Quantum squeezing for Virgo and future generation gravitational-wave detectors

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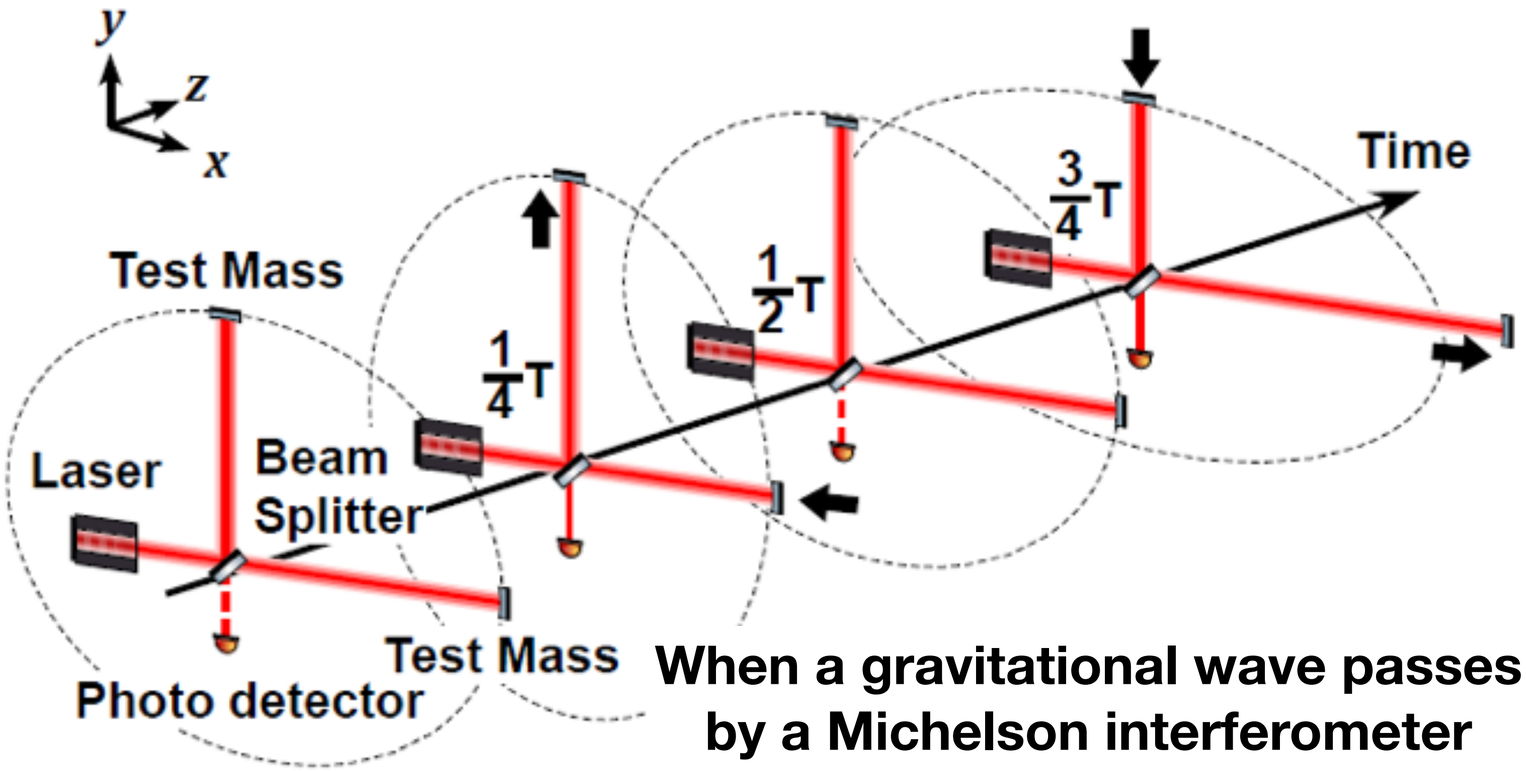
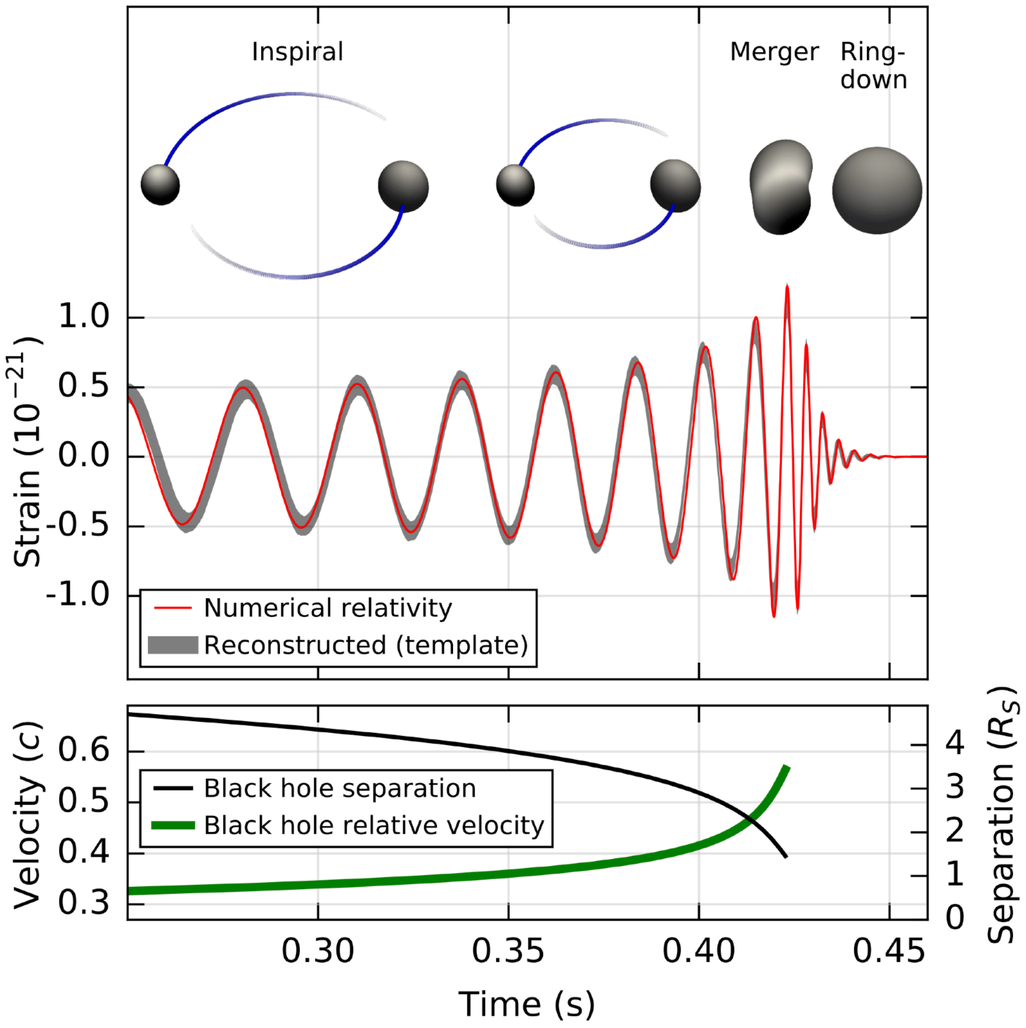
29, Mar. 2023

