

# Enhanced cavity optomechanics with quantum-well exciton polaritons

Titta

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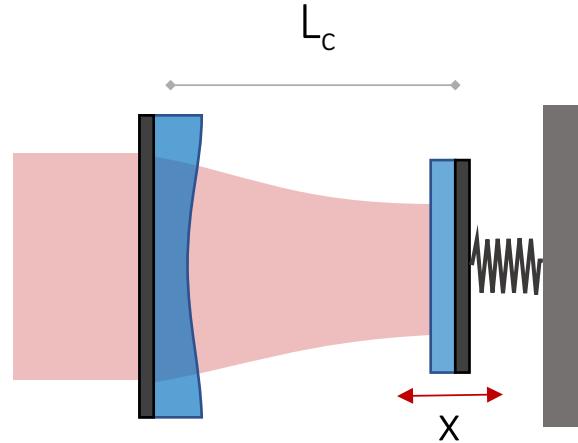
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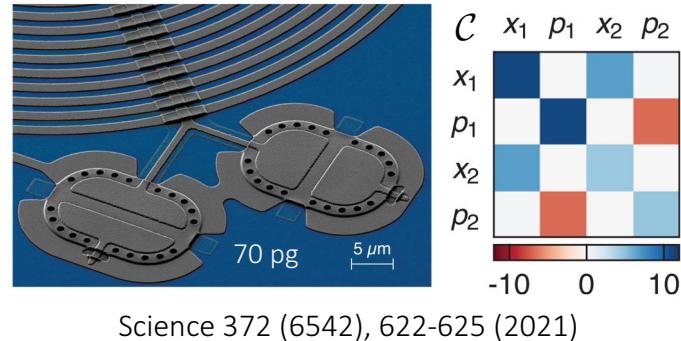
# Coupling light and mechanical motion



$$\omega[\hat{x}] = \frac{hc}{L_c[\hat{x}]} \approx \omega_0 - G_{om}\hat{x}$$

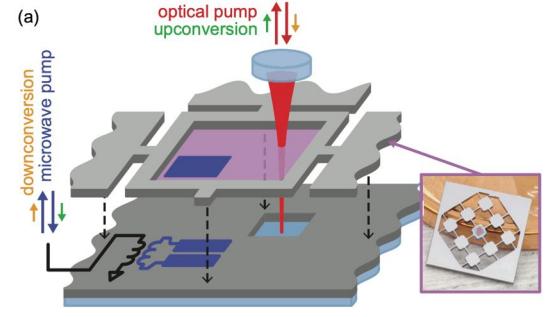
$$H_{om} = -G_{om} \hat{a}^\dagger \hat{a} \hat{x}$$

Fundamental aspects of QM  
in mesoscopic systems



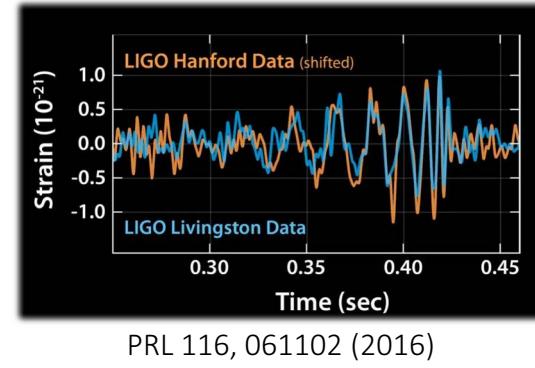
Science 372 (6542), 622-625 (2021)

Quantum transducers



PRX 12, 021062 (2022)

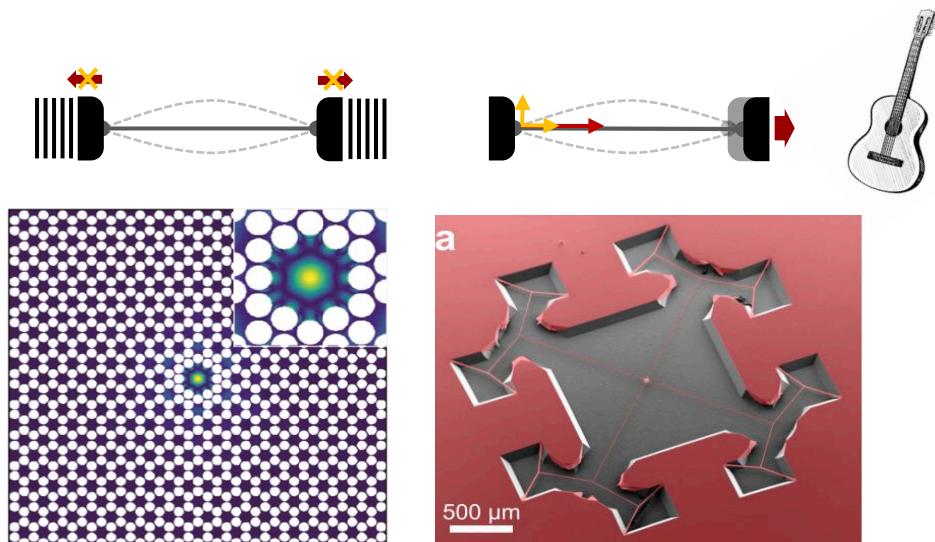
Sensing



PRL 116, 061102 (2016)

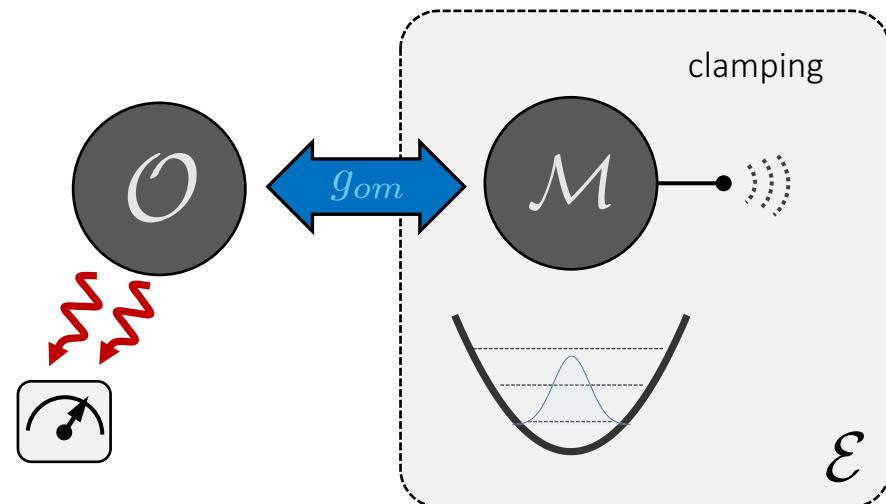
# Pristine Harmonic Oscillators

Phononic shields and dissipation dilution  
(strain) to suppress mechanical losses



$$Q_m \sim 10^9$$

How to break out of the Gaussian state prison?

