All-optical realisation of PT symmetric amplifier

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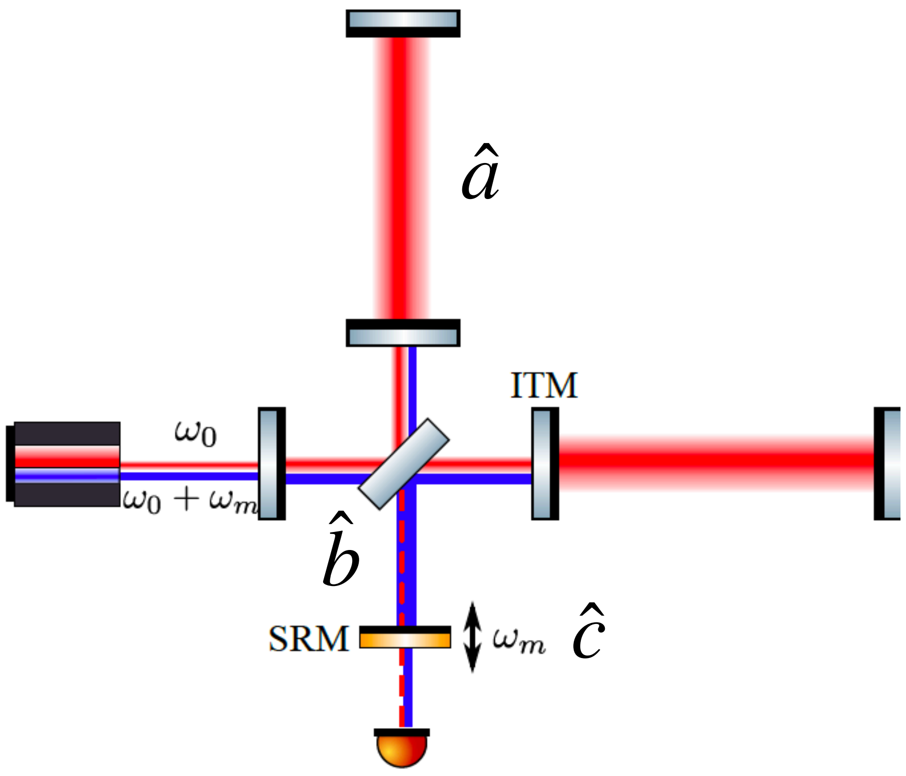
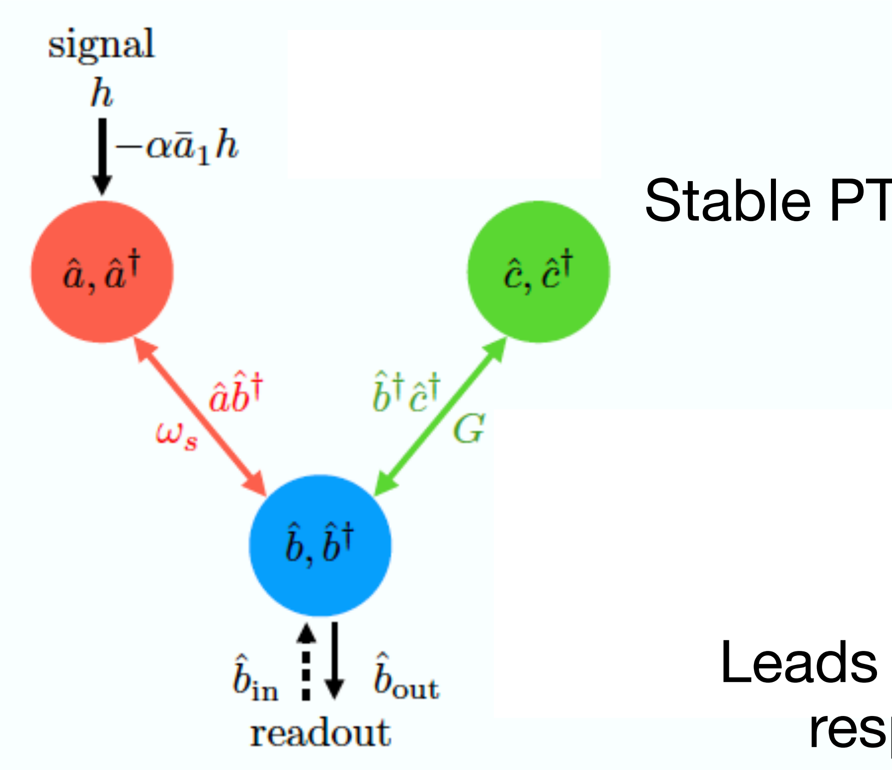
Background

