Intra-cavity filtering schemes

Haixing Miao

Reporting joint work by:

California Institute of Technology: Yanbei Chen

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University of Western Australia: Yiqiu Ma, and Chunnong Zhao

Outline

- **Background**
  - Input filtering—frequency-dependent squeezing
  - Output filtering—frequency-dependent readout
- **Intra-cavity filtering with passive components**
  - Evading radiation-pressure noise
  - Realizing a speed meter
  - Achieving a broadband enhancement
- **Intra-cavity filtering with active components**
  - Stable active filters
  - Unstable active filters

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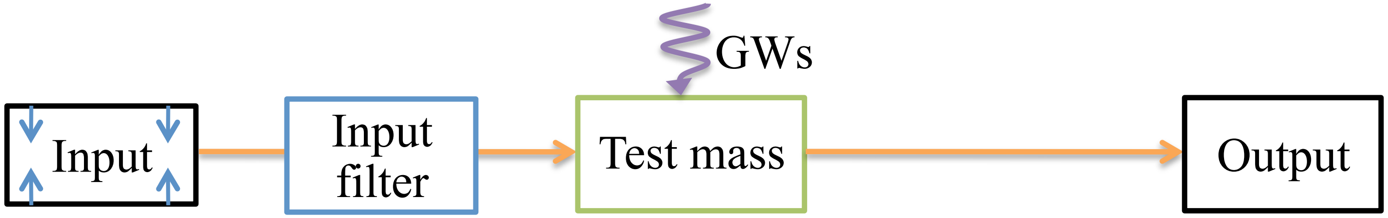
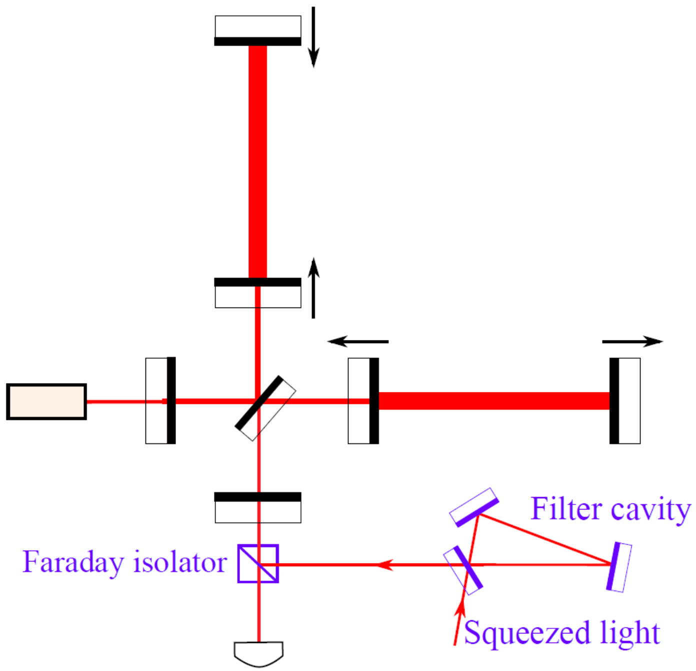
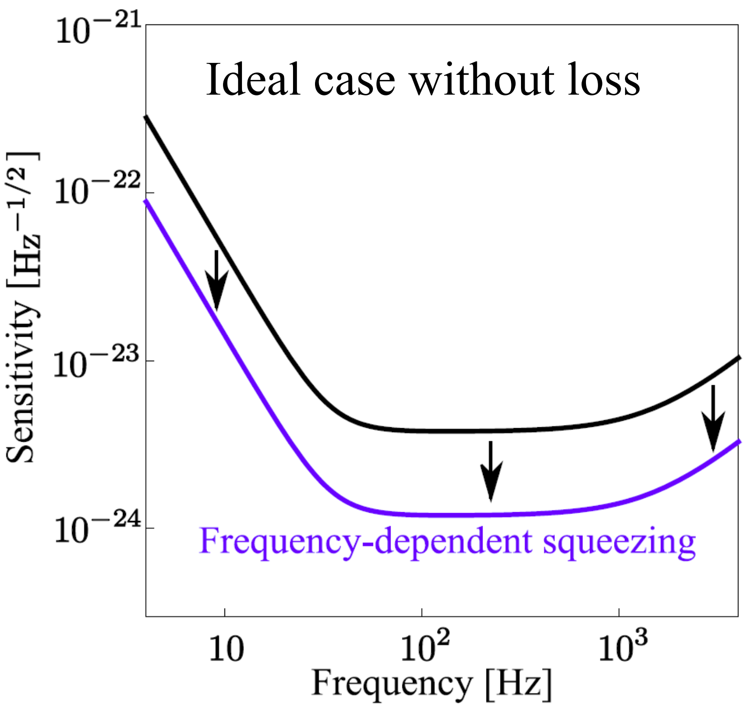
Input filtering

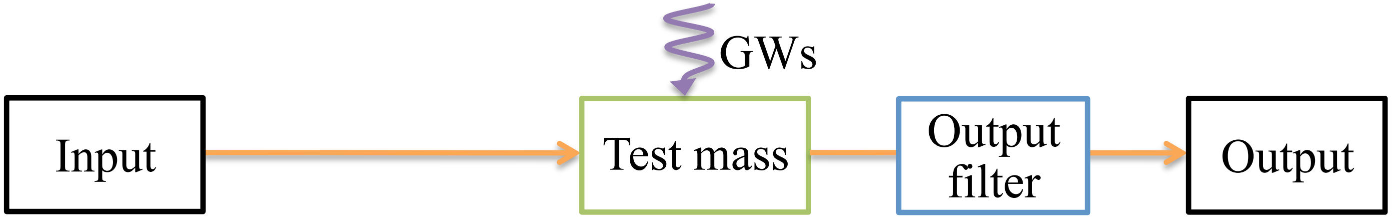


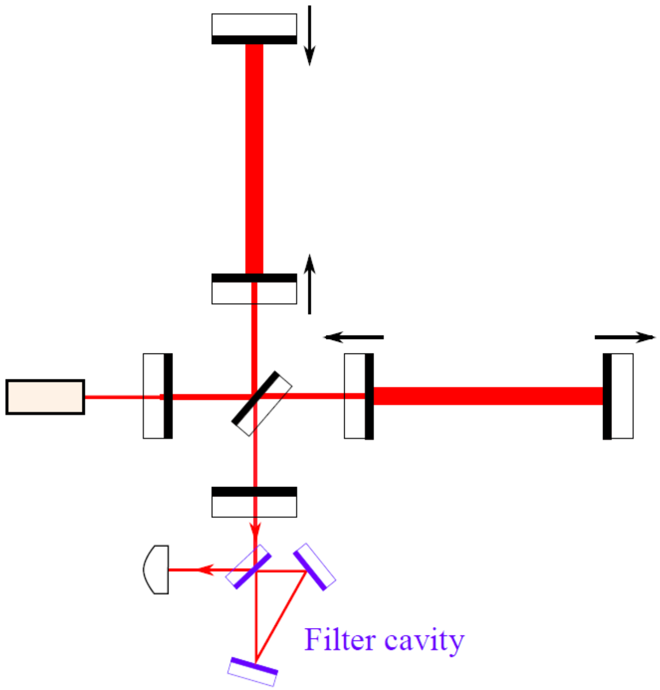


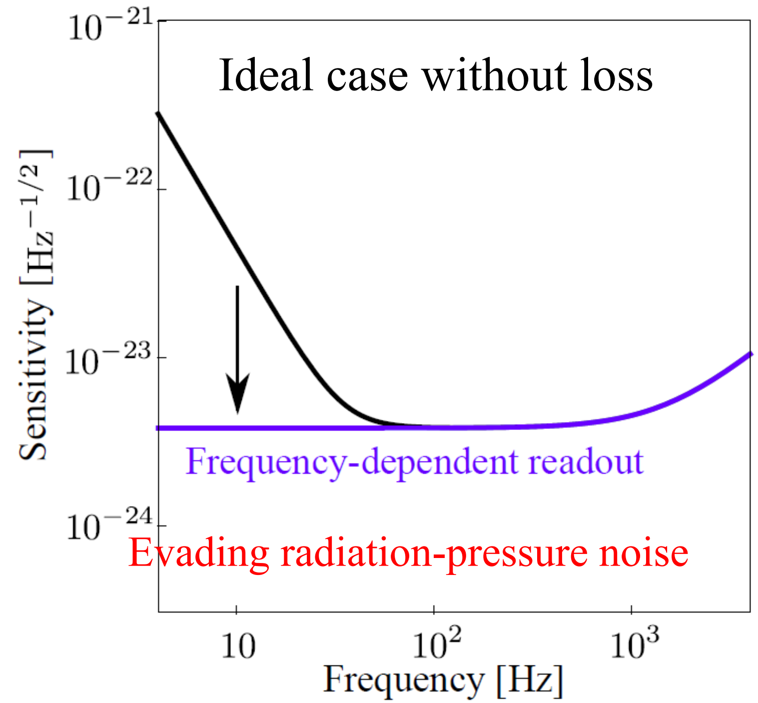


Reference: H. Kimble, Y. Levin, A. Matsko, K. Thorne, and S. Vyatchanin, PRD 65, 022002 (2001)

