Quantum Noise in Gravitational Waves Interferometrical Detectors and Status of Quantum Noise Reduction system in AdV+

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on behalf of

VIRGO *Collaboration*

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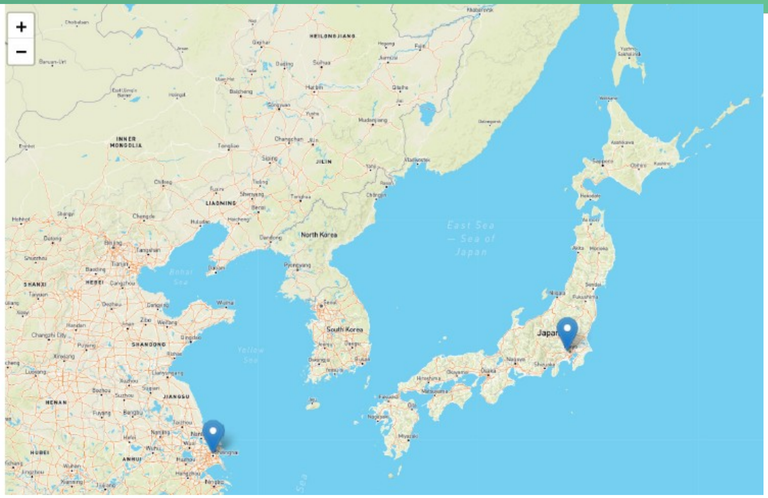
XXV SIGRAV Conference on General Relativity and Gravitation

Sep 4 – 8, 2023

SISSA (Miramare campus)

Europe/Rome timezone

Virgo Collaboration



- More than 820 Members in the Virgo Collaboration, representing 138 Institutions in 15 different countries (as for Jan 2023)

- Virgo Detector @ EGO, in Cascina (Pisa -Italia)

Summary

→ **QUANTUM NOISE IN INTERFEROMETRICAL GW DETWCTORS**
→ **QUANTUM NOISE REDUCTION via SQUEEZED VACUUM**
→ **SQUEEZED VACUUM GENERATION**
→ **Squeezing degradation**
→ **Quantum Noise Reduction System for AdV+**

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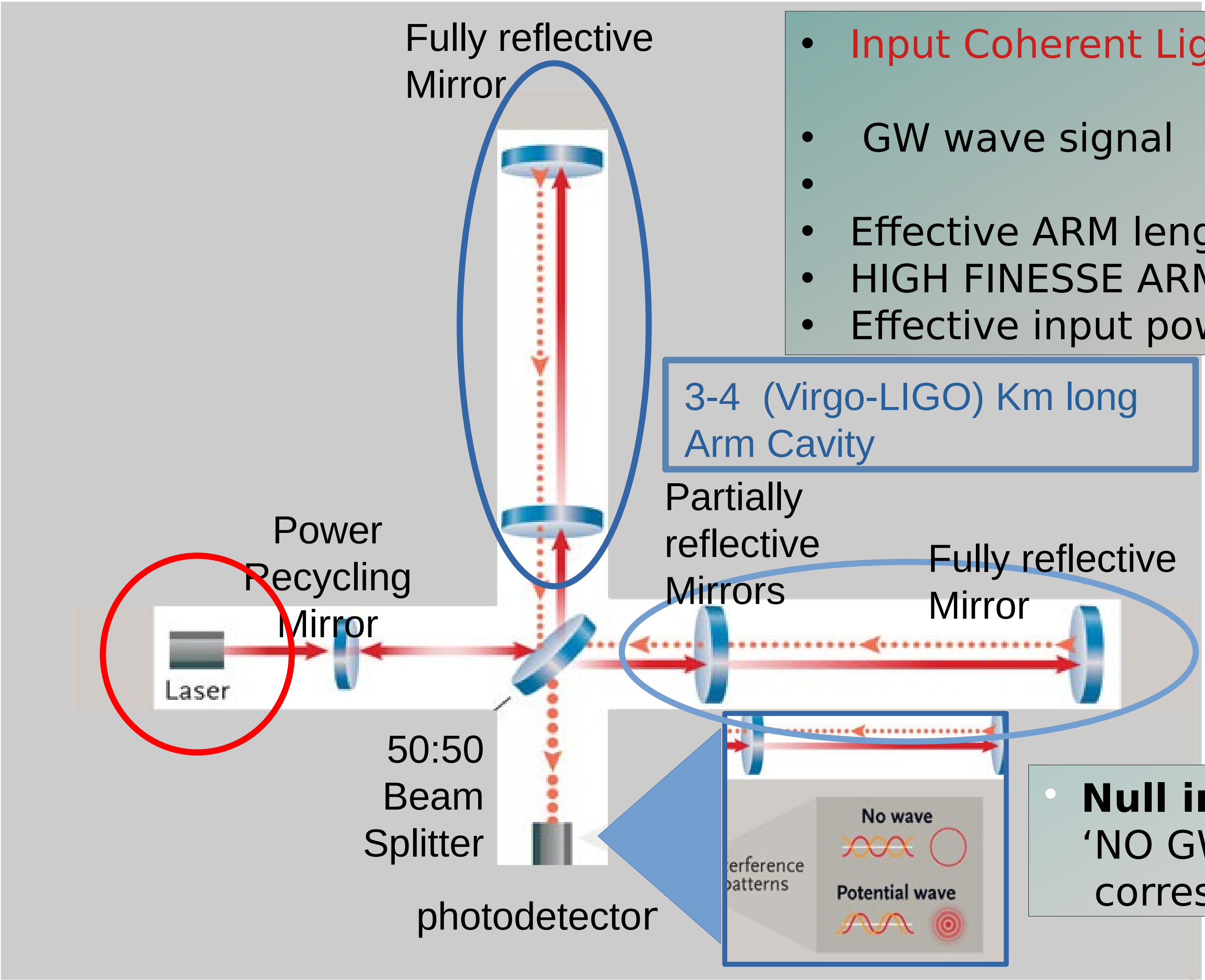
GW interferometer Basic Configuration



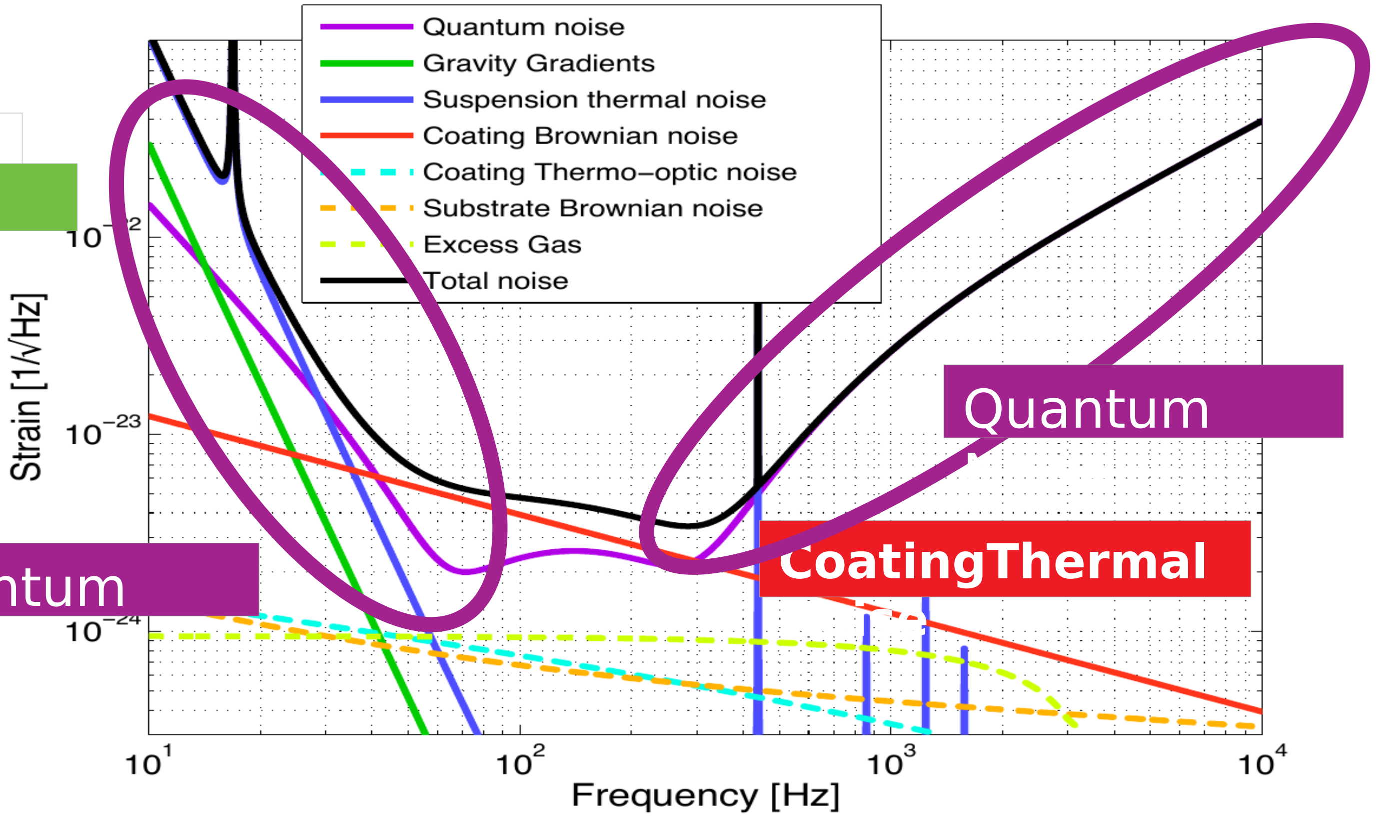
- Input Coherent Light
- GW wave signal $h_{GW} \propto \frac{\Delta L}{L}$
- Effective ARM length increased by
- HIGH FINESSE ARMS Cavities (F~400)
- Effective input power increased by Power Recycling Cavity

- **Null instrument:**
  'NO GW SIGNAL' state
  corresponds *NO LiGHT on photodetector*

GW interferometer Fundamental Noises

- Seismic
- Newtonian

Suspension Thermal Noise



Quantum

Quantum

CoatingThermal

@ High Frequency the ***Quantum Noise limits the ITF sensitivity***

@ Low Frequency the Quantum Noise is one of the fundamental noise

Interferometer Quantum Noise

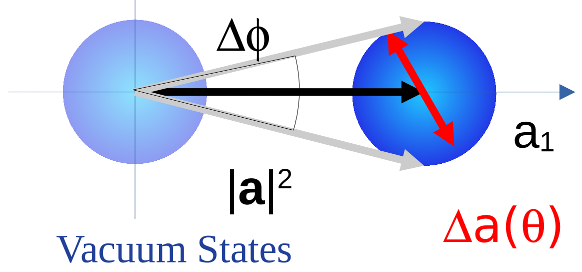
INTRINSIC NOISE due to the **quantum nature of the laser light** used to interrogate them

Laser States are Coherent states: Amplitude and Phase Uncertainties according with **Heisenberg Principle**

Coherent States

$\boxed{\mathbf{a}=\mathbf{a}_1\exp(-i\omega t)+\mathbf{a}_2\exp(i\pi/2-i\omega t)}$

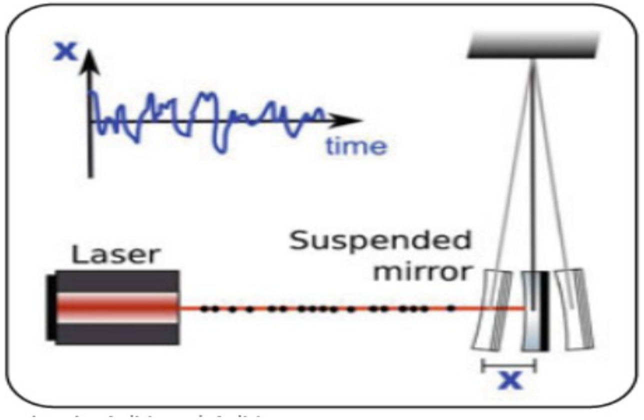
$\boxed{\Delta\mathbf{a}(\theta)\Delta\mathbf{a}(\theta+\pi/2)=1,\ \Delta\mathbf{a}(\theta)=1}$



a(q=0)=a_1, Amplitude Quadrature
a(q+p/2)=a_2. Phase Quadrature

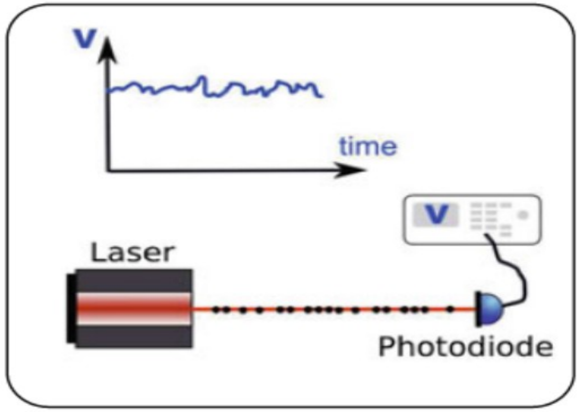
Amplitude fluctuations

suspended mirrors momentum fluctuation



Phase Fluctuation (Fluctuation of the Arriving Number of photon inunit time)

Out signal phase fluctuation

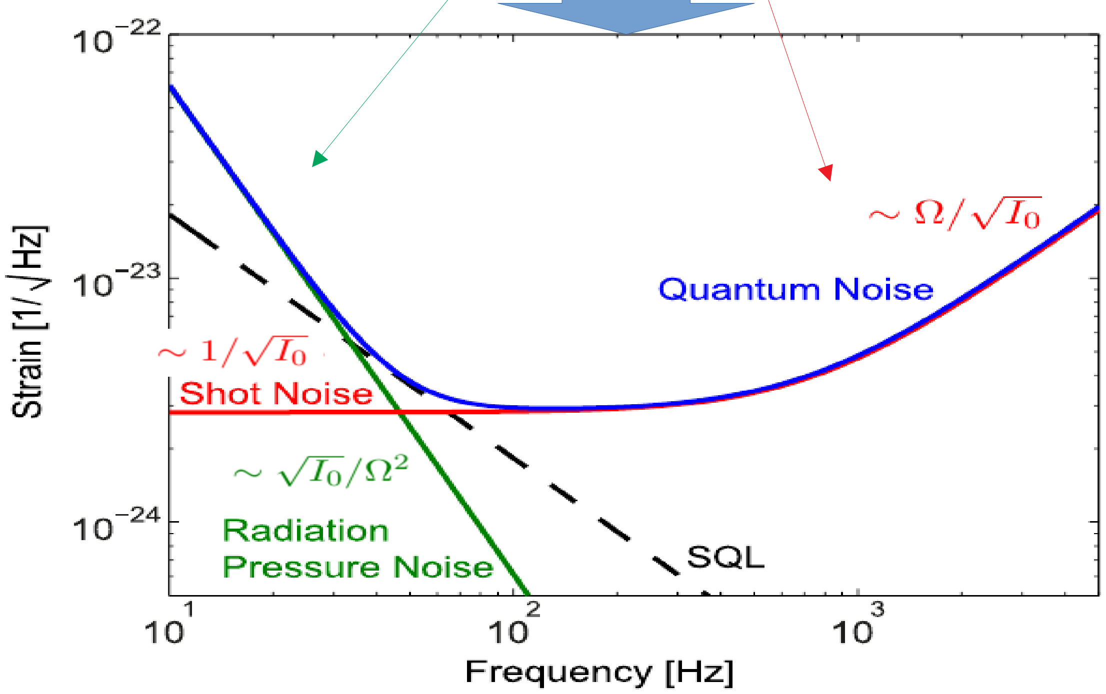


Interferometer Quantum Noise

ITF OPTOMECHANICAL RESPONSE ***frequency dependent*****, K(Ω):**
in the device band the ***quadratures fluctuations are***
frequency dependently 'weighed'

