OUTPUT ANTISQUEEZING

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GWADW 2015 May 17-22, 2015 Girdwood, Alaska

Gravitational Waves' Interferometric Detectors as Squeezers

$$S_h = \frac{h_{SQL}^2}{2}\left(\mathcal{K} + \frac{1}{\mathcal{K}}\right)$$

Radiation Pressure Noise

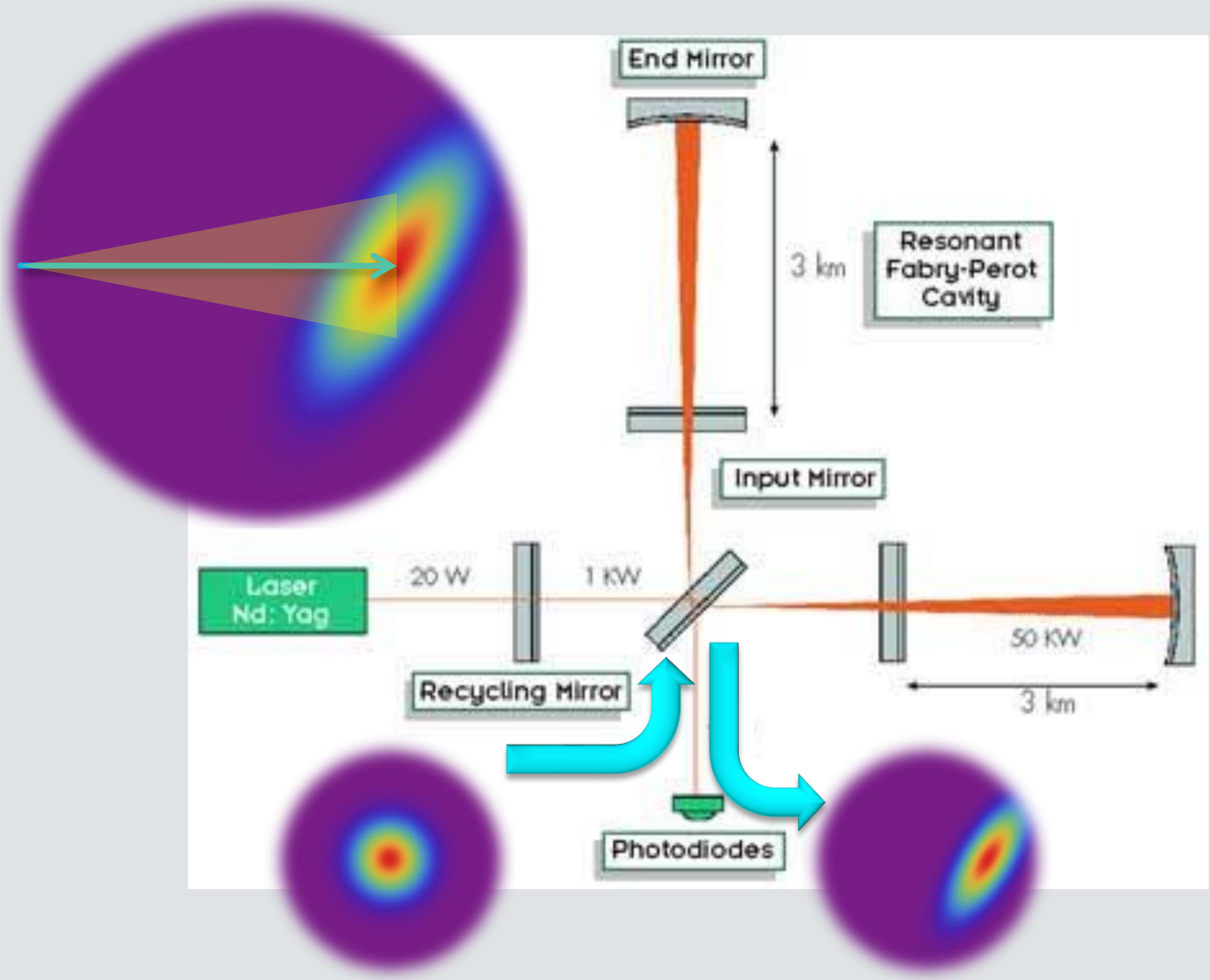
Shot Noise

$$\mathcal{K} = \frac{I_0}{I_{SQL}} \frac{2\gamma^4}{\Omega^2\left(\gamma^2 + \Omega^2\right)}$$

