Frequency dependent squeezing experiment at NAOJ: status and future

Y. Zhao, N. Aritomi, E. Capocasa, M. Leonardi, M. Eisenmann, Y. Guo, E. Polini, A. Tomura, K. Arai, Y. Aso, Y. Huang, R.-K. Lee, H. Lueck, O. Miyakawa, P. Prat, A. Shoda, M. Tacca, R. Takahashi, H. Vahlbruch, M. Vardaro, C.-M. Wu, M. Barsuglia, R. Flaminio

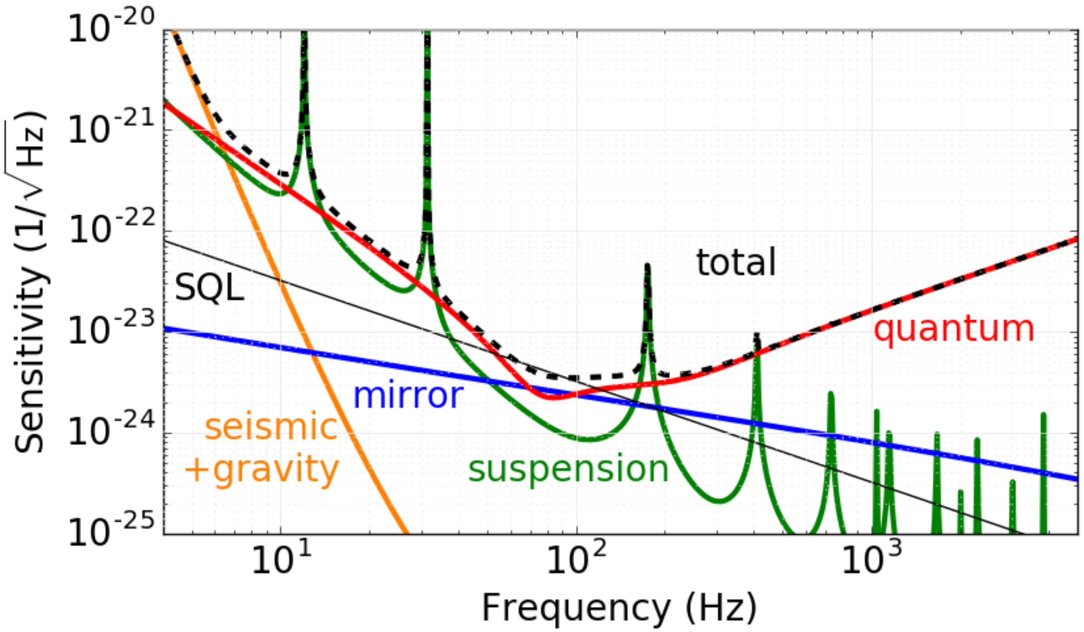
Useful links:

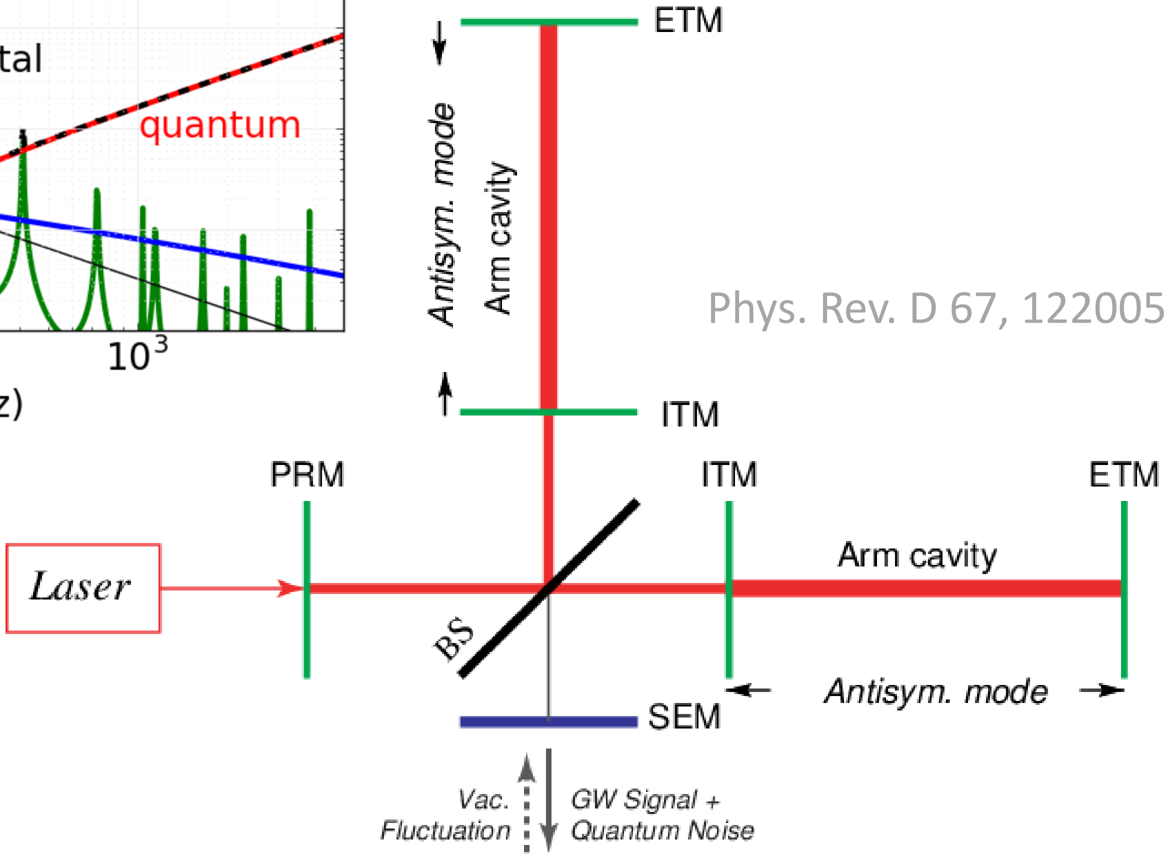
http://www2.nao.ac.jp/~gw-elog/osl/?c=1

https://gwpo.nao.ac.jp/wiki/FilterCavity

TOC

Noises in GW detectors



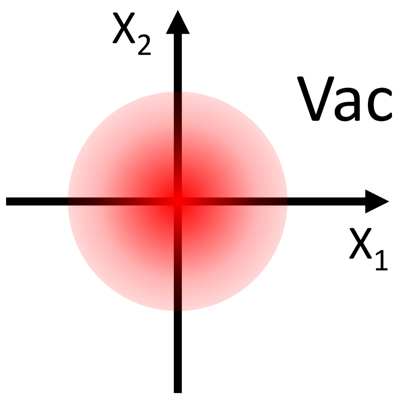


Phys. Rev. D 67, 122005

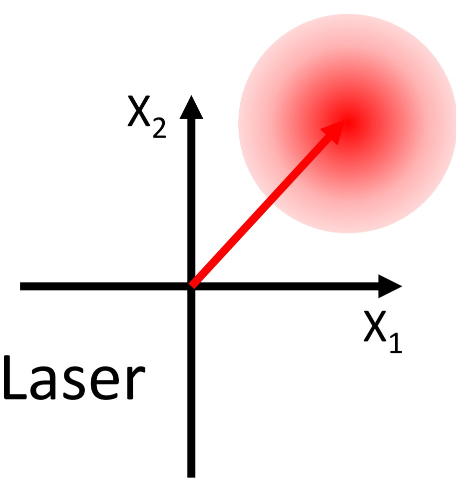
Quantum noise is generated by vacuum fluctuation entering the interferometer anti-symmetric port (output port)

Squeezed state of light

Coherent states:

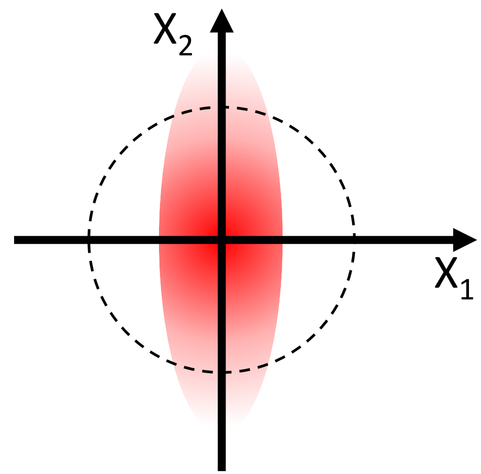


Vacuum



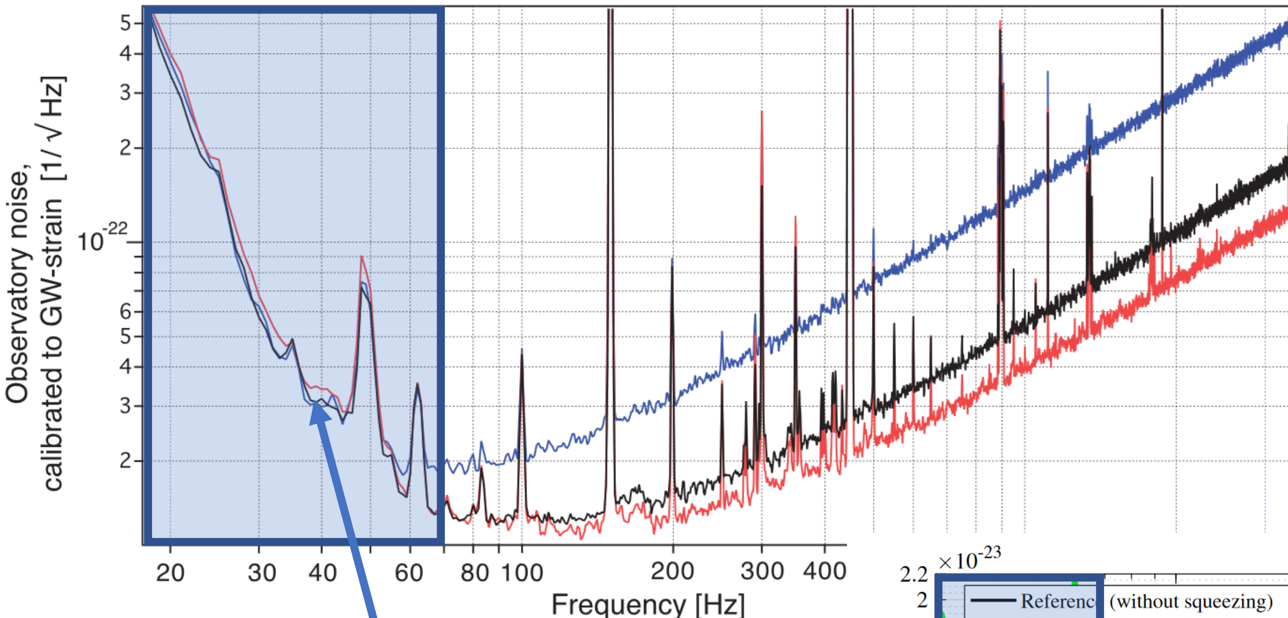
Laser

Squeezed states:



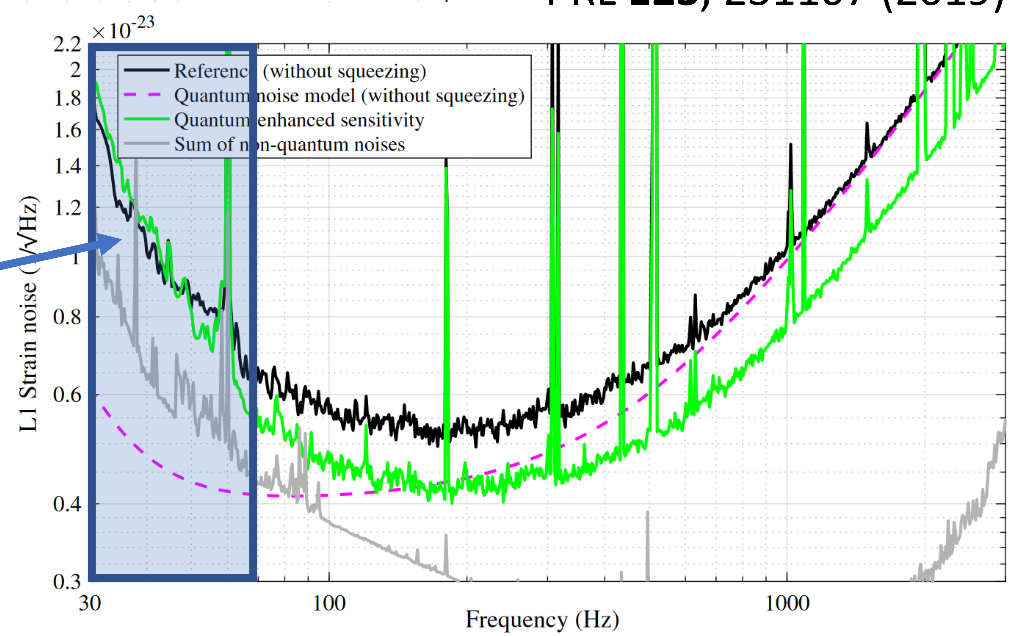
Are realized by taking coherent states and building correlation between quadratures

Squeezing application in O3



PRL **123**, 231108 (2019)

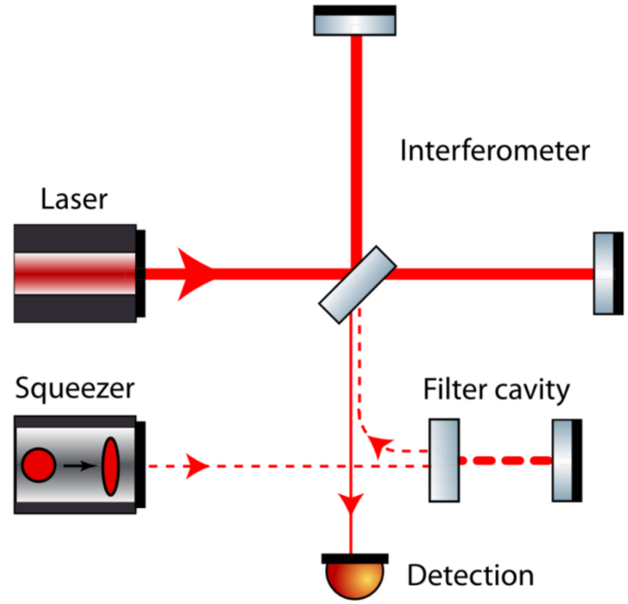
PRL **123**, 231107 (2019)



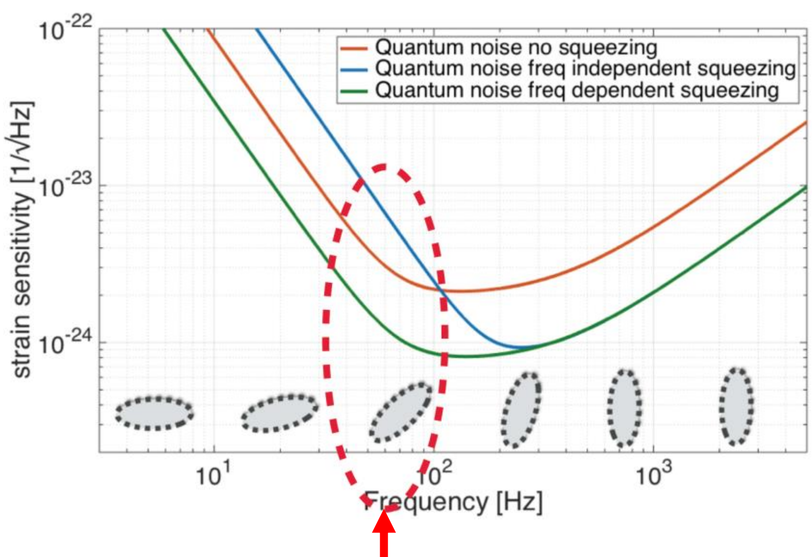
"anti-squeezed" radiation pressure is already limiting the low frequency

Frequency Dependent Squeezing

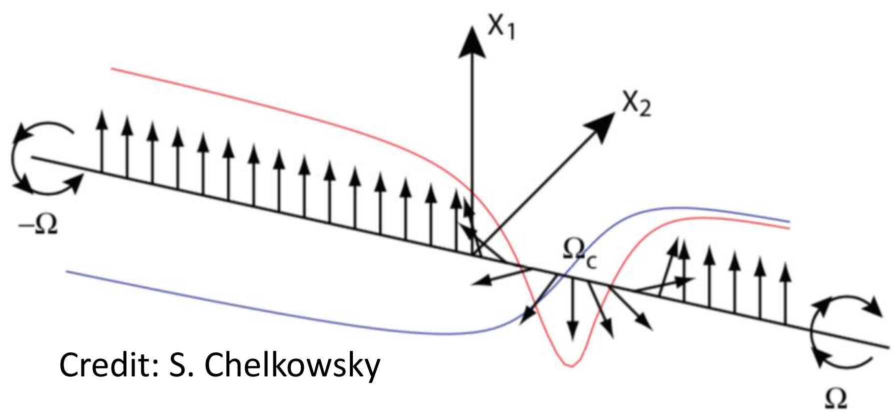
- Reflect frequency independent squeezing off a detuned Fabry-Perot cavity
- Rotation frequency depends on the cavity optical properties



