Broadband quantum noise reduction in Virgo using frequency dependent squeezing

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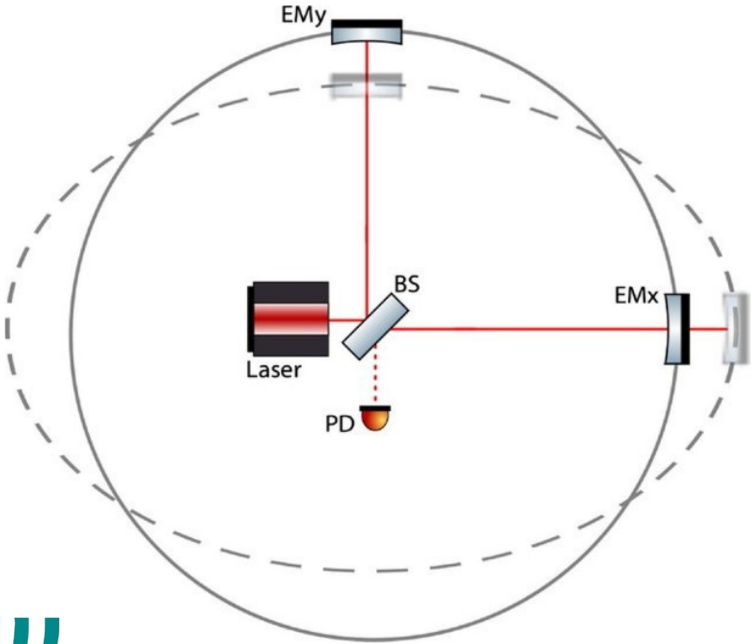
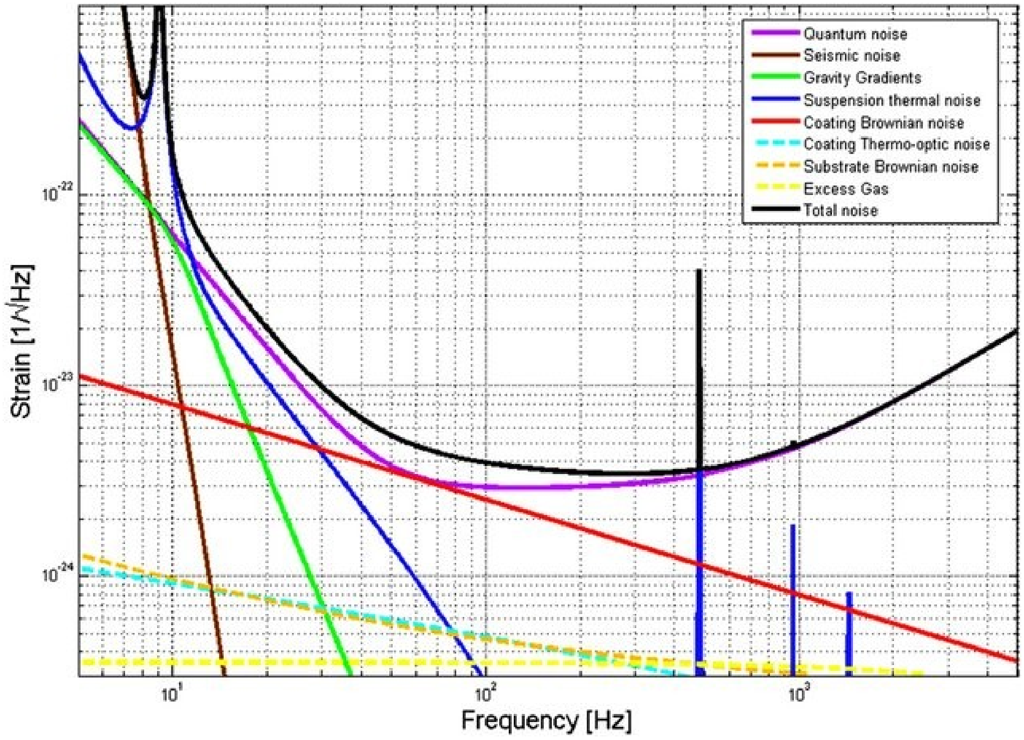
13th April 2021 - Journée Instrumentation GDR

- **Detection principle:** Michelson interferometer measures the difference in phase associated to the passing gravitational wave (GW)

$$\delta\phi_{\mathrm{GW}} = \frac{4\pi}{\lambda}\delta L_{\mathrm{GW}} \longrightarrow h = \frac{2\,\delta L_{\mathrm{GW}}}{L}$$

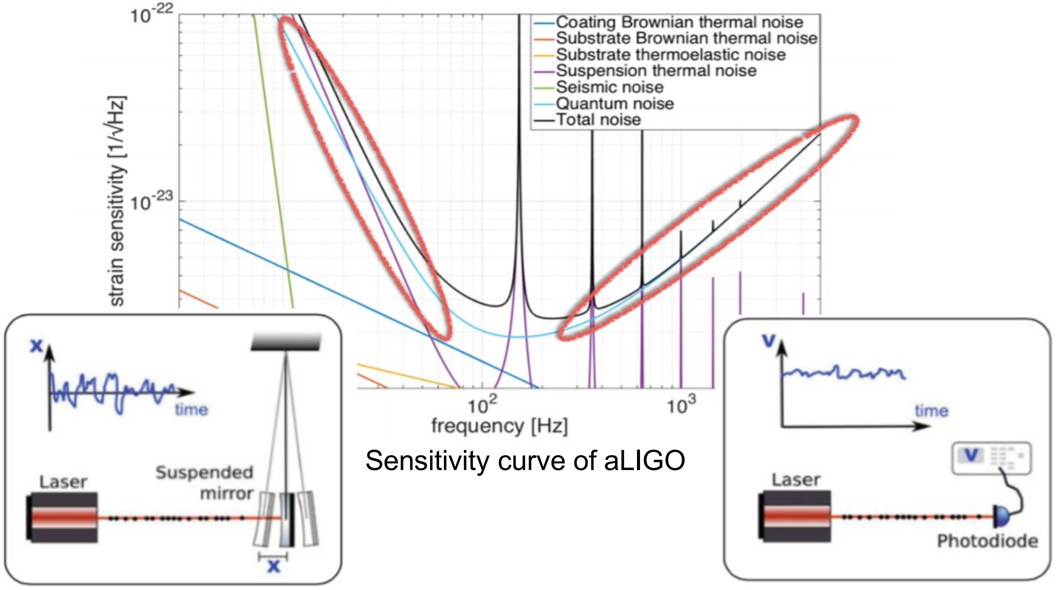




- **Introduction:**

✓ *Quantum noise (QN)* limits the sensitivity of GW detectors

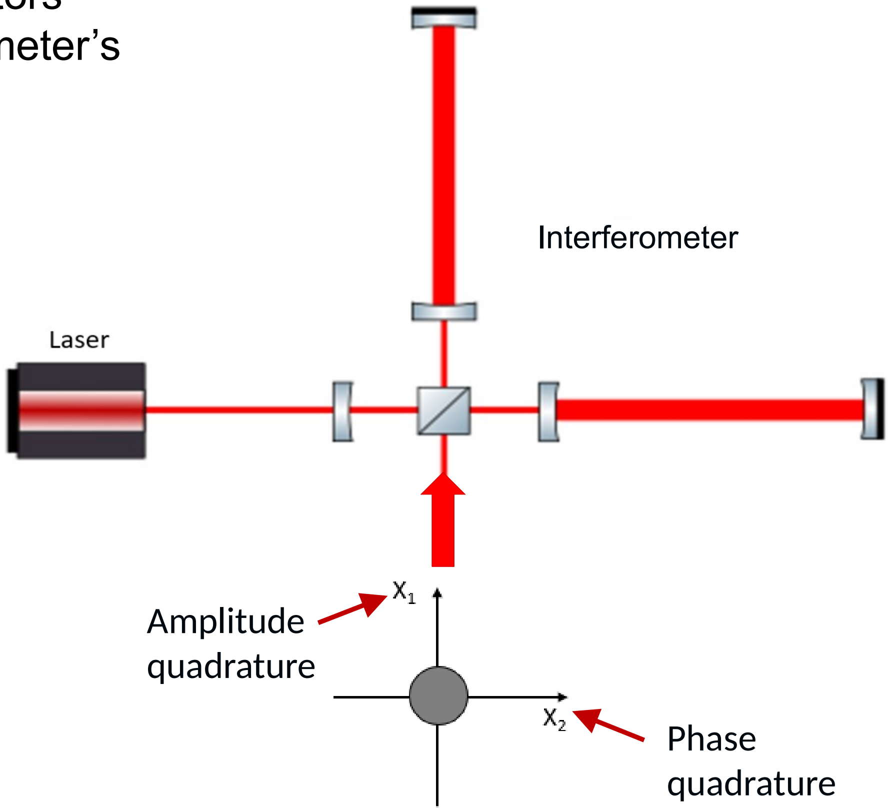
✓ *QN due only to vacuum fluctuations* entering interferometer's output port



