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

## using frequency-dependent squeezing with EPR entanglement

**Catherine Nguyen (APC laboratory)**
*on behalf of Virgo Collaboration (EPR – squeezing collaboration)*
*INFN – APC laboratory*

# Frequency-dependent squeezing (FDS)

- **Radiation pressure noise** will limit the future upgrade of Advanced Virgo.

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

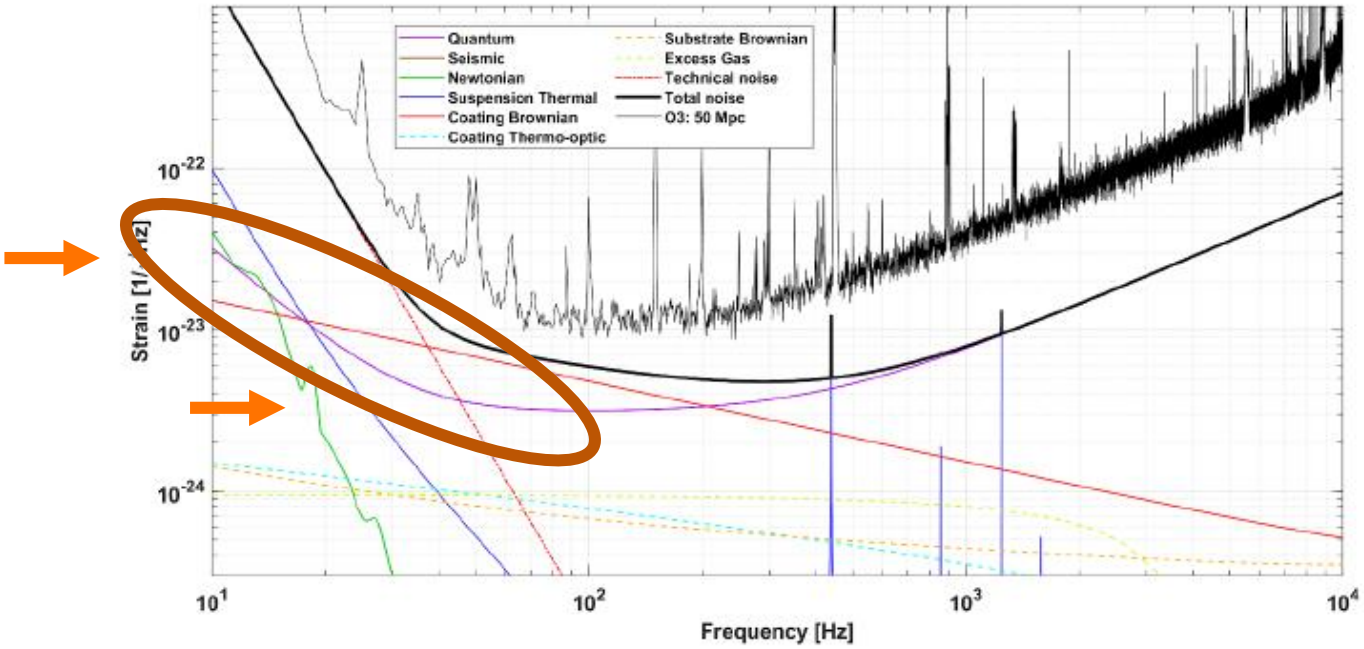


Figure 2. Anticipated best sensitivity of AdV+ during Phase I. For comparison the sensitivity at the beginning of O3 is shown.

**Credit: Advanced Virgo PlusDesign Report (VIR-0596A-19)**

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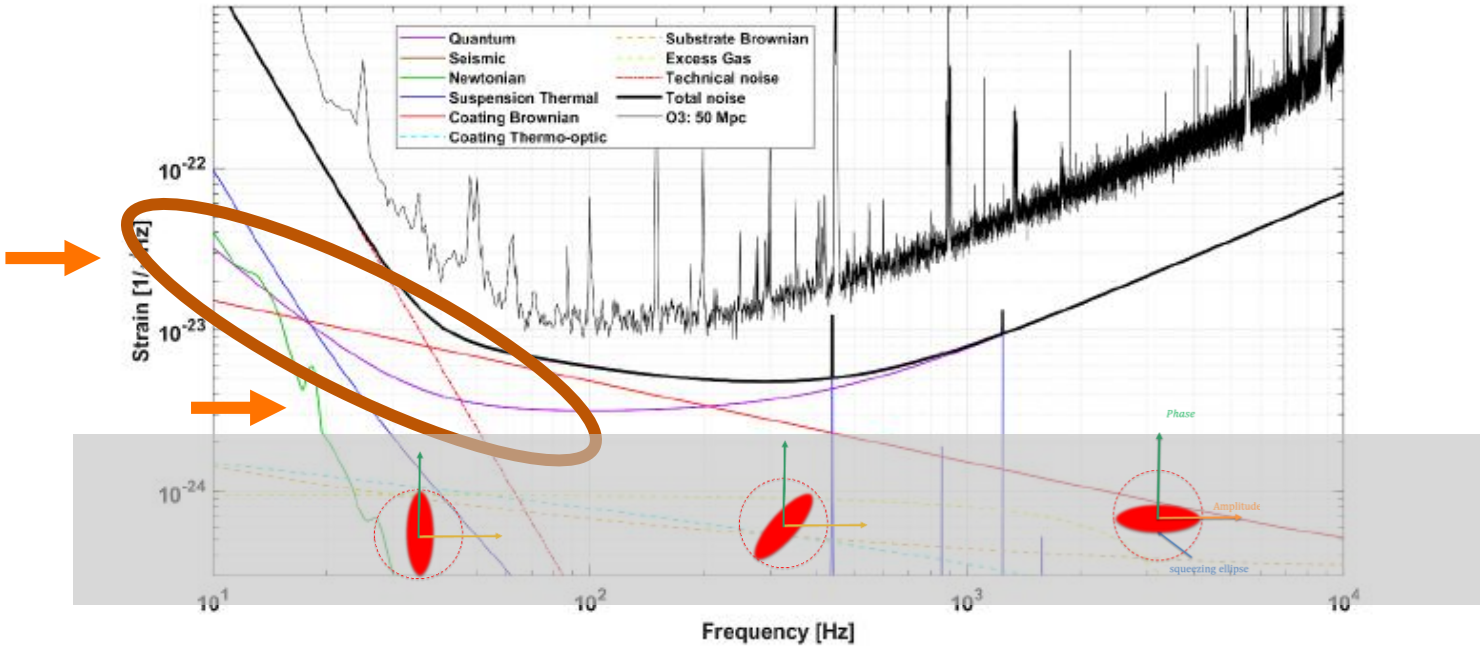