Output filtering

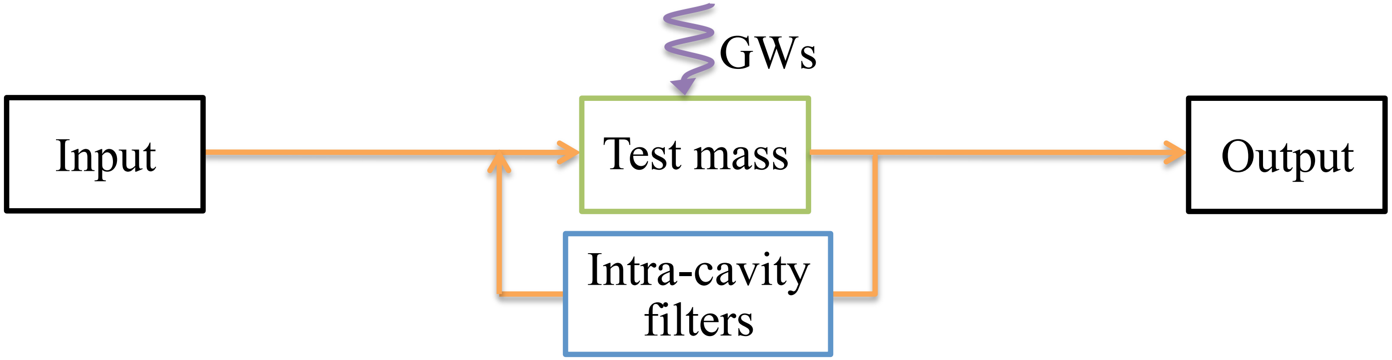


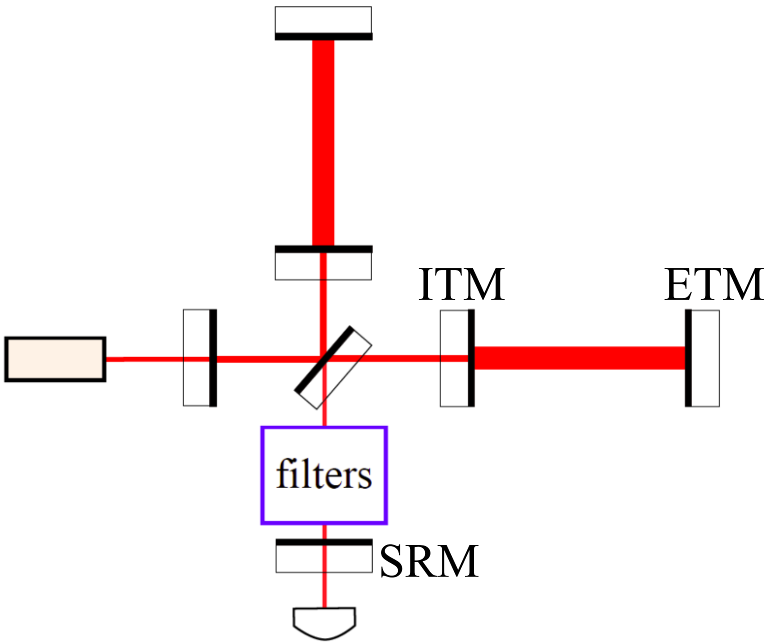




Reference: H. Kimble, Y. Levin, A. Matsko, K. Thorne, and S. Vyatchanin, PRD **65**, 022002 (2001).

Intra-cavity filtering





Reference: M. Wang, H. Miao, A. Freise, and Y. Chen, PRD **89**, 062009 (2014)

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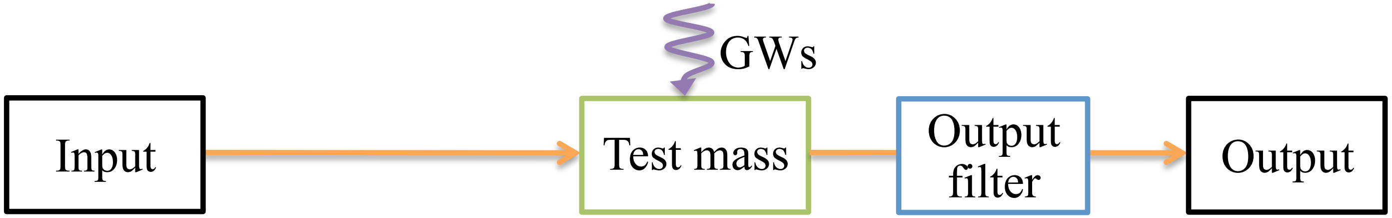
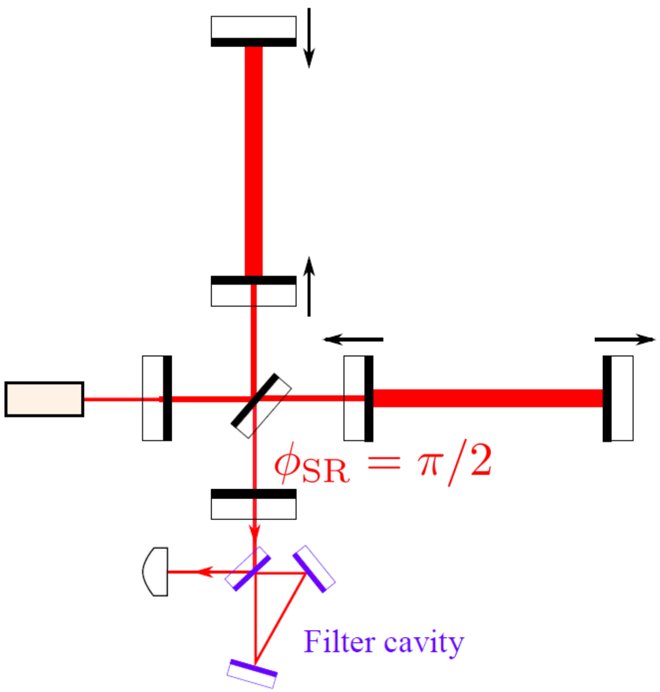
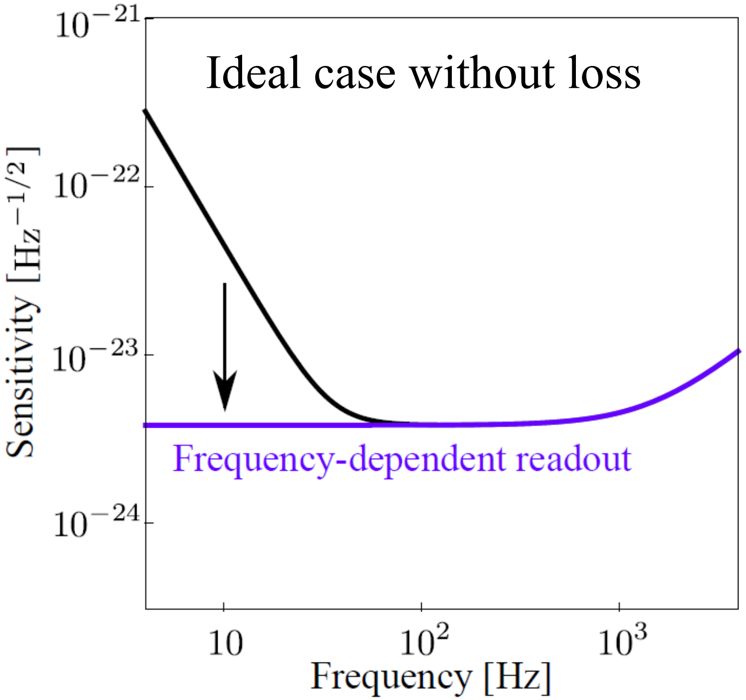
Evading radiation pressure noise

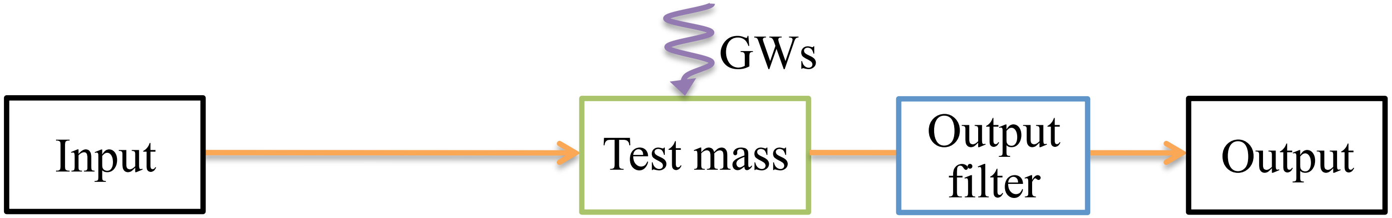


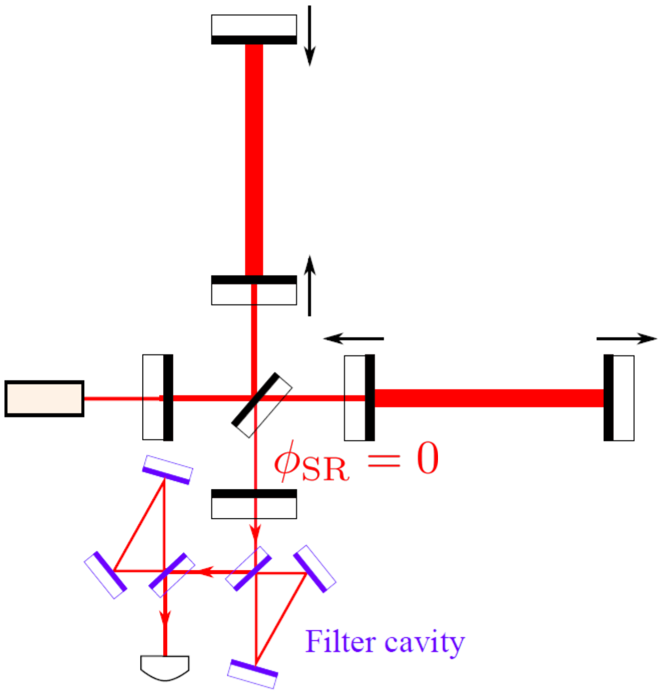




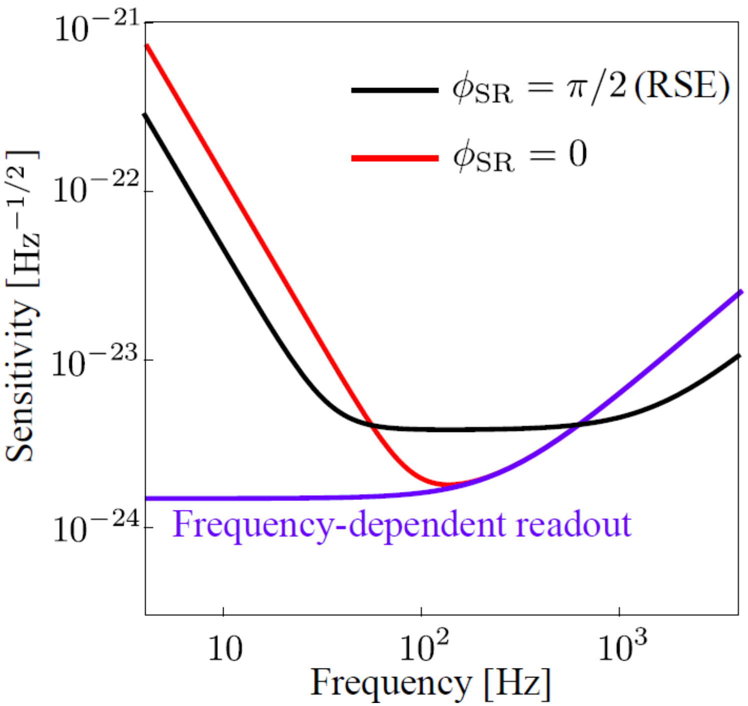
Resonant sideband extraction (RSE)—Broadband configuration

