Squeezed Light in a Nutshell

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Squeezed Light?

GRAVITY | RESEARCH UPDATE

Quantum squeezing boosts performance of LIGO and Virgo gravitational-wave detectors

10 Dec 2019 Hamish Johnston

Squeezed state-of-the-art: LIGO team members install equipment as part of the squeezed-light upgrade. (Courtesy: LIGO/Caltech/MIT/Matt Heintze)

REVIEW

Squeezed vacuum states of light for gravitational wave detectors

Lisa Barsotti[1], Jan Harms[2,3] and Roman Schabel[4]

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GRAVITATIONAL-WAVE ASTRONOMY

Squeezed Light Success at Virgo

The gravitational-wave observatory near Pisa listens deeper into the cosmos with technology from Hanover

December 05, 2019

A squeezed-light source developed by researchers at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute; AEI) for the Virgo gravitational-wave detector near Pisa has impressively demonstrated its capabilities in recent months. This is shown by the latest data published from the third observation run (O3) of the international detector network. The squeezed-light source reduces the dominant quantum mechanical detector background noise by about one third. This allows Virgo, for example, to detect gravitational waves from merging neutron stars up to 26% more frequently. The use of squeezed light also plays an important role for planned third-generation detectors such as the Einstein Telescope. The squeezed-light source was delivered and commissioned at the beginning of 2018. Since the start of O3 on April 1, 2019, it has provided significantly improved Virgo sensitivity.

Quantum mechanics limits the sensitivity of gravitational-wave observatories

Contents

Prerequisites

QM 101

some optics

Methodology

General picture instead of exact theory

Intended Learning Outcome

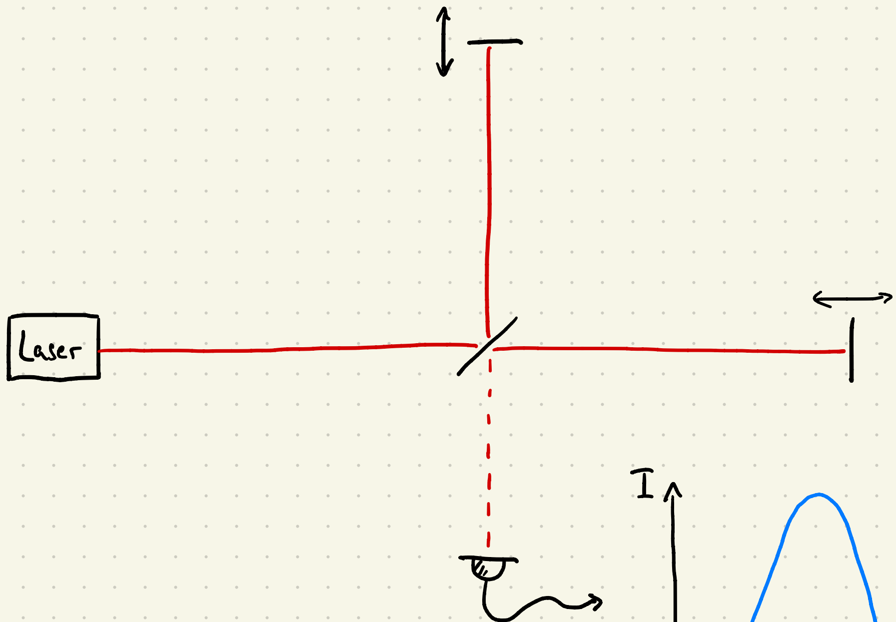
Squeezing isn't magic, but it is still cool.

Technical Details

iPad, GoodNotes & Zoom.

Never tried before, so what could possibly go wrong?!

Michelson Interferometer



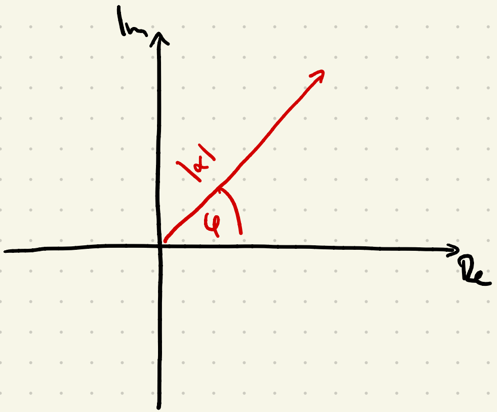
$$\Delta\varphi = \frac{\Delta L}{\lambda} \cdot 2\pi$$

$$I \propto P_{IN} \sin^2(\Delta\varphi)$$

Phasor Diagram

Go to co-rotating frame:

