Broadband quantum noise reduction via frequency dependent squeezing for Advanced Virgo Plus

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on behalf of Virgo-AEI collaboration and KAGRA squeezing group

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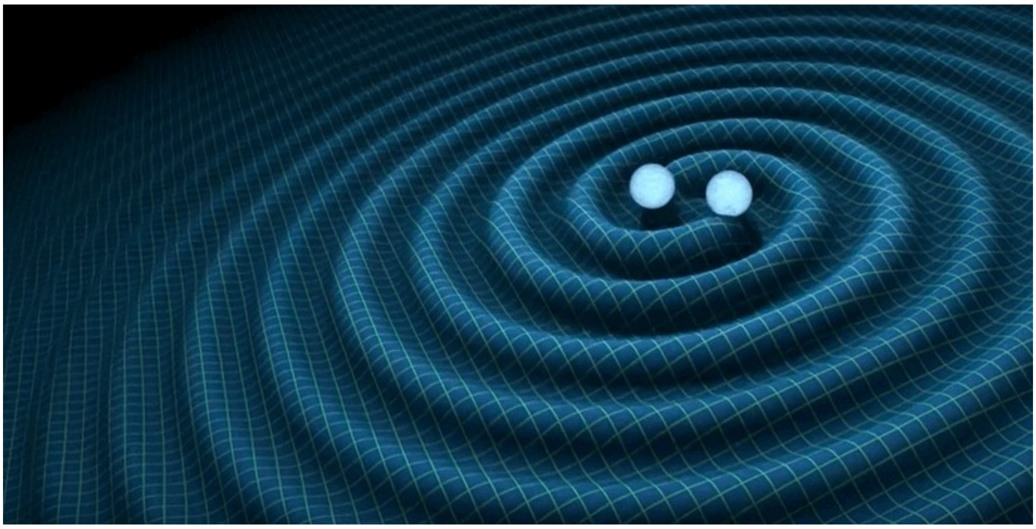
Abstract: Quantum noise is limiting the sensitivity of ground based gravitational wave detectors both at high frequency, in the form of shot noise, and low frequency, in the form of radiation pressure noise. In the last observing run, the injection of frequency independent squeezing improved Virgo and LIGO sensitivities at high frequency, slightly worsening the performance at low frequency. A broadband quantum noise reduction can be achieved using frequency dependent squeezing, i. e. rotating the vacuum squeezed ellipse below 100 Hz by reflecting the squeezed vacuum off a Fabry-Perot cavity, called filter cavity. The first demonstration of this technique at the right configuration to reduce quantum noise in the whole observation bandwidth, has been obtained using the former TAMA facility at the National Astronomical Observatory of Japan. The experiment uses a 300 meter long filter cavity, similar to the ones planned to be installed in Virgo and LIGO. Once the frequency dependent squeezing is produced, it has to be injected into the interferometer. The interface between the squeezing setup and Virgo is not trivial, since it requires the installation of additional benches and a 285 meter long cavity and also to couple the rotating squeezed vacuum with the detector. An important issue which can worsen the performance of frequency dependent squeezing or directly the interferometer sensitivity is the stray light. To avoid the propagation of additional stray light, we traced the ghost beam on squeezing benches, inside linking tubes and inside the filter cavity and we will install several diaphragms and baffles to limit this problem.

Detection of gravitational waves (GWs)

Gravitational waves are '*ripples*' in the fabric of space-time (travelling at the speed of light) caused by some of the most violent and energetic processes in the Universe.

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

→ small perturbation of the metric tensor

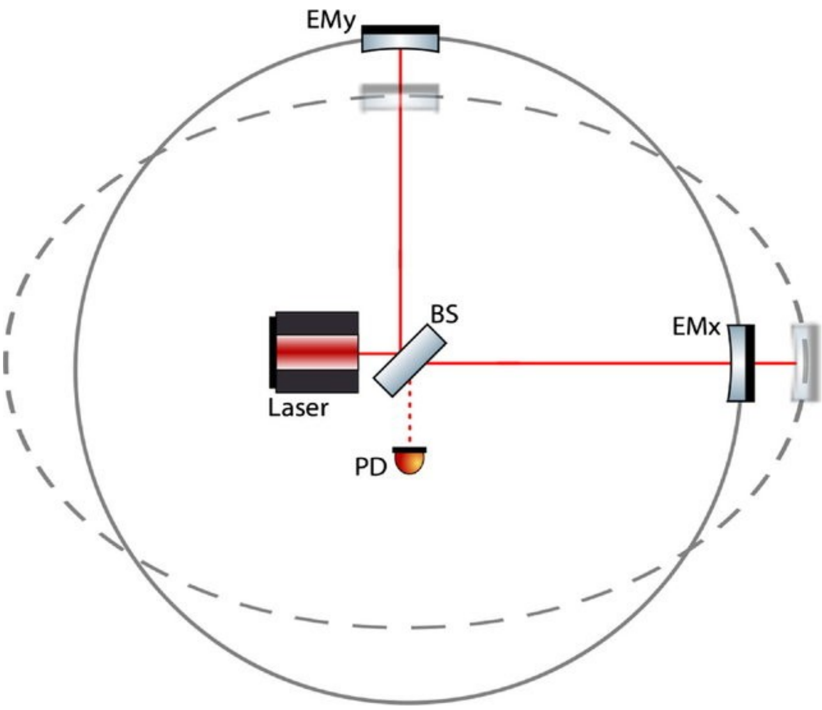


Detection principle:
Michelson interferometer measures the difference in phase caused by the passing gravitational wave (GW)

$$\delta\phi_{\mathrm{GW}} = \frac{4\pi}{\lambda}\delta L_{\mathrm{GW}}$$

↓

$$h = \frac{2\,\delta L_{\mathrm{GW}}}{L}$$



Hammond, G., Hild, S., & Pitkin, M. (2014). Advanced technologies for future ground-based, laser-interferometric gravitational wave detectors. *Journal of Modern Optics*, *61*(sup1), S10-S45.

Quantum noise in GW detectors

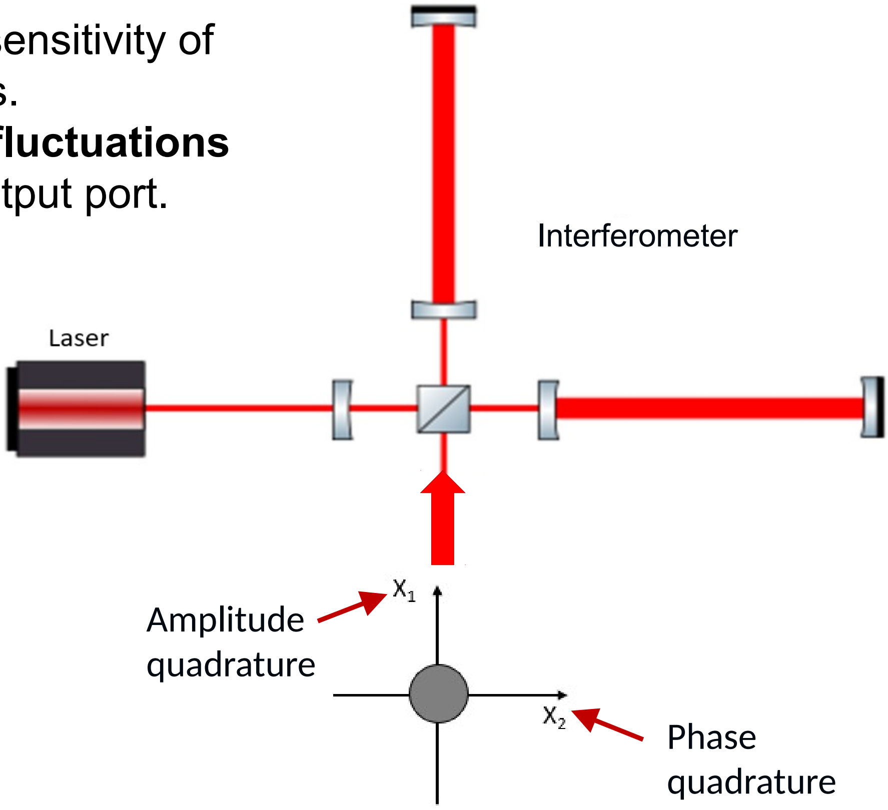
Introduction:

Quantum noise limits the sensitivity of gravitational wave detectors.
It can be seen as **vacuum fluctuations** entering interferometer's output port.

