Status of Frequency Dependent Squeezing Experiment at TAMA

K. Arai, Y. Aso, M. Barsuglia, E. Capocasa, E. Polini, M. Eisenmann, R. Flaminio, Y. Guo, M. Leonardi, H. Lueck, M. Marchiò, L. Pinard, P. Prat, R. Schnabel, E. Schreiber, K. Somiya, M. Tacca, R. Takahashi, D. Tatsumi, A. Tomura, M. Vardaro, H. Vahlbruch, C. Wu, S. Wu, **Yuhang Zhao**

SOKENDAI(The Graduate University of Advanced Studies)/NAOJ

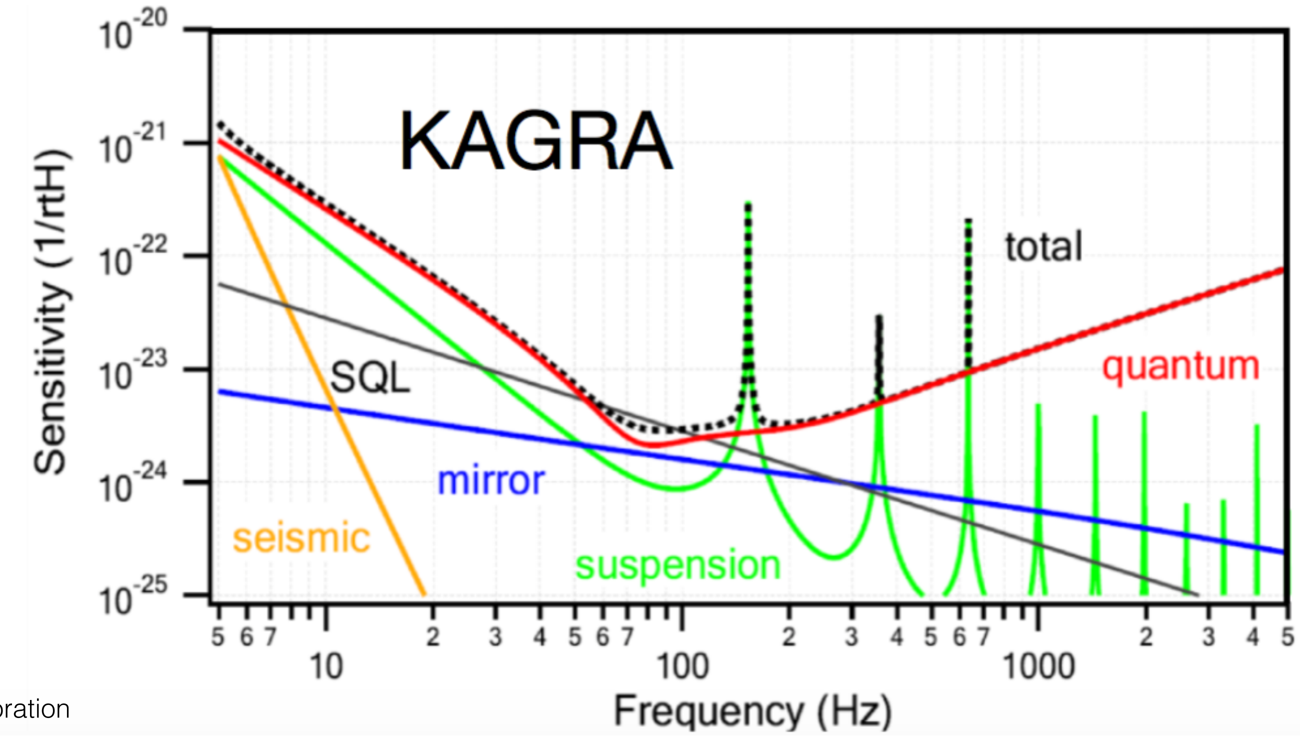
Content

- Frequency dependent squeezing for GW detector
- Construction of squeezer and measurement of squeezing
- Matching of squeezer and filter cavity
- Summary and future plan

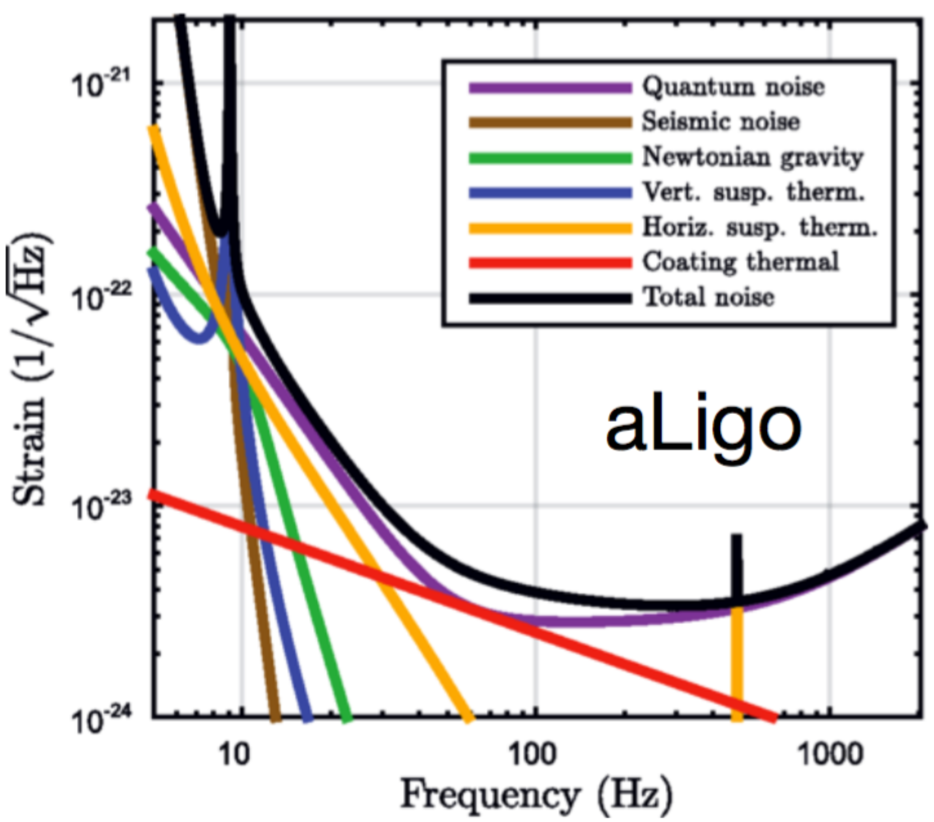
Design sensitivity of current gravitational wave detectors

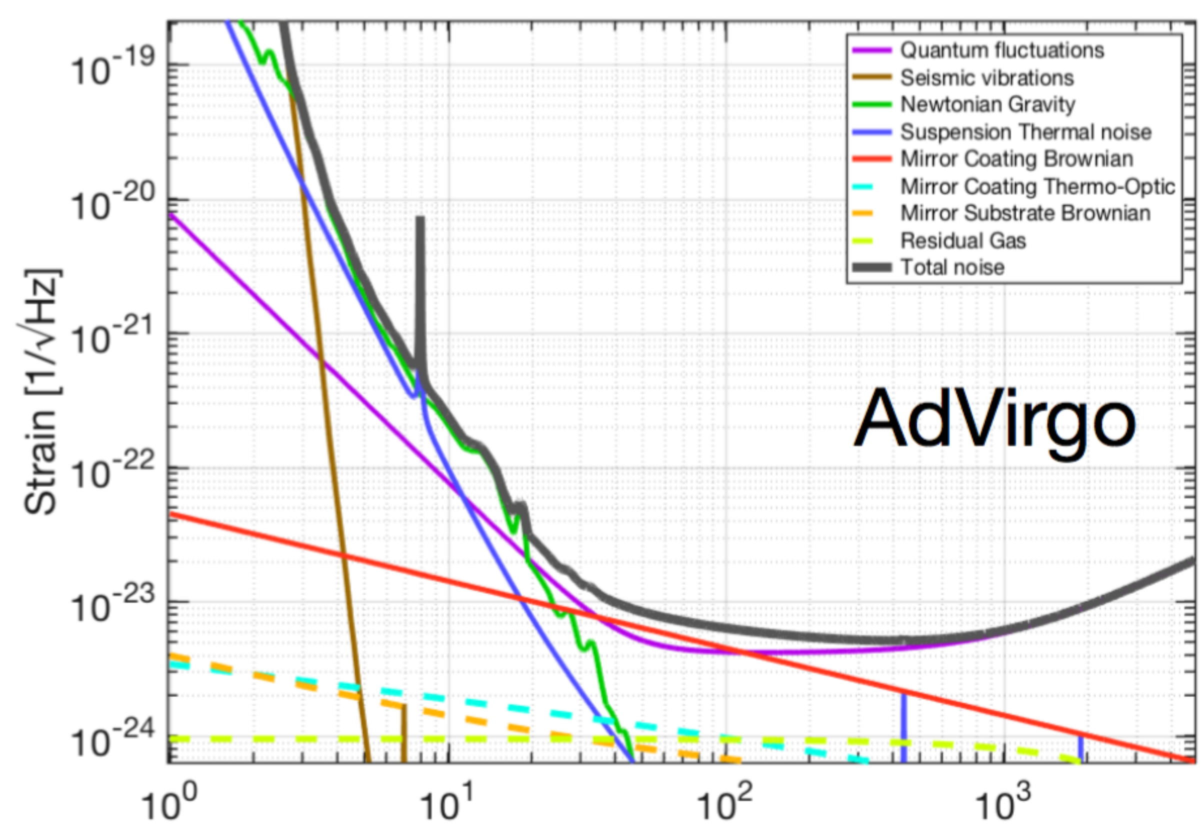
Quantum noise is limiting all the 2nd generation gravitational wave detectors' design sensitivity

