M.Bawaj, D. Bonavena, R. Bonnand, E. Capocasa,
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B.Garaventa, A. Grimaldi, Y.Guo,
M. Mehmet, E. Polini,V. Sequino, F. Sorrentino, M. Tacca,
H. Valhbruch, M.Vardaro,
Y. Zhao,J-P. Zendri

On behalf of the *QNR AdV+ System*
and *Virgo Collaboration*

Status of

Quantum Noise Reduction system in AdV+

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INFN Napoli — Istituto Nazionale di Fisica Nucleare, Sezione di Napoli

CONTENTS

→ Quantum Noise Reduction in Gravitational Waves **I**n**T**er**F**erometrical Detectors
→ Quantum States interaction with Optical Devices
→ Quantum Noise Redection System in AdV+
→ AdV+ Quantum Noise Reduction System commissioning

Quantum Noise in GW detectors

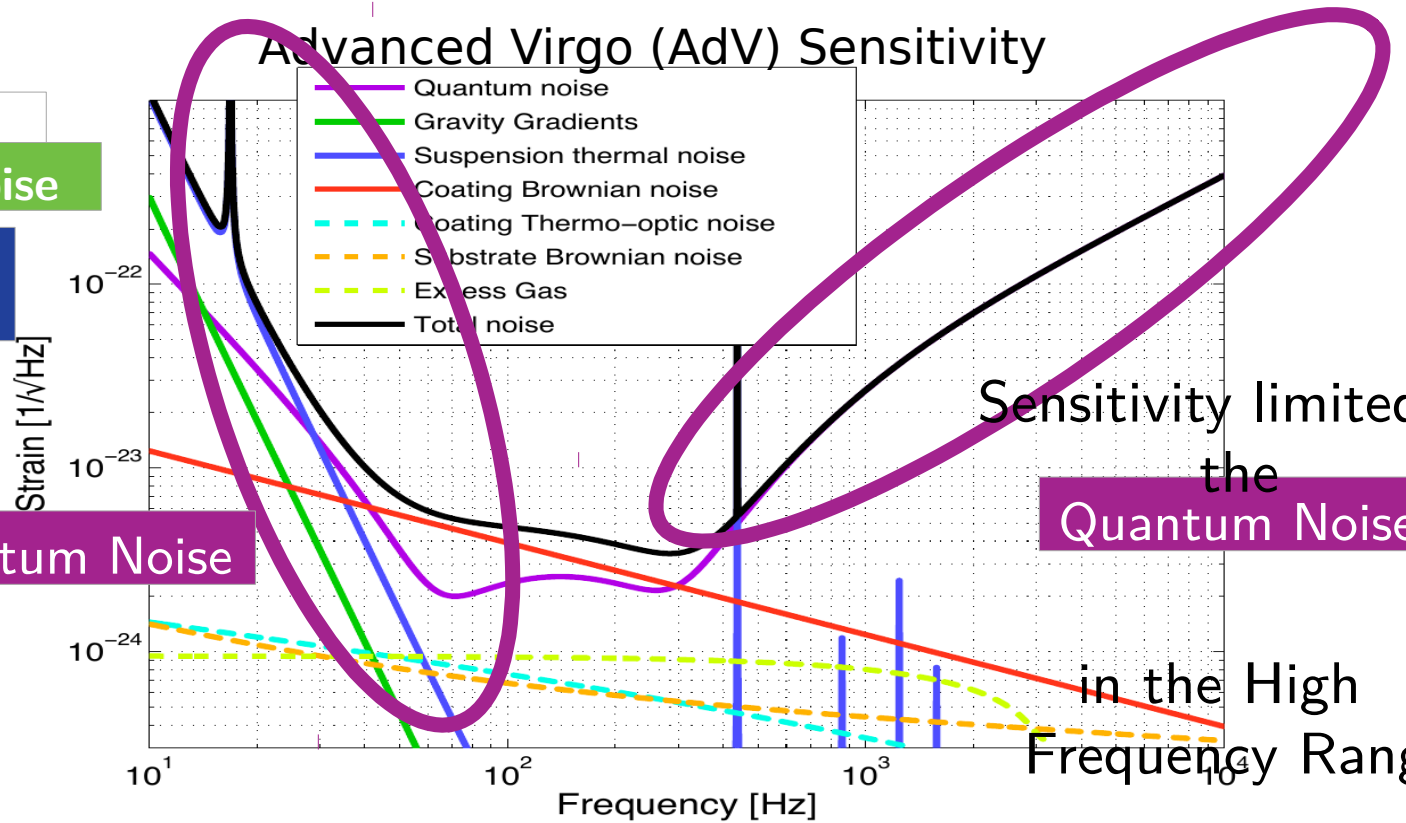
Noise in GW Interforemeters

Low Frequency Range

Seismic vibrations

Newtonian Noise

Suspension Thermal Noise



Quantum Noise

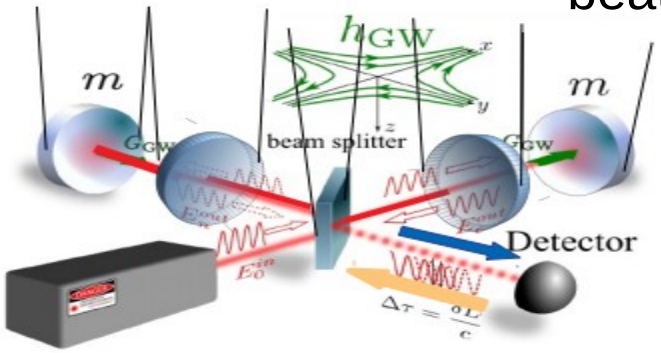
Sensitivity limited by the Quantum Noise in the High Frequency Range

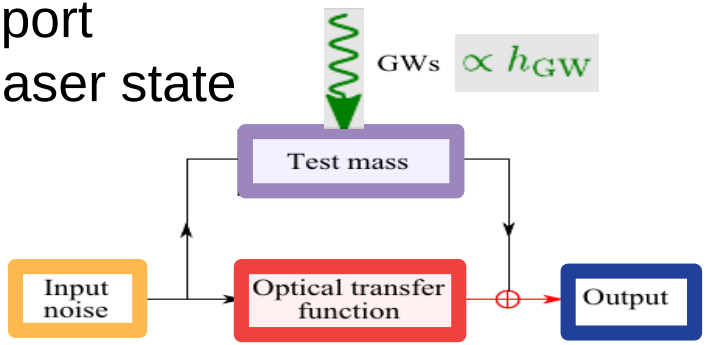
Mid Frequency Range

Coating Thermal Noise

Interferometer Quantum Noise

Quantum Noise: **coherent vacuum** in the dark ITF port
beats with the classical ITF laser state





ITF optomechanical response

(depend on the specific optical configuration)

couples input amplitude and phase quadratures with output phase quadrature

amplitude quadrature (b1)
phase quadrature(b2)
of the *out optical state*

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

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

(a1) amplitude quadrature
(a2) phase quadrature
of the input vacuum optical state

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

(Ω Gravitational Wave frequency)

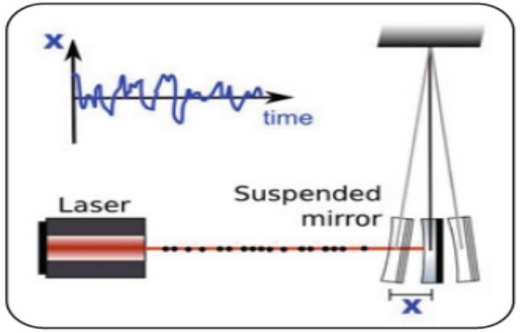
Interferometer Quantum Noise

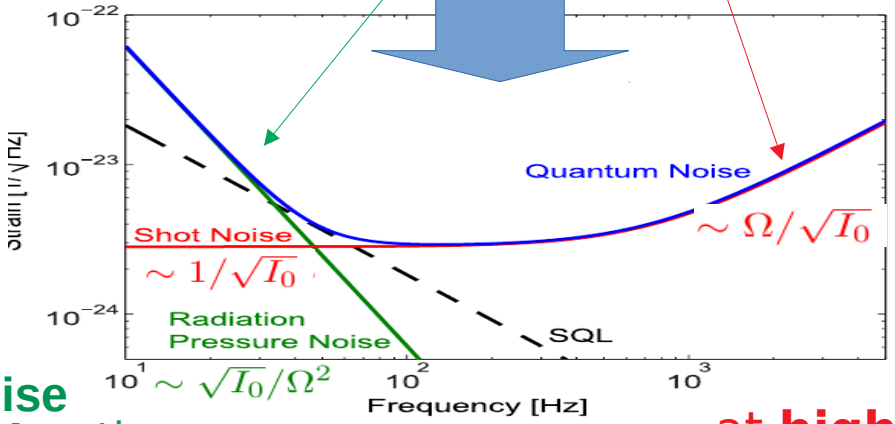
ITF OUPLING FUNCTION, $\mathcal{K}(\Omega)$, *frequency dependent*: in the device band the *quadratures noise* is *frequency dependently 'weighed'*

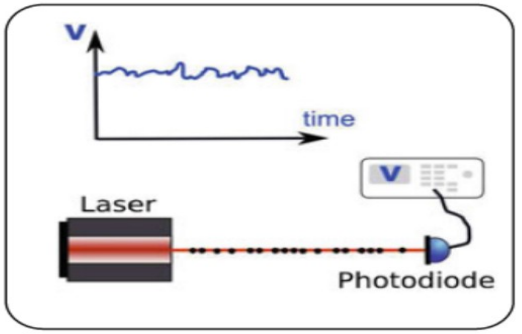
$$\hat{h}_n(\Omega) = S_h(\Omega)^{1/2} = \left[\mathcal{K}(\Omega) + \frac{1}{\mathcal{K}(\Omega)}\right] \frac{h_{\mathrm{SQL}}^2}{2}^{1/2}$$

Ω, Gravitational Wave frequency

$(\Omega/\gamma<<1)$







Radiation Pressure Noise

At **low frequency dominates** the effect of the input **amplitude quadrature noise**

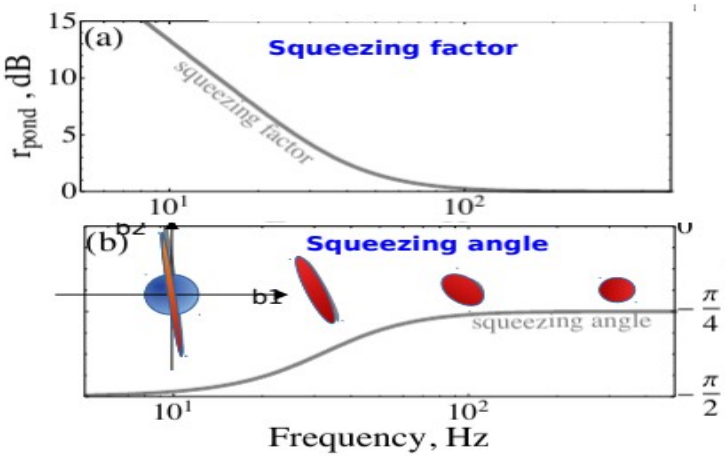
The light amplitude fluctuations *transfer* a fluctuating momentum to the mirror

