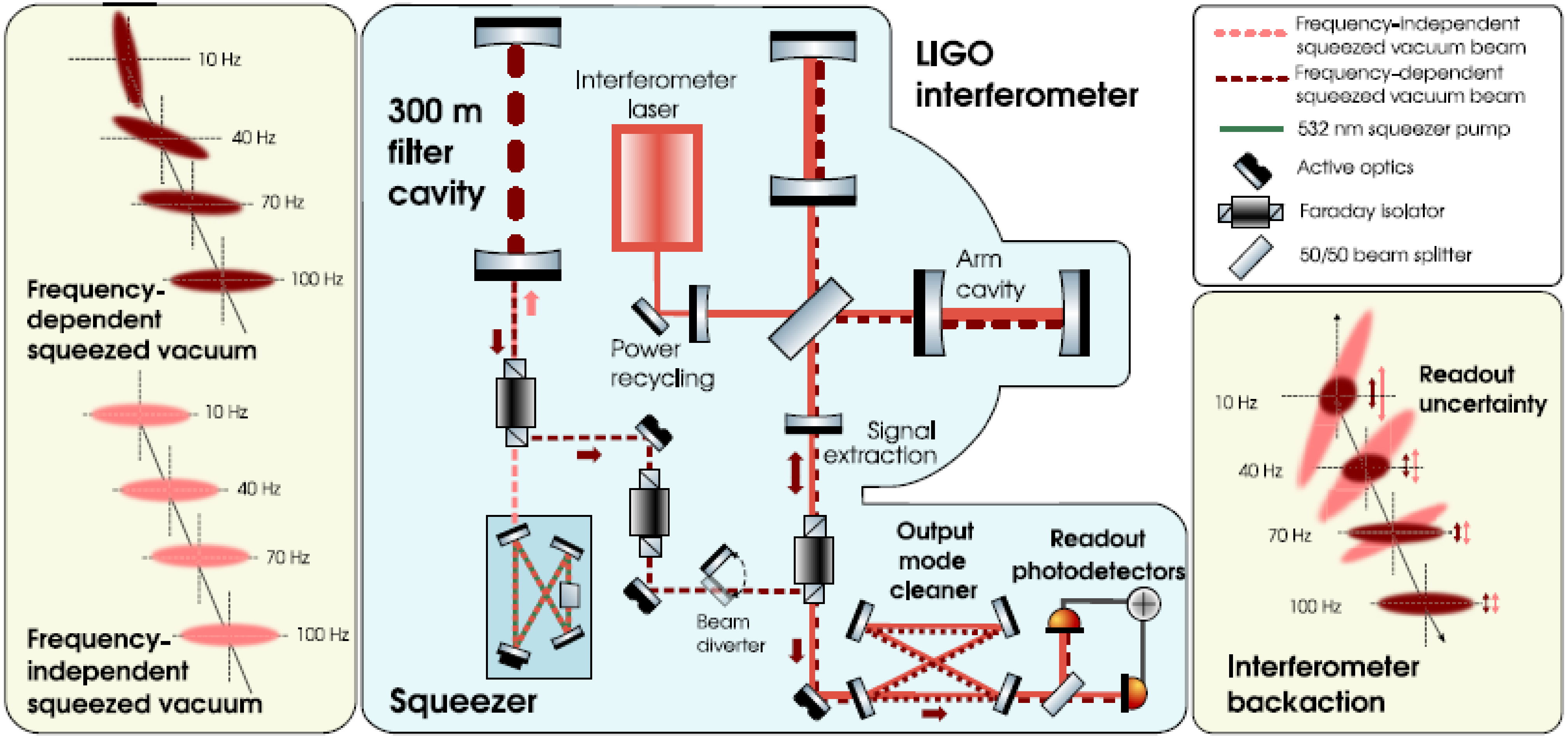
Intensity squeezing



Phase squeezing

Chelkowski,… Schnabel, Phys. Rev. A **71**, 013806 (2005)

