Current progress of the CALVA experiment

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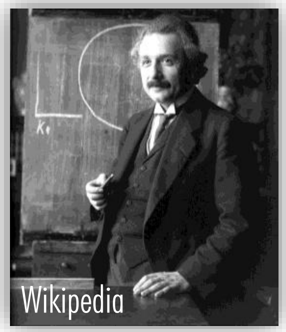
Gravitational Waves (GW)



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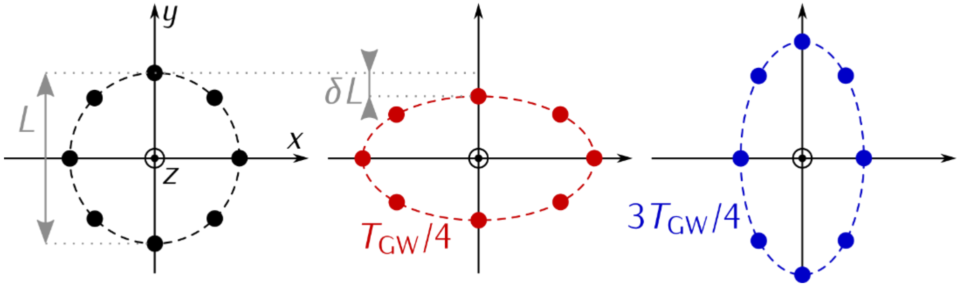
A. Einstein, 1916



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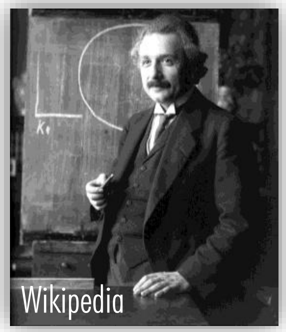

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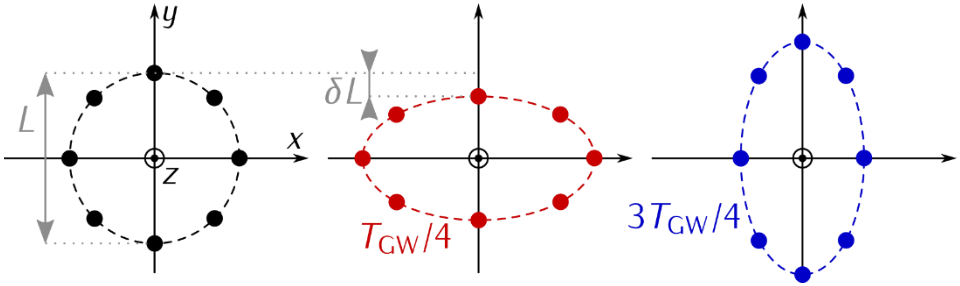

Amplitude of a gravitational wave

- Amplitude of space-time strain at distance r given by:

$$\delta L/L = h(r)/2 \propto 1/r$$

- Example : coalescence of black-hole binaries (1st observation, 2015)

  $m_1 = m_2 = 30\ M_\odot$, distance $r = 400$ Mpc

$$\Rightarrow \delta L/L \sim 10^{-21}$$

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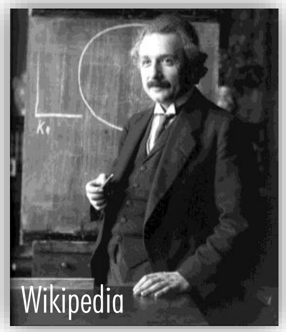

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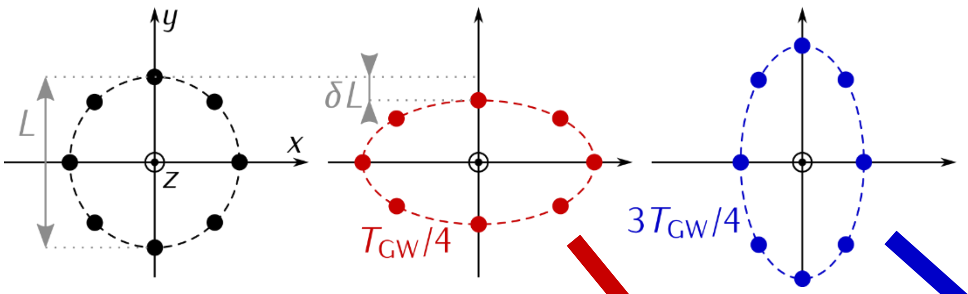
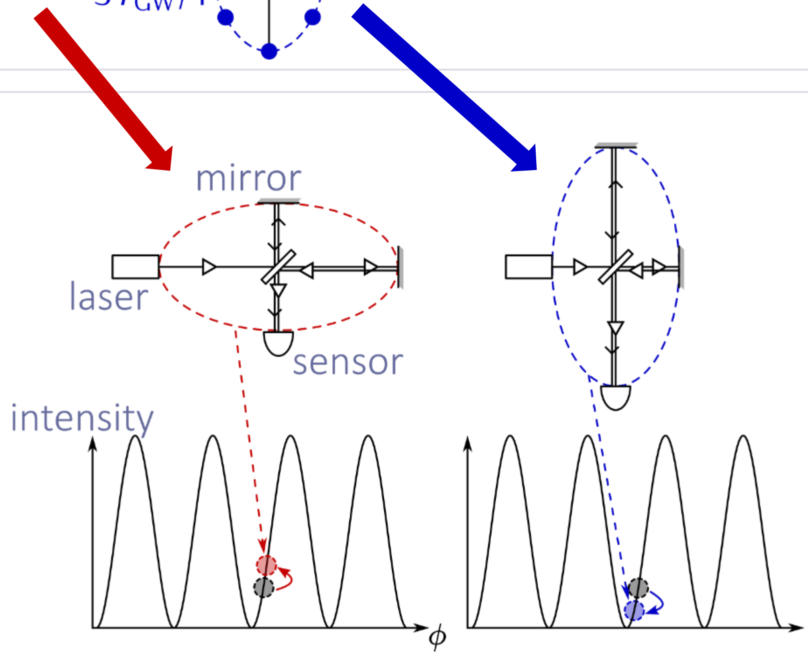


GW detection: Michelson interferometer

Examples: LIGO / Virgo / KAGRA

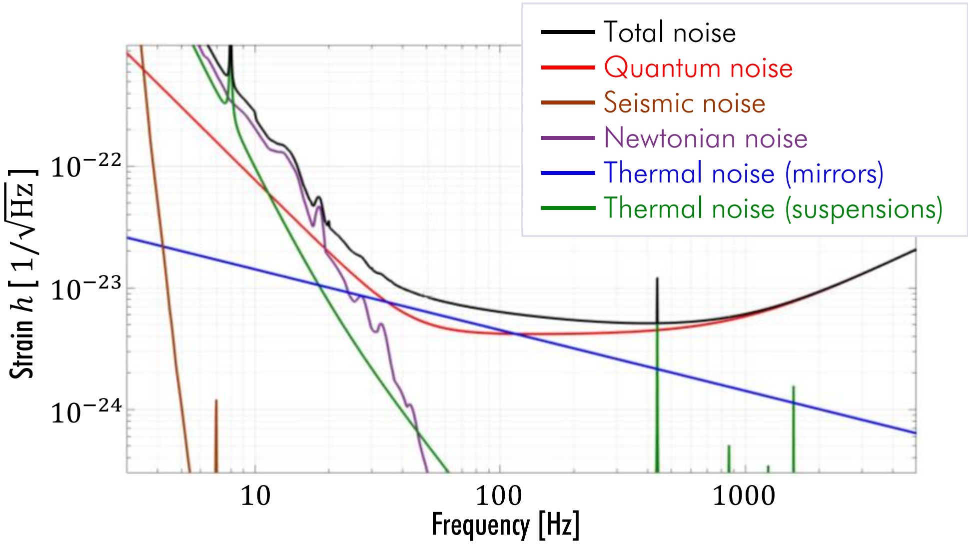
- State-of-the-art sensitivity $\leq 10^{-23}$
- Arms length $\sim$ 3–4 km ($\delta L \sim 10^{-20}$ m)
- Suspended mirrors
- Fabry-Perot cavities
- Vacuum interferometer



Main noise sources affecting ground-based GW detectors

Classical noise sources

- Mechanical noise
  - – Seismic + Newtonian
  - ➢ Solution: underground/spaceborne (upcoming projects ET/CE…)



Source: *ADV+ TDR*

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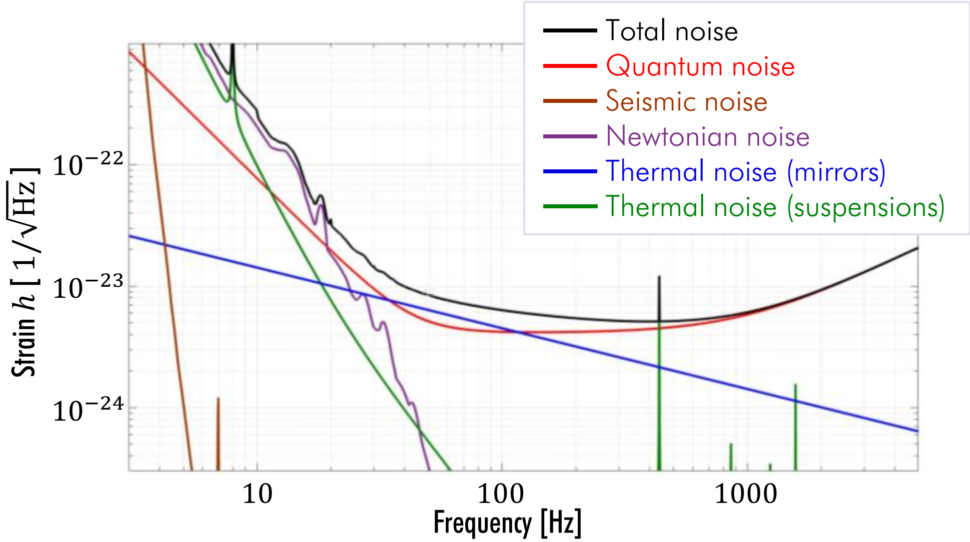

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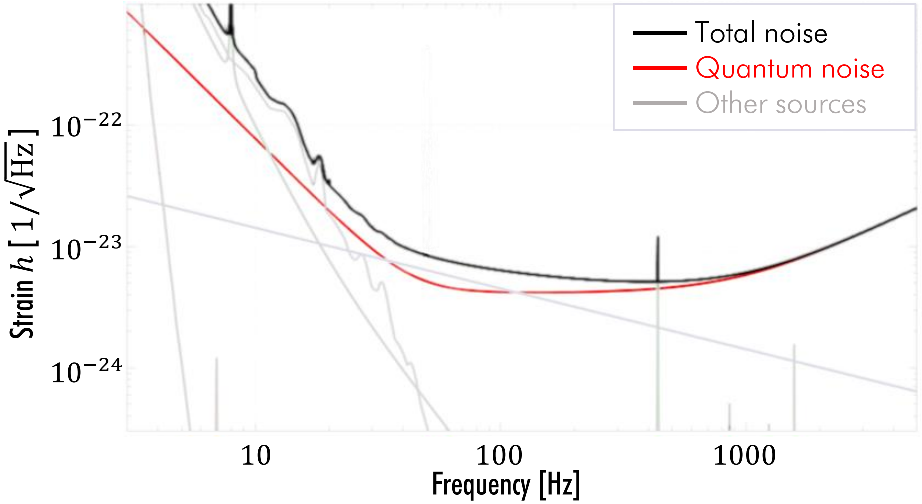

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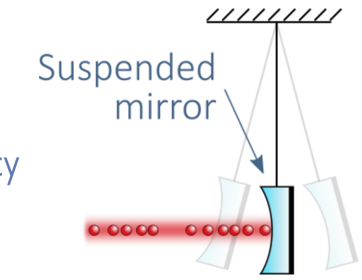
- Radiation pressure noise
  - Dominates at low frequency
  - Amplitude-noise-related



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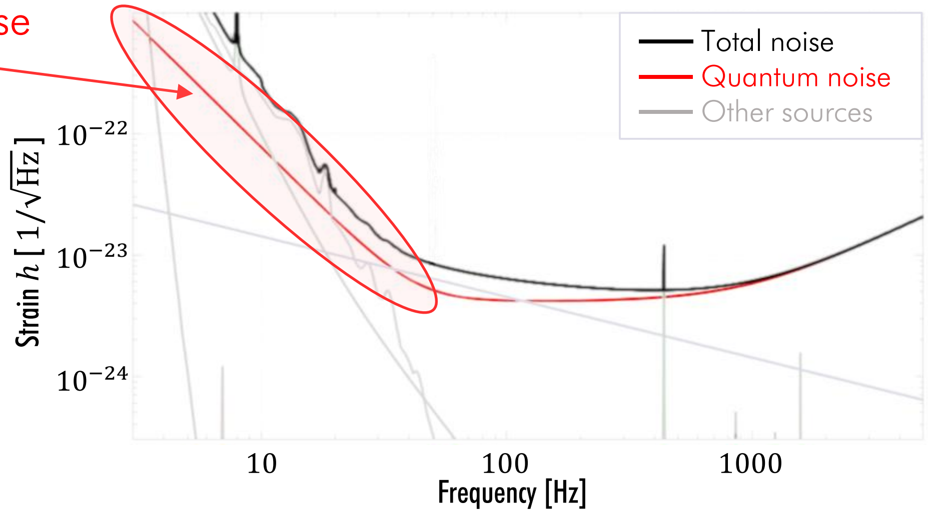

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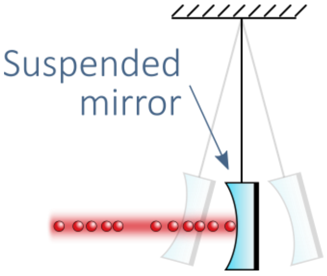
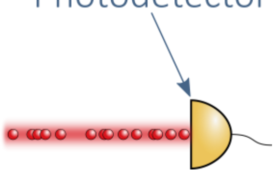
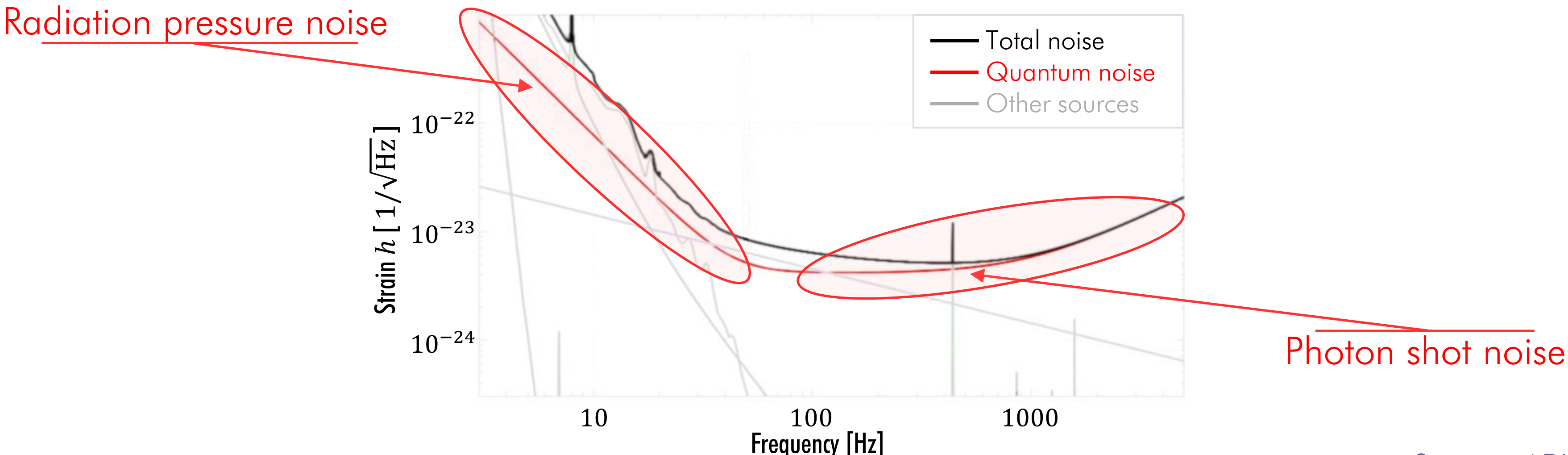