PRD 88, 022002 (2013)



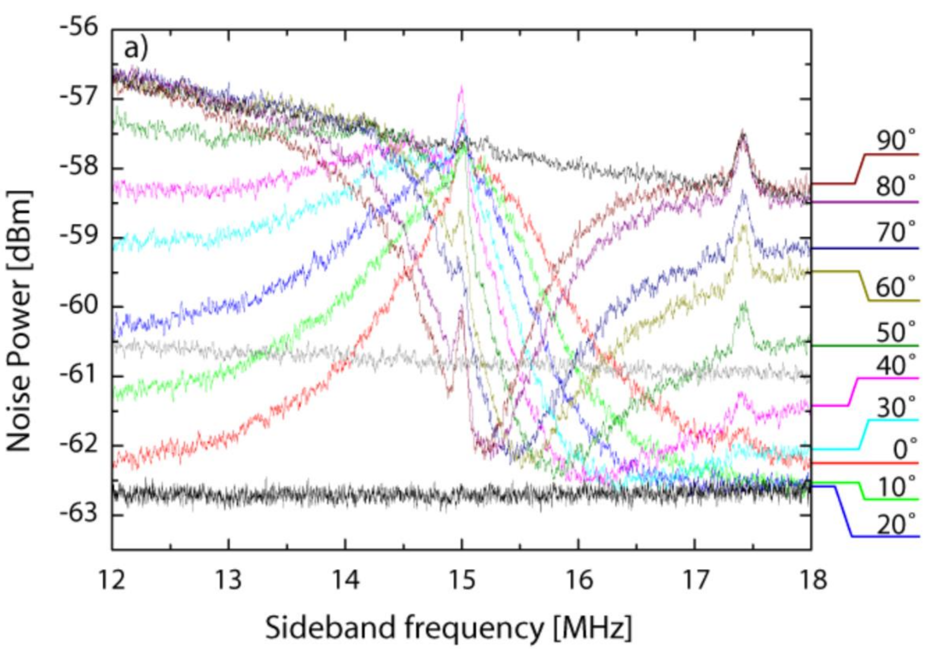
Optimal rotation frequency between 40 and 75 Hz



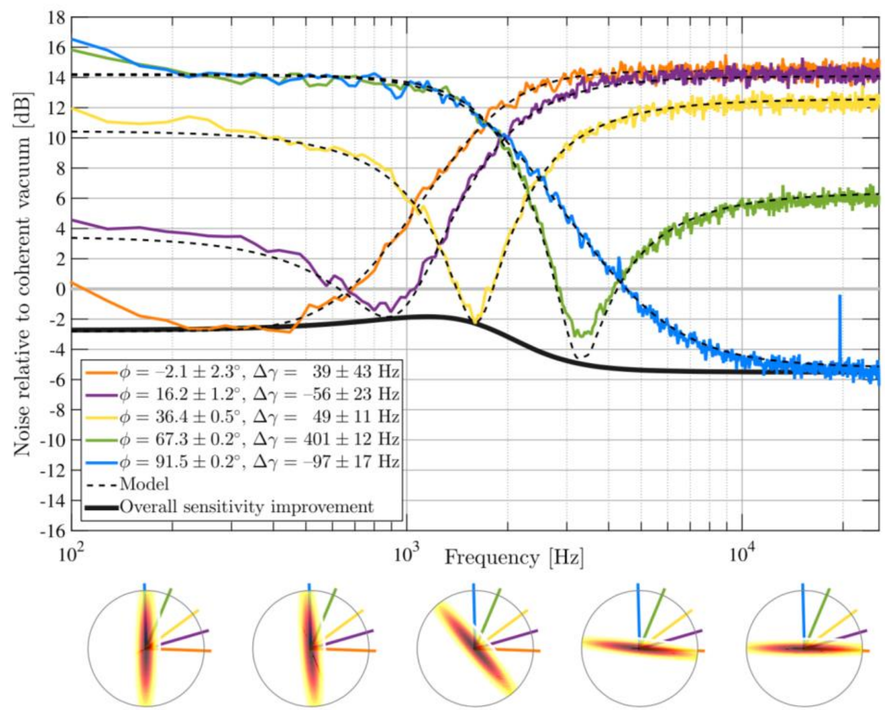
Credit: S. Chelkowsky

FDS experimental results

- Already demonstrated at MHz and kHz squeezing rotation frequency



S. Chelkowsiki et al, PRA 71, 013806 (2005)



E. Oelker et al, PRL 116, 041102 (2016)

TAMA Filter Cavity project overview

GOAL: achieve frequency dependent squeezing (squeeze angle rotation around 75 Hz – FC detuning of approx. 54Hz) by reflecting 9dB of frequency independent squeezing off a 300m long filter cavity

Project milestones:

- **April 2015**: project begins
- **Spring 2016**: FC design
- **June 2017**: first FC lock
- **Spring 2018**: FC RTL measurement
- **January 2019**: first FIS measurement (200kHz)
- **October 2019**: FDS with large FC detuning (50kHz)
- **January 2020**: first FDS with sub-100Hz detuning
- **Spring 2020**: analysis of new FC locking scheme
- **Autumn 2020**: implementation of new locking

See Aritomi-san's presentation

Supported by JSPS (15H02095 and 18H01235) and by NAOJ

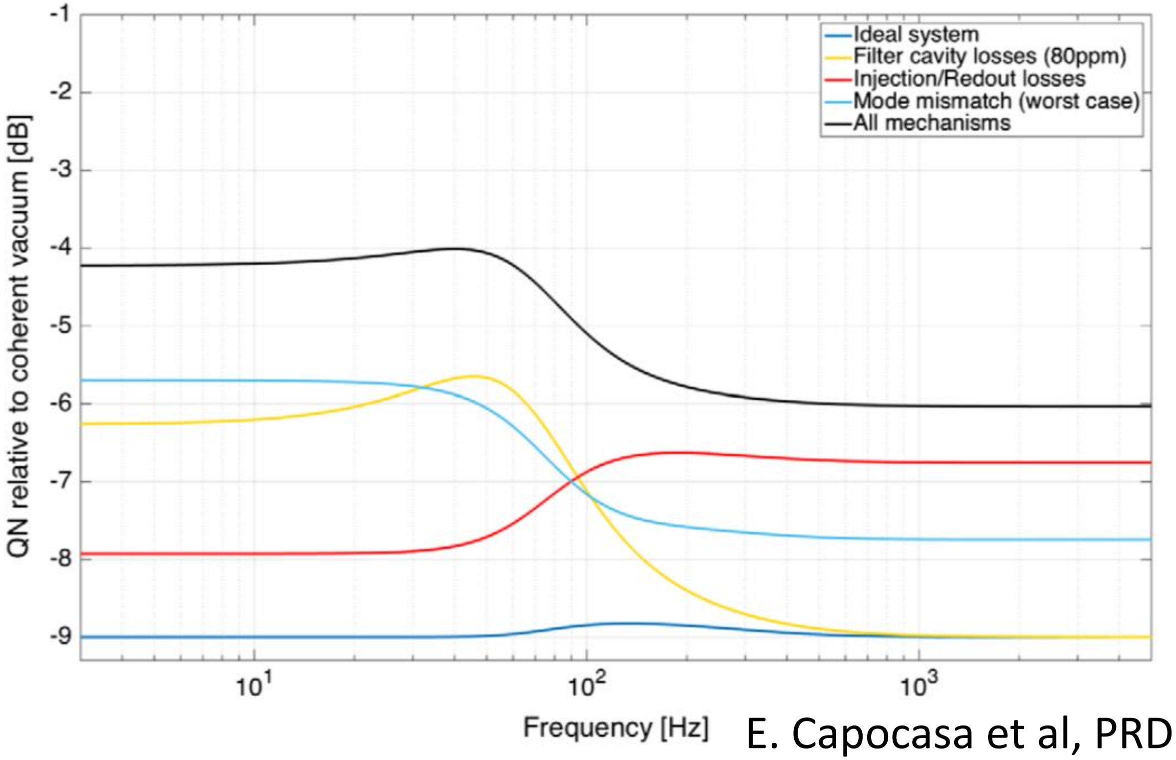
FDS degradation budget (design)

Low frequency:

- FC round trip losses
- Mode mismatch

High frequency:

- Inj./readout losses



E. Capocasa et al, PRD 93, 082004 (2016)

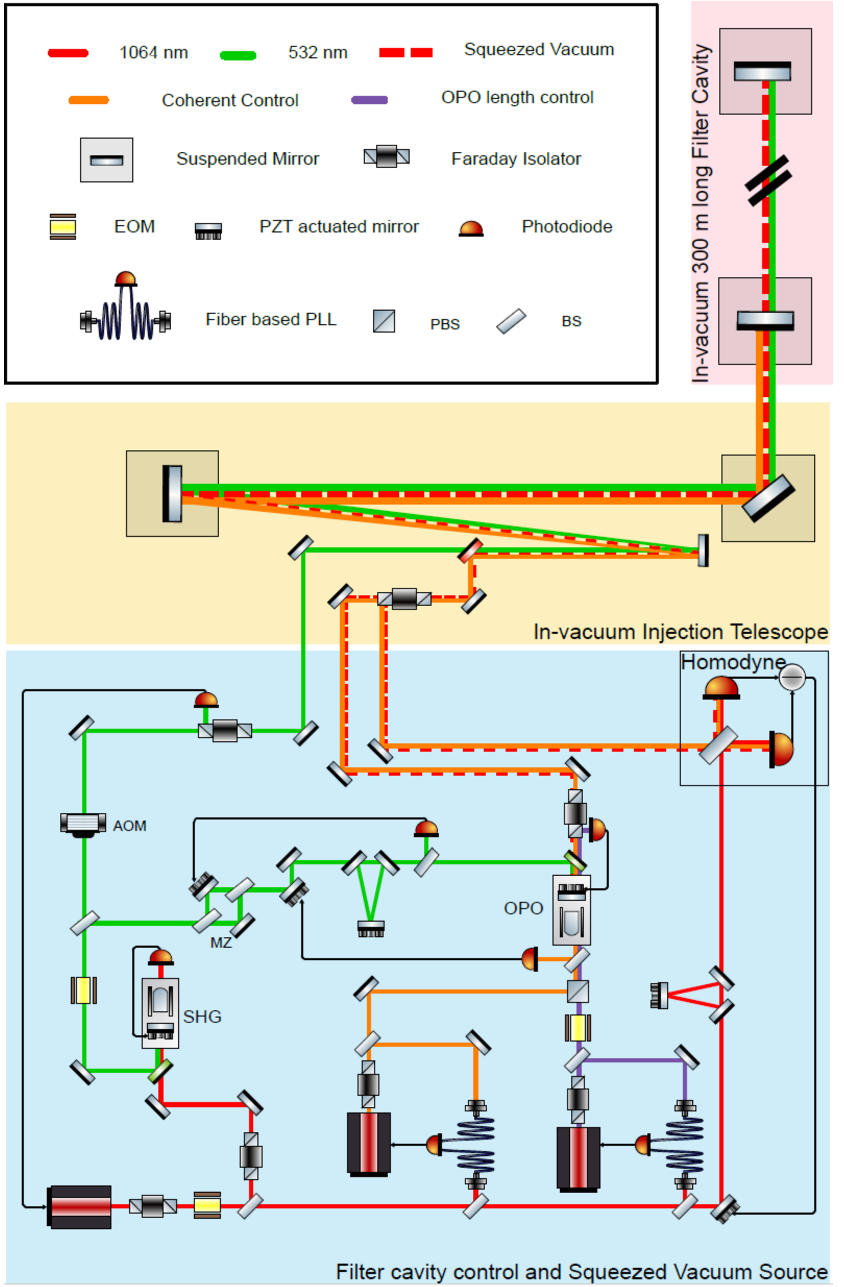
Experimental setup

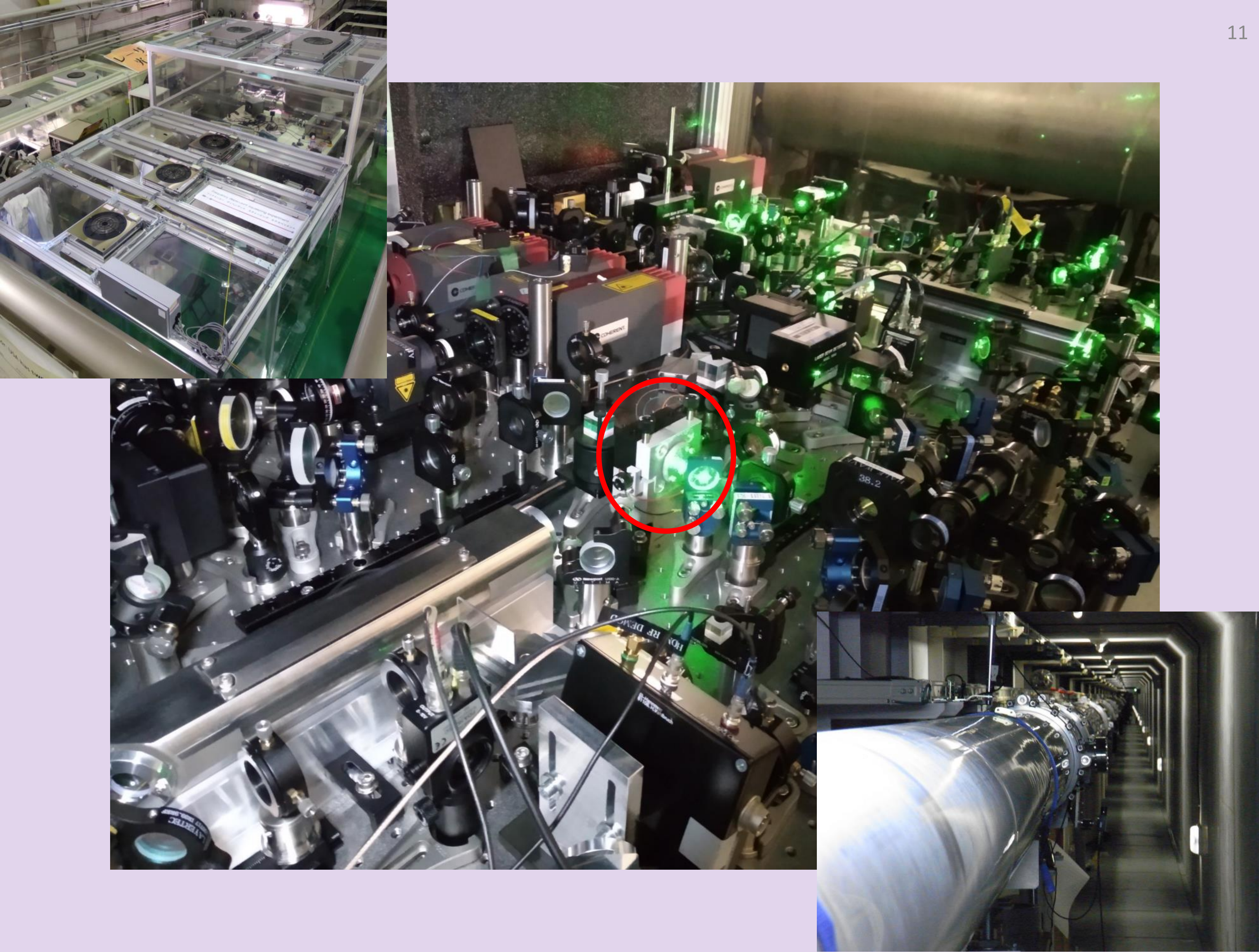
300m long cavity (TAMA South arm):

- Finesse = 4400 (4425) @1064nm
- RTL = 80ppm (60-90ppm)
  - Initial Virgo class mirror
  - TAMA suspension (double pendulum)

