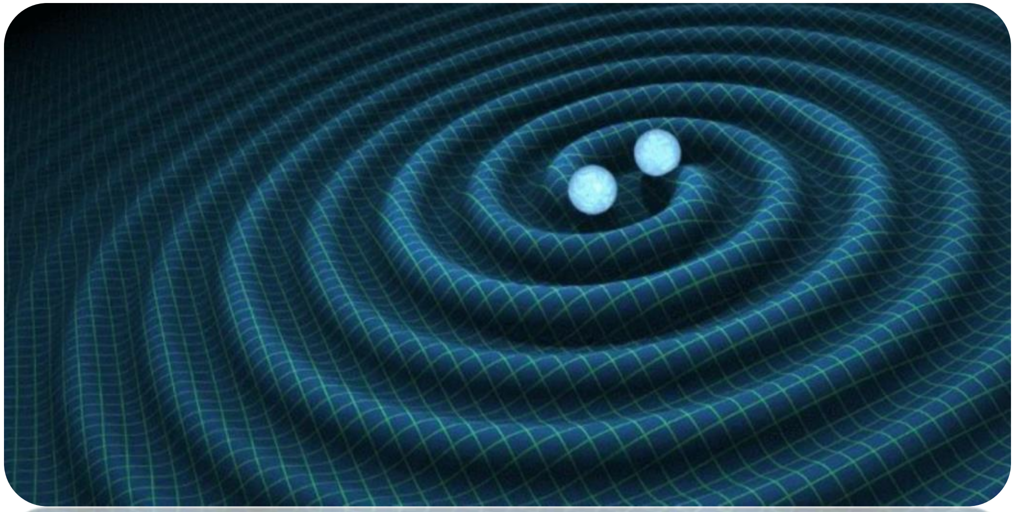
Quantum-Noise Reduction to improve Gravitational-Wave Detectors

1. Aims of the CALVA experiment

- Develop quantum-optics tools for gravitational-wave detectors
- Enable exploration of new astrophysical sources: more massive and/or more distant

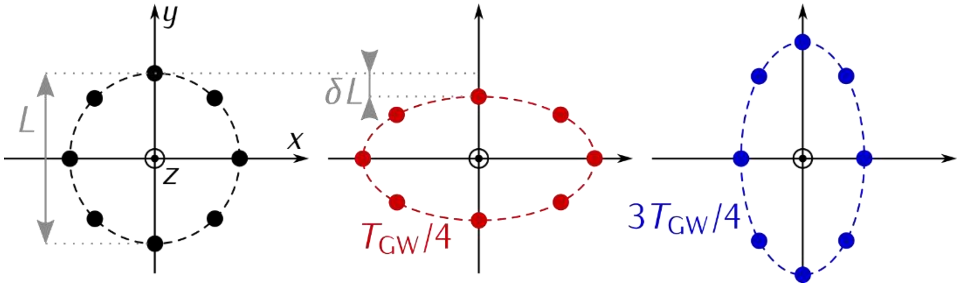
2. Participation of CALVA in the Refimeve+ network & collaboration



Gravitational waves (GW)

Origin and effects of GW (Einstein, 1916)

> "Oscillations of the space-time curvature produced by accelerated masses, and propagating at the speed of light in vacuum."



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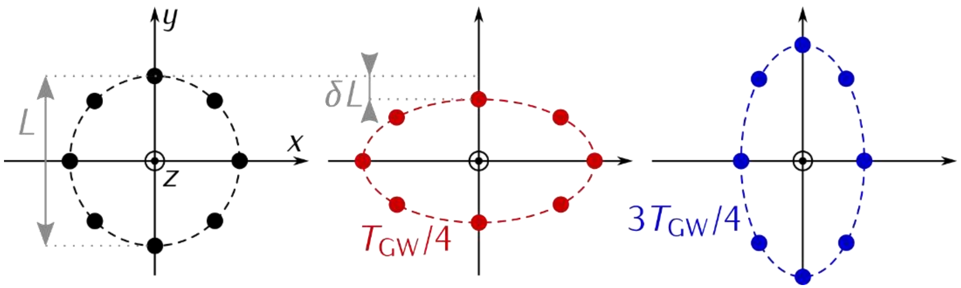

Amplitude of a gravitational wave

- 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 $r = 400\ \mathrm{Mpc}$

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

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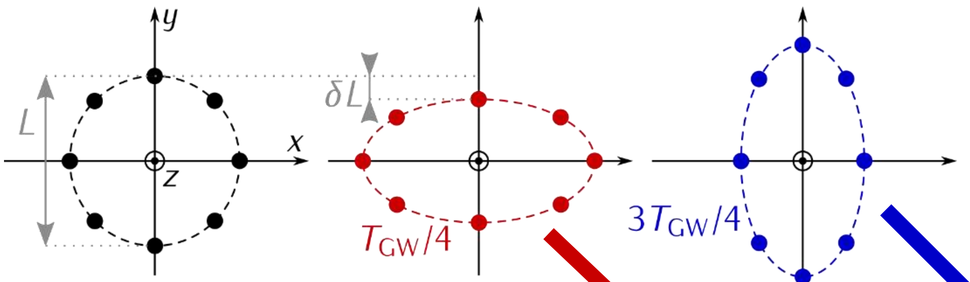
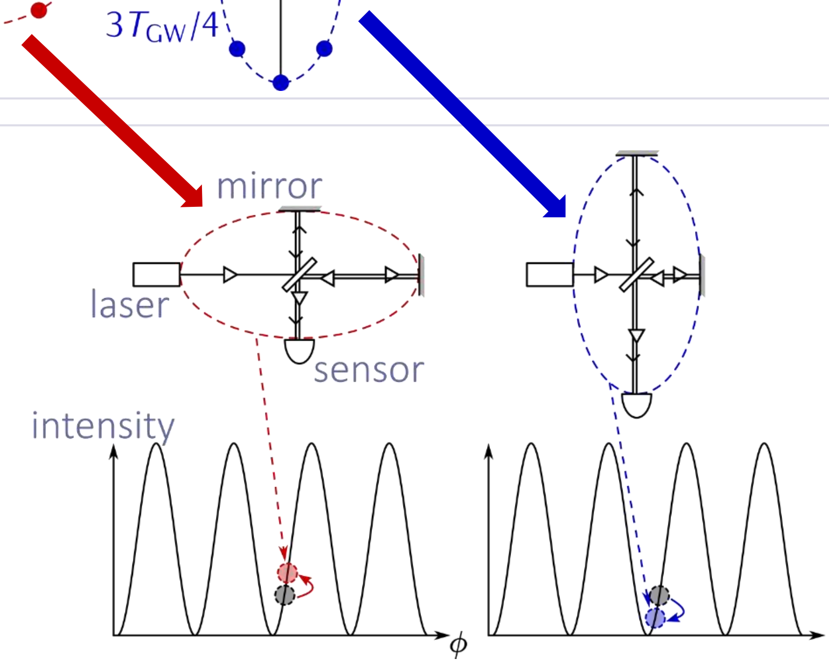


GW detection: Michelson interferometer

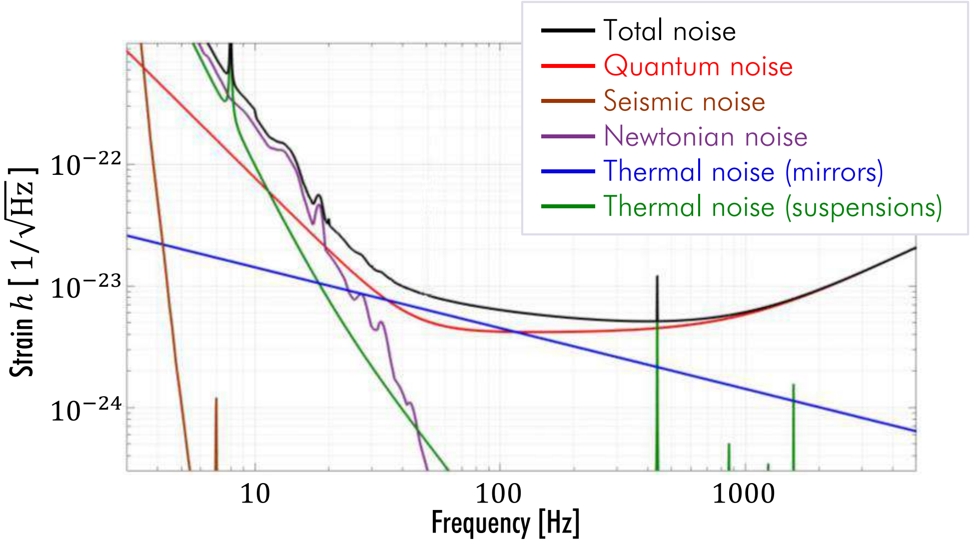
- Examples: LIGO / Virgo / KAGRA
  - State-of-the-art sensitivity $\leq 10^{-23}$
  - Arms length ~ 3–4 km ($\delta L \sim 10^{-20}$ m)
  - Suspended mirrors
  - Fabry-Perot cavities
  - Vacuum interferometer



Main noise sources affecting GW detection

Classical noise sources

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



Source: *ADV+ TDR*

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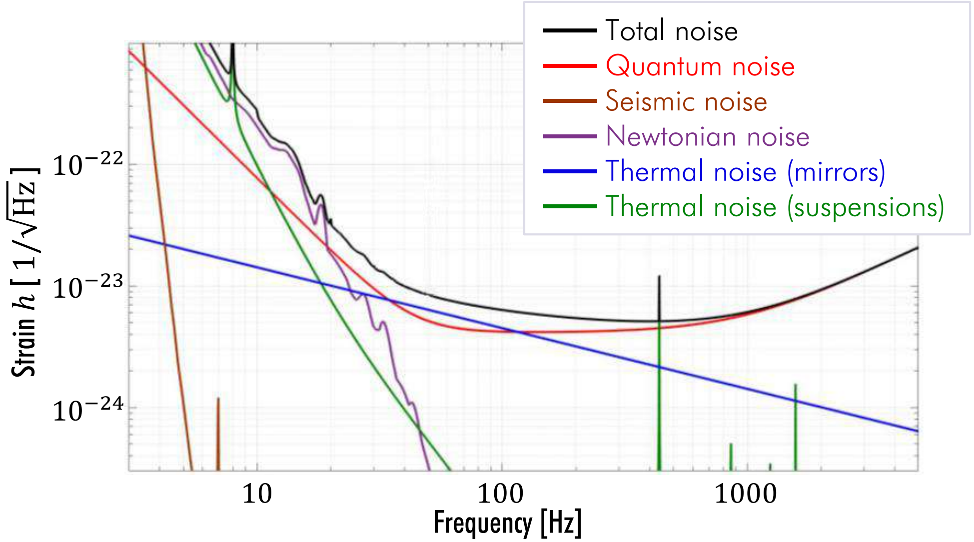

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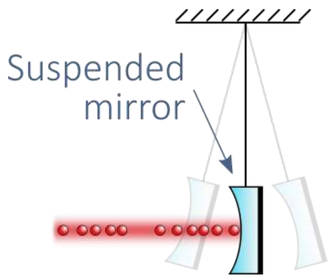
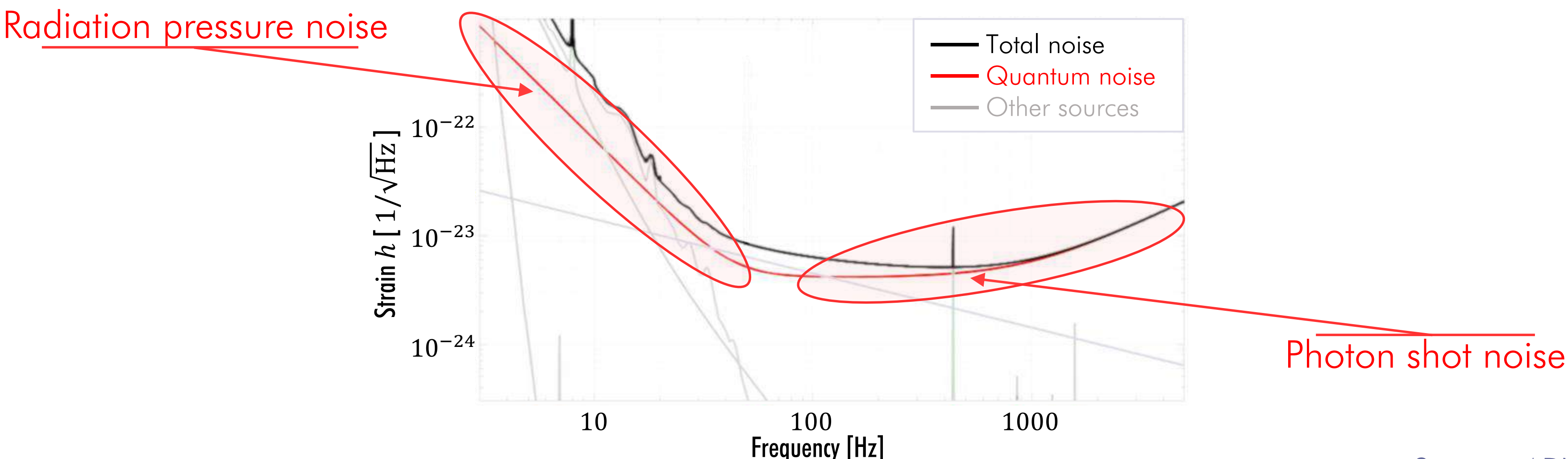
Quantum noise sources

