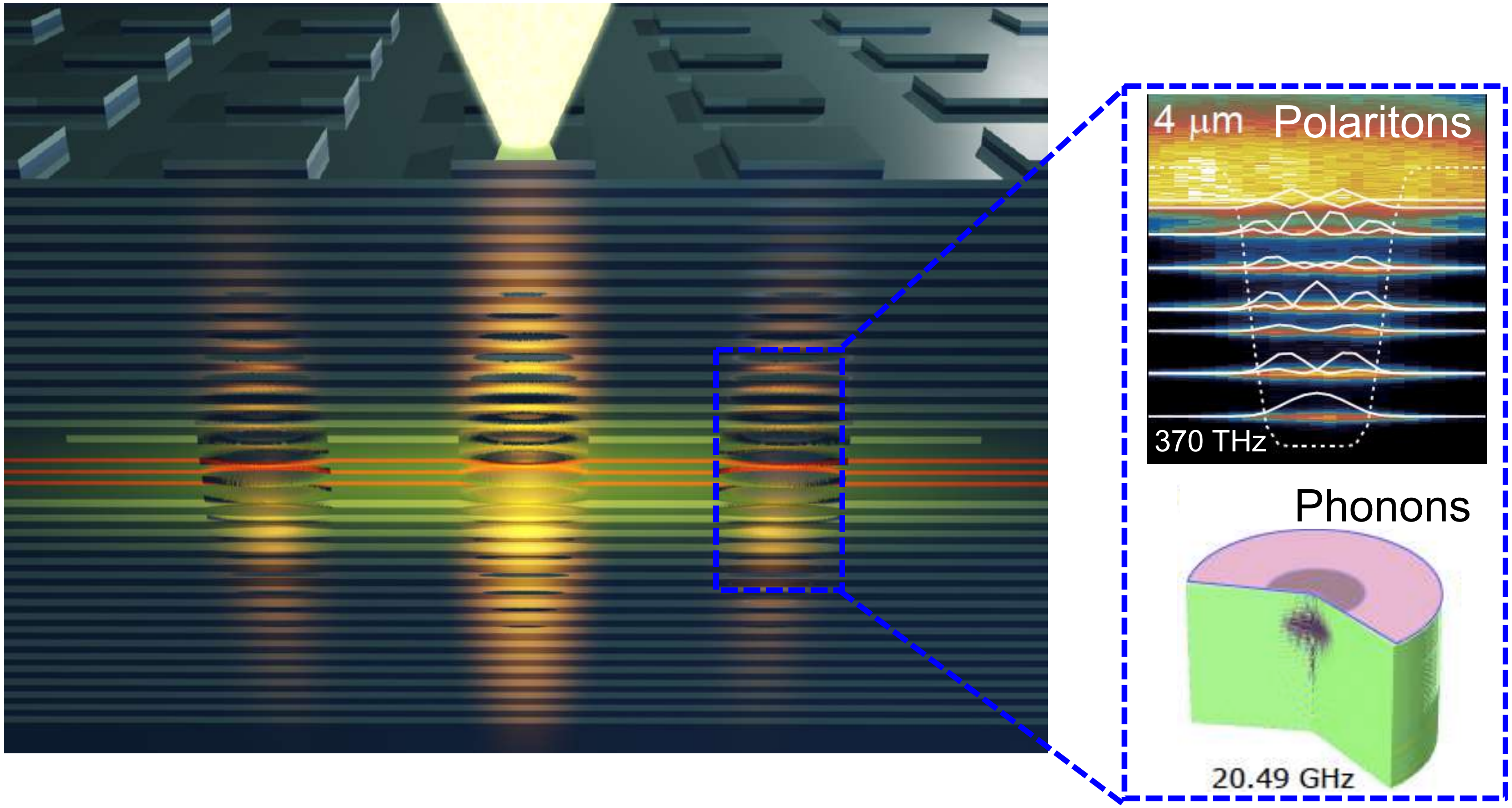
Cavity Optomechanics with Polariton Fluids

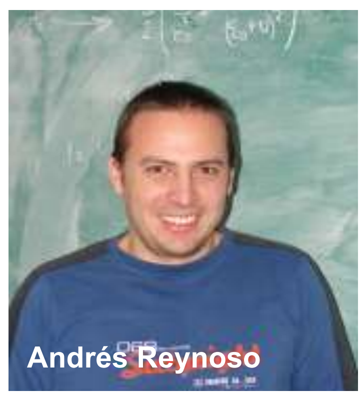
Alex Fainstein

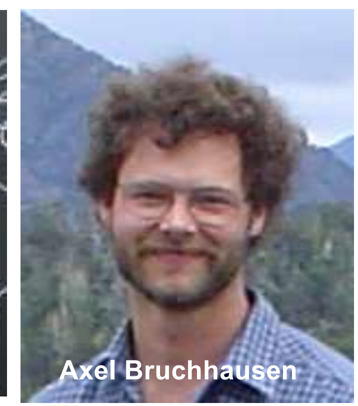


Photonics and Optoelectronics Lab
Instituto Balseiro, Bariloche, Argentina
Paul-Drude-Institut für Festkörperelektronik

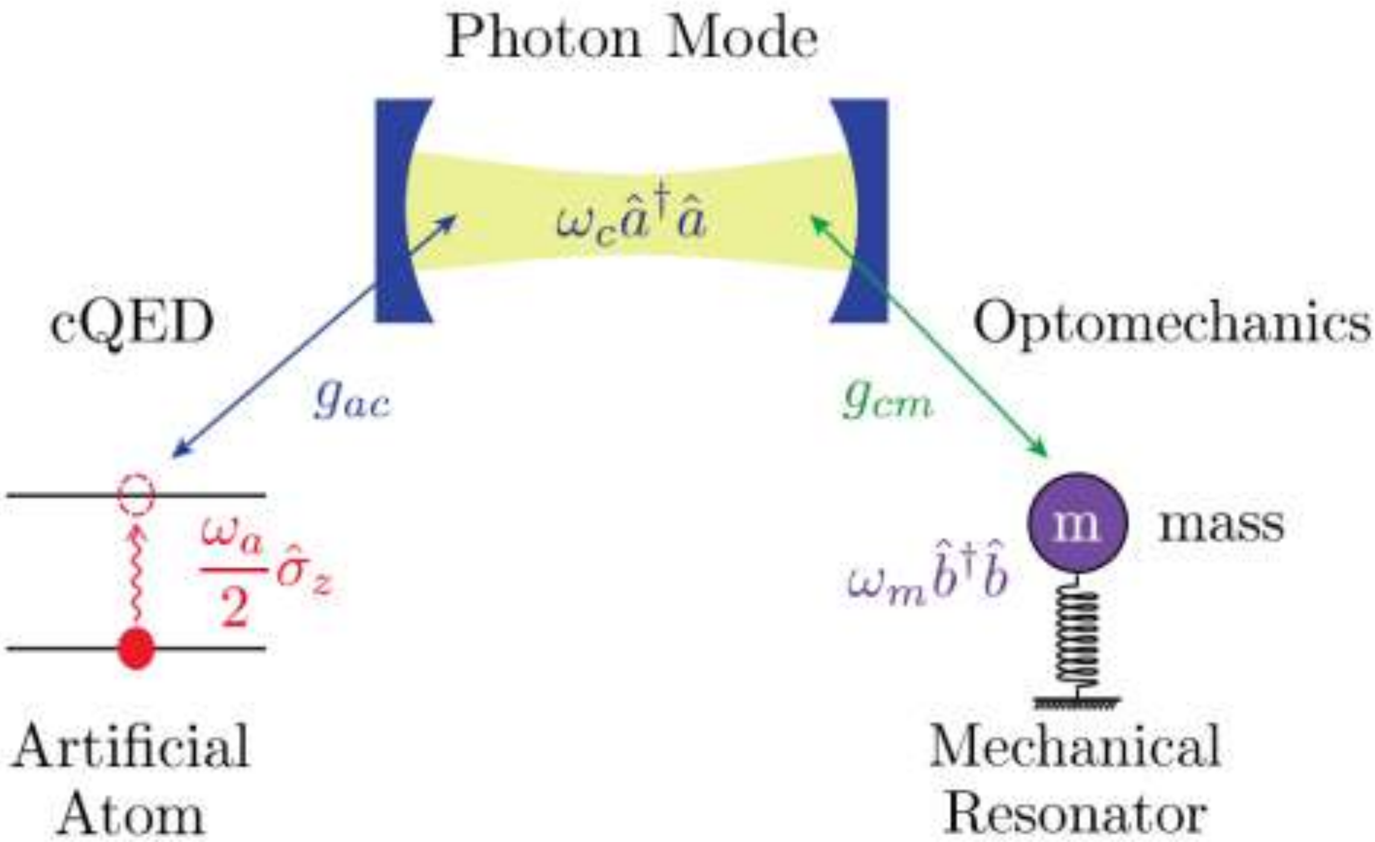
Paul-Drude-Institut
für Festkörperelektronik

Instituto
Balseiro





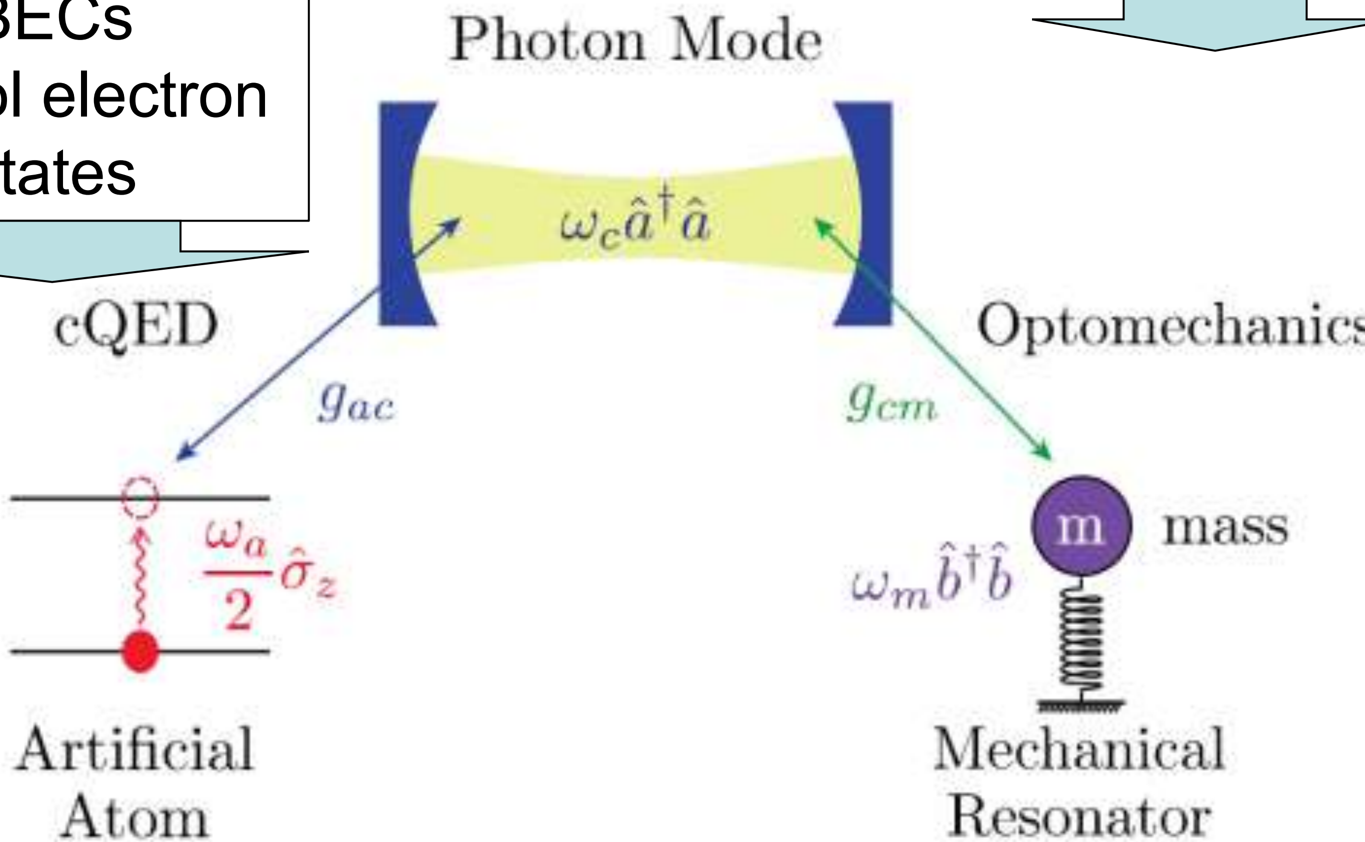
The concept: cavity optomechanics + atom @ resonance ($\omega_c \sim \omega_a$) in solid state platform



The concept: cavity optomechanics + atom @ resonance ($\omega_c \sim \omega_a$) in solid state platform

Strong-coupling BECs
Control electron states

Enhance g_0



The concept: cavity optomechanics + atom @ resonance ($\omega_c \sim \omega_a$) in solid state platform