Evading radiation pressure noise

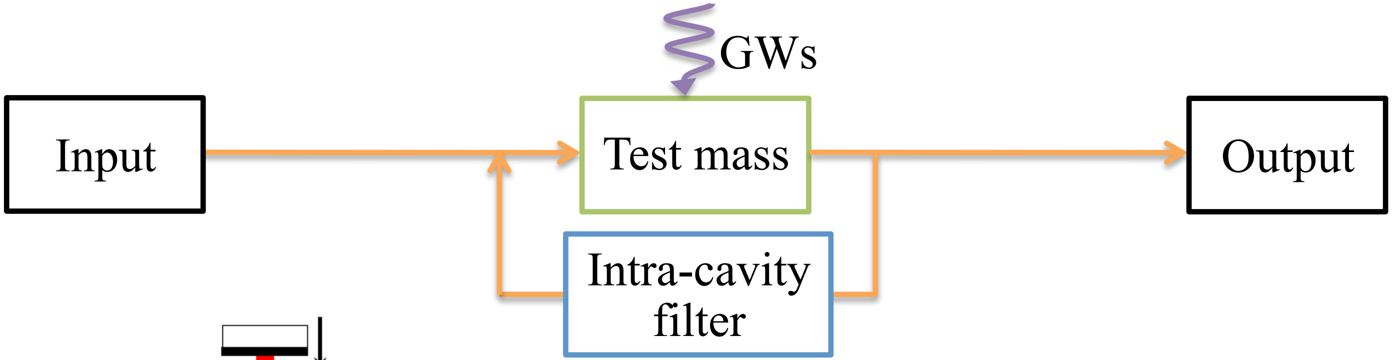


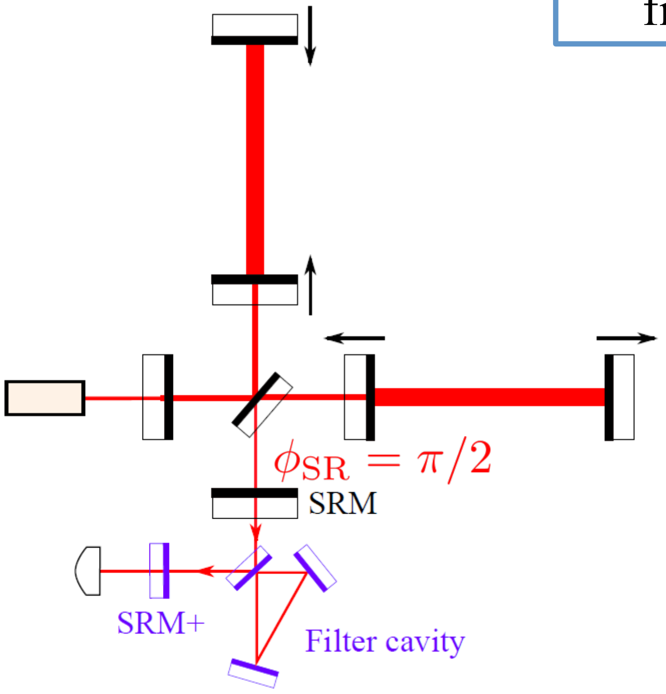


Narrowband tuned



Evading radiation pressure noise



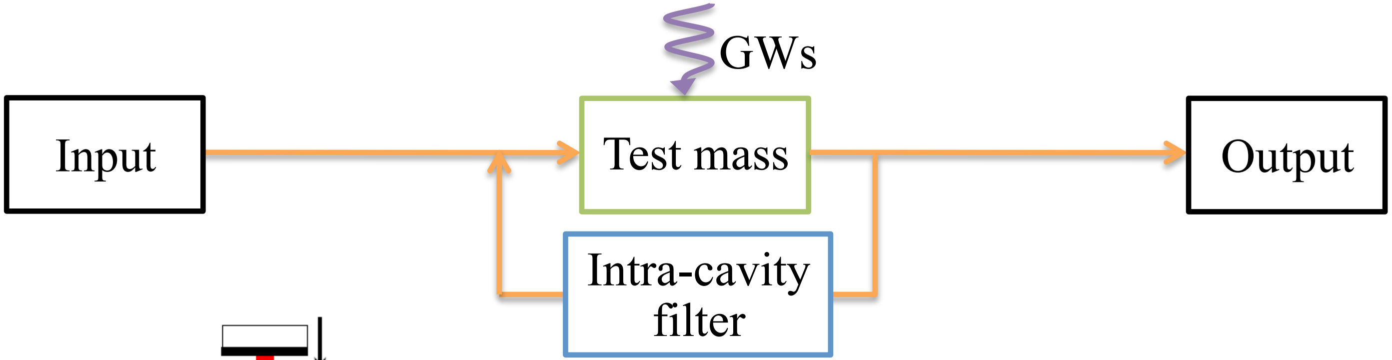


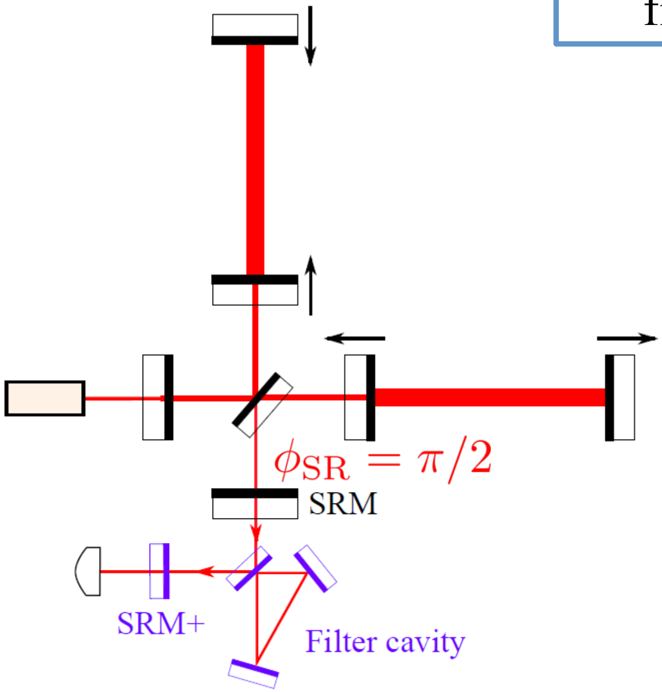
Use only one filter cavity

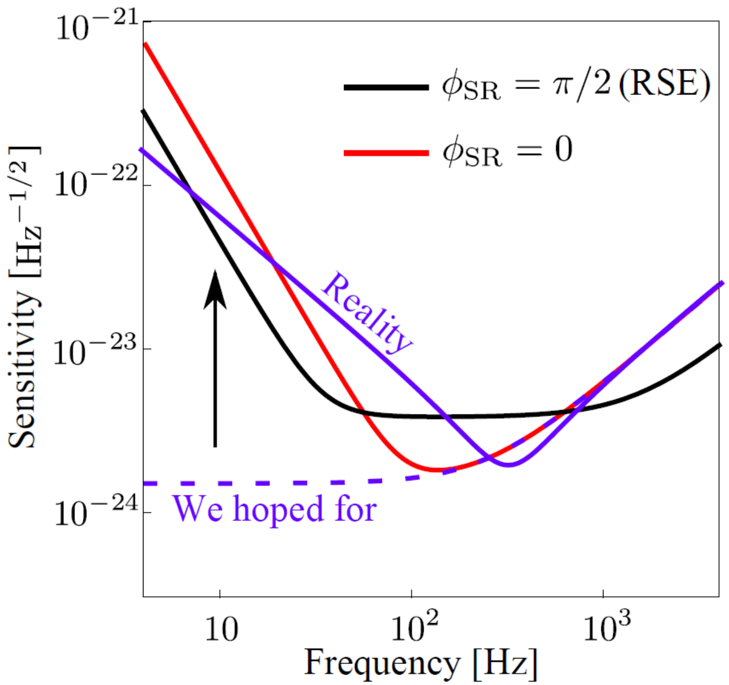
?