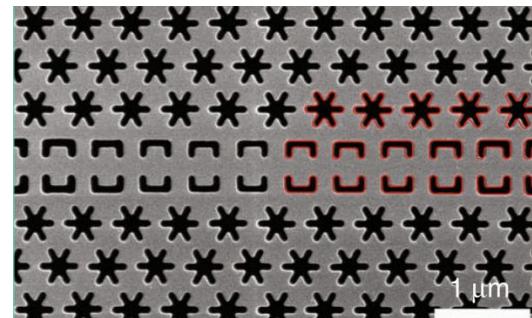


W.P. Bowen, G.J. Milburn - Quantum Optomechanics  
Ch. 6, CRC Press (2015)

# Single-photon quantum cooperativity

$$C_q = \frac{4g_0^2}{\kappa\Gamma} \frac{1}{n_{\text{th}}} = \frac{2G_0^2}{\kappa\Gamma} \frac{\hbar}{\tilde{m}k_B T}$$

$$C_q \sim 0.2$$

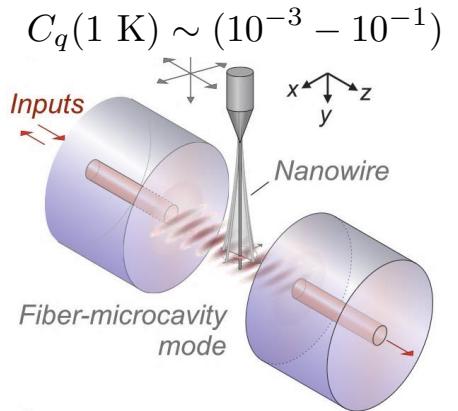


H. Ren et al. Nat. Comm. 11, 3373 (2020)

1. Boost OM interactions

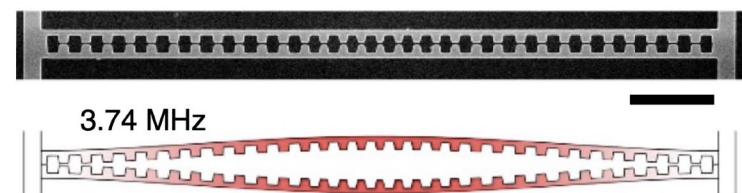
2. Isolate from environment

3. Low temperatures, light oscillators



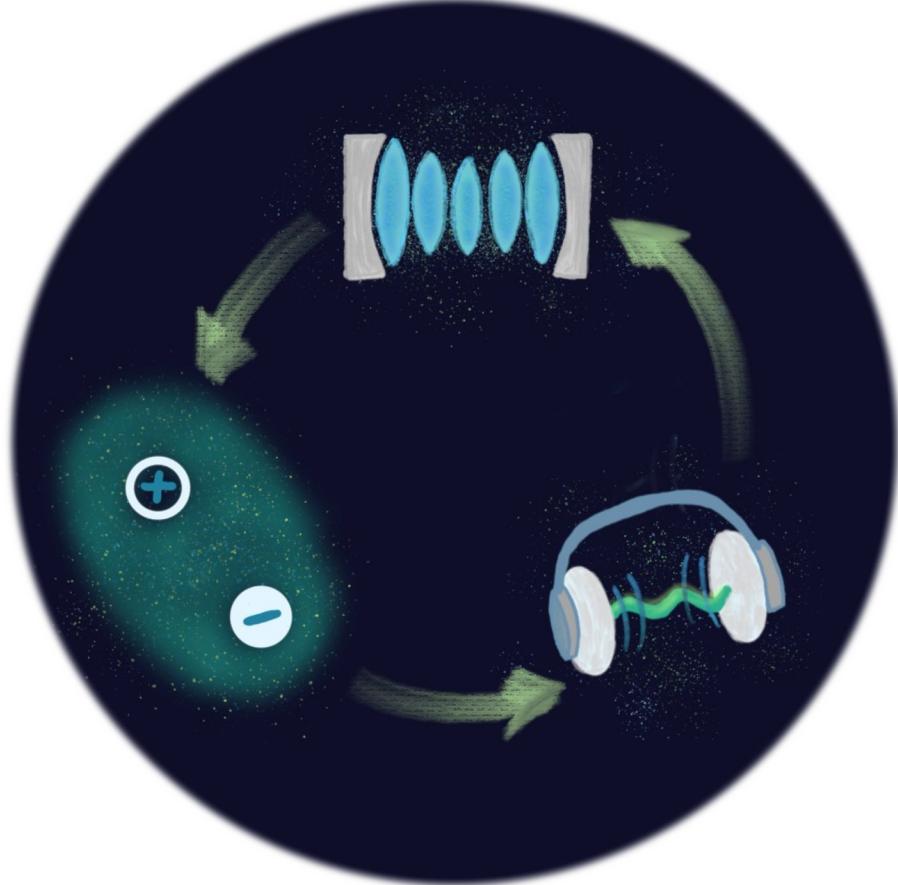
F. Fogliano et al. PRX 11, 021009 (2021)