Broadband quantum noise reduction will allow for major improvements

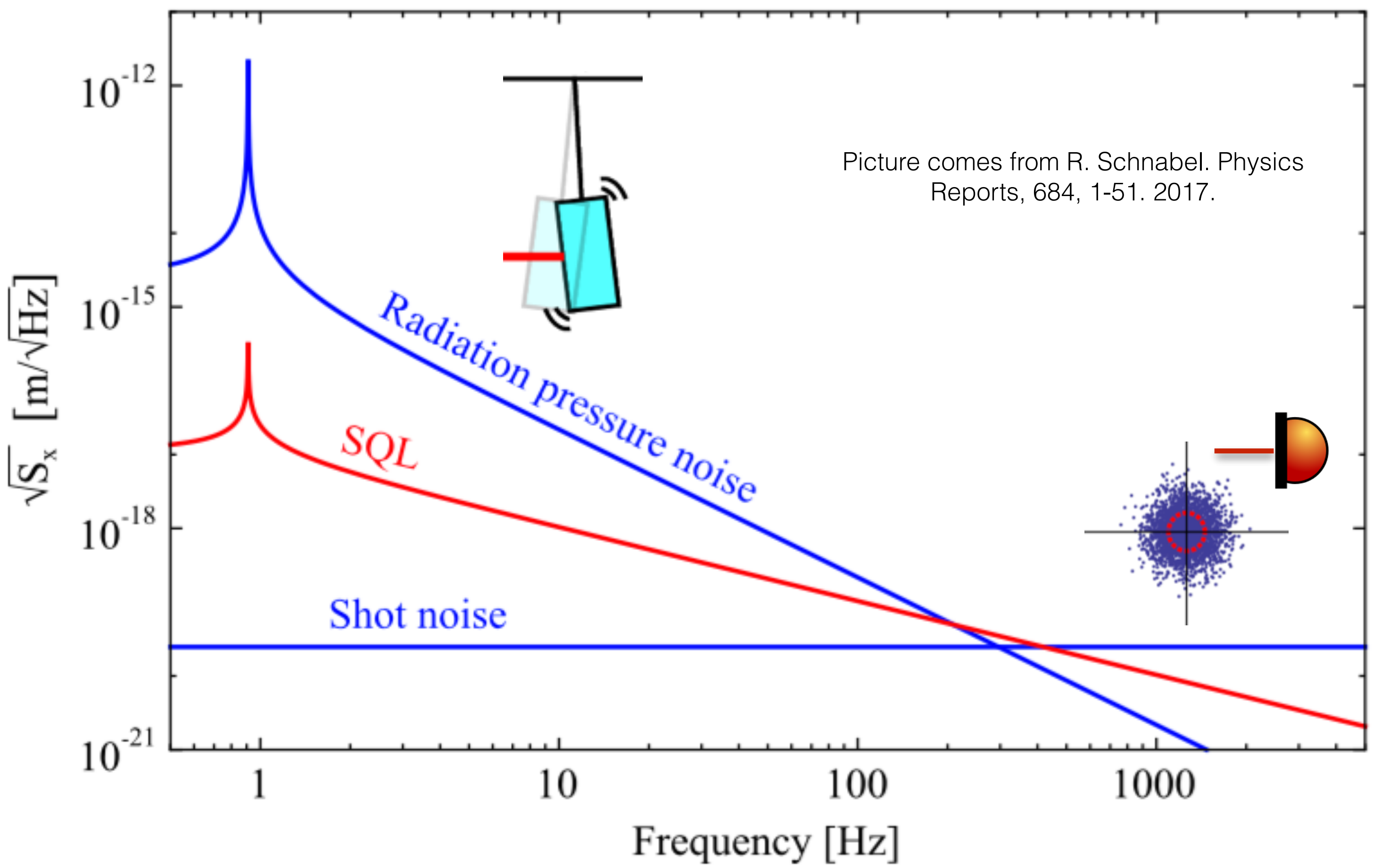


Pictures from LSC/KAGRA Collaboration





Quantum noise component

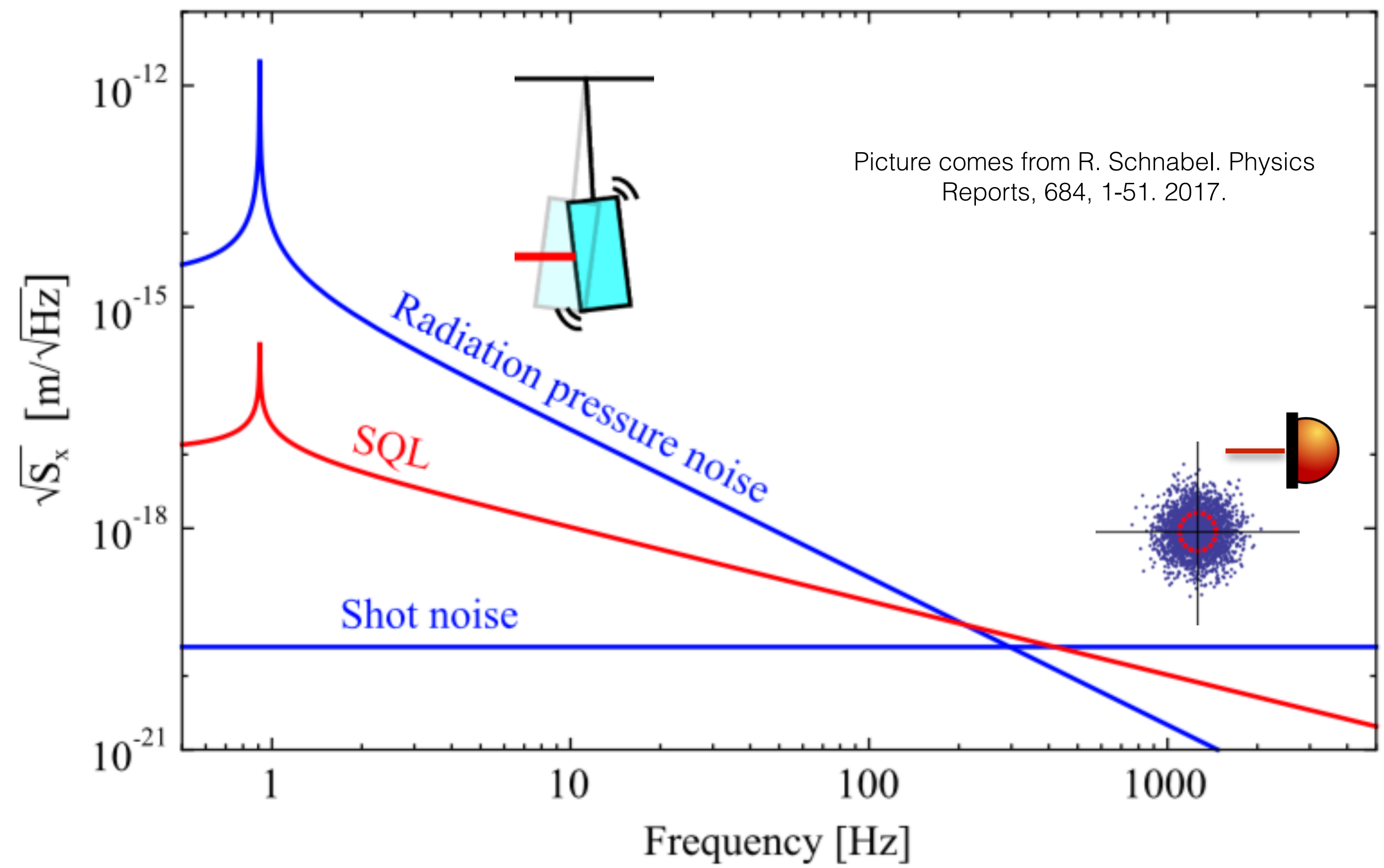


The random arrival of photons

Radiation pressure noise:
Amplitude quadrature fluctuation of laser beam shakes mirrors differentially

Shot noise:
Phase quadrature fluctuation of interferometer output laser beam

Quantum noise component

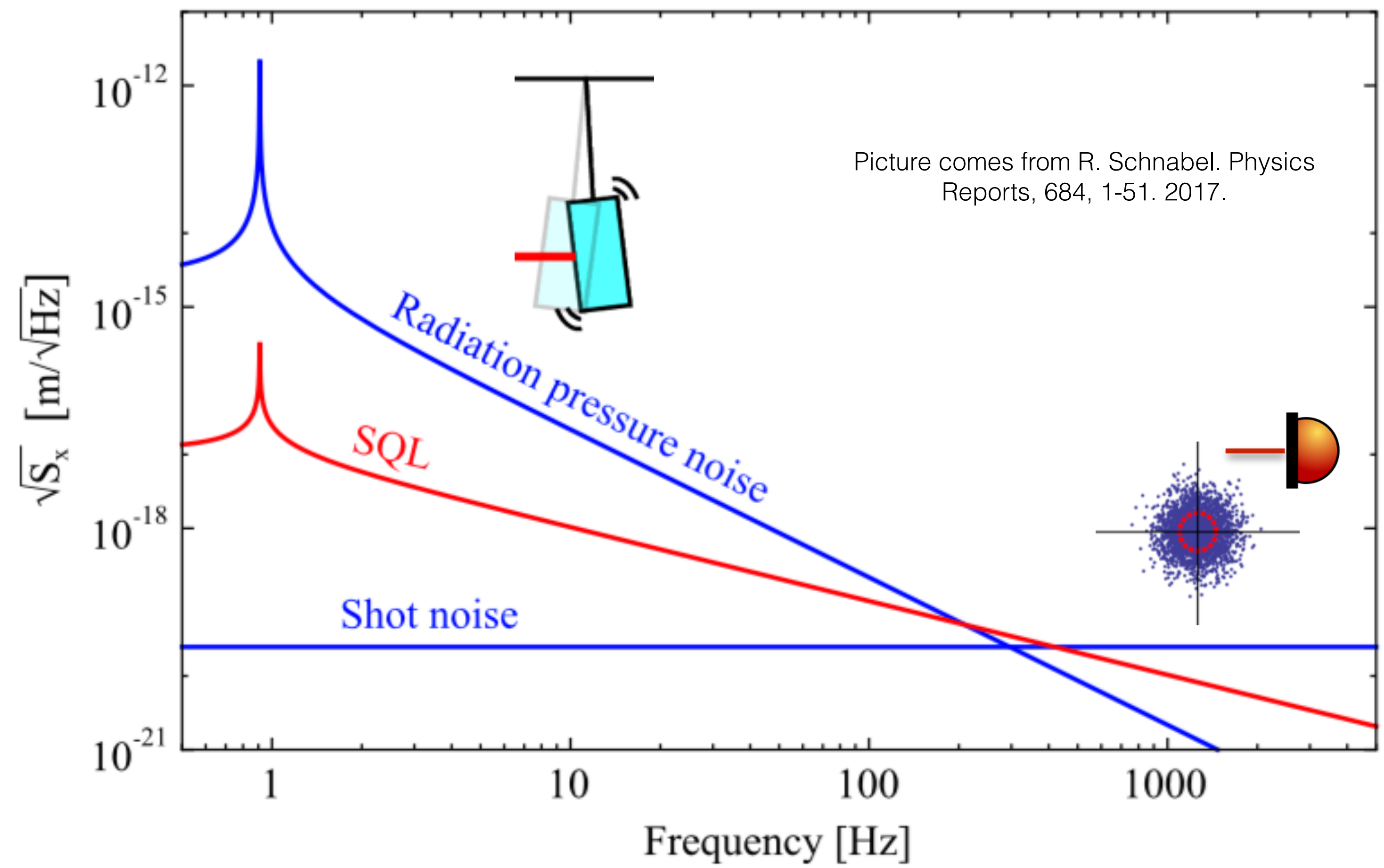


Applying frequency independent phase squeezing

Radiation pressure noise:
Amplitude quadrature fluctuation of laser beam shakes mirrors differentially

Shot noise:
Phase quadrature fluctuation of interferometer output laser beam

Quantum noise component

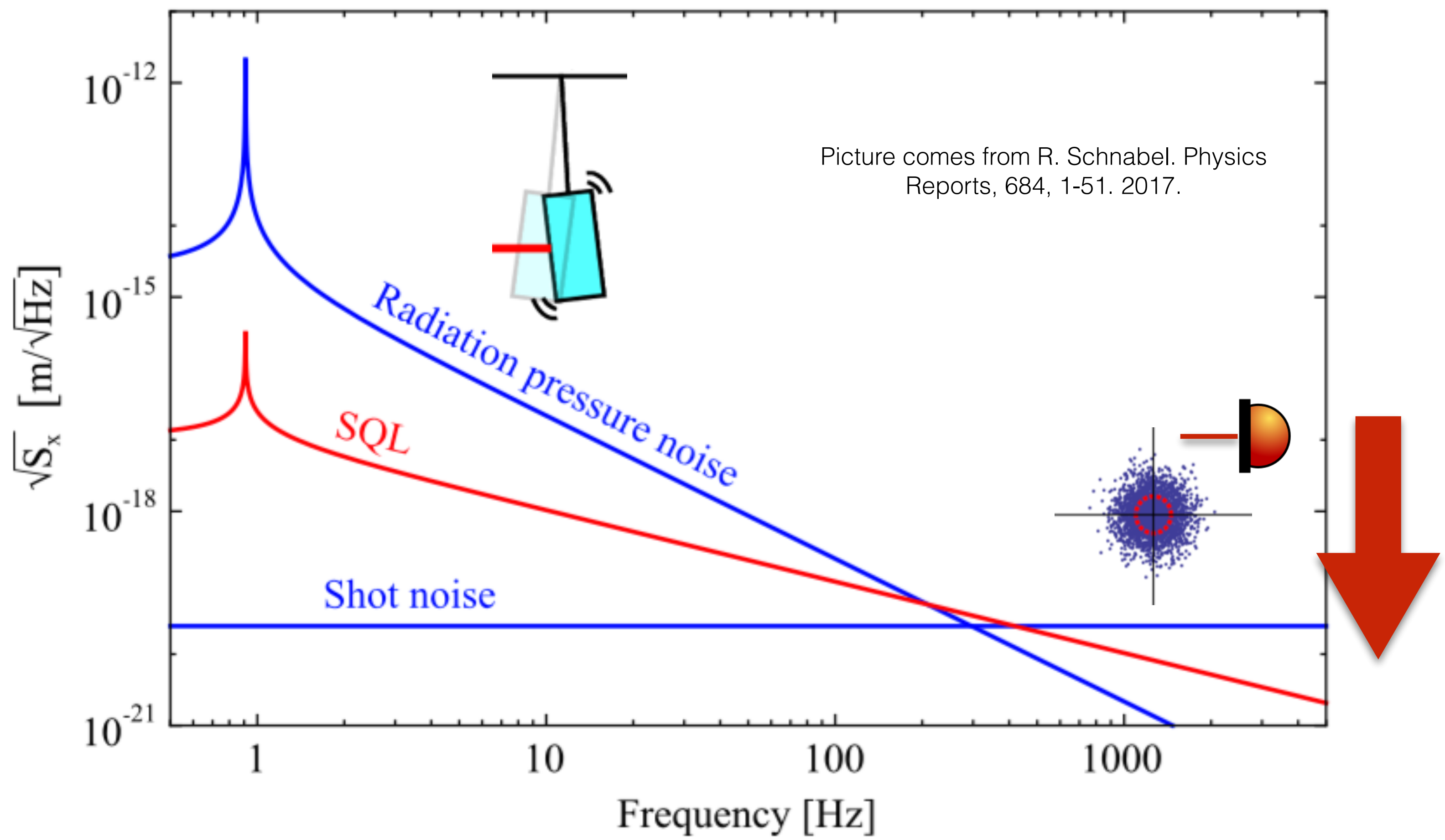


Applying frequency independent phase squeezing

Radiation pressure noise:
Amplitude quadrature fluctuation of laser beam shakes mirrors differentially

Shot noise:
Phase quadrature fluctuation of interferometer output laser beam

Quantum noise component

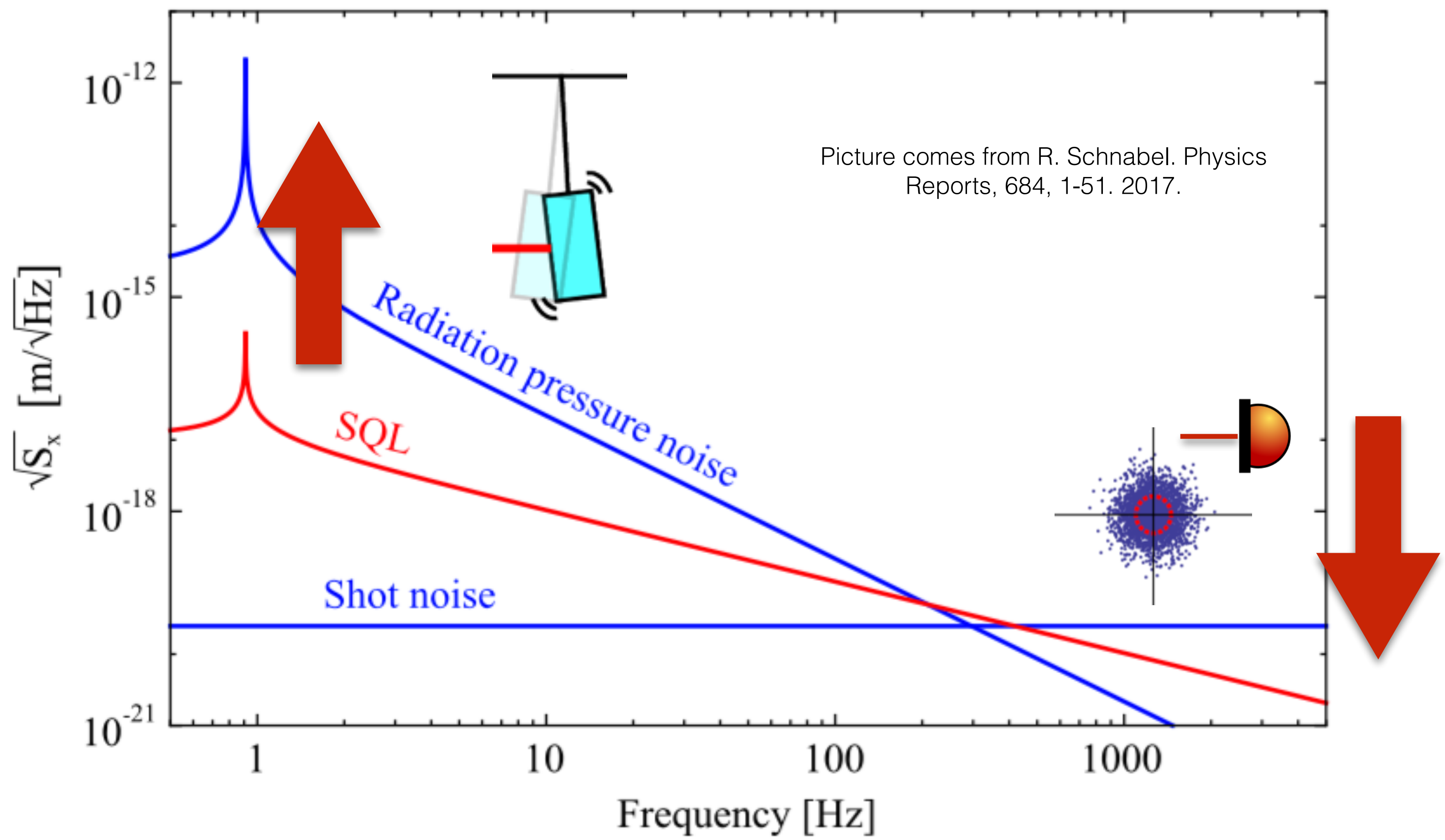


Applying frequency independent phase squeezing

Radiation pressure noise:
Amplitude quadrature fluctuation of laser beam shakes mirrors differentially

