ExSqueez

Quantum trick to improve the detection of gravitational waves

Angélique Lartaux

Parcours

2013-2016 : Magistère de Physique Fondamentale d'Orsay

L3 et M1 de Physique Fondamentale
M2 Noyaux, Particules, Astroparticules et Cosmologie (NPAC)

2016-2020 : Thèse à IJCLab

Dépasser la limite quantique standard pour le détecteur d'ondes gravitationnelles Advanced Virgo

2020-2021 : Postdoc au SYRTE

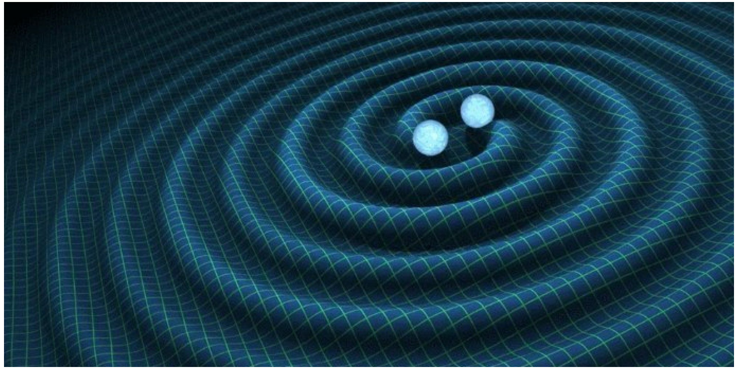
Développement d'un laser ultra-stable à 1542 nm

2021 : Recrutement CRCN à IJCLab par la voie contractuelle

Groupe Ondes Gravitationnelles

Gravitational waves

are ripples in the spacetime curvature
predicted by Albert Einstein in 1916



Some properties

- emitted by accelerating masses with amplitude h,
- propagate at the speed of light

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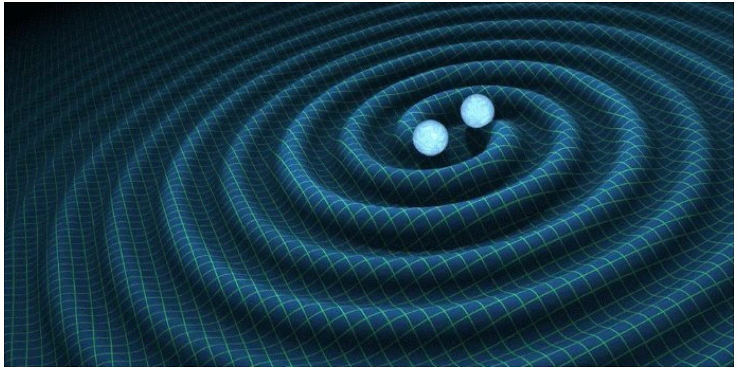

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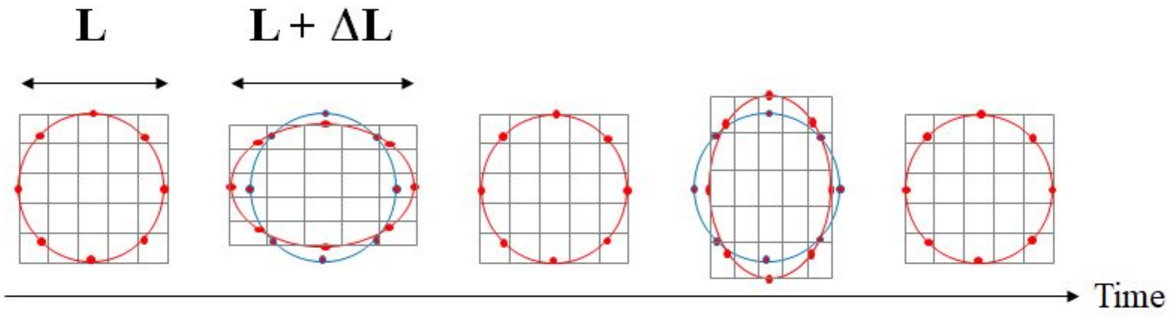
Gravitational-wave detection



Differential deformation of spacetime with $\frac{\Delta L}{L} \simeq \frac{h}{2}$

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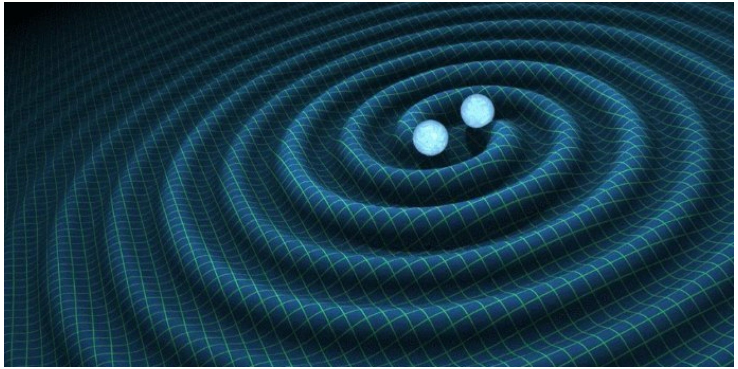

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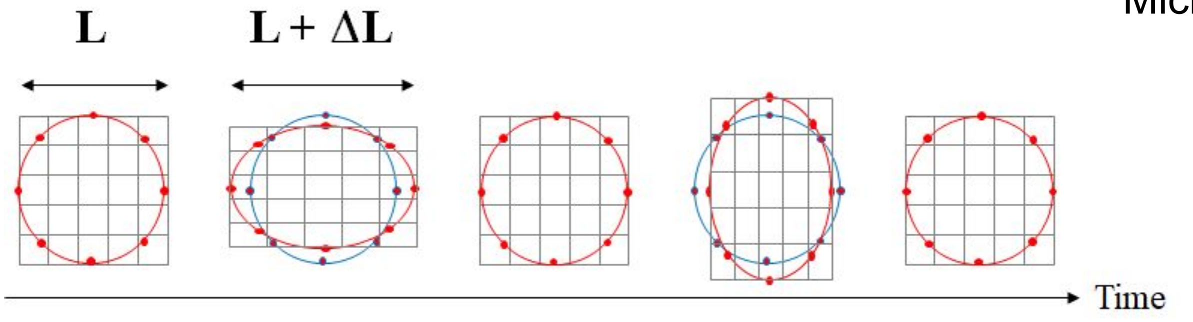
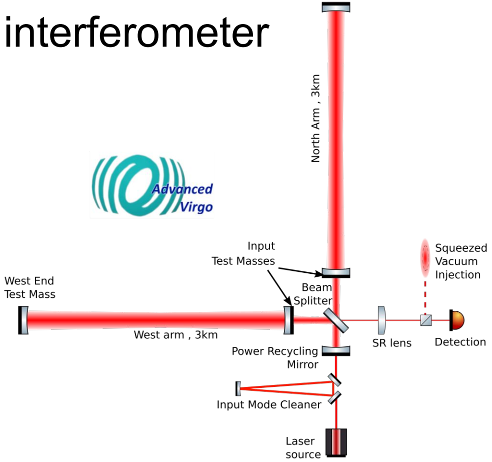


Differential deformation of spacetime with $\frac{\Delta L}{L} \simeq \frac{h}{2}$

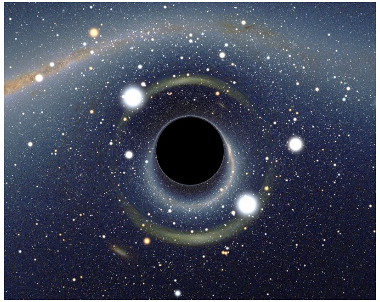
Michelson interferometer

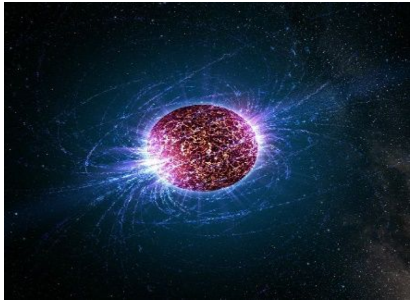


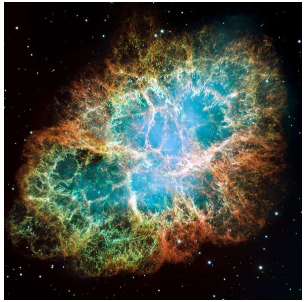
The detectable gravitational waves on Earth

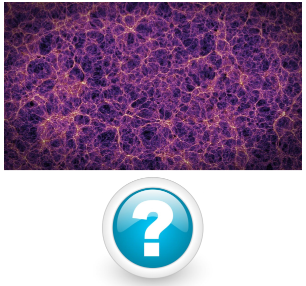
come from astronomical sources like compact binary systems (black holes and/or neutron stars), supernovae, etc.

