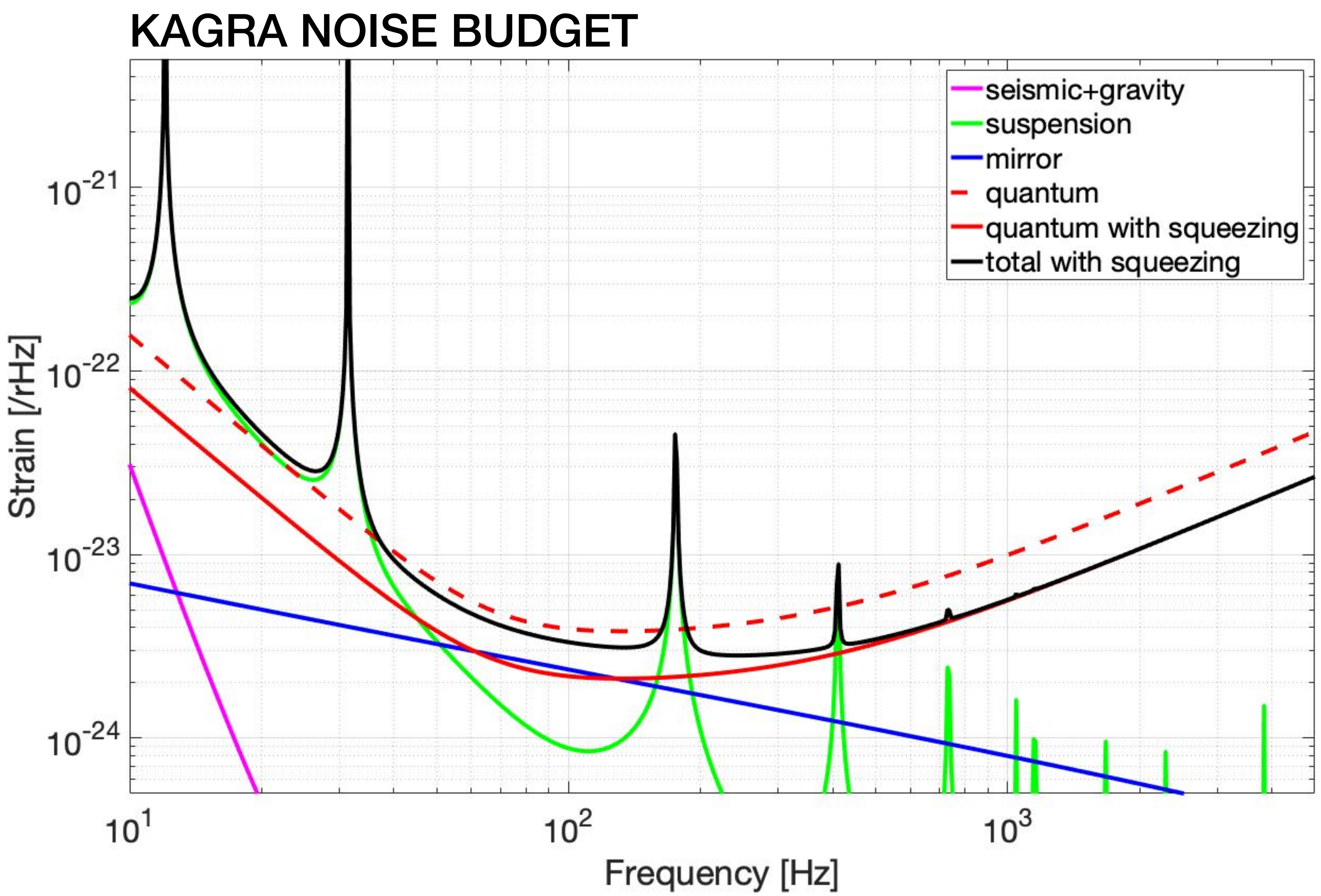
Status of the frequency dependent squeezing experiment at TAMA

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

Supported by the JSPS Grant-in-Aid for Scientific Research (Grant code 15H02095 & 18H01235)

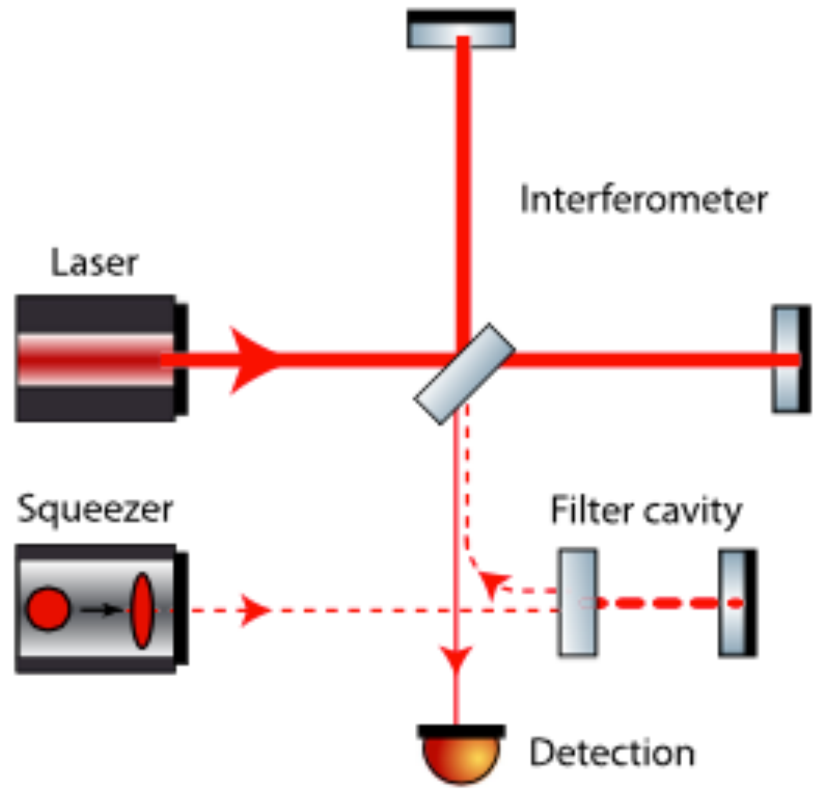
Motivation and context

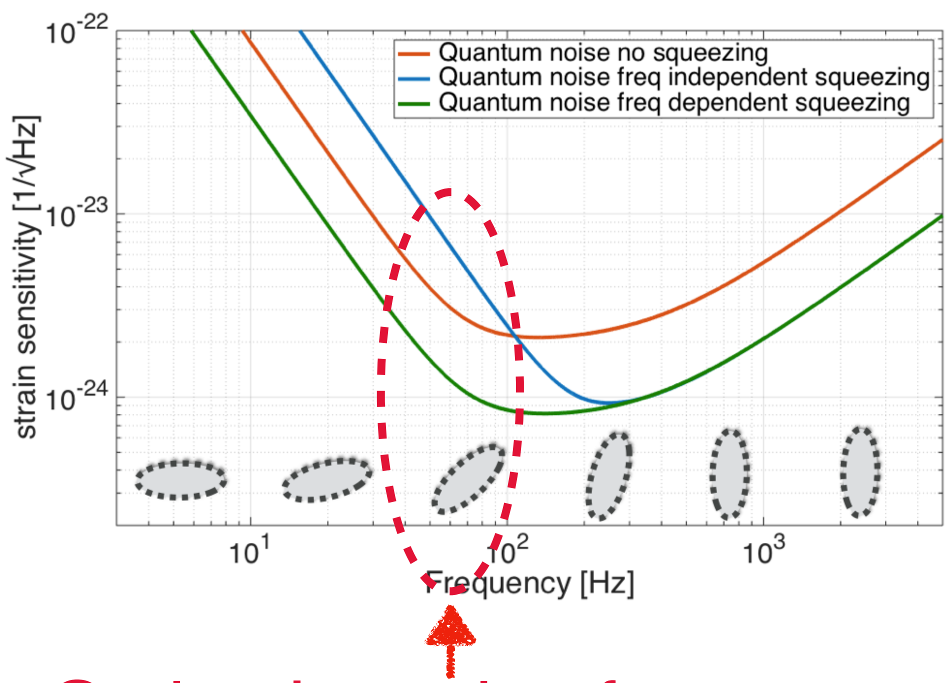
- Frequency dependent squeezing goal: **broadband quantum noise reduction**
- 300 m filter cavities planned for A+ and AdVirgo+ in O4
- Considered among the upgrades of KAGRA+



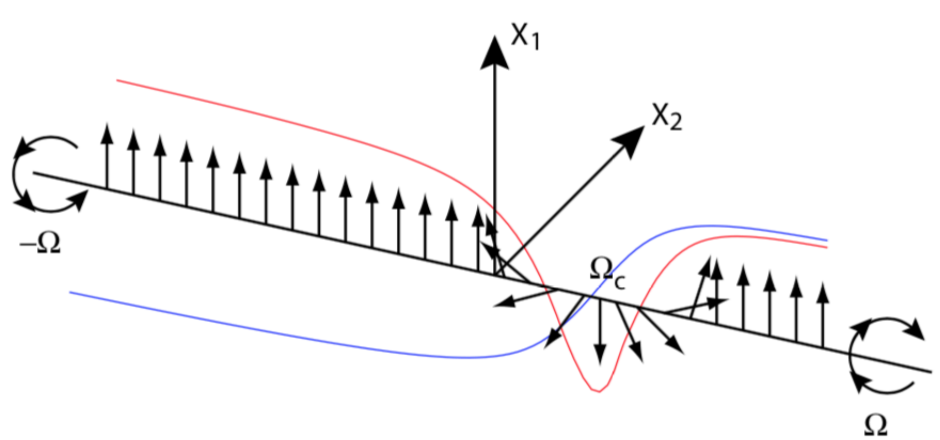
How to produce frequency dependent squeezing?

- Reflect frequency independent squeezing off a detuned cavity
- Rotation frequency depends on the cavity line-width
- Performances strongly affected by round trip loss per unity length



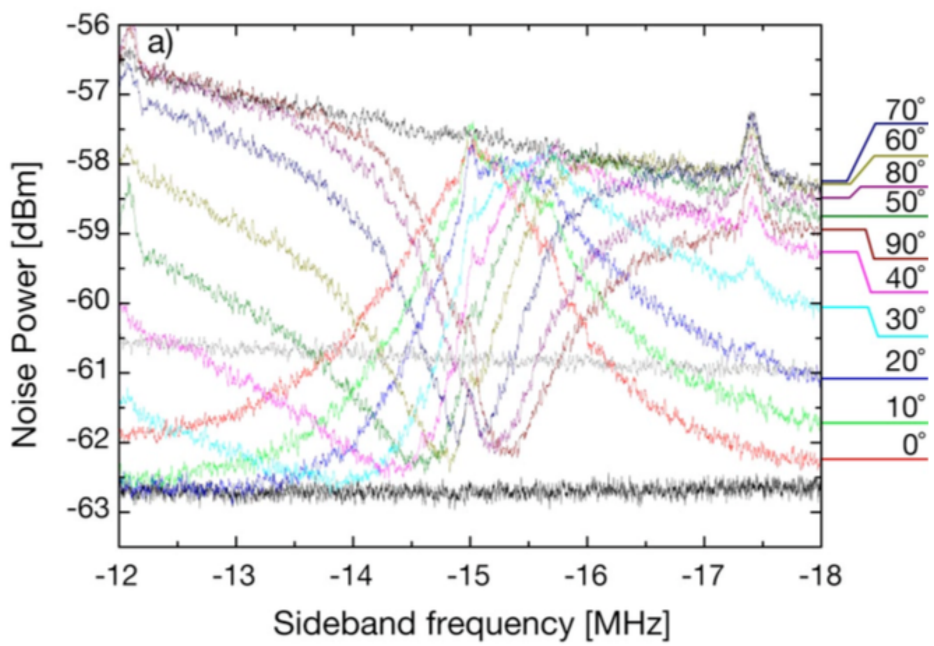


Optimal rotation frequency between 40 and 70 Hz



Squeezing angle rotation already demonstrated

@ MHz frequency

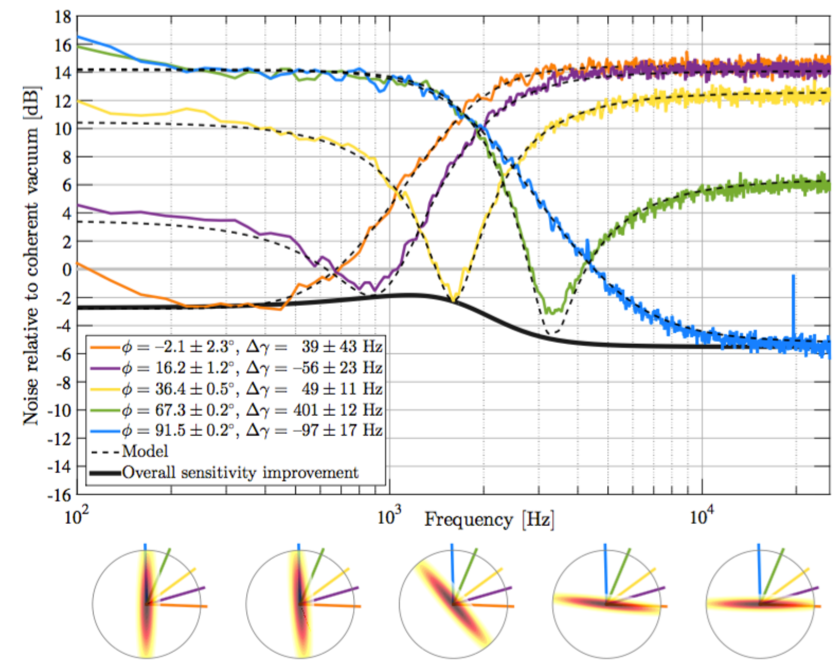


PHYSICAL REVIEW A **71**, 013806 (2005)