Shot noise:
Phase quadrature fluctuation of interferometer output laser beam

Quantum noise component



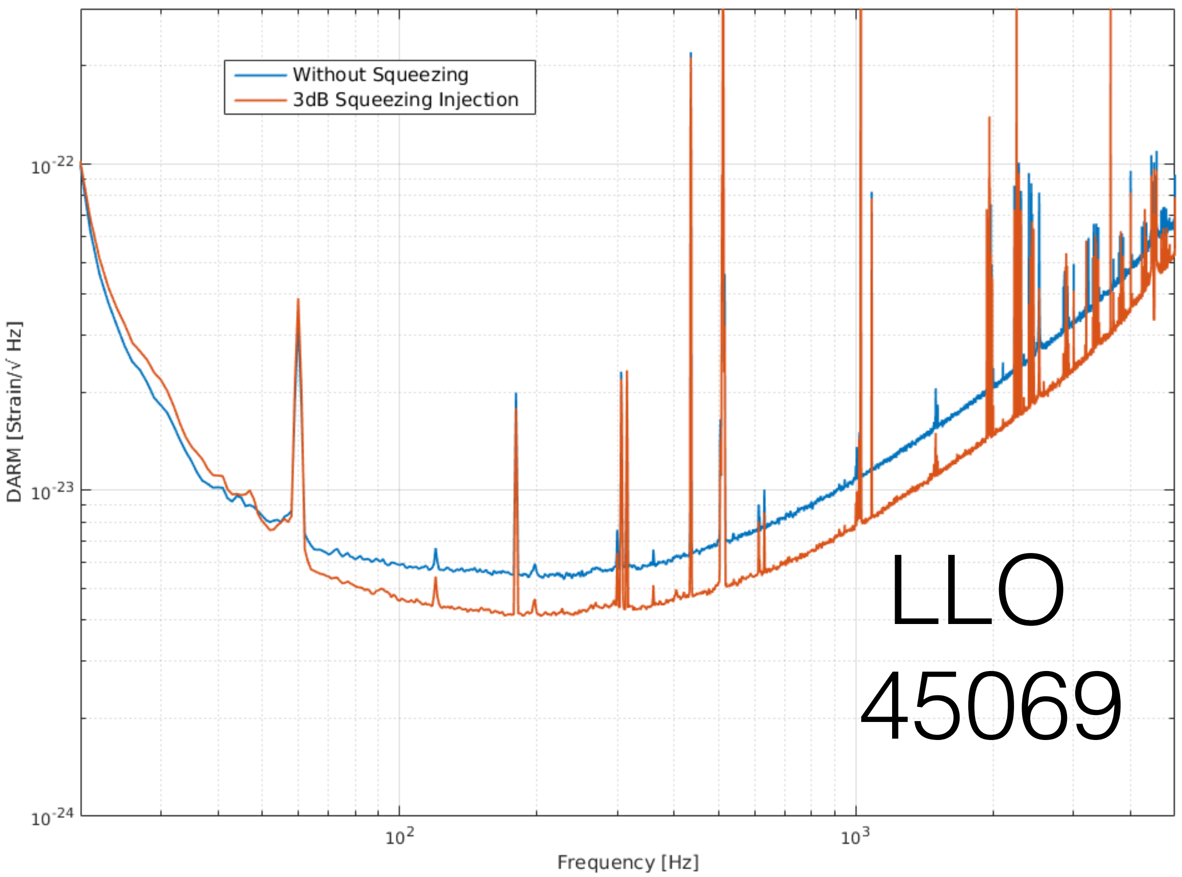
Applying frequency independent phase squeezing

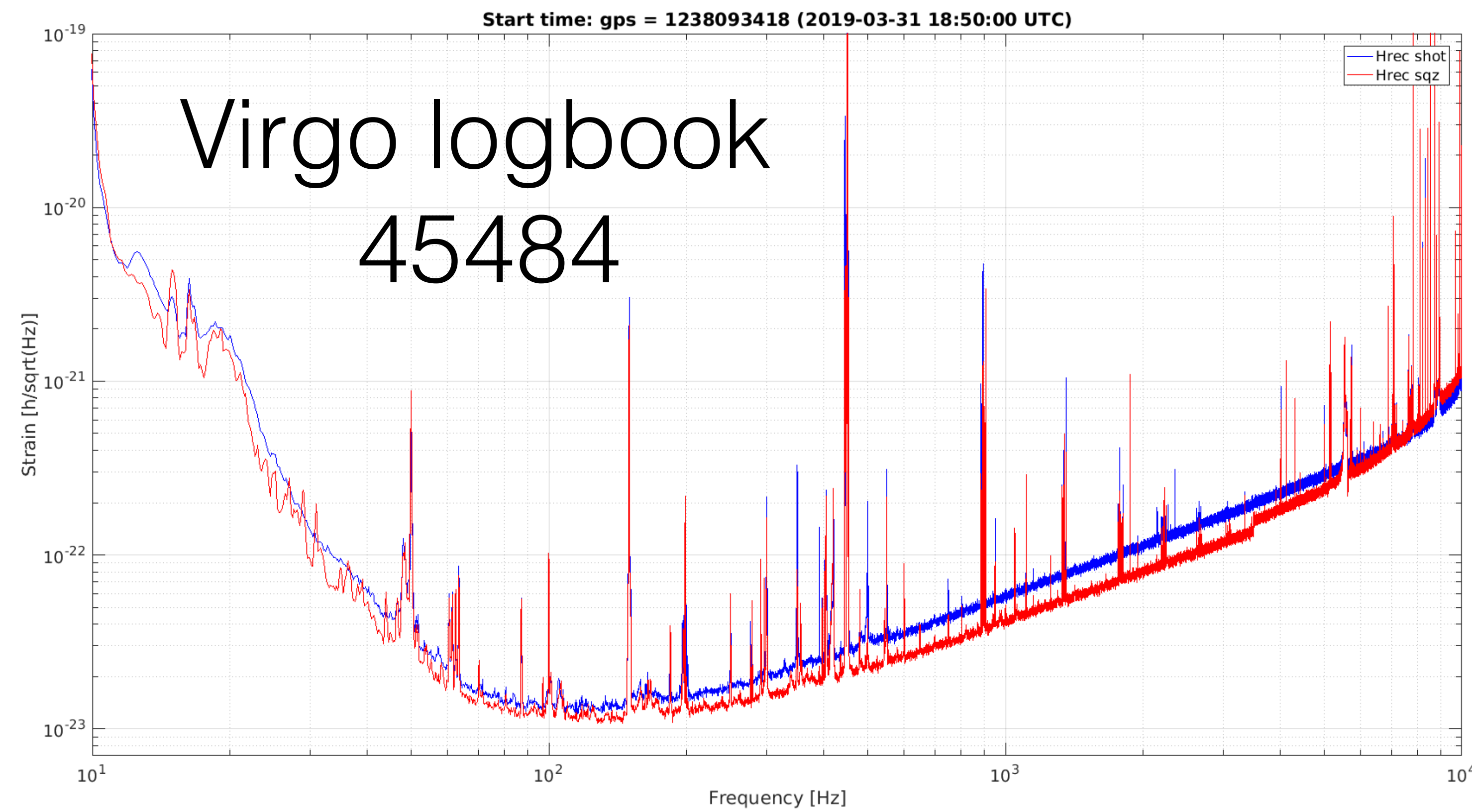
Radiation pressure noise:
Amplitude quadrature fluctuation of laser beam shakes mirrors differentially

Shot noise:
Phase quadrature fluctuation of interferometer output laser beam

Squeezing implemented into GW detectors

Frequency independent squeezing (FIS) has been implemented in the second observation run which started this April.

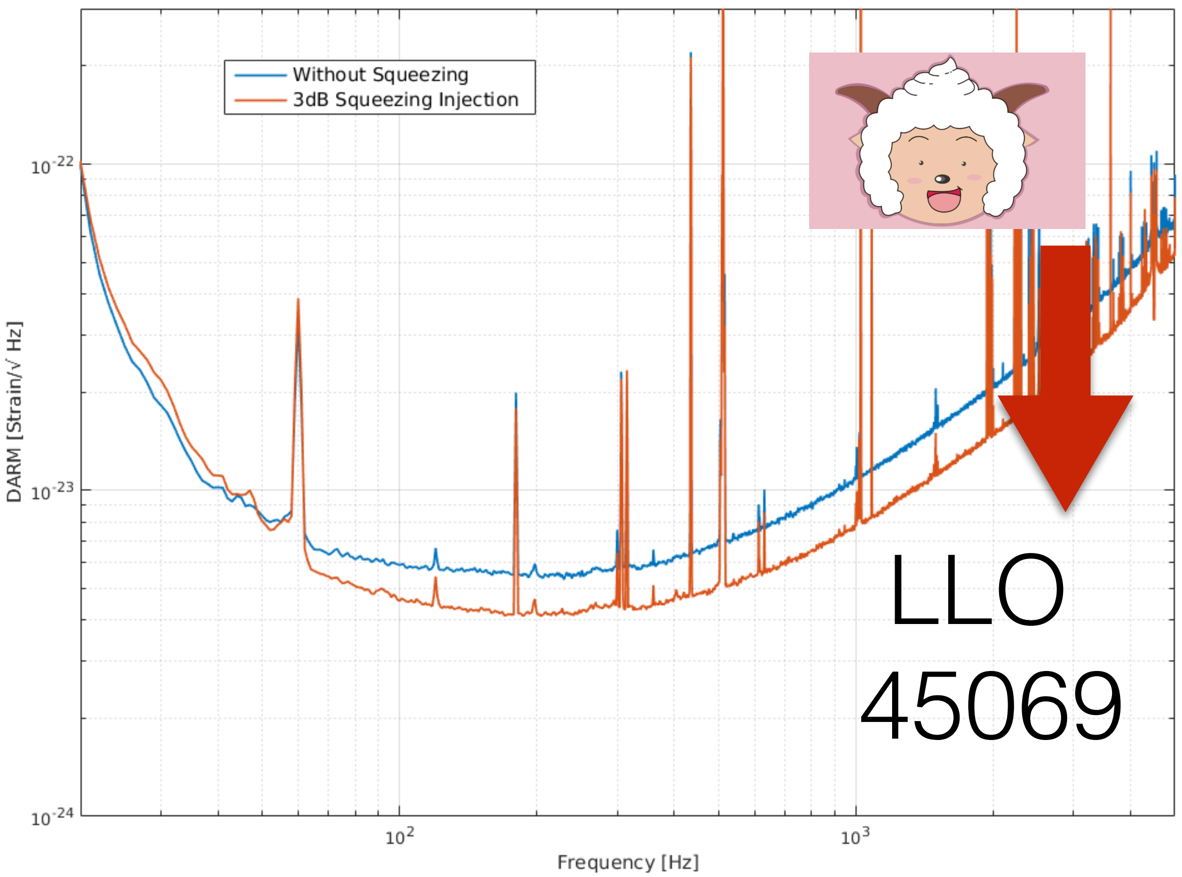


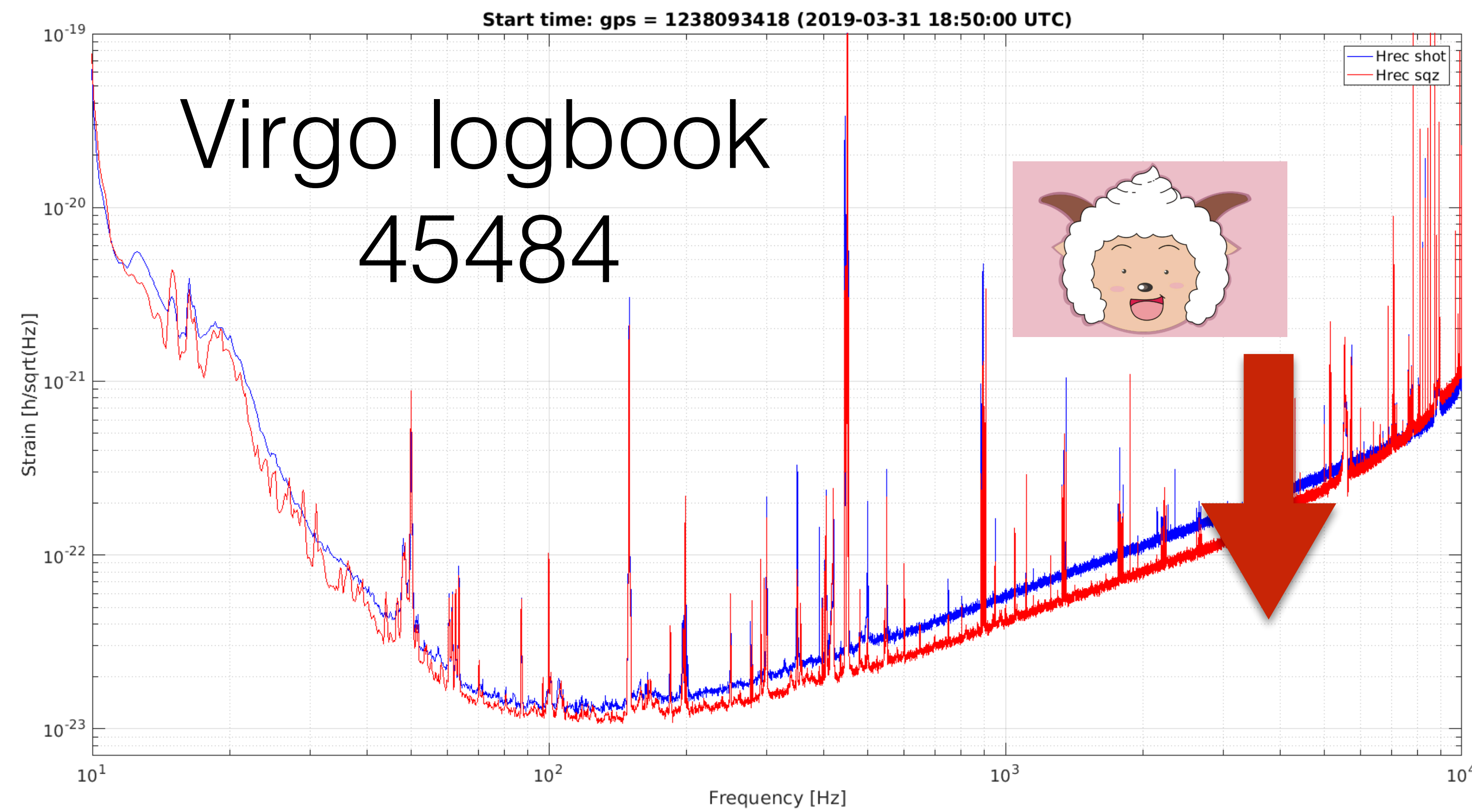


When quantum noise will limit the entire detection bandwidth, a strategy for the broadband quantum noise reduction will be mandatory

Squeezing implemented into GW detectors

Frequency independent squeezing (FIS) has been implemented in the second observation run which started this April.