Sensitivity curve of aLIGO

Radiation pressure noise

Shot noise



Quantum noise in GW detectors

- **Introduction:**

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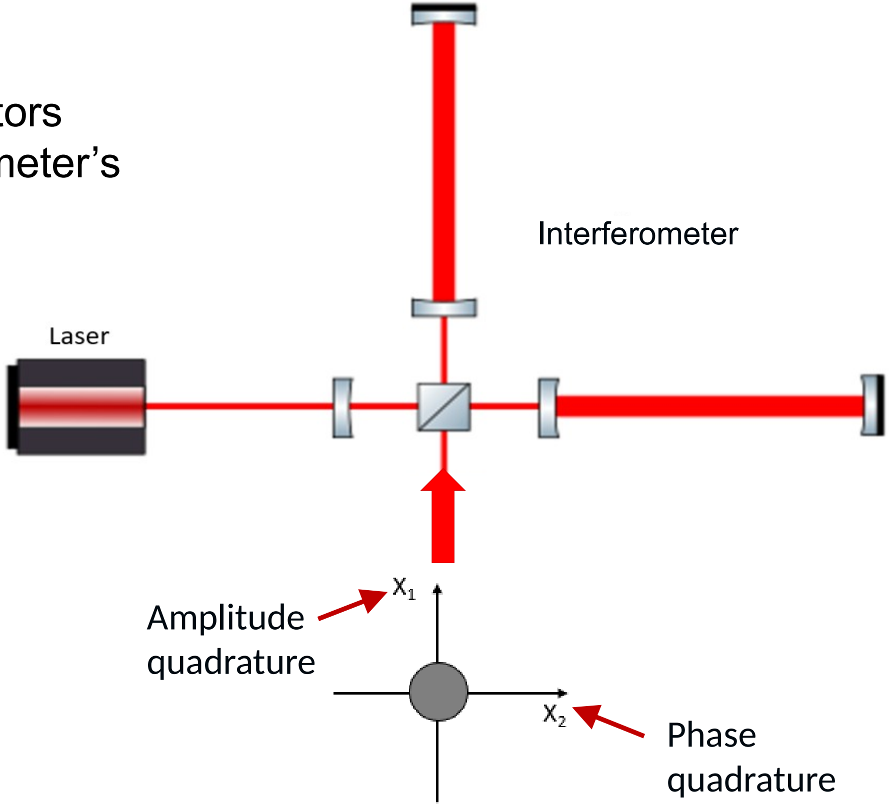
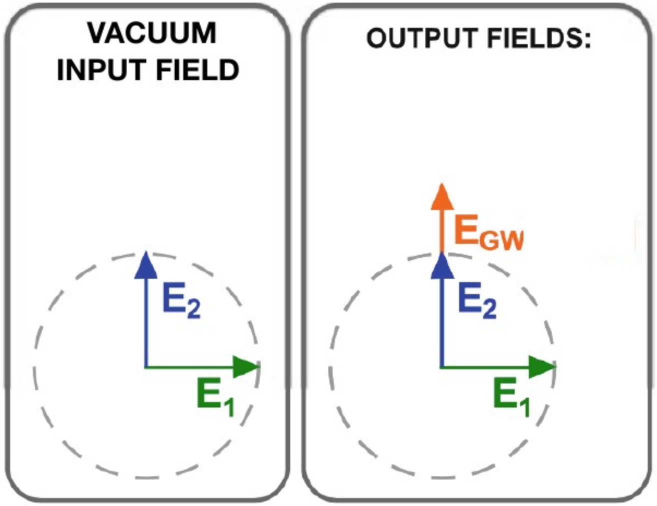


$$\hat{E}(t) = \left[E_0 + \hat{E}_1(t)\right]\cos\omega_0 t + \hat{E}_2(t)\sin\omega_0 t$$



$$\hat{\mathcal{H}} = \hbar\omega\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right) \rightarrow \hat{\mathcal{H}} = \hbar\omega\left(\hat{X}_1^2 + \hat{X}_2^2\right)$$

Minimal noise at Ω frequency is called the *standard quantum limit* (SQL):

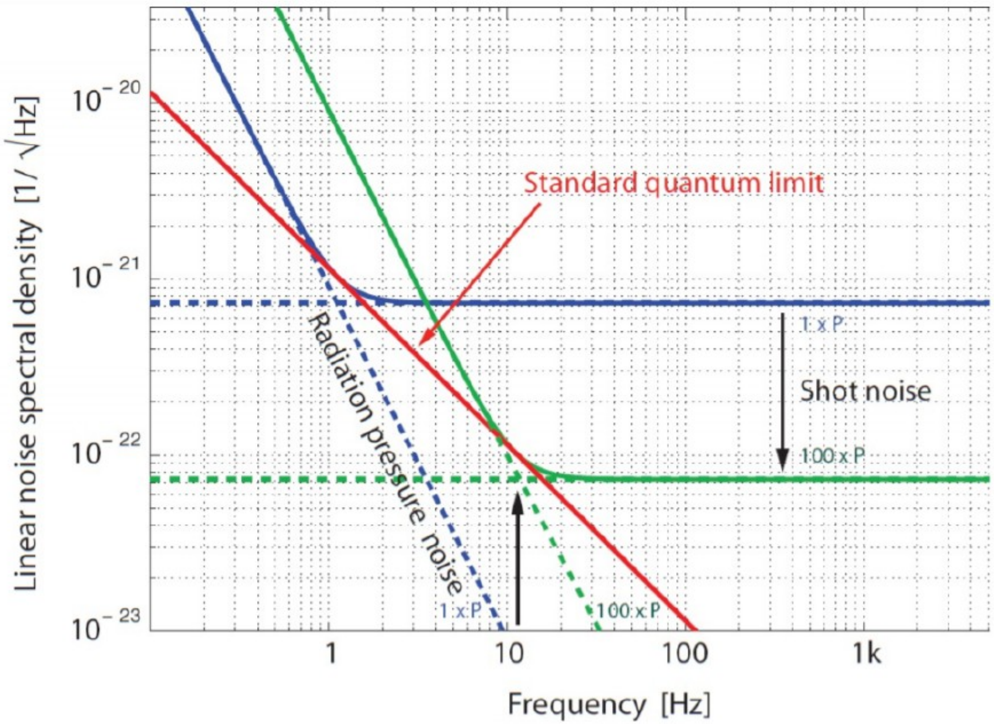
$$h^{SQL} \approx \sqrt{\frac{\hbar}{\pi^2 m L^2 \Omega^2}}$$

EM field Hamiltonian:

$$\hat{\mathcal{H}} = \hbar\omega\left(\hat{X}_1^2 + \hat{X}_2^2\right)$$

Heisenberg Uncertainty Principle:

$$(\Delta X_1)^2 (\Delta X_2)^2 \geq \frac{1}{16}$$

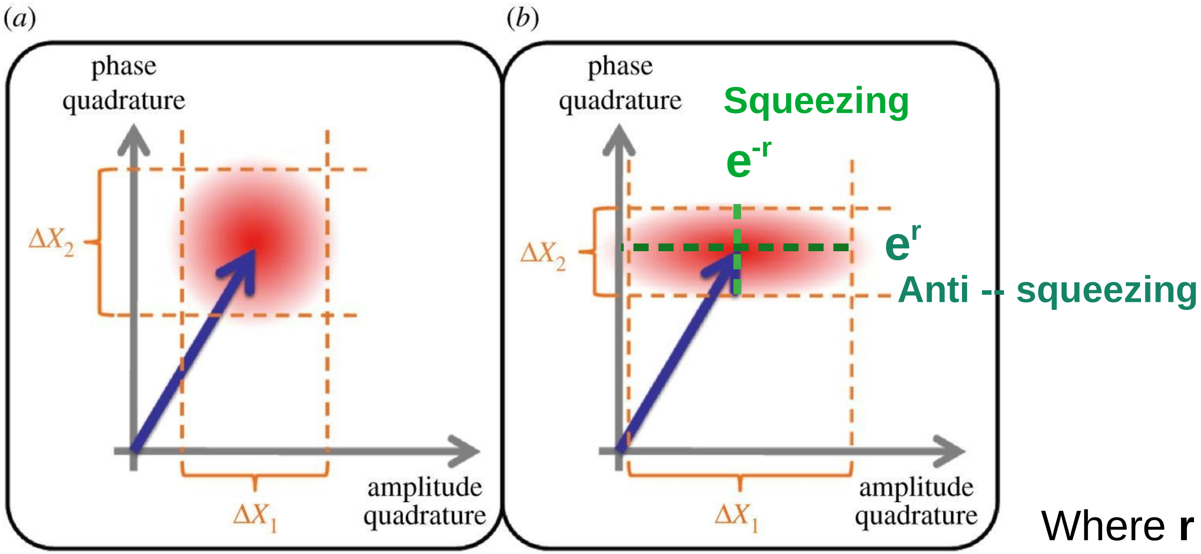


Coherent states are so-called minimum uncertainty states:

$$(\Delta X_1)^2 (\Delta X_2)^2 = \frac{1}{16}$$

Squeezed states fulfil Heisenberg Uncertainty Principle decreasing the variance in one quadrature and increasing it in the orthogonal one:

$$\left(\Delta \hat{X}_\theta\right)^2 = \frac{1}{4} e^{-2r} \qquad \left(\Delta \hat{X}_{\theta+\pi/2}\right)^2 = \frac{1}{4} e^{2r}$$



