Increasing future gravitational-wave detectors sensitivity by means of amplitude filter cavities and quantum entanglement

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1. CMW
2. CMW + Entanglement
3. CMW + Entanglement + Broadened interferometer
4. Conclusion

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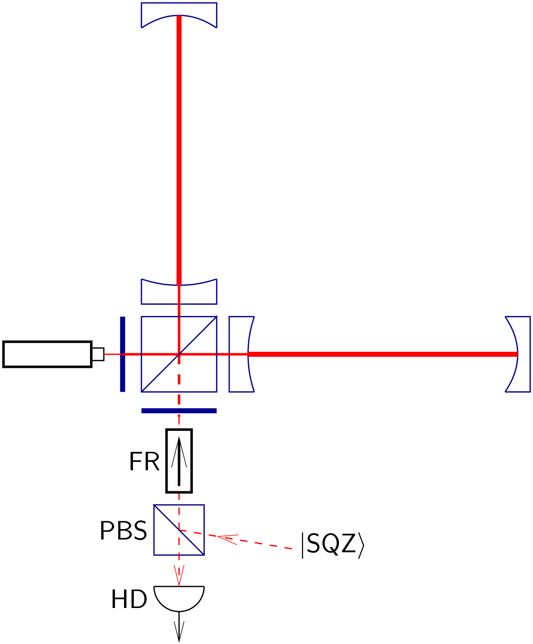
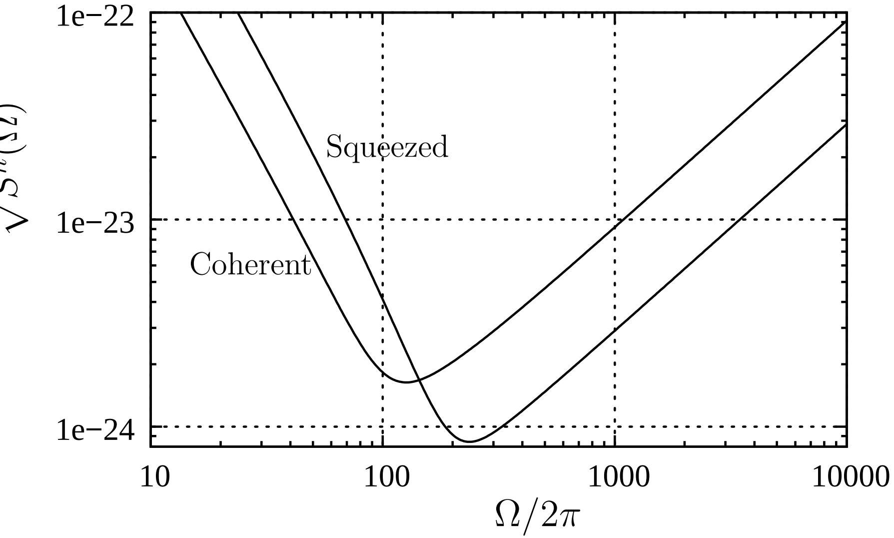
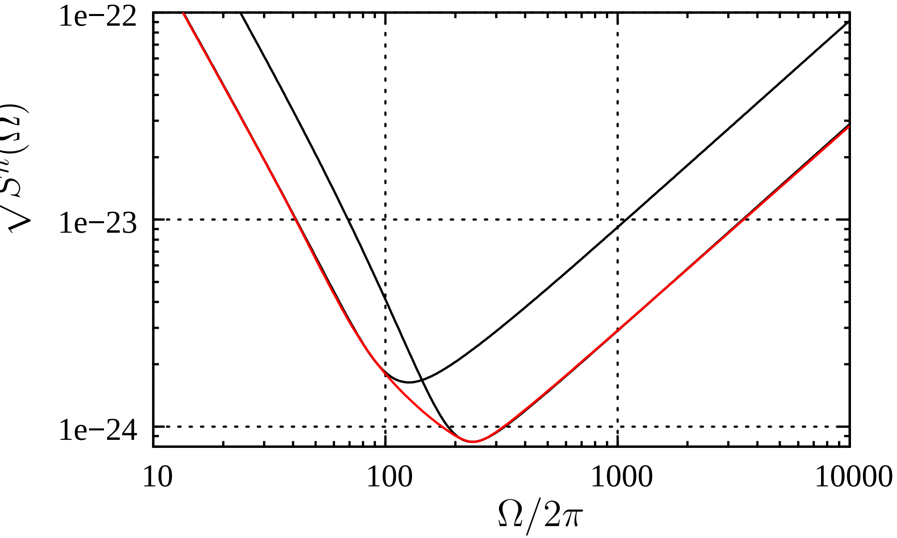
Squeezed interferometer



