Quantum entangled beams to improve the sensitivity of gravitational wave interferometers

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on behalf of Virgo EPR-squeezing group

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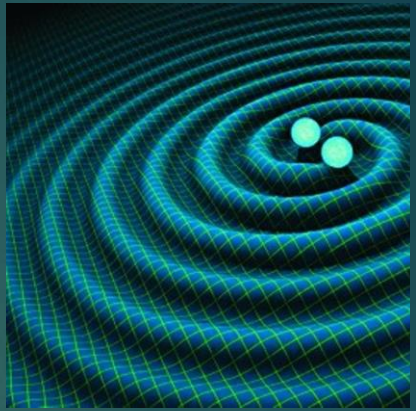
KAIST

KASI Korea Astronomy and Space Science Institute

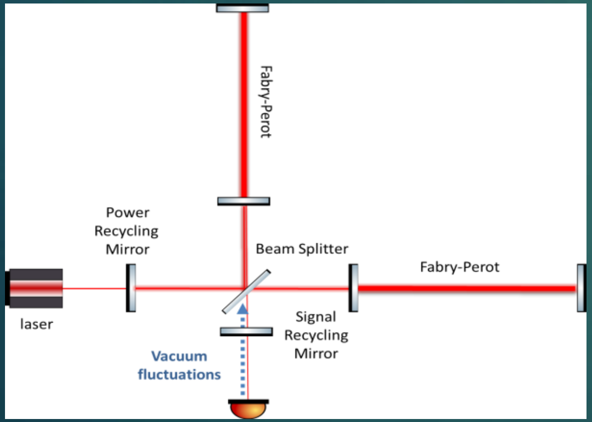
Gravitational waves

Gravitational waves (GW) are **transverse perturbations of the space-time**, produced by non-spherically symmetric accelerating masses.

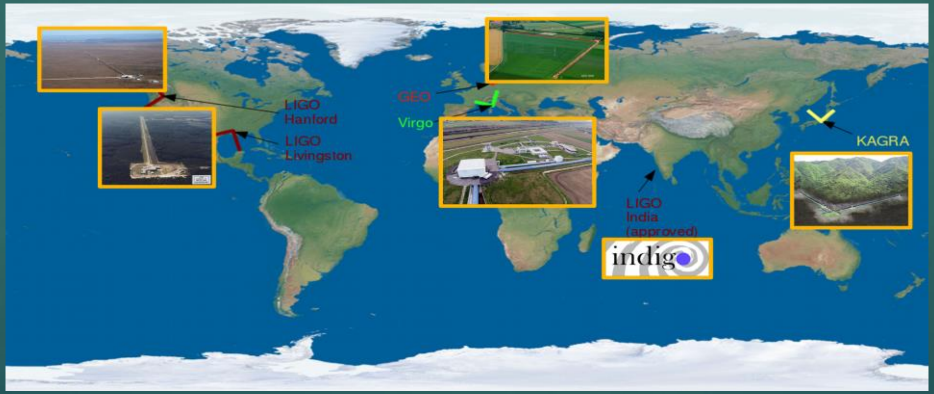


They were predicted by Albert Einstein in 1916 and they were detected about 100 years later using **interferometric detectors**.

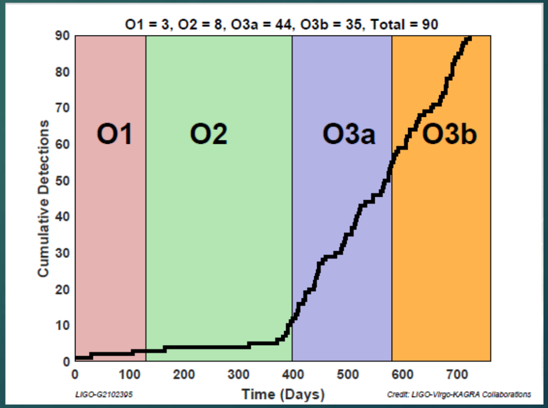
Interferometric GW detector



GW detector network

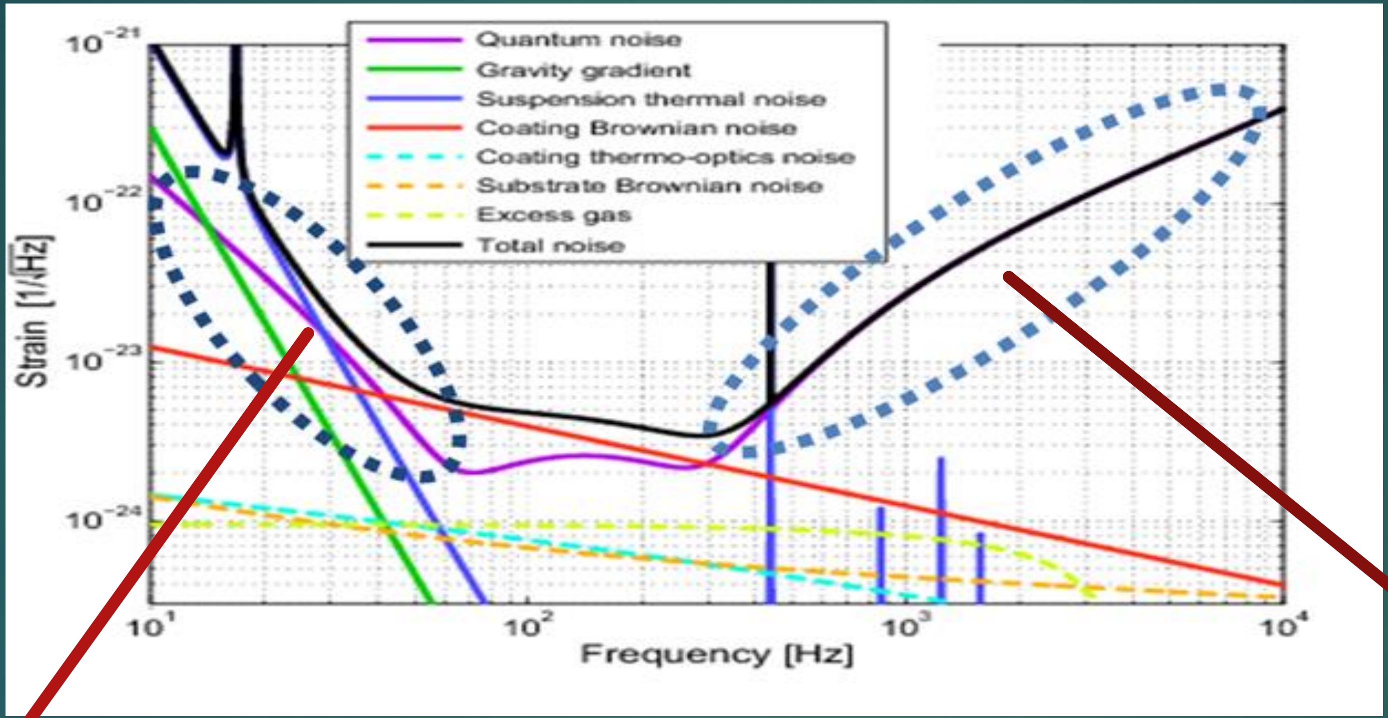


90 GW signals detected up to now



Quantum noise in gravitational wave detectors

Advanced Virgo sensitivity curve



RADIATION PRESSURE NOISE

Vacuum amplitude-fluctuations, more evident at lower frequencies.

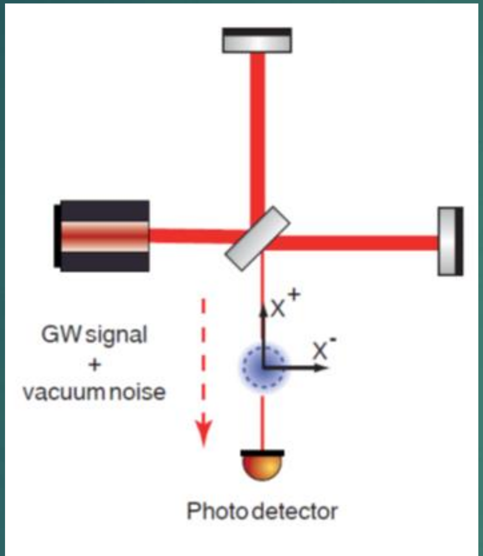
SHOT NOISE

Vacuum phase-fluctuations more evident at higher frequencies

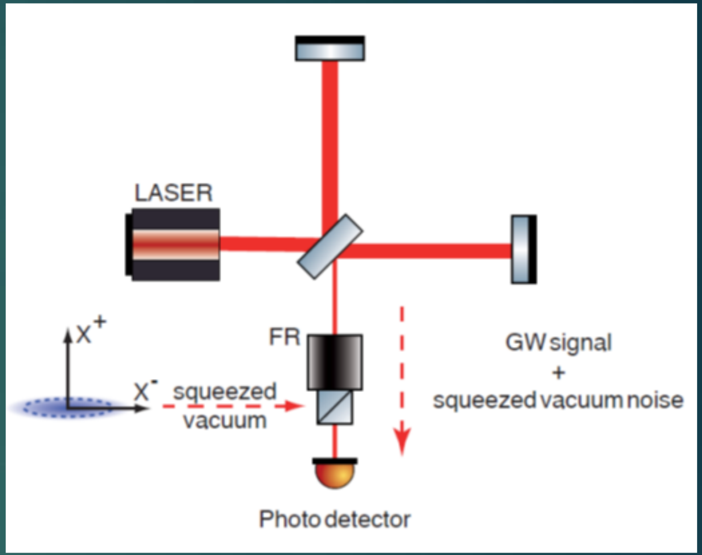
Quantum noise reduction via 'squeezed' states

C. M Caves. Physical Review D, 23(8):1693, 1981

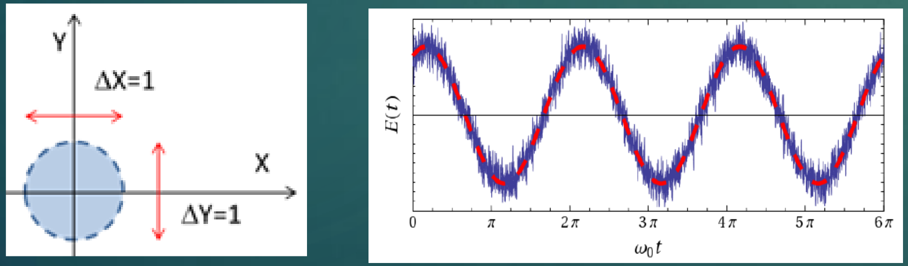
Quantum noise comes from **vacuum fluctuations** entering the interferometer



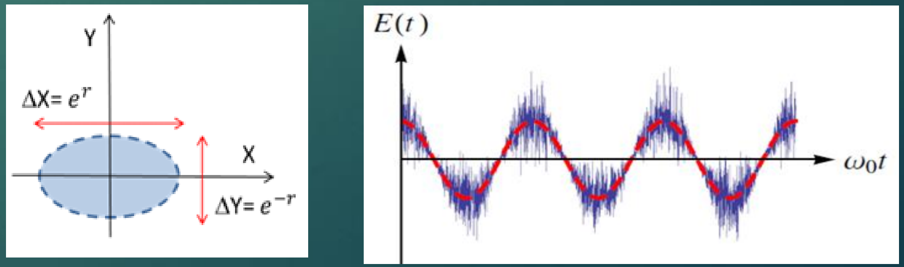
The injection of quantum vacuum states with reduced noise in amplitude or phase can reduce quantum noise.