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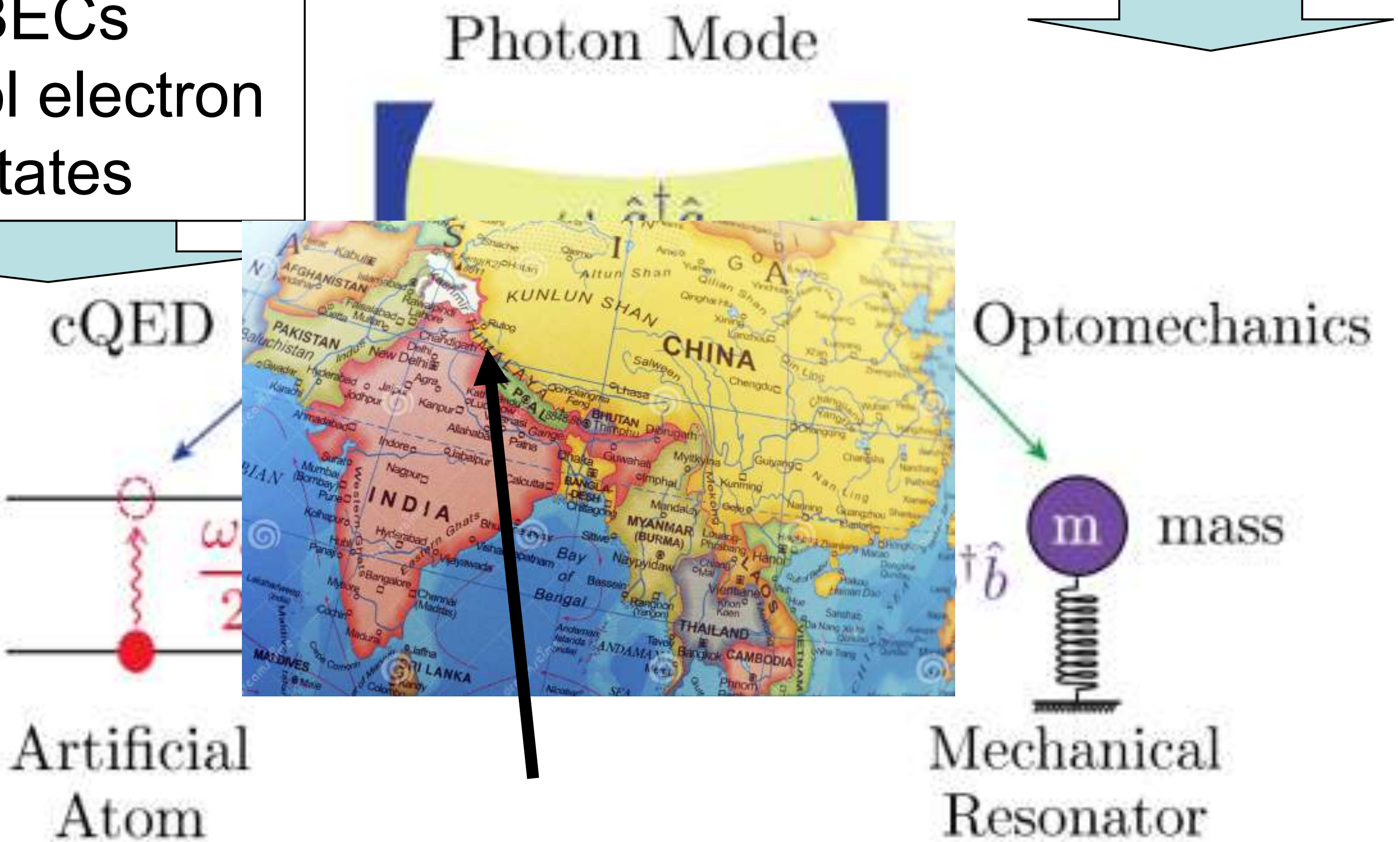
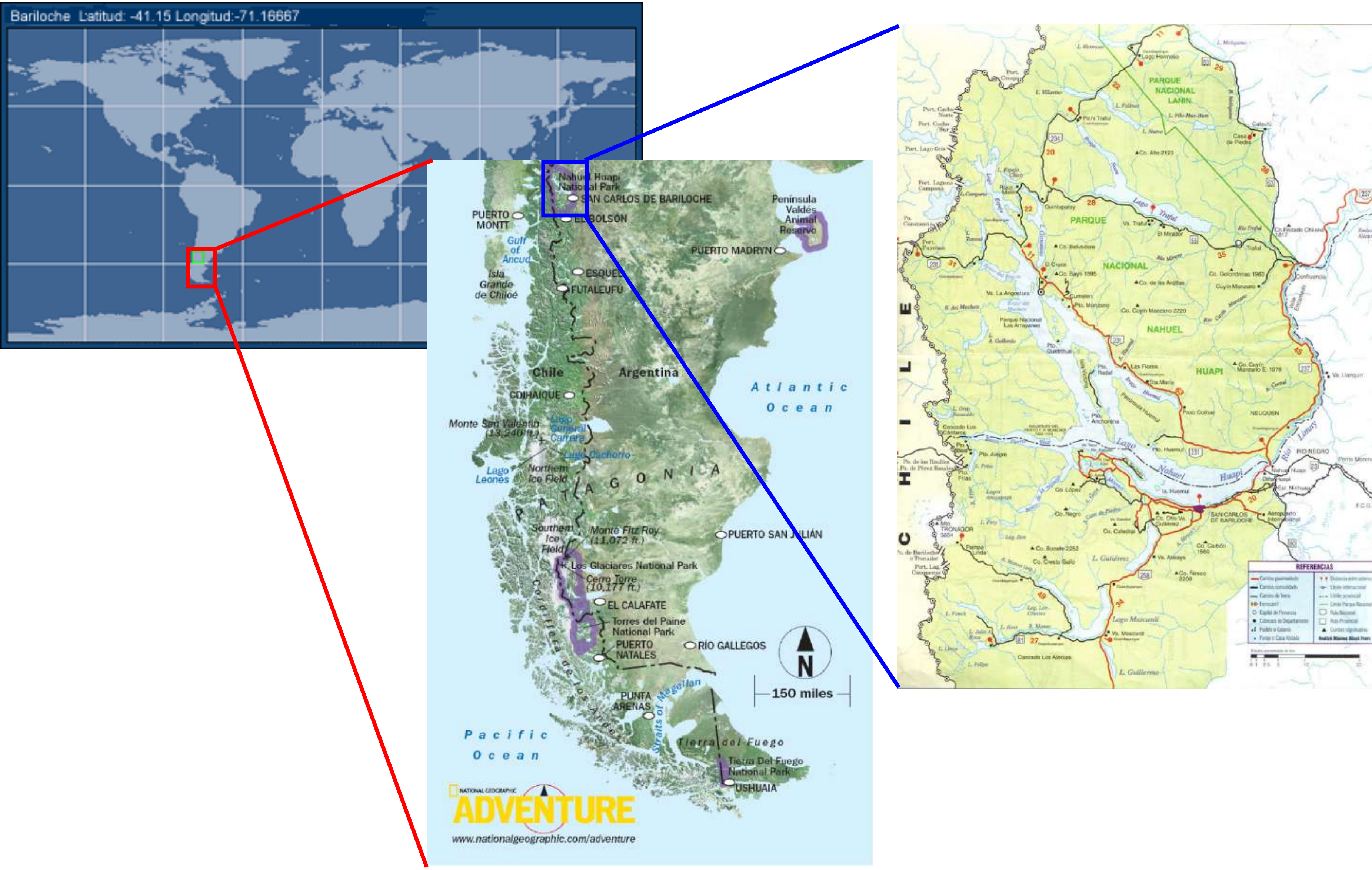


Bariloche in Patagonia - Argentina



How light excerts force on matter

(and what we can do with it)

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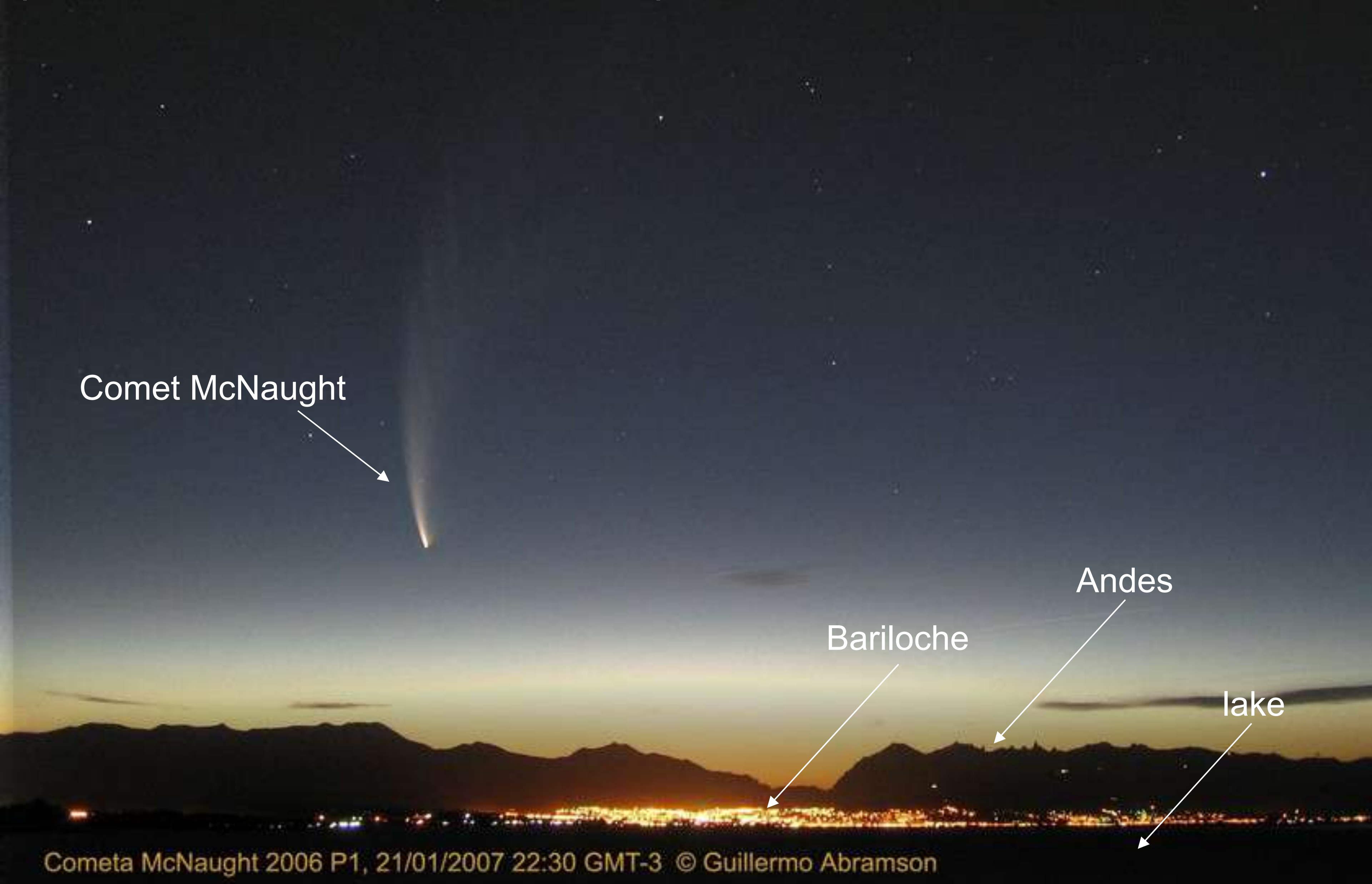

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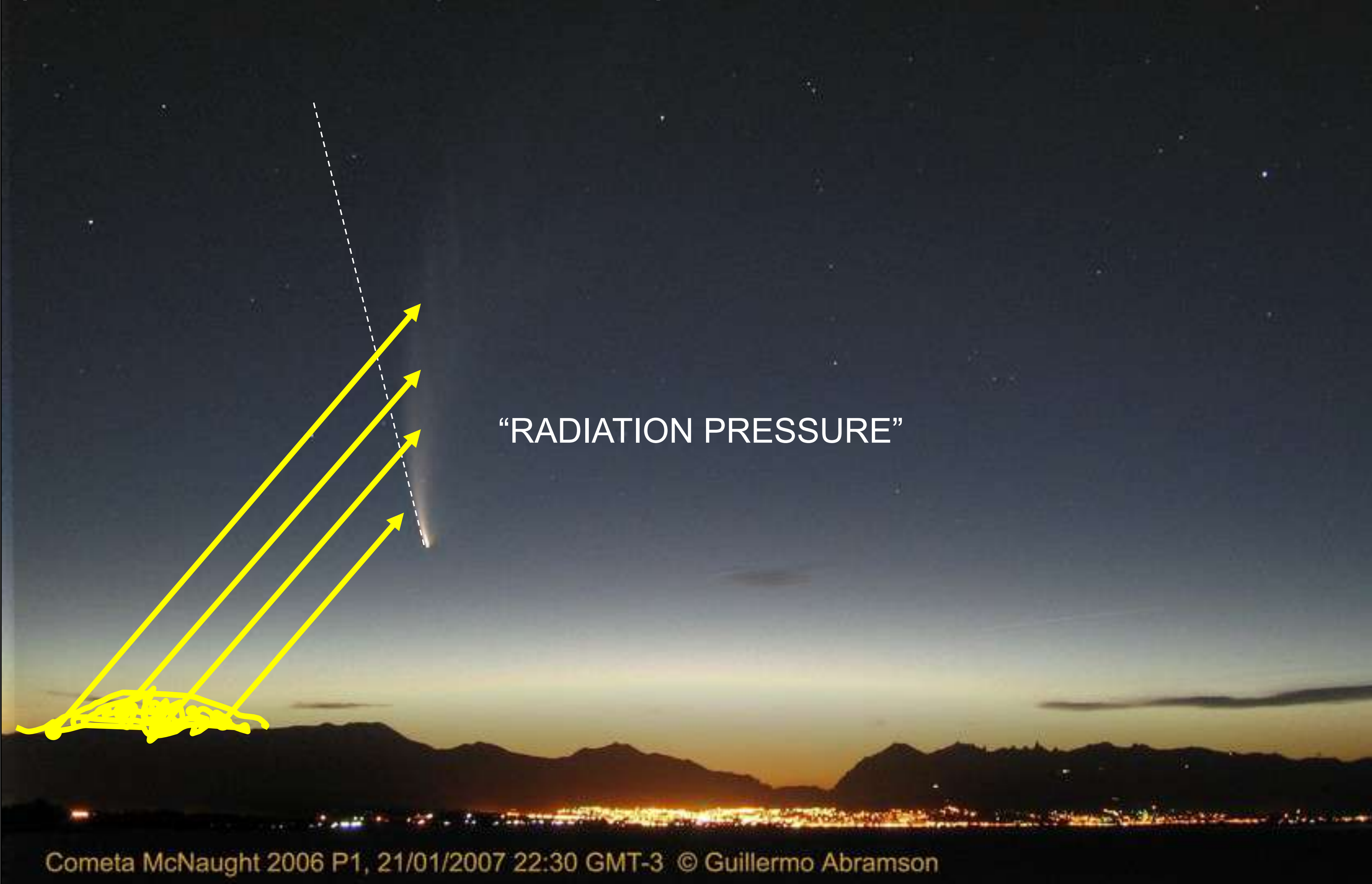
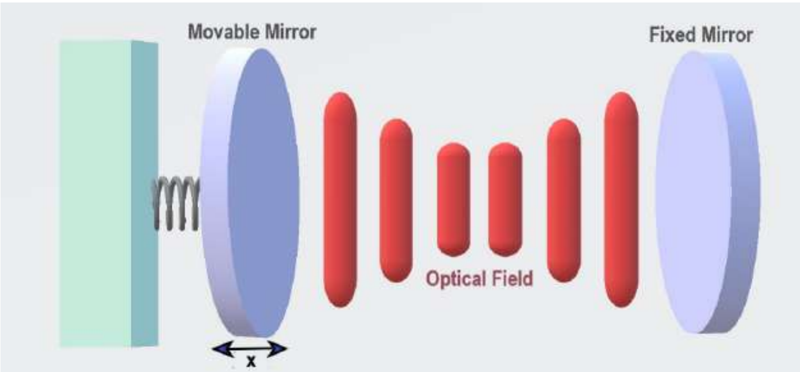
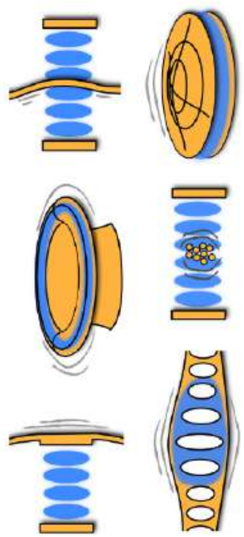
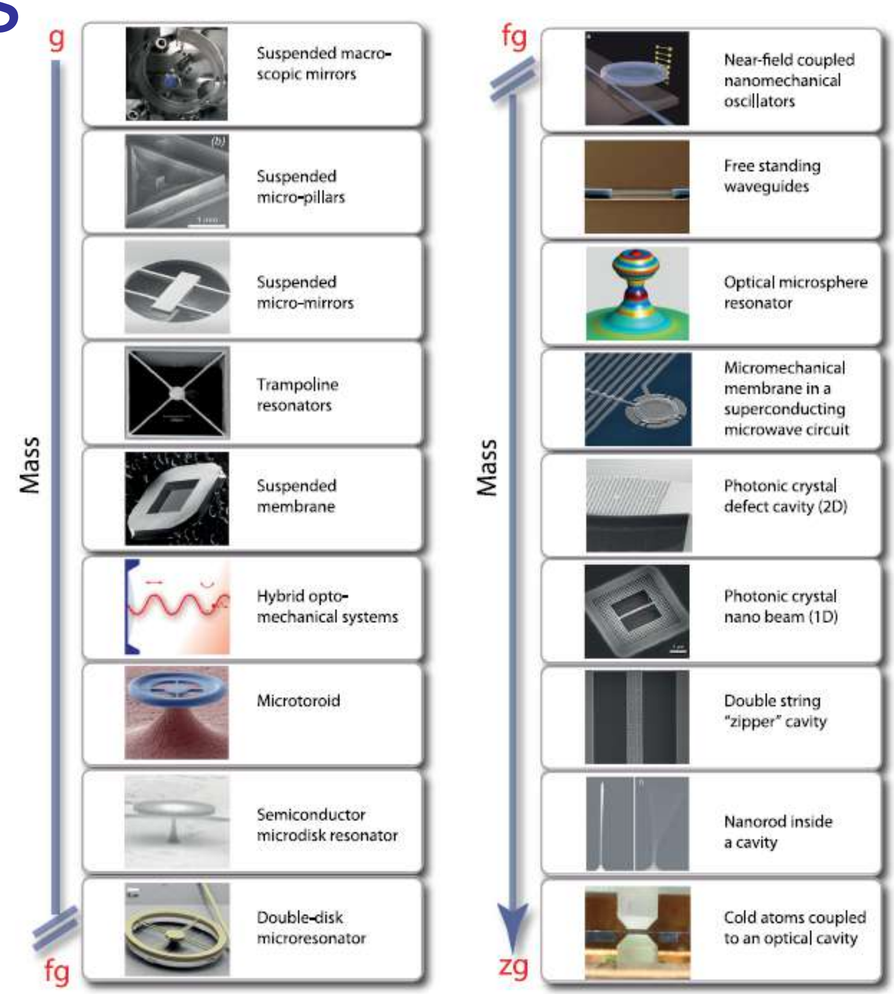


