Broadband quantum noise reduction in Advanced Virgo Plus

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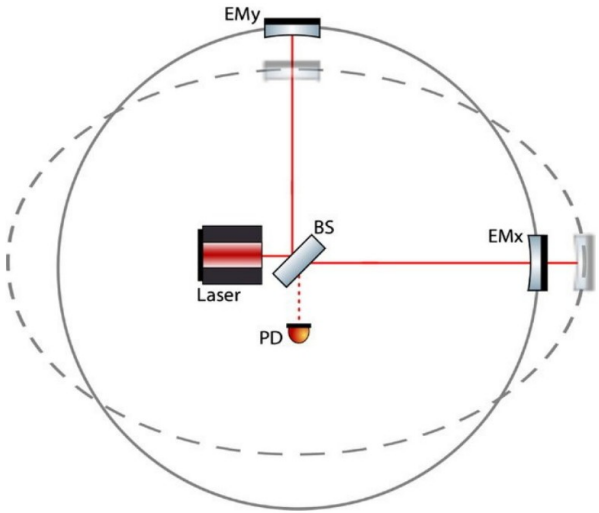
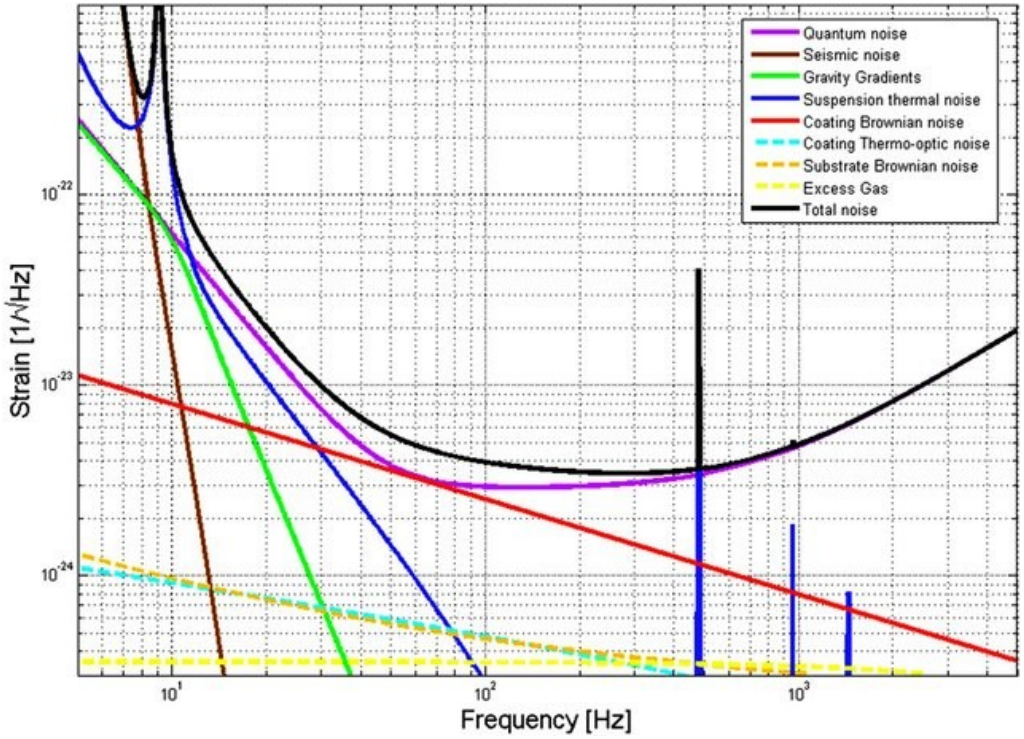
Detection of gravitational waves

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

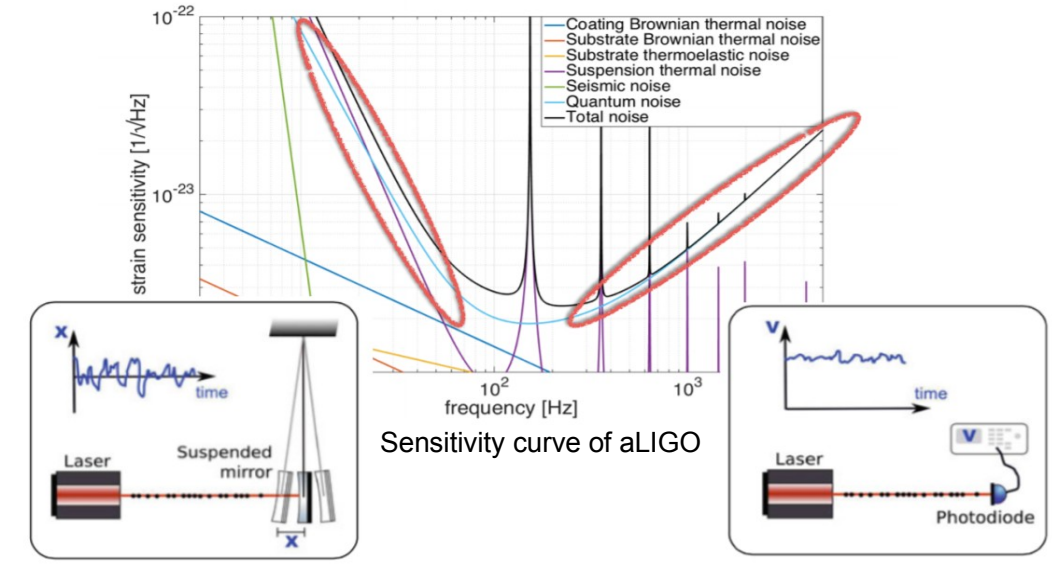
$$\delta\phi_{\mathrm{GW}} = \frac{4\pi}{\lambda}\delta L_{\mathrm{GW}} \longrightarrow h = \frac{2\,\delta L_{\mathrm{GW}}}{L}$$





Quantum noise in ground based detectors

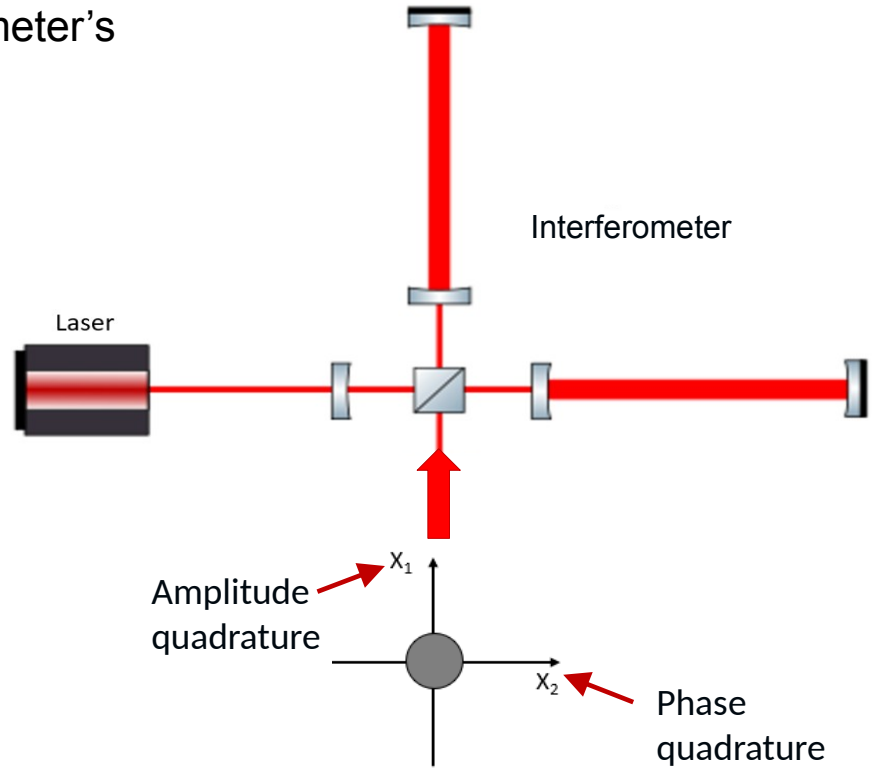
- ✓ *Quantum noise (QN)* limits the sensitivity of GW detectors
- ✓ *QN due only to vacuum fluctuations* entering interferometer's output port



Sensitivity curve of aLIGO

Radiation pressure noise

Shot noise



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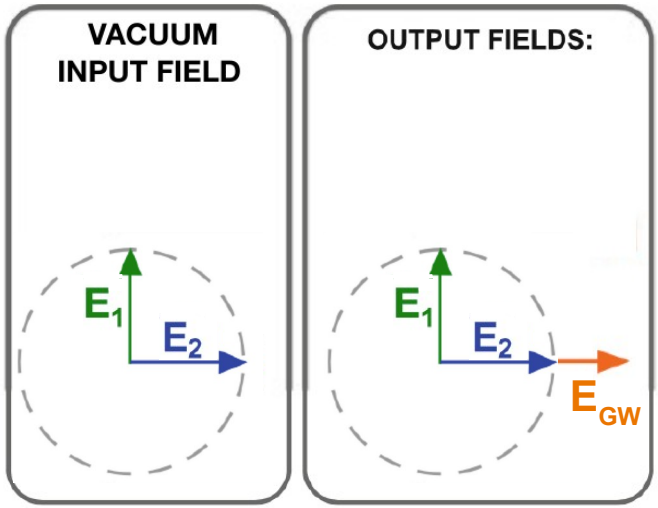
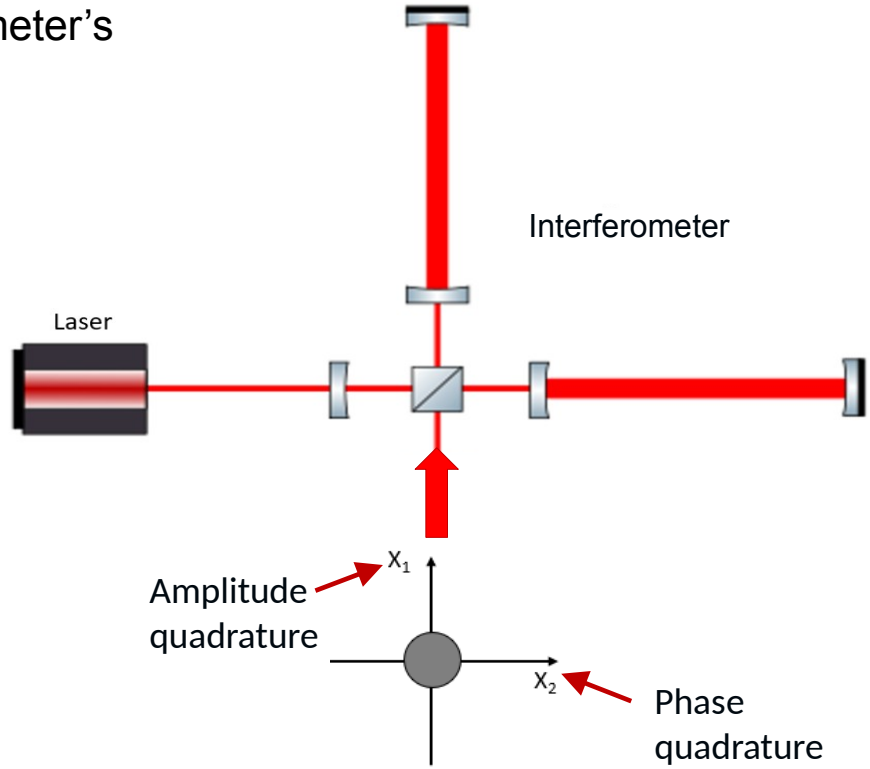
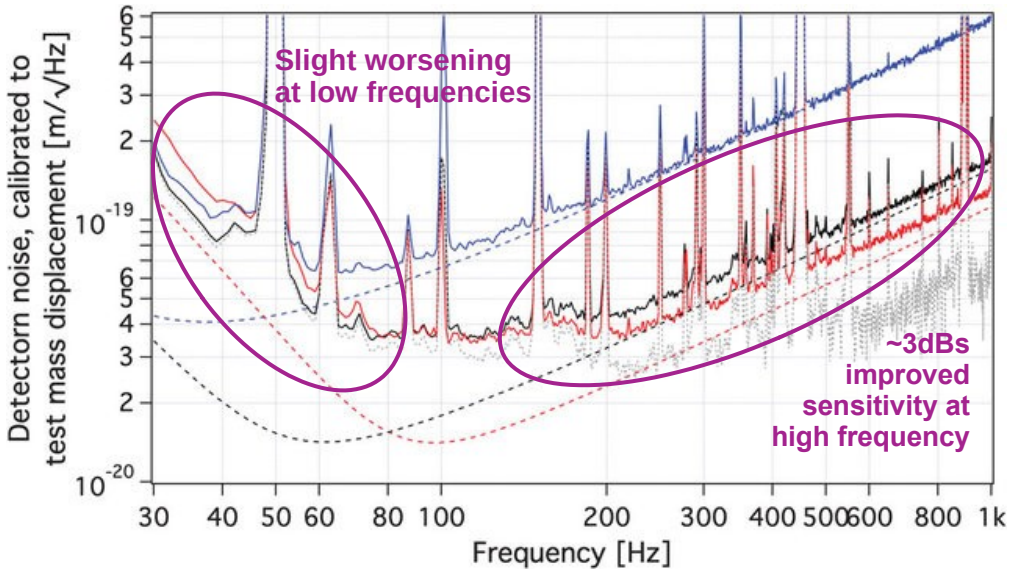
$$\hat{E}(t) = \left[E_0 + \hat{E}_1(t)\right] \cos\omega_0 t + \hat{E}_2(t) \sin\omega_0 t$$



