Squeezing

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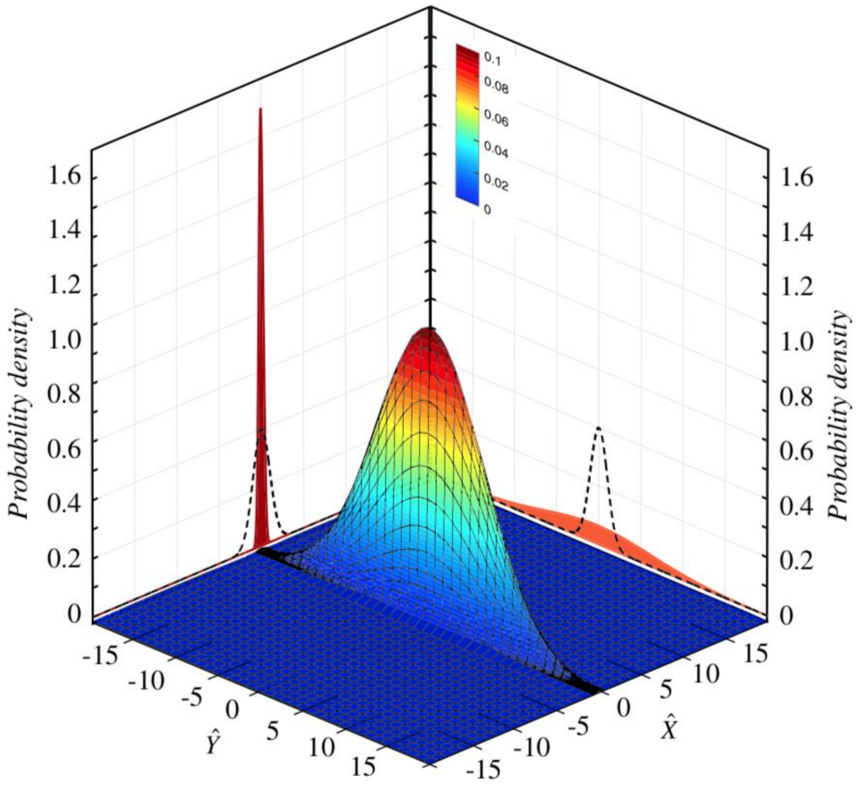
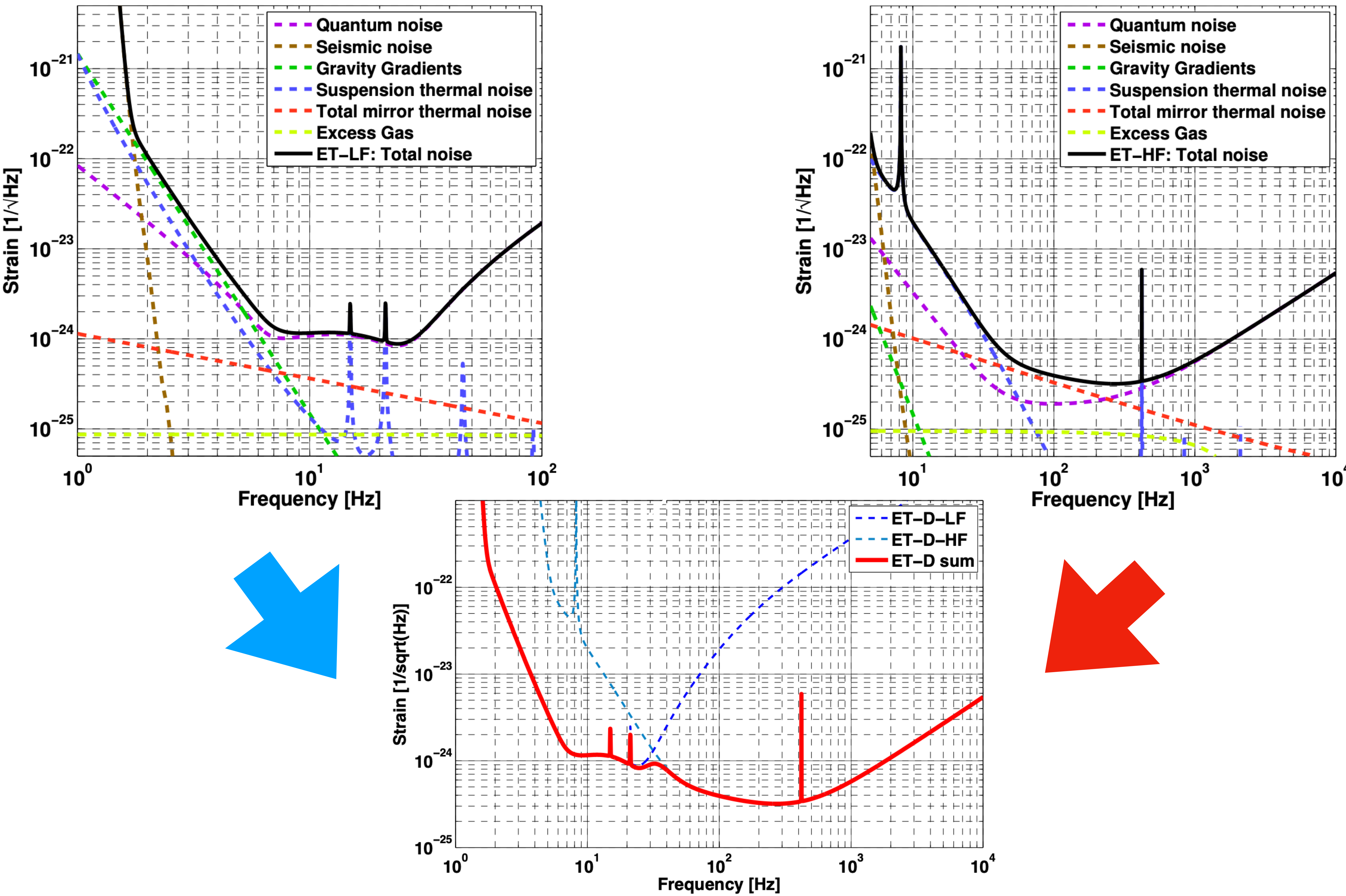
AEI Hannover

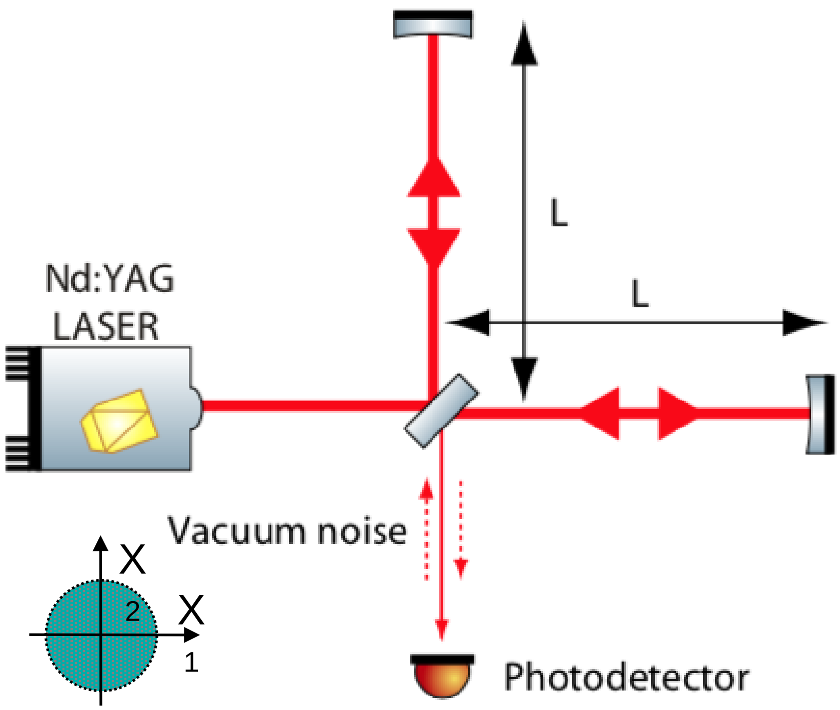


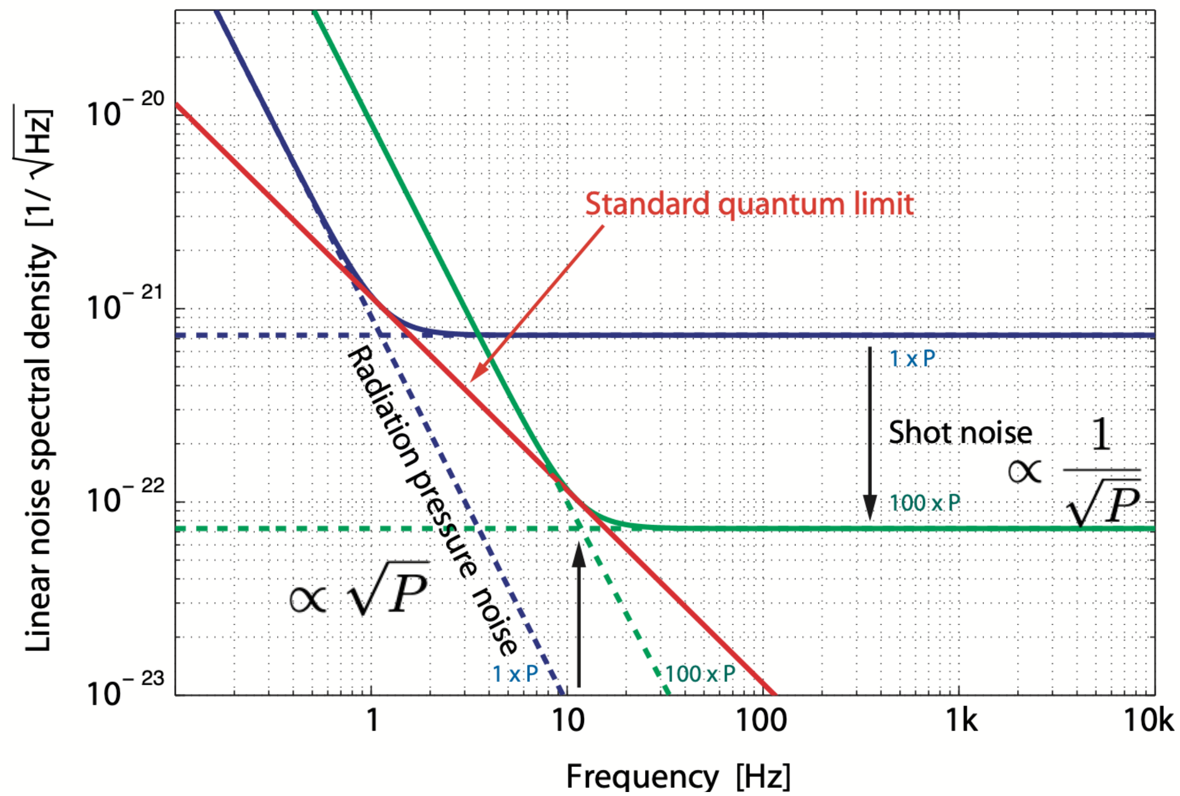
Einstein-Telescope: German Community Meeting