Cavity optomechanics







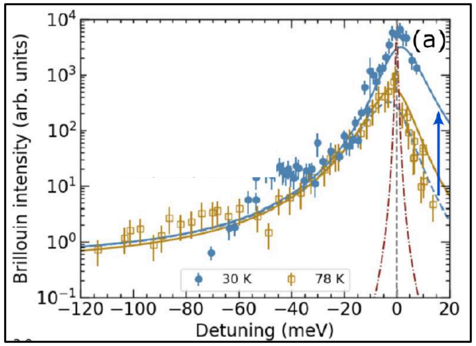
MAspelmeyer, TJK, FM, Rev. Mod. Phys. **86**, 1391 (2014)

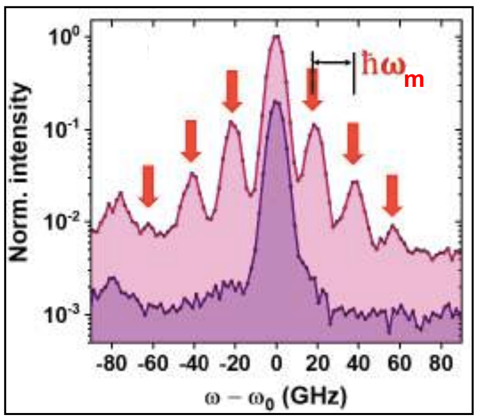
$$H = \hbar\omega_c c^+ c + \hbar\omega_m b^+ b + \hbar g_0 c^+ c\,(b + b^+)$$

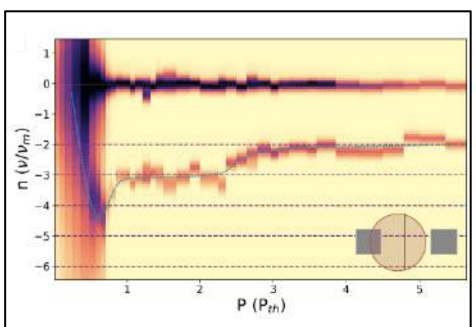
optomechanical coupling

phonon displacement

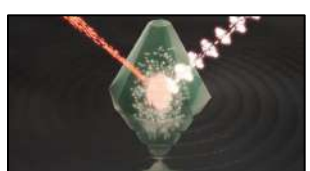
Index







- **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

(poster by D. Chafatinos)

Our system: GaAs/AlAs (micropillar) cavities

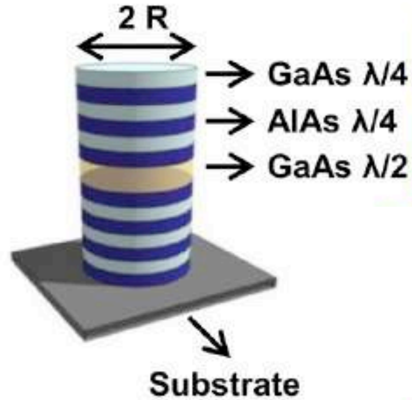

Physics — Physics 6, 6 (2013)

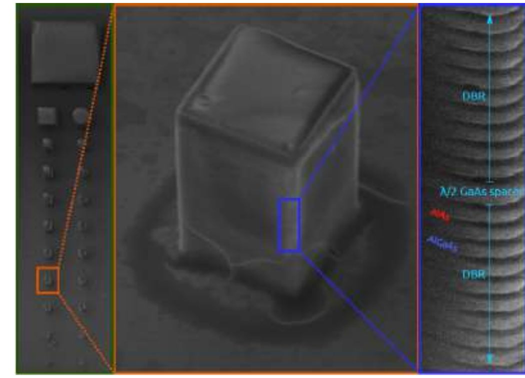
Viewpoint

Double Magic Coincidence in an Optomechanical Laser Cavity

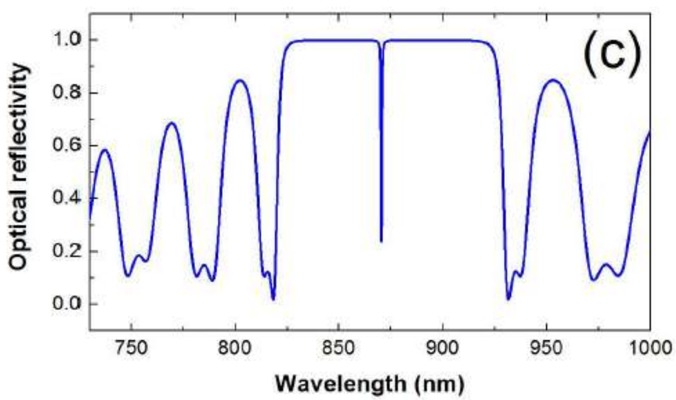
Yoan Léger
FOTON Laboratory, Université Européenne de Bretagne, CNRS-INSA-UR1, F-35708 Rennes, France

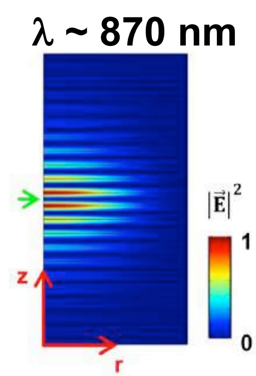
A Viewpoint on:
Strong Optical-Mechanical Coupling in a Vertical GaAs/AlAs Microcavity for Subterahertz Phonons and Near-Infrared Light
A. Fainstein, N. D. Lanzillotti-Kimura, B. Jusserand, and B. Perrin
Phys. Rev. Lett. 110, 037403 (2013) – Published January 14, 2013





