Multi-carrier optimization of future laser gravitational-wave detectors

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Motivation 1

Sources of noise in LIGO

Classical: seismic, thermal, laser, ...

Motivation 2

- III generation GW detectors: quantum noise limited
- Noises of quantum origin

Standard Quantum Limit

- Back-action noise
- Shot noise

SQL

When this noises become equal, we have the point of best sensitivity.

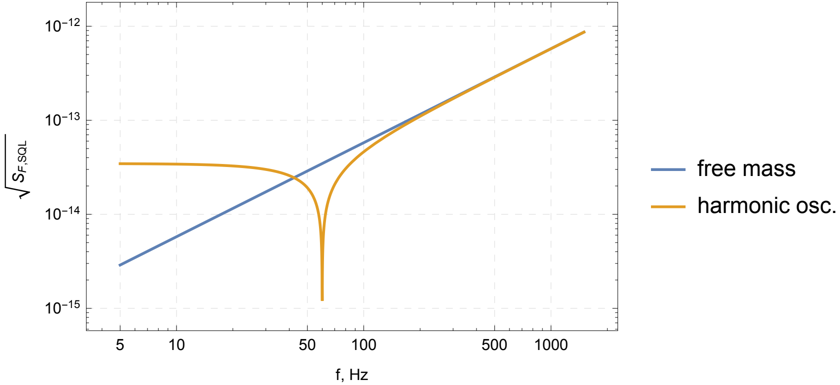
$$S_F^{SQL}(\Omega) = 2\hbar \left|\chi^{-1}(\Omega)\right|$$

It is not a fundamental limit!

$$\chi^{-1}(\Omega) = \frac{x(\Omega)}{F(\Omega)} \quad \text{susceptibility,}$$

$x(\Omega)$ - displacement, $F(\Omega)$ - force.

Change the SQL

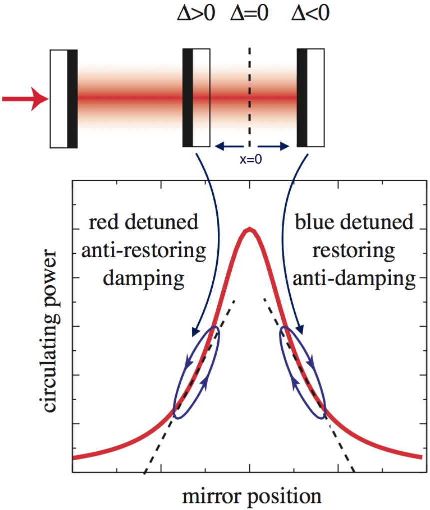


$$\chi^{-1}_{f.m.}(\Omega) = -M\Omega^2 \qquad \chi^{-1}_{h.o.}(\Omega) = -M(\Omega^2 - \omega_m^2)$$

Detuned cavity

- Use scaling law to transform interferometer to single cavity [A. Buonanno, Y. Chen, 2003].
- Position of the mirror, if $x \ll \lambda$:

$$F_{opt}(x) \approx F_0 - k_{opt} x$$



Negative Inertia

Optical rigidity changes the susceptibility of test mass:

$$\chi^{-1}(\Omega) = -M\Omega^2 + K(\Omega)$$

If $\delta \gg \Omega, \gamma$:

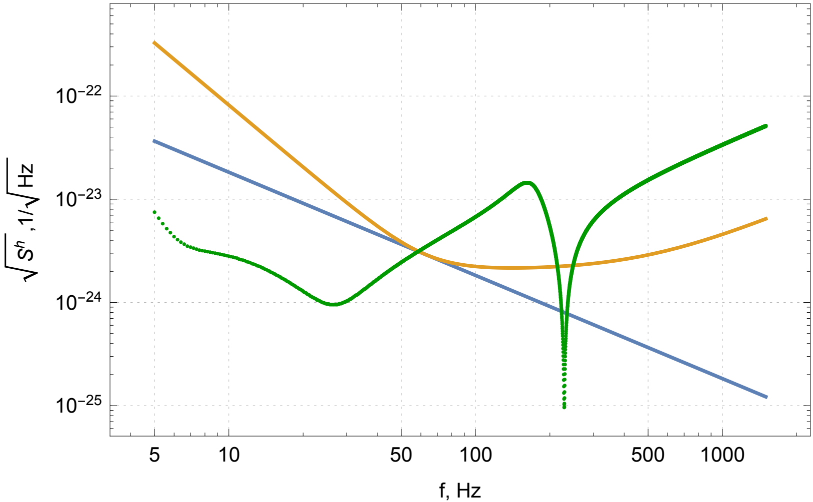
$$K(\Omega) \approx \bar{K}_{stc} - i\Gamma_{dmp}\Omega - m_{inr}\Omega^2 + O(\Omega^3)$$

$$\bar{K}_{stc} = \frac{mJ\delta}{\Delta^2} \qquad \Gamma_{dmp} = -\frac{2mJ\gamma}{\Delta^4} \qquad m_{inr} = -\frac{mJ\delta}{\Delta^4}$$

- Let's use two pumps to eliminate static rigidity and damping.
- Also, let's eliminate the positive inertia: $M + m_{inr} + m_{inr} = 0$

$$\chi^{-1}(\Omega) = -M\Omega^2 + K_1(\Omega) + K_2(\Omega)$$

Negative Inertia Plot



Tolerant to losses.