At a distance r from the source $h \propto \frac{1}{r}$
⇒ need strong event to be detectable on Earth









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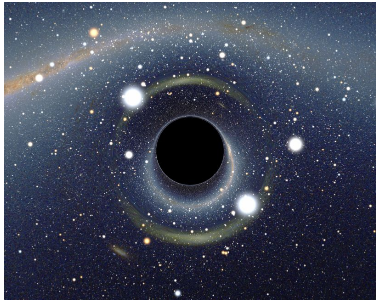
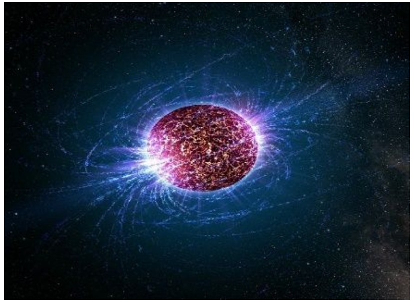
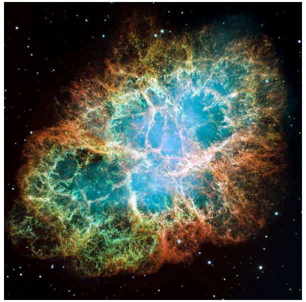
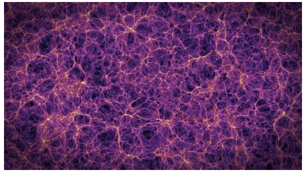
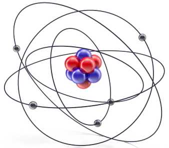
with $h \sim 10^{-21}$



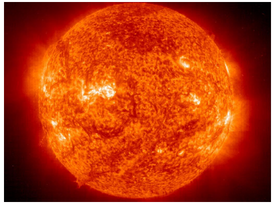








1 atom change (10^{-10} m)



over 150 million kms ($1{,}5.10^{11}$ m)

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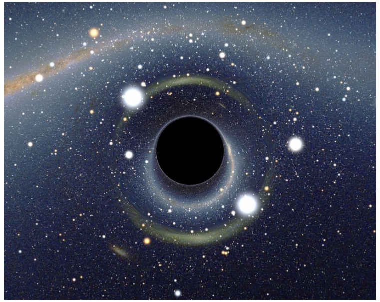

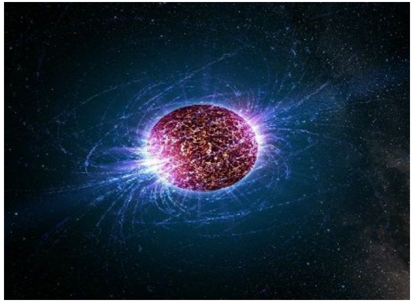

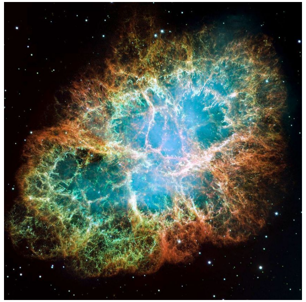

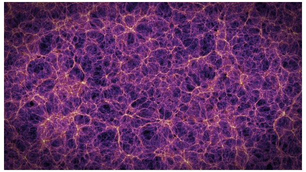

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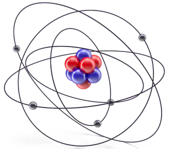
⇒ need strong event to be detectable on Earth with $h \sim 10^{-21}$



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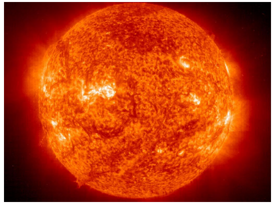


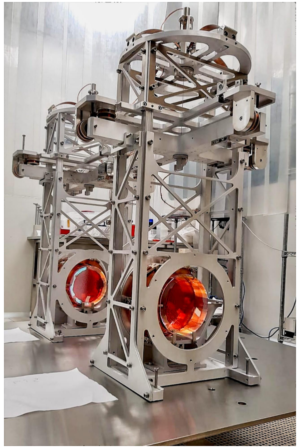
1/300 proton change over 3 km arms

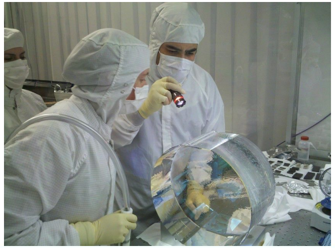
is the sum of several noises

Some interferometer improvements

Under vacuum Fabry-Perot cavities in the arms
(10 000 m³ at 10^{-9} mbar)

Mirrors and benches suspended





Best mirror quality (surface and reflectivity)

Gravitational-wave detectors sensitivity

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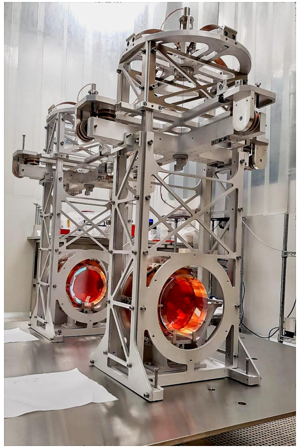

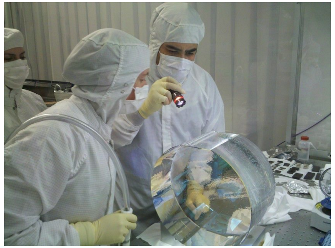

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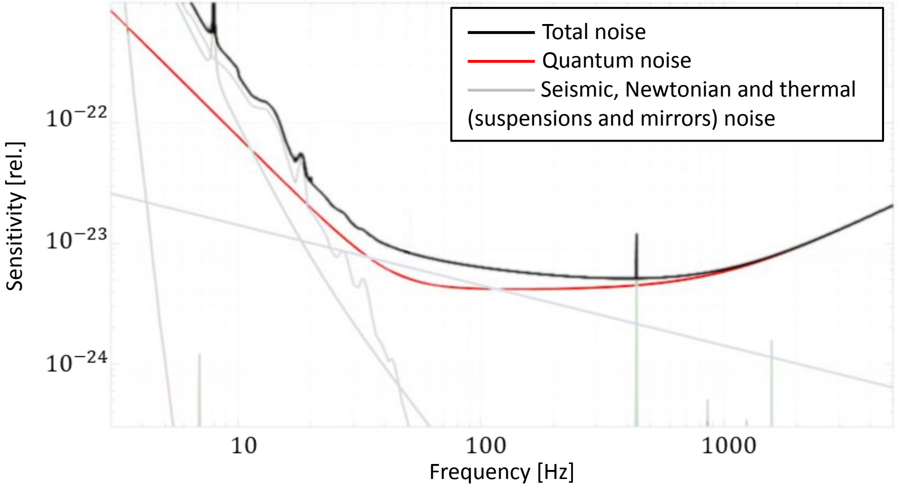
Sensitivity curve



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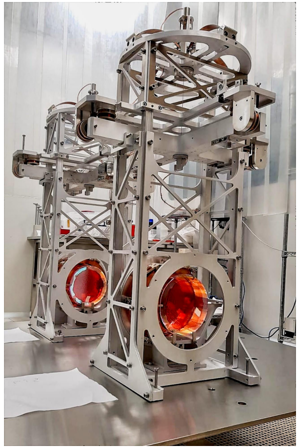

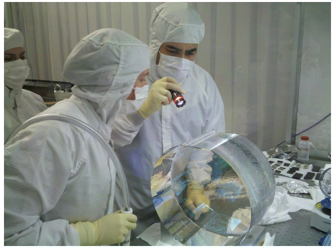

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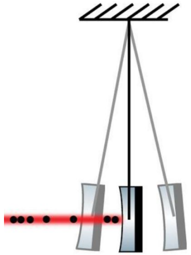
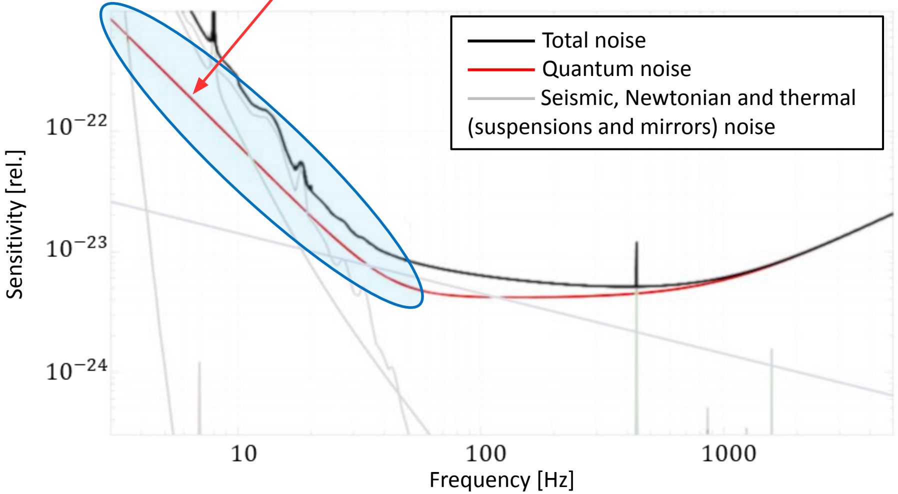
Sensitivity curve

Radiation pressure noise

(amplitude noise)





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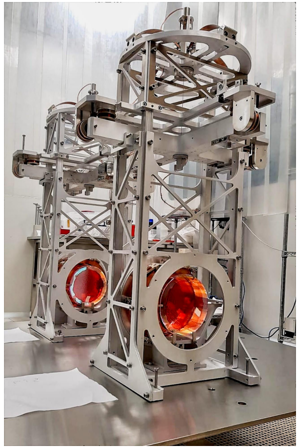

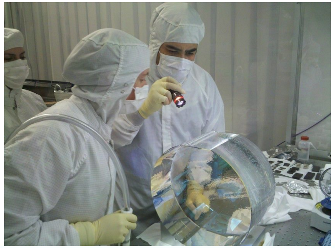

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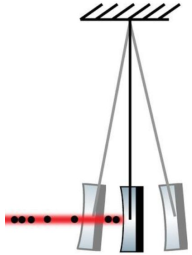

