Einstein-Podolsky-Rosen conditional squeezing for next generation Gravitational-Wave detectors

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16th Pisa Meeting on Advanced Detectors - La Biodola (Elba Island – Italy), May 26th – June 1st, 2024

Abstract

The LIGO, Virgo, and KAGRA Gravitational-Wave (GW) advanced detectors are severely limited by Quantum Noise in most of their detection bandwidth (10 Hz –10 kHz). The state-of-the-art method to obtain broadband Quantum Noise reduction is represented by frequency-dependent squeezed (FDS) states of light, which are passed through a 300m-long detuned filter cavity, coupled to the interferometer [Kwee+ 2014].

Our table-top prototype will probe a cheaper, more compact and more flexible strategy for broadband Quantum Noise reduction, based on two-mode Einstein-Podolsky-Rosen (EPR) entangled squeezed light [Ma+ 2017]. This novel scheme works without the presence of any filter cavity in the detector. The EPR-entangled beams will propagate in a small-scale suspended interferometer with high-finesse arm-cavities. This experiment aims at being the first to validate the EPR conditional squeezing at audio frequencies, suited for GW detection [Bawaj+ 2020], implementing also innovative optical techniques (see e.g. poster n. 95 by S.Lee). Before the experimental proof, simulations are required to support the validity of the chosen setup and to realistically evaluate the sensitivity improvement brought by the EPR scheme in GW detectors. In this regard, feasibility studies are ongoing also for Einstein Telescope, the European next generation detector [Peng+ 2024].

Comparison of the effect of EPR conditional squeezing scheme with state-of-the-art techniques

Quantum Noise dominates the high frequency band ($f \gtrsim 200$ Hz) of GW detectors sensitivity, and it will be soon limiting also below the arm linewidth frequency $\gamma \approx 2\,\pi \cdot 50$ Hz. Its power spectrum is reported below [Kimble+ 2001]

Radiation Pressure Noise

Backaction effect due to the optomechanical coupling between radiation pressure quantum fluctuations and mirrors' motion, given by

$$\mathrm{K}(\Omega) \propto \boldsymbol{P_{in}} \frac{\gamma^4}{\Omega^2(\Omega^2+\gamma^2)}$$

It dominates below the SQL frequency.

