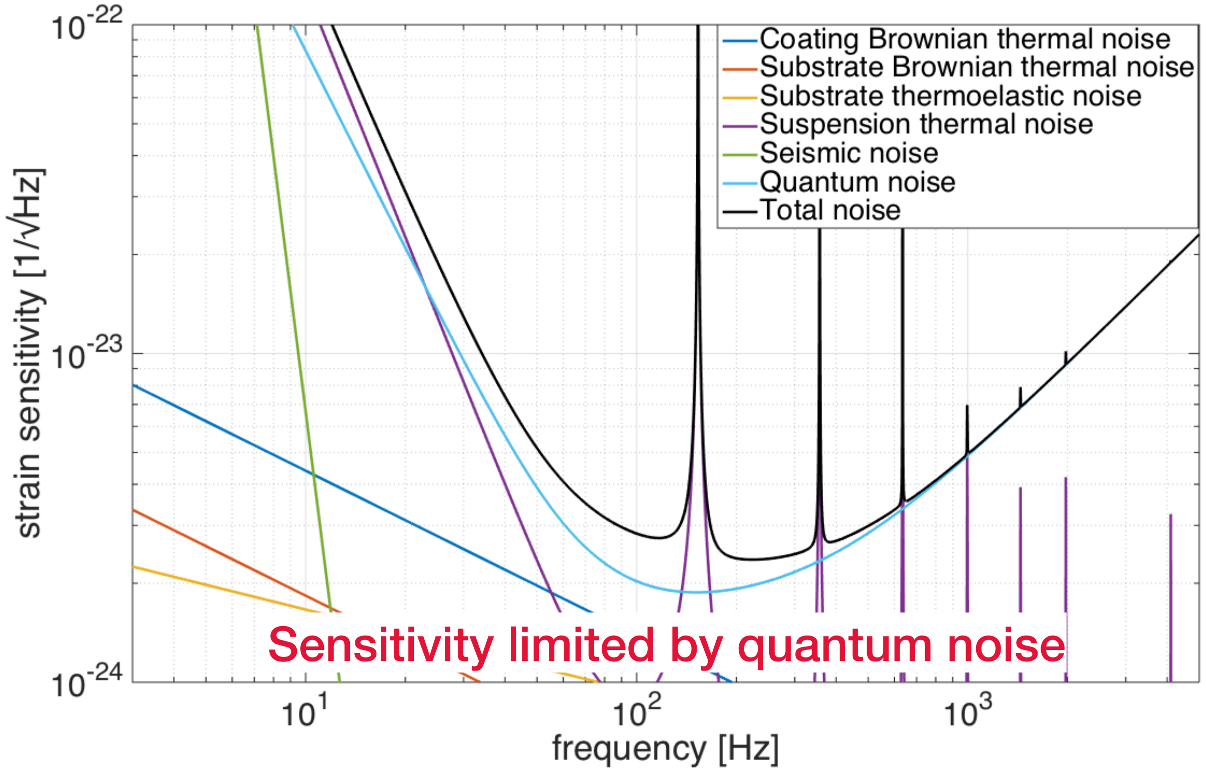
Status of the frequency dependent squeezing experiment at TAMA

K. Arai, Y. Aso, M. Barsuglia, E. Capocasa, M. Eisenmann, R. Flaminio, Y. Guo,
M. Leonardi, M. Marchiò, L. Pinard, P. Prat, R. Schnabel, E. Schreiber,
K. Somiya, M. Tacca, R. Takahashi, D. Tatsumi, A. Tomura, M.Vardaro, Y. Zhao

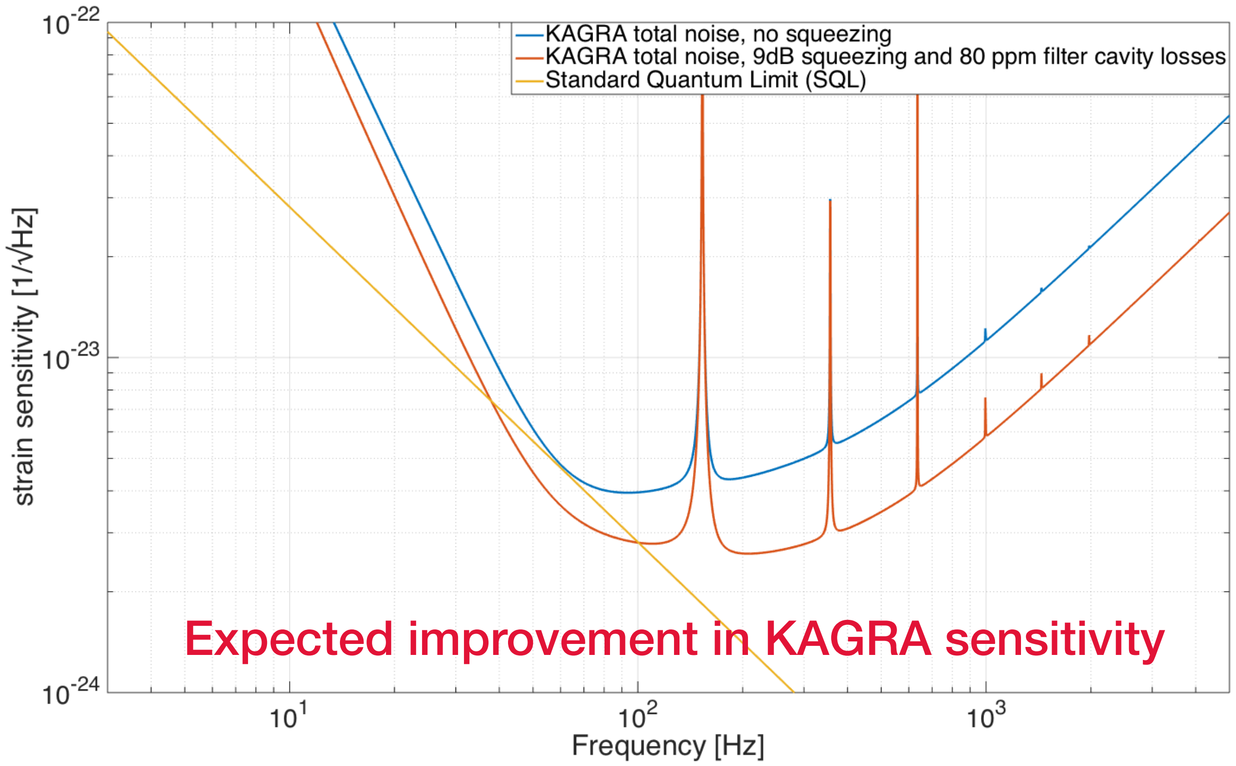
KAGRA F2F meeting, Toyama University, 24-26 August 2018

Motivation

- Broadband quantum noise reduction



Sensitivity limited by quantum noise



Expected improvement in KAGRA sensitivity

PHYSICAL REVIEW D **93**, 082004 (2016)

Estimation of losses in a 300 m filter cavity and quantum noise reduction in the KAGRA gravitational-wave detector

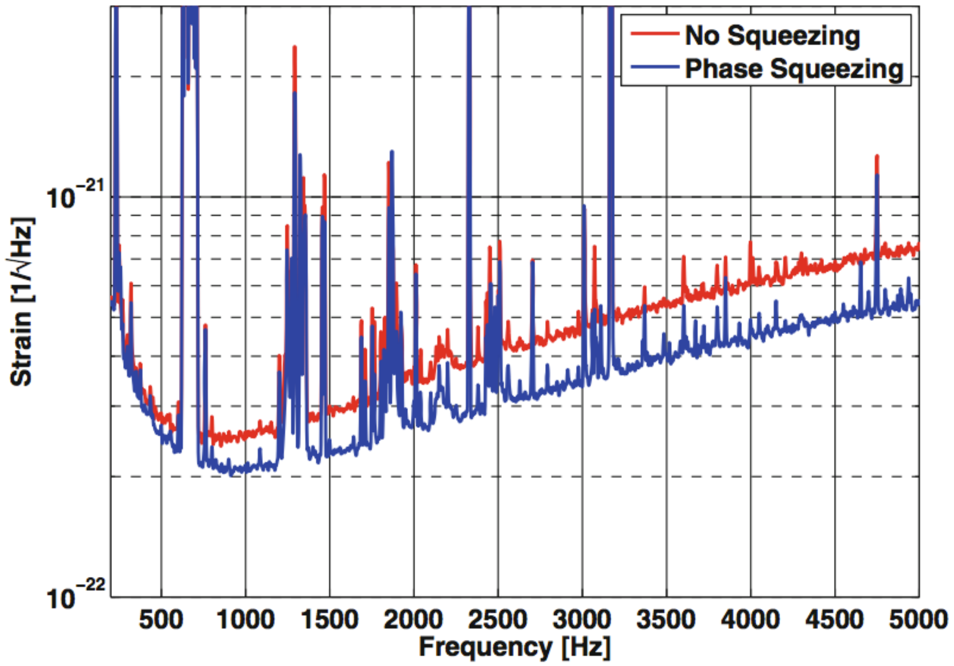
300 m filter cavity planned for ALigo and AdVirgo in O4

Frequency (in)dependent squeezing effect

Frequency independent squeezing:

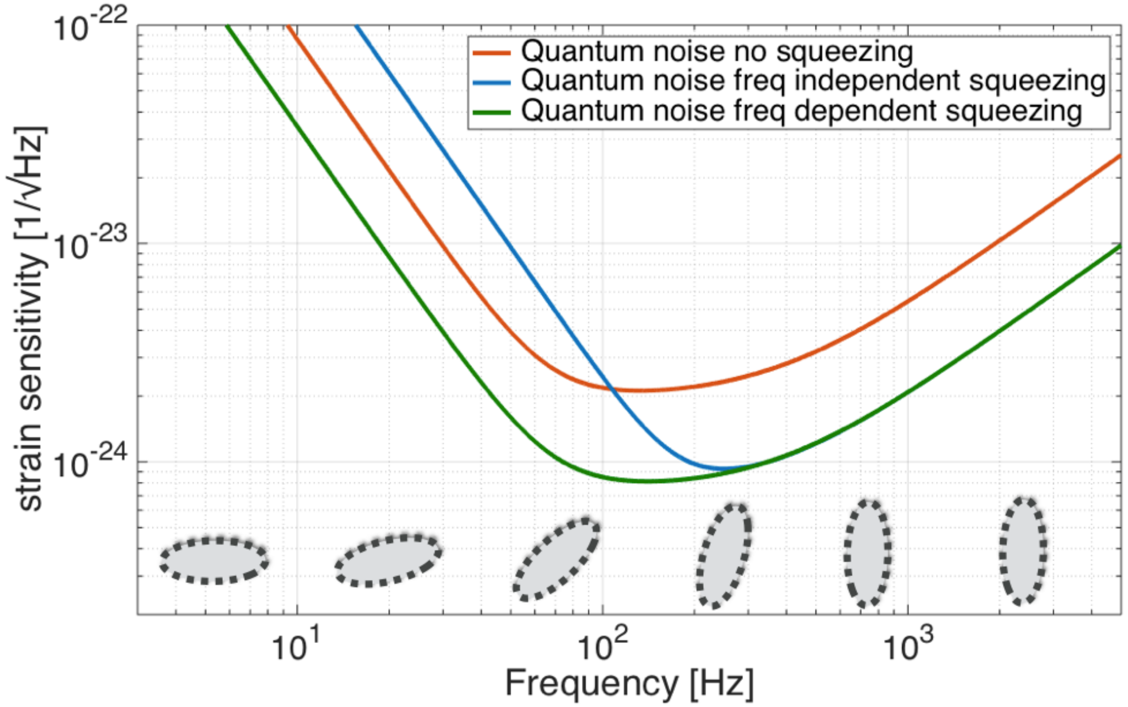
- Already successfully tested in GEO and LIGO
- Installed in LIGO and Virgo for O3
- Improvements at high frequency only

Phys. Rev. Lett. 110, 181101 (2013)



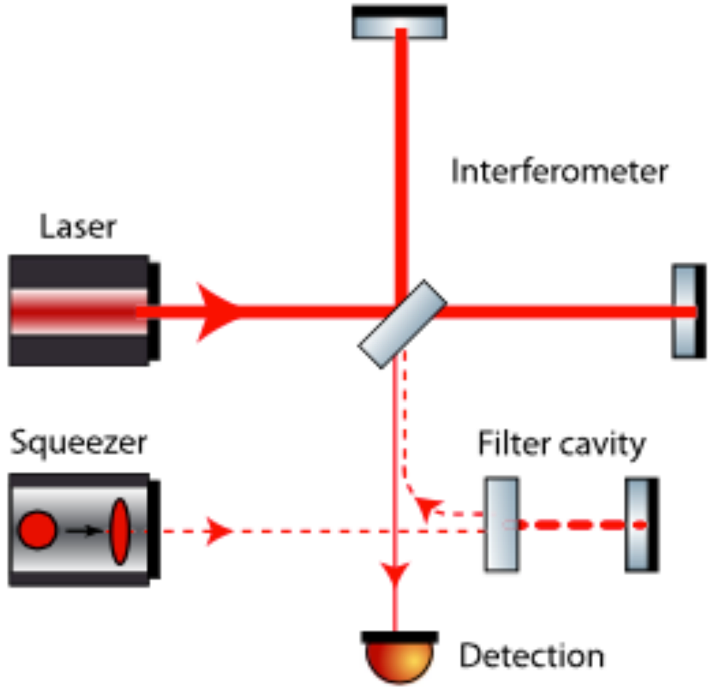
Frequency dependent squeezing:

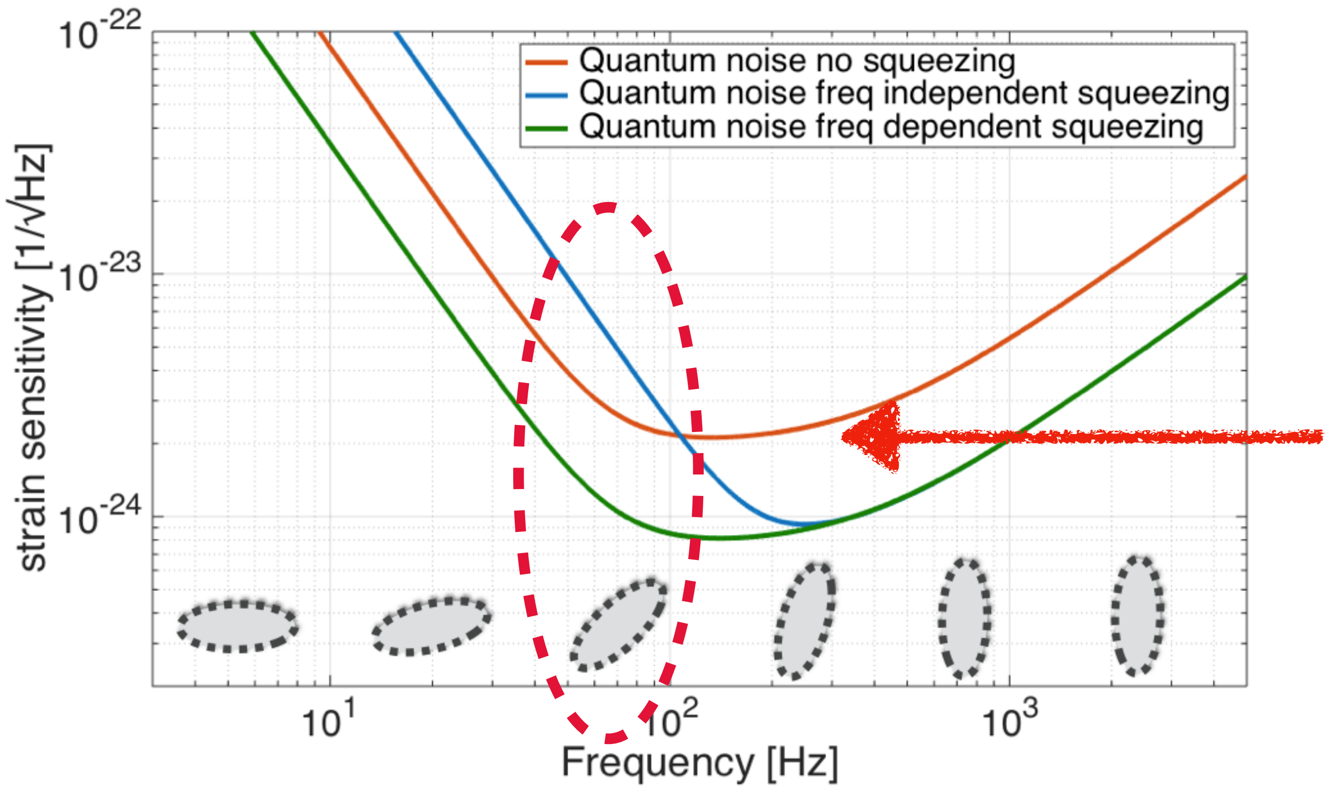
- Counteract IFO squeezing rotation
- Planned for O4 in LIGO and Virgo
- Broadband quantum noise reduction



How to produce frequency dependent squeezing?