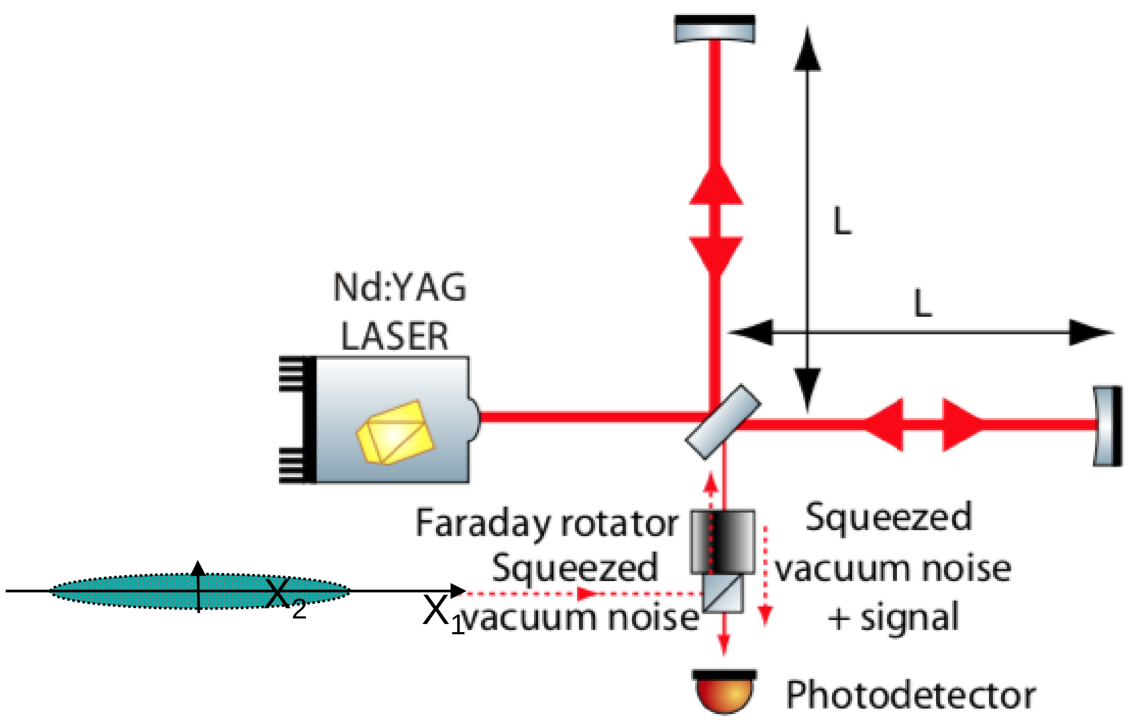
Einstein Telescope xylophone strategy

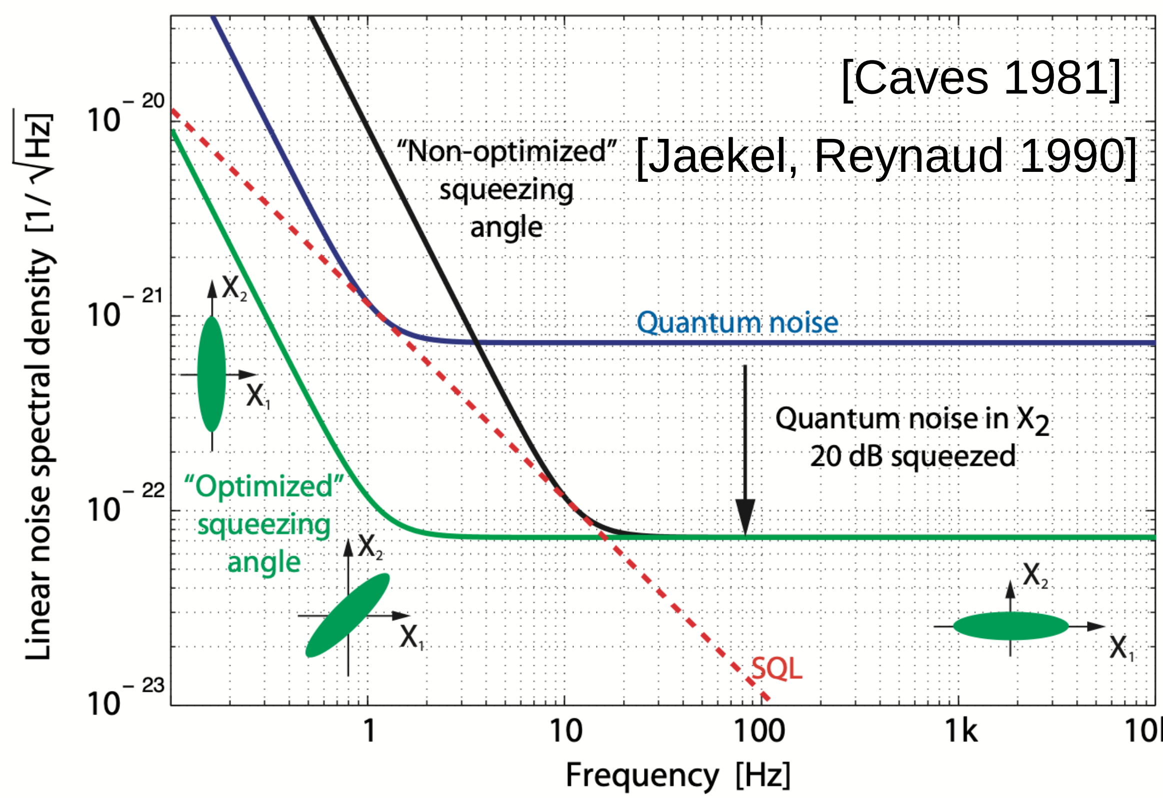


Quantum noise



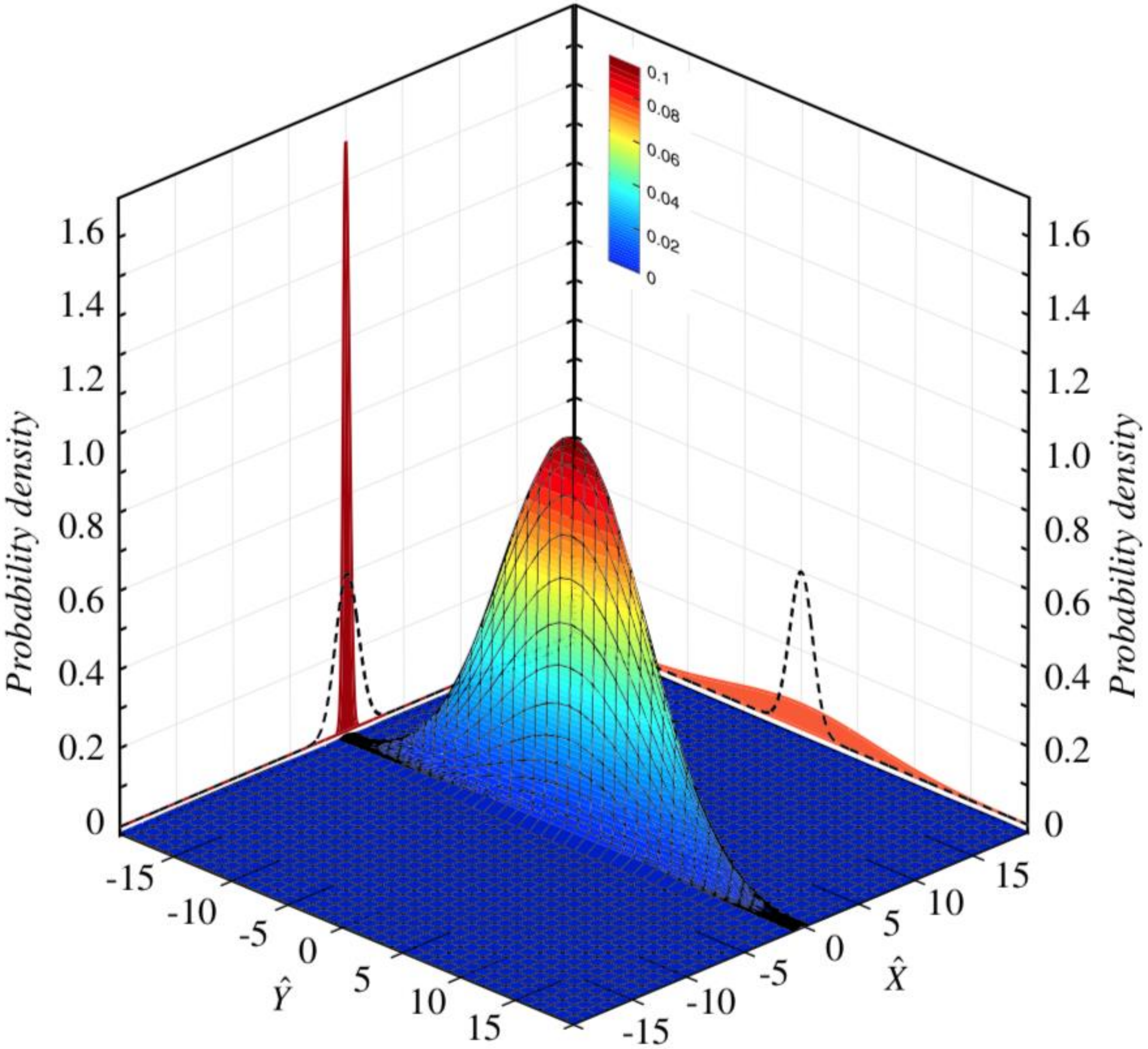






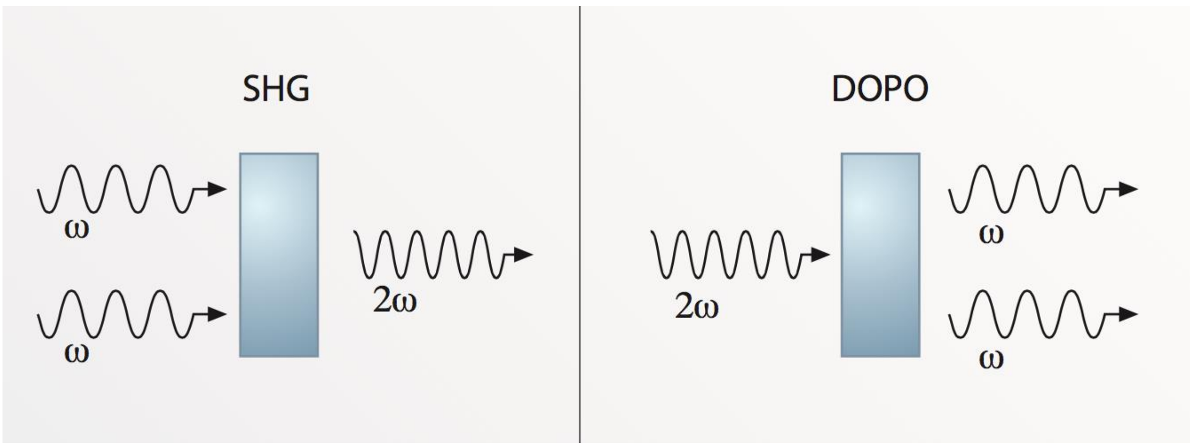
ET squeezing

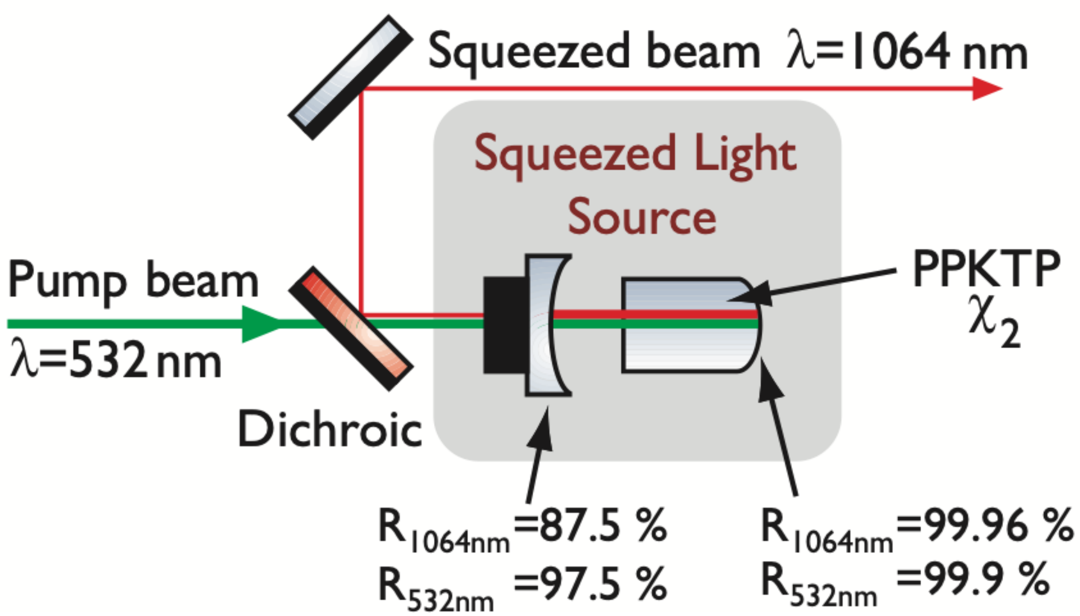
- Aiming for 10dB detected squeezing!
- Squeezed light sources at 1064nm and 1550nm providing 15dB of squeezing



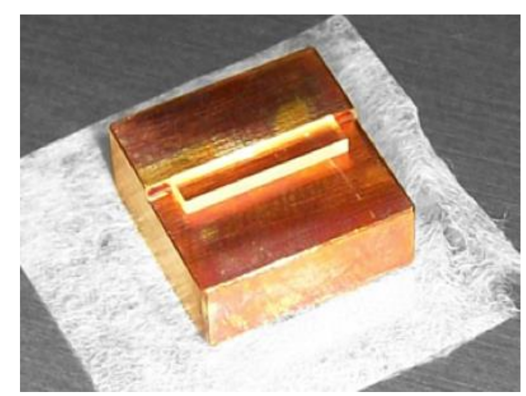
Squeezed light generation

Upconversion Downconversion



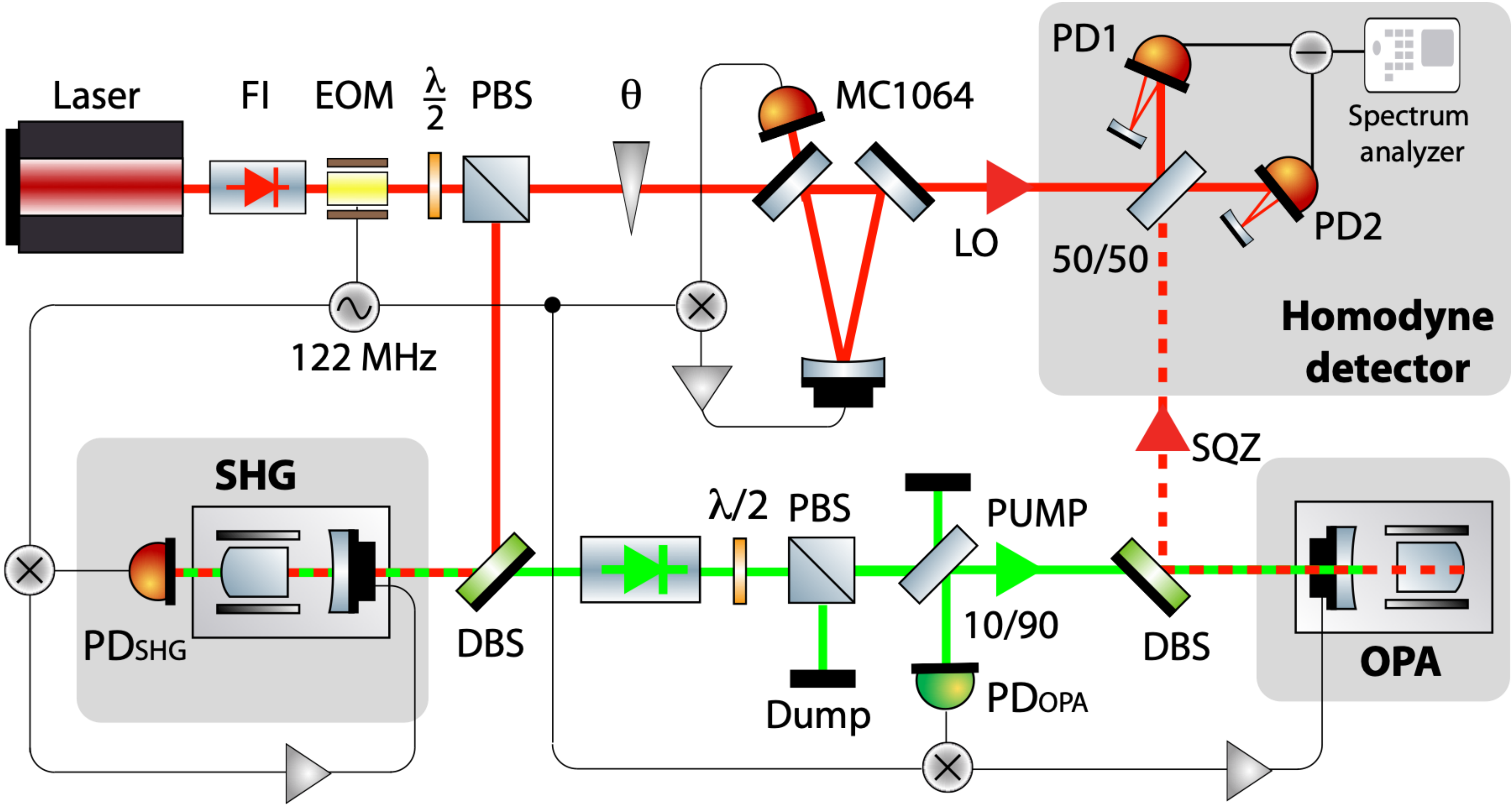


- Squeezed light generation via parametric down-conversion
- Linear cavity design with a high intrinsic mechanical stability
- Single or doubly resonant OPA design
- Low optical loss, high escape efficiency



