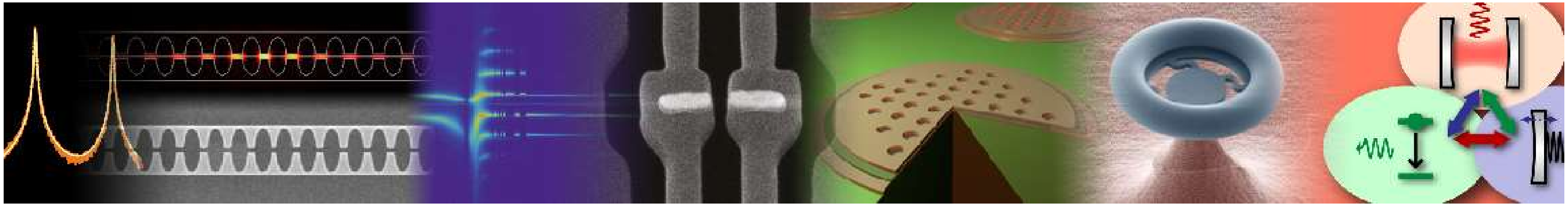
Cavity optomechanics with extreme coupling rates in silicon photonic crystals

Juha Muhonen, Rick Leijssen, Lars Freisem,
Giada La Gala, and Ewold Verhagen



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Marie Skłodowska-
-Curie Actions

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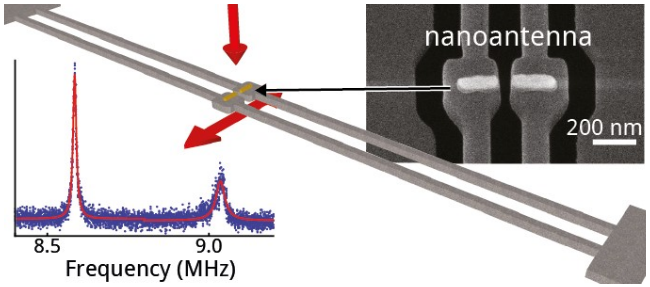
Optomechanics with subwavelength light fields

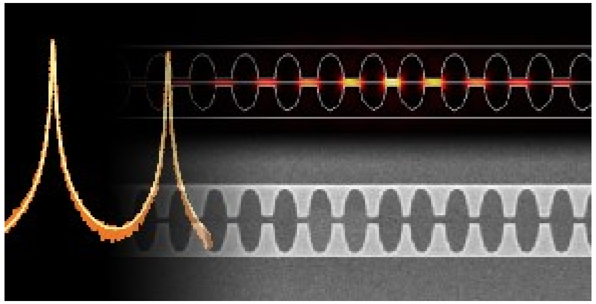
Nano-confined light fields:

- **Giant optomechanical interaction rates at practical bandwidth**
- Bad cavity limit → can we use this to our advantage?
  - Measurement bandwidth faster than mechanics

Plasmonic optomechanics



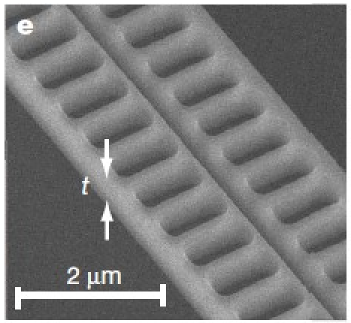
Nano-optomechanics in Si



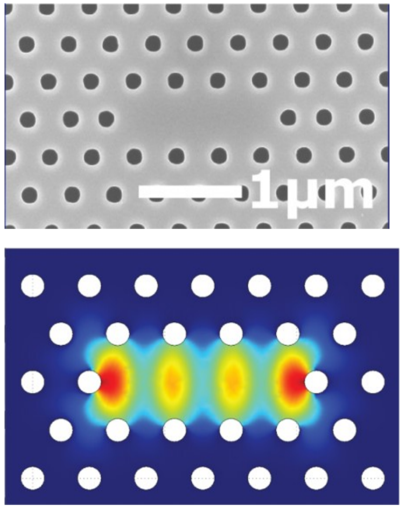
Thijssen et al. Nano Lett., ***15,*** 3971 (2015)

Optomechanics with photonic crystals

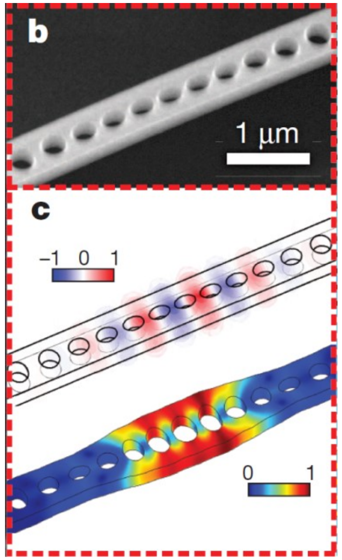
Co-localization of optical and acoustic modes at wavelength scale allows large coupling strengths



Eichenfield et al.,
Nature 459, 550 (2009)



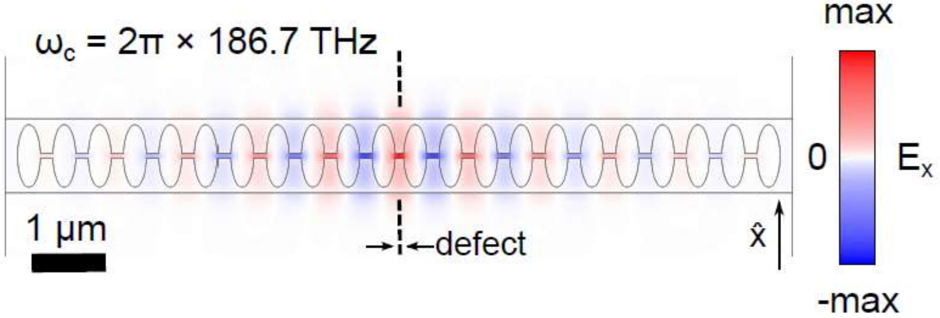
Gavartin et al.,
PRL 106, 203902 (2011)



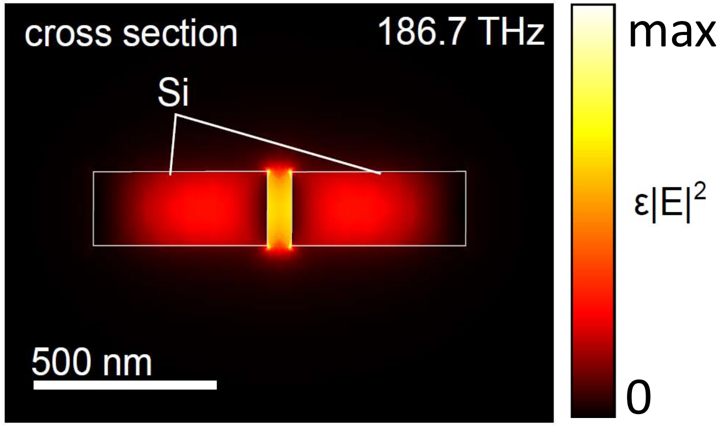
Chan et al,
Nature 478, 89 (2011)

