Squeezing: APC and IJCLab contribution to ET

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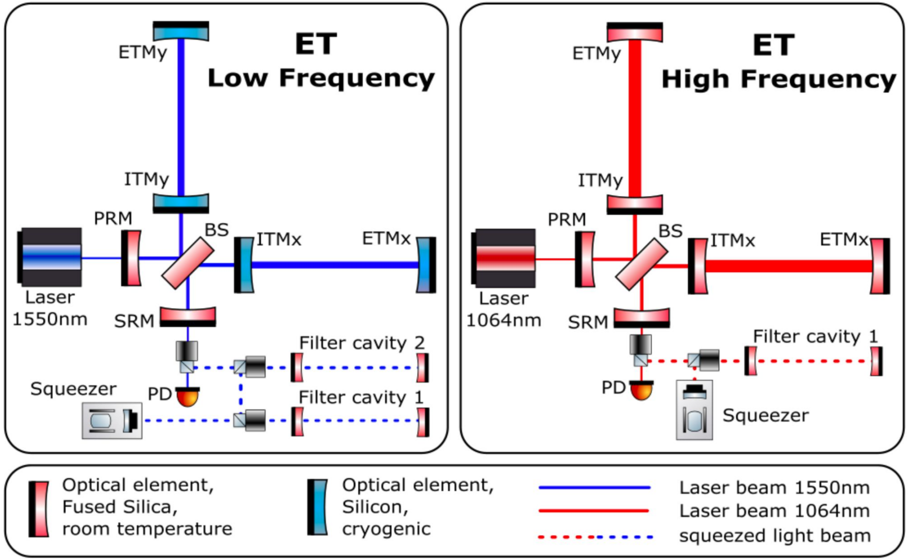
Introduction:

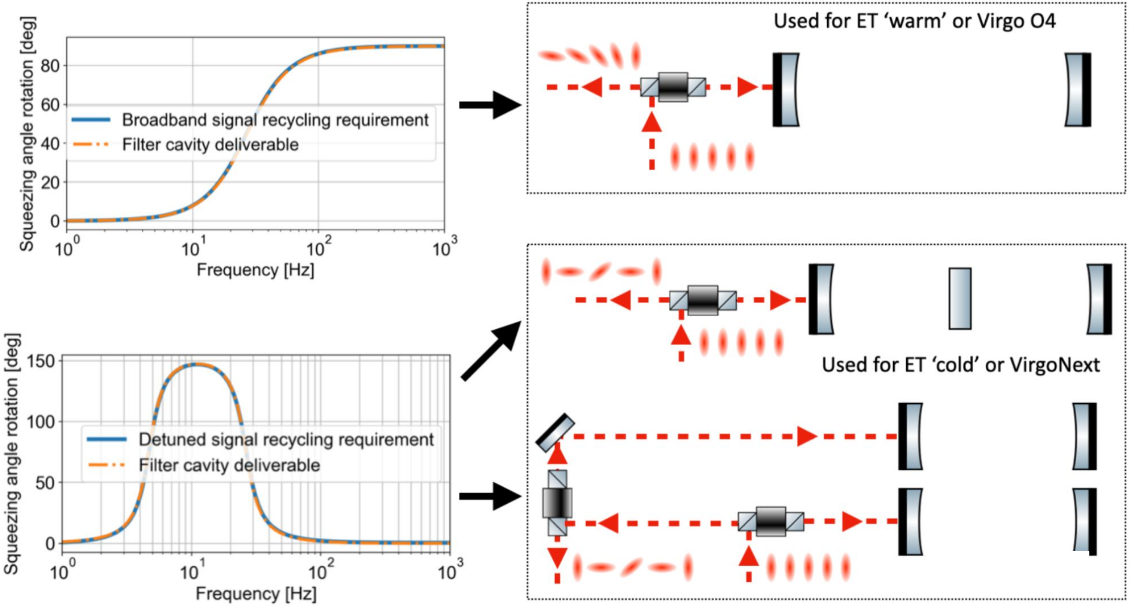
- Current frequency dependent squeezing (FDS) with a single filter cavity cannot be directly applied to a detuned GW detector



- Current proposal: to use **two filter cavities** for the ET-LF (with detuned SR)

