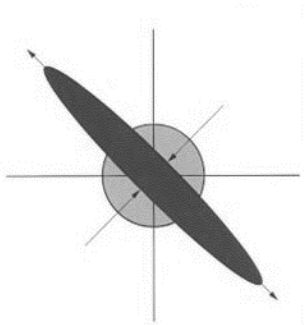
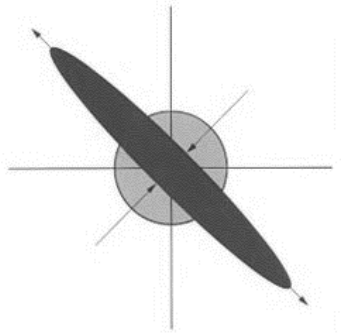
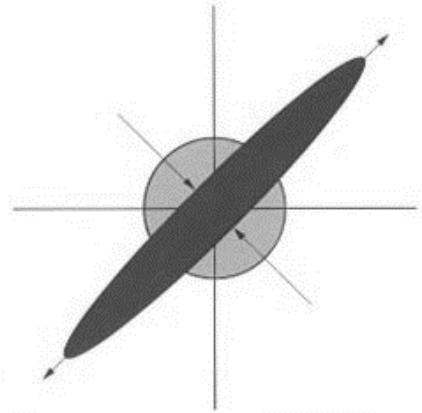
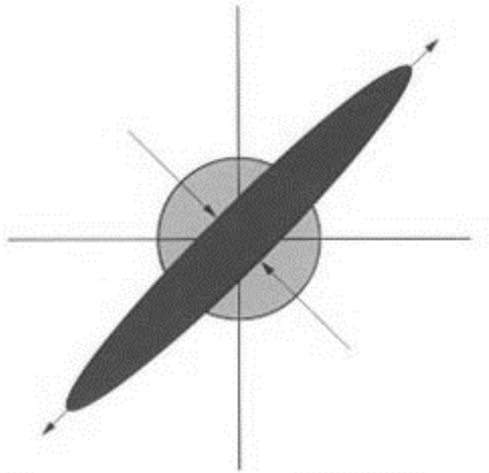






GdR Ondes Gravitationnelles
3ème Assemblée Générale
15/10/2020



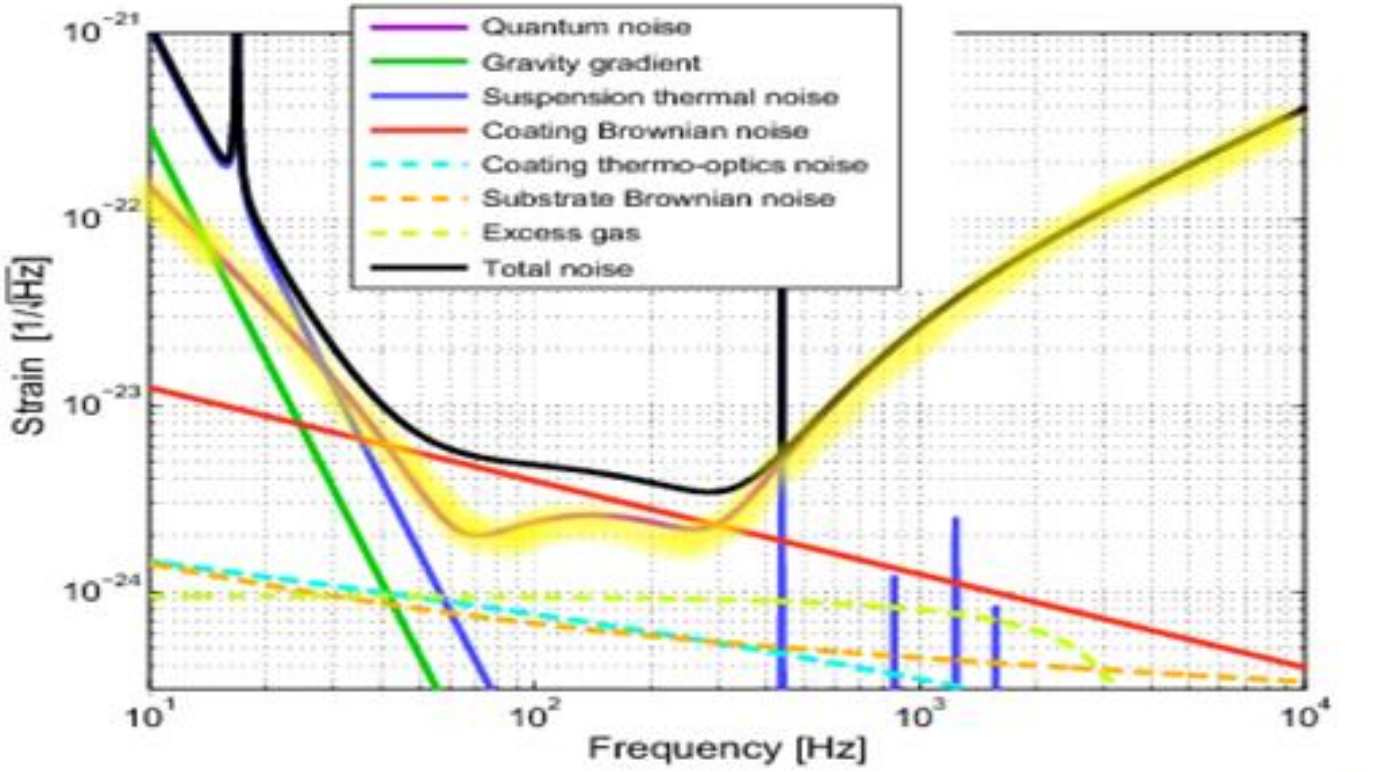
Reducing quantum noise for Advanced Virgo and future gravitational-wave detectors