$$\alpha = |\alpha| e^{i\varphi}$$

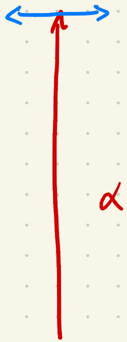


E field $\propto \mathrm{Re}(\alpha)$

$\rightsquigarrow$ Interference becomes simple vector addition

MODULATIONS

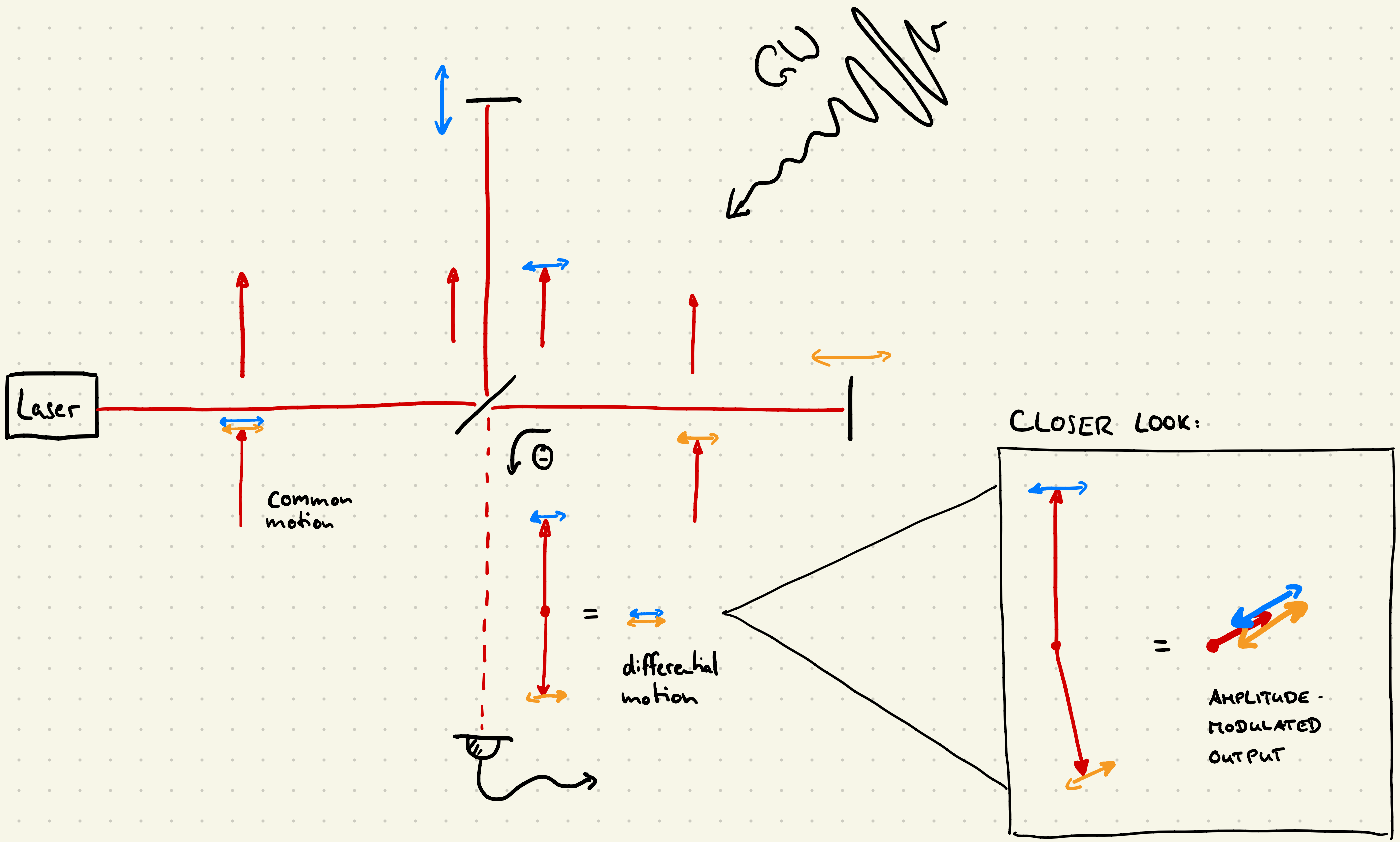
AMPLITUDE MODULATION



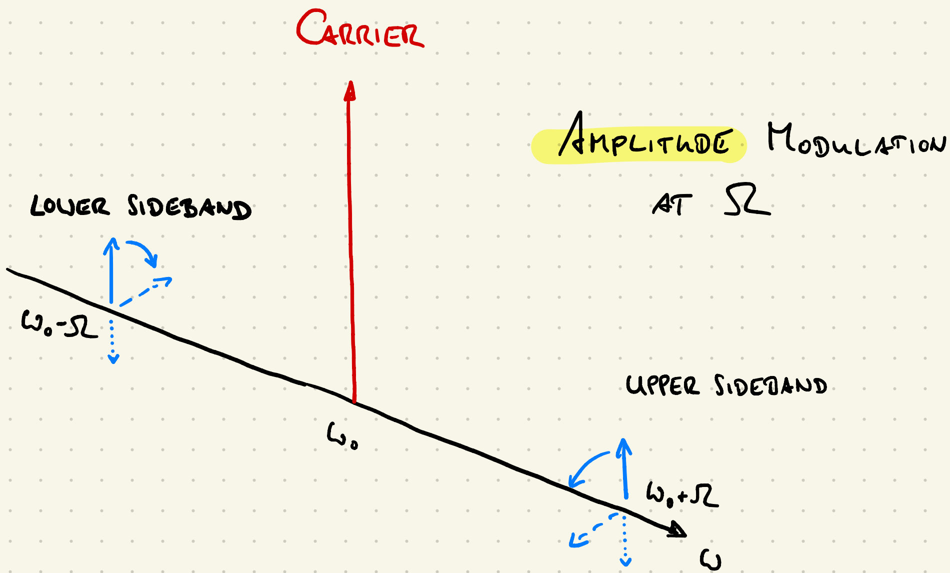
PHASE MODULATION

<u>Assumption</u> Modulation index small, $|\alpha|$ does not change

Signal in Michelson Interferometer



Modulations in the Sideband Picture



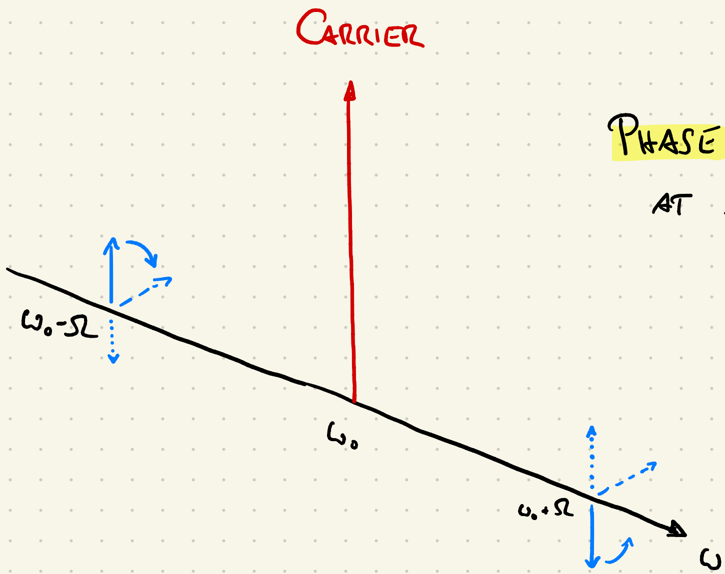
Measurement

$$P \propto |E|^2 = \left|\alpha\left(1 + \frac{m}{2}e^{i\Omega t} + \frac{m}{2}e^{-i\Omega t}\right)\right|^2$$

$$= |\alpha|^2 \left(1 + m\cos\Omega t\right) + O(m^2)$$

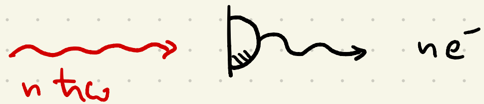
Modulations in the Sideband Picture

Phase Modulation at Ω



Detection and Shotnoise

Can treat the complete interferometer in a classical wave picture, except for the detection step:



Photons uncorrelated (Poisson statistics) $\rightarrow$ $\Delta n = \sqrt{n}$

output $\quad o = \bar{n}\sin^2\varphi$

$$\Delta o = \sqrt{\bar{n}\sin^2\varphi}$$

Signal $\quad \dfrac{\partial o}{\partial \varphi} = \bar{n}\cos(\varphi)\sin(\varphi) \approx \bar{n}\sin(\varphi)$

small φ, close to dark output

SNR $\quad \dfrac{\bar{n}\sin(\varphi)}{\sqrt{\bar{n}\sin^2(\varphi)}} = \sqrt{\bar{n}} = \sqrt{\dfrac{P_{IN}}{\hbar\omega}}$

Quantum Mechanics of Light

Classical field energy $\quad H = \frac{1}{2} \int \left[\varepsilon_0 \vec{E}^2(\vec{r},t) + \frac{1}{\mu_0} \vec{B}^2(\vec{r},t) \right] dV$

It's a harmonic oscillator! $\quad \hat{H} = \frac{1}{2}\left(\hat{p}^2 + \omega^2 \hat{q}^2\right)$

$= \hbar\omega\left(\hat{n} + \frac{1}{2}\right)$ photon number picture

$= \hbar\omega\left(\hat{X}_1^2 + \hat{X}_2^2\right)$ quadrature field picture

$\hat{E} \propto \hat{X}_1 \cos(\omega t) + \hat{X}_2 \sin(\omega t)$

$90°$ out of phase $\hat{=}$ in quadrature

ladder operators

$\hat{a}|n\rangle = \sqrt{n}\,|n-1\rangle$

$\hat{a}^\dagger|n\rangle = \sqrt{n+1}\,|n+1\rangle$

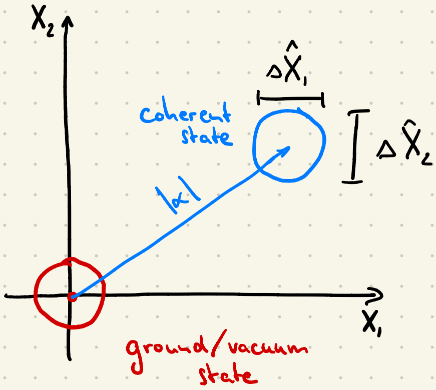
$\hat{n} = \hat{a}^\dagger \hat{a}$

Phase Space Representation

$$\hat{H} = \hbar\omega\left(\hat{n} + \frac{1}{2}\right) = \hbar\omega\left(\hat{X}_1^2 + \hat{X}_2^2\right) \rightarrow \hat{X}_{1,2}^2 \text{ not zero, even for zero photons}$$

"$\frac{1}{4}$ photon in each"

