Status of the frequency dependent squeezing experiment at TAMA

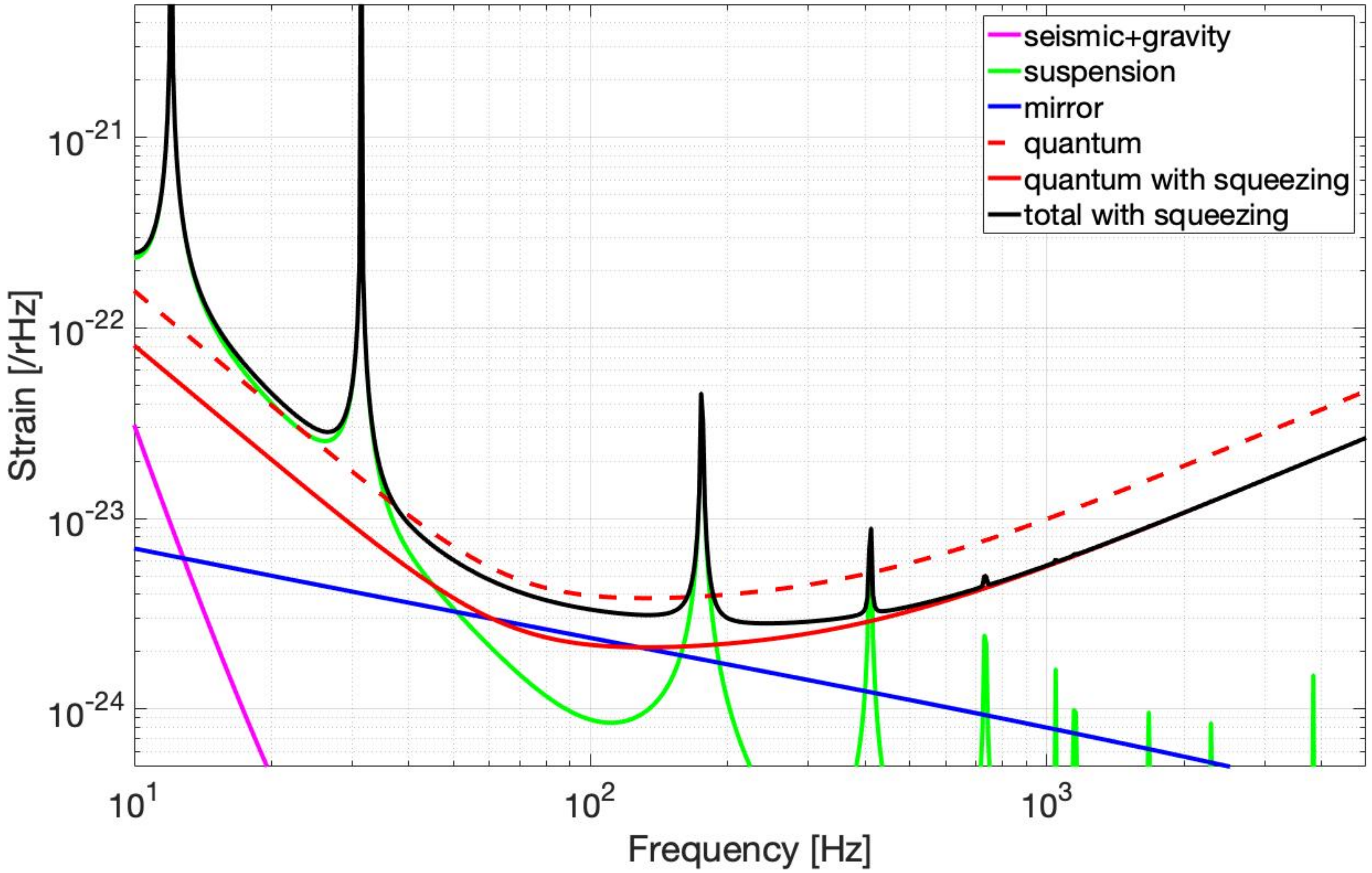
K. Arai, N. Aritomi, Y. Aso, M. Barsuglia, E. Capocasa, M. Eisenmann, R. Flaminio, Y. Guo, R. Lee, M. Leonardi, H. Lück, M.Marchiò, L. Pinard, P. Prat, R. Schnabel, E. Schreiber, K. Somiya, M. Tacca, R. Takahashi, D. Tatsumi, A. Tomura, H. Valbruch, M. Vardaro, C.Wu, S. Wu, Y. Zhao

supported by the JSPS Grant-in-Aid for Scientific Research (Grant code 15H02095)

1st KAGRA-Virgo-3G Detectors Workshop **16/02/2019 Perugia**

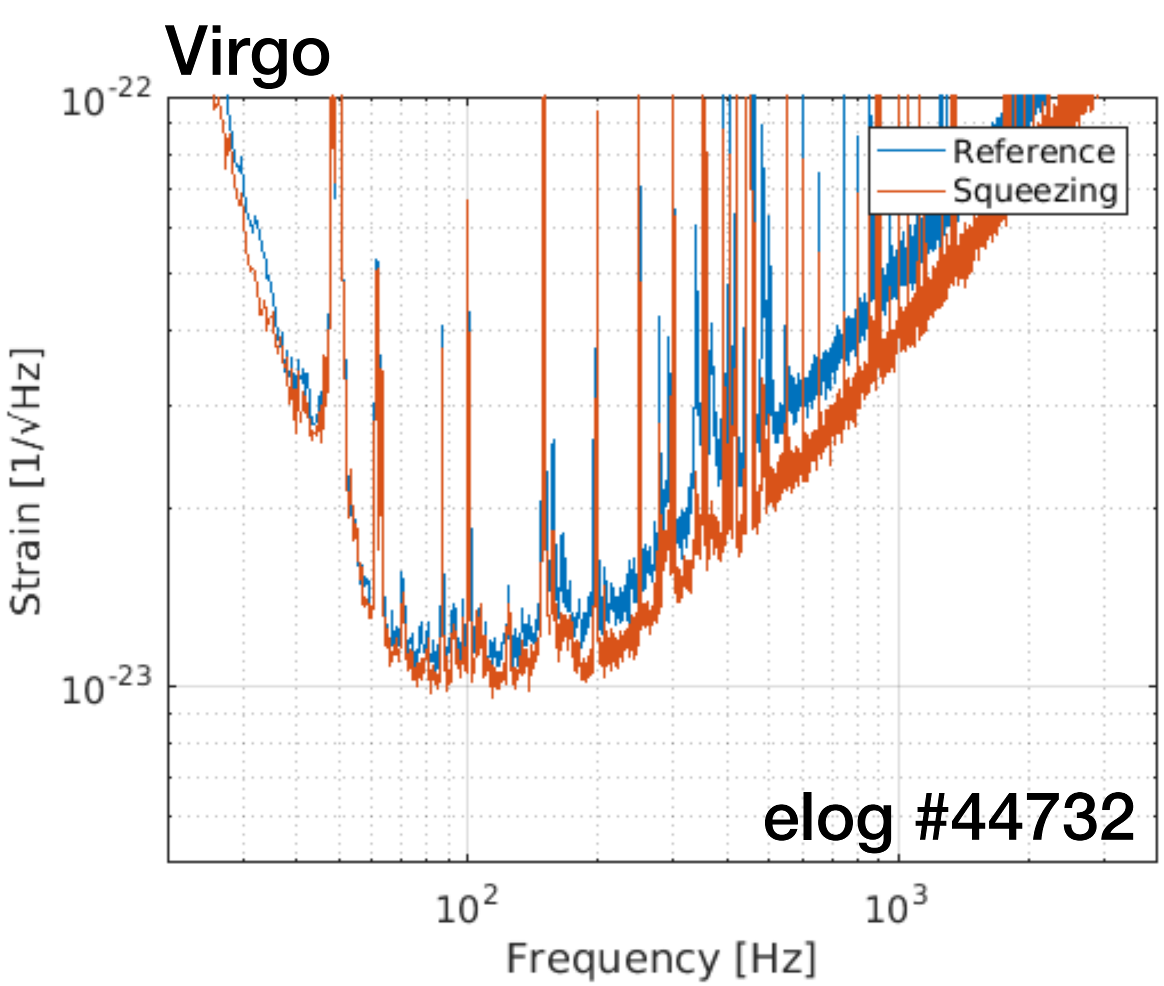
Motivation and context

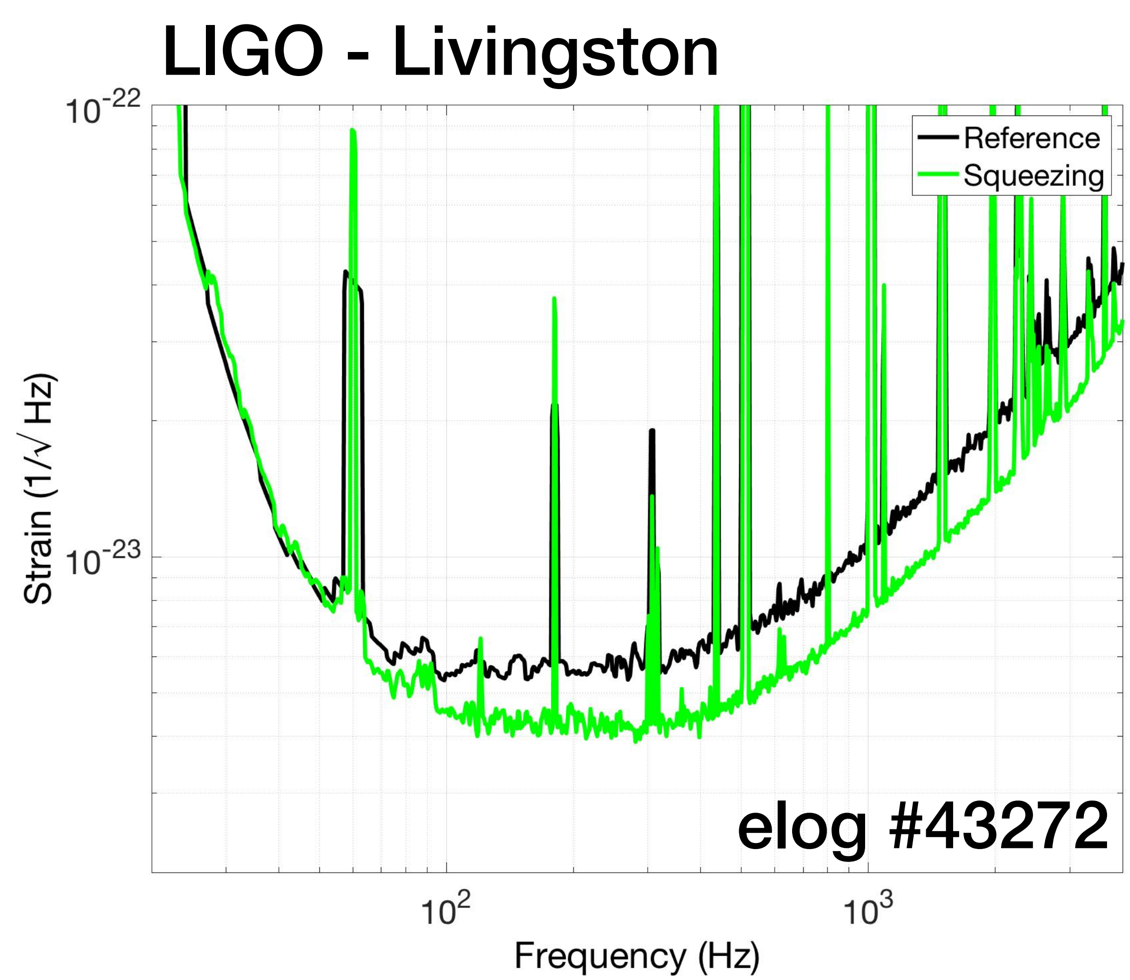
- Frequency dependent squeezing goal: broadband quantum noise reduction
- Especially beneficial for KAGRA (larger quantum noise limitation, difficult to increase power)
- 300 m filter cavities planned for LIGO and Virgo in O4
- KAGRA future plan committee is including filter cavity among future upgrades in the white paper



Frequency independent squeezing

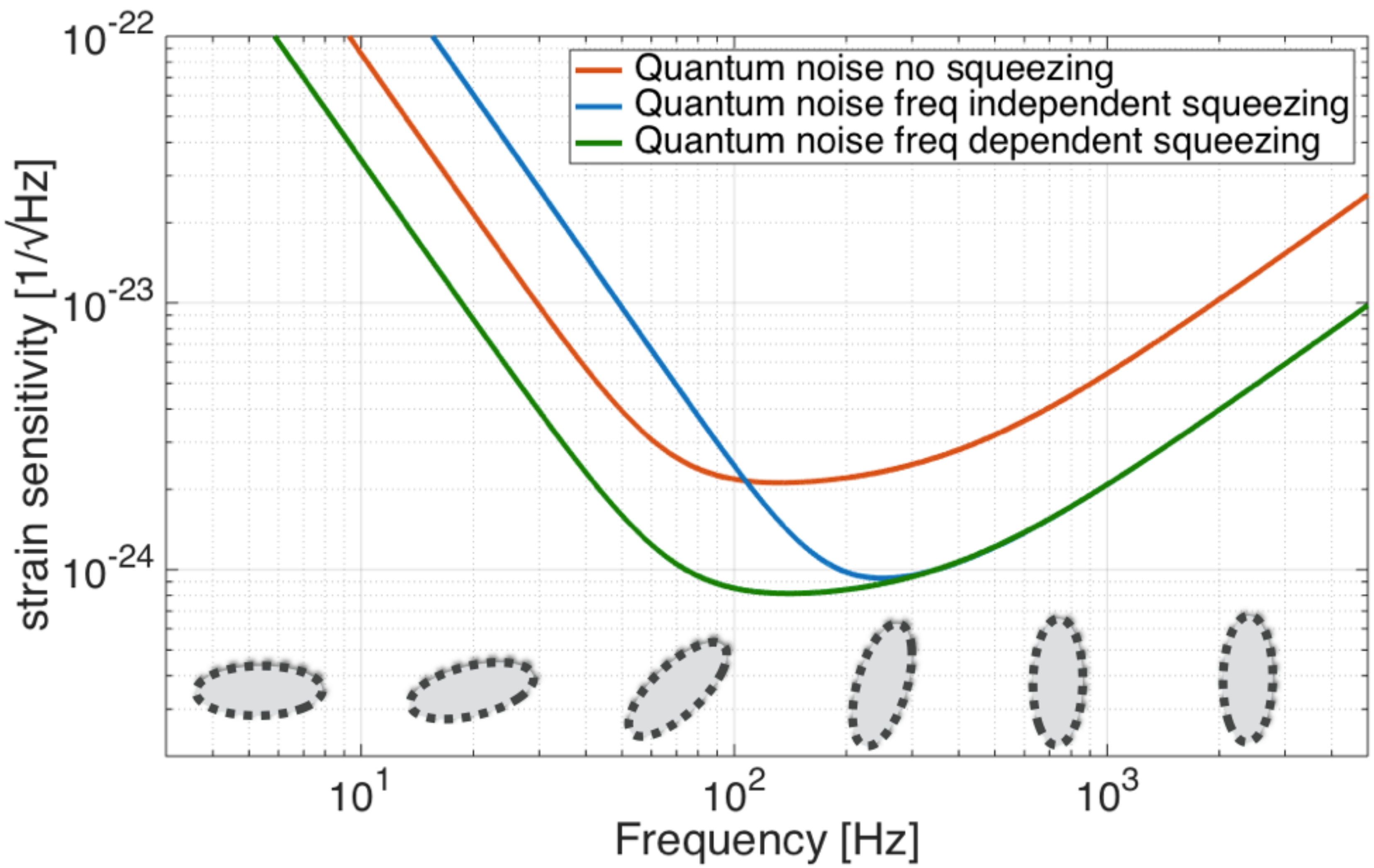
- Installed in LIGO and Virgo for O3
- Can only improve the high frequency (shot noise)





