Quantum Noise Spectrum of QND RSE Using Mod-Demod Scheme

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Abstract

- Detuned RSE can beat SQL because of optical spring as is shown by A. Buonanno and Y. Chen (2001).
- It can beat SQL even without homodyne detection, which is used in the above paper.
- By the way, homodyne detection needs more investigation to use in practice, so it is necessary to think about conventional modulation-demodulation scheme.
- We need two modifications to apply optical spring to modulation-demodulation scheme.

(1)One may think it is equivalent to the case of homodyne phase $\zeta=\pi/2$, but it isn't.

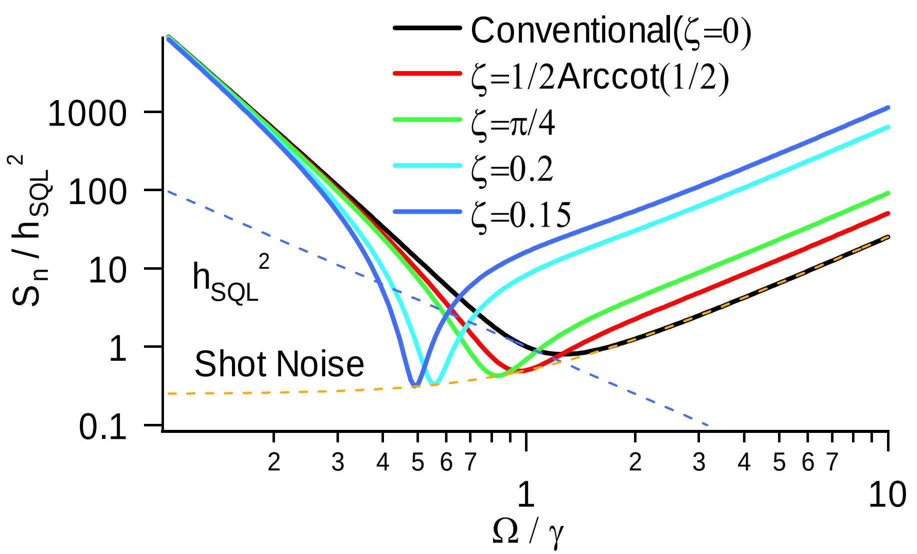
(2)Extra noise exists as is indicated by B. Meers and K. Strain (1991), which A. Buonanno and Y. Chen would explain in detail before long.

Contents

- Review of Conventional QND Interferometer
- Regard RSE Optical Spring as an Input Squeezed IFO
- Equivalent Homodyne Phase for Mod-Demod Scheme
- Extra Noise of Mod-Demod Scheme
- Modified Quantum Noise Spectrum for Advanced LIGO

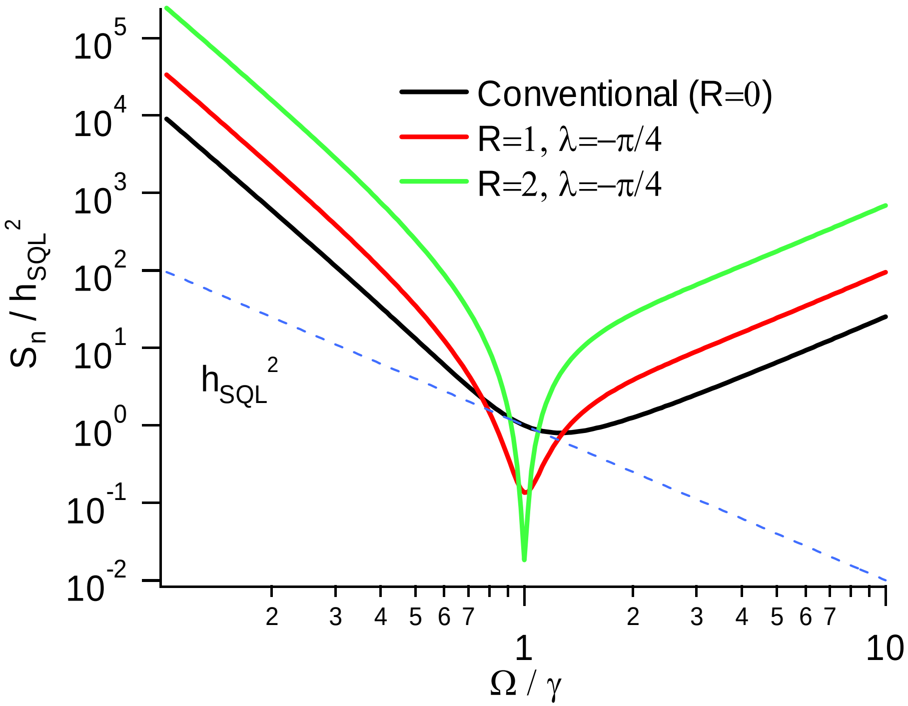
Two ways to overcome SQL for conventional interferometer

(1)Homodyne Detection



Use homodyne detection instead of conventional photodetection.