$\frac{\hbar\omega}{2}$ zero-point energy, vacuum fluctuations



"ball-on-stick" picture

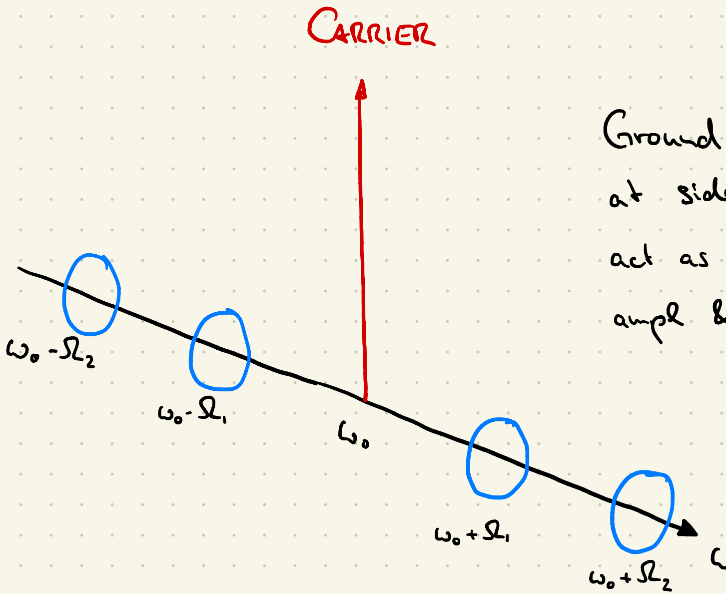
Uncertainty Relations

$$\Delta^2 \hat{X}_1^2 \, \Delta^2 \hat{X}_2 \geq \frac{1}{16}$$

Coherent States $|\alpha\rangle$

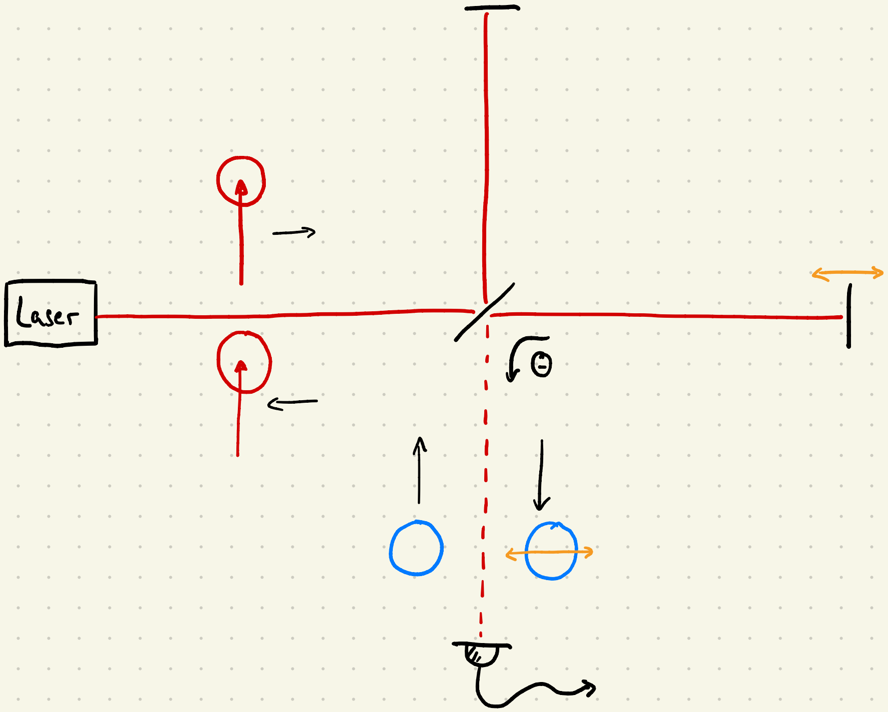
Eigenstates of $\hat{a}$, so that all photons are independent. $\hat{a}|\alpha\rangle = \alpha|\alpha\rangle$, $\alpha \in \mathbb{C}$

(Quantum) Shotnoise in Sideband Picture

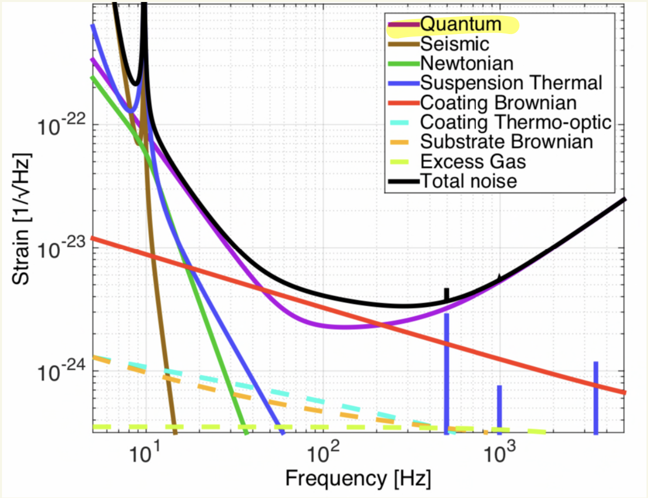


Ground-state fluctuations at sideband frequencies act as small random ampl & phase modulations.

Shotnoise in the Michelson Interferometer

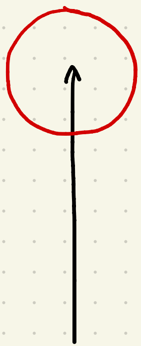


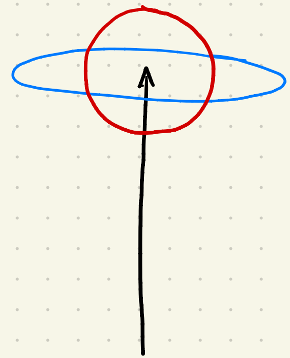
Advanced LIGO Design Sensitivity

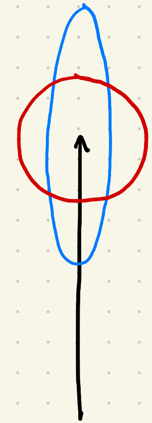


Squeezed States of Light

Reminder: $\Delta^2 \hat{X}_1^2 \, \Delta^2 \hat{X}_2^2 \geq \frac{1}{16}$







Also for $\alpha = 0$

→ "Squeezed Vacuum"

Coherent State ("=")

or Thermal State (">")

$$\Delta^2 \hat{X}_1^2 = \Delta^2 \hat{X}_2^2 \geq \frac{1}{16}$$

Amplitude Squeezed State

$$\Delta^2 \hat{X}_1^2 < \Delta^2 \hat{X}_2^2$$

Phase Squeezed State

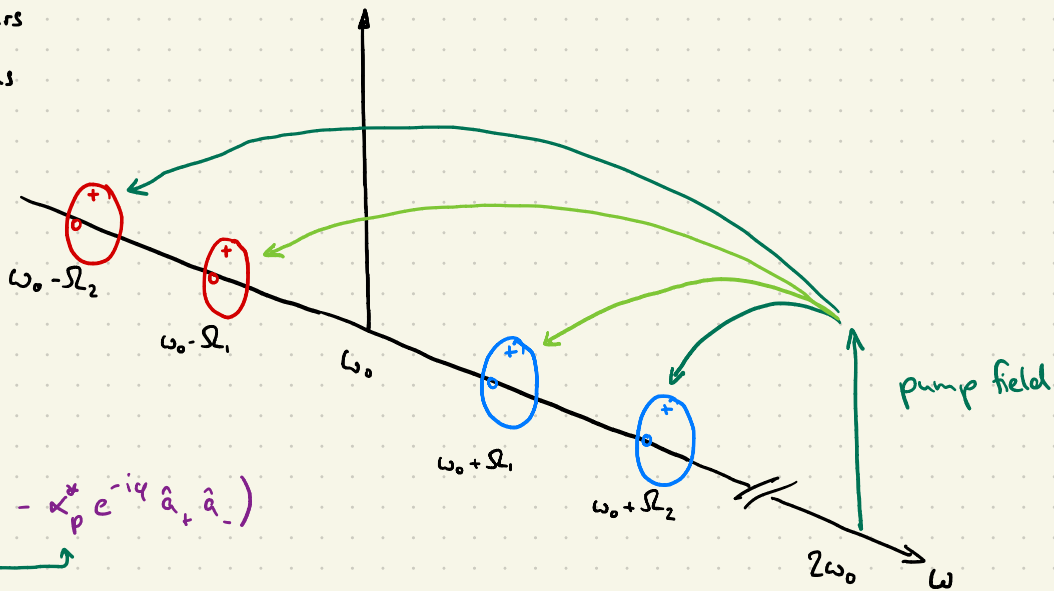
$$\Delta^2 \hat{X}_1^2 > \Delta^2 \hat{X}_2^2$$