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





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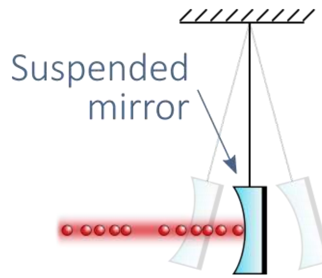

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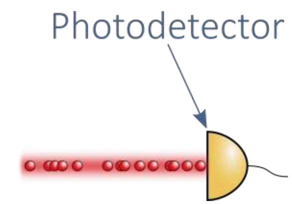
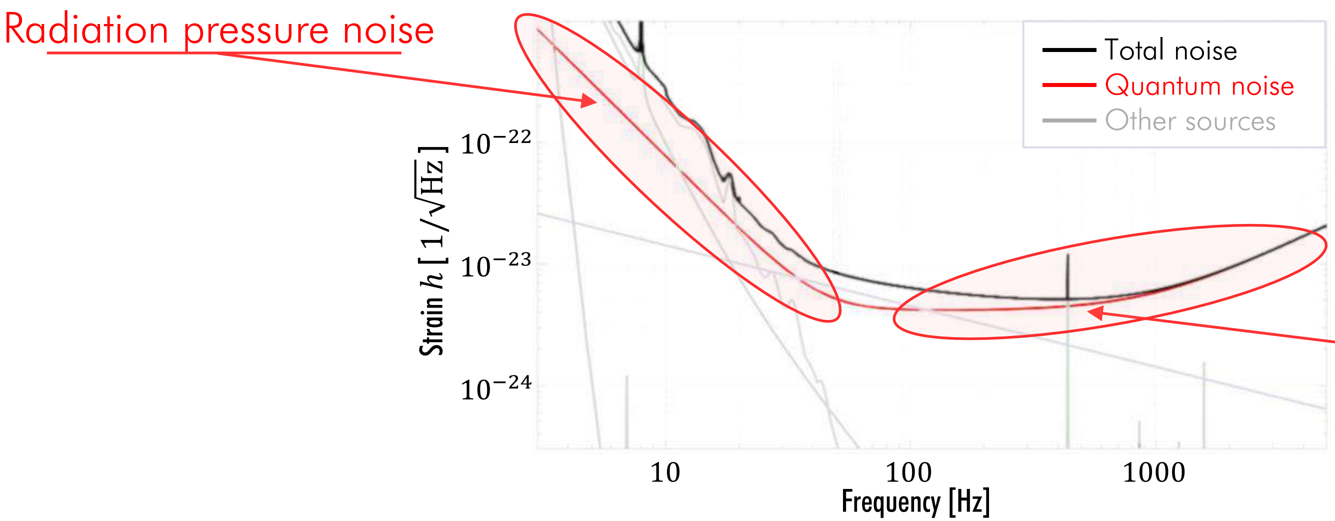


- Photon shot noise
  - Dominates at high frequency
  - Phase-noise-related



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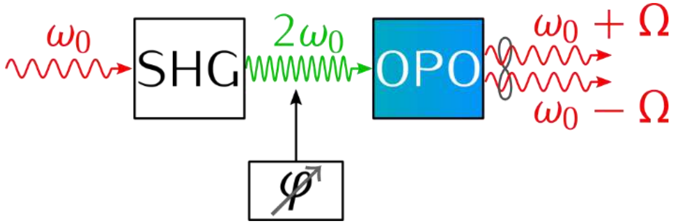
Squeezed states of light

Harnessing Quantum properties of light to reduce noise

- Optical Parametric Oscillator (OPO): quantum entanglement between 2 photons



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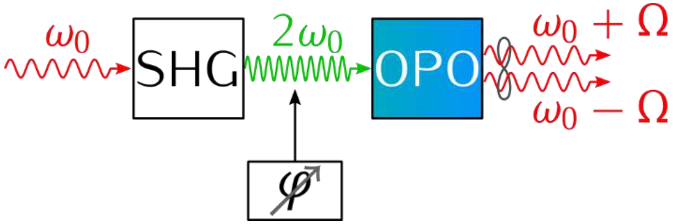
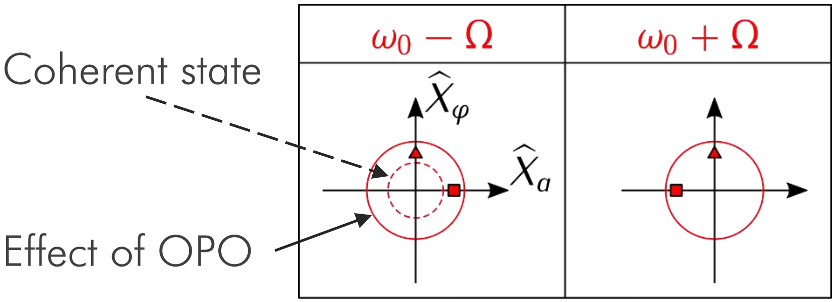
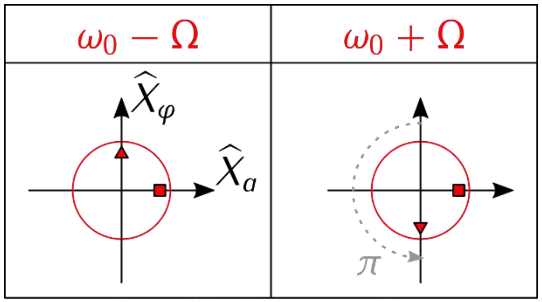




Phase squeezing



Amplitude squeezing

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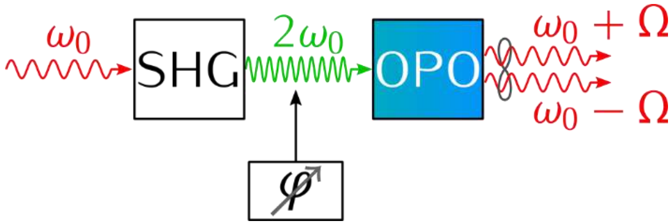

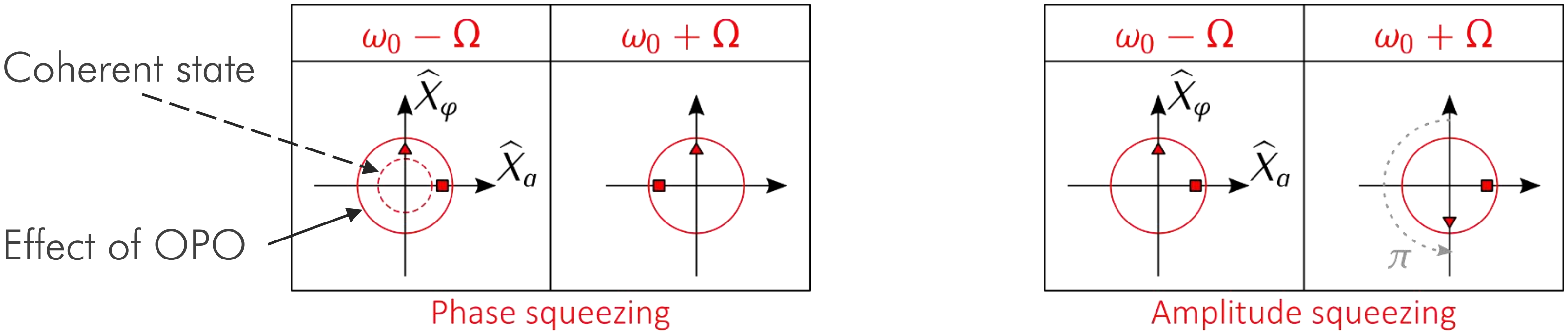

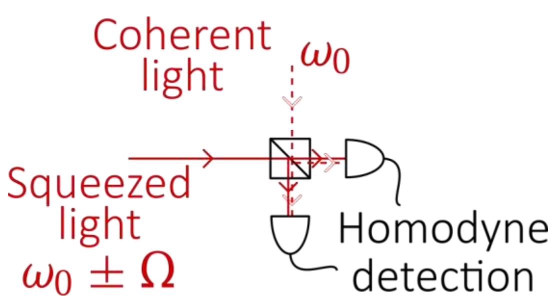

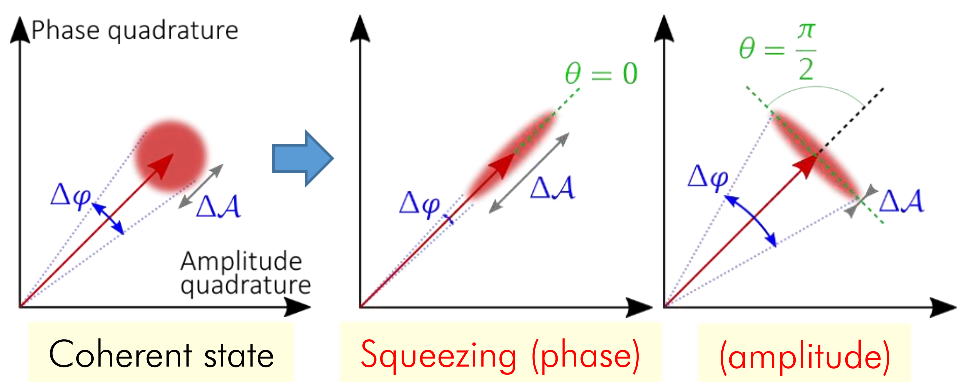

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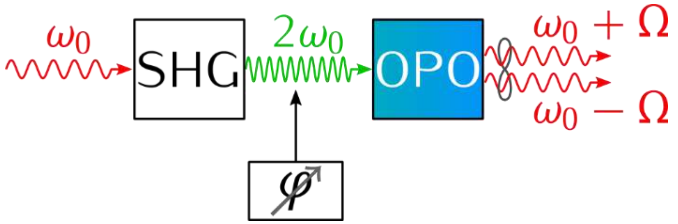

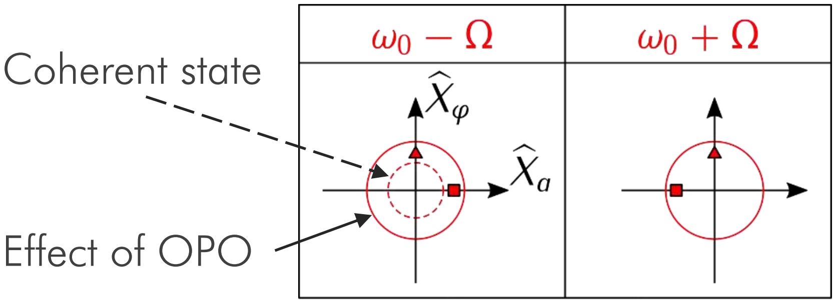

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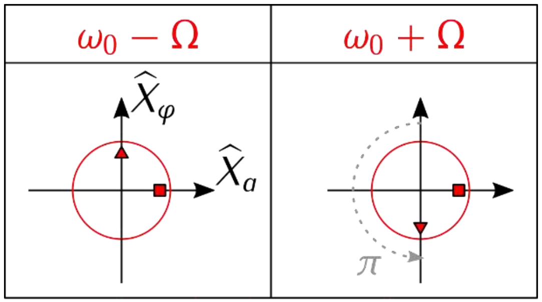
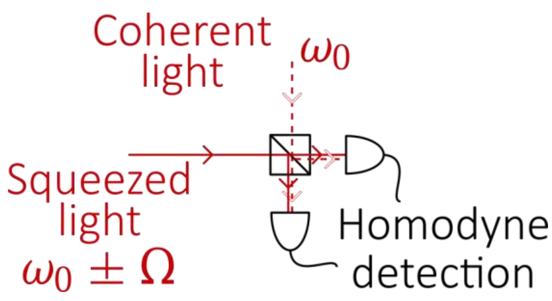
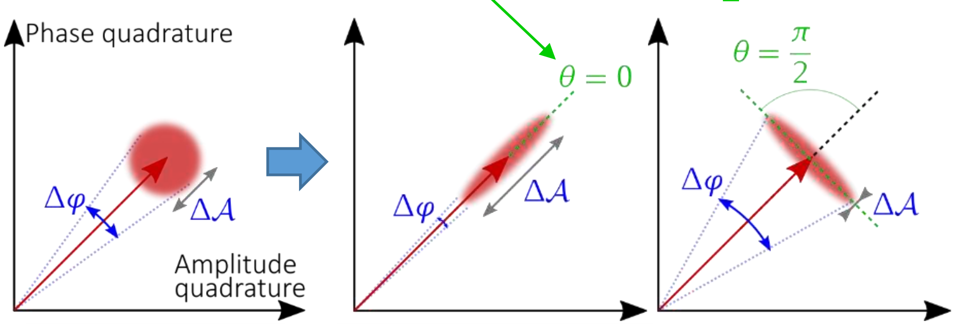