Subwavelength field confinement in sliced PCs

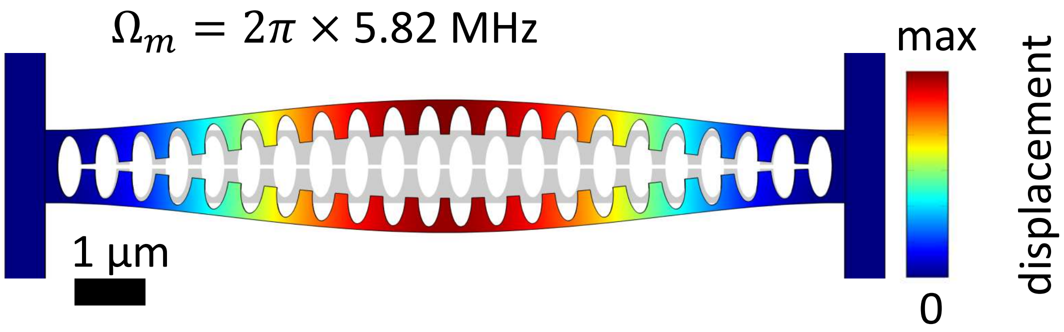
- Sliced photonic crystal nanobeam; defect cavity

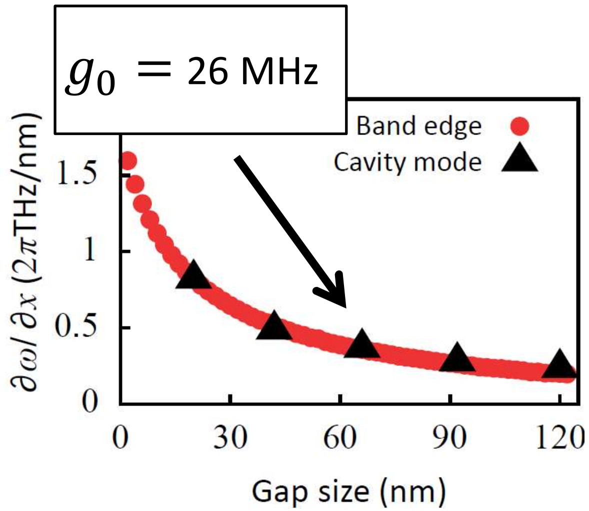


Mode volume 10% of $\left(\frac{\lambda}{2}\right)^3$ in vacuum

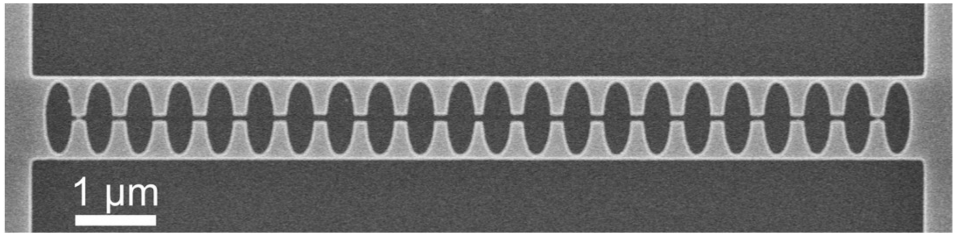


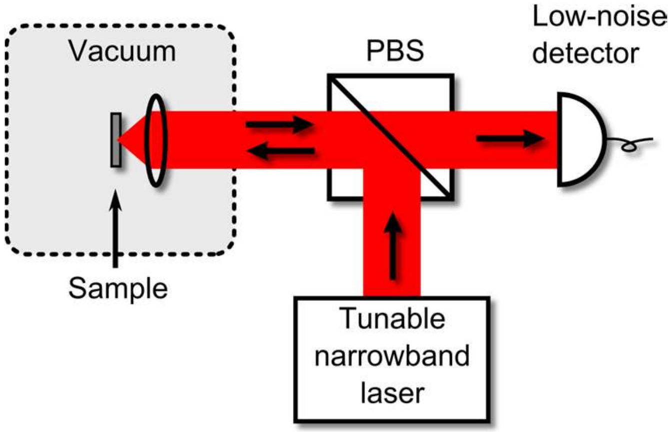
- Antisymmetric mechanical mode

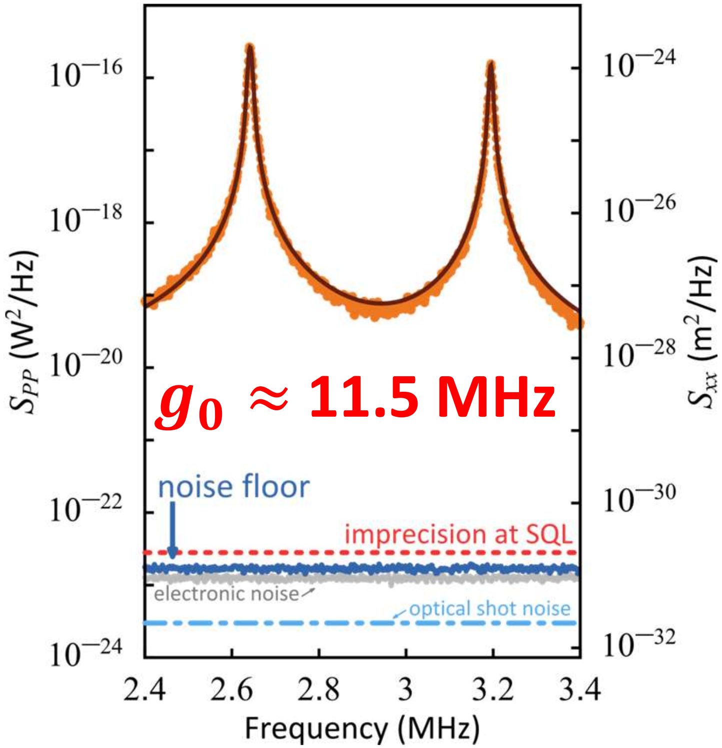


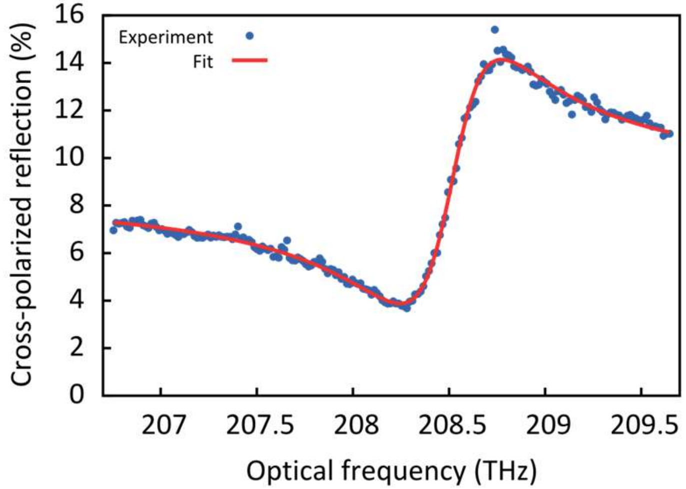


Highly sensitive readout









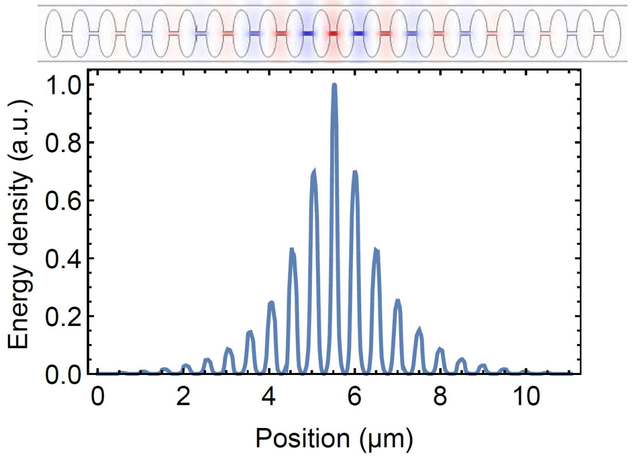