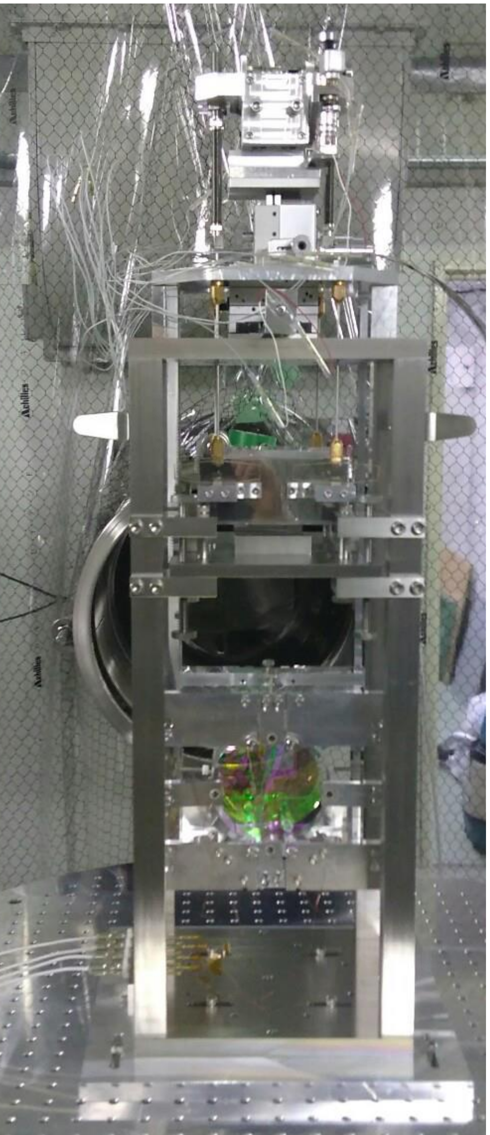
FIS source:

- 9dB (6dB) above 10Hz
- Based on AEI design (GEO600 squeezer)



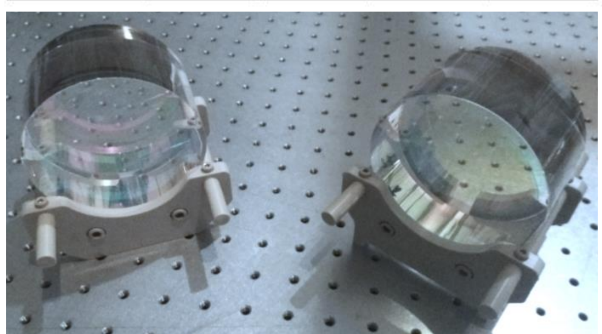


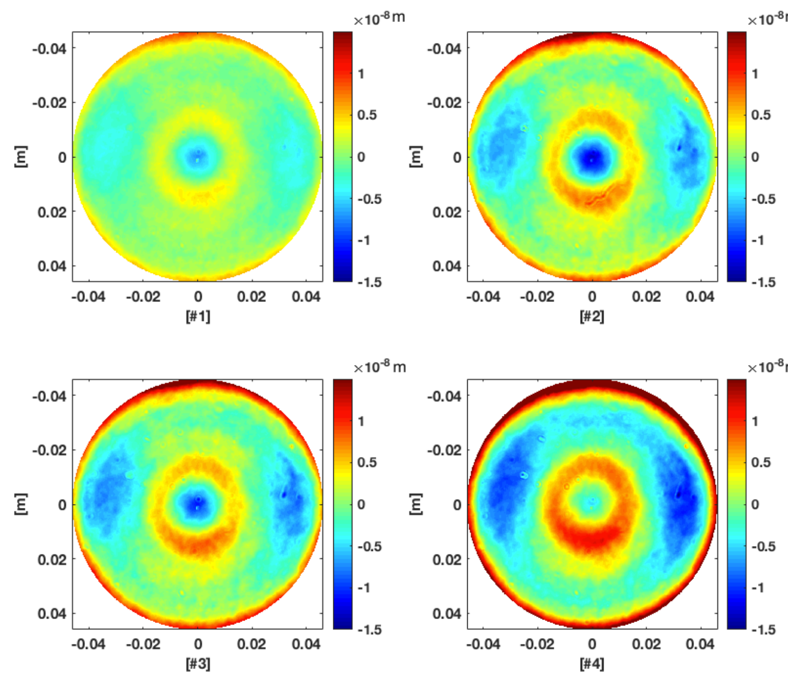
Cavity mirrors and suspensions



- TAMA vibration isolation stack and double pendulum suspension
- TAMA size mirrors: Ø = 10cm, t = 6cm
  - Beam radius: ~1cm

	diameter 0.05 m		diameter 0.02 m	
Mirror	RMS (nm)	PV (nm)	RMS (nm)	PV (nm)
#1	1.96	11.5	0.52	3.28
#2	2.09	12.2	0.52	3.28
#3	1.5	8.3	0.48	3.36
#4	1.94	14.8	0.48	3.28

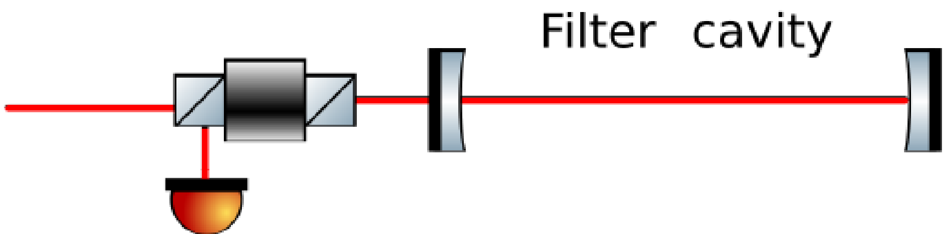




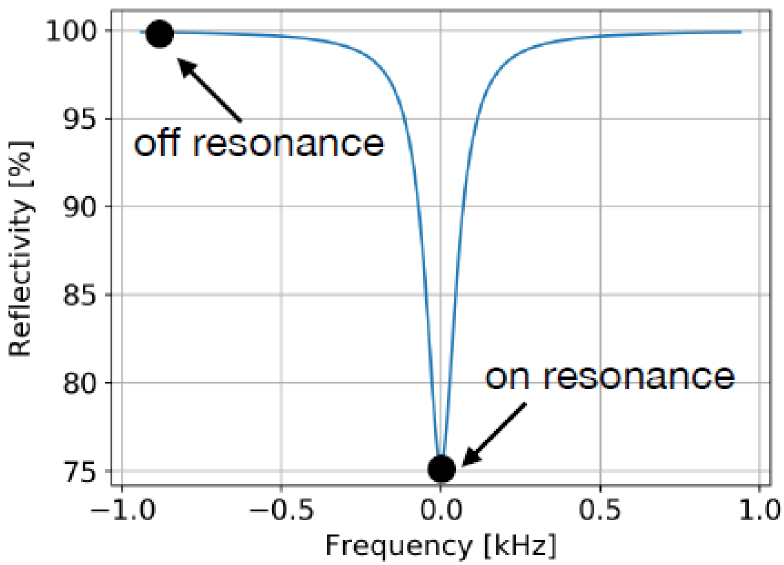
E. Capocasa et al, PRD 93, 082004 (2016)

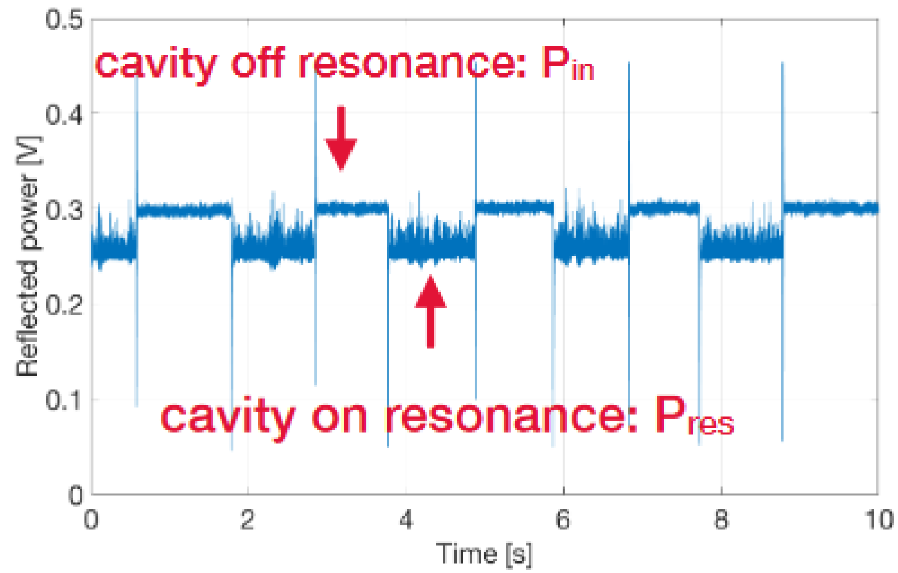
RTL characterization method

Set of on/off resonances switches to measure the cavity reflectivity.