Experimental characterization of frequency-dependent squeezed light

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

@ kHz frequency



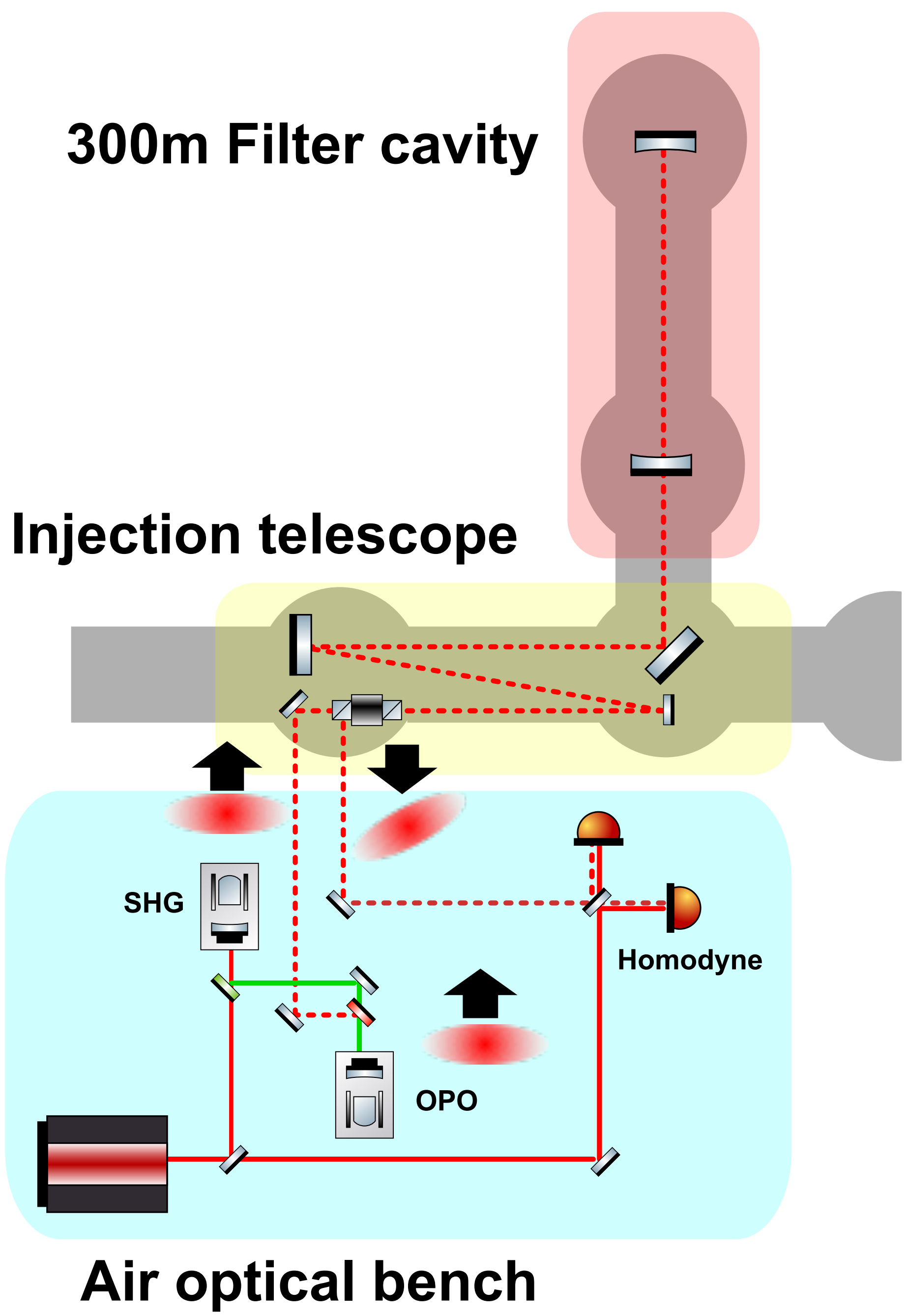
PRL **116**, 041102 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

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 around 70 Hz**

Experiment overview



FILTER CAVITY

- Installed @ TAMA facility at NAOJ
- Finesse 4400
- Round trip losses 45-85 ppm

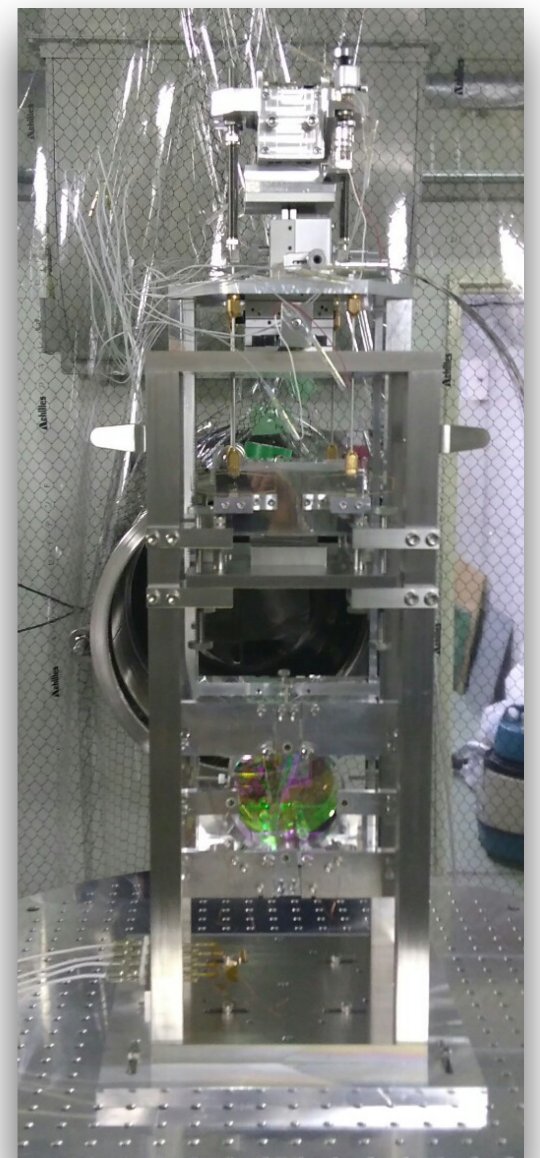
FREQ. IND. SQUEEZED VACUUM SOURCE

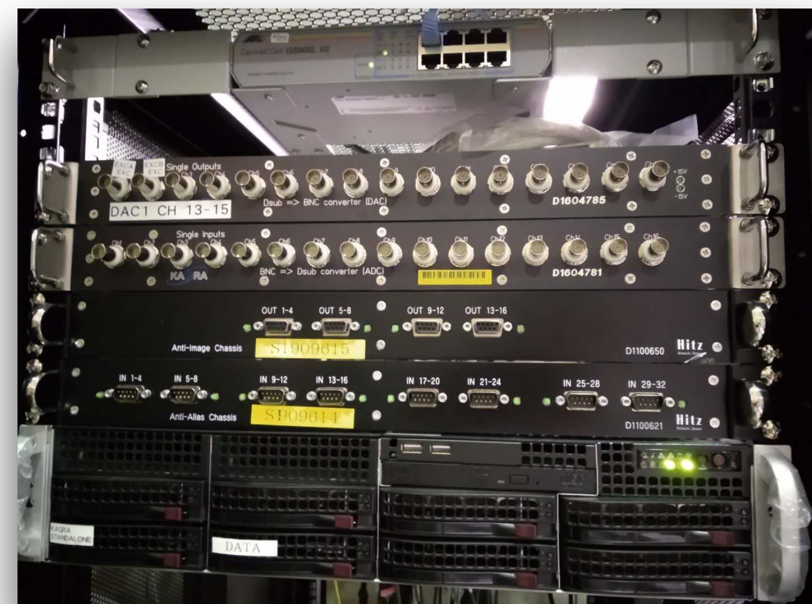
- Based on AEI design
- Target 9dB from 10 Hz

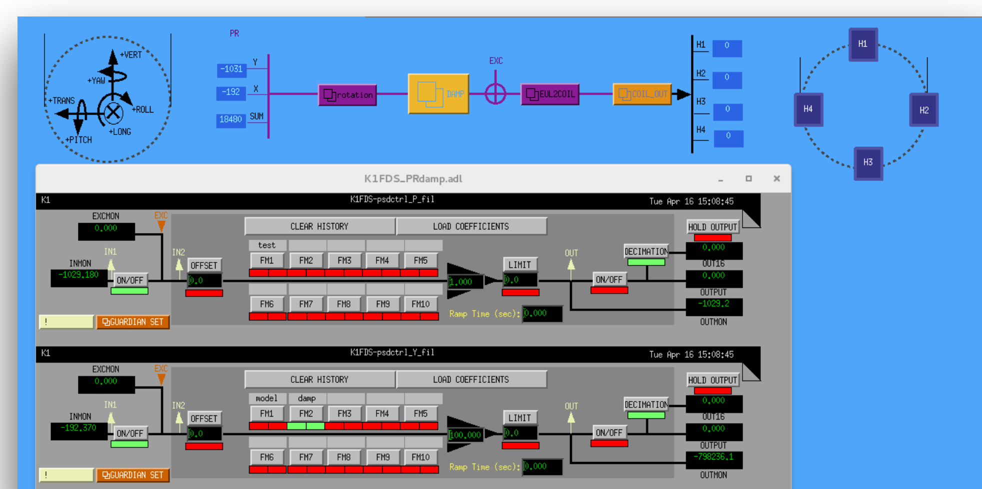
More details on Yuhang Zhao's poster

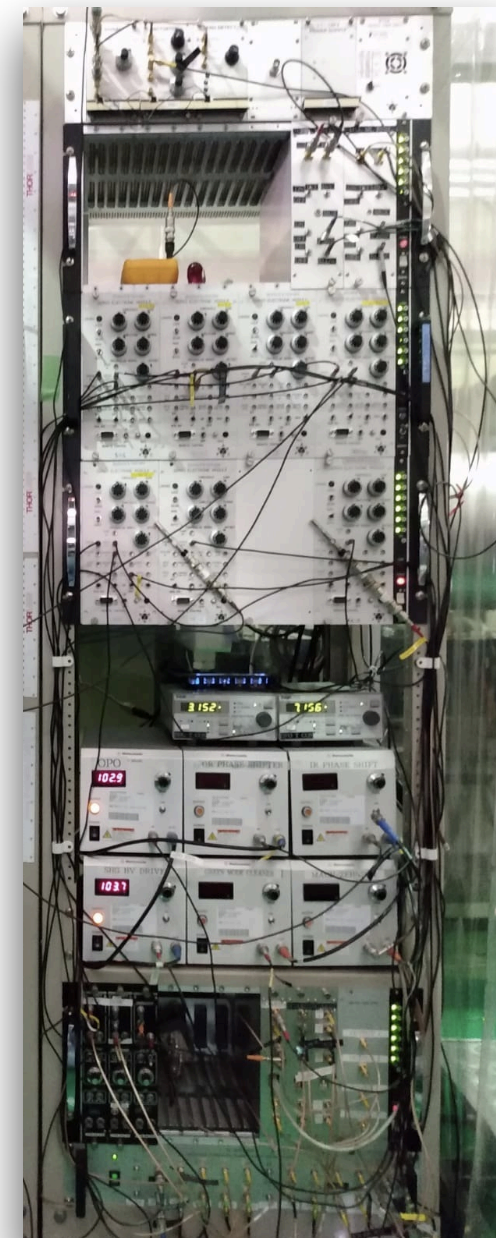
Filter cavity: suspensions and digital control system

- Double pendulum suspensions (so-called KAGRA Type C)
- Digital system for local control recently changed from old TAMA LabVIEW to KAGRA DGS