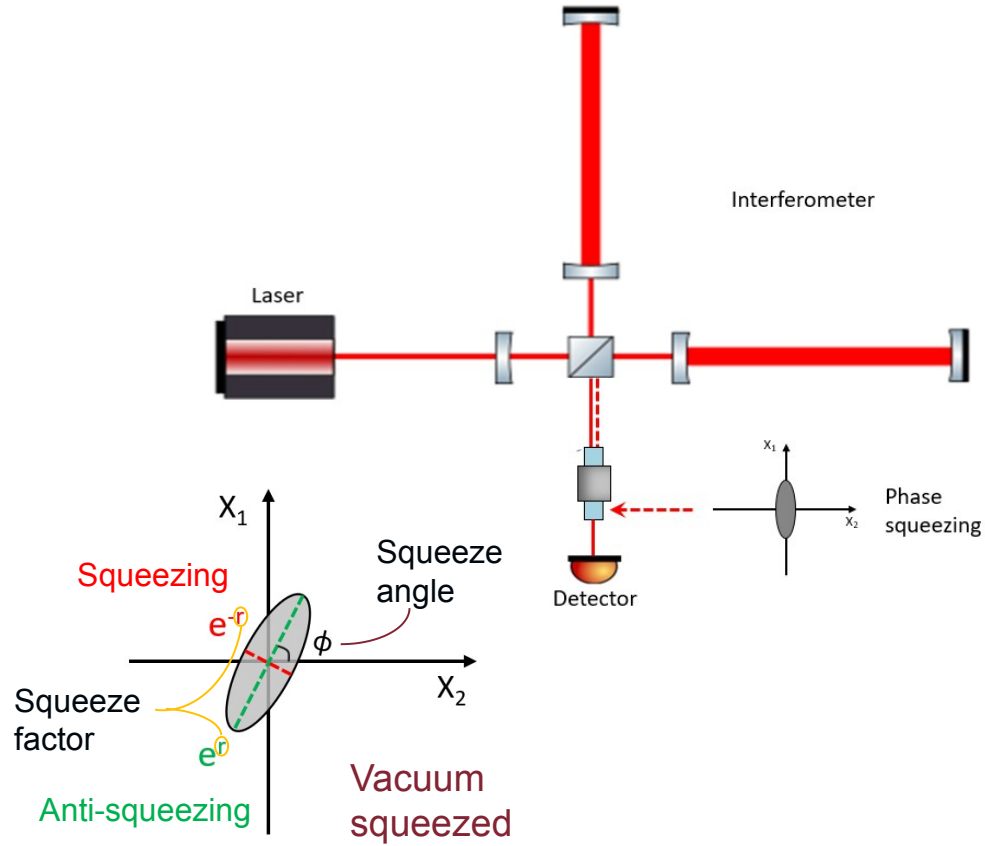


Quantum noise reduction in Advanced Virgo

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



Acernese et all. (2020)



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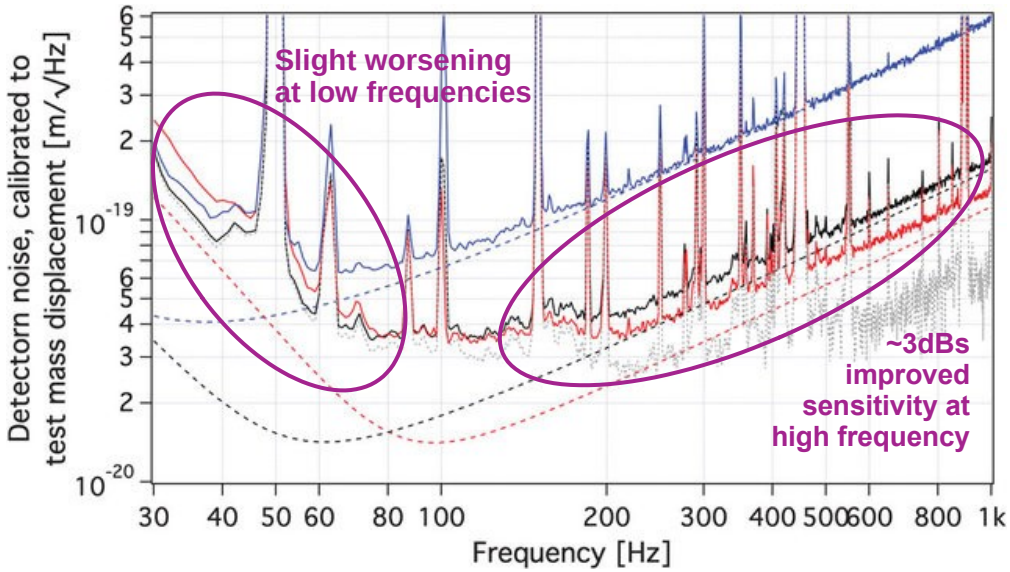
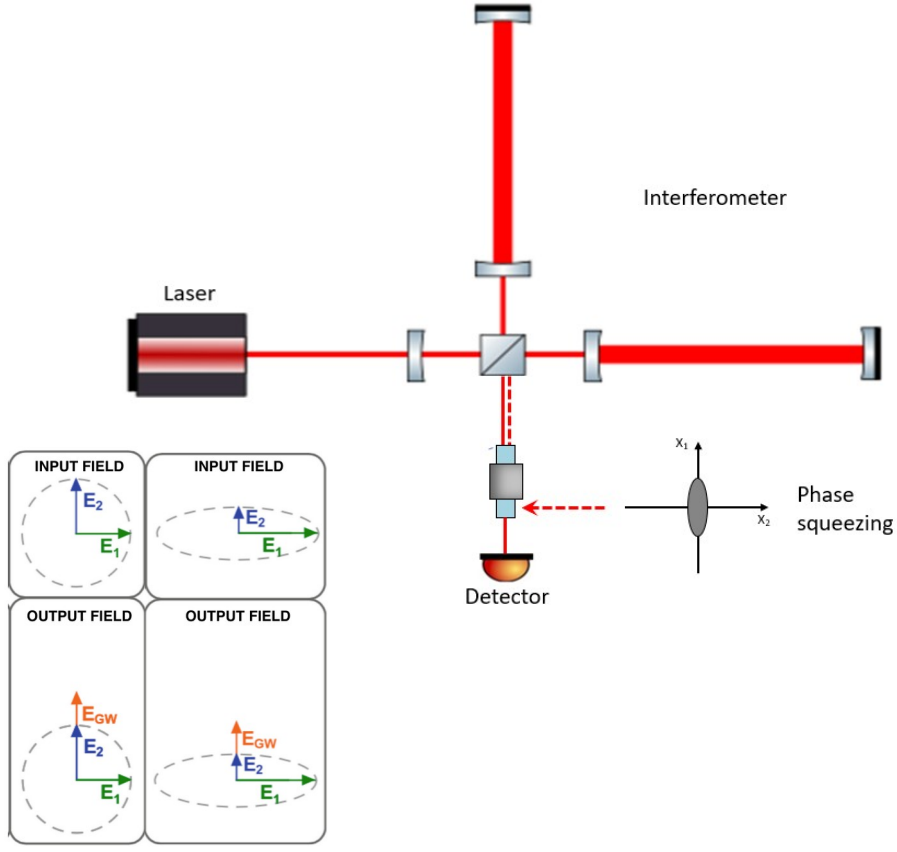
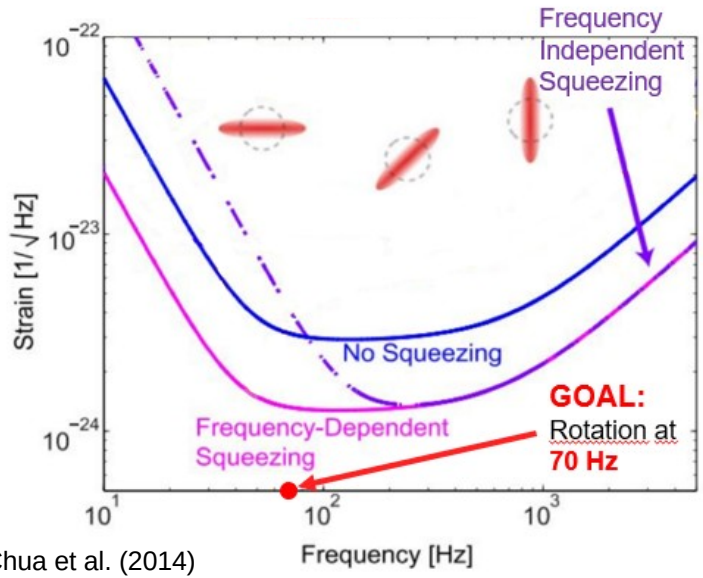


Acernese et all. (2020)

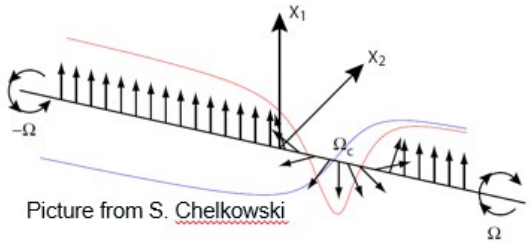


Quantum noise reduction in Advanced Virgo Plus (AdV+)

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



Chua et al. (2014)