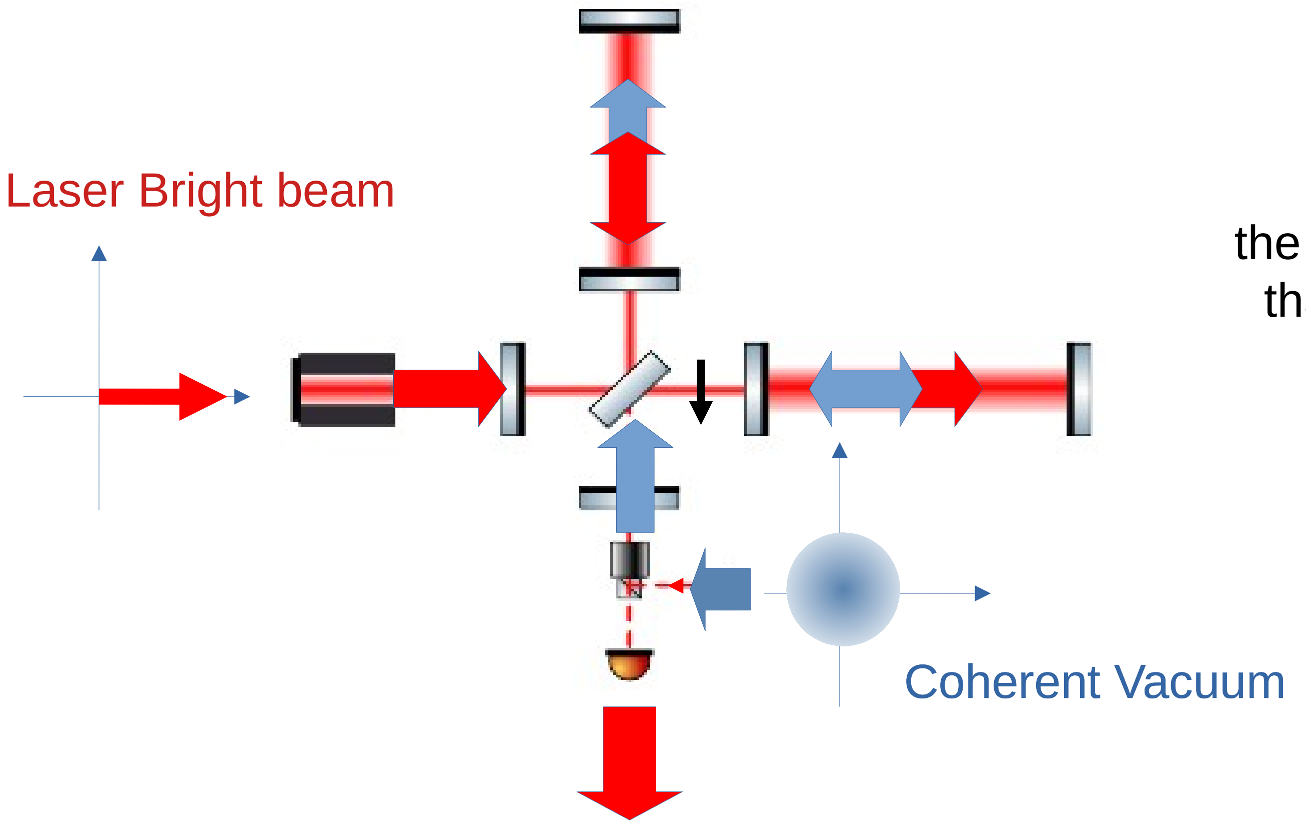
$$\hat{h}_n(\Omega) = S_h(\Omega)^{1/2} = \left[\left[\mathcal{K}(\Omega) + \frac{1}{\mathcal{K}(\Omega)}\right]\frac{h^2_{SQL}}{2}\right]^{1/2}$$

Radiation Pressure Noise:
@ frequency enough smaller than the ARM cavity linewidth $\Omega/\gamma_c \ll 1$ dominates the Effect of the input Amplitude quadrature noise



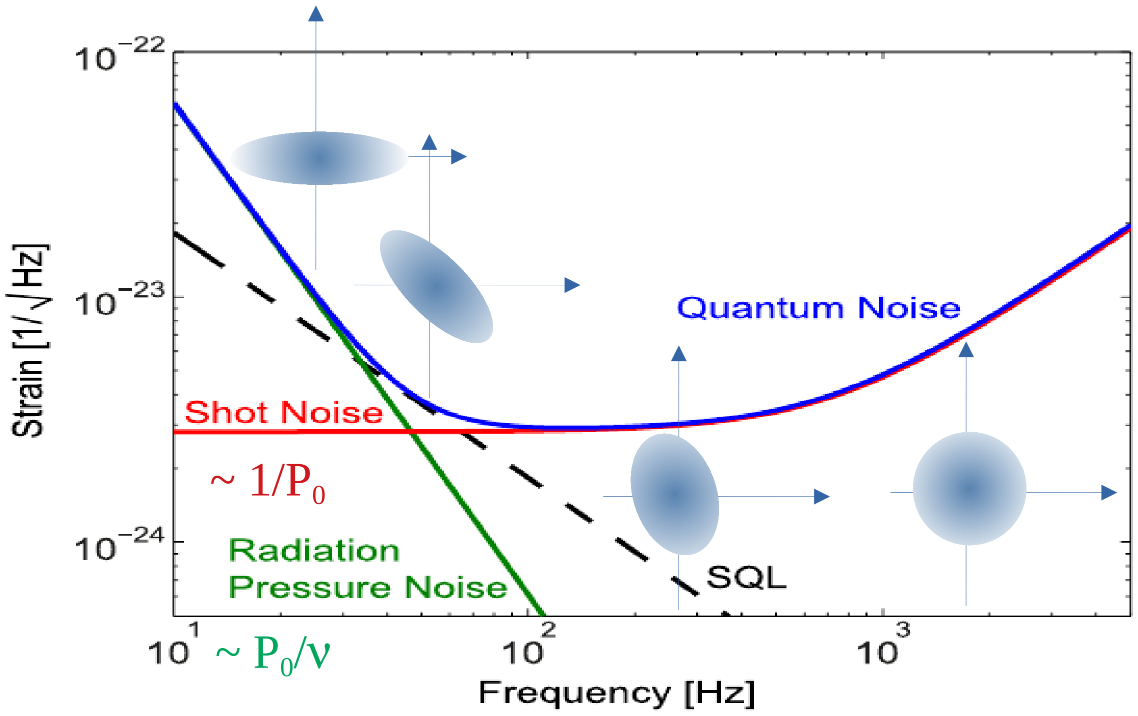
Shot Noise**:**
@ high frequency dominates
the effect of the input
phase quadrature noise

Interferometer Quantum Noise



Caves, Phys. Rev. D 23 (1693–1708), 1981

Quantum Optics description:
Quantum Noise in an interferometer
described as **beat between**
the **classical input** beam **and** the coherent **vacuum**
that enters in the unused port of the beam splitter
(dark port of interferometer)



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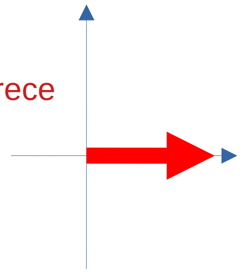
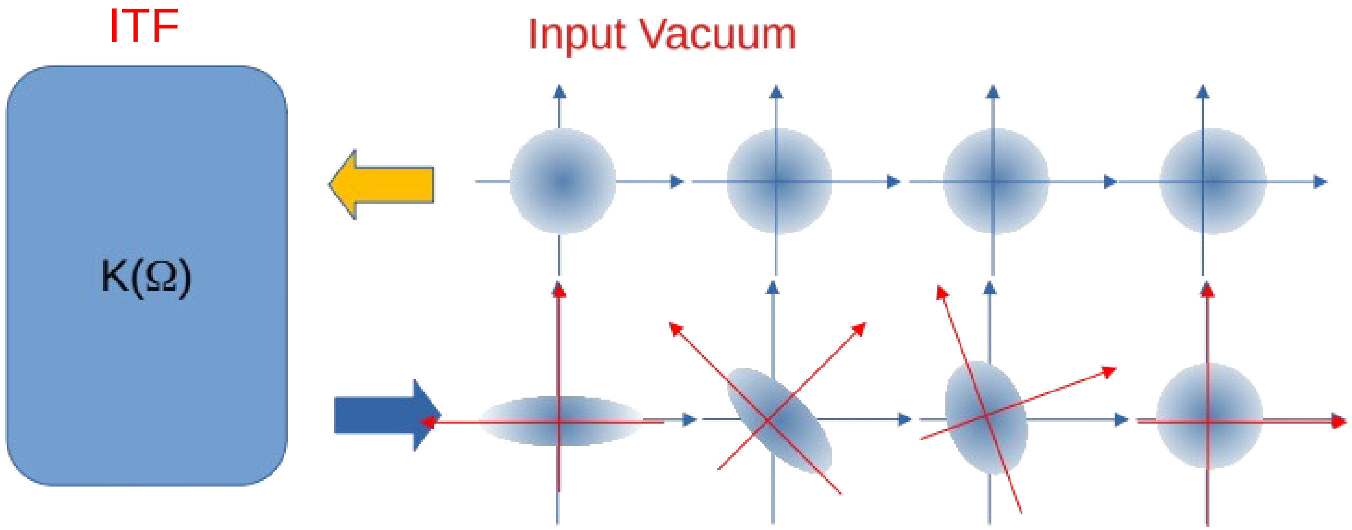
Interferometer Quantum Noise

An useful alternative 'view'..

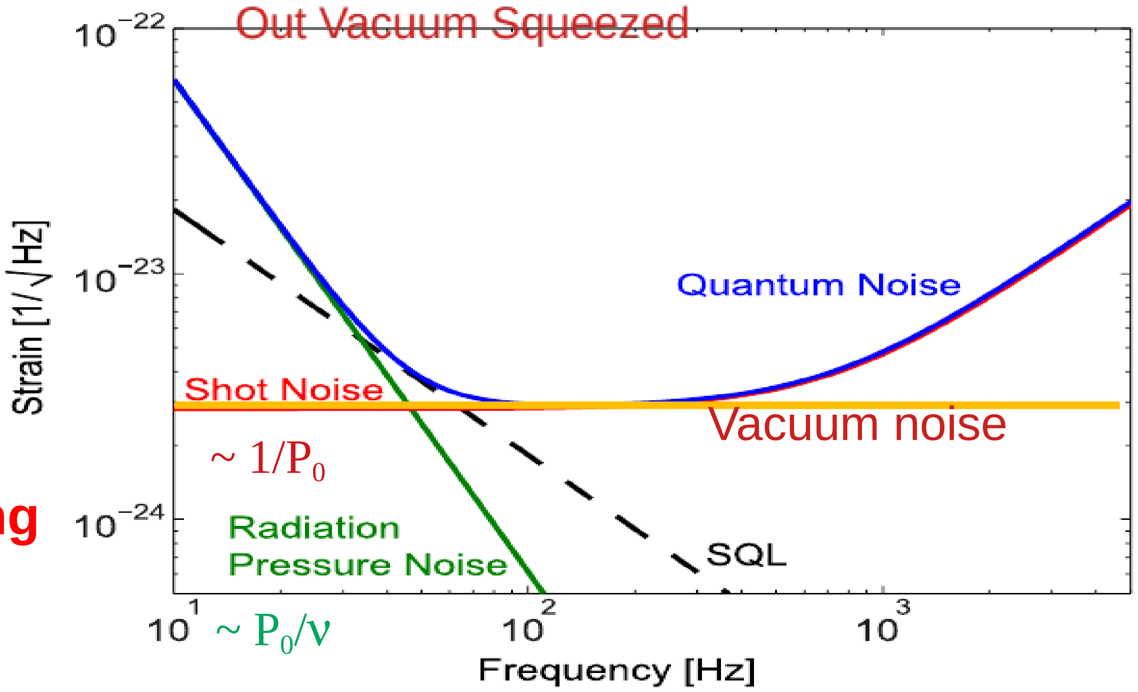
Phase Space Referece
Given by the
Input laser
Phase Space





The ***frequency dependent response of the ITF.*** *K(Ω),*
squeezes and r**otates** *the*
***out phase quadratures* variance**
of the entering frequency independent vacuum
with different squeezing factor and angle:

frequency dependent ponderomotive squeezing of the input coherent vacuum



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Interferometer Quantum Noise

Quantum Noise: **coherent vacuum** in the dark ITF port **beats** with the **classical ITF input laser** state and the ***frequency dependent* optomechanical ITF** response couples **input amplitude and phase quadratures with output phase quadrature**

(depend on the specific optical configuration)

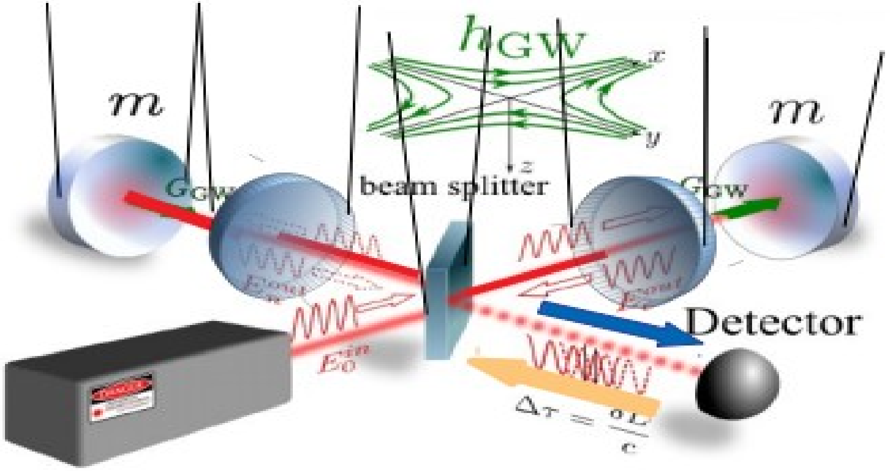
(a1) amplitude quadrature
(a2) phase quadrature

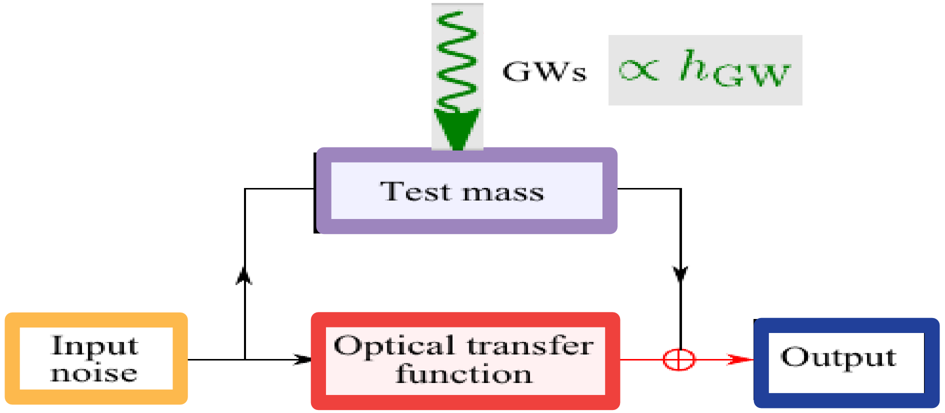
(Ω Gravitational Wave frequency)