using frequency-dependent squeezing with EPR entanglement

Catherine Nguyen

On behalf of the EPR-squeezing team of the Virgo Collaboration

Sensitivity and quantum noise for AdV+



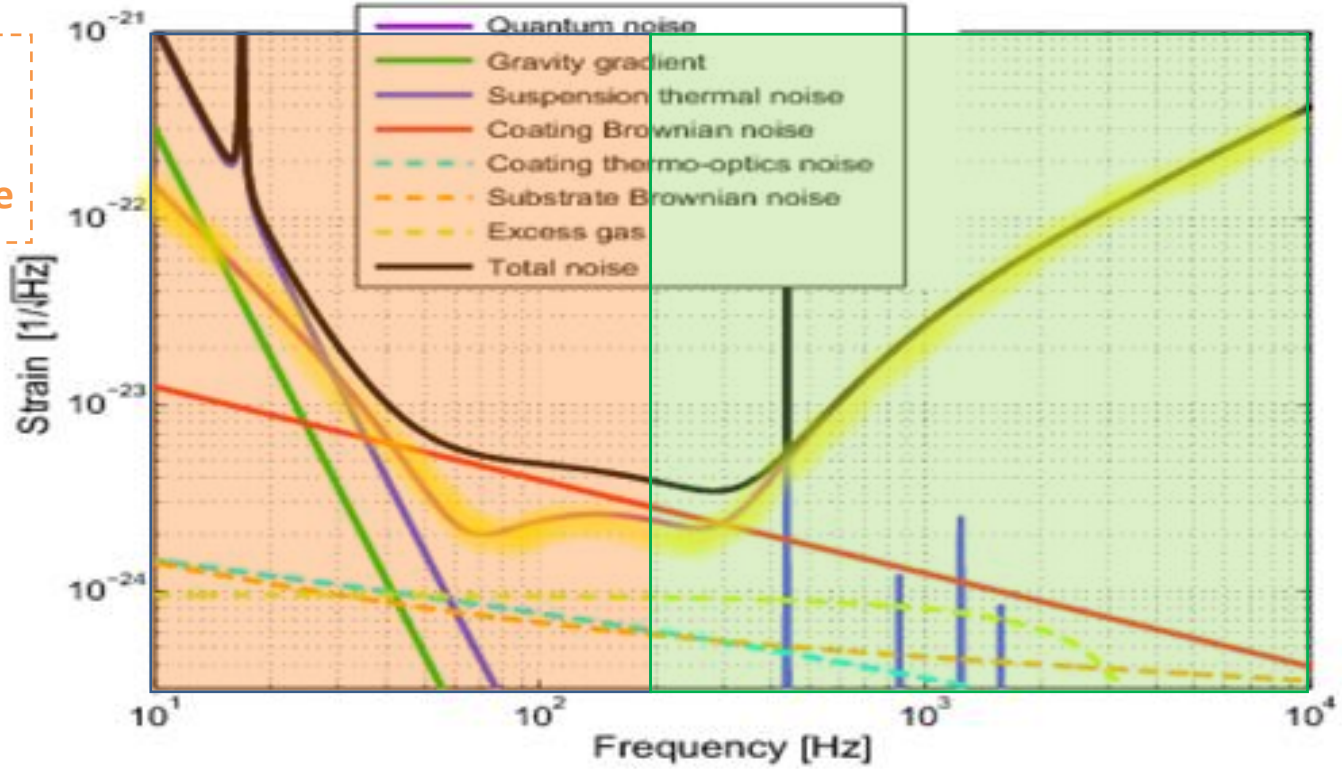
Advanced Virgo sensitivity curve

- Quantum noise is one of the major sources of noise

Sensitivity and quantum noise for AdV+

At low frequency

Radiation pressure noise



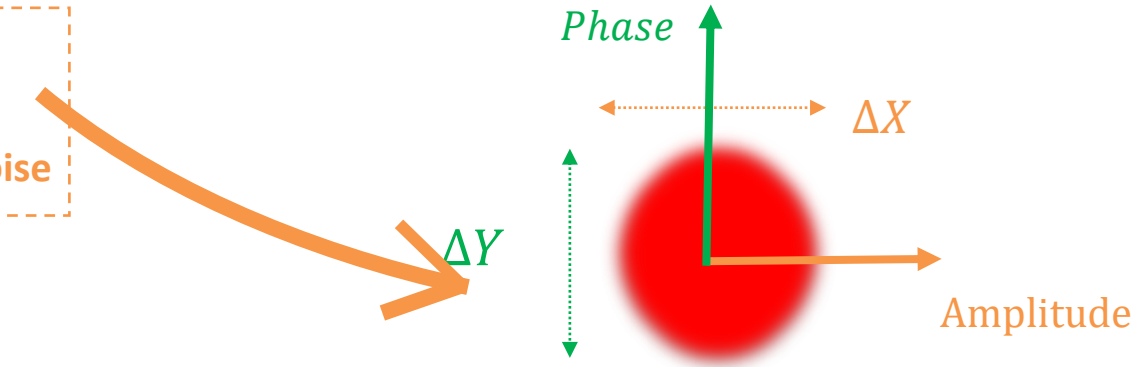
At high frequency

Shot noise

Heisenberg and squeezing

At low frequency

Radiation pressure noise



Quantum fluctuations in quadrature space

At high frequency

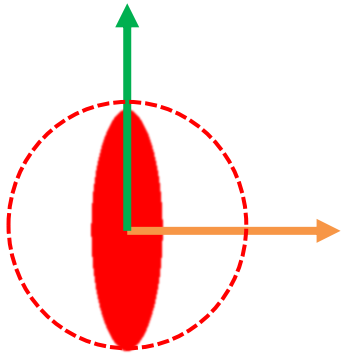
Shot noise

$$(\Delta X)^2(\Delta Y)^2 \geq \frac{1}{16}$$

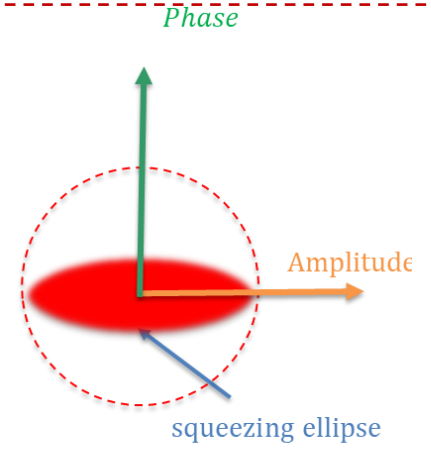
Heisenberg uncertainty principle

➢ A multiplicative limit !

INJECTION OF SQUEEZED STATES OF LIGHT

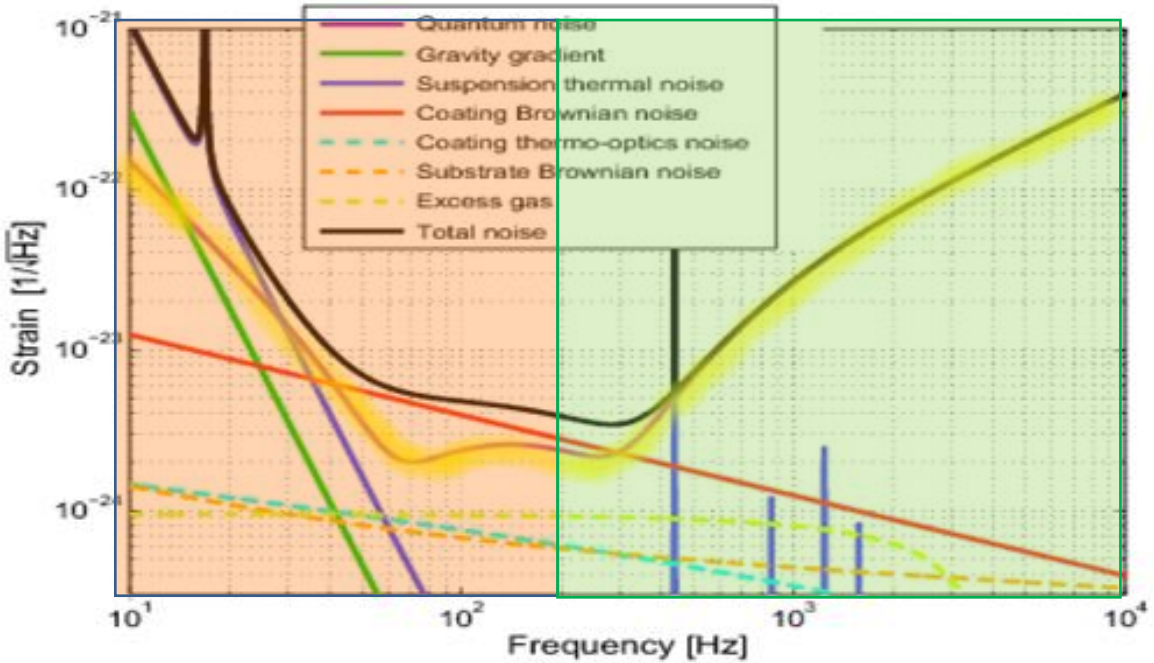


Amplitude-squeezed



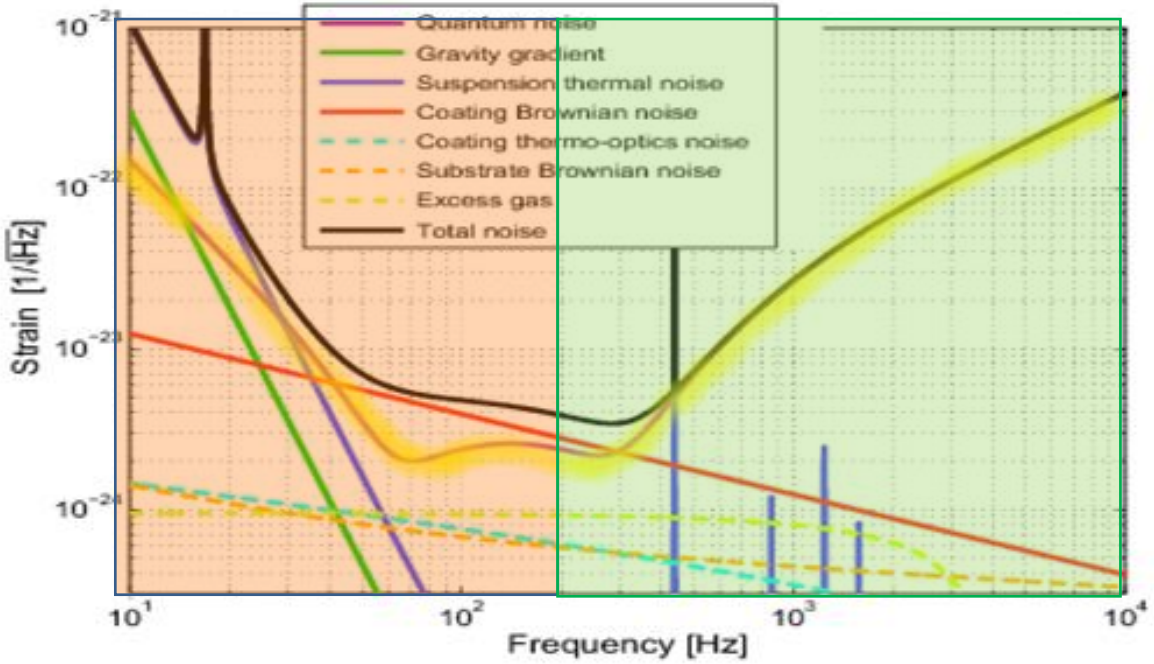
phase-squeezed

Frequency-dependent squeezing for AdV+



- We need **Frequency-dependent squeezing** to induce squeezed light ellipse rotation: broadband reduction of quantum noise

