COOLING AND SQUEEZING OF A MECHANICAL OSCILLATOR

Chan U Lei

Emma Wollman

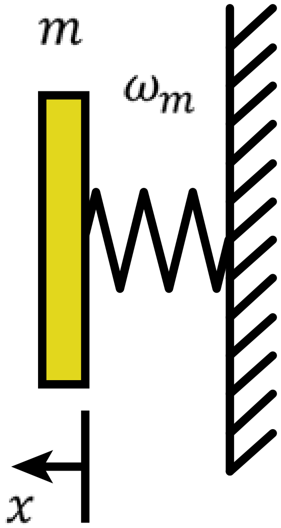
Aaron Weinstein

Junho Suh

Keith Schwab

Mechanical Oscillator

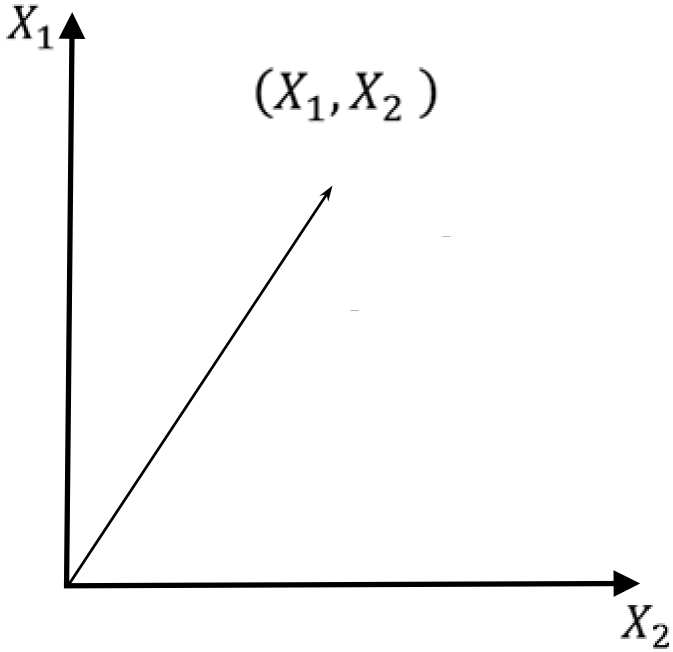
$$x = A\sin(\omega_m t + \phi) \quad (A, \phi)$$

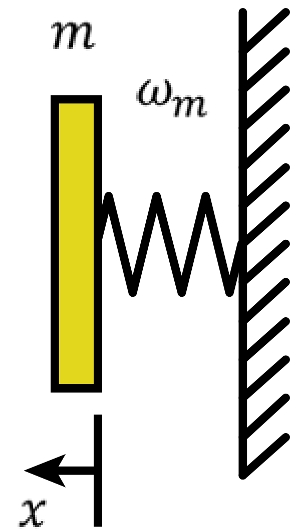


Mechanical Oscillator

$$x = A\sin(\omega_m t + \phi) \quad (A, \phi\ )$$

$$x = \sqrt{2}x_{zp}[X_1\cos(\omega_m t) + X_2\sin(\omega_m t)] \qquad x_{zp} = \sqrt{\frac{\hbar}{2m\omega_m}}$$





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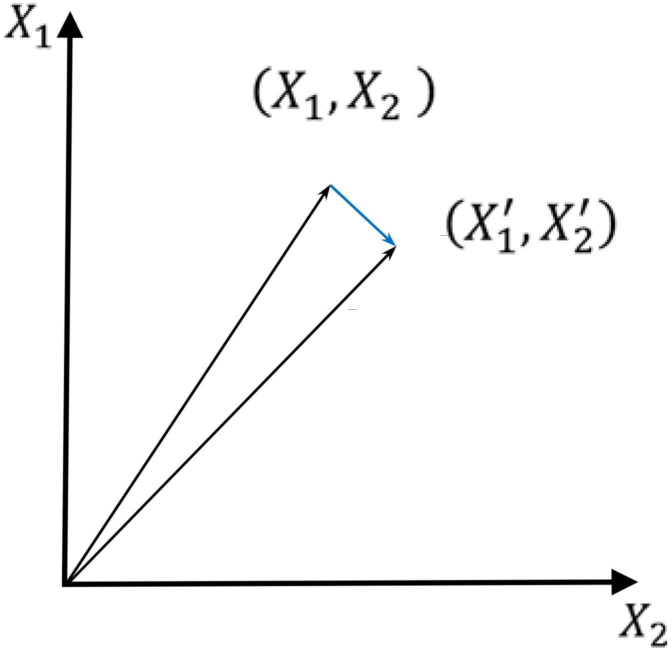
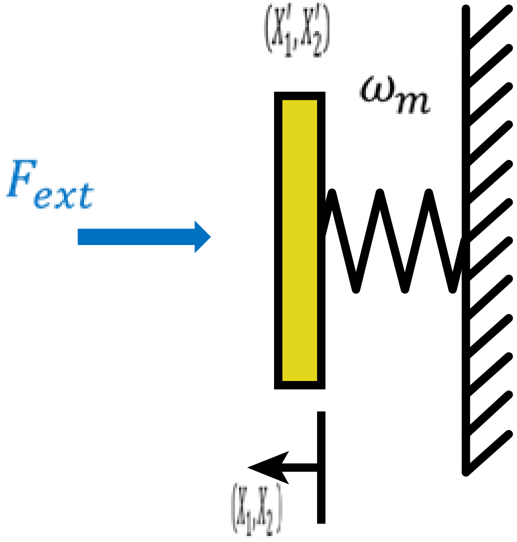
$$x = \sqrt{2}x_{zp}[X_1 \cos(\omega_m t) + X_2 \sin(\omega_m t)]$$





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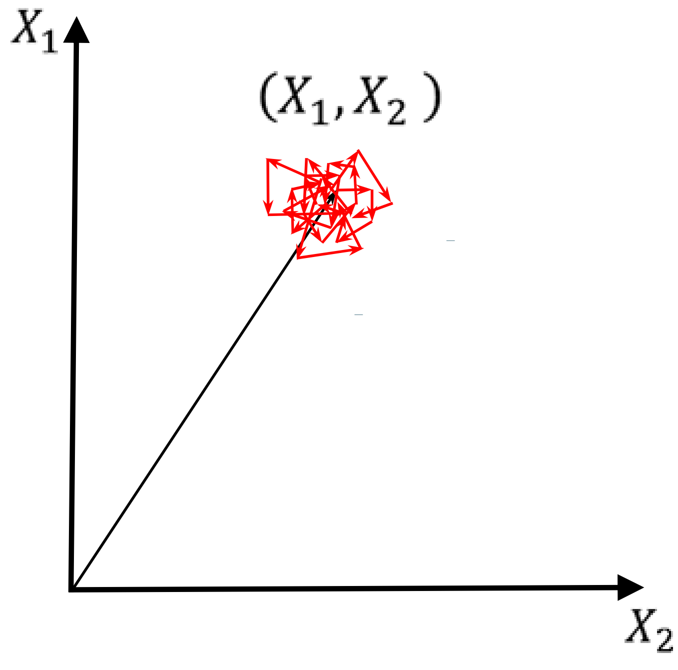