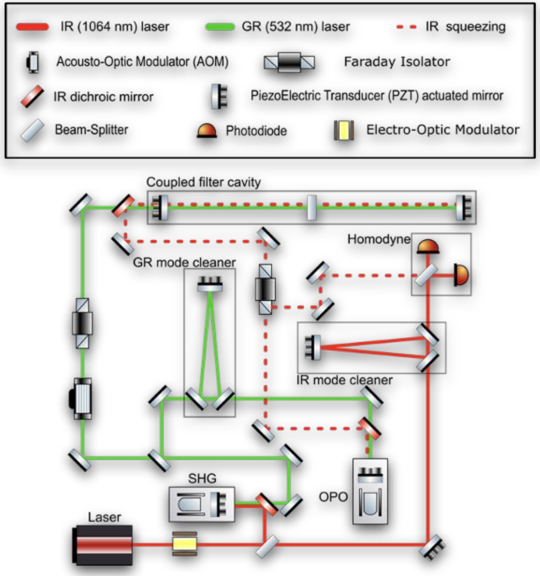
Introduction:

- Non-trivial squeezing ellipse rotation can be achieved with **two cavities** or with **a coupled cavity**



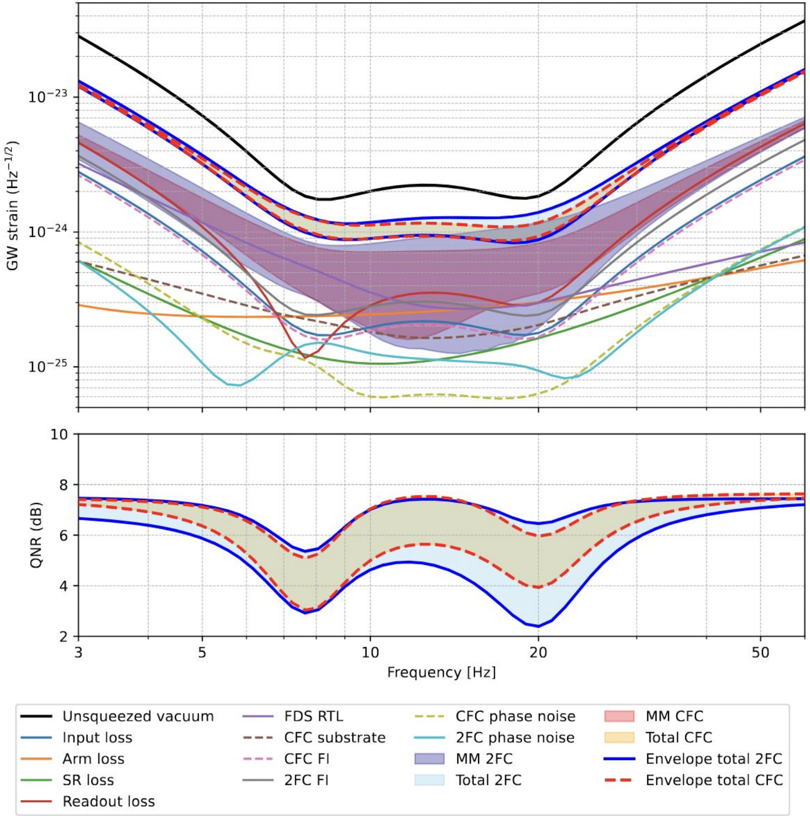
Quantum FRESCO project:

- **4 year ANR JCJC project (started in 2024)**
- **Goal:** demonstrate non-trivial squeezing rotation with a table top experiment
  - With two cavities
  - With a couple cavity



Simulation:

- Performance comparison 2 filter cavities (5km+5km) and coupled filter cavity (10 km)
- Round trip losses, length fluctuations: similar
- Mode mismatch cascade: slight advantage for the coupled filter cavity



Performance of multiple filter-cavity schemes for frequency-dependent squeezing in gravitational-wave detectors

Jacques Ding[1,2,*], Eleonora Capocasa[1], Isander Ahrend[1], Fangfei Liu[1,3], Yuhang Zhao[1], and Matteo Barsuglia[1]