- Photon shot noise
  - Dominates at high frequency
  - Phase-noise-related





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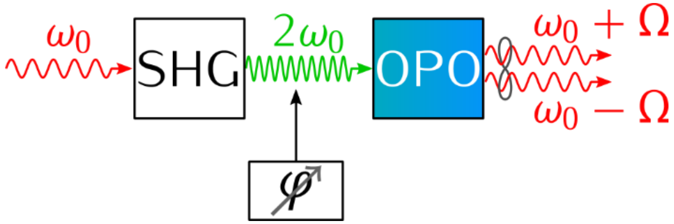
Squeezed states of light

Harnessing Quantum properties of light to reduce noise

- Optical Parametric Oscillator (OPO):
  quantum entanglement between 2 photons
  → squeezed mode at ω_0



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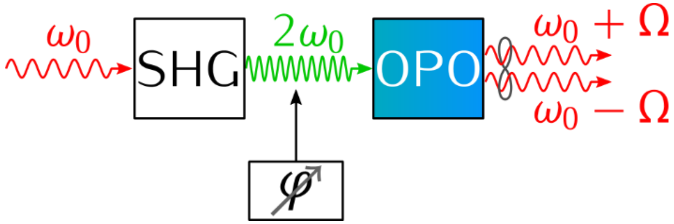
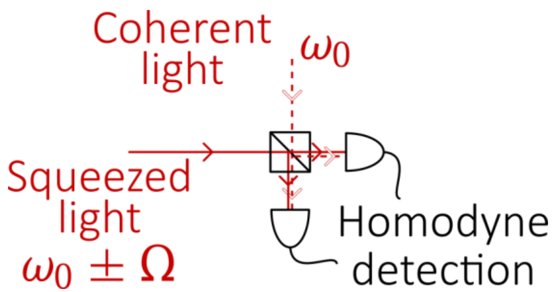
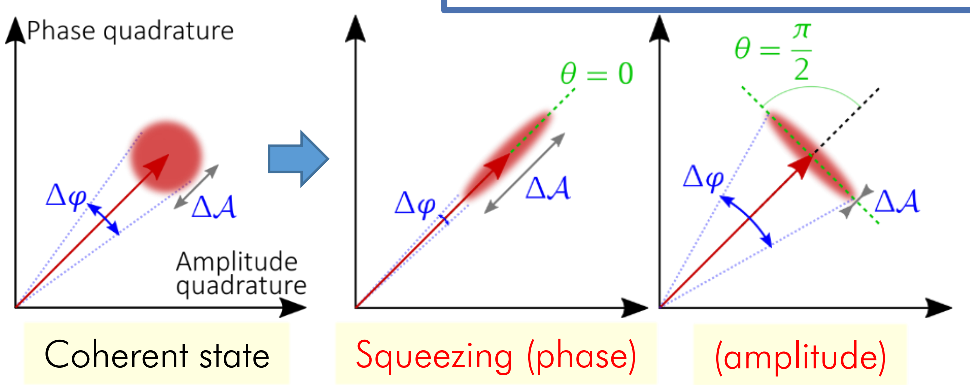


Heisenberg's uncertainty relation:
$\Delta\mathcal{A} \times \Delta\varphi = \hbar/2$





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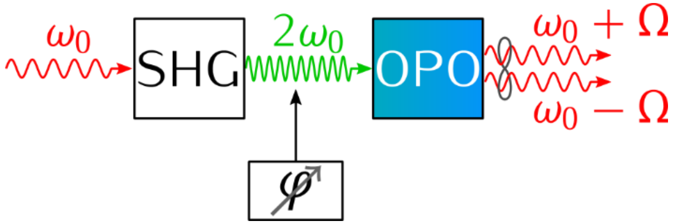

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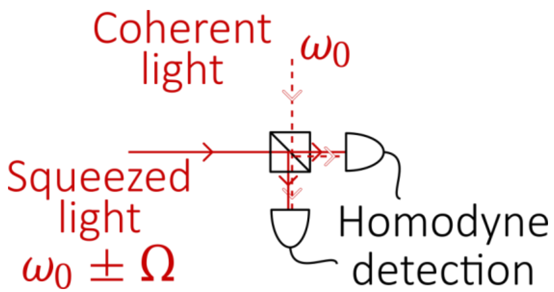
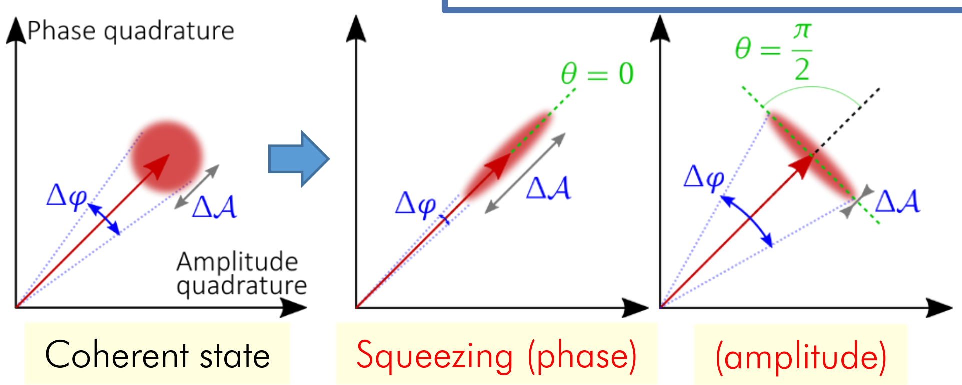
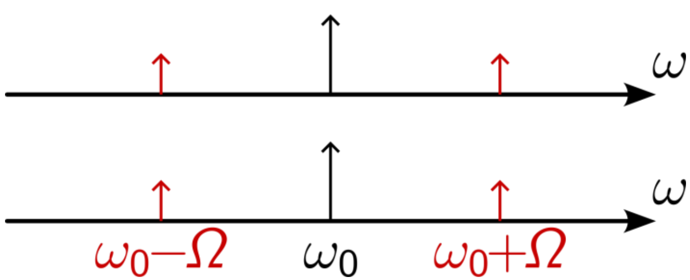




GW sidebands

Entangled sidebands



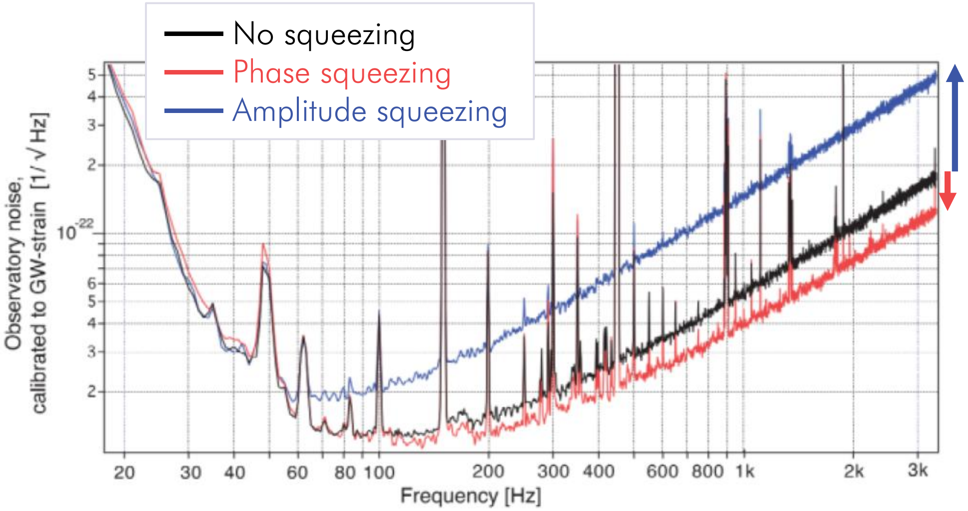
→ **Quantum noise reduction!**

Implementation of squeezed states of light for Advanced-Virgo

Current progress

✓ Phase squeezing implemented on Advanced Virgo

- 3 dB gain at high frequency
- Low-frequency noise not yet dominated by quantum sources



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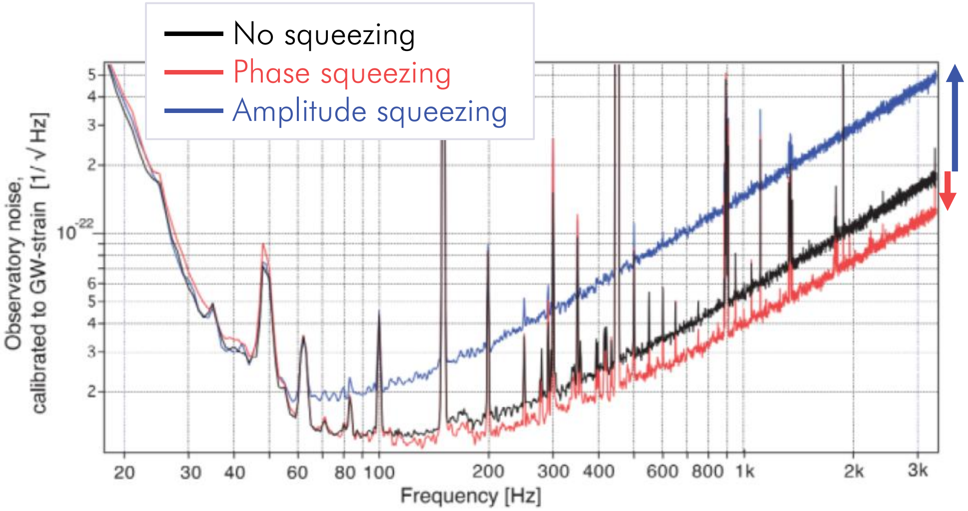

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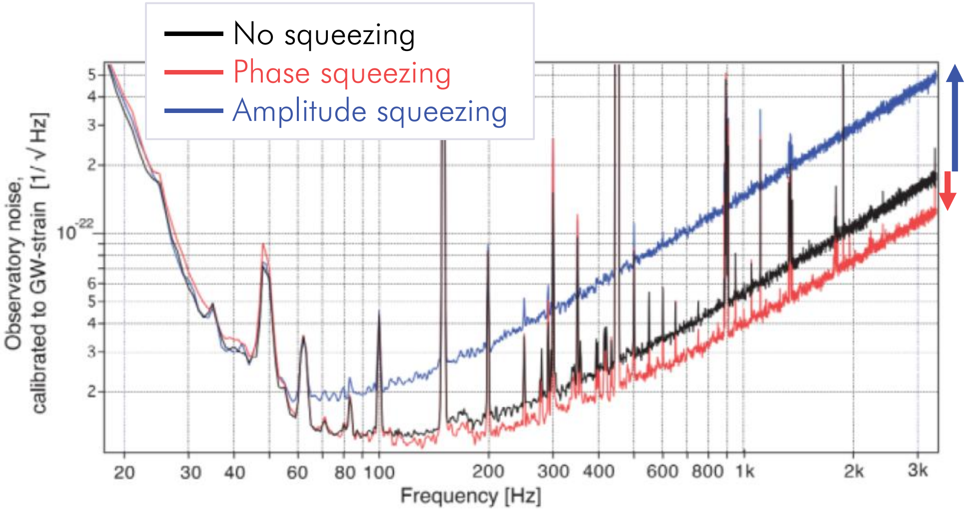

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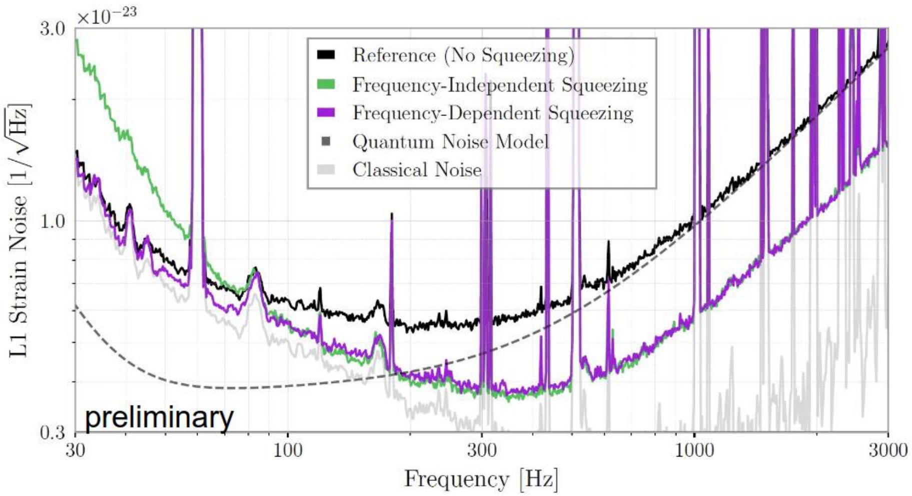
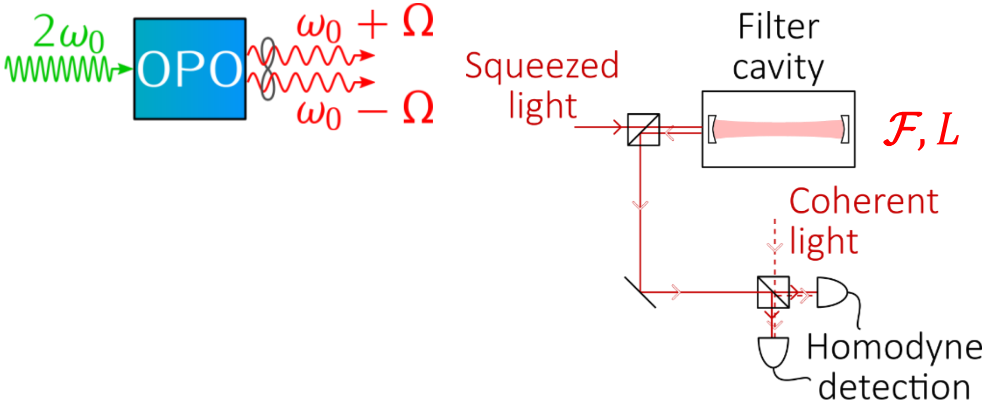


