A table-top experiment for implementing EPR conditional squeezing in 2nd and 3rd Generation GW detectors

Francesco De Marco (Sapienza University of Rome and INFN Rome)
on behalf of the EPR-SIPS Team

GWADW (Gravitational-Wave Advanced Detectors Workshop)
21-27 May 2023 - Isola d'Elba (Italy)

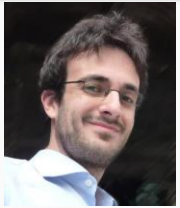
VIR-0482A-23

Introducing EPR-SIPS team

Valeria Sequino **(PI)** Martina De Laurentis

University of Naples “Federico II” & INFN-Naples

Università degli Studi di Napoli Federico II



Sibilla Di Pace Luca Naticchioni Laura Giacoppo Francesco De Marco

Sapienza University of Rome & INFN-Rome

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Mateusz Bawaj

University of Perugia and INFN-Perugia

Università degli Studi di Perugia

- Chang-Hee Kim (KASI)
- Hojae Ahn (KHU)
- Sungho Lee (KASI)
- Soojong Pak (KHU)
- June-Gyu Park (Yonsei University)
- Sumin Lee (KHU)
- Yunjong Kim (KASI)

KASI Korea Astronomy and Space Science Institute

Kyung Hee University

Yonsei University

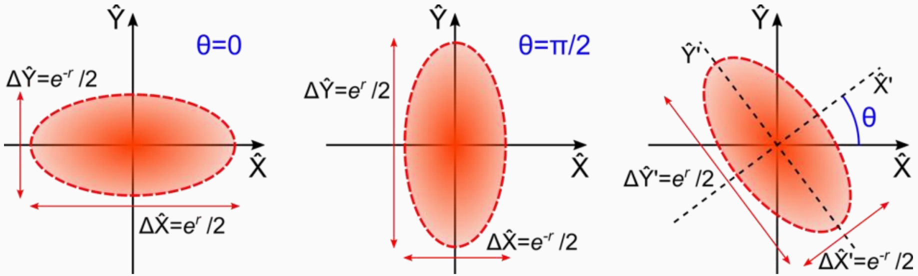
Fiodor Sorrentino
University of Genova
INFN-Genova

Barbara Garaventa
INFN-Genova

INFN Istituto Nazionale di Fisica Nucleare

Quantum Noise Reduction in GW detectors

- **Quantum Noise (QN)** limits the sensitivity of GW detectors in a wide range of their spectrum
- ***Frequency-Dependent Squeezed (FDS)*** light provides broadband QN reduction

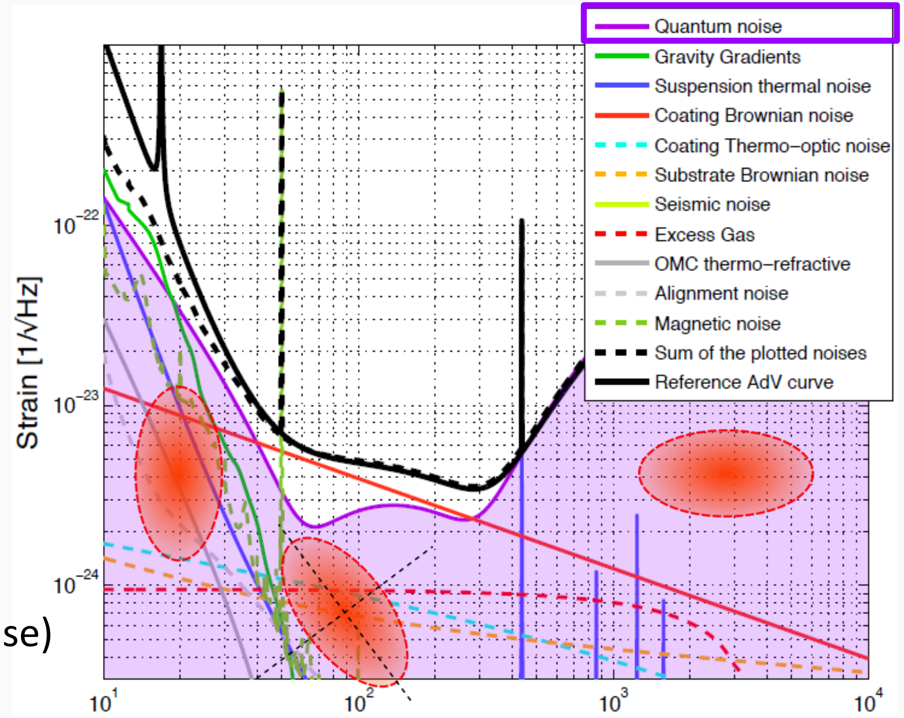


Electromagnetic field quadratures:

- X quadrature ⟶ Amplitude (Radiation Pressure Noise)
- Y quadrature ⟶ Phase (Shot Noise)

AdV sensitivity curve

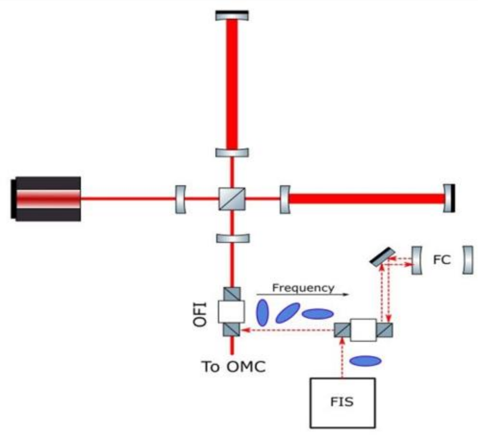
Virgo Coll. - Class. Quant. Grav. 32 024001 (2015)



FDS with Filter Cavity

- Squeezing ellipse can be rotated in a frequency-dependent manner with a detuned linear cavity (**Filter Cavity**)
- Central rotation angle @ ~50 Hz implies
  - Long cavity L=285 m
  - High finesse F=11000
- Round-trip losses in AdV+ FC: **50-90 ppm**

Zhao - Report VIR-1133A-22 (2022)



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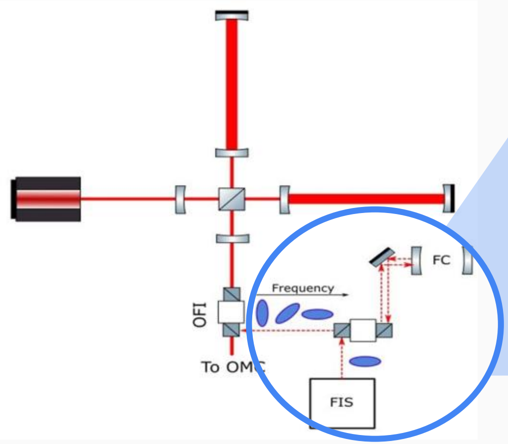