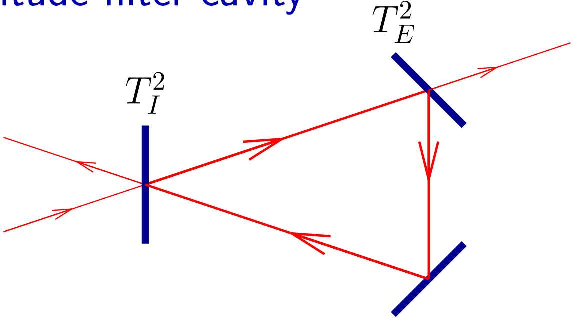
Conventional vs. squeezed



Conventional + squeezed (dream)



The amplitude filter cavity

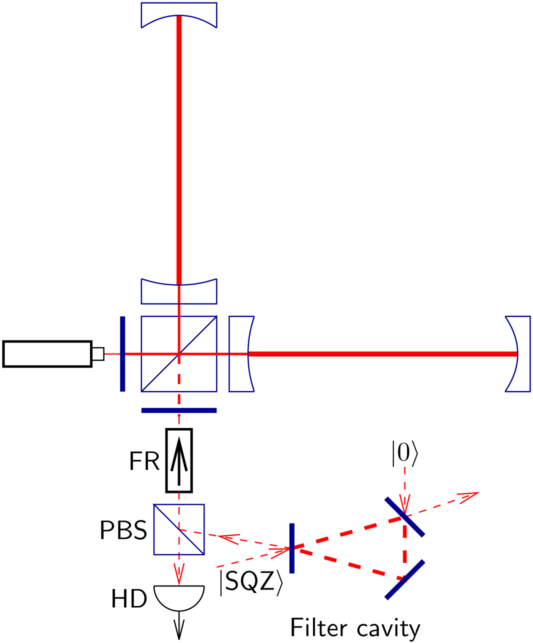


$$T_I^2 = T_E^2 + A^2$$

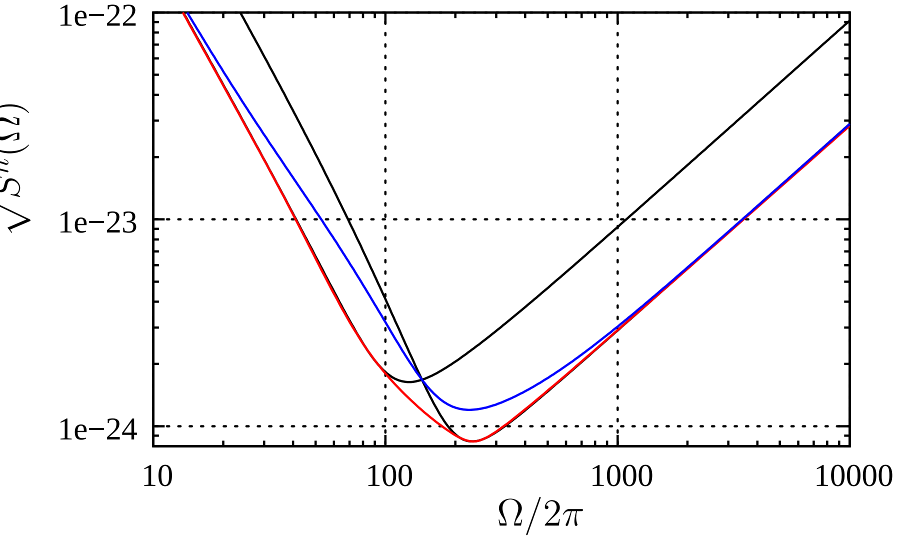
The cavity is transparent at $\Omega < \gamma_f = \dfrac{cT_I^2}{2L_f}$
and (almost) completely reflective at $\Omega > \gamma_f$.