Antisymmetric pair

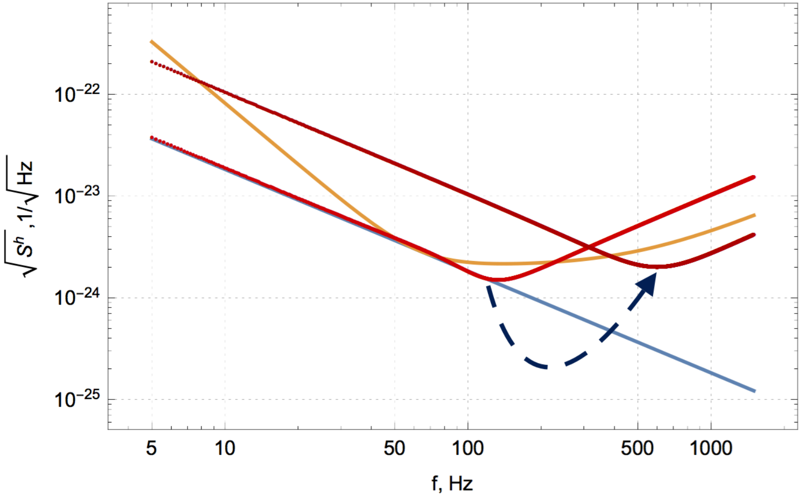
Two carriers with parameters:

$$J_1 = J_2 \quad \text{optical power}$$
$$r_1 = r_2 \quad \text{squeezing factor}$$
$$\Gamma_1 = \Gamma_2 \quad \text{bandwidth}$$
$$\beta_1 = -\beta_2 \quad \text{detuning}$$
$$\zeta_1 = -\zeta_2 \quad \text{homodyne angle}$$
$$\theta_1 = -\theta_2 \quad \text{squeezing angle}$$

Features

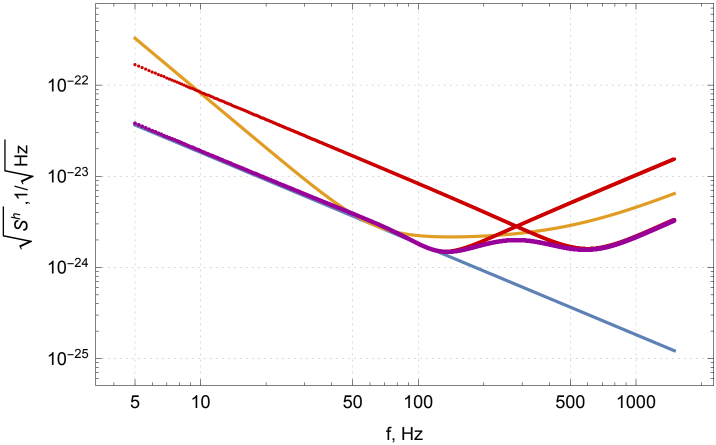
- Same as SQL frequency dependence of back-action noise
- We can increase power without low-frequency sensitivity degradation

Antisymmetric pairs Plot



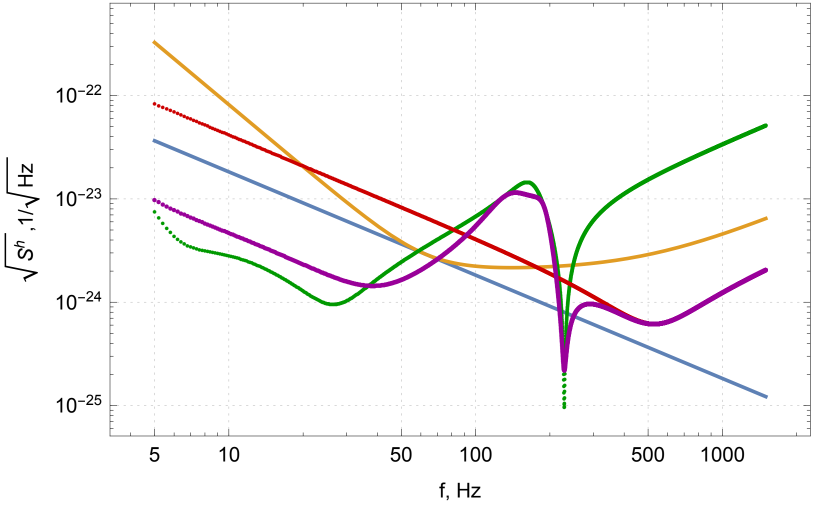
Sensitive to losses.

Interferometer Xylophone



$$S_{xx}^{sum}(\Omega) = \left[\frac{1}{S_{xx}^{(1)}} + \frac{1}{S_{xx}^{(2)}}\right]^{-1} \Longrightarrow \text{high-frequency improvement}$$

Results



10^{-22}
10^{-23}
10^{-24}
10^{-25}
$\sqrt{S^h}, 1/\sqrt{\text{Hz}}$
5
10
50
100
500
1000
f, Hz

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Results (no losses)

	Baseline	Negative Inertia		Antisymmetric pairs	
I_c, kW	1680	6263	9382	11986	11986
γ	$2\pi \times 500$	9.91	13.14	1166.96	1166.96
δ	0	800.26	-1198.90	-1513.84	1513.84
ζ	$\pi/2$	-1.5702	1.5708	-0.9132	0.9132
r, dB	0	6	6	6	6
θ	0	-0.6084	-1.4350	0.8898	-0.8898

I_c optical power

Γ bandwidth

β detuning

ζ homodyne angle

r squeezing factor

θ squeezing angle