- Reflect frequency independent squeezing off a detuned Fabry-Perot cavity
- Rotation frequency depends on the cavity line-width

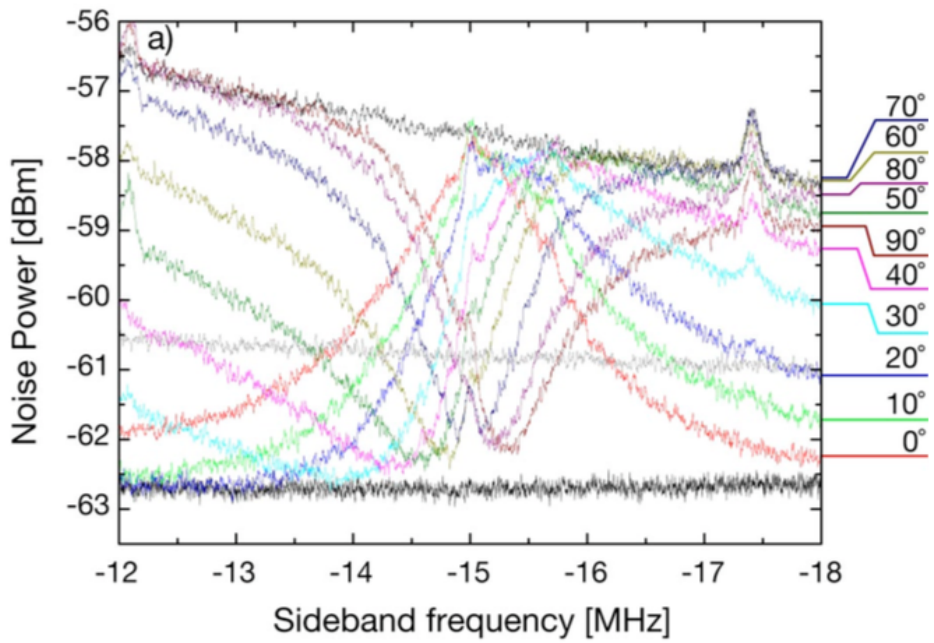


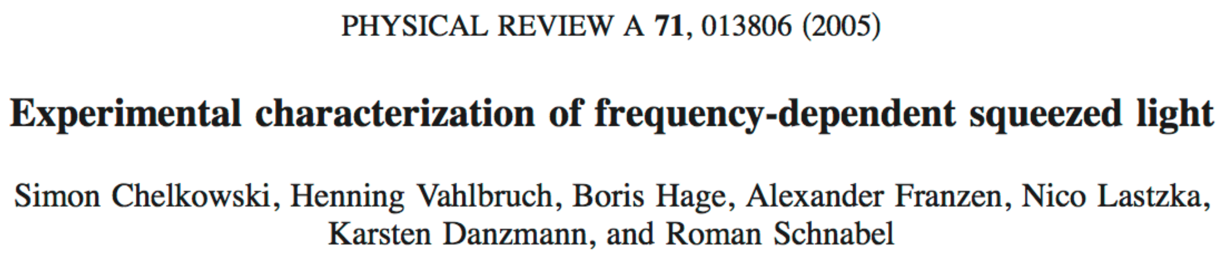


Optimal rotation frequency between 40 and 70 Hz

Squeezing angle rotation already realized

@ MHz frequency



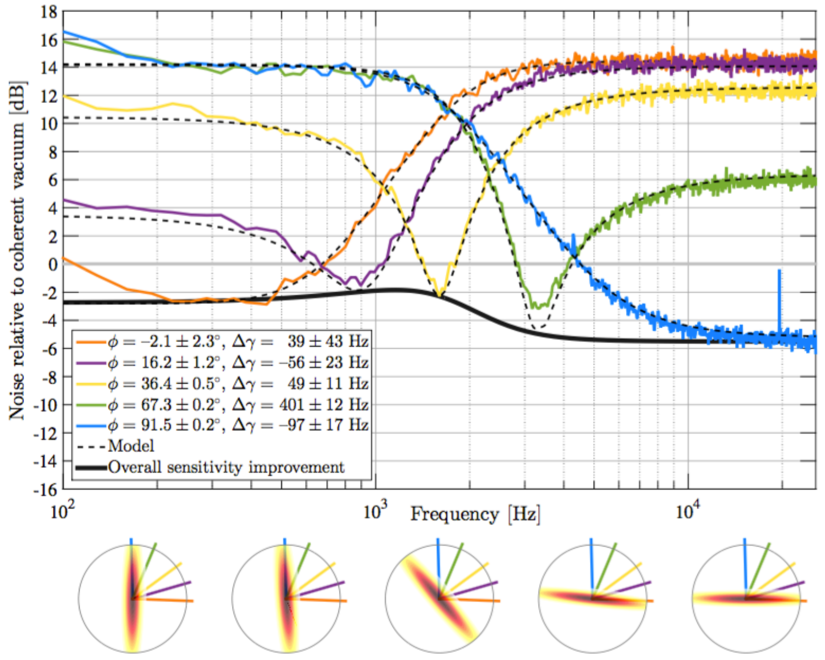


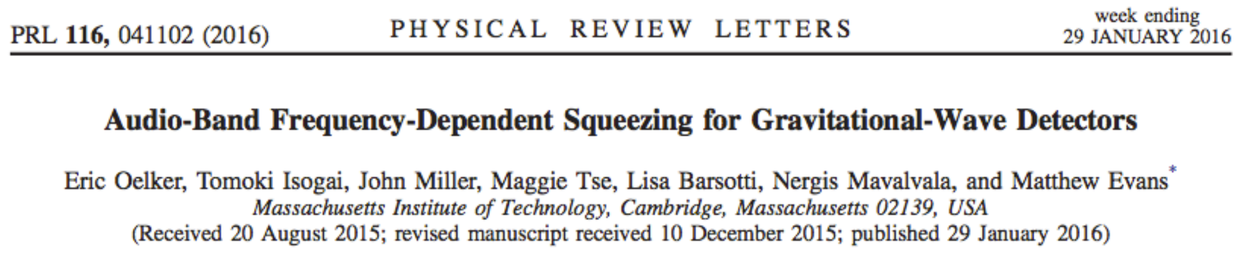
PHYSICAL REVIEW A **71**, 013806 (2005)

Experimental characterization of frequency-dependent squeezed light

Simon Chelkowski, Henning Vahlbruch, Boris Hage, Alexander Franzen, Nico Lastzka,
Karsten Danzmann, and Roman Schnabel

@ kHz frequency





PRL **116**, 041102 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

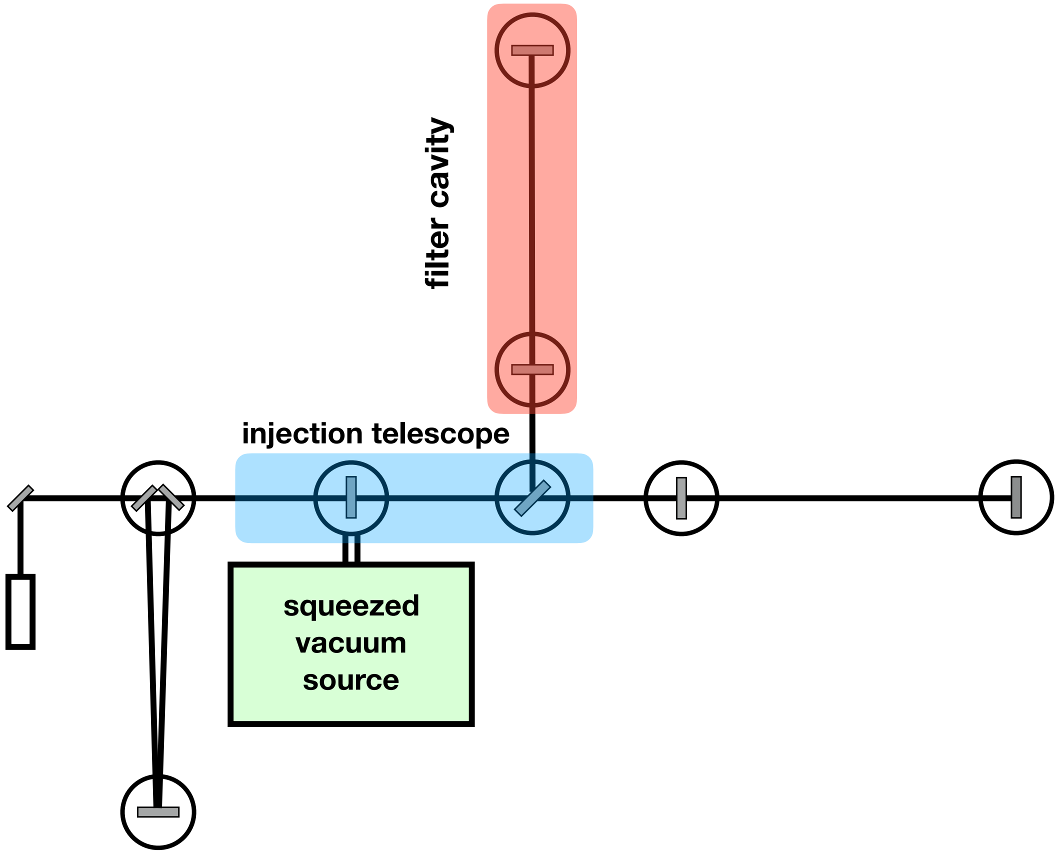
Audio-Band Frequency-Dependent Squeezing for Gravitational-Wave Detectors

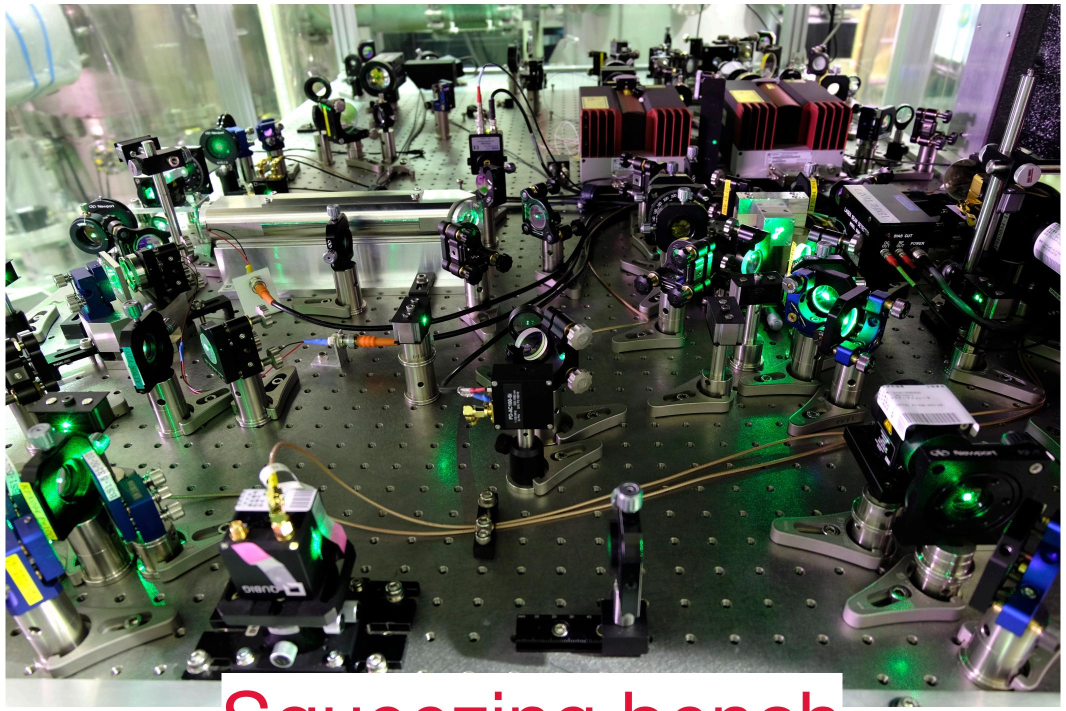
Eric Oelker, Tomoki Isogai, John Miller, Maggie Tse, Lisa Barsotti, Nergis Mavalvala, and Matthew Evans*
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
(Received 20 August 2015; revised manuscript received 10 December 2015; published 29 January 2016)

Our goal: **full scale filter cavity** prototype to demonstrate frequency dependent squeezing with **rotation at 70 Hz**