$$I_{SQL} = \frac{ML^2\gamma^4}{2\omega_0}$$

Standard Quantum Limit

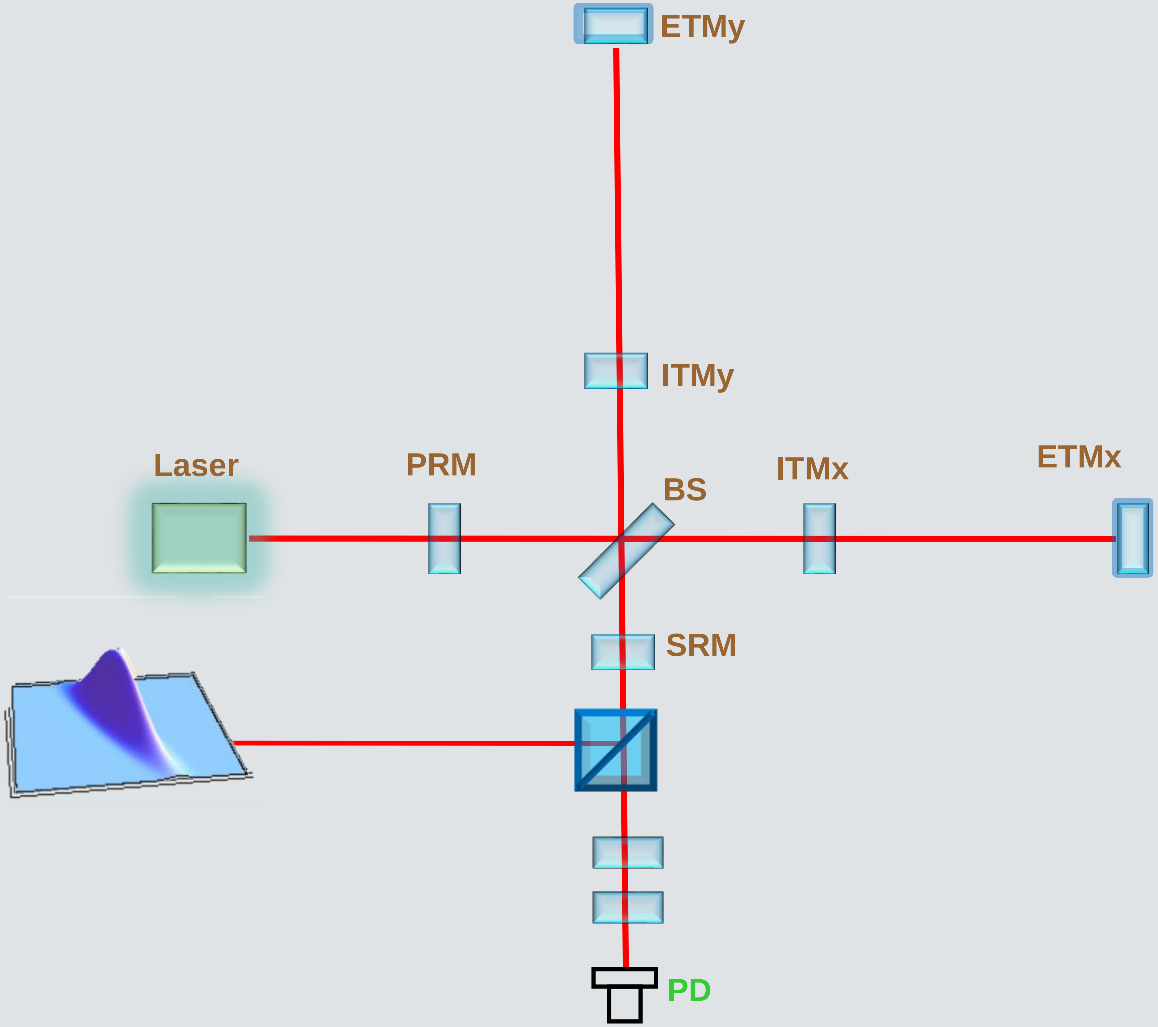
$$h_{SQL} = \frac{2}{\Omega L}\sqrt{\frac{\hbar}{M}}$$



Beating the Standard Quantum Limit

Several stategies for SQL evasion have been proposed:

- Signal recycling
- Optimized quadrature detection (frequency dependent homodyne)
- Injection of a squeezed vacuum in the dark port
- "Optical spring"
- ....
- In each case there is a more or less direct connection with squeezed states of light produced by or injected in the detector
- Squeezing state injection is tested now



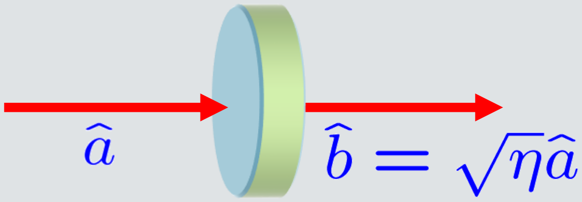
Optical Losses

Losses are unavoidable in a real optical apparatus:

- Absorption of the materials which interact with light
- Scattering

How to describe this at a quantum level?