Coherent states



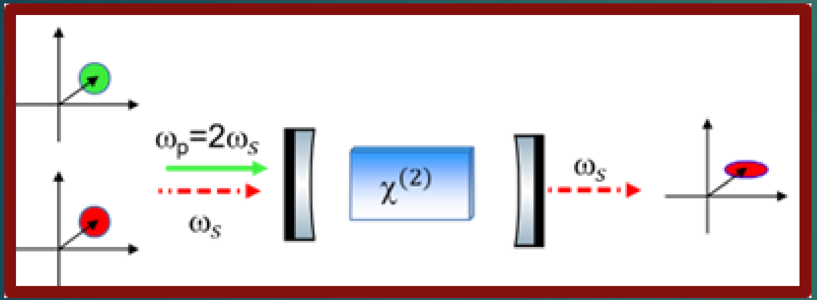
Phase-squeezed states



Squeezed vacuum generation

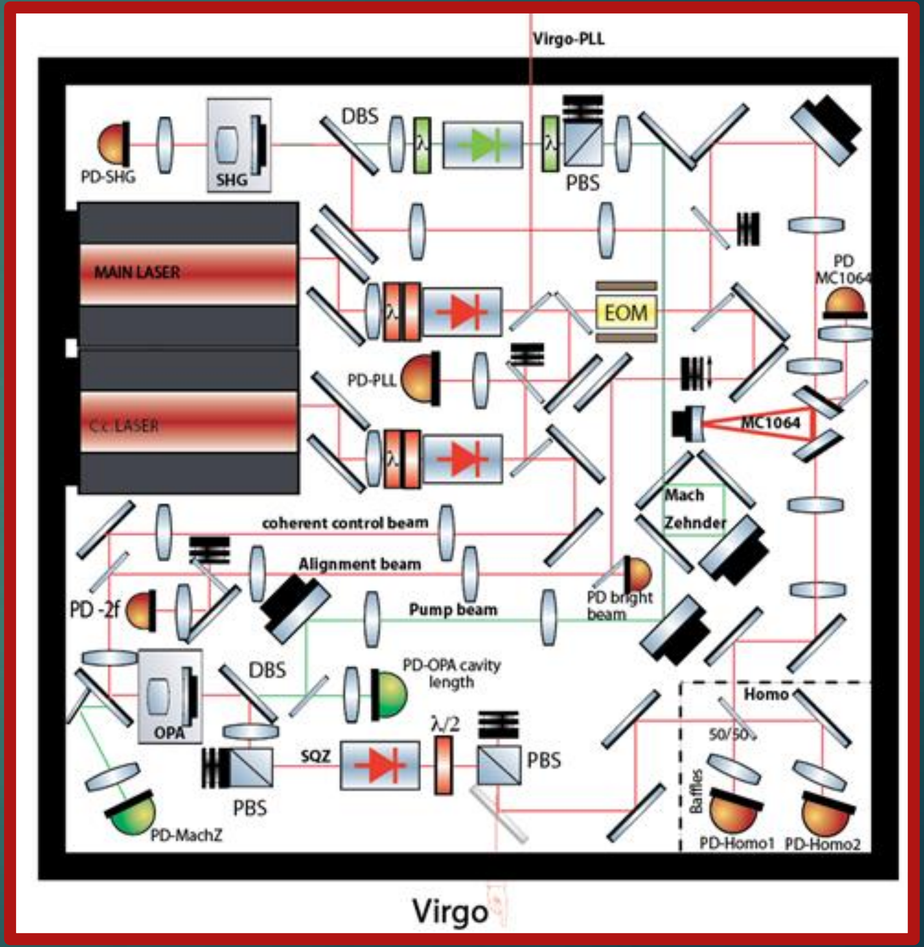
Squeezed-states of light can be produced via a **second order non-liner crystal**.

OPO (Optical Parametric Oscillator)



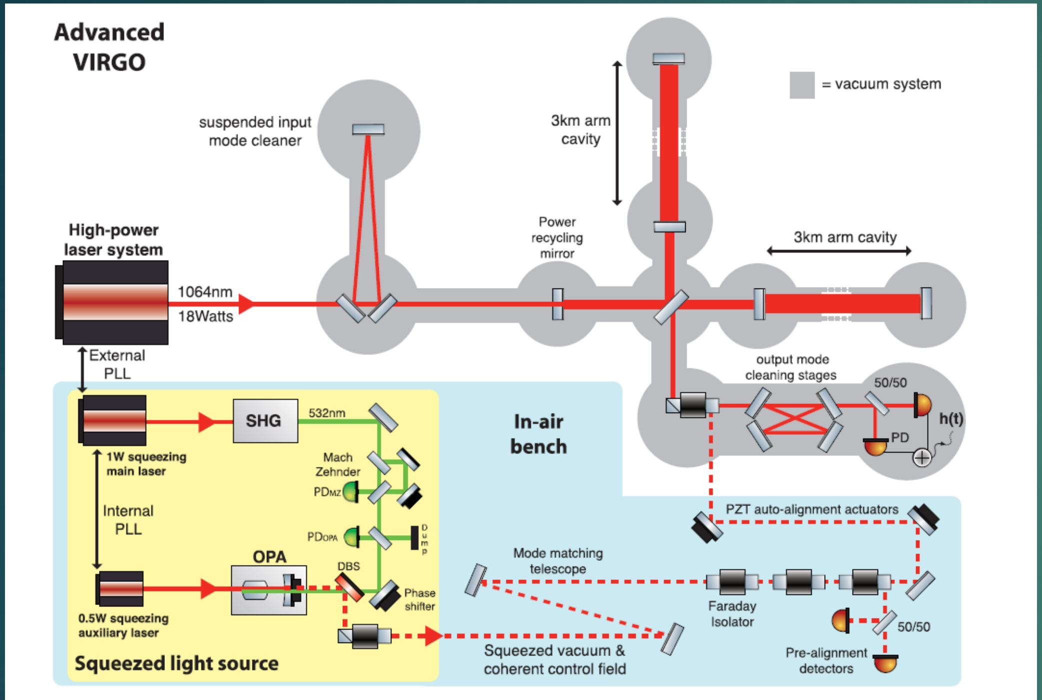
A complete squeezed light source is much more complex…

Squeezed-light source used in Advanced Virgo

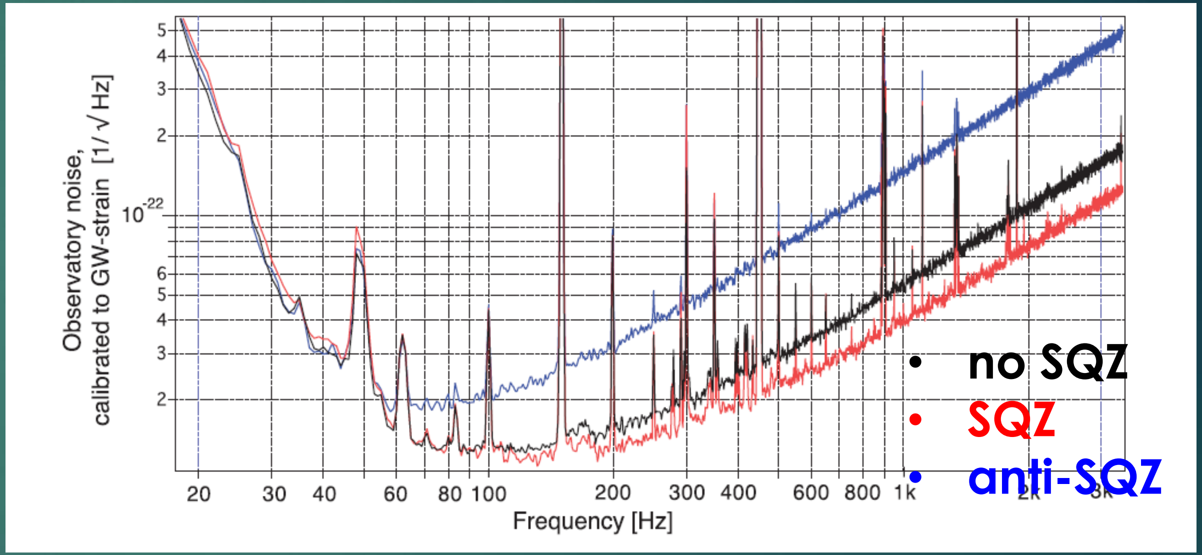


Results achieved in Advanced Virgo

Squeezed vacuum injection in Advanced Virgo



Advanced Virgo was only limited by shot-noise that dominates at frequencies more than 200 Hz



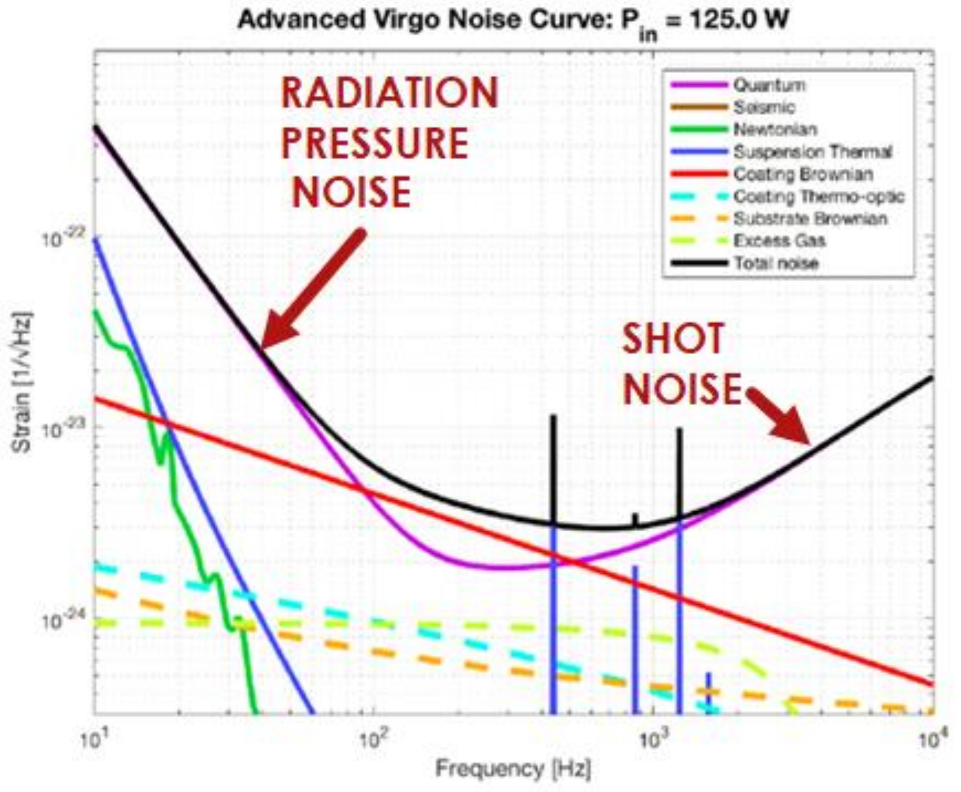
5% - 8% overall sensitivity improvement of the detector

Measured squeezing level:
3.2 ± 0.1 dB
Measured anti-squeezing level:
8.5 ± 0.1 dB

Acernese, F., et al. *Physical Review Letters* 123.23 (2019): 231108

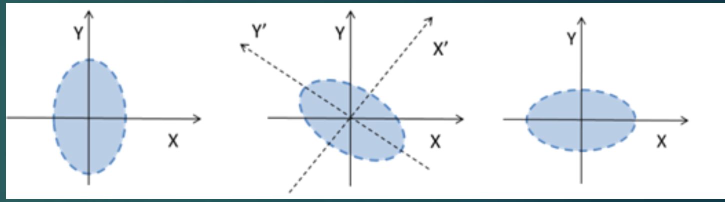
Quantum noise in the next generation of GW detectors

Radiation pressure noise (RPN) and shot noise (SN) both limit the sensitivity of GW detectors