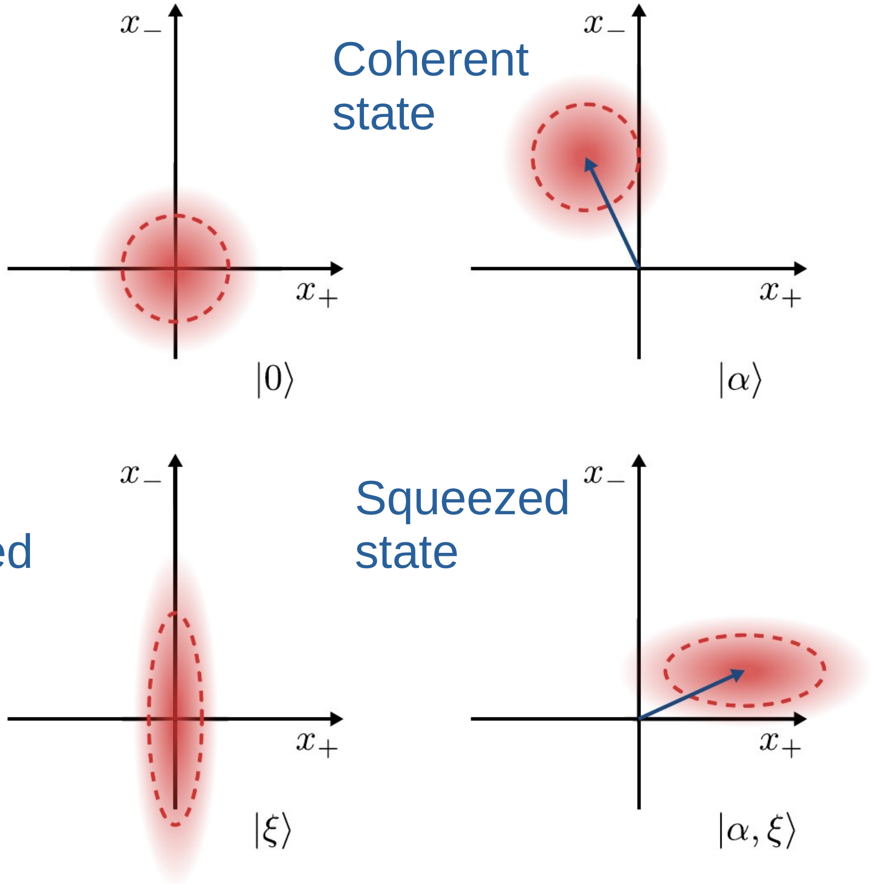
Where **r** = squeeze factor

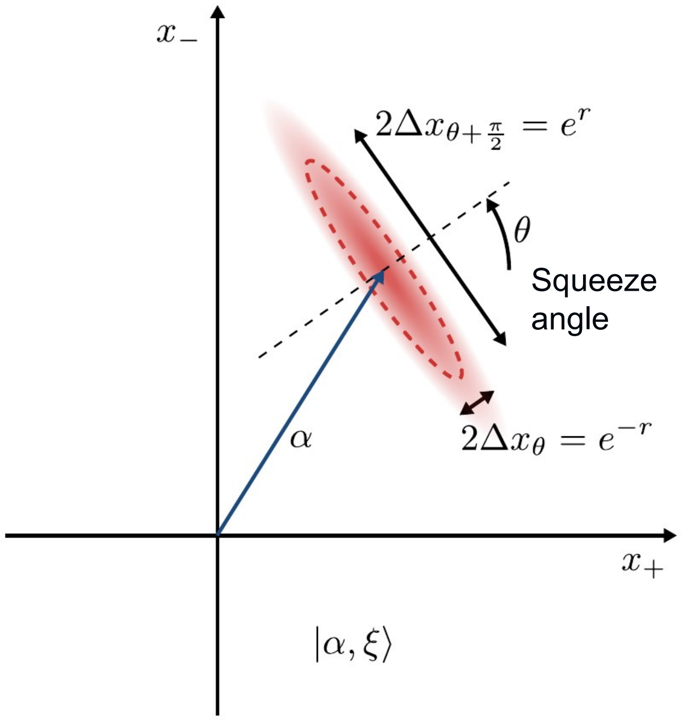
Vacuum state

Coherent state

Vacuum squeezed state

Squeezed state

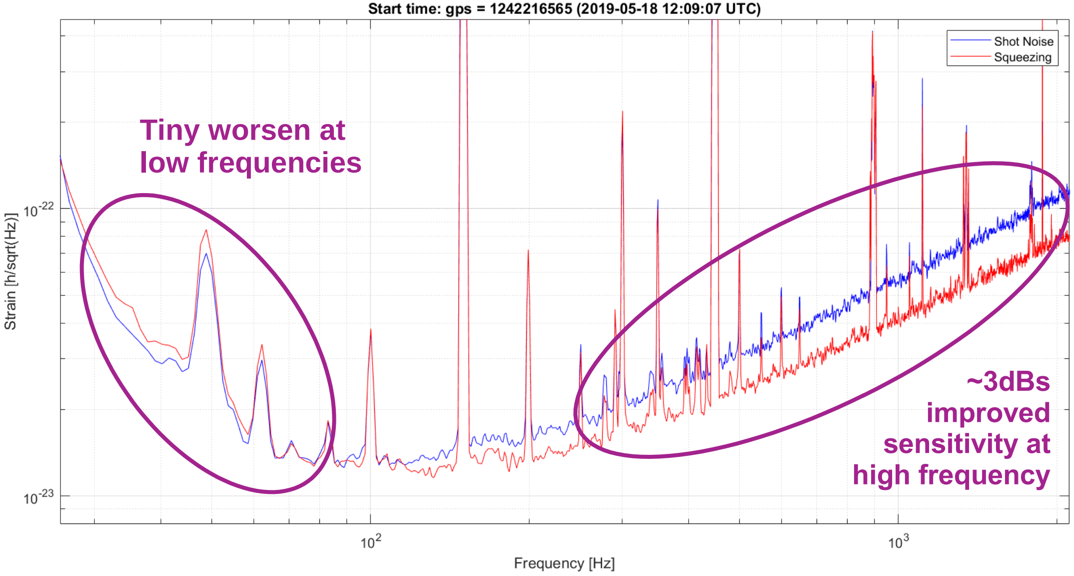




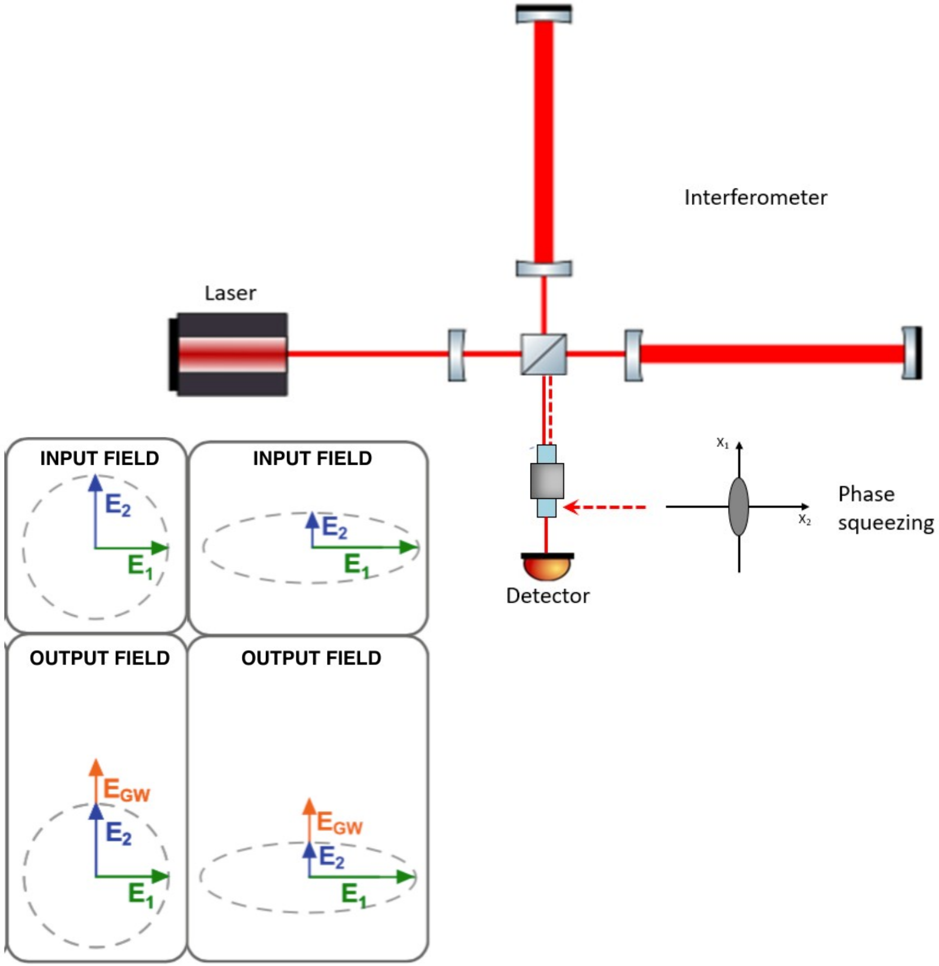
Squeezed state rotated by θ

- **First step:**
- ✓ Injecting squeezed vacuum states from the output port to improve sensitivity, run O3
- ✓ Implemented in AdVirgo and aLIGO