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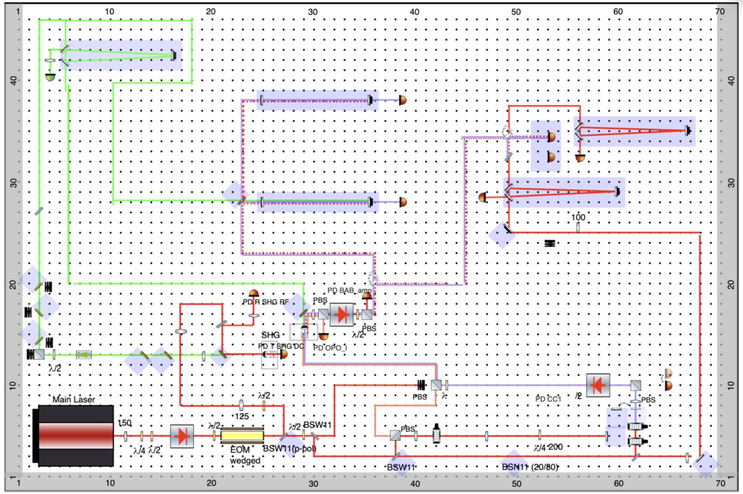
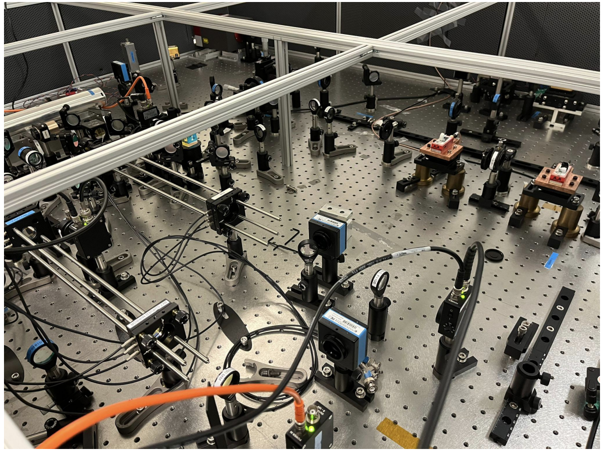
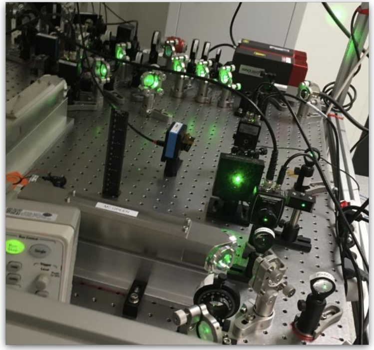
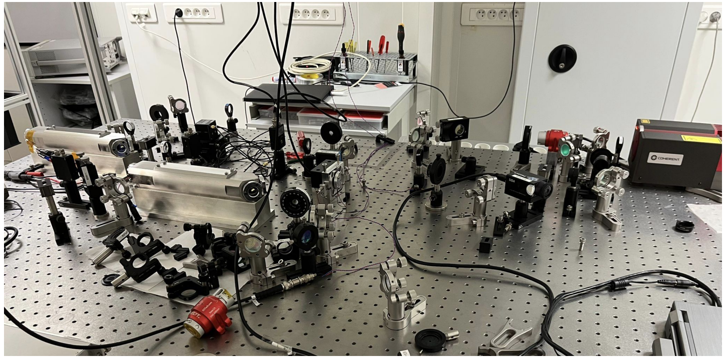
Status of the experiment:



- SHG assembled and locked
- OPO assembled
- Filter cavities locked (with dummy mirrors)
- Homodyne detector in construction







Other activities connected to squeezing :

- Participation in the quantum noise reduction system design within ET squeezing workpackage
- Experimental demonstration of complex squeezing (https://arxiv.org/pdf/2410.09976)
- Modematching optimization

Simultaneous Misalignment and Mode Mismatch Sensing in Optical Cavities Using Intensity-Only Measurements

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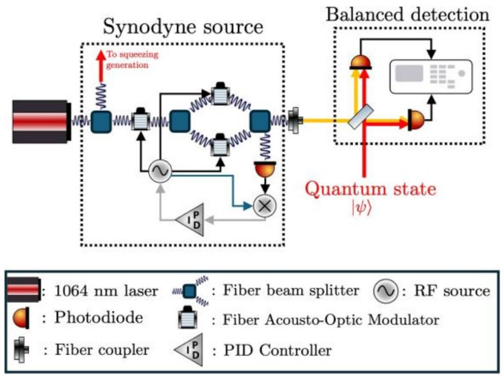
Submitted to Optics Express