$$\frac{\kappa}{2\pi} \approx 500\ \mathrm{GHz}$$

$\kappa_{ex}/\kappa \approx 0.29$

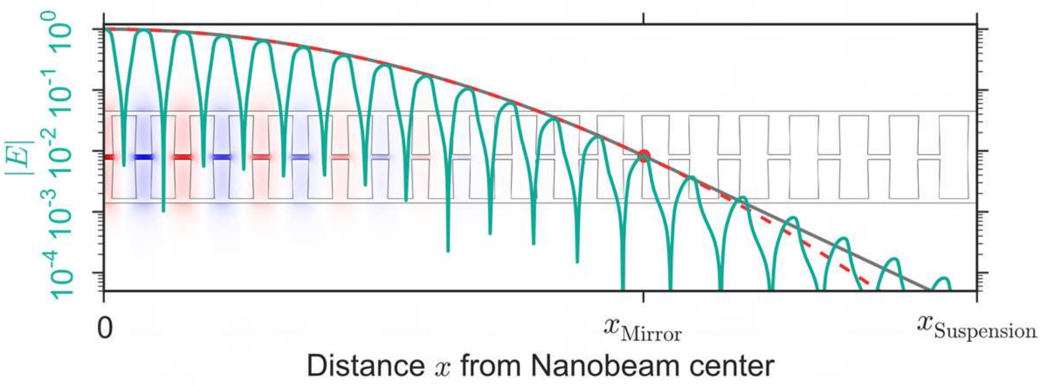
Leijssen and Verhagen, Sci. Rep. 5, 15794 (2015)

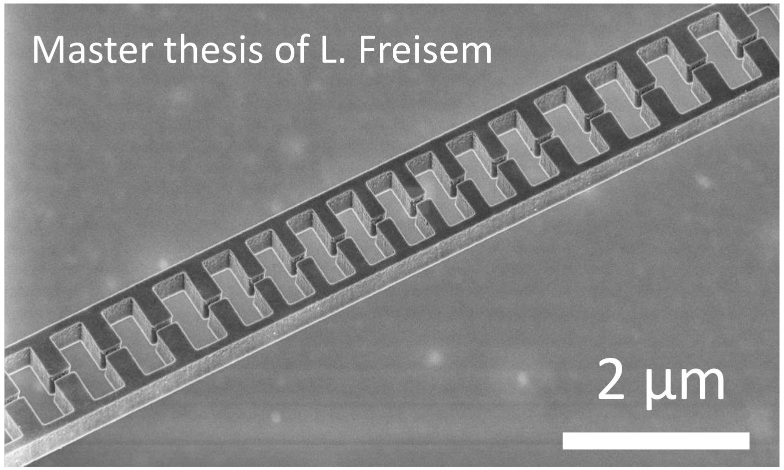
Reducing loss through tapering design

Single defect: exponential field profile



Tapered design: gaussian field profile
→ minimizing radiating wavevectors





Simulations

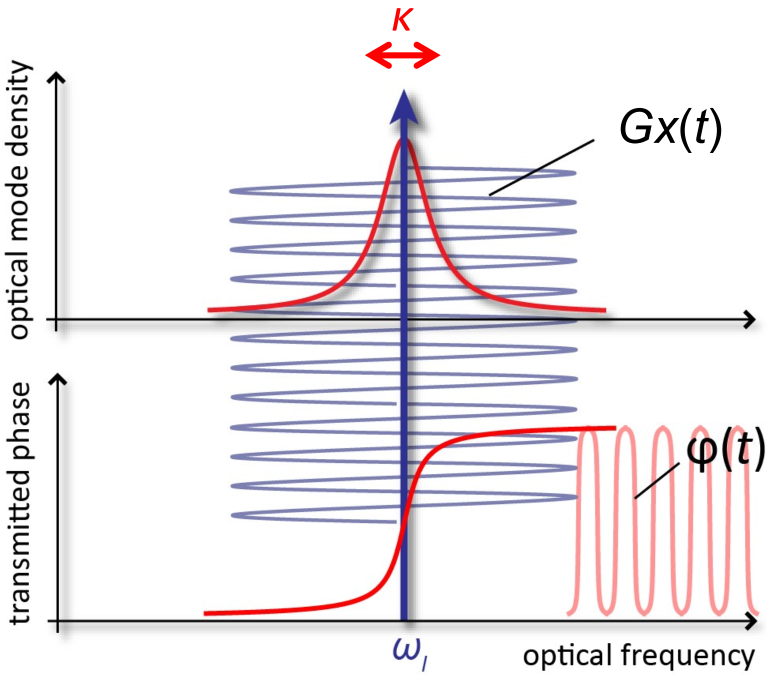
$\kappa \approx 2$ GHz

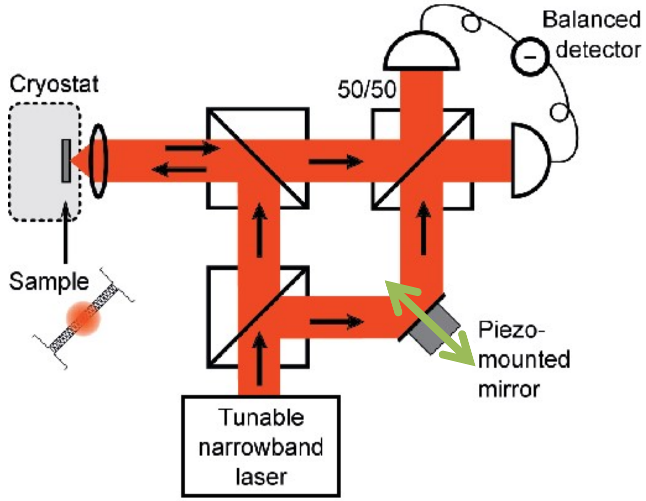
Thermomechanical frequency fluctuations:

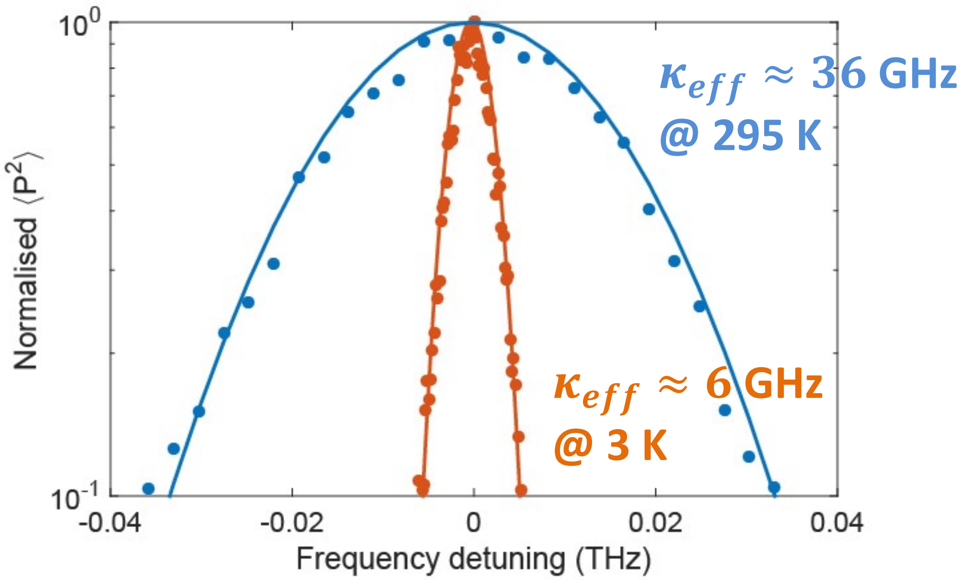
Apparent $\kappa \approx 40$ GHz

Large g_0/κ effects

Thermomechanical frequency modulations $Gx_{th} \gg \kappa$

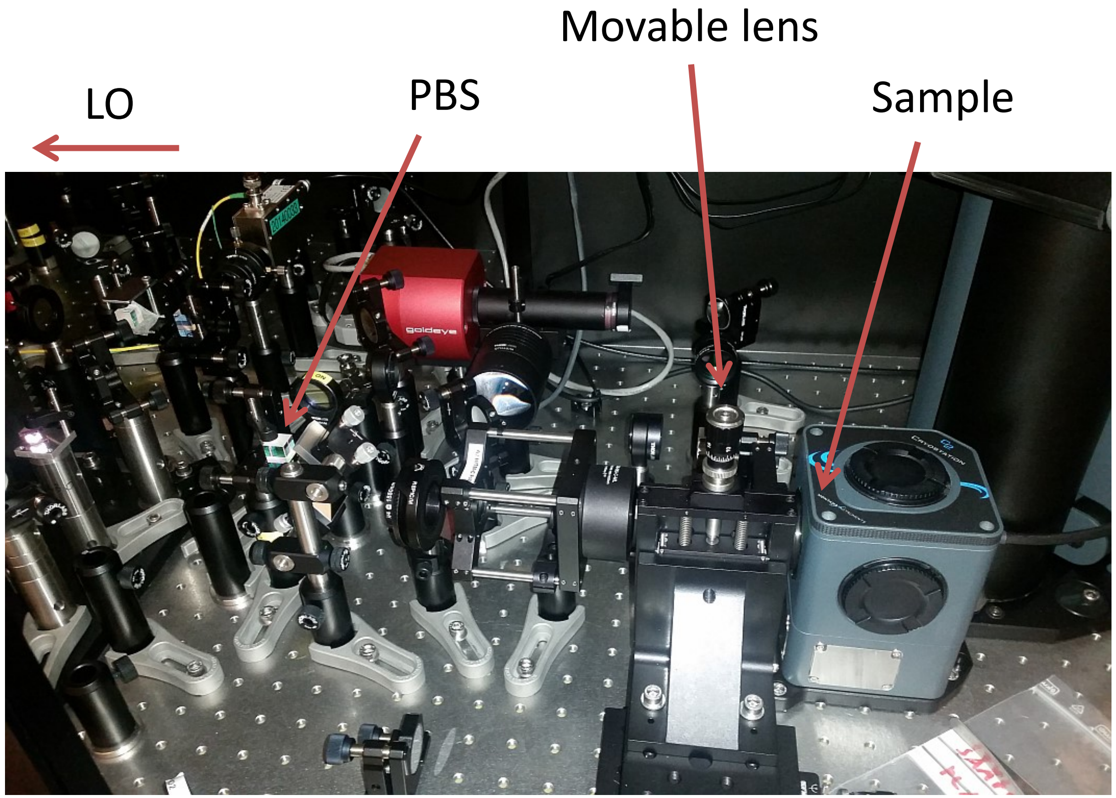




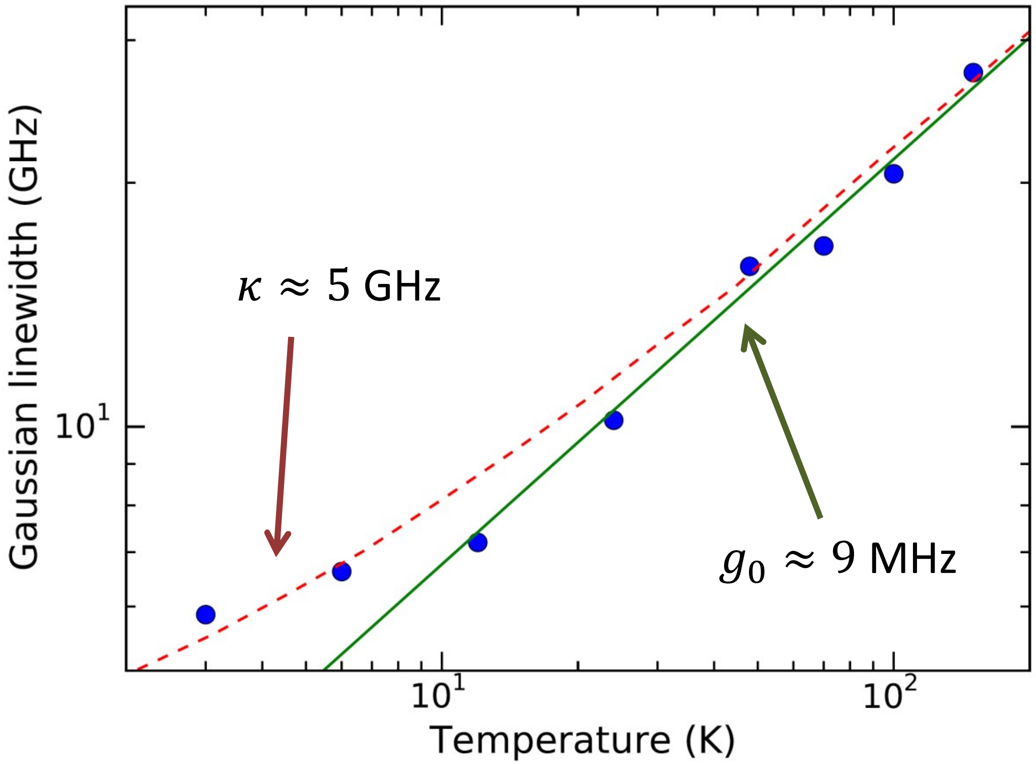


Montana instruments Cryostation C2

- Temperature range 3-350 K
- Vibrations < 5 nm

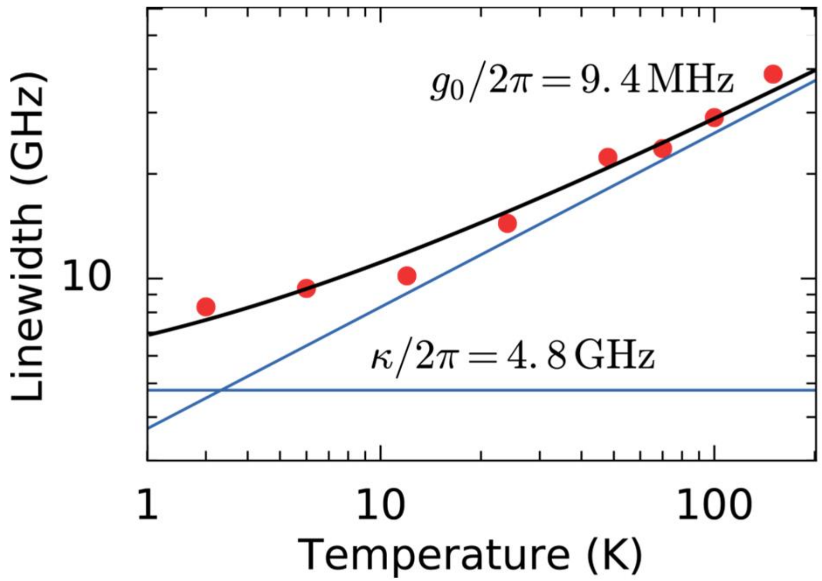


Experiments varying the temperature



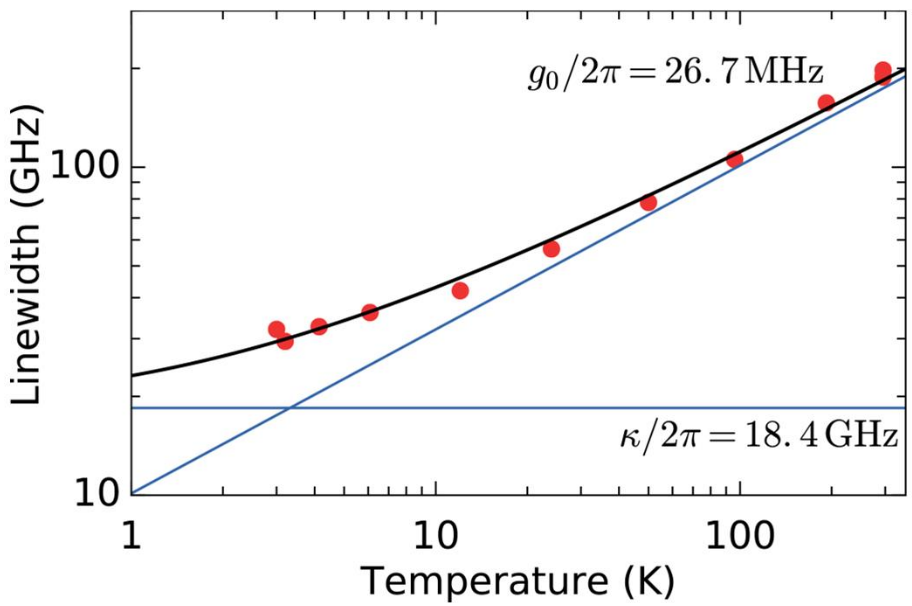
$\kappa_{eff} \propto g_0\sqrt{T}$