Experiment overview

- Cavity length: 300 m
- Finesse: 4400
- 9 dB freq. independent squeezing

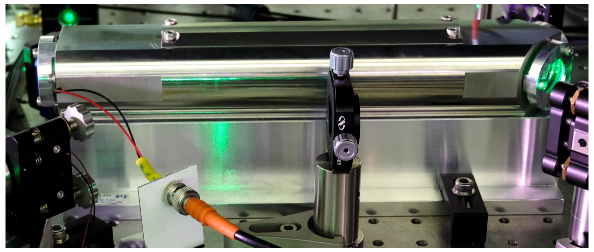




Squeezing bench

TAMA central building

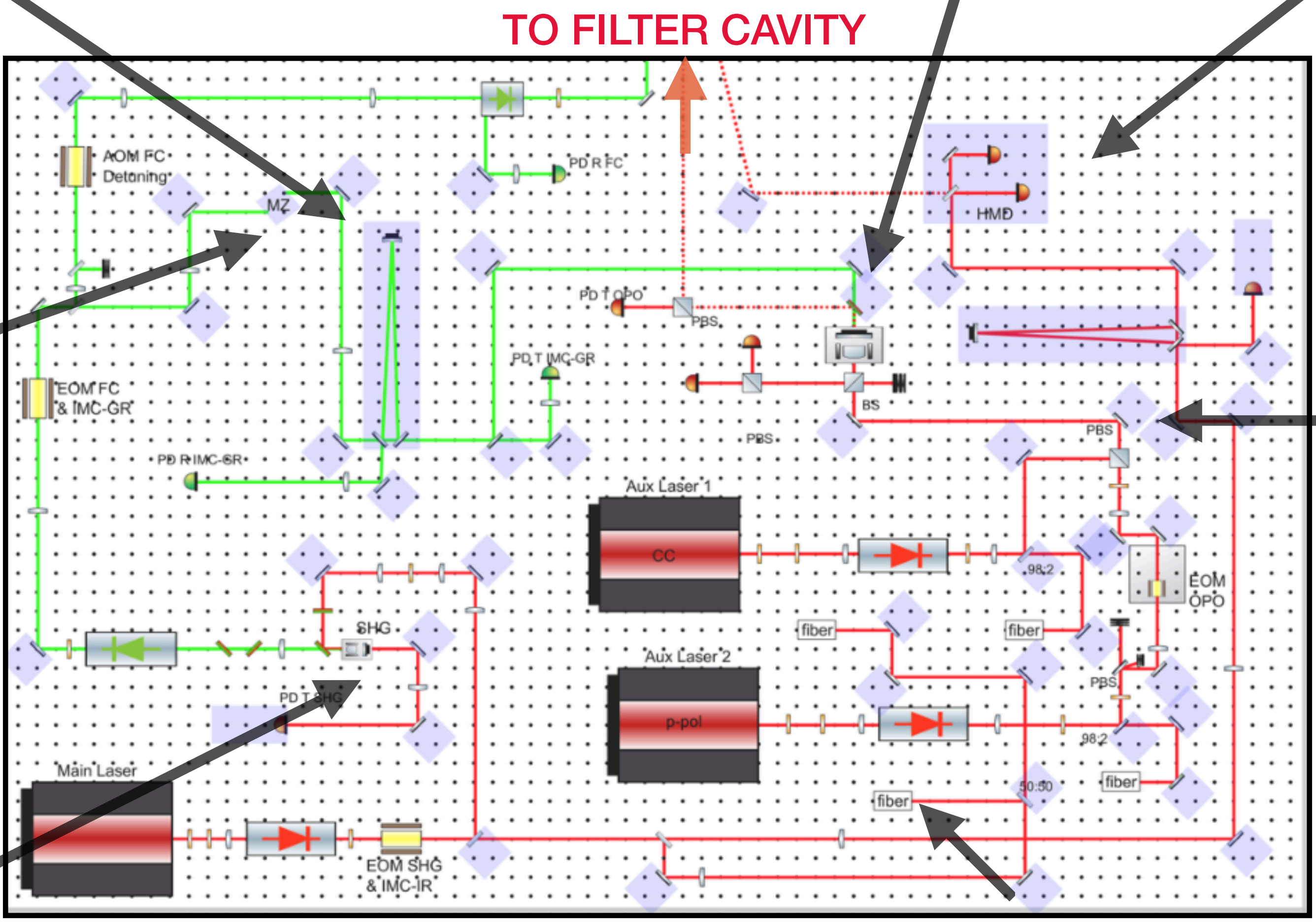
Squeezed vacuum source

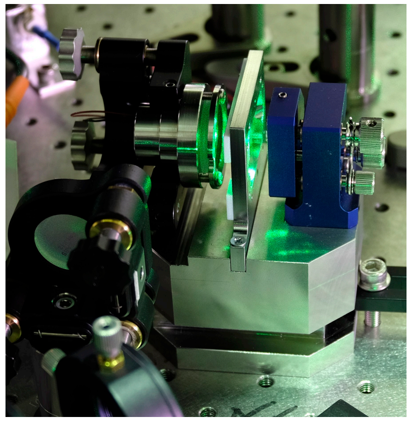


Geen mode cleaner and Mach-Zhender locked

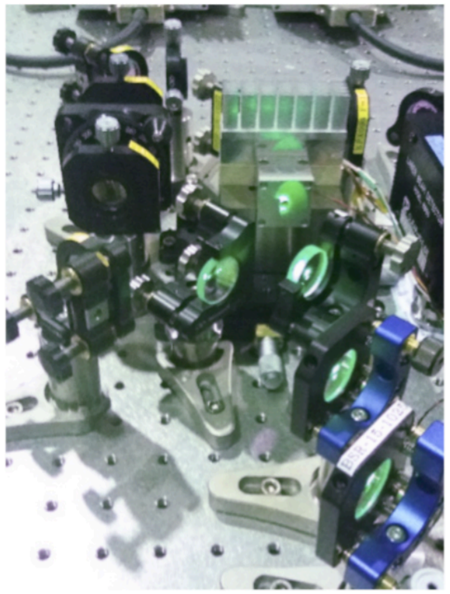
OPO assembled, alignment ongoing

Homodyne detector in progress (in collaboration with AEI, Hannover)

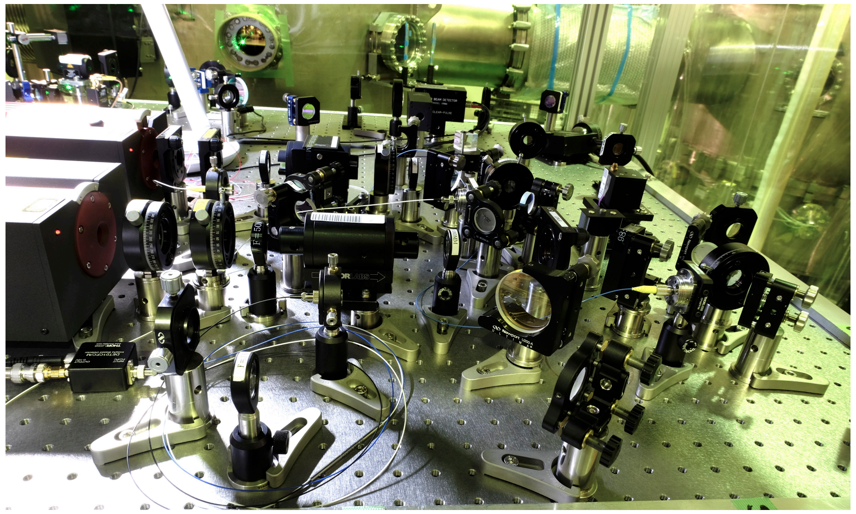




IR mode cleaner assembled



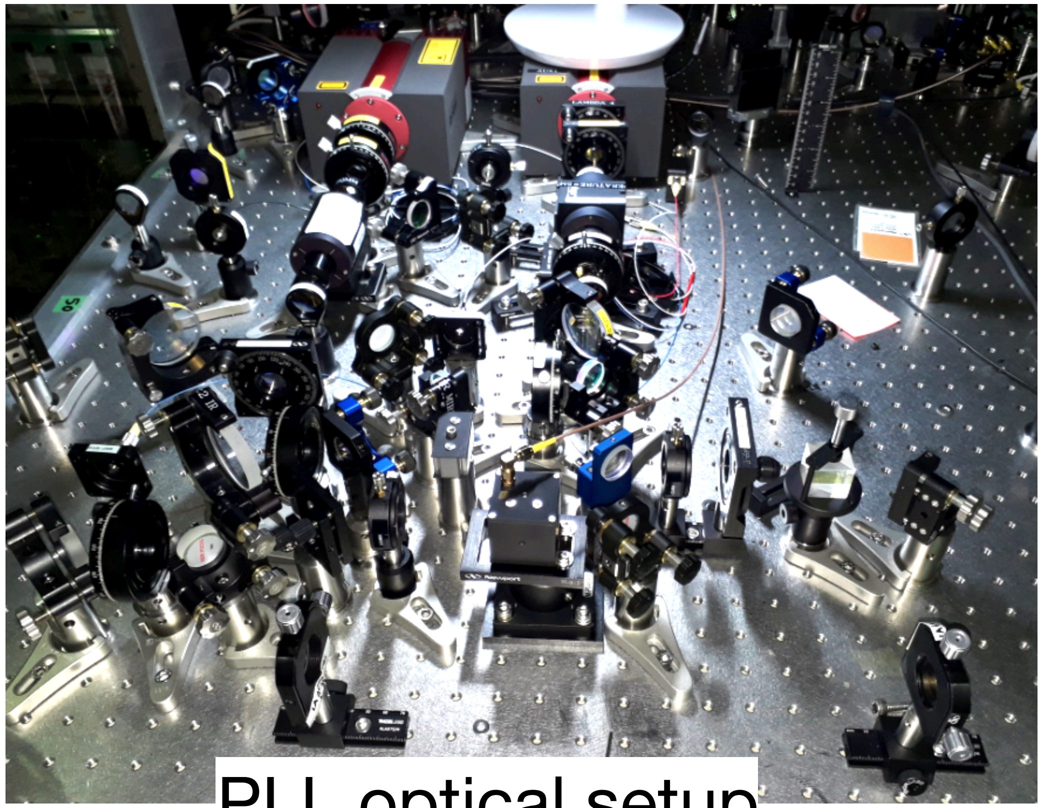
SHG assembled and operated



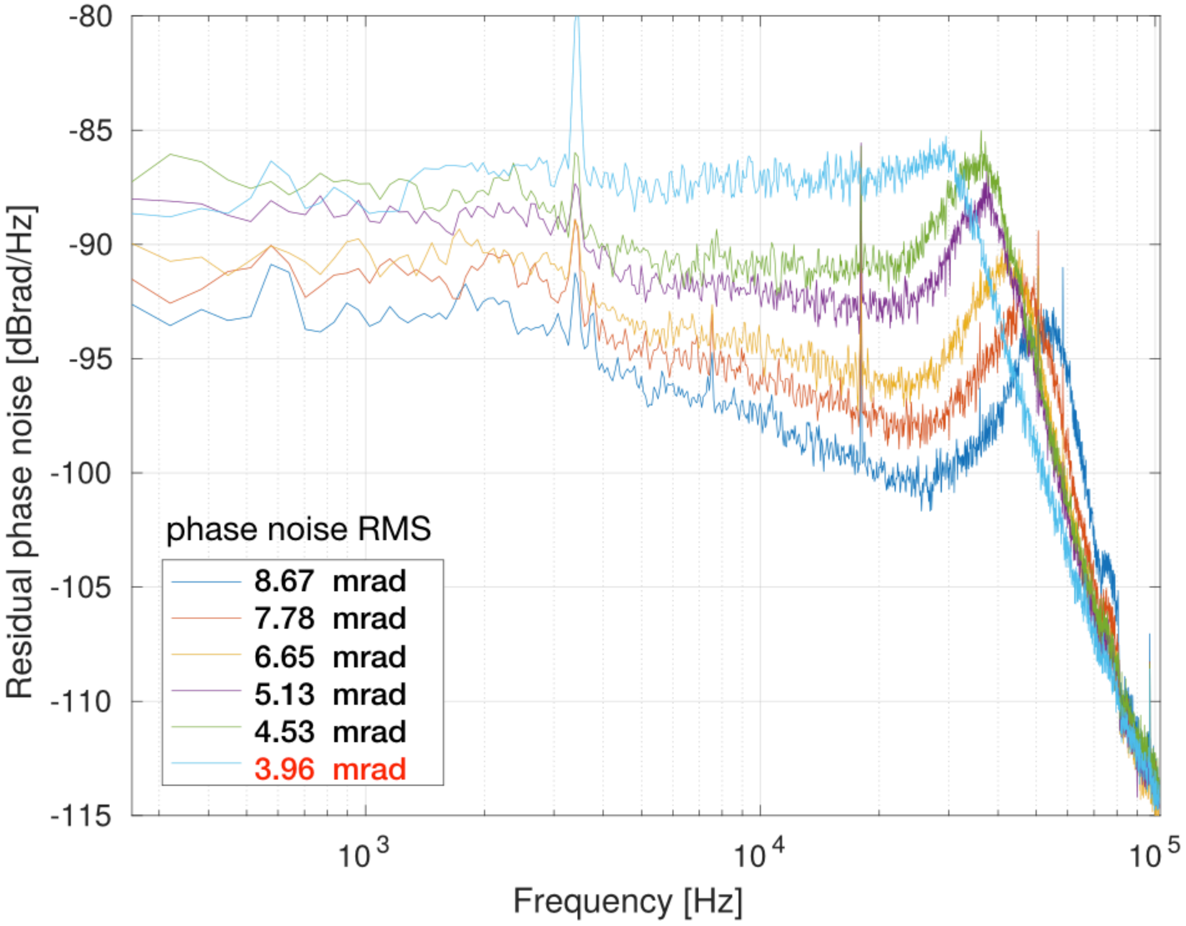
PLL for AUX lasers installed and locked

Phase lock loop (PLL) for AUX lasers

- Two AUX lasers are used for OPO length lock and control of the squeezing field phase (coherent control). They need to be phase locked to the main laser
- PLLs realized with fibered beam splitter and fiber coupled photodiode
- Electronics based on commercial Phase Frequency Detector (ADF4002)
- Residual phase noise ~4 mrad RMS between 100 Hz and 100 kHz



PLL optical setup

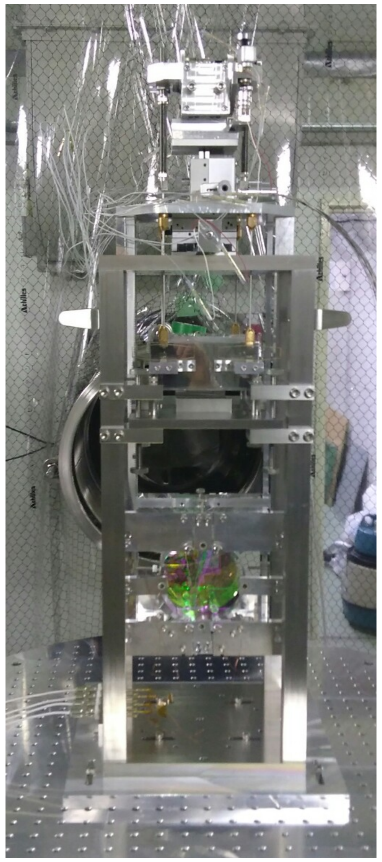


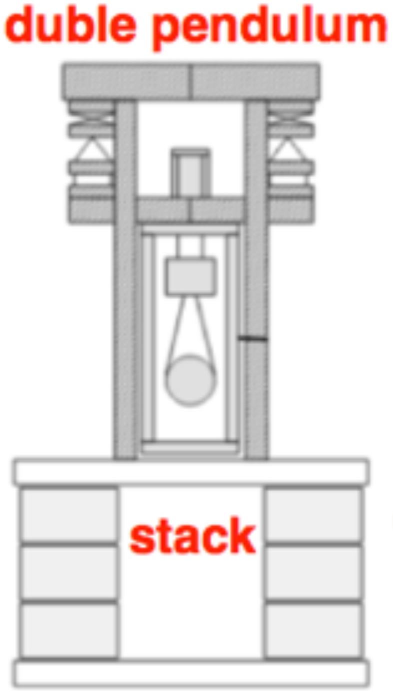
contribution from visitor Marco Vardaro

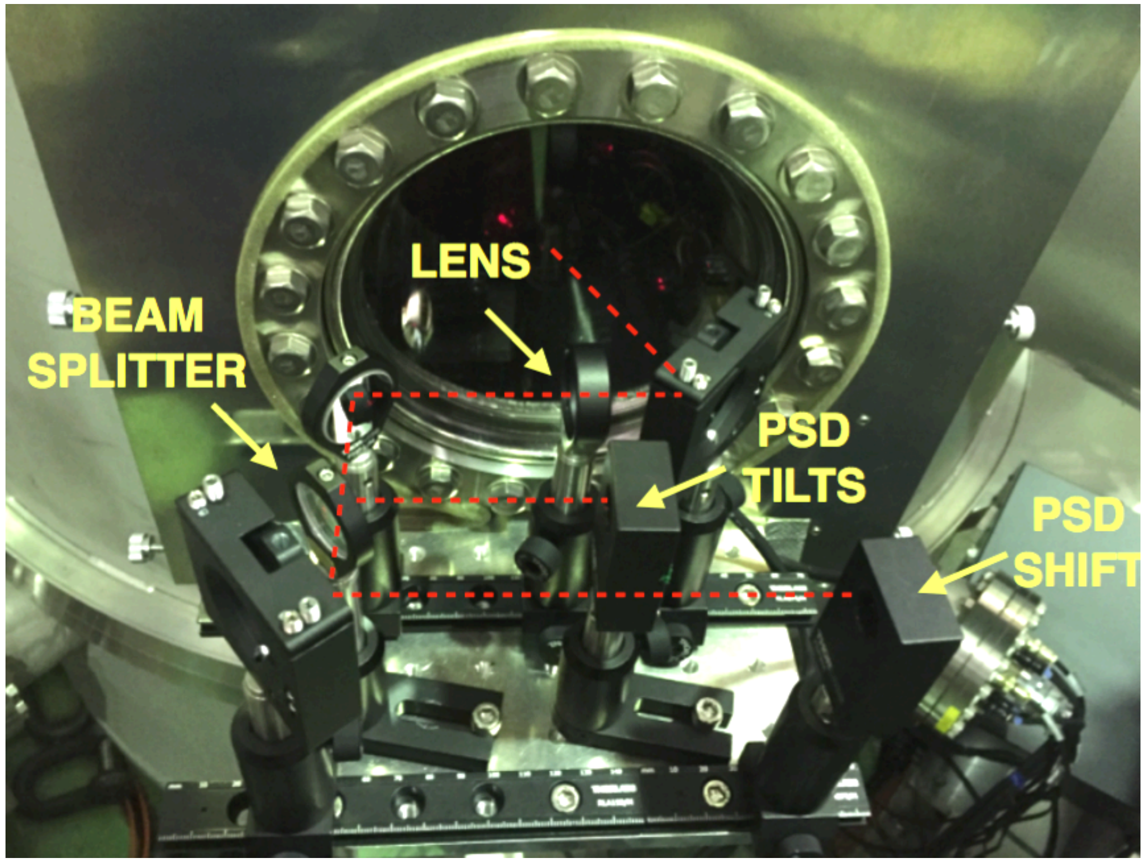
Cavity mirror suspensions

- Tama vibration isolation stack and double pendulum suspension (type C)

