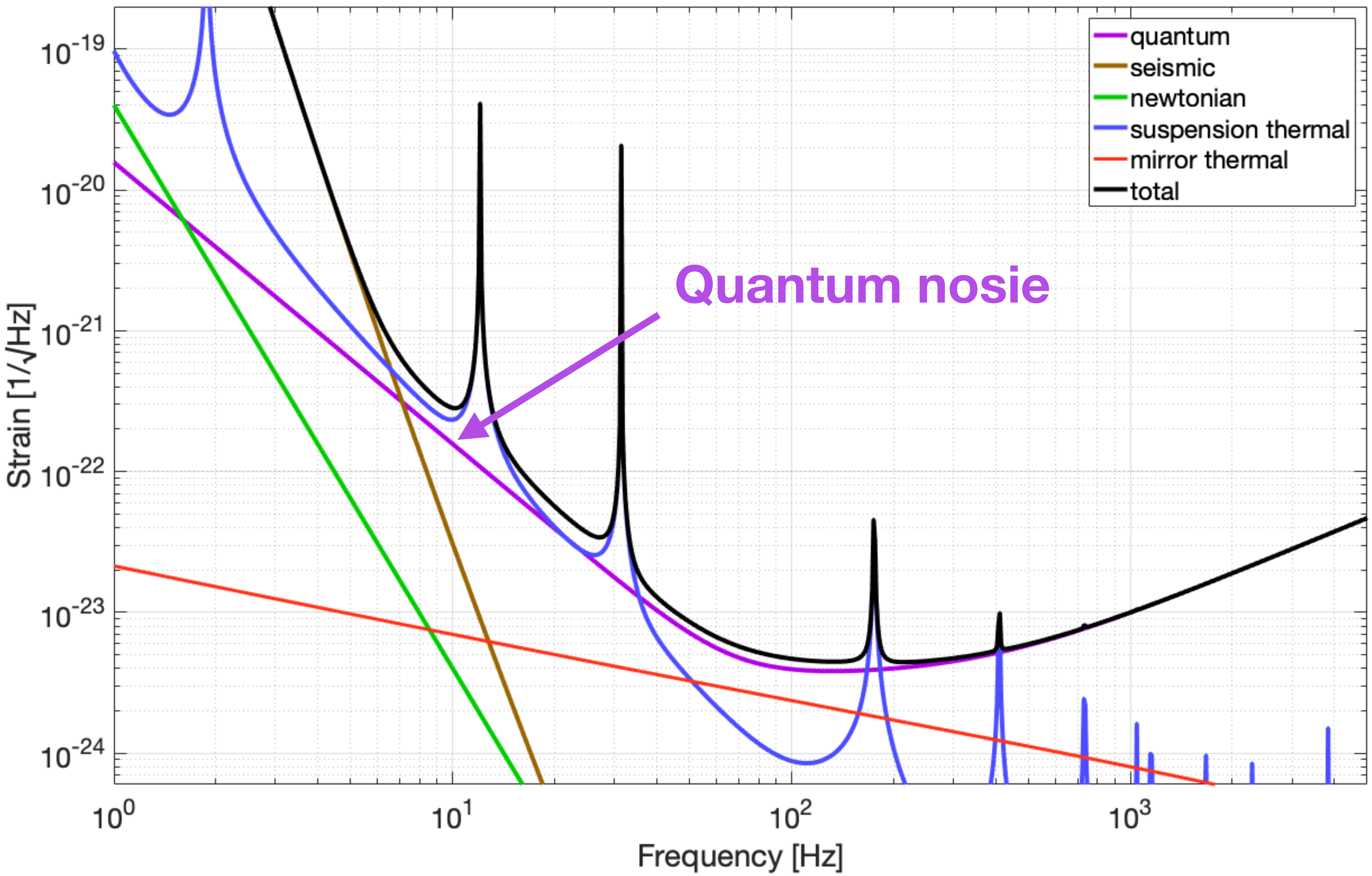
PCCP LECTURES COURSE

The physics of KAGRA Gravitational Wave detector

Reducing the quantum noise: squeezed vacuum techniques

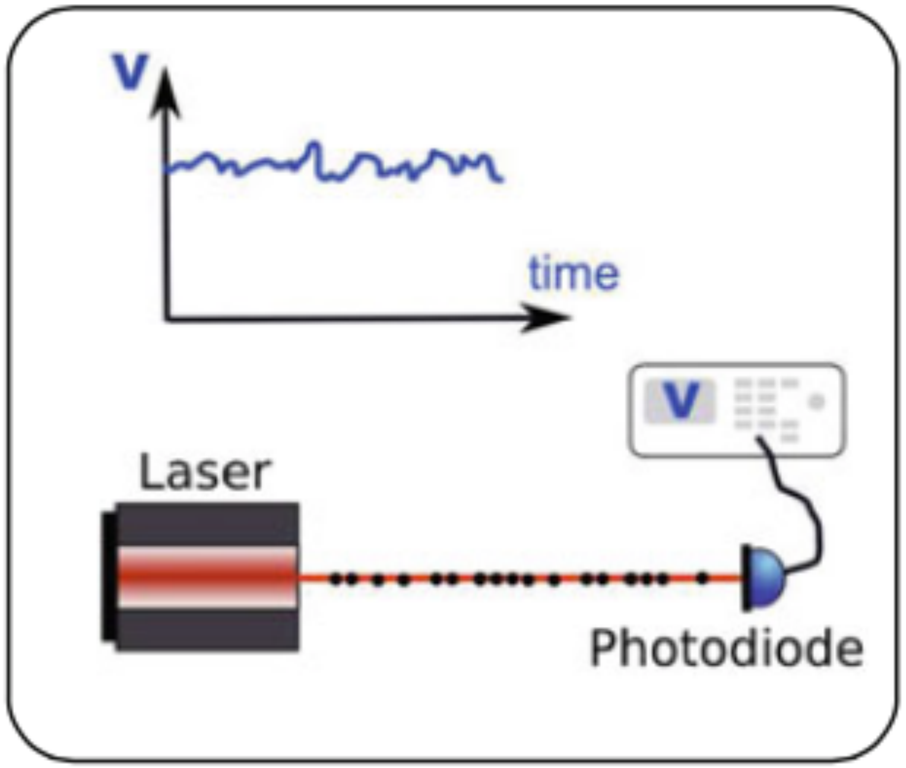
Eleonora Capocasa

KAGRA: expected sensitivity



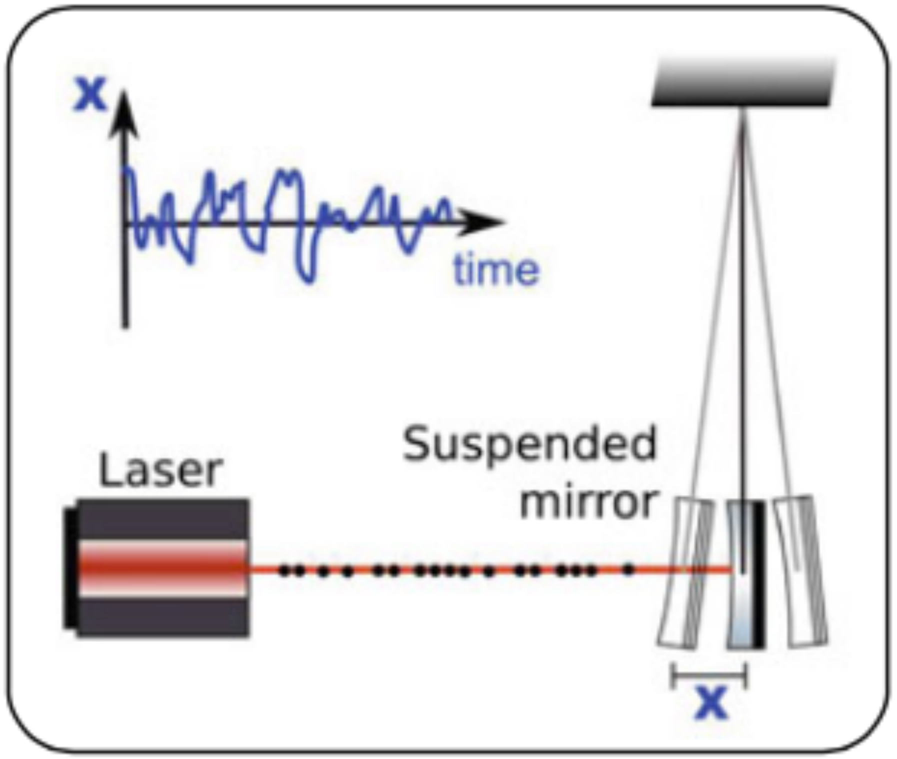
Quantum noise in a semiclassical picture

Shot noise



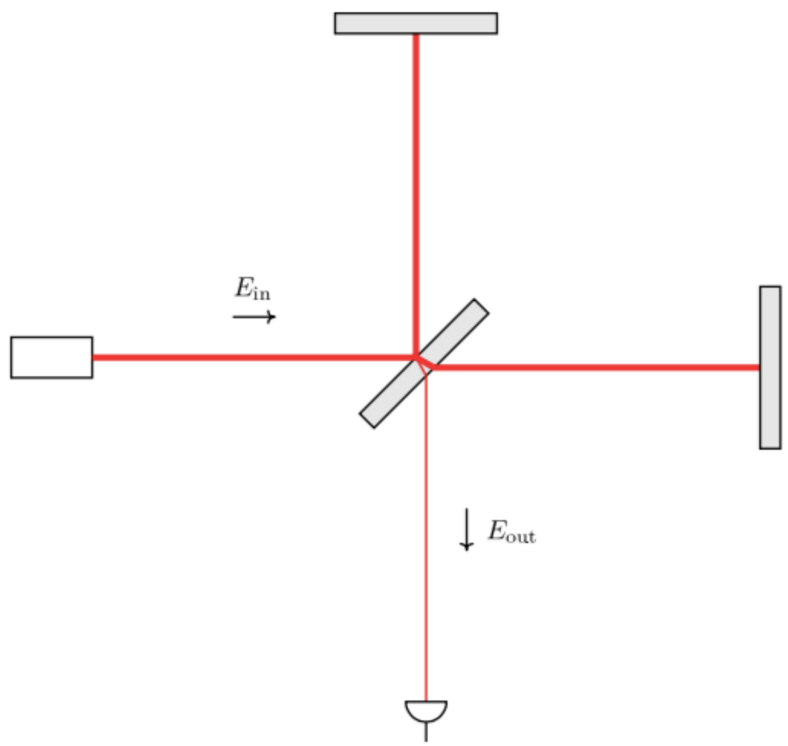
- Poissonian statistics on the photon arrival time

Radiation pressure noise



- Fluctuation in the momentum transferred to the mirror

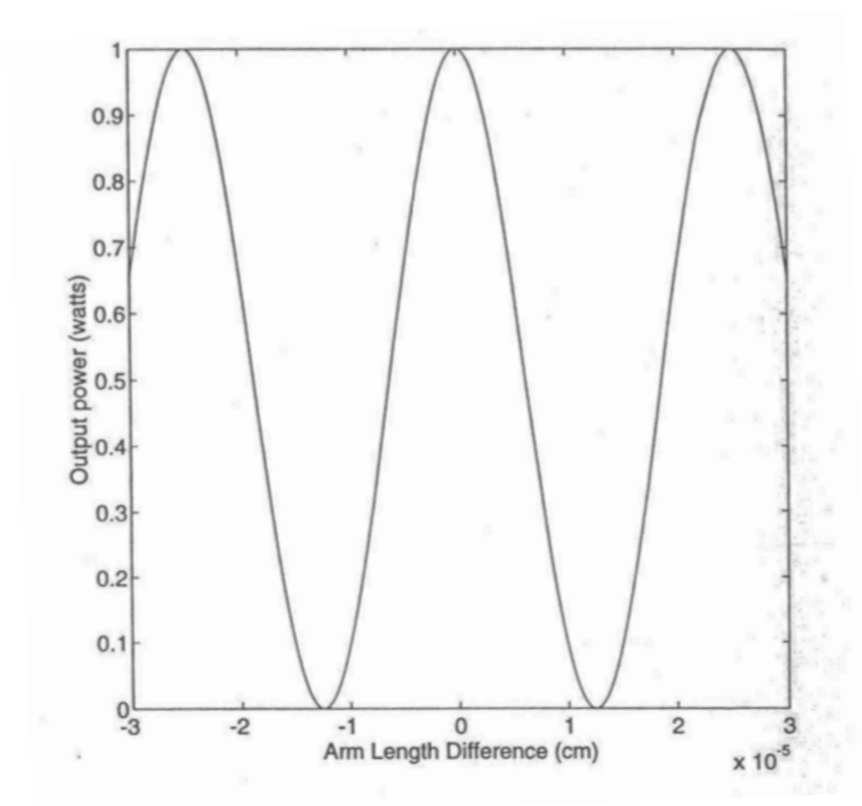
Shot noise derivation



$$P_{\rm out} = \frac{P_{\rm in}}{4}(R_1 + R_2)(1 + C\cos\phi)$$

Contrast $C = \dfrac{2 r_1 r_2}{R_1 + R_2}$

$$P_{\rm out} = \frac{P_{\rm in}}{2}[1 + C\cos(\phi_{\rm sta}) - C\sin(\phi_{\rm sta})\phi_{\rm gw}]$$



$$\delta P_{\rm gw} = \frac{P_{\rm in}}{2} C \sin(\phi_{\rm sta})\phi_{\rm gw}$$

P. Saulson "Fundamentals Of Interferometric Gravitational Wave Detectors "

What is the minimum phase change we can measure?

- Arrival time of photon: poissonian process

$$P(N) = \frac{\bar{N}^N e^{-\bar{N}}}{N!} \qquad \sigma = \sqrt{\bar{N}}$$

- Average number of impinging photons

$$\bar{N} = \frac{\eta P_{\text{out}} \delta T}{\hbar\omega} \qquad \delta P_{\text{shot}} = \sqrt{\bar{N}} \frac{\hbar\omega}{\eta \delta T}$$

- Ratio between the power change due to GW and shot noise

$$\frac{\delta P_{\text{gw}}}{\delta P_{\text{shot}}} = \sqrt{\frac{\eta P_{\text{in}} \delta T}{\hbar\omega}} \frac{C \sin\phi}{\sqrt{(1 + C\cos\phi)}} \phi_{\text{gw}}$$

- It is maximized close to the dark fringe

What is the minimum phase change we can measure?

- Minimum detectable phase change

$$\delta P_{\mathrm{gw}} = \delta P_{\mathrm{shot}}$$

$$\downarrow$$

$$\delta\phi_{\mathrm{min}} = \sqrt{\frac{\hbar\omega}{\eta P_{\mathrm{in}} \delta T}}$$

- Shot noise amplitude spectral density

$$\boxed{h_{\mathrm{shot}} = \frac{\lambda}{2\pi L}\sqrt{\frac{\hbar\omega}{\eta P_{\mathrm{in}}}} \simeq 5 \cdot 10^{-21} \left[\frac{1}{\sqrt{\mathrm{Hz}}}\right]}$$

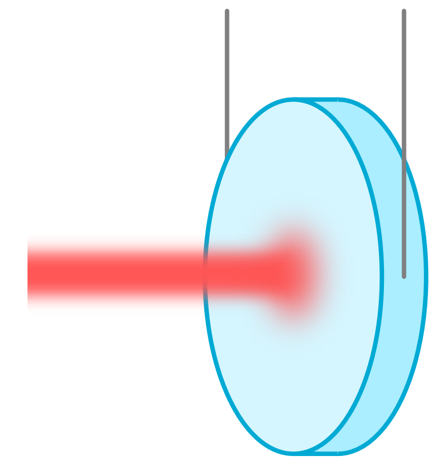
$$\lambda = 1064\,\mathrm{nm},\ L = 3\,\mathrm{km},\ P_{\mathrm{in}} = 20\,\mathrm{W}$$

Radiation pressure noise

- Variable force induced by power fluctuation acting on the mirrors

$$\delta F = \frac{2\delta P}{c}$$

$$F(f) = \sqrt{\frac{8\pi\hbar P}{c\lambda}}$$



- Corresponding displacement spectrum of each test mass

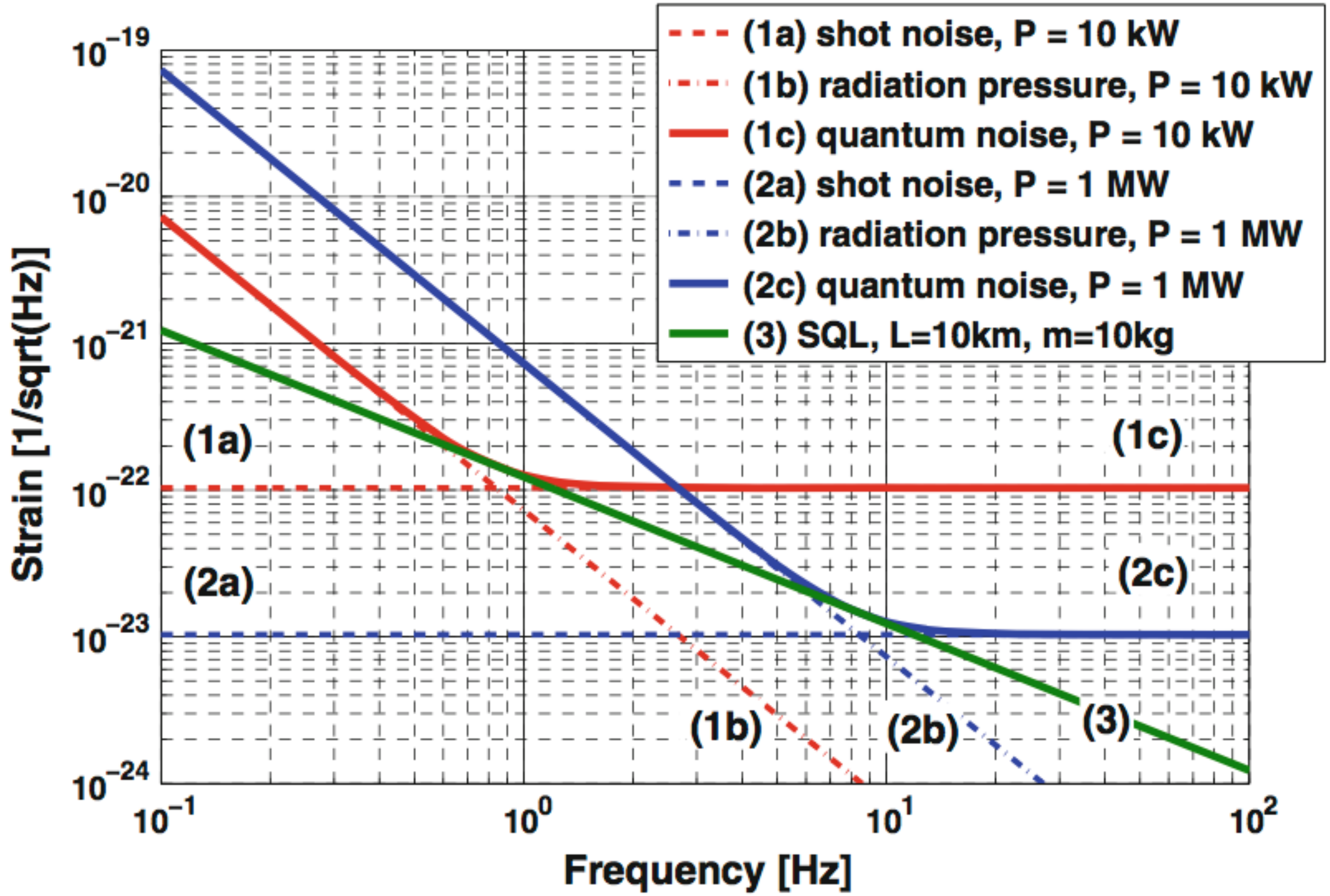
$$x(f) = \frac{F(f)}{M(2\pi f)^2} = \frac{1}{M(2\pi f)^2}\sqrt{\frac{2\pi\hbar P}{c\lambda}}$$

$$h_{\mathrm{rp}(f)} = \frac{2}{L}x(f)$$

- Total quantum noise

$$h_{\mathrm{qn}} = \sqrt{h_{\mathrm{shot}}^2 + h_{\mathrm{rp}}^2}$$

Quantum noise in a semiclassical picture



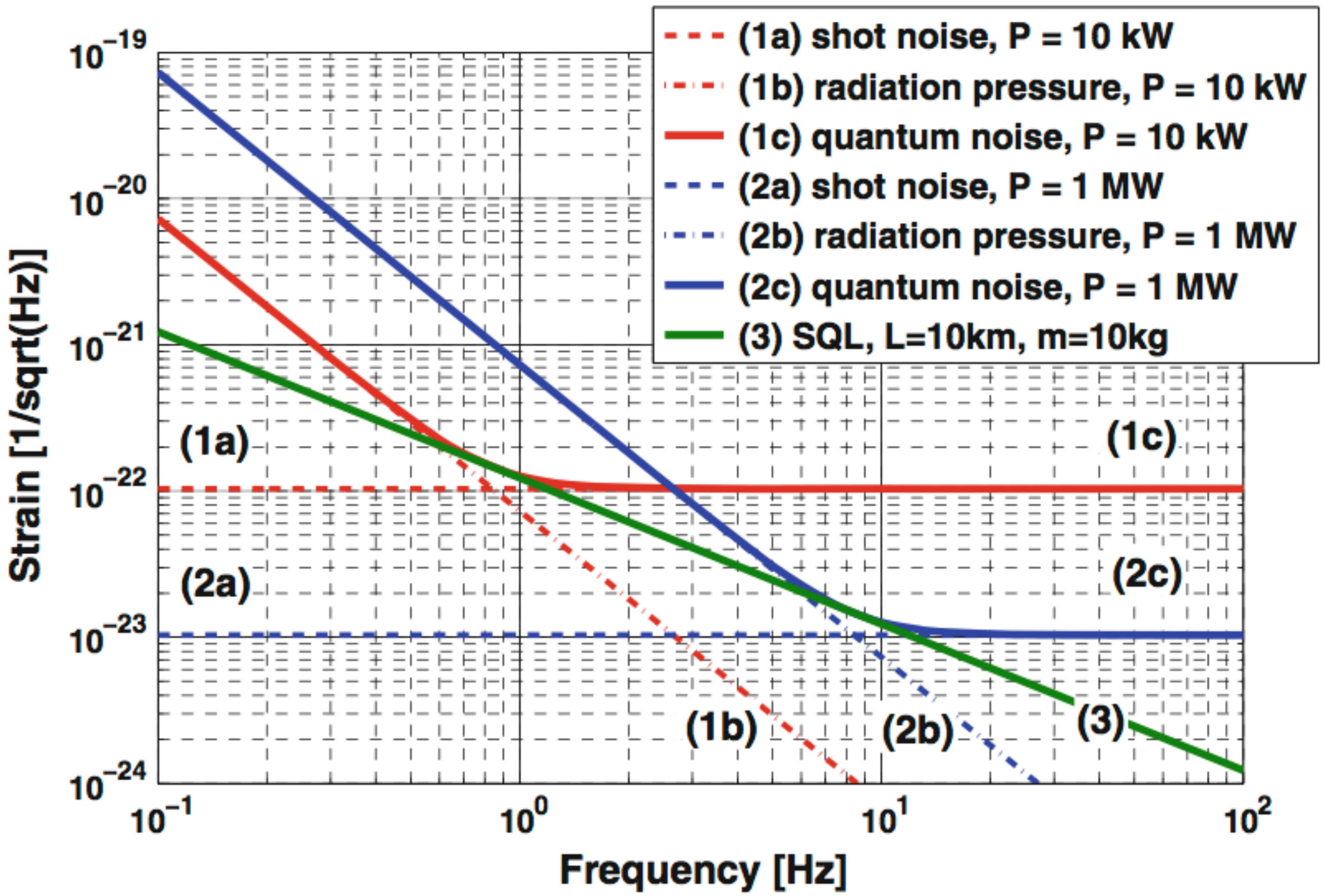
Radiation pressure noise

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

Shot noise

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

The standard quantum limit (SQL)



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

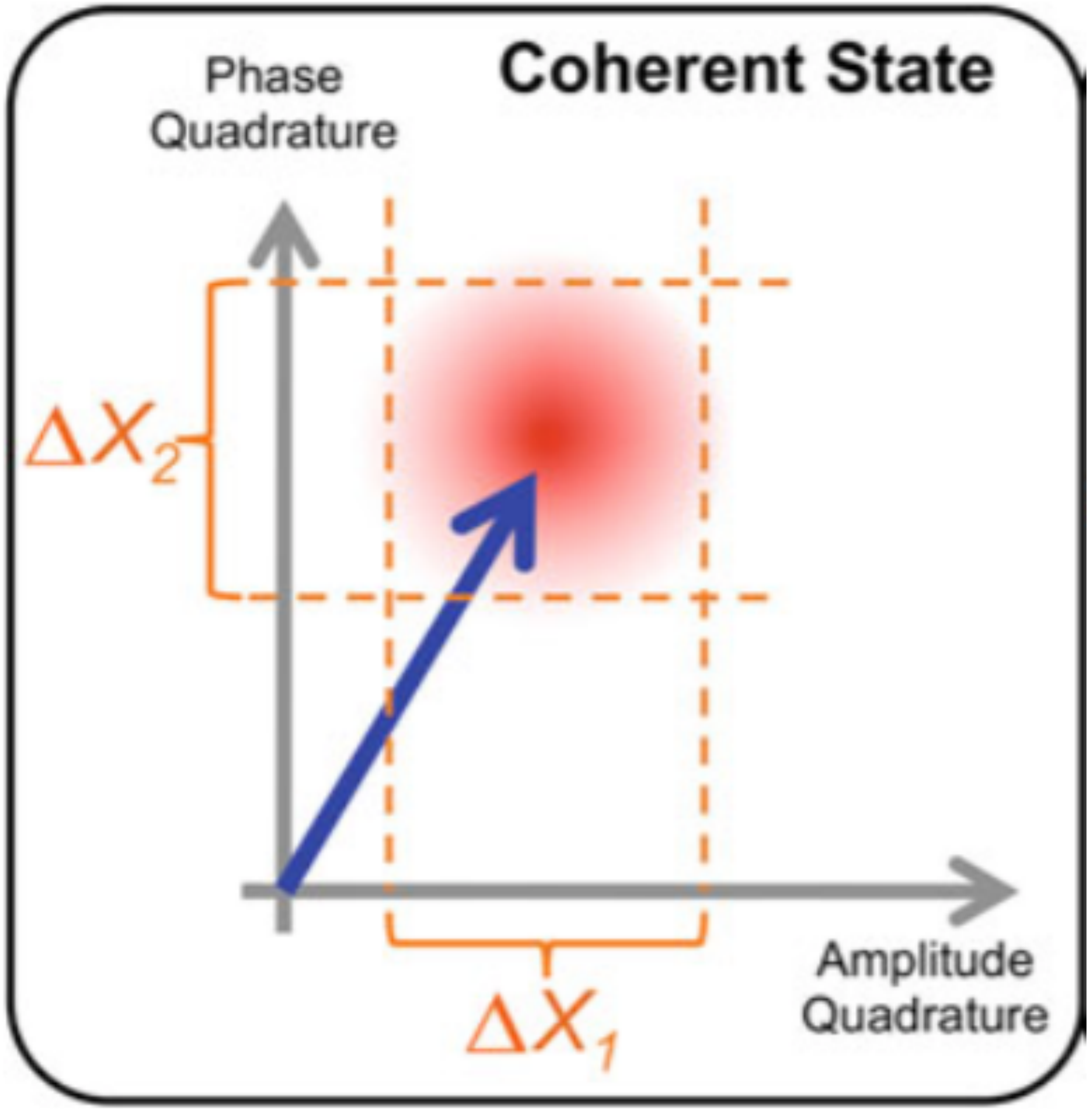
- It comes from Heisenberg uncertainty principle
- It is not a fundamental limit for our measurements

