Microwave-mechanical-optical transducer in a dilution refrigerator

Electromechanics

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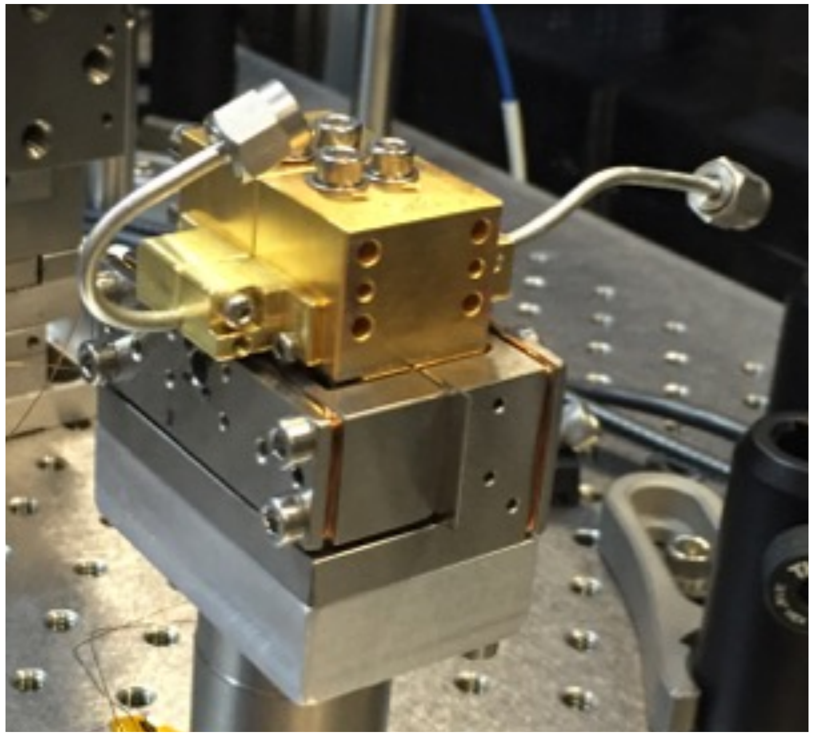
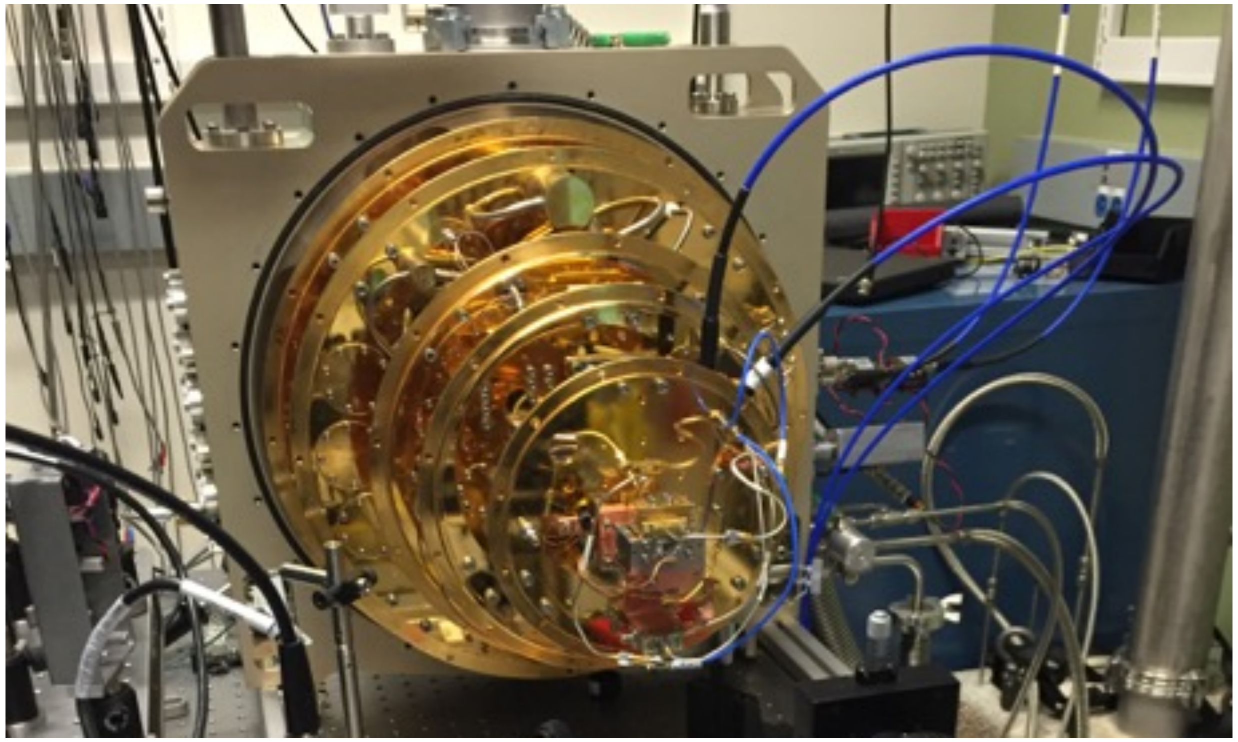
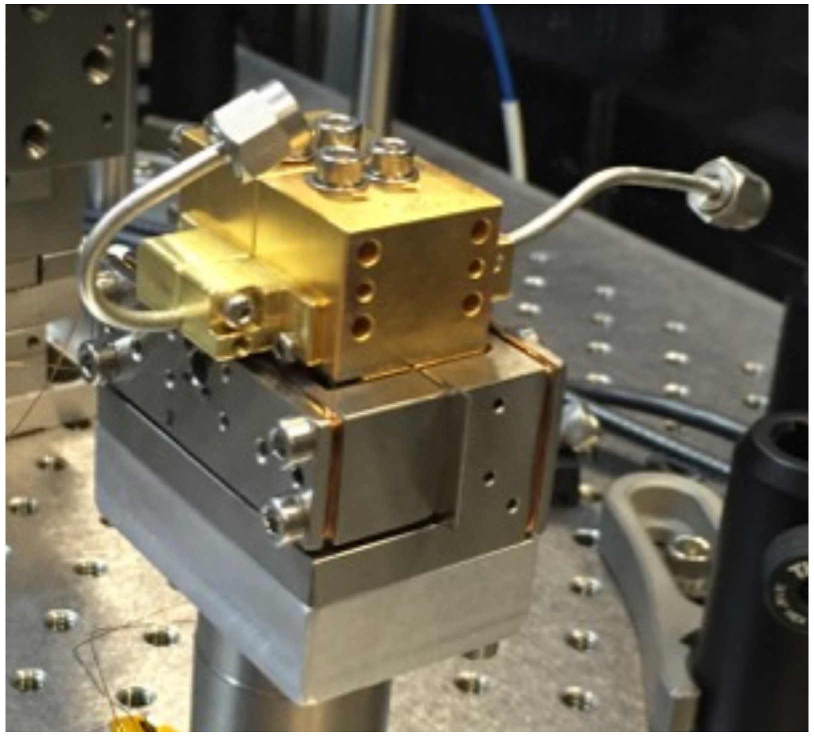
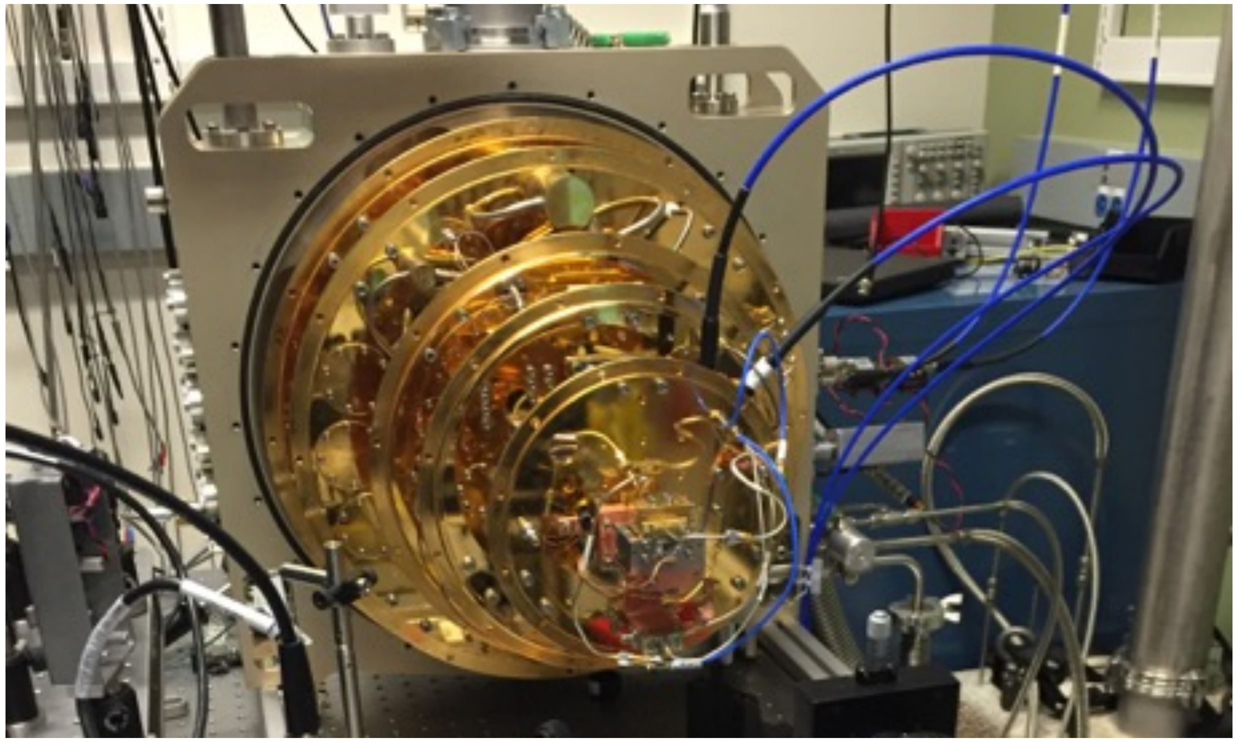




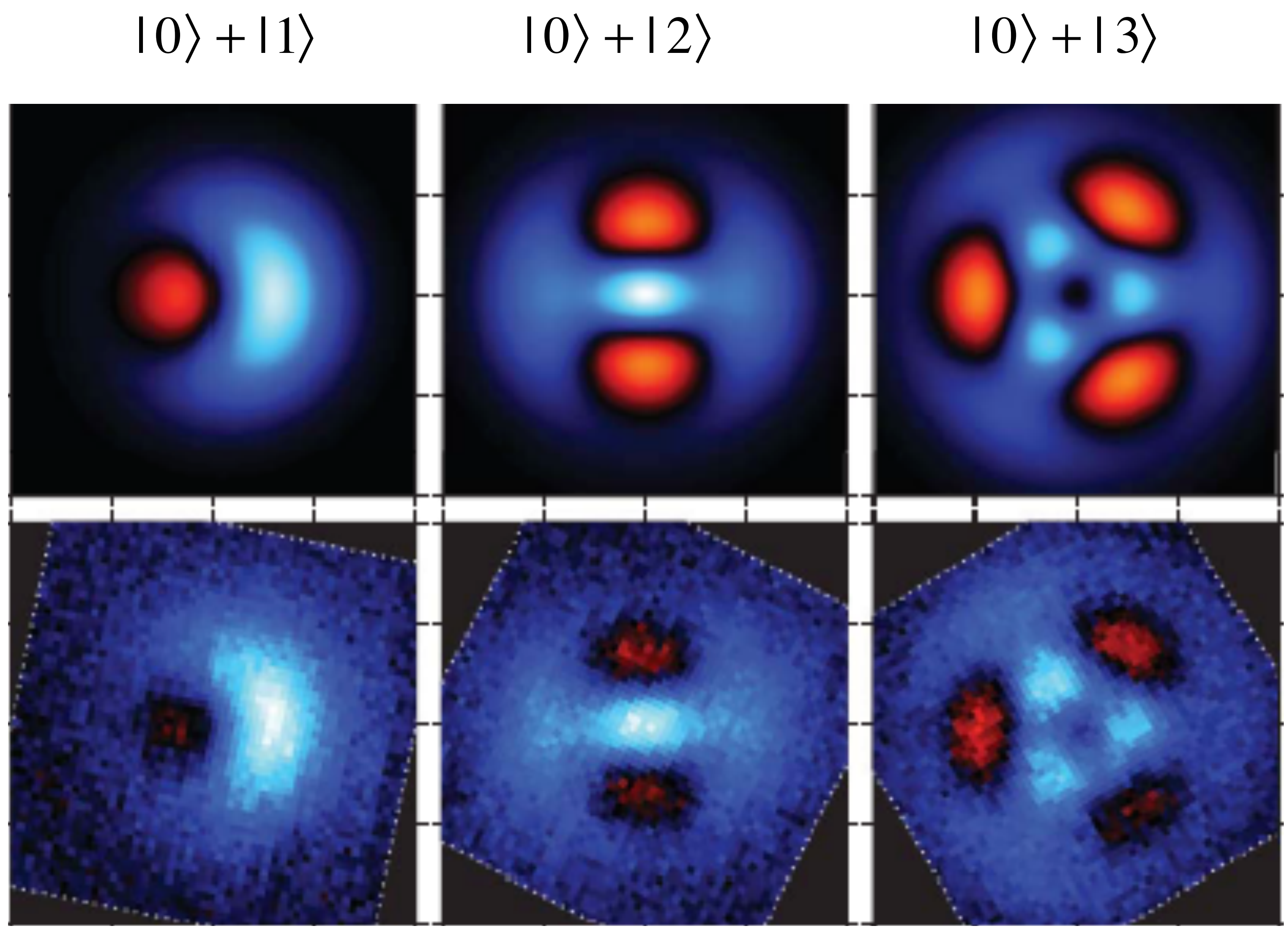
Outline

- Review of classical converter at 4 K
- Classical conversion at 100 mK NEW
- Projections for microwave-optical entanglement





Flexible control of microwave photons with superconducting circuits

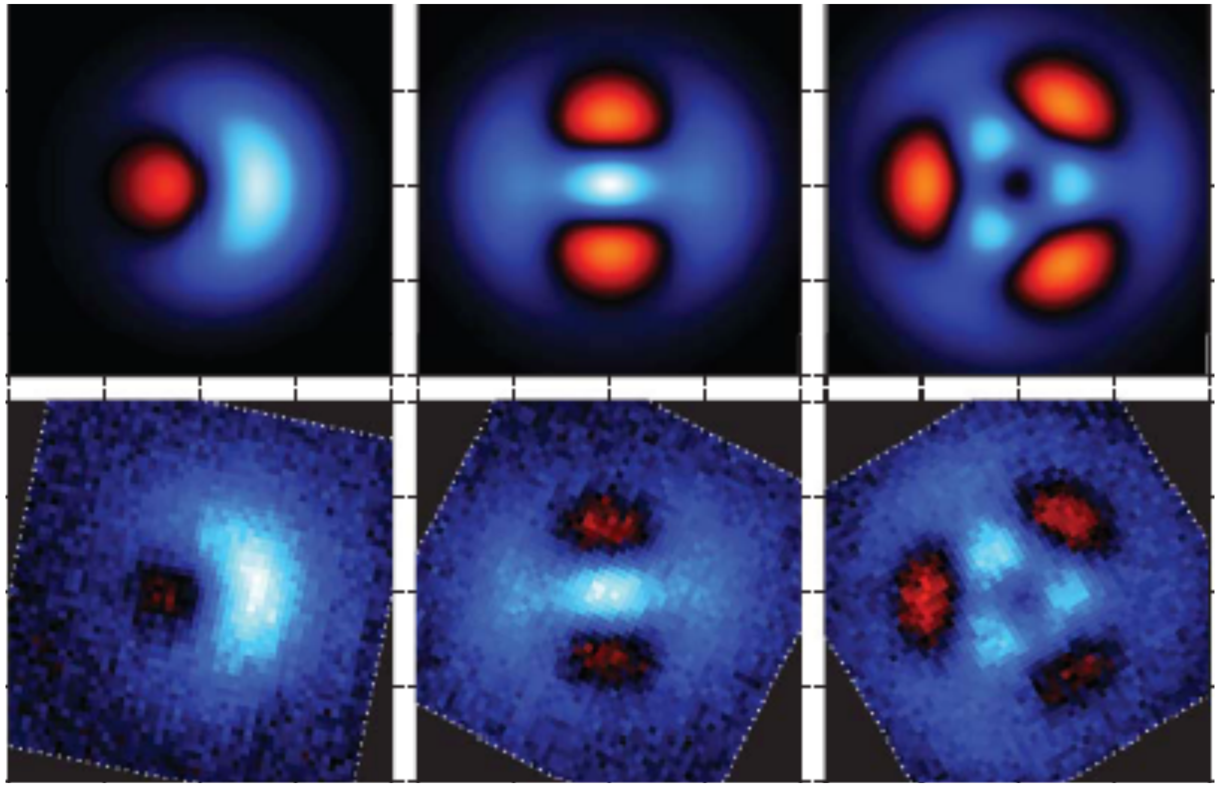


Hofheinz…Martinis, Cleland, Nature (2009)

Flexible control of microwave photons with superconducting circuits

cryostat - 50 mK

$|0\rangle + |1\rangle$ $|0\rangle + |2\rangle$ $|0\rangle + |3\rangle$

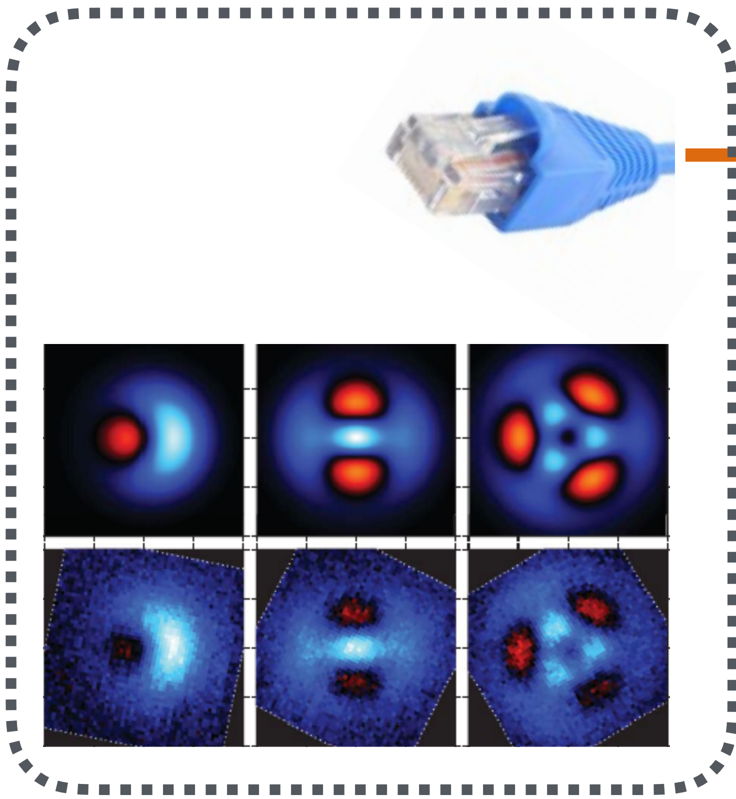


Hofheinz…Martinis, Cleland, Nature (2009)

$$\frac{\hbar\omega}{k_b} \sim 0.3\ \mathrm{K},\ \mathrm{T_c} \sim 1\ \mathrm{K}$$

How can we plug-in to superconducting qubits?

cryostat - 50 mK

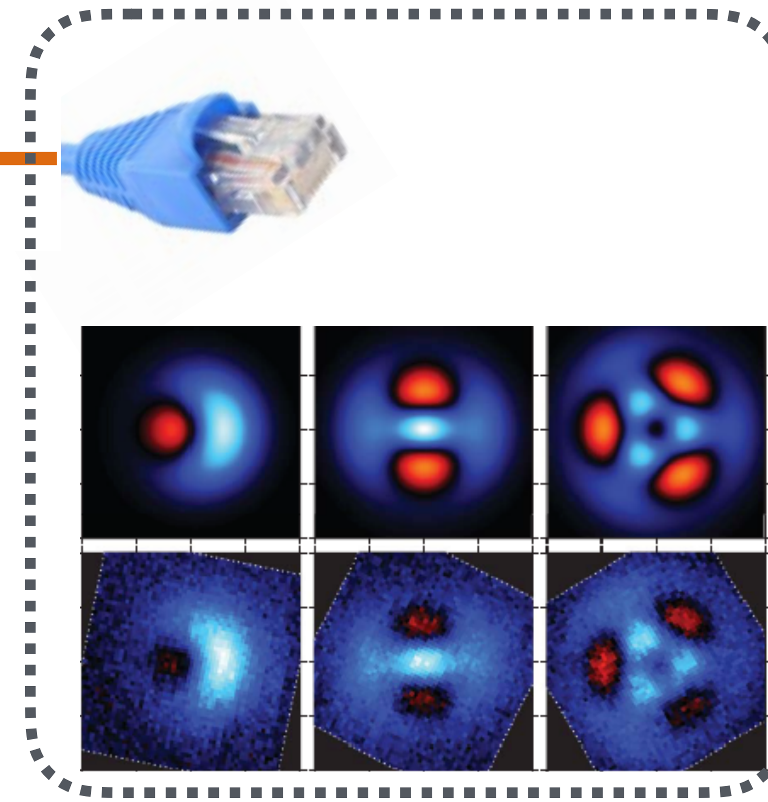


$$\frac{\hbar\omega}{k_B} \sim 0.3 \text{ K}$$

optical network - 300 K

$$\frac{\hbar\omega}{k_B} \sim 10^4 \text{ K}$$

cryostat - 50 mK

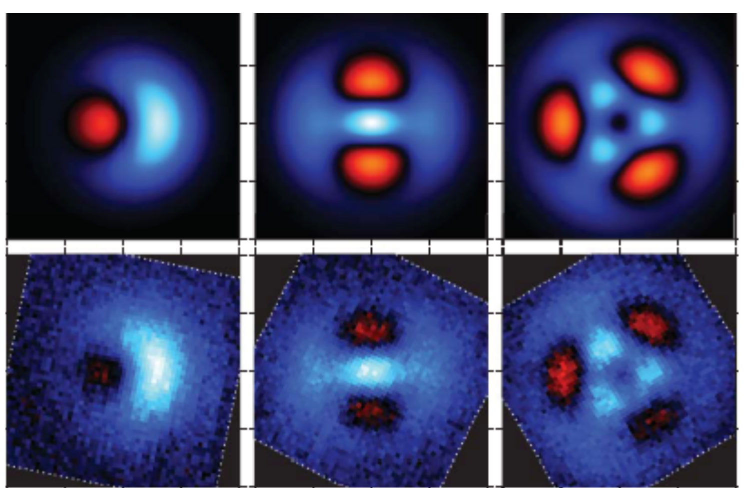


$$\frac{\hbar\omega}{k_B} \sim 0.3 \text{ K}$$

Our approach: low-frequency mechanical oscillators

microwave

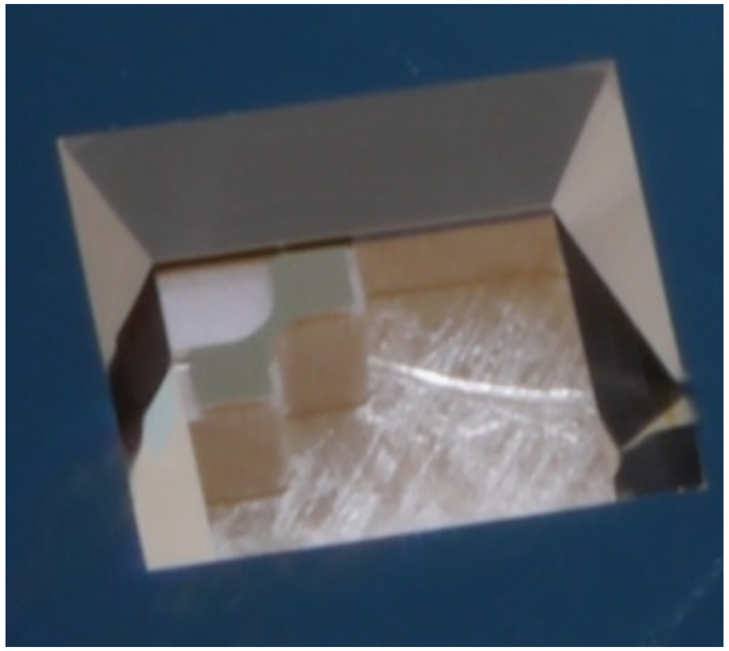
$$\frac{\hbar\omega}{k_b} \sim 0.3\ \text{K}$$