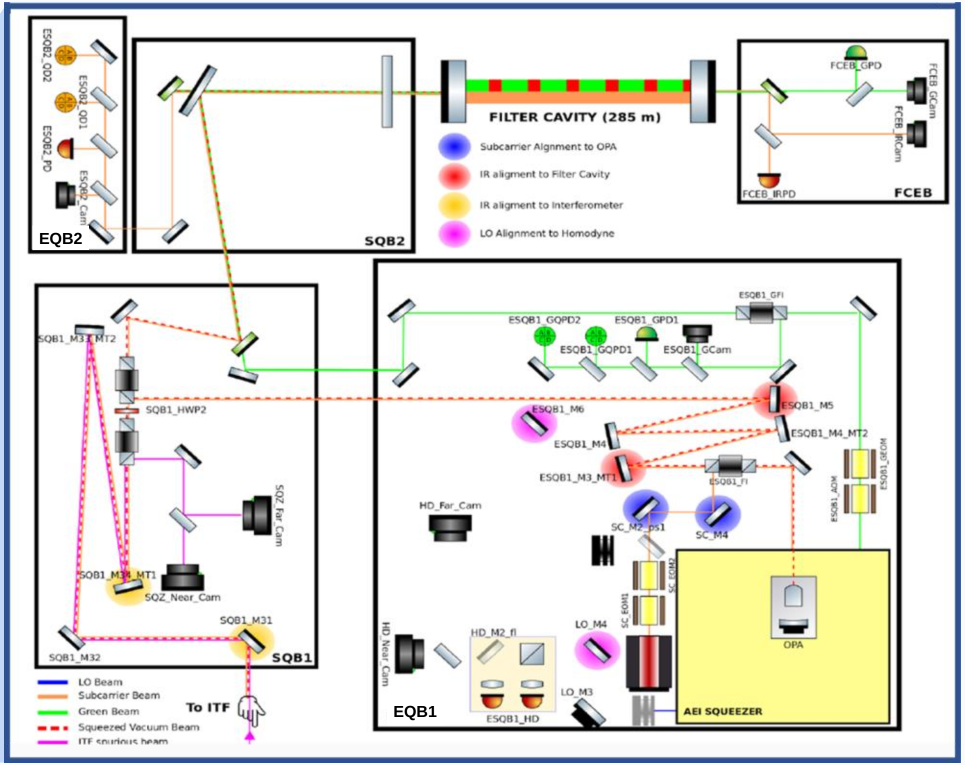

Credits: Virgo Coll. - Report VIR-0596A-19 (2019) and Di Pace - Phys. Scr. 96 124054

EPR proposal: a little bit of "history"

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]

Theoretical proposal (2017)
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Experimental demonstrations (2020)

Südbeck *et al.* - Nature Phot. 14 240-244 (2020)

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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*

Yap *et al.* - Nature Phot 14, 223-226 (2020)

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

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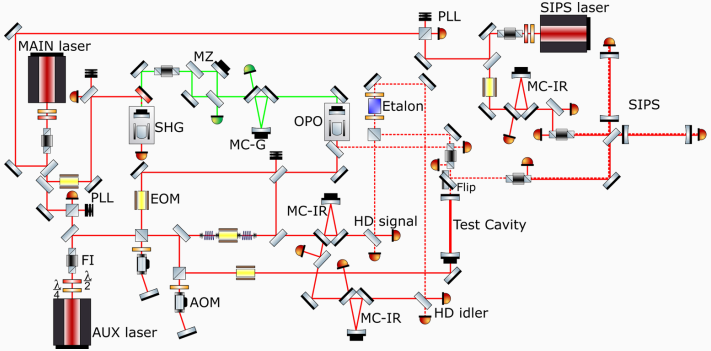
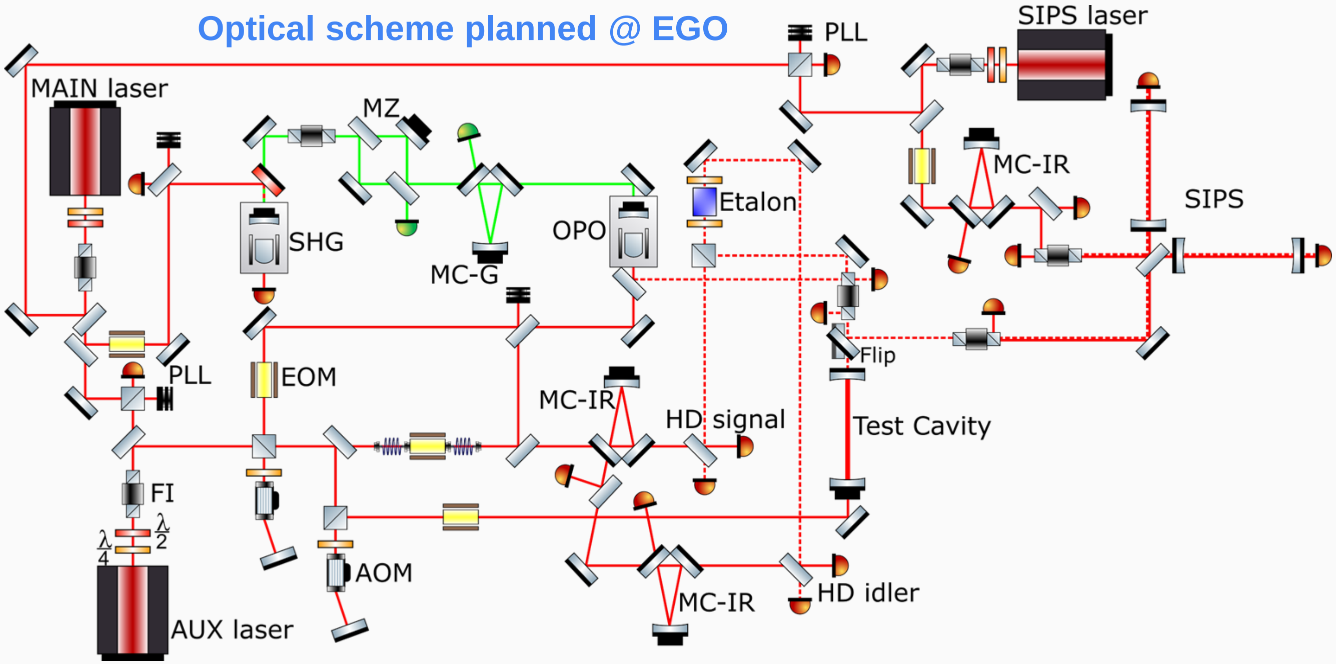


Table-top experiment in a small-scale interferometer **(ongoing at EGO)**

- Optical simulations and design
- Laboratory work

EPR working principle



Pros:

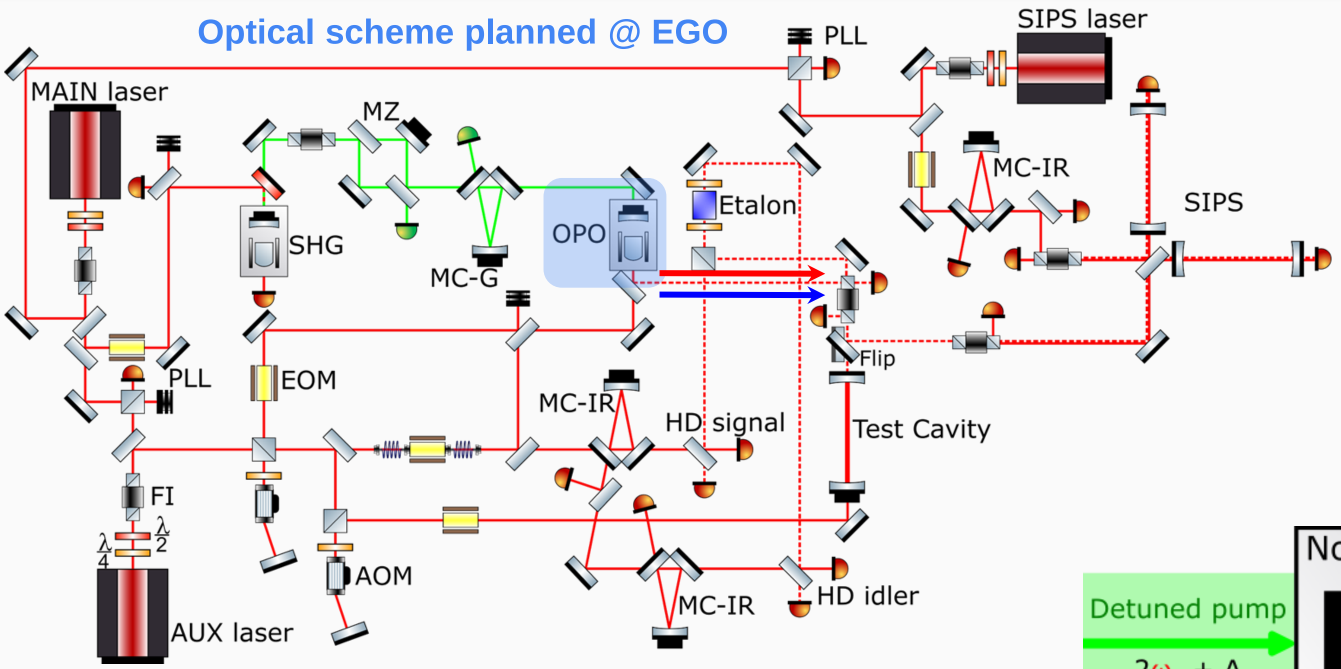
- More compact and cheaper
- More flexible vs SR
- Avoids FC optical losses