Gravitational wave detection principle

- Gravitational wave (GW) is transverse wave

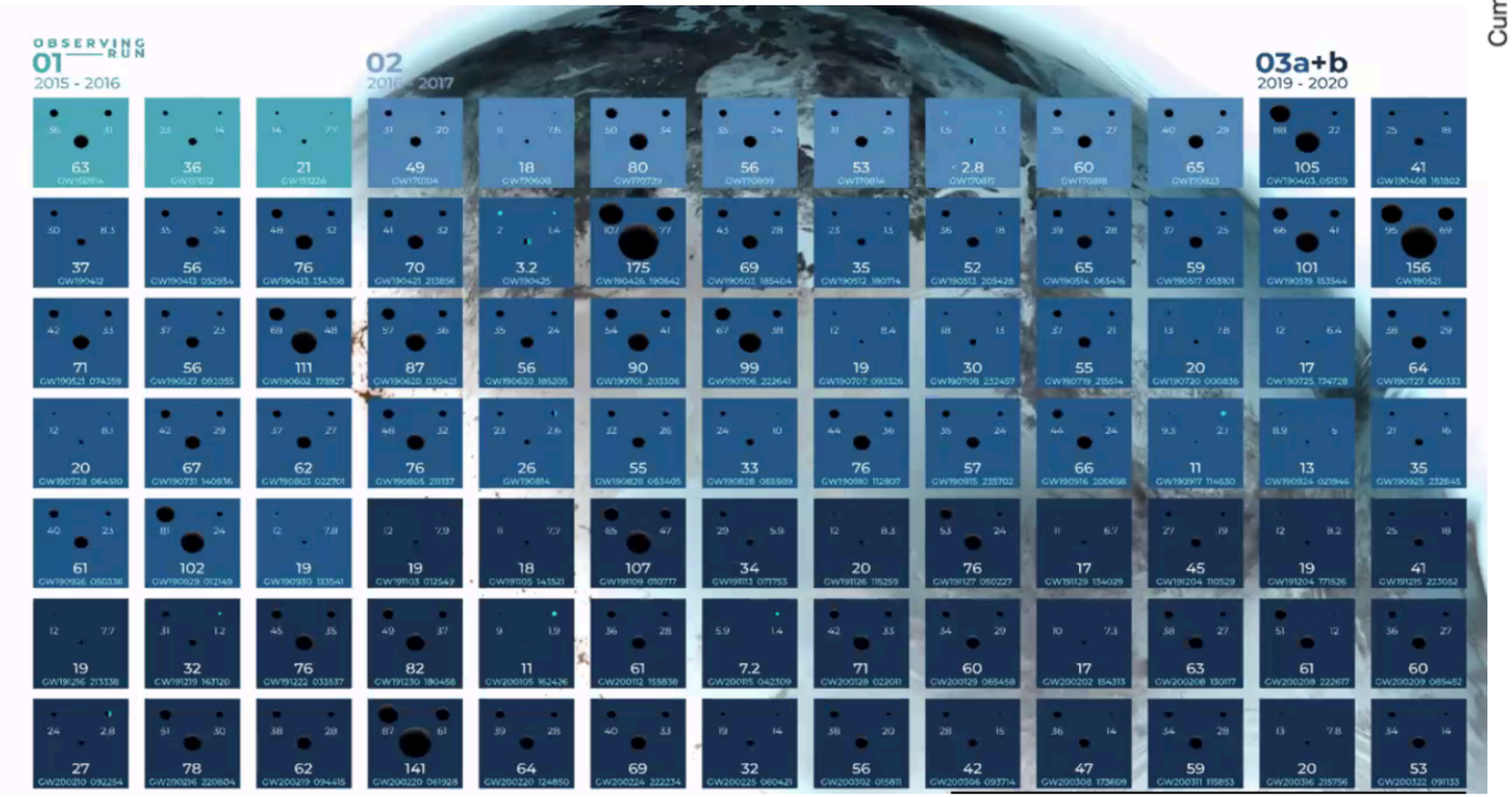


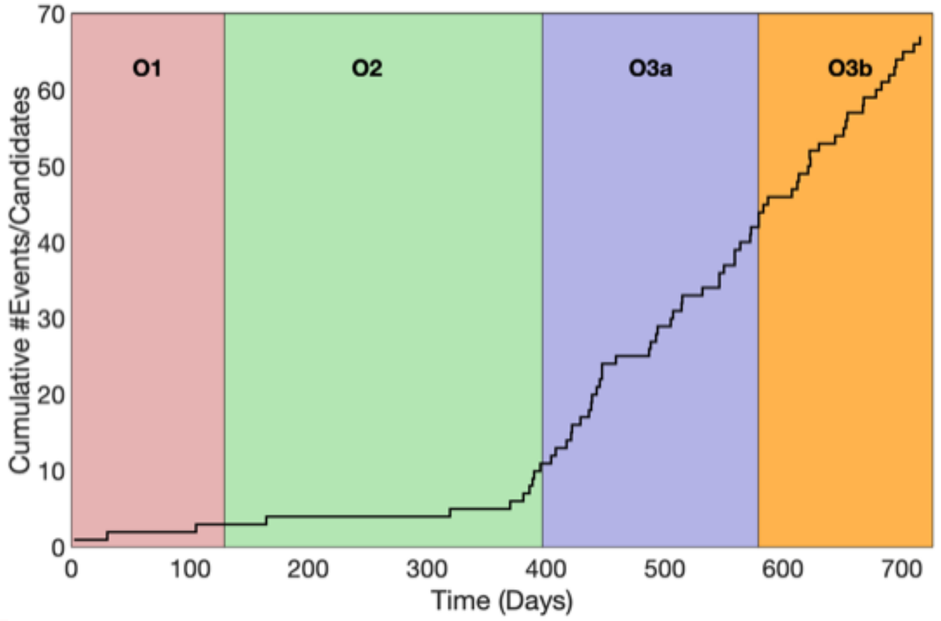
When a gravitational wave passes by a Michelson interferometer



Detected gravitational waves

- From 2015 to 2020, about 90 signals are detected, which leads to an intensive research related to these signals





- New observation run will start from the end of May this year

LIGO

Advanced Virgo

KAGRA

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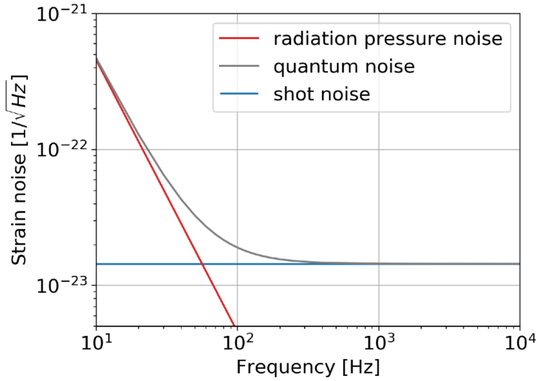
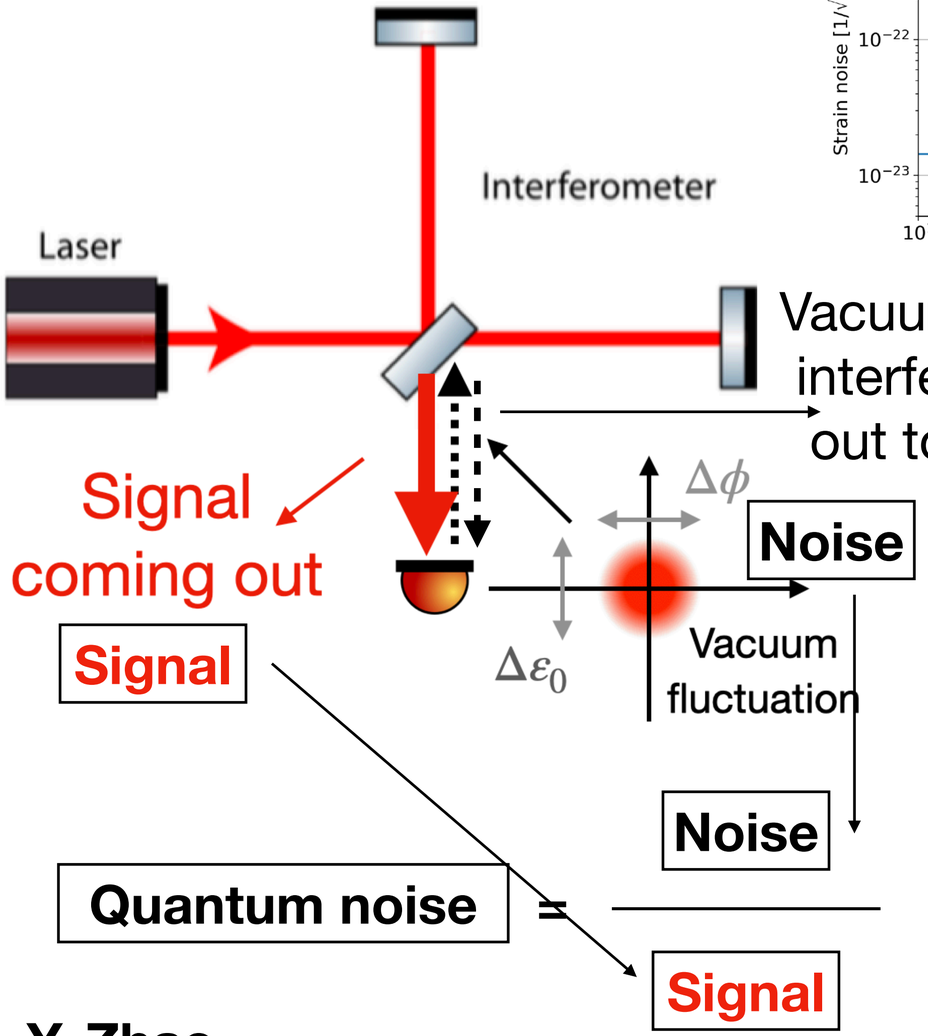
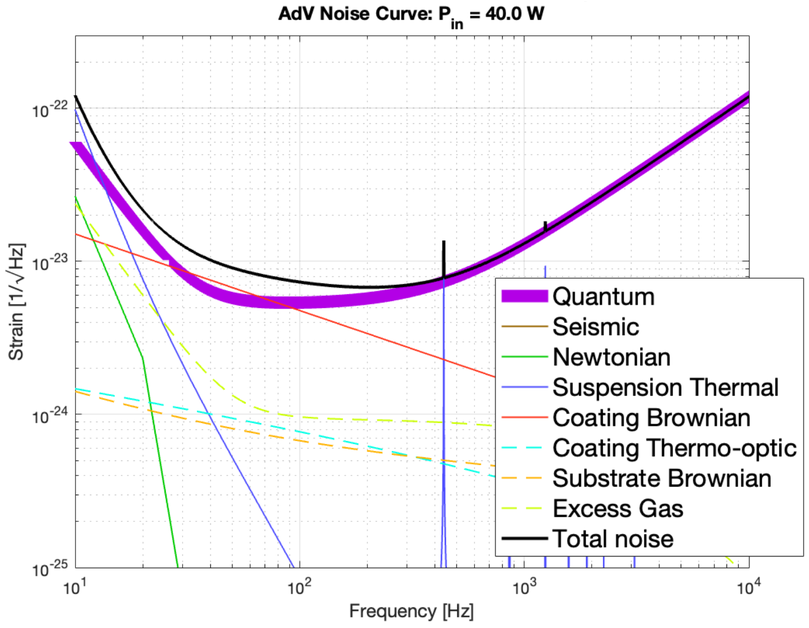
Quantum noise in gravitational wave detectors

- The following simplified scheme illustrates how quantum noise is defined





Vacuum fluctuation enters interferometer and come out together with signal



- To reduce quantum noise, one way would to reduce the vacuum fluctuation

vacuum state → squeezed state (squeezing)

Due to Heisenberg uncertainty principle, we cannot reduce $\Delta\varepsilon_0$ and $\Delta\phi$ simultaneously