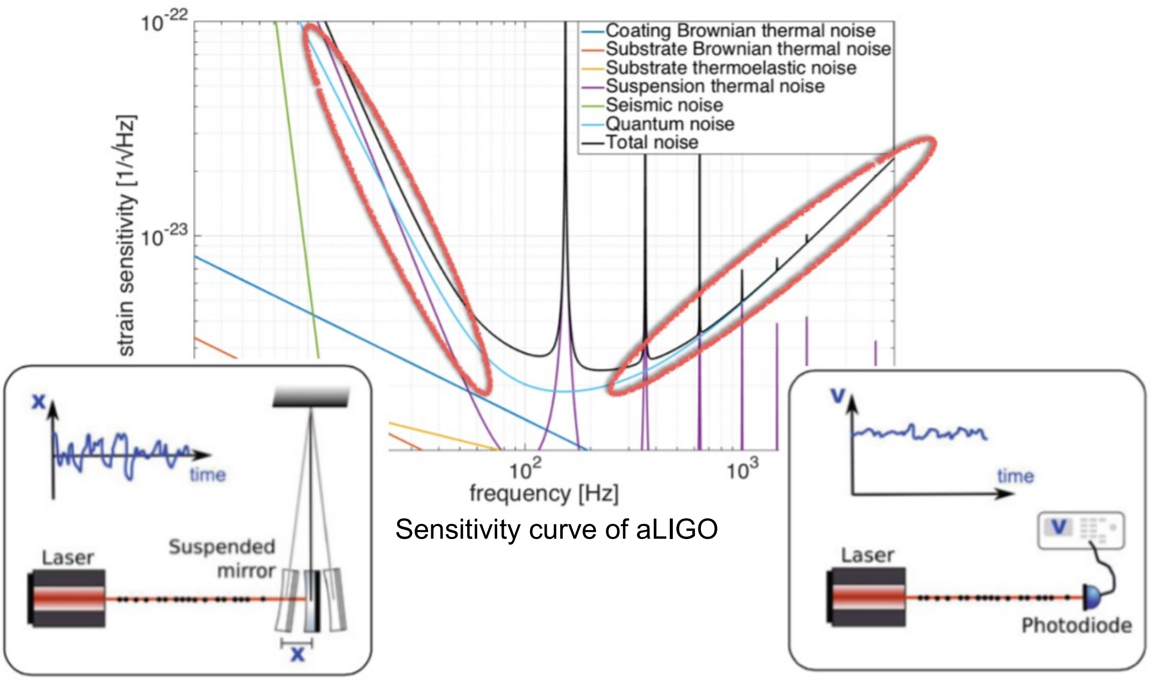
$$\hat{\mathcal{H}} = \hbar\omega\left(\hat{a}^{\dagger}\hat{a} + \frac{1}{2}\right)$$

↓

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



Vacuum state



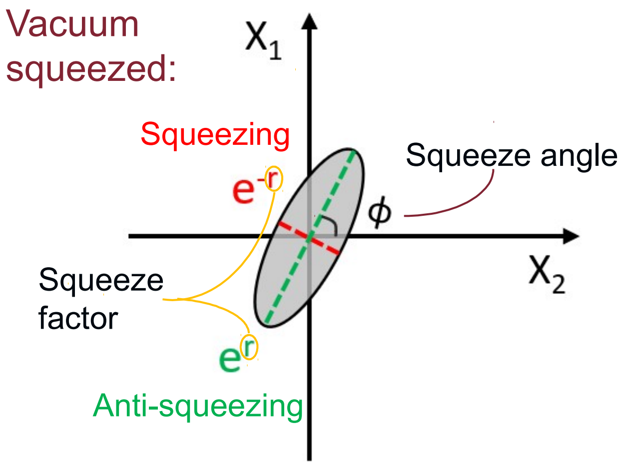
Sensitivity curve of aLIGO

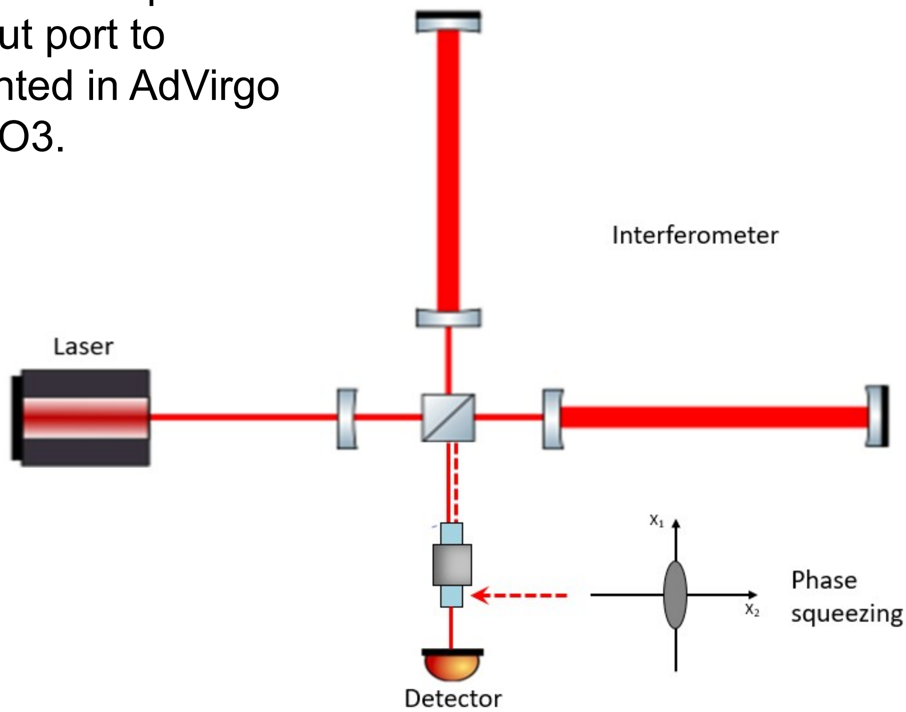
Radiation pressure noise

Shot noise

Quantum noise reduction

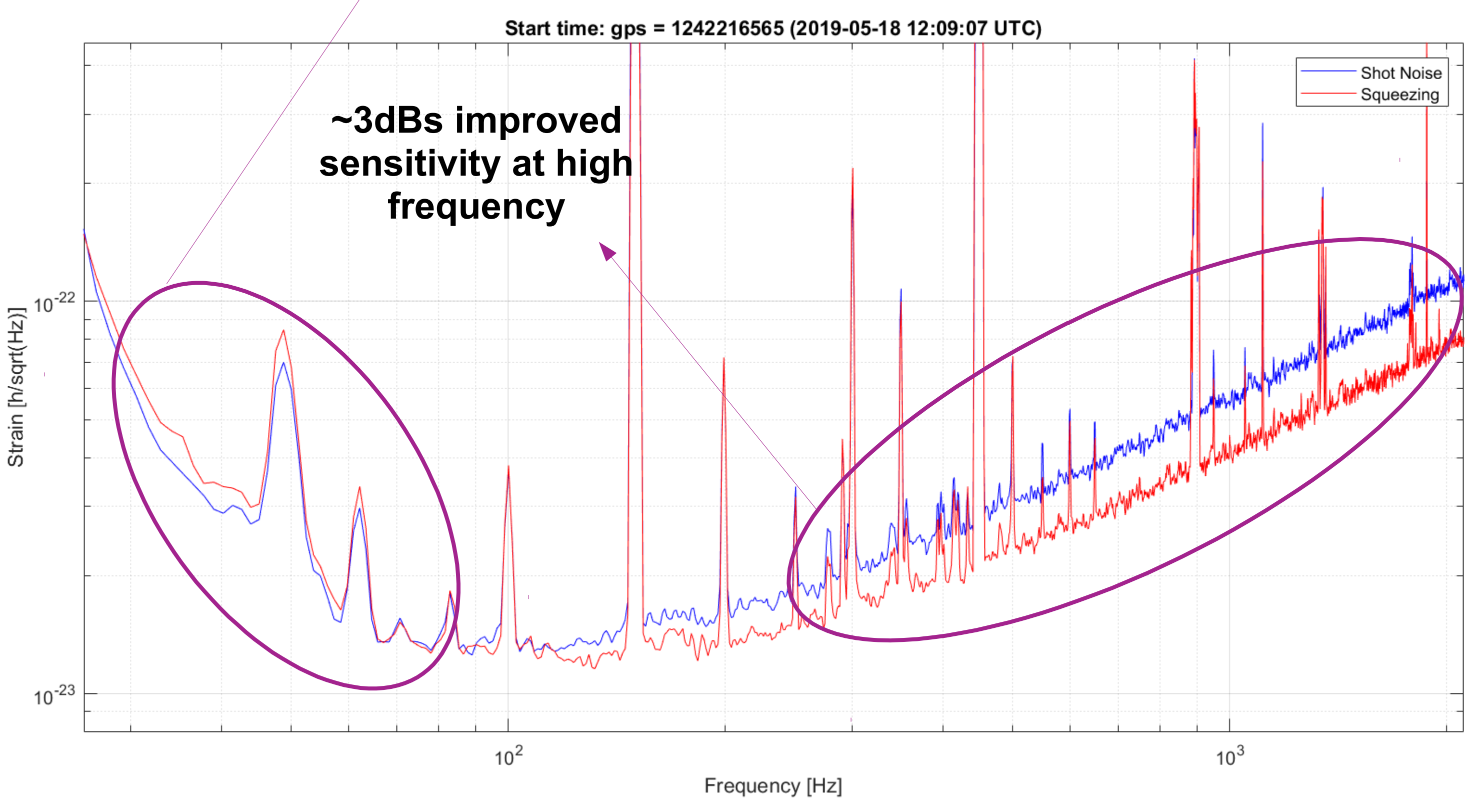
First step:
Injecting **frequency independent** squeezed vacuum states from the output port to improve sensitivity. Implemented in AdVirgo and aLIGO, observation run O3.