Cons:

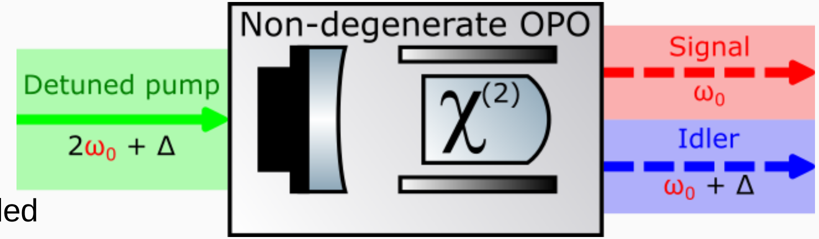
- 2 squeezed beams to be handled
- 3 dB penalty w.r.t. optimal squeezing rotation ellipse

EPR working principle

Optical scheme planned @ EGO



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



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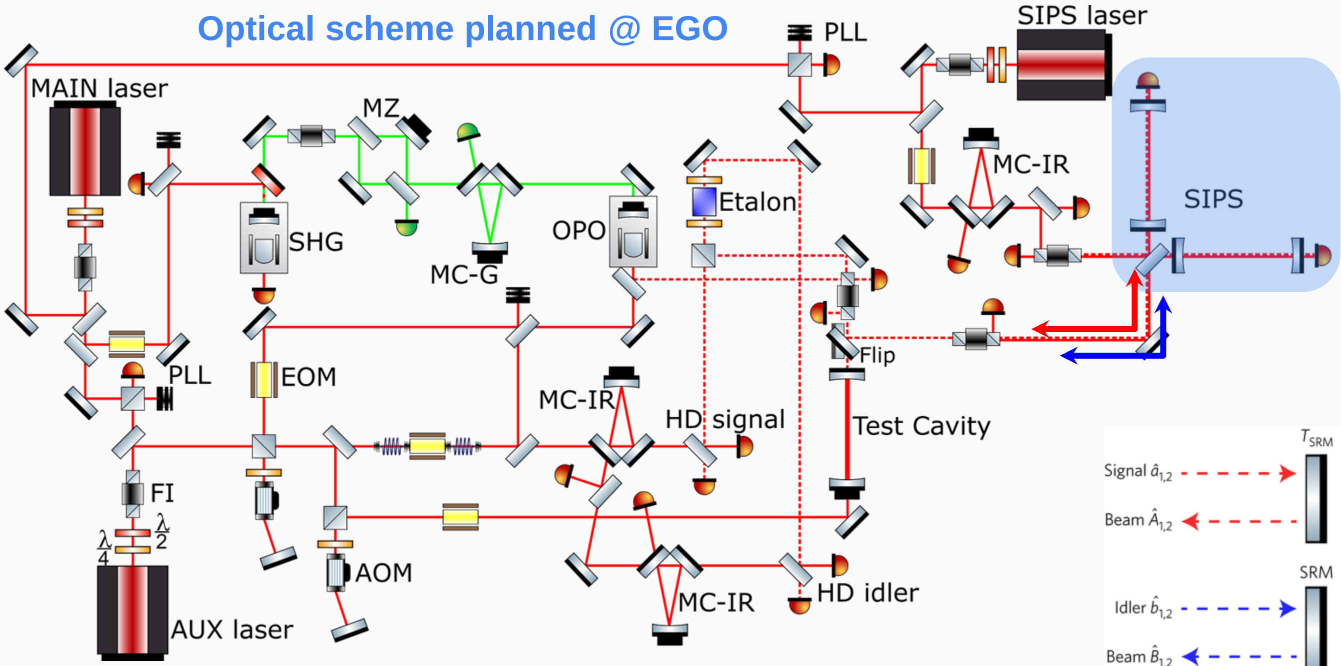

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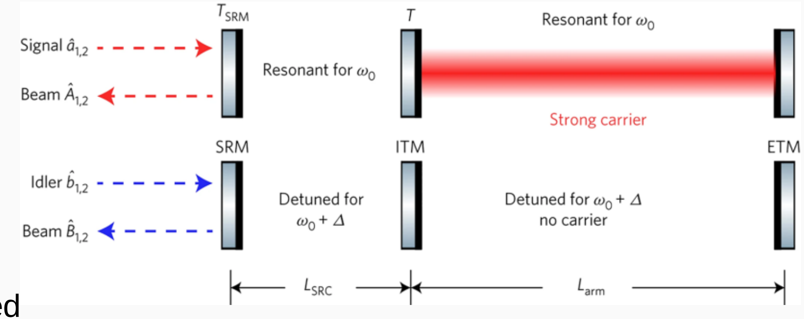
2. The **idler** acquires frequency-dependence in SIPS due to its detuning



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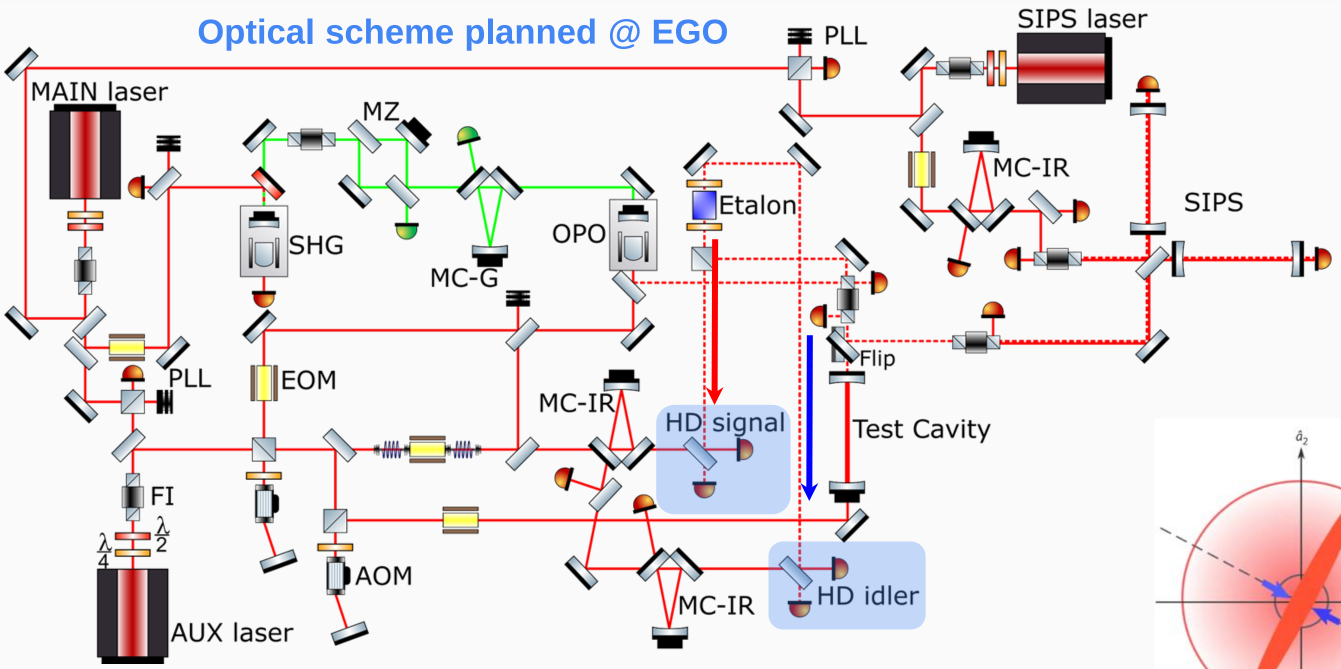
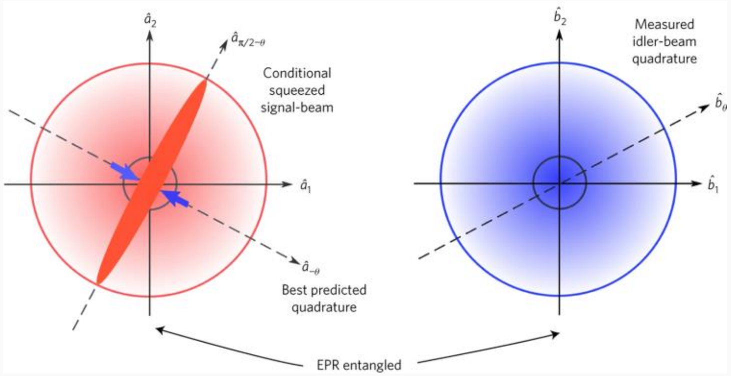


