Back-Action Evading Measurement in Gravitational Wave Detectors to Overcome Standard Quantum Limit, Using Negative Radiation Pressure

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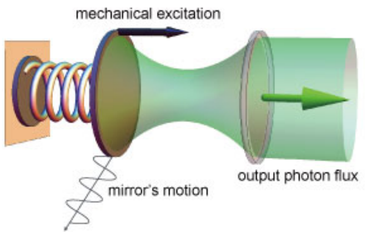
Noise and Sensitivity in GW Detection

The noise we deal with–

- Seismic noise
- Thermal noise
- Detector noise (electronic noise)
- **Quantum noise**

Basic Optomechanical Setup



$$H = \frac{1}{2}\omega_m^2(X_M^2+P_M^2)-\Delta_0 a^\dagger a - g_0 a^\dagger a X_M$$

$$\begin{bmatrix}\dot{X}\\ \dot{Y}\\ \dot{q}\\ \dot{p}\end{bmatrix} = \begin{pmatrix} -\kappa & -\Delta & -G\sin(\phi) & 0\\ \Delta & -\kappa & G\cos(\phi) & 0\\ 0 & 0 & 0 & 1/m\\ \frac{\hbar}{2}G\cos(\phi) & \frac{\hbar}{2}G\sin(\phi) & -m\omega_m^2 & -\eta/m \end{pmatrix}\begin{bmatrix}X\\ Y\\ q\\ p\end{bmatrix} + \begin{bmatrix}\sqrt{2\kappa}X_{in}\\ \sqrt{2\kappa}Y_{in}\\ 0\\ \tilde{F}\end{bmatrix}$$

$$\begin{bmatrix}X_{out}\\ Y_{out}\end{bmatrix} = \begin{bmatrix}\frac{k+i\omega}{k-i\omega} & 0\\ -K(\omega) & \frac{k+i\omega}{k-i\omega}\end{bmatrix}\begin{bmatrix}X_{in}\\ Y_{in}\end{bmatrix} + \begin{bmatrix}0\\ \sqrt{2K(\omega)}\end{bmatrix}\frac{\tilde{F}(\omega)}{\tilde{F}_{sql}} \quad (1)$$

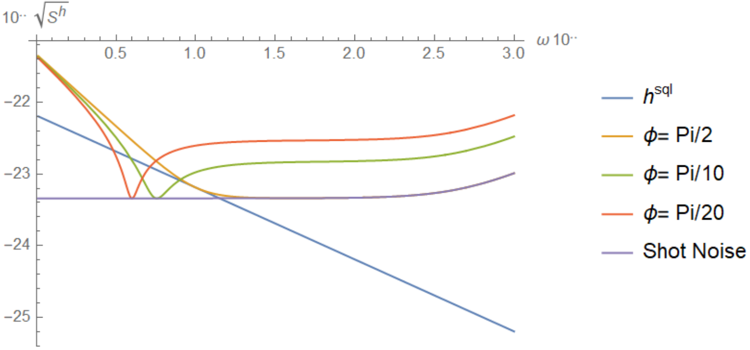
$$K(\omega) = -\frac{\kappa\chi_M\left(2\Delta D_{M0}(\omega)+\hbar G^2\right)}{D_c(\omega)} \approx -\frac{\hbar\kappa^2\Gamma_M\chi_M(\omega)}{(\kappa-i\omega)^2},\ \tilde{F}_{sql} = i\sqrt{\hbar m\omega^2} \approx i\sqrt{\frac{\hbar}{\chi_M}}$$

- Sensitivity increment for optical high-precision measurements
- squeezed mode generation at output modes
  $S^{\theta}_{\omega} = 1/2\langle\{X^{\theta}_{\omega}, X^{\theta}_{-\omega}\}\rangle$ – with $X^{\theta}_{\omega} = 1/\sqrt{2}\left(a^{\dagger}_{-\omega}e^{i\theta} + a_{\omega}e^{-i\theta}\right)$
- Avoiding quantum optomechanical back action

$$S^{h}(\omega) = h^{2}_{SQL}\frac{H^{T}_{L}TS^{in}T^{\dagger}H_{L}}{|H^{T}_{L}.t|} \quad (2)$$

Rotational matrix $H_L = \begin{bmatrix}\cos\phi_L \\ \sin\phi_L\end{bmatrix}$ $S^{in} = \frac{1}{2}\langle in|\begin{bmatrix}\{X, X^{\dagger}\} & \{Y, X^{\dagger}\} \\ \{X, Y^{\dagger}\} & \{Y, Y^{\dagger}\}\end{bmatrix}|in\rangle$

$$S^h(\omega) = \frac{h_{SQL}^2}{2}\left[\frac{(K(\omega) - \cot\phi_L)^2 + 1}{K(\omega)}\right]$$