(2)Input Squeezing



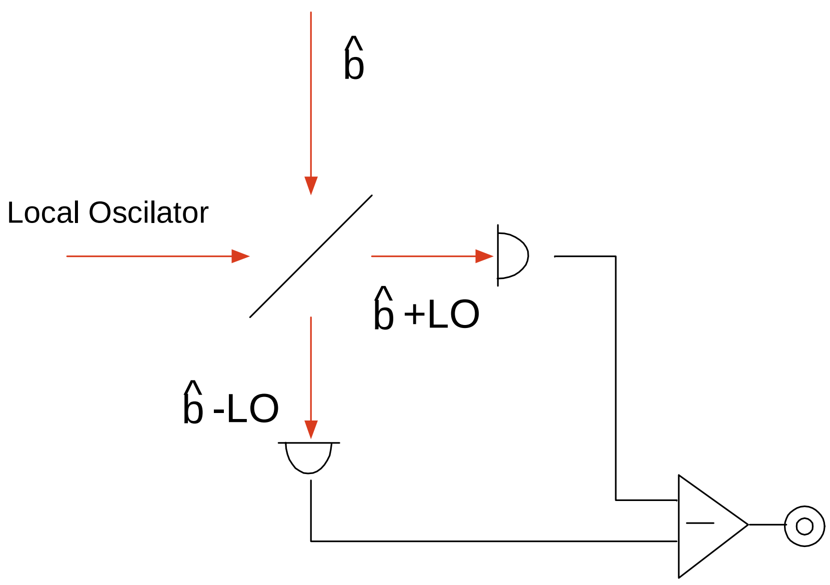
Make vacuum fluctuation from dark port squeezed (with non-linear optics).

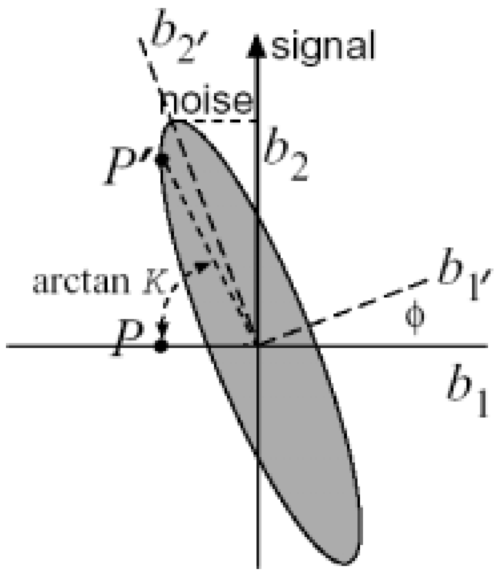
Homodyne Detection

$$\left\langle out \left\| \hat{b}_1 \cos\omega t + \hat{b}_2 \sin\omega t + \beta e^{i\omega t} \right|^2 \right| out \right\rangle$$

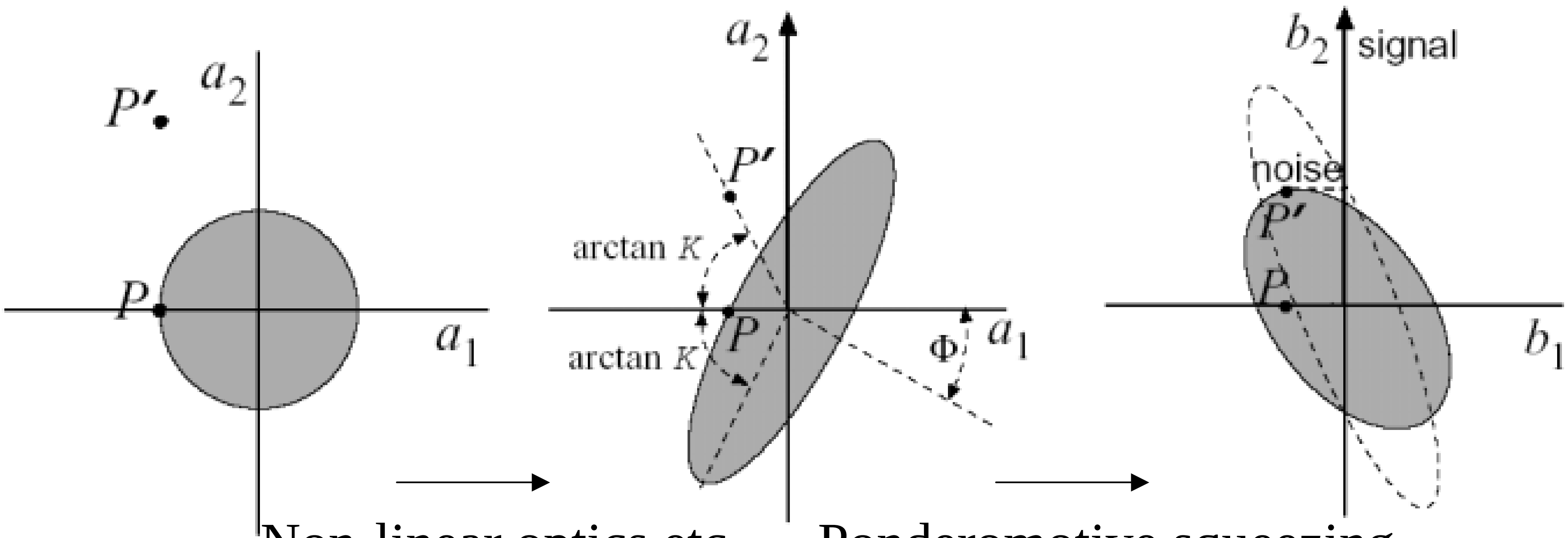
$$- \left\langle out \left\| \hat{b}_1 \cos\omega t + \hat{b}_2 \sin\omega t - \beta e^{i\omega t} \right|^2 \right| out \right\rangle$$