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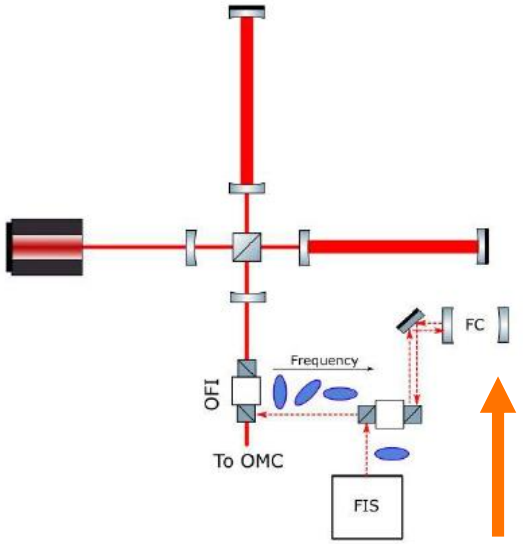
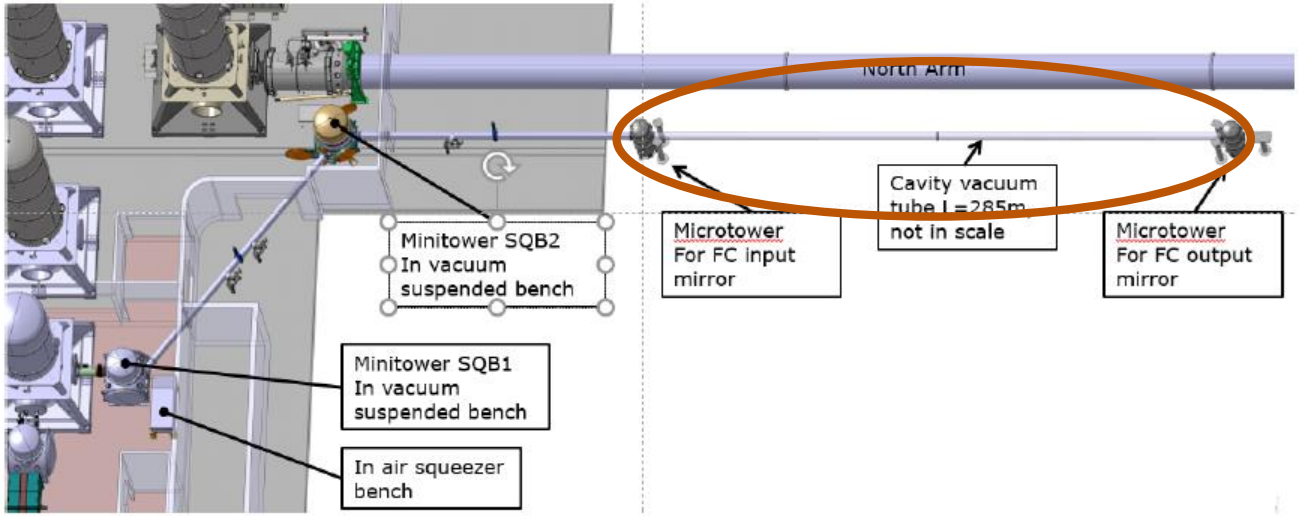
# Frequency-dependent squeezing (FDS)

## ➢ Filter Cavity (FC)

- ❑ Frequency-independent squeezing injected into a filter cavity (Fabry-Perot cavity)
- ❑ planned for O4 for AdV+ and aLIGO




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

# 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

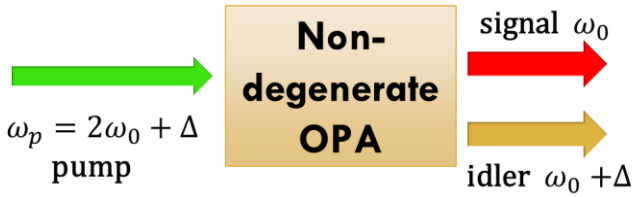
But…

- 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 $\Delta$)







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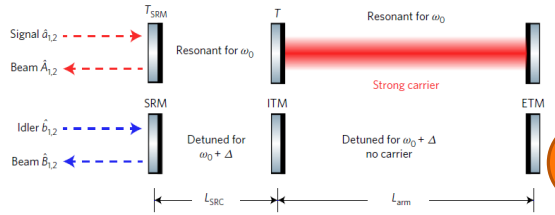
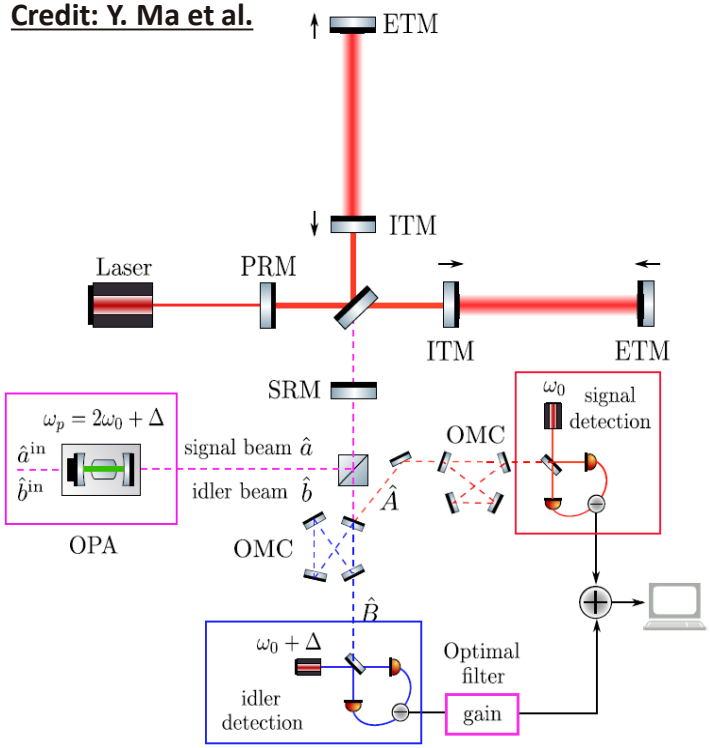



Figure 3 | The differential mode of the interferometer as seen by the signal (upper panel) and idler (lower panel) beams.

1 **Detune pumping frequency** (of $\Delta$)

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

**Credit: Y. Ma et al.**

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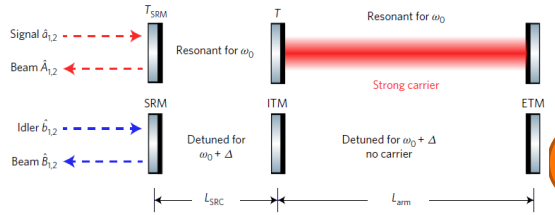


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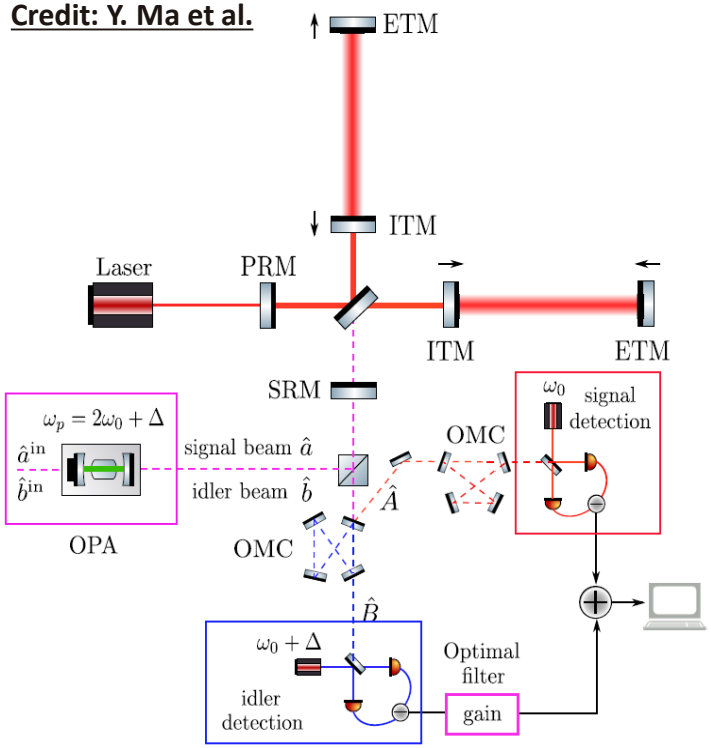
3 **Detection**