- 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)

Quantum representation: the quadrature picture



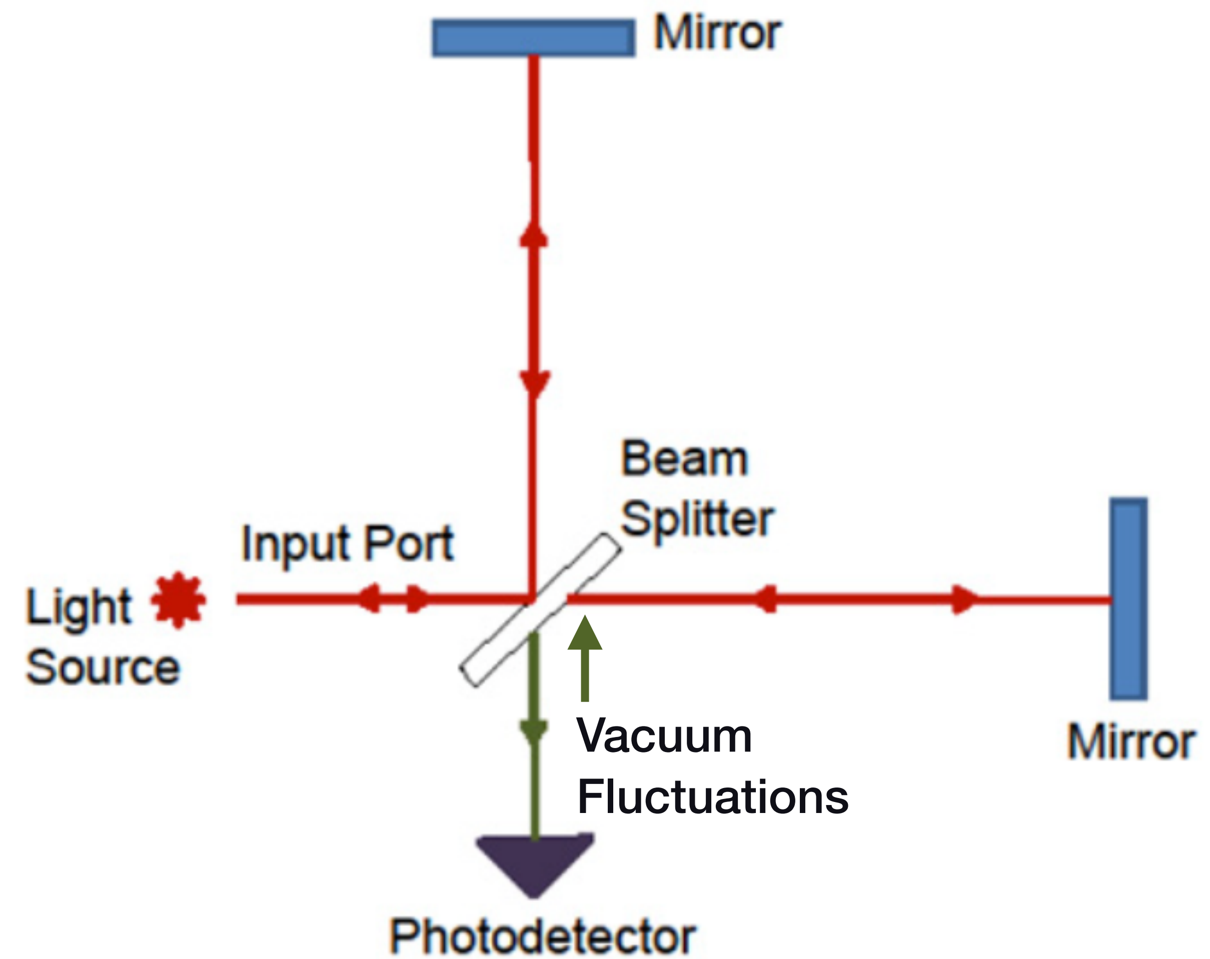
- Quantization of the EM field
- Amplitude and phase fluctuations equally distributed and uncorrelated
- In frequency domain is described by two quantum operators accounting for quantum fluctuation in each quadrature

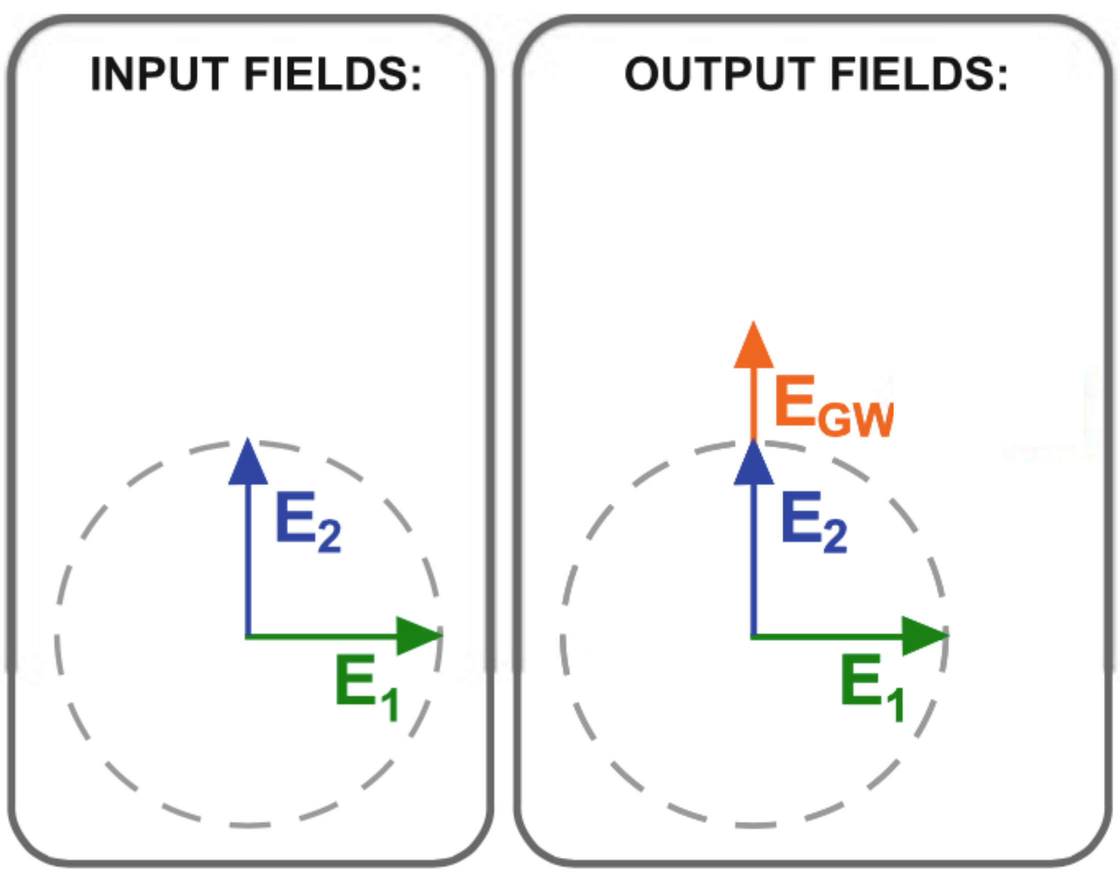
$$\hat{E}(t) = \left[E_0 + \hat{E}_1(t)\right] \cos \omega_0 t + \hat{E}_2(t) \sin \omega_0 t$$

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

Quantum noise in GW interferometers

- Vacuum fluctuation entering the dark port need to be considered
- Strangely enough, if the cavities are symmetric only vacuum fluctuations are responsible for quantum noise[1]

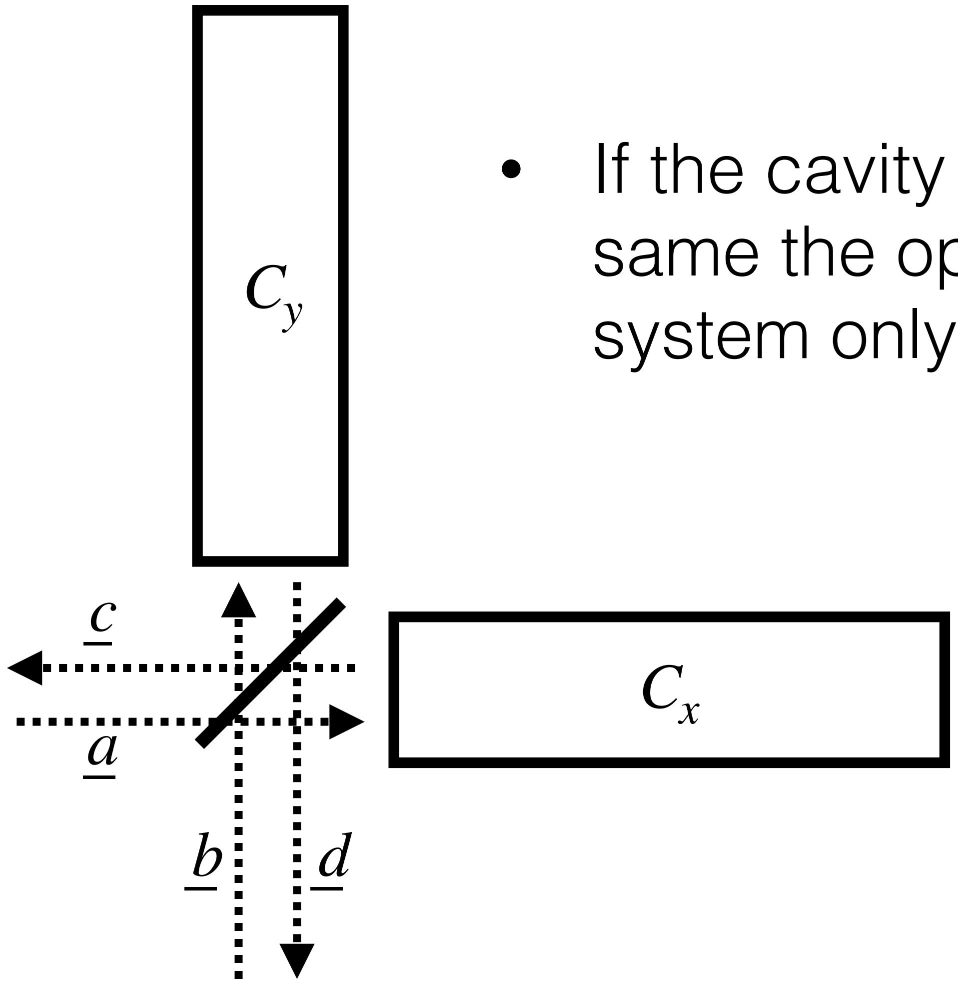




[1] C.Caves "Quantum-mechanical noise in an interferometer" Phys. Rev. D 23 (1981)

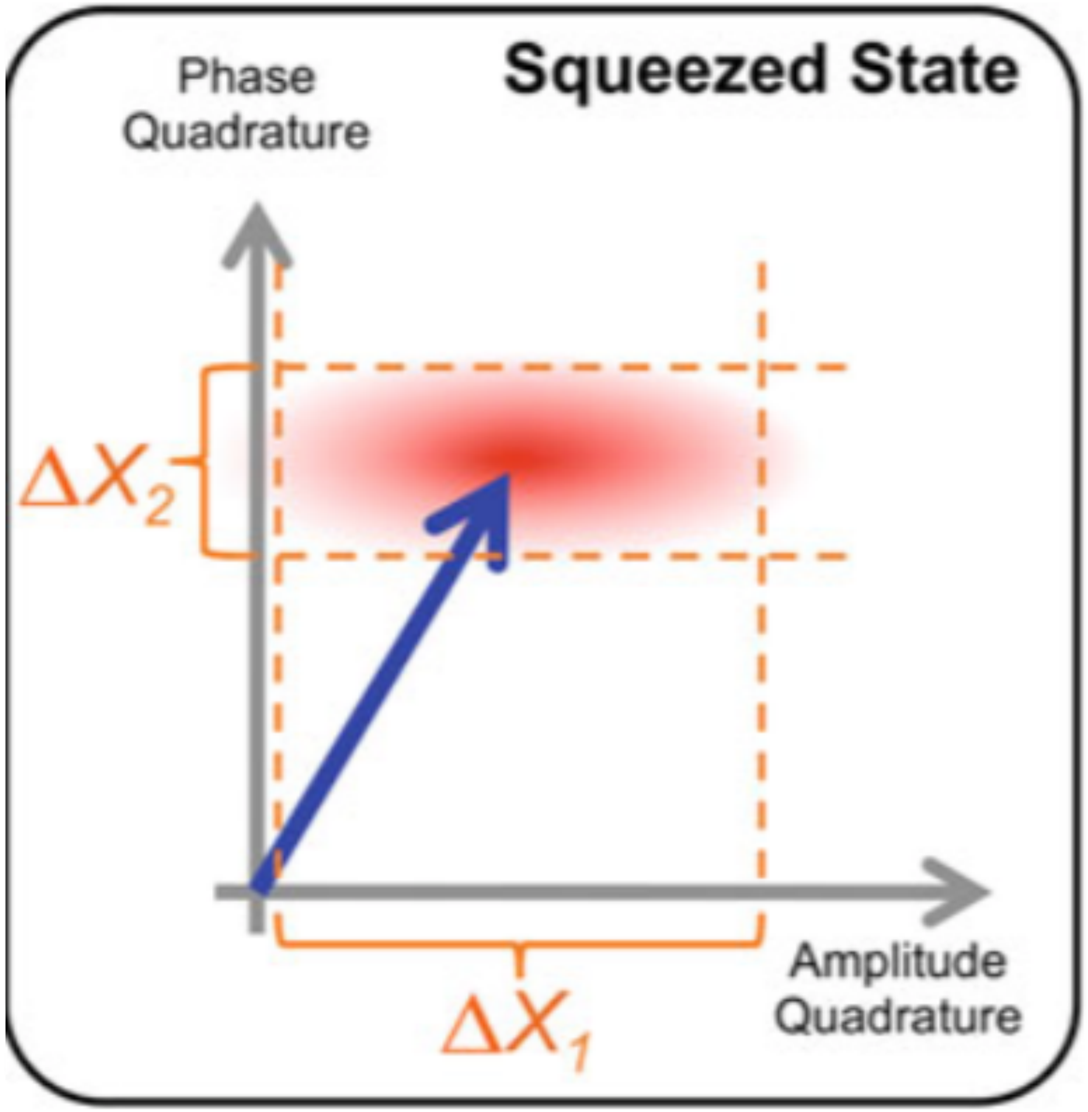
Quantum noise in GW interferometers

$$\underline{d} = tC_x(-r\underline{a} + t\underline{b}) + rC_y(t\underline{a} + r\underline{b}) = tr(C_y - C_x)\underline{a} + (t^2C_x + r^2C_y)\underline{b}$$



- If the cavity parameters are exactly the same the optical fluctuation enter the system only from the antisymmetric port

Quantum representation: squeezed states



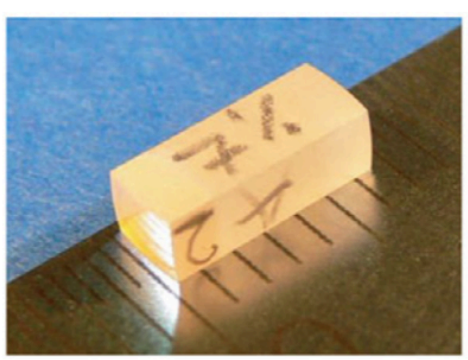
- Non classical light state
- Noise in one quadrature is reduced with respect to the one of a coherent state
- Correlations are introduced between amplitude and phase fluctuations

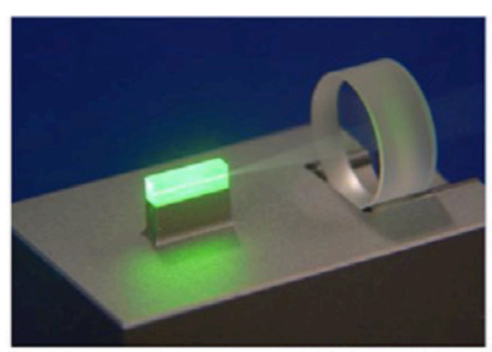
Each state is characterized by

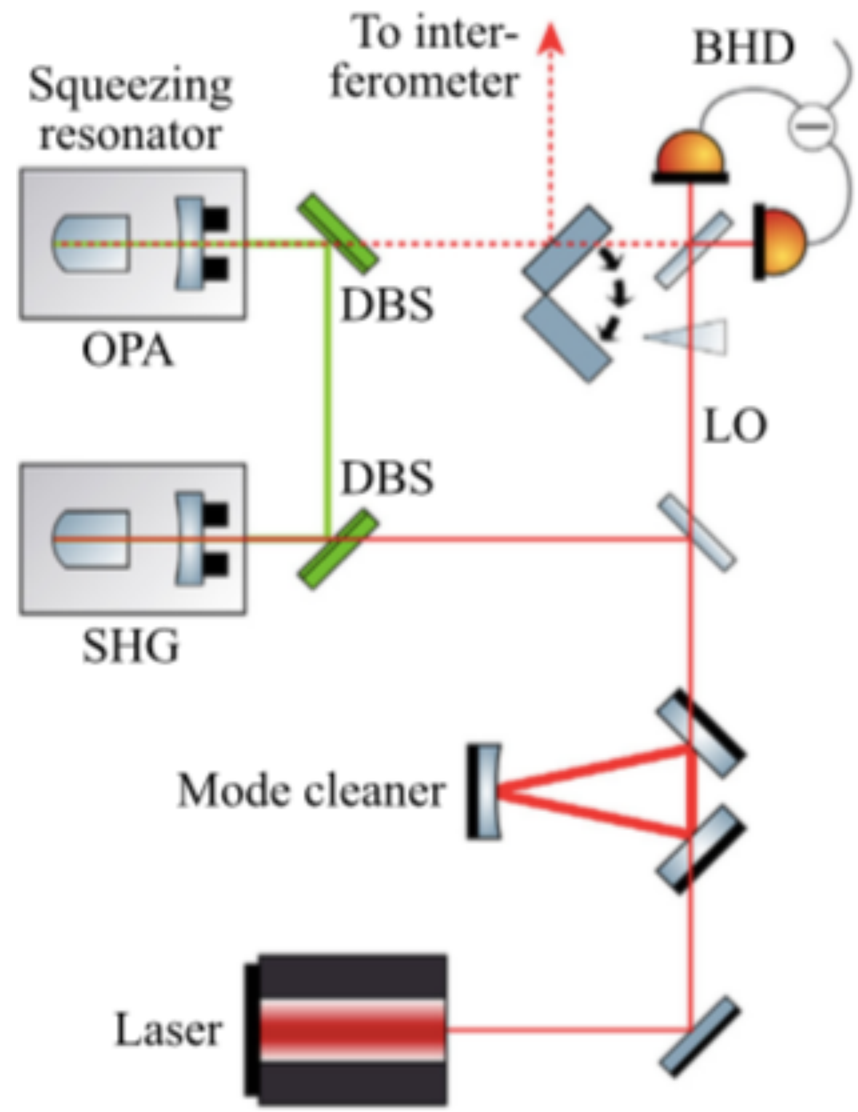
- Squeezing factor (magnitude of the squeezing)
- Squeezing angle (orientation of the ellipse)

How to generate a squeezed state

- 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

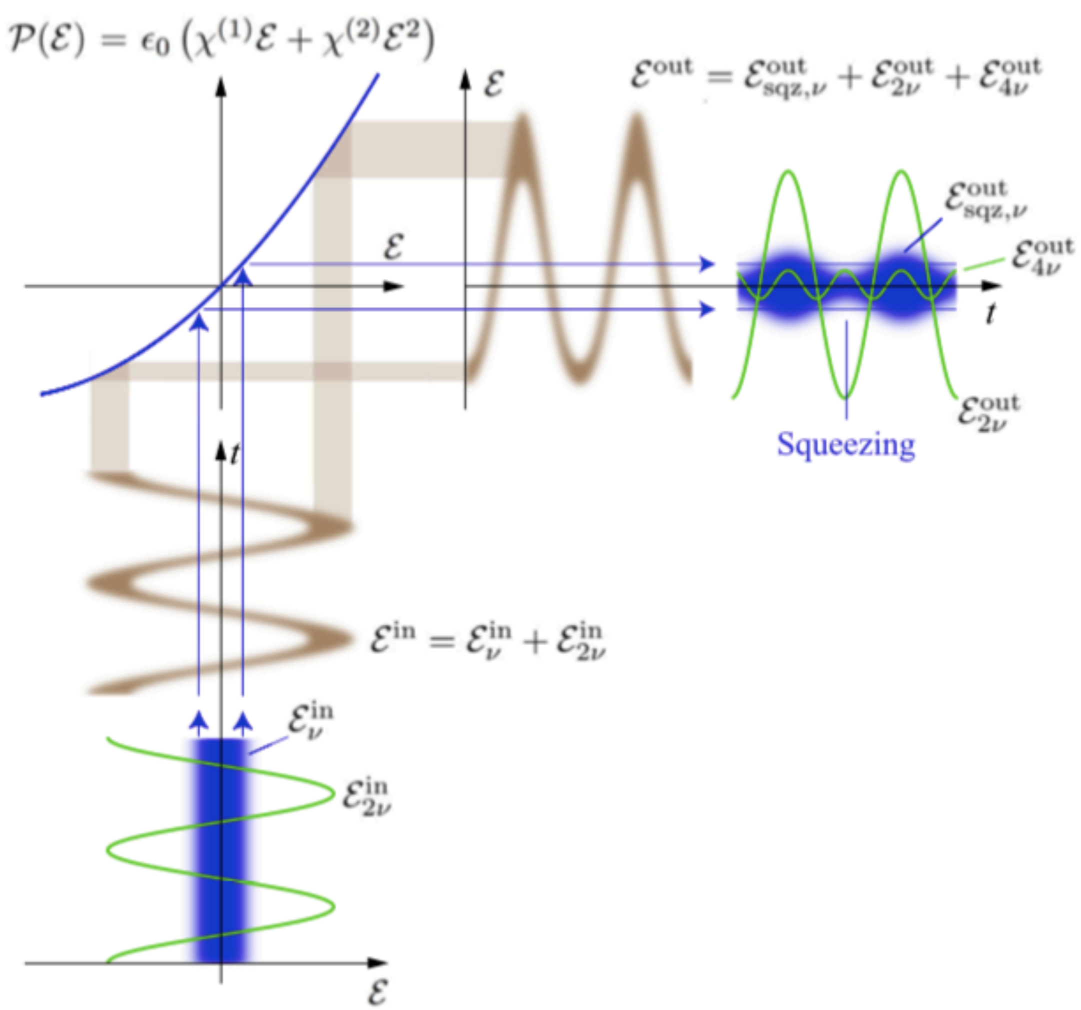






R. Schnabel- Physics Reports 684 (2017) 1–51

How to generate a squeezed state



- Optical parametric amplification of a vacuum state
- The input field (vacuum and pump) is transferred into a time-dependent dielectric polarization that is the source of the output field

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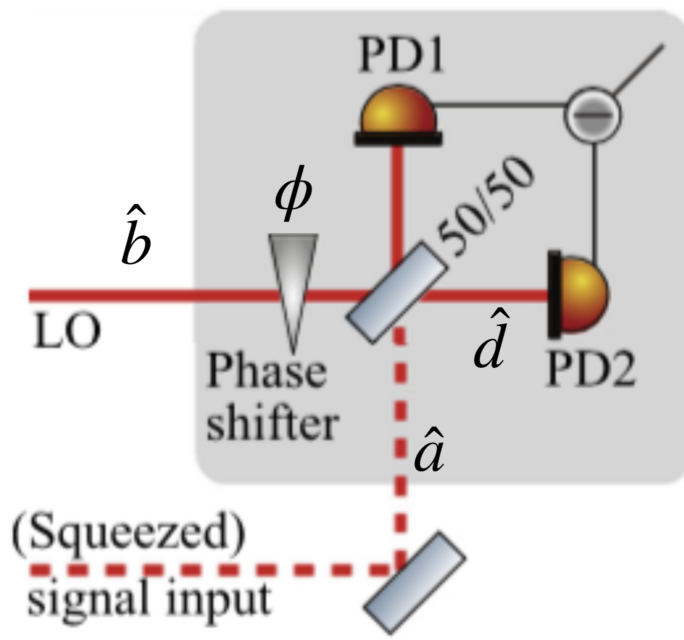
How to measure a squeezed state

- Balanced Homodyne detector

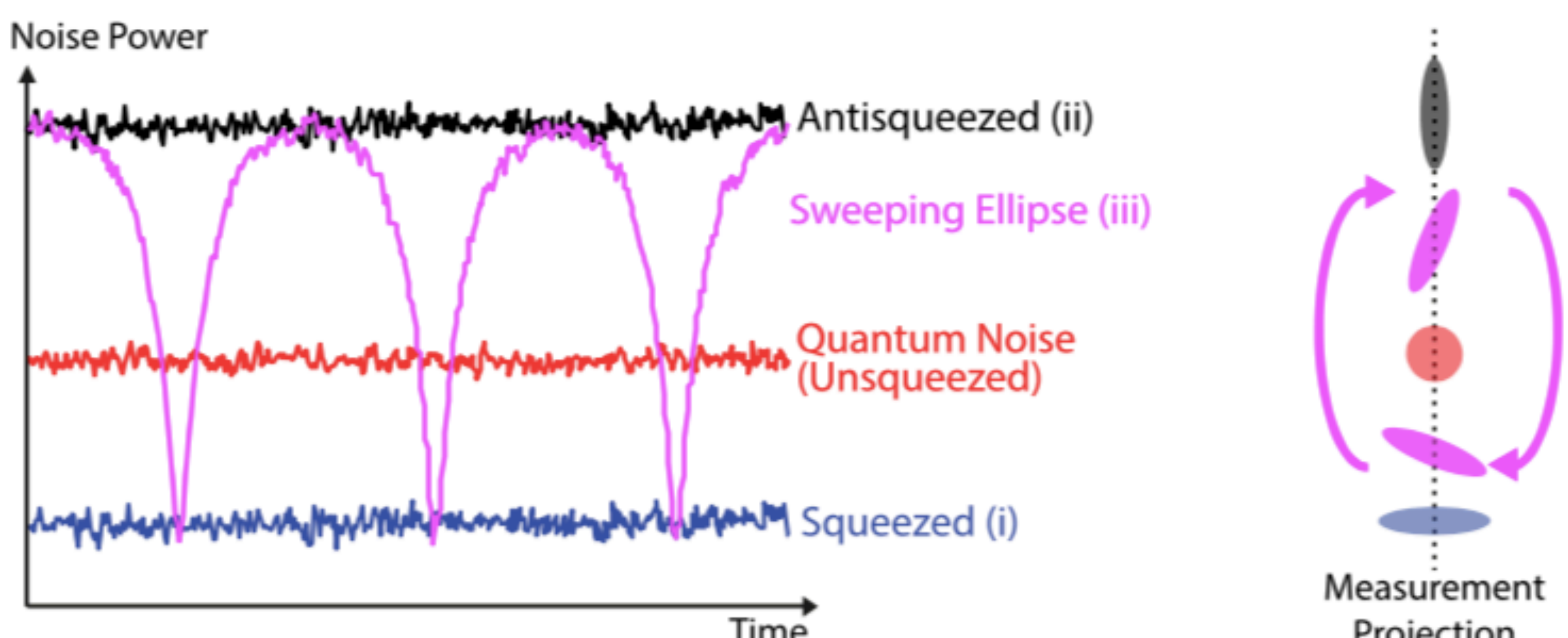


$$\hat{a} = \alpha + \delta\hat{a} \quad \hat{b} = (\beta + \delta\hat{b})e^{i\phi}$$