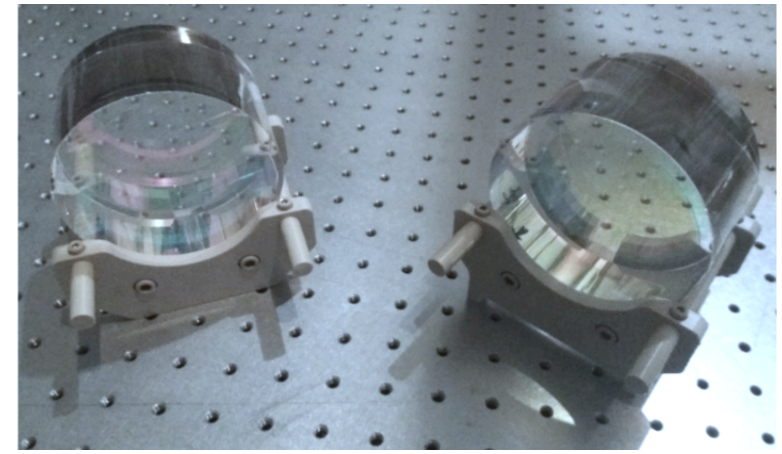


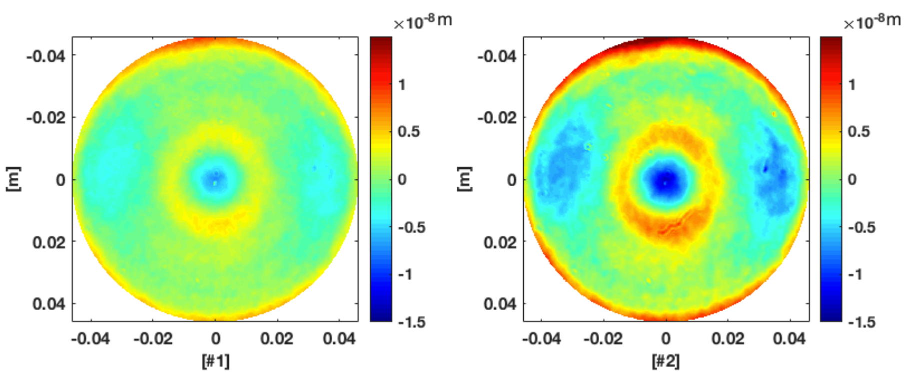




Filter cavity: the mirrors

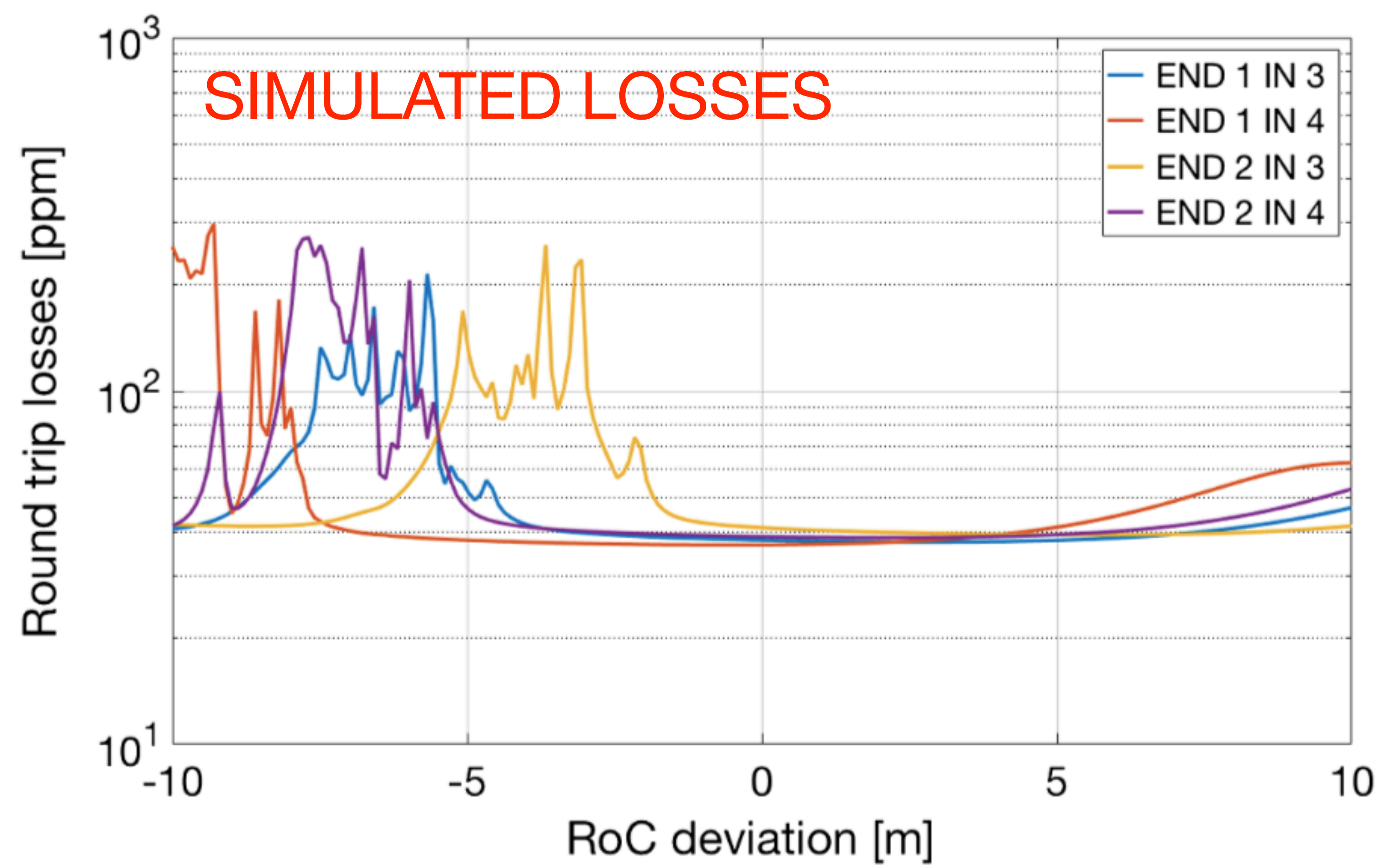
- Tama size: 10 cm diameter, 6 cm thickness
- Beam radius: ~1 cm
- Requirement on surface quality set to have **80 ppm of round trip losses**





	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
#4	1.94	14.8	0.48	3.28

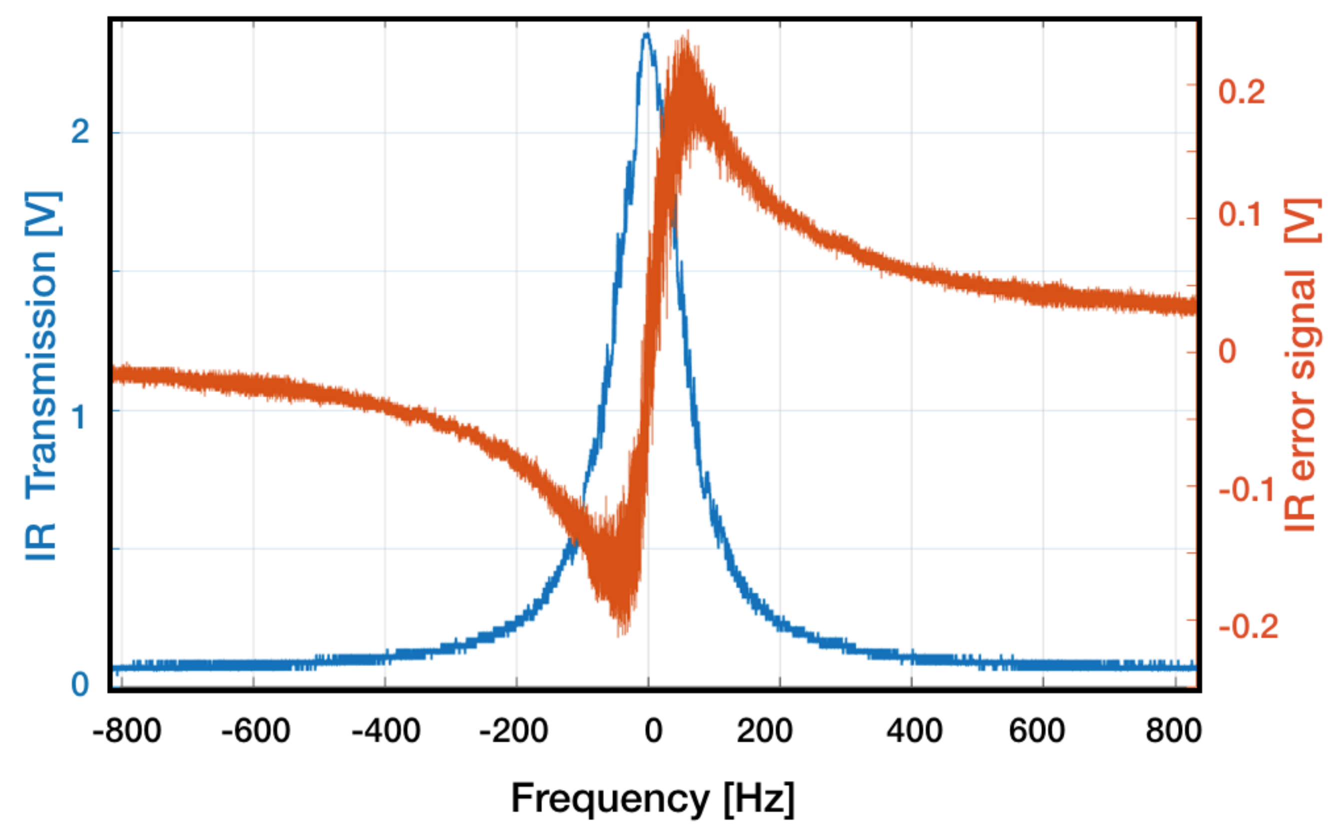
Substrates coated and characterized at LMA



Filter cavity: the control

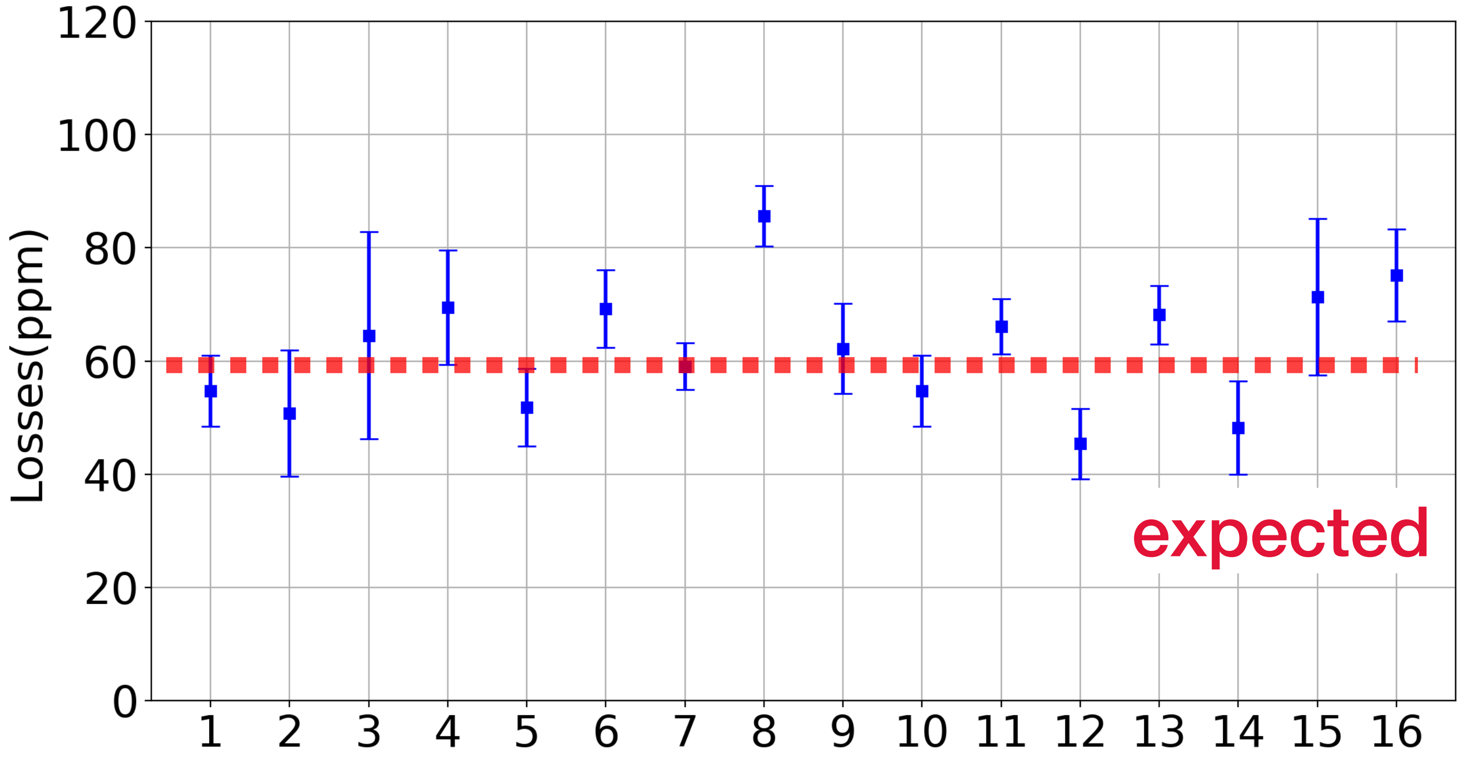
- Laser frequency locked on the cavity length
- Auxiliary green beam used (finesse ~170)
- IR detuning controlled with AOM on green path
- Alternative control strategy with coherent control sidebands is being studied (**see Naoki Aritomi's poster**)