$$C_q(1 \text{ K}) \sim 0.2$$



R. Leijssen et al. Nat Comm. 8, 16024 (2017)

# Hybrid systems

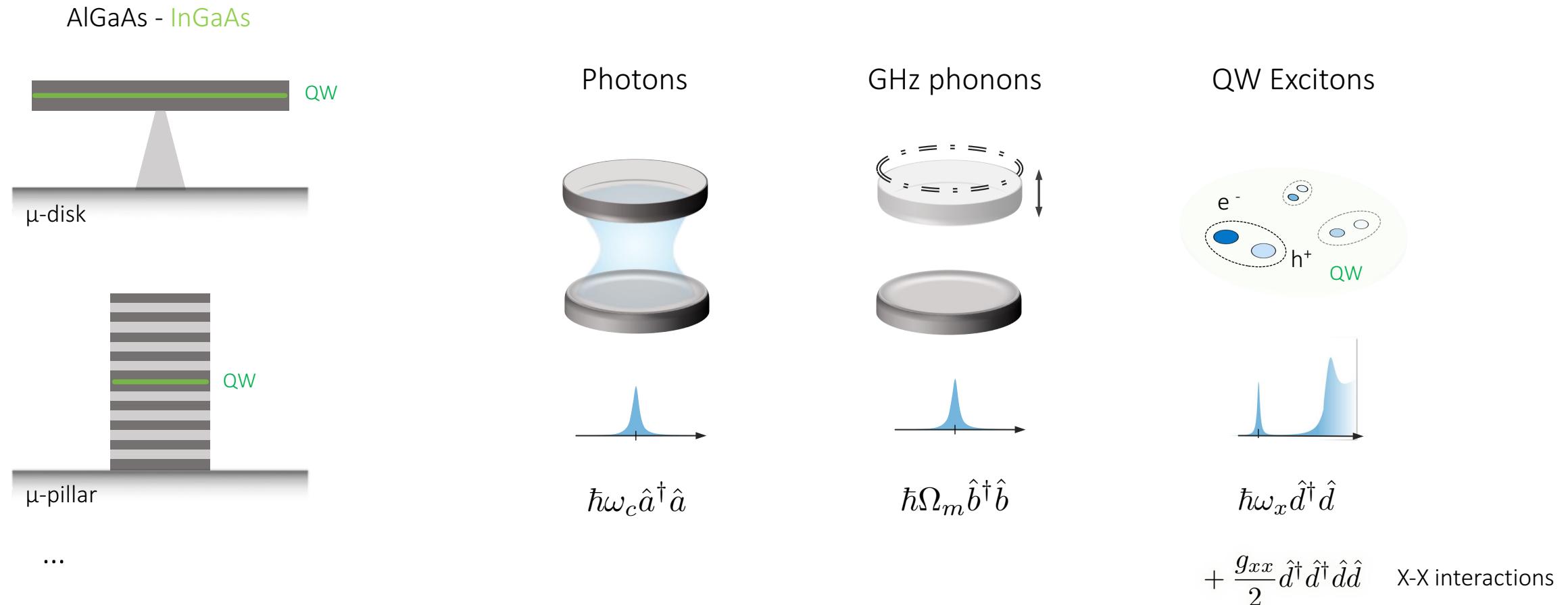


$$C_q(1K) \sim 1$$

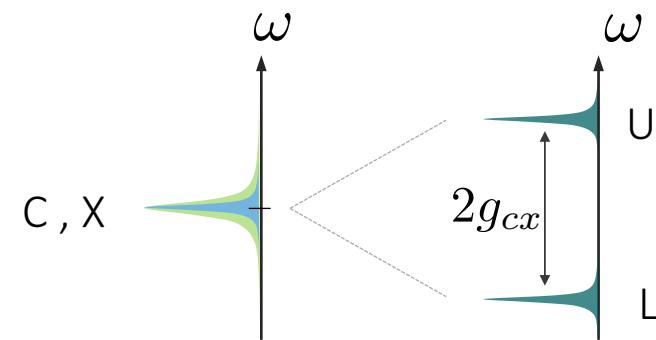
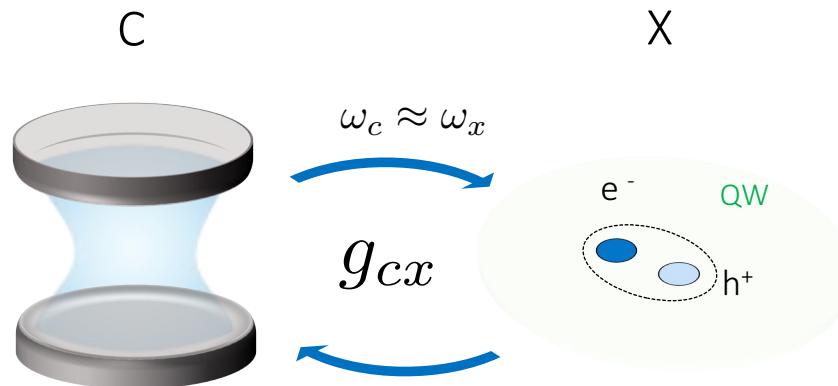
Hybrid optomechanical system showing:

1. Giant effective OM interaction
2. Moderate  $Q_c$  and  $Q_m$
3. Light  $\mu$ -resonators, GHz frequencies

# Semiconductor microresonators



# Exciton photon coupling - Polaritons



$$\hat{H}_{cx} = g_{cx}(\hat{a}^\dagger \hat{d} + \hat{a} \hat{d}^\dagger)$$

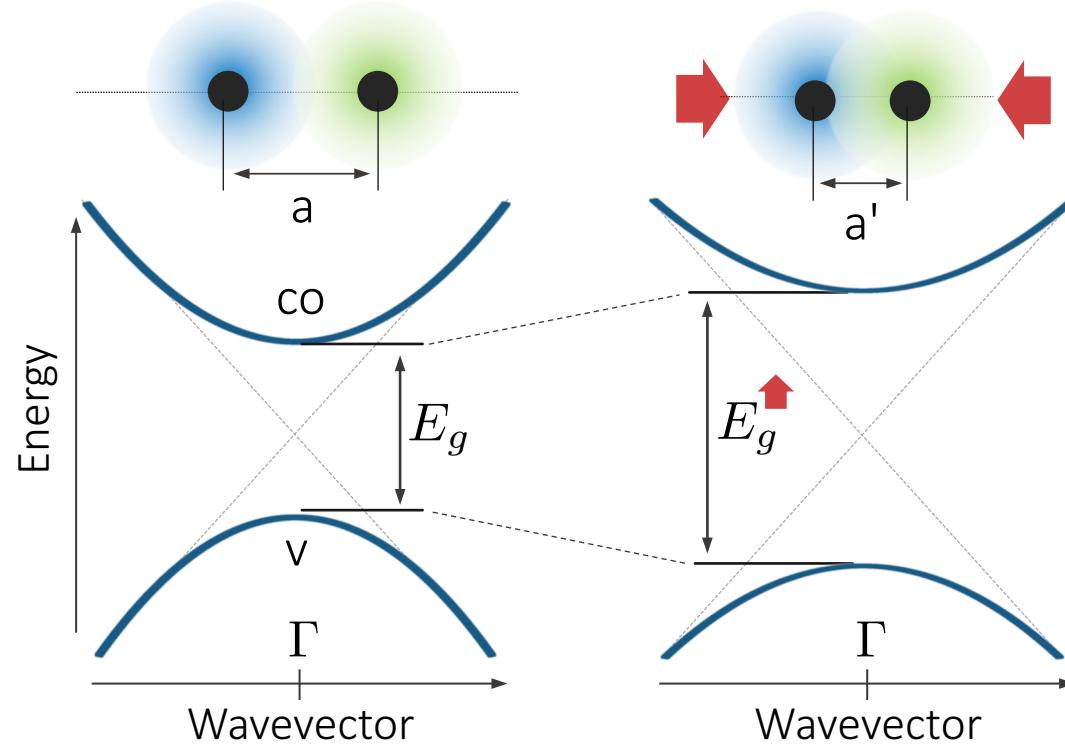
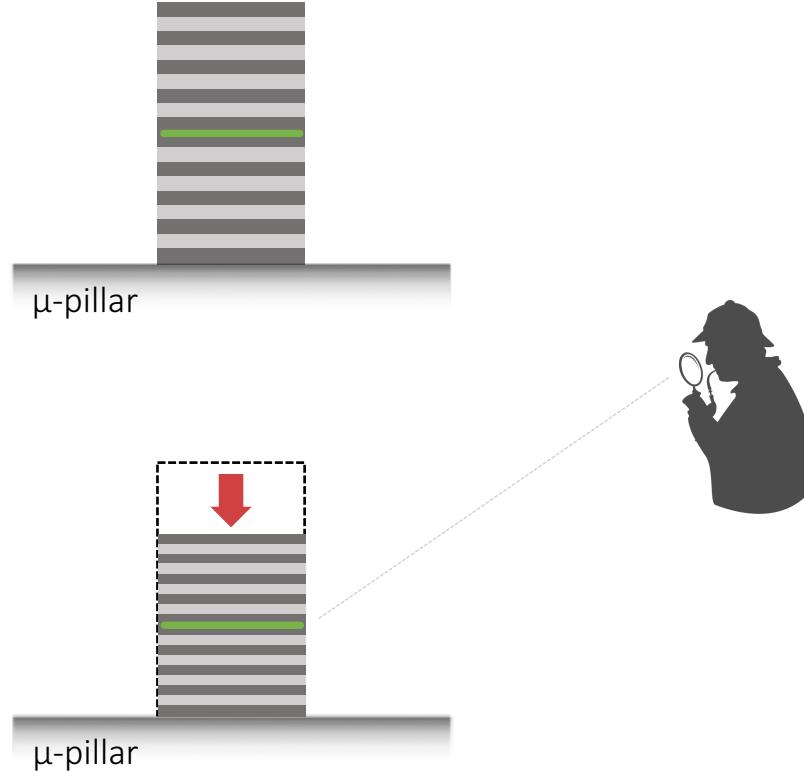
$$g_{cx}/2\pi \ (0.5 - 1.0) \text{ THz}$$