Source: LIGO

Frequency-dependent squeezing



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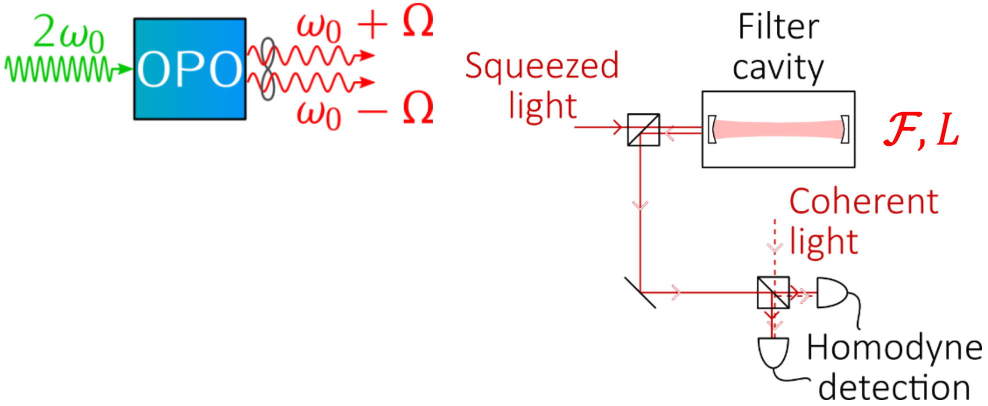

Squeezing-ellipse angle

$$\theta = \frac{\Delta\phi(\omega_0 + \Omega) + \Delta\phi(\omega_0 - \Omega)}{2}$$

$\Delta\phi$: cavity phase shifts

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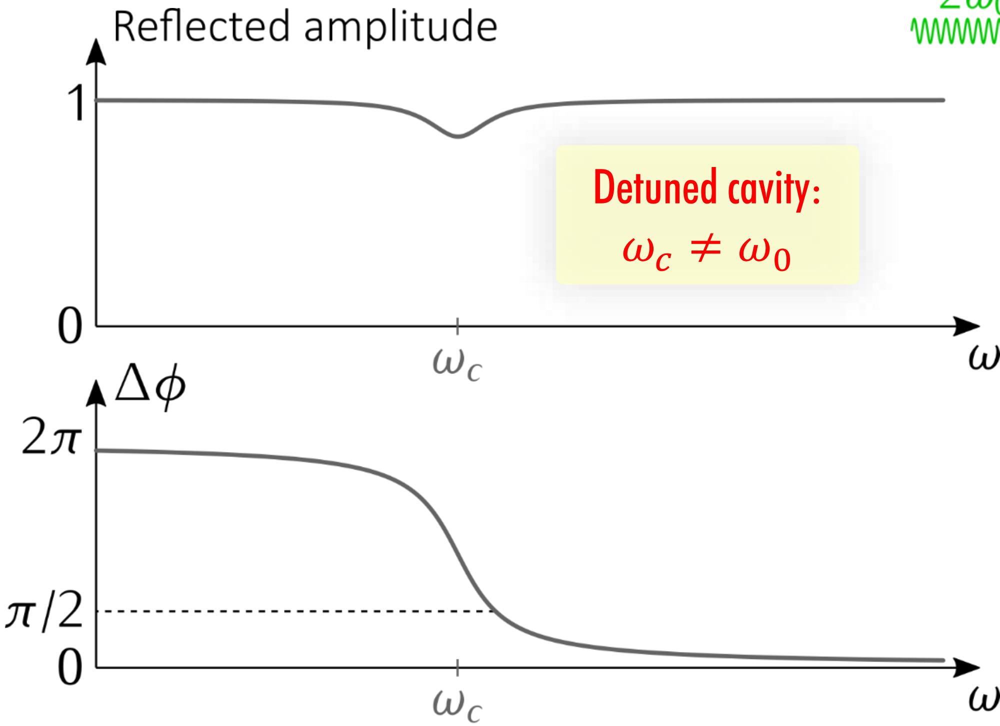

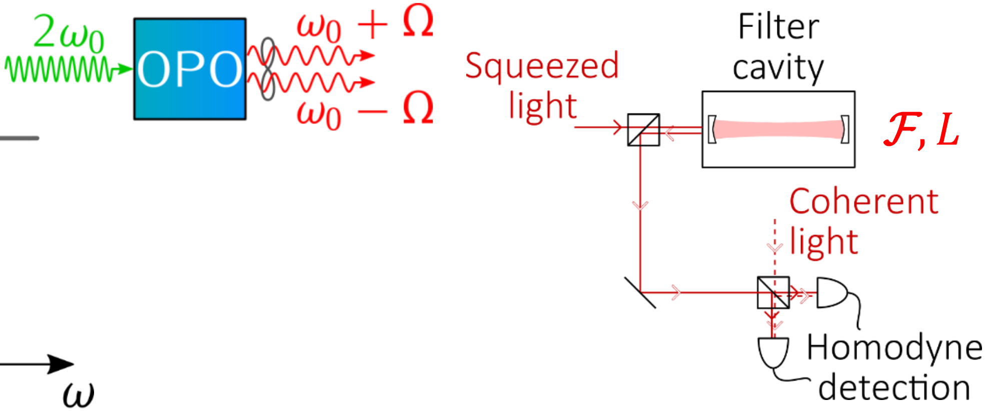

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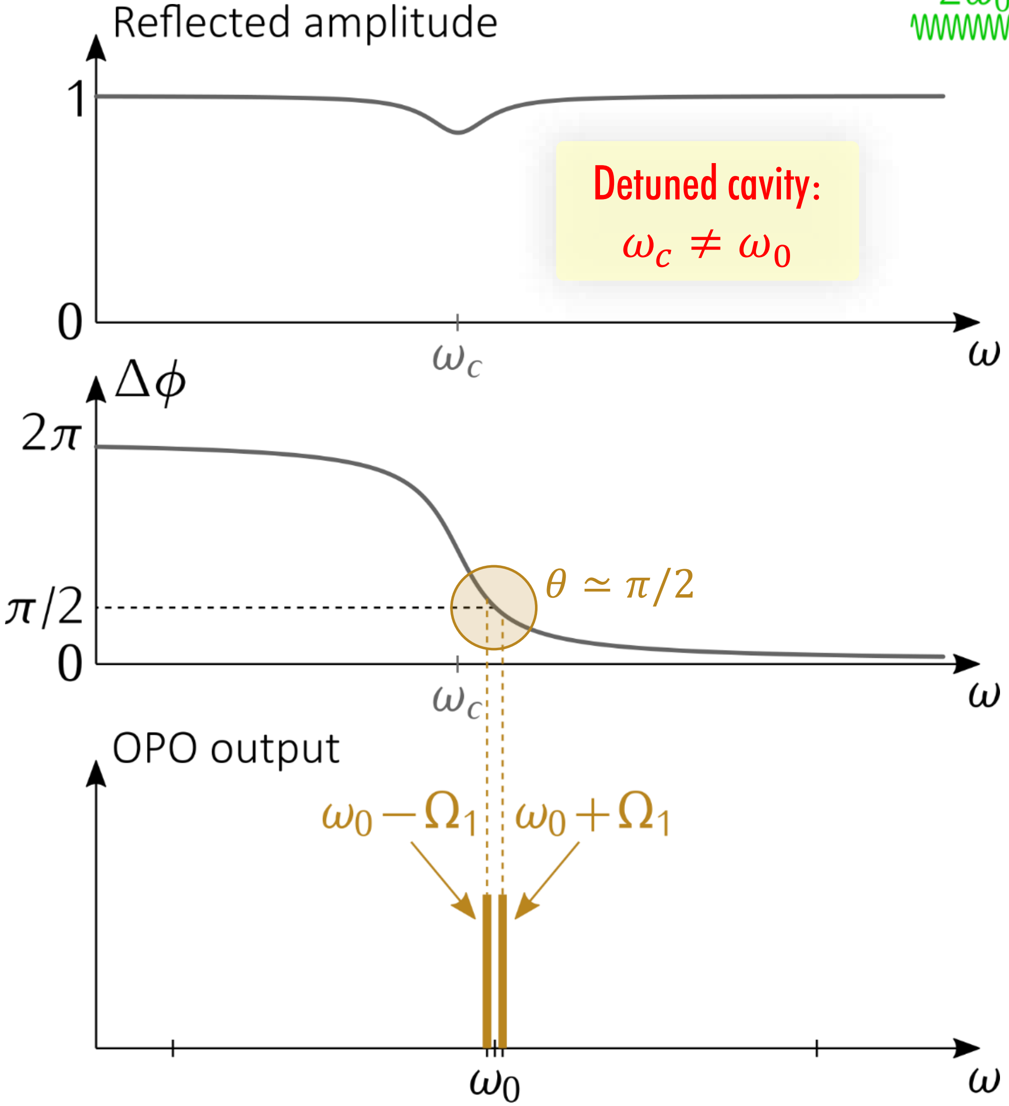

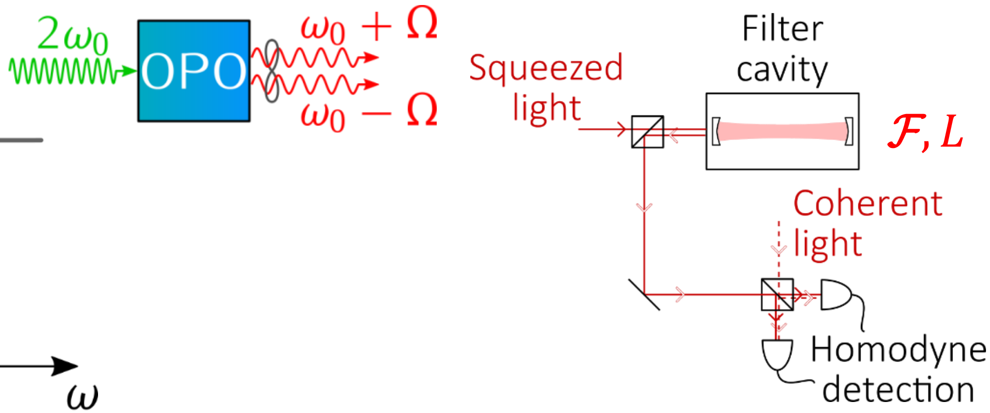

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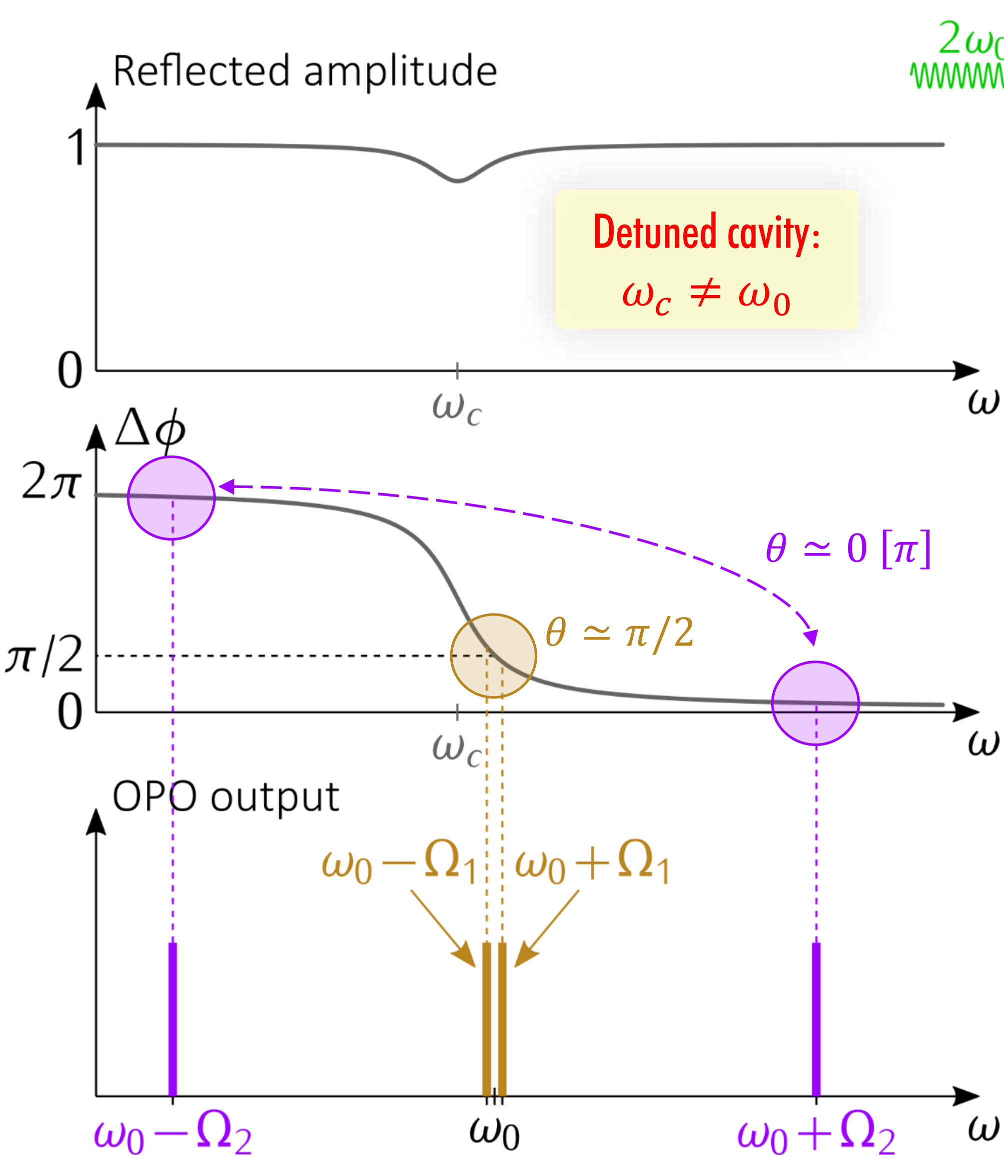