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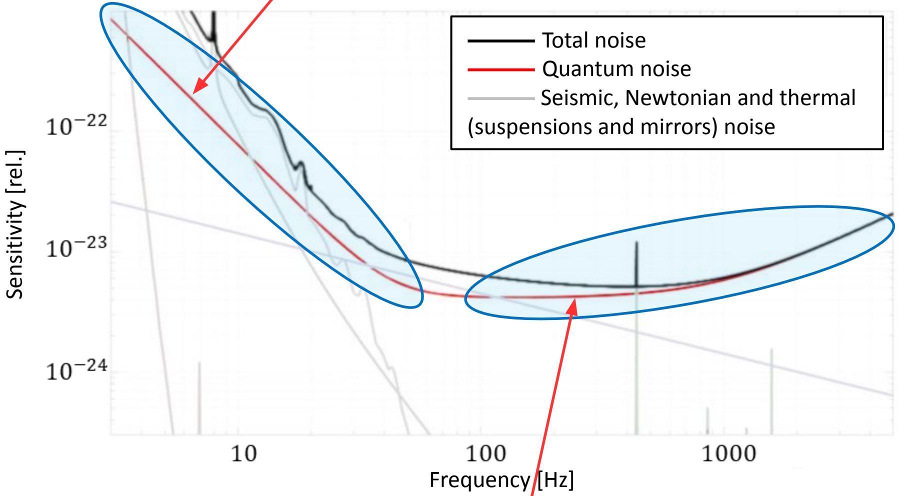


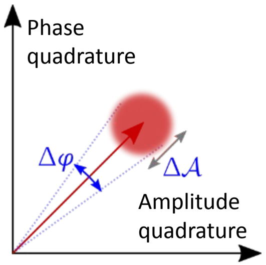
Shot noise
(phase noise)

Squeezed states of light

can be used to reduce quantum noise

Take advantage of quantum properties of light

Heisenberg uncertainty relation: $\Delta A \times \Delta\varphi \geq 1$



Coherent state

can be used to reduce quantum noise

Take advantage of quantum properties of light

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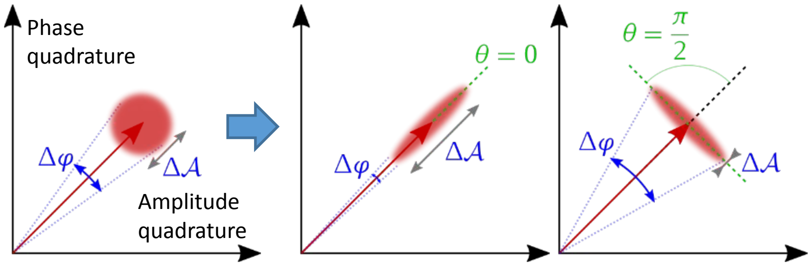

Coherent state Squeezing (phase) (amplitude)

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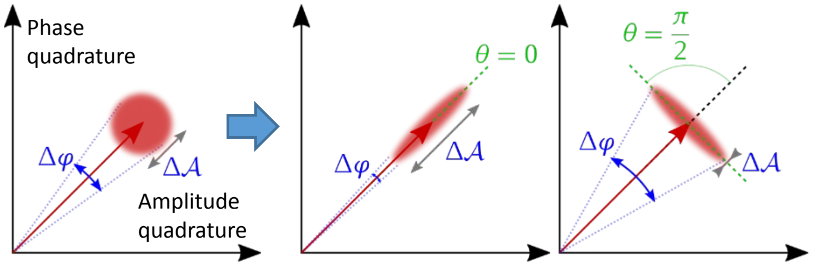
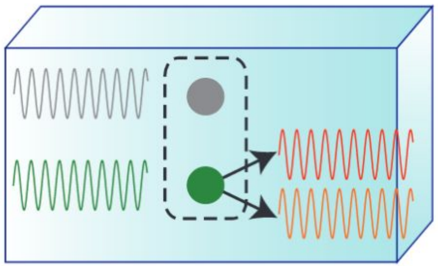


Coherent state | Squeezing (phase) | (amplitude)

2-photon squeezing production via nonlinear interaction



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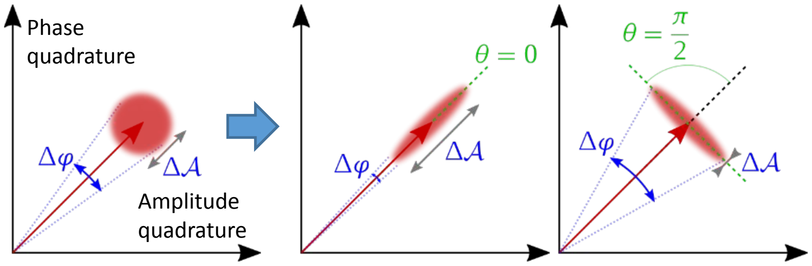

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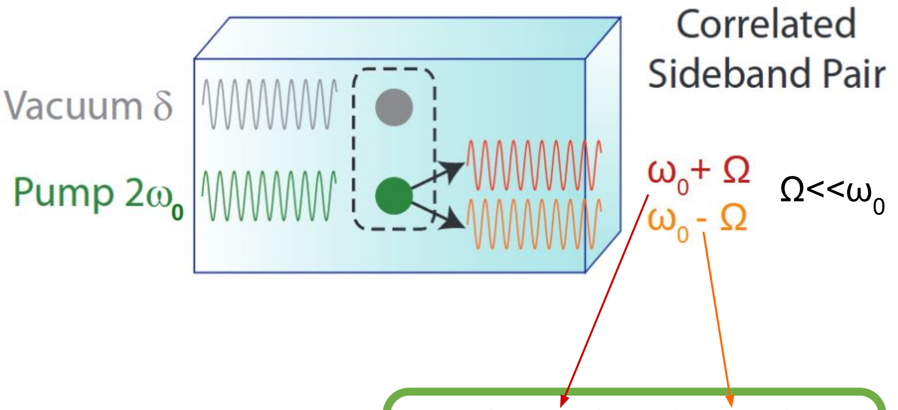
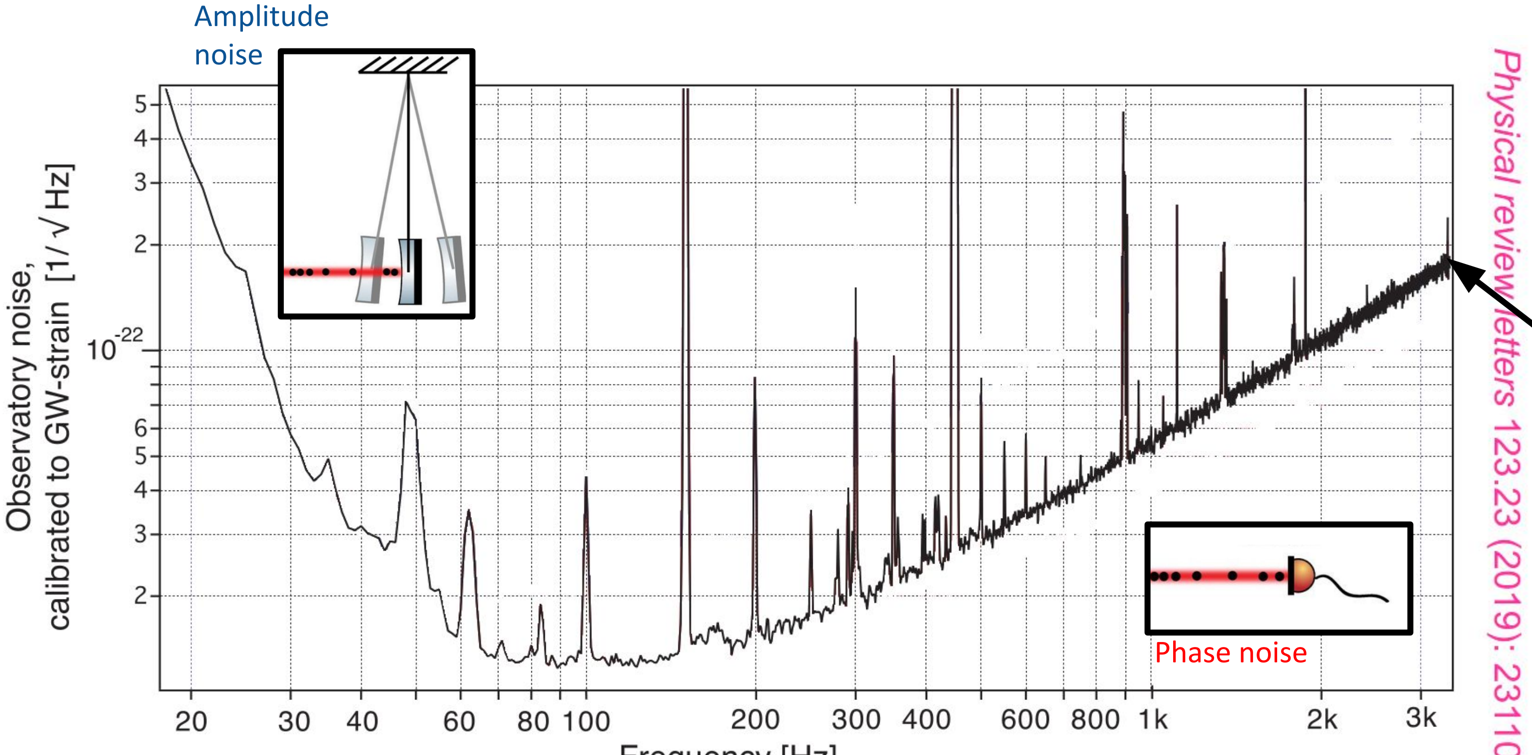


