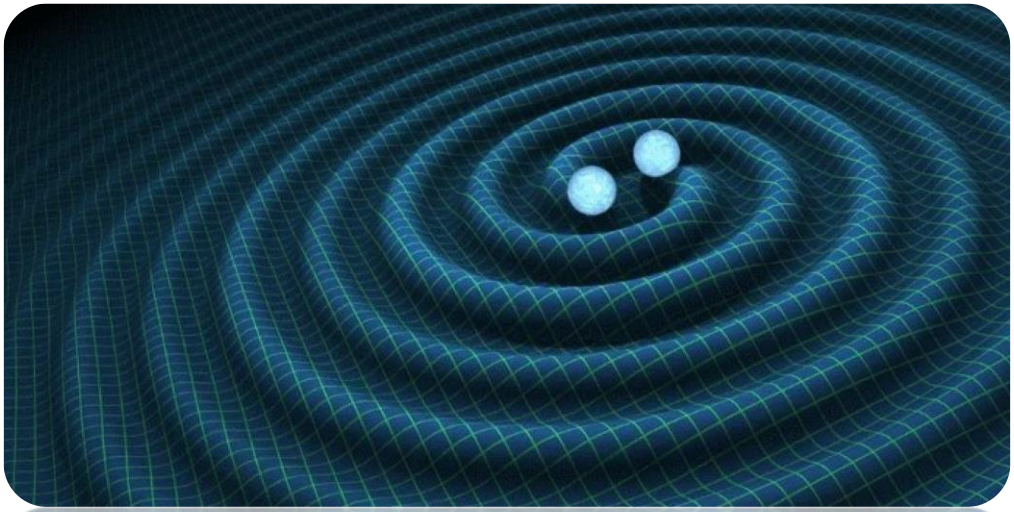
Research at IJCLab: ”Gravitational Waves„ group

“ USING VACUUM SQUEEZED STATES TO BEAT THE STANDARD QUANTUM LIMIT IN GRAVITATIONAL-WAVE DETECTORS ”

AIMS OF THE CALVA EXPERIMENT

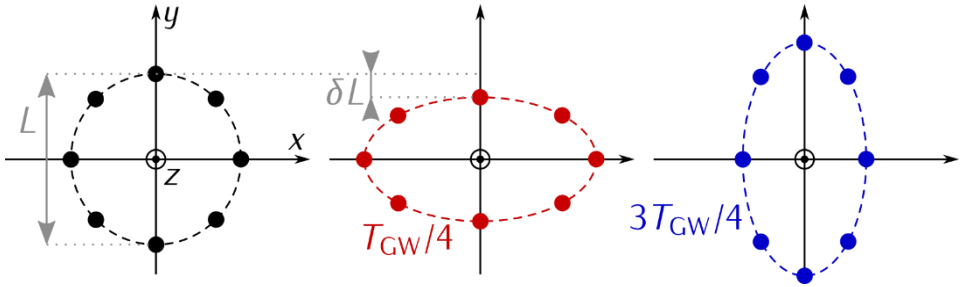
- Develop quantum-optics tools for gravitational-wave detectors
- Enable exploration of new astrophysical sources: more massive and/or more distant



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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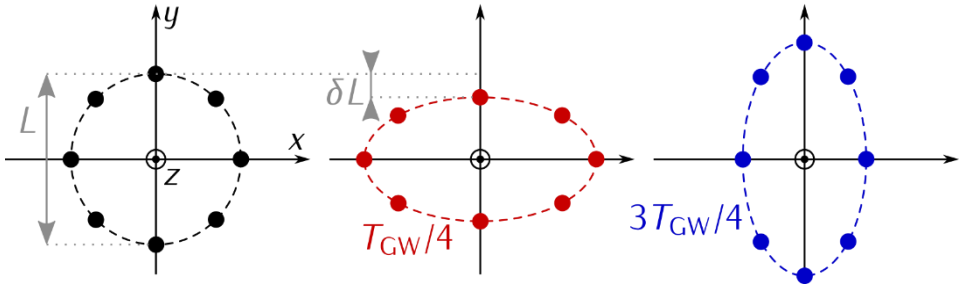

Amplitude of a gravitational wave

- 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 $r = 400$ Mpc

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

Gravitational-wave (GW) detection

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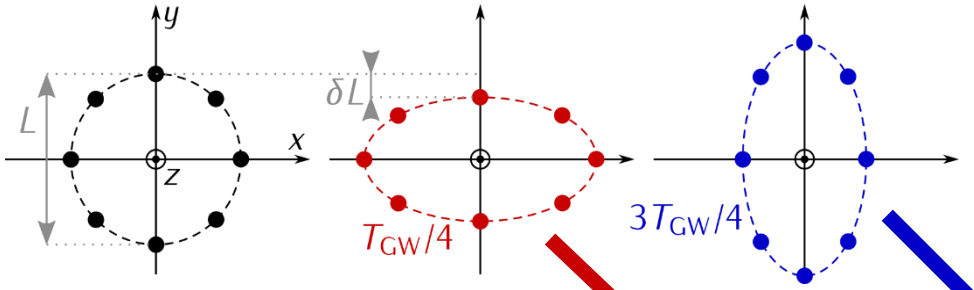
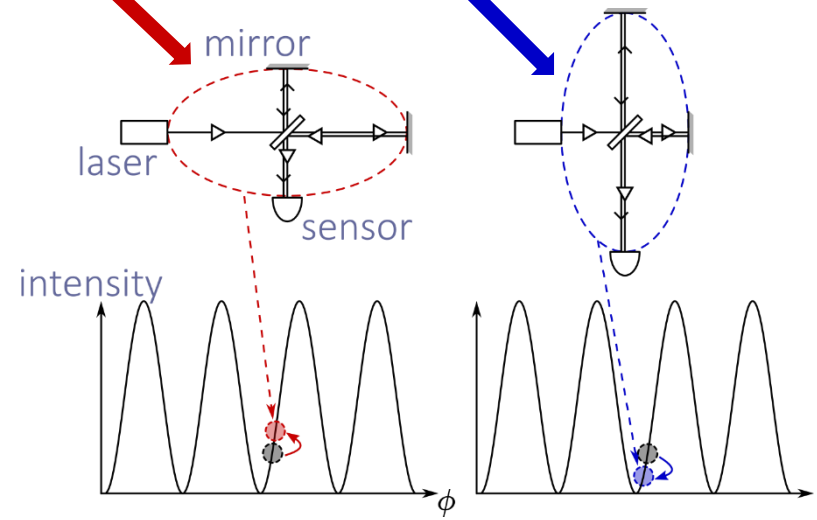


GW detection: Michelson interferometer

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



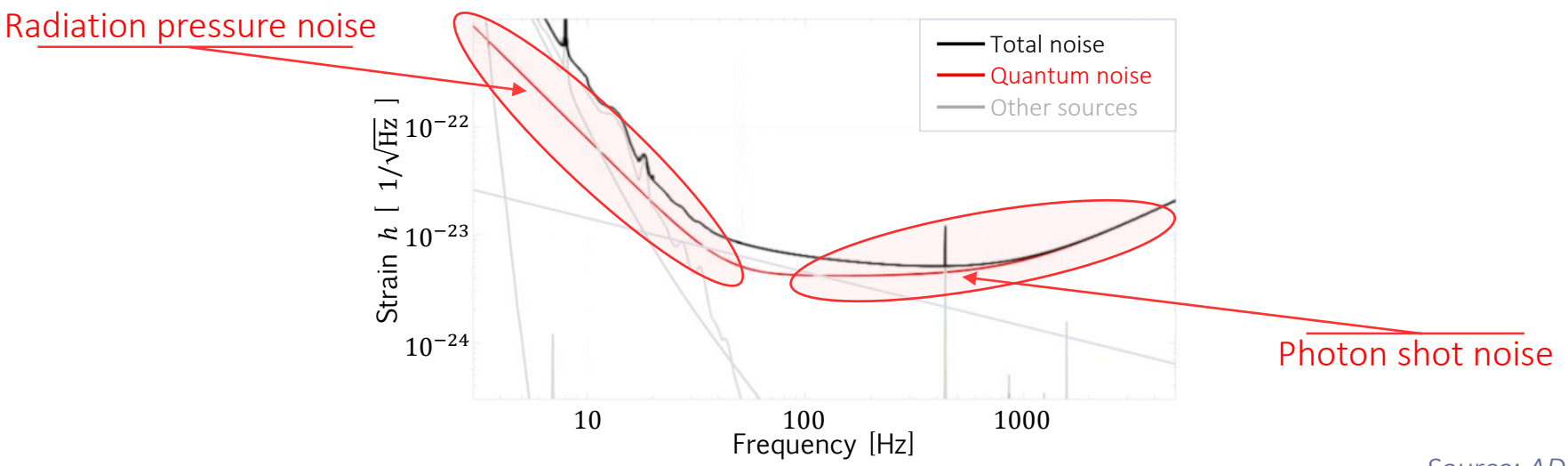
Main noise sources affecting GW detection

Classical noise sources

- Main sources:
  - Mechanical noise
  - Thermal (Brownian) noise
- Will be reduced in upcoming generations of GW detectors

Quantum noise sources

- Radiation pressure noise
  - Dominates at low frequency
  - Amplitude-noise-related
- Photon shot noise
  - Dominates at high frequency
  - Phase-noise-related

