Decoherence and degradation in quantum filter cavities

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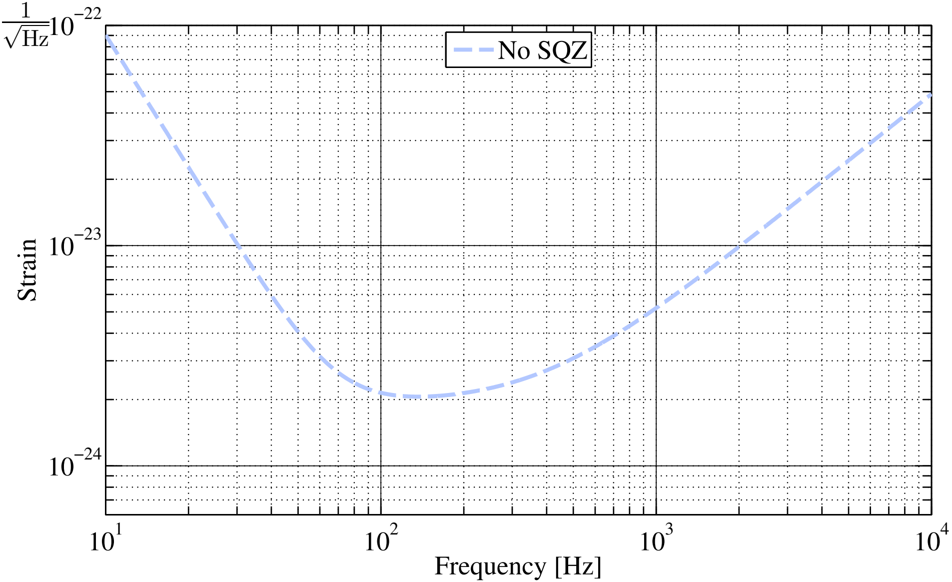
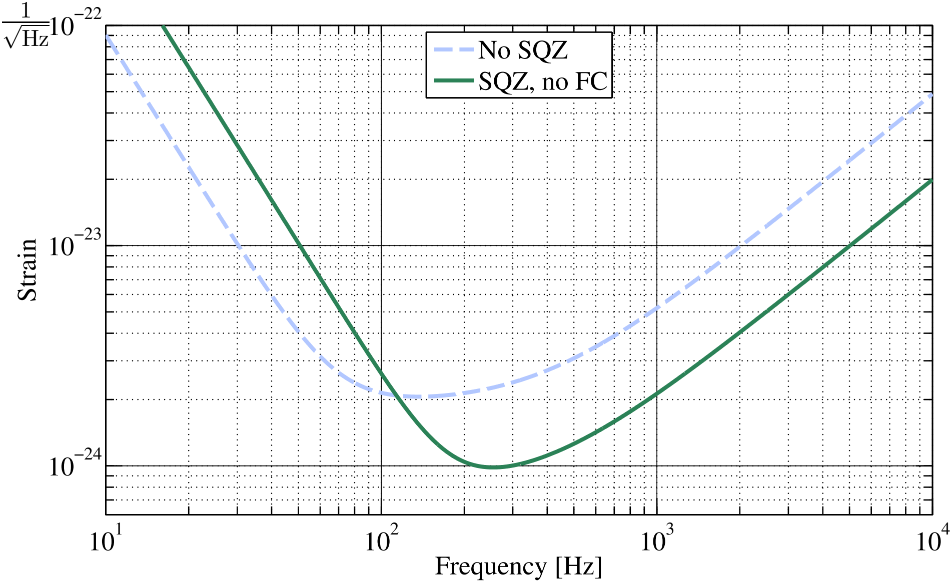
The paper