T.Corbitt, N.Mavalvala, and S.Whitcomb, PRD 70, 022002 (2004)

The CMW scheme



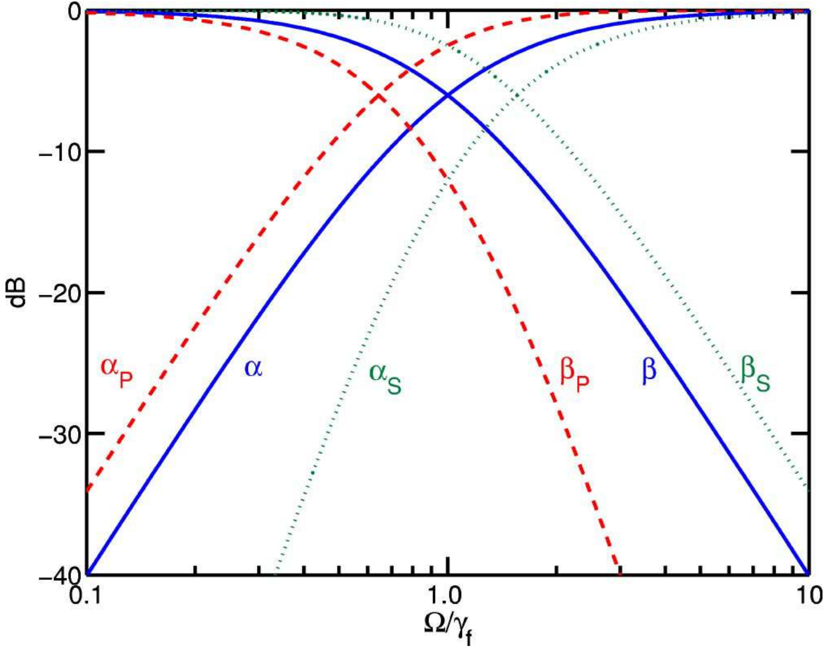
Conventional vs. squeezed vs. CMW



Conventional vs. squeezed vs. CMW

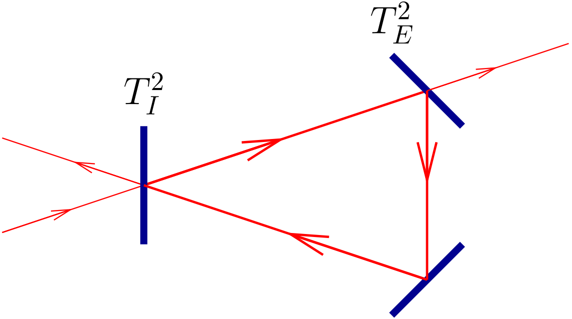
The origin of the sensitivity degradation at
$\Omega \sim \gamma_f$:

"grey" area around γ_f where incoherent mix of
$|0\rangle$ and $|\mathrm{SQZ}\rangle$
is pumped into the the dark port.



T.Corbitt, N.Mavalvala, and S.Whitcomb, PRD 70, 022002 (2004)

The amplitude filter cavity



$$T_I^2 = T_E^2 + A^2$$

$$L_F \sim 30\,\mathrm{m},\ \gamma_f \sim 10^4\,\mathrm{s}^{-1} \ \Rightarrow$$

$$T_I^2 \sim 10^{-4} \gg A^2 \sim 10^{-5}\,.$$

The filter cavity optical noises

Squeeze factors of phase and amplitude quadratures at the filter cavity input mirror:

$$S_{\varphi,\mathsf{I}}(\Omega) = \frac{\Omega^2 e^{-2r} + \gamma_f^2}{\Omega^2 + \gamma_f^2}\,, \quad S_{A,\mathsf{I}}(\Omega) = \frac{\Omega^2 e^{2r} + \gamma_f^2}{\Omega^2 + \gamma_f^2}\,.$$

The product

$$S_{\varphi,\mathsf{I}}(\Omega) S_{A,\mathsf{I}}(\Omega) = 1 + \frac{4\Omega^2\gamma_f^2 \sinh^2 r}{(\Omega^2 + \gamma_f^2)^2} > 1$$

$\Rightarrow$ we have a mixed quantum state at $\Omega \sim \gamma_f$.