PT symmetric quantum amplifier





Stable PT symmetric case

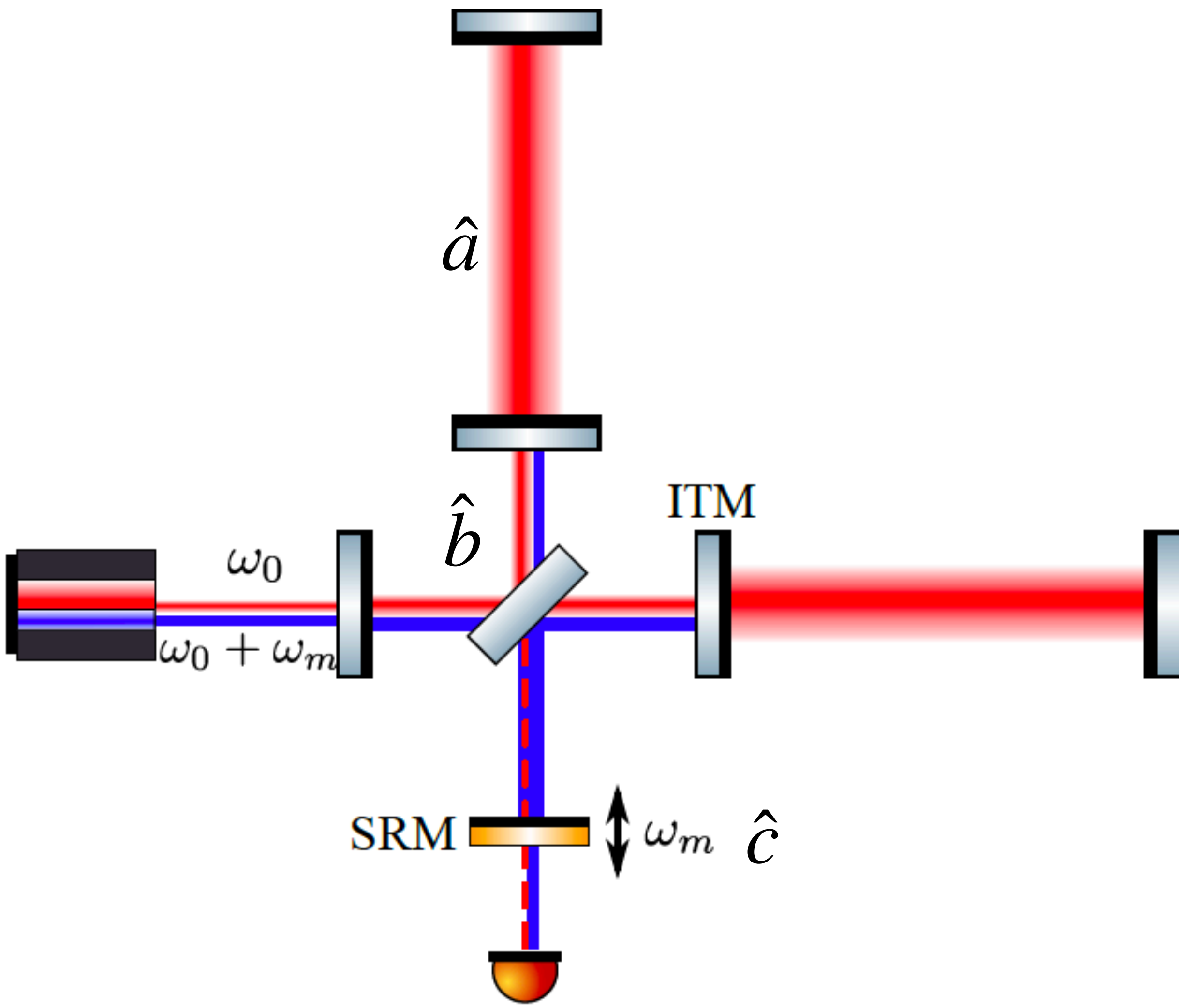
$$G = \omega_s$$

Leads to infinite signal response at DC

The oscillator can be either **mechanical** or **optical**

[*Xiang Li et al. Broadband sensitivity improvement via coherent quantum feedback with PT symmetry, arXiv:2012.00836 (2020).*]

Optomechanical realisation



$$\hat{H}_{\text{int}} = -\hbar G(\hat{b}\hat{c} + \hat{b}^\dagger \hat{c}^\dagger) - \hbar\omega_s(\hat{a}\hat{b}^\dagger + \hat{a}^\dagger \hat{b})$$

$\hat{a}$: arm cavity mode

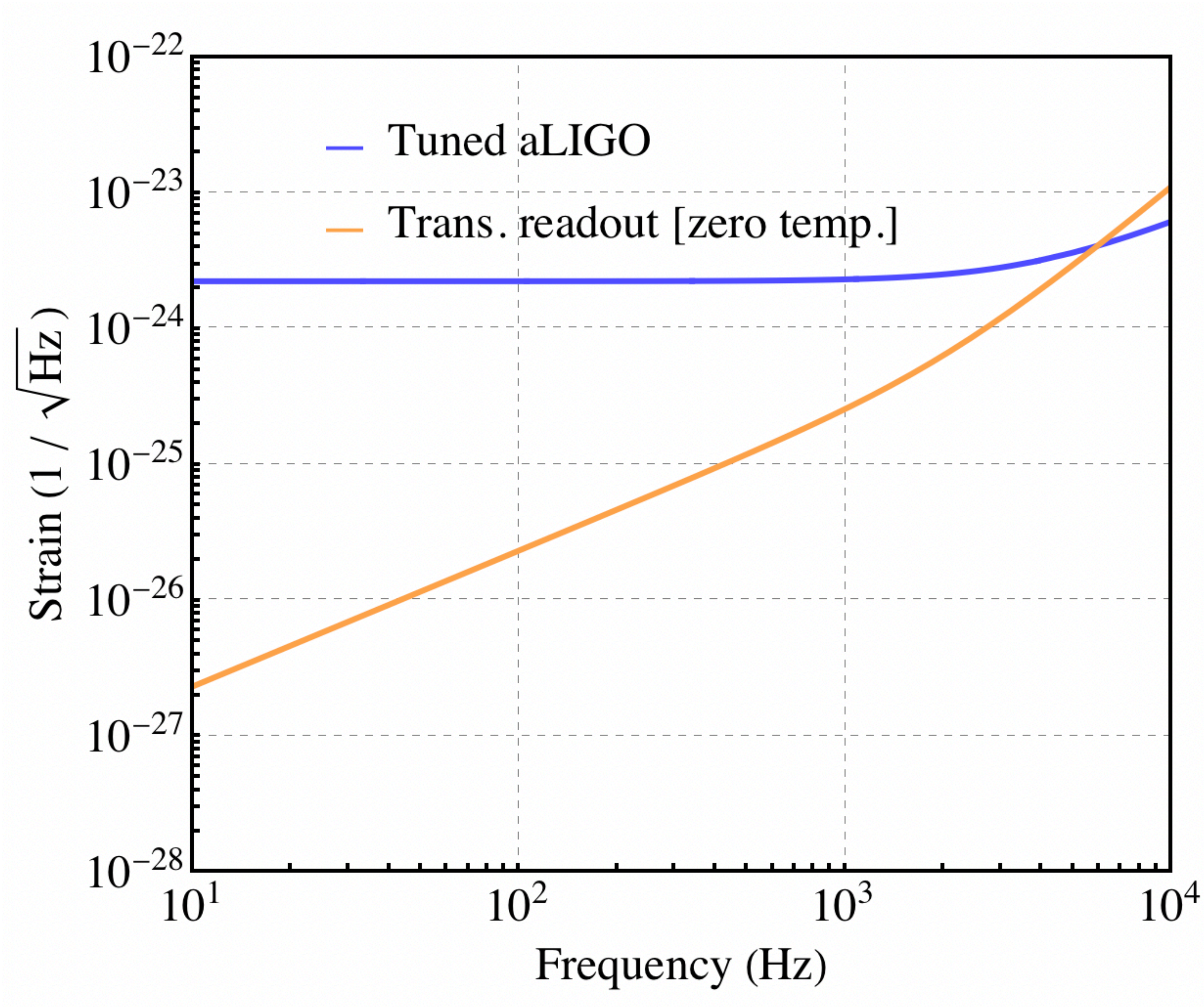
$\hat{b}$: SRC mode

$\hat{c}$: mirror mode @ ω_m

$$G = \sqrt{\frac{8\pi P_{\text{pump}}}{m\lambda\omega_m L_{\text{SRC}}}} \qquad \omega_s = \frac{c\sqrt{T_{\text{ITM}}}}{2\sqrt{L_{\text{SRC}} L_{\text{arm}}}}$$