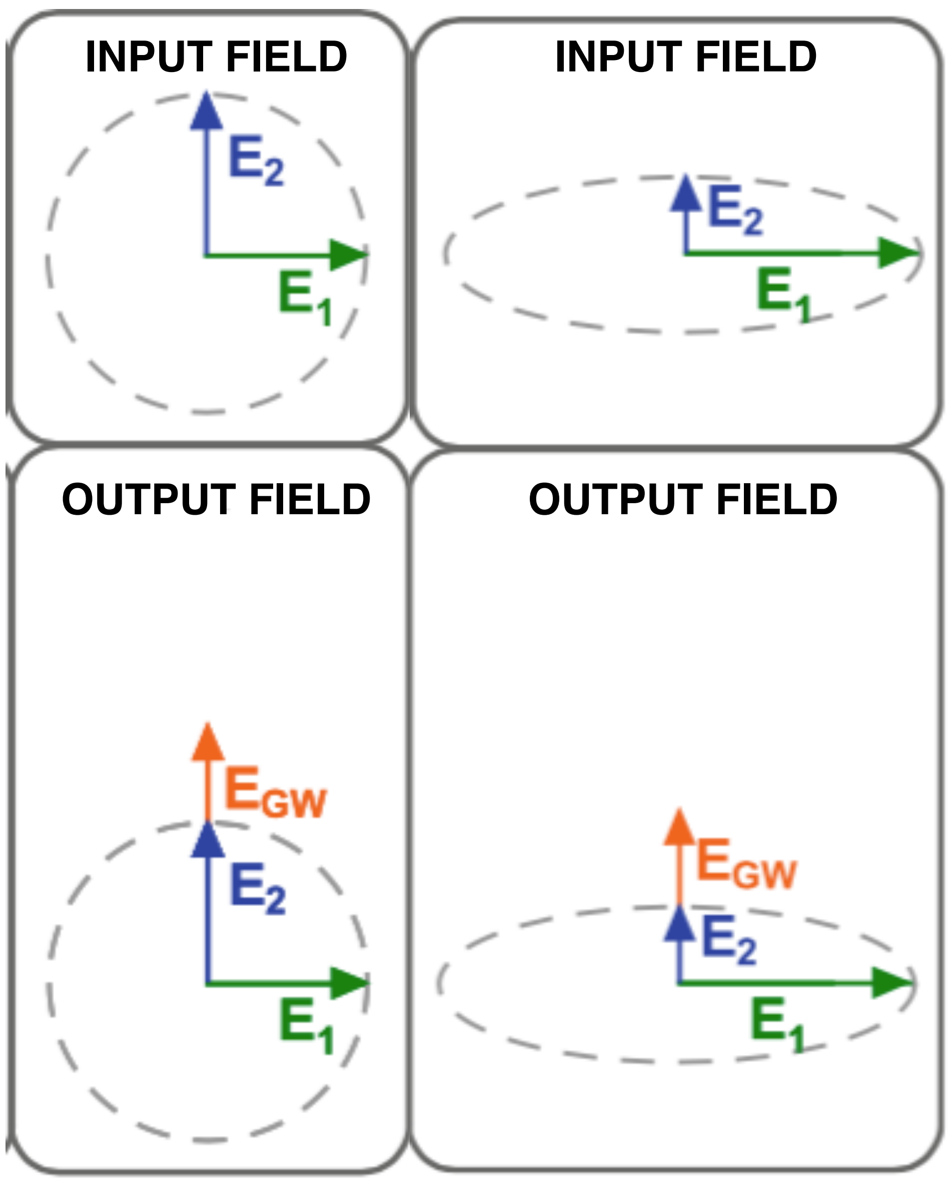
$$\hat{c} = \frac{1}{\sqrt{2}}(\hat{a} + \hat{b}) \quad \hat{d} = \frac{1}{\sqrt{2}}(\hat{a} - \hat{b})$$

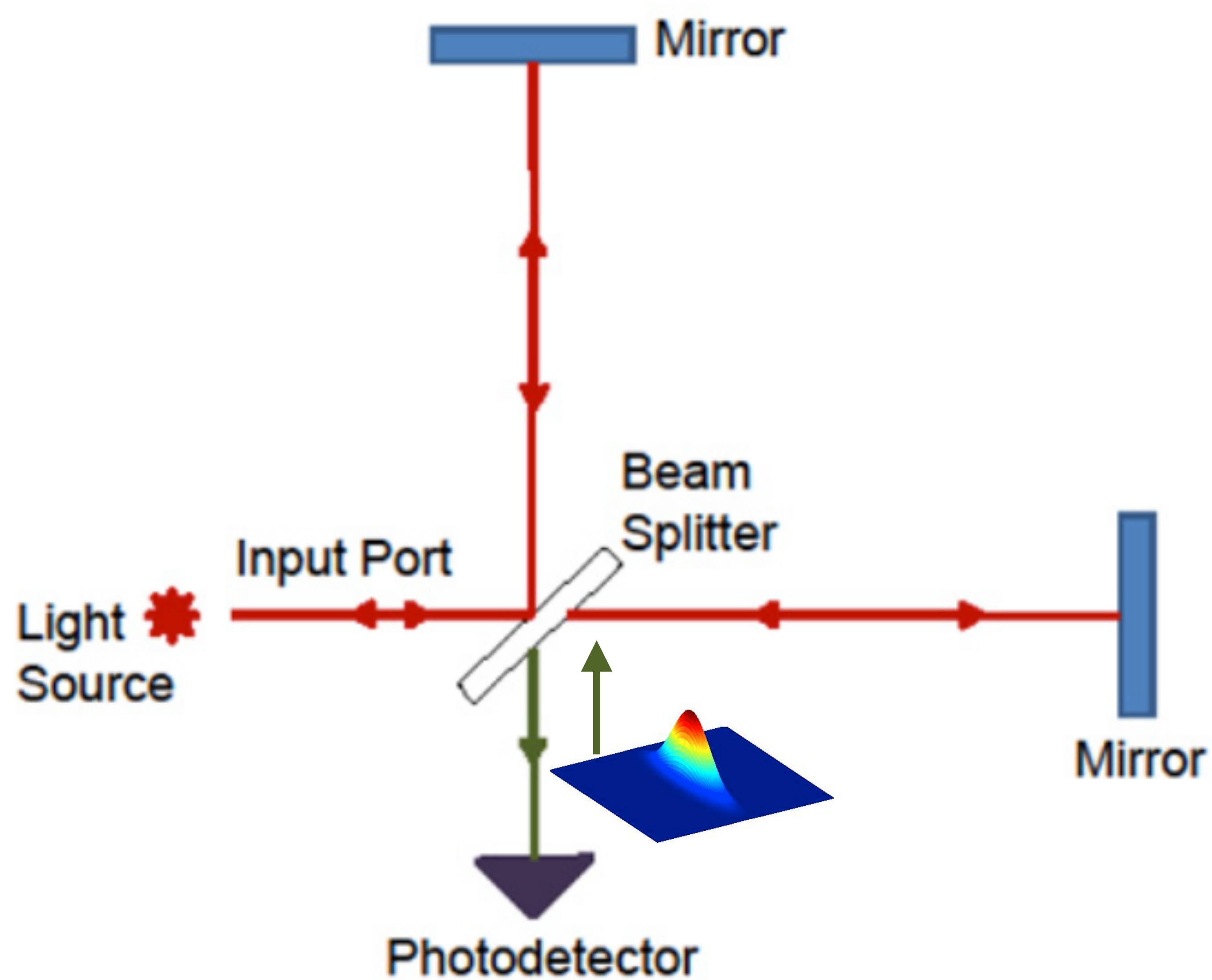
$$\delta\hat{X}_1^a = \delta\hat{a}^\dagger + \delta\hat{a} \text{ and } \delta\hat{X}_2^a = i(\delta\hat{a}\dagger + \delta\hat{a}).$$

$$I_1 - I_2 \simeq \beta(\cos(\phi)\delta\hat{X}_1^a + \sin(\phi)\delta\hat{X}_2^a) = \beta\delta\hat{X}_\phi^a$$

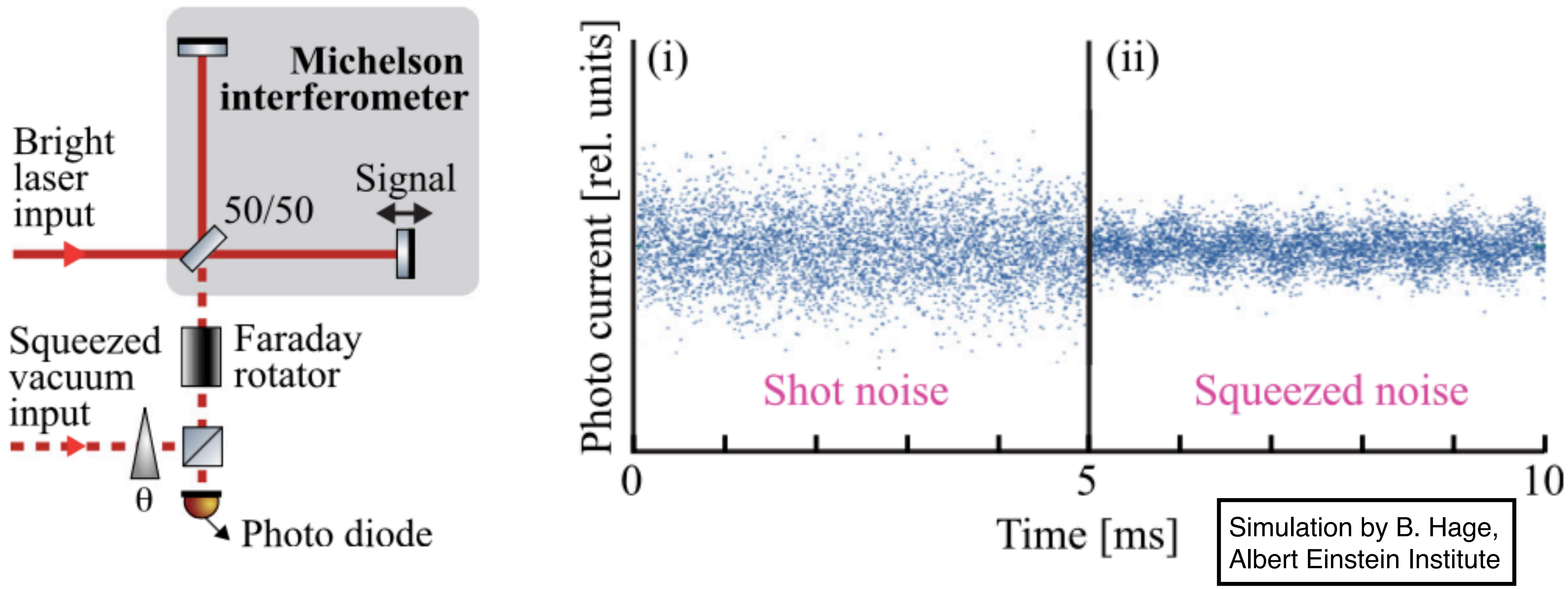


Quantum noise reduction using squeezed light



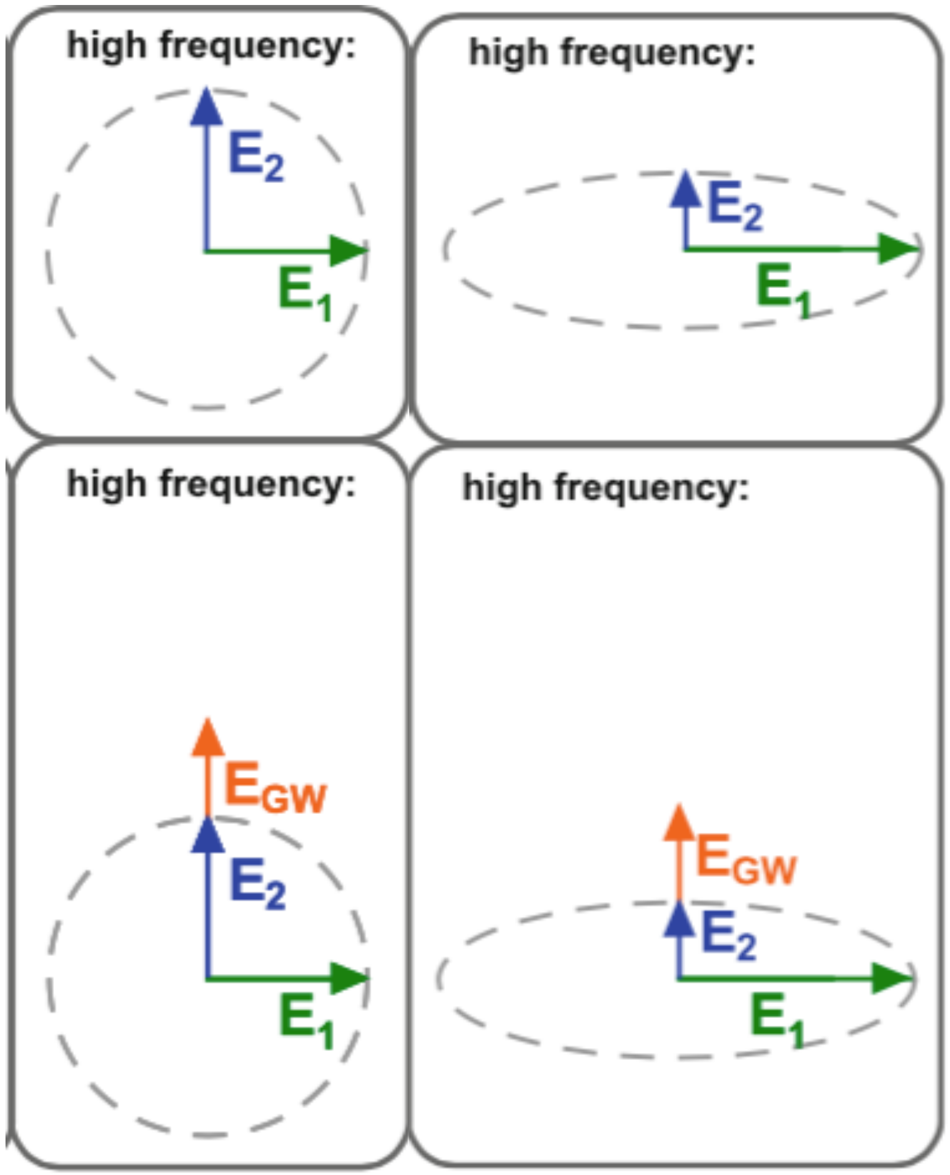


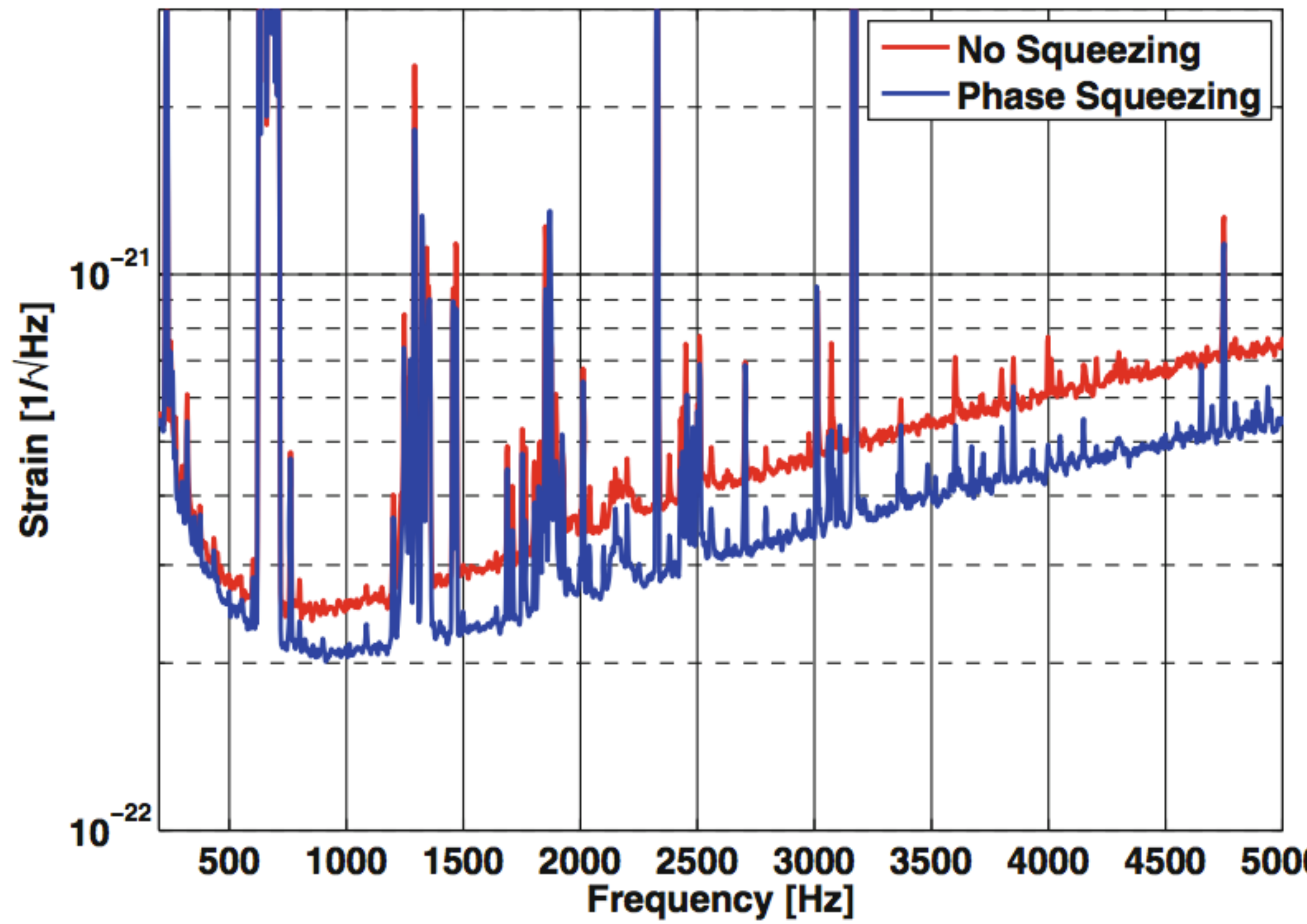
Quantum noise reduction using squeezed light



- Simulated output of Michelson interferometer where a signal is produced by modulating the relative arm length
- With squeezing the shot noise is reduced and a sinusoidal signal is visible

Quantum noise reduction using squeezed light



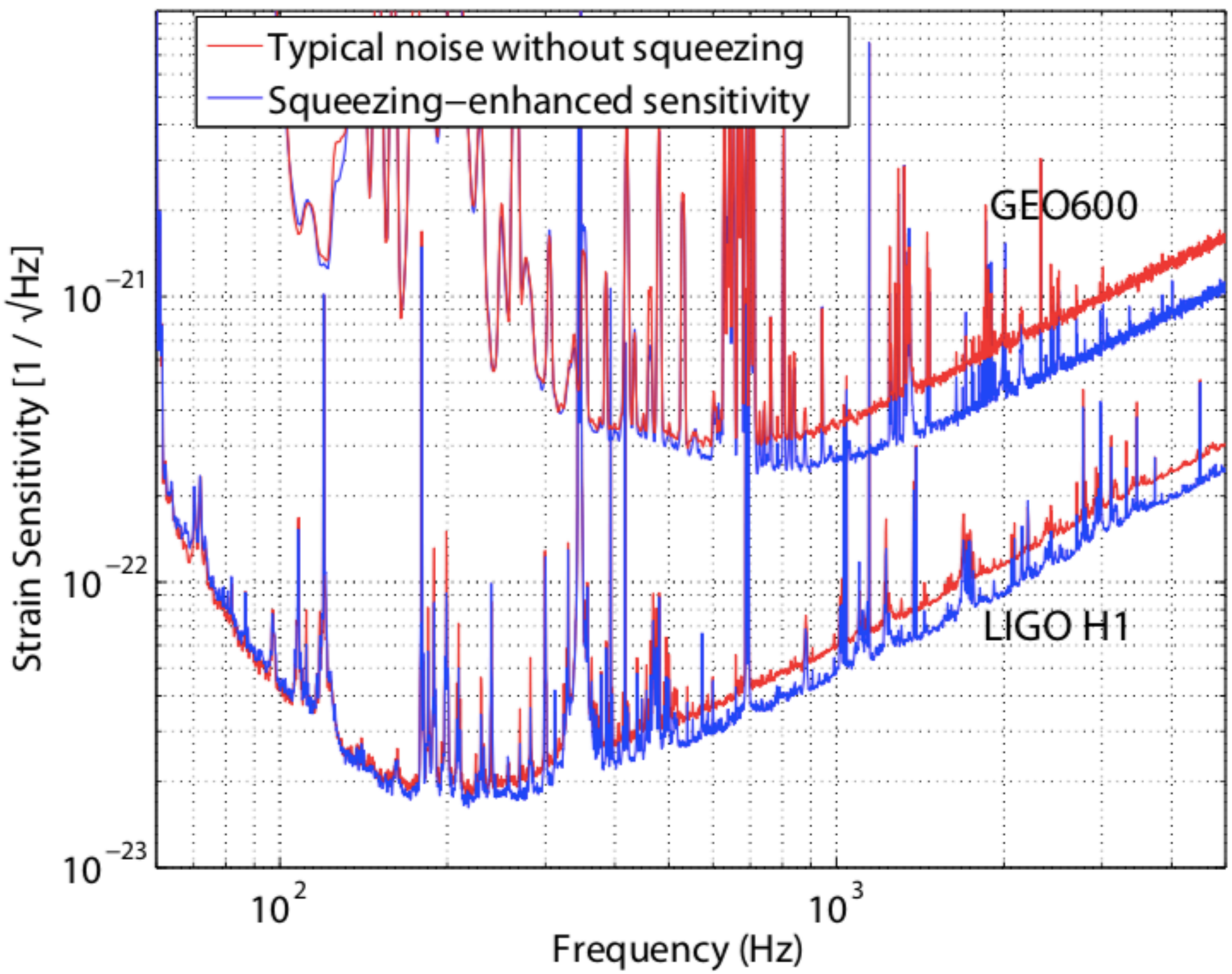


Injecting squeezed vacuum from the output port is a tested strategy to reduce quantum noise[1]

[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)

Quantum noise reduction using squeezed light

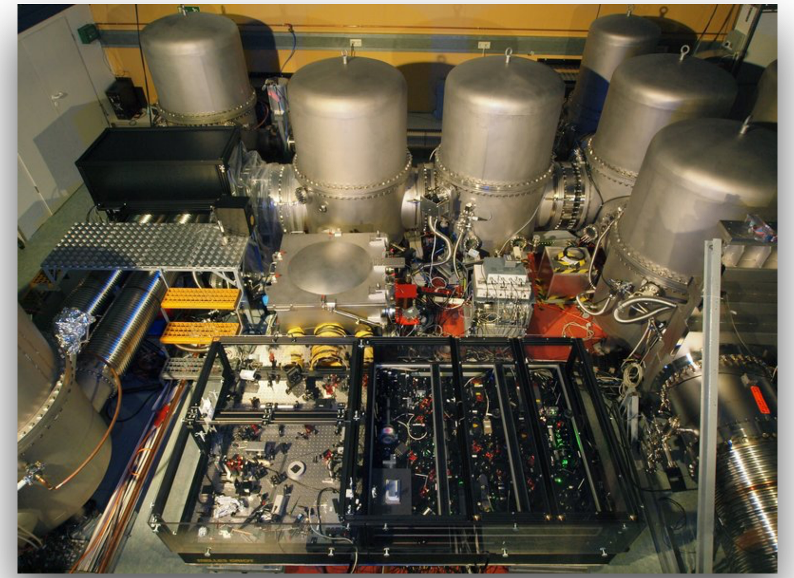
- Successfully tested also in LIGO



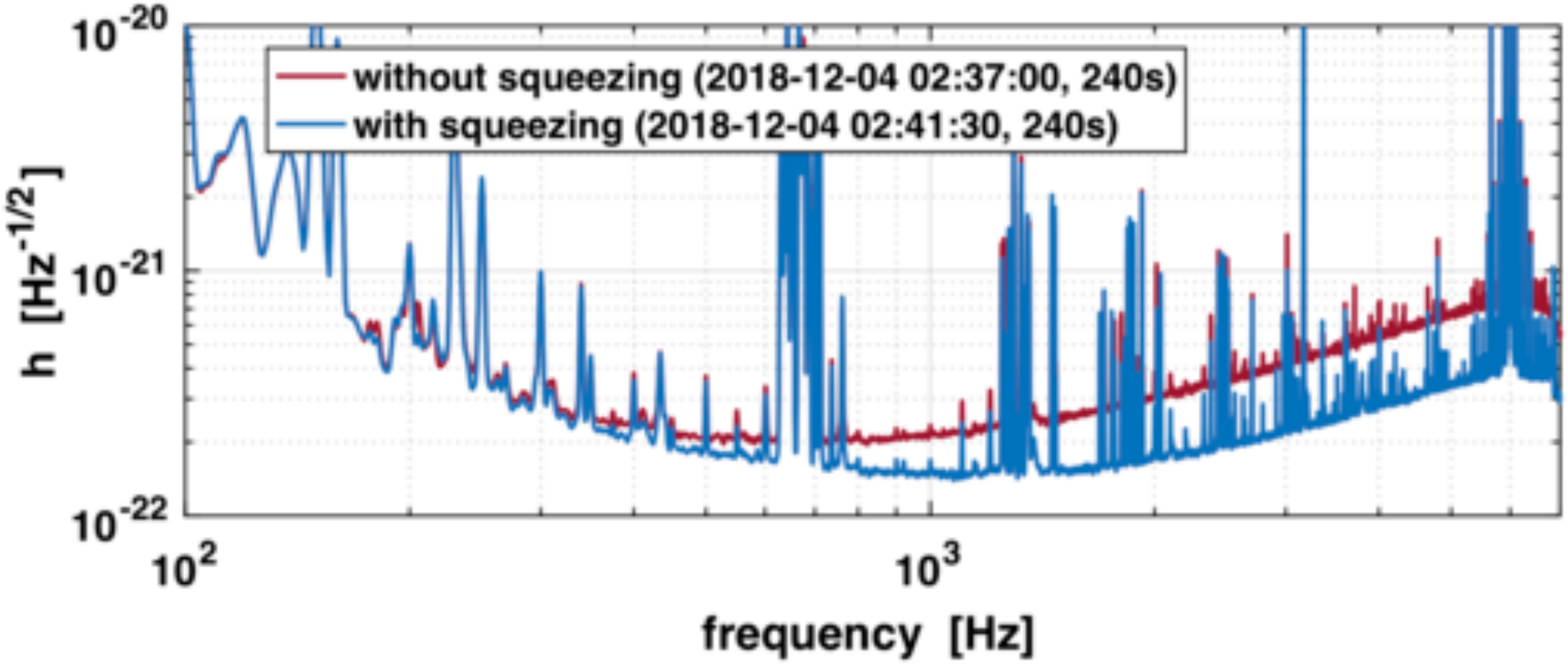
LIGO Scientific Collaboration, J. Aasi et al., “Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light”, Nat Photon 7 no. 8, (Aug, 2013) 613–619.