The filter cavity optical noises

On the other hand, there is a cross-correlation *i.e.*
Quantum Entanglement
between two filter cavity ports:

$$S_{\varphi,\mathsf{IE}}(\Omega) = -\frac{i\Omega\gamma_f(1-e^{-2r})}{\Omega^2+\gamma_f^2} \neq 0\,,$$

$$S_{A,\mathsf{IE}}(\Omega) = \frac{i\Omega\gamma_f(e^{2r}-1)}{\Omega^2+\gamma_f^2} \neq 0\,,$$

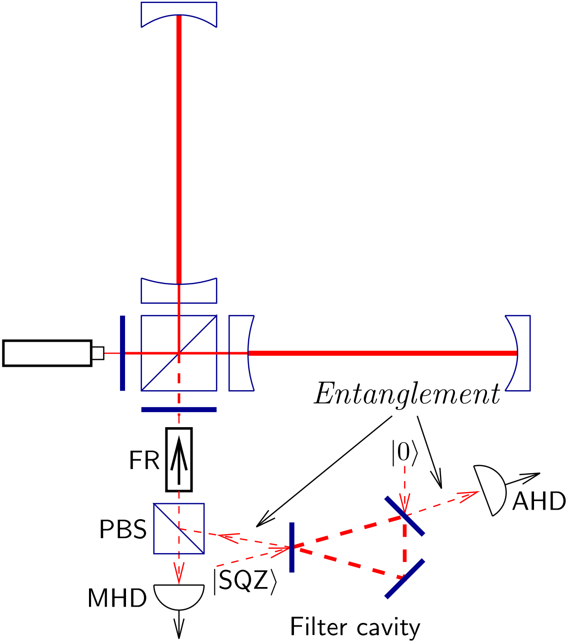
which means that the information leaks into the idle port.

The filter cavity optical noises

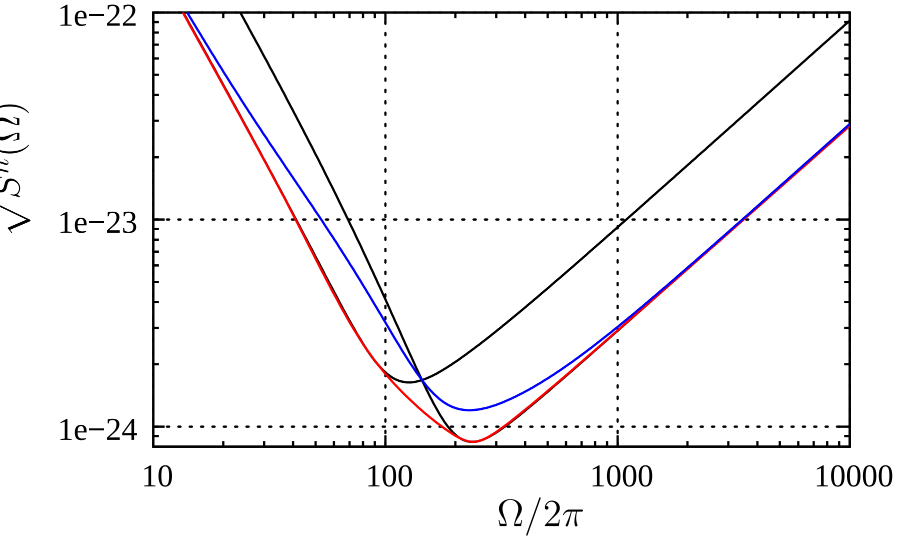
The idea:

catch this escaping information by an additional homodyne detector and thus purify the light entering the interferometer.