$$\kappa_{c,x}/2\pi \sim \text{GHz}$$

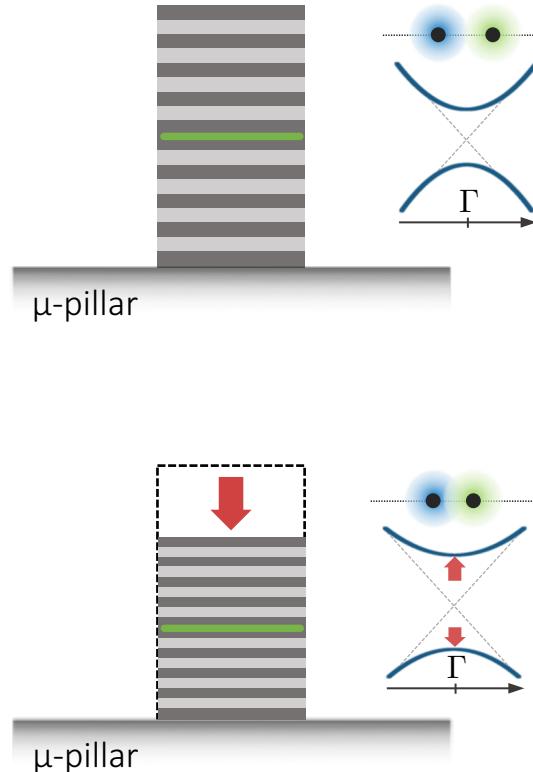
A diagram illustrating a polariton state. It shows a light source emitting a wave packet, which is represented by a wavy line. This wave packet is coupled to a cavity mode (cav) and an exciton mode (exc). The resulting state is labeled  $|pol\rangle = c_k|cav\rangle + x_k|exc\rangle$ .

- Large Kerr nonlinearity
- Large quality factor

# Exciton-phonon coupling



# Exciton-phonon coupling



$$\omega_x[\hat{x}] \rightarrow H_{xm} \approx -g_{xm}\hat{d}^\dagger \hat{d}(\hat{b}^\dagger + \hat{b})$$

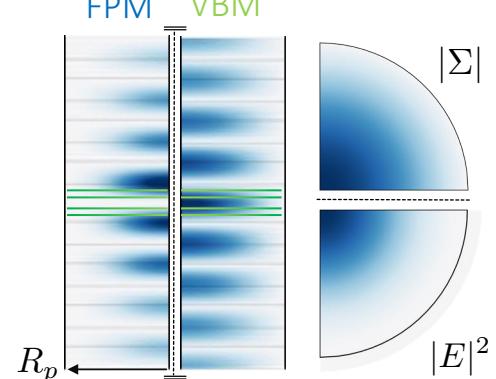
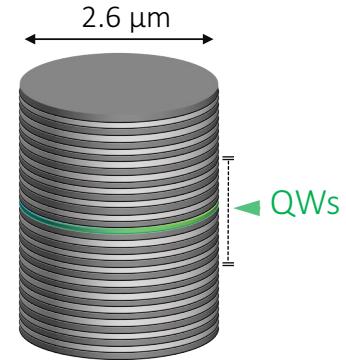
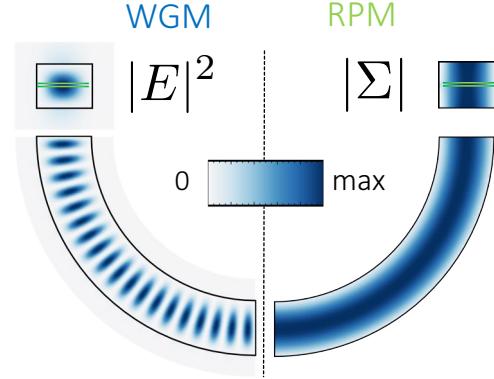
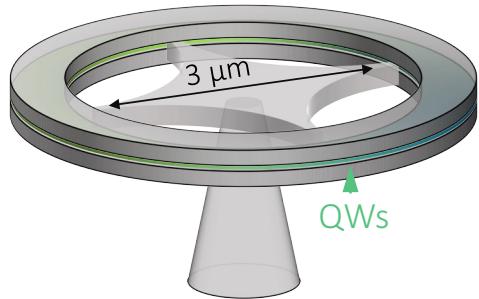
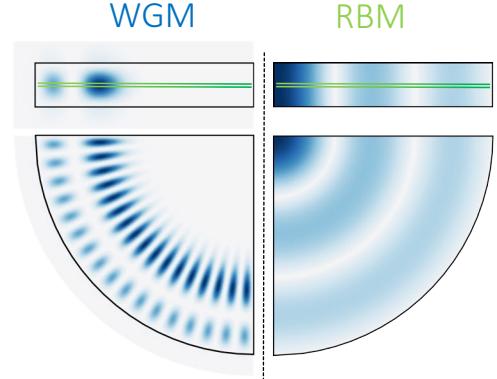
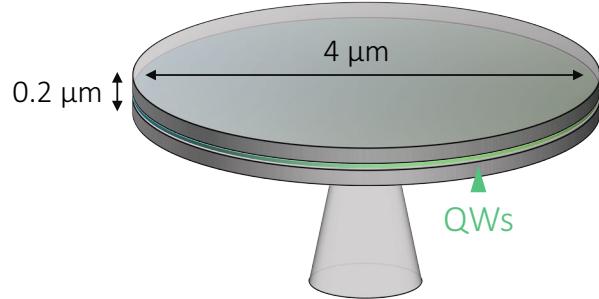
Assuming strong C-X coupling and  $a_B/\lambda_m \ll 1$

$$g_{xm}^{(n,m)} \approx (a_h - a_e) \int_S d\mathbf{R} |E_m(\mathbf{R})|^2 \Sigma_n(\mathbf{R}, z_{\text{QW}})$$