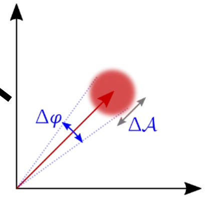
Squeezing ellipse angle: $\theta = \frac{\varphi(\omega_0+\Omega)+\varphi(\omega_0-\Omega)}{2} \; [\pi]$

Frequency-independent squeezing

is not enough to improve the sensitivity of gravitational-wave detectors



O3 observing run (from 2019-04-01 to 2020-03-27)



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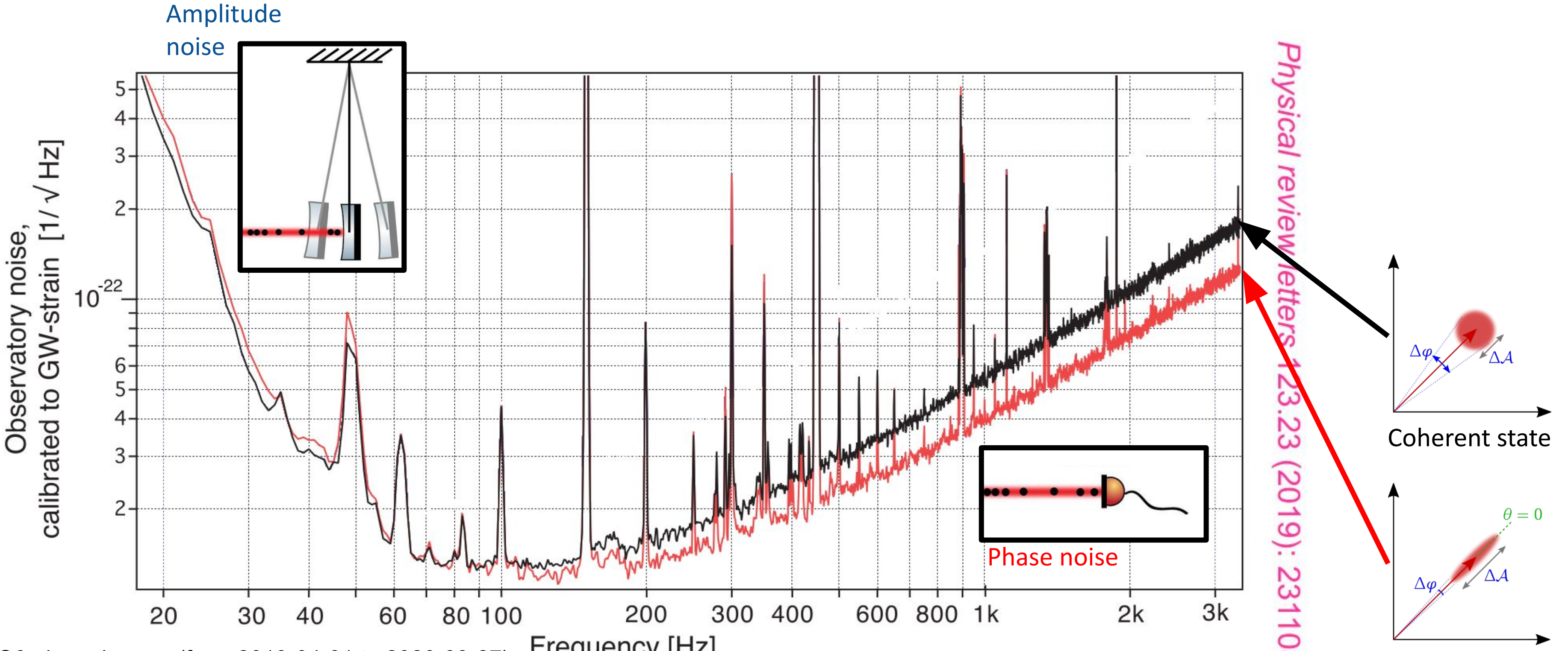

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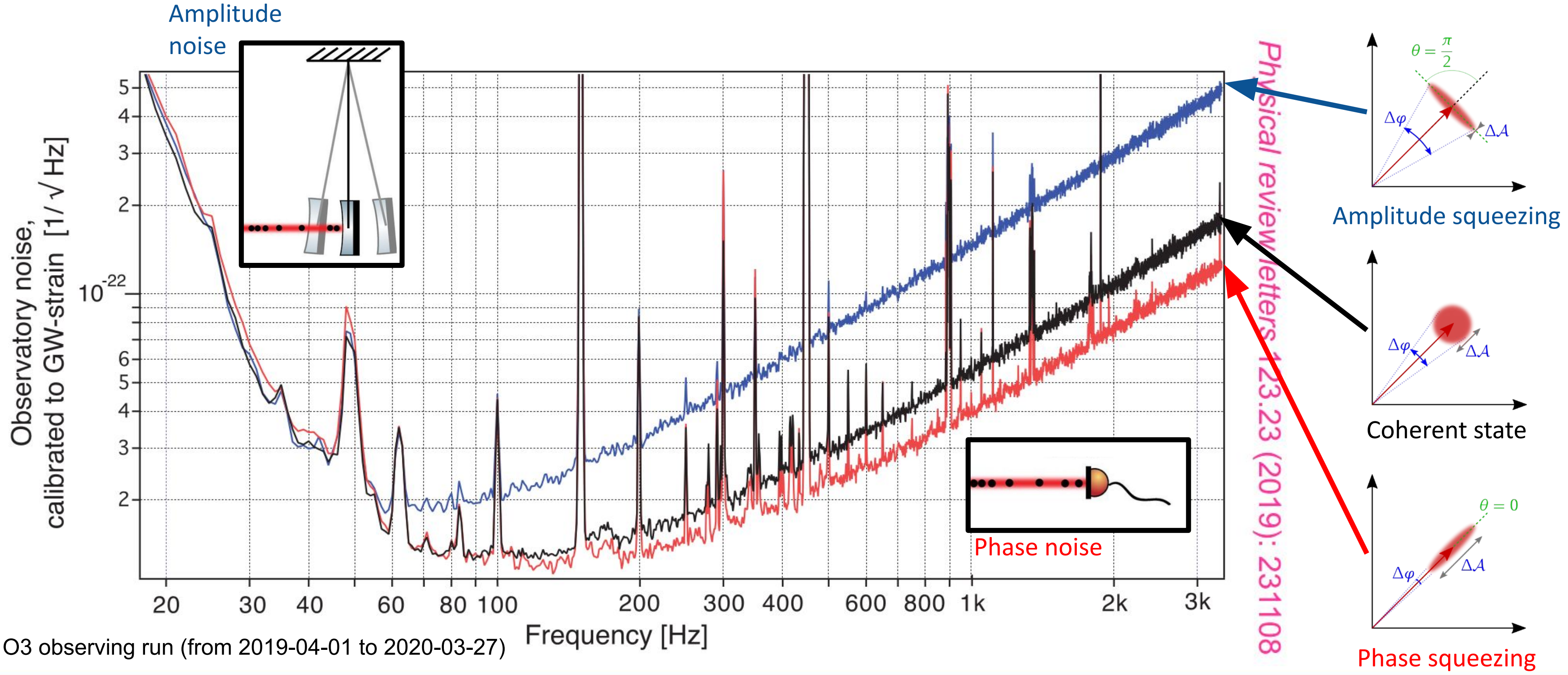

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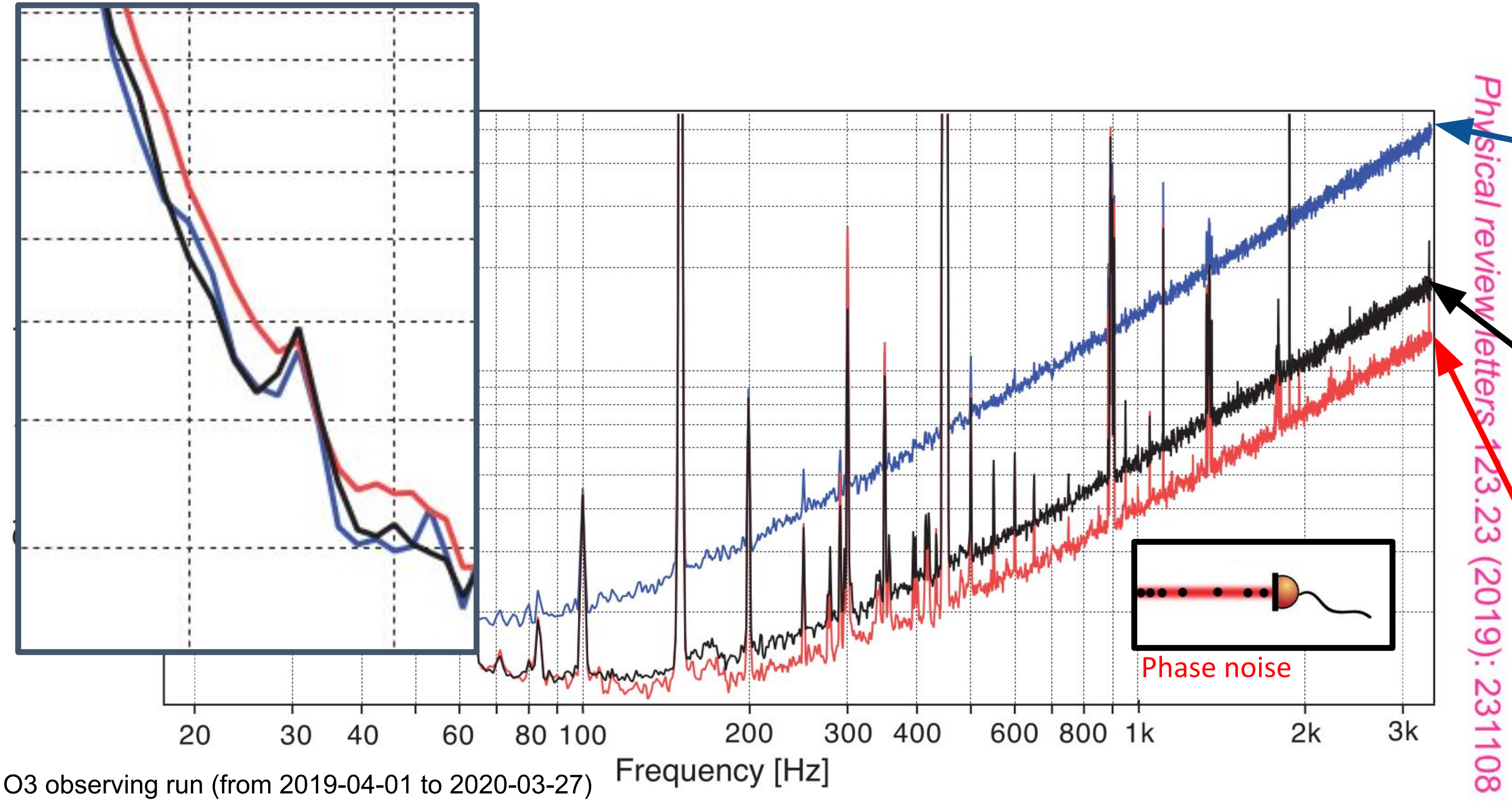