IR resonance crossing by driving AOM

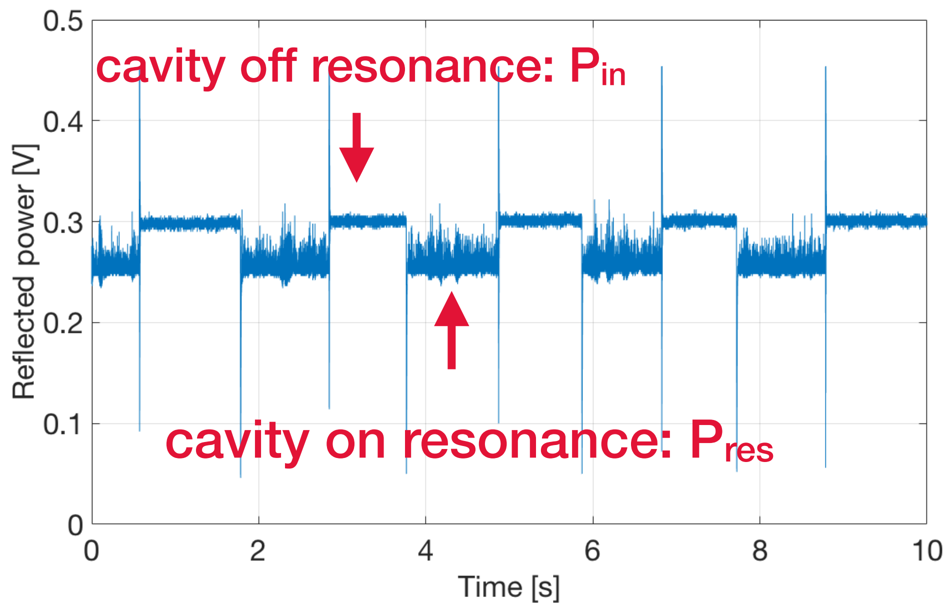


Filter cavity: round trip loss characterization

- Round trip losses between 45 and 85 ppm



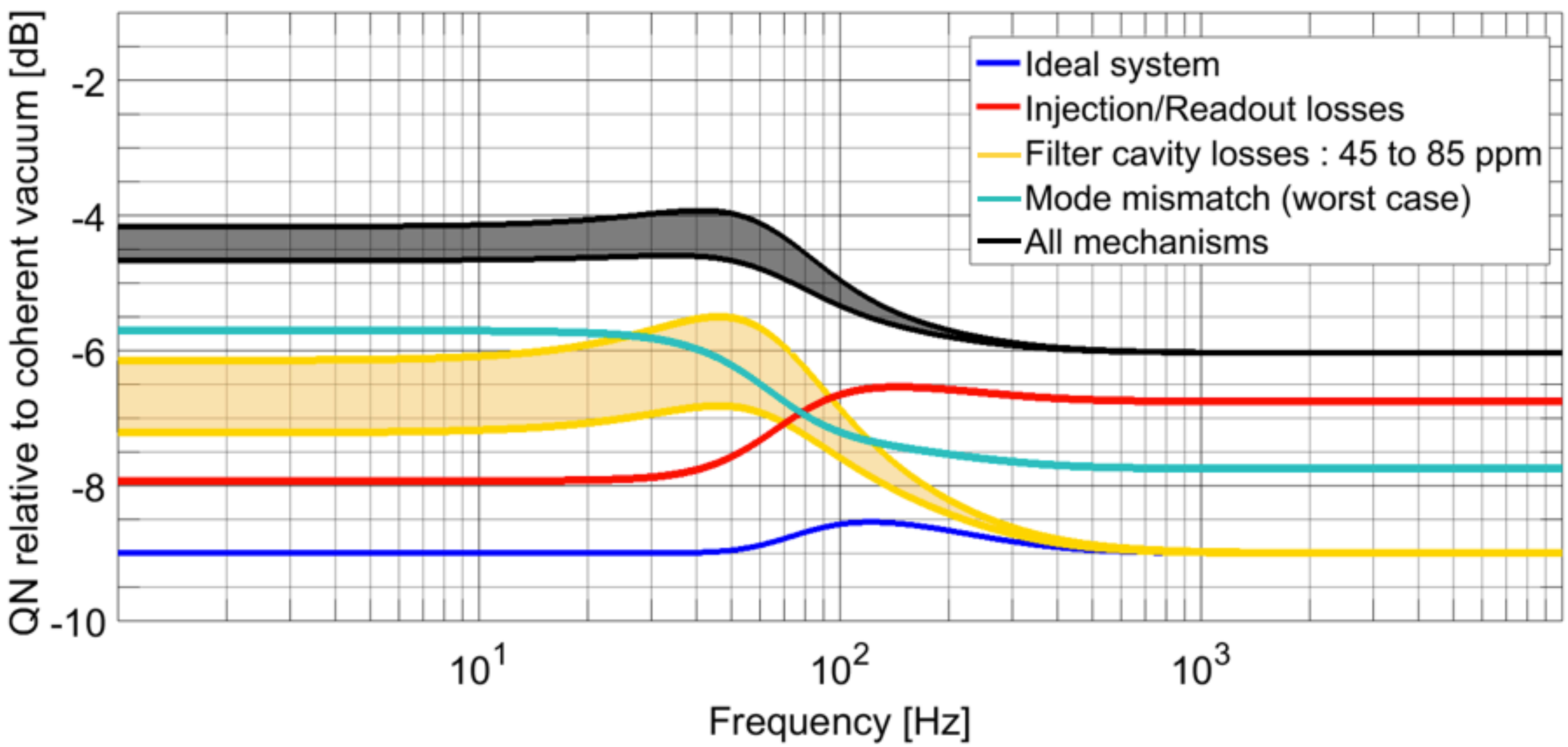
- Round trip losses extracted from reflectivity measurements



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

Expected squeezing level

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



injection losses	5%
readout losses	5%
squeezer-filter cavity mismatch	2%
squeezer-local oscillator mismatch	5%
δL (rms)	0.3 pm

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

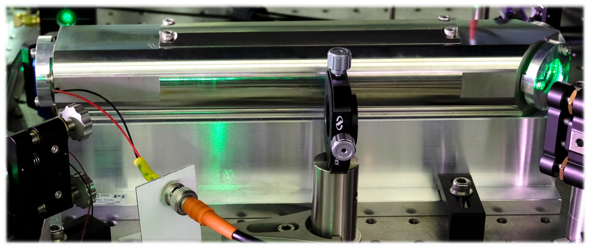
Measurement of optical losses in a high-finesse 300 m filter cavity for broadband quantum noise reduction in gravitational-wave detectors

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]

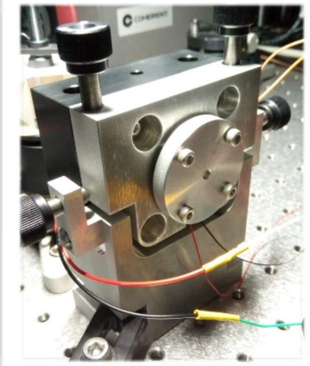
(Received 27 May 2018; published 31 July 2018)

Squeezed vacuum source: integration completed

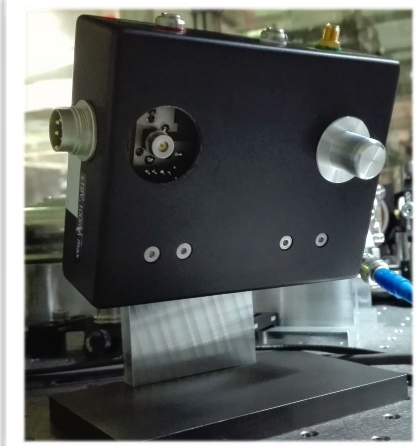
Green mode cleaner



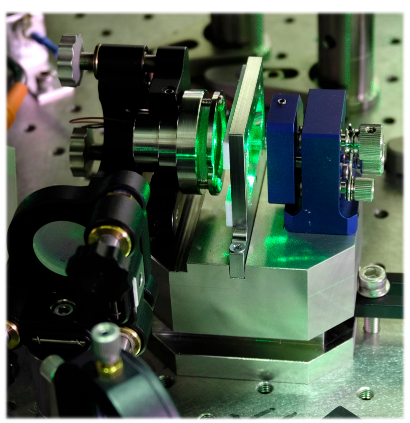
OPO to produce squeezed vacuum

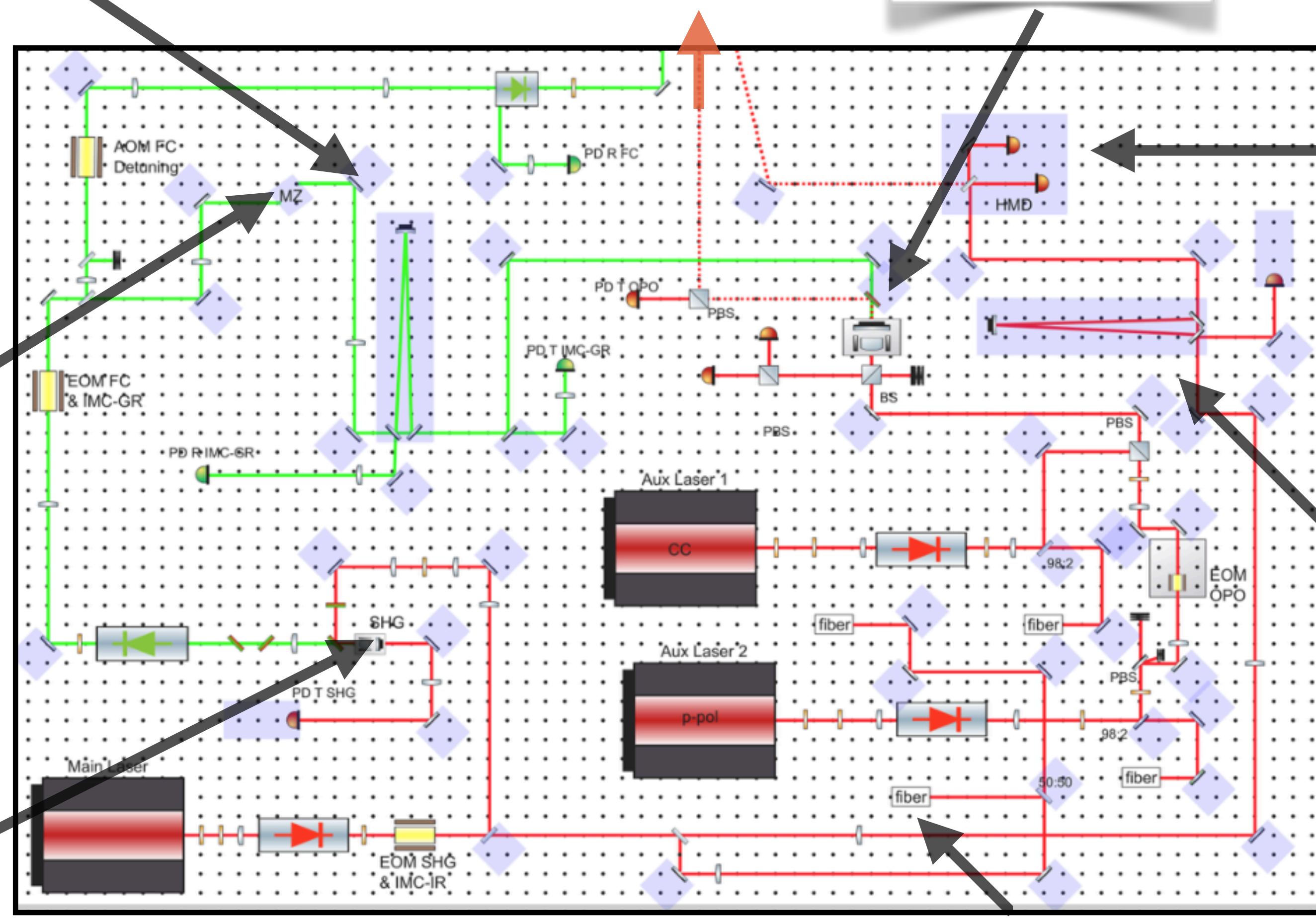


Homodyne detector (in collaboration with AEI, Hannover)

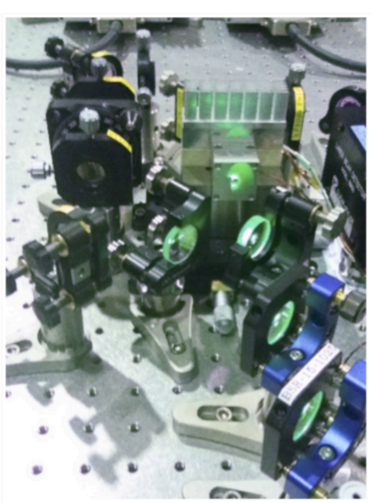


Mach-Zhender to stabilize and tune the green pump

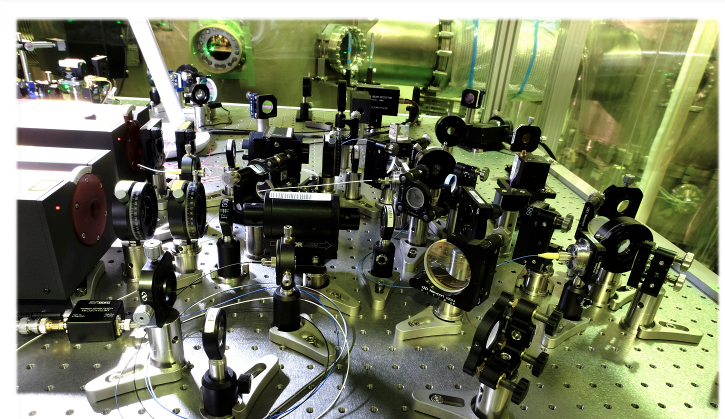




IR mode cleaner



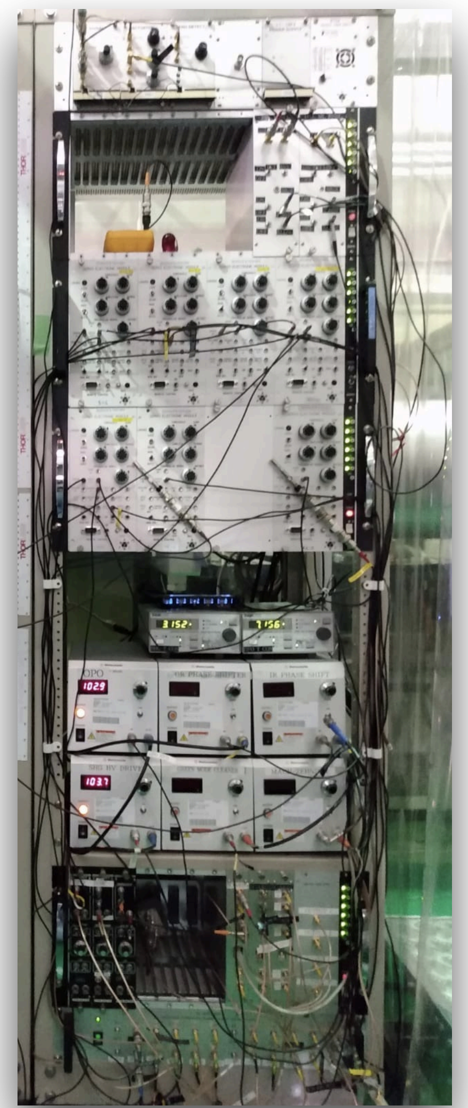
Second Harmonic Generator to produce green pump