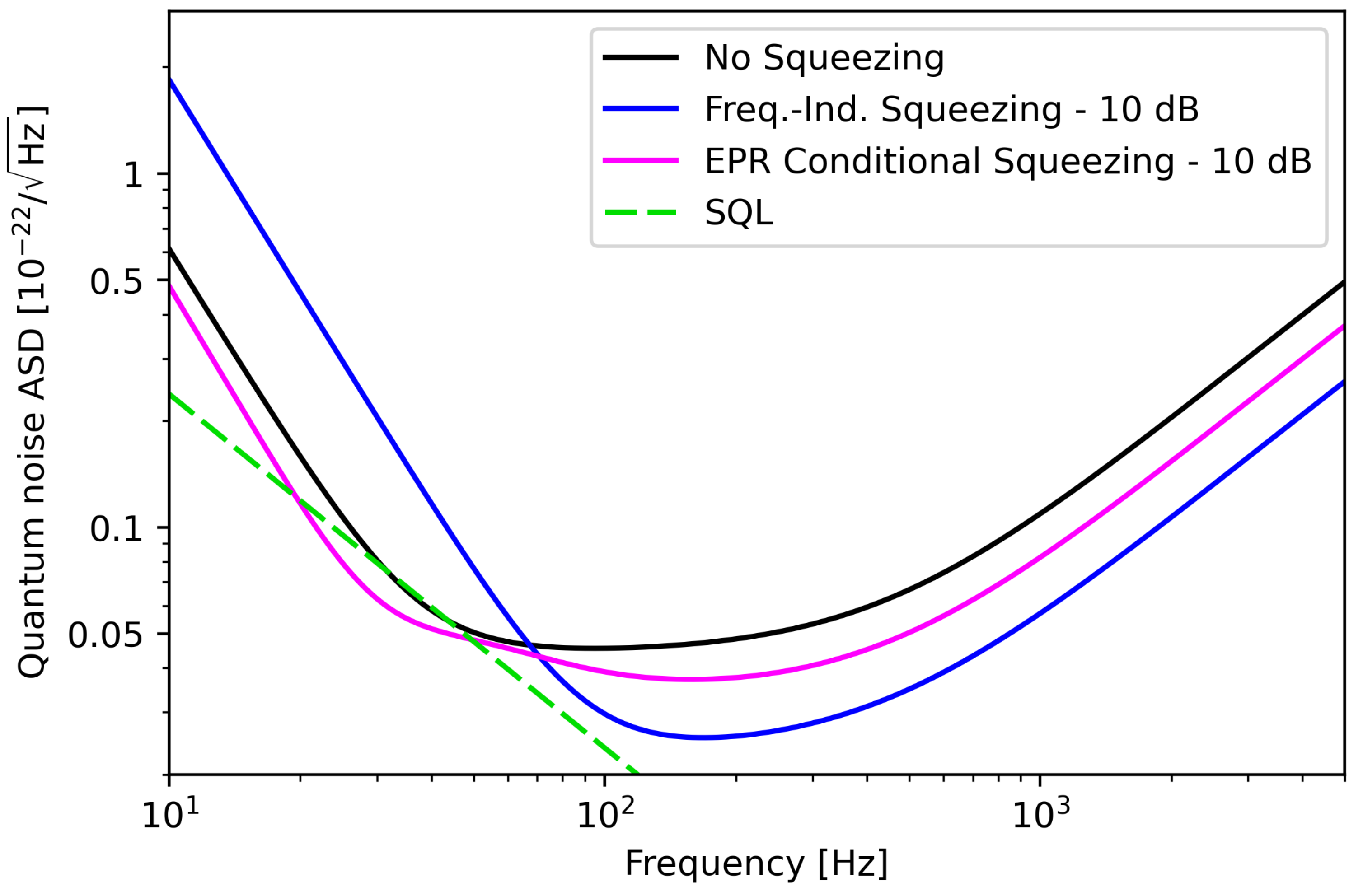
Standard Quantum Limit

It holds for conventional measurement schemes

Shot Noise

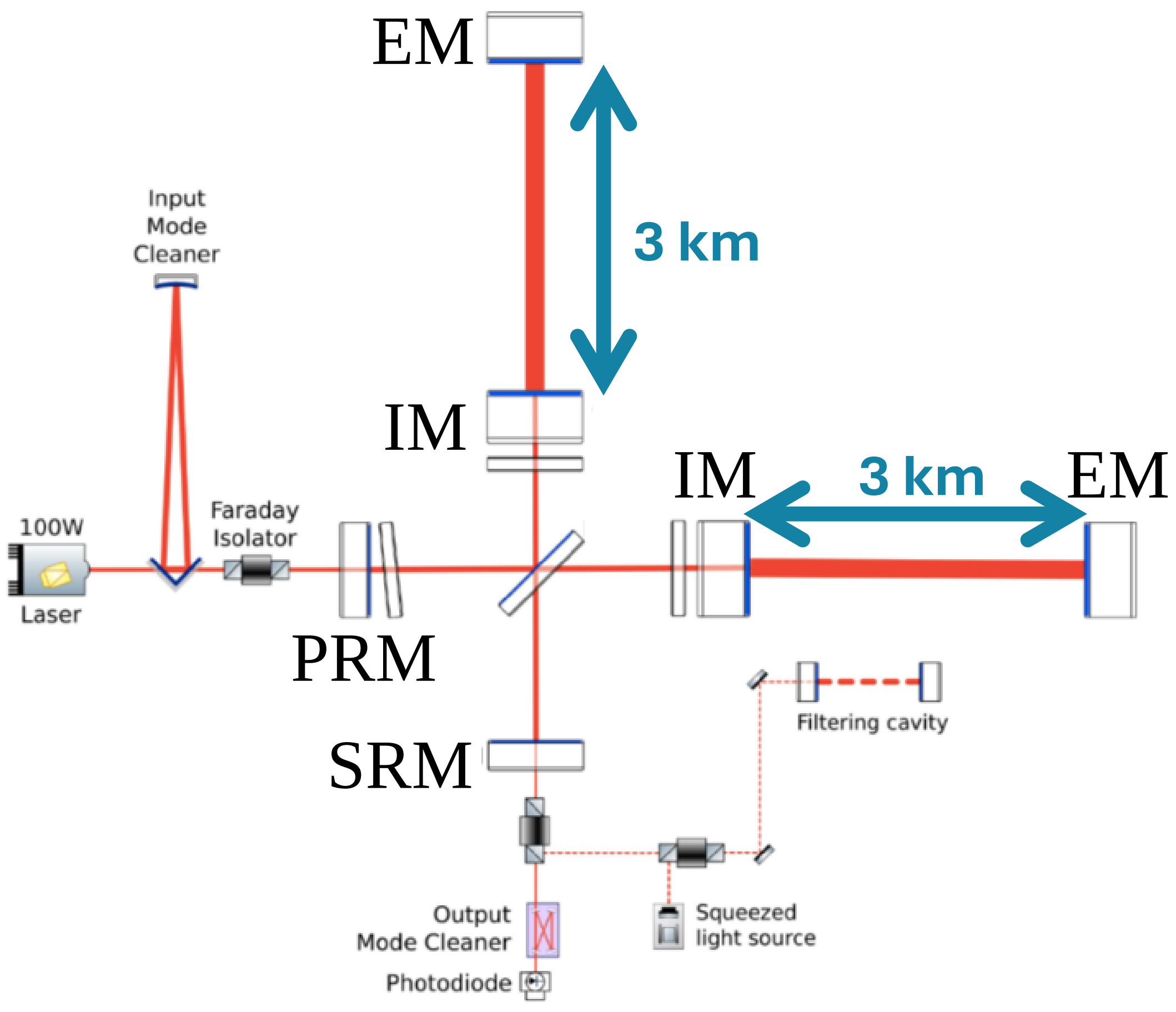
Readout effect, caused by photons' number fluctuations on the detection photodiode. It improves with higher circulating optical power, and it dominates above the SQL frequency.

