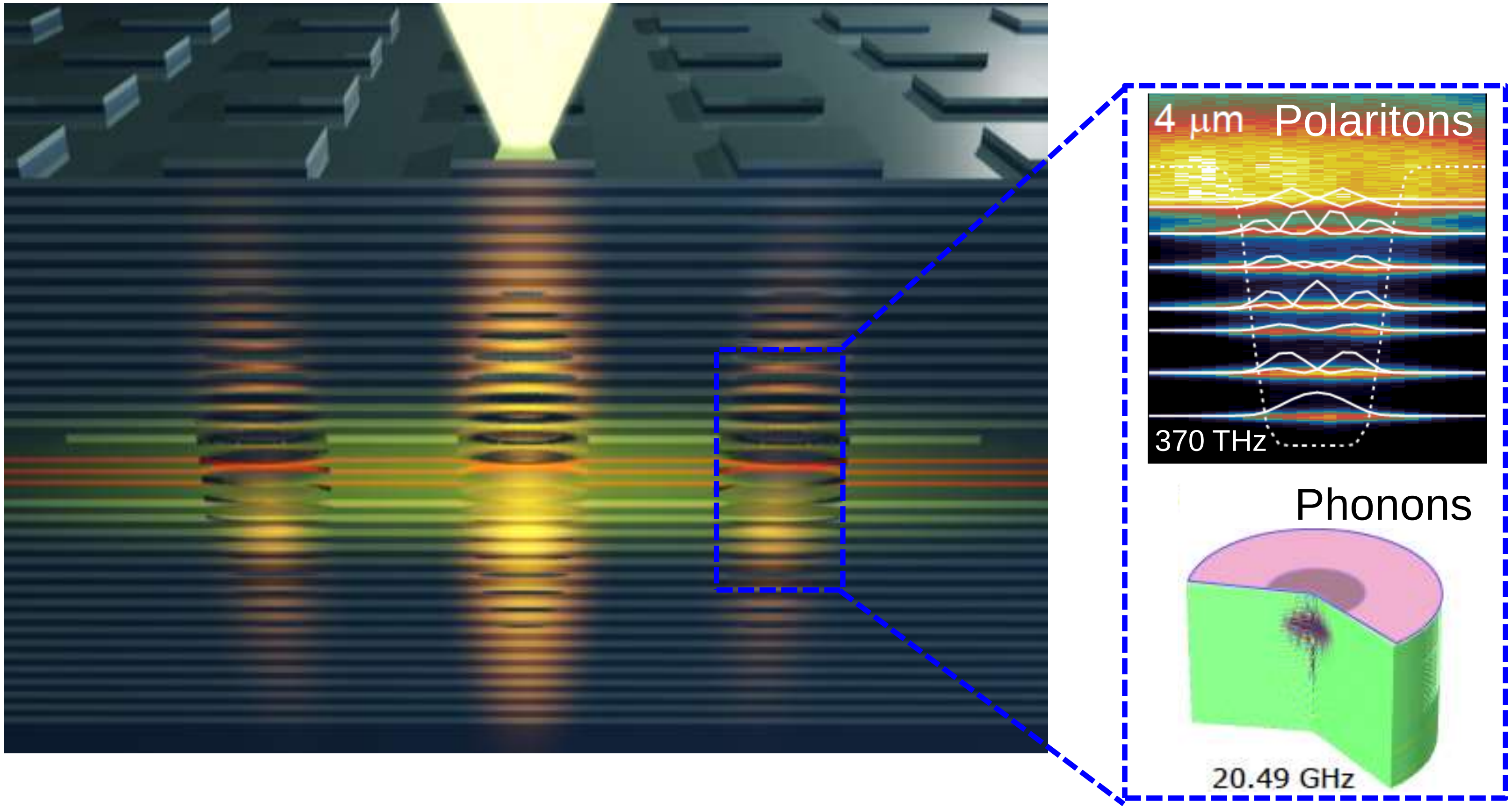
Cavity Optomechanics with Polariton Fluids

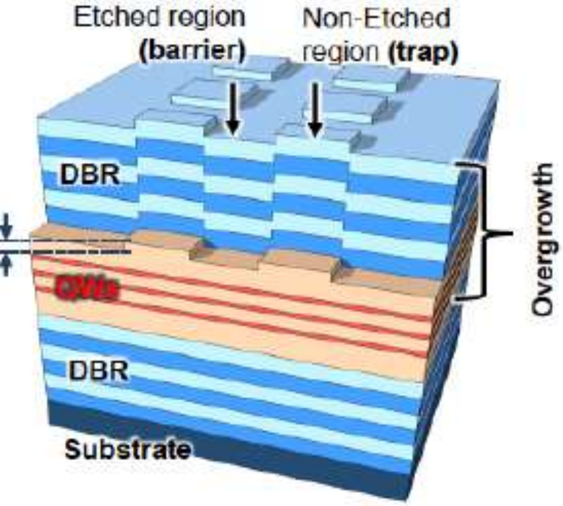
Alex Fainstein



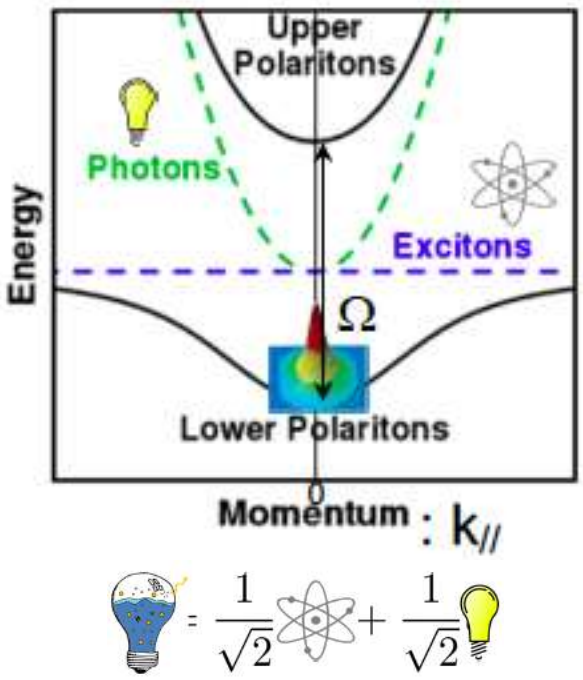
Photonics and Optoelectronics Lab
Instituto Balseiro, Bariloche, Argentina

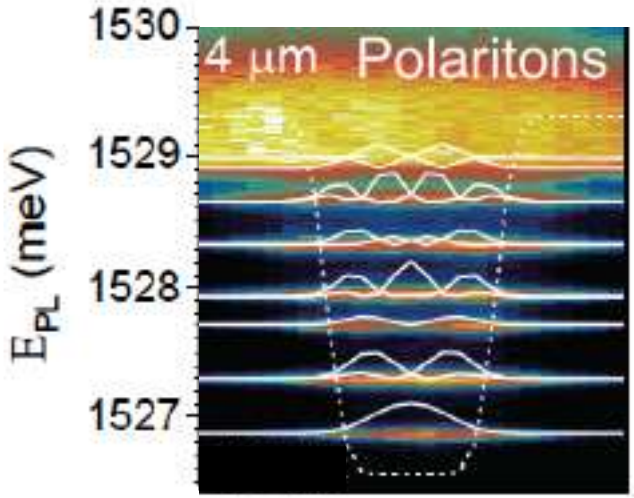
Paul-Drude-Institut
für Festkörperelektronik

Day #1 wrap-up



$$\boxed{\psi = \sqrt{N}\, e^{i\theta}}$$



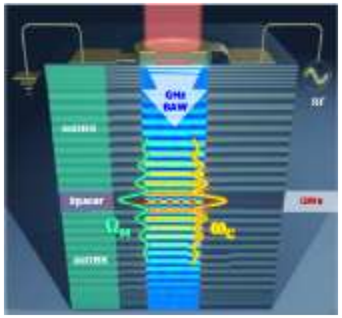


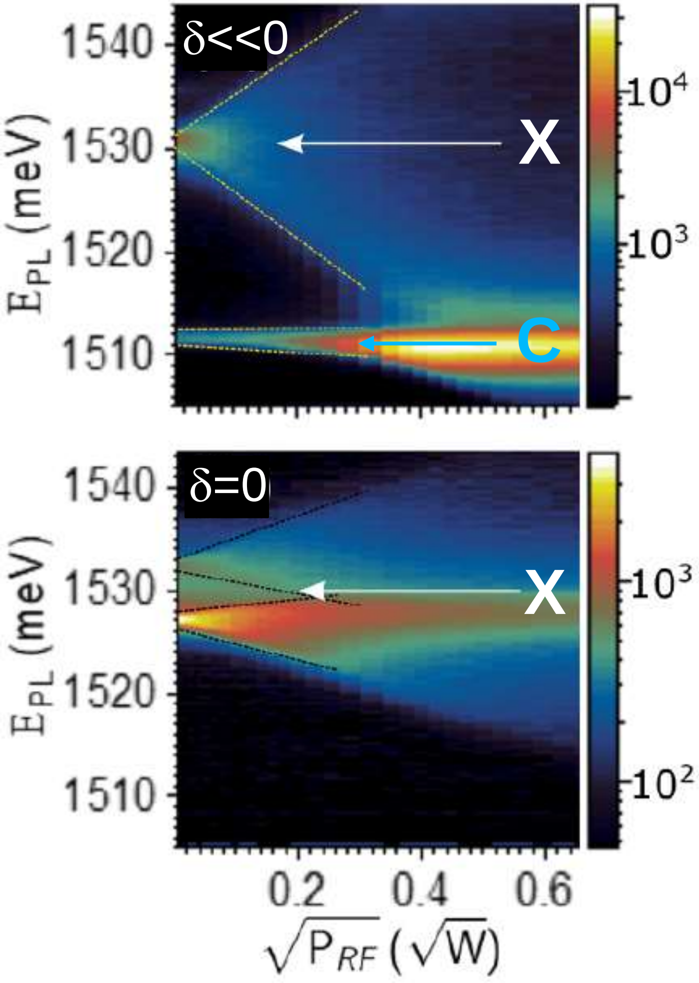
Day #1 wrap-up

- Concept: CQED (polaritons) + cavity optomechanics
- What are these polaritons: tunable superposition of photon and X states, low-mass, strong interactions, Bose-Einstein condensation, superfluidity.
- The structures and their properties
- Strong X-mediated enhancement of g_0
- Tailored polariton and phonon lattices

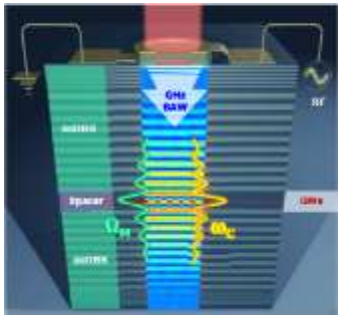
$$H = \hbar\omega_c c^+ c + \hbar\omega_m b^+ b + \hbar \underset{\text{optomechanical coupling}}{g_0} c^+ c \underbrace{(b + b^+)}_{\text{phonon displacement}}$$

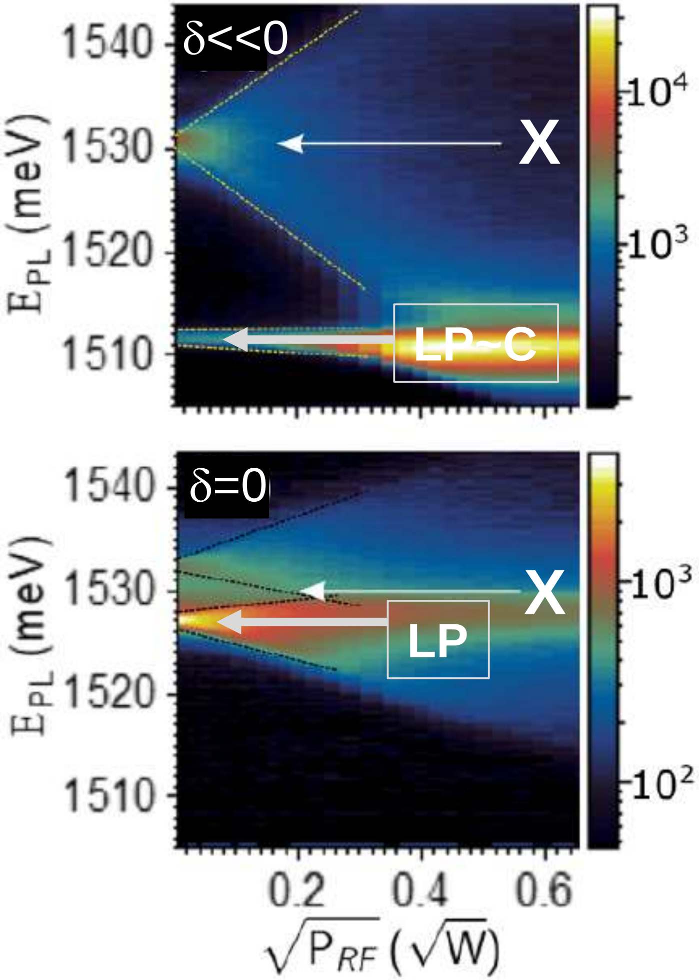
The OM coupling: RF driving



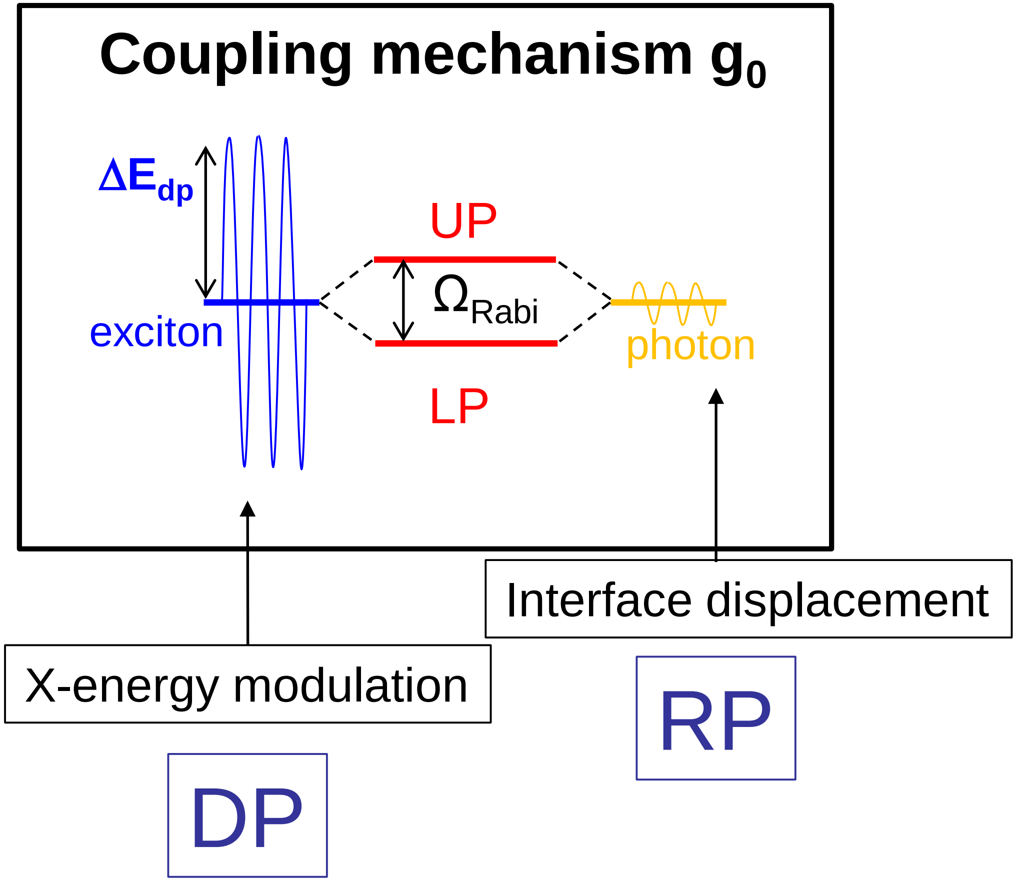


The OM coupling: RF driving





$\Psi = \alpha$ ⚠ $+ \beta$ ⚛



Coupling mechanism g_0

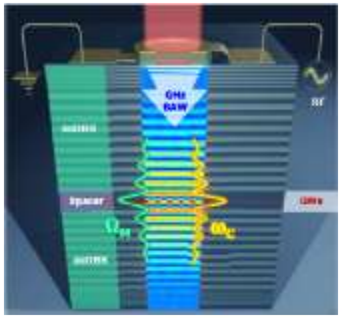
Interface displacement

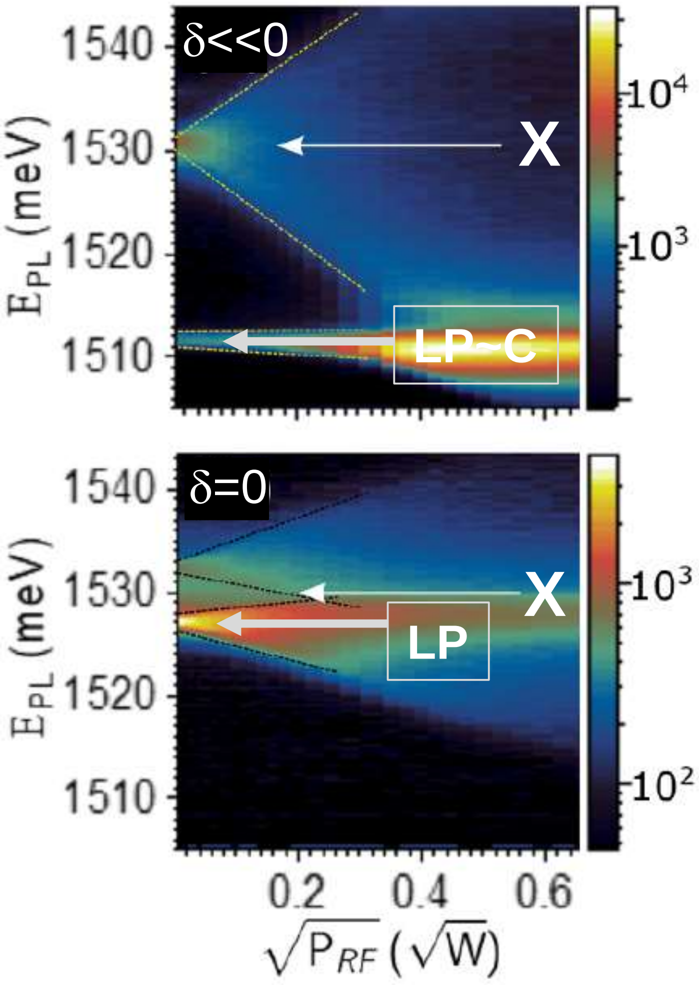
X-energy modulation

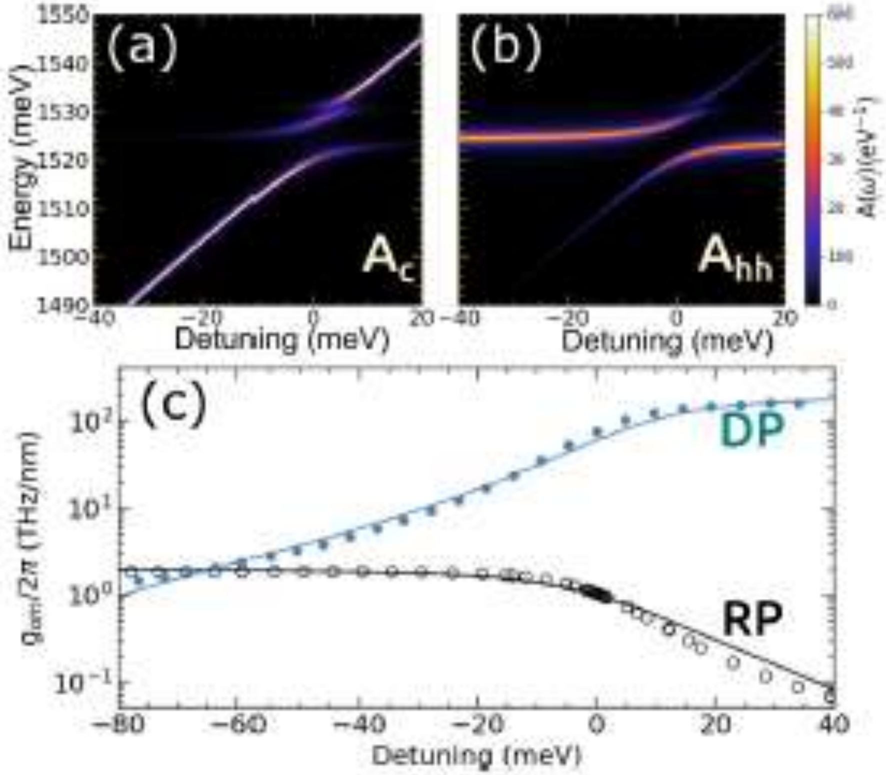
RP

DP

The OM coupling: Modeling







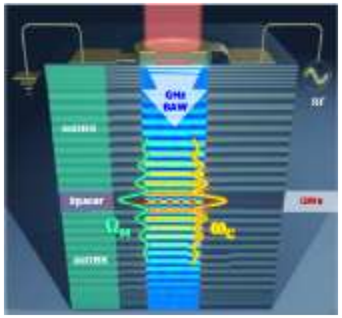
$$g_0 = S_c\, g_0^{RP} + S_x\, g_0^{DP}$$

