Einstein-Podolsky-Rosen quantum entanglement squeezing for future gravitational-wave detectors

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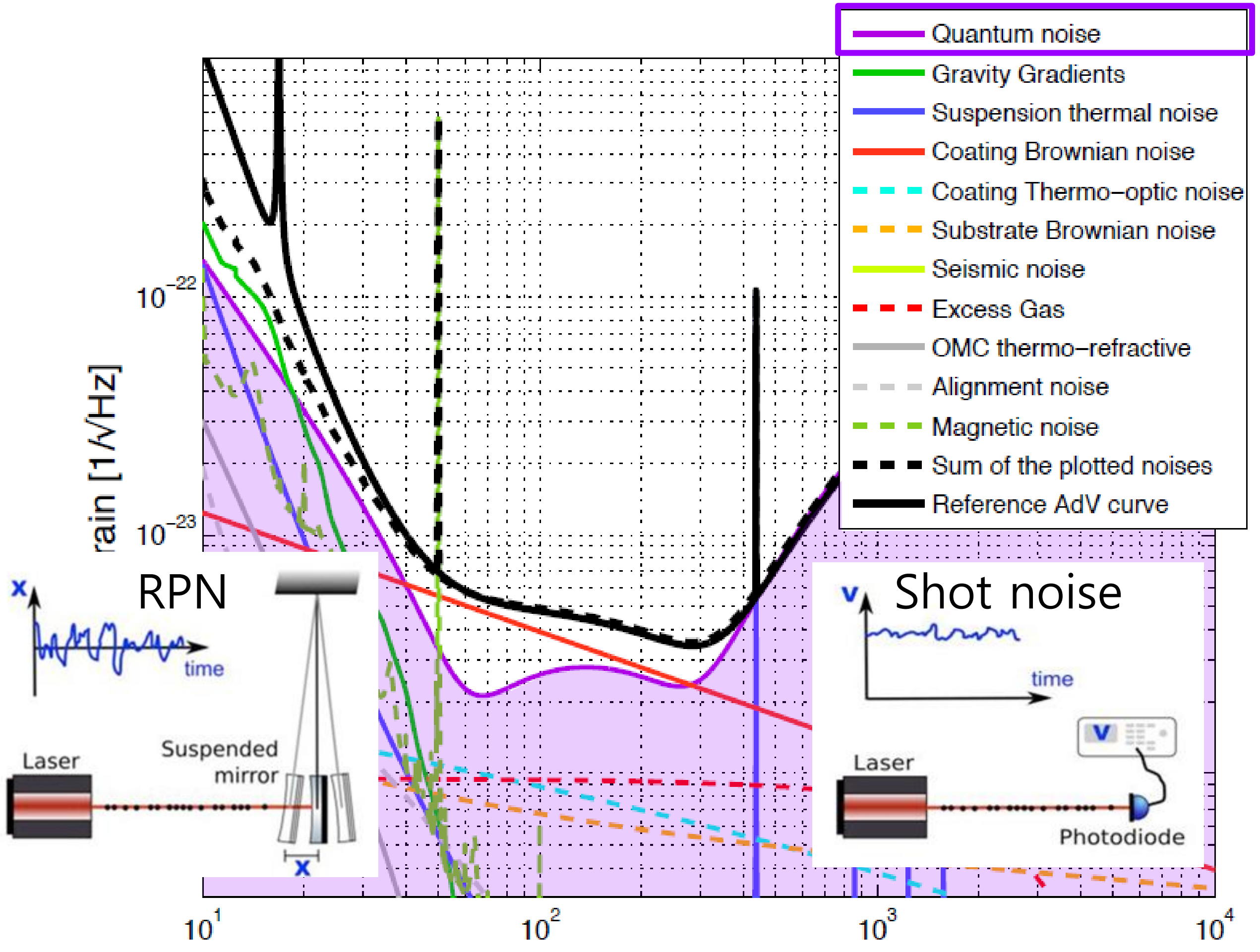
Quantum Noise Reduction in Current GW detectors

- Quantum Noise (QN) originates from vacuum field fluctuations
- QN limits the sensitivity of GW detectors in a wide range of their spectrum
- In Low frequency band, Radiation pressure noise (RPN) Limits the sensitivity
- In High frequency band, Shot noise Limits the sensitivity

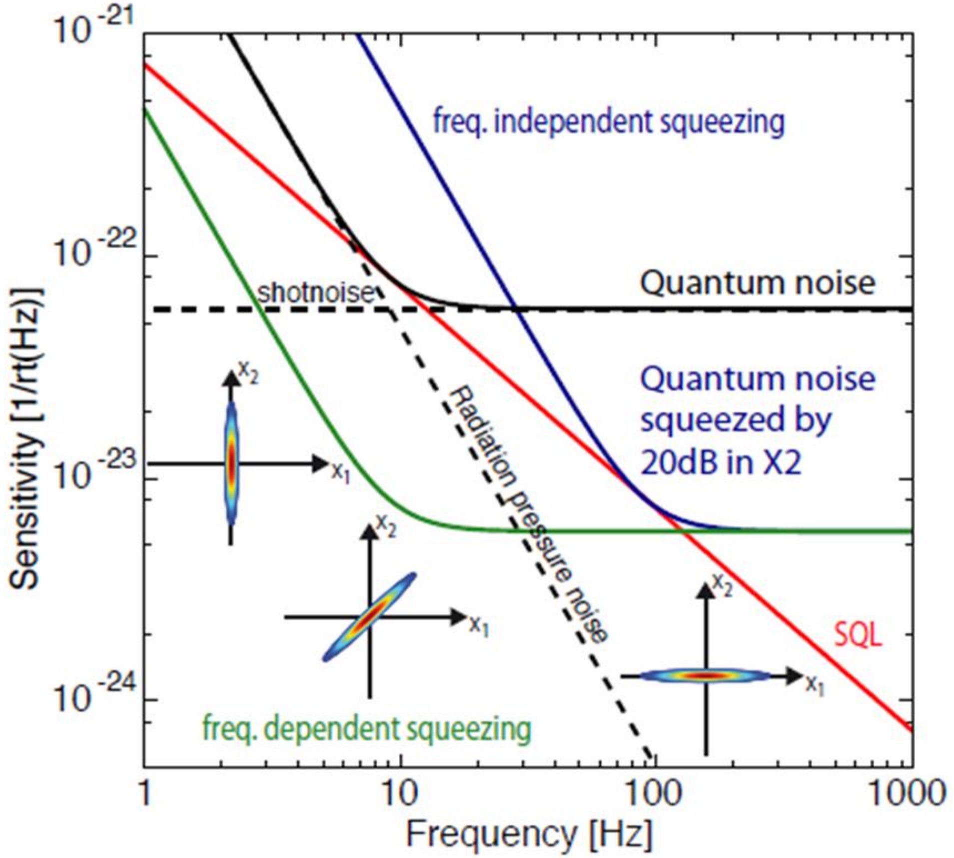


Advanced VIRGO sensitivity curve

VIRGO Collaboration+15

Quantum Noise Reduction in Current GW detectors

- The minimum Quantum Noise, at a given frequency is achieved when RPN and SN are equal -> Standard Quantum Limit (SQL)
- To improve GW detector's sensitivity we should implement a technique capable to overcome SQL in all its frequency band