-9.7 eV !      Optical density      Strain field

$$= (a_h - a_e) (x_{\text{ZPF}} k_m) \mathcal{I}_g \eta_S$$

# Coupling parameters – analytical model



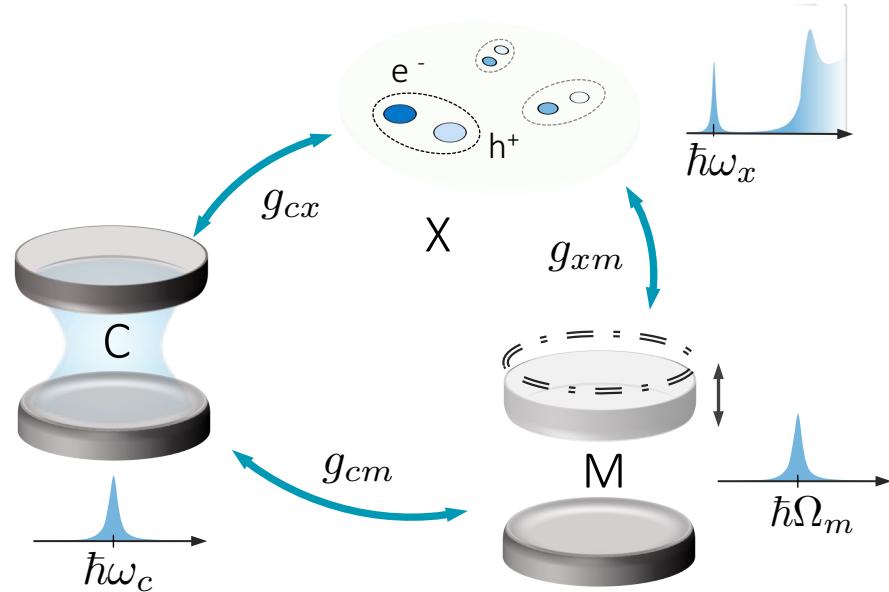
$$E_c \approx E_x = 1.46 \text{ eV}$$

$$g_{xm} \sim \Delta a_{eh} k_m \mathcal{I}_g$$

	$\Omega_m/2\pi$	2.9	4.1	19.6	GHz
$g_{xm}/2\pi$	2.3	5.5	24.2	MHz	
$g_{cm}/2\pi$	0.8	1.6	0.2	MHz	
$g_{cx}/2\pi$	1.03	1.03	0.53	THz	

See supplemental: N. Carlon Zambon, Z. Denis et al. PRL 129, 093603 (2022)

# Effective radiation pressure Hamiltonian



$$\hat{H}_{tot} = \hat{H}_m + \hat{H}_l + \hat{H}_u + \hat{H}_{lu}$$

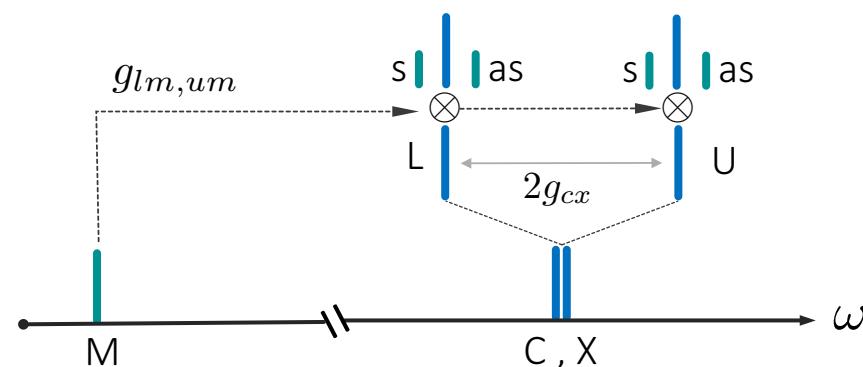
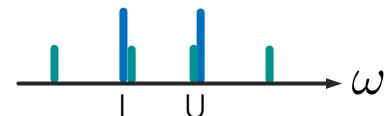
Kerr OM oscillators:

$$\hat{H}_j = \left[ \omega_j + \frac{\chi_j}{2}(\hat{n}_j - 1) - g_{jm}(\hat{b}^\dagger + \hat{b}) \right] \hat{n}_j$$

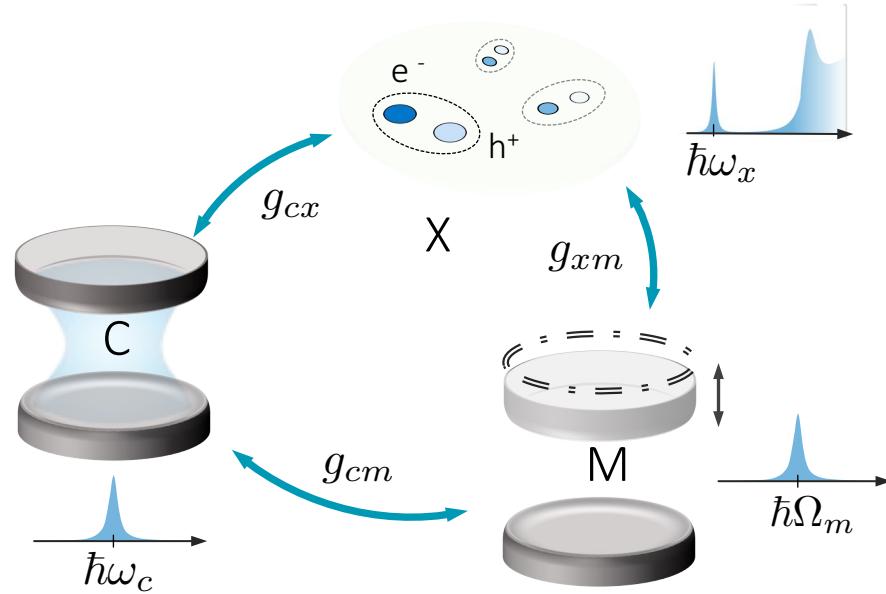
Mechanically assisted coupling between polariton branches

$$\hat{H}_{lu} \sim (\hat{b}^\dagger + \hat{b})(\hat{l}^\dagger \hat{u} + \hat{l} \hat{u}^\dagger)$$

Resonant if  
 $\Omega_m \approx \delta_{lu}$



# Effective radiation pressure Hamiltonian



L,U decouple. Consider a single polariton branch:

$$\hat{H}_{l,m} = \left[ \omega_l + \frac{\chi_l}{2}(\hat{n}_l - 1) - g_{lm}(\hat{b}^\dagger + \hat{b}) \right] \hat{n}_l + \hat{H}_m$$

Effective OM coupling

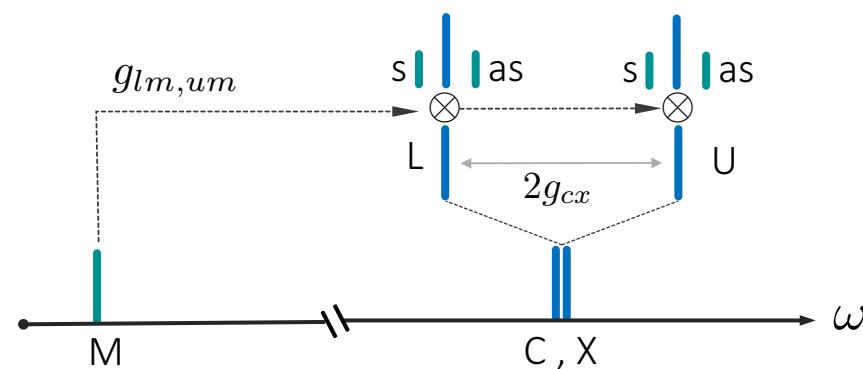
$$g_{lm} = g_{xm} \sin^2 \theta_{cx} + g_{cm} \cos^2 \theta_{cx}$$

A schematic diagram showing an effective optical-mechanical coupling element. It consists of two vertical blue bars labeled 'as' (acoustic spring) connected by a horizontal dashed line. A vertical dashed line labeled 'L' connects the top of the left bar to the bottom of the right bar. A horizontal double-headed arrow between the bars is labeled  $2g_{cx}$ . A blue arrow labeled  $g_{lm,um}$  points from the left side towards the coupling element.

