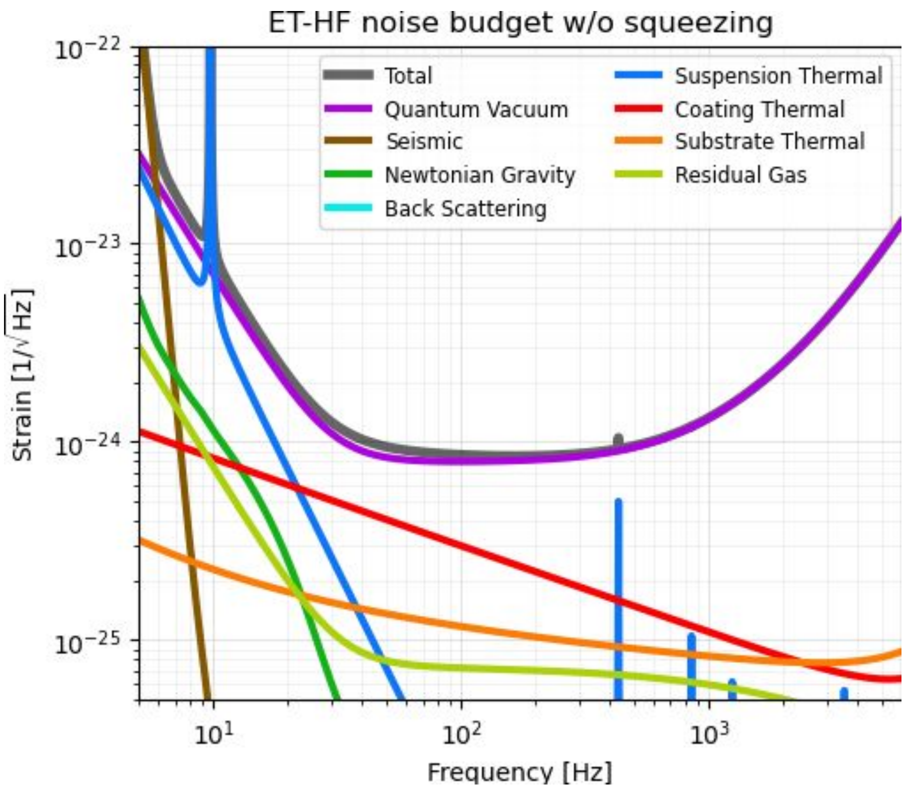
Squeezed light in GW detectors.

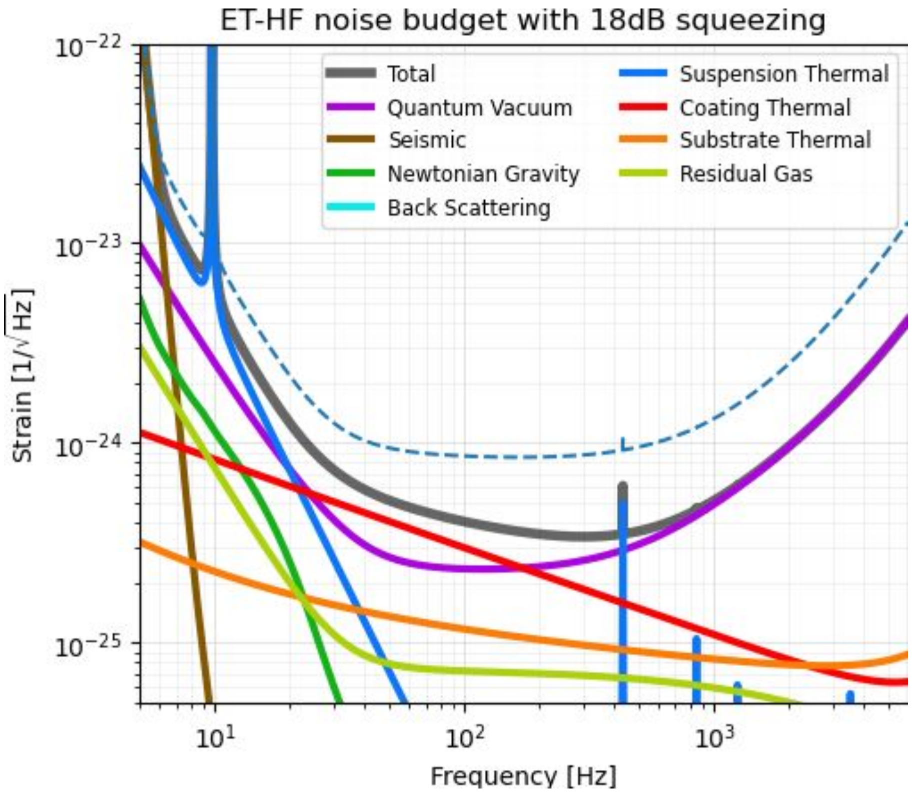
What is it and why we need it?

S. Danilishin

ETMOST Meeting, July 9, 2025

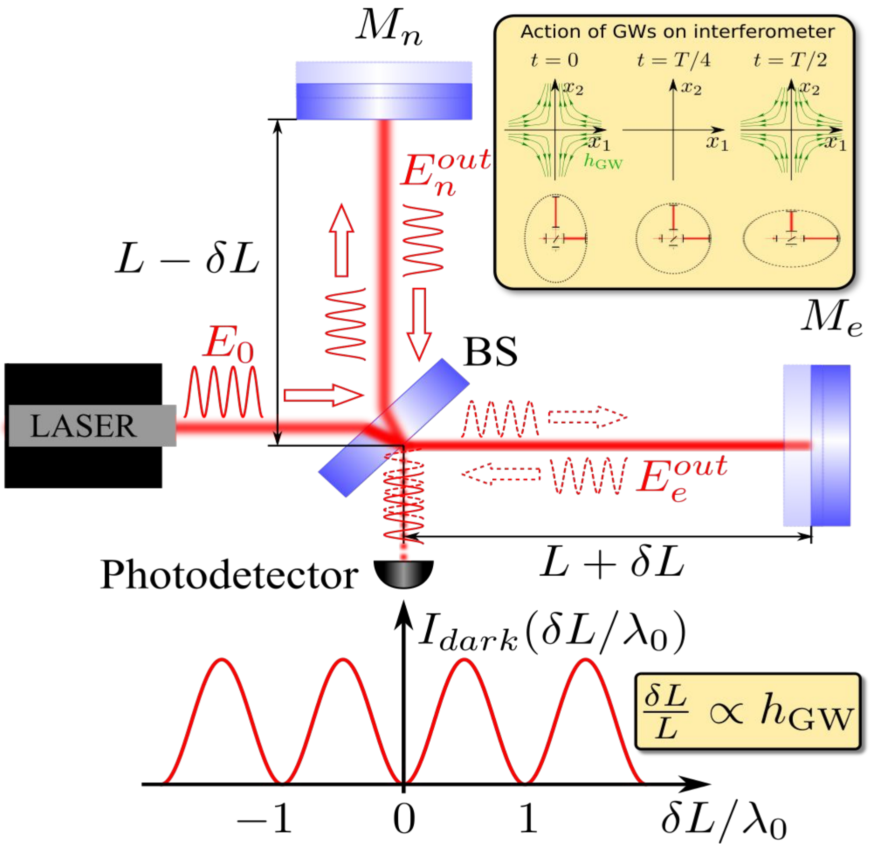
Why do we need squeezing in GW detectors?





Design sensitivity for ET (and other detectors) can only be achieved with squeezing injection

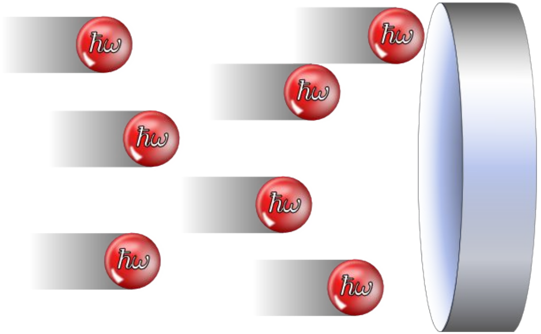
How do we measure GW with light?



GW interferometer is, essentially, a laser light **phase shift meter**!