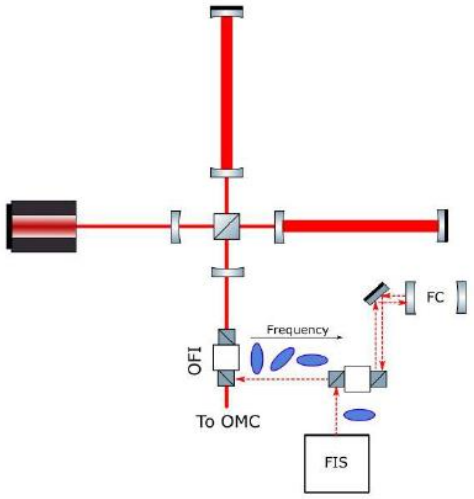
FDS with a filter cavity



- We need **Frequency-dependent squeezing** to induce squeezed light ellipse rotation: *broadband reduction of quantum noise*

➢ Solution n°1 : Filter Cavity [adopted]

- ❑ Inject frequency-independent squeezing into a Fabry-Perot cavity
- ❑ planned for O4 for AdV+ and aLIGO



Advanced Virgo Plus Design Report (VIR-0596A-19)

R. Flaminio - Virgo France (VIR-0827A-20)

A new technique

nature physics

Article | Published: 15 May 2017

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

Yiqiu Ma ✉, Haixing Miao, Belinda Heyun Pang, Matthew Evans, Chunnong Zhao, Jan Harms, Roman Schnabel & Yanbei Chen

Nature Physics **13**, 776–780 (2017) | Download Citation ⬇

A new technique

- Less components
- Less expensive
- More flexible
- no need of controls

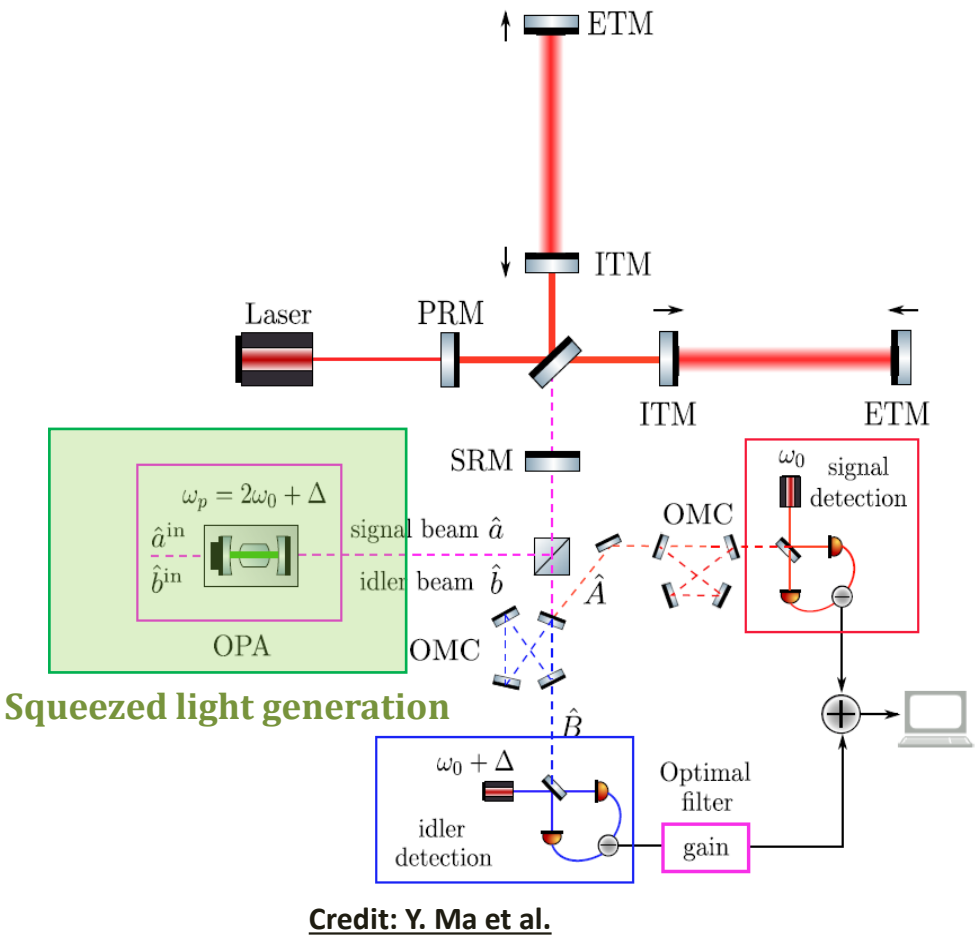
But…

- 3 dB penalty
- Other losses

EPR-entanglement technique: principles

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

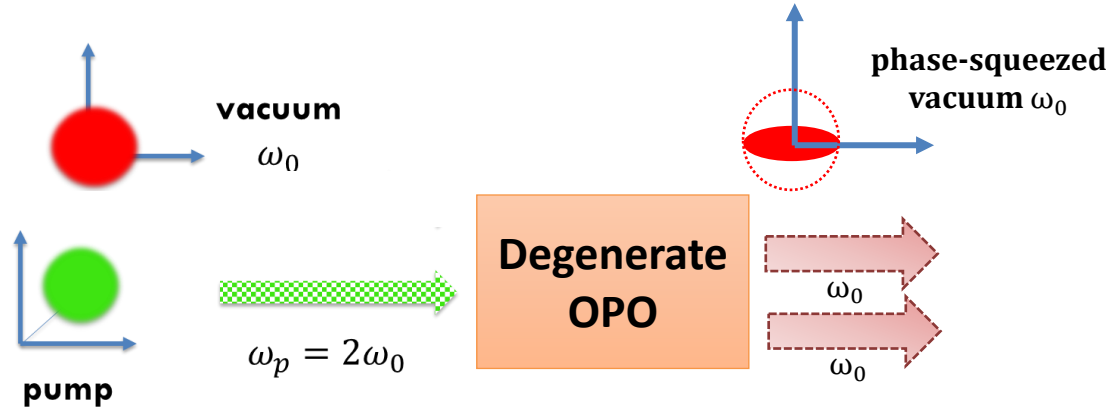
1 Detune pumping frequency (of Δ)

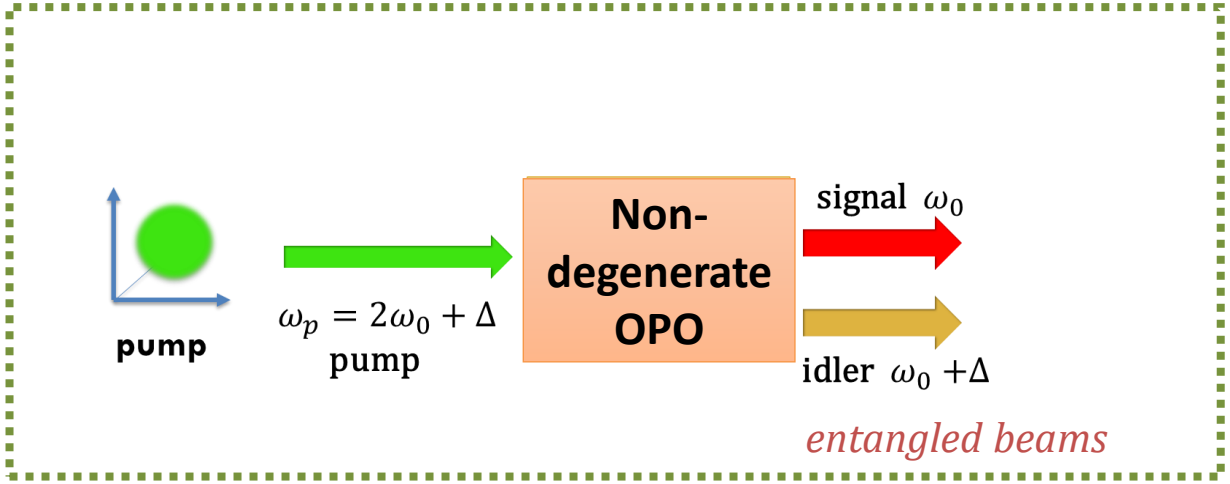


Squeezed light generation

Credit: Y. Ma et al.