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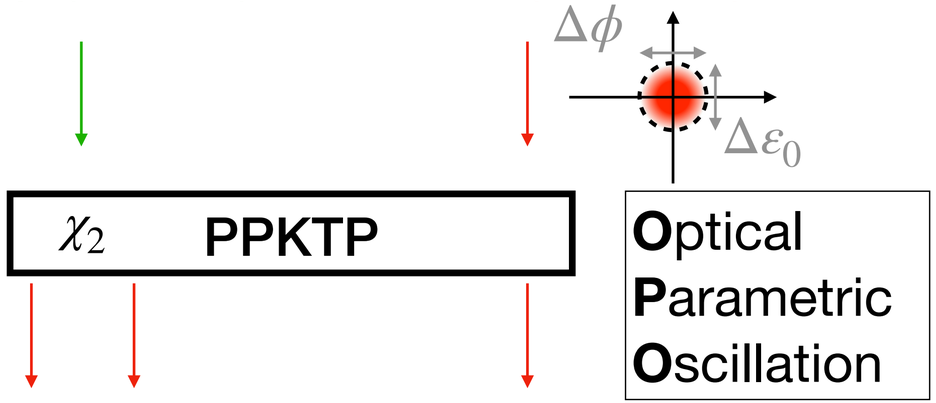
Squeezing production in Virgo

- 532nm light gets down-converted to photons at 1064nm
- Down-converted 1064nm photons interfere with vacuum fluctuation and generate squeezed vacuum

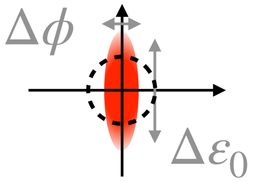
$$\varepsilon_1 \cos(2\omega t + \phi) + \varepsilon_2 \cos(\omega t)$$

pump (532nm) vacuum (1064nm)



Optical
Parametric
Oscillation

squeezed vacuum (1064nm)



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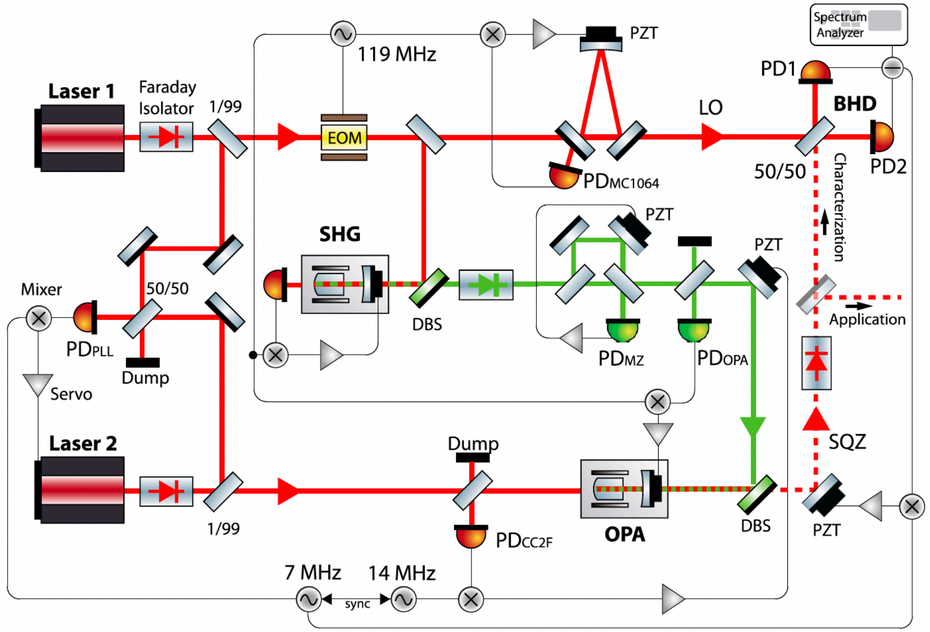
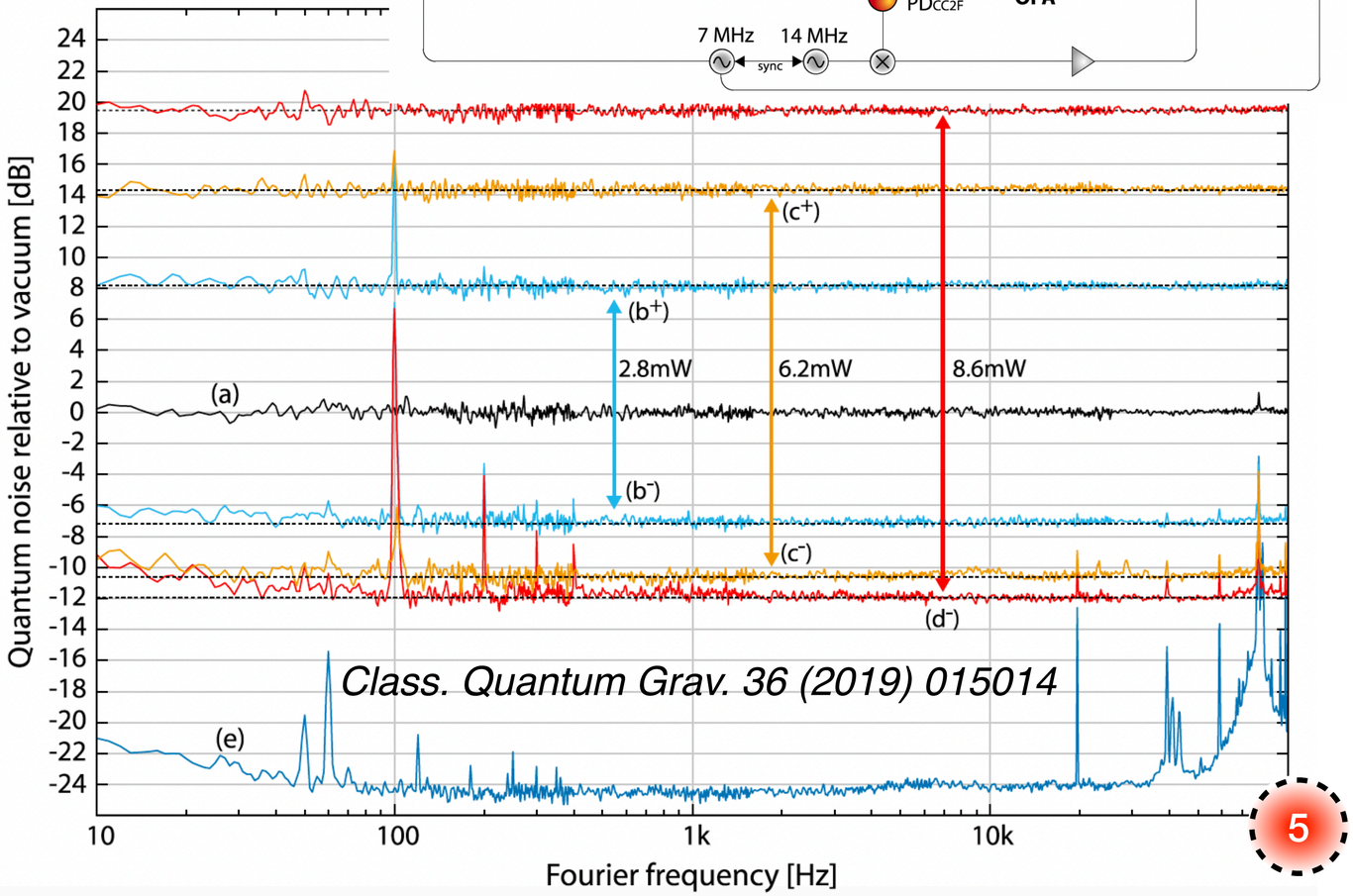
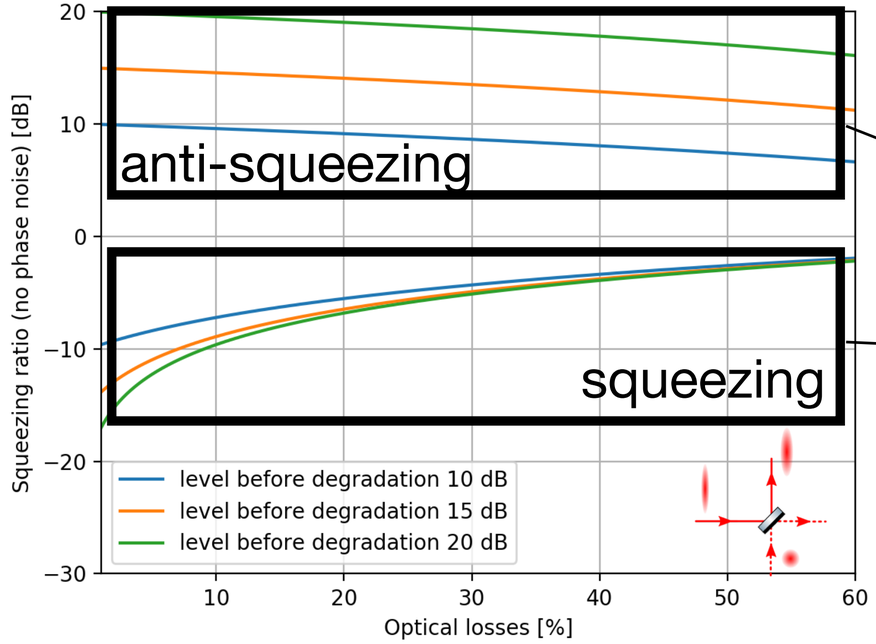
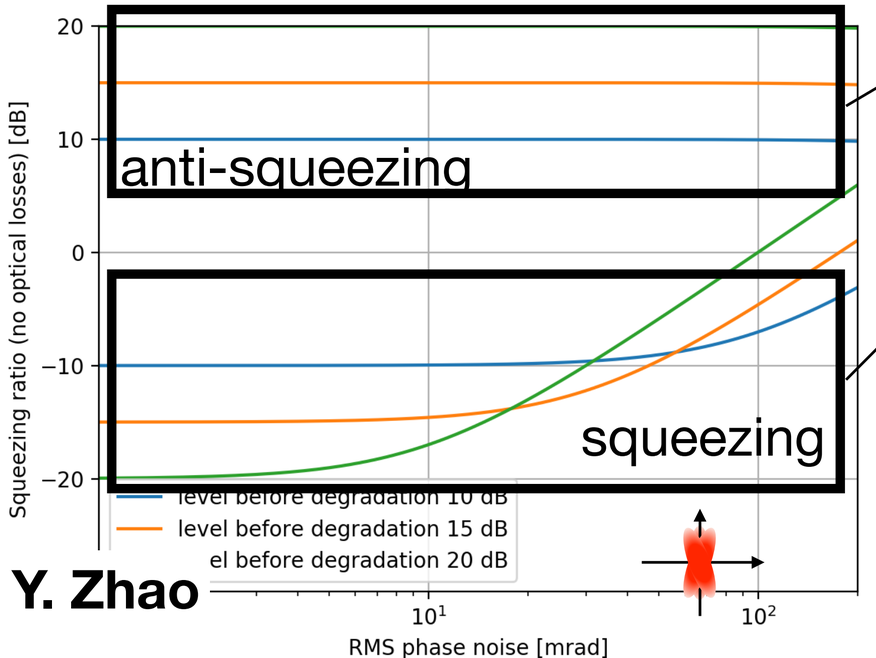