**CONDITIONNAL SQUEEZING WITH SQUEEZED SIGNAL IN A FREQUENCY-DEPENDENT WAY**

**Credit: Y. Ma et al.**

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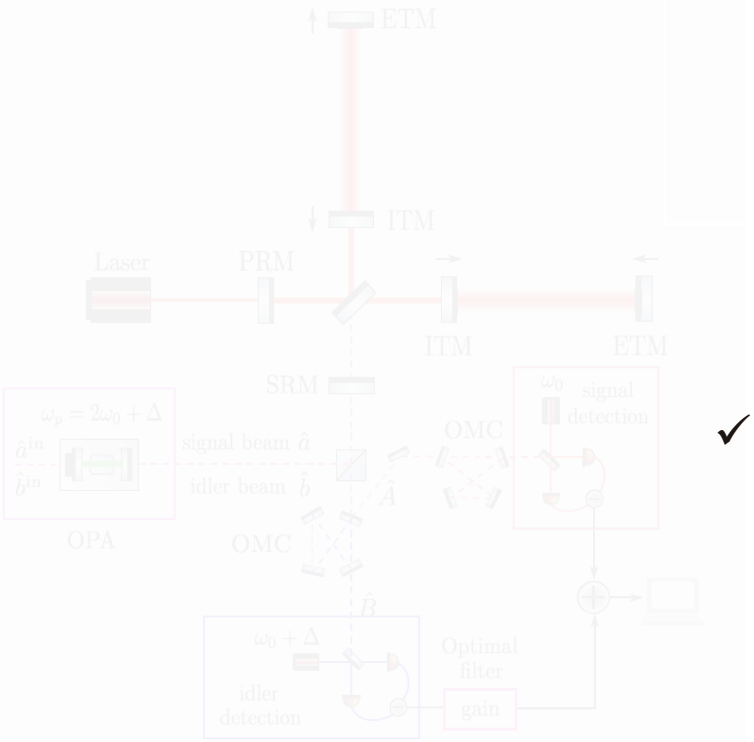
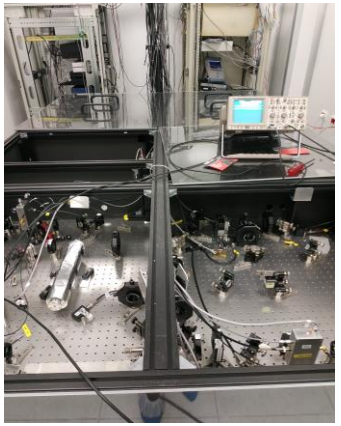



- ✓ Recent **proof-of-principle experiments** was performed by the University of Hamburg and by the Australian National University

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

# On-going work on EPR experiment

- Preparatory frequency-independent squeezing bench at EGO to be transformed in an EPR bench