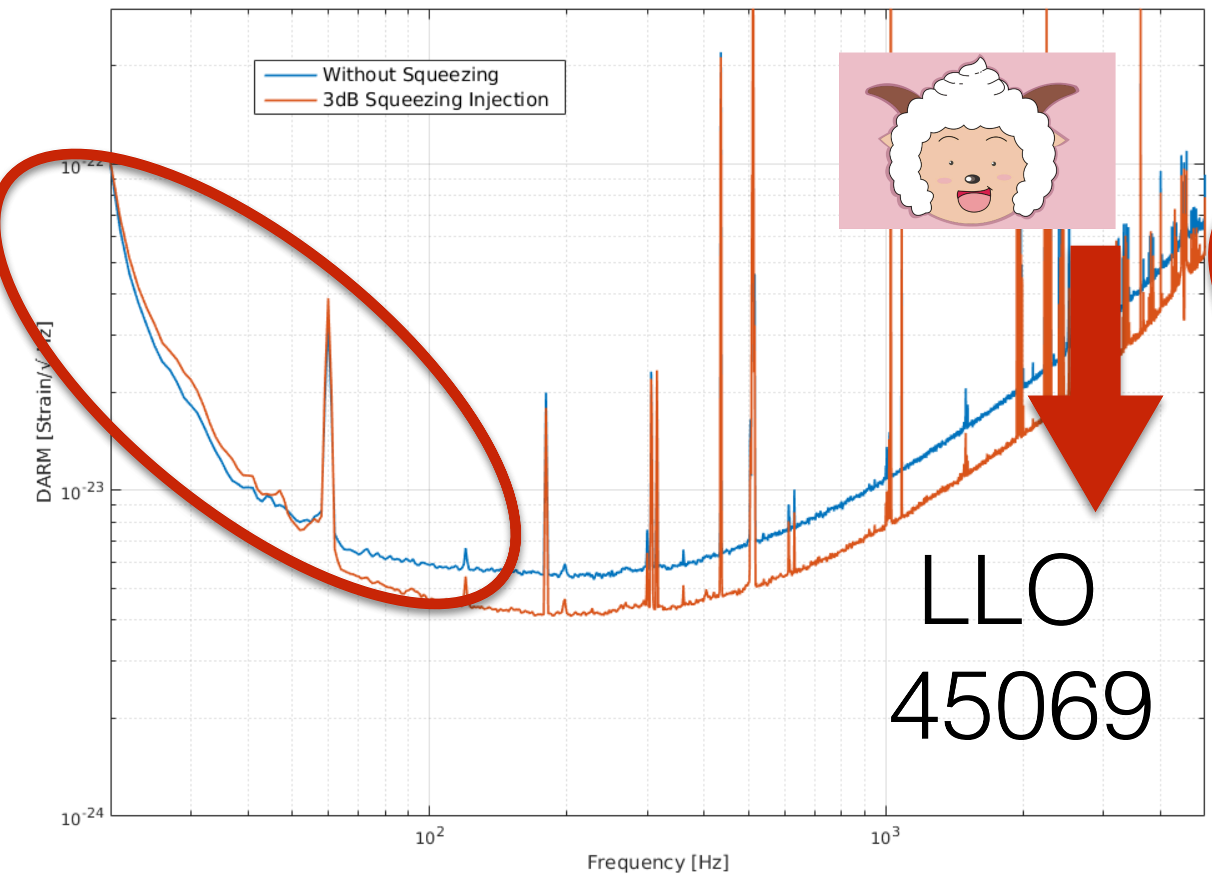


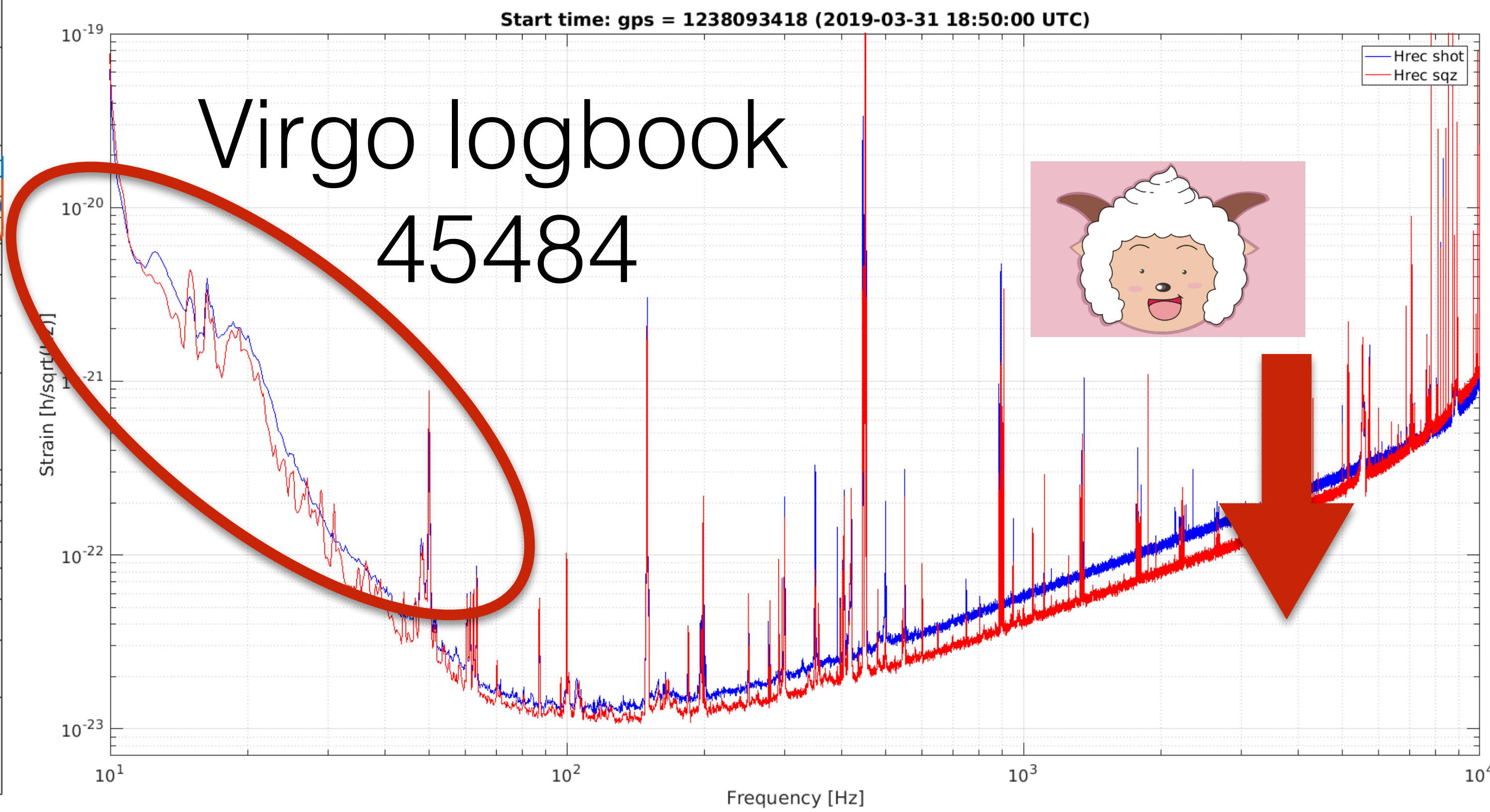


When quantum noise will limit the entire detection bandwidth, a strategy for the broadband quantum noise reduction will be mandatory

Squeezing implemented into GW detectors

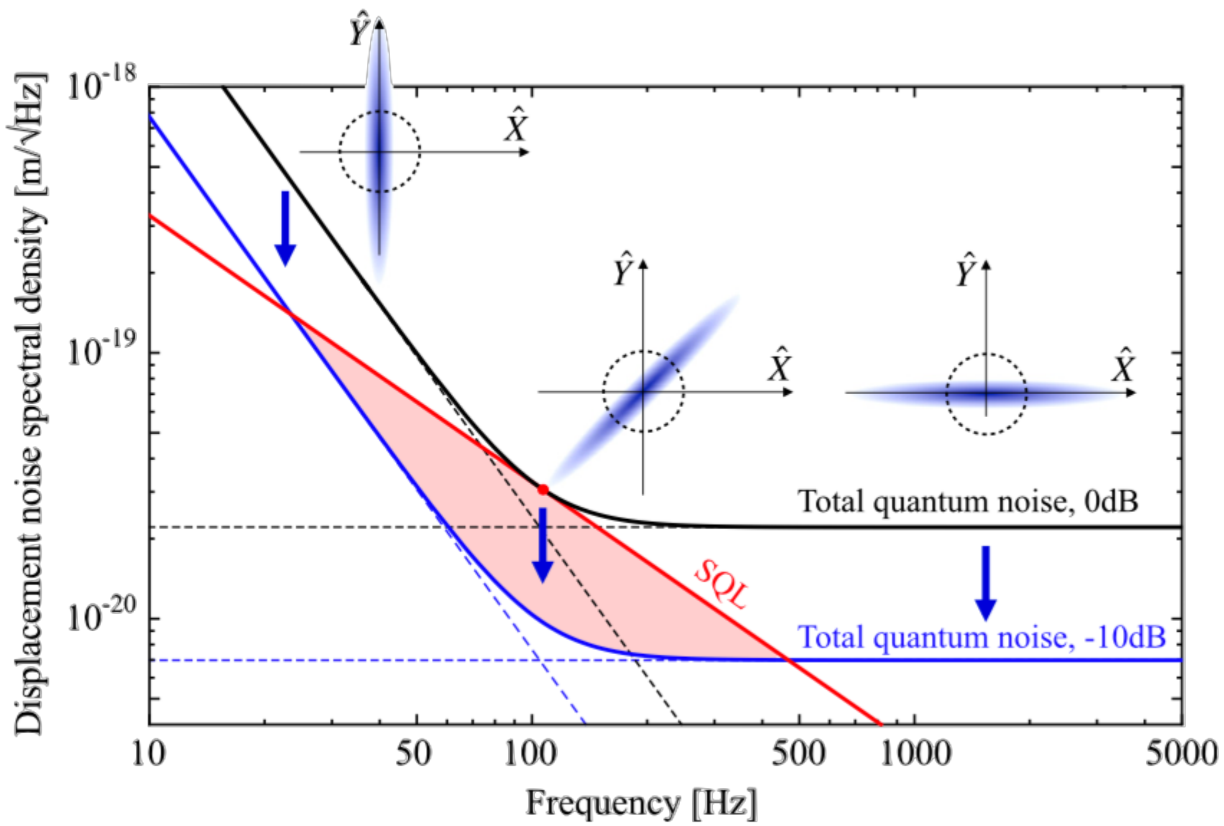
Frequency independent squeezing (FIS) has been implemented in the second observation run which started this April.





When quantum noise will limit the entire detection bandwidth, a strategy for the broadband quantum noise reduction will be mandatory

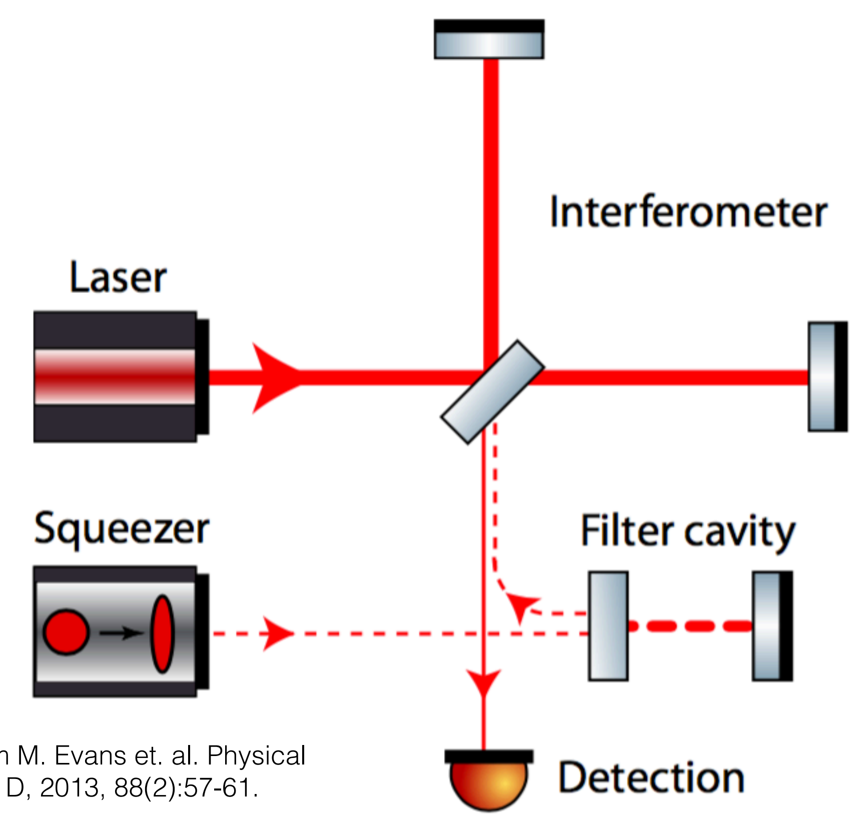
Broadband Quantum noise reduction



Picture from R. Schnabel. Physics Reports, 684, 1-51. 2017.