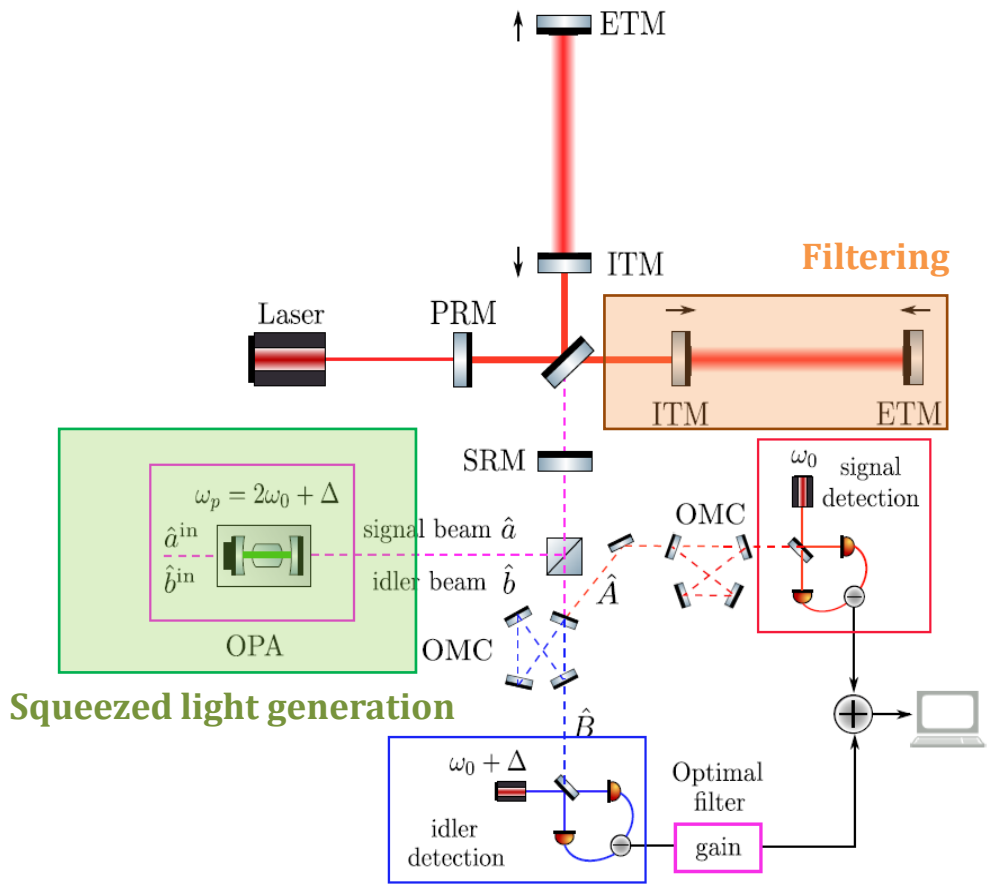
FREQUENCY-INDEPENDENT SQUEEZING





EPR-entanglement technique: principles

2 **Auto-filtering** of the signal and idler beams with the interferometer arm



Credit: Y. Ma et al.

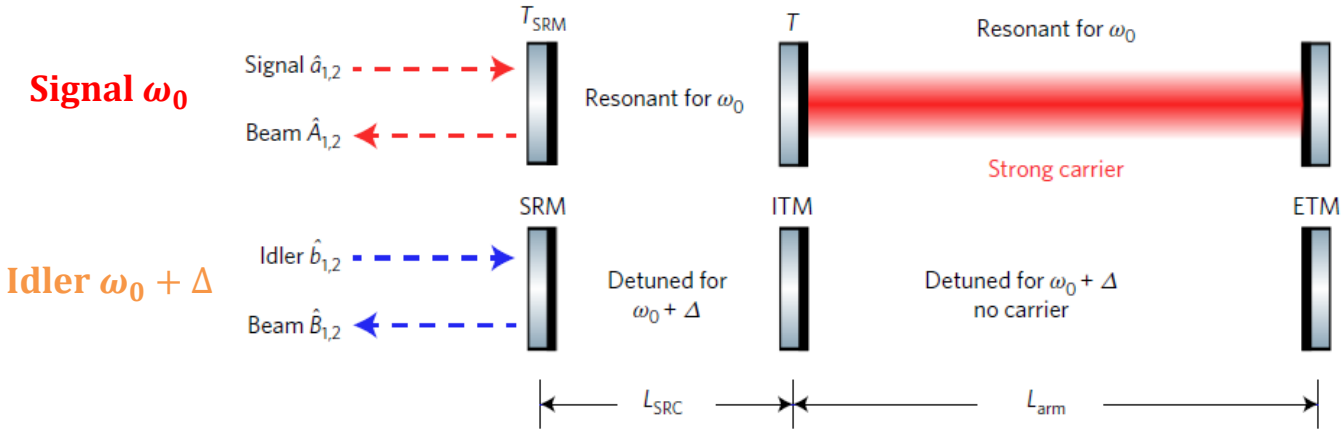
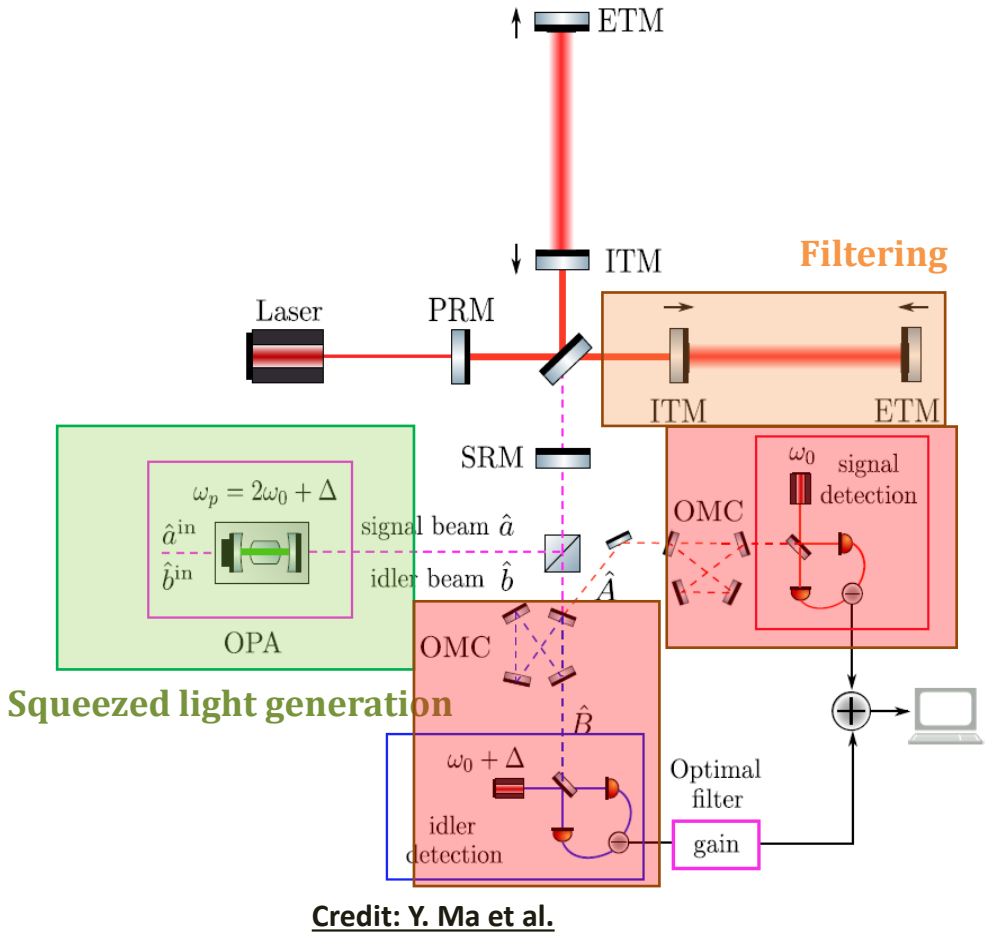


Figure 3 | The differential mode of the interferometer as seen by the signal (upper panel) and idler (lower panel) beams.

Credit: Y. Ma et al.