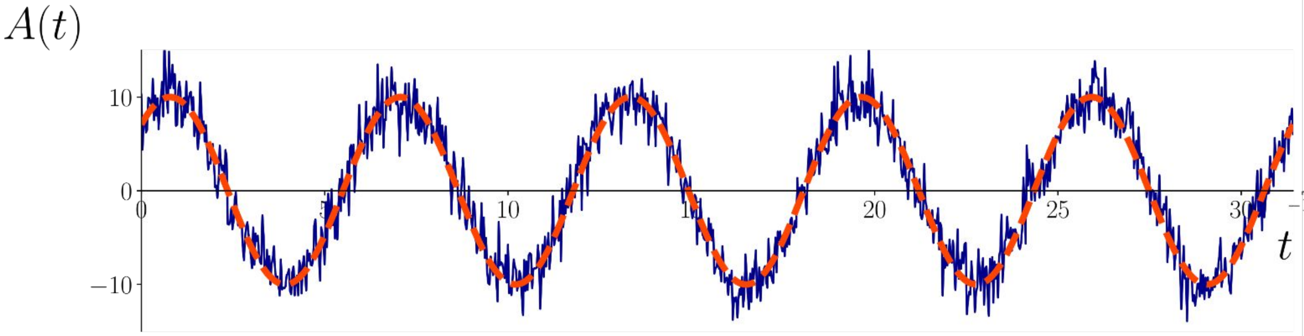
- ❖ Relative **displacement** of end test masses (ETMs) → **phase shift** between light waves reflected from the arms;
- ❖ **No GW signal** = destructive interference on photofdetector → **no photocurrent**
- ❖ **GW signal** = Phase shift between arms → interference on photodetector → **photocurrent** ~ GW strain

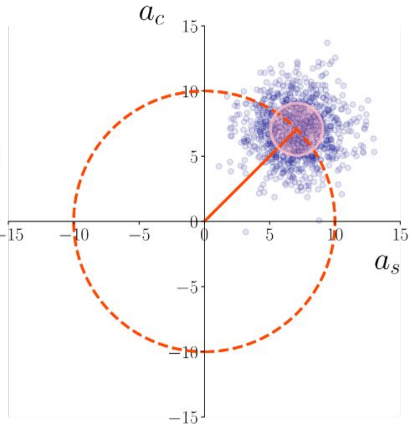
But light is quantum and noisy!



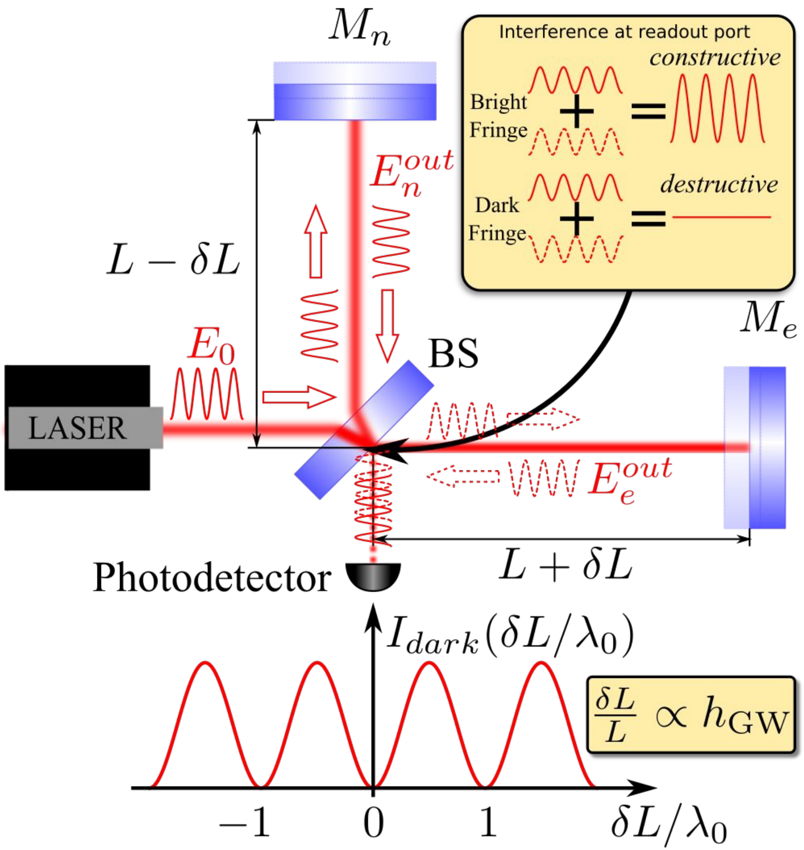
- Light is a flux of particles - **photons**
- Photons arrive at random time - **phase uncertainty**
- Number of photons at given time and place is random - **amplitude/power uncertainty**
- Amplitude and phase uncertainties linked by **Heisenberg relation:**

(Δ Amplitude × (Δ Phase) ≥ ħ

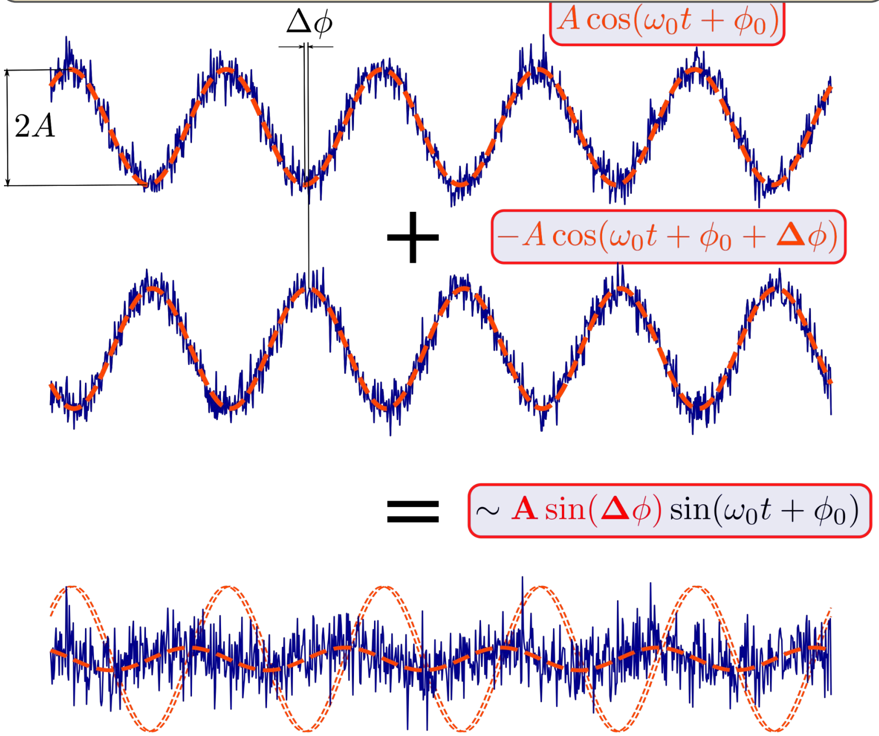




Why is that a problem for phase measurement?



GW sensitivity = how well can one discern two *"fuzzy"* shifted sinusoids

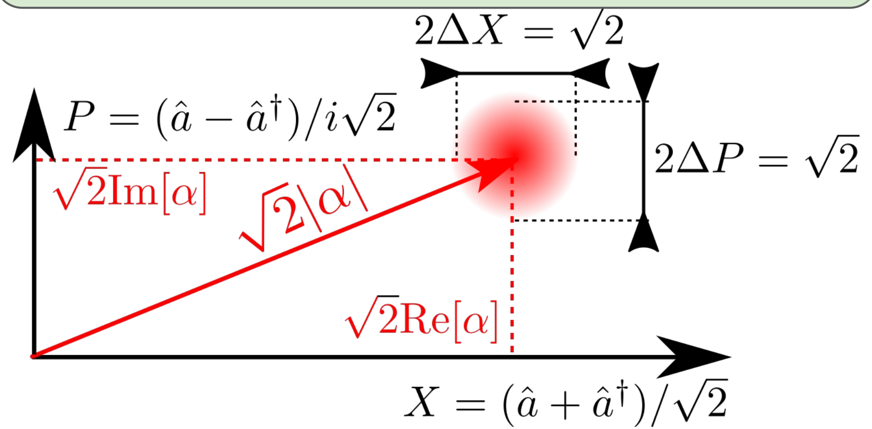


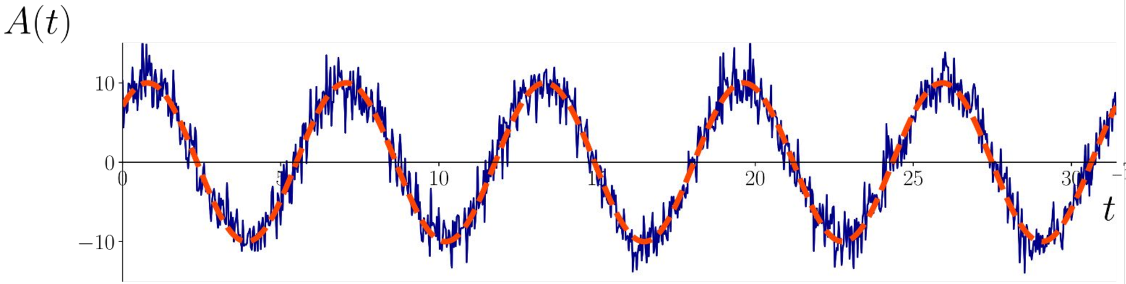
Quantum state of light as phasor diagram

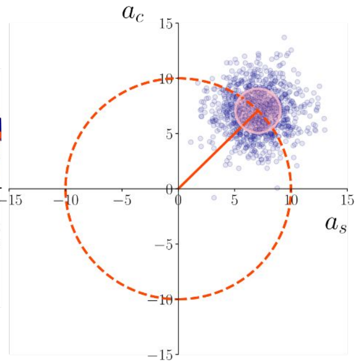
Quantum state of light can be visualised on “coordinate”-”momentum” diagram (phasor diagram)

- ❖ Arrow = classical light (mean value)
- ❖ Fuzzy blob = quantum fluctuations on top of classical mean
- ❖ Blob = 1σ-area of 2D-Gaussian distribution
- ❖ Size along the arrow = Amplitude uncertainty
- ❖ Size across the arrow = Phase uncertainty