- Virgo-like optical levers



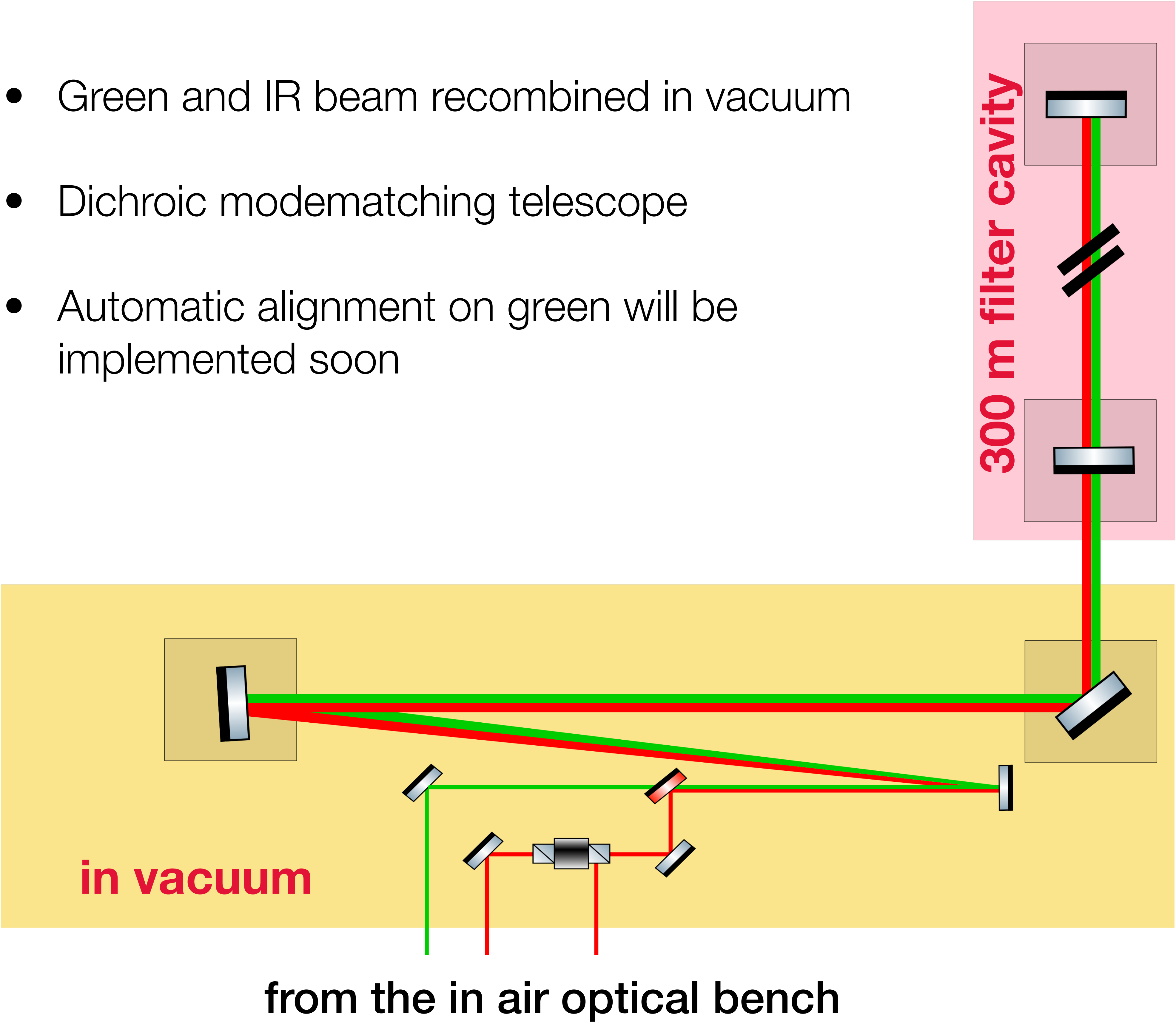




New control system needed to replace old TAMA LABview

Injection path and alignment

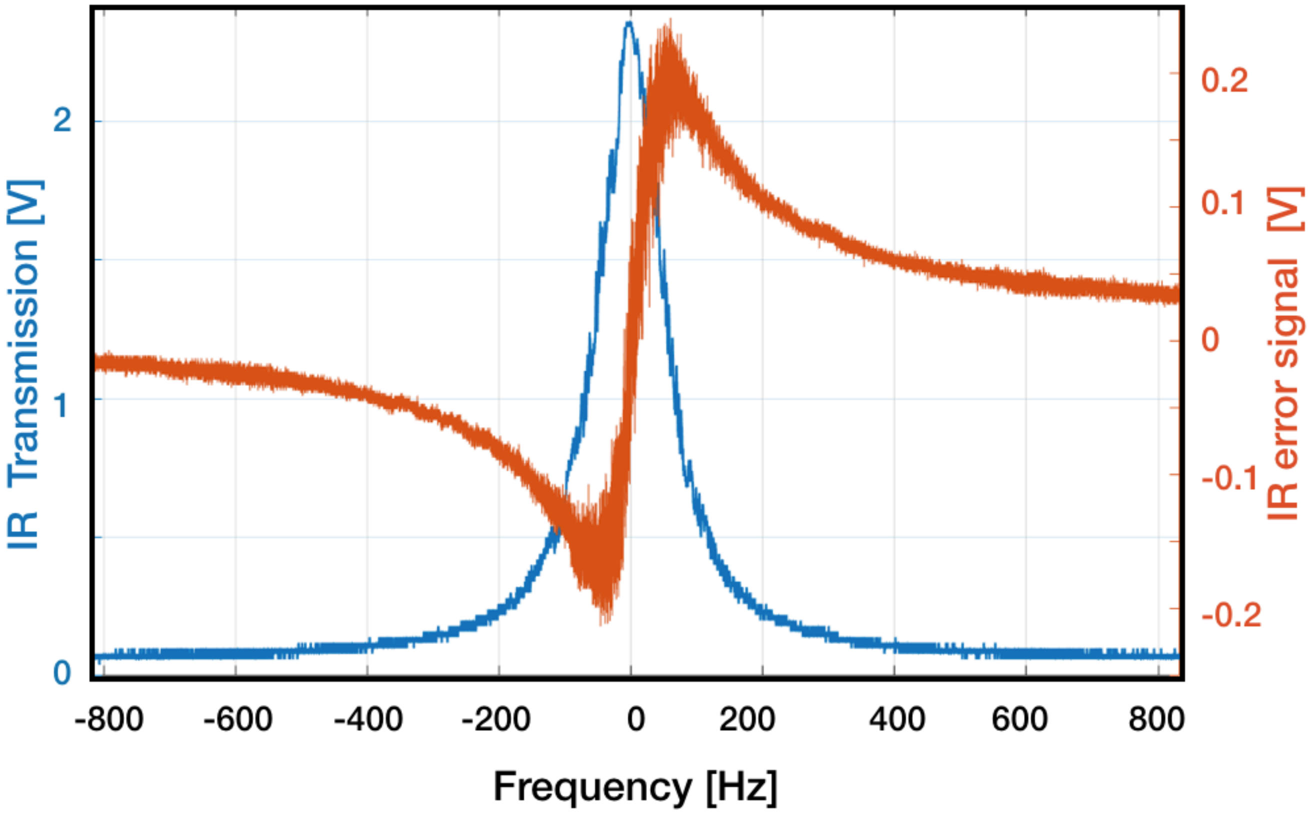
- Green and IR beam recombined in vacuum
- Dichroic modematching telescope
- Automatic alignment on green will be implemented soon



Cavity control

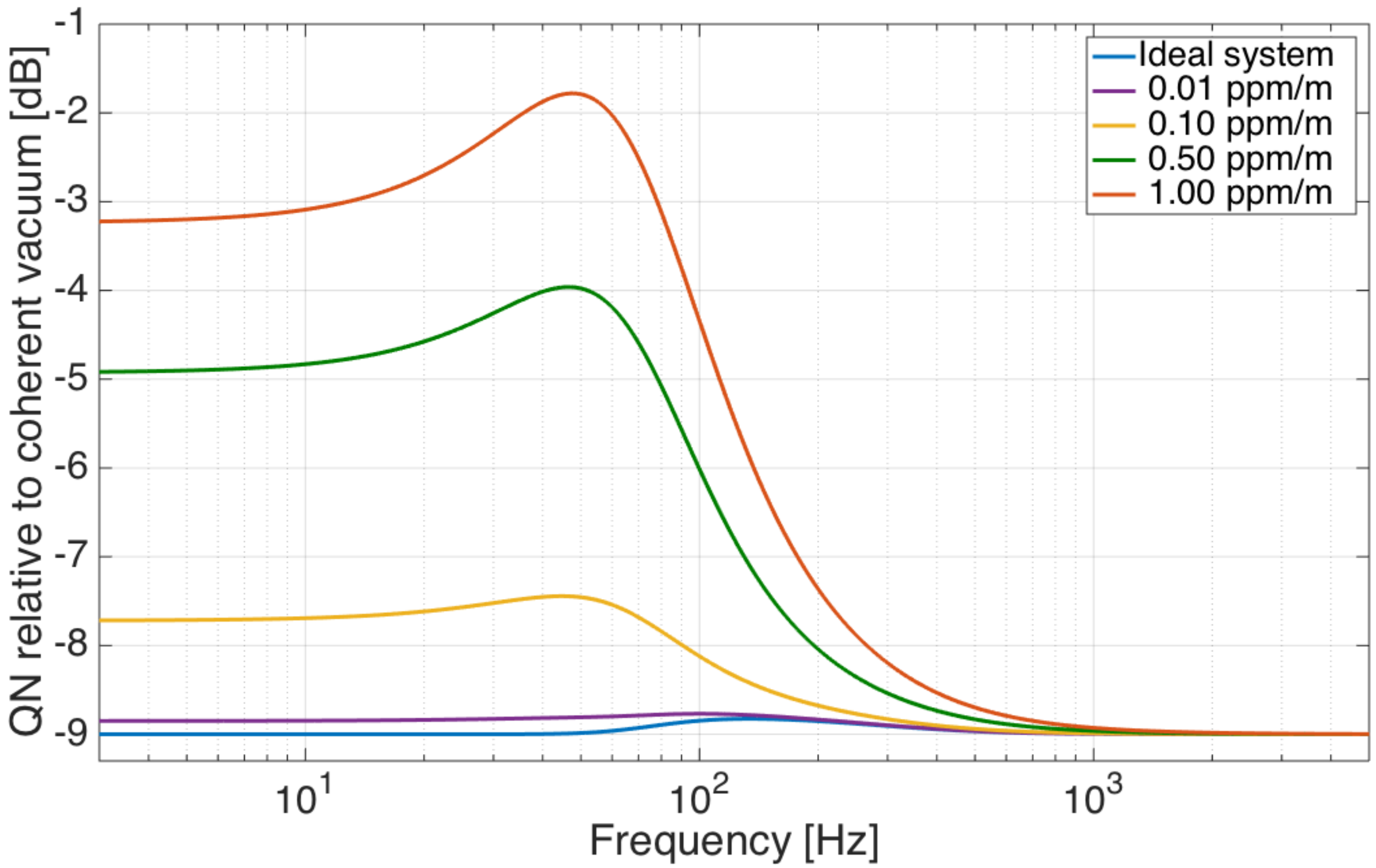
- Main laser locked on the cavity length using a part of the green beam from SHG.
- Analog servo with 20 kHz bandwidth (green beam finesse: 170)
- IR beam detuning controlled with a AOM on the green path

IR resonance crossing by driving AOM



Cavity characterisation: round trip losses measurement

- Important quantity for the squeezing degradation: losses per unity length
- Crucial measurement for designing filter cavities in GW detectors upgrades