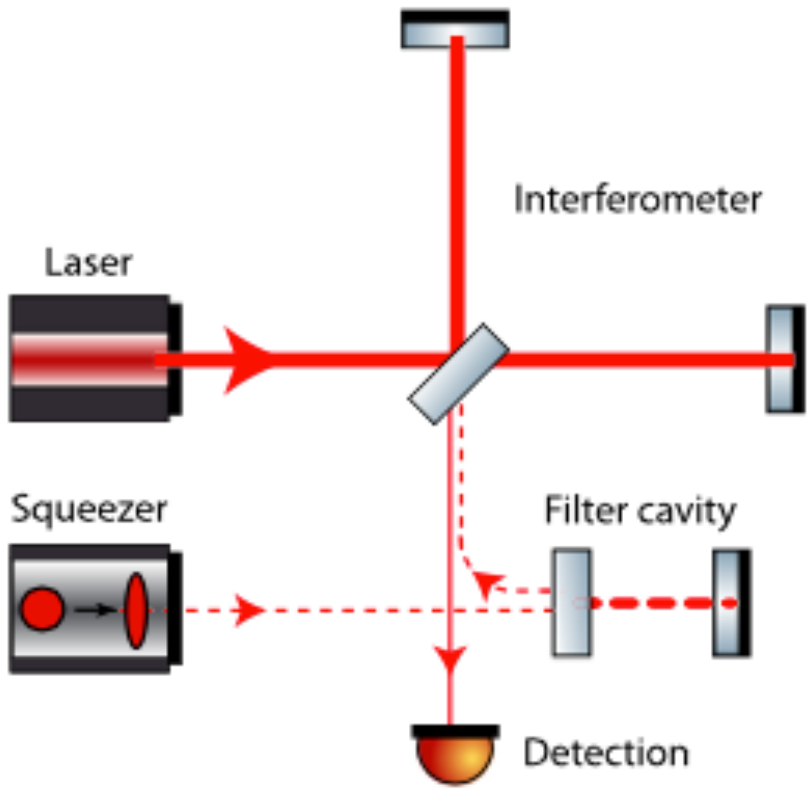
Frequency dependent squeezing

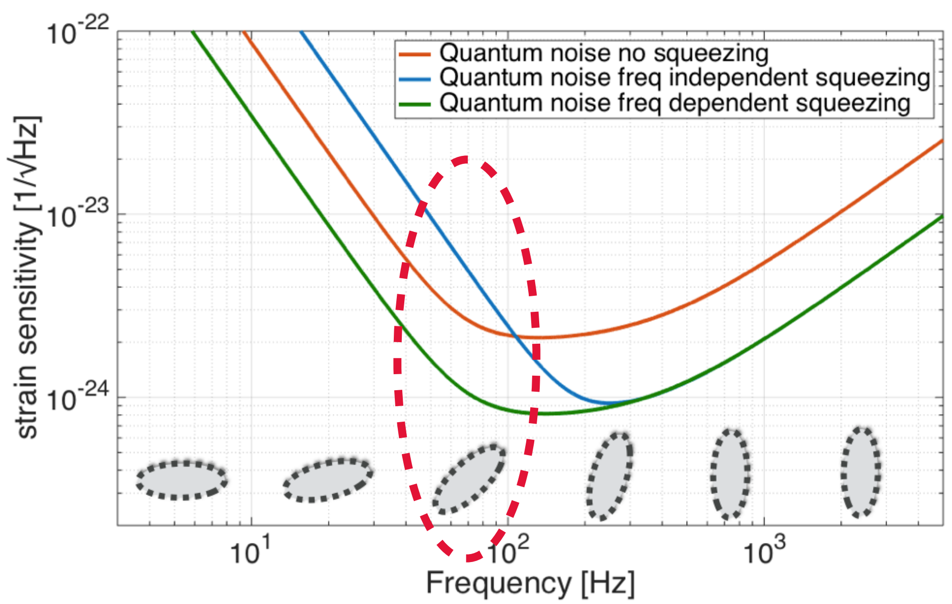
- Counteract IFO squeezing rotation
- Planned for O4 in LIGO and Virgo
- Broadband quantum noise reduction

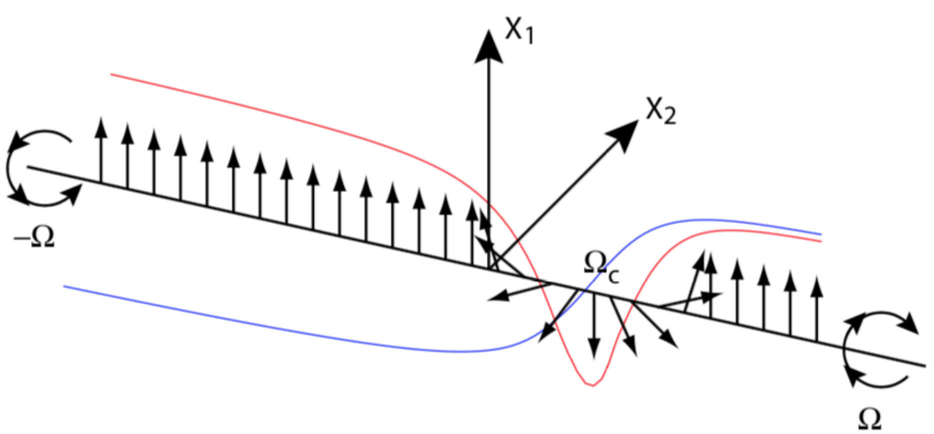


How to produce frequency dependent squeezing?

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



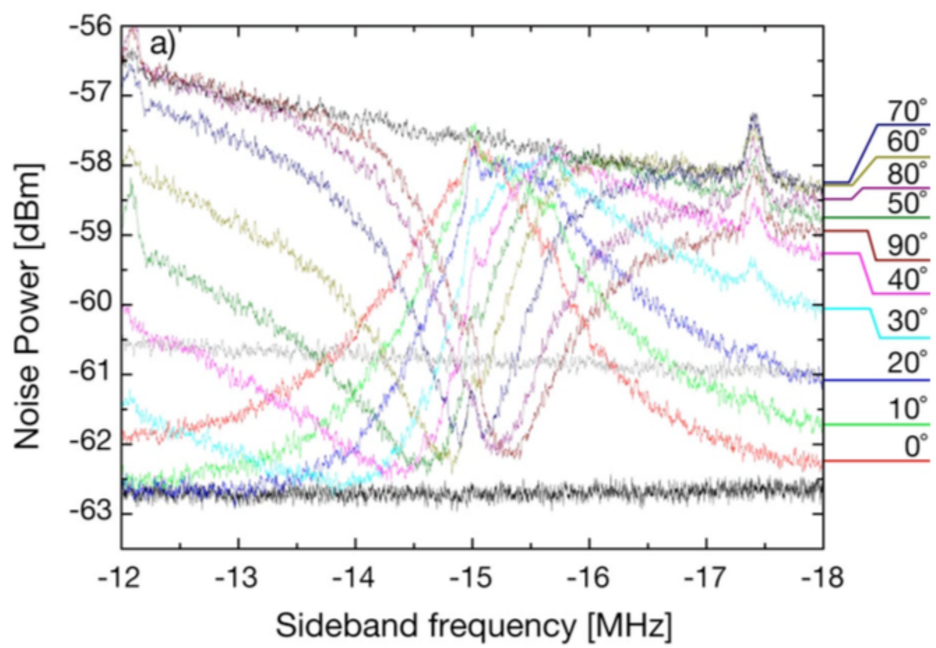




Optimal rotation frequency between 40 and 70 Hz

Squeezing angle rotation already realized

@ MHz frequency

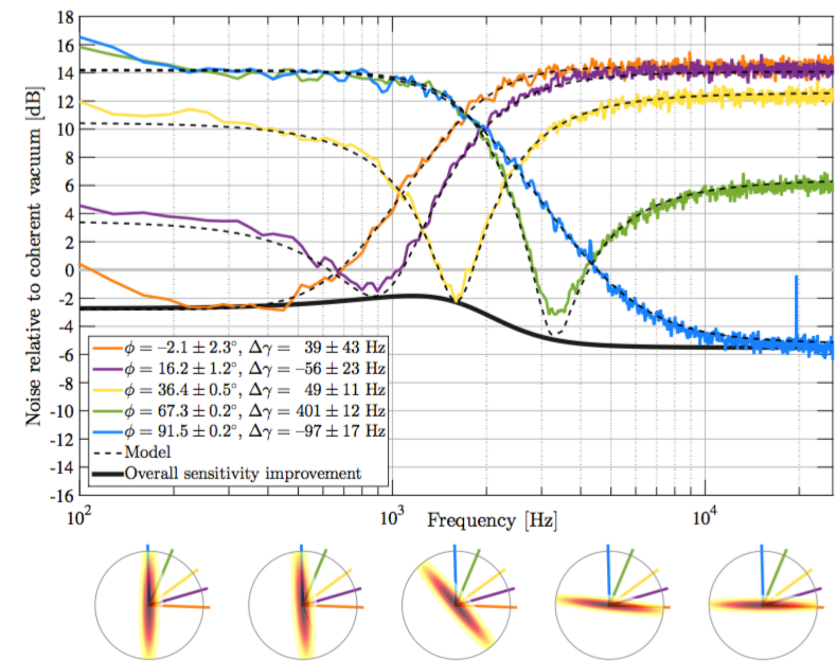


PHYSICAL REVIEW A **71**, 013806 (2005)

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*

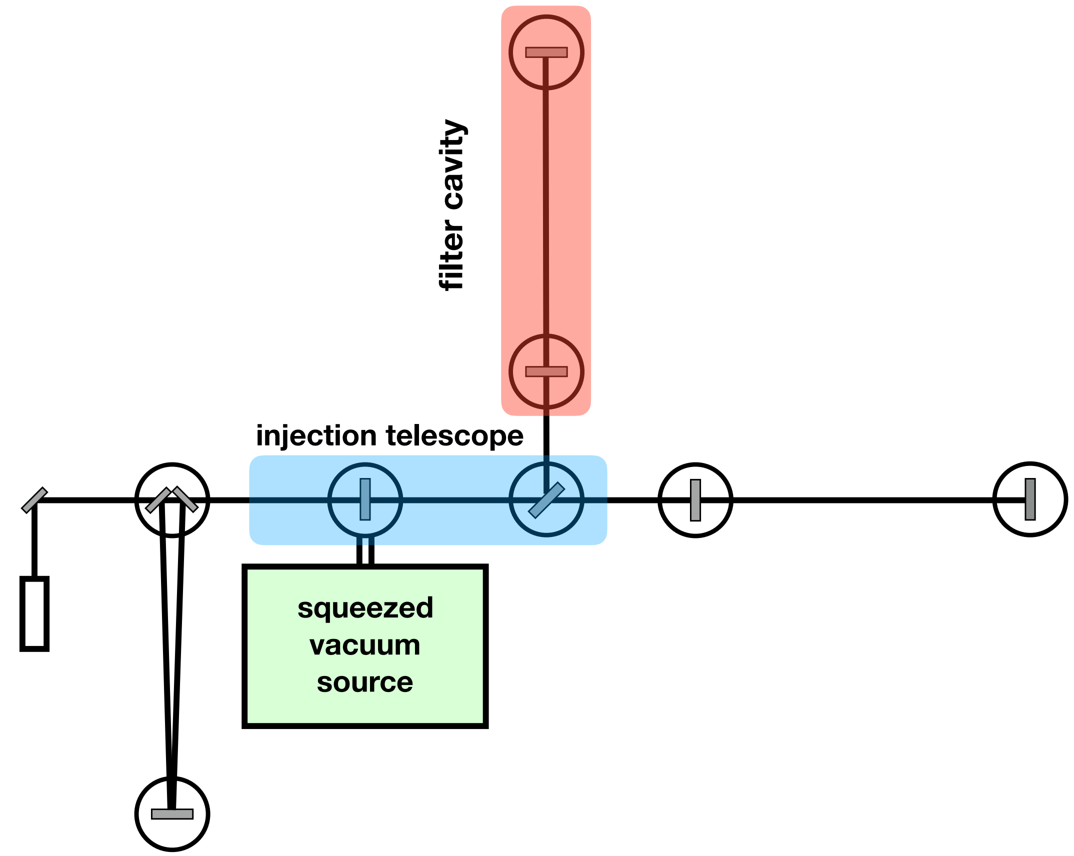
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

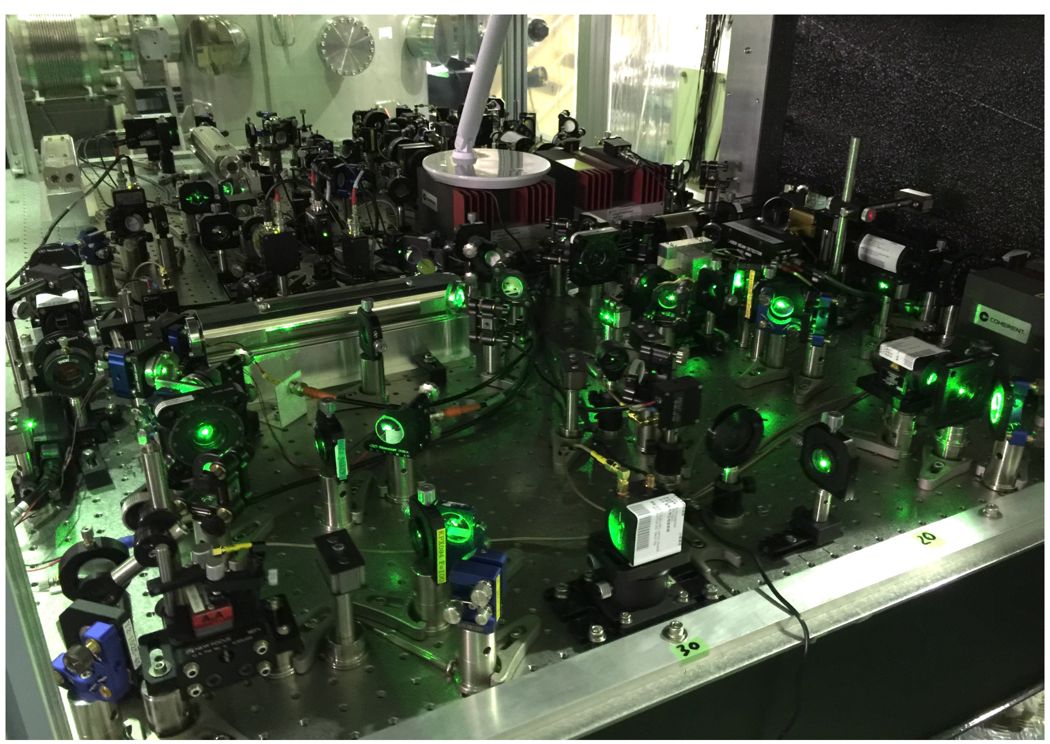
(Received 20 August 2015; revised manuscript received 10 December 2015; published 29 January 2016)

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

Experiment overview

- Cavity length: 300 m (TAMA arm)
- Finesse: 4400
- Freq. independent squeezing source based on AEI/Virgo design