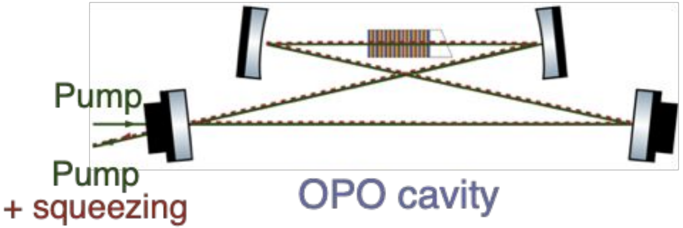
The CALVA experiment and the QFilter/ICETEA Project:

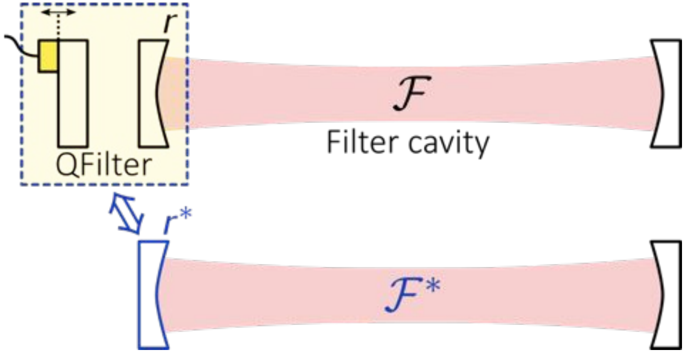
- Squeezing source geometry and in-vacuum generation

- New filter cavity geometry for an improved flexibility

- Participation of CALVA in the Refimeve research infrastructure & collaboration for high-finesse long cavity control

- Suspended periscope for delivering squeezing to the ITF





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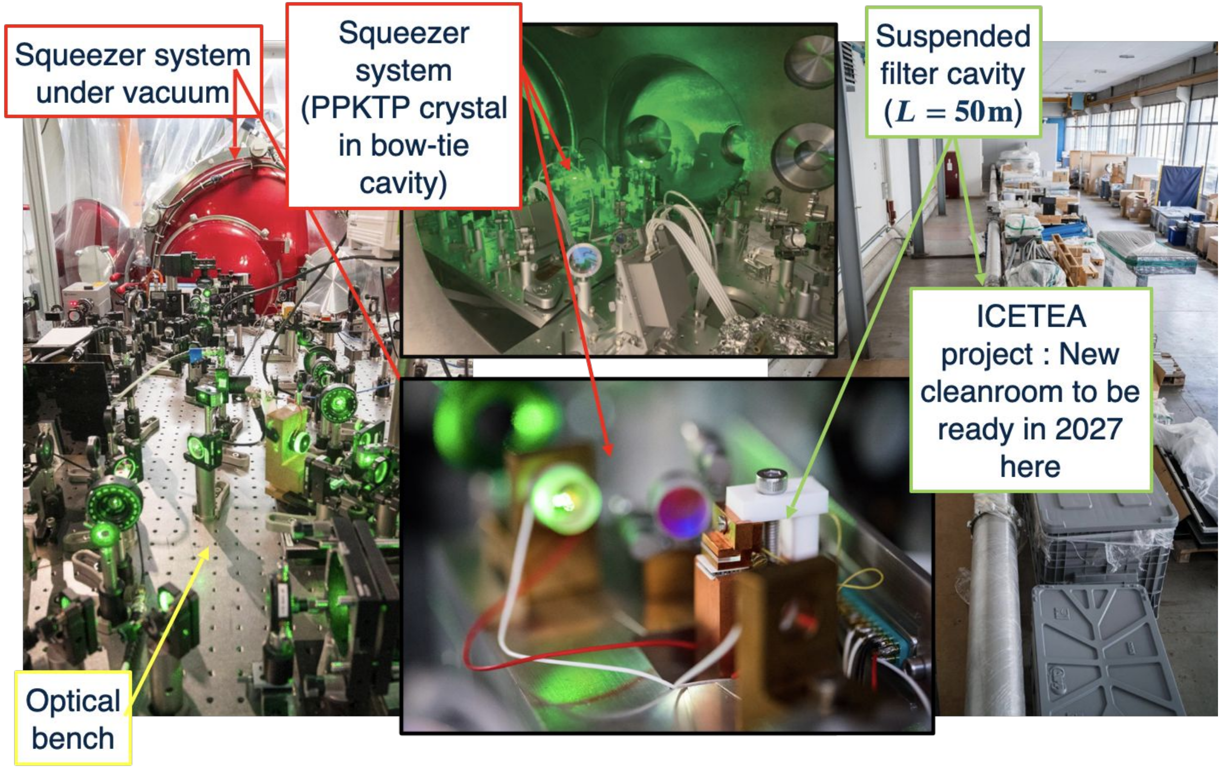
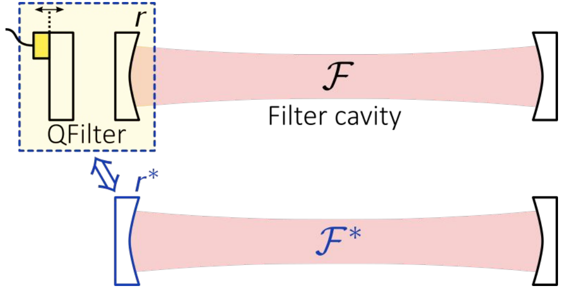