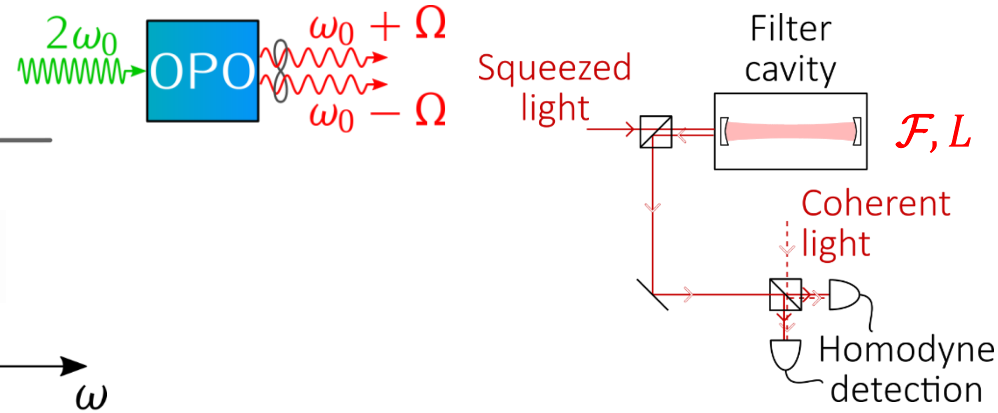

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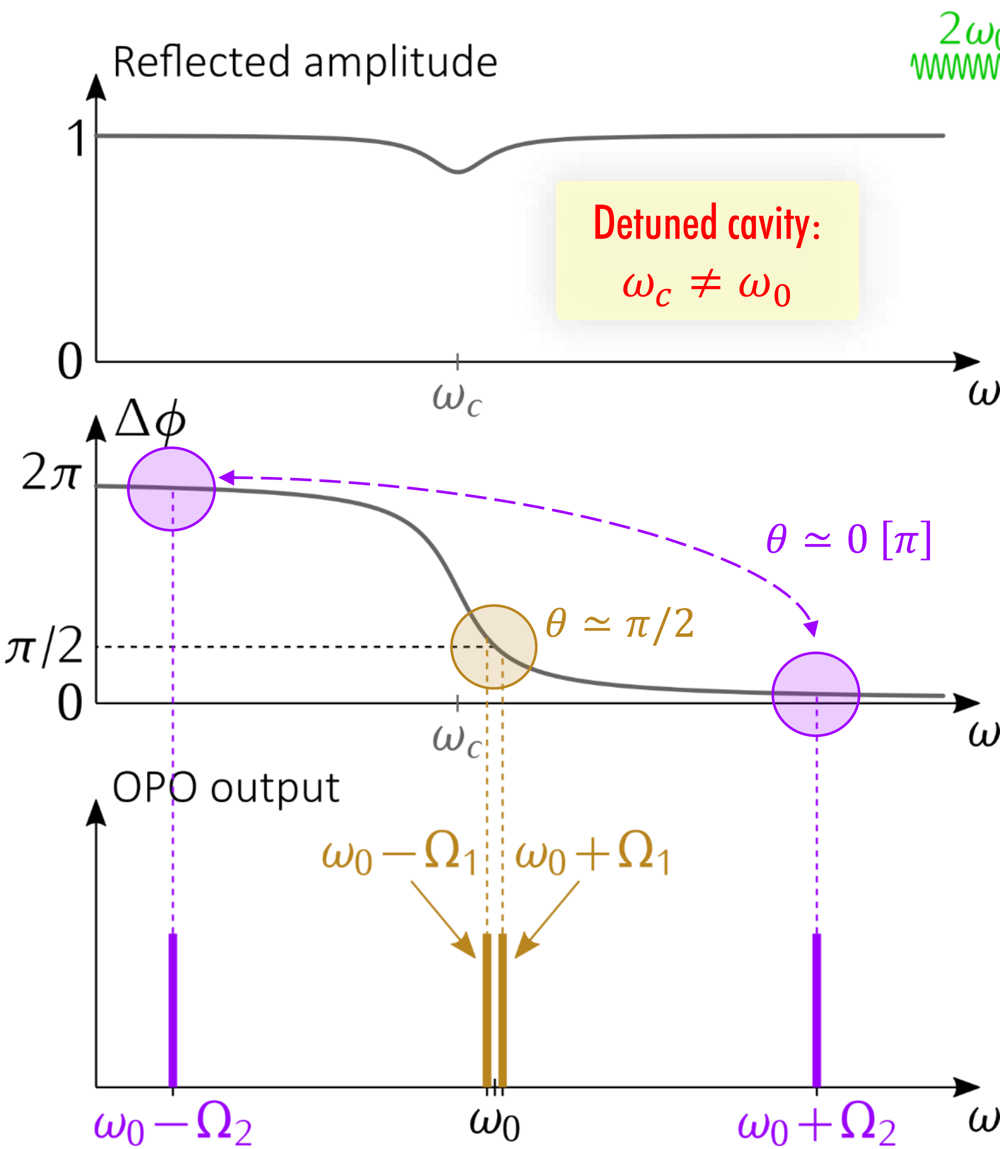

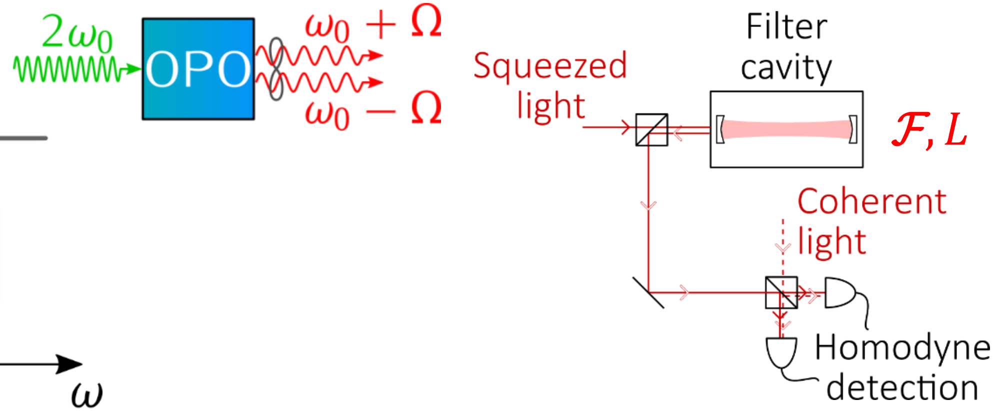

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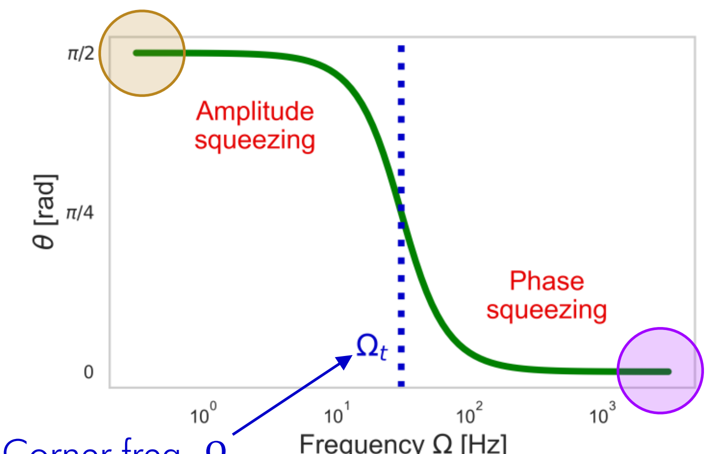
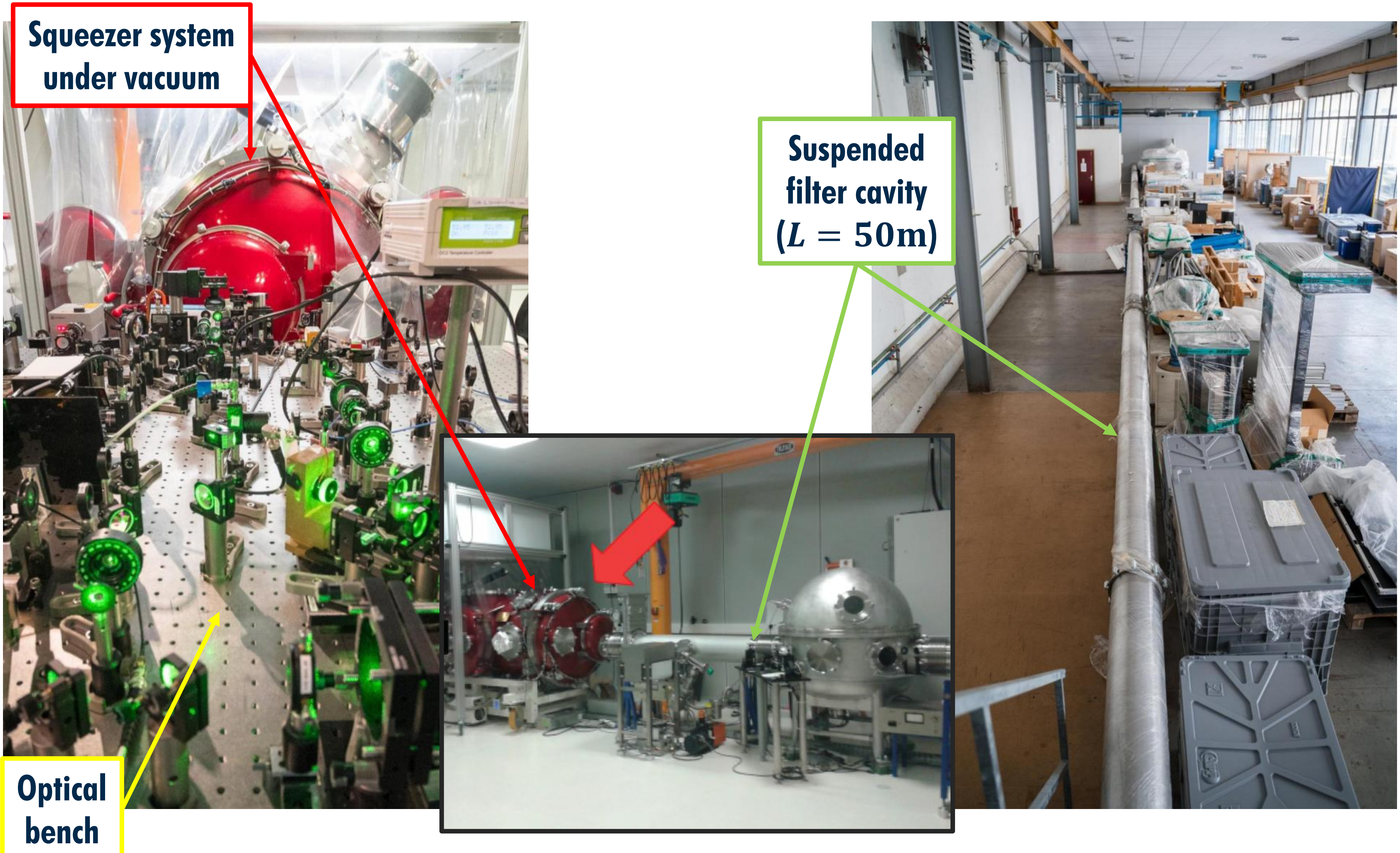


Corner freq. Ω_t depends on $\mathcal{F}, L$ etc.

The Exsqueez project and CALVA experiment



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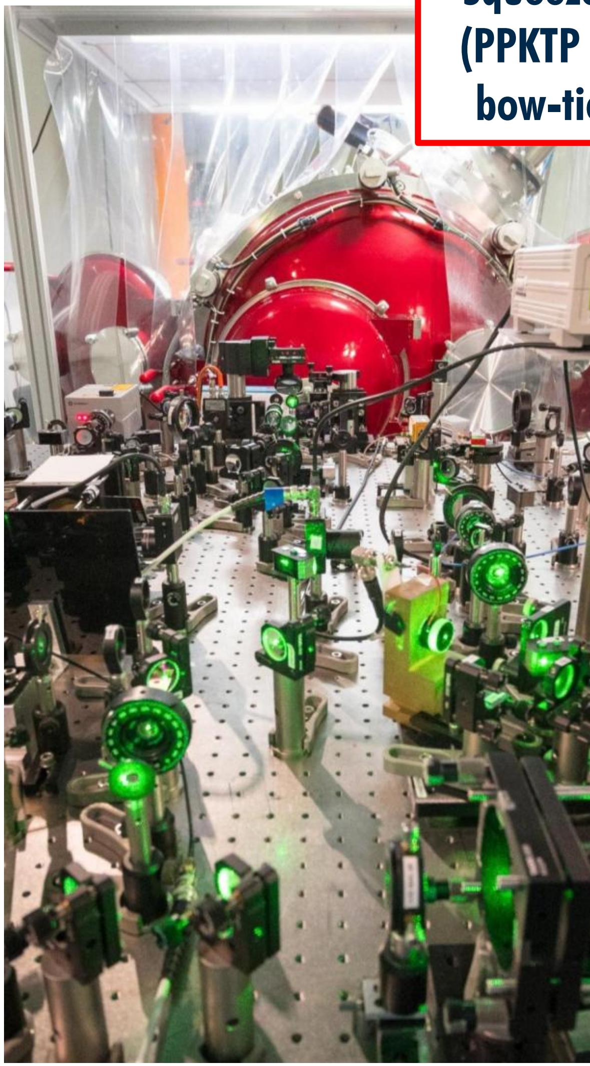
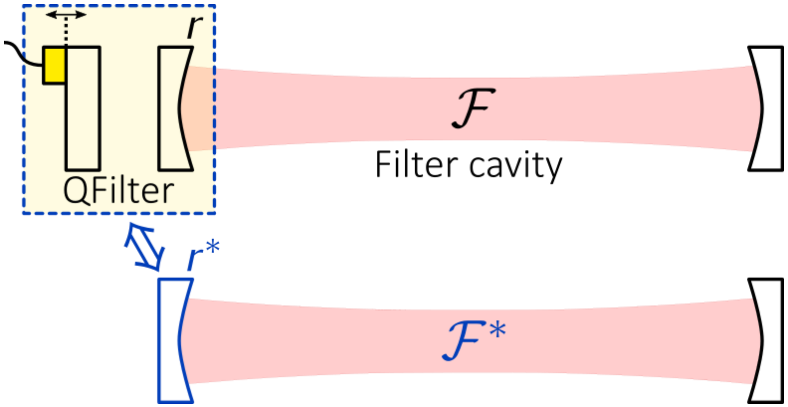


Reducing quantum noise over the whole frequency range

Adapting the squeezing corner frequency

- Control finesse of filter cavity
  - Tunable mirror “QFilter”
  - Pre-cavity ⇔ mirror with tunable reflectivity



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  - 700 Hz (Exsqueez, no QFilter) → 30 Hz (Exsqueez, with QFilter ⇔ Adv. Virgo)
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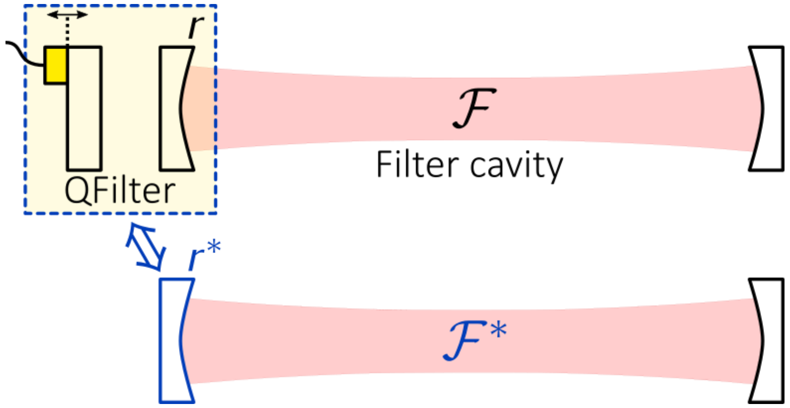