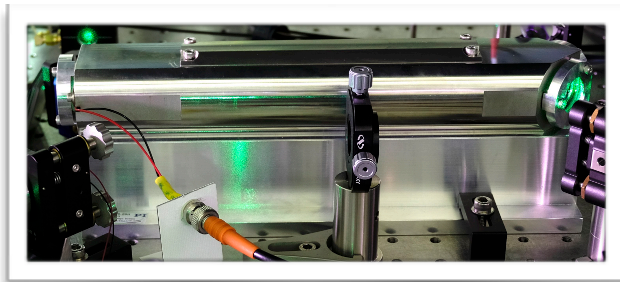


Squeezing bench

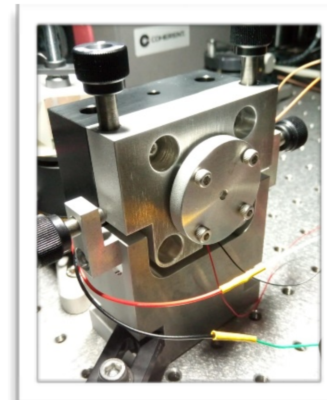
TAMA central building

Squeezed vacuum source

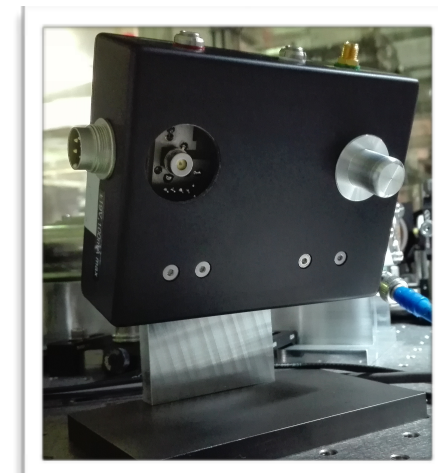
Green mode cleaner



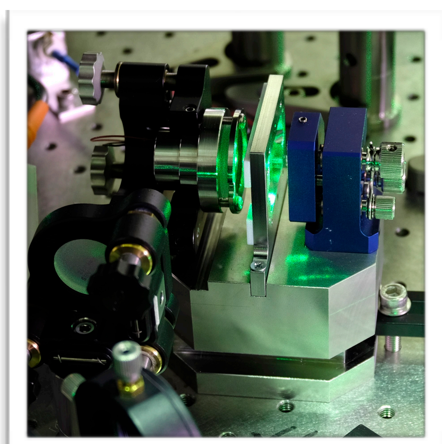
OPO to produce squeezed vacuum



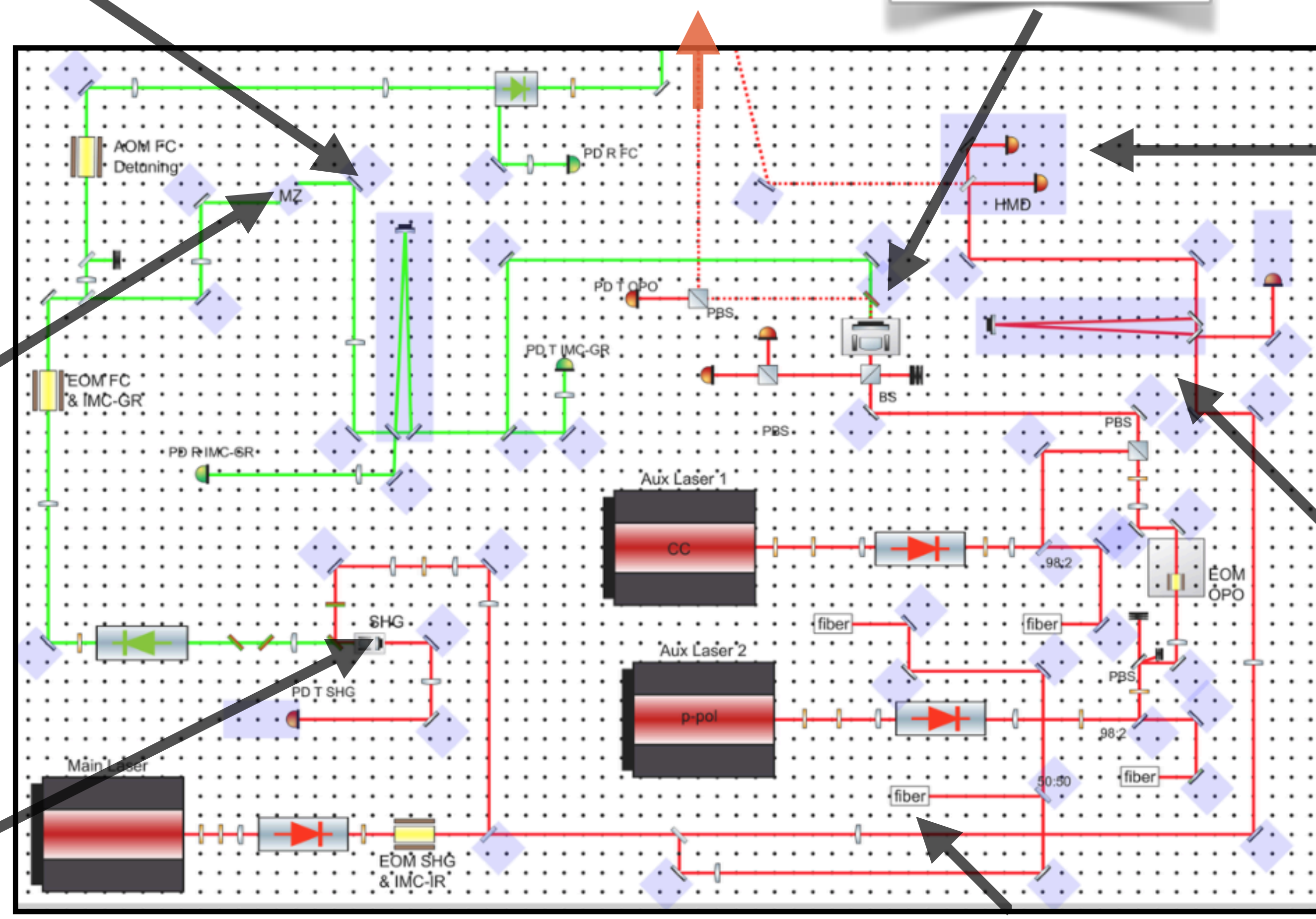
Homodyne detector (in collaboration with AEI, Hannover)



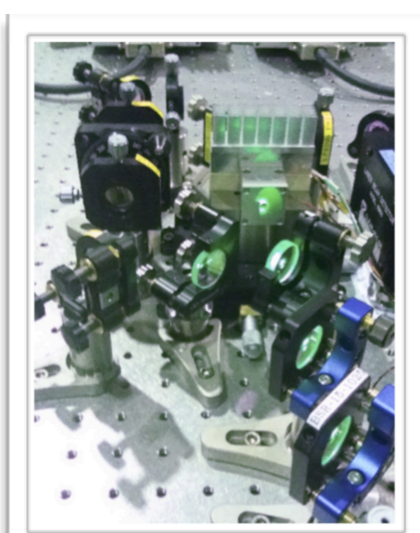
Mach-Zhender to stabilize the green pump



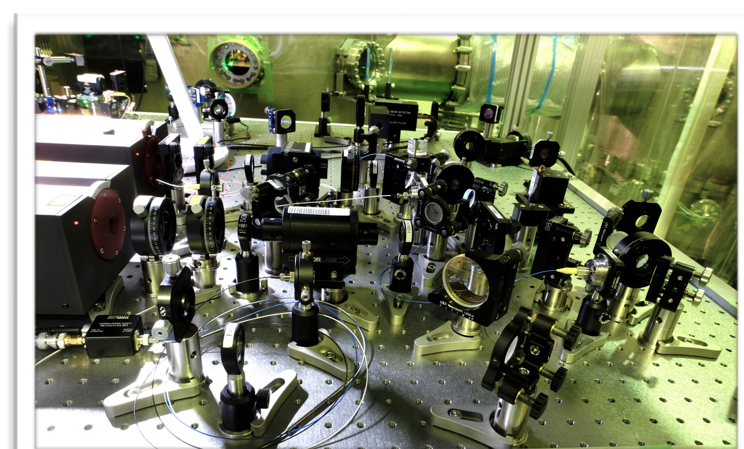
TO FILTER CAVITY



IR mode cleaner



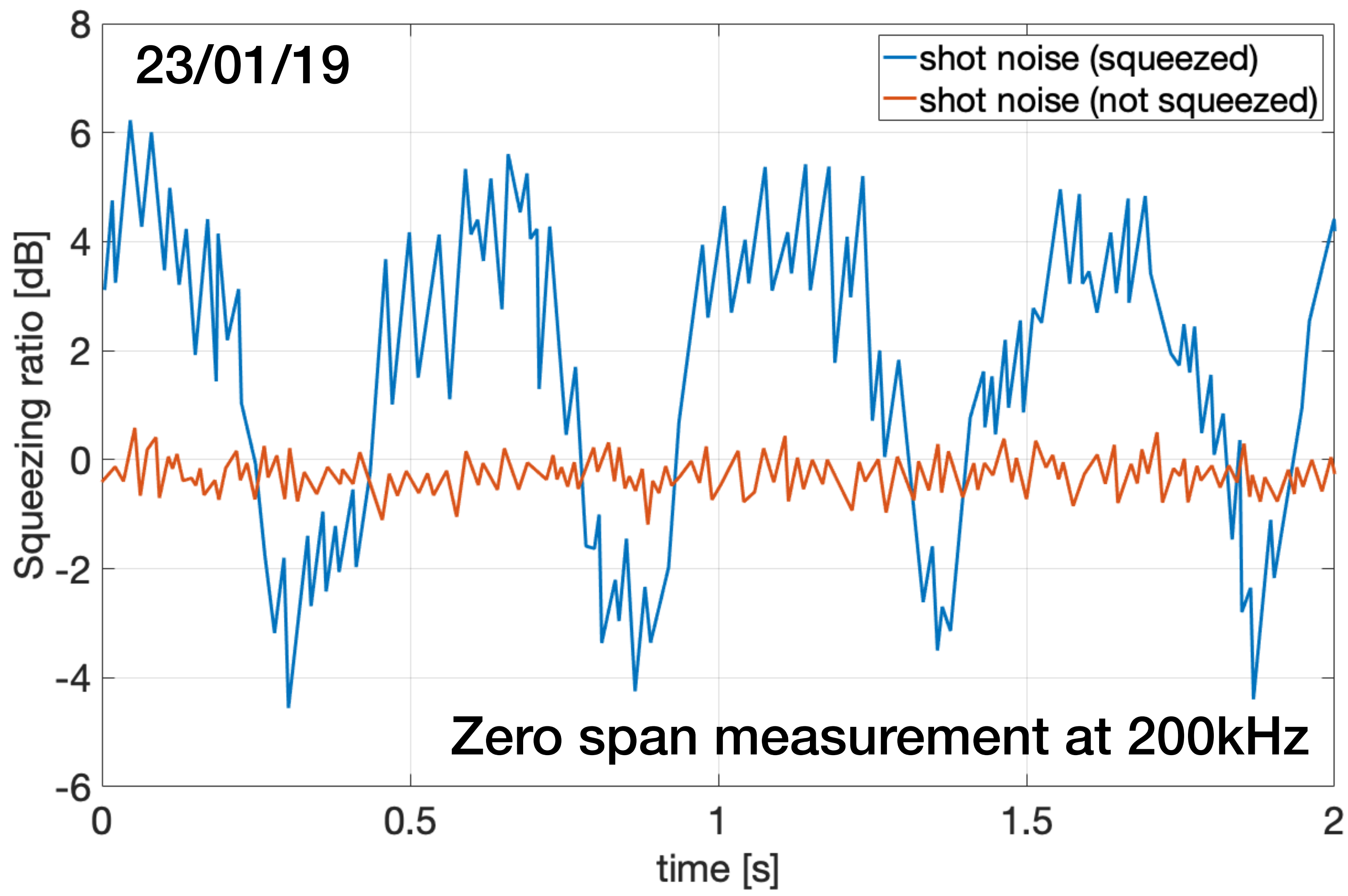
Second Harmonic Generator to produce green pump



PLL with main laser and auxiliary lasers

First squeezing measurement done!

- About 3 dB of squeezing (and 5dB of anti-squeezing) down to ~100 kHz



Squeezed vacuum source: ongoing

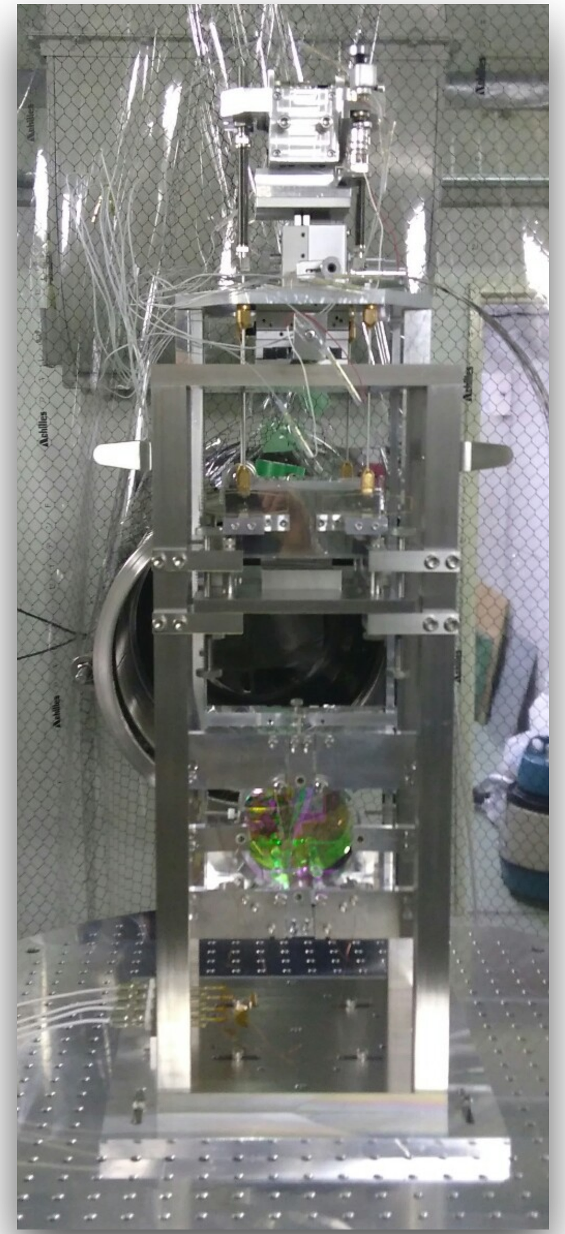
- Implementation of a control loop to reduce phase noise (coherent control)

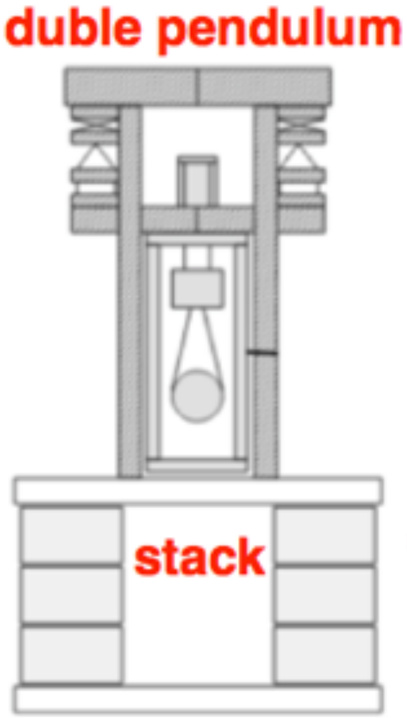
- Upgrade and automation of the analog servos for the control of cavities and other loops on the bench

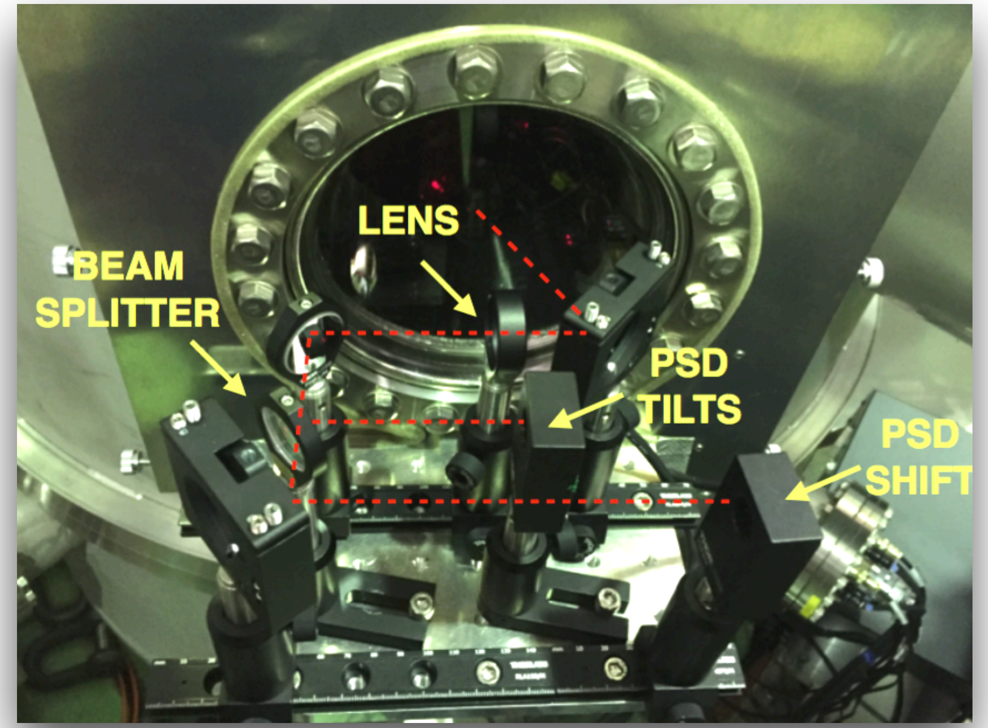
- Noise hunting to reach low frequency squeezing (~tens of Hertz)

Cavity mirror suspensions

- TAMA vibration isolation stack and double pendulum suspension (type C)
- Virgo-like optical levers used for local control damping