Clickable link to LIGO DCC

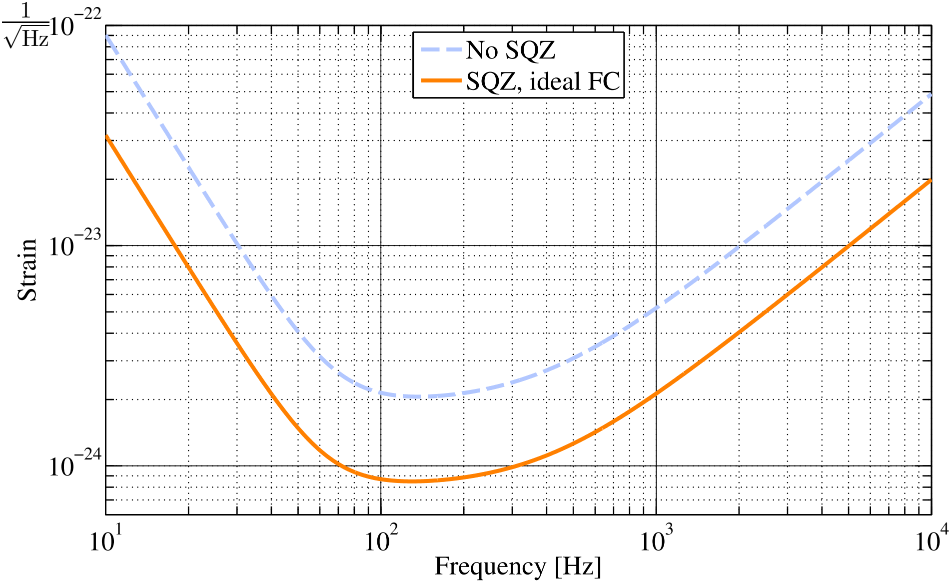
Quantum noise



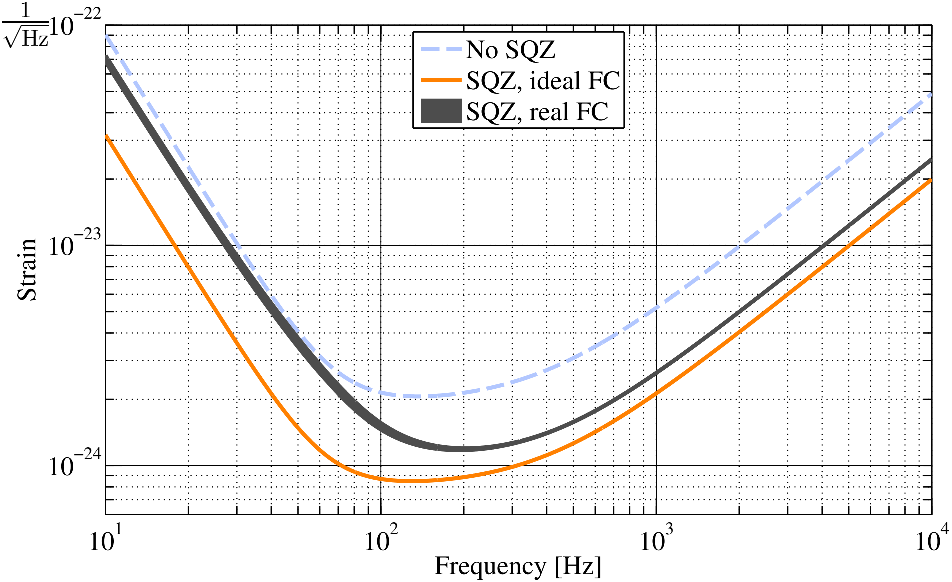
Squeezing makes noise worse