$$S_{QN}(\Omega) = \frac{1}{2}\boldsymbol{h^2_{SQL}(\Omega)}\left(\mathrm{K}(\Omega) + \frac{\mathbf{1}}{\mathrm{K}(\Omega)}\right)\boldsymbol{e^{-2r}}$$



Advanced Virgo layout

Credits: Virgo Collaboration



Frequency-dependent squeezing suppression

Squeezed states of light have reduced uncertainty along one quadrature of the electromagnetic field. The uncertainties along the **amplitude** and **phase** quadratures are related to the radiation pressure and shot noise. Hence, they can be both reduced in the frequency regimes where they dominate, provided an optimal frequency-dependent squeezing angle: $\theta = -\,\mathrm{arccot}(\mathrm{K}(\boldsymbol{\Omega}))$

Phase squeezing *Amplitude squeezing*

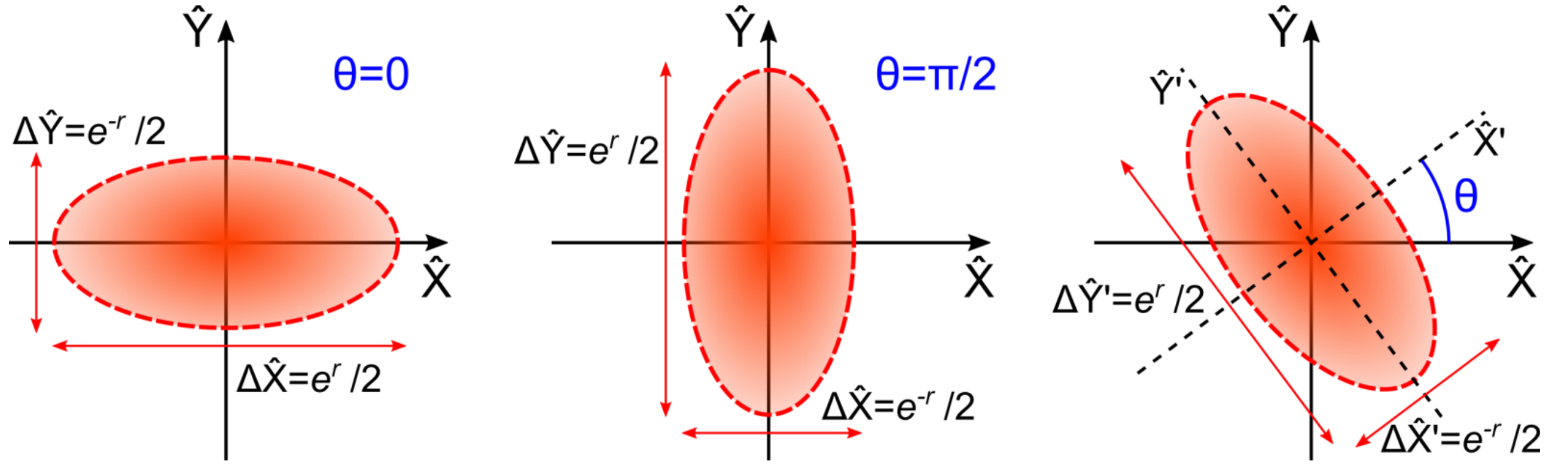
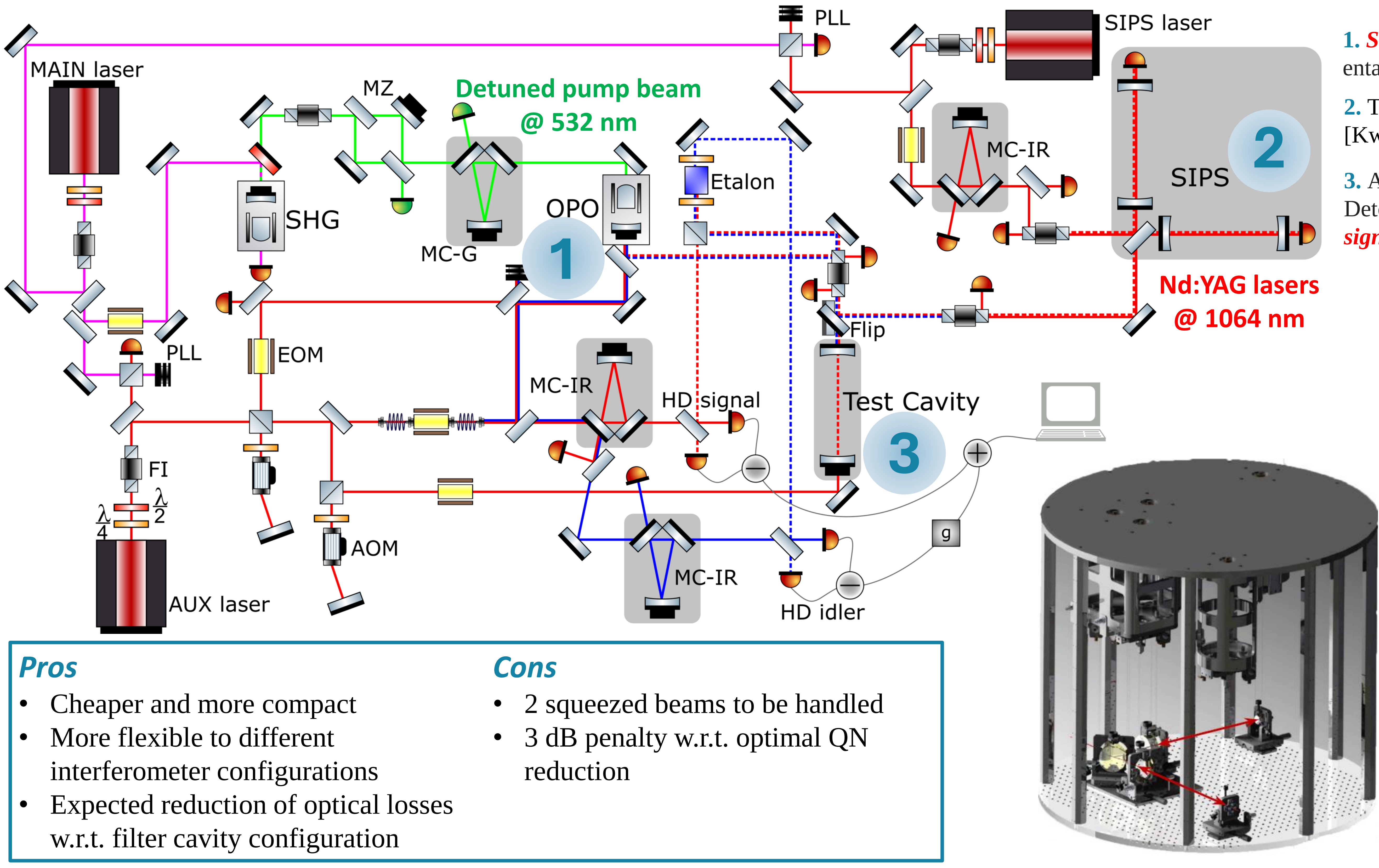
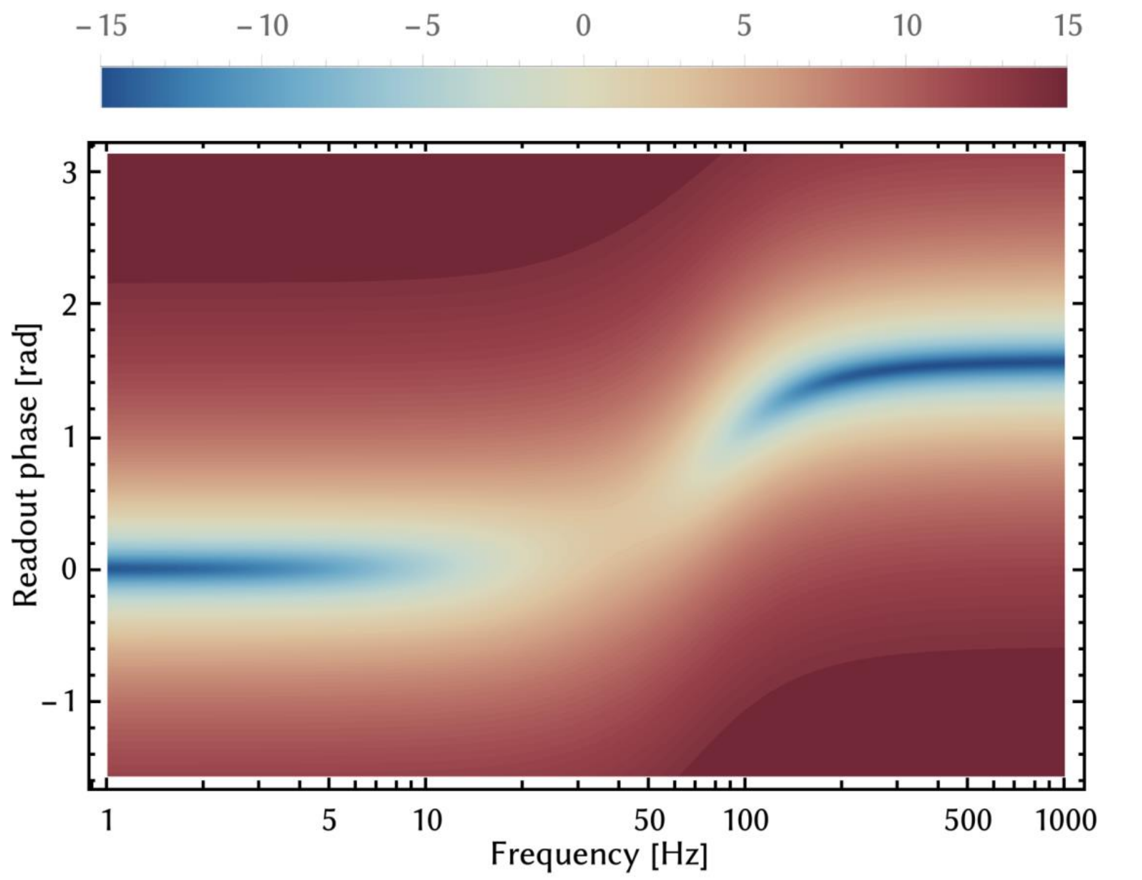