$$= \quad \left\langle out \left| \hat{b}_1 \cos\varsigma + \hat{b}_2 \sin\varsigma \right| out \right\rangle + \mathrm{RF}$$





Input Squeezing



Non-linear optics etc. Ponderomotive squeezing

QND RSE

Explanation As an Optical Spring

1. Conventional IFO

   Differential modes and common modes are quadrature.

2. Extreme RSE

   With RSE mirror, differential return as differential and common return as common.

3. Detuned RSE

   Both modes are mixed and return to the interferometer. Inserted common modes become the radiation pressure which appears on the differential modes. That modes are mixed in inserted common modes because of detuning, and it makes a spring. $\ddot{x} = -kx$

Explanation As an Input Squeezed IFO

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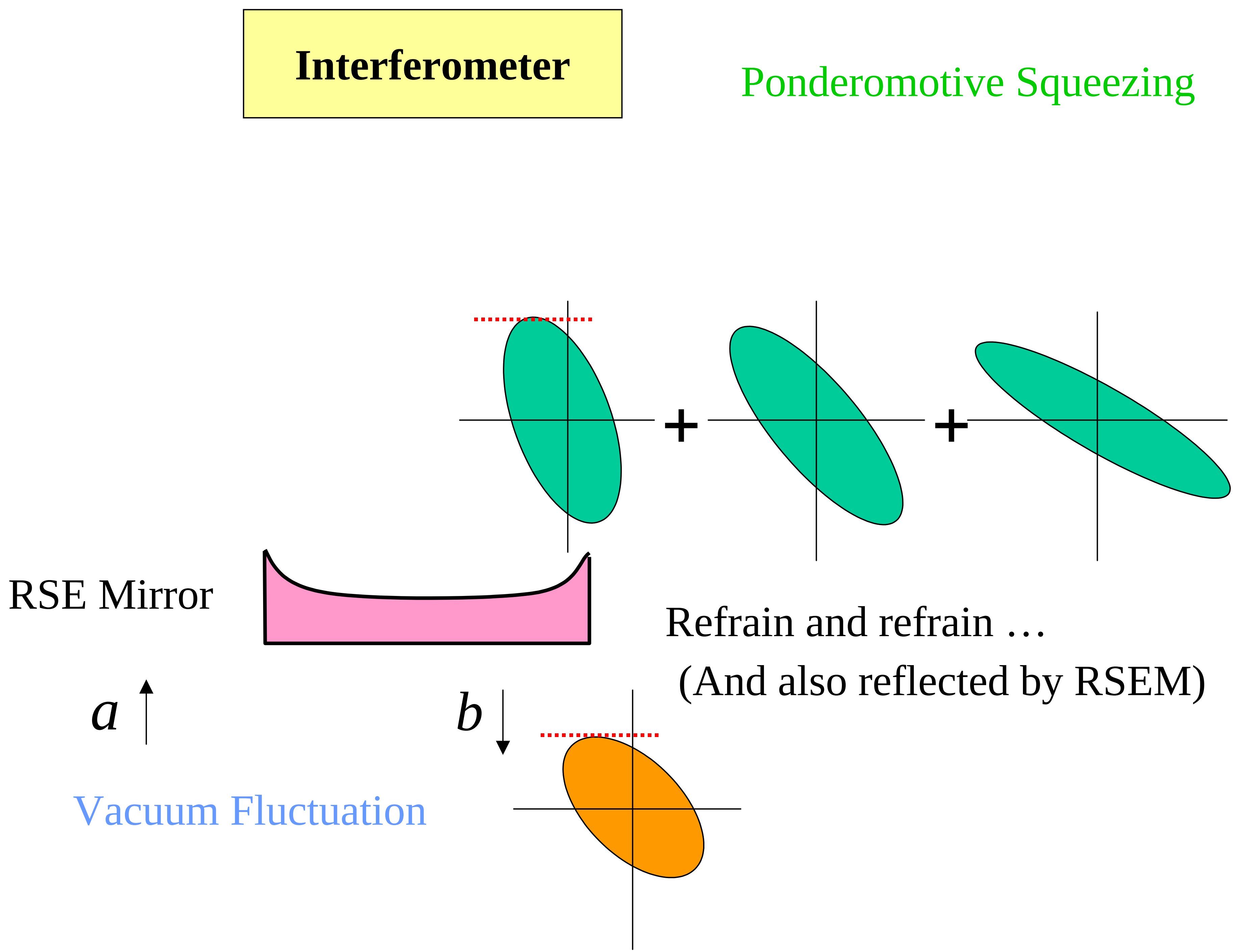