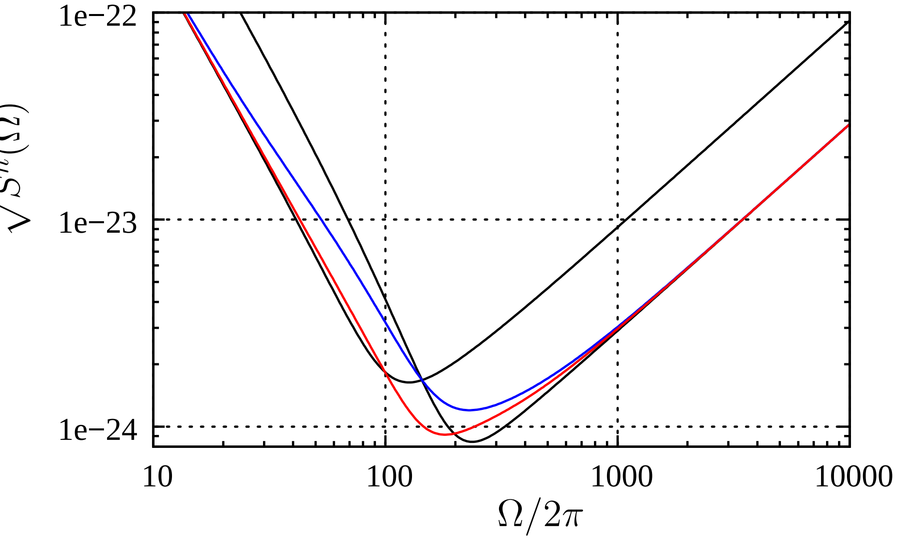
Modified CMW scheme



Conventional vs. squeezed vs. CMW



Conventional vs. squeezed vs. CMW



Simplifications & parameters values

Simplifications

Homodyne angle $\phi = 0$ (minimum of the shot noise)

Detuning $\delta = 0$ (no rigidity; just for simplicity)

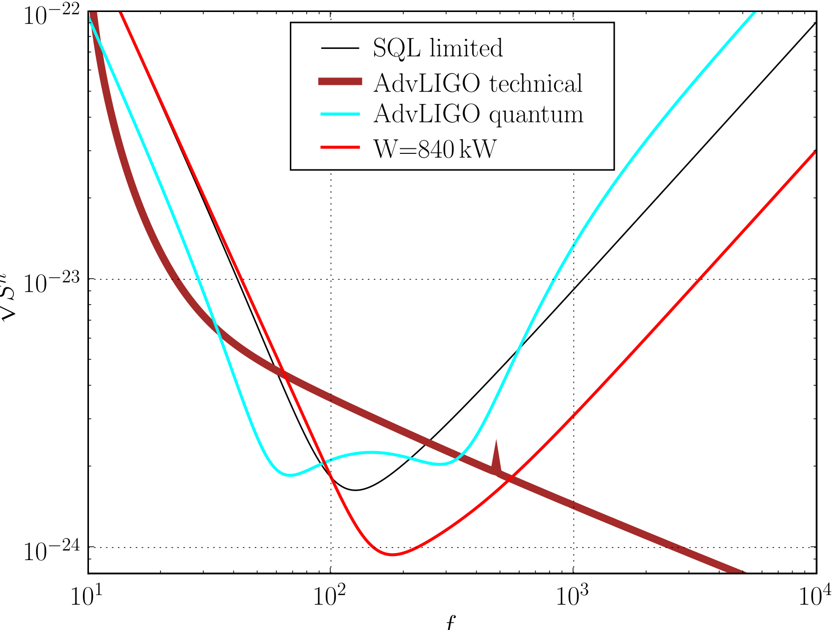
Filter cavity parameters

Losses per bounce	$A^2 = 10^{-5}$
Cavity length	$L_f = 30\,\mathrm{m}$

General parameters

Quantum efficiency	$\eta = 0.99$
Squeeze factor	$e^{-2r} = 0.1$

Conventional interferometer



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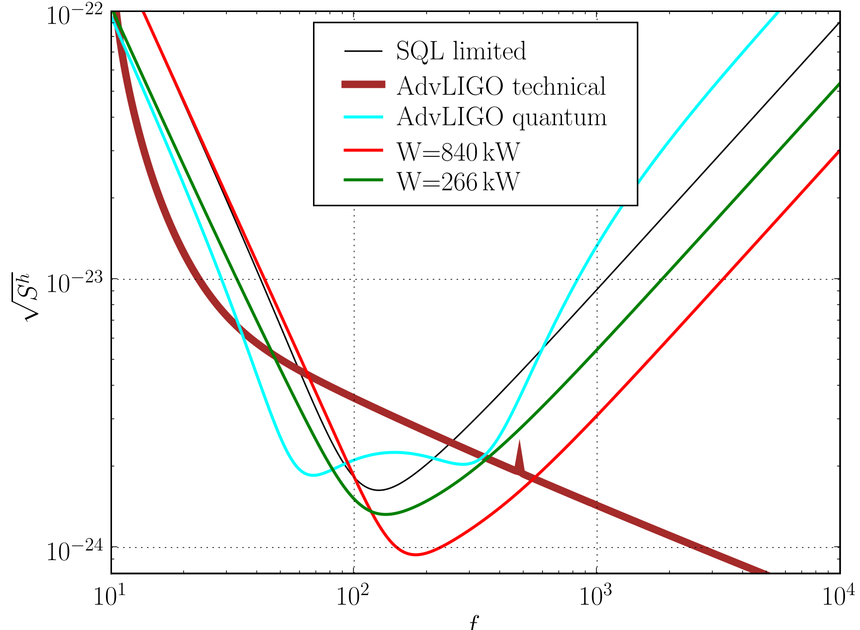