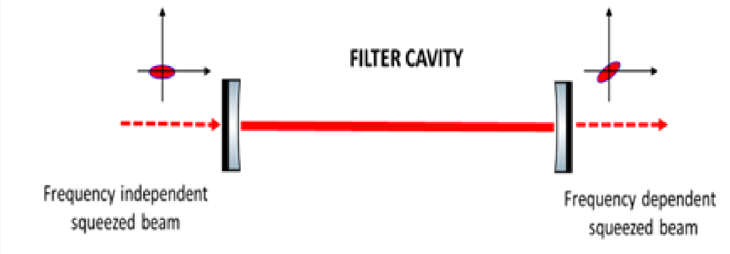


A **rotation of the squeezing angle** is needed

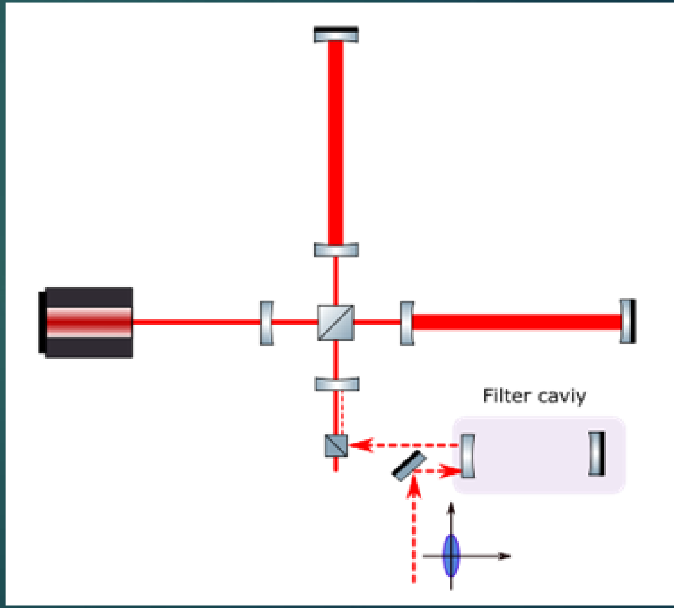
RPN → amplitude noise
SN → phase noise



This is achievable using a 300 m long **detuned** cavity



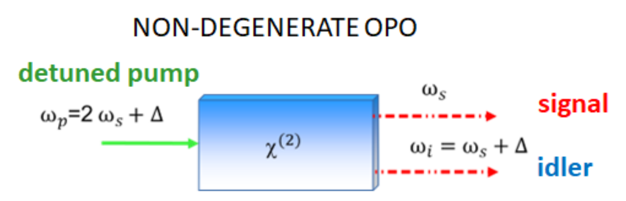
$$\theta_{fc}(\Omega) = \arctan\left(\frac{2\gamma_{fc}\Delta\omega_{fc}}{\gamma_{fc}^2 - \Delta\omega_{fc}^2 + \Omega^2}\right)$$



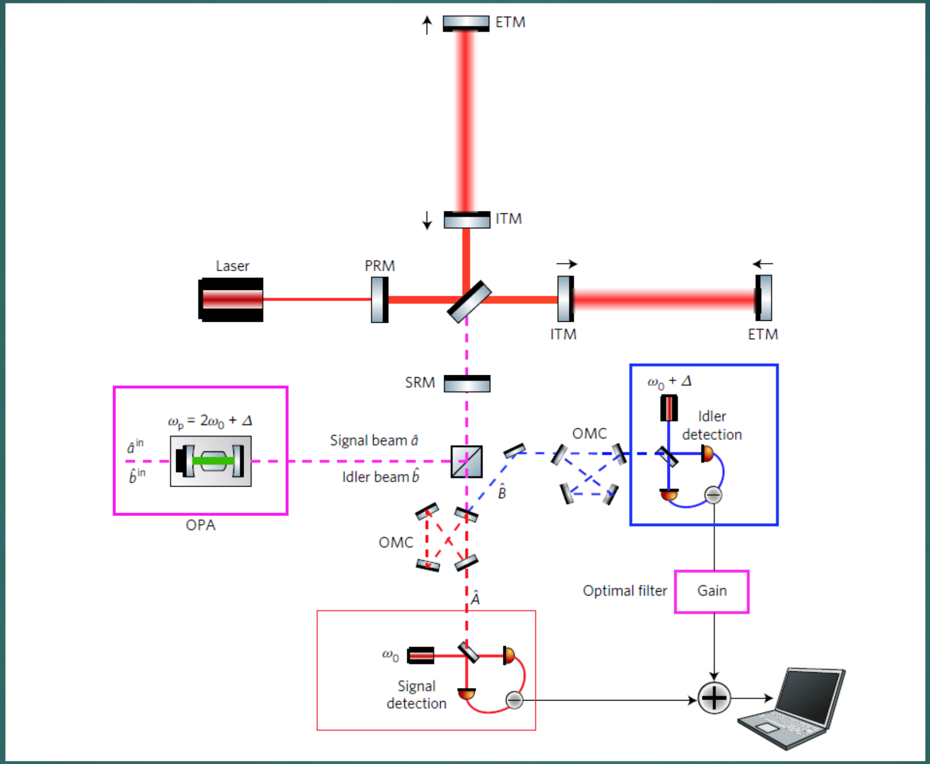
Frequency-dependent squeezing using EPR-entangled states

Y. Ma et al. Nat Phys 13 no. 8, (Aug, 2017) 776–780

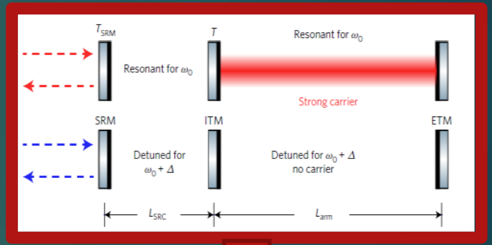
Non-degenerate OPO produces two entangled fields (signal and idler)



The two fields are injected into the GW interferometer and separated once they exit the interferometer.



One of the beams, the signal, is resonant inside the optical cavities which are **detuned** for the idler.

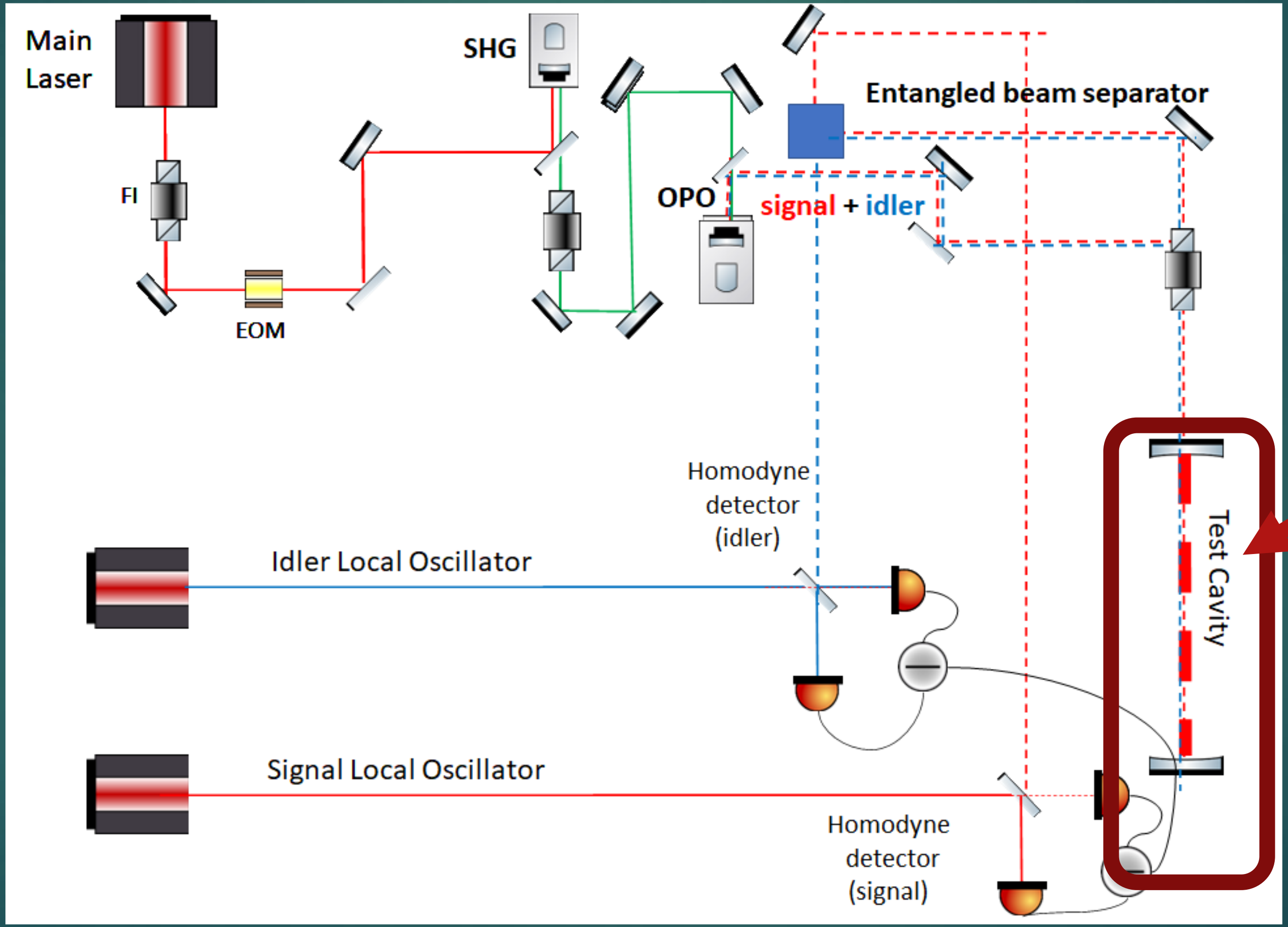


- The idler experiences ‘frequency-dependent squeezing;
- The signal will be ‘‘conditionally’’ squeezed.

This represents a **valid alternative to filter-cavity technique**, being a **cheaper and more compact system**.

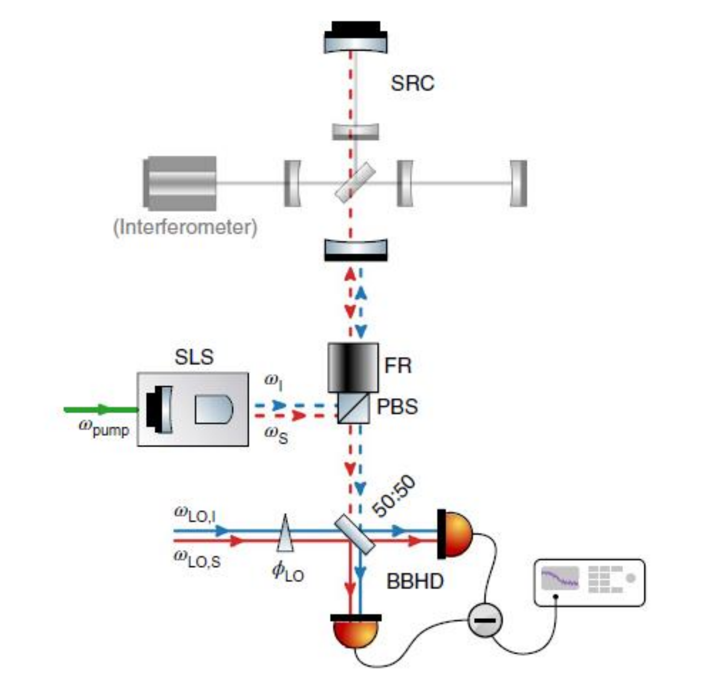
A table-top EPR-experiment: conceptual design

A test-cavity is used instead of the interferometer

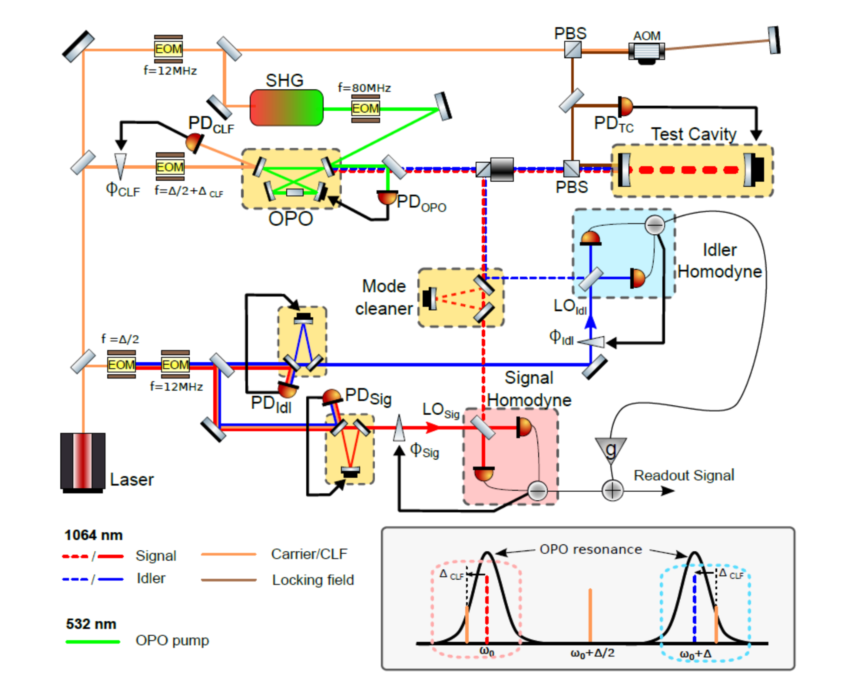


Preliminary demonstrations

Two independent table-top experiments provided a proof of principle of this technique, using semplified setups.