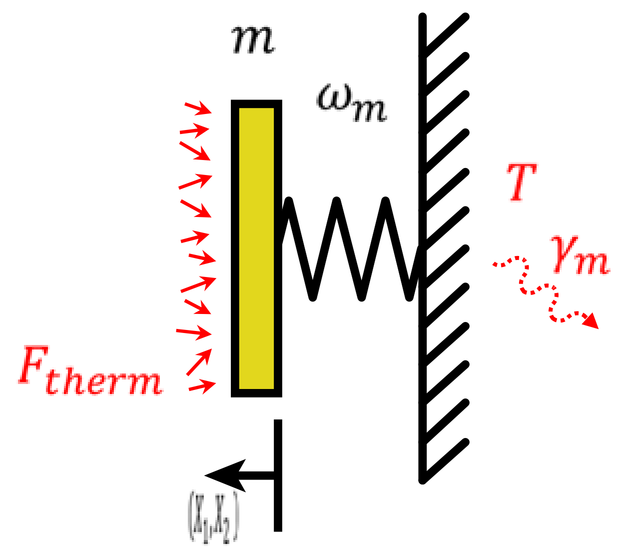

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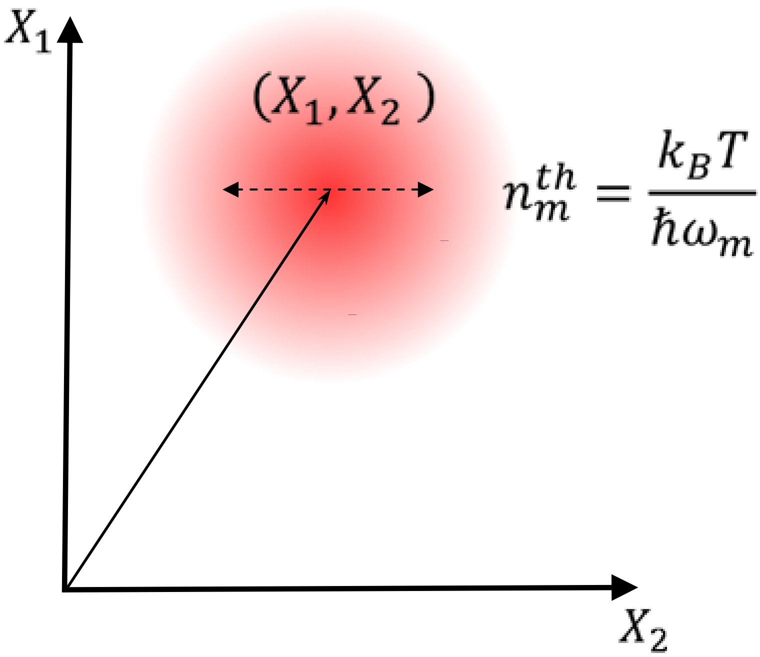
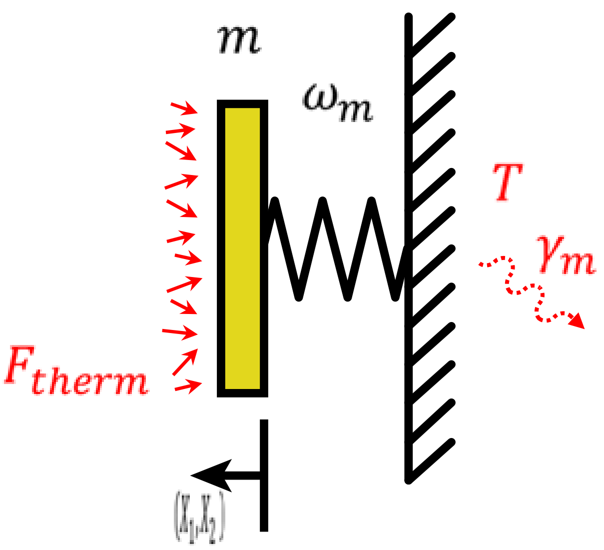
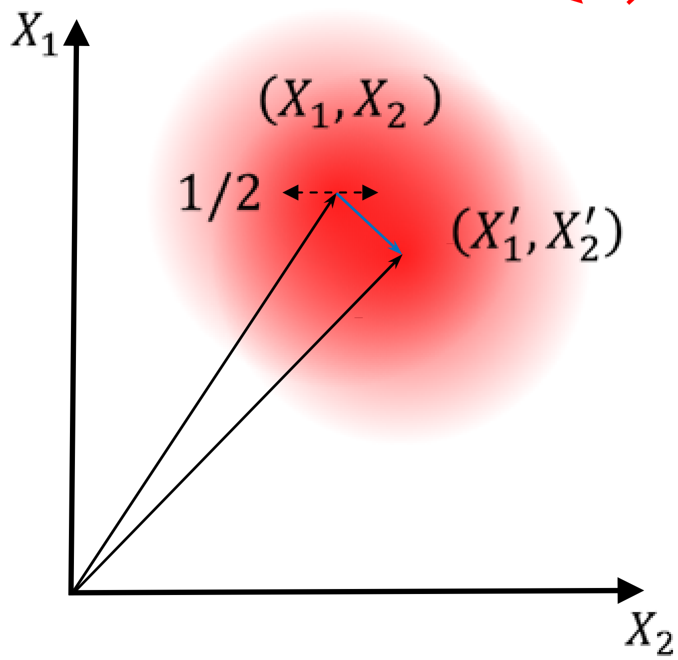