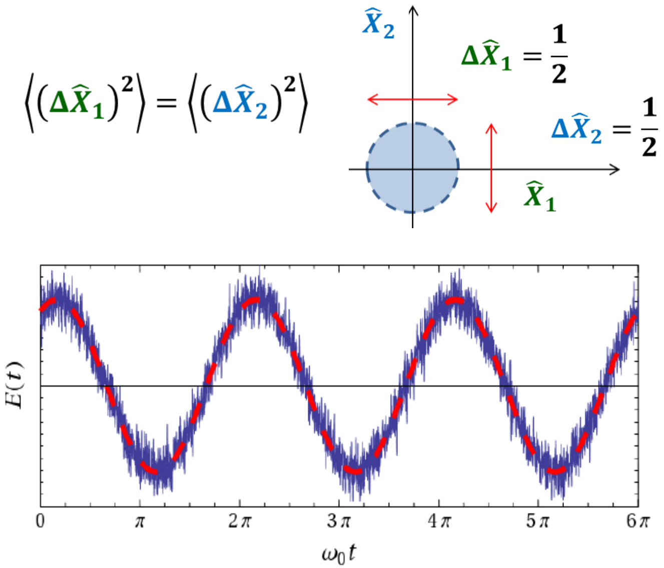


SQL line in the sensitivity curve

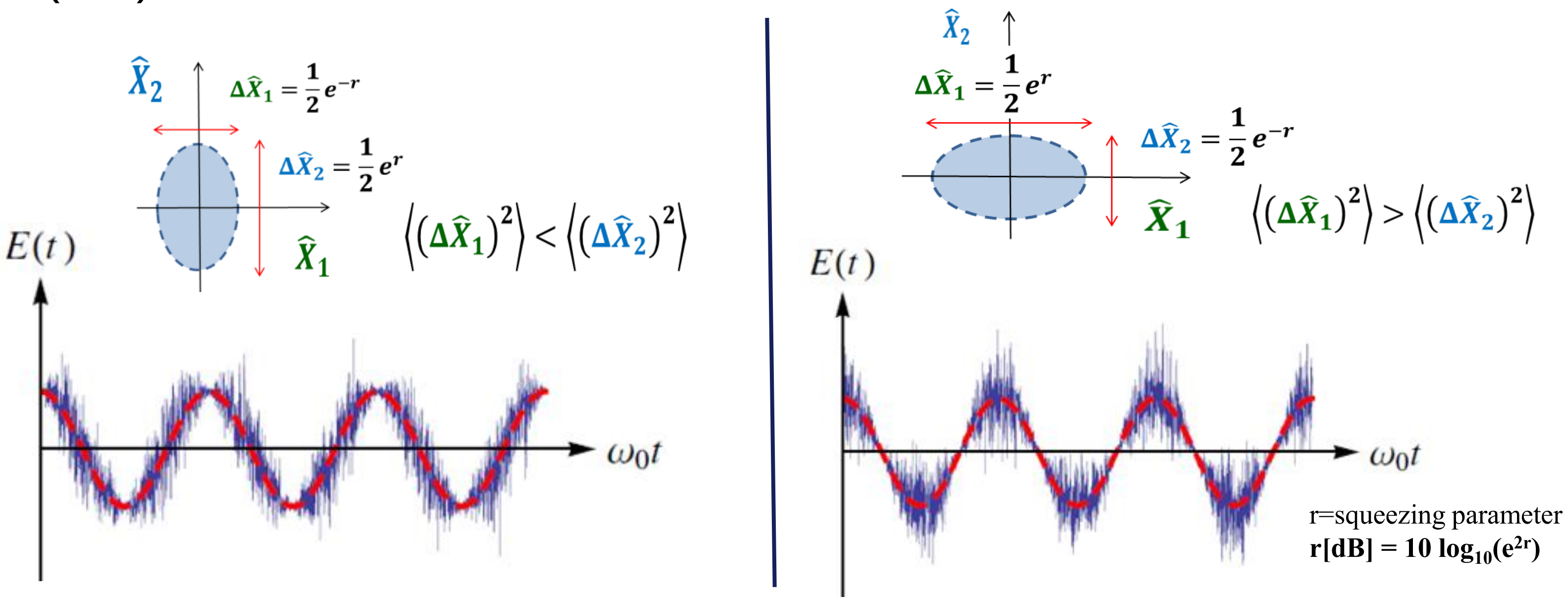
Vahlbruch+08

Quantum Noise Reduction in Current GW detectors

- RPN and SN are related to the uncertainties of EM-field quadrature and linked by the Heisenberg Uncertainty Principle
  - X quadrature ($\Delta\hat{X}_1$) → Amplitude (RPN)
  - Y quadrature ($\Delta\hat{X}_2$) → Phase (SN)



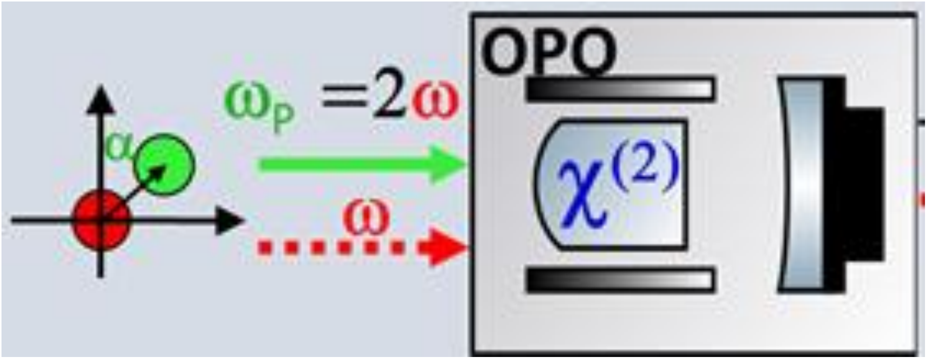
Coherent state : Equal uncertainties



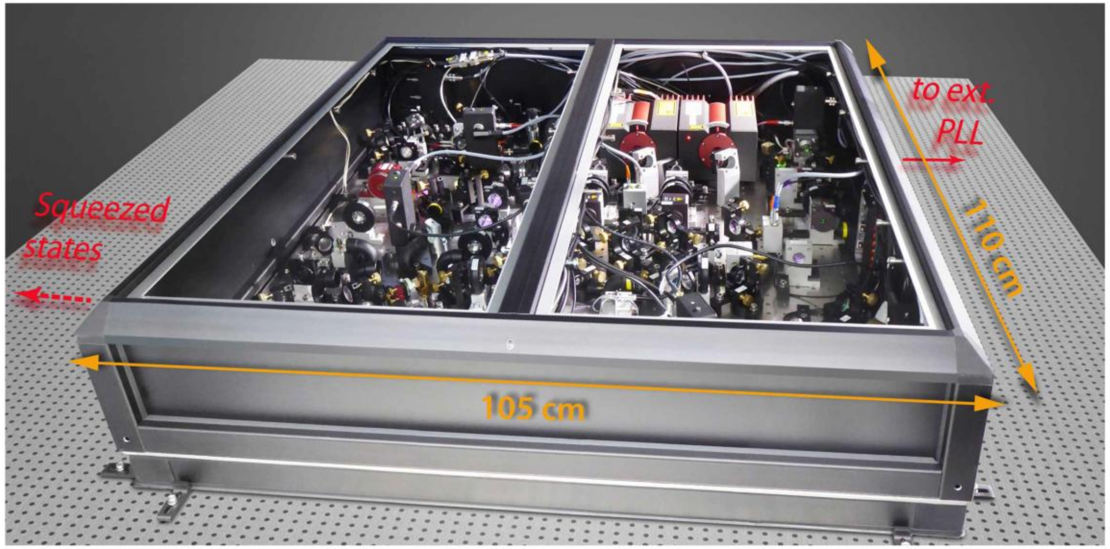
Squeezed states : Reduced uncertainty on one quadrature (L: Amplitude squeezing, R: Phase Squeezing)

Quantum Noise Reduction in Current GW detectors

- Phase squeezed vacuum field generated from an Optical Parametric Oscillator (OPO) via non-linear optical process, which enables Spontaneous parametric down-conversion (SPDC)
- This method is called Frequency Independent Squeezing, and reduces only shot noise



OPO generates twice of the wavelength beam of the injected pump beam while generates squeezed field



OPO included squeezed light source of VIRGO

Mehmet+20

Quantum Noise Reduction in Current GW detectors

- Frequency-Dependent Squeezed (FDS) light provides broadband QN reduction via squeezing ellipse rotation

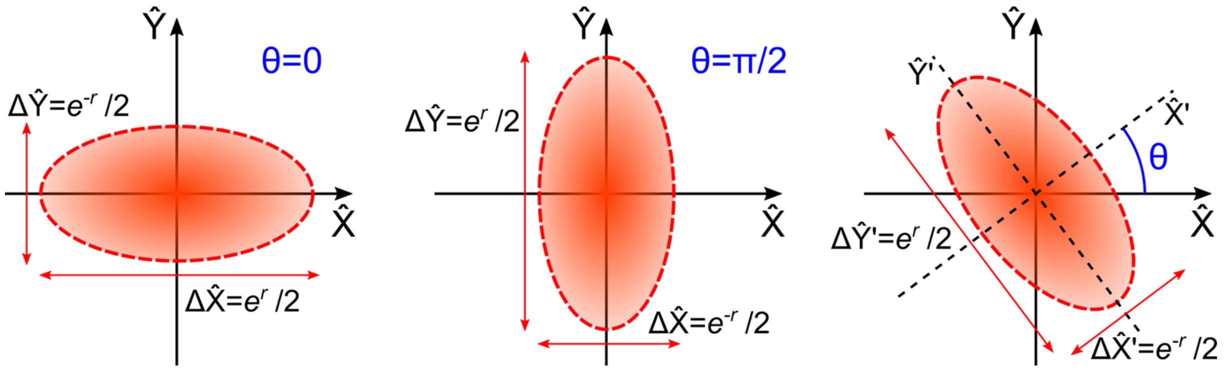
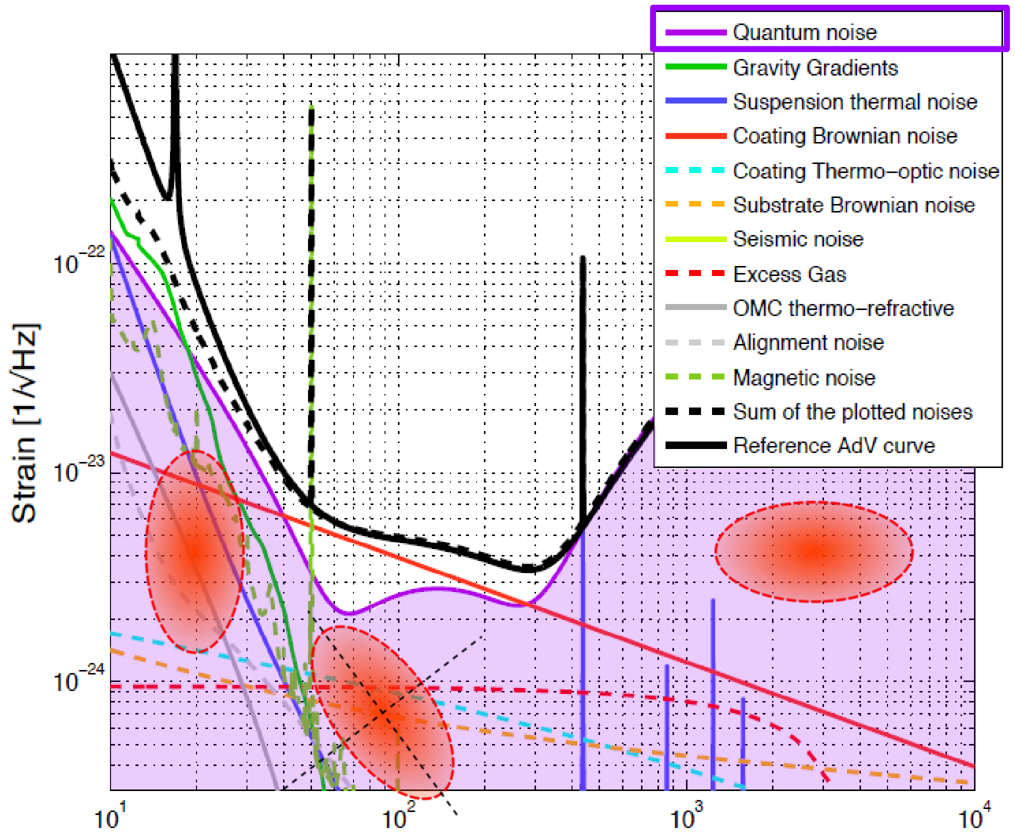