[Bentley et al. Phys.Rev.D 99, 102001 (2019)]

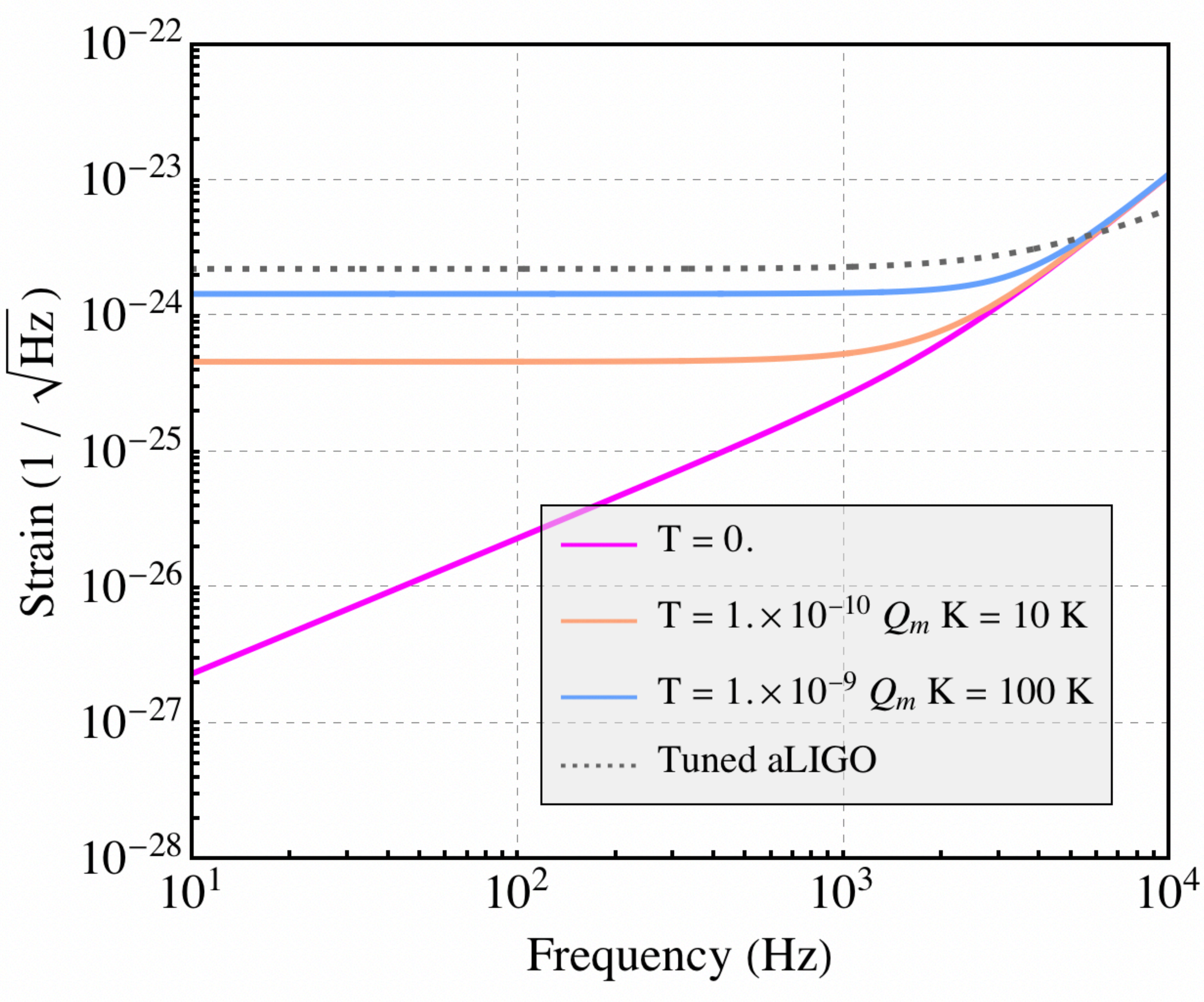
Quantum noise



Parameters

Arm length	4 km
Test mass	$\rightarrow \infty$
ITM trans	2%
SRM trans	1%
SRC length	56 m
Arm power	750 kW
Laser λ	1064 nm