Sensitivity

Evading radiation pressure noise







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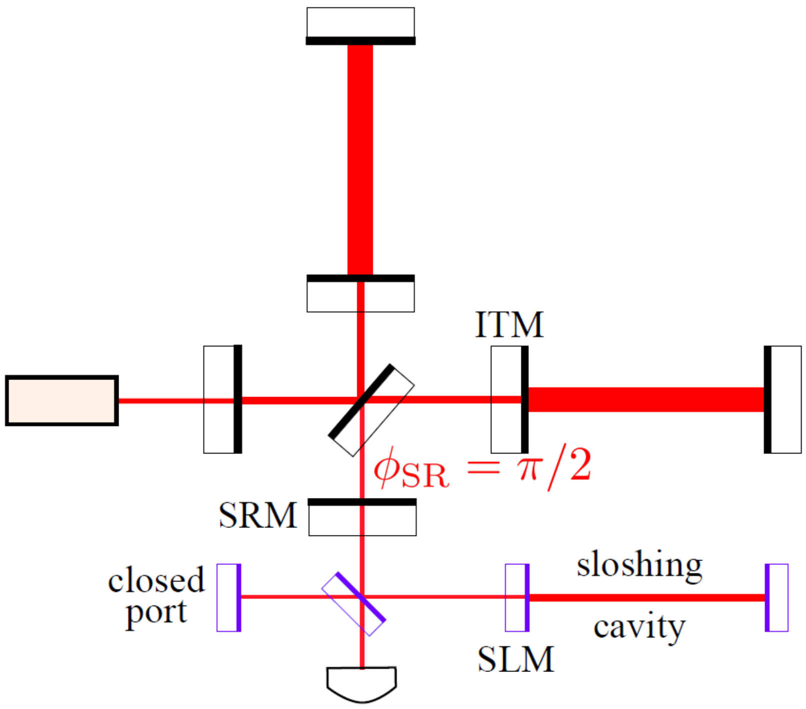
Realizing a speed meter

Speed meter with a sloshing cavity



SRM:

$$T_{\rm SRM} = T_{\rm ITM} \qquad \phi_{\rm SR} = \pi/2$$

Speed response:

$$y_{\rm out} \propto x(t) - x(t - \tau_s) \approx \tau_s \frac{\rm d}{{\rm d}t} x(t)$$

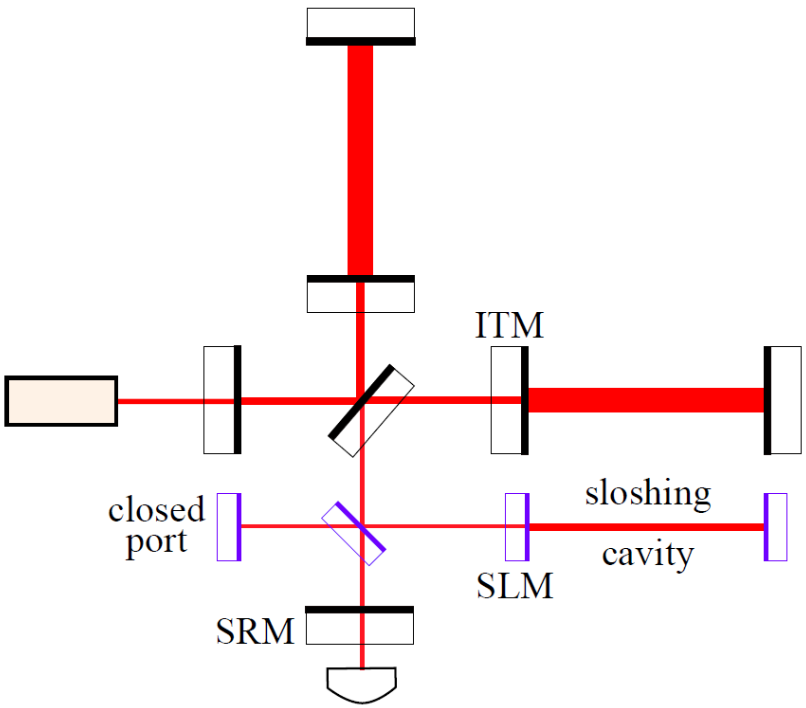
Sloshing Frequency:

$$\tau_s^{-1} \approx \omega_s \equiv \frac{c\sqrt{T_{\rm SLM}}}{2\sqrt{L_s L_{\rm arm}}}$$

Reference: P. Purdue and Y. Chen, PRD **66**, 122004 (2002).

Realizing a speed meter

Intra-cavity filtering scheme as a speed meter



SRM:

For tuning the bandwidth.

Speed response:

$$y_{\text{out}} \propto x(t) - x(t - \tau_s) \approx \tau_s \frac{\mathrm{d}}{\mathrm{d}t} x(t)$$

Sloshing Frequency:

$$\tau_s^{-1} \approx \omega_s \equiv \frac{c\sqrt{T_{\text{SLM}} T_{\text{ITM}}}}{2\sqrt{L_s L_{\text{arm}}}}$$

Sloshing frequency is determined by compound mirror (ITM and SLM).

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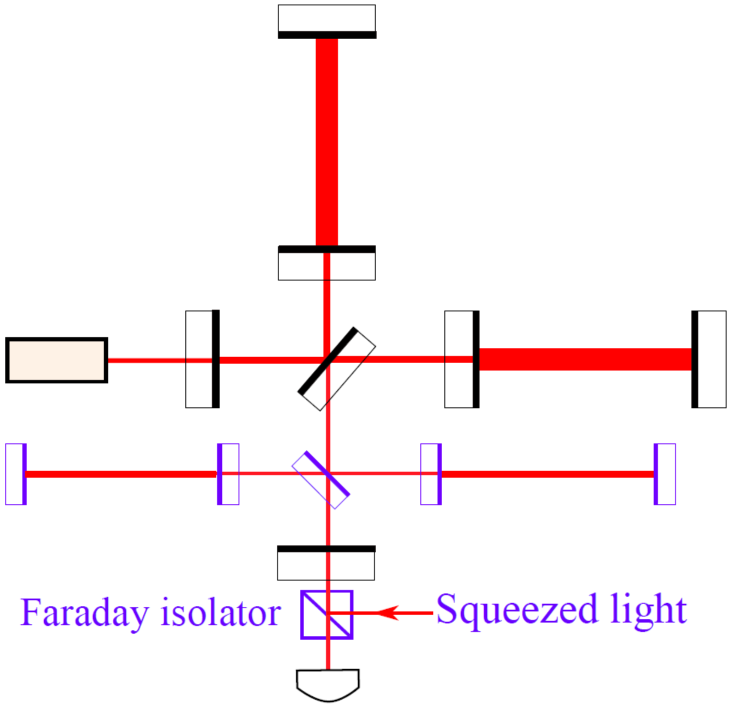
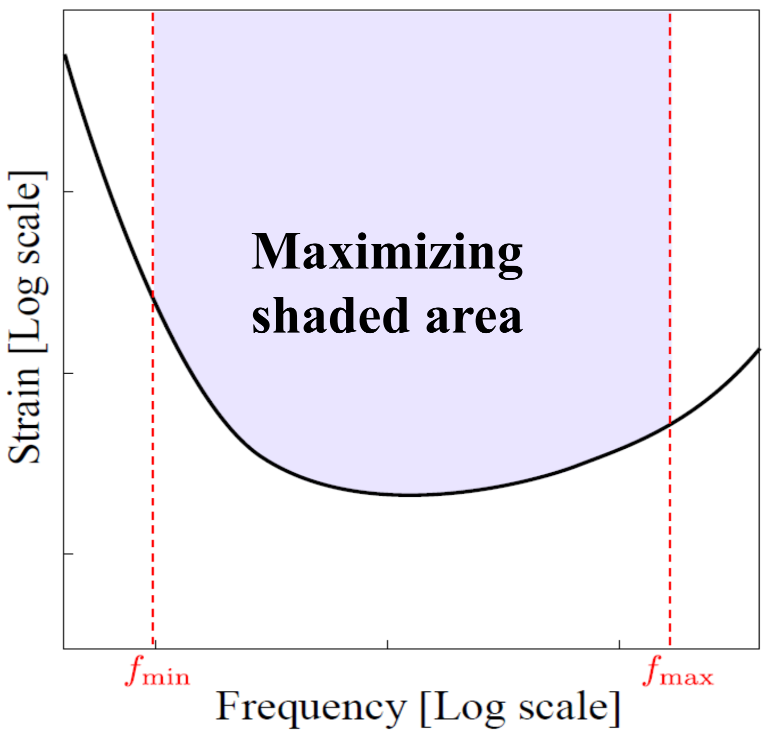
Achieving a broadband enhancement

Allows the parameters for additional optics to be tunable

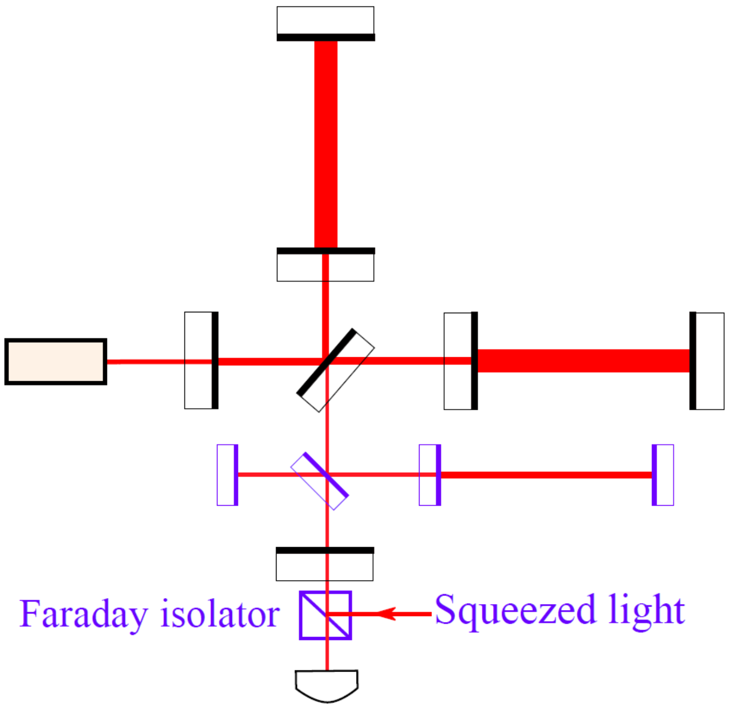


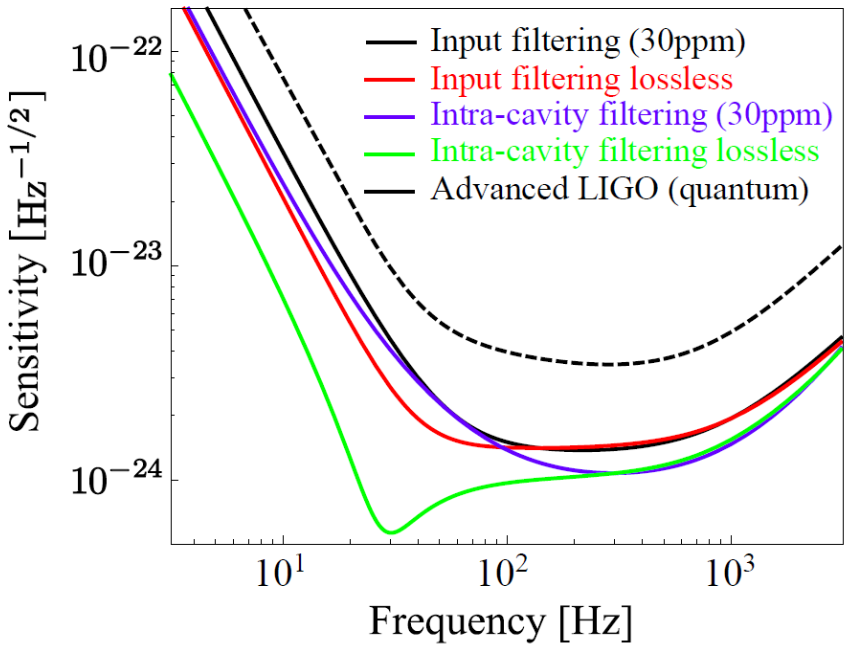


Use a cost function to maximize the broadband sensitivity.