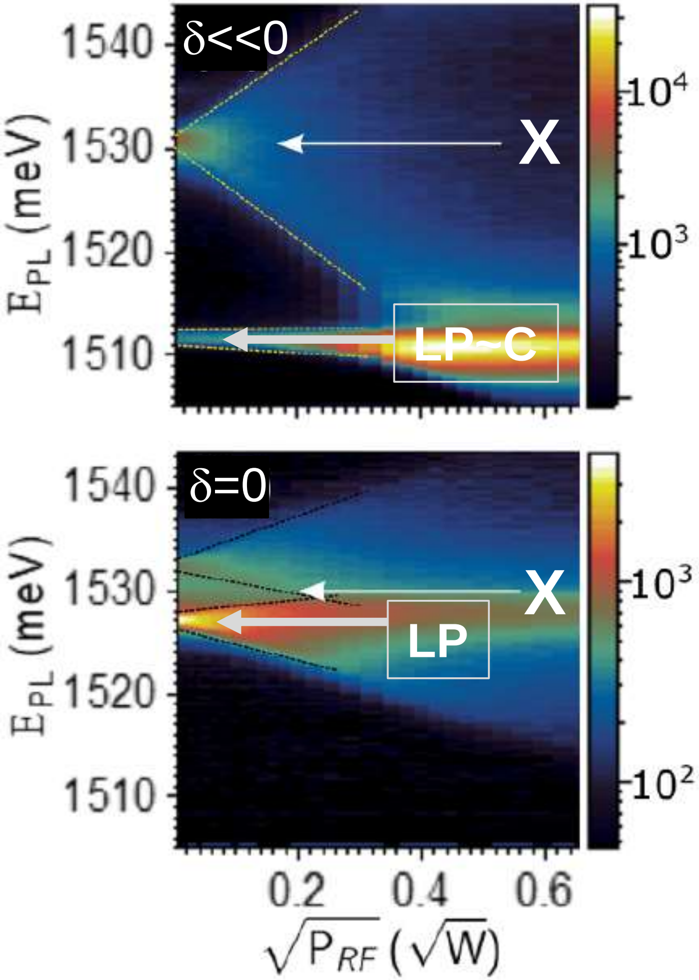
Interface displacement

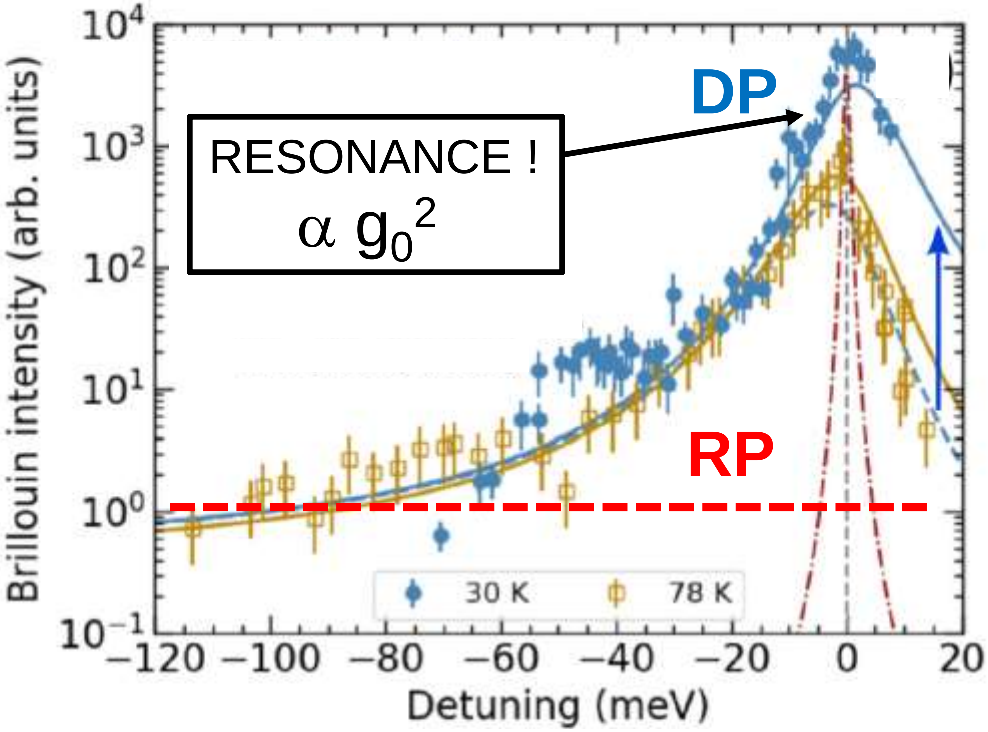
X-energy modulation

$$\boxed{g_0^{DP} \sim 100\, g_0^{RP} \sim 20\ MHz}$$

The OM coupling: LP Brillouin scattering





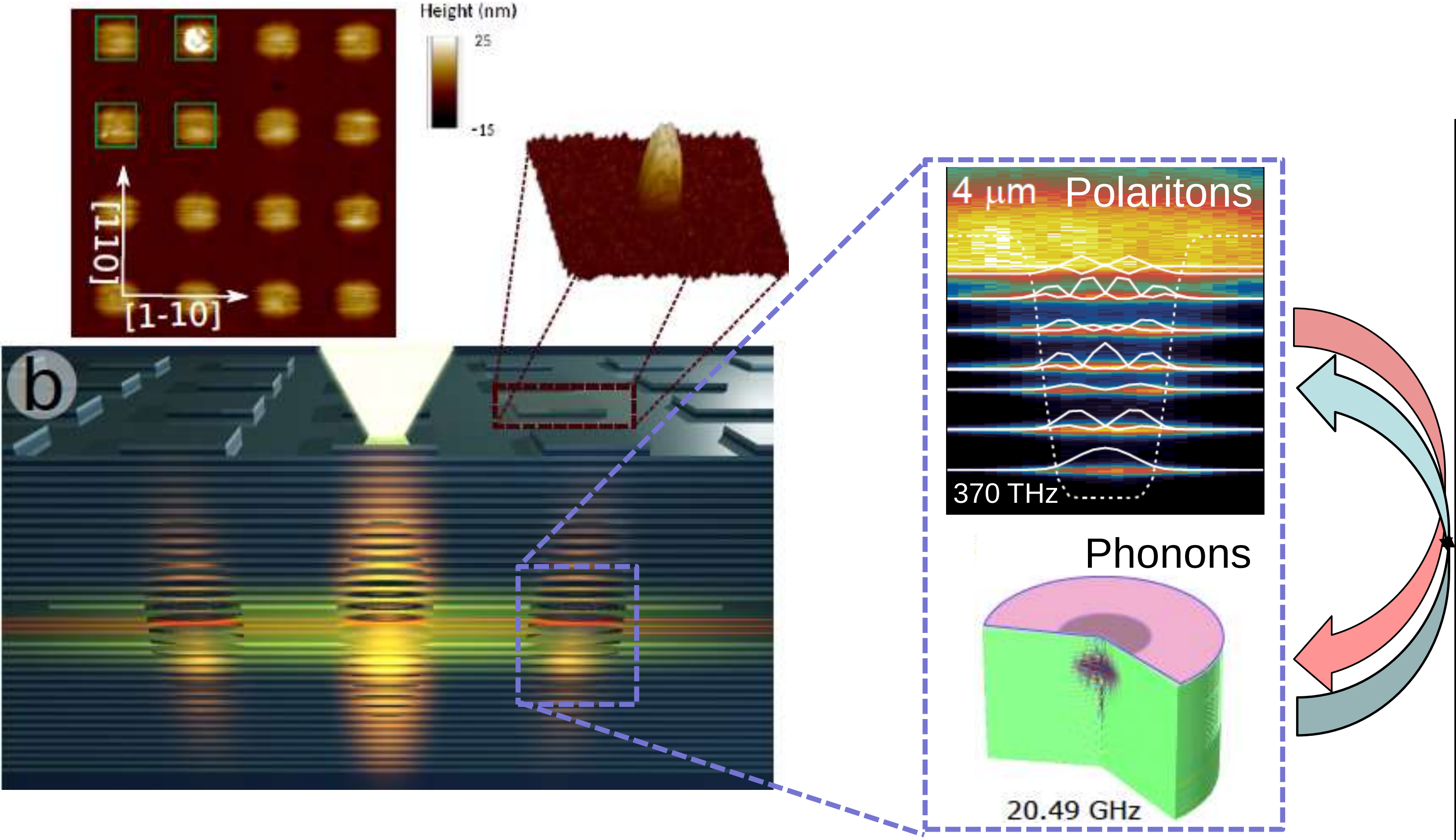


RESONANCE !

$\alpha\ g_0^2$

$$g_0^{DP} \sim 100\, g_0^{RP} \sim 20\ MHz$$

Polaromechanical “Metamaterials”



Exciton-mediated
back-action

+ exciton-exciton Coulomb interactions!

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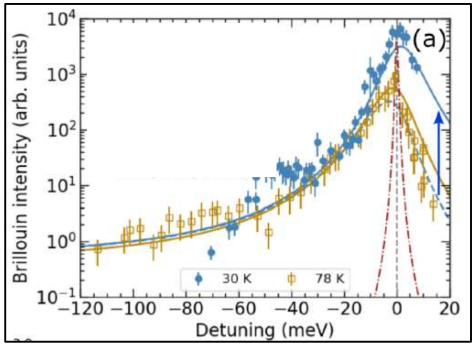
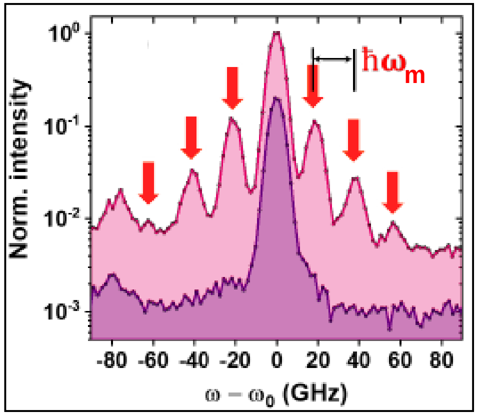
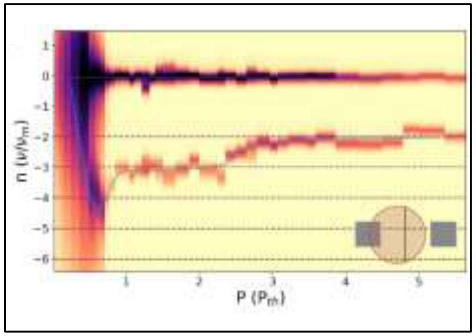


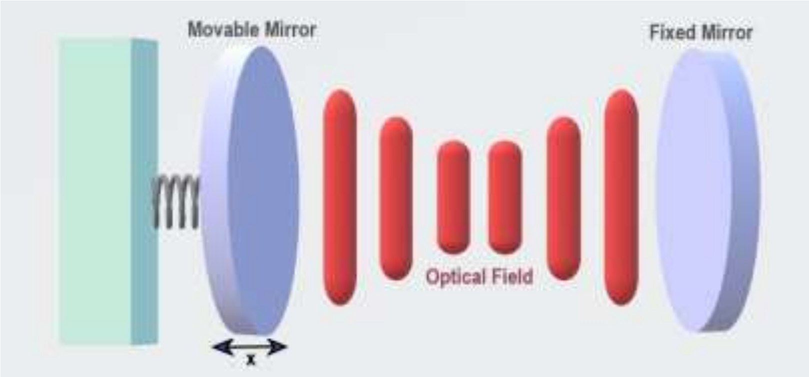


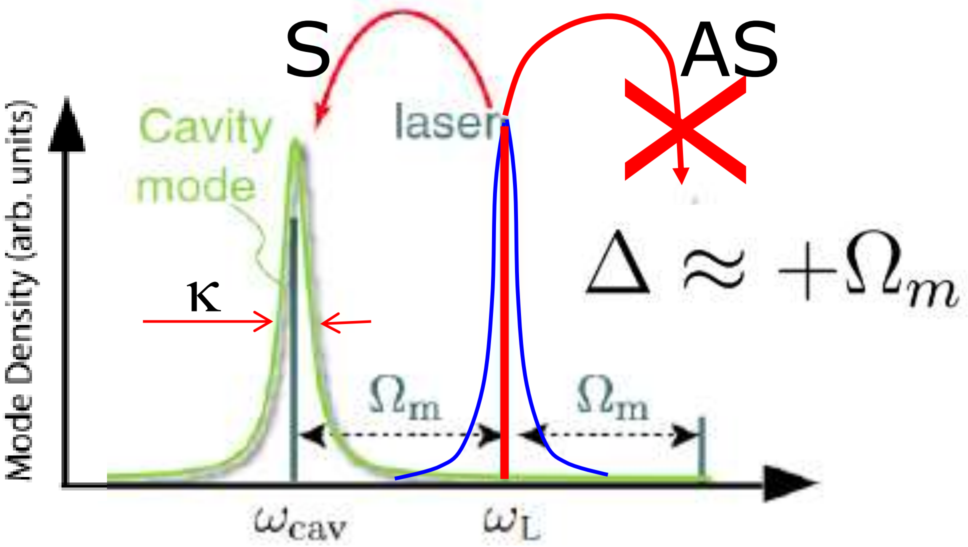


- **Day #1: cavity polaritons**, resonant exciton mediated optomechanical interaction
- **Day #2: self-oscillation**, the optomechanical parametric oscillator
- **Day #3: synchronization,** OM asynchronous locking of polariton states

Bonus: Friday talk, time crystals

Cavity optomechanics: **excitation** (2 modes)

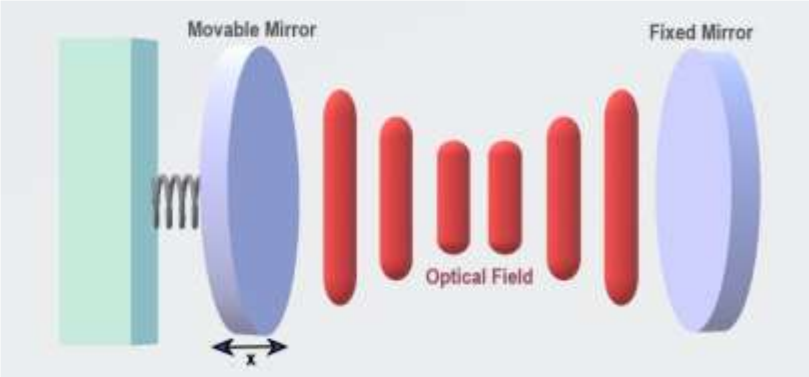


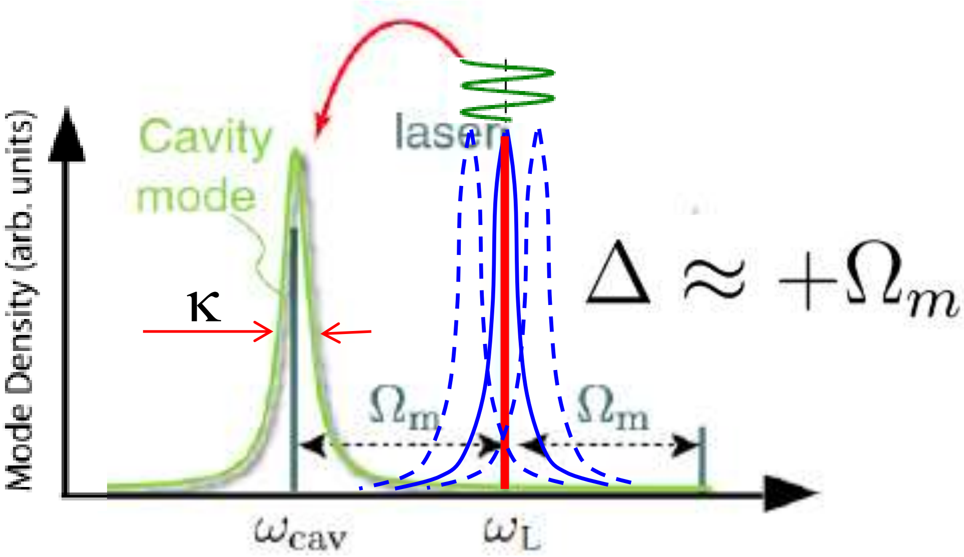


$$H = \hbar\omega_1 a_1^\dagger \hat{a}_1 + \hbar\omega_2 a_2^\dagger a_2 + \hbar\Omega_m b_m^\dagger b_m - \hbar g_0^m (a_2^\dagger a_1 b_m + b_m^\dagger a_1^\dagger a_2)$$

M. Aspelmeyer, TJK, FM, Cavity Optoemchanics, Rev. Mod. Phys. **86**, 1391 (2014).
P. Kharel *et al.*, High-frequency cavity optomechanics using bulk acoustic phonons, Sc. Adv. **5**, eaav0582 (2019).