What we measure is the ***b2 variance***

$$\begin{bmatrix} b_1(\Omega)\\ b_2(\Omega)\end{bmatrix} = e^{2i\beta(\Omega)}\begin{bmatrix}1 & 0\\ -\mathcal{K}(\Omega) & 1\end{bmatrix}\begin{bmatrix}a_1(\Omega)\\ a_2(\Omega)\end{bmatrix} + e^{i\beta(\Omega)}\begin{bmatrix}0\\ \sqrt{2\mathcal{K}(\Omega)}\end{bmatrix}\frac{h(\Omega)}{h_{\mathrm{SQL}}}$$

detector response to the *gravitational-wave strain* h(Ω)



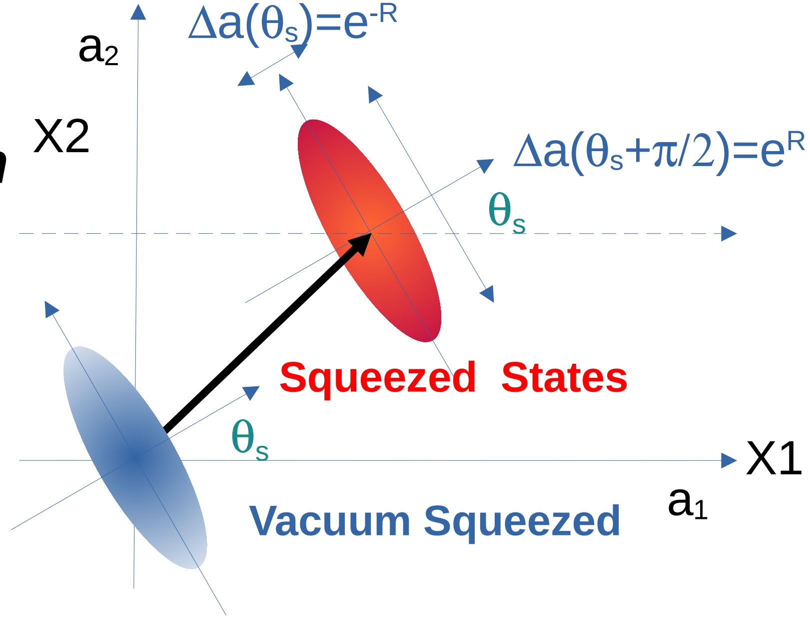


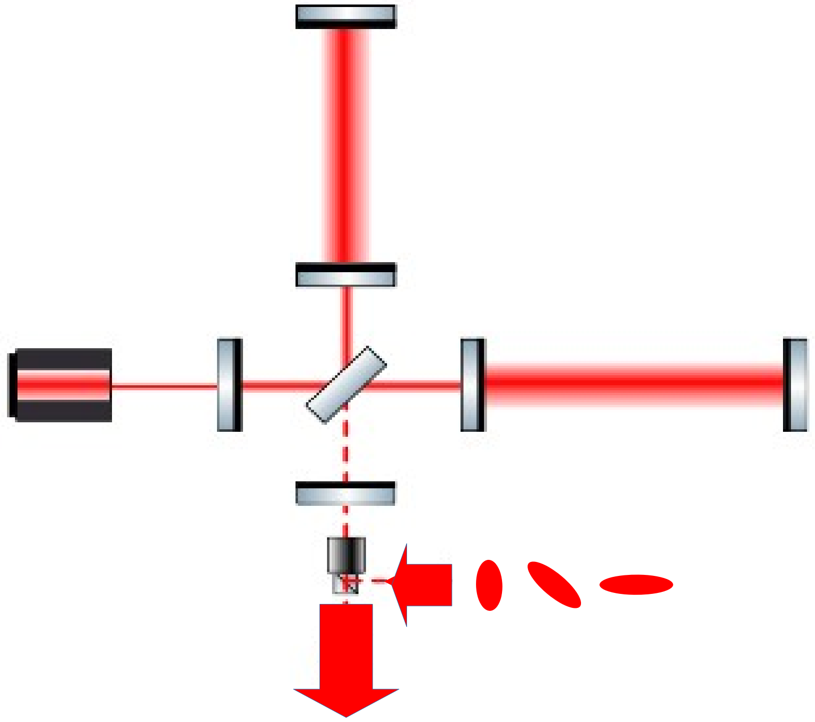
Danilishing et al,, Living Reviews in Relativity, n. , 2019

Quantum Noise Reduction

Caves, Phys. Rev. D 23 (1693–1708), 1981

Quantum Noise reduction





Squeezed Vacuum injection

Injection of squeezed Vacuum with the right SQUEEZING angle at RIGHT FREQUENCY:

QNR reduction in the whole ITF bandwidth

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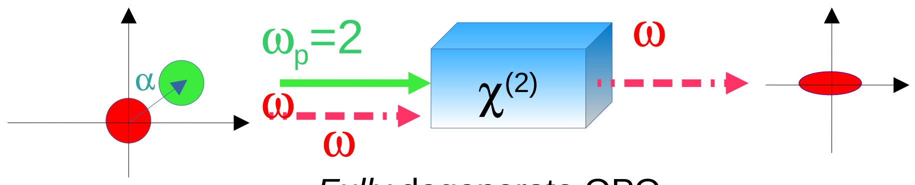
Vacuum Squeed Generation

Squeezed states → ***quadrature fluctuations***
correlated



Fully degenerate OPO
(polarizations and frequencies degeneracy)

2th order nonlinear susceptibilities induces the correlation between the phase and amplitude fluctuations In an Optical Parametric Oscillator

At present the OPOs result to be the more efficient light squeezerr

→ *High squeezing factor reached in the GW frequency band (15 dB)*
→ *Tested long time operation* *(GEO, LIGO and VIrgo)*

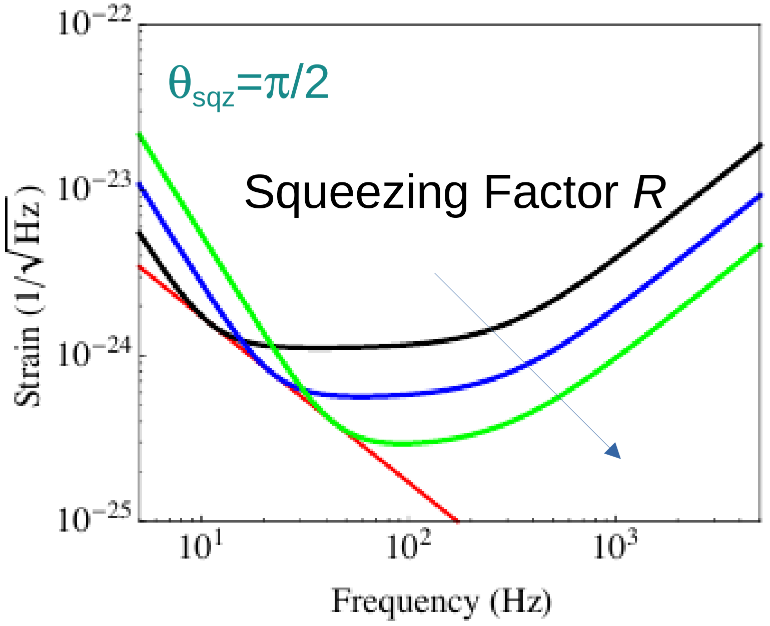
OPO produce PHASE SQUEEZED VACUUM;
Tipical bandwidth: 4 GHz => w.r.t. GW ITF is ‘white’:
it is FREQUENCY INDEPENDENT SQUEEZING

QN OPTIMIZATION

Squeezing the phase noise
increaseas the amplitude noise that is
most weighted at low frequency

$$S_h \simeq \frac{h^2_{\mathrm{SQL}}}{2}\left(\frac{1}{\mathcal{K}}+\mathcal{K}\right)e^{-2R}.$$

By increasing a lot the injected squeezing
(squeezing factor, R)
*the **sensitivity*** **increases at high frequencies** *but*
makes worsen at low frequencies,
→ **rembember: K=K(Ω)**

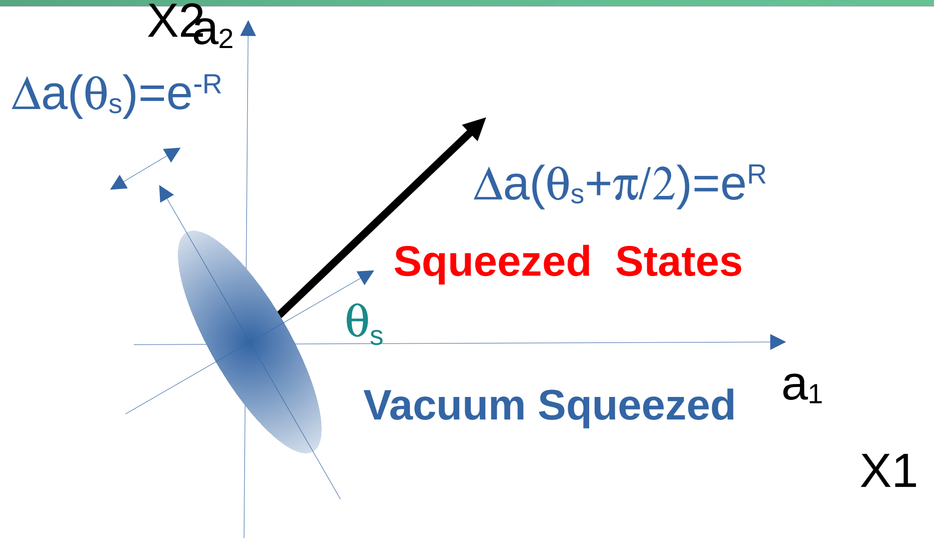


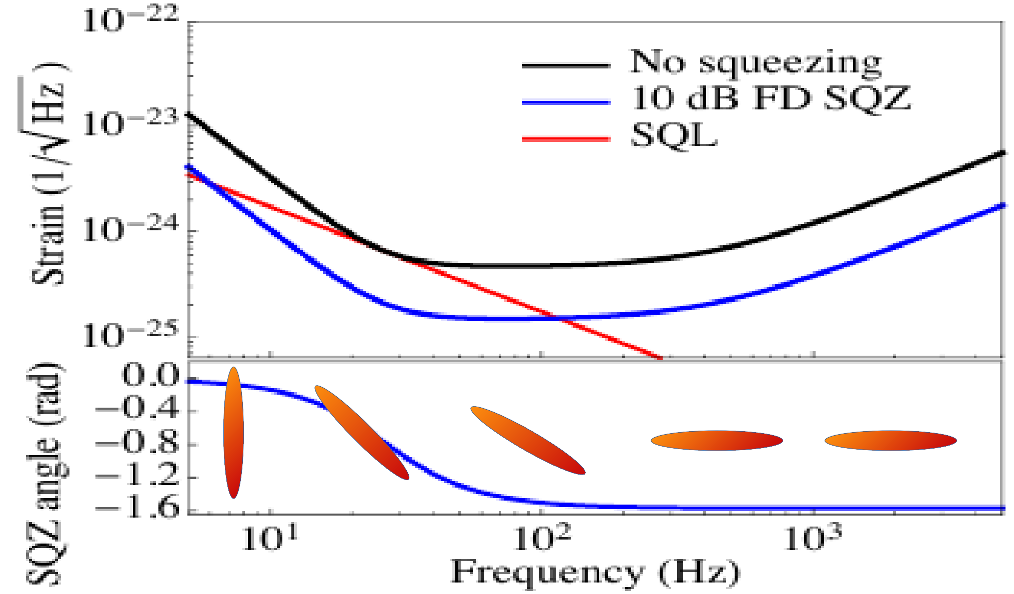
QN OPTIMIZATION

A **frequency dependent squeezing is needed:** an optimized input squeezing angle in each region of the detector band (**R(θ$_\sigma$(Ω))**)

Frequency dependent rotation of the injected Vacumm phase squeezed produced by the OPO

$$S_h = \frac{h_{\mathrm{SQL}}^2}{2}\left(\frac{1}{e^{2R}\mathcal{K}} + e^{2R}\mathcal{K}\right)$$

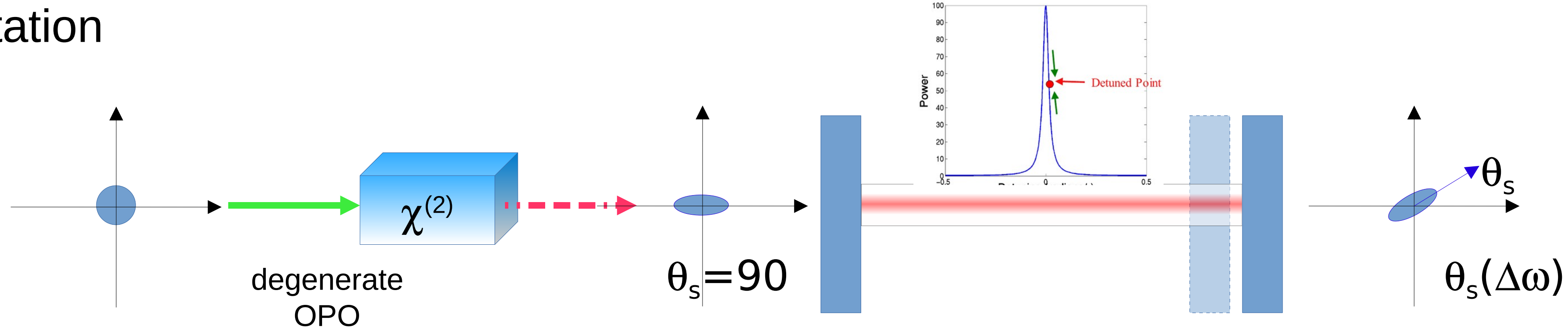




FDS GENERATION

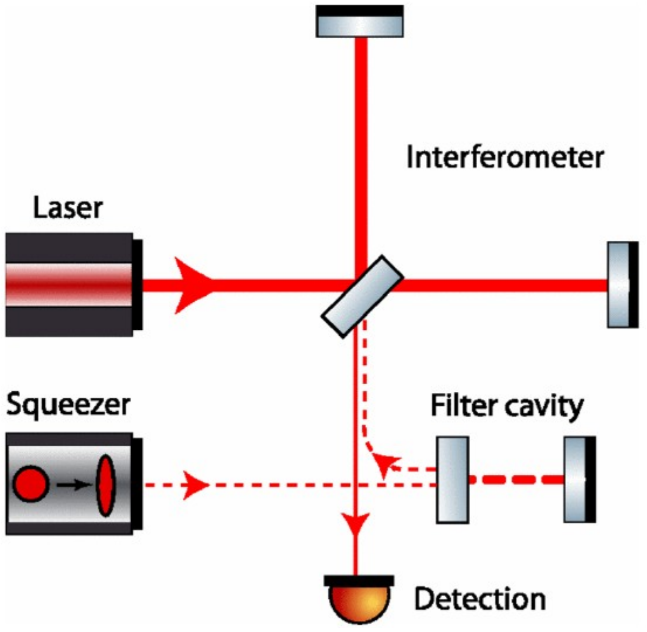
DETUNED CAVITY acts as filter (*Filter Cavity*) that in its band (cavity linewidth γ_{FC}) and **rotates the field quadratures, I.e. the squeezing ellipse**

