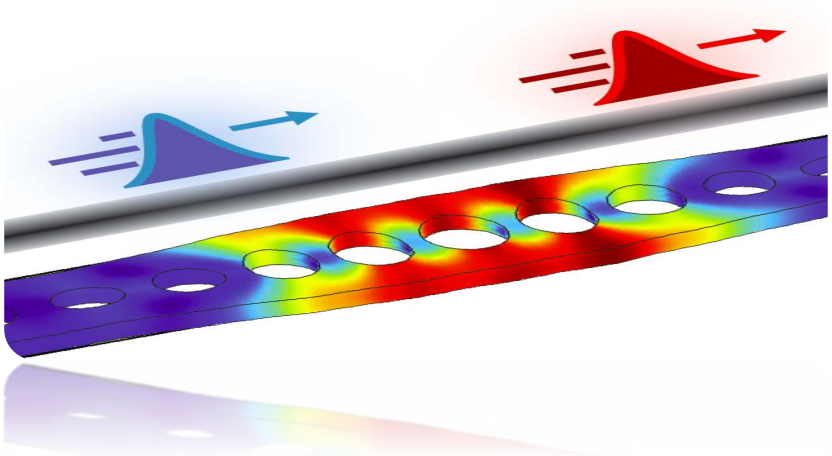
KITP Program on Synthetic Quantum Matter
October 4, 2016

Integrated Optomechanical (and Superconducting) Quantum Circuits



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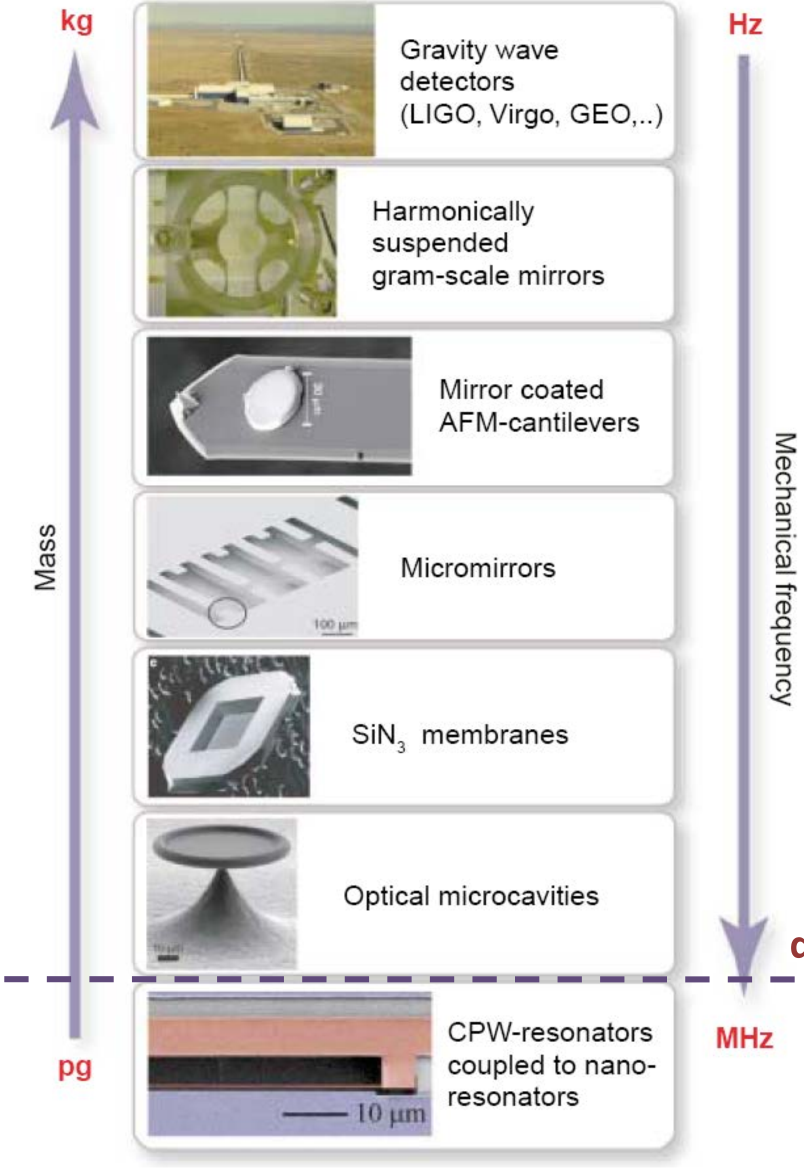
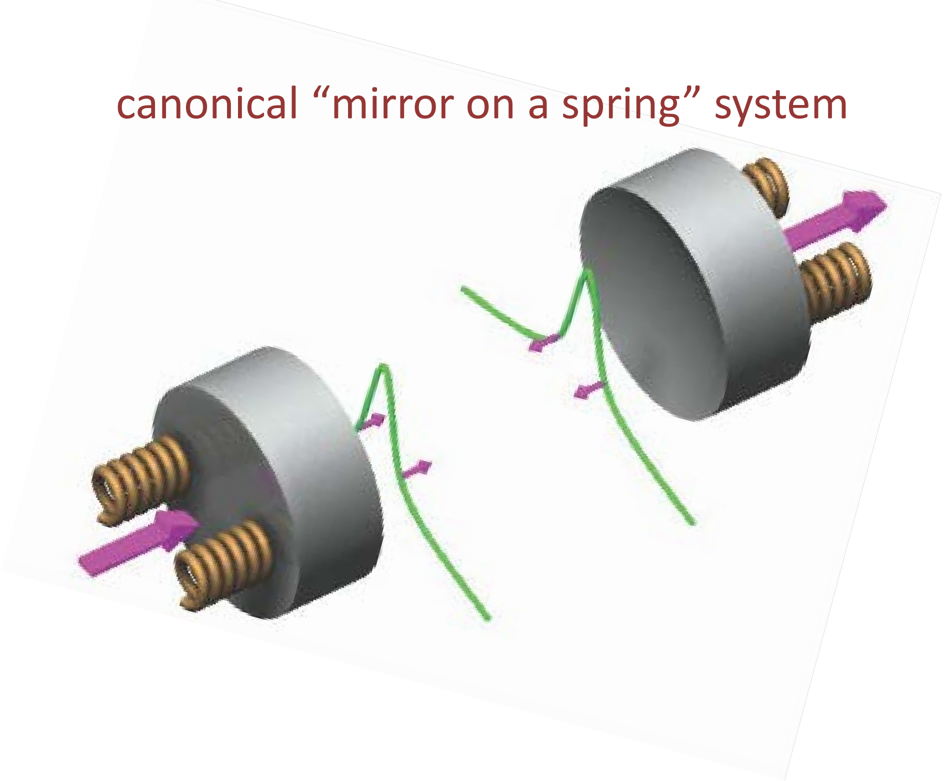
Cavity-Optomechanics: scale and geometry



diffraction limit

Cavity Optomechanics: Back-Action at the Mesoscale
T. J. Kippenberg, *et al.*
Science **321**, 1172 (2008);
DOI: 10.1126/science.1156032



canonical "mirror on a spring" system

cavity-optomechanics: quantum back-action

Cavity Optomechanics: Back-Action at the Mesoscale
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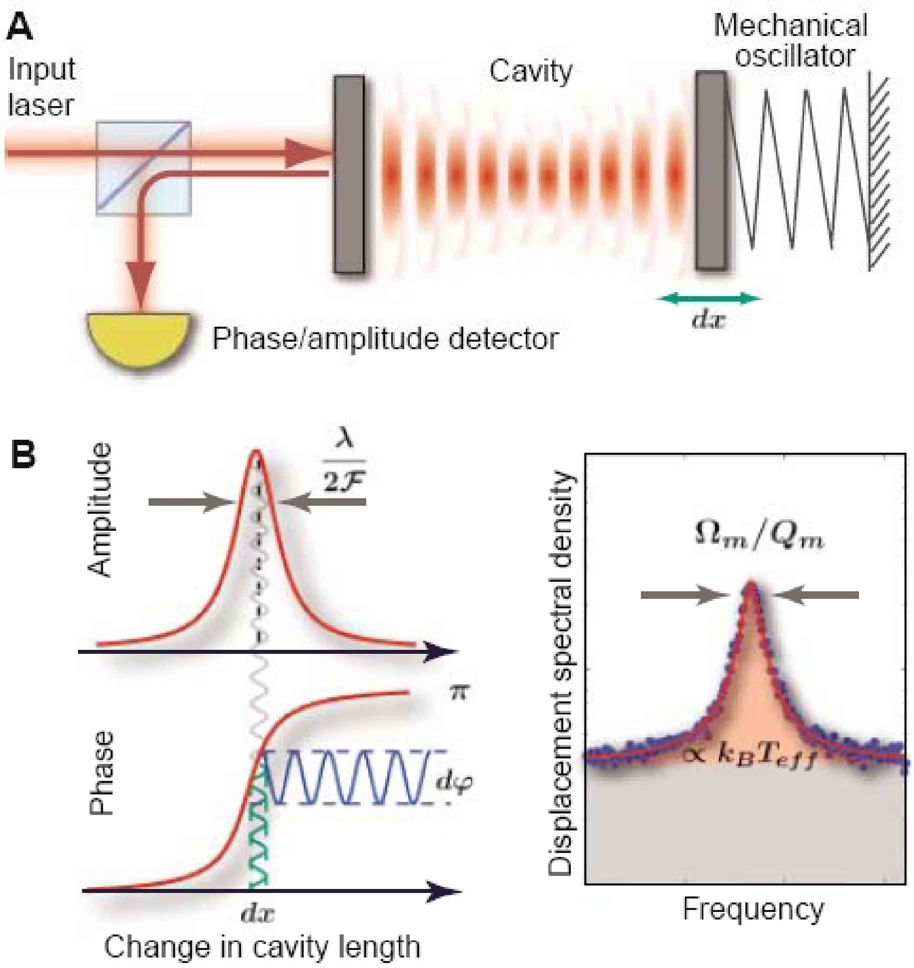
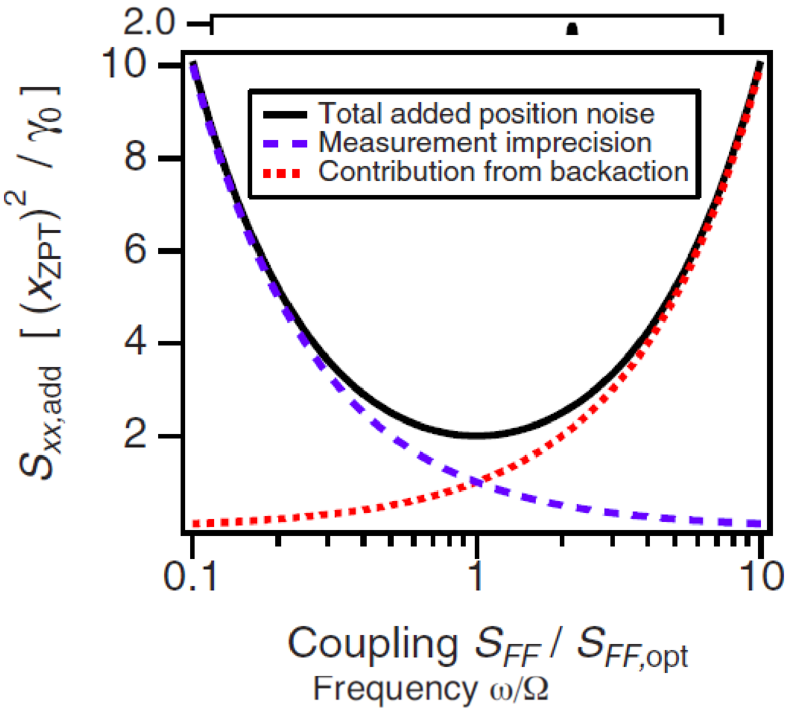


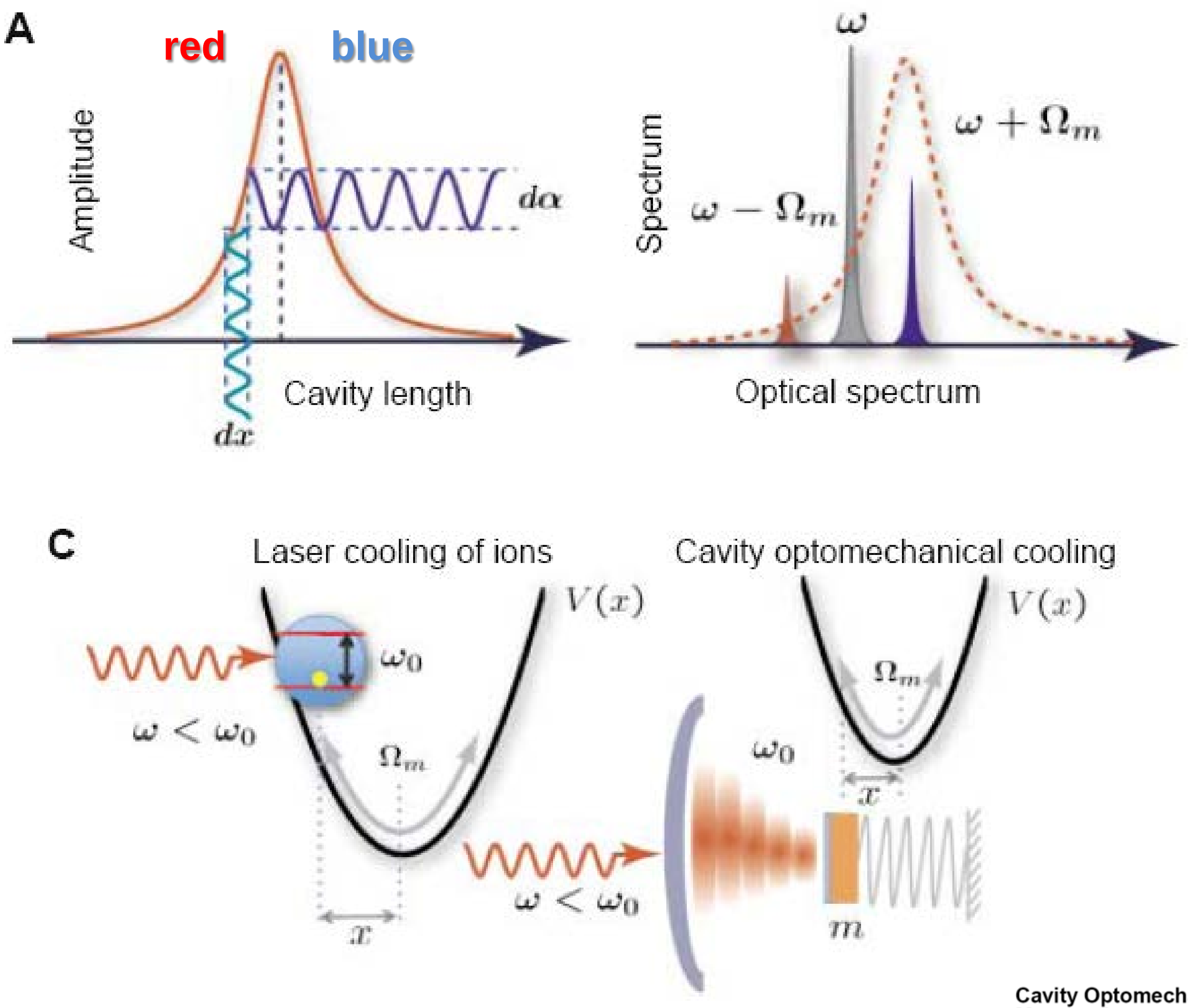
- ideal detection (no optical loss)
- no correlation between sensing noise and back-action (on-resonance probing)

$$\boxed{\bar{S}^{\mathrm{I}}_{xx}\bar{S}_{FF} = \frac{\hbar^2}{4}}$$



*Brooks, et al., Nature Physics (gas-phase atoms);
Purdy, et al., Science 2013 (nanomebrane)