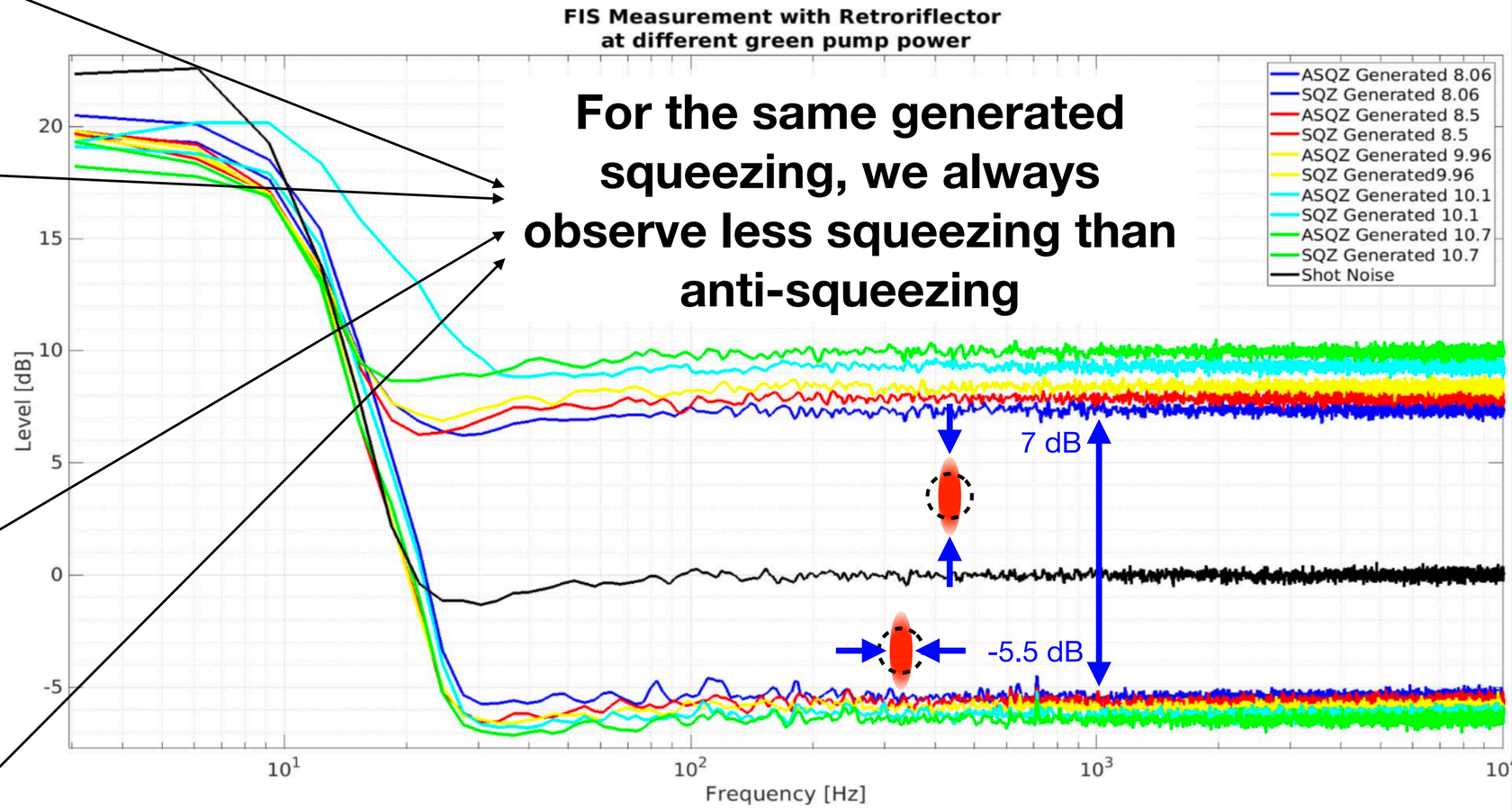


Squeezing degradation and characterization in Virgo





- Squeezing can be degraded by **optical losses** and **phase noise**



- The difference between squeezing and anti-squeezing let us understand degradation sources

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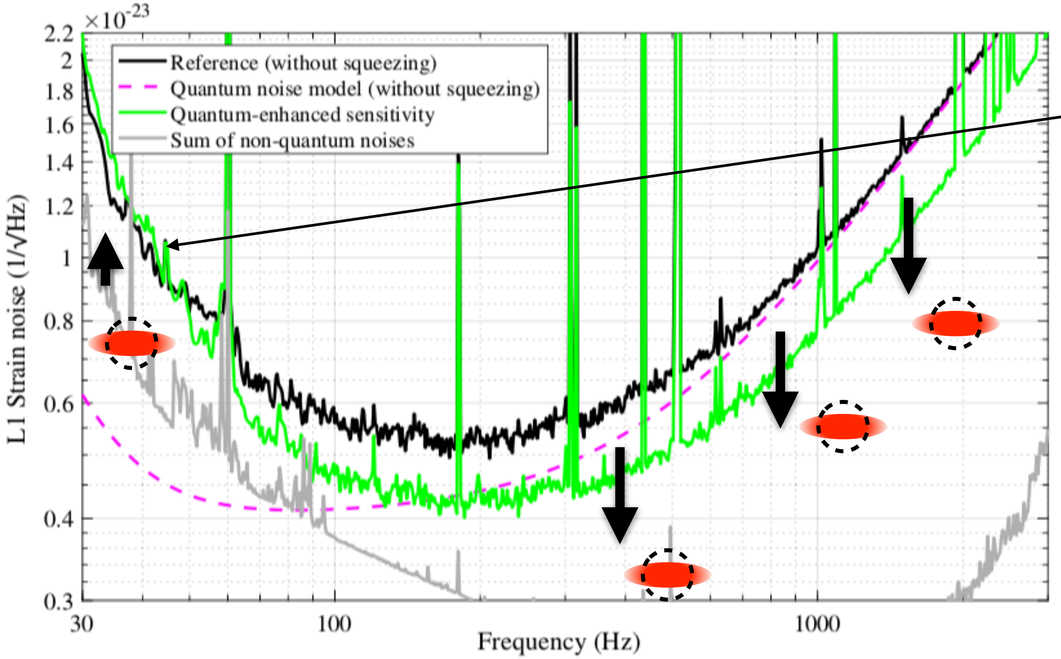
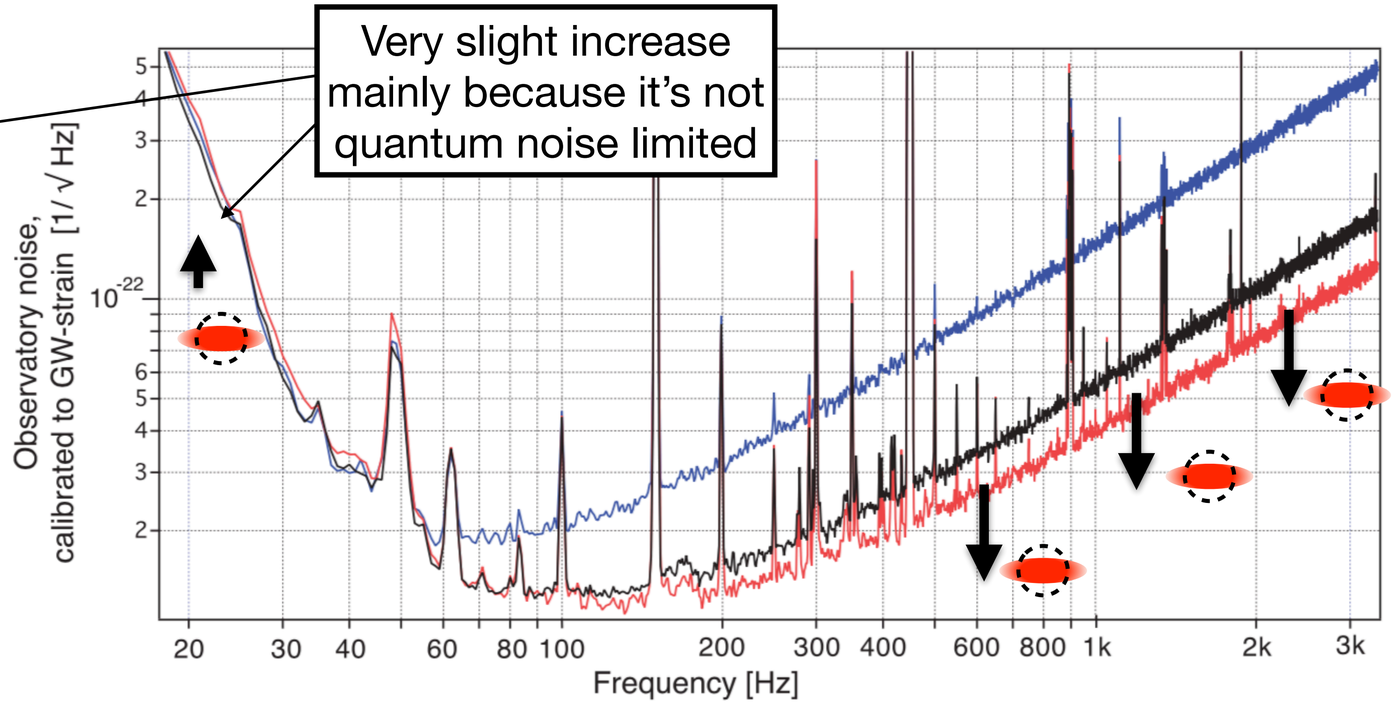
Squeezing used in LIGO and Virgo in 2019