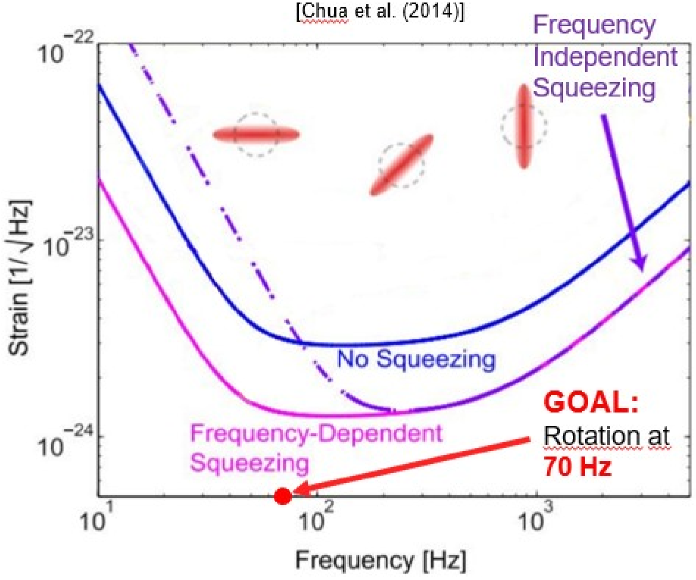
Advanced Virgo



Plot from M. Vardaro

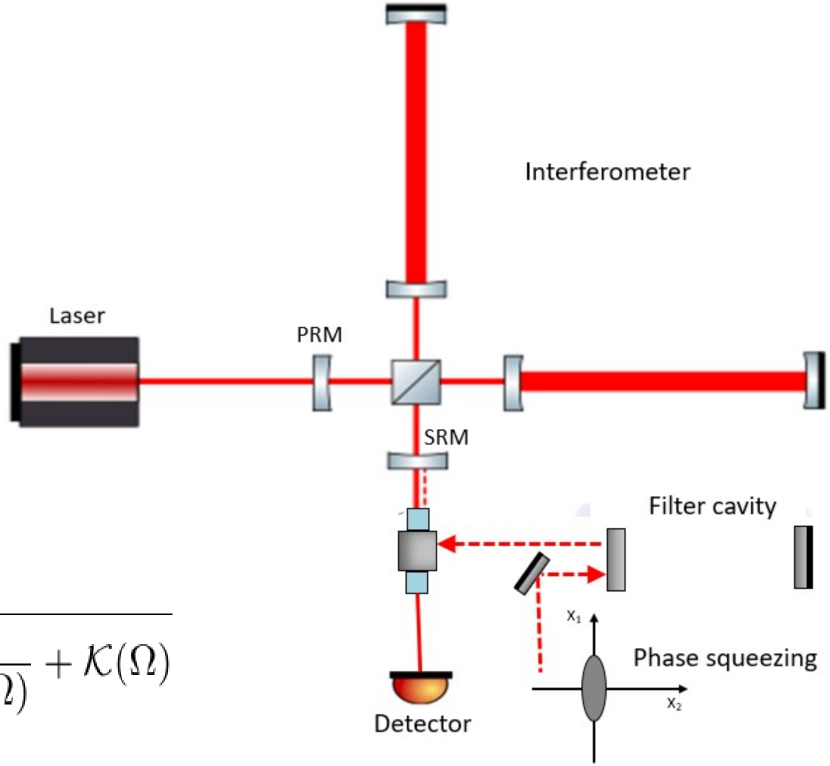


- **Next step:**
- ✓ Vacuum squeezed state angle become frequency dependent when reflected by a detuned Fabry-Perot filter cavity
- ✓ Implementation in GW detectors in O4



$$h(\Omega) = \frac{h_{SQL}}{\sqrt{2}} e^{-r} \sqrt{\frac{1}{\mathcal{K}(\Omega)} + \mathcal{K}(\Omega)}$$

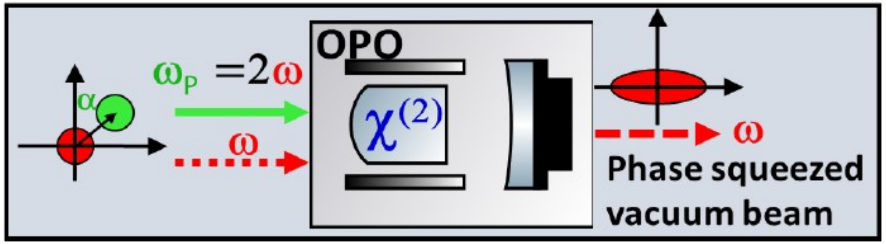
Broadband reduction factor

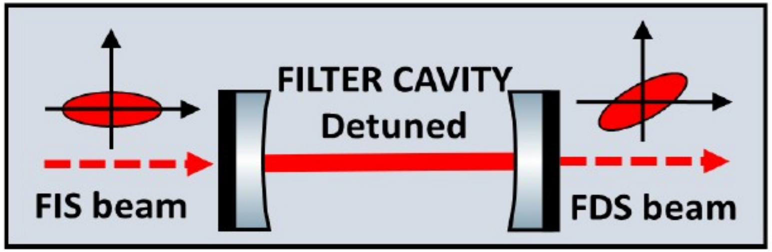


Frequency dependent squeezing states generation

Squeezing generation by **Optical Parametric Oscillator** (non-linear optical process in PPKTP crystal)

Filtered by a detuned cavity (FC)





Credit S. Di Pace

SQZ angle θ_{fc} rotation induced by a FP cavity at frequency Ω:

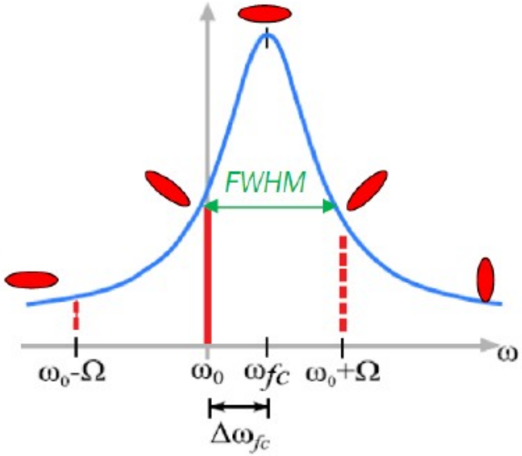
$$\theta_{fc}(\Omega) = arctg\left(\frac{2\,\gamma_{fc}\,\Delta\omega_{fc}}{\gamma_{fc}{}^2 - \Delta\omega_{fc}{}^2 - \Omega^2}\right)$$

AdVirgo+: rot. @20-30Hz
AdLIGO: rot. @50Hz

FC resonates at $\omega_{fc} = \omega_0 + \Delta\omega_{fc}$

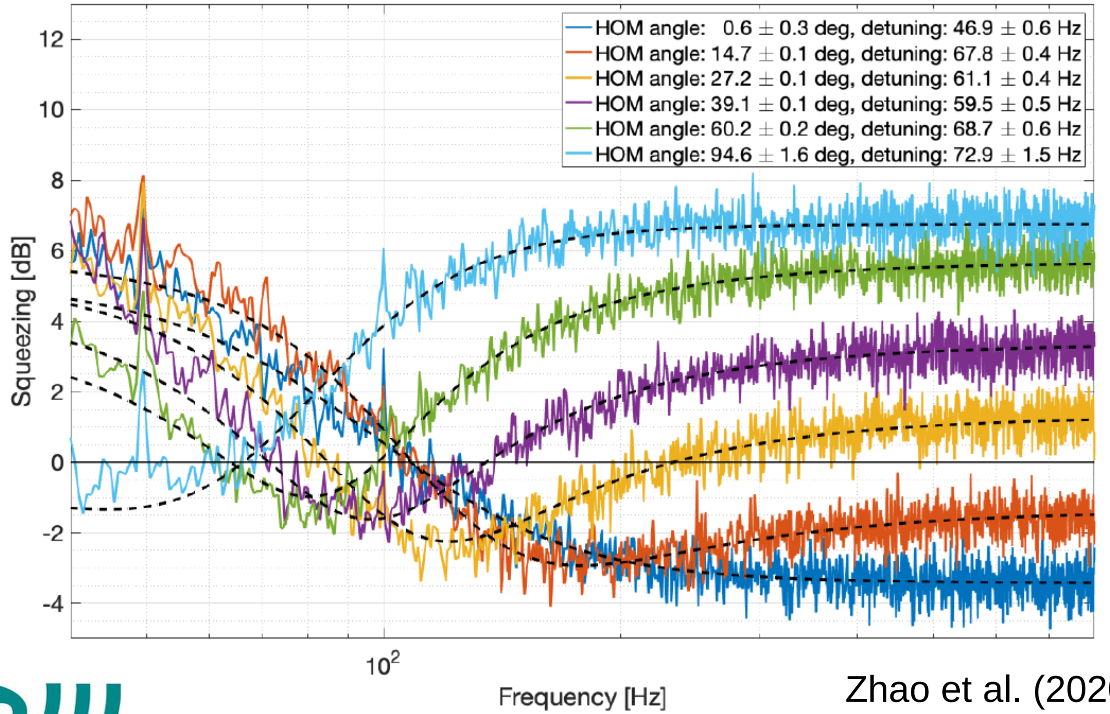
Parameters to consider:

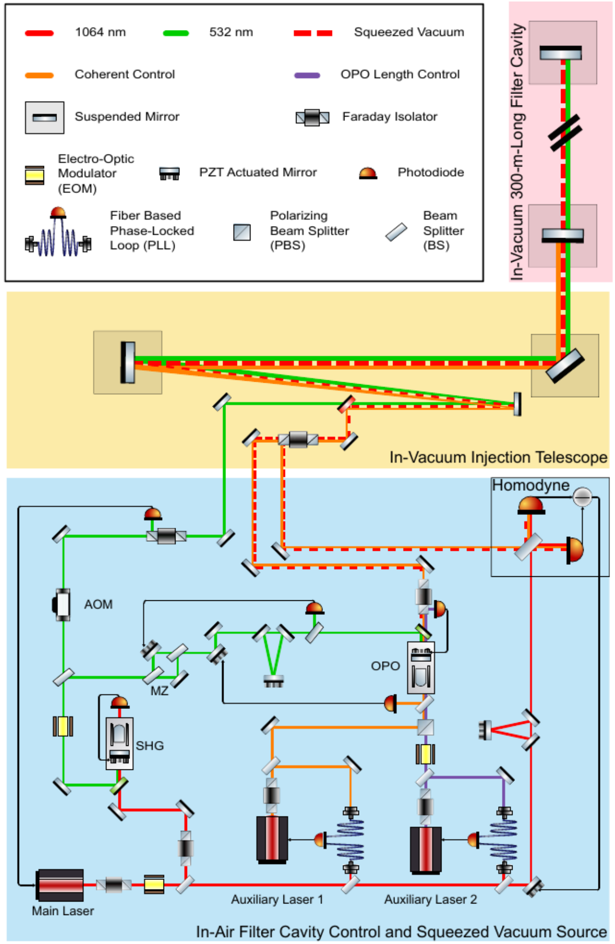
- Linewidth γ_{fc} = FWHM/F
- Detuning $\Delta\omega_{fc}$



Frequency dependent squeezing (FDS) demonstration

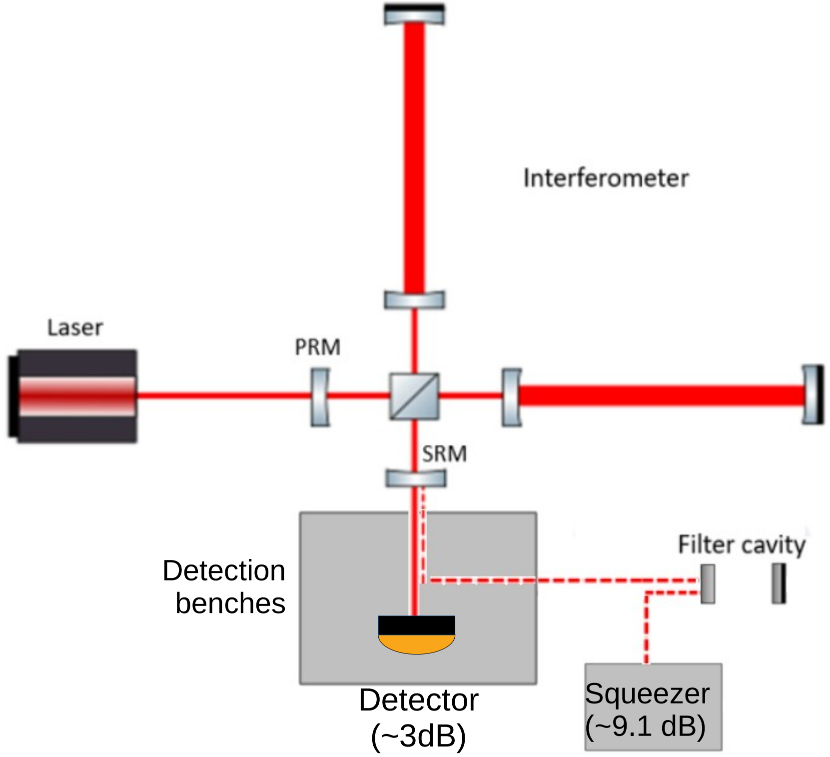
R&D experiment at NAOJ, Tokyo, Japan, was the first demonstration (2020) of a frequency dependent squeezed vacuum source, realized with a 300 m suspended filter cavity. The squeezing rotation takes place in the frequency region (~ 100 Hz) needed to reduce the quantum noise in the whole spectrum of advanced GW detectors.

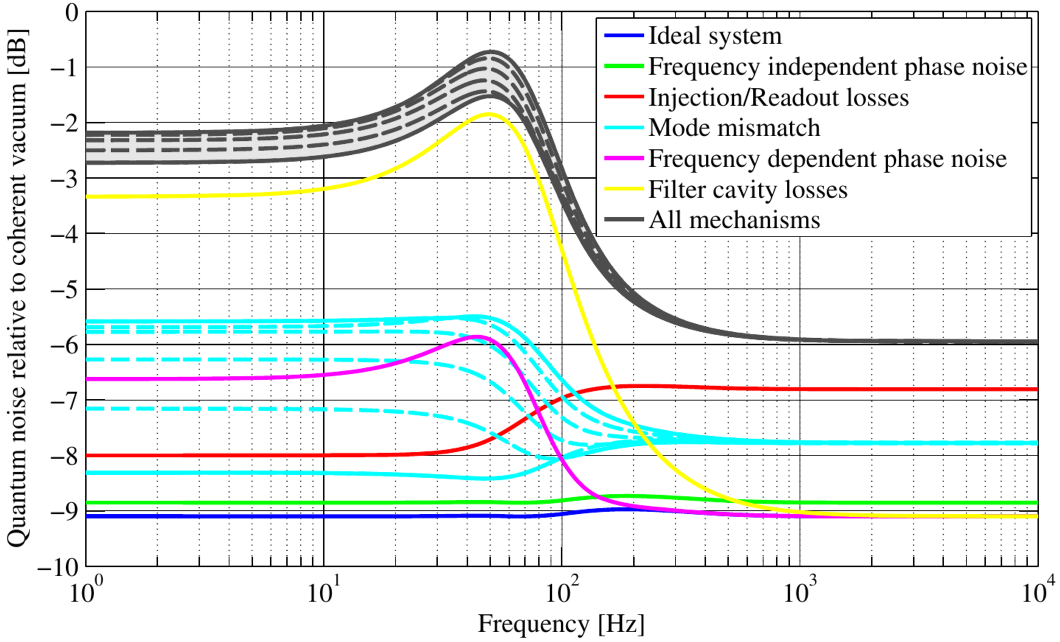




Zhao et al. (2020)

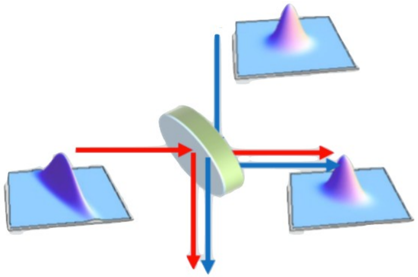
Decoherence (**optical losses + mode mismatch**) and degradation (phase noise due to phase lock errors + **stray light** + cavity length fluctuations) mechanisms limit the experimentally achievable QN reduction.