Creating Squeezing - Concept

Idea

Add correlated photon pairs into upper and lower sidebands

→ Modulations that are less random than zero-point fluctuations

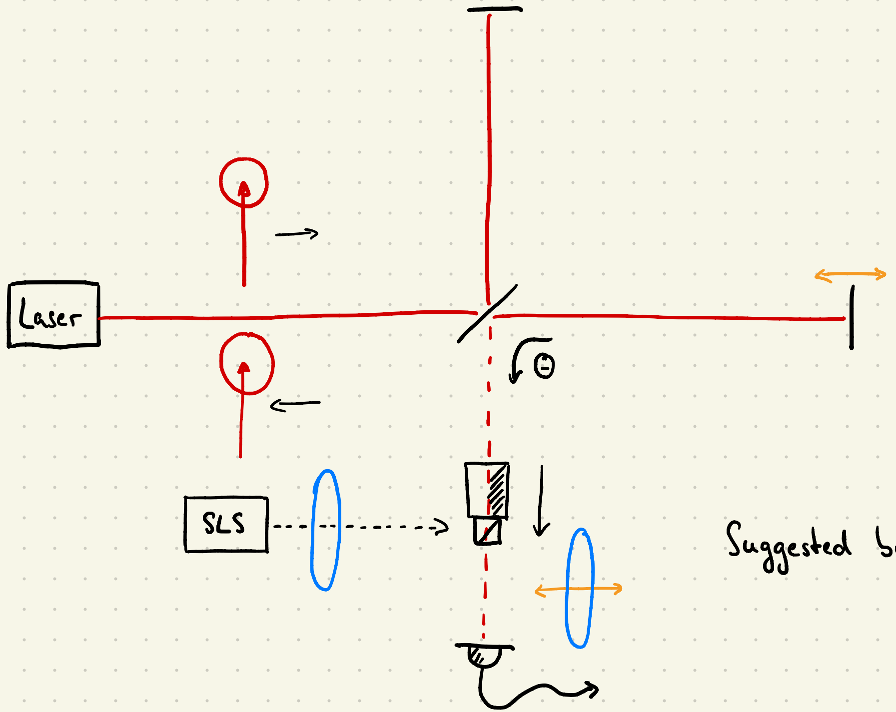


Roughly:

$$\hat{H} = i\hbar g \left(\alpha_p e^{i\varphi} \hat{a}_+^\dagger \hat{a}_-^\dagger - \alpha_p^* e^{-i\varphi} \hat{a}_+ \hat{a}_- \right)$$

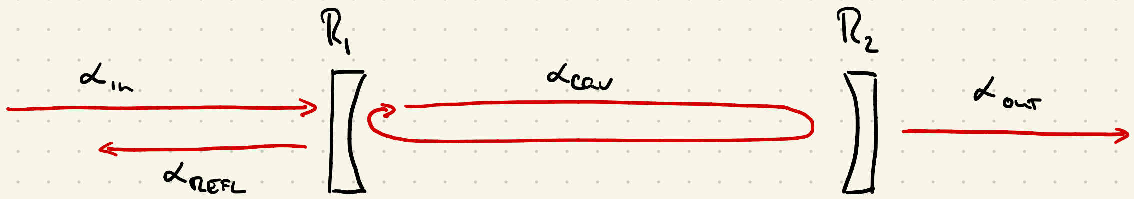
pump field

Squeezed Light in the Michelson Interferometer



Suggested by Carlton Caves in 1981!

How To Produce Squeezing: Step I

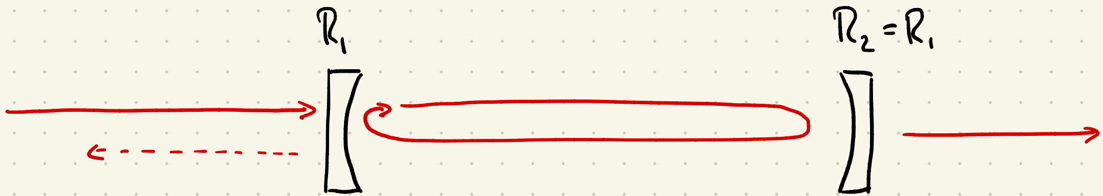


$$\alpha_{refl} = -\sqrt{R_1}\,\alpha_{in} + \sqrt{1-R_1}\,\alpha_{cav}$$

$$\alpha_{out} = \sqrt{1-R_2}\,\alpha_{cav}$$

How To Produce Squeezing: Step II

- Impedance Matched Case

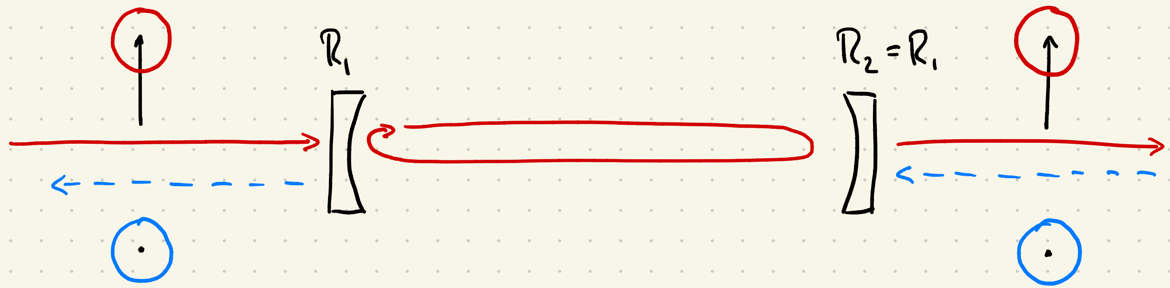


everything transmitted, $\alpha_{OUT} = \alpha_{IN}$ $\longrightarrow$ $\alpha_{CAV} = \dfrac{\alpha_{IN}}{\sqrt{1-R_1}}$

... does that mean that all the noise is gone in reflection of the cavity?