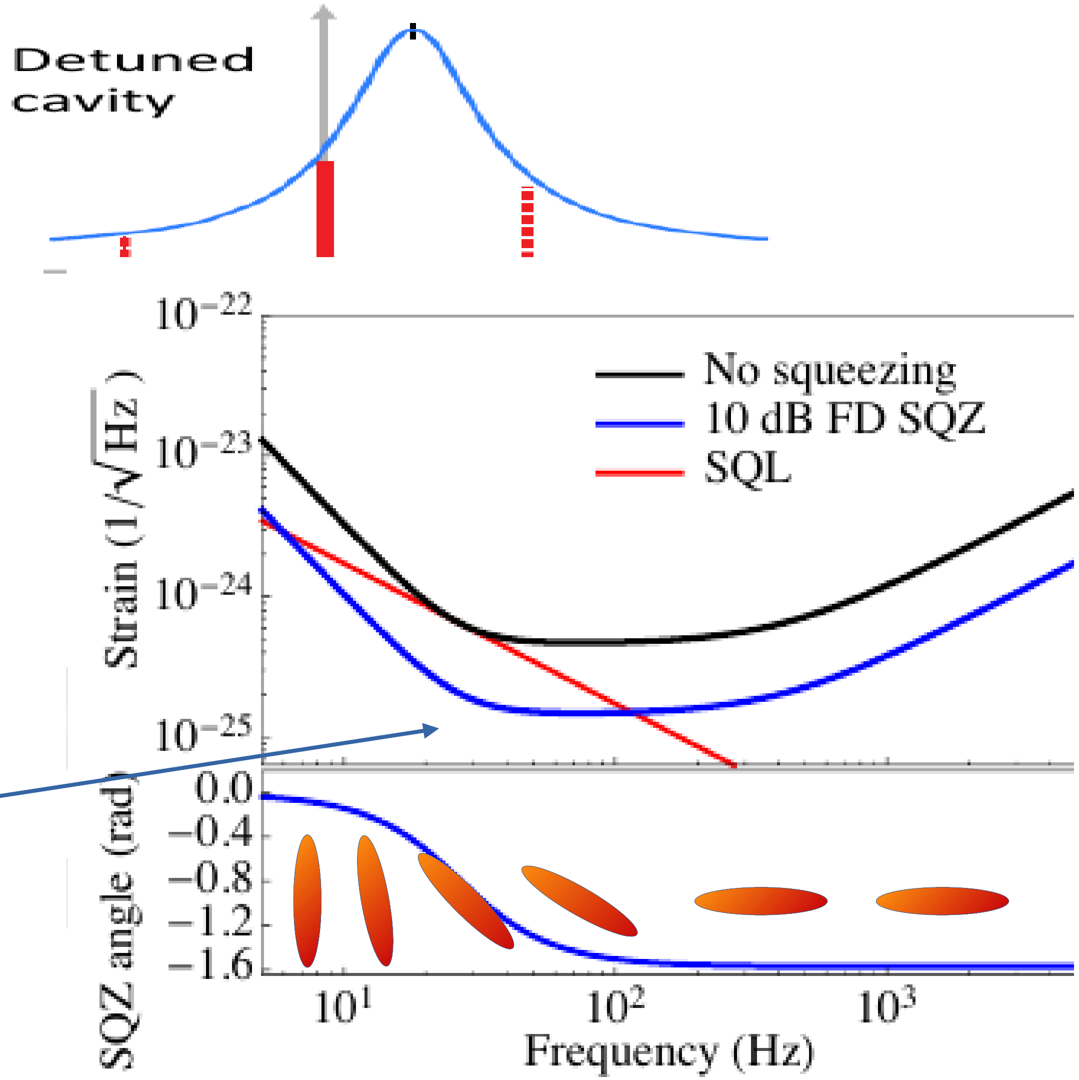
According with the cavity detuning, the sidebans experience a different phase and quadratures rotation



Degenerate OPO + detuned cavities *to rotate* the squeezing quadrature

FDS GENERATION





The squeezing angle can be suitable tuned in the detector band with a suitable choice of the cavity linewidth, γ_{FC}, and detuning $\Delta\omega$

Optimal choice:

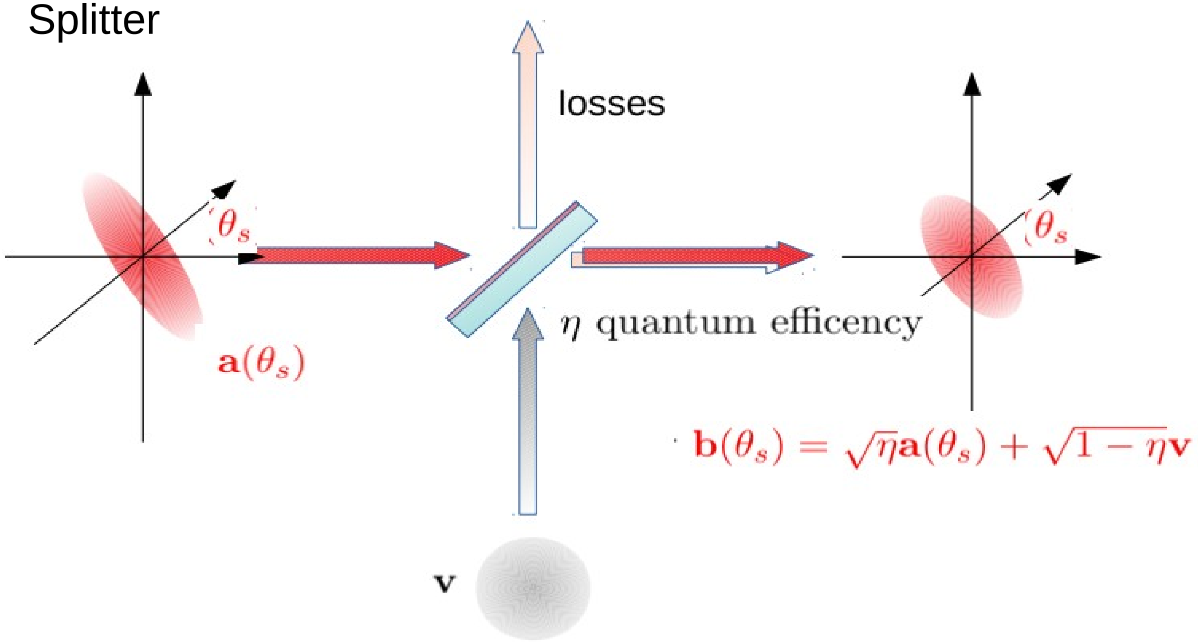
$\Delta\omega = \gamma_{FC}/2 = f(SQL)$

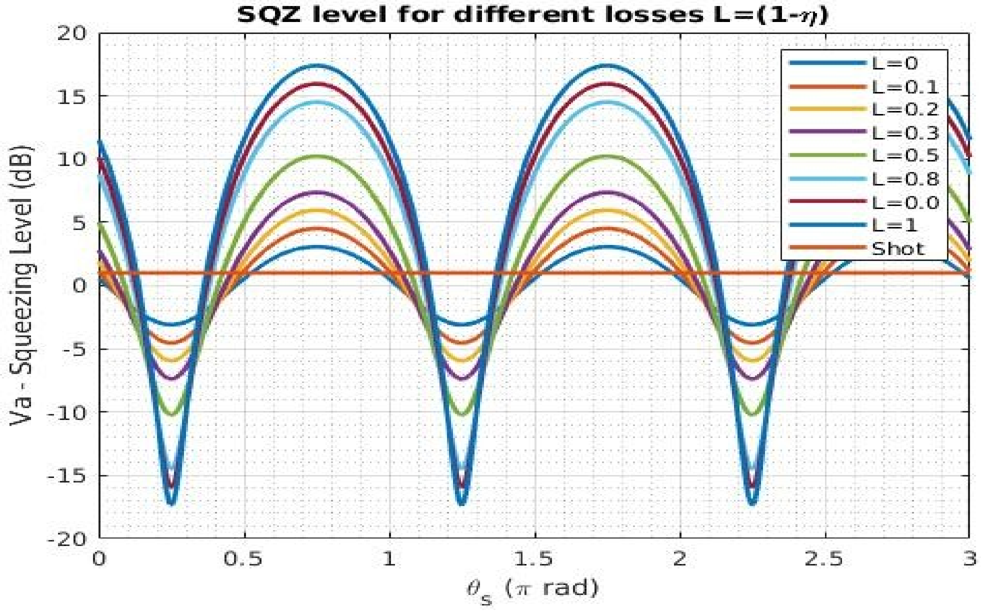
AdV+ FC Length ~300 m, Finesse ~10000, $\gamma_{FC}/2$ ~ 25 Hz

Quantum Interaction with Optical Devices

Losses in no*t phase sensitive devices*

Ex:Beam
Splitter





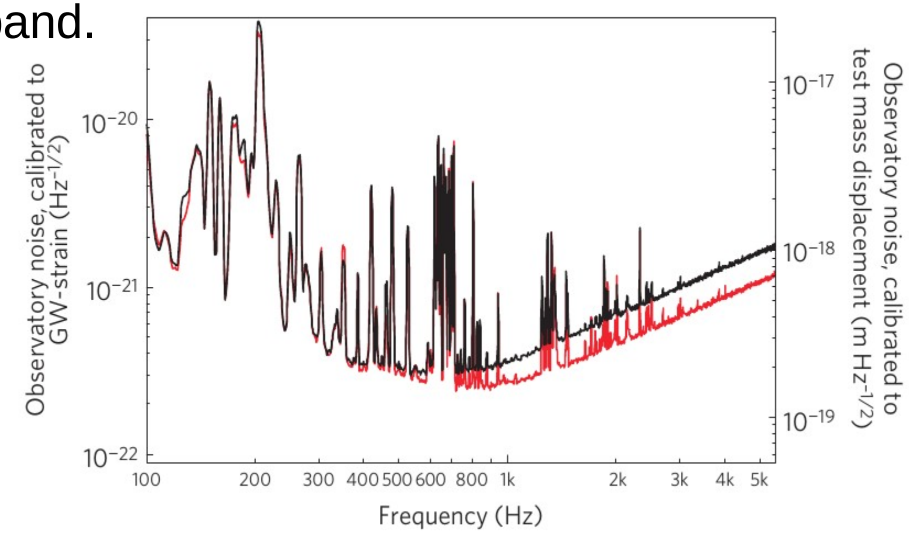
squeezing factor reduction

→ **Optical losses** during the propagation trough NOT PHASE SENSITIVE devices (absorption, input mode mismatch* …) can be described **as the effect of a beam splitter** with **reduced quantum efficiency** (BS transmittivity, $\eta=1-L<1$)

First Experimental FIS Sensitivity Enhancement

- GEO600

broadband noise reduction of up to 3.5 dB (red trace) in the shot-noise-limited frequency band.

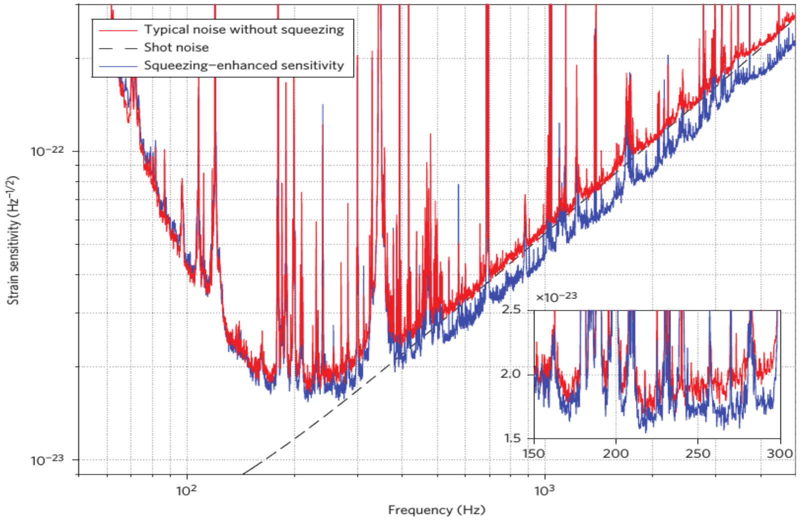


Losses 10 dB produced,
3.5 dB injected

LIGO Scientific Collaboration et al.
"A gravitational wave observatory operating beyond the quantum shot-noise limit".
In: Nature Physics 7.12 (2011), pp. 962–965.

- LIGO H1 detector

up to 2.15 dB in the shot-noise-limited frequency band



J Aasi et al.
"Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light".
In: Nature Photonics 7.8 (2013), pp. 613–619.

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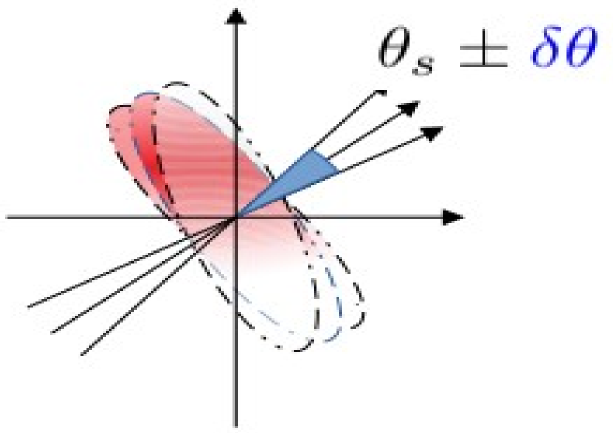
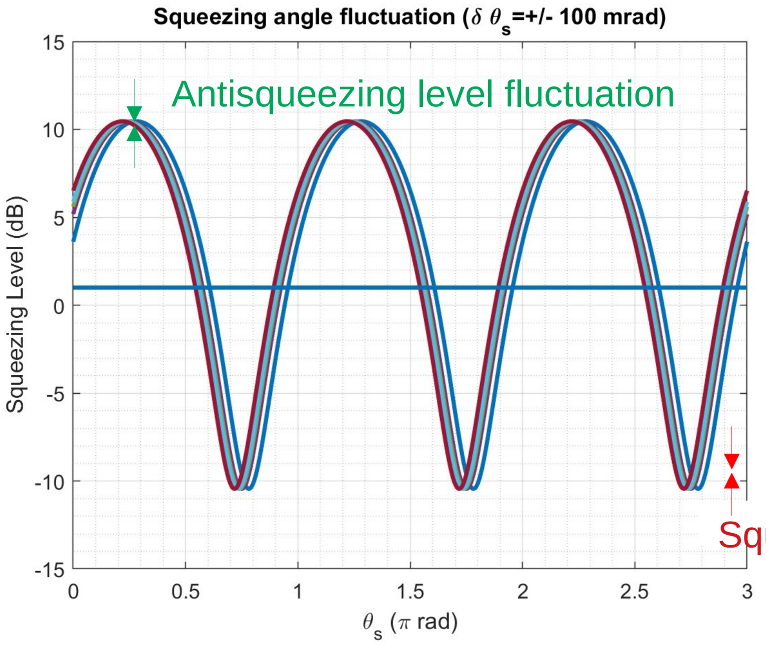
→ **Quantum Noise Reduction System for AdV+**