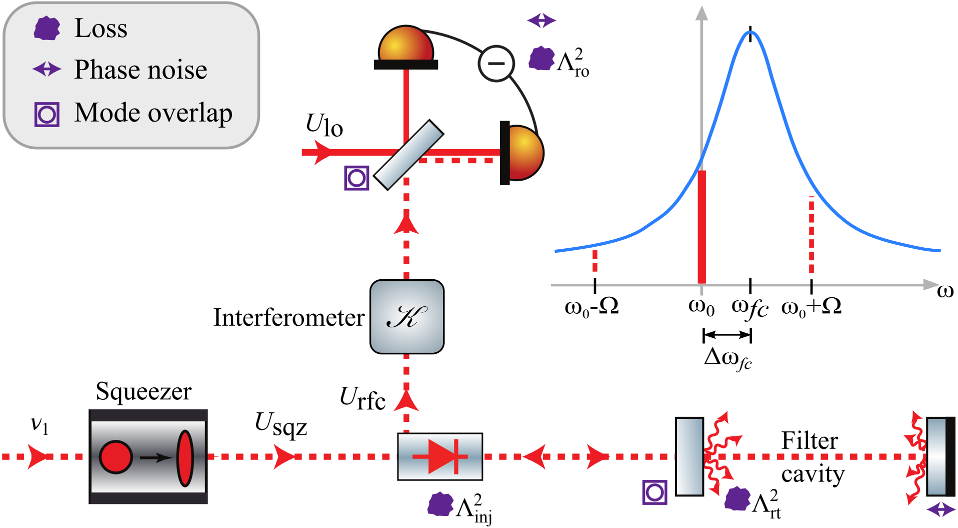
Theoretical filter cavity



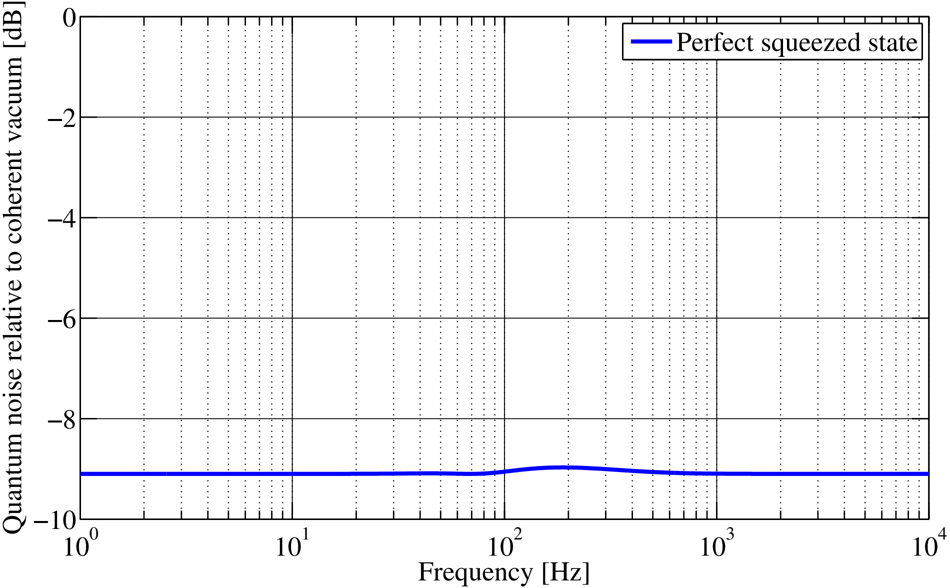
Real filter cavity



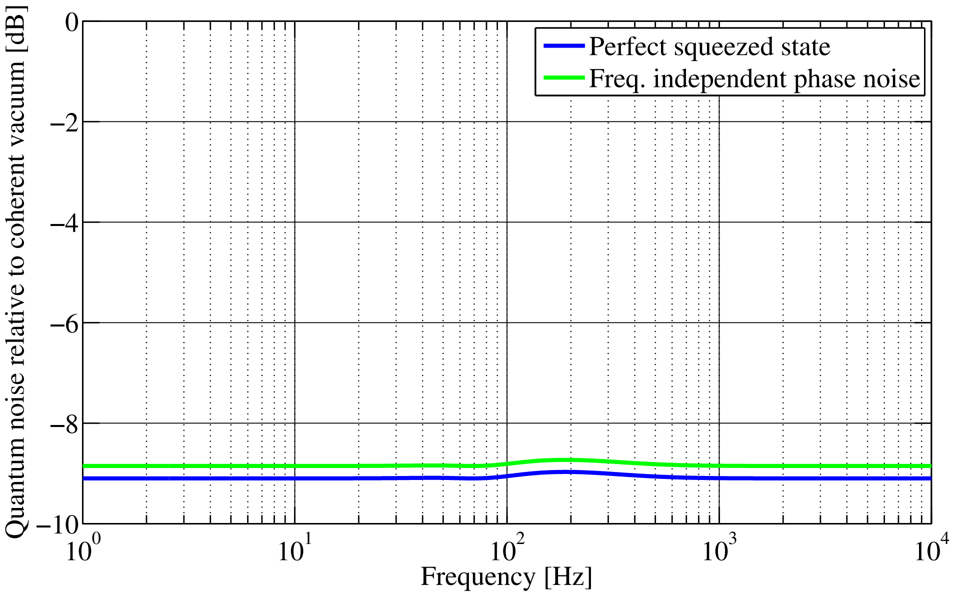
System under study