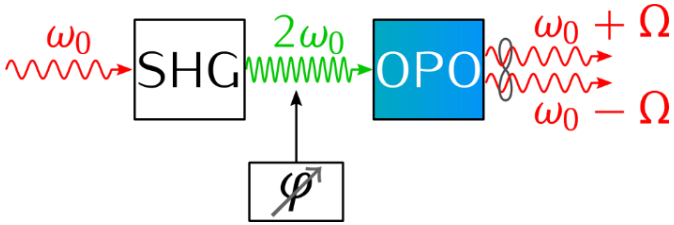


Source: ADV+ TDR

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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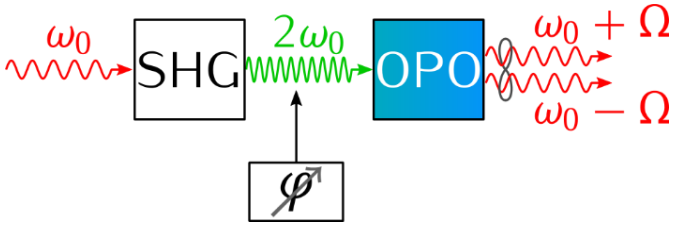
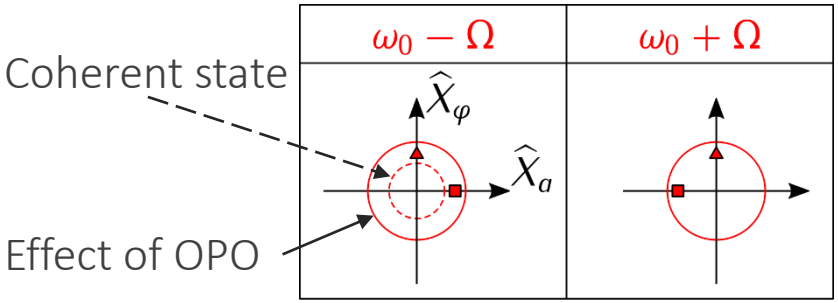
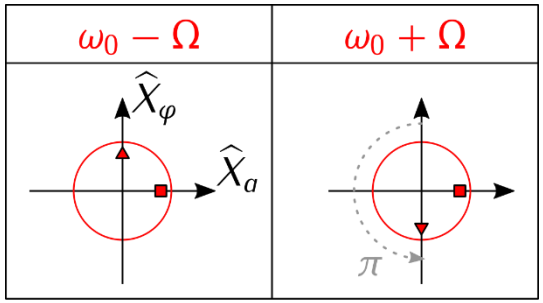




Phase squeezing



Amplitude squeezing

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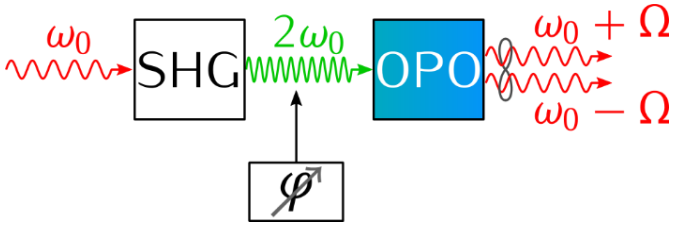

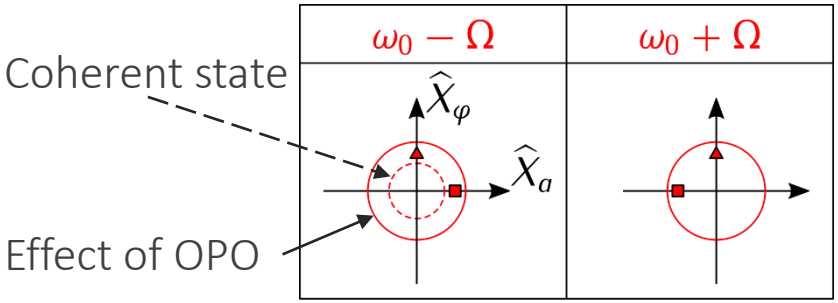

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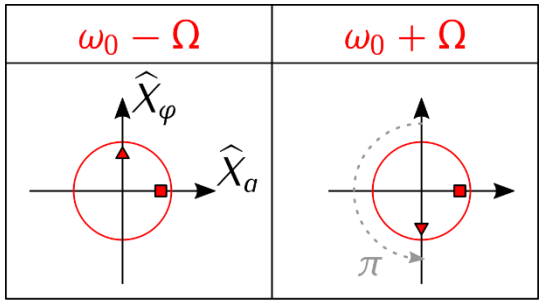

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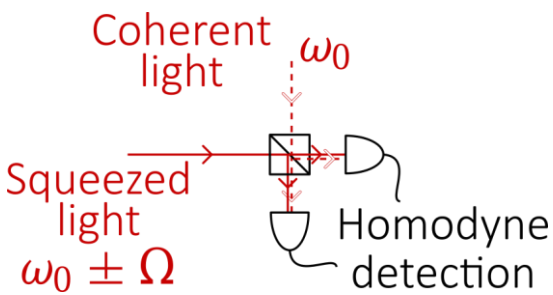

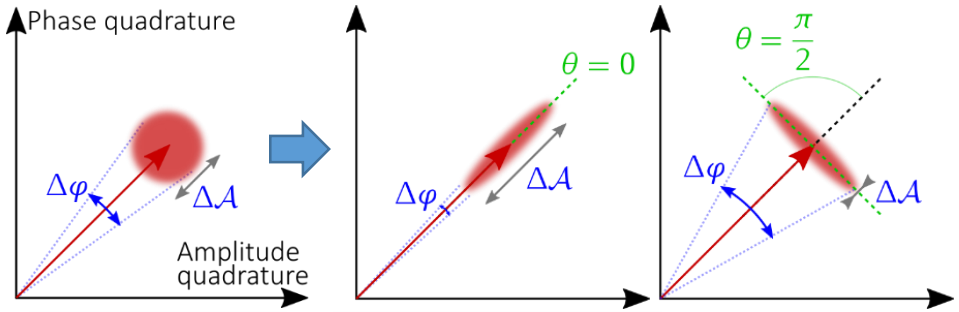

Coherent state | Squeezing (phase) | (amplitude)

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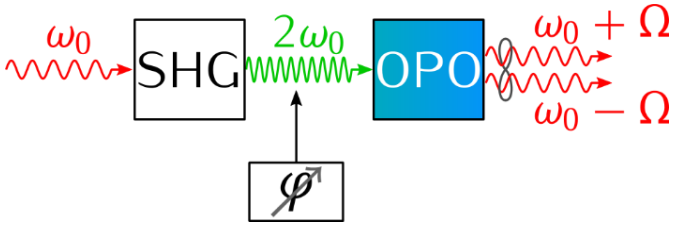

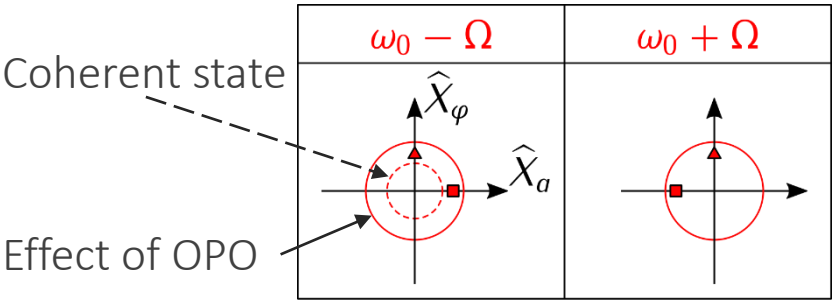

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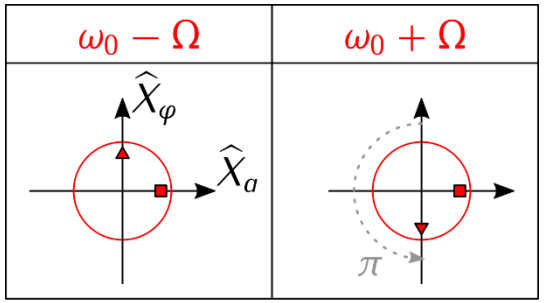
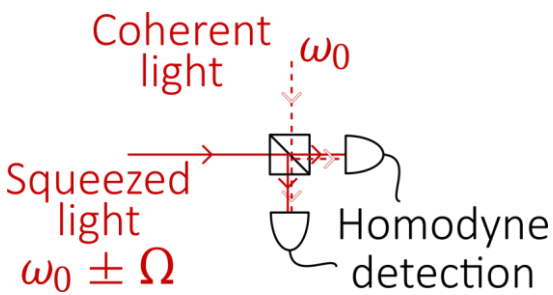
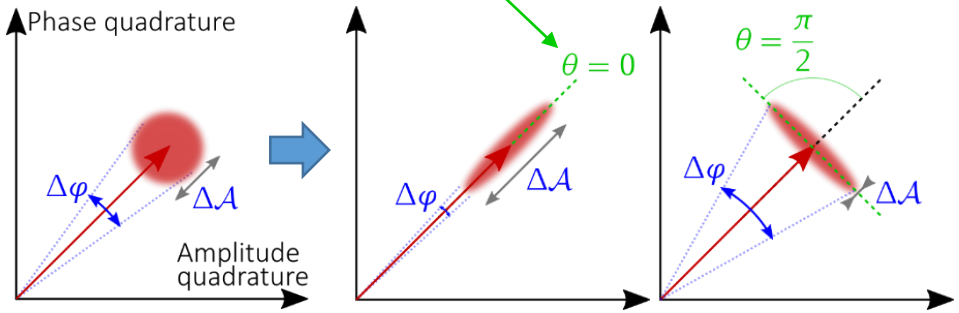


Amplitude squeezing

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





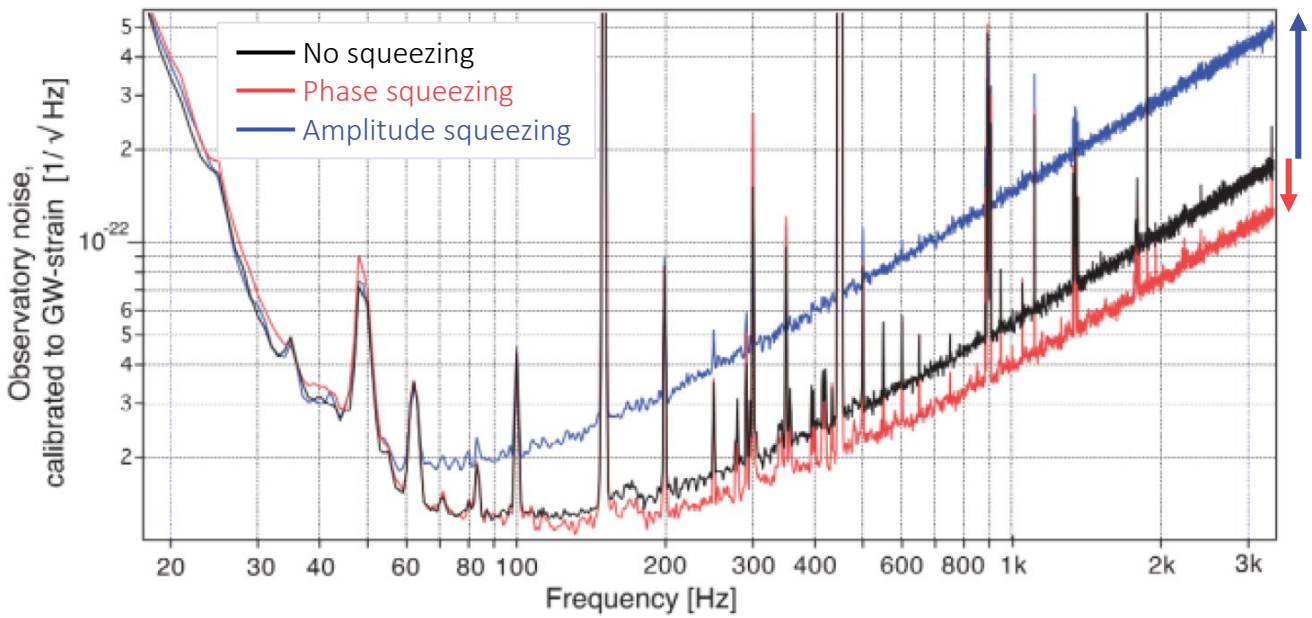
Coherent state | Squeezing (phase) | (amplitude)