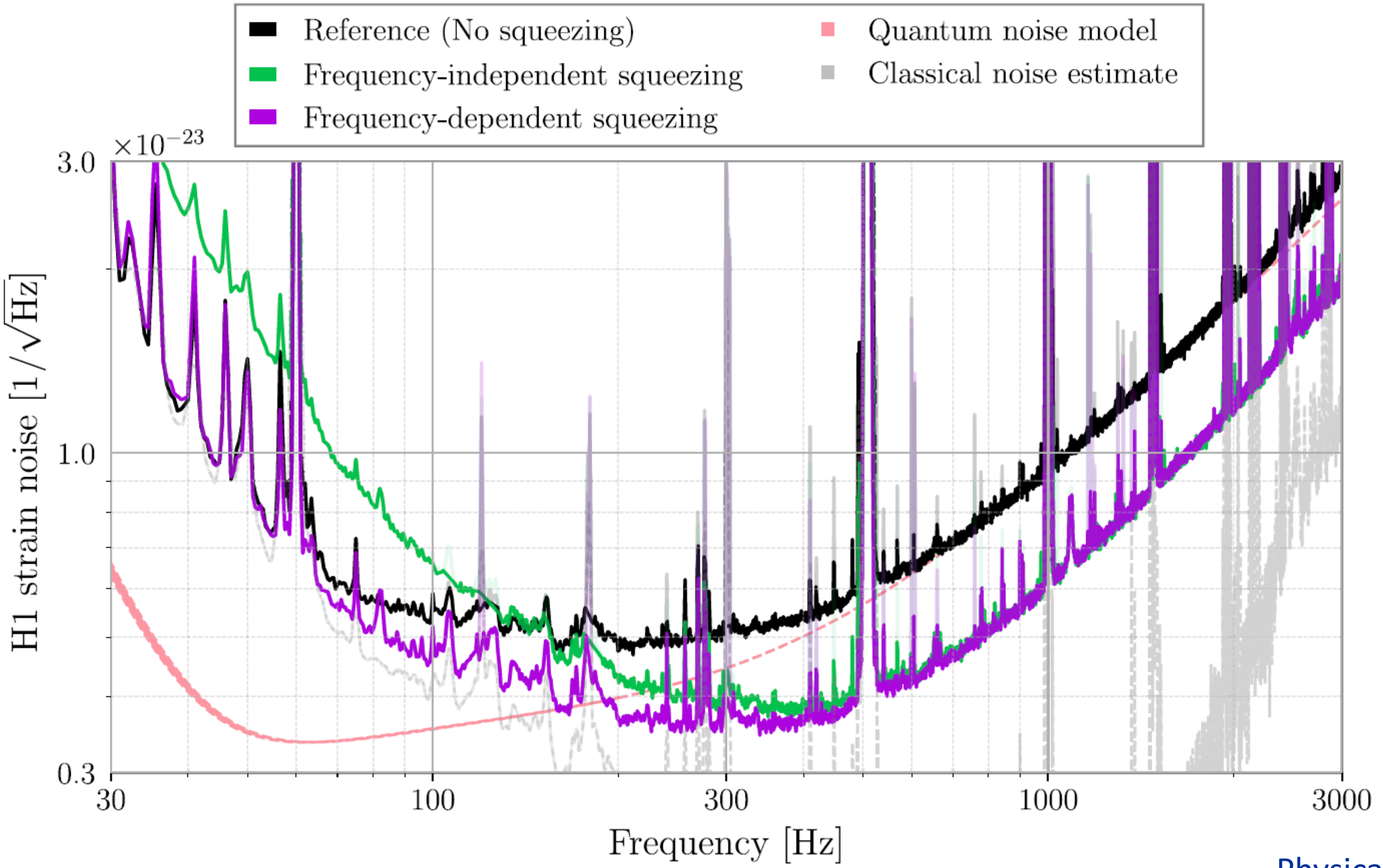
Frequency-dependent squeezing for Advanced LIGO



Corner frequency below 100 Hz
⇔ light spends more than 10ms
(⇔ travels more than 3000 km)