1. **Signal** and **idler** are vacuum squeezed beams, EPR-entangled and detuned by Δ
2. The **idler** acquires frequency-dependence in SIPS due to its detuning
3. Combined measurement with optimal filter gain transfers the frequency dependence to the **signal** via EPR entanglement



Credits: Ma *et al.* - Nature Phys 13, 776–780 (2017)

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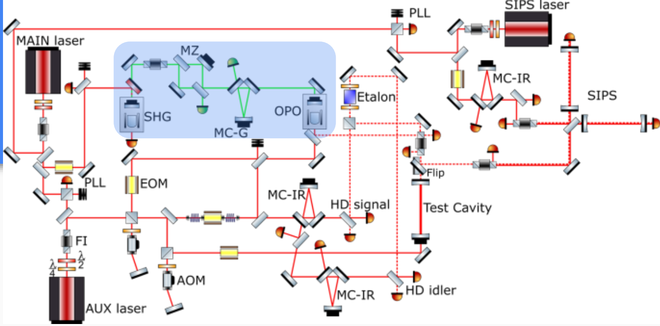
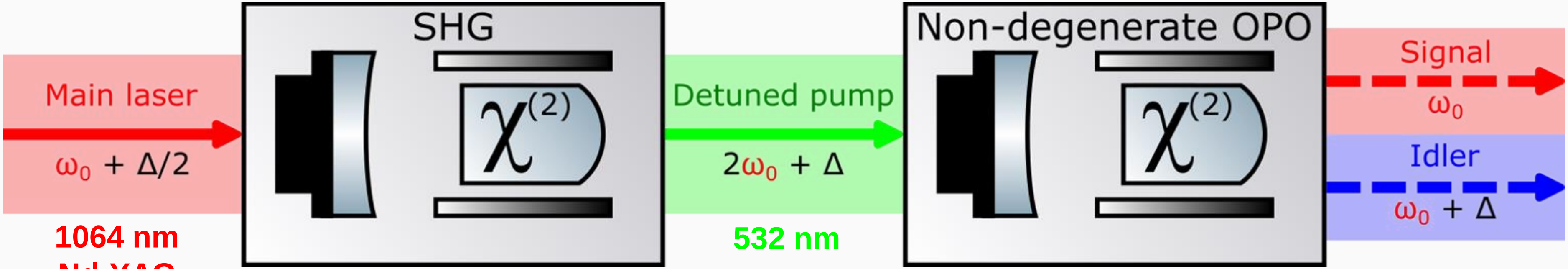
Non-linear cavities: SHG and OPO



- The frequency of an electromagnetic wave can be modified only via non-linear propagating medium, i.e. $\chi^{(2)} \neq 0$
- We will use two identical hemilithic optical cavities
  - **Second-Harmonic Generator (SHG)** generates green pump beam
  - **Optical Parametric Oscillator (OPO)** generates vacuum squeezed EPR-entangled beams
- The green beam has to be power-controlled (**Mach-Zehnder**) and purely Gaussian (**mode cleaner**)



1064 nm
Nd:YAG

532 nm

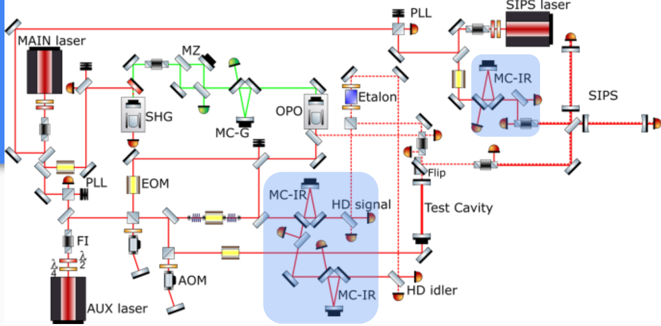
Conversion efficiency: **>60%**

Measured SQZ level (previous setup): **-5.7 dB**

Nguyen, Bawaj *et al.* - Rev. Sci. Instrum. 92, 054504 (2021)

Both the cavities are ready for use: SHG with MC-G and MZ are installed on the bench

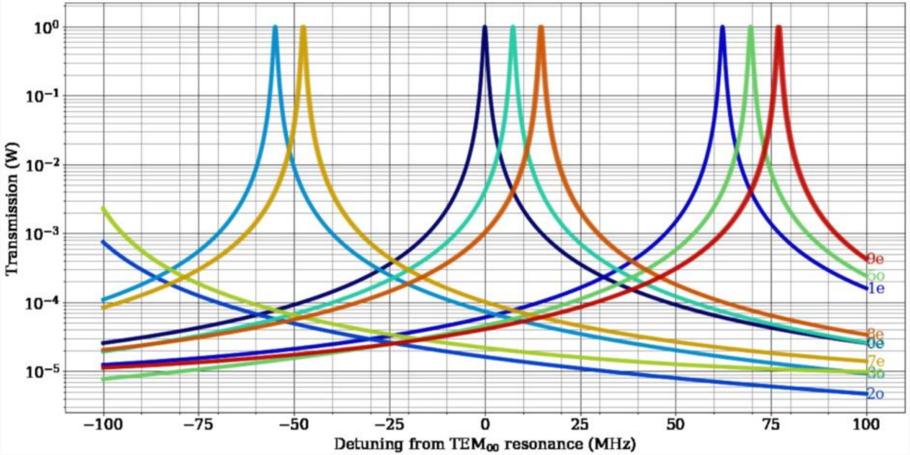
Mode Cleaner (MC) IR cavities

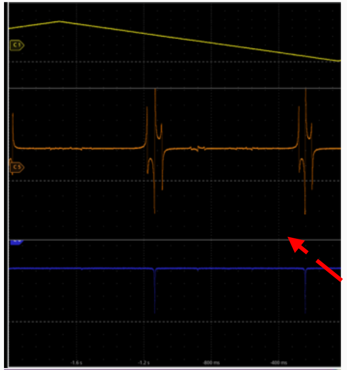


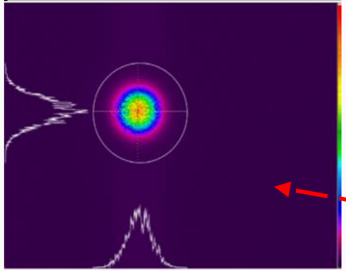
- A mode cleaner (MC) cavity is used to reflect out the Higher Order Modes (HOMs) in the transverse intensity profile of a laser
- We have 3 MC-IR in our setup, for the most sensitive parts
  - Homodyne Detectors for Local Oscillators of signal and idler (KASI team)
  - SIPS Interferometer (Roma1 team)

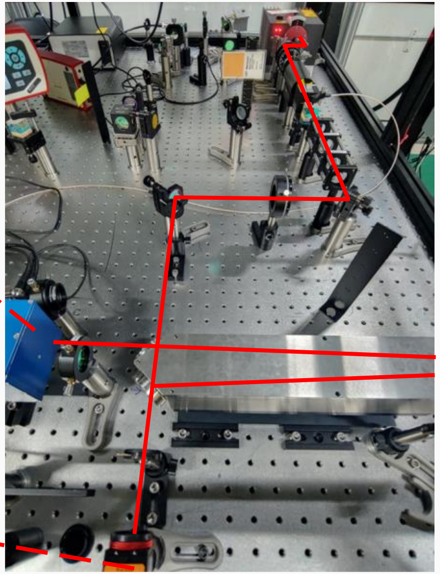
Local Oscillator mode cleaners

Credits: Chang-Hee Kim, June-Gyu Park









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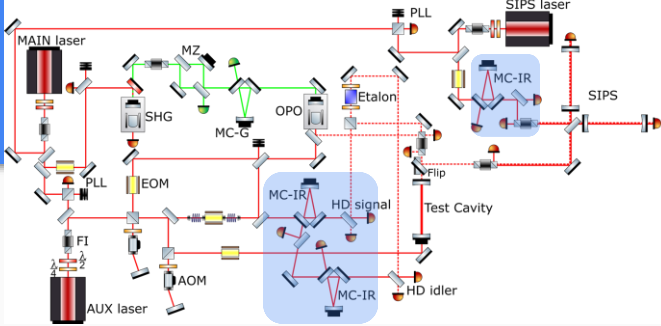