Naïve model:

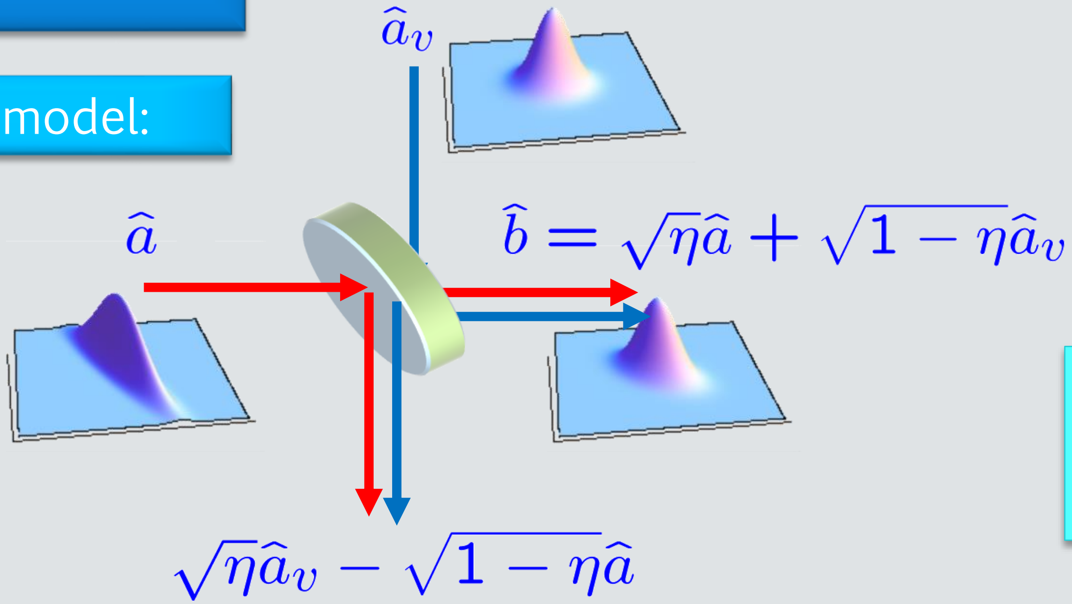


<u>Not consistent</u> commutation rules are not preserved:

$$[\hat{a}, \hat{a}^{+}] = 1$$

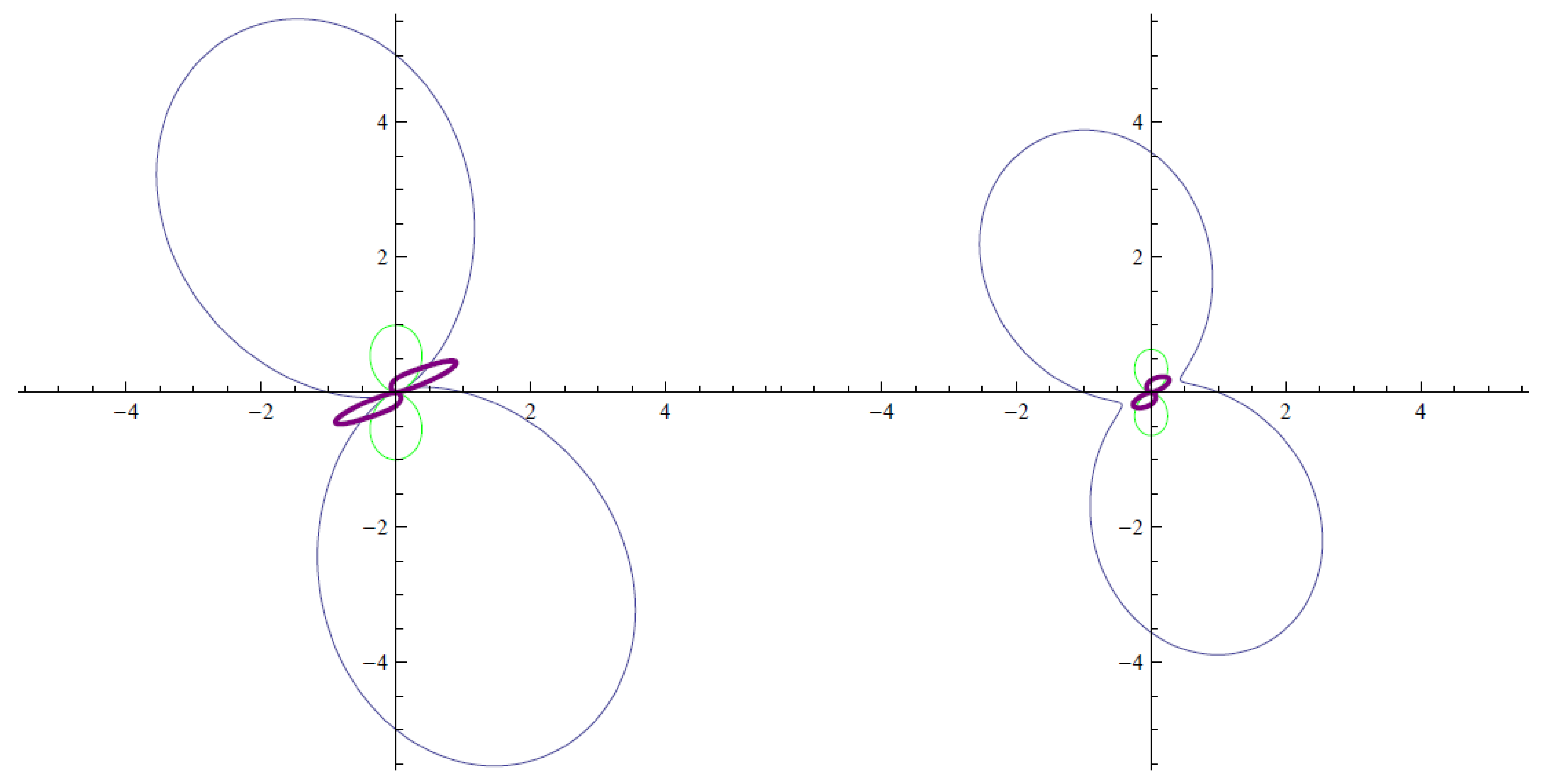
$$[\hat{b}, \hat{b}^{+}] = \eta \neq 1$$