Kerr term

$$\chi_l = g_{xx} \sin^4 \theta_{cx}$$

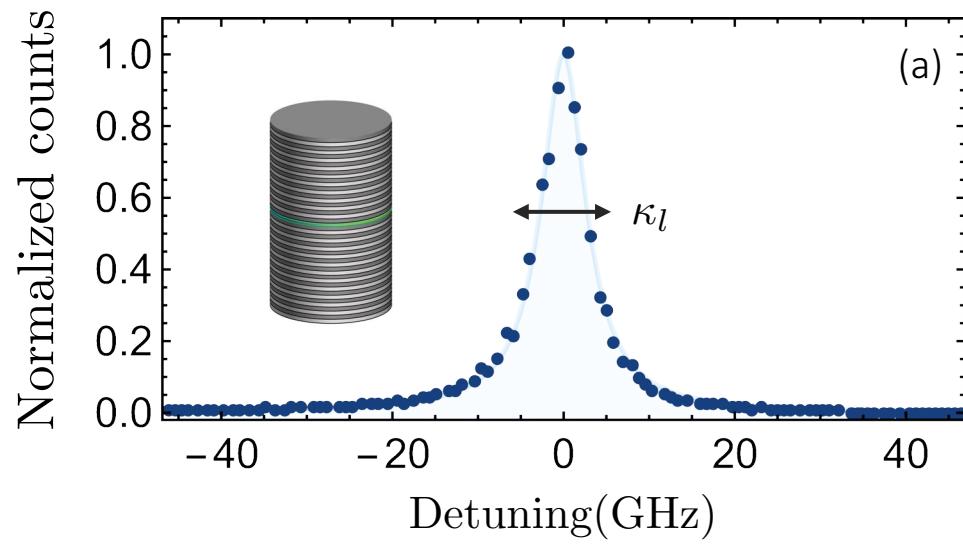
A schematic diagram showing a Kerr-like nonlinearity. It features a central green oval with a red starburst pattern around it, representing a nonlinear medium. A blue arrow labeled  $g_{xx}$  points towards this central region.



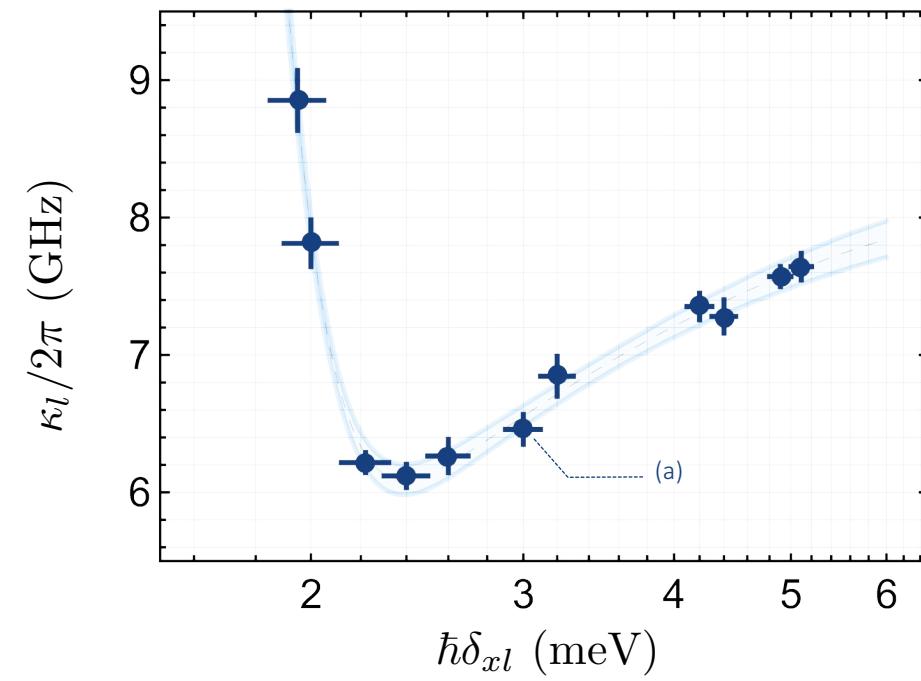
# Polariton linewidth under resonant excitation

$$\kappa_l = \kappa_c \cos^2 \theta_{cx} + [\kappa_x + 2\pi\delta_{xl}^2\rho(\delta_{xl})] \sin^2 \theta_{cx}$$

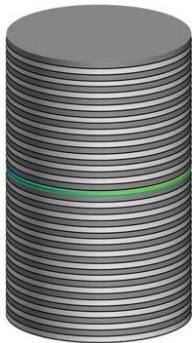
I. Dinitz et al., PRA 84, 063810 (2011)



$\kappa_c/2\pi$ (GHz)	$\kappa_x/2\pi$ (GHz)	$\sigma_{inh}$ meV
7.2(1)	4.8(1)	0.51(4)