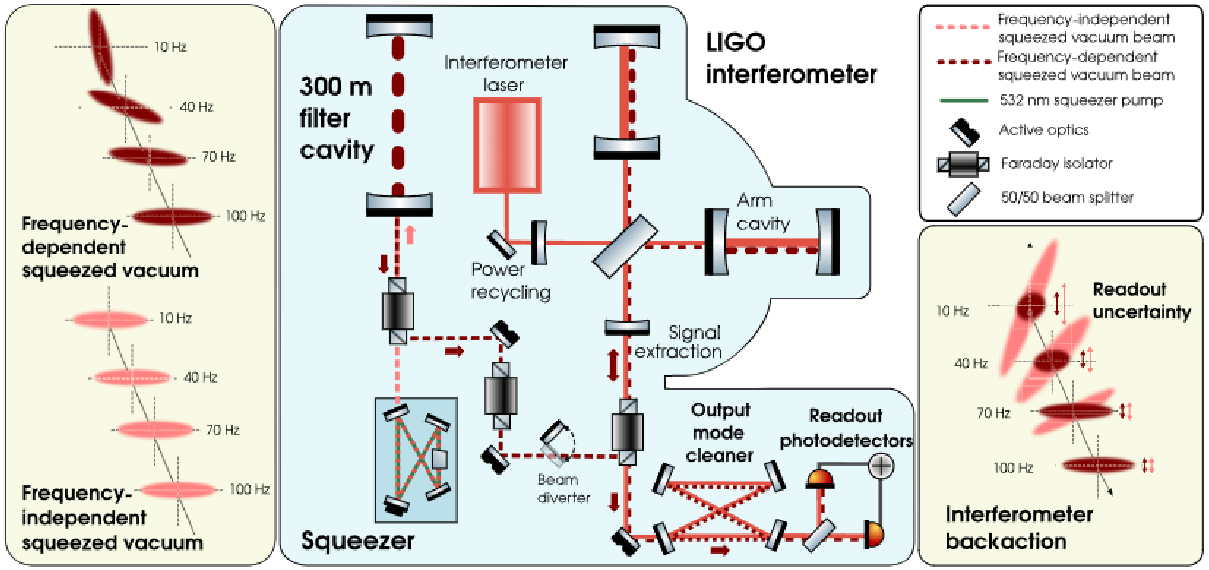
Diagram of squeezing ellipse rotation
EM field quadrature:
X quadrature → Amplitude (Radiation Pressure Noise)
Y quadrature → Phase (Shot Noise)



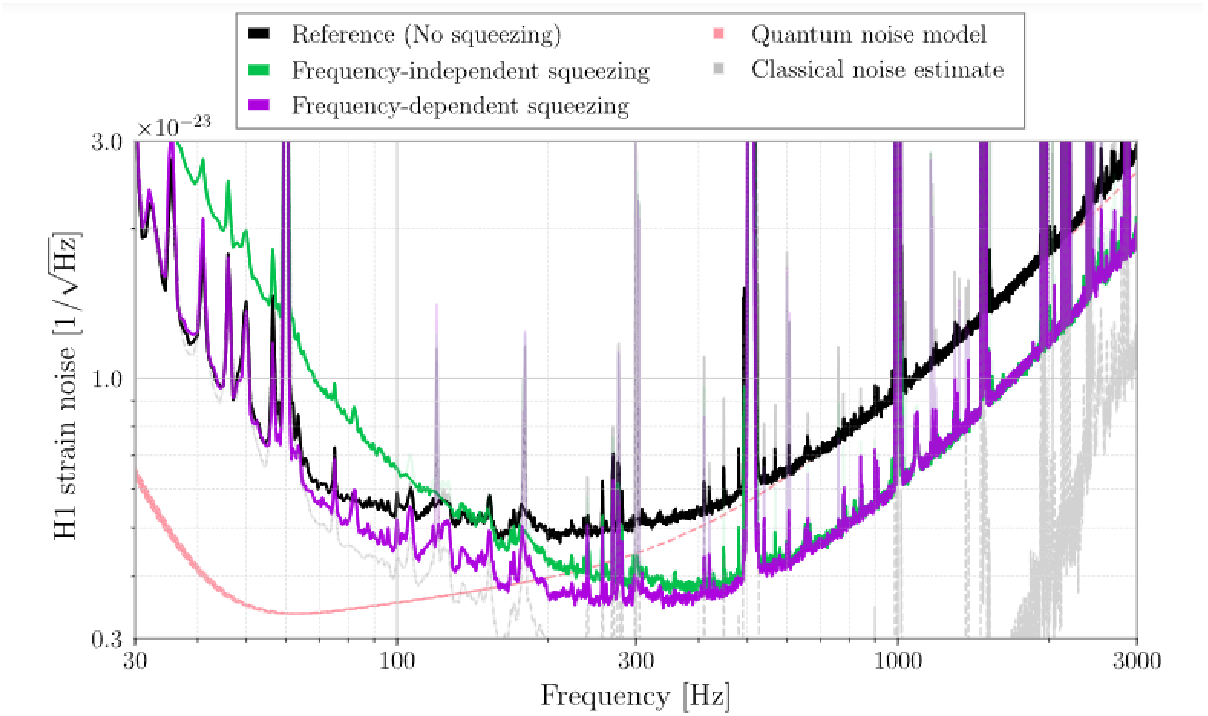
Advanced VIRGO sensitivity curve

Quantum Noise Reduction in Current GW detectors

- FDS realized via Filter cavity (FC), Which rotates the squeeing ellipse via frequency-dependent phase shift in the 300m linear cavity



LIGO quantum noise reduction system layout

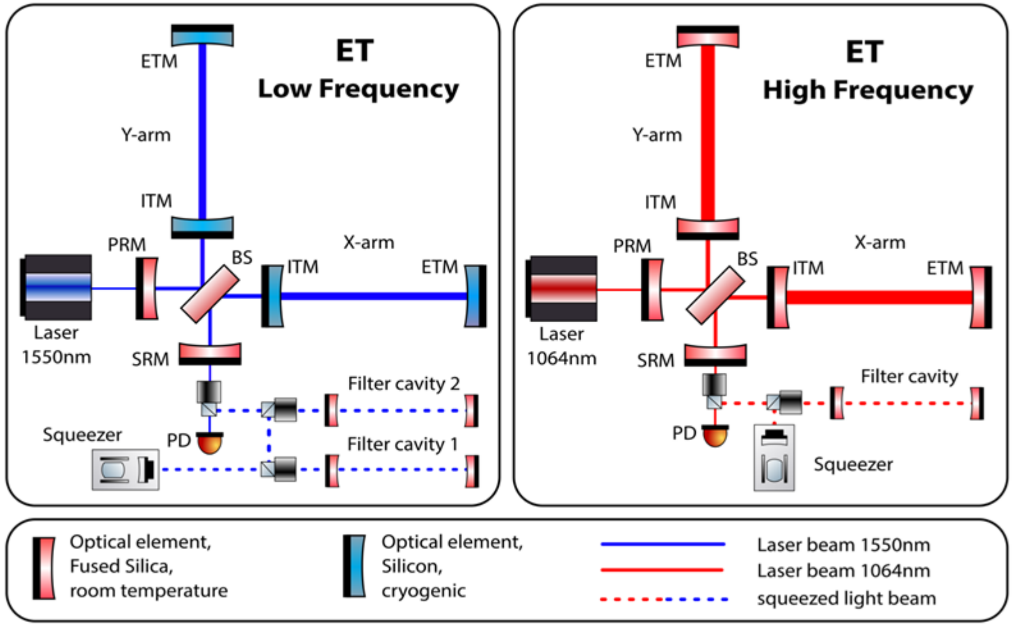


LIGO Hanford sensitivity curve during O4a run with Filter cavity

Ganapathy+23

Quantum Noise Reduction in **Einstine telescope**

- ~300m long filter cavities are successfully adopted to Virgo and LIGO
- For future detectors, Filter cavity requires extra resources
  - More excavation of tunnels (Two 5km FC for ET-LF, One 1km FC for ET-HF)



ET layout including FCs


285m long Virgo FC

ET official document ET-0028A-20 (2020)