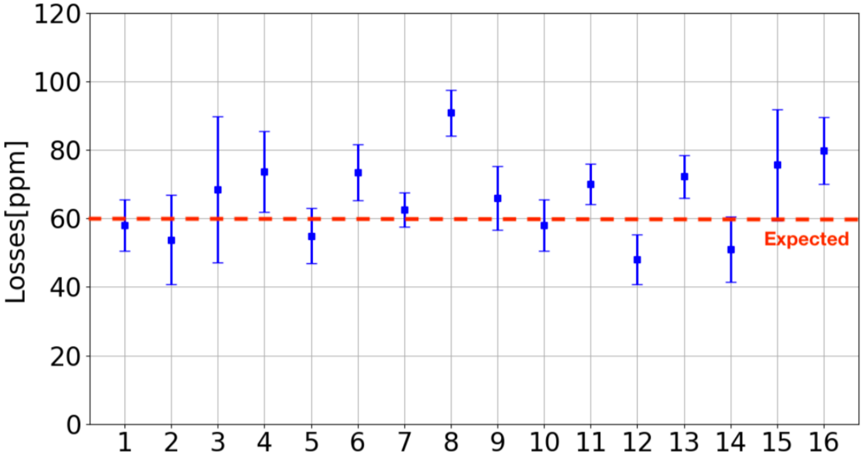
$$L \sim \frac{T_1}{2} \frac{1 - P_{\mathrm{res}}/P_{\mathrm{in}}}{1 + P_{\mathrm{res}}/P_{\mathrm{in}}}$$



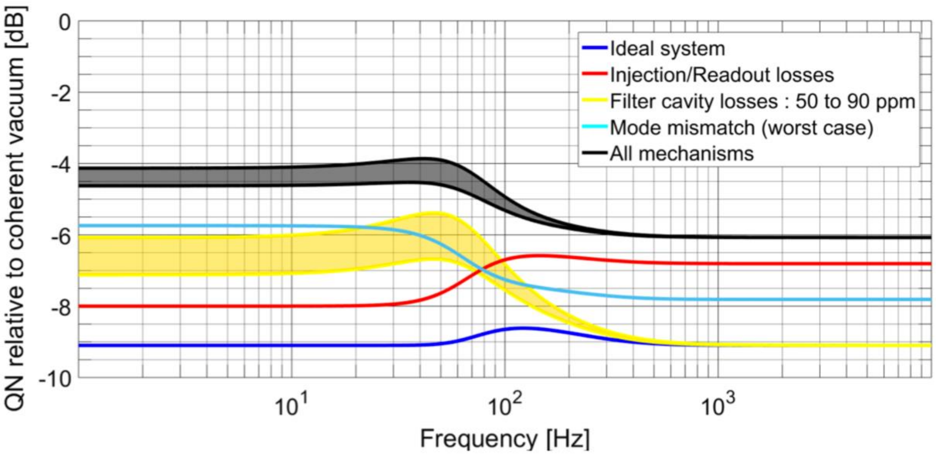


RTL characterization

Set of on/off resonances switches to measure the cavity reflectivity.



E. Capocasa et al, PRD 98, 022010 (2018)

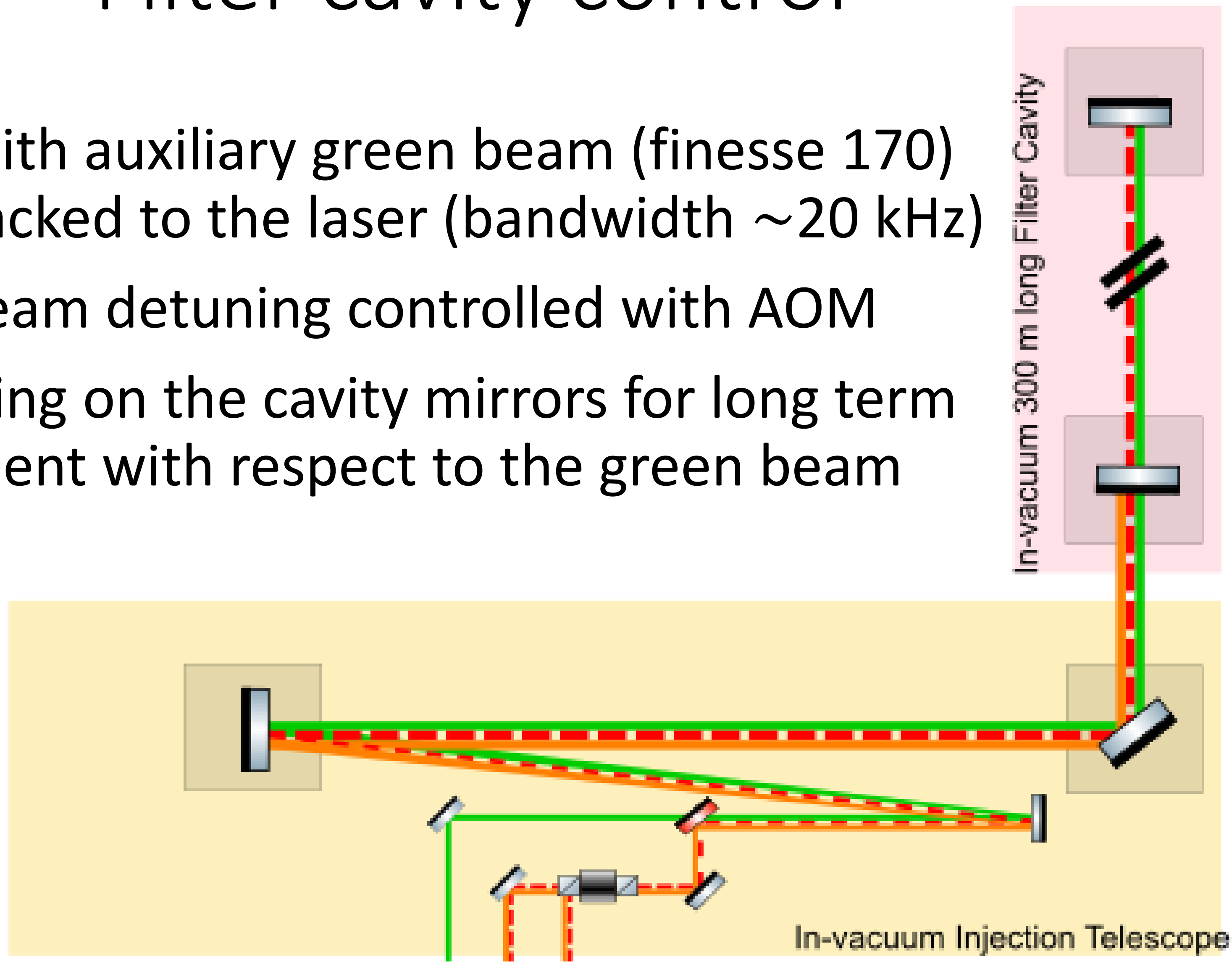


Measured RTL = 50-90ppm

Measured finesse = 4425

Filter cavity control

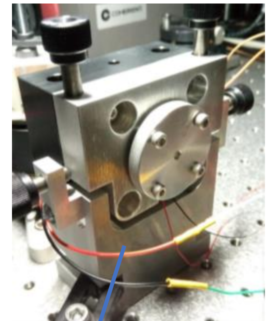
- PDH with auxiliary green beam (finesse 170) feedbacked to the laser (bandwidth ~20 kHz)
- SQZ beam detuning controlled with AOM
- Dithering on the cavity mirrors for long term alignment with respect to the green beam



In-air bench (FIS source)