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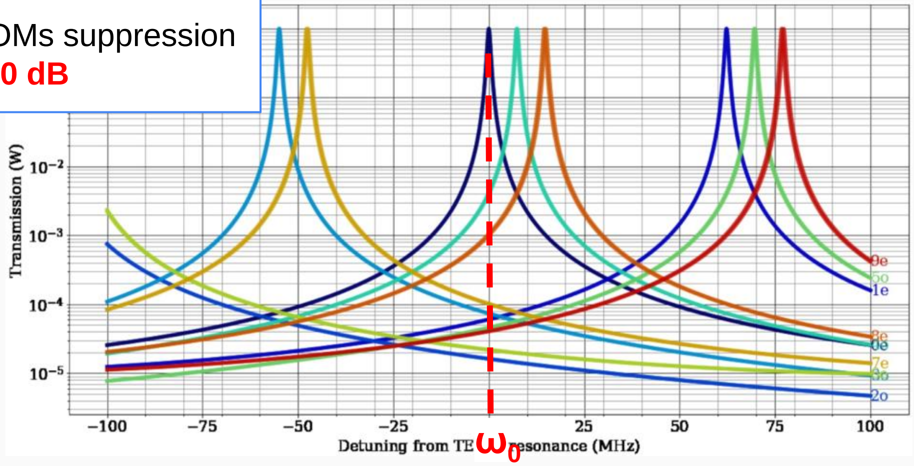
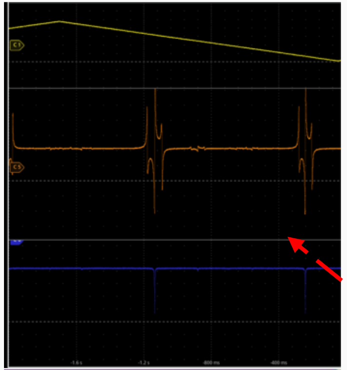
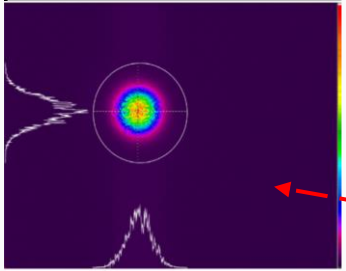
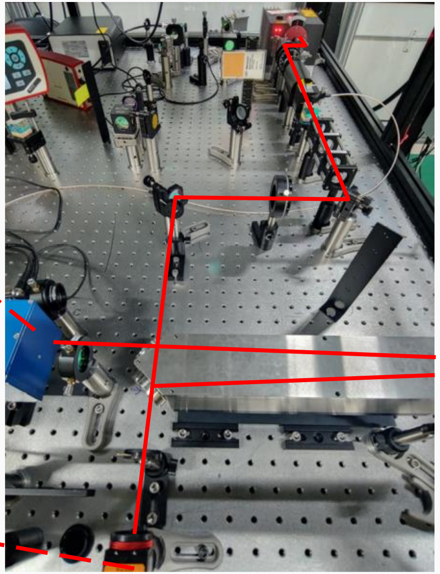
HOMs suppression **>20 dB**







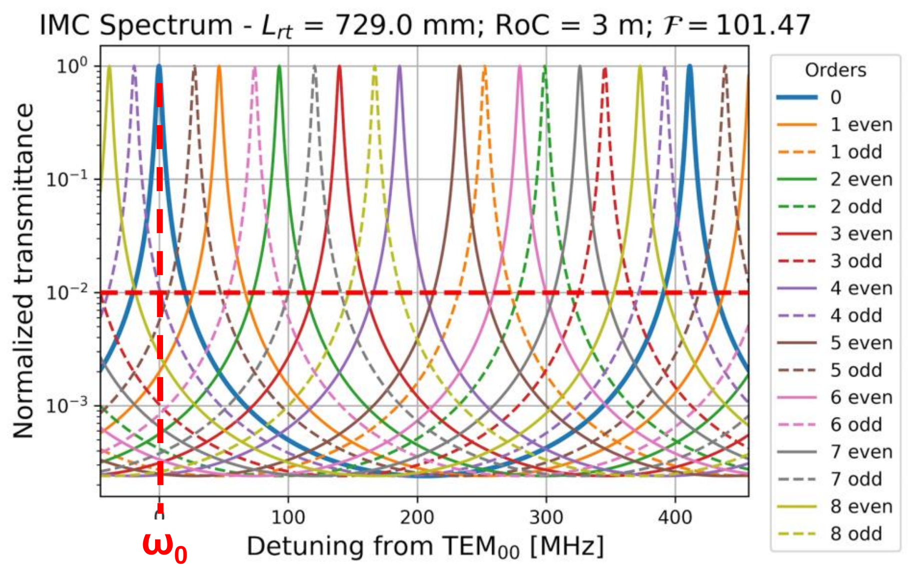


Credits: Chang-Hee Kim

MC-IR for SIPS

SIPS input mode cleaner

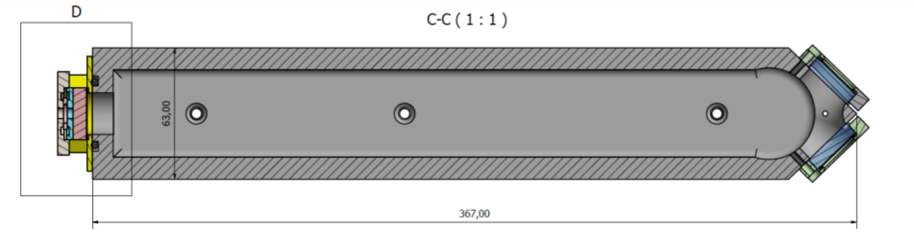
Credits: De Marco - M.Sc. thesis (2022)
and De Marco *et al.* - Proc. of GRASS2022