Amplitude squeezing

$$\theta = \frac{\phi(\omega_0+\Omega)+\phi(\omega_0-\Omega)}{2}\ [\text{mod. } \pi]$$





Coherent state

Squeezing (phase)

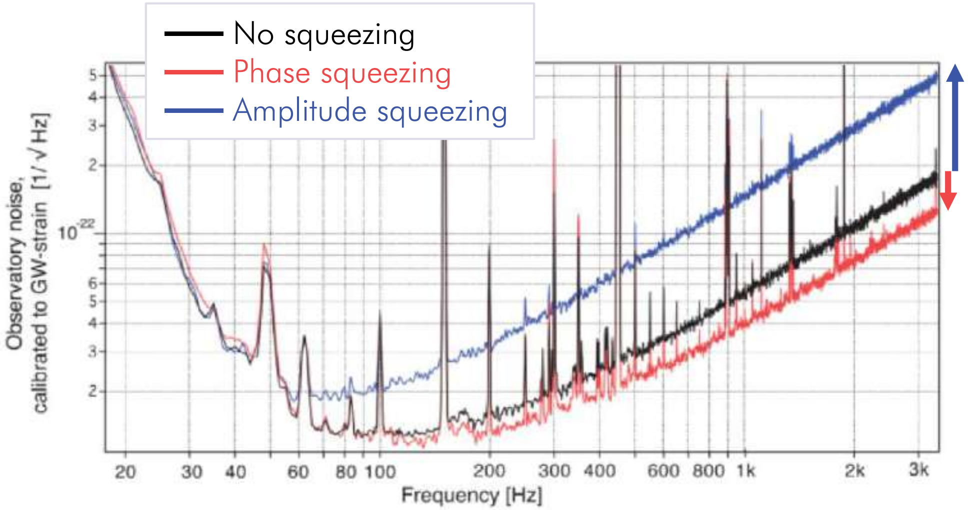
(amplitude)

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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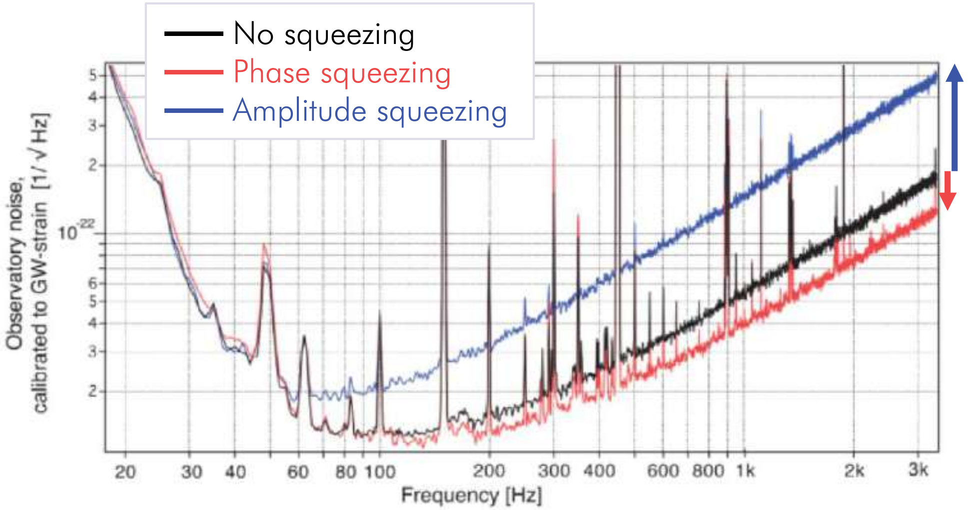

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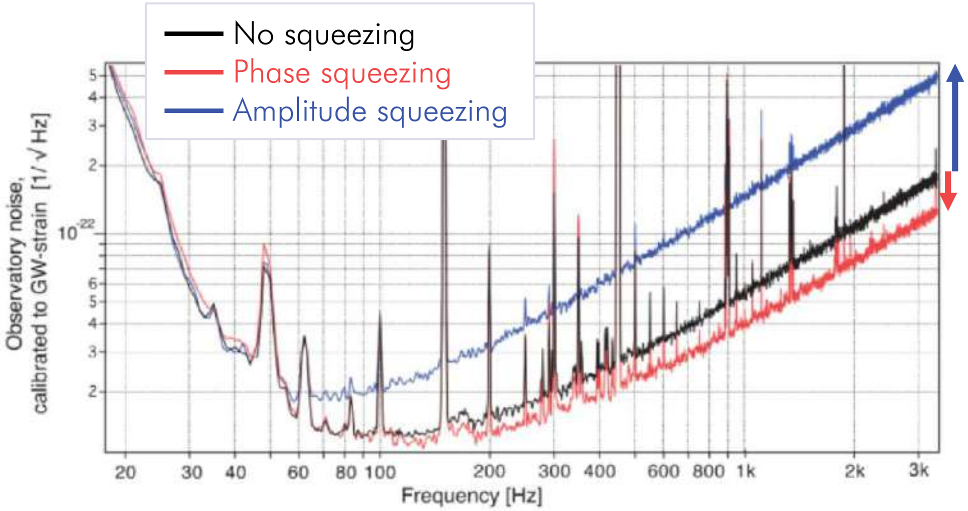

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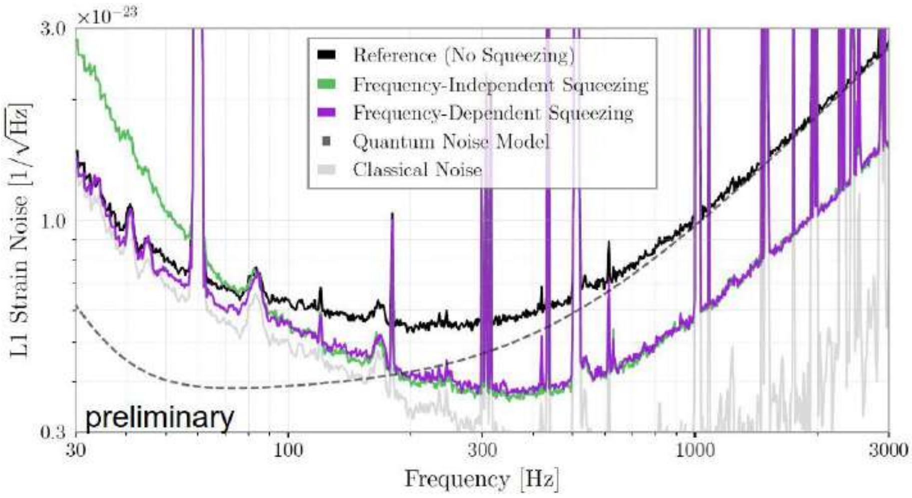
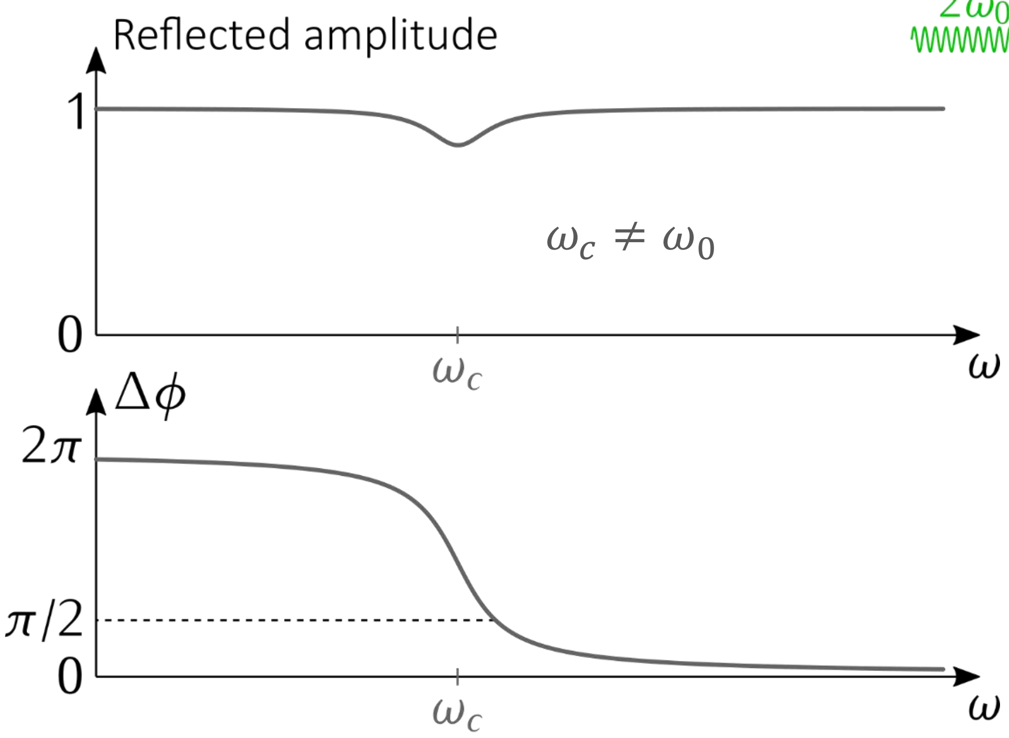
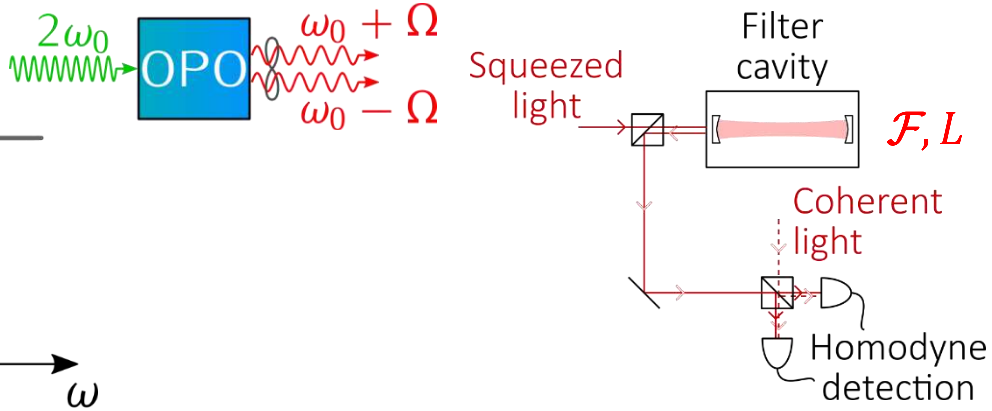


Source: LIGO

Frequency-dependent squeezing





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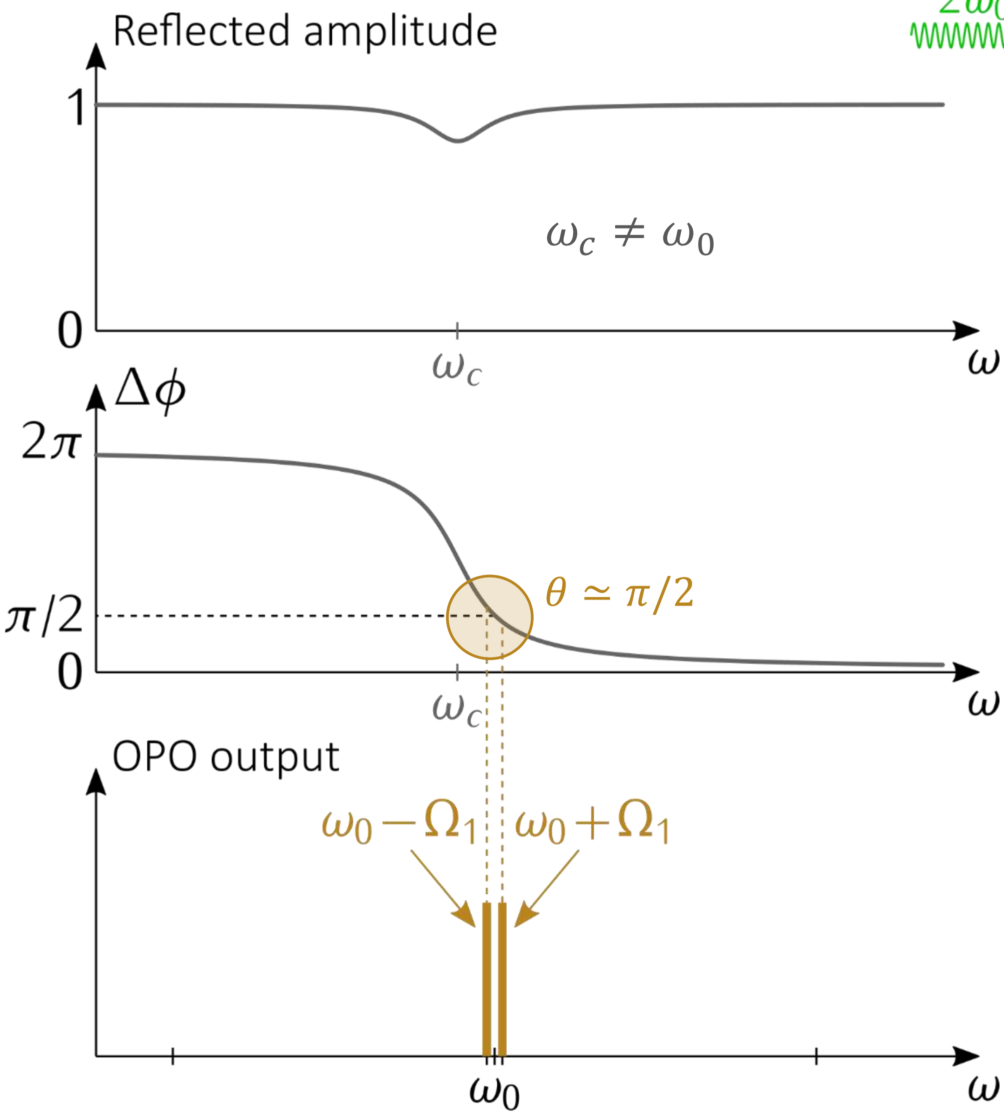