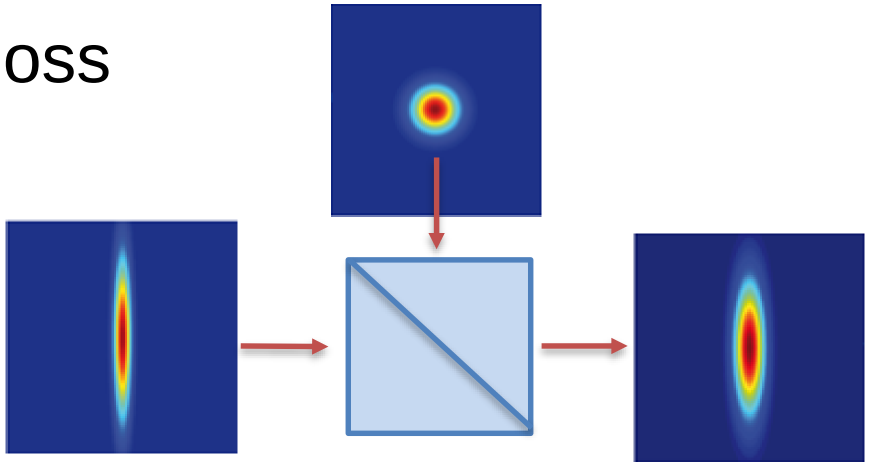
Nonlinear medium

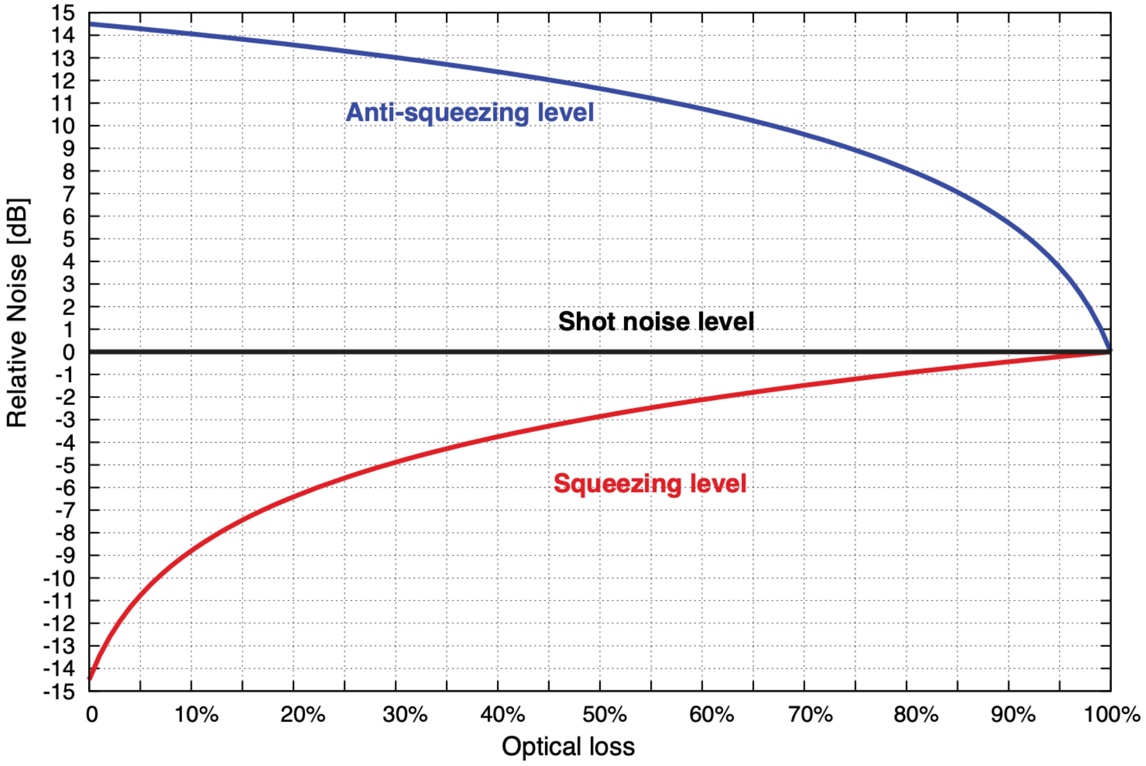
Generic squeezing setup



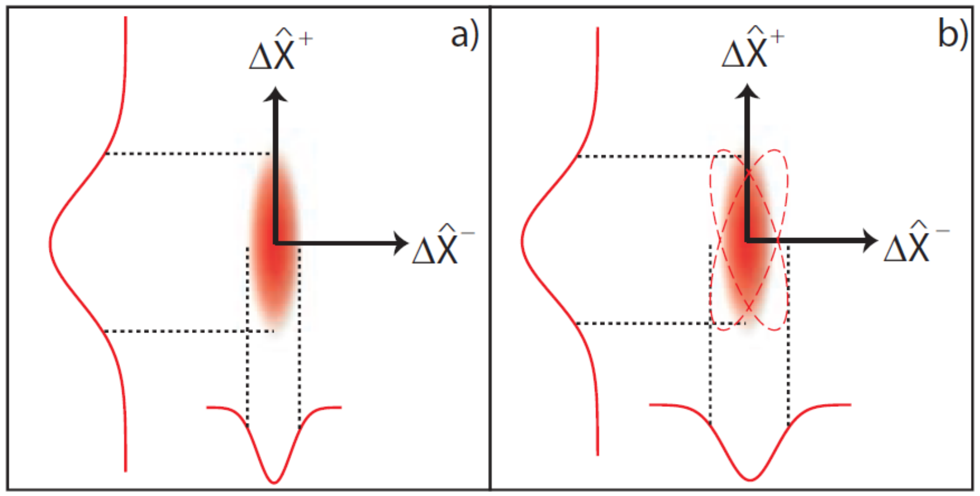
Squeezing degradation mechanism

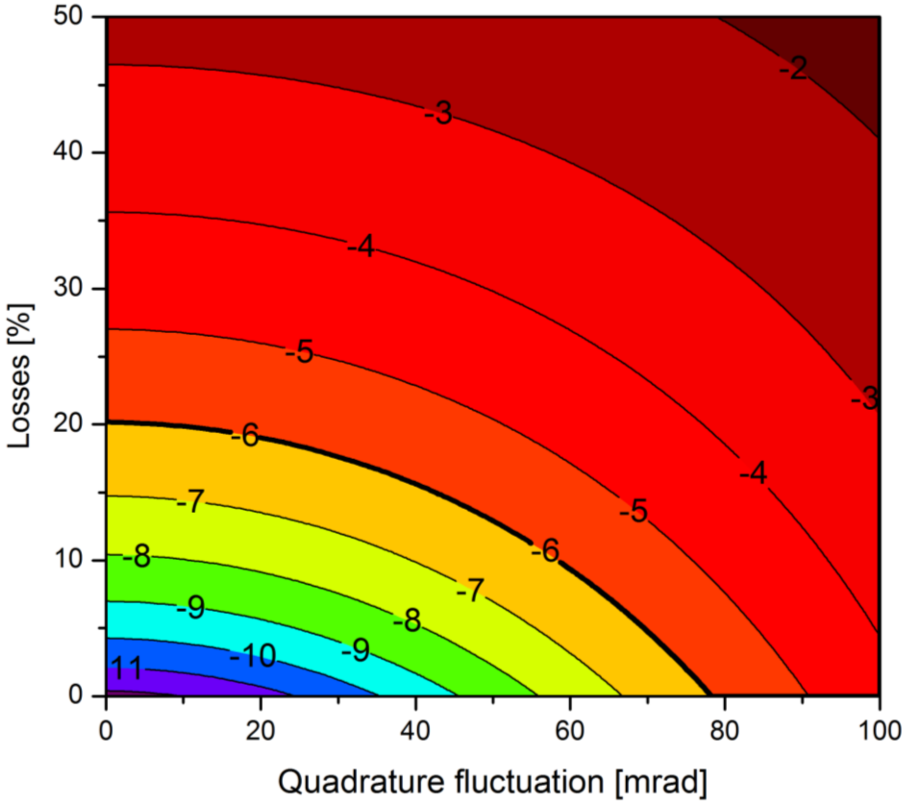
- Optical loss





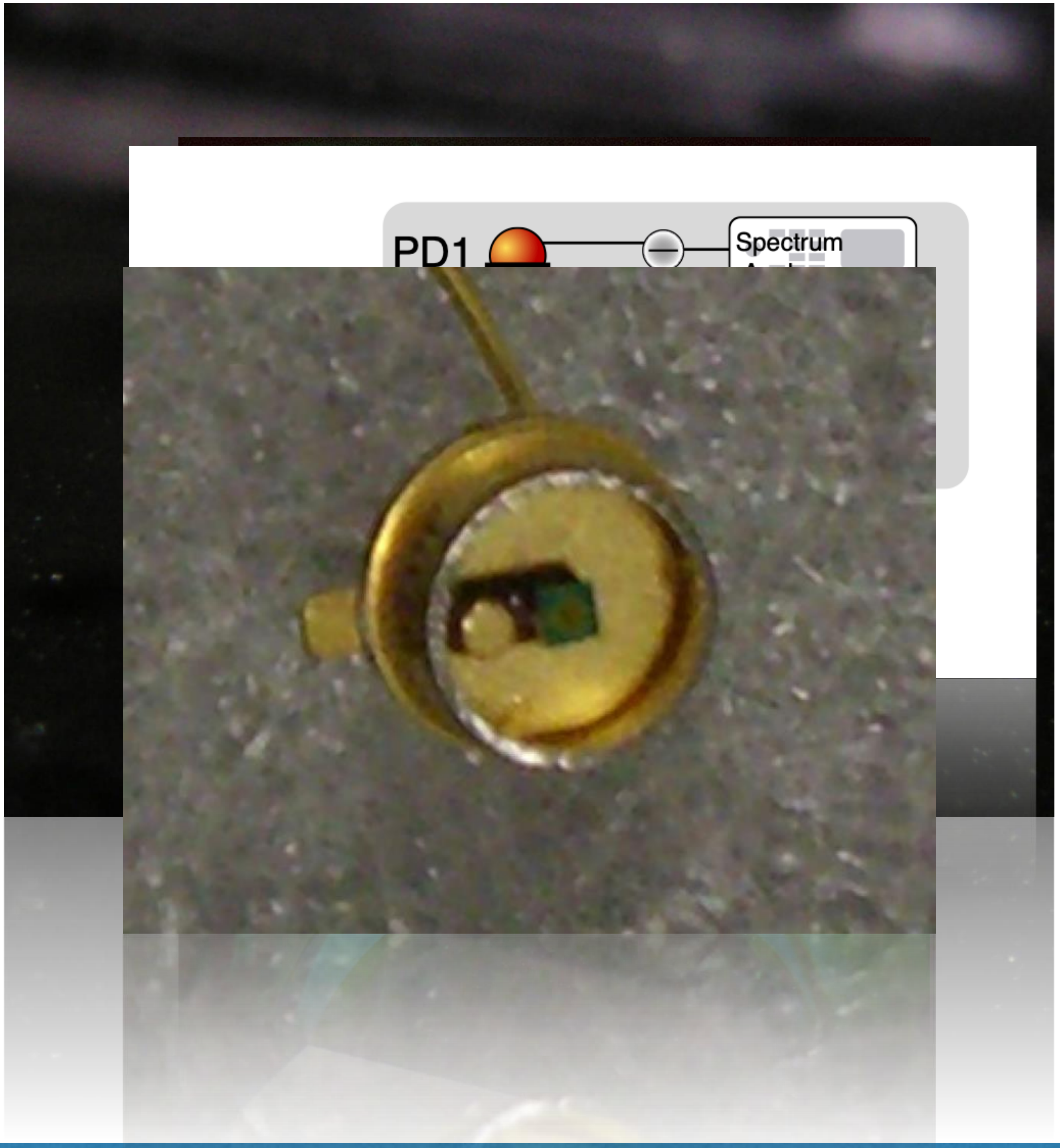
- Phase noise





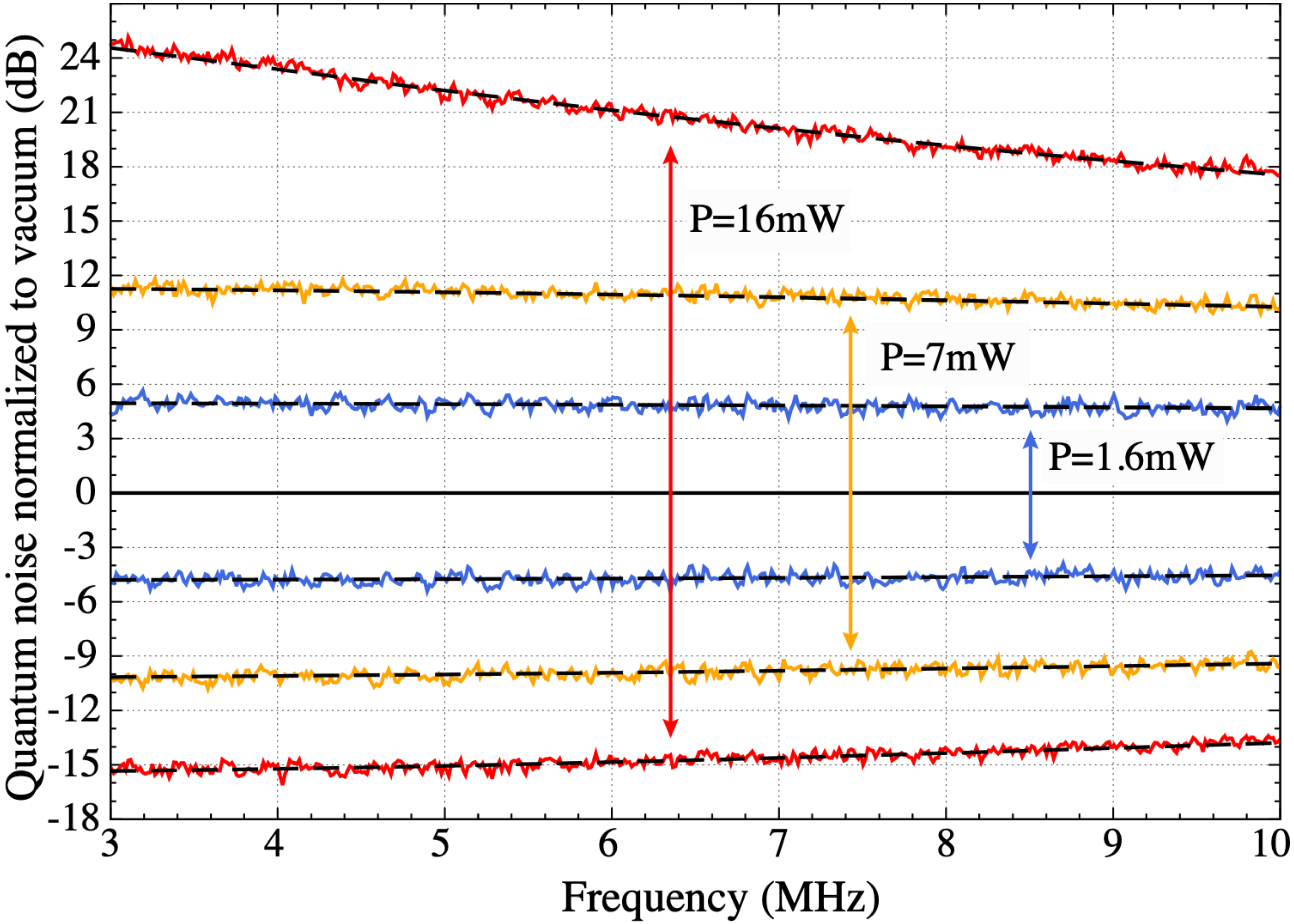
Squeezing degradation mechanism

- Escape efficiency
- Propagation loss
- Homodyne efficiency
- Detection efficiency