Filter cavity adaptability : a key challenge !



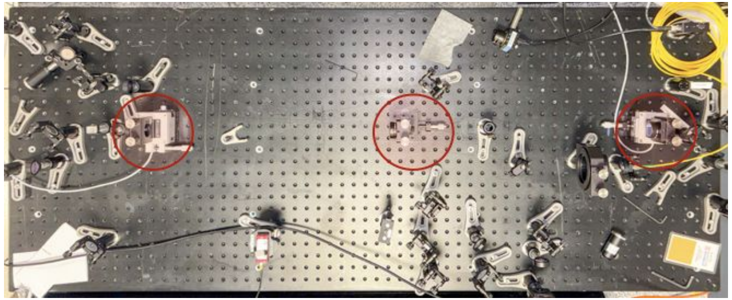
Adapting the squeezing transition frequency, why ?

- ET optimal sensitivy suppose suitability between frequency dependant squeezing nature transition frequency and the transition frequency between shot noise and radiation pressure noise dominance in quantum noise.
- Some ET parameters won't be perfectly known before installation which can affect this suitability.
- ET-LF Laser power will evolve and the suitability need to be concerved during it's 50 years lifetime

Adapting the squeezing transition frequency, How ?

- Control finesse of filter cavity:
    - Tunable mirror "QFilter"
    - Pre-cavity = mirror with tunable reflectivity
- Three-mirror cavity model developed in our team[1]

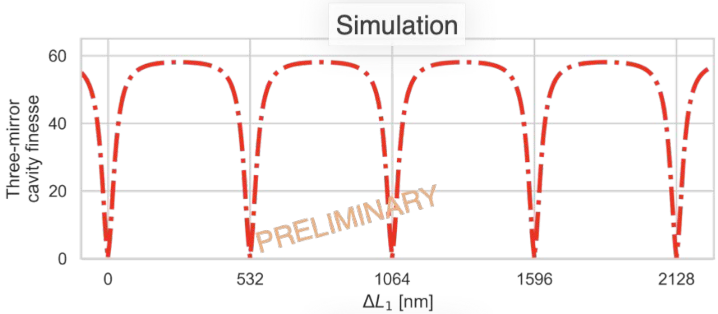
Tabletop experiment is ongoing !

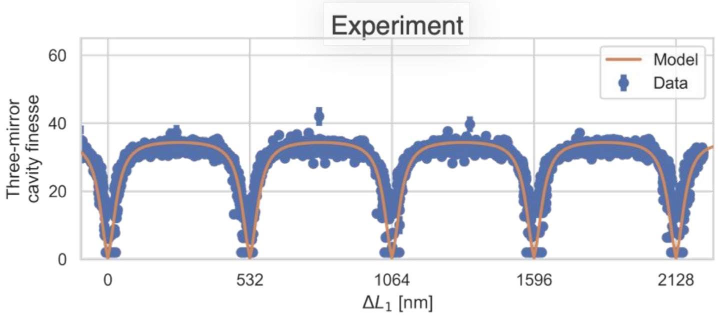


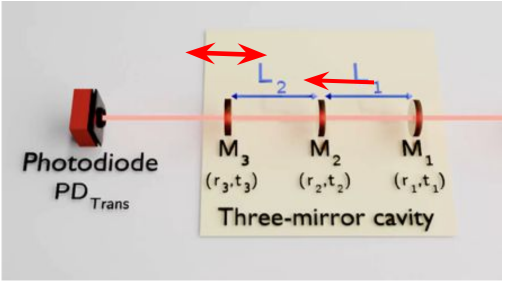
[1] P. Stevens et al., Class. Quantum Grav. 42, 065014 (2025). [DOI]