Consistent model:



A squeezed states is easily destroyed by losses

SNR Reduction



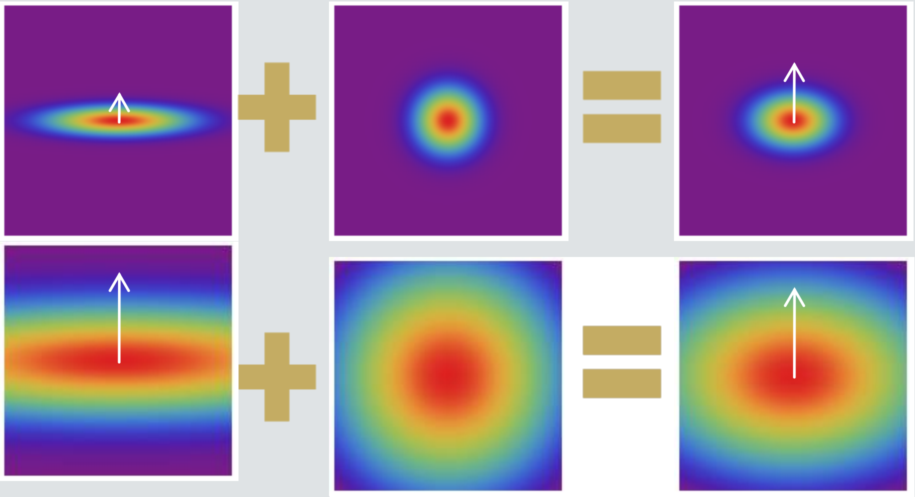
Polar representation of SNR^2 when $K = 2$ and $T = 1$ (left) or $T = 0.8$ (right). The squared signal is in green, the squared noise in blue and the SNR^2 is in violet.

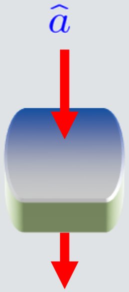
Amplification and Quantum Mechanics

- **Most obvious approach:**
amplify the signal <u>before</u> the losses

- **Naive implementation does not work**
not compatible with Quantum Mechanics rules