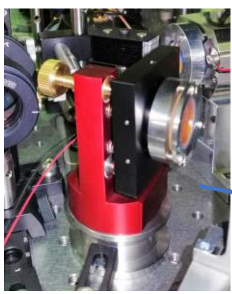
Mach-Zehnder

Green Mode Cleaner

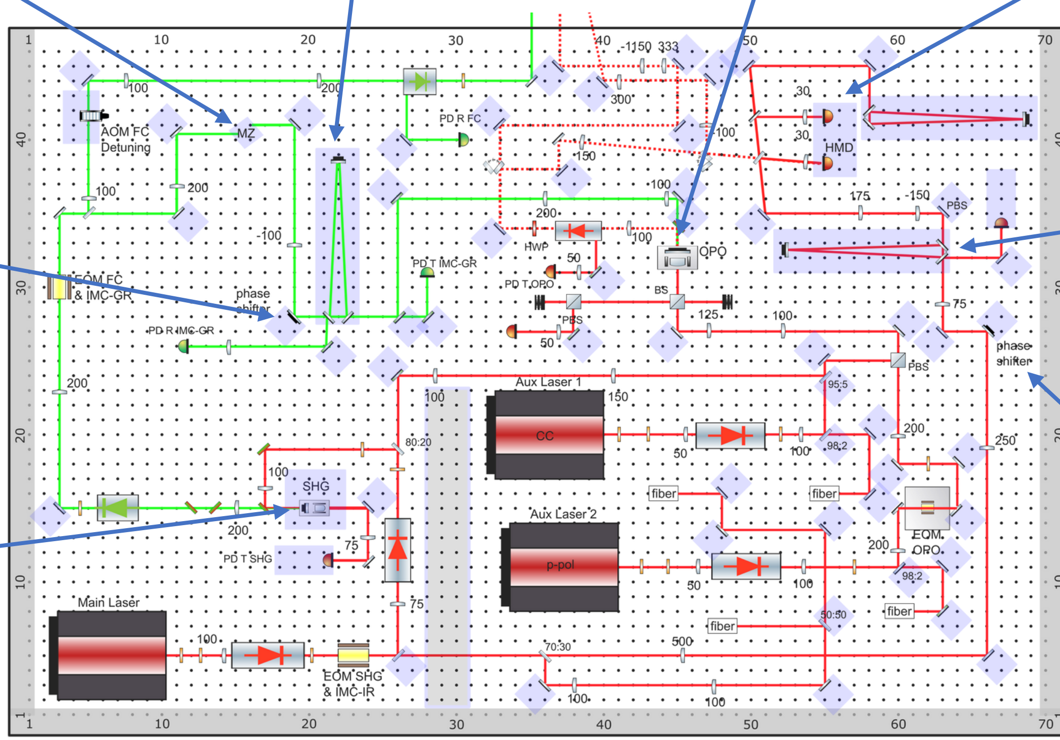


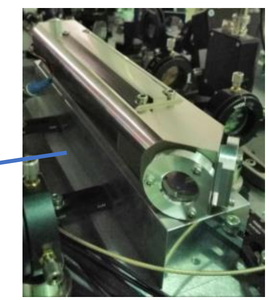
Optical Parametric Oscillator

Balanced Homodyne Detector

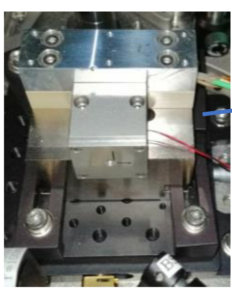


Green Phase Shifter

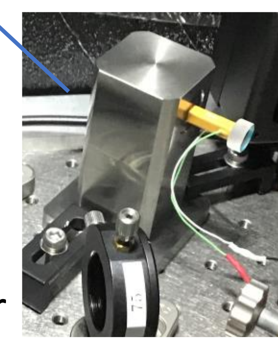




IR Mode Cleaner



Second Harmonic Generator



IR Phase Shifter

FIS source control

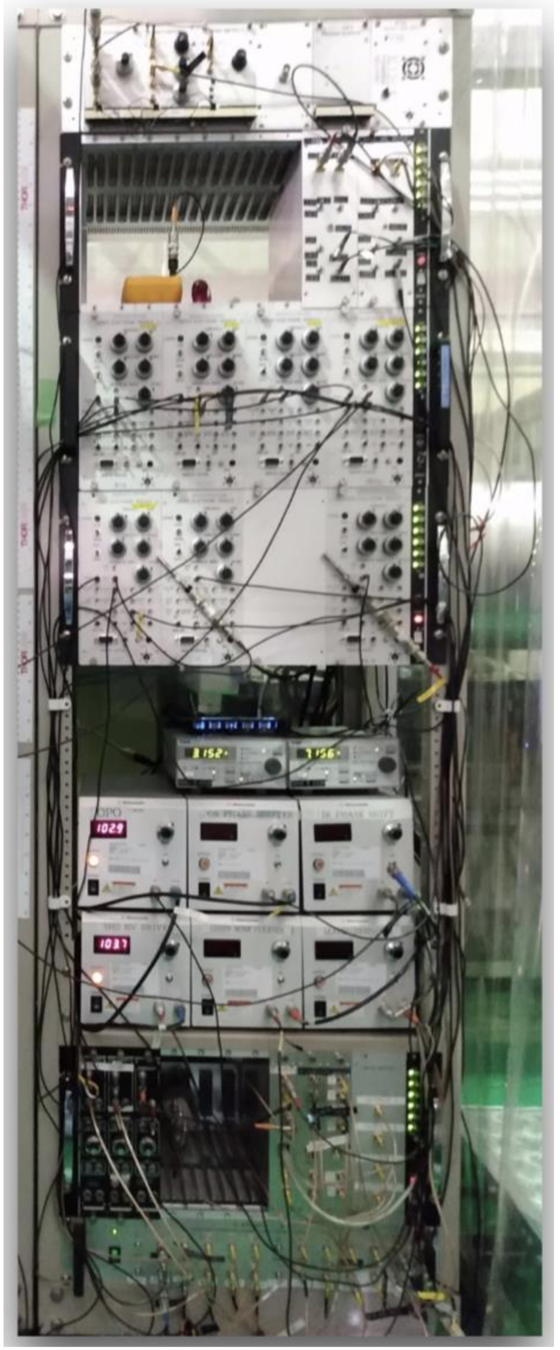
The FIS source needs several control loops:

- 4 PDH (SHG, OPO, GRMC, IRMC)
- 1 DC control (MZ)
- 2 temperature control (SHG, OPO)
- 2 PLL (AUX1 and AUX2 to ML)
- 2 coherent control

And several other electronics:

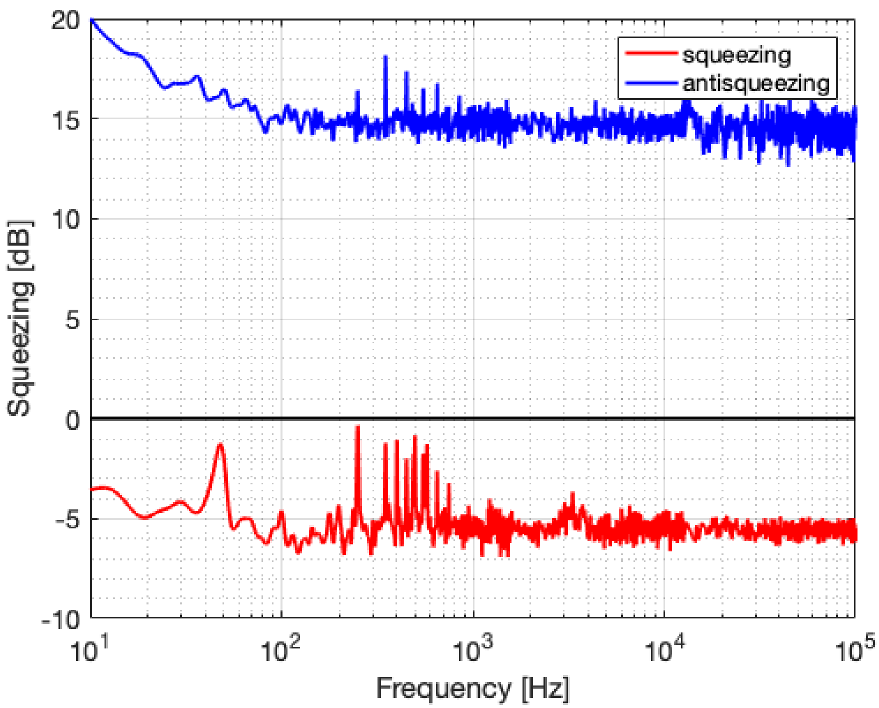
- DDS (12 RF channels)
- Homodyne
- …

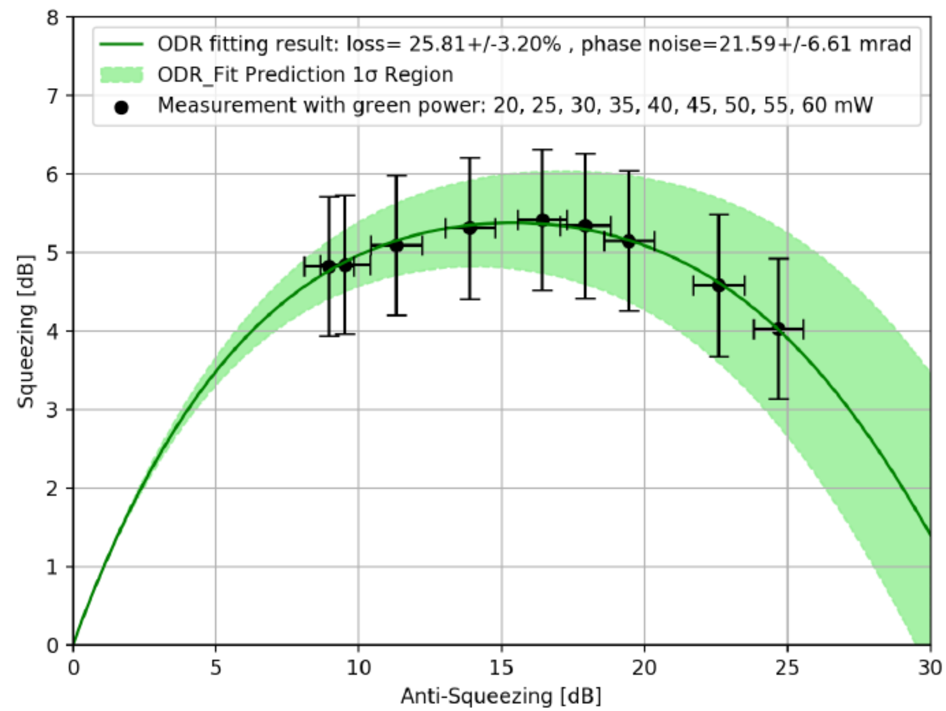
Most of it is custom and it has been developed in collaboration with APC, AEI and UniPd/INFN PD groups