# Single polariton quantum cooperativity



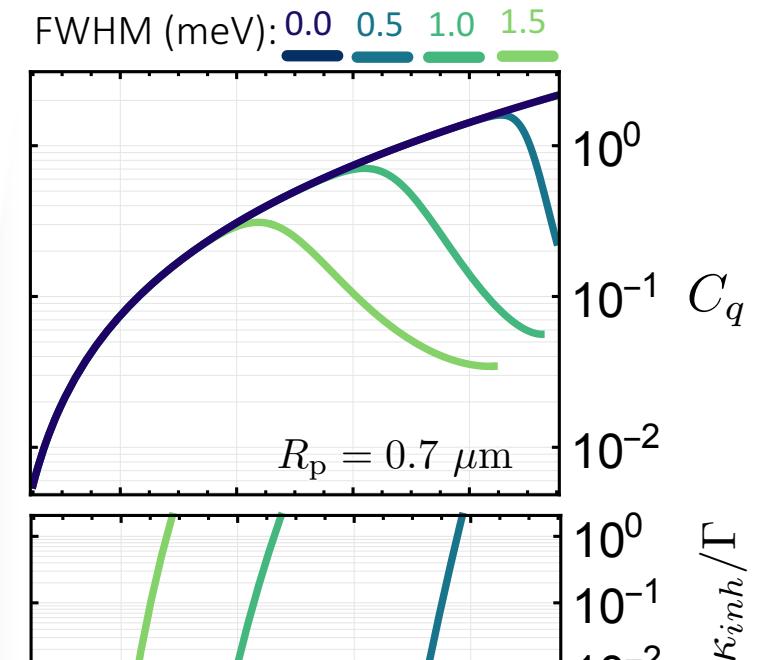
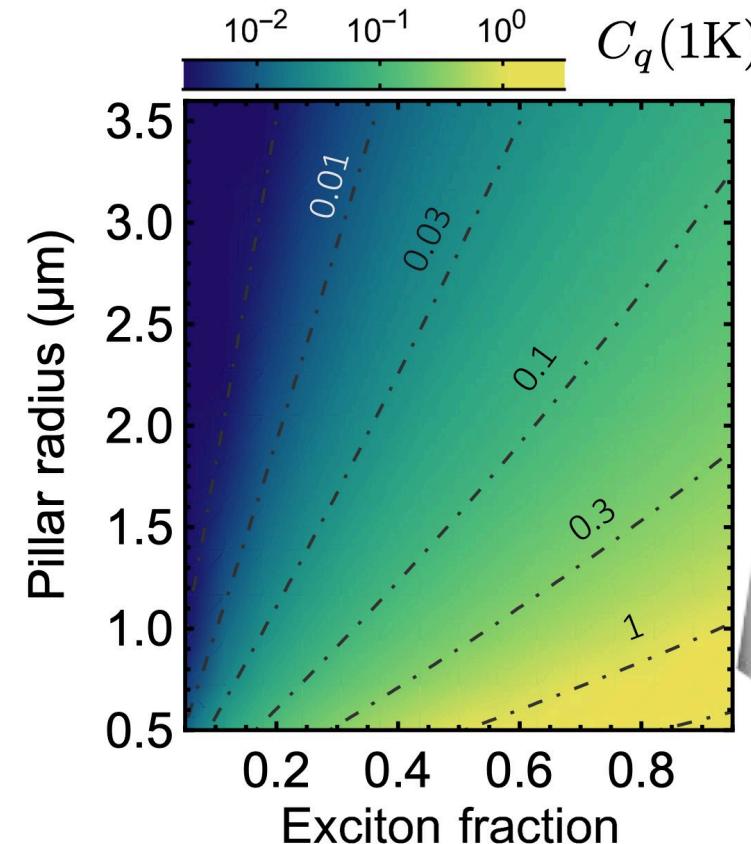
Parameters:

$$\begin{aligned}\Omega_m &\sim 20 \text{ GHz} \\ \Gamma/2\pi &= 0.65 \text{ GHz} \\ \kappa_c/2\pi &= 7.2 \text{ GHz} \\ \kappa_x/2\pi &= 4.8 \text{ GHz}\end{aligned}$$

@1K  $n_{th}=1$  so  $C_0 \approx C_q$

Inhomogeneous X broadening does not play a role if

$$\text{FWHM}/(2g_{cx}) \ll 1$$



# Polariton dynamical back-action

Linearized QLEs:

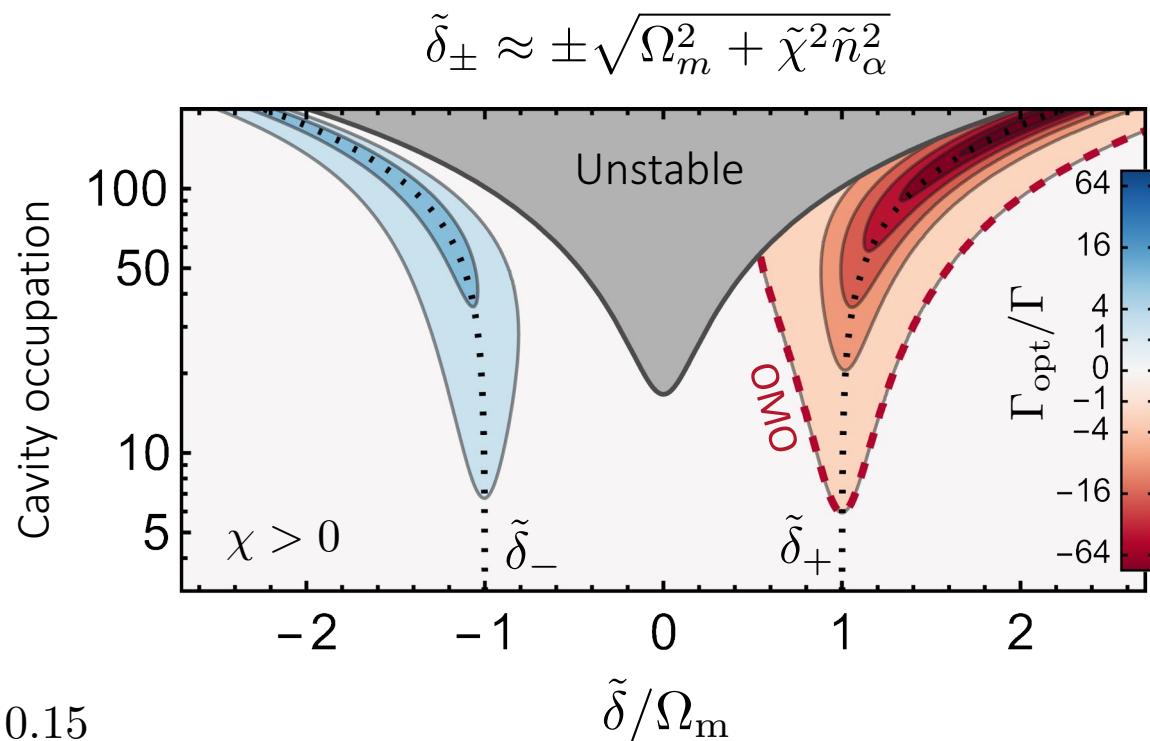
$$\begin{pmatrix} \delta\dot{\hat{\alpha}} \\ \delta\dot{\hat{\alpha}}^\dagger \end{pmatrix} = \begin{pmatrix} \text{blue} & \text{green} \\ \text{green} & \text{blue} \end{pmatrix} \begin{pmatrix} \delta\hat{\alpha} \\ \delta\hat{\alpha}^\dagger \end{pmatrix} + g_{lm} + \text{OMC} + \text{Noise}$$

Squeezing transformation

$$\theta_s = 0 \quad \rightarrow$$

M. Asjad et al.  
Opt. Expr. 27, 32427 (2019)

$$\begin{pmatrix} \delta\dot{\hat{\alpha}}_s \\ \delta\dot{\hat{\alpha}}_s^\dagger \end{pmatrix} = \begin{pmatrix} \text{blue} & \text{white} \\ \text{white} & \text{blue} \end{pmatrix} \begin{pmatrix} \delta\hat{\alpha}_s \\ \delta\hat{\alpha}_s^\dagger \end{pmatrix} + g_{lm}e^{-r} + \text{OMC}_s + \text{Sq.Noise}$$



$$C_0 \approx 0.15$$

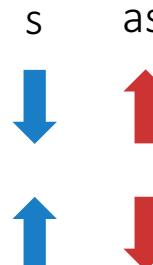
Sq. parameter  $2r = \text{arctanh}(-\chi\tilde{n}_\alpha/\tilde{\delta})$

$$\chi > 0$$

$$\chi < 0$$

$$g_{lm}e^{-r}$$

$$g_{lm}e^{-r}$$



# Nonlinear sideband cooling

Sidebands

$$\tilde{\delta}_{\pm} \approx \pm \sqrt{\Omega_m^2 + \tilde{\chi}^2 \tilde{n}_\alpha^2}$$