PLL between main laser and auxiliary lasers

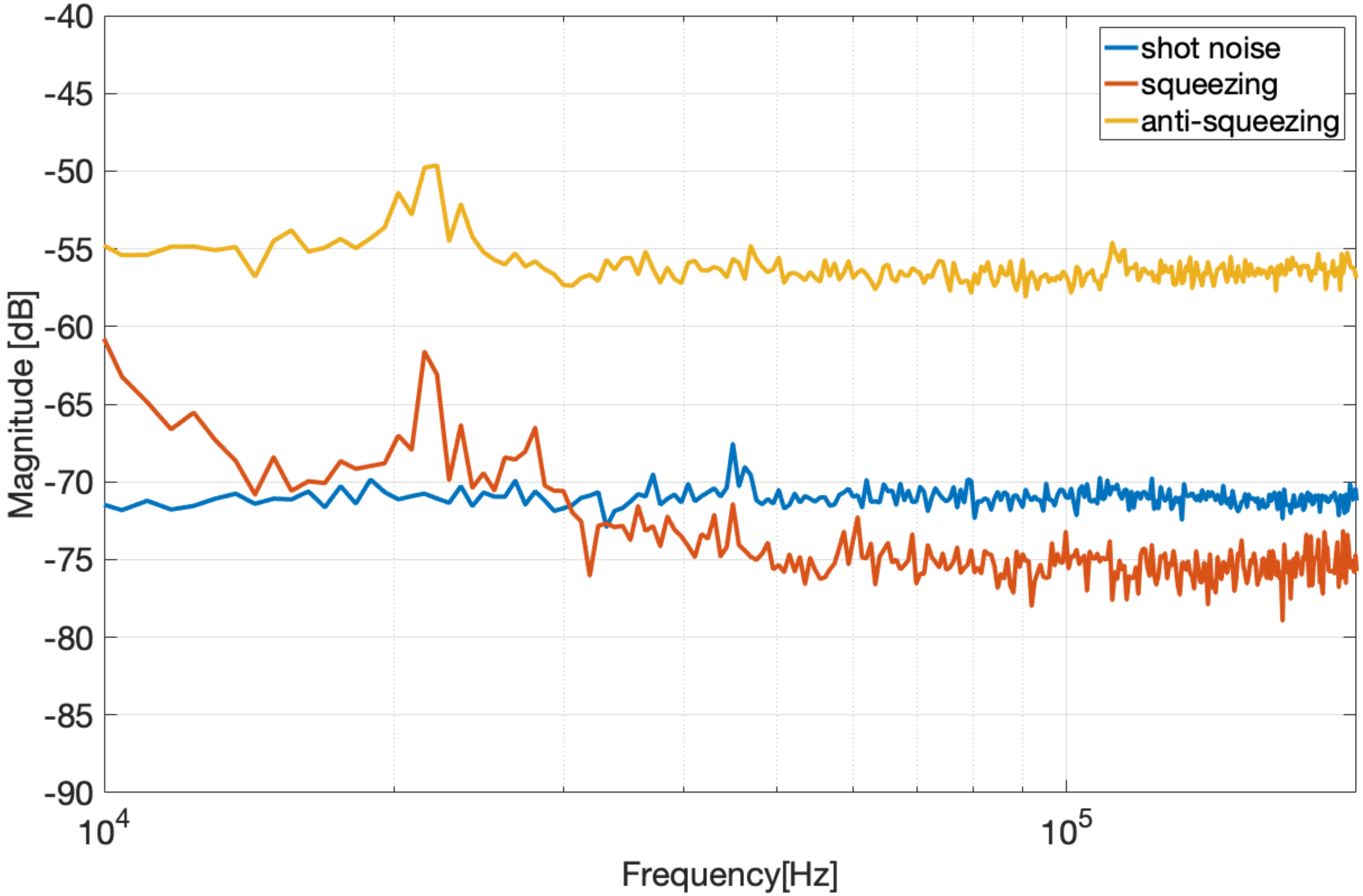
Squeezed vacuum source: analog control servos

- Developed in collaboration with APC
- 7 servos: 4 optical cavity, 1 Mach-Zehnder, 2 Coherent control loops
- Hierarchical auto-lock implemented
- Parameters controlled on the front panel or remotely



Current squeezing performance

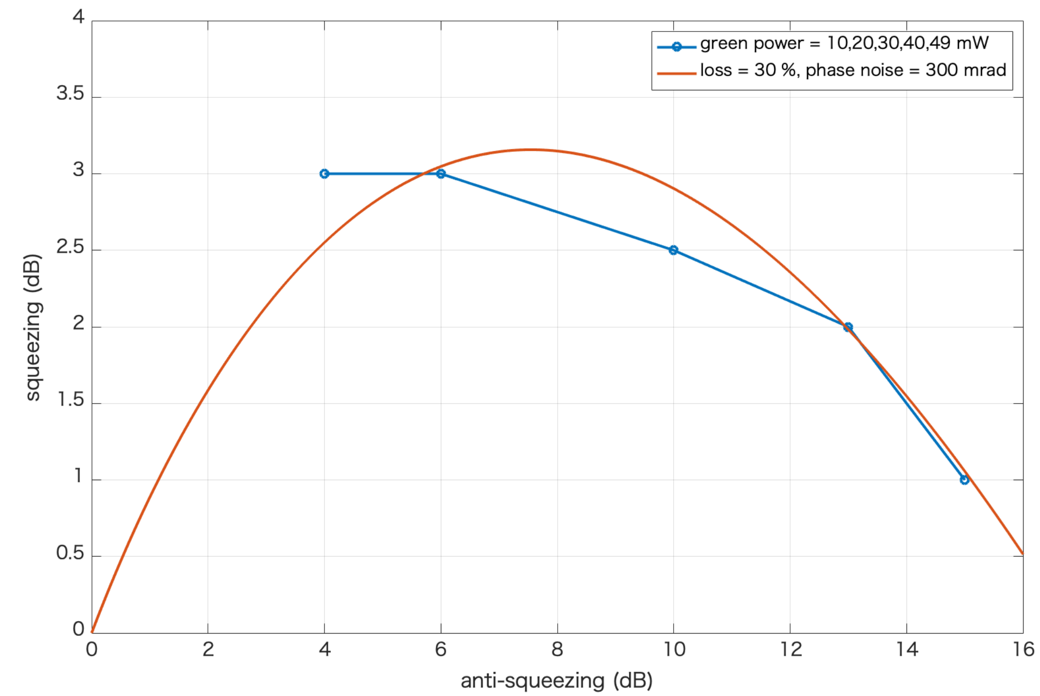
- About 4.5 dB of squeezing (and 15 dB of anti-squeezing) down to ~30 kHz



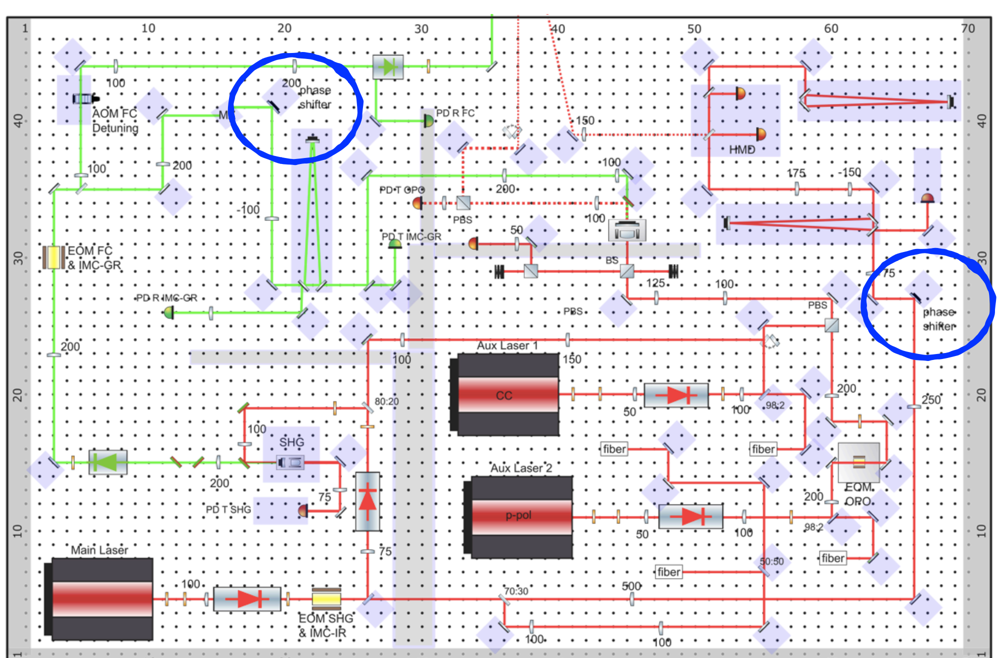
Phase noise reduction

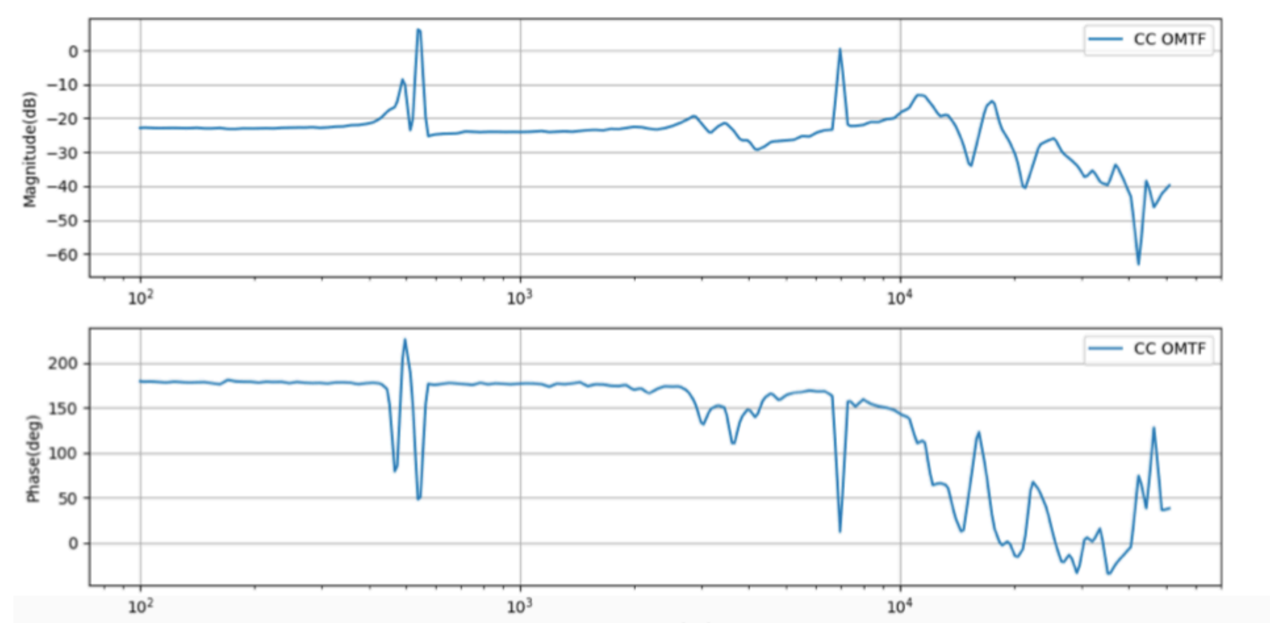
- Since measured squeezing is lower when we increase the pump power, we believe that it is **limited by phase noise**