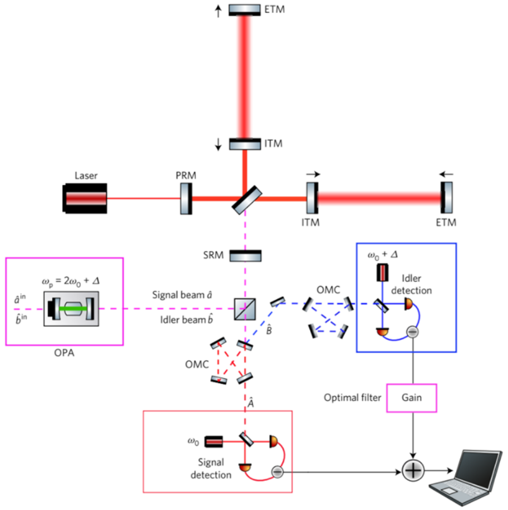
Acernese+23

The EPR proposal

ARTICLES
PUBLISHED ONLINE: 15 MAY 2017 | DOI: 10.1038/NPHYS4118
nature physics

Proposal for gravitational-wave detection beyond the standard quantum limit through EPR entanglement

Yiqiu Ma[1*], Haixing Miao[2], Belinda Heyun Pang[1], Matthew Evans[3], Chunnong Zhao[4], Jan Harms[5,6], Roman Schnabel[7] and Yanbei Chen[1]



Ma+17

Theoretical proposal (2017)

- Avoids at least one filter cavity
- Can work with detuned interferometer

nature photonics
ARTICLES
https://doi.org/10.1038/s41566-019-0583-3

Demonstration of interferometer enhancement through Einstein–Podolsky–Rosen entanglement

Jan Südbeck, Sebastian Steinlechner, Mikhail Korobko and Roman Schnabel*

Südbeck +20

nature photonics
LETTERS
https://doi.org/10.1038/s41566-019-0582-4

Generation and control of frequency-dependent squeezing via Einstein–Podolsky–Rosen entanglement

Min Jet Yap*, Paul Altin, Terry G. McRae, Bram J. J. Slagmolen, Robert L. Ward and David E. McClelland

Yap+20

Experimental demonstrations (2020)

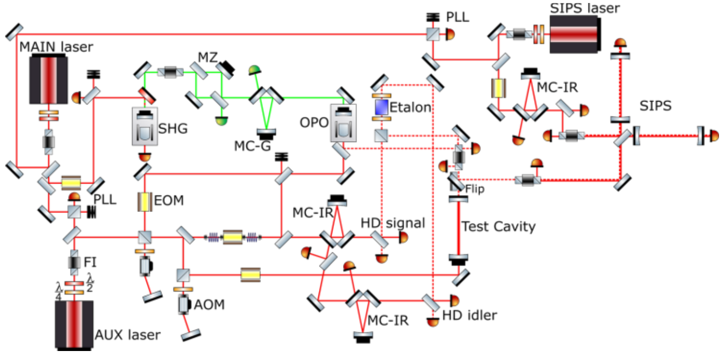
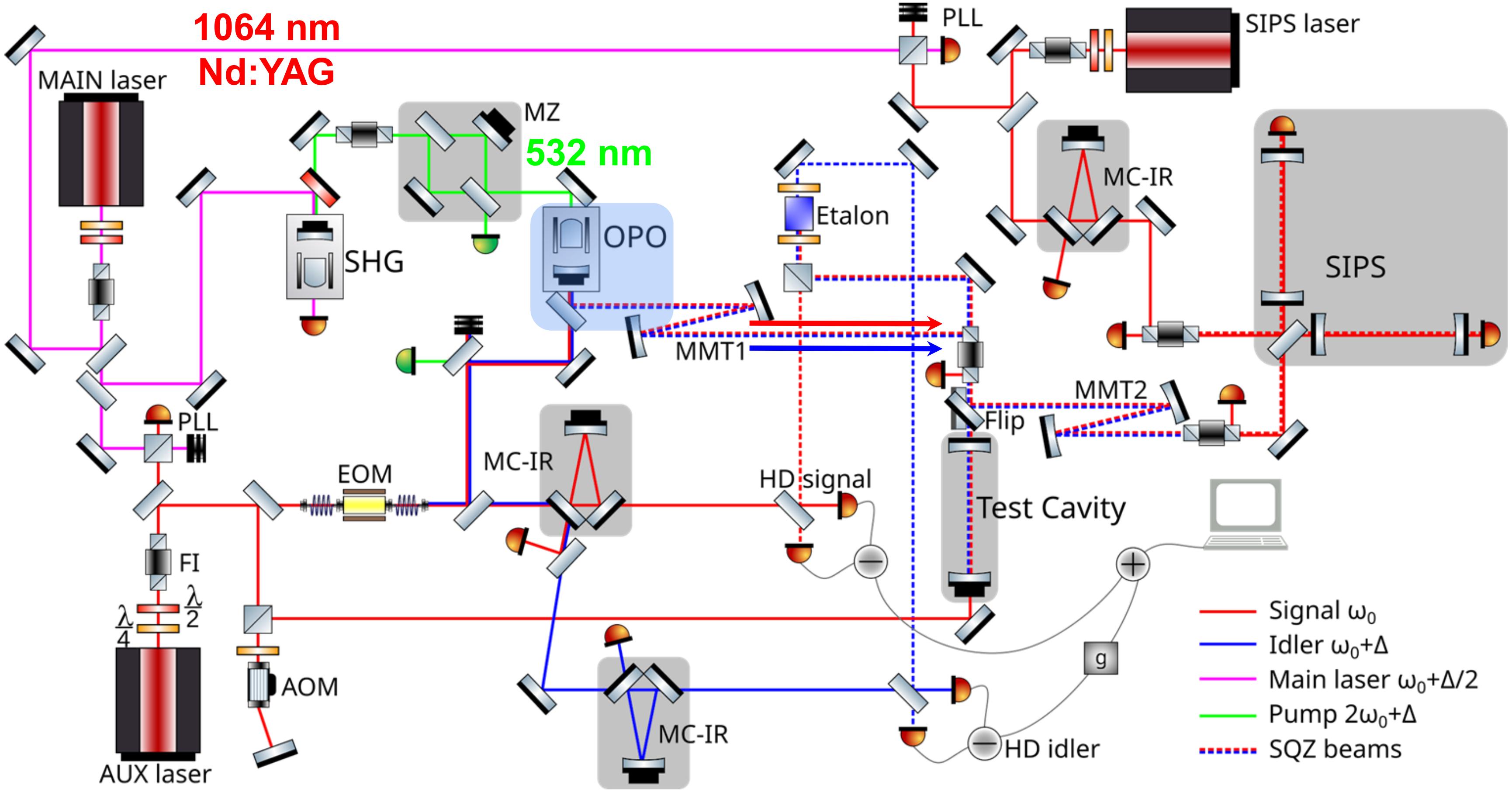
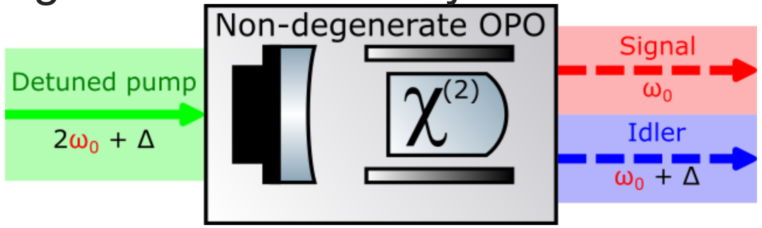