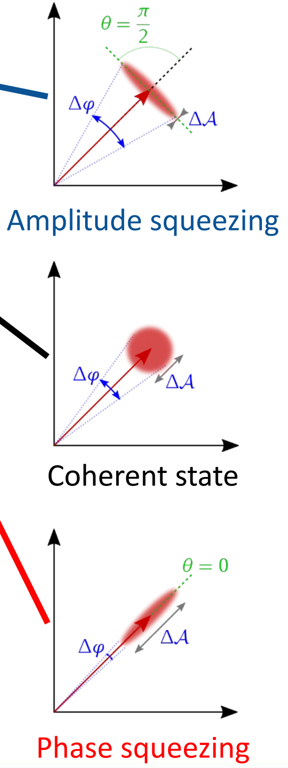

O3 observing run (from 2019-04-01 to 2020-03-27)

Frequency-independent squeezing

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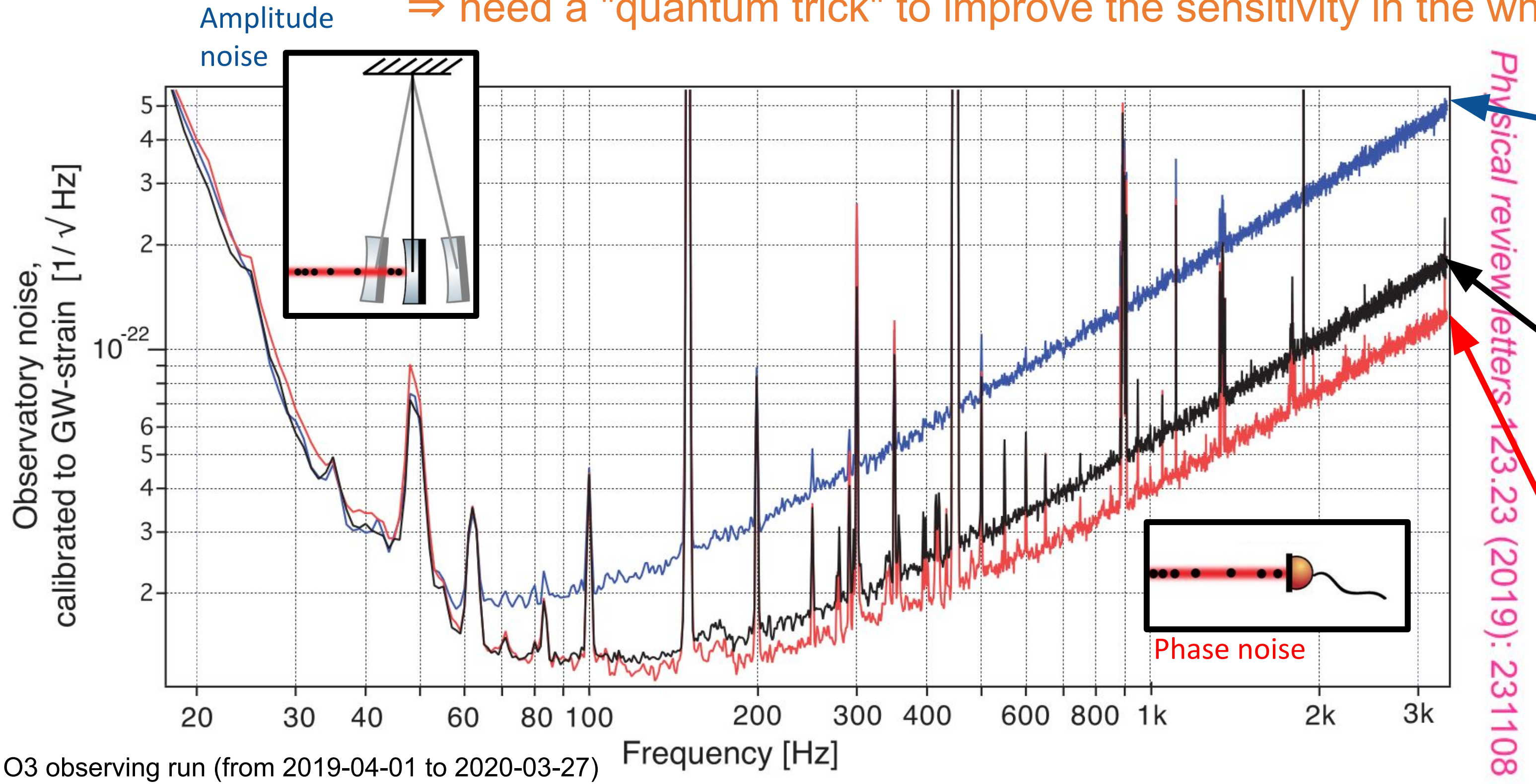
⇒ need a "quantum trick" to improve the sensitivity in the whole bandwidth



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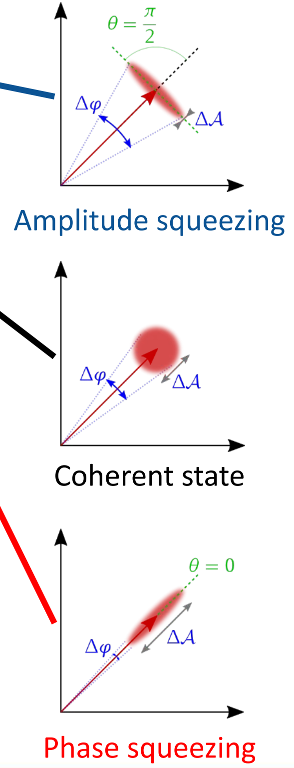
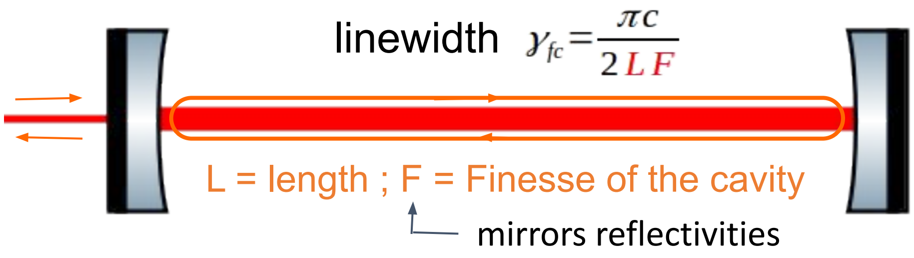
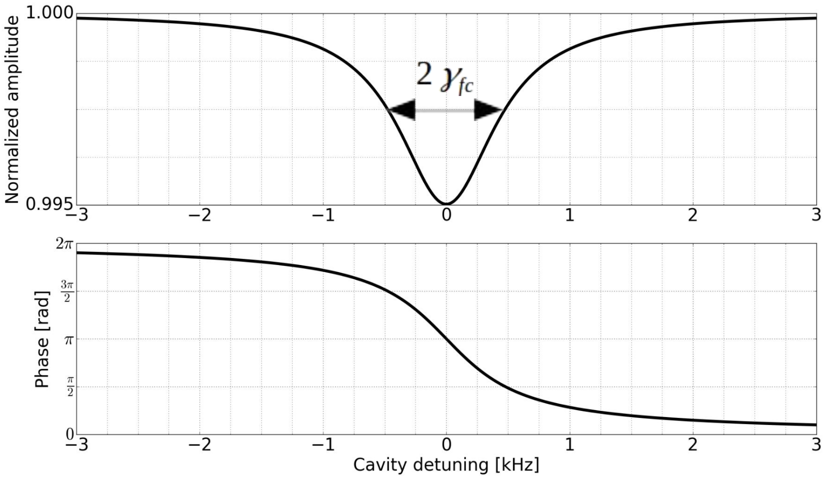