Hofheinz…Martinis, Cleland, Nature (2009)

mechanical

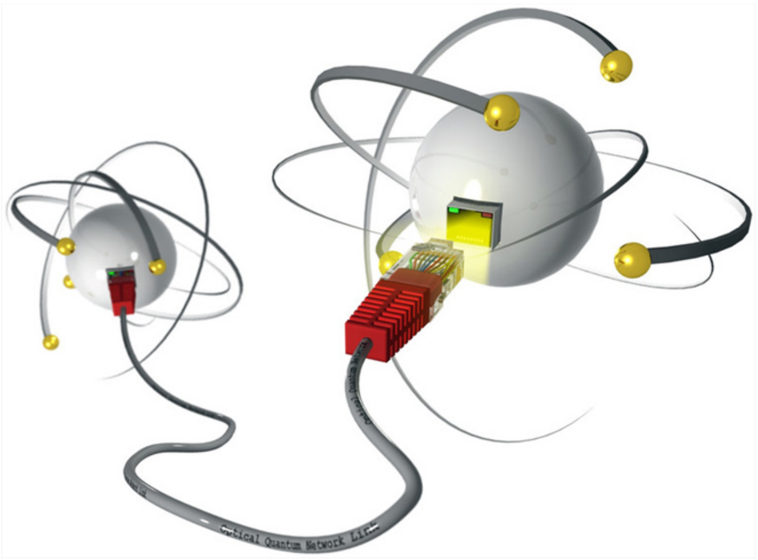
$$\frac{\hbar\omega}{k_b} \sim 50\ \mu\text{K}$$



$$n_{th}\gamma_m = 2\pi \times 8\ \text{kHz}$$

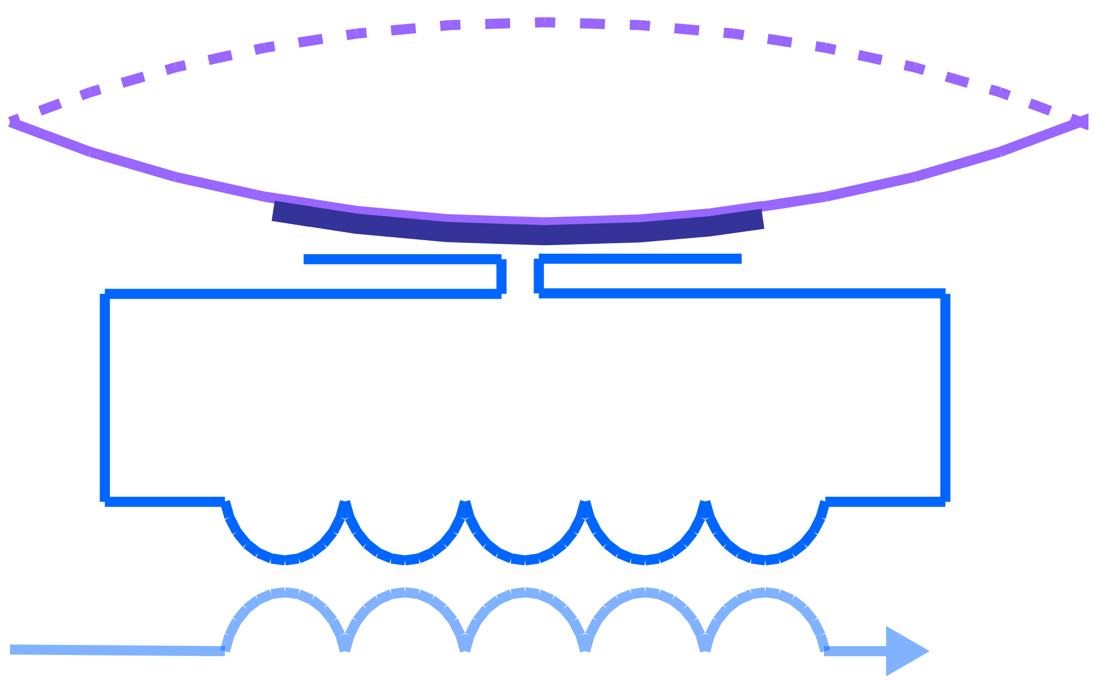
optical

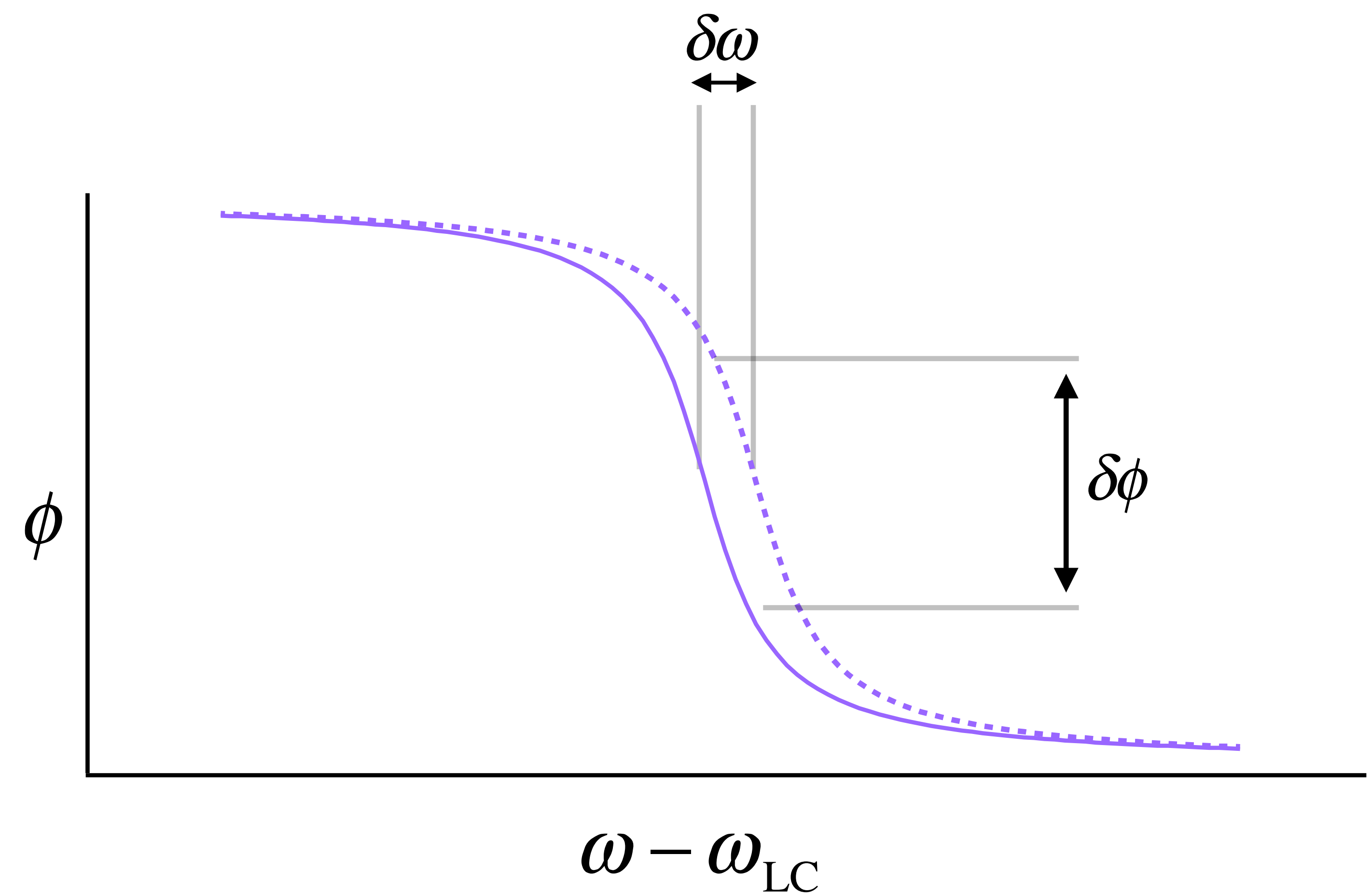
$$\frac{\hbar\omega}{k_b} \sim 10^4\ \text{K}$$



Ritter…Rempe, Nature (2012)

Electromechanics interaction:
Static mechanical displacement causes phase shifts

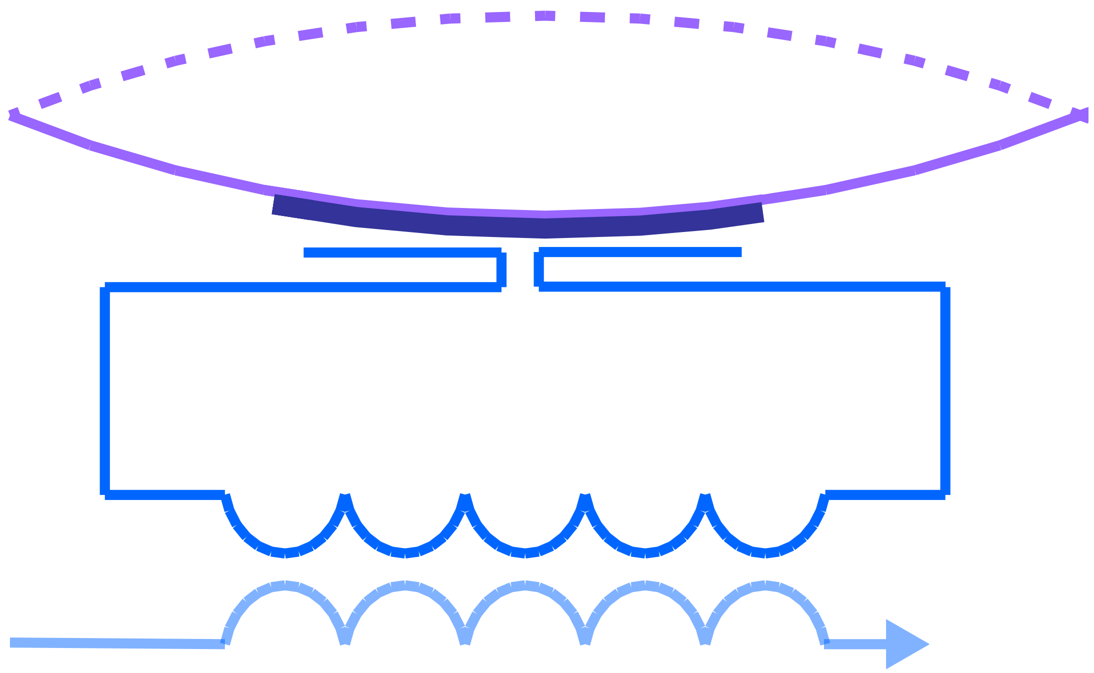


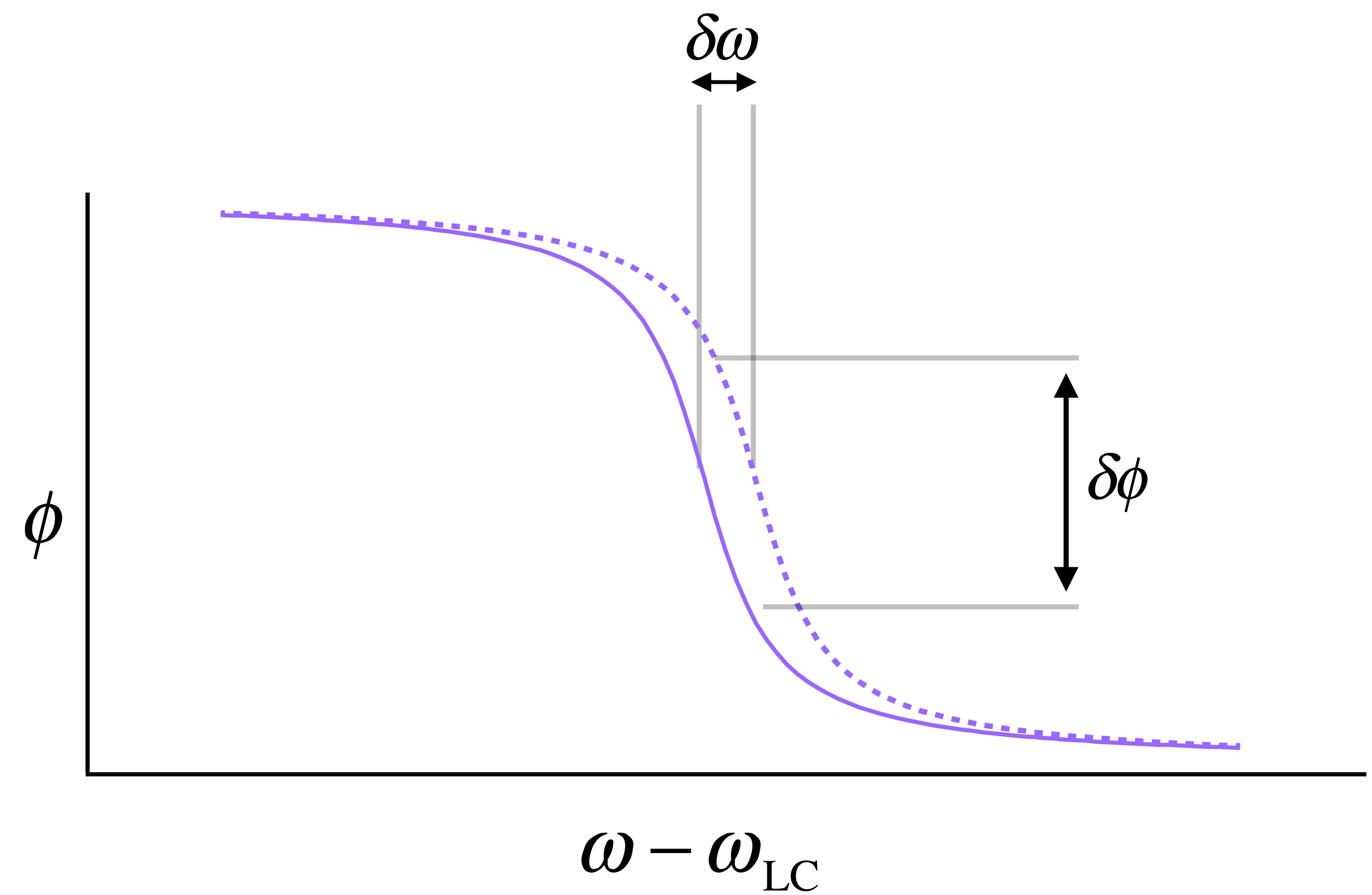


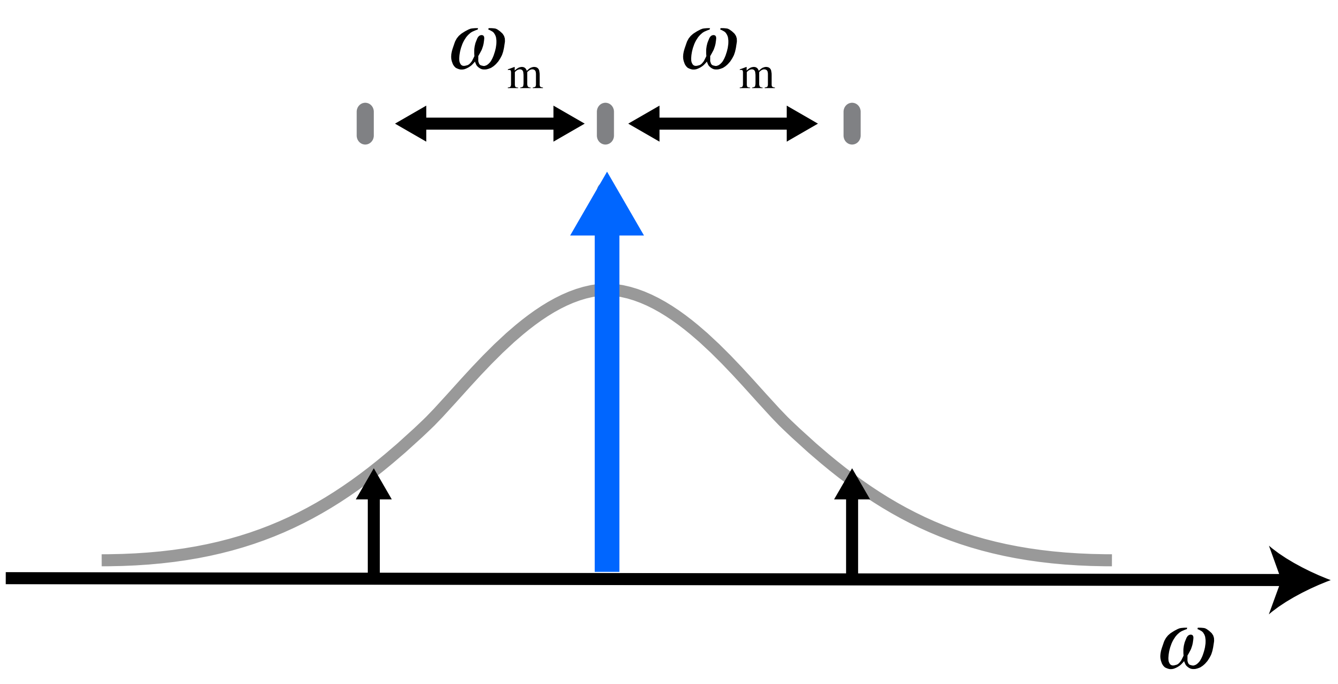
$$\omega = \frac{1}{\sqrt{LC}}$$

$$\delta\omega = \frac{d\omega}{dC}\delta C$$

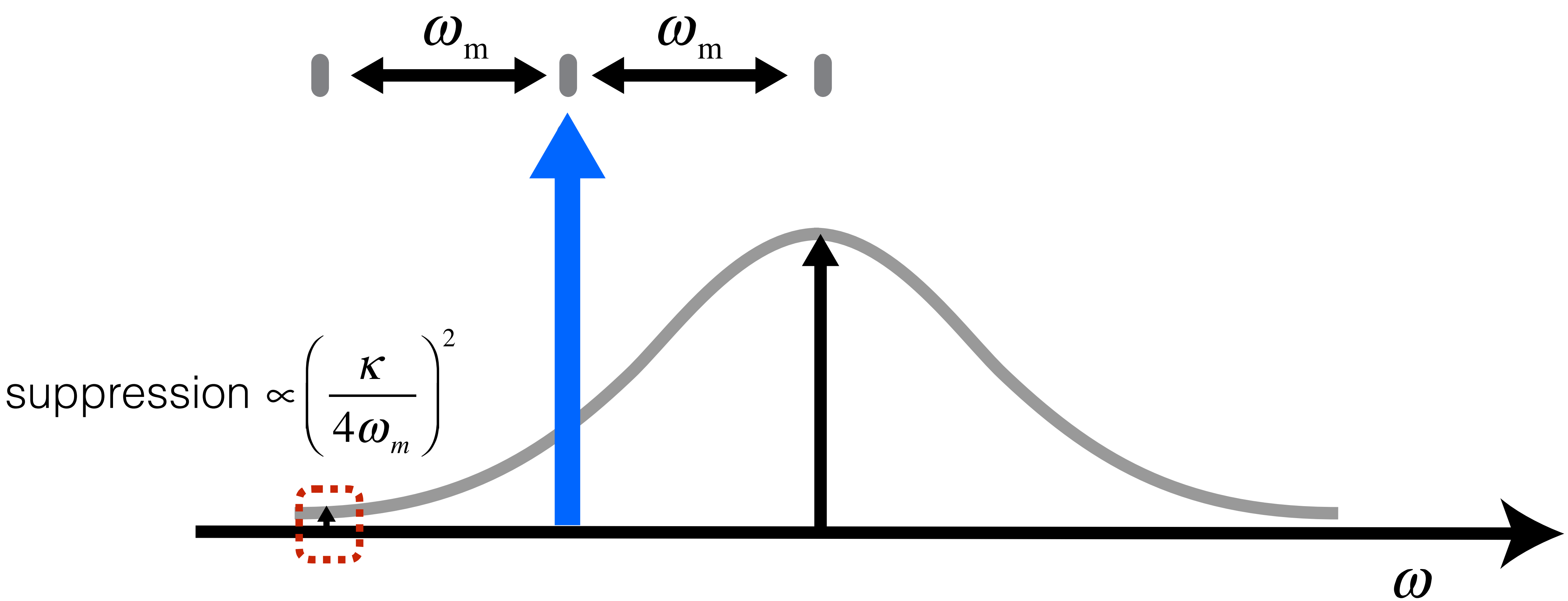
Electromechanics:
Oscillating displacement causes PM sidebands



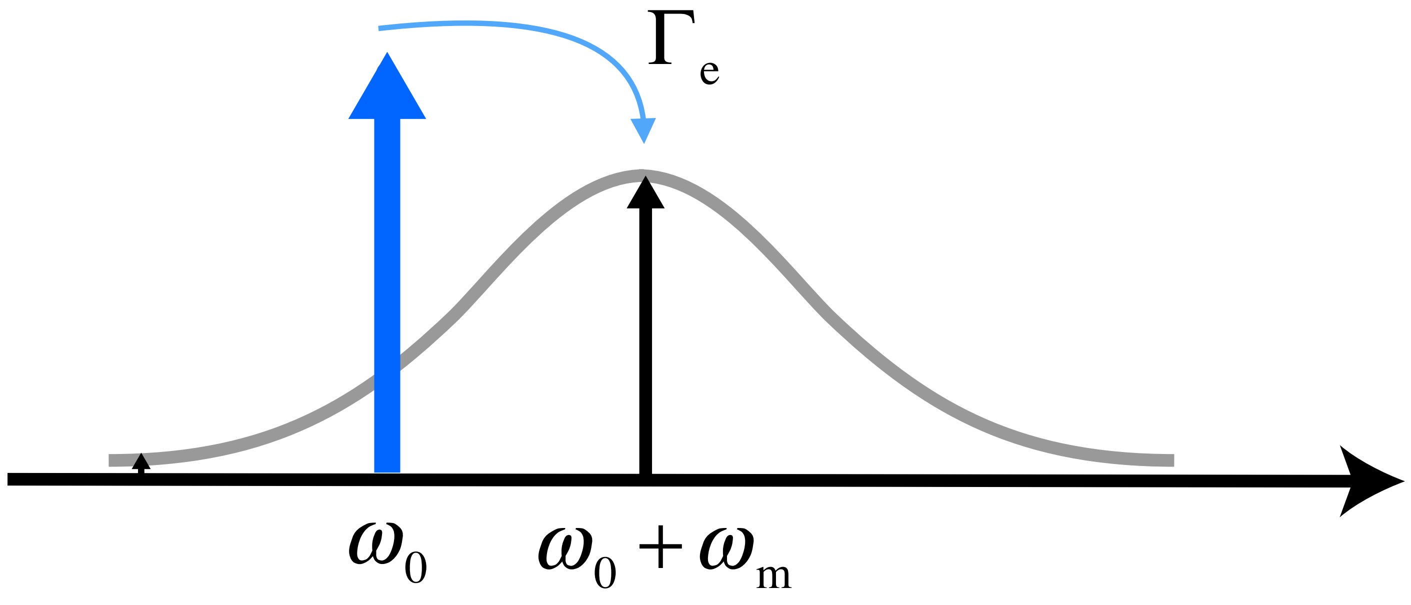




Selecting a sideband with cavity density of states

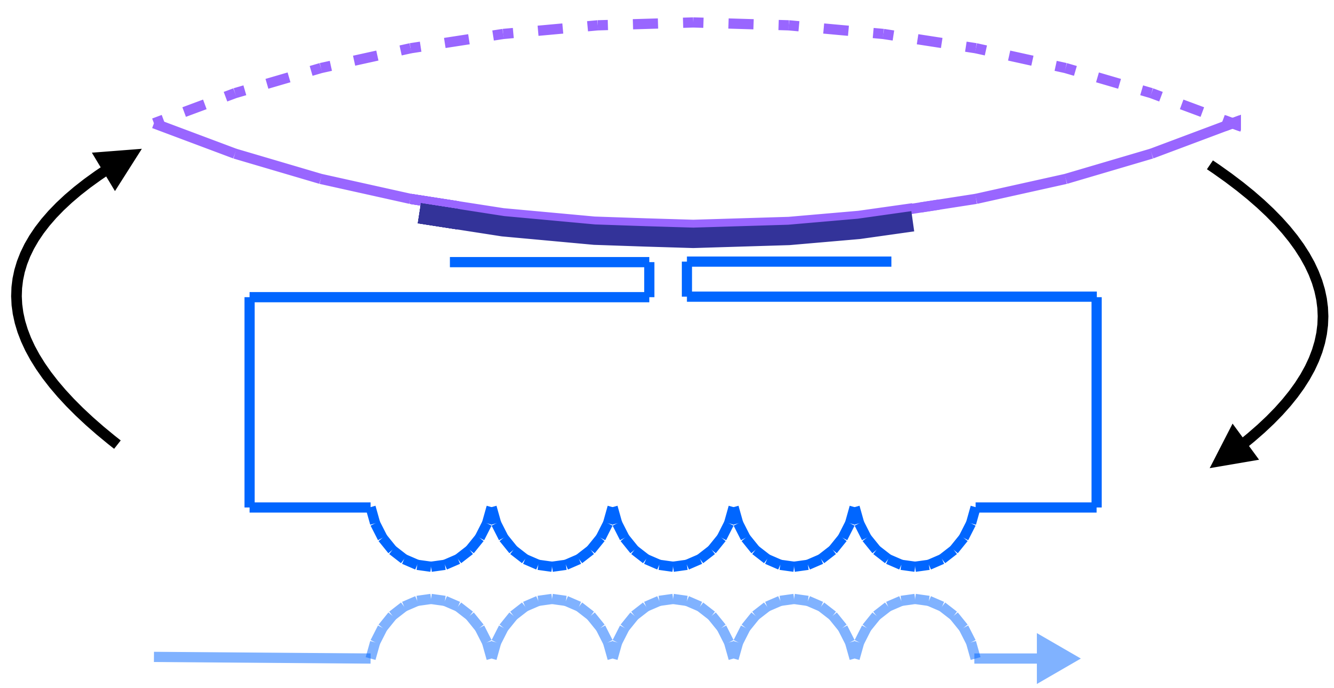


Energetics of the upper sideband: swapping photons and phonons



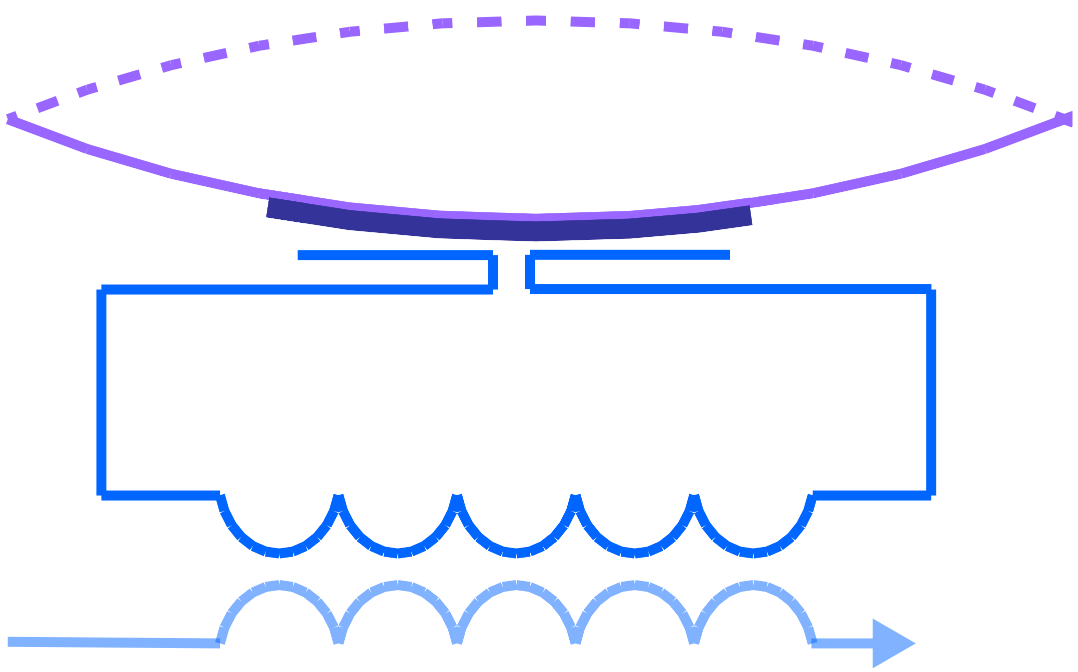
$$H_{int} = \hbar g_0 a_{mw}^{\dagger} a_{mech} + \text{h.c.}$$

generates mech-mw swaps



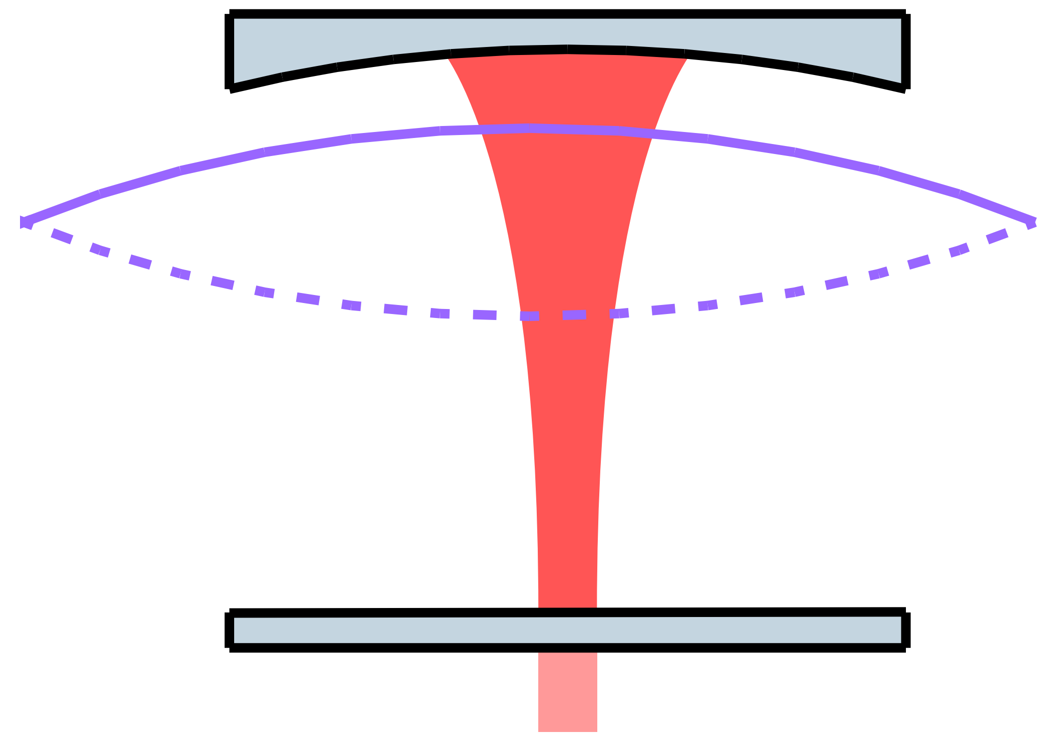
Microwave-mechanical-optical strategy for state transduction