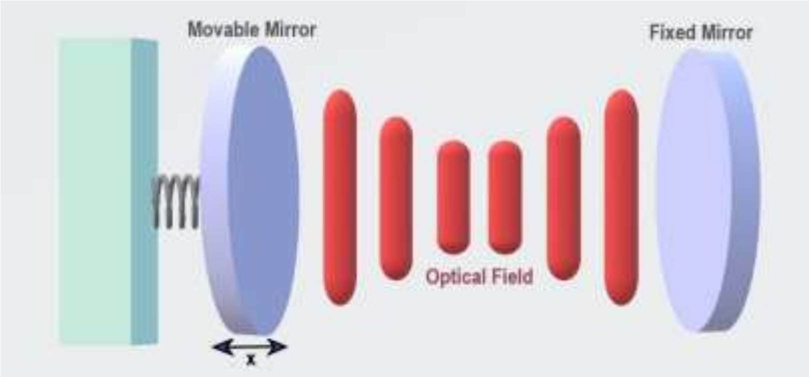
Cavity optomechanics: **back-action**

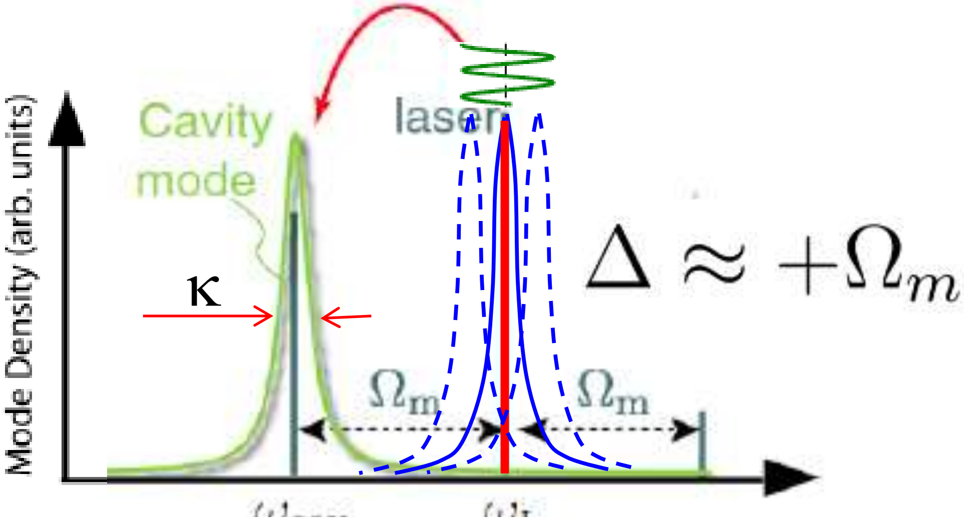


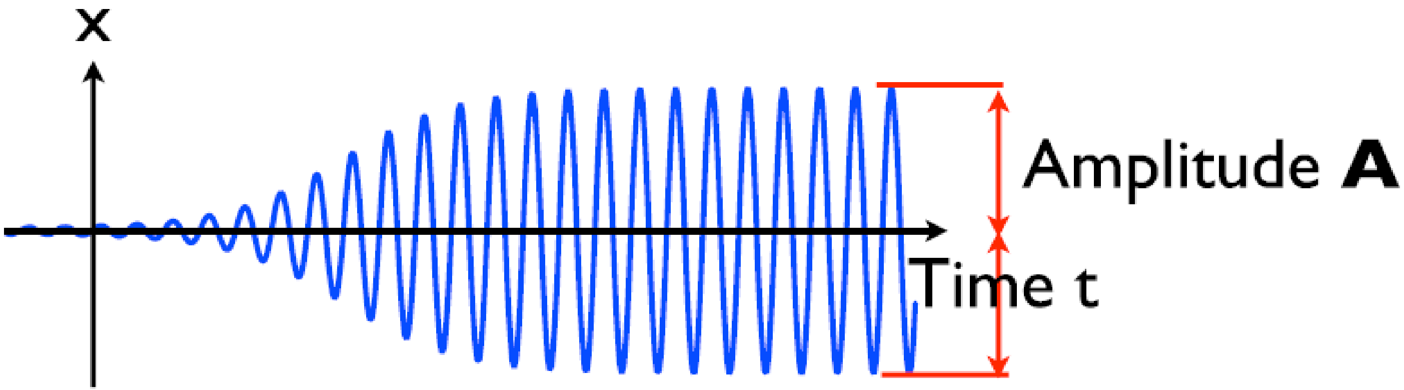


$$\Delta \approx +\Omega_m$$

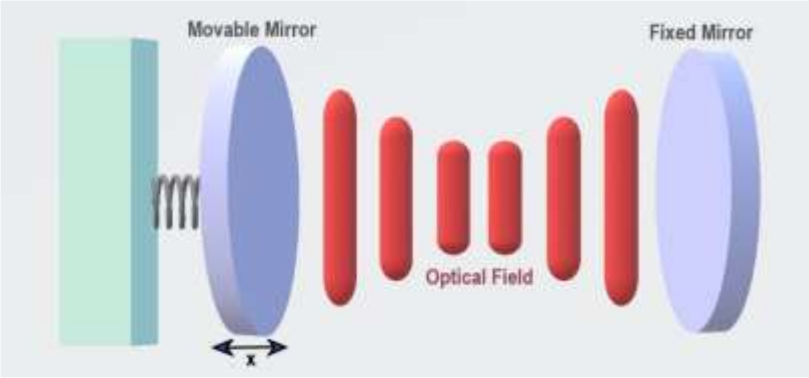
Cavity optomechanics: **self-oscillation**

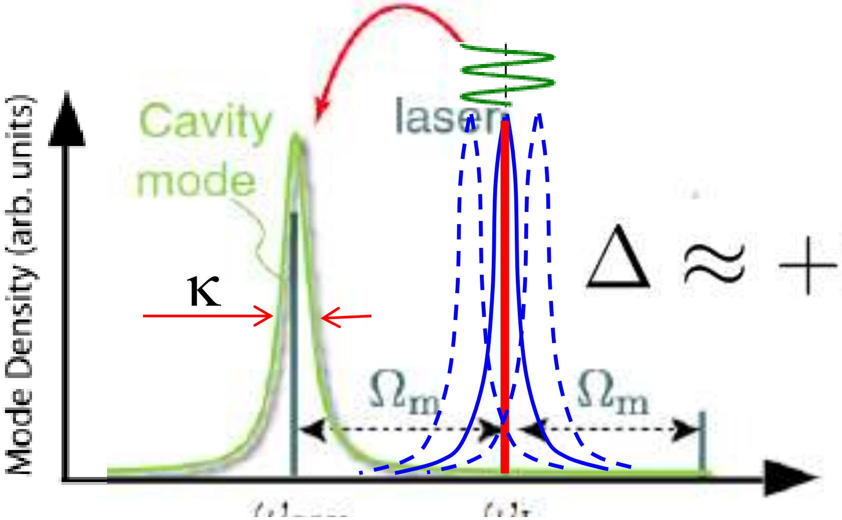




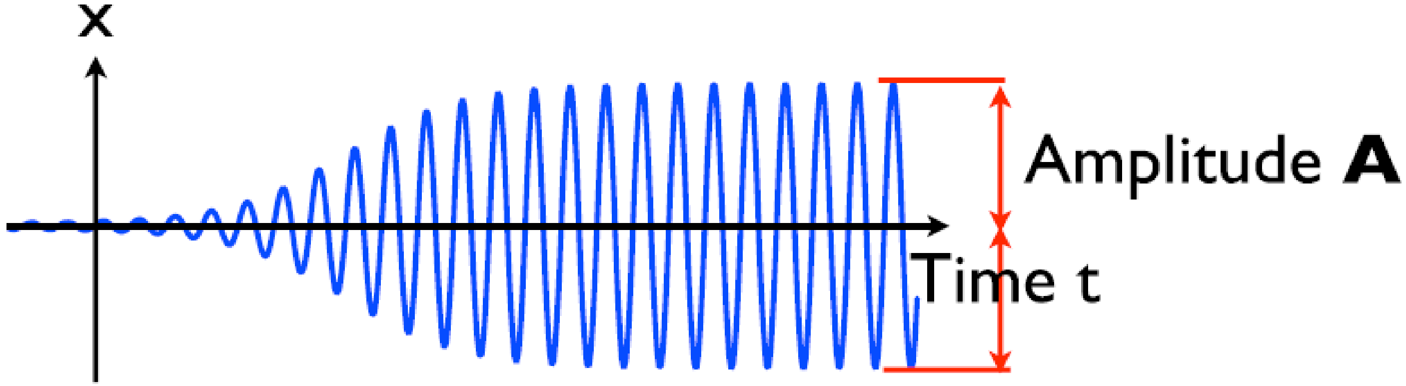


Cavity optomechanics: **self-oscillation**





$$\Delta \approx +\Omega_m$$



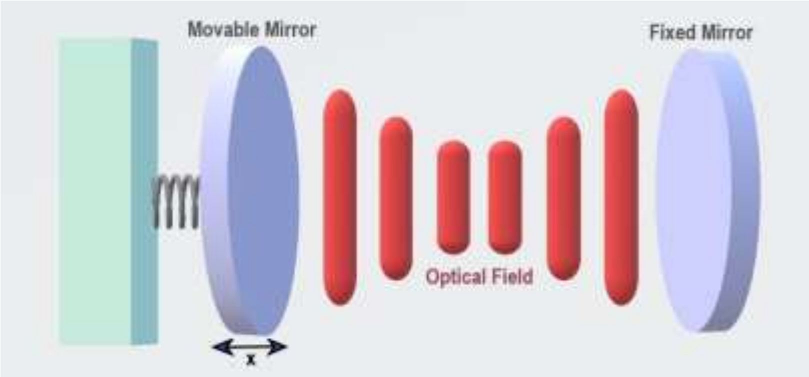
$$\Gamma_{\rm eff} = \Gamma_m (1 - C)$$

OM cooperativity

Optically "dressed" decay rate

Phonon bare decay rate

Cavity optomechanics: OM cooperativity



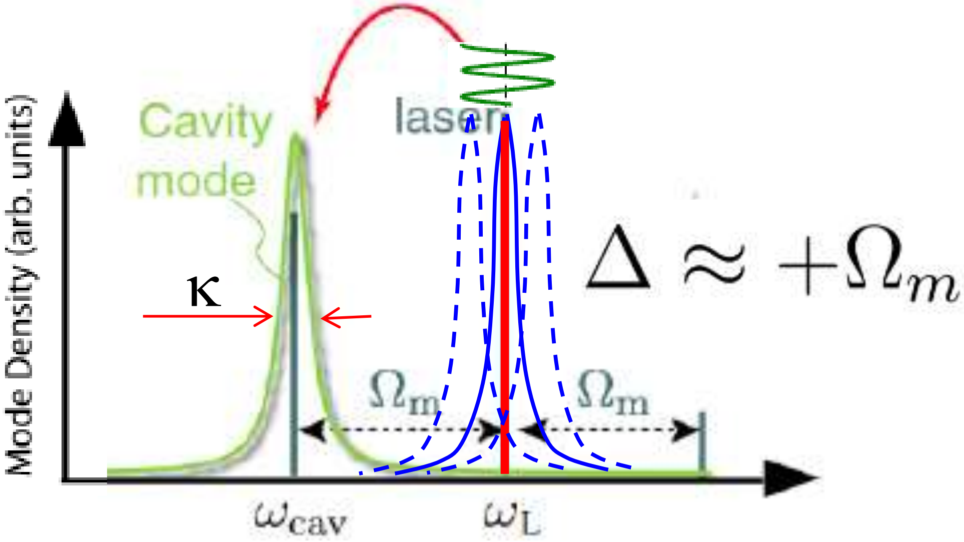


Figure of merit:

OM coupling

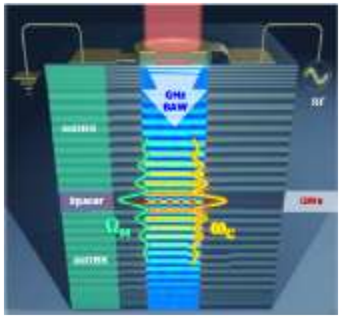
Number of photons

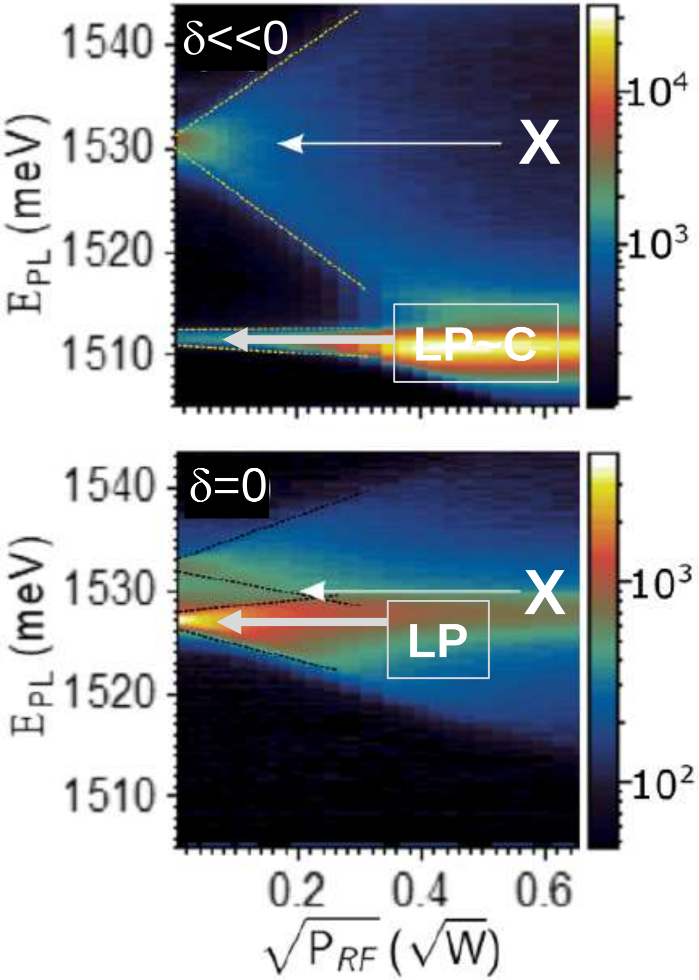
$$C = \frac{4 g_0^2 n_{cav}}{\kappa \Gamma_m} > 1$$

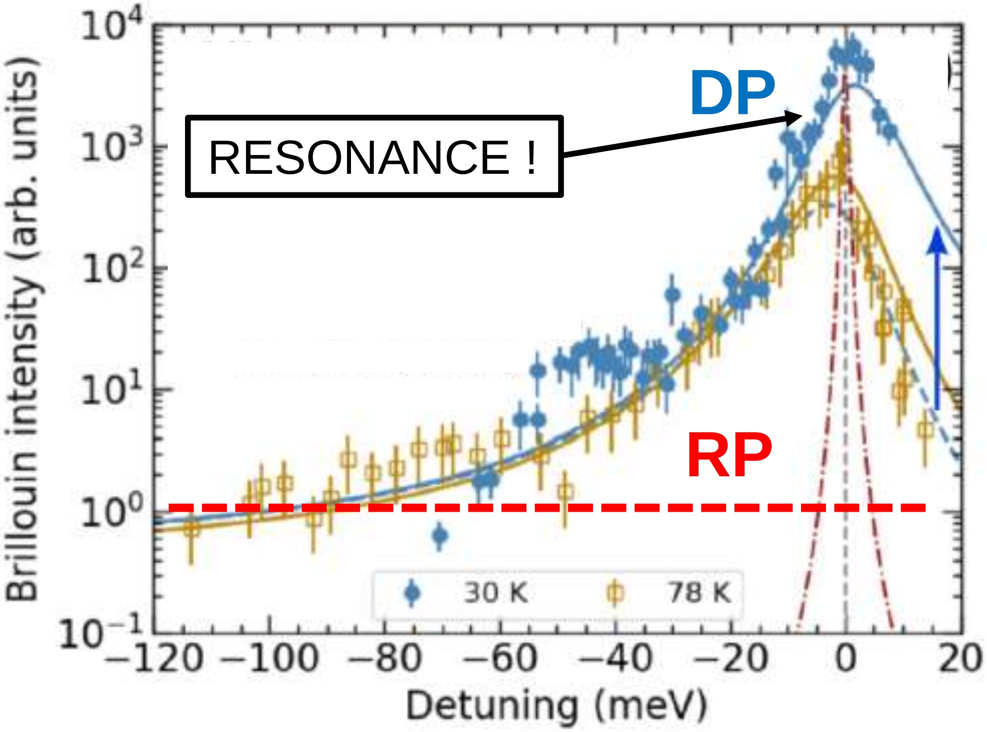
photon decay rate

phonon decay rate

The OM coupling: LP Brillouin scattering







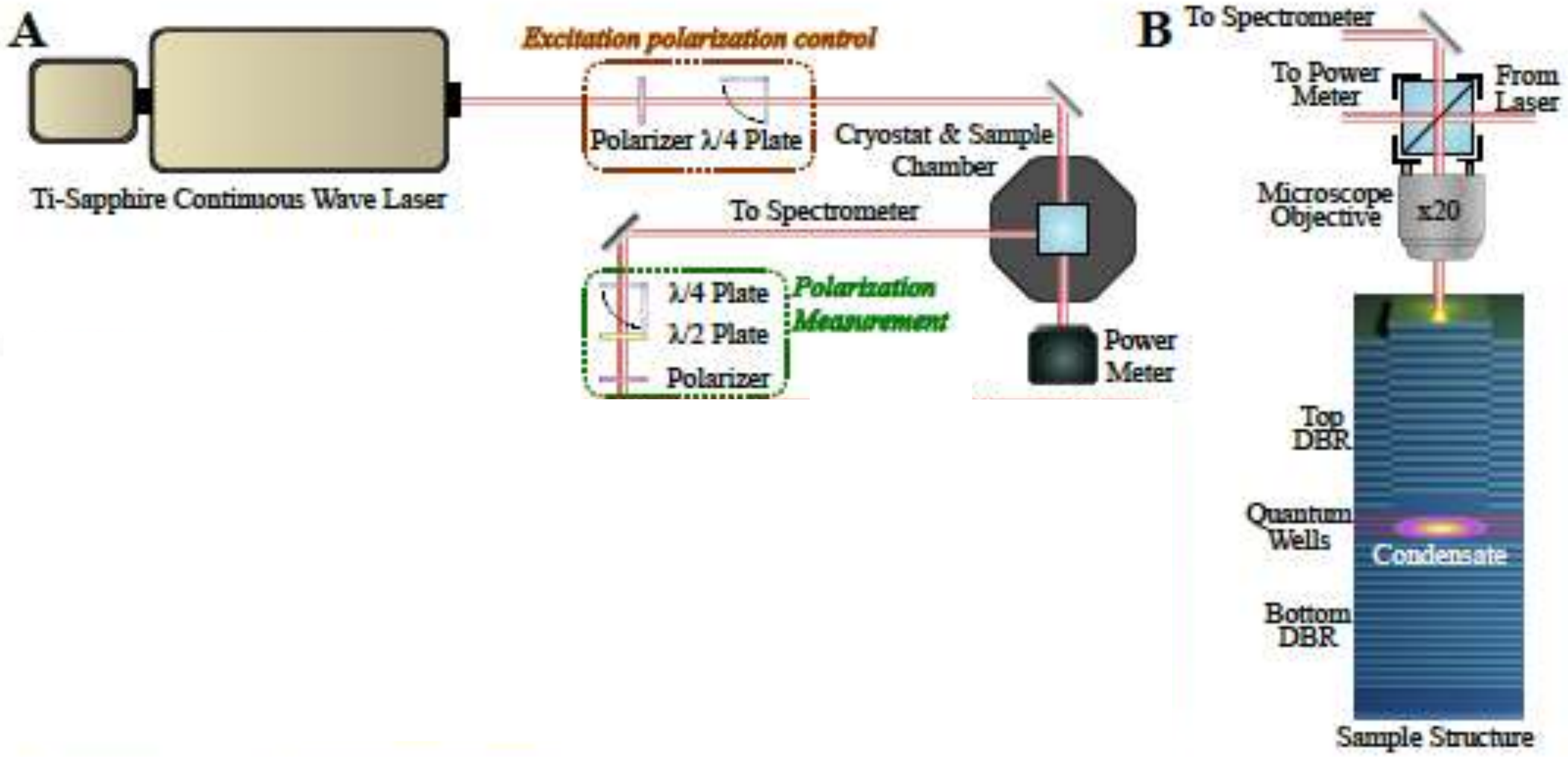
$$g_0 = S_c\, g_0^{RP} + S_x\, g_0^{DP}$$