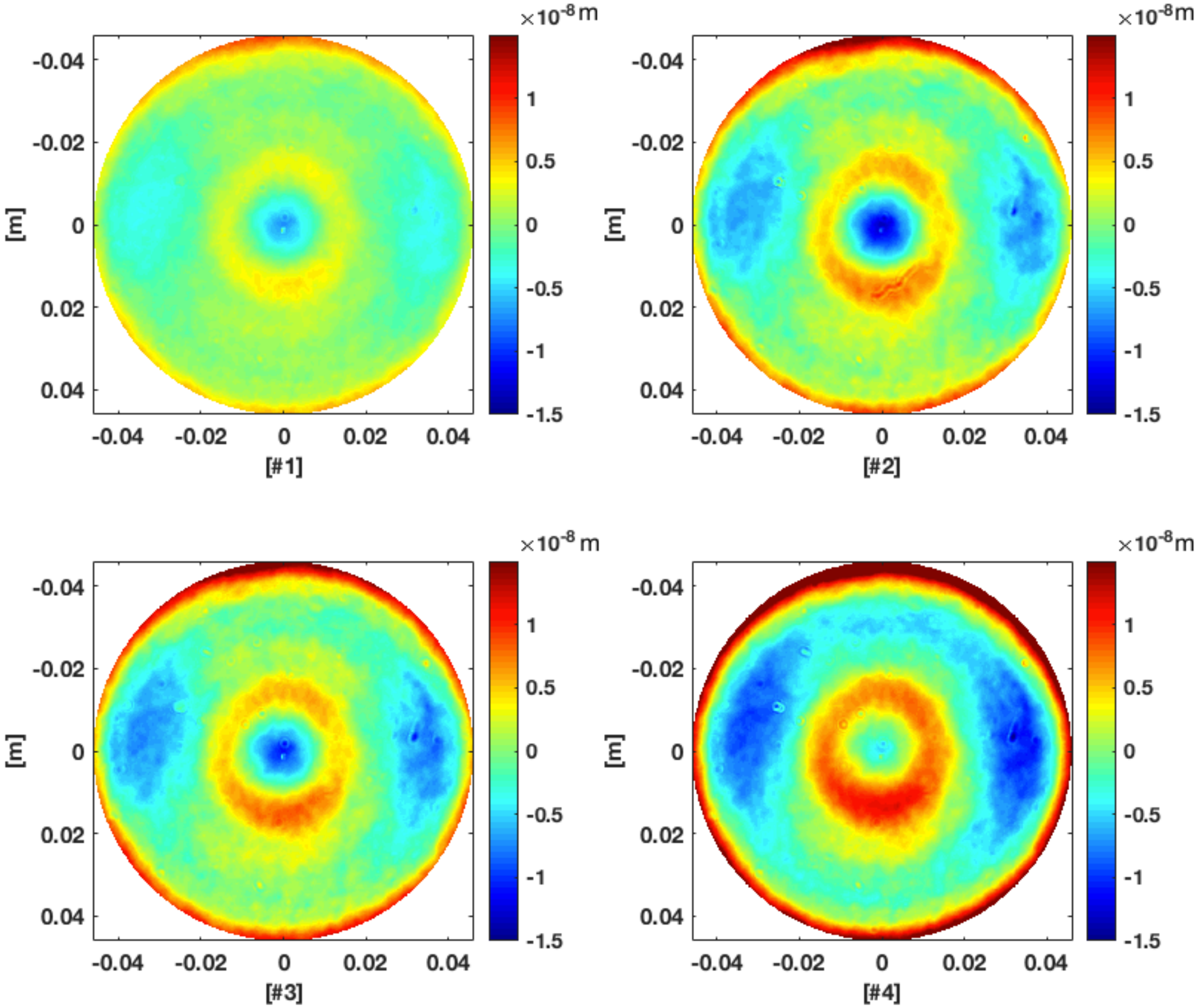


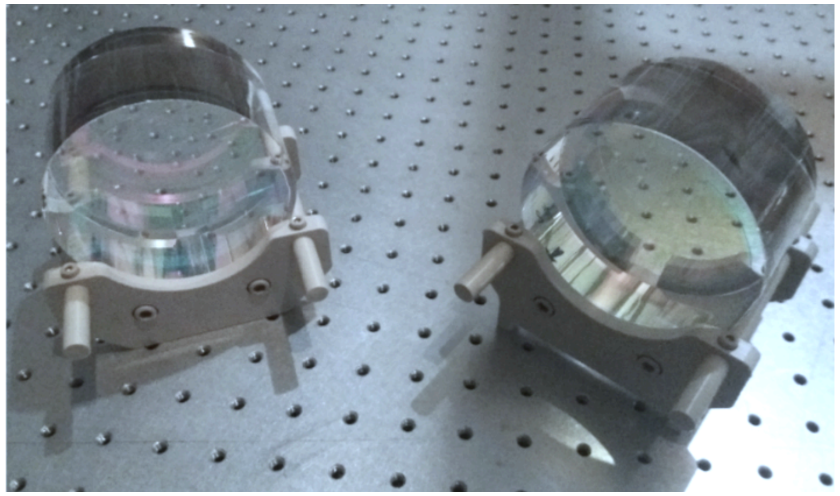
Squeezing degradation for different round trip losses values

Cavity mirrors characterisation

- Tama size: 10 cm diameter, 6 cm thickness
- Beam radius: ~1 cm
- Requirement on surface quality set to have 80 ppm of round trip losses

	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

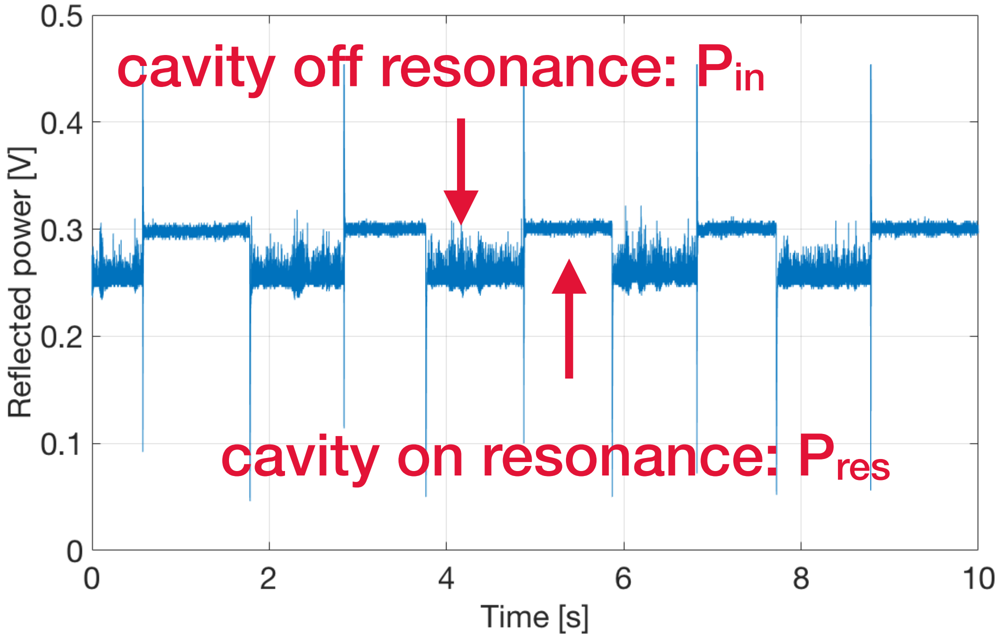




Substrates coated and characterised at LMA

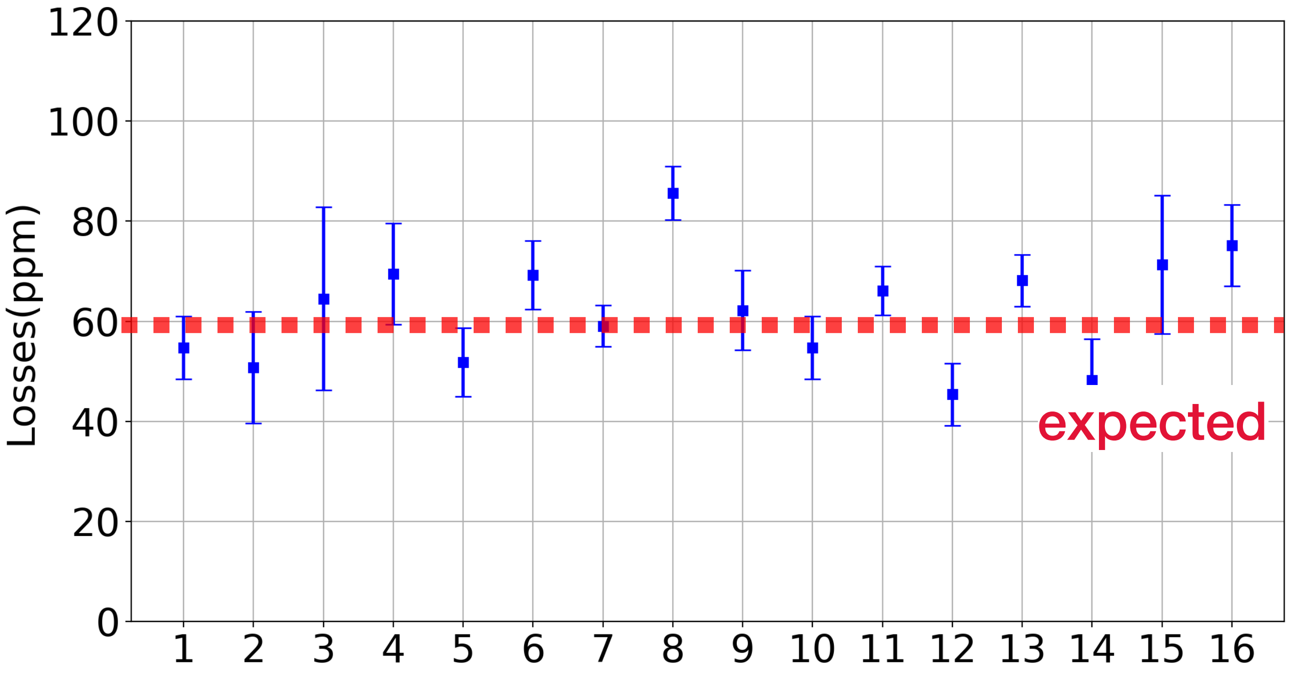
Round trip losses measurement

- Set of on/off resonances switches to measure the cavity reflectivity
- Round trip losses computed from cavity reflectivity



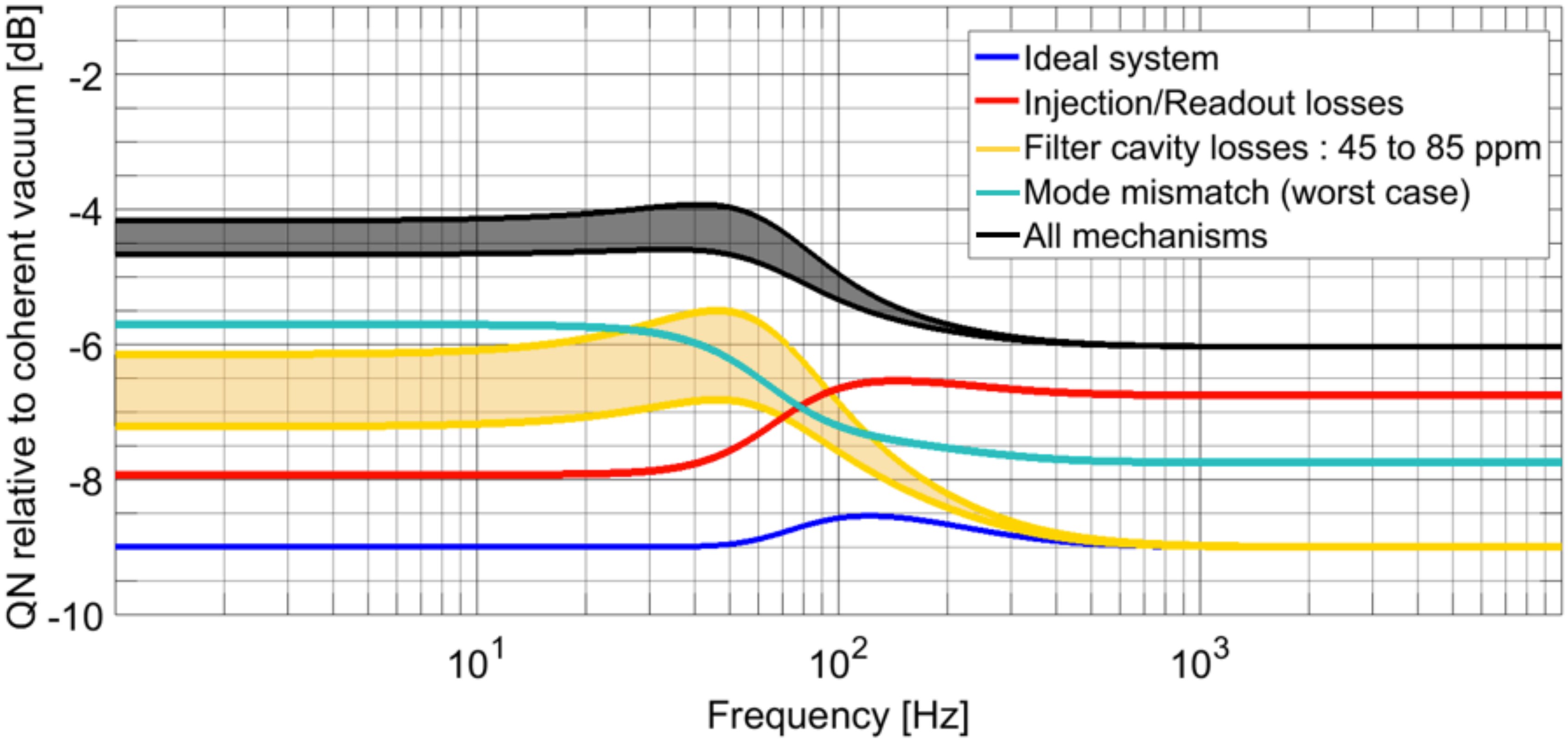
$$L \sim \frac{T_1}{2}\frac{1 - P_{\mathrm{res}}/P_{\mathrm{in}}}{1 + P_{\mathrm{res}}/P_{\mathrm{in}}}$$

- **Round trip losses between 45 and 85 ppm**



Expected squeezing level

- Round trip losses below 85 ppm are allows for ~ 4 dB of squeezing at low frequency (assuming 9 dB of injected squeezing)



PHYSICAL REVIEW D **98,** 022010 (2018)

Measurement of optical losses in a high-finesse 300 m filter cavity for broadband quantum noise reduction in gravitational-wave detectors

Eleonora Capocasa,[1,2,*] Yuefan Guo,[3] Marc Eisenmann,[4] Yuhang Zhao,[1,5] Akihiro Tomura,[6] Koji Arai,[7]
Yoichi Aso,[1] Manuel Marchiò,[1] Laurent Pinard,[8] Pierre Prat,[2] Kentaro Somiya,[9] Roman Schnabel,[10]
Matteo Tacca,[11] Ryutaro Takahashi,[1] Daisuke Tatsumi,[1] Matteo Leonardi,[1]
Matteo Barsuglia,[2] and Raffaele Flaminio[4,1]

(Received 27 May 2018; published 31 July 2018)

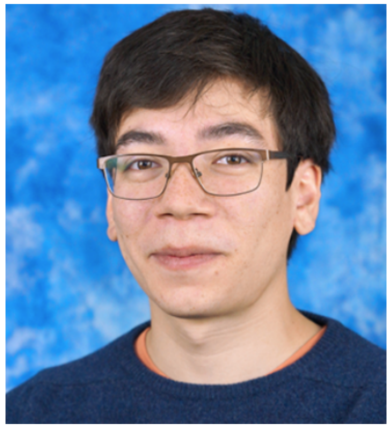
Visitors and new collaboration

- Many contributions given from visitors

Emil Schreiber
GEO600/AEI

Marco Vardaro
Padova University

Matteo Barsuglia
APC/CNRS



Marc Eisenmann
LAPP/CNRS

Yuefan Guo
Beijing Normal University

Pierre Prat
APC/CNRS

Visitors and new collaboration

- Visit of Ray-Kuang Lee's quantum optics group from National Tsing Hua University, Taiwan
- Discussion about future collaboration with them

國立清華大學
NATIONAL TSING HUA UNIVERSITY

Summary and perspectives

Status

- Filter cavity installed and controlled
- Cavity round trip losses between 45 and 85 ppm
- Squeezed vacuum source integration almost completed

Next steps

- Operation of the squeezing vacuum source before the end of FY2018
- Cavity automatic alignment implementation
- Upgrade of the digital control system
- Final step: injection of freq. independent squeezing into the filter cavity

More in formation can be found on our wiki page:

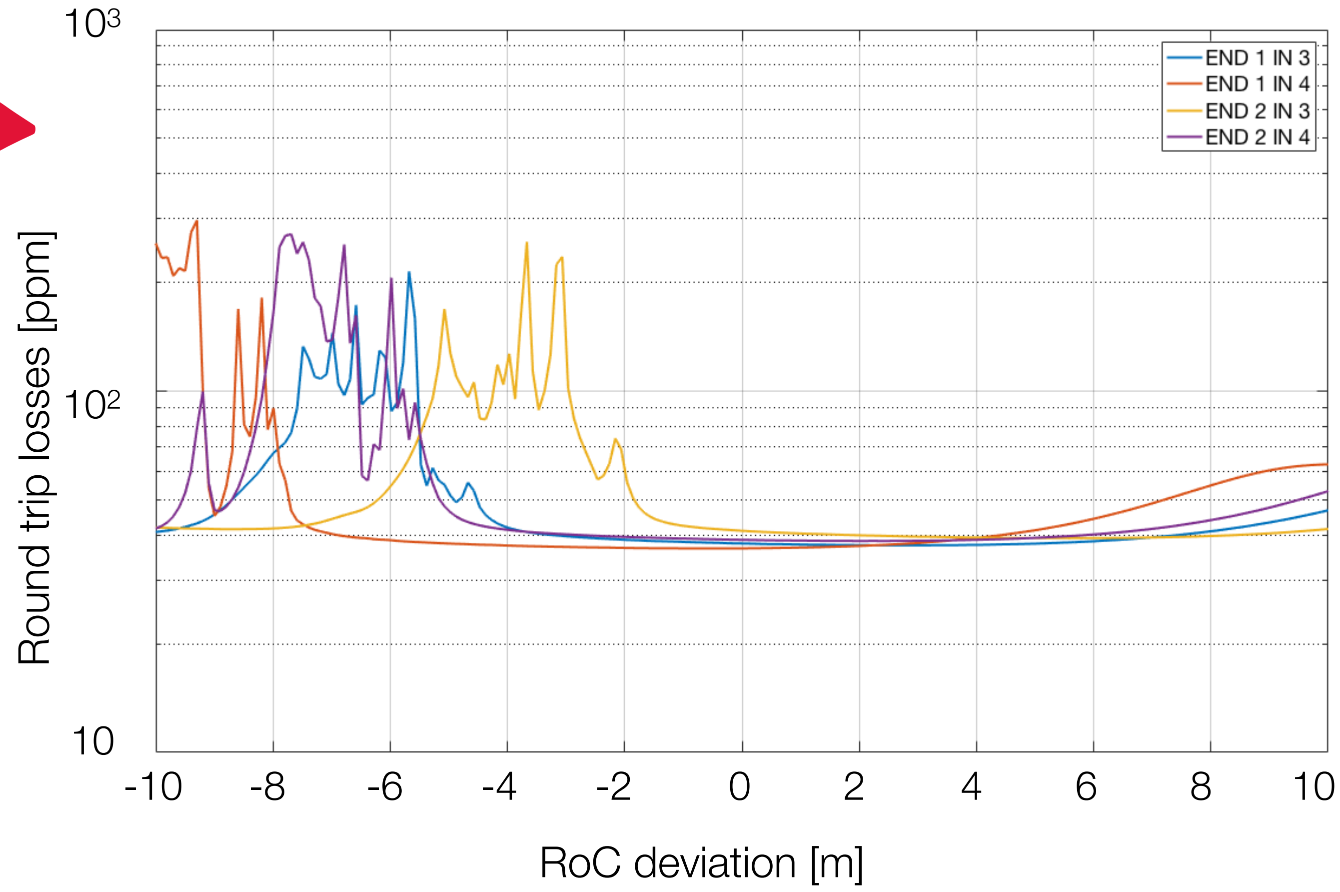
https://gwpo.nao.ac.jp/wiki/FilterCavity

EXTRA SLIDES

Round trip losses budget

RTL REQUIREMENT : 80 ppm

- **~ 40 ppm** from flatness (simulation)
- **~ 15 ppm** from roughness and point defect (measured)
- **~ 5 ppm** from absorption and transmission (measured)



TOTAL EXPECTED RTL : ~ 60 ppm

How to measure round trip losses?

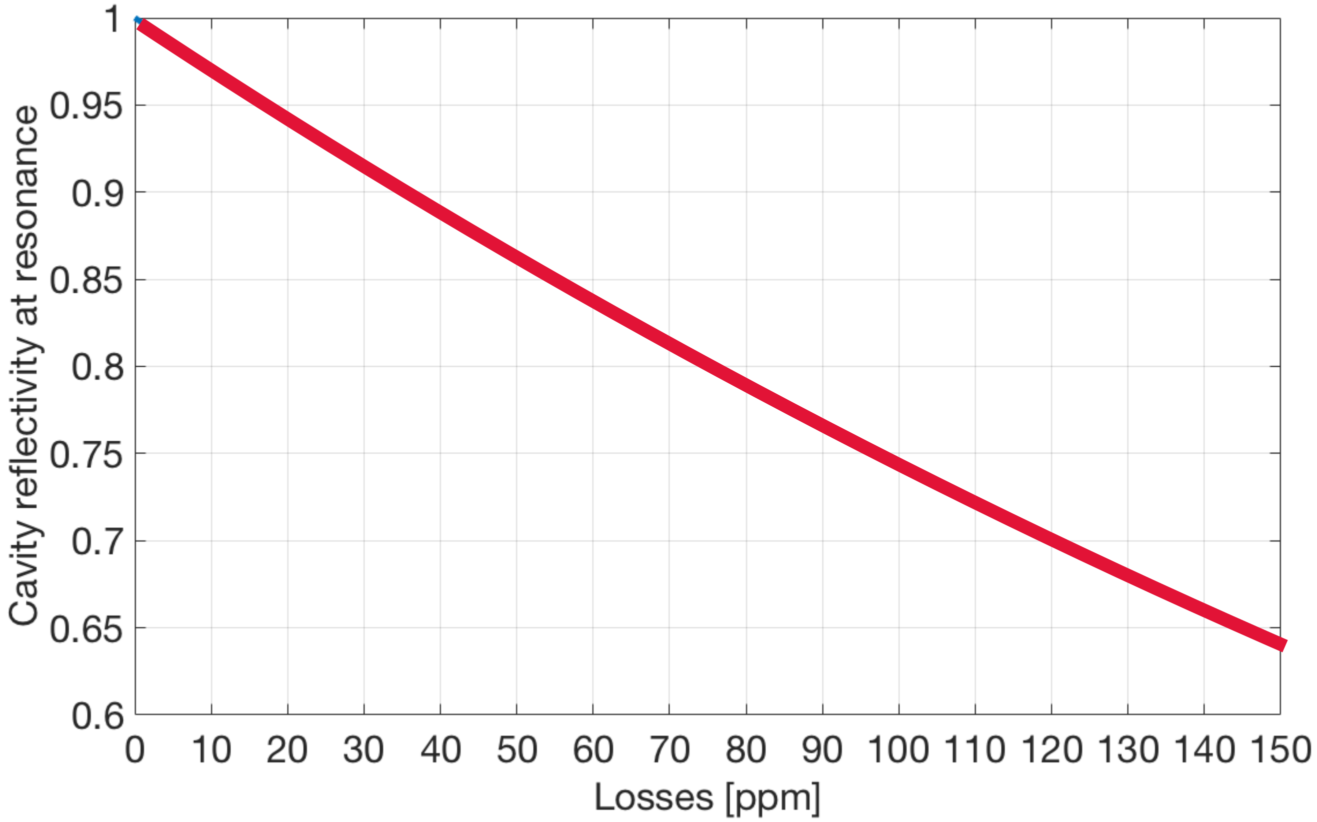
- From the cavity reflectivity at resonance
- Reflectivity is less affected from the input mirror transmissivity
  (with respect to finesse or decay time)

$$R_{\mathrm{cav}} = \left[\frac{r_1 - r_2}{1 - r_1 r_2}\right]^2$$

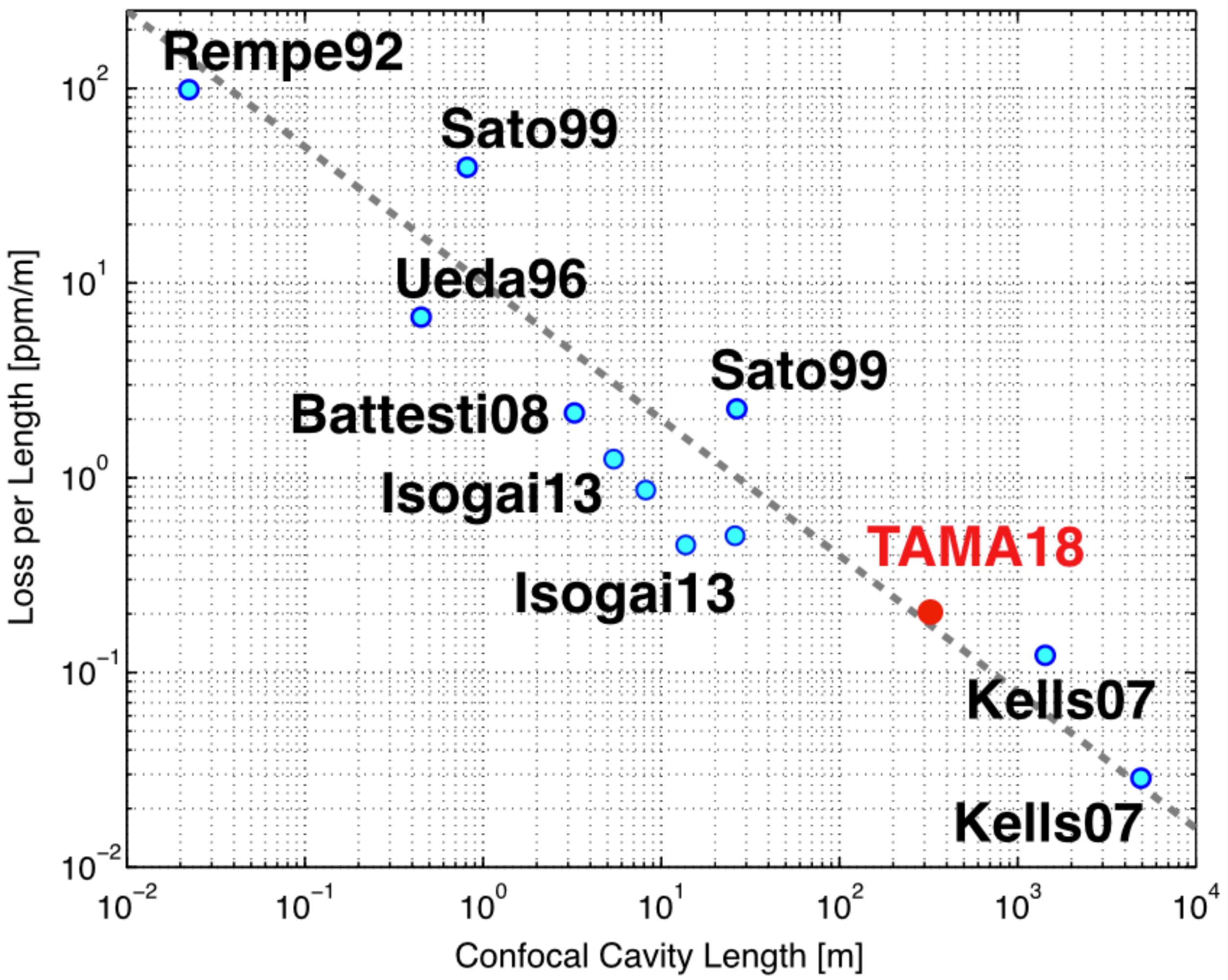
$$r_2 = \sqrt{1 - T_2 - L} \simeq \sqrt{1 - L}$$

$$\downarrow$$

$$\boxed{L = \frac{T_1}{2} \cdot \frac{1 - R_{\mathrm{cav}}}{1 + R_{\mathrm{cav}}}}$$

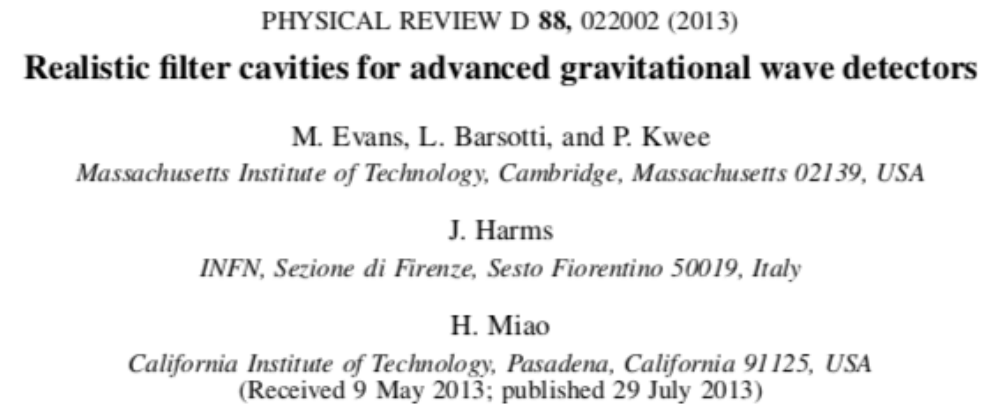


Comparison with round trip losses in literature



$$L_{\mathrm{rt}}(\mathscr{L}_{\mathrm{confocal}}) = 10\ \mathrm{ppm}\cdot\left(\frac{\mathscr{L}_{\mathrm{confocal}}}{1\ \mathrm{m}}\right)^{0.3}$$

Lconfocal is the length of the confocal cavity which has the same spot size at its mirrors as the cavity whose losses are reported


PHYSICAL REVIEW D **88,** 022002 (2013)

Realistic filter cavities for advanced gravitational wave detectors

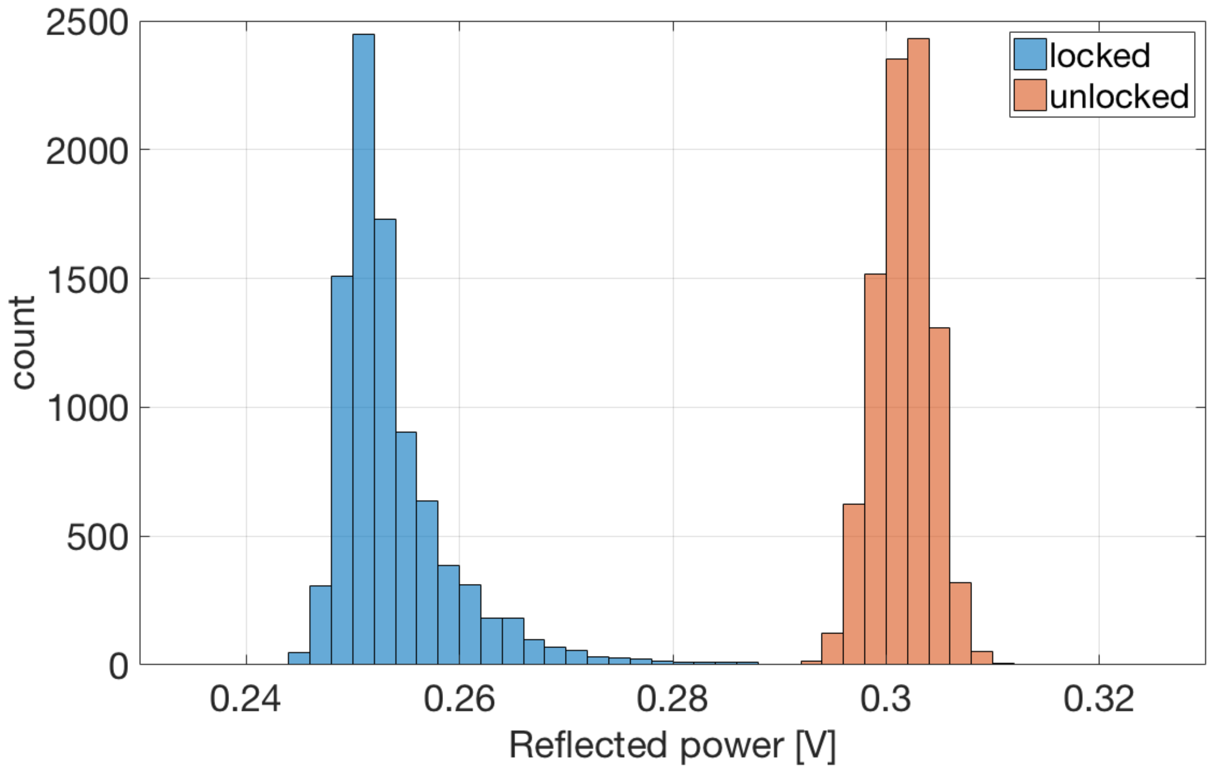
M. Evans, L. Barsotti, and P. Kwee
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

J. Harms
INFN, Sezione di Firenze, Sesto Fiorentino 50019, Italy

H. Miao
California Institute of Technology, Pasadena, California 91125, USA
(Received 9 May 2013; published 29 July 2013)

How to estimate the reflected power

- Power reflected has some fluctuation which show different features if the cavity is locked or unlocked