For optimal quantum noise reduction, the squeezing ellipse angle needs to be optimized for each frequency

Frequency dependent squeezing can be achieved by reflecting frequency independent squeezing off a detuned optical cavity



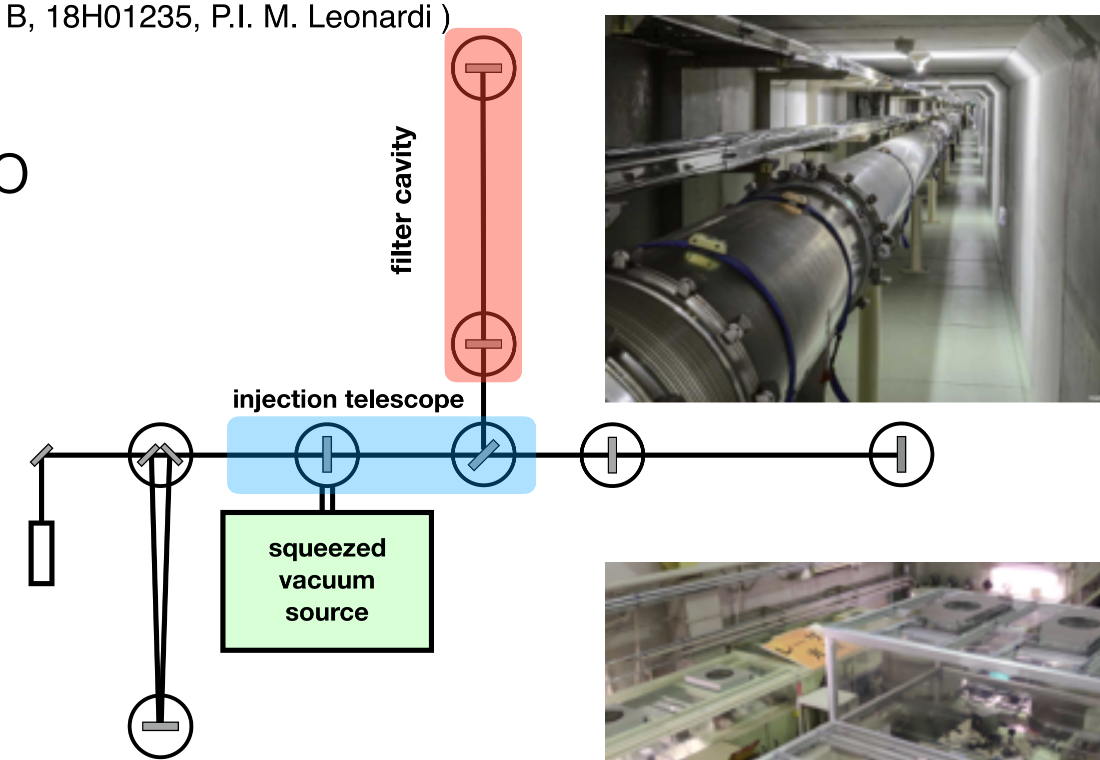
Picture from M. Evans et. al. Physical Review D, 2013, 88(2):57-61.

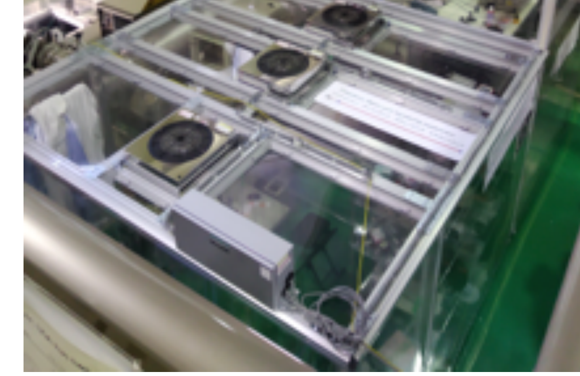
Frequency dependent squeezing project overview

funded by JSPS (Scientific Research A 15H02095, P.I. R. Flaminio and Scientific Research B, 18H01235, P.I. M. Leonardi)

Goal: Full scale filter cavity prototype to demonstrate frequency dependent squeezing with rotation around 70Hz.

Key features:
- Cavity length: 300m
- Finesse: 4400 @1064nm
- Storage time: 2.8ms @1064nm
- Losses (round trip): 80ppm





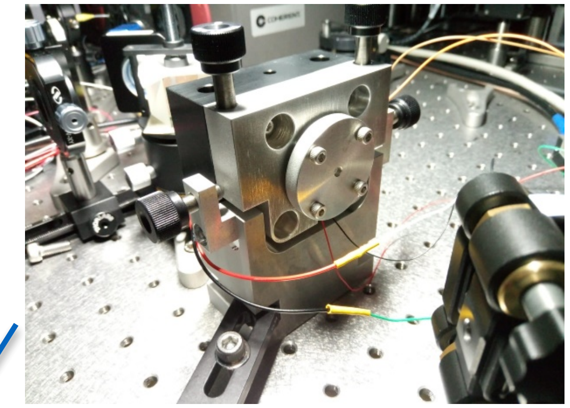
- The experiment is using TAMA facility
- Squeezed vacuum source is in air
- The injection telescope and filter cavity are in vacuum and suspended by TAMA suspension

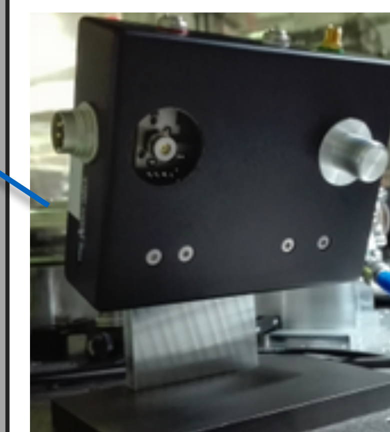
Content

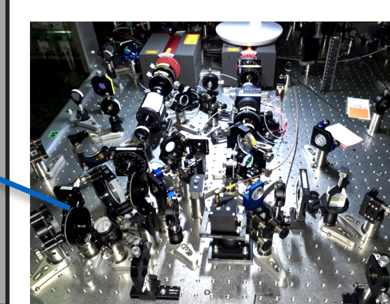
- Frequency dependent squeezing for GW detector
- Construction of squeezer and measurement of squeezing
- Matching of squeezer and filter cavity
- Summary and future plan

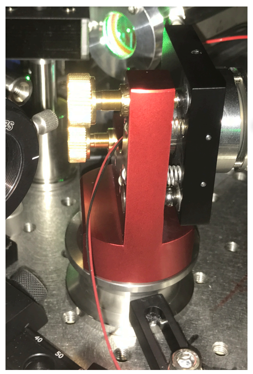
Construction of Frequency Independent squeezed source

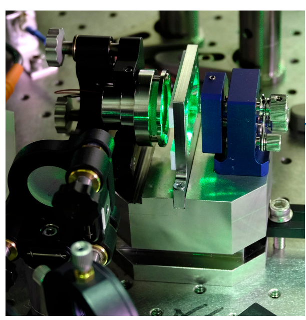
Squeezer construction was finished recently
(commissioning is on going)