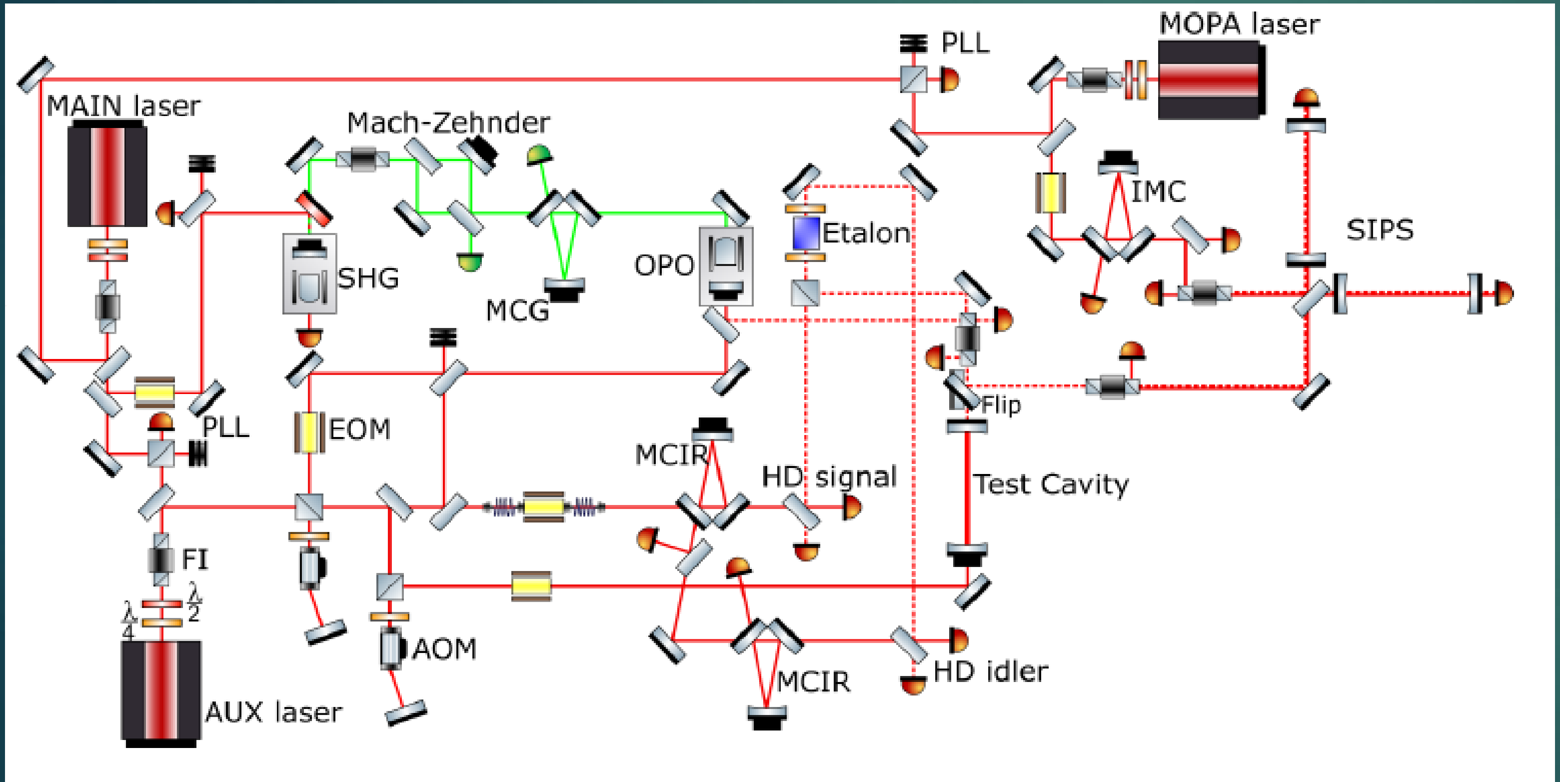
Südbeck, Jan, et al. *Nature photonics* 14.4 (2020): 240-244.



Yap, Min Jet, et al. *Nature Photonics* 14.4 (2020): 223-226.

Our experiment

We propose, for the first time, to inject EPR-squeezed fields in a scaled suspendended interferometer sensitive either to radiation pressure noise and shot noise, depending on the observation frequency. In this way a frequency-dependent reduction of quantum noise will be achieved.



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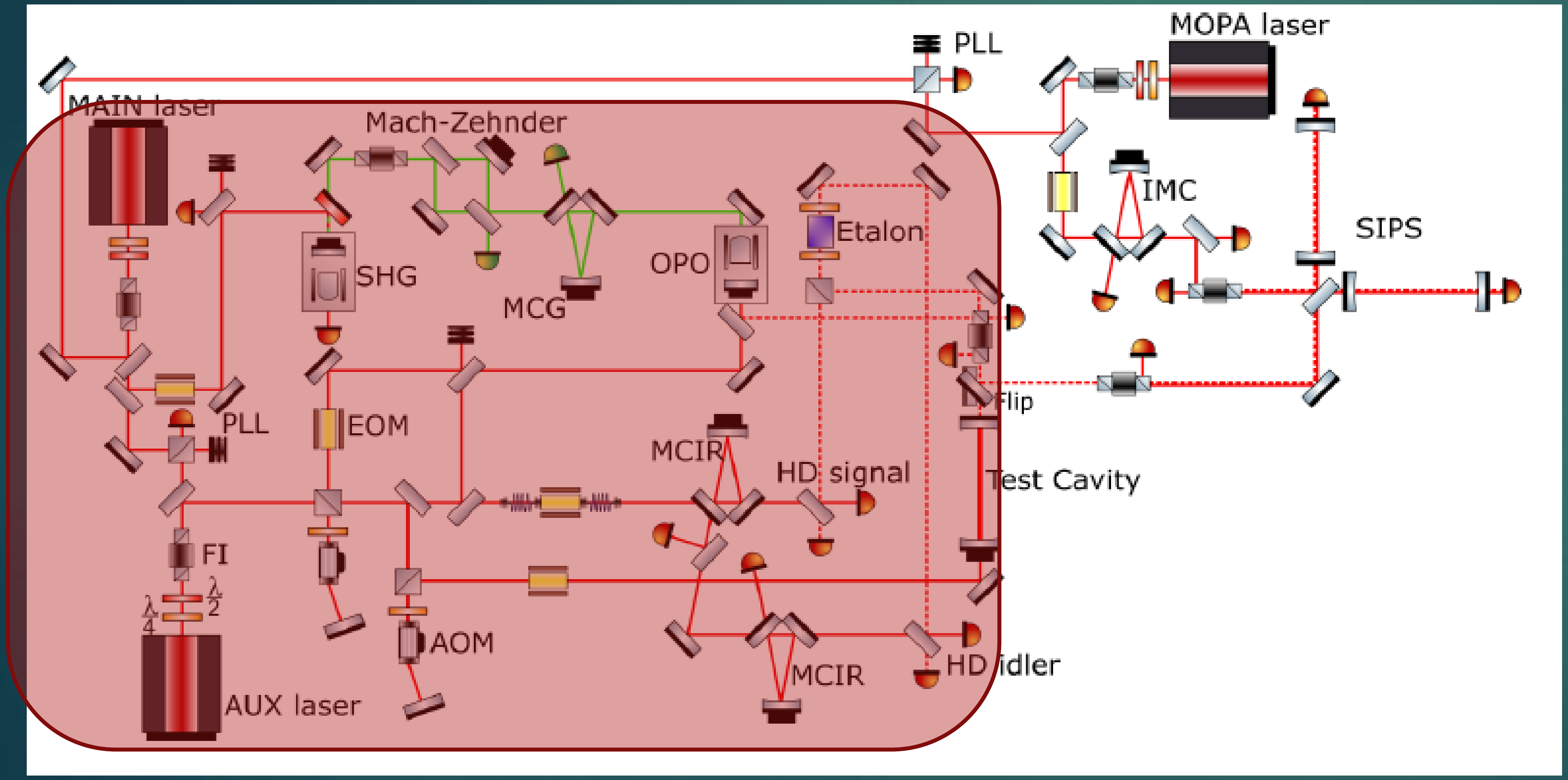

EPR-SQUEEZING TABLE TOP EXPERIMENT

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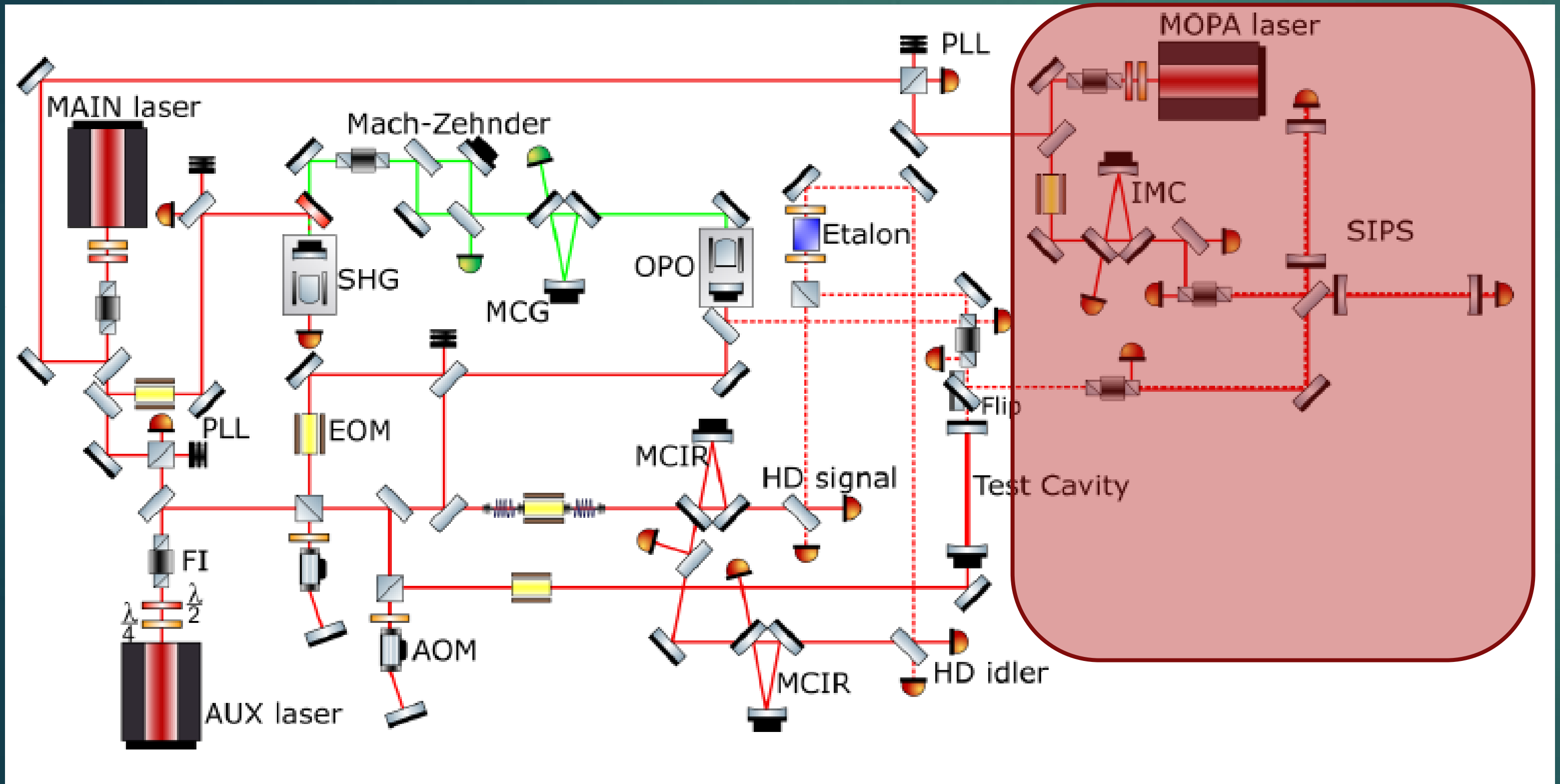