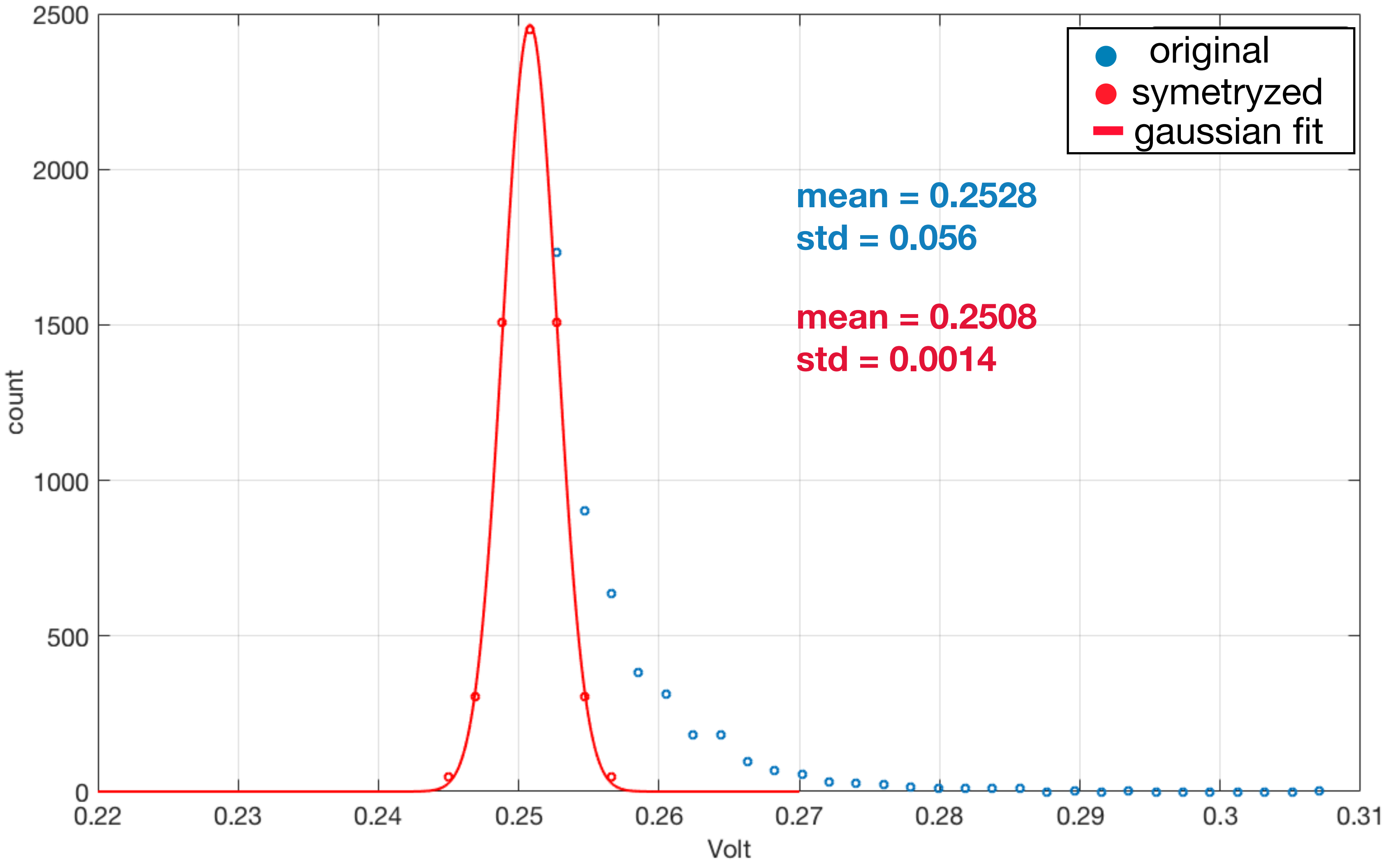


- Cavity unlocked: Gaussian histogram. Main influence: input power fluctuations

- Cavity unlocked: asymmetric distribution. Influence of the input power fluctuations, cavity alignment fluctuations, finite lock accuracy

How to estimate the reflected power

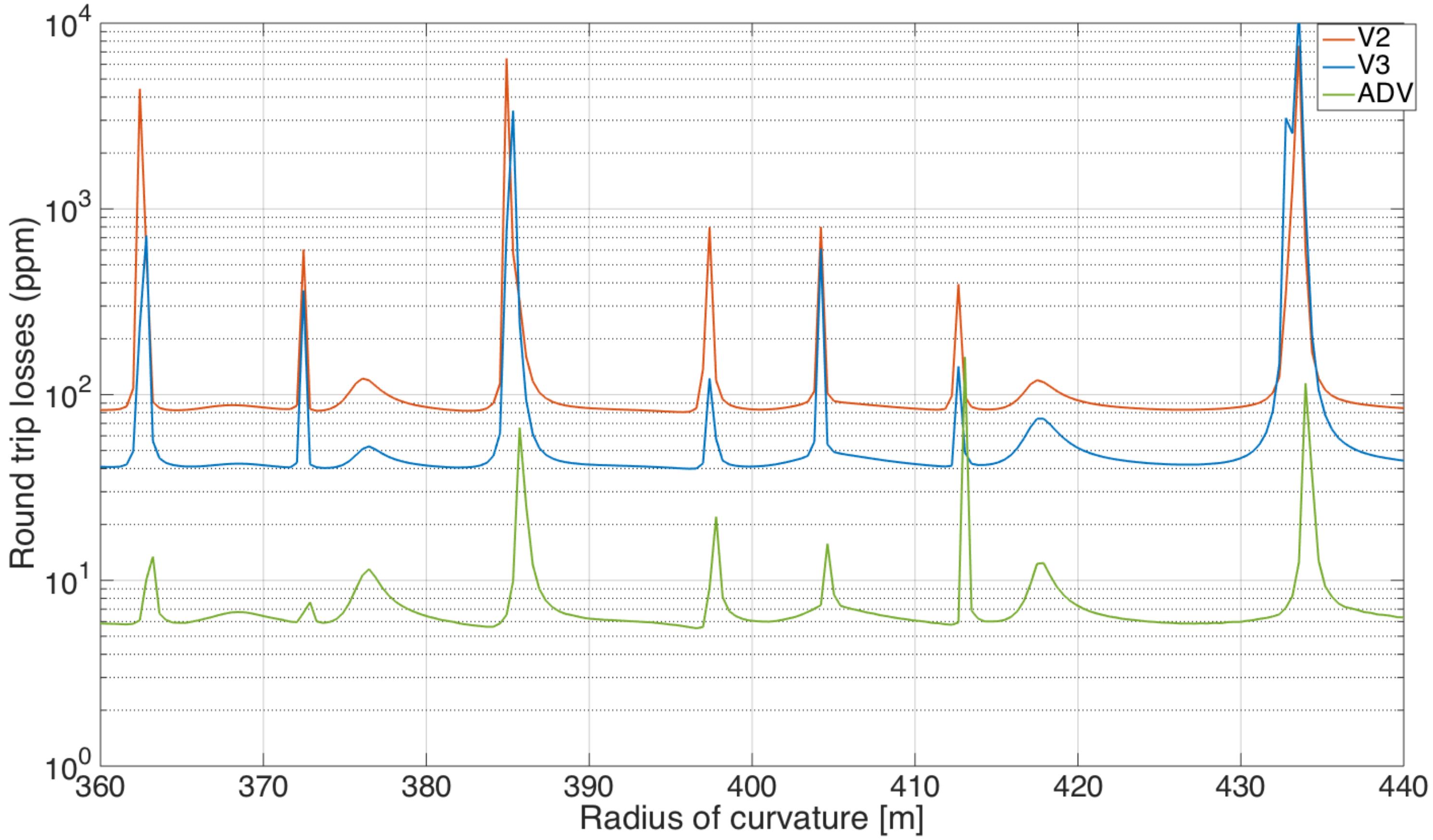
- Since the fluctuation which tends to increase the power (e.g. those of the lock accuracy) can bring to an underestimation of the losses) **we decided to consider the mode of the fluctuation histograms instead of the mean**



- The difference in the estimated losses is < 5 ppm. Results is not strongly dependent on this choice

Cavity design: requirement on the mirrors flatness

FFT simulation to measure RTL using real Virgo Mirror map



80 ppm

41 ppm

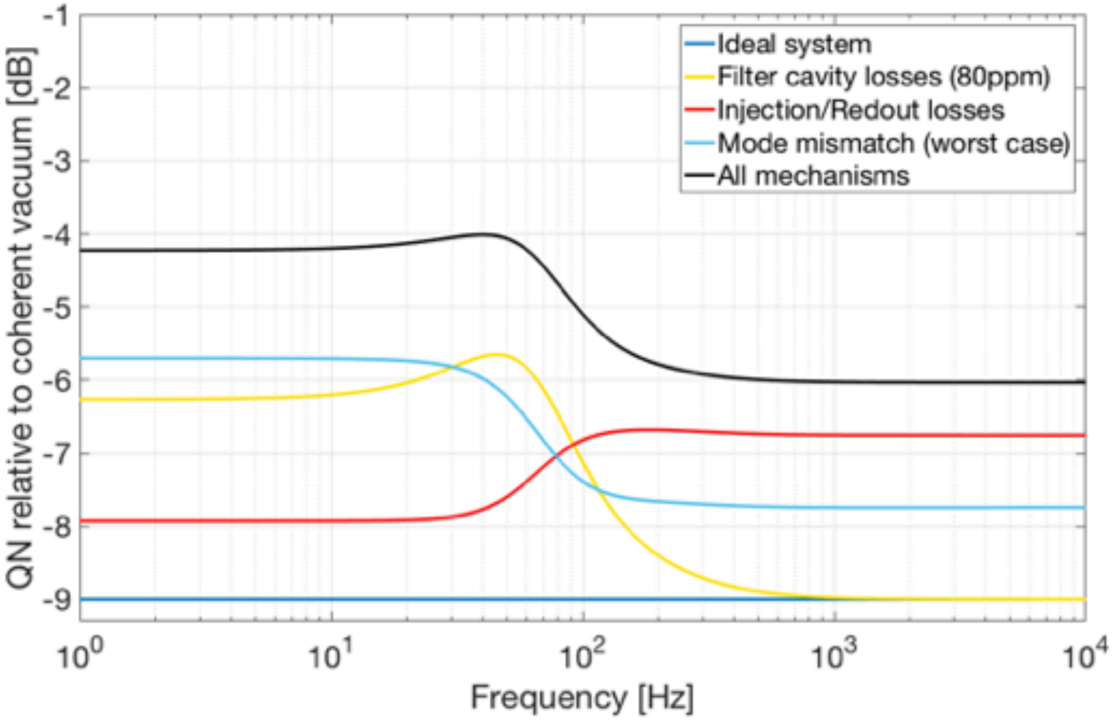
5.7 ppm

	diameter[m]	
	0.05	**0.01**
RMS [nm]	1.23	0.81
RMS [nm]	1.36	0.53
RMS [nm]	0.27	0.18

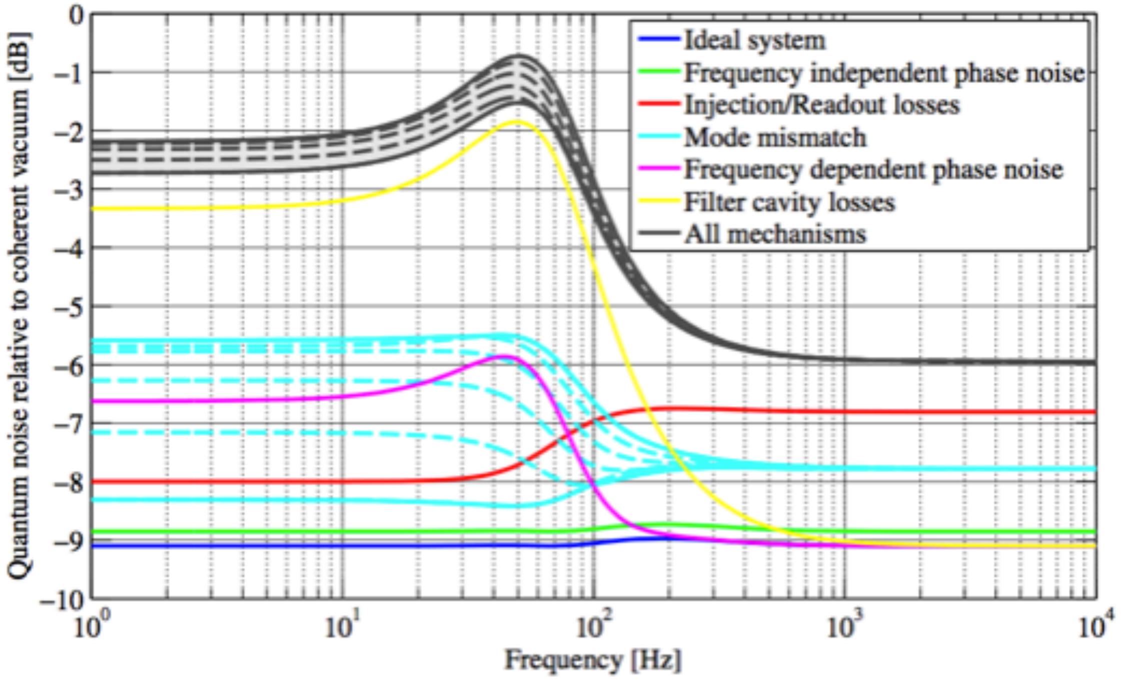
In order to set the RTL threshold we need to consider the other squeezing degradation sources

Squeezing degradation budget

TAMA 300 filter cavity



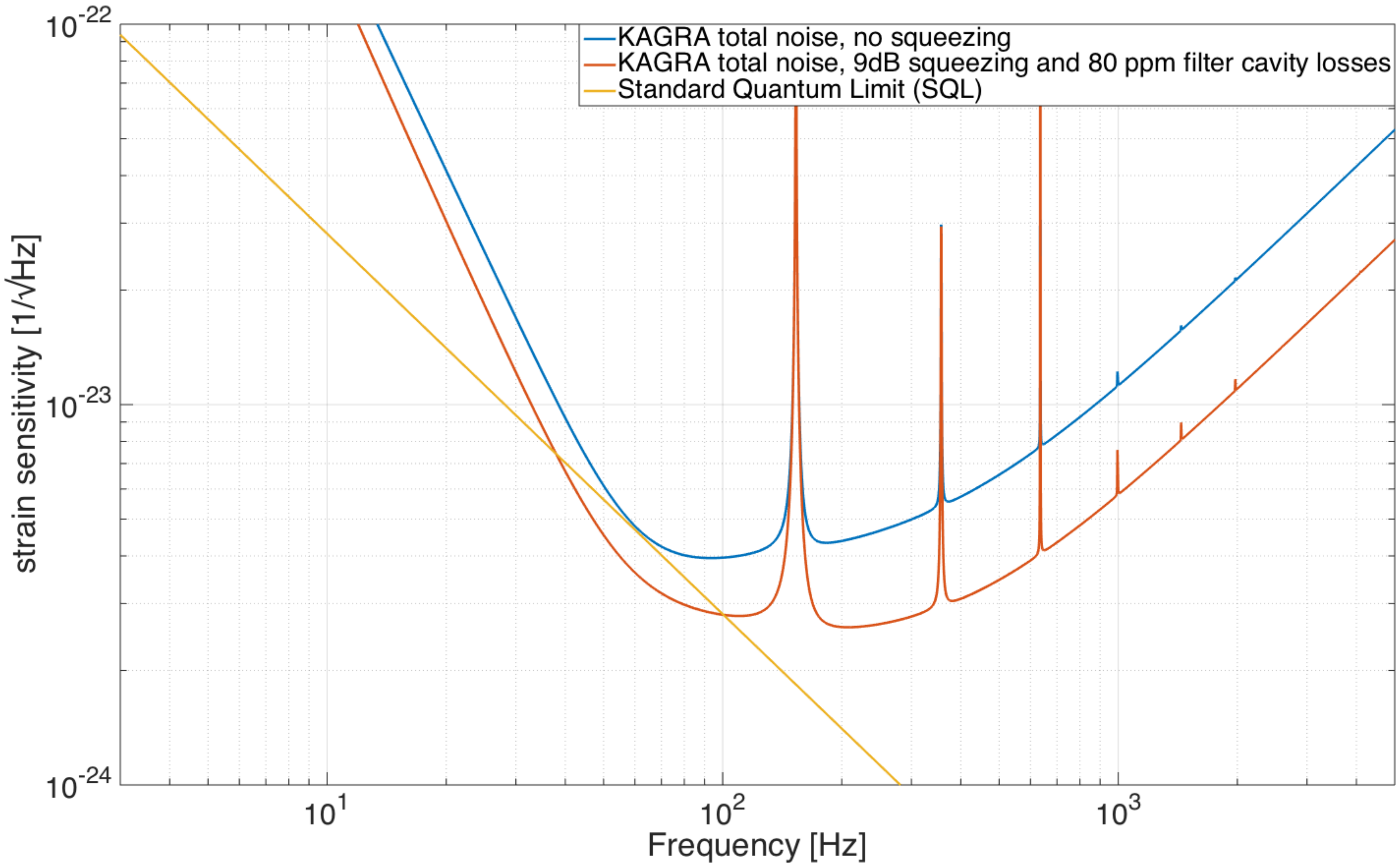
16 m filter cavity at MIT



length	16 m 300 m
RTL00	16ppm 40ppm
injection losses	5%
readout losses	5%
squeezer-filter cavity mismatch	2%
squeezer-local oscillator mismatch	5%
δL (rms)	0.3 pm