microwave ⟷ mechanics



Lehnert group

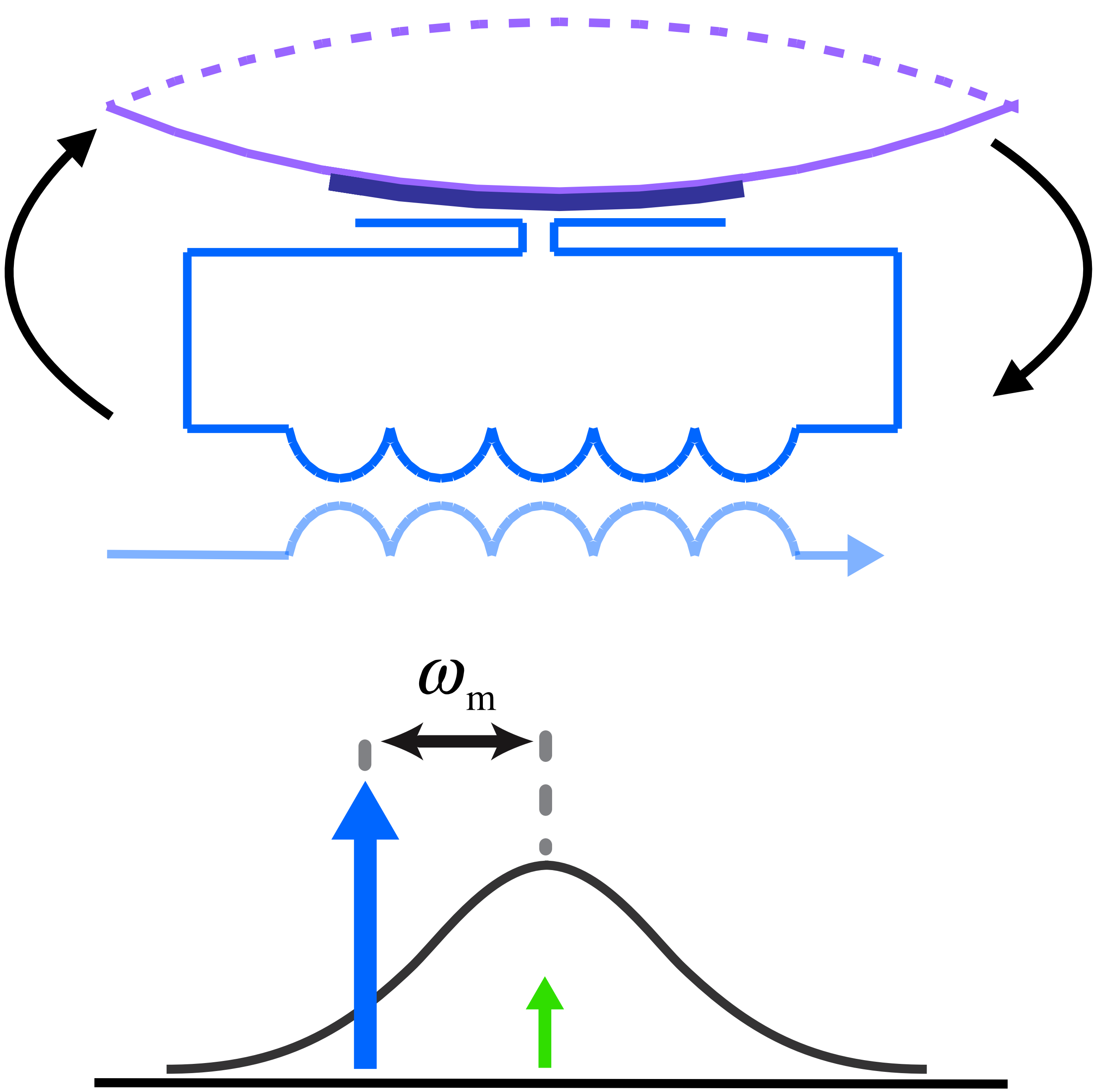
mechanics ⟷ optics



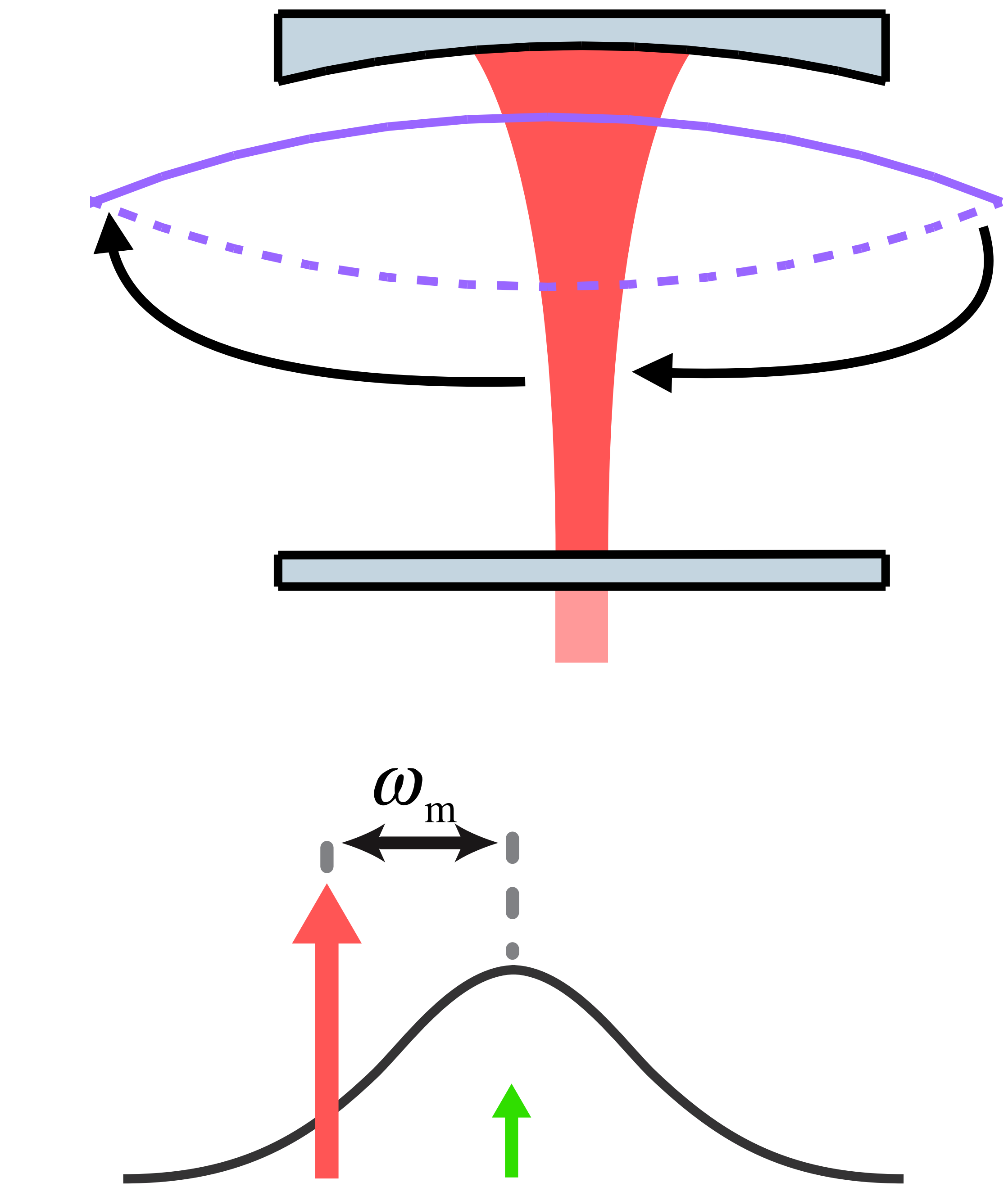
Regal group

Strategy for state conversion

$$H_{\text{int}} = \hbar g_0 a^{\dagger}_{\text{mw}} a_{\text{mech}} + \text{h.c.}$$



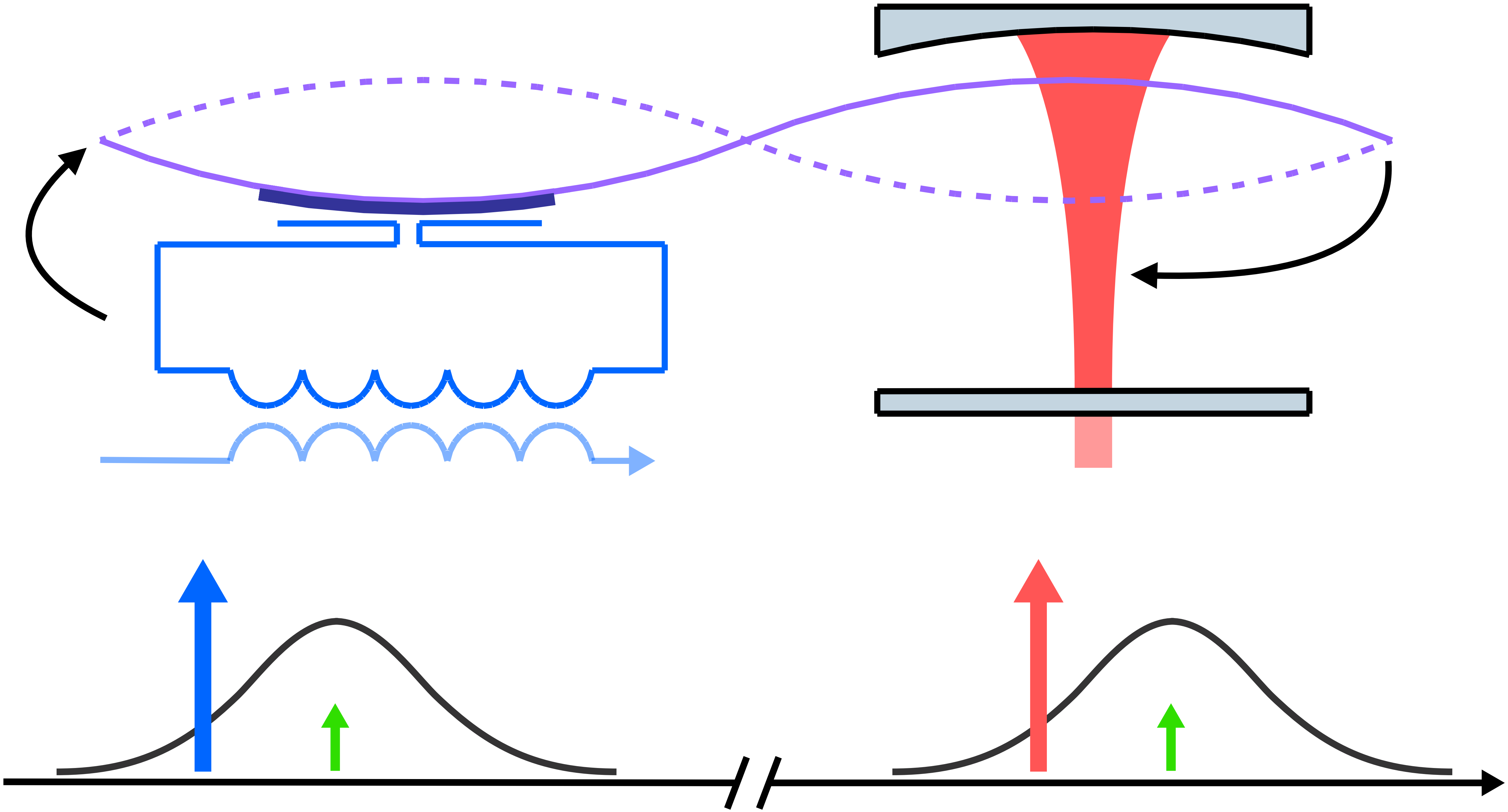
$$H_{\text{int}} = \hbar g_0 a^{\dagger}_{\text{opt}} a_{\text{mech}} + \text{h.c.}$$



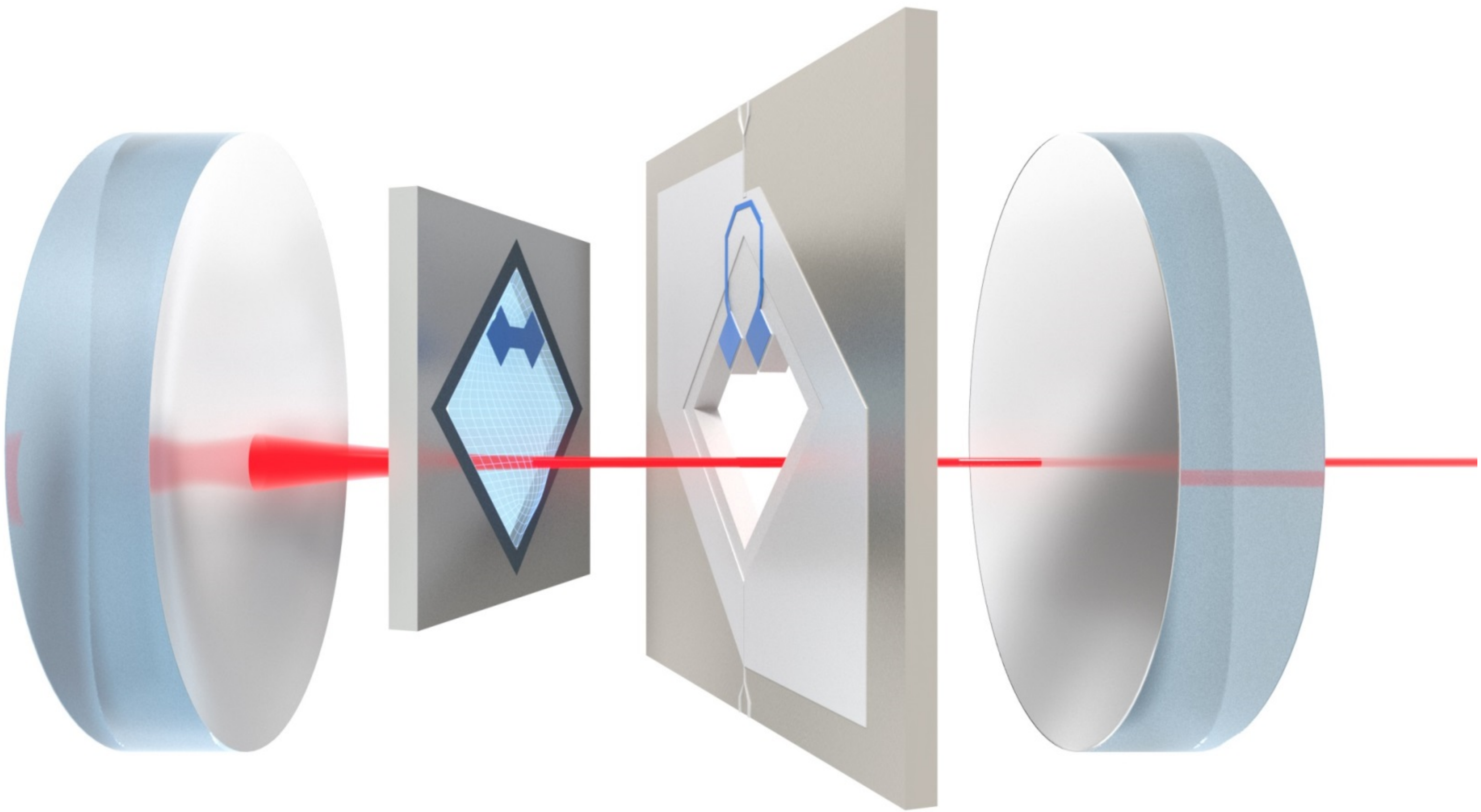
Strategy for state conversion

$$H_{\text{int}} = \hbar g_0 a_{\text{mw}}^{\dagger} a_{\text{mech}} + \text{h.c.}$$

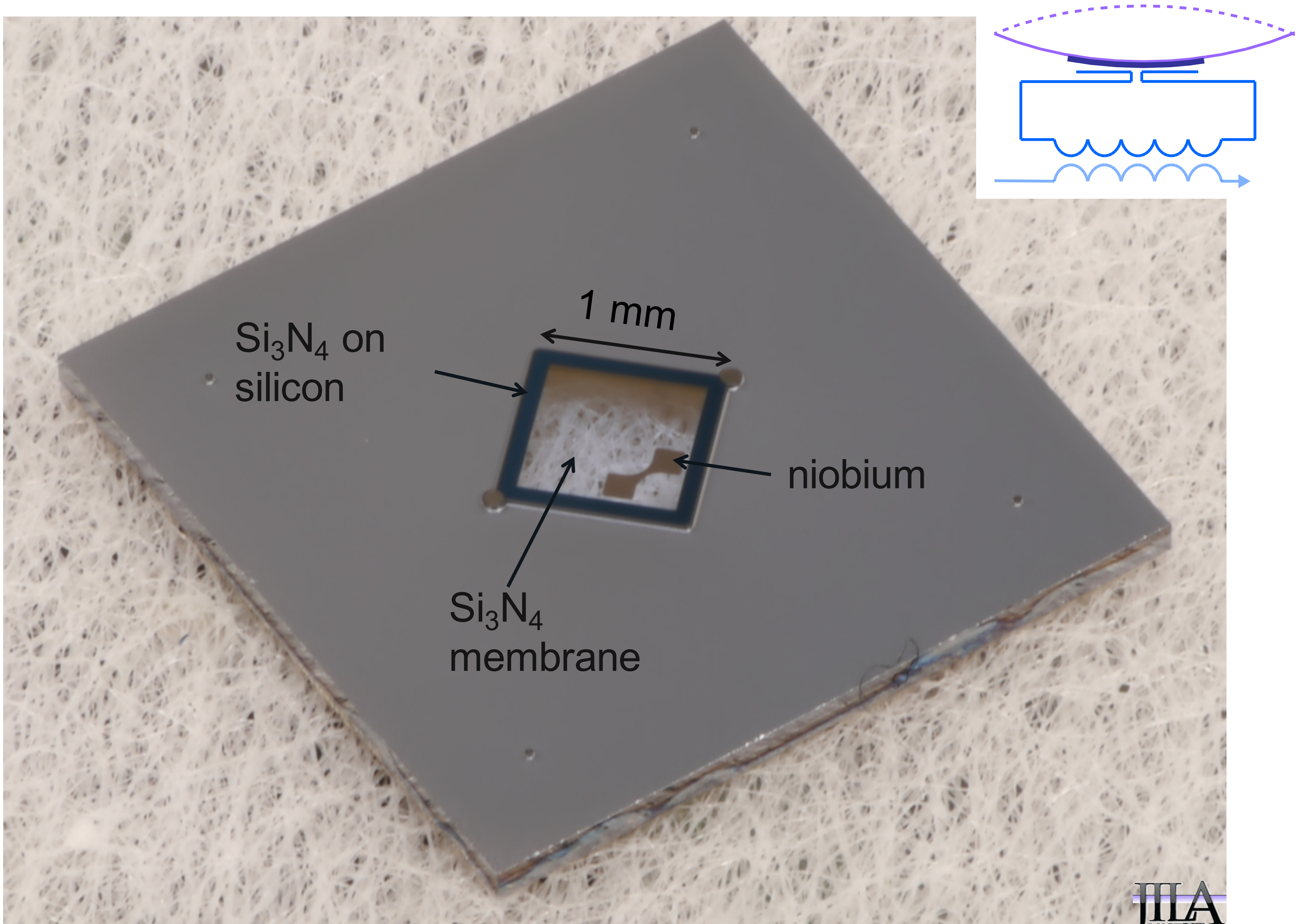
$$H_{\text{int}} = \hbar g_0 a_{\text{opt}}^{\dagger} a_{\text{mech}} + \text{h.c.}$$