- **Solution:**
amplify one quadrature at the expense of the other

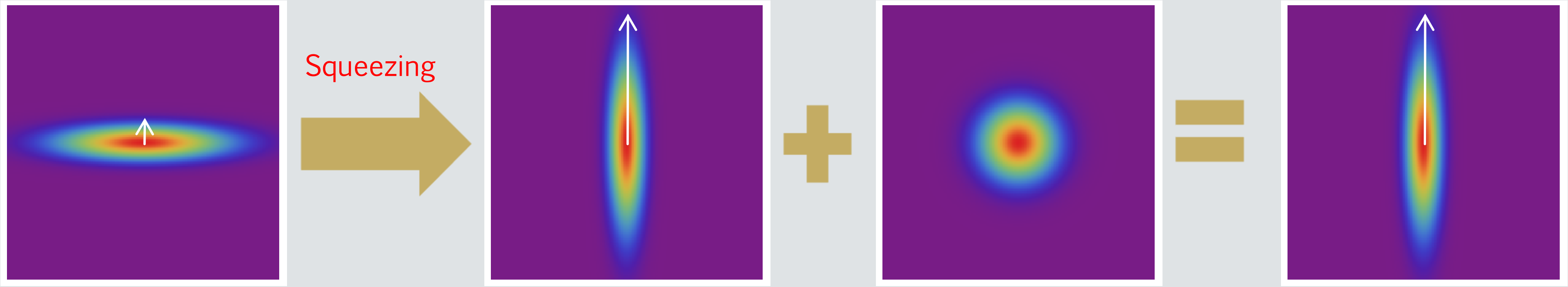




$$\hat{b} = \alpha\hat{a} + \beta\hat{a}_v + \gamma\hat{a}_v^\dagger$$

$$|\gamma|^2 = |\alpha|^2 + |\beta|^2 - 1$$

Additional fluctuations introduced unacceptable:
squeezing is destroyed again

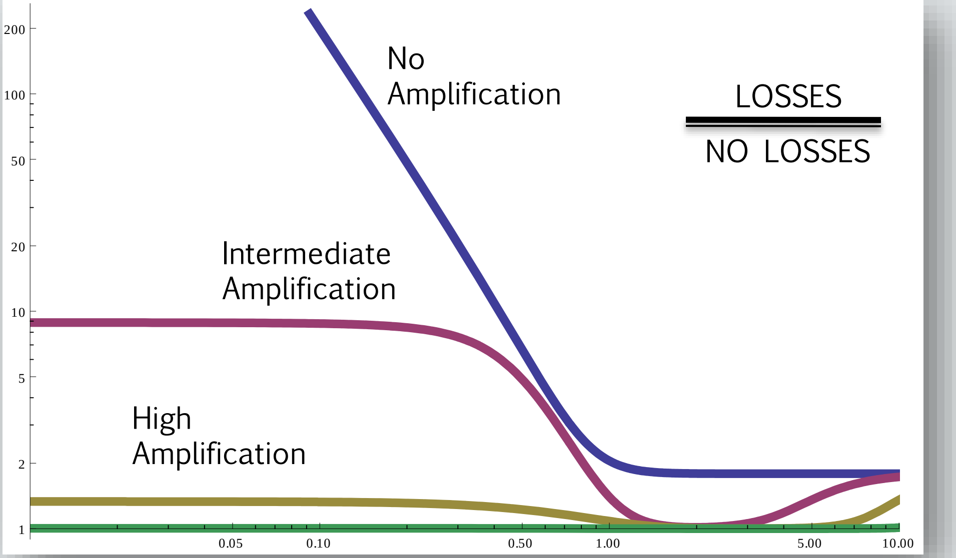


Effect of an (optimal) Quantum Amplification

$$S_h = \frac{h^2_{SQL}}{2}\left[\left(e^{-r}+\frac{\varepsilon^2}{(1-\varepsilon^2)}\right)\frac{1}{\mathcal{K}}+\frac{\varepsilon^2}{(\varepsilon^2 e^{r}+(1-\varepsilon^2)e^{-r})}\mathcal{K}\right]$$

- Simplest application: reduction of the effect of photodiode quantum (in)efficiency
- Low frequency: losses reintroduce radiation pressure noise
- High frequency: losses set a limit on the possible reduction of shot noise

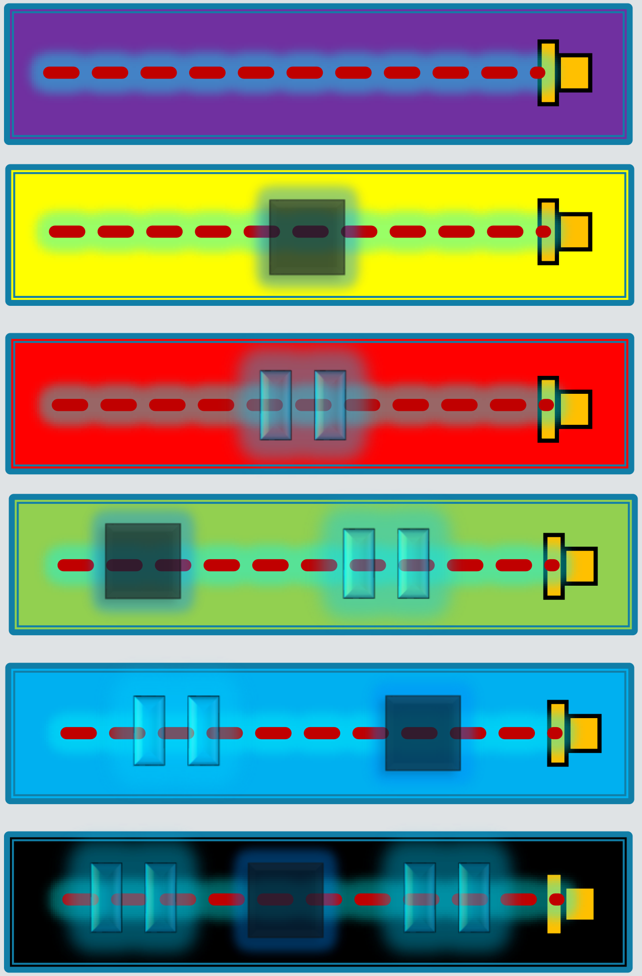
Sensitivity Ratio (r=2)