$$g_0^{DP} \sim 100\, g_0^{RP} \sim 20\ MHz$$

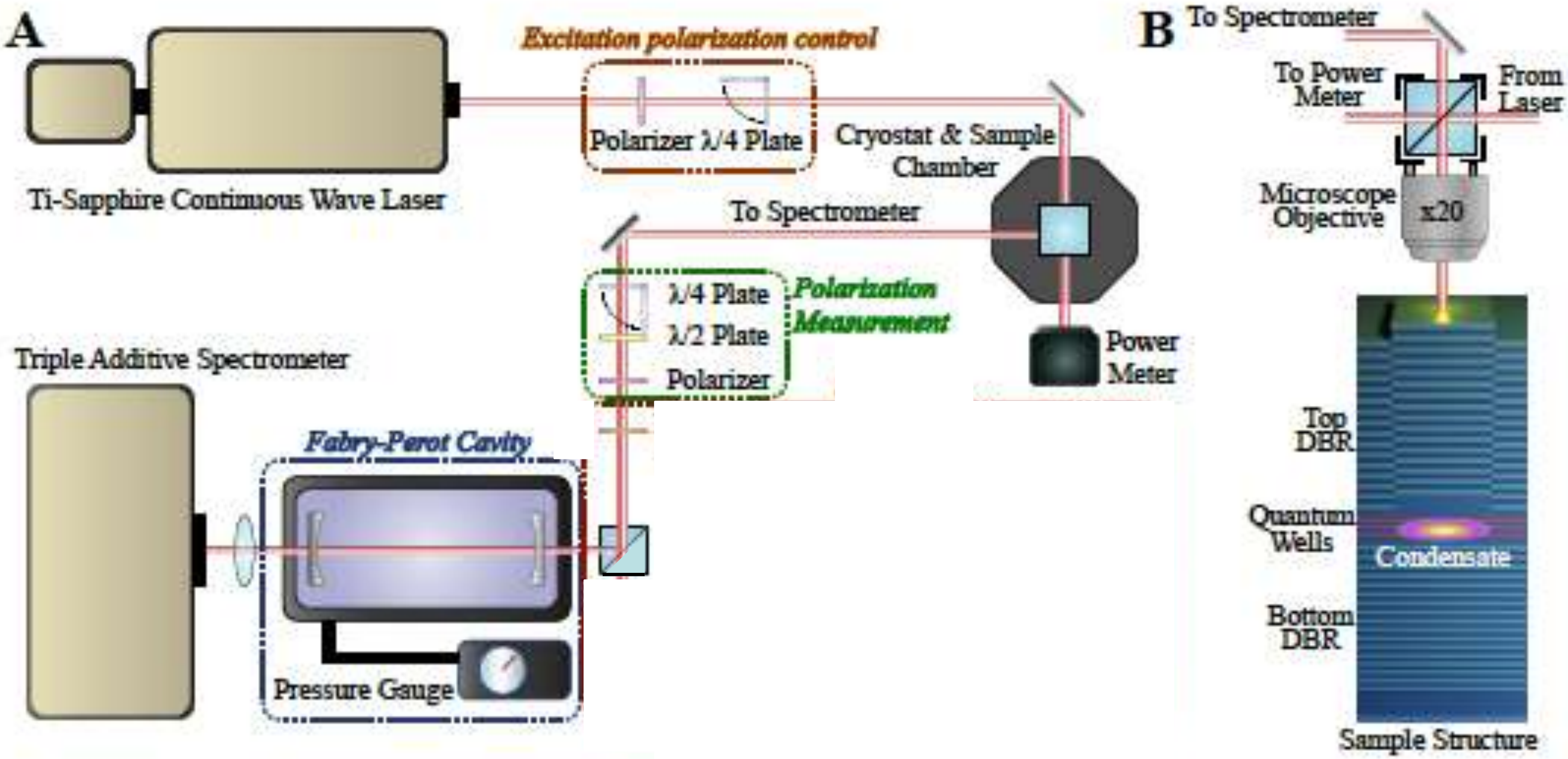
$$\boxed{C_0 = 4g_0^2/\kappa\Gamma > 1}$$

x 10^6

Experimental set-up

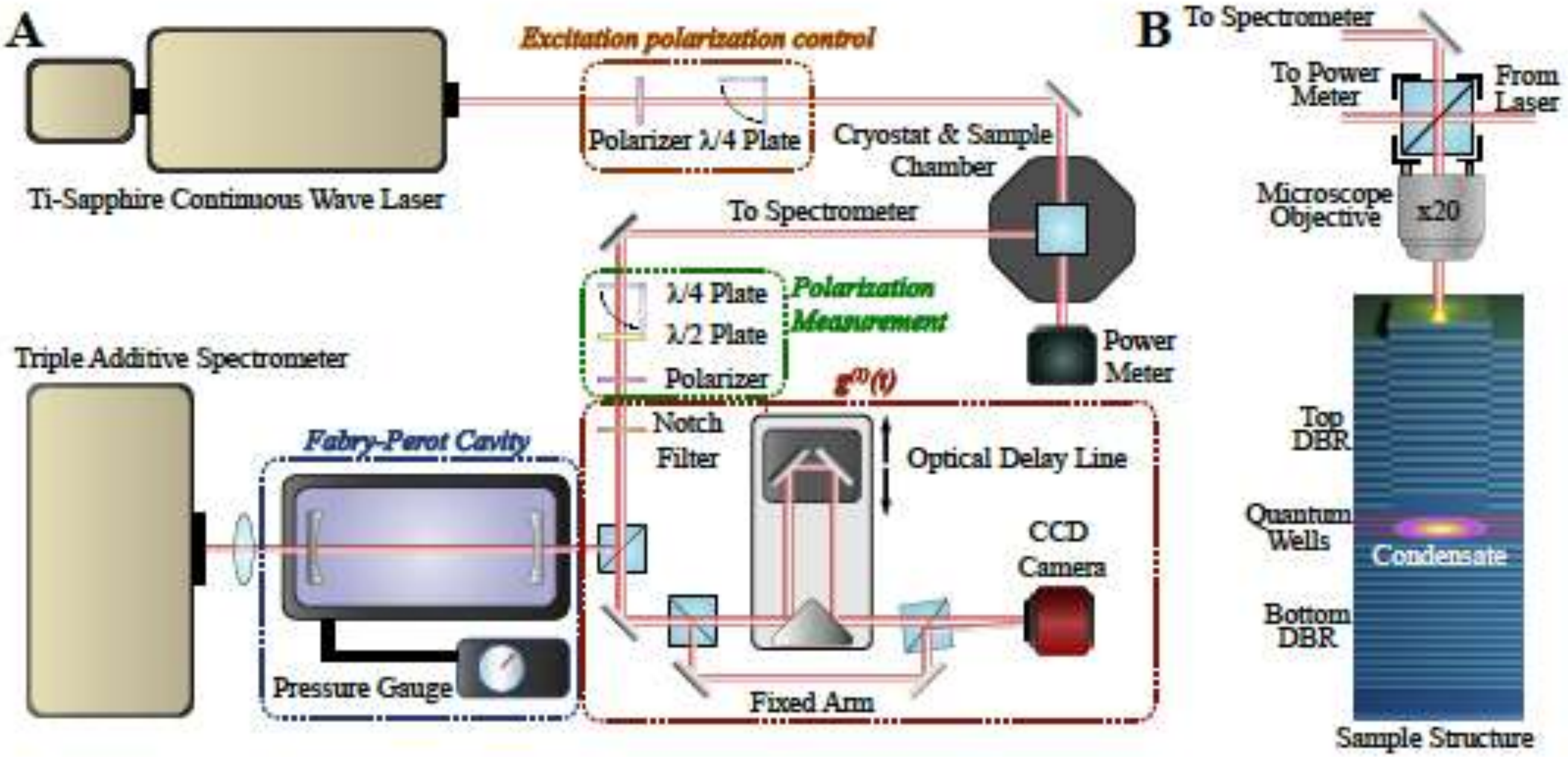


Experimental set-up



$\delta\varepsilon \sim 5\text{GHz} \longrightarrow 0.3\text{GHz}$

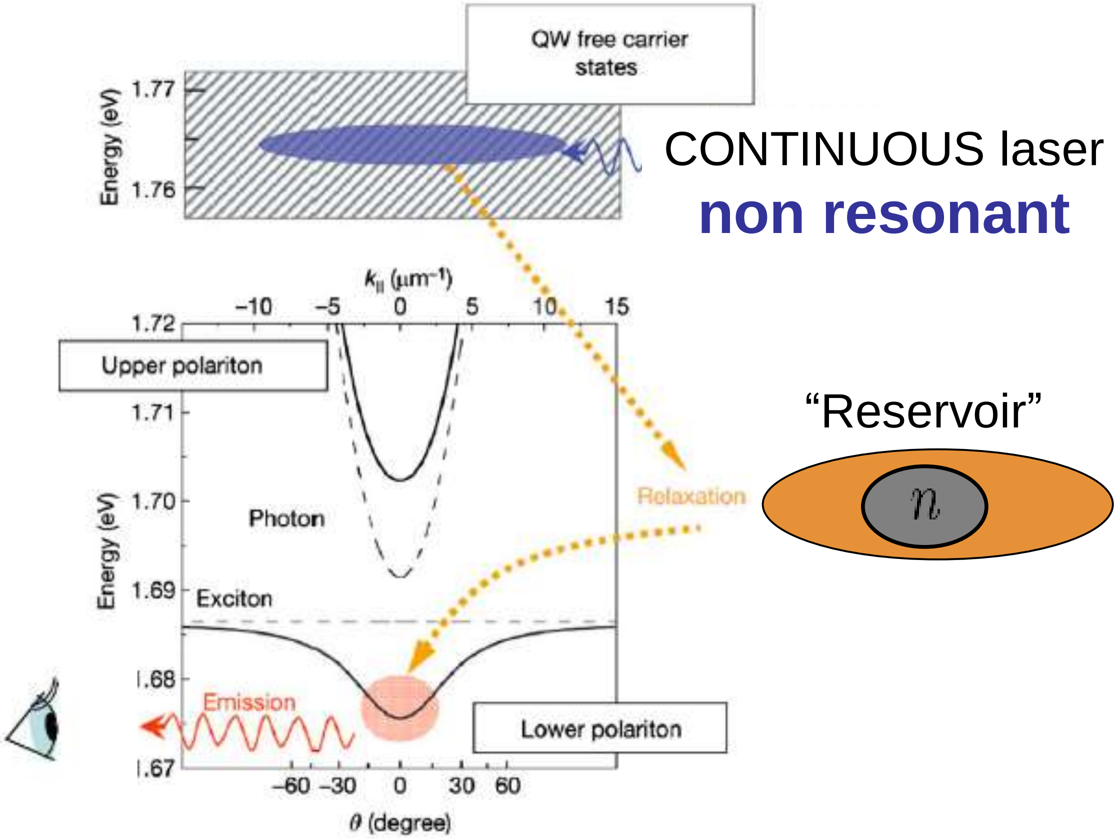
Experimental set-up



$\delta\varepsilon$ ~ 5GHz ⟶ 0.3GHz

$g^{(1)}(\tau)$

Non-resonant excitation

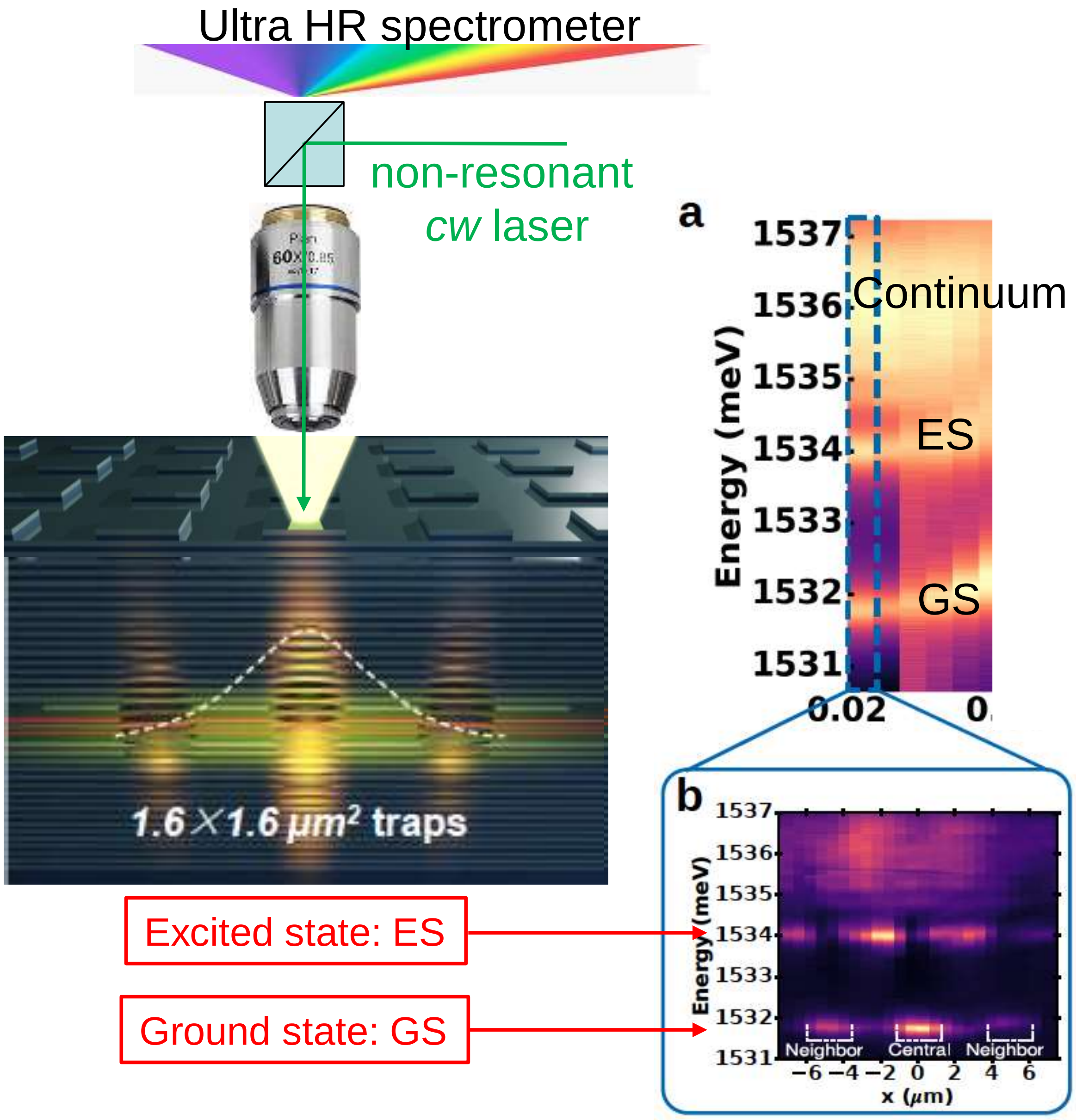


CONTINUOUS laser

non resonant

“Reservoir”

The experiment: *cw* NON-RESONANT excitation



Ultra HR spectrometer

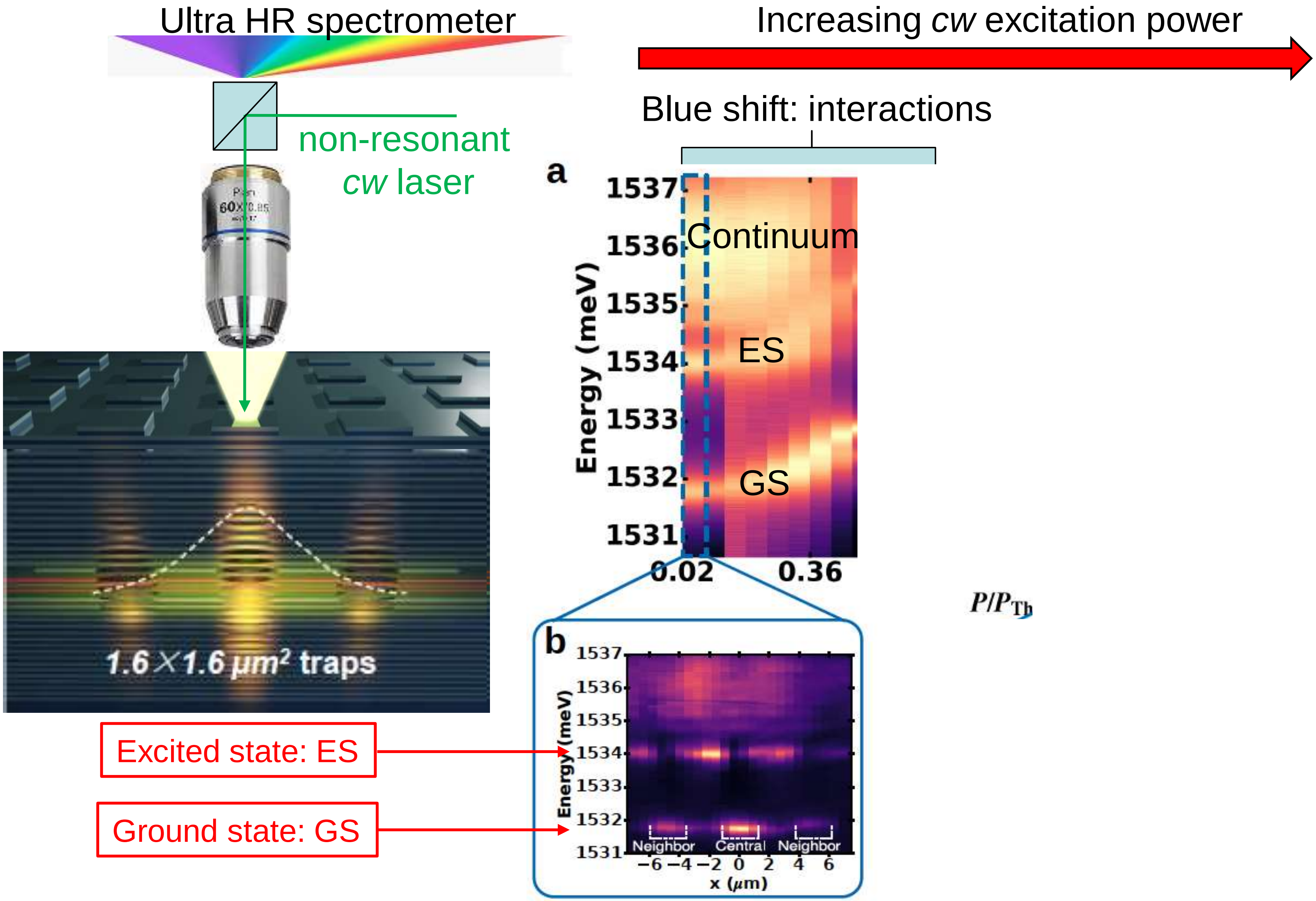
non-resonant *cw* laser

Excited state: ES

Ground state: GS

D. Chafatinos *et al*, NatComm **11**, 4552 (2020)

The experiment: *cw* NON-RESONANT excitation



Ultra HR spectrometer

non-resonant *cw* laser

Increasing *cw* excitation power

Blue shift: interactions

Continuum

ES

GS

Excited state: ES

Ground state: GS

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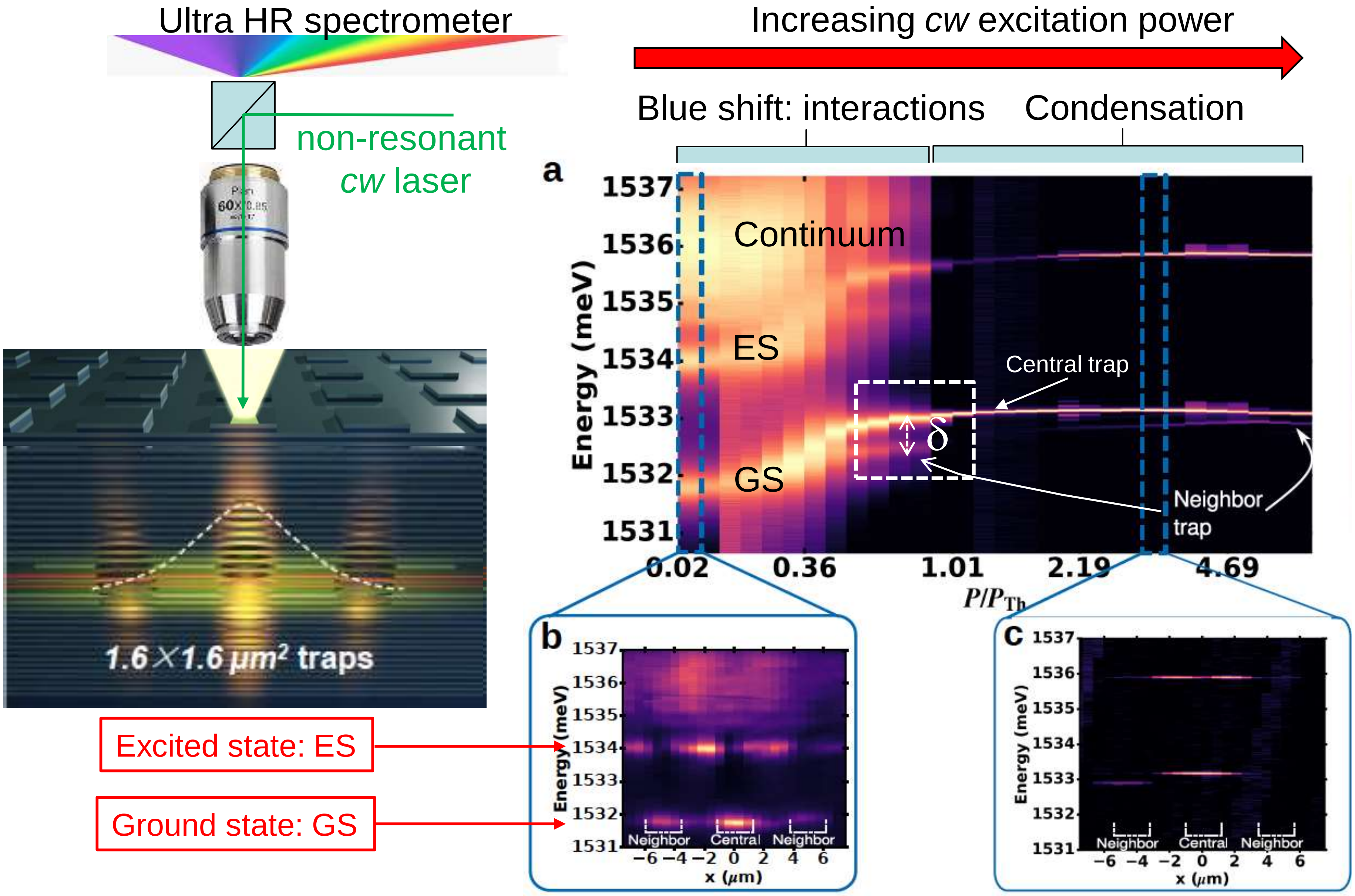
The experiment: *cw* non-resonant excitation