***Shot Noise*:**

at **high frequency dominates** the effect of the input **phase quadrature noise**

The fluctuation of the Number of impinging photon In the time units, *determines* a phase fluctuation on the output signal

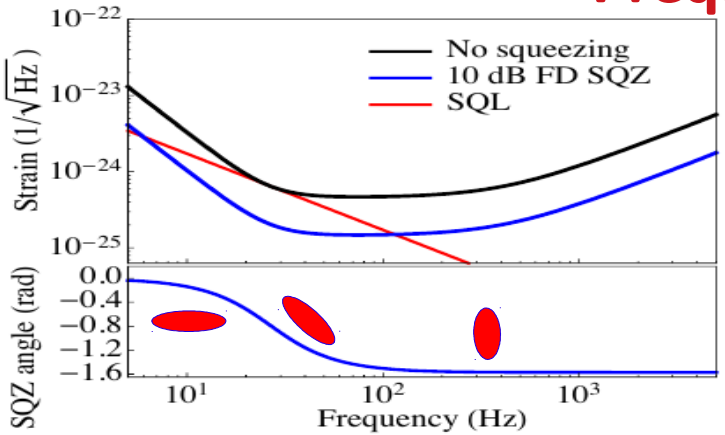
Interferometer Quantum Noise



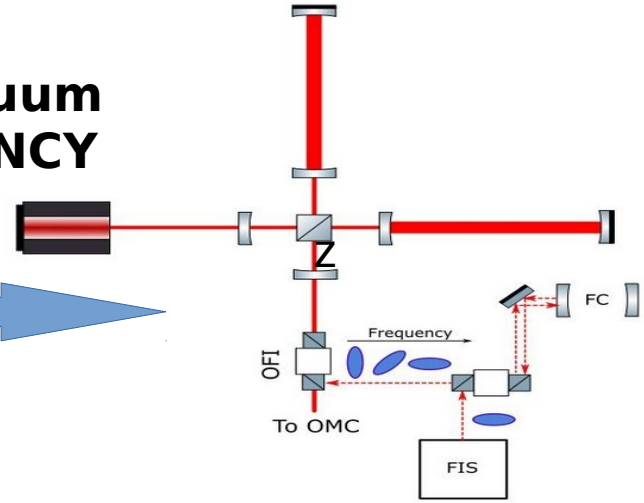
An useful alternative 'view':
***out phase quadrature* variance** is **'squeezed'** and **rotated inside the ITF band** *with different squeezing factor and angle*:
frequency dependent ponderomotive squeezing of the input coherent vacuum

solution

Frequency Dependent Squeezing (FDS) injection:



Injection of
RIGHT SQUEEZING vacuum
@ THE RIGHT FREQUENCY



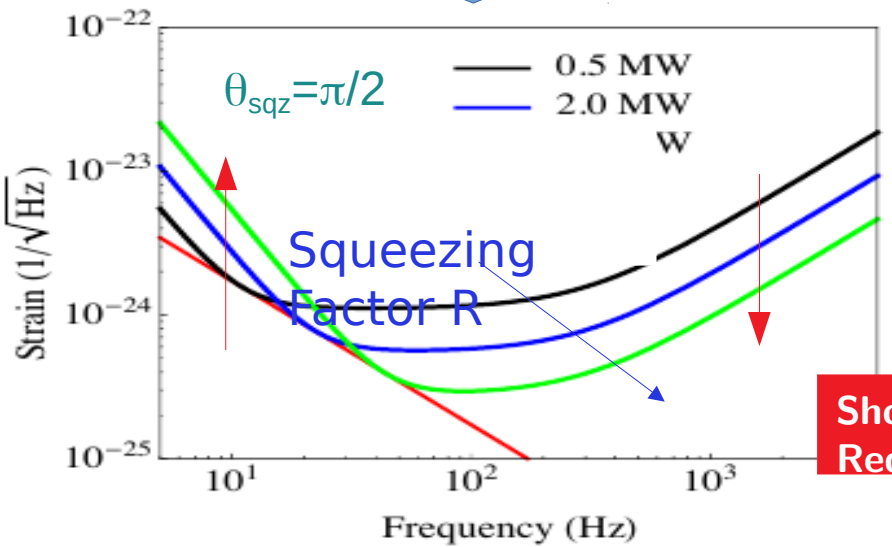
Frequency Independent Squeezing (FIS)

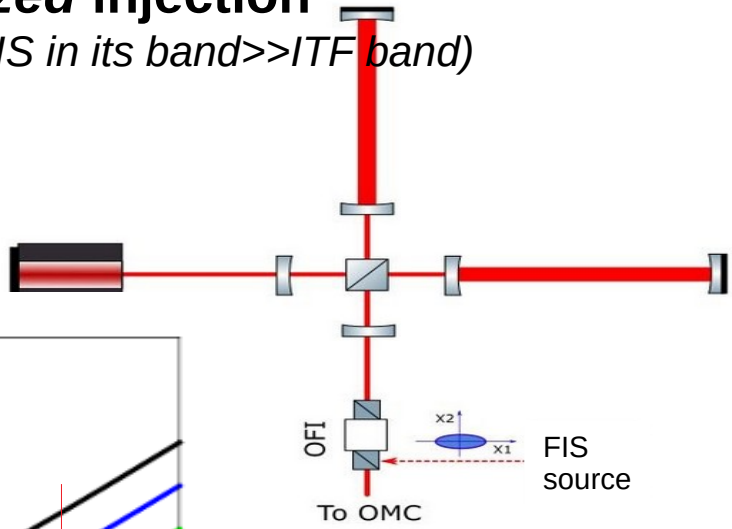
***Frequency Independent Vacuum Squeezed* injection**

(Current used Vacuum Squeezing sources (OPO) produce FIS in its band>>ITF band)

Anti-squeezed Amplitude *quadrature Variance*

Radiation Pressure Noise incresing



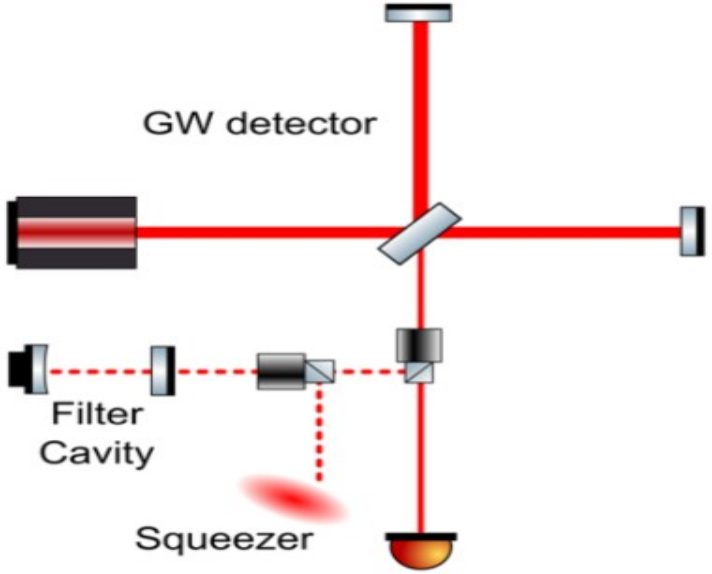


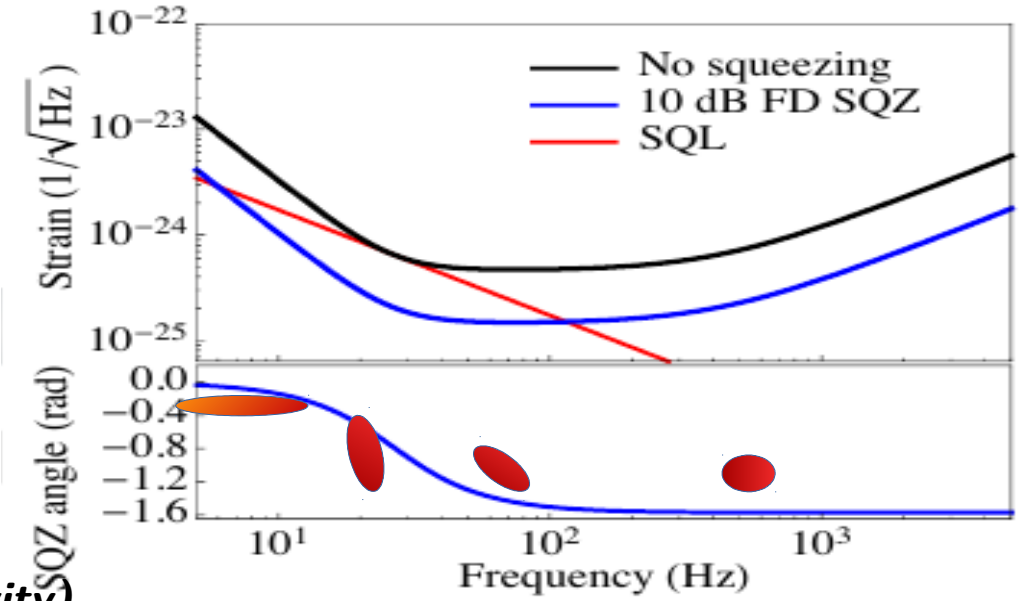
Squeezed *phase quadrature Variance*

Shot Noise Reduction

The Squeezing Factor can be increased until the antisqueezing at low frequency remains below the other low frequency noise

Frequency Dependent Squeezing (FDS)

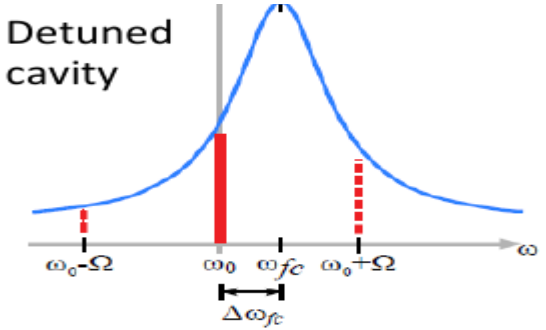




Squeezing through detuned cavity *(Filter Cavity)*

Sidebands Squeezing angle rotation inside the cavity bandwidth

QNR reduction in the full GWD bandwidth



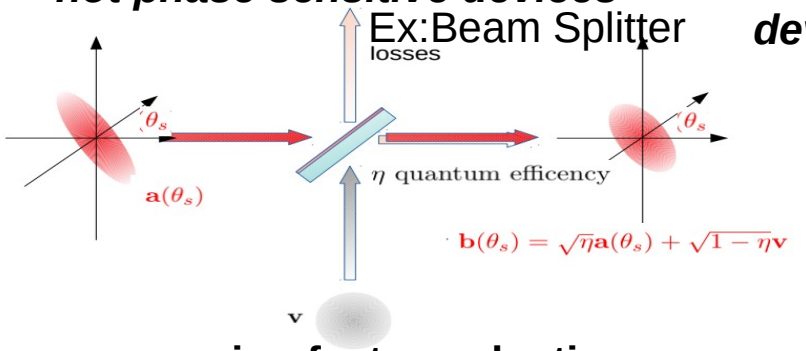
Quantum States
Interaction with the Optical Devices