EPR-entanglement technique: principles

3 **Detection :** signal and idler are detected separately and the outcome of one detector is conditioned by the outcome of the other detection (scaling factor g)



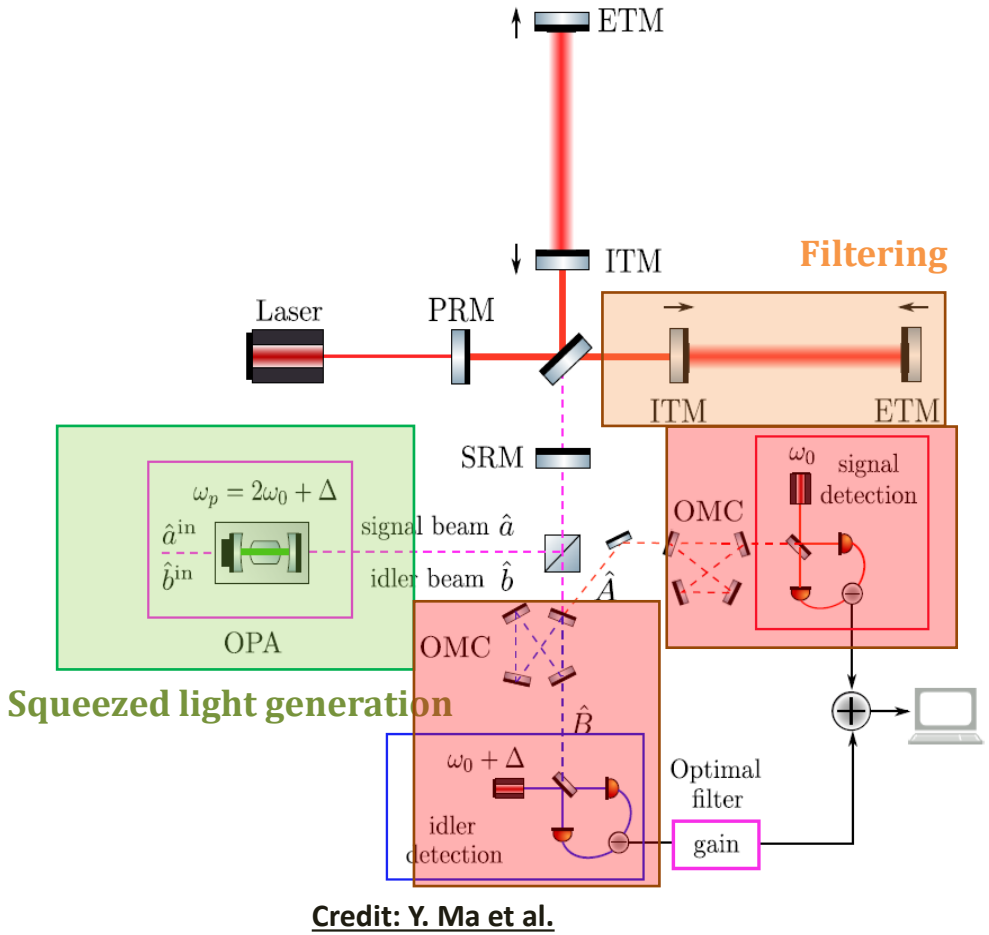
Credit: Y. Ma et al.

CONDITIONNAL SQUEEZING

WITH SQUEEZED SIGNAL IN A FREQUENCY-DEPENDENT WAY

EPR-entanglement technique: principles

3 **Detection :** signal and idler are detected separately and the outcome of one detector is conditioned by the outcome of the other detection (scaling factor g)



Credit: Y. Ma et al.

CONDITIONNAL SQUEEZING

WITH SQUEEZED SIGNAL IN A FREQUENCY-DEPENDENT WAY

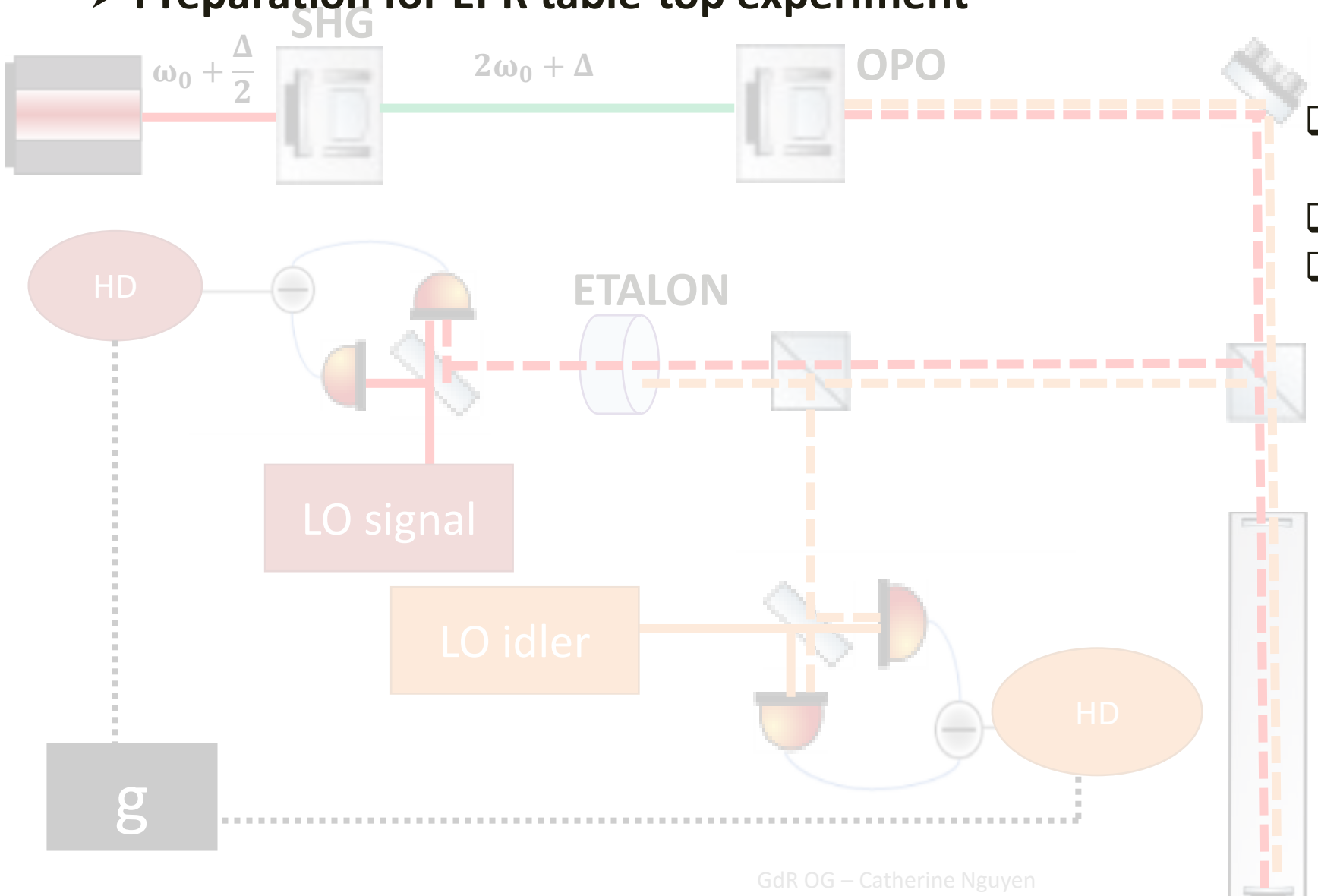
✓ Recent **proof-of-principle experiments** was performed by the University of Hamburg and by the Australian National University with a simplified setup.