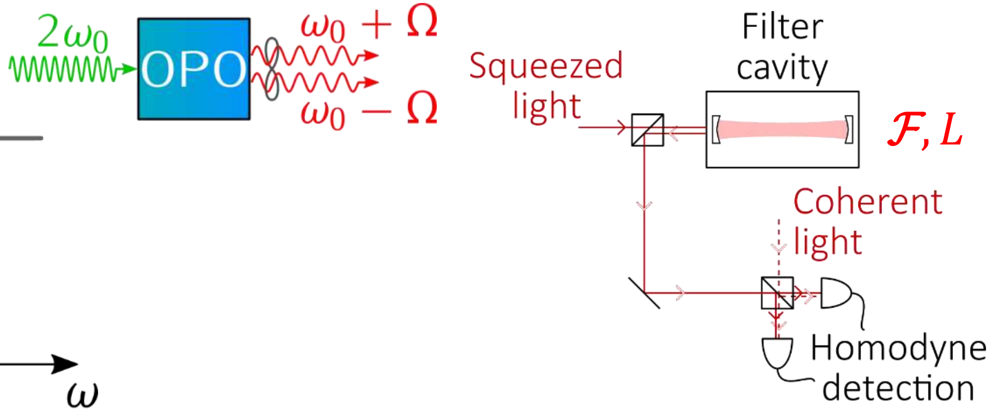

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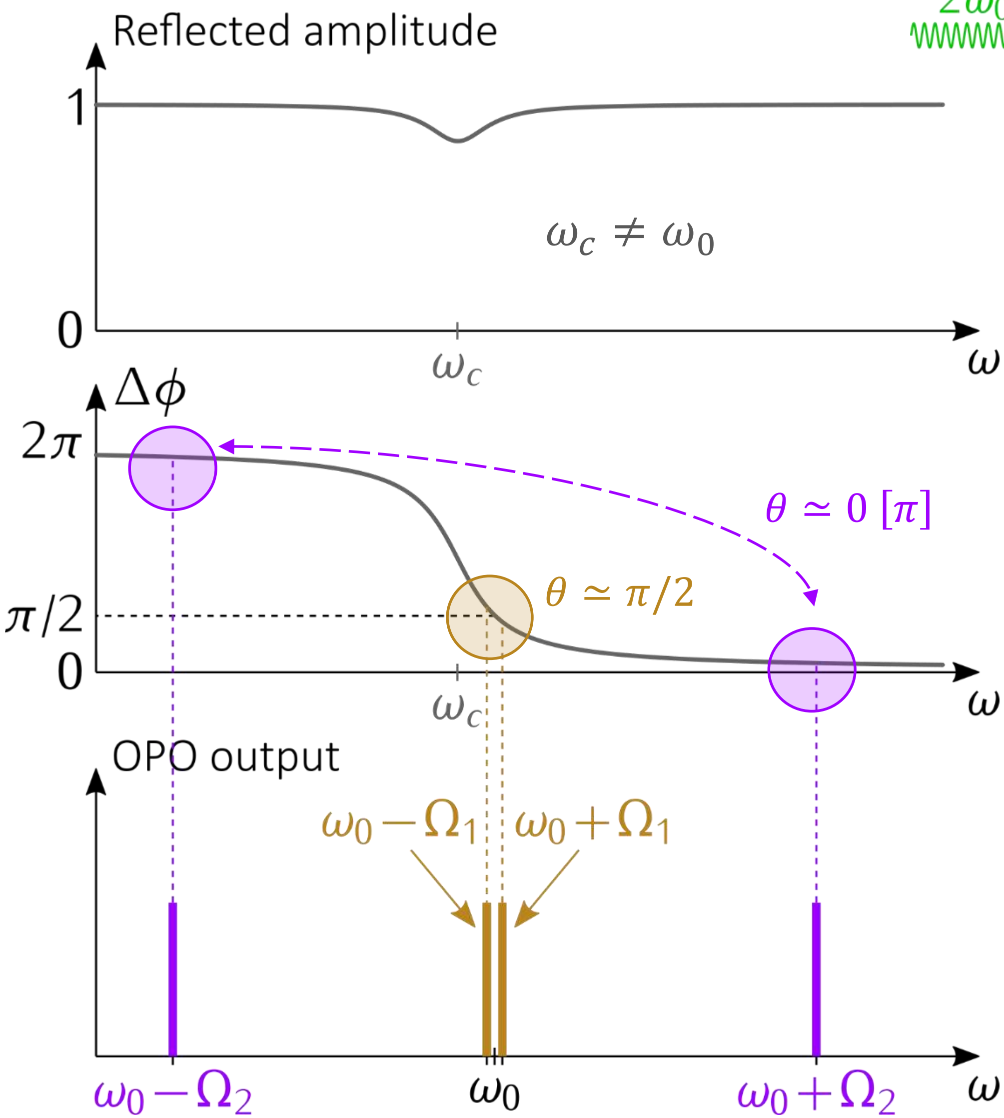

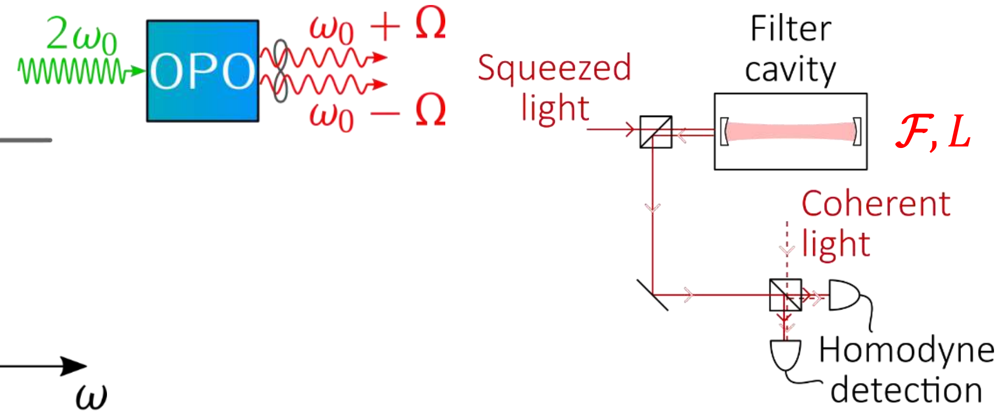

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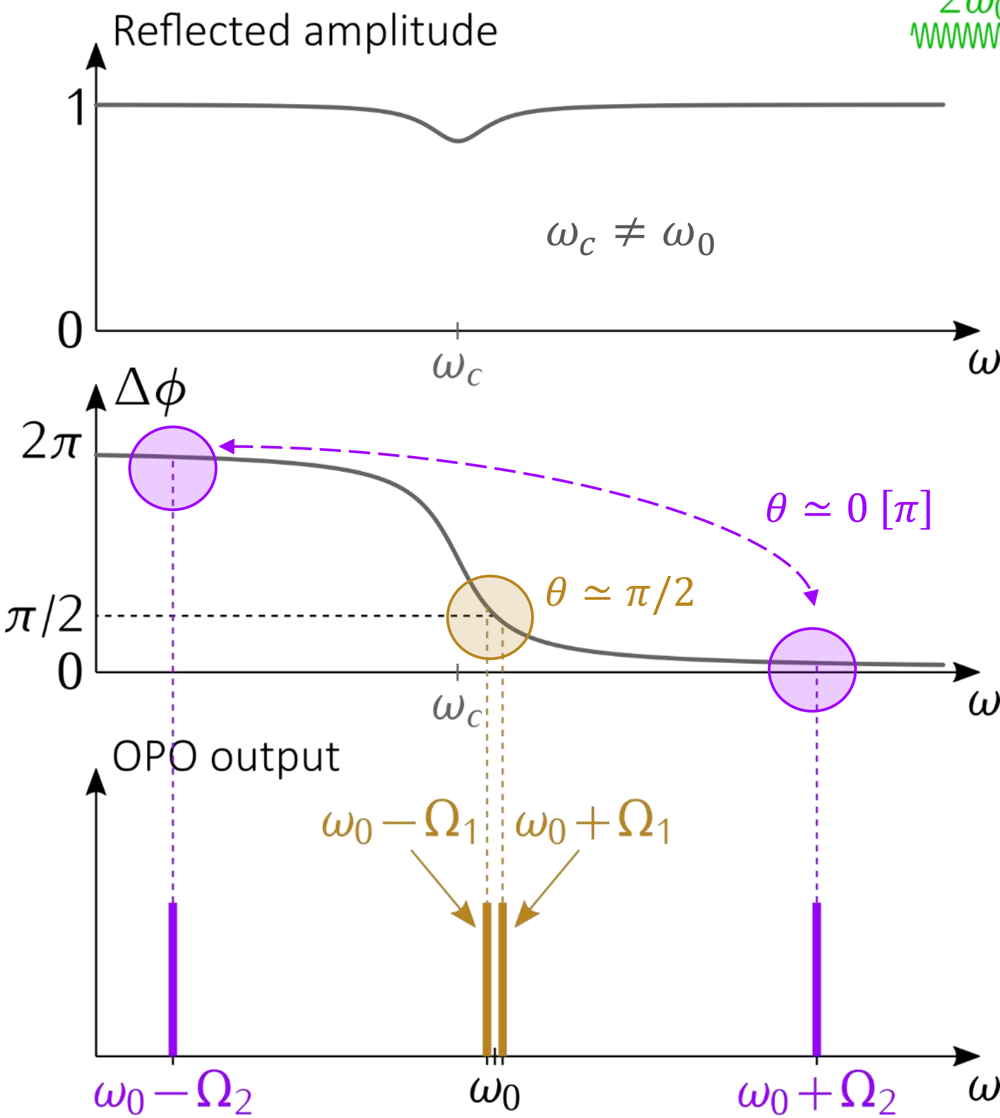