Experiments varying the temperature



$\Gamma_m/2\pi \approx 500\ Hz$

Modified design

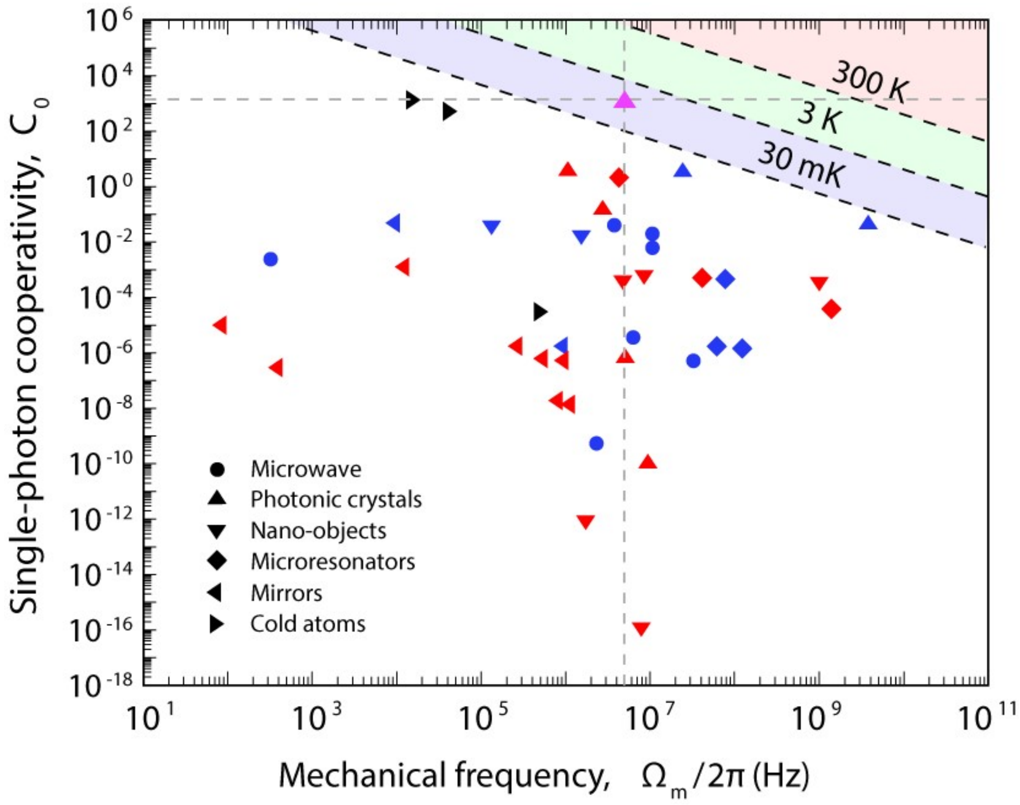


$\Gamma_m/2\pi \approx 100\ Hz$

$$C_0 = \frac{4g_0^2}{\kappa\Gamma_m} \approx \mathbf{150}$$

$$C_0 = \frac{4g_0^2}{\kappa\Gamma_m} \approx \mathbf{1500}$$

Compared to the state-of-the-art



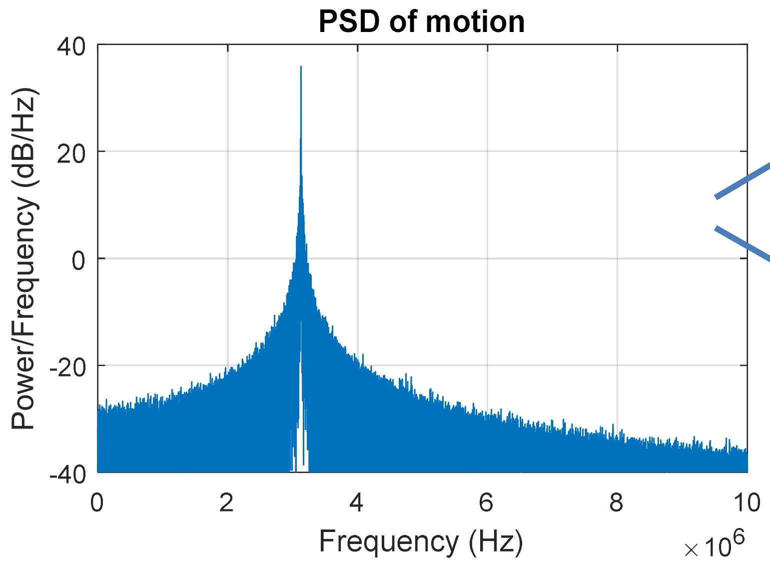
However, our measurement efficiency ($\eta = \frac{\kappa_{ex}}{\kappa} \approx 1\%$) is lagging behind other systems