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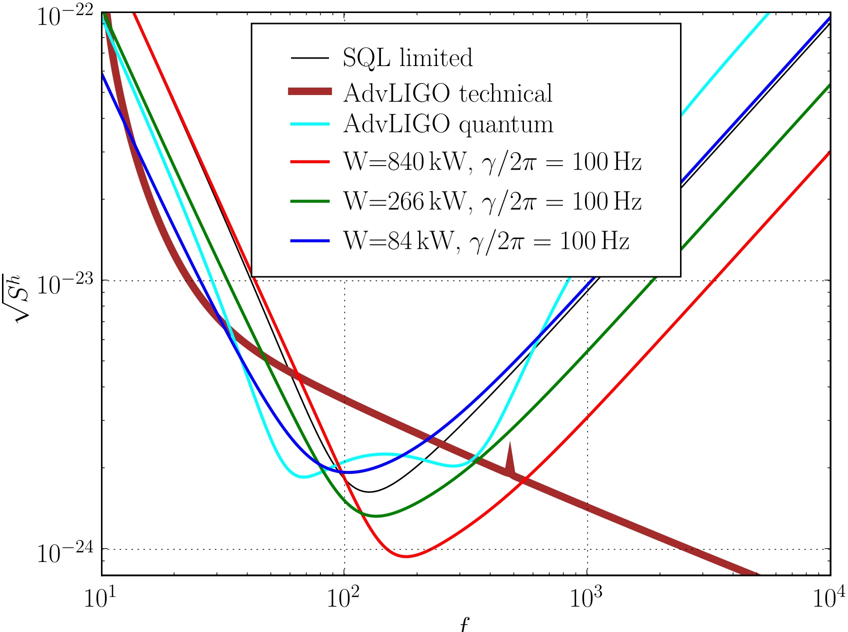

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4. Conclusion

Spectral density asymptotics

$$S^h(\Omega) \propto \begin{cases} \dfrac{W}{\Omega^4 \gamma}\,, & \text{if } \Omega \to 0\,, \\ \dfrac{\Omega^2}{4W\gamma}\, e^{-2r}\,, & \text{if } \Omega \to \infty\,. \end{cases}$$

Spectral density asymptotics

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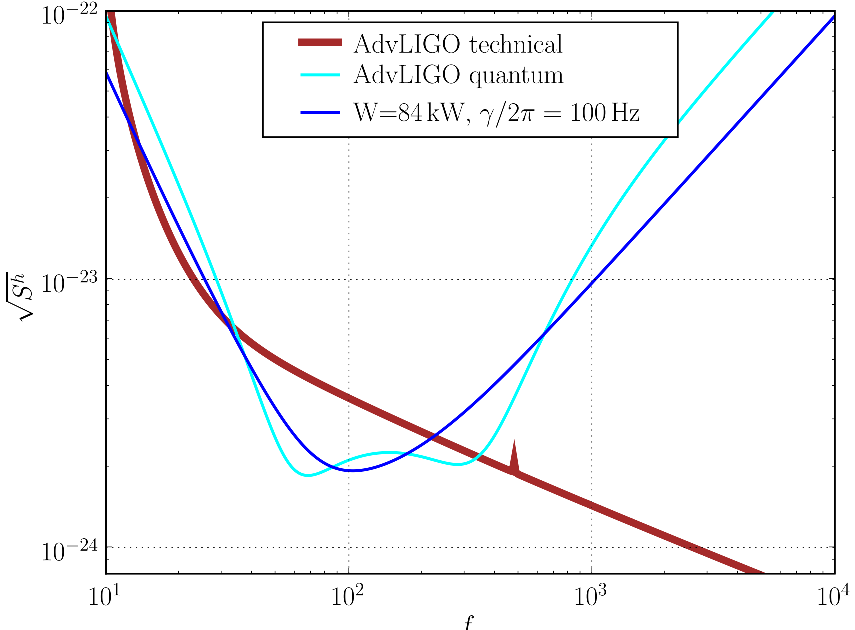
Therefore, increasing W and γ and keeping $W/\gamma = \text{const}$, it is possible to improve the high-frequency sensitivity without degradation of the low-frequency one.