Optical

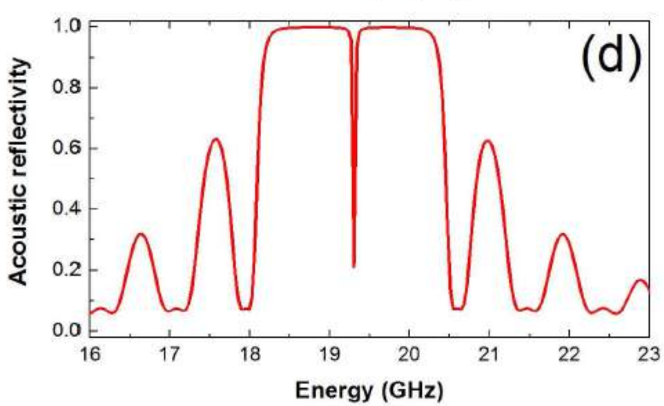


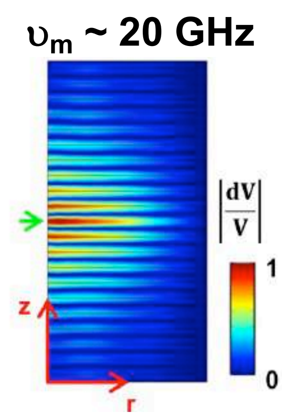


Optical

Q's ~ 10^5

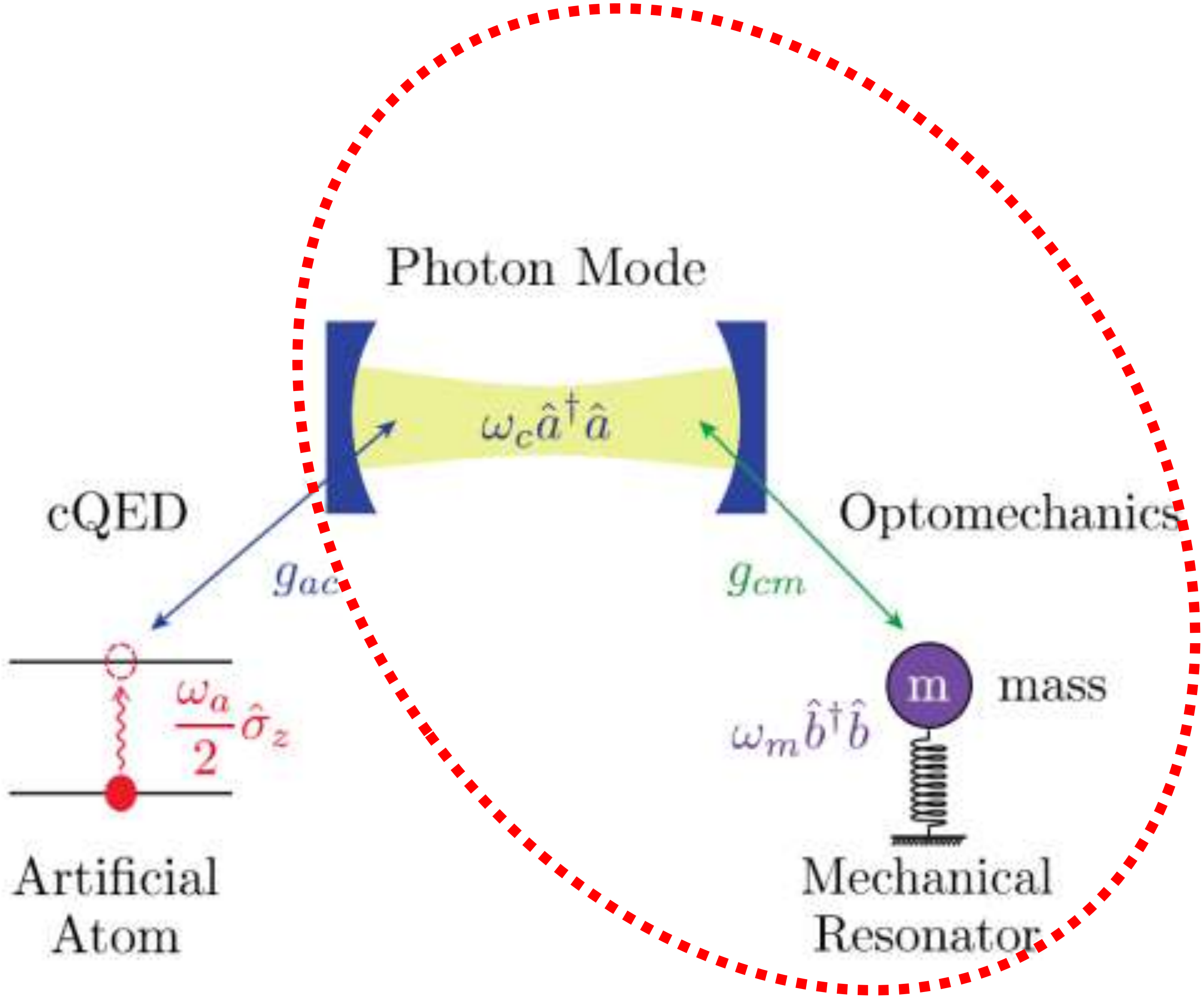
Mechanical



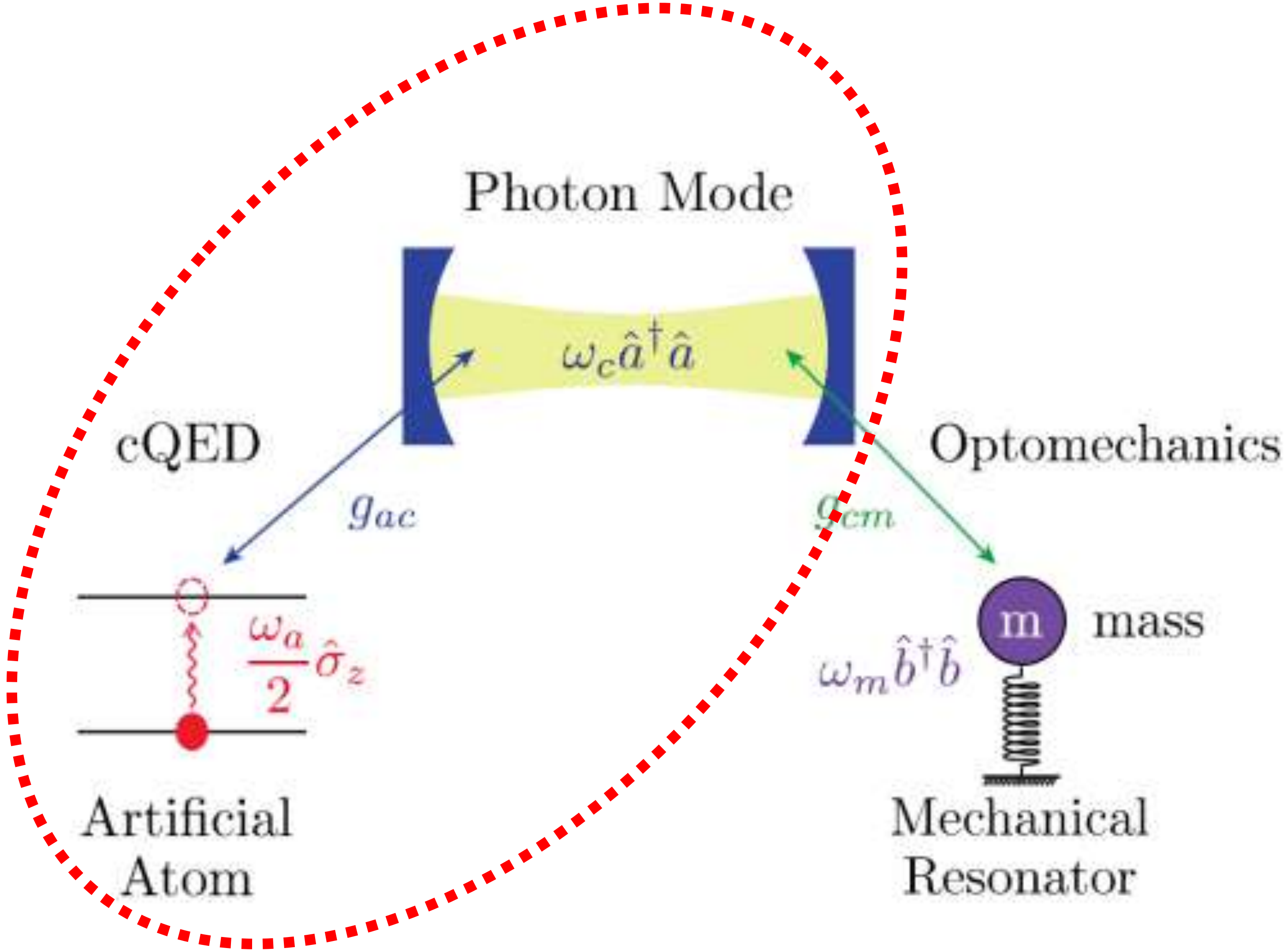


Mechanical

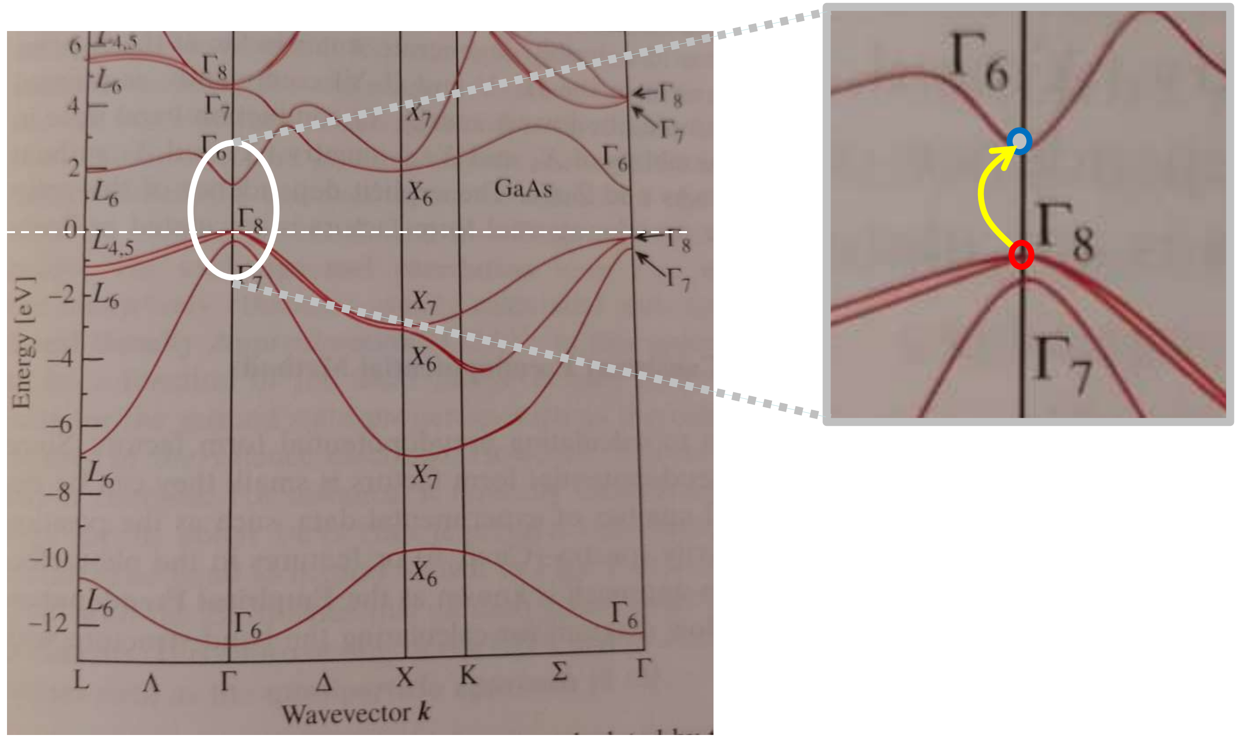
The concept: cavity optomechanics



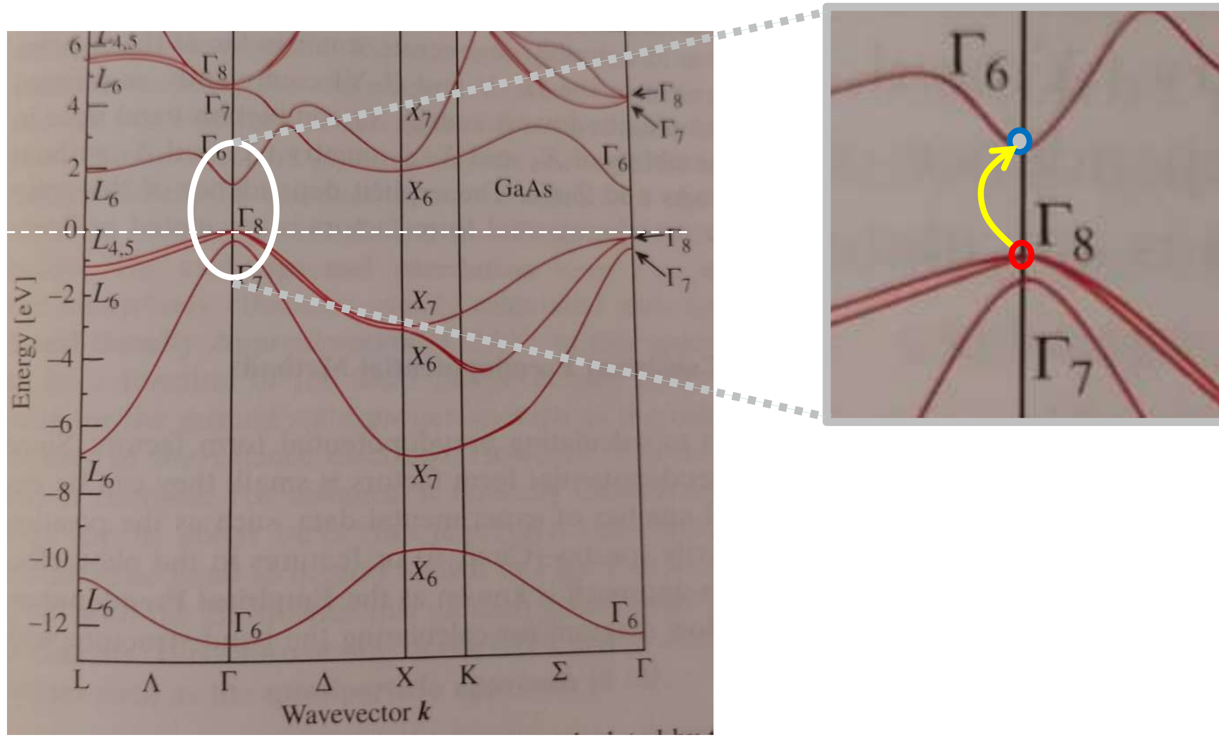
The concept: cavity polaritonics

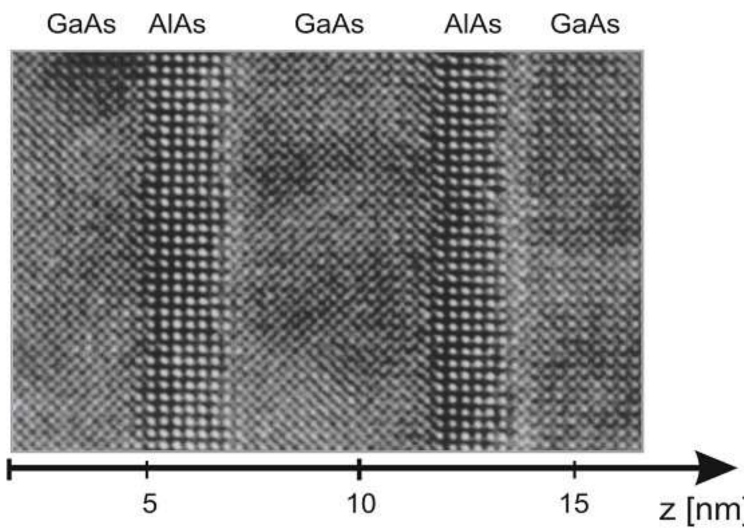


GaAs electronic band structure: optoelectronics



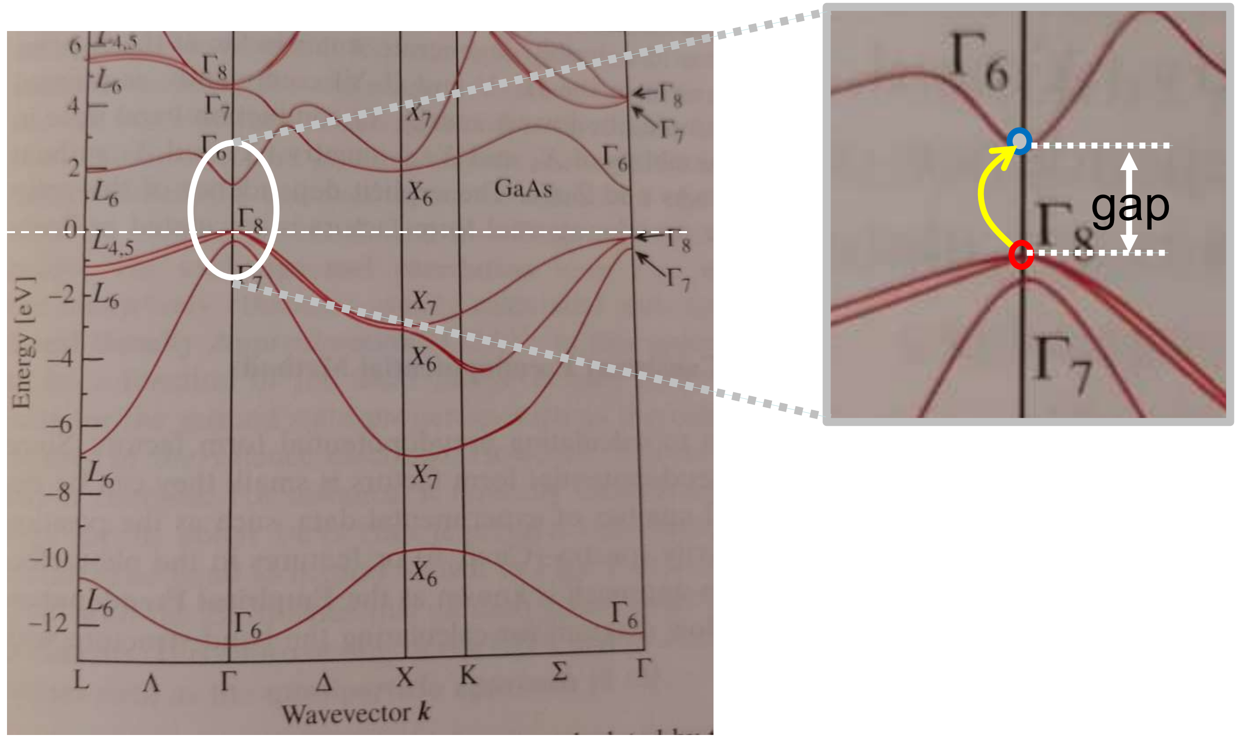
GaAs electronic band structure: MBE



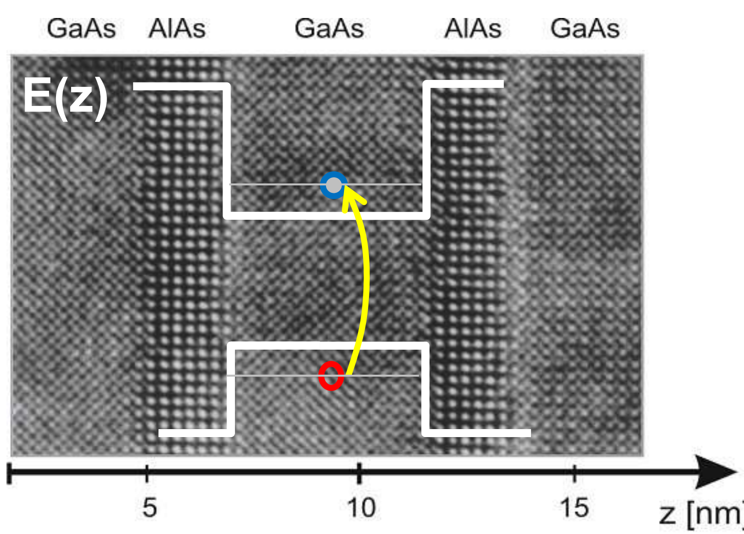


Molecular Beam Epitaxy (MBE)

GaAs electronic band structure: quantum wells

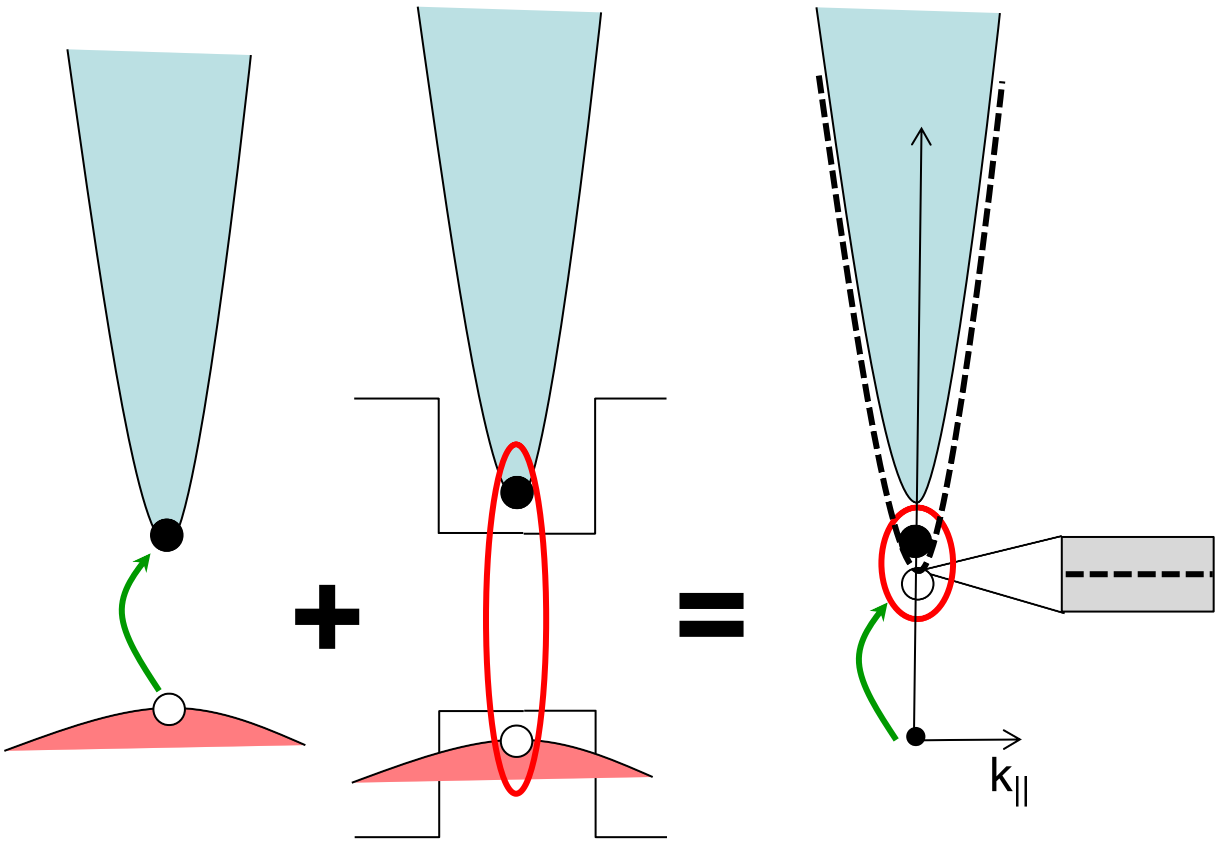


A
“quantum well”