Cavity-optomechanics: dynamical back-action



Cavity Optomechanics: Back-Action at the Mesoscale
T. J. Kippenberg, *et al.*
Science **321**, 1172 (2008);
DOI: 10.1126/science.1156032

Hamiltonian

$$\hat{H} = \hbar\omega_{\text{cav}}(\hat{x})\hat{a}^\dagger\hat{a} + \hbar\Omega\hat{b}^\dagger\hat{b} + \ldots$$

$$\Delta = \omega_L - \omega_{\text{cav}}$$

$$\hat{x} = x_{\text{ZPF}}(\hat{b}^\dagger + \hat{b})$$

Interaction picture:

$$\hat{H}_{\text{om}} = -\hbar\Delta\hat{a}^\dagger\hat{a} + \hbar\Omega\hat{b}^\dagger\hat{b} - \hbar g_0(\hat{b}^\dagger + \hat{b})\hat{a}^\dagger\hat{a} + \hbar\alpha_L(\hat{a}^\dagger + \hat{a}).$$

Strong coherent (optical) drive:

$$-\hbar g_0(\hat{b}^\dagger + \hat{b})\hat{a}^\dagger\hat{a} \rightarrow -\hbar g_0(\hat{b}^\dagger + \hat{b})\left(\bar{\alpha}^2 + \bar{\alpha}(\hat{a}^\dagger + \hat{a}) + \hat{a}^\dagger\hat{a}\right)$$

$$-\hbar G(\hat{b}^\dagger + \hat{b})(\hat{a}^\dagger + \hat{a})$$

$$G = \bar{\alpha}g_0 = \sqrt{n_c}g_0$$

RWA

$$\hat{a} \sim e^{+i\Delta t}; \quad \hat{b} \sim e^{-i\Omega t}$$

$$\Delta = -\Omega \text{ (red detuned)}$$

$$\hat{H}_I = -\hbar G(\hat{b}^\dagger\hat{a} + \hat{b}\hat{a}^\dagger)$$

beam-splitter; state-transfer

$$\Delta = +\Omega \text{ (blue detuned)}$$

$$\hat{H}_I = -\hbar G(\hat{b}^\dagger\hat{a}^\dagger + \hat{b}\hat{a})$$

parametric amplifier; squeezing

Nonlinear quantum optomechanics

P. Rabl, Phys. Rev. Lett. 107, 063601 (2011)

A. Nunnenkamp, K. Børkje, and S. M. Girvin, Phys. Rev. Lett. 107, 063602 (2011)

Single-photon displacement (static)

$$\Delta x = \frac{\hbar g_{\mathrm{OM}}}{m\Omega^2} = 2\frac{g_0}{\Omega} x_{\mathrm{ZPF}}$$

Back-action on cavity

$$\frac{g_{\mathrm{OM}}\Delta x}{\kappa} = 2\frac{g_0^2}{\Omega\kappa} \geq 1$$

Compare to requirement for quantum nonlinearities in atom-photon QED

$$[C_o = g_o^2/\kappa\gamma_i > 1]$$

Consider the momentum transferred by a single photon during its lifetime in the cavity:

$$\Delta p = \frac{c}{2L}\frac{1}{\kappa}\frac{2\hbar\omega_{\mathrm{cav}}}{c} = 2\frac{g_0}{\kappa} p_{\mathrm{ZPF}}$$

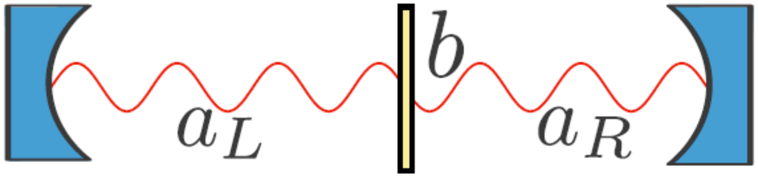
So is it possible then, that quantum nonlinearities might be possible with the (less restrictive) constraint:

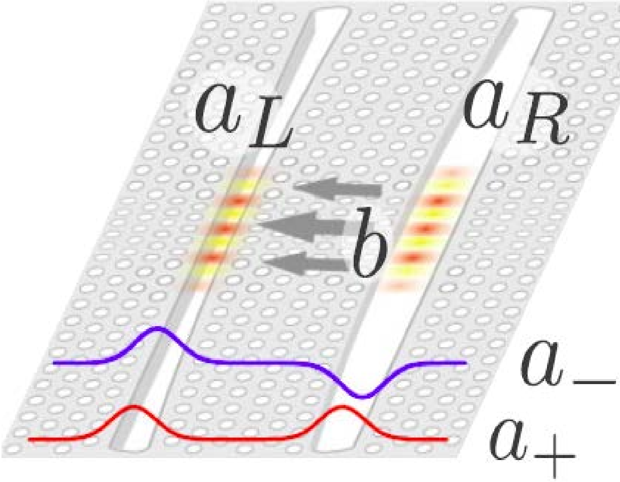
$$g_0 \gtrsim \kappa \text{ but } g_0^2 \ll \Omega\kappa$$

…the two-cavity case

M. Ludwig, Phys. Rev. Lett. 109, 063601 (2012)

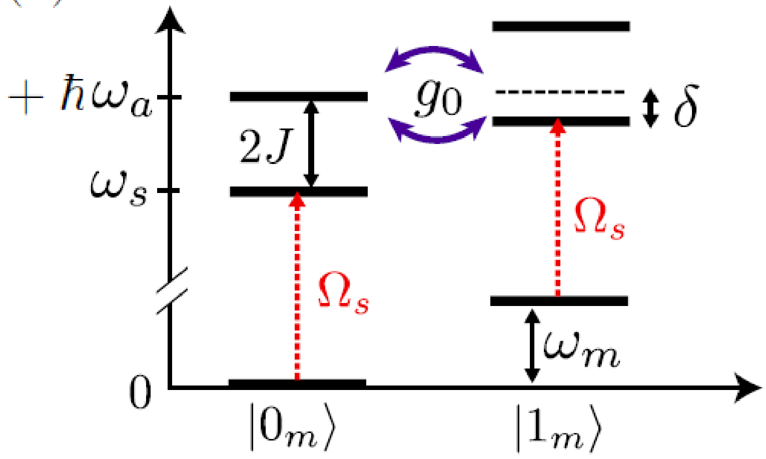
K. Stannigel, et al., Phys. Rev. Lett. 109, 013603 (2012)





$$\hat{H} = \hbar\omega_+(0)\hat{a}^\dagger_+\hat{a}_+ + \hbar\omega_-(0)\hat{a}^\dagger_-\hat{a}_- + \hbar\omega_m\hat{b}^\dagger\hat{b}$$

$$g_1 = -g_2 = g_0$$



$i_+\Big)\,\hat{x}$

$$g_o/\kappa \geq 1; \Omega/\kappa \geq 1 \rightarrow \text{quantum nonlinearities}$$

figures of merit

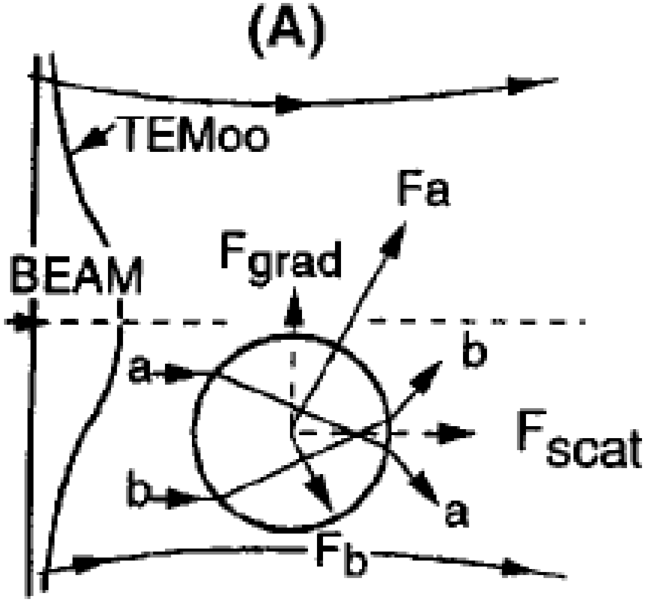
- Optical force per photon: $F_{ph} = \hbar g_{\mathrm{OM}} = \hbar(\partial\omega_c/\partial x)$
- Mechanical zero-point cavity shift: $g_0 = g_{\mathrm{OM}} x_{\mathrm{zpf}}$
- Cavity-resolved motion: $g_0/\kappa > 1 \rightarrow x_{\mathrm{zpf}}$ resolvable
- Single-photon displacement: $g_0/\omega_m > 1 \rightarrow \delta x > x_{\mathrm{zpf}}$
- Sideband resolution: $\omega_m/\kappa > 1 \rightarrow$ RSB limit
- Single-photon cooperativity: $g_0^2/\kappa\gamma_i$
- Other rates and ratios: $g_0^2/\kappa\omega_m > 1 \rightarrow$ quantum nonlinearities

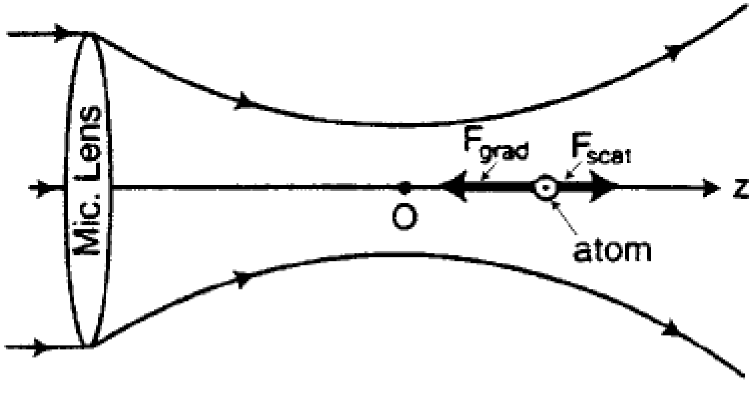
Optical (Laser) Forces

IEEE JOURNAL ON SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 6, NO. 6, NOVEMBER/DECEMBER 2000 841

History of Optical Trapping and Manipulation of Small-Neutral Particle, Atoms, and Molecules