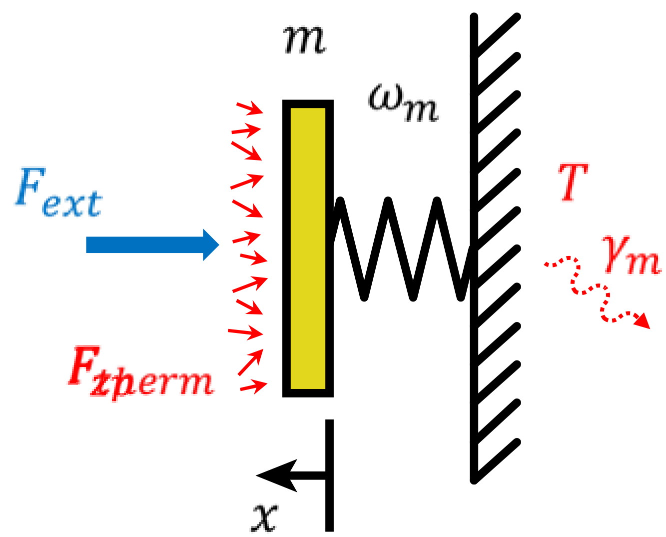


Mechanical Oscillator

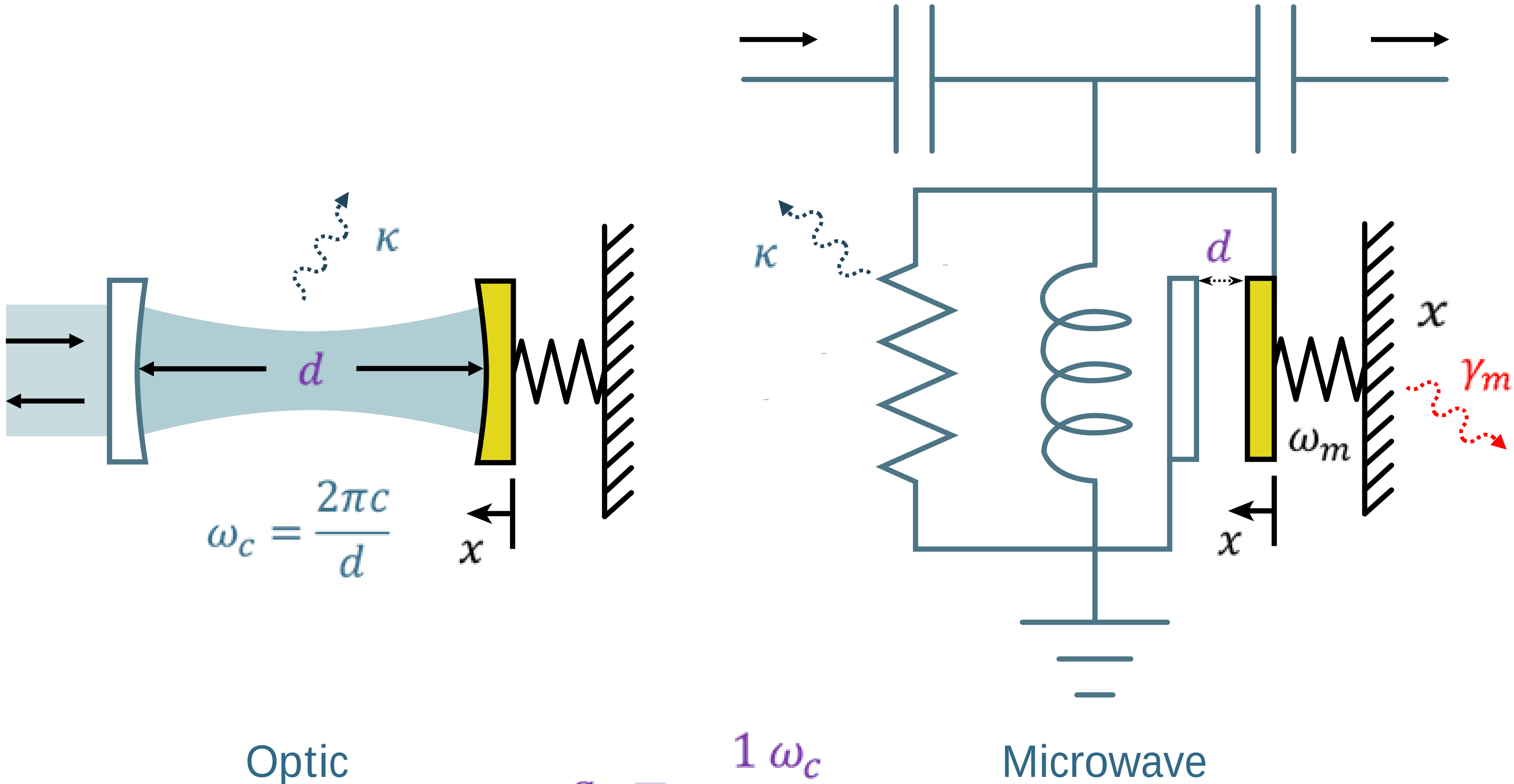
$$x = \sqrt{2}x_{zp}[X_1 \cos(\omega_m t) + X_2 \sin(\omega_m t)]$$

$$\Delta x \Delta p \geq \frac{\hbar}{2} \qquad \Delta X_1 \Delta X_2 \geq \frac{1}{2}$$





Detection

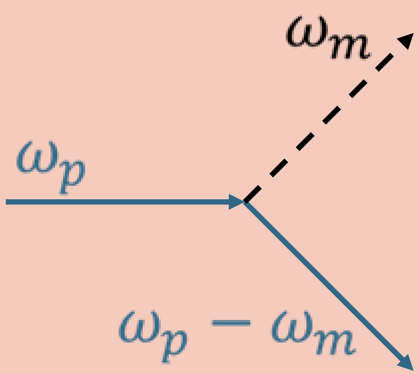


$$g_0 = -\frac{1}{2}\frac{\omega_c}{d}$$

$$\hat{H}/\hbar = (\omega_c + g_0\hat{x})\hat{a}^\dagger\hat{a} + \omega_m\hat{b}^\dagger\hat{b}$$

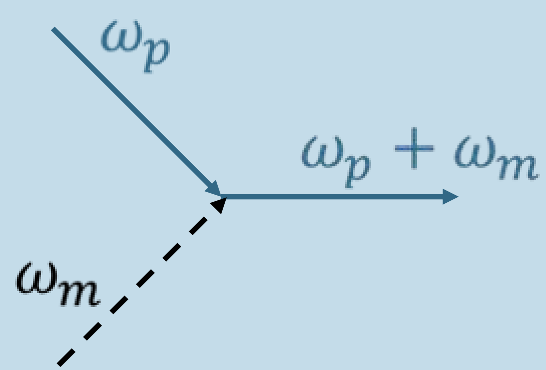
Raman Scattering

$$\hat{H}_{int}/\hbar = g_0 \hat{x} \hat{a}^\dagger \hat{a} = g_0 x_{zp} \left(\hat{b}^\dagger \hat{a}^\dagger \hat{a} + \hat{b} \hat{a}^\dagger \hat{a} \right)$$