Tiny worsen sensitivity at low frequencies

See **Valeria Sequino's talk**

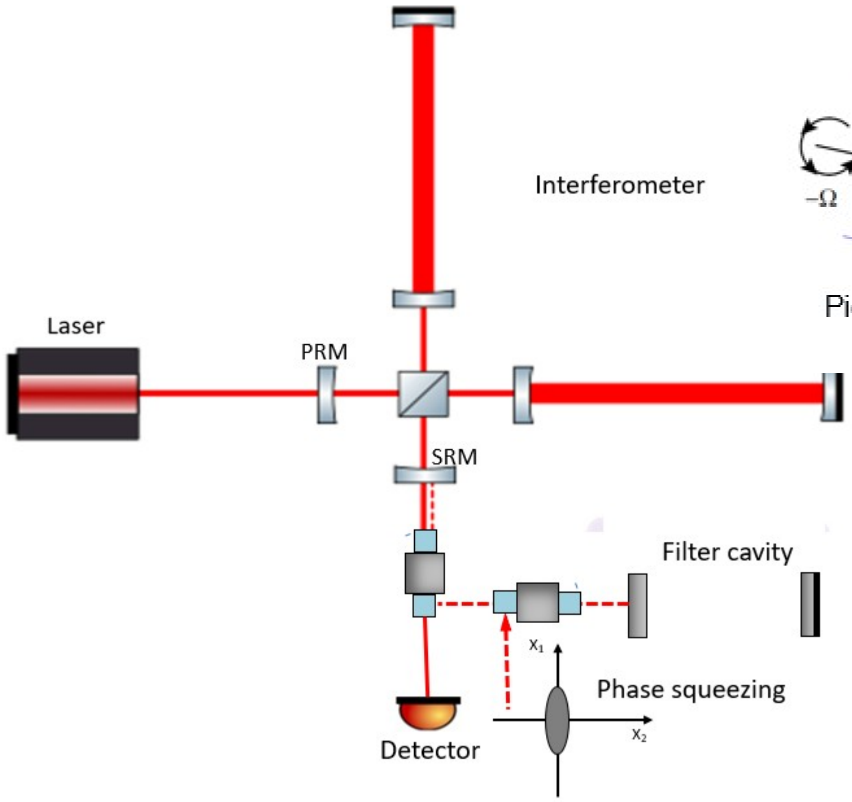


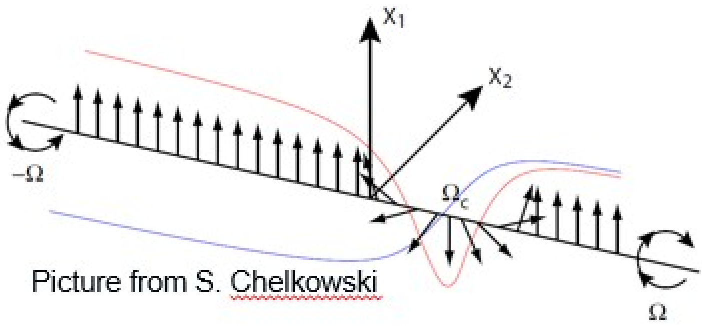
Plot from M. Vardaro

Quantum noise reduction

Next step:

Vacuum squeezed state angle becomes **frequency dependent (FDS)** when reflected by a detuned Fabry-Perot filter cavity.
FDS implementation in GW detectors in O4 in order to obtain a broadband reduction of quantum noise.



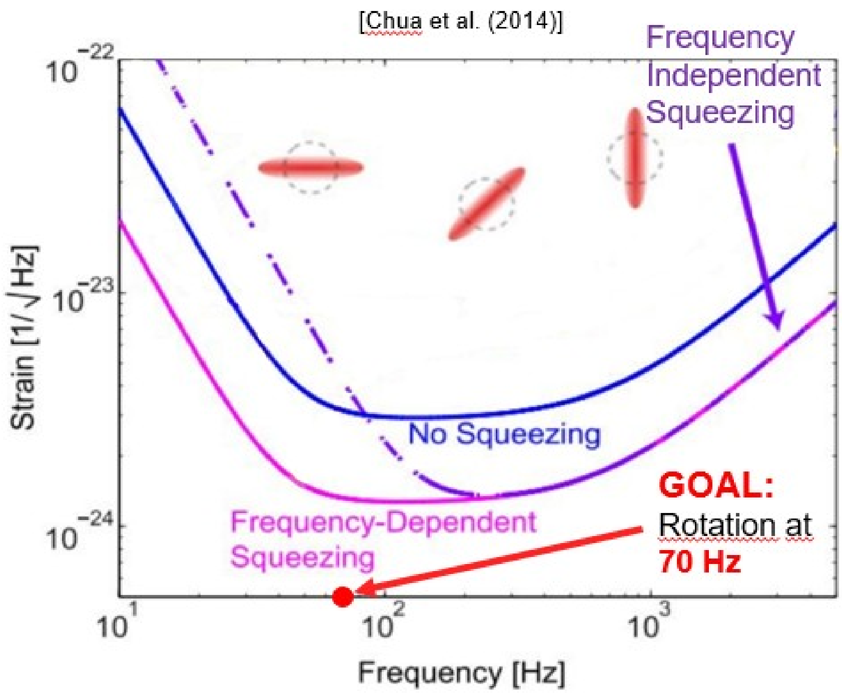


Sideband picture of a phase squeezed vacuum state reflected by a slightly detuned cavity. In red: frequency-dependent reflectivity. In blue: dispersion of the cavity.