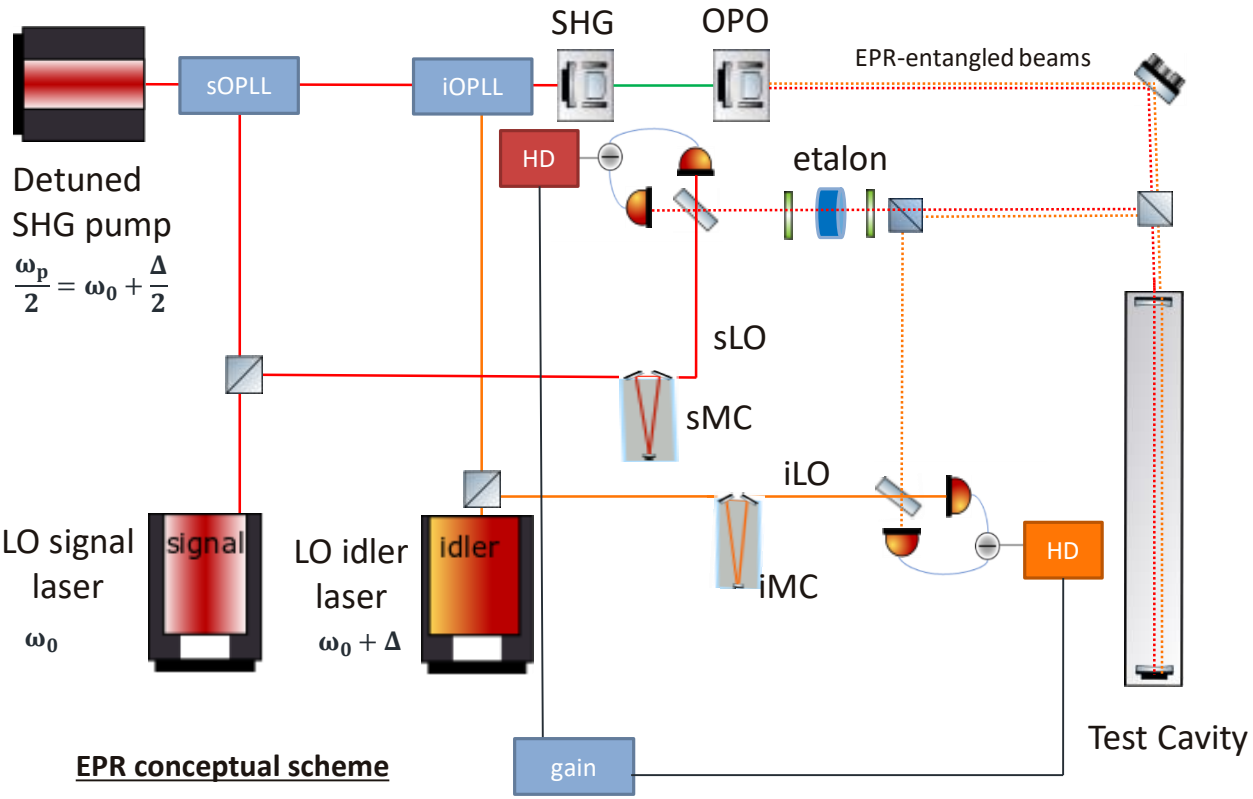


# On-going works on EPR experiment



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

  *Virgo Collaboration*



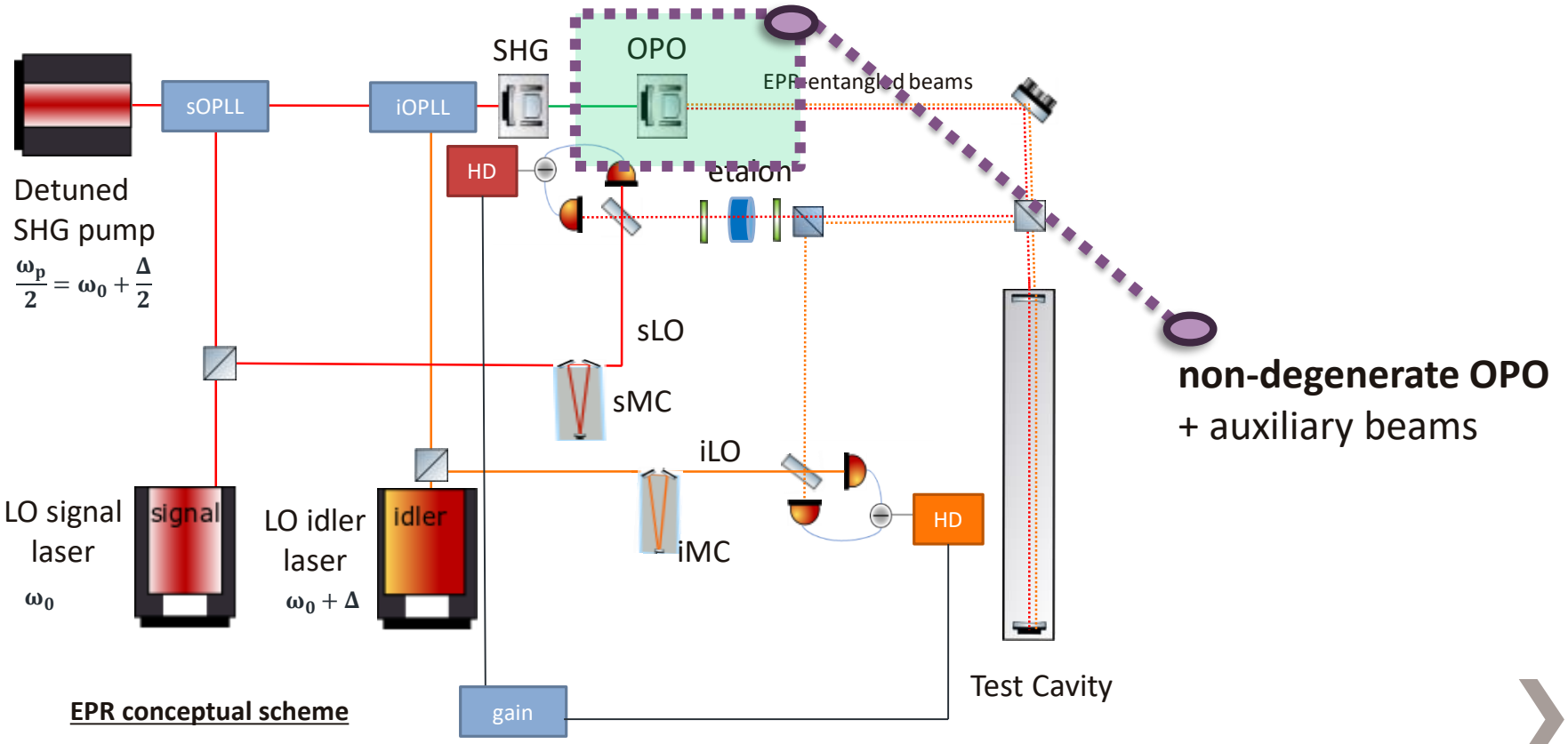

**EPR conceptual scheme**

- ❑ Final optical layout almost fixed
- ❑ Preparation for components

MC = mode-cleaner, LO = local oscillator, HD = homodyne detector, SHG = second harmonic generator, OPO = optical parametric oscillation, OPPL = optical phase-locked loop

# On-going work on EPR experiment

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

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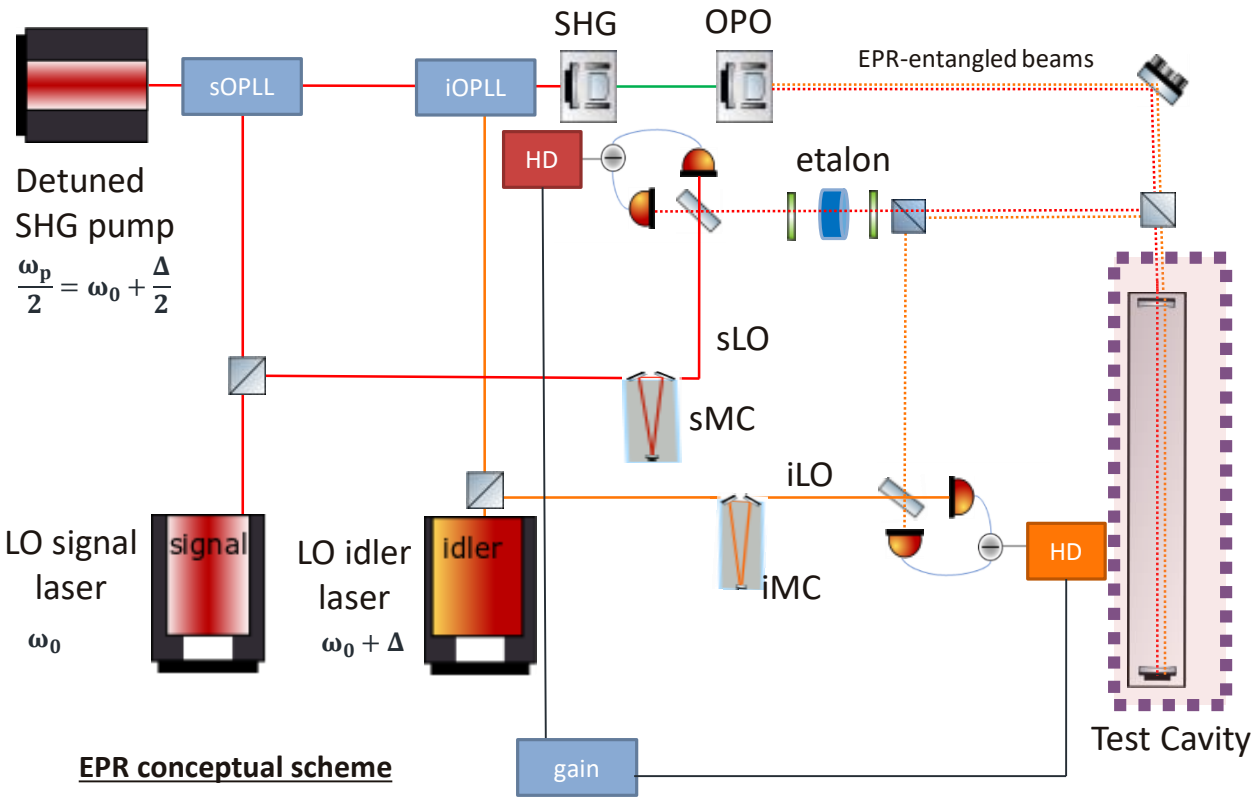


**mimic the ITF arm**

MC = mode-cleaner, LO = local oscillator, HD = homodyne detector, SHG = second harmonic generator, OPO = optical parametric oscillation, OPPL = optical phase-locked loop

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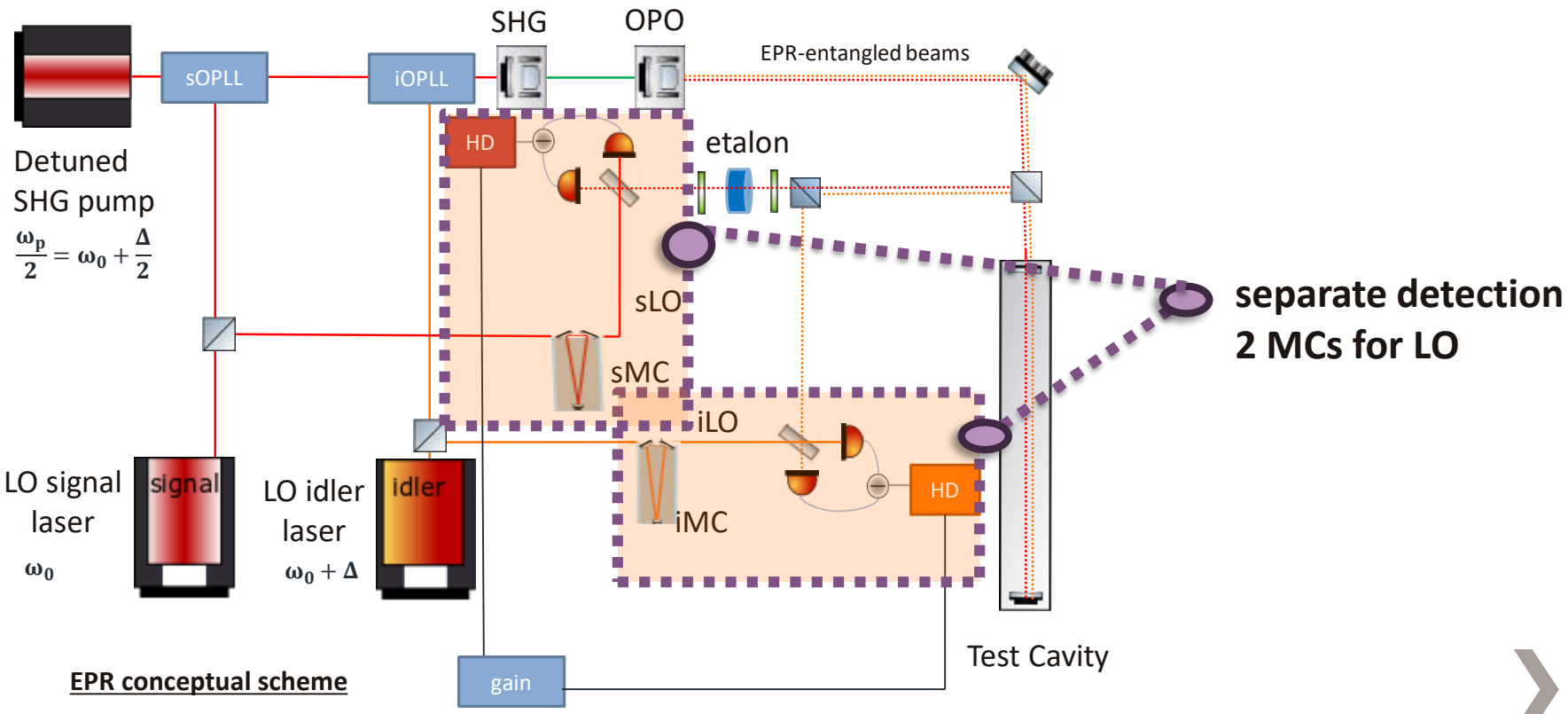


