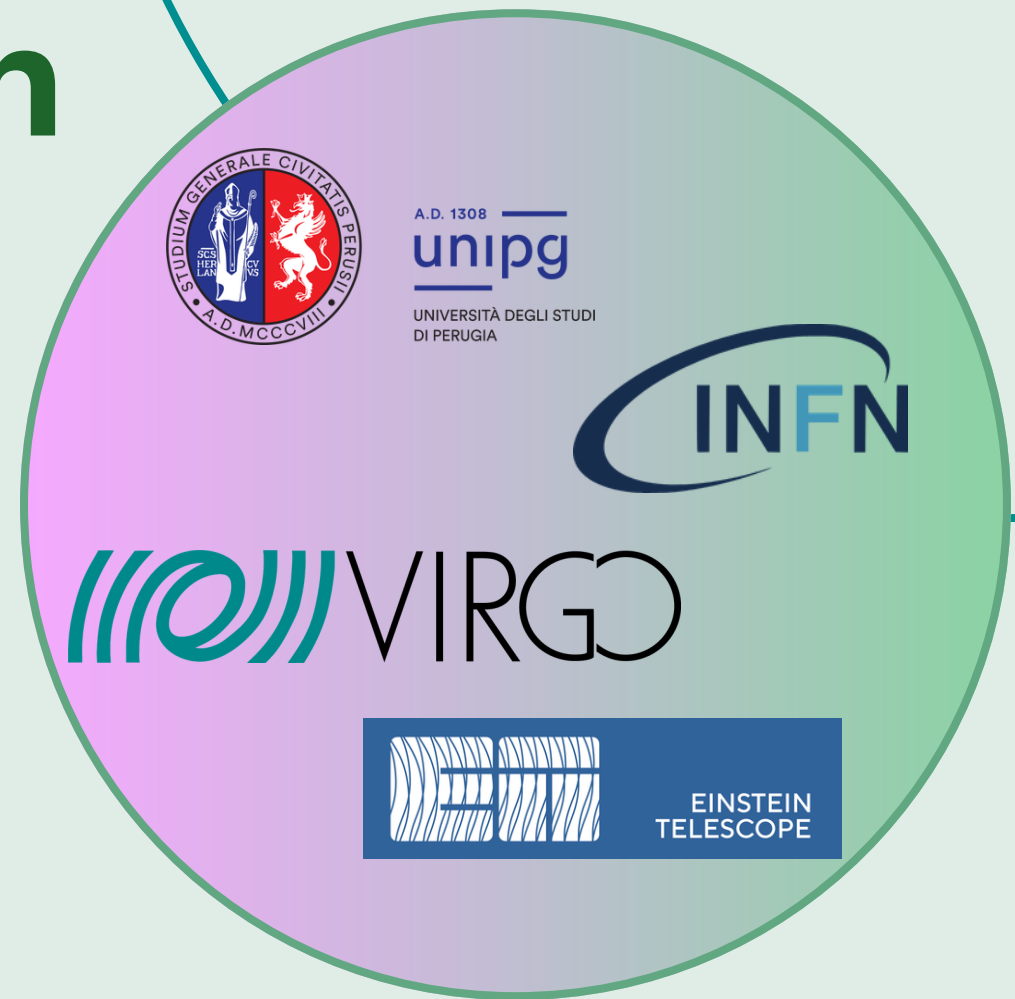


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Numerical Modeling of Quantum Noise in Gravitational Wave Detectors



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Abstract

Research Goal

Simulate quantum noise spectral density from interferometer characteristics across multiple configurations.

Configurations

Analyze no squeezing, frequency independent, frequency dependent (with filter cavity), and EPR squeezing.