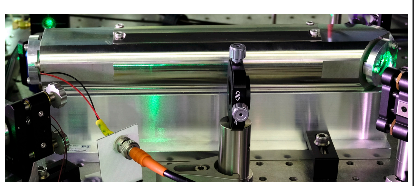


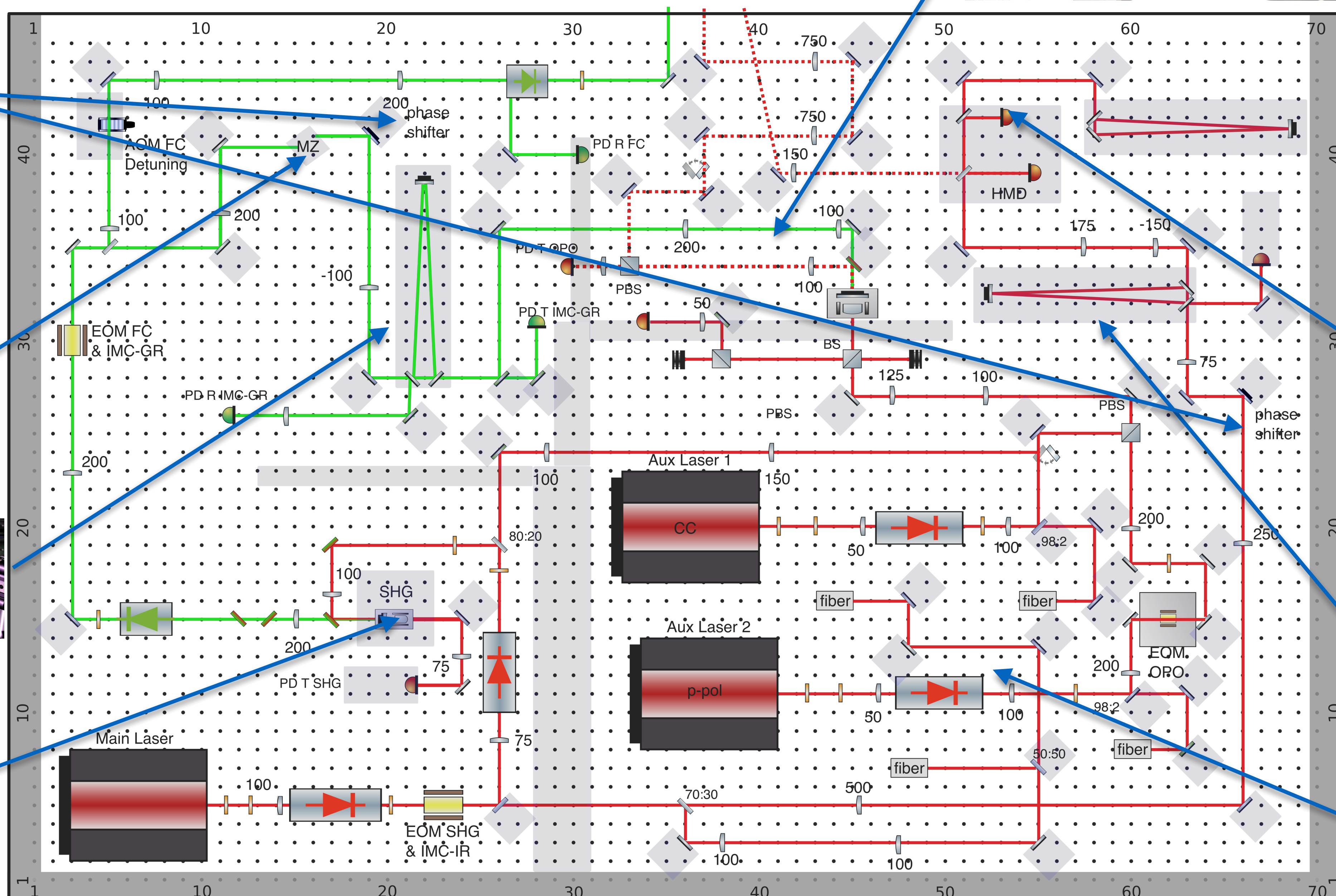




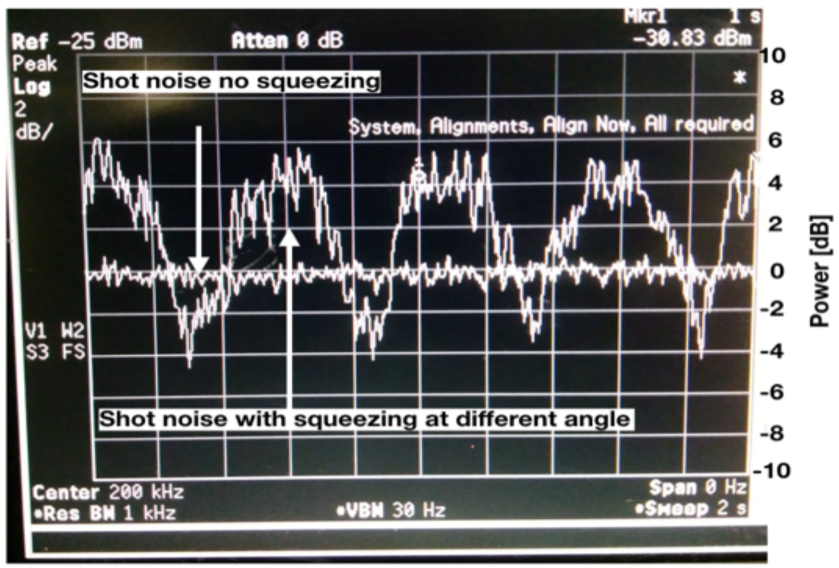


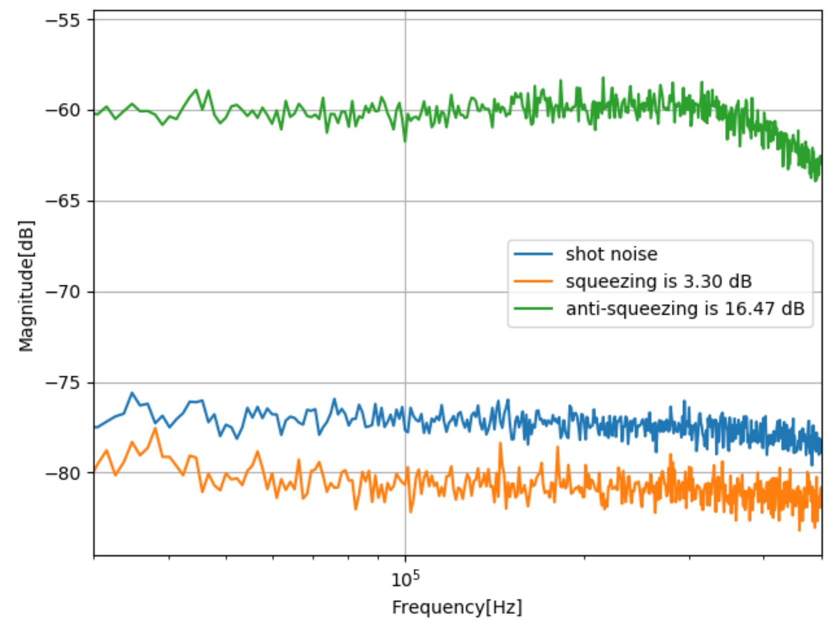


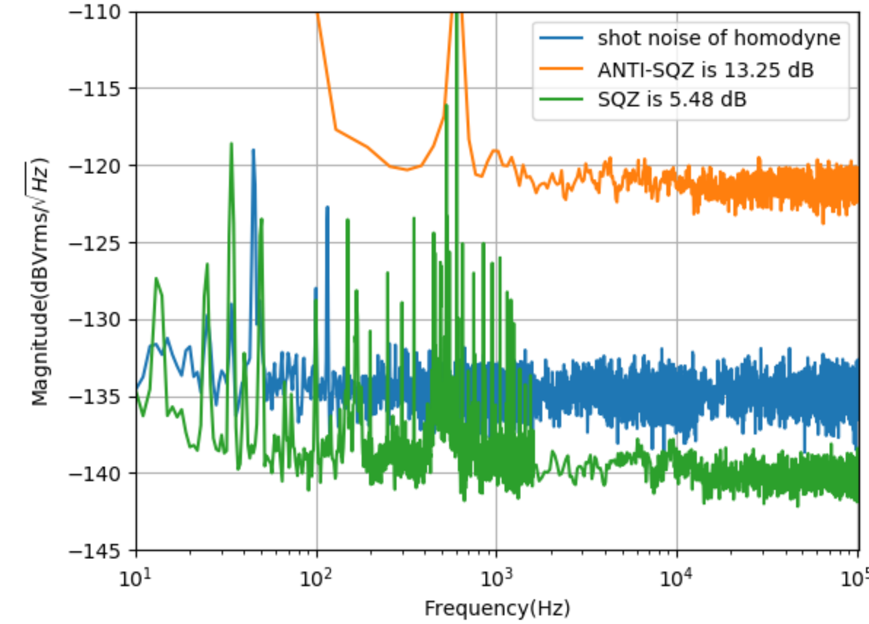




Squeezing measurement timeline







January 2019	April 2019	June 2019
zero span measurement at 200kHz	measurement with coherent control down to 30kHz	measurement with coherent control down to 50Hz
~3dB	3.3dB	5.5dB

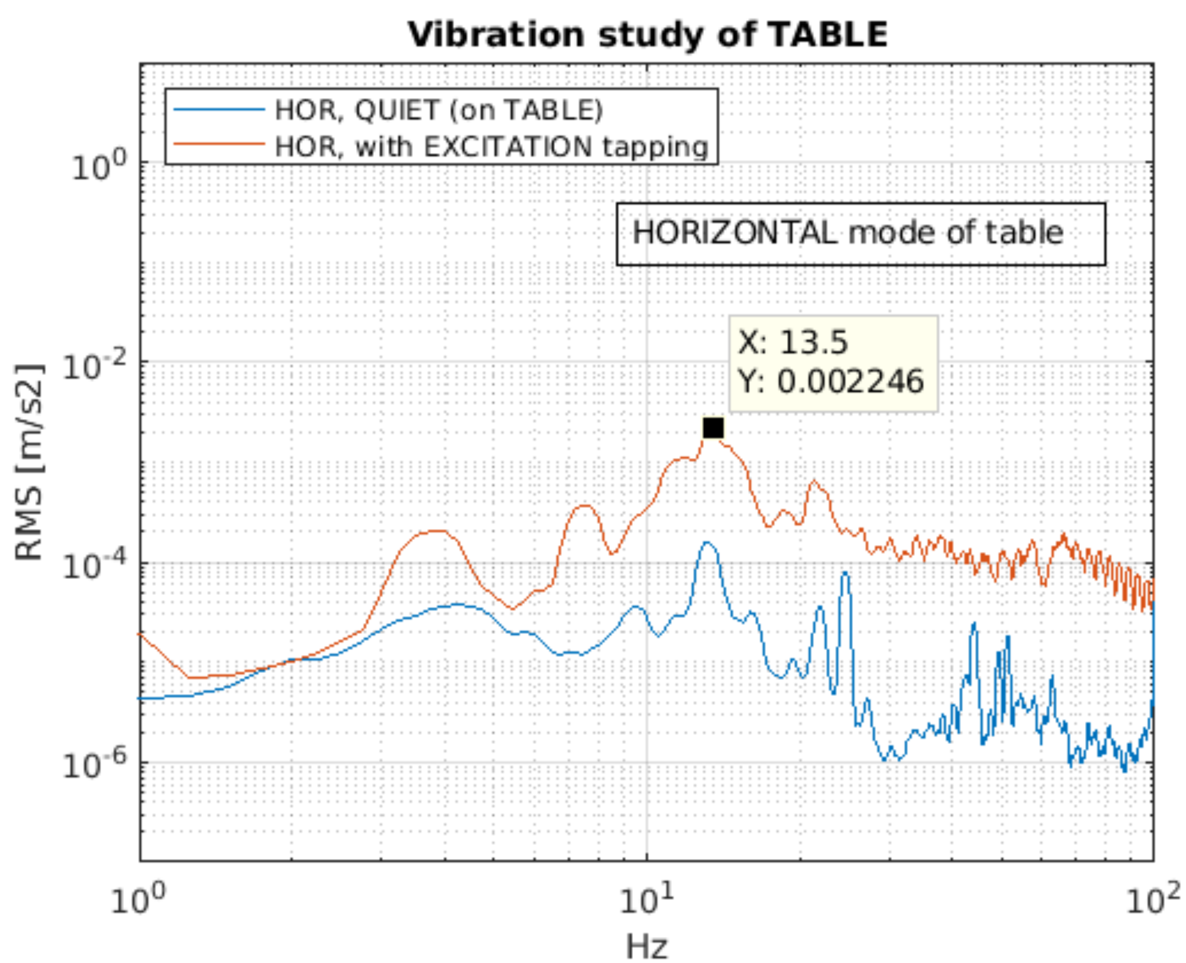
Detection of squeezing

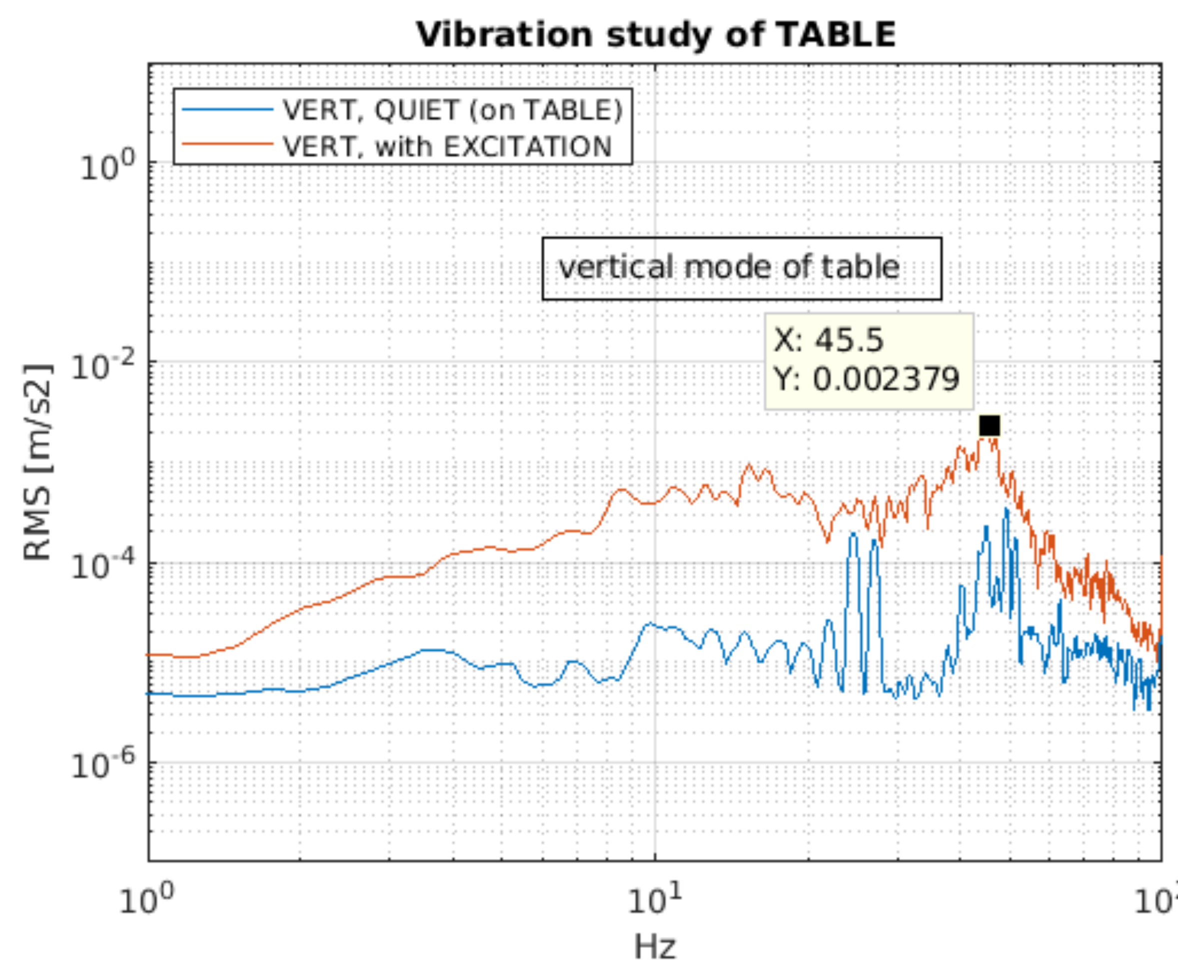
anti-squeezing and squeezing generated inside squeezer should be the same

What is the limiting factor?

Characterization of environmental noise sources

- Work done in collaboration with F. Paoletti and I. Fiori from EGO
- Accelerometers and microphones used to characterized the seismic and acoustic noise sources
- Mechanical resonances of many components have been characterized

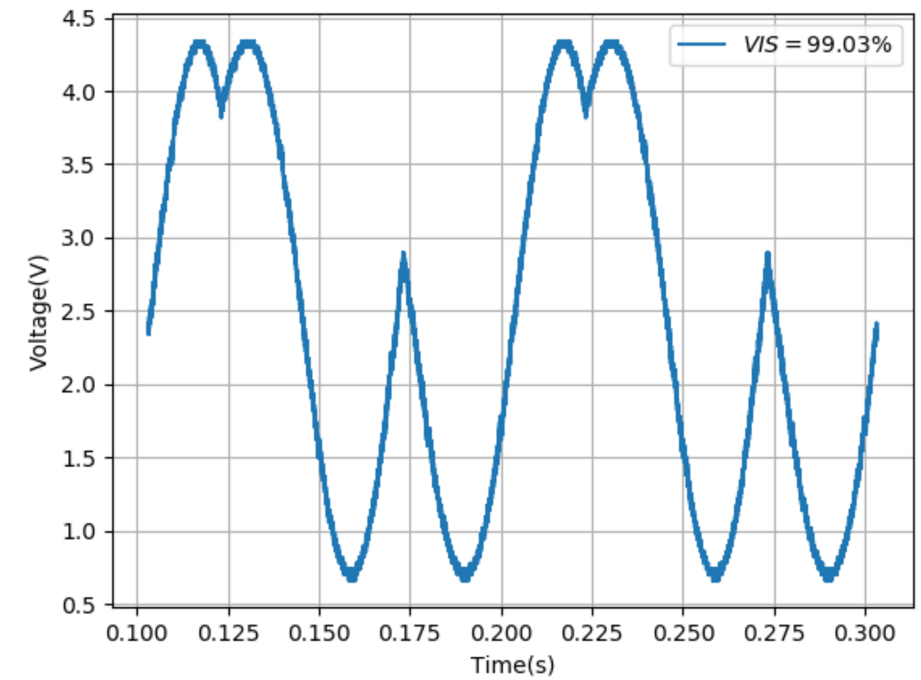




The limiting factor for squeezing

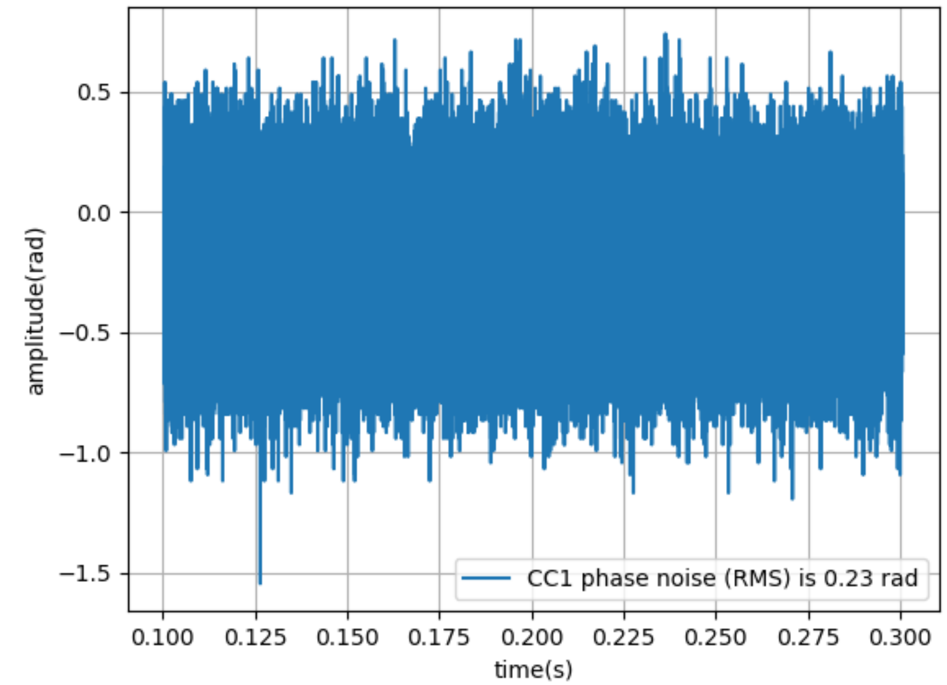
Optical losses: not limiting

- Optical losses from OPO to homodyne: < 1%
- Homodyne visibility: > 99%
- Photodiode quantum efficiency: >99%
- No clipping on Homodyne