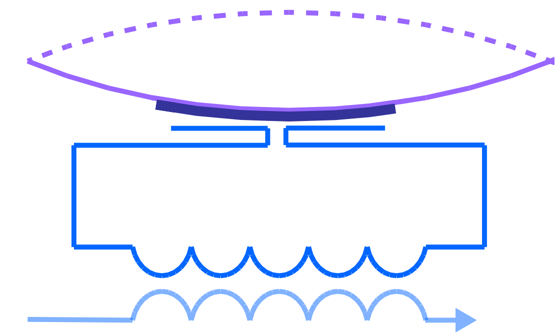
Flip chip in an optical cavity



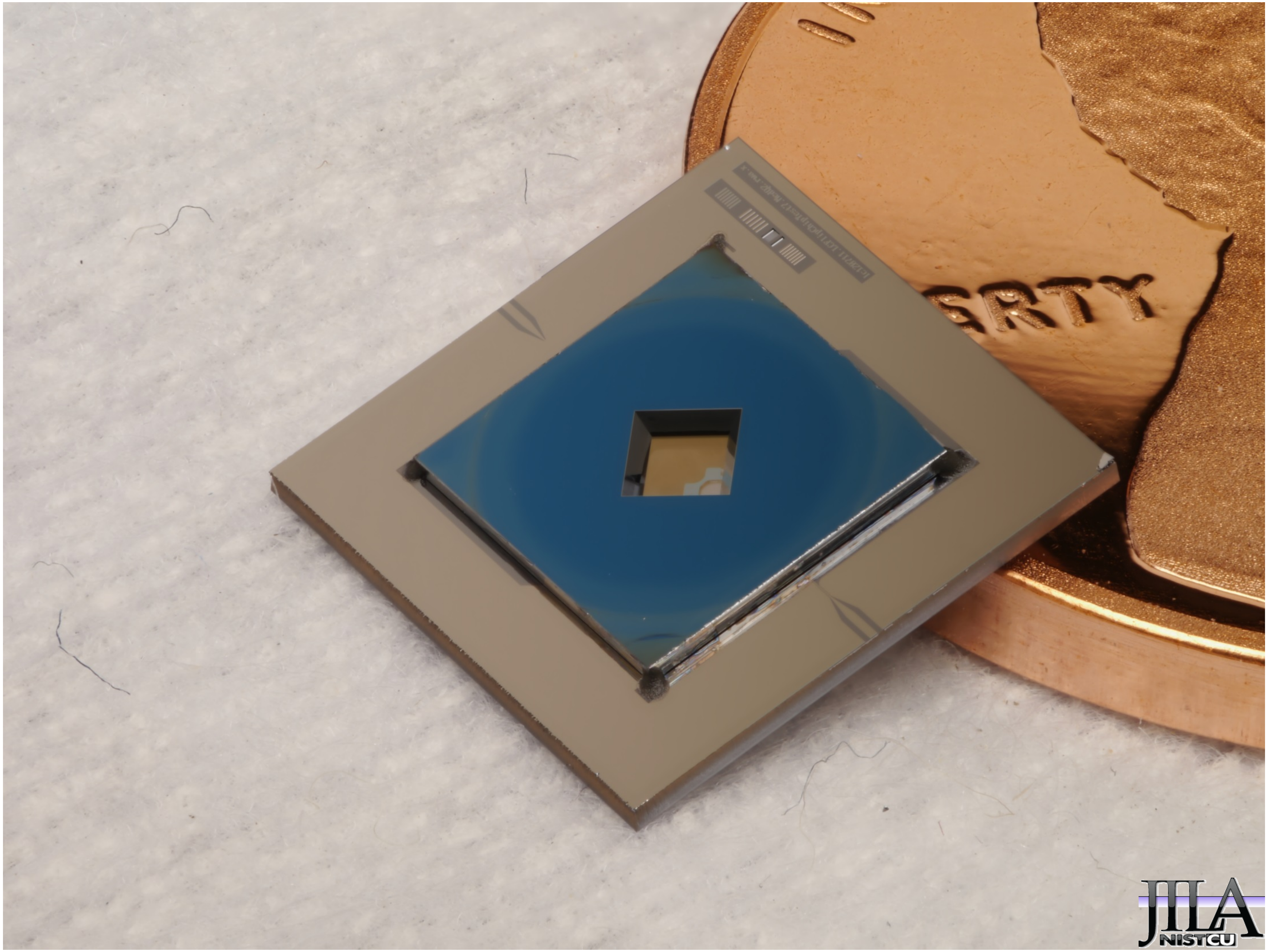
Top chip layout



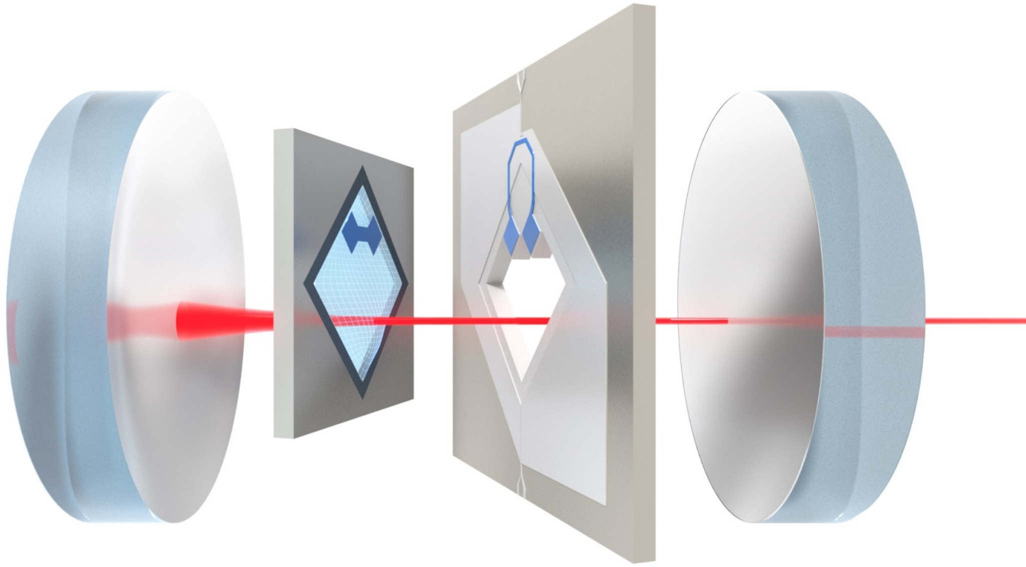
Bottom chip layout

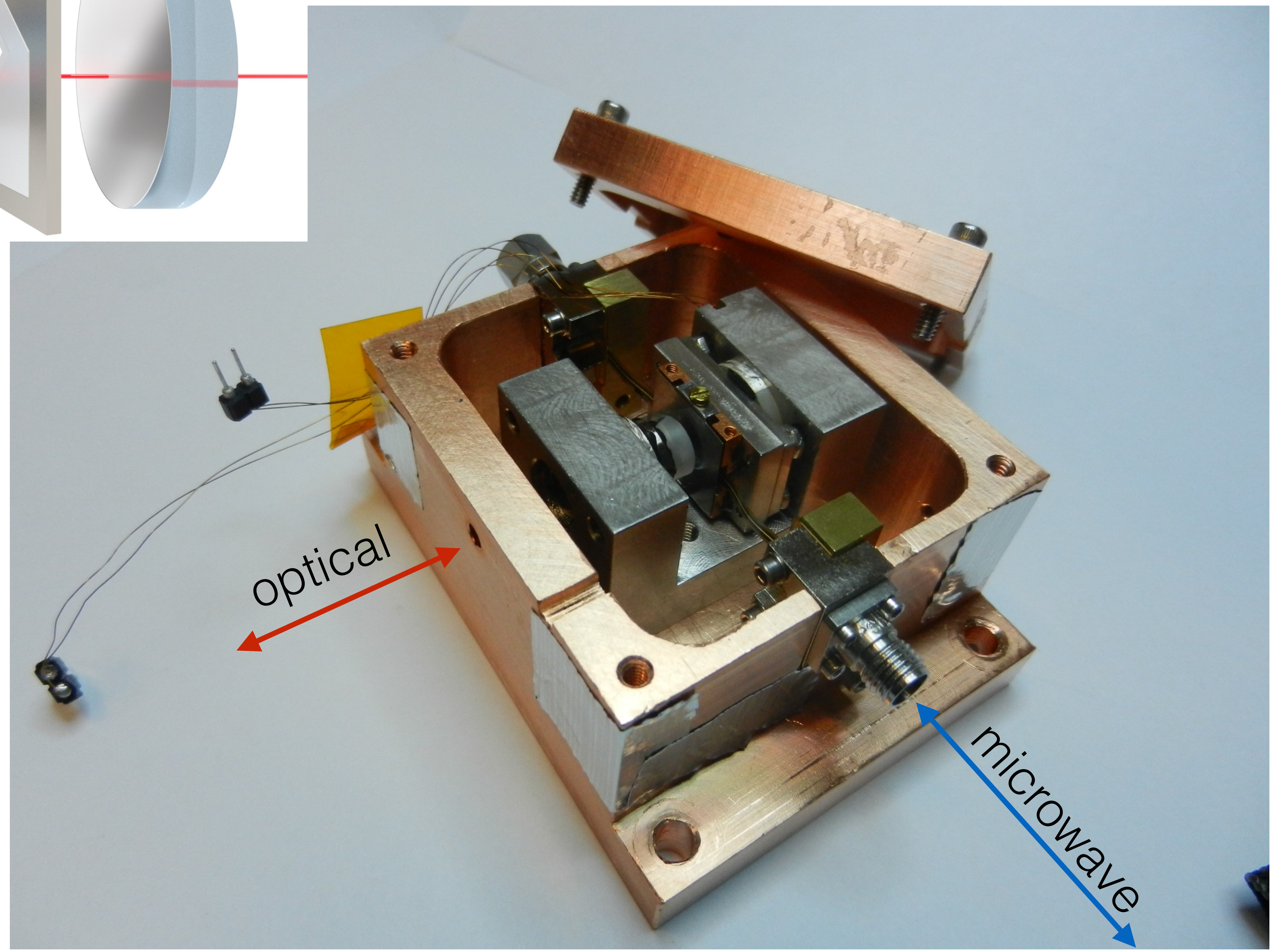


Assembled flip-chip

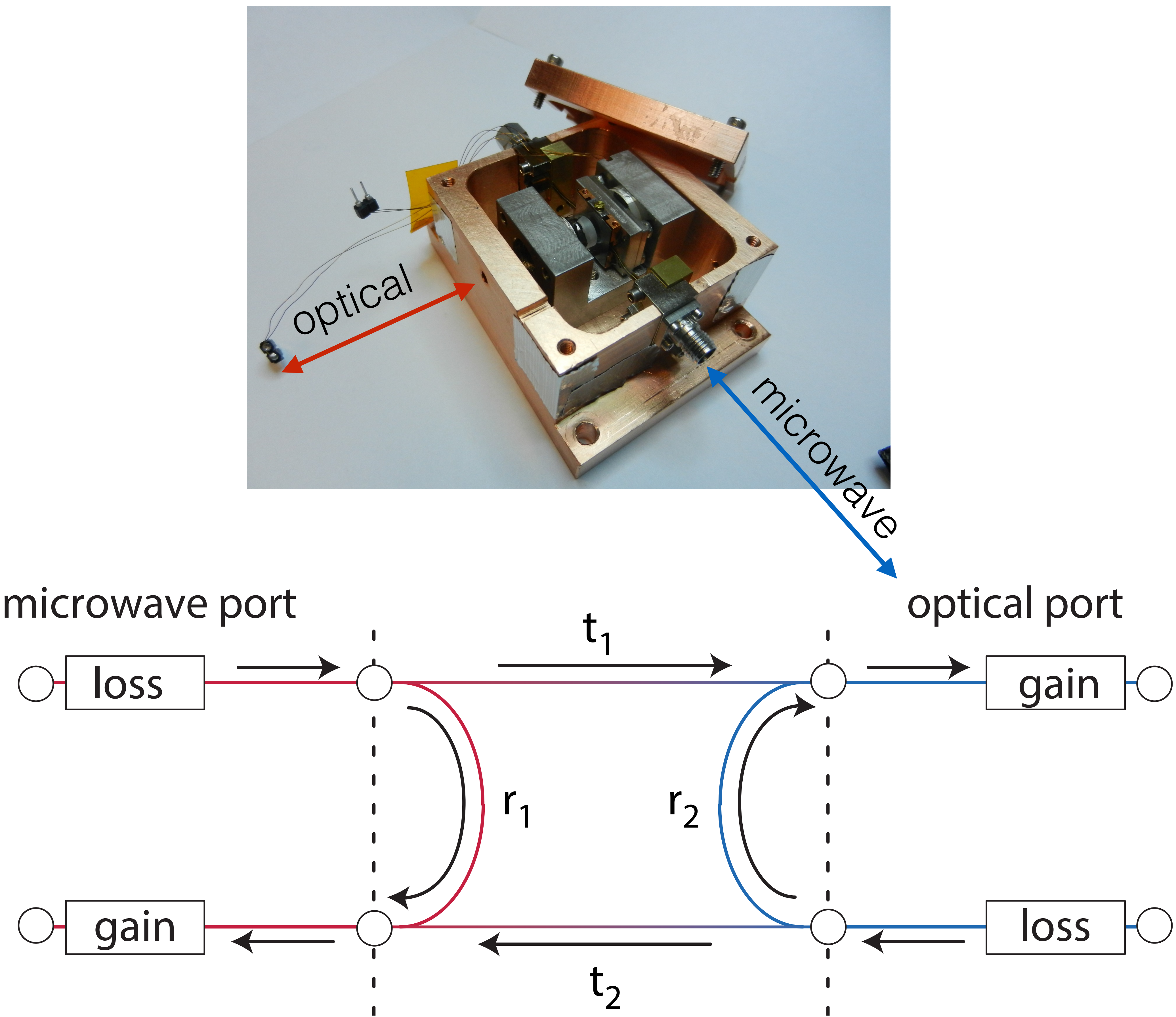


Microwave-mechanical-optical setup

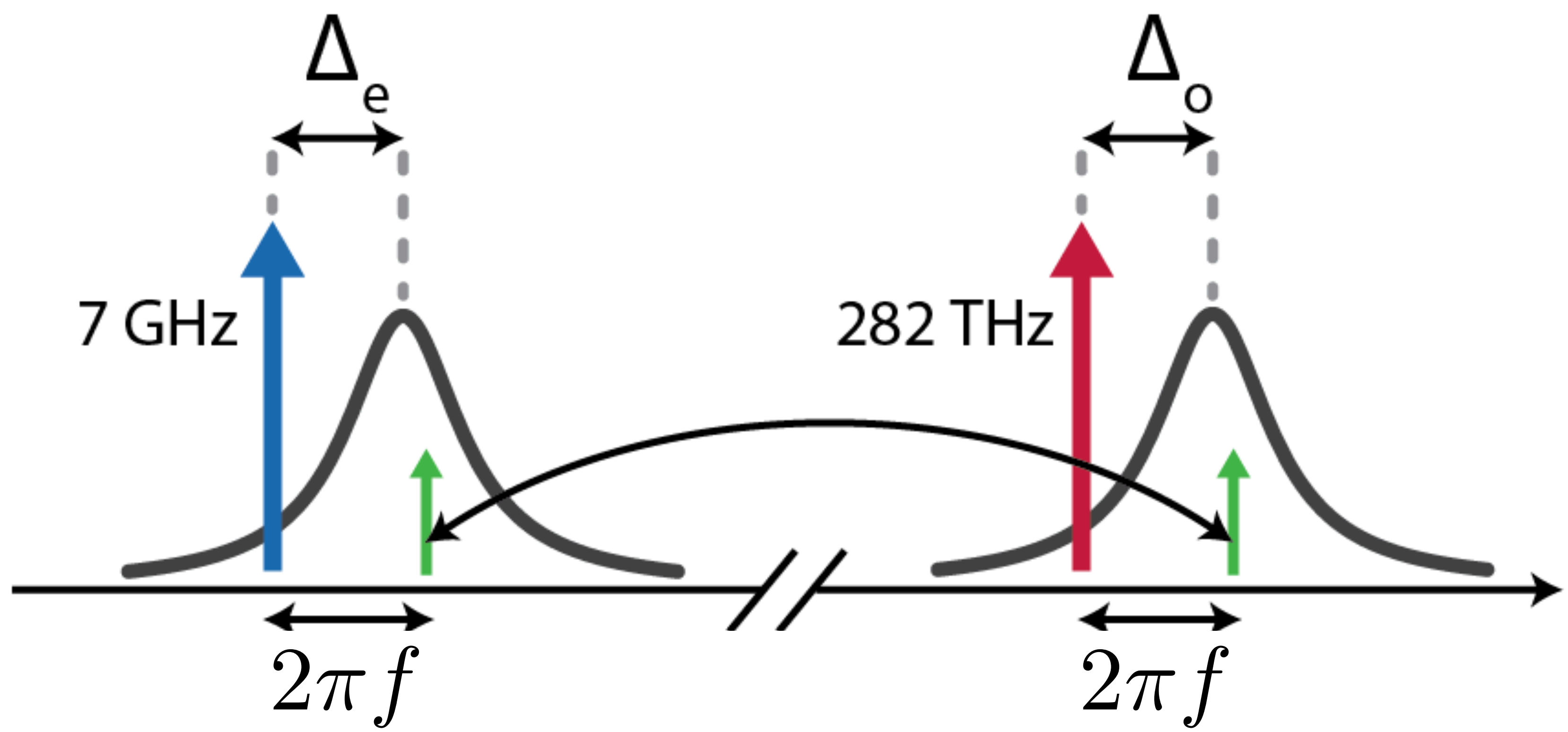


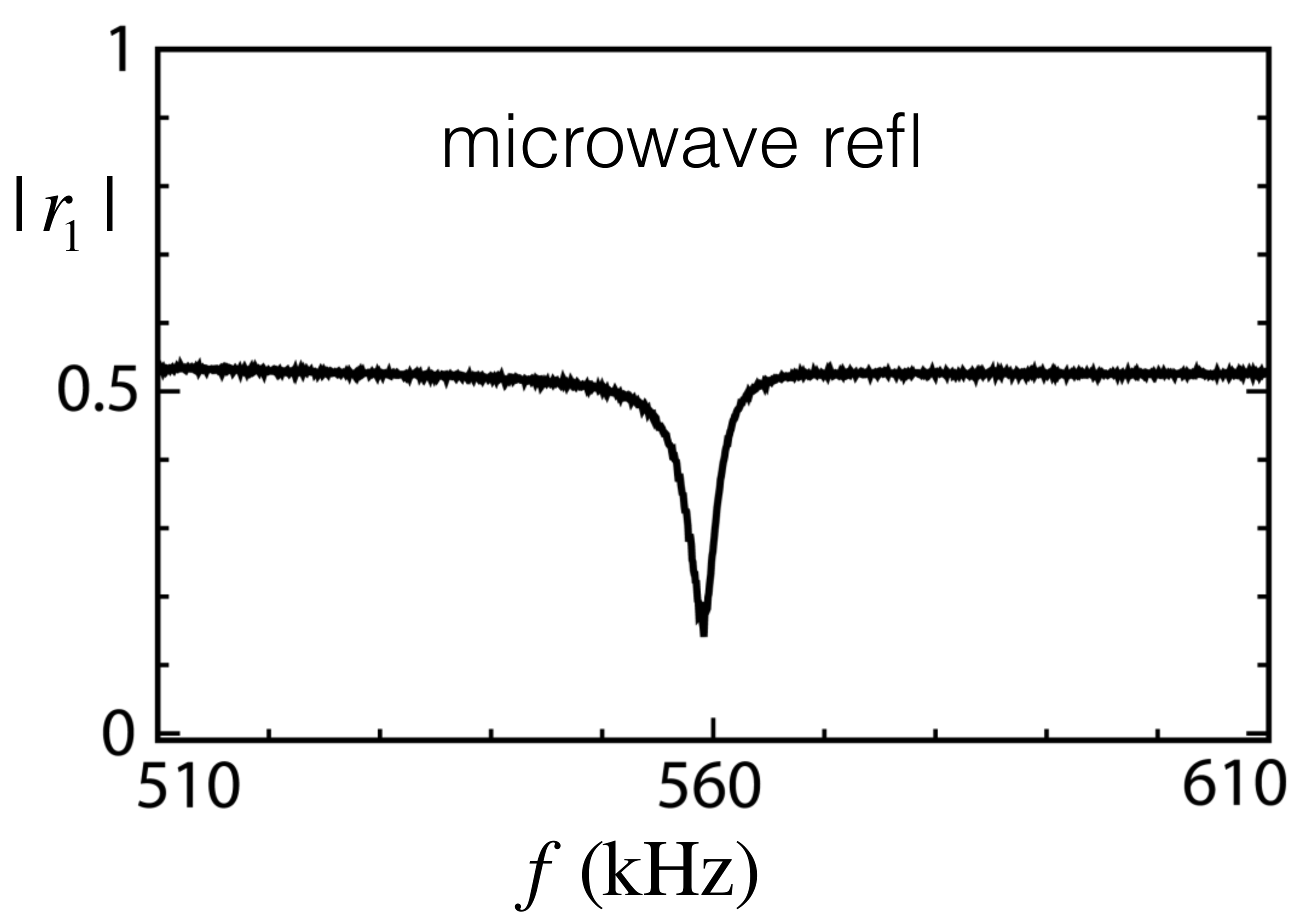


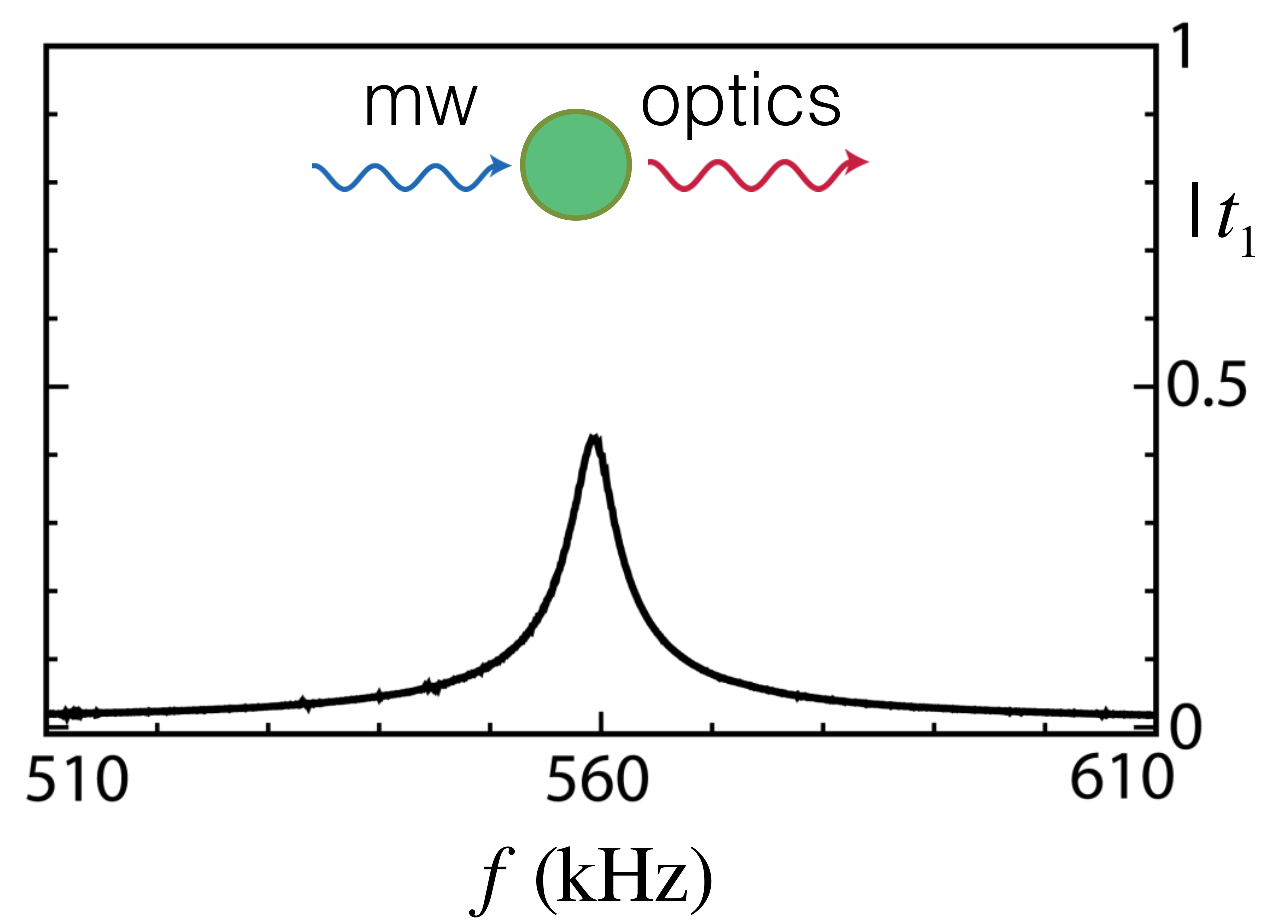
Classical network analysis



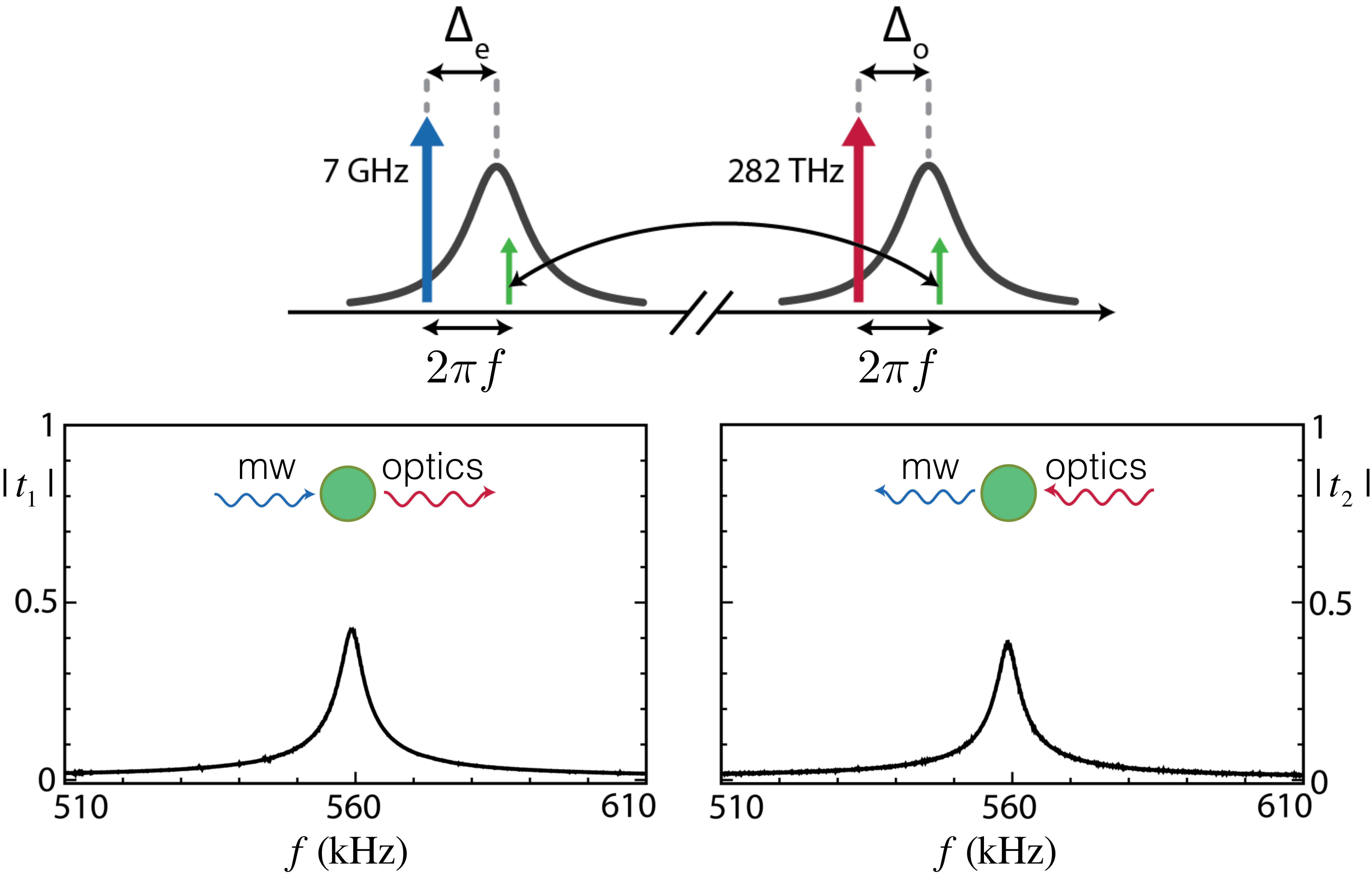
Microwave to optical conversion



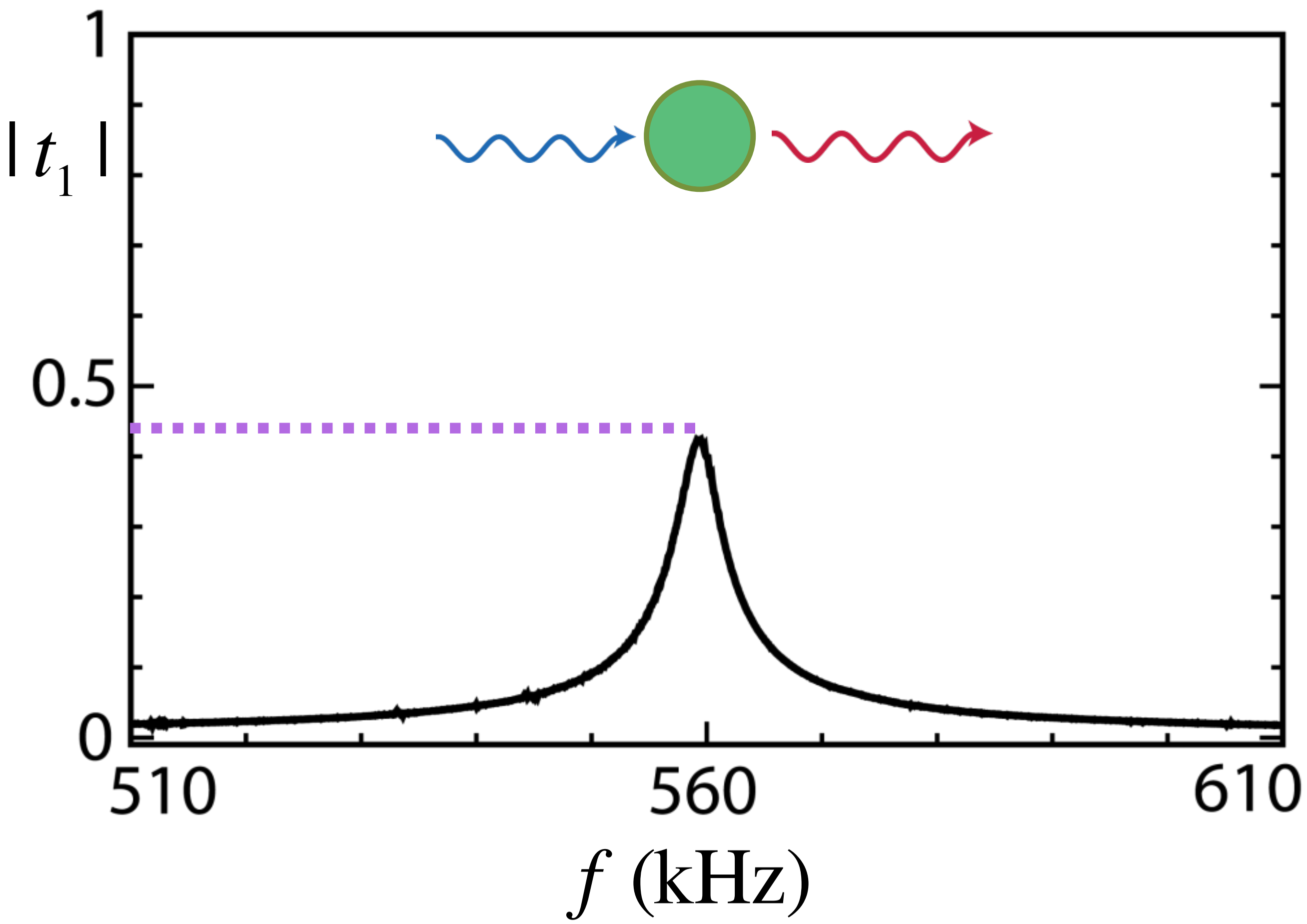


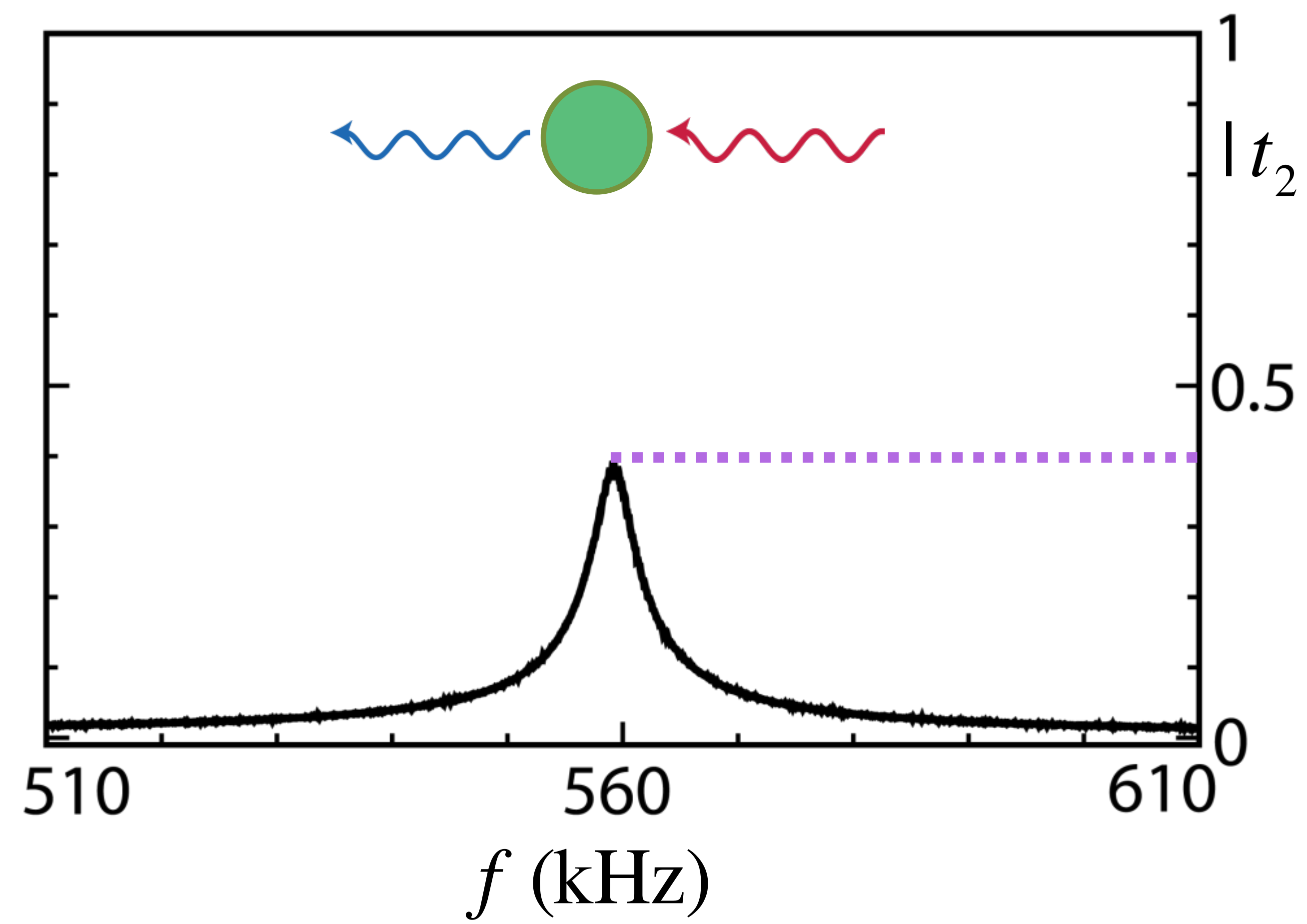


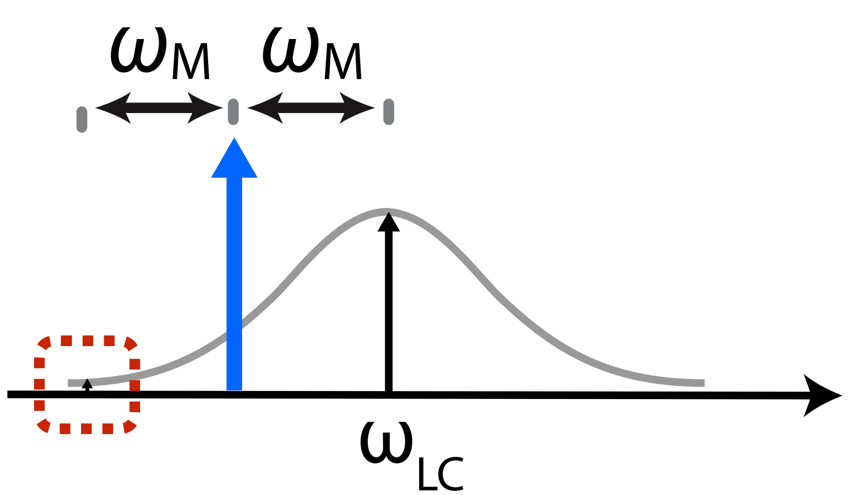
Bidirectional conversion



Transfer efficiency







apparent efficiency: $|t_1 t_2| = 0.18$

total gain: $\left[1+\left(\frac{\kappa_e}{4\omega_m}\right)^2\right] \times \left[1+\left(\frac{\kappa_o}{4\omega_m}\right)^2\right]$