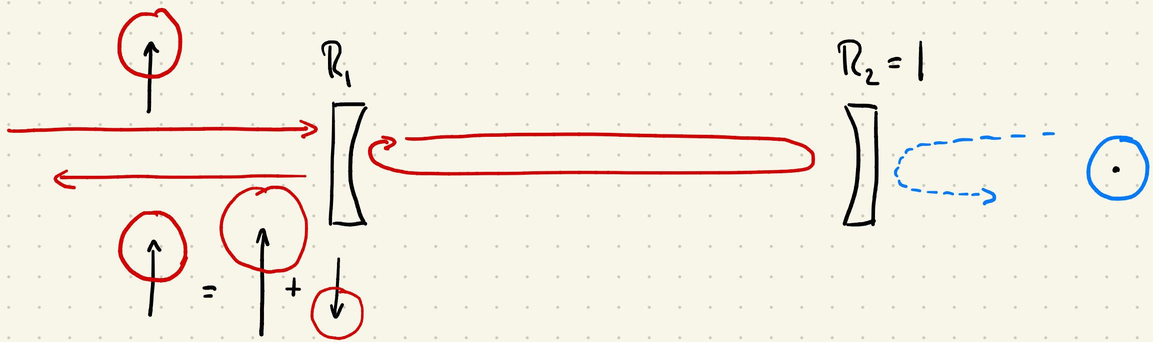
How To Produce Squeezing: Step II

- Impedance Matched Case



HOW TO PRODUCE SQUEEZING: STEP III

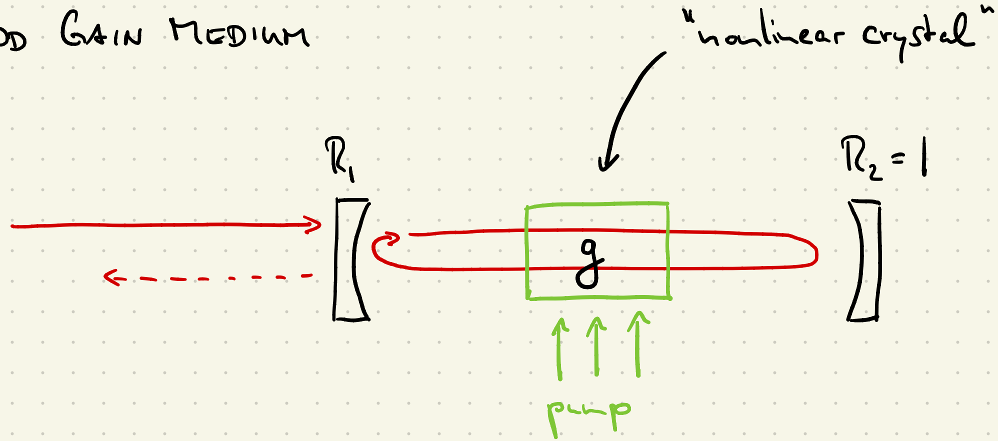
- FULLY OVERCOUPLED CASE



everything reflected, $\alpha_{REFL} = \alpha_{IN}$ $\longrightarrow$ $\alpha_{CAV} = \dfrac{1+\sqrt{R_1}}{\sqrt{1-R_1}}\,\alpha_{IN}$

How To Produce Squeezing: Step IV

- Add Gain Medium



gain g

$$\alpha_{CAV} = \frac{1+\sqrt{R_1}}{\sqrt{1-R_1}}\,\alpha_{IN} \quad \xrightarrow{\;g = \frac{1}{1+\sqrt{R_1}}\ (*)\;} \quad \alpha_{cav} = \frac{\alpha_{IN}}{\sqrt{1-R_1}}$$

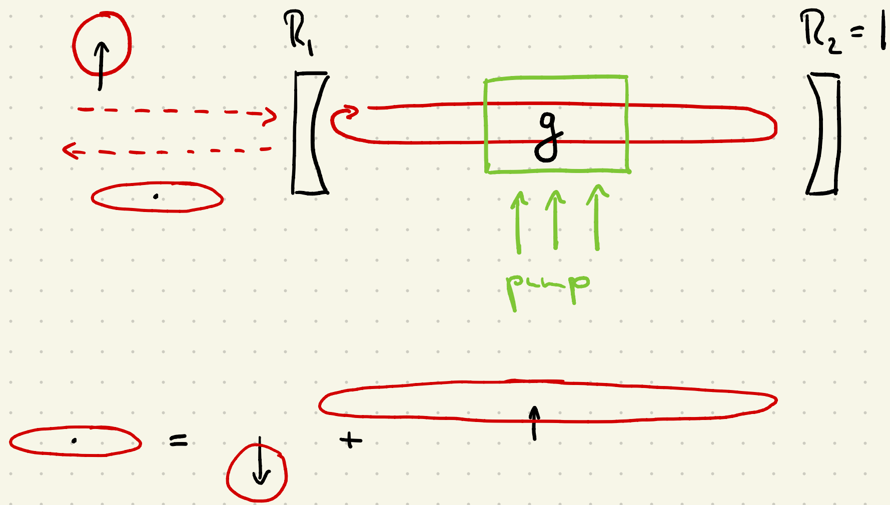
impedance-matched case, no reflection!

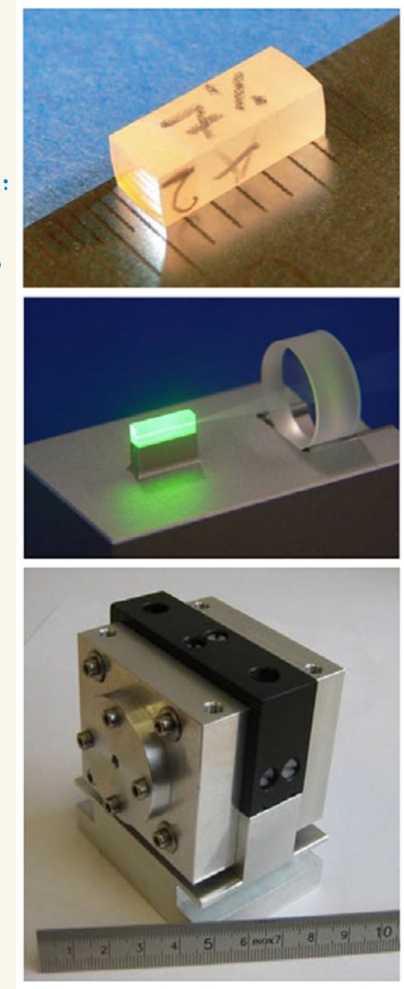
(*) per roundtrip: $\frac{\sqrt{R_1}}{1+\sqrt{R_1}}$

How to Produce Squeezing: Step V

nonlinear crystal, here:

$MgO:LiNbO_3$

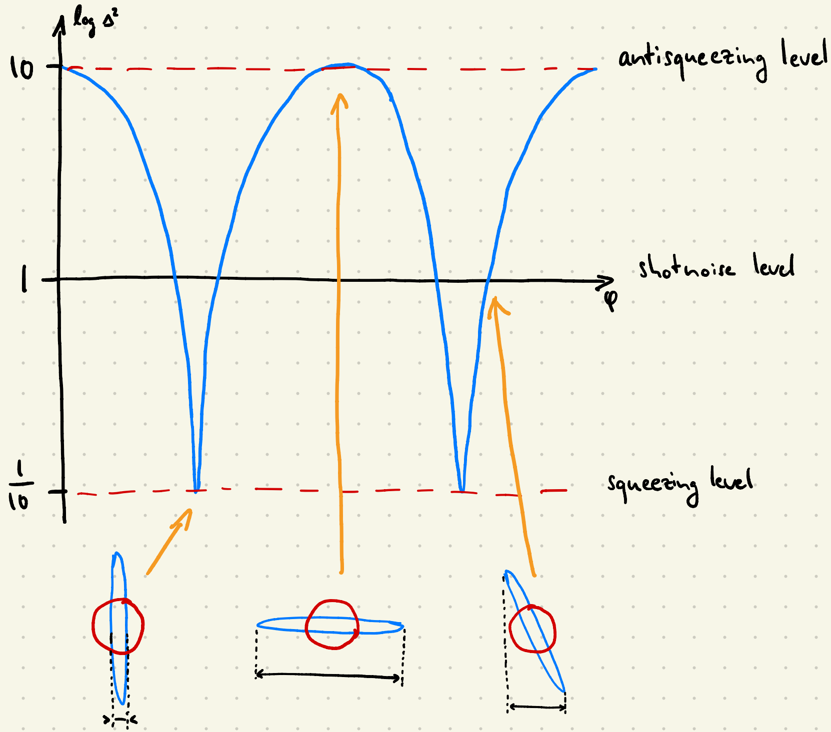




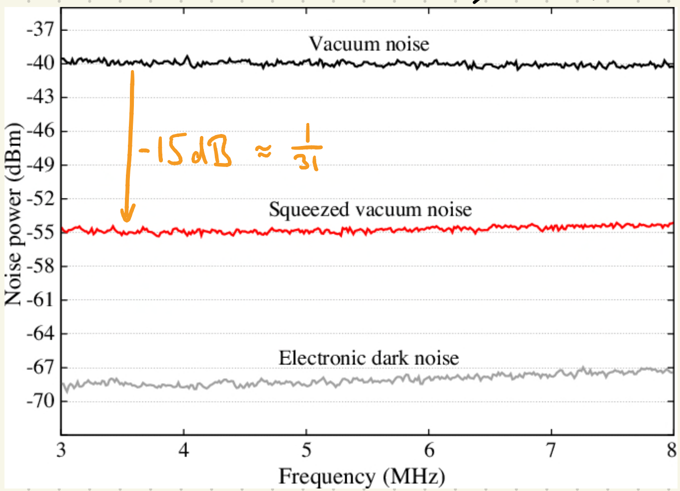
"Oven"