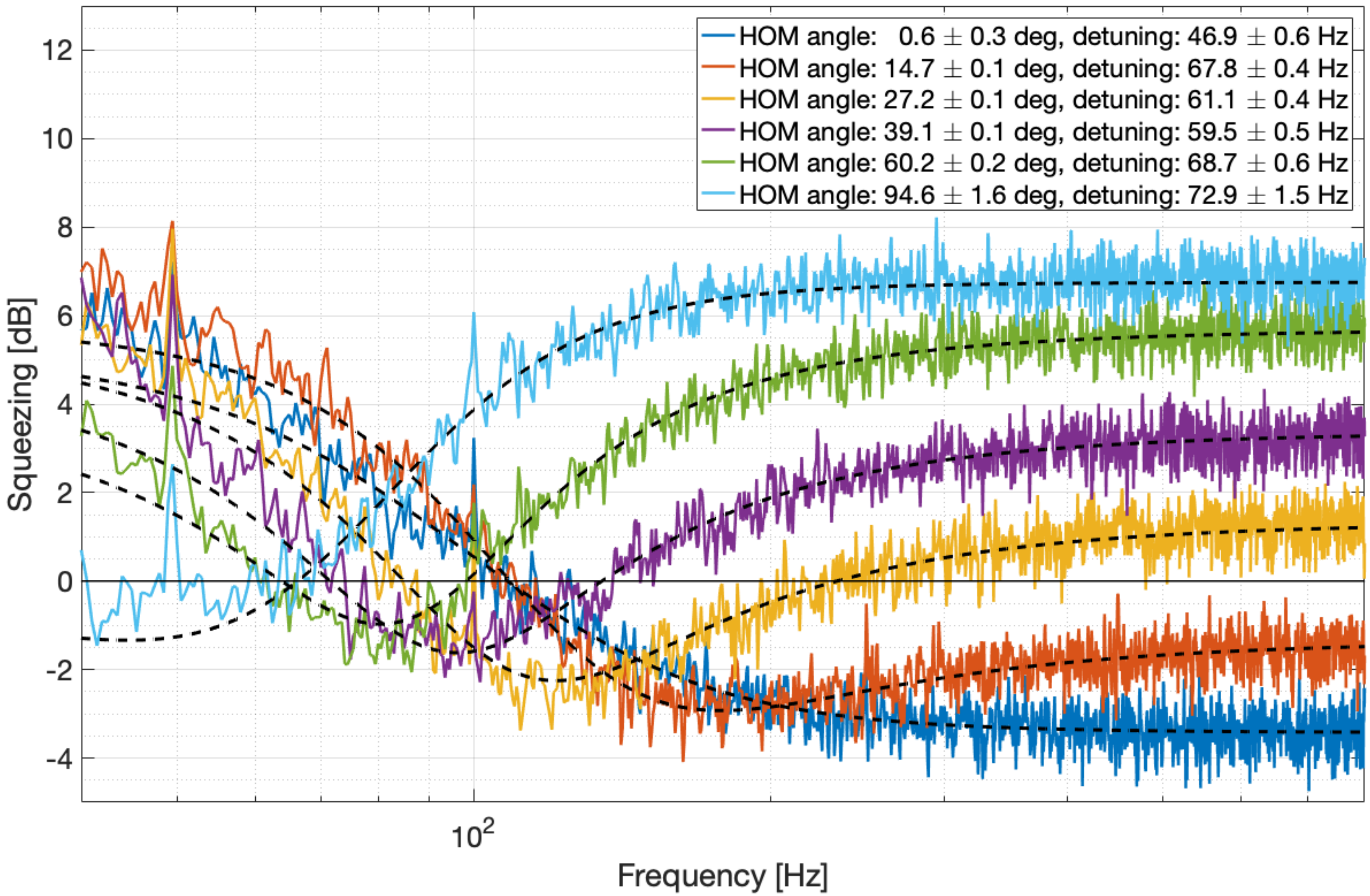
FIS performances

- ~6dB of squeezing and ~14dB of anti-squeezing
- Losses and phase noise characterized
  - OPO escape efficiency (~92%) and CC loops main limitations





Frequency dependent squeezing measurement



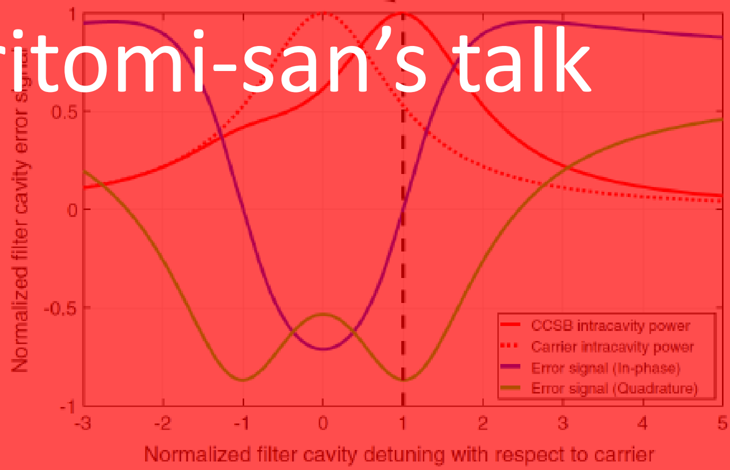
Y. Zhao, *et al.*, A frequency-dependent squeezed vacuum source for broadband quantum noise reduction in advanced gravitational-wave detectors, [Phys. Rev. Lett. 124, 171101 (2020)]

FC length control with coherent control sidebands

- Novel technique to lock the FC length degree of freedom with minimal hardware modification

$$\Omega_{cc} = n \times \omega_{FSR} + \Delta\omega_{fc,0}$$

Optimal detuning



For more see Aritomi-san's talk

N. Aritomi et al, PRD 102, 042003 (2020)

What’s next?

Achieved:

- First Frequency Independent Squeezing at audio-frequencies within KAGRA collaboration
- First Frequency Dependent Squeezing sub 100Hz in the world

To do (in TAMA):

- Implement Automatic Alignment system (ongoing)
- Test alternative Filter Cavity locking schemes (ongoing)
- Analyze and reduce squeezing degradation sources

To do (in KAGRA):

- Design the Frequency Dependent Squeezed vacuum source for KAGRA

Pre-corona visitors and collaborators


Emil Schreiber
GEO600/AEI


Shu-Rong Wu
Tsing Hua University


Marco Vardaro
Padova University


Matteo Barsuglia
APC/CNRS


Eleonora Polini
La Sapienza Roma


Matteo Tacca
Nikhef


Federico Paoletti
INFN-Pisa


Marc Eisenmann
LAPP/CNRS


Yuefan Guo
Nikhef


Chien-Ming Wu
Tsing Hua University


Pierre Prat
APC/CNRS


Marco Banzan
Padova University


Irene Fiori
EGO

Come to visit us!

As soon as the pandemic is gone…

Published results

- Estimation of losses in a 300 m filter cavity and quantum noise reduction in the KAGRA gravitational-wave detector Phys. Rev. D 93, 082004 (2016)
- Measurement of optical losses in a high-finesse 300 m filter cavity for broadband quantum noise reduction in gravitational-wave detectors Phys. Rev. D 98, 022010 (2018)
- Frequency-Dependent Squeezed Vacuum Source for Broadband Quantum Noise Reduction in Advanced Gravitational-Wave Detectors Phys. Rev. Lett. 124, 171101 (2020)
- Control of a filter cavity with coherent control sidebands Phys. Rev. D 102, 042003 (2020)
- Demonstration of sub-Hz precision filter cavity length control with coherent control sidebands (tentative title) – paper in preparation