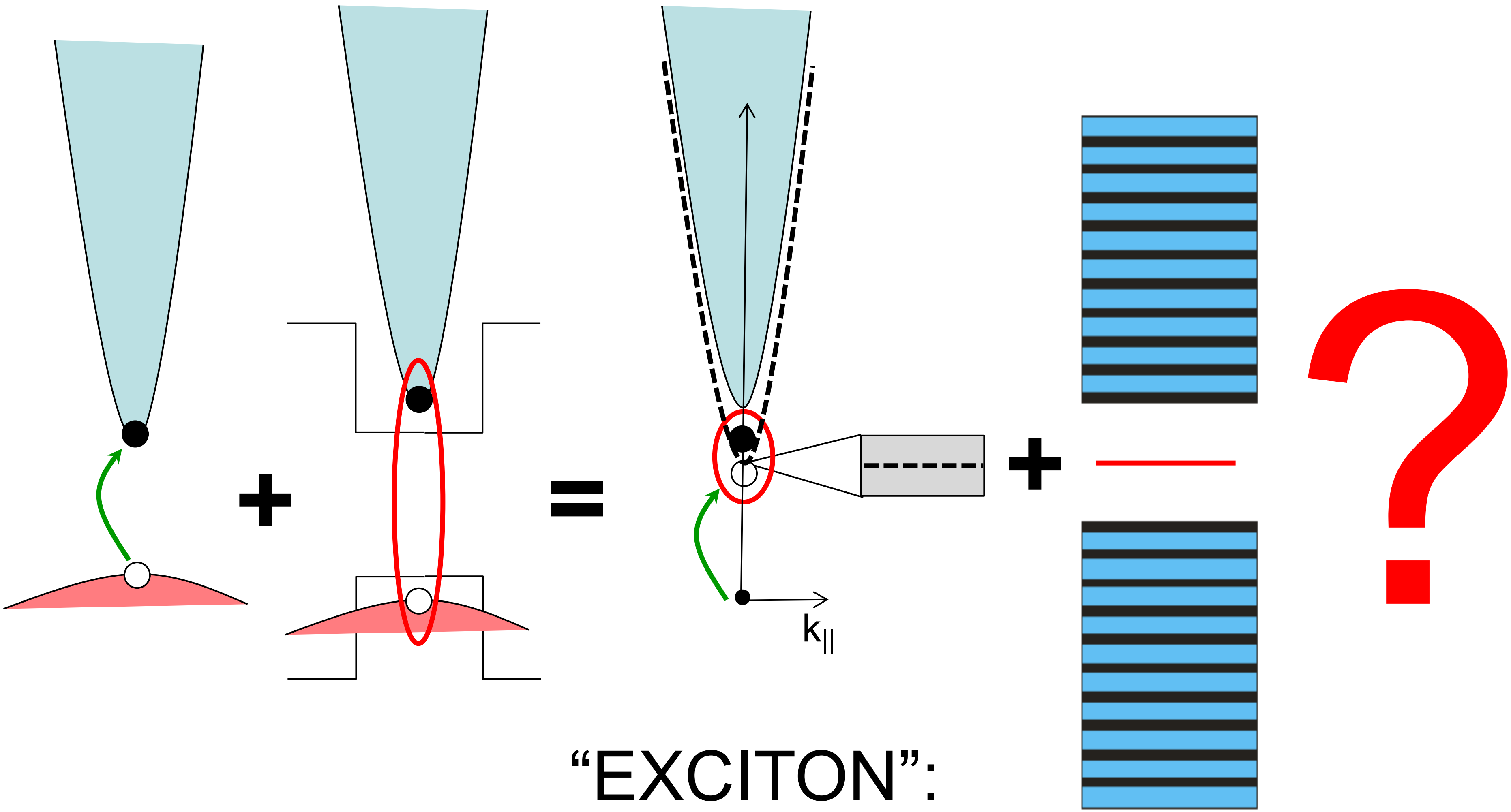
Molecular Beam Epitaxy (MBE)

Exciton



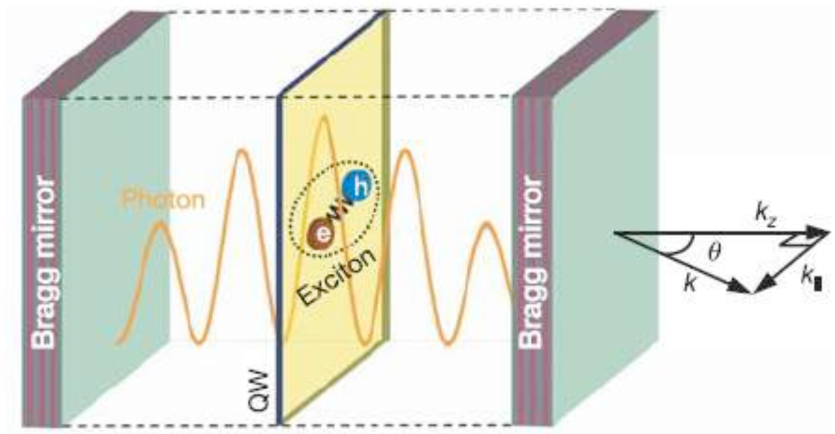
"EXCITON":
a discrete H-like
e-h state

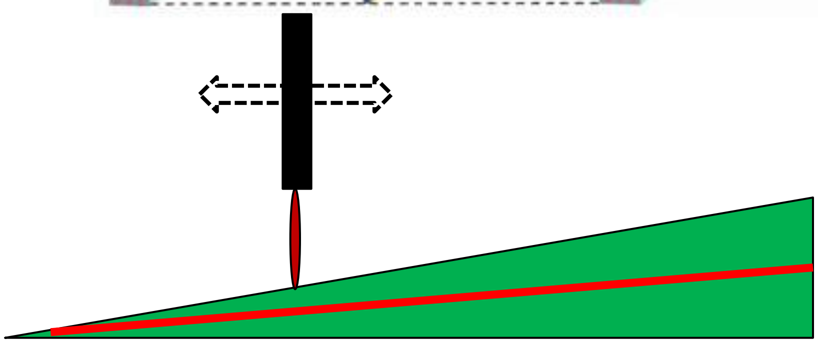
Exciton + cavity QED



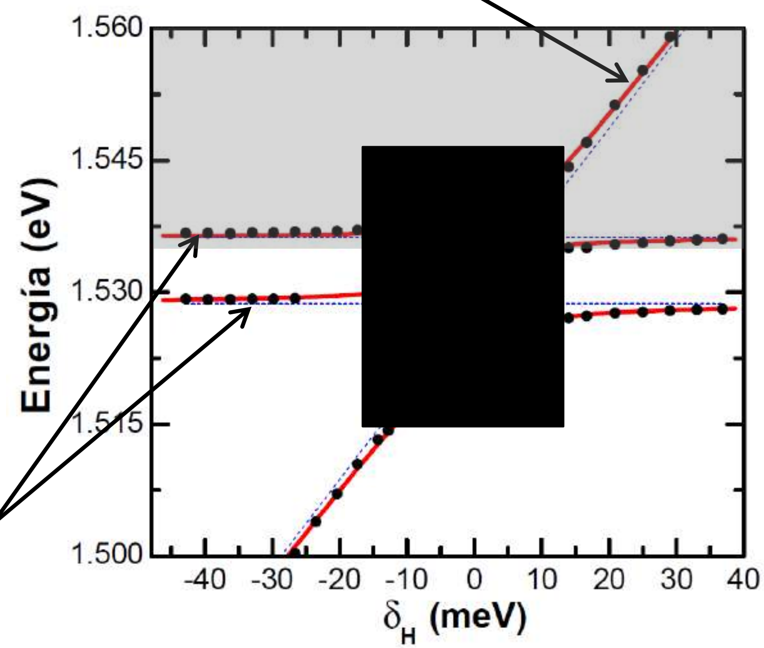
"EXCITON":
a discrete H-like
e-h state

Light-matter coupling in optical microcavities



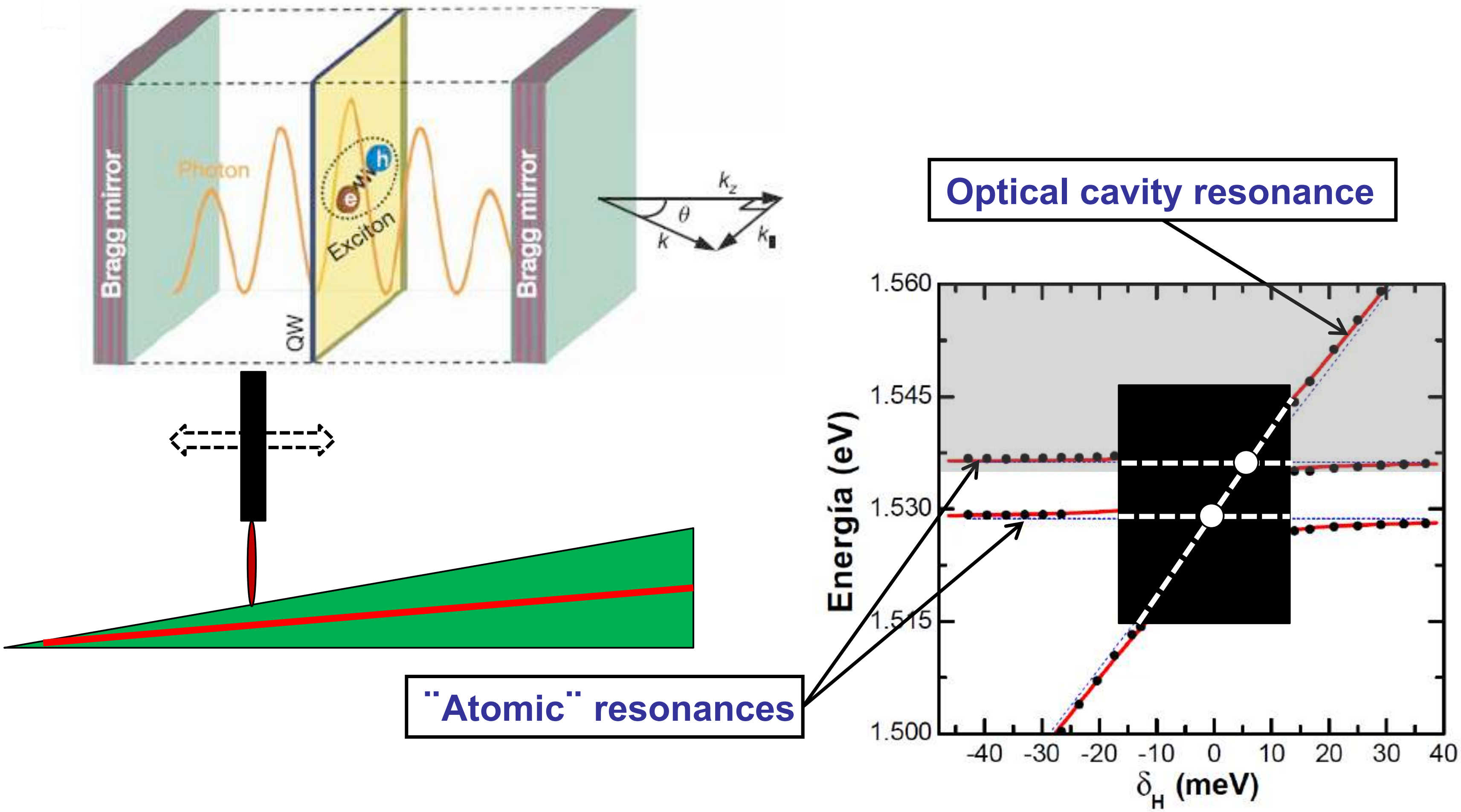


Optical cavity resonance

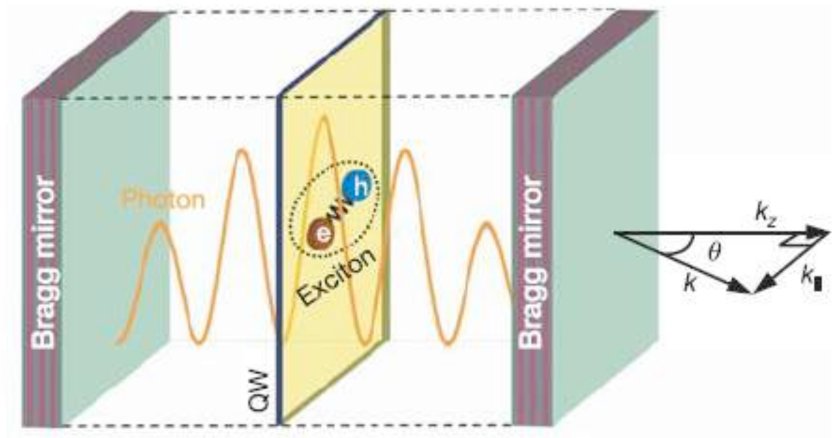


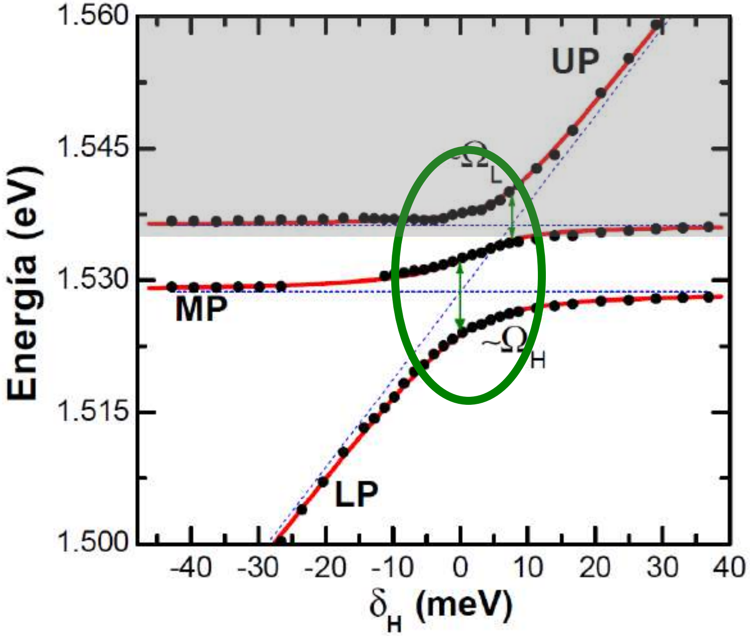
¨Atomic¨ resonances

Enhancement and inhibition of emission?