Measuring Squeezing

"McDonald's plot"

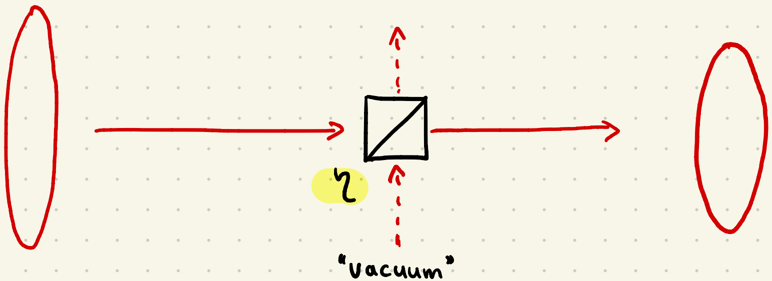


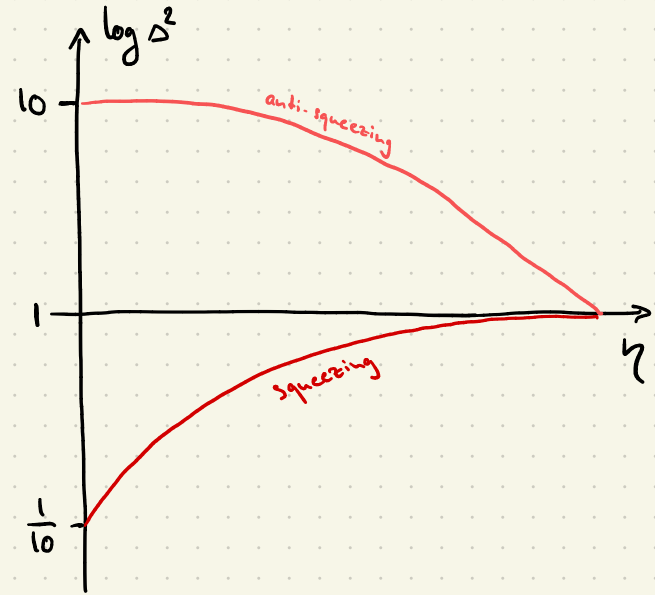
Vahlbruch et al., PRL 117, 110801



Major Challenge: Optical Loss

Destroys correlations between photon pairs



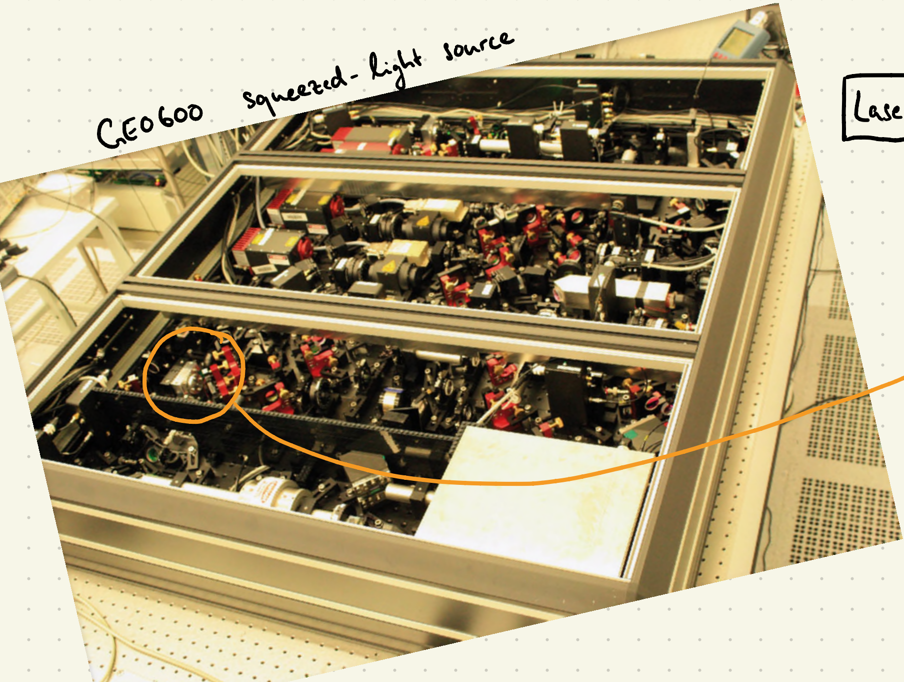


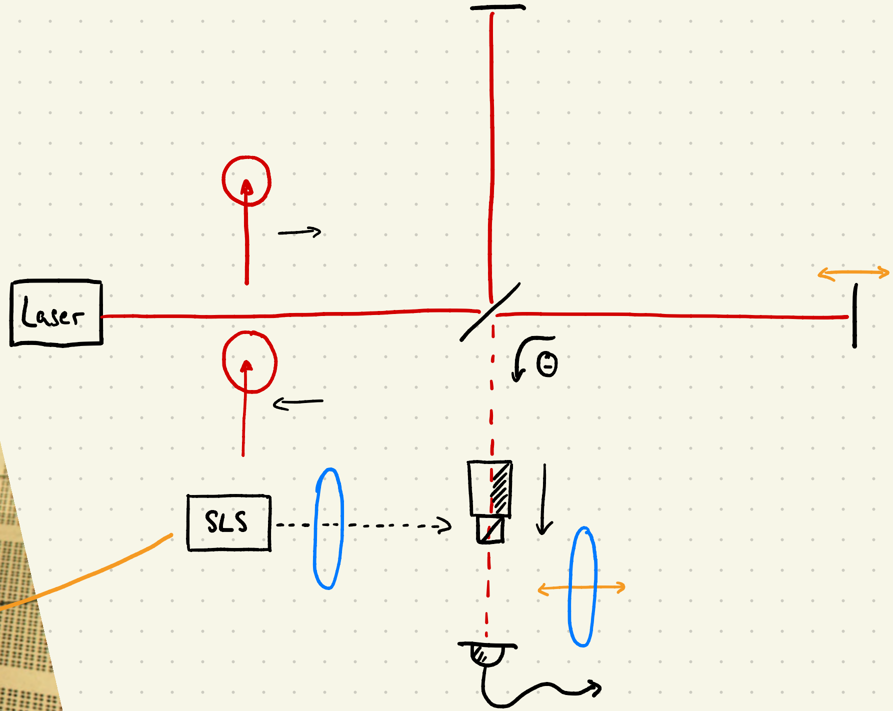
$$\Delta^2 \hat{X}^{out}_{1,2} = (1-\eta)\,\Delta^2 \hat{X}^{in}_{1,2} + \eta\,\Delta^2 \hat{X}^{vac}_{1,2}$$