Table-top experiment in a small-scale interferometer **(ongoing at EGO)**

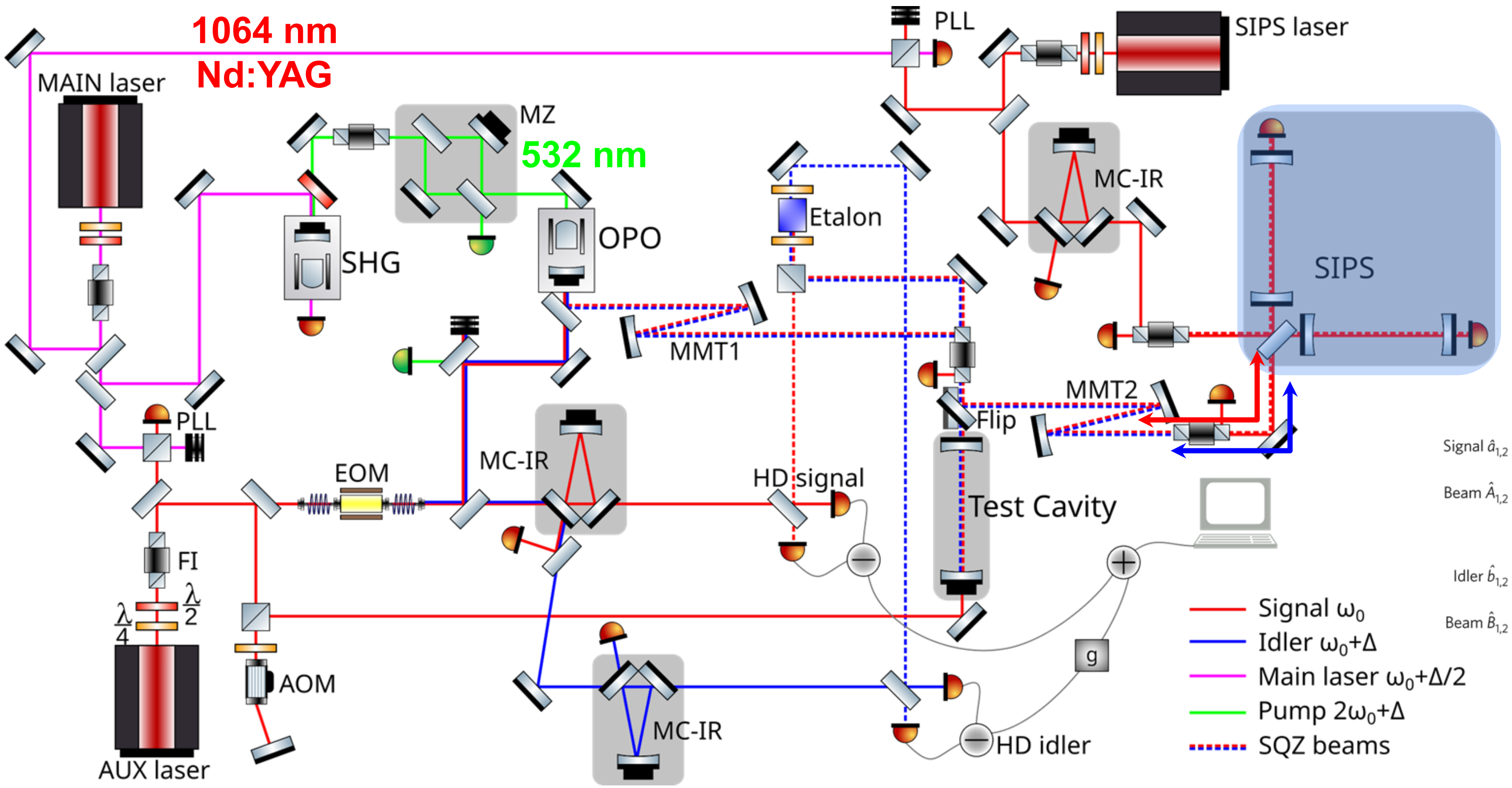
EPR experiment at EGO



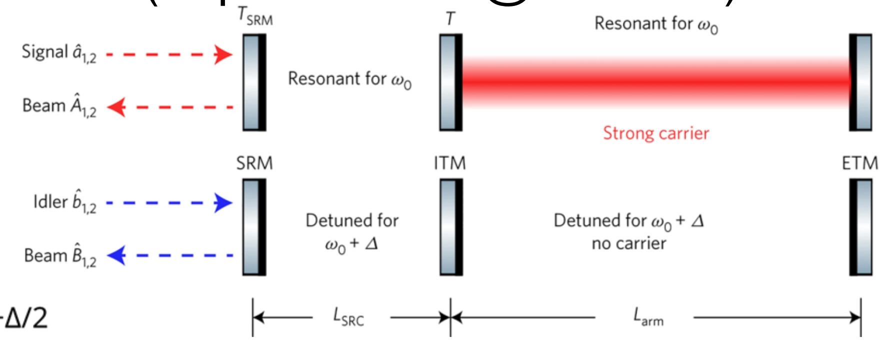
1. **Signal** and **idler** are vacuum squeezed beams, EPR-entangled and detuned by Δ



EPR experiment at EGO



1. **Signal** and **idler** are vacuum squeezed beams, EPR-entangled and detuned by Δ
2. The **idler** sees the interferometer as a filter cavity and acquires frequency-dependence (ellipse rotation @ **2100 Hz**)



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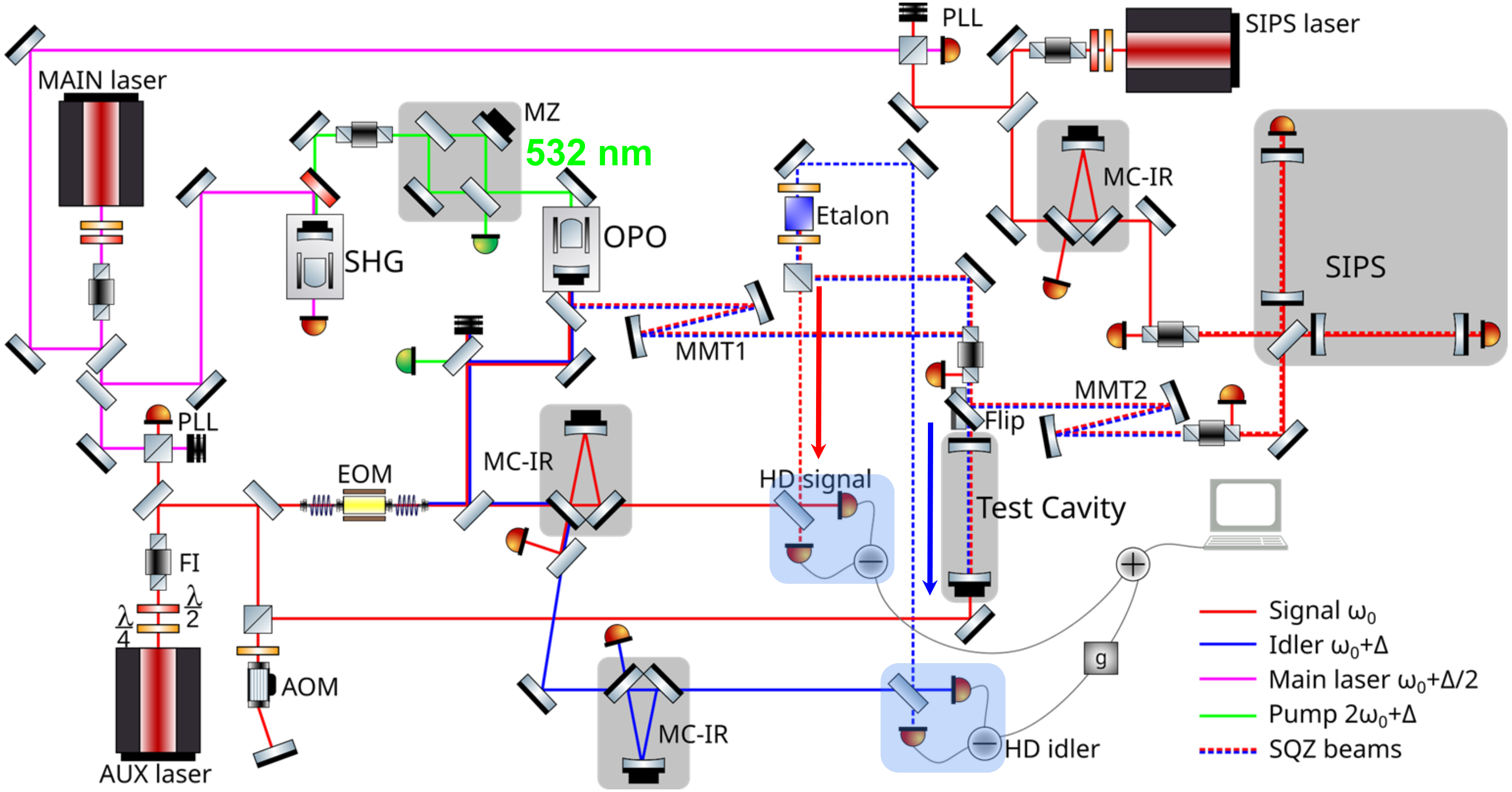
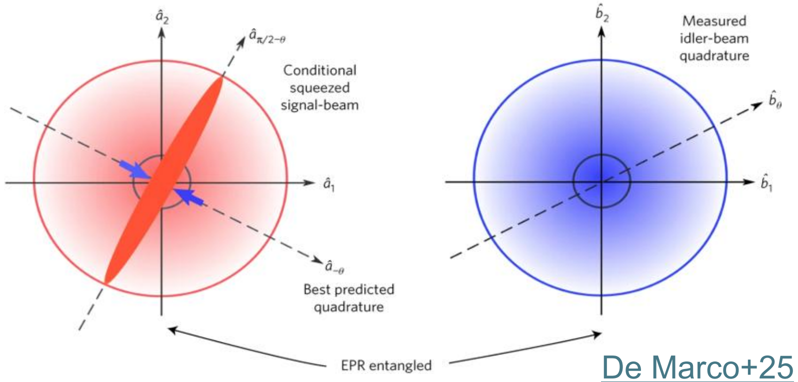
EPR experiment at EGO



1. **Signal** and **idler** are vacuum squeezed beams, EPR-entangled and detuned by Δ
2. The **idler** sees the interferometer as a filter cavity and acquires frequency-dependence (ellipse rotation @ **2100 Hz**)
3. Combined measurement transfers the frequency dependence to the **signal** via EPR entanglement