Quantum Interaction with Optical Devices

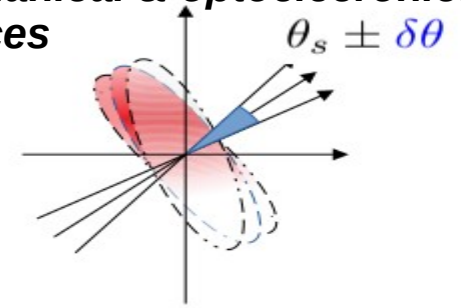
not phase sensitive devices

Ex:Beam Splitter

losses

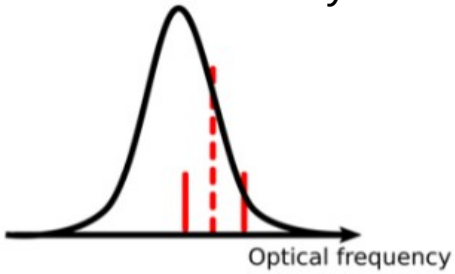


mechanical & optoelecronical devices

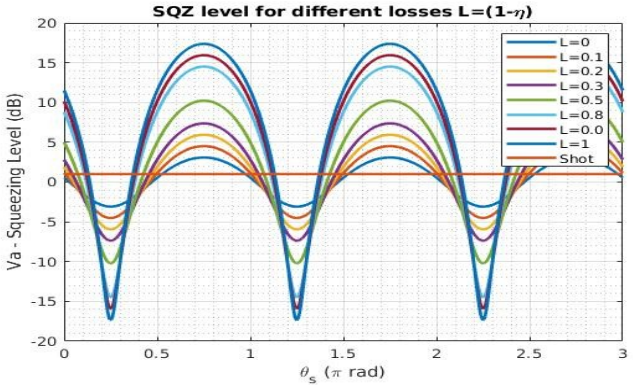


phase sensitive devices

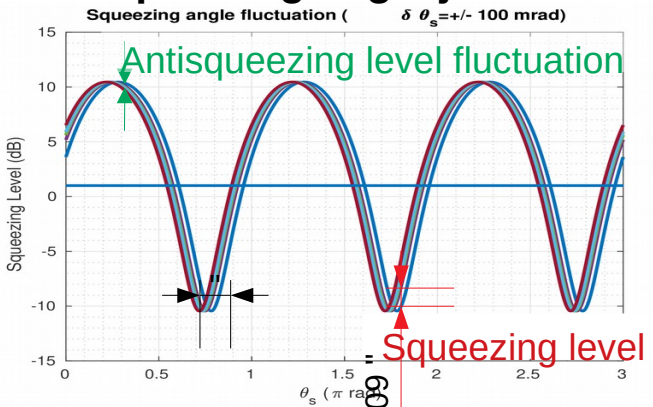
Ex: detuned cavity



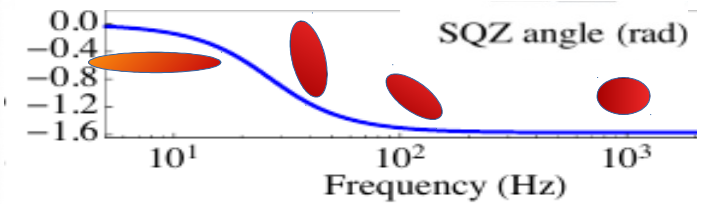
squeezing factor reduction



squeezing angle jitter



squeezing angle rotation

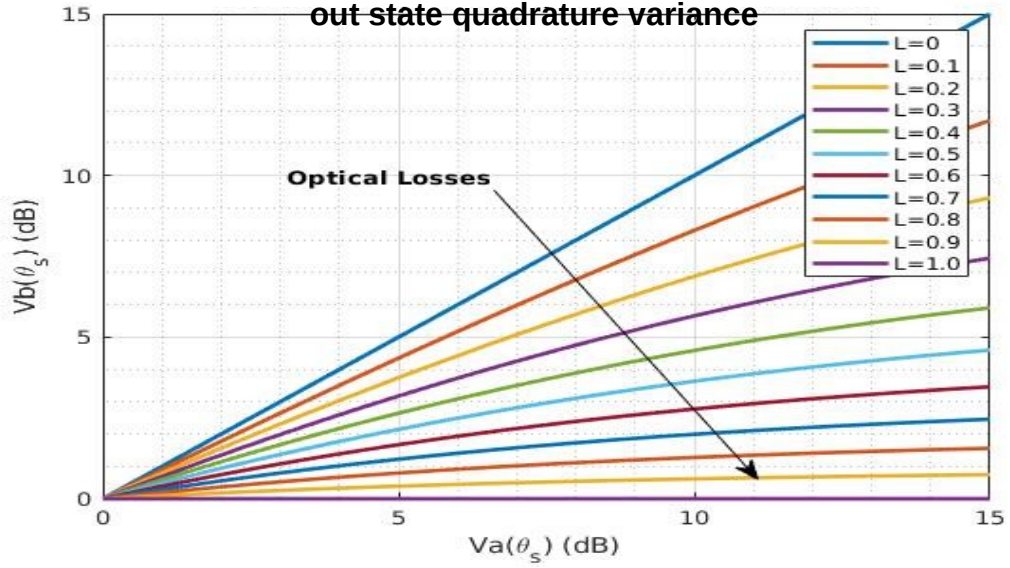


➞ **Optical losses** during the propagation (mode mismatch, absorption …) can be described as the effect of a beam splitter with **reduced quantum efficiency** (BS transmittivity, $\eta = 1-L < 1$)

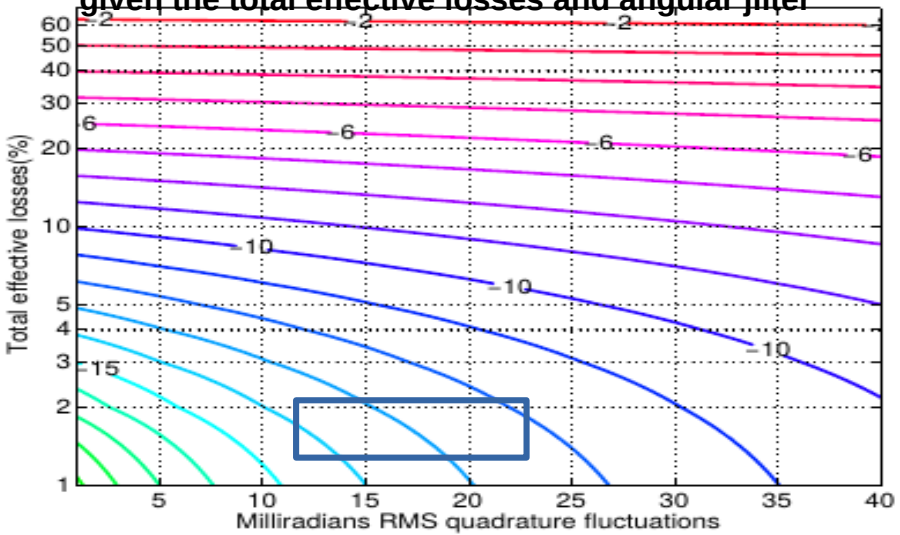
➞ **Technical noise** (*photodetector dark noise, scattered light, mechanical vibration..*) gives effects similar to the **SQUEEZING ANGLE jitter** ***(quadratures fluctuations)***

Quantum Interaction with the Optical Devices

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

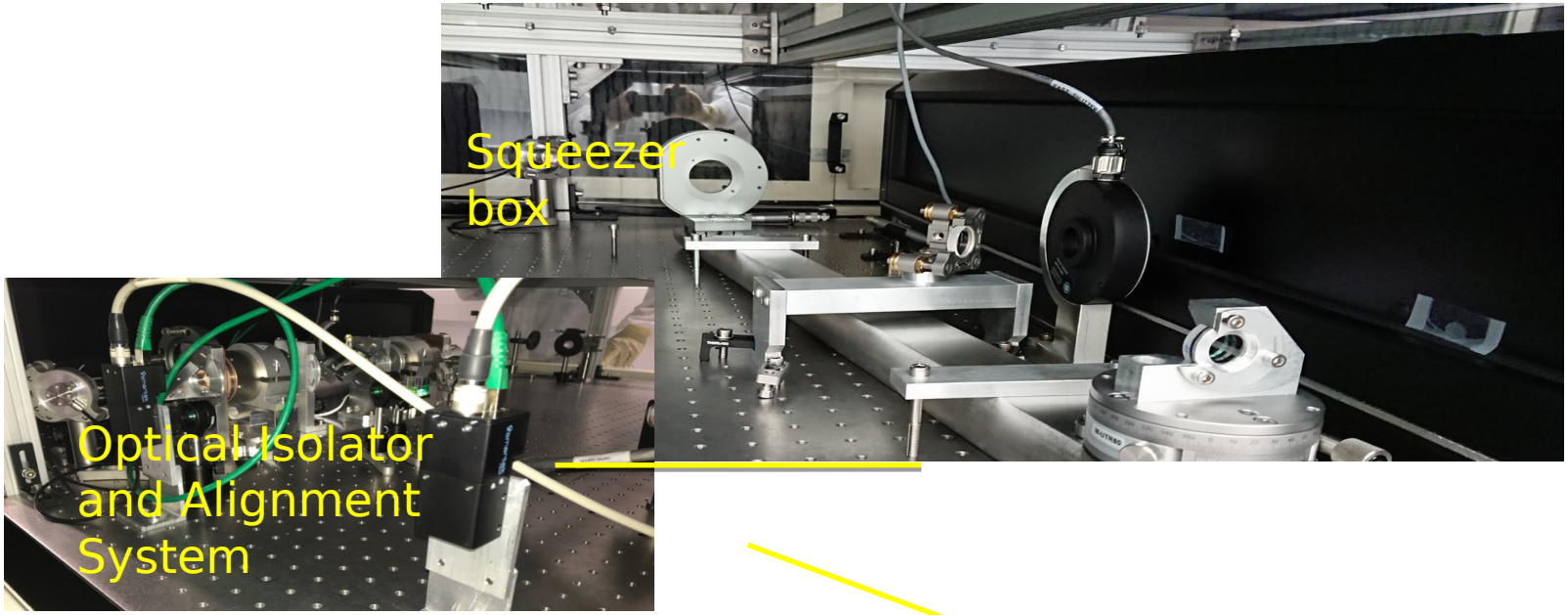
Higher is the squeezing level and higher must be the losses reduction to avoid to spoil it