15dB squeezing @ 1064nm

PRL 117, 110801 (2016)



- Total loss of 2.5%
- Photodiode quantum efficiency of 99.5%
- 15.3dB squeezing if dark noise corrected

$$\eta_{\text{homodyne}} = 99.2^{+0.1}_{-0.1}\ \%$$

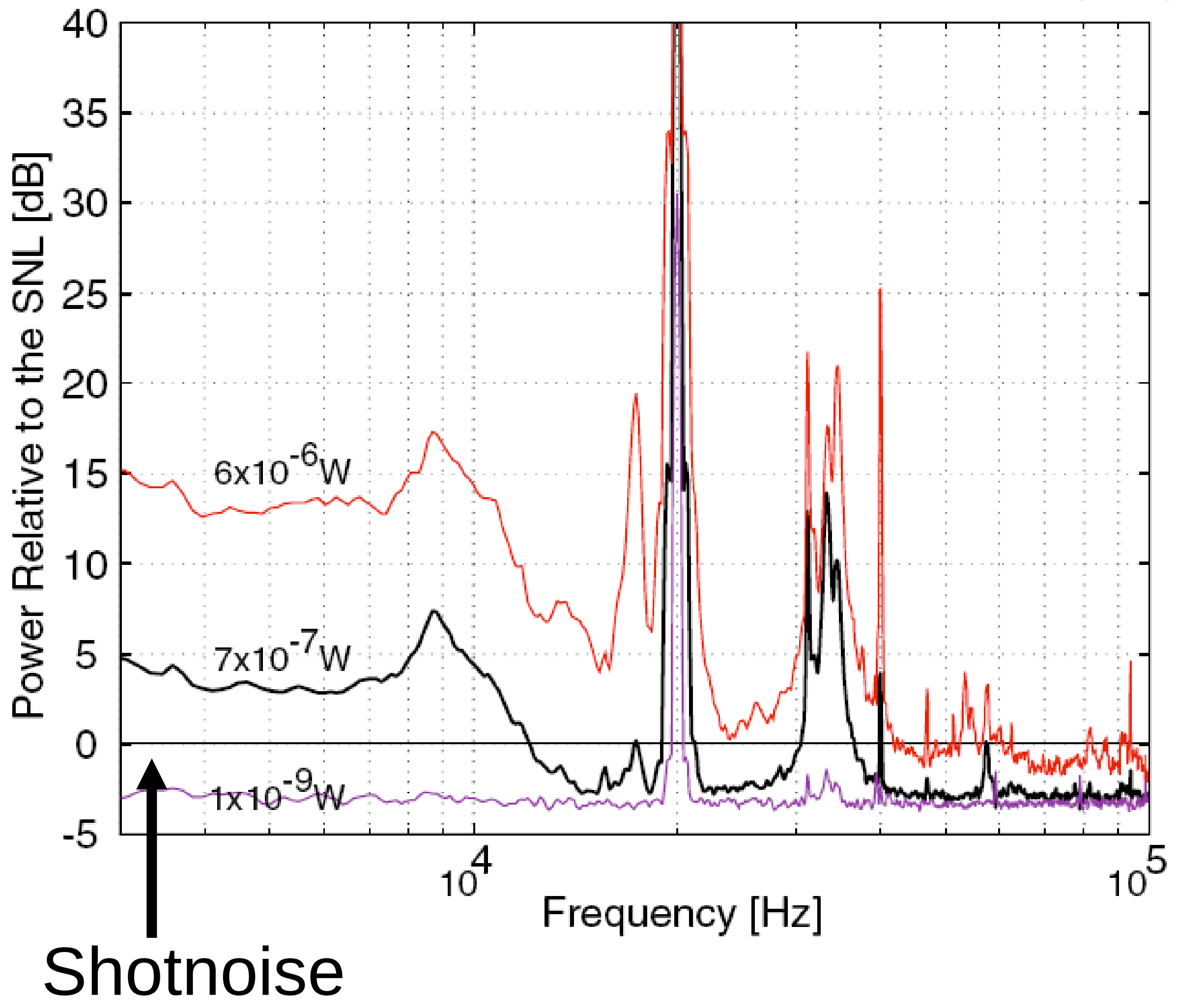
$$\eta_{\text{propagation}} = 99.8^{+0.01}_{-0.01}\ \%$$

$$\eta_{\text{escape}} = 99.05^{+0.4}_{-0.45}\ \%$$

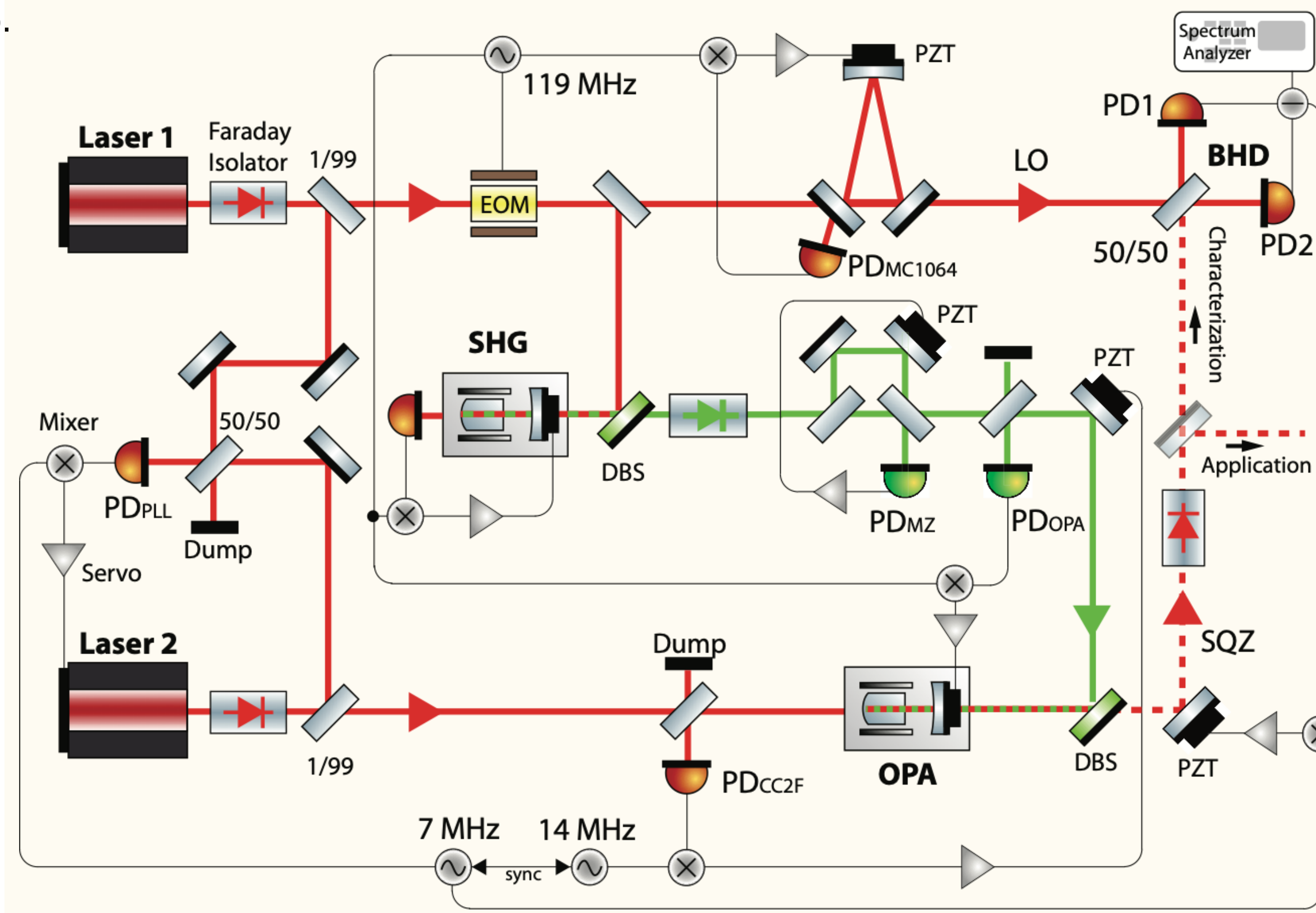
$$2.0^{+0.5}_{-0.6}\ \%$$

Audio-band squeezing setup

K.McKenzie et al. ,PRL 93,161105 (2004).



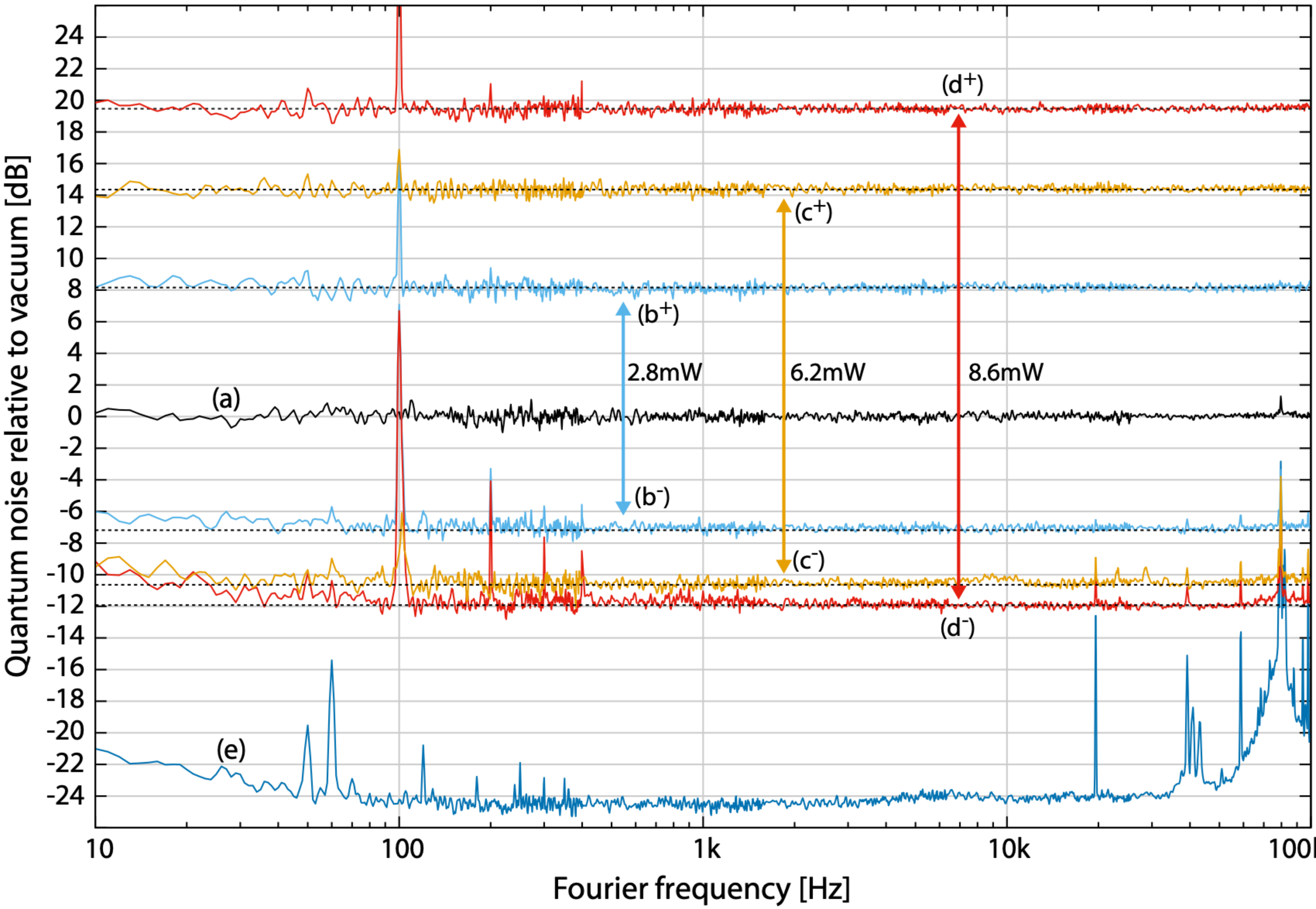
M.Mehmet and H.Vahlbruch, CQG 36, 015014 (2019)



- At audio-band frequencies technical laser noise can easily mask the squeezed noise.
- Frequency shifted coherent control scheme is required to control all degrees of freedom.

Audio-band squeezing @1064nm

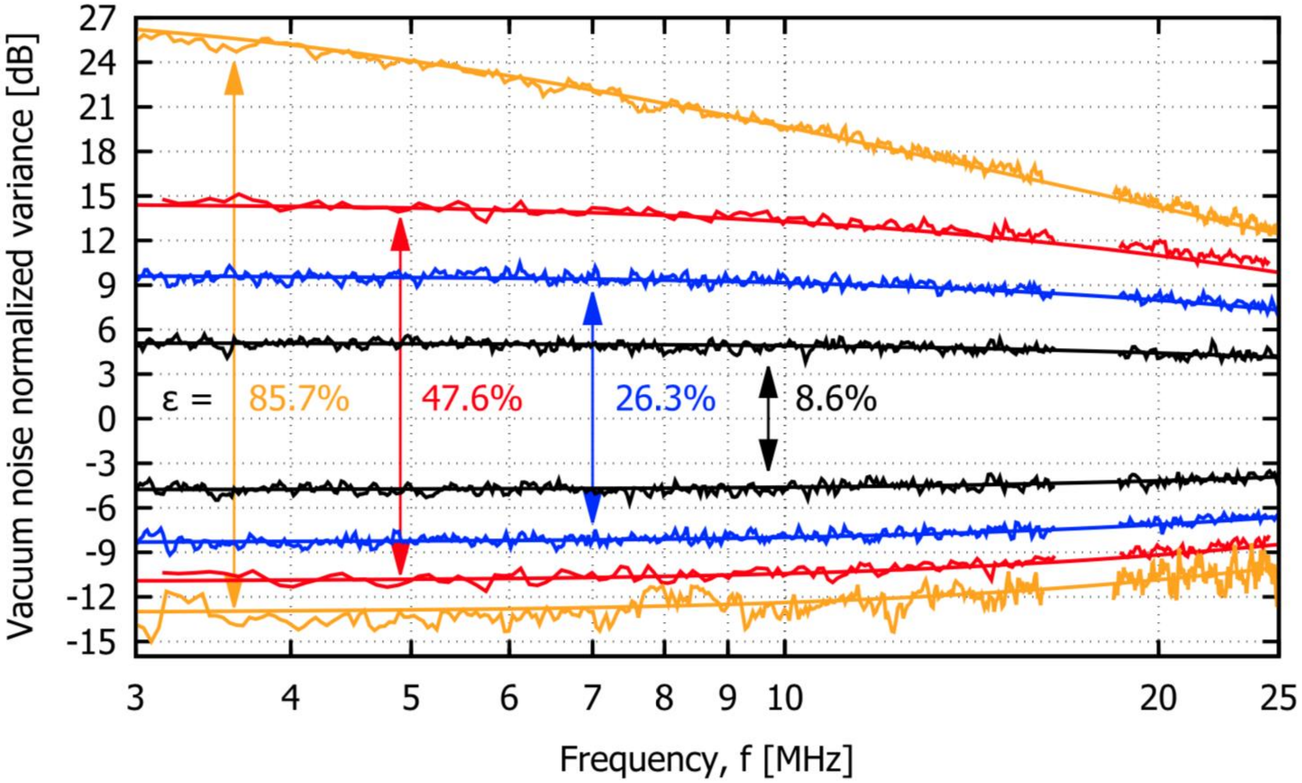
M.Mehmet and H.Vahlbruch, CQG 36, 015014 (2019)