Table-top experimental setup



1. ***Signal*** and ***idler*** are vacuum squeezed and EPR-entangled beams, born with a mutual frequency shift
2. The ***idler*** sees the interferometer as a detuned filter cavity [Kwee+ 2014] and acquires frequency-dependence
3. A combined squeezing level measurement via Homodyne Detectors (HD) transfers the frequency dependance to the ***signal*** via EPR entanglement [Ma+ 2017]



Credits: [Korobko 2020]

SIPS (Suspended Interferometer for Ponderomotive Squeezing) is the small-scale test bench for EPR effect. It is radiation-pressure-limited in the GW detection band, having a very high arm-cavity finesse, suspended optics, monolithic suspensions and operating in vacuum [Di Pace+ 2020, Giacoppo 2023].

Pros	*Cons*
Cheaper and more compact More flexible to different interferometer configurations Expected reduction of optical losses w.r.t. filter cavity configuration	2 squeezed beams to be handled 3 dB penalty w.r.t. optimal QN reduction

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Acknowledgements

The authors wish to acknowledge the Istituto Nazionale di Fisica Nucleare (INFN), the European Gravitational Observatory (EGO) consortium, and Sapienza University, for funding and hosting the EPR and SIPS experiments. Moreover, the authors gratefully thank M. Perciballi, who performed the mechanical design of SIPS and of parts of the EPR experiment.