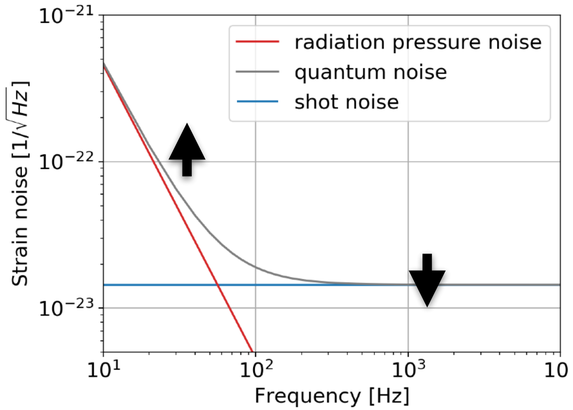
- Squeezed vacuum was successfully implemented in the third observation run of LIGO and Virgo



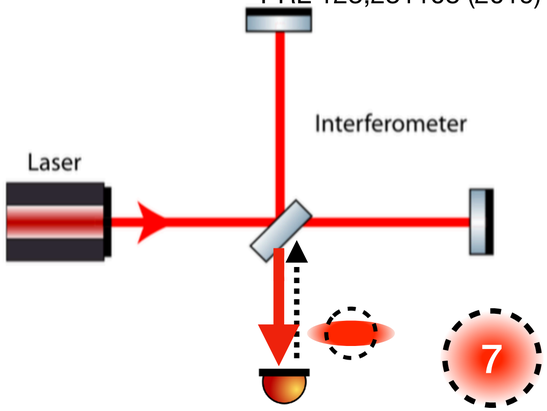
PRL 123,231107 (2019)



- 50% increase of the binary neutron star detection rate
- But we start to see the noise increase at low frequency



PRL 123,231108 (2019)



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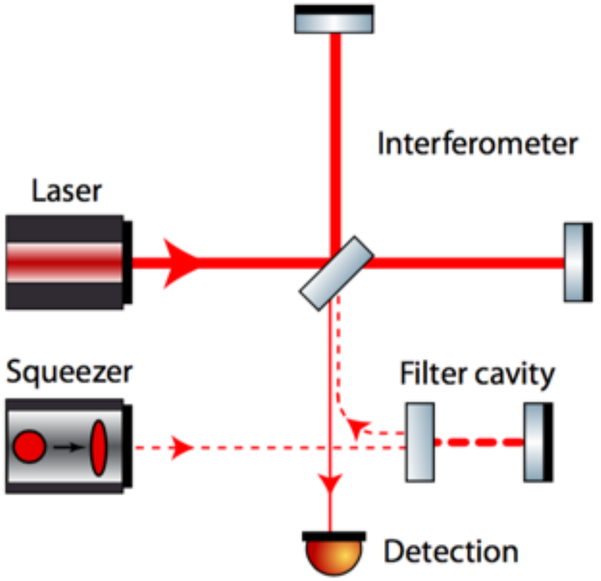
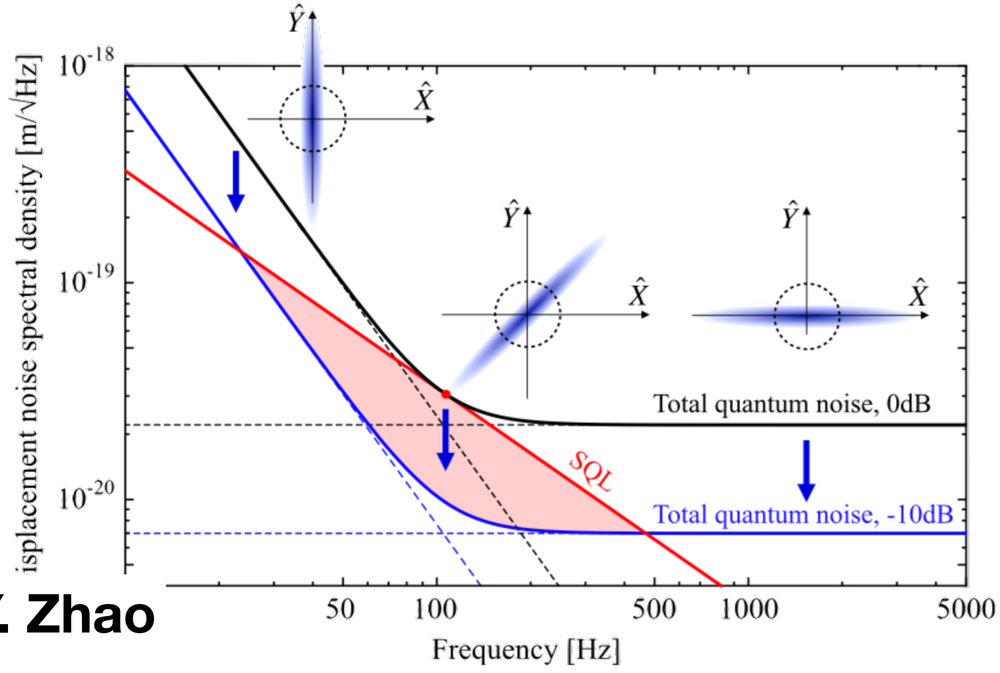
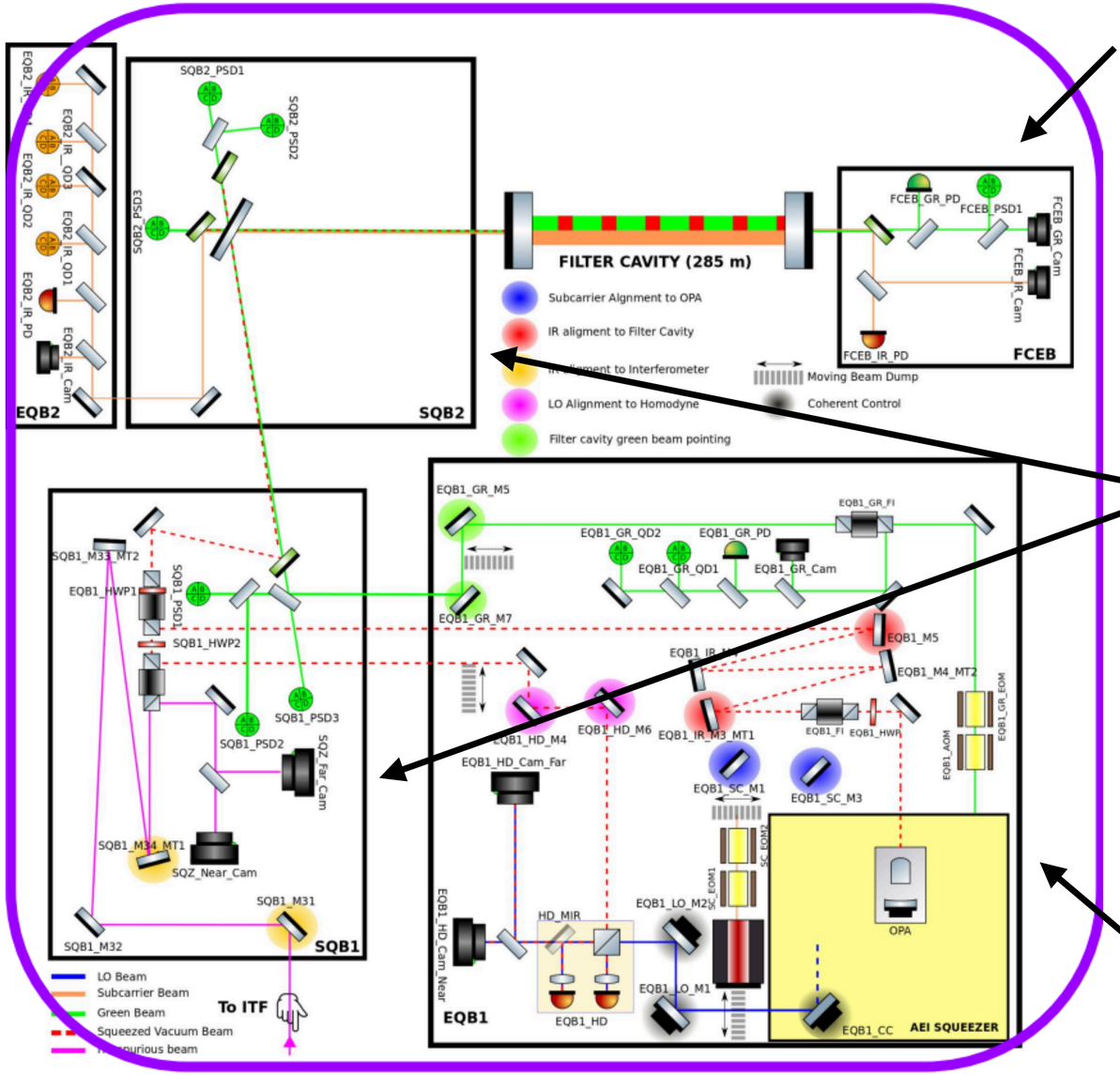
Quantum noise reduction plan in Virgo

- To avoid the low frequency radiation pressure noise increase, Virgo set up a filter cavity to rotate it