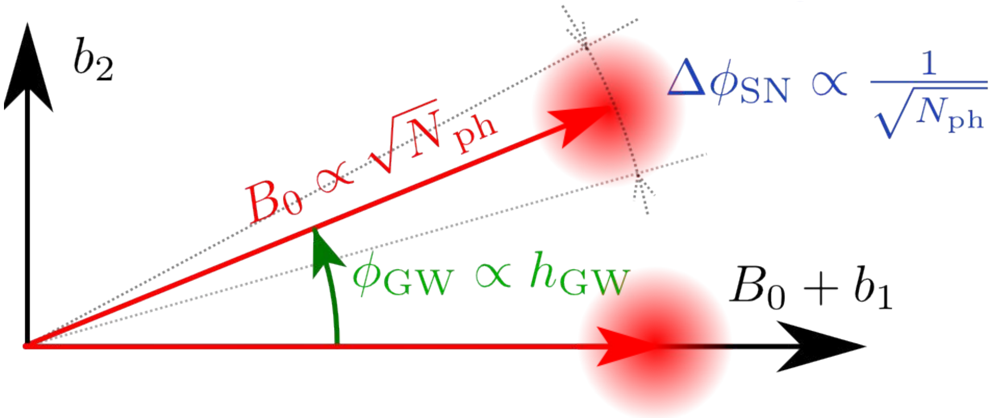
Quantum state of ideal laser light = *coherent state*

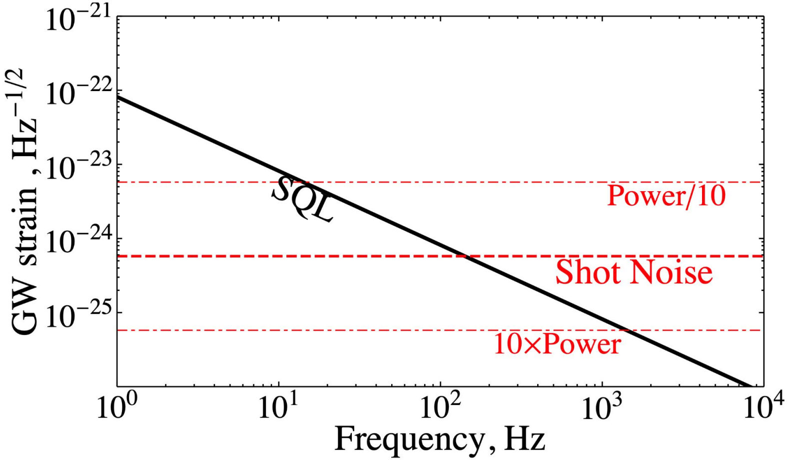






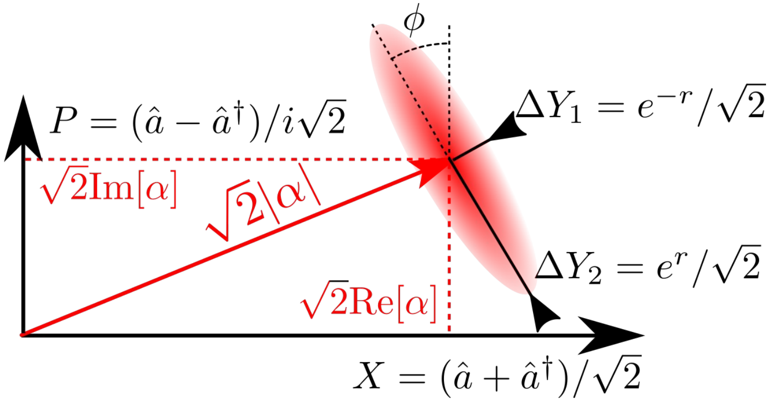
Quantum Shot Noise for coherent state

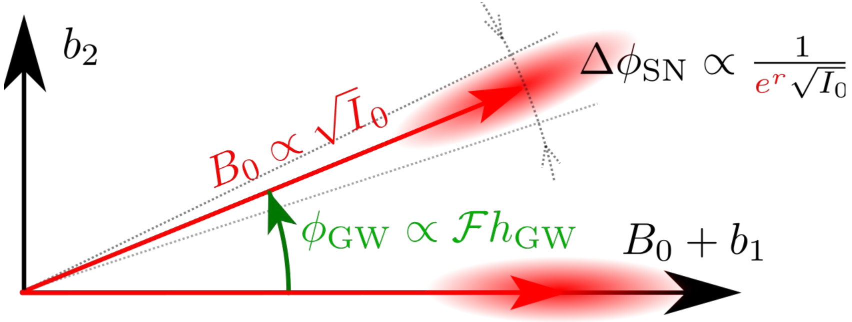




- Measuring phase = discerning angle of rotation of the “blob-on-the-stick”
- Minimum phase resolution = angular size of the “blob” = 1/(classical amplitude) = $1/(N_{ph})^{1/2}$
- This phase measurement uncertainty is the same at all frequencies and times and known as **Quantum Shot Noise (QSN) limit**

Can we do better than QSN limit?

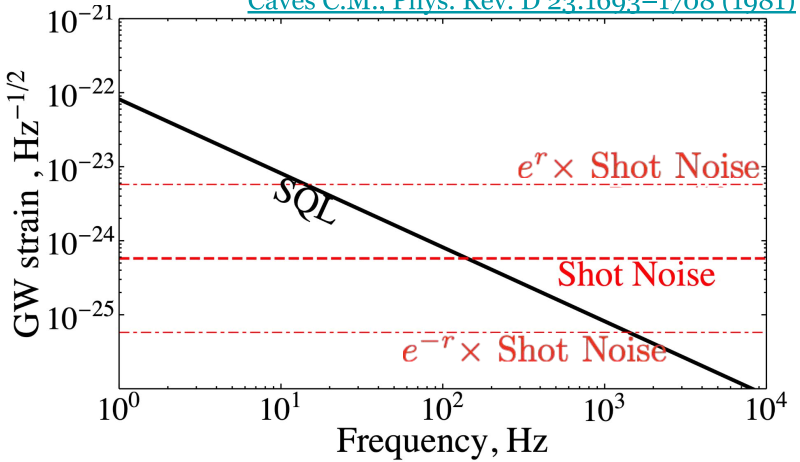




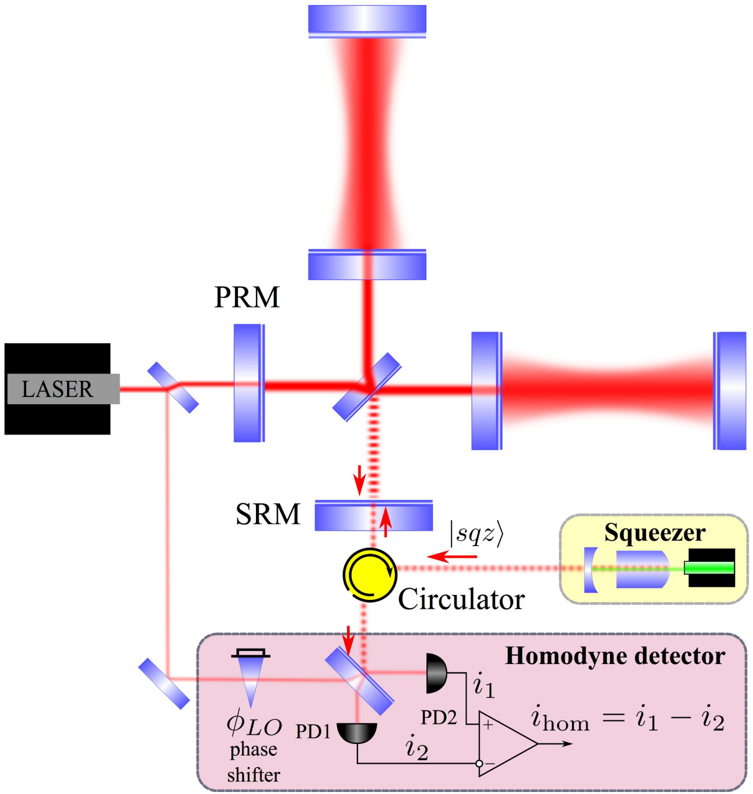
YES, we can!