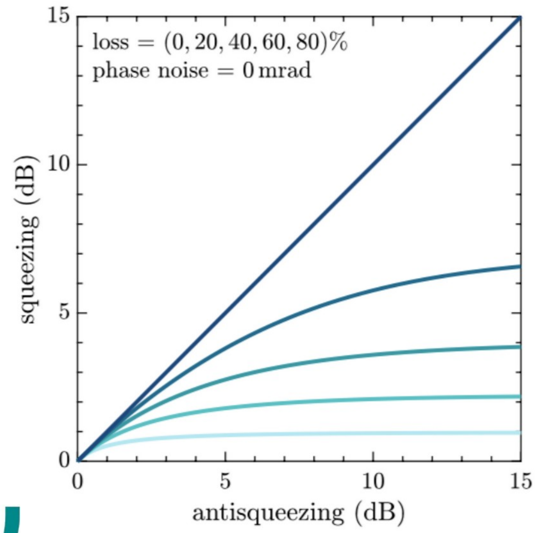




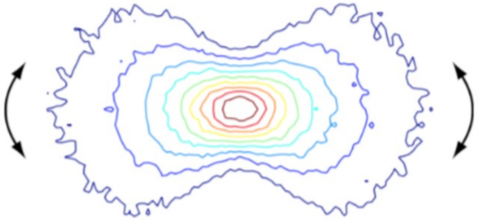
Kwee et al. (2014)

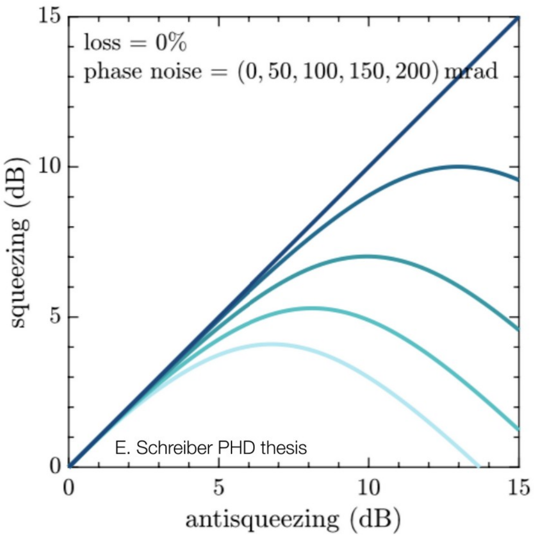
Losses: recombination of the squeezing with the ordinary vacuum

