Quantum noise reduction in GW Detectors

Jean-Pierre Zendri
INFN Sezione di Padova
Virgo & ET collaboration

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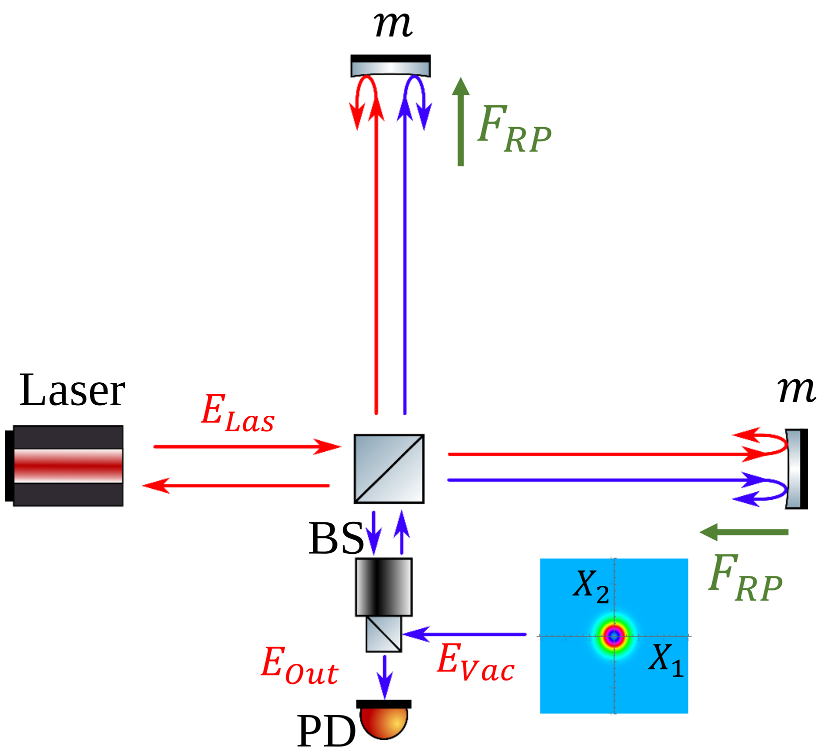
Quantum noise in Michelson Interferometers

- Quantum noise results from quantum vacuum fluctuations entering the detection port

$$\hat{E}_{Vac} = [\hat{X}_{Vac1}]Cos(\omega_0 t) + [\hat{X}_{Vac2}]Sin(\omega_0 t)$$

$$\langle X_{Vac1}\rangle = \langle X_{Vac2}\rangle = \langle X_{Vac1}X_{Vac2}\rangle = 0 \ , \qquad \Delta X_{Vac1}\Delta X_{Vac2} \geq 1$$



- Quantum noise manifests in two contributions

$$\hat{E}_{Out} = [\hat{X}_{Out\_1}]Cos(\omega_0 t) +$$

$$[A(\Omega)h(\Omega) + Exp[2i\Omega\tau](\hat{X}_{Vac2}(\Omega)) - \kappa[\Omega]\,\hat{X}_{Vac1}(\Omega))]Sin(\omega_0 t)$$

Signal — **Shot noise** — **Back action noise**

- The optomechanical coupling parameter $\kappa[\Omega]$ is configuration and frequency dependent. For Michelson interferometers $\kappa \propto (P_{laser} \times 1/(m\Omega^2))$

- Quantum limited strain sensitivity

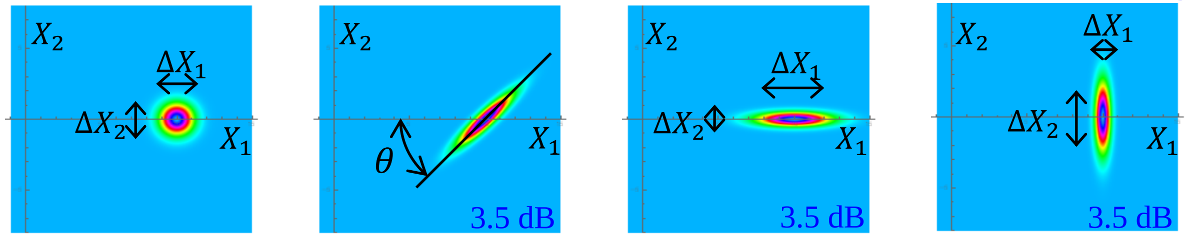
BA ↓ Shot ↓

$$S_{hh}[\Omega] = \frac{2\hbar}{m\Omega^4 L^2|\kappa[\Omega]|}\{\kappa[\Omega] + 1/\kappa[\Omega]\}=$$

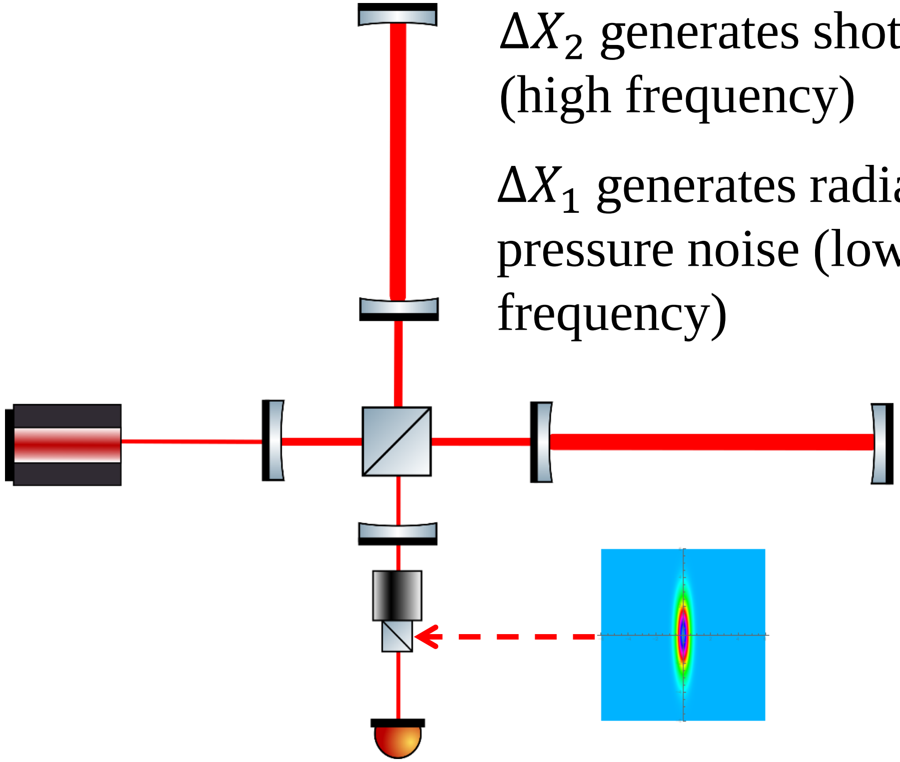
minimum at $\kappa[\Omega] = 1$ **Standard quantum limit**

Michelson interferometer QN manipulation with squeezing

Coherent State | **Squeezed State** | **Phase Squeezing** | **Ampl. Squeezing**



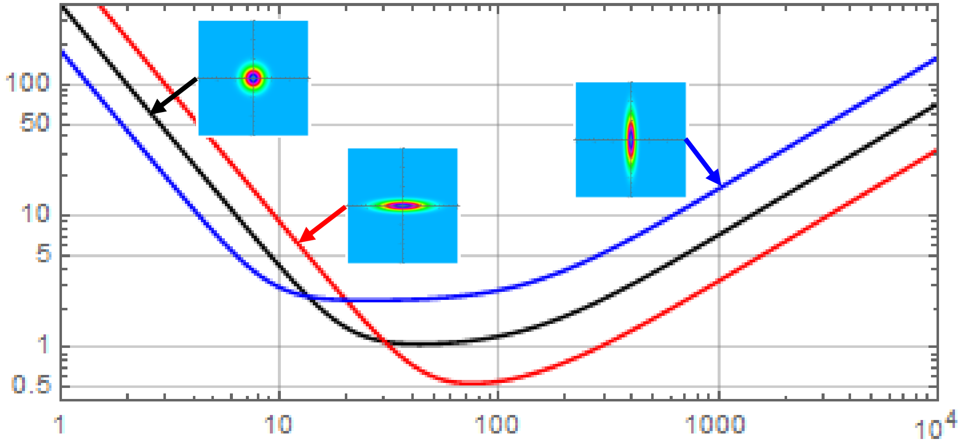
- Squeezed states: $\Delta X_1 \Delta X_2 = 1$
  - r squeezing factor $\Delta X_{SQZ}/\Delta X_{Cohe} = e^{-r}$
  - θ Squeezing angle