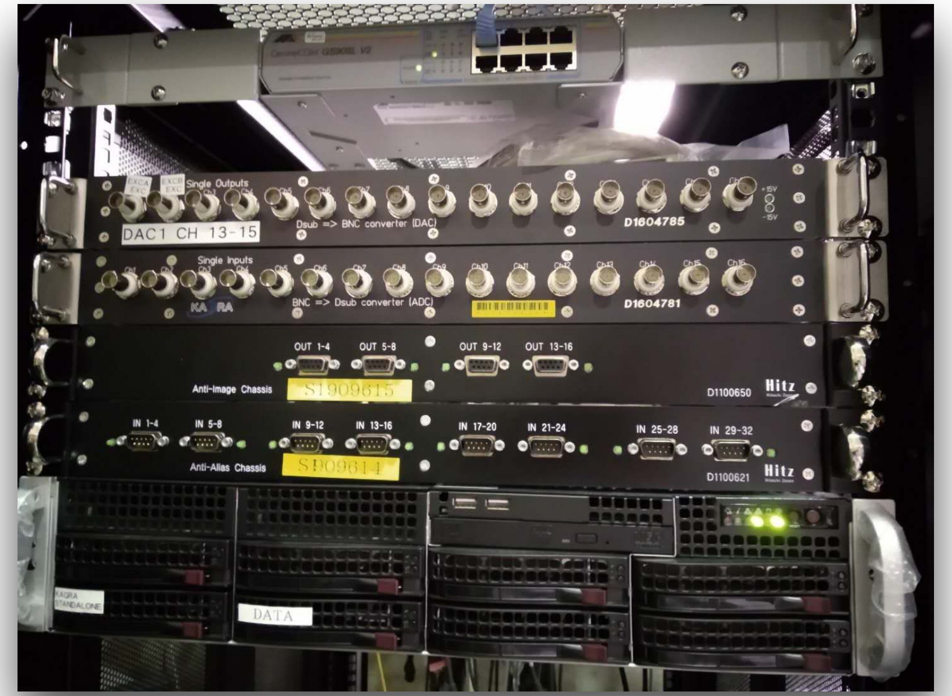


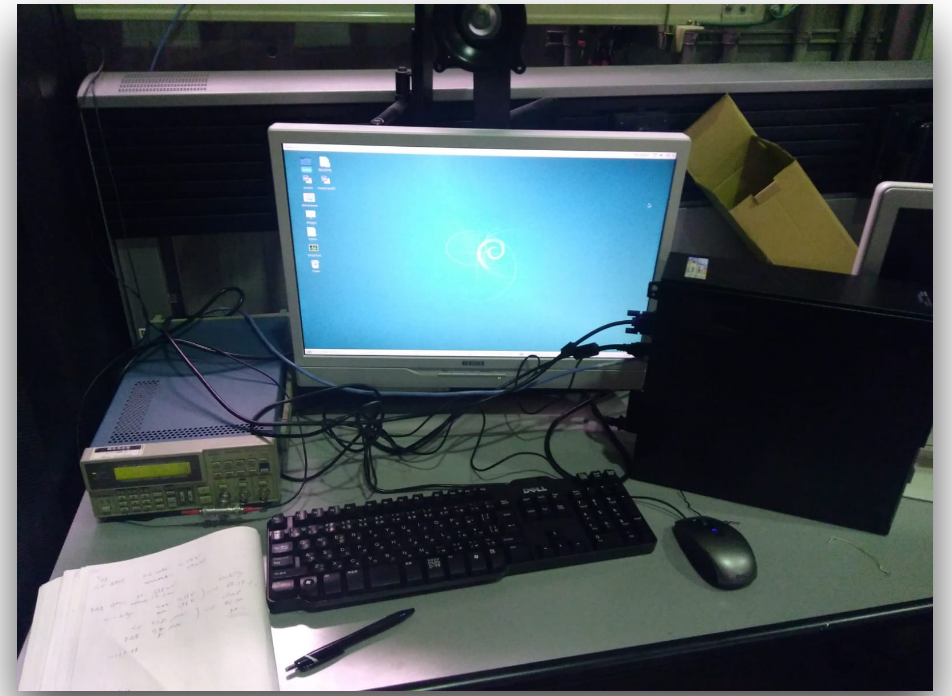




Control system upgrade on-going

- Thanks to the help of KAGRA DGS people, we are replacing our old LabVIEW based control system with a standalone KAGRA digital system

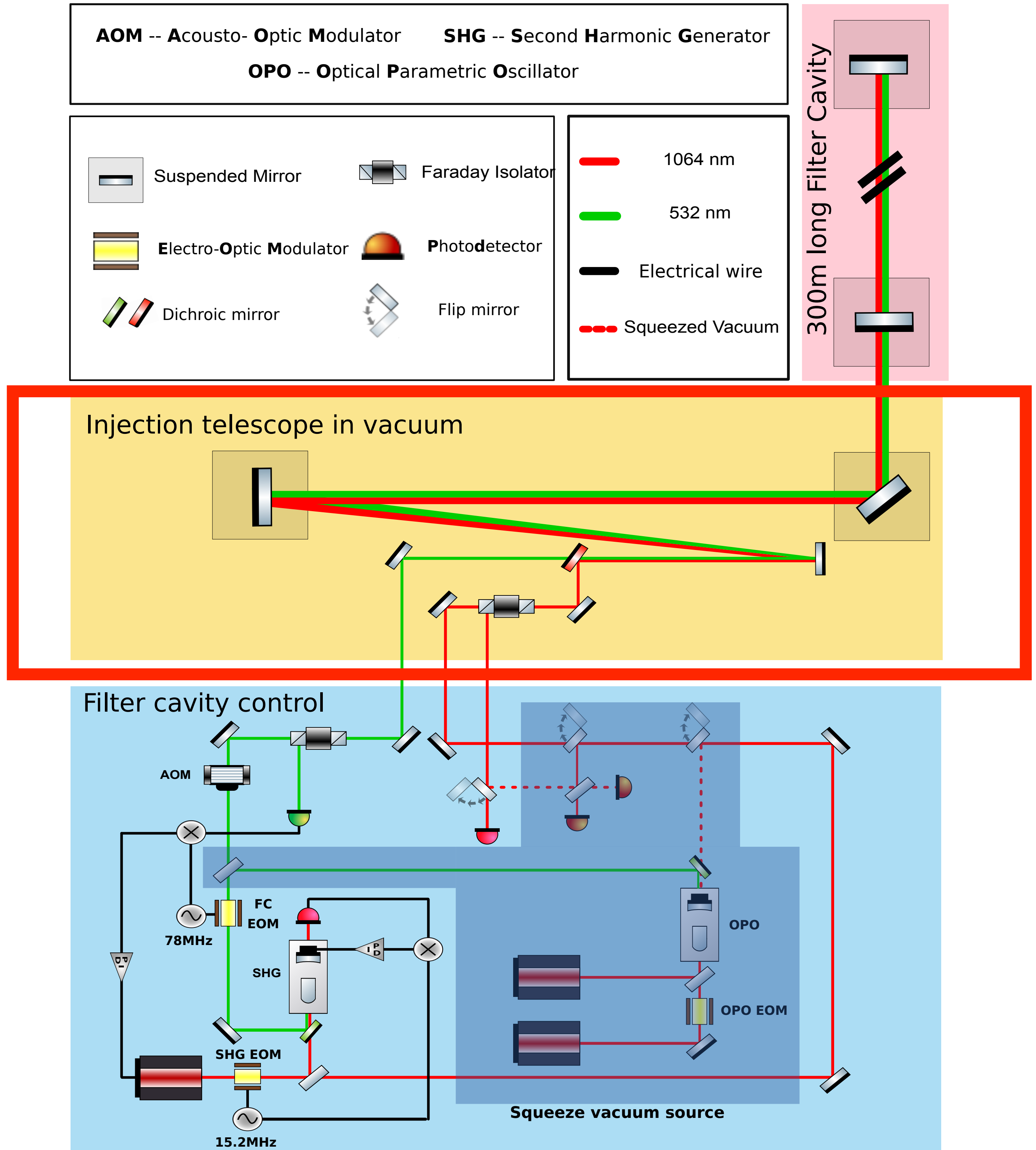




- Useful to train students who will work on KAGRA site and for future use of TAMA infrastructure

Injection path and alignment

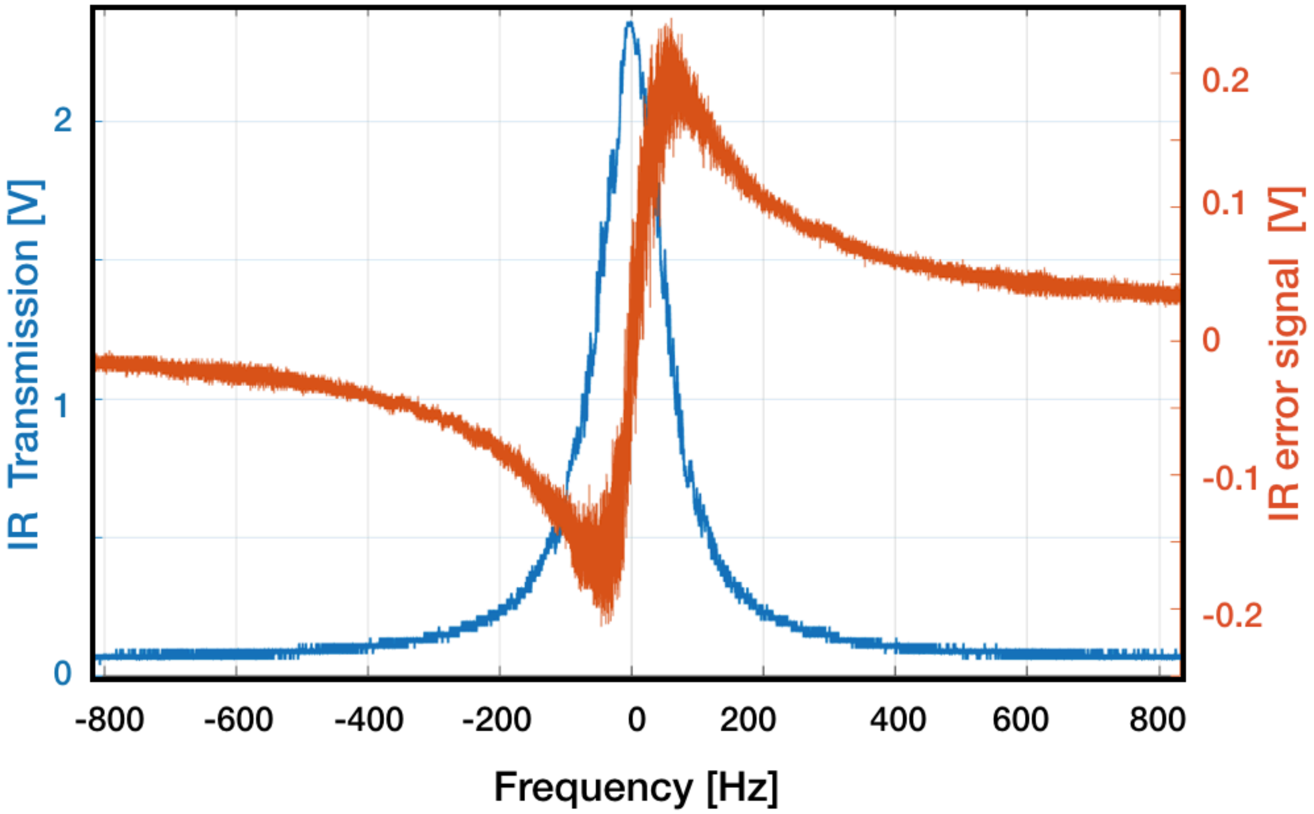
- IR beam and green beam (used for the control) recombined in vacuum
- Dichroic mode matching telescope
- Automatic alignment on green will be implemented soon



Cavity control

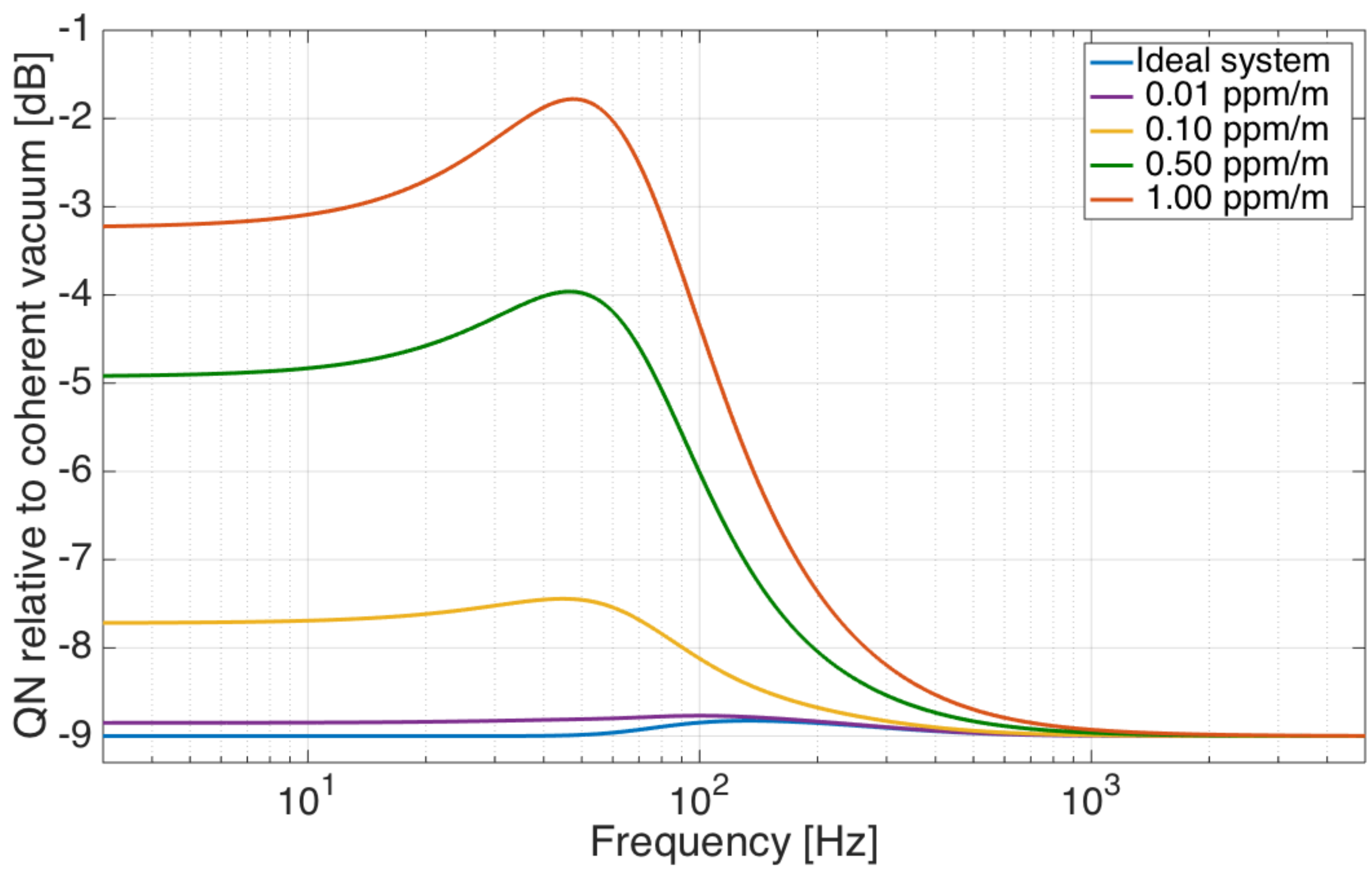
- Main laser locked on the cavity length using a part of the green beam from SHG
- Analog servo with 20 kHz bandwidth (green beam finesse: 170)
- IR beam detuning controlled with a AOM on the green path

IR resonance crossing by driving AOM



Cavity characterization: round trip losses measurement

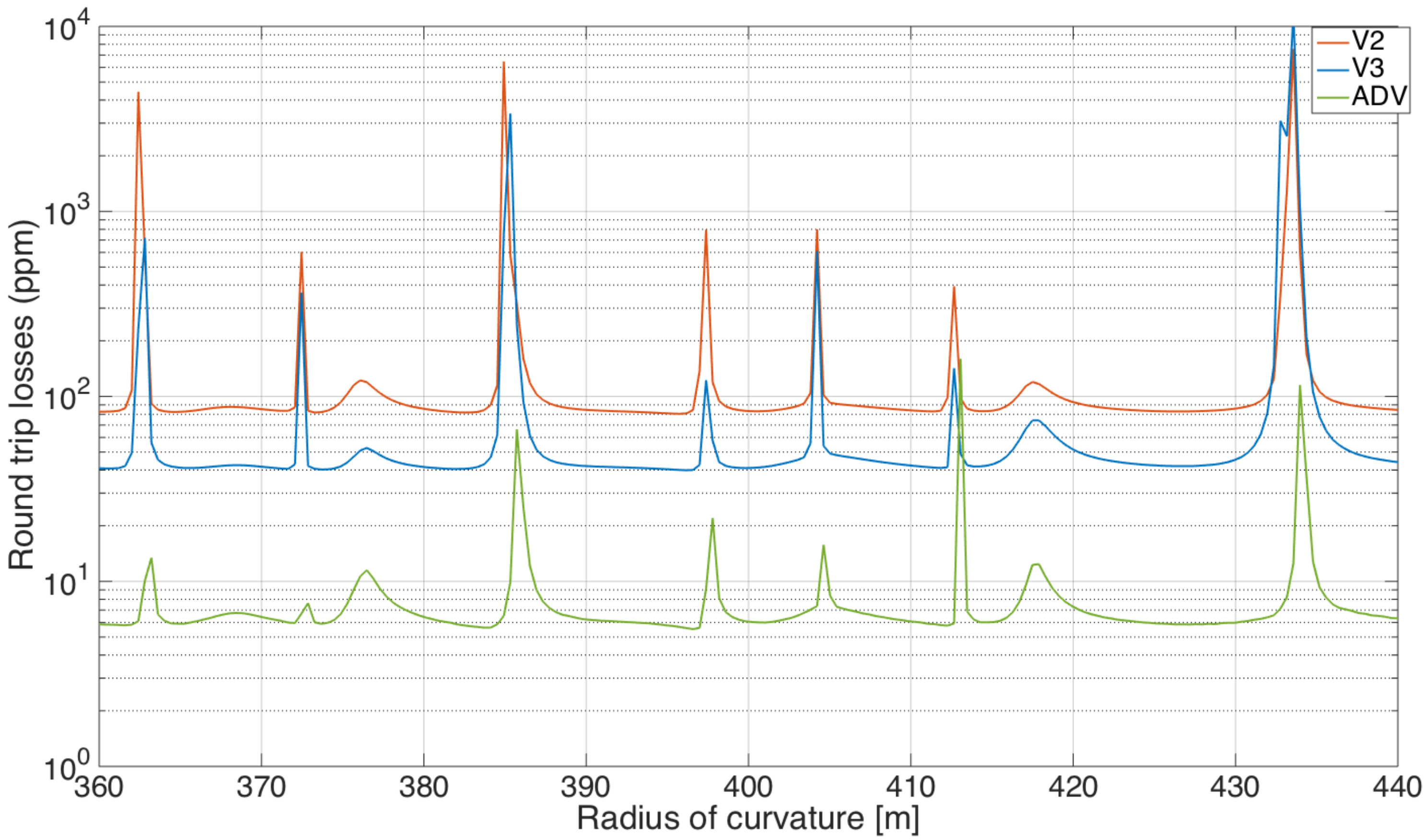
- Important quantity for the squeezing degradation: losses per unity length
- Crucial measurement for designing filter cavities in GW detectors upgrades