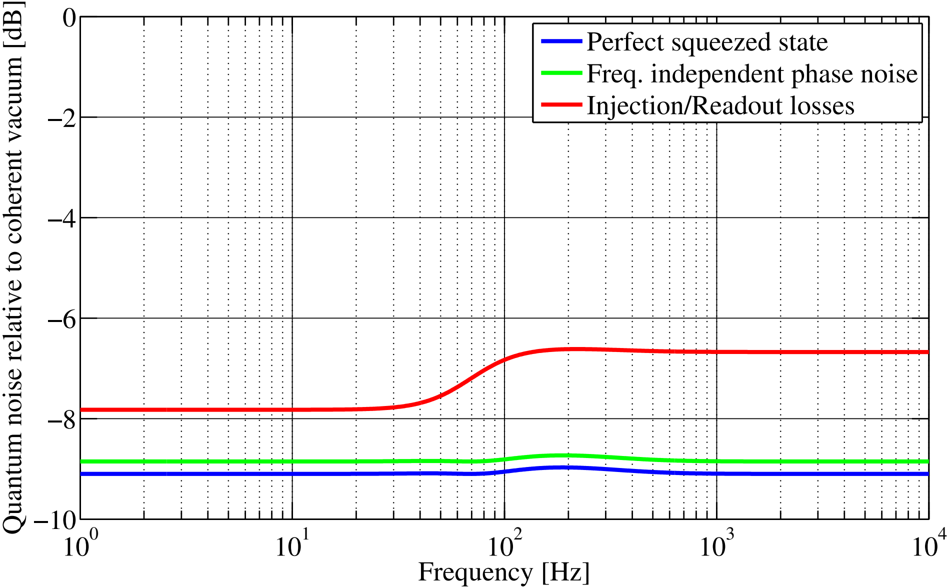
Perfect squeezed state, $\sim$9 dB



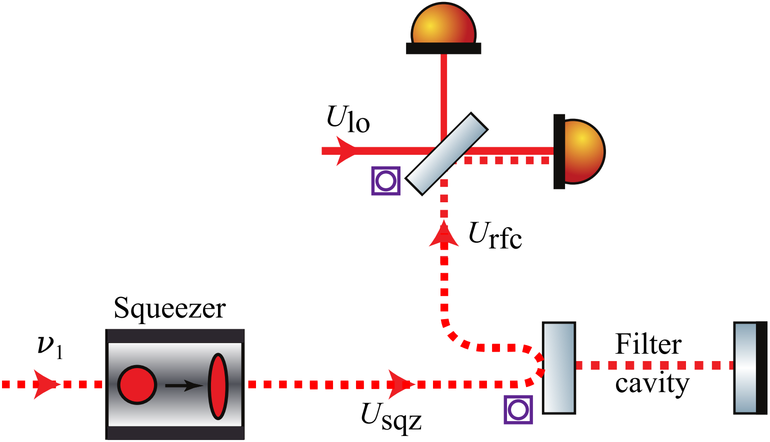
Frequency independent phase noise, 30 mrad