New squeezing record at GEO 600

- The AEI team at GEO recently reached a squeezing level of 5.7 dB
- It corresponds to a quantum noise suppression of a factor 2

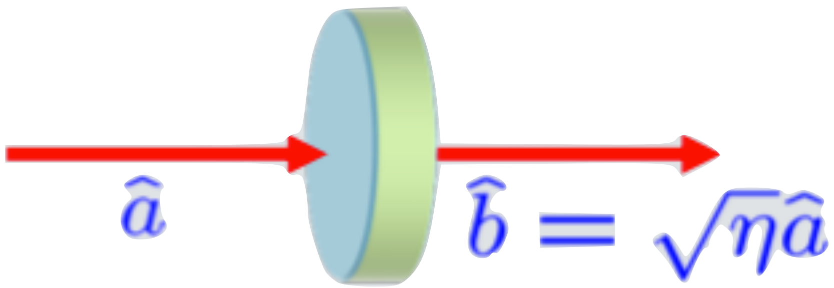


Inside the central building of the gravitational-wave detector GEO600.



Optical losses degrades squeezing

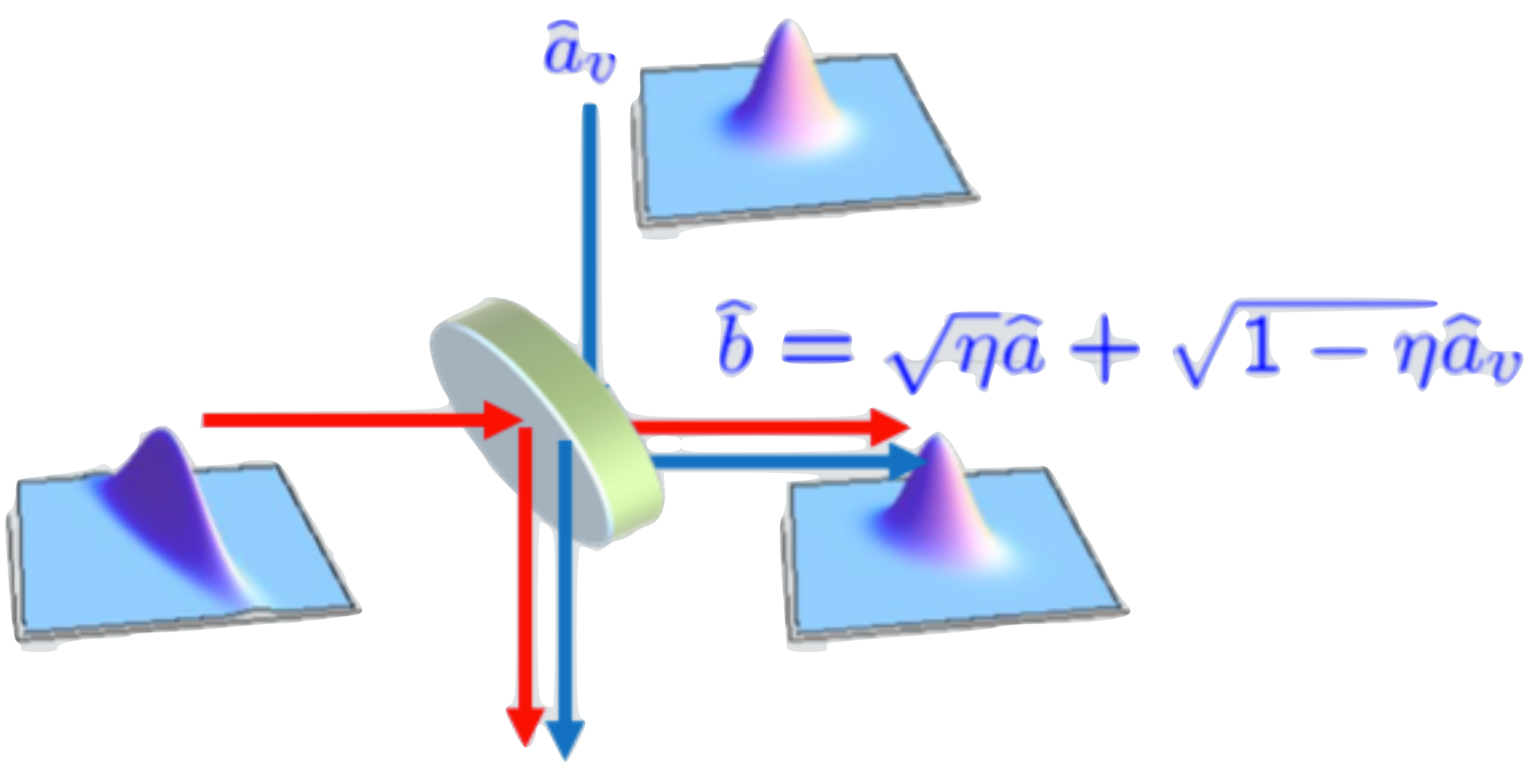
- Naive model



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

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

- Consistent model

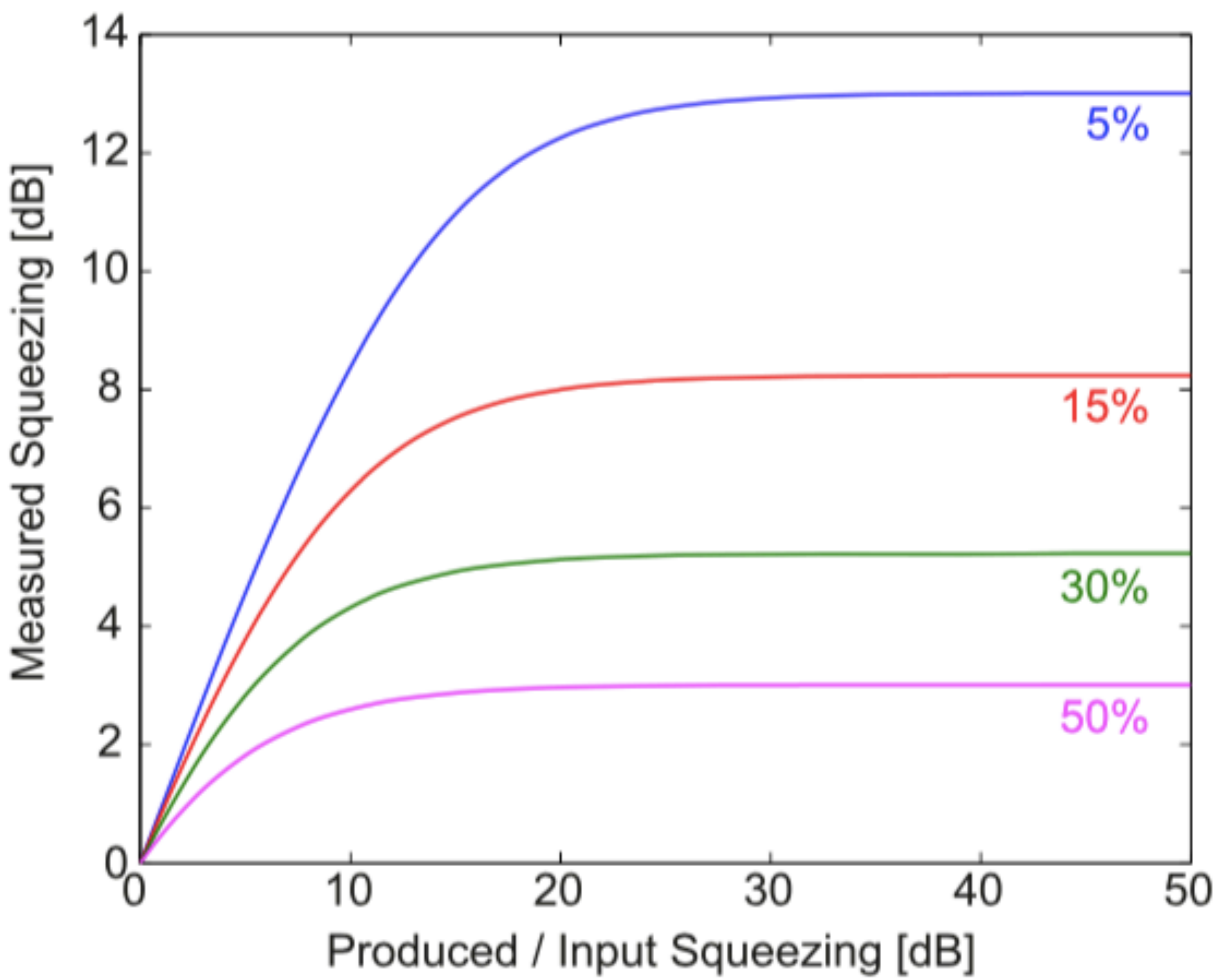


Squeezing deteriorated because of its recombination with non squeezed vacuum

Optical losses degrades squeezing

- Measured squeezing as a function of the input squeezing foe different loss levels

$$V_{\mathrm{sqz-m}} = \eta V_{\mathrm{sqz-in}} + (1 - \eta)$$

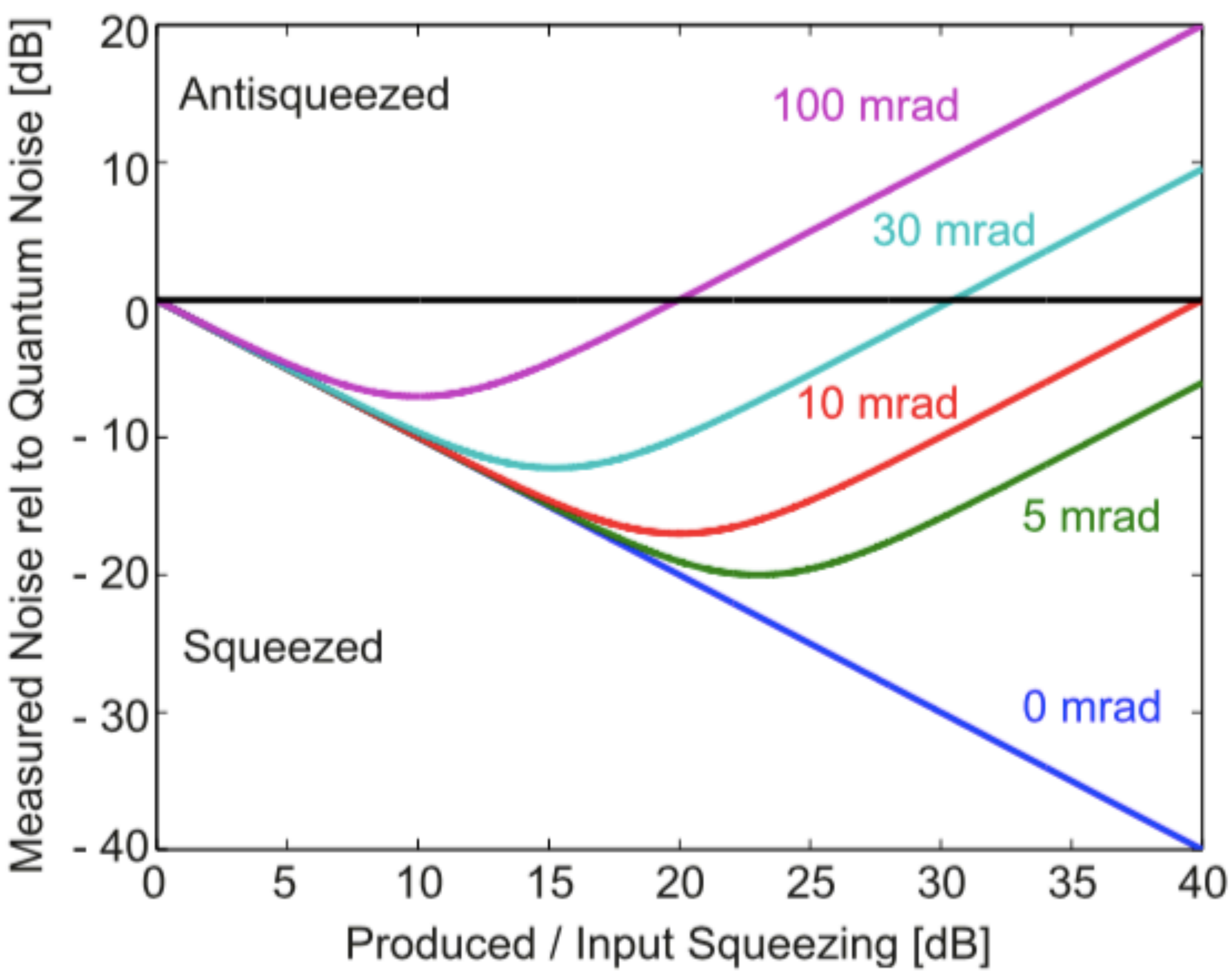


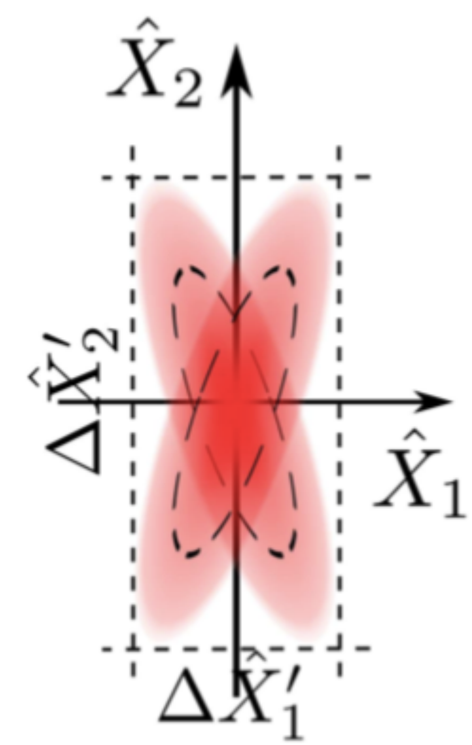
S. Chua et al. Class. Quantum Grav. 31 (2014)

Phase noise effect

- Measured squeezing as a function of the input squeezing for different phase noise levels

$$V_{\mathrm{sqz-m'}} = V_{\mathrm{sqz-in}} \cos^2\left(\tilde{\theta}\right) + V_{\mathrm{asqz-in}} \sin^2\left(\tilde{\theta}\right)$$

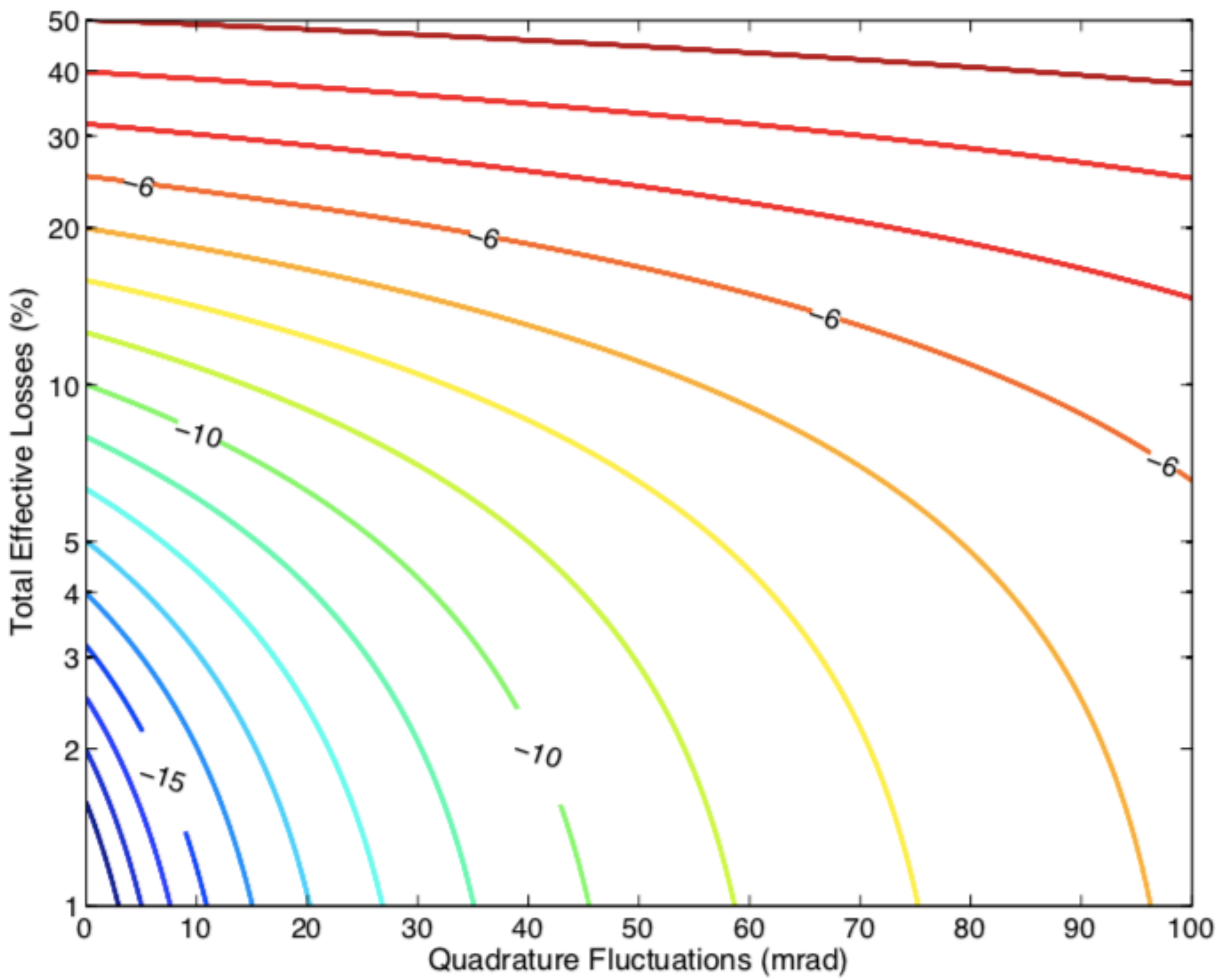




S. Chua et al. Class. Quantum Grav. 31 (2014)

Optical losses and phase noise effect

- Maximum level of squeezing measurable in the presence of **optical losses** and **phase noise** (a.k.a squeezed quadrature fluctuations)



REVIEW- Squeezed vacuum states of light for gravitational wave detectors
Lisa Barsotti, Jan Harms and Roman Schnabel
Published 18 December 2018
Reports on Progress in Physics, Volume 82, Number 1

Optical losses and phase noise effect

- Injecting more squeezing is not always beneficial
- Coupling from anti squeezing can increase the noise

Range v squeezing

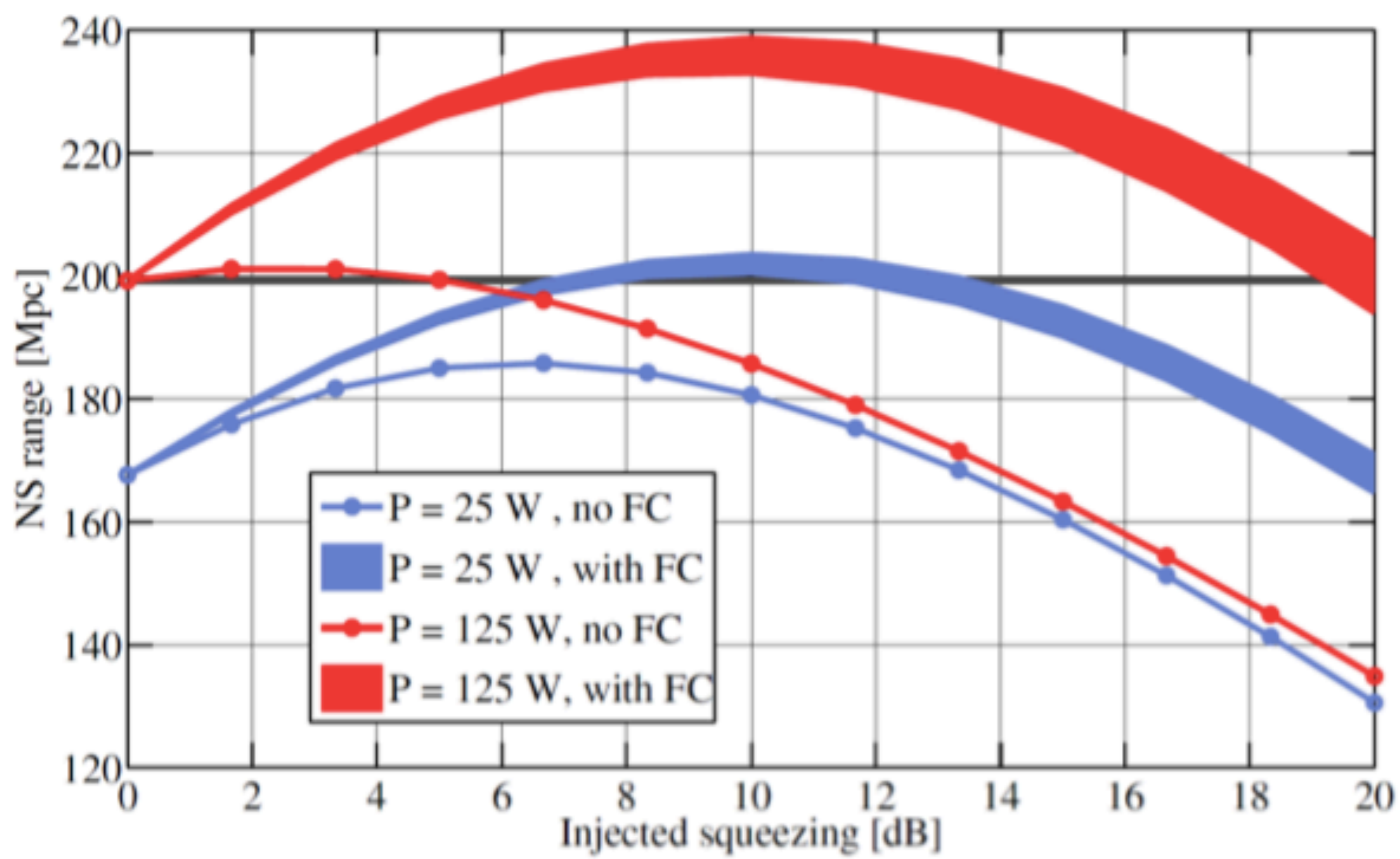
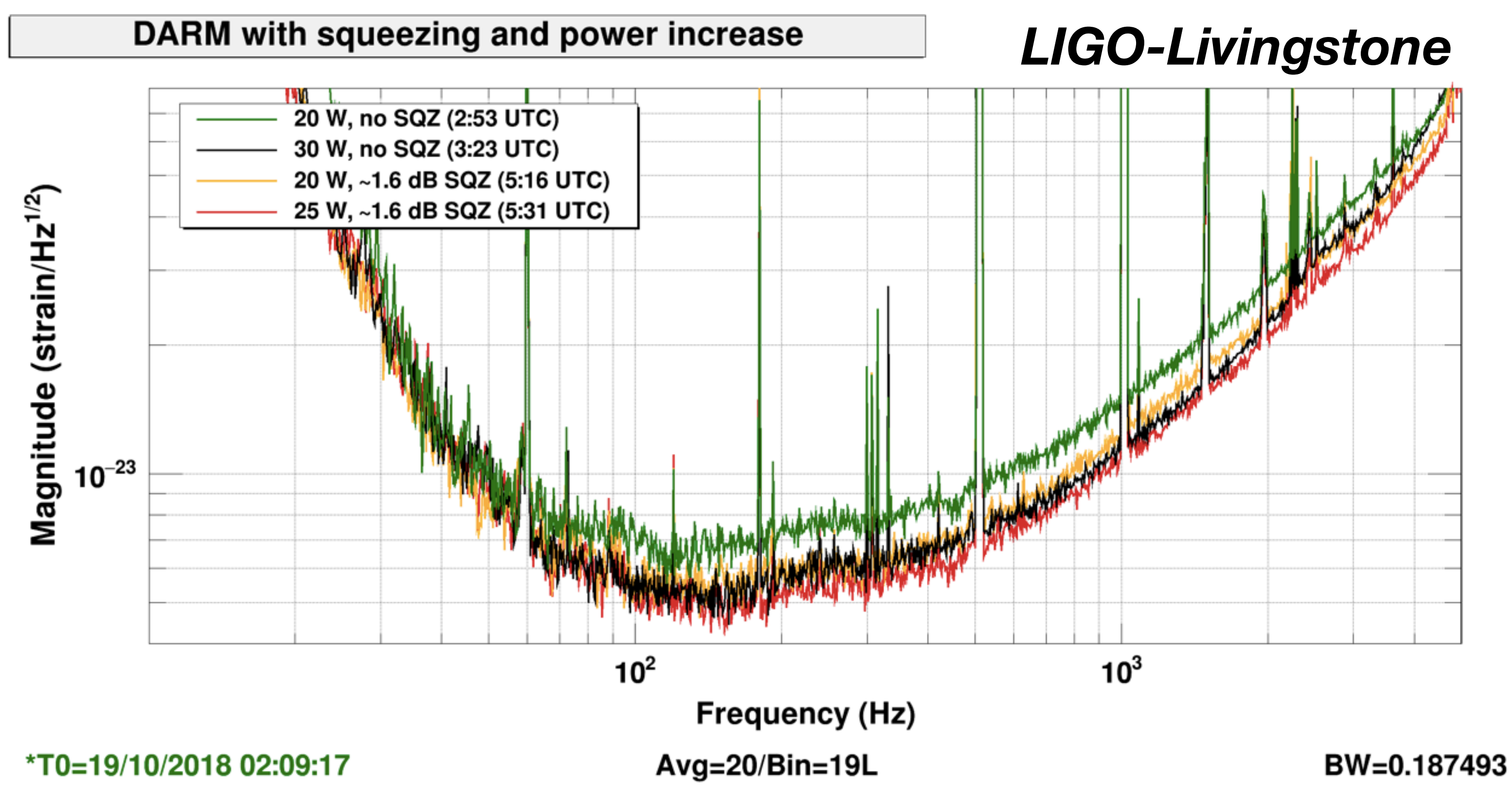


Figure Credit: John Miller

Squeezed light in 2nd generation GW detectors

- Frequency independent squeezer are now installed both in Advanced Virgo and Advanced Ligo as upgrade between 02 and 03



L1 SQZ (ISC, SQZ)

maggie.tse@LIGO.ORG - posted 01:38, Friday 19 October 2018 - last comment - 15:17, Saturday 20 October 2018(41250)

Squeezing with IFO 20W, and then squeezing with IFO 25W

[Anamaria, Matt, Lisa, Valera, Carl, Terra, Maggie]

Today, after powering up to 30W, we also tried two more tests that improved our range.