Quantum Noise Reduction System In AdV+

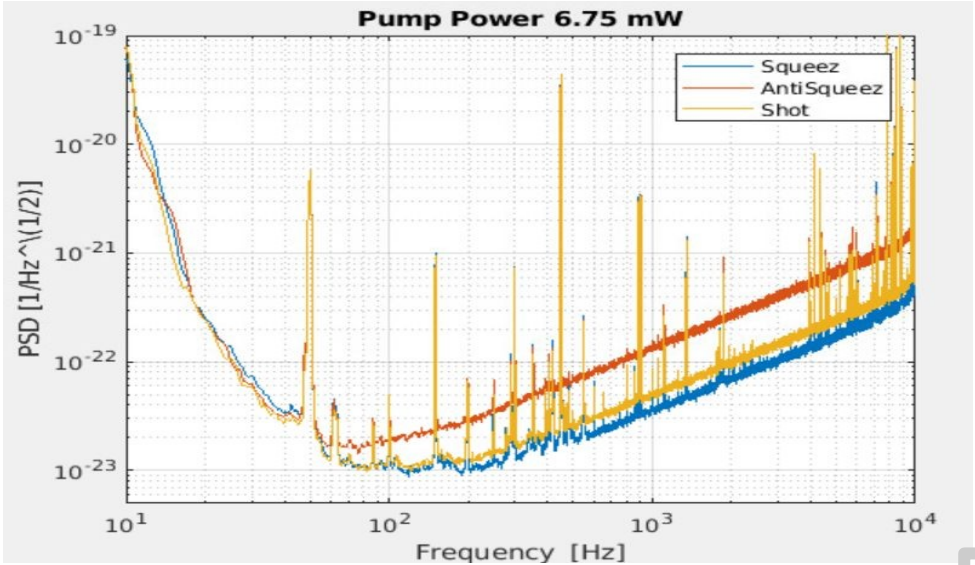
Motivation

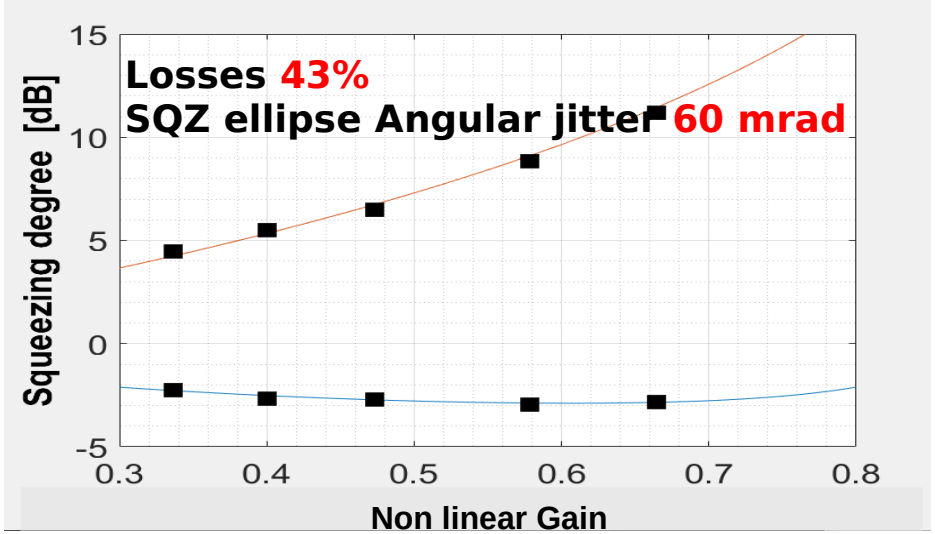
→ Improve the sensitivity at high frequencies for O3

→ A fundamental step towards the Frequency Dependent Squeezing



FIS in AdV O3 results

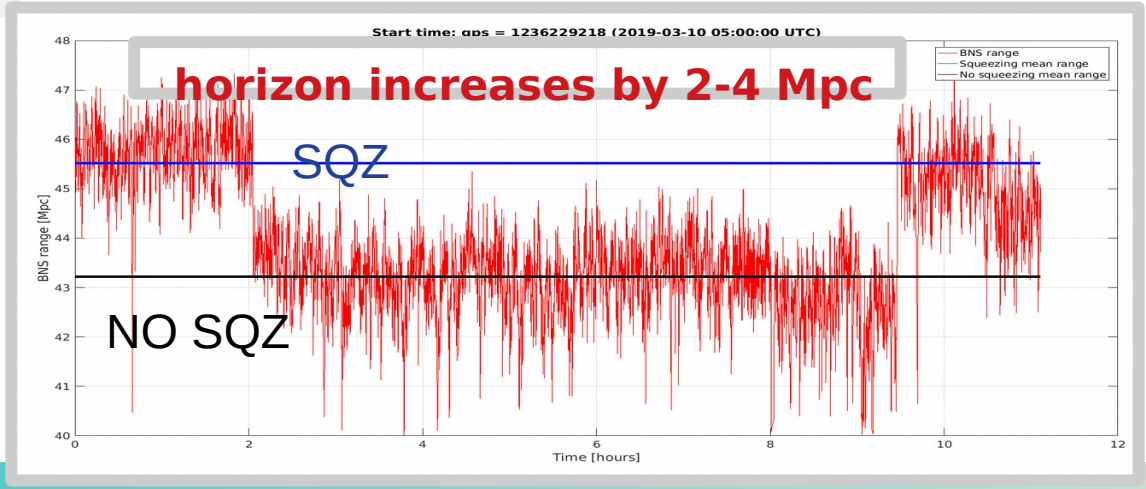




Maximun HF
sensitivity improuvement: **3 dB**

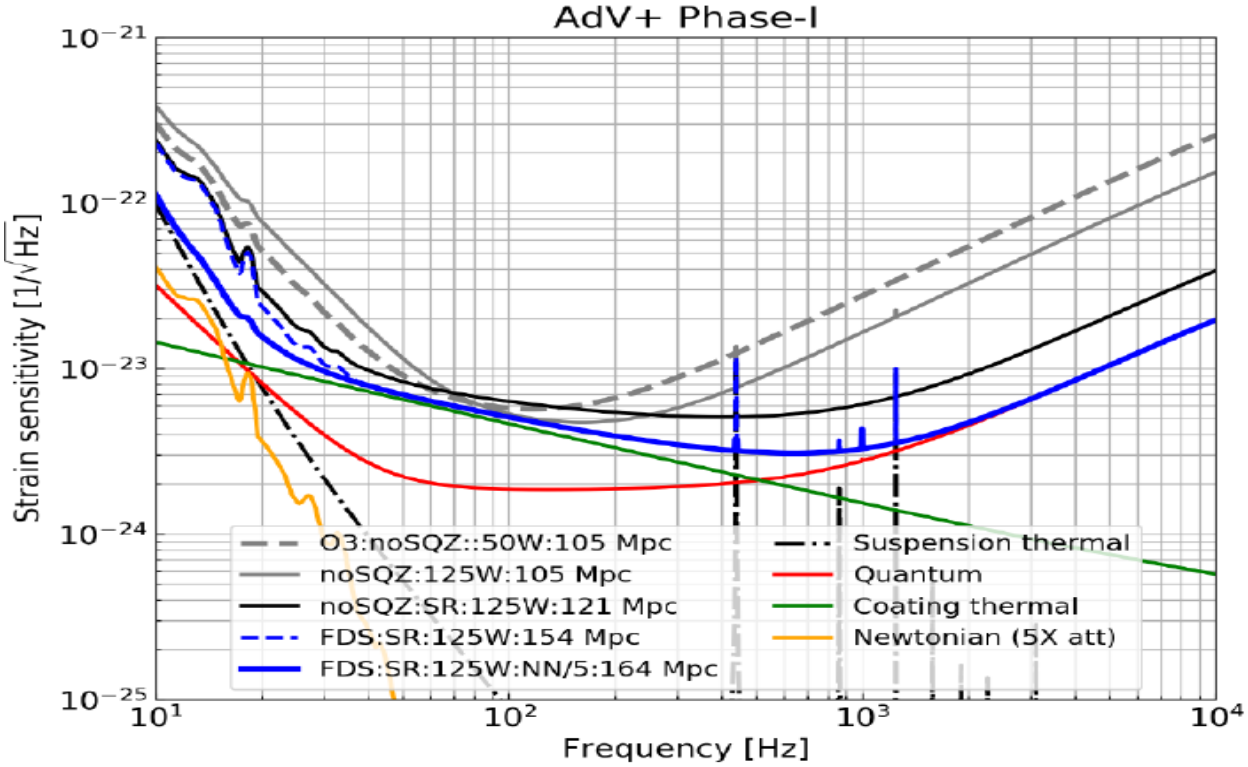
- **7dB produced**

(12 dB Maximun produced achivable)