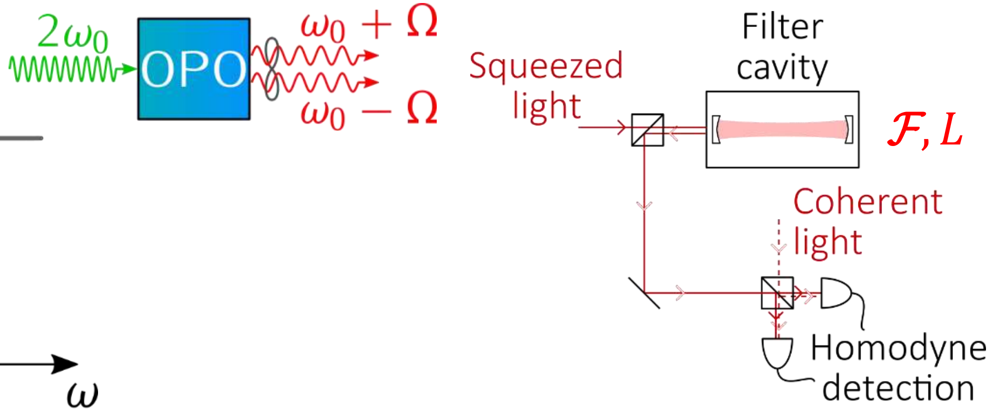

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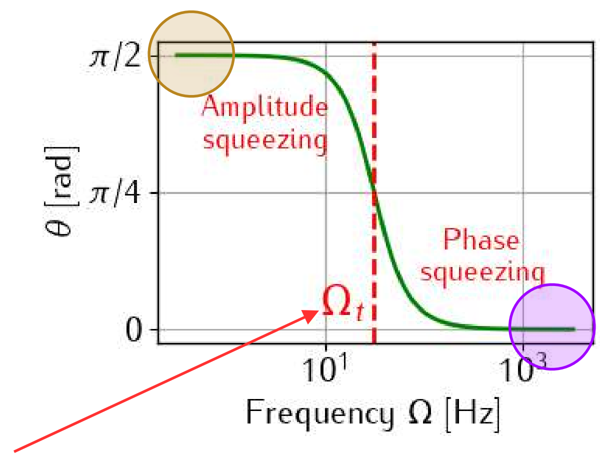
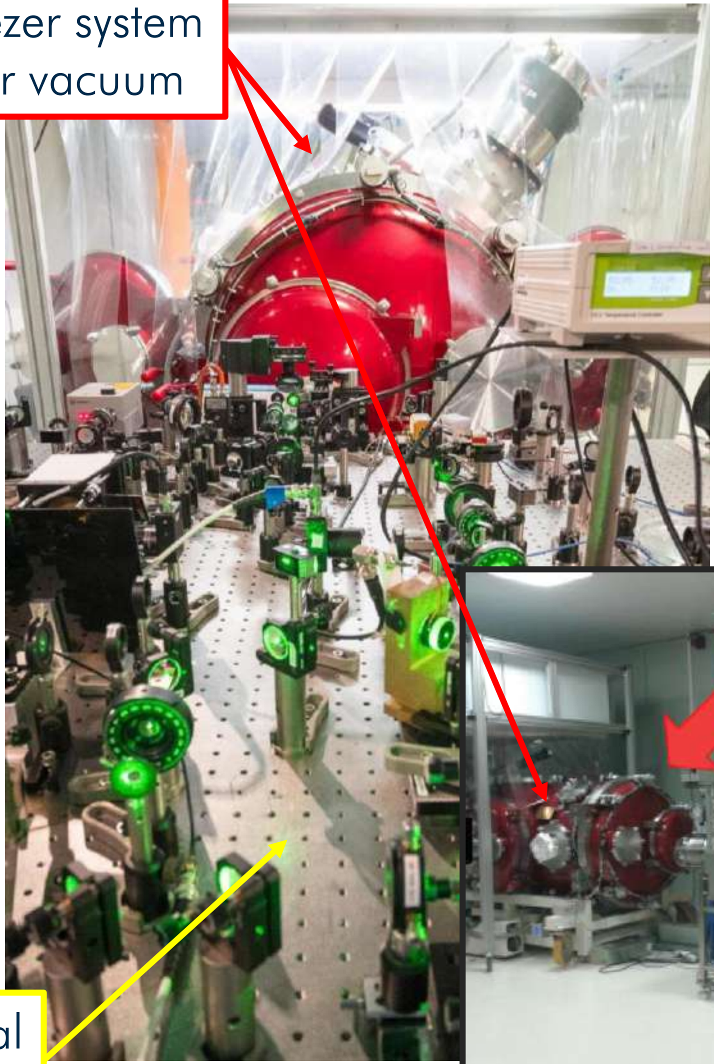
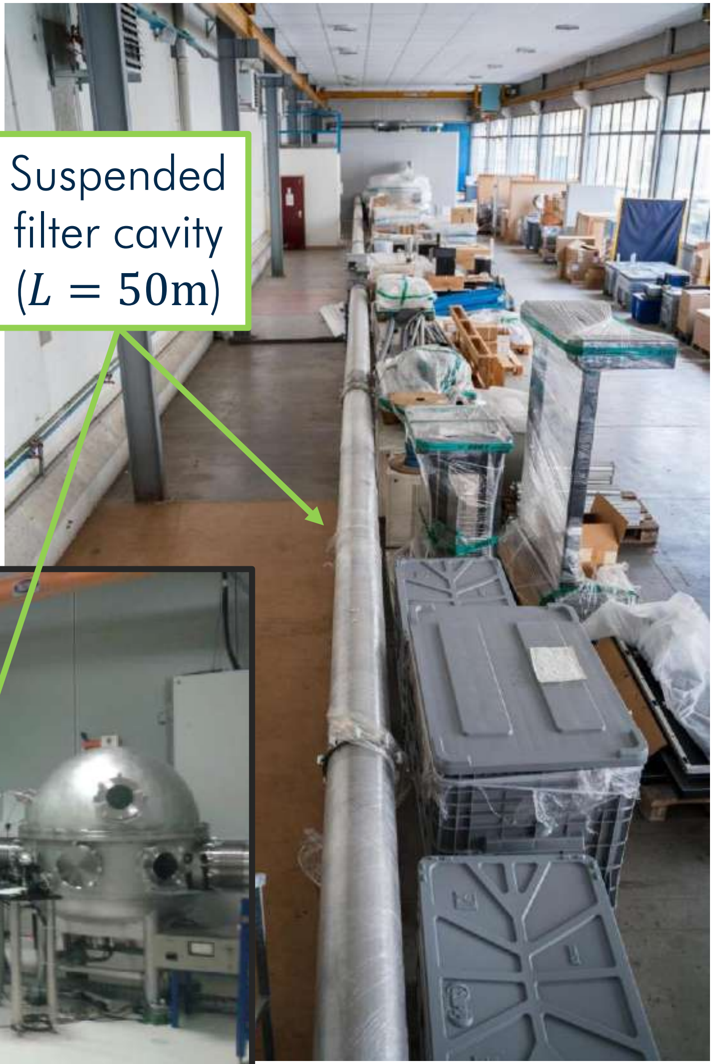


$\Omega_t = f(\mathcal{F}, L)$

The Exsqueez project and CALVA experiment





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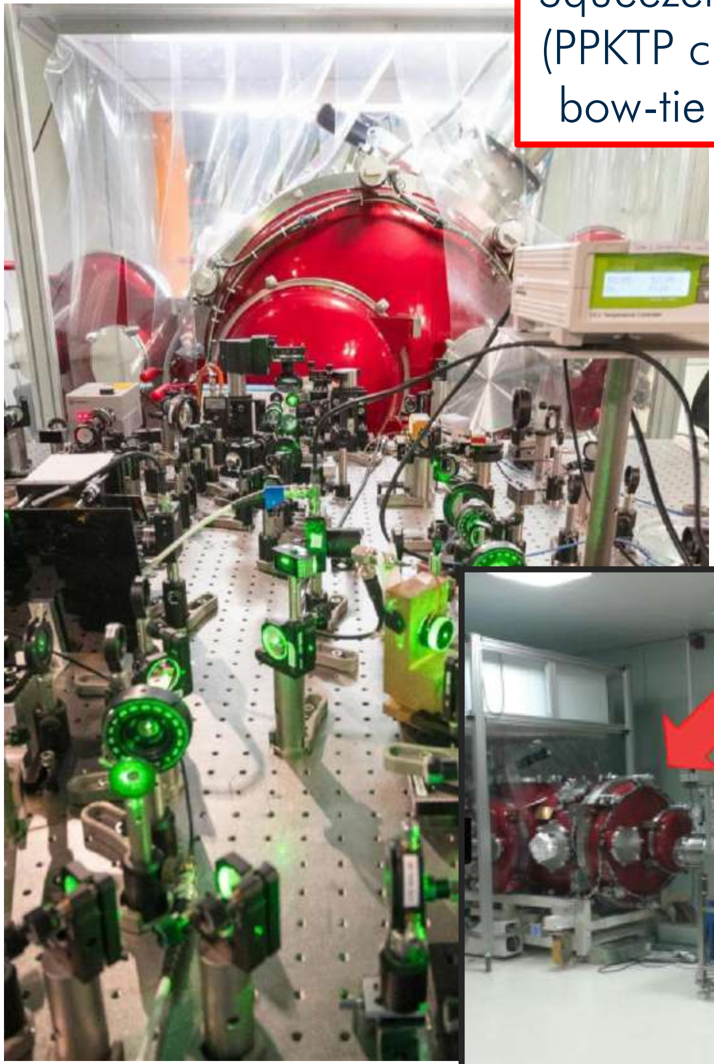
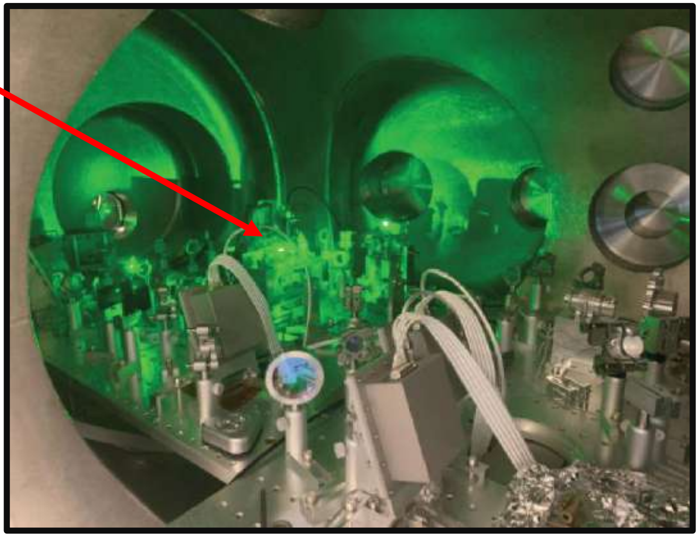
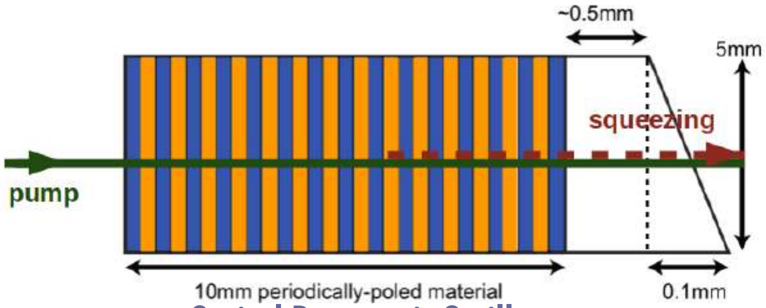


Squeezer system (PPKTP crystal in bow-tie cavity)



The Optical Parametric Oscillator and its cavity

- 532nm pump through PPKTP crystal → Squeezed beam at 1064nm



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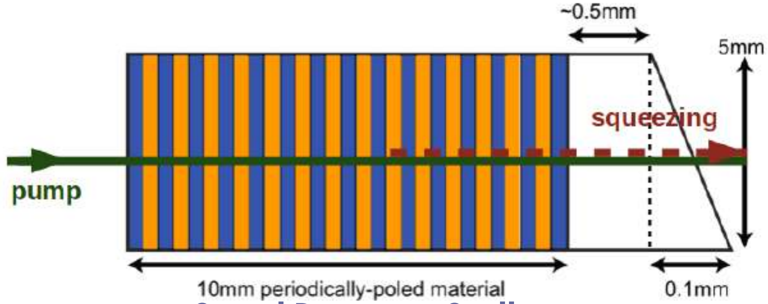
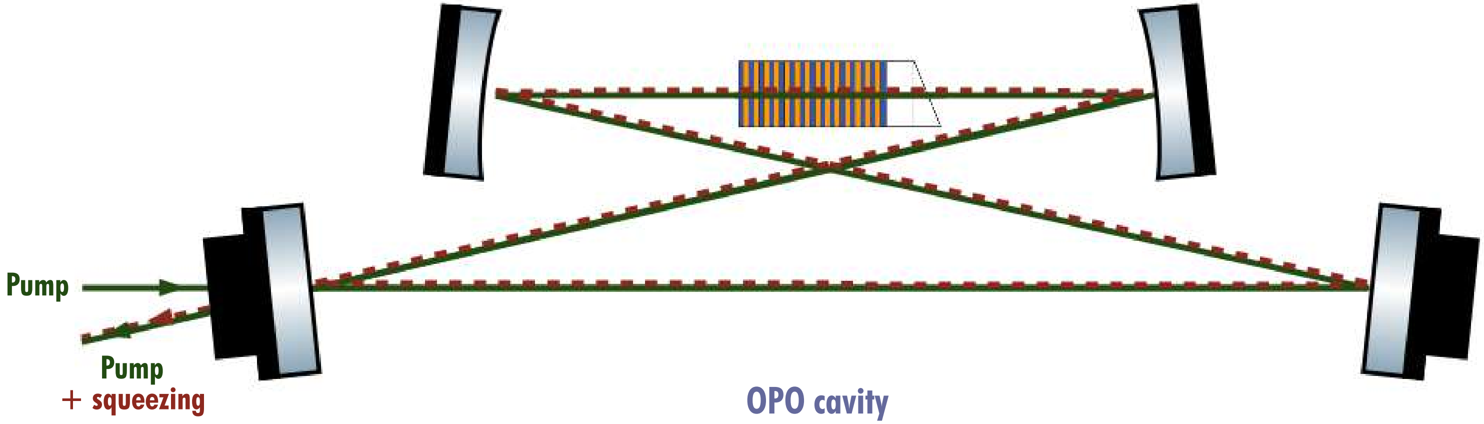


Optical Parametric Oscillator

- Cavity used to improve OPO efficiency (different design from Virgo)
- Crystal wedge → tuning of *cavity coresonance* through lateral positioning
- Crystal is temperature-controlled for quasi-phase-matching



OPO cavity

Control of Squeezing ellipse angle

- Aim: phase-lock local oscillator and squeezing beams
  - Squeezing beam too dim (a few femto Watt!) $\rightarrow$ need auxiliary beam "MCL" (and "PL")