Squeezing degradation for different round trip losses values

Cavity design: requirement on the mirrors flatness

- FFT simulation to measure round trip losses using real Virgo Mirror map
- In order to set the loss threshold we needed to consider also the other squeezing degradation sources



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

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

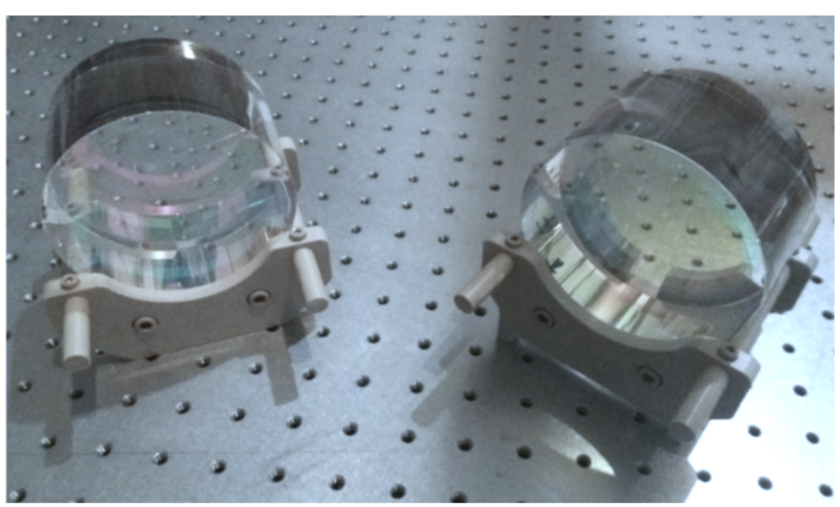
Estimation of losses in a 300 m filter cavity and quantum noise reduction in the KAGRA gravitational-wave detector

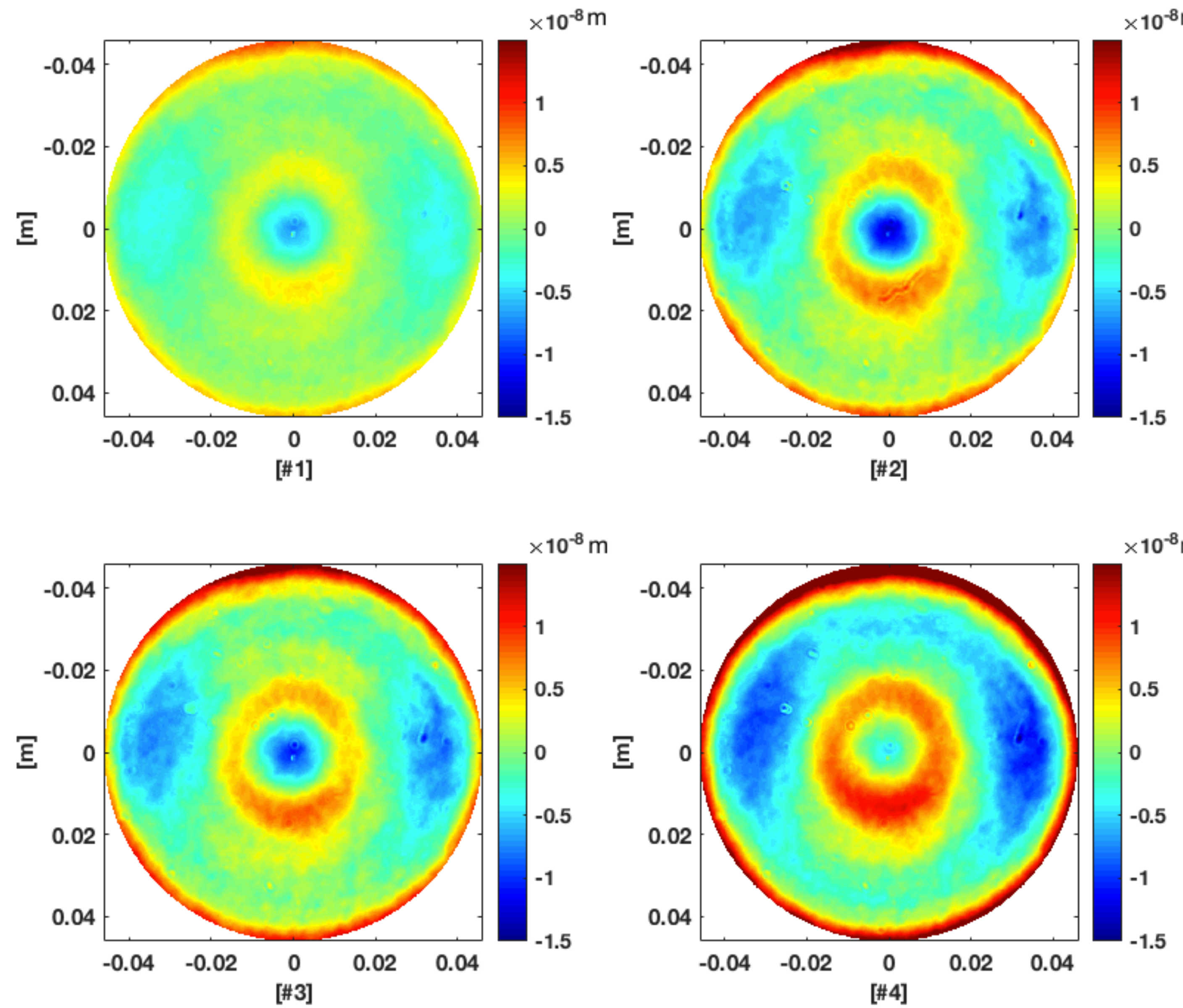
Eleonora Capocasa,[1,2,*] Matteo Barsuglia,[1] Jérôme Degallaix,[3] Laurent Pinard,[3] Nicolas Straniero,[3] Roman Schnabel,[4] Kentaro Somiya,[5] Yoichi Aso,[2] Daisuke Tatsumi,[2] and Raffaele Flaminio[2]

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

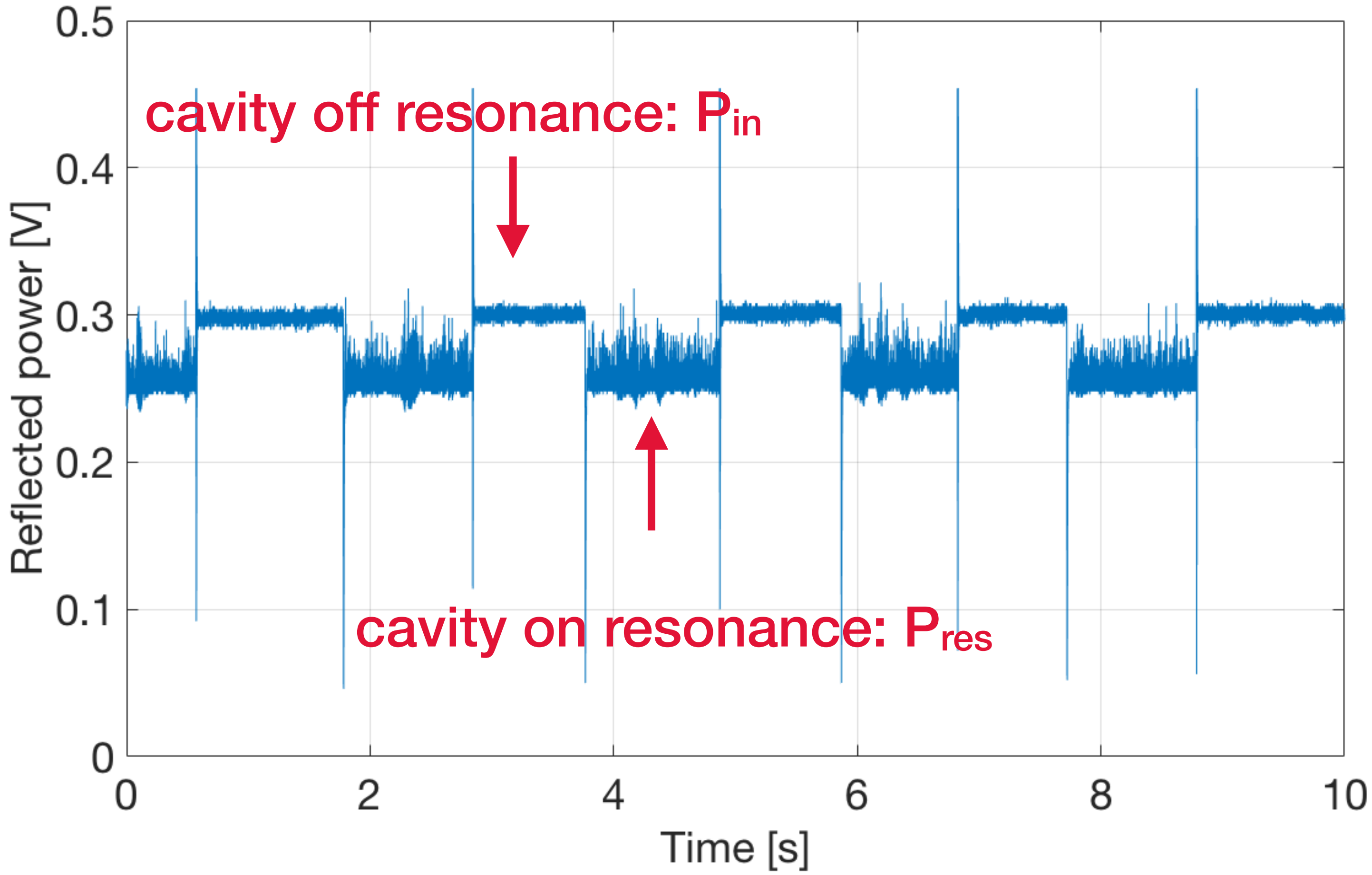




Substrates coated and characterised at LMA

Round trip losses measurement

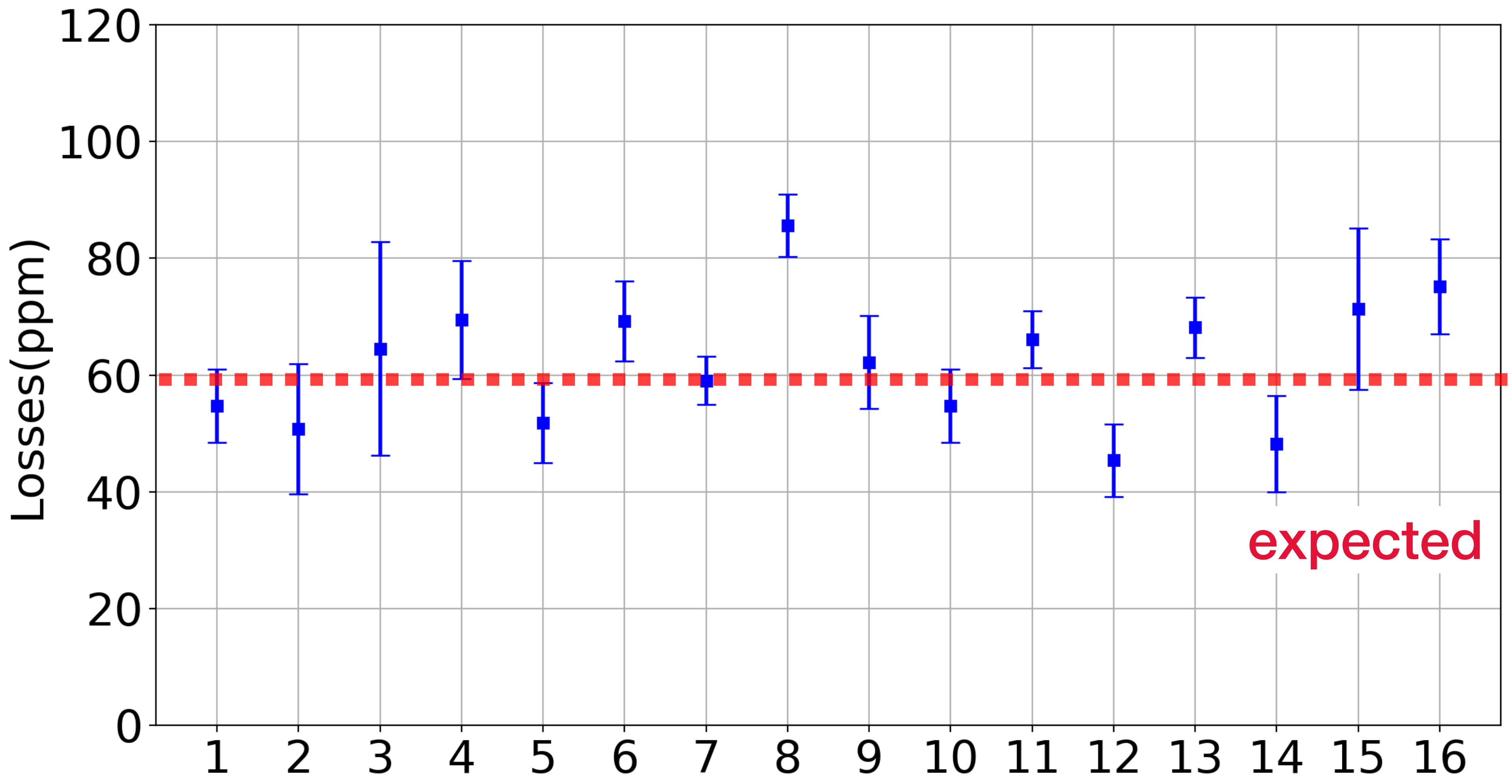
- Round trip losses computed from cavity reflectivity
- Set of on/off resonances switches to measure the cavity reflectivity



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

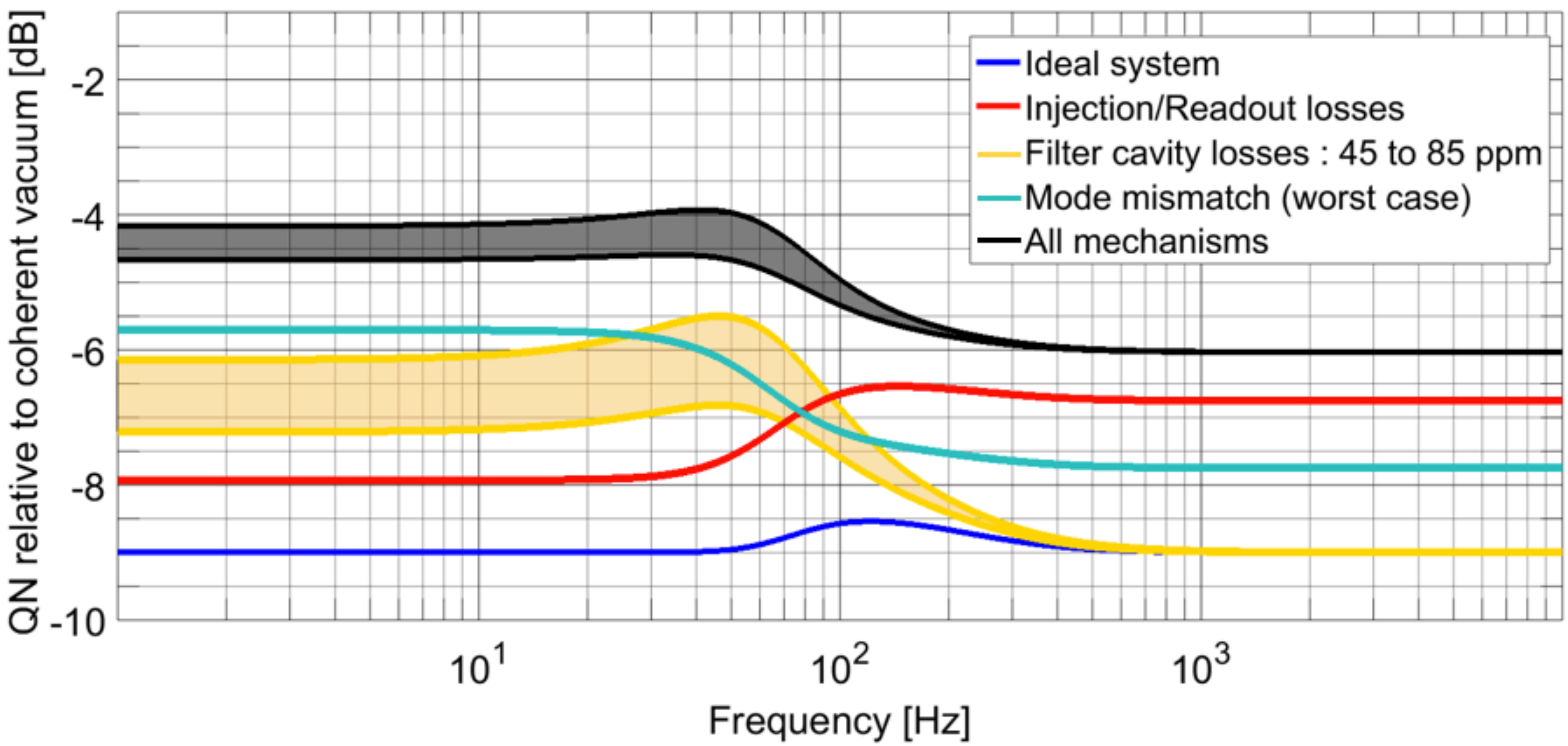
Round trip losses measurement

- Round trip losses between 45 and 85 ppm in agreement with what expected



Expected squeezing level

- Round trip losses below 85 ppm 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 collaborations