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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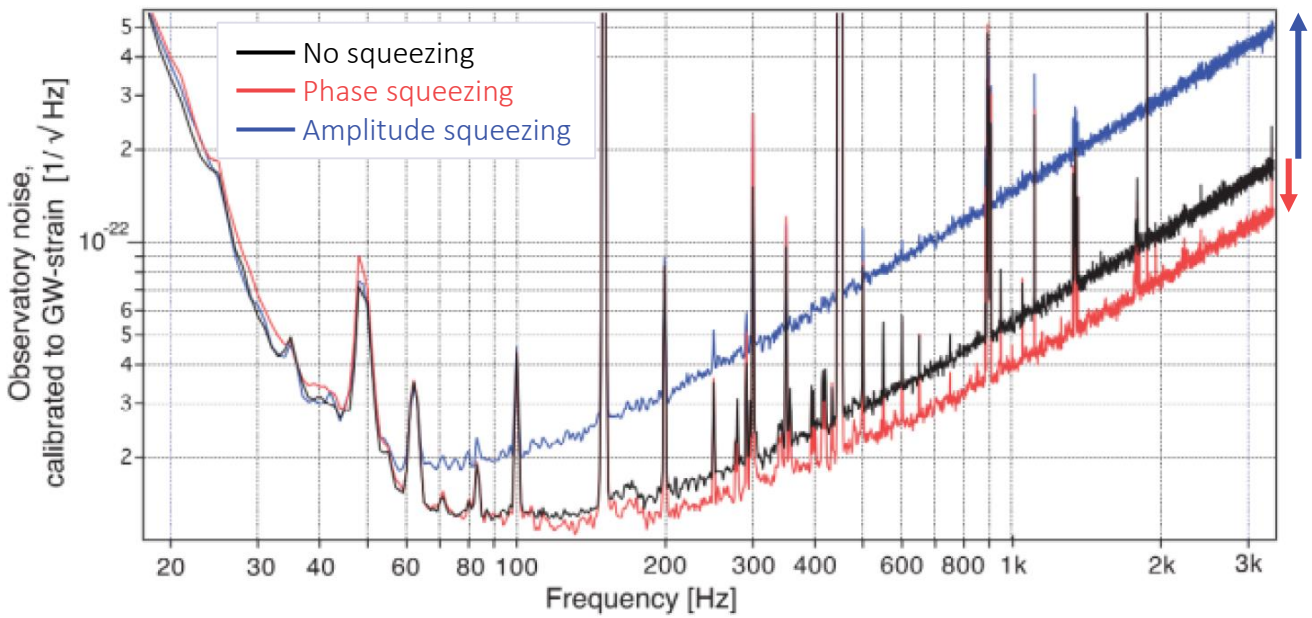
→ Reduce quantum noise in the whole frequency range?



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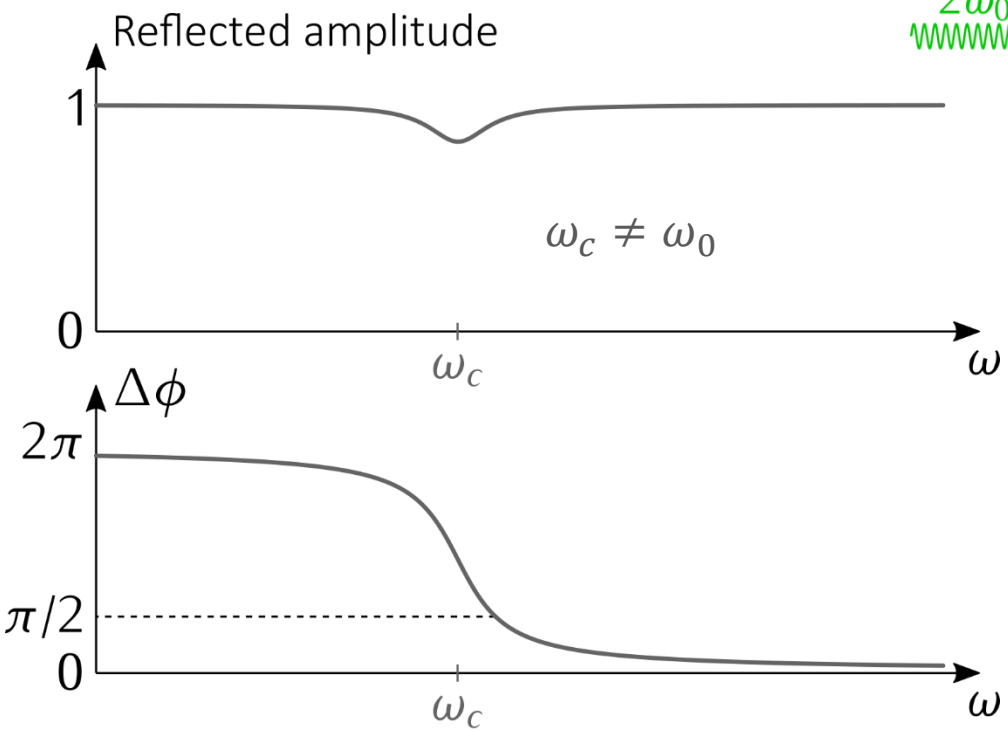

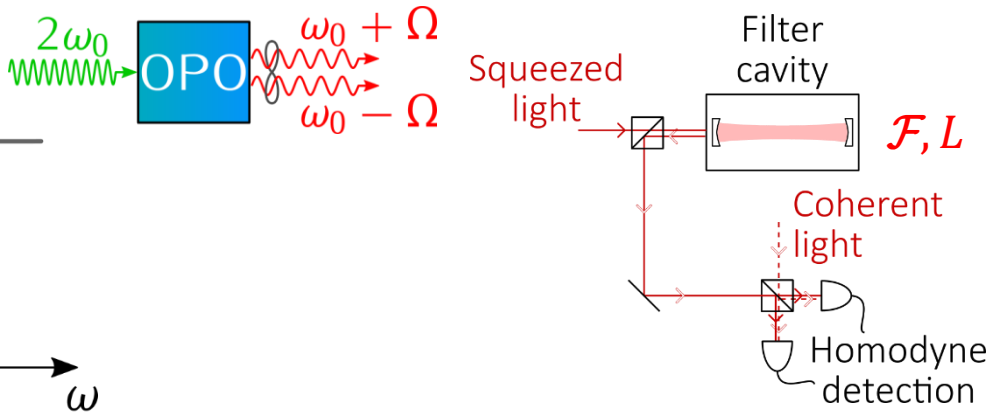

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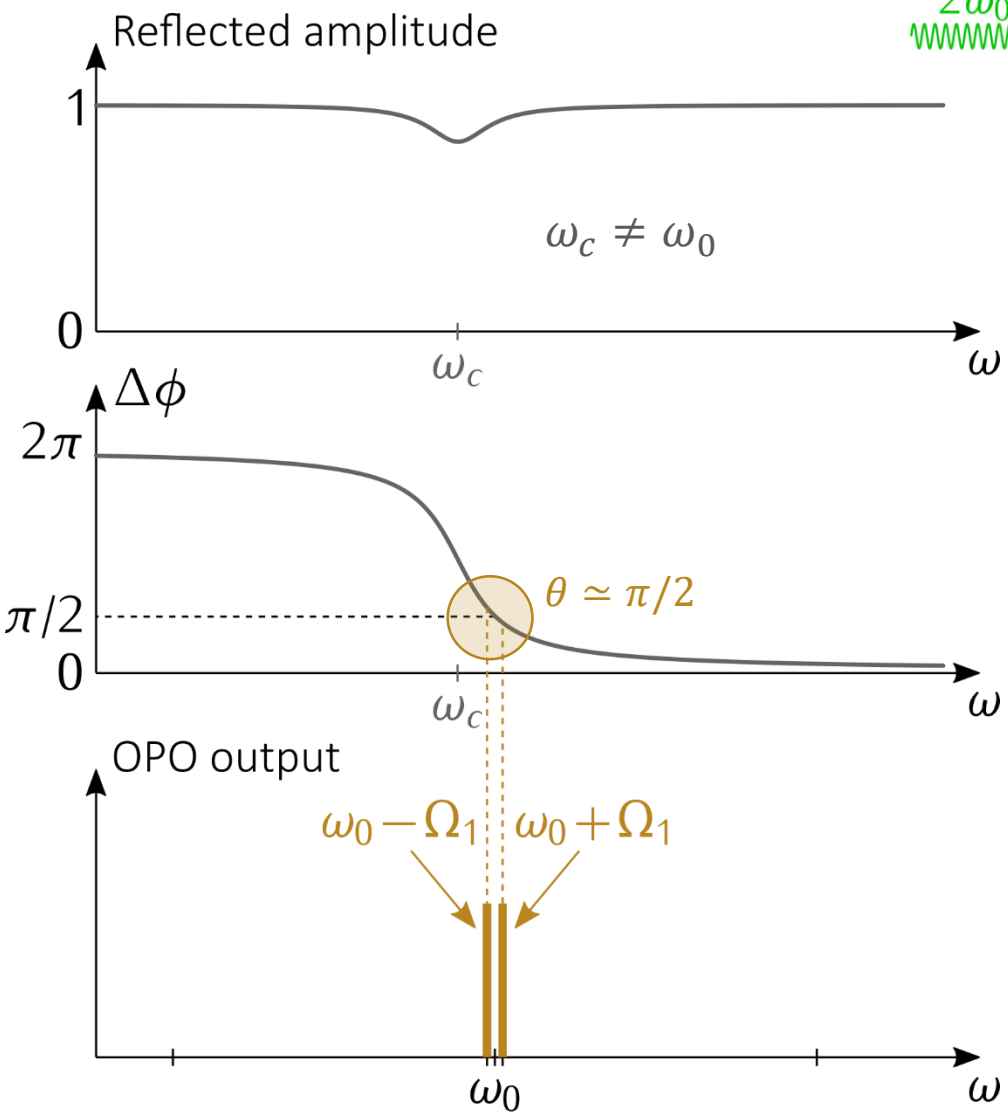