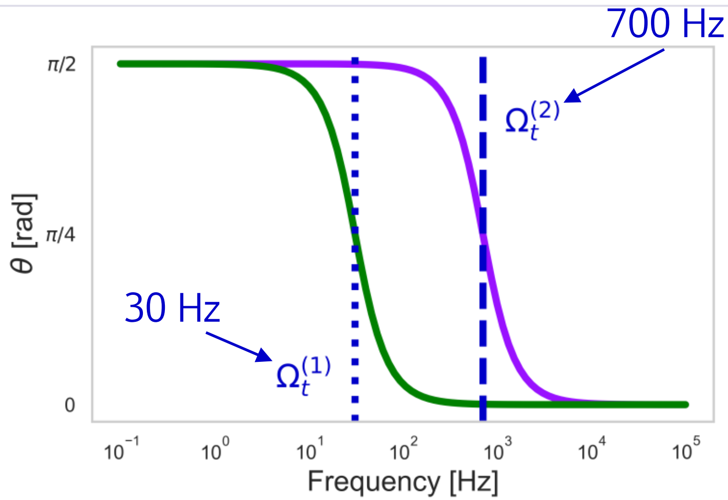

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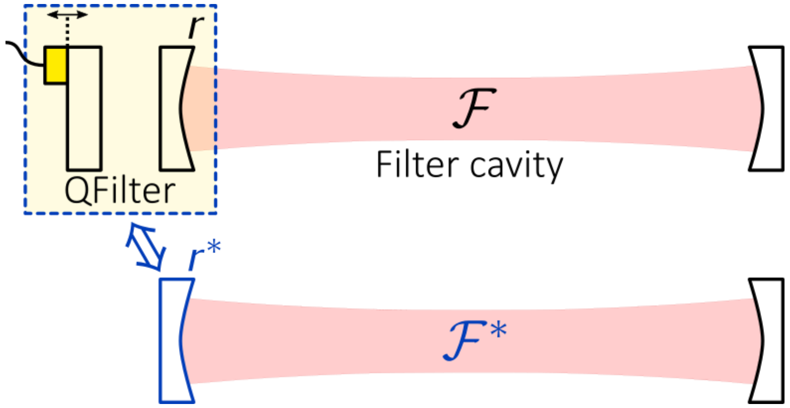
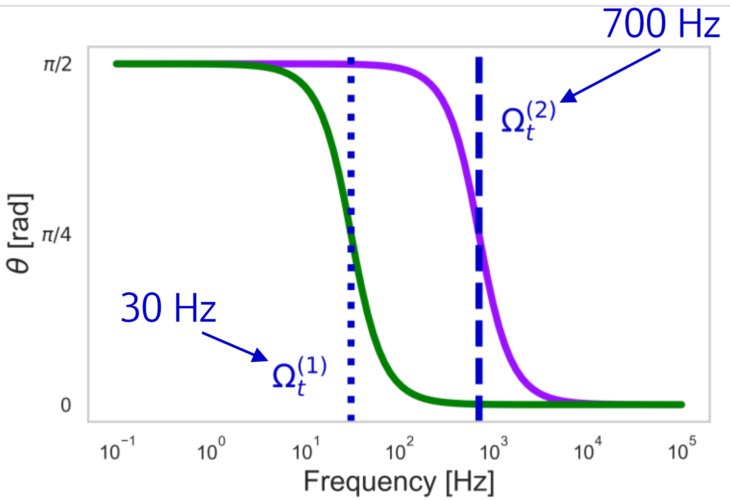
- Three-mirror cavity model developed in our team[1]



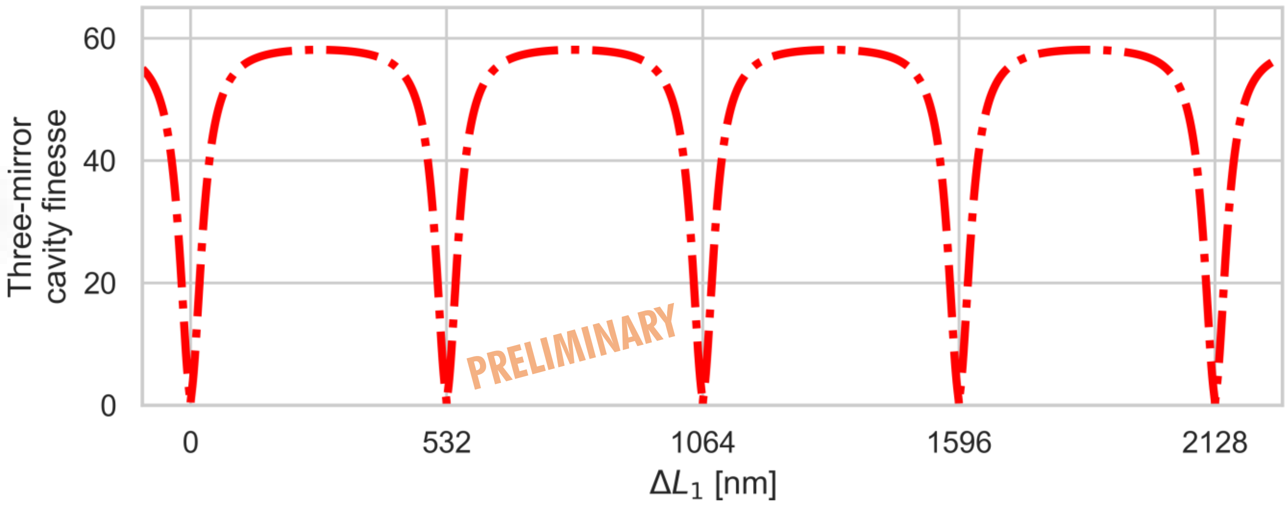


[1] P. Stevens et al., Class. Quantum Grav. 42, 065014 (2025). [DOI]

Three-mirror cavities: variable finesse (1/2)

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

Simulation



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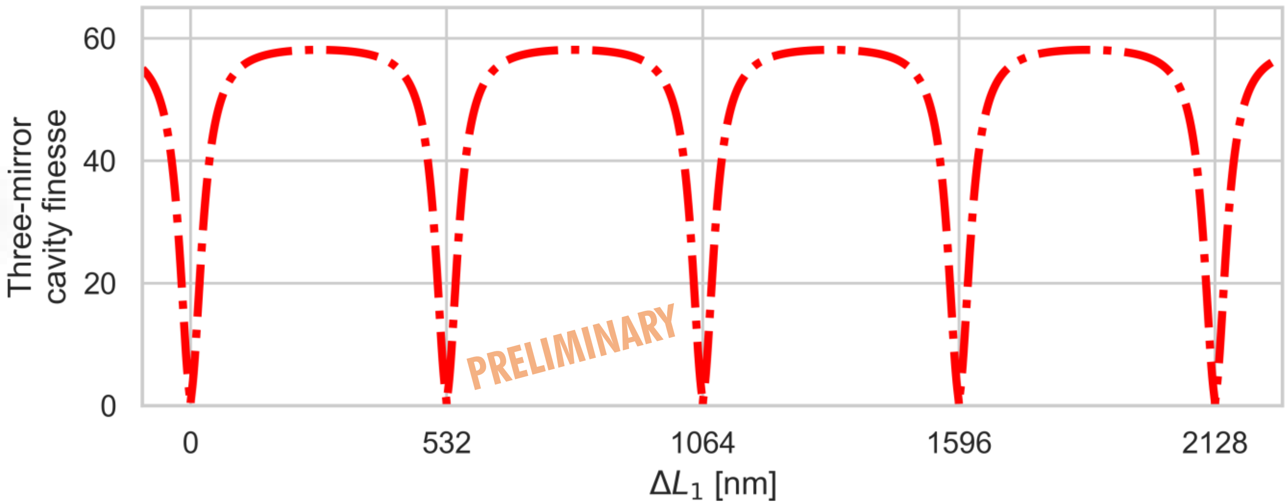
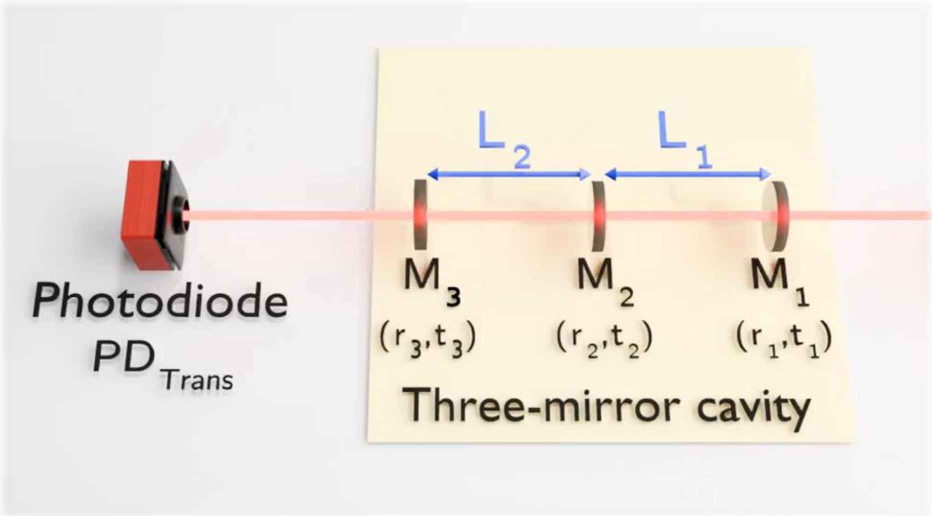


Experiment



Three-mirror cavities: variable finesse (2/2)

- Inconsistent maximum finesse possibly due to mirror misalignments

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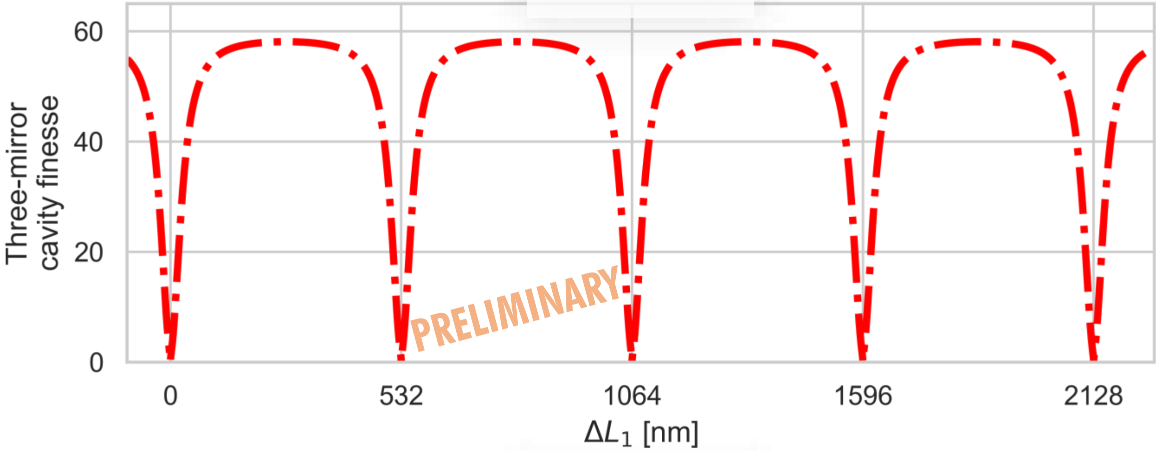

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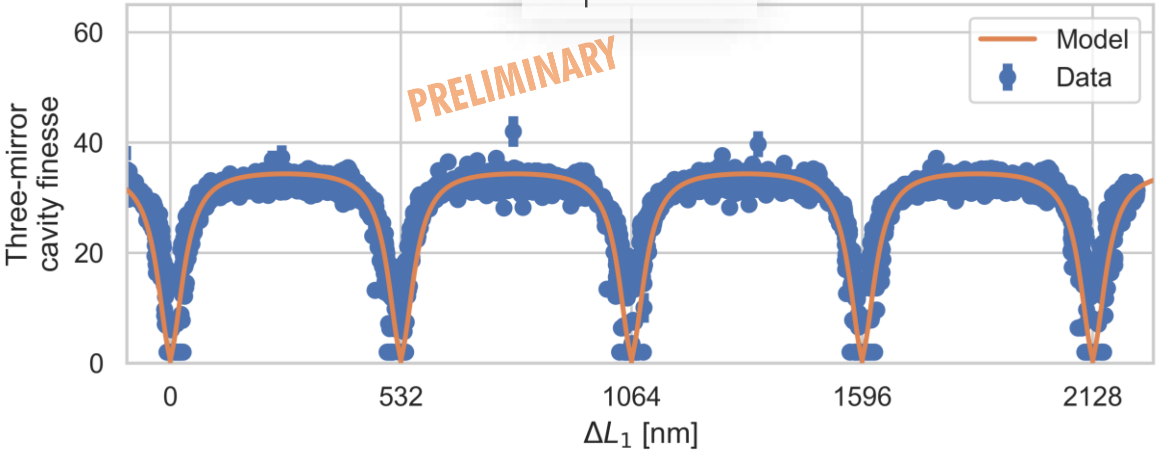

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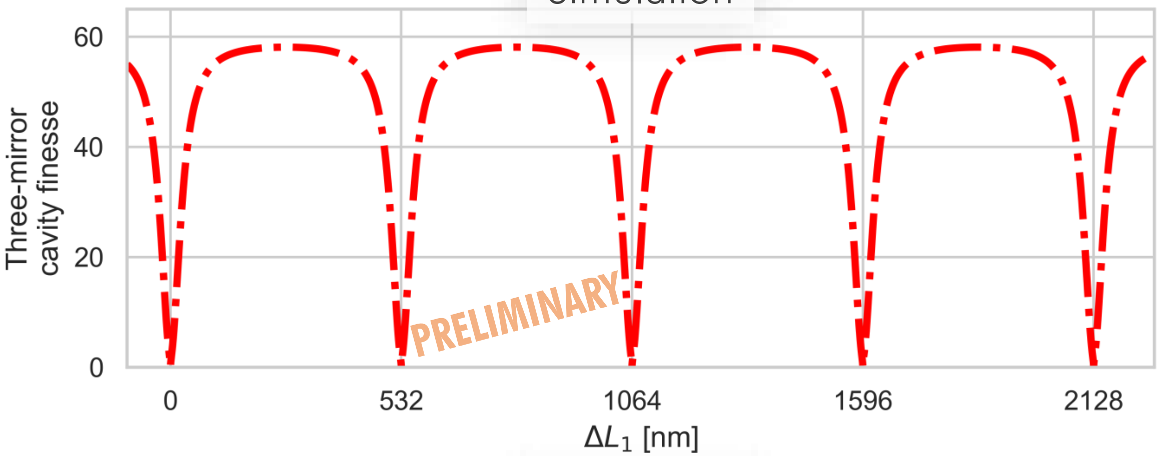