ΔX_2 generates shot noise (high frequency)

ΔX_1 generates radiation pressure noise (low frequency)

- Quantum noise can be manipulated with squeezed light
  - $\kappa \Longrightarrow \kappa e^{\mp r}$
  - The Standard Quantum Limit cannot be surpassed for $\theta = 0, \pi/2$



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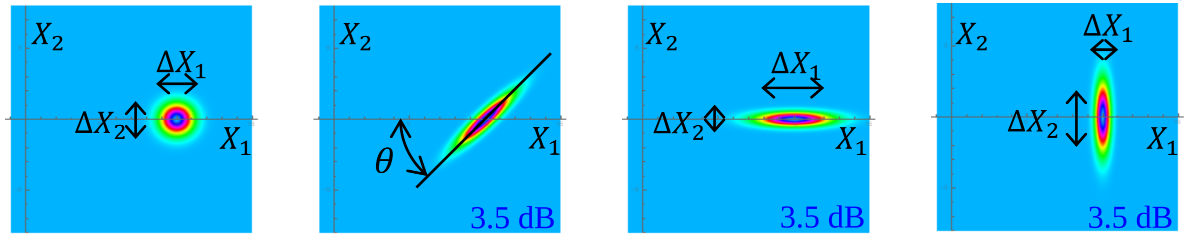

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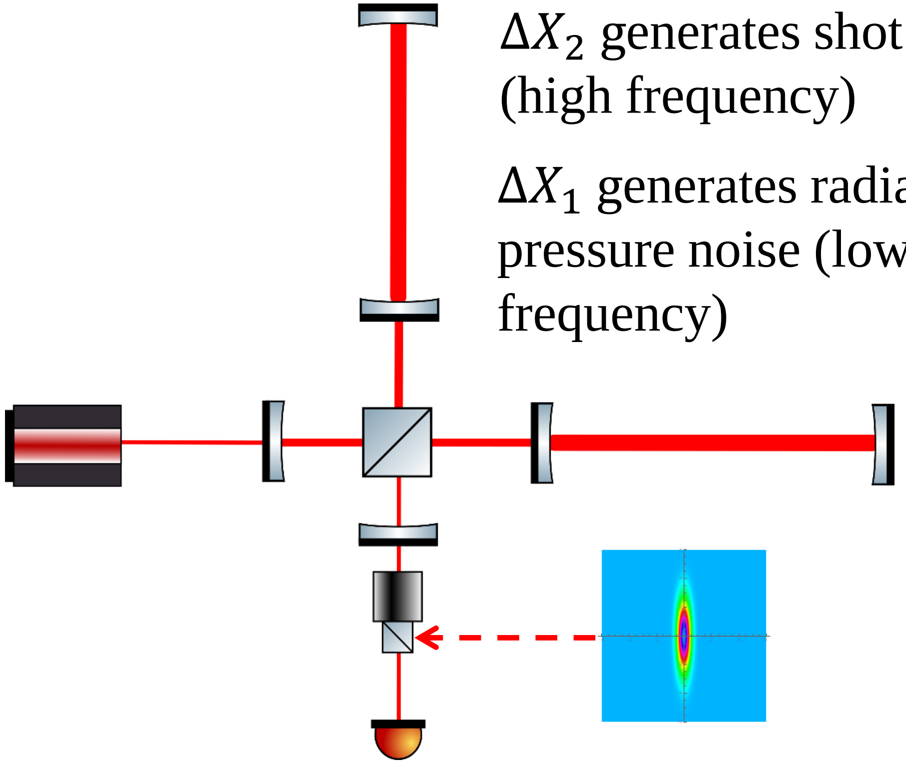
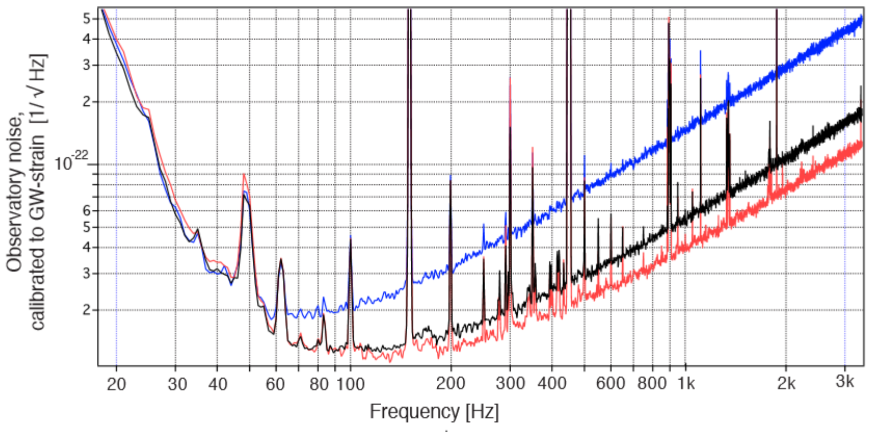
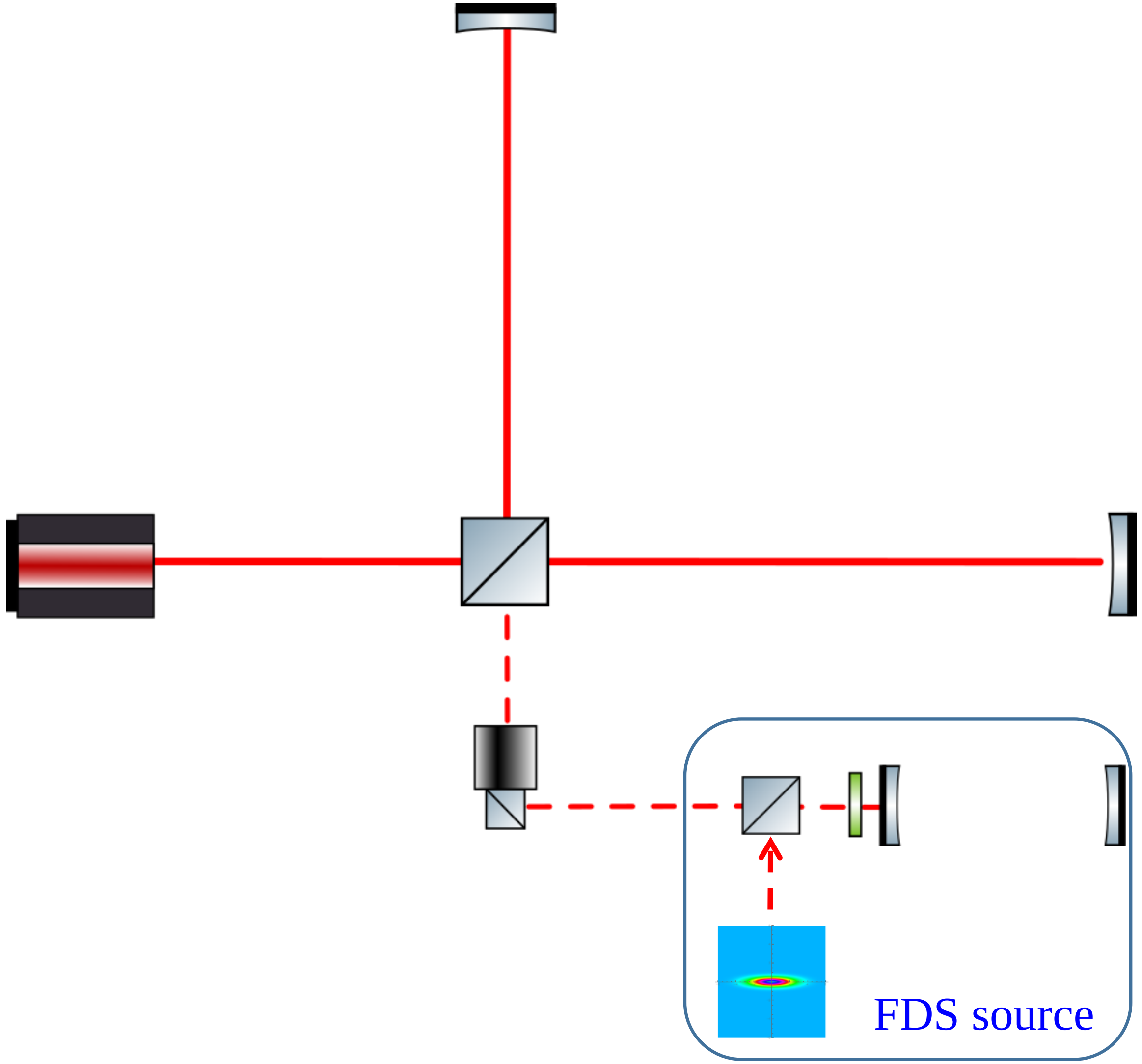