- Inject **squeezed light** into the interferometer instead of coherent state
- Make sure that light is **squeezed in phase**
- Phase resolution is improved by e^{-r} times
- Squeezing is equivalent to higher power

Unruh, W.G., Phys. Rev. D, 19, 2888–2896,(1979)
Caves C.M., Phys. Rev. D 23:1693–1708 (1981)

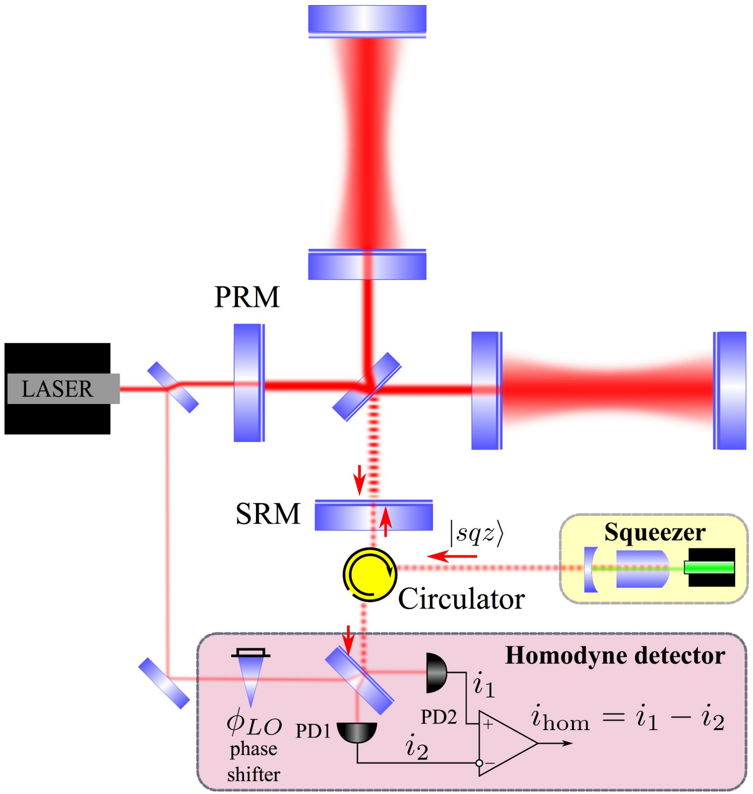


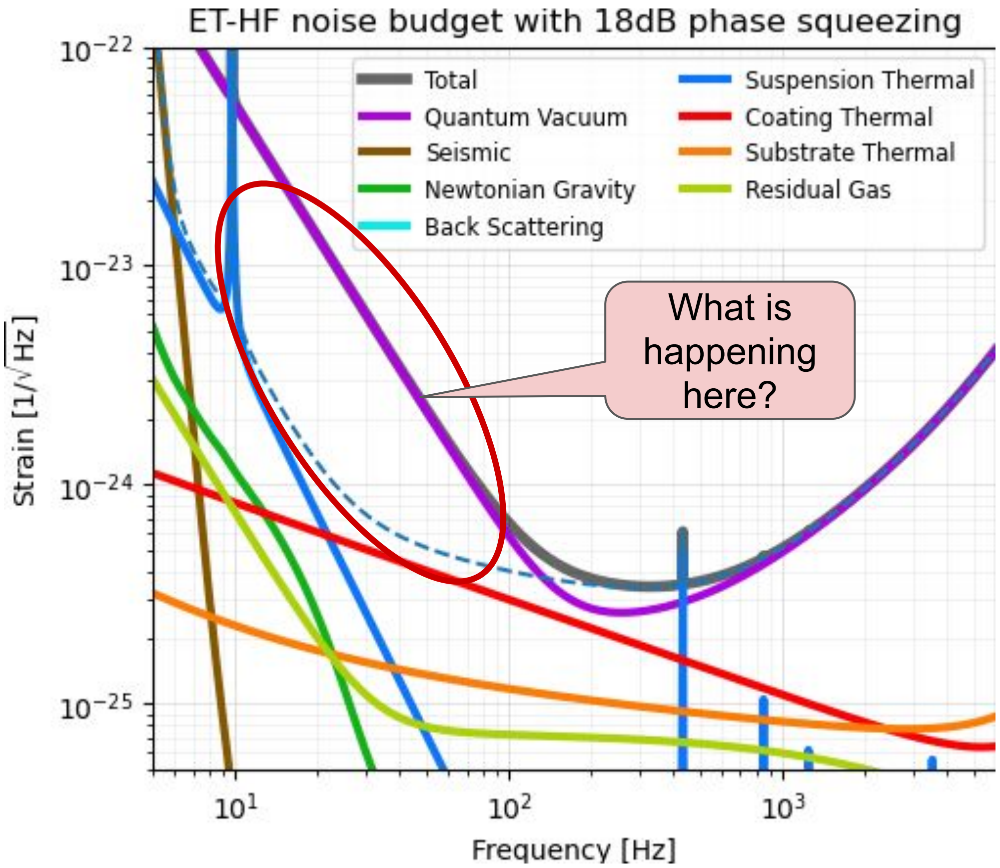
Phase squeezing in GW interferometer



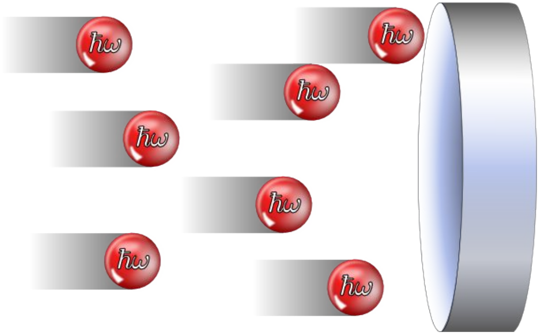
- In GW interferometers, squeezed light is **injected in the detection port**
- It is produced by device, which uses non-linear optical crystal (we'll talk about it later) to generate **squeezed vacuum**
- Phase **squeezed vacuum** enters the interferometer and improves its phase sensitivity by the factor of squeezing, e^{-r}
- But, there is a catch …

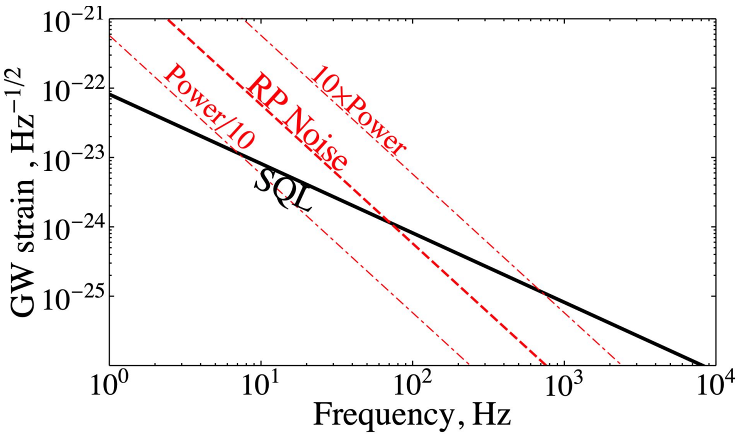
Phase squeezing in GW interferometer





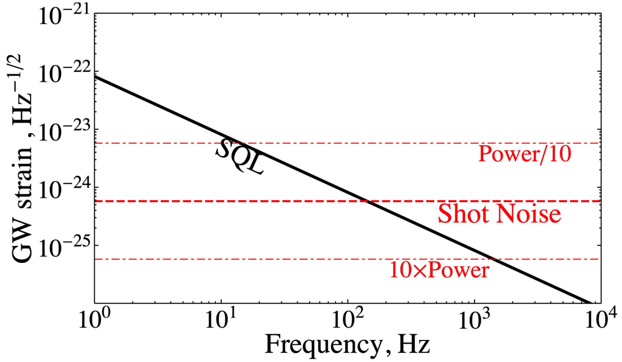
Quantum radiation-pressure noise





- ❖ Photon transfers momentum, $2\hbar k$, to the mirror, when reflected → **radiation-pressure force** on the mirror
- ❖ Random numbers of photons get reflected at each moment → fluctuations of radiation-pressure force → **Quantum Radiation-Pressure Noise (QRPN)**
- ❖ QRPN makes mirror move randomly → random phase shifts → **extra phase uncertainty**
- ❖ QRPN grows with incident power → more photons = more kicks = more QRPN
- ❖ QRPN depends strongly on frequency ~ $1/(\text{Frequency})^2$ → rises sharply and **dominates at low frequencies**, where inertia of the mirror's mass is lower

Standard Quantum Limit



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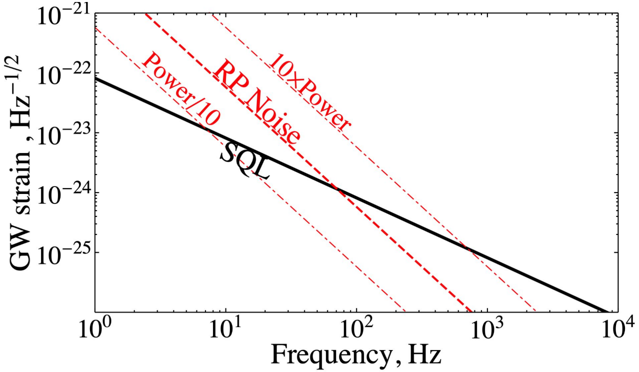

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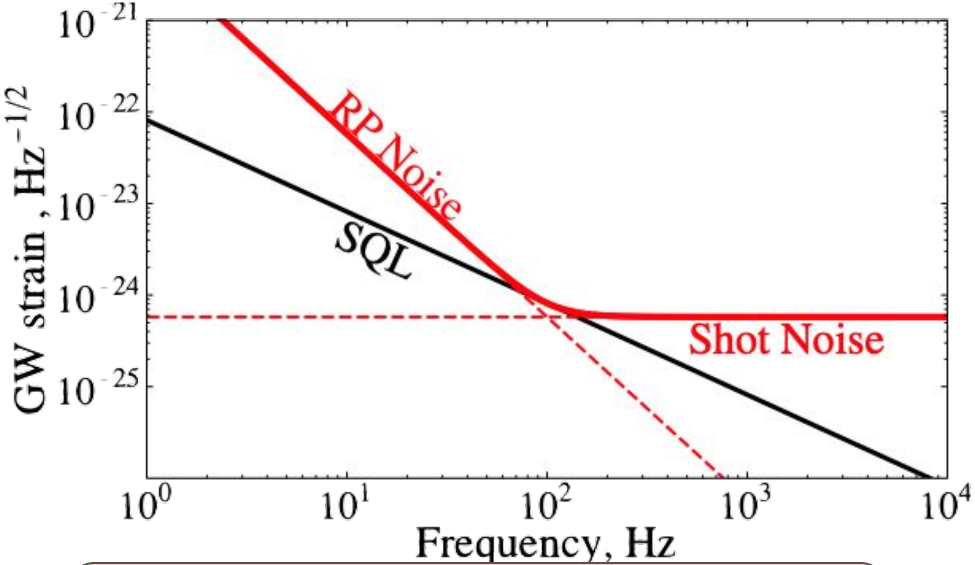
$$\mathrm{QN} = \mathrm{QSN} + \mathrm{QRPN} = \frac{a}{\mathrm{Power}} + b \times \mathrm{Power}$$



$$\min[QN] \xrightarrow[\mathrm{Power} \to \sqrt{a/b}]{} 2\sqrt{ab} = \mathrm{SQL}$$