Excited state: ES

Ground state: GS

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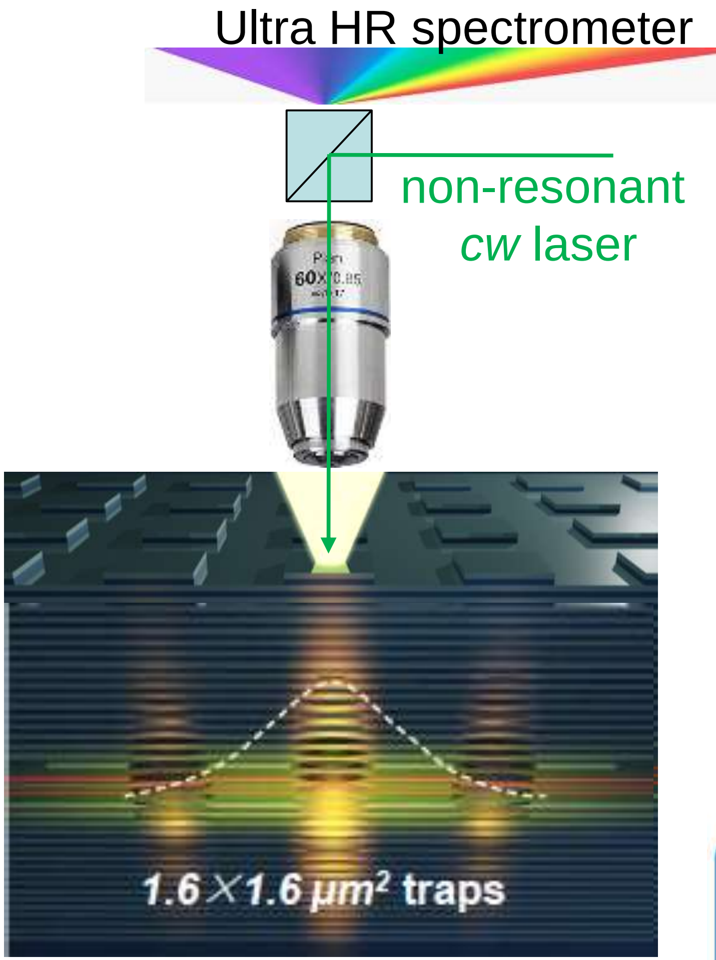
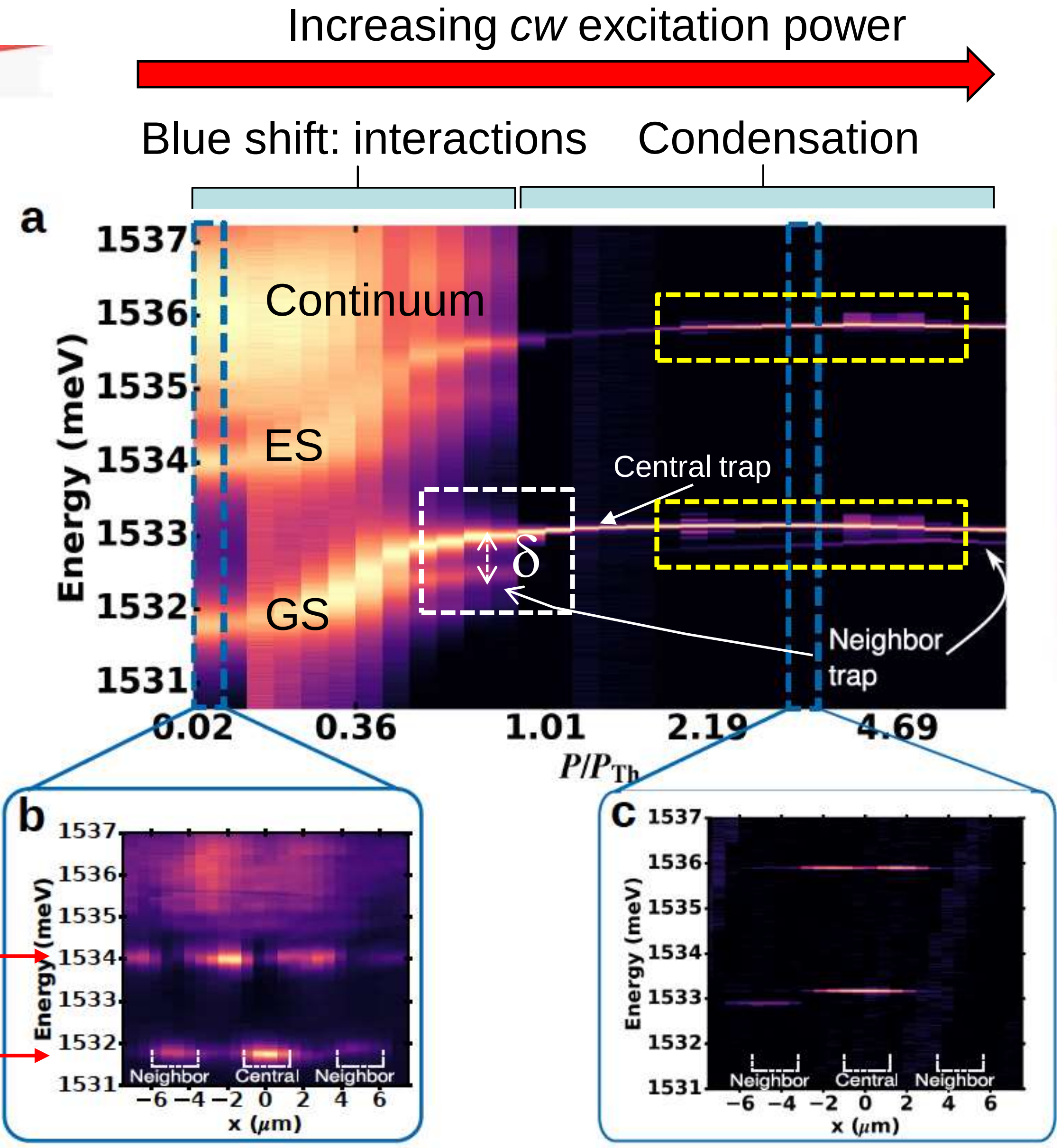
The experiment: *cw* non-resonant excitation





Excited state: ES

Ground state: GS

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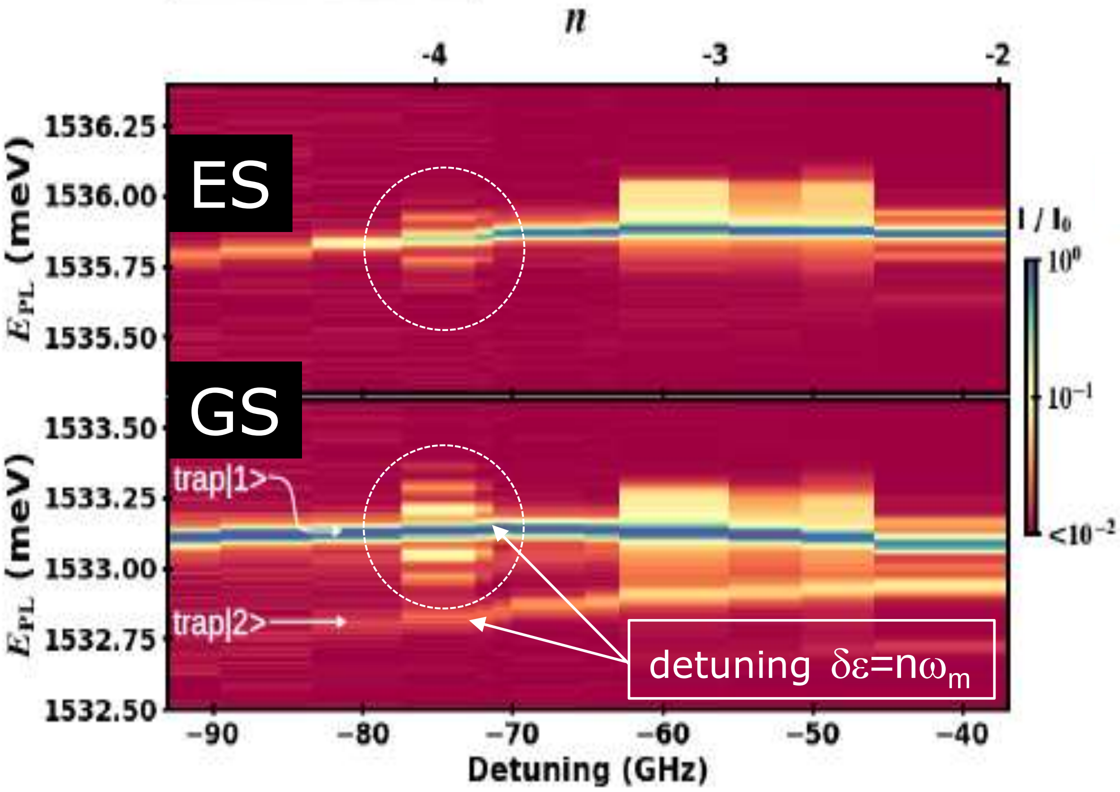
Mechanical self-oscillation



detuning $\delta\varepsilon=n\omega_m$

Detuning between traps

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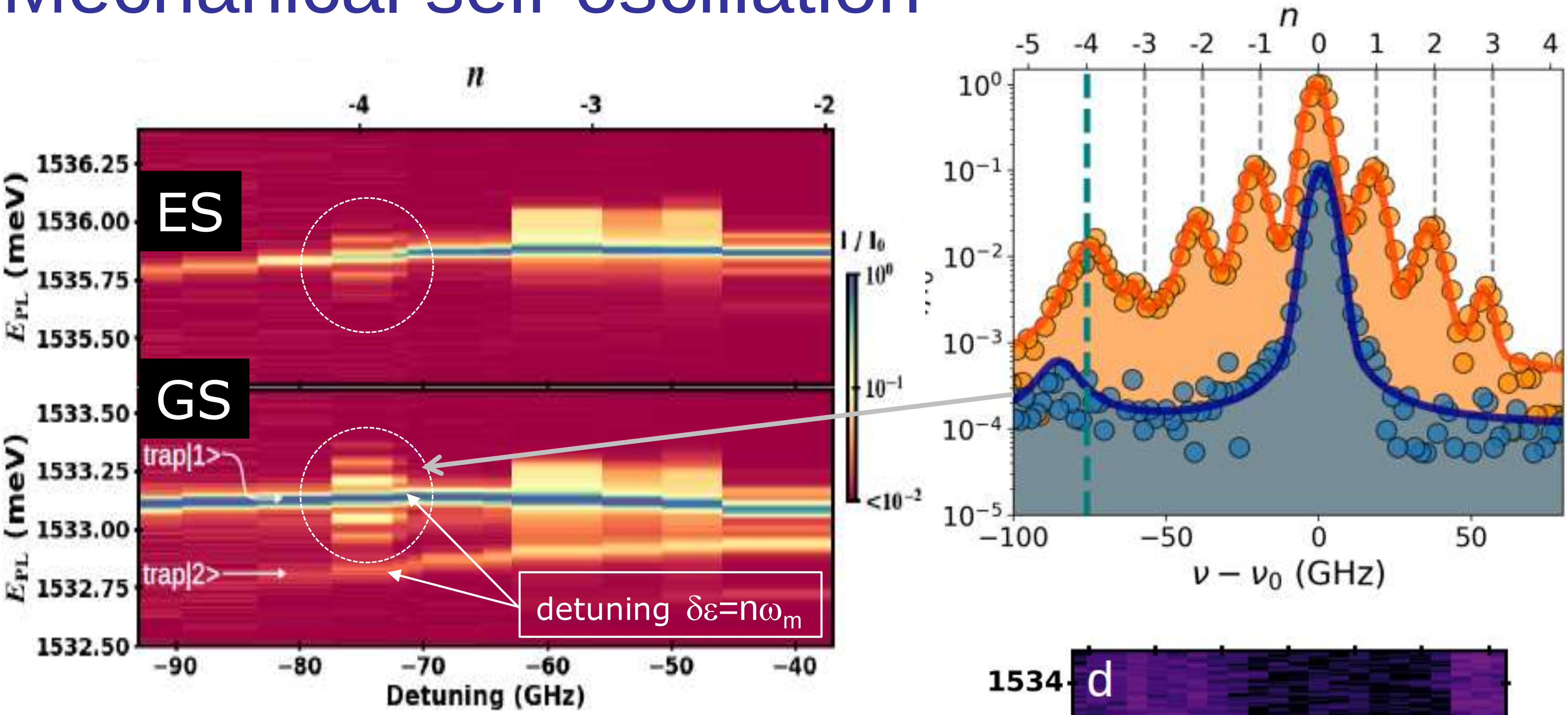
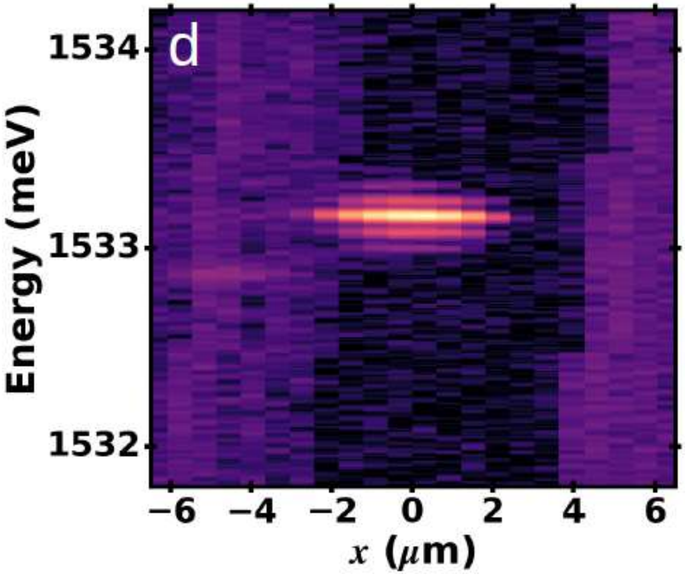
Mechanical self-oscillation



Detuning between traps



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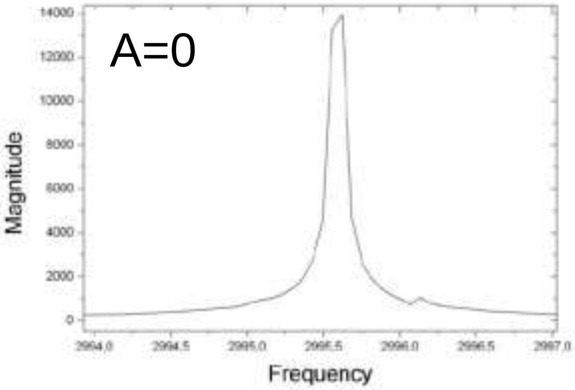
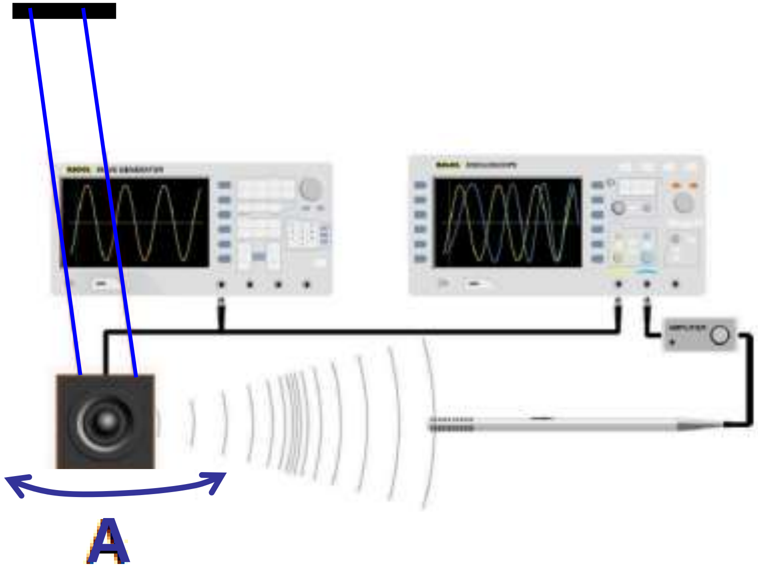
And how do we know that it is oscillating?