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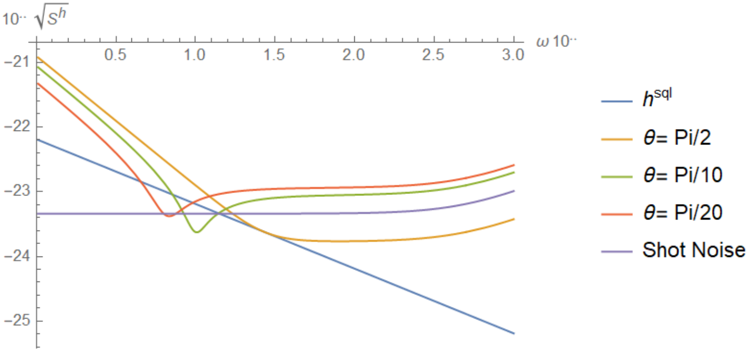
[1] Living Reviews in Relativity volume 22, 2 (2019)

Squeezed Vacuum Injection

$$S^h(\omega) = \frac{h^2_{SQL}}{2K_{MI}(\omega)}\left[e^{-2r}(\sin\theta - \cos\theta K_{MI}(\omega))^2 + e^{2r}(\sin\theta K_{MI}(\omega) + \cos\theta)^2\right]$$



[2]

[2] Living Reviews in Relativity volume 22, 2 (2019)

Different Schemes

- Frequency dependent squeezing
- EPR entanglement based conditional squeezing

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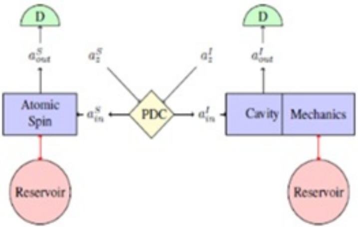
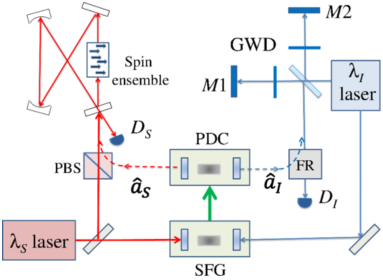
[3] Living Reviews in Relativity volume 22, 2 (2019)

Spin-optomechanical Hybrid Model

- Heterodyne detection [4]
- The measurement is performed by two entangled beams of light, probing the GWD and an auxiliary atomic spin ensemble.



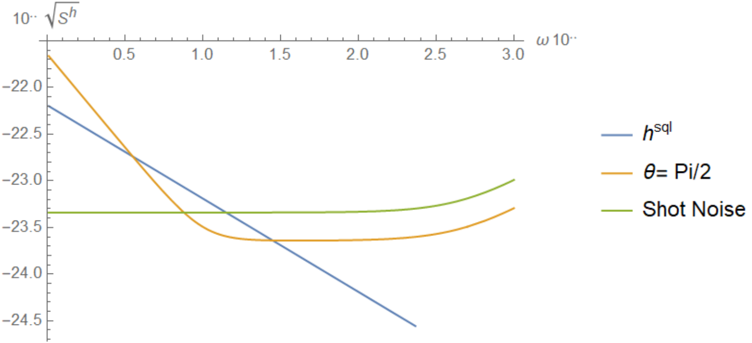


[4] PRL 121, 031101, (2018)

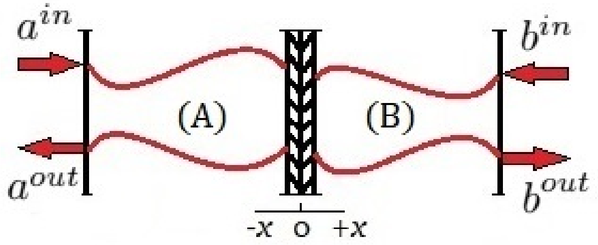
Squeezing in Hybrid System

$$\chi_M = \chi_S \rightarrow \omega_m = \omega_s,\, \gamma_m = \gamma_s$$
$$\Gamma_M = \Gamma_S$$

$$S^h(\omega) = h_{SQL}^2 \frac{H_L^T T S^{in} T^\dagger H_L}{|H_L^T.t|} \rightarrow \frac{h_{SQL}^2}{2\,\mathbf{cosh2r}} \left[\frac{1}{K(\omega)} + K(\omega)\right]$$



Negative pressure optomechanics



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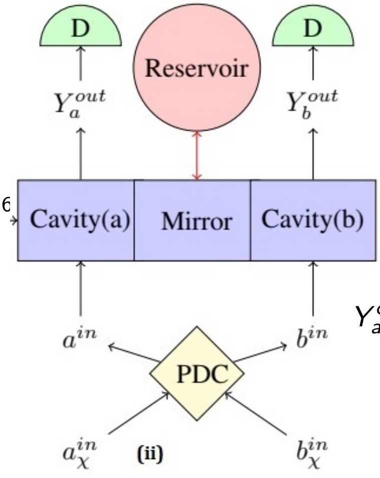
$$Y^{(out)}_{a,b} = e^{2i\beta_{a,b}} Y^{(in)}_{a,b} + K_{ab} X^{(in)}_{b,a}$$
$$-K_{a,b} X^{(in)}_{a,b} + i\sqrt{2K_{a,b}} \frac{F^S \pm F^{th}_{a,b}}{F^{sql}} \qquad (3)$$