Three-mirror cavities: variable finesse

- Microscopic change in sub-cavity length = tuning of cavity finesse







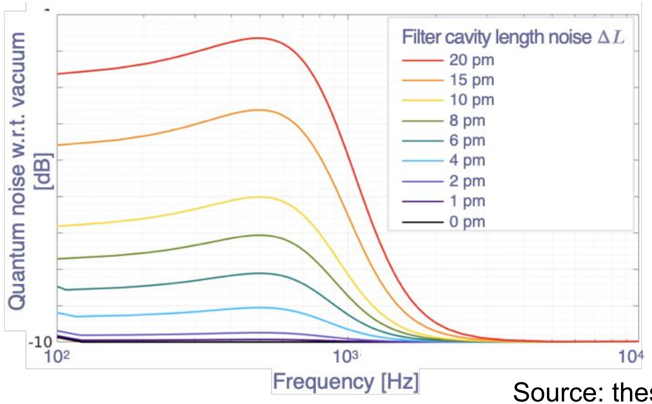
Currently working on the control of each sub-cavity

Impact of filter-cavity-length noise on squeezing:

Controlling length of filter cavity:

- High finesse (~ 3000)
- Length control via control laser (frequency f):
    - $\Delta L/L = \Delta f/f$
    - Aim: < 1dB squeezing degradation (10dB produced)
        - We need $\Delta L < 4$ppm
        - Translates into $\Delta f < 20$ Hz (50 m cavity at 1064nm)

→ We need state-of-the-art frequency stabilisation!



Source: thesis of A. Lartaux-Vollard

Refimeve Network:

- Currently used in state-of-the-art international comparisons of atomic clocks
- Equivalent stability = 1 Hz at 1s (at 1064 nm)
    - Close to the stability reached by LIGO/Virgo

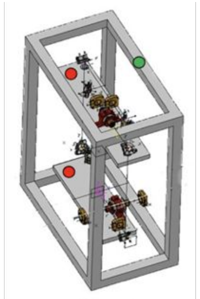
Design of a suspended periscope:

To reduce infrastructure cost, Einstein Telescope will require vertical periscope to bring the squeezed beams from filter cavities level to interferometer level:

- 2 meters periscope for ET HF (both 2L and triangle configuration) and ET LF in 2L configuration
- 4 meters periscope for ET LF in triangle configuration

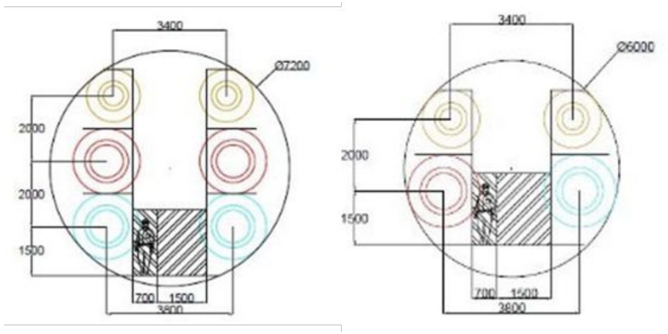
Thoses periscopes are 10 times taller than what has been implemented so far in GW detectors (monolithic periscopes):

- Careful study on suspension stability an controllability but also polarization mixing must be done



D. Douillet

PRELIMINARY STUDY



Triangle 2L

Squeezing for ET in the european landscape

R&D activities / expertise (non-exhaustive list)

France

- Contribution to ET design (SQZ work-package coordinators: Eleonora Capocasa, Angélique Lartaux -> Matteo Leonardi)
- Filter cavities (APC, IJCLab)
- New lab for quantum optics in Artemis (E. Polini)

Germany

- Squeezing sources and tests on GEO600 (Hanover)
- Squeezing sources, EPR, and mode-matching investigations (Hamburg)

Squeezing for ET in the european landscape

Belgium / Netherlands

- Squeezing sources at 1550 nm and 2000 nm for ET Pathfinder (Maastricht, Brussels)

Italy

- Low-loss Faraday isolators at 1550 nm (Genoa)
- Balanced homodyne detection at 1550 nm (Rome)
- EPR squeezing activities (Rome, Naples, Genoa)
- Integrated / fibered squeezing sources at 1550 nm (Padua, Trento, Naples)