Achieving a broadband enhancement

Allows the parameters for additional optics to be tunable



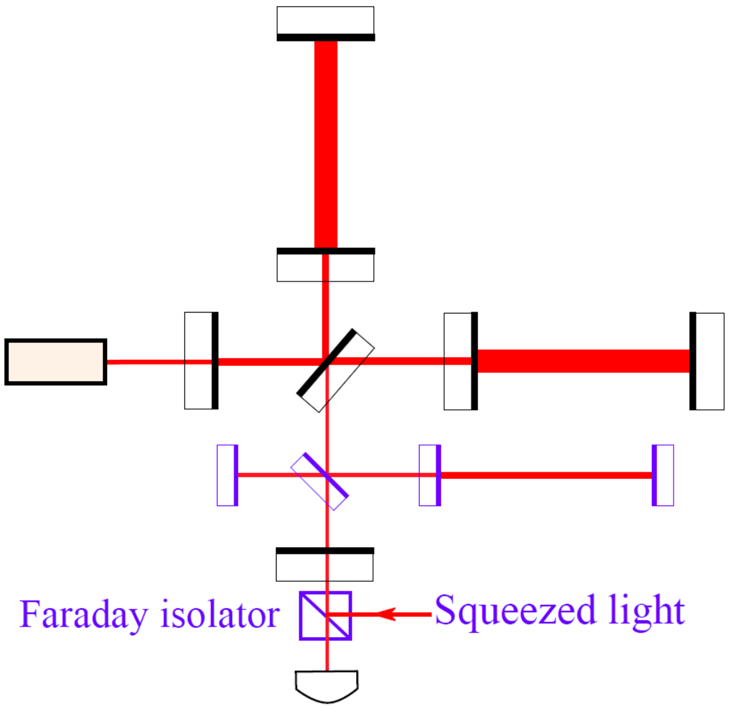


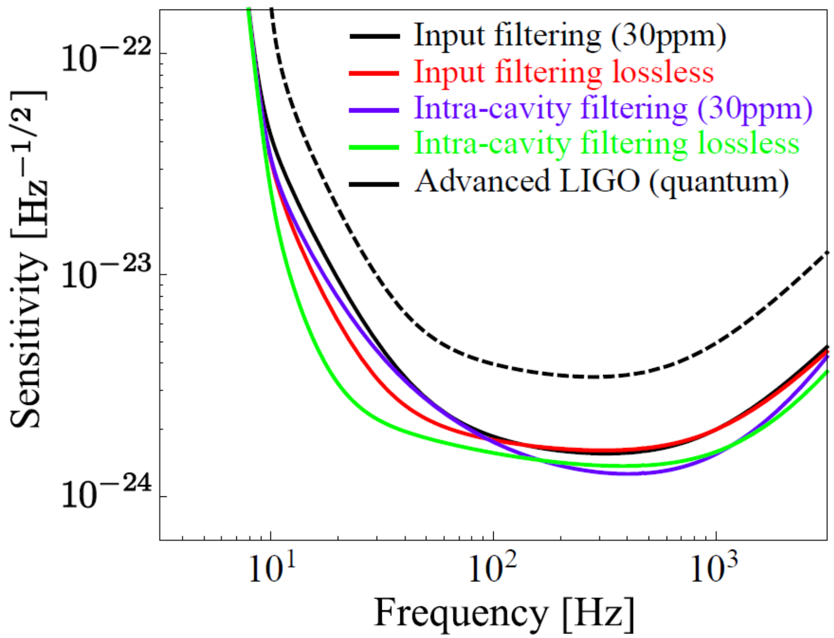
Quantum-noise only

Use a cost function to maximize the broadband sensitivity.

Achieving a broadband enhancement

Allows the parameters for additional optics to be tunable





Include classical noises

Use a cost function to maximize the broadband sensitivity.

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Using active components

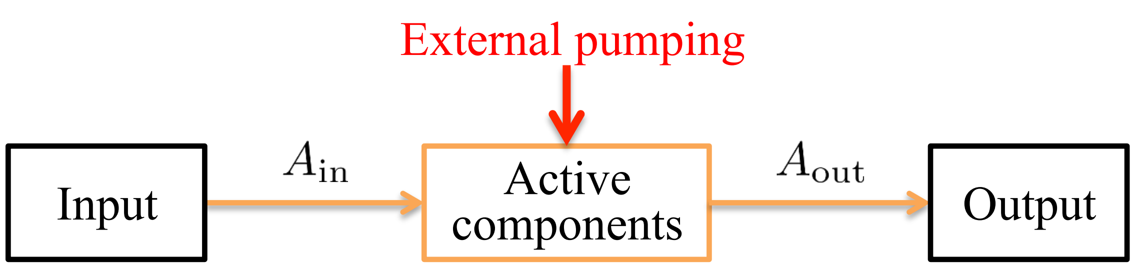
Passive:

No external energy input, e.g., usual optics.

Lossless: $|A_{\rm in}(\Omega)|^2 = |A_{\rm out}(\Omega)|^2$ (Energy conservation)

Active:

With external energy input, e.g., optical amplifiers.

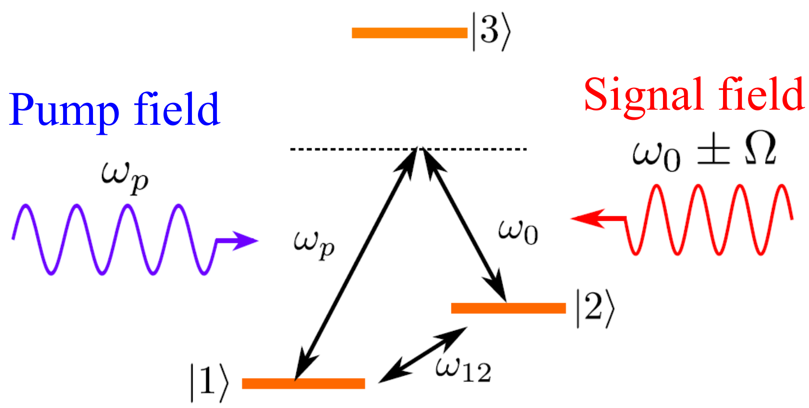


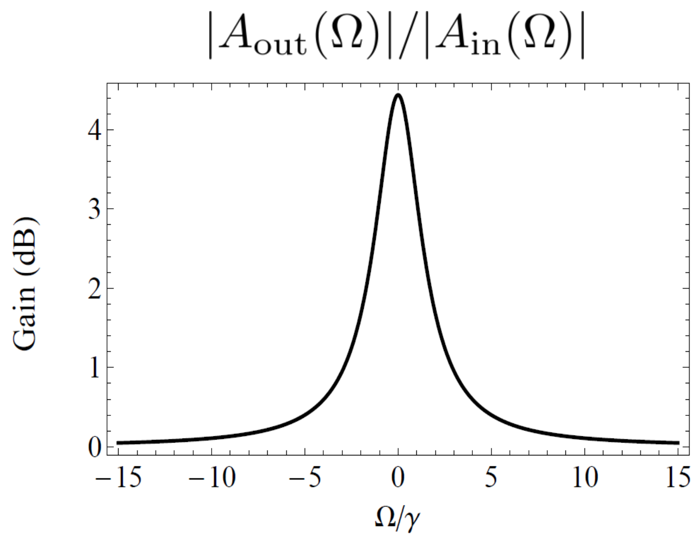
$$|A_{\rm in}(\Omega)|^2 < |A_{\rm out}(\Omega)|^2$$

Using active components

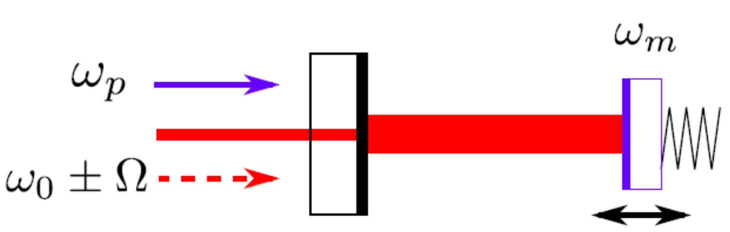
Examples (general nonlinear optics):

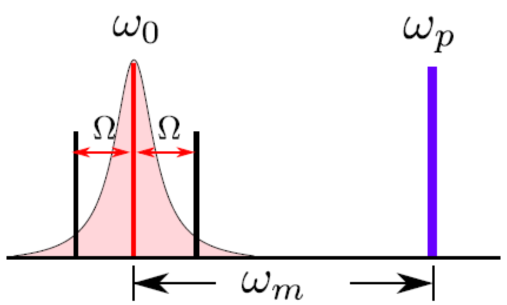
1. Raman amplifier (atomic system):