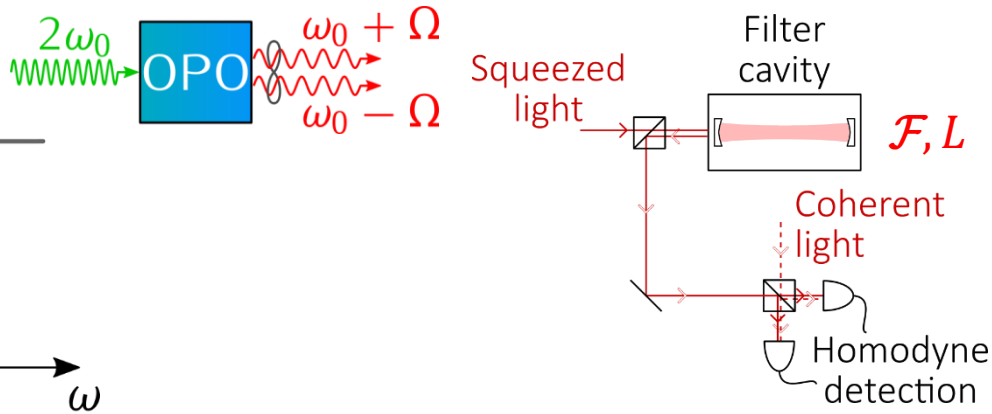

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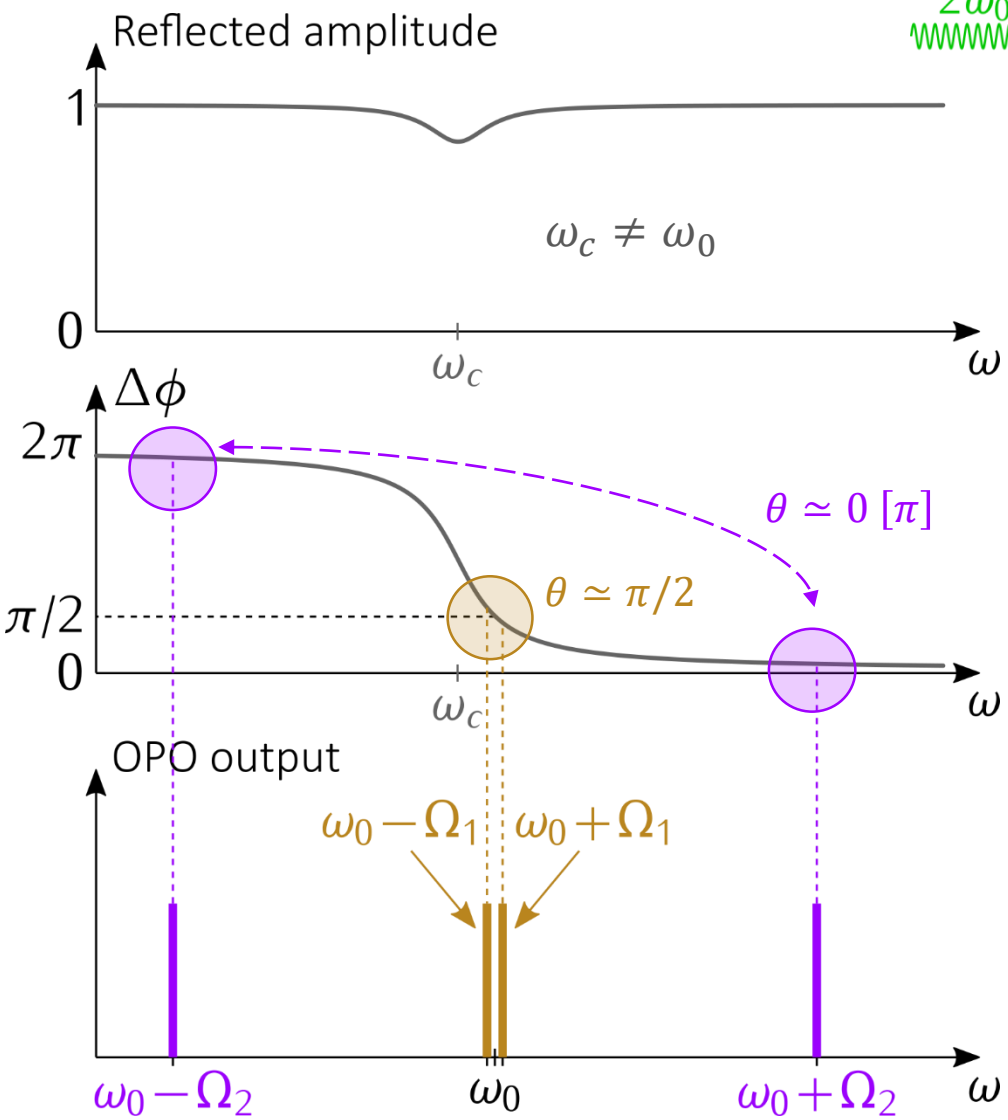

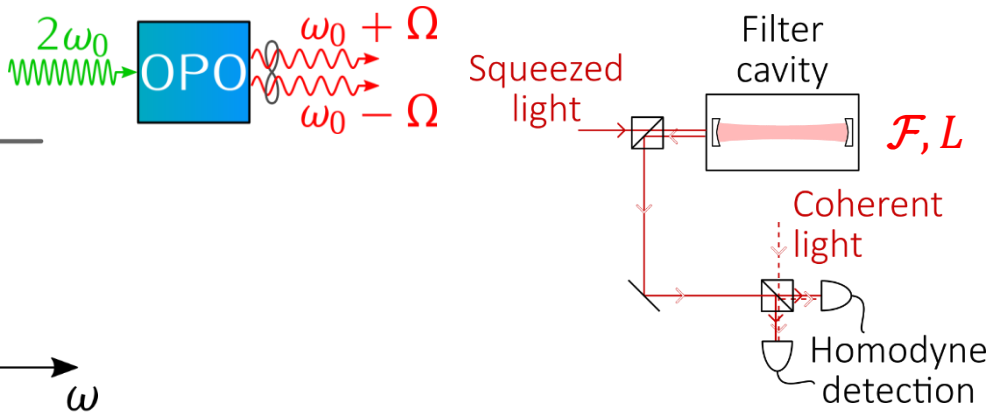

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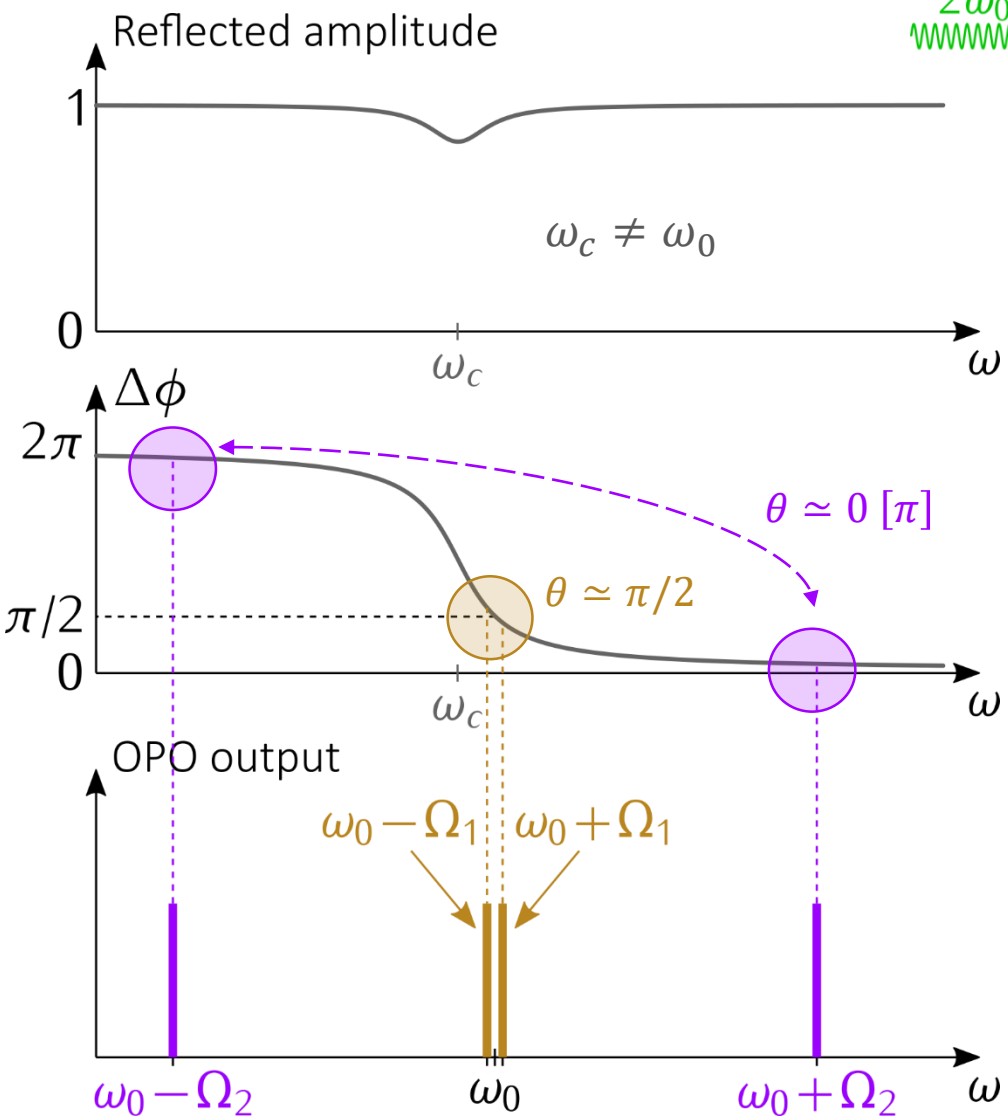