Doppler pendulum: 1st course on experimental physics





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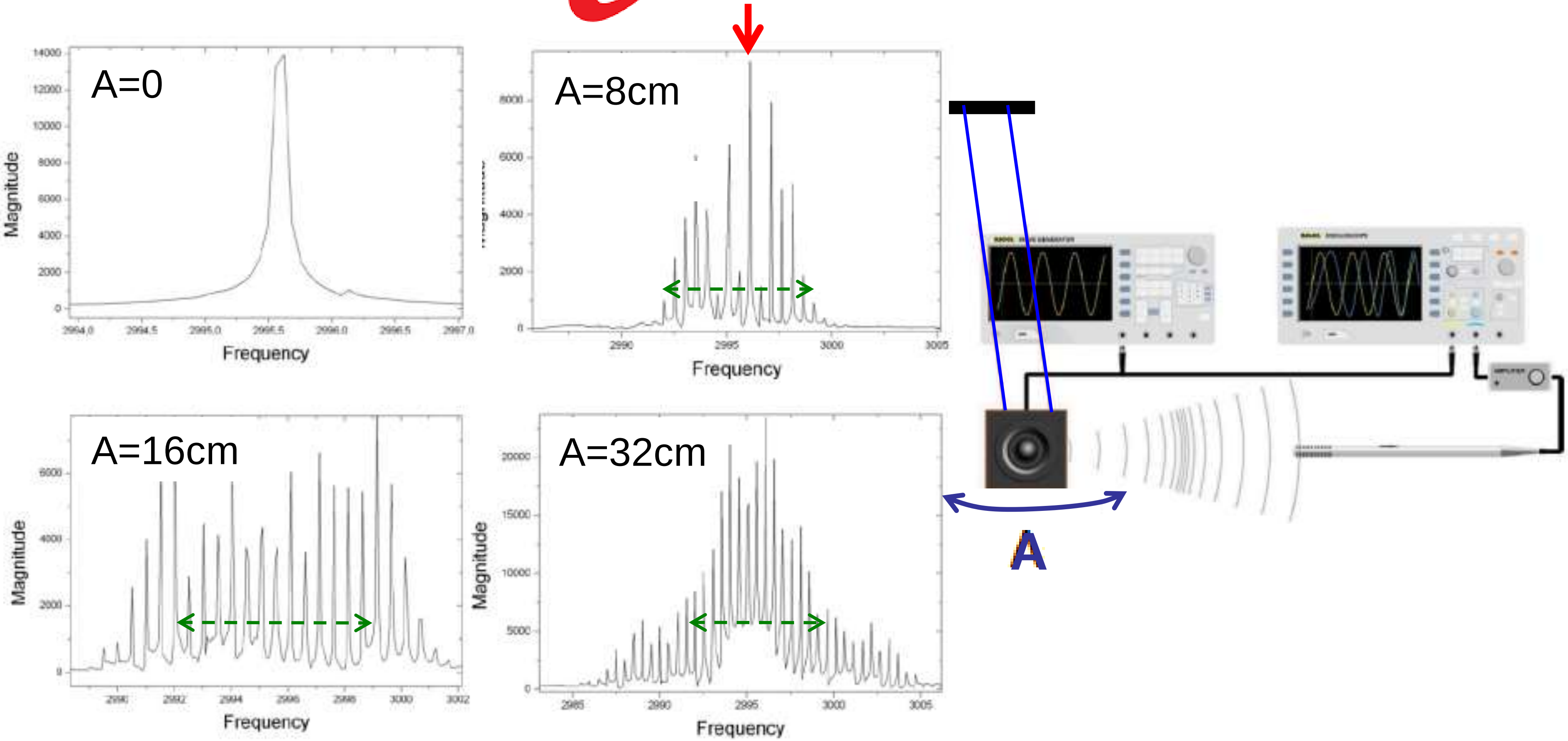
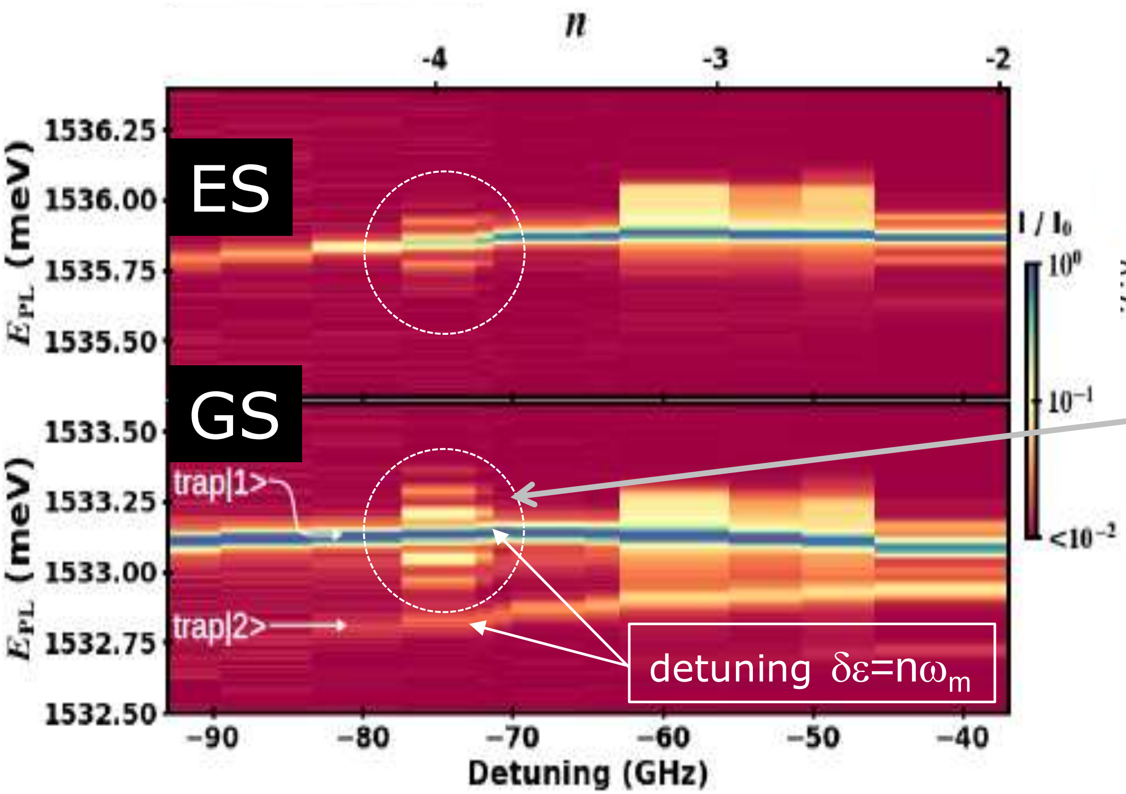
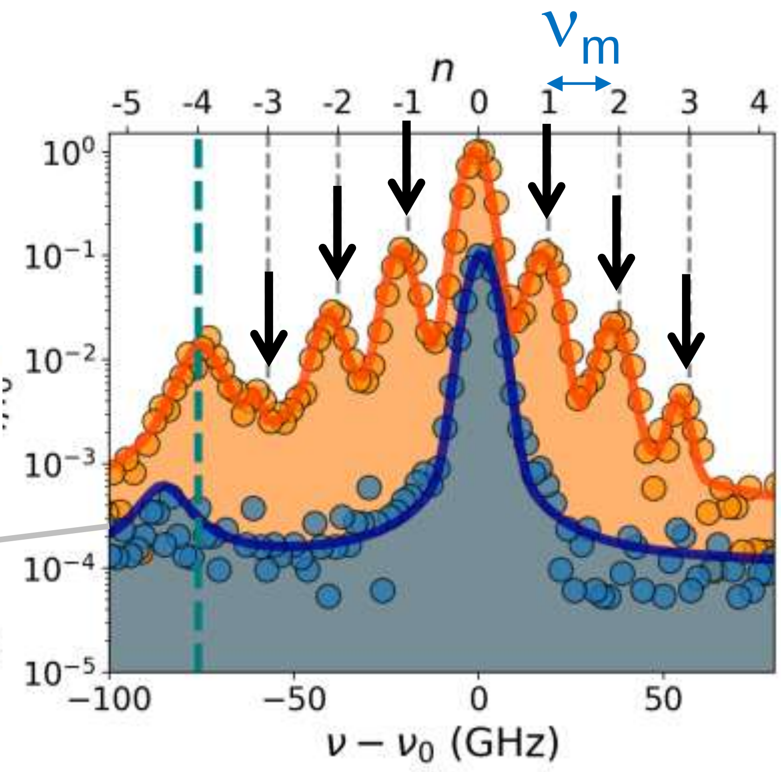


Mechanical self-oscillation





Detuning between traps

$$\langle N \rangle_{\text{Thermal}} \sim 5$$

$$\langle N \rangle \sim 2 \times 10^5$$

$$P[\omega] = \sum_{n=-\infty}^{\infty} \frac{J_n^2(\chi)}{[\omega - (\omega_{\text{BEC}} - n\omega_{\text{d}})]^2 + \gamma^2}$$

"sideband-resolved regime"

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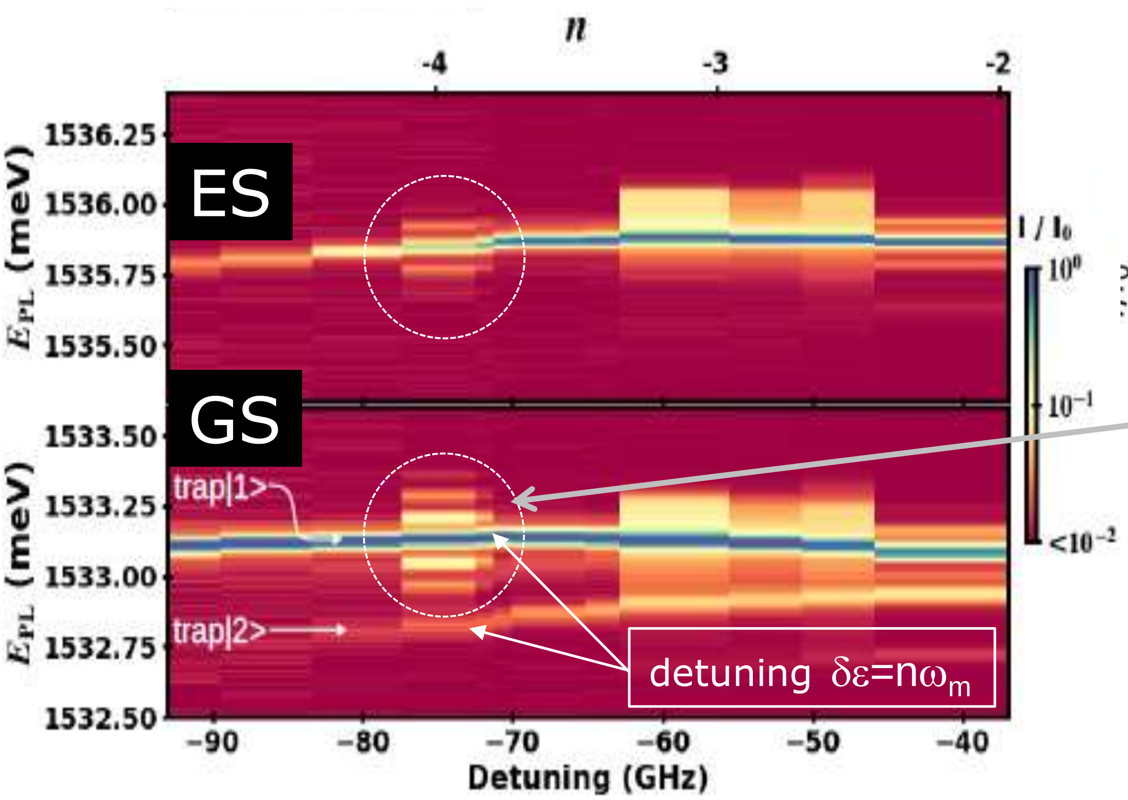
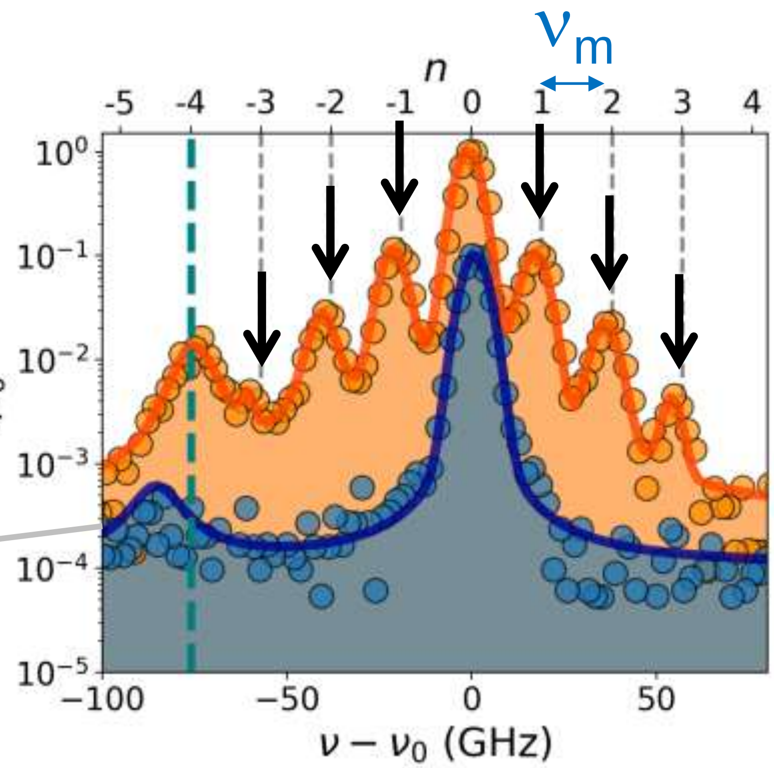
A phonon laser





Detuning between traps

$$\langle N\rangle_{\text{Thermal}} \sim 5$$

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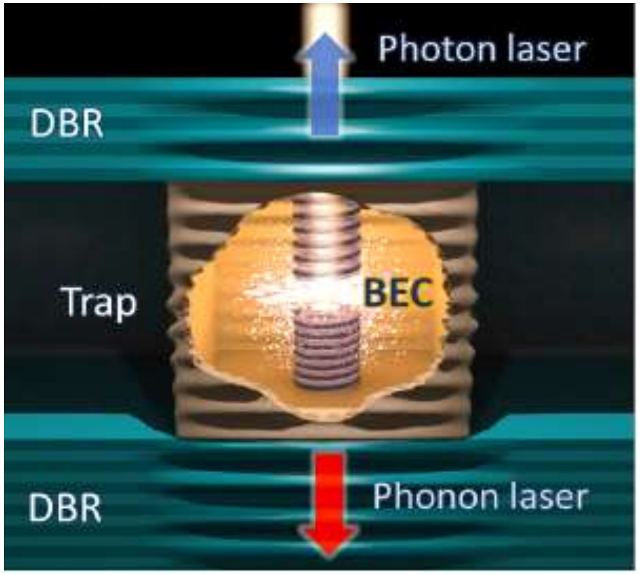

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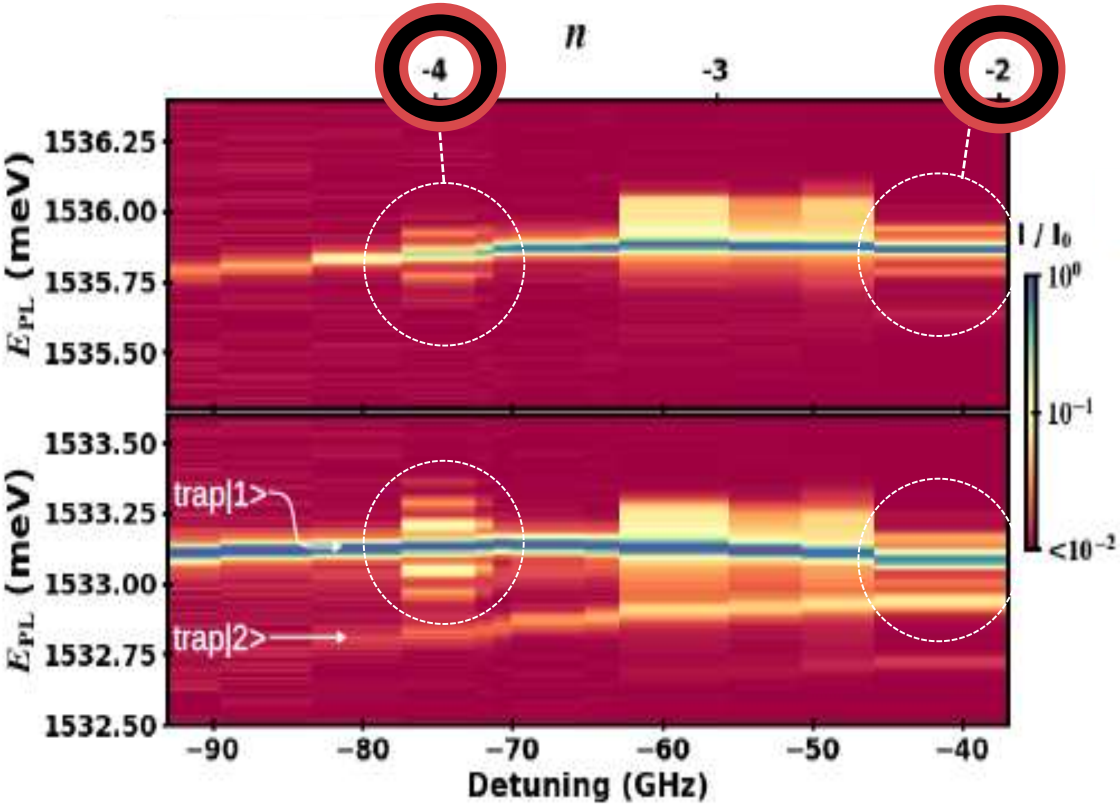
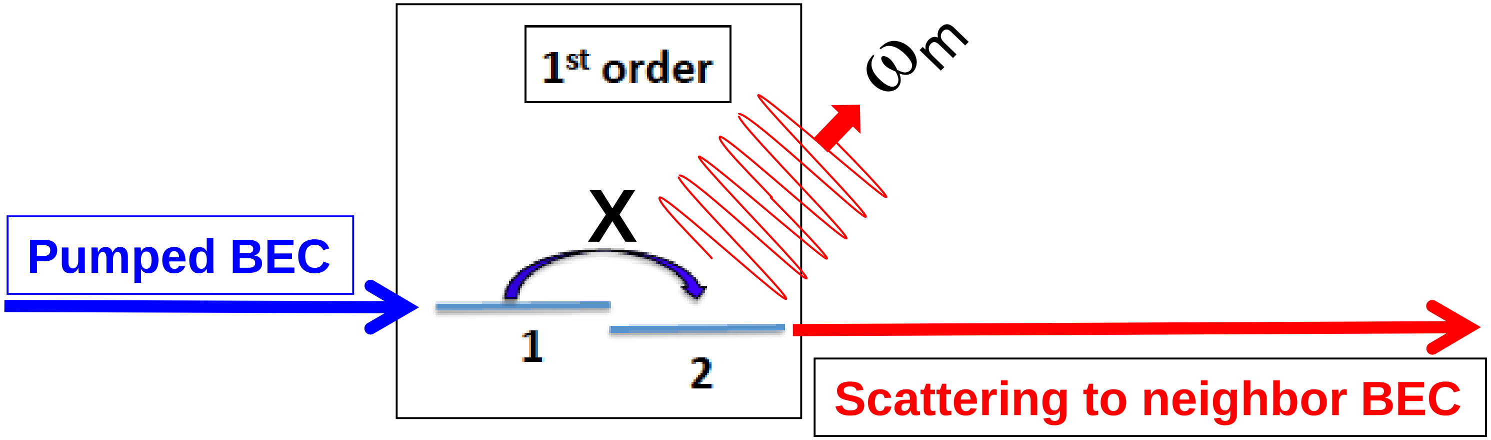
But…. the Devil is in the details…