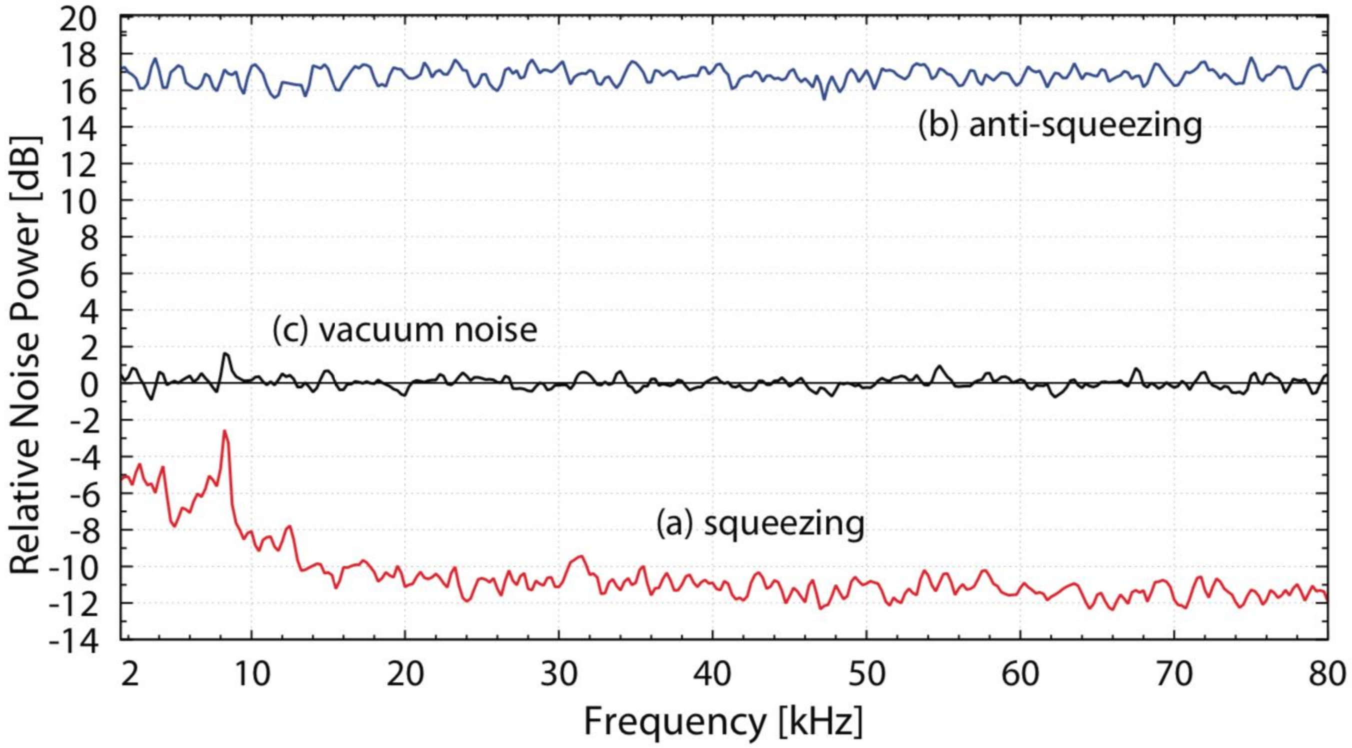
- Excluding the optical loss introduced by the diagnostic homodyne detector, this squeezer can provide 14-15dB of squeezing for downstream application (1064nm).

Squeezing @ 1550nm

Schönbeck et.al, Optics Letters 43, No.1 (2018)

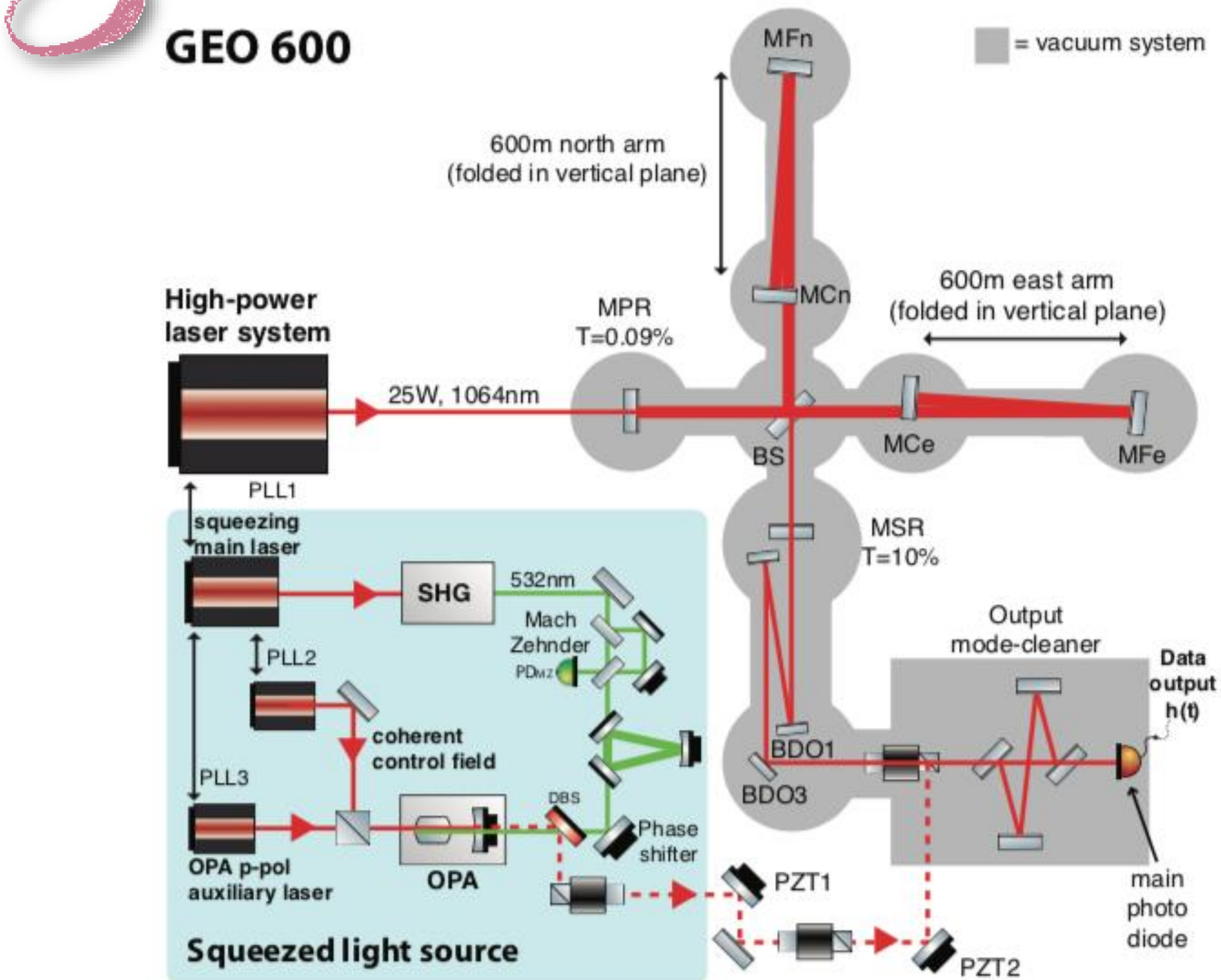


Mehmet et.al, Optics Express 19, No.25 (2011)



- Comparable performance to 1064nm squeezers
- Up to 13dB squeezing measured at MHz
- Squeezing at >kHz frequencies demonstrated in a not fully stabilized setup (w/o coherent control scheme)
- No showstoppers expected

Squeezing in application



- GEO600 was the first km-scale detector to apply squeezing in 2010.
- 10 years experience now
- Long term stable application was pioneered
- Continuously improved interfacing

•„A gravitational wave observatory operating beyond the quantum shot-noise limit“, The LSC, Nature Physics, Vol 7 (2011).

•„First Long-Term Application of Squeezed States of Light in a Gravitational-Wave Observatory „ H.Grote et.al, Physical Rev. Lett. 110, 181101 (2013).

•*„Phase control of squeezed vacuum states of light in gravitational wave detectors“*, K. Dooley et al., Opt. Express 23, 8235–8245 (2015).

•*„Alignment sensing and control for squeezed vacuum states of light“*, E. Schreiber et. al, Opt. Express 24, Issue 1, pp. 146-152 (2016).

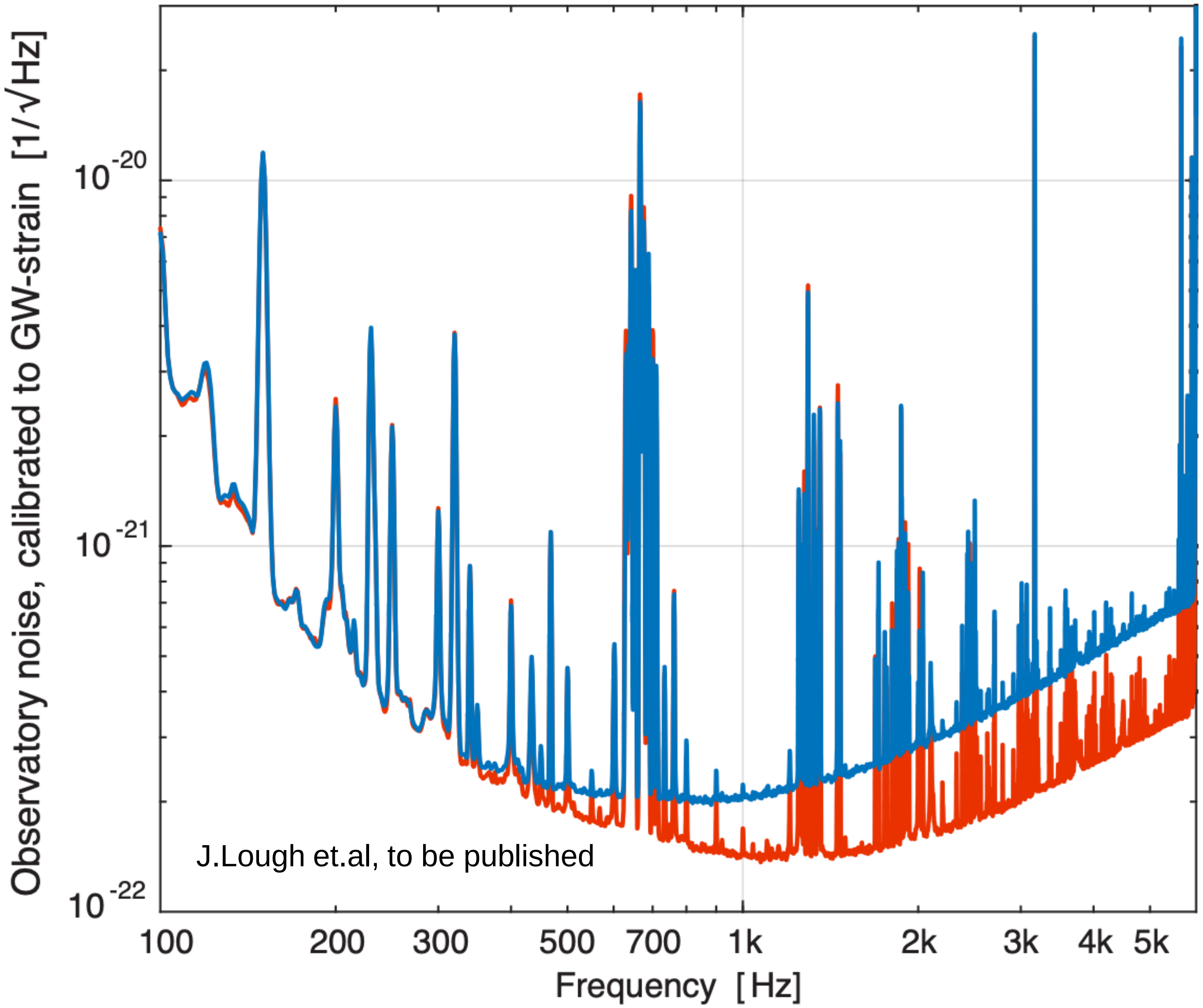
•*“High power and ultra-low-noise photodetector for squeezed-light enhanced gravitational wave detectors“* , H. Grote et al., Opt. Express 24, 20107 (2016).