10 dB squeezing (factor $\frac{1}{10}$) $\rightsquigarrow$ max 10% loss

Squeezed Light in the Michelson Interferometer

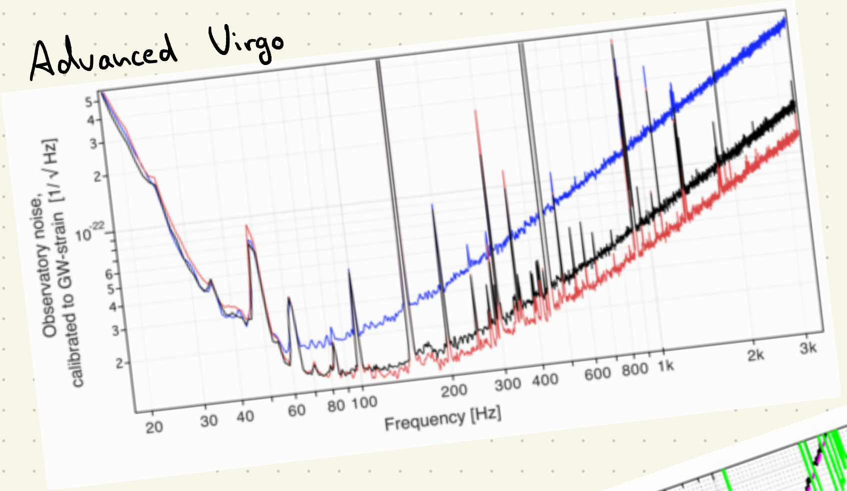
GEO 600 squeezed-light source



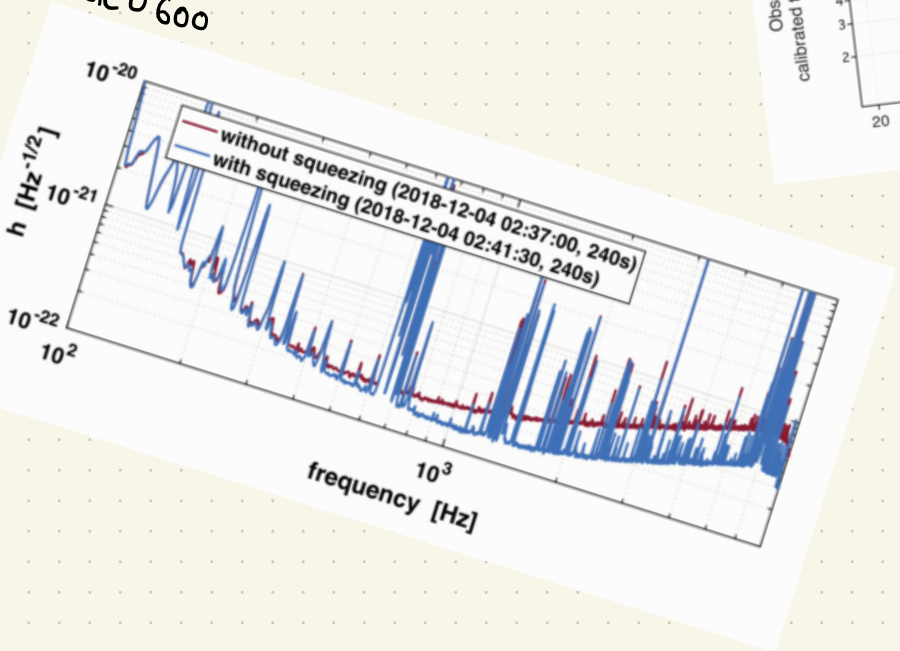


Results

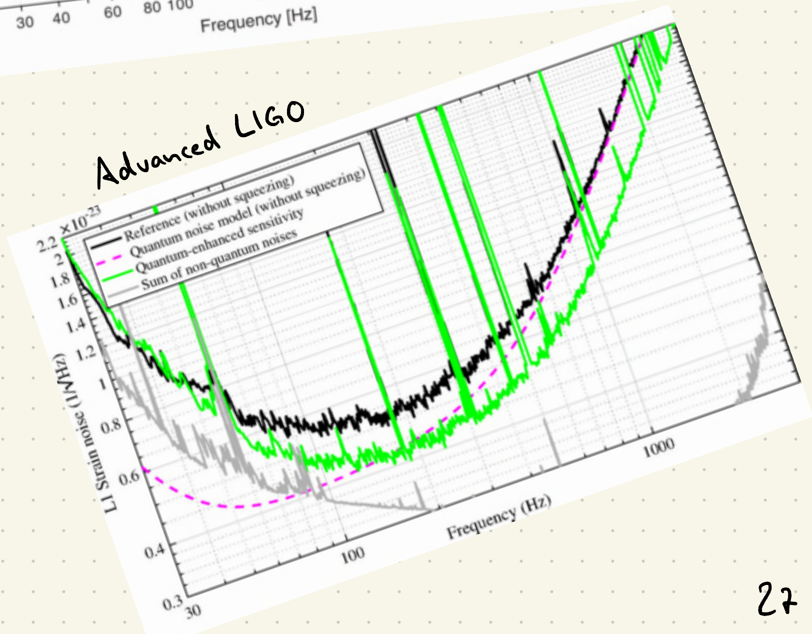
Advanced Virgo



GEO 600

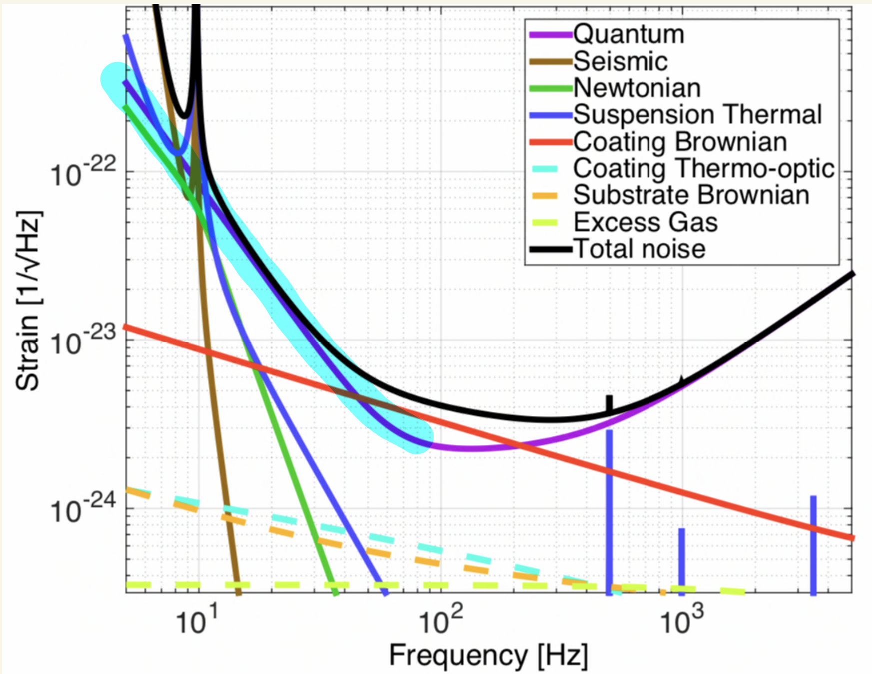


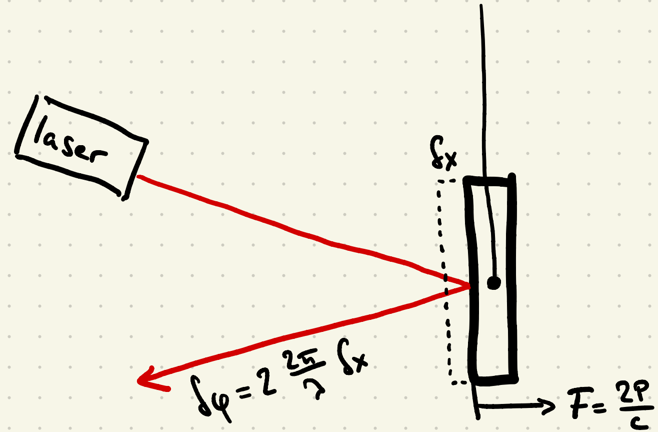
Advanced LIGO



Outlook: Radiation-Pressure Noise

Advanced LIGO Design Sensitivity



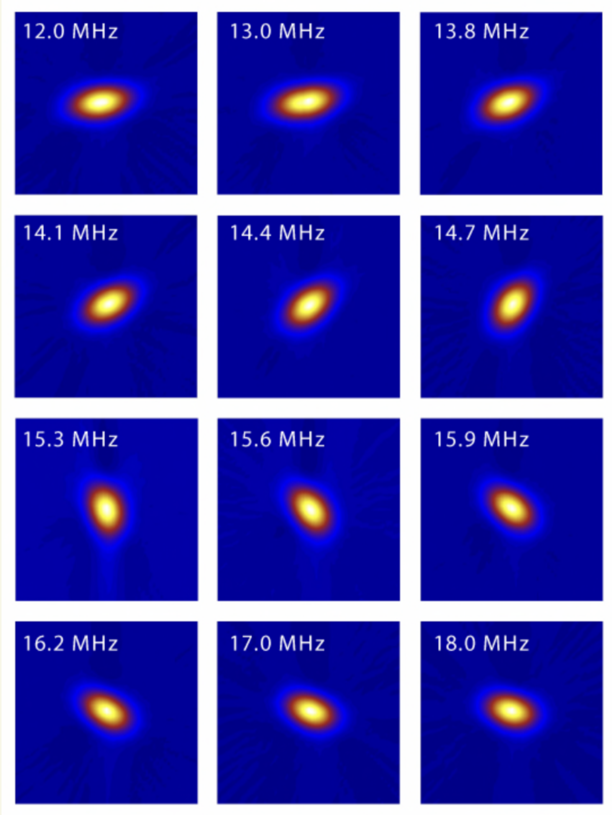


→ converts amplitude noise into measurement phase noise, $\propto \frac{1}{f^2}$ because of inertia of pendulum mass (mirror).