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

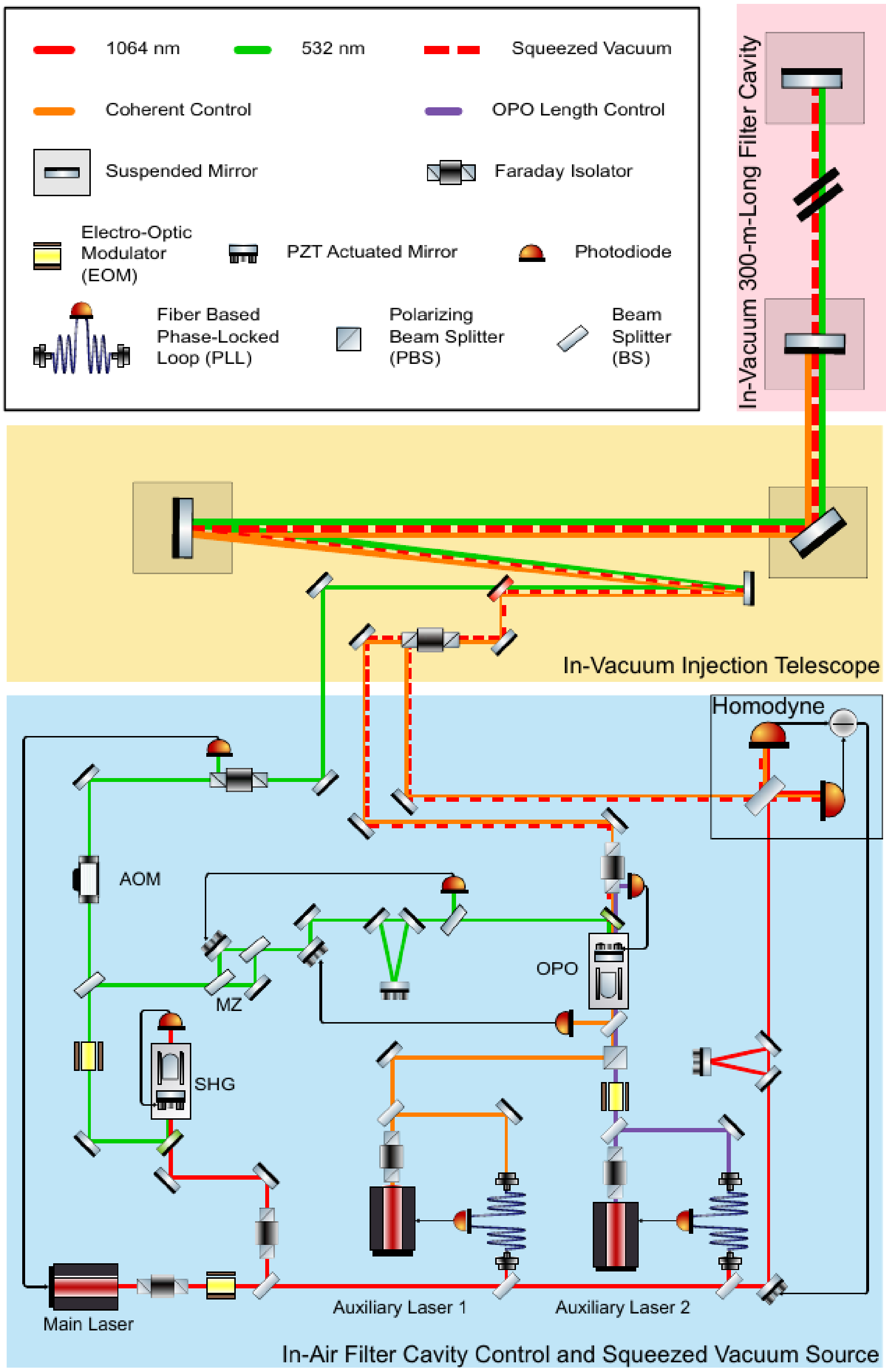
↓

Broadband reduction factor



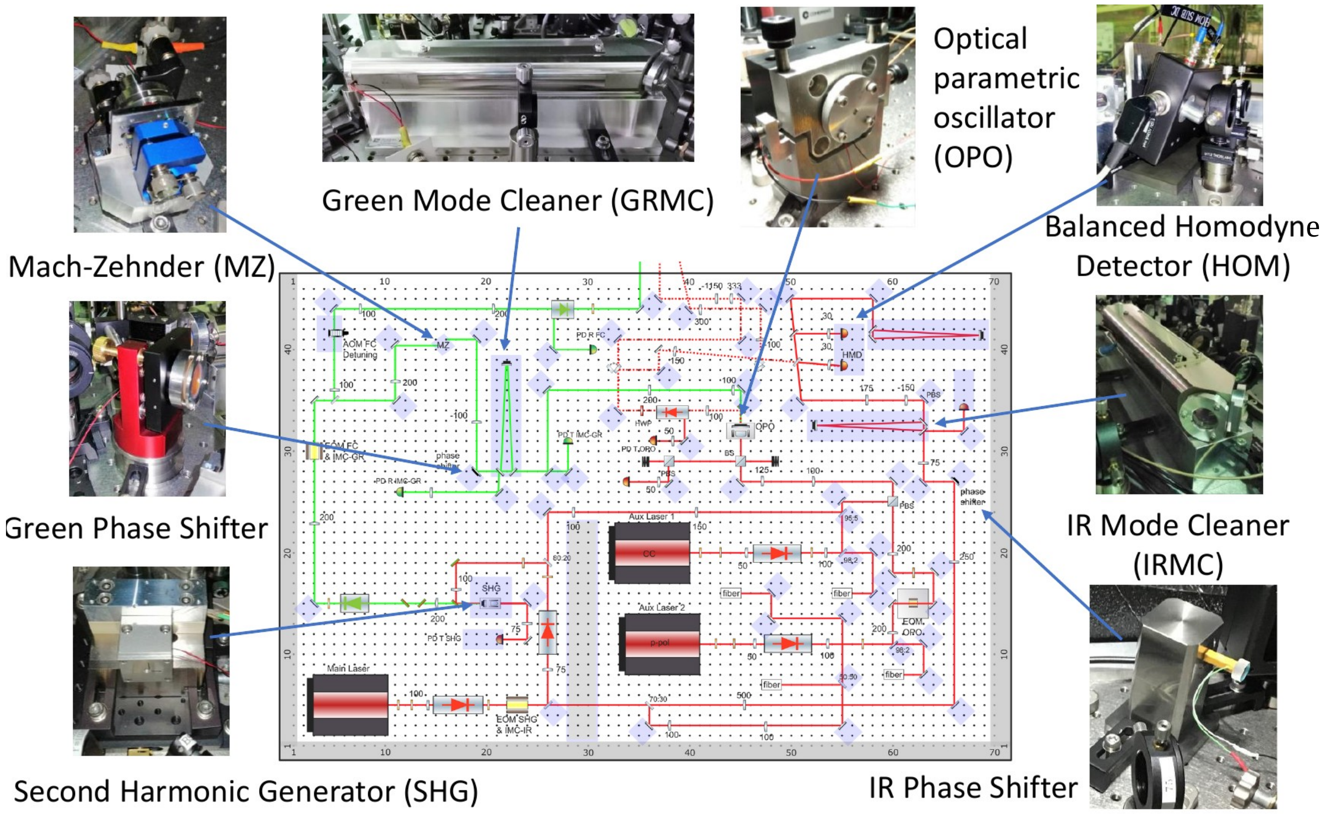
Frequency Dependent Squeezing (FDS) experiment at NAOJ

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

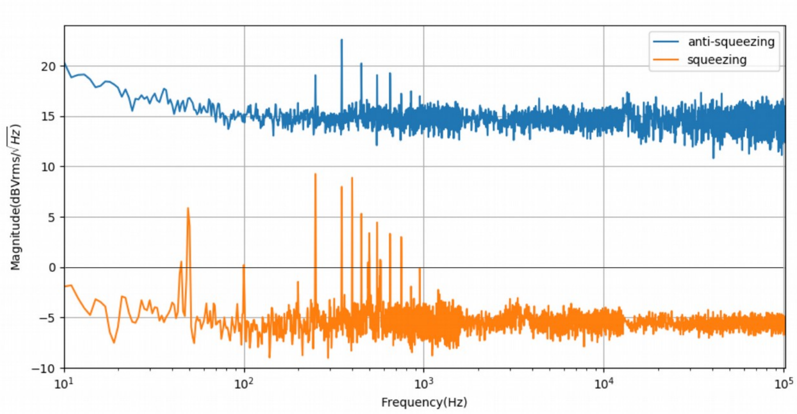


Zhao Y., Aritomi N., Capocasa E., Leonardi M., Eisenmann M., Guo Y., Polini E. et al. "Frequency-Dependent Squeezed Vacuum Source for Broadband Quantum Noise Reduction in Advanced Gravitational-Wave Detectors." *Physical Review Letters* 124, no. 17 (2020): 171101.

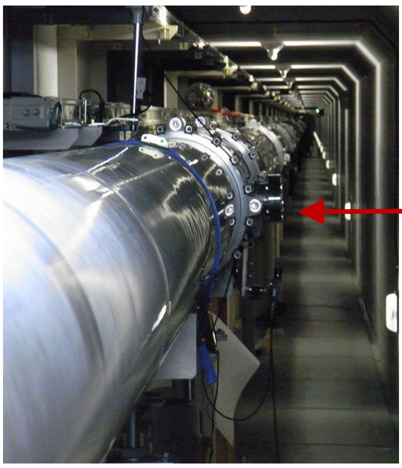
Frequency Dependent Squeezing (FDS) experiment at NAOJ



In air squeezer (based on AEI design) which produced <u>6dBs of vacuum squeezed</u> down to 10Hz.



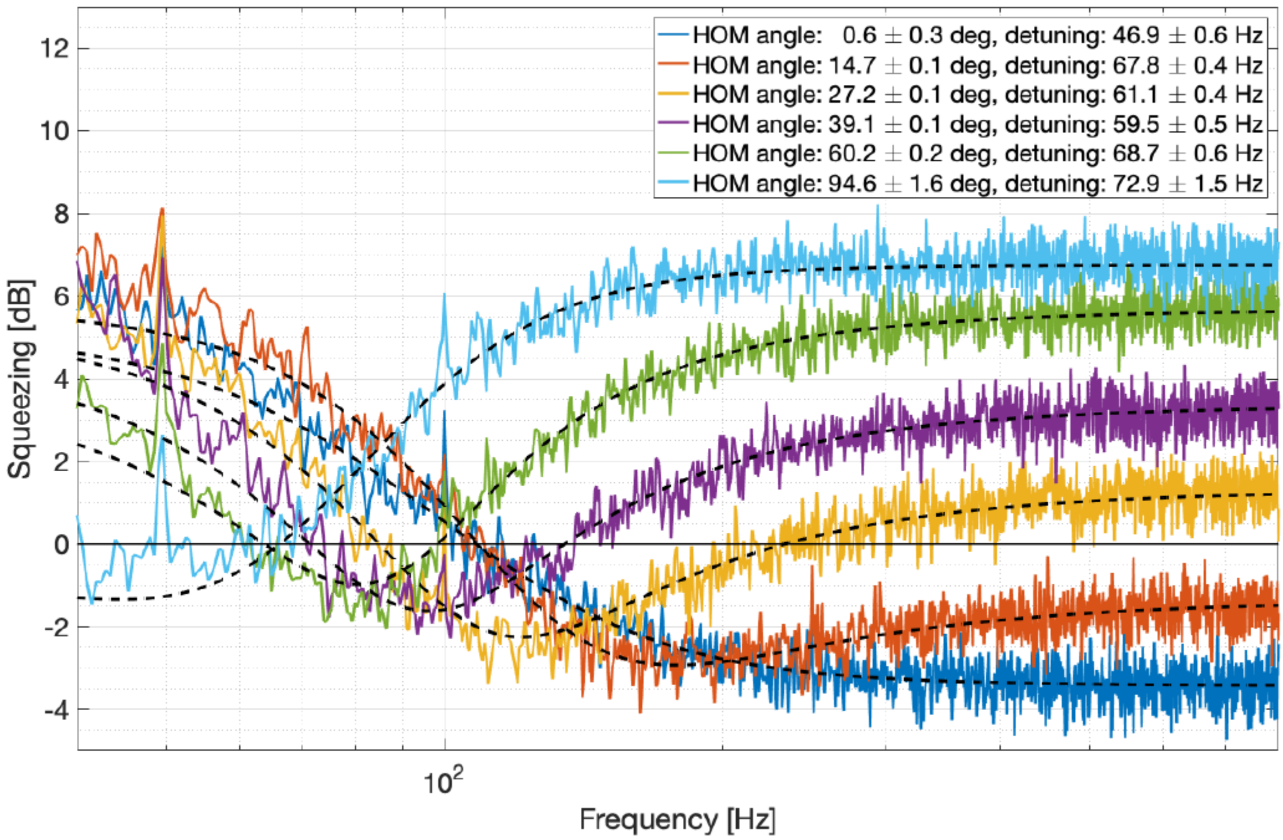
Graph from Y. Zhao



Filter cavity:

- South arm of TAMA
- Length **300m** – AdV+ scale
- Finesse 4400 @ 1064nm
- Round trip losses 80ppm
- Storage time 3ms @ 1064nm

Frequency Dependent Squeezing (FDS) measurement at NAOJ



Zhao Y., Aritomi N., Capocasa E., Leonardi M., Eisenmann M., Guo Y., Polini E. et al. "Frequency-Dependent Squeezed Vacuum Source for Broadband Quantum Noise Reduction in Advanced Gravitational-Wave Detectors." *Physical Review Letters* 124, no. 17 (2020): 171101.