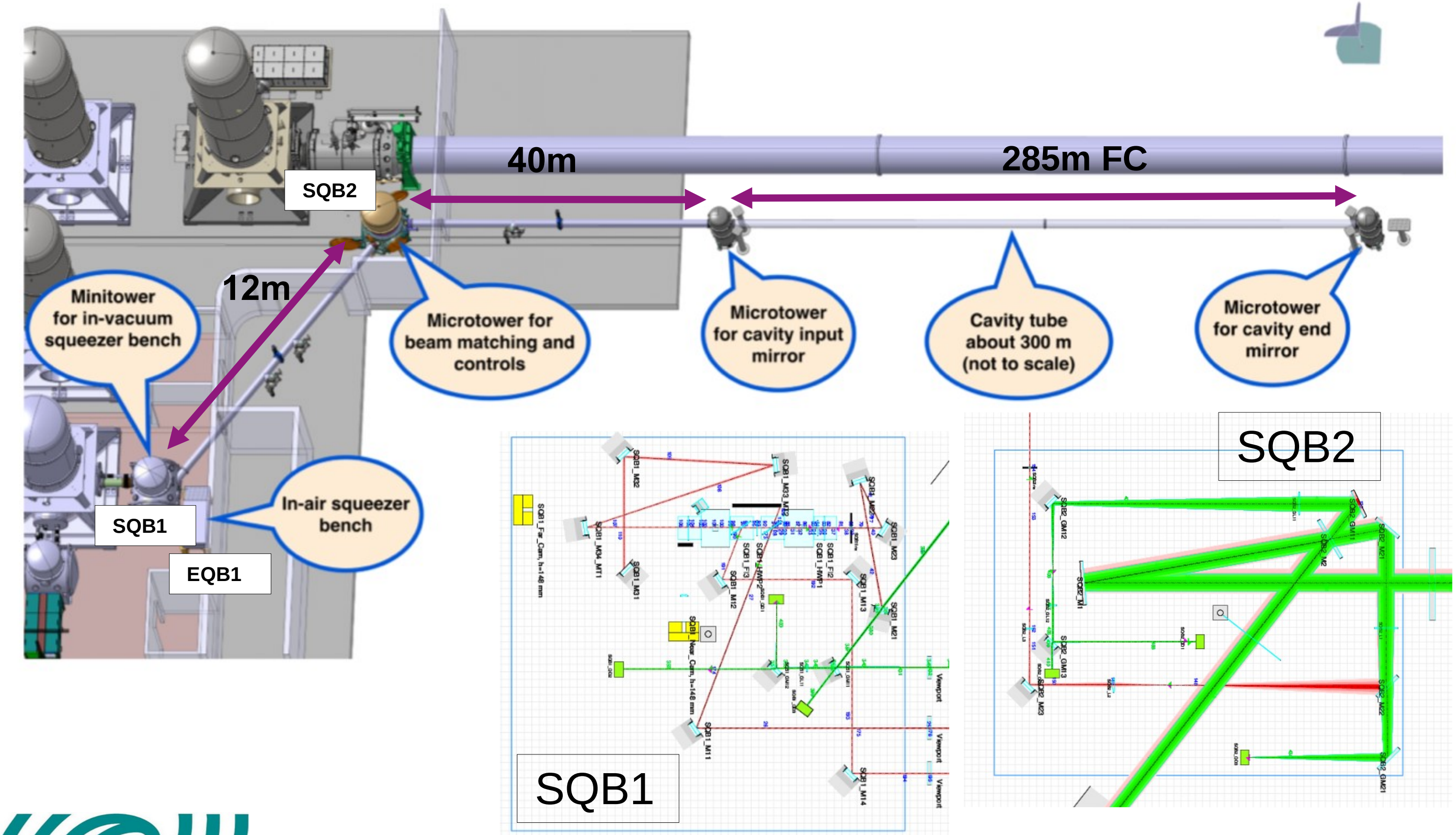


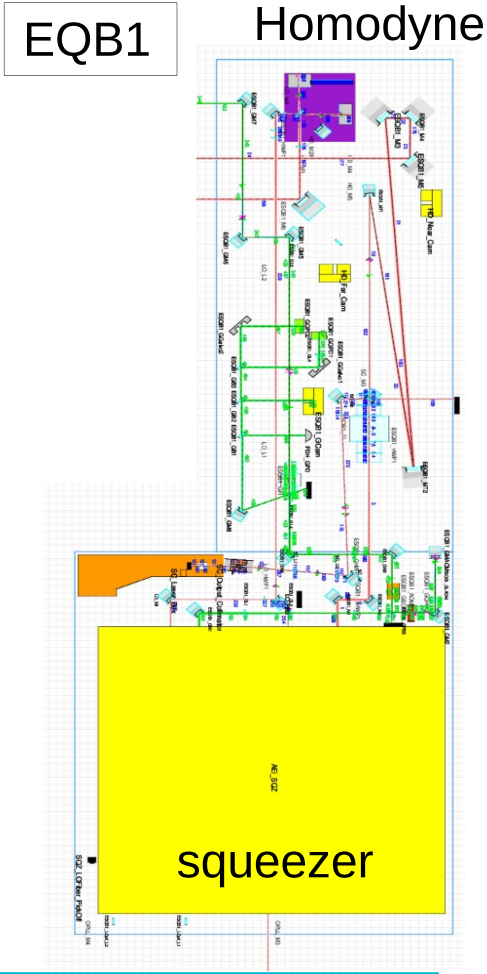


Phase noise: shaking of the squeezing ellipse

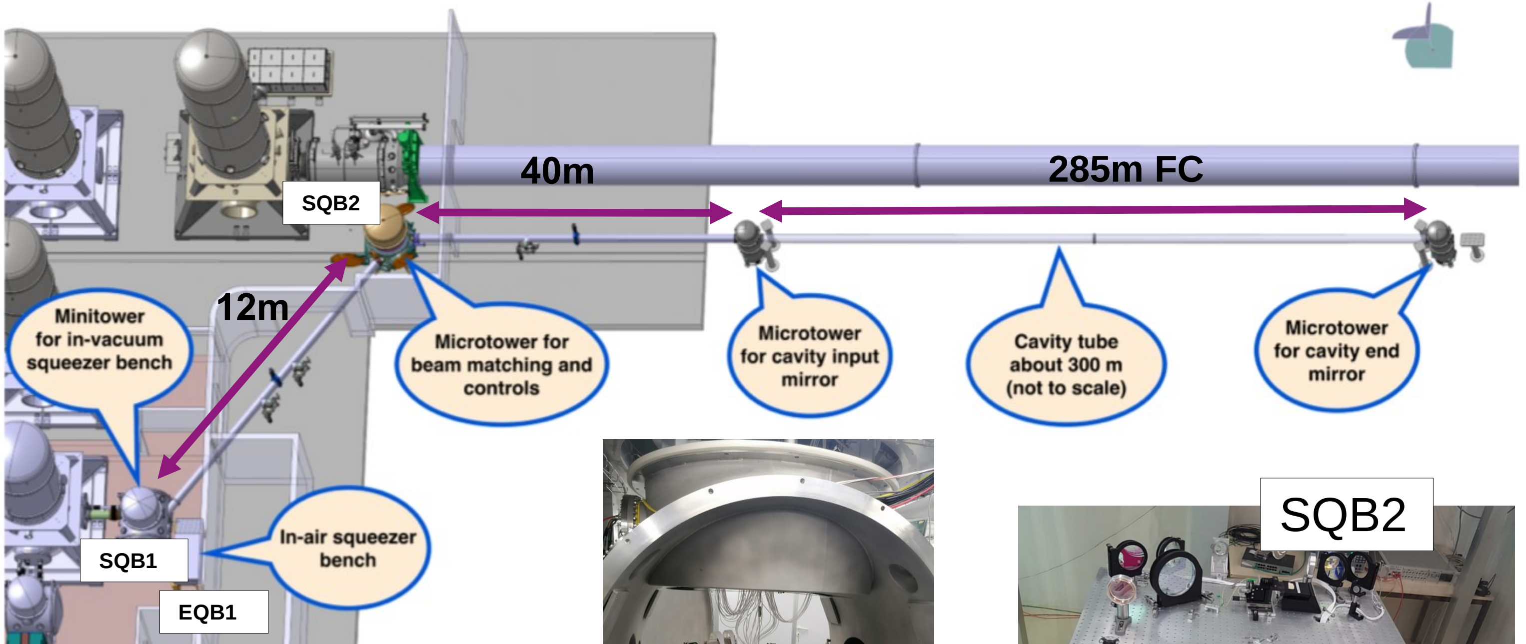





40m
285m FC
SQB2
12m
Minitower
for in-vacuum
squeezer bench
Microtower for
beam matching and
controls
Microtower
for cavity input
mirror
Cavity tube
about 300 m
(not to scale)
Microtower
for cavity end
mirror
In-air squeezer
bench
SQB1
EQB1
SQB1
SQB2

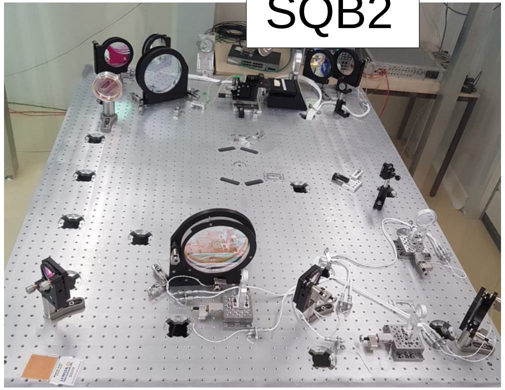

EQB1
Homodyne
squeezer

FDS implementation in AdV+



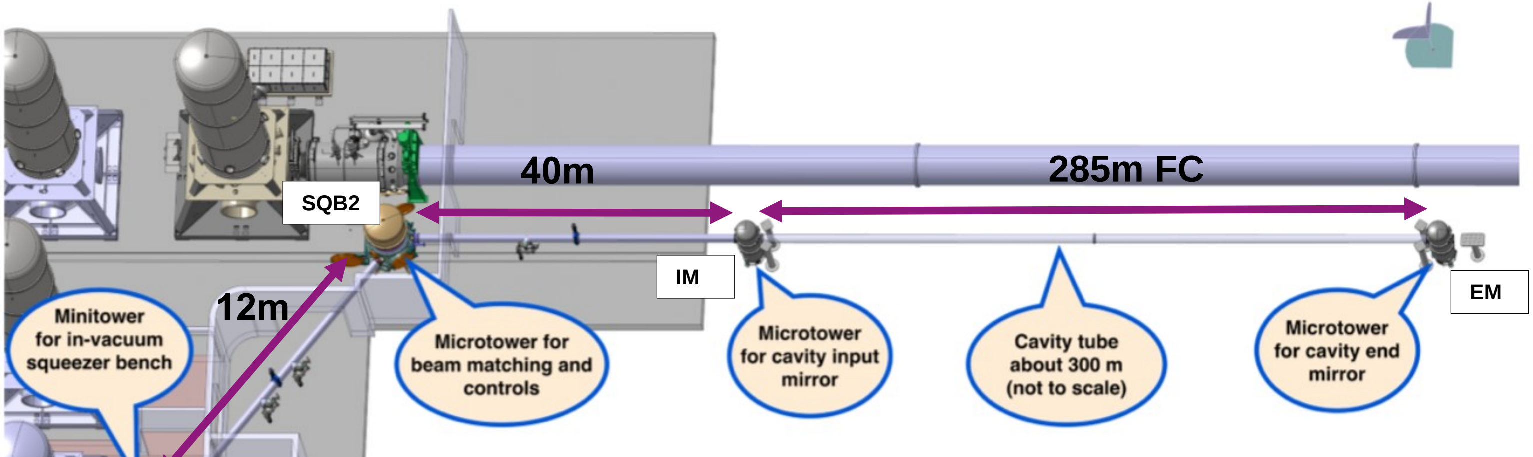
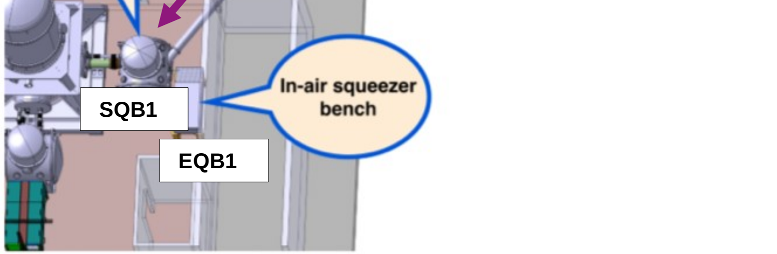
SQB1

SQB2

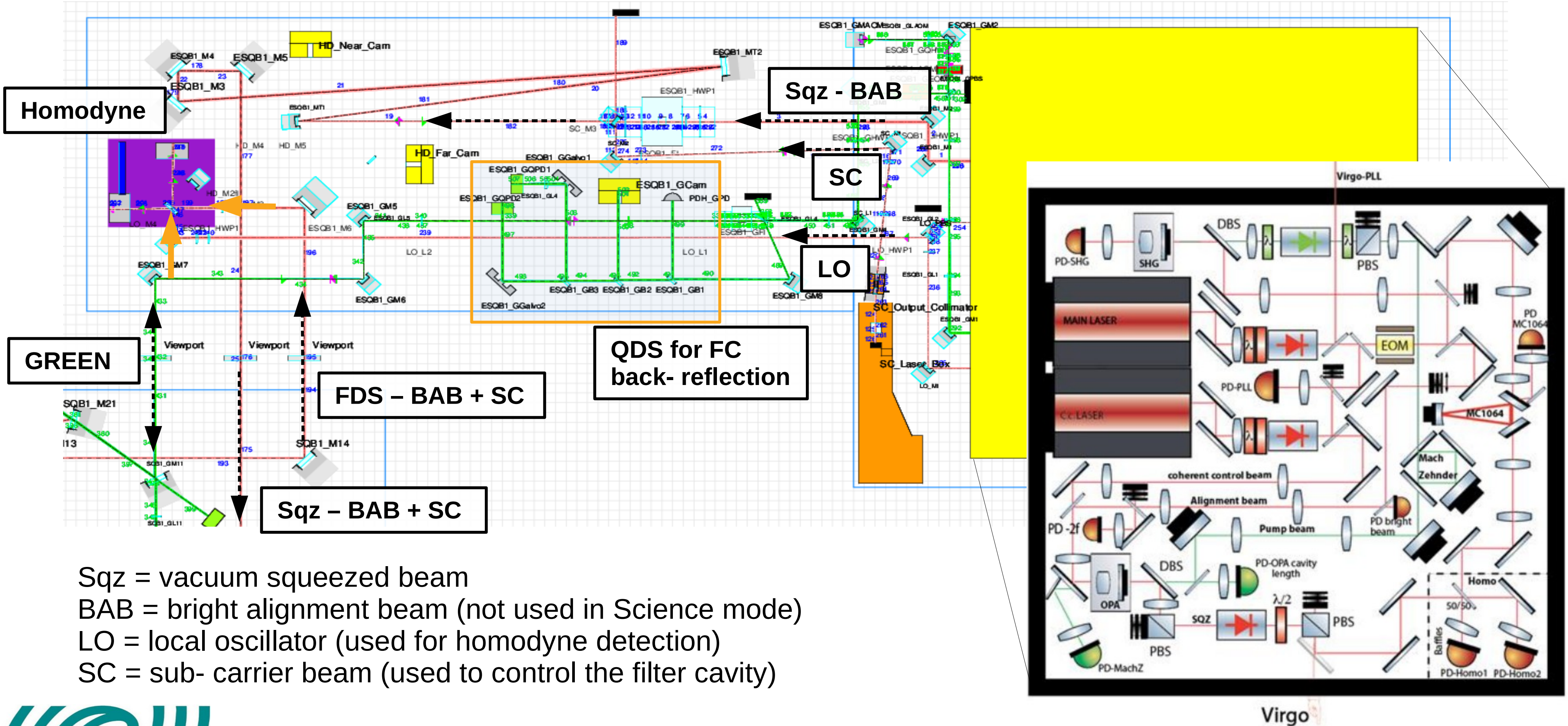


EQB1

FDS implementation in AdV+

Filter Cavity parameters:
- Cavity length: 285 m
- Mirrors diameter: 150 mm
- RoC mirrors: 558 m
- Finesse@1064nm = 11000
- Finesse@532nm = 100
- SQZ rotation: 20-30 Hz
- Round-trip losses < 40ppm