Phase noise: limiting

- Residual phase noise from coherent control loop is ~230mrad
- <u>This level of phase noise will degrade squeezing from ~15dB to ~5dB</u>

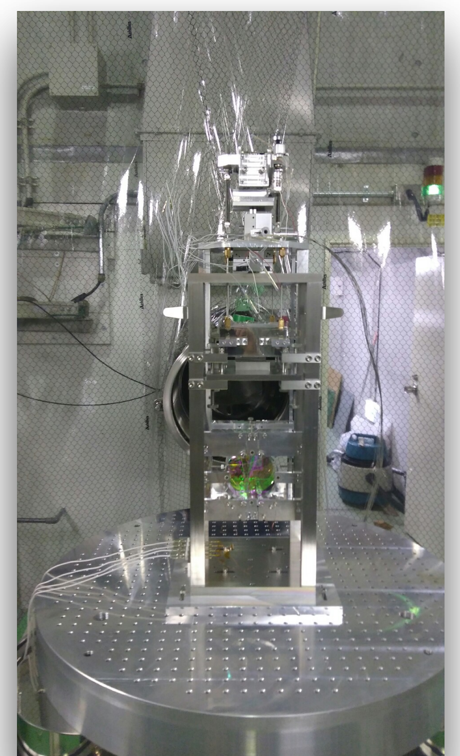


Content

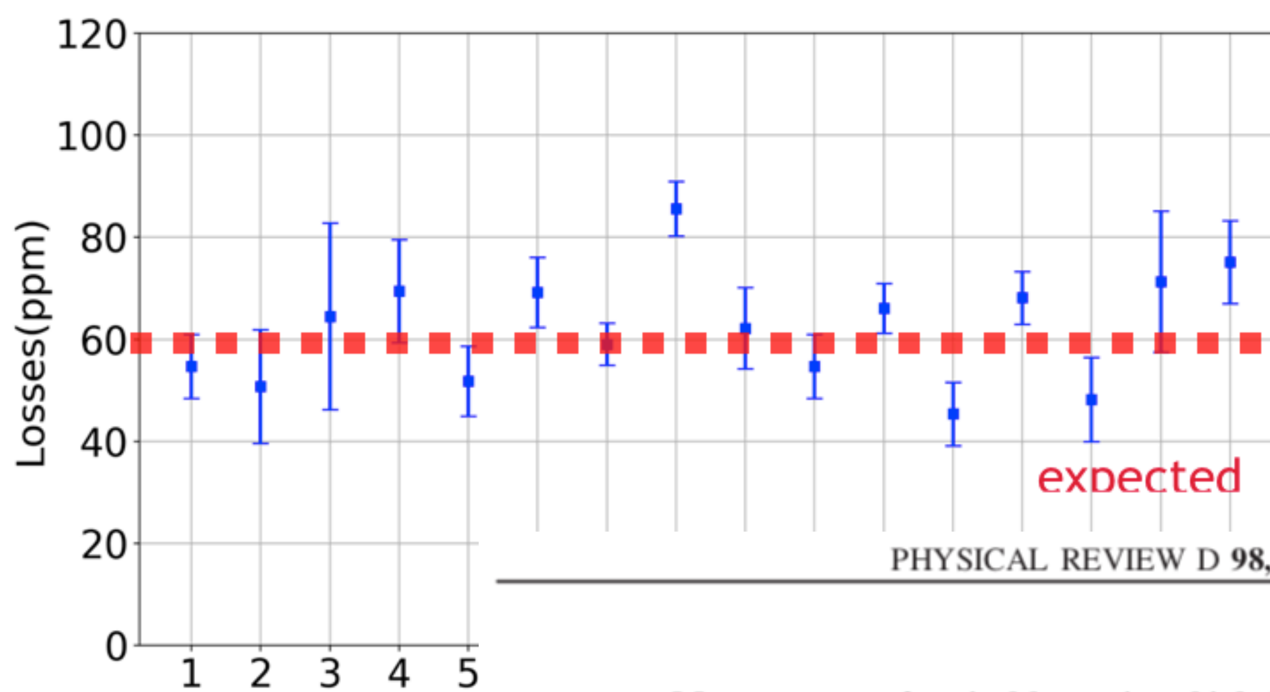
- Frequency dependent squeezing for GW detector
- Construction of squeezer and measurement of squeezing
- Matching of squeezer and filter cavity
- Summary and future plan

Filter cavity status

- Cavity controlled using an auxiliary green beam
- AOM used to tune the co-resonant condition between green and IR beam (squeezed)
- Round trip losses measured: between 45 and 85 ppm



cavity mirror suspension



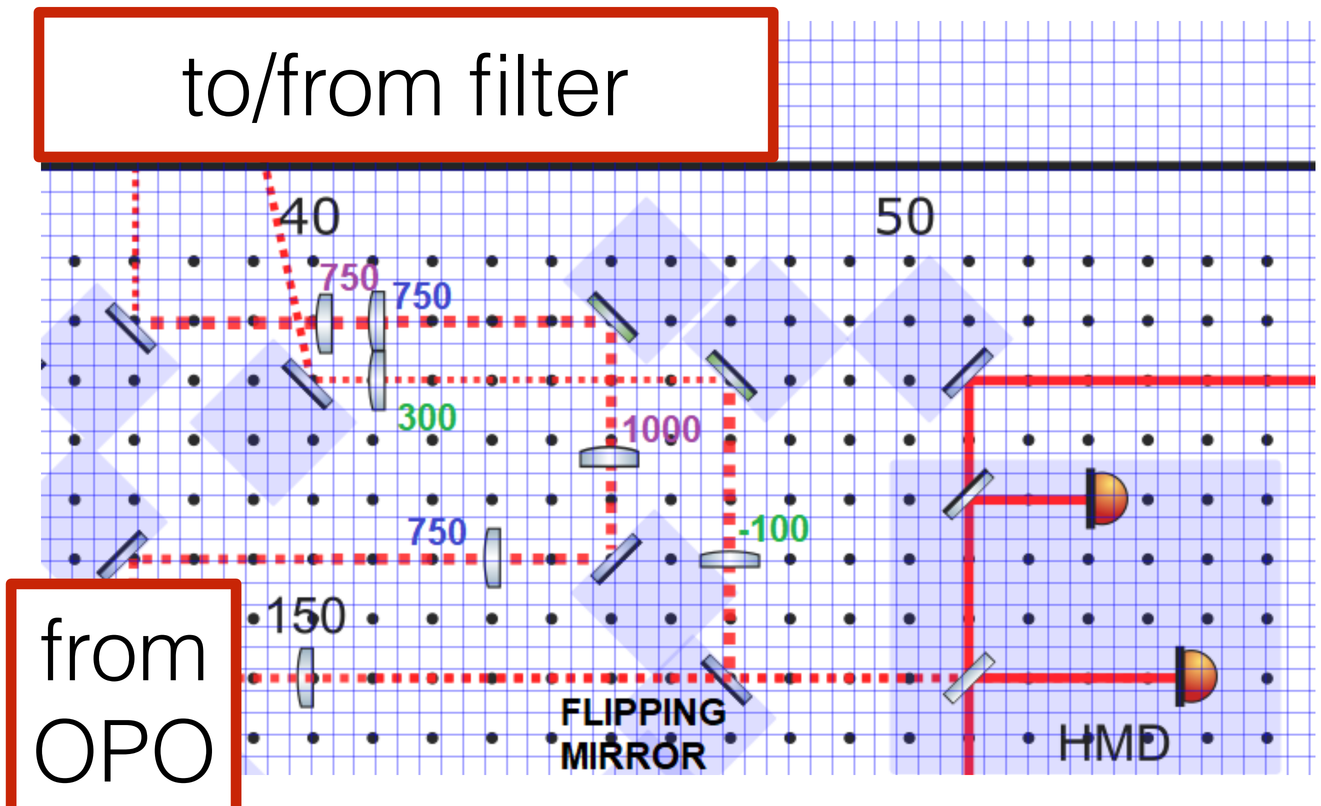
PHYSICAL REVIEW D **98,** 022010 (2018)

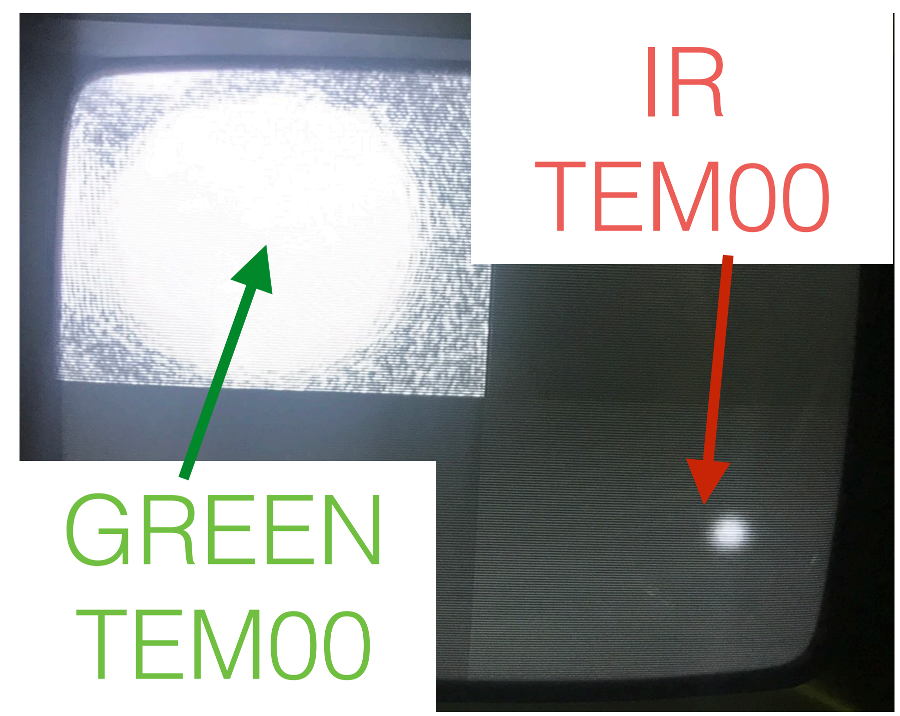
Measurement of optical losses in a high-finesse 300 m filter cavity for broadband quantum noise reduction in gravitational-wave detectors

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]

Alignment and match between squeezer and filter cavity

- Robust telescope designed using large focal length lenses
- IR probe beam (co-aligned with squeezing) amplified inside OPO
- Matching and alignment optimization on going





Content

- Frequency dependent squeezing for GW detector
- Construction of squeezer and measurement of squeezing
- Matching of squeezer and filter cavity
- Summary and future plan

Summary

- Frequency independent squeezing measured: 5.5dB down to ~50Hz
- Filter cavity assembled, controlled, characterize and matched with squeezer

Future plan

- Reduce phase noise which is currently limiting squeezing performances
- Optimize squeezer’s matching into filter cavity
- Test of a novel locking scheme for the filer cavity
- **Inject frequency independent squeezing into the filter cavity**

Collaborations

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

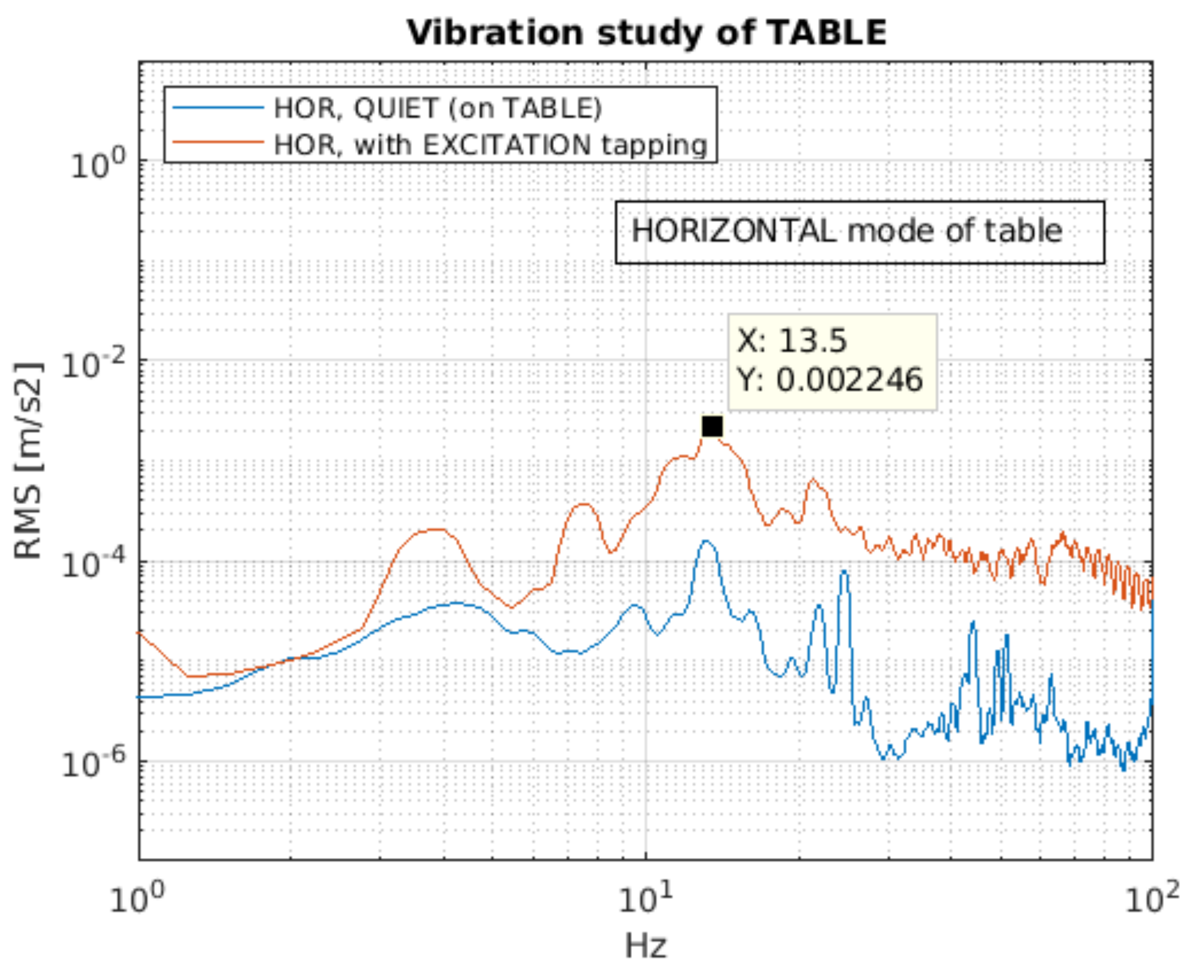
A lot of help from our collaborators!