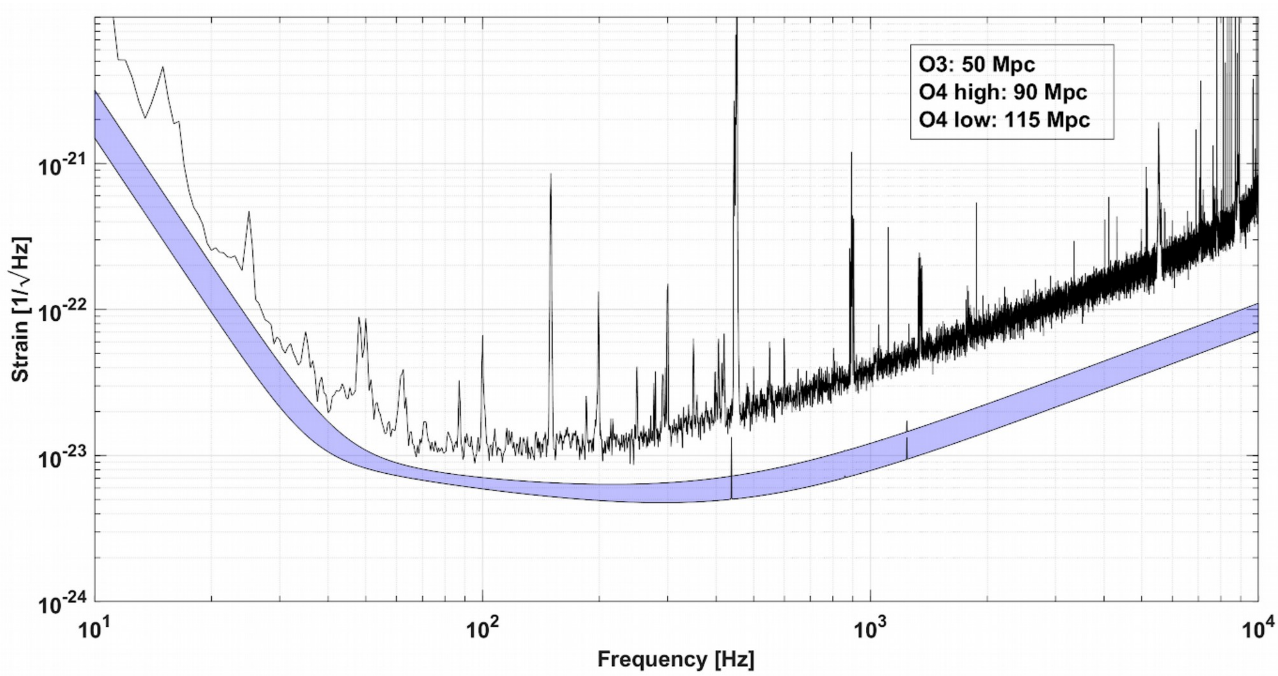
Results and conclusions:

- Rotation at the correct frequency (below 100Hz) of squeezed vacuum states reflected off a 300meters filter cavity, as needed in Advanced GW detectors, i.e. 20-30Hz for Virgo and 60-70Hz for KAGRA.
- Maximum quantum noise reduction of (3.4±0.2)dB above the rotation frequency and ∼1dB below rotation frequency.
- Going to be implemented in GW detectors to reduce the quantum noise over all the frequency spectrum.

Advanced Virgo Plus

Many upgrades are ongoing for Advanced Virgo Plus (see **Sibilla Di Pace's talk**):
- Installation of Signal Recycling (SR) mirror to have a dual recycled ITF (Power and Signal Recycling cavities);
- Laser upgrade up to 40W, from 25W;
- New Input Mode Cleaner (IMC) payload and instrumented baffles;
- New Output Mode Cleaner (OMC);
- Scattered light mitigation;
- Frequency Dependent Squeezing installation.

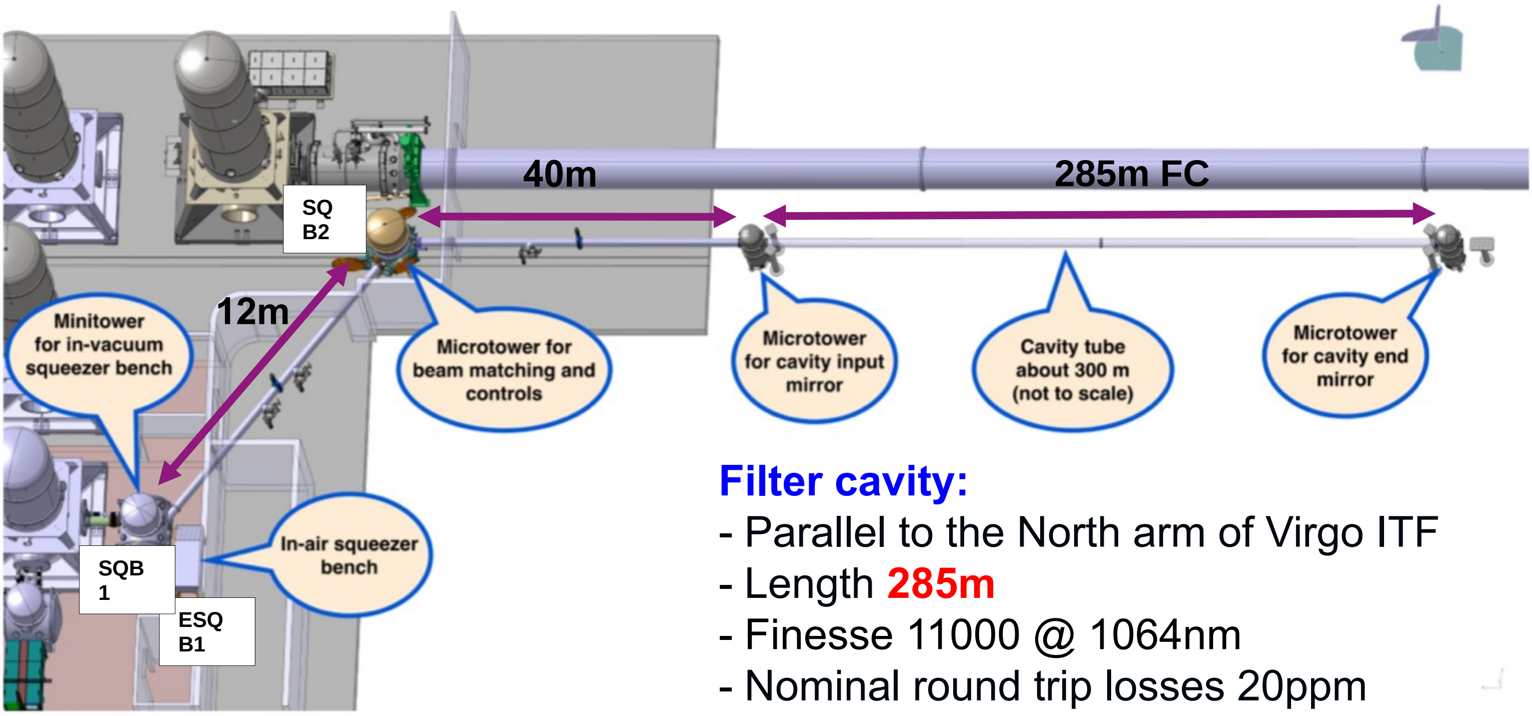
The sensitivity during the next observation run O4, supposed to start in January 2022, will increase, in terms of BNS range, from 50Mpc up to 115Mpc.



The blue curve shows the expected sensitivity curve during O4 while the black spectrum is O3 one, from *Advanced Virgo Plus Design Report.*

FDS implementation in Advanced Virgo Plus

To improve the sensitivity at low and high frequencies, we will inject vacuum squeezed light frequency dependent from Virgo's dark port. To couple these states into the ITF, we need a complex setup composed by: Suspended Squeezing Bench 1 (SQB1) and 2 (SQB2), External Squeezing 1 (ESQB1) and 2 (ESQB2), Filter Cavity (FC), linking tubes SQB1-SQB2 and SQB2-FC.



Filter cavity:
- Parallel to the North arm of Virgo ITF
- Length **285m**
- Finesse 11000 @ 1064nm
- Nominal round trip losses 20ppm

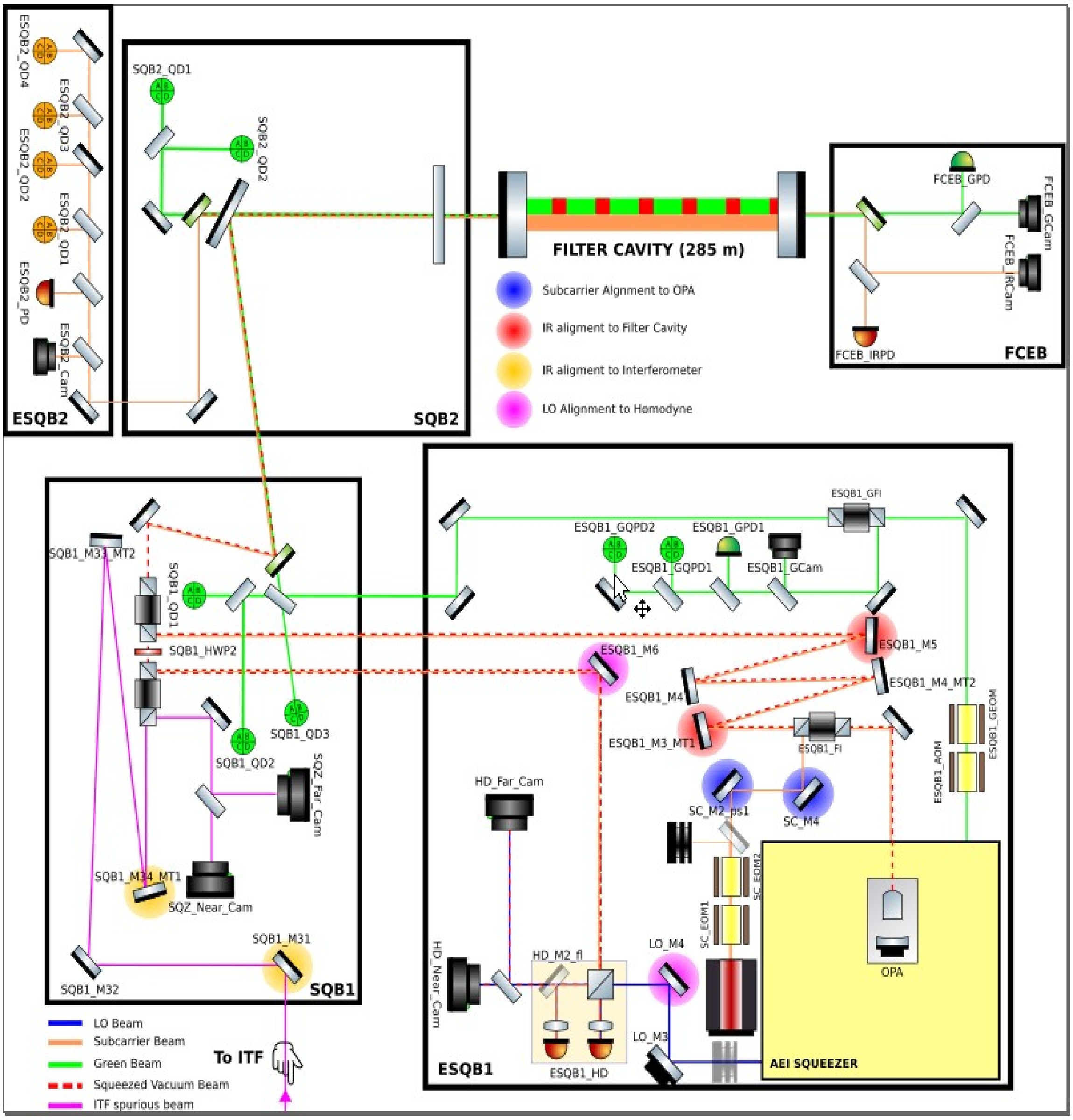
Scheme of FDS setup in AdV+ from *Advanced Virgo Plus Design Report.*

Benches and cavity installation on Virgo site ongoing (almost finalized). Optics installation and pre-alignment (SQB1 and SQB2) at LAPP in October and at Virgo in November.