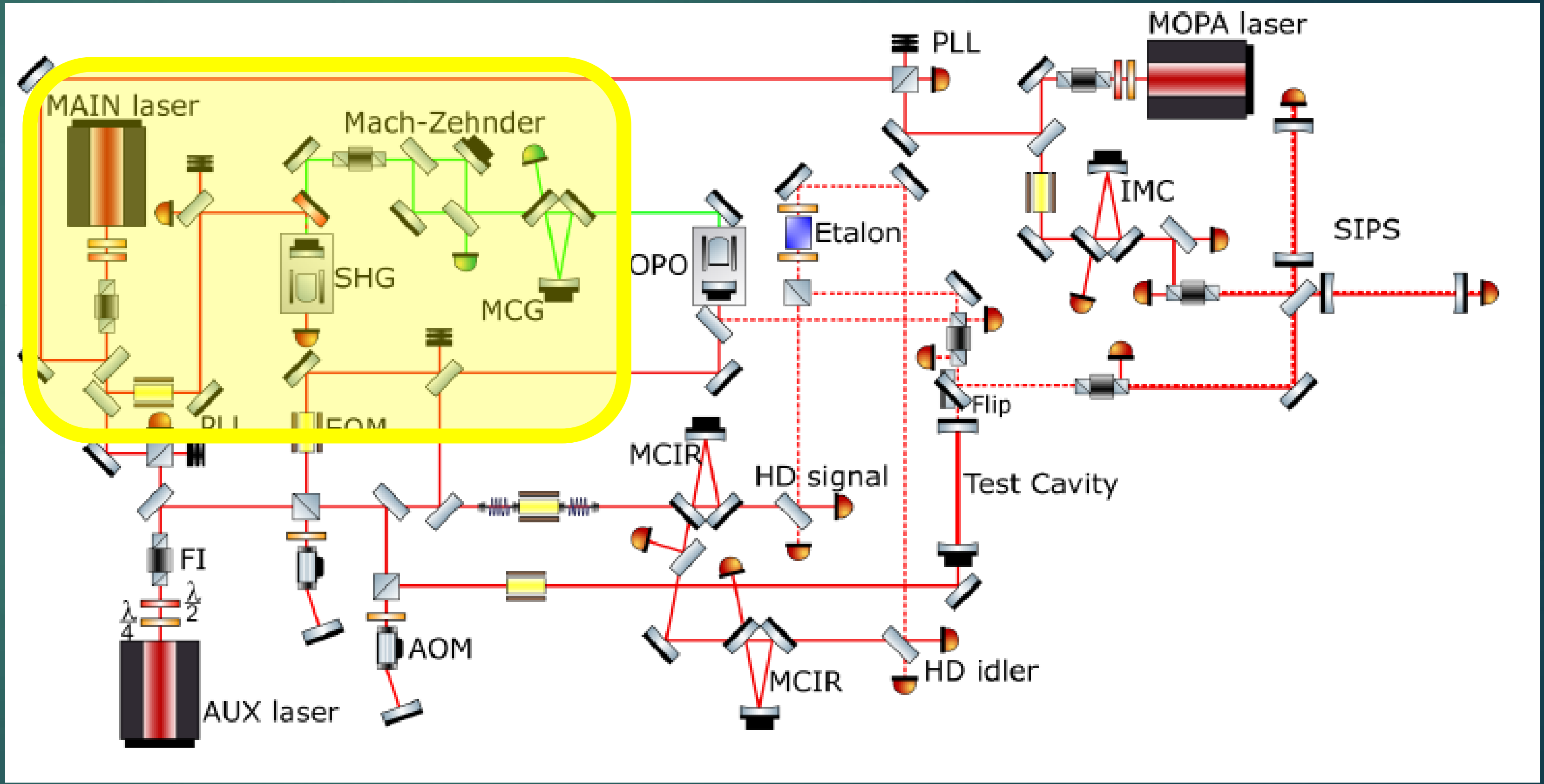
INJECTION IN A SMALL SUSPENDED INTERFEROMETER SIMILAR TO VIRGO DETECTOR

See talks by S. Di Pace and L. Giacoppo

EPR table-top experiment

A test-cavity is used instead of the interferometer

- Pump beam generation;
- Entangled beams production;
- Injection into the test cavity;
- Separation of the two beams;
- Separate homodyne detection
- Combination of the two measurements



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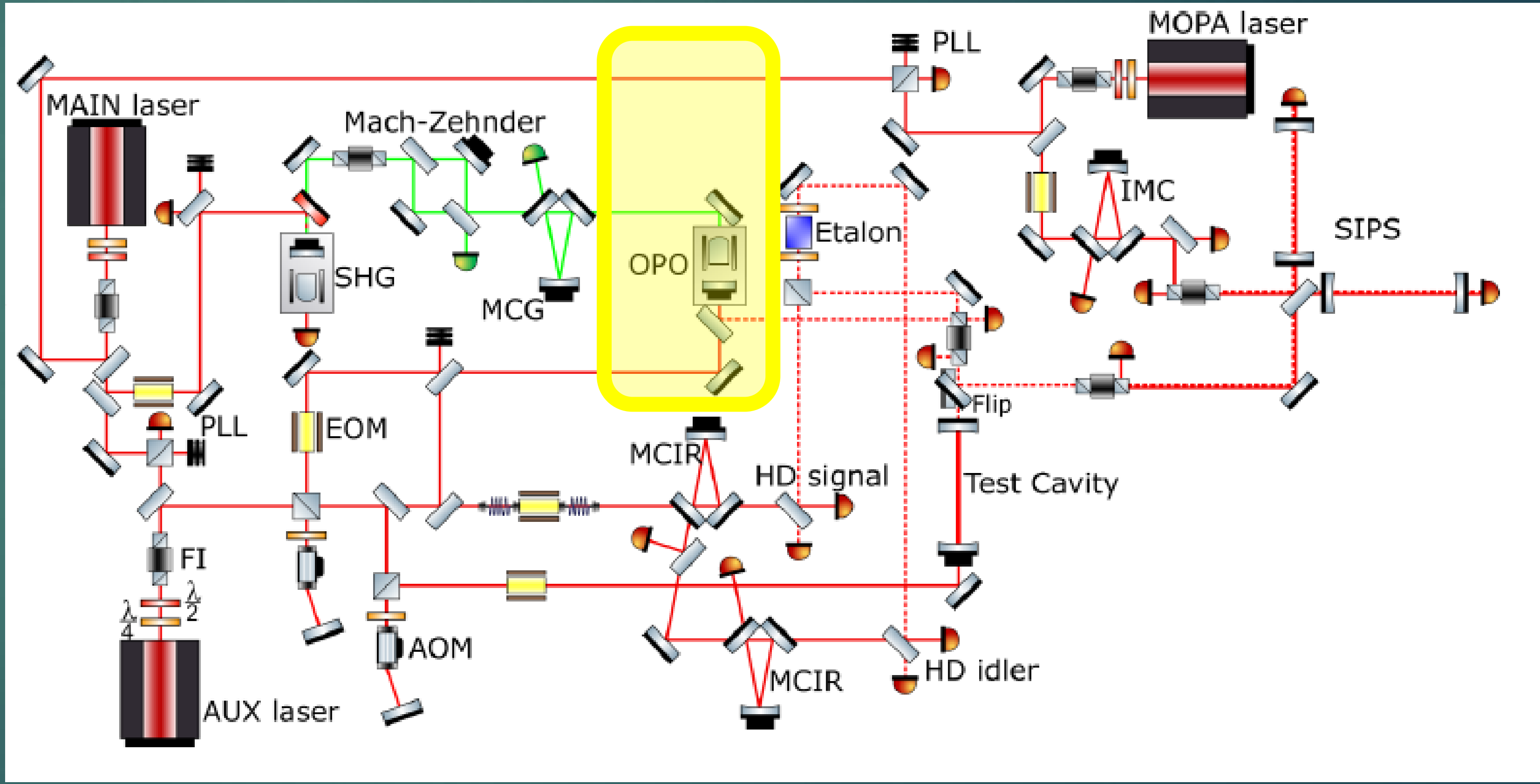
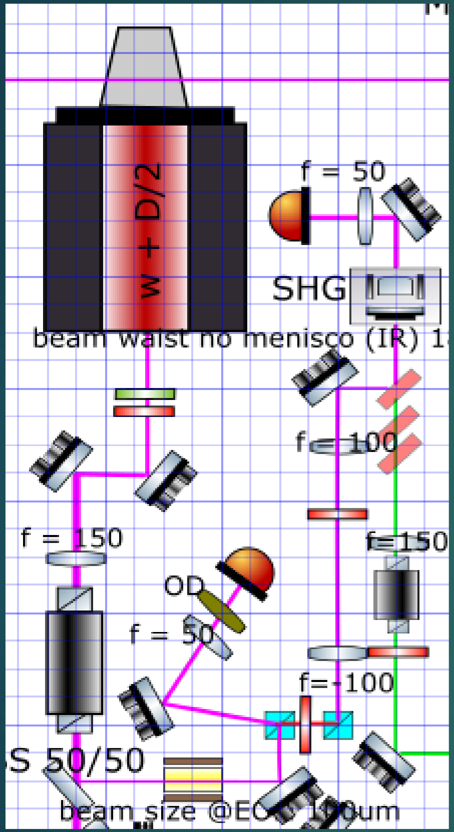
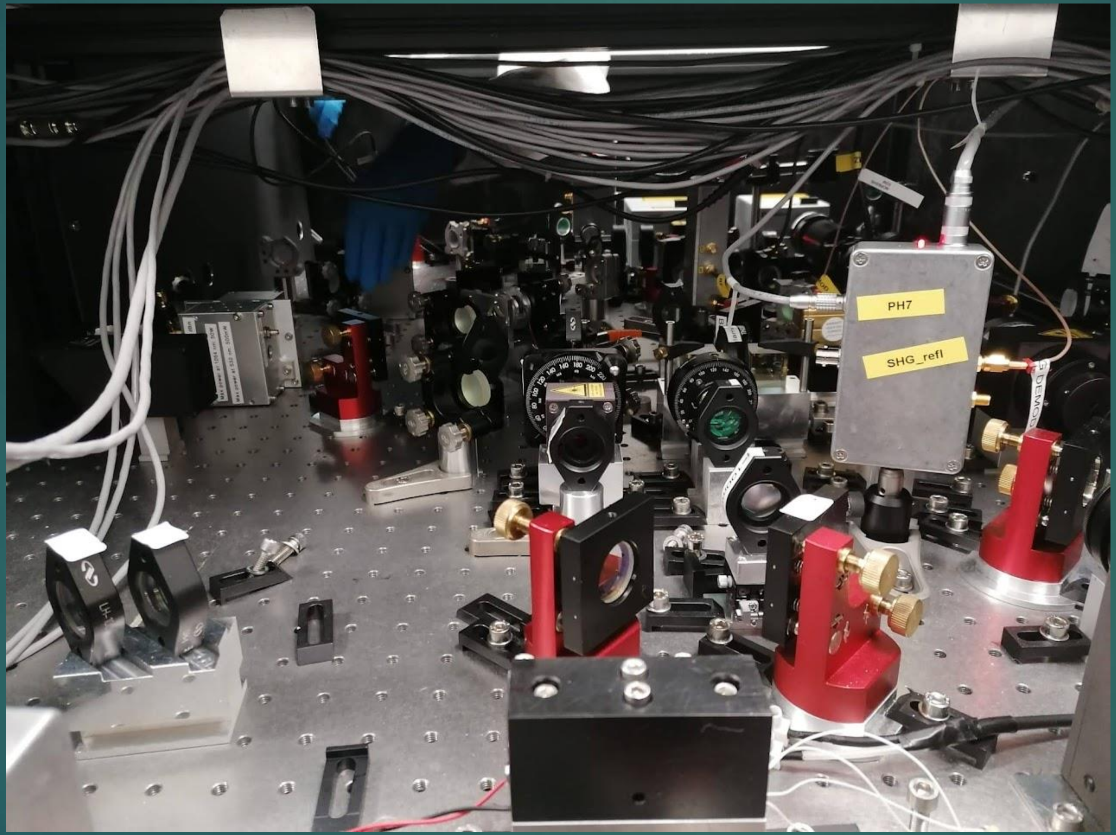
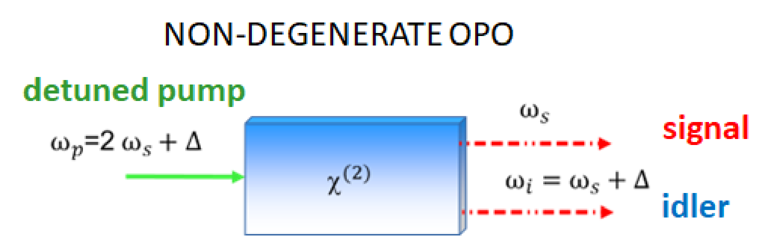