Interferometer
Ponderomotive Squeezing
+
+
RSE Mirror
Refrain and refrain …
(And also reflected by RSEM)
a
b
Vacuum Fluctuation

Modification (1) : Equivalent Homodyne Phase

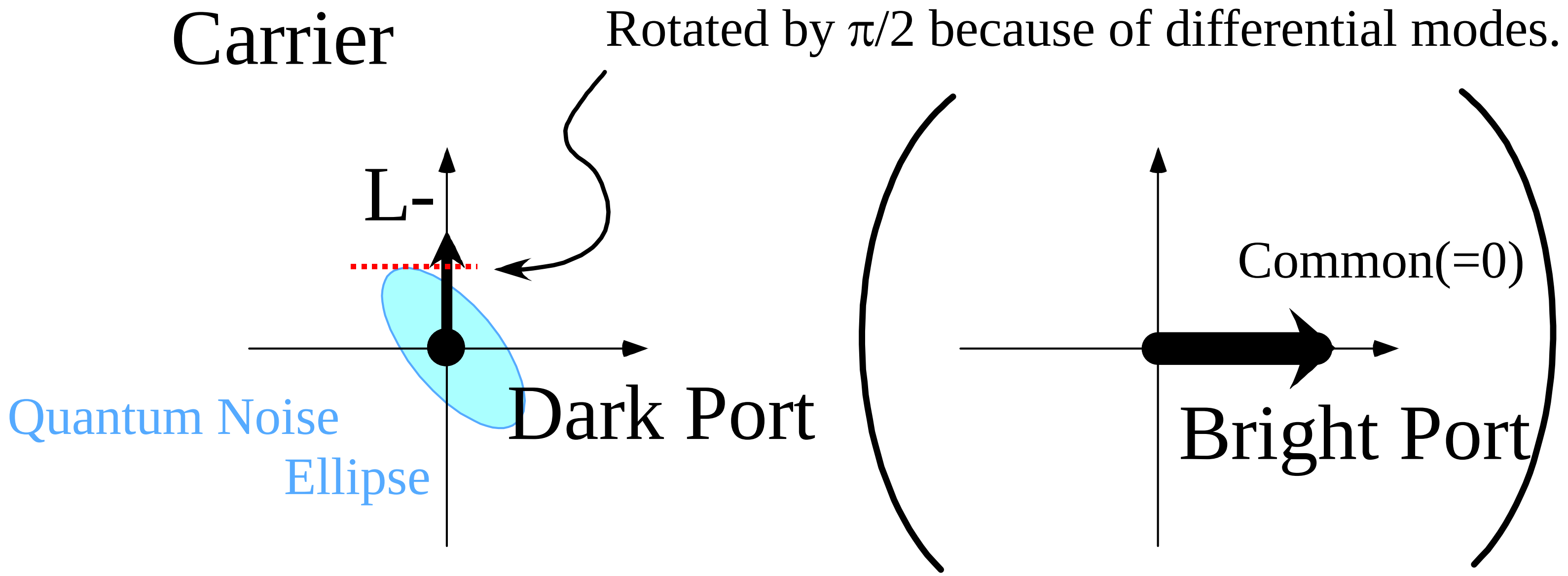
Ponderomotive-squeezed state transforms to another squeezed state and the quantum noise can overcome SQL even with homodyne phase $\varsigma = \pi / 2$ or 0 .