SQB1 vacuum tank

FDS implementation in Advanced Virgo Plus

To make FDS system work, several components and control loops are needed. We need to produce vacuum squeezed states with the squeezer provided by AEI. Then, this frequency independent light is inject into the 285m filter cavity operated in a detuned configuration. Finally, the frequency dependent states are sent into the ITF, superimposed with the laser beam.

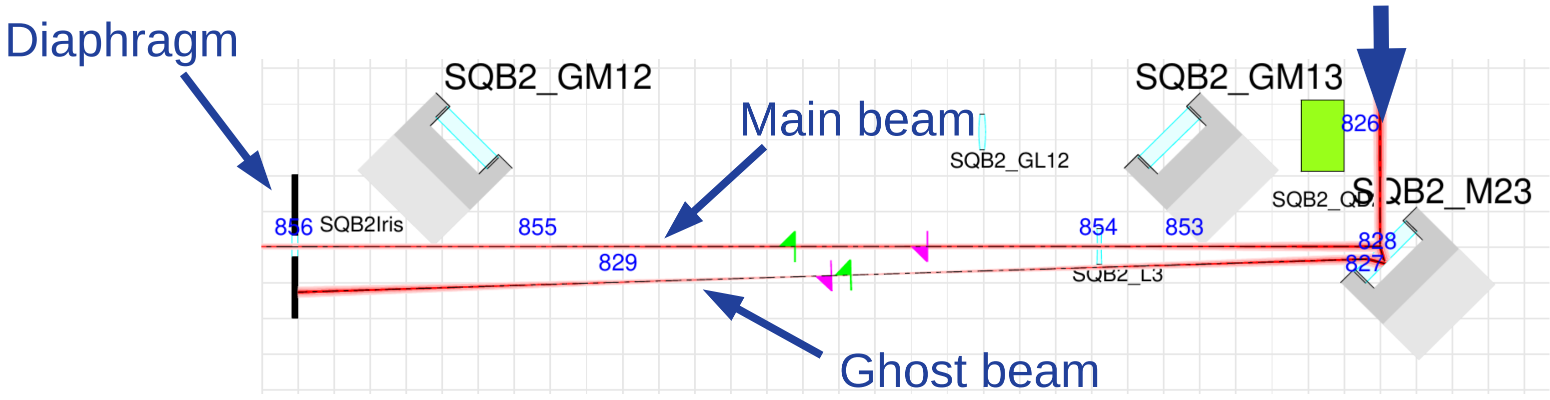


Scheme of FDS setup in AdV+ from *Advanced Virgo Plus Design Report.*

Stray light and Ghost Beams study on FDS system

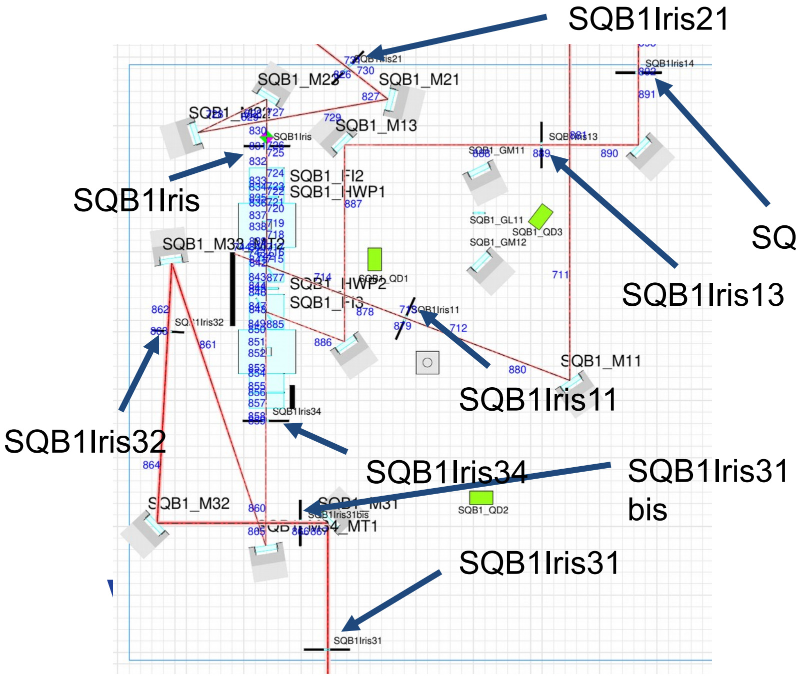
Ghost beams *are secondary beams generated by not perfect HR and AR coatings:*

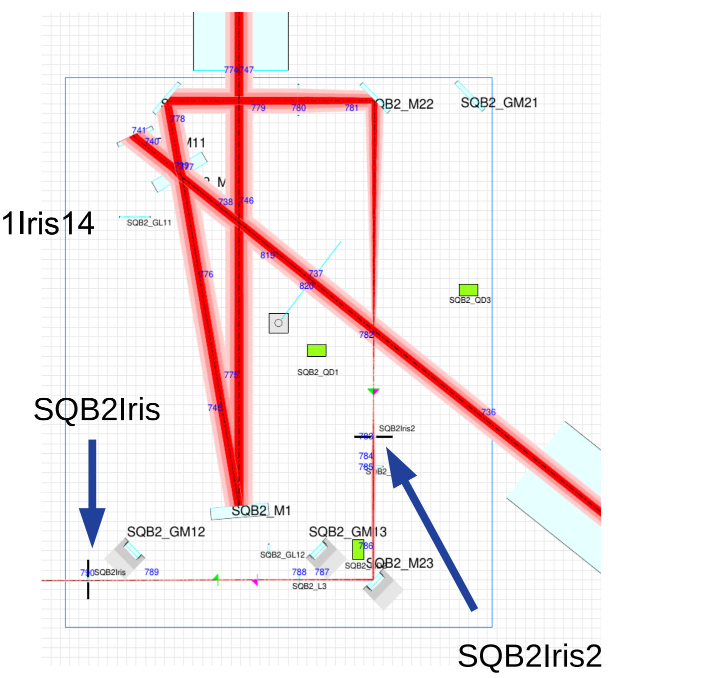
1) we want to dump these beams to **avoid scattered light** on squeezing benches and tubes (it has been proved that the squeezing sensitivity enhancement is affected by stray light: [Virgo Logbook #48337](), [#44990]());



Dumping diaphragm on SQB1

Dumping diaphragm on SQB2



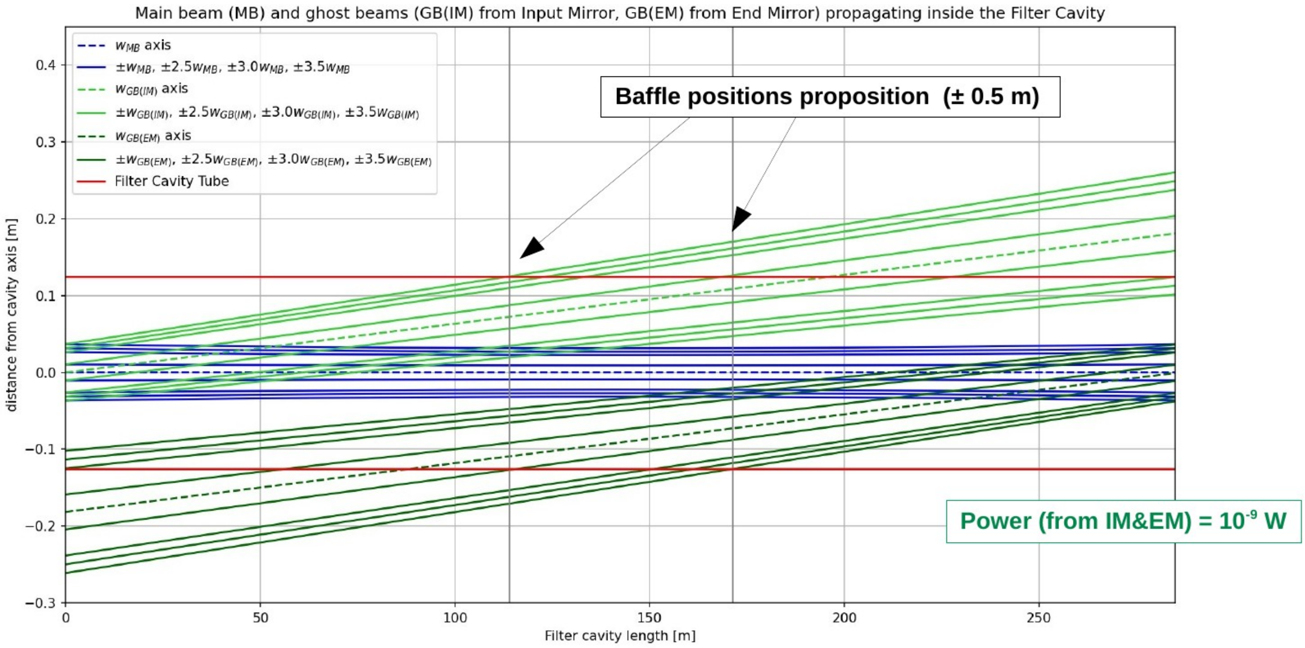


[AdV TDS: VIR-0549B-20]()