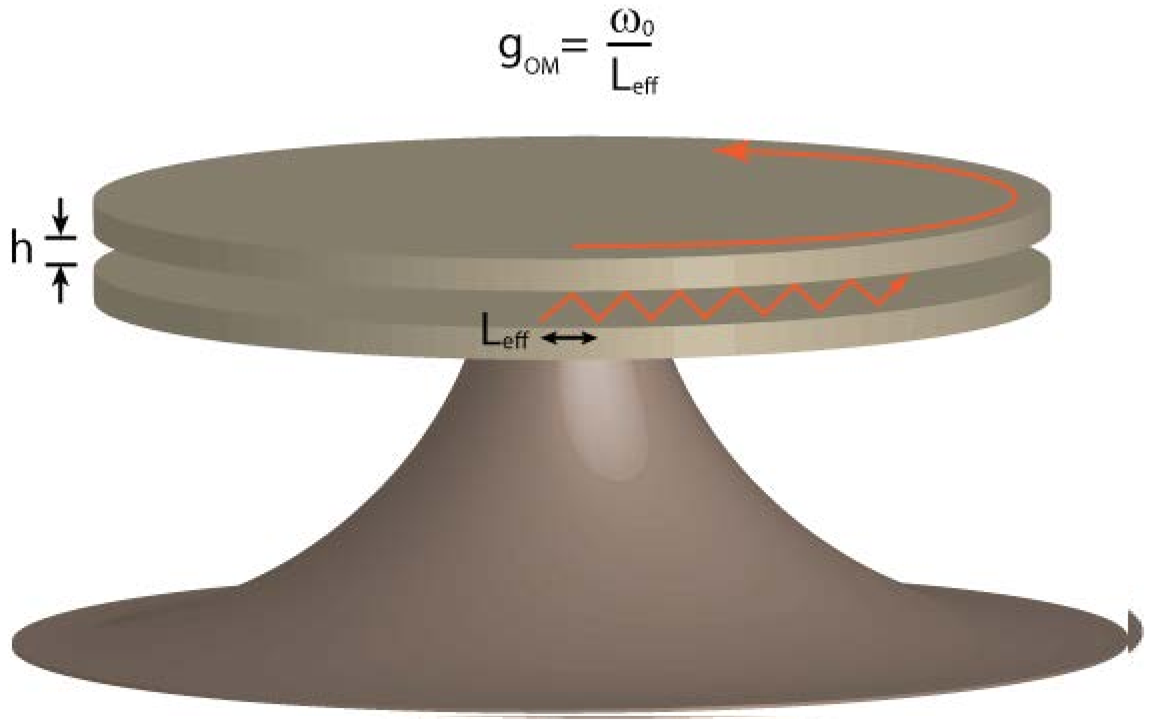
A. Ashkin, *Life Fellow, IEEE*





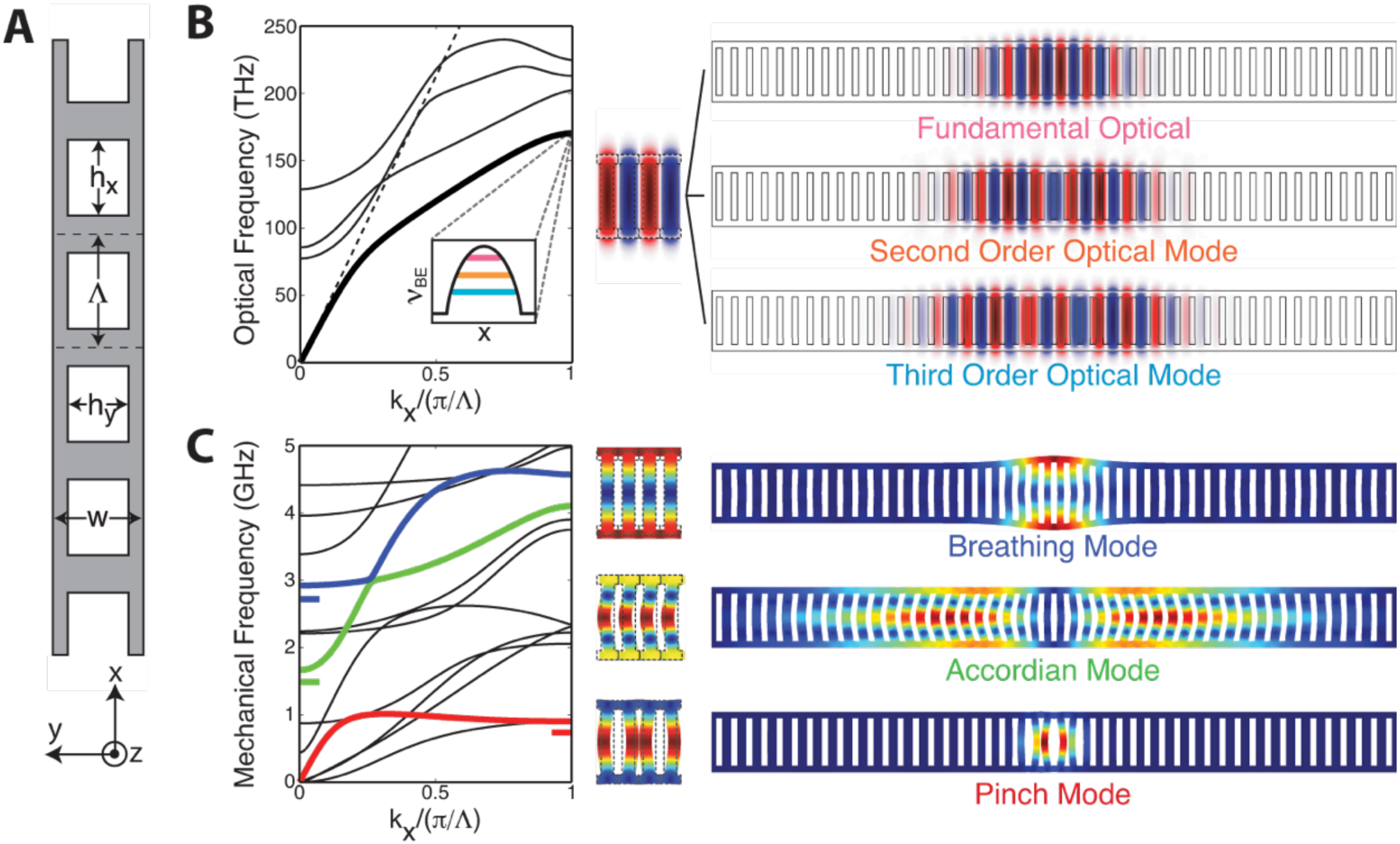
TWEEZERS TRAP

scattering versus gradient forces


$g_{OM} = \frac{\omega_0}{L_{eff}}$

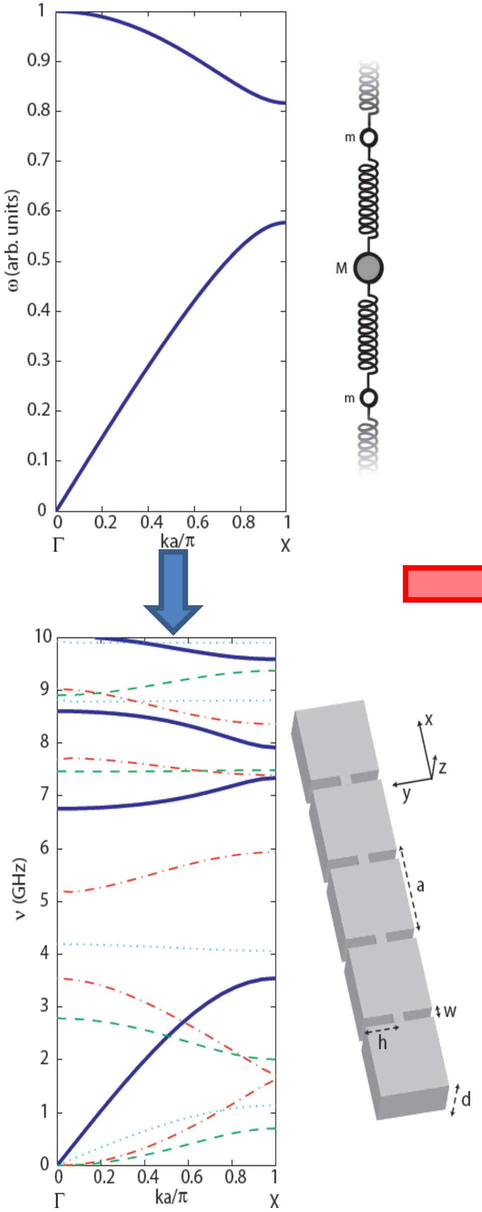
cavity length (mechanical mass) and per-photon force are decoupled

Optomechanical crystal (OMC)

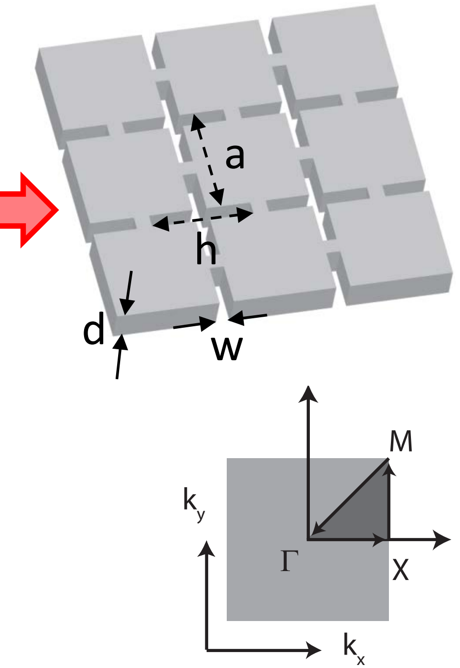


Eichenfield, et al., “Optomechanical Crystals”, Nature (2009)

GHz acoustic bandgaps

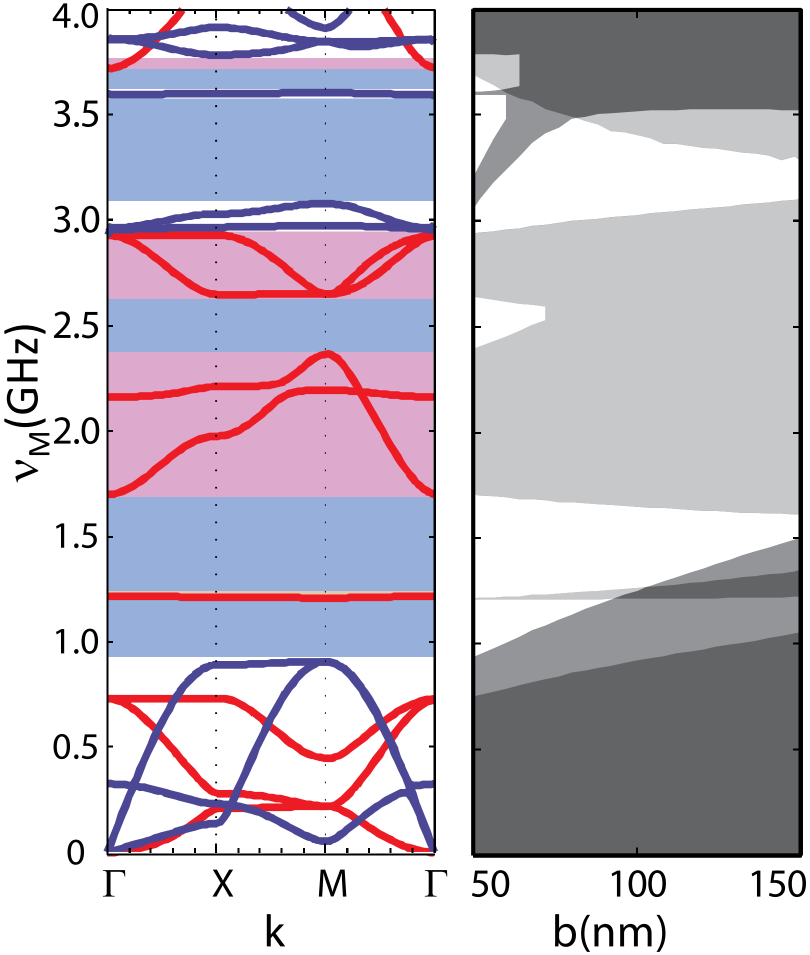


2D-Phononic Crystal Slab



2D Band-Diagram

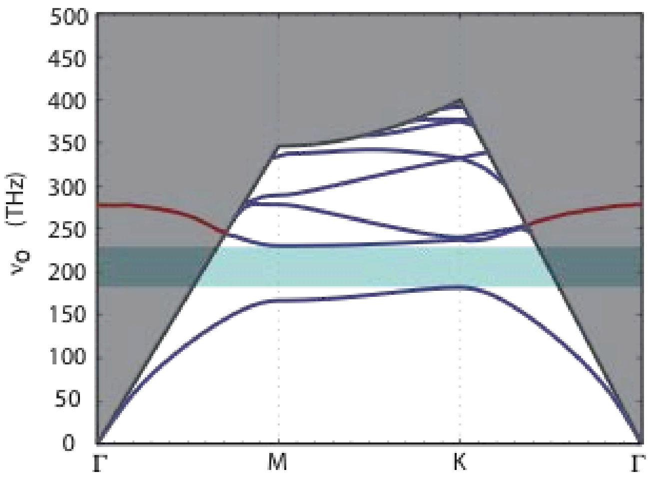
Gap Map

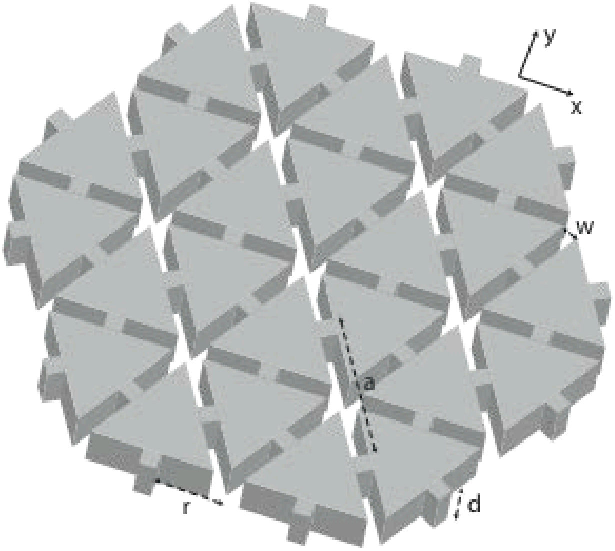


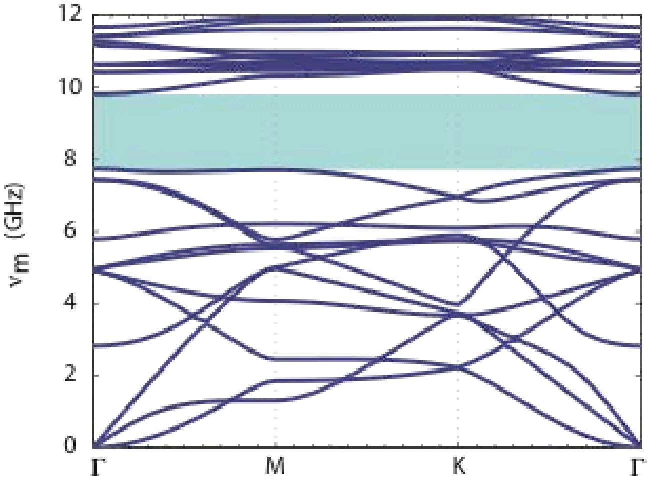
A. H. Safavi-Naeini et. al, Optics Express, **18**, 14926 (2010).

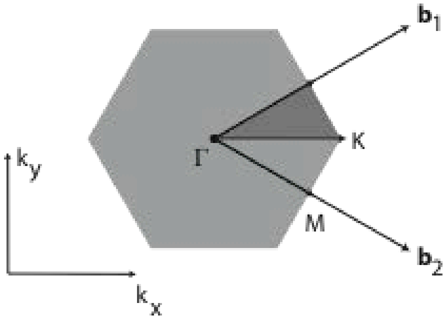
T. P. Mayer Alegre, et. al., Optics Express, **19**, No. 6 5658 (2011).