MECHANICAL and OPTOELECTRONIC devices



squeezing angle jitter

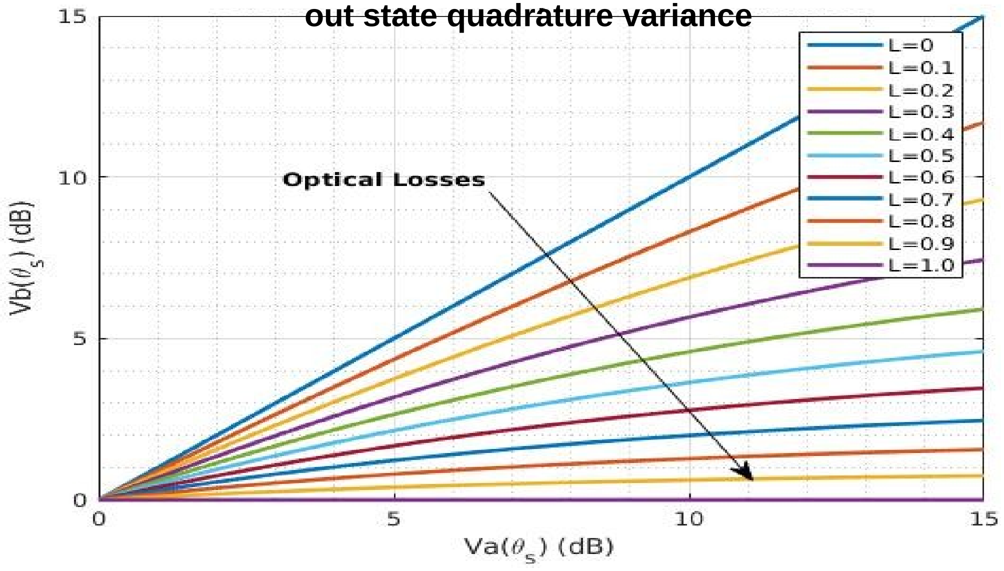


Squeezing level fluctuation → rms

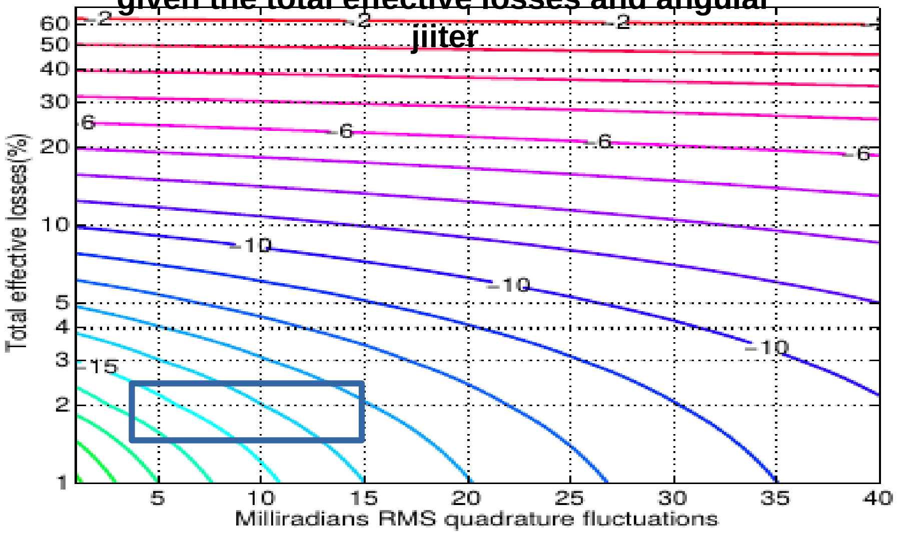
→ **Technical noise** (*photodetector dark noise, scattered light, mechanical vibration..*) gives effects similar to the **SQUEEZING ANGLE jitter** ***(quadratures fluctuations)***

Squeezing degradation

Effect of the losses on the out state quadrature variance



Effective squeezing achievable given the total effective losses and angular jiiter



CARE IN THE INJECTION DESIGN

Higher is the squeezing level and
higher must be the losses reduction to avoid to spoil it

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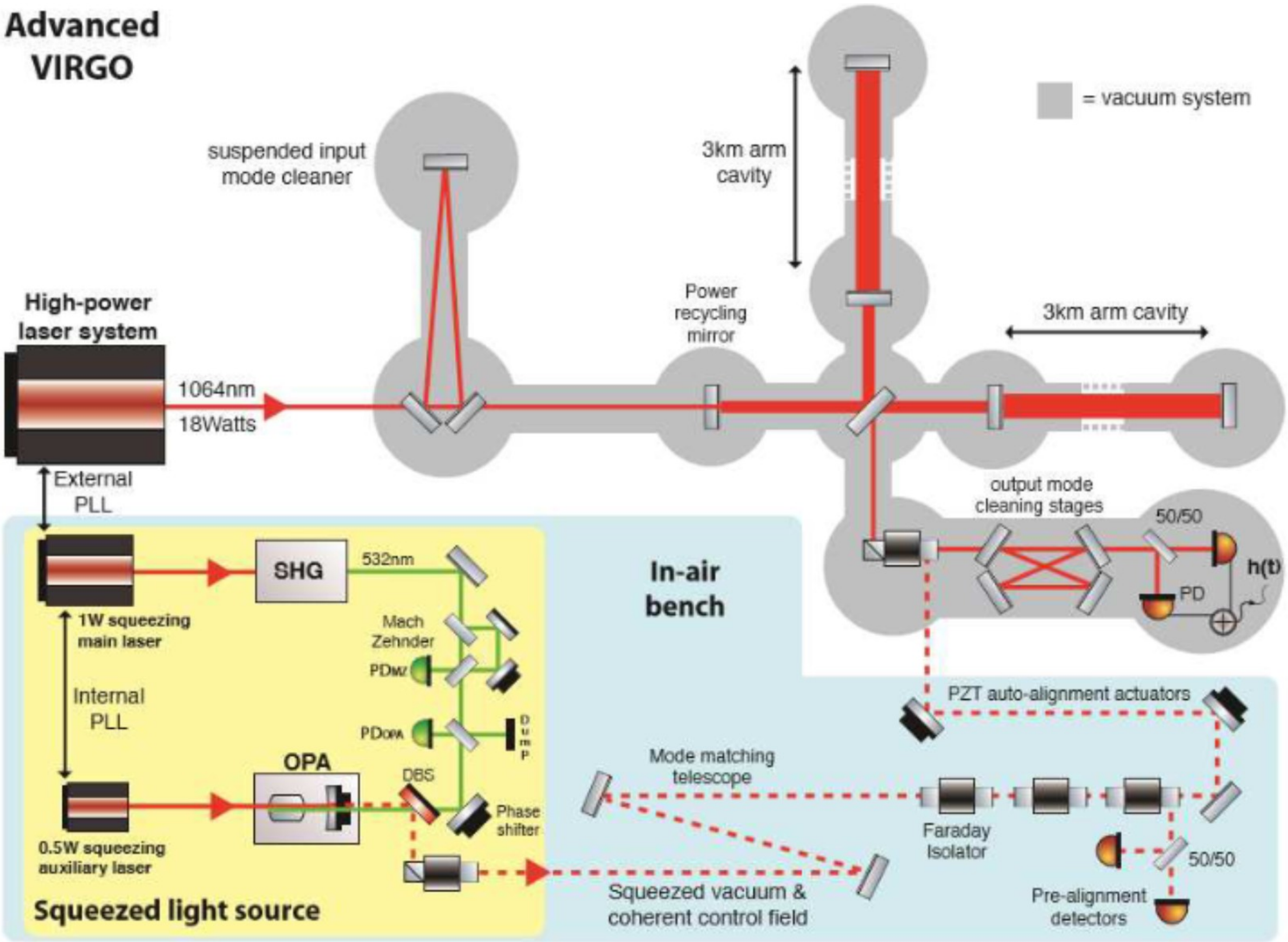
Motivation:

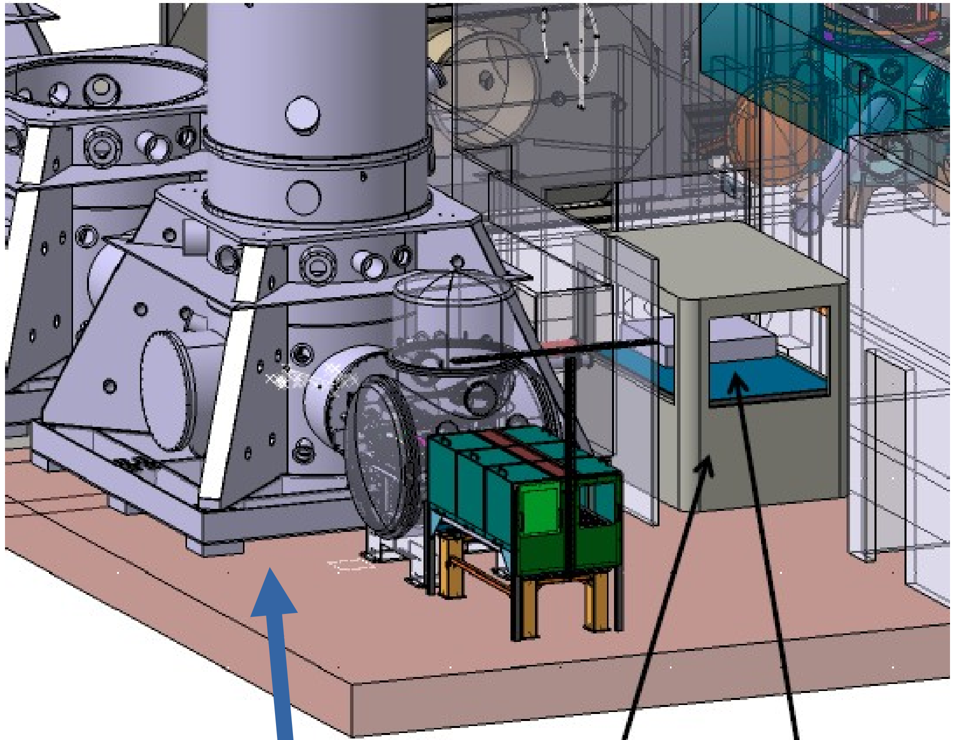
→ **Improve the sensitivity at high frequencies** for **O3** (April 2019 – March 2020)

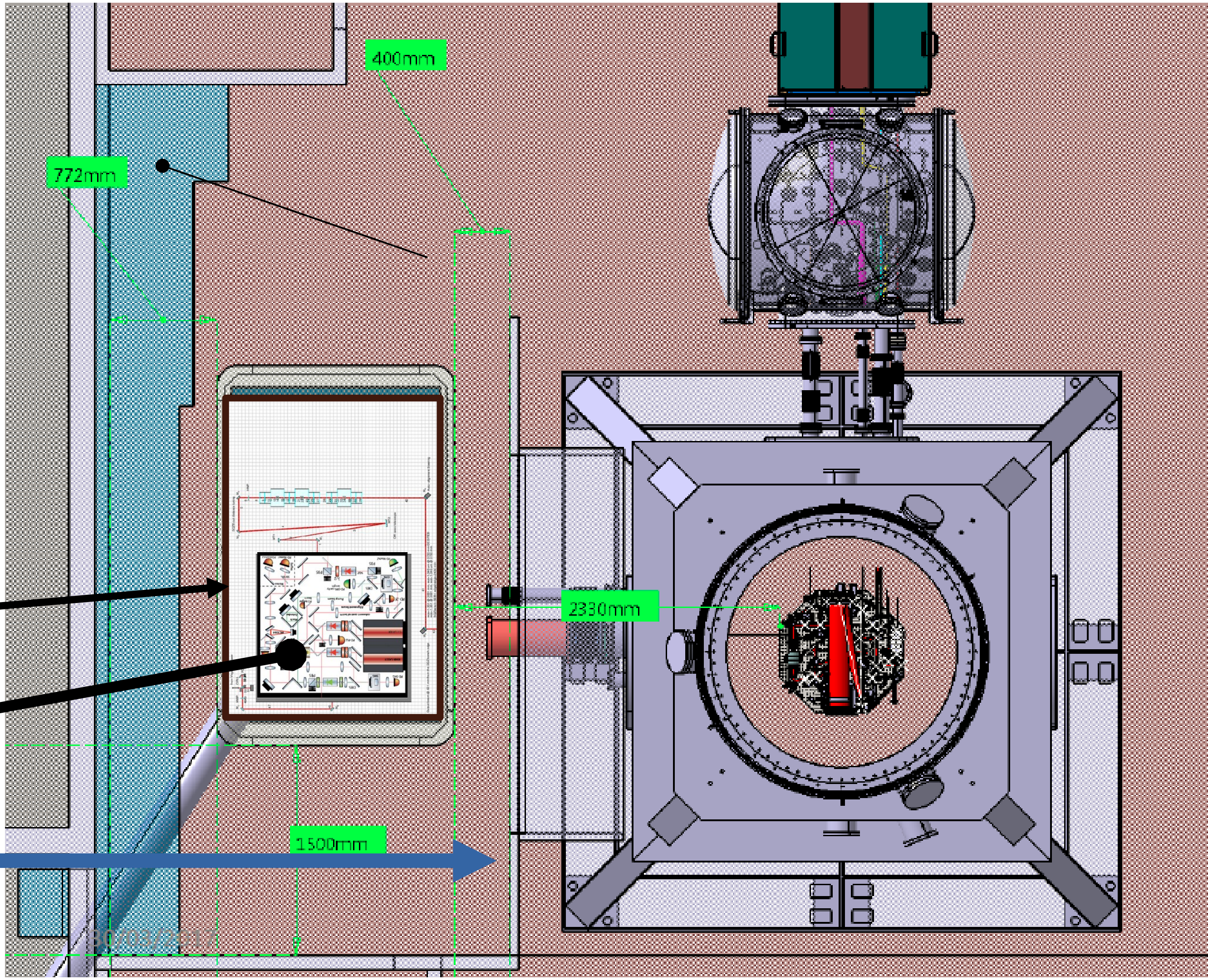
→ **A fundamental step towards the Frequency Dependent Squeezing**