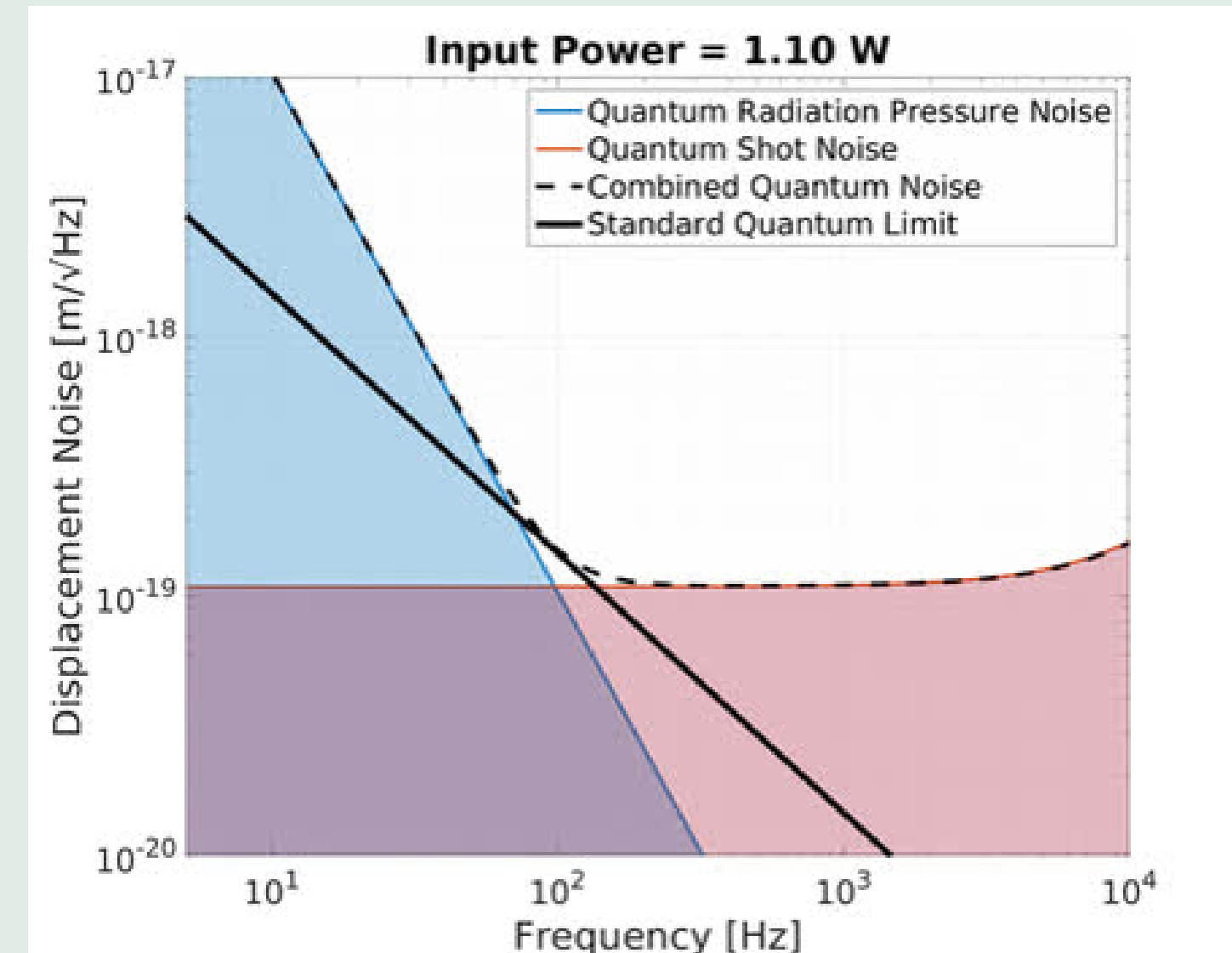
Losses Modeling

Include substrate and intra-cavity arm losses and detection to evaluate their effect on the spectrum

Why quantum noise?

Gravitational wave detectors will soon be limited by quantum noise in the biggest part of the spectrum because the standard quantum limit is intrinsic in the interferometer configuration.

There are some ways to overcome the SQL, one of them is the injection of squeezed vacuum from the dark port of the interferometer, but different configurations are possible.



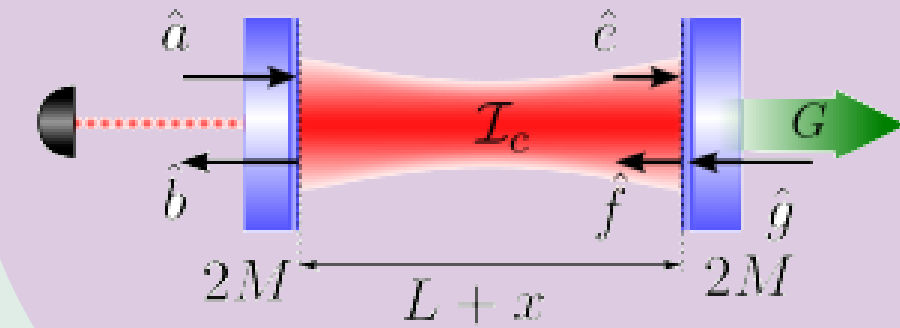
source: <https://10m.aei.mpg.de/standard-quantum-limit-sql/>

Theoretical Framework

Simulation Basis

The simulation is based mainly on the formalism developed by Danilishin and Khalili in [1]

Scaling Law



We construct the components of the full transfer matrix of the interferometer starting from the separated contribution of shot noise and radiation pressure noise

$$S^h = \frac{4}{M^2 L^2 \Omega^4} \frac{1}{|\chi_{eff}(\Omega) \chi_{OF}(\Omega)|^2} \mathbf{H}^\top[\phi_{LO}] \{ \text{MSM}^\dagger - \text{TT}^\dagger + \epsilon_d^2 \} \mathbf{H}[\phi_{LO}]$$