Quasi-2D "snowflake" crystals



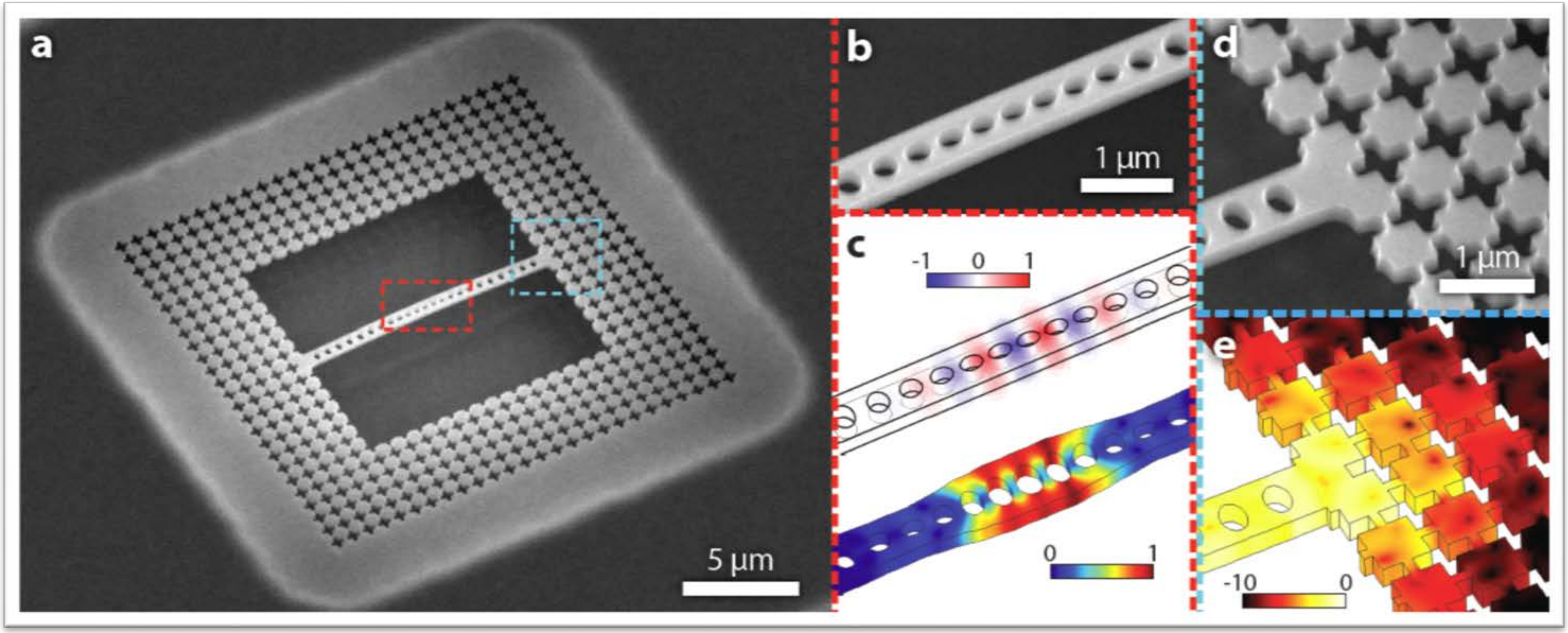






Full photonic and phononic bandgap

Cavity-Optomechanical Circuits

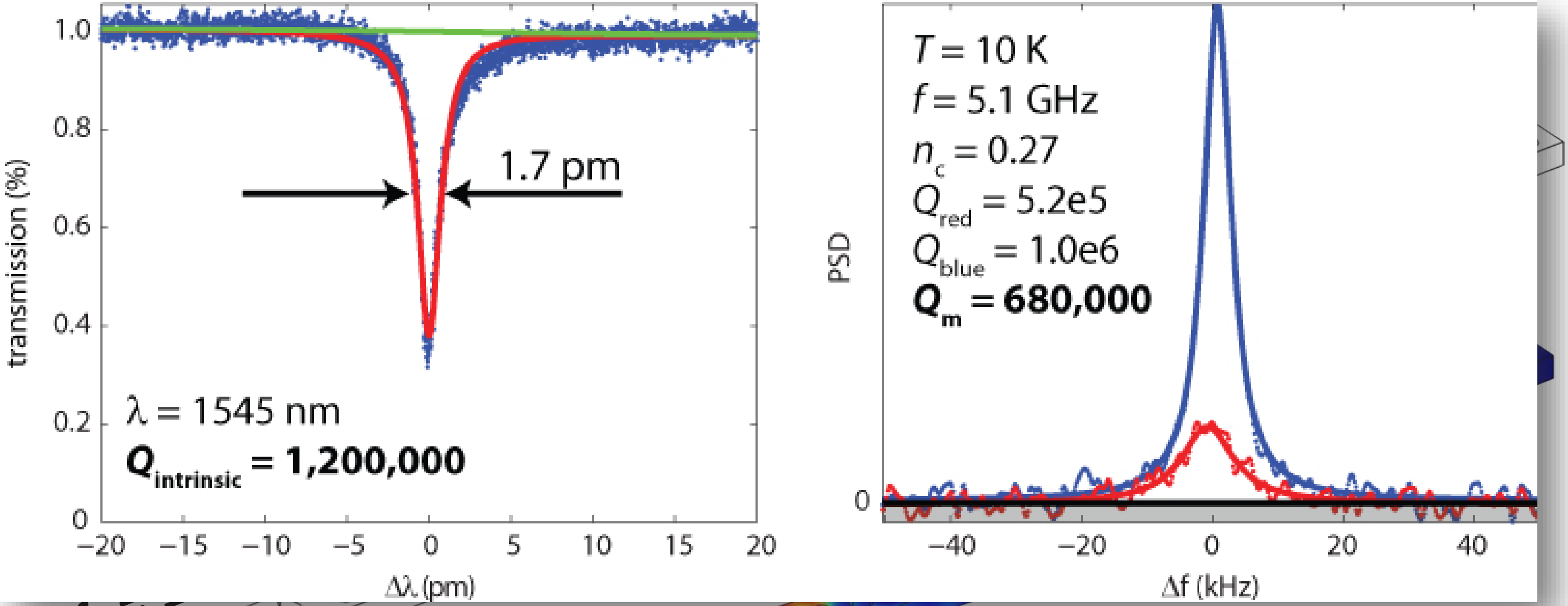


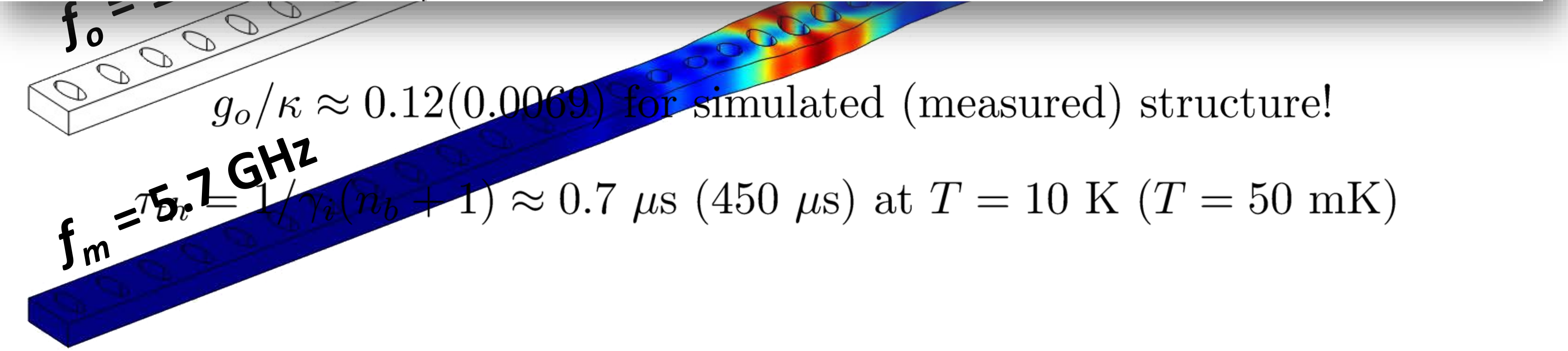
J. Chan, et. al, *Nature*, v478, pg. 89–92 (2011)

- ✓ "printable" circuits for photons and phonons formed in the thin-film surface layer of a microchip
- ✓ Independent routing of acoustic and optical waves
- ✓ Strong localization of acoustic and optical energy leading to large radiation pressure effects

1D nanobeam OMC: state-of-the-art

$g_{\text{moving boundary}}$ = -96 kHz (theory)





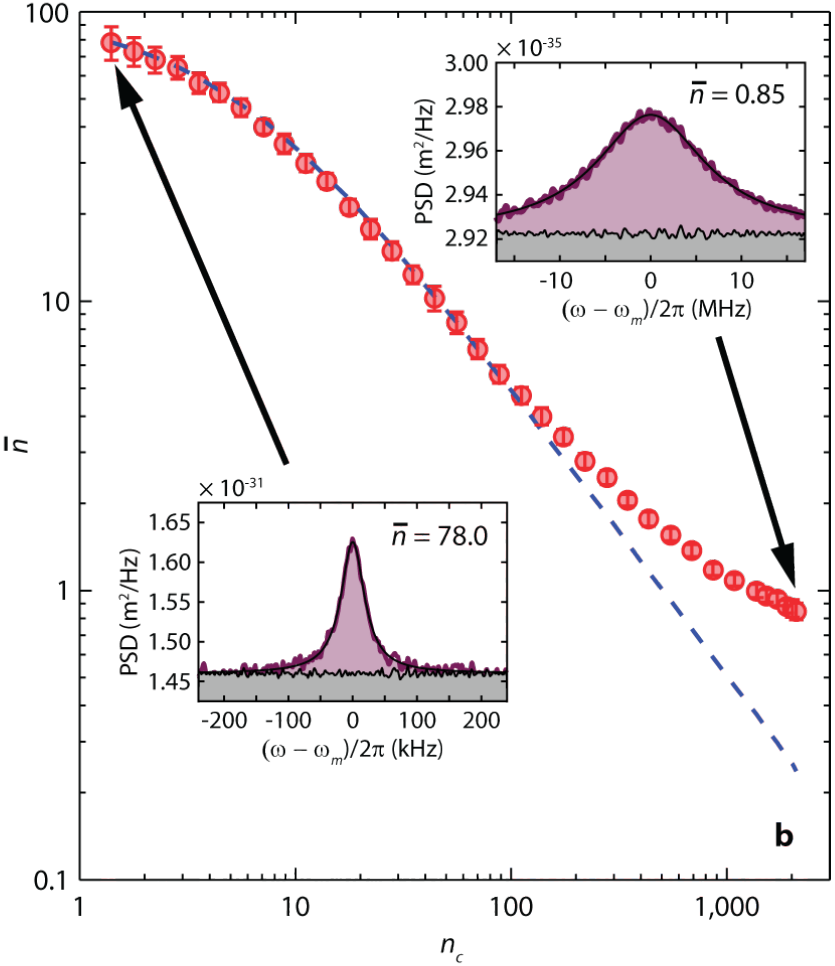
$g_o/\kappa \approx 0.12(0.0069)$ for simulated (measured) structure!

$\tau_r = 1/\gamma_i(n_b + 1) \approx 0.7\ \mu s\ (450\ \mu s)$ at $T = 10$ K ($T = 50$ mK)

1D-OMC experiments…

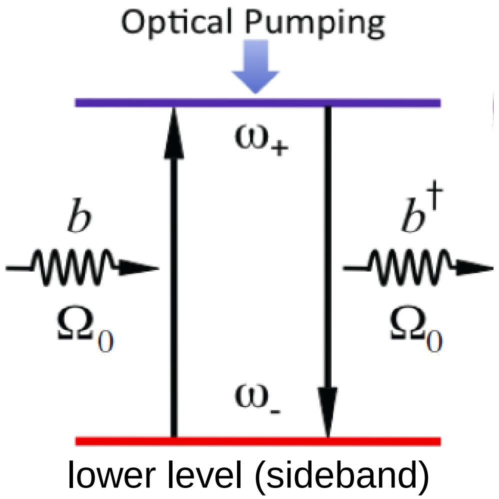
- Electromagnetically induced transparency/amplification (EIT/EIA) and slow light [1]
  - Optical delay ~50 ns (advance ~1.4μs)
- Ground-state cooling [2]
  - $\langle n \rangle_{\min} = 0.85 \pm 0.09$
- Quantum zero-point motion [3]
  - 40% asymmetry in Stokes/Anti-Stokes scattering sideband at 2.6 ± 0.2 phonon occupancy
- Coherent wavelength conversion [4]
  - 93(2)% internal (external) conversion efficiency between 1400 nm and 1500 nm telecom wavelength bands
- Optical squeezing [5]
  - Modest squeezing of ~5% below shot-noise demonstrated by reflecting coherent laser light off of a silicon micromechanical resonator

[2] Chan *et al.*, *Laser cooling of a nanomechanical oscillator into its quantum ground state*, Nature **2011**

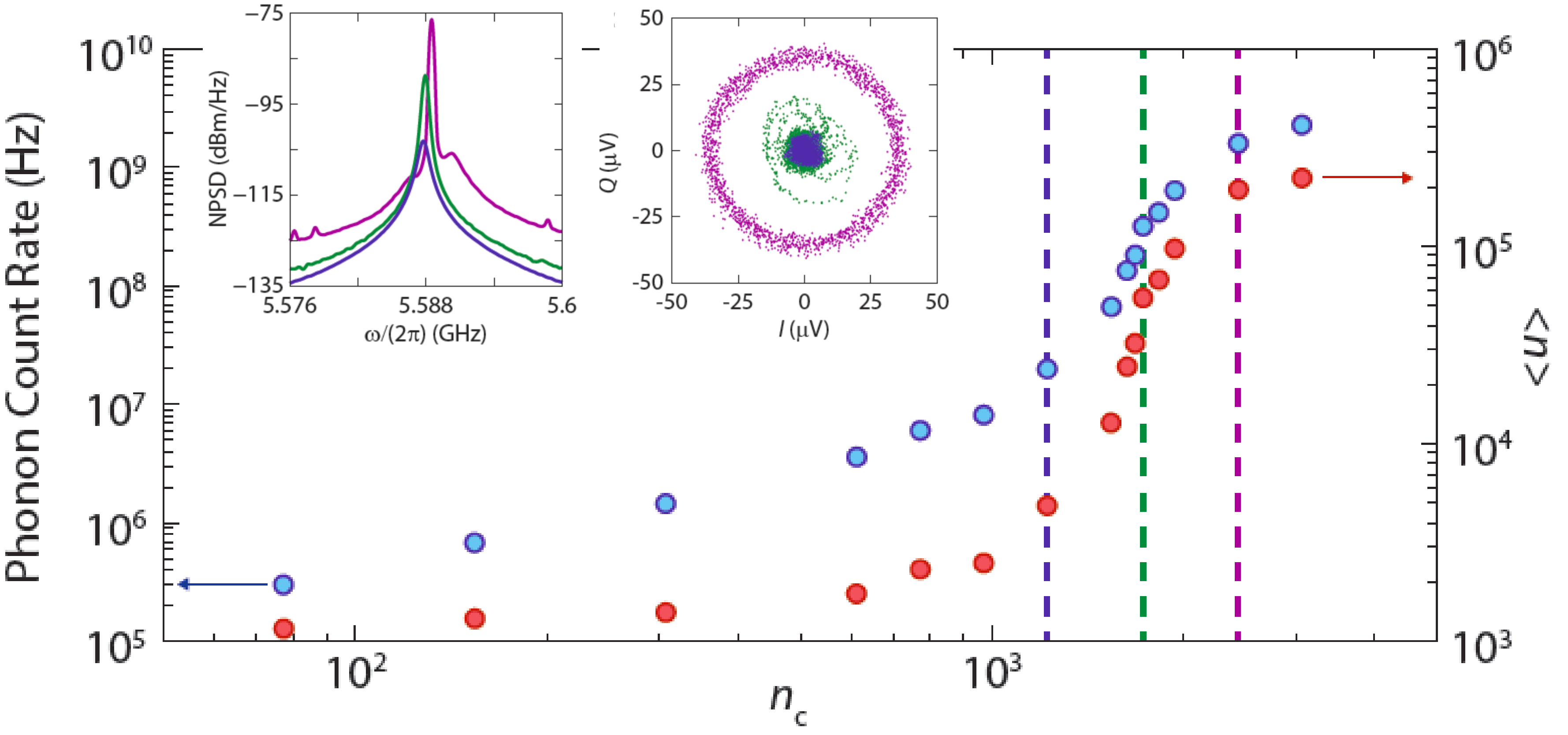


[1] Safavi-Naeini, Alegre *et al.*, *Electromagnetically Induced Transparency and Slow Light with Optomechanics*, Nature **2011**
[3] Safavi-Naeini *et al.*, *Observation of quantum motion of a nanomechanical resonator*, Phys. Rev. Lett. **2012**
[4] Hill *et al.*, *Coherent wavelength conversion via cavity-optomechanics*, Nature Communications **2012**
[5] Safavi-Naeini *et al.*, *Squeezed light from a Silicon micromechanical resonator*, in press **2013**