Thermal noise

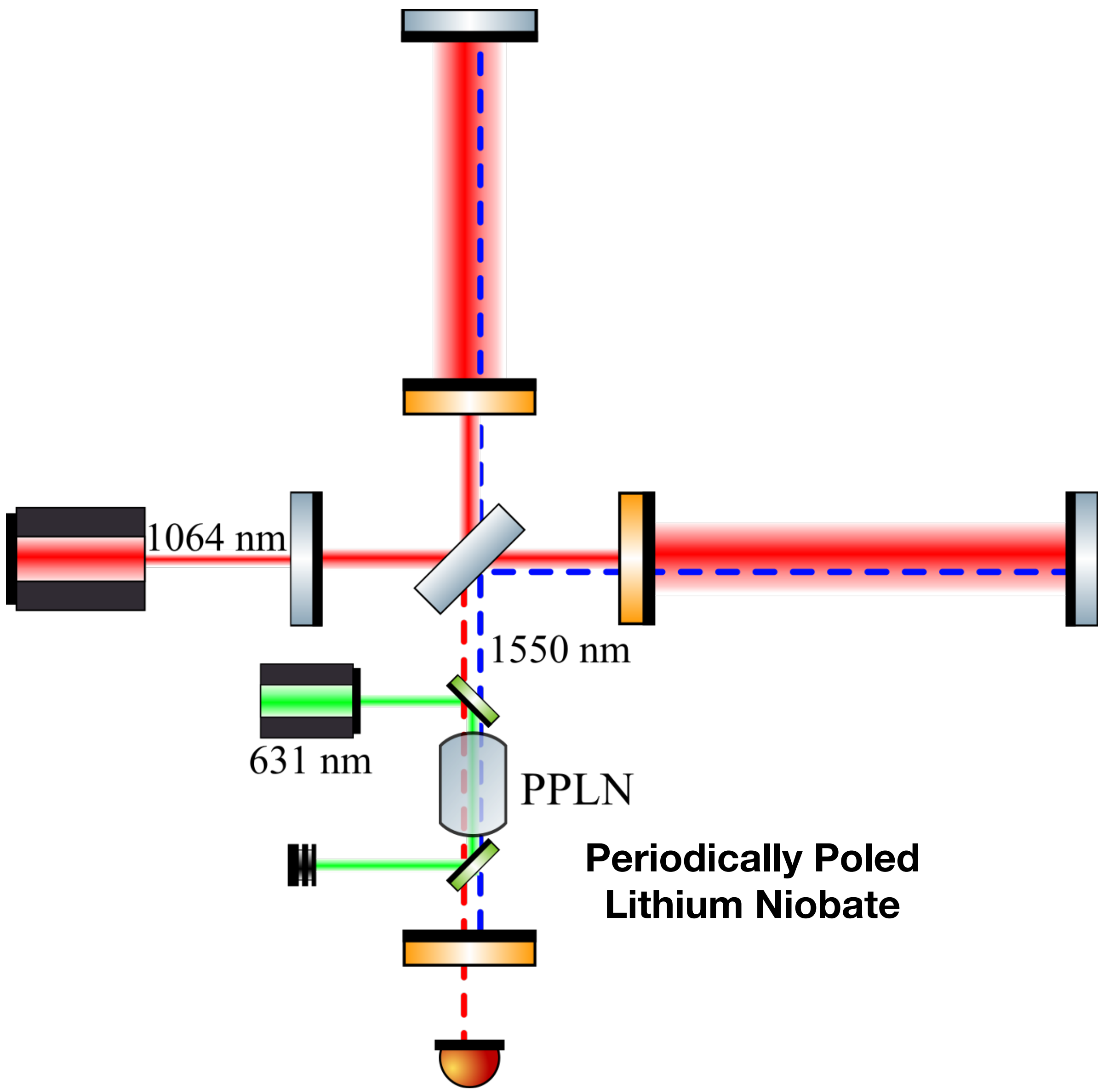


Parameters

Mirror freq. ω_m	10^5 Hz
Mirror mass	10^{-5} kg
Quality factor Q_m	10^{11}

Even with extreme parameters thermal noise is a big problem for this setup

All optical realisation



$$\hat{H}_{\text{int}} = -\hbar G(\hat{b}\hat{c} + \hat{b}^{\dagger}\hat{c}^{\dagger})$$

$\hat{b}$: SRC mode

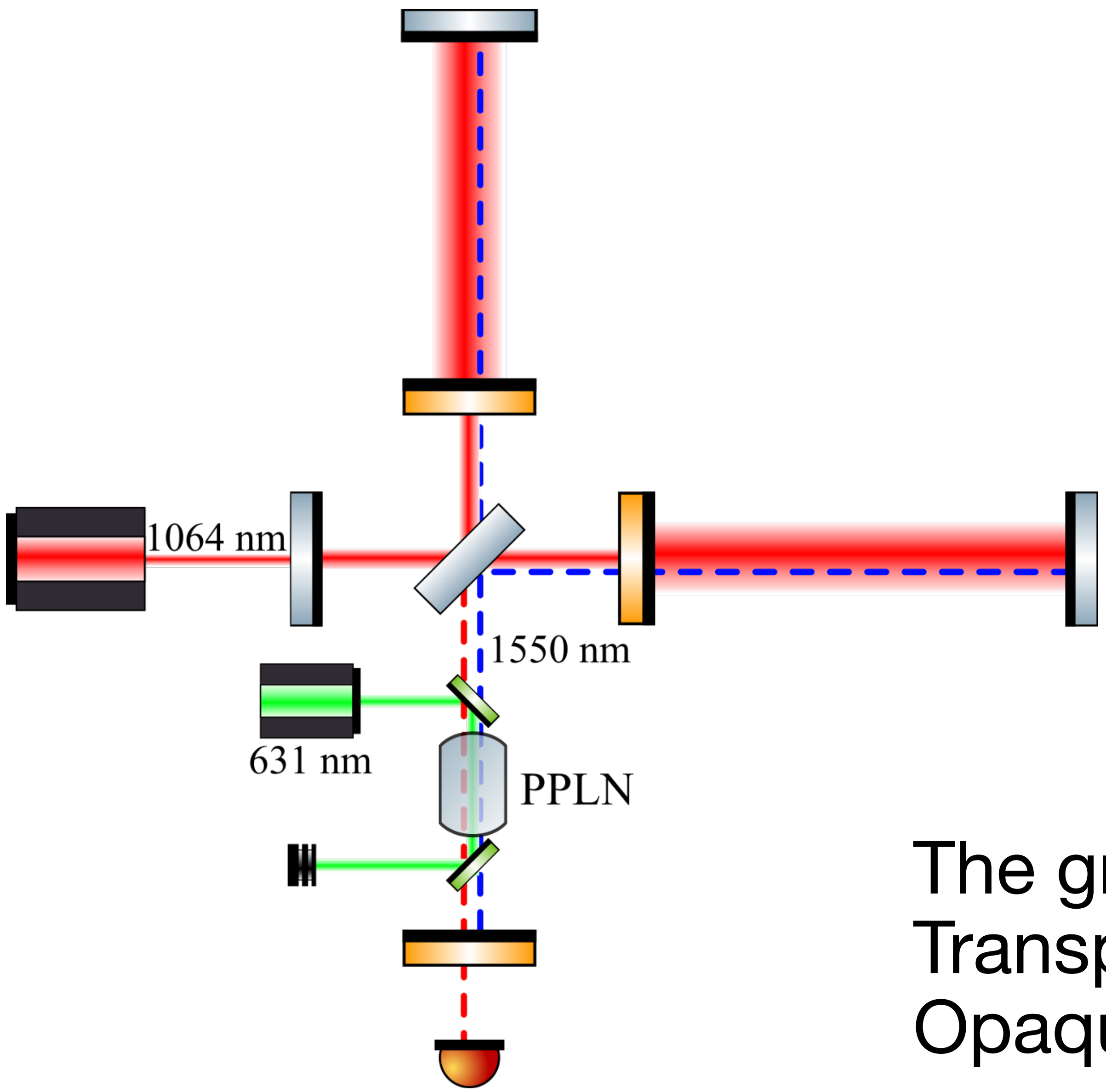
$\hat{c}$: another optical mode @ 1550 nm

$$\frac{1}{1064\text{nm}} + \frac{1}{1550\text{nm}} = \frac{1}{631\text{nm}}$$

Crystal down-converts signal to idler (and the reverse process)