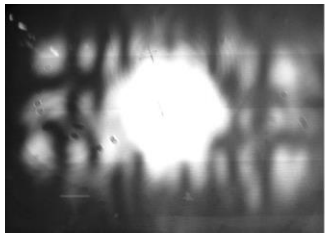
6dB squeezing @ GEO600

- Squeezer upkeep:
  - SHG replaced
  - MC532 replaced
  - broken OPA crystal
  - laser degradation

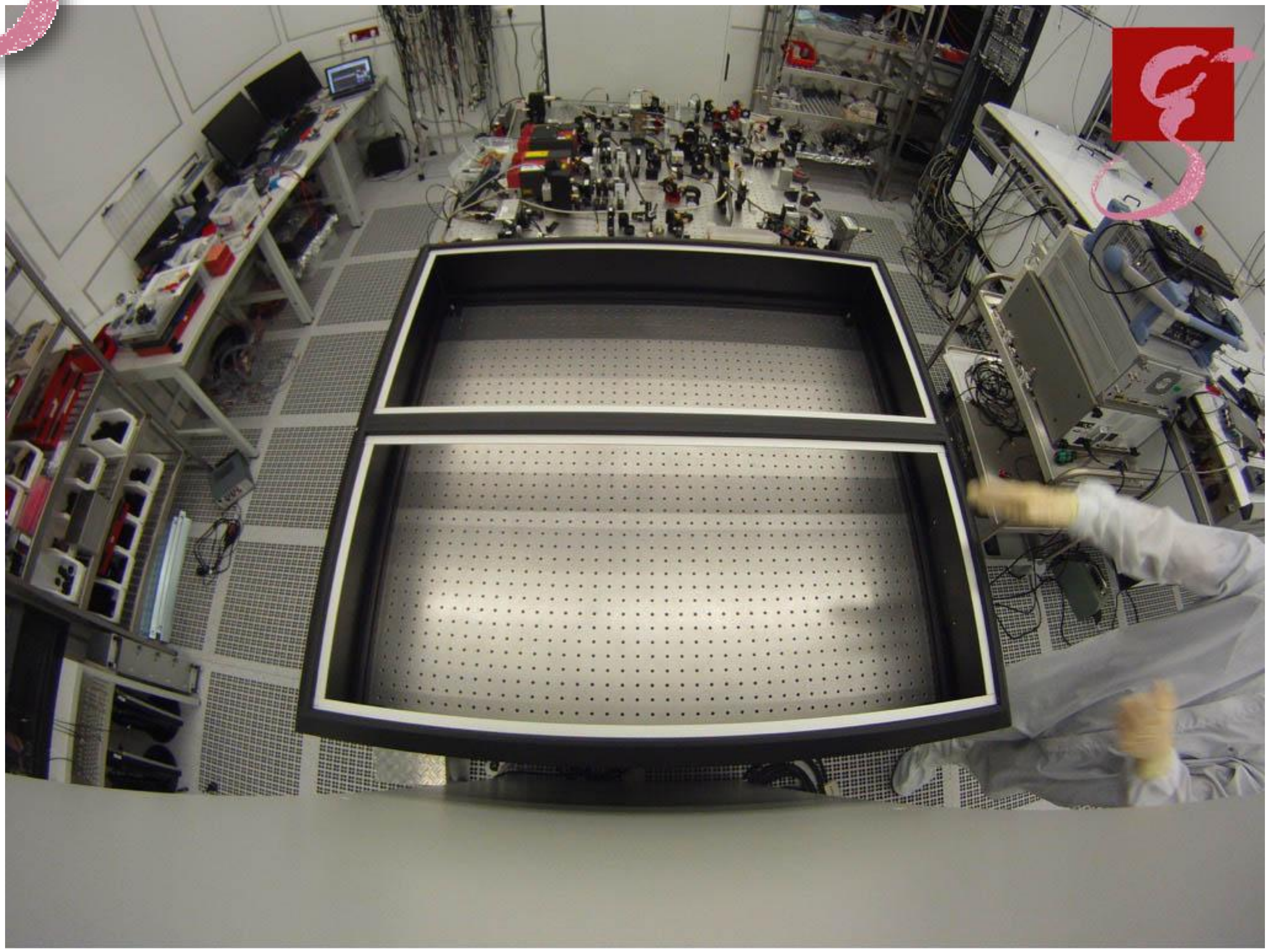
- Continuously improved interfacing, recently achieved up to 6dB shot noise reduction due to squeezing!

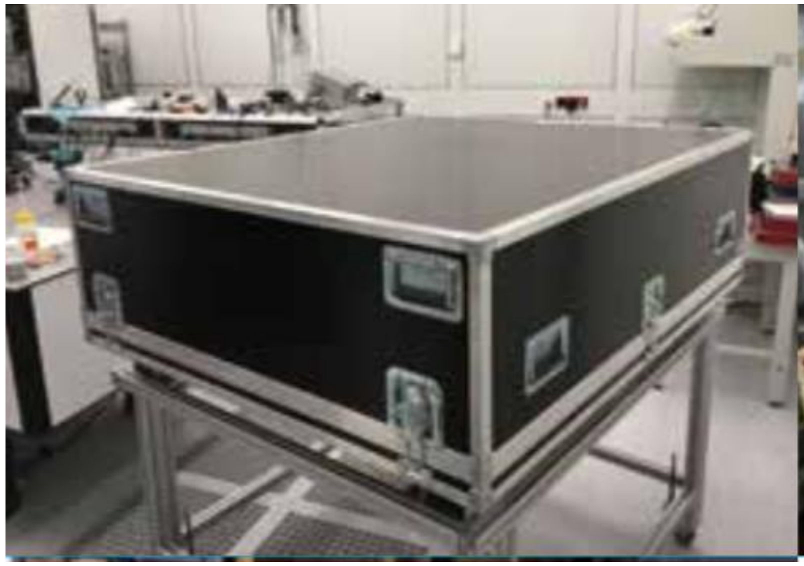
Source	Loss (%)
OPA escape efficiency	1.0
Squeezed light source after OPA	1.3
In-air injection path	1.8
In-vacuum optics up to OMC	6.6
BDO1 transmission	2.0
SRC reflection	1.4
OMC mode matching - 2nd order	1.3
OMC additional mismatch	5.0
OMC alignment control dither	0.25
PD quantum efficiency	1.0
Dark noise equivalent	0.1
Total	19.9




broken OPA crystal

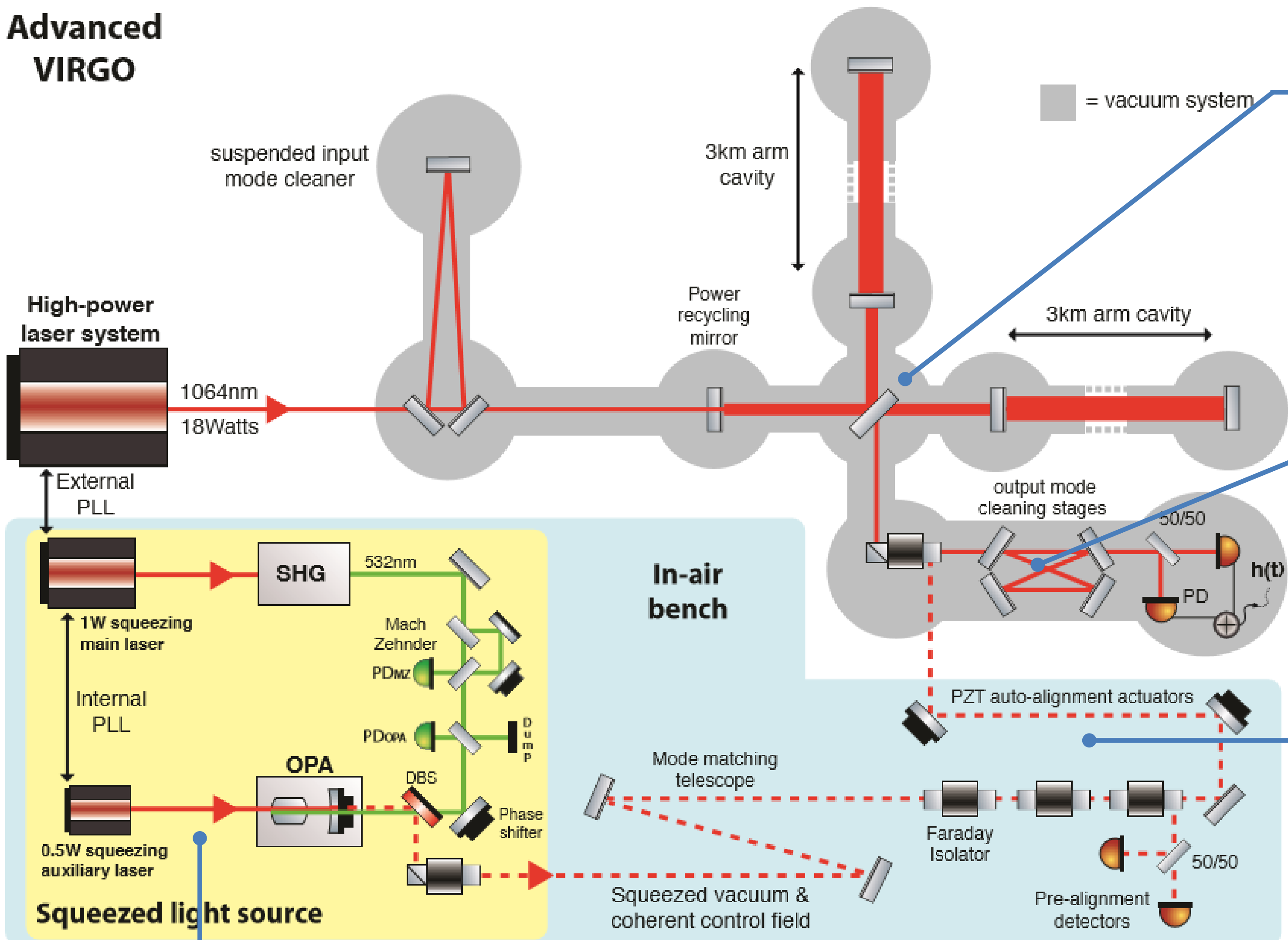
Assembling and transport of a squeezer to Virgo





Advanced Virgo squeezing injection

F. Acernese et al., PRL **123**, 231108 (2019).



Interferometer Losses (5-11)%

- Optics
- Arm cavities losses
- Alignment

Detection Losses (13-24)%

- In vacuum Faraday
- OMC losses
- Mode matching ITF -> OMC
- Quantum efficiency of PDs
- Dark noise / technical noise