Reflection point

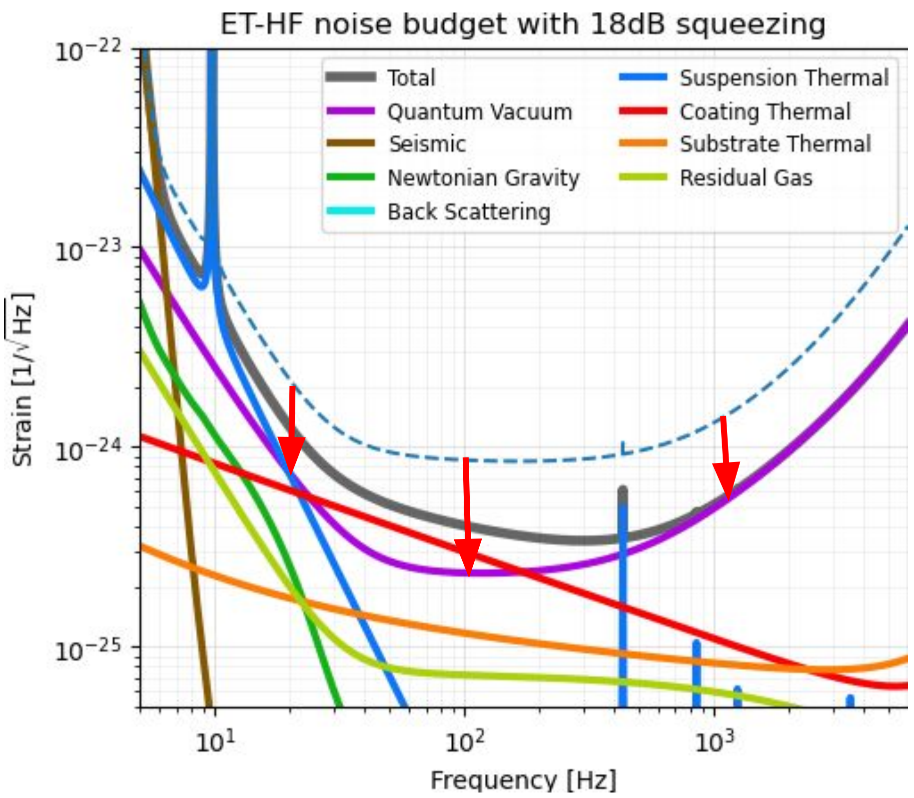
- GW interferometers are, essentially, measuring **phase shift of light**
- Light is quantum and thus has **quantum uncertainties of phase and amplitude**
- These two give rise to **QSN** (phase) and **QRPN** (amp) components of quantum noise, which both **contribute to uncertainty of phase** we try to measure
- **QSN** can be **reduced** either by **increase** of light **power**, or by **injecting phase-squeezed light**
- **QRPN** can be **reduced** either by **decrease** of light **power**, or by **injecting amplitude-squeezed light**
- One can **reduce either QSN or QRPN**, **but not both** → **Standard Quantum Limit**

Is there a way around SQL?

Well, obviously YES!

Otherwise how would one get the ETHF sensitivity like this ⟶

Technique is known as
Frequency-Dependent Squeezing (FDS)

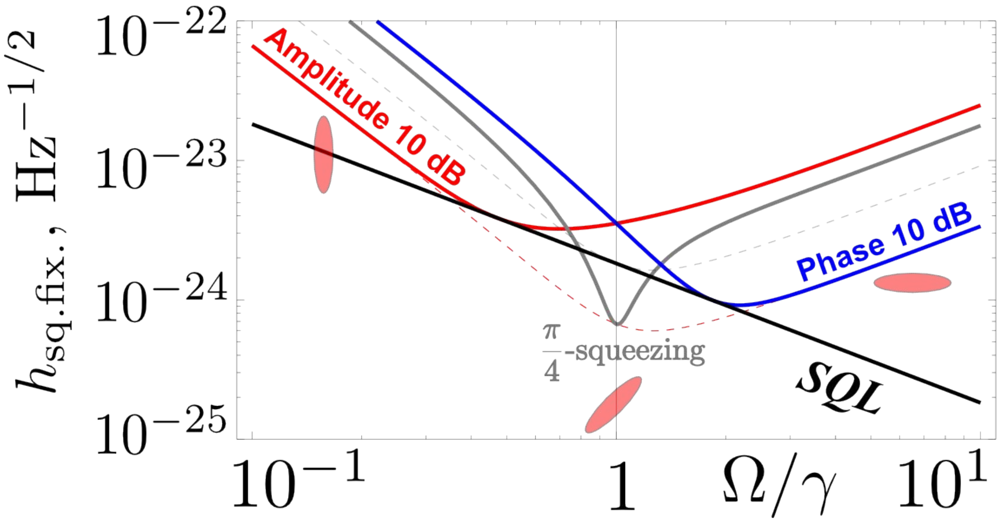


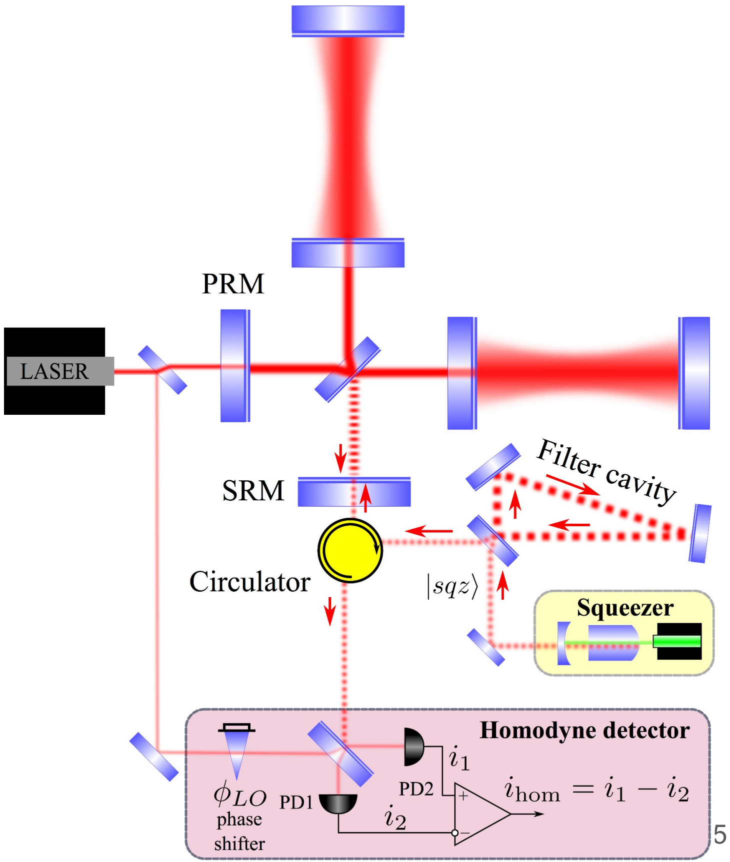
[Kimble HJ, Levin Y, Matsko AB, Thorne KS, Vyatchanin SP, Phys Rev D 65:022002 (2002)]

Frequency-Dependent Squeezing

The idea of **Frequency-Dependent Squeezing (FDS):**

- ❖ Inject phase-squeezed light only where QSN dominates (high frequencies)
- ❖ Inject amplitude-squeezed light where QRPN dominates (low frequencies)
- ❖ Use optical cavity to rotate squeezing ellipse in frequency-dependent way