- **118 Mpc: Injecting SQZ, IFO at 20W input power**
- **120 MPc: Powering IFO up to 25W while continuing to inject SQZ**

These periods are annotated in the range plot in Figure 1.

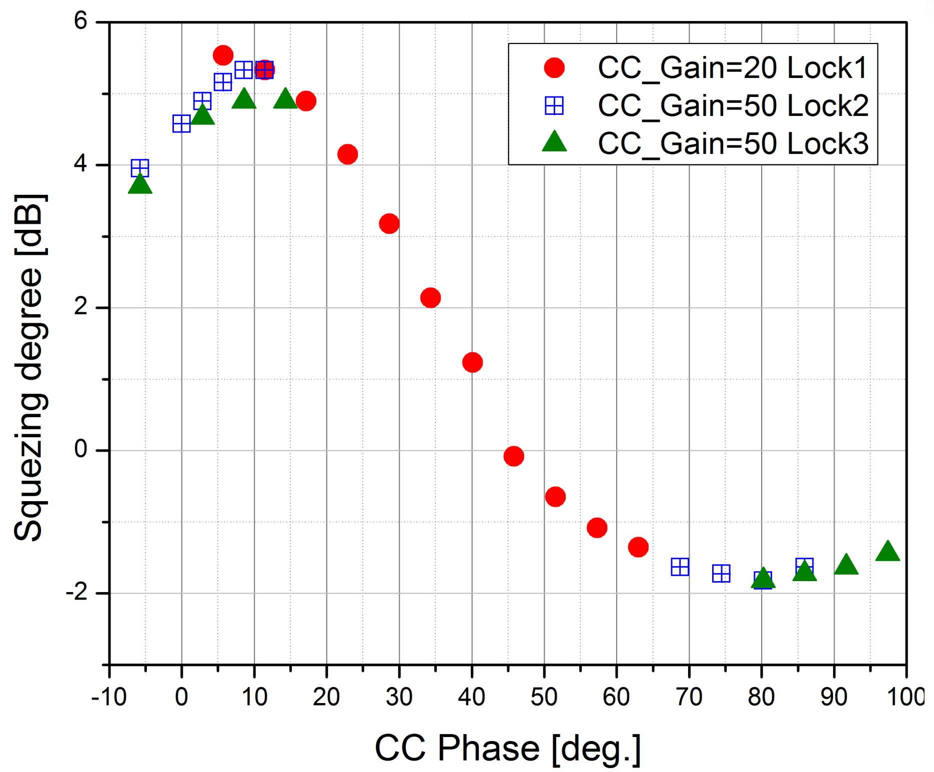
DARM spectra shown in Figure 2, for a) 20 W input, b) 30 W input, c) 20 W input with 1.5-1.6 dB squeezing, d) 25 W input with 1.5-1.6 dB squeezing.

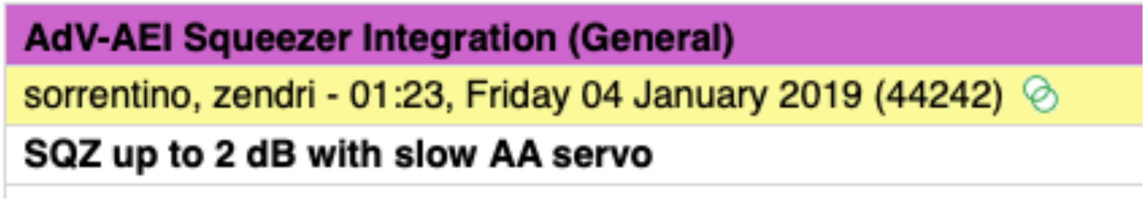
More analysis on squeezing parameters and setup coming tomorrow.

Squeezed light in 2nd generation GW detectors

- Squeezer from AEI installed on Virgo site
- Commissioning on-going

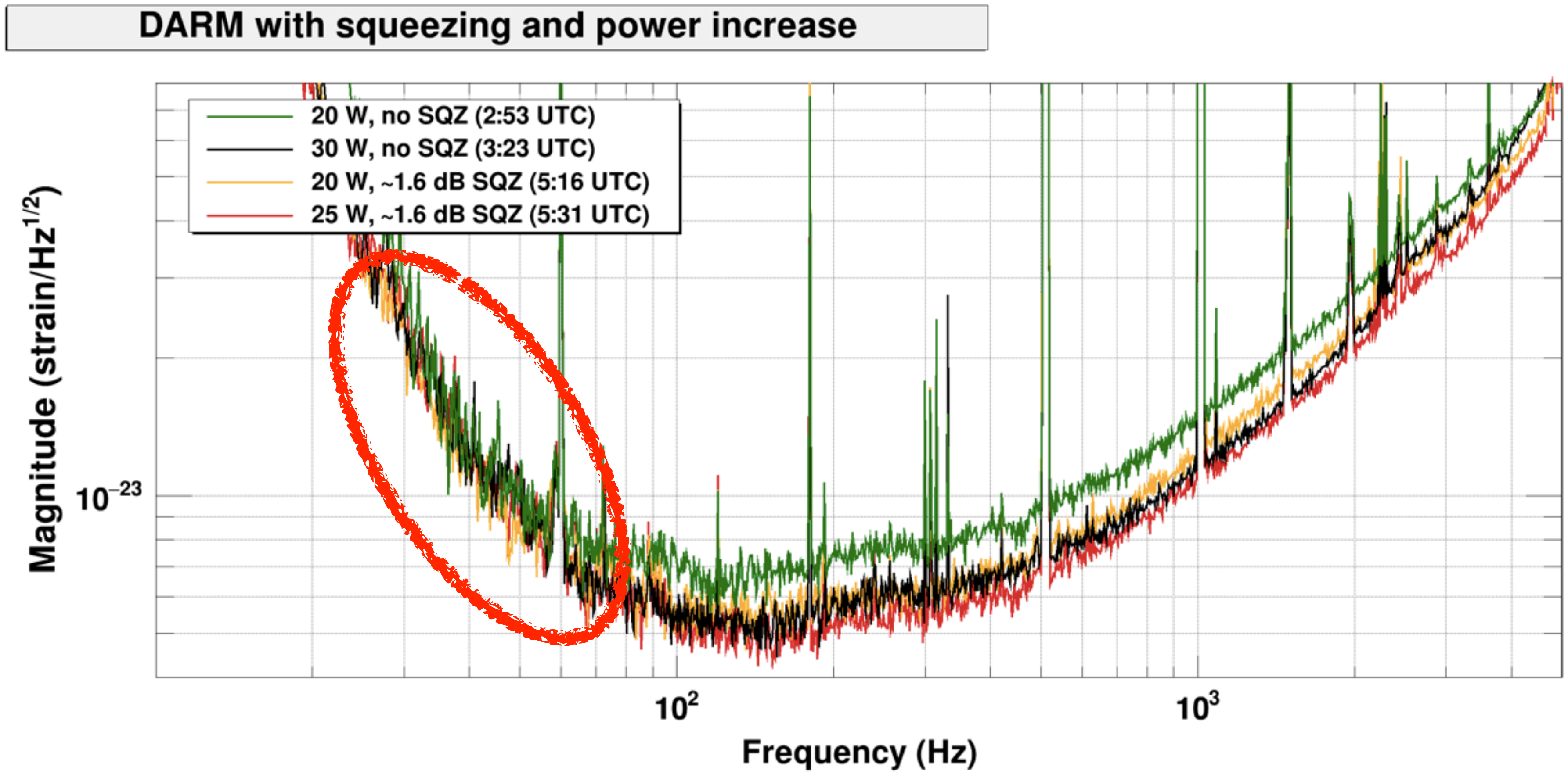
Credit: H. Lück/B. Knispel/Max Planck Institute for Gravitational Physics





Broadband quantum noise reduction?

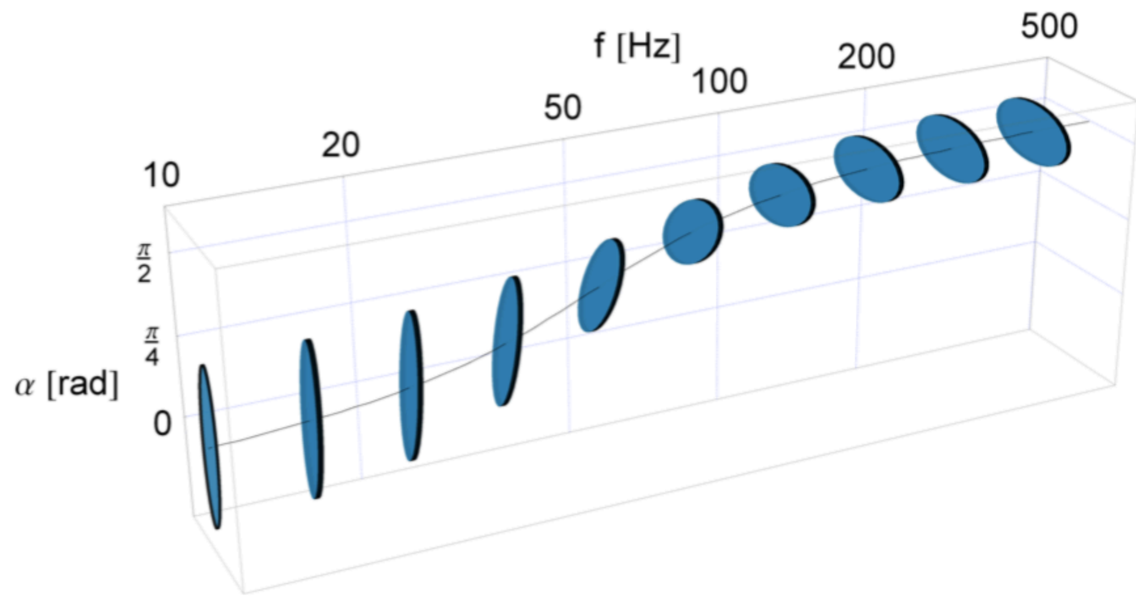
- Frequency independent squeezing can only improve high (or low) frequency noise
- If we inject phase squeezed noise we reduce shot noise but increase radiation pressure noise
- The effect has not been observed yet since radiation pressure noise is not yet limiting the sensitivity



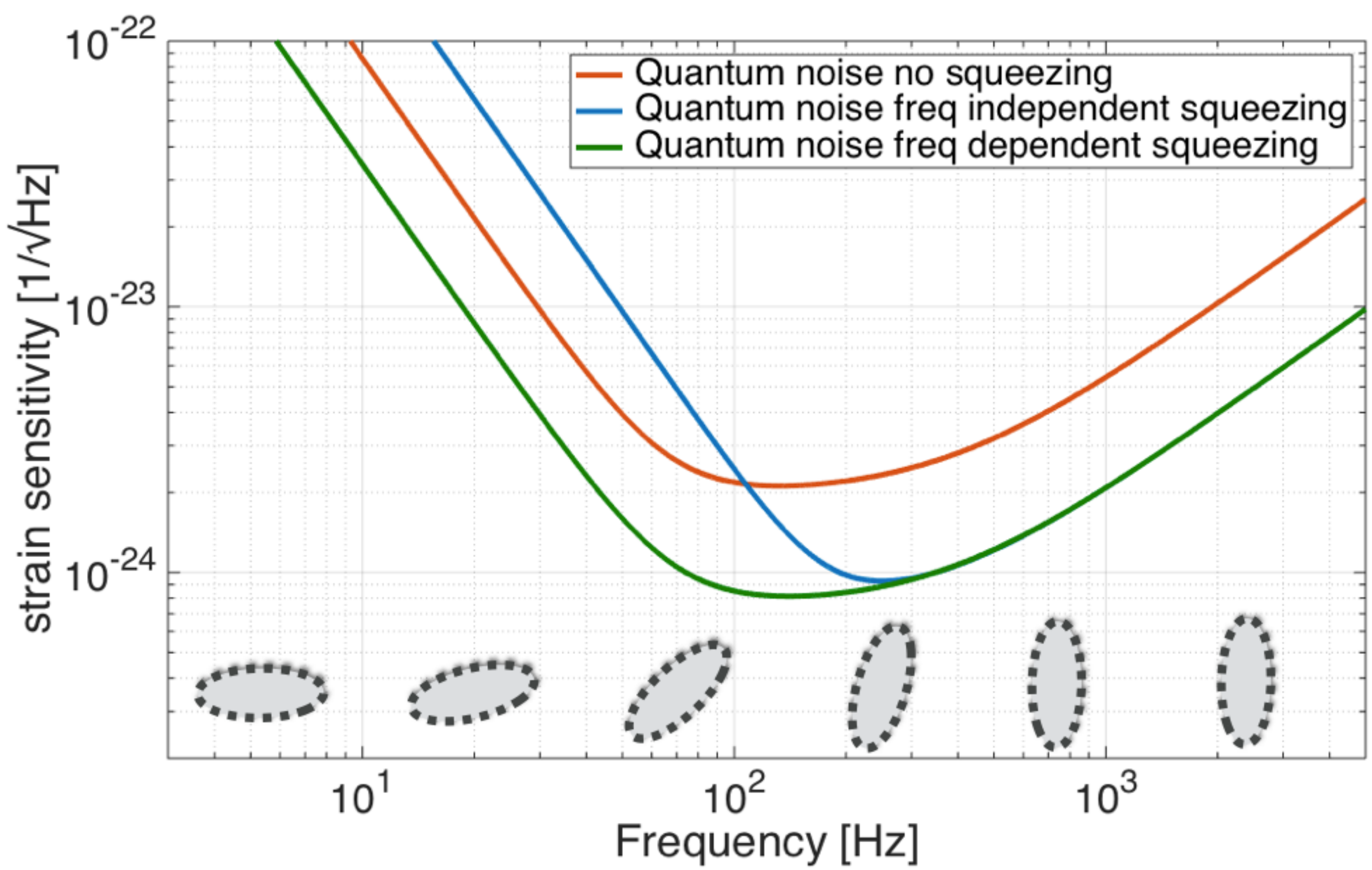
- It should be visible at the design sensitivity in 2nd generation detectors

Broadband quantum noise reduction

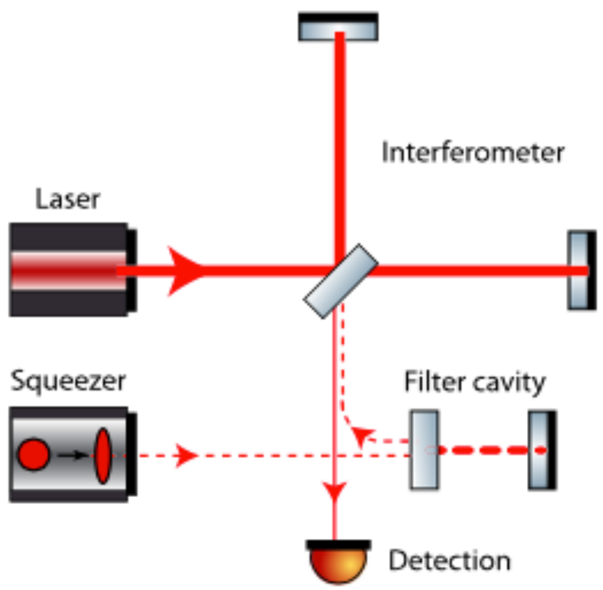
- Squeezing ellipse undergoes a rotation inside the interferometer



- Squeezing angle should change with the frequency for optimal noise reduction



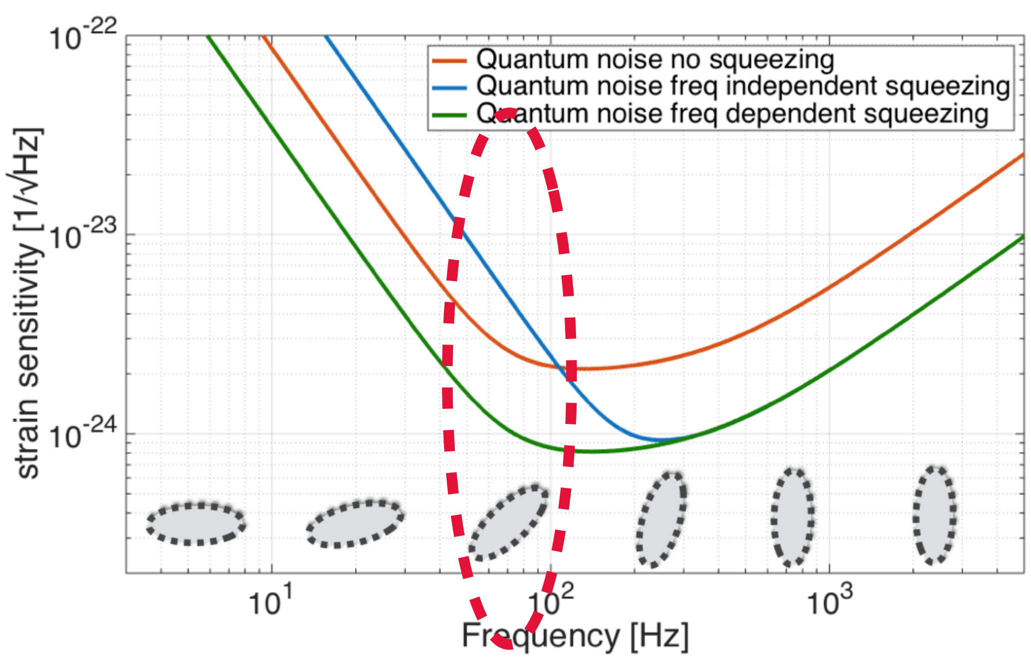
Frequency dependent squeezing

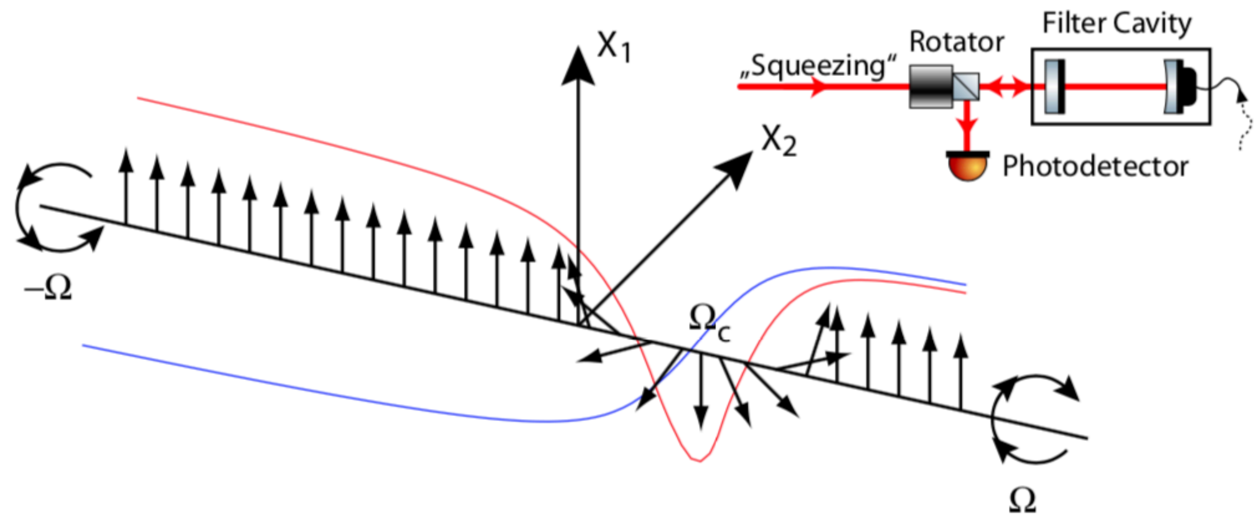


- Reflect frequency independent squeezing off a detuned Fabry-Perot cavity

- Rotation frequency depends on cavity detuning and finesse

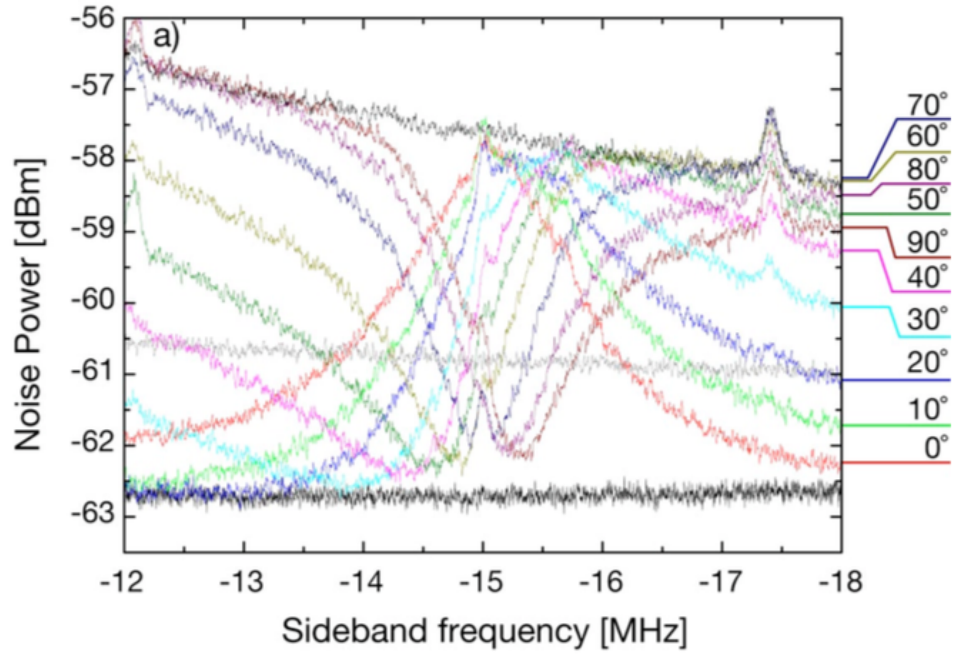
$$\alpha_p = \mathrm{atan}\left(\frac{2\gamma_{\mathrm{fc}}\Delta\omega_{\mathrm{fc}}}{{\gamma_{\mathrm{fc}}}^2 - {\Delta\omega_{\mathrm{fc}}}^2 + \Omega^2}\right)$$





- Optimal rotation frequency between 40 and 70 Hz

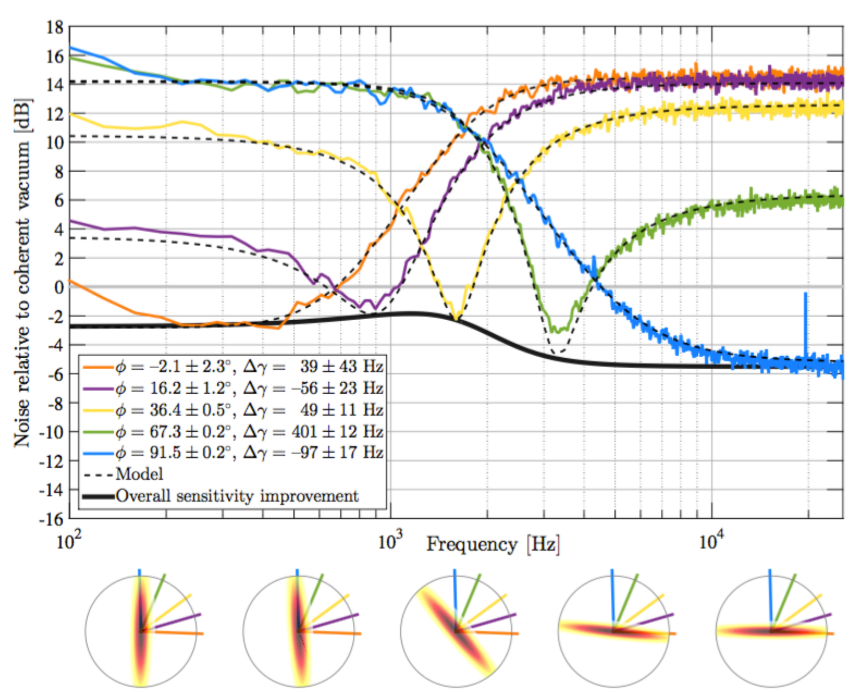
What has been done in the past?