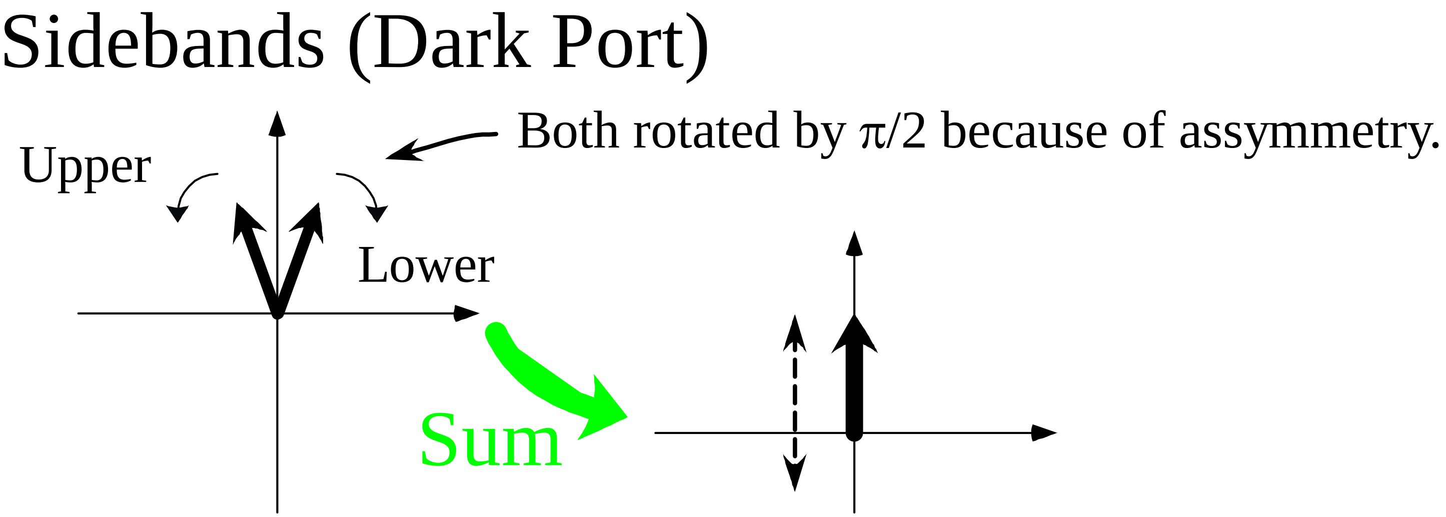
For conventional interferometer or extreme RSE, the equivalent homodyne phase is $\varsigma = \pi / 2$ or 0 .

Is it also true for detuned RSE ? No.

→ Let's see the phaser diagram.

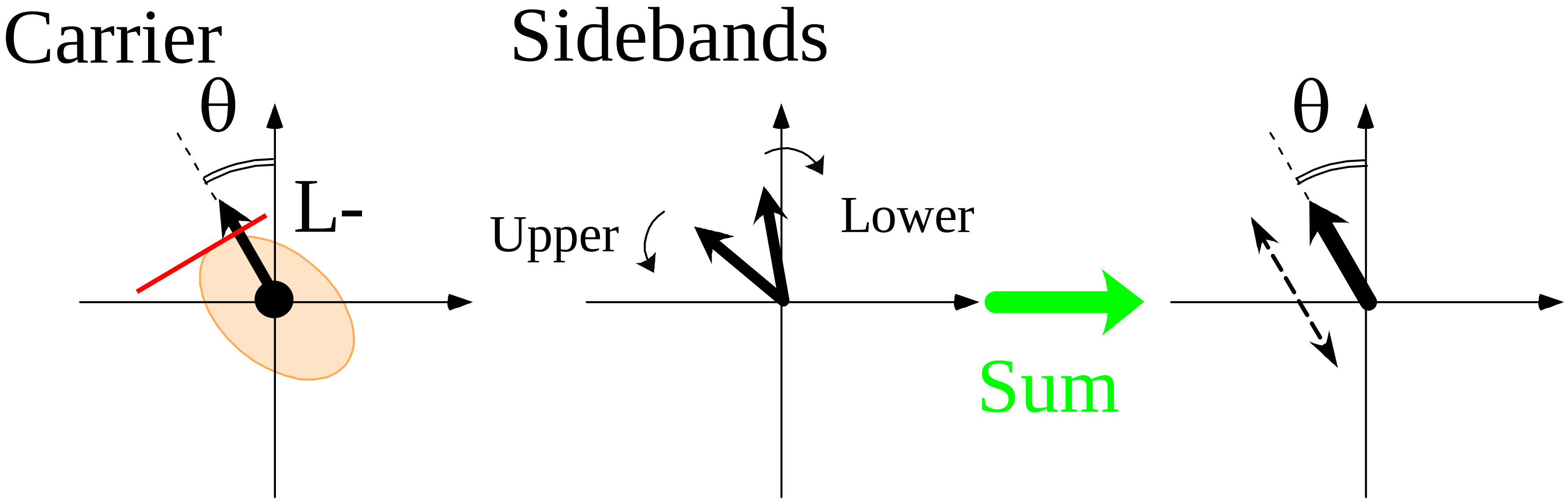
Phaser Diagram (Conventional IFO or ERSE)





The equivalent homodyne phase is π/2 and GWS is on that direction.