$$g_0 x_{zp} \hat{b}^\dagger \hat{a}^\dagger \hat{a}$$

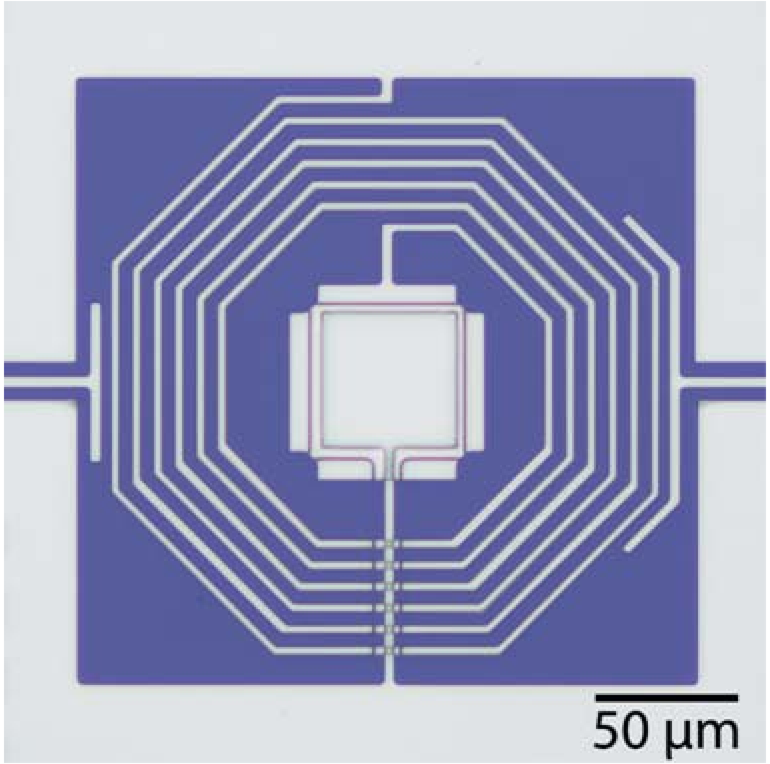
Stokes

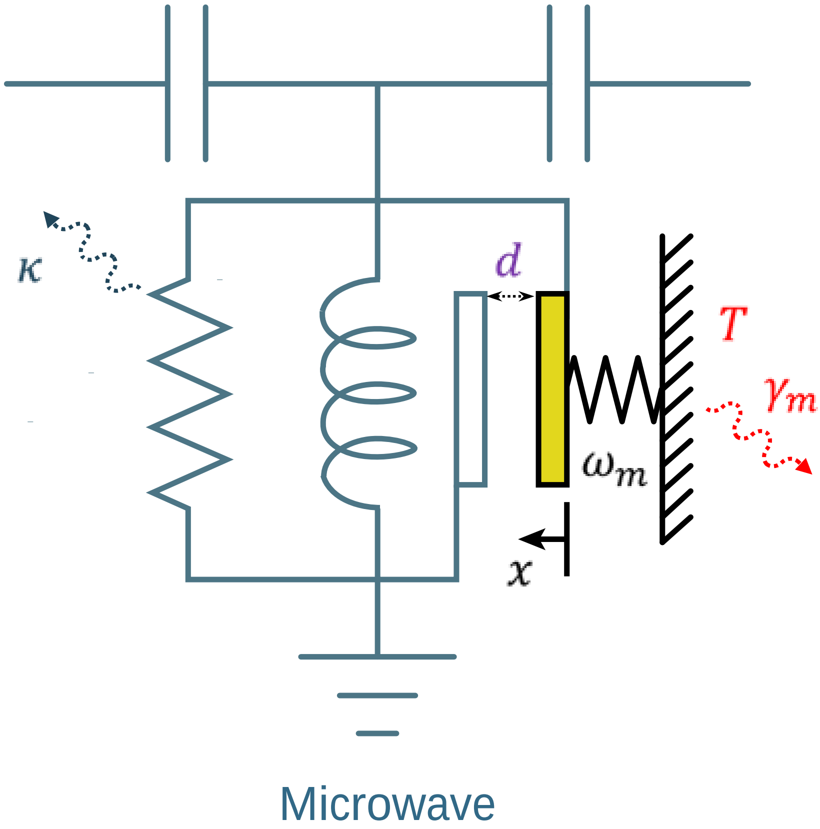


$$g_0 x_{zp} \hat{b} \hat{a}^\dagger \hat{a}$$

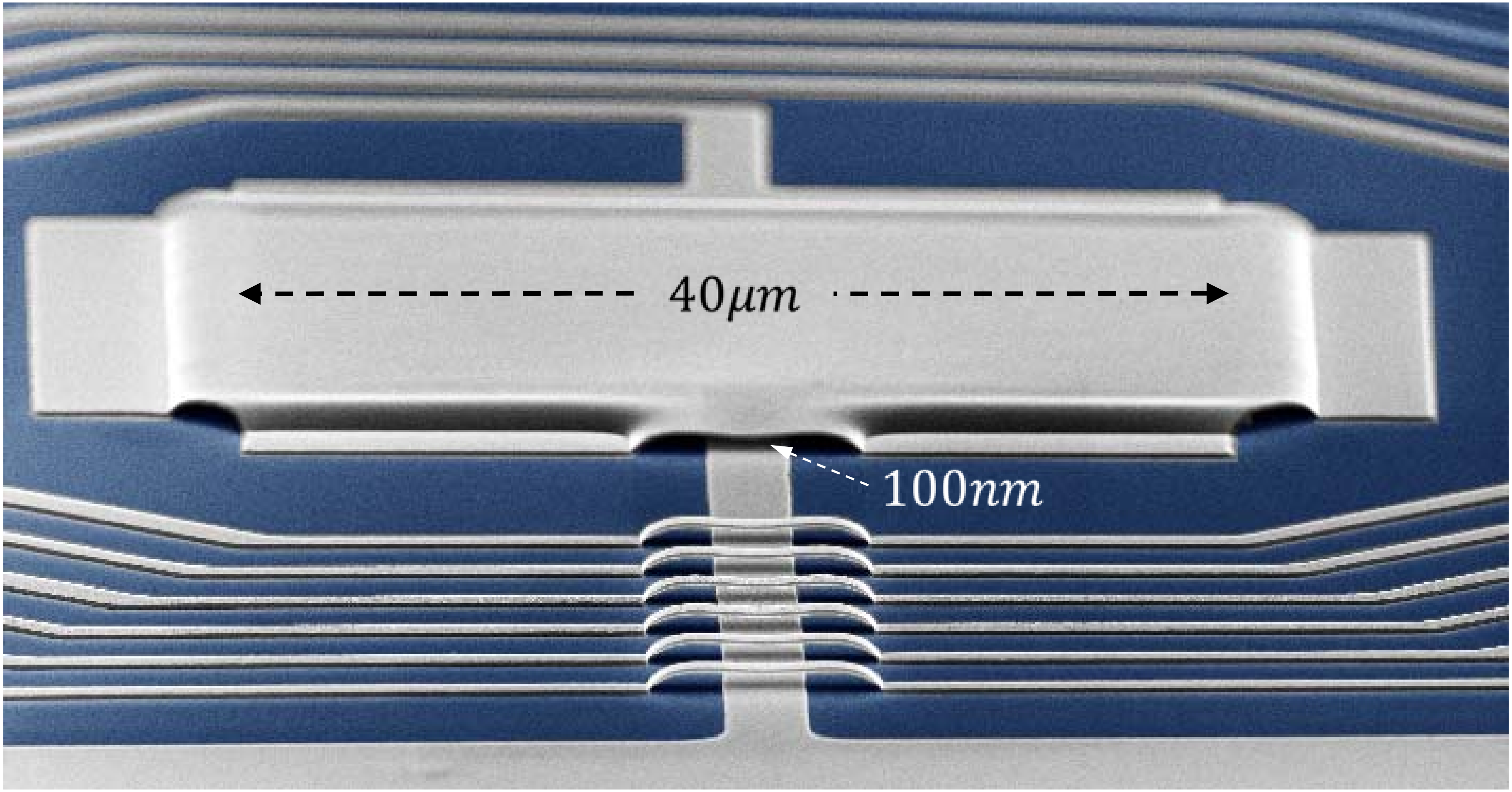
Anti-Stokes

Device





$\omega_c = 2\pi \times 5.1GHz$ $\kappa = 2\pi \times 800kHz$ $T = 8mK$ $n_c \simeq 0$



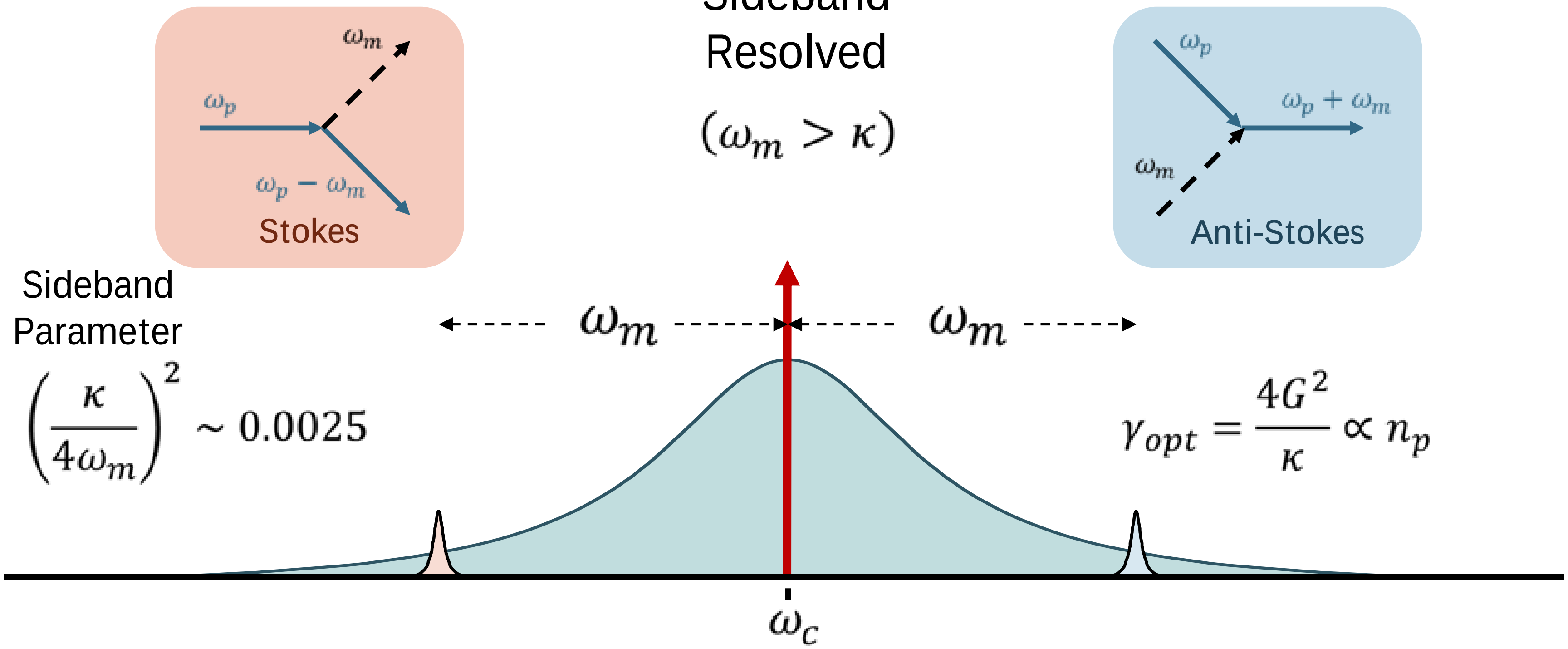
$\omega_m = 2\pi \times 4.0MHz$ $\gamma_m = 2\pi \times 10Hz$ $T = 8mK$ $n_m^{th} = \frac{k_B T}{\hbar \omega_m} \simeq 44$