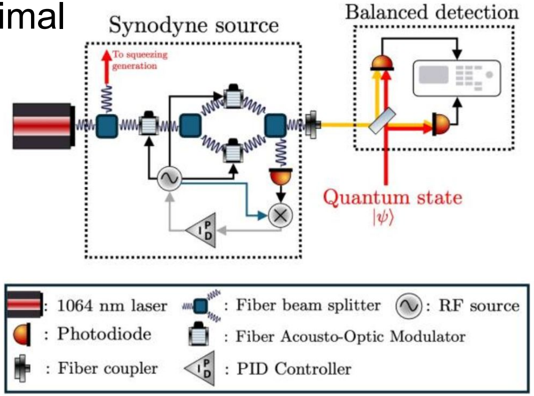
Sweden

- Integrated / fibered squeezing sources at 1550 nm (Stockholm KTH)

Thank you !!

Complex squeezing

- Collaboration between APC Virgo (J.Ding) and MIT LIGO led to a theoretical framework introducing complex squeezing (https://arxiv.org/pdf/2410.09976)
- Spectral correlations are generally complex-valued → standard homodyne detection (real-part only) is insufficient
- Synodyne detection can be used to overcome this limitation and achieve optimal quantum state tomography
- This approach gives access to previously hidden quantum resources



CFC Vs 2FC bonus:

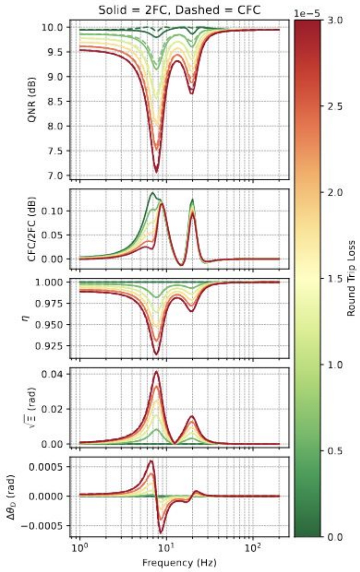


FIG. 4. Squeezing degradation for Round Trip Loss per cavity Λ for 2FC (solid lines) and CFC (dashed lines), for a total length $L_1 + L_2 = L_a + L_c = 5\text{km} + 5\text{km} = 10$ km. From top to bottom: Quantum noise reduction (for 10 dB of input squeezing); Relative quantum noise reduction between CFC and 2FC (a positive value means that CFC performs better than 2FC); the squeezing efficiency η, the dephasing $\sqrt{\Xi}$ and the misphasing $\Delta\theta_D$.

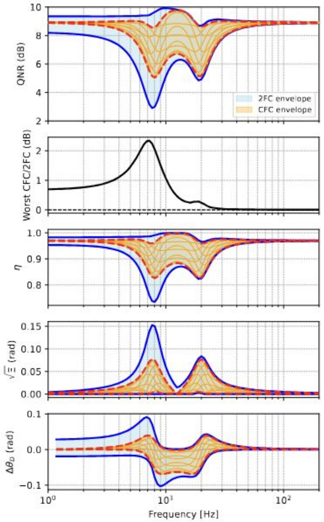


FIG. 5. Squeezing degradation from quadratic mode mismatch in 2FC (blue, solid envelope) and CFC (red, dashed envelope), for a total length $L_1+L_2 = L_a+L_c = 5\text{km}+5\text{km} = 10$ km. The blue and orange regions are determined by calculating squeezing curves for the values of Υ_I, Υ_O, Υ_{12} and Υ_a from Table I, and sweeping the mode mismatch phases $(\psi_{mmO} - \psi_{mmI})$ and $(\psi_{mm12} - \psi_{mmI})$. The inter-cavity mode mismatch 2FC is $\Upsilon_{12} = 0.01$. Some examples of CFC squeezing curves are plotted in orange. From top to bottom: quantum noise reduction with mismatch; ratio of the lower envelopes of CFC to 2FC; efficiency; dephasing; misphasing.