- **Important quantity: ppm per meter**
- RTL of 80 ppm (corresponding to Virgo mirrors quality) are low enough
- RTL of 6 ppm (corresponding to AdVirgo mirrors quality) makes degradation from cavity losses completely negligible

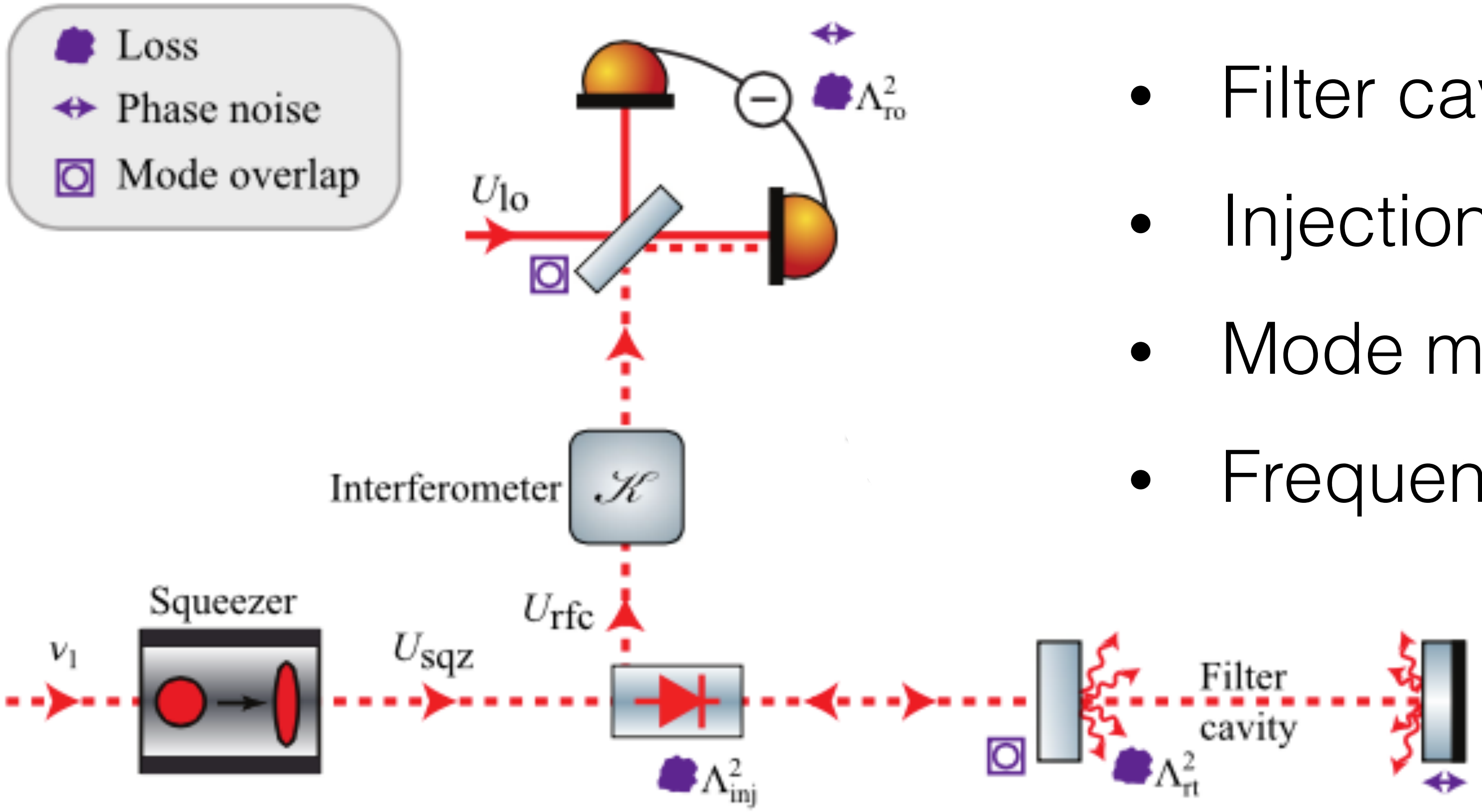
Expected improvement on KAGRA sensitivity



Horizon without squeezing	BNS = 360 Mpc	BBH = 3.28 Gpc
Horizon with squeezing	BNS = 509 Mpc	BBH = 4.42 Gpc

E.Capocasa et al “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)

Squeezing degradation sources



P.Kwee et al. “Dechoerence and degradation of squeezed states in quantum filter cavities” Phys. Rev. D 90 062006 (2014)

- Filter cavity losses
- Injection/readout losses
- Mode mismatch
- Frequency-dependent phase noise

Quantum fluctuation entering with the losses should be taken into account

$$N(\zeta) = |\bar{\mathbf{b}}_\zeta \cdot \mathbf{T_1} \cdot \underset{\uparrow}{v_1}|^2 + |\bar{\mathbf{b}}_\zeta \cdot \mathbf{T_2} \cdot \underset{\uparrow}{v_2}|^2 + |\bar{\mathbf{b}}_\zeta \cdot \mathbf{T_3} \cdot \underset{\uparrow}{v_3}|^2$$

squeezed field

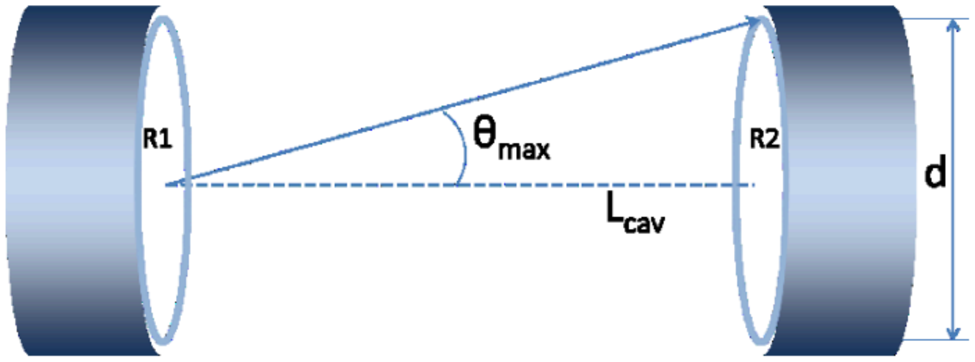
vacuum fluctuation due to losses before the ITF

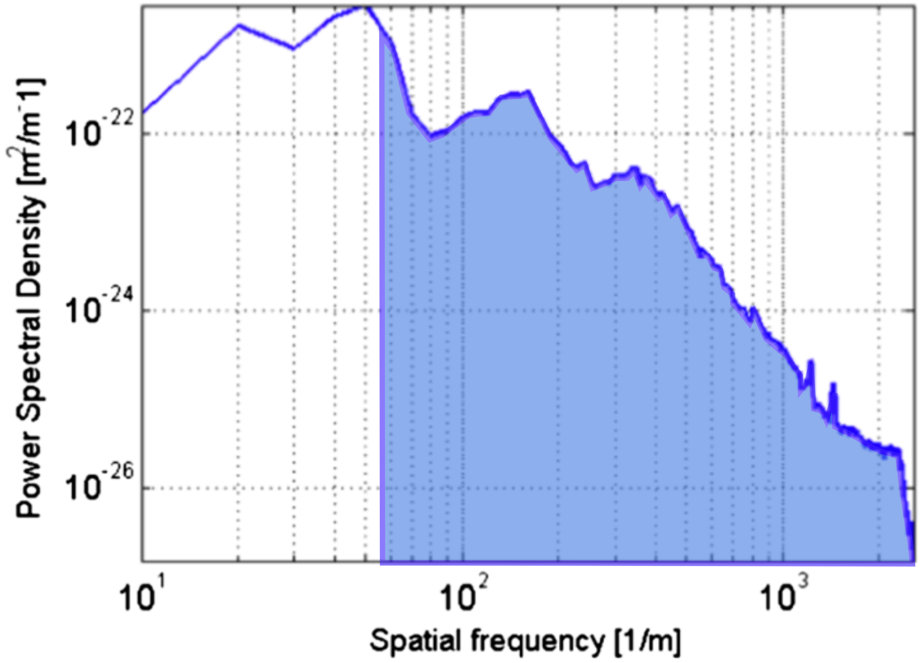
vacuum fluctuation due to losses after the ITF

Scattering from mirror defects

Diffraction angle: $\theta = \lambda \times f$

$$f_{\text{limit}} = \frac{d}{2L \times \lambda}$$





$$\sigma^2 = \int_{f_1}^{f_2} PSD(f)df$$

- Flatness: $10 \text{ m}^{-1} - 10^3 \text{ m}^{-1}$
- Roughness: $10^3 \text{ m}^{-1} - 10^5 \text{ m}^{-1}$
- Point defects $> 10^5 \text{ m}^{-1}$

Scattering golden rule:

$$\text{losses}_{(f>f_{\text{limit}})} = \left(\frac{4\pi \times \sigma}{\lambda}\right)^2$$

Why ppm/meter are important?

Total losses: RTL per number of round trip $N \sim 1/T_f$

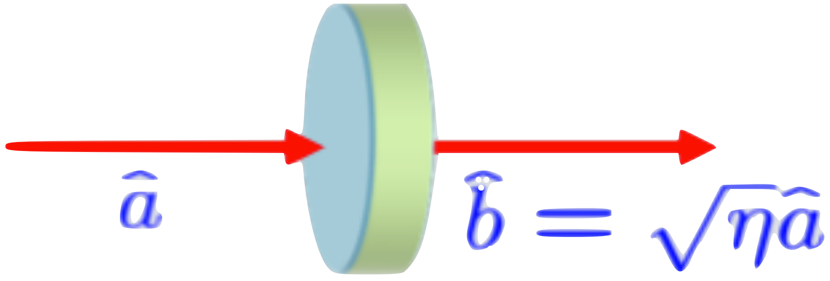
$$\mathcal{E} \approx \frac{\epsilon}{T_f}$$

Optimal rotation: filter Cavity bandwidth comparable with ITF bandwidth γ

$$T_f \approx \frac{4\gamma L_f}{c} \quad \longrightarrow \quad \mathcal{E} \approx \frac{c\,\epsilon}{4\gamma L_f} \propto \frac{\epsilon}{L_f}$$

Optical losses degrade squeezing

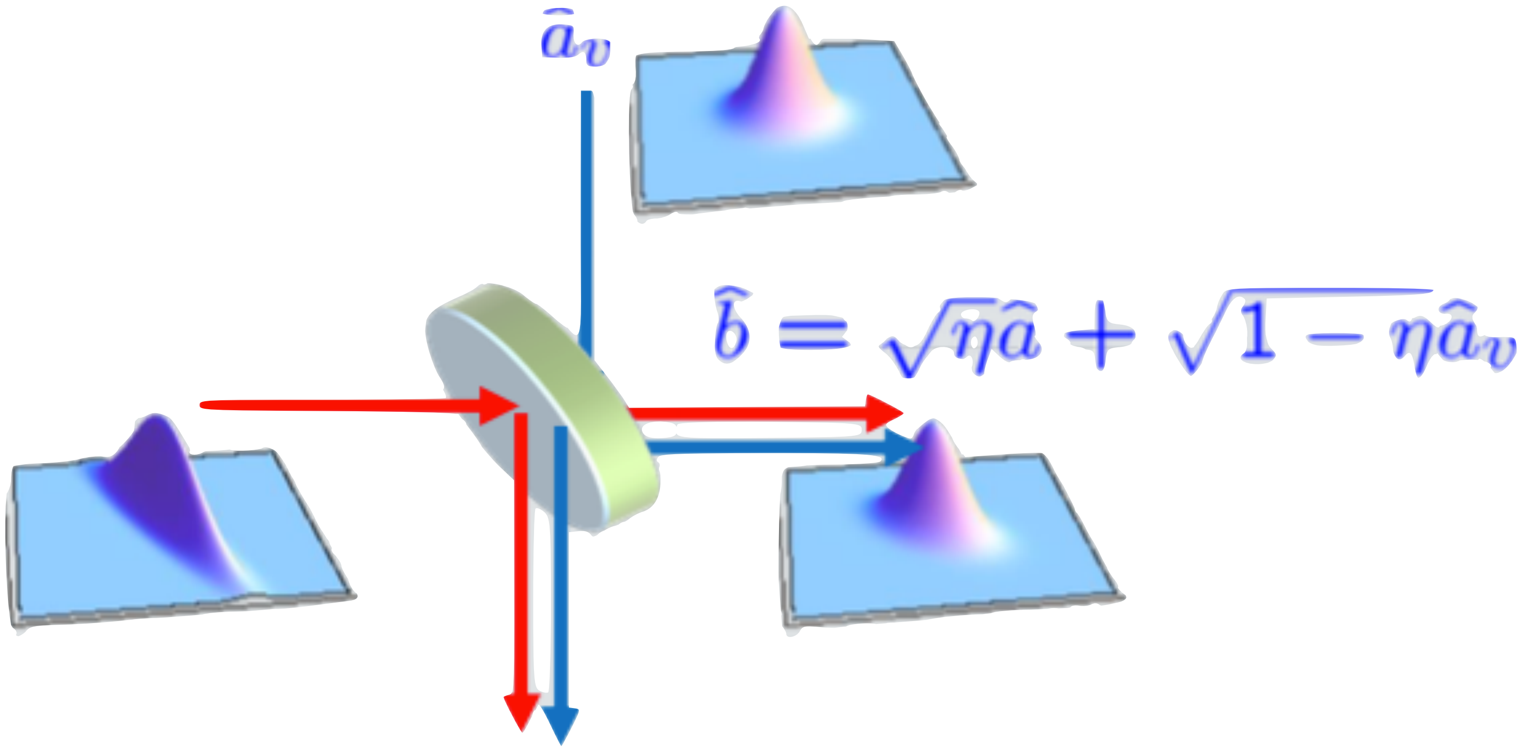
- Naive model



$$[\hat{a}, \hat{a}^{+}] = 1$$

$$[\hat{b}, \hat{b}^{+}] = \eta \neq 1$$

- Consistent model



Squeezing degraded because of its recombination with non squeezed vacuum