$x_{zp} \simeq 2fm$ $g_0 x_{zp} = 2\pi \times 16Hz$

Ground State Cooling

Sideband Resolved

$(\omega_m > \kappa)$



Sideband Parameter

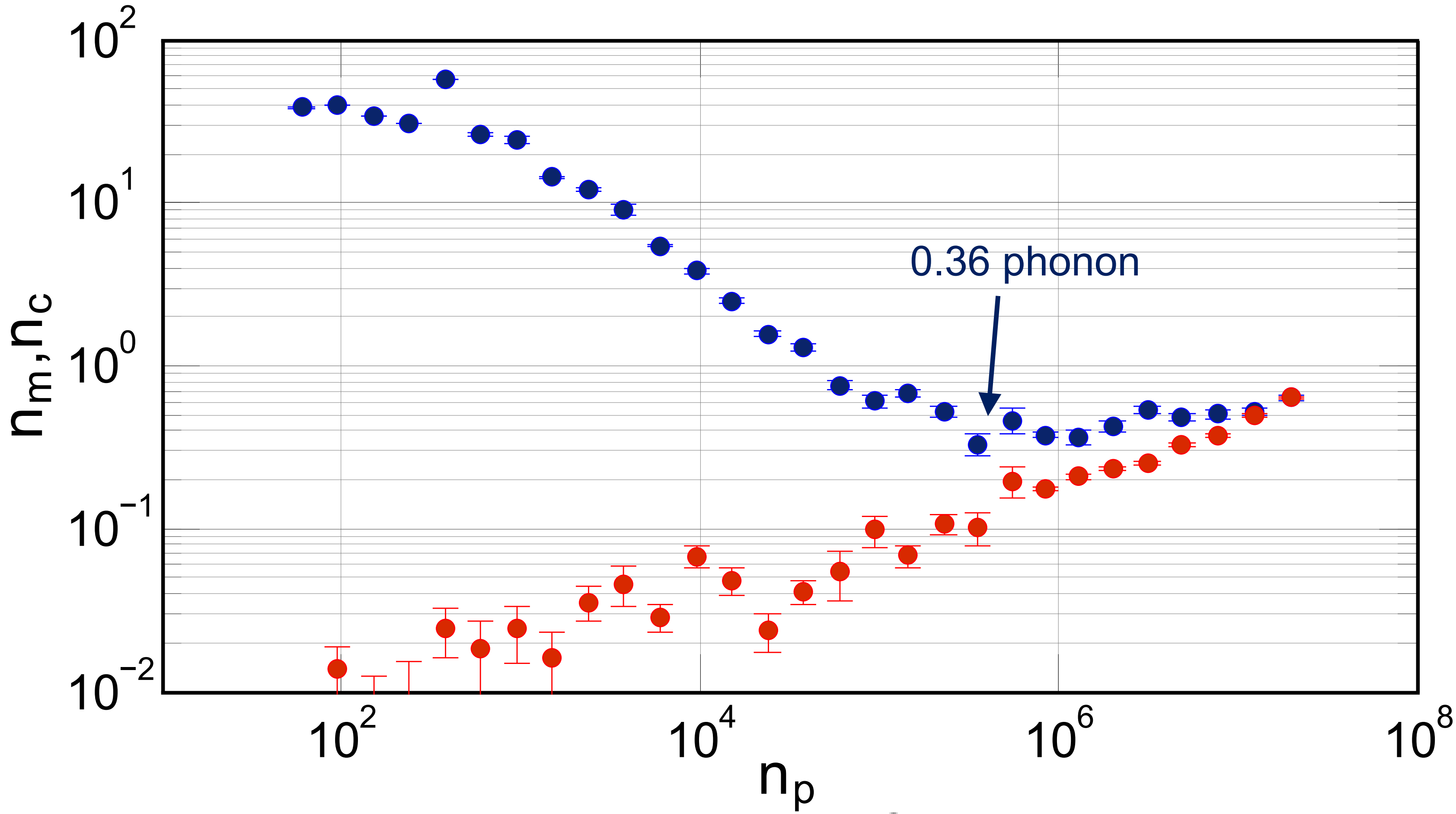
$$\left(\frac{\kappa}{4\omega_m}\right)^2 \sim 0.0025$$

$$\gamma_{opt} = \frac{4G^2}{\kappa} \propto n_p$$

Linear & RWA $\quad \hat{H}_{int}/\hbar = -G\left(\hat{b}^\dagger \hat{a} + \hat{b}\hat{a}^\dagger\right) \quad G = g_0 x_{zp}\sqrt{n_p}$

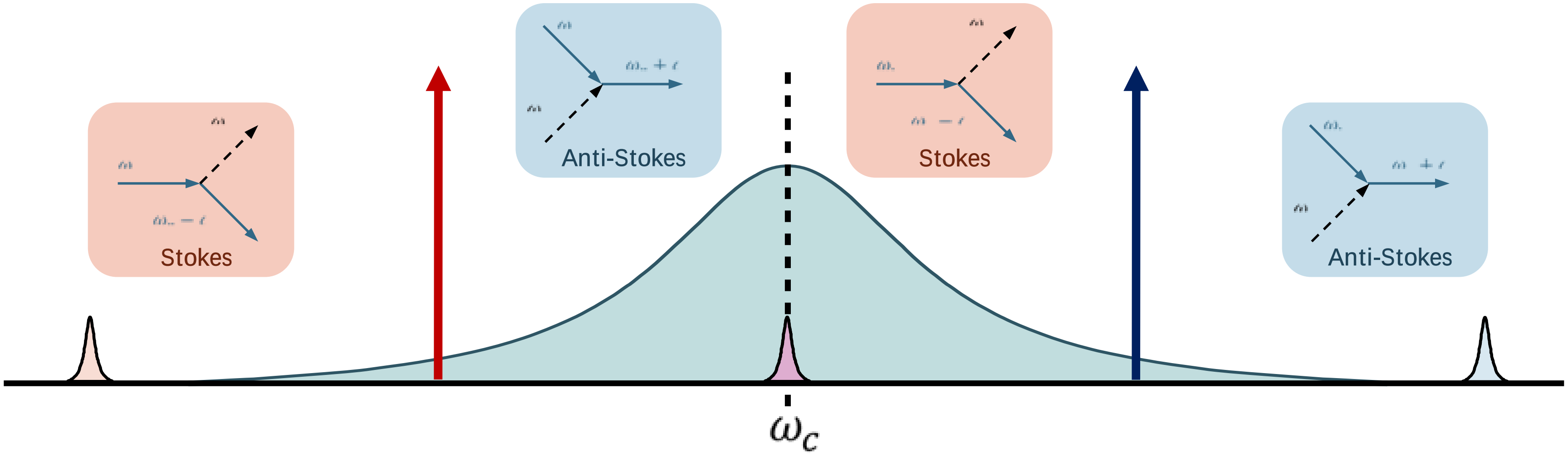
Marquardt, et al, *Phys. Rev. Lett.* (2007)