efficiency: $\frac{|t_1 t_2|}{\text{Gain}} = 8\%$

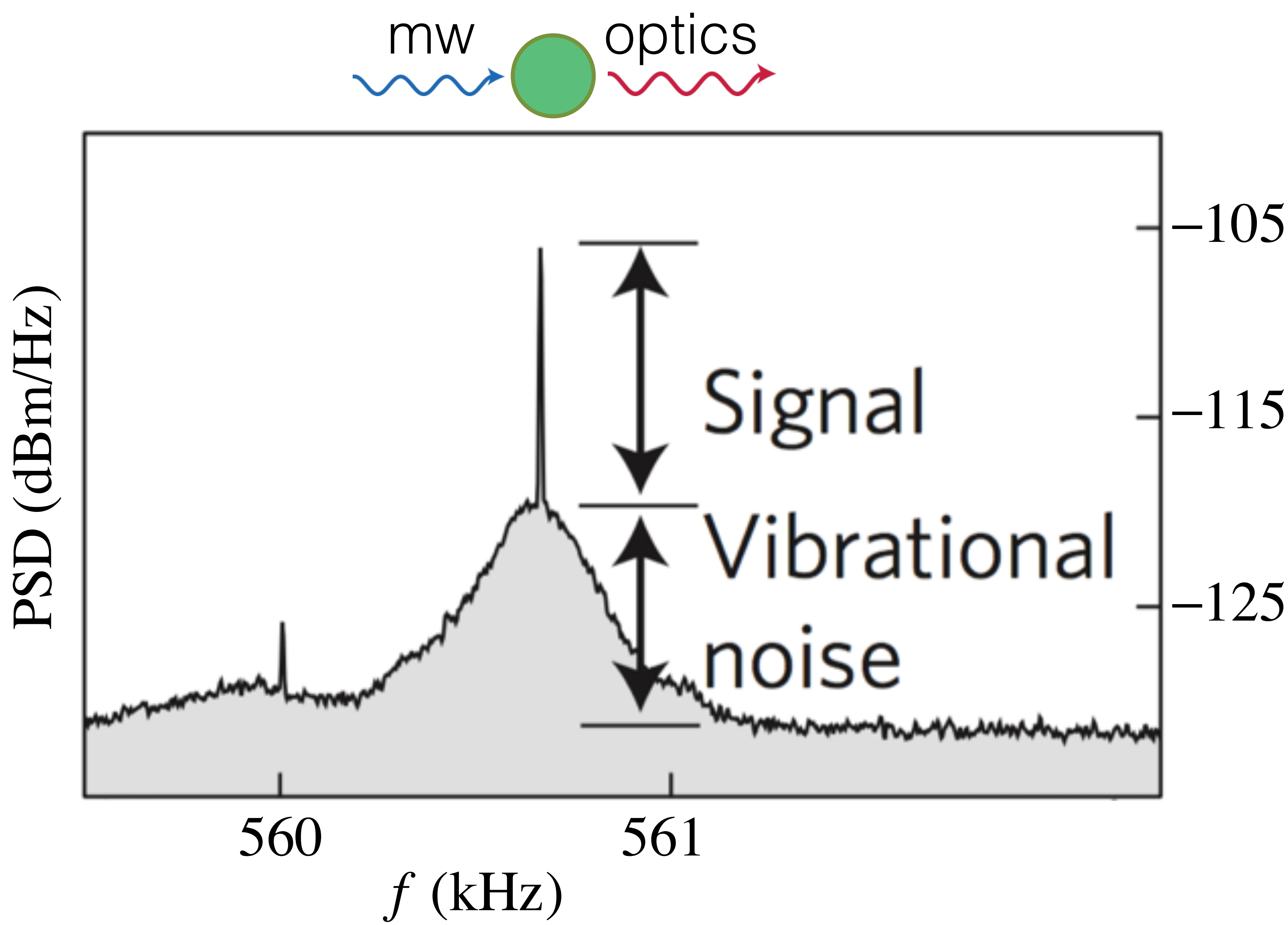
R. W. Andrews et . al. , Nat. Phys. (2014)

Added noise

best-case added noise:

$$\frac{n_{\mathrm{th}}\gamma_{\mathrm{m}}}{\Gamma_{\mathrm{eo}}} \sim 20 \text{ phonons}$$

at $T = 4$ K



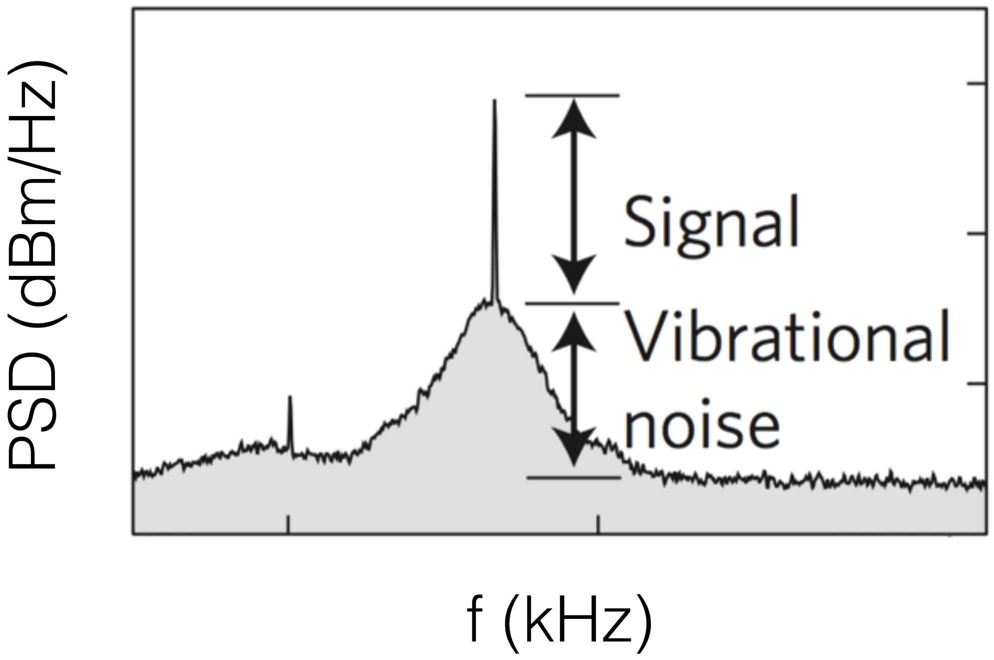
R. W. Andrews et . al. , Nat. Phys. (2014)

Added noise dominated by mechanics

Added noise accounting:

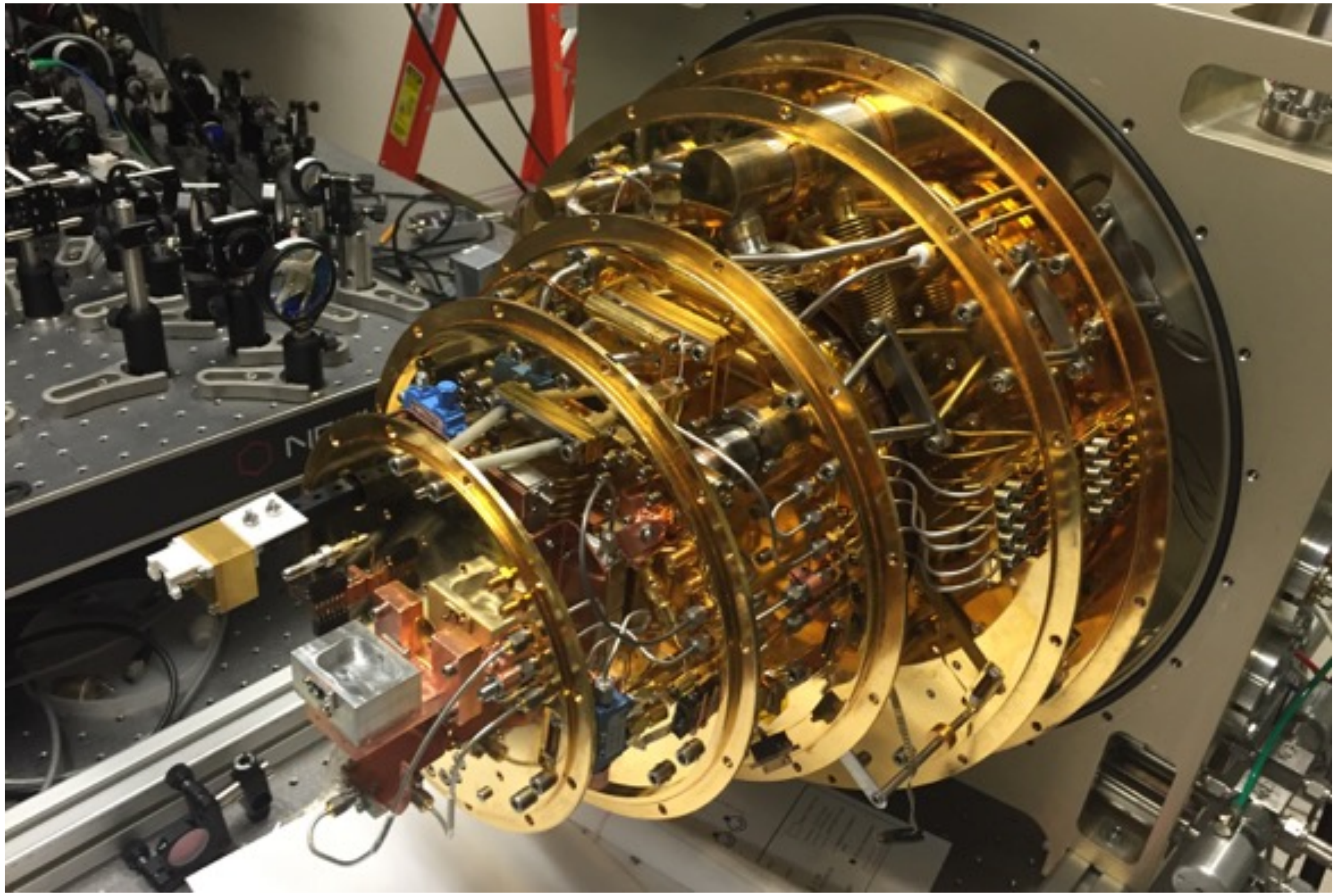
Opt. sideband: 0.5
Microwave sideband: 0.5
\+ Mechanics: 20

Overall: 21 quanta



To reduce added noise, move to a dilution refrigerator

$$\frac{n_{th}\gamma_m}{\Gamma_{eo}} \sim 20 \text{ phonons}$$ at T = 4 K $$n_{th} \sim \frac{k\,T}{\hbar\,\omega}$$



$$\frac{n_{th}\gamma_m}{\Gamma_{eo}} \sim 0.1 \text{ phonons}$$ at T = 100 mK

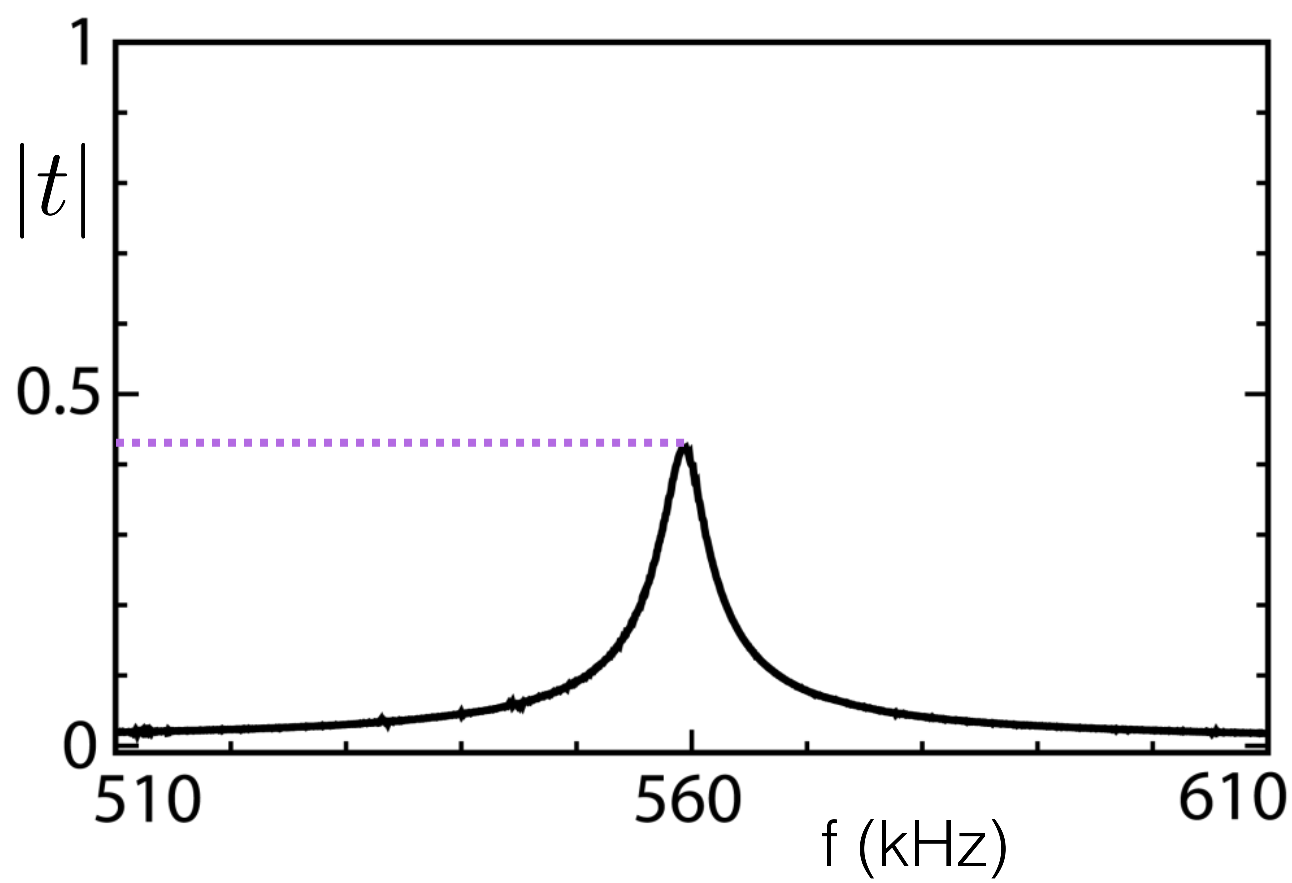
R. W. Peterson et . al. , PRL (2016)

Inefficiency dominated by optical cavity

Efficiency accounting:

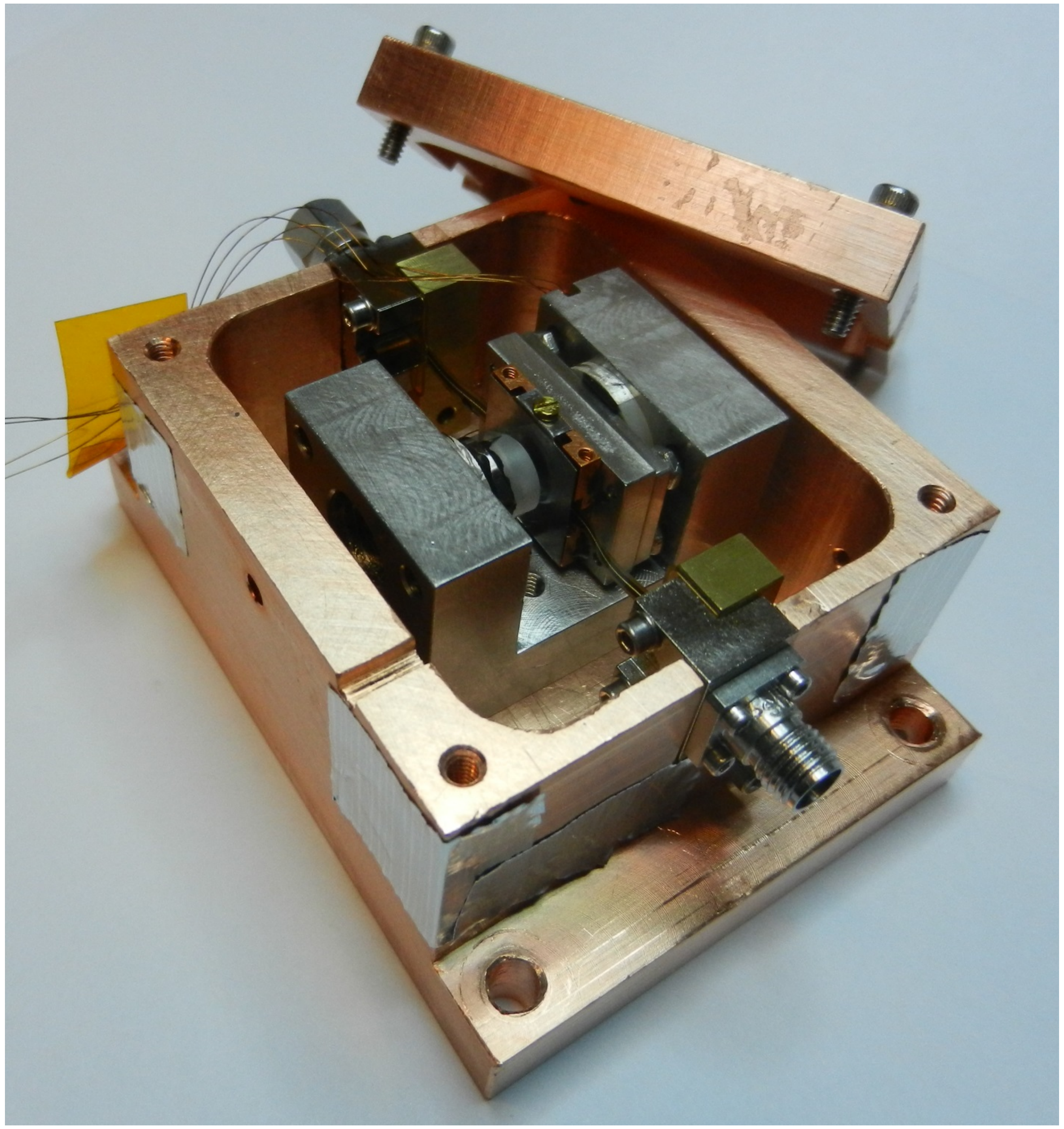
Optical cavity loss: 0.23
Opt. modematching: 0.5
Microwave loss: 0.76
X Mechanical loss: 0.9998

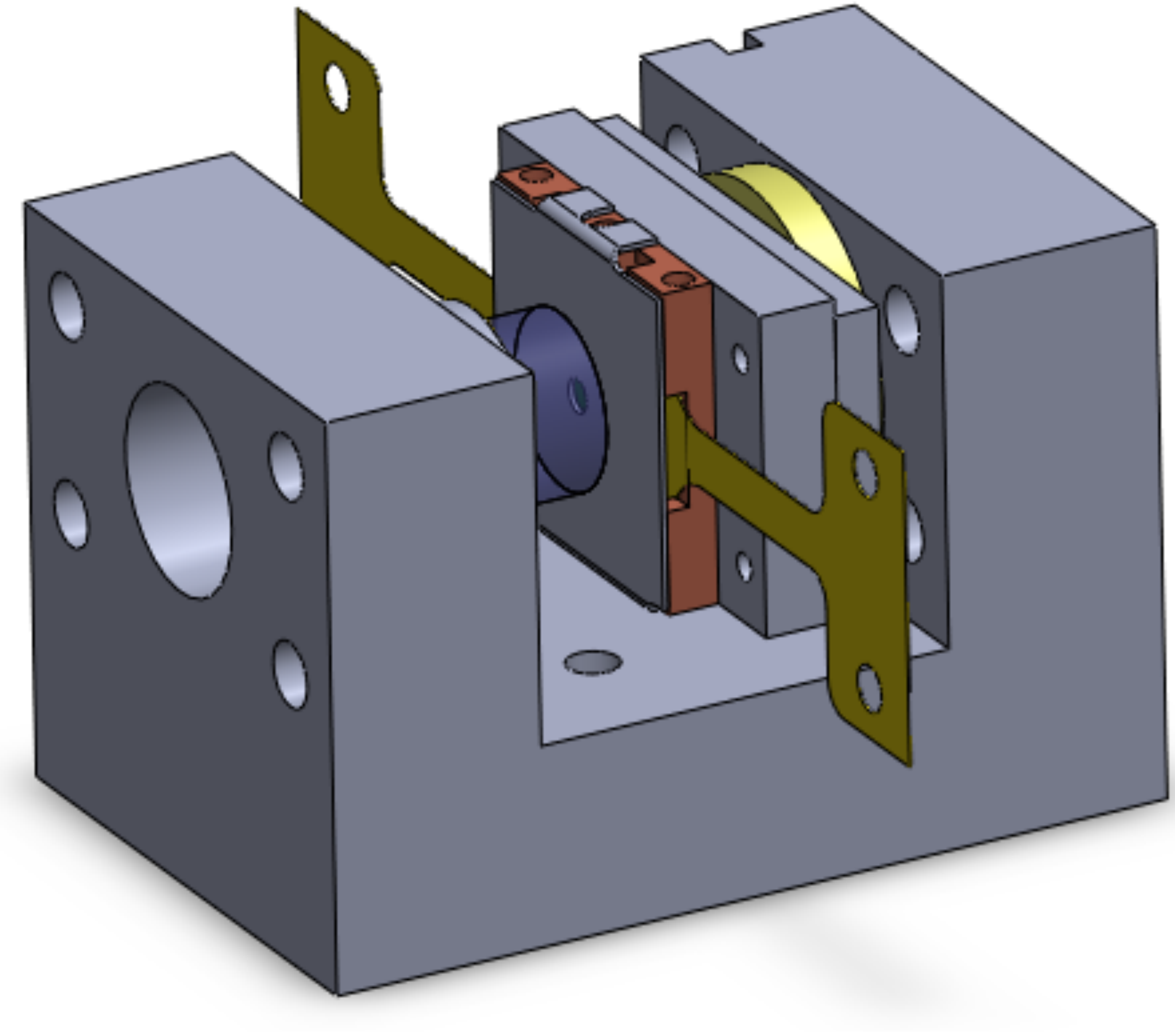
Overall efficiency: 8.7%



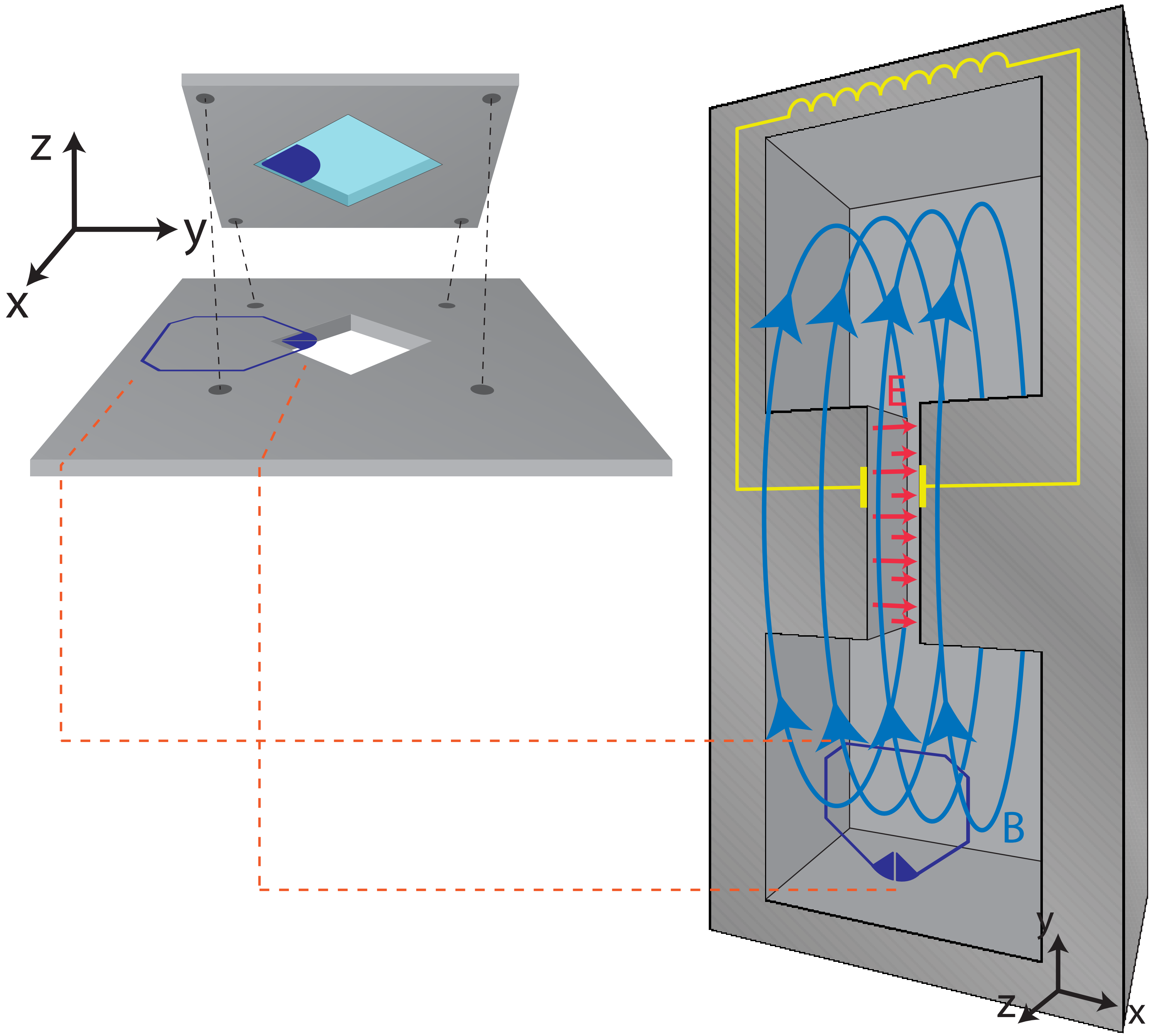
R. W. Andrews et . al. , Nat. Phys. (2014)