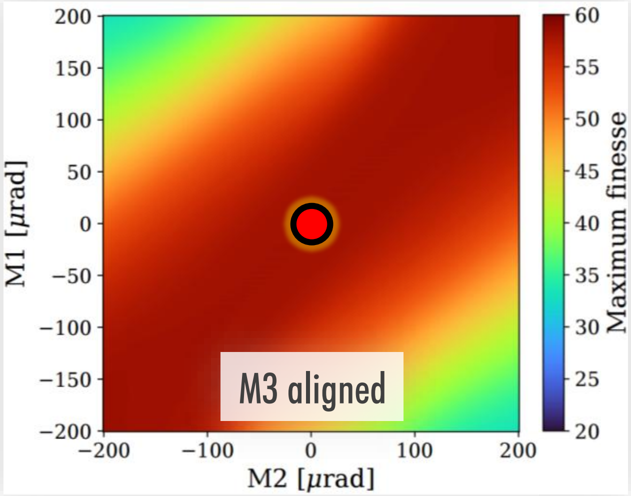

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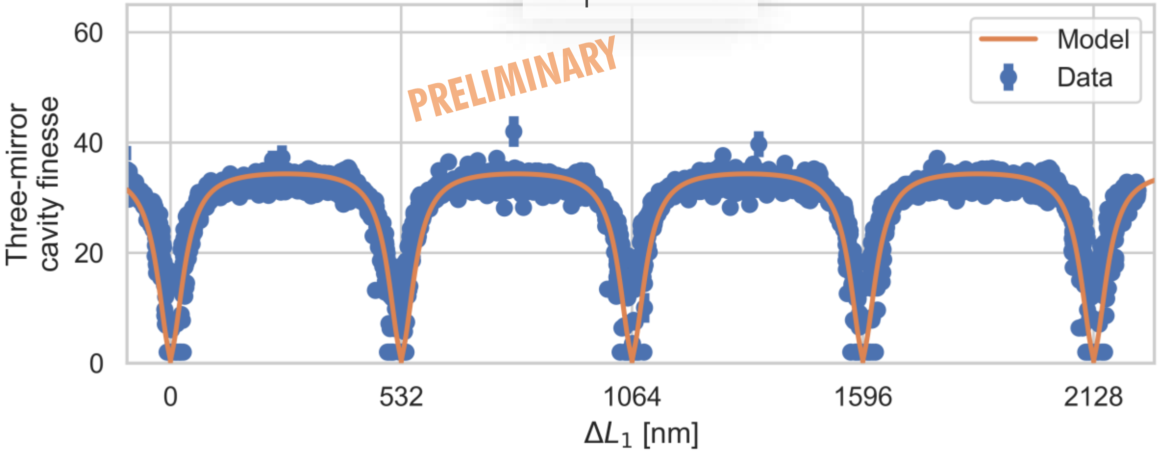

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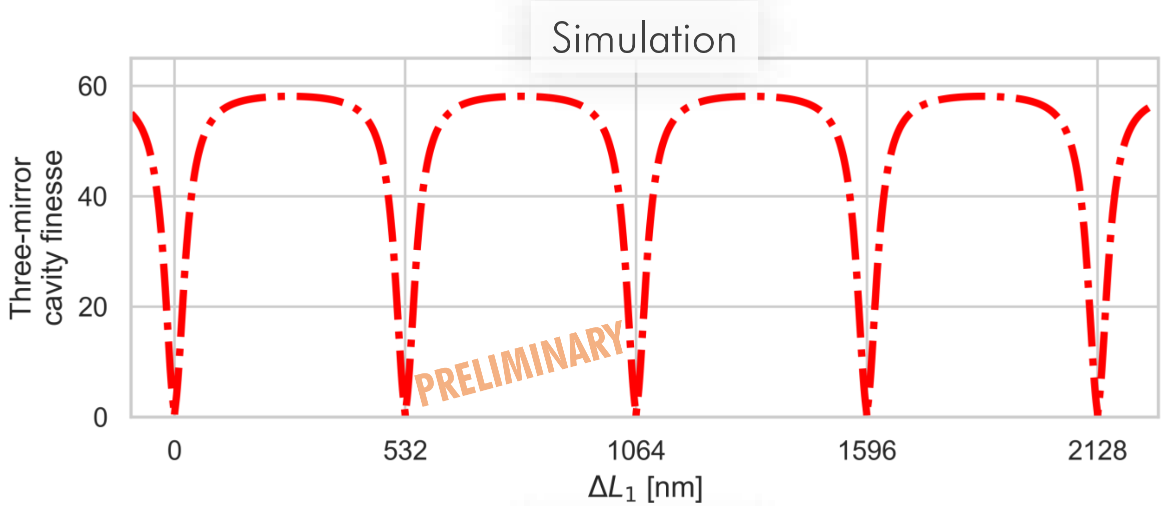
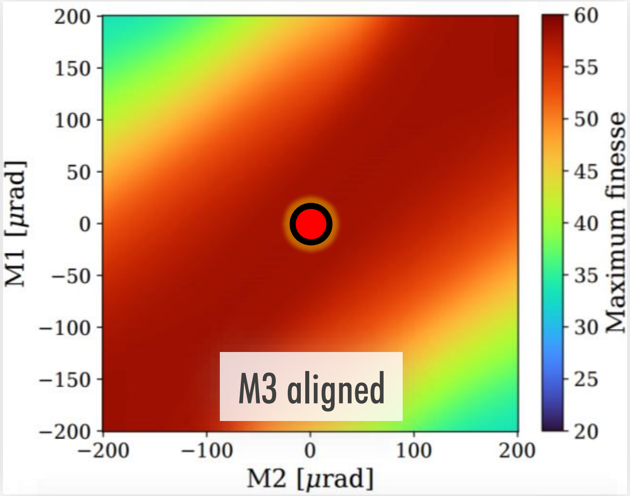
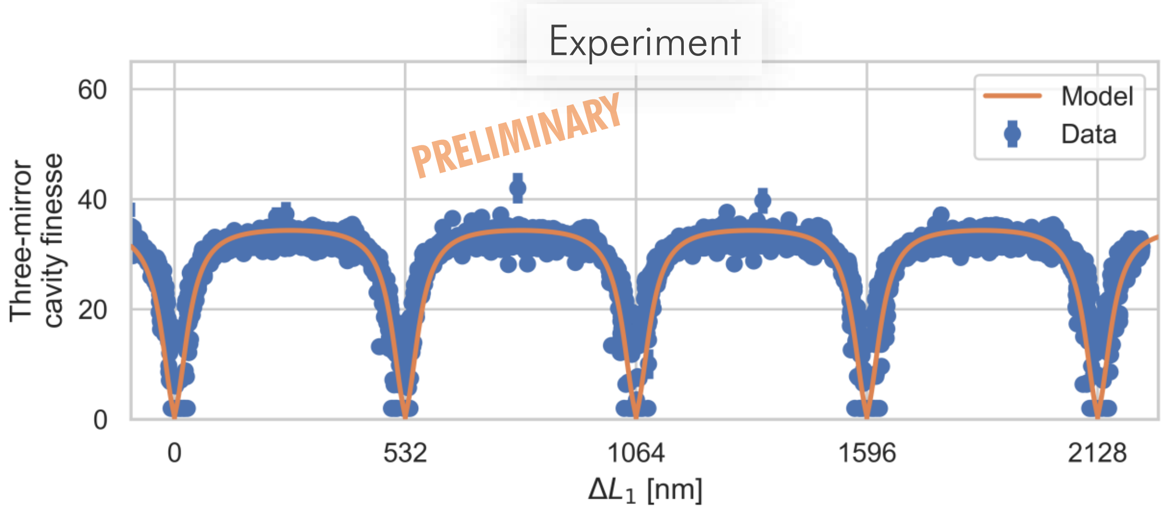
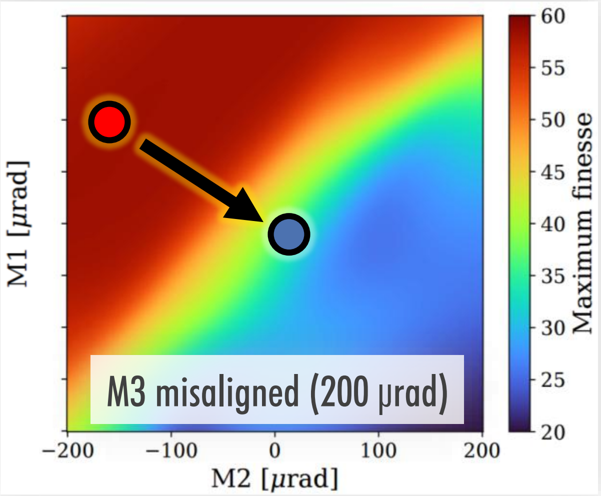


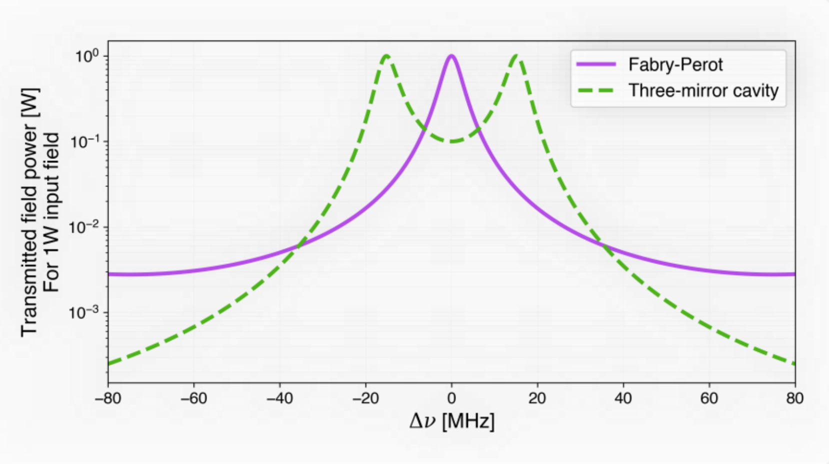






Three-mirror cavities: resonant behaviour

- Resonant behaviour ≠ 2 Fabry-Perot cavities
- Shows single or double resonance peak
- Benefits for GW detection:
  - Single peak → tuneability of corner freq. Ω_t
  - Double peak → 2 corner freq. $\Omega_t^{(1)}$ and $\Omega_t^{(2)}$



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

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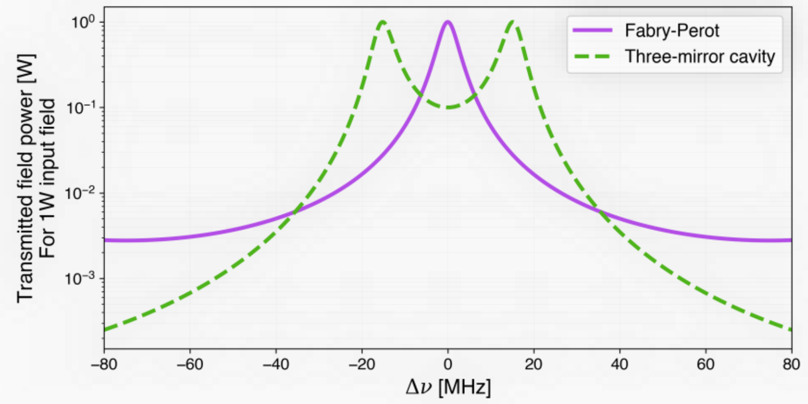
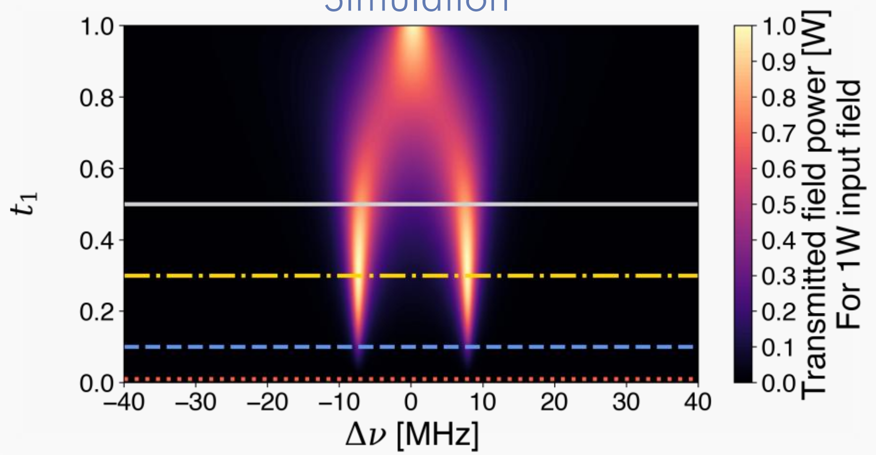


Simulation



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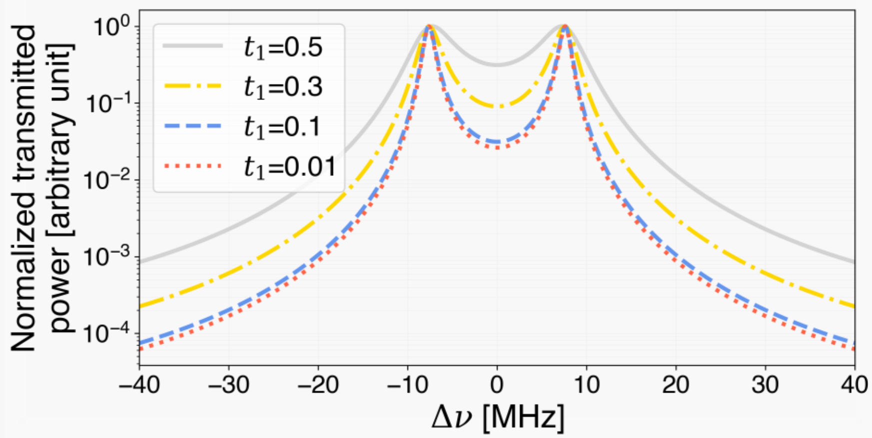

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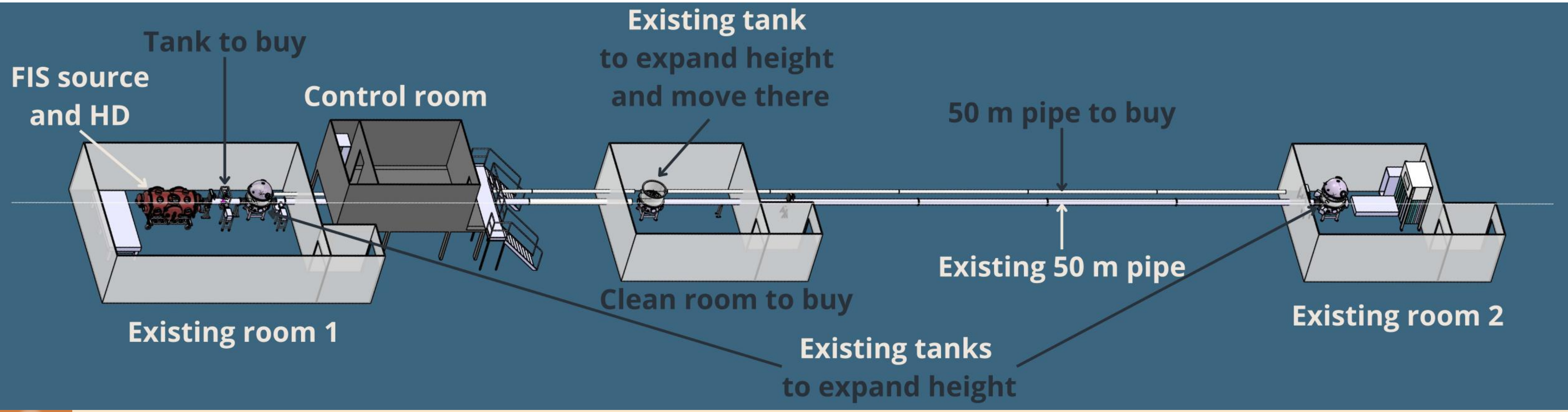
Large-scale three-mirror cavity in CALVA