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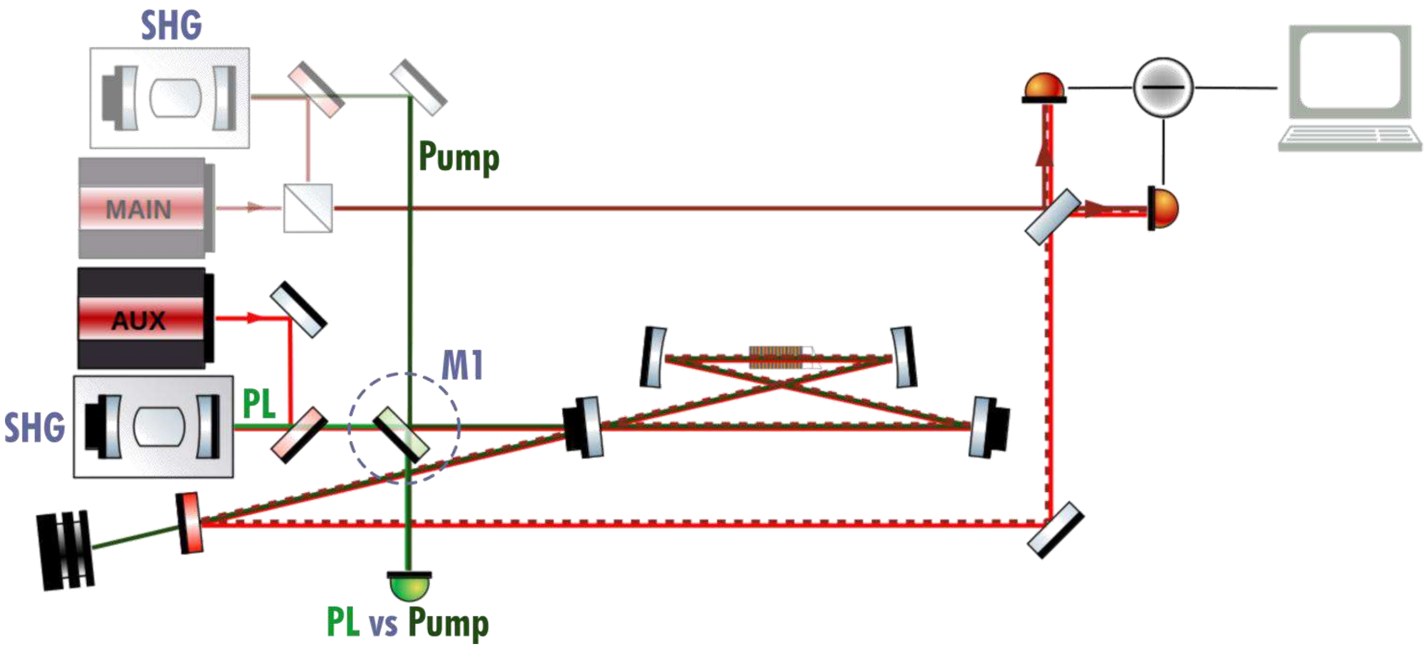

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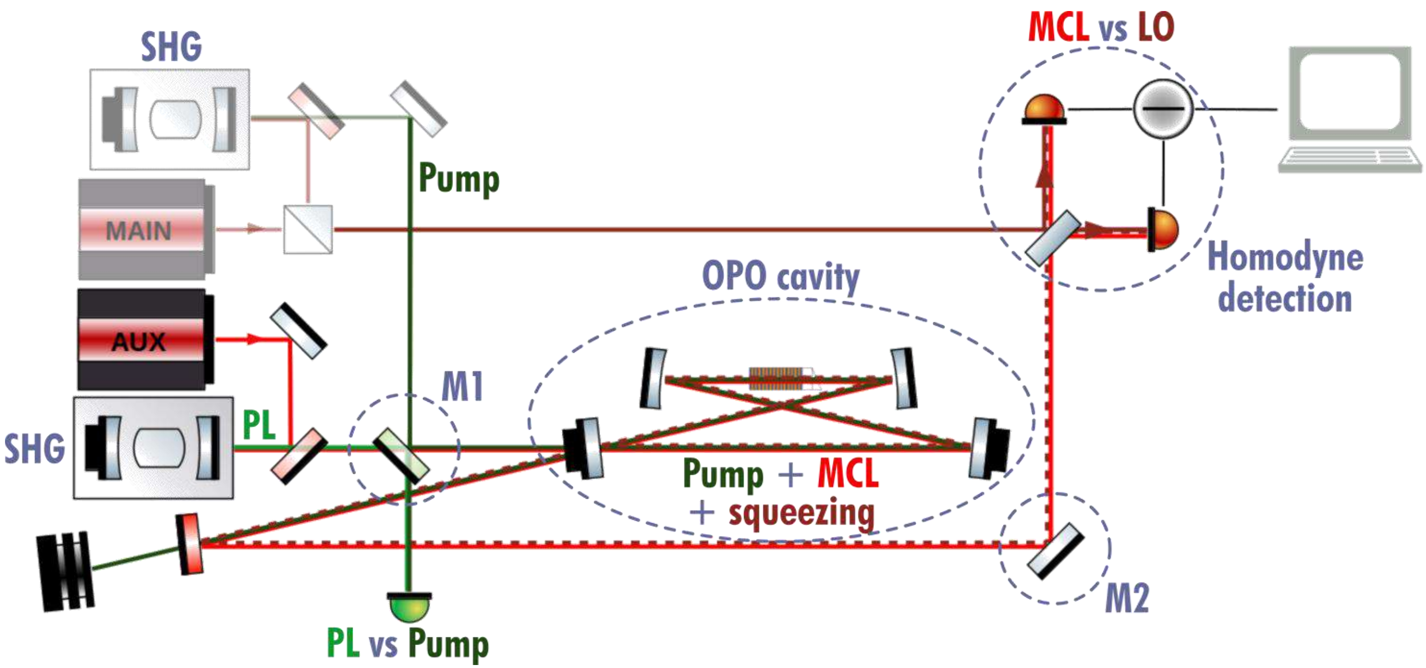

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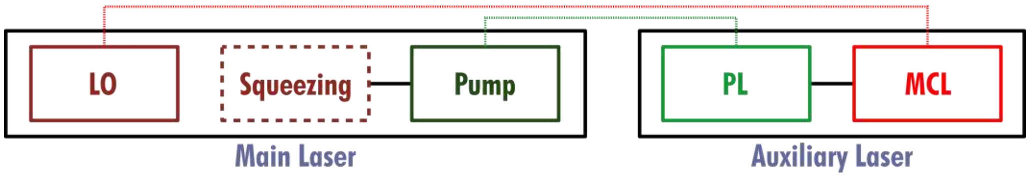

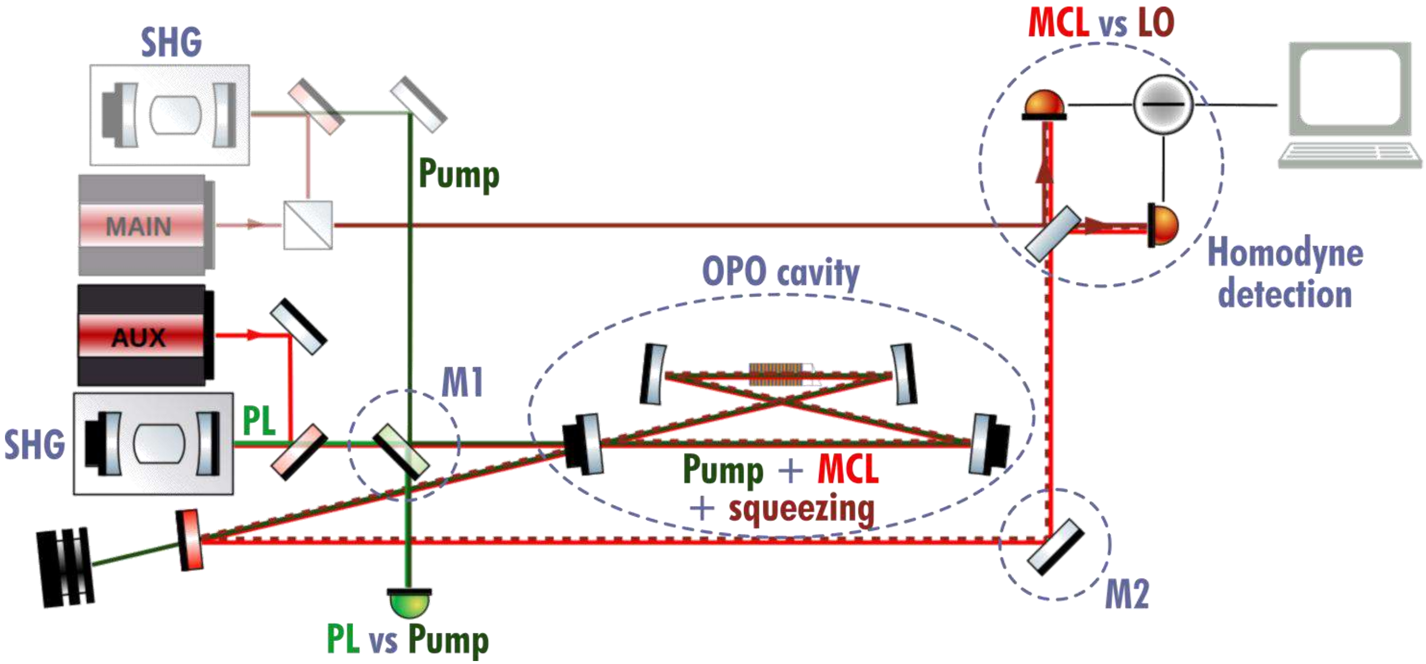

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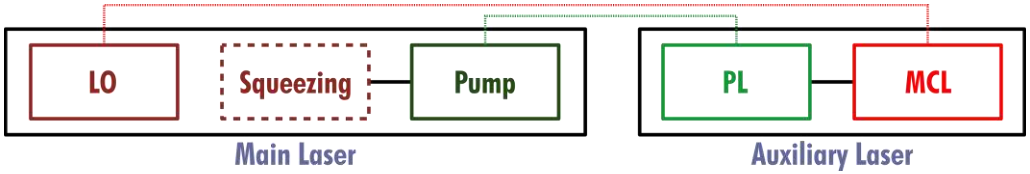
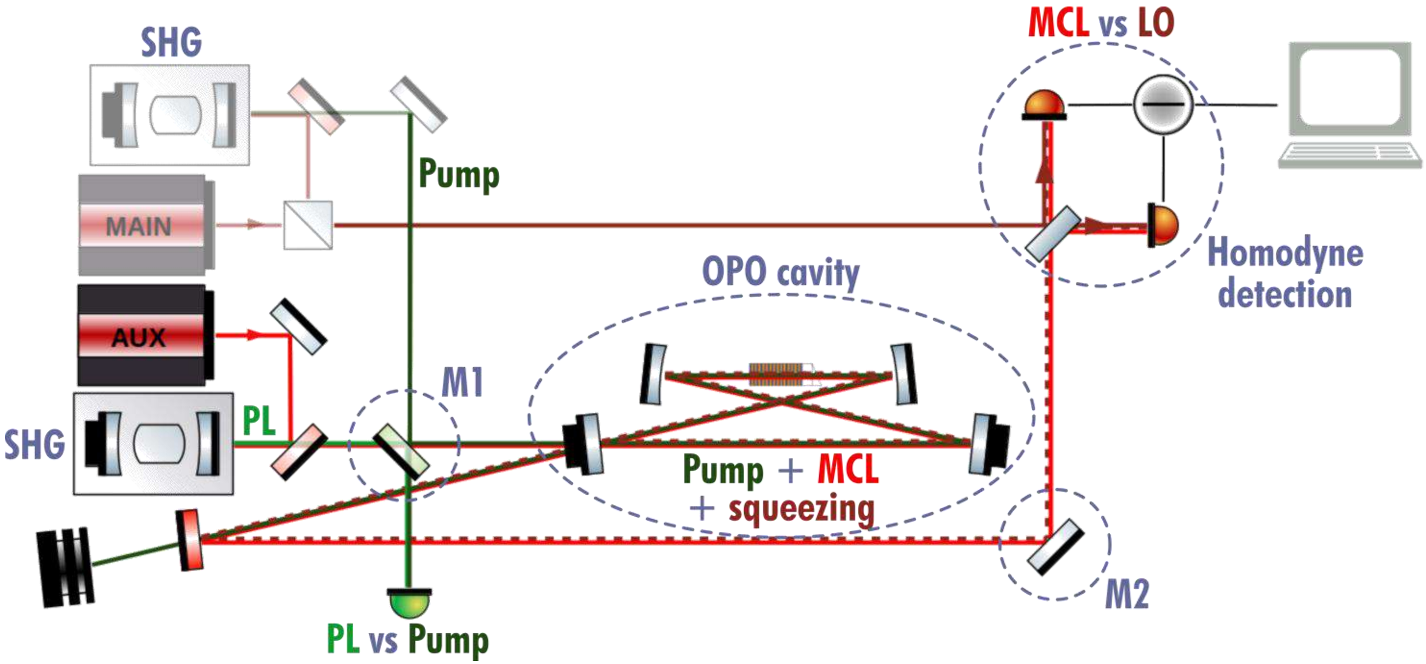