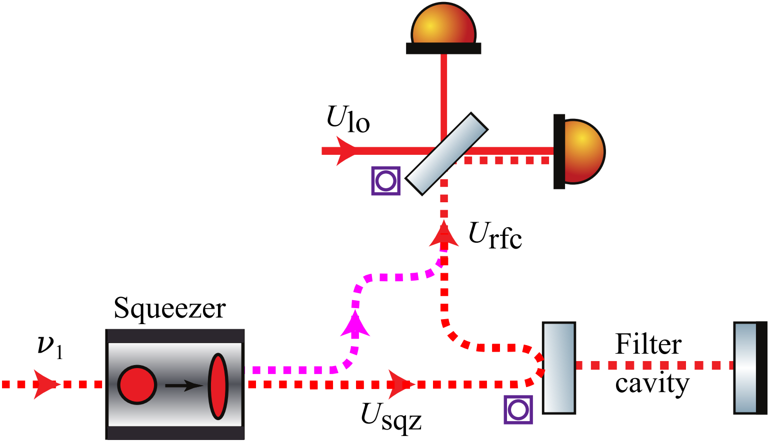
Injection and readout losses, both 5%



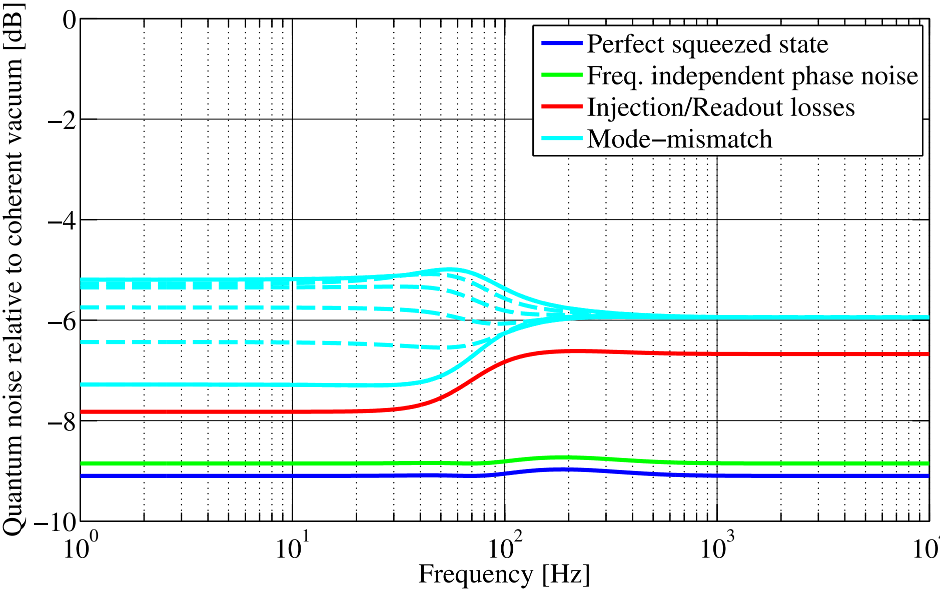
Mode matching



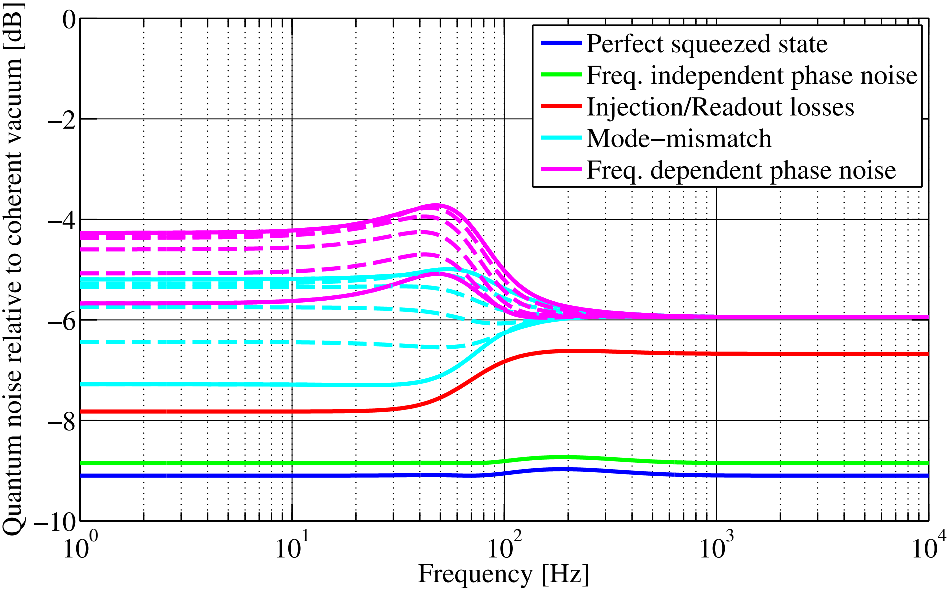
Mode matching

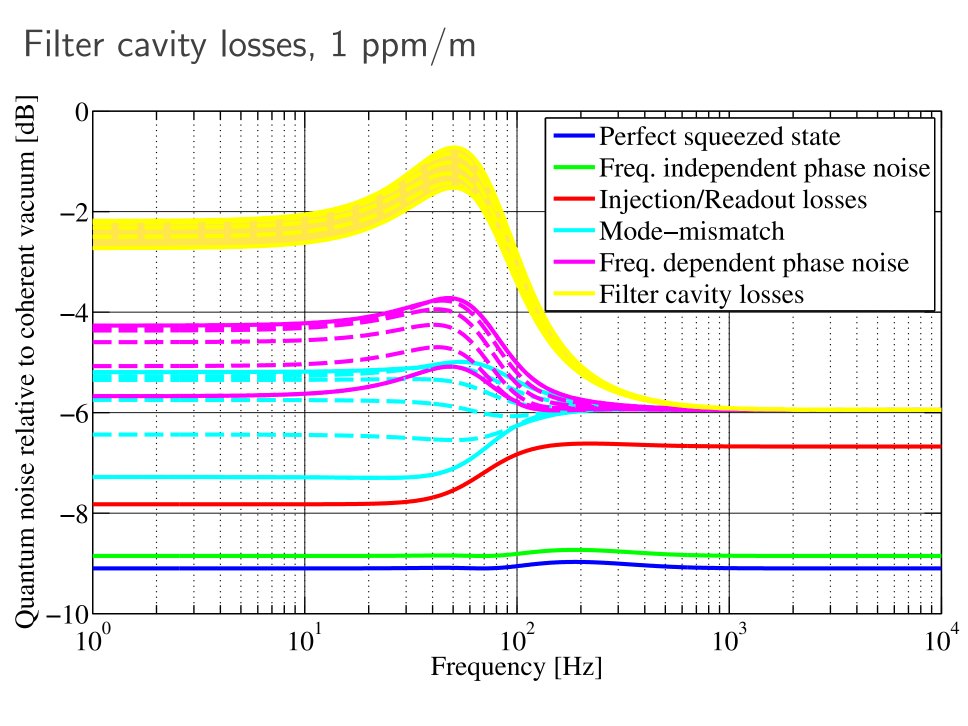


Mode matching, 95% & 98%



Frequency dependent phase noise, 0.3 pm




Filter cavity losses, 1 ppm/m
Quantum noise relative to coherent vacuum [dB]
0
−2
−4
−6
−8
−10
10^0
10^1
10^2
10^3
10^4
Frequency [Hz]
Perfect squeezed state
Freq. independent phase noise
Injection/Readout losses
Mode−mismatch
Freq. dependent phase noise
Filter cavity losses

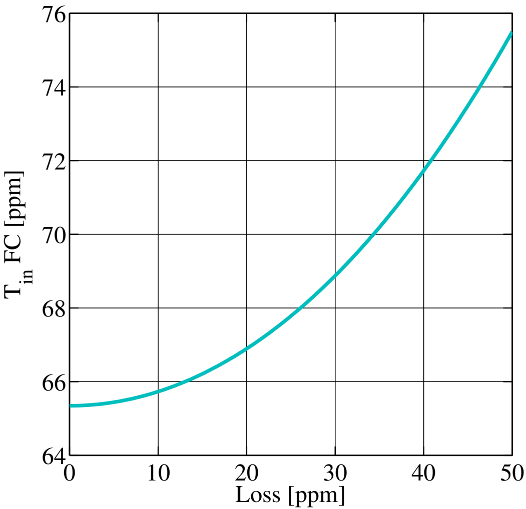
Bandwidth with losses

- Losses (ϵ), bandwidth (γ) and detuning ($\Delta\omega$)

$$\gamma_{\mathrm{fc}} = \sqrt{\frac{2}{(2-\epsilon)\sqrt{1-\epsilon}}}\ \frac{\Omega_{\mathrm{sql}}}{\sqrt{2}}$$

$$\Delta\omega_{\mathrm{fc}} = \sqrt{1-\epsilon}\ \gamma_{\mathrm{fc}}$$

- Naive approach incorrect
- Losses up; bandwidth up

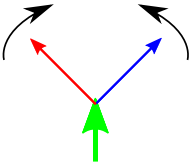


Coherent dephasing

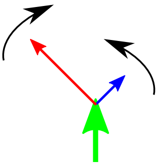
$$\mathbf{T}_{\rm fc} \sim \underbrace{\mathbf{R}_{\alpha_p}}_{\text{lossless}} \underbrace{\left(\rho_p\ \mathbf{I} - i\rho_m\ \mathbf{R}_{\pi/2}\right)}_{\text{lossy}}$$