1st order

ω_m

X

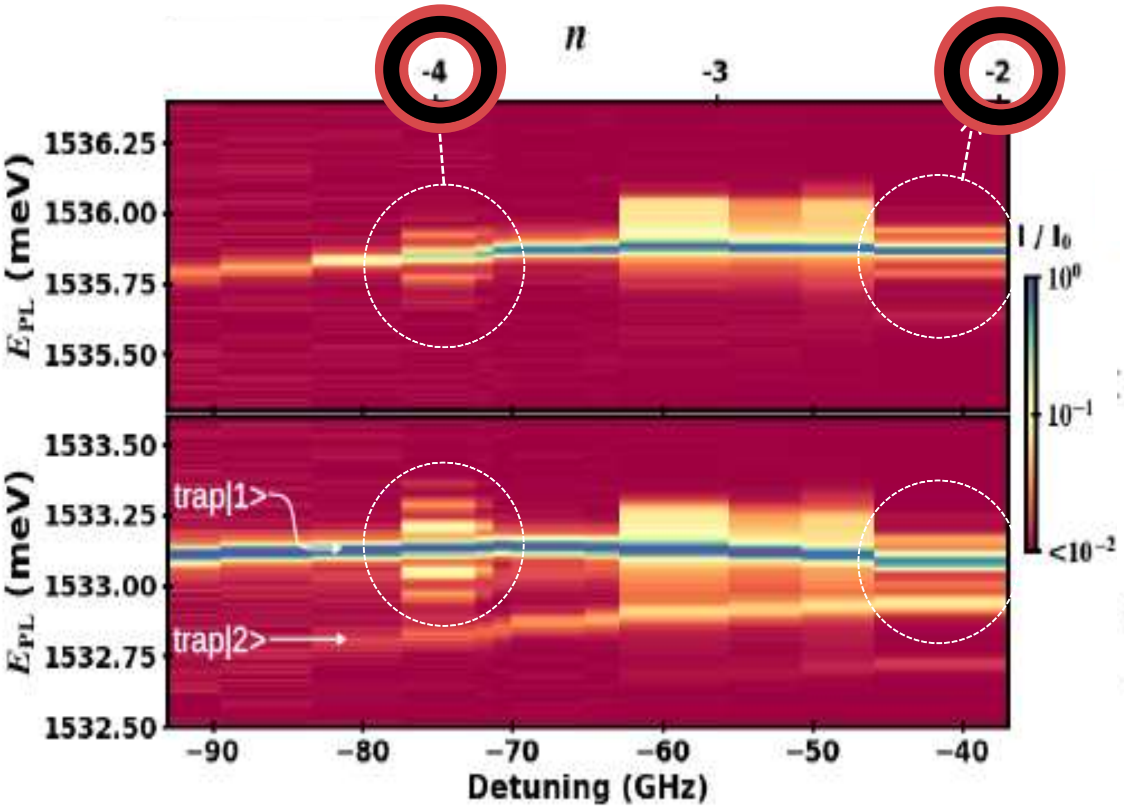
1

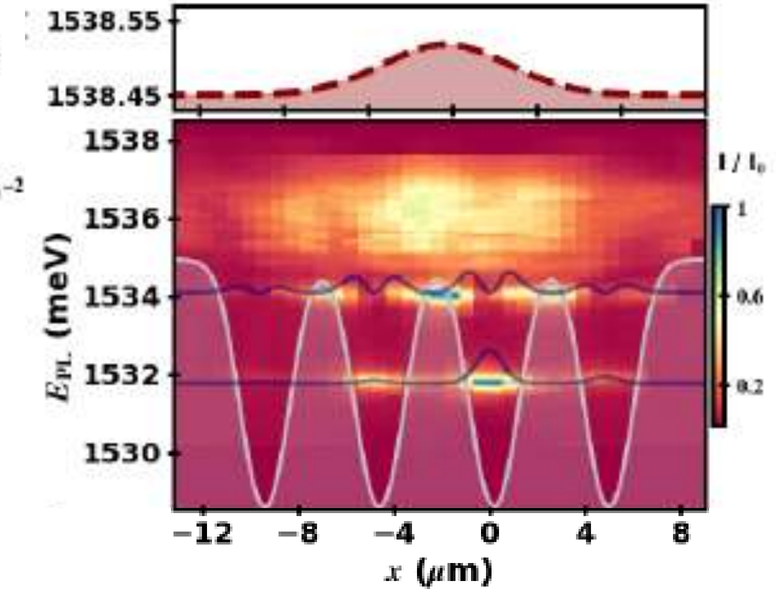
2

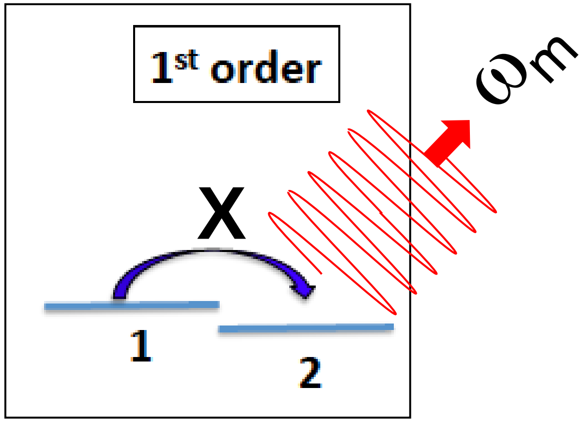
Pumped BEC

Scattering to neighbor BEC

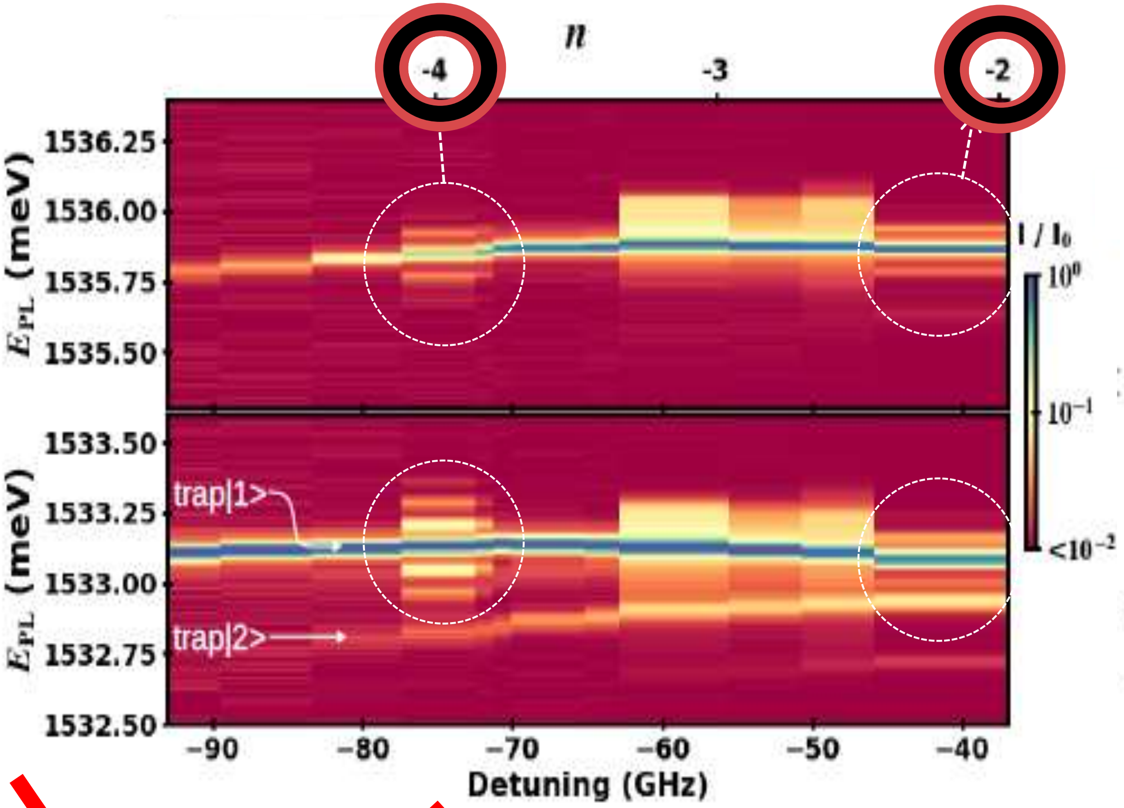
The polaromechanical conundrum

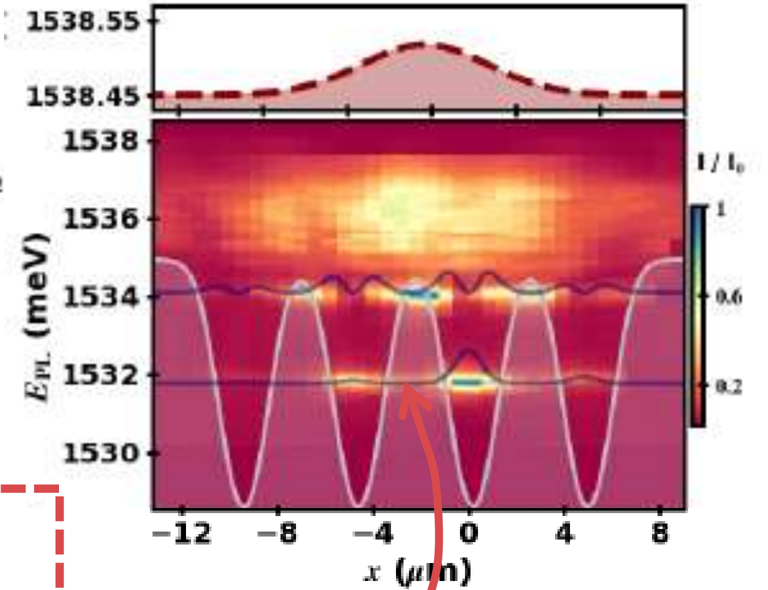


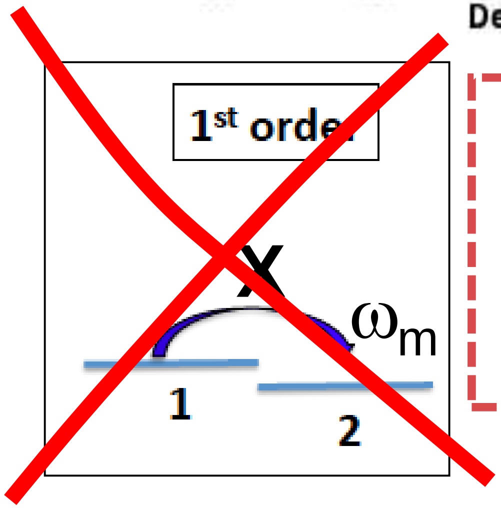




The polaromechanical conundrum

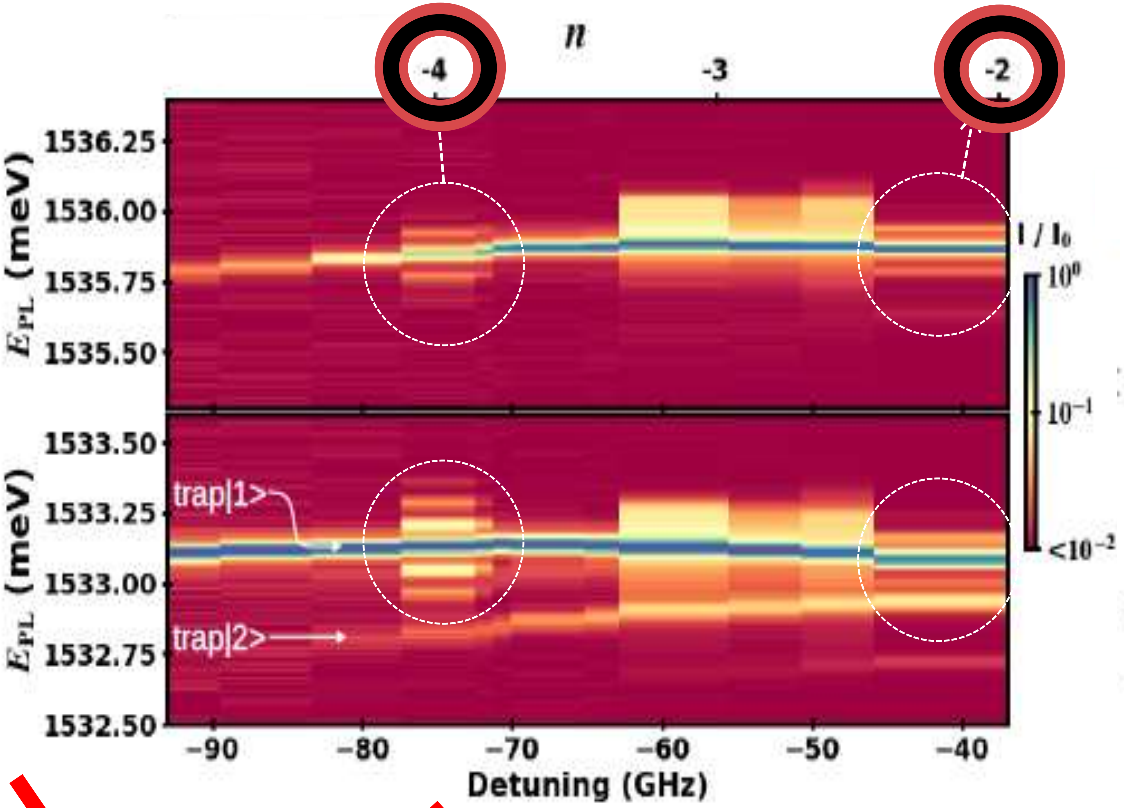




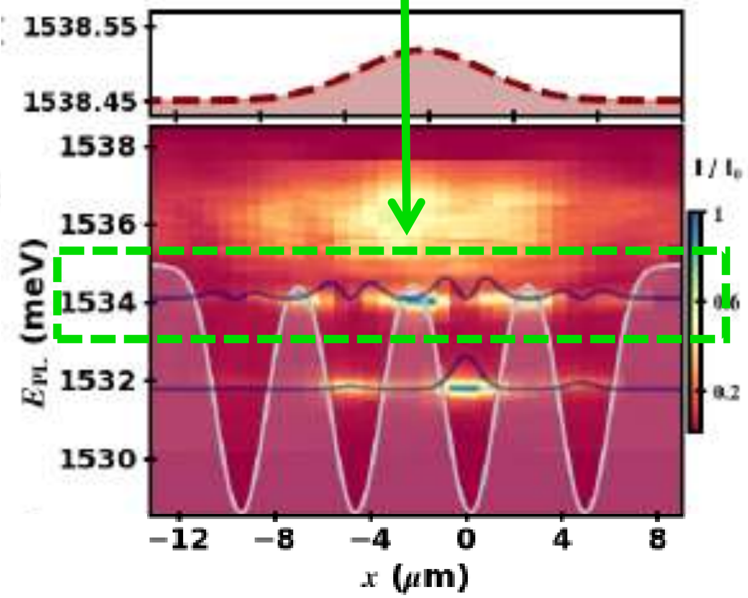


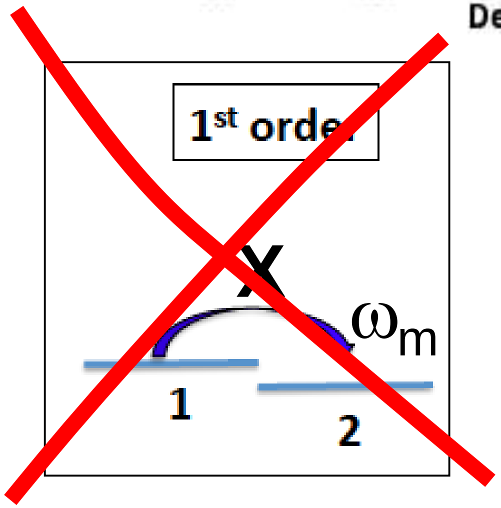
Ground state overlap integral ~10^{-4}

The polaromechanical conundrum

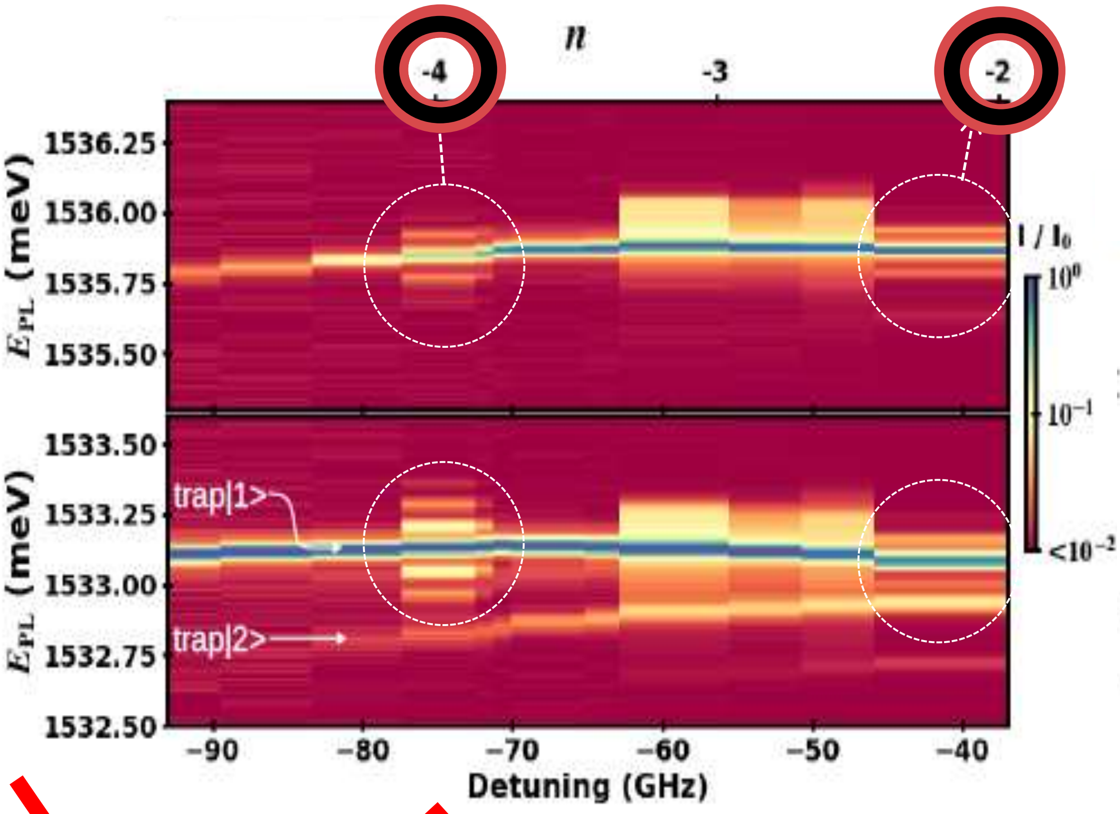


Highly extended excited state!

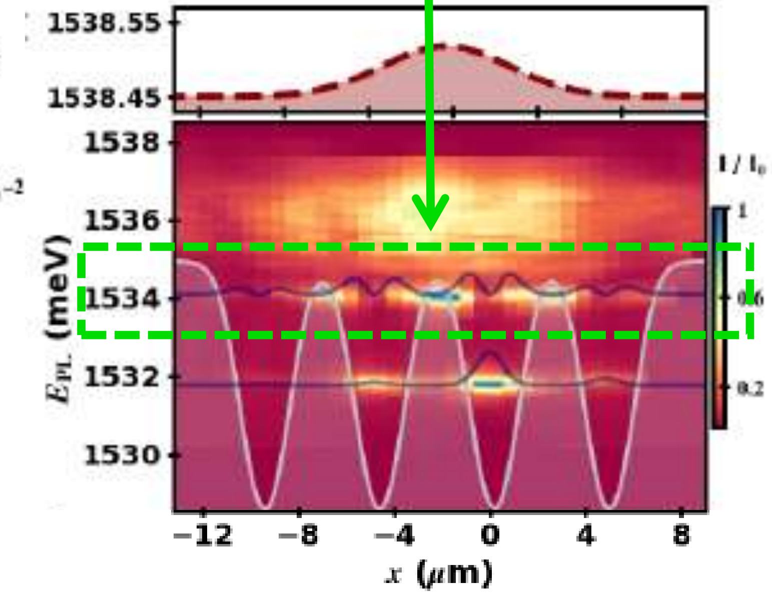


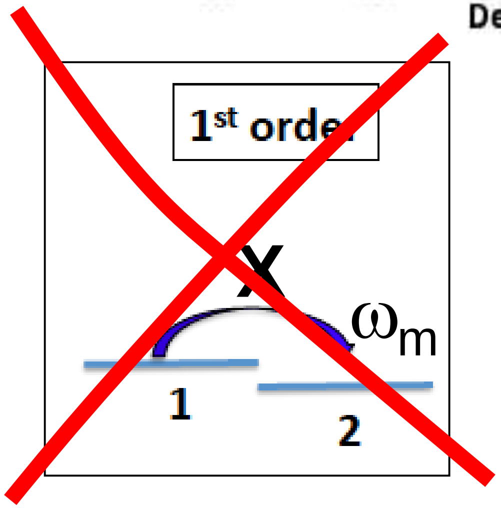


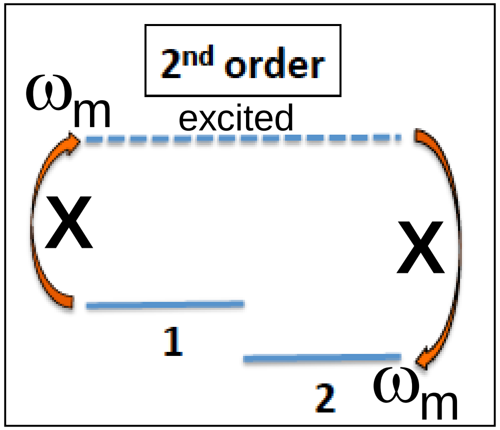
The polaromechanical conundrum



Highly extended excited state!