Spectrum of the field entering the dark port of the ITF

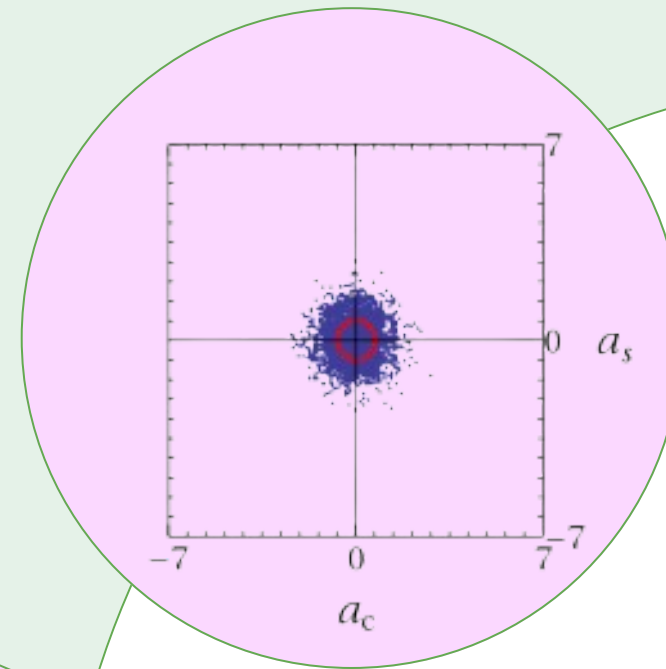
Detection losses

Spectrum of the loss field entering the end port of the ITF

Configurations

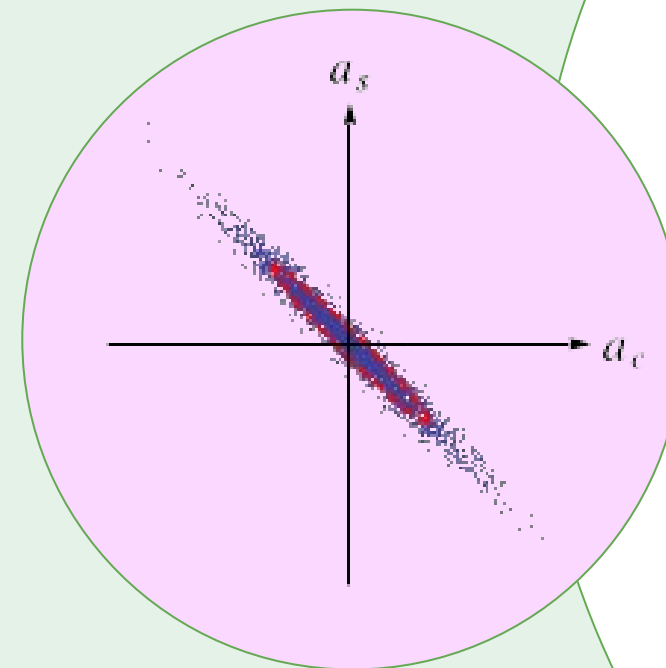
Frequency Independent Squeezing

FIS reduces quantum noise at specific frequencies but cannot simultaneously reduce shot and radiation pressure noise.

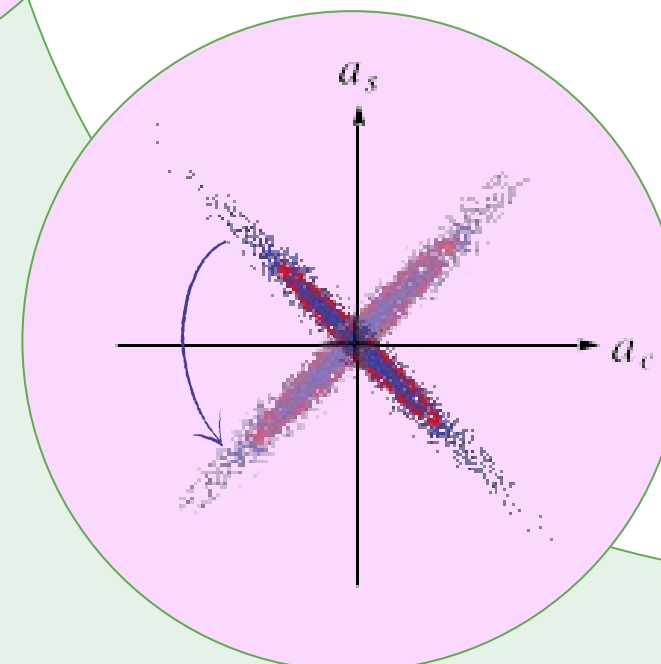


No Squeezing (Baseline)

Baseline configuration with no squeezing injection provides reference measurements for comparing sensitivity improvements.