$$\rho_{m}^{p} = \frac{|r(+\Omega)| \pm |r(-\Omega)|}{2}$$

$$\begin{aligned} N(\zeta) &= \left|\bar{\mathbf{b}}_\zeta \cdot \mathbf{T}_{\rm fc} \cdot v_{\rm in}\right|^2 \\ &\sim \sin^2(\zeta)\rho_p^2 A^2 + \cos^2(\zeta)\rho_m^2 A^2 \\ &\quad + \cos^2(\zeta)\rho_p^2\phi^2 + \sin^2(\zeta)\rho_m^2\phi^2 \\ &\sim A^2\left[\sin^2(\zeta)\rho_p^2 + \cos^2(\zeta)\rho_m^2\right] \end{aligned}$$

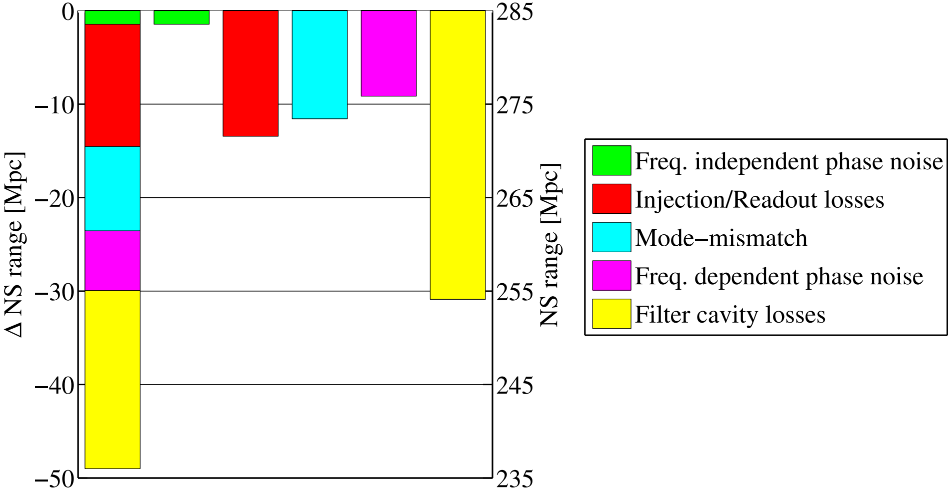


Balanced

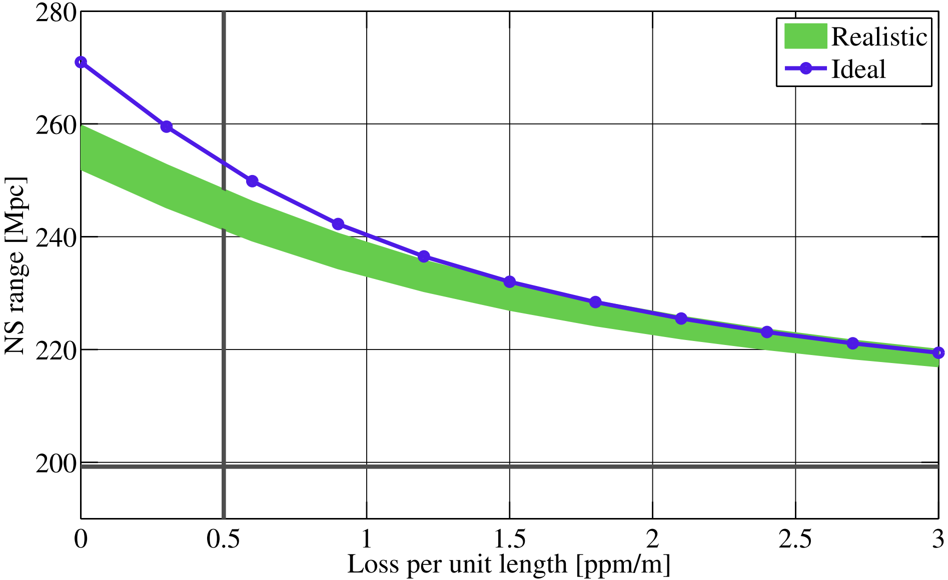


Unbalanced