Outlook: Freq.-Dependent Squeezing

Want

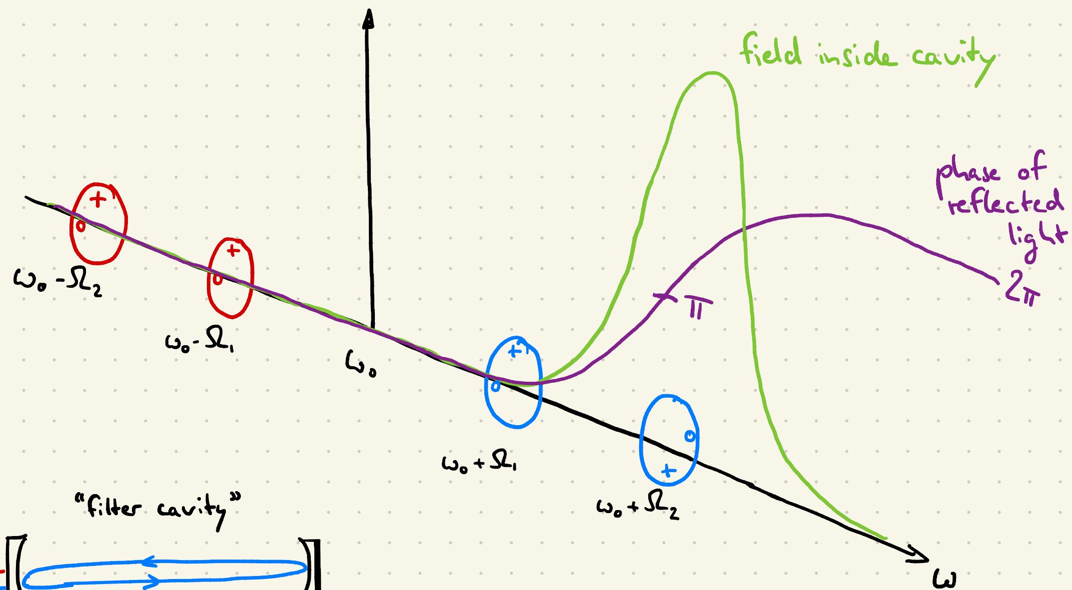
- amplitude squeezing where RPN dominates (low f)
- phase squeezing where we want to improve readout of phase signal (high f)



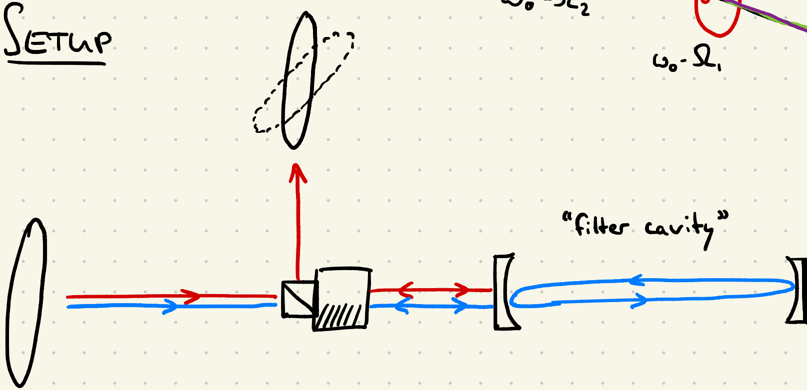
Chelkowski et al., 2005

Outlook: Freq-Dependent Squeezing

Reflect squeezing from detuned cavity!

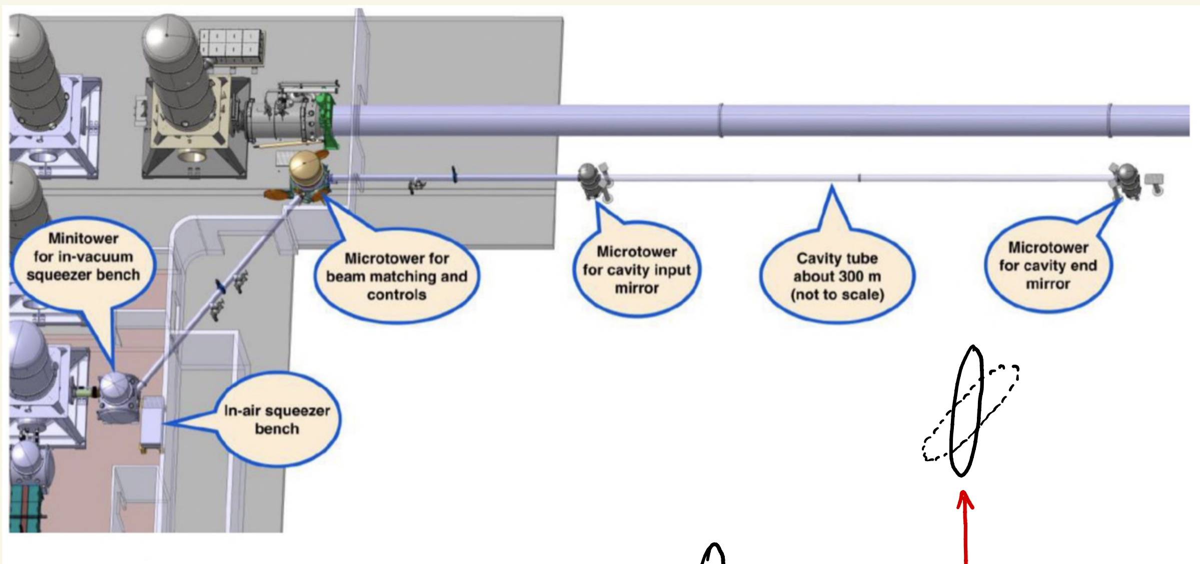


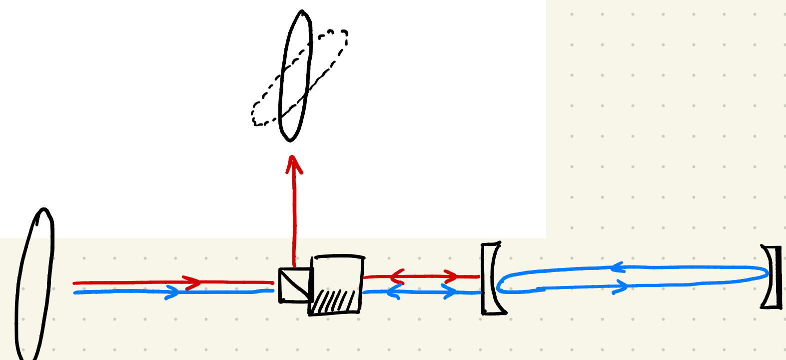
Setup



Outlook: Freq-Dependent Squeezing

Nikhef plays major role in building filter cavity for Adv Virgo





That's all Folks!

Literature

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