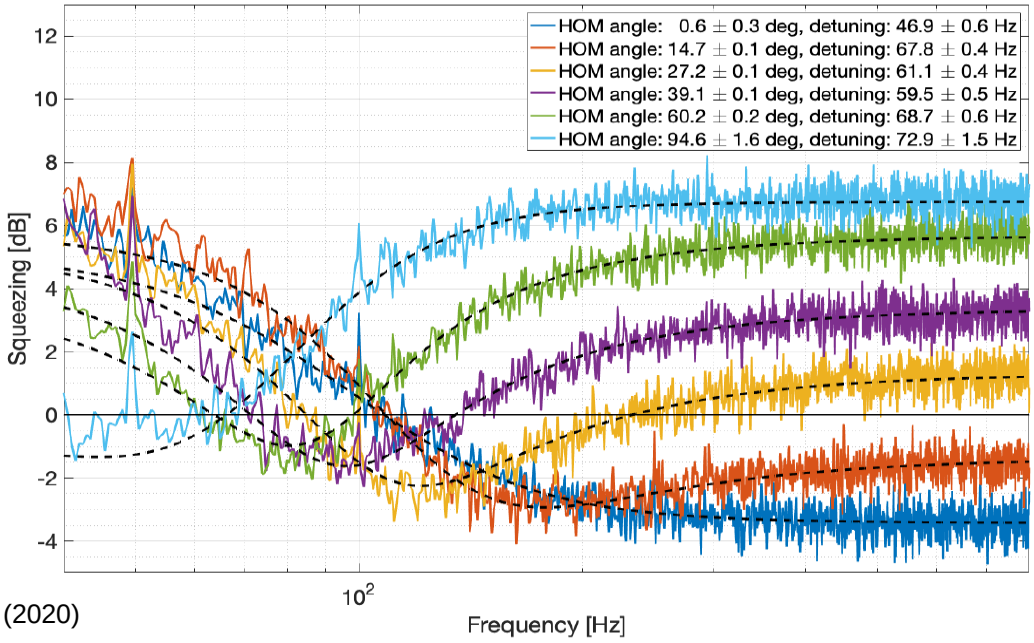


$$h(\Omega) = \frac{h_{SQL}}{\sqrt{2}} e^{-r} \sqrt{\frac{1}{\mathcal{K}(\Omega)} + \mathcal{K}(\Omega)}$$

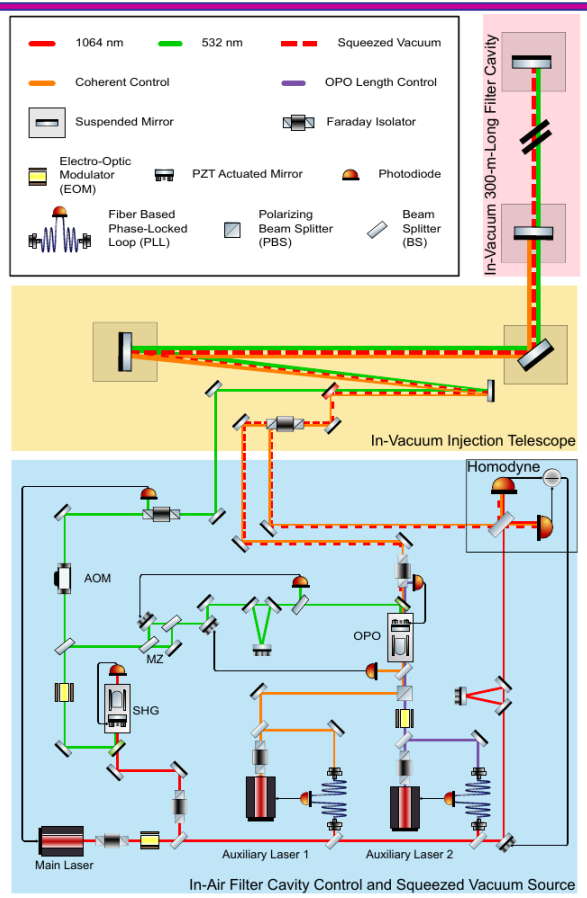
Broadband reduction factor

Frequency dependent squeezing at NAOJ

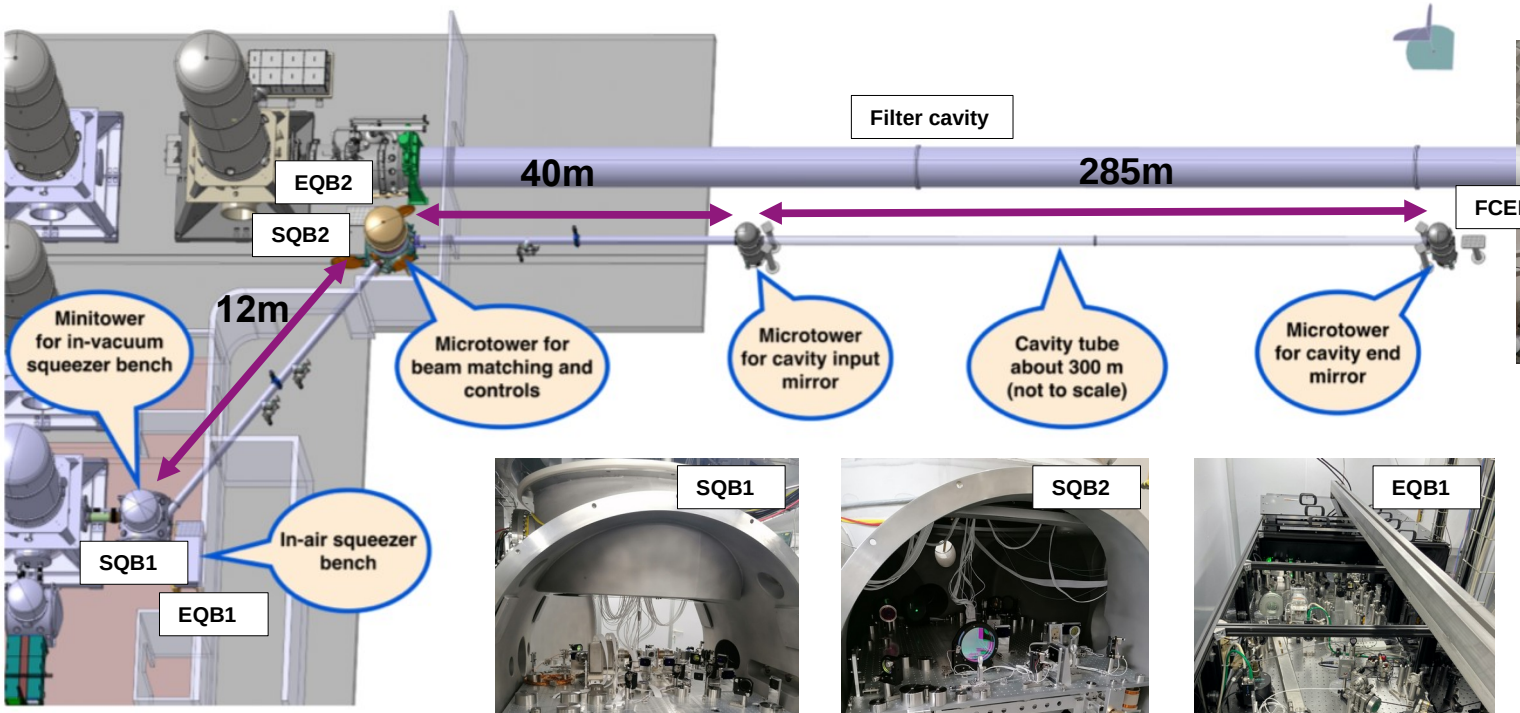
First demonstration (NAOJ, Japan, 2020) of a frequency dependent squeezed vacuum source, realized with a 300 m suspended filter cavity. The squeezing rotation takes place in the frequency region (~ 100 Hz) needed to reduce the quantum noise in the whole spectrum of advanced GW detectors.

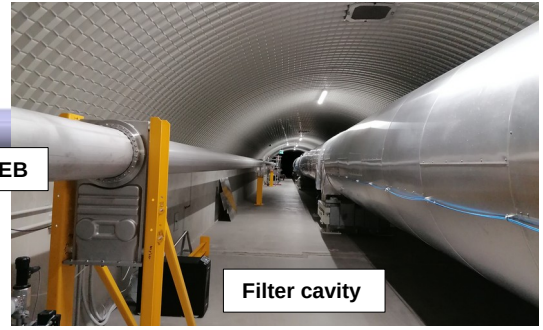


Zhao et al. (2020)



Frequency dependent squeezing in AdV+

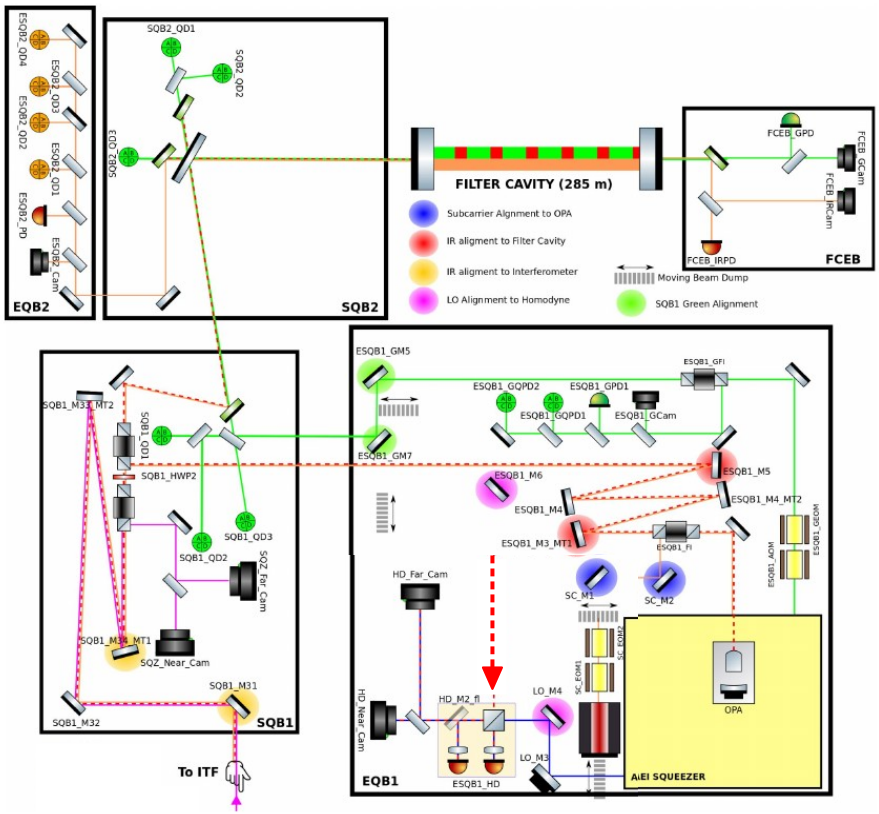




Technical Design Report (2019)

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

Frequency dependent squeezing in AdV+



Credit M. Vardaro

Green Beam : to lock the cavity at the beginning

LO Beam (Local Oscillator Beam) : to perform homodyne detection

Subcarrier Beam : to lock the cavity with the IR beam

Squeezed Vacuum Beam

ITF spurious beam

Frequency dependent squeezing in AdV+

EQB2

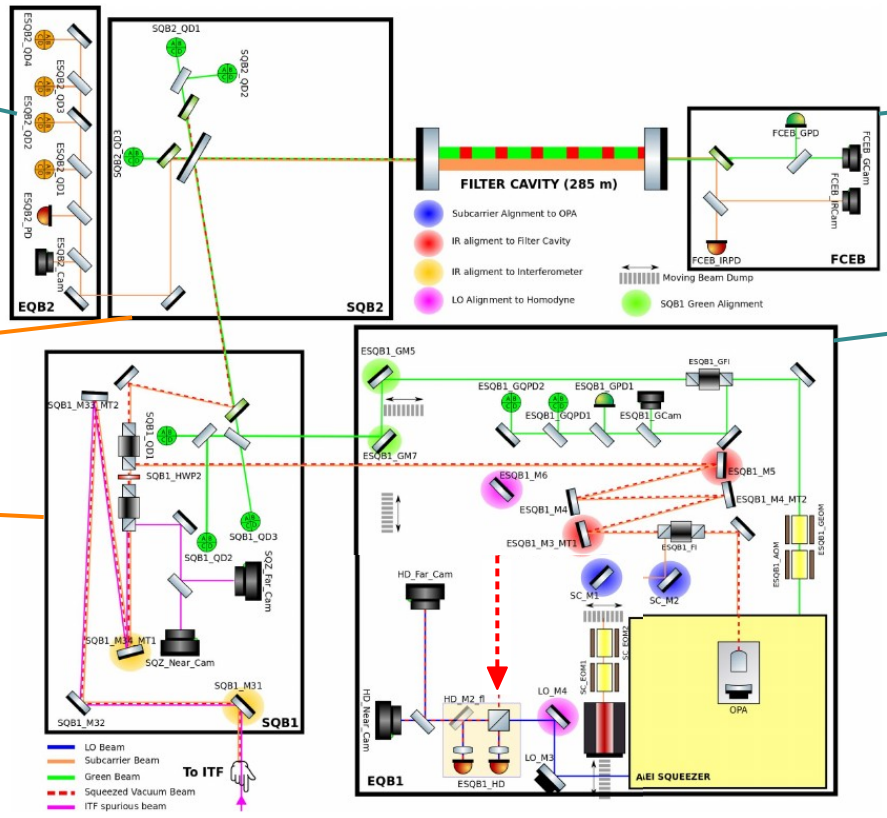
- IR longitudinal PD and RF QPD
- Mode converter telescope