AdV with FIS for O3 scheme



FIS system INSTALLATION in EGO for O3





Acoustic enclosure

Injection bench

AEI squeezer

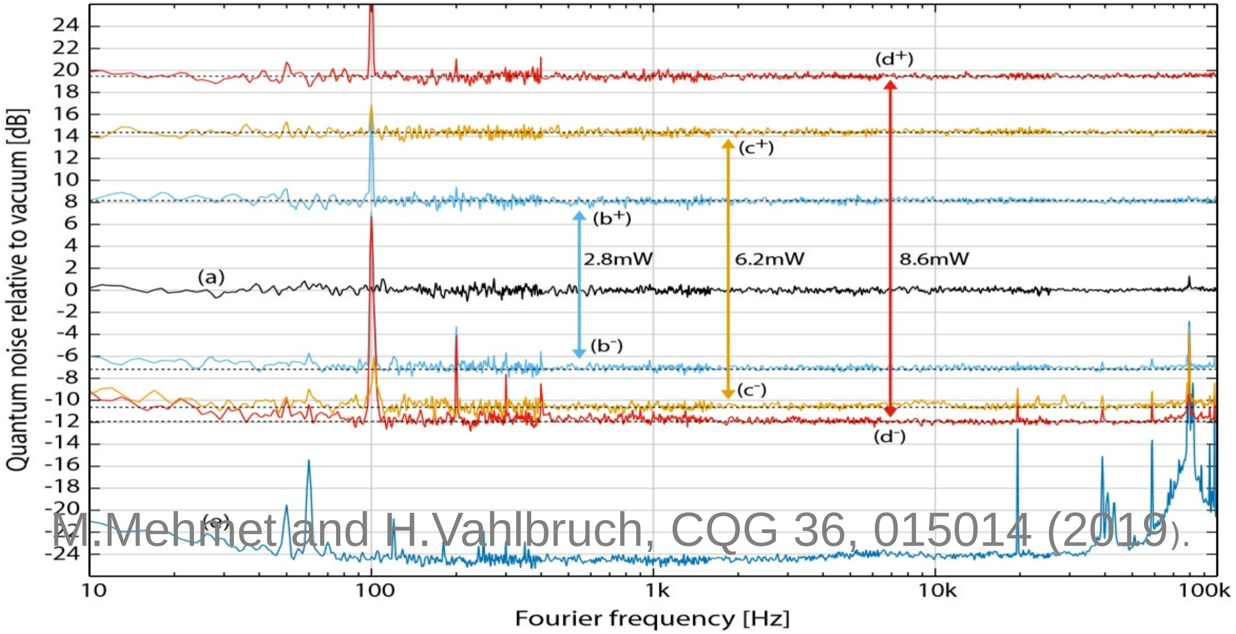
DETECTION Bench Minitower

The AEI squeezer

- stand alone in-air squeezer in a 1x1 mq box

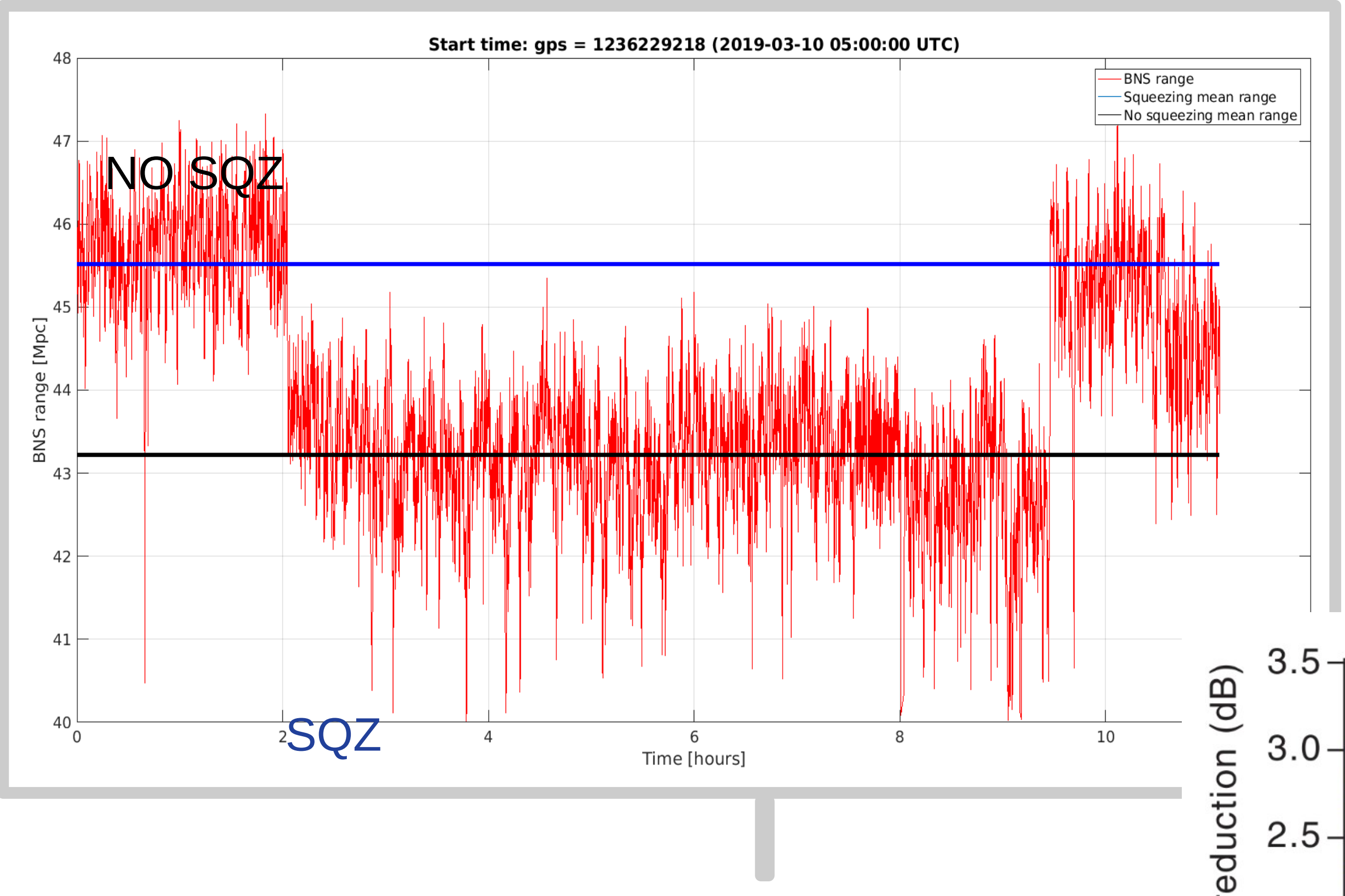
Vacuum Squeezed degenerate OPO source (PPKTP non linear crystal in ldoubly resonant optica cavity)

- Up to **12 dB of squeezing measured in AUDIO BAND** *(GW bandwidth)* with diagnostic homodyne detector
- **Delivered in Cascina on January 2018**

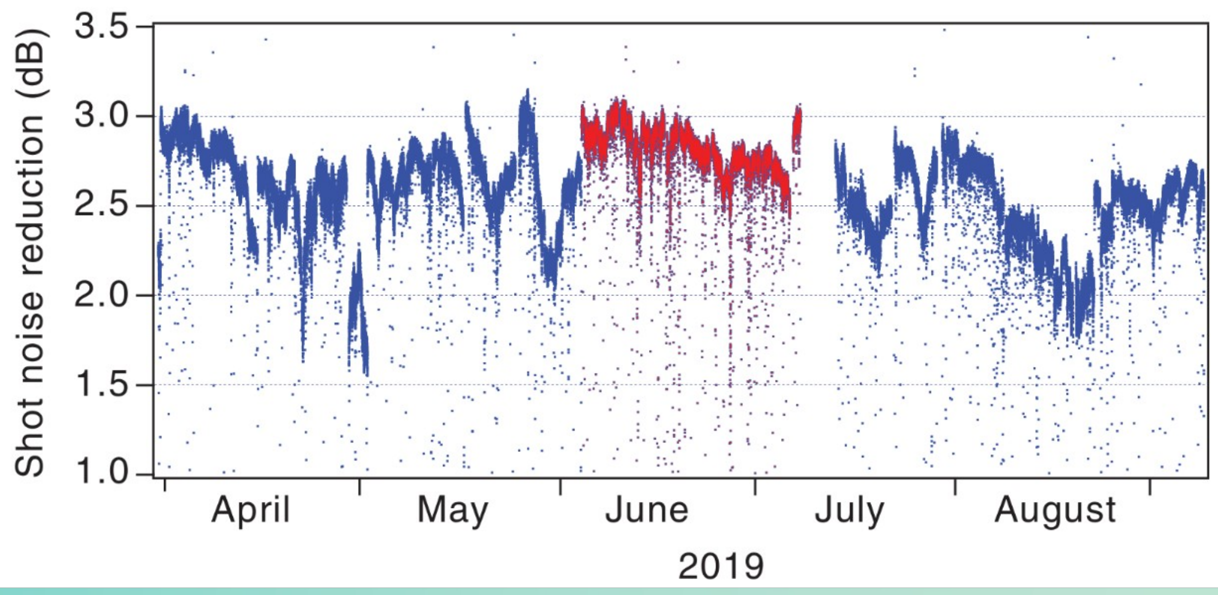


M.Mehmet and H.Vahlbruch, CQG 36, 015014 (2019).

FIS in AdV O3 results

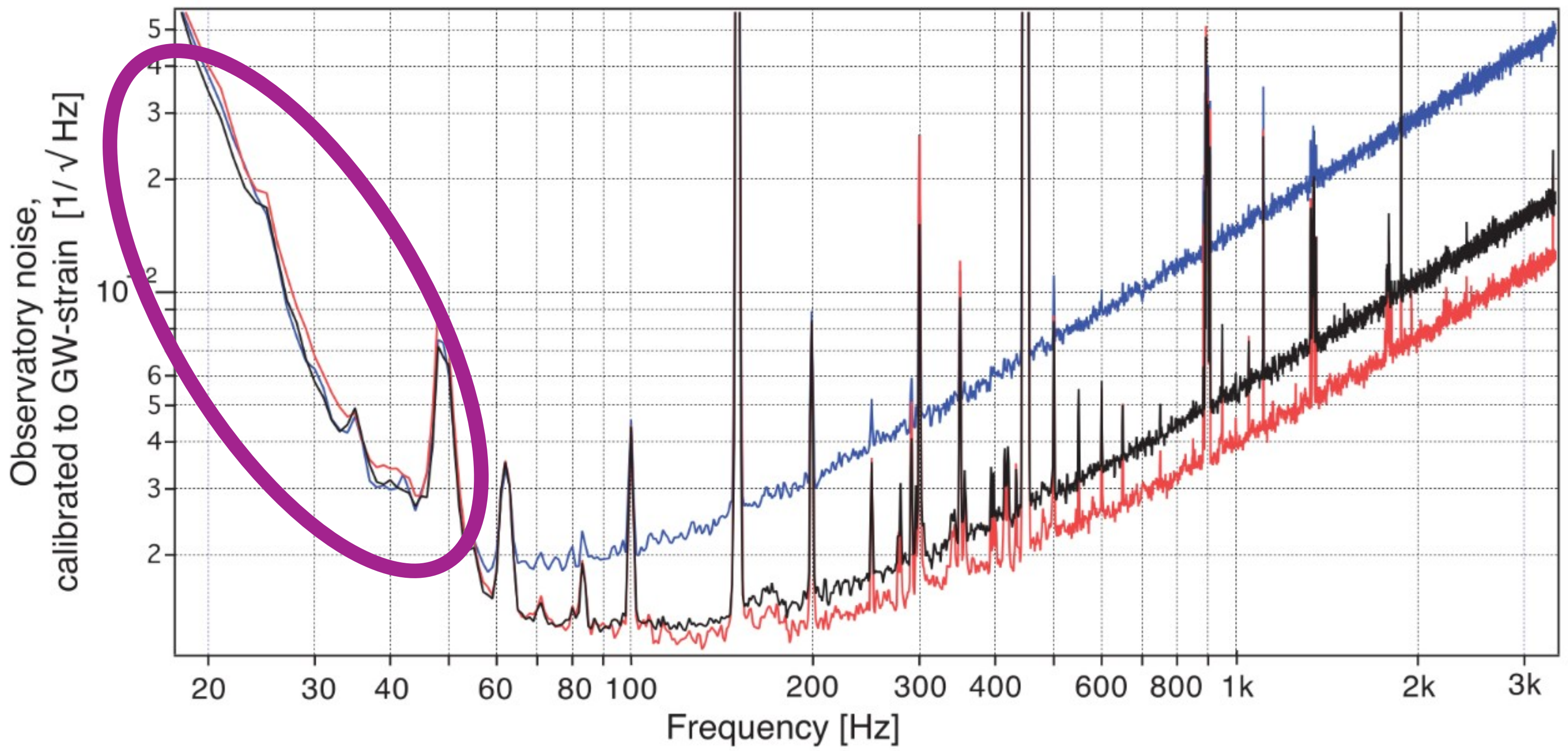


- Up to 3.2+/- 0.1 dB of SN reduction
- with 7-10 dB injected (47+/- 5 % Losses almost well characterized
- BNS Horizon increase: 2-4 Mpc
- Long term operation during O3



FIS in AdV O3 results

PHYSICAL REVIEW LETTERS **123,** 231108 (2019)



→ Amplitude Squeezing injection SQZ angle =0 rad)

→ NO SQZ

→ Phase Squeezing injection (SQZ angle = $\pi/2$ rad

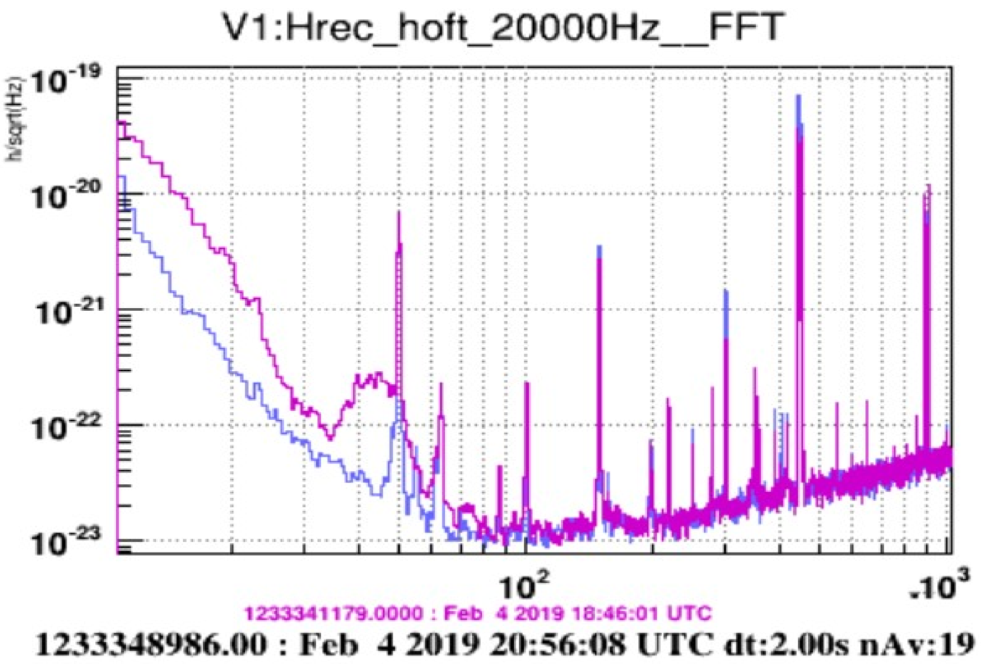
→ TOTAL estimated losses: 37+/-5 %

First evidence of **Radiation Pressure noise increasing** by phase squeezing injection **on a 43 kg test mass (PRL 125, 131101)****

**For LIGO: Nature 583, 43 (2020)

Stray Light

- It was observed that when the alignment of injection is not optimized or/and the OFI reflected power is not minimized, the ITF low frequency sensitivity is worsened



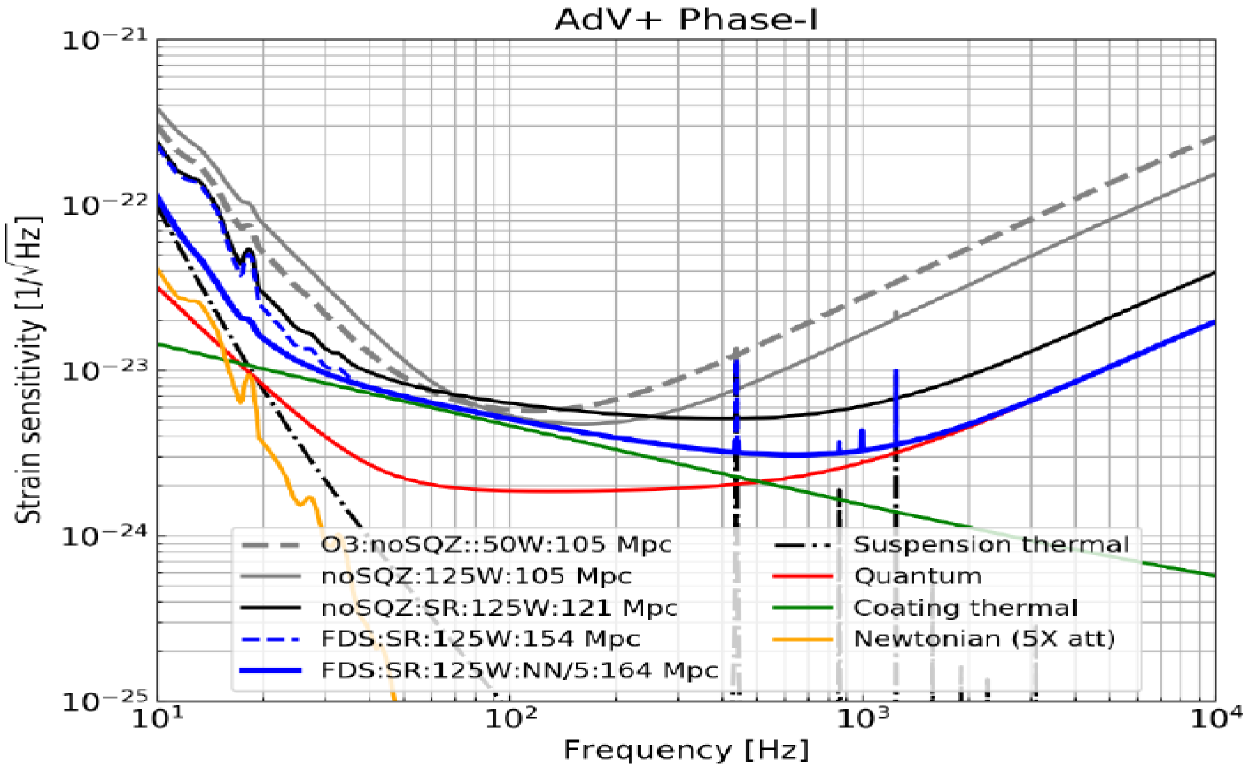
Artificially increasing the OFI reflection by rotating the motorized HWP it comes evident that the dominant contributor are the final Faraday Isolator and steering mirror1 which have mechanical resonancein the region 30-150 Hz observed in the strain PSD for large OFI reflection.