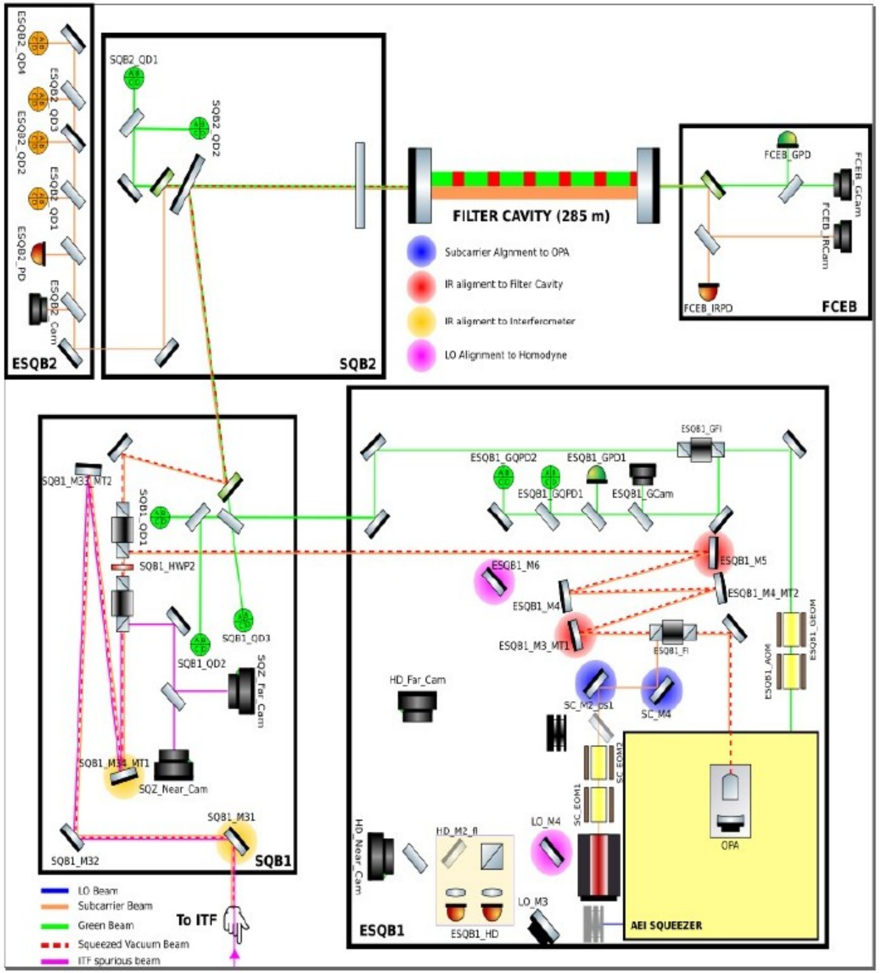


Sqz = vacuum squeezed beam
BAB = bright alignment beam (not used in Science mode)
LO = local oscillator (used for homodyne detection)
SC = sub- carrier beam (used to control the filter cavity)

Sensors:
- PSDs
- Quadrants
- Photodiodes
- LVDTs
- Cameras

Actuators:
- LVDTs
- Mirror coils
- Mirrors
- Lenses

Phase Lock Loops:
1. Virgo – Main laser squeezer = 80 MHz
2. SQZ main laser – Coherent Control = 4 MHz
3. SQZ main laser – Sub Carrier = 1.2 GHz



- Quantum noise limits detectors sensitivity both at high and low frequencies
- Quantum noise is generated by quantum fluctuations entering the output port of the interferometer
- First step done in Advanced Virgo and Advanced LIGO: frequency independent squeezing injection to improve the sensitibity at high frequency
- Work ongoing for AdV+ and aLIGO+: frequency dependent squeezing injection to improve the sensitivity at high and low frequencies
- AdV+ situation: infrastructure constructed, commissioning ongoing
- Thanks to FDS we will see a volume 8 times bigger of our Universe in the next run!

THANK YOU FOR THE ATTENTION

- **First step:**
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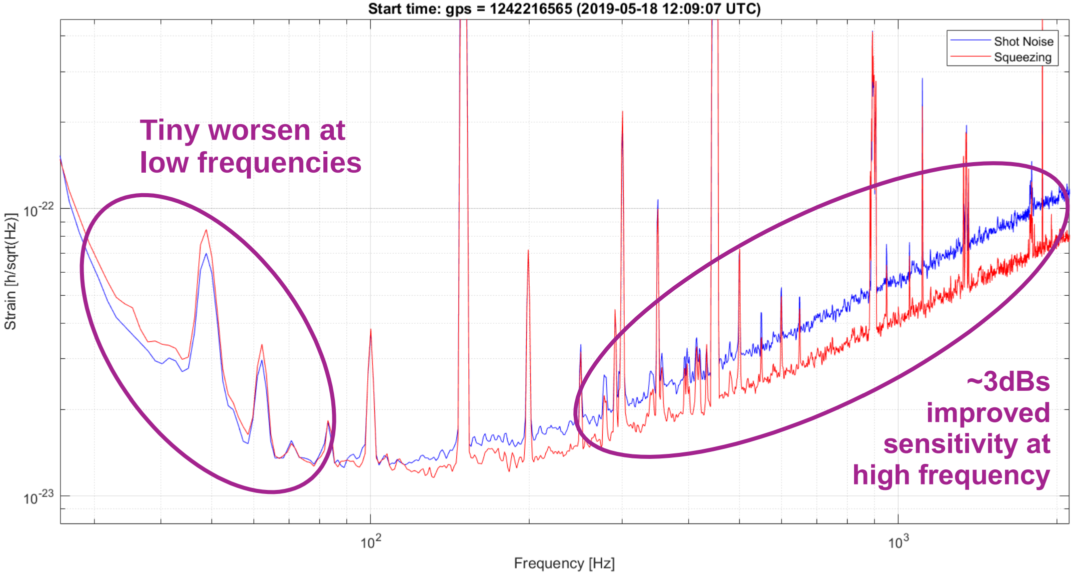
  - ✓ Implemented in AdVirgo and aLIGO

Advanced Virgo



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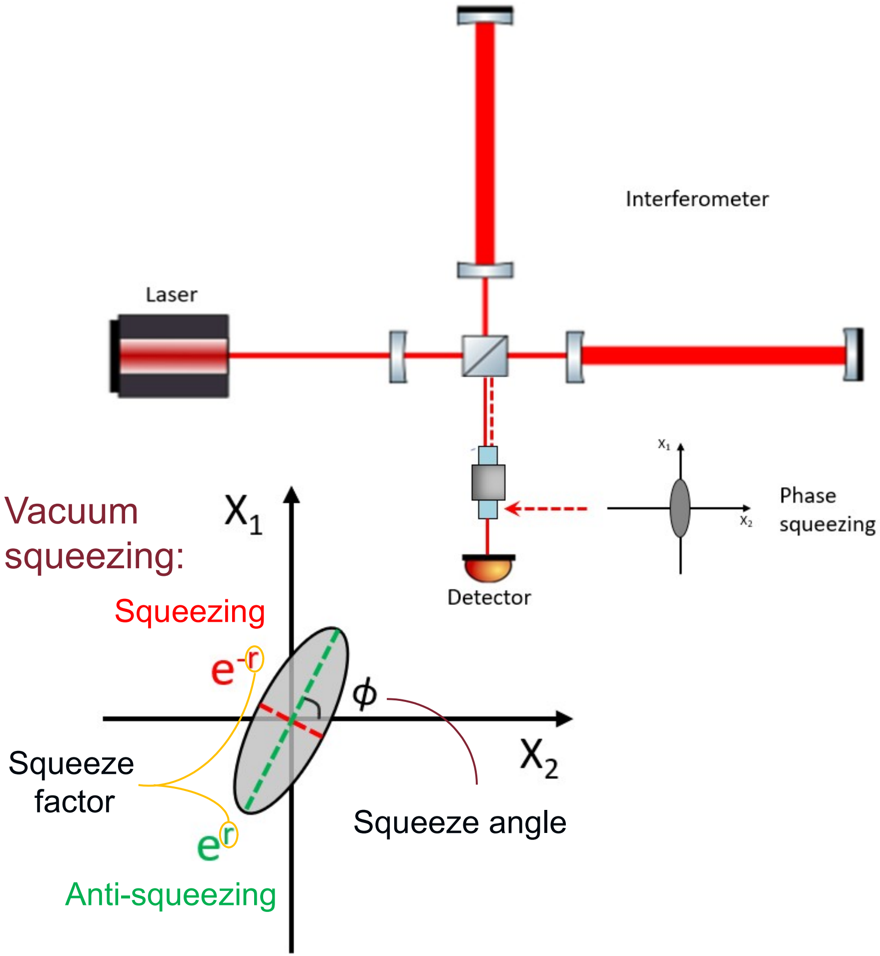

Losses and **phase noise** estimation from squeezing and anti-squeezing measurements at NAOJ.