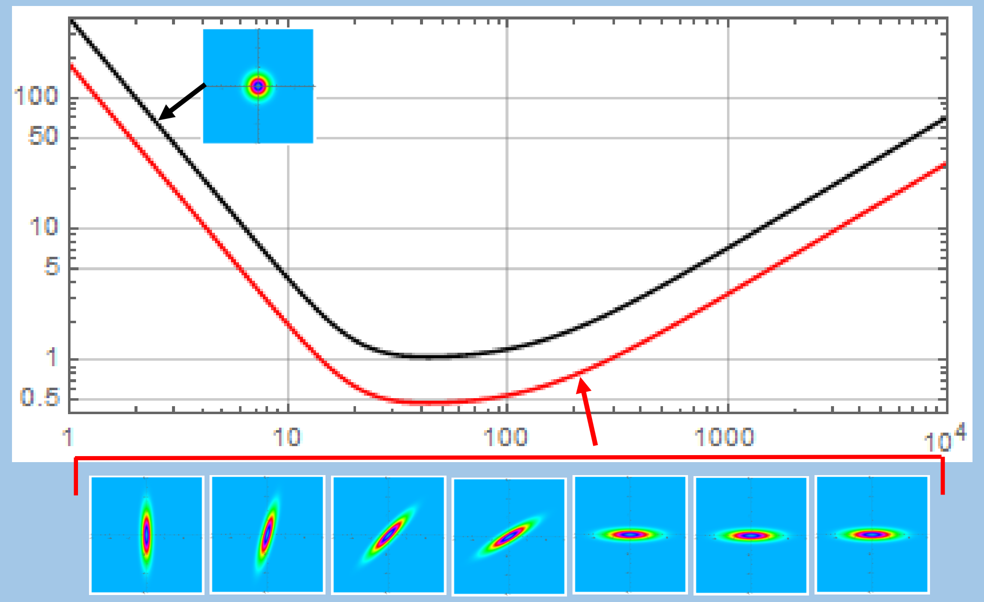


Phys. Rev. Lett. 123, 231108 (2019)

Frequency dependent squeezing (FDS)



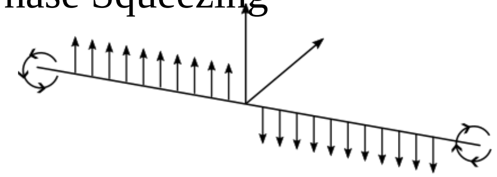
- The injected squeezing ellipse angle is rotate as a function of the frequency to compensate from the rotation resulting from the optomechanical coupling with the interferometer.



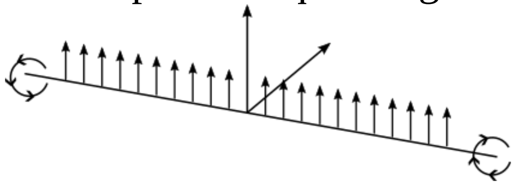
- The minimum of the output noise is always aligned with the signal quadrature.
Quantum noise is suppressed by a factor e^{-r} over the all the whole detection band.

Frequency dependent squeezing

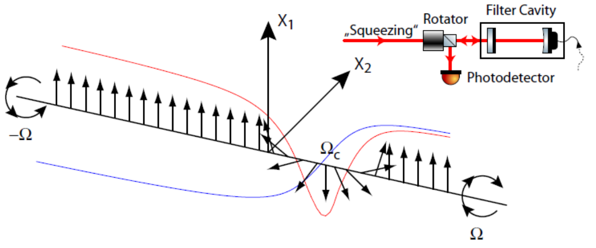
Phase Squeezing



Amplitude Squeezing



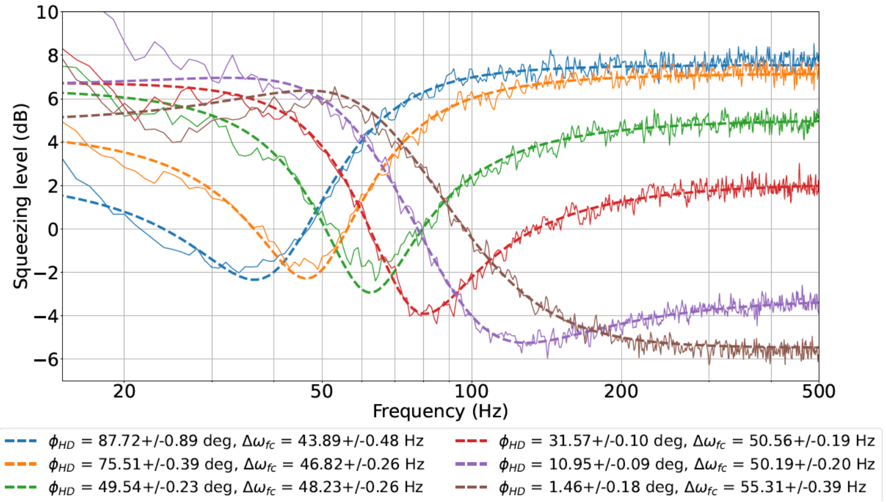
Frequency dependent squeezing



- Frequency dependent squeezing is generated by exploiting the dispersion in the reflection of a frequency independent squeezing source from detuned optical cavities.

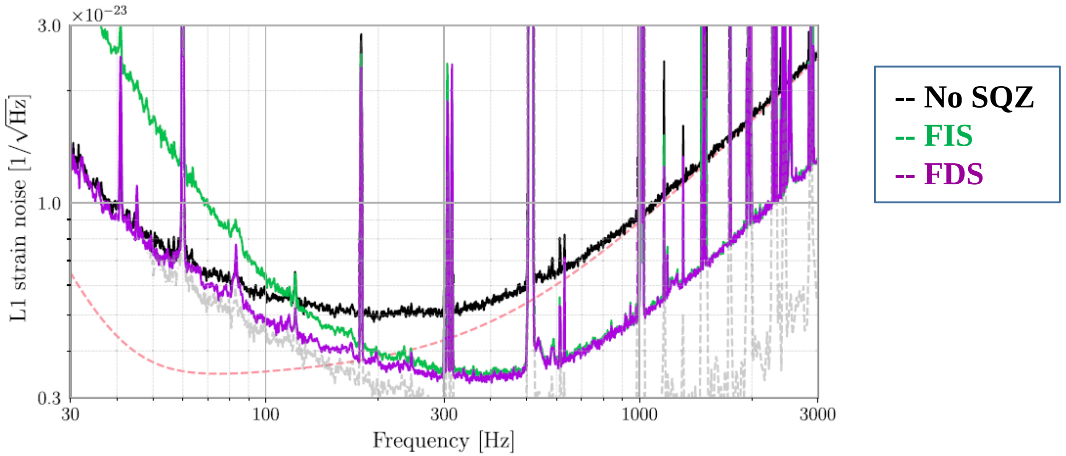
- For the configurations explored so far by Virgo and LIGO a single cavity of optimum length of about 300 metres is enough.