Relative contributions

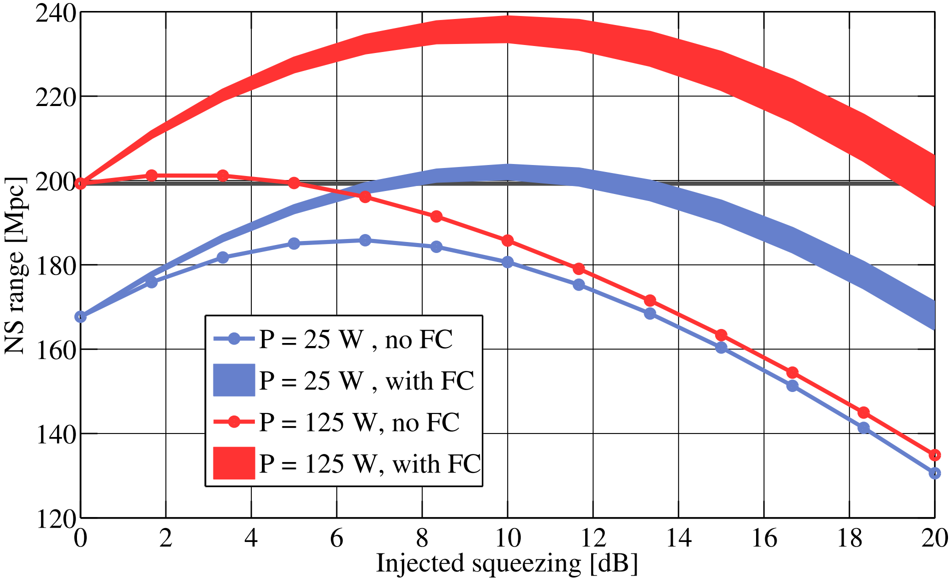


Range v loss

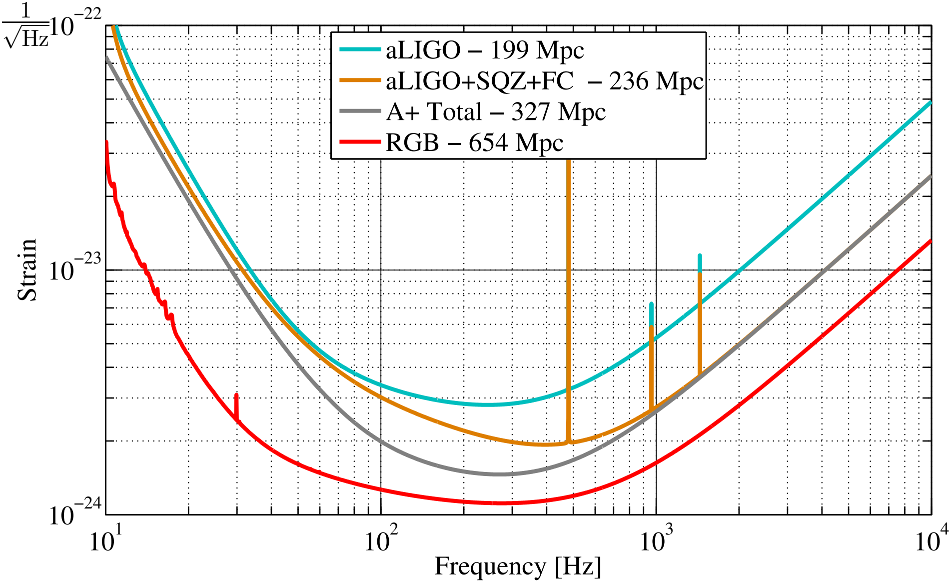


280
260
240
220
200
NS range [Mpc]
0
0.5
1
1.5
2
2.5
3
Loss per unit length [ppm/m]
Realistic
Ideal

Range v squeezing



A new baseline?



Conclusions

- Developed an analytical model of a filter cavity
- Need to add more realism to future IFO designs
- Low frequency is hard, it's more than FC losses
- More squeezing doesn't help (yet)
- One ∼10 m cavity is good enough