No thermal noise but need to consider optical loss due to the crystal

All optical setup mirrors



$$\frac{1}{1064\mathrm{nm}} + \frac{1}{1550\mathrm{nm}} = \frac{1}{631\mathrm{nm}}$$

ITM should be dichroic:
Partially reflective for 1064nm (signal)
Transparent to 1550nm (idler)

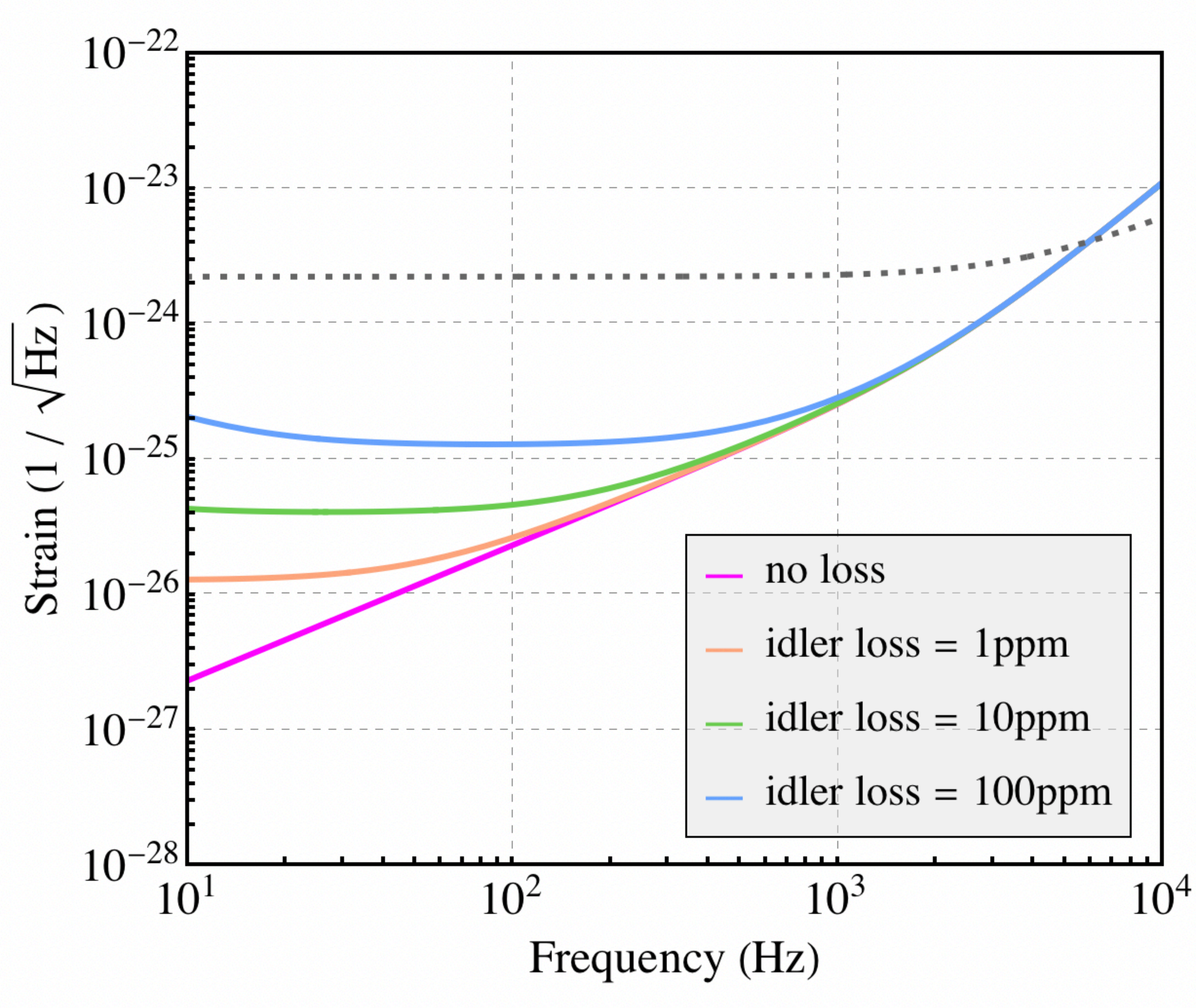
So that the idler mode has a smaller bandwidth than signal mode, and also so that the idler loss is suppressed

The green mirrors should be trichroic:
Transparent to 1550nm and 1064nm
Opaque to 631nm (pump)