Broadened interferometer



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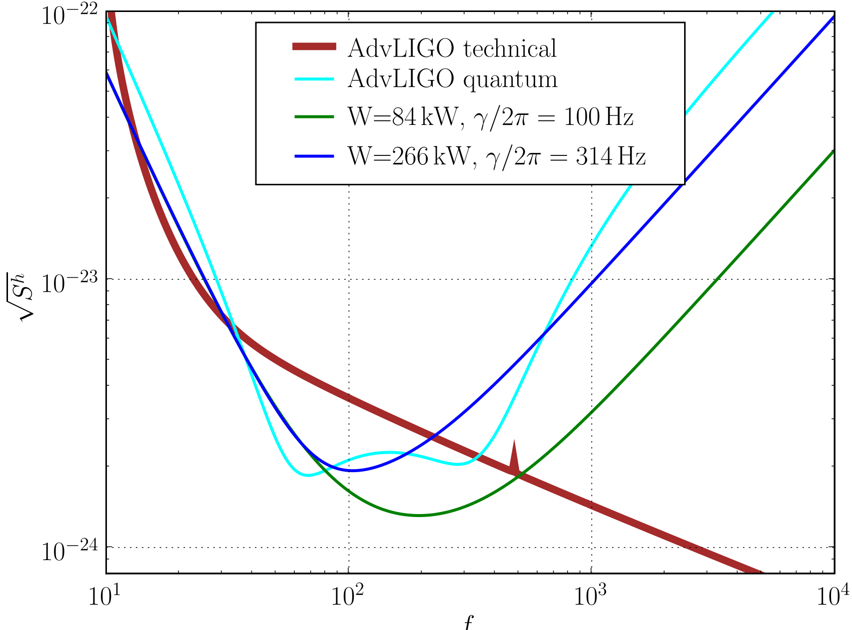

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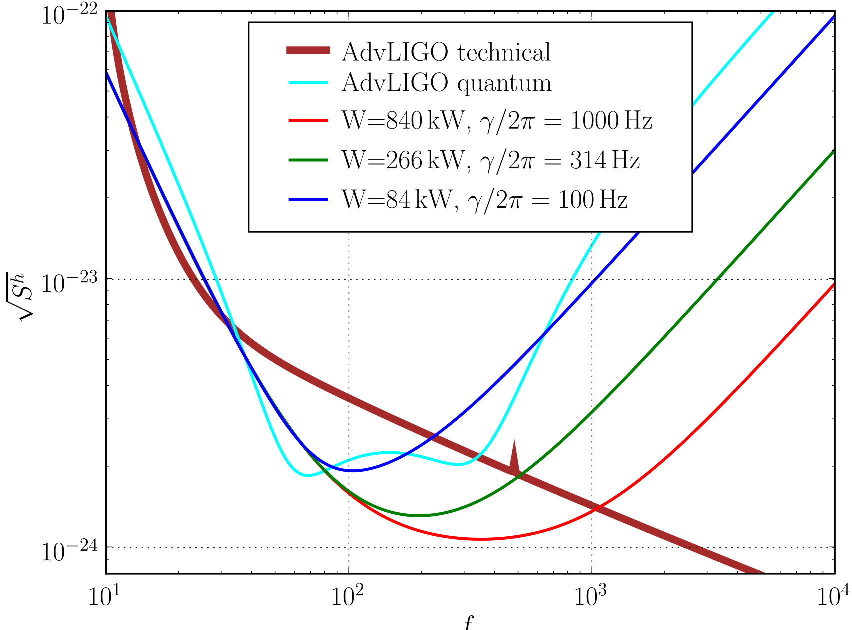
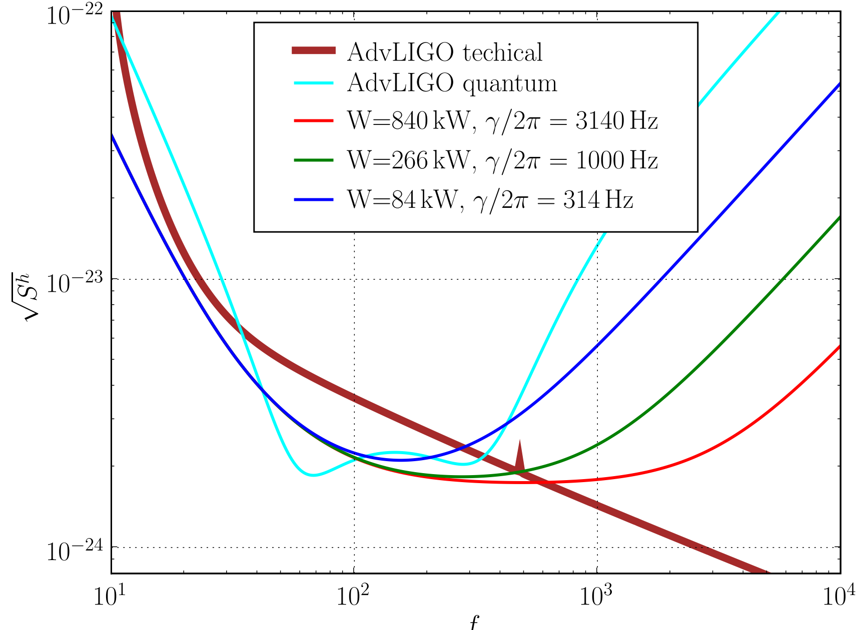