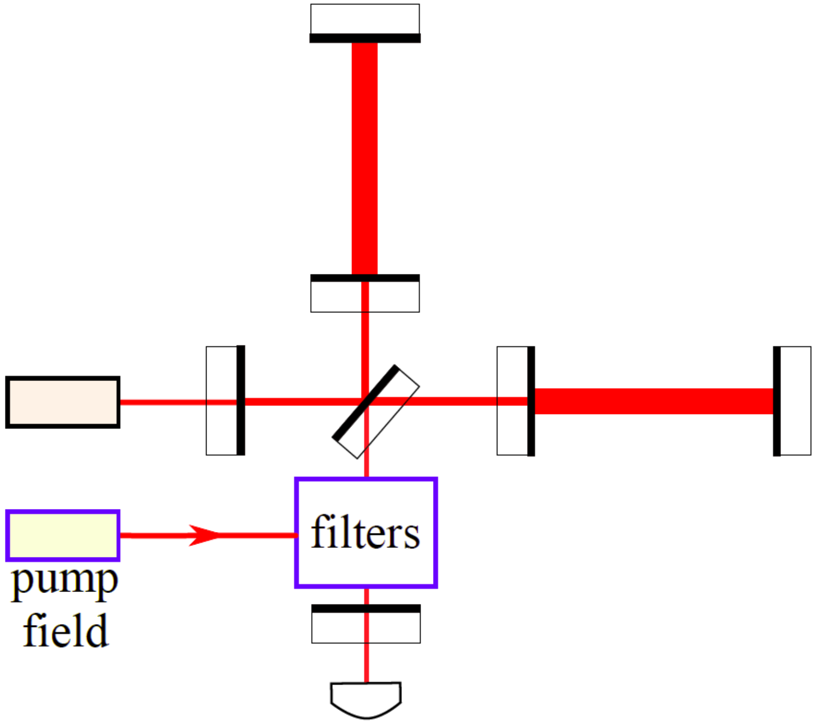


2. Optomechanical system:





Active intra-cavity filtering



Motivation:

To obtain frequency-dependent phase different from passive filters.

Example:

Negative dispersion **without absorption**: $\frac{d\phi(\Omega)}{d\Omega} < 0 \quad \frac{|A_{out}|}{|A_{in}|} \approx 1$

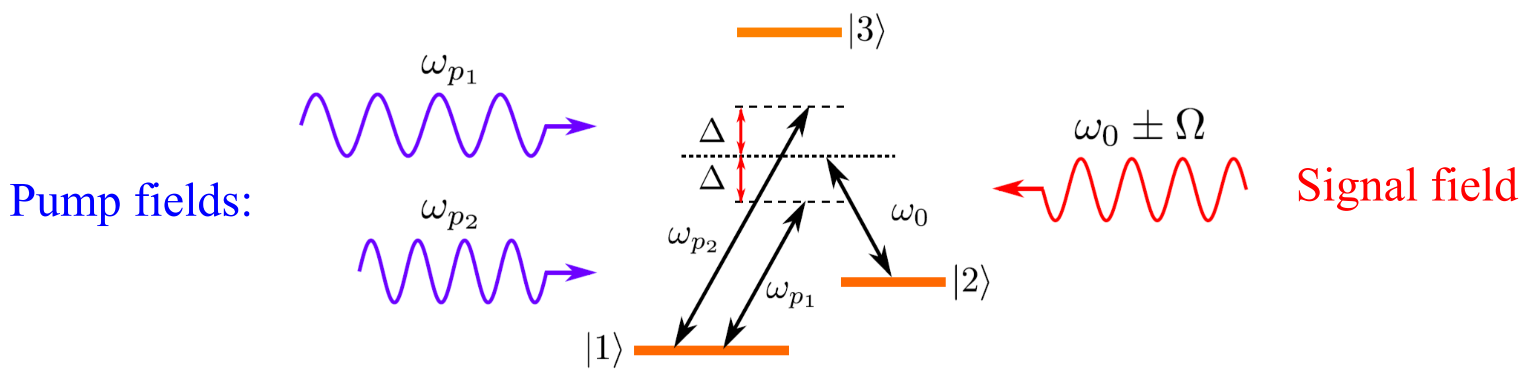
Active intra-cavity filtering

Example:

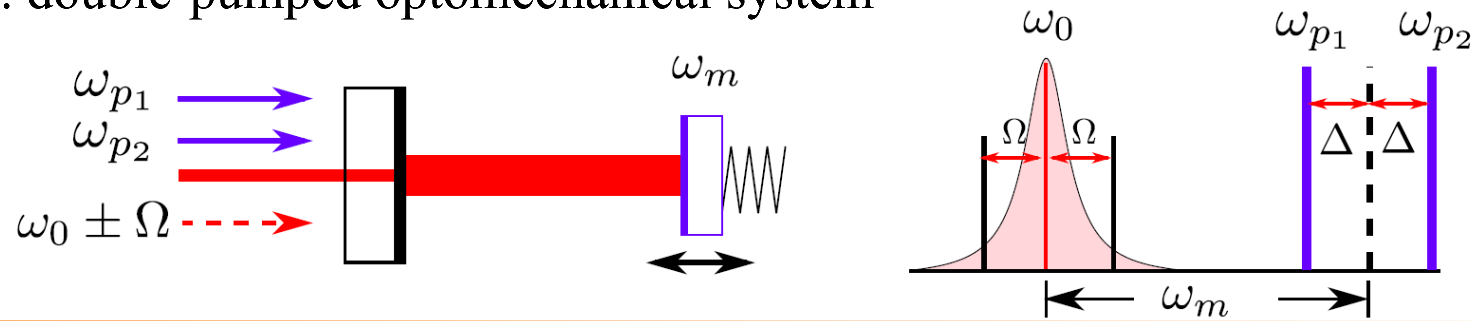
Negative dispersion **without absorption**: $\frac{d\phi(\Omega)}{d\Omega} < 0$ $\frac{|A_{out}|}{|A_{in}|} \approx 1$

Realization :