PHYSICAL REVIEW A **71**, 013806 (2005)

Experimental characterization of frequency-dependent squeezed light

Simon Chelkowski, Henning Vahlbruch, Boris Hage, Alexander Franzen, Nico Lastzka, Karsten Danzmann, and Roman Schnabel

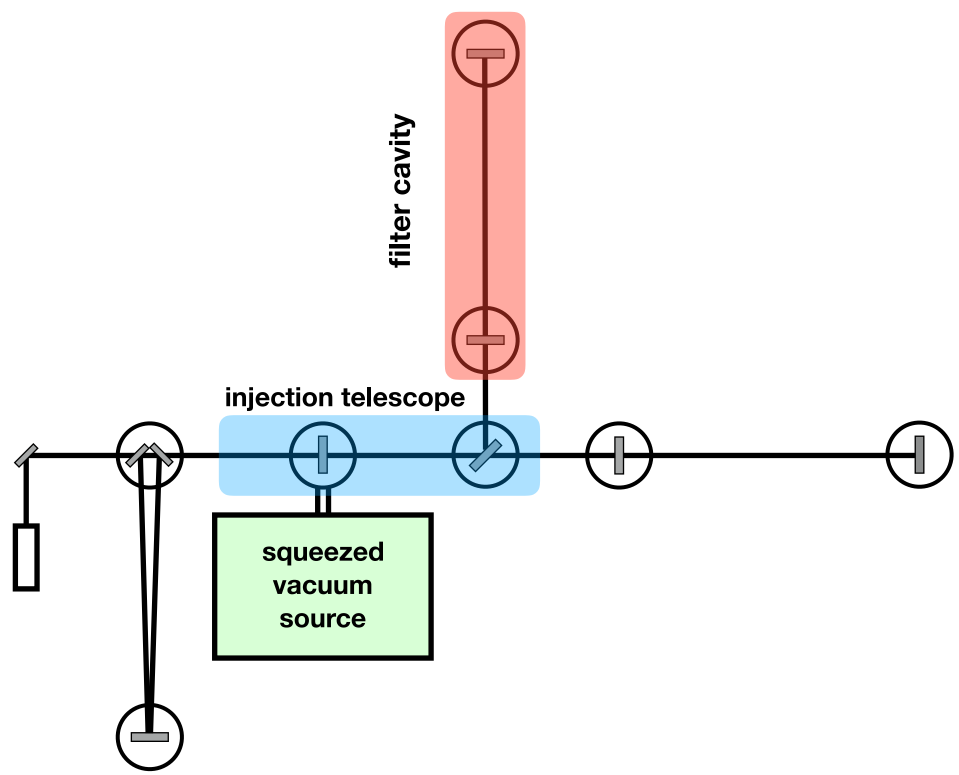


Audio-band frequency-dependent squeezing

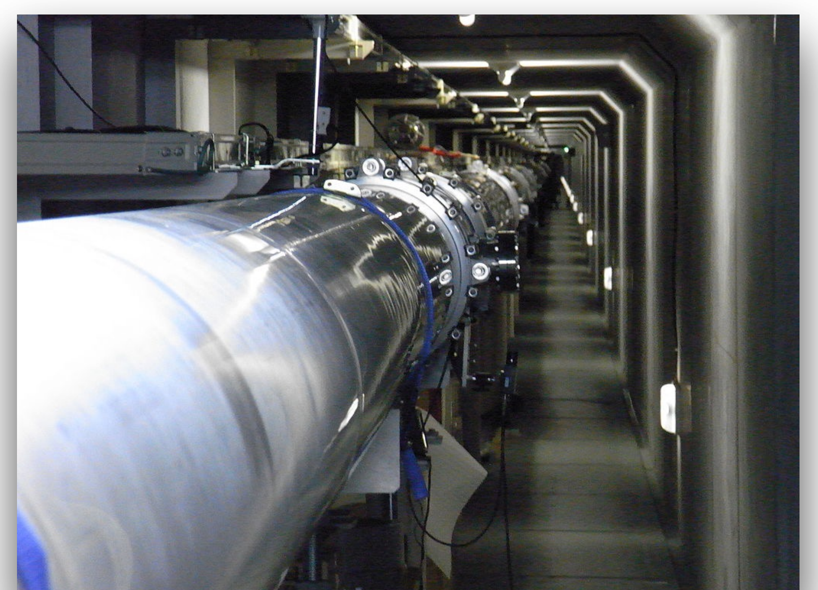
Eric Oelker, Tomoki Isogai, John Miller, Maggie Tse, Lisa Barsotti, Nergis Mavalvala, and Matthew Evans
Massachusetts Institute of Technology, Cambridge, MA 02139, USA
(Dated: August 20, 2015)

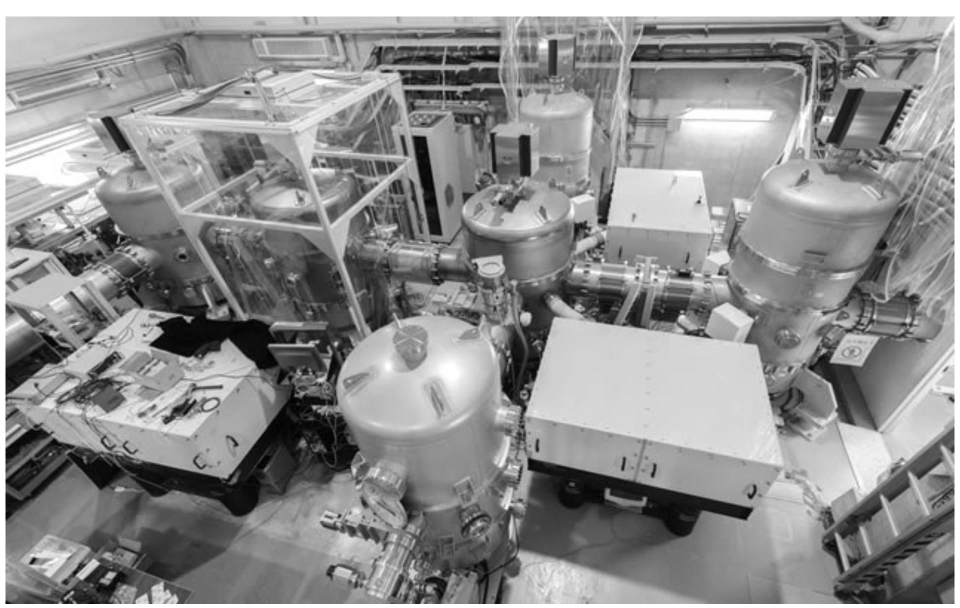
300 m filter cavity at TAMA (NAOJ)

GOAL: full scale filter cavity prototype to demonstrate frequency dependent squeezing with rotation at 70 Hz



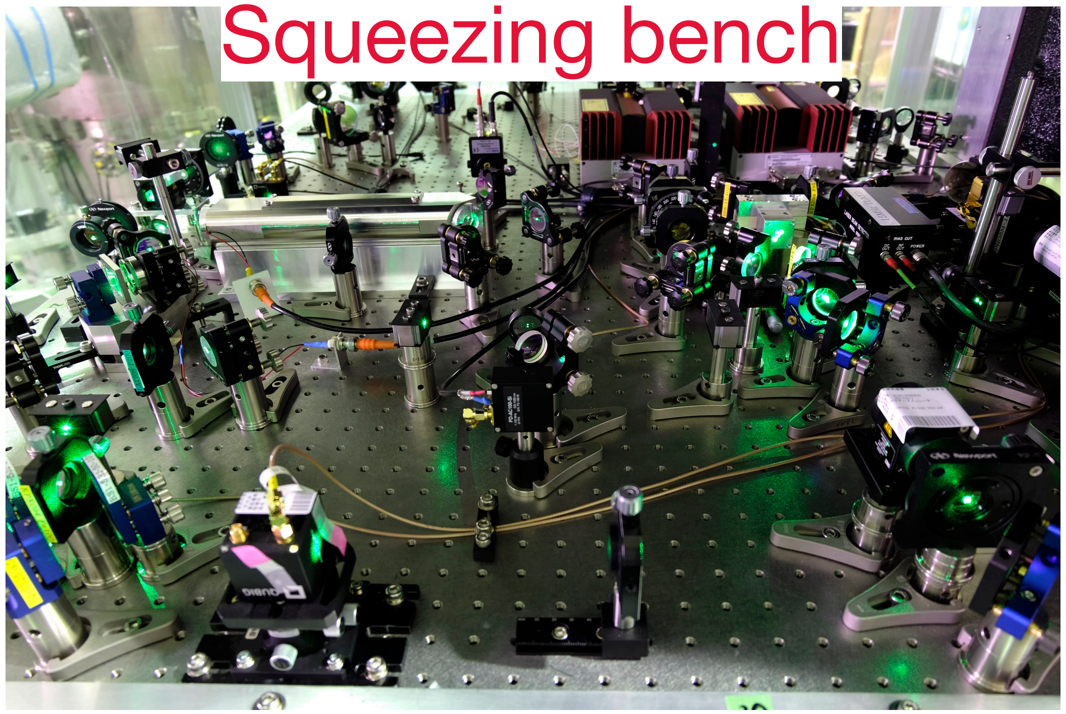
- Cavity length: 300m
- Finesse: 4500
- Storage time: 3 ms
- 9 dB freq. independent squeezing





Experiment overview

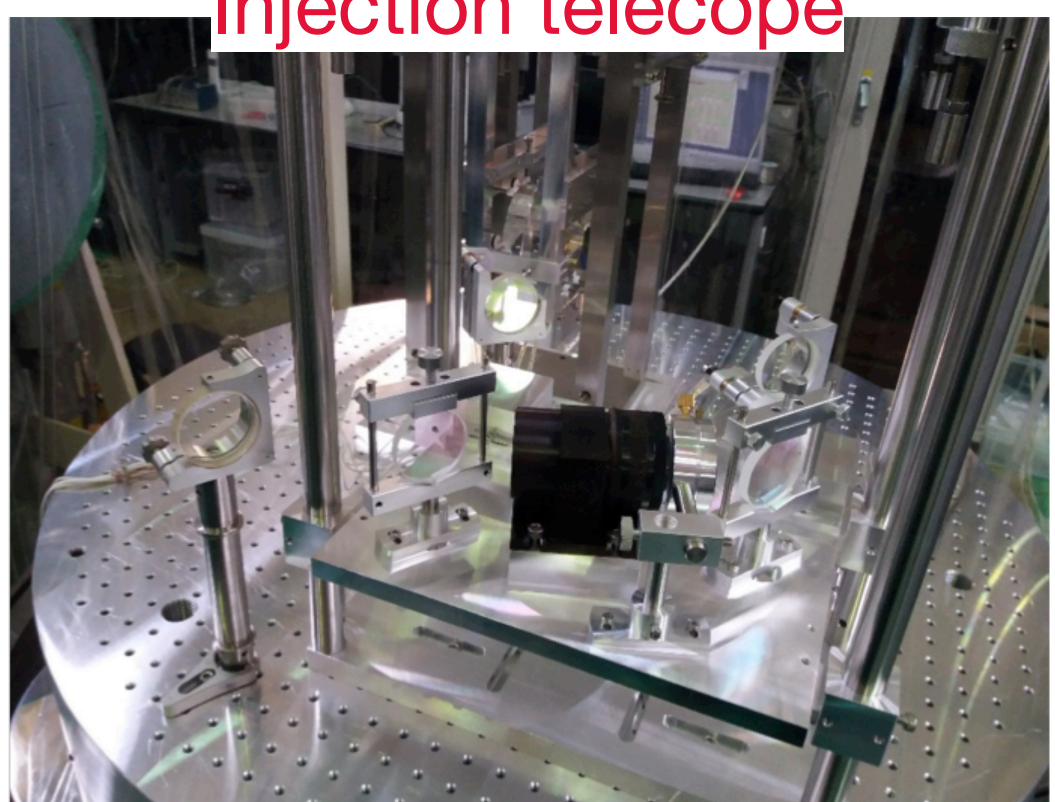
Squeezing bench



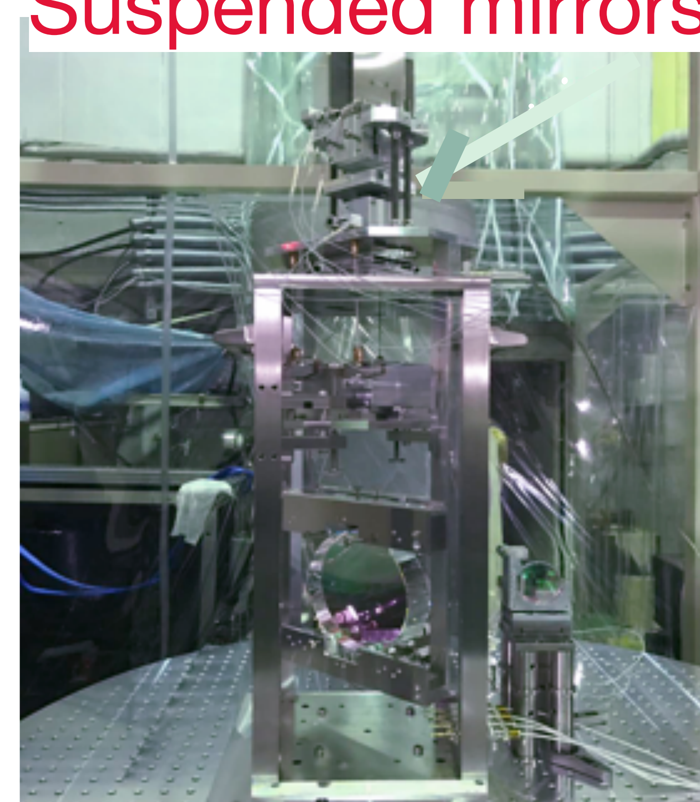
TAMA central building

Cleanroom
Class 1000

Injection telecope



Suspended mirrors

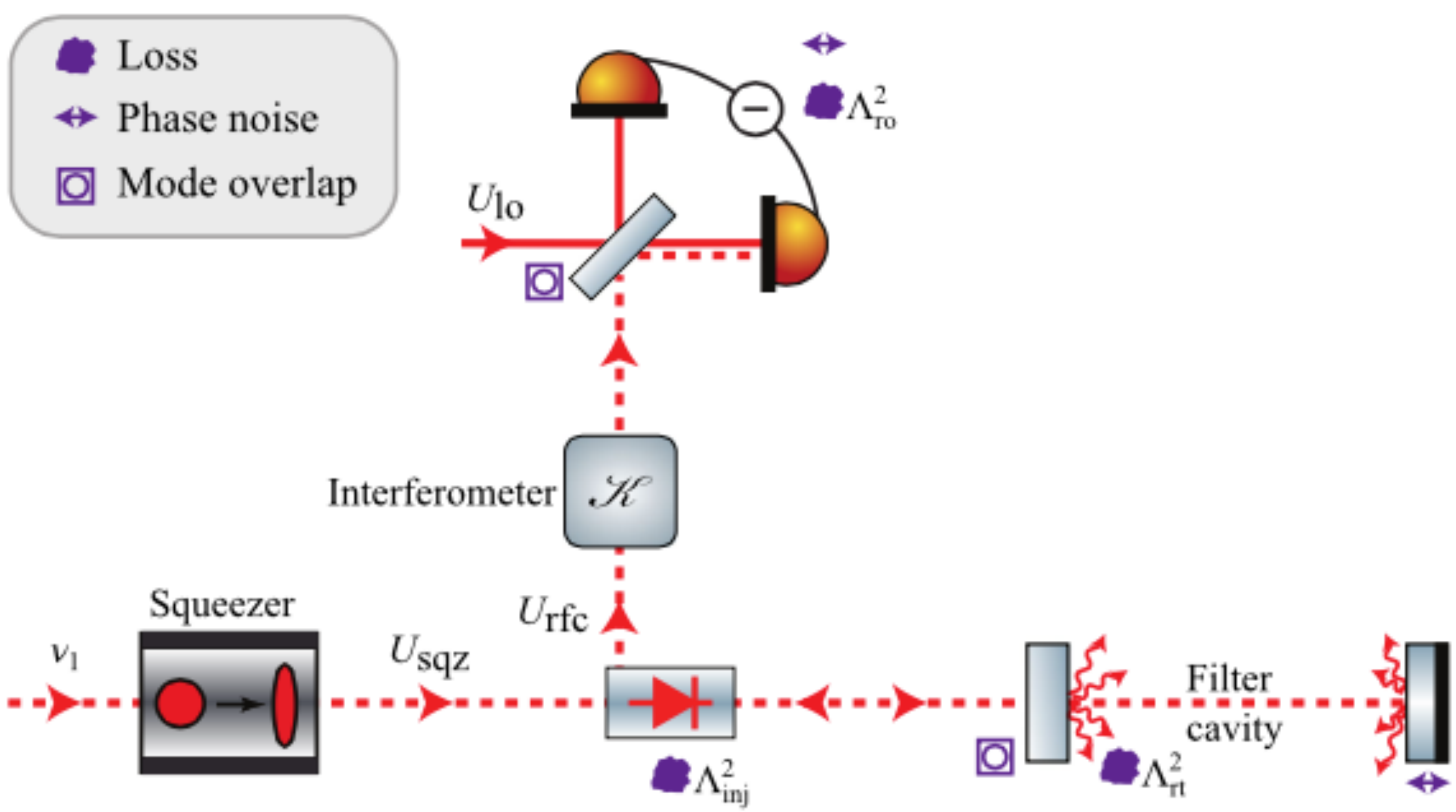


Many loss source can degrade the squeezing

PHYSICAL REVIEW D 90, 062006 (2014)

Decoherence and degradation of squeezed states in quantum filter cavities

P. Kwee, J. Miller,* T. Isogai, L. Barsotti, and M. Evans



- Filter cavity losses
- Injection/readout losses
- Mode mismatch
- Frequency-dependent phase noise

Quantum fluctuation entering with losses should be taken into account

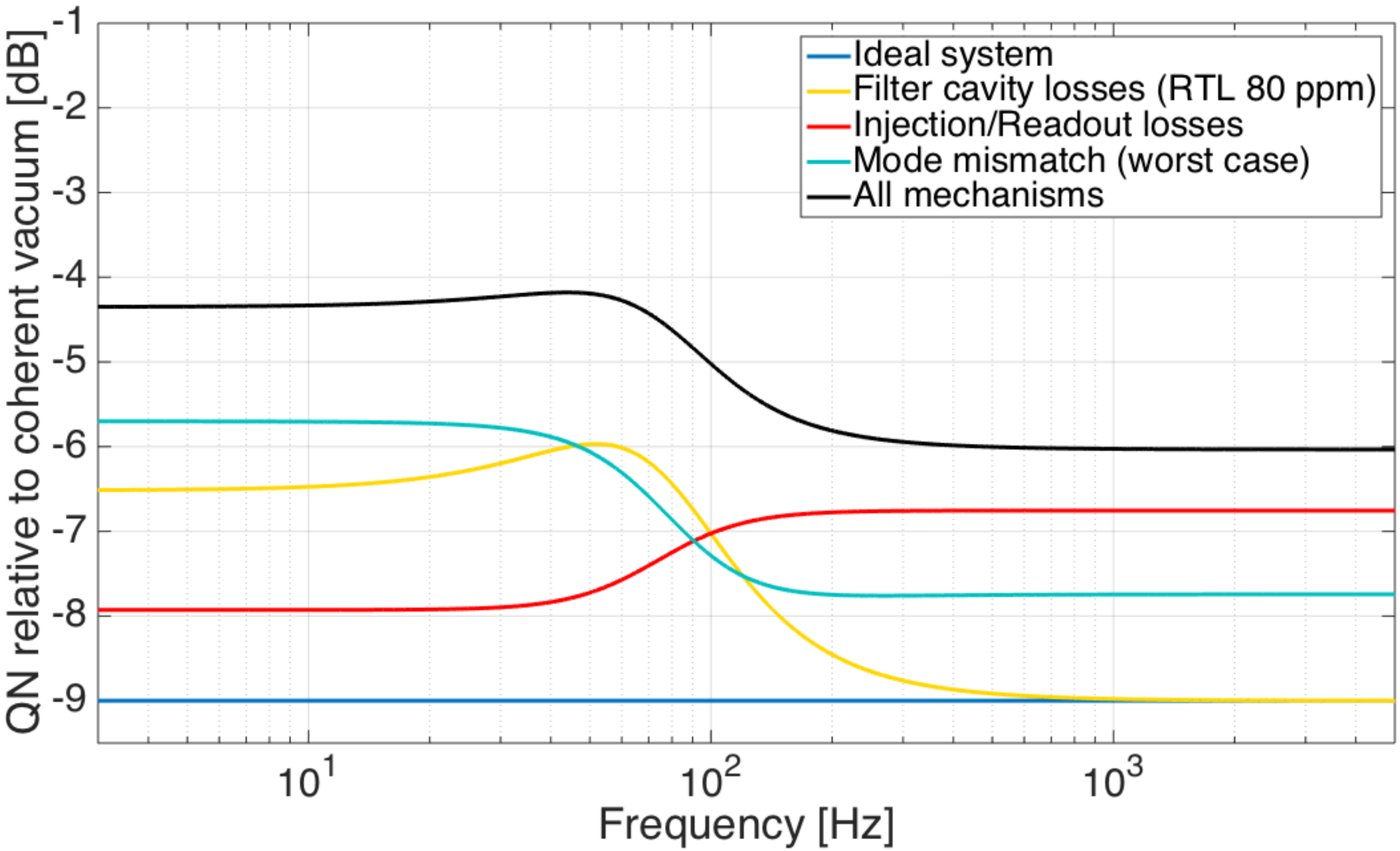
$$N(\zeta) = |\bar{\mathbf{b}}_\zeta \cdot \mathbf{T_1} \cdot v_1|^2 + |\bar{\mathbf{b}}_\zeta \cdot \mathbf{T_2} \cdot v_2|^2 + |\bar{\mathbf{b}}_\zeta \cdot \mathbf{T_3} \cdot v_3|^2$$

squeezed field

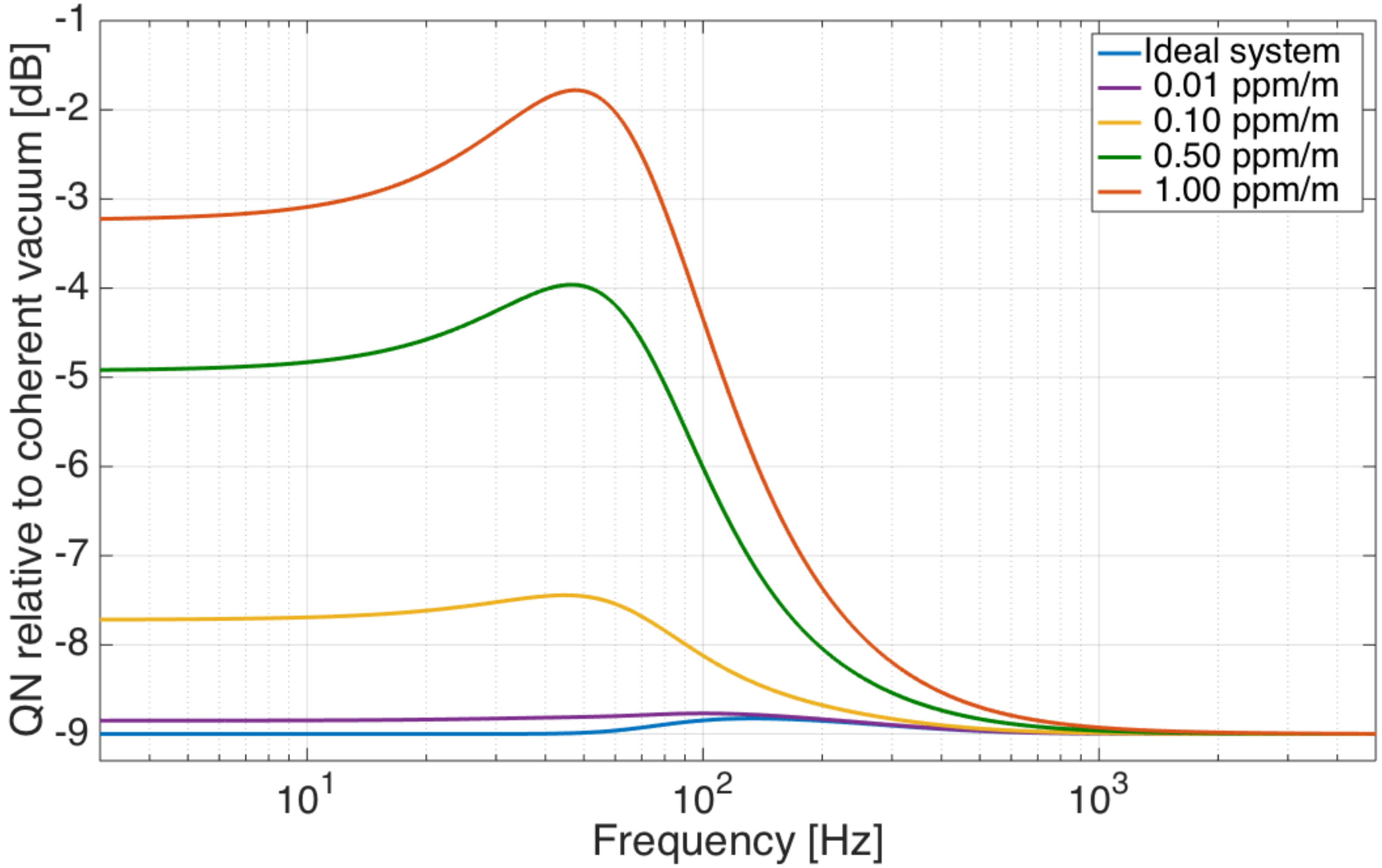
vacuum fluctuation due to losses before the ITF

vacuum fluctuation due to losses after the ITF

Squeezing degradation



Squeezing degradation from filter cavity losses



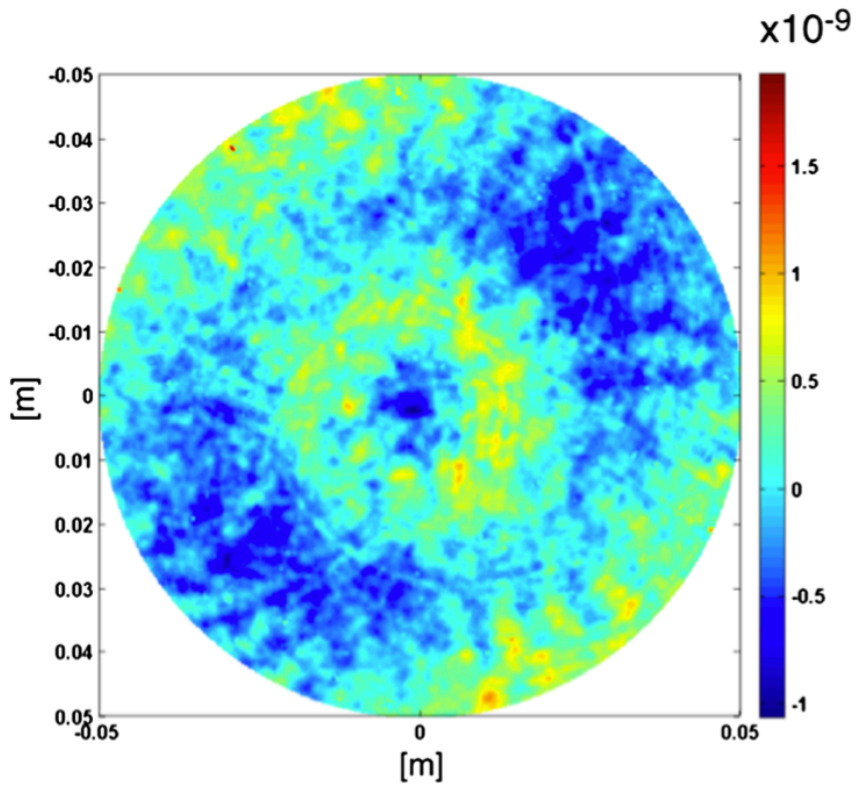
- Losses are more influent at low frequency where the squeezing experiences the rotation

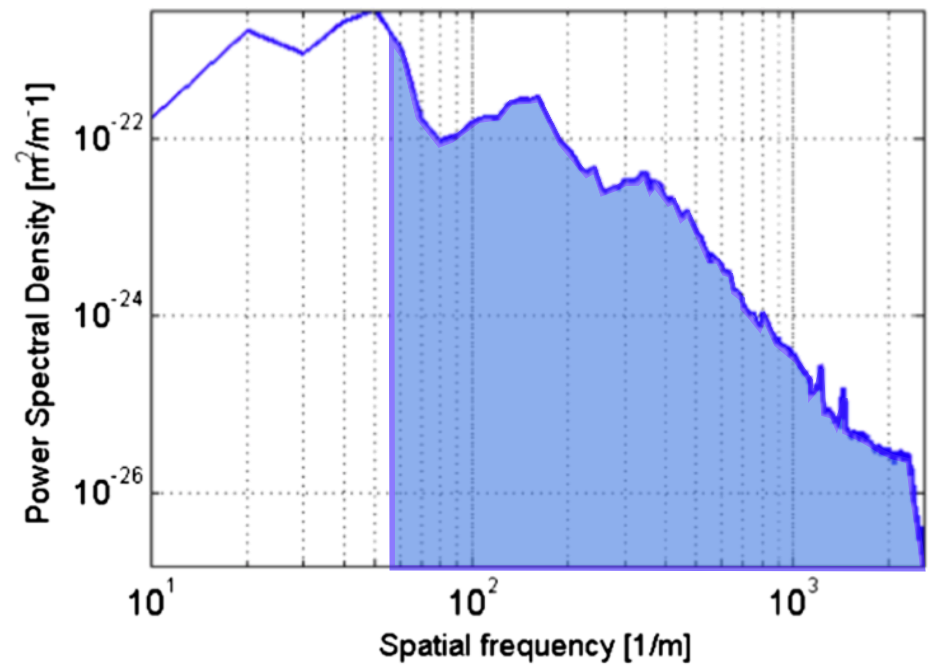
- The cavity performance depends on the loss per unit length