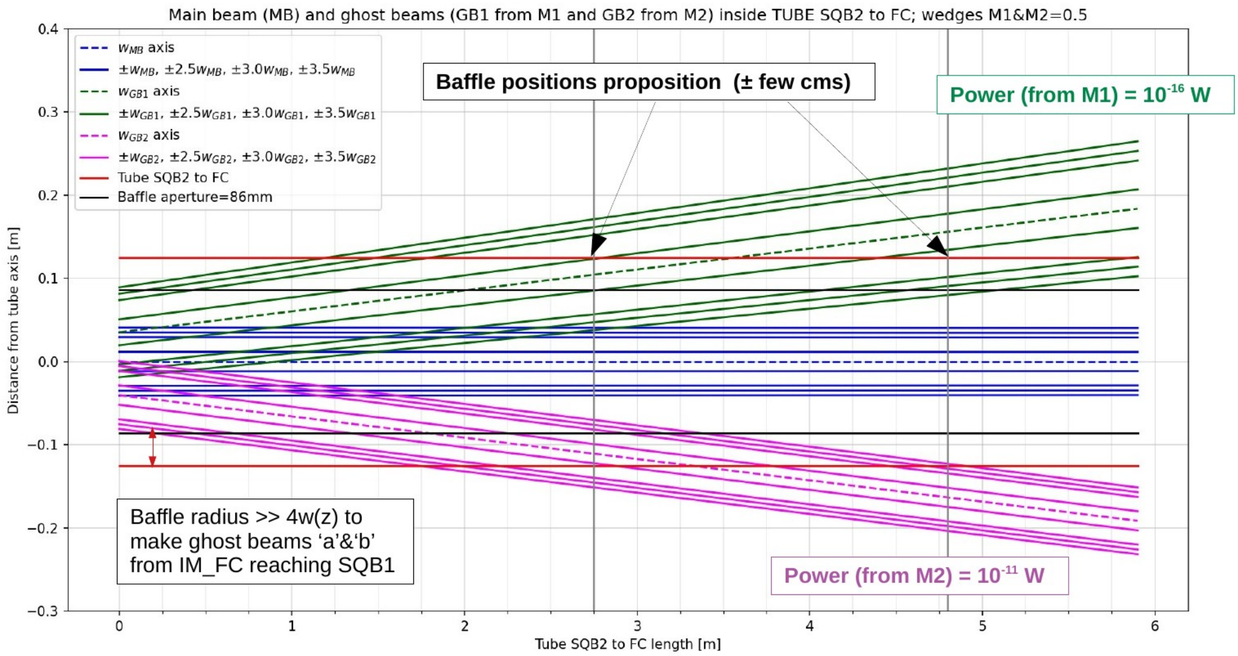
Stray light and Ghost Beams study on FDS system

Main beam and Ghost beams propagation inside the tubes and baffle positions (AdV TDS: VIR-0585A-20).

Filter Cavity



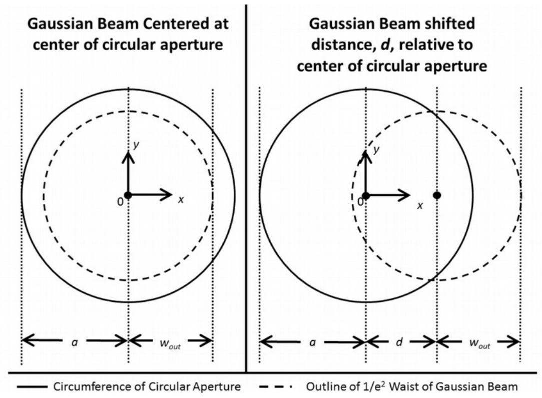
Tube SQB2-FC



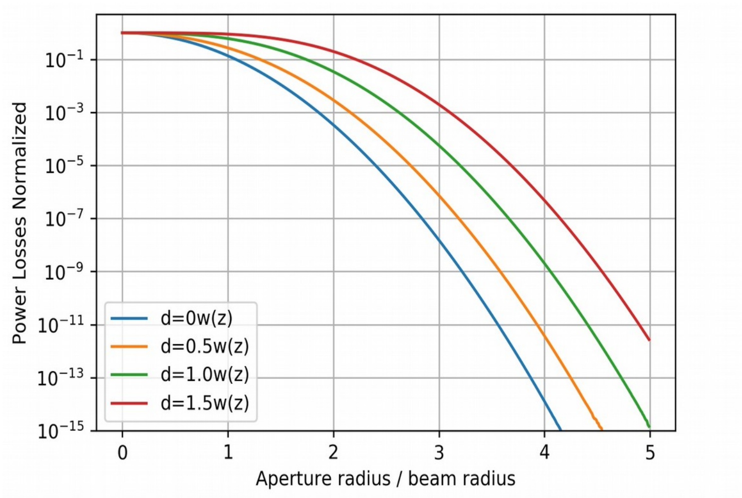
Stray light and Ghost Beams study on FDS system

2) we need to chose an <u>optimal size of diaphragm/baffle apertures</u> to **limit losses** on the main beam;

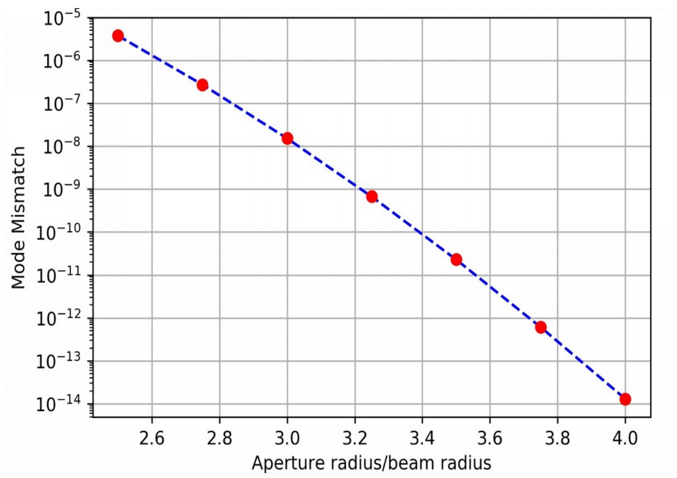
Power losses
Since the HR coating has 3ppm power losses, we want to stay under 1ppm losses, up to 1 w(z) displacement.



AdV TDS: VIR-0518A-20



Mode mismatch losses
The MM requirement for FDS is 1%, to be sure we can consider 0.1%.
We can conclude that diffraction losses are **negligible**.



Conclusions: Aperture size is chosen to be ***a* = *3.5 w(z)*** for diaphragms and ***a = 4 w(z)*** for baffles.

Conclusions

- Quantum noise is limiting the sensitivity of advanced gravitational waves detectors both at low and high frequencies
- Injecting frequency independent squeezing in AdVirgo and aLigo, sensitivity at high frequency has been improved but at low frequency has been tiny worsen
- Rotation at the right angle (~100Hz) of squeezed vacuum states reflected by a 300 meters filter cavity has been proved for the first time in Japan, at NAOJ
- The implementation of this new technique is ongoing at Virgo site
- To limit different type of losses, i.e. is important to maximize the performances of FDS on Virgo
- Goal: broadband quantum noise reduction leading to an higher sensitivity fundamental to better explore the universe (hoping to detect other neutron stars, to further develop multi-messenger astronomy!)