Filter cavity

Interface optics

Squeezer

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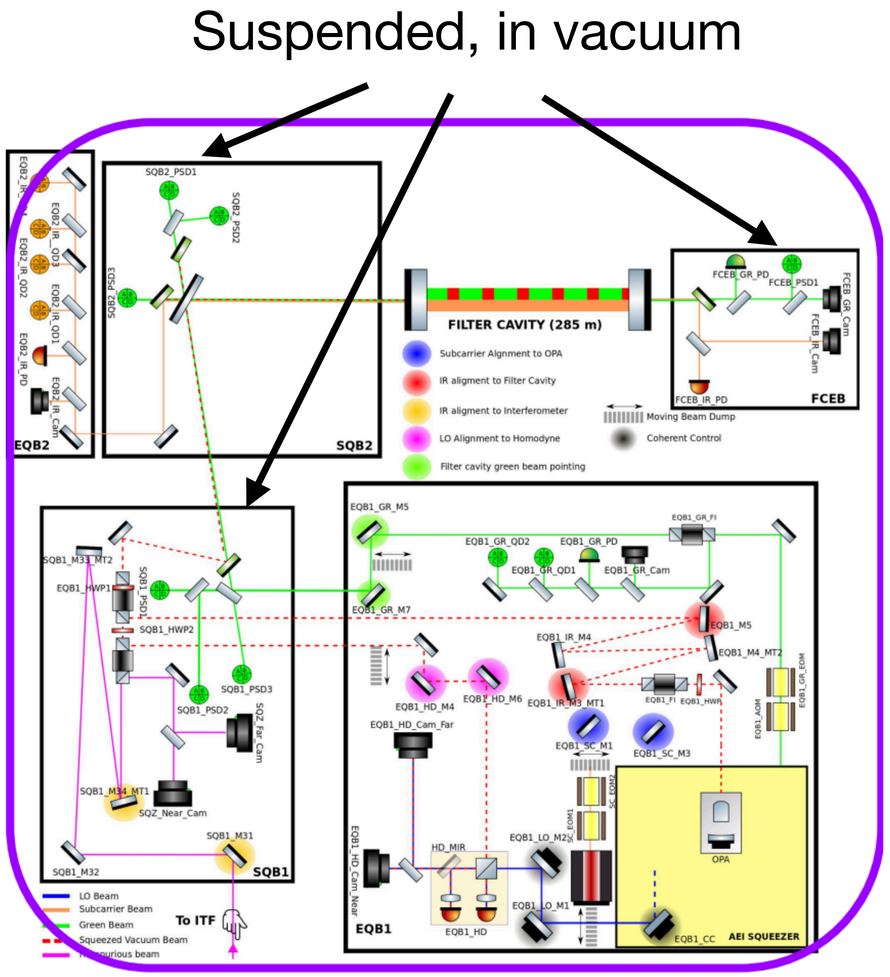
Quantum noise reduction plan in Virgo

- Suspended optics to steer squeezing beams are enclosed in a vacuum system



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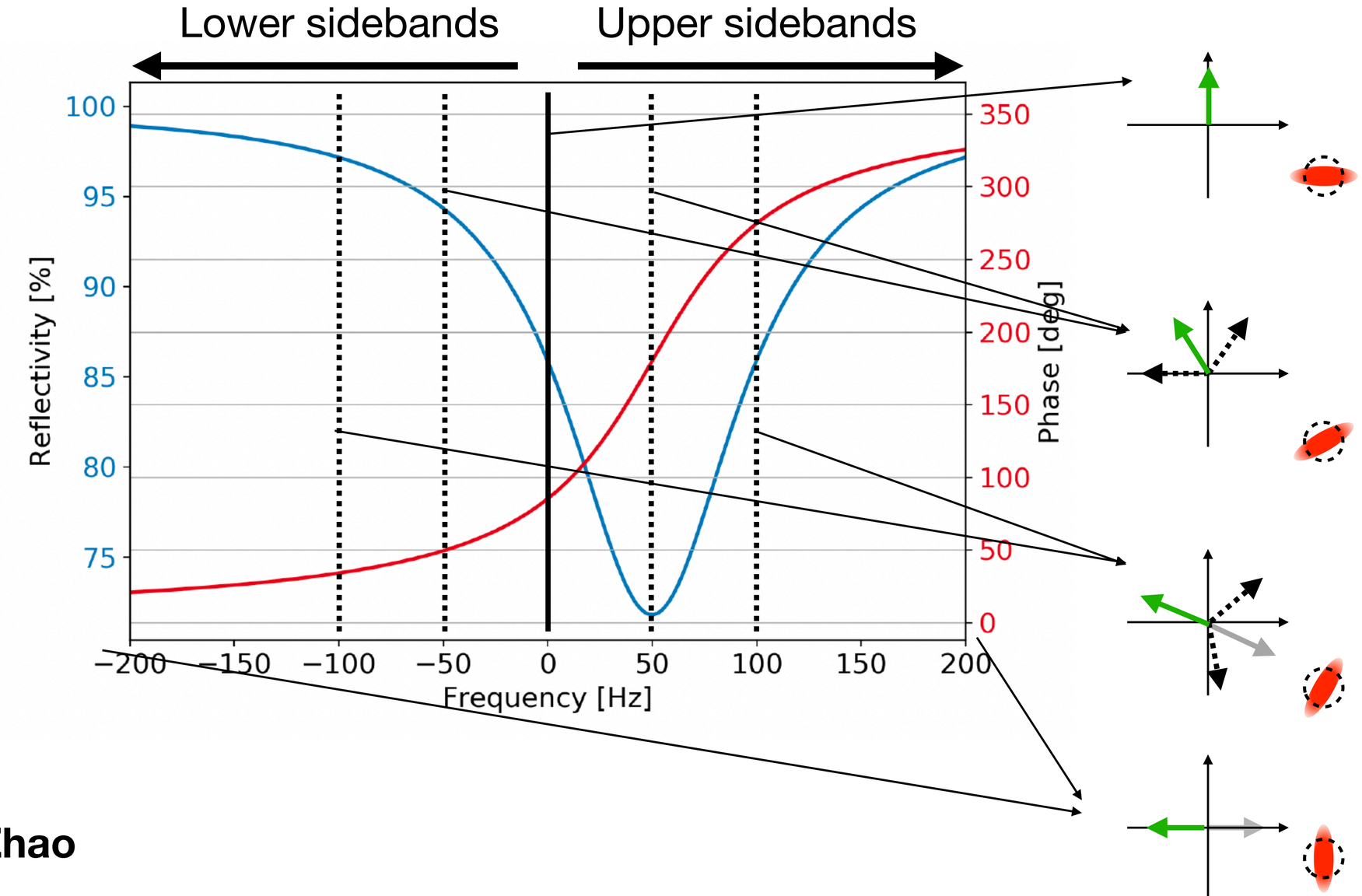
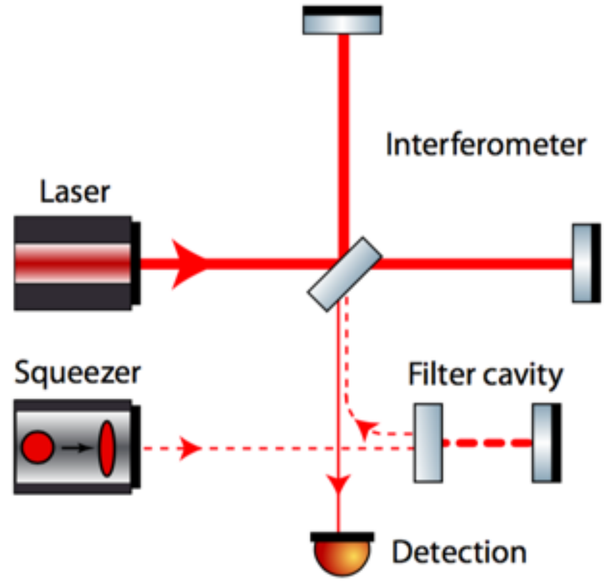
Frequency dependent squeezing (FDS)

- At each frequency, the response is determined by upper and lower sidebands



- Therefore, a rotation of 90 degrees is introduced after reflecting squeezing from the filter cavity