1. double-pumped three-level atomic system

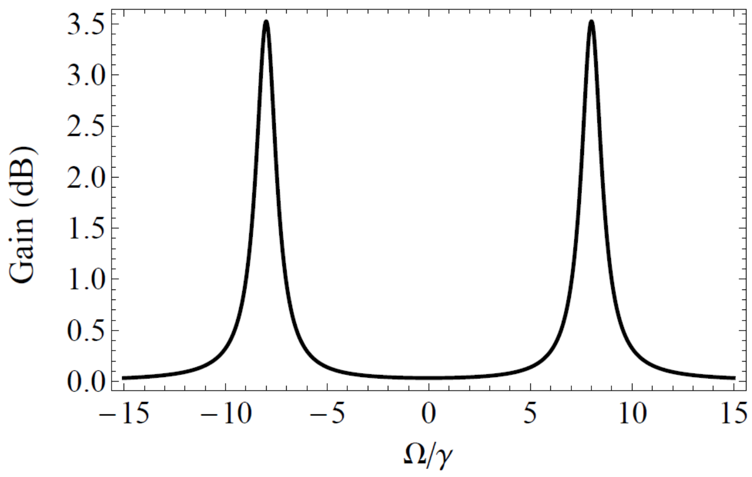


2. double-pumped optomechanical system

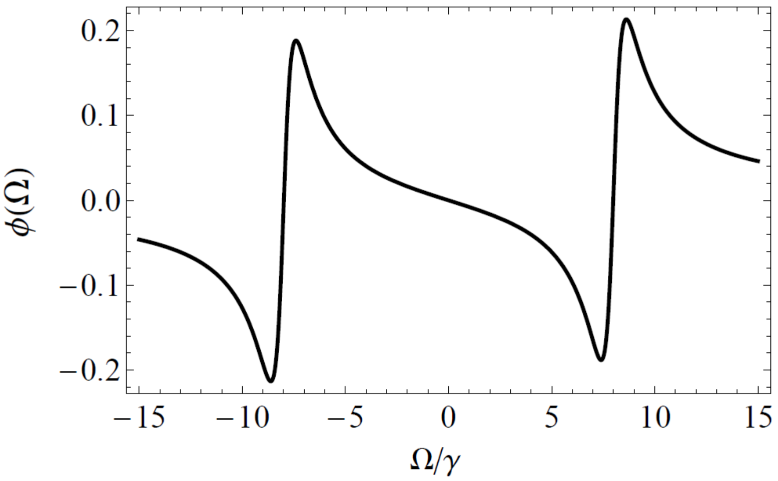


Active intra-cavity filtering

$|A_{\rm out}|/|A_{\rm in}|$



$\arg(A_{\rm out}/A_{\rm in})$



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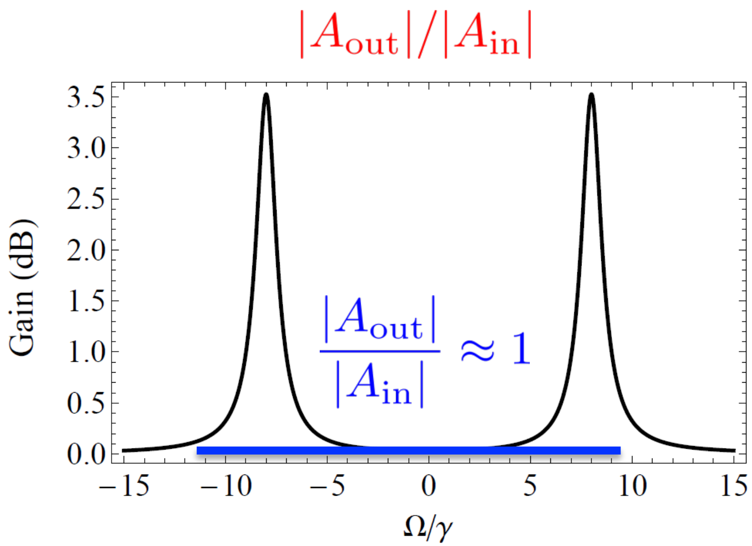
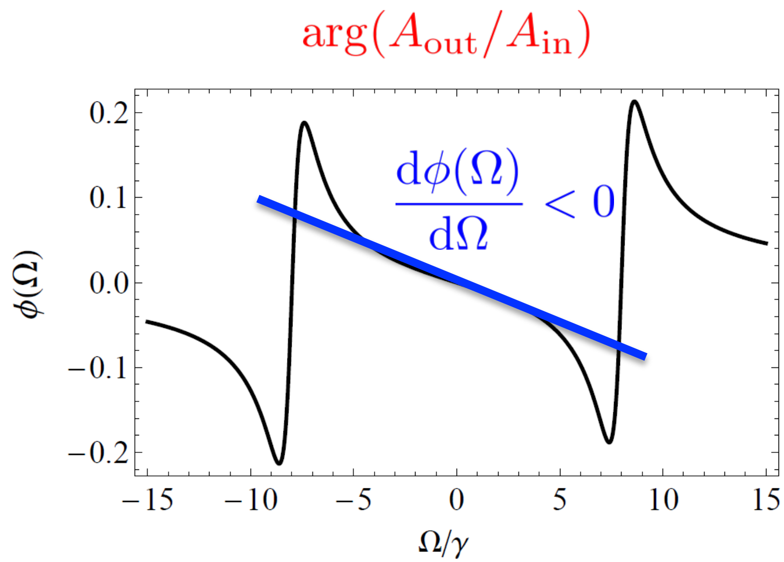
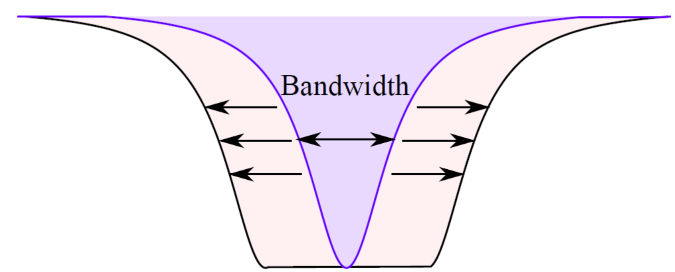




White-light cavity idea: cancelling propagation phase delay

$$\frac{d\phi(\Omega)}{d\Omega} = -\frac{L_{\rm arm}}{c}$$

Resonant at a broad frequency band

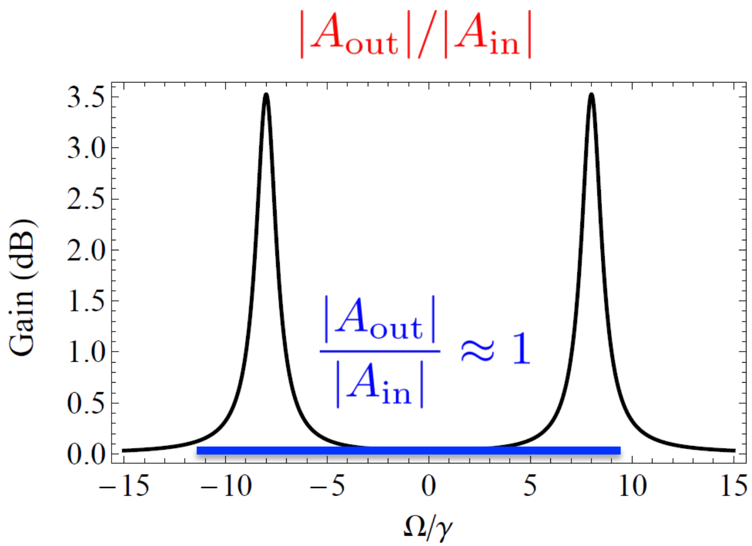


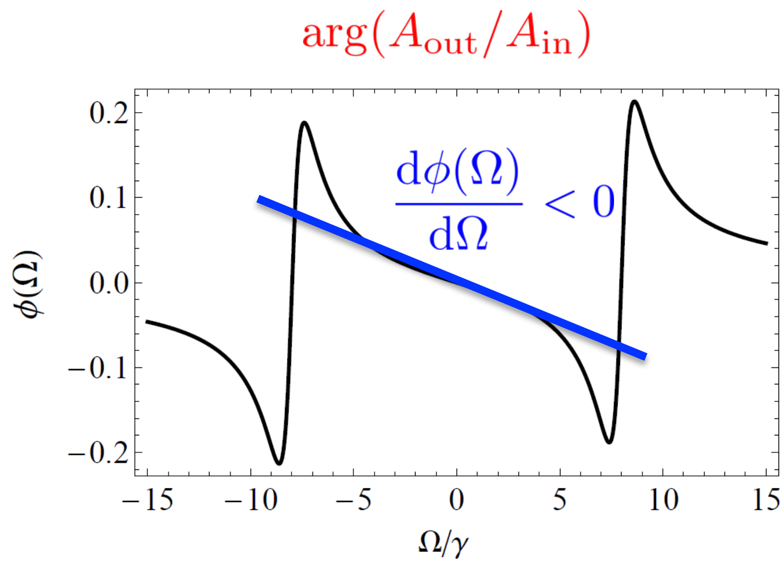
References:

[1] A.Wicht, K. Danzmann, M. Fleischhauer, M. Scully, G. Mueller, and R. Rinkleff (1997).

[2] G. S. Pati, M. Salit, K. Salit, and M. S. Shahriar (2007).

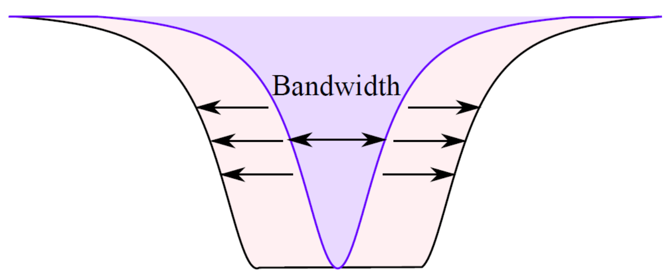
Active intra-cavity filtering





White-light cavity idea: cancelling propagation phase delay

Really works?



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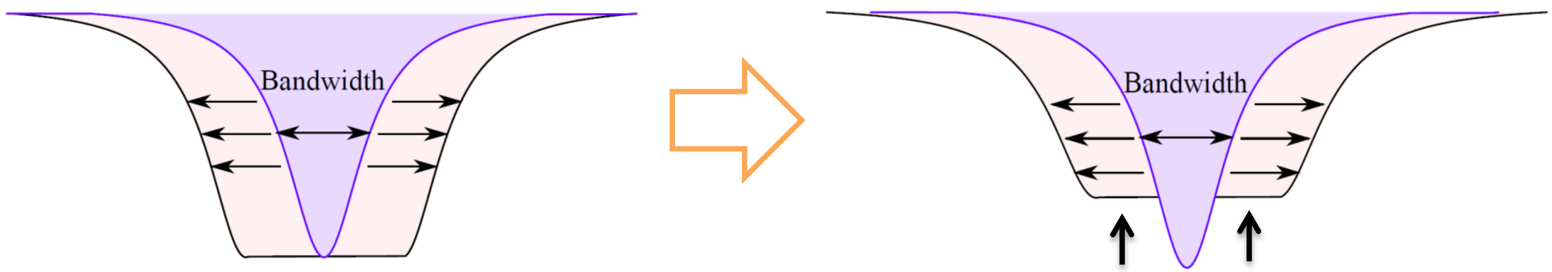
Active intra-cavity filtering

Detailed quantum-noise analysis:

$$\hat{A}_{\rm out}(\Omega) = G\,\hat{A}_{\rm in}(\Omega) + \sqrt{1-G^2}\,\hat{n}^\dagger(-\Omega)$$

Additional noise



Plus stability requirement:

Do not allow for enhancement in principle.

Reference:

Yiqiu Ma, H. Miao, C. Zhao and Y. Chen (in preparation).

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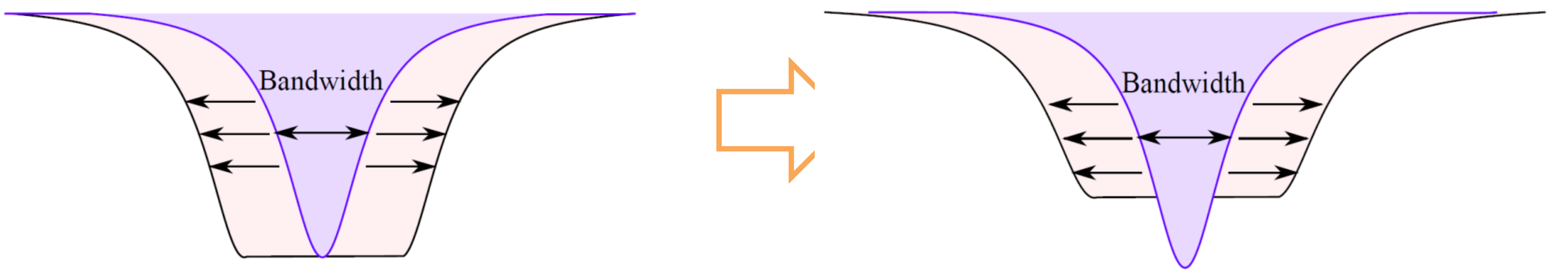

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Is this applied to general **stable** active filters?