- Fruitful collaboration with groups from Virgo and Taiwan
- Many contributions given from visitors

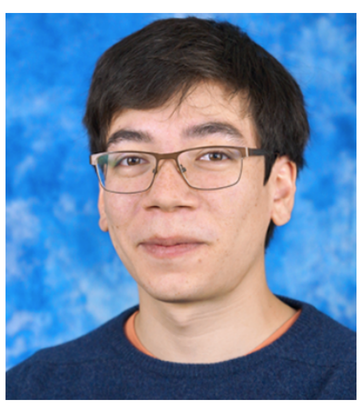
Emil Schreiber
GEO600/AEI

Shu-Rong Wu
Tsing Hua University

Marco Vardaro
Padova University

Matteo Barsuglia
APC/CNRS

Matteo Tacca
Nikhef



Marc Eisenmann
LAPP/CNRS

Yuefan Guo
Nikhef

Chien-Ming Wu
Tsing Hua University

Pierre Prat
APC/CNRS

Marco Banzan
Padova University

visits supported by JSPS Core-to-Core Program, A.Advanced Research Networks EU under the Framework Program 7 (FP7) 'People' project ELiTES (Grant Agreement No. 295153)
EU Horizon 2020 Research and Innovation Programme under the Marie Sklodowska-Curie Grant Agreement No.734303

Summary

- ~100 m scale filter cavities planned in near term upgrades of 2nd generation detectors
- Integration of squeezed vacuum source in TAMA completed
- First measurement of squeezed vacuum achieved:
  - ~3dB of squeezing and 5dB of anti-squeezing down to ~100 kHz
- Filter cavity installed, controlled and characterized:
  - Cavity round trip losses between 45 and 85 ppm, in agreement with the requirement

Next steps

- Increase the squeezing level and reach the low frequency
  - Phase noise control implementation
  - Servos upgrade and automation
  - Intensive noise-hunting
- Upgrade of the filter cavity control
  - Switch to KAGRA digital control system
  - Automatic alignment implementation
- Preparation for squeezing injection into the filter cavity
- Meanwhile: study of the filter cavity implementation in KAGRA

Useful experience for designing filter cavities planned for near term upgrades of 2nd generation GW detectors

Thanks for your attention!

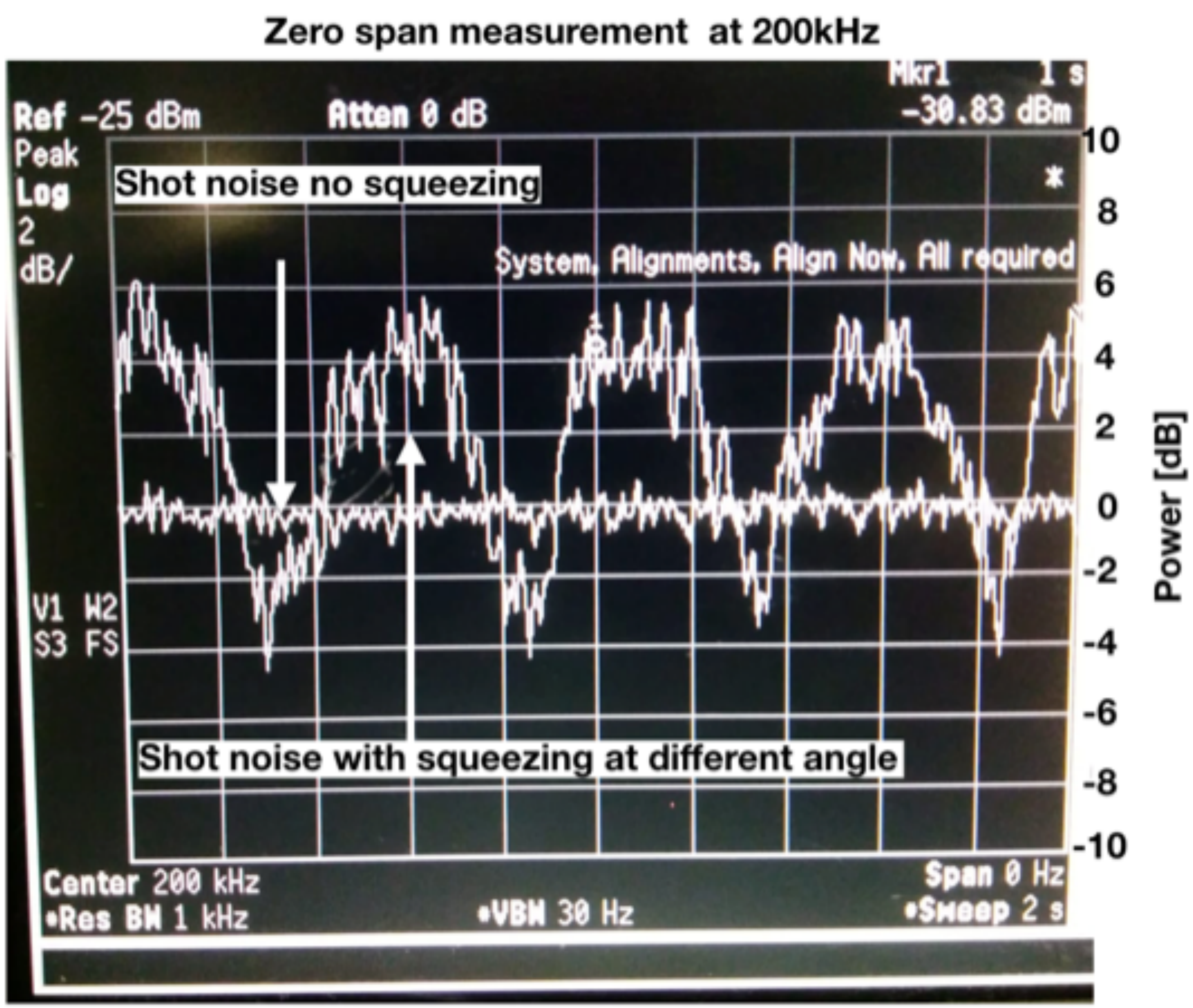
More information can be found on our wiki page:

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

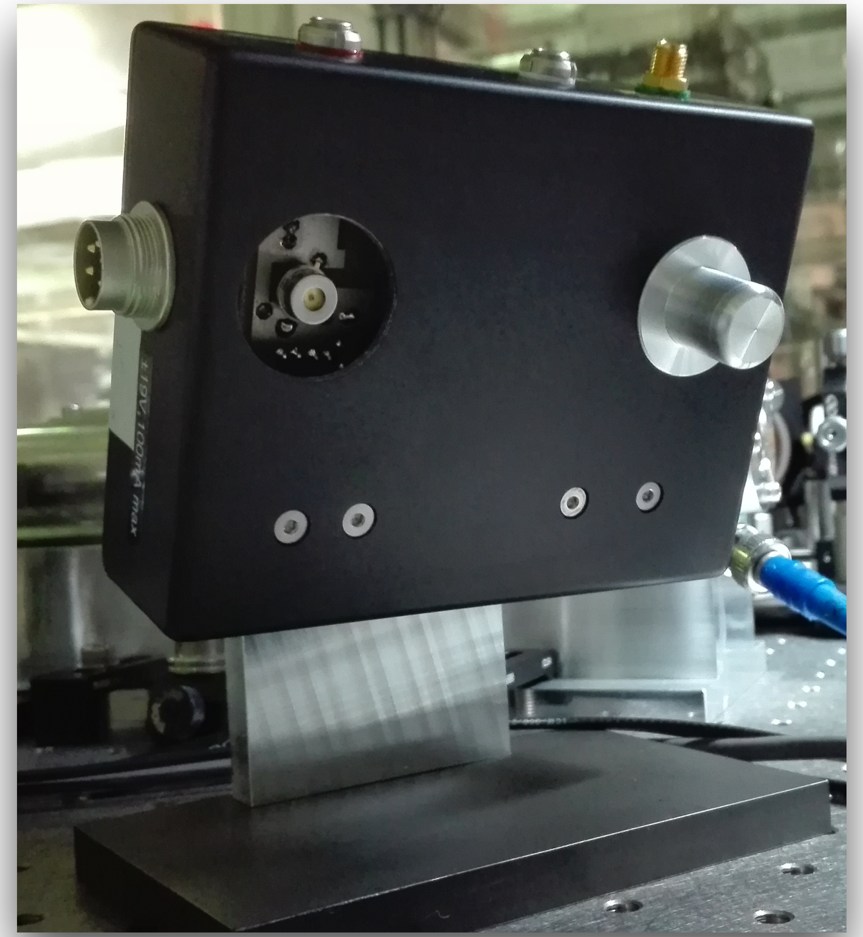
EXTRA SLIDES

First squeezing measurement done!

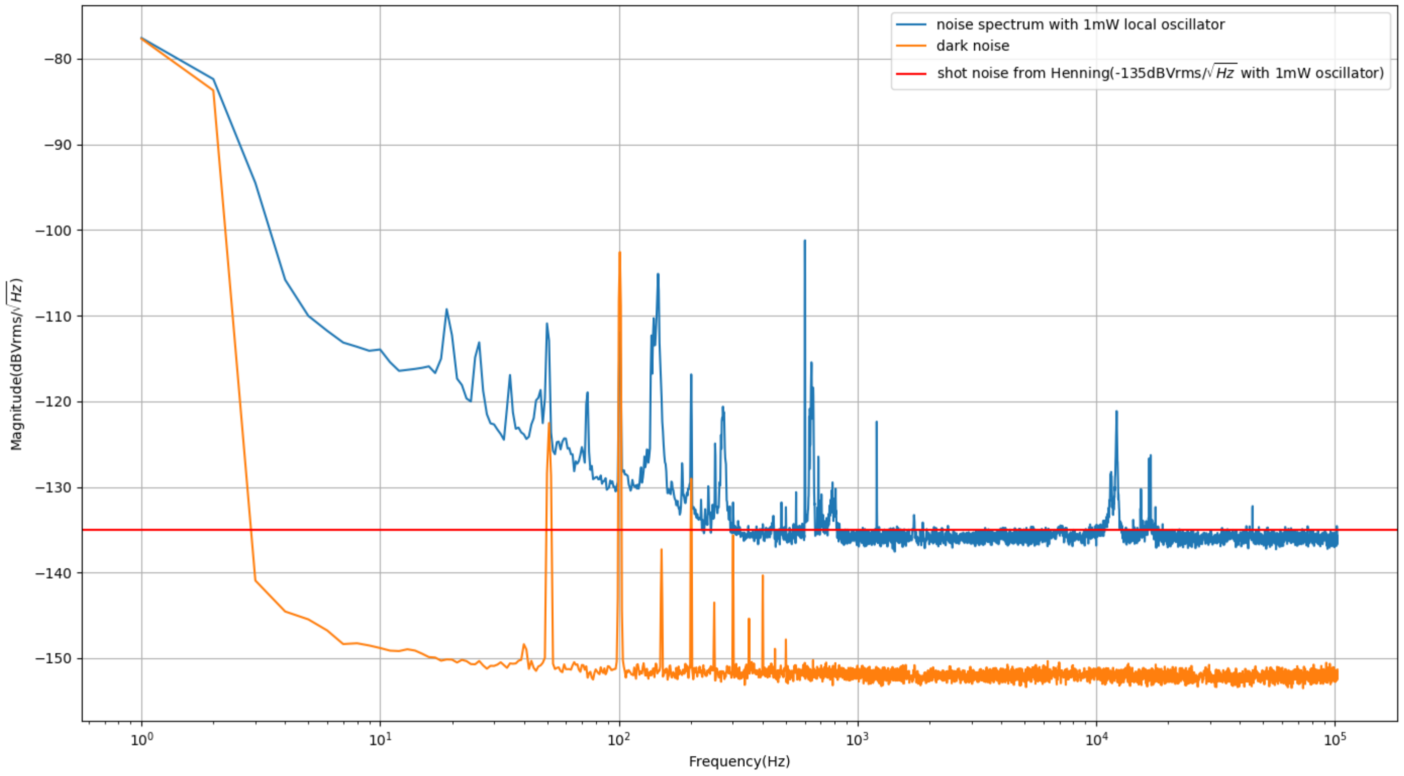
- ~3 dB of squeezing and (5db of anti squeezing) down to ~100 kHz



Homodye detection

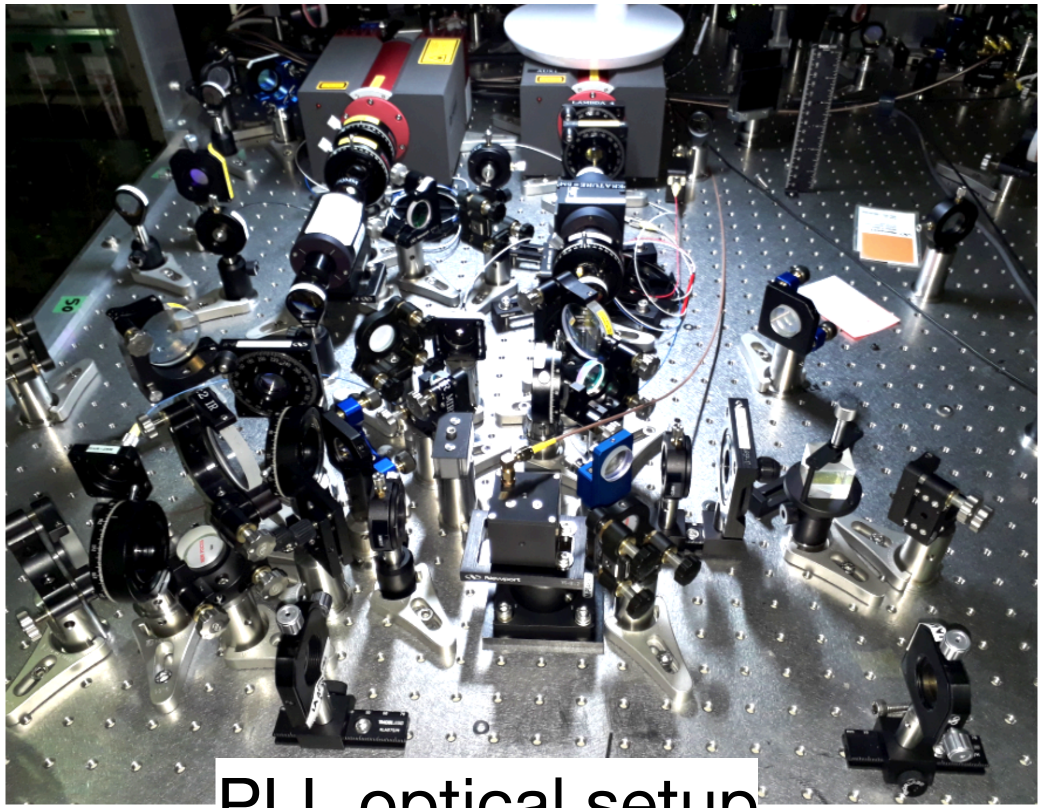


- Developed at AEI
- Successfully shipped to NAOJ
- Clearance >20 dB
- Shot noise limited down to 1kHz
- Noise hunting ongoing