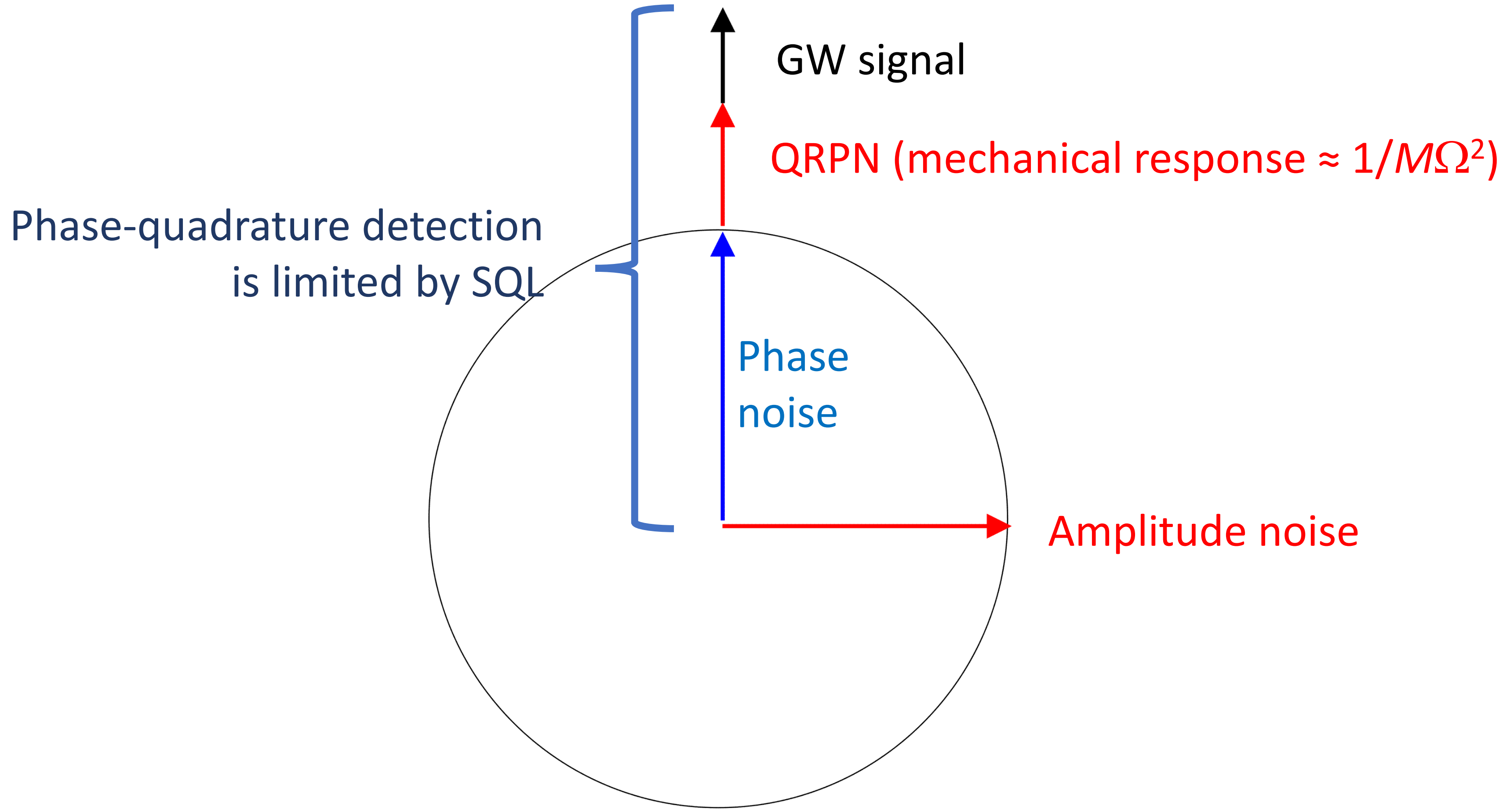
Physical Review X **13**, 041021 (2023)