Frequency-dependent squeezing

allows for quantum-noise reduction at low and high frequencies

Filter cavity





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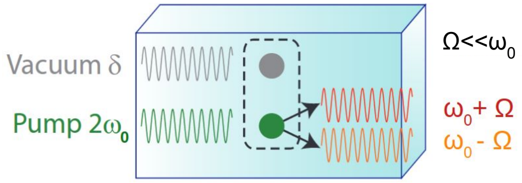
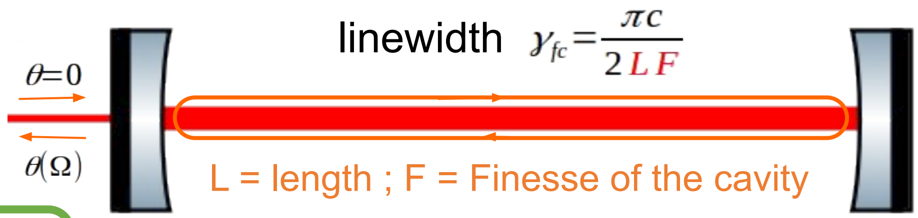
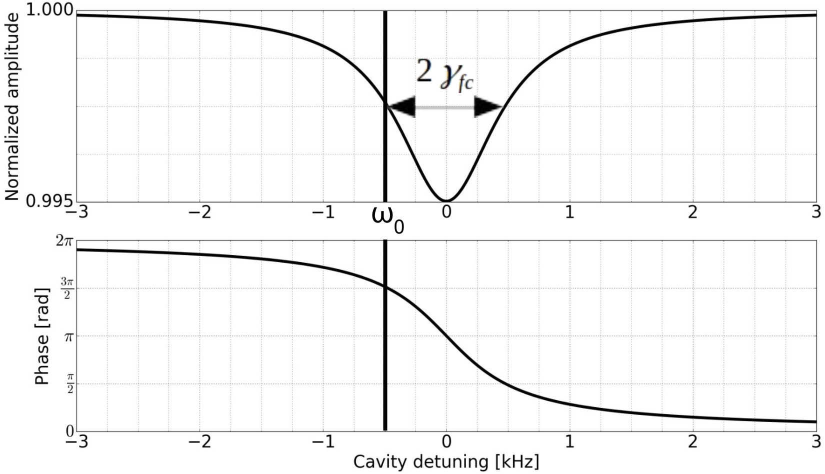




Squeezing ellipse angle: $$\theta = \frac{\varphi(\omega_0 + \Omega) + \varphi(\omega_0 - \Omega)}{2} \quad [\pi]$$



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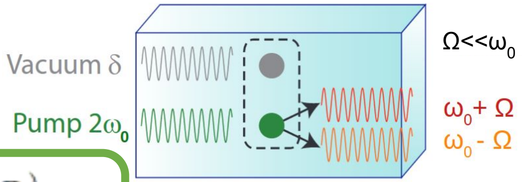

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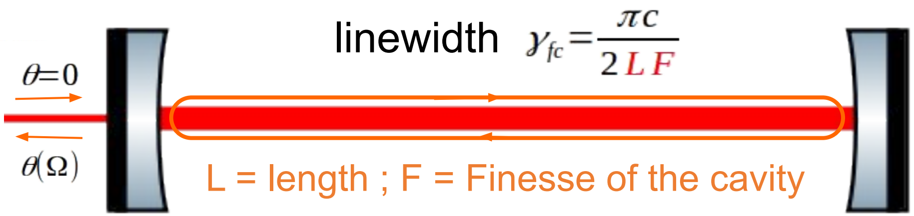
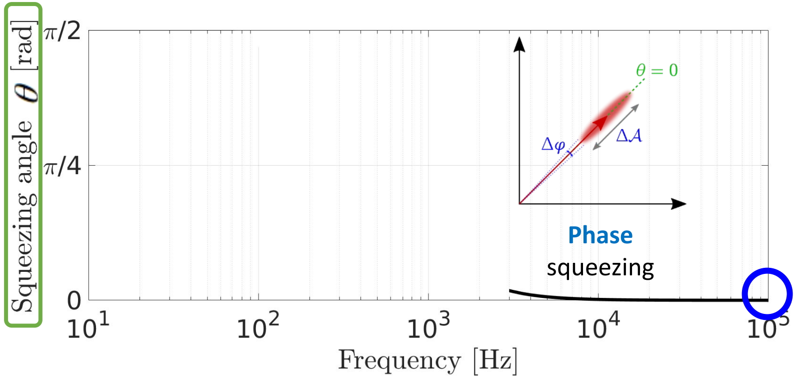
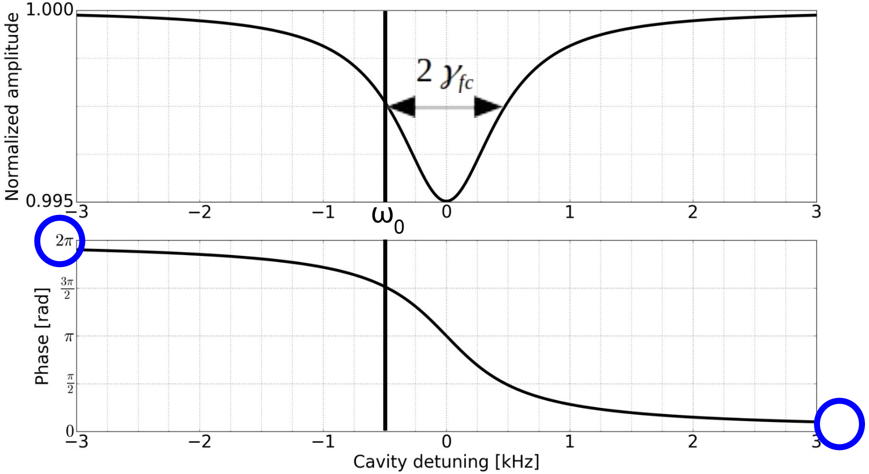


After reflection:

If $\Omega \gg \sqrt{2}\,\gamma_{fc}$ ⇒ 2θ = 0 + 2π ⇒ θ = π = 0 [π]





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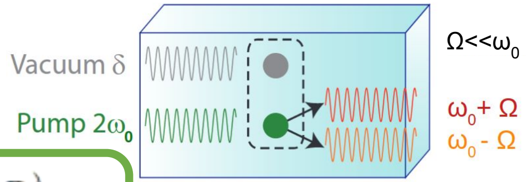

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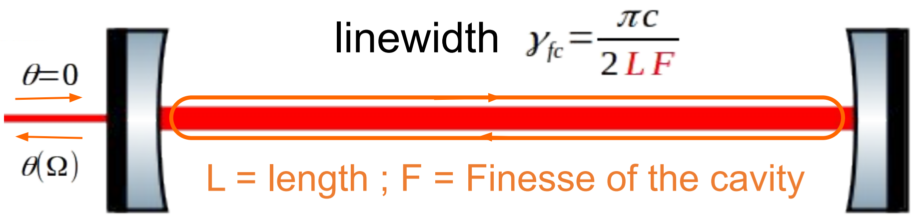
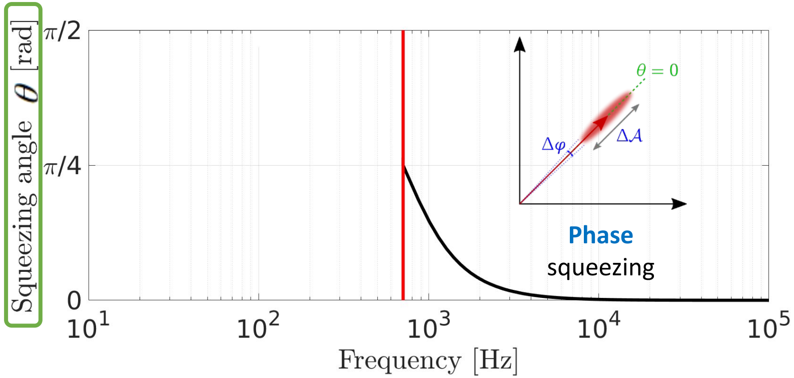
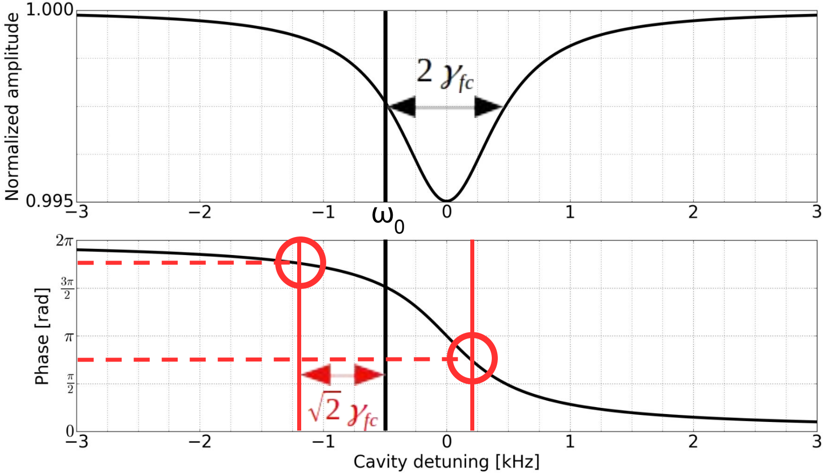


After reflection:
If $\Omega = \sqrt{2}\,\gamma_{fc} \Rightarrow 2\theta = 3\pi/4 + 7\pi/4 \Rightarrow \theta = 5\pi/4 = \pi/4\ [\pi]$