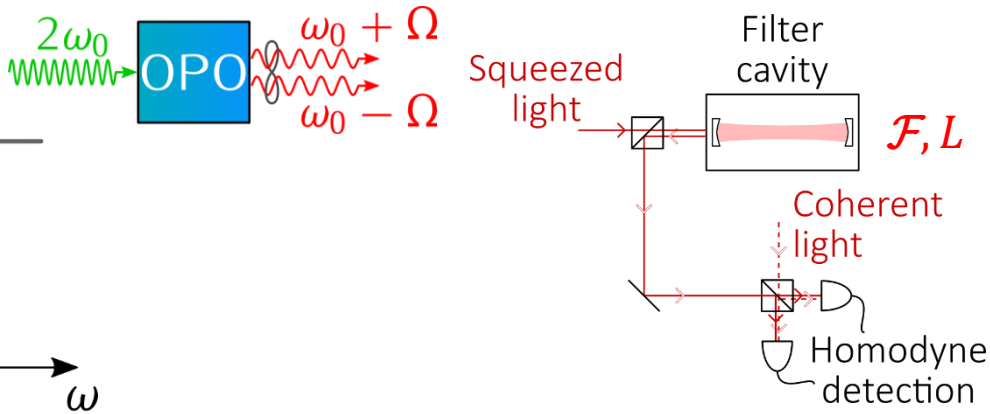

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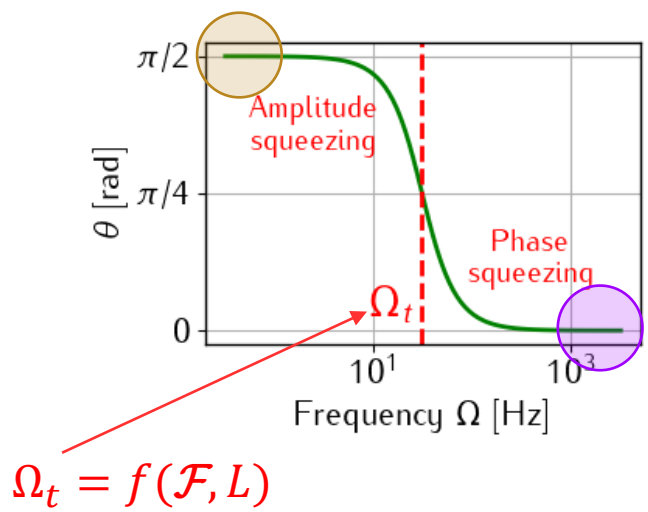
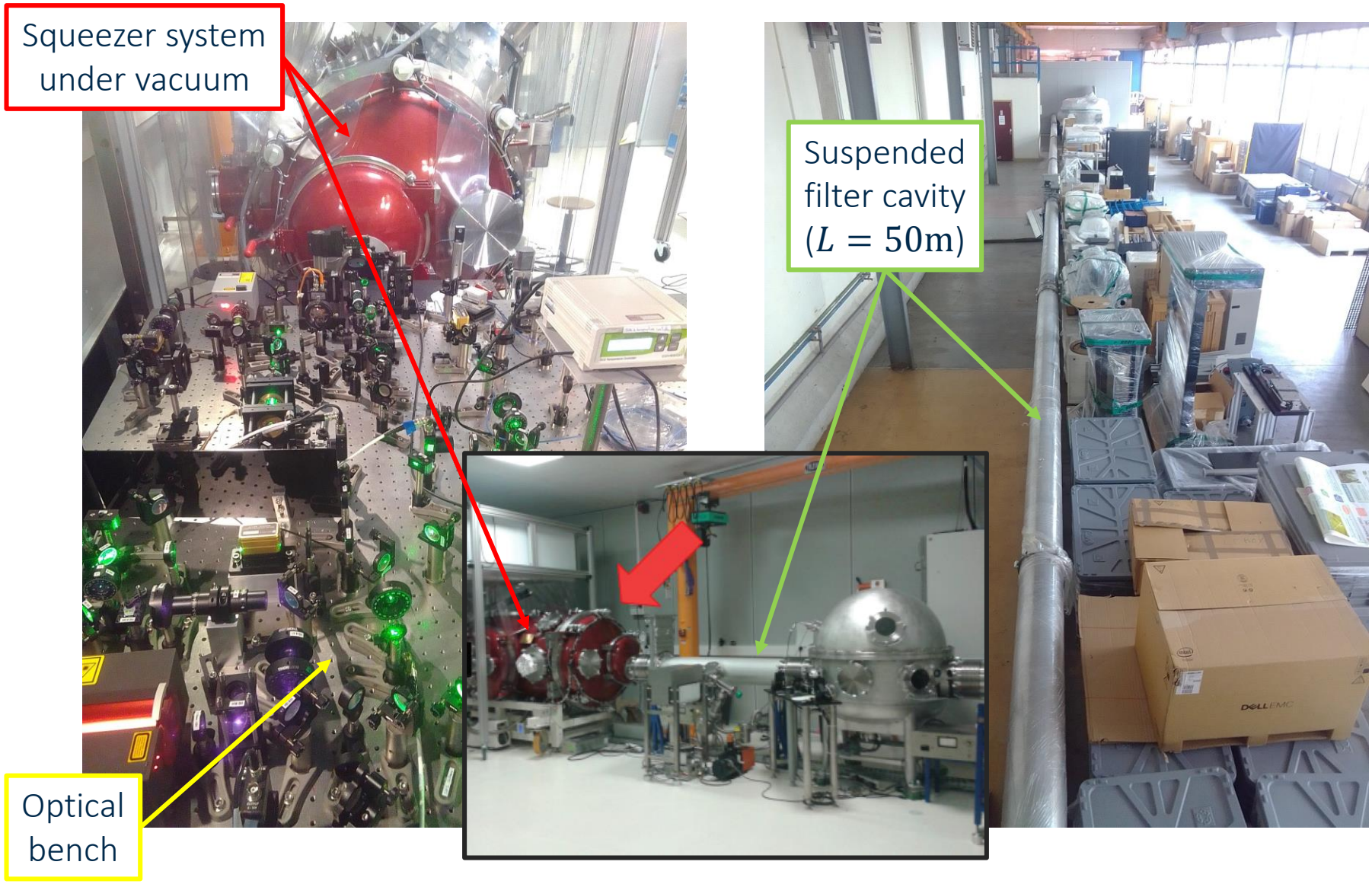


The Exsqueez project and CALVA experiment



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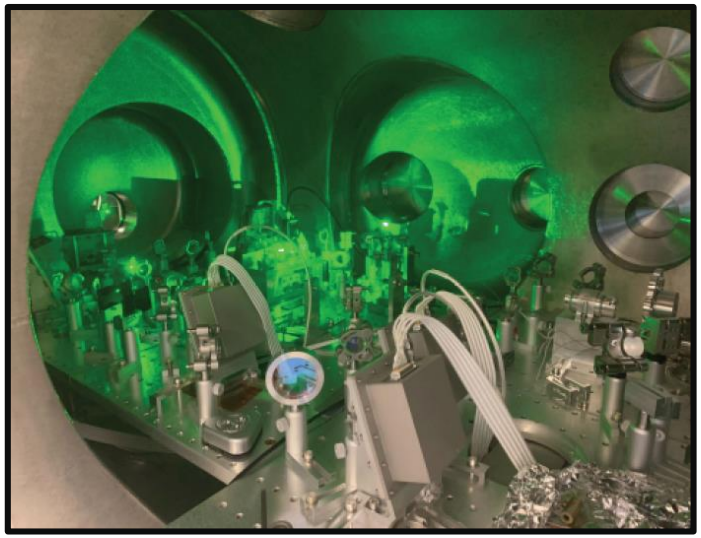
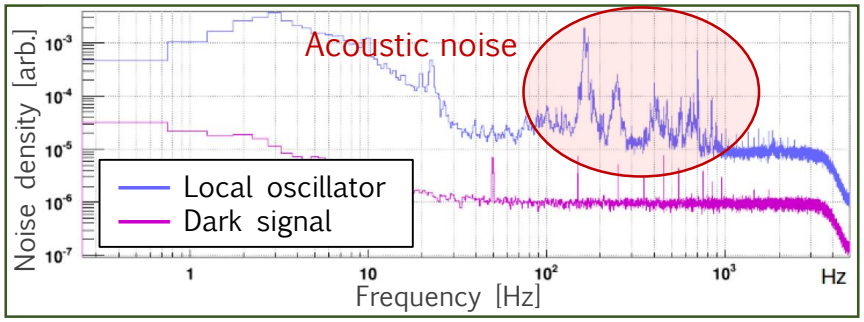


Reducing factors leading to squeezing degradation (1)

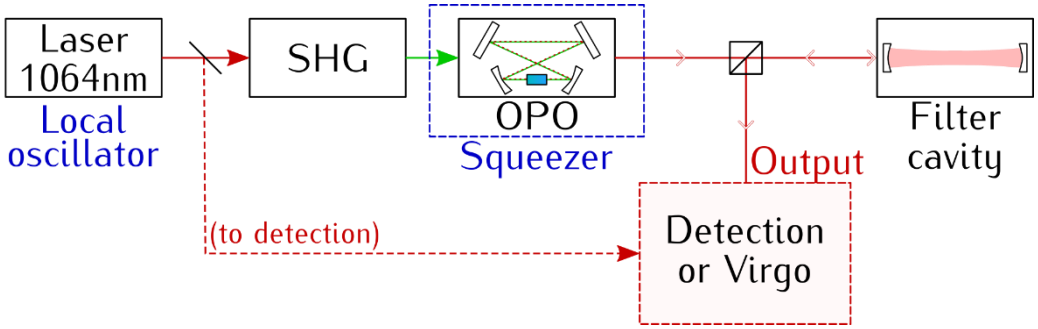
This work is carried out at IJCLab on ANR project « Exsqueez »