New clean room will be built to accommodate third mirror (upcoming late 2026)

Two possible configurations:

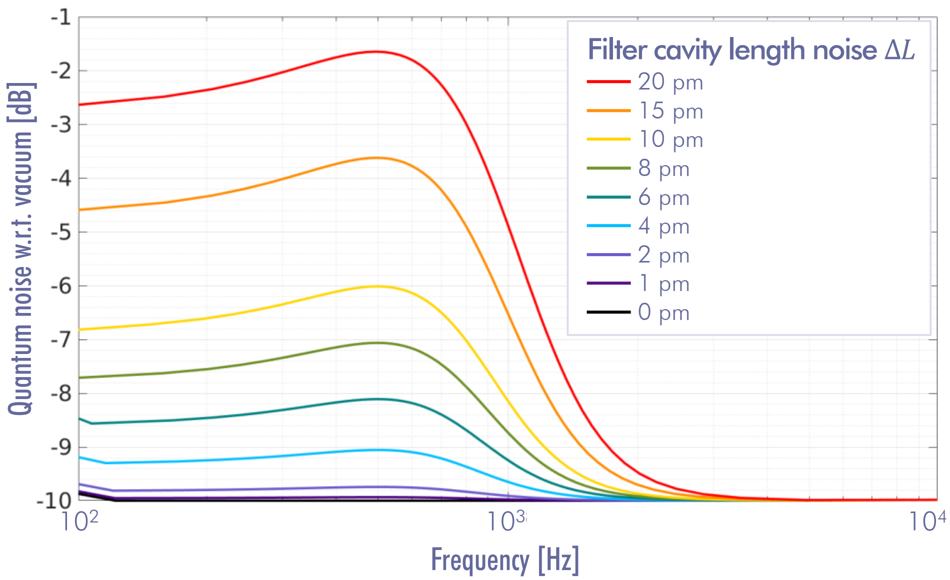
- Symmetric cavities (25 m | 25 m)
  → double-peak feature (ET-LF)
- Asymmetric cavities (19 m | 31 m)
  → variable finesse (ET-LF, ET-HF, CE...)



Impact of filter-cavity-length noise on squeezing

CONTROLLING LENGTH OF FILTER CAVITY

- High finesse ($\sim$ 3000)
- Length control via control laser (frequency f)
  - $\frac{\Delta L}{L} = \frac{\Delta f}{f}$
  - Aim: ≤1dB squeezing degradation (10dB produced)
    - ➢ We need $\Delta L \leq 4$ pm
    - ➢ Translates into $\Delta f \leq 20$ Hz ($L = 50\text{m},\ \lambda_{\text{laser}} = 1064\text{nm}$)



Source: thesis of A. Lartaux-Vollard

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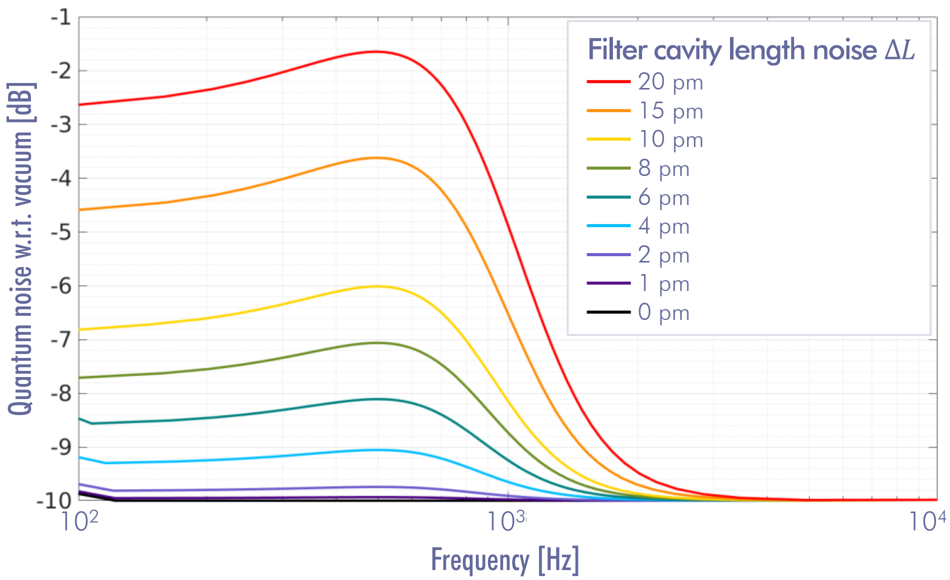

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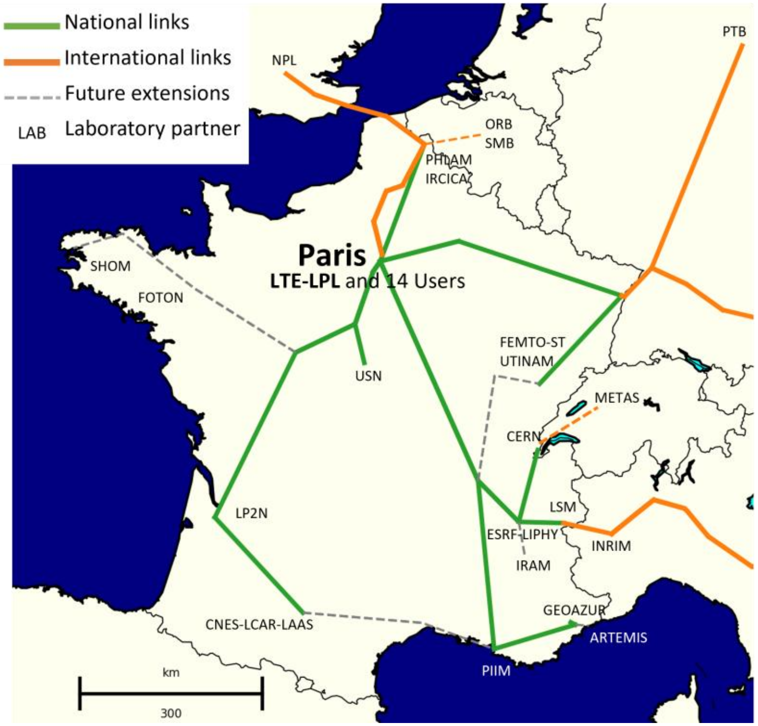
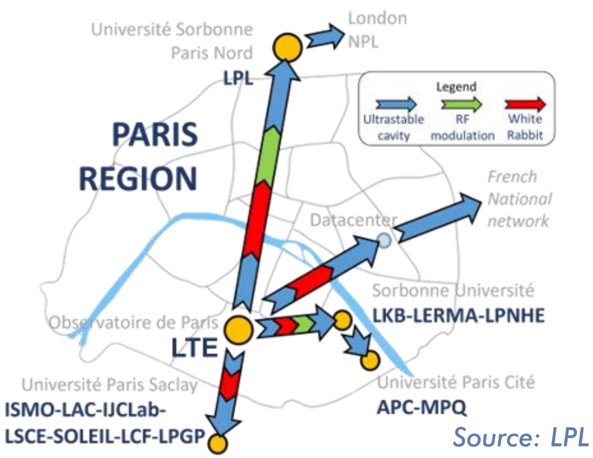
Refimeve research infrastructure

RÉSEAU FIBRÉ MÉTROLOGIQUE À VOCATION EUROPÉENNE

- National research infrastructure funded by PIA/Equipex projects
- Dissemination of time/frequency references
  - Currently used in state-of-the-art international comparisons of atomic clocks
- Signal now available at IJCLab / CALVA





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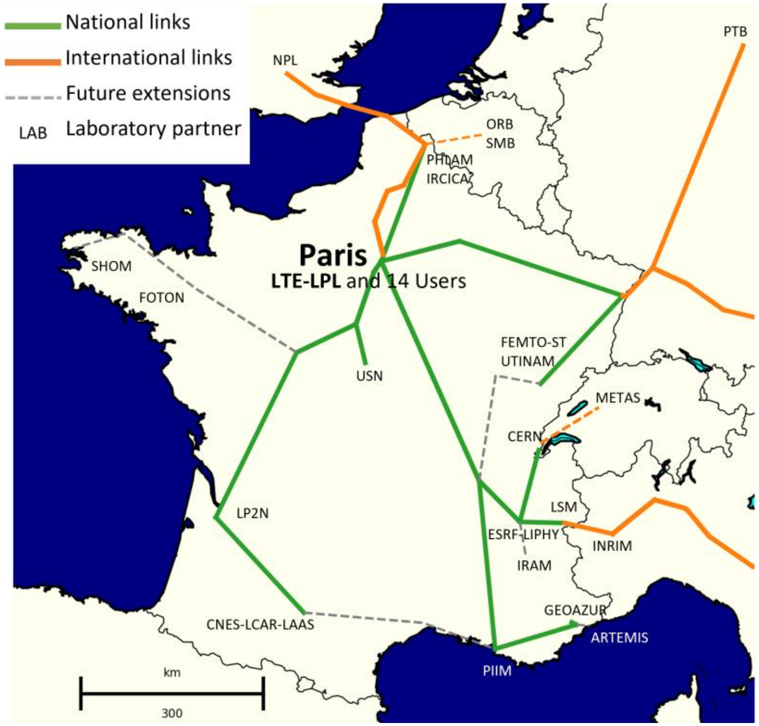
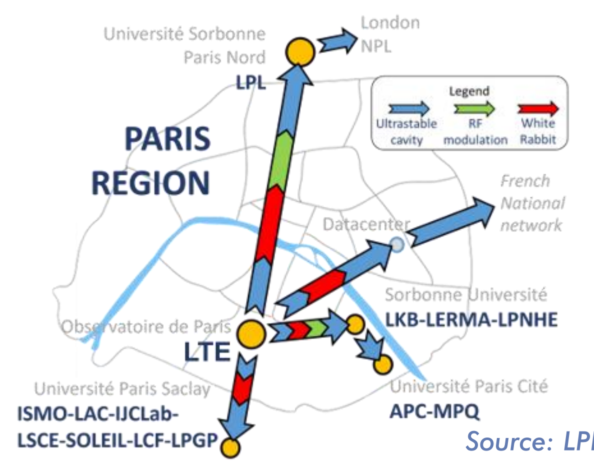


STABILITY OF REFIMEVE SIGNAL (1542nm)

- Equivalent stability ~ 1 Hz at 1s (at 1064 nm)
  - Close to the stability reached by LIGO/Virgo
- Transfer stability from 1542 mn to 1064 nm?

→ Optical frequency comb



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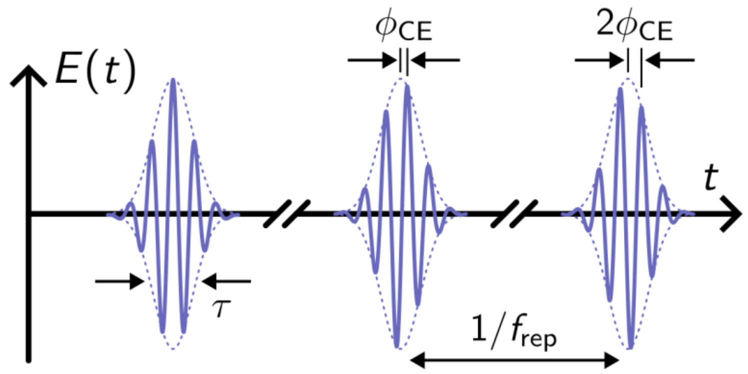
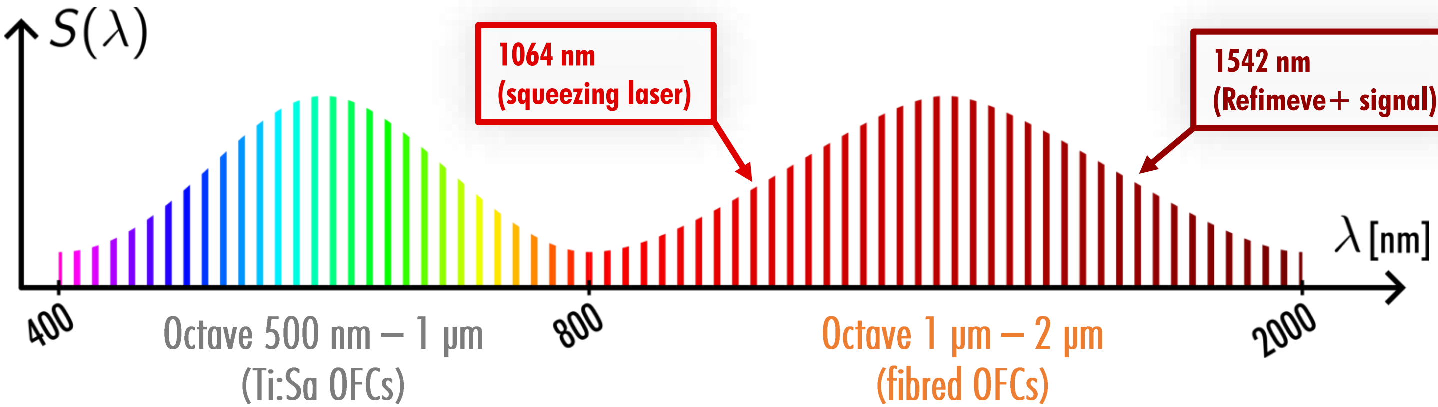
Optical Frequency Comb (OFC)

Working principle

- Brief pulses, controlled repetition rate
- Acts as a frequency "ruler" with evenly-spaced "teeth" ($f_{rep} \simeq 80$ MHz)
- Covers an octave of frequencies