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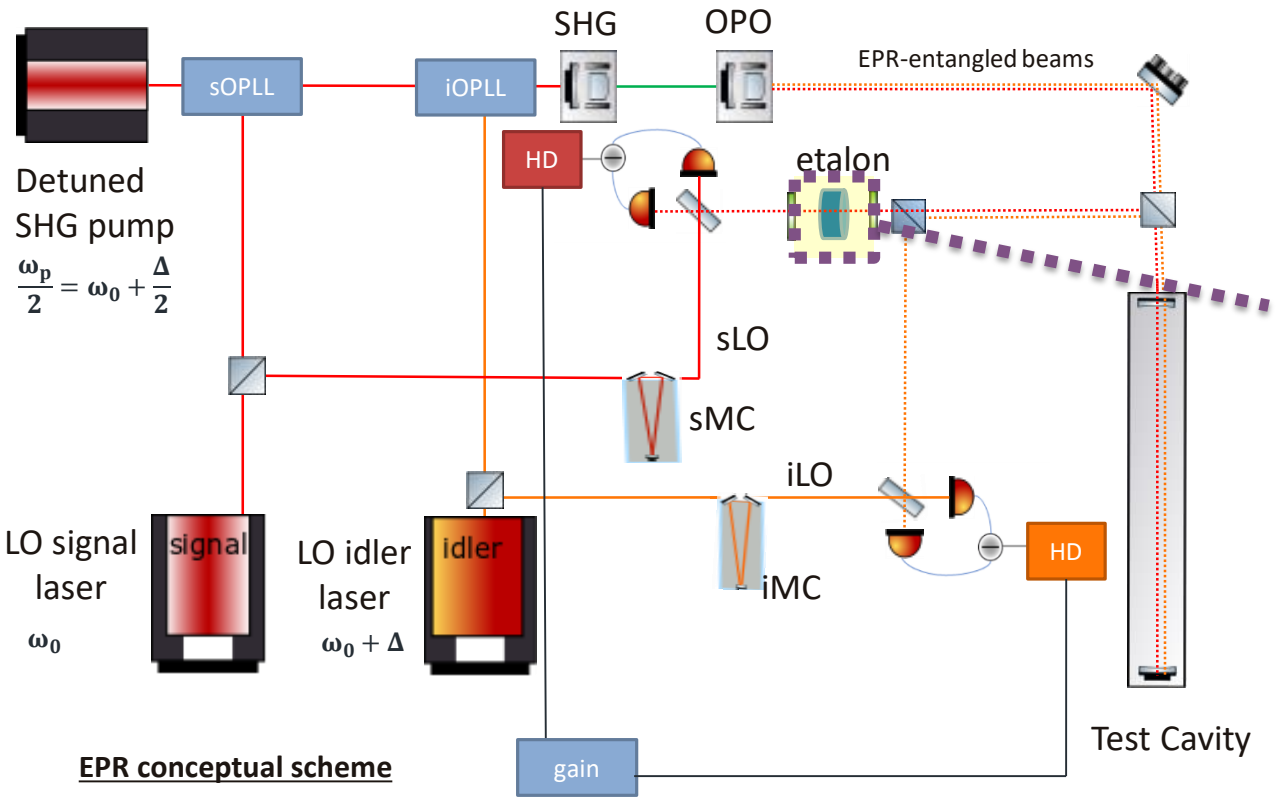
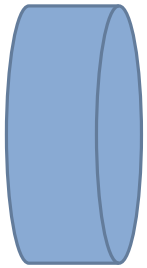



**Separate the two EPR-entangled beams**

MC = mode-cleaner, LO = local oscillator, HD = homodyne detector, SHG = second harmonic generator, OPO = optical parametric oscillation, OPPL = optical phase-locked loop

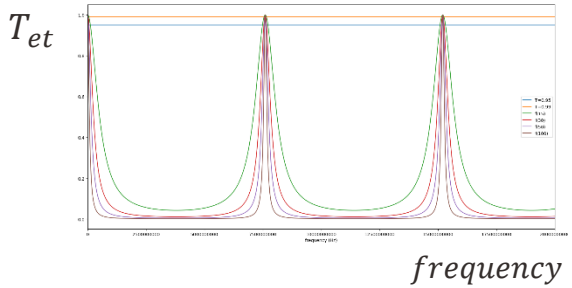
# Work on etalon at APC

*For APC : J.-P. Baronick, M. Barsuglia, E. Bréelle, C. Nguyen, P. Prat*



- separate EPR- entangled beams
- no locking system
- needs a good thermal control
- Delivery ongoing (with our dimensioning)

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



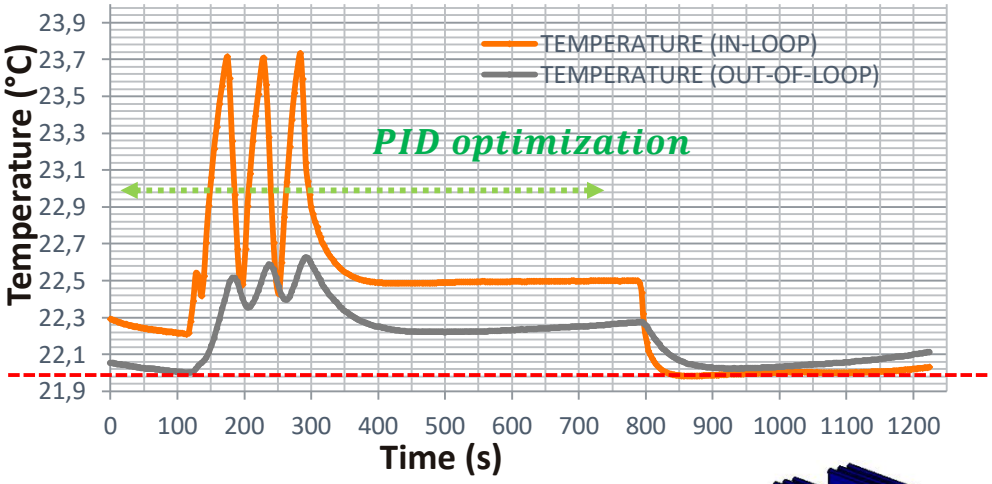

## ➢ Thermal control of the etalon

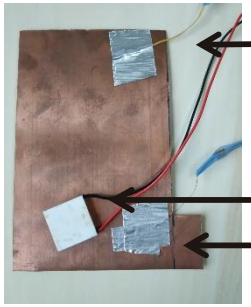
- ✓ We want a temperature stabilization of ± 0.03°C
- ✓ We use temperature controller to find the working point.