SQB2

- Steering optics
- IR pick-off (0.1%) for EQB2
- Matching telescope second mirror

SQB1

- Steering optics
- Double stage FI
- Matching telescope first mirror
- Sensors for alignment to ITF



FCEB

- IR and green FC transmission sensors

EQB1

- Squeezing Source
- Sub-Carrier source
- IR steering optics and telescope
- Homodyne detector
- PLLs
- Green longitudinal PD and RF QPD
- AA actuators

Suspended benches

Not suspended benches

Credit M. Vardaro

Frequency dependent squeezing in AdV+

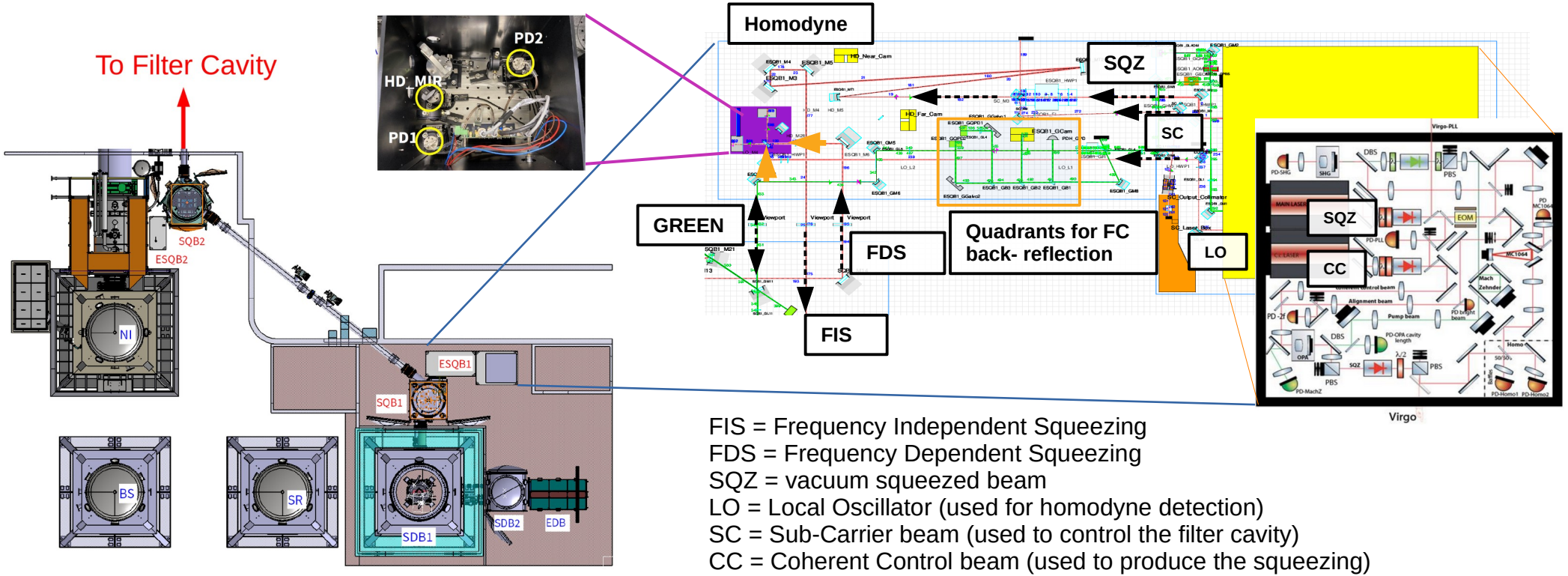
- **Installation of the infrastructure:**
  - EQB1 bench + acoustic enclosure
  - SQB1/SQB2 vacuum chambers
  - SQB1/SQB2 suspended benches
  - SQB1/SQB2 electronics
  - Filter cavity tube
  - Filter cavity micro-towers
  - New Optical Parametric Amplificator (OPA) inside the squeezing source

- **Pre – commissioning:**
  - EQB1 controls tested
  - Preliminary squeezing measurements on EQB1
  - Sub-Carrier laser installed and characterized
  - SQB1/SQB2 suspended and controlled with coils (LVDTs)
  - Green and infrared beams pre-aligned on the benches
  - Filter cavity mirrors suspended and controlled

- **Commissioning:**
  - Green and infrared beams aligned with the filter cavity
  - Filter cavity locked on the green beam
  - Automatic alignment to keep the cavity aligned on the green
  - IR beam pre-aligned towards the ITF
  - Measured frequency independent squeezing (FIS) reflected from SQB1

Squeezing Vacuum Source system (SVS)

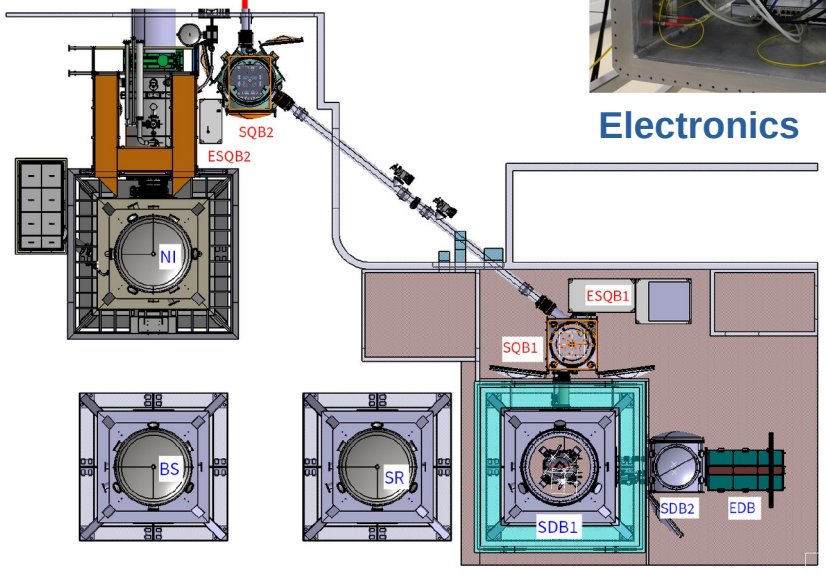
- Installation of the infrastructure: Squeezing Vacuum Source bench (SVS)

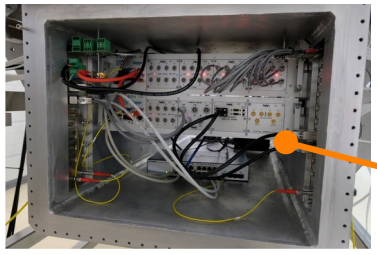


FIS = Frequency Independent Squeezing
FDS = Frequency Dependent Squeezing
SQZ = vacuum squeezed beam
LO = Local Oscillator (used for homodyne detection)
SC = Sub-Carrier beam (used to control the filter cavity)
CC = Coherent Control beam (used to produce the squeezing)

Squeezing Injection system (SIN)

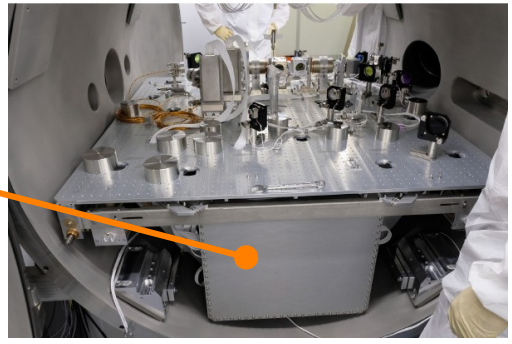
- Installation of the infrastructure: Squeezing Injection system (SIN)



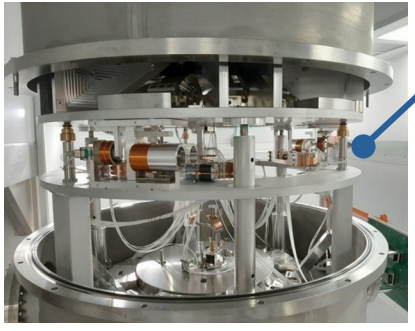


Electronics

Bench



Suspension

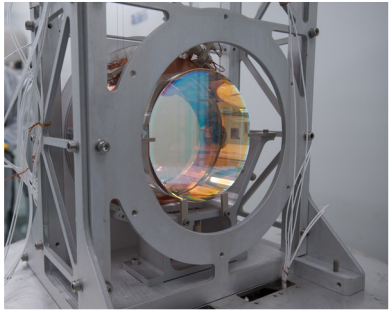


Vacuum chamber

Filter cavity system (FLT)

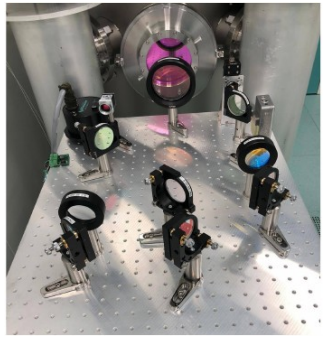
- Installation of the infrastructure: Filter cavity (FLT)

Suspension

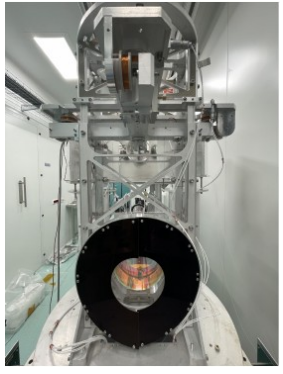


Mirror

Tube (285 m)