Advanced LIGO sensitivity for O4



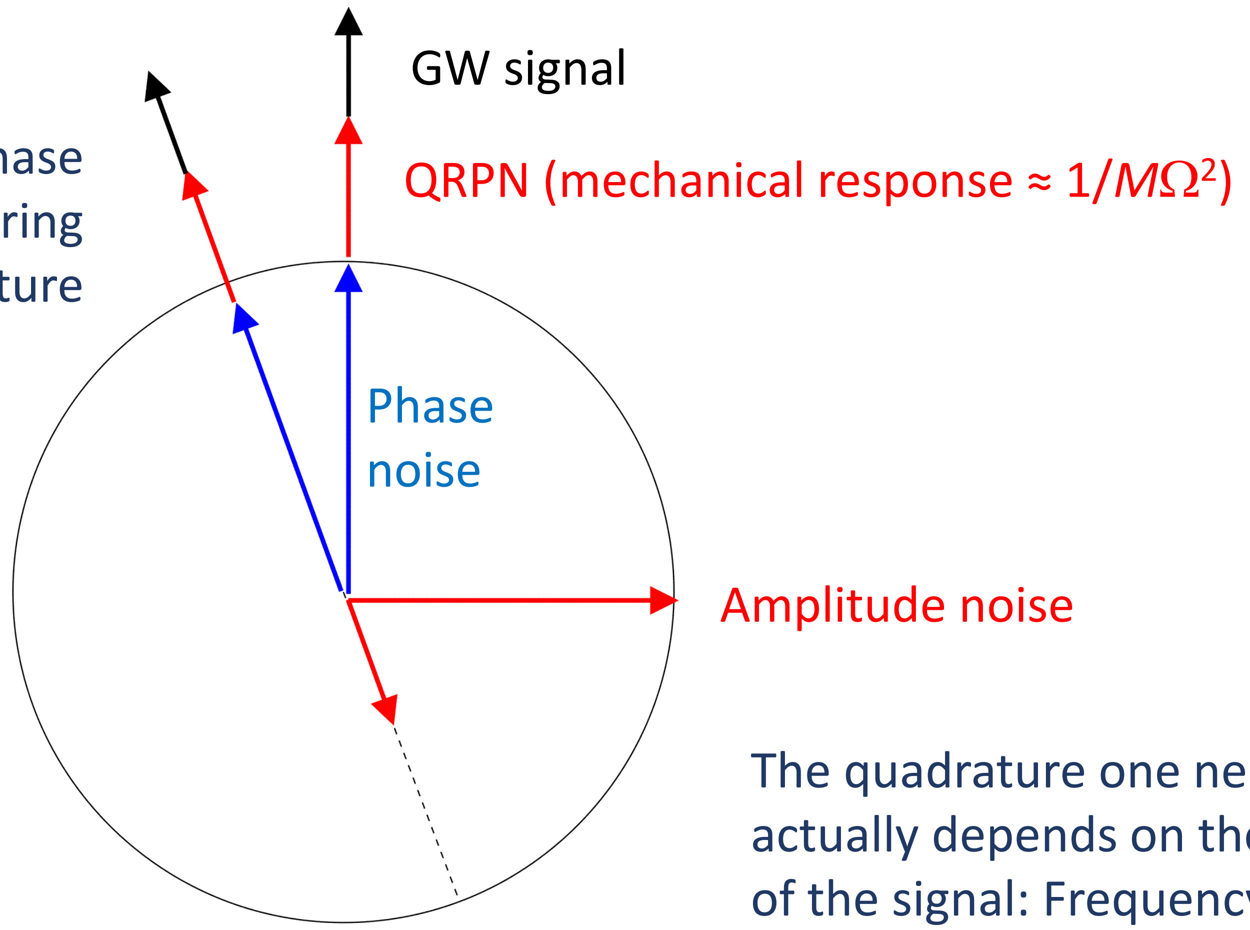
Physical Review X **13**, 041021 (2023)

Variational measurement



Variational measurement

One can take advantage of intensity-phase correlations to cancel **QRPN** by measuring an intermediate quadrature



The quadrature one needs to measure actually depends on the frequency of the signal: Frequency-dependent homodyne detection ?

EPR beams

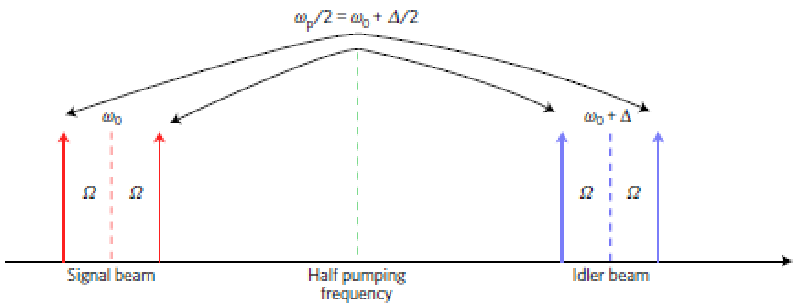
Non-degenerate OPO to entangle two beams:

- One to inject into the GWI
- One to measure (correlated) QN

$$2\omega_0+\Delta = \omega_0 + \omega_0+\Delta$$

to GWI

Non-resonant in GWI



Pros:

- Additional long cavities not needed

Cons:

- No experimental demonstration (yet)
- 3 dB less gain w.r.t. current techniques
- New ITF readout scheme needed (Local Oscillators)