**Scheme of temperature control set-up**

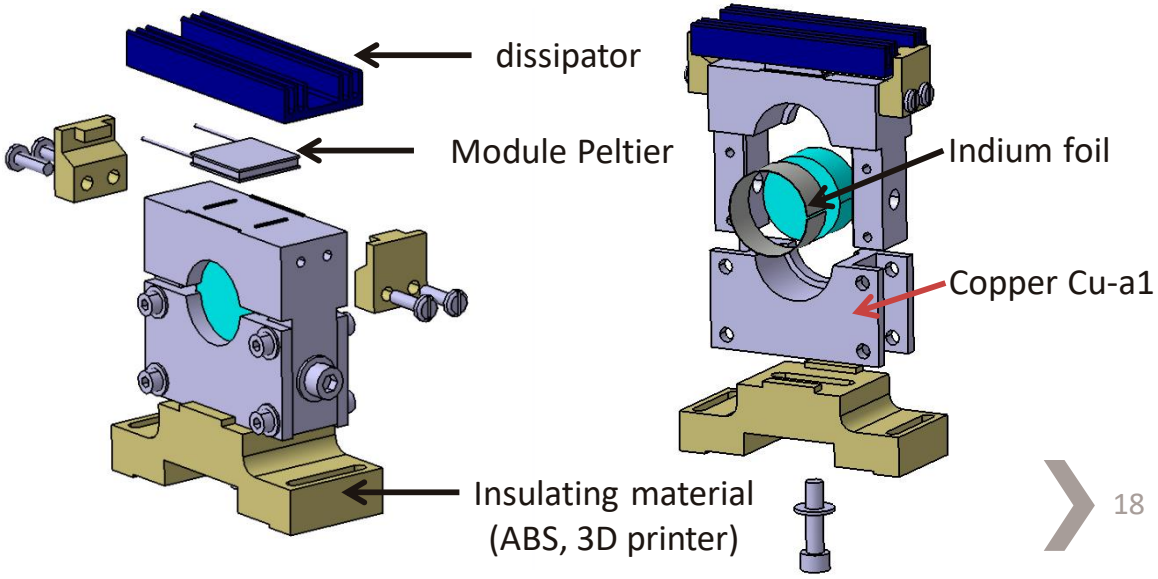
# Work on etalon at APC

➢ **Temperature control preliminary tests**




**Mechanical design of the etalon holder**




*Design of Jean-Pierre Baronick (APC)*

➢ Will be machined at APC mechanical workshop

# Work on etalon at APC

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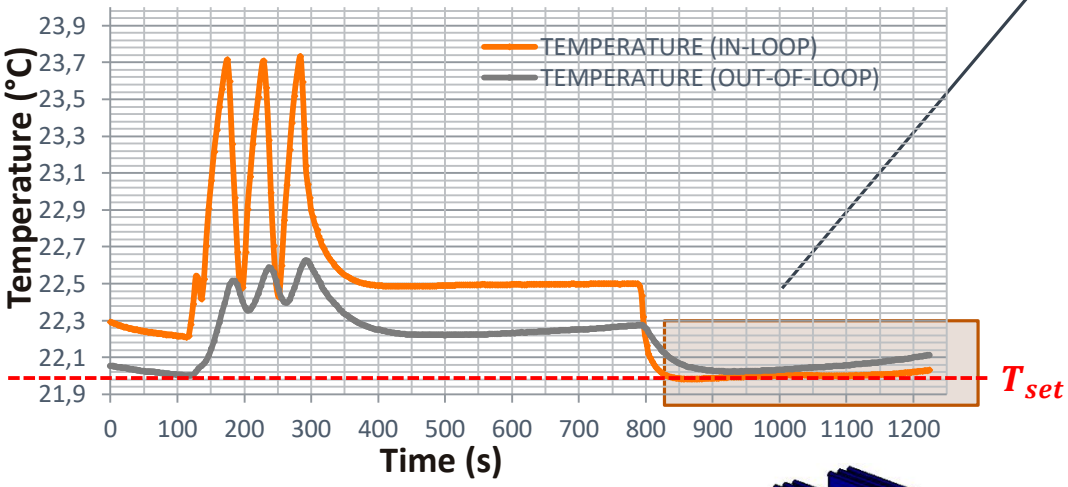
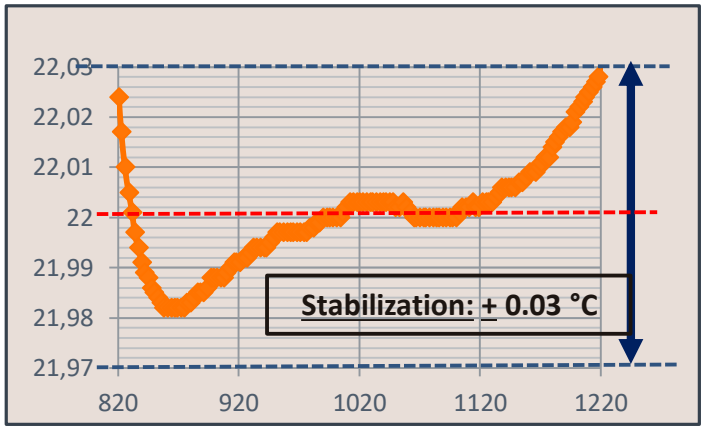
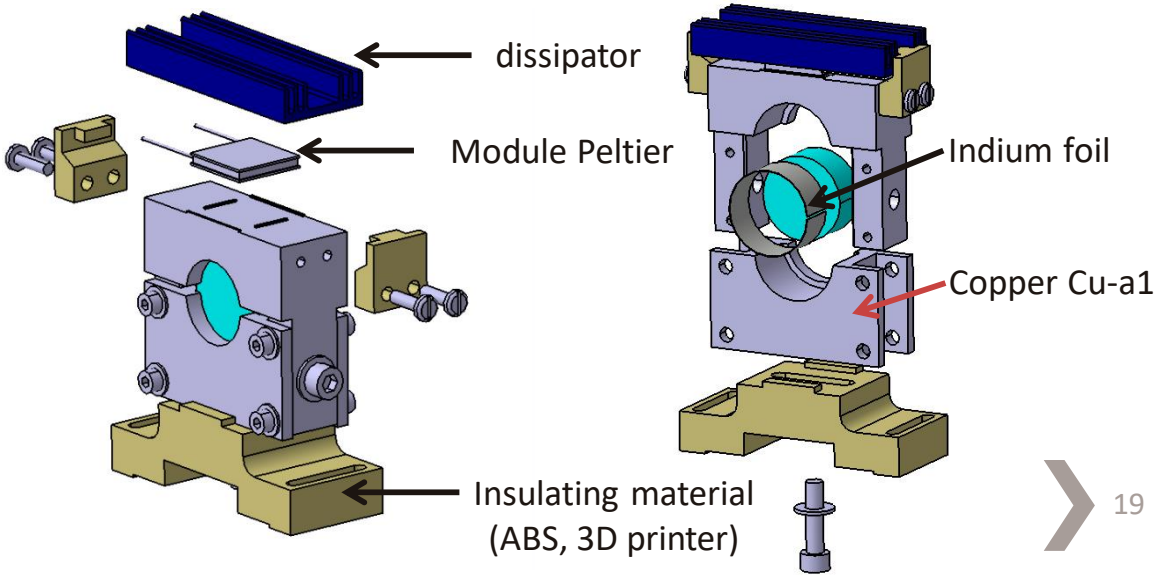