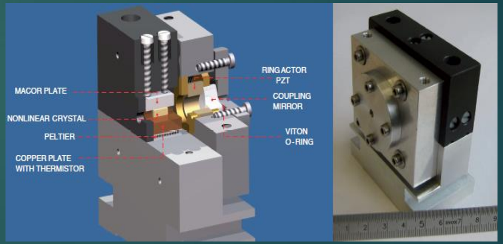
Pump beam generation and entangled beam production





The produced beam will be used as pump beam for the OPO





Credit to A. Khalaidovski

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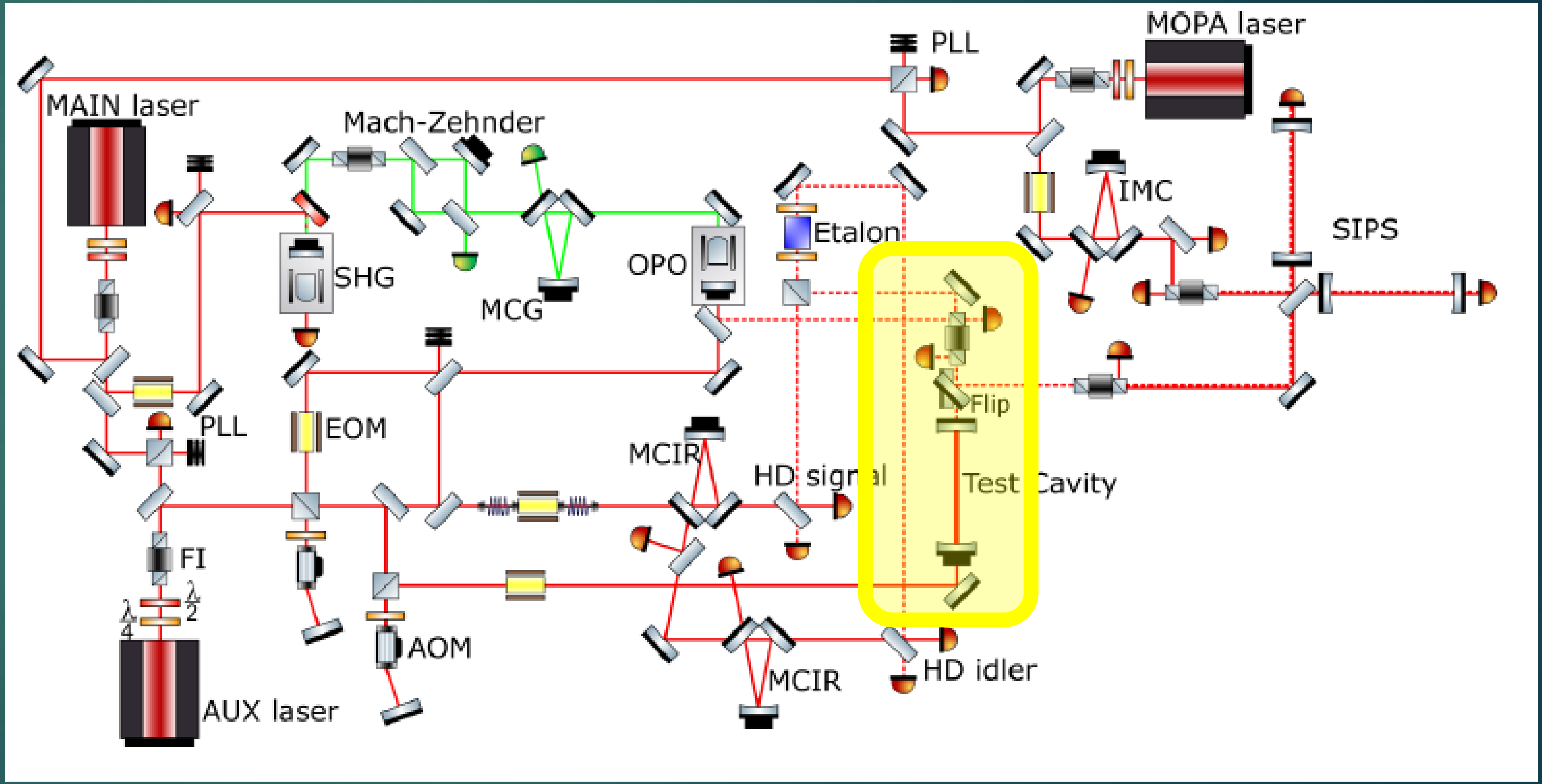
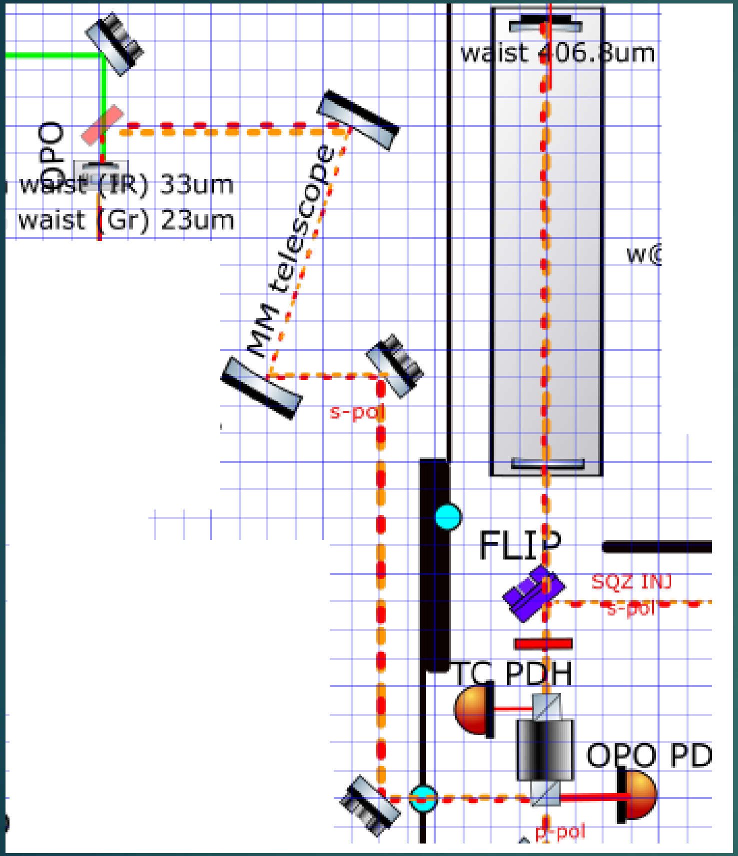
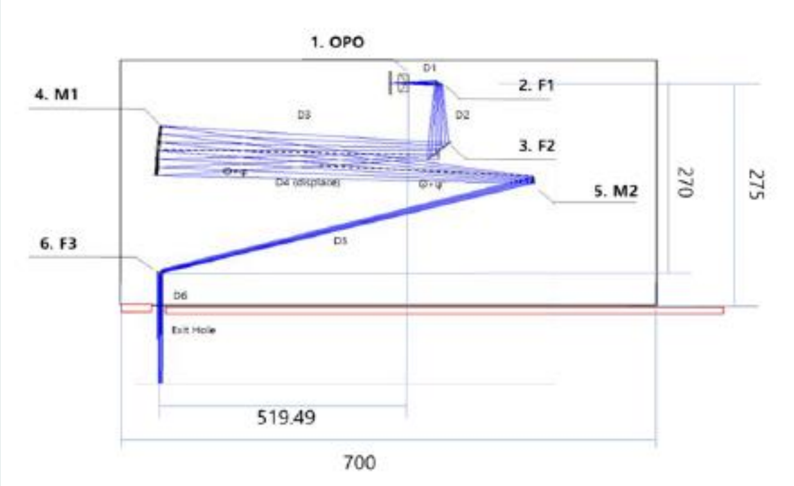


Injection into the test cavity: mode matching telescope

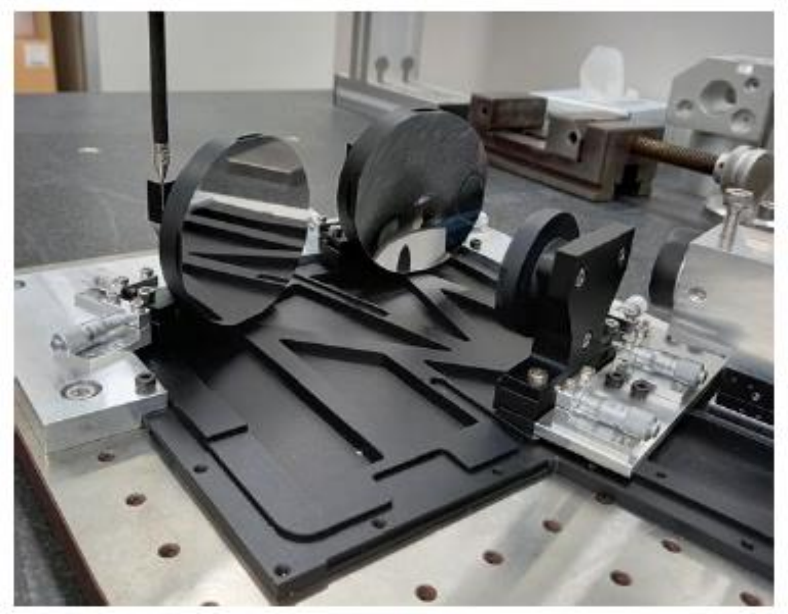


Mode-matching telescope to adapt the shape of the entangled beams to the test cavity.