Ground State Cooling



$$n_m = \frac{1}{1+C} n_m^{th} + \frac{C}{1+C}\left[n_c + \left(\frac{\kappa}{4\omega_m}\right)^2 \right] \qquad C = \frac{\gamma_{opt}}{\gamma_m} \propto n_p$$

Back-action Evasion



$$\hat{H}_{int} = -\hbar\bar{A}\hat{a}^\dagger\hat{a}\left[\hat{X}_1(1 + \cos\cancel{2\omega_m t}) + \hat{X}_2 \sin\cancel{2\omega_m t}\right]$$

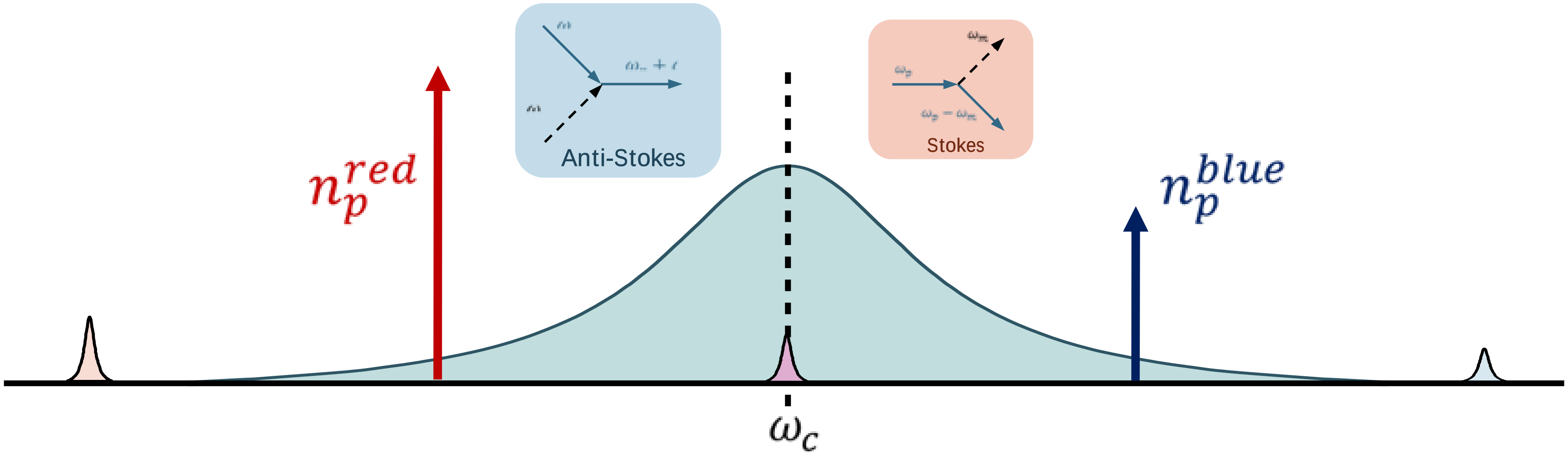
Sideband Resolved $(\omega_m > \kappa)$ $\longrightarrow$ $\hat{H}_{int} \sim -\hbar\bar{A}\hat{a}^\dagger\hat{a}\hat{X}_1$

Braginsky, Vorontsov, & Thorne. *Science* (1980)

Clerk, Marquardt, & Jacobs. *New J. Phys.* (2008)

J. Suh et al. *Science* (2014)

Mechanical Squeezing



$$\hat{H}_{int} = -\hbar \bar{G}\left(\hat{\beta}^\dagger \hat{a} + \hat{\beta}\hat{a}^\dagger\right) \qquad \bar{G} = \sqrt{G_{red}^2 - G_{blue}^2}$$

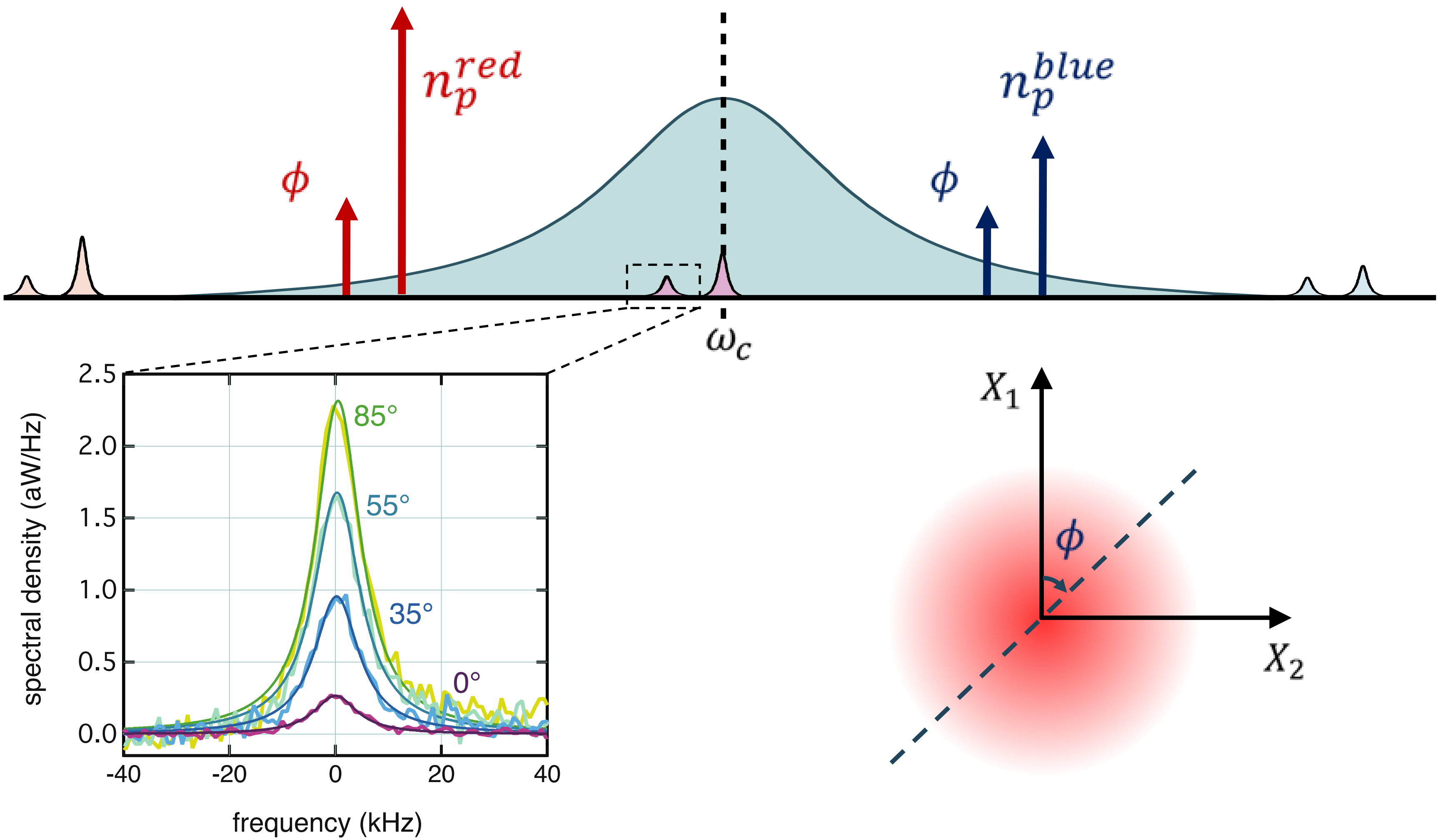
$$\hat{\beta} = \hat{b}\cosh r + \hat{b}^\dagger \sinh r \qquad \tanh r = G_{blue}/G_{red} = \sqrt{n_p^{blue}/n_p^{red}}$$