$T_{set} = 22°C$




- during more than 400s

**Mechanical design of the etalon holder**

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*Design of Jean-Pierre Baronick (APC)*

# Take-away messages

- **Frequency-dependent squeezing technique is needed for a broadband reduction of quantum noise.**

- **For Observation Run O4, FDS technique using a filter cavity is planned for AdV+ and aLIGO.**

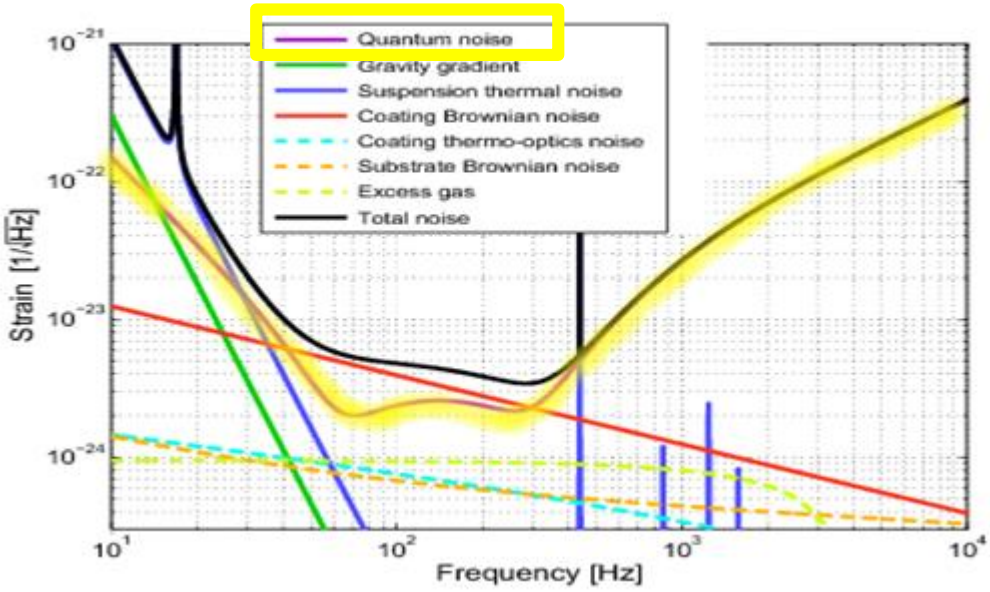
- **Squeezing using EPR entanglement is a technique to avoid using a filter cavity and an experiment will be built to test its application to Advanced Virgo.**

- **EPR squeezing is a promising technique for future detectors as Einstein Telescope.**

# Thank you for your attention !

# Any questions ?

# Noise budget and quantum noise




Advanced Virgo sensitivity curvec

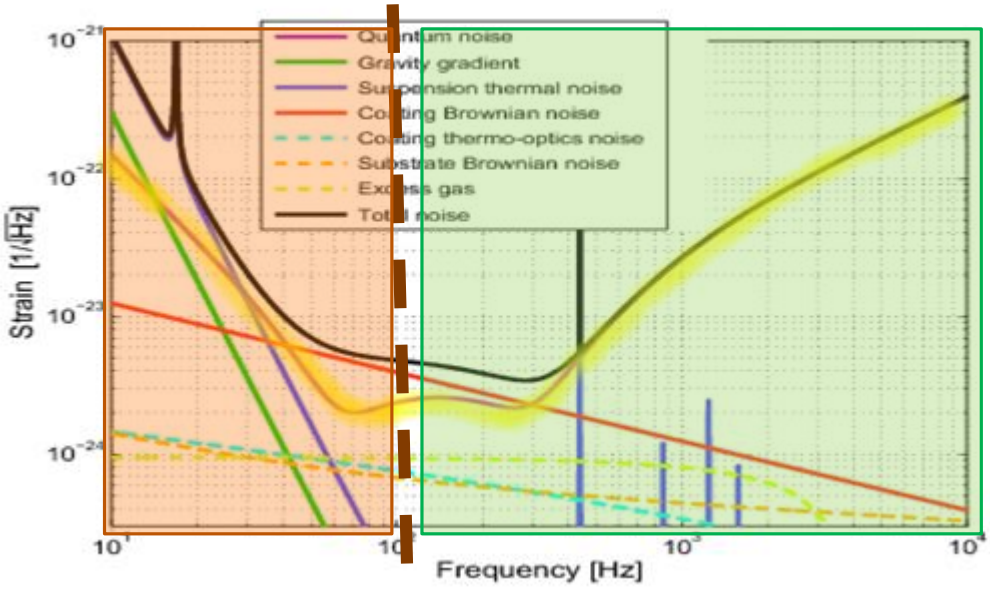
- **Quantum noise (QN) is one of the major sources of noise**

# Noise budget and quantum noise

*At low frequency*

**Radiation pressure noise (RPN)**

*does not limit the current Advanced Virgo sensitivity*




*At high frequency*

**Shot noise**

*Limits the sensitivity at f > 400 Hz*

# Heisenberg uncertainty principle

*At low frequency*

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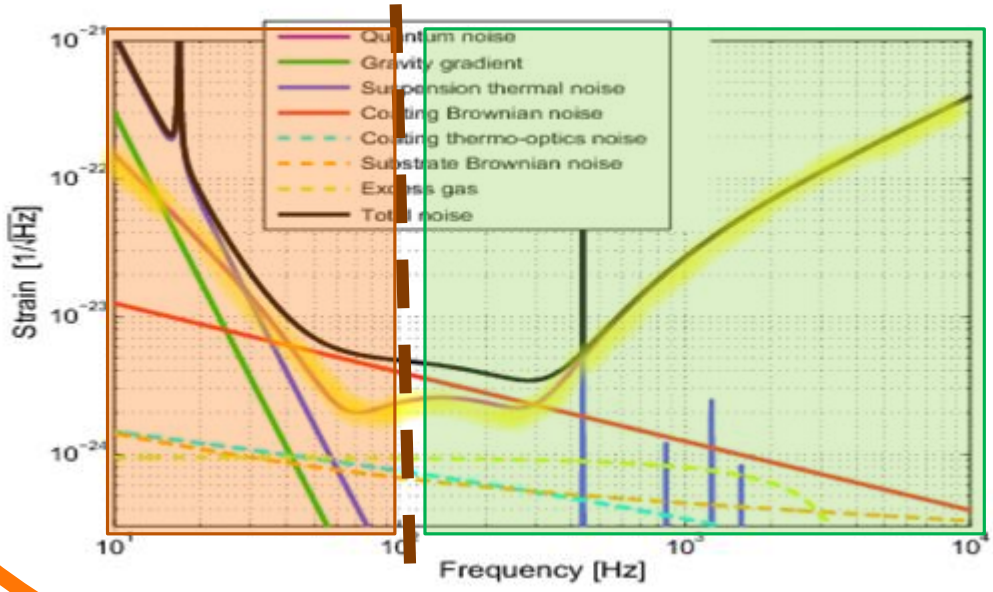