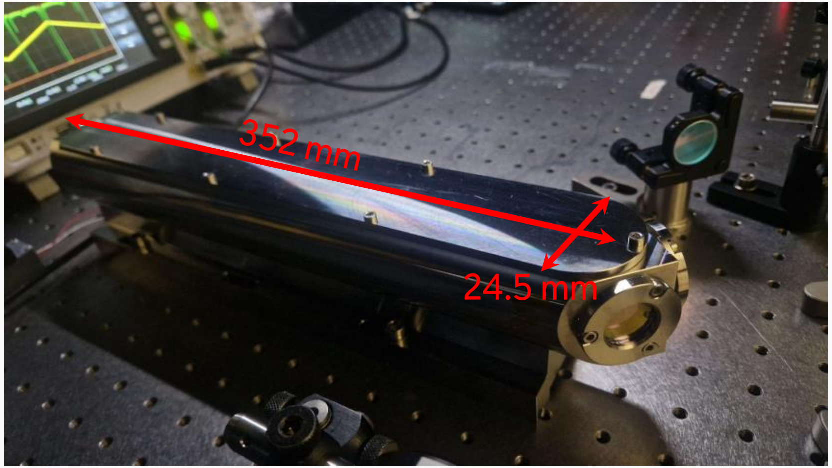


- Delivers up to **3.9 W** to SIPS
- HOMs suppression **>20 dB**

Mechanical design

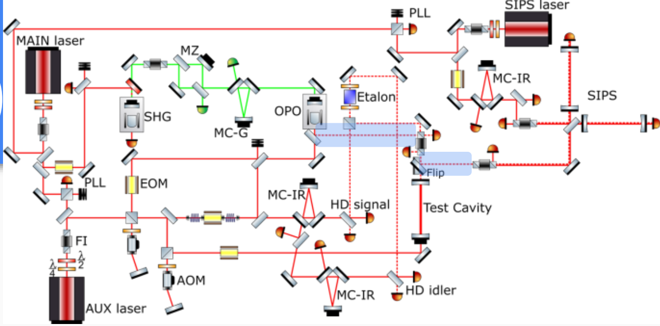
Credits: M. Perciballi





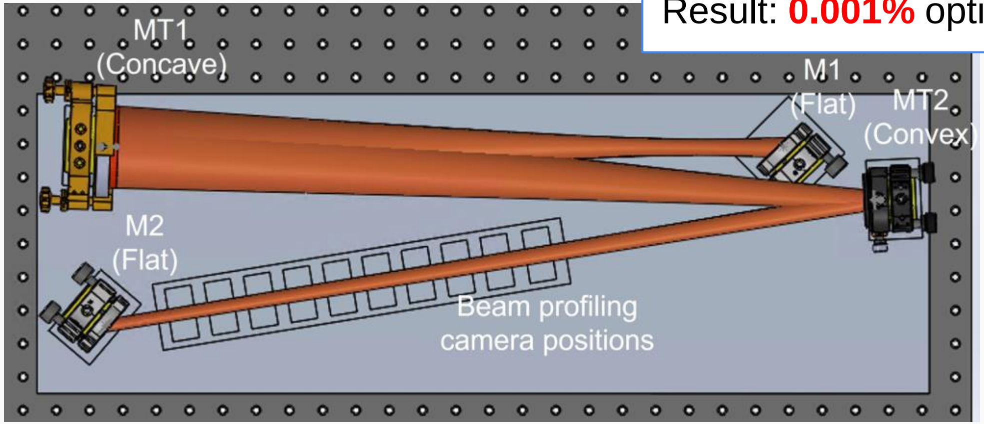
All the MC-IR are ready to be integrated in the EPR setup

Mode-Matching Telescopes (MMTs)

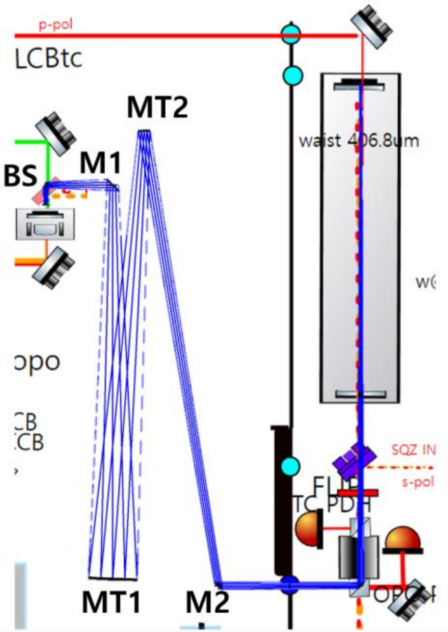


- The beam mode exiting from the OPO cavity needs to be matched to the Gaussian eigenmode of the interferometer
- One step before: linear test cavity (design and production by Naples team)

Requirement: <2% overall optical losses
Result: **0.001%** optical losses by design

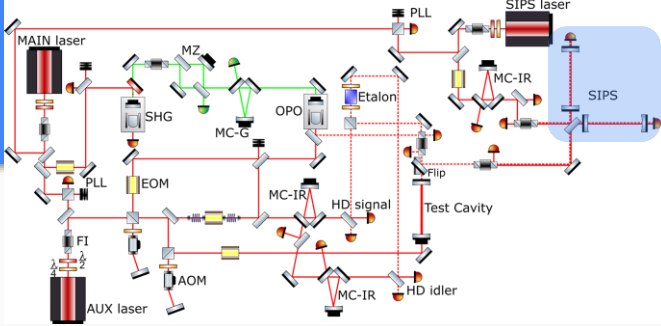


Credits: Hojae Ahn, Sumin Lee, Soojong Pak



1. Test cavity MMT designed and produced by KASI-KHU team: ready in July 2023
2. SIPS MMT: to be designed

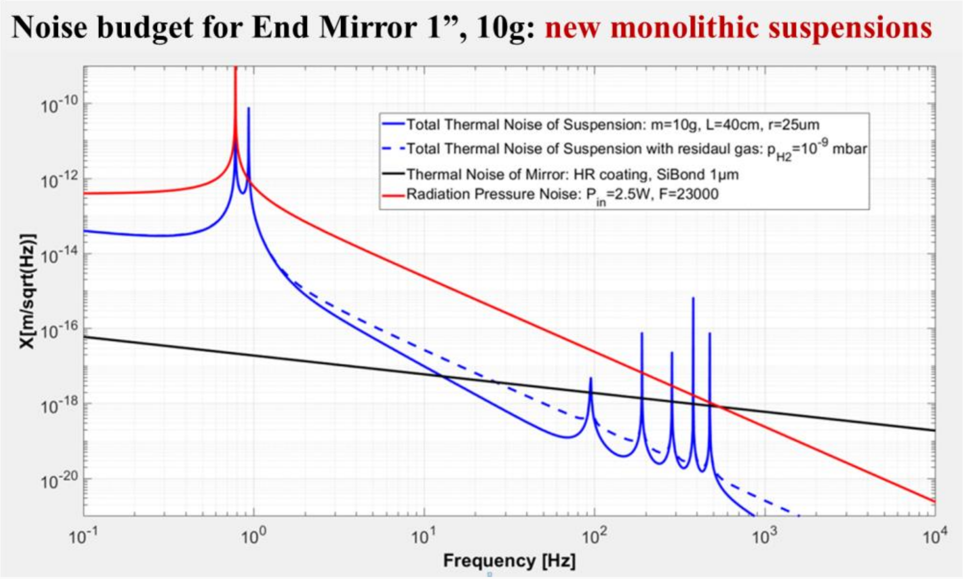
SIPS interferometer



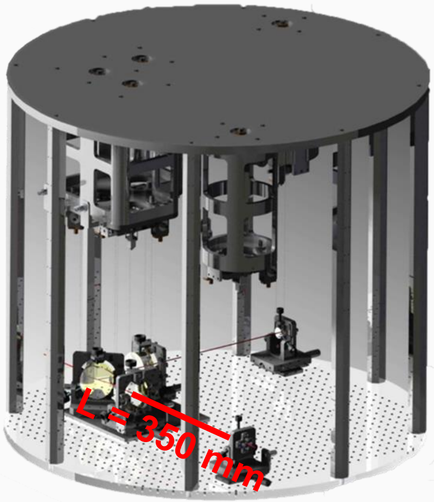
- SIPS (Suspended Interferometer for Ponderomotive Squeezing) was initially conceived for ponderomotive squeezing (design and production by Roma1 and Naples team)
- Configuration: non-recycled Michelson Fabry-Perot interferometer
- Now it will be used to **test the EPR squeezing**

Noise budget

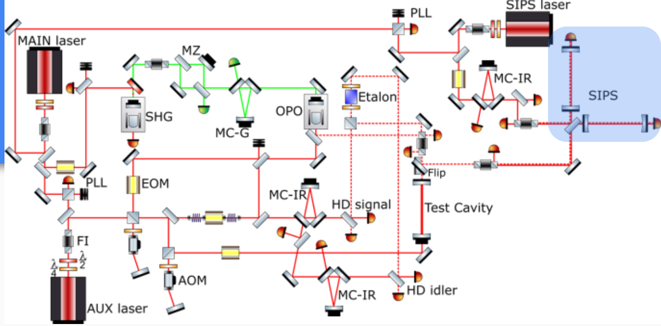
Credits: Di Pace *et al.* - Eur. Phys. J. D 74, 227 (2020)
and Giacoppo - PhD thesis (2023)