The origin of filter cavity losses

- Light scattered from mirror defects

$$f_{\text{limit}} = \frac{d}{2L \times \lambda}$$



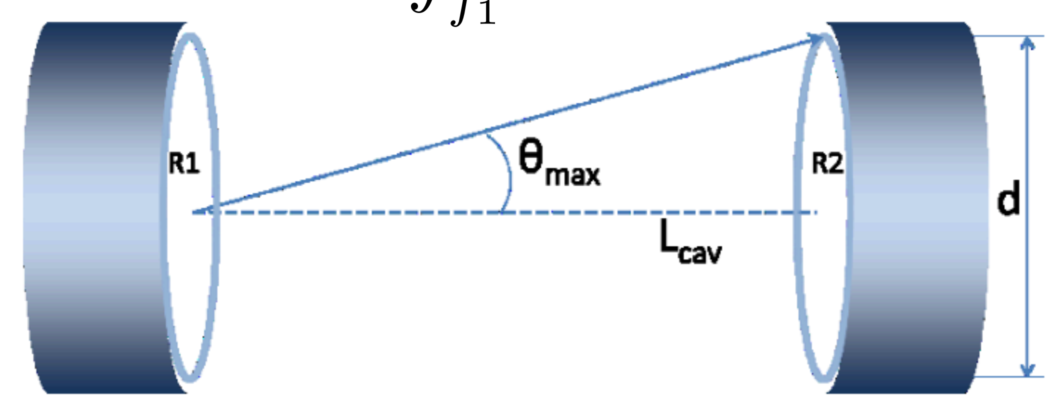


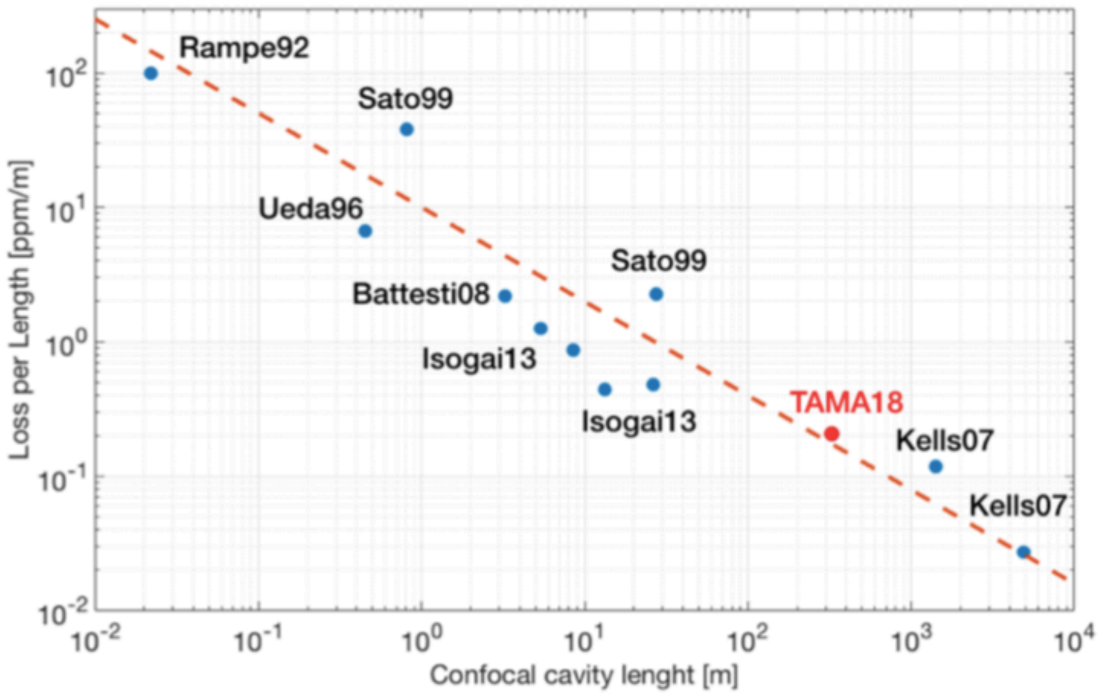
Diffraction angle: $\theta = \lambda \times f$

$$\sigma^2 = \int_{f_1}^{f_2} PSD(f)df$$

Scattering golden rule:

$$\text{losses}_{(f > f_{\text{limit}})} = \left(\frac{4\pi \times \sigma}{\lambda}\right)^2$$





The loss per unit length are observed to decrease with cavity length

How to minimise the effect of the losses?

Increasing cavity length

Improve the mirrors quality (which are the limits?)

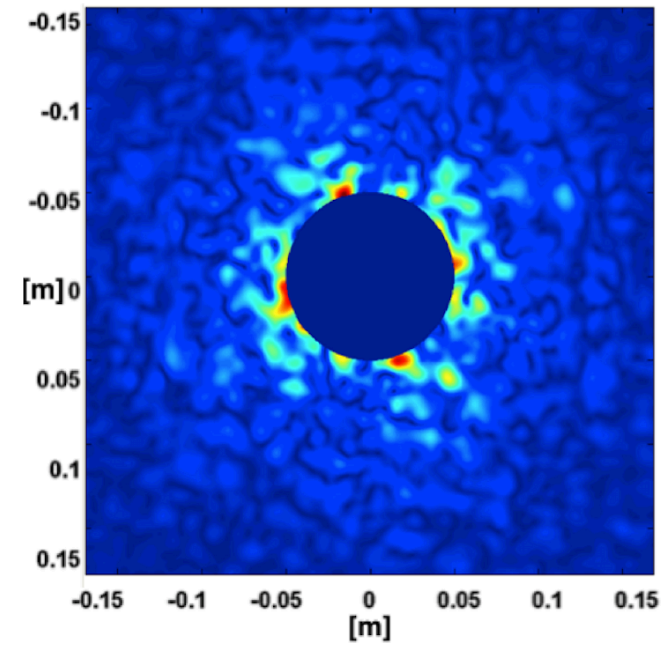
Squeezing degradation from filter cavity losses

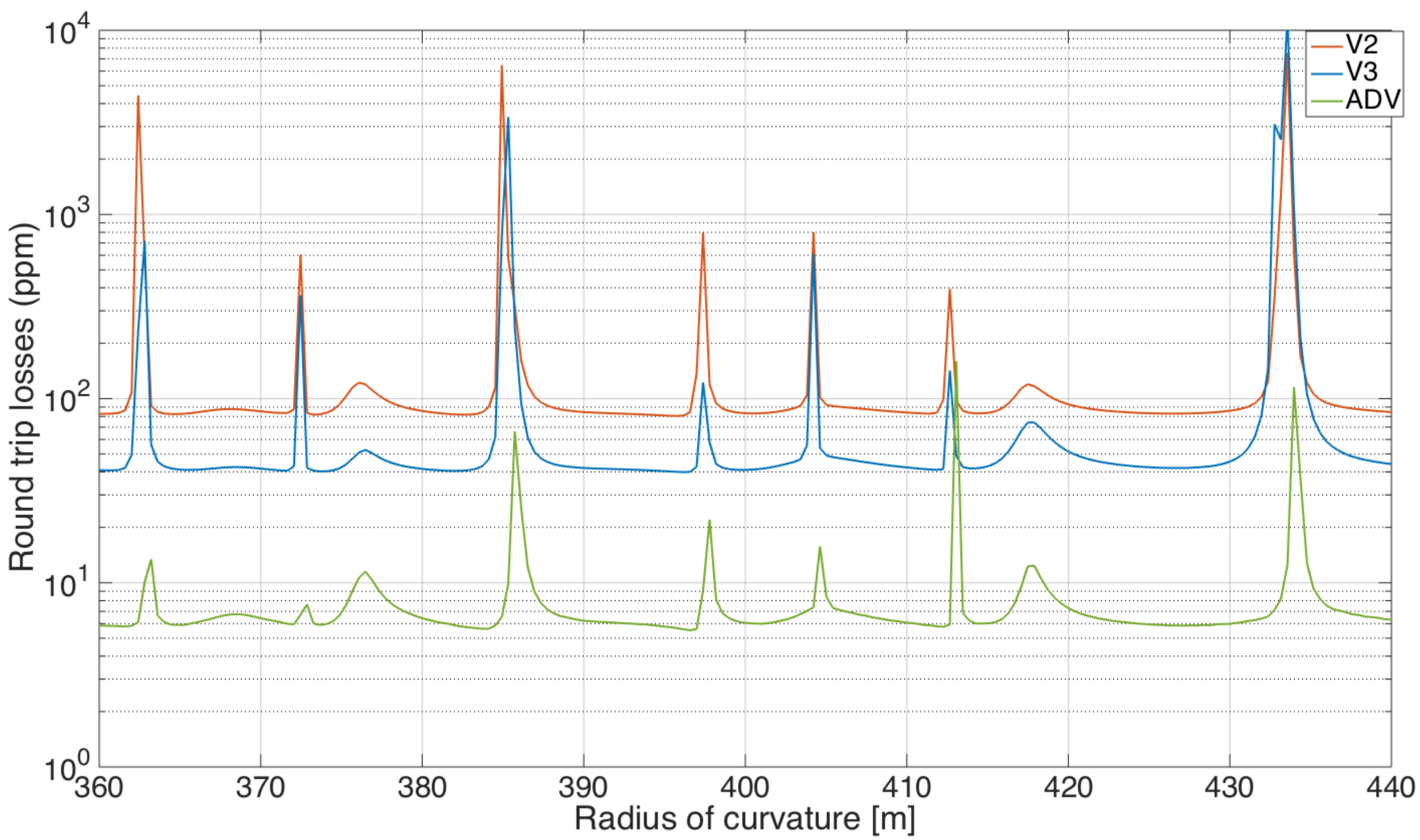
- Simulation to measure losses associated to different mirror quality

PHYSICAL REVIEW D **93**, 082004 (2016)

Estimation of losses in a 300 m filter cavity and quantum noise reduction in the KAGRA gravitational-wave detector

Eleonora Capocasa,[1,2,*] Matteo Barsuglia,[1] Jérôme Degallaix,[3] Laurent Pinard,[3] Nicolas Straniero,[3] Roman Schnabel,[4] Kentaro Somiya,[5] Yoichi Aso,[2] Daisuke Tatsumi,[2] and Raffaele Flaminio[2]



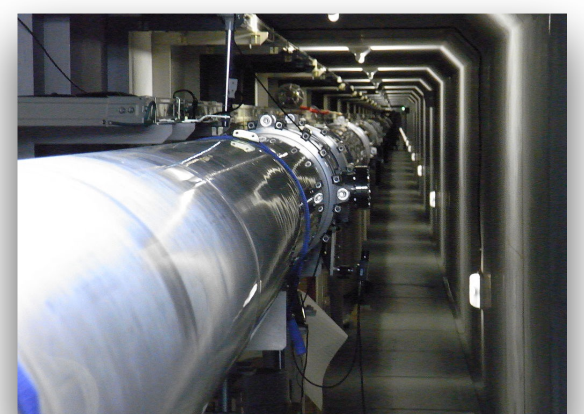


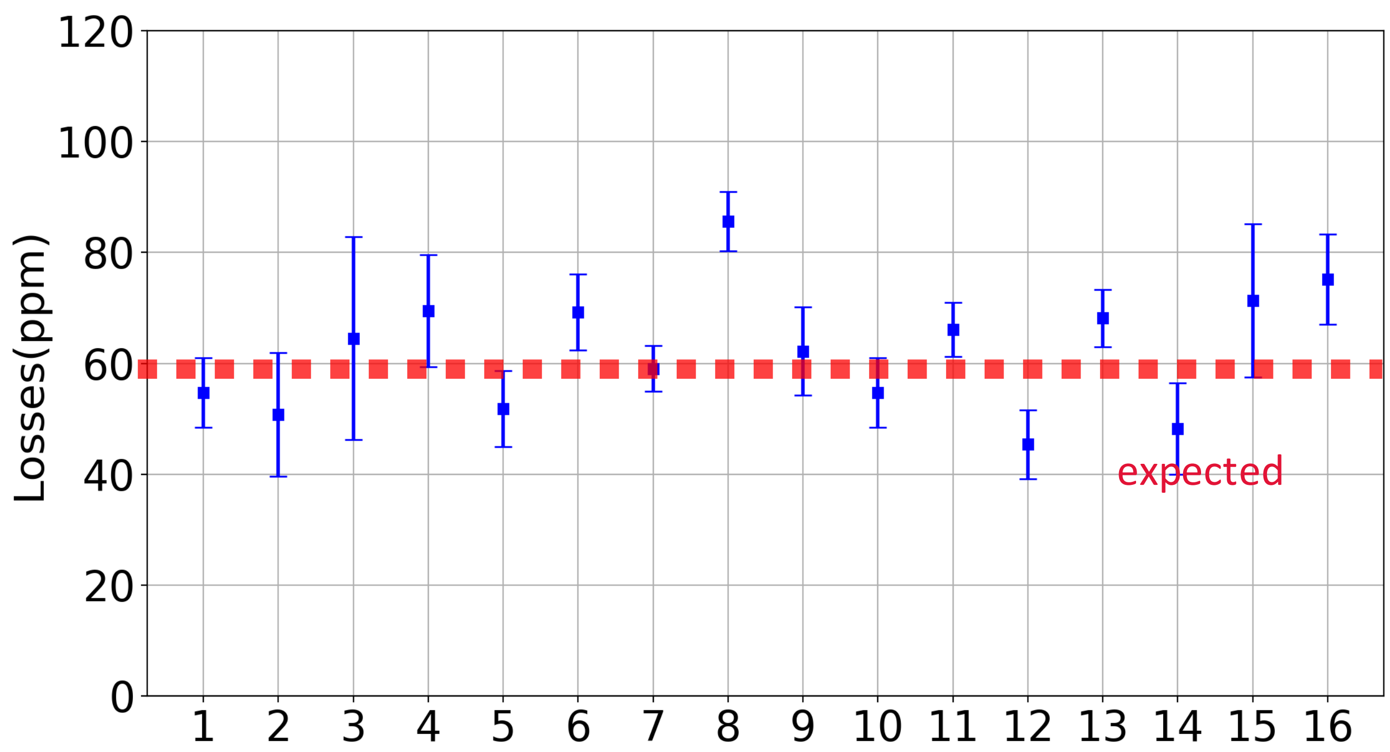
80 ppm
41 ppm
5.7 ppm

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

Filter cavity operation and characterization

- Main laser locked on the cavity length
- Cavity characterization performed: losses compliant with the requirement of 80 ppm



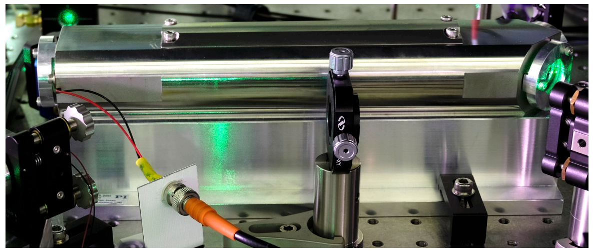


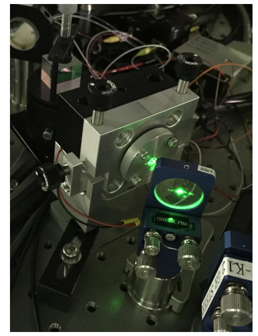
PHYSICAL REVIEW D **98,** 022010 (2018)

Measurement of optical losses in a high-finesse 300 m filter cavity for broadband quantum noise reduction in gravitational-wave detectors

Eleonora Capocasa,[1,2,*] Yuefan Guo,[3] Marc Eisenmann,[4] Yuhang Zhao,[1,5] Akihiro Tomura,[6] Koji Arai,[7] Yoichi Aso,[1] Manuel Marchiò,[1] Laurent Pinard,[8] Pierre Prat,[2] Kentaro Somiya,[9] Roman Schnabel,[10] Matteo Tacca,[11] Ryutaro Takahashi,[1] Daisuke Tatsumi,[1] Matteo Leonardi,[1] Matteo Barsuglia,[2] and Raffaele Flaminio[4,1]

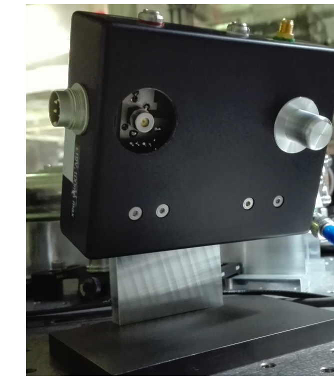
Squeezing optical bench





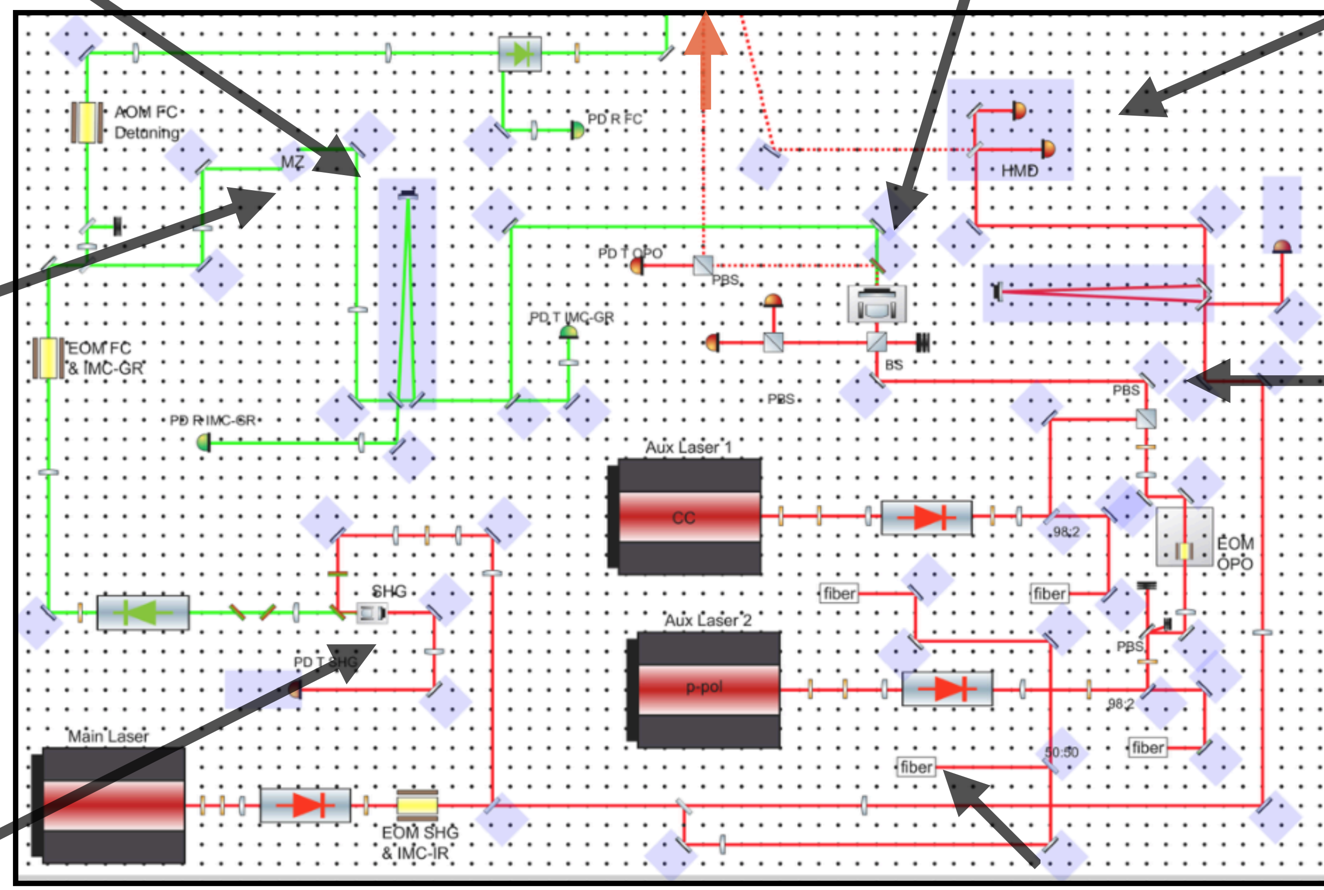
OPO installed an locked

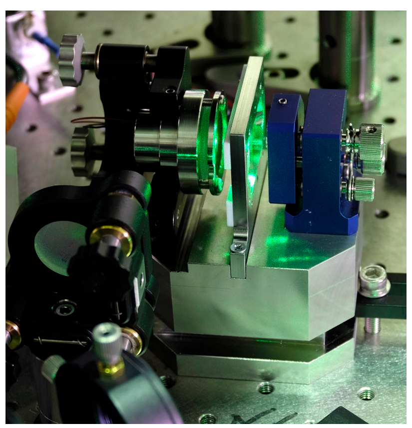
Homodyne detector installed



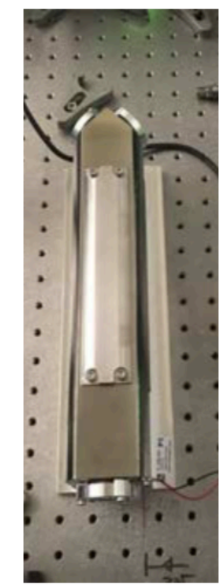
Geen mode cleaner and Mach-Zhender for power stabilization locked