The Virgo FDS source



Phys. Rev. Lett. 131, 041403 (2023)

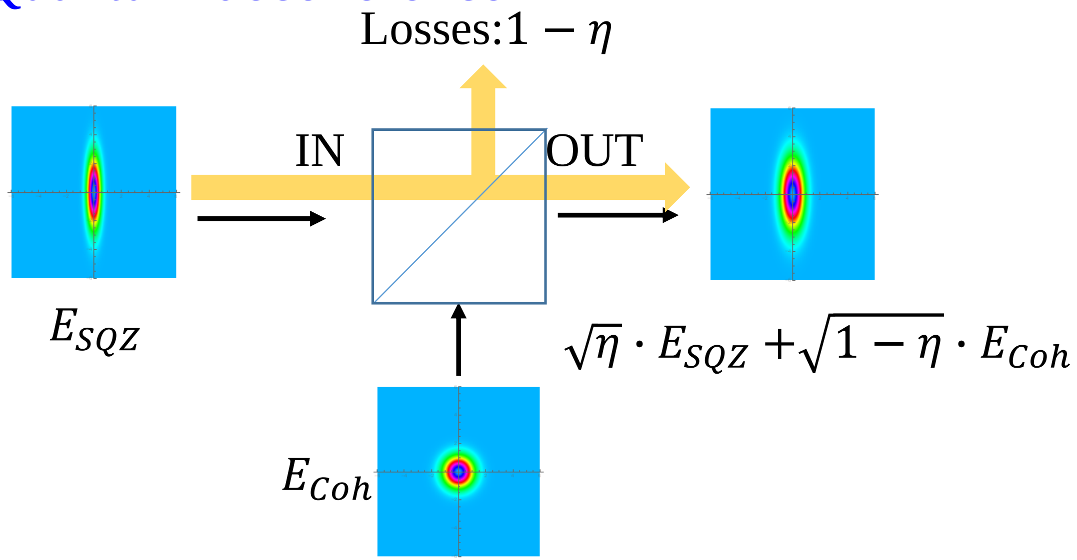
LIGO (Livigston) sensitivity with FDS



Phys. Rev. X 13, 041021 (2023)

Squeezing degradation

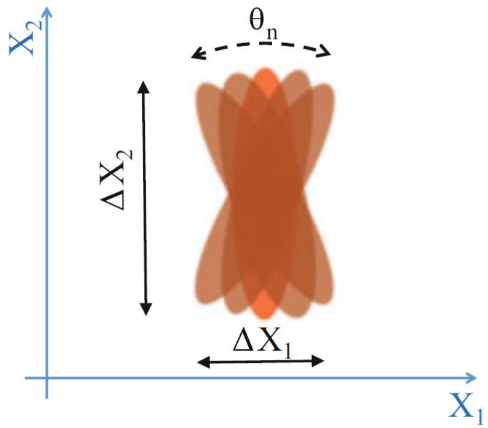
- Quantum decoherence



Loss mechanism (frequency dependent)

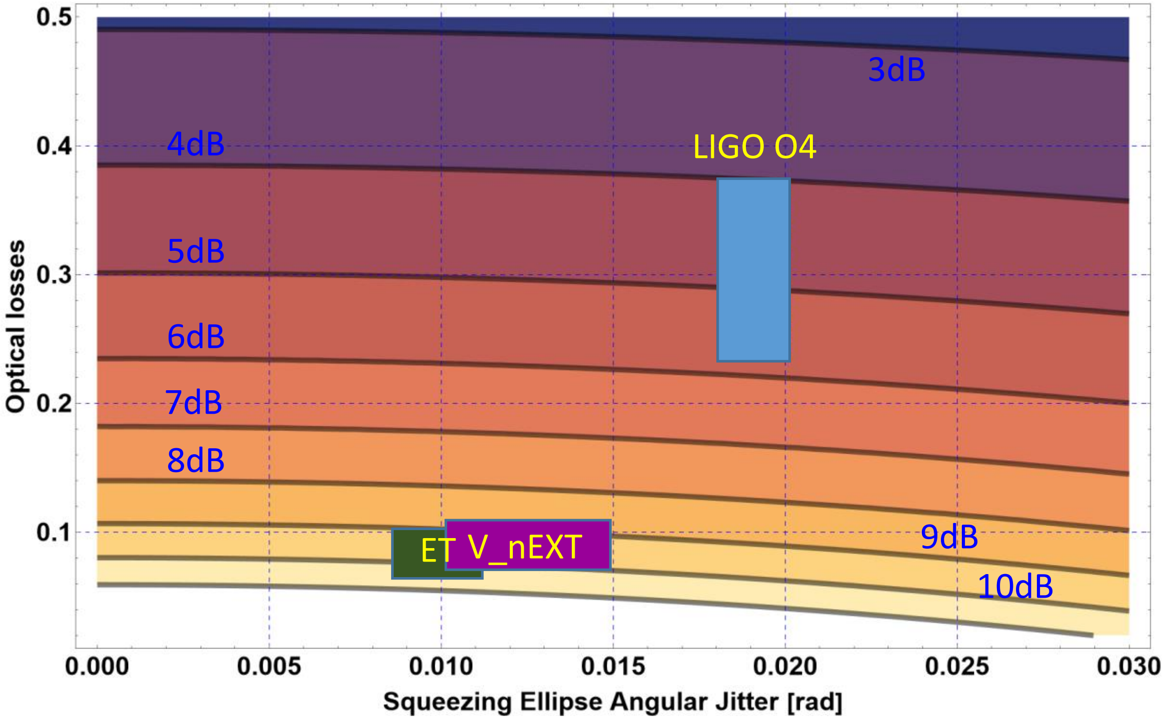
- Absorption, clipping and scattering
- Misalignment and geometrical mode mismatch
- Polarization mismatch
- Photodetector quantum efficiency

- Dephasing



- Generated by a phase jitter between the LO (ITF carrier) and the squeezed field which manifests with a squeezing angular jitter.

Squeezing degradation: past, present & future



Einstein Telescope

- Target >10 dB at high frequency

Virgo O3

- Losses (41±2)% angular jitter about 40 mrad rms

Virgo O4

- The mirrors scattered light couple to the high order modes resulting in a loss in the fundamental mode. Particularly efficient mechanism with marginally stable cavities. SR Losses about 20%, total 55%
- SR cavity misalignment causes significant optical losses. Total losses >90%

Virgo O5

- The use of stable recycling cavities should bring optical losses to the levels expected for O4 (i.e. 5-6 dB of Squeezing)

Virgo_nEXT (post O5)

- Overall improvement of optical efficiency
- Using adaptive optics to improve mode matching (partially also in O5)
- Balanced homodyne detection
- Goal (VIR-0497D-22). Initial 7.5 dB (generated 12dB), Final 10 dB (generated 16 dB)