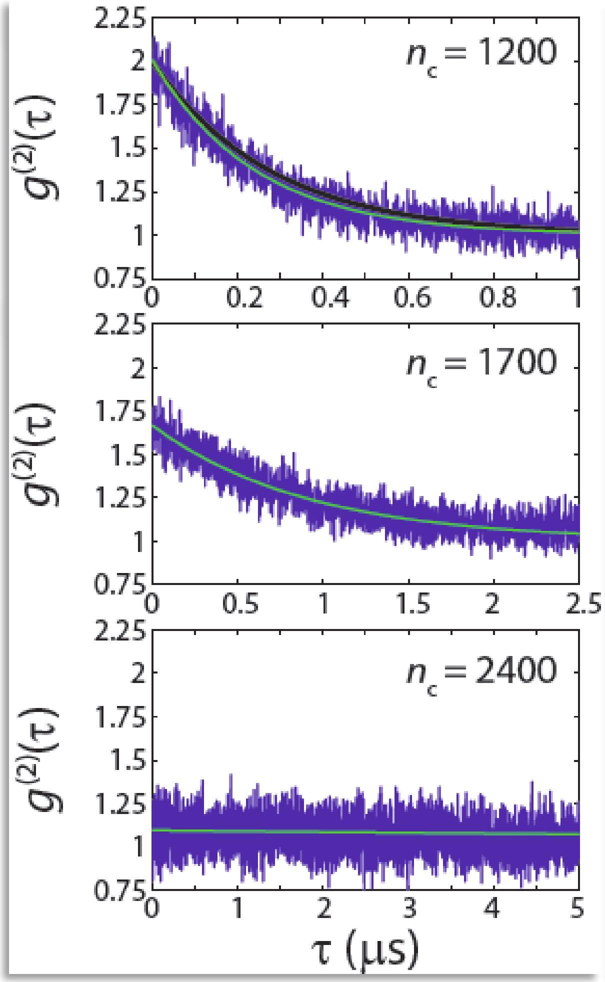
Blue Detuned Pumping: Self-Oscillation (“phonon lasing”)

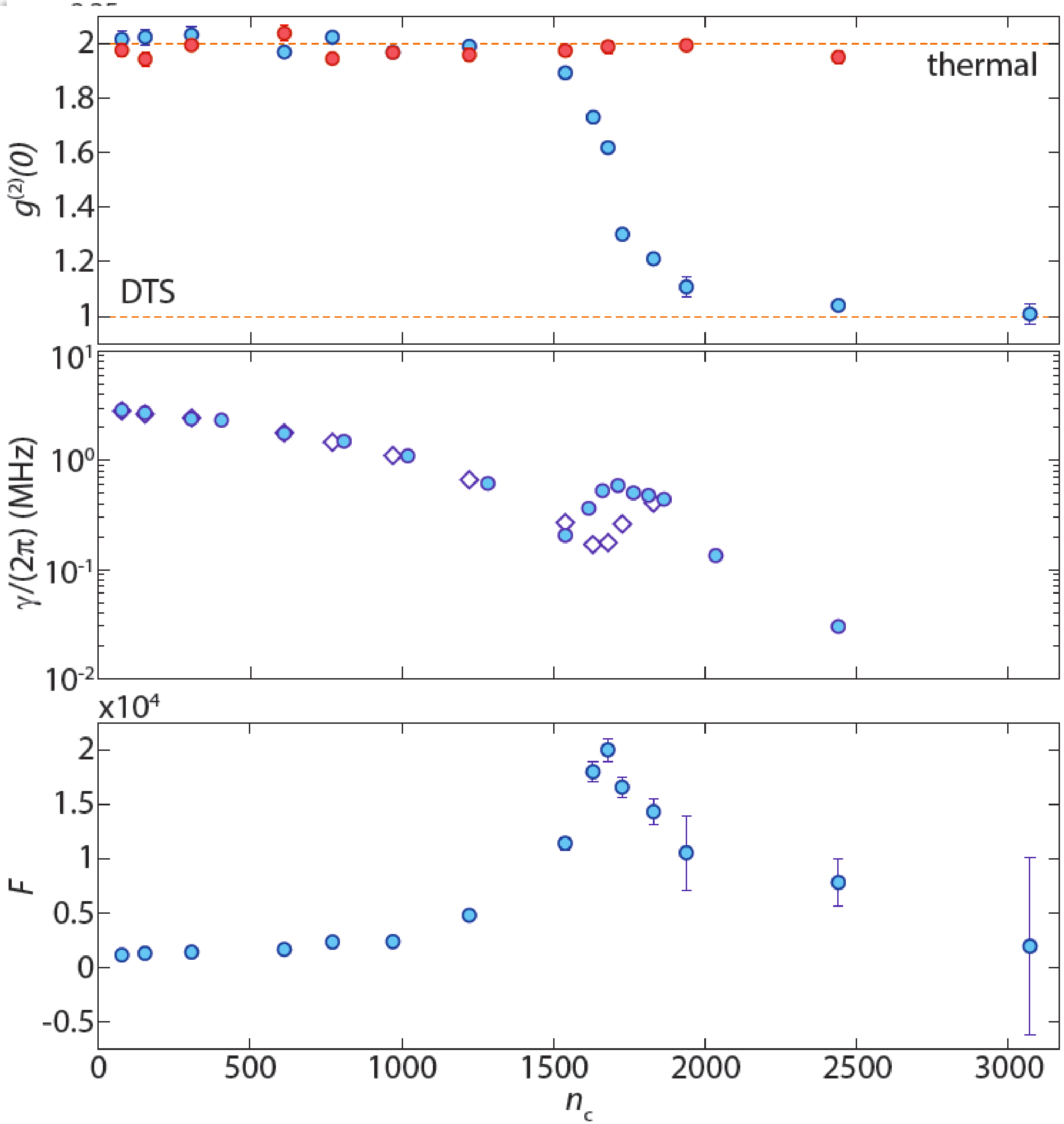


- In a cavity optomechanical system with photon decay rate >> mechanical decay rate, a direct analogy between the parametric instability resulting in self-oscillation and a laser can be made [*Grudinin, et al., **PRL**, 104, 083901 (2010)*]



Phonon Intensity Correlations

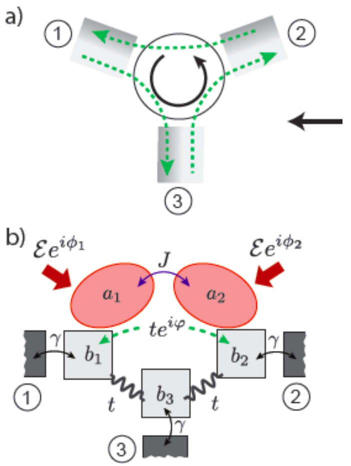




Multi-element optomechanical circuits

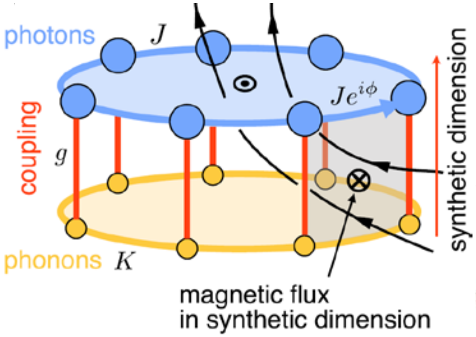
Phononic quantum networks

[S. Habraken, et al, NJP art. 115004 (2012)]



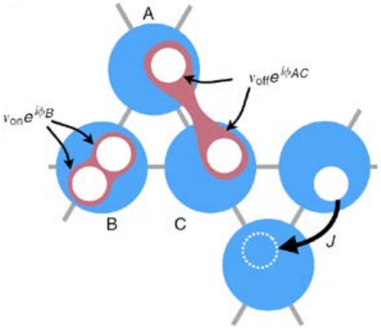
Synthetic magnetic field for photons on a lattice

[S. Schmidt, et al, Optica, doi:10.1364/OPTICA.2.000635]



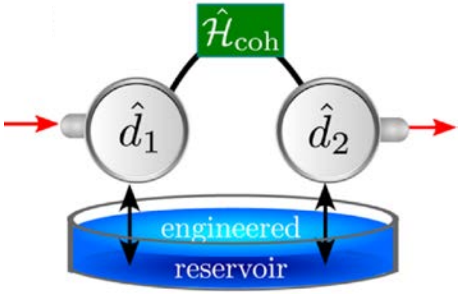
Topological phase transitions and chiral inelastic transport induced for particle non-conserving interactions

[V. Peano, et al, Nat. Comm., doi: 10.1038/ncomms10779]

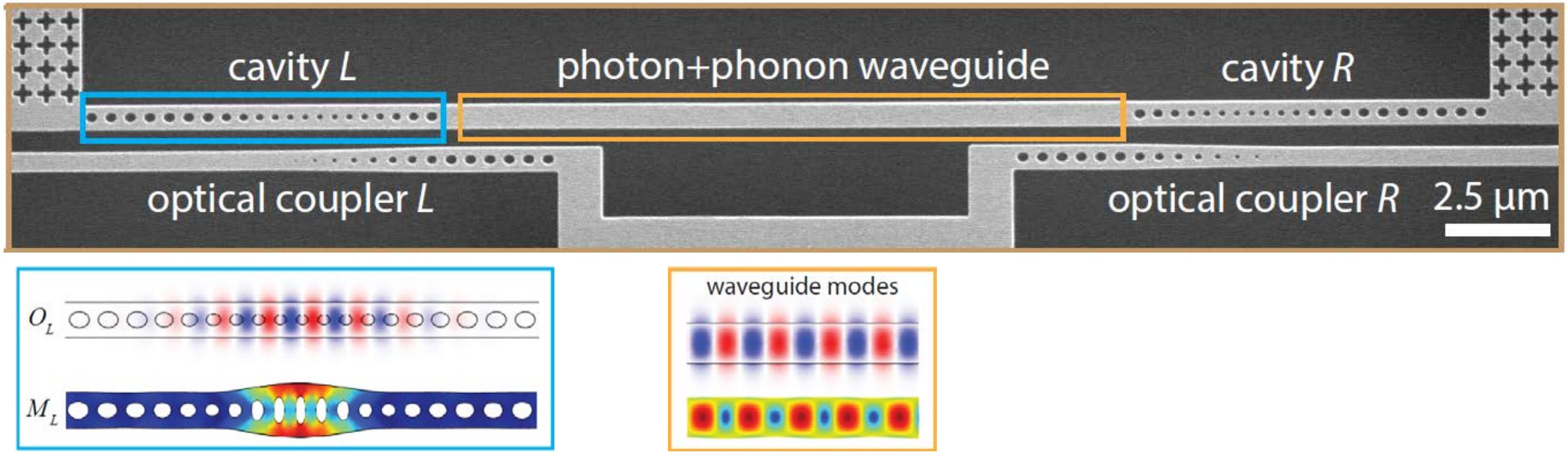


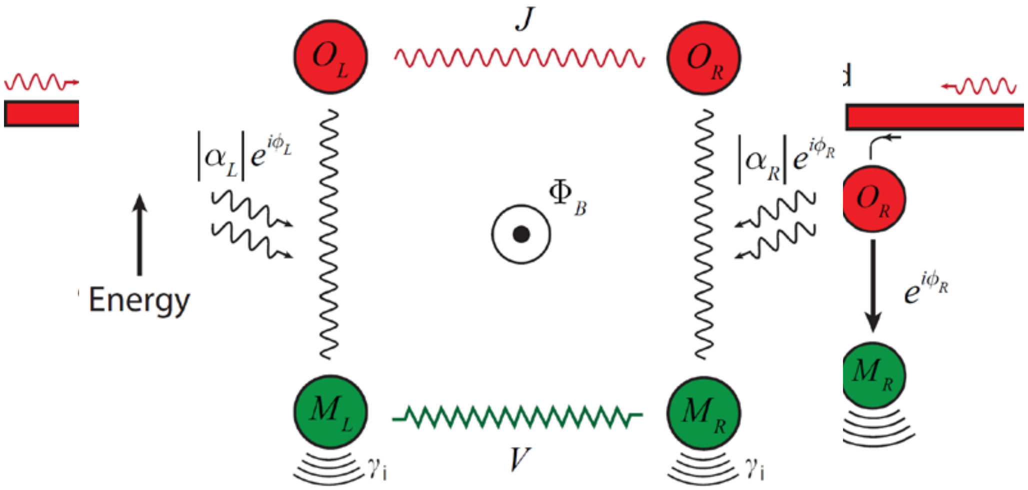
Nonreciprocal photon transmission and amplication via reservoir engineering

[A. Mettelmann and Aash Clerk, PRX, art. 021025 (2015)]



Optomechanical directional amplifier circuit



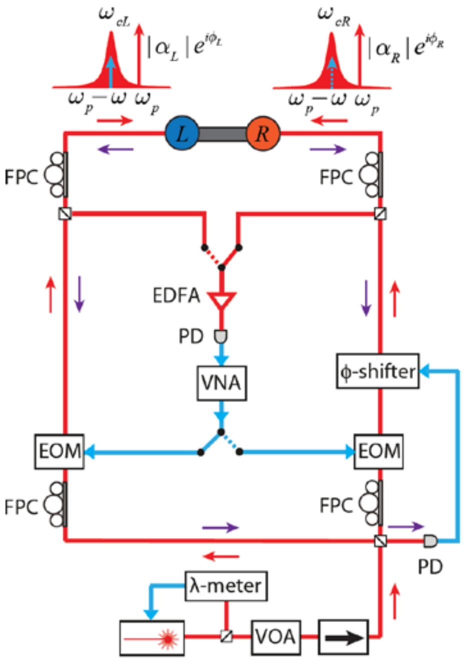


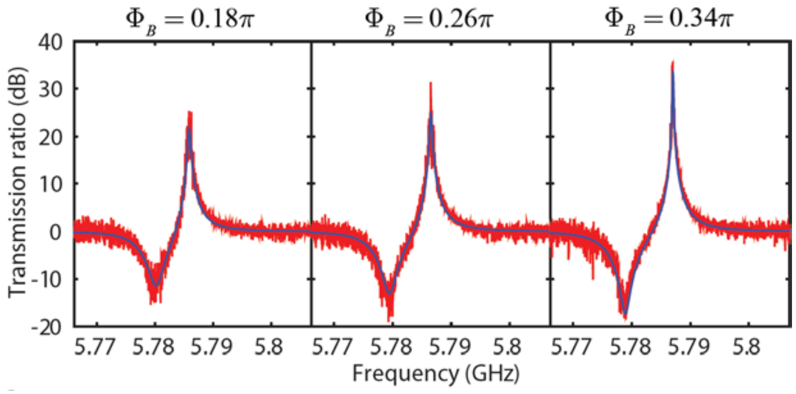
$$T_{\mathrm{L}\to\mathrm{R}}[\omega; \Delta = \pm\omega_{\mathrm{m}}] = A_{\pm}[\omega]\left(J - \Gamma_{\pm}[\omega]e^{\mp i\Phi_{\mathrm{B}}}\right)$$