In ground state $2\langle \hat{X}_1^2 \rangle \simeq e^{-2r}$

Kronwald, Marquardt, & Clerk, *Phys. Rev. A.* (2013)

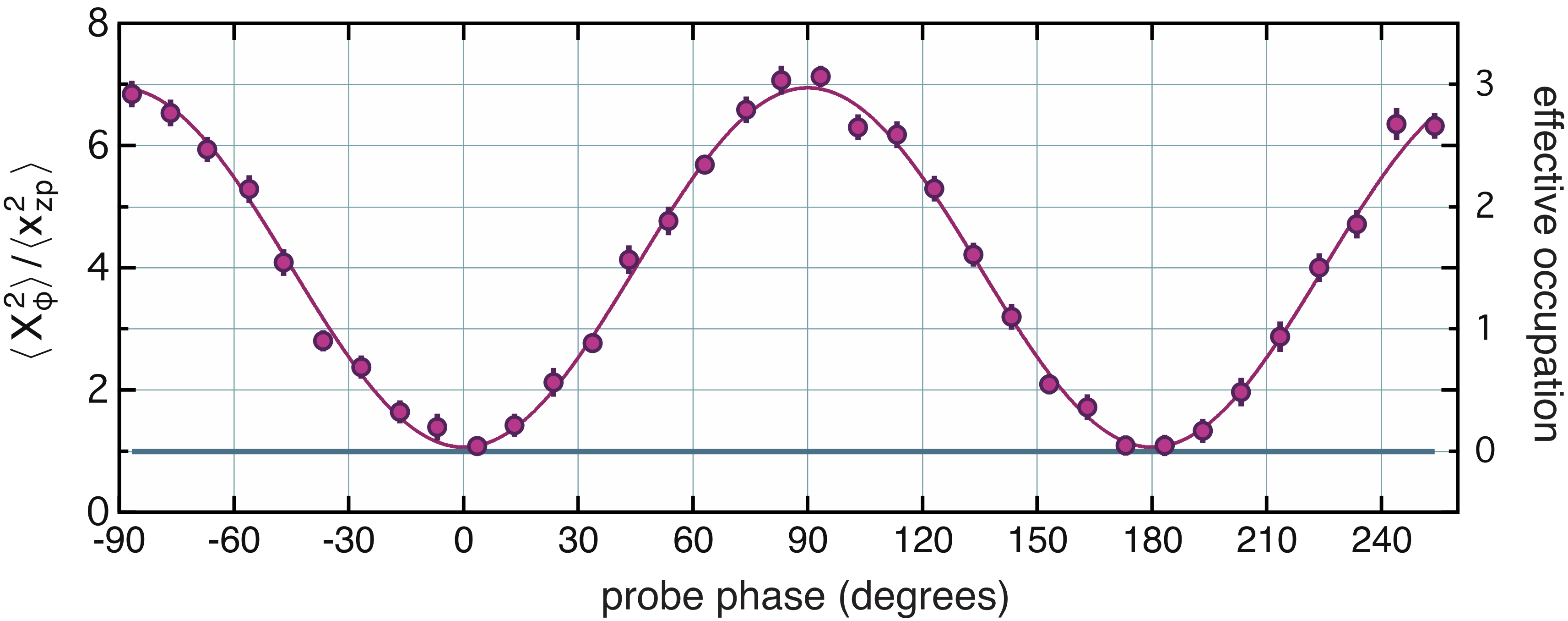
Experiment

$$\langle \hat{X}_\phi^2 \rangle = \langle \hat{X}_1^2 \rangle \cos^2 \phi + \langle \hat{X}_2^2 \rangle \sin^2 \phi$$



Phase Sensitive Measurement

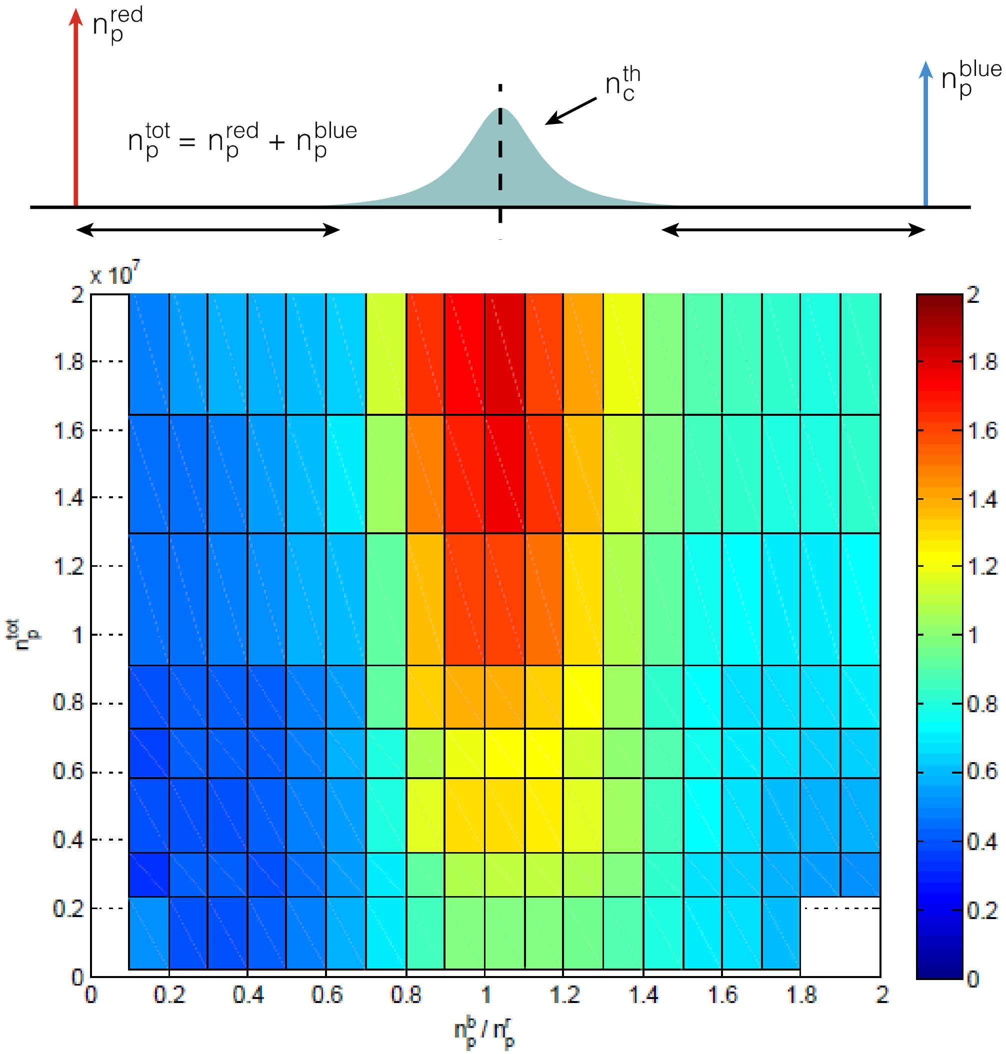
$$\langle \hat{X}_\phi^2 \rangle = \langle \hat{X}_1^2 \rangle \cos^2\phi + \langle \hat{X}_2^2 \rangle \sin^2\phi$$