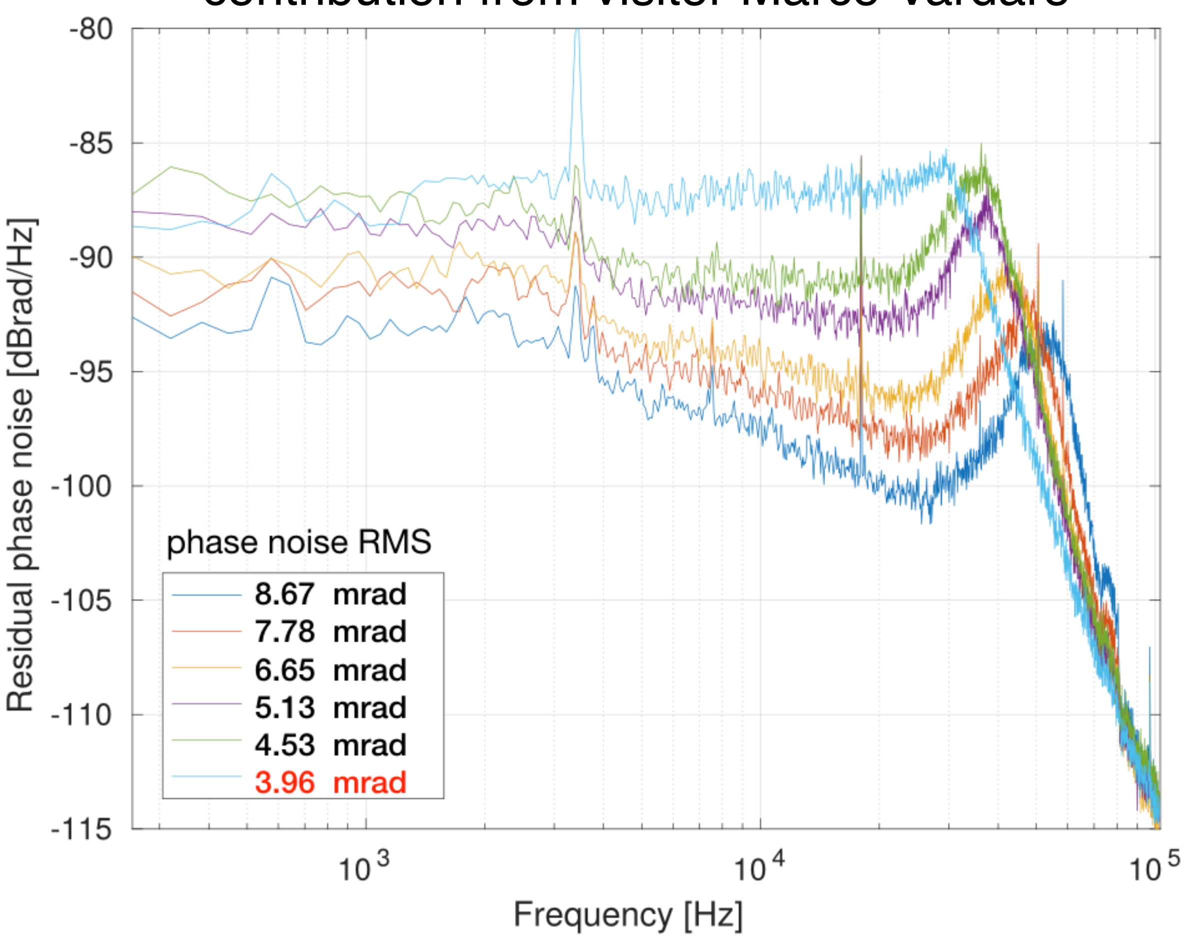


Phase lock loop (PLL) for AUX lasers

- 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

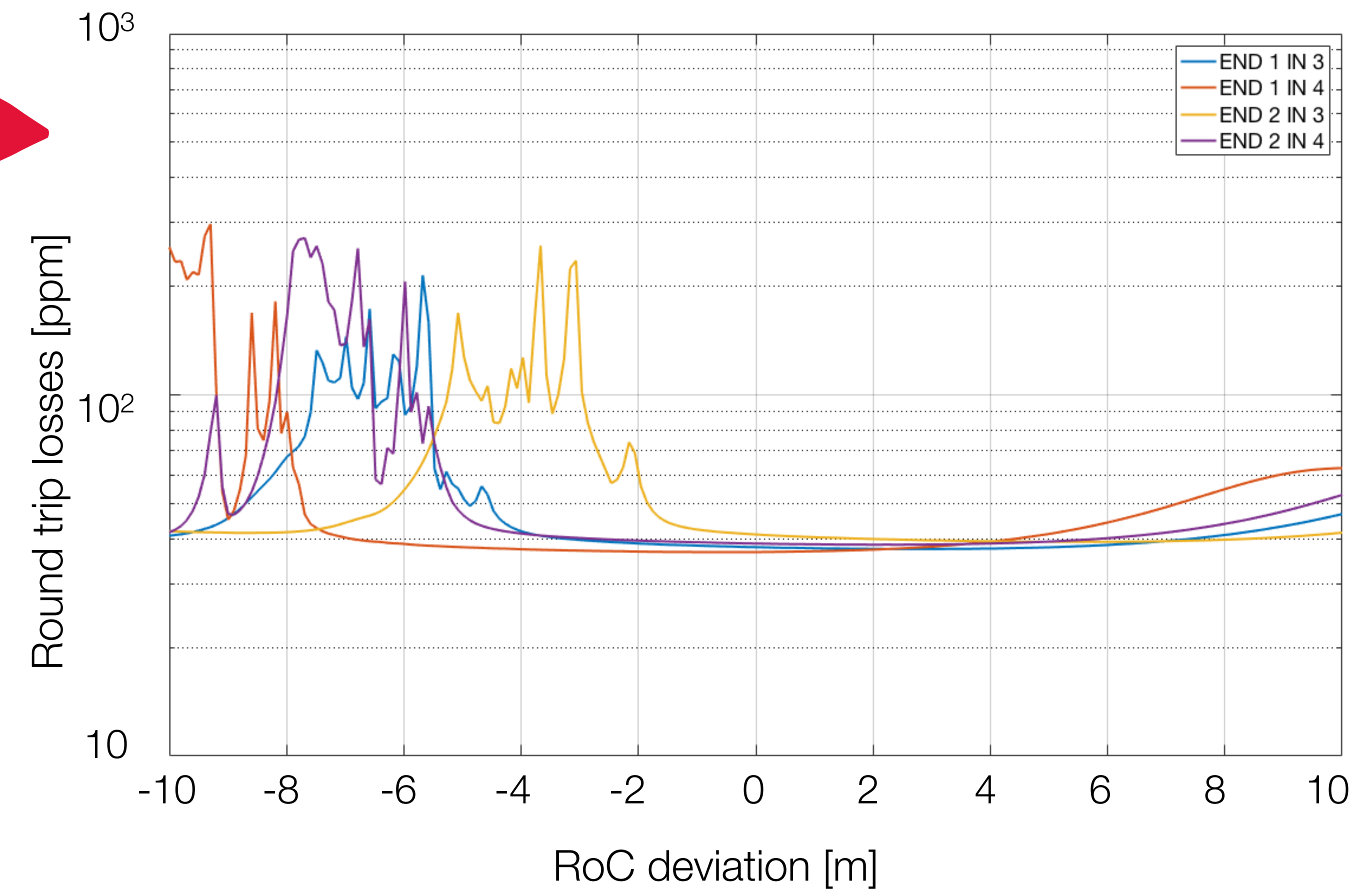
contribution from visitor Marco Vardaro



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

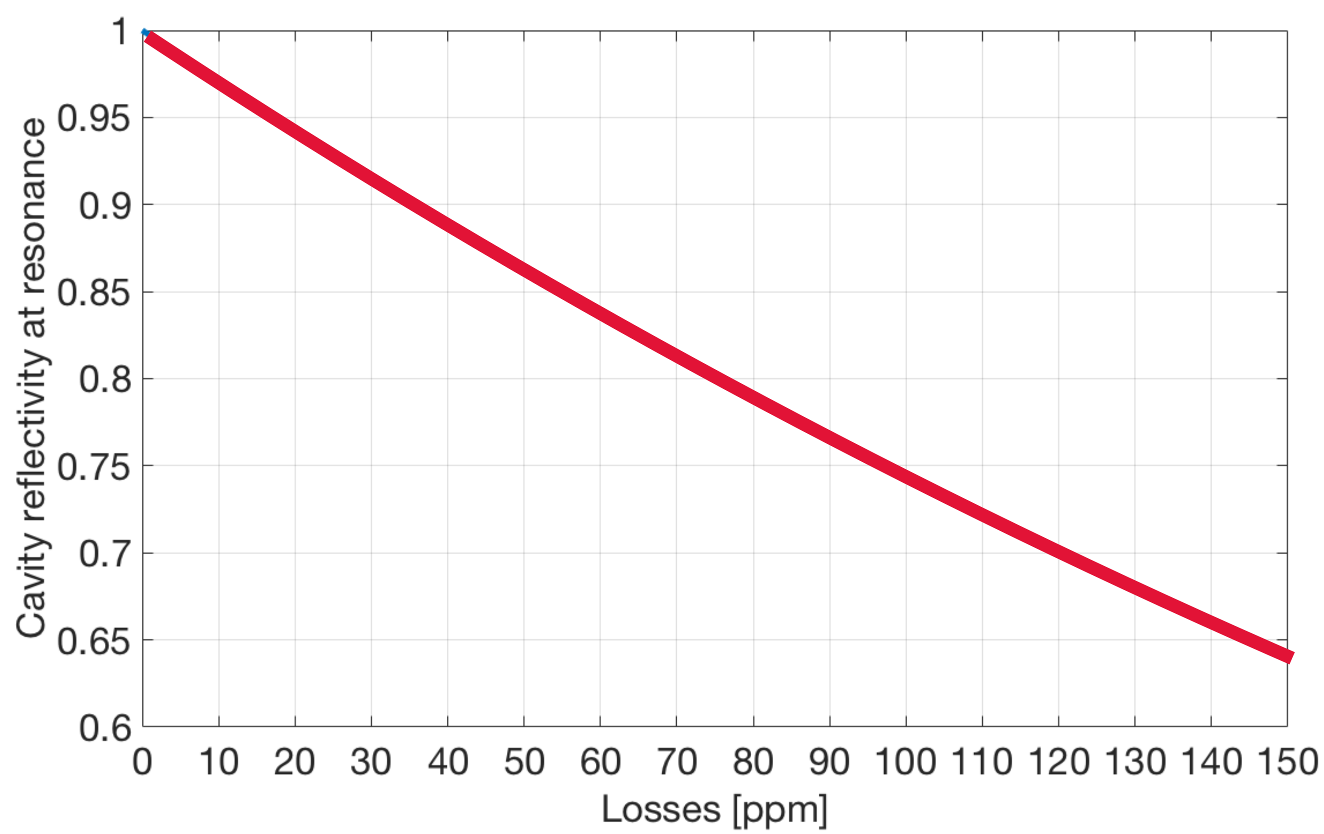
How to measure round trip losses?

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

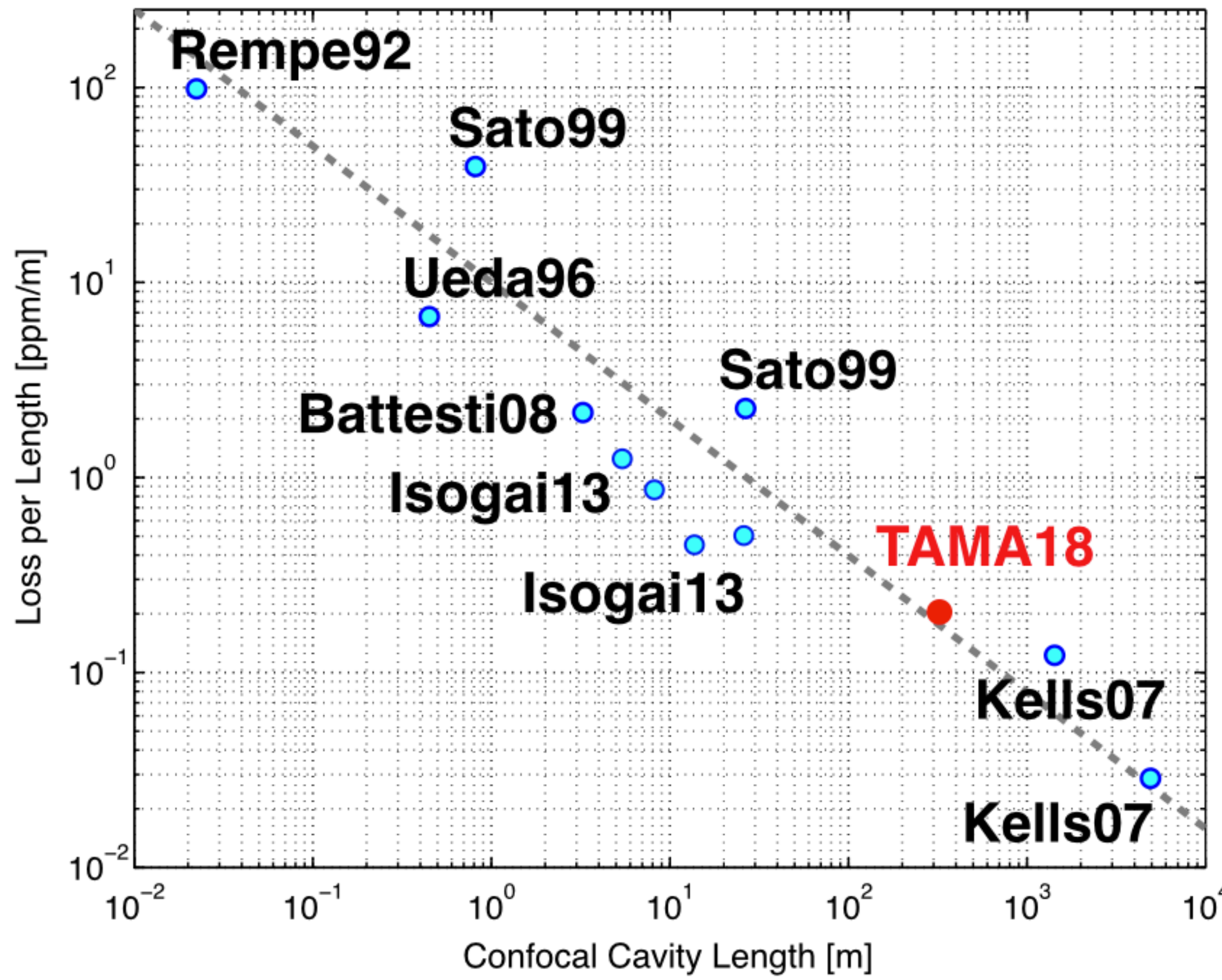
$$R_{\rm cav} = \left[\frac{r_1 - r_2}{1 - r_1 r_2}\right]^2$$

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

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



Comparison with round trip losses in literature



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

L_{confocal} 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

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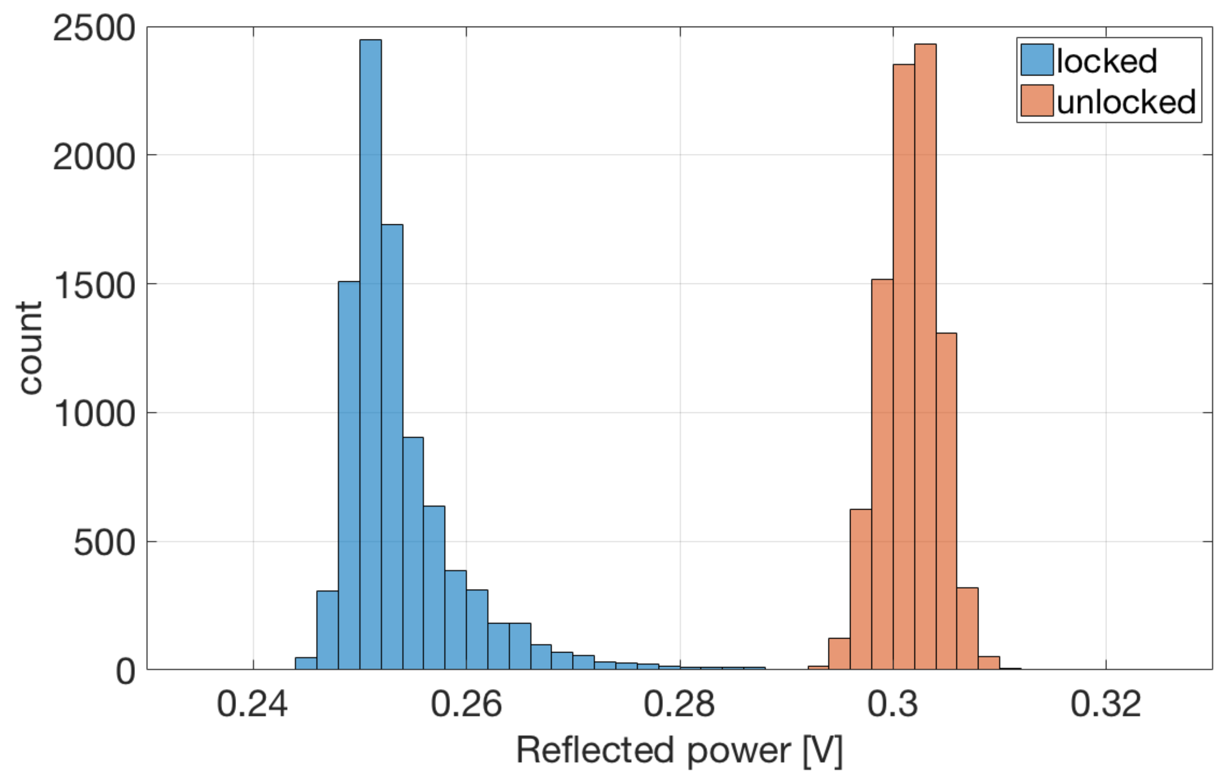
H. Miao
California Institute of Technology, Pasadena, California 91125, USA
(Received 9 May 2013; published 29 July 2013)