- Coherent control optimization is our first priority



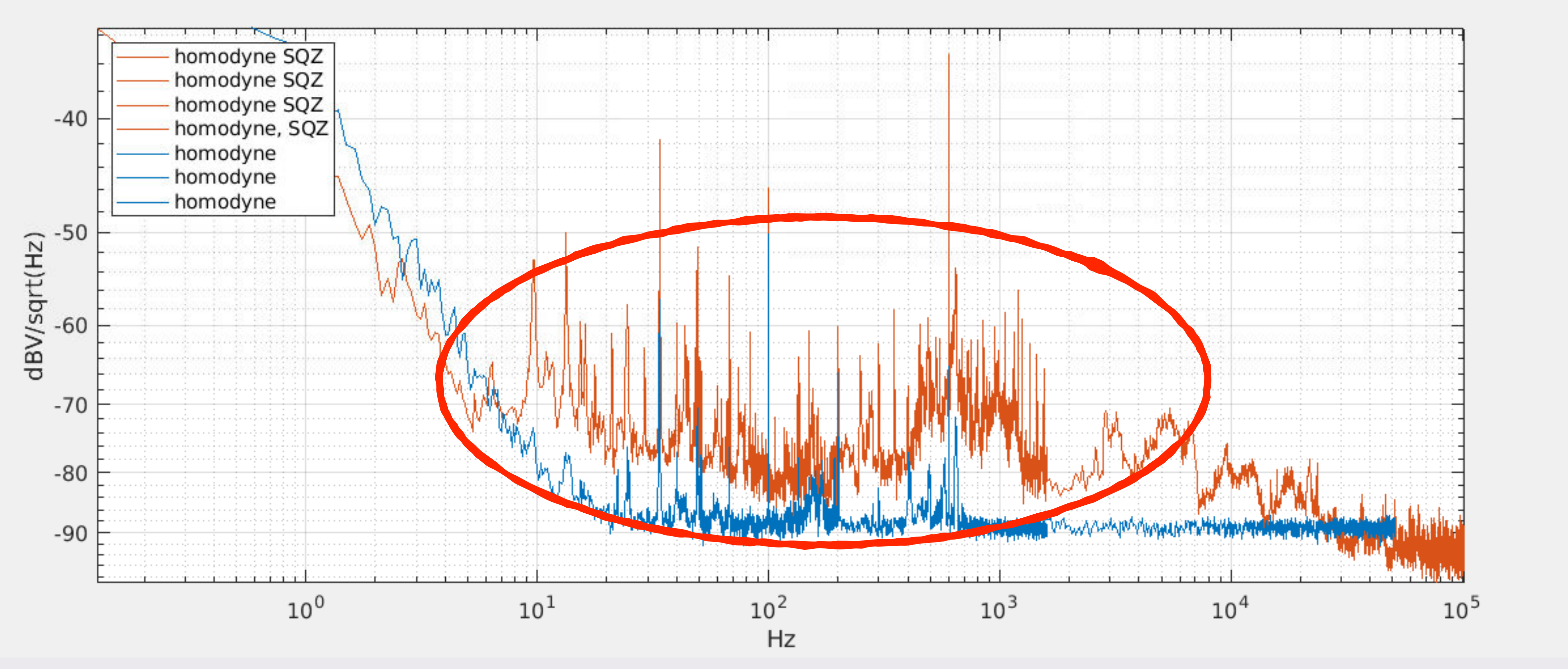
- Coherent control loop bandwidth is limited to 80 Hz because of mechanical resonances of the piezo phase shifter -> stiffer mounts are being installed





Low frequency noise hunting

- We start investigation on low frequency peaks, looking for correlations with mechanical resonances and environmental sensors
- Preliminary actions to be taken :
  - improve bench seismic isolation
  - Improve bench acoustic isolation



Summary

- Integration of squeezed vacuum source in TAMA completed
  - ~4.5 dB of squeezing down to ~30 kHz
  - Current performances limited by phase noise
- 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 loop improvement
  - Intensive low frequency noise-hunting
- Upgrade of the filter cavity control
  - Automatic alignment implementation
  - Test of new control scheme
- Preparation for squeezing injection into the filter cavity
- Design for filter cavity integration in KAGRA

Visitors and collaborations

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

Emil Schreiber
GEO600/AEI

Shu-Rong Wu
Tsing Hua University

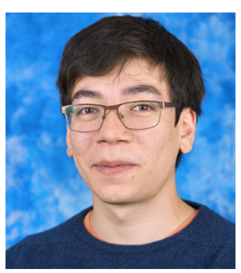
Marco Vardaro
Padova University

Matteo Barsuglia
APC/CNRS

Eleonora Polini
La Sapienza Roma

Matteo Tacca
Nikhef

Federico Paoletti
INFN-Pisa



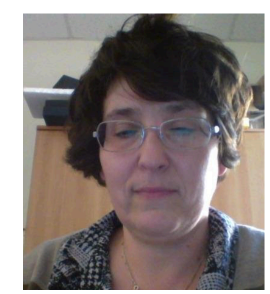
Marc Eisenmann
LAPP/CNRS

Yuefan Guo
Nikhef

Chien-Ming Wu
Tsing Hua University

Pierre Prat
APC/CNRS

Marco Banzan
Padova University

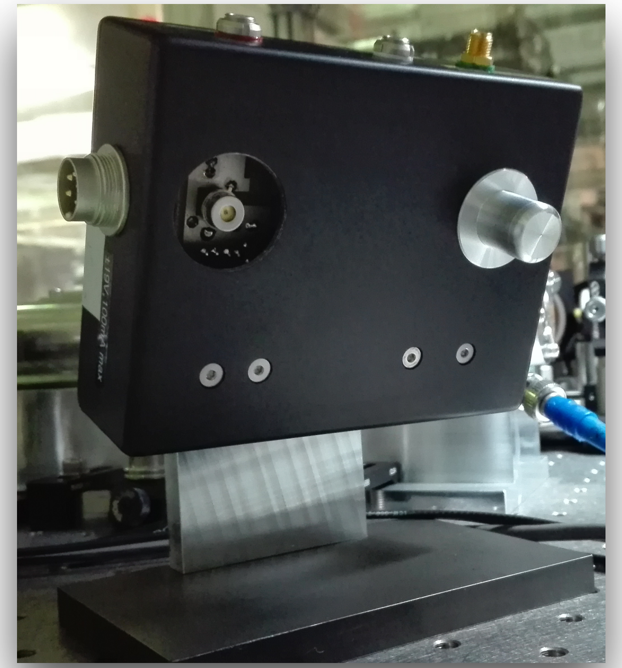


Irene Fiori
EGO

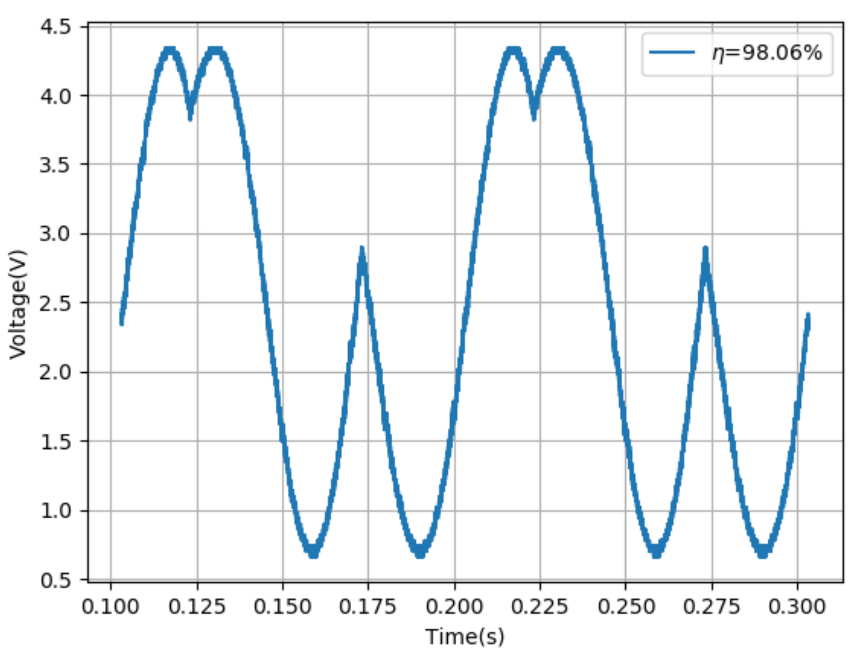
visits supported by JSPS Core-to-Core Program, A.Advanced Research Networks EU under the Framework Program 7 (FP7) ’People’ project ELiTES (Grant Agreement No. 295153)
EU Horizon 2020 Research and Innovation Programme under the Marie Sklodowska-Curie Grant Agreement No.734303

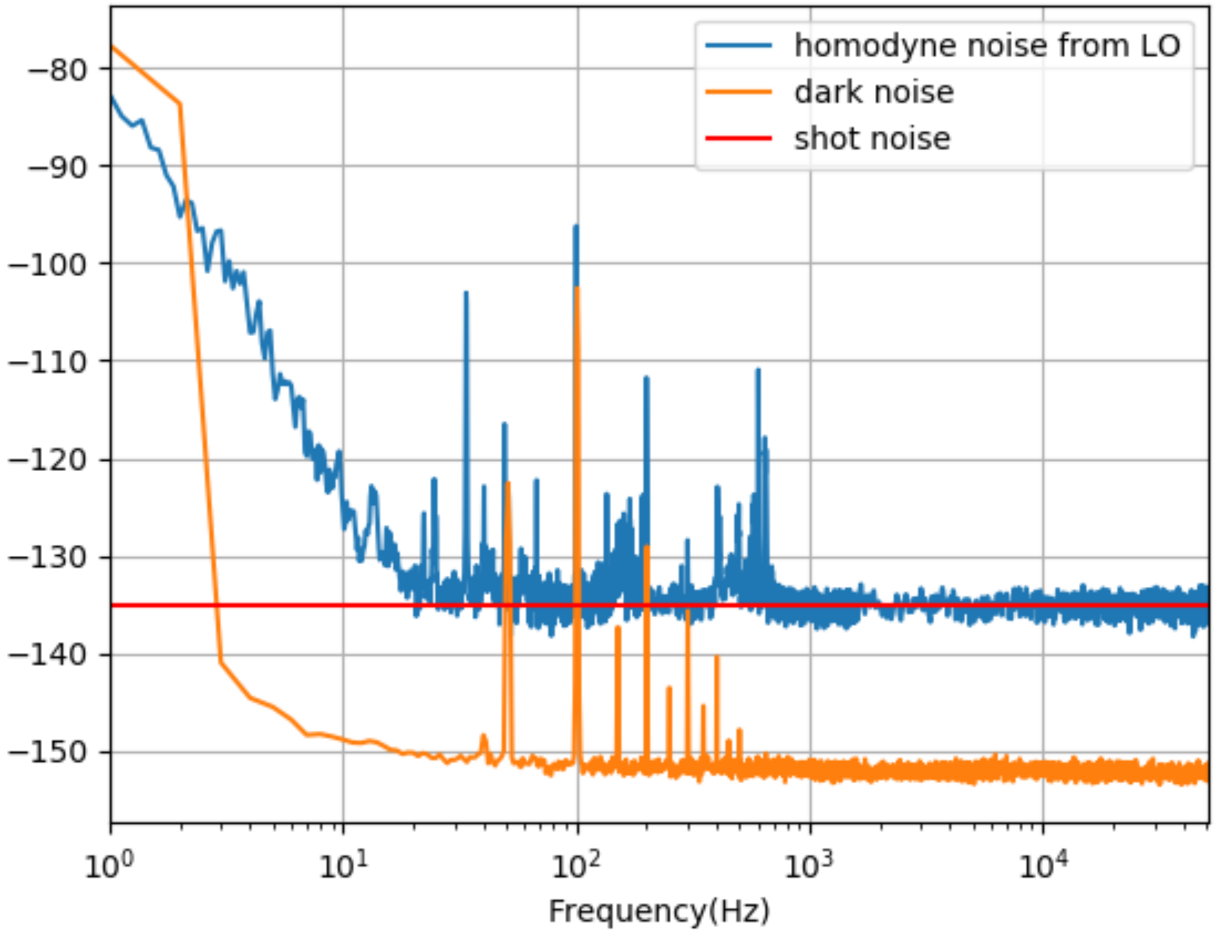
EXTRA SLIDES

Homodyne detector



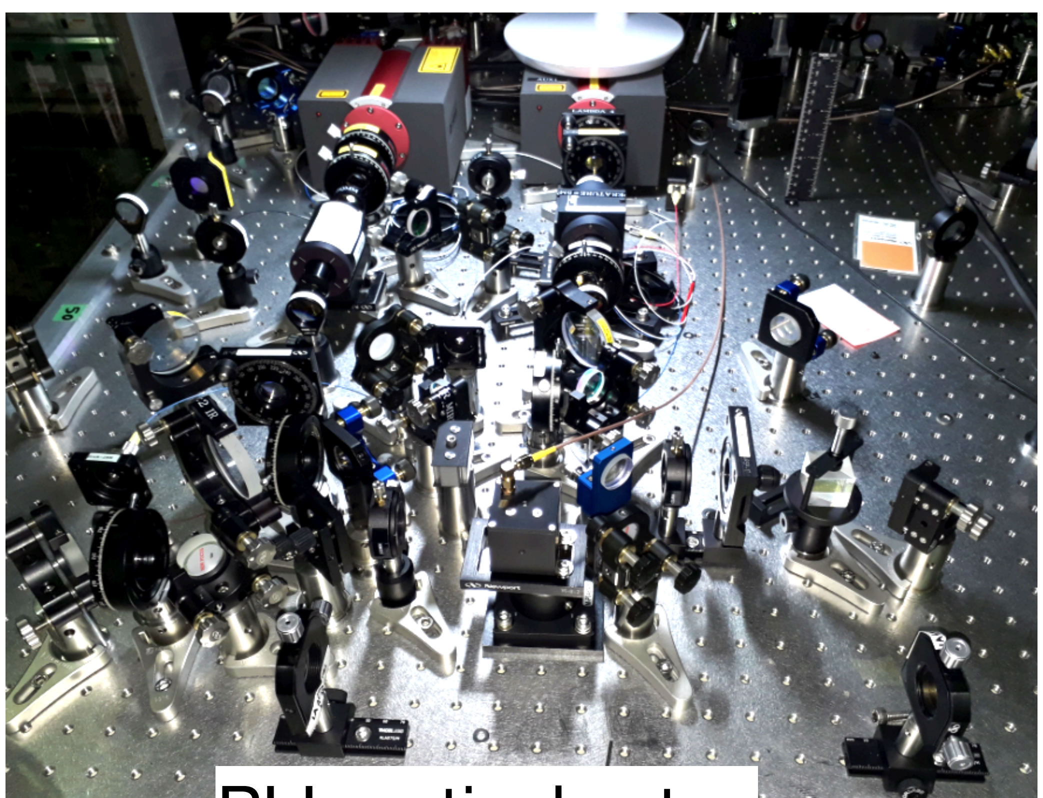
- Developed at AEI
- Clearance >15 dB
- Visibility ~ 99 %
- Shot noise limited down to 20 Hz
- Investigation on residual peaks and structures ongoing