Detuned RSE

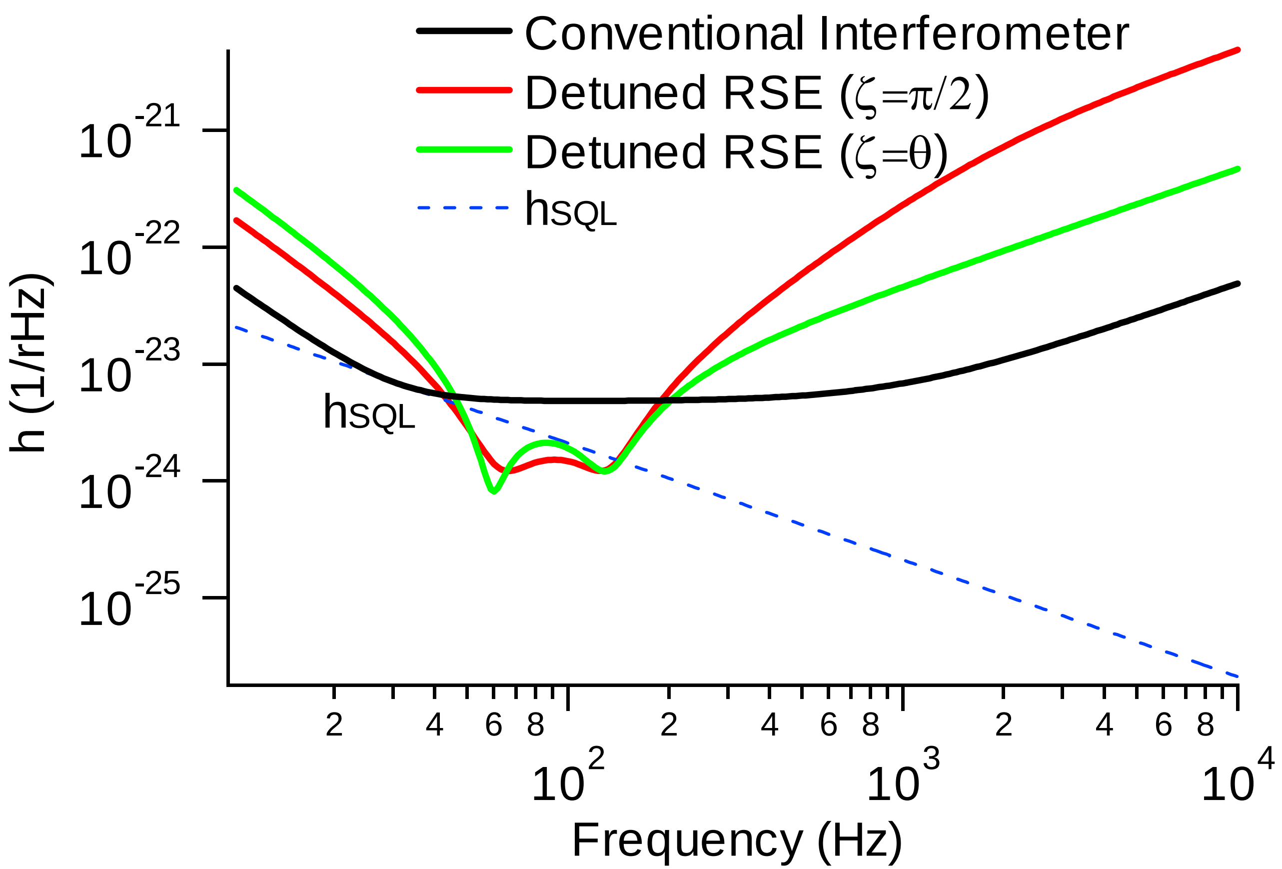


$$\mathrm{SB} \approx i\cos\omega_m t \times \tau\left(e^{i\phi} - \rho e^{3i\phi} + \rho^{5i\phi} - \cdots\right)$$

$$= \frac{i\cos\omega_m t}{1+\rho^4+2\rho^2\cos 2\phi}\tau\, e^{i\phi}\left[1+\rho^4+2\rho^2\cos 2\phi - \rho e^{2i\phi} - \rho^3\right]$$

$$\theta = \phi - \arctan\left[\frac{\rho\sin 2\phi}{1+\rho^4+2\rho^2\cos 2\phi - \rho^3 - \rho\cos 2\phi}\right]$$