Reducing acoustic noise

- Contribution of acoustic noise on detection



A. Lartaux-Vollard's thesis (2020)



➢ Place squeezer under vacuum (work in progress)

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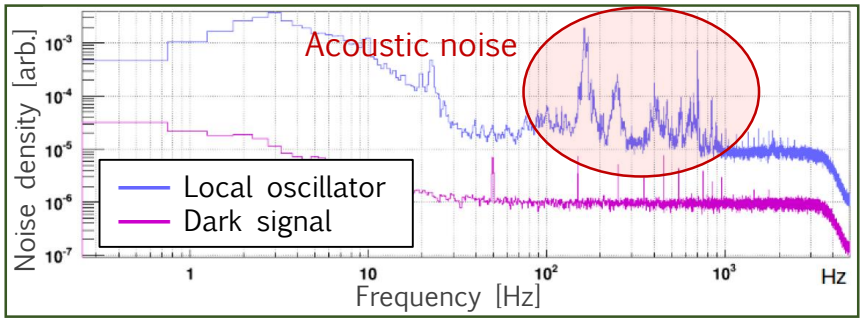

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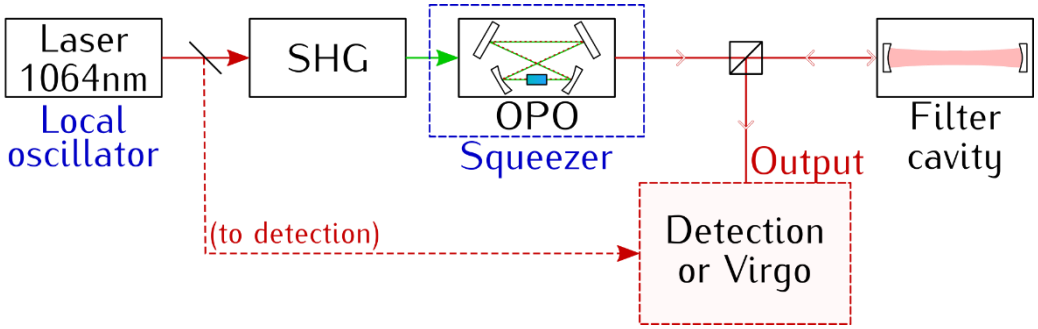

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Other factors degrading the squeezing

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

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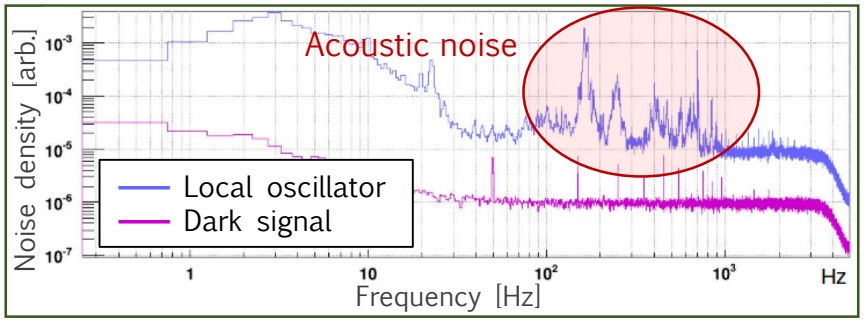

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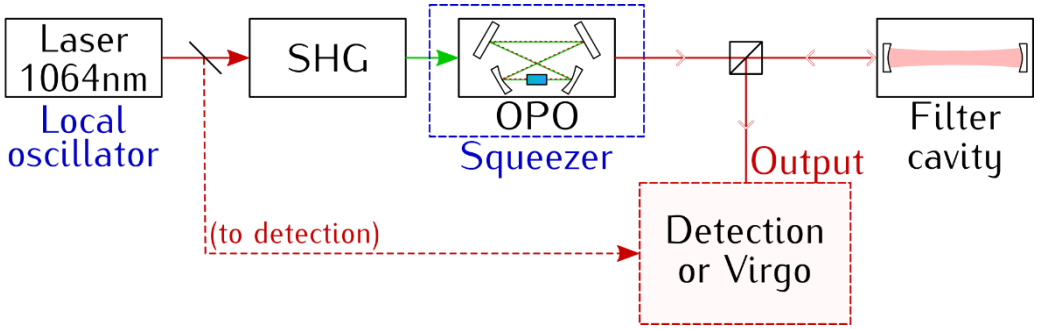

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Implementation on Advanced Virgo

- In-air, frequency-dependent squeezing: O4 (2022—2023)
- Under vacuum for O5 (2024?) depending on Exsqueez findings

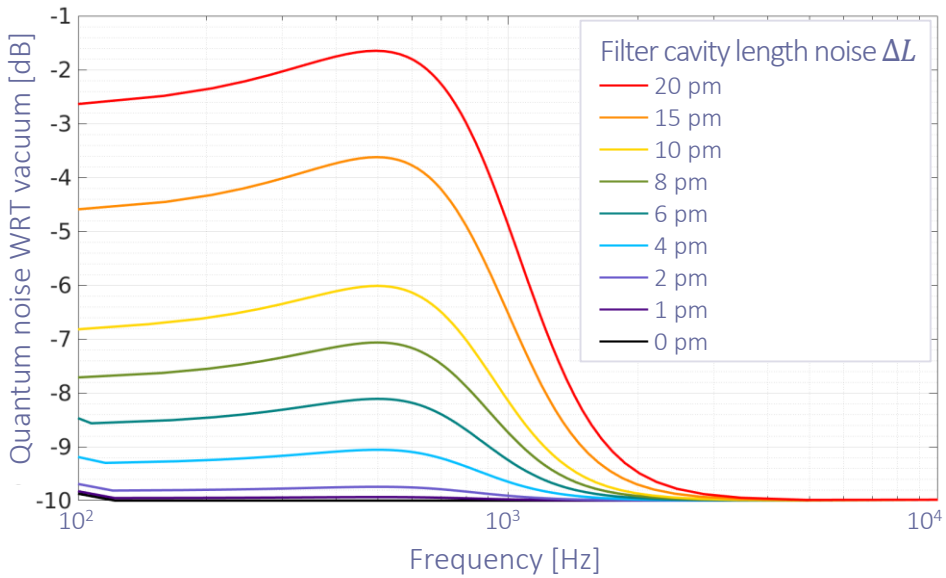
Reducing factors leading to squeezing degradation (2)

Controlling length of filter cavity

- State-of-the-art performance sought after
- Length control via control laser
  - $\frac{\Delta L}{L} = \frac{\Delta f}{f}$
  - Example:
    - $\Delta f \simeq 20\ \mathrm{Hz} \Leftrightarrow \Delta L = 4\ \mathrm{pm}$ $(L = 50\mathrm{m}, \lambda_{laser} = 1064\mathrm{nm})$
    - Corresponds to ~1 dB of squeezing degradation (for 10 dB of squeezing produced)

Characterising stabilisation of squeezing pump laser

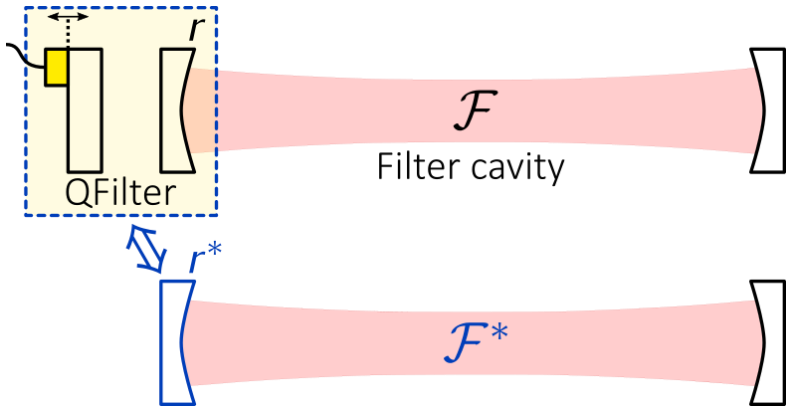
- 1st study of impact on squeezing quality



Reducing quantum noise over the whole frequency range

Adapting the squeezing transition frequency

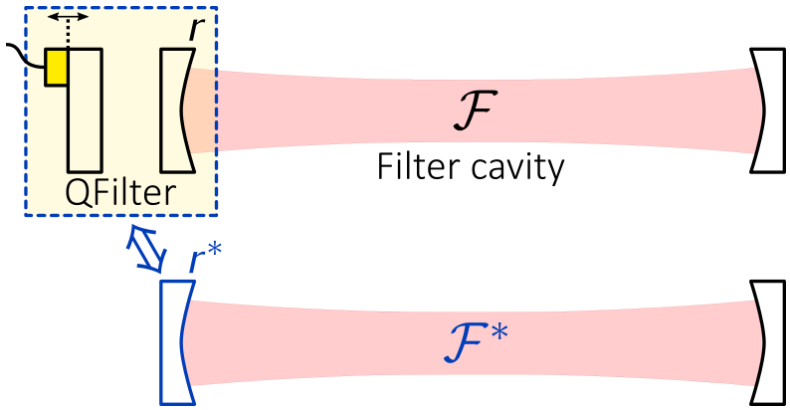
- Control finesse of filter cavity
  - Tunable mirror ”QFilter„
  - Pre-cavity ⇔ mirror with tunable reflectivity