Our objective

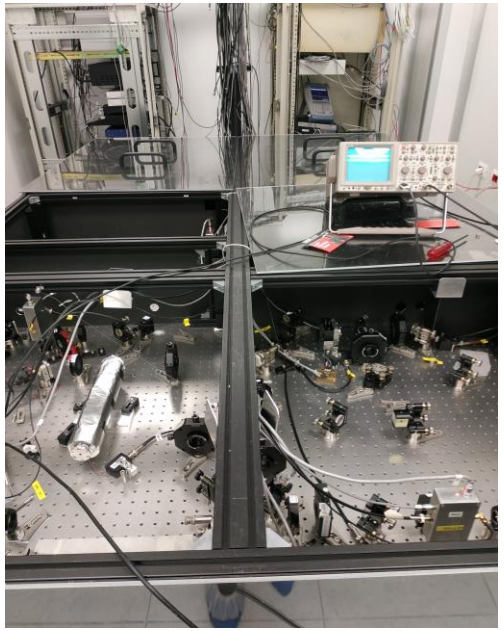
Build a complete set-up to be implemented to Advanced Virgo

On-going work on EPR experiment

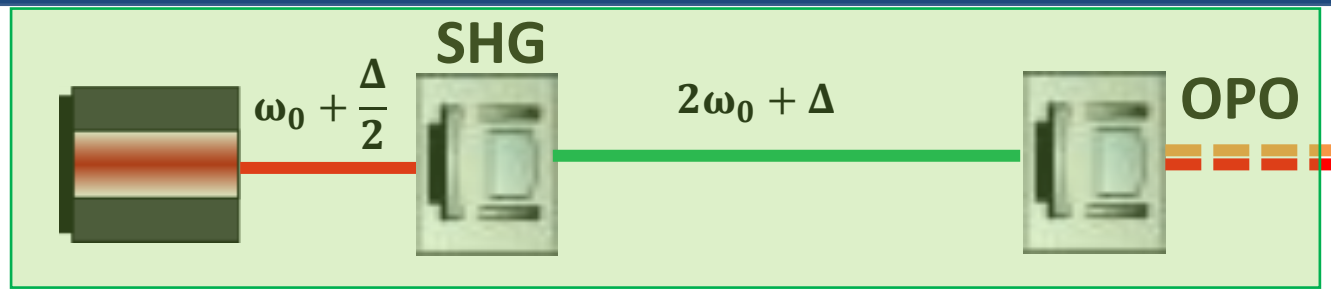
➢ **Preparation for EPR table-top experiment**



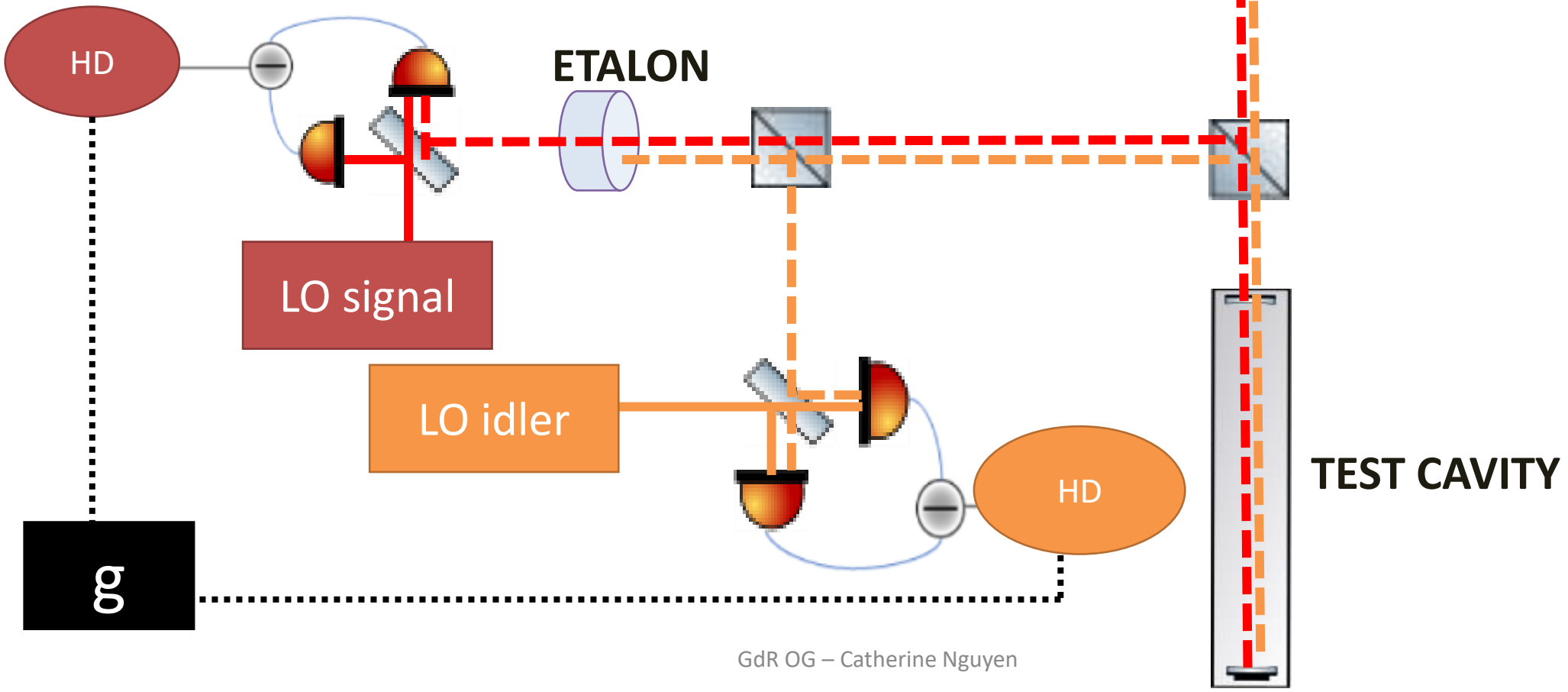
- ❑ Final optical layout almost fixed
- ❑ Preparation for components
- ❑ Preparatory bench at EGO to be transformed in an EPR bench