Even more broadened interferometer



Estimates of h_{SQL}/h

NSNS:

$$\frac{h_{\mathrm{SQL}}}{h} = \sqrt{\frac{\displaystyle\int_{f_c}^{f_{\mathrm{ISCO}}} \frac{f^{-7/3}}{S^h(2\pi f) + S^h_{\mathrm{tech}}(2\pi f)}\, df}{\displaystyle\int_{f_c}^{f_{\mathrm{ISCO}}} \frac{f^{-7/3}}{S^h_{\mathrm{conv}}(2\pi f) + S^h_{\mathrm{tech}}(2\pi f)}\, df}}$$

High-frequency:

$$\frac{h_{\mathrm{SQL}}}{h} = \sqrt{\frac{S^h_{\mathrm{conv}}(2\pi f) + S^h_{\mathrm{tech}}(2\pi f)}{S^h(2\pi f) + S^h_{\mathrm{tech}}(2\pi f)}}\,\Bigg|_{2\pi f \gg \gamma}$$

Estimates of h_{SQL}/h

	W	$\gamma/2\pi$	NSNS	$\gtrsim 1\,\mathrm{kHz}$
SQL-limited	840 kW	100 Hz	1	1
AdvLIGO	840 kW		1.18	0.50
CMW Conv.	84 kW	100 Hz	1.17	0.95
	266 kW	100 Hz	1.15	1.7
	840 kW	100 Hz	1.10	3.0
CMW Broad.	84 kW	100 Hz	1.17	0.95
	266 kW	314 Hz	1.28	3.0
	840 kW	1000 Hz	1.33	9.5
	84 kW	314 Hz	1.24	1.7
	266 kW	1000 Hz	1.28	5.3
	840 kW	3140 Hz	1.30	16.0

Conclusion

- Squeezed light in combination with the short amplitude filter cavity and the broadened interferometer configuration allows to obtain sensitivity better than the AdvLIGO one at low frequencies, and significantly better — at high frequencies, using mush smaller optical power.

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- Squeezed light in combination with the short amplitude filter cavity and the broadened interferometer configuration allows to obtain sensitivity better than the AdvLIGO one at low frequencies, and significantly better — at high frequencies, using mush smaller optical power.
- The low-frequency quantum noise can be reduced down to the level below the technical noises.

Conclusion

- The photodetectors non-unity quantum efficiency $\eta < 1$ significantly cripples the squeezed state based schemes, limiting the squeeze factor by the value

$$e^{-2r_{\text{eff}}} = e^{-2r} + \frac{1-\eta}{\eta}\,.$$

  If, for example, $\eta = 0.9$, then only $10\,\text{dB}$ effective squeezing is possible.

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  My question to experimentalists: what is the real quantum efficiency at $1.064\,\mu$? (avalanche does not help!)