Microwave wiring likely misaligns optical cavity, leading to loss

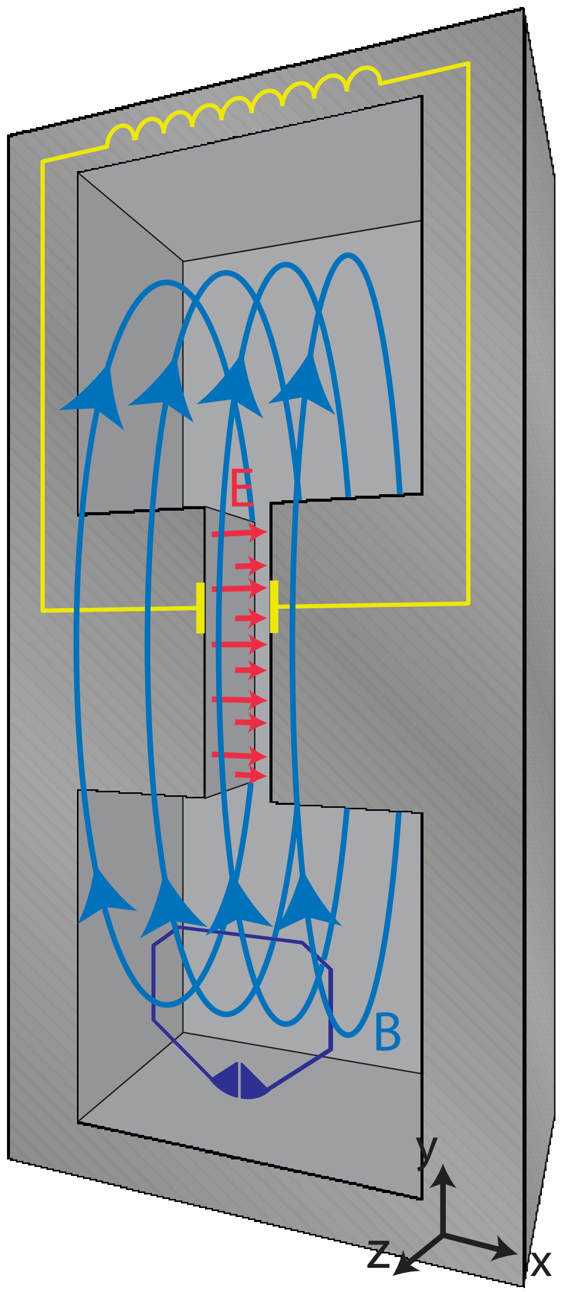


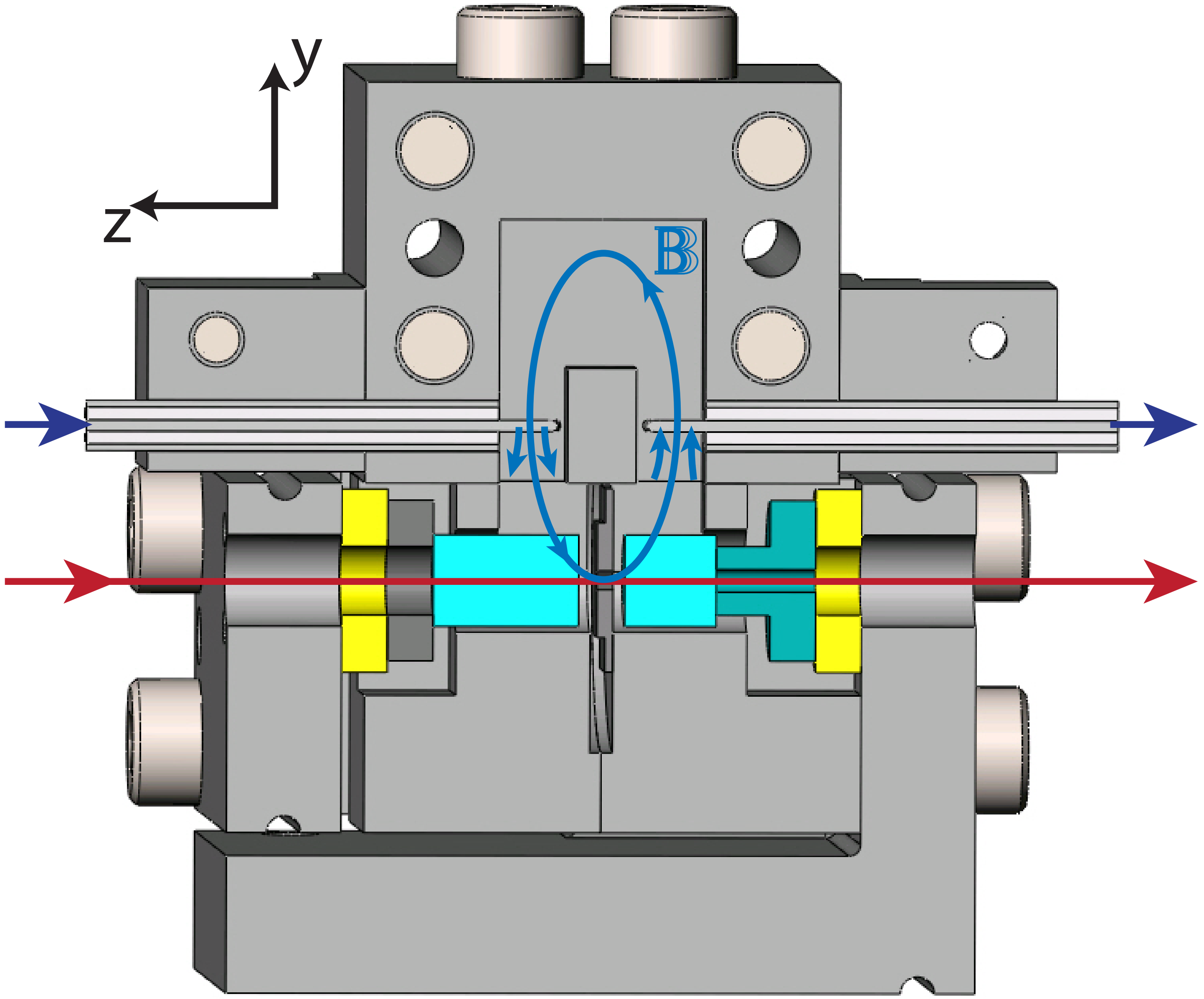


Wireless approach to microwave coupling



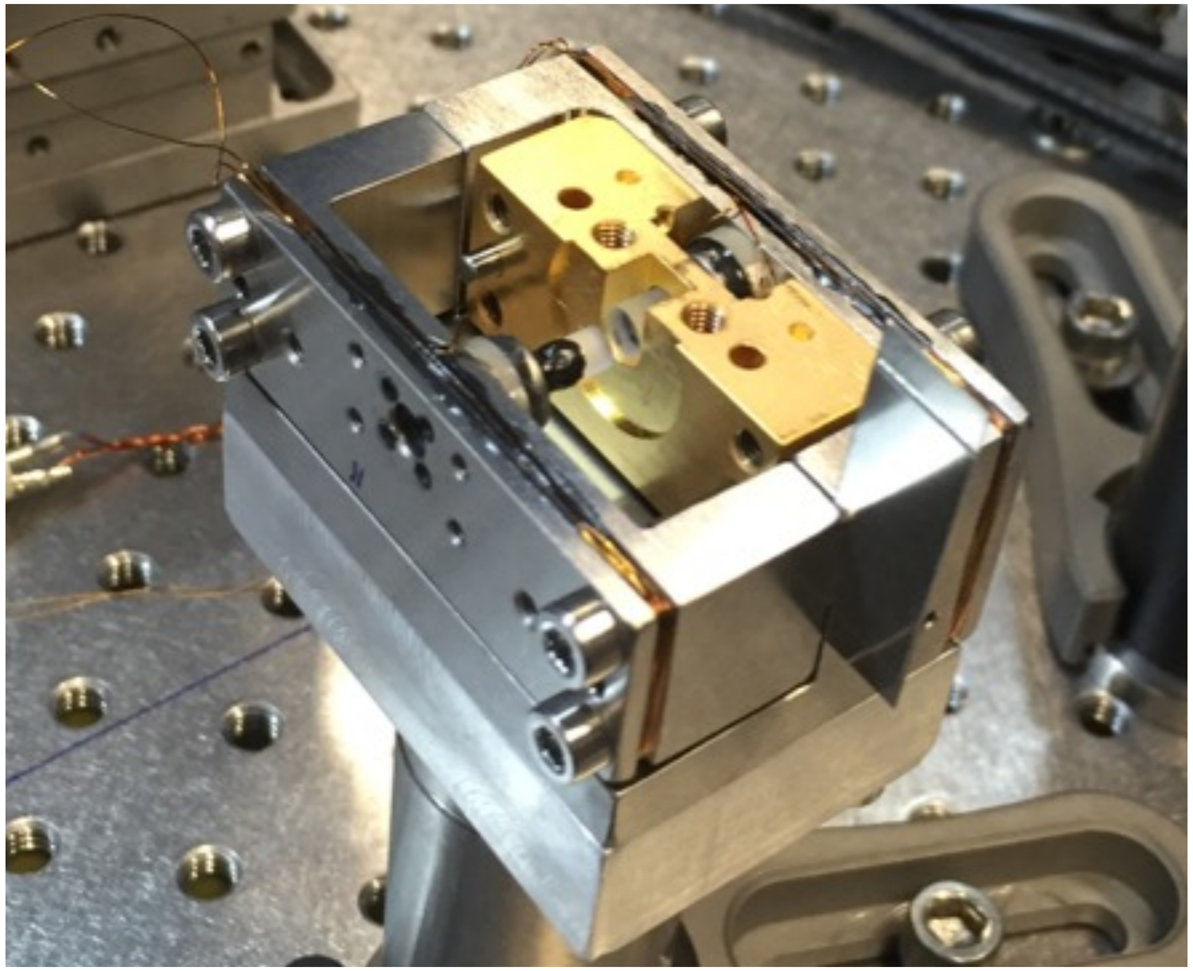
Adding an optical port

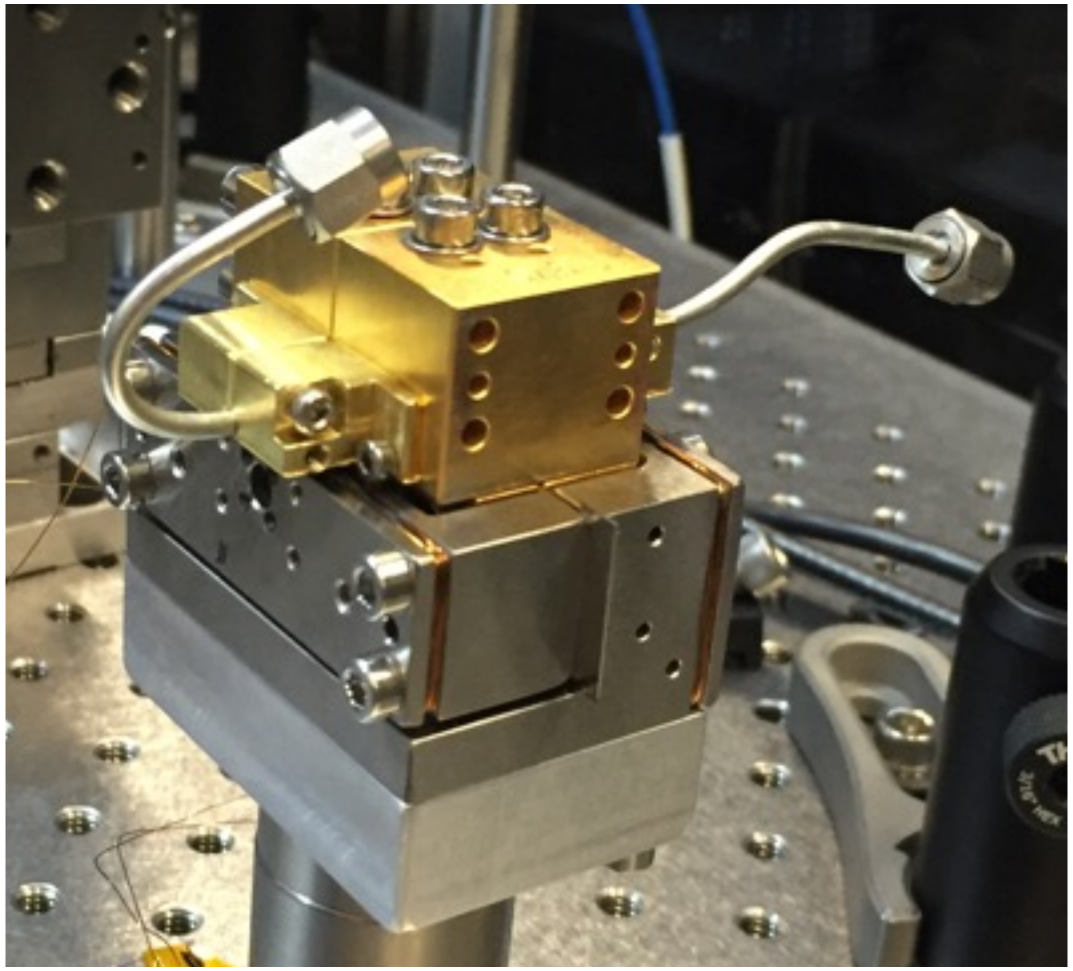


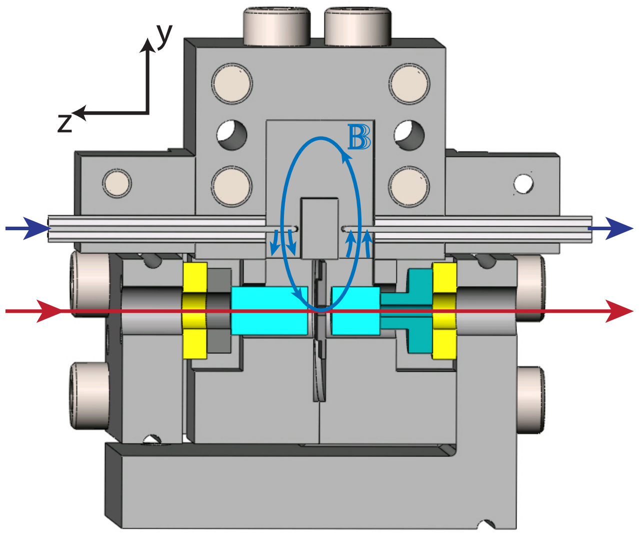


cavity-lc coupling efficiency: 0.9

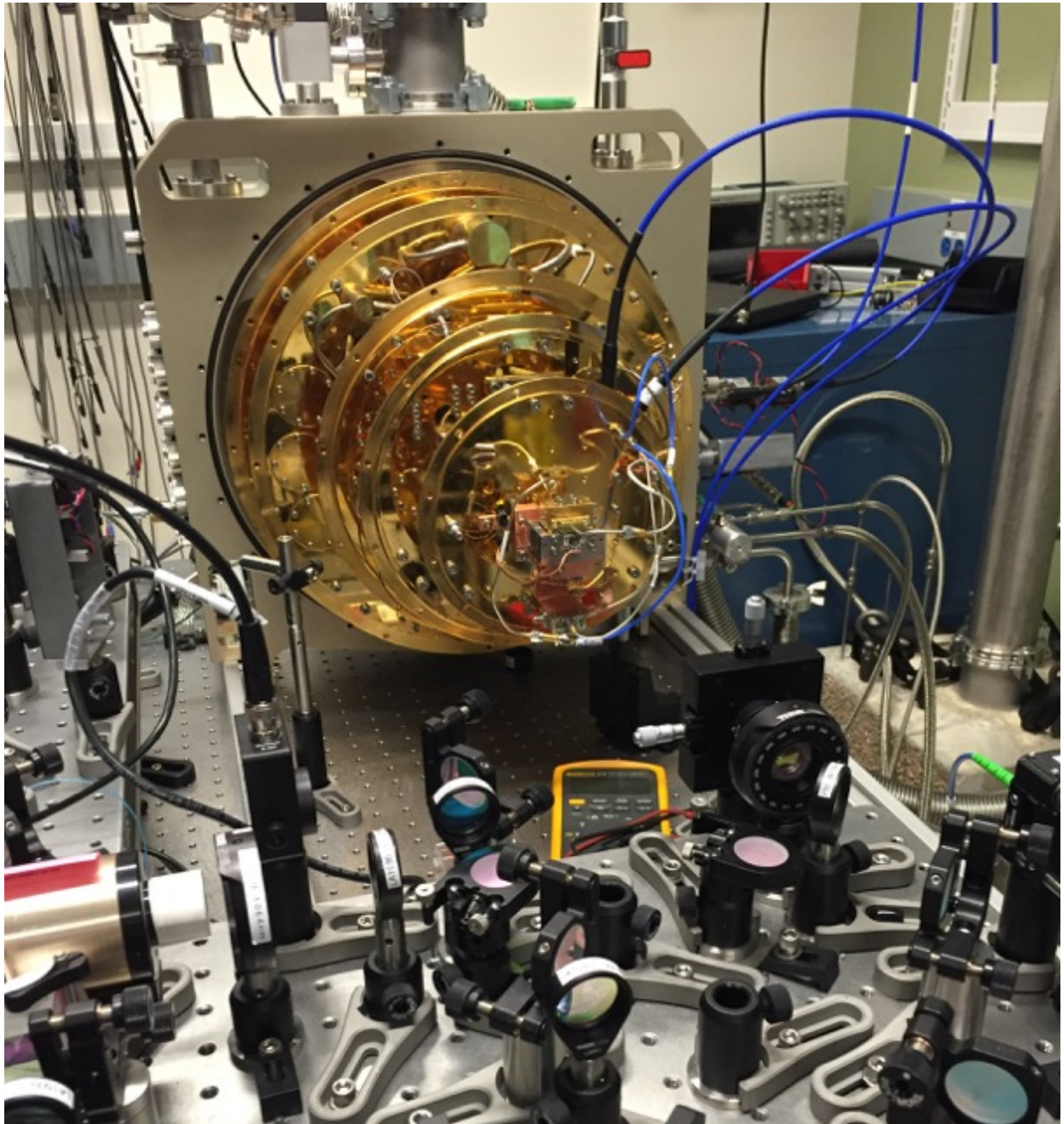
Assembling the converter



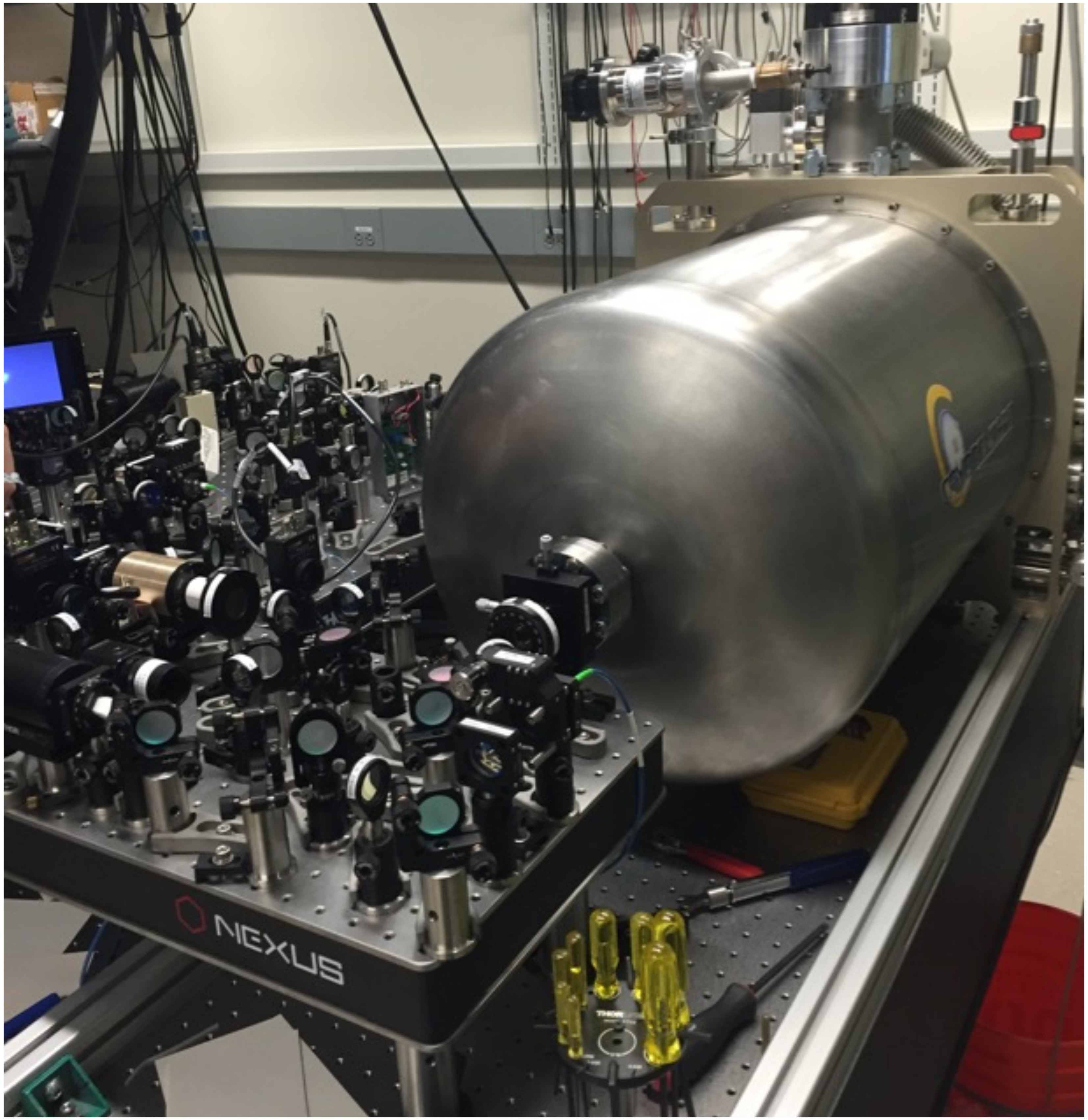




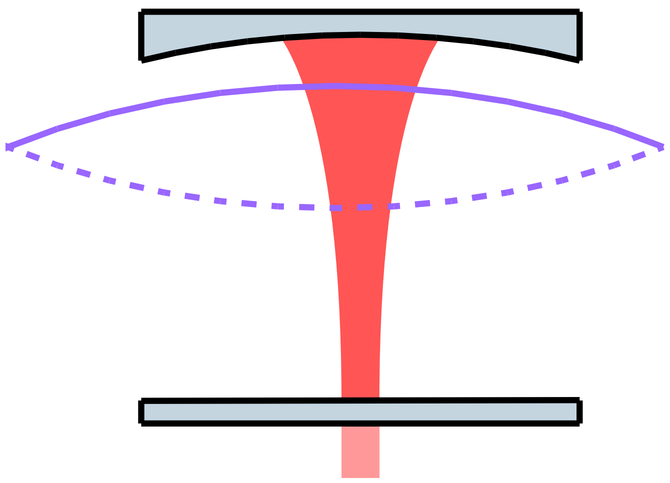
Converter in the cryostat



Cold!