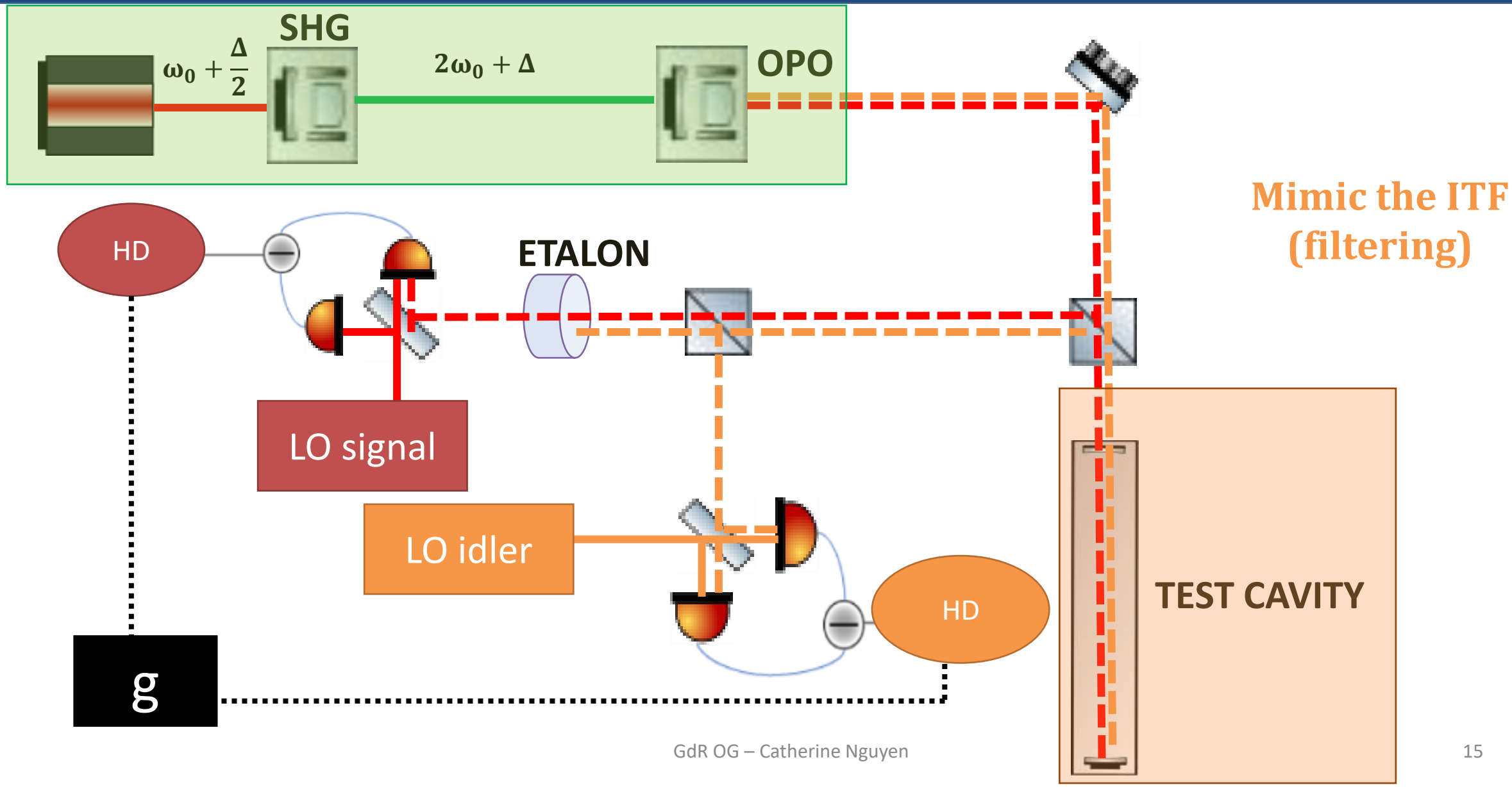
On-going work on EPR experiment



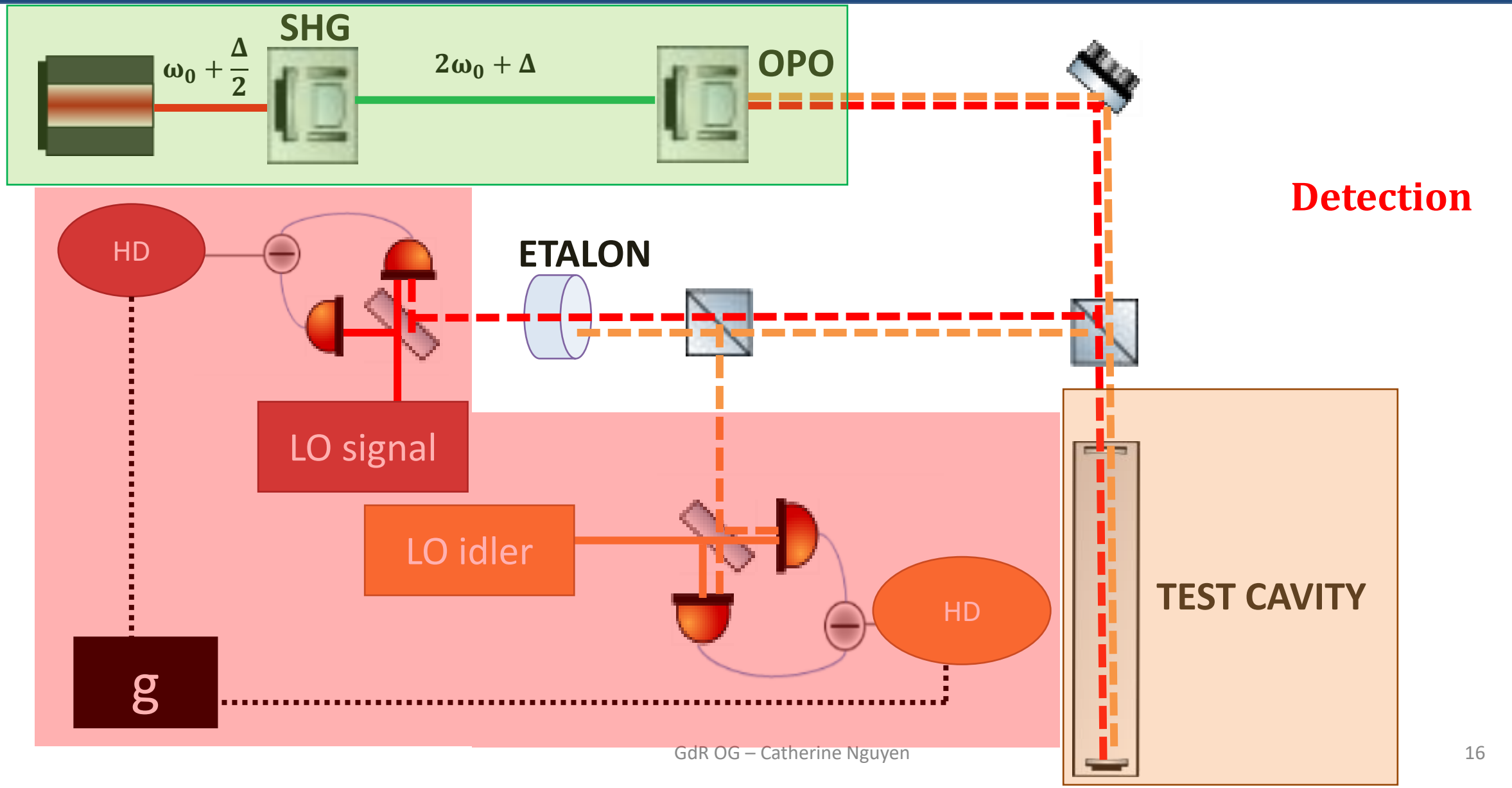
Squeezed light generation : non-degenerate OPO



On-going work on EPR experiment



On-going work on EPR experiment

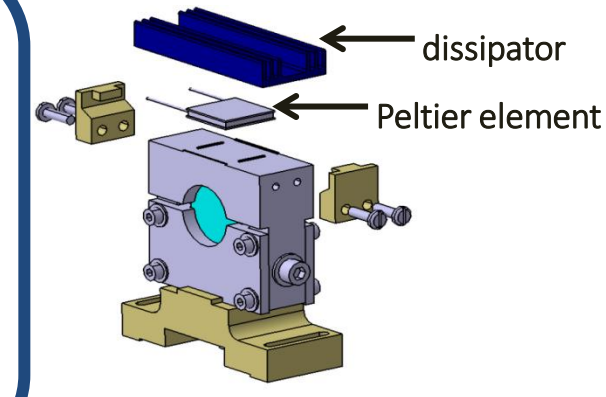


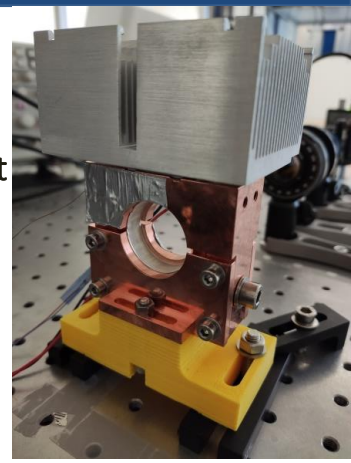
Etalon thermal control

Etalon design and tests at APC

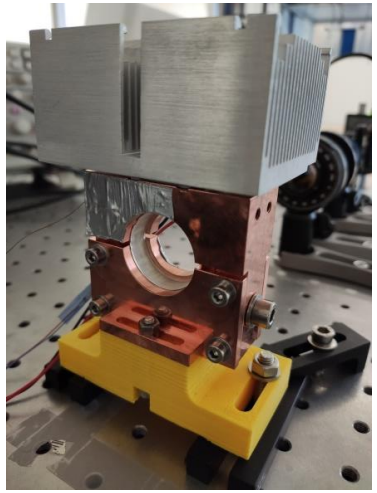
- separate EPR entangled beams
- no locking system
- needs a good thermal control

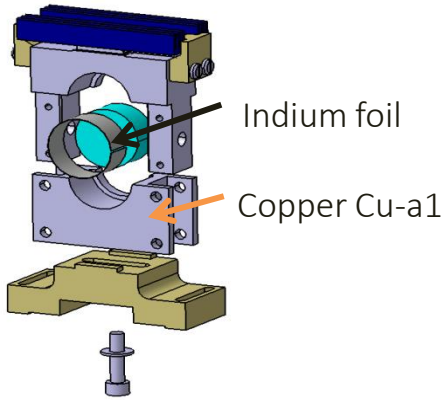
(temperature fluctuations < 0.03 °C for >95% efficiency)