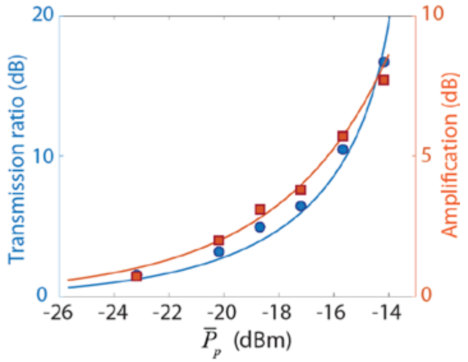
$$\Gamma_{\pm}[\omega] = \frac{V G_{\mathrm{L}} G_{\mathrm{R}}}{(i(\omega - \omega_{\mathrm{mL}}) \pm \frac{\gamma_{\mathrm{iL}}}{2})(i(\omega - \omega_{\mathrm{mR}}) \pm \frac{\gamma_{\mathrm{iR}}}{2}) + V^2}$$

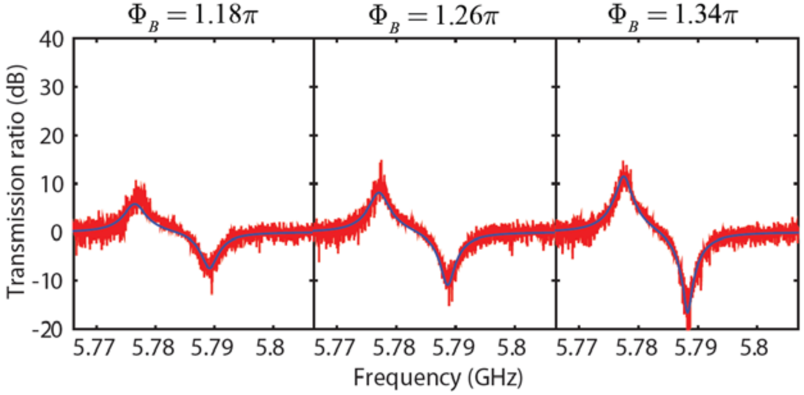
$$\left(\frac{T_{\mathrm{L}\to\mathrm{R}}}{T_{\mathrm{R}\to\mathrm{L}}}\right)[\omega; \Delta = \pm\omega_{\mathrm{m}}] = \frac{J - \Gamma_{\pm}[\omega]e^{\mp i\Phi_{\mathrm{B}}}}{J - \Gamma_{\pm}[\omega]e^{\pm i\Phi_{\mathrm{B}}}}$$

Measured circuit properties





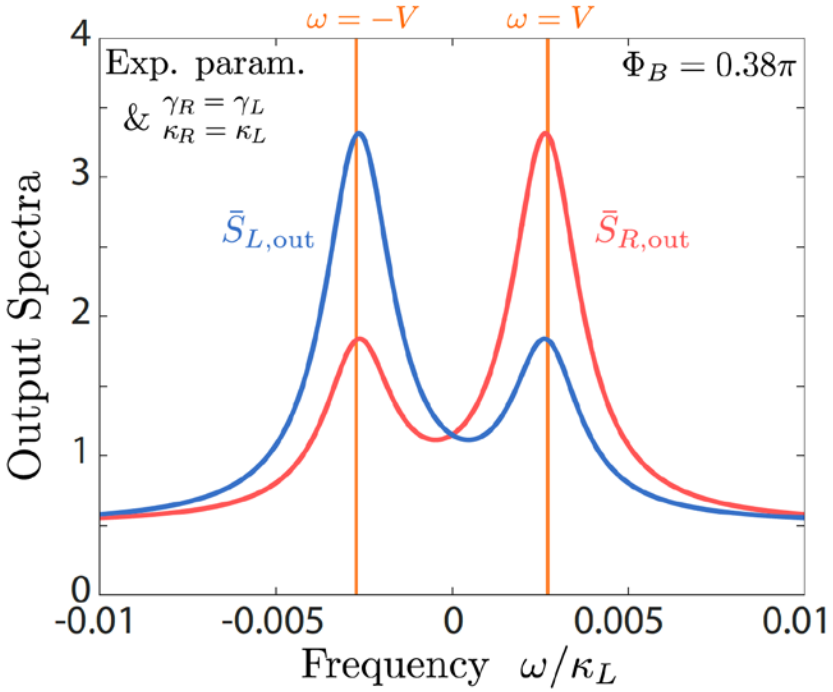


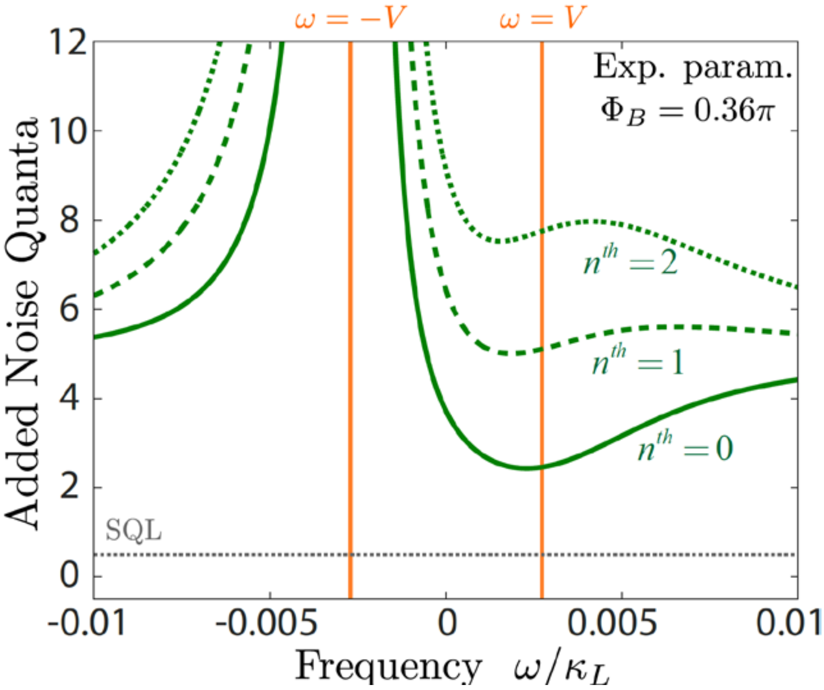


circuit parameters

$$J/2\pi \approx 110\ \text{MHz}$$
$$V/2\pi \approx 2.8\ \text{MHz}$$
$$\kappa/2\pi \approx 1\ \text{GHz}$$
$$\gamma/2\pi \approx 3\ \text{MHz}$$

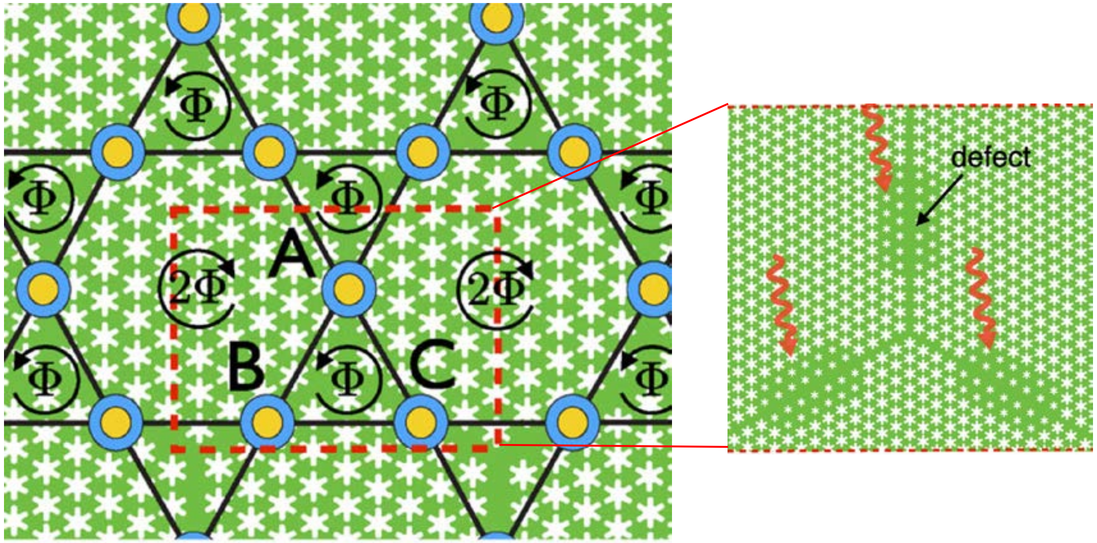
Noise properties (theory)



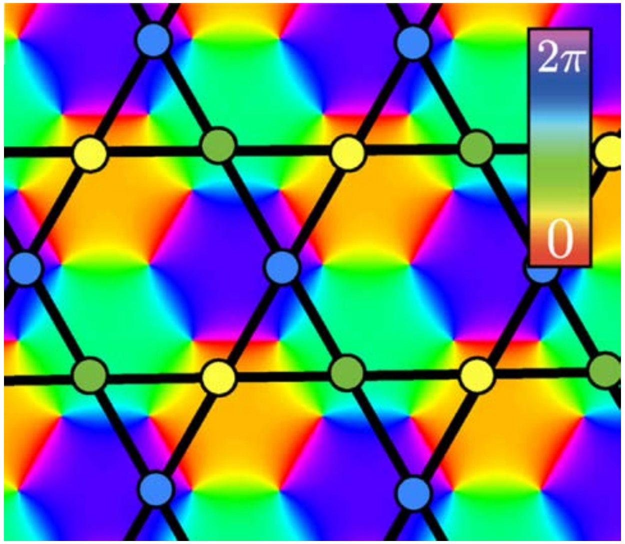


OMC lattice: Chern Insulator for phonons/photons

Topological Phases of Sound and Light
[V. Peano, et al, Phys. Rev. X, DOI: 10.1103/PhysRevX.5.031011]



🔵 optical defect mode
🟡 mechanical defect mode



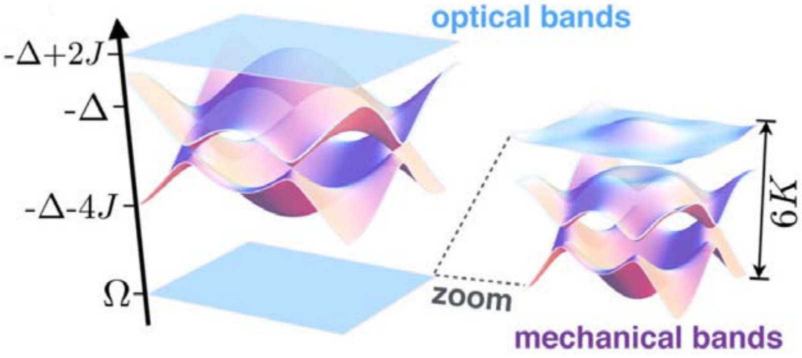
Phase pattern of 3 interfering laser beams of the same frequency but 120 degrees rotated from each in other in plane

OMC lattice: Chern Insulator for phonons/photons

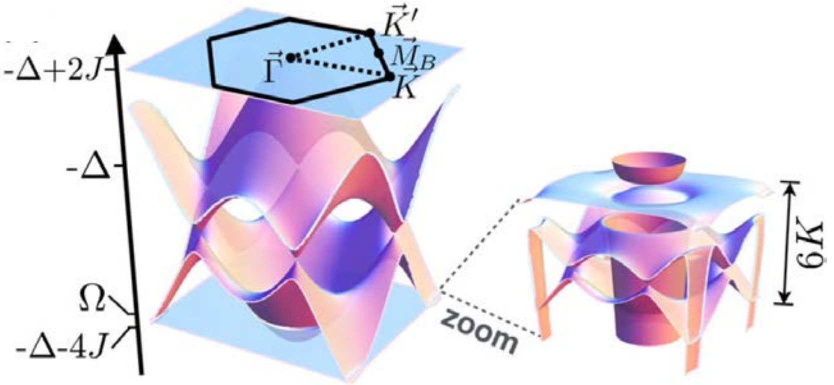
Topological Phases of Sound and Light

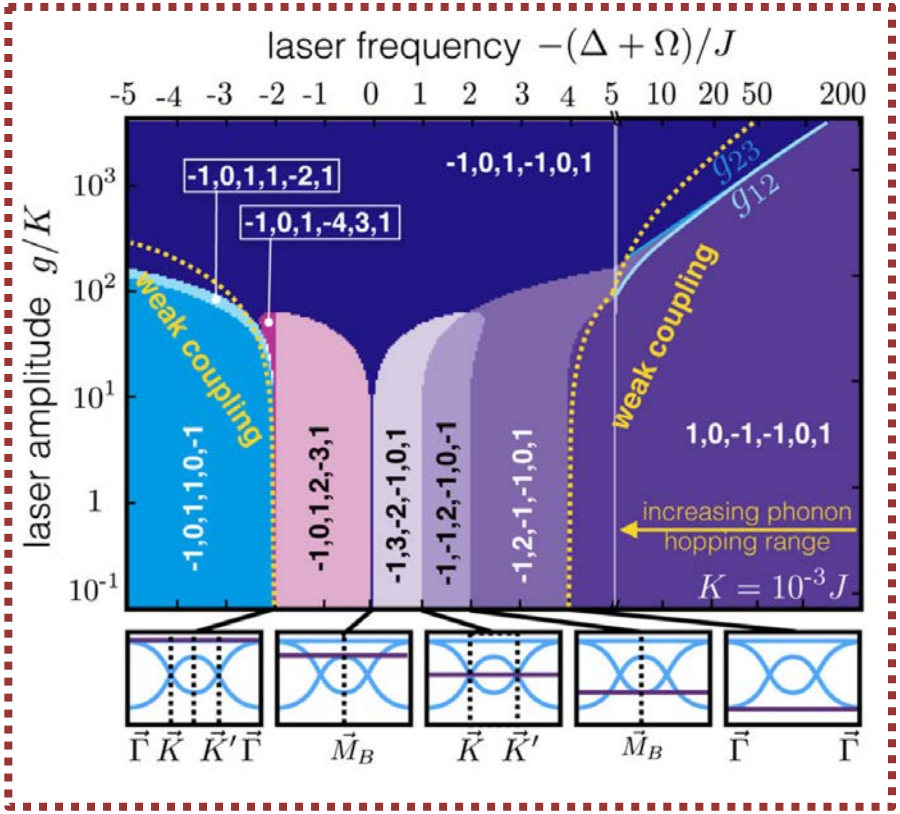
[V. Peano, et al, Phys. Rev. X, DOI: 10.1103/PhysRevX.5.031011]