Korea Astronomy and Space Science Institute

The telescope is aligned through a coordinate measurement machine



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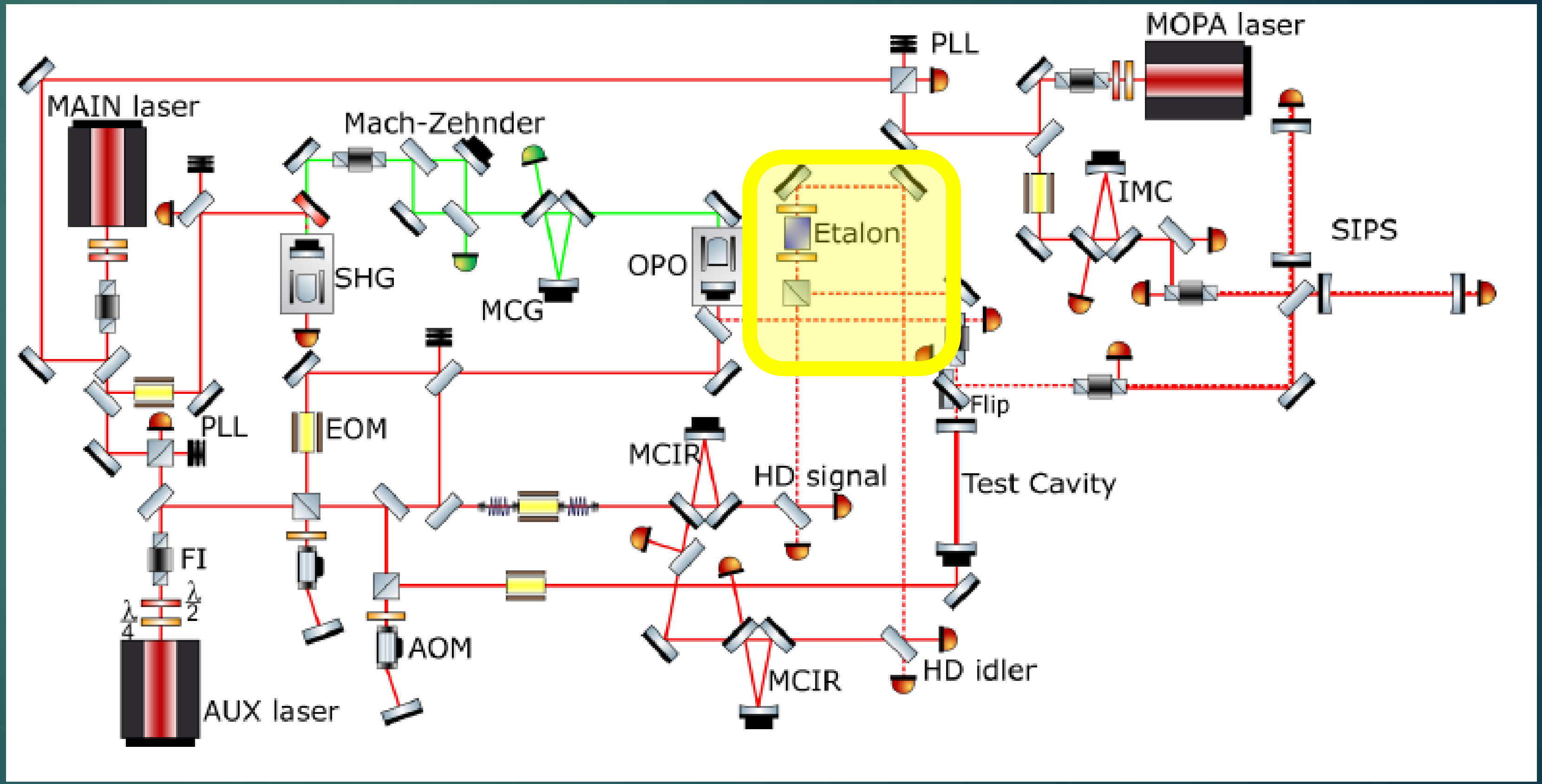
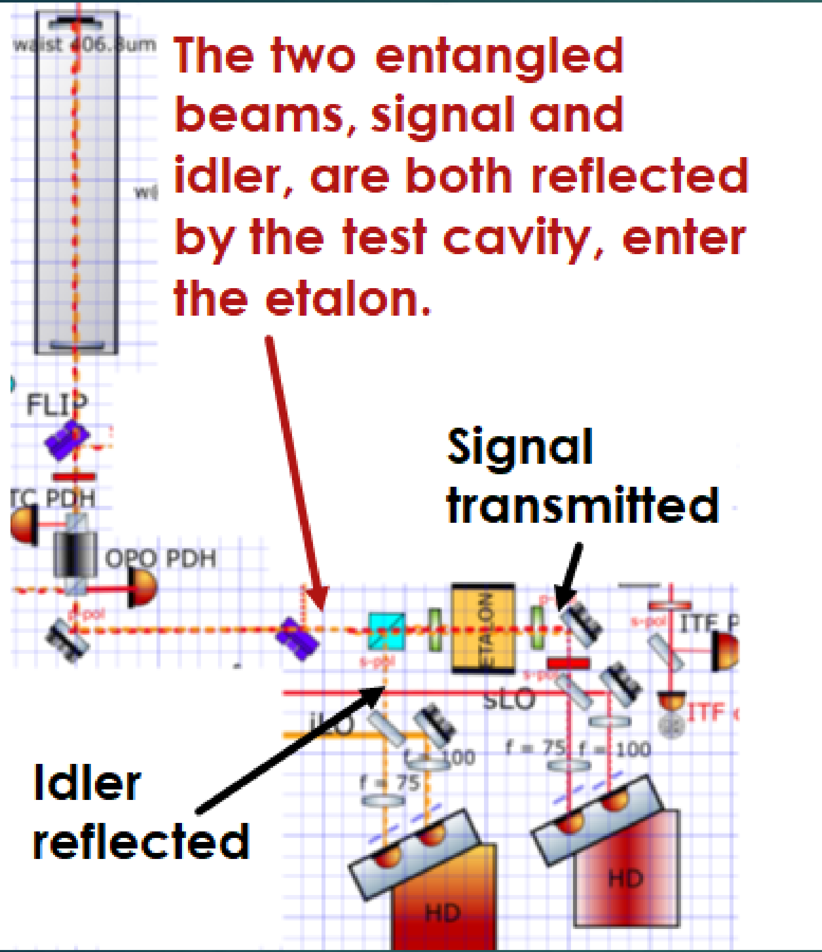
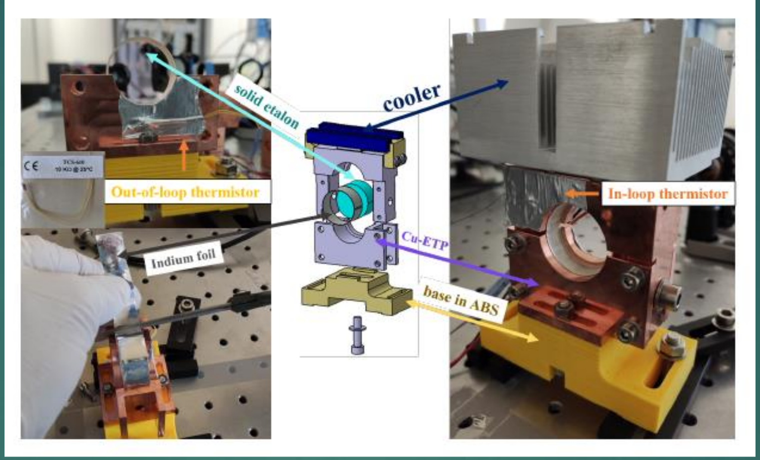
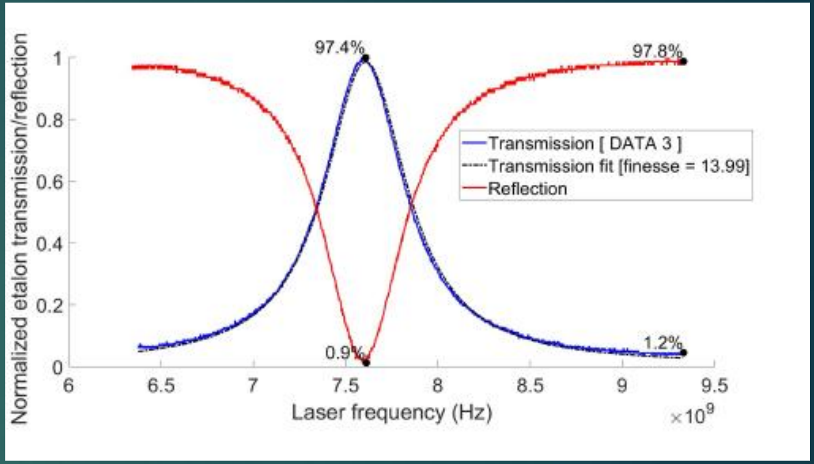


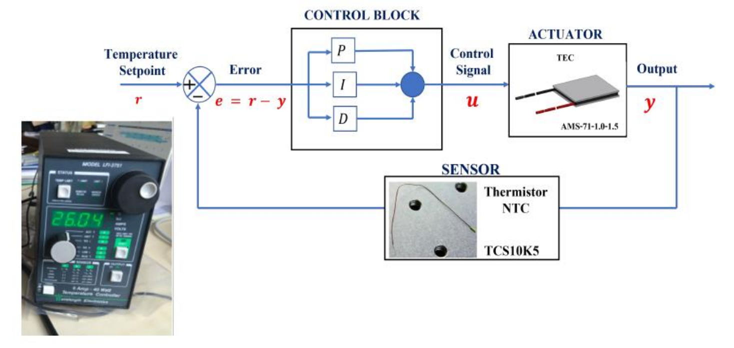
Etalon for entangled beam separation





System thermally controlled





This system is able to separate the two entagled beams (signal trasmitted at 97.4% and idler reflected at 97.8%). Each of them will be detected by two separate homodyne detectors.

Nguyen, C., Bréelle, E., Barsuglia, M., Capocasa, E., De Laurentis, M., Sequino, V., & Sorrentino, F. (2022). *Applied Optics*, *61*(17), 5226-5236.