- Currently working on RedPitaya-based improvement of MCL vs LO lock



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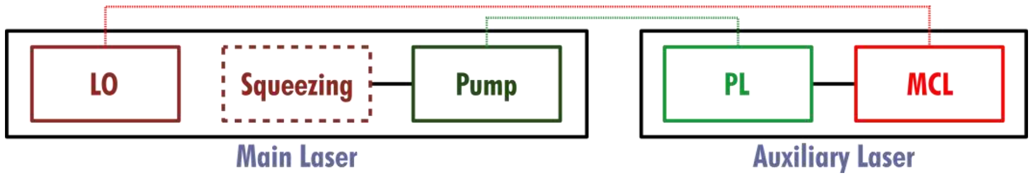

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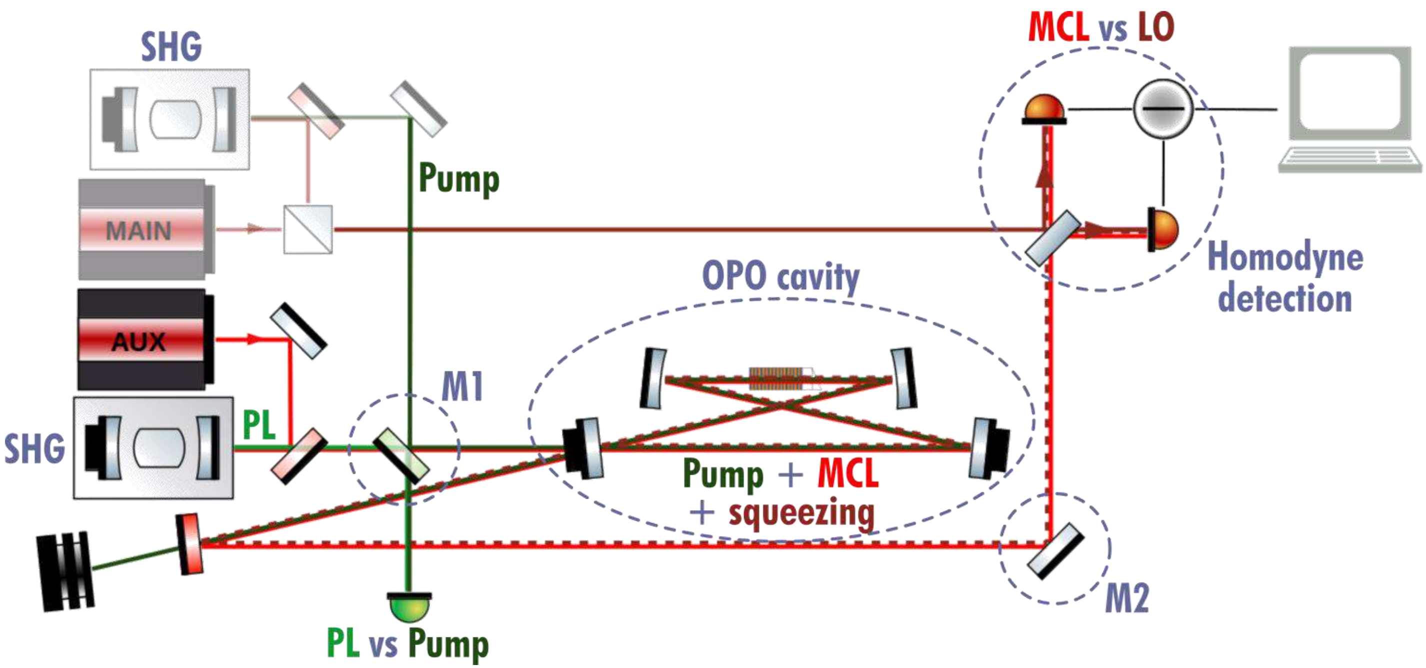


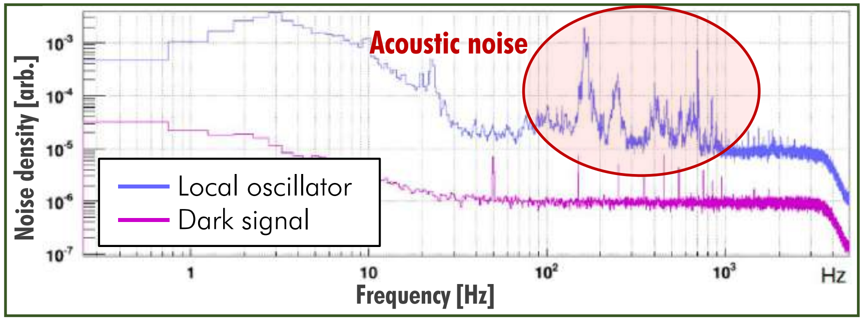
→ We want to generate 15 dB squeezing, measure 10 dB

Reducing factors leading to squeezing degradation

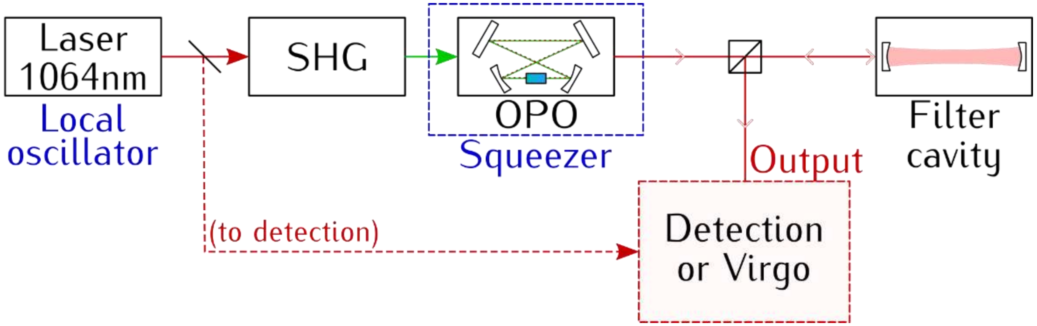
This work started at IJCLab during ANR project « Exsqueez »

Reducing acoustic noise

- Contribution on homodyne detection?
- Contribution on squeezing generation?



A. Lartaux-Vollard's thesis (2020)



➢ Place squeezer and/or homodyne detection under vacuum (work in progress)

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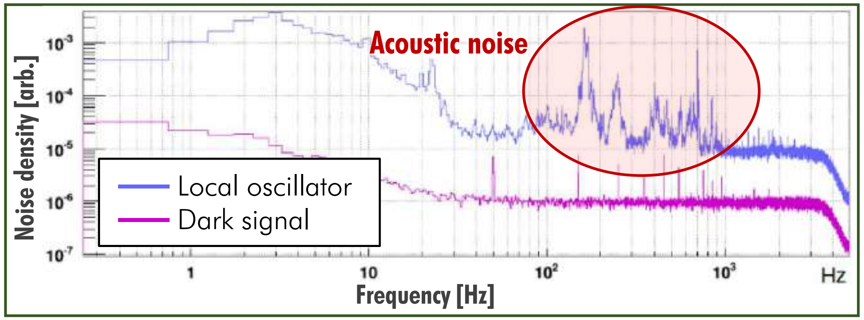

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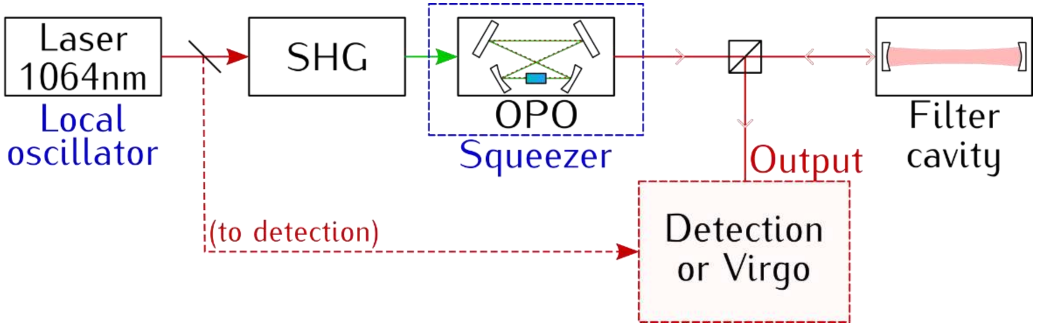


➢ Place squeezer and/or homodyne detection under vacuum (work in progress)

Other factors degrading the squeezing

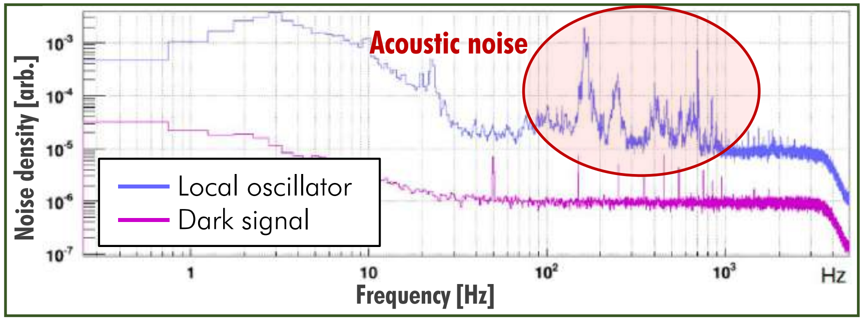
- Imperfect optical mode-matching
- Optical loss
- Squeezer instability

Reducing factors leading to squeezing degradation

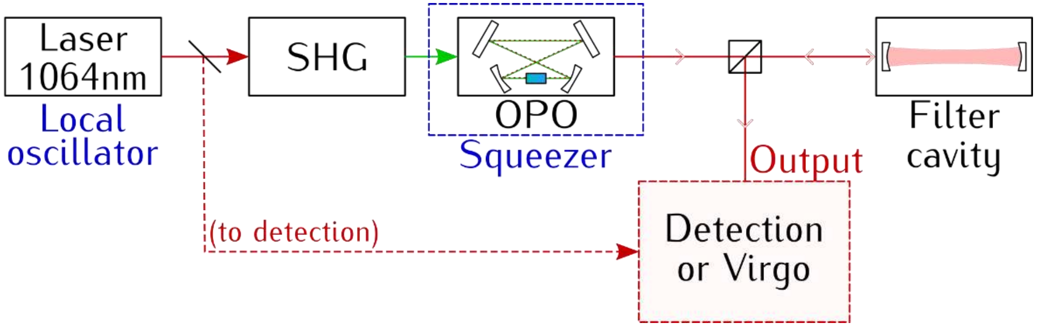
This work started at IJCLab during ANR project « Exsqueez »

Reducing acoustic noise

- Contribution on homodyne detection?
- Contribution on squeezing generation?



A. Lartaux-Vollard's thesis (2020)



➢ Place squeezer and/or homodyne detection under vacuum (work in progress)

Other factors degrading the squeezing

- Imperfect optical mode-matching
- Optical loss
- Squeezer instability

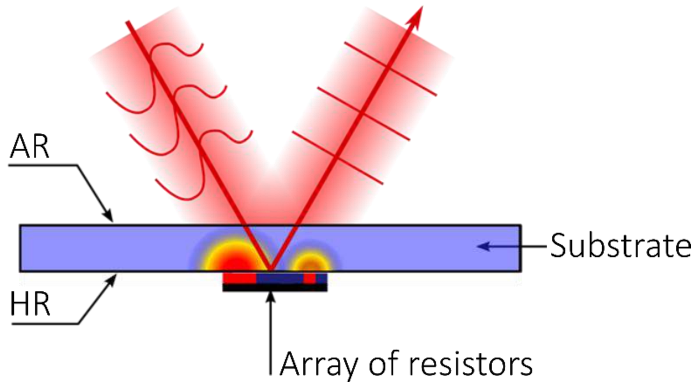
Implementation on Advanced Virgo

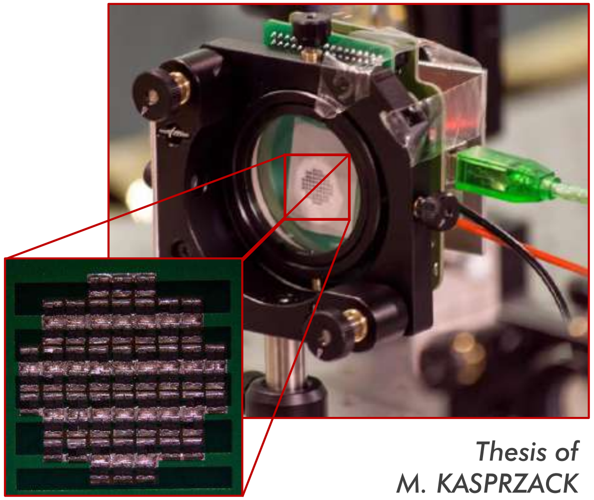
- In-air, frequency-dependent squeezing: O4 (2023–2025)
- Under vacuum for post-O5 (≥2028?) depending on Exsqueez findings