How to estimate the reflected power

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

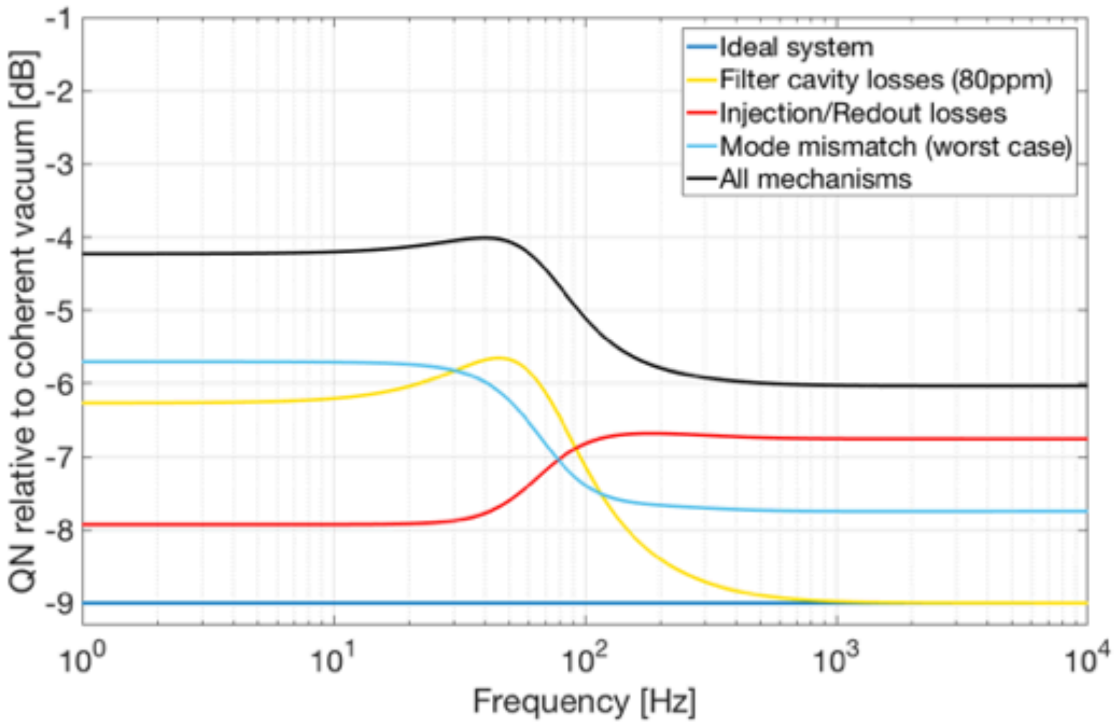


- Cavity unlocked: Gaussian histogram. Main influence: input power fluctuations

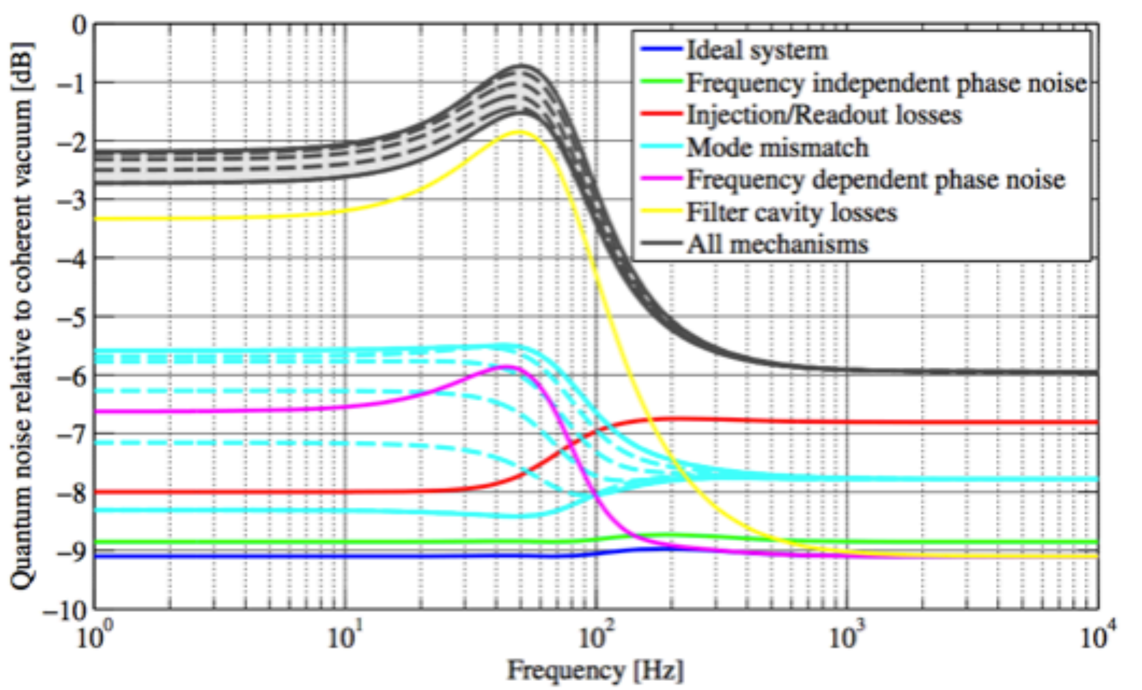
- Cavity unlocked: asymmetric distribution. Influence of the input power fluctuations, cavity alignment fluctuations, finite lock accuracy

Squeezing degradation budget

TAMA 300 filter cavity



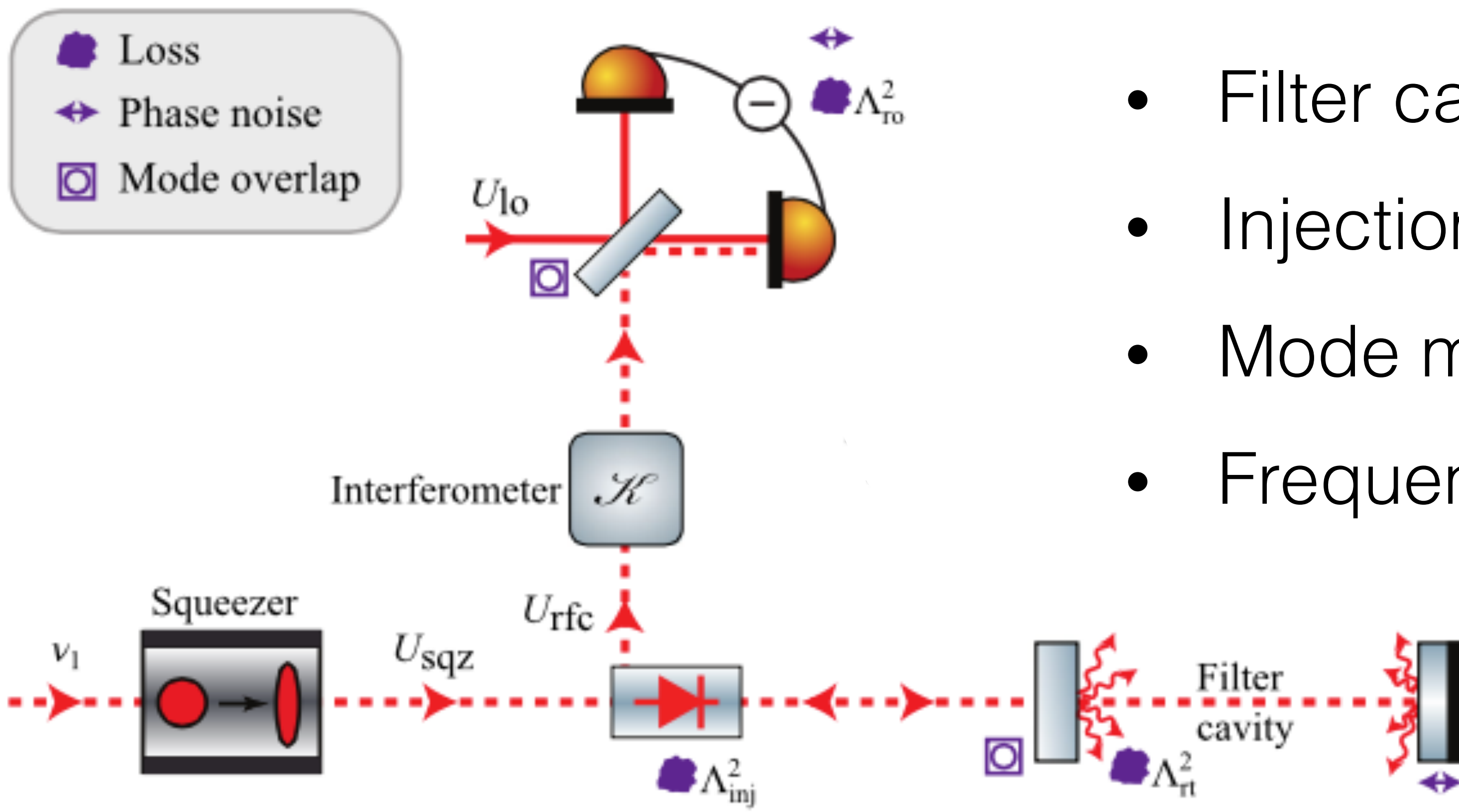
16 m filter cavity at MIT



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

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

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

squeezed field

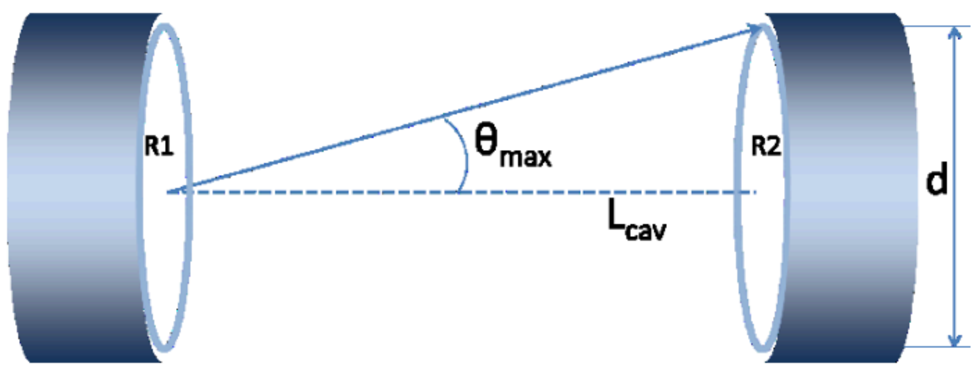
vacuum fluctuation due to losses before the ITF

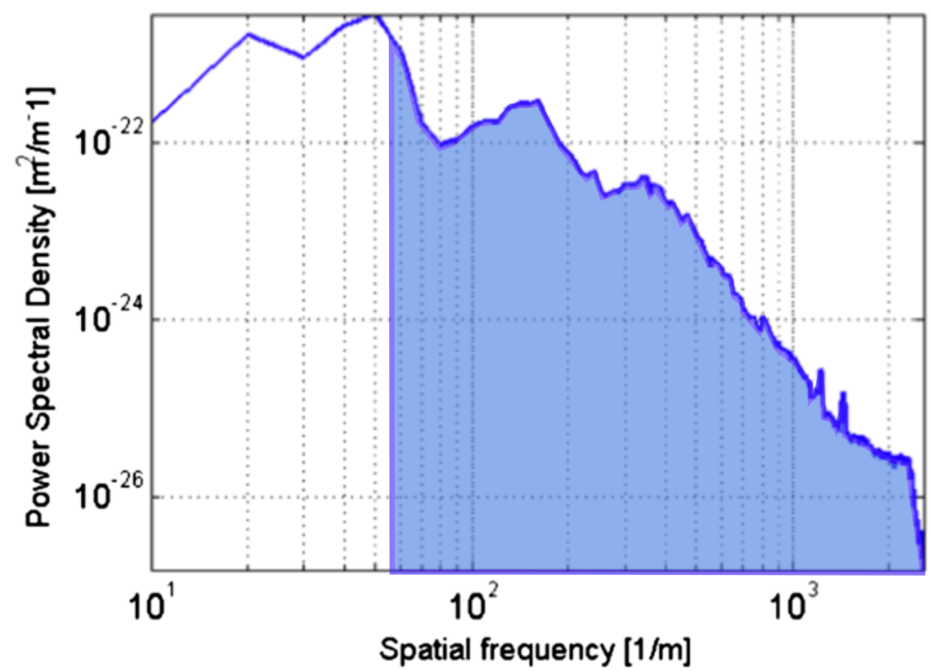
vacuum fluctuation due to losses after the ITF

Scattering from mirror defects

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

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





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

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

Scattering golden rule:

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

Why ppm/meter are important?

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

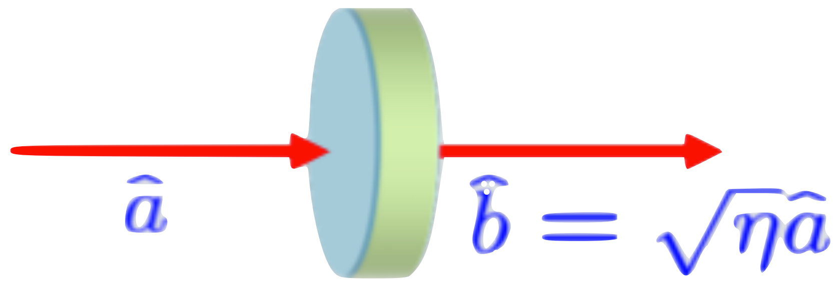
$$\mathcal{E} \approx \frac{\epsilon}{T_f}$$

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

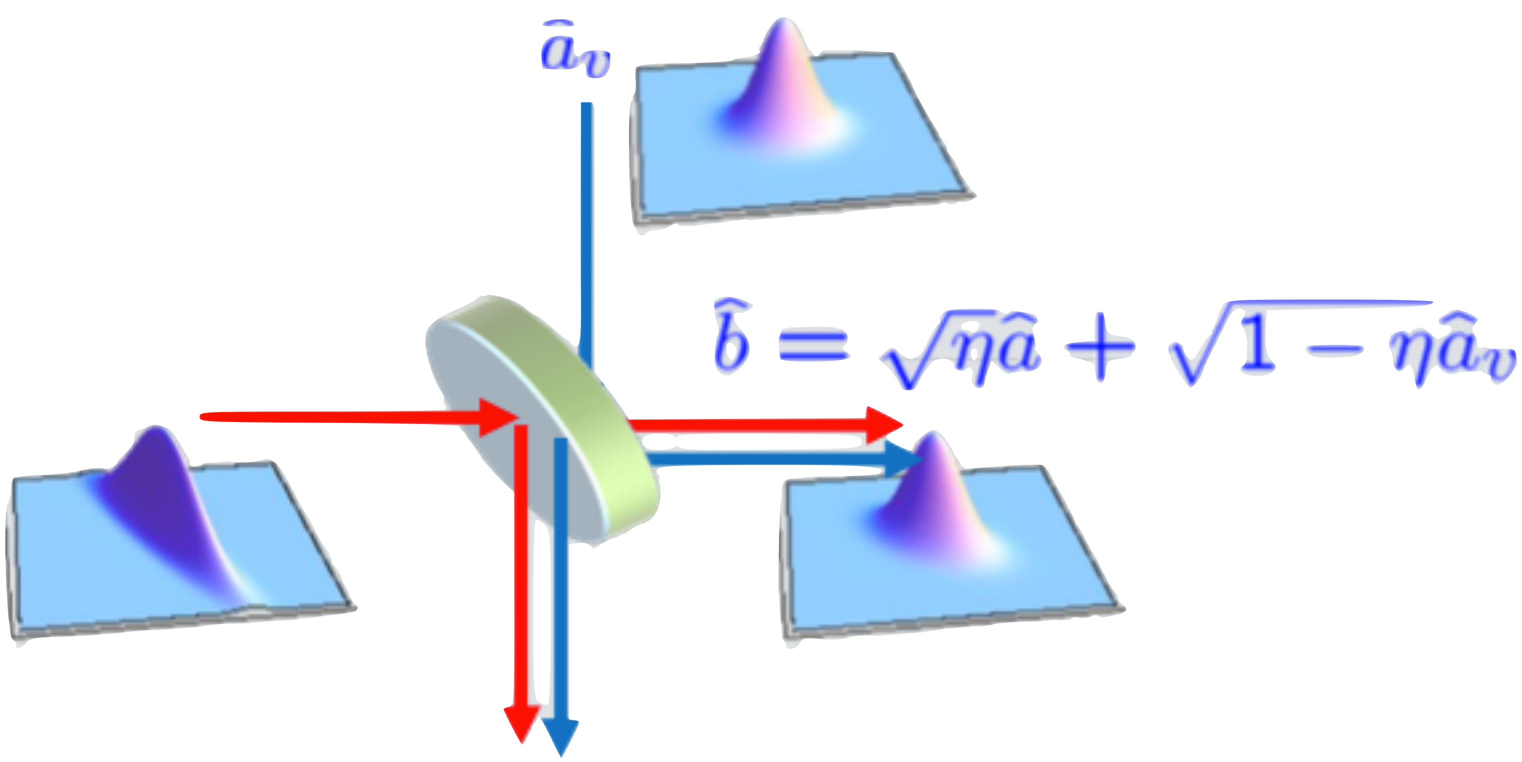
- Naive model



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

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

- Consistent model



Squeezing degraded because of its recombination with non squeezed vacuum