Setup



SIPS interferometer



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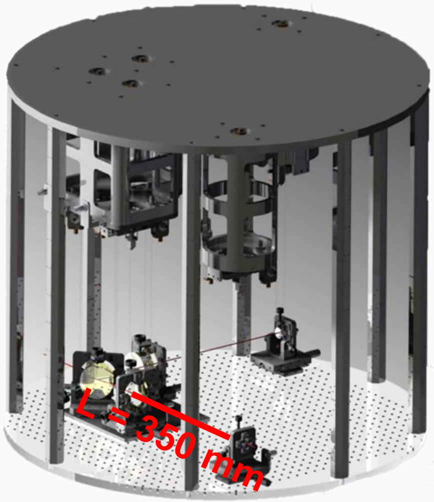

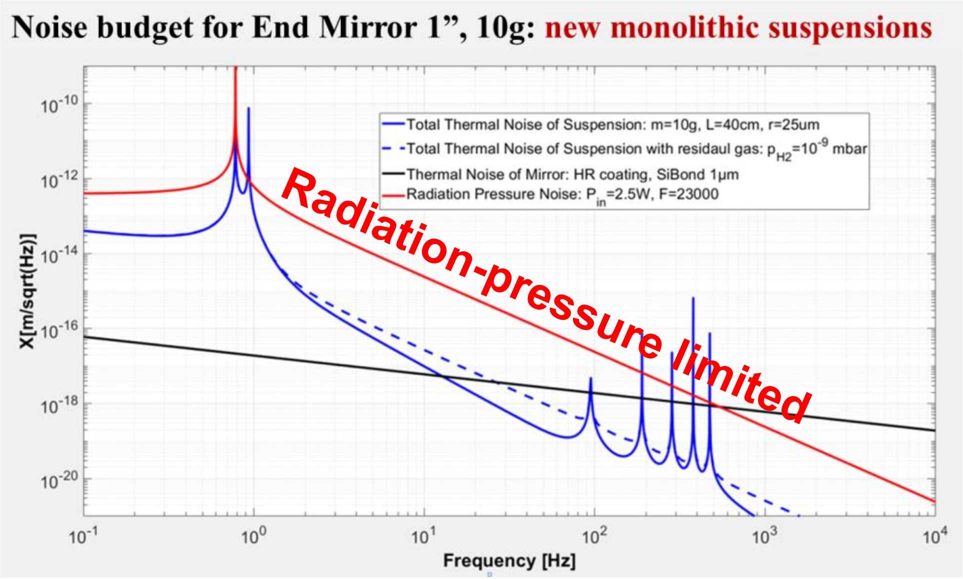

SIPS interferometer

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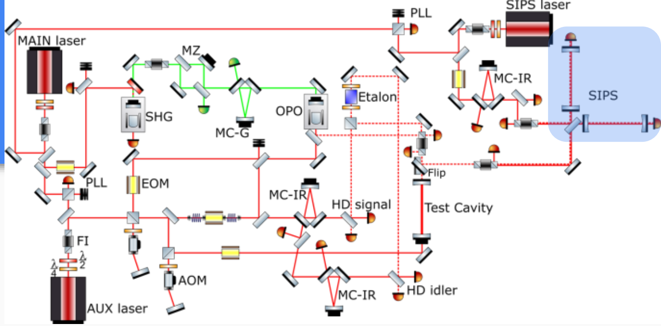

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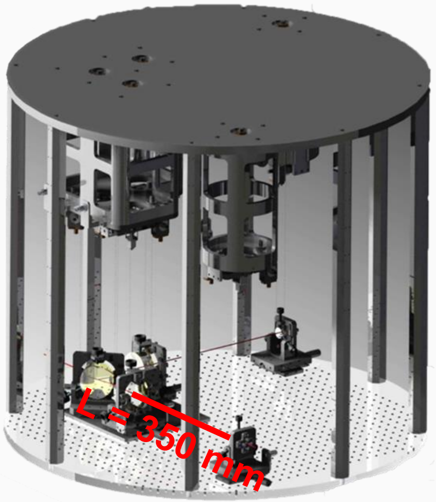

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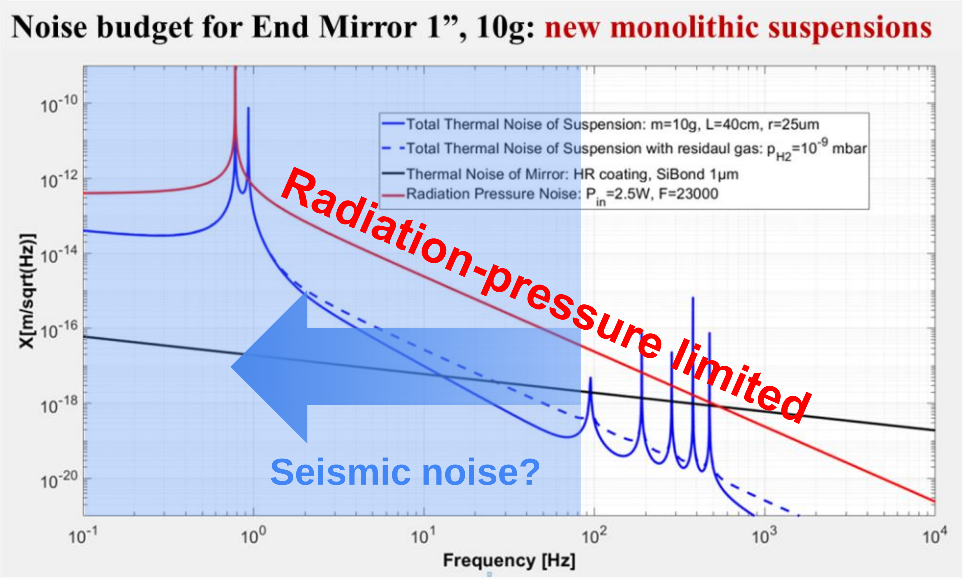
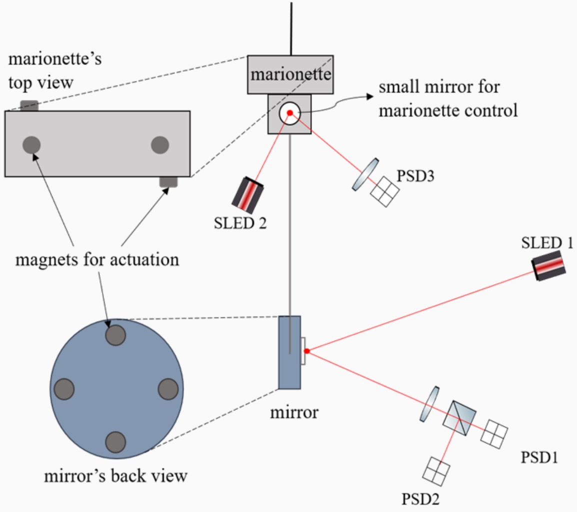


SIPS interferometer - local control

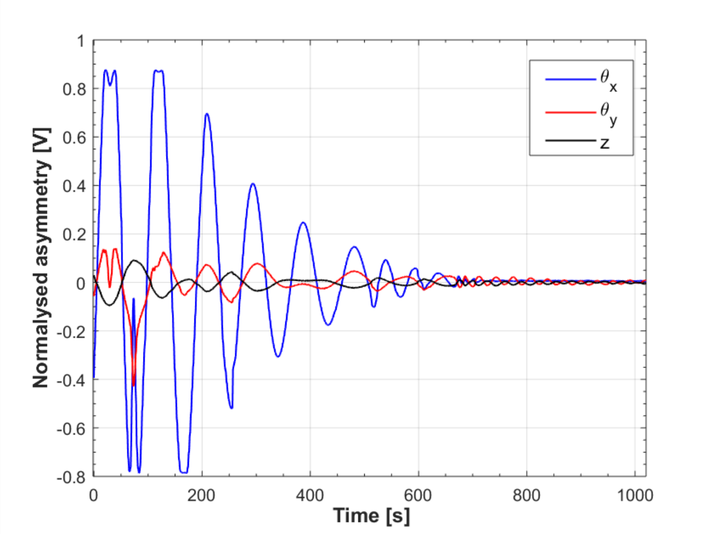
- SIPS local control will be improved with new mechanics and 4 suspension wires for each mirror Giacoppo - PhD thesis (2023)
- Readout: optical lever