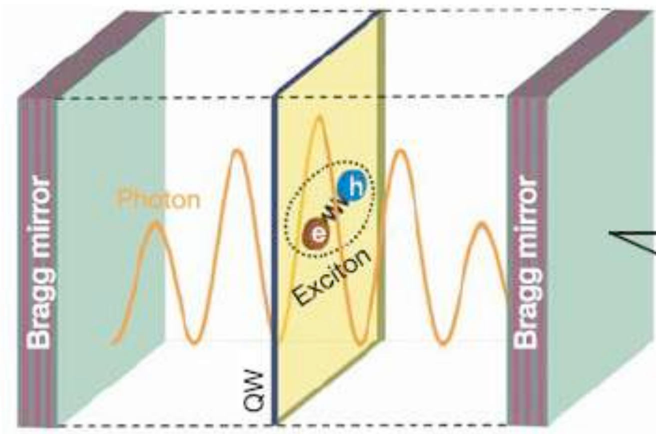


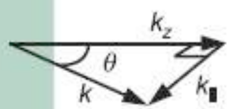
Strong-coupling: cavity exciton-polaritons





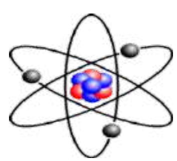
Strong-coupling: cavity exciton-polaritons



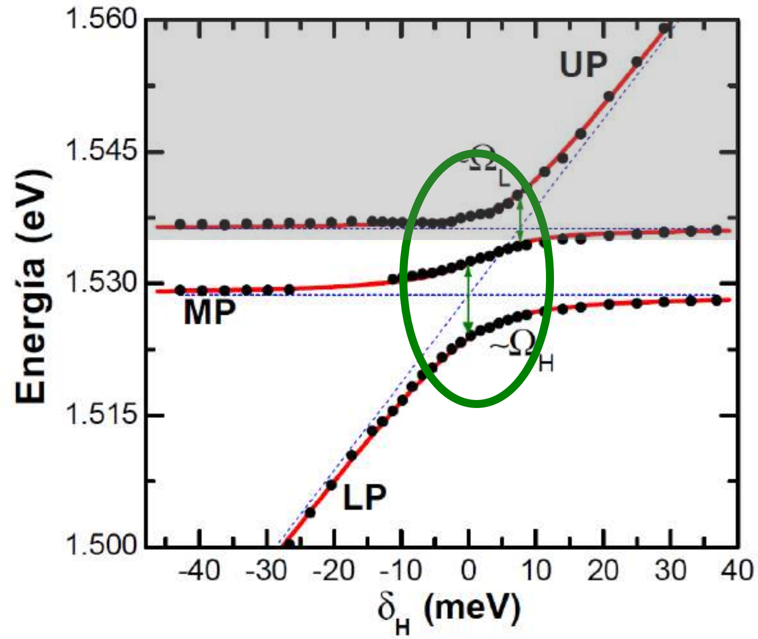


$$H_{pol} = \begin{pmatrix} E_{cav}(\theta) & \frac{\Omega}{2} \\ \frac{\Omega}{2} & E_X \end{pmatrix}$$

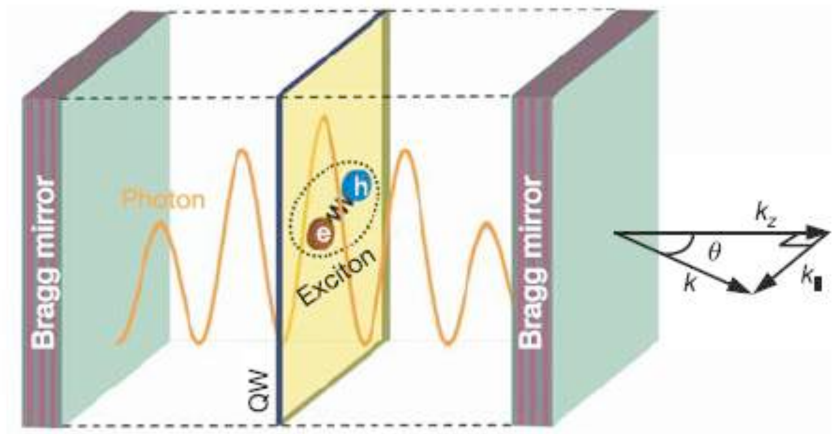
$$|P\rangle = A^P_{Cav}(\theta)|Cav\rangle + A^P_X|X\rangle$$

$\Psi = \alpha$  $+ \beta$ 

$$\Omega > \Gamma_c, \Gamma_x$$



Strong-coupling: cavity exciton-polaritons



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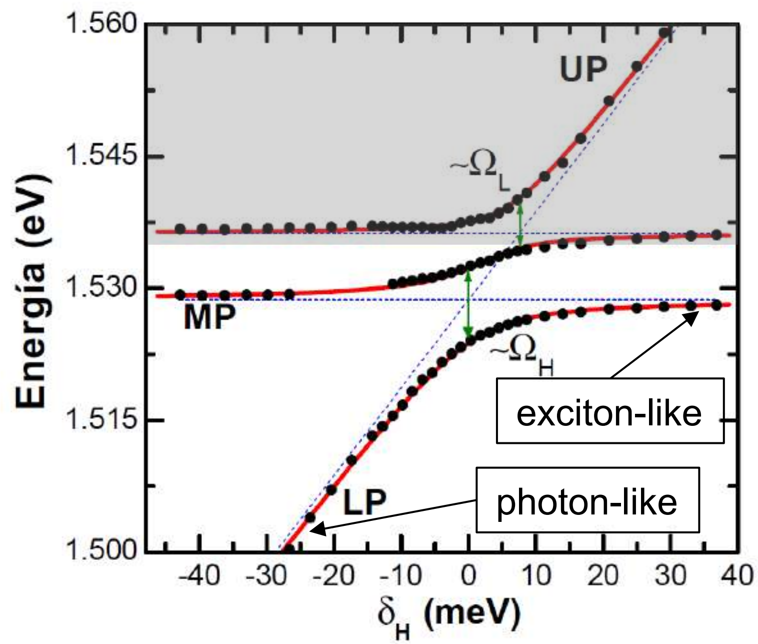
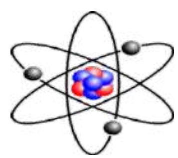


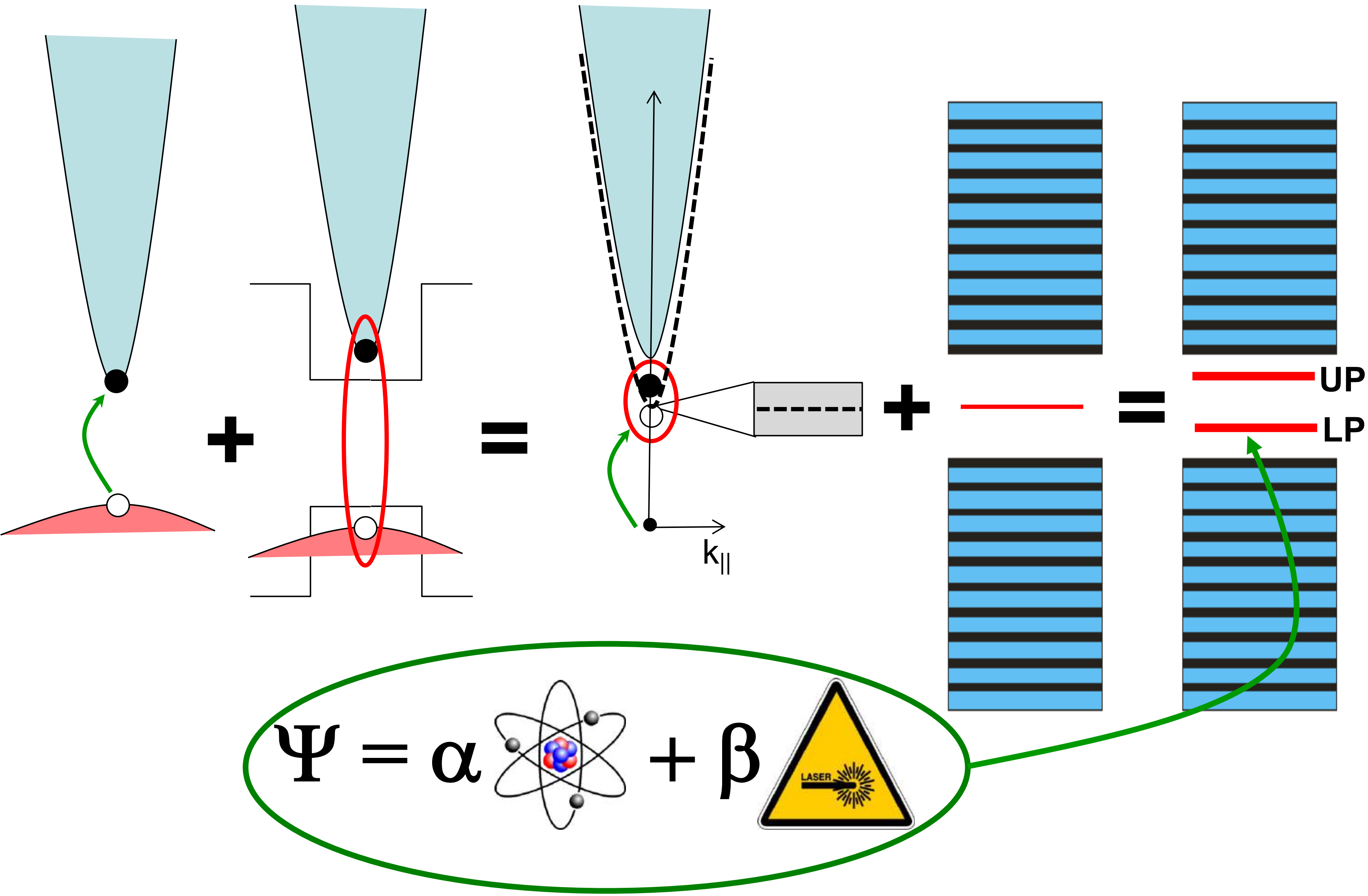
$\Psi = \alpha$  $+ \beta$ 

$$S^{LP}_{Cav} = \left|A^{LP}_{Cav}\right|^2$$

$$S^{LP}_{X} = \left|A^{LP}_{X}\right|^2$$

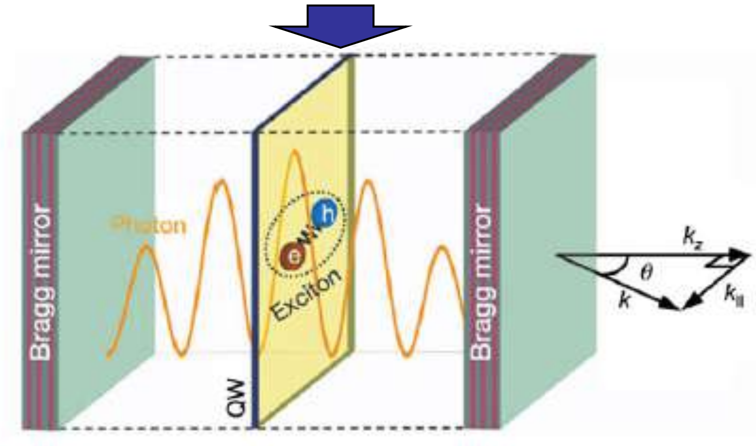
"Hoppfield coefficients"

Strong-coupling: cavity exciton-polaritons

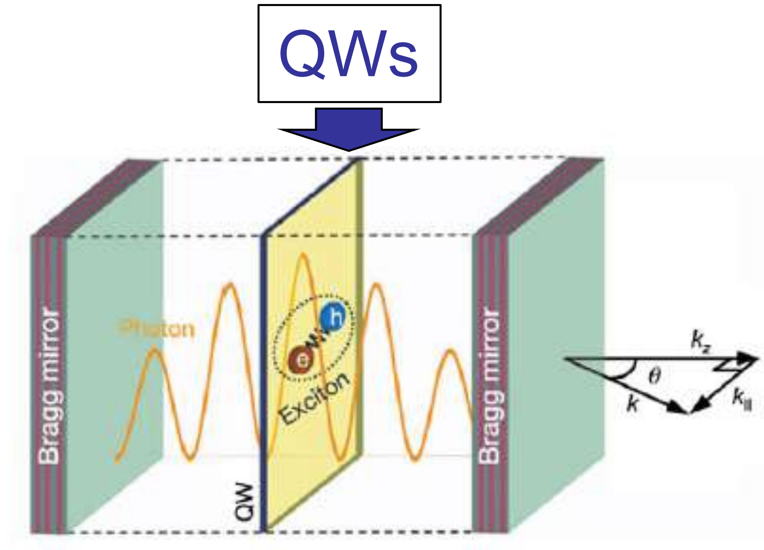


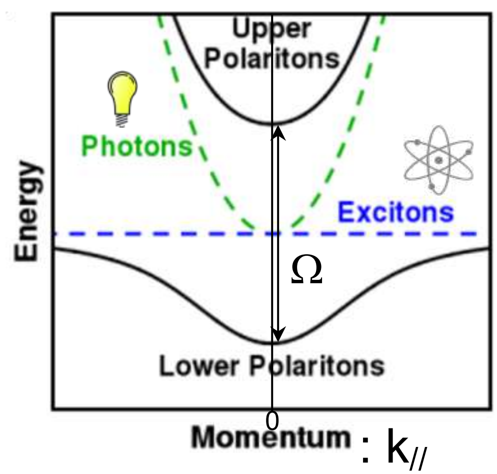
Cavity exciton-polaritons

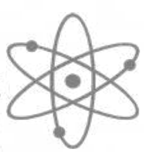
QWs



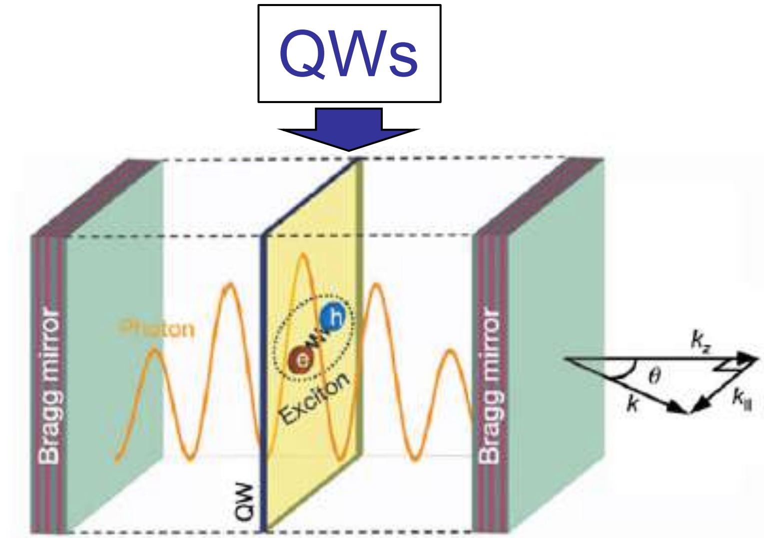
Cavity exciton-polaritons: in-plane dispersion