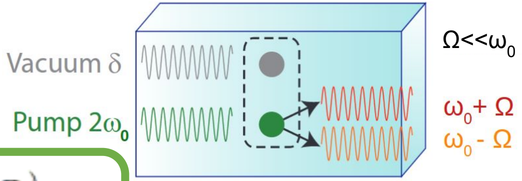




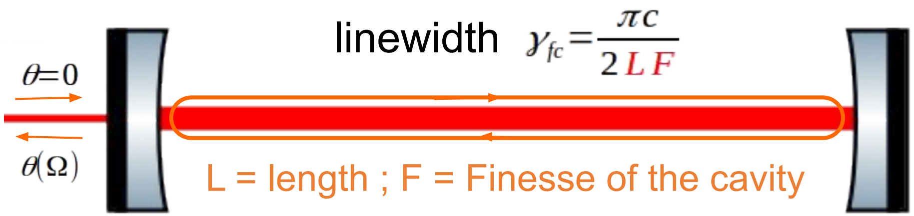
Frequency-dependent squeezing

allows for quantum-noise reduction at low and high frequencies

Filter cavity

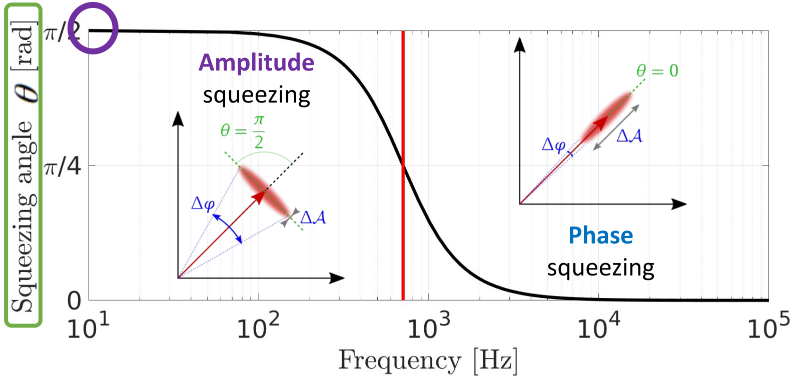


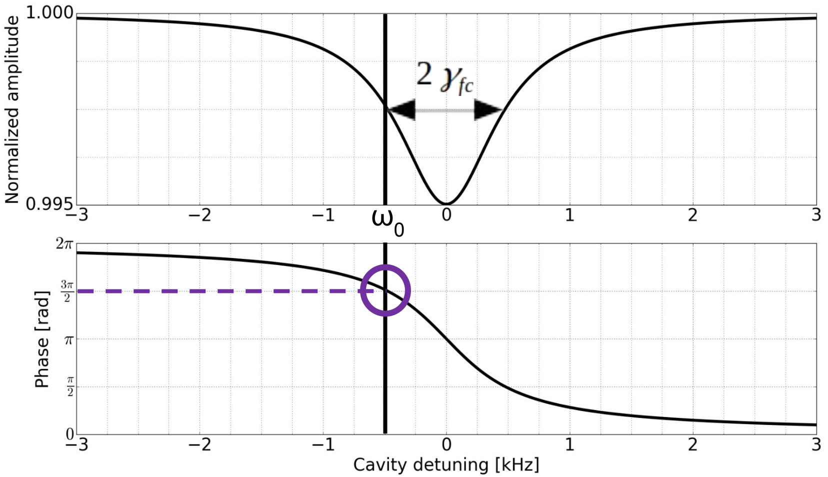
$$\theta = \frac{\varphi(\omega_0+\Omega)+\varphi(\omega_0-\Omega)}{2} \; [\pi]$$



After reflection:

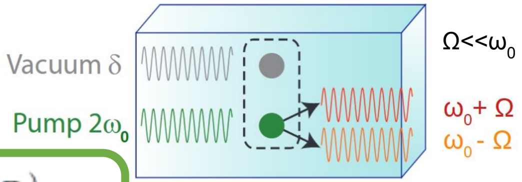
If $\Omega=0 \Rightarrow 2\theta = 3\pi/2 + 3\pi/2 \Rightarrow \theta = 3\pi/2 = \pi/2\ [\pi]$



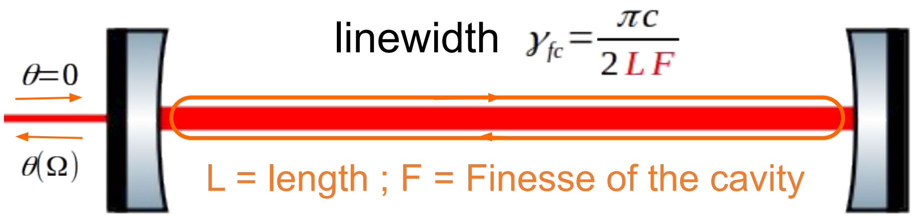


allows for quantum-noise reduction at low and high frequencies

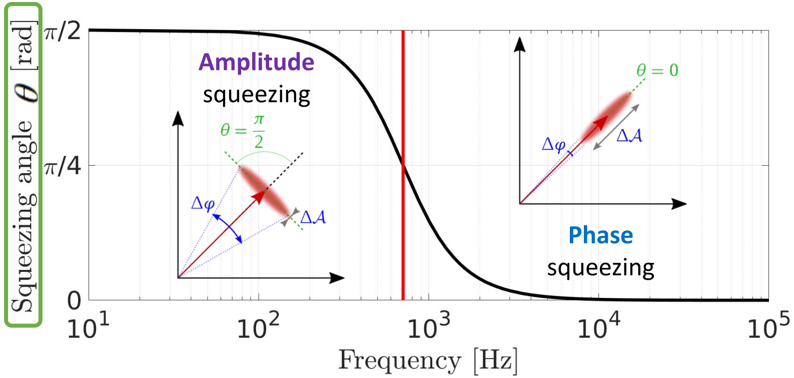
Filter cavity

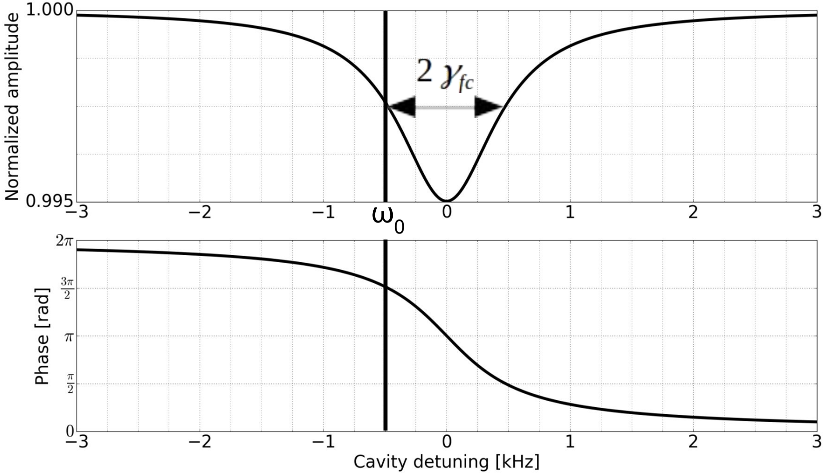


$$\theta = \frac{\varphi(\omega_0+\Omega)+\varphi(\omega_0-\Omega)}{2} \quad [\pi]$$



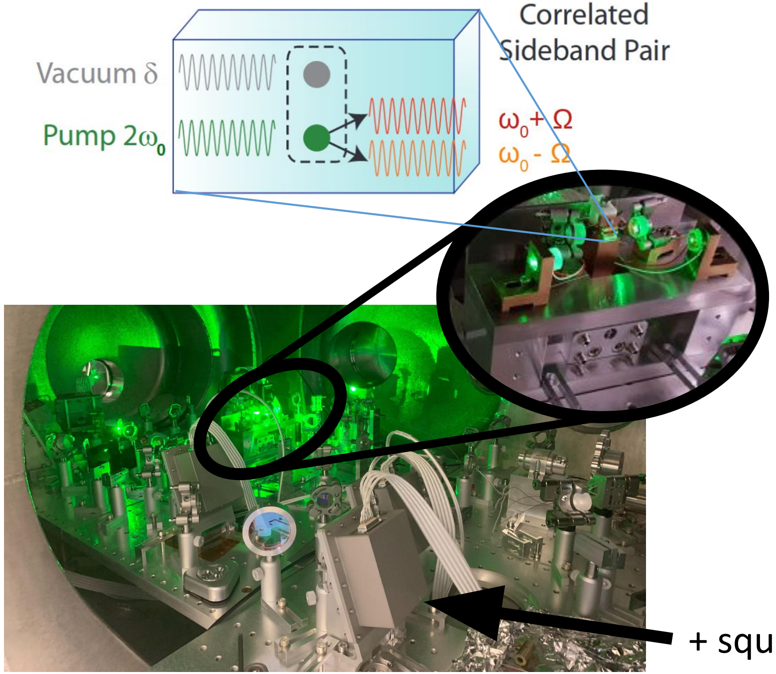
⇒that is the "quantum trick"