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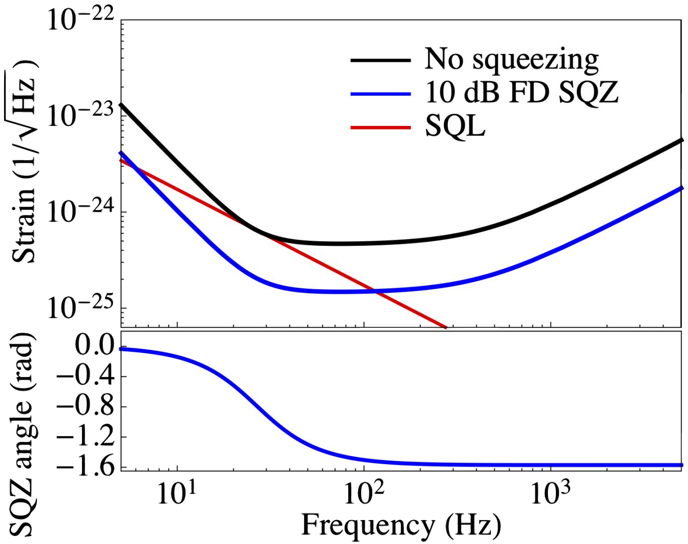
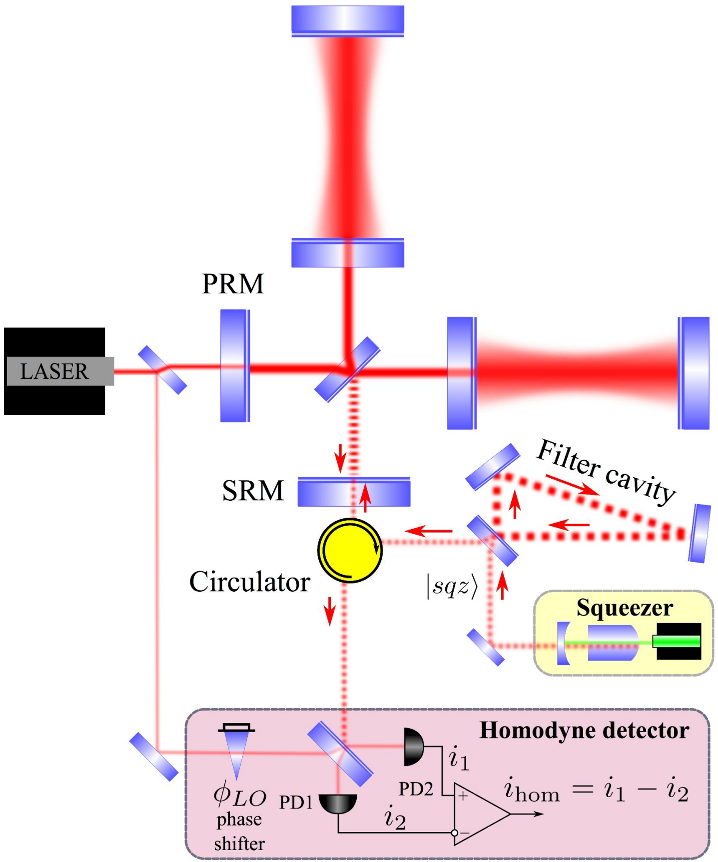


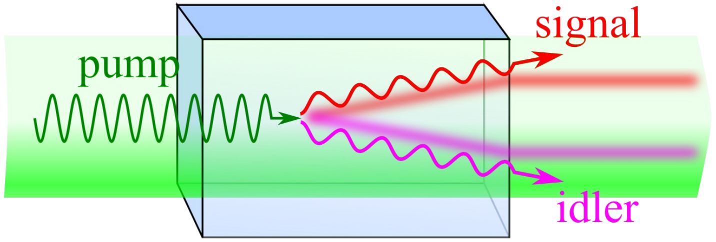


But how does one squeeze light?

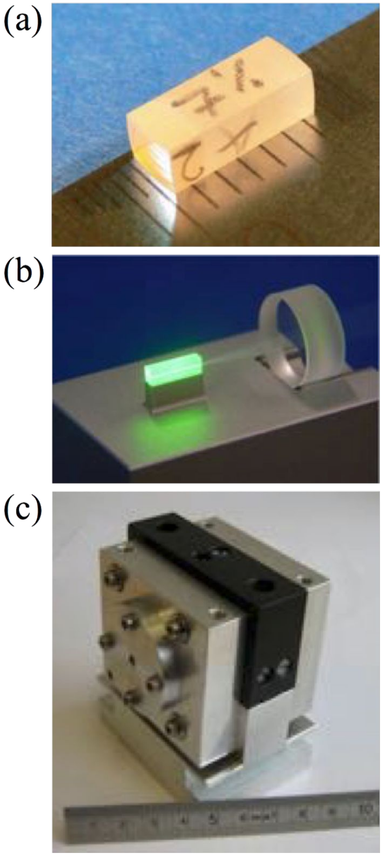
Squeezing is the result of light interaction with **optical (Kerr) non-linearity**

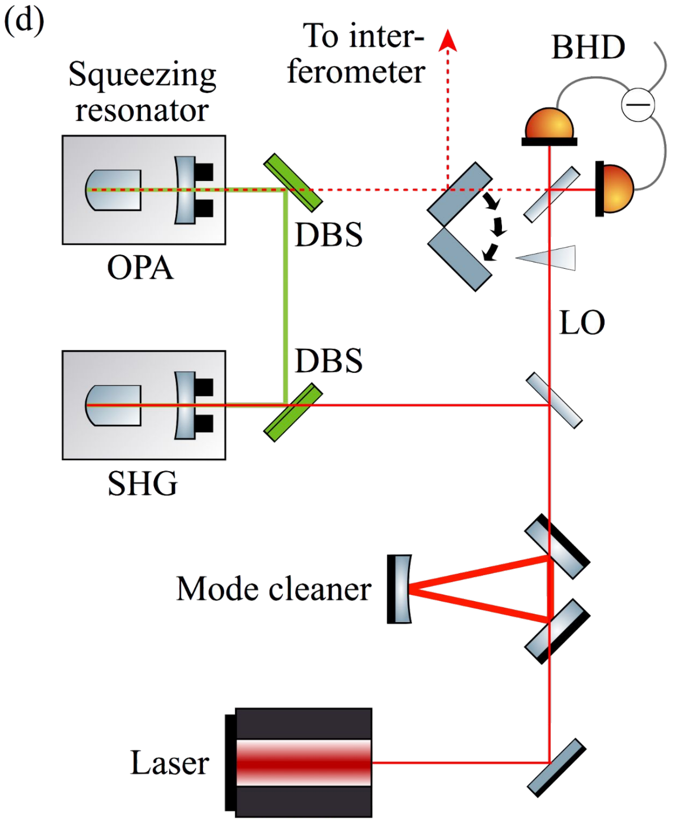
Resulting in the process known as **Parametric Down-Conversion (PDC)**

$$P_{nl} = \epsilon_0 \chi^{(2)} E^2(t)$$



$$2\omega_p = \omega_s + \omega_i$$





from R. Schnabel Phys. Rep. 684, 1 (2017)

Physics of squeezing

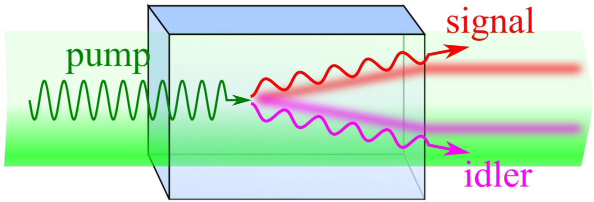
Maastricht University
Nikhef

Light traveling through medium induces polarisation (dipole moment per unit volume) which is nonlinear (NL) in electric field:

$$P(t) = \epsilon_0 \left[\chi^{(1)} E(t) + \chi^{(2)} E^2(t) + \chi^{(3)} E^3(t) + \ldots\right]$$

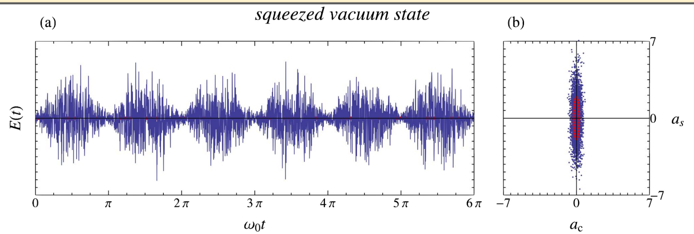
where $\chi^{(n)}$ is the n-order nonlinear susceptibility of the medium

$$P_{nl} = \epsilon_0 \chi^{(2)} E^2(t)$$

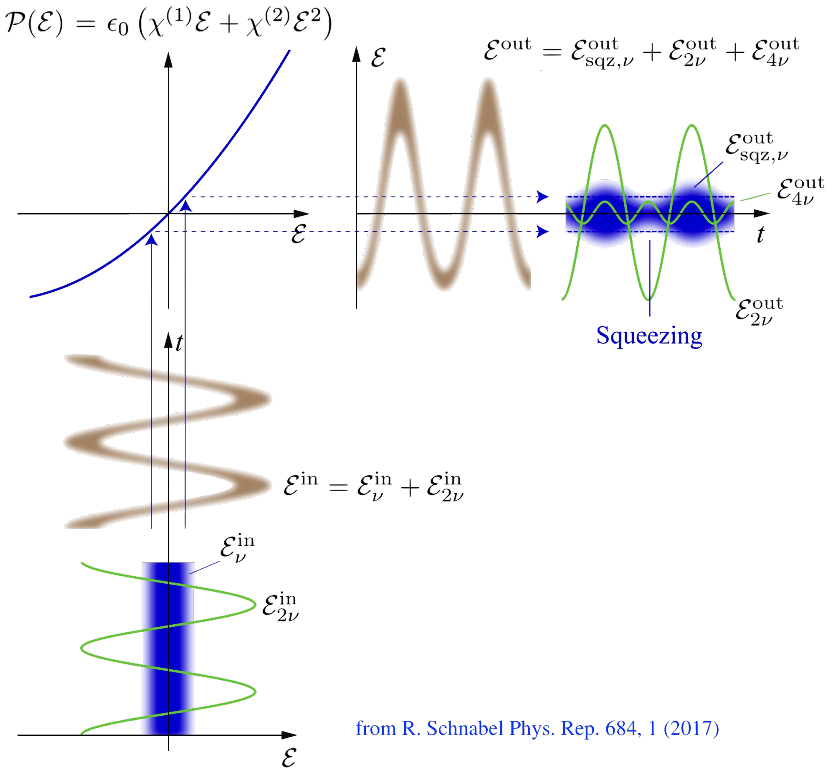


$$2\omega_p = \omega_s + \omega_i$$

- Strong **pump** at double frequency $2\omega_p$ produces correlated pairs of photons in **signal** and **idler** modes in PDC process (Quantum picture)
- Classically, pump field creates periodically (twice per wavelength) modulated refractive index, n(z), for signal and idler fields, which parametrically amplify or deamplify them.