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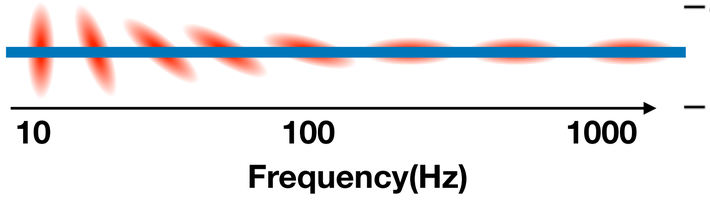
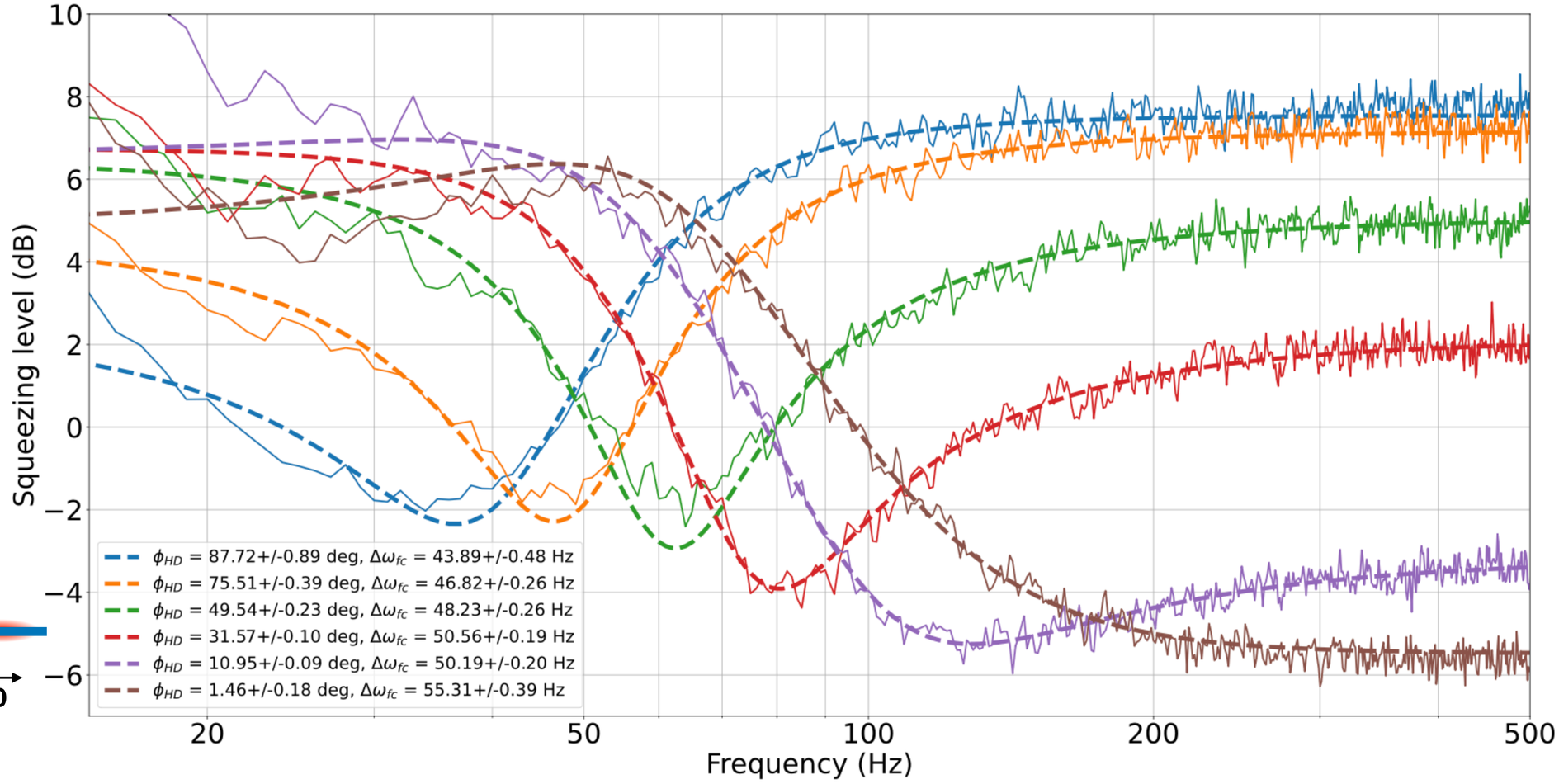
Squeezing rotation achieved

- The right side plot shows homodyne measurement of frequency dependent squeezing
- Each curve is a measurement at a fixed homodyne angle
- For example,

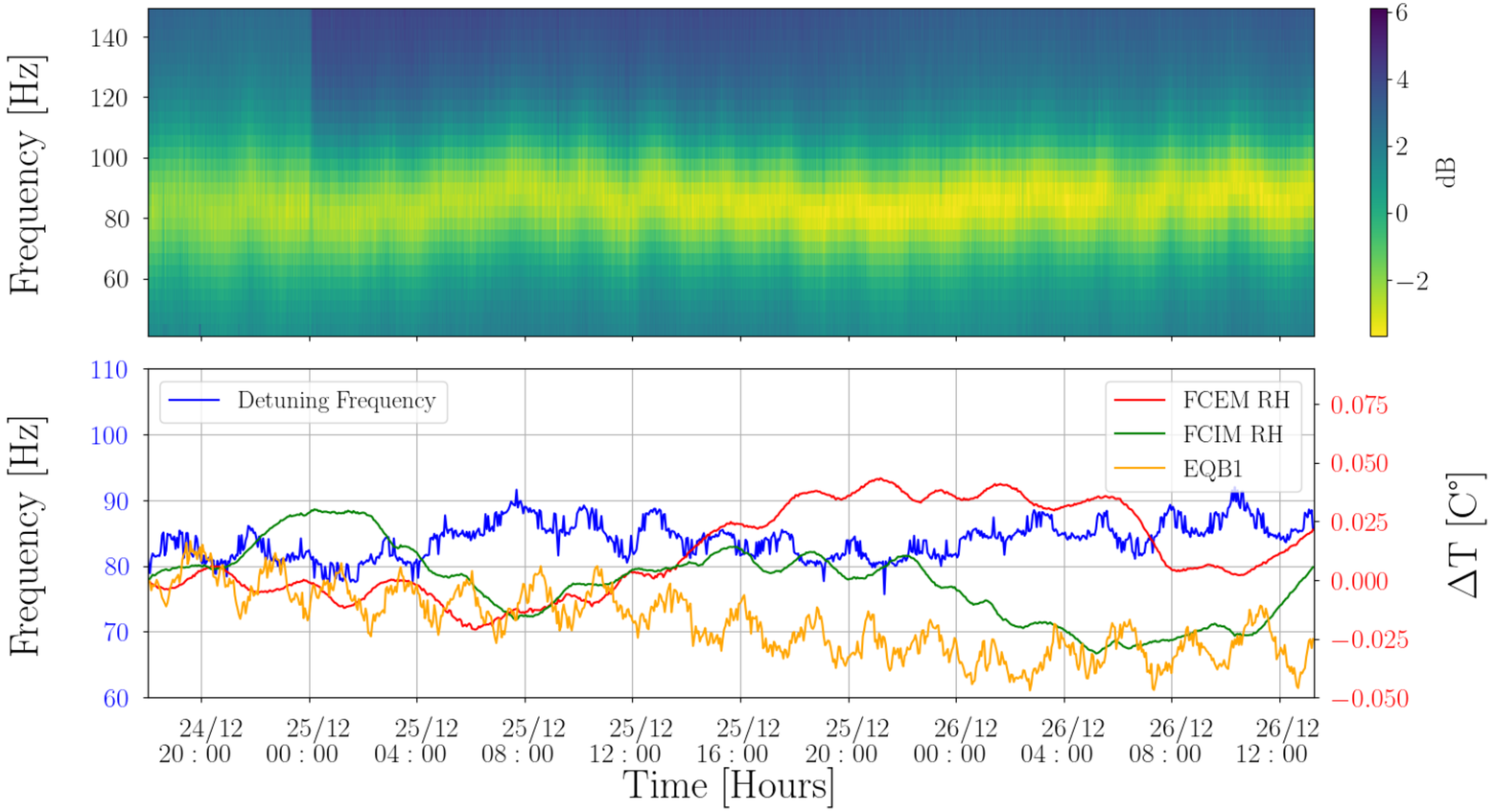




- We confirm that a 90 degrees phase rotation has been achieved, which is required for Virgo broadband quantum noise reduction

A 40 hours stable FDS measurement

- With temperature controlled, we have achieved a stable FDS measurement



- Detuning around 90 Hz
- Continuous operation
- Detuning fluctuation smaller than 10 Hz
- Submitted to PRL

Frequency dependent squeezed vacuum source for the Advanced Virgo gravitational wave detector

F. Acernese *et al.* (the Virgo Collaboration),
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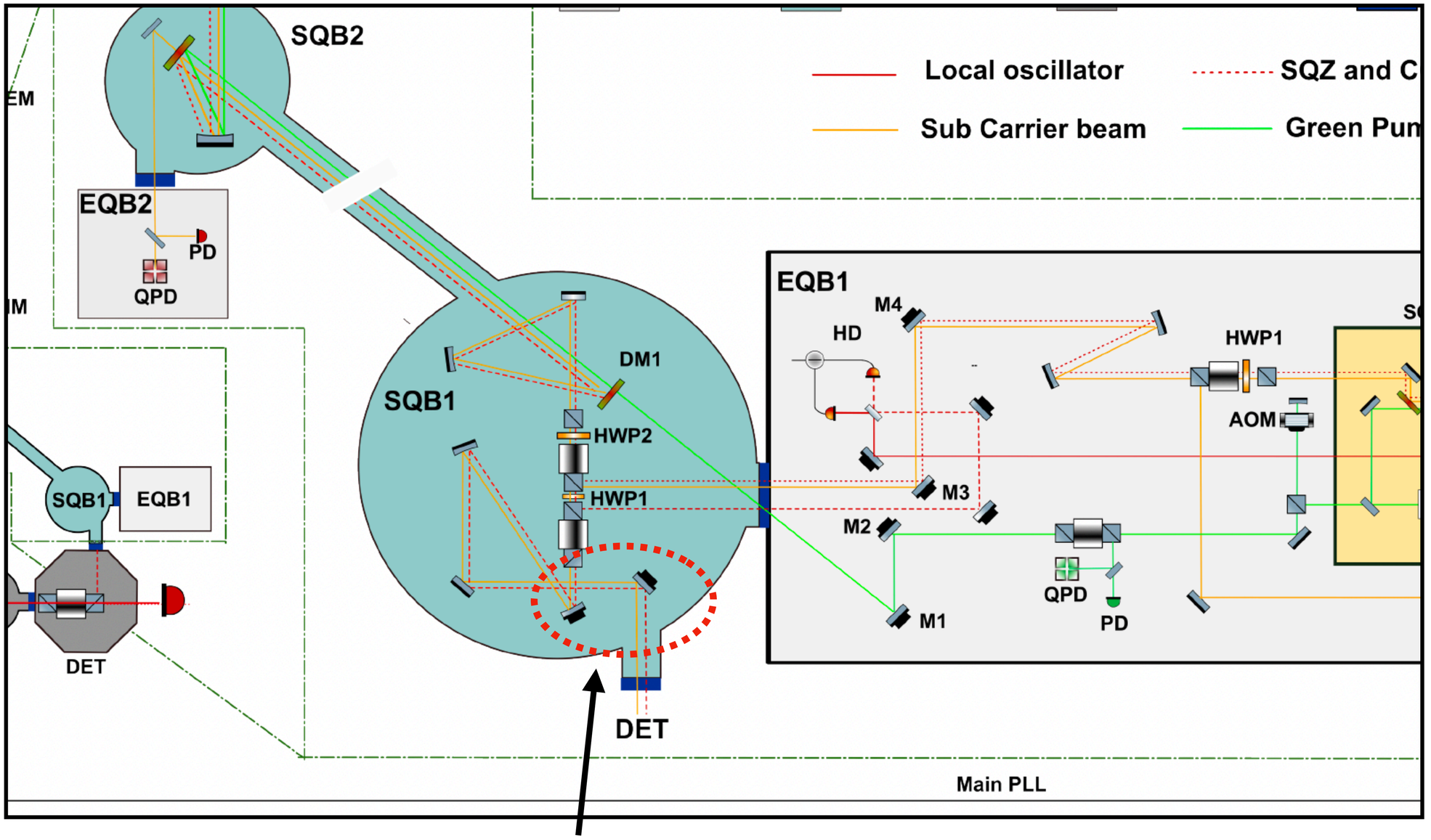
Institut für Gravitationsphysik, Leibniz Universität Hannover and Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut), Callinstr. 38, 30167 Hannover, Germany