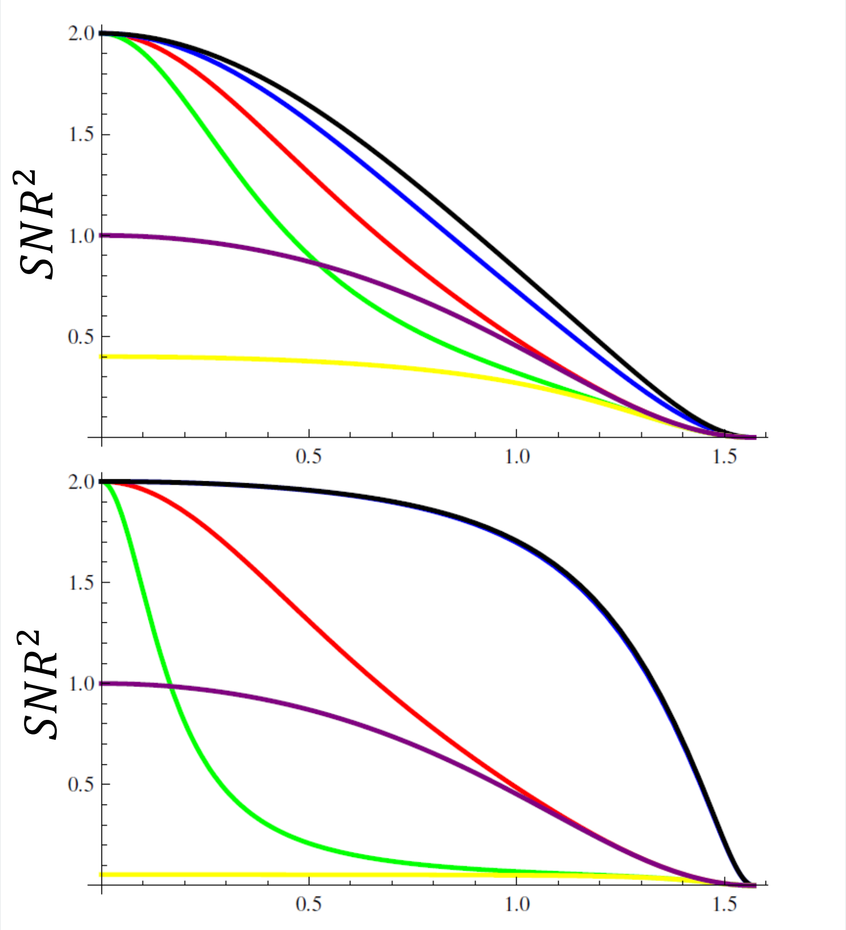


Frequency (in FP cut off frequency units)

Using ponderomotive and detuned cavities as building blocks

SNR^2 reduction as a function of the loss angle, with different strategies.