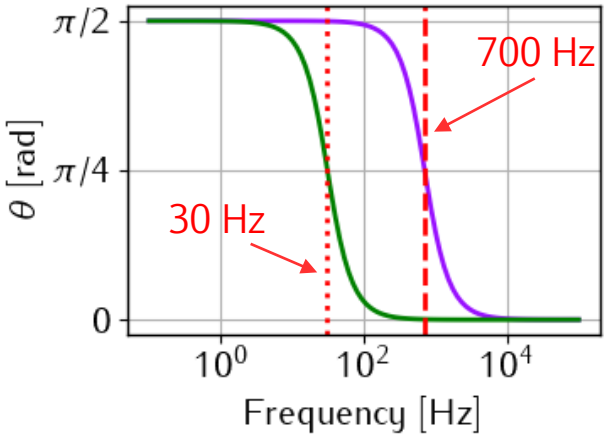


Reducing quantum noise over the whole frequency range

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 (Adv Virgo)
  - Equivalent to $\mathcal{F}^* = \mathcal{F} \times 20$





Long-term perspectives of the CALVA experiment

Einstein Telescope (low-frequency part LF)

- Adapt Exsqueez and QFilter to a new wavelength (1.55 µm?)
  - Cryogenic environment 10—20 K (↘ thermal noise)
  - Change materials for the mirrors → crystalline silicon
  - But crystalline silicon absorbs light at 1064 nm (Virgo)…

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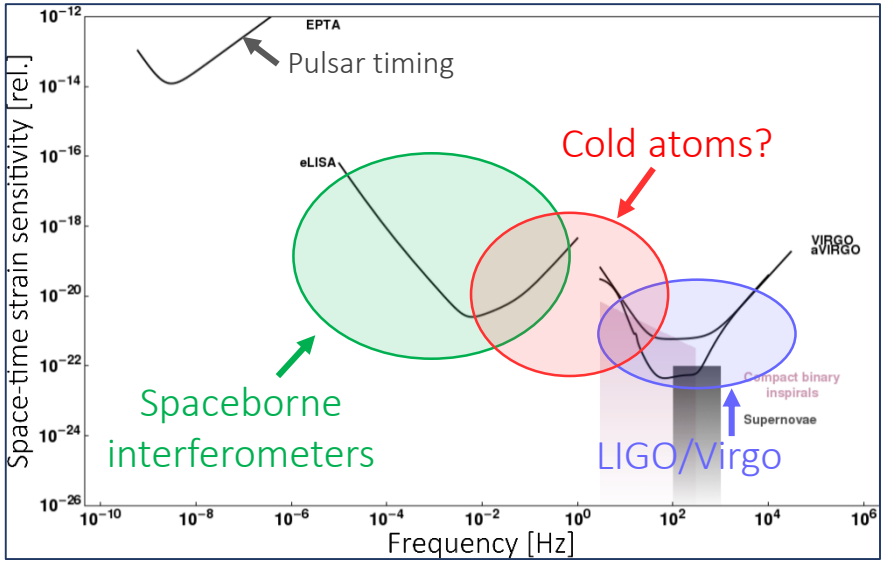
Export know-how to other types of GW detectors?

- International collaborations
  - Spaceborne interferometers
  - Cold atoms
  - …

✓ Team harbours many different skills which could be useful in that context



Adapted from Moore et al., Classical and Quantum Gravity, 32(1):015014, 2015

Backup slides

Main noise sources affecting GW detection

Classical noise sources

- Mechanical noise
  - Seismic + Newtonian
  - ➢ Solution: underground/spaceborne (upcoming projects ET/LISA)
- Thermal (Brownian) noise
  - Mirrors + suspensions
  - ➢ Solution: cryogenic environment (upcoming projects)

Quantum noise sources

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- Photon shot noise
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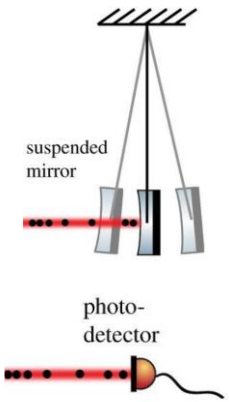
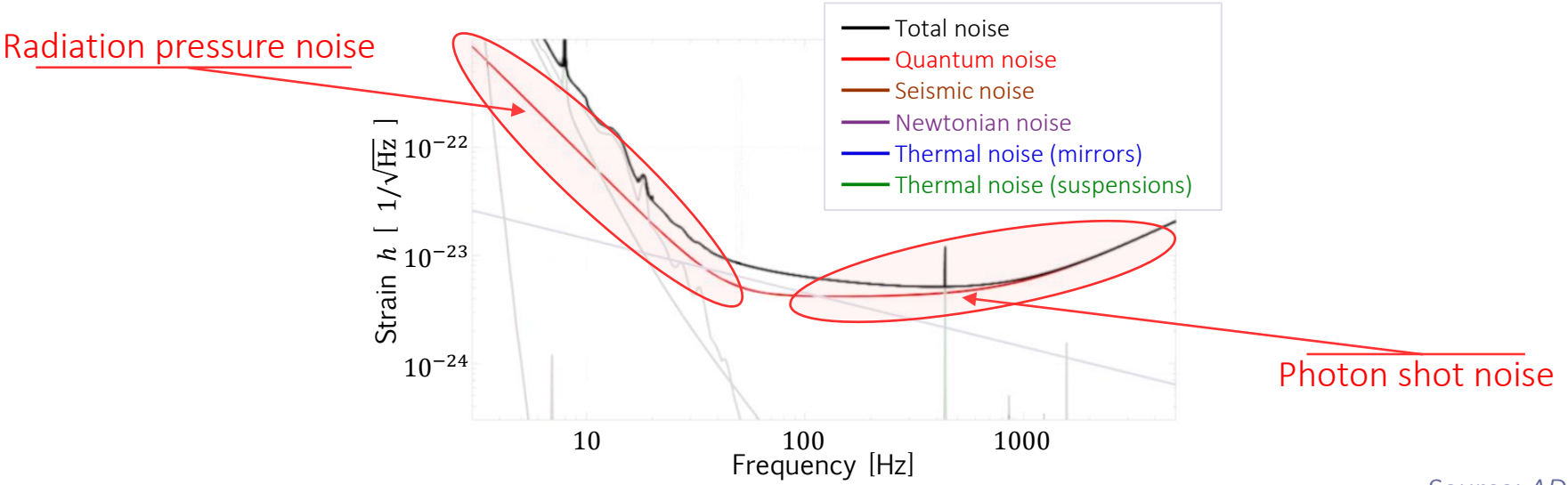
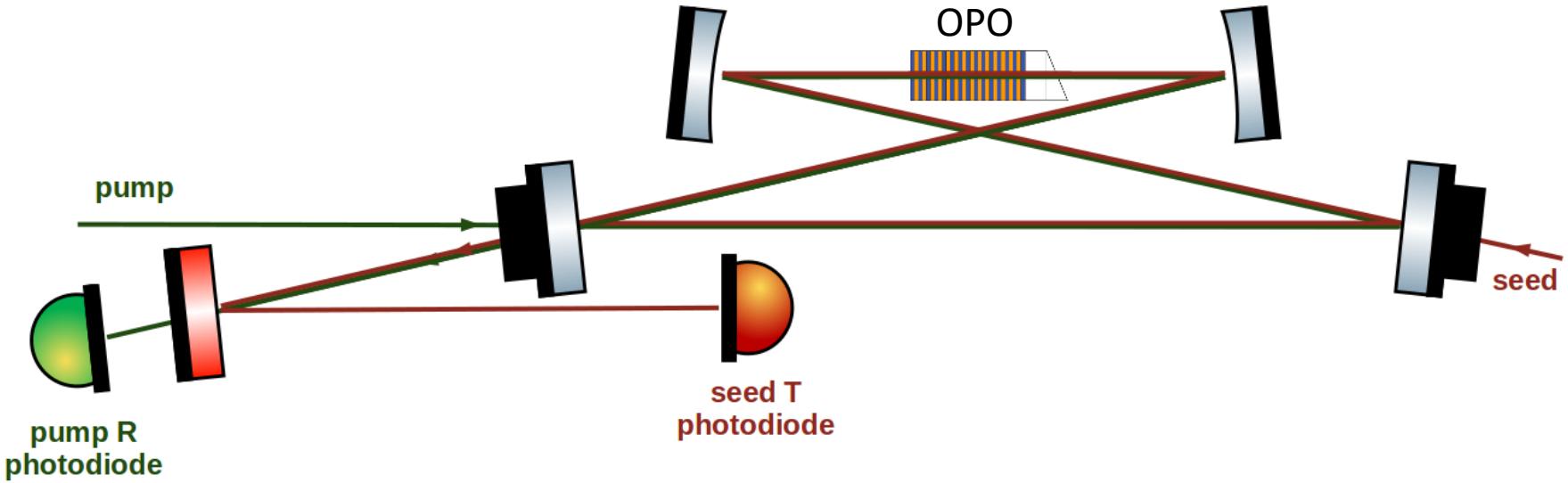