(Dated: March 2, 2023)

FDS source is ready to be used in Virgo

- Squeezed beam aligned and matched with the interferometer (95% mode matching)
- Phase lock between squeezed beam and interferometer laser is ready (in observation mode)
- Automatic-alignment between squeezer and interferometer is ready



Two steering mirrors for the SQZ alignment

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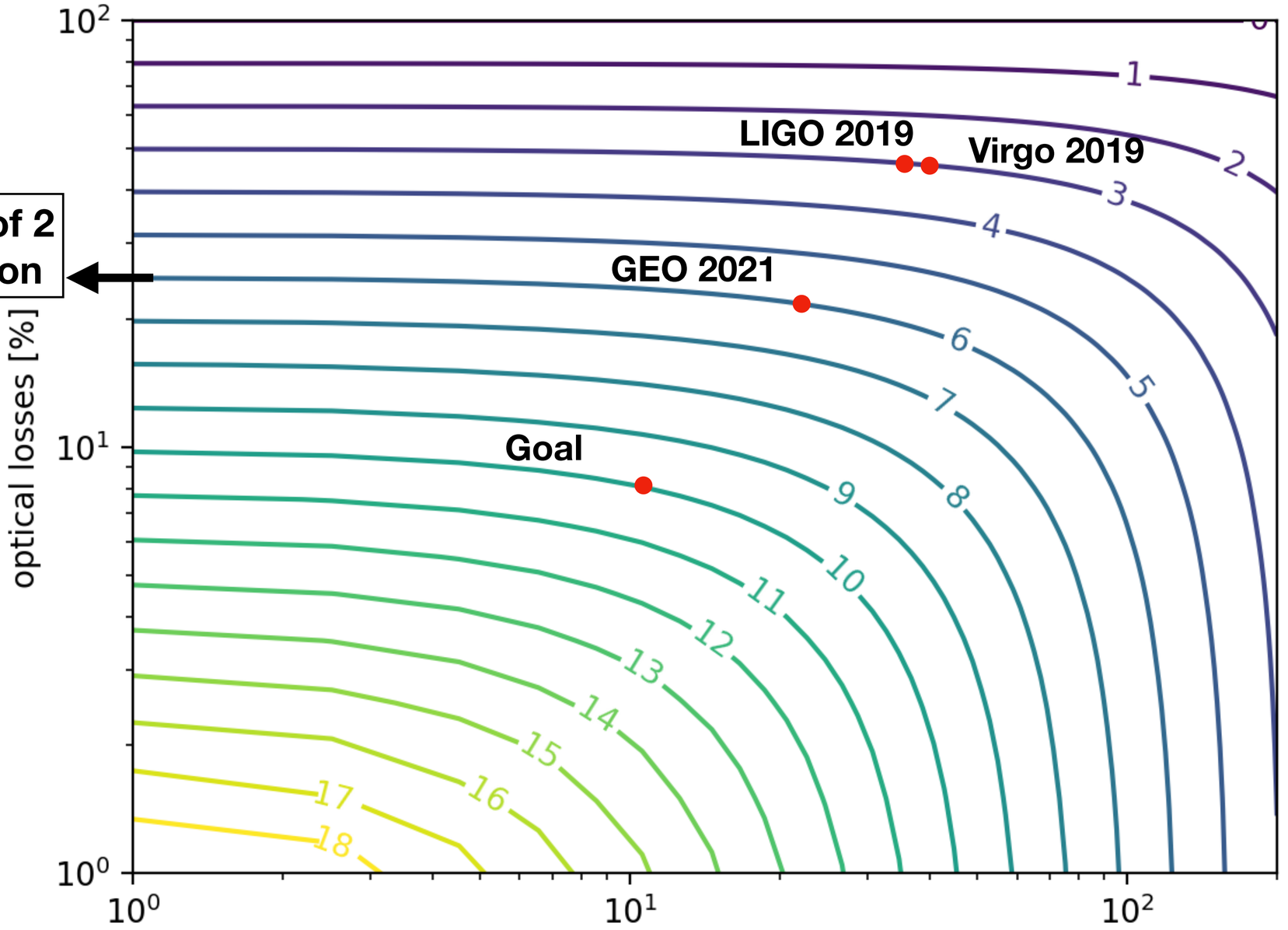
Squeezing towards next generation gravitational wave detectors

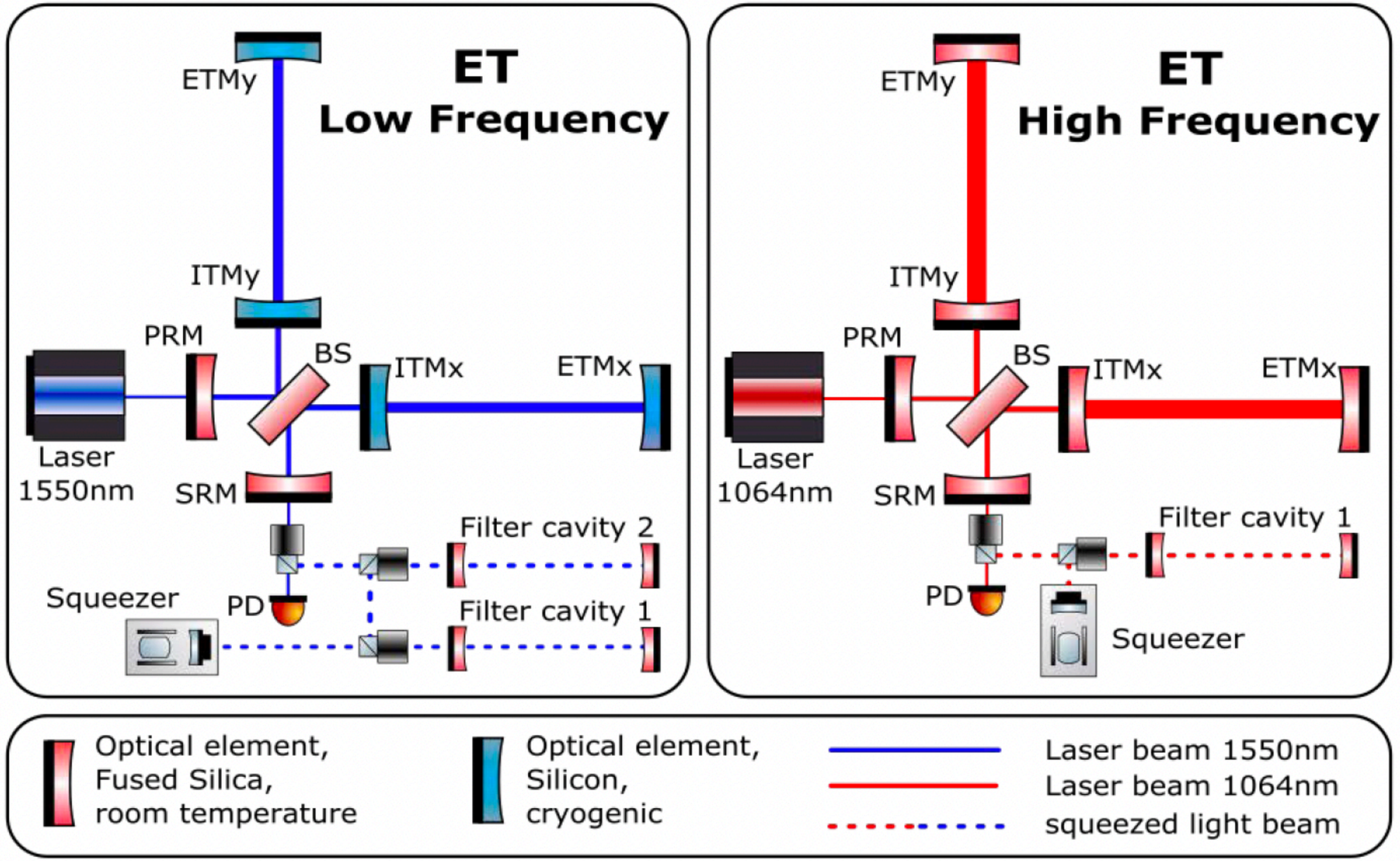
- The goal of next generation gravitational wave detectors is to achieve 10dB of squeezing
- This means that we should achieve about 8% optical losses and 11mrad phase noise
- Reduce the number of Faraday isolators, mitigate better scattered noise, improve mode matching and alignment



- Note that this plot assumed an optimal squeezing level is used, but this may not be exactly the situation in each cited point
- The cited year is from publication

Squeezing towards next generation gravitational wave detectors

- More complex frequency dependent squeezing will be required as well



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Conclusion

- Quantum noise is a main limiting noise source for gravitational wave detectors
- Frequency dependent squeezing can be used to achieve broad band quantum noise reduction
- Virgo has produced a frequency dependent squeezed vacuum source, ready for injecting into interferometer
- Future gravitational wave detectors will require to achieve about 10% and 10mrad losses and phase noise, and more complex squeezing rotation

Thank you for your attention!