Not evidence of any contribution coming from the OPA.

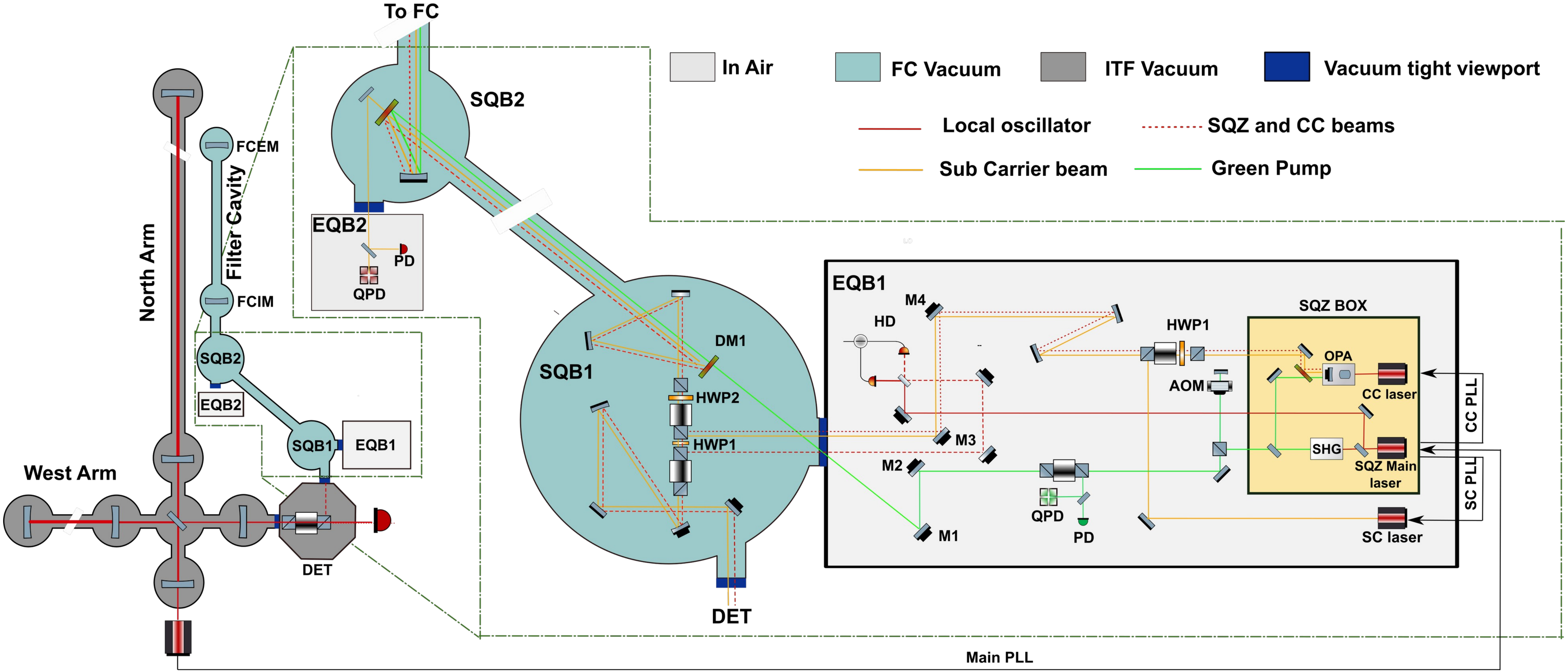
When the squeezer injection is well aligned and the Faraday Isolators are well tuned, there is no evidence of low frequency stray light effect

Motivation

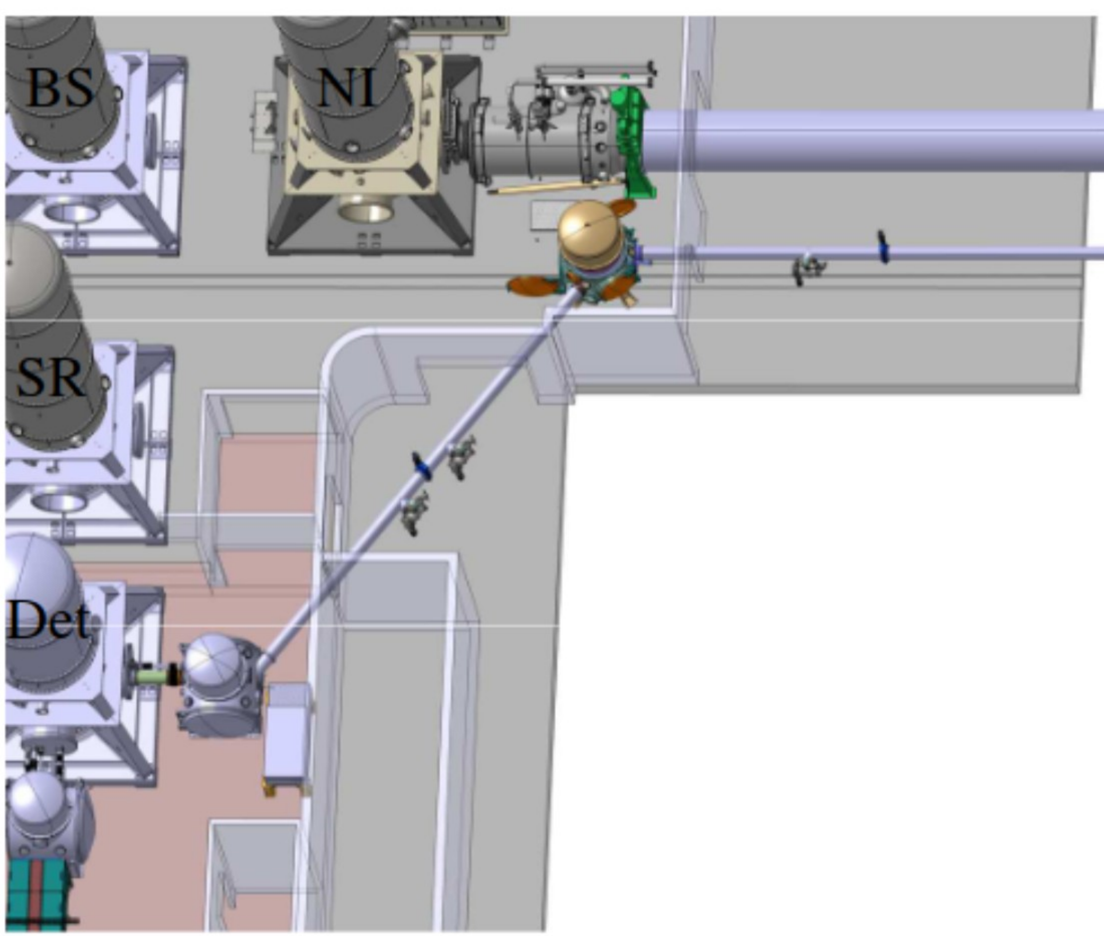
→ **Improve** the **sensitivity in all ITF** frequency **band** for the next scientific run O4 *by injection of* **7 dB** of **Frequency Dependent Squeezing**

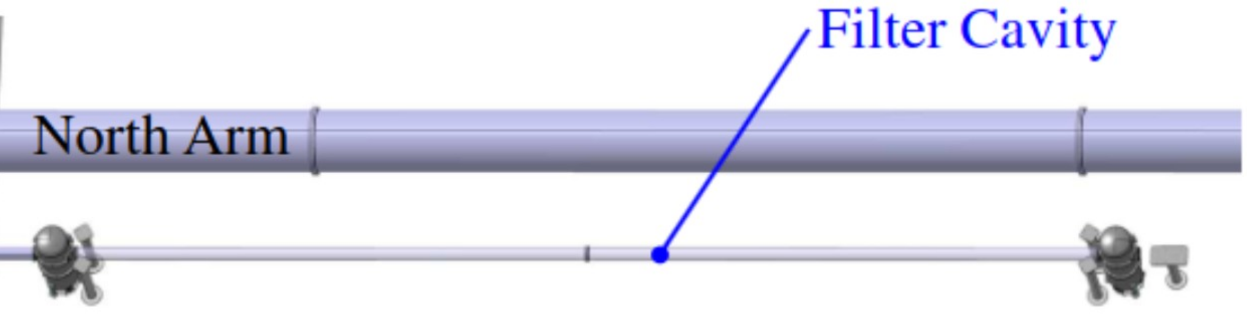


AdV+ FDS system scheme



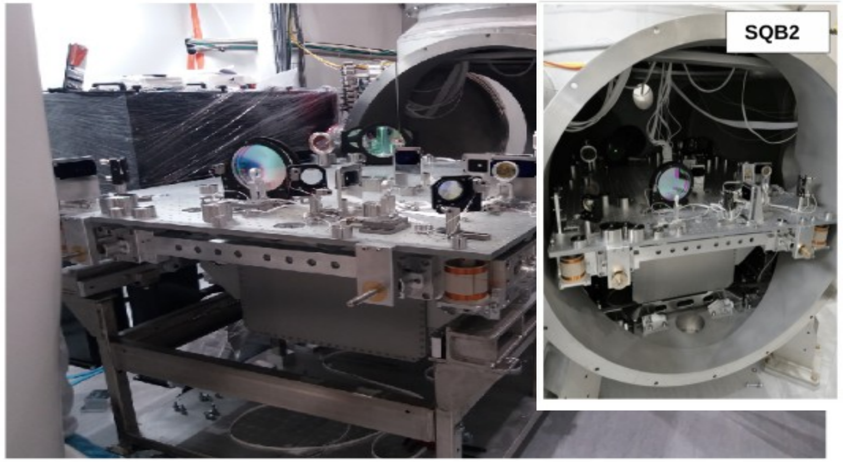
Infrastructure modification for AdV+ FDS