“weak” coupling → $K_{ij}^{(\mathrm{eff})} \approx K + e^{-i2\pi/3} Jg^2/(\Delta+\Omega)^2 \equiv K^{(\mathrm{eff})} e^{i\Phi/3}$; $\Phi = -\frac{3\pi}{2} + 3\arctan\frac{2K(\Delta+\Omega)^2 - Jg^2}{\sqrt{3}Jg^2}$

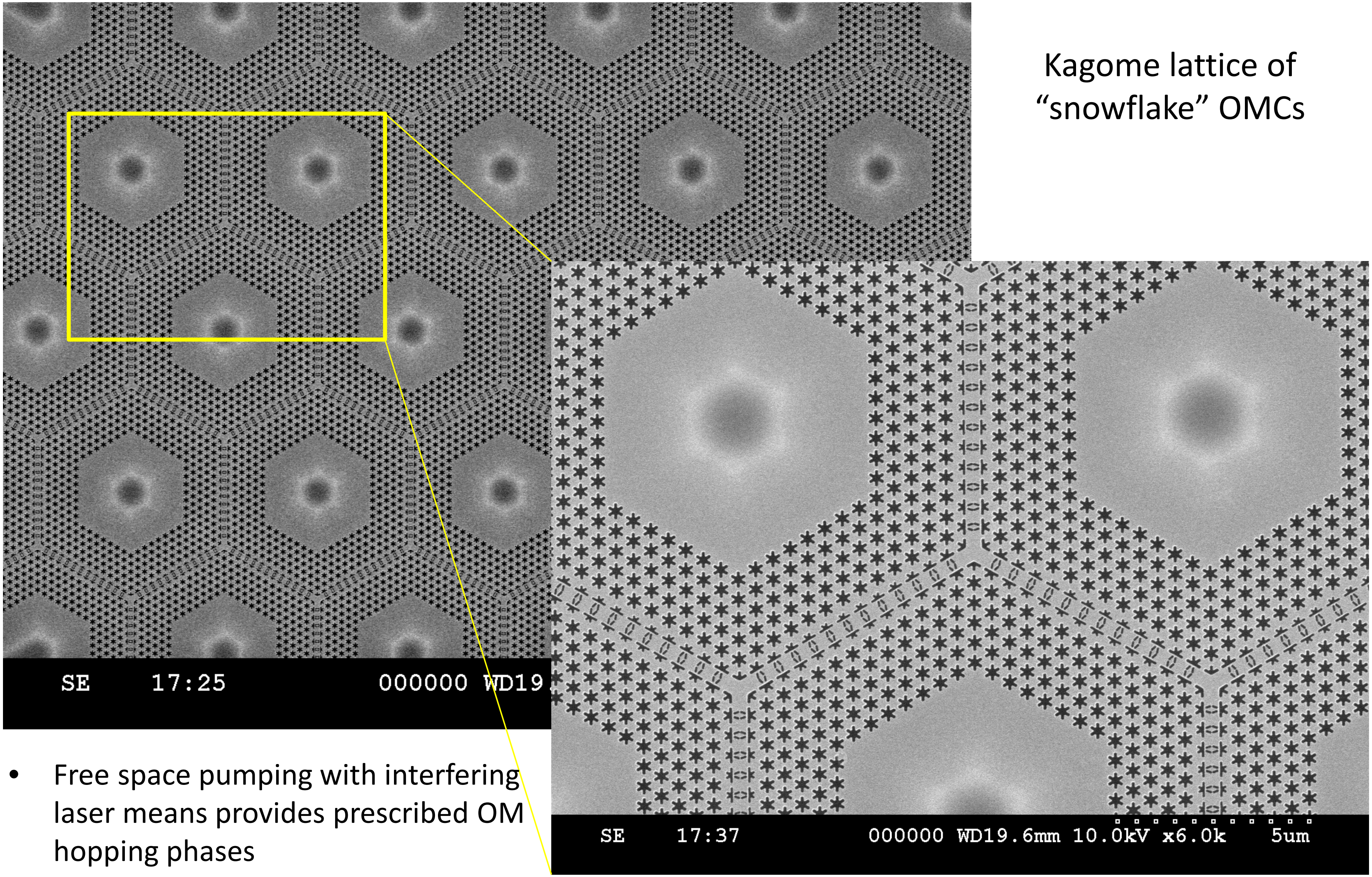


“strong” coupling [$\Delta_{34} \equiv -\Delta - 4J - \Omega + 2K \gg g$]



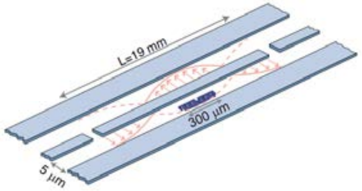


Snowflake OMC lattice…work in progress

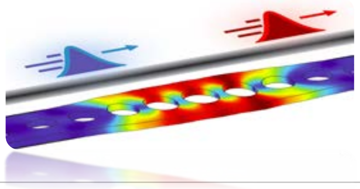


Kagome lattice of
“snowflake” OMCs

- Free space pumping with interfering laser means provides prescribed OM hopping phases



Circuit QED + OMCs



μw Circuits + Optomechanics: ‘Quantum Microwave Photonics‘

Microwaves

- Good qubits
- Very large g

→ Processing

Optics

- Low loss
- Noise resilient

→ Communication

AO transducer

- State synthesis and distribution
- Interface for circuits and atoms
- ‘Quantum Internet’

μw Circuits + Acoustic Cavities: ‘Microwave Phonon Circuits‘

GHz acoustics

- No active cooling
- Acoustic waveguides & circuits
- Phonon interference, entanglement

Why with microwaves?

- Less heating
- Circuit QED toolbox
- Fully engineered

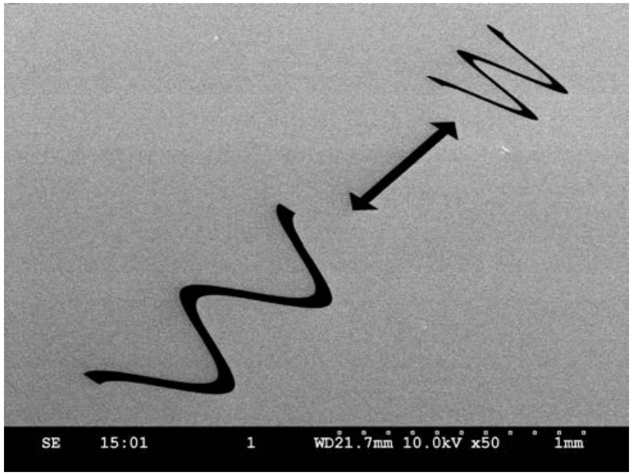
Challenges

- Losses & materials
- Complex fabrication

- Size mismatch → small g_{em}
- Low bandwidth

- Heating
- Quasiparticles

Squishing a microwave photon down to the optical scale



- In optomechanics:

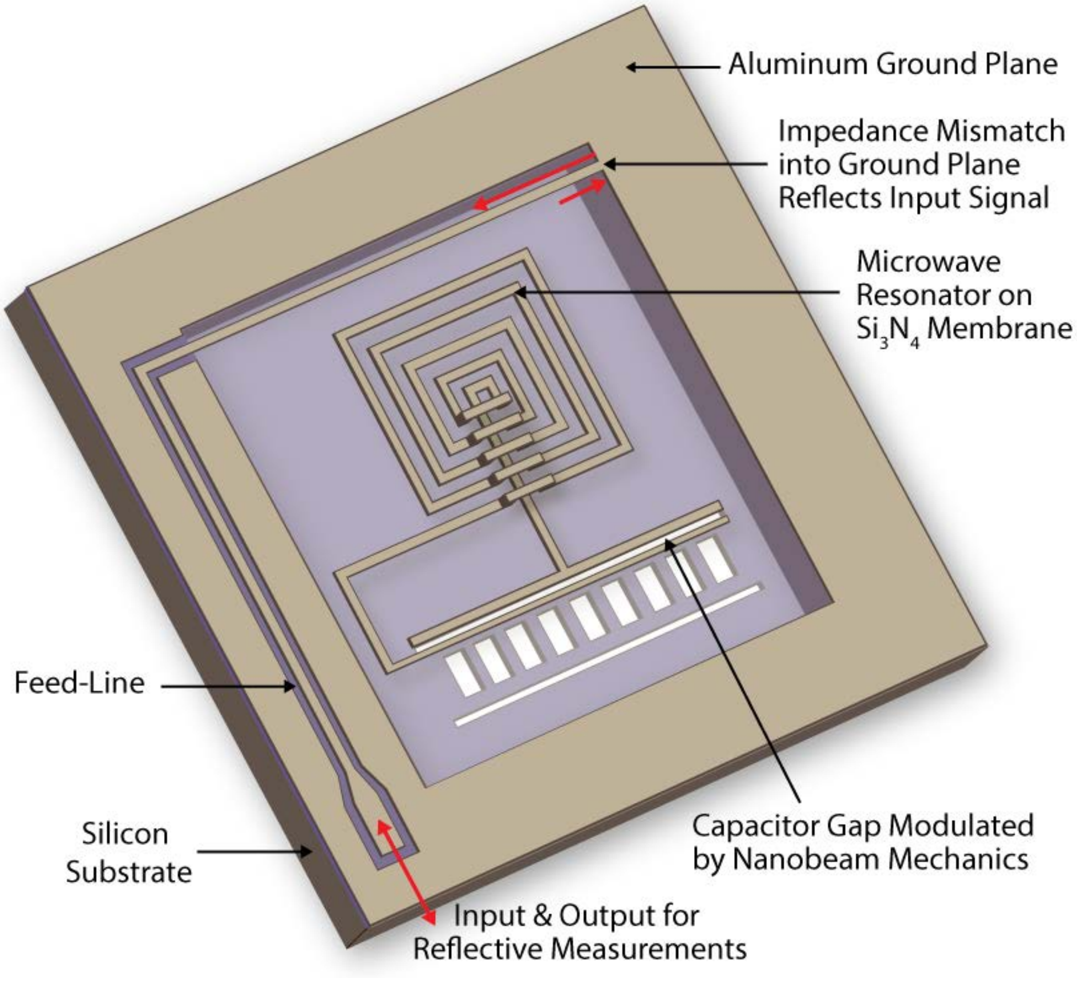
$$g_{0,\mathrm{o}} \approx \omega_\mathrm{o}\left(\frac{x_\mathrm{zpf}}{L_\mathrm{cav}}\right) \sim \omega_\mathrm{o}\left(\frac{x_\mathrm{zpf}}{\lambda_\mathrm{o}}\right) \sim \frac{1\ \mathrm{MHz}}{[\mathrm{fm}][\mu\mathrm{m}^{-1}]}$$

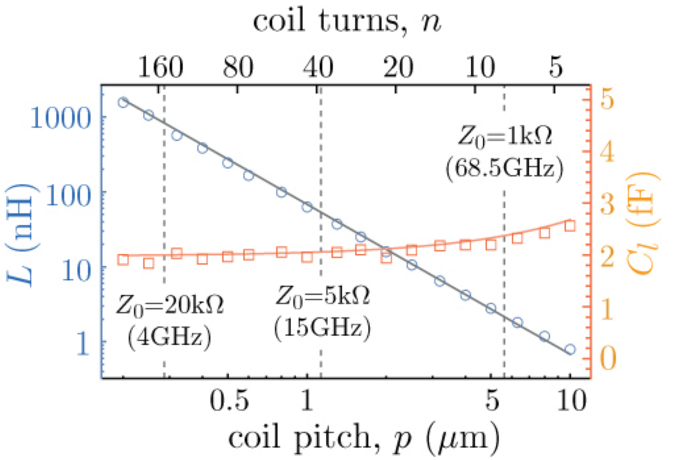
- In electromechanics:

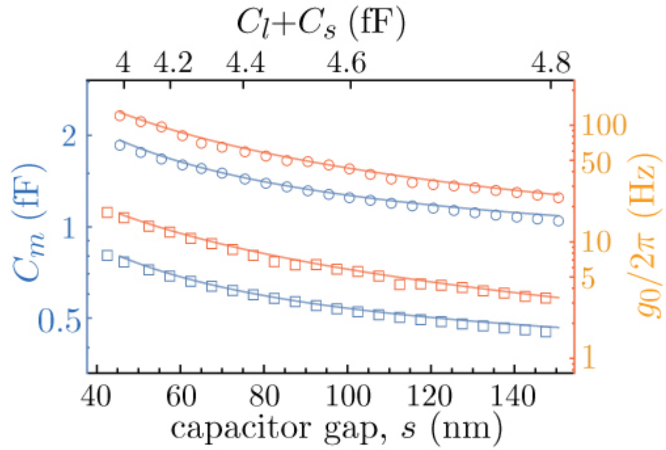
$$g_{0,\mathrm{LC}} \approx (\eta/2)\,\omega_\mathrm{LC}\left(\frac{x_\mathrm{zpf}}{x_g}\right);\ \eta \equiv \frac{C_\mathrm{m}}{C_\mathrm{m}+C_\mathrm{s}};\ x_g \equiv \text{capacitor gap}$$

$$\approx \left(\frac{C_\mathrm{m}V^2_{\mathrm{LC,ph}}}{2\hbar}\right)\left(\frac{x_\mathrm{zpf}}{x_g}\right) \sim \frac{10\ \mathrm{Hz}}{[\mathrm{fF}][\mu\mathrm{V}]^2[\mathrm{fm}][\mathrm{nm}^{-1}]}$$