Injection Losses (5-13)%

- Faraday
- Optics
- Alignment
- Mode matching to Output mode cleaner

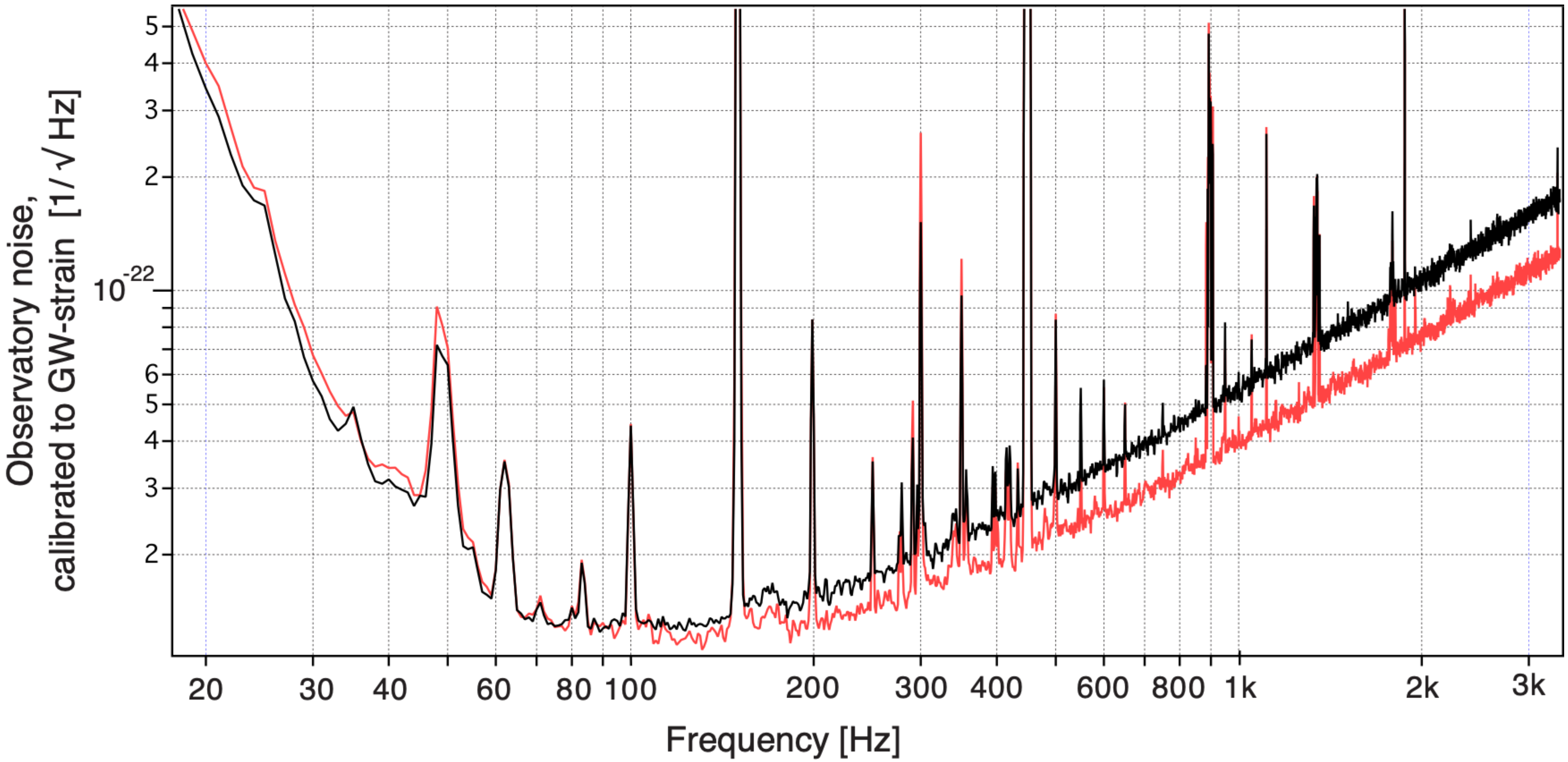
Squeezer Losses (2.5-3.5) %

- OPA escape efficiency
- Faraday Isolator

❑ Residual squeezing ellipse angular jitter with CC loop on: 60 mrad

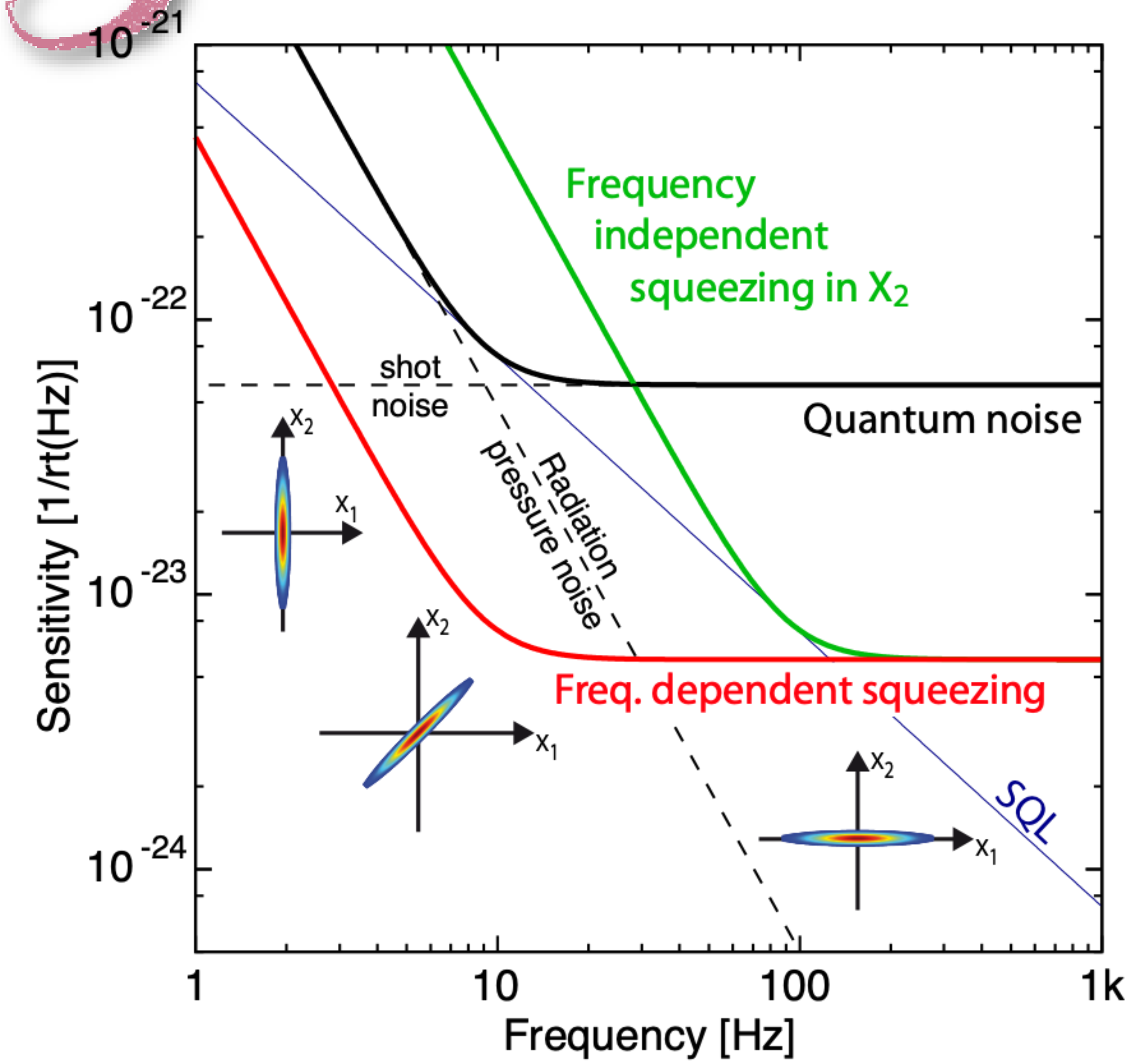
3dB squeezing @ Advanced Virgo

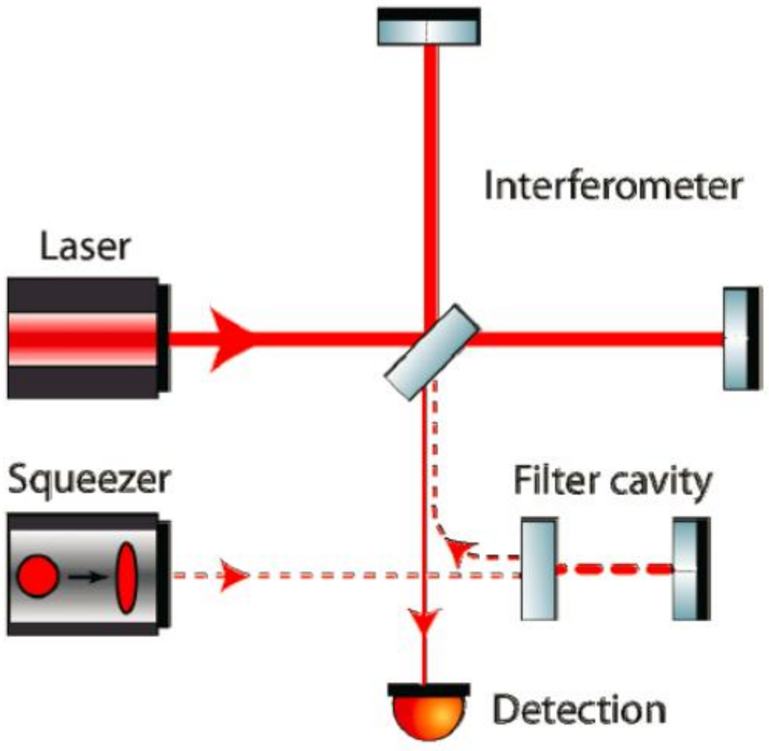
F. Acernese et al., PRL **123**, 231108 (2019)



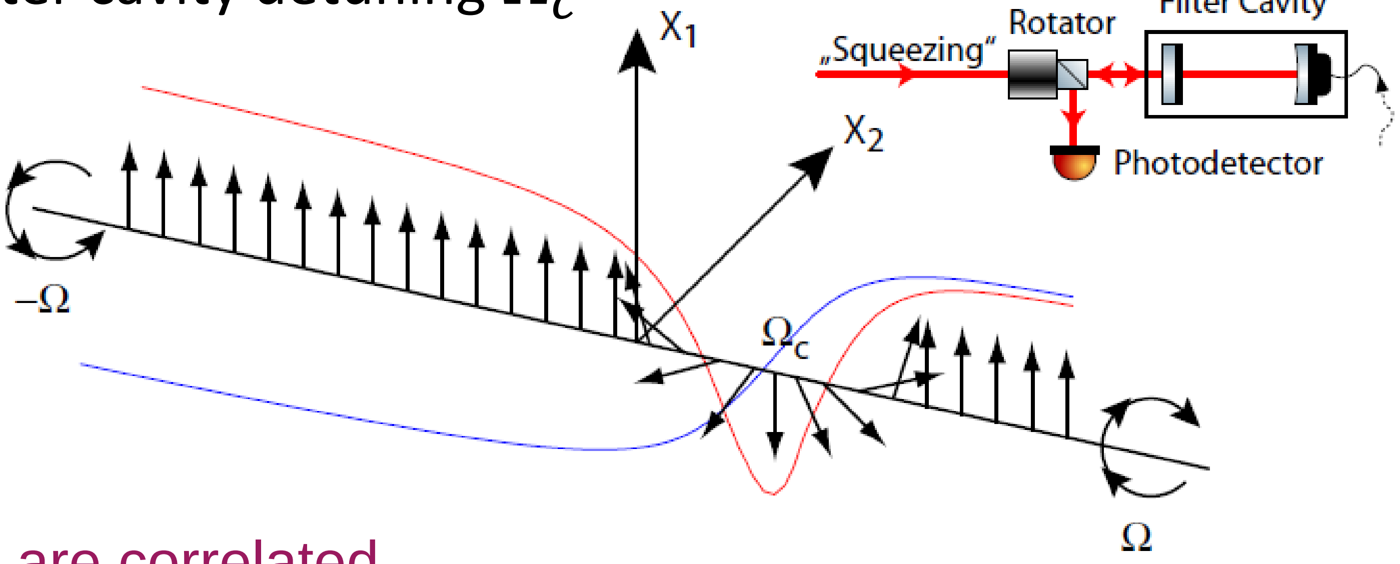
- Up to 3dB squeezing measured in the shot noise limited frequency band
- Injectable squeezing level limited by anti-squeezing at low frequencies!
- Frequency dependent squeezing required for further improvements

Frequency dependent squeezing





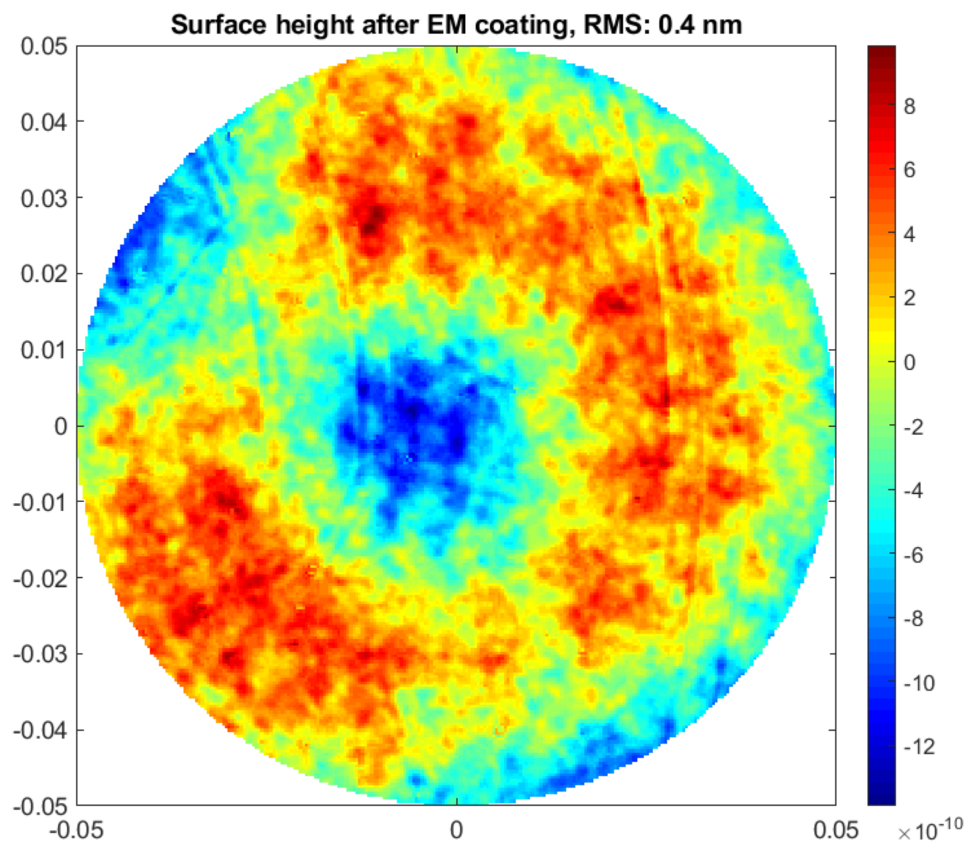
Filter cavity detuning Ω_c



- Squeezing: sideband quantum fluctuations are correlated
- Detuned filter cavity provides frequency dependent squeezing ellipse rotation

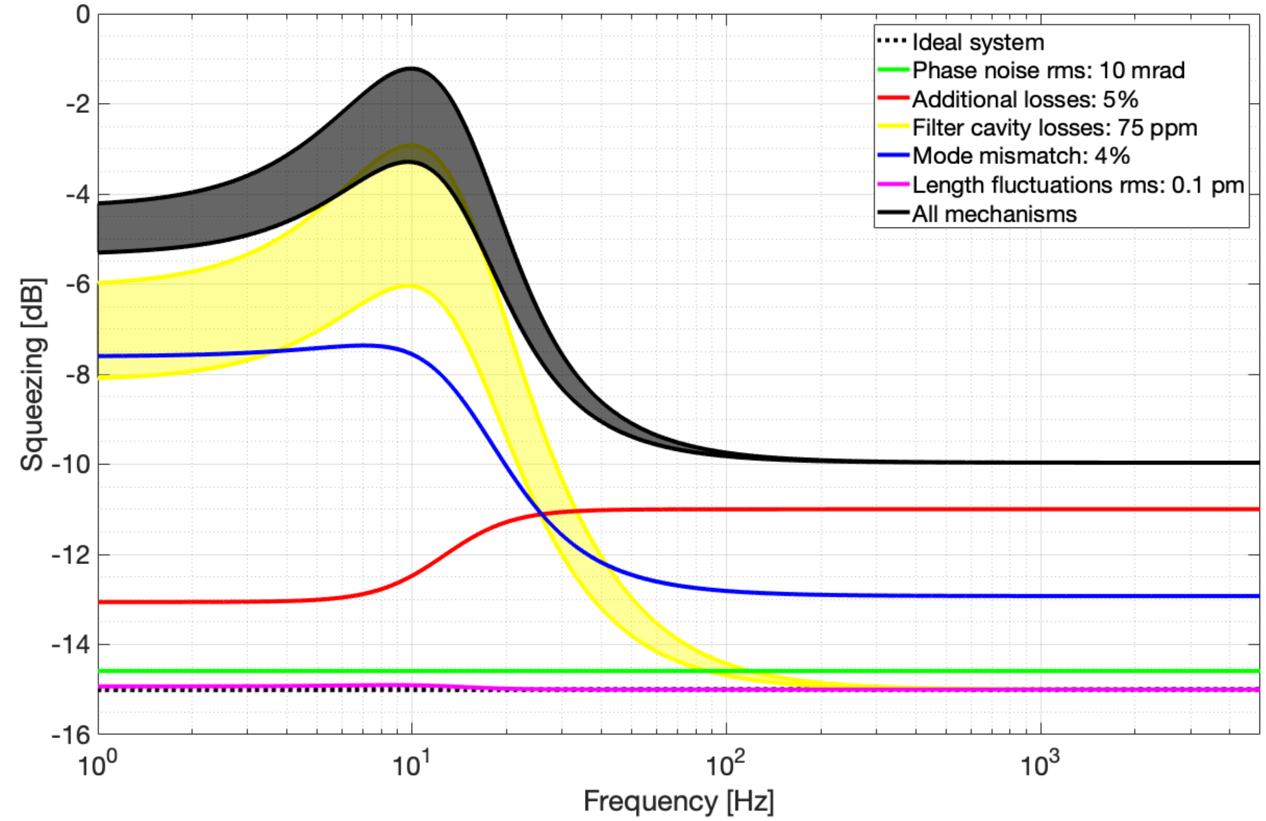
FDS challenges

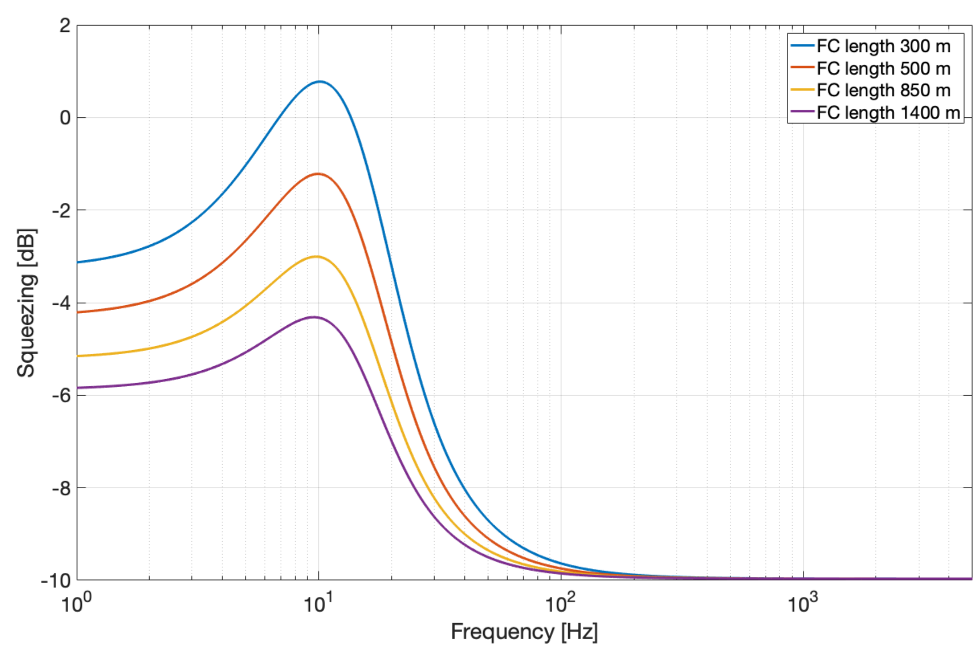
- Cavity round trip loss
- Mode mismatch
- Phase noise



provided by J. Degallaix/LMA

- Preliminary simulations for ET:





credits:E. Capocasa
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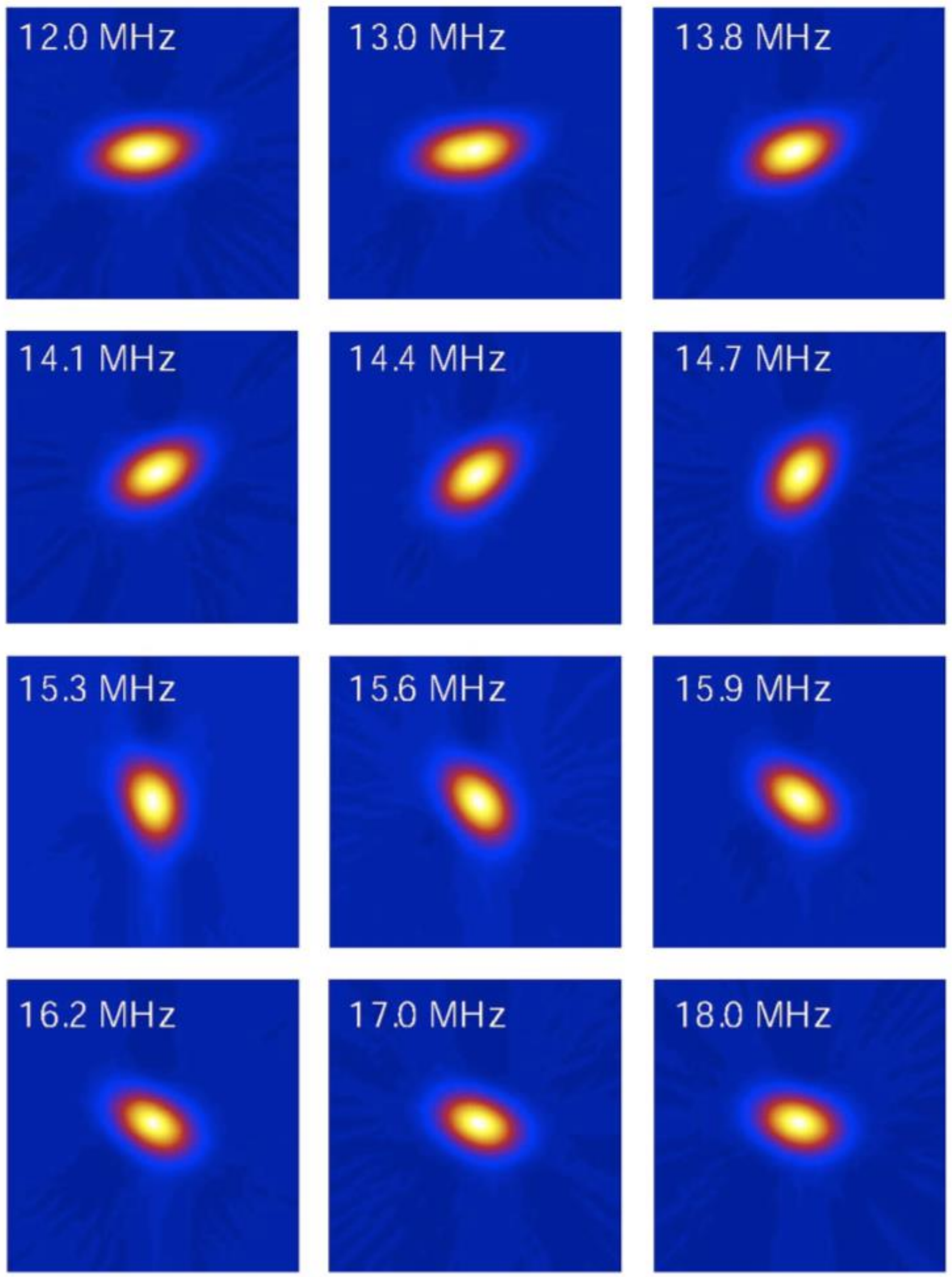
Frequency dependent squeezing

- Table top experiment



S.Chelkowski, PRA 71, 013806 (2005)
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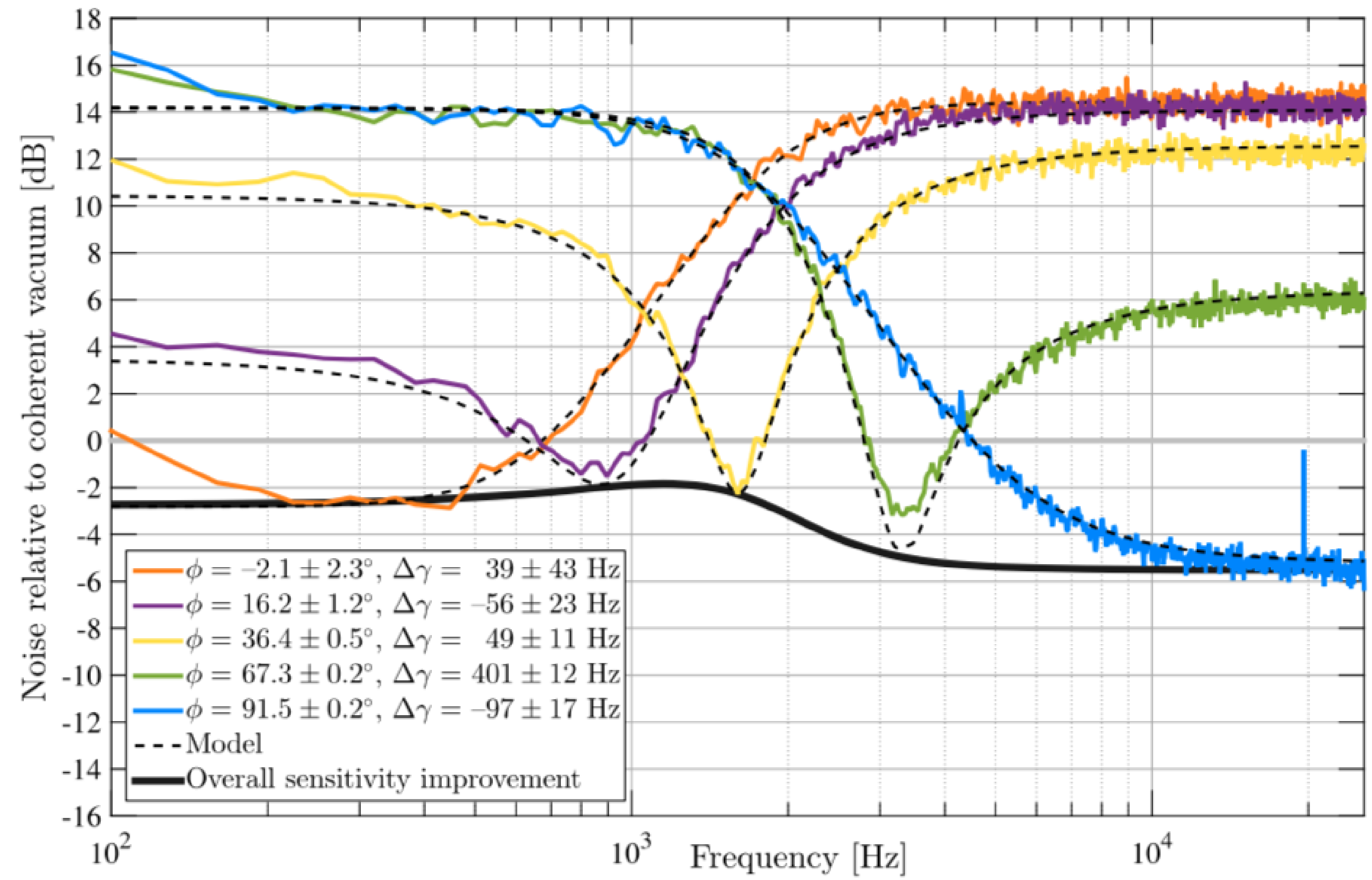
- 90° quadrature rotation at kHz



E.Oelker, PRL 116, 041102 (2016)

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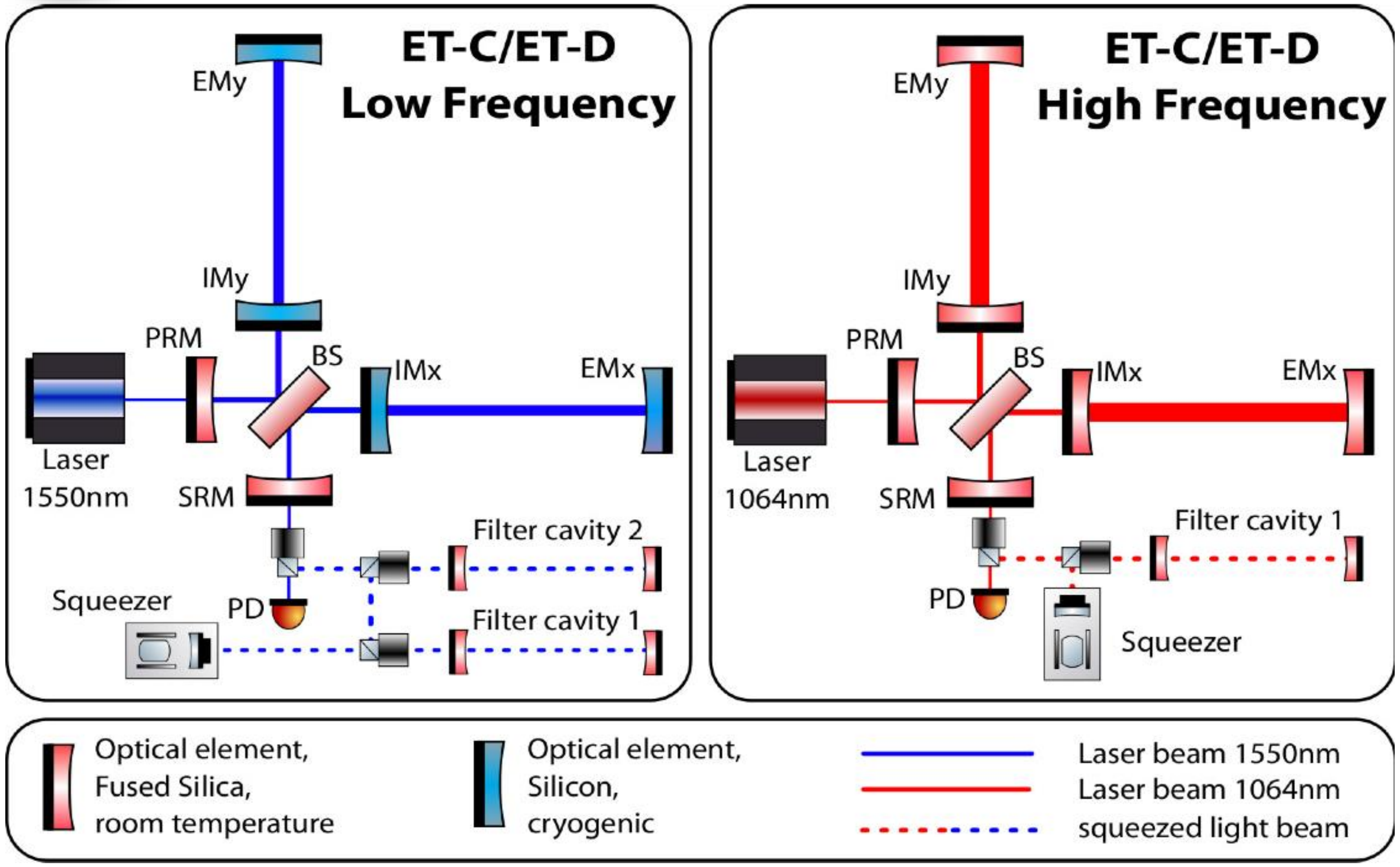
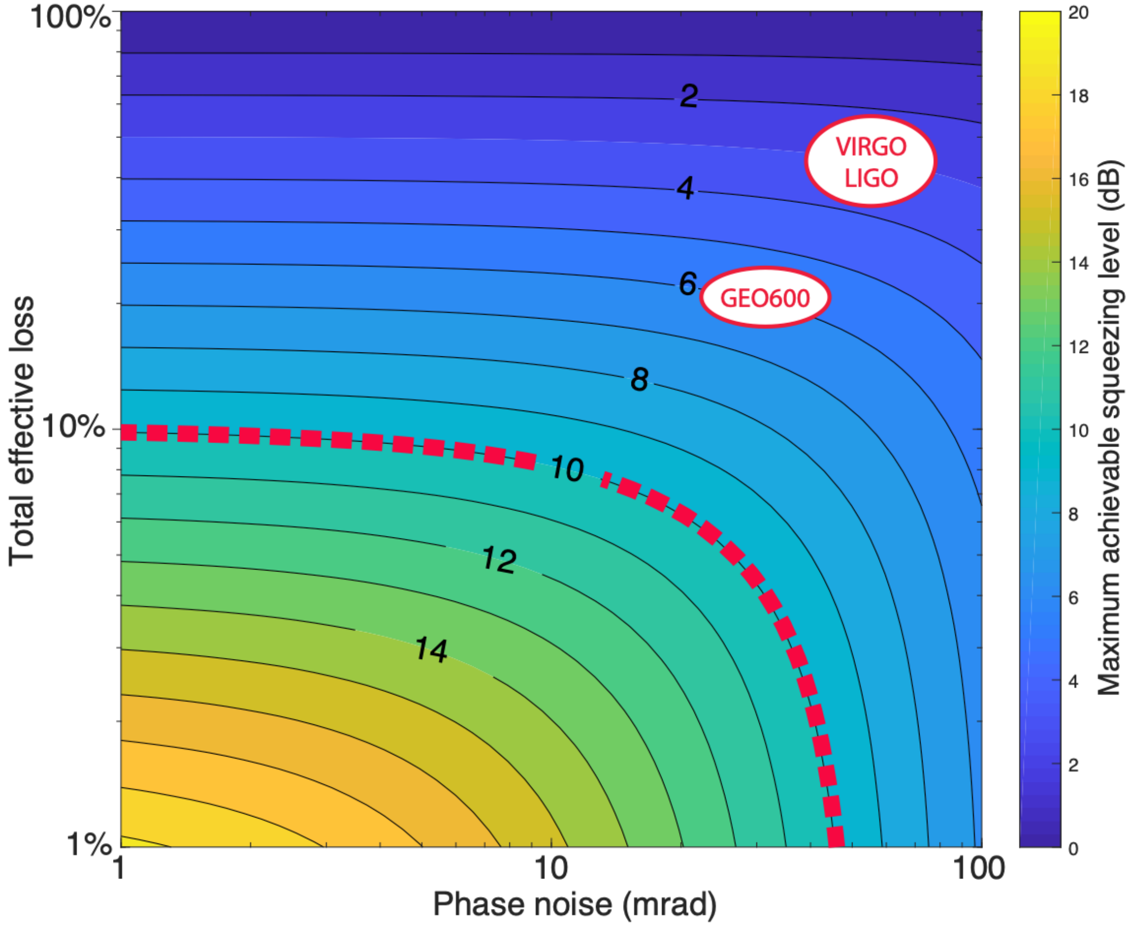
- 300m long cavity is currently under test at the National Observatory of Japan (NAOJ) aiming for rotation below 100Hz.

Summary





- A total of six independent squeezed light sources will be required for ET.
- To reach „10dB detected squeezing" goal only 10% of optical loss is acceptable!
- This requires super low loss optics and subsystems (e.g. Faraday Isolators, filter cavities), advanced mode-matching strategies, low phase noise etc.