Alternative methods to beat the SQL: detuned SR

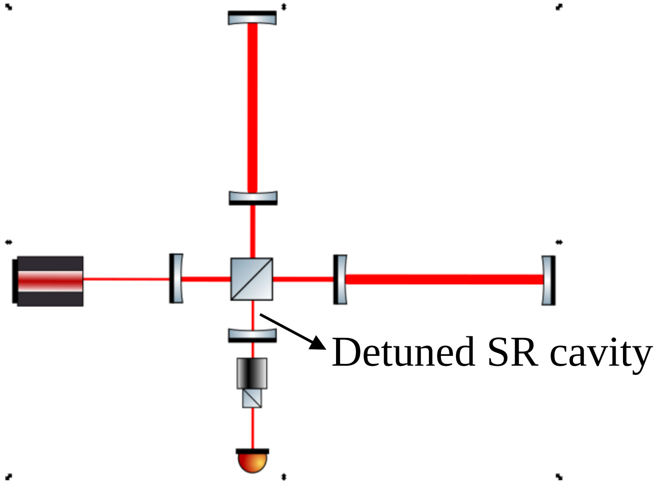
1. The SQL can be overcome by modifying the dynamics of the tests mass ($\kappa[\Omega]$ enhancement)

$$S_{hh}[\Omega] = \frac{2\hbar}{m\Omega^4 L^2 |\kappa[\Omega]|}\{\kappa[\Omega] + 1/\kappa[\Omega]\}=$$

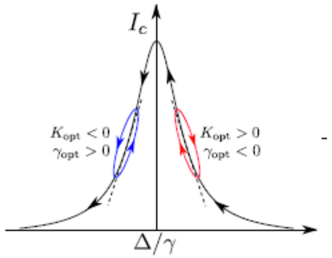
2.Creating correlations between the shot noise (*Shot*) and the back-action noise (*BA*)

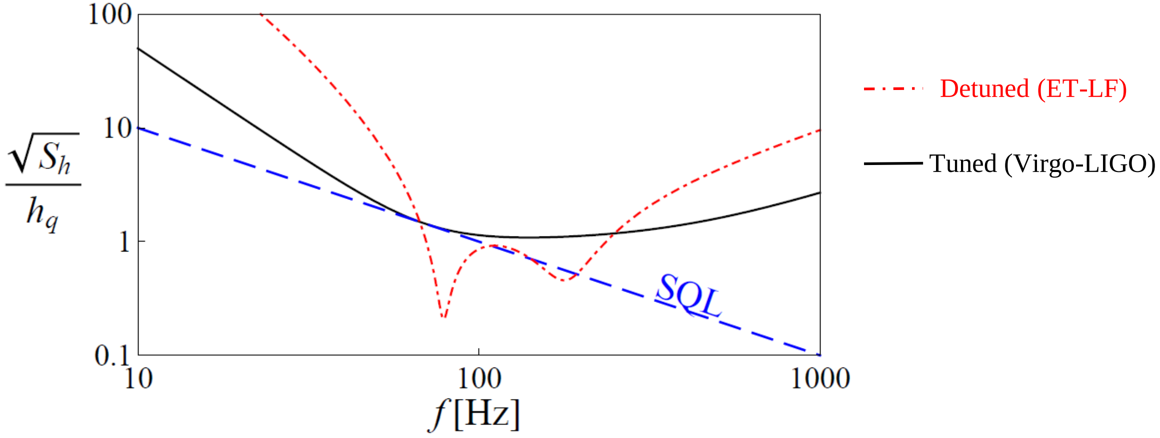
$$S_{hh}[\Omega] = \frac{8}{L^2}\{S_{Shot} + S_{BA}|\kappa[\Omega]|^2 + 2Re\{S_{Shot-BA}\,\kappa^*[\Omega]\}\}$$

- Both methods are realized in the detuned signal recycled configuration



Optical Spring

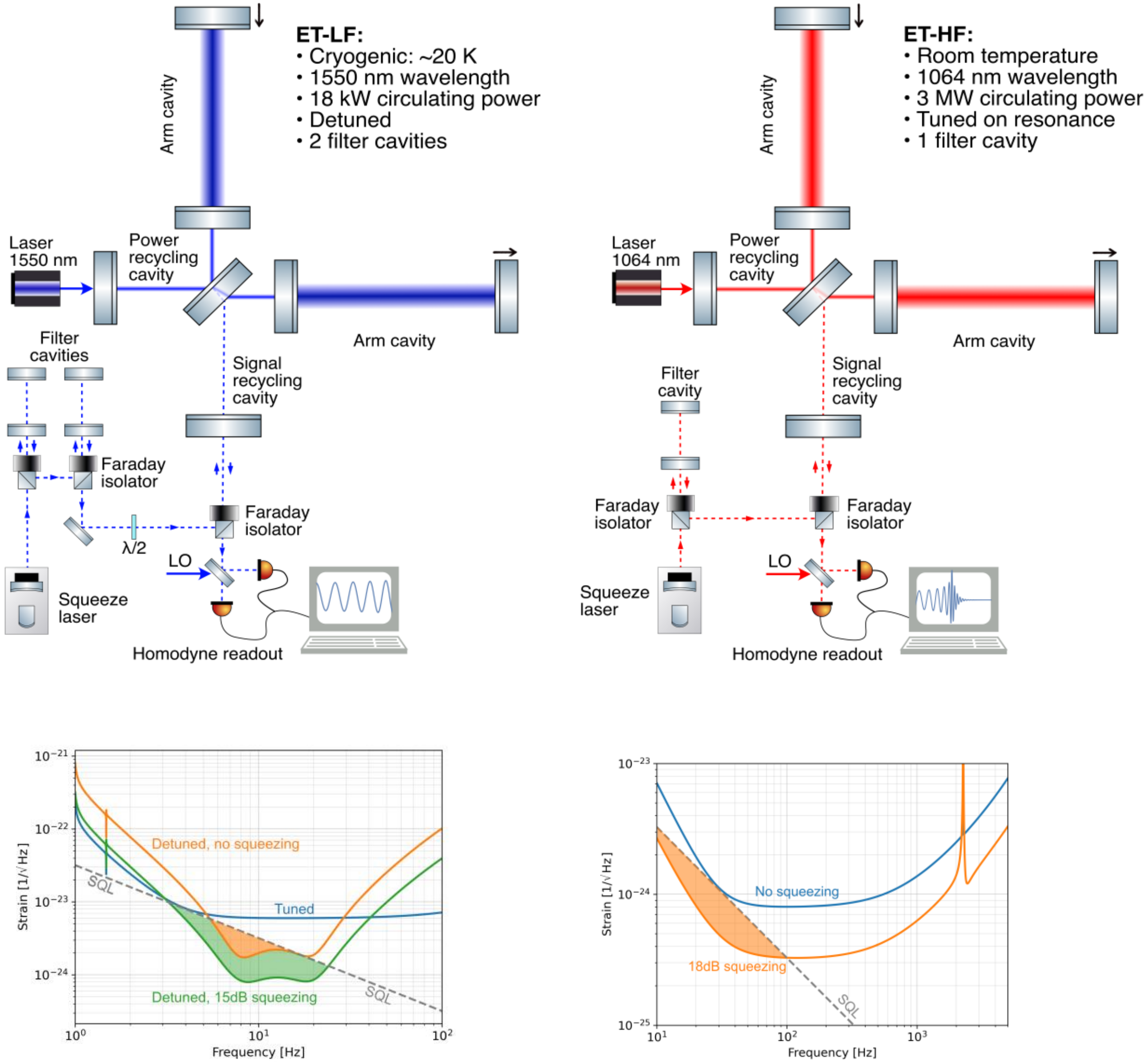




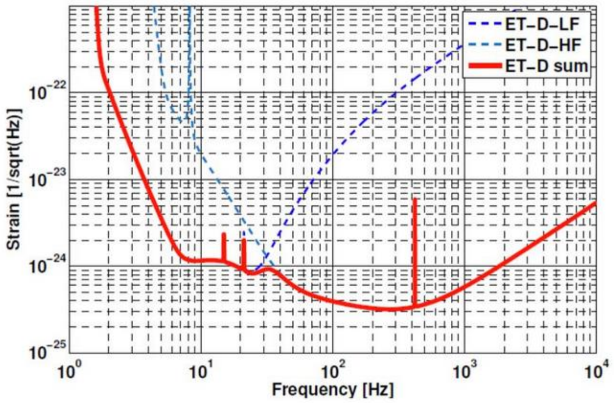
H. Miao PhD thesis

ET-HF & ET-LF

M Korobko, Galaxies **2025**, 13, 11.