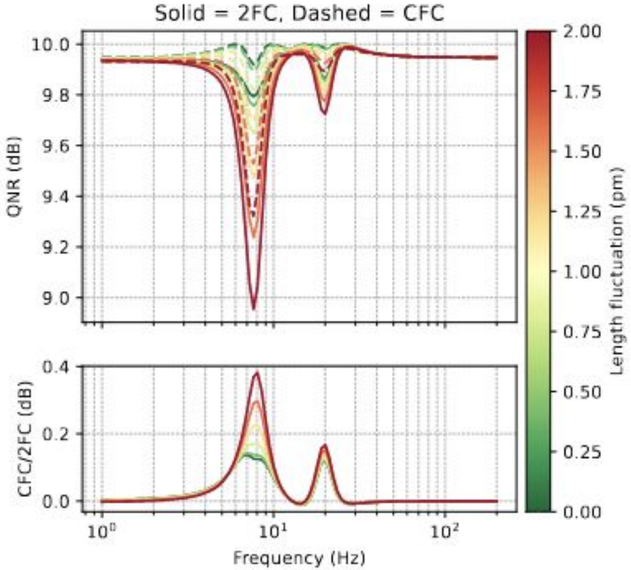


FIG. 6. Squeezing degradation for length fluctuation δL for 2FC (solid lines) and CFC (dashed lines), for a total length $L_1 + L_2 = L_a + L_c = 5\text{km} + 5\text{km} = 10$ km.

CFC bonus:

- Middle mirror transmissivity Ta=6.75 ppm (10km) comparable Virgo FC end mirror (for 2km Ta=0.3 ppm difficult):
  Ta quadratic with FC length

- Sub-cavities seem loss dominated but when doing equivalent mirror we see the actual cavity is not: Teff = [210 ppm, 10600 ppm],

- Small deviation from Ta can be thermally compensated or input squeezing angle, and the two detuning can be used for compensation

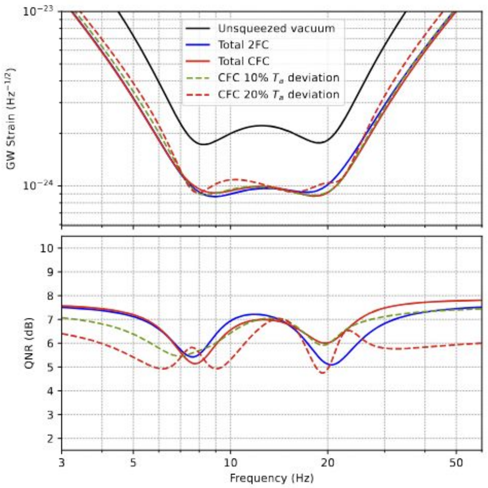


FIG. 3. Squeezing degradation for the CFC caused by 10% (dashed green) or 20% (dashed red) deviations of the middle mirror's transmission T_a, compared to the CFC model with the optimal T_a (solid red) and the two FC case (blue). The sensitivity without squeezing (solid black) is plotted for reference. The 10% and 20% T_a deviations are being partly compensated by adjusting the detunings of the CFC sub-cavities and the injected squeezing angle. Losses are detailed in Table I and Section III D. Top: Noise spectral density comparison for a single L-shaped interferometer. Bottom: Quantum enhancement in dB.

CFC bonus:

- Substrate losses: 5 cm and conservative 2 ppm/cm losses

- If substrate in c-cavity squeezing not degraded by more then 0.5 dB compared to 2FC

- CFC intracavity mode mismatch: 1e-5 3 orders of magnitude below other MM degradations

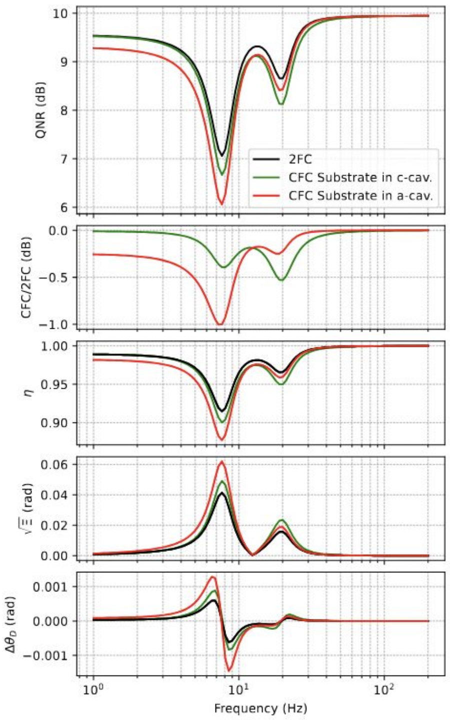


FIG. 11. Comparison of CFC vs 2FC when only optical losses are considered, with extra 20 ppm round trip loss in CFC due to the substrate of the middle mirror.