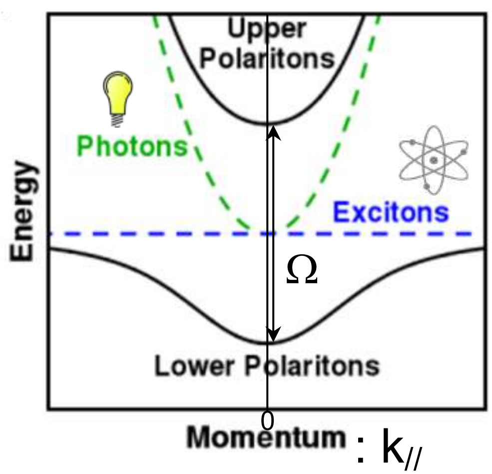


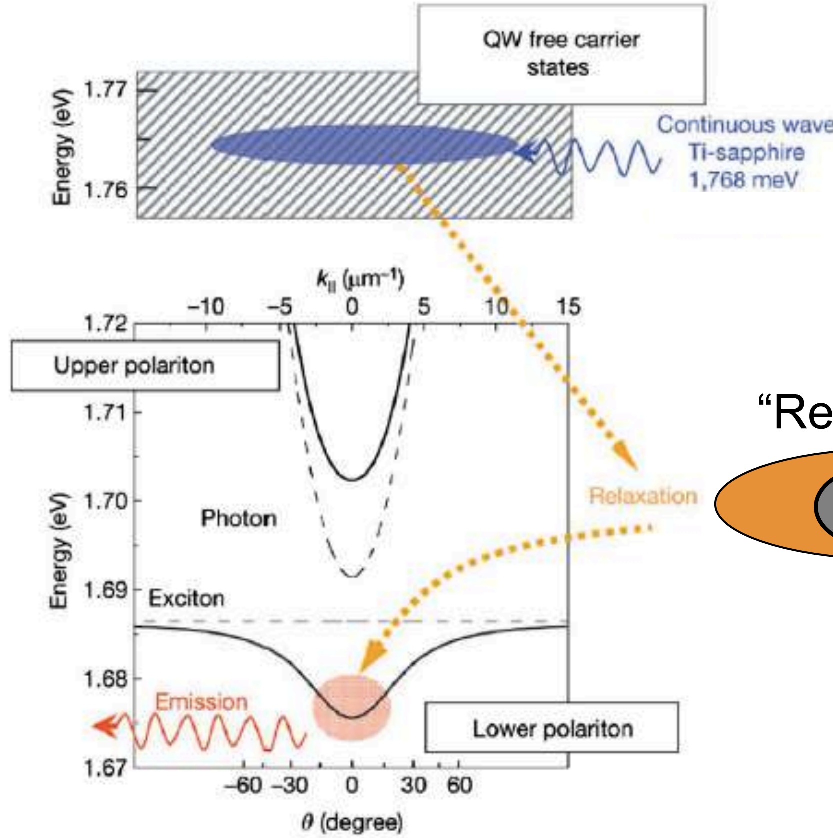


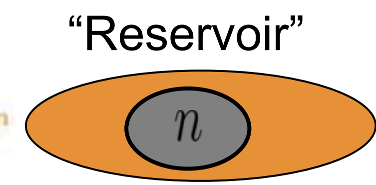
$$\psi = \frac{1}{\sqrt{2}}$$  $$+ \frac{1}{\sqrt{2}}$$ 

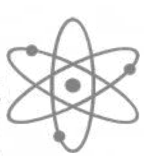
Cavity exciton-polaritons: non-resonant excitation



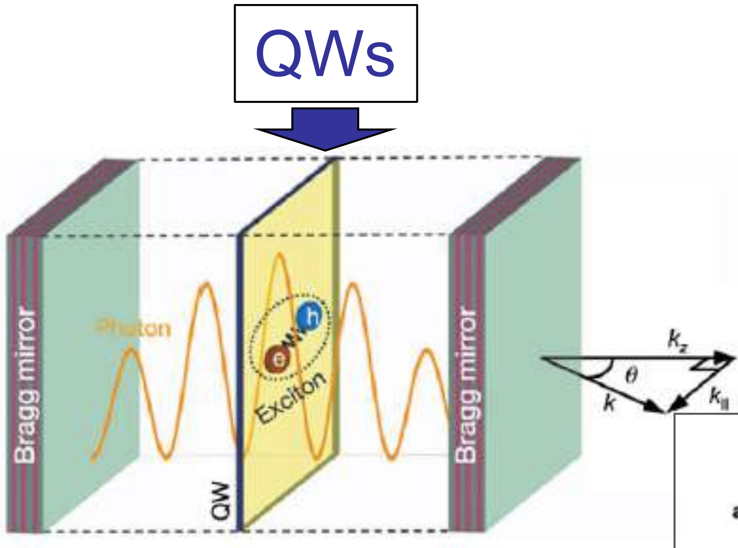


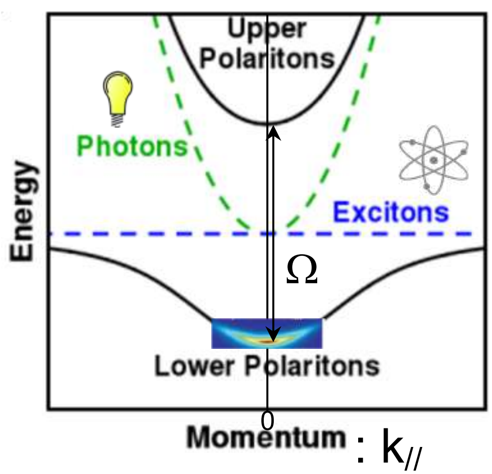


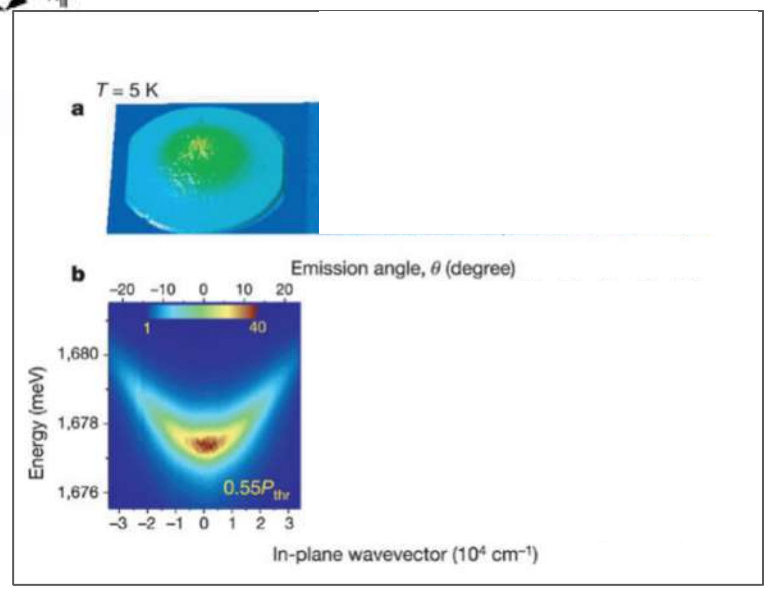


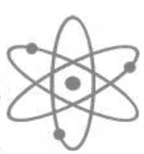
$\psi = \frac{1}{\sqrt{2}}$  $+ \frac{1}{\sqrt{2}}$ 

Cavity exciton-polaritons: low power

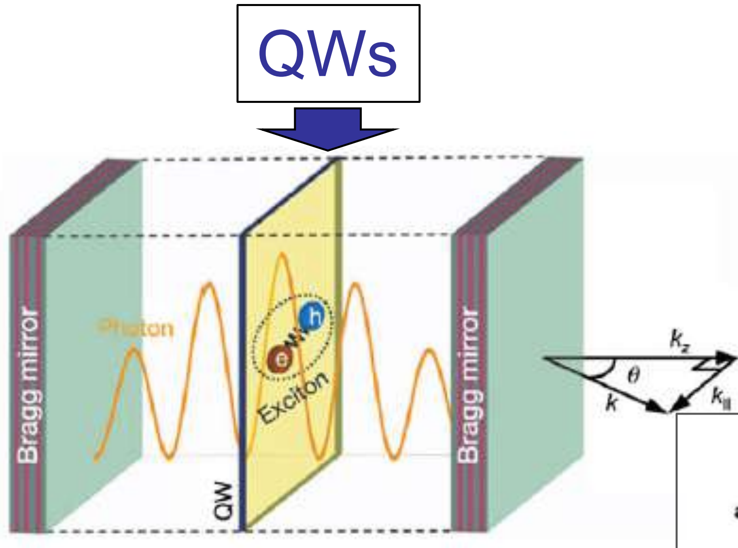




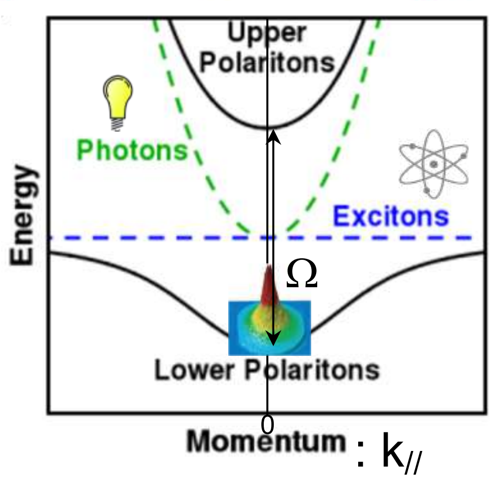


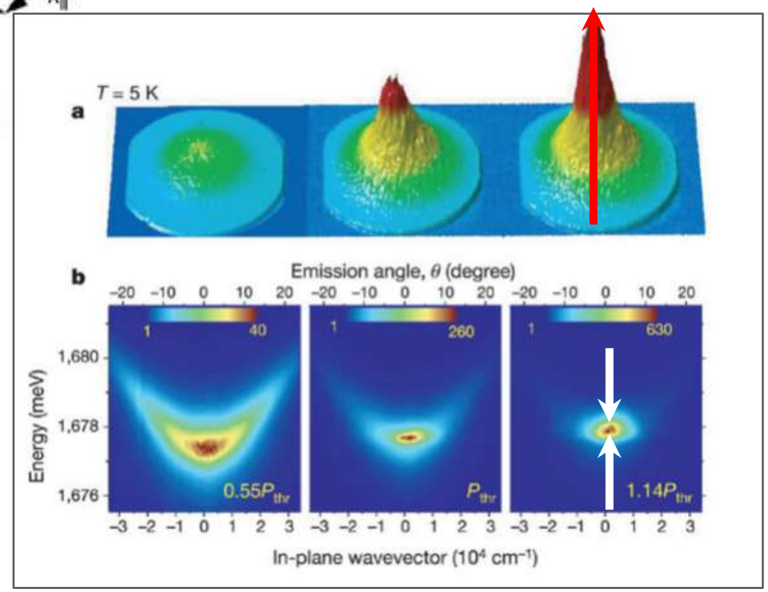
$\psi = \frac{1}{\sqrt{2}}$  $+ \frac{1}{\sqrt{2}}$ 

Cavity exciton-polaritons: high power

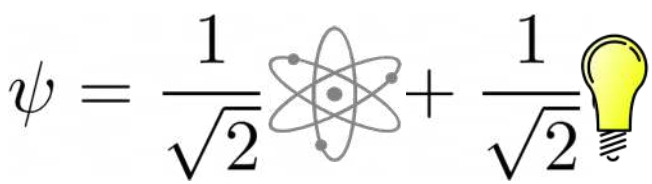


Kasprzak, *et al.* "**Bose–Einstein condensation** of exciton polaritons." *Nature* 443.7110 (2006)

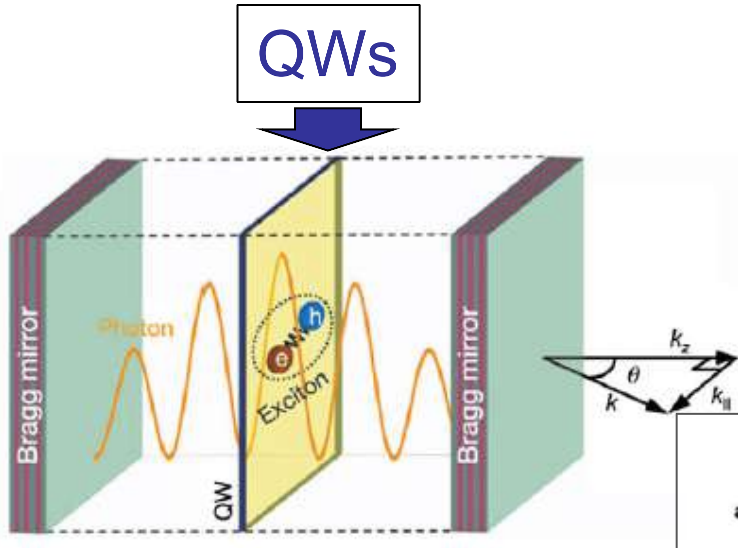


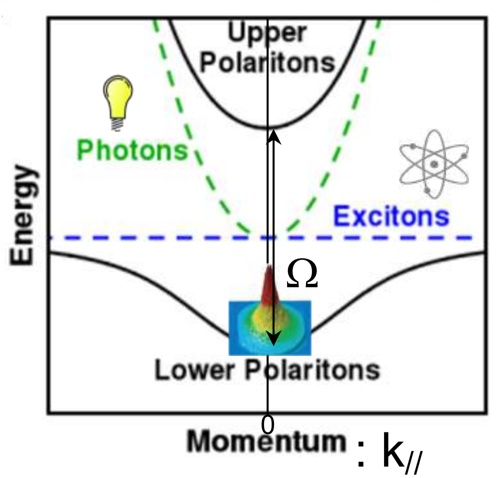


Increasing power



Cavity exciton-polaritons: “fluids of light”





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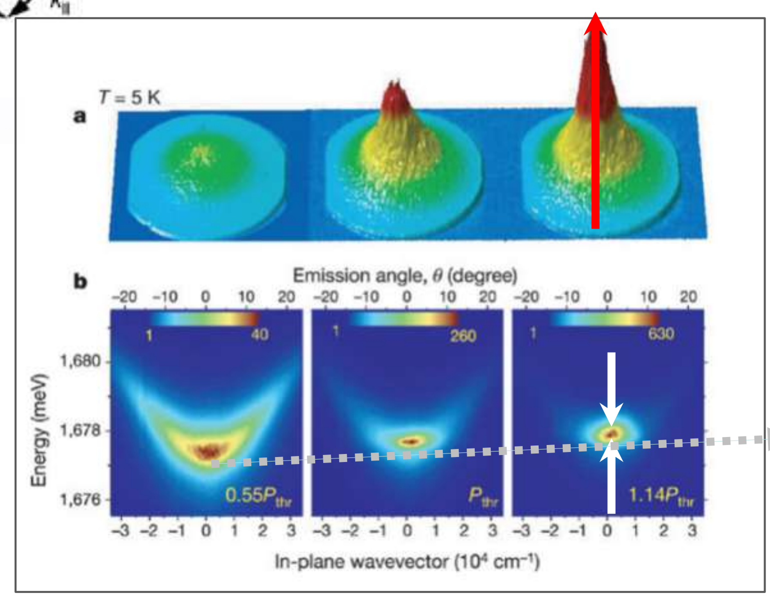
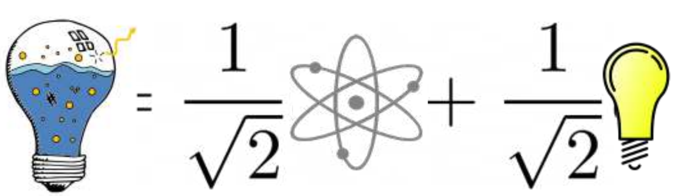
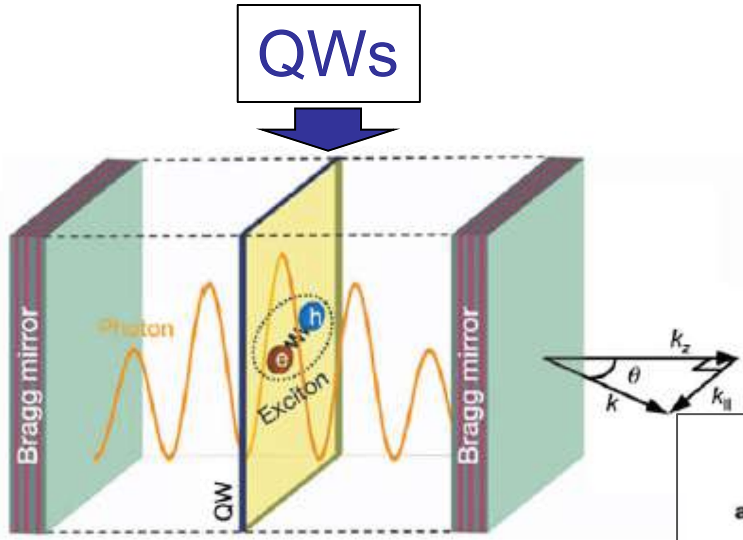