Squeezing Configurations



FDS with Filter Cavity & EPR

FDS with filter cavity enables frequency-dependent rotation of squeezing angle for broadband sensitivity improvement.

Advanced Virgo+ O4

Parameters based on Advanced Virgo+ O4 low target configuration for realistic detector modeling.

Versatility

The simulator allows to simulate the spectrum of different interferometers by passing the parameter values in a json file

Losses

Implementation

Substrate, detection and intra-cavity losses in the arms incorporated to accurately model sensitivity degradation.

Key Parameters

- R2) End test mass reflectivity
- A1) Input test mass absorption coefficient
- A_rt) Round-trip losses in the arms
- A_p) Power recycling mirror absorption coefficient
- detEff) Homodyne detection efficiency



Simulation Parameters

Impact of Optical Losses

Reduced Circulating Power

Optical losses reduce circulating power in the interferometer arms, directly impacting detector sensitivity.

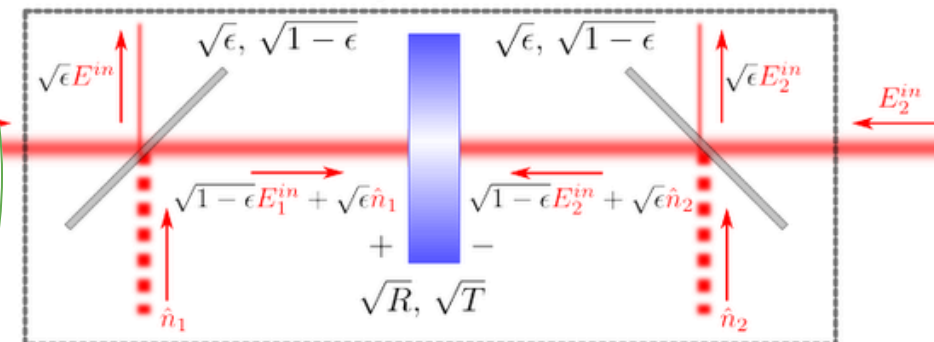
$$r_{eff} = \sqrt{r^2 - a_{rt}^2}$$

$$P_{circ} = \frac{1}{2} P_0 \frac{t_P^2 t^2}{(1 + r_p r_{eff} - (r_{eff} + r_p r_2))^2}$$

$$t = \sqrt{1 - r^2 - a^2}$$

Vacuum Field Degradation

Vacuum fields enter the interferometer through loss channels, degrading squeezing performance and adding noise.



EPR Squeezing

Beams Propagation

The signal beam has frequency ω_0 and is resonant in the arm.
The idler is detuned from the signal, having a frequency of $\omega_0 + \Delta$

Key feature

The separation of contributions of shot and radiation pressure noises allows to easily set to 0 the radiation pressure for the idler