End bench

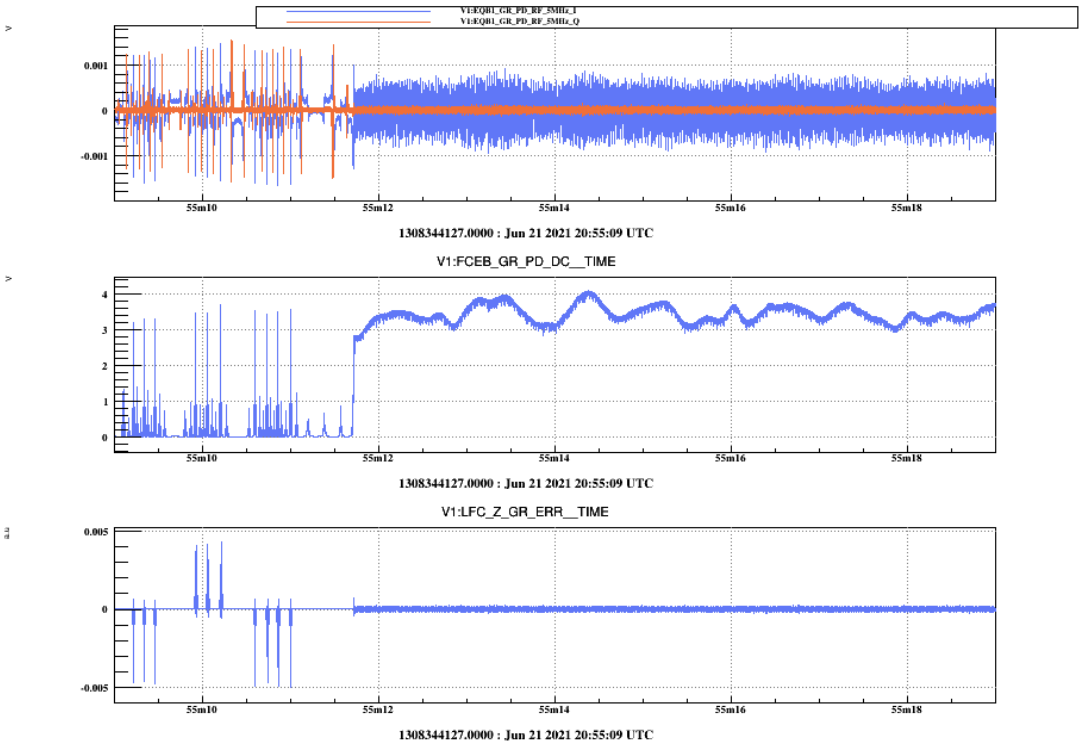


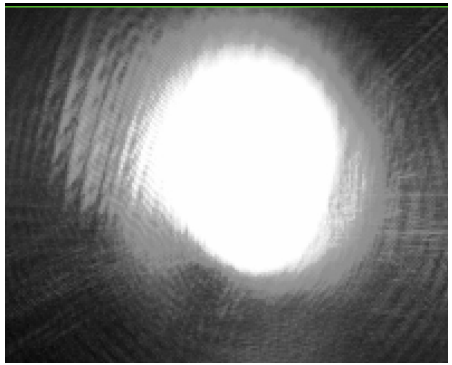
Baffle

Vacuum chamber

Filter cavity locked with the green

- Commissioning: filter cavity aligned and locked on the green



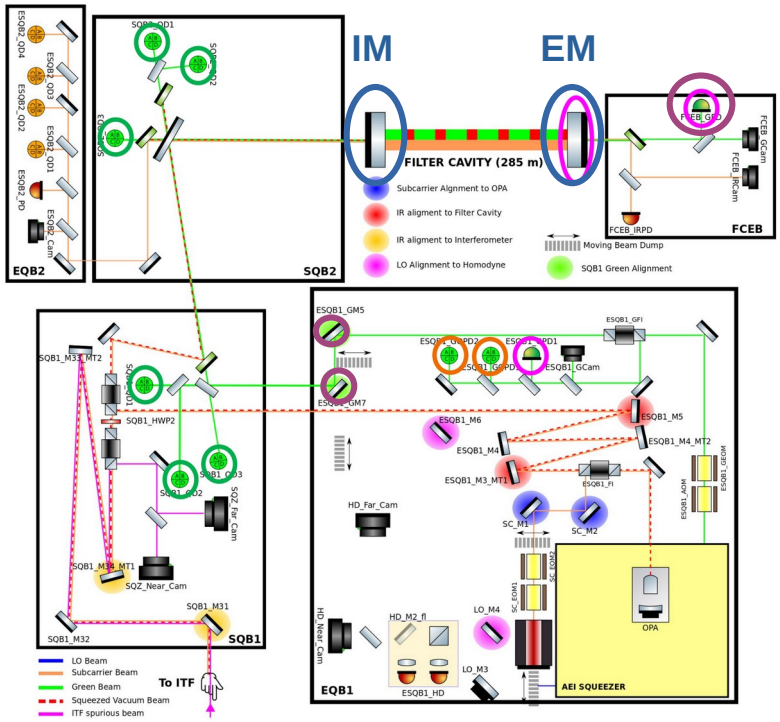


Green beam on FC transmission camera

Sensor: PD on EQB1 in reflection from the FC
Actuator: coils on the End Mirror

FC Automatic Alignment

- Commissioning: Automatic Alignment (AA) of the green in the FC



1. Lock of the FC

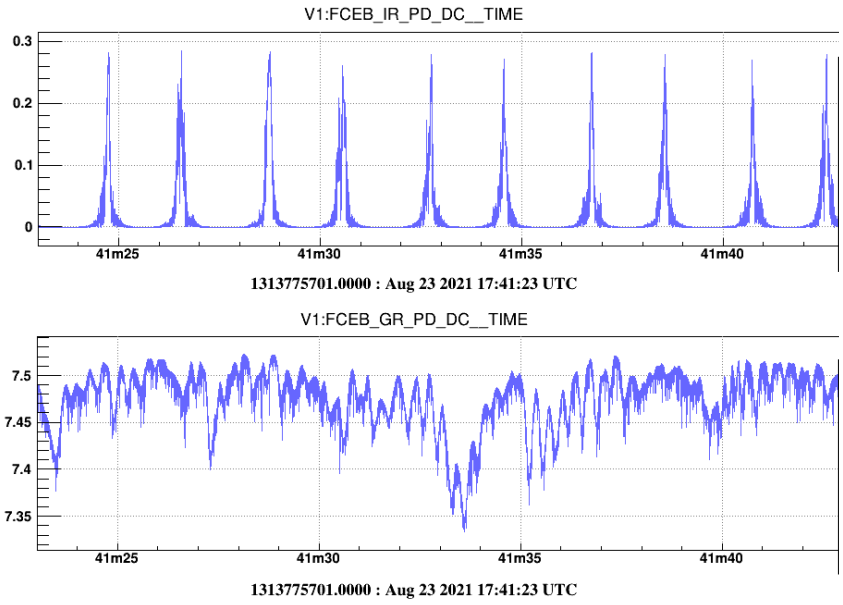
2. Beam pointing control (to center the beam on IM and EM):
- injection of dither lines on IM and EM
- check correction of FC length
- change set points to minimize the lines

3. Drift control (to keep FC transmission max)
- move M5 and M7 (last motorized mirrors on EQB1)
- check if FC transmission is maximum demodulating the PD DC signal at the lines frequency

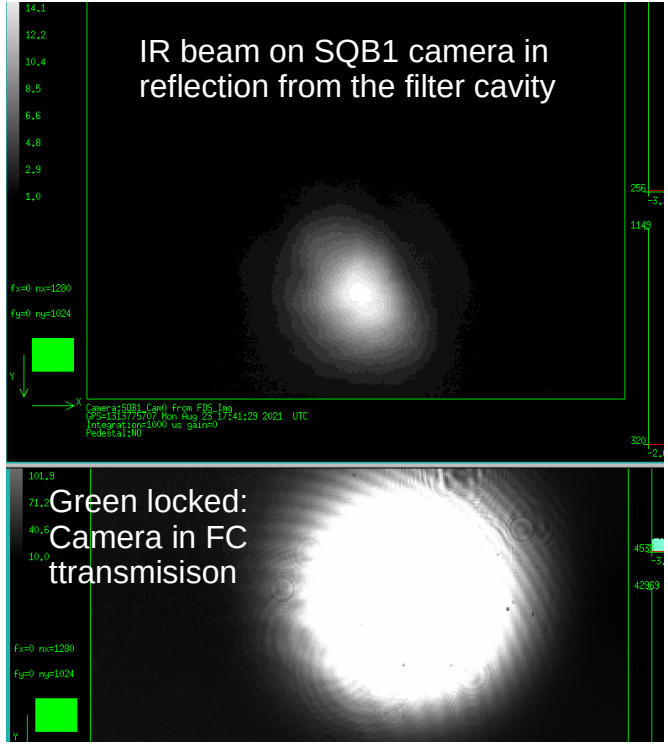
Filter cavity is stably locked with the drift control engaged

IR beam overlapped with the green

- Commissioning: IR beam overlapped with the green beam



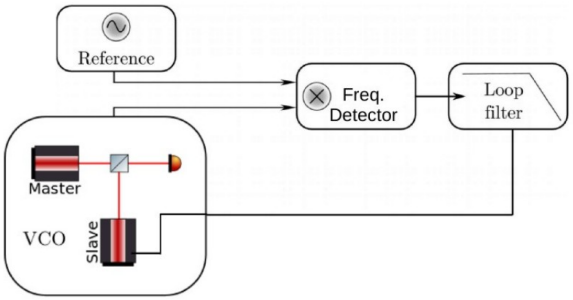
Filter cavity locked on the green.
AOM scanned. Signals in FC transmission.



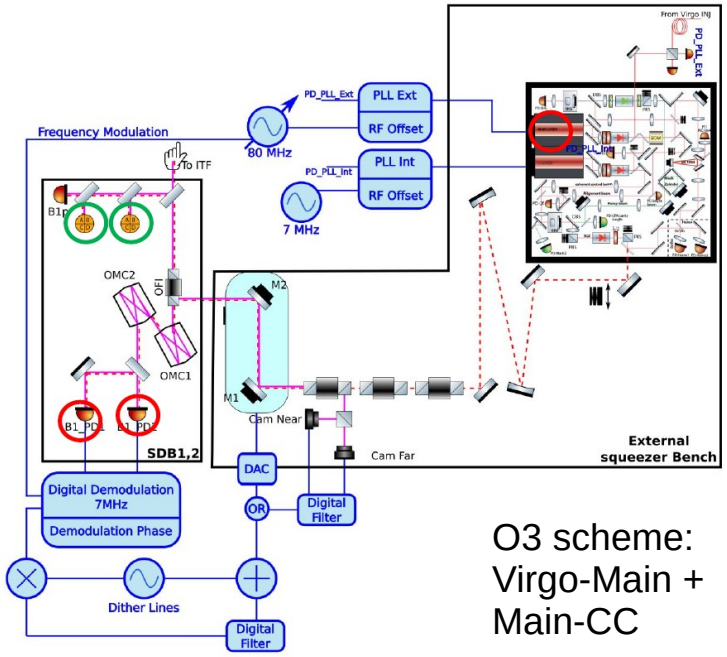
Phase Lock Loops (PLLs)

- Commissioning: Phase Lock Loops (PLLs) - an optical PLL is a feedback system aimed to fix the difference in frequency between two lasers

1. Virgo – Main laser squeezer = 0 MHz
2. SQZ main laser – Coherent Control = 4 MHz
3. SQZ main laser – Sub Carrier = 1.2 GHz



Slow loop: on laser temperature for the long term stability
Fast loop: on laser PZT



O3 scheme:
Virgo-Main +
Main-CC

Frequency Independent Squeezing measurement

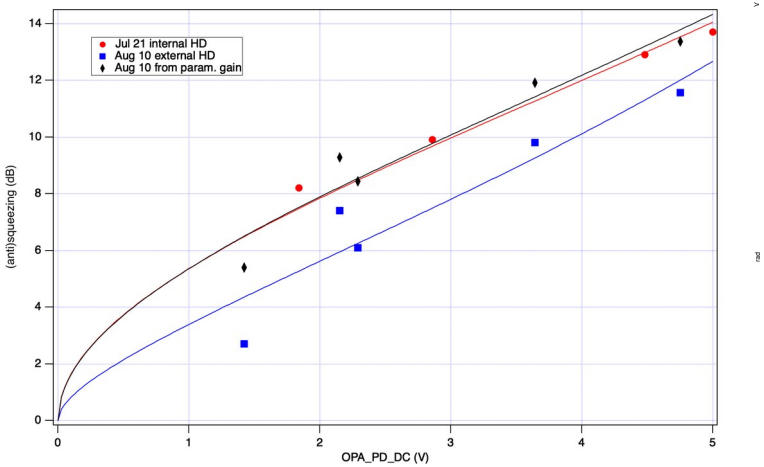
- Commissioning: Frequency Independent Squeezing (FIS) measurement
  1) on EQB1 and 2) coming back from SQB1