Difference of quantum noise spectrum



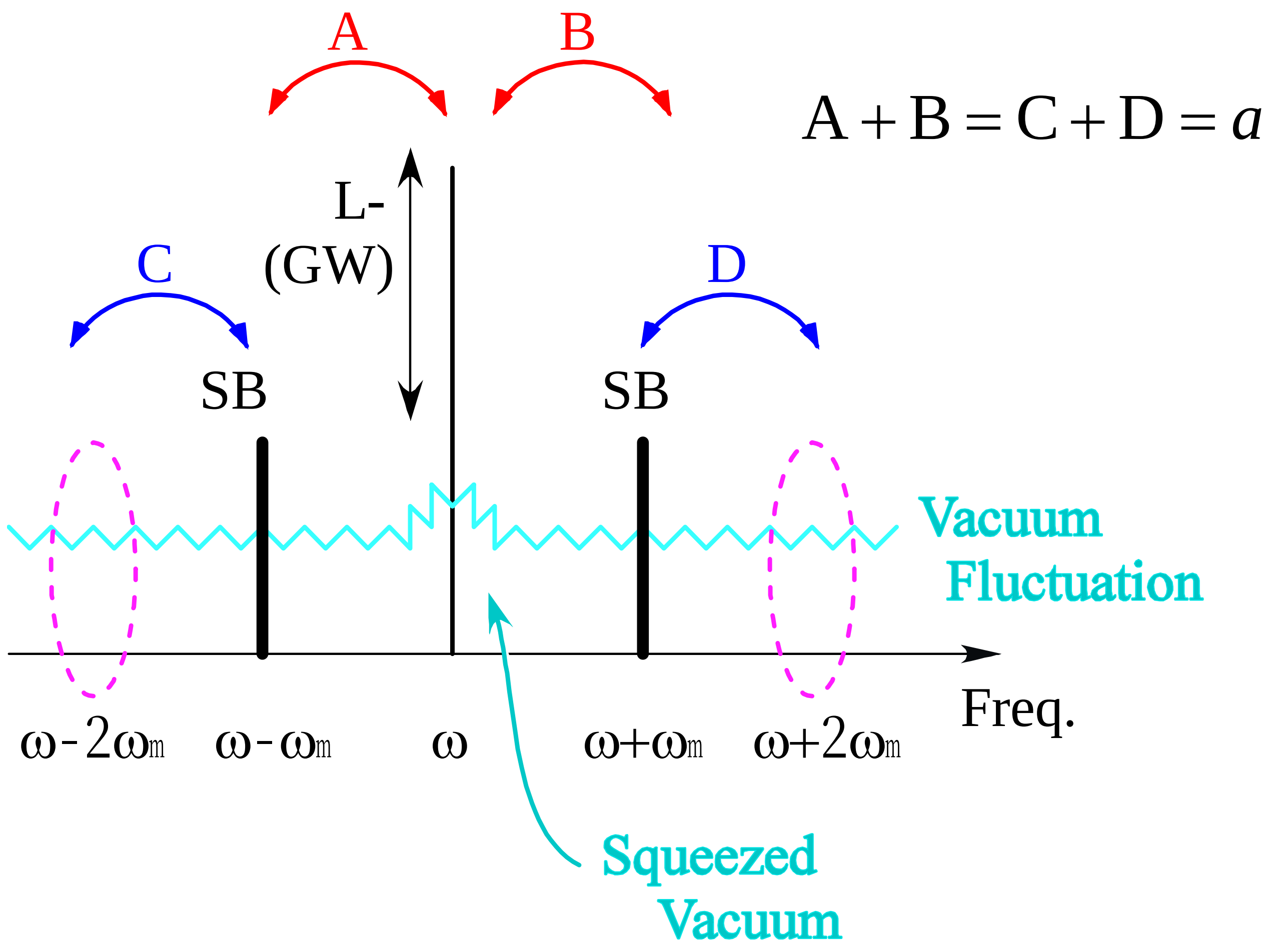
I_0~5kW, T=0.033, ρ=0.9, ϕ=π/2–0.6

Difference is remarkable with small ρ and large ϕ.

(Adv. LIGO parameter :

I_0~2.1kW, T=0.005, ρ=0.96, ϕ~π/2–0.05)

Modification (2) : Extra Quantum Noise



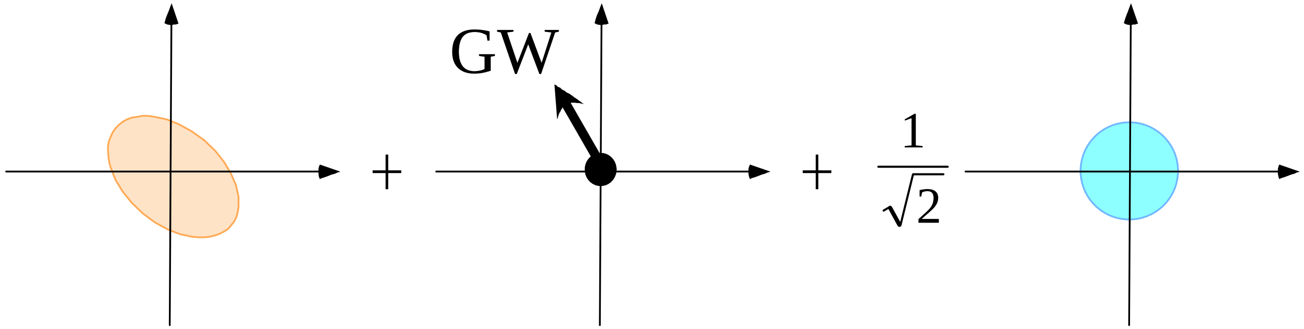
Total noise and signal are

$$(A + B)^2 + C^2 + D^2 \quad \to GWS + \frac{3}{2} a^2 \ (\text{non} - \text{squeezed})$$

Radiation pressure should be taken into account.