Finally SRM is dichroic: opaque to idler

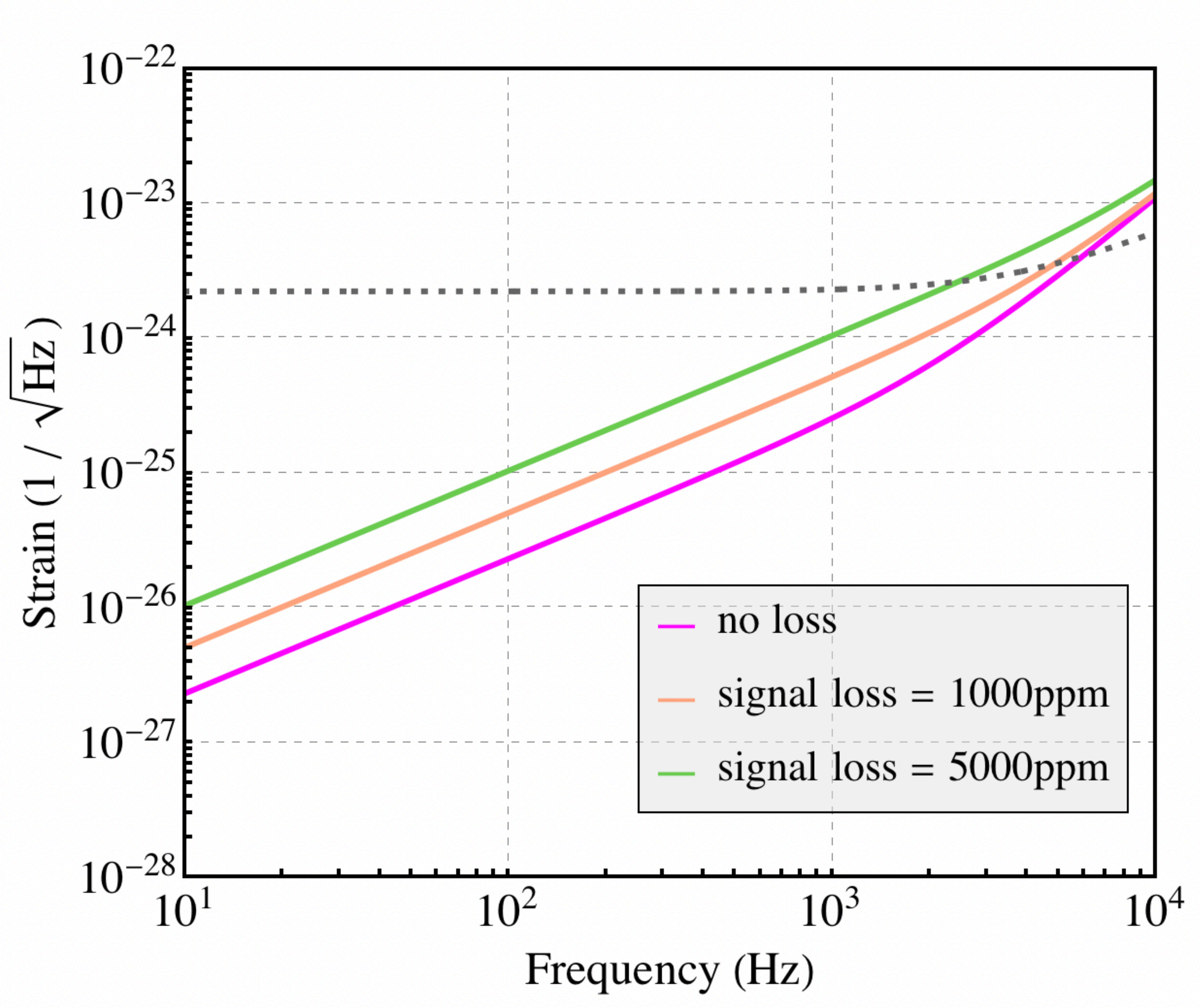
Optical loss from idler mode

Idler mode loss breaks PT symmetry, but loss reduced by making ITM transparent to idler (1550nm)