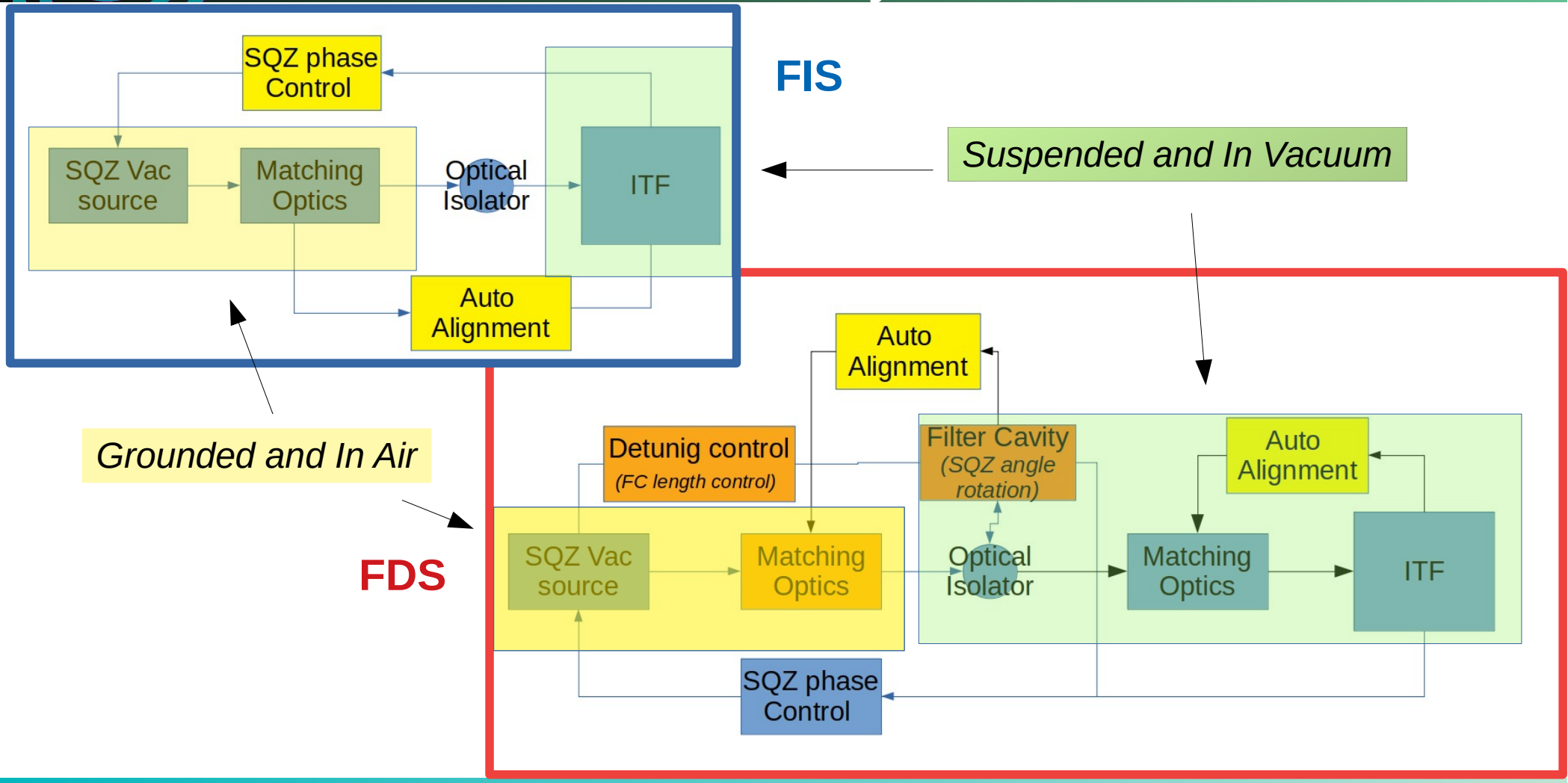


Motivation

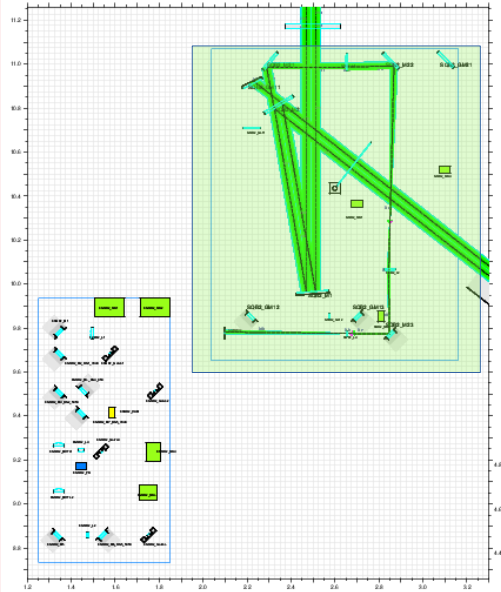
→ **Improve** the **sensitivity in all ITF** frequency **band** for the next scientific run (O4) *by injection of* **7 dB** of **Frequency Dependent Squeezing**



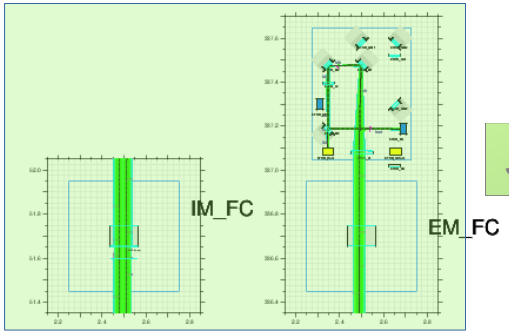
FIS vs FDS systems



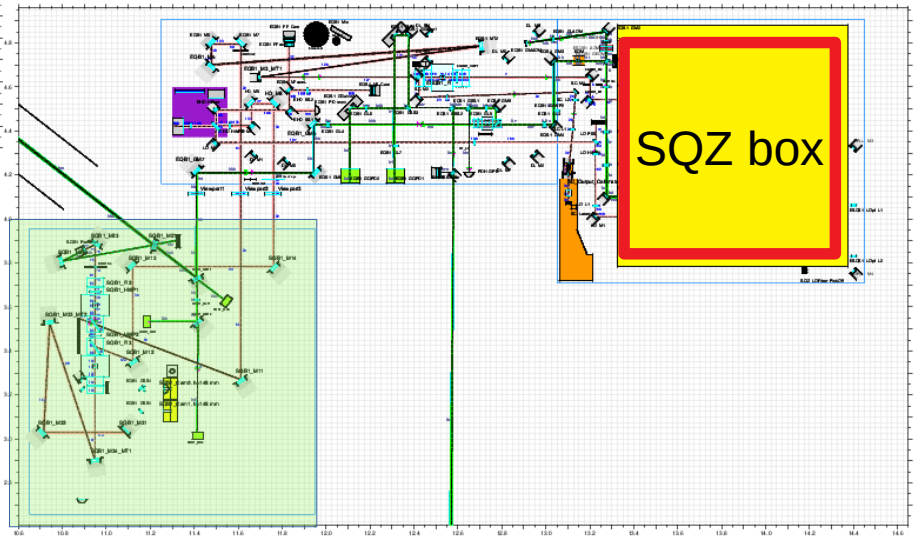
FDS vs FIS systems



Suspended sQueezing Bench 2 (SQB2) & ESQB112



Input Mirror Filter Cavity (IMFC) End Mirror Filter Cavity (EMFC)



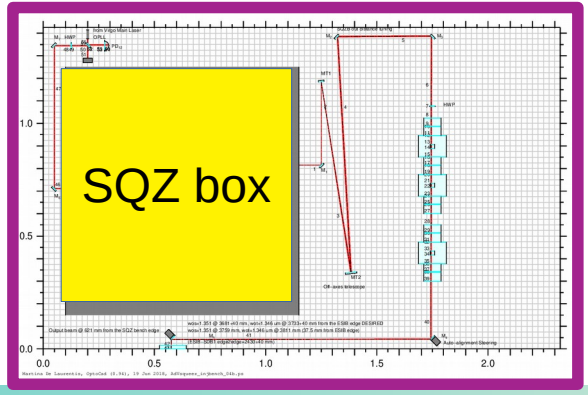
Suspended sQueezing Bench 1 (SQB1) & External Squeezing Bench 1

Advanced Virgo

AdV+ FDS optical Layout

Suspended and In Vacuum

AdV 03 FIS optical Layout



FDS system for Advanced Virgo +

Dec 2020 — Infrastructure work completed

Mar 2021 — FC mirrors suspended

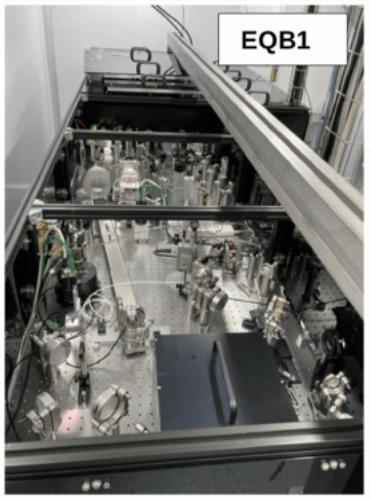
Jun 2021 — FC locked on Green

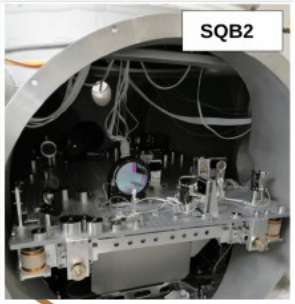
Oct 2021 — FC locked on IR

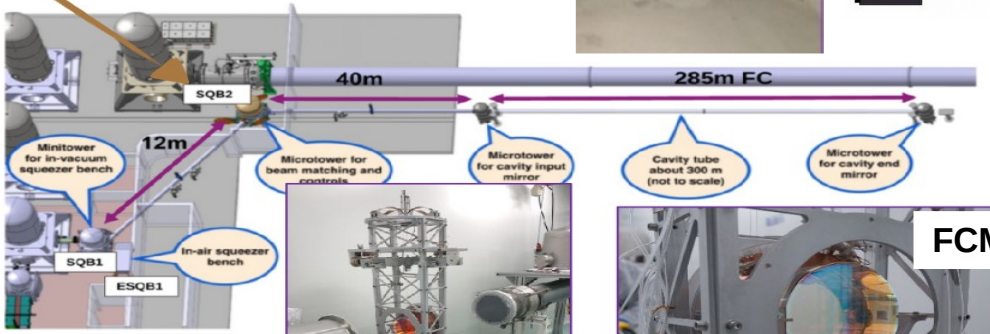
Nov 2021 — FDS measurement @ Detuning ~ 300 Hz