Mechanical holder



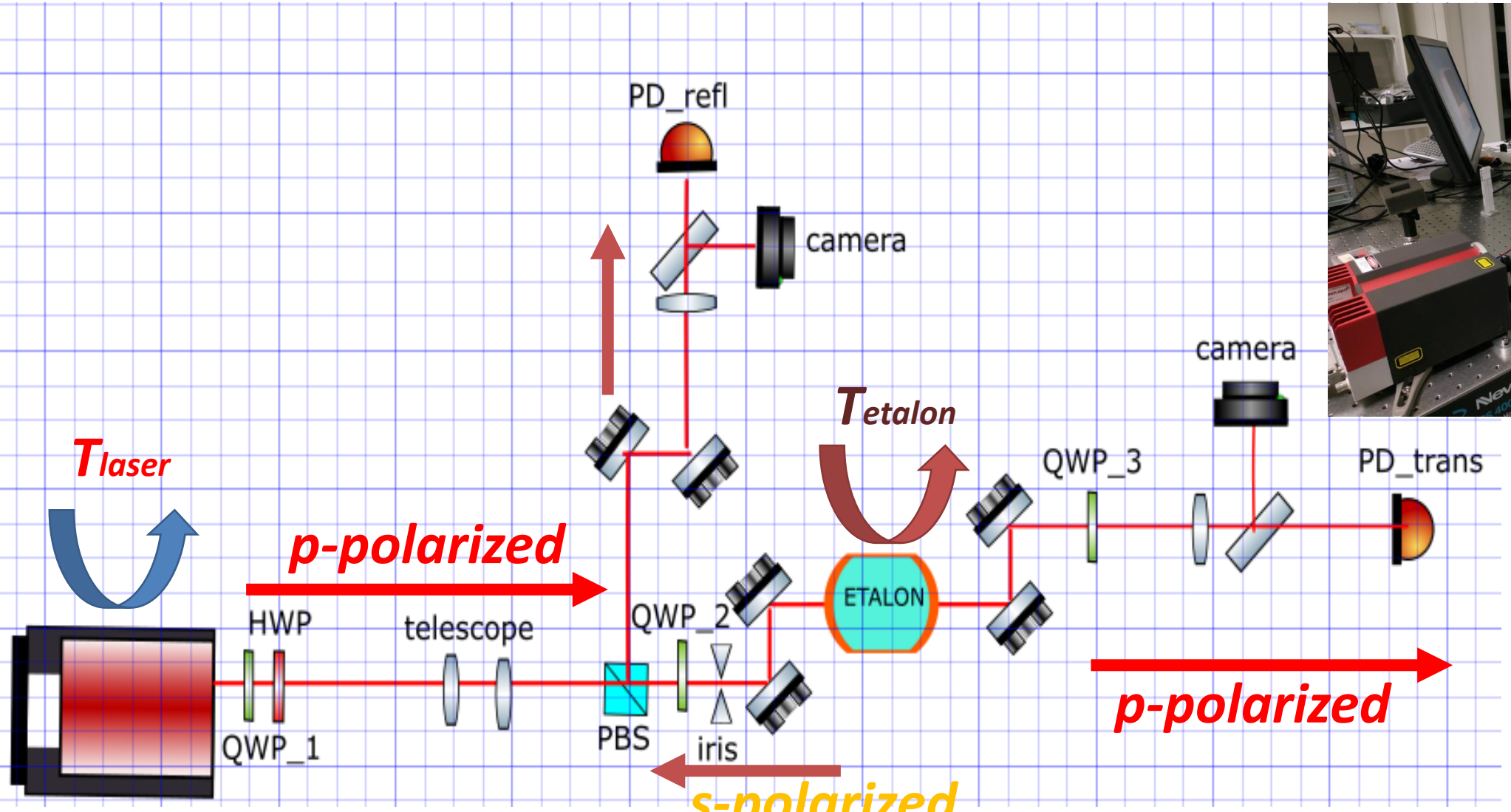


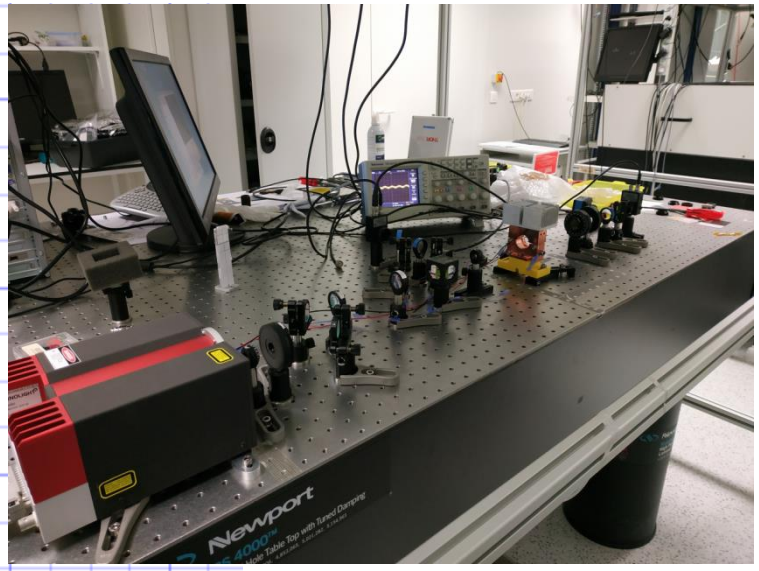
Design of Jean-Pierre Baronick

Temperature controller

- User set the temperature
- read the temperature with a thermistor on the holder
- drive the current for the Peltier element
- PID system to stabilize at the set temperature

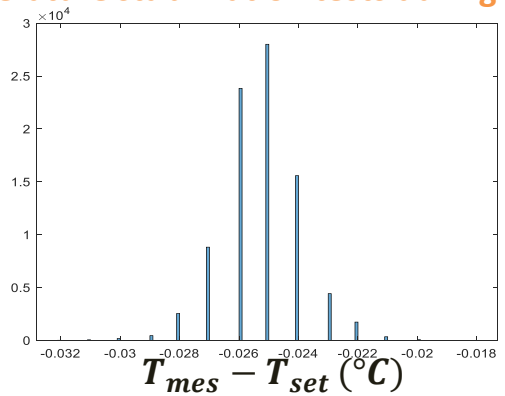
Etalon test bench





Thermal control & etalon caracterization

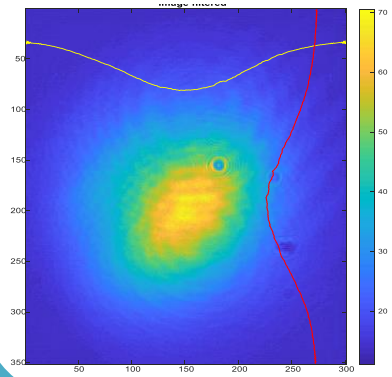
Temperature stabilization tests during 3 days



Within ± 0.03°C fluctuations

OVERLAP INTEGRAL

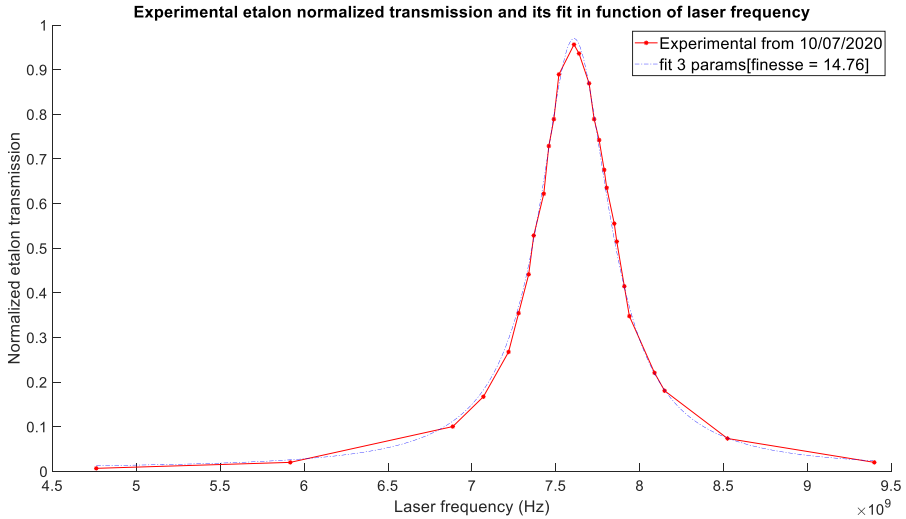
$$\gamma_{mes \leftrightarrow th} = \frac{\iint I_{mes}(x,y) I_{th}(x,y) dxdy}{\sqrt{\iint I_{mes}(x,y)^2 dxdy} \sqrt{\iint I_{theory}(x,y)^2 dxdy}}$$



- Overlap with a theoretical gaussian beam

> 99

FINESSE



$$T_{et} = T(0) * \frac{1}{1 + \left(\frac{finesse}{\pi}\right)^2 . \sin\left(\frac{\varphi}{2}\right)^2}$$

Finesse = 14.7 ± 0.8

Supplier data: finesse = 14

Take-away messages

- Squeezing using EPR entanglement is a technique to avoid using a filter cavity and an experiment will be built to test its application to Advanced Virgo.
- EPR beams separation will be operated by an etalon. Etalon characterization and thermal control system tests are almost finished.
- **EPR squeezing is a promising technique for future detectors as Einstein Telescope.**

Thank you for your attention !

>> Any questions ?