Reducing factors leading to squeezing degradation (2)

Mastering optical wavefronts

- Maximise coupling between beams (improve squeezing quality)
- Thermally-Deformable Mirrors (TDM)
  - Array of resistors to induce local dephasing
  - Real-time control and correction of wavefronts
  - Compatible with vacuum operation



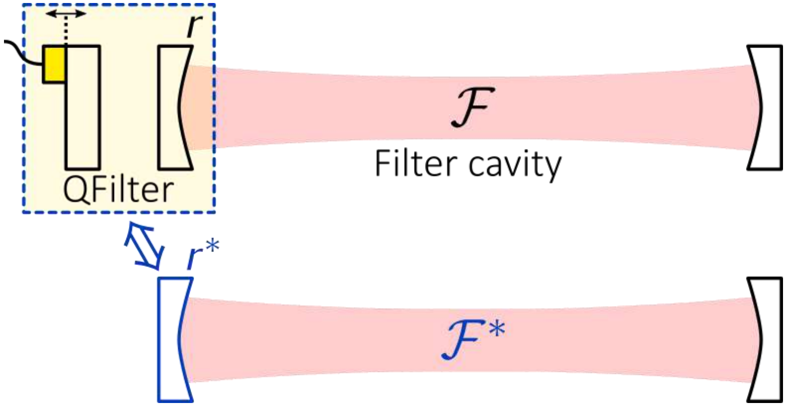


Thesis of M. KASPRZACK

Reducing quantum noise over the whole frequency range

ADAPTING THE SQUEEZING TRANSITION FREQUENCY

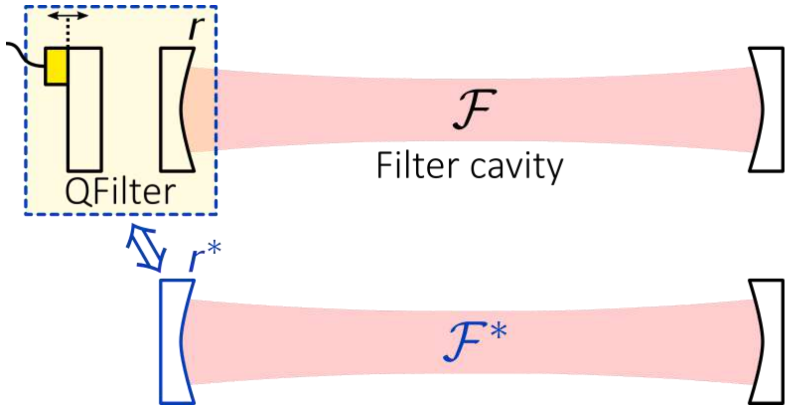
- Control finesse of filter cavity
  - Tunable mirror "QFilter"
  - Pre-cavity ⇔ mirror with tunable reflectivity

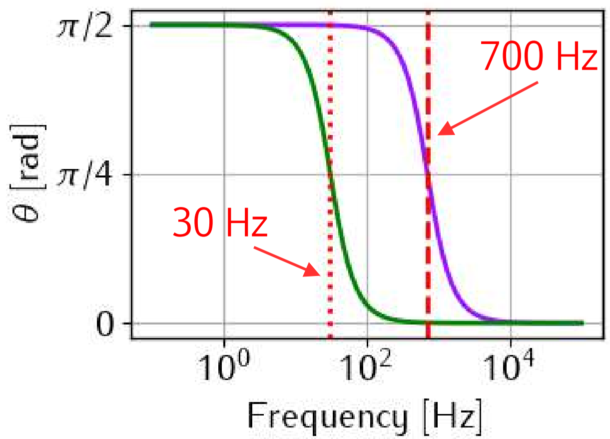


Reducing quantum noise over the whole frequency range

Adapting the squeezing transition frequency

- Control finesse of filter cavity
  - Tunable mirror "QFilter"
  - Pre-cavity ⇔ mirror with tunable reflectivity
- Allows for tunability of Ω_t
  - 700 Hz (Exsqueez, no QFilter) → 30 Hz (Exsqueez, with QFilter ⇔ Adv. Virgo)
  - Equivalent to $\mathcal{F}^* = \mathcal{F} \times 20$





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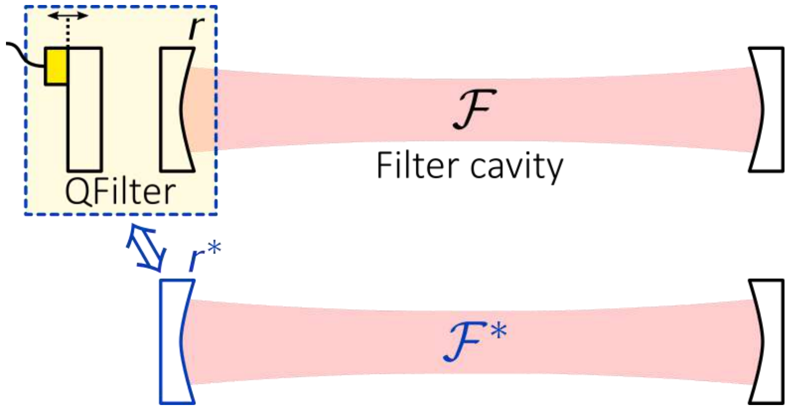
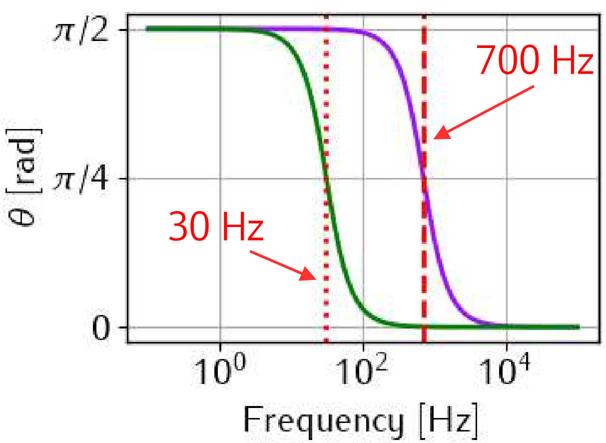
- Three-mirror cavity model under study

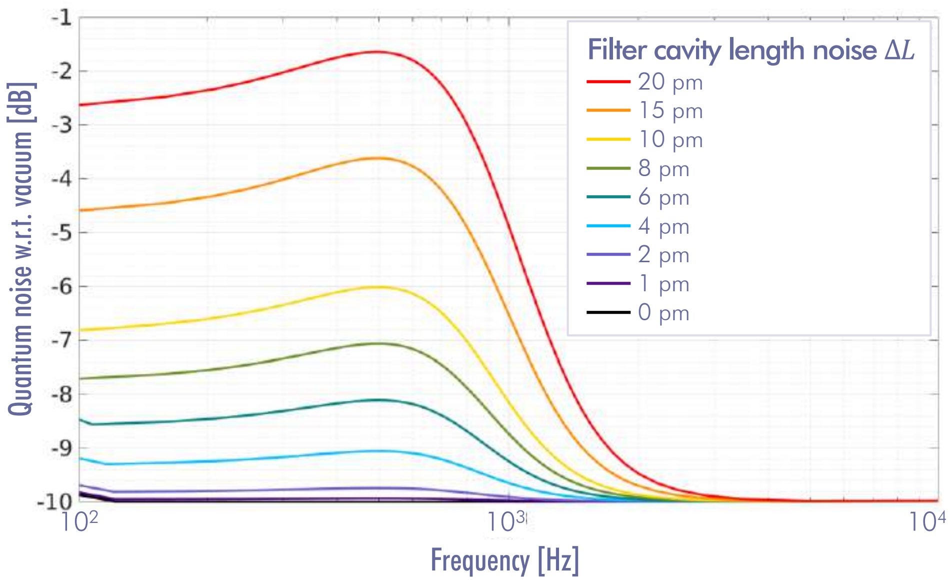




Benefits of the Refimeve+ network for CALVA

Controlling length of filter cavity

- High finesse ($\sim$ 3000)
- Length control via control laser
  - $\frac{\Delta L}{L} = \frac{\Delta f}{f}$
  - Example:
    - $\Delta f \simeq 20 \text{ Hz} \Leftrightarrow \Delta L = 4 \text{ pm}$ ($L = 50\text{m}, \lambda_{laser} = 1064\text{nm}$)
    - Corresponds to ~1 dB of squeezing degradation (for 10 dB of squeezing produced)



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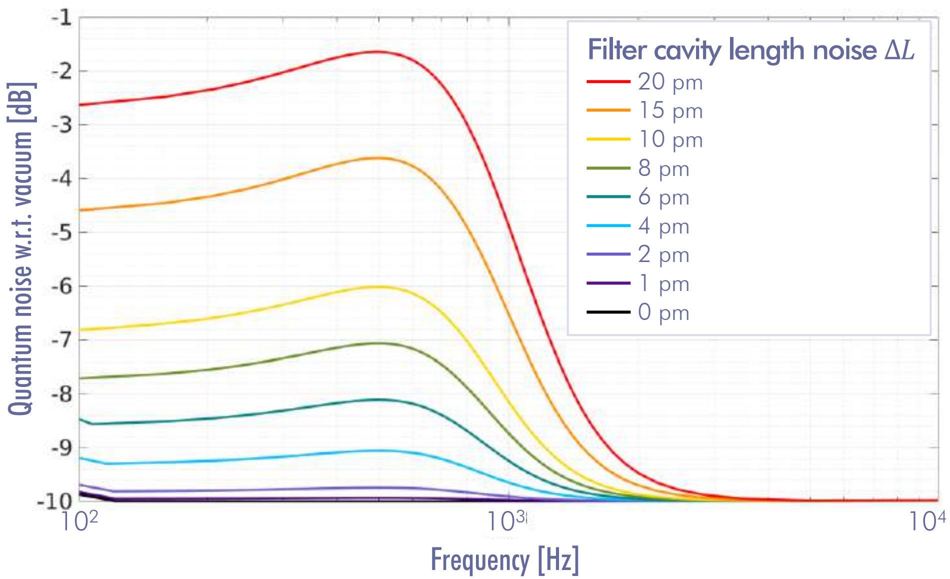
Characterising stabilisation of squeezing pump laser

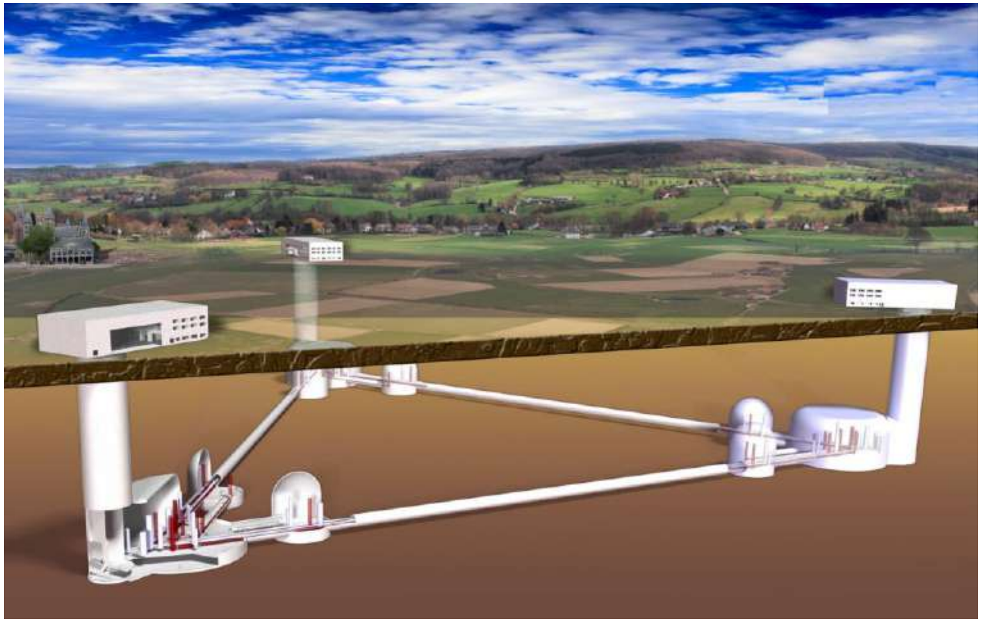
- First study of impact of laser stabilisation on squeezing quality
- Several test possibilities: with/without stabilisation, vacuum/in-air (detection and/or squeezer)...



Involvement in the Einstein Telescope project

Upcoming European GW detector (2035 – 2040 for now…)

- Arms length 10km (vs. 3km for Virgo)
- Underground (better control of seismic vibrations)
- Likely triangular shape (i.e. 3 intertwined interferometers → better sensitivity)
  - Each one is composed of a low- and a high-frequency interferometer (ET-LF / ET-HF)
  - ET-LF requires cryogenic operation
  - 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

- New wavelength: ET-LF at $1.55\ \mu m$?
  - Cryogenic materials considered may be incompatible with 1064nm
  - CALVA can adapt its wavelength thanks to QFilter!
- Testbed for upcoming (frequency-dependent) squeezing techniques
  - 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