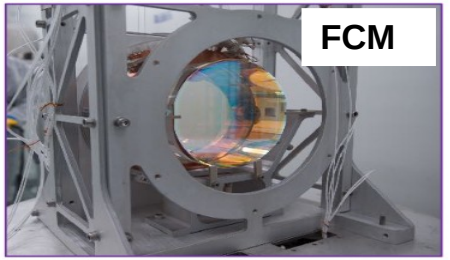
Feb 2022 — FDS measurement @ ~ 40 Hz

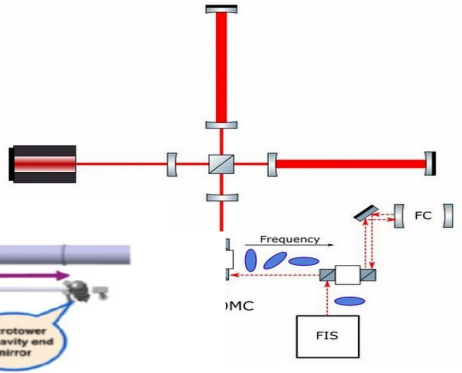
Jun 2022 — FDS measurement @ ~ 25 Hz





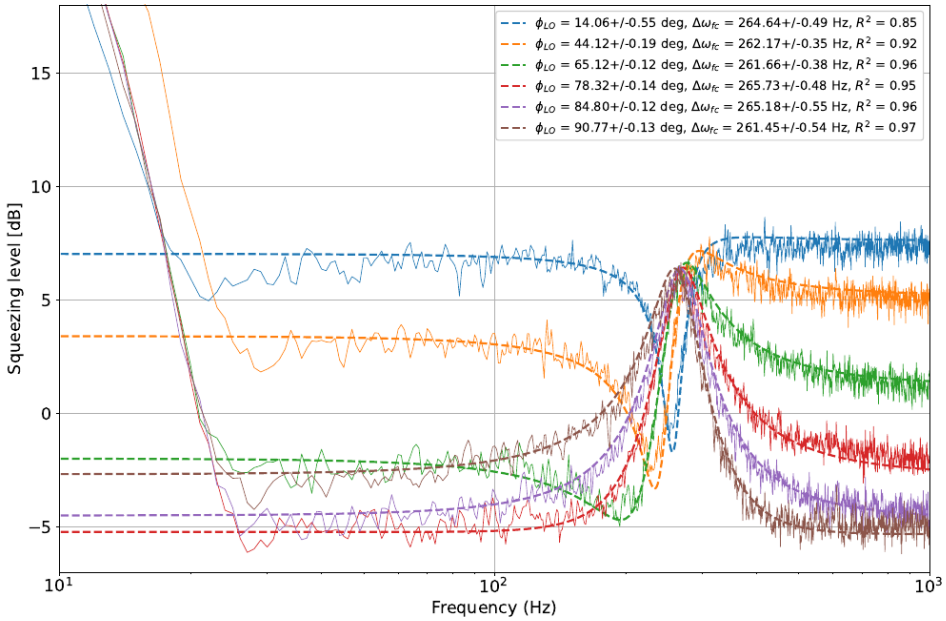






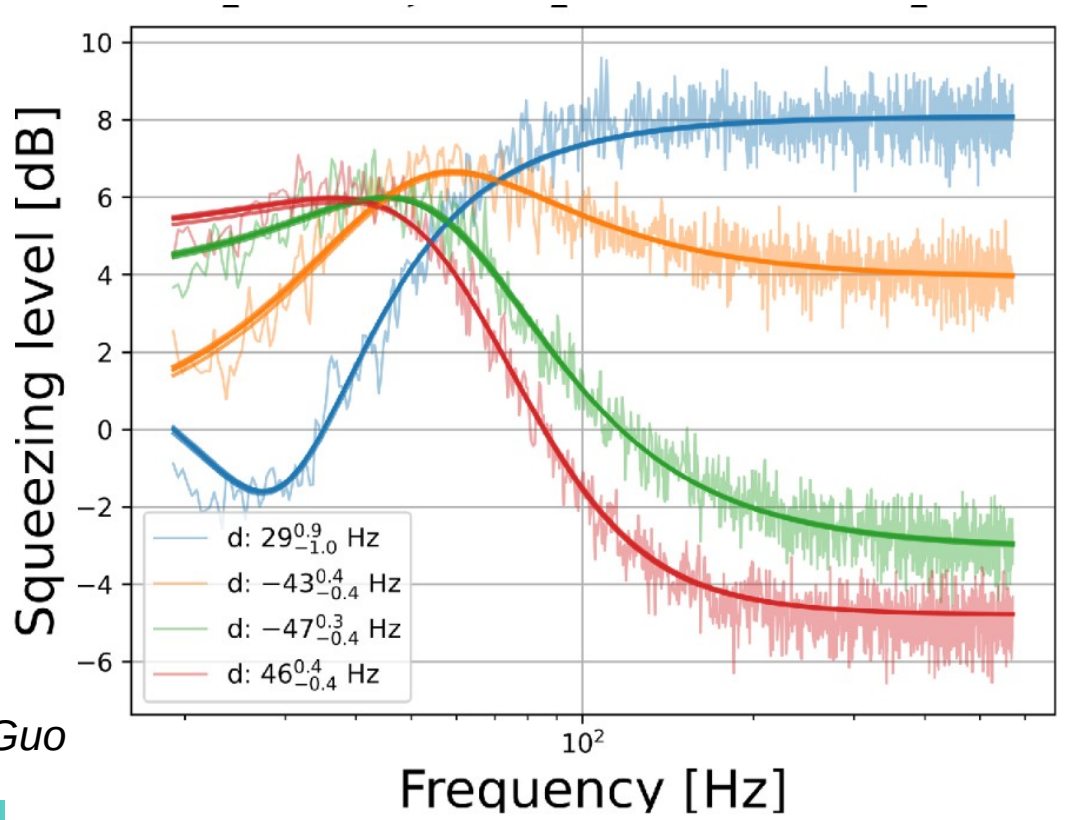
AdV+ Quantum Noise Reduction System Commissioning