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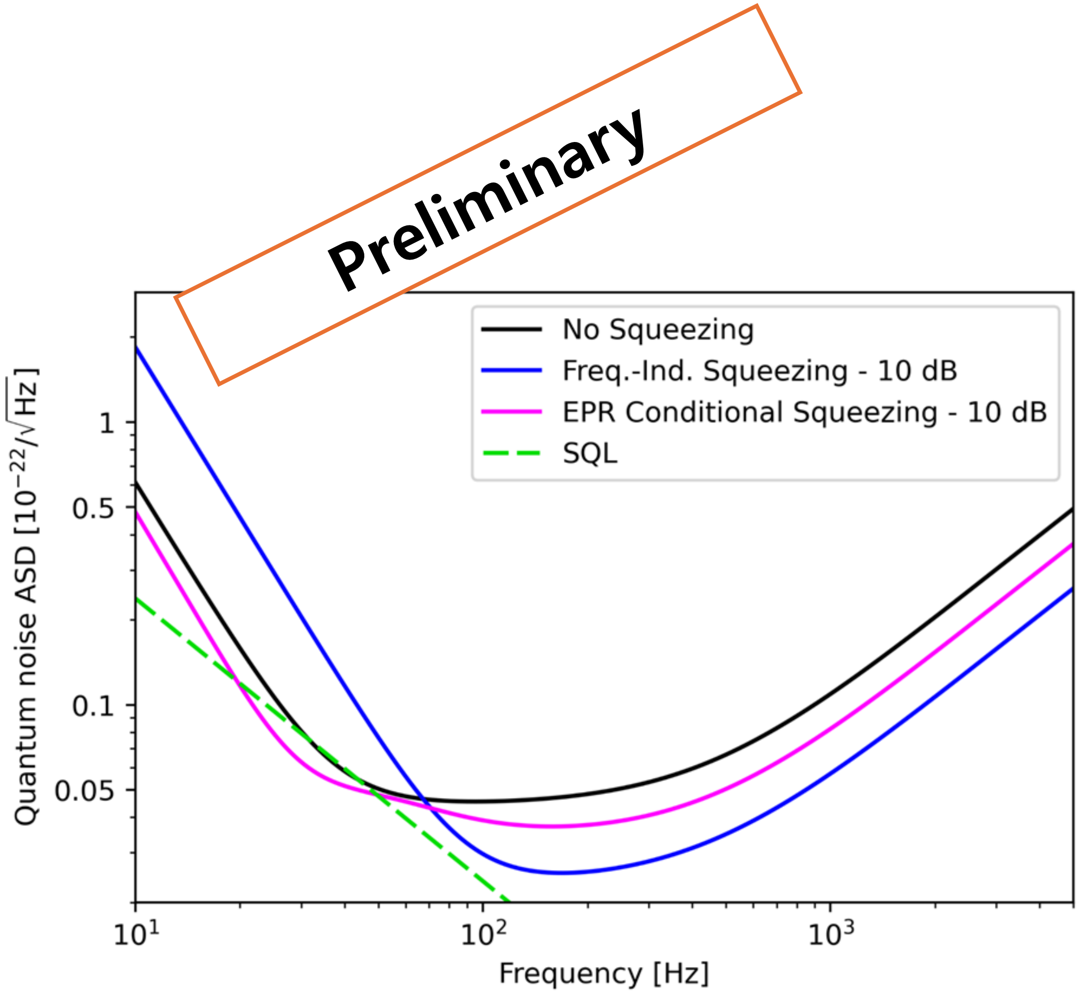
EPR experiment simulation

- Fundamental to assess potential advantage against filter cavity for ET and 3rd gen detectors
- Lack of a tool for EPR simulation available to the GW community
- We aim to provide EPR results in all the possible configuration with an `EPRsimulator`
- Preliminary result with realistic losses in Advanced Virgo+ (150 ppm loss arms, 300 ppm loss BS, 10% INJ and DET)



Simulated VIRGO noise curve with EPR squeezer

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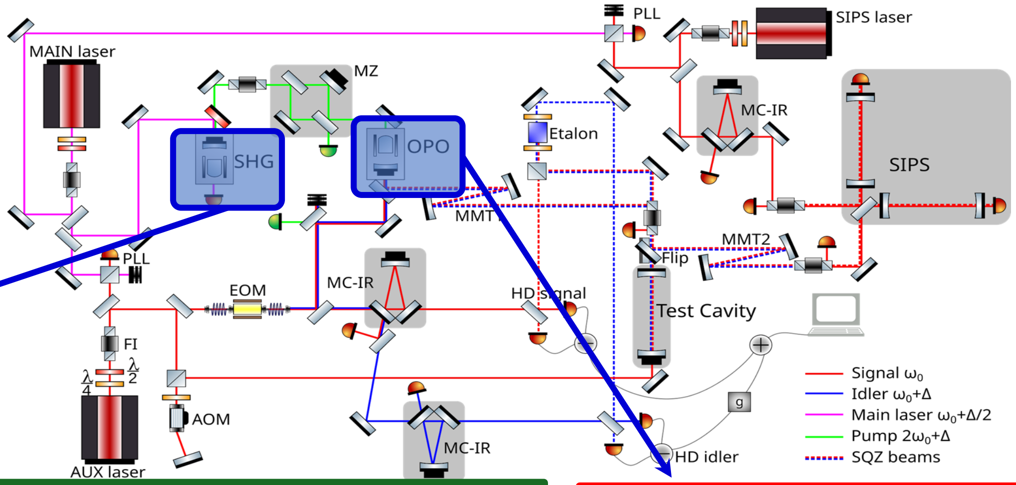
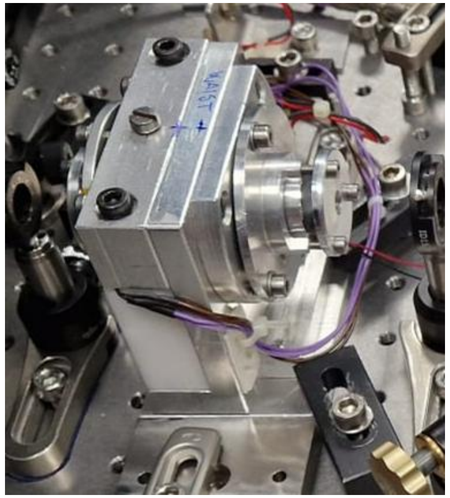
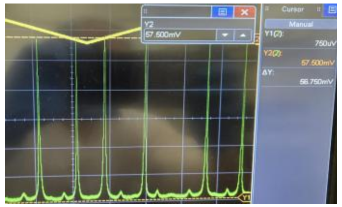
EPR experiment: Status of non-linear cavities

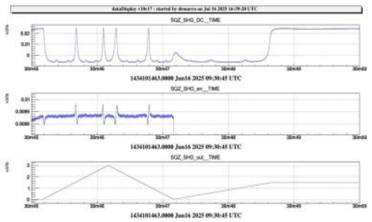


SHG

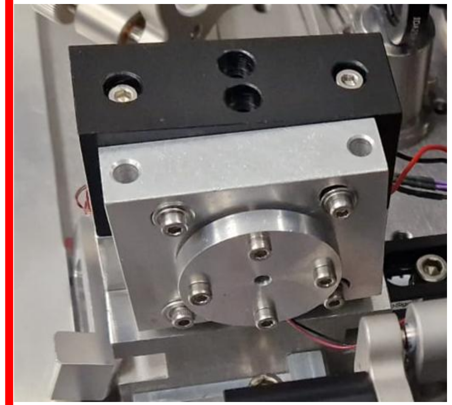


- PPKTP crystal
  with 2 flat AR faces,
  2 coupling mirrors.
- Best Mode Matching:95%

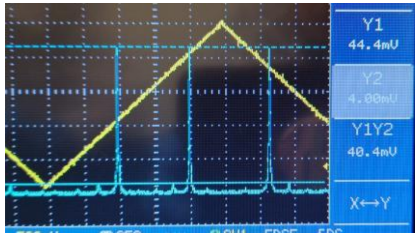


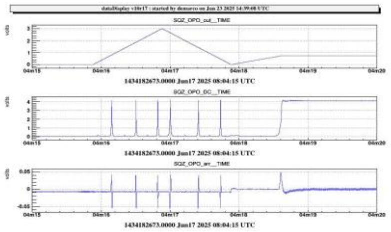


OPO



- PPKTP crystal
  with a flat AR face, a curved
  HR face,1 coupling mirror
- Hemilitic configuration
- Best mode matching 92%





EPR experiment: Mode matching telescope

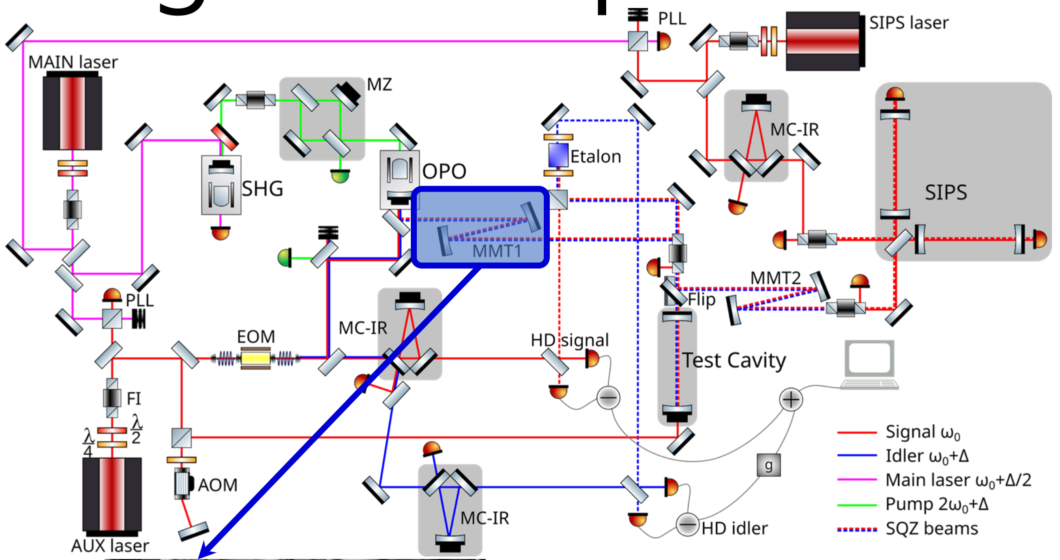
- Squeezing is heavily affected by optical losses. Need for a low-losses beam coupling elements.