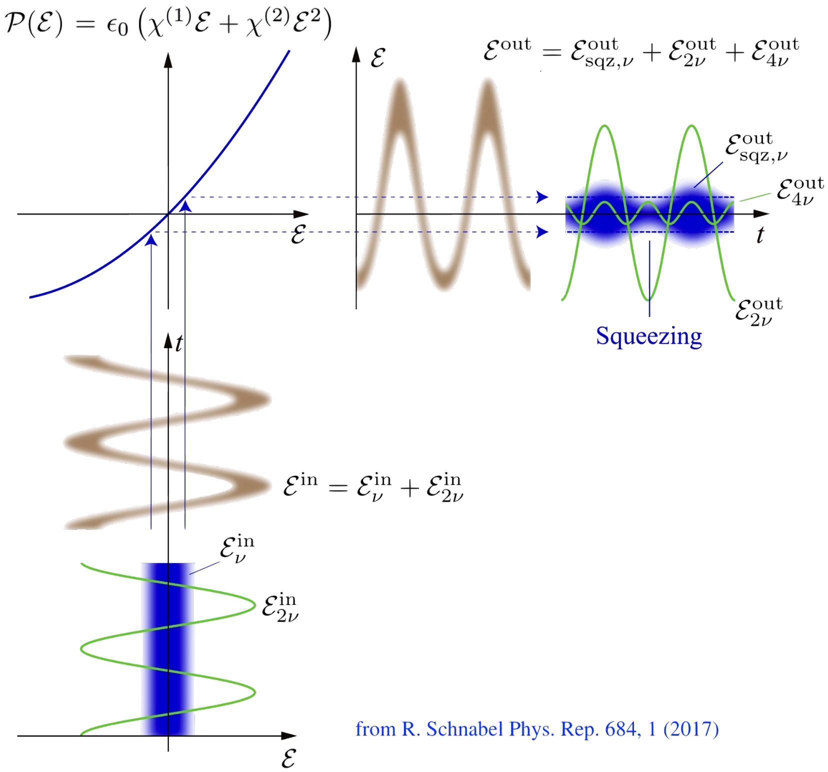
Squeezing as parametric amplification



from R. Schnabel Phys. Rep. 684, 1 (2017)

- Consider weak classical signal mode:
$$\mathcal{E}^{in}_{\omega_0} = S\cos(\omega_0 t + \varphi_0)$$
and strong pump mode:
$$\mathcal{E}^{in}_{2\omega_0} = P\cos(2\omega_0 t)$$
- Linear polarisation $P_{lin}(\mathcal{E}_{in}) = \varepsilon_0\chi^{(1)}\left(\mathcal{E}^{in}_{\omega_0} + \mathcal{E}^{in}_{2\omega_0}\right)$:
$$\varepsilon_0\chi^{(1)}\Big(S\cos(\omega_0 t + \varphi_0) + P\cos(2\omega_0 t)\Big)$$
- Non-linear polarisation $P_{nl}(\mathcal{E}_{in}) = \epsilon_0\chi^{(2)}\left(\mathcal{E}^{in}_{\omega_0} + \mathcal{E}^{in}_{2\omega_0}\right)^2$
$$\epsilon_0\chi^{(2)}\Big\{\frac{1}{2}S^2\left[1+\cos(2\omega_0 t + 2\varphi)\right] + \frac{1}{2}P^2\left[1 + \cos 4\omega_0 t\right]$$
$$-PS\left[\cos(\omega_0 t - \varphi) + \cos(3\omega_0 t + \varphi)\right]\Big\}$$

Squeezing as parametric amplification



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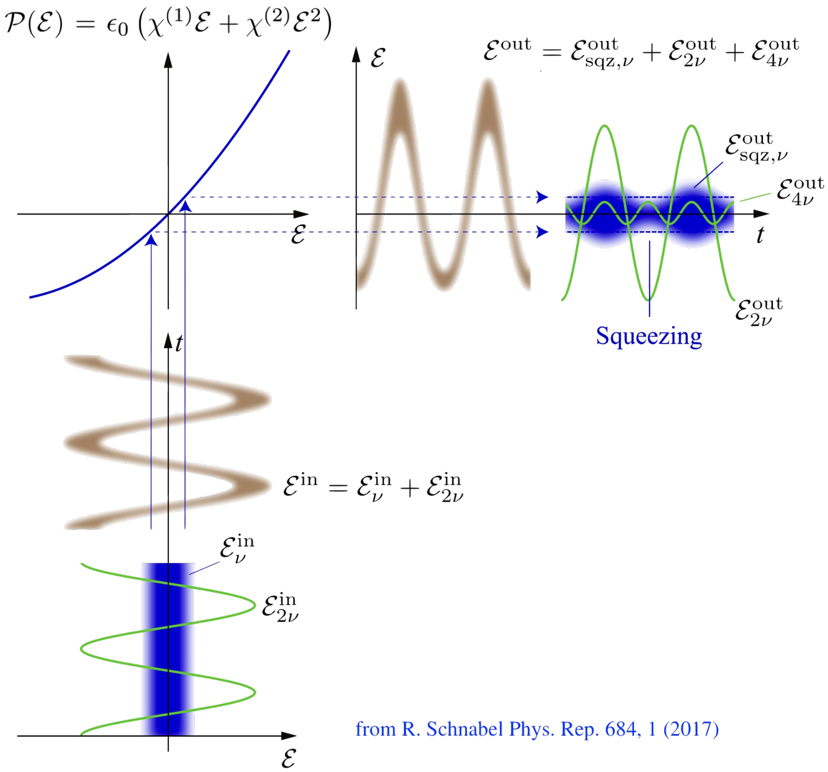

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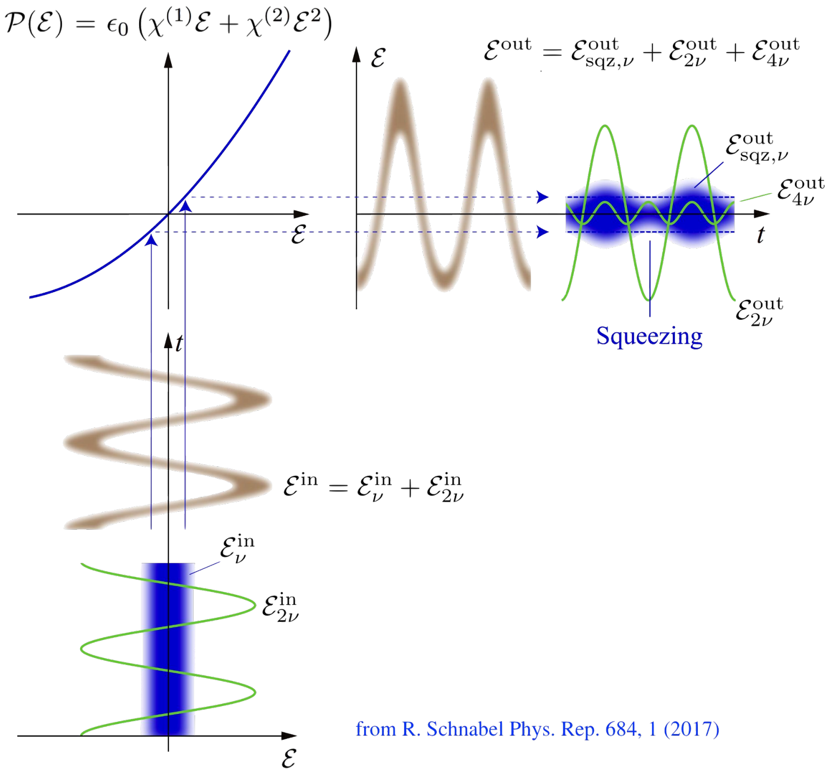

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- Non-linear polarisation $P_{nl}(\mathcal{E}_{in}) = \epsilon_0\chi^{(2)}\left(\mathcal{E}^{in}_{\omega_0} + \mathcal{E}^{in}_{2\omega_0}\right)^2$

$$\epsilon_0\chi^{(2)}\left\{\frac{1}{2}S^2\left[1+\cos(2\omega_0 t + 2\varphi_0)\right] + \frac{1}{2}P^2\left[1+\cos 4\omega_0 t\right] - PS\left[\cos(\omega_0 t - \varphi_0) + \cos(3\omega_0 t + \varphi_0)\right]\right\}$$