FDS commissioning RESULTS



Credits: J. DIng

Demonstrated SQZ rotation
in the whole ITF bandwidth
up to below 40 Hz

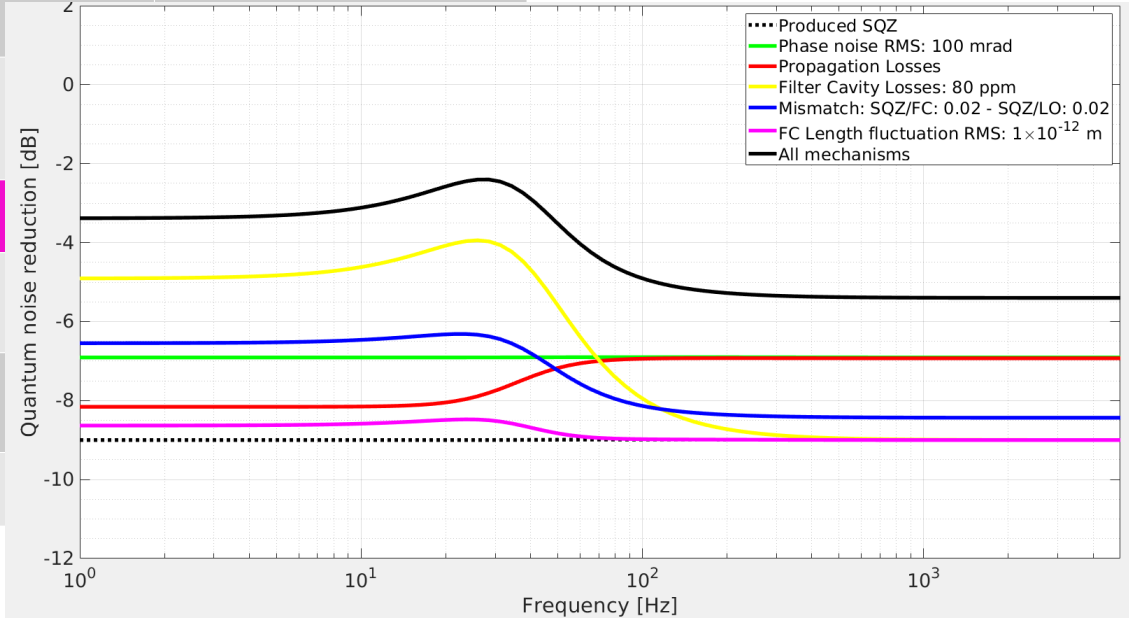


Credits: Y. Guo

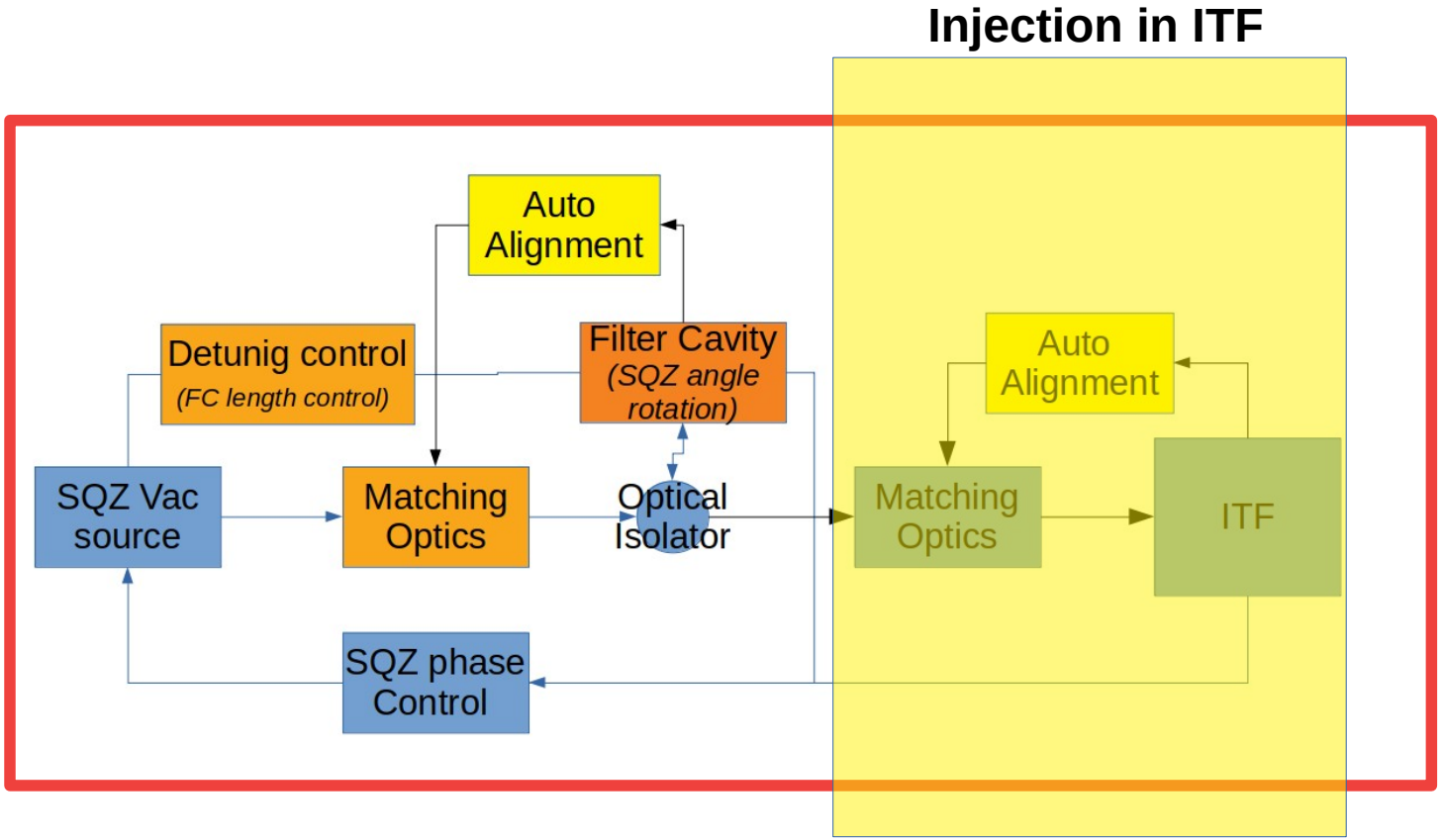
FDS commissioning RESULTS

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



FDS commissioning Next Step

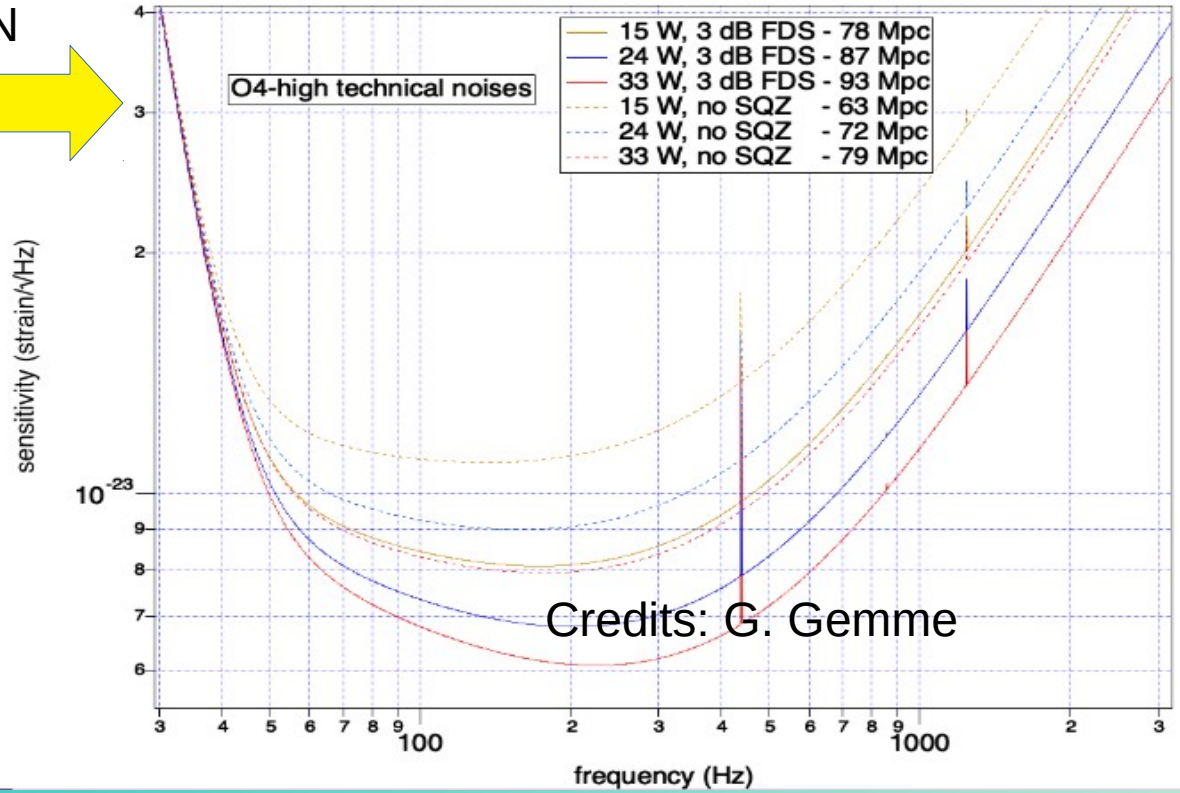


FDS commissioning CONCLUSION

- Estimated Losses Budget
- *Max produced SQZ =12 dB;*

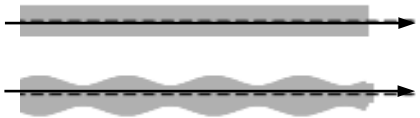
We can assure 4 dB reduction in ITF QN

→ **NEXT step: injection in ITF**

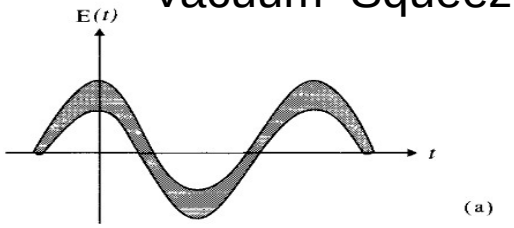


Thanks a lot!!!

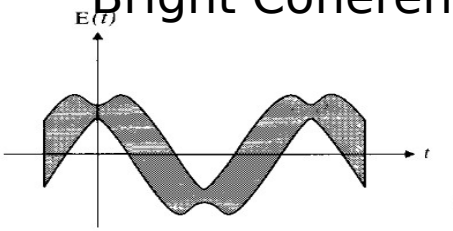
States of Light and vacuum fluctuation



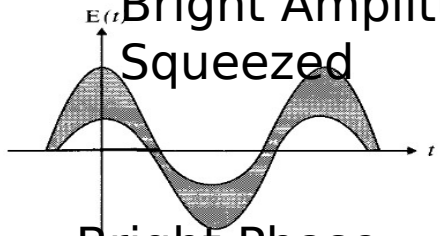
Vacuum Squeezed



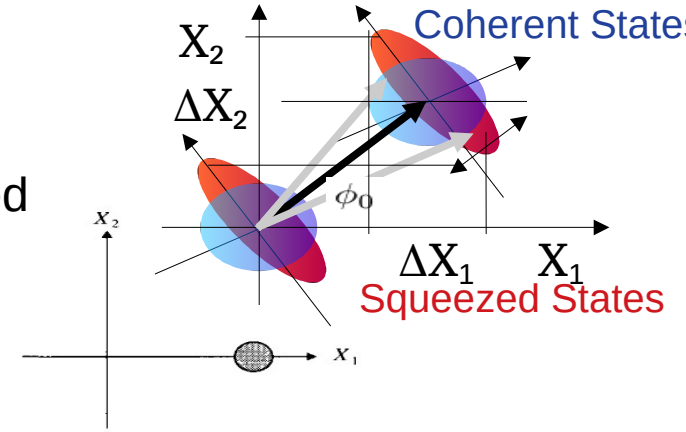
Bright Coherent

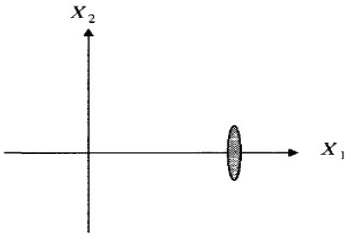


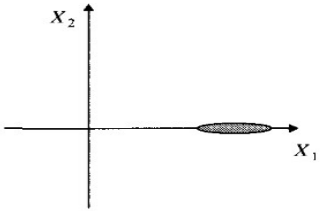
Bright Amplitude Squeezed



Bright Phase Squeezed







Minimum Uncertainty States

$$\Delta X_1 \Delta X_2 = \frac{1}{4}$$

A **bright beam** has
the same quadrature fluctuations
of the vacuum

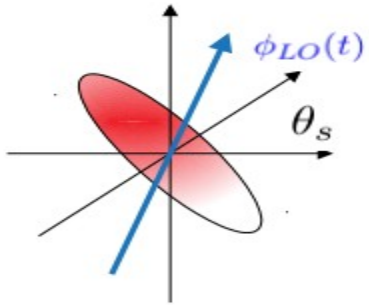
Light as *'sensitive'* element

its intrinsic quantum fluctuations
determines the final sensitivity

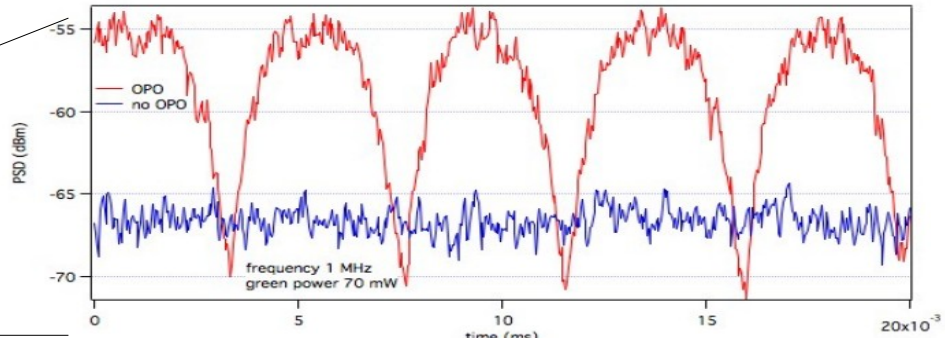
We cannot violate the *Uncertainty Principle*
but
we can *squeeze* the quantum fluctuations on one quadrature and 'use' that quadrature as sensitive element

Squeezed States

Squeezing Measurement: Homodyne Detector



Spectrum Analyzer



$$N_{i\_} = \sqrt{(\Omega) V \mathbf{i}\_(\Omega)} \propto \sqrt{\alpha^2 V \mathbf{b}_{\phi_{LO}}(\Omega)}$$

Homodyne Detector

Vaccum Squeezed state

$\mathbf{a}(\omega_0 + \Omega)$

OPO

$\mathbf{p}(2\omega_0)$

OPO pump field

SHG

$\alpha_{LO}(\omega_0)e^{i\phi_{LO}}$

Coherent Bright ~ classic state

Main Laser

ω_0

$\phi_{LO}(t)$

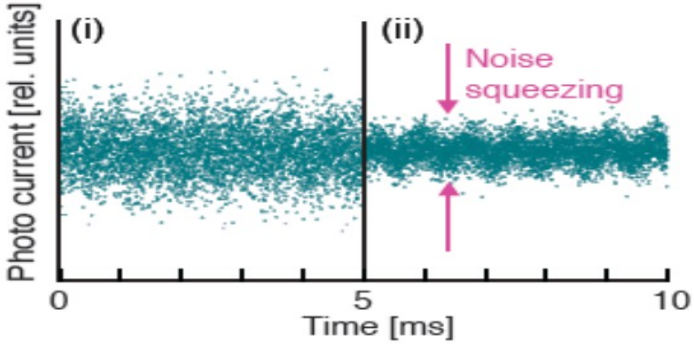
+/-

$$\mathbf{i}\_(\Omega) \propto \alpha_{LO}\mathbf{b}_{\phi_{LO}}(\Omega) \simeq \alpha_{LO}\left(\mathbf{b_1}(\Omega)\cos\phi_{LO} + i\mathbf{b_2}(\Omega)\sin\phi_{LO}\right)$$