$n_p^{red} = 16e6 \quad n_p^{blue} = 3.2e6$

Minimum measured variance is $1.09 \pm 0.05 \langle \hat{x}_{zp}^2 \rangle$

Heating



n_p^{red}
n_p^{blue}
n_c^{th}
$n_p^{tot} = n_p^{red} + n_p^{blue}$
x 10^7
n_p^{tot}
n_p^b / n_p^r
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2

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Ari
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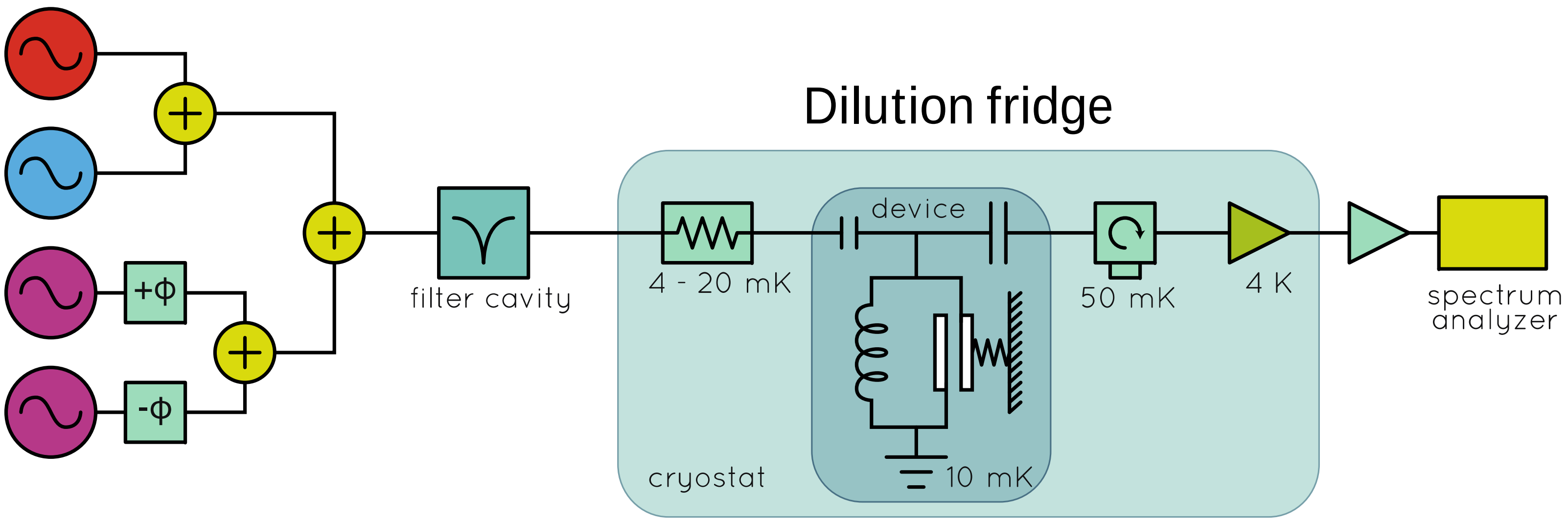
Emma
Wollman

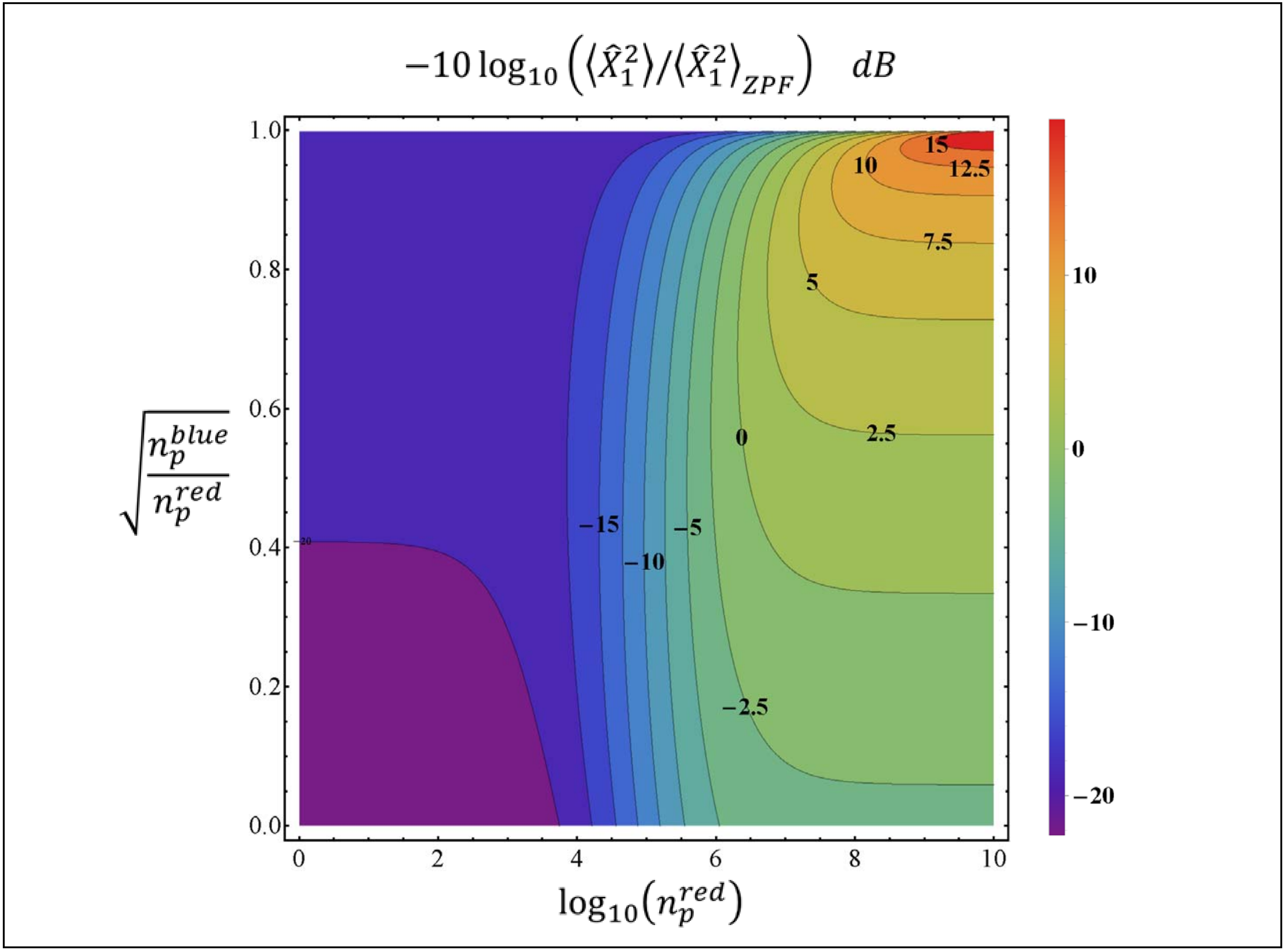
Summary

- We cool the mechanical oscillator down to 0.36 phonon.
- Back-action evasion measurement is useful tool in measuring phase-dependent states such as squeezed state.
- With the imbalance pump scheme, mechanical squeezing below the level of zero point fluctuations should be possible with current technology.
- Heating appears to be the major problem with our current device.

Measurement Setup



J. Suh et al. *Science* (2014)


$-10\log_{10}\left(\langle\hat{X}_1^2\rangle/\langle\hat{X}_1^2\rangle_{ZPF}\right)\quad dB$
$\sqrt{\frac{n_p^{blue}}{n_p^{red}}}$
$\log_{10}(n_p^{red})$
0.0
0.2
0.4
0.6
0.8
1.0
0
2
4
6
8
10
15
10
12.5
7.5
5
2.5
0
−2.5
−5
−10
−15
−20

Heating