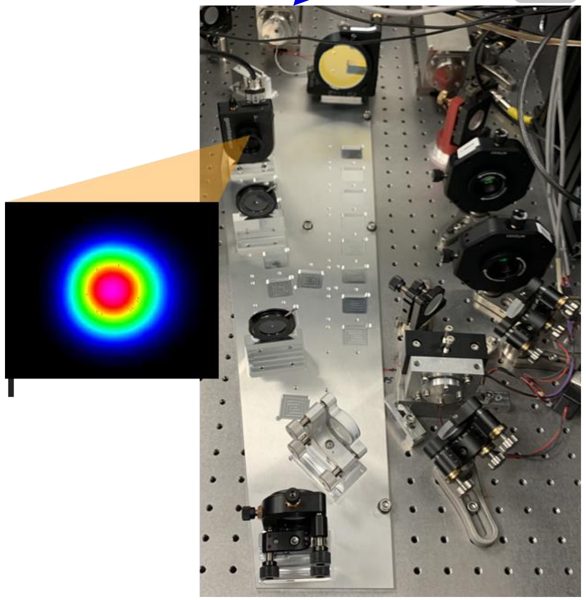
- We have developed, installed and tested a reflective and low-astigmatism Mode-Matching Telescope (Beam expander) from OPO to the test cavity

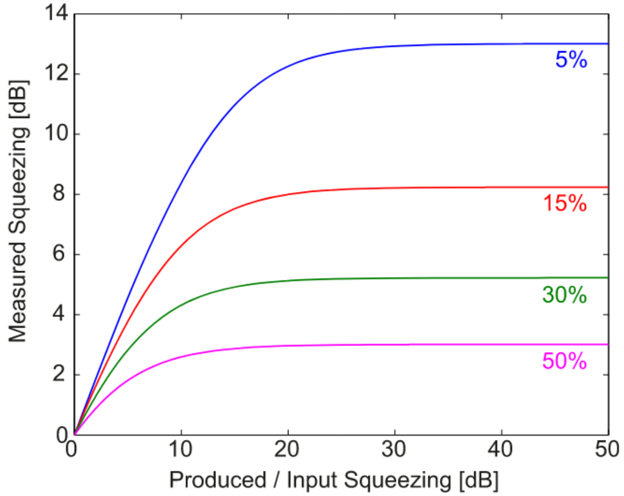
- We obtained 99.85% of matc g

- Second telescope b en test cavity and I nterferomete e fabricated

My contribution!



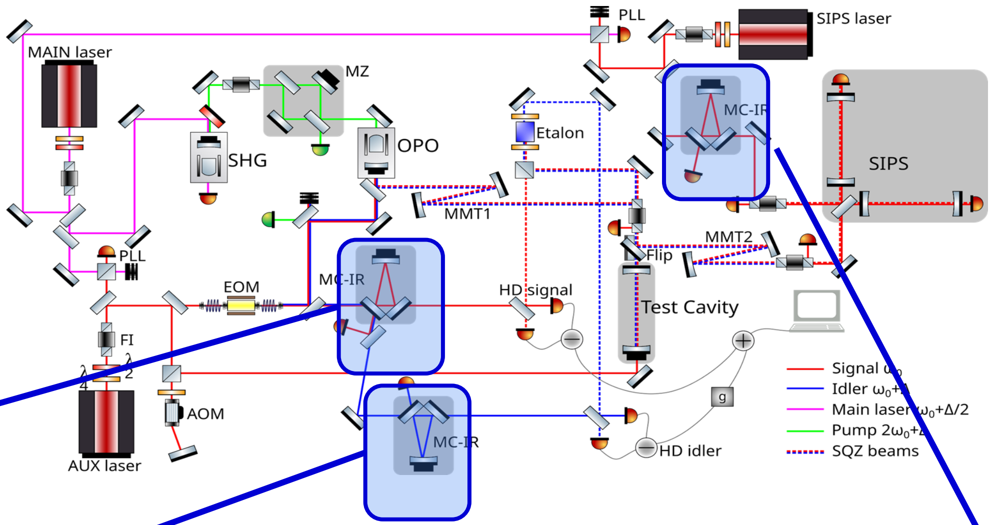


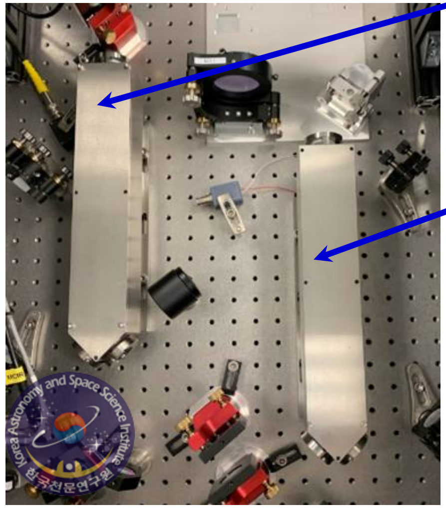


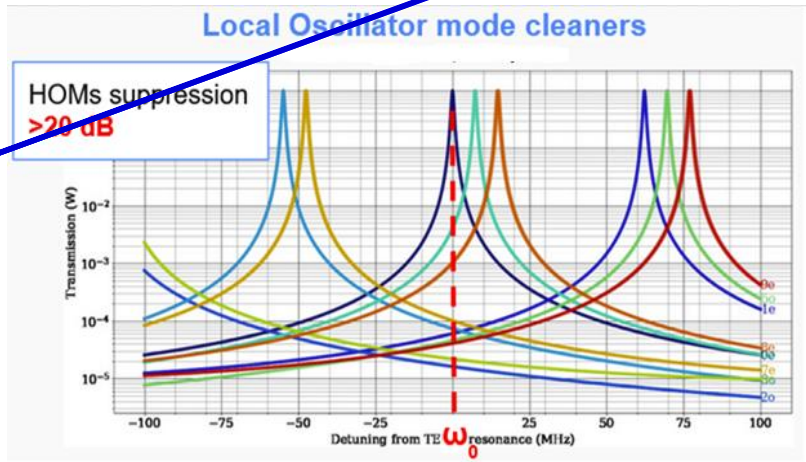
Reduction of Squeezing level due to the optical loss

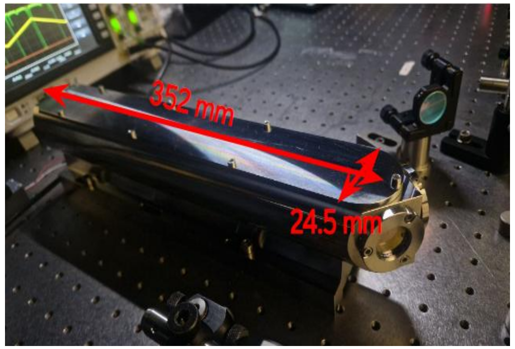
Chua+14

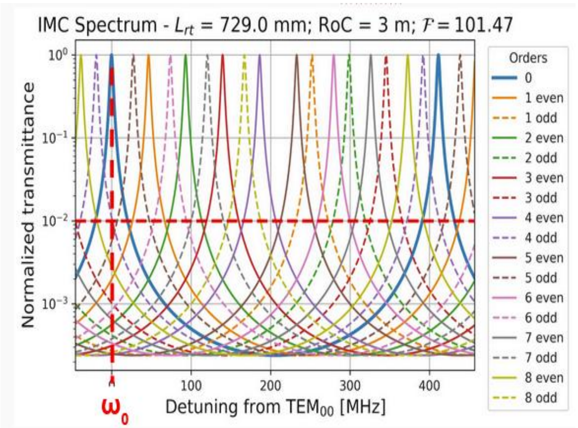
EPR experiment: Mode C~~c~~leaners









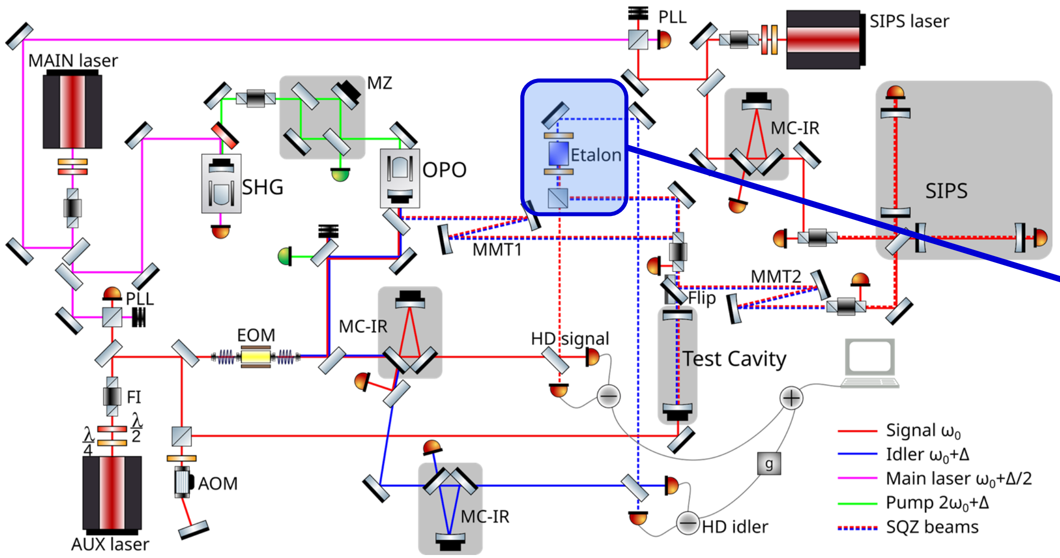


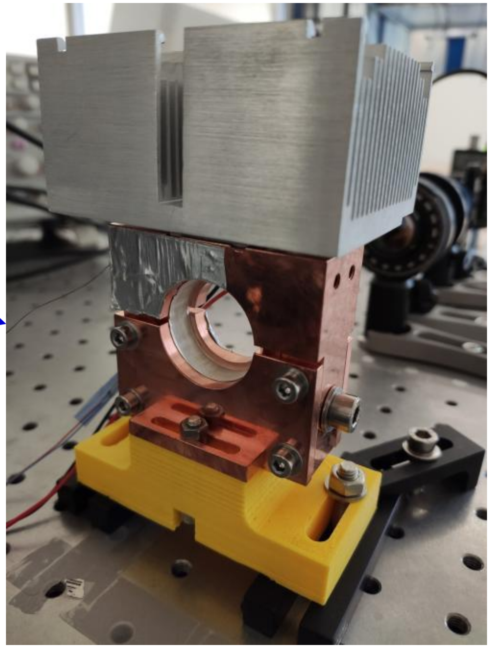
2 MC cavities are required for signal and idler Local Oscillator beams for balanced Homodyne detection