Sq. parameter

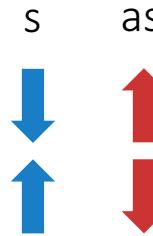
$$2r = \operatorname{arctanh}(-\chi \tilde{n}_\alpha / \tilde{\delta})$$

$\chi > 0$

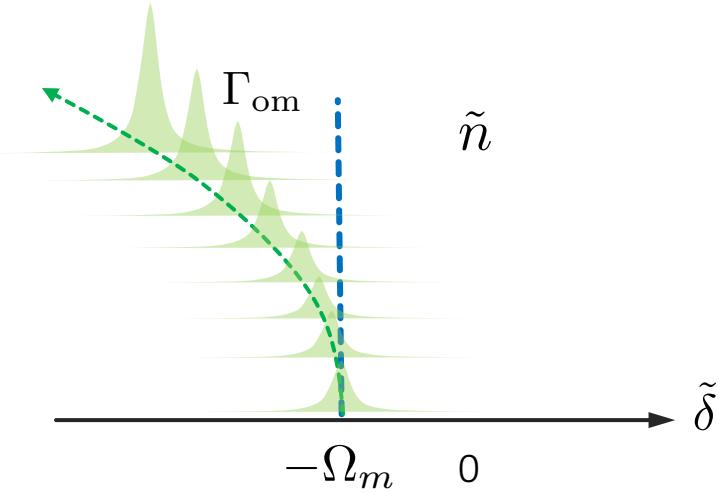
$$g_{lm} e^{-r}$$

$\chi < 0$

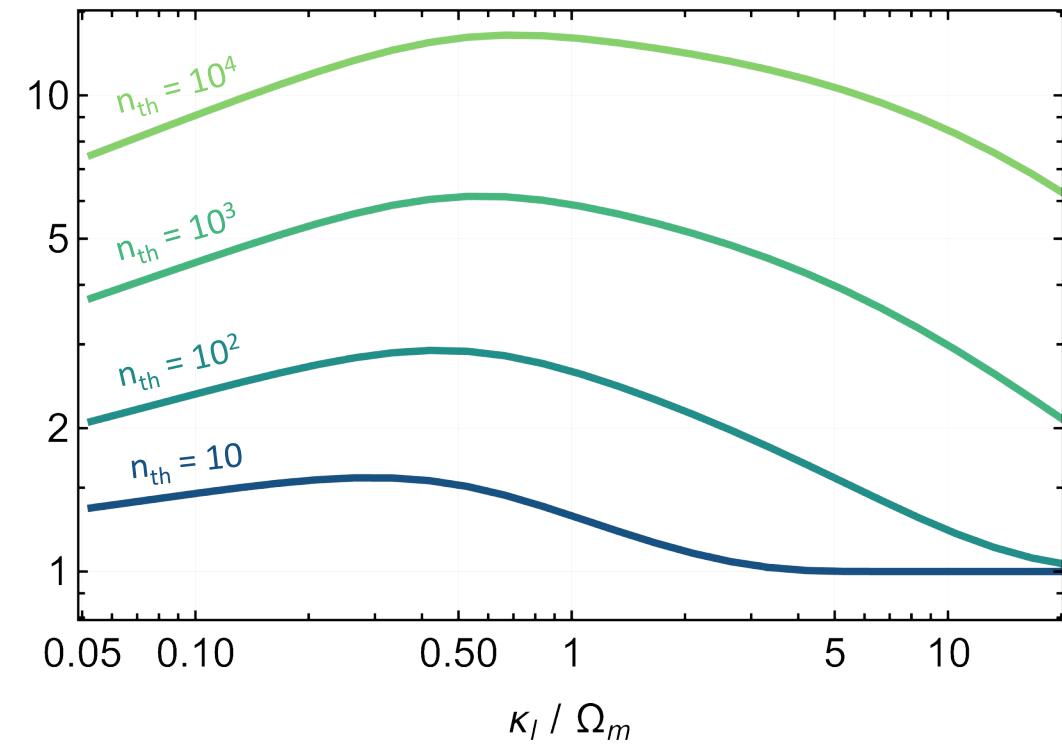
$$g_{lm} e^{-r}$$

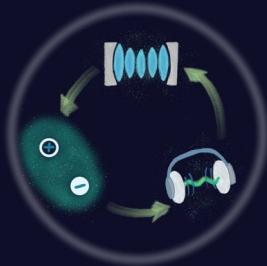


The M frequency does not shift!  
Trade-off between OMC enhancement and



Optimal cooling enhancement



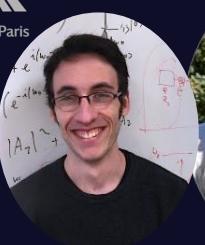


# Summary

1. Analytical theory of tripartite exciton-photo-phonon interactions in semiconductor microresonators.
2. State of the art  $\mu$ -resonators may reach a single polariton  $C_q \sim 1$
3. Nonlinearities as a resource for back-action cooling or amplification



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C. Ciuti



I. Favero



J. Bloch

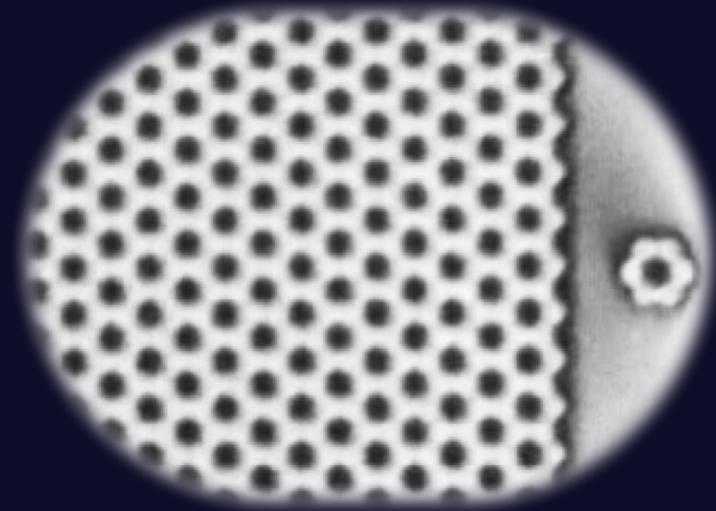


S. Ravets



## WHATS NEXT ?

1. Proof of principle experiments
2. When  $C_q \sim 1$  also the blockade parameter  $\sim 1$
3. Scaling up to arrays of microresonators:  
Topological phonon transport



N. Carlon Zambon, Z. Denis et al. PRL 129, 093603 (2022)