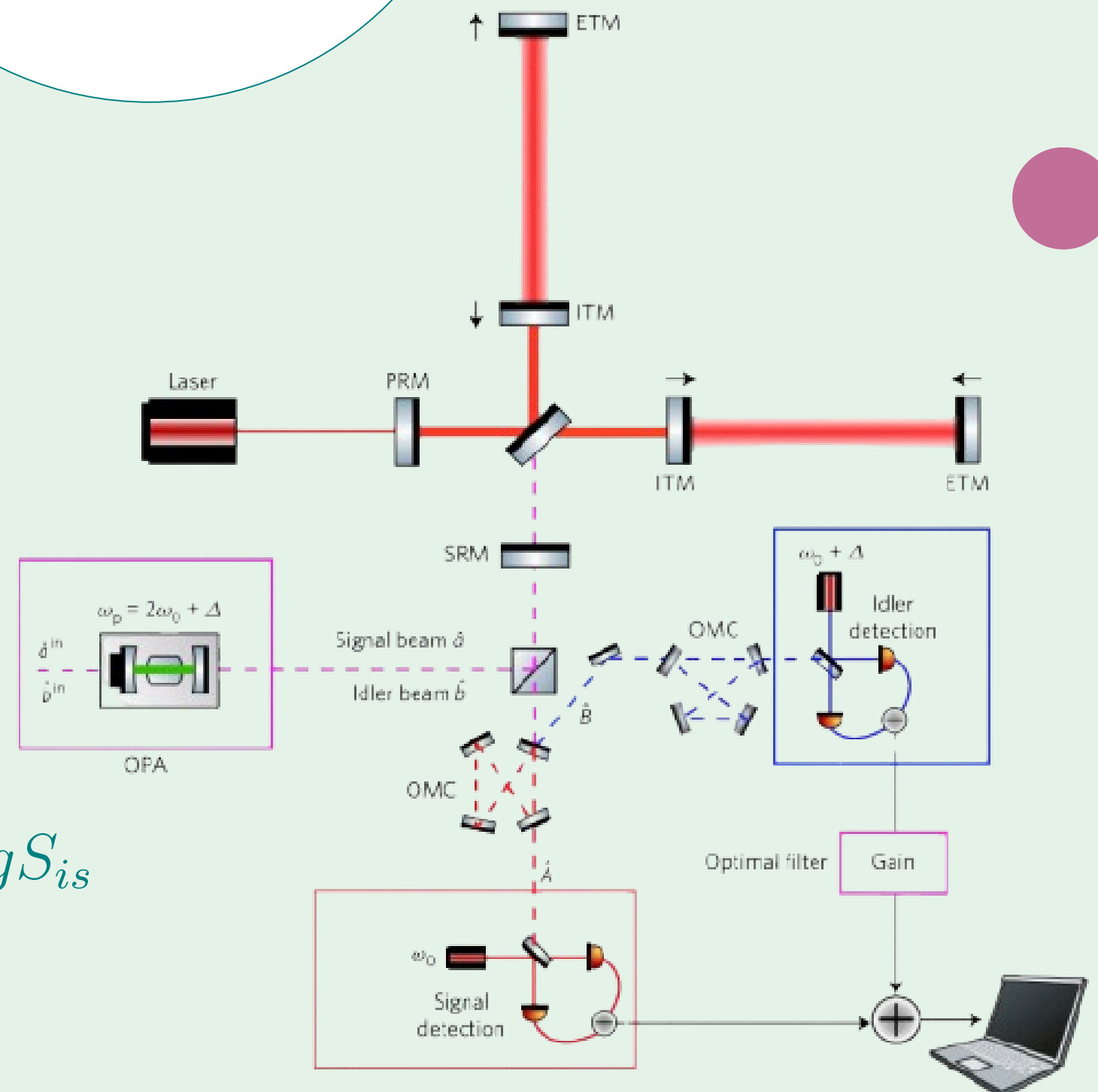
Quadrature Correlation

The idler sees the arm as a detuned Fabry-Perot cavity, experiencing squeezing angle rotation
Correlated quadratures between signal and idler beams enable frequency dependent squeezing angle rotation without a filter cavity.