*At high frequency*

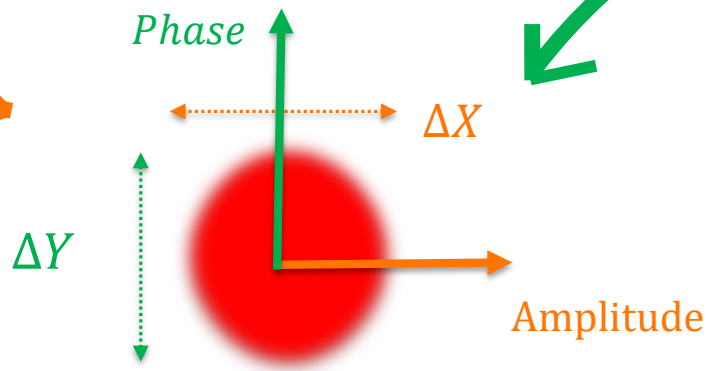
**Shot noise**

*Limits the sensitivity at f > 400 Hz*

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

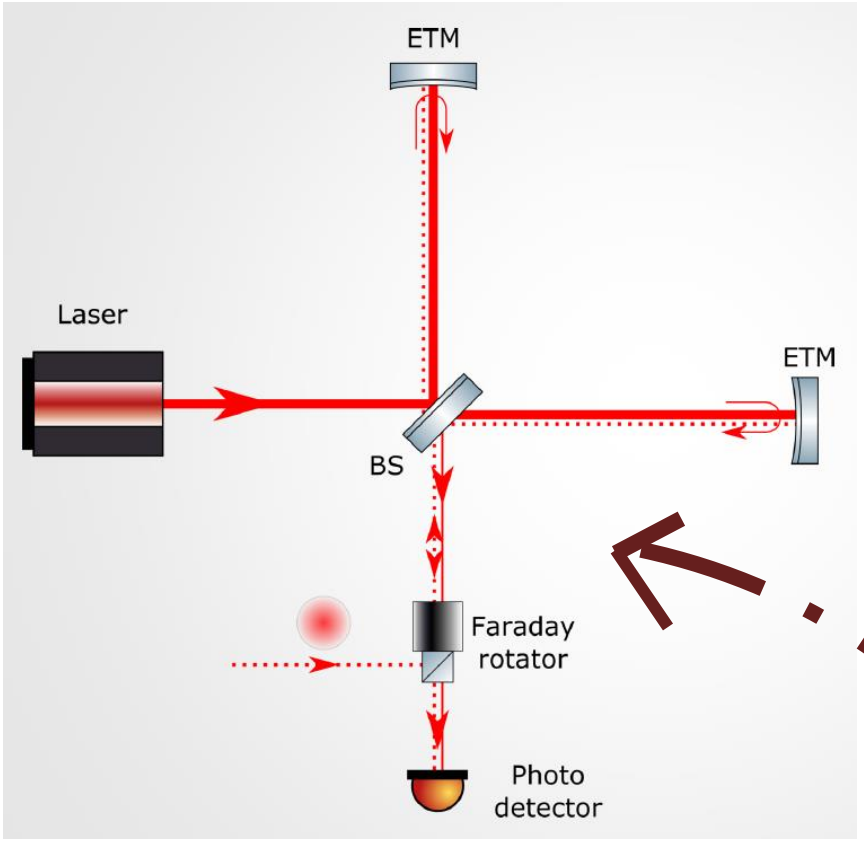
**Heisenberg uncertainty principle**

➢ **A multiplicative limit !**

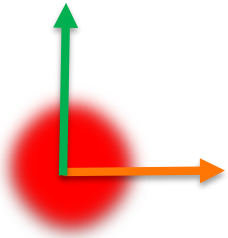



*Quantum fluctuations* in quadrature space

# Origin of quantum noise

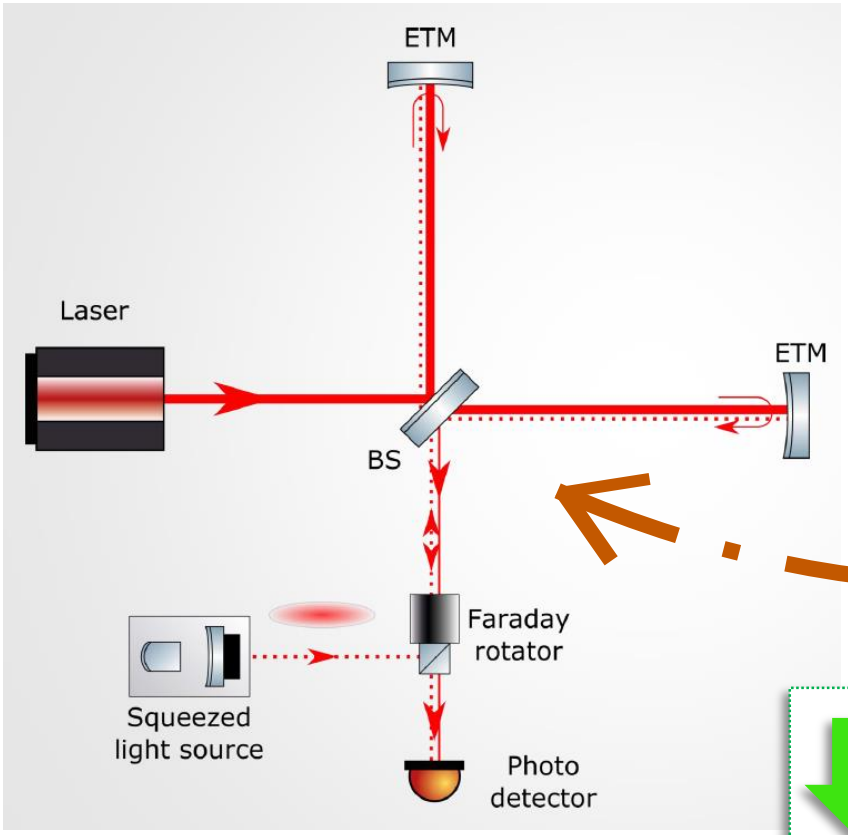


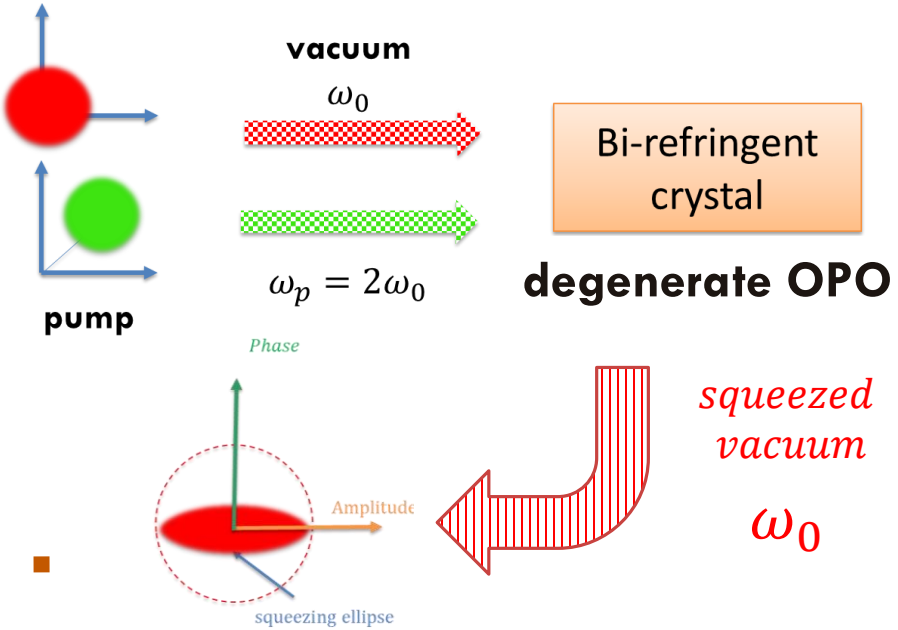

Jan Gniesmer & Min Jet Yap, GWADW 2019



**Quantum noise is due to vaccuum fluctuations entering the dark port of the interferometer**

# Frequency-independent squeezing (FIS)




Jan Gniesmer & Min Jet Yap, GWADW 2019

**Shot noise**

**RPN**
= Anti-squeezing

- **Sensitivity improvement**

**Advanced Virgo : 3.1 dB, aLIGO: L 3.1 dB, H 2.2 dB, GEO 600: 6 dB**