And we are at the bad cavity limit.

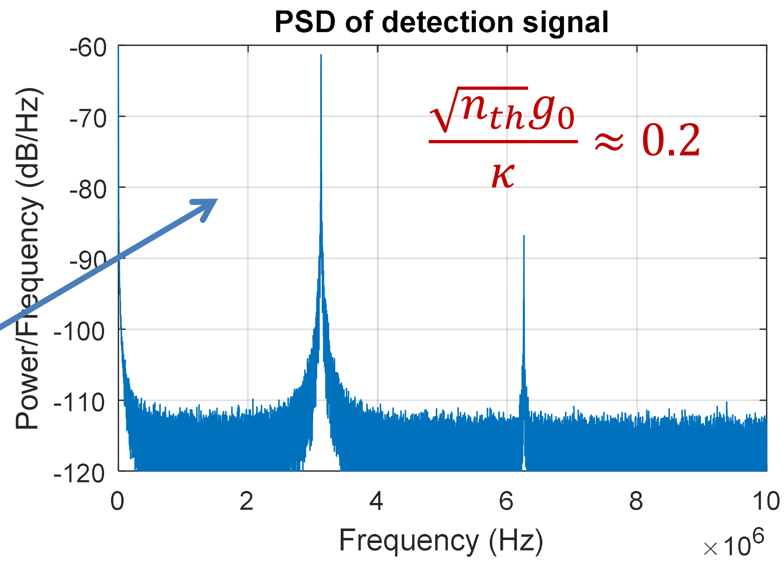
Aspelmeyer, Kippenberg, Marquardt, RMP **86**, 1391 (2014)
Schilling *et al.*, Phys. Rev. Appl. **5**, 054019 (2016)

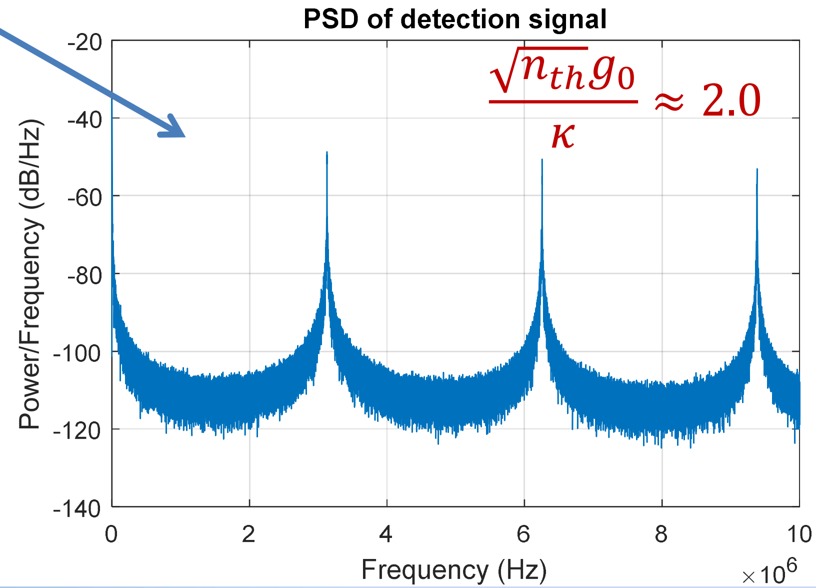
Non-linear transduction, numerical simulations

Large $\sqrt{n_{th}}g_o/\kappa$ leads to very nonlinear detection signal



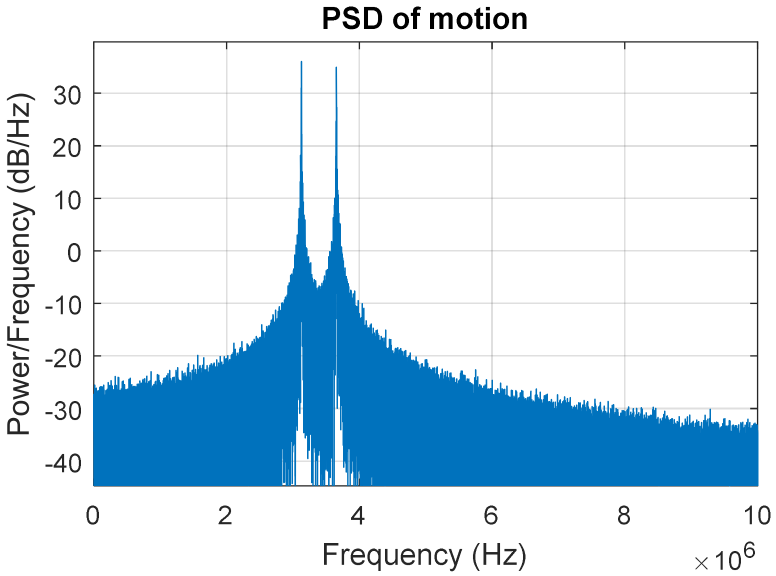
These are averaged over all homodyne angles.