this is what my experiment looks like

Squeezing generation inside a vacuum tank

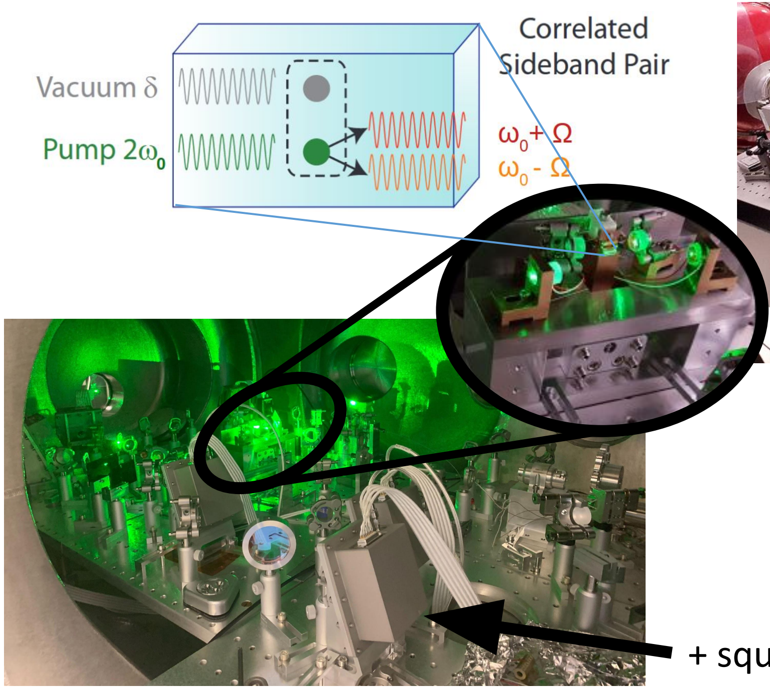


+ squeezing measurement

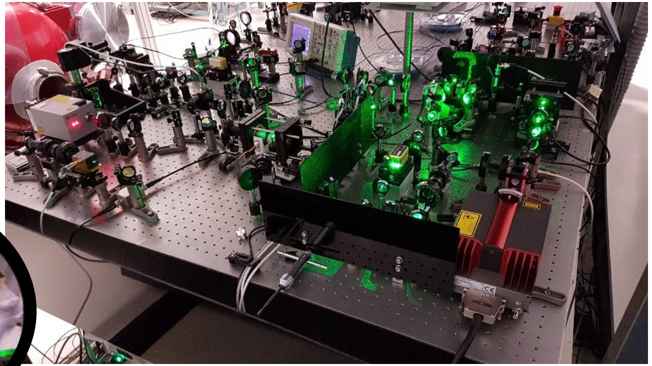
In practice

this is what my experiment looks like

Squeezing generation inside a vacuum tank



In-air beams preparation bench (7 beams need from 2 laser heads)

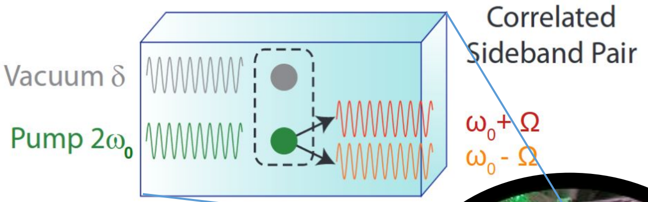


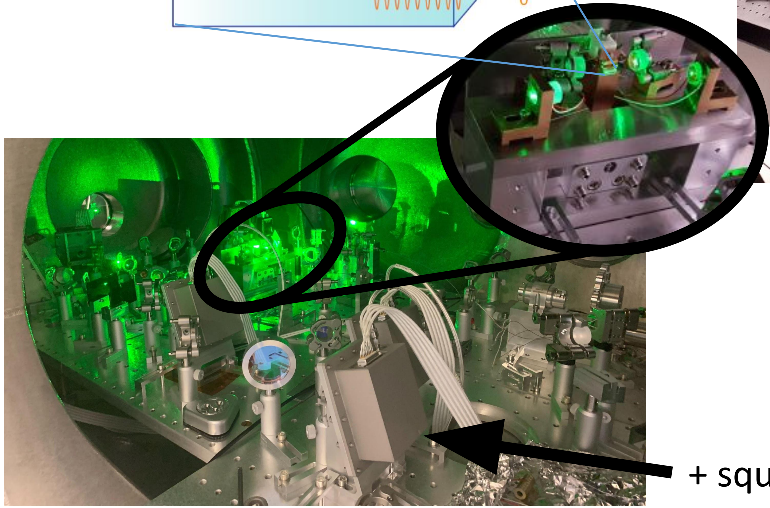
+ squeezing measurement

In practice

this is what my experiment looks like

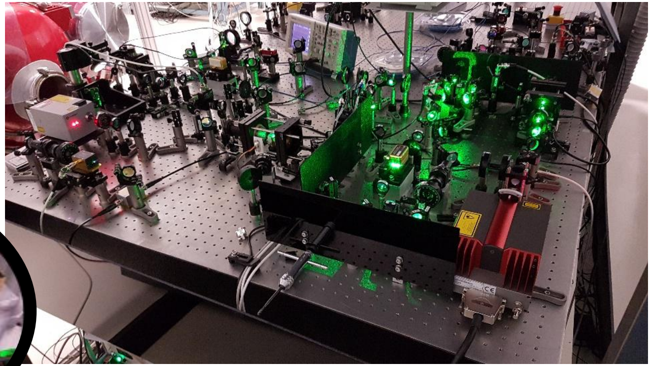
Squeezing generation inside a vacuum tank



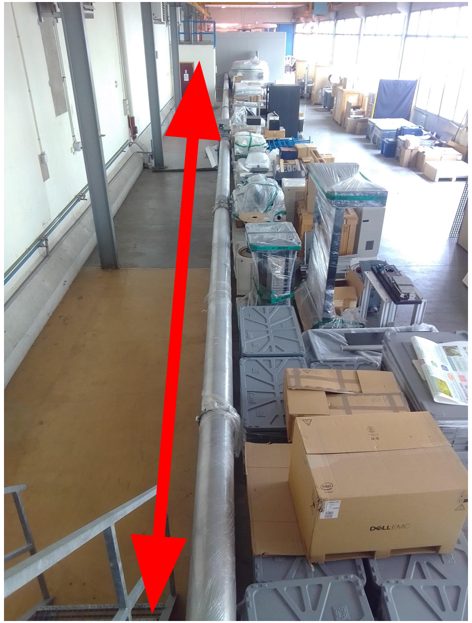


+ squeezing measurement

In-air beams preparation bench (7 beams need from 2 laser heads)



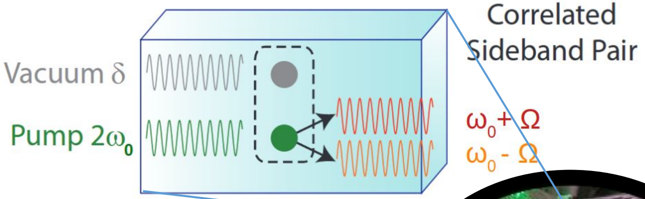
50-m filter cavity (CALVA facility)

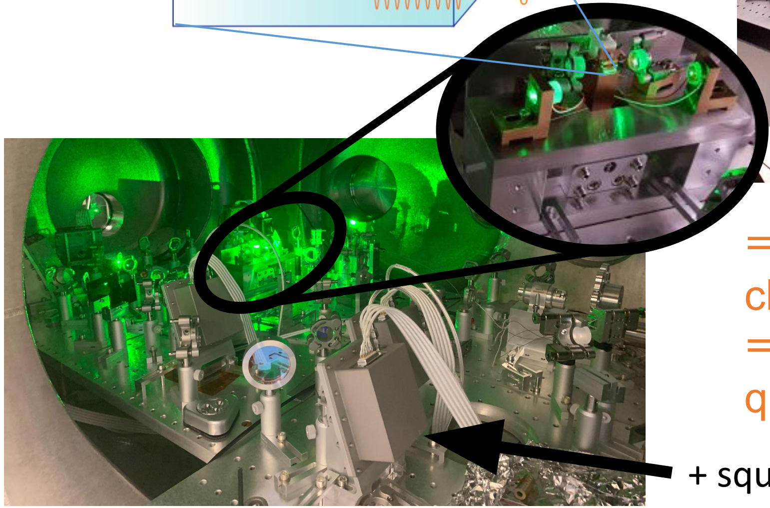


In practice

this is what my experiment looks like

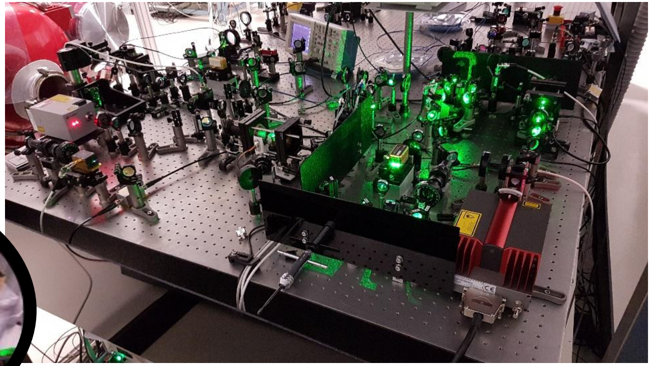
Squeezing generation inside a vacuum tank





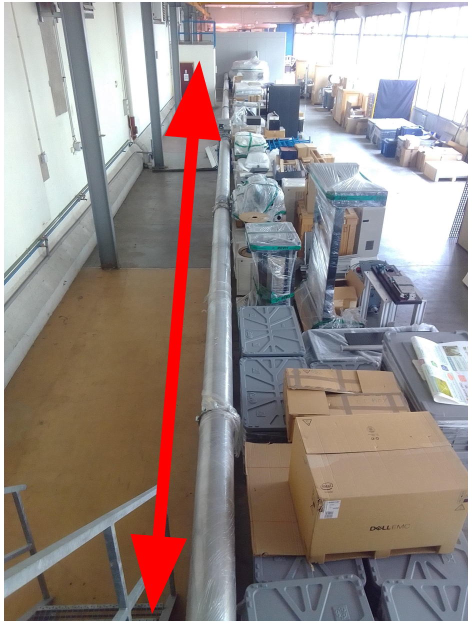
+ squeezing measurement

In-air beams preparation bench (7 beams need from 2 laser heads)



⇒ implementation and first characterizations done
⇒ next step will be to measure quantum noise reduction

50-m filter cavity (CALVA facility)



Thank you!