(In the case of detuned RSE)

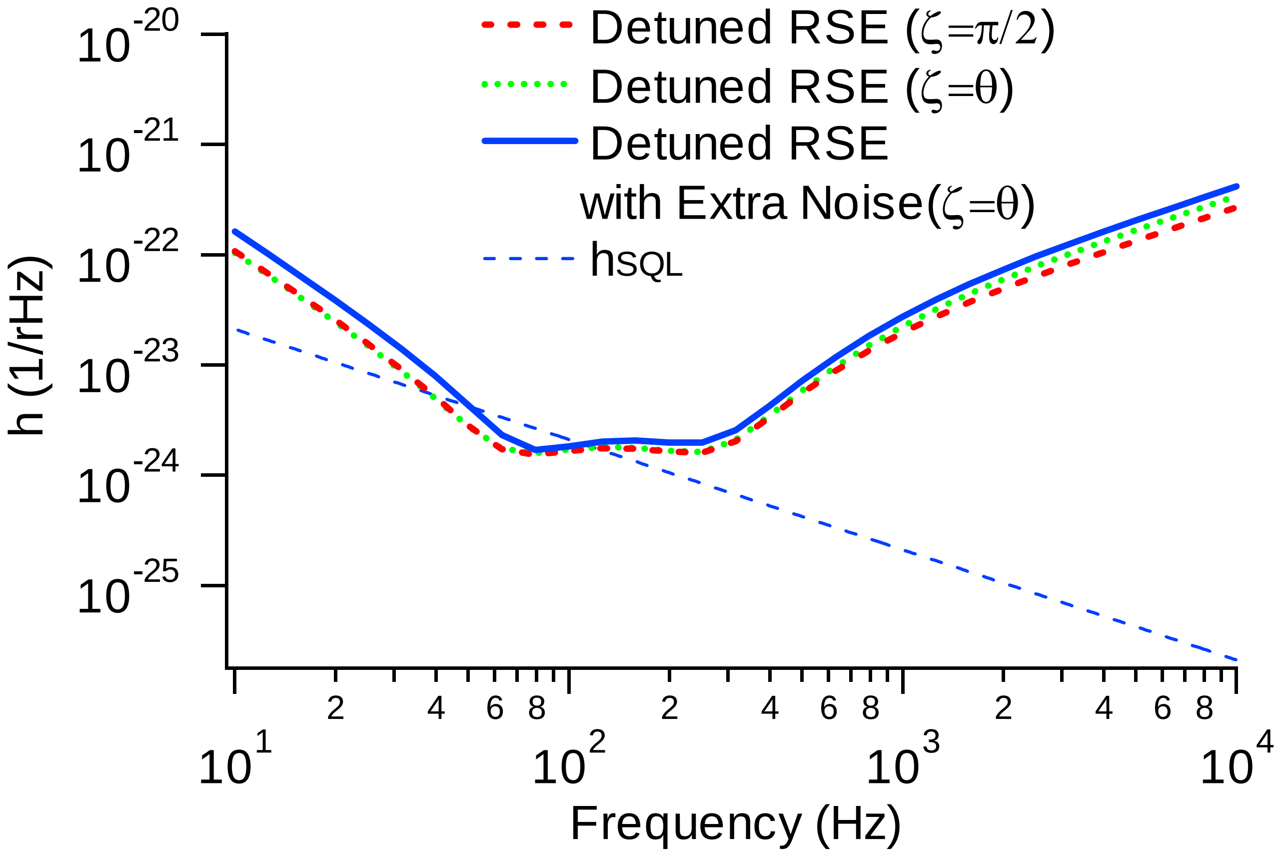
ω_m components =



$$\begin{pmatrix} D_1 \\ D_2 \end{pmatrix} h_n = \frac{h_{SQL}}{\tau\sqrt{2\kappa}} \left\{ e^{i\beta} \begin{pmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} + \frac{M}{\sqrt{2}M'} e^{-i\beta} \begin{pmatrix} E_{11} & E_{12} \\ E_{21} & E_{22} \end{pmatrix} \begin{pmatrix} a_1' \\ a_2' \end{pmatrix} \right\}$$

A little bit worse than homodyne detection.

Advanced LIGO Quantum Noise Spectrum



Conclusion

- Quantum noise spectrum with detuned QND RSE with mod-demod scheme needs two modification from homodyne detection.
- The effect of RF sidebands detuning is remarkable when detuning phase is big and/or RSE finnesse is low.
- The effect of extra quantum noise, which would be minutely explained before long by A. Buonanno and Y. Chen, is also calculated.
- For Adv. LIGO, total difference from the case of equivalent homodyne phase $\pi/2$ is about 10~60% worse, but it can still beat SQL.

Notes

We have calculated the case of conventional detection since those homodyne detection needs more investigation before practically used. (It also needs some more modification from this for DC readout scheme.)

By the way, is there any other way to make homodyne detection possible than using external local oscillator?

Here we introduce a couple of new ways to make it.

(1) Unbalanced sideband scheme

(2) Sideband locking scheme,

which would be shown before long.

END