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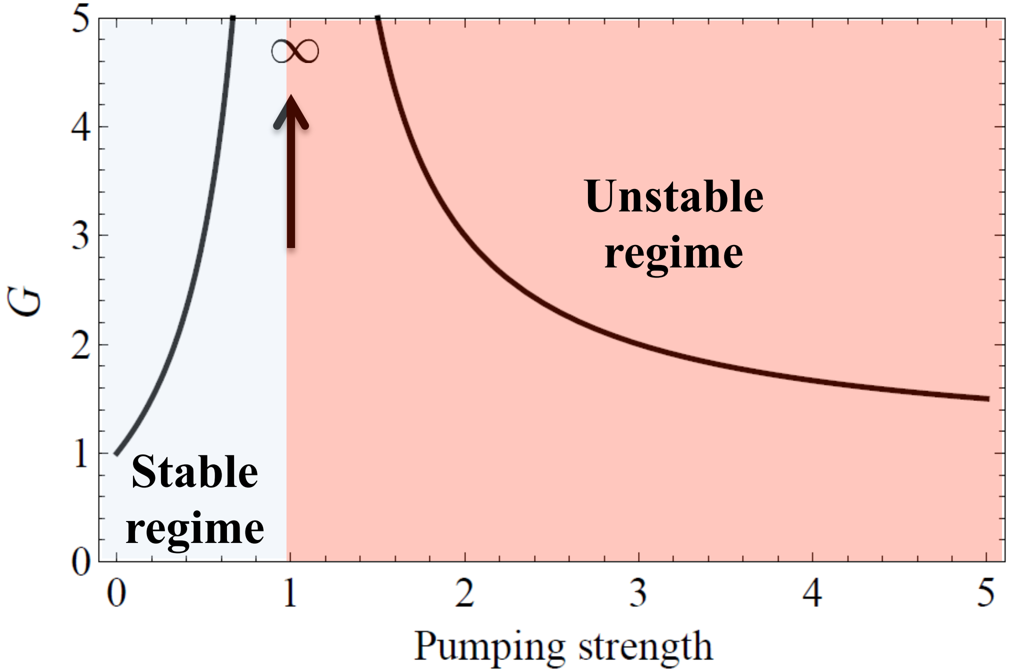
Unstable active filters

General input-output relation:

$$\hat{A}_{\rm out}(\Omega) = G\,\hat{A}_{\rm in}(\Omega) + \sqrt{1-G^2}\,\hat{n}^\dagger(-\Omega)$$

Gain vs pumping strength:



Very high pumping:

$$G \to 1$$

$$\sqrt{1-G^2} \to 0$$

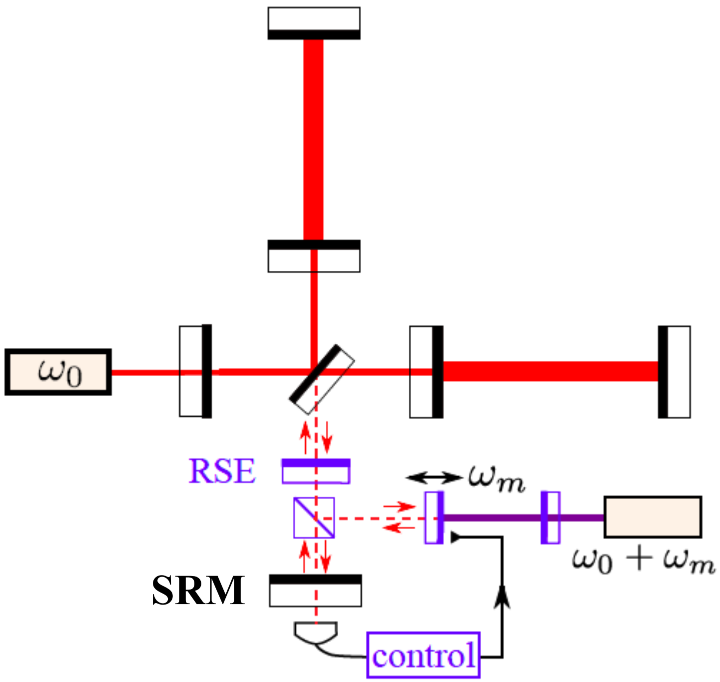
Additional noise gets suppressed.

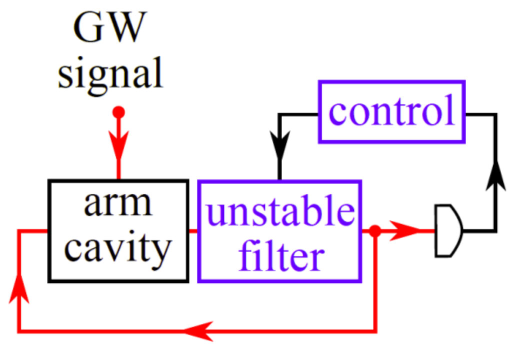
Unstable regime and phase is always in advance.

Unstable active filters

Together with feedback control

Example: unstable optomechanical filter





Signal recycling

Reference:

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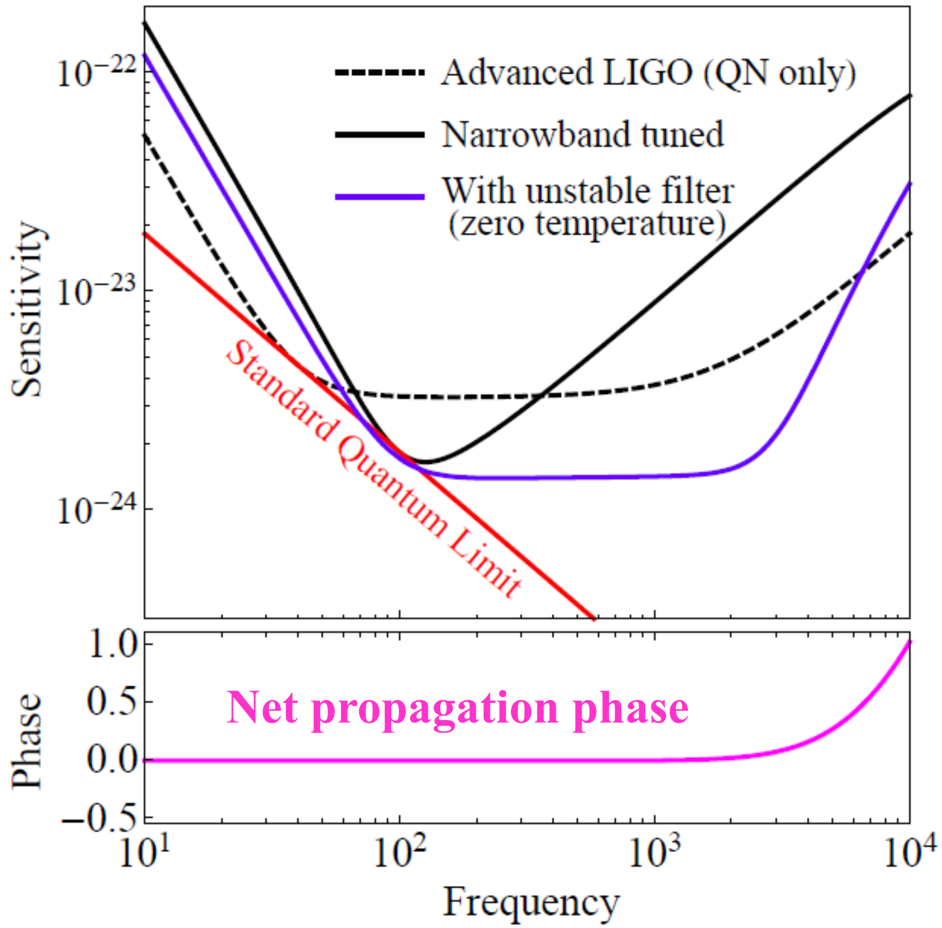
Unstable active filters

Resulting sensitivity curve:

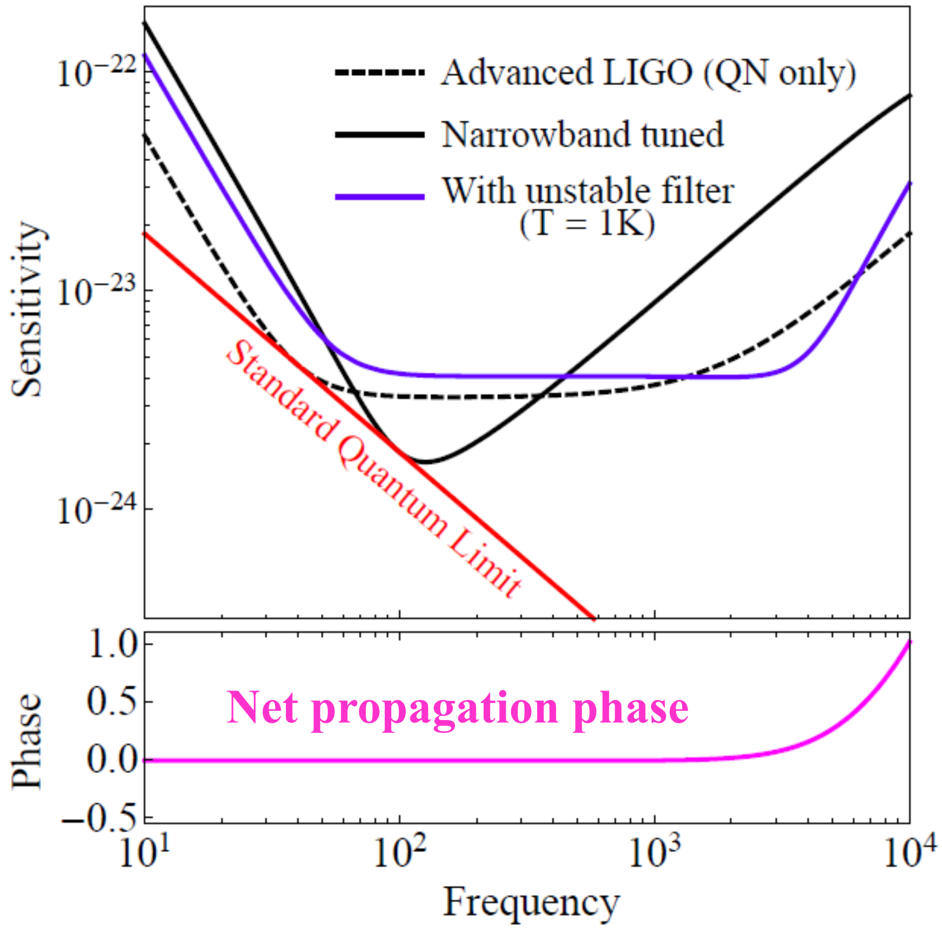


Sample parameters for optomechanical filter:

$$m = 1\mu\text{g}$$
$$\omega_m = 10\text{MHz}$$
$$Q_m = 5 \times 10^7$$
$$P_c = 6\text{W}$$
$$L = 5\text{cm}$$
$$\mathcal{F} = 3 \times 10^5$$

Unstable active filters

Resulting sensitivity curve:



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Bottom line:

Works in principle. Difficult to realize with optomechanical system due to thermal noise.

Any general argument?

The end

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