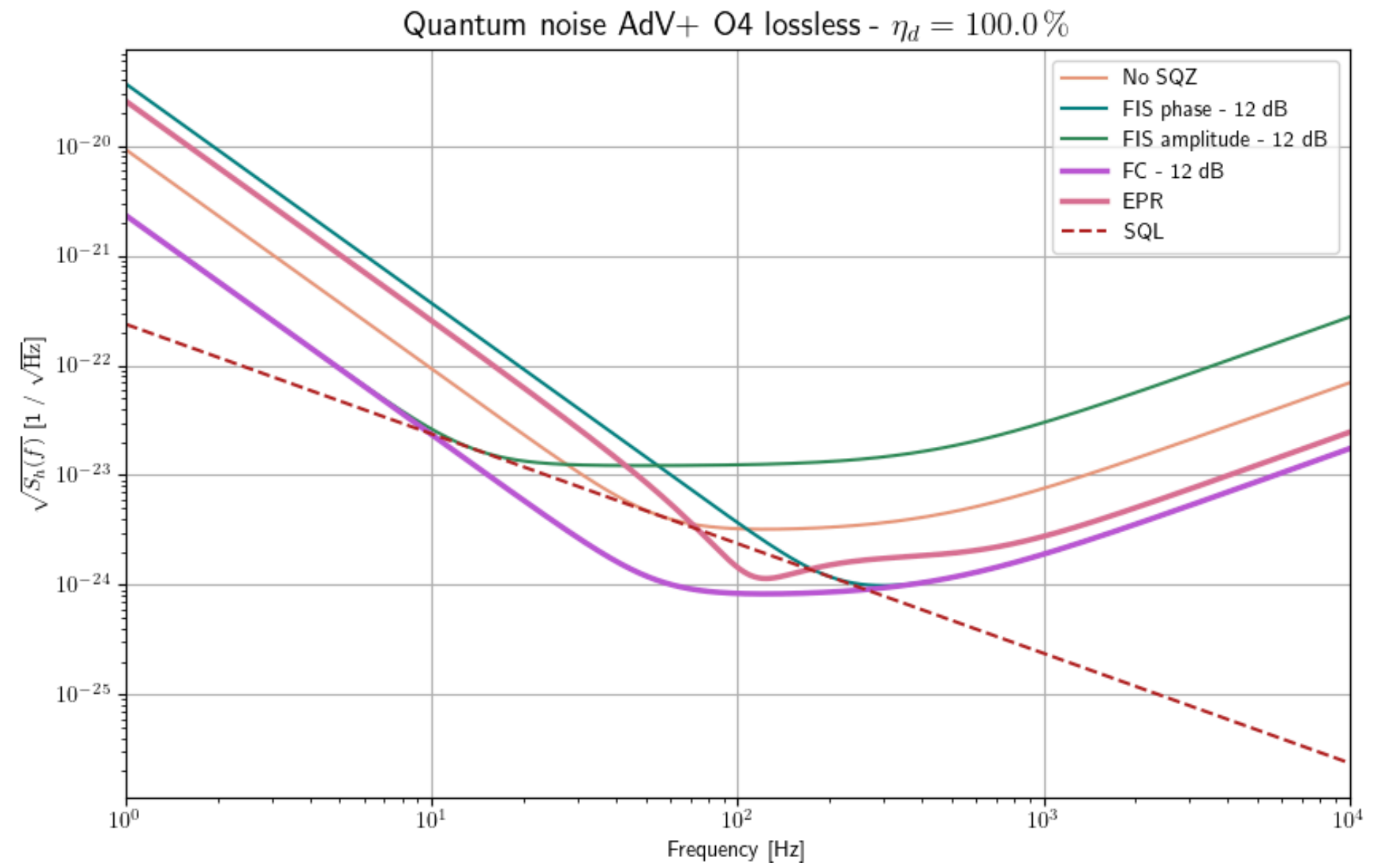
Conditioned Measurement

Conditioned measurement combines signal and idler outputs with optimal gain factor g to achieve broadband noise reduction.

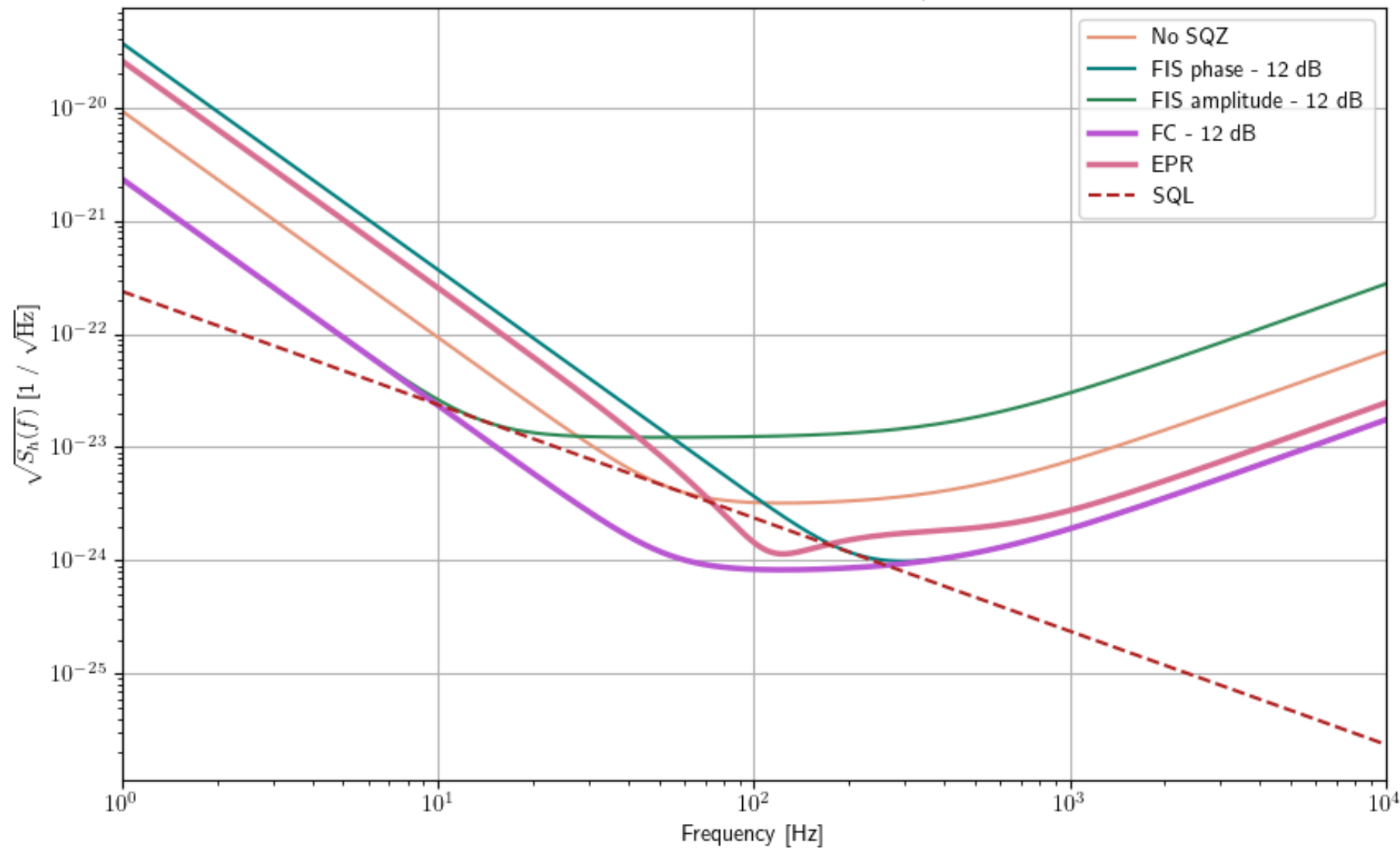
$$S = S_{sig} + |g|^2 S_{idl} - g^* S_{si} - g S_{is}$$