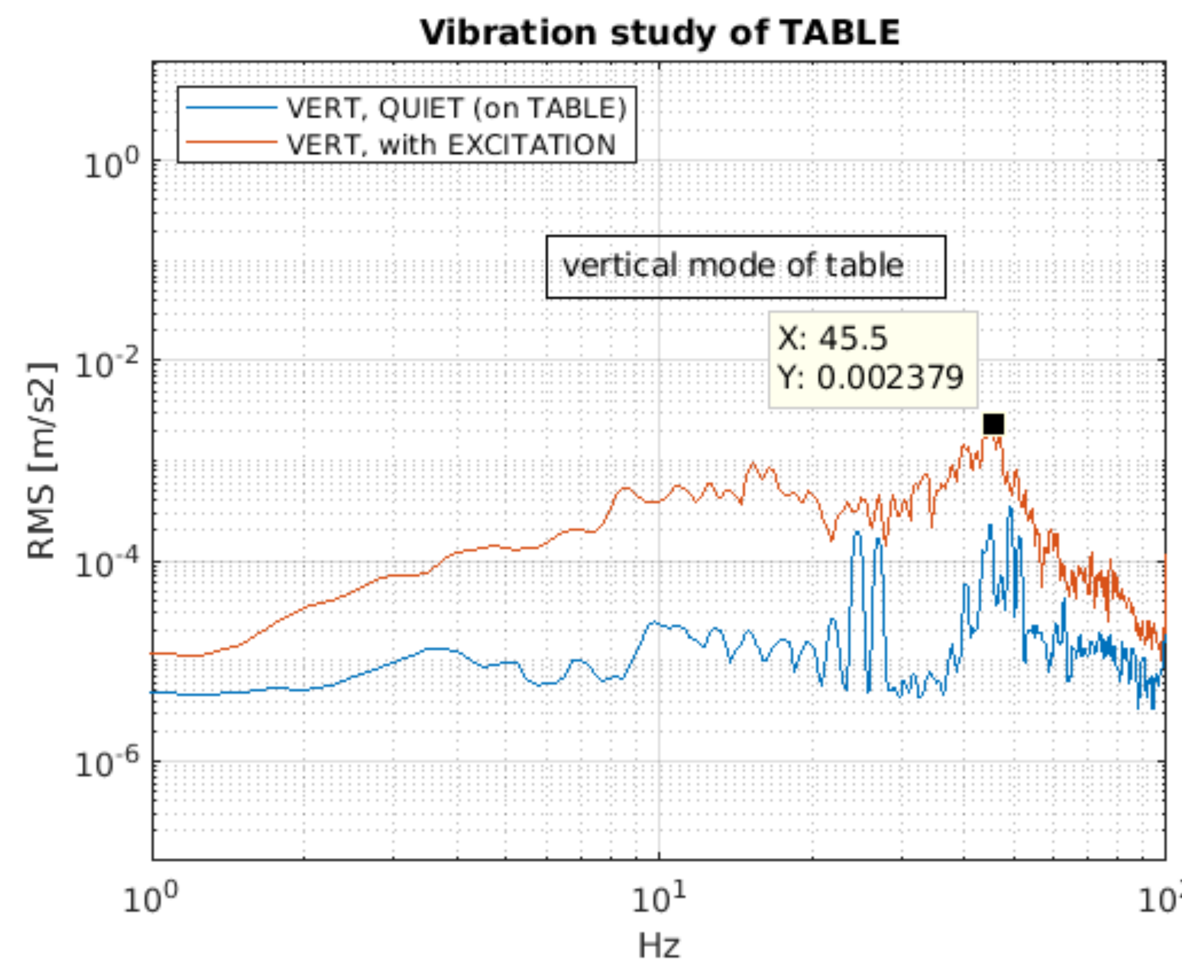
Thank you!

Back-up slides

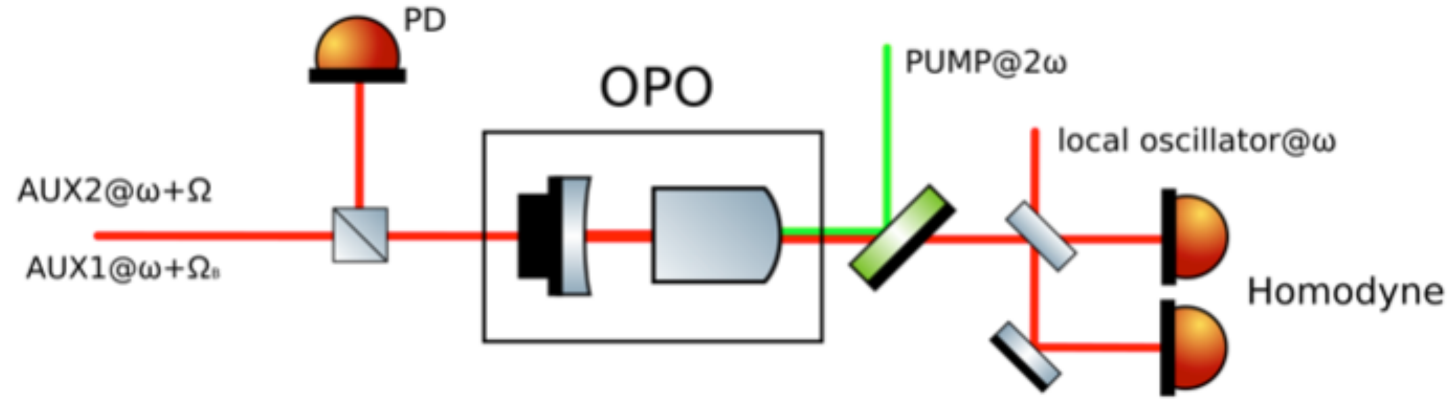
Characterization of seismic noise and acoustic noise

- Optical bench resonance: 13.5Hz(horizontal) and 45Hz(vertical)
- Mirror mount resonance: 468Hz(horizontal) and 1212Hz, 1748Hz(vertical)
- Homodyne resonance: 132Hz, 281Hz, 393Hz and 508Hz
- Moving peaks: 26.75Hz(on/off), 34-37Hz(moving back and forth)
- Rotary pump: 24.75Hz Turbo pump: 604Hz





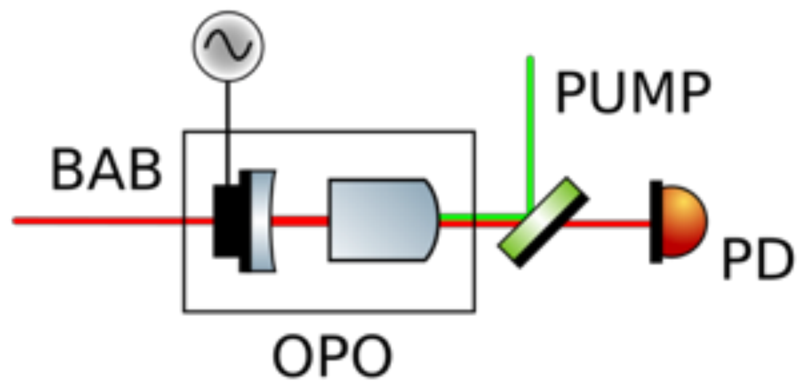
Squeezing measurement scheme

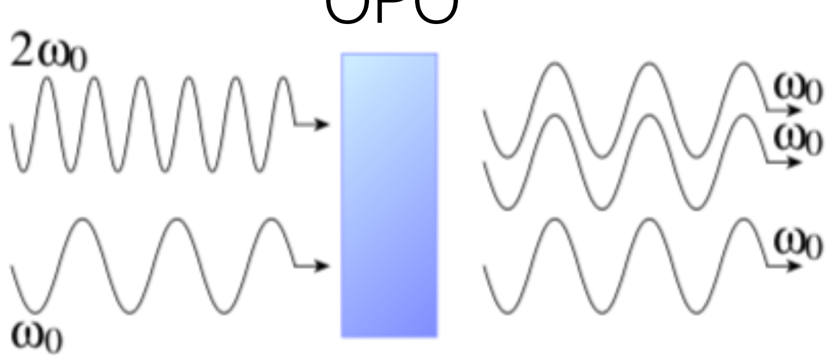


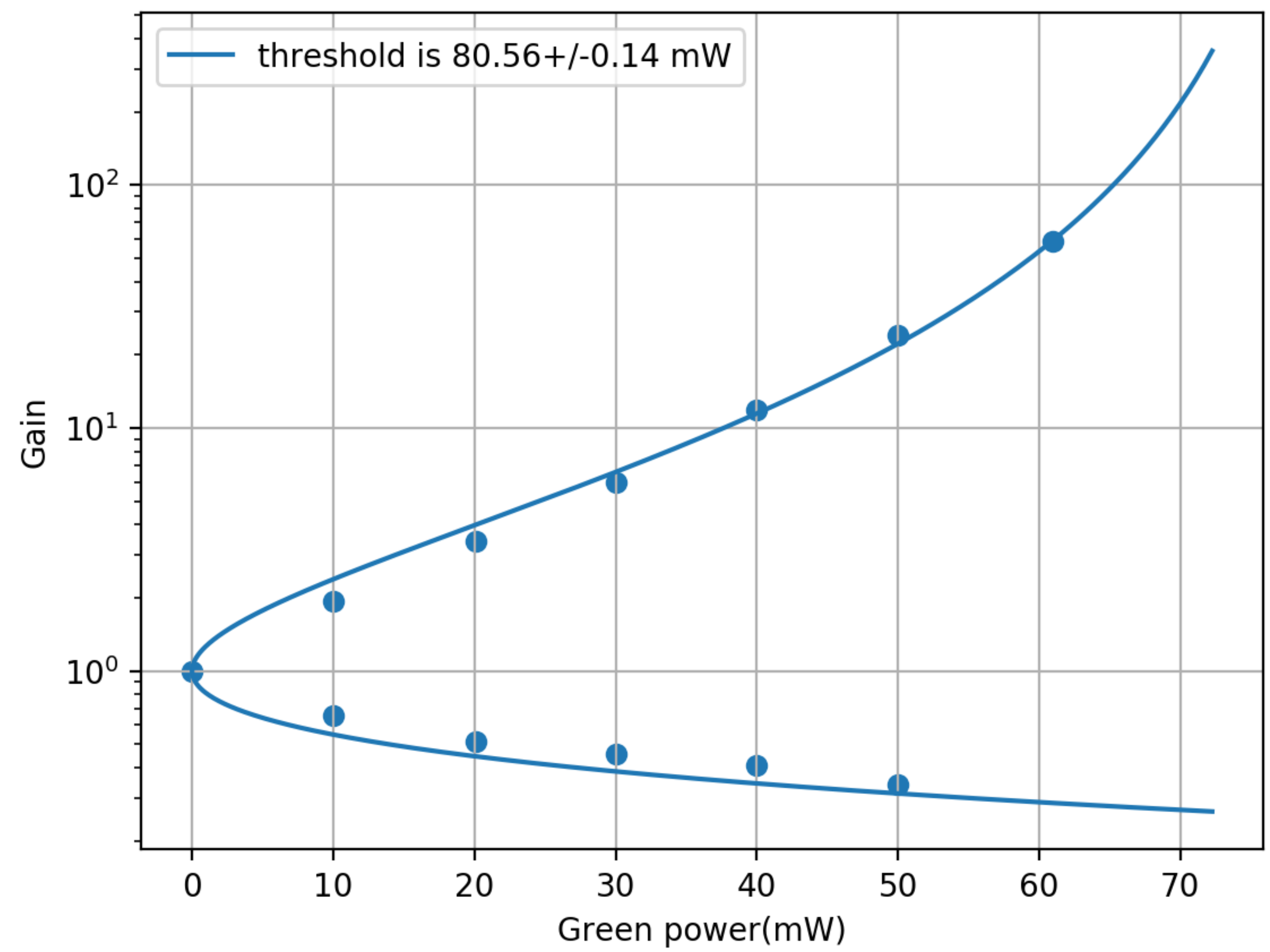
1. Pump beam is used to generate the squeezed vacuum source
2. AUX1 and AUX2 are used to provide control signal so that OPO can be stabilized
3. Homodyne is used to detect squeezing

Parametric (de)amplification measurement

To characterize the optical parametric oscillator (OPO) non-linear gain, the classical parametric amplification and de-amplification gain was measured







To produce squeezed vacuum, the OPO is operated below threshold. The measured threshold is ~80mW, which is close to the expected value (76mW)