- Tests with previous design carried out with dummy mirror

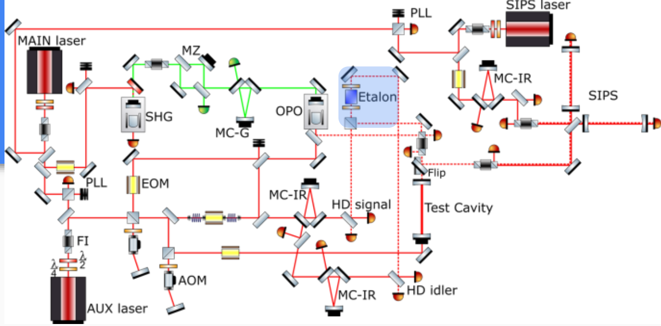
Pre-alignment of the end mirror

Credits: Giacoppo *et al.* - Phys. Scr. 96 114007 (2021)



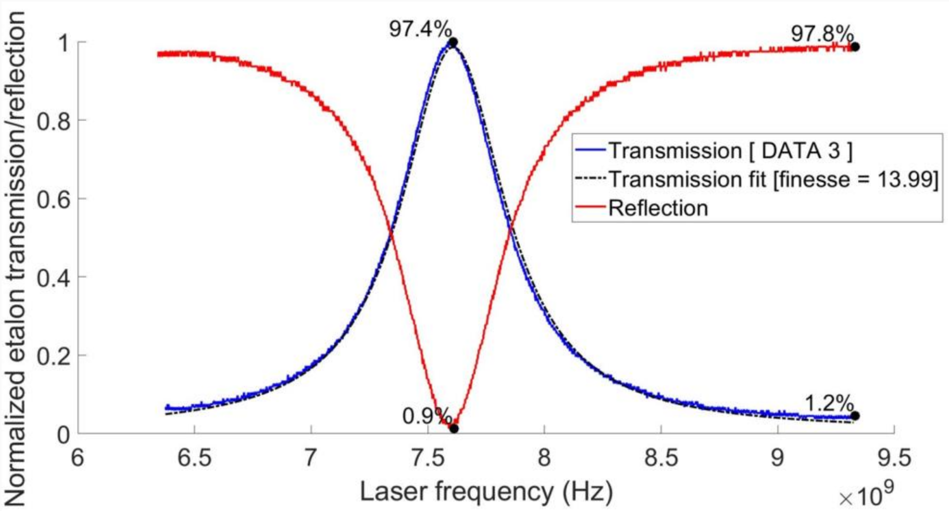
Next goal: improving the **10 nrad** and **0.1 μm** performance of the previous system

Etalon

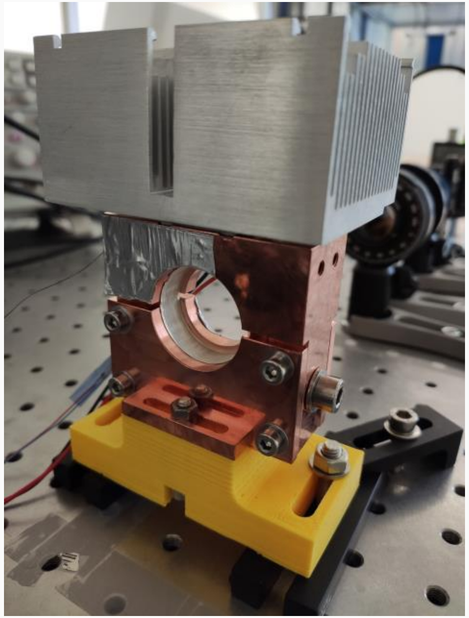


- An etalon is used for separating the outgoing **signal** and **idler** beams
- It has been already developed, produced and tested by APC-Paris team

Frequency scan



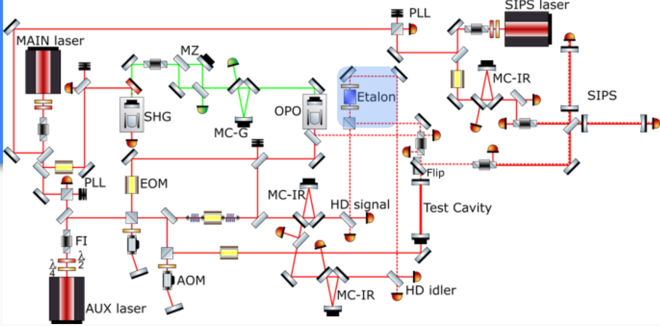
- Monolithic
- Temperature controlled



Credits: Nguyen *et al.* - Appl. Opt. 61 17 (2022)

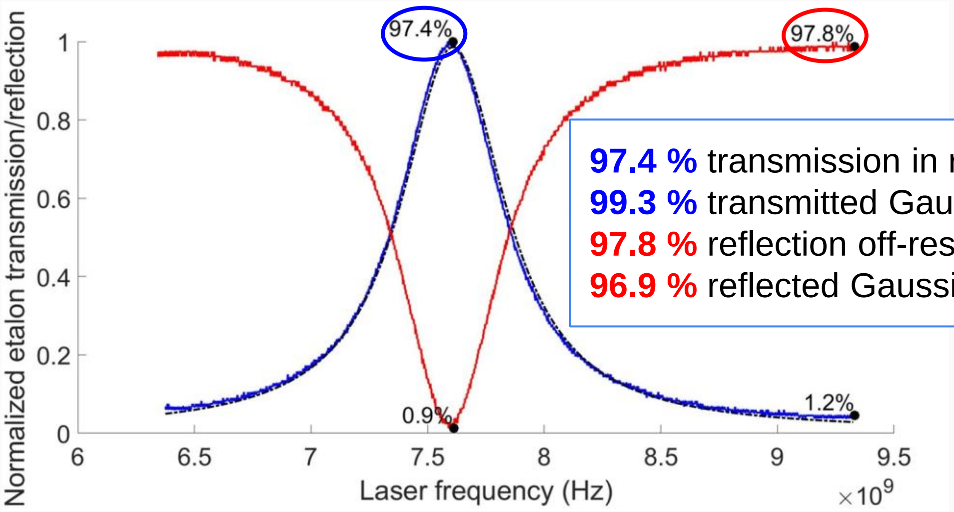
The etalon is currently on the EPR optical bench at EGO

Etalon



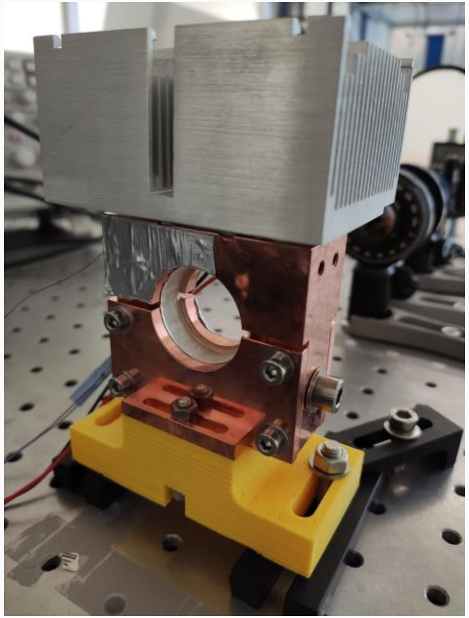
- An etalon is used for separating the outgoing **signal** and **idler** beams
- It has been already developed, produced and tested by APC-Paris team

Frequency scan



97.4 % transmission in resonance
99.3 % transmitted Gaussian mode
97.8 % reflection off-resonance
96.9 % reflected Gaussian mode

- Monolithic
- Temperature controlled



Credits: Nguyen *et al.* - Appl. Opt. 61 17 (2022)

The etalon is currently on the EPR optical bench at EGO

Conclusions and outlook

- We are implementing a table-top prototype to test EPR conditional squeezing scheme in a small-scale suspended interferometer

- Most of the main optical elements are already designed and produced

- Further steps to be taken include the improvement of several elements

- Optical simulations are needed to support the experimental goal

- An EPR squeezer will be even more important for 3rd generation detectors (e.g. Einstein Telescope and Cosmic Explorer)

Thank you for your attention

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VIR-0482A-23