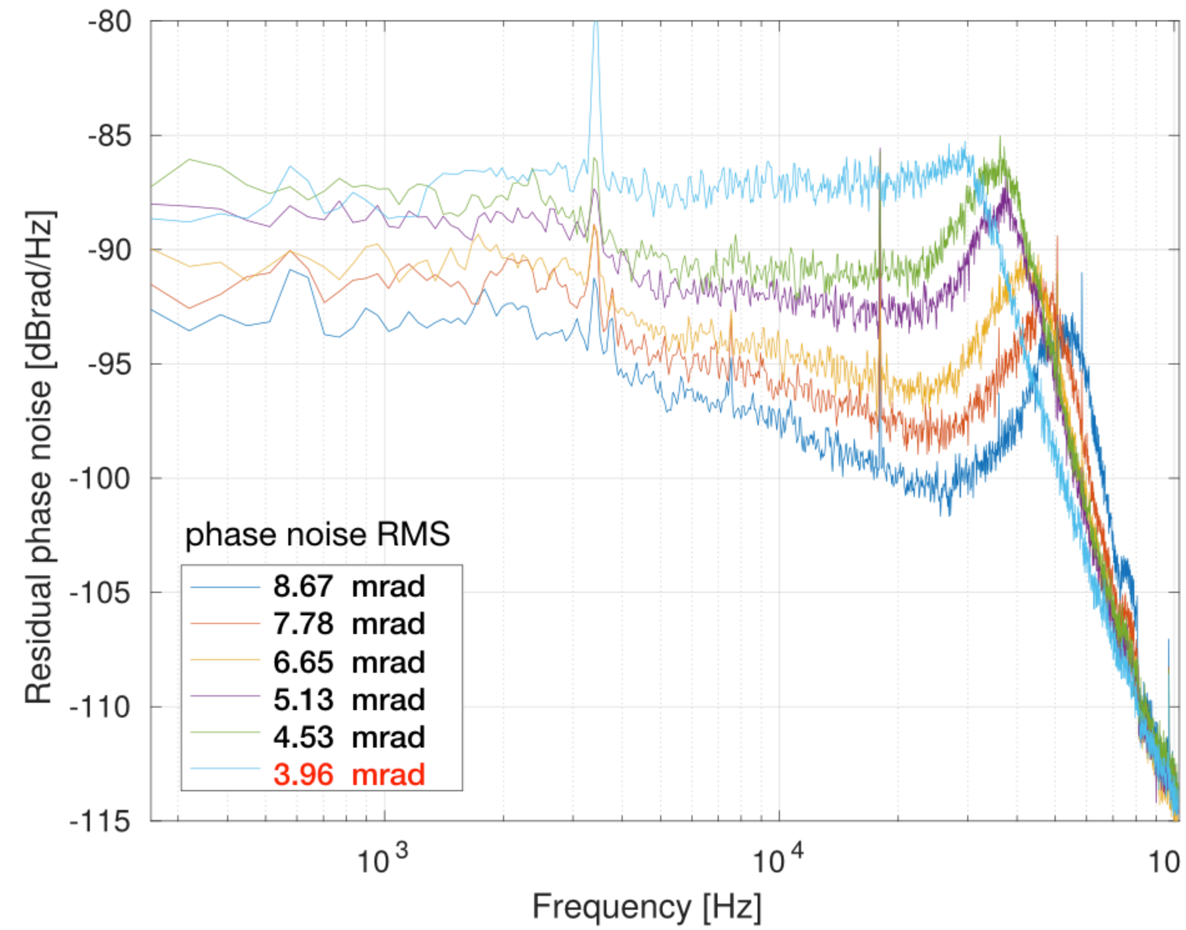


Phase lock loop (PLL) for AUX lasers

- 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

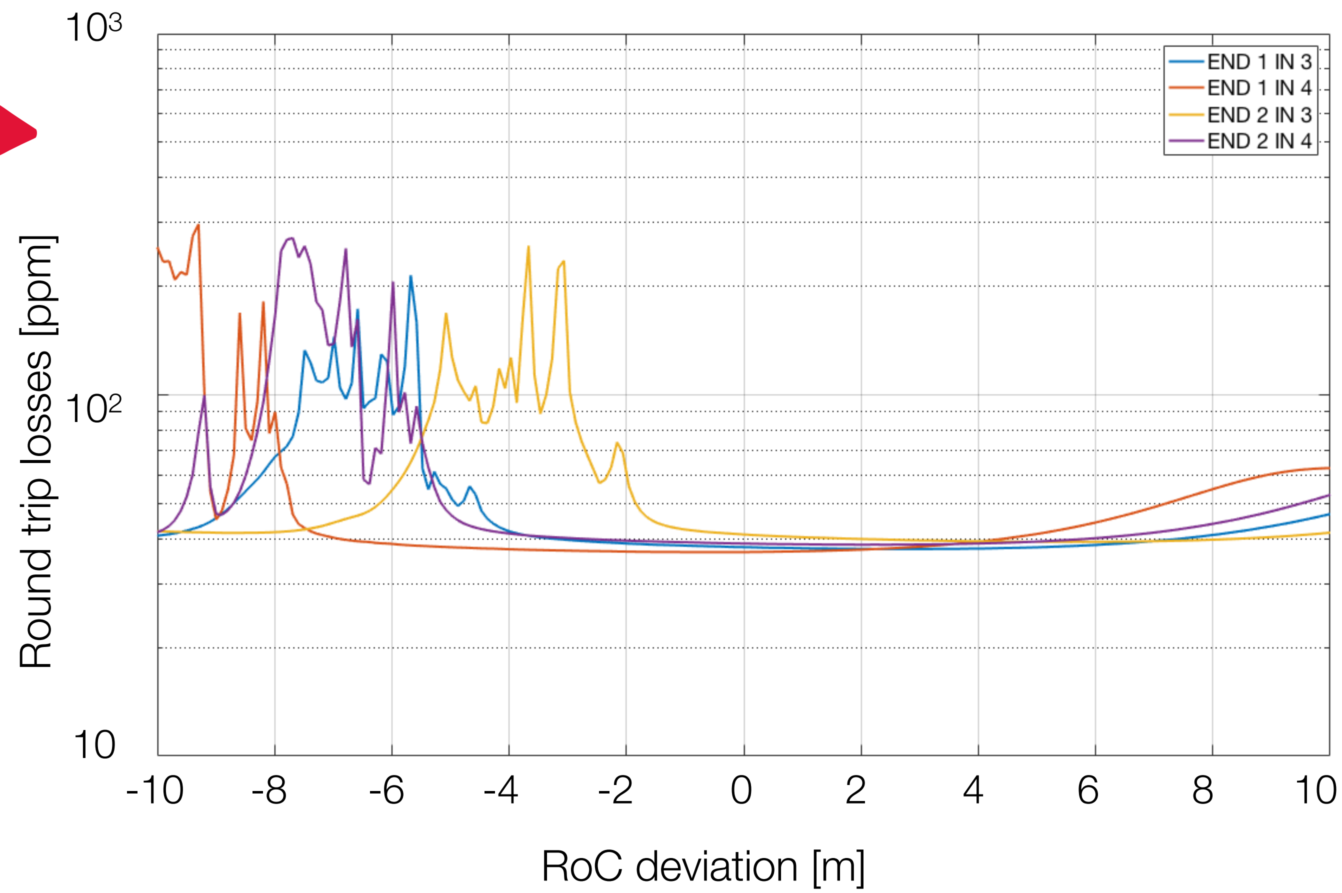
contribution from visitor Marco Vardaro



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

Why ppm/meter are important?

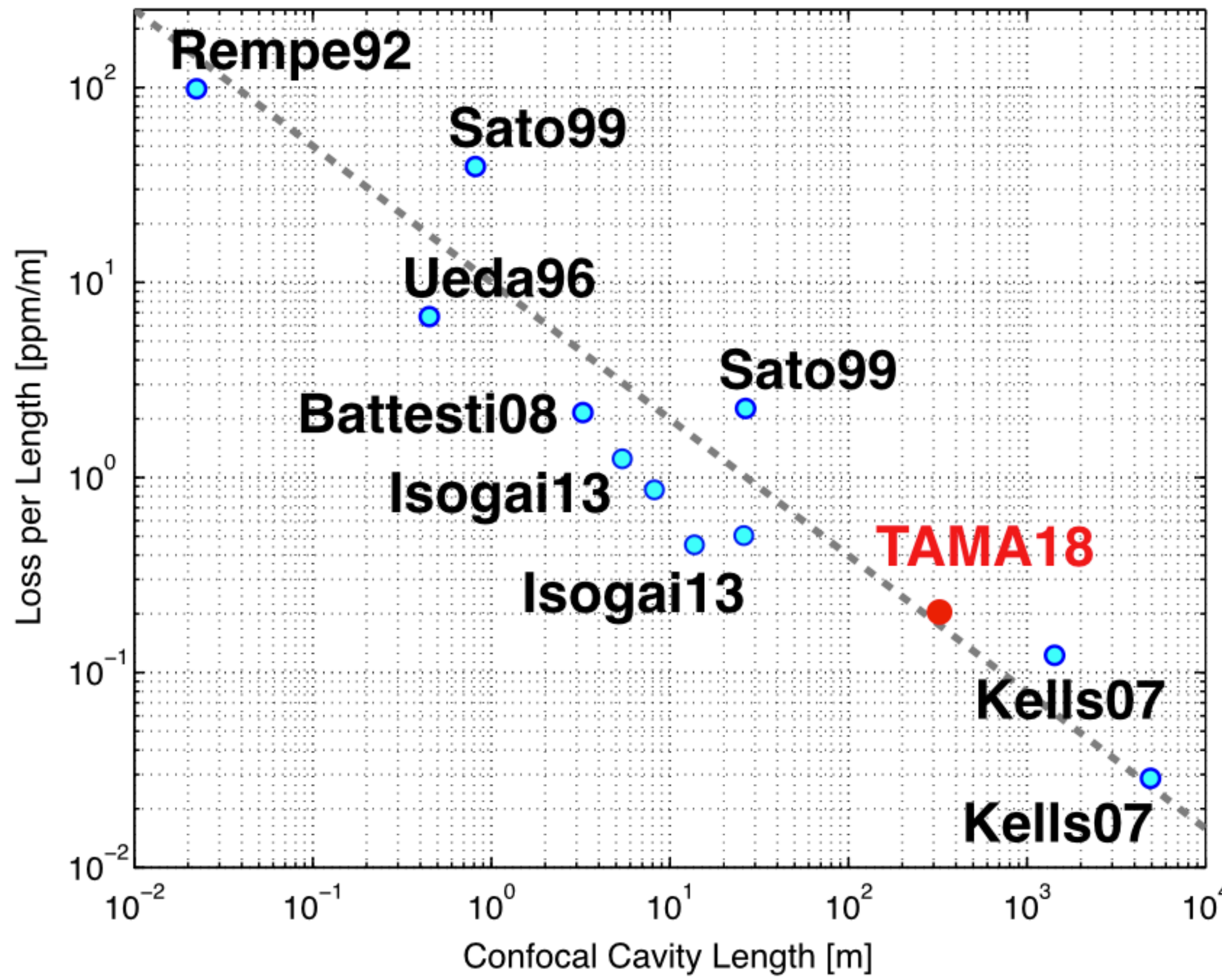
Total losses: RTL per number of round trip $N \sim 1/T_f$