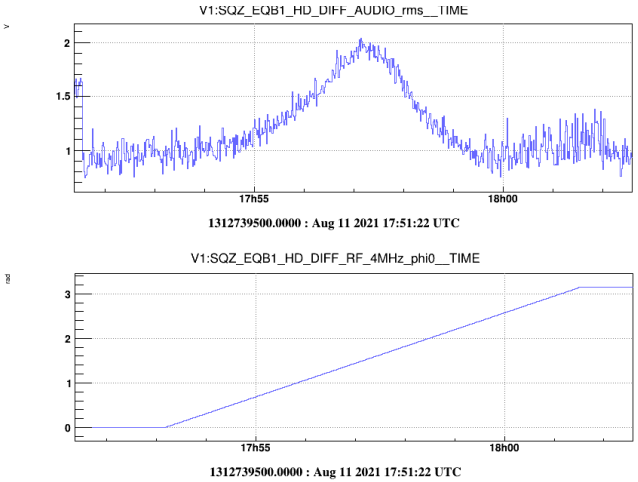
1) SQZ level 3.02 dB at 2.77 rad

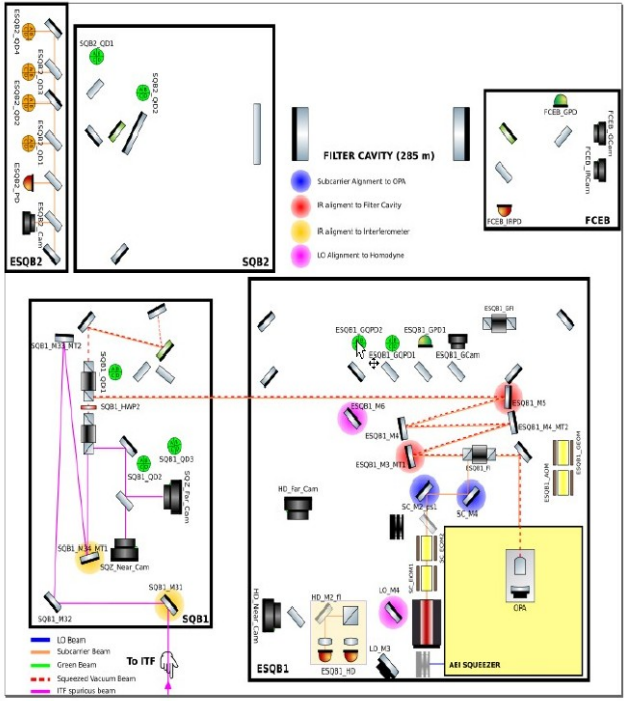
ASQZ level 7.4 dB at 1.41 rad

2) SQZ Level = 1.9 dB at 2.55 rad

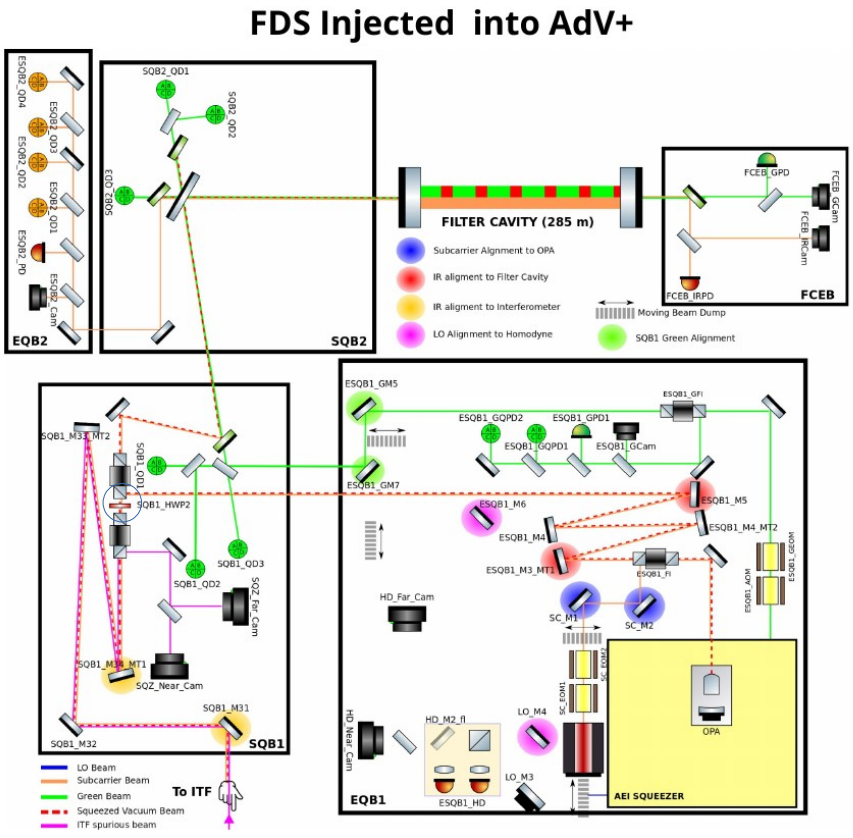
ASQZ level = 6.1 dB at 1.5 rad

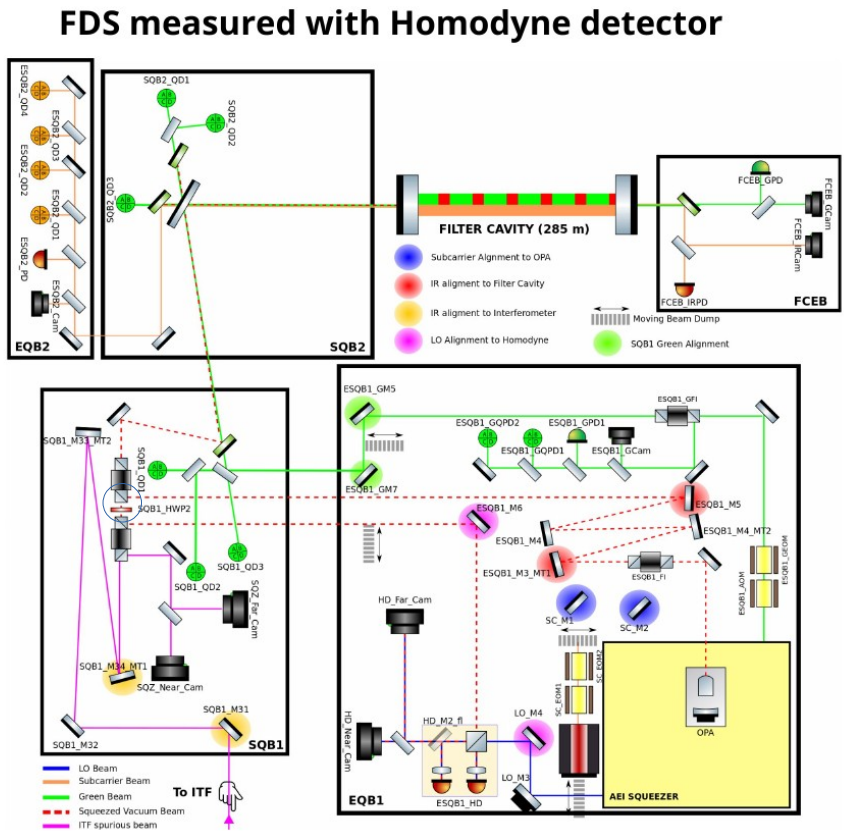






FDS measurement





Credit M. Vardaro

Next steps

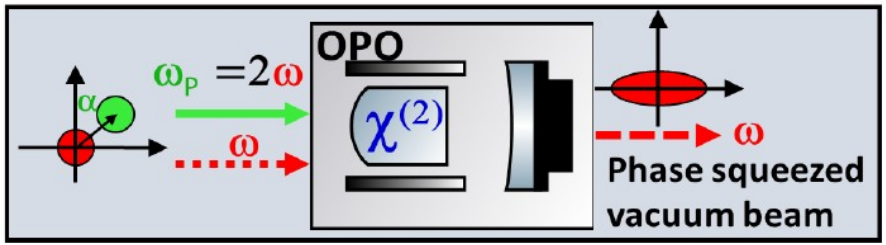
- Lock of the filter cavity with the infrared beam
- Control of suspended benches with the Position Sensor Devices
- Automatic alignment of the filter cavity with the IR
- Measurement of Frequency Dependent Squeezing (FDS)!
- Match the beam from the ITF on SQB1
- Injection of FDS in the ITF!

Thanks for the attention

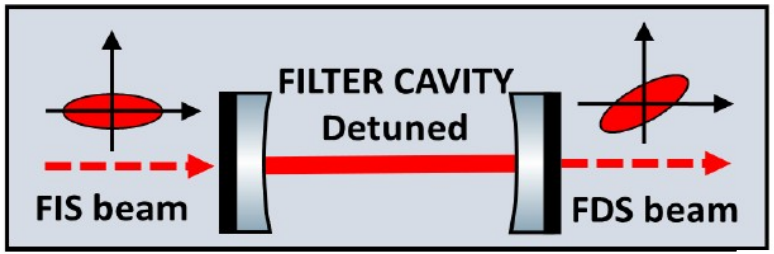
EXTRA SLIDES

Frequency dependent squeezing states generation

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



Filtered by a detuned cavity (FC)



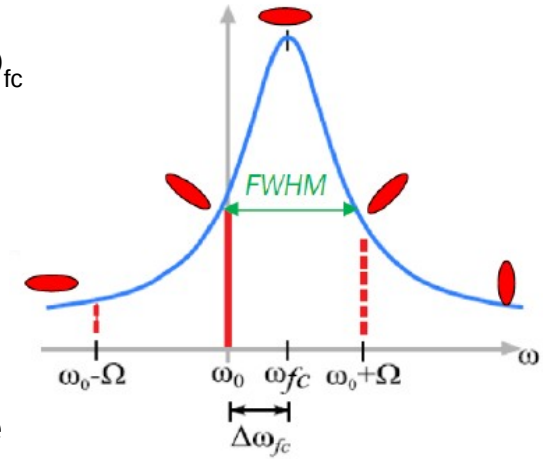
SQZ angle θ_{fc} rotation induced by a Fabry-Perot cavity at frequency Ω:

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

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

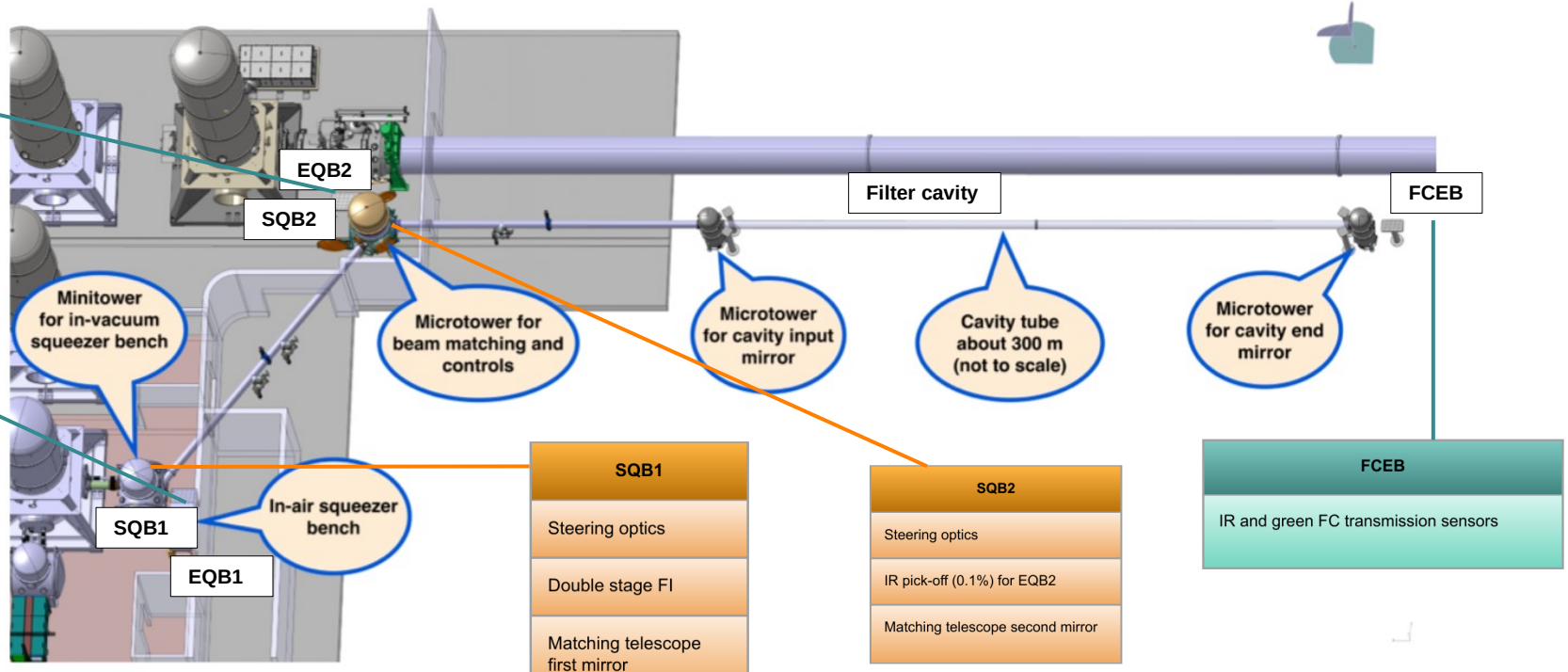
FC resonates at $\omega_{fc} = \omega_0 + \Delta\omega_{fc}$

Parameters to consider:
- Linewidth γ_{fc} = FWHM/F
- Detuning $\Delta\omega_{fc}$



Credit S. Di Pace

Frequency dependent squeezing in AdV+

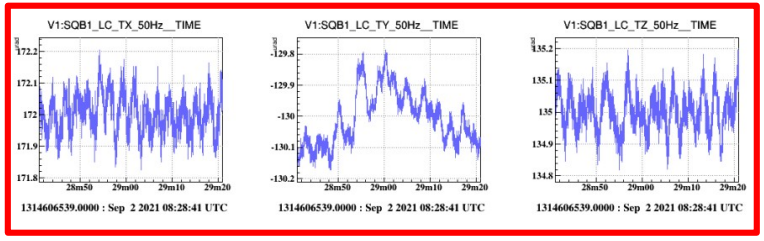


Technical Design Report (2019)

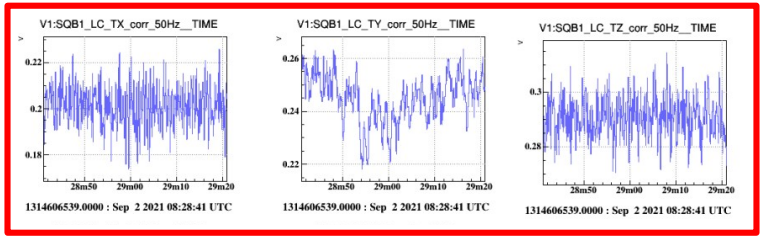
SIN pre-commisisoning

- Pre – commissioning: suspended benches controlled

Angular dofs: controlled with LVDTs on the bench and the frame

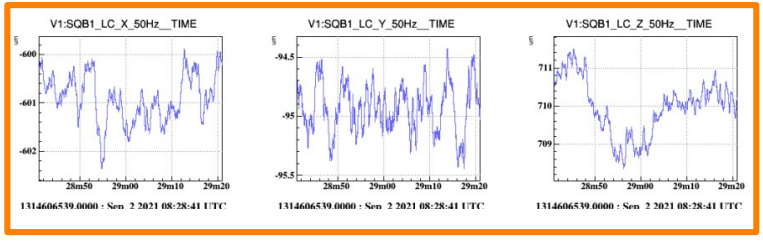


Nominal angular values

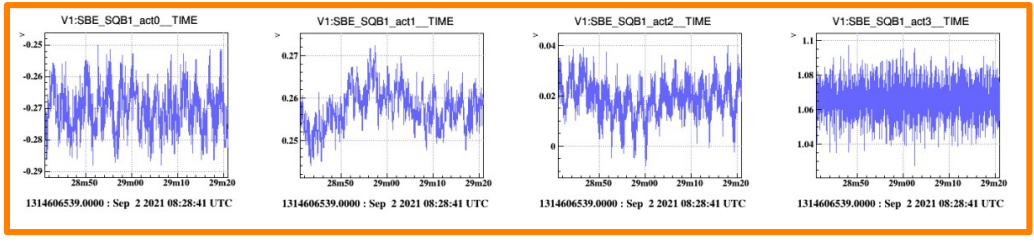


Corrections on bench actuators

Position dofs: controlled with LVDTs on the suspension



Nominal position values

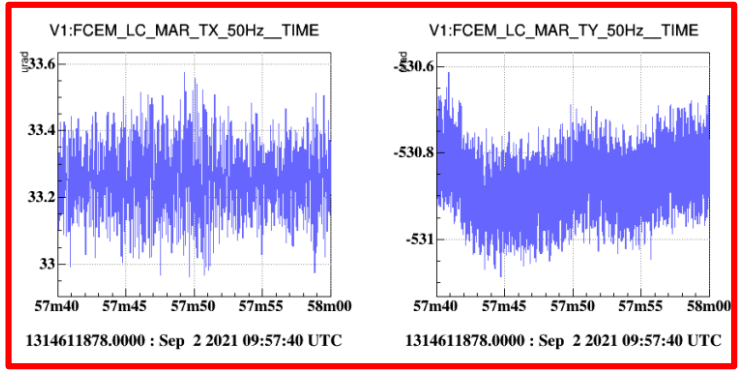


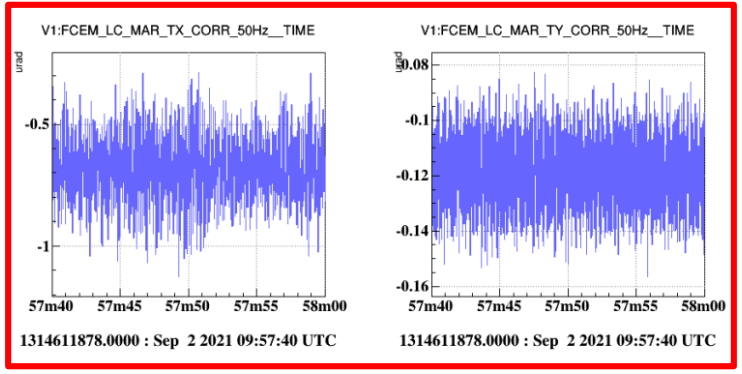
Corrections on suspension actuators

FLT pre-commissioning

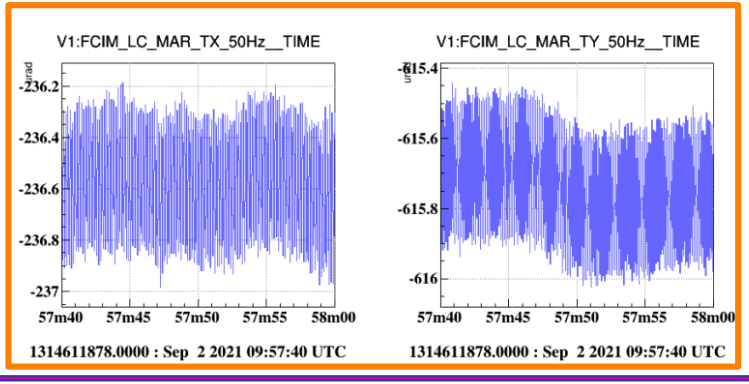
- Pre – commissioning: filter cavity mirrors controlled

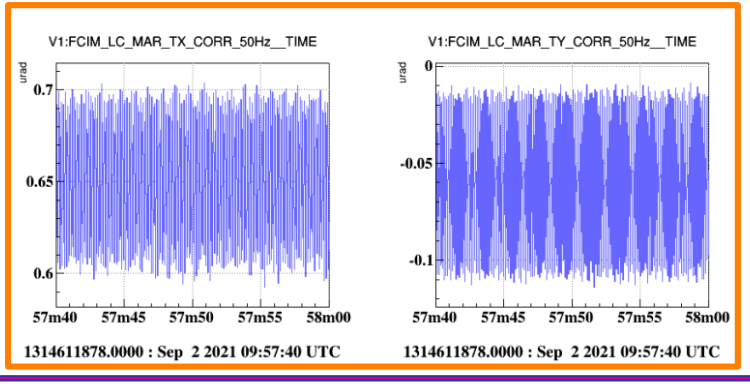
End mirror





Input mirror



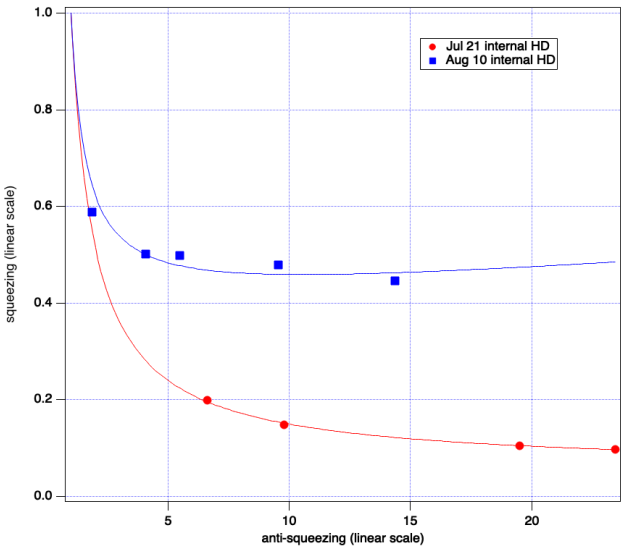


Frequency Independent Squeezing measurement

- Commissioning: Frequency Independent Squeezing (FIS) measurement
  1) on EQB1 and 2) coming back from SQB1