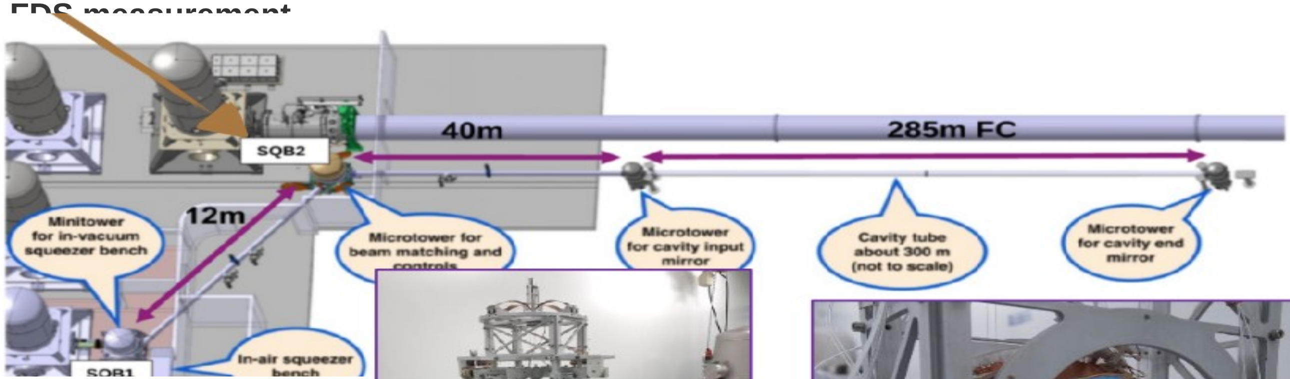


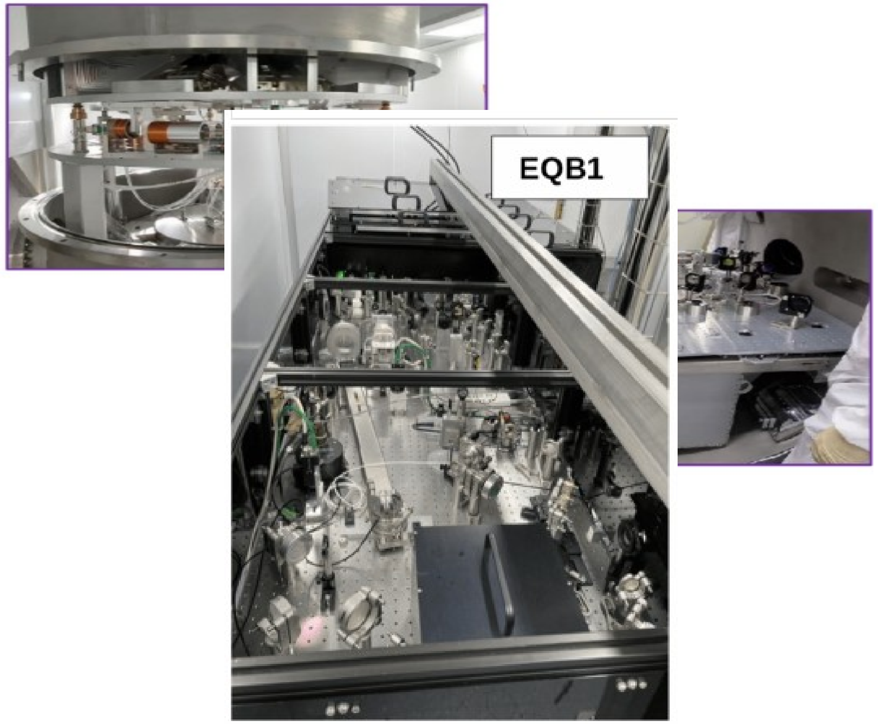


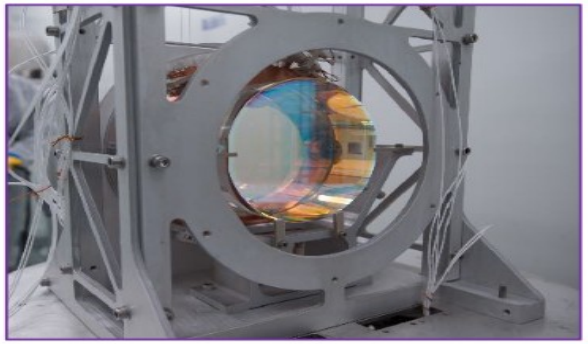
North Arm and FC tubes

AdV+ FDS system



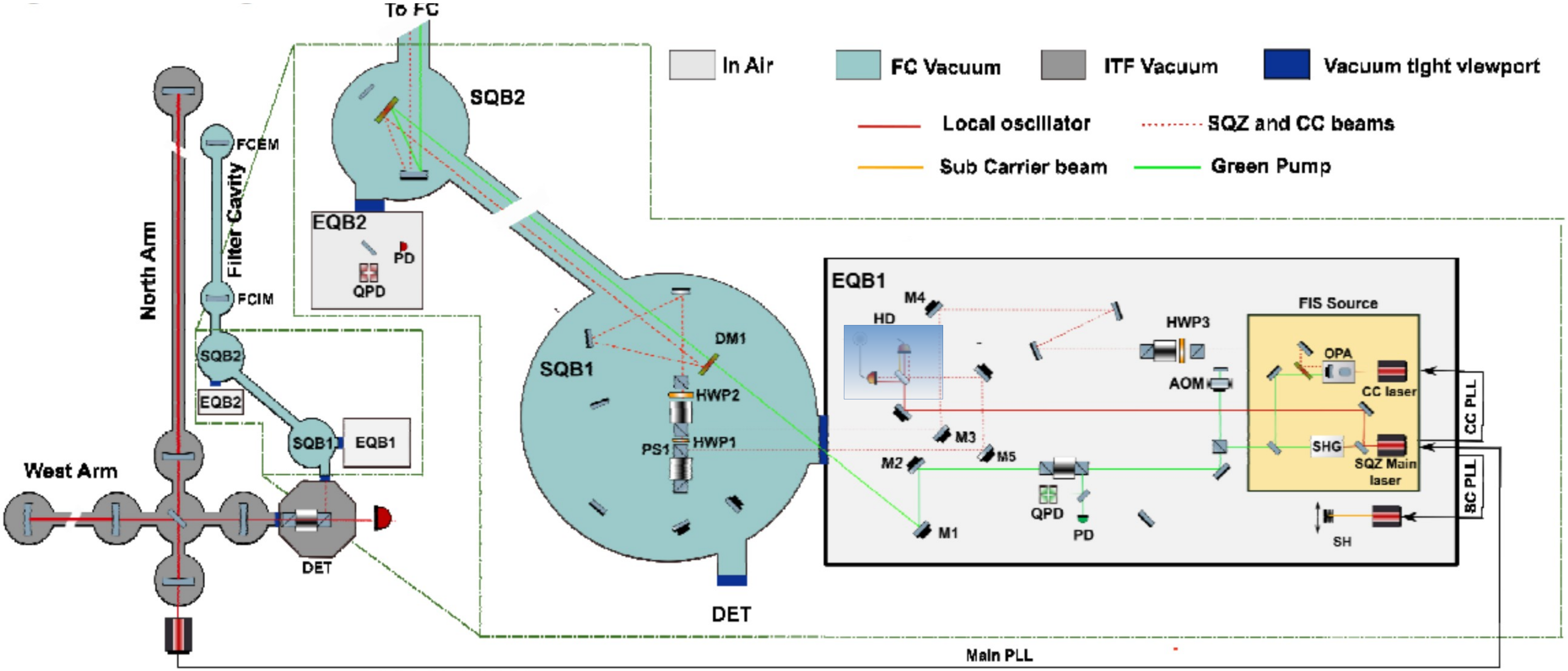






FC suspendes Mirror

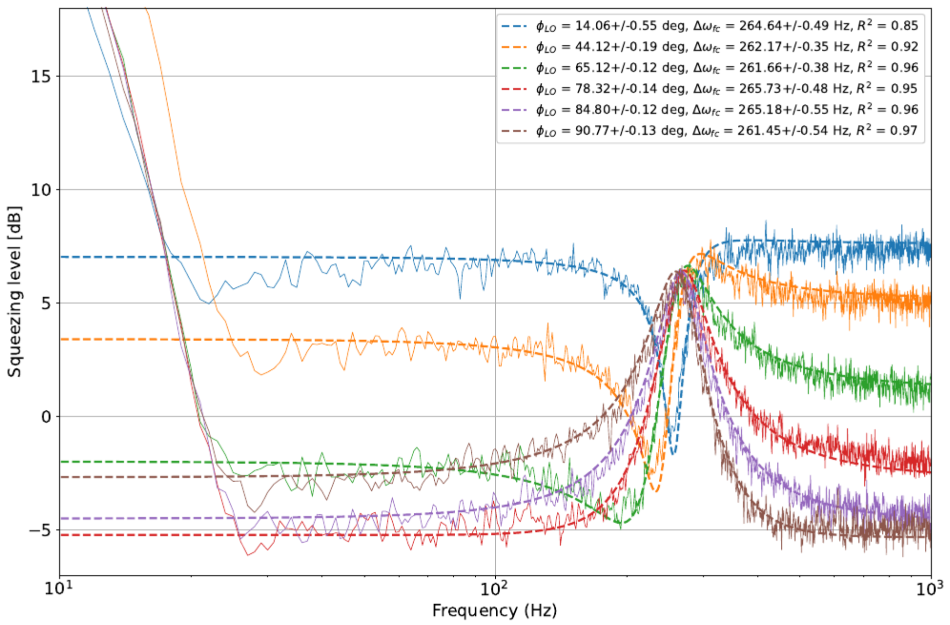
AdV+ FDS system diagnostic configuration

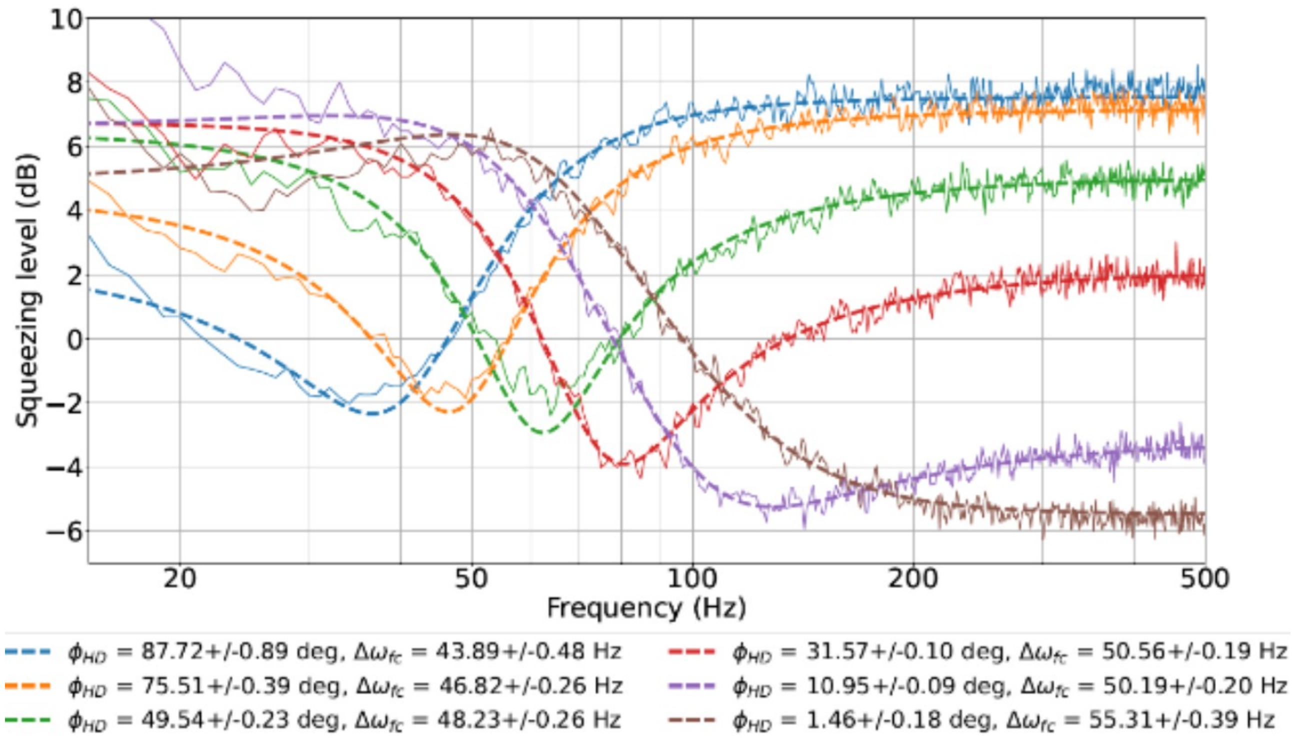


the SQZ beam is send back on the External Squeezing bench to the Homodyne Detector

AdV+ QNR system Installation and commissioning

- **Dec 2020**
- **Mar 2021** — **FC mirrors suspended**
- **Jun 2021** — **FC locked on Green**
- **Oct 2021** — **FC locked on IR**
- **Nov 2021** — **FDS measurement @ Detuning ~ 300 Hz**
- **Feb 2022** — **FDS measurement @ ~ 40 Hz**
- **Jun 2022** — **FDS measurement @ ~ 25 Hz**



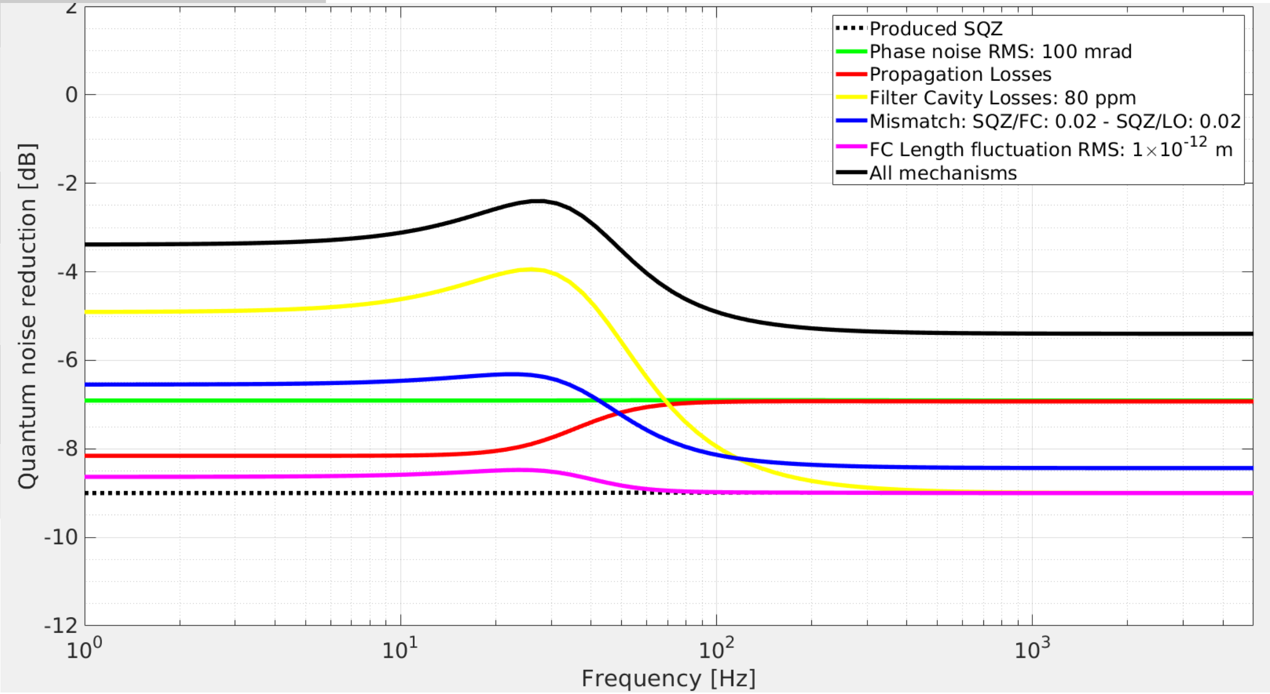


AdV+ FDS commissioning RESULTS

System Characterization

SQZ beam Propagation Losses	4.5 +/ 0.3 %	**SQZ alignment On FC**	**~ 0.1 %**
FC Round Trip Losses	80 +/- 10 ppm		
SQZ/FC beams MIsMatch	1.5 +/-0.5 %		
SQZ/LO Mis-Match	2.0 +/-0.5 %		
Lock Precision	~1 (Hz)	$\Delta L \sim 10^{-12}$ m	
CC Phase Noise	40 +/-10 mrad		
Residual Phase Noise	60 -/+ 10 mrad		

We can assure 4 dB reduction in ITF QN (@ ITF input power 40W, according with Kwee and al. model)



AdV+ FDS commissioning RESULTS

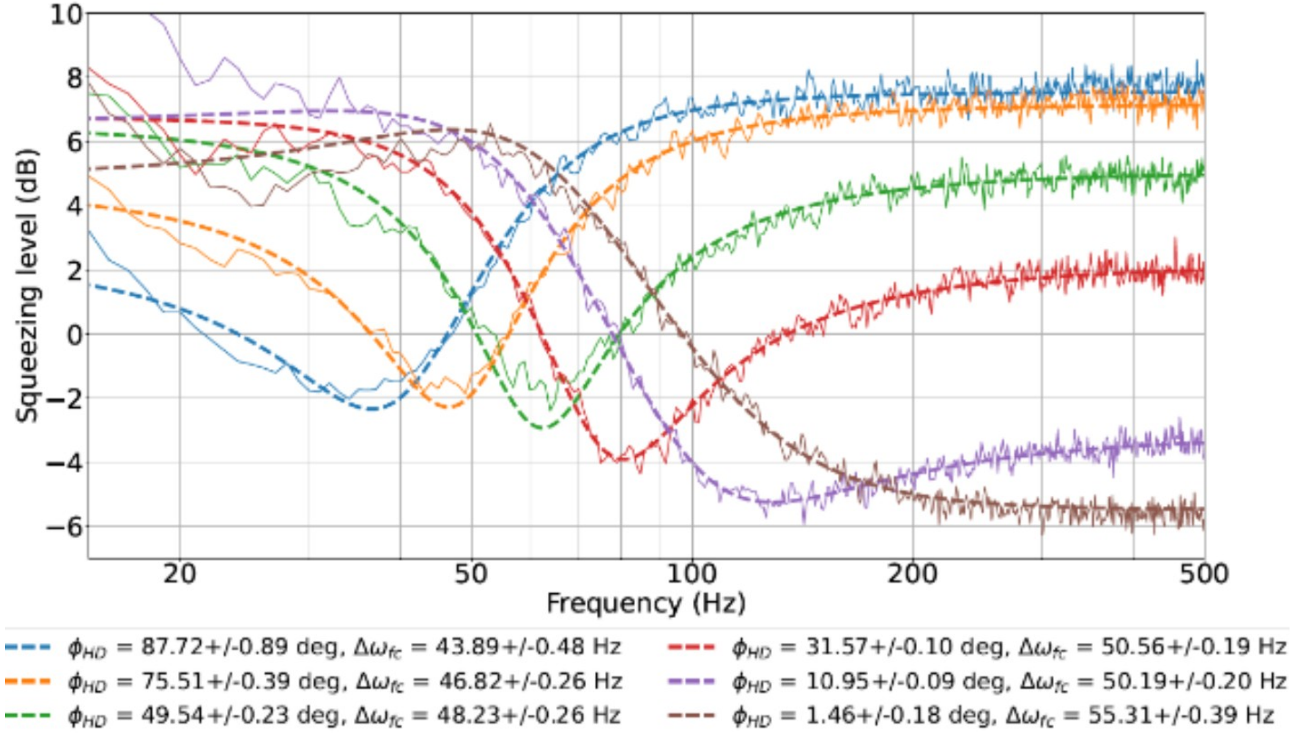
System Characterization

Open Access

Frequency-Dependent Squeezed Vacuum Source for the Advanced Virgo Gravitational-Wave Detector

F. Acernese *et al.* (Virgo Collaboration)

Phys. Rev. Lett. **131**, 041403 – Published 25 July 2023



Thanks a lot!!!