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

Optimal rotation: filter Cavity bandwidth comparable with ITF bandwidth γ

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

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

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H. Miao
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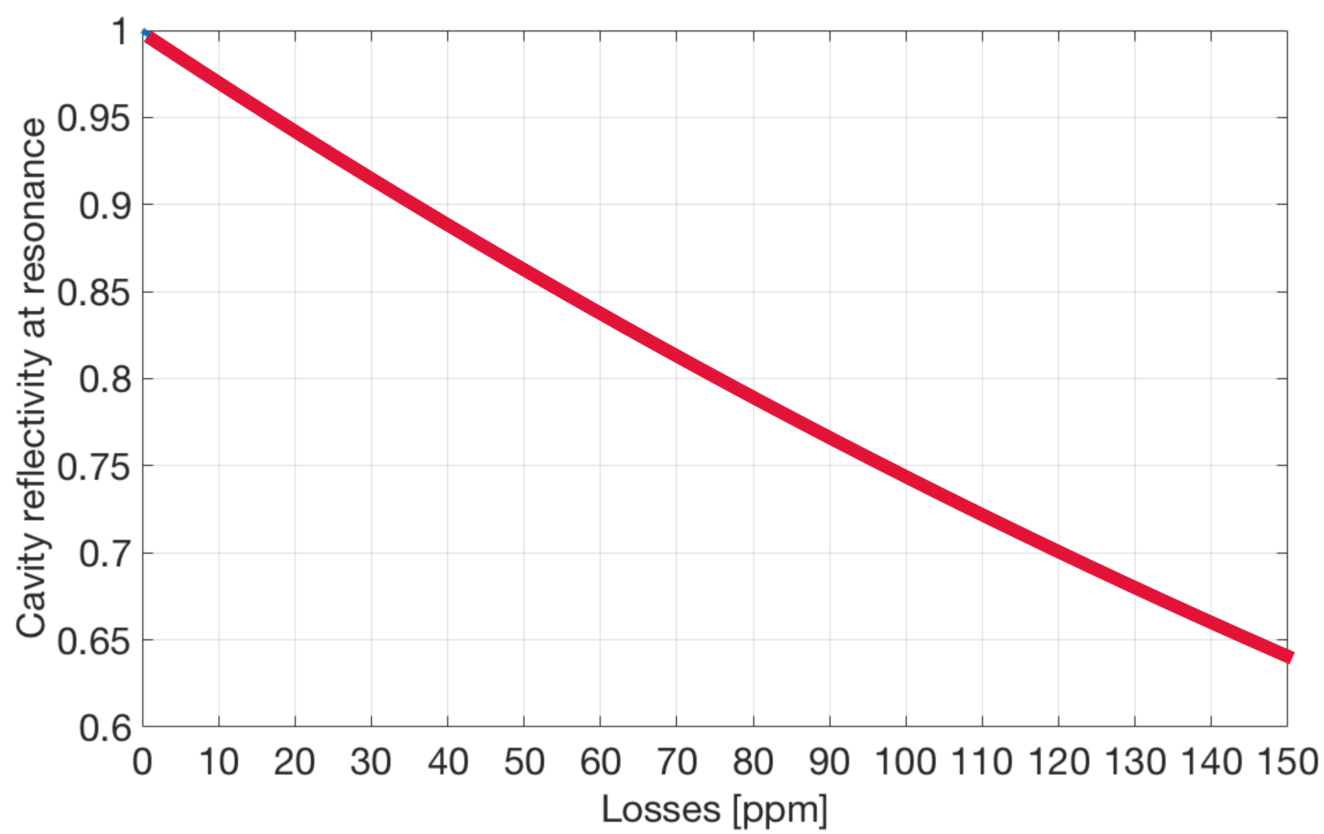
(Received 9 May 2013; published 29 July 2013)

How to measure round trip losses?

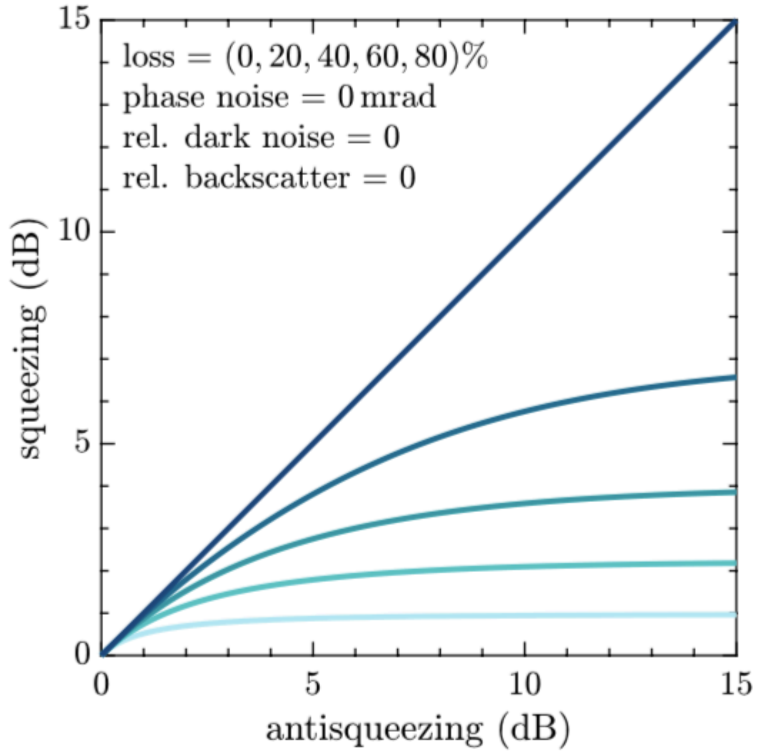
- From the cavity reflectivity at resonance
- Reflectivity is less affected from the input mirror transmissivity (with respect to finesse or decay time)

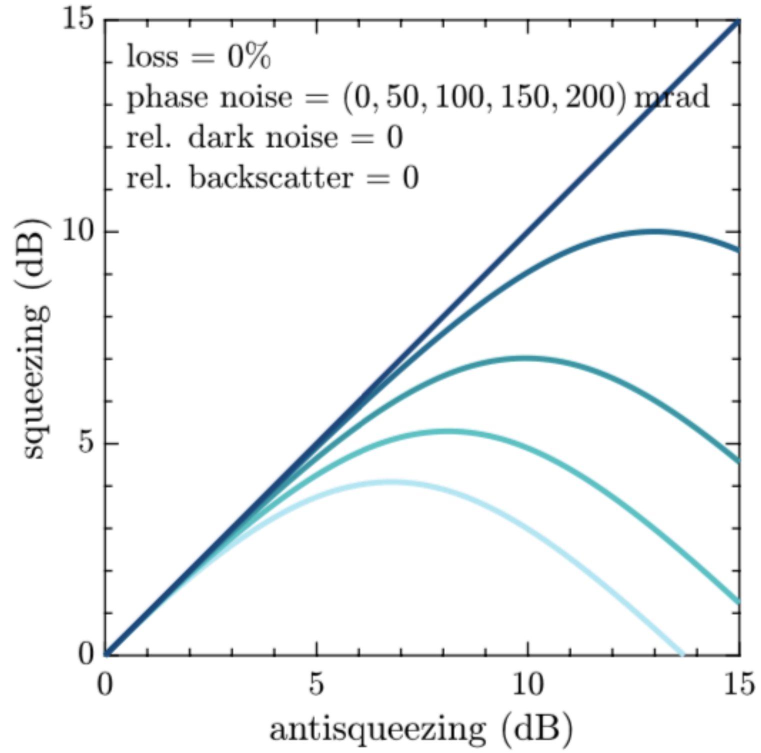
$$R_{\mathrm{cav}} = \left[\frac{r_1 - r_2}{1 - r_1 r_2}\right]^2 \qquad r_2 = \sqrt{1 - T_2 - L} \simeq \sqrt{1 - L}$$

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

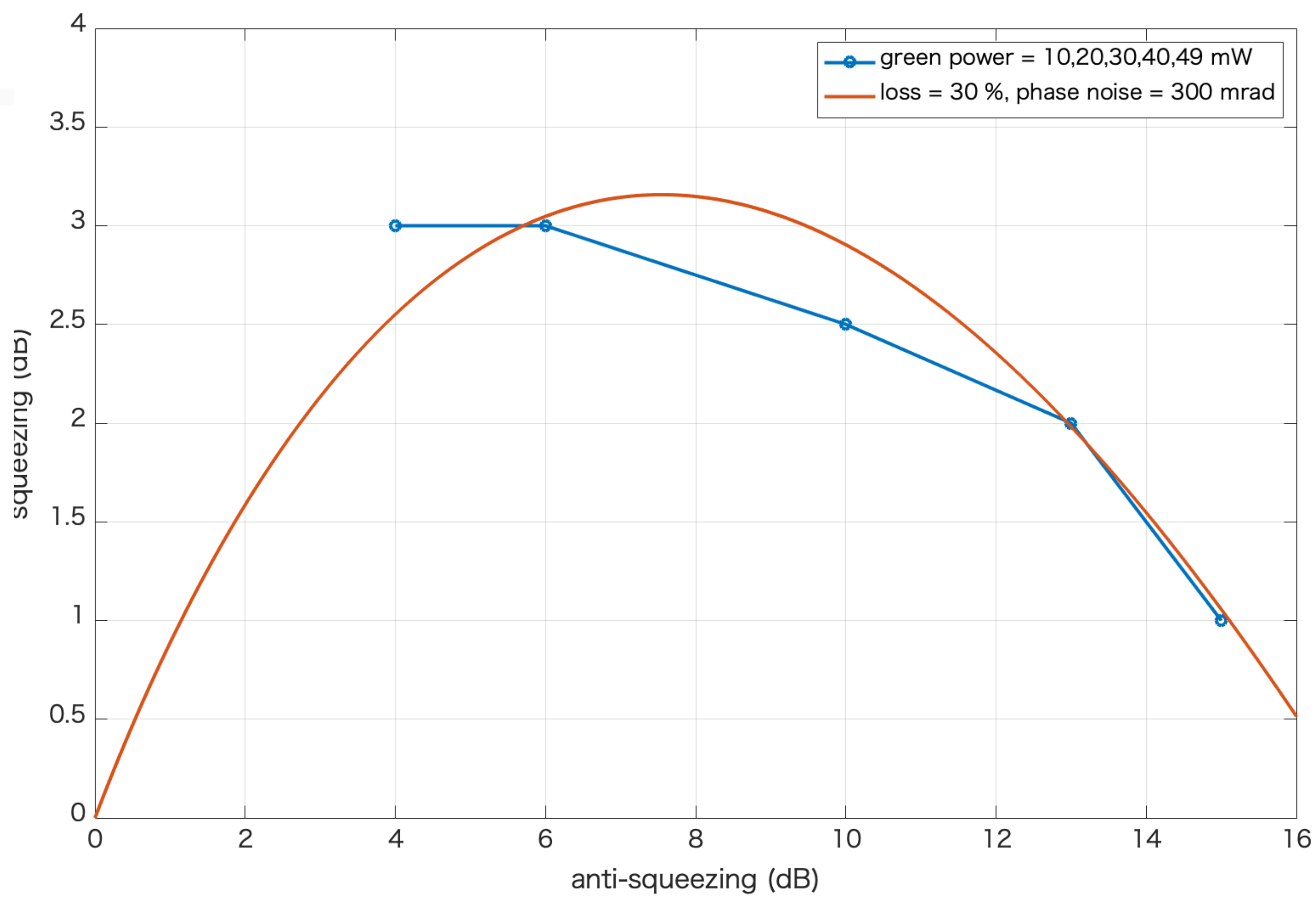


Phase noise vs optical losses



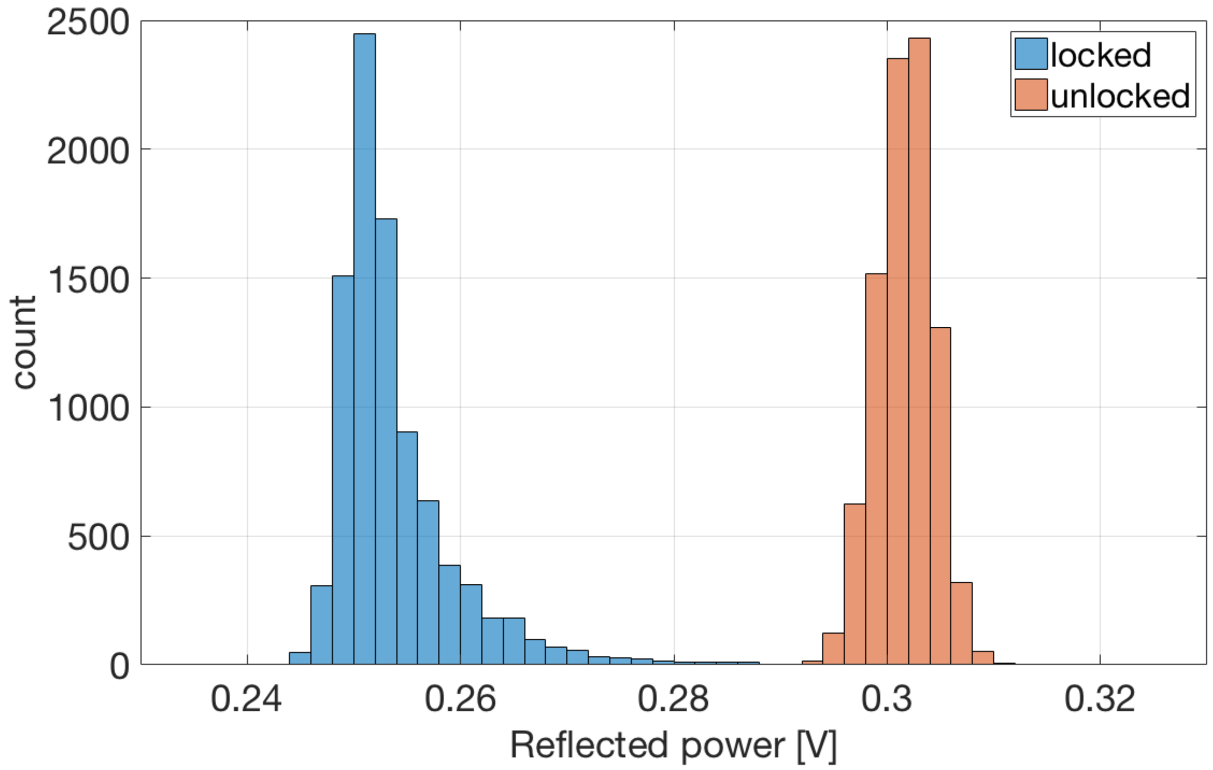


From E.Schreiber thesis



How to estimate the reflected power

- Reflected power has some fluctuations 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