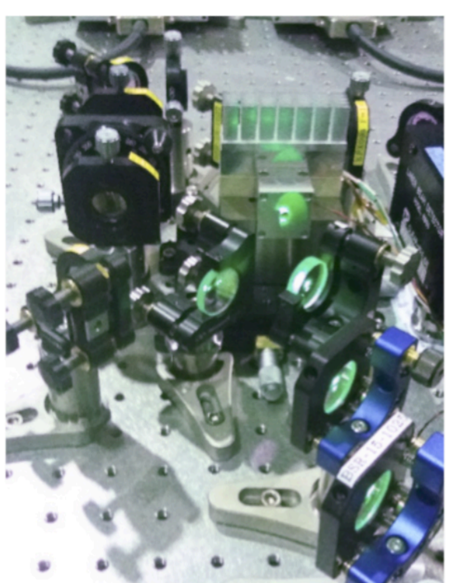
TO FILTER CAVITY



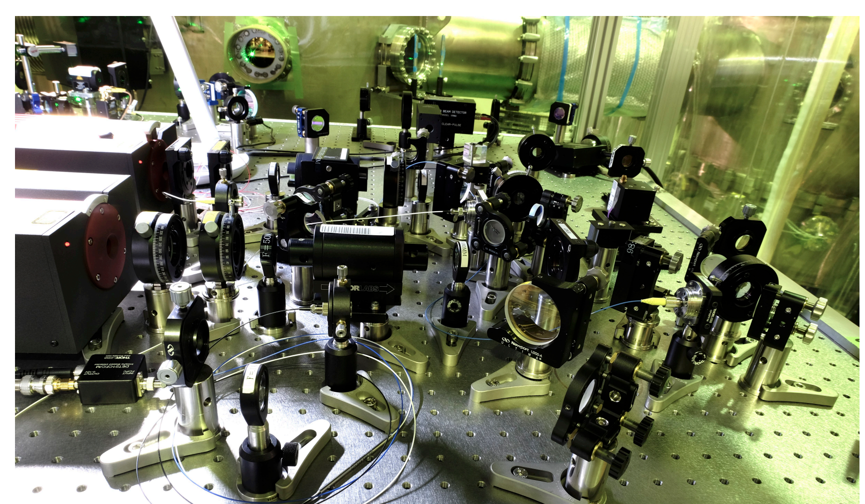


IR mode cleaner assembled and locked



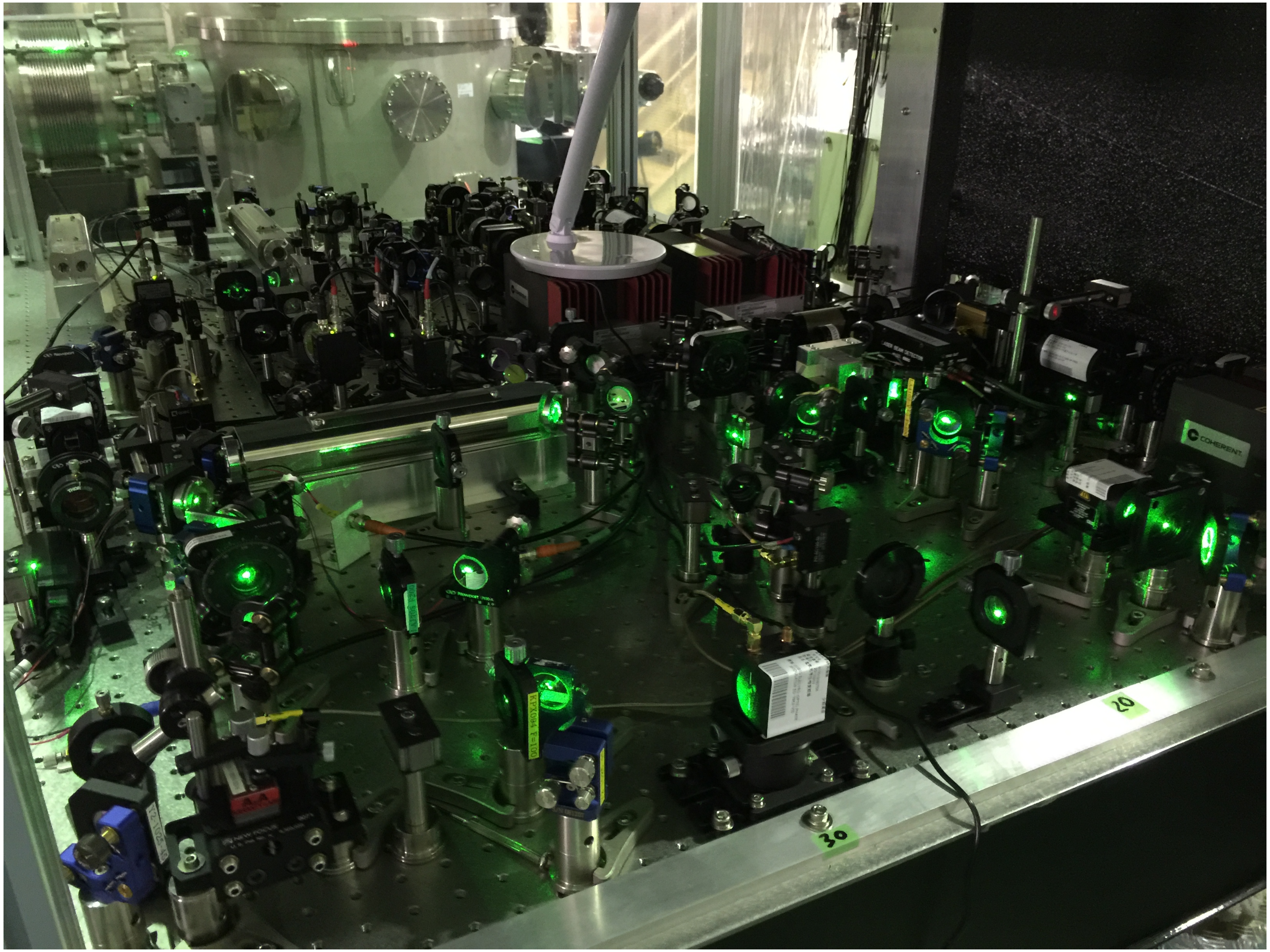


Second harmonic generator (SHG) assembled and operated



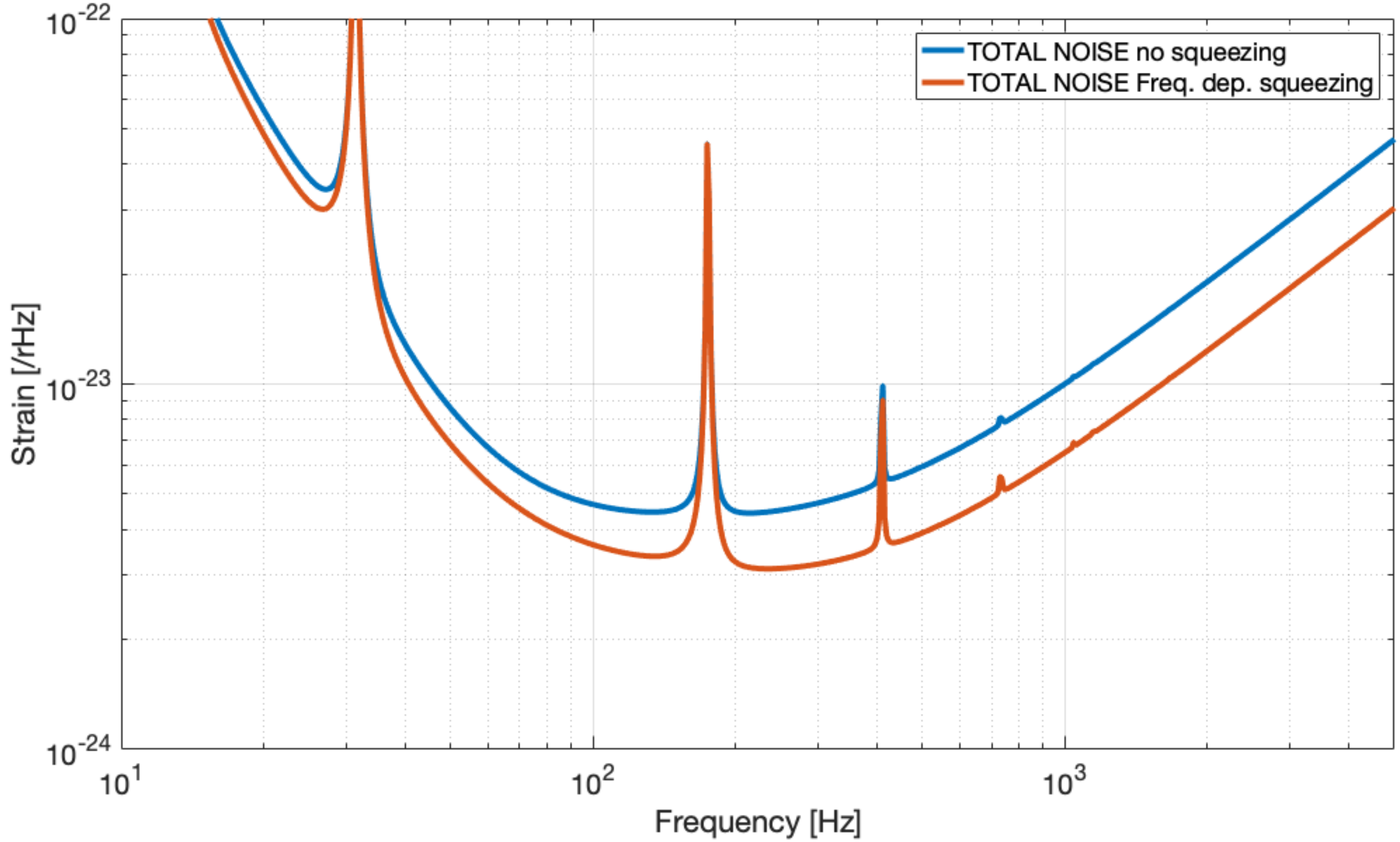
Phase locked loop (PLL) for Auxiliary lasers installed and locked

Squeezing optical bench



First squeezing measurement expected soon!

Expected improvement on KAGRA sensitivity

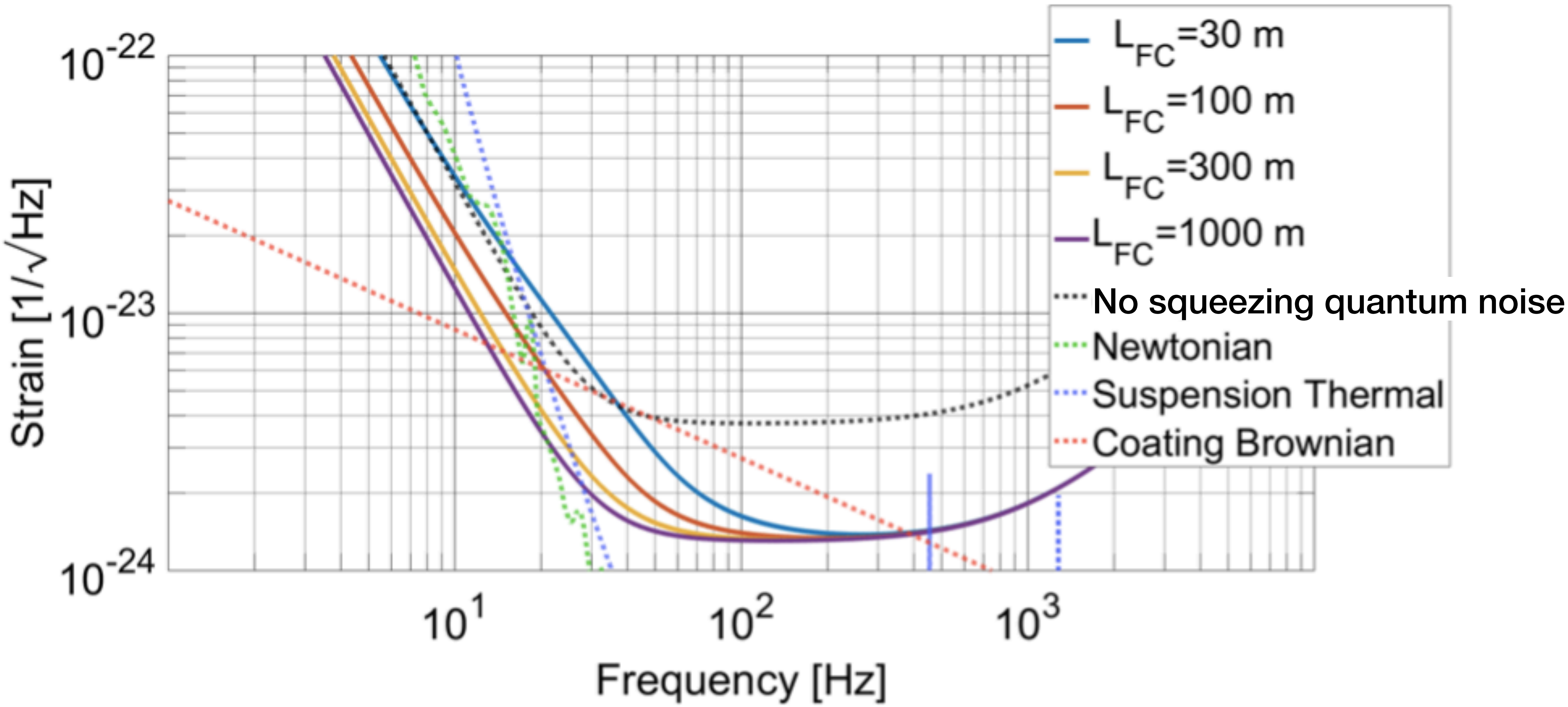


Horizon without squeezing BNS = 289 Mpc BBH = 2.26 Gpc

Horizon with squeezing BNS = 374 Mpc BBH = 2.89 Gpc

Filter cavity in 2nd generation detectors

- 300 m filter cavity are planned for Advanced Virgo and Advanced Ligo upgrade
- Further increasing the length seems not so convenient



Eisenmann et al. VIR-0312A-18

Filter cavity in 2nd generation detectors

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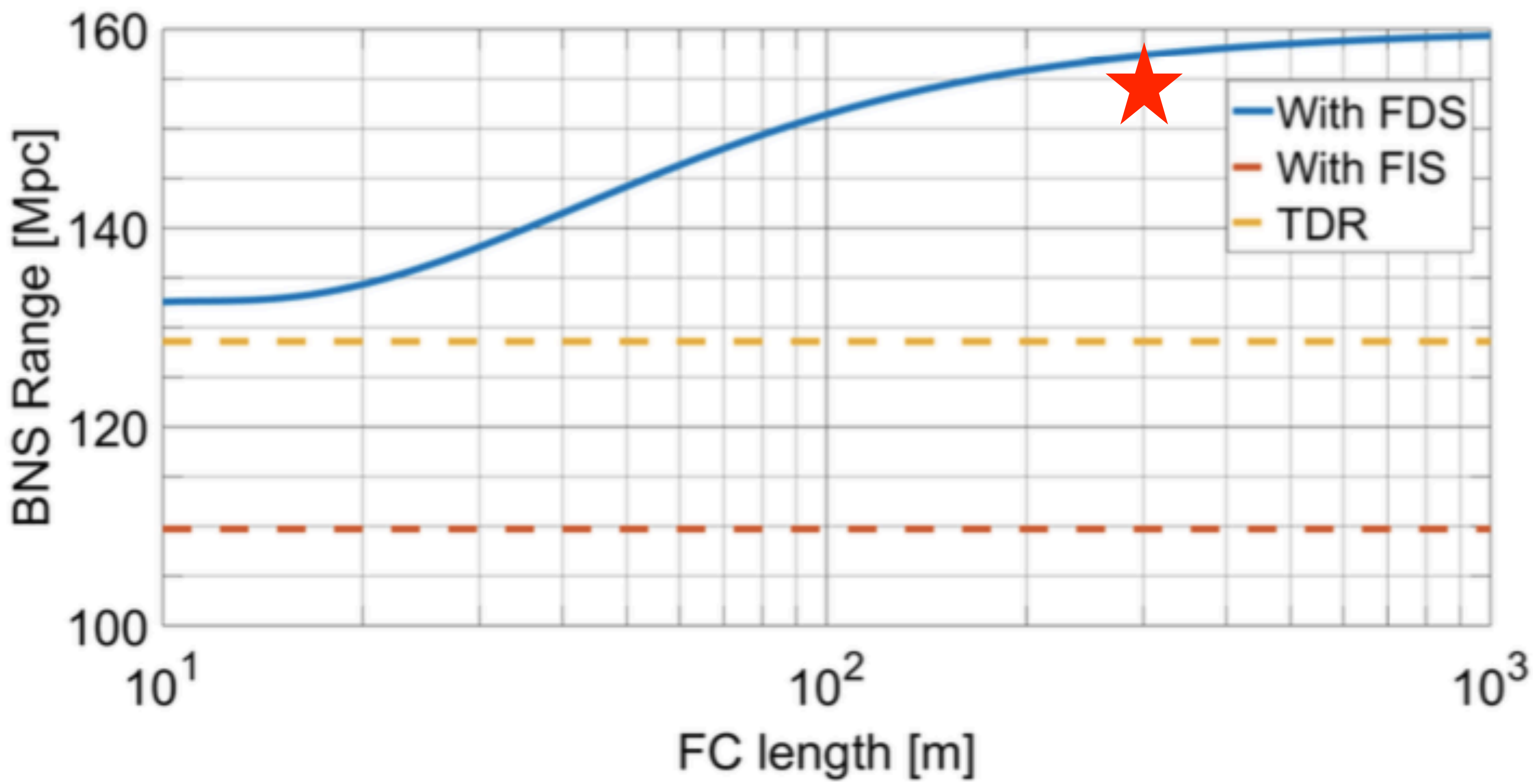
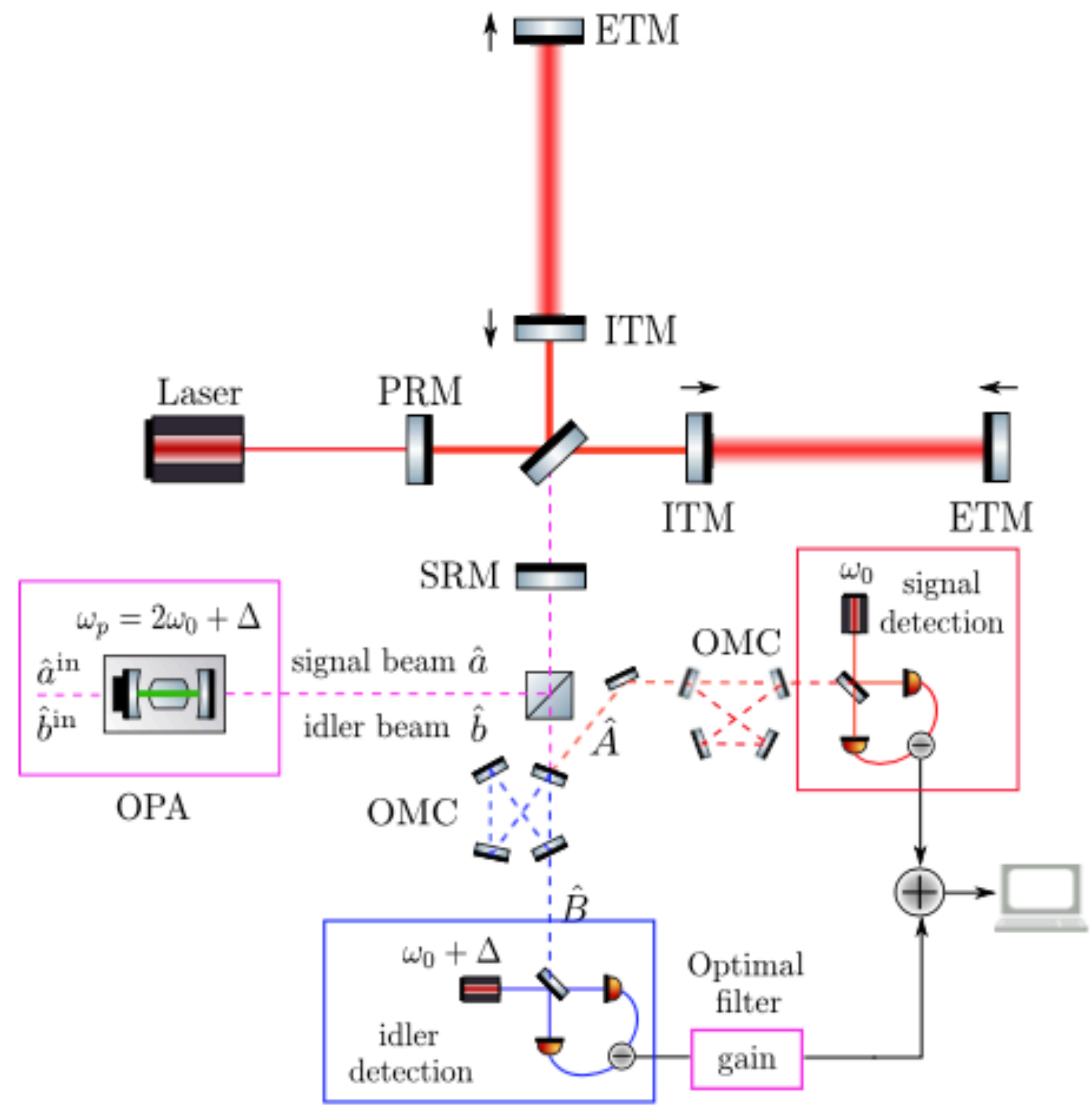
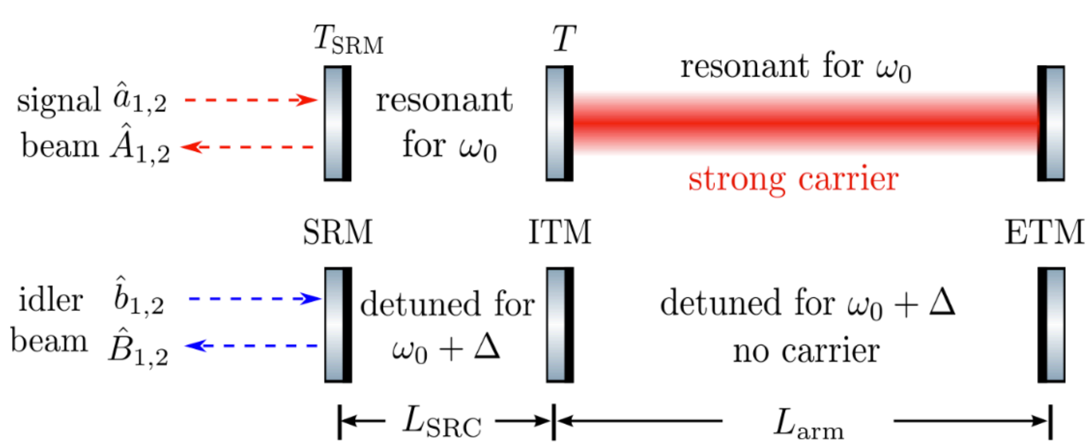


Eisenmann et al. VIR-0312A-18

Frequency dependent squeezing via EPR entanglement

- The main idea: inject a pair of EPR-entangled beams from the ITF dark port
- If one of the beams is detuned from the carrier, it will see the ITF as a detuned cavity -> thus it will experience frequency dependent squeezing
- Measuring a fixed quadrature of the detuned beam will allow to conditionally squeeze the other beam in a frequency dependent way





ARTICLES

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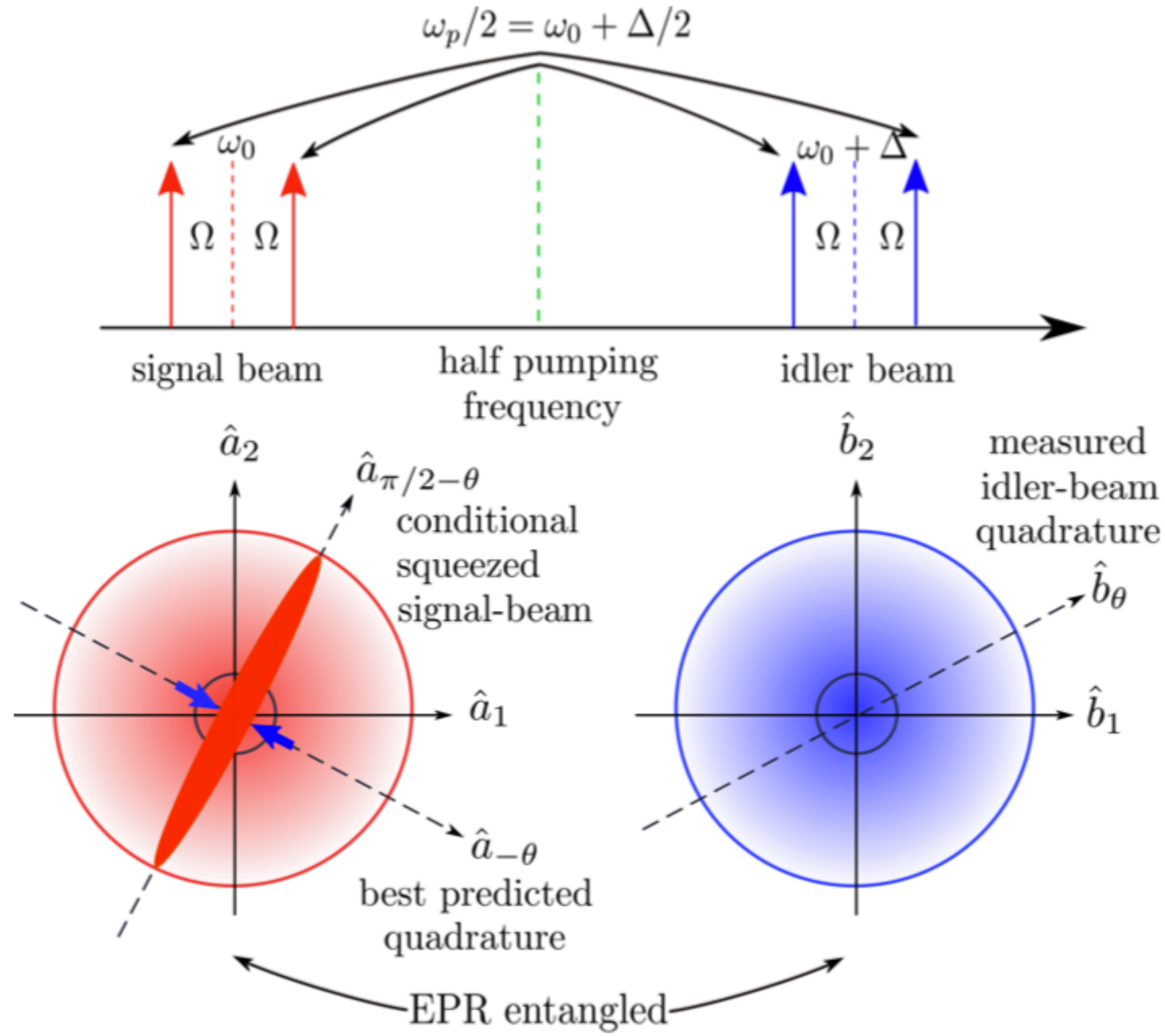
nature physics

Proposal for gravitational-wave detection beyond the standard quantum limit through EPR entanglement

Yiqiu Ma[1]*, Haixing Miao[2], Belinda Heyun Pang[1], Matthew Evans[3], Chunnong Zhao[4], Jan Harms[5,6], Roman Schnabel[7] and Yanbei Chen[1]

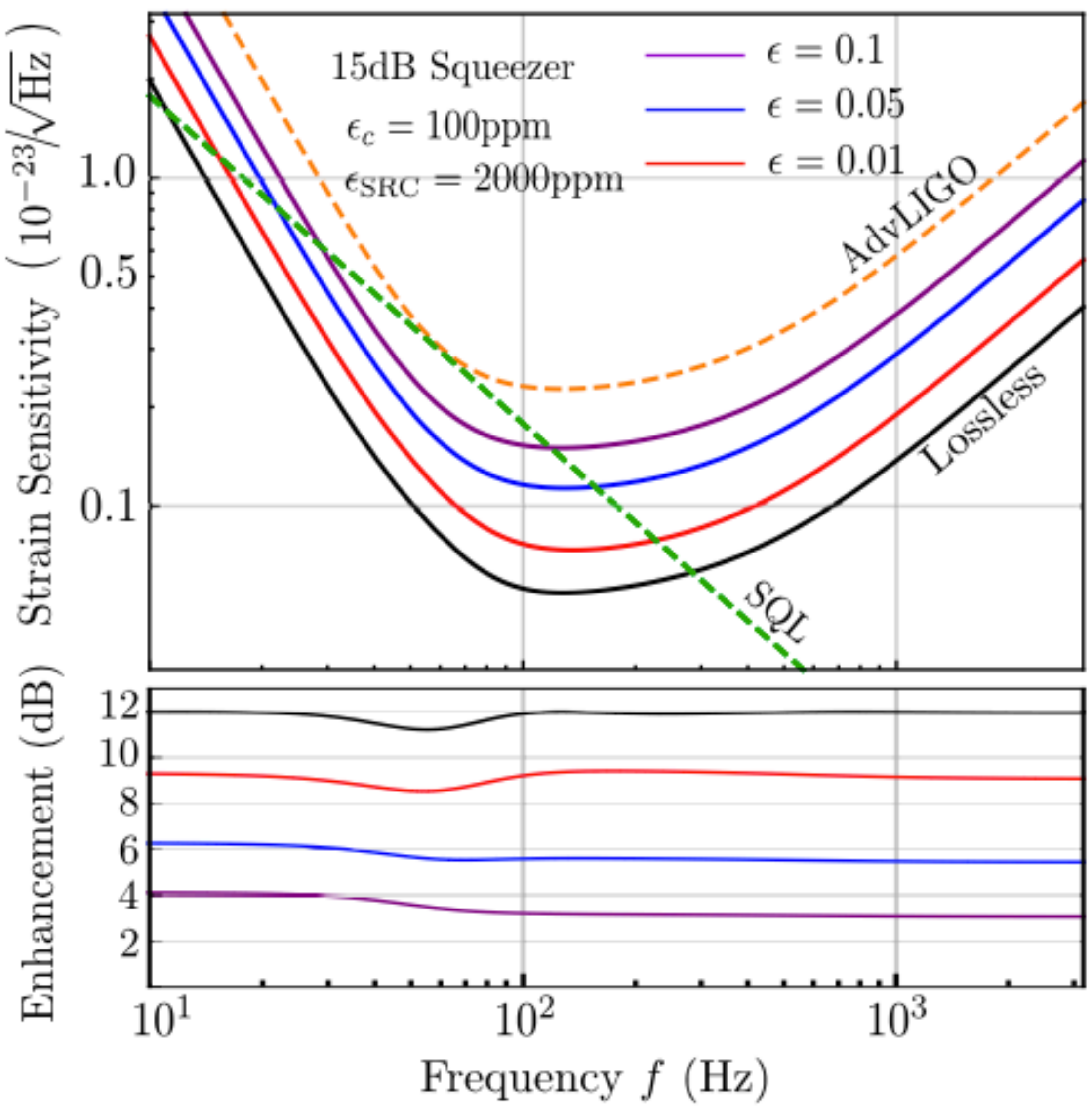
EPR entangled beam generation

- EPR entangled beams realized by detuning the pumping frequency of the Optical Parametric Oscillator (OPO)
- If the pump frequency is shifted of Δ, correlations will be created between upper and lower symmetric sidebands around half of the pumping frequency $\omega_p/2 = \omega_0 + \Delta/2$



Nature Physics
Volume 13. 776–780 (2017)

Pros and cons with respect to filter cavity



Nature Physics
Volume 13. 776–780 (2017)

- ✔ No need of a filter cavity
- ✔ Reduced cavity losses
- ✘ Larger effect of input/output losses (they count twice, as there are two beams)
- ✘ Complexity of the conditional measurement

Conclusions

- Quantum noise is limiting the 2nd generation detector in a large fraction of the spectrum
- Frequency independent squeezing (FIS) is a mature technology able to mitigate quantum noise in the high frequency region
- FIS are now integrated in both AdLIGO and AdVirgo and are currently under commissioning
- Frequency dependent squeezing (FDS) would be able to bring a broadband quantum noise reduction
- The most mature technique to produce FDS makes use of ~100 scale filter cavity. Full scale demonstration on-going
- Another more sophisticated technique, the so-called EPR technique has been proposed and it’s currently being tested
- FDS will be a key technology for 3rd generation detectors