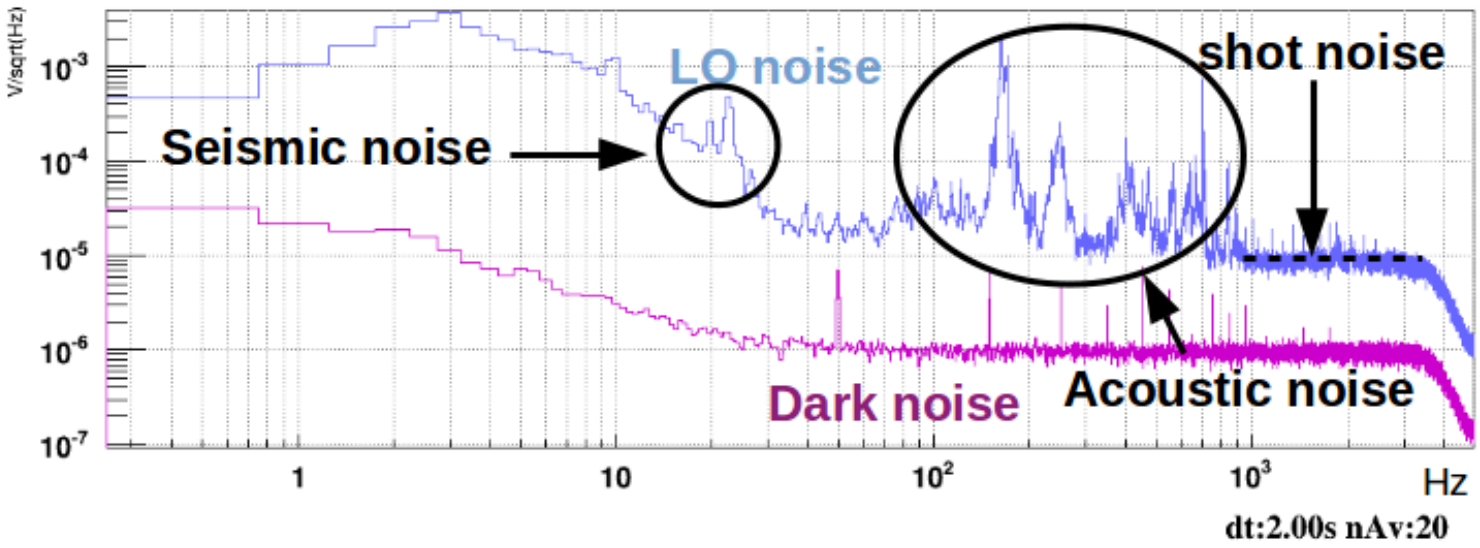


Source: ADV+ TDR

The Optical Parametric Oscillator



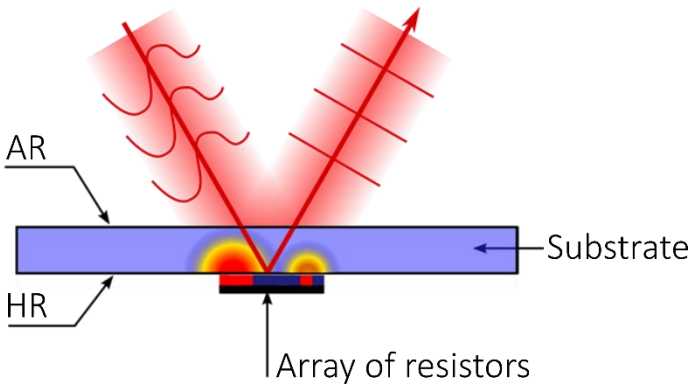
Characterisation of acoustic noise

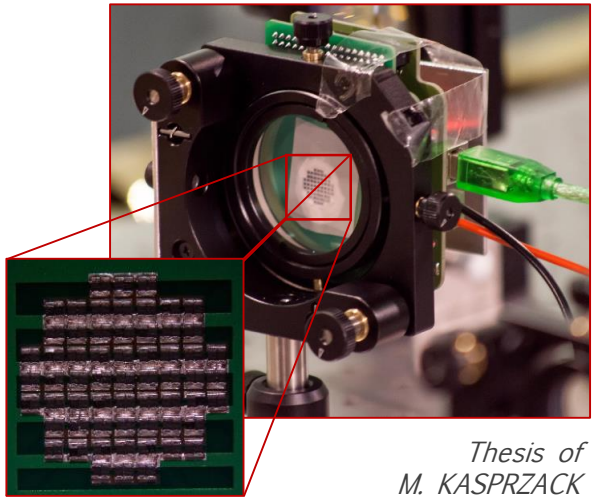


Reducing quantum noise over the whole frequency range (2)

Mastering optical wavefronts

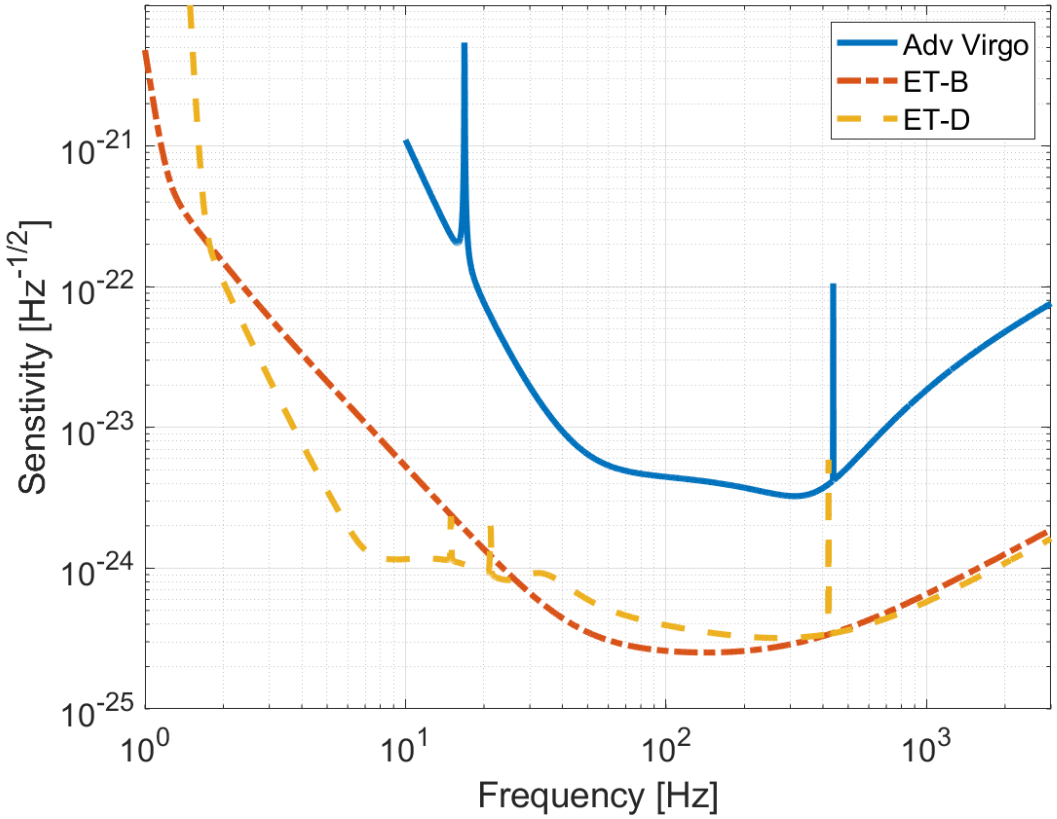
- Maximise coupling between beams (improve squeezing quality)
- Thermally-Deformable Mirrors (TDM)
  - Real-time control and correction of wavefronts
  - Compatible with vacuum operation





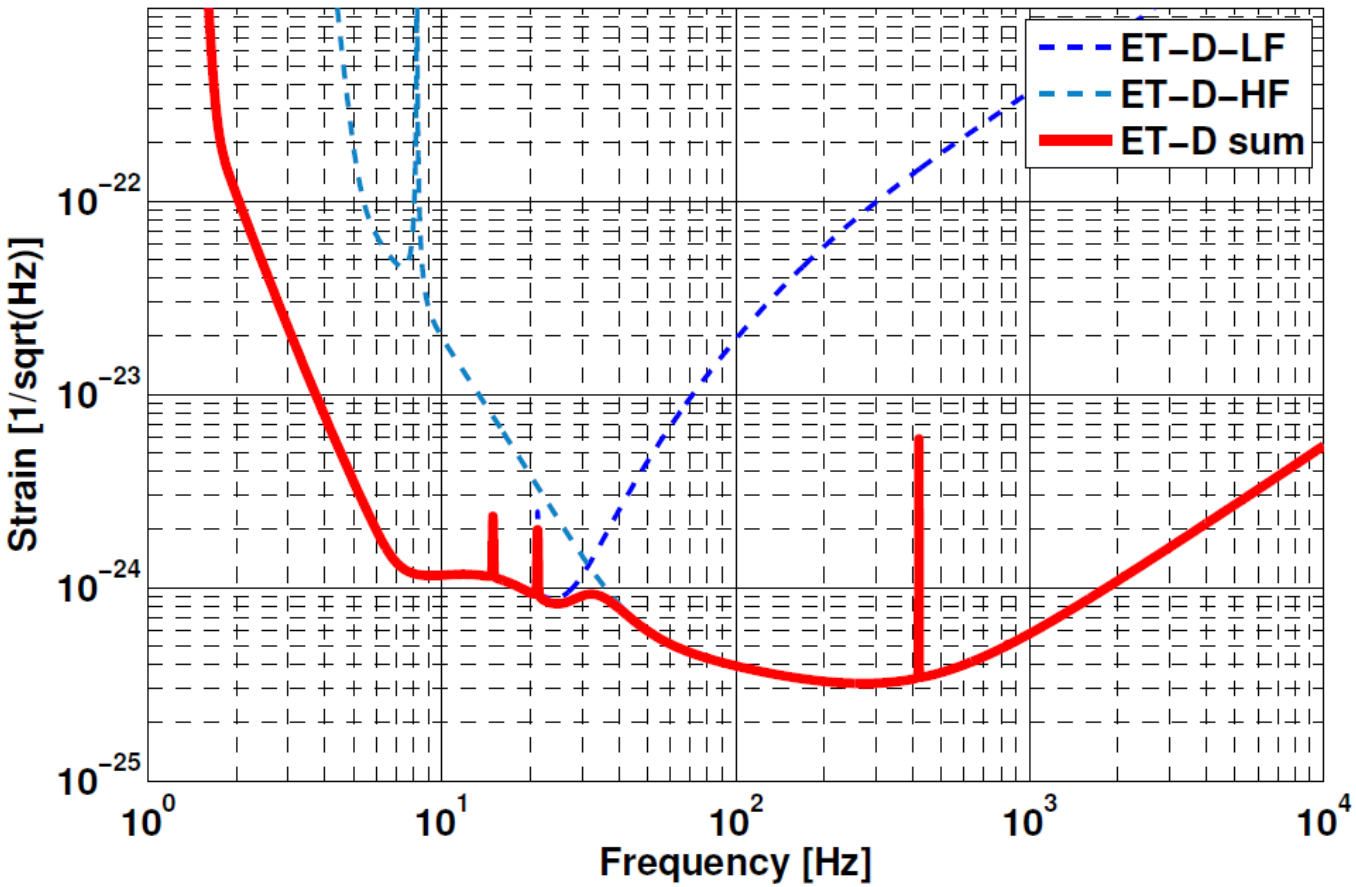
Thesis of M. KASPRZACK

Einstein Telescope: preliminary sensitivity



Maggiore et al., arXiv:1912.02622v4 (2020)

Einstein Telescope: LF and HF parts



Maggiore et al., arXiv:1912.02622v4 (2020)