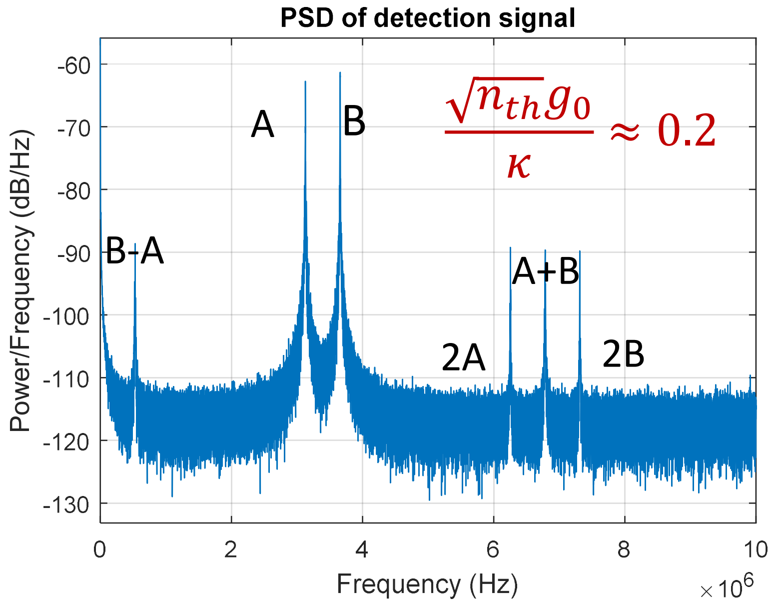


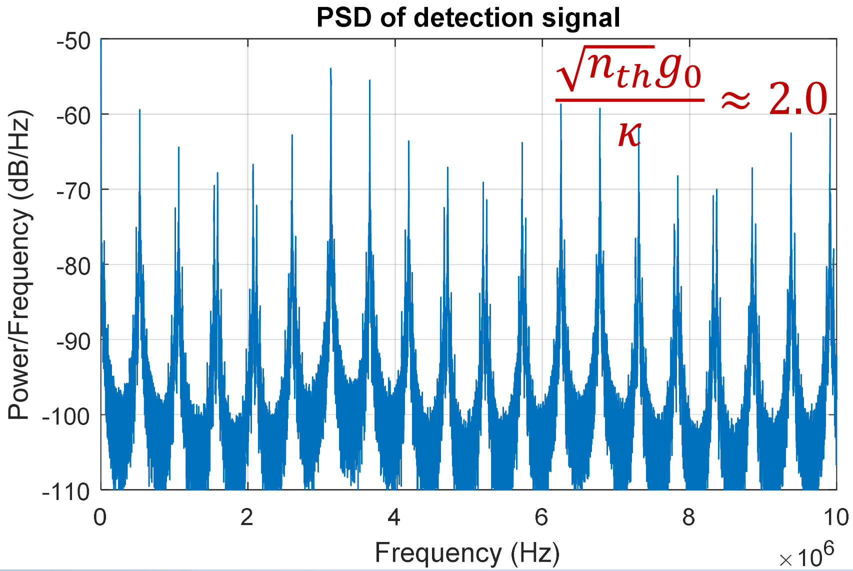
Non-linear transduction with two modes

Numerical simulations including second mechanical mode



These are averaged over all homodyne angles.