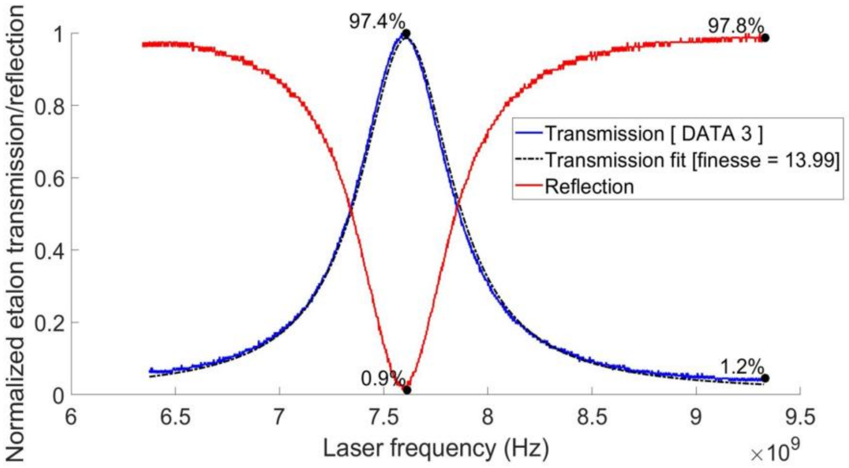
An input Mode Cleaner (MC) triangular cavity is required for MOPA laser for the interferometer

EPR experiment: Etalon

- An etalon is used for separating the signal and idler beams prior to homodyne detection
- It is monolithic and temperature-controlled

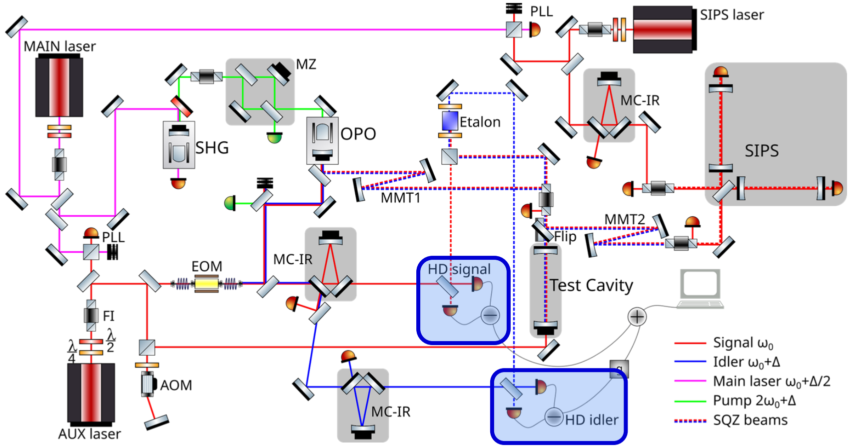


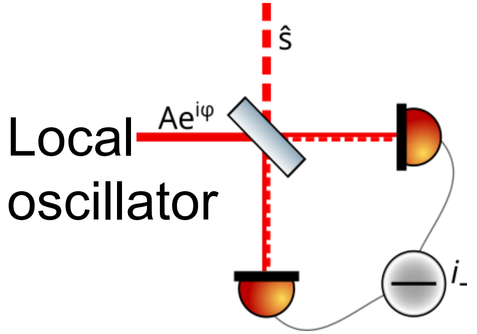




EPR experiment: Balanced homodyne detector (HD)

- Squeezing level is measured w.r.t. to the shot noise of a local oscillator with a Balanced homodyne detector
- Twin detectors in EPR scheme
- Measured: Clearance 17dB (3.2 mW of LO), Common mode rejection ratio (CMRR) 60dB





Homodyne detection

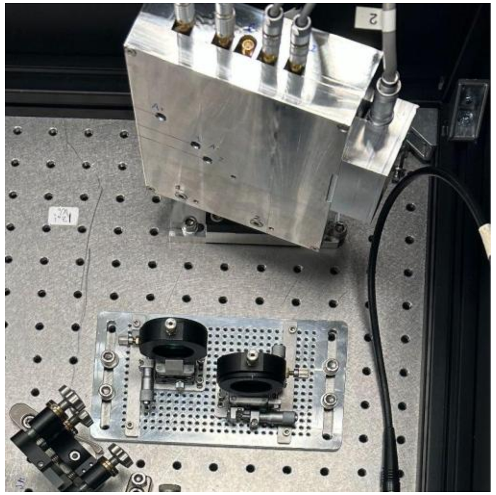
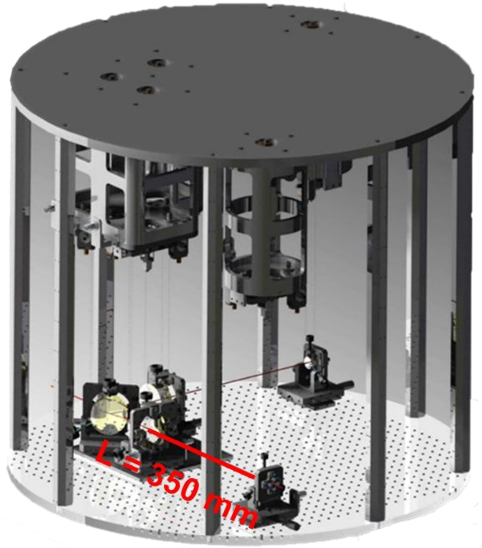


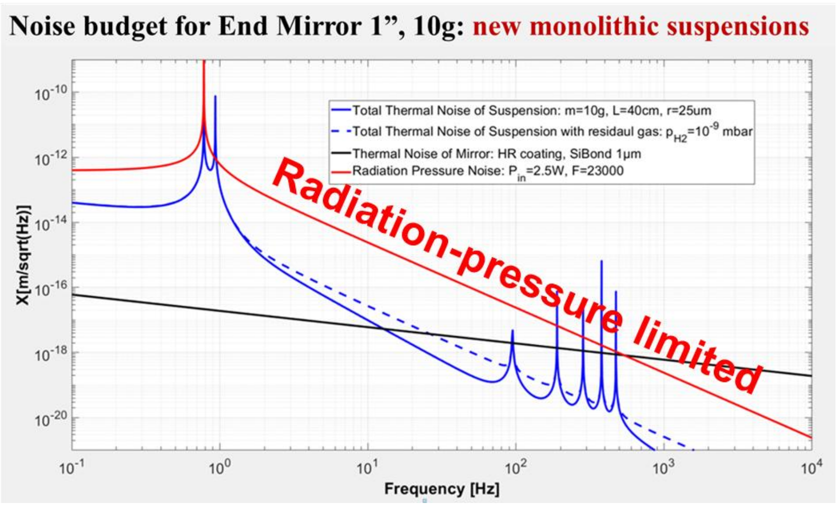
Image of HD

EPRs experiment: Interferometer

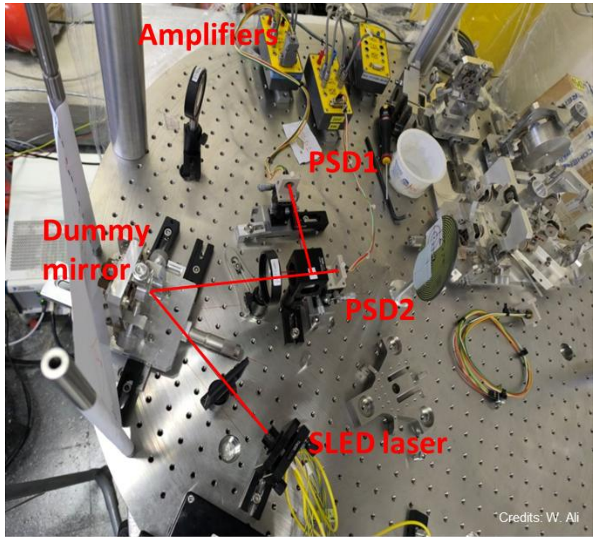
- Suspended Interferometer ponderomotive squeezing (SIPS) will used to test EPRs Squeezing in audio frequency band
- Non-recycled Michelson Fabry-Perot interferometer, with suspended optics and high-finesse arms
- New suspension system and local controls of the mirrors under installation



CAD drawing of SIPS



Noise curve of the SIPS (RPN limited)



Local control development of SIPS in Rome

Giacoppo+21

Conclusion

- Frequency Independent Squeezing (FIS) in O3 improved the astrophysical reach:
  → 5-8% increase in BNS horizon
- For broadband GW detectors sensitivity improvement Frequency Dependent Squeezing (FDS) is required and fundamental
- The EPR experiment is investigating an alternative technique to achieve frequency dependent squeezing in ET with less infrastructural and economical impact
- Primary scientific goal is the experimental validation of the EPR effect in the 100 Hz - 10 kHz band
- In expansion, we aim at demonstrating EPR squeezing in the frequency range of interest of GW detectors via the injection into a small scale suspended interferometer limited in by radiation pressure noise (SIPS)

Thank you!

Email : lee.sumin@yonsei.ac.kr

ET TDS link: https://apps.et-gw.eu/tds/?r=19817