[5] arXiv:2301.09974

Two-cavity optomechanics



$$X^{in}_{a,b} = \cosh r X^{\chi}_{a,b} + \sinh r X^{\chi}_{b,a}$$
$$Y^{in}_{a,b} = \cosh r Y^{\chi}_{a,b} - \sinh r Y^{\chi}_{b,a}, \qquad (4$$

$$Y_a^{out} + Y_b^{out}\tanh 2r = Y_a^{in} + Y_b^{in}\tanh 2r - \frac{K_a}{\cosh^2 2r}(X_{a,in} - \tanh 2r X_{b,in}) + i\frac{\sqrt{2K_a}}{\cosh^2 2r}\frac{F^{th}}{F^{sql}} + i\sqrt{2K_a}\frac{F^S(1+\tanh^2 2r}{F^{sql}} \qquad (5)$$

[6] arXiv:2301.09974

Two-cavity optomechanics

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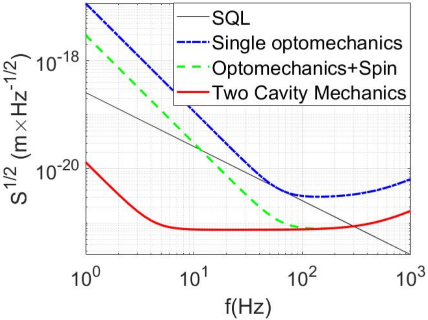

$$S^h(\omega) = h_{SQL}^2 \frac{H_L^T T S^{in} T^\dagger H_L}{|H_L^T . t|}$$

$$\rightarrow \frac{h_{SQL}^2}{(\mathbf{1} + \tanh^{\mathbf{2}} \mathbf{2r})^{\mathbf{2}} \mathbf{cosh2r}} \left[\frac{1}{K(\omega)} + \frac{1}{\mathbf{cosh^4 2r}} K(\omega) \right]$$

[7] arXiv:2301.09974

Practical Implementation - GW Interferometer

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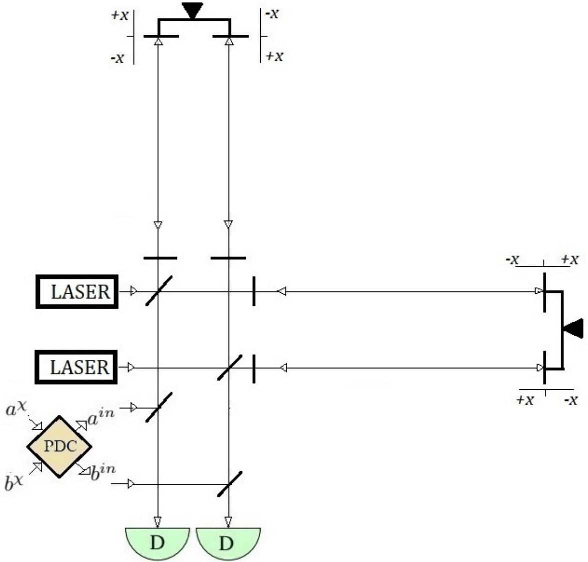

[8] arXiv:2301.09974

Mirror Design

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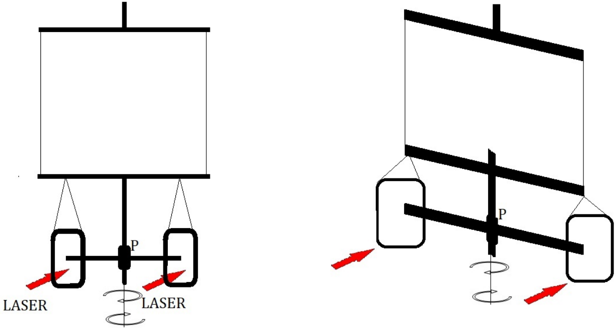
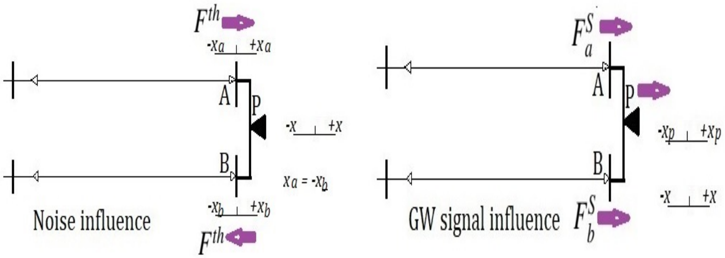


[9] arXiv:2301.09974

GW vs Optomechanical Interaction



[10]

[10] arXiv:2301.09974

Conclussion

Compared to the schemes proposed before, our scheme appears to be much more efficient for–

- not demanding any auxiliary spin system, therefore there is no need to design a negative mass spin system with a lower Larmor frequency and bandwidth
- it has the ability to suppress the QBA noise more than the spin-optomechanical hybrid scheme, along with the same rate of the suppression of shot noise.
- it suppresses the thermal noise simultaneously with good efficiency.

[11]

[11] arXiv:2301.09974

Looking for opportunity to execute the experiment

Thank you