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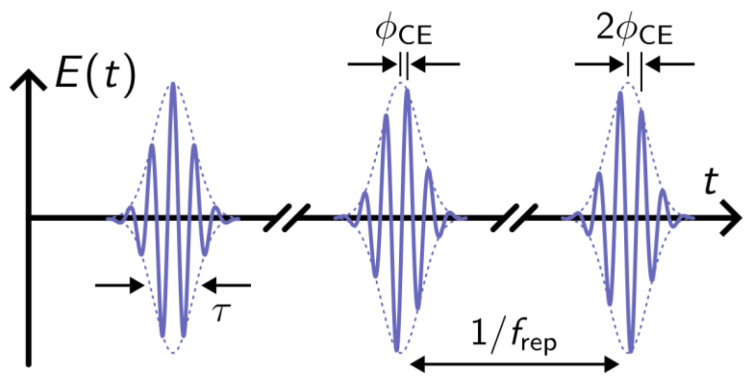
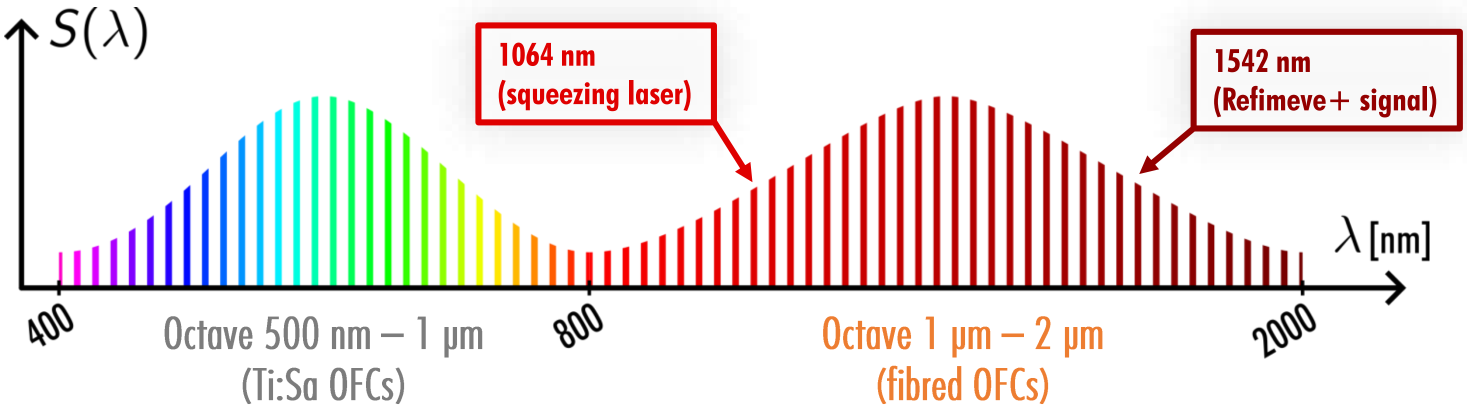


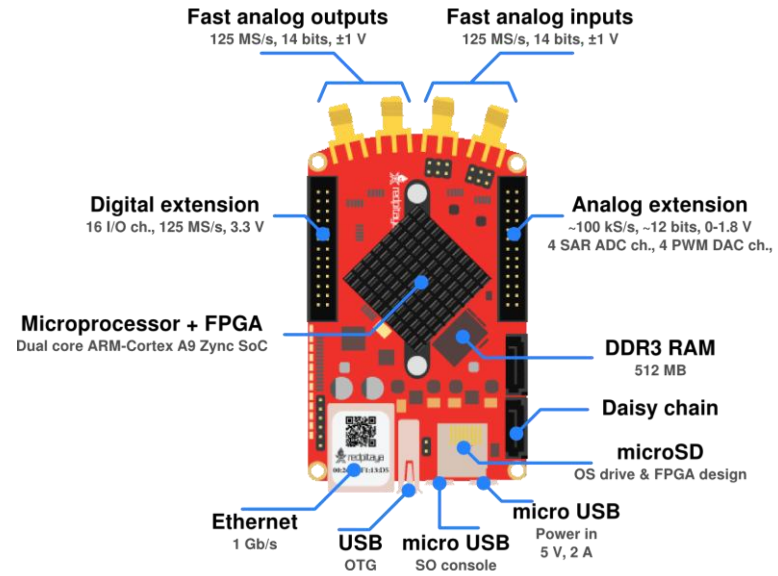


Application to our project: frequency stabilisation of OFC on Refimeve signal, then 1064 nm laser on OFC

→ 2 upcoming internships on this topic!

Other recent research efforts at CALVA in a nutshell

- RedPitaya-based control of squeezing-ellipse angle with higher bandwidth



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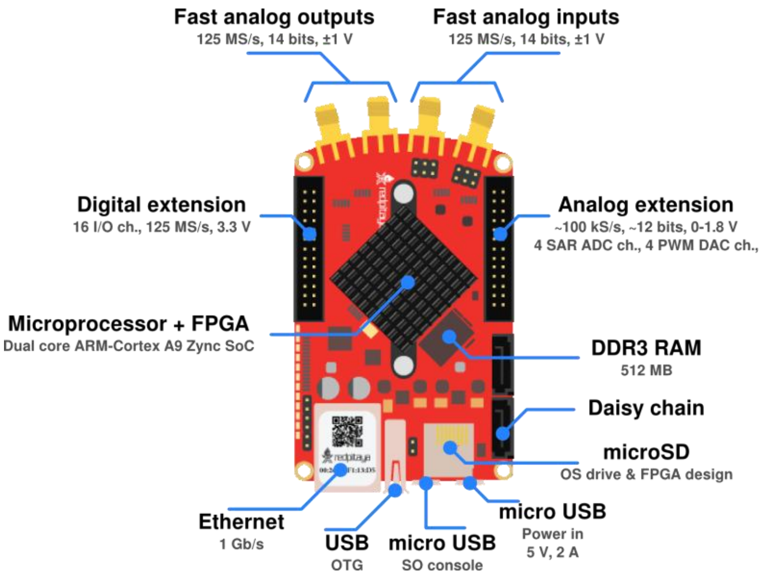

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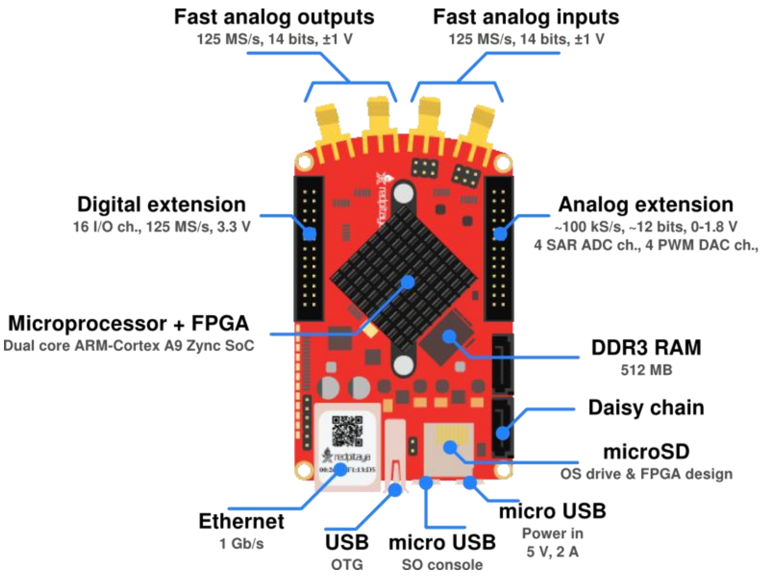

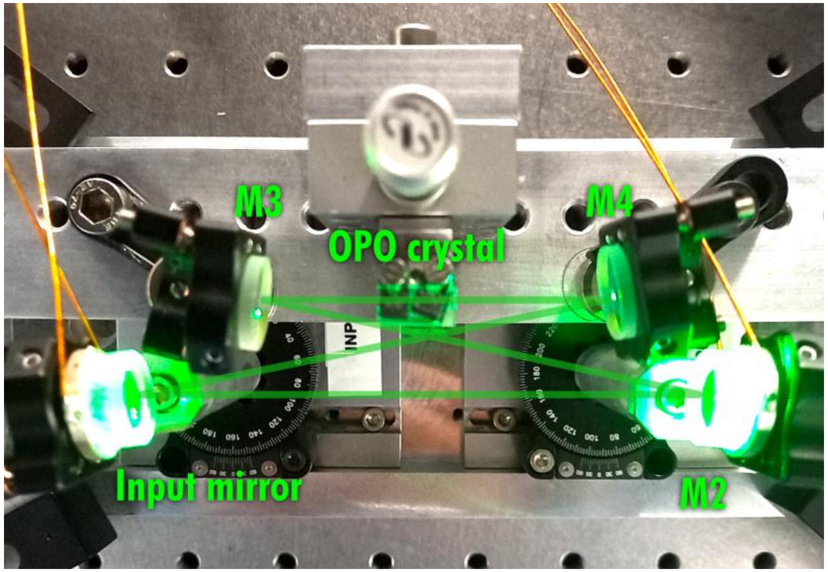

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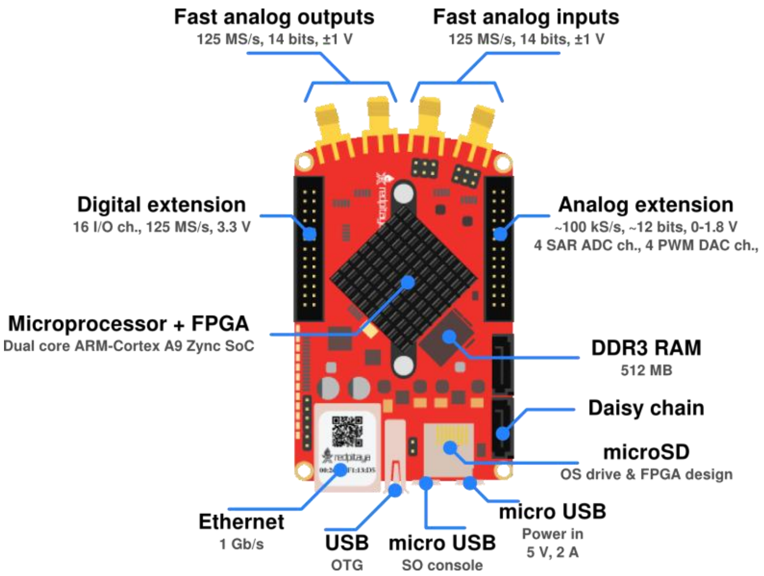
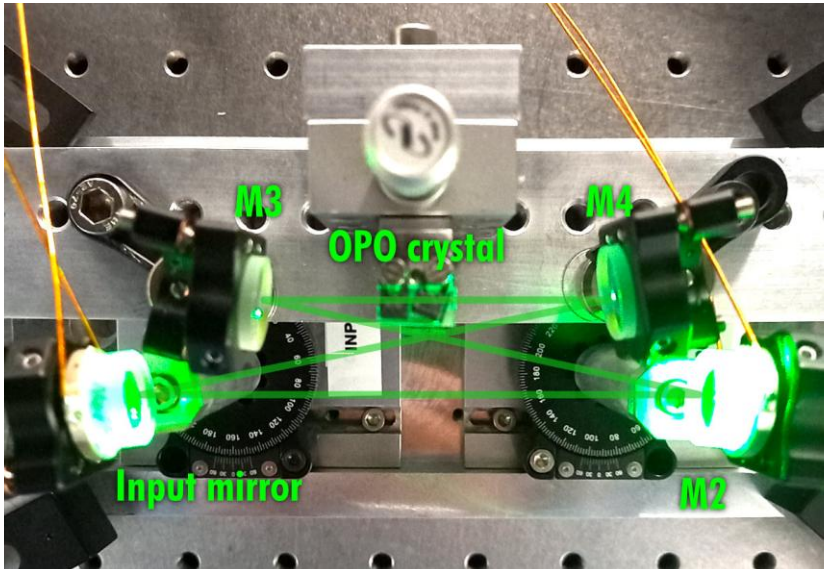
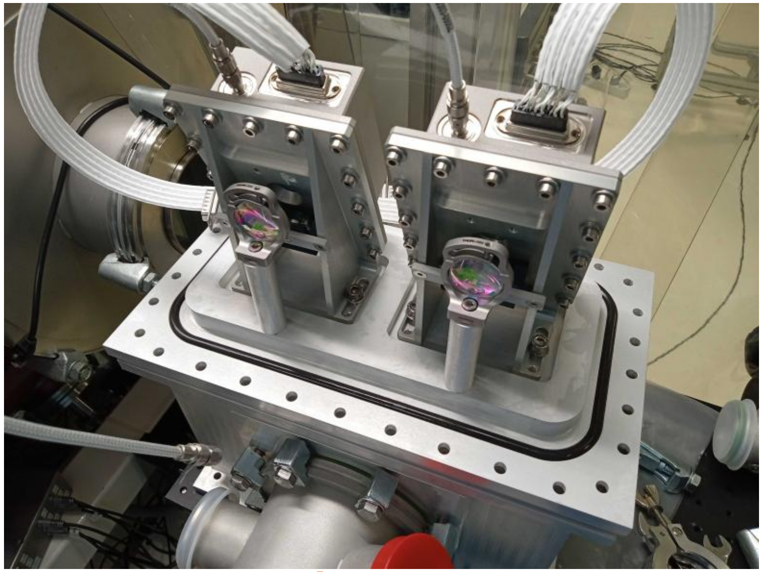
- Vacuum operation for Homodyne Detection





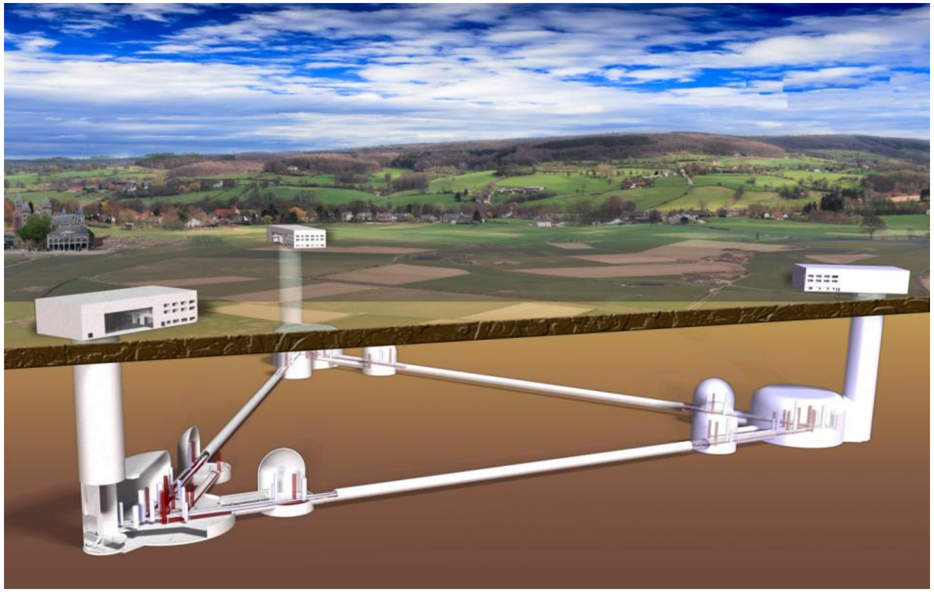


Homodyne Detection

Involvement in the Einstein Telescope project

UPCOMING EUROPEAN GW DETECTOR (2035 – 2040 FOR NOW…)

- Single triangular shape (10 km) or two “L” shapes (20 km)
- Underground (better control of seismic vibrations)
- Low- and a high-frequency interferometers (ET-LF / ET-HF)
  - ET-LF will require cryogenic operation (may require changing wavelength to 1.55 μm)
  - ET-HF will use more optical power



Source: Einstein Telescope / EGO (https://www.et-gw.eu/)

Involvement in the Einstein Telescope project (2)

CALVA in the context of Einstein Telescope

- Testbed for upcoming (frequency-dependent) squeezing techniques
  - CALVA filter cavity can adapt thanks to our work on 3-mirror cavities!
  - Unique feature: state-of-the-art laser stabilisation through Refimeve!
- The group is also involved in simulation, optics and technical aspects of ET's design

XIII ET Symposium, Cagliari, May 2023

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