ϕ-quadrature of the field $\mathbf{b}(\Omega)$

Local Oscillator amplitude

Signal seen on Oscilloscope



Advanced Virgo configuration +AEI Squeezer

Input Mode Cleaner for reducing beam jitter

High-power laser

Power Recycling for increasing input power

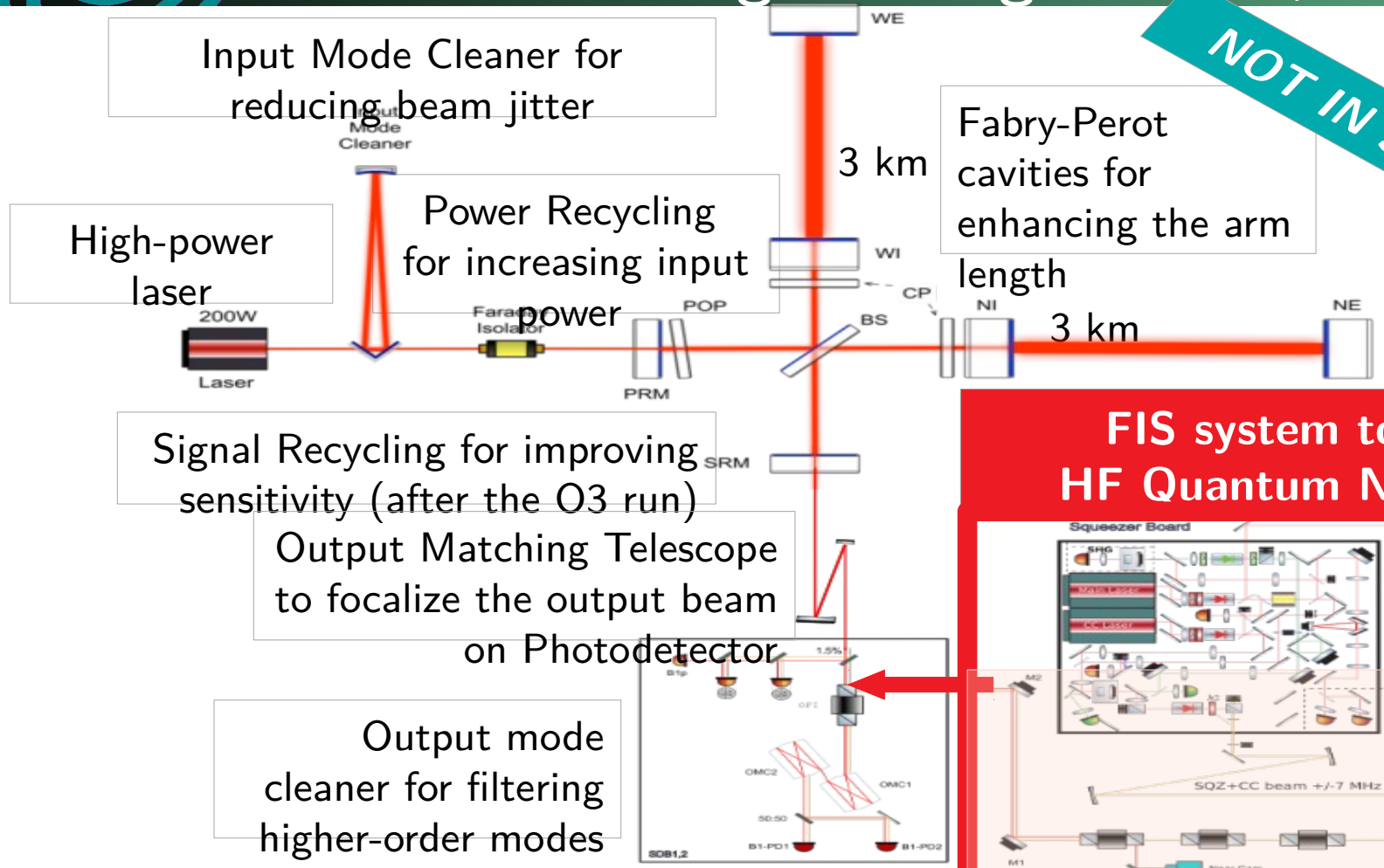
Signal Recycling for improving sensitivity (after the O3 run)

Output Matching Telescope to focalize the output beam on Photodetector

Output mode cleaner for filtering higher-order modes

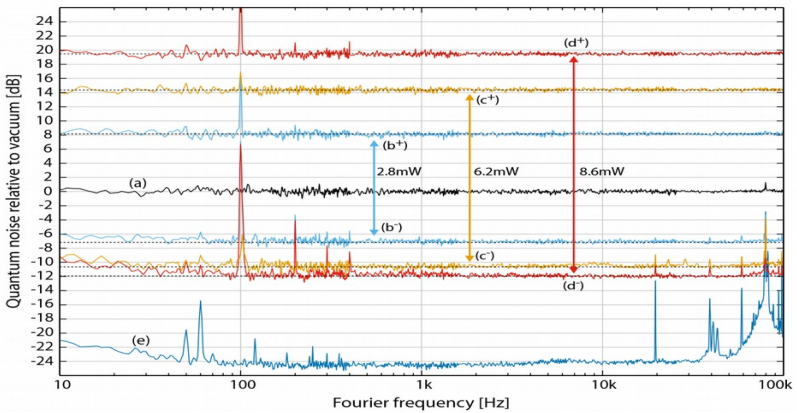
Fabry-Perot cavities for enhancing the arm length

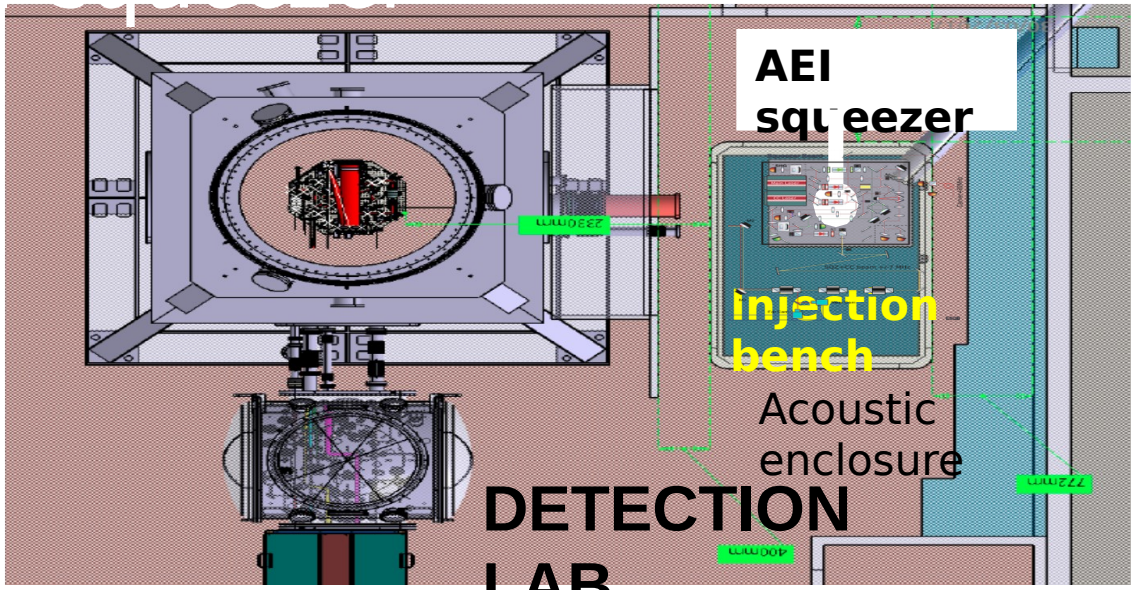
NOT IN SCALE



FIS system to reduce the HF Quantum Noise Reduction

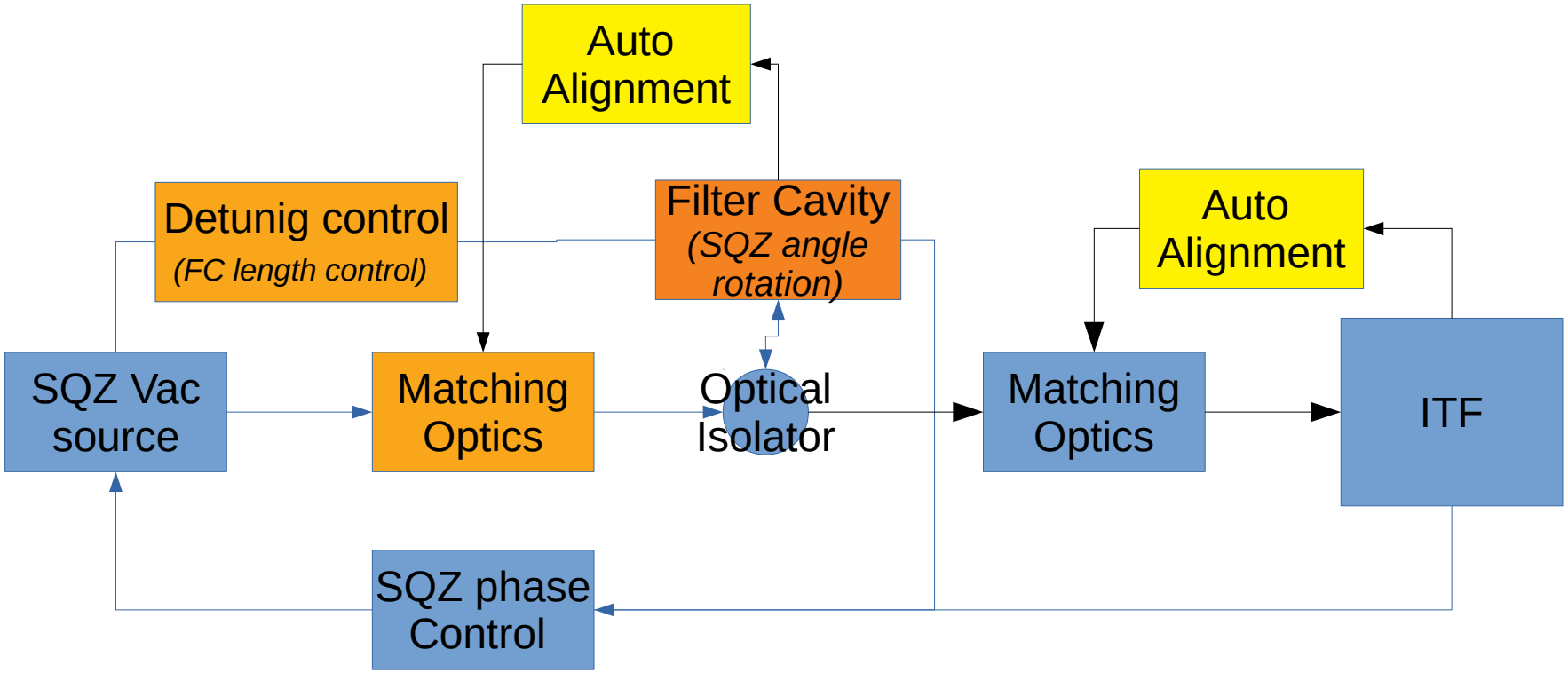
The AEI squeezer





- stand alone in-air squeezed that can provide **up to 14dB of squeezing** for downstream application at very low pump powers.
- **12dB measured** with diagnostic homodyne detector introducing additional loss, therefore
- **Delivered in Cascina on January 2018**.

FDS vs FIS system



FDS vs FIS system