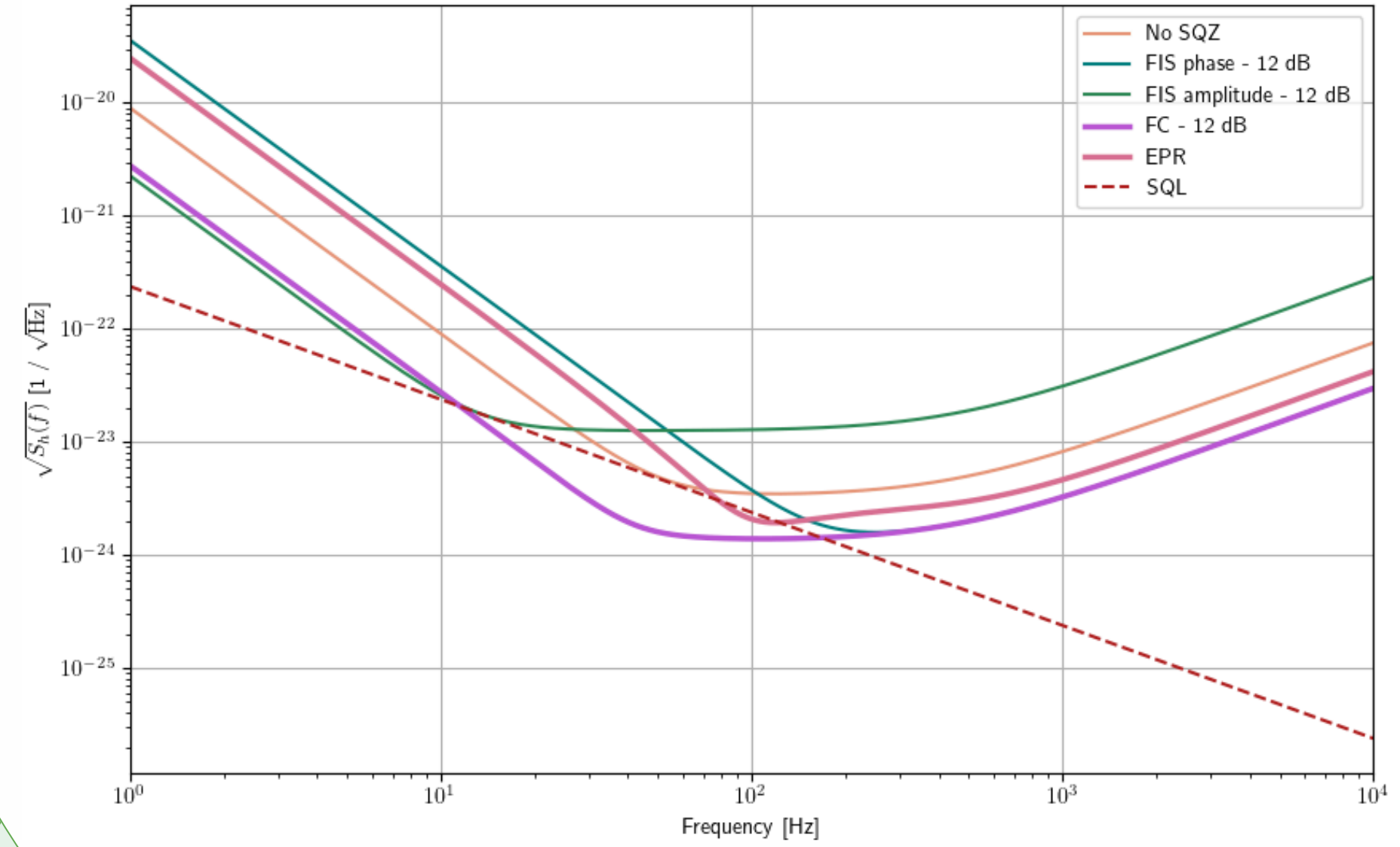
Results



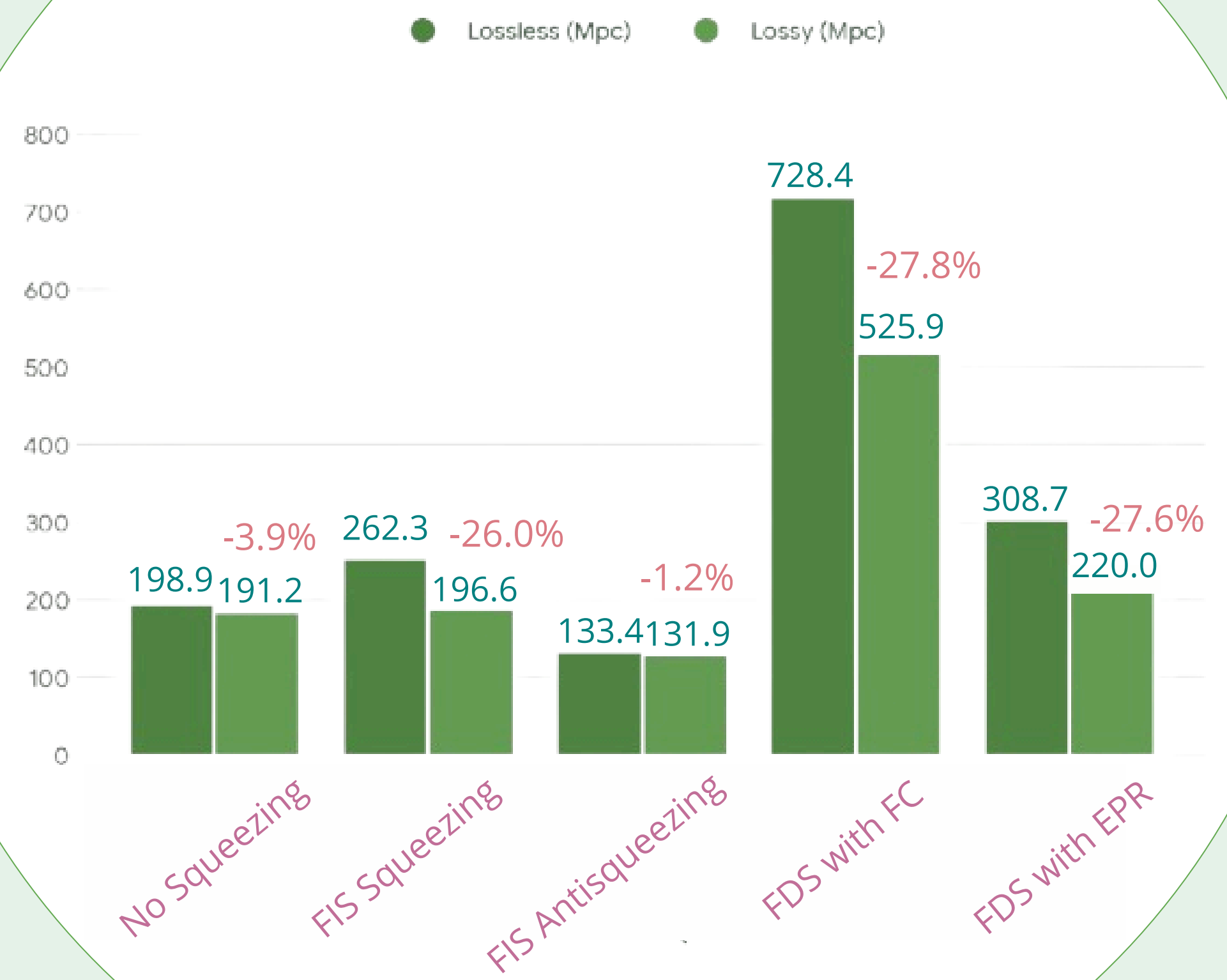
Quantum noise AdV+ O4 lossless - $\eta_d = 100.0\%$



Quantum noise AdV+ o4 low - $\eta_d = 90.0\%$



BNS Range



Future Developments

EPR Optimization

Optimize idler beam parameters for EPR squeezing to maximize quantum noise reduction benefits.

SRC Loss Implementation

Implement comprehensive losses in the signal recycling cavity for more accurate sensitivity modeling.

Thank You

References & Contact



Danilishin & Khalili (2012), Arxiv



Ma et al. (2017), Nature Physics



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