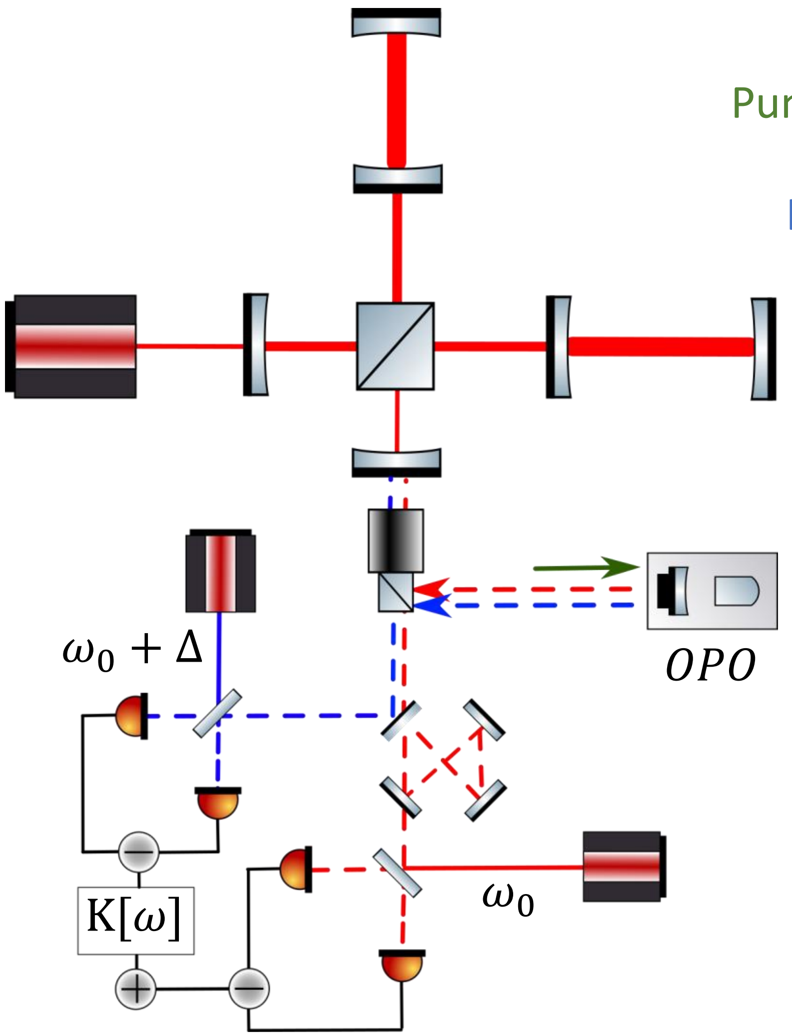
- “Xylophone” configuration



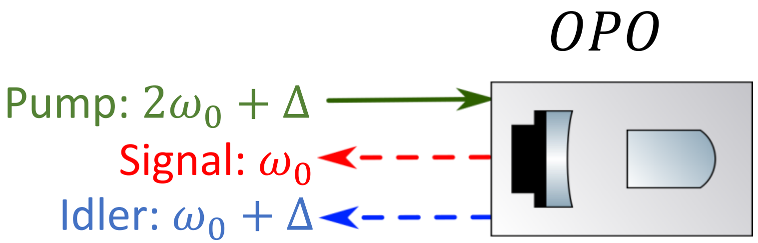
[S. Hild et al., CQG 27 (2010), ET note ET-0135B-10]

- **Quantum noise reduction with SQZ**
  - Two filter cavities required for ET-LF
  - Kilometre-scale filter cavities are required for broadband quantum noise reduction.

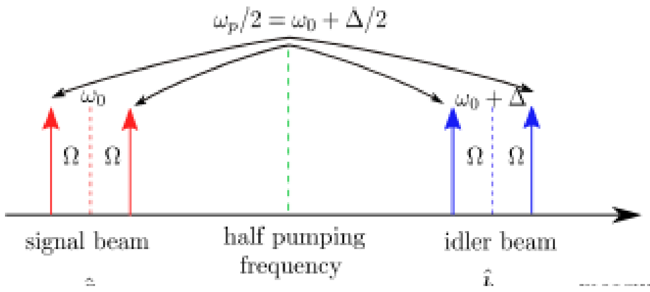
EPR-FDS squeezing



Y. Ma et al, Nature Phys 13, 776 (2017)



Sidebands entaglement



Energy conservation: $\omega_0 + \Omega + \omega_0 - \Omega + \Delta = 2\omega_0 + \Delta$C

Advantage:

- No needs of filter cavity

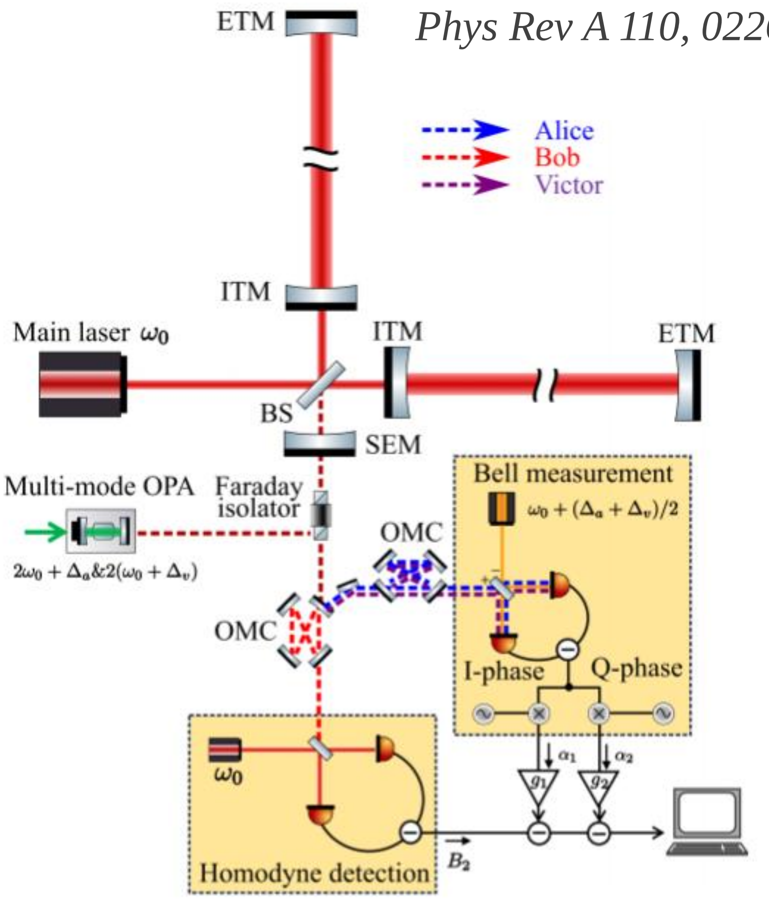
Drawback:

- 3dB loss of squeezing
- Not effective for SR detuned configuration

See presentations (INFN Gr.2)
-Francesco De Marco
-Ali Wajid

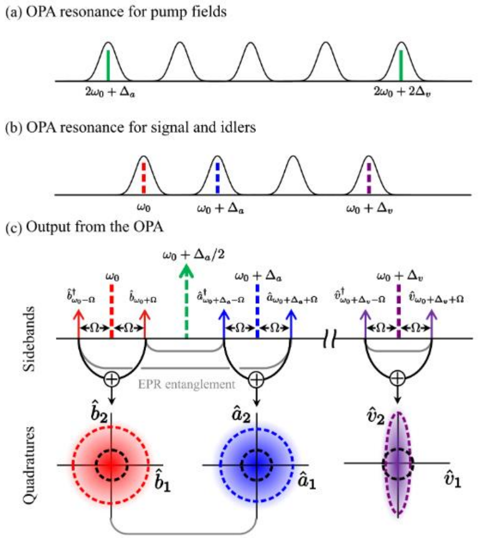
FDS through quantum teleportation

Phys Rev A 110, 022601 (2024)



$$\begin{pmatrix} B_1 \\ B_2 \end{pmatrix} = \begin{pmatrix} b_1 \\ b_2 \end{pmatrix} + \begin{pmatrix} v_1 + a_1 \\ v_2 - a_2 \end{pmatrix} \xrightarrow{\text{EPR}} \begin{pmatrix} v_1 \\ v_2 \end{pmatrix}$$

Output Bob Bell Meas. FDS



- *Bob* and *Alice* EPR entangled

$$\Delta(a_1 + b_1) \xrightarrow{\text{EPR}} 0$$
$$\Delta(a_2 - b_2) \xrightarrow{\text{EPR}} 0$$

- *Victor* squeezed

Advantage:
- No needs of filter cavities for the SR detuned configuration (ET-LF)

Drawback:
- 4.8 dB of squeezing penalty

Proof of concept expected in "**QuTe**" Gr5
P.I. **Andrea Grimaldi** (INFN Gr5 young grant 2025)

Conclusions

- The baseline design for broadband quantum noise reduction in operating (Ligo, Virgo..) and future (ET, Cosmic Explorer) GW detector involves the use of FDS sources generated with detuned external cavities. A significant improvement is expected by reducing optical losses

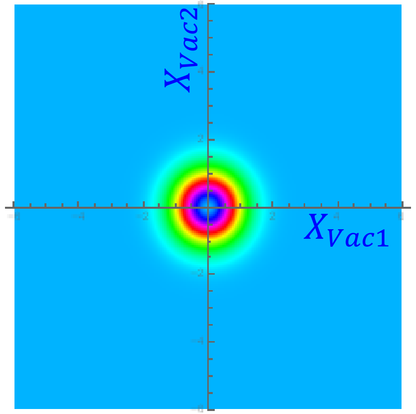
- Internal generation of FDS with EPR is also considered but at the price of a reduced level of squeezing degree (**F. De Marco and A. Wajid presentation**).

- Other methods aimed to to partialy suppress the back-action (variational readout, speed-meter, **negative mass see A. Grimaldi** presentation) or broadband signal amplification (white light cavies) have been proposed are in the bench-test demonstration phase but further work is neededed before they can be installed in large detectors.

Backup Slides

Michelson Interferometers: FDS

Input field

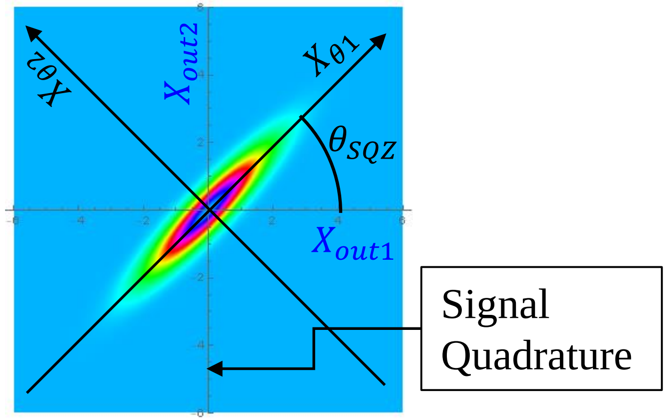


- *Ponderomotive Squeezing* Due to the radiation pressure contribution ($\kappa[\Omega] \neq 0$) the variance of the two output quadratures are different and becomes frequency dependent

$$\hat{X}_{Out_1} = \hat{X}_{Vac_1}(\Omega)$$

$$\hat{X}_{Out_2} = Exp[2i\Omega\tau](\hat{X}_{Vac_2}(\Omega) + \kappa[\Omega]\hat{X}_{Vac_1}(\Omega))$$

Output field



$$\kappa[\Omega] = \frac{4\omega_0 P_{arm}}{m\,\Omega^2 c^2}$$ Simple Michelson Interferometer

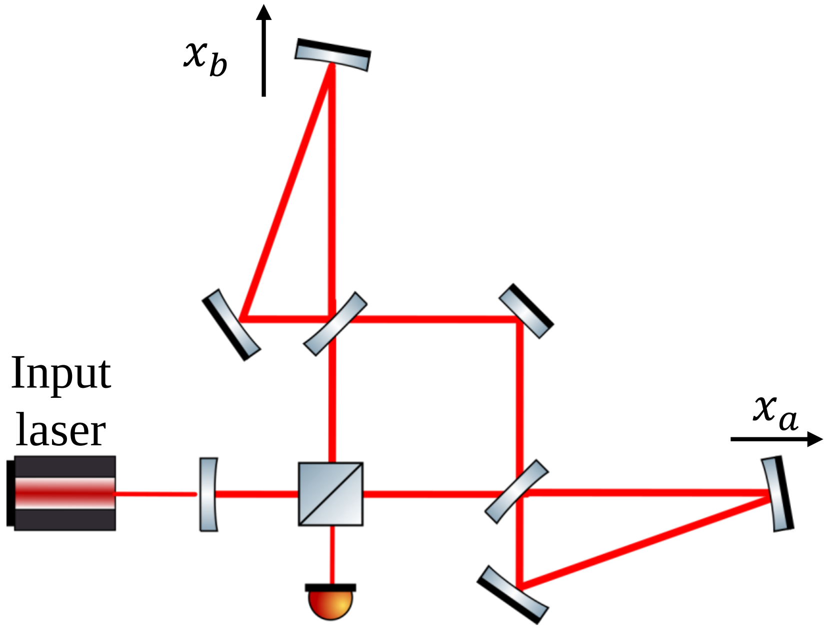
$$\kappa[\Omega] = \frac{16\omega_0 P_{arm}}{mLc}\frac{\gamma}{\Omega^2(\Omega^2+\gamma^2)}$$ Tuned Dual Recycled configuration (Virgo and LIGO so far)

Two poles for the detuned dual recycled interferometer (ET-LF)

- *Frequency Dependent Squeezing (FDS)*: the input squeezing ellipse is rotated by the ponderomotive effect. In general, this leads to a misalignment between the signal quadrature and that of lower noise. To compensate this effect a frequency-dependent vacuum squeezed field is injected into the interferometer

Speed meters

Zero Area Sagnac interferometer



$$\delta\phi \approx x_a(t) + x_b(t+\tau) - x_b(t) + x_a(t) \approx 2\,\mathrm{v}\,\tau$$

τ: propagation time   v: speed

- The generalized momentum “p” is a *quantum non demolution* observable (not affected by back action)

$$[\hat{p}(t), \hat{p}'(t')] = 0$$

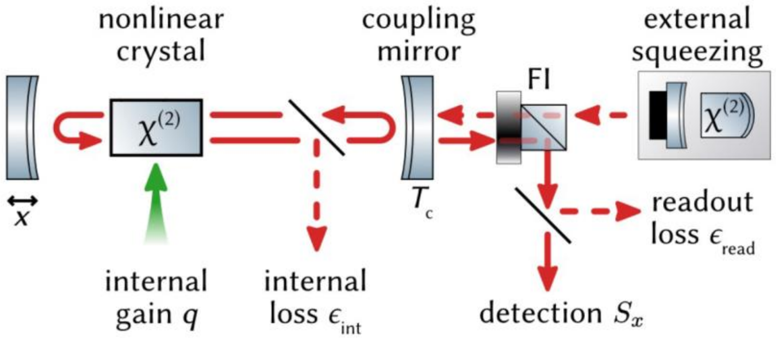
- The momentum of the test mass is a quasi quantum non demolution observable