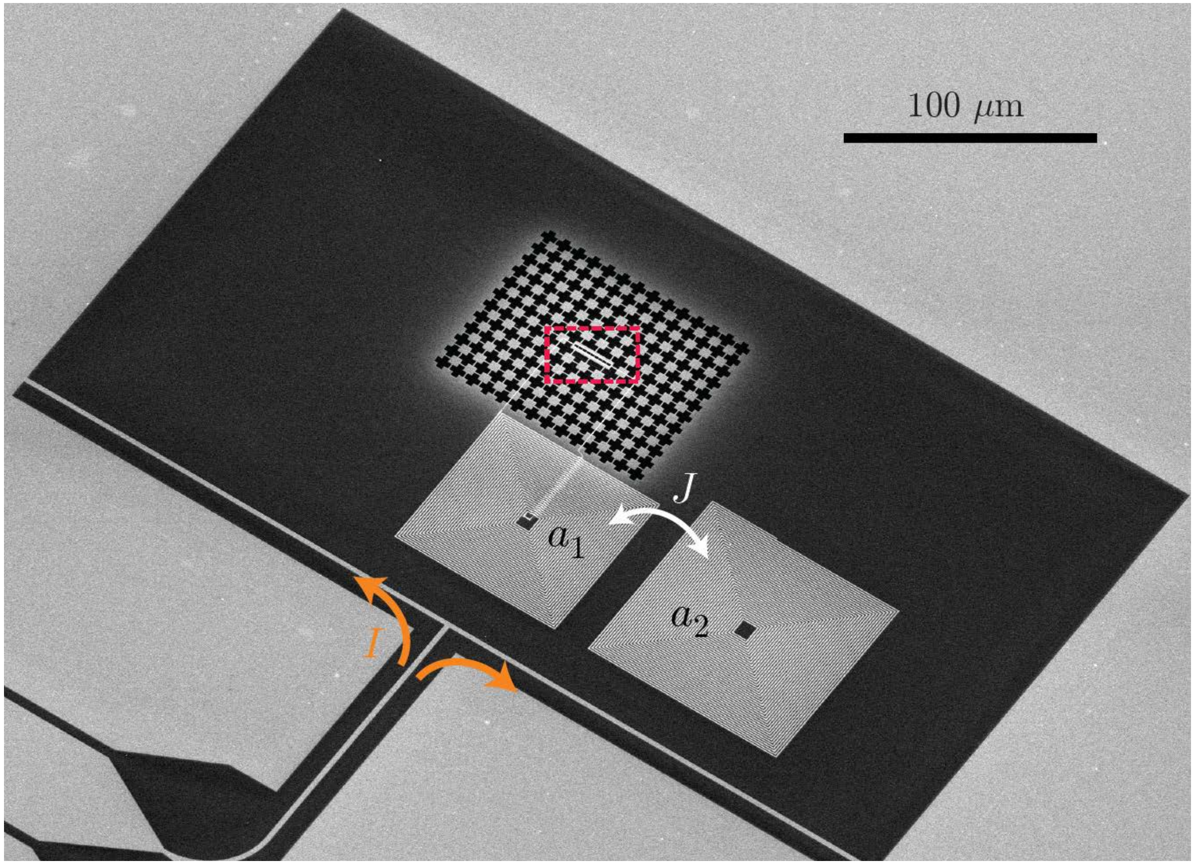
High impedance superconducting coils

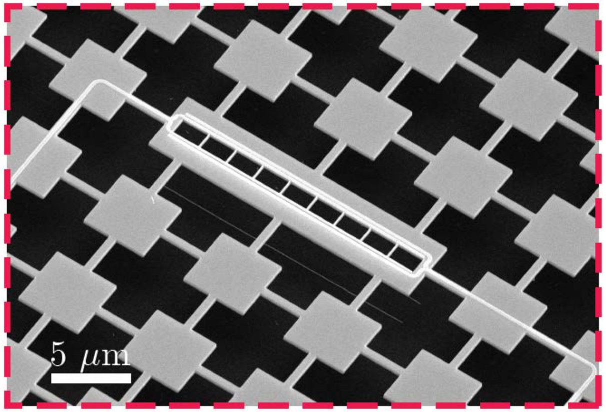


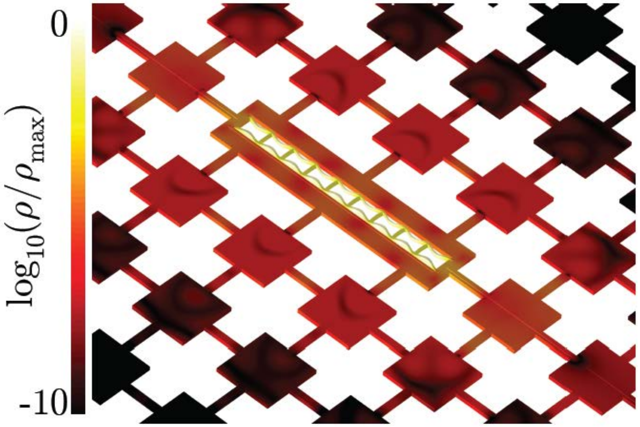


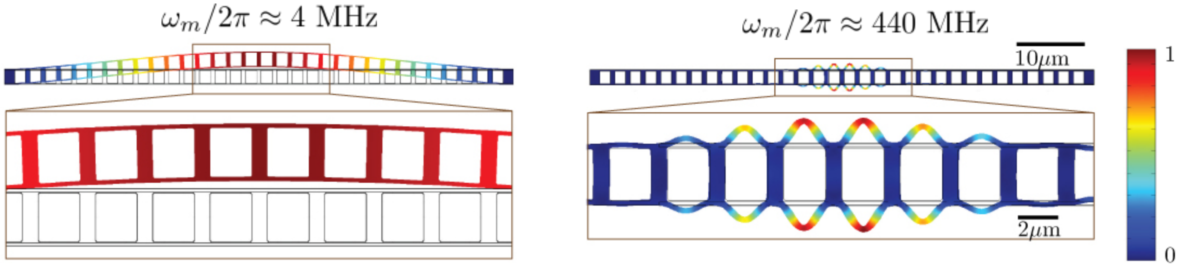


Electro-mechanical crystals (EMCs)



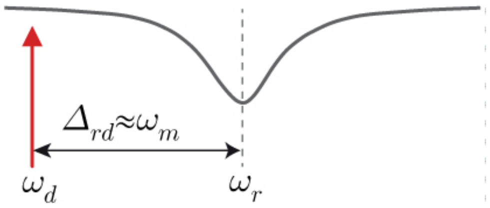


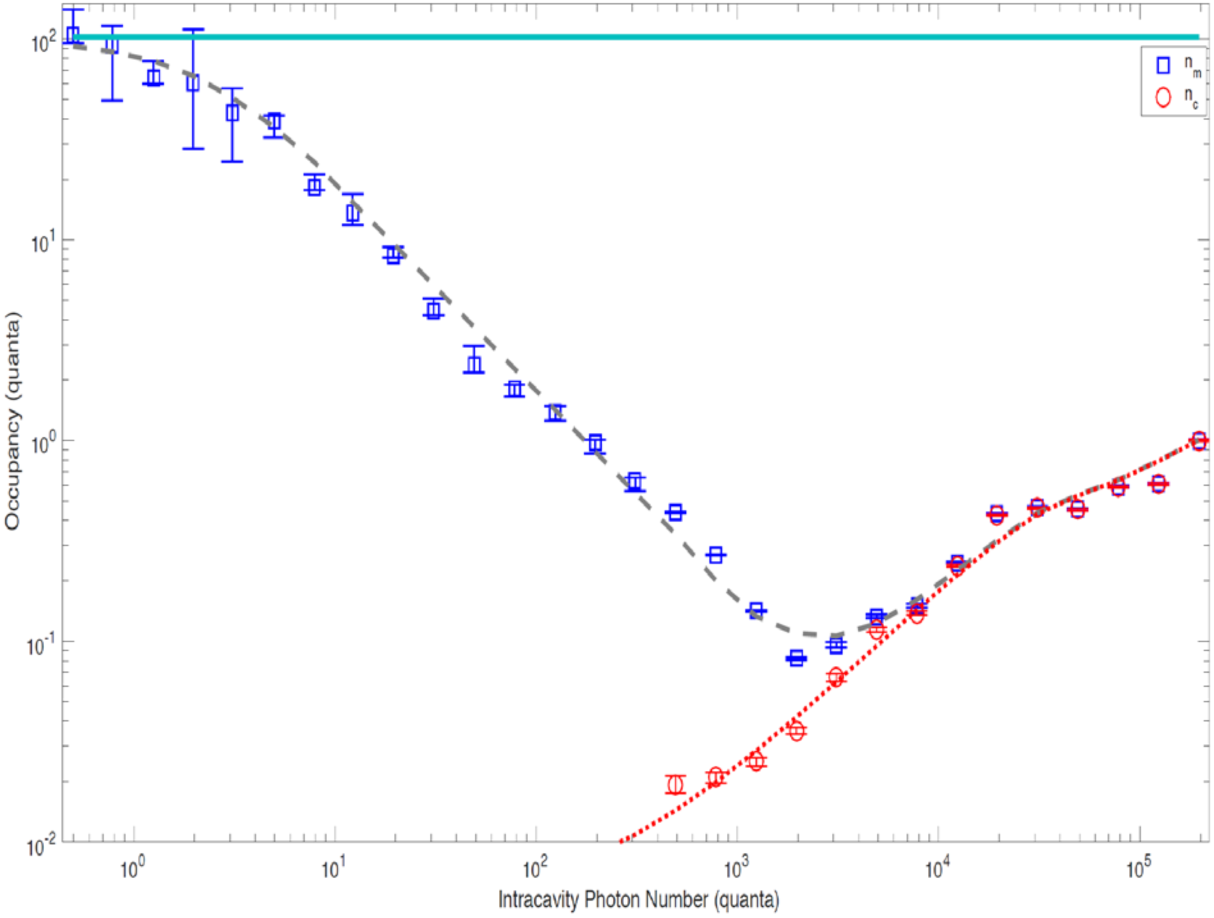




Microwave back-action cooling of SOI resonator

$$\boxed{T_f = 11\ \mathrm{mK}}$$



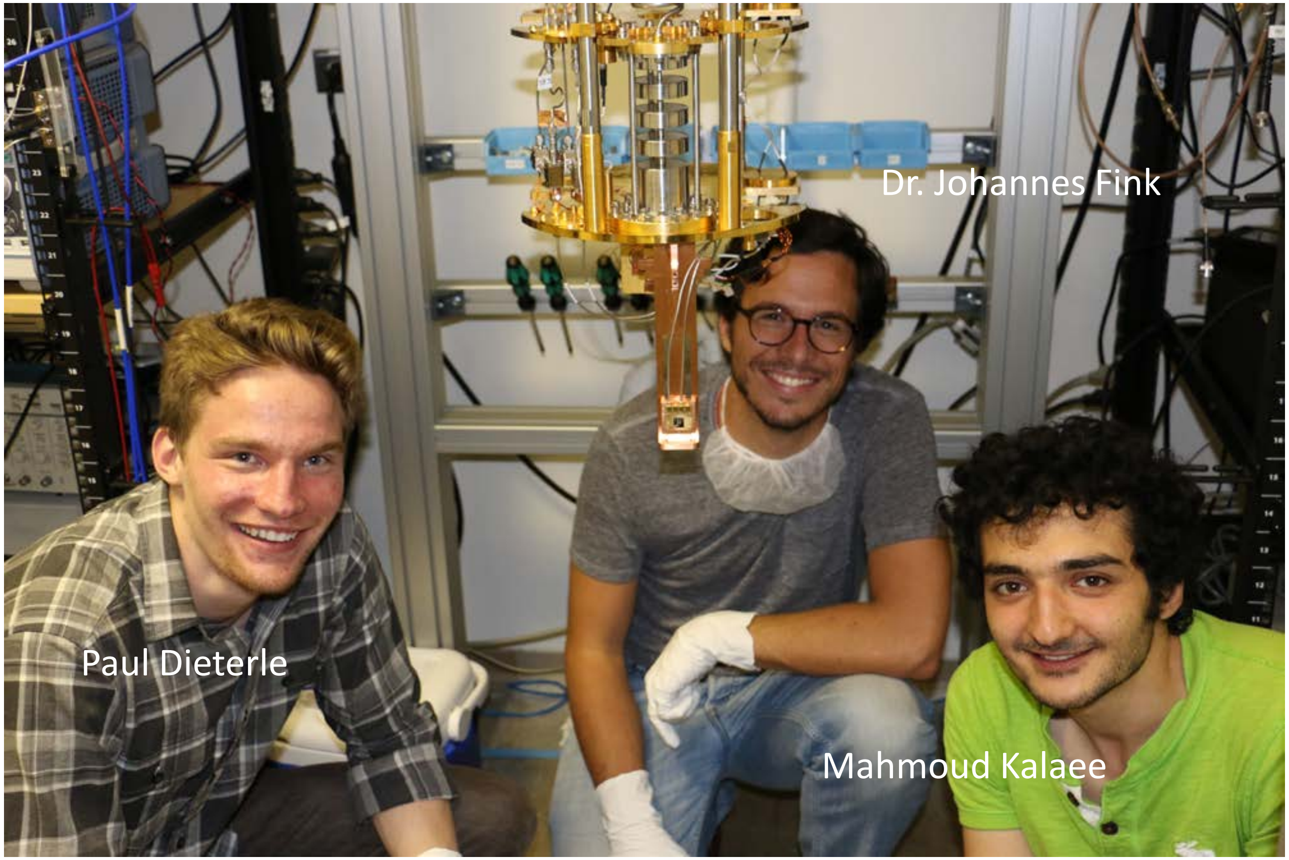


- Redesigned device with minimum motional mass → $\frac{g_0}{2\pi} = 270$ Hz
- Low microwave loss ($Q_{LC} \geq 5\text{x}10^5$)
- $Q_m = 2\text{x}10^6$ at $T_f =$ 11mK (30mK?)
- $C = 1$ at $n_d = 2$ photons
- ground state cooling at $n_d = 200$ photons
- negligible microwave cavity heating ($n_c < 10^{-2}$ photons)

Outlook and next steps

1. SOI looks to be an excellent material for (microwave) electro-opto-mechanical devices
   - mechanical damping in SOI thin-film devices is extremely low @ 10mK ($Q_m = 5\text{x}10^{10}$; f-Q product = $2.5\text{x}10^{20}$)
   - GHz-frequency mechanical occupancy is ≈ 0.02 @ 10mK (in the dark)
   - microwave resonator $Q > 10^5$ on SOI (ρ = 750 Ohm-cm; currently testing SOI with ρ > 5 kOhm-cm)
2. Push to higher frequency microwave circuits
   - large direct electro-mechanical coupling can be realized to 10-20 GHz LC resonators (C_s < 1 fF), enabling phonon "memory" elements
3. Further development of Si/SOI superconducting circuits
   - transmon-like qubits on SOI (in progress; T_1~18μs)
   - wideband JJ-based paramps, circulators/isolators, etc.
   - 2D arrays of highly connected transmon-like qubits
   - Integration with acoustic elements/circuits

Acknowledgments



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