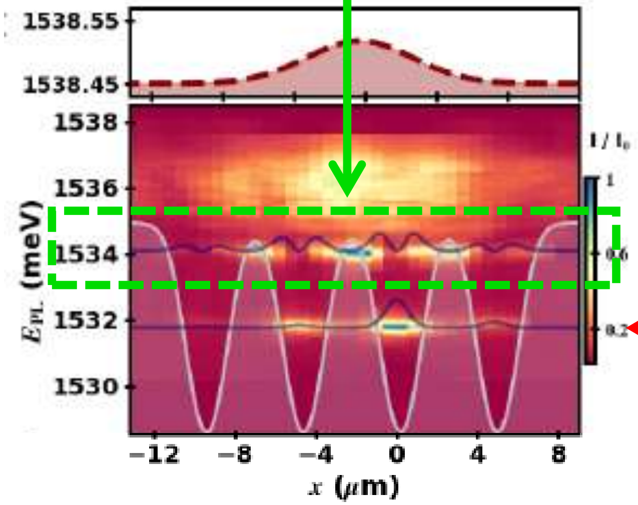




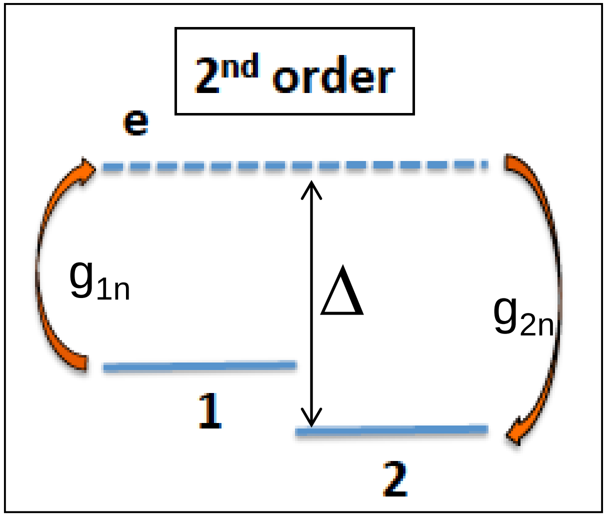


Mechanical SO: 2nd order coupling

Highly extended excited state



Strongly localized ground state



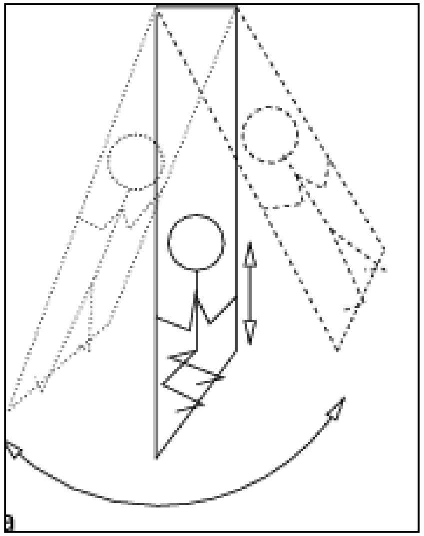
$$\sum_{n,m}\frac{\hbar g_{1n}g_{2m}}{\Delta}\underbrace{(\hat{a}_1^\dagger\hat{a}_2+\hat{a}_2^\dagger\hat{a}_1)(\hat{b}_n^\dagger+\hat{b}_n)(\hat{b}_m^\dagger+\hat{b}_m)}_{\text{2nd order inter-trap coupling}}.$$

Mechanical SO: “Parametric” process

$$\ddot{x}_n + \Gamma_n \dot{x}_n + \tilde{\Omega}_n^2 x_n = 0$$

$$\tilde{\Omega}_n^2 = \Omega_n^2 + 4\Omega_n \frac{g_0^2}{\Delta}\left(\underbrace{2n_3^0 - \sum_{j=1}^{2} n_j^0}_{\text{Frequency renormalization}} + \overbrace{2\sqrt{n_1^0 n_2^0}\cos\left(\underset{\textbf{Trap \#1}}{\omega_1} - \underset{\textbf{Trap \#2}}{\omega_2}\right)t}^{\text{Parametric driving}}\right)$$

$$\boxed{\omega_1 - \omega_2 = 2\omega_m}$$



D. Chafatinos *et al*, NatComm **11**, 4552 (2020)
A. A. Reynoso *et al,* PRB **105**, 195310 (2022)

An OM parametric oscillator

$$\ddot{x}_n + \Gamma_n \dot{x}_n + \tilde{\Omega}_n^2 x_n = 0$$

$$\tilde{\Omega}_n^2 = \Omega_n^2 + 4\Omega_n \frac{g_0^2}{\Delta}\left(\underbrace{2n_3^0 - \sum_{j=1}^{2} n_j^0}_{\text{Frequency renormalization}} + \overbrace{2\sqrt{n_1^0 n_2^0}\cos\left(\omega_1 - \omega_2\right)t}^{\text{Parametric driving}} \right)$$

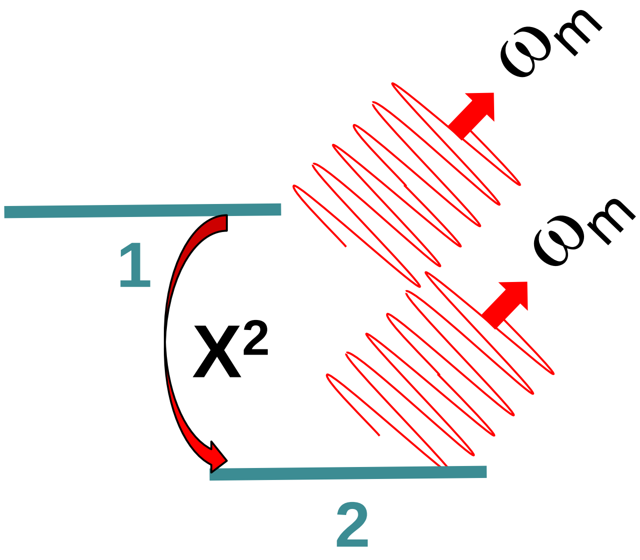
Trap #1

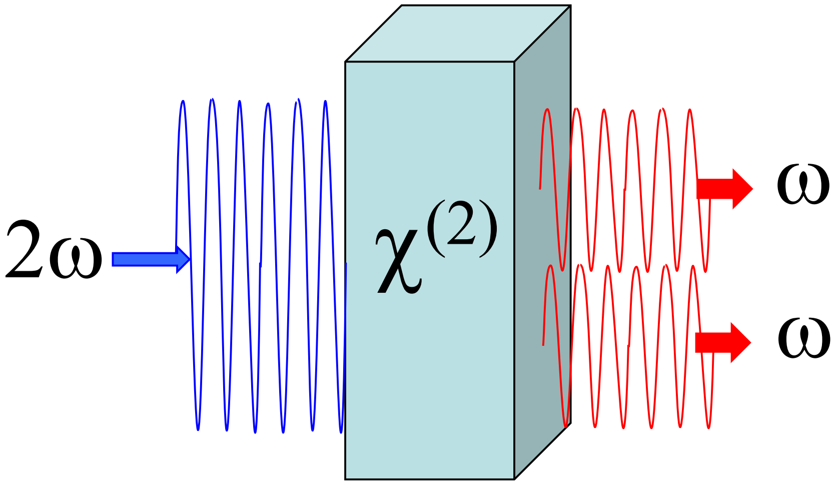
Trap #2

OMPO

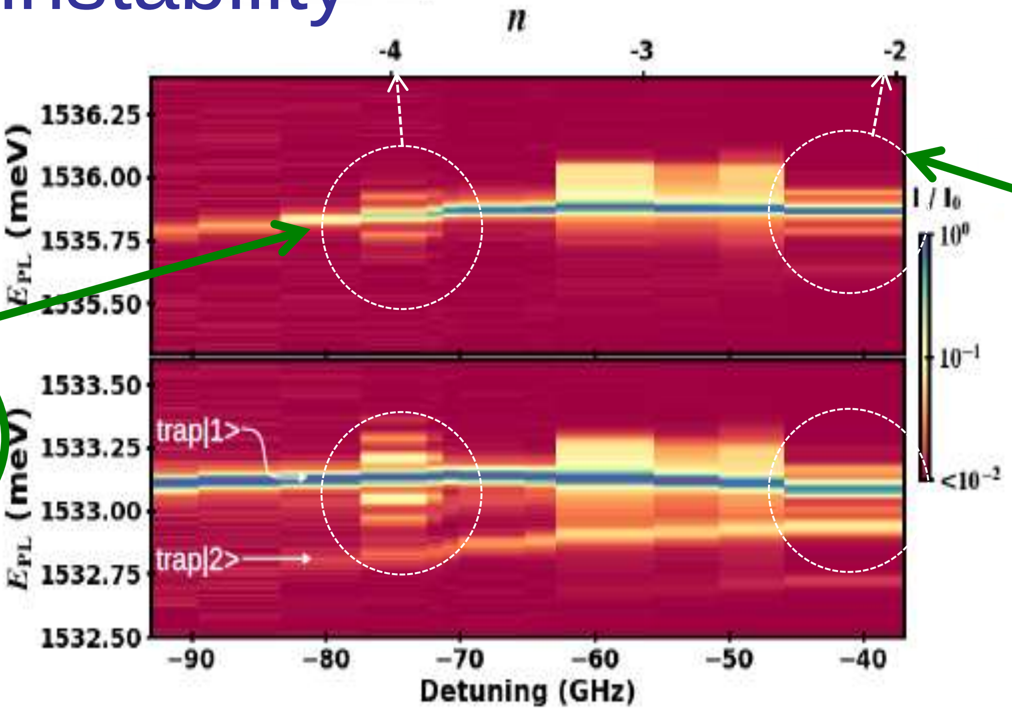
$$\boxed{\omega_1 - \omega_2 = 2\omega_m}$$

OPO





Parametric instability



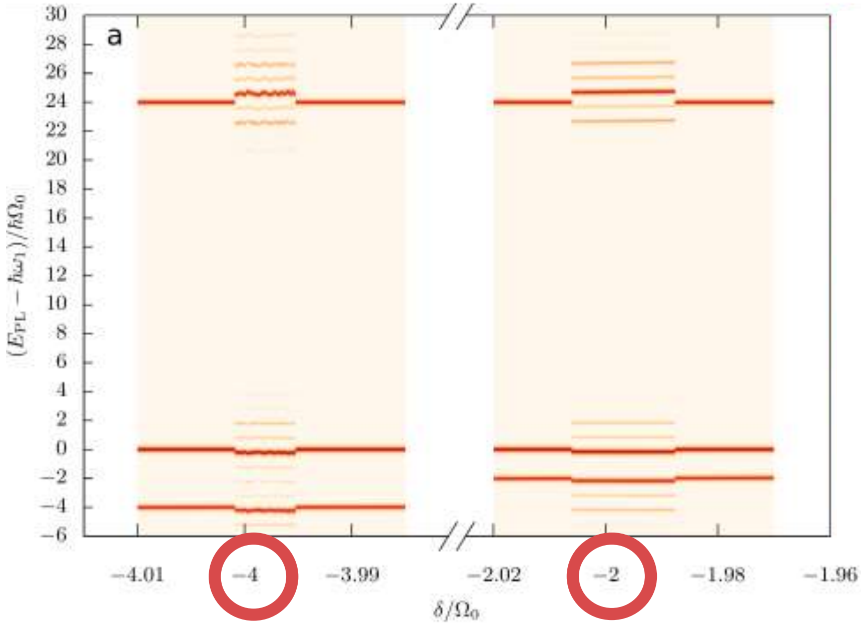
$\delta = \omega_m^0 + \omega_m^1$

~ 19 + 57 GHz

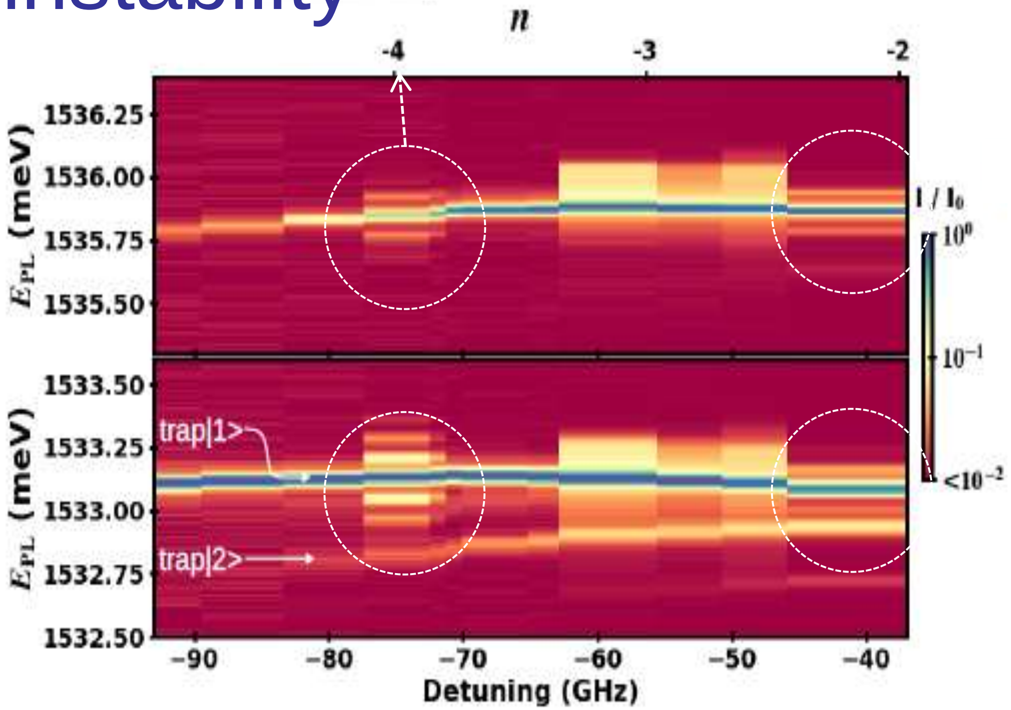
$\delta = 2\omega_m^0$

~ 2 x 19GHz

Theory

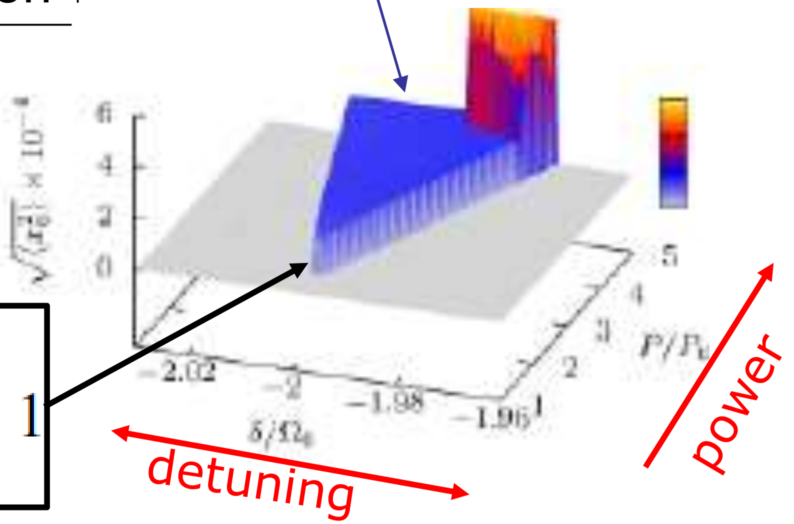


Parametric instability



Phonon occupation

“Arnold tongue”



Threshold condition

$$\boxed{\frac{4g_0^2}{\Delta\Gamma}\sqrt{n_1^0 n_2^0} > 1}$$

Another consequence of quadratic coupling

nature communications

Microcavity phonoritons – a coherent optical-to-microwave interface

Received: 3 November 2022

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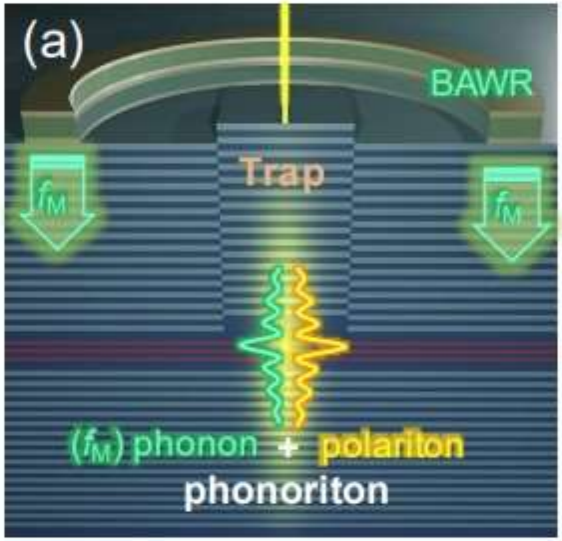
Alexander Sergeevich Kuznetsov[1], Klaus Biermann[1], Andres Alejandro Reynoso[2,3,4], Alejandro Fainstein[2,3] & Paulo Ventura Santos[1]

$$\hat{H}_{\text{int}} = \hbar G_2(\hat{a}_u^\dagger \hat{a}_l + \hat{a}_l^\dagger \hat{a}_u)(\hat{b}^\dagger + \hat{b})^2$$

$$\hat{a}_u \to \alpha_u + \delta\hat{a}_u \qquad \hat{a}_l \to \alpha_l \qquad \hat{b} = \alpha_b + \delta\hat{b}$$



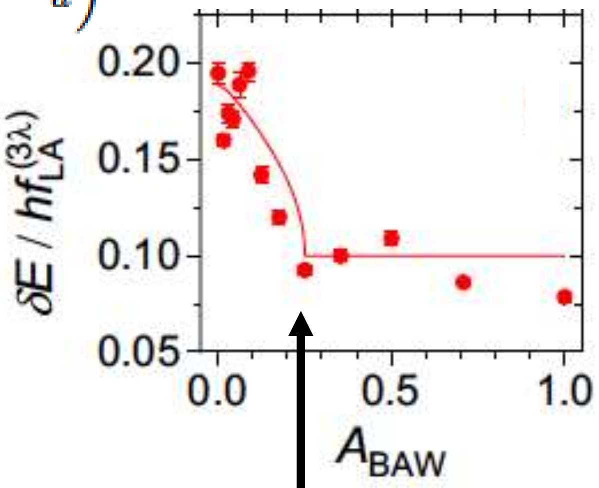
$$\hat{H}_{m,u} = \hbar\Delta_m \hat{b}^\dagger\hat{b} + \hbar\Delta_u \delta\hat{a}_u^\dagger \delta\hat{a}_u + \hbar 2G_2\sqrt{n_b n_l}\left(\delta\hat{a}_u^\dagger \delta\hat{b} + \delta\hat{b}^\dagger \delta\hat{a}_u\right)$$

$$\boxed{g_2 = 2\sqrt{N_{MP} n_b} G_2}$$

$$\delta E = \frac{\gamma_{MP}}{2} + \text{Im}\left[\sqrt{g_2^2 - \frac{\gamma_{MP}^2}{4}}\right]$$

γ_{MP} if $g_2 << \gamma_{MP}/2$

$\frac{\gamma_{MP}}{2}$ if $g_2 \geq \gamma_{MP}/2$

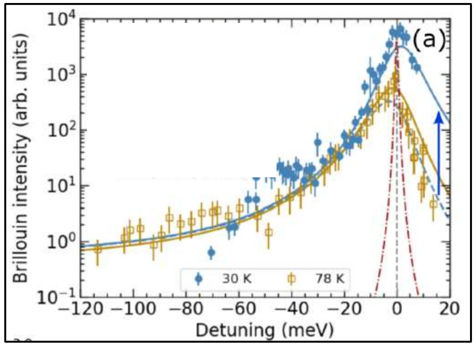


$$\boxed{g_2 \geq \gamma_{MP}/2}$$

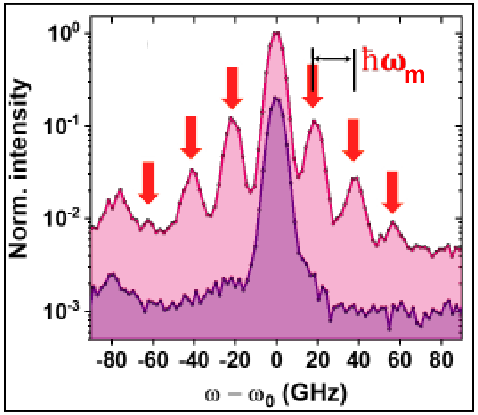
Day #2 wrap-up

- Self-oscillation in standard OM systems
- Polariton-induced phonon lasing with non-resonant excitation
- The OMPO: quadratic OM coupling
- RF boosted OM strong-coupling: the “phonoriton”

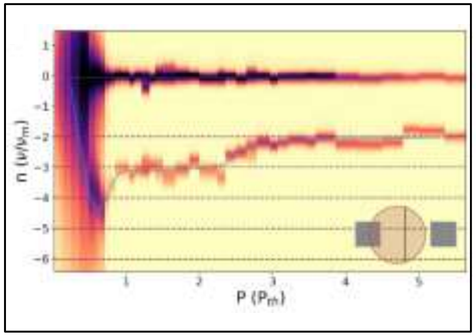
Index



- **Day #1: cavity polaritons**, resonant exciton mediated optomechanical interaction



- **Day #2: self-oscillation**, the optomechanical parametric oscillator



- **Day #3: synchronization,** OM asynchronous locking of polariton states

Bonus: Friday talk, time crystals