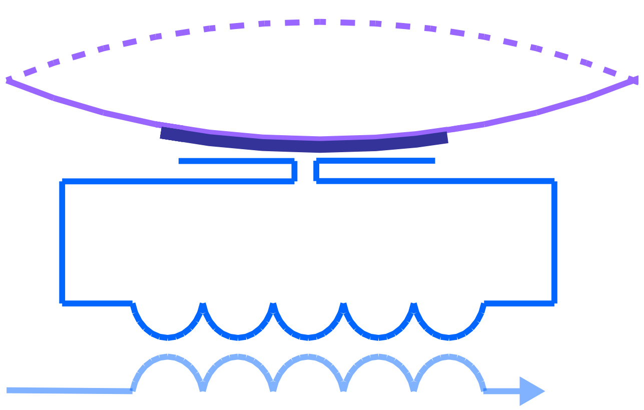
System parameters at 100 mK



optical linewidth: $\kappa_{\rm o} = 2\pi\ 1.8\ \rm MHz$

optical efficiency: $\eta_{\rm o} = \dfrac{\kappa_{\rm o,ext}}{\kappa_{\rm o}} = 0.7$

optical mode-matching: $\epsilon = ?$

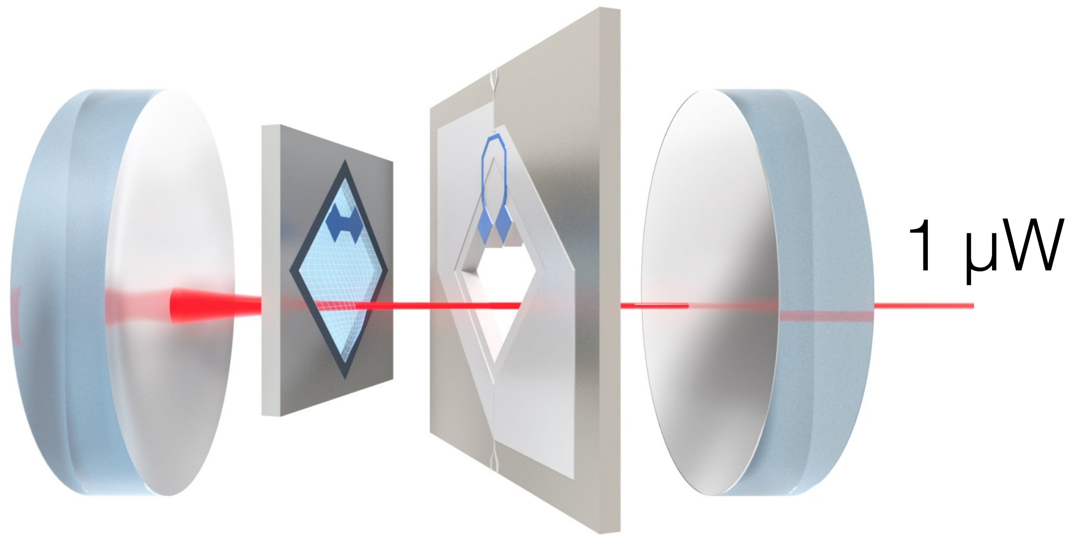


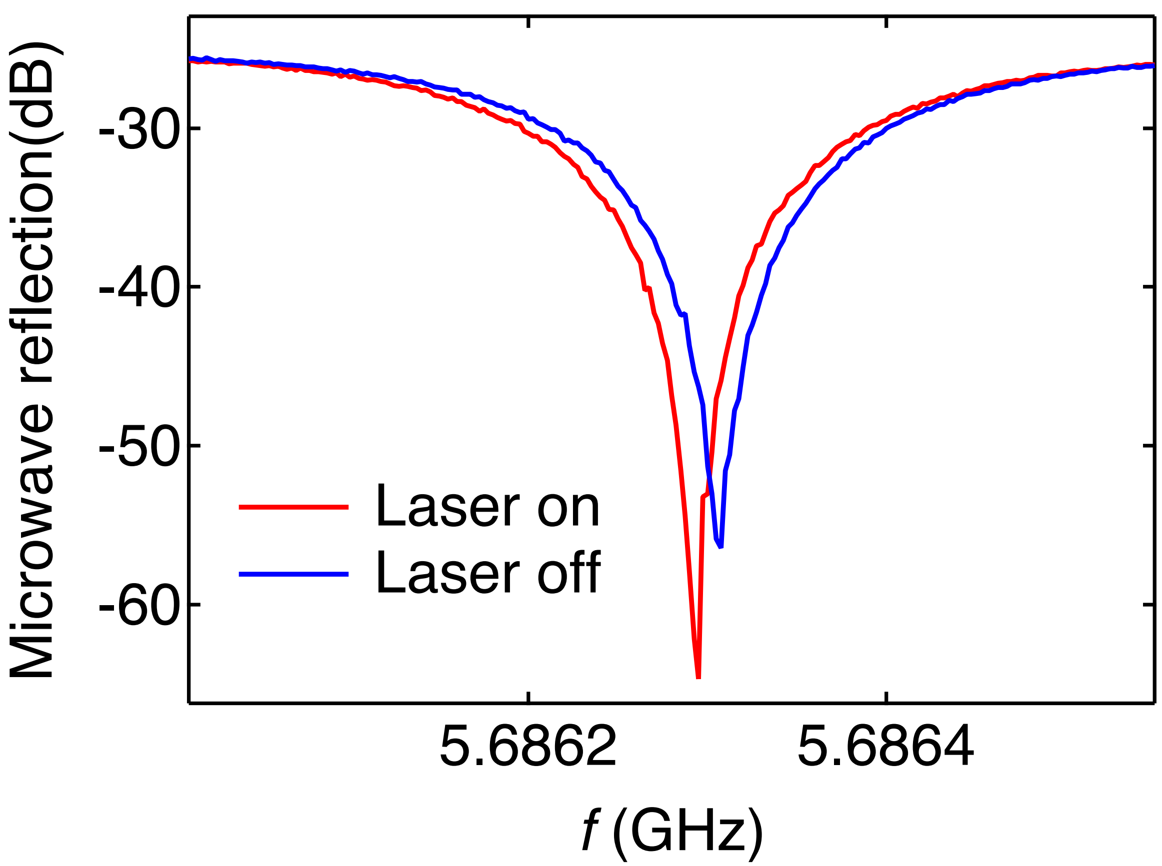
microwave linewidth: $\kappa_e = 2\pi\ 0.3\ \rm MHz$

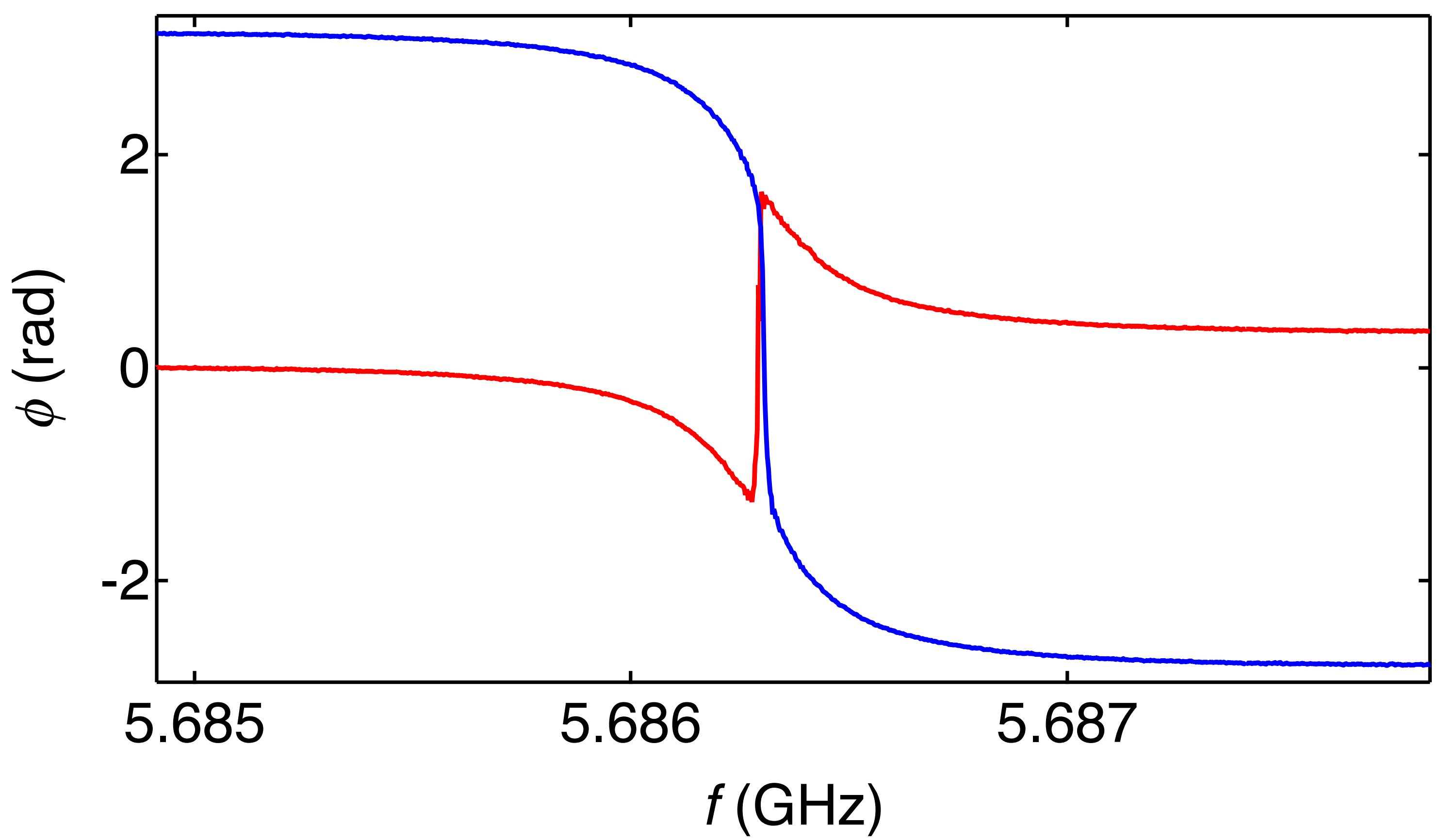
microwave efficiency: $\eta_{\rm e} = \dfrac{\kappa_{\rm e,ext}}{\kappa_{\rm e}} = 0.5$

expect transfer efficiency: $\epsilon \cdot 35\%$

Effect of optical power on superconducting circuit

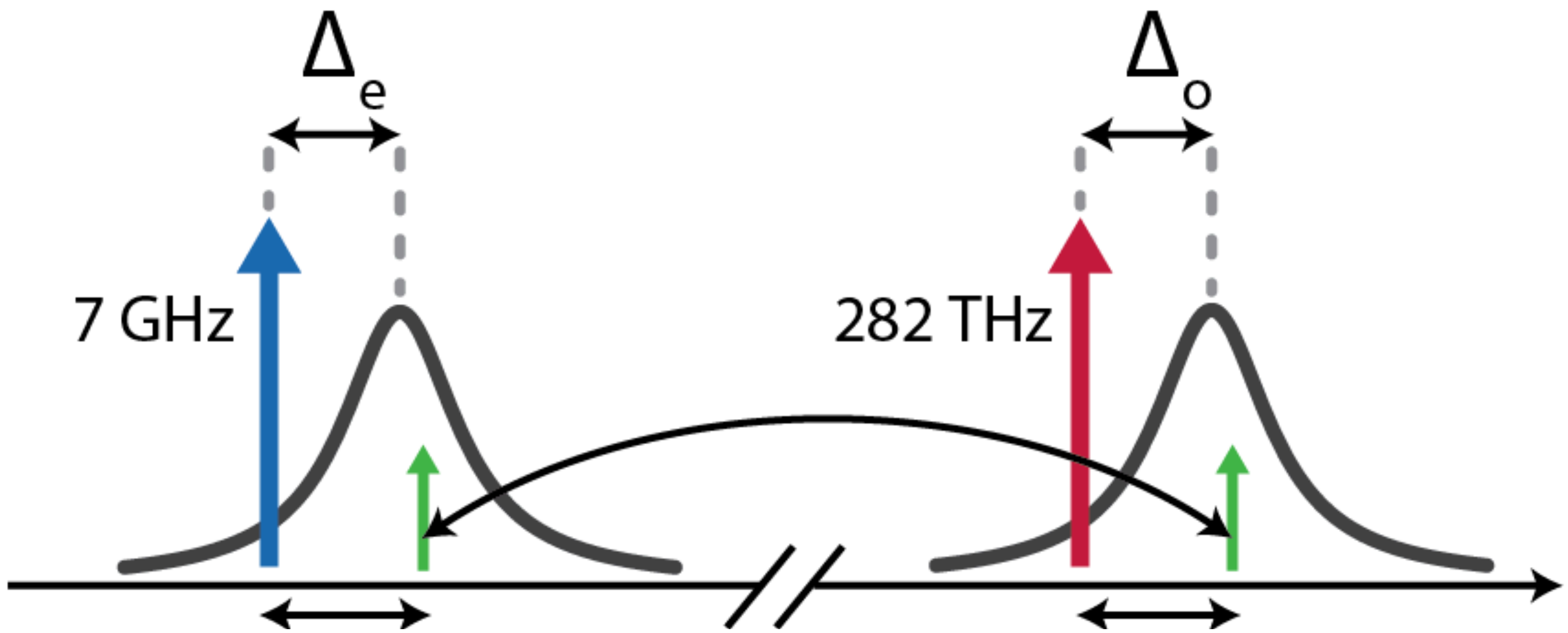


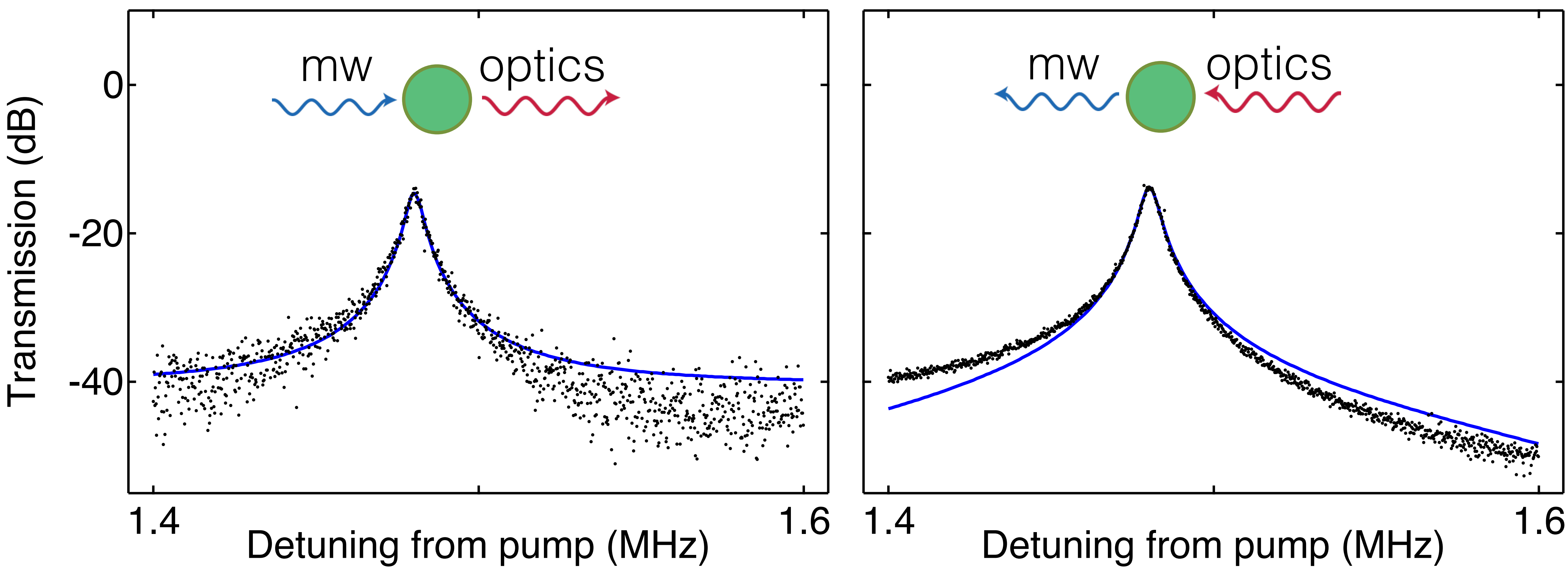




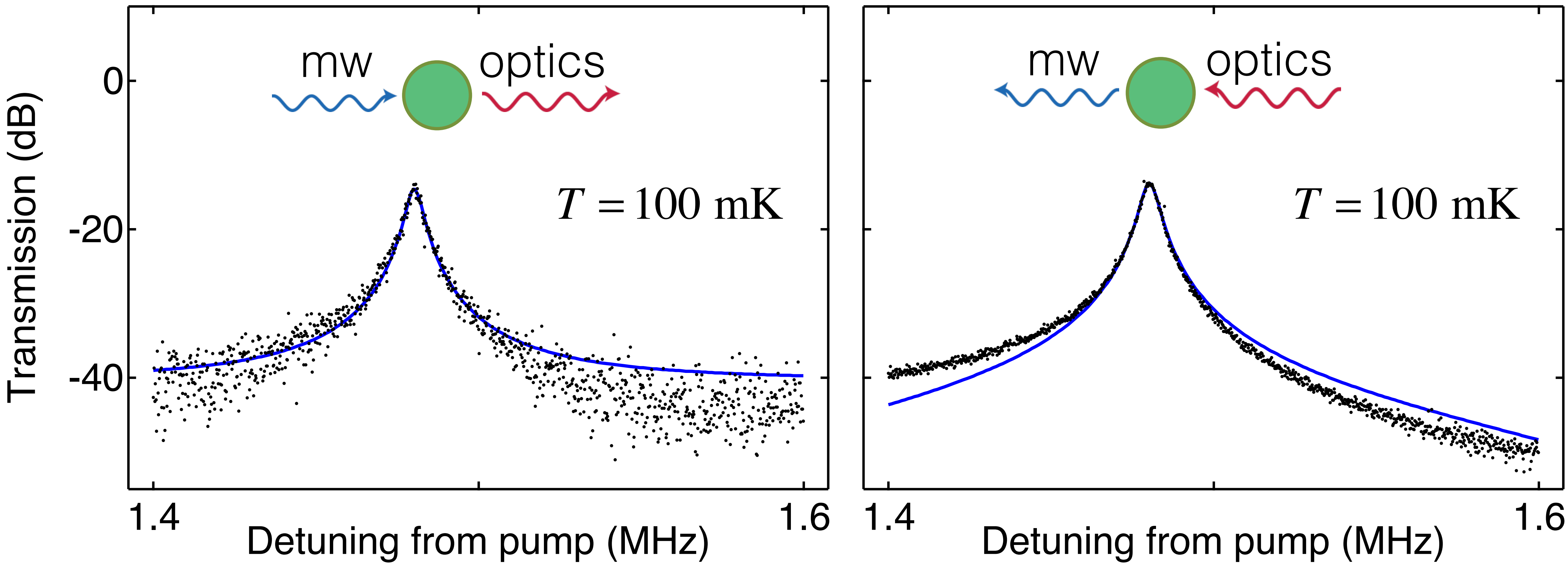
1 μW incident induces 20 kHz of microwave loss

State conversion at 100 mK





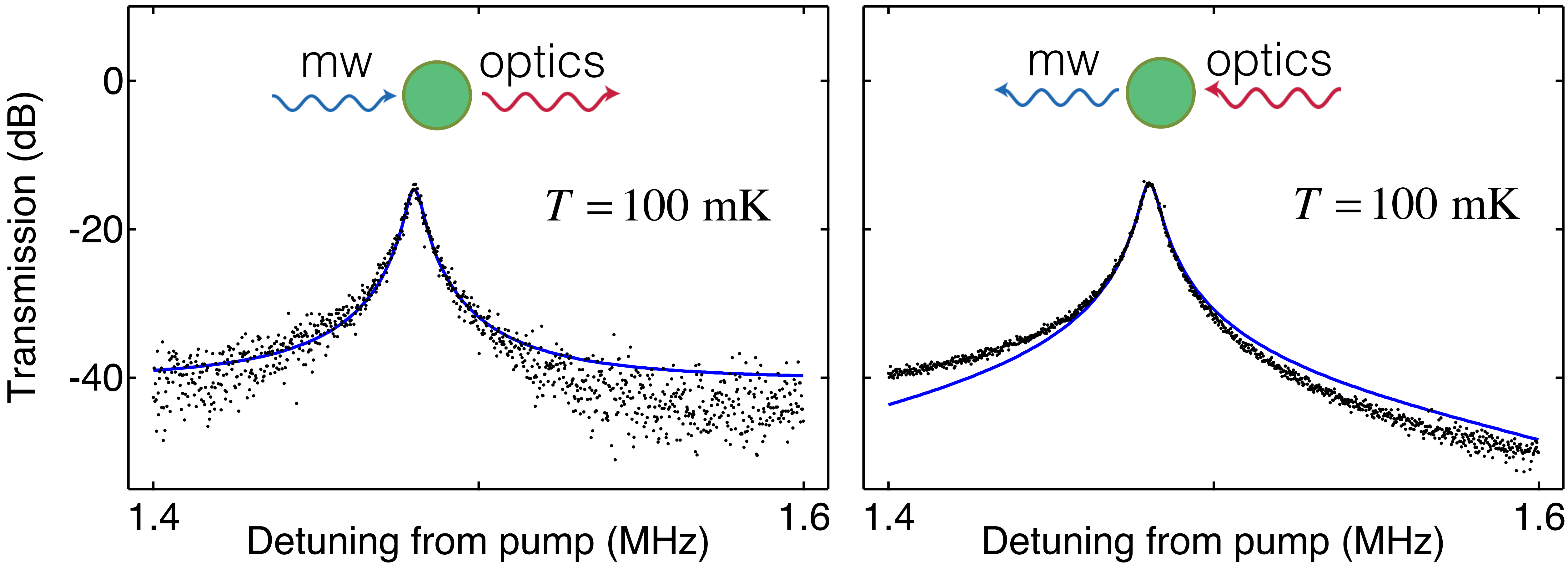
Efficiency of state conversion



apparent efficiency: $|t_1 t_2| = 0.038$

efficiency: $\dfrac{|t_1 t_2|}{\text{Gain}} = 3.5\%$

Main limitation: optical mode matching

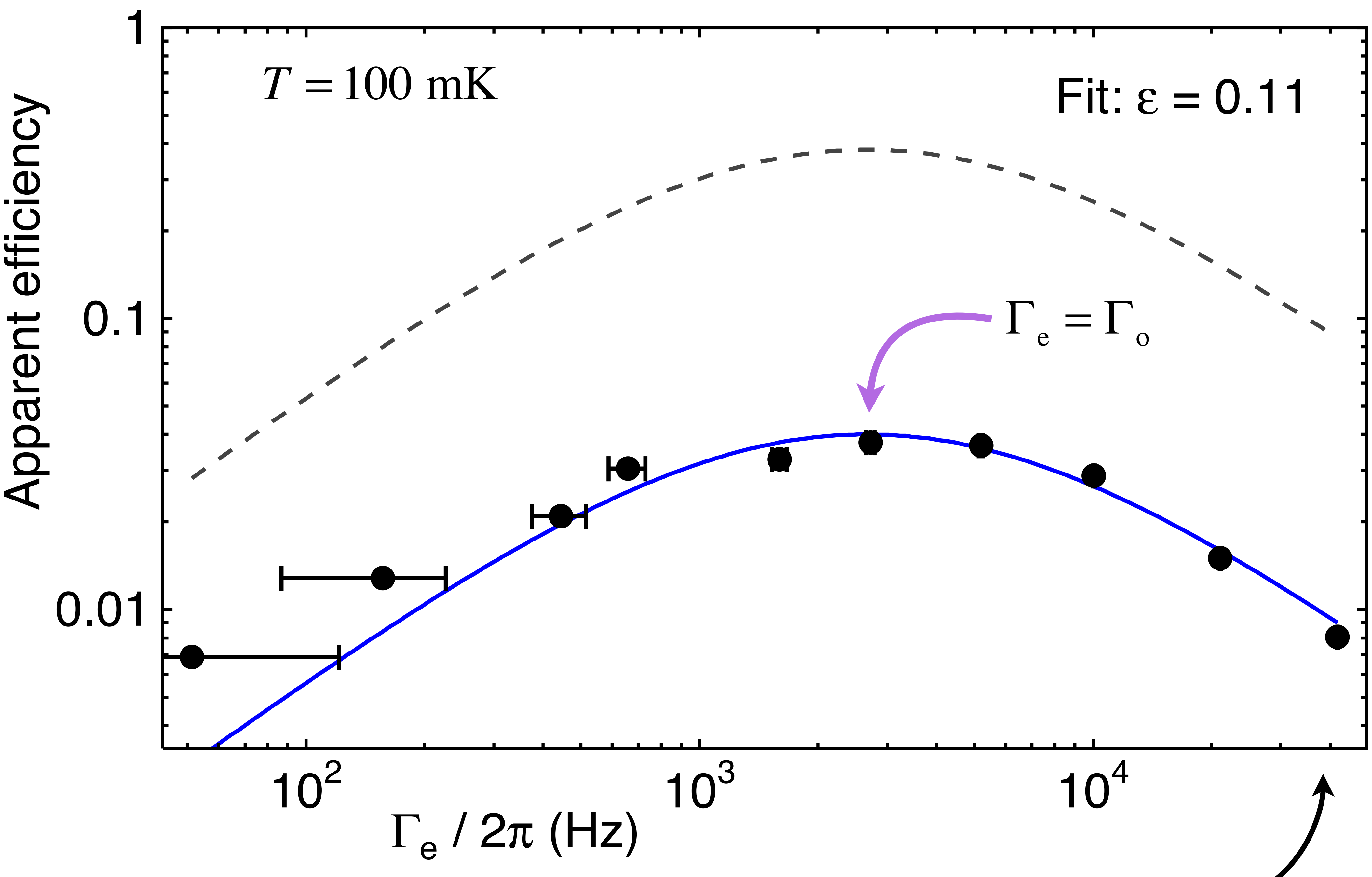


expected efficiency: $\epsilon \cdot 35\%$

efficiency: $\dfrac{|t_1 \cdot t_2|}{\text{Gain}} = 3.5\%$

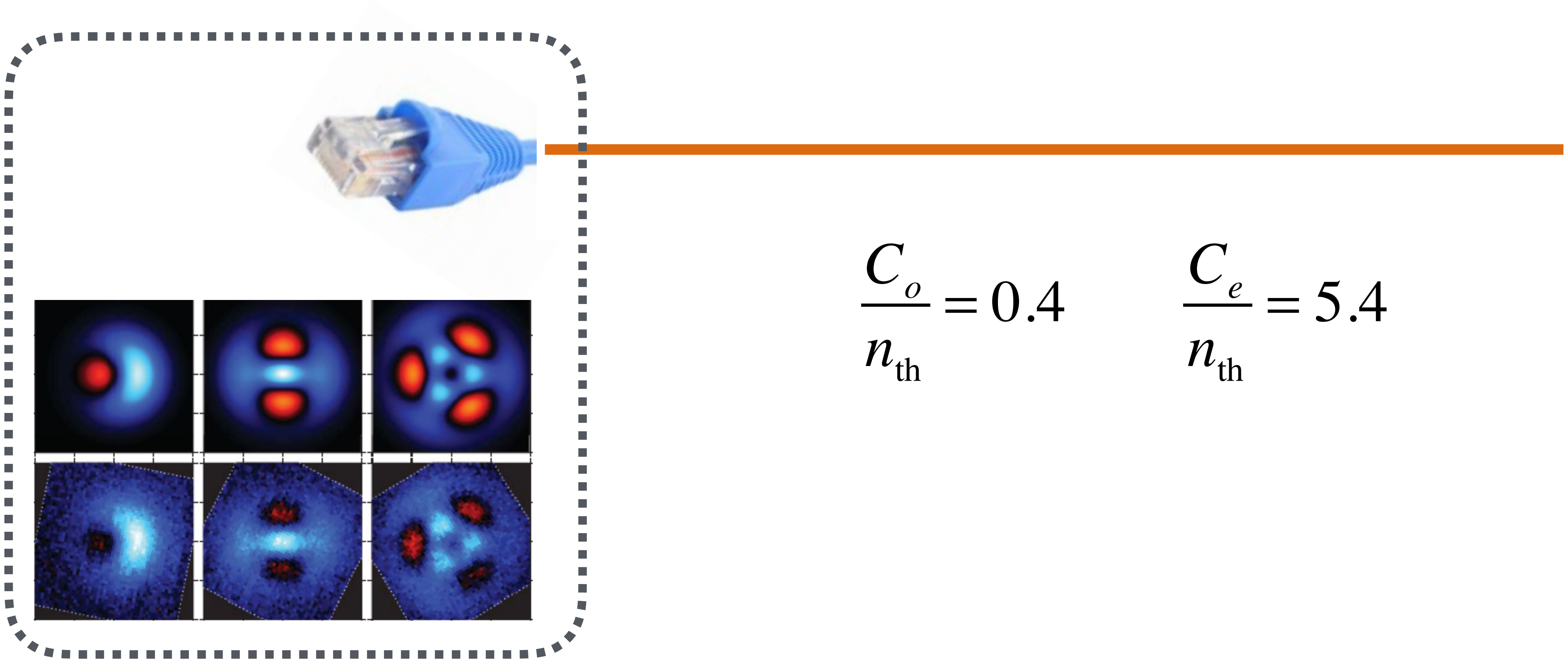
estimate mode matching: $\epsilon = 0.10$