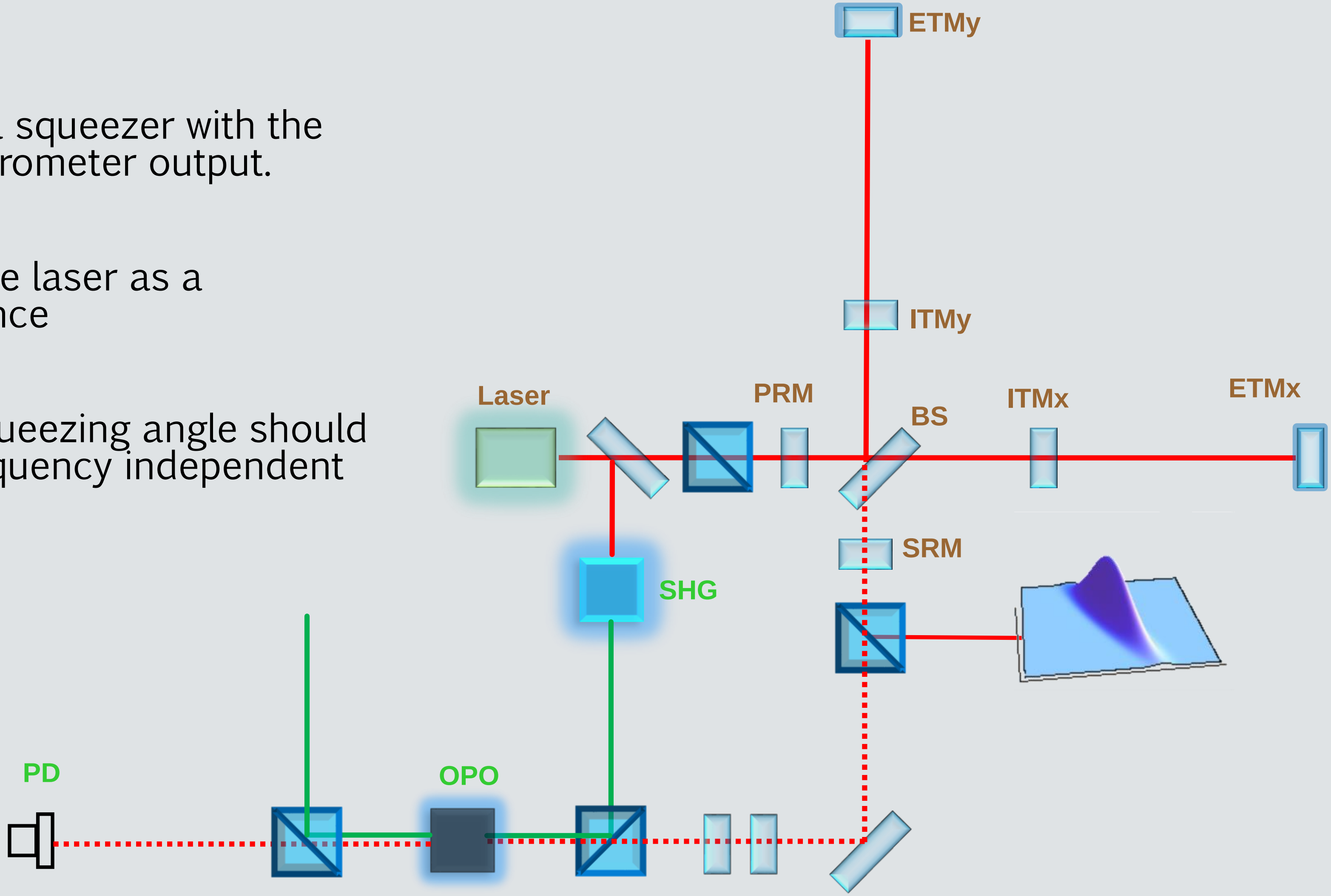
Loss angle θ: $T = \cos\theta$

Implementation: nearly most obvious approach

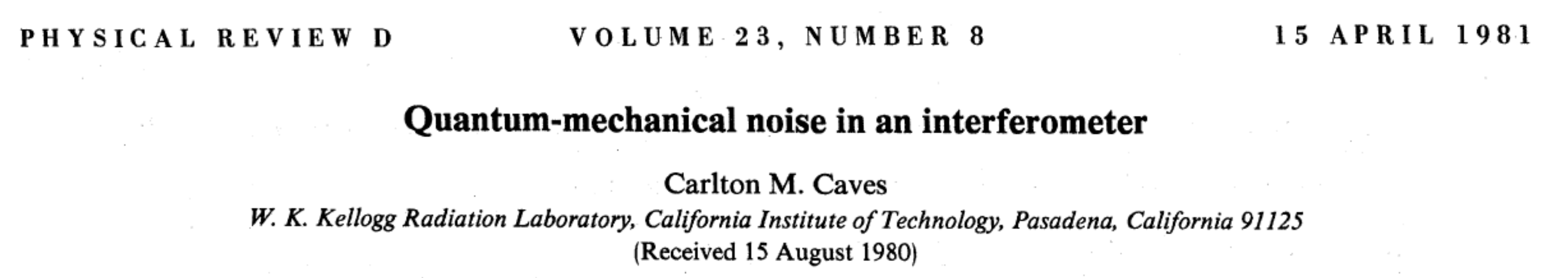
Feed a squeezer with the interferometer output.

Use the laser as a reference

Antisqueezing angle should be frequency independent



…so obvious that it could not be new!



PHYSICAL REVIEW D VOLUME 23, NUMBER 8 15 APRIL 1981

Quantum-mechanical noise in an interferometer

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(Received 15 August 1980)

Many thanks to Lisa for pointing me to the Khalili's presentation at CALTECH which contain the reference