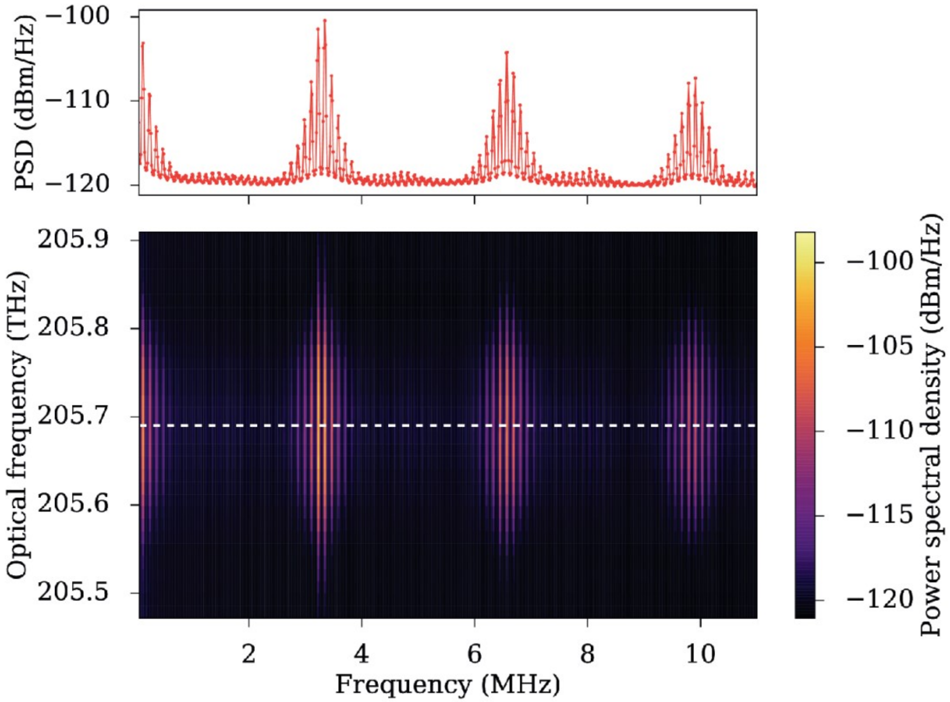




Non-linear transduction, measurement data

Large $\sqrt{n_{th}}g_o/\kappa$ leads to very nonlinear detection signal

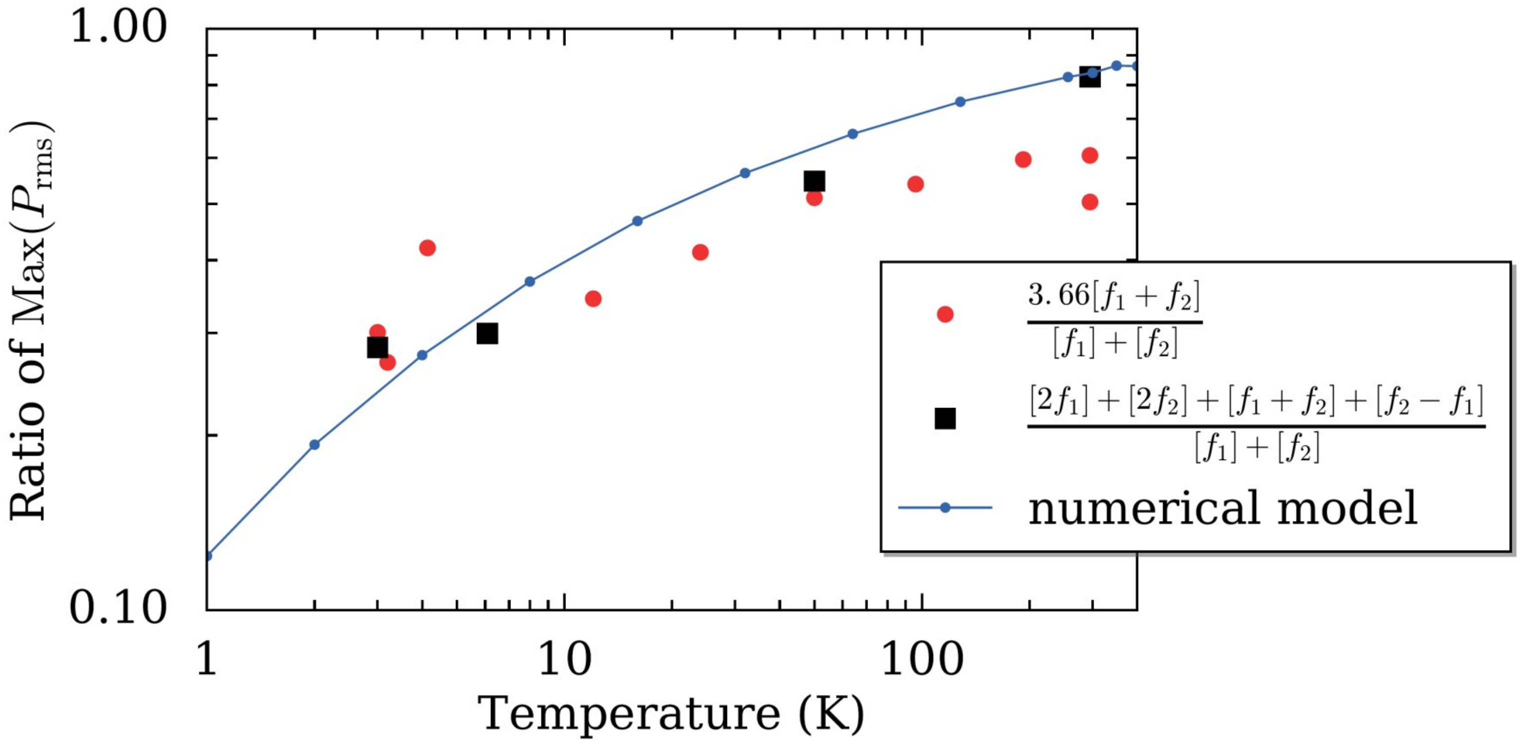
Spectrum at room temperature:



This is while sweeping the LO phase, so averaged over all homodyne angles

By locking the angle it is possible to achieve sensitivity to only the odd or even harmonics

g_0/κ from the peak ratios



This is consistent with the previously extracted g_0/κ

What can we do with it?

Back-action evading pulsed measurements

Non-resolved sideband regime $\kappa \gg \omega_m$, measurement bandwidth much larger than mechanical frequency

To measure position below zero-point motion, need a pulse containing

$$N_p > \frac{\kappa^2}{64 g_0^2}$$

Generally pulse intensity limited by power handling of cavities
→ relatively large κ helps

$$n_{cav} = \frac{4N_p}{\kappa\tau} = \frac{\kappa}{16 g_0^2 \tau}$$

$\tau = 10\ ns, \kappa = 2\ GHz, g_0 = 35\ MHz \Rightarrow$
$n_{cav} > \mathbf{10}$

Need to still account for our measurement efficiency.

What can we do with it?

Measurement based feedback cooling

Necessary requirement to cool to ground state:

$$\Gamma_{meas} \geq \Gamma_{th} = n_{th}\Gamma_m$$

(measurement rate larger than thermal decoherence)

This translates to: $\dfrac{\eta C_o n_{cav}}{n_{th}} = \eta C_{qu} > 1$

Our parameters: $C_0 \approx 1500, \eta \approx 0.01, n_{th} \approx 10^4$

→ Need $\boldsymbol{n_{cav} \approx 700}$

BUT also need to account for other imprecision sources.

See: Wilson *et al.,* Nature **524**, 325 (2015)

What can we do with it?

Non-linear measurements

$$P_{det}^{1} = \frac{\partial P}{\partial x} x = \frac{\partial P}{\partial \omega_c} \frac{\partial \omega_c}{\partial x} x$$

$$P_{det} = P_{det}^{1} + \frac{1}{2} \frac{\partial^2 P}{\partial \omega_c^2} \left(\frac{\partial \omega_c}{\partial x} \right)^2 x^2$$

Note that we are NOT considering the e.g. membrane in the mdidle case:

$$P_{det} = P_{det}^{1} + \frac{1}{2} \frac{\partial P}{\partial \omega_c} \left(\frac{\partial^2 \omega_c}{\partial x^2} \right) x^2$$

To create non-classical states, need:

i) $\frac{4\eta\ \ _{cav} g_0^4}{\kappa^3} > n_{th} \Gamma_m$ Measurement rate larger than thermal decoherence

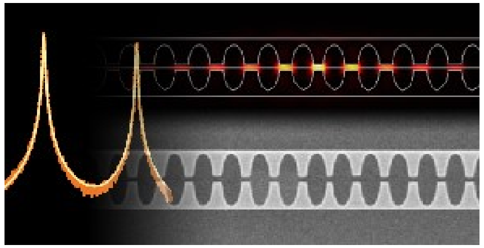
ii) $\frac{g_0^2}{\kappa^2} > (1 - \eta)/2\eta$ Suppress linear back-action

Second criteria hard, but not impossible in our system

See: Brawley *et al.,* Nature Comm. **7**, 10988 (2016)

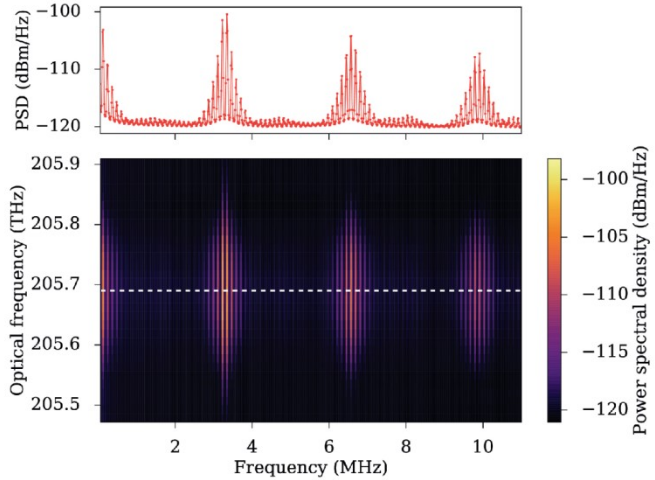
Conclusions

- Using subwavelength light fields makes optical systems extremely sensitive to displacement



- Sliced silicon nanobeam: field confinement allows record g_0 and regime of nonlinear transduction

- Our device should be well suited for measurement based quantum state preparation schemes (pulsed, feedback, non-linear)



Thank you!

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