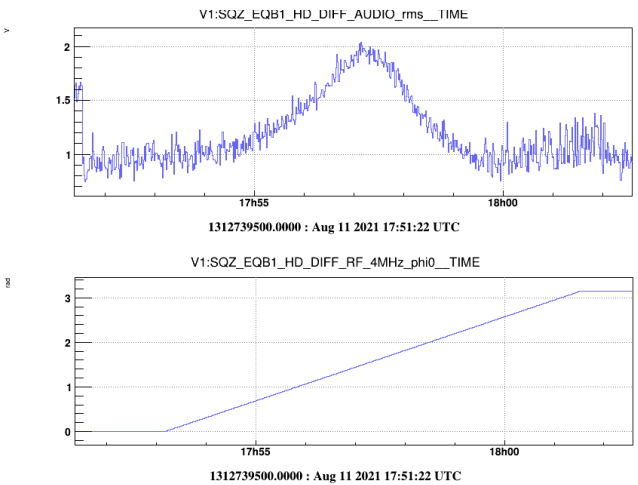
1) SQZ level 3.02 dB at 2.77 rad

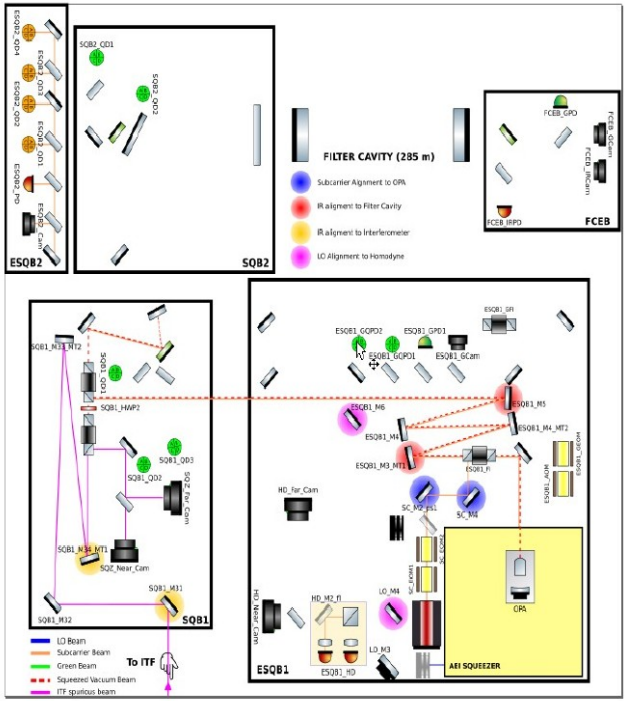
ASQZ level 7.4 dB at 1.41 rad



2) SQZ Level = 1.9 dB at 2.55 rad

ASQZ level = 6.1 dB at 1.5 rad





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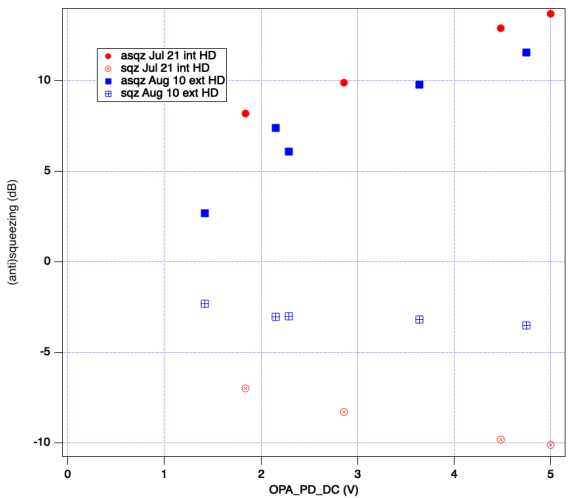

2) SQZ Level = 1.9 dB at 2.55 rad

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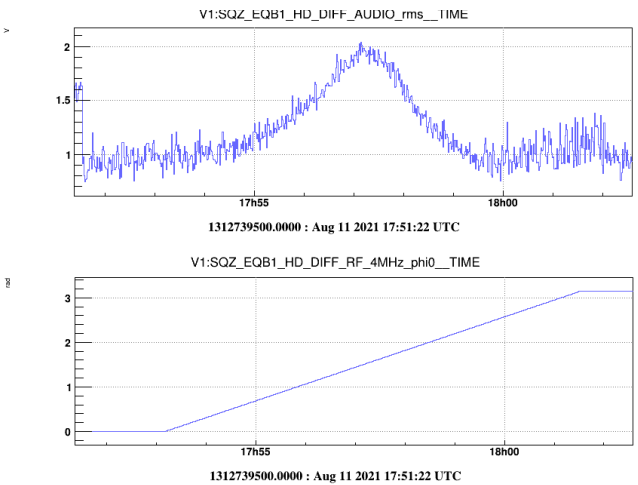
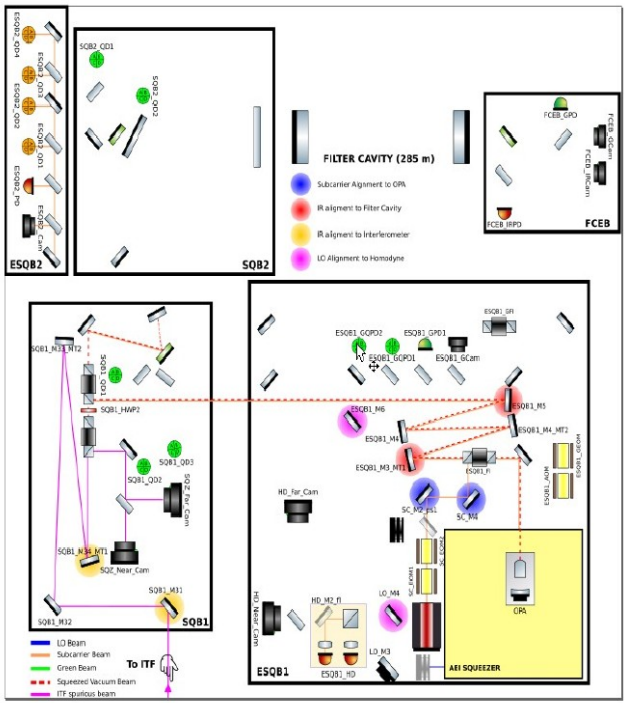
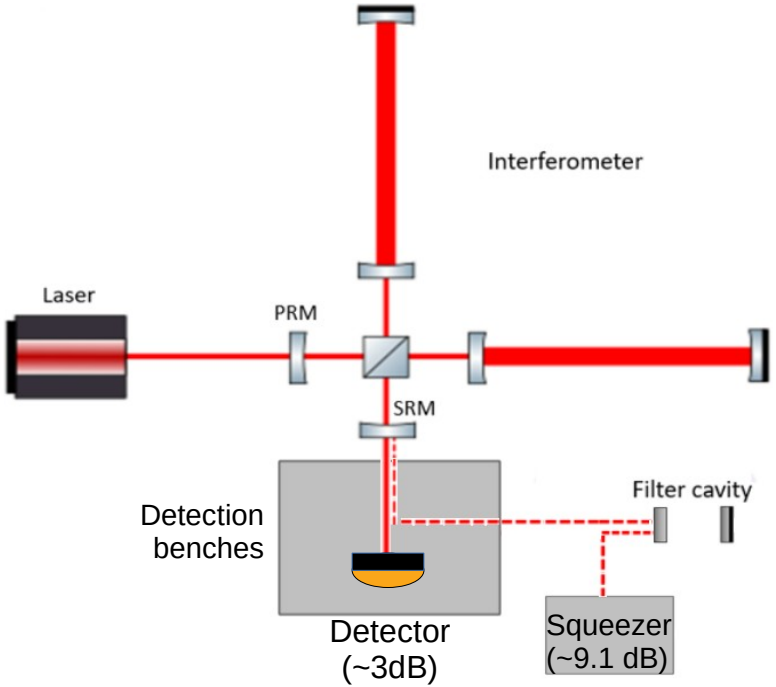
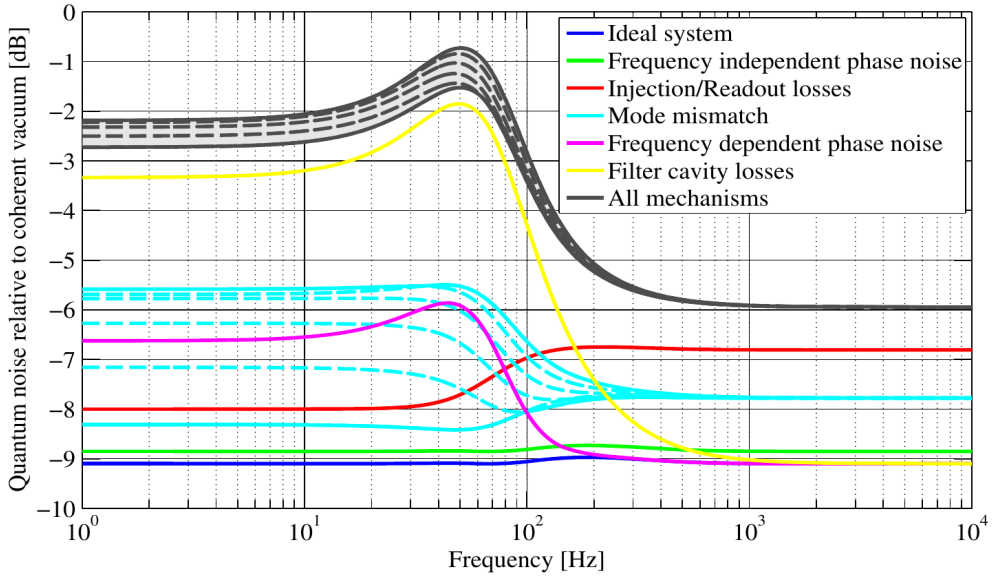




Decoherence and degradation of FDS

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

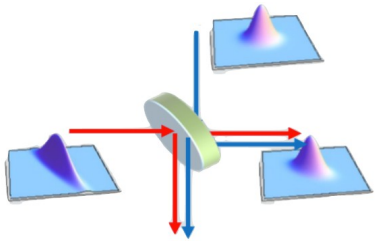


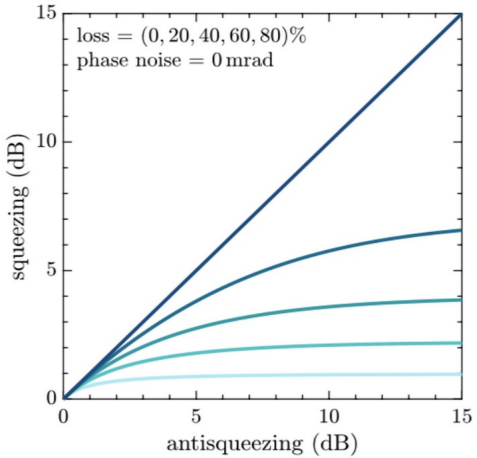


Kwee et al. (2014)

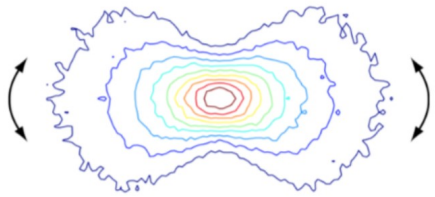
Losses and Phase noise

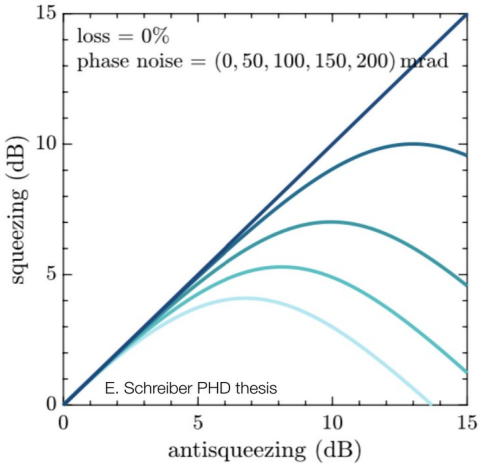
Losses: recombination of the squeezing with the ordinary vacuum





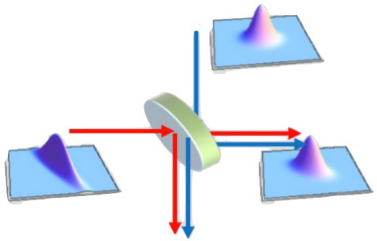
Phase noise: shaking of the squeezing ellipse

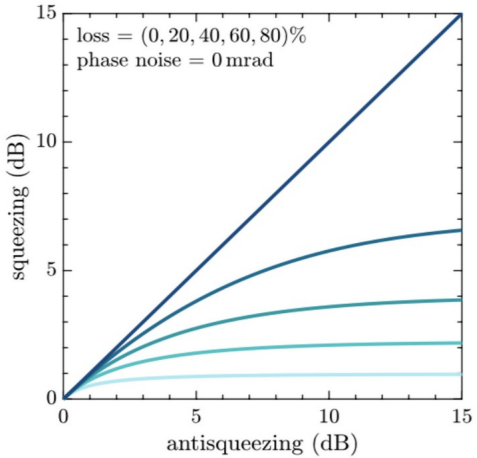




Losses and Phase noise

Losses: recombination of the squeezing with the ordinary vacuum





Phase noise: shaking of the squeezing ellipse