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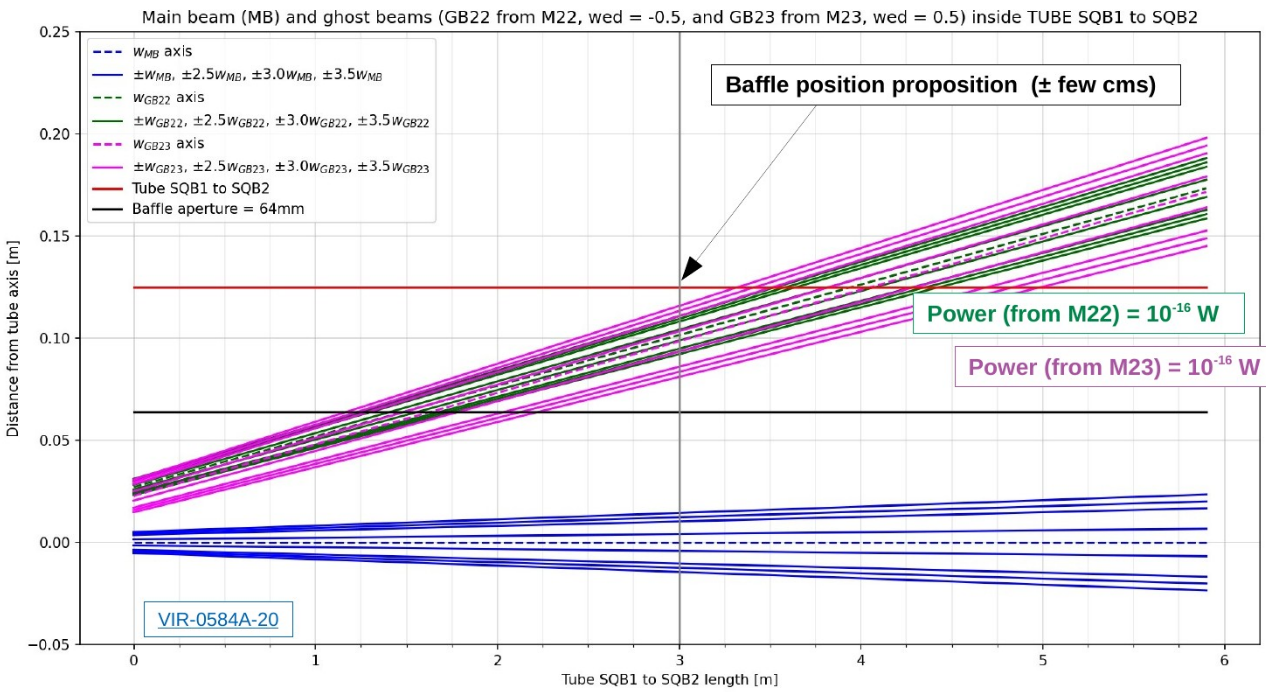
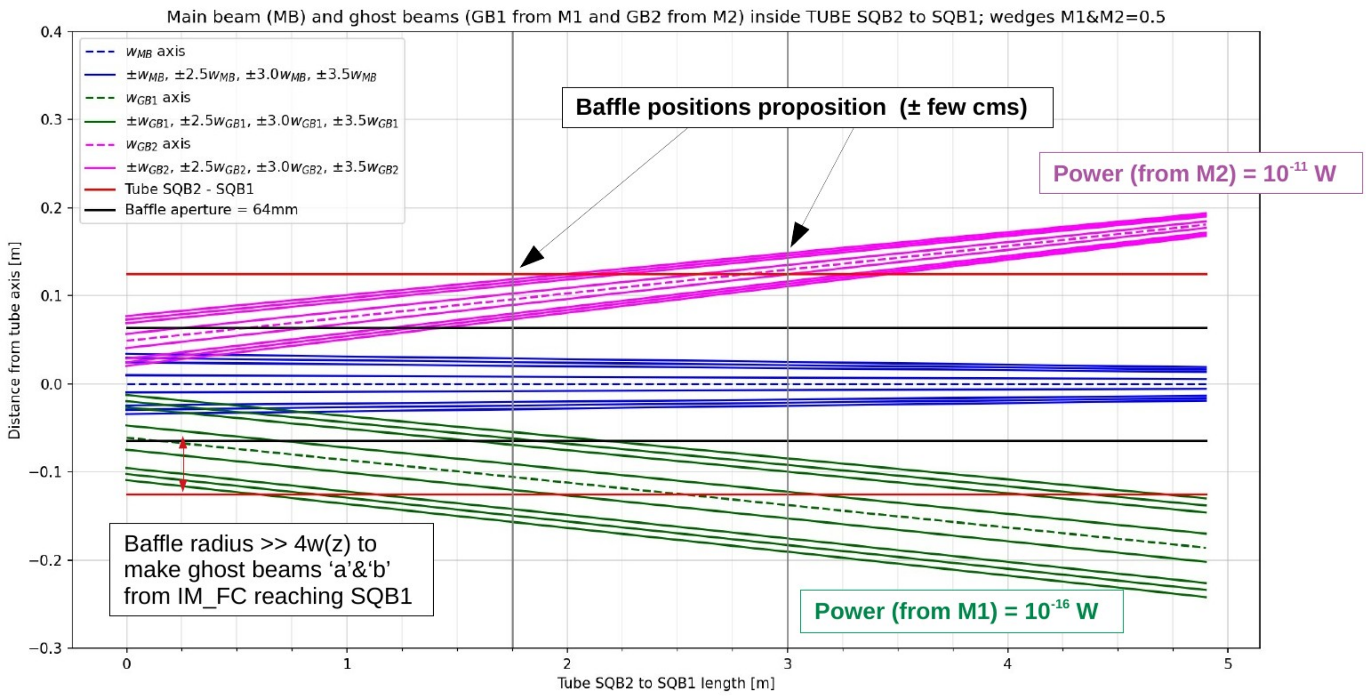
EXTRA SLIDES

Stray light and Ghost Beams study on FDS system

Tube SQB1-SQB2

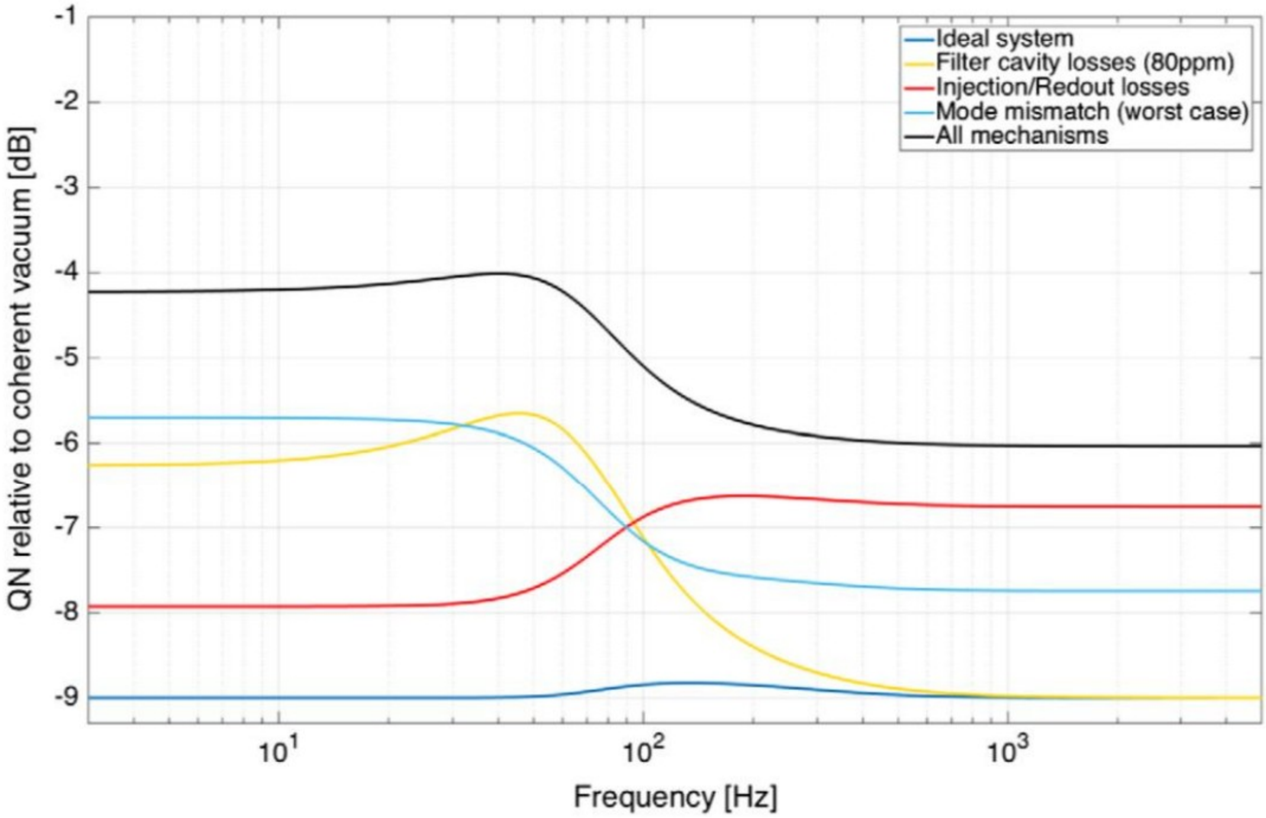


Tube SQB2-SQB1



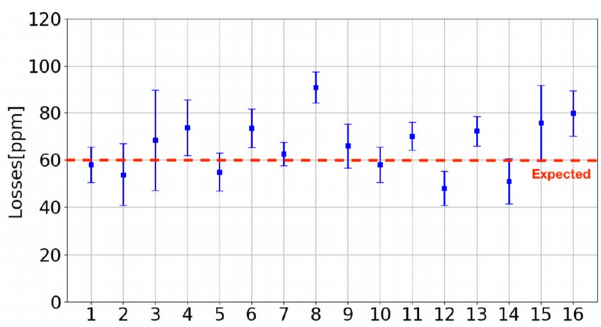
FDS estimated losses at NAOJ

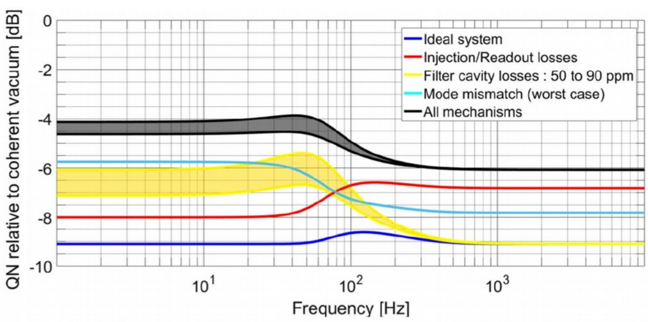
Squeezing degradation budget:



E. Capocasa et al (2016). Estimation of losses in a 300 m filter cavity and quantum noise reduction in the KAGRA gravitational-wave detector. Physical Review D, 93(8), 082004.

Mesured and predicted round trip losses:





E. Capocasa et al (2018). Measurement of optical losses in a high-finesse 300 m filter cavity for broadband quantum noise reduction in gravitational-wave detectors. Physical Review D, 98(2), 022010.