- Two basic schemes
  - Michelson interferometer plus external “sloshing” cavity
  - Speed meter

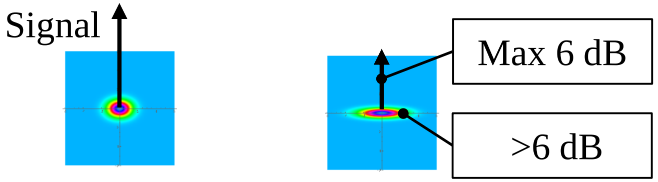
https://link.springer.com/article/10.1007/s41114-019-0018-y

- Large scale proof of principle still lacking
- New configurations compatible with the michelson interferometer configuration are being considered

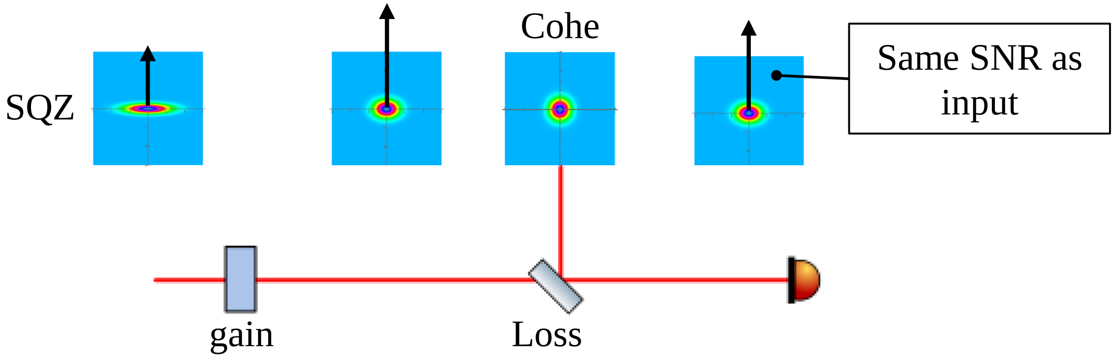
Dechoerence mitigation:Internal squeezing



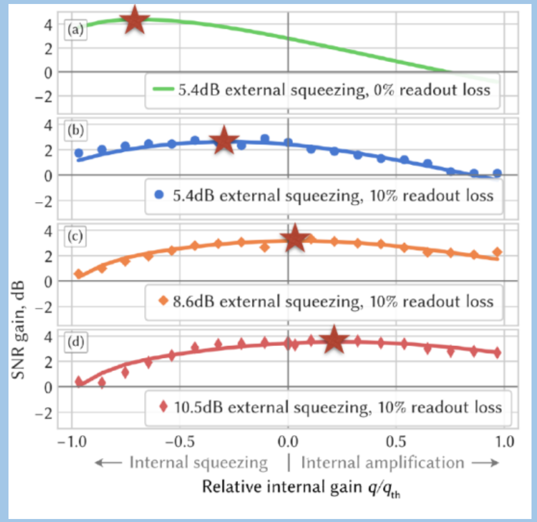
1)Low readout losses dominant: parametric deamplification



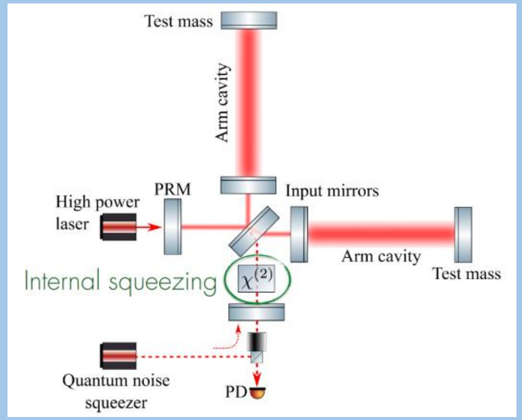
2)Low internal losses dominant: parametric amplification



- Proof of concept
  arXiv:2303.09983

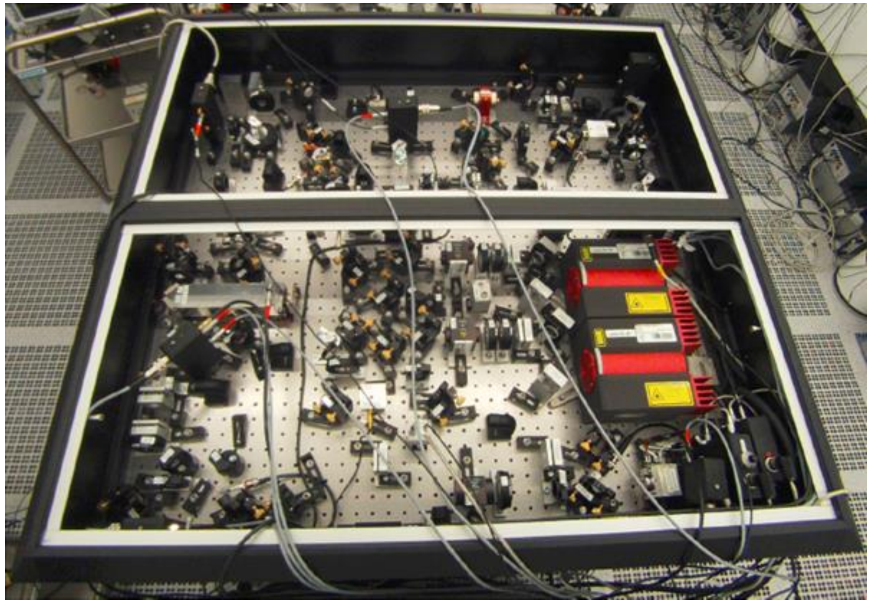


- Applicable for GW detectors?



- Several technological problems to deal with
- To be combined with quantum back-action evading techniques

Squeeze



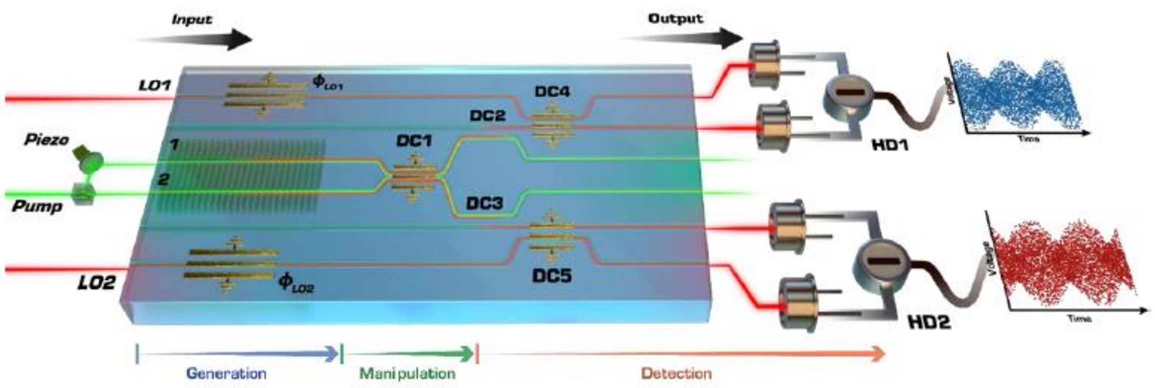
Virgo AEI squeezer

In addition to the OPO a squeezer board includes

- Pump power generator (SHG:Second Harmonic Generator)
- Pump power stabilizer (MZI:Mach Zehnder Interferometer)
- Phase and frequency modulators (EOM, AOM)
- Auxiliary control laser (coherent control laser, Sub Carrier laser..)
- Beam mode cleaners
- Faraday isolators
- Phase Locked Loop optical set-up
- Diagnostic homodyne detector

Most of these components can be integrated in a LNOI chip

LNOI:Lithium Niobate On Isulator



Squeeze: Development of an integrated optics squeezing generator (Trento, Padova)