EPR table-top experiment

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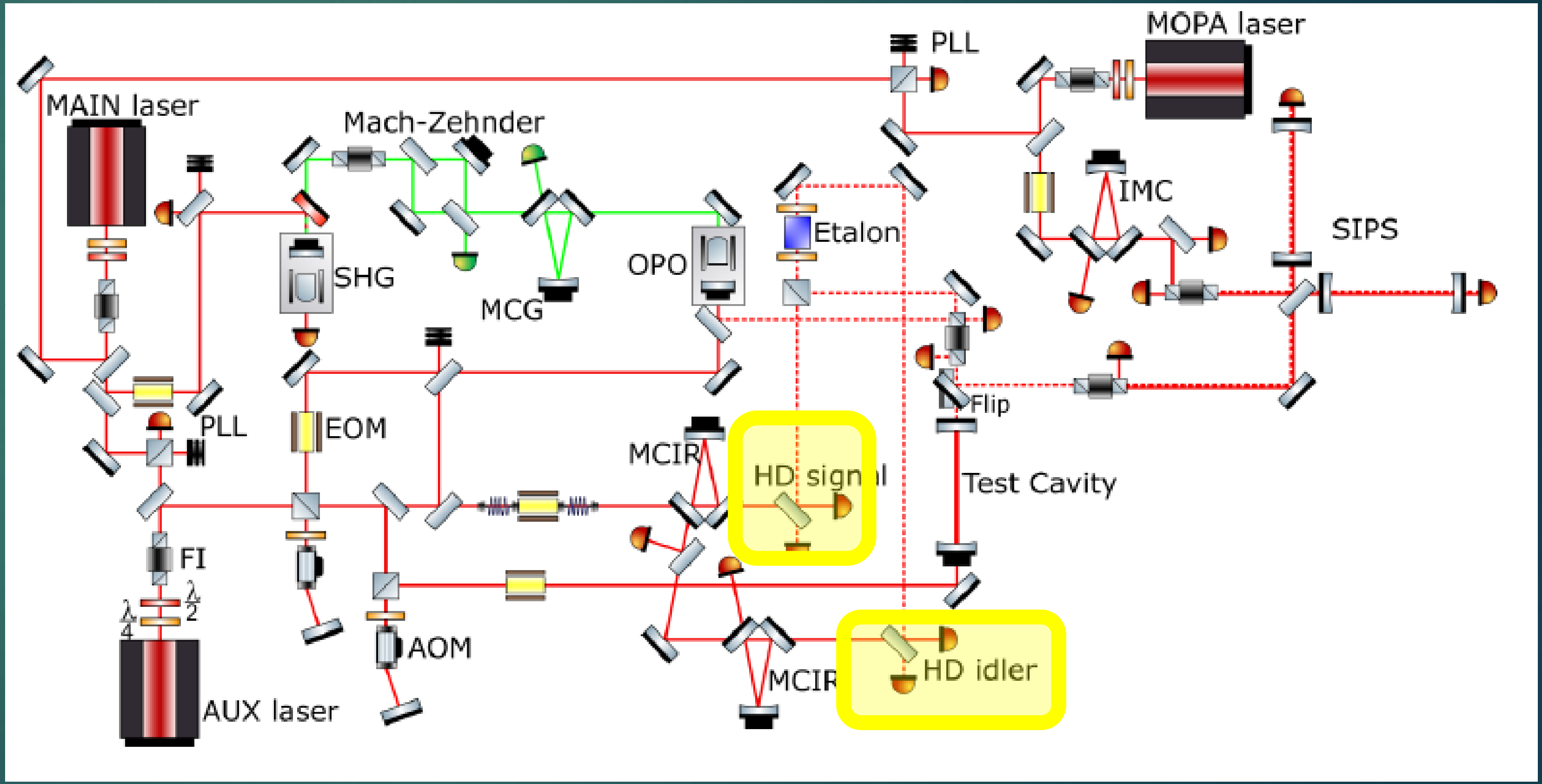
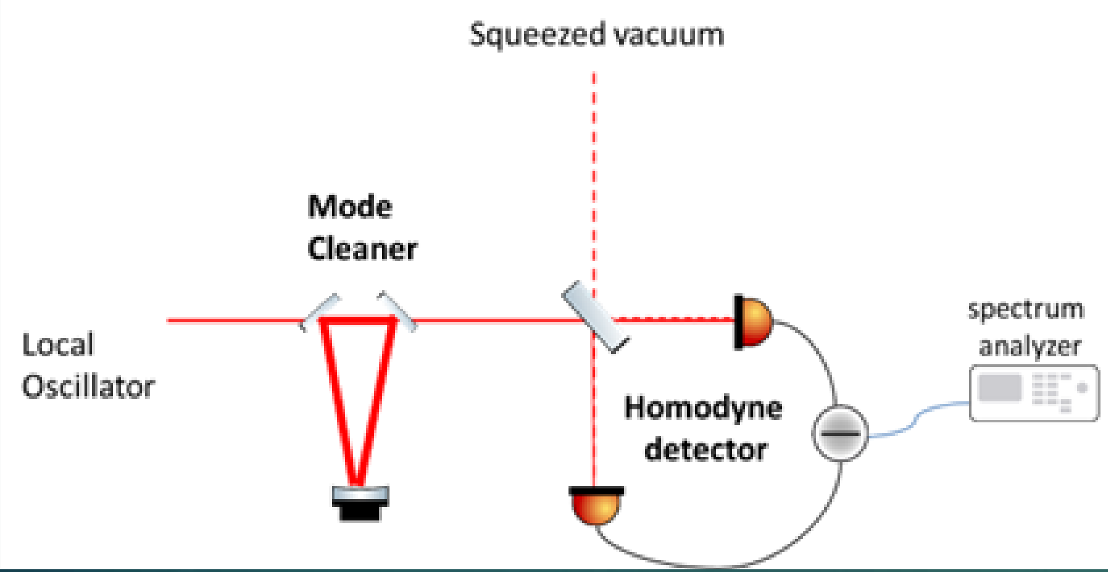


Homodyne detector

Once separated by the etalon, each squeezed beam interferes with a reference beam (local oscillator) at a 50:50 beam splitter. The two identical beams exit the output ports of the beam splitter and arrive at two high efficiency photodiodes whose photo-currents will be subtracted so that classical noise will be cancelled and only quantum noise will survive. The presence of the squeezed beam will reduce the quantum noise of the reference beam.



Two reference beams (local oscillators) are provided by an external laser.

EPR table-top experiment

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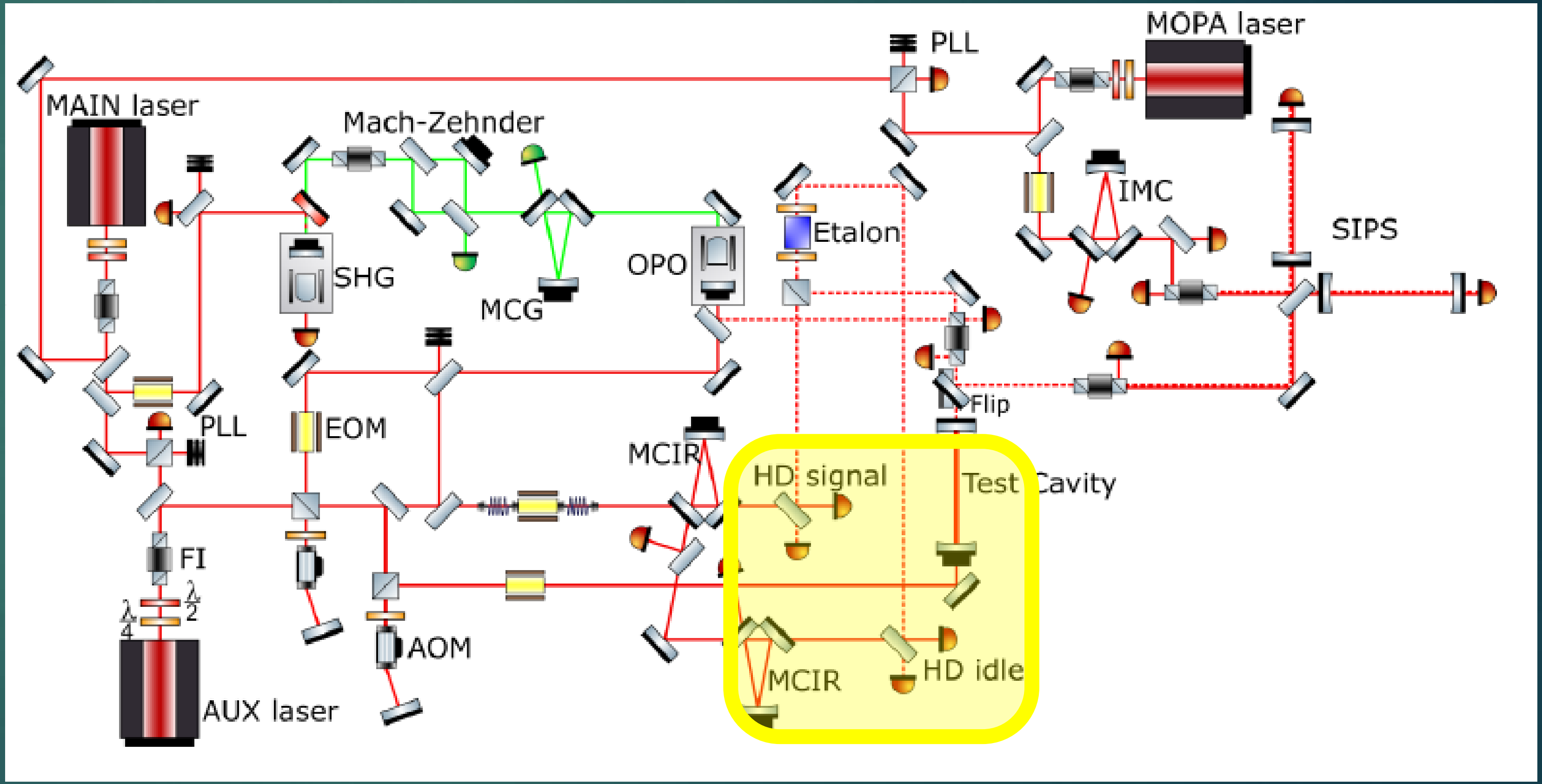
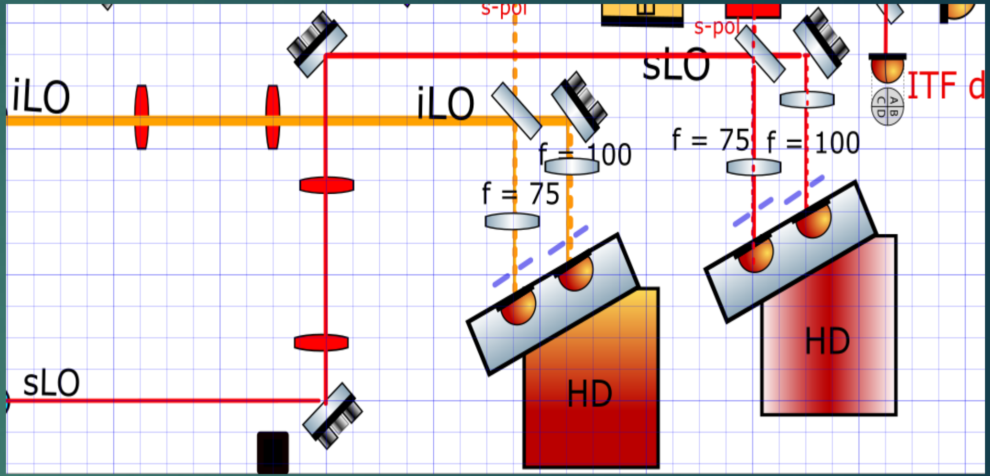


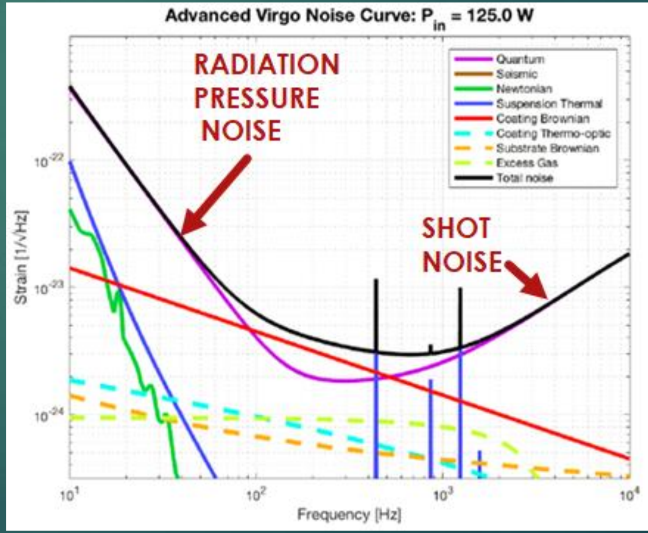
Combined squeezing measurement

In our experiment, the idler that is detuned with respect to the test cavity, experiences a frequency-dependent reduction of quantum noise.

The entanglement of signal and idler assure that also the signal will be squeezed in a frequency-dependent manner.



Using these beams inside a gravitational wave interferometer, will assure a frequency-dependent reduction of quantum noise, thus an improvement of the detector sensitivity in the whole detection bandwidth,



Conclusions

- Gravitational wave detectors are affected by **quantum noise due to vacuum fluctuations;**
- **Squeezed vacuum states represent a solution** for this problem as it was demonstated by in the past generation of gravitational wave detectors. This solution contributed to GW detection;
- The **new generation of gravitational wave detectors** (as Advanced Virgo Plus) will be affected by quantum noise in the whole detection bandwidth → a **frequency-dependent squeezing** technique must be used;
- At present in Virgo and LIGO frequency-dependent squeezing **technique based on filter cavity** is in phase of commissioning (see B. Garaventa talk);
- Here we showed **an alternative technique based on EPR-entangled beams** and the progresses of our experiment whose final goal is to inject, for the first time, these beams in a system sensitive to quantum noise in the whole detection bandwidth at the same frequencies of GW detectors.