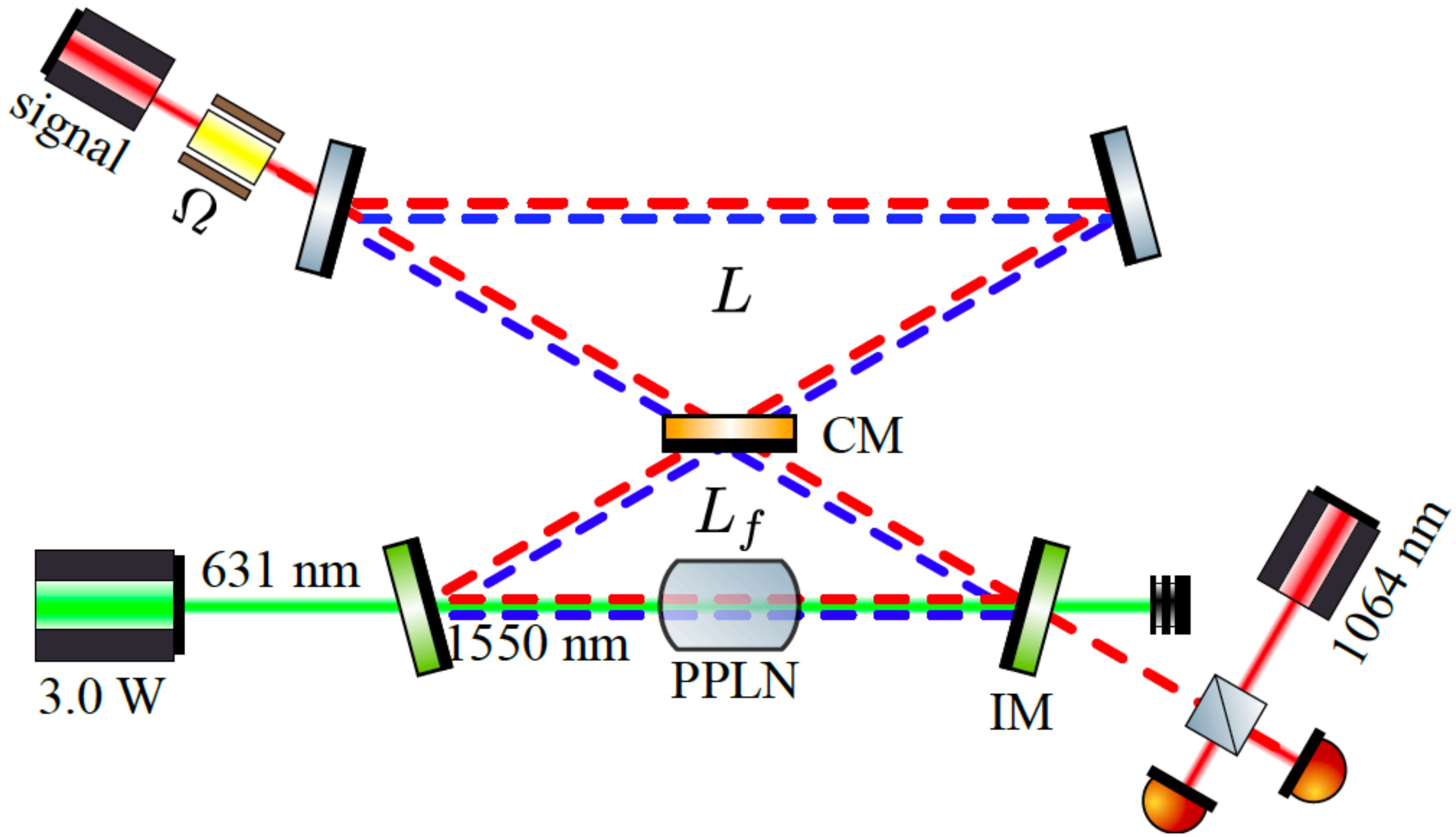


Optical loss from SRC mode

Loss in SRC signal mode does not break PT symmetry



Tabletop experiment proposal



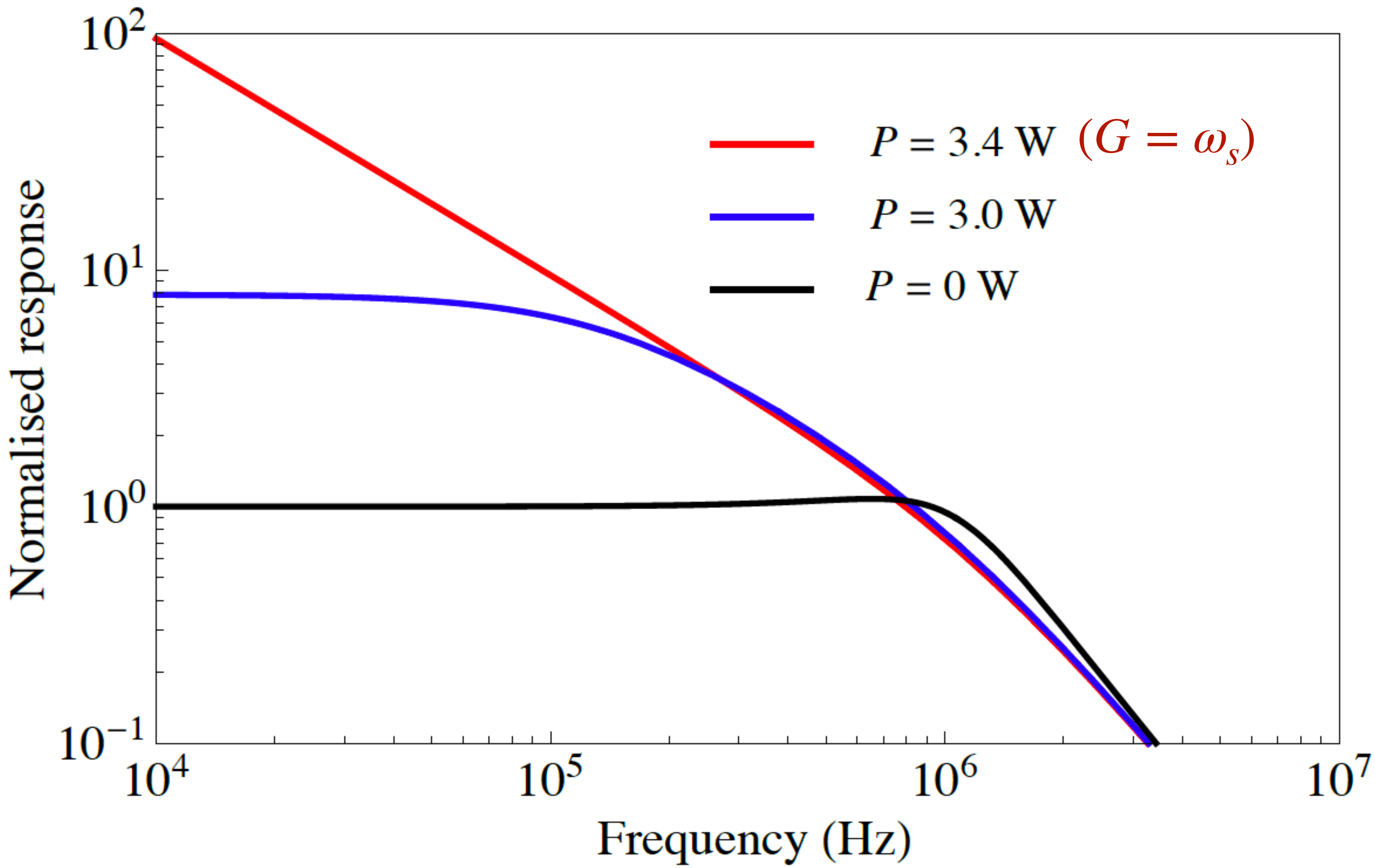
$$L = 50\,\mathrm{cm}$$
$$L_f = 10\,\mathrm{cm}$$
$$T_{\mathrm{IM}} = 0.01$$
$$T_{\mathrm{CM}} = 100\,\mathrm{ppm}$$
$$L_{\mathrm{LN}} = 1\,\mathrm{cm}$$
$$\chi_2 = 5.0\,\mathrm{pm/V}$$
$$w_0 = 70\,\mu\mathrm{m}$$

$$\frac{1}{1064\mathrm{nm}} + \frac{1}{1550\mathrm{nm}} = \frac{1}{631\mathrm{nm}}$$