Extracting the optical mode-matching factor



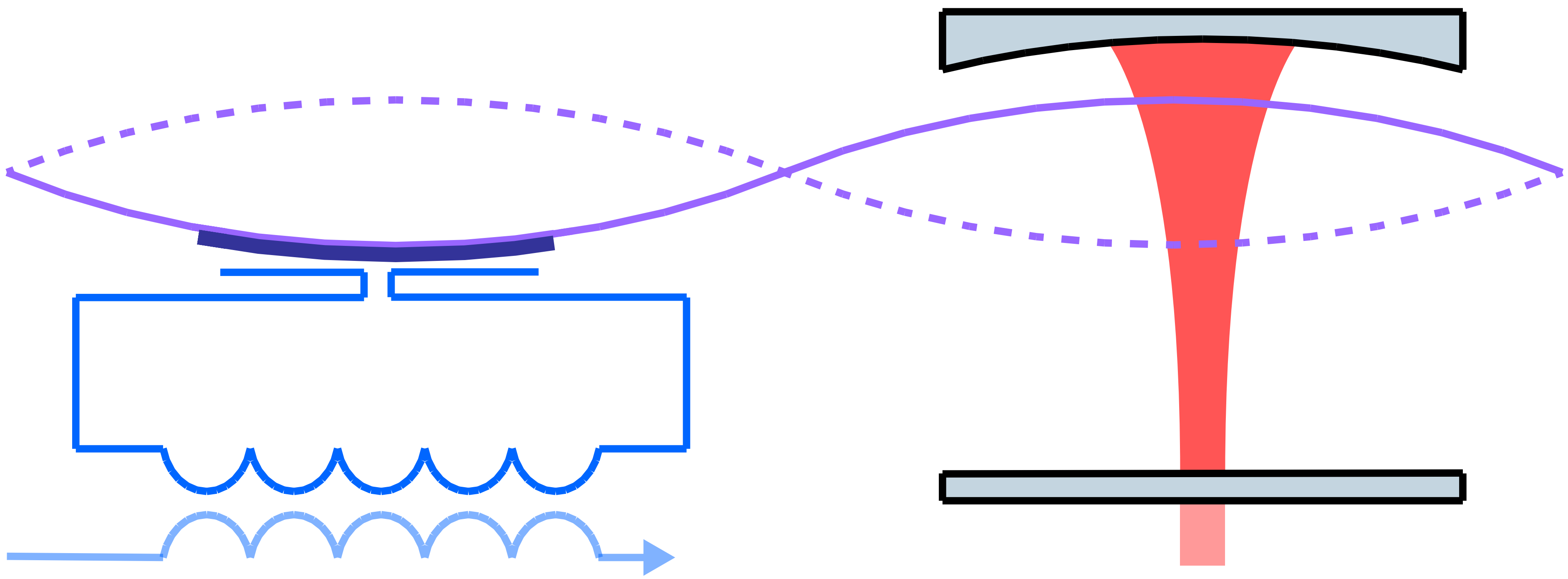
operation near the quantum regime: $\frac{C_o}{n_{th}} = 0.4$ $\frac{C_e}{n_{th}} = 5.4$

What is the first quantum experiment we can do?



$$\frac{C_o}{n_{\mathrm{th}}} = 0.4 \qquad \frac{C_e}{n_{\mathrm{th}}} = 5.4$$

Microwave-optical two-mode squeezing

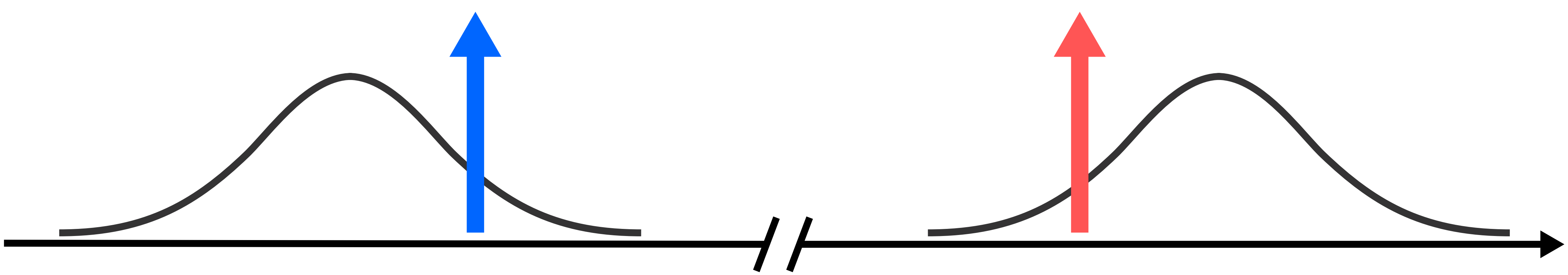


$$H_{\text{int}} = \hbar g_0 a^{\dagger}_{\text{mw}} a^{\dagger}_{\text{mech}} + \text{h.c.}$$

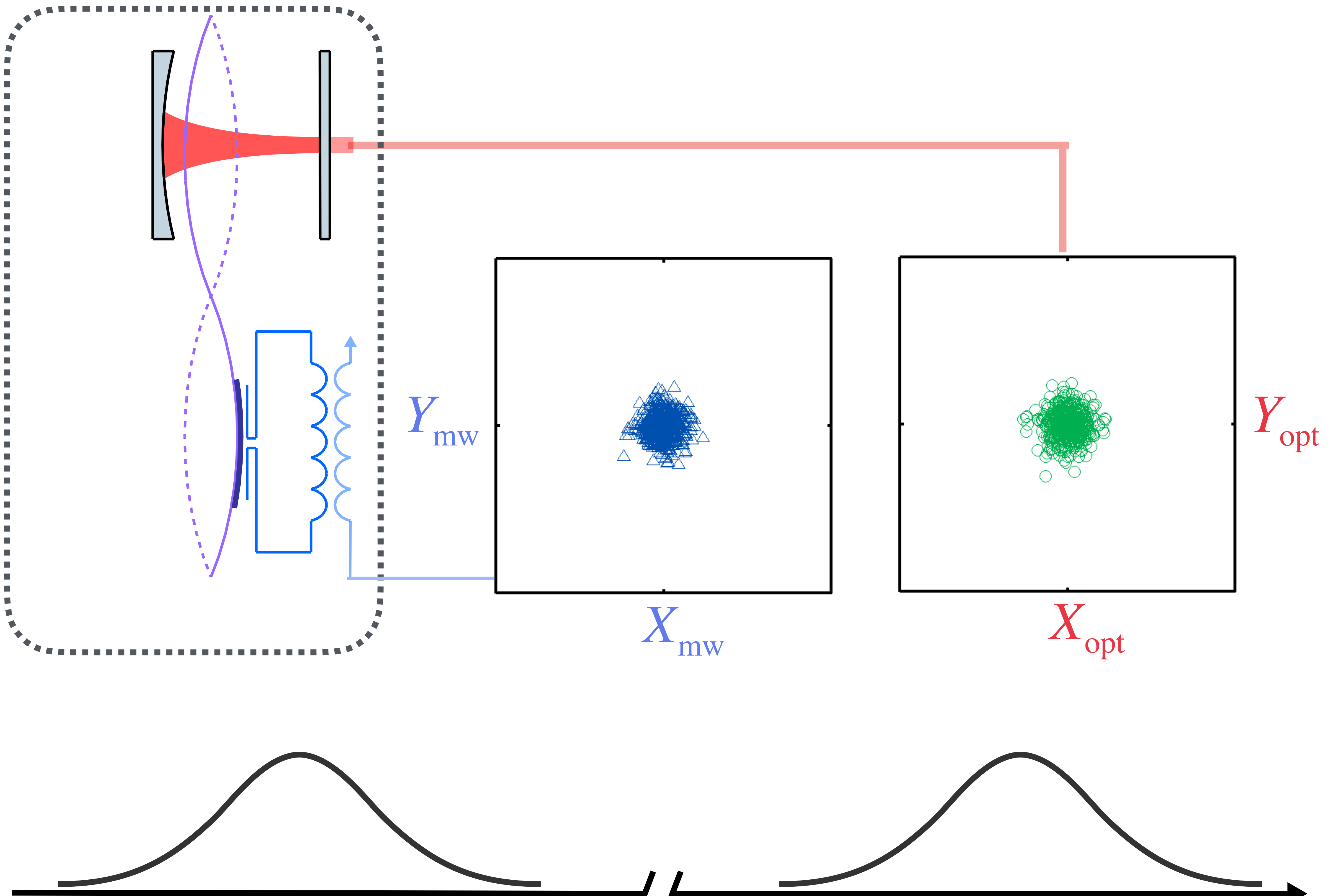
mw-mech entanglement

$$H_{\text{int}} = \hbar g_0 a_{\text{mech}} a^{\dagger}_{\text{opt}} + \text{h.c.}$$

swap mech to optics



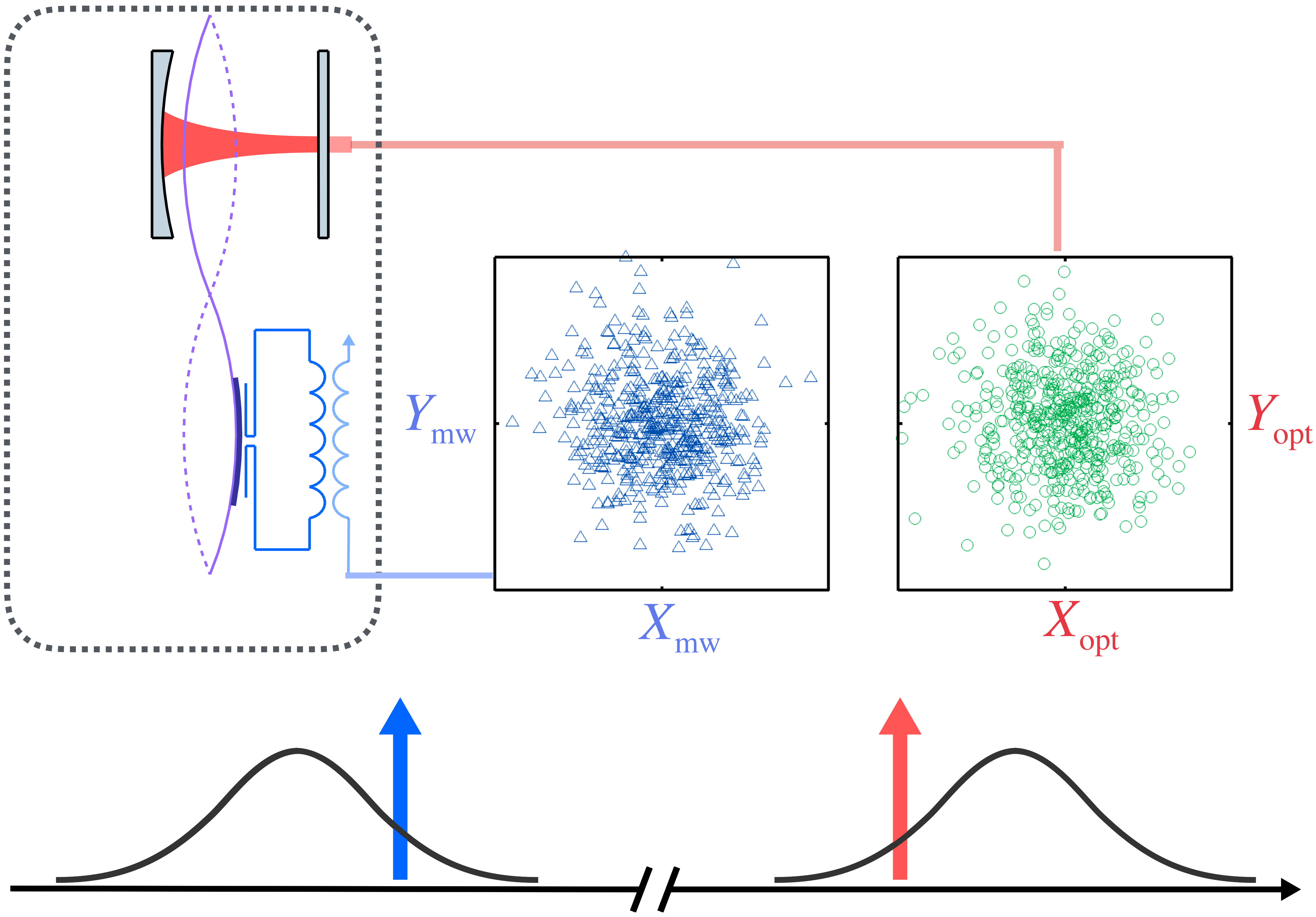
Two-mode squeezing



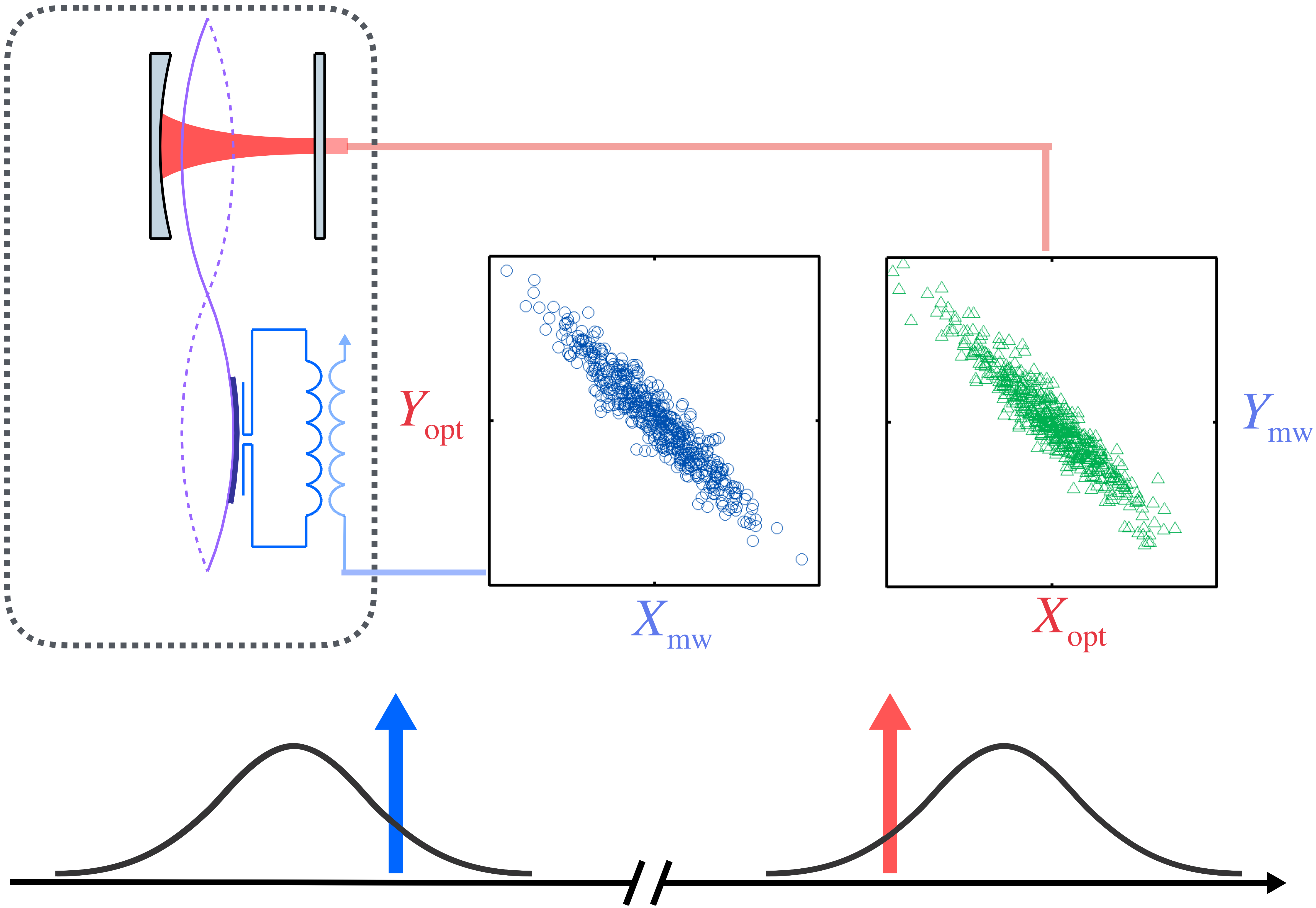
$$H_{\text{int}} = \hbar g_0 a_{\text{mw}}^{\dagger} a_{\text{mech}}^{\dagger} + \text{h.c.}$$

$$H_{\text{int}} = \hbar g_0 a_{\text{mech}} a_{\text{opt}}^{\dagger} + \text{h.c.}$$

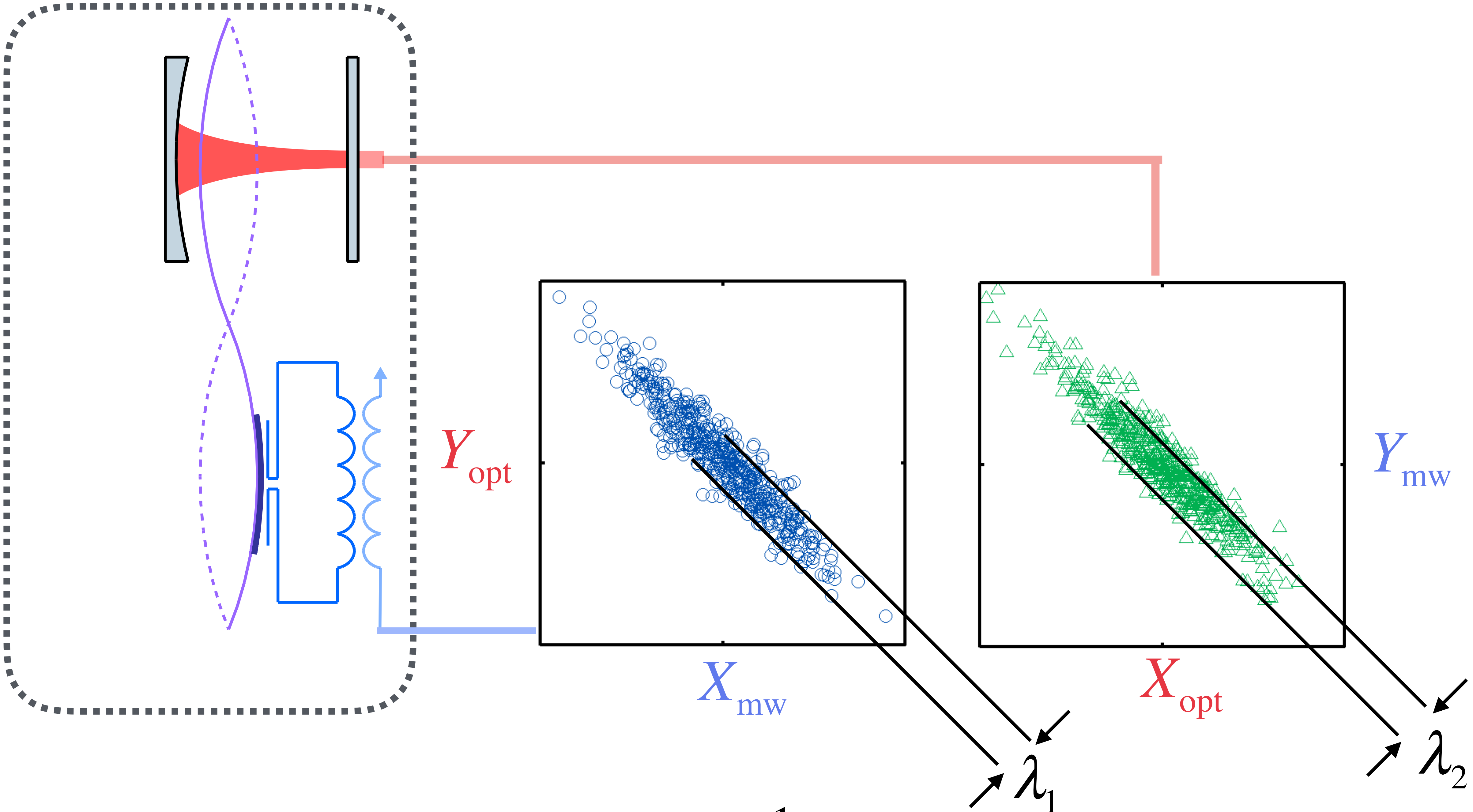
Two-mode squeezing



Two-mode squeezing



Two-mode squeezing



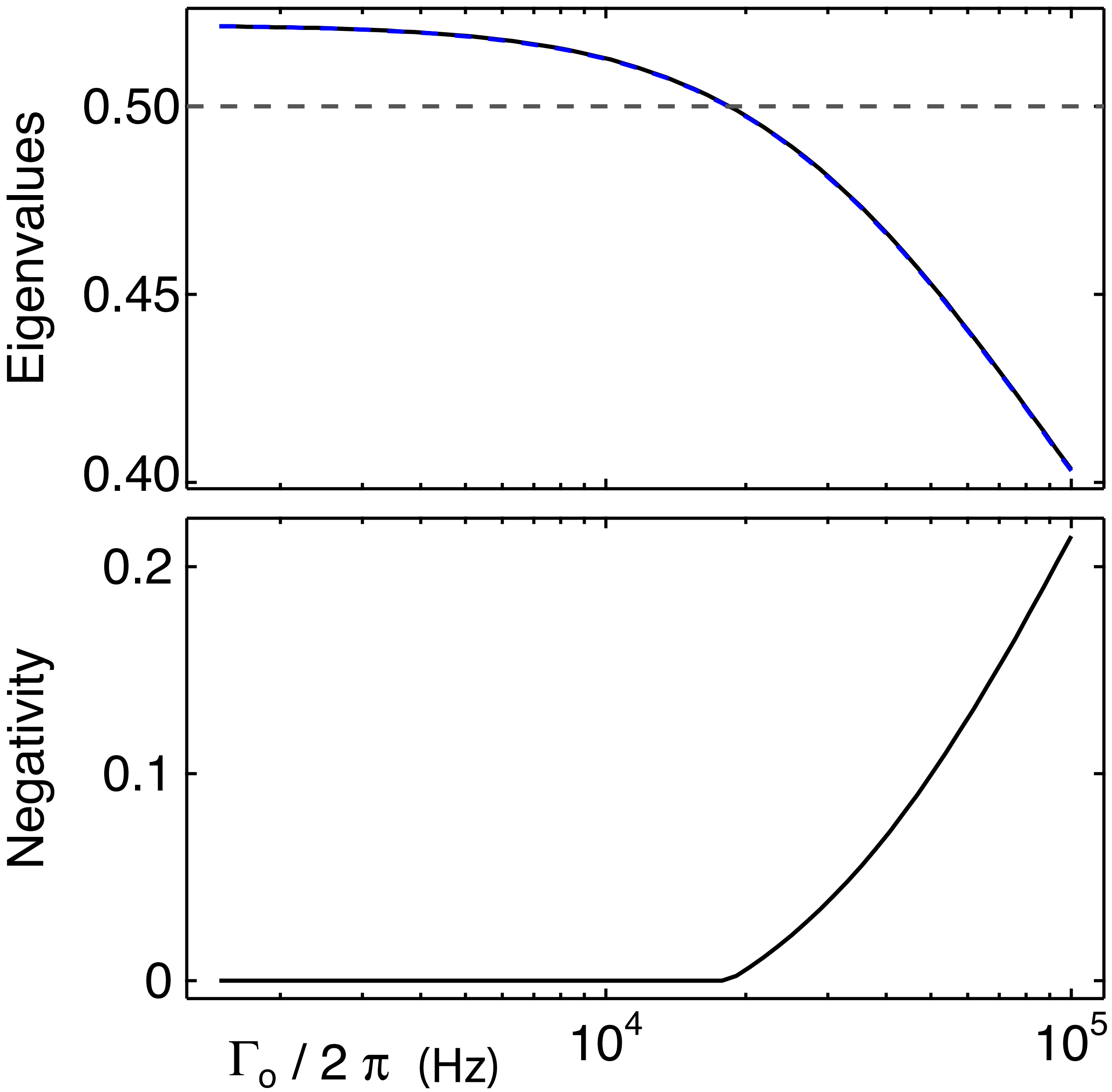
two-mode squeezing: $\lambda_1, \lambda_2 < \frac{1}{2}$

entanglement measure: $E_{\mathrm{N}} = -\ln\left(\lambda_1 \lambda_2 / 4\right)$

Two-mode squeezing: quantitative expectations

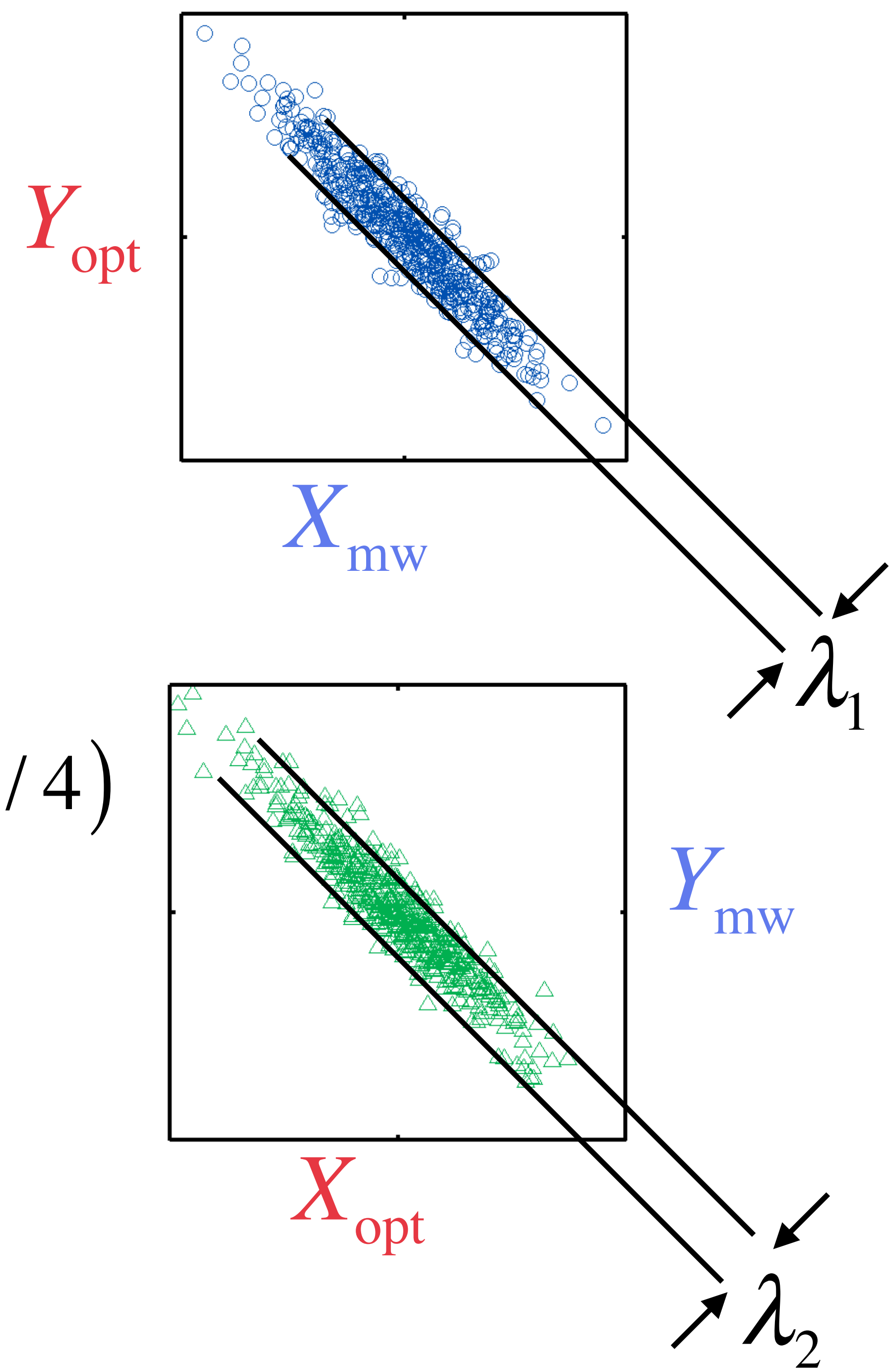
Theory from: Genes, Mari, Tombesi, Vitali PRA **78** (2008)
Barzanjeh, Abdi, Milburn, Tombesi, Vitali PRL **109** (2012)

Equations of motion + in/out theory → spectral density → covariance matrix



$$\lambda_1, \lambda_2 < \frac{1}{2}$$

$$E_N = -\ln\left(\lambda_1\lambda_2 / 4\right)$$



Summary

- Classical conversion in a dilution refrigerator
- Operation near quantum regime
- Microwave-optical entanglement within reach