https://dcc.ligo.org/LIGO-G1500313

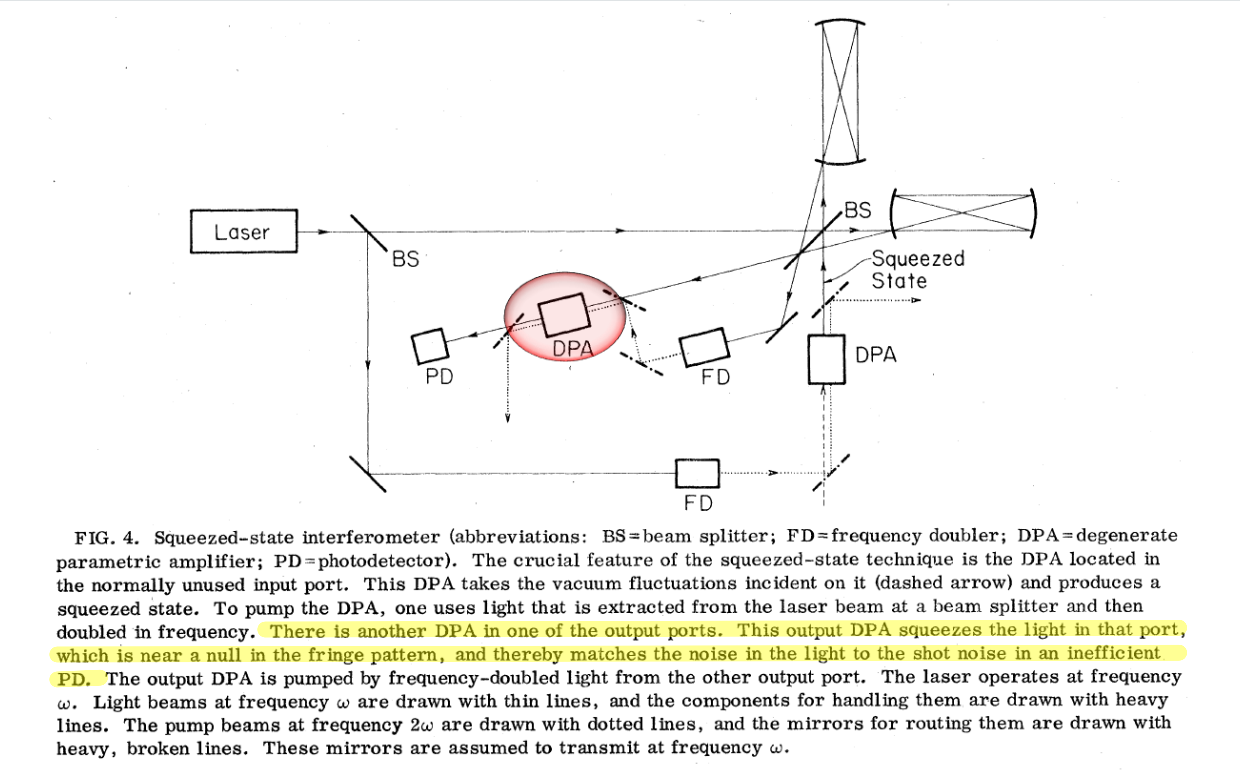
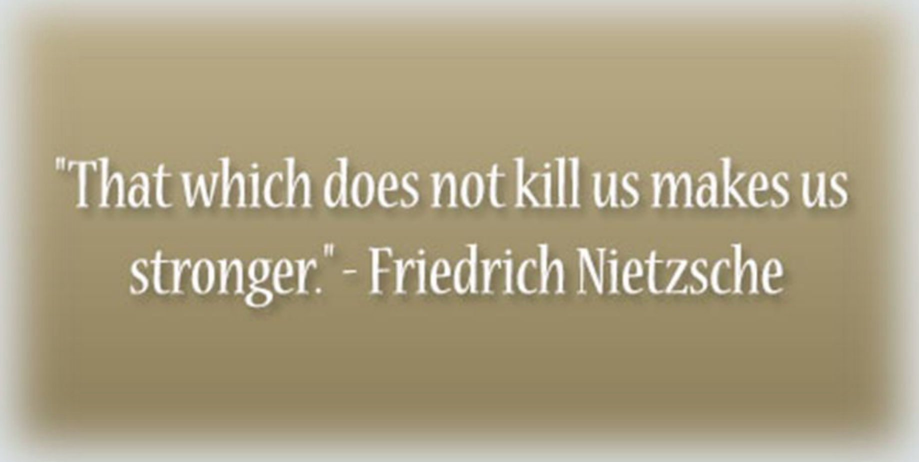


FIG. 4. Squeezed-state interferometer (abbreviations: BS = beam splitter; FD = frequency doubler; DPA = degenerate parametric amplifier; PD = photodetector). The crucial feature of the squeezed-state technique is the DPA located in the normally unused input port. This DPA takes the vacuum fluctuations incident on it (dashed arrow) and produces a squeezed state. To pump the DPA, one uses light that is extracted from the laser beam at a beam splitter and then doubled in frequency. There is another DPA in one of the output ports. This output DPA squeezes the light in that port, which is near a null in the fringe pattern, and thereby matches the noise in the light to the shot noise in an inefficient PD. The output DPA is pumped by frequency-doubled light from the other output port. The laser operates at frequency ω. Light beams at frequency ω are drawn with thin lines, and the components for handling them are drawn with heavy lines. The pump beams at frequency 2ω are drawn with dotted lines, and the mirrors for routing them are drawn with heavy, broken lines. These mirrors are assumed to transmit at frequency ω.

So, I will add myself a philosophical slide



"That which does not kill us makes us stronger." - Friedrich Nietzsche

(I hope)

…we are exploring a few issues now:

- Fill the details

- There are losses in a squeezer
    - How they impact on the antisqueezing performances?
    - Realistically, what can be done now and in the near future

- Injection of a squeezed state in a ponderomotive cavity
    - Could be interesting, in the context of macroscopic ponderomotive experiments?
    - Could give a signature of ponderomotive effects that is (relatively) easy to detect?

Conclusion, and my answer to the «Inspiring Questions»

- Antisqueezing, as discussed, is an effective option to reduce the effects of losses *after the light exits the cavities.*
- It is not an universal solution to losses problems (i.e. intracavity losses)
- Current and near future realistic performances should be evaluated…
- …and tested
- **Q1:** Is this topology/technology ready to be used in GW detectors 10-20 years from now?
  - In my opinion, most probably yes. No really new technology. Difficulty comparable with frequency dependent squeezing.
- **Q2:** Is this topology/technology in particular useful for $> 4km$ (i.e. $10 - 40km$) facilities?
  - In principle yes: increasing length is the most direct way to decrease mirror position fundamental noises compared with the optical one. If squeezing will be the choice for quantum noise, we need to protect at some point the SNR from external losses.
  - But: maybe technology improvements will be able to reduce losses directly.

Thank you for your attention and patience.