As before, green are trichroic and orange is dichroic

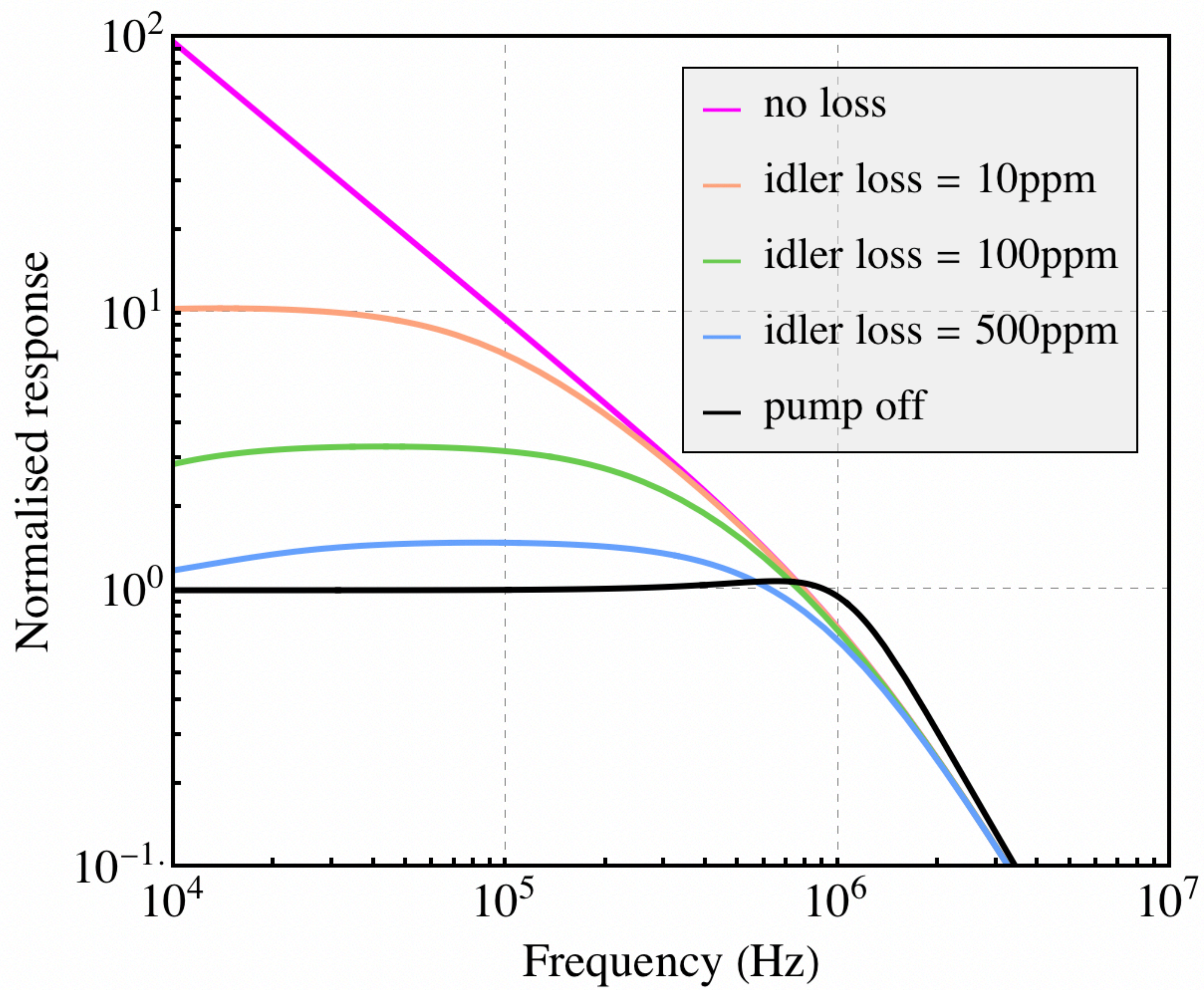
Frequency conversion process (for 532nm -> 1550nm & 810nm) detailed in Roman's paper: [Phys. Rev. Lett. 112, 073602]

Signal Response



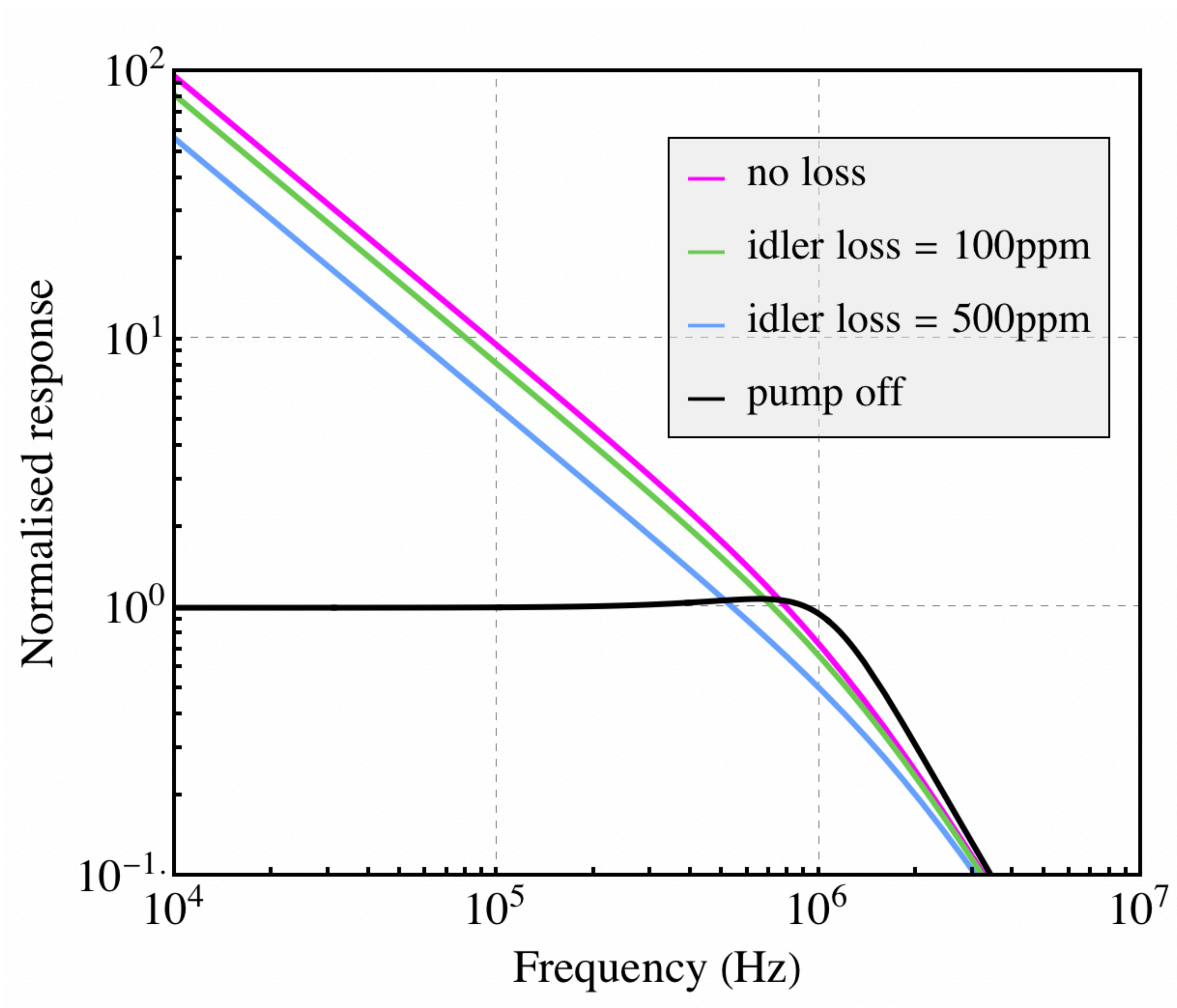
Optical loss from idler mode

Again breaks PT symmetry, but letting idler propagate in both cavities reduces the effect



Optical loss from SRC mode

SRC signal mode loss does not break PT symmetry



Thanks for listening