Squeezing as parametric amplification

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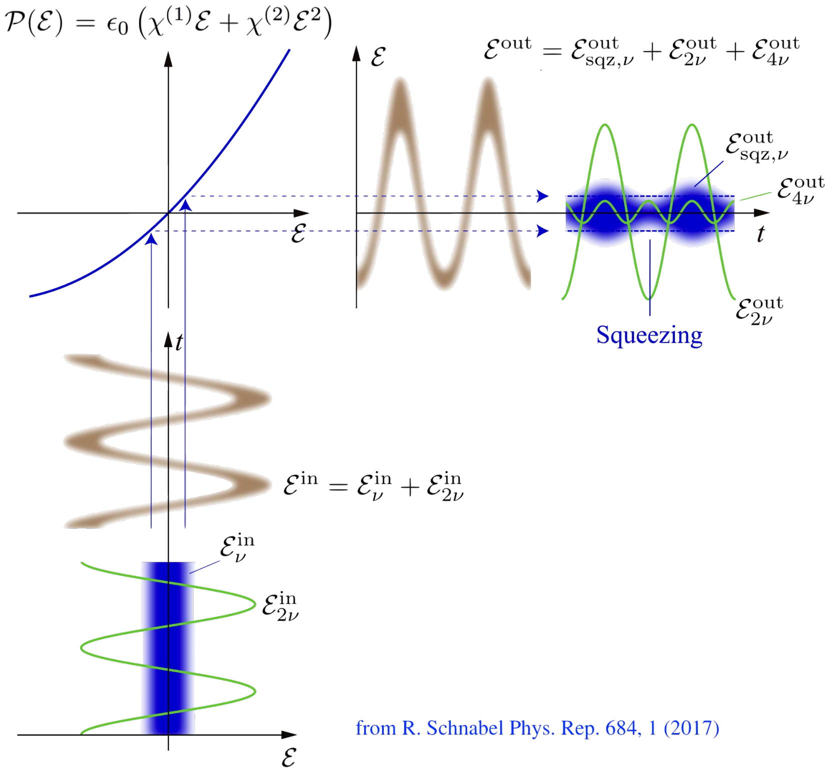

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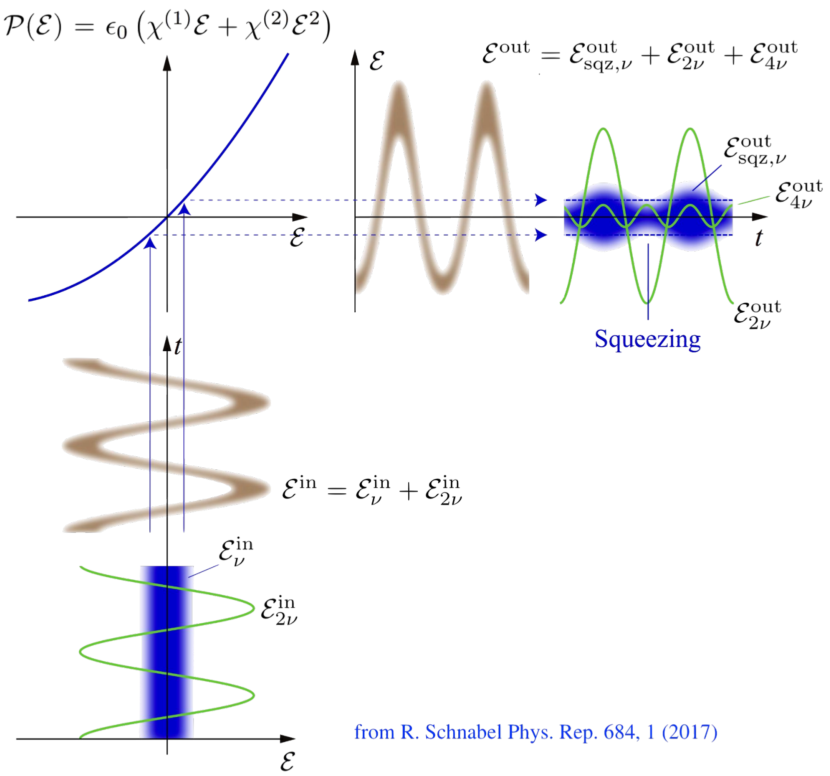
$$\left. -PS\left[\cos(\omega_0 t - \varphi_0) + \cos(3\omega_0 t + \varphi_0)\right]\right\}$$

- ω_0-Components of $P_{lin}(\mathcal{E}_{in})|_{\omega_0}$ and $P_{nl}(\mathcal{E}_{in})|_{\omega_0}$ interfere to (de-)amplify the signal dep. on φ_0

$$P(\mathcal{E}_{in})|_{\omega_0} = \varepsilon_0\left\{\chi^{(1)}S\cos(\omega_0 t+\varphi_0) - \chi^{(2)}PS\cos(\omega_0 t-\varphi_0)\right\}$$

Squeezing as parametric amplification



from R. Schnabel Phys. Rep. 684, 1 (2017)

$$P(\mathcal{E}_{in})|_{\omega_0} = \varepsilon_0\left\{\chi^{(1)} S\cos(\omega_0 t+\varphi_0) - \chi^{(2)} P S\cos(\omega_0 t-\varphi_0)\right\}$$

- Amplification happens when $\varphi_0 = \pi/2,\ 3\pi/2,\ \ldots$ with amplification (anti-squeezing) factor:

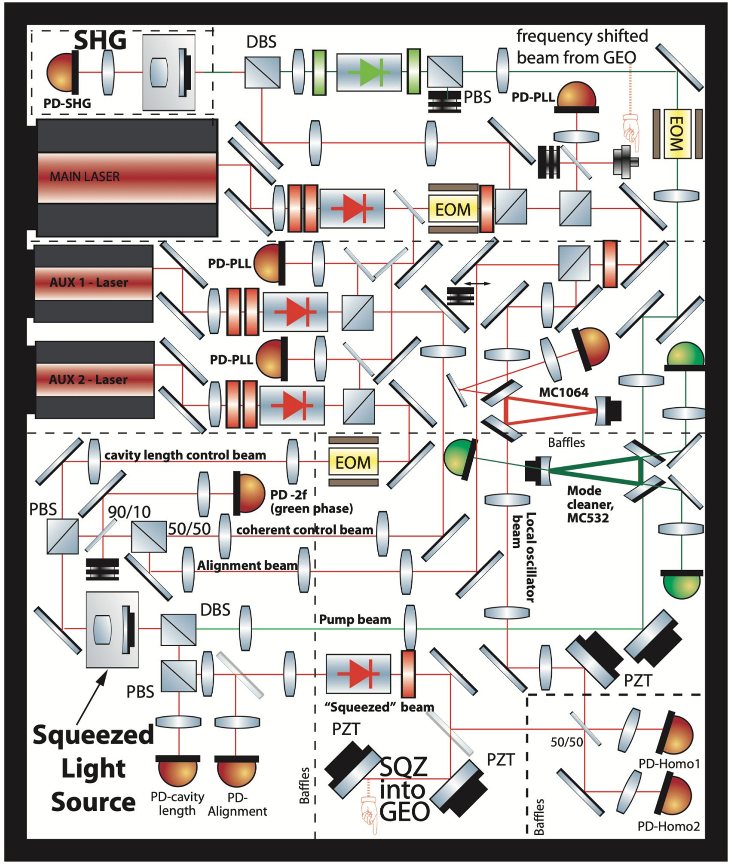
$$e^{r} = 1 + \frac{\chi^{(2)}}{\chi^{(1)}} P$$

- De-amplification corresponds to $\varphi_0 = 0,\ \pi,\ \ldots$ and de-amplification (squeezing) factor:

$$e^{-r} = 1 - \frac{\chi^{(2)}}{\chi^{(1)}} P$$

- Phase, $\varphi_0 = kx$, defines where in the NL crystal signal field gets amplified and where de-amplified

Squeezing in GW detectors



Naturally, real squeezer is much more complex and intricate than just a simple slab of nonlinear crystal.

- For one, optical nonlinearity is extremely small. One needs to enhance amplification by enclosing NL medium in the high-finesse cavity to increase interaction path;
- Also, the phase matching conditions must be maintained for the pump and the signal over the front of Gaussian beam, which requires special design of nonlinear crystal (periodic poling)

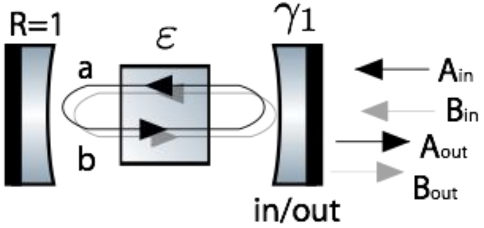


Image courtesy: M. Mehmet & H. Vahlbruch

- Sensitivity of current (LIGO, Virgo, KAGRA, GEO600) and future (ET & CE) GW interferometers is limited by Quantum Noise in a very wide range of frequencies;
- To achieve design sensitivity, we relate on advanced quantum techniques like injection of squeezed light;
- Squeezing of light is the consequence of Heisenberg Uncertainty Principle and quantum nature of light
- Generation of squeezed light is based on parametric amplification/de-amplification effect in non-linear medium and requires intricate, carefully built optical squeezers
- To fully use squeezing potential, one has to use Frequency-Dependent squeezing injection by means of long additional filter cavities.

THANK YOU

FOR YOUR ATTENTION!