Blue-shift: strong Interactions

Increasing power

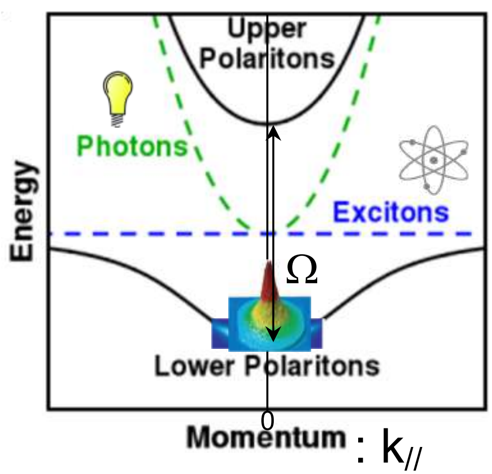


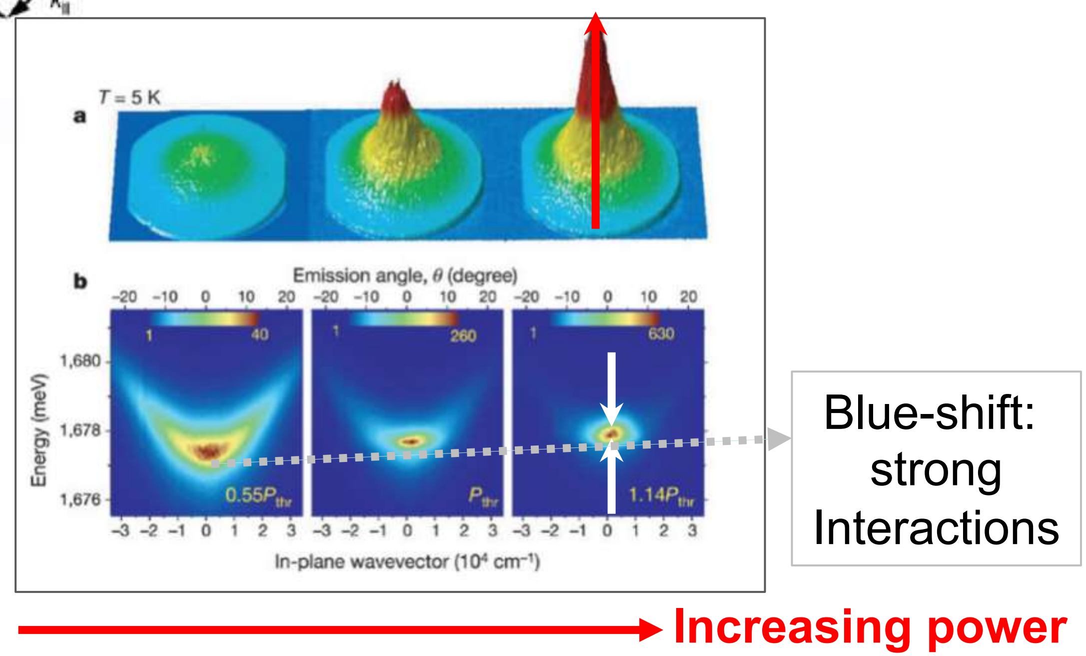
Cavity exciton-polaritons: a coherent state

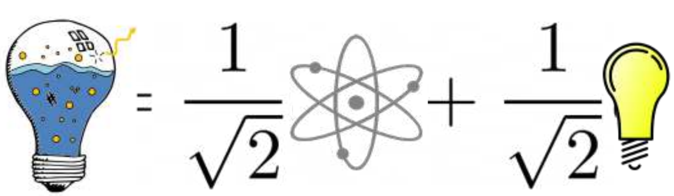


$$\psi = \sqrt{N}\, e^{i\theta}$$

Kasprzak, *et al.* "**Bose–Einstein condensation** of exciton polaritons." *Nature* 443.7110 (2006)







Superfluidity of polariton coherent states

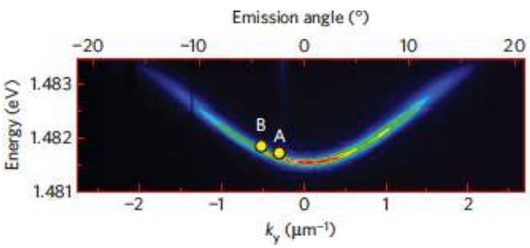
nature physics

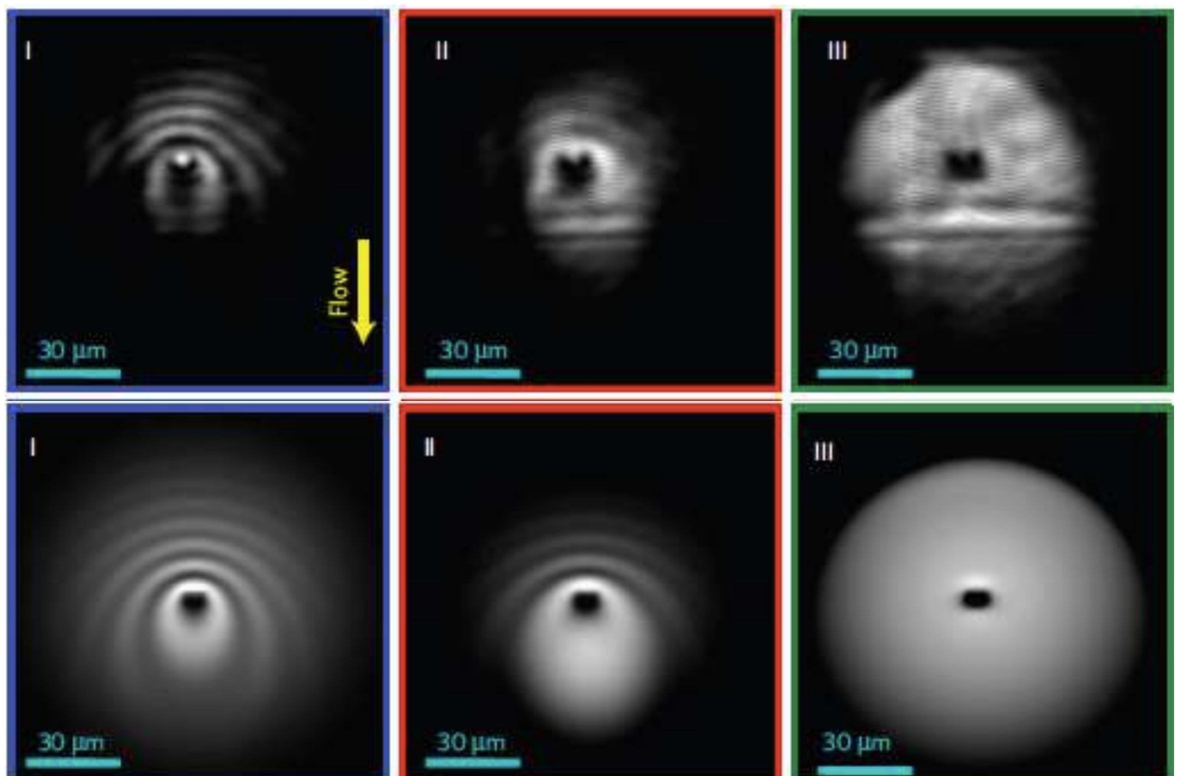
LETTERS

PUBLISHED ONLINE: 20 SEPTEMBER 2009 | DOI: 10.1038/NPHYS1364

Superfluidity of polaritons in semiconductor microcavities

Alberto Amo[1]*, Jérôme Lefrère[1], Simon Pigeon[2], Claire Adrados[1], Cristiano Ciuti[2], Iacopo Carusotto[3], Romuald Houdré[4], Elisabeth Giacobino[1] and Alberto Bramati[1]*

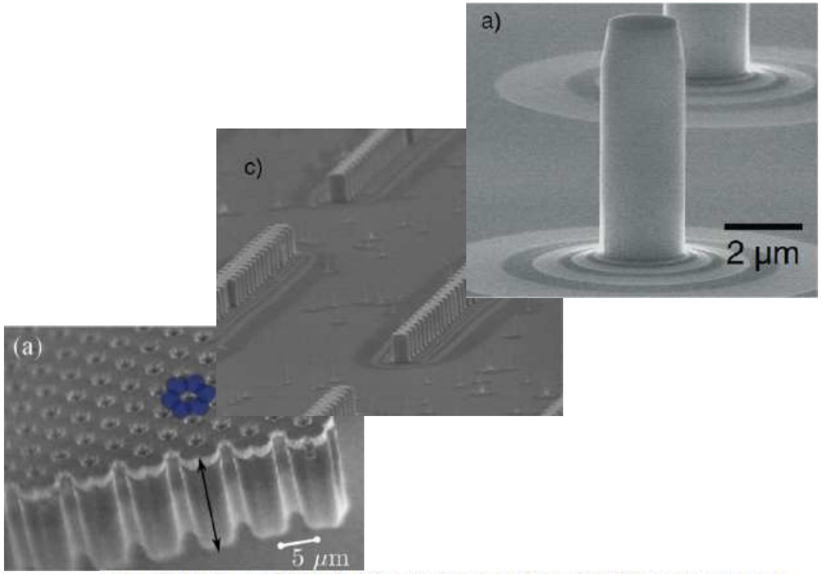




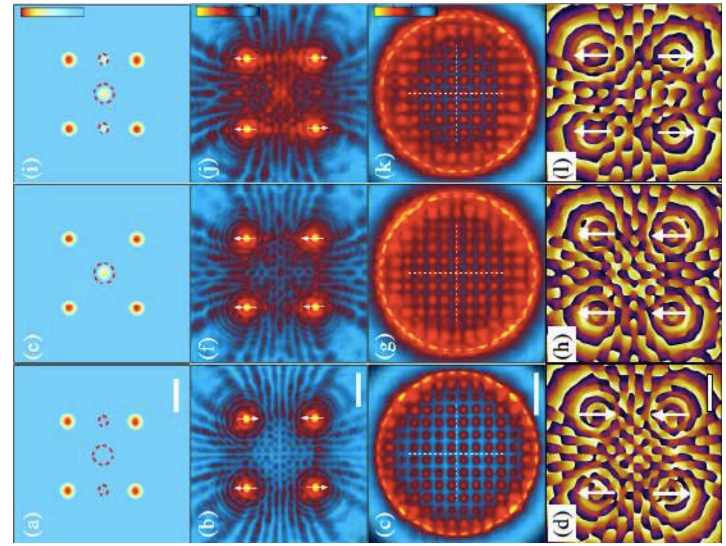
Experiment

Theory

Arrays of cavity-polariton traps



Jacqmin T *et al* 2014 Direct observation of Dirac cones and a flatband in a honeycomb lattice for polaritons *Phys. Rev. Lett.* **112** 116402



PHYSICAL REVIEW LETTERS **124**, 207402 (2020)

Optical Control of Couplings in Polariton Condensate Lattices

S. Alyatkin,[1] J. D. Töpfer,[1,2] A. Askitopoulos,[1] H. Sigurdsson,[1,2] and P. G. Lagoudakis[1,2,*]

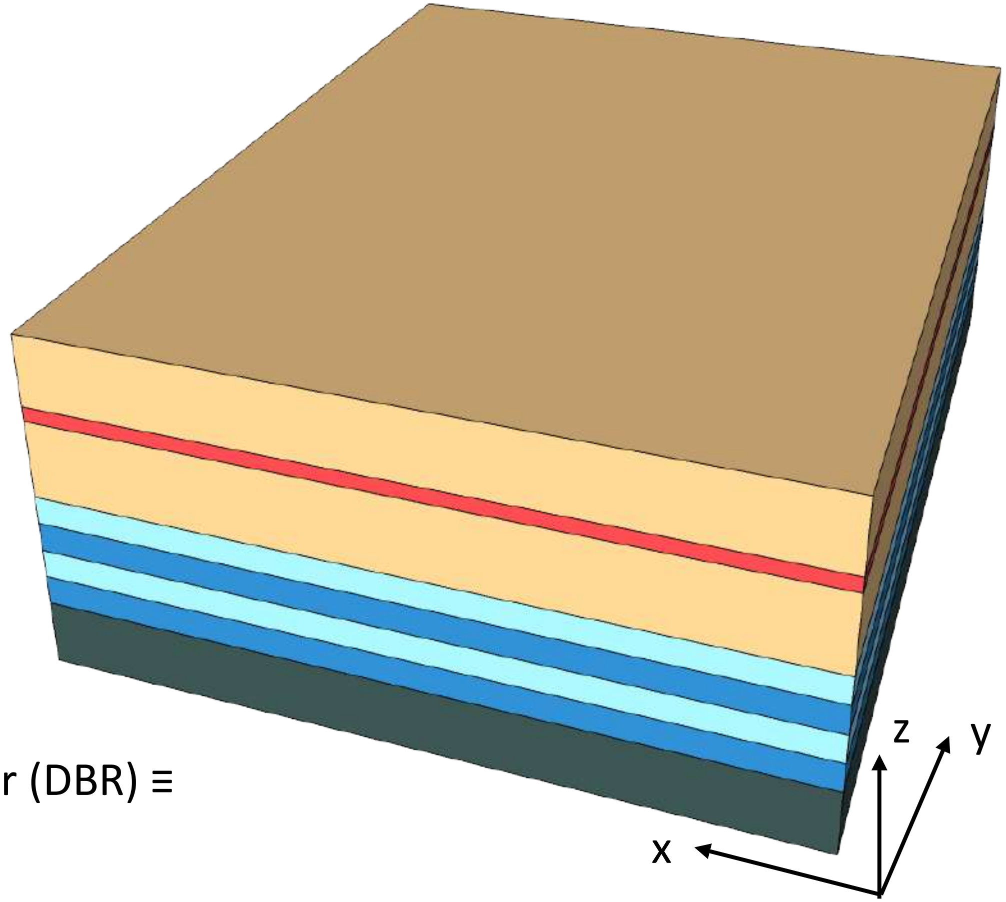
Polariton condensates for classical and quantum computing

Alexey Kavokin[1] ✉, *Timothy C. H. Liew*[2], *Christian Schneider*[3], *Pavlos G. Lagoudakis*[4,5], *Sebastian Klembt*[6,7] *and Sven Hoefling*[6,7]

Nature Reviews Physics **4**, 435–451 (2022)

Sample fabrication

Molecular beam epitaxy
MBE



Distributed Bragg Reflector (DBR) ≡ interference mirror

O. El Daif *et al*., APL **88**, 061105 (2006)
K. Winkler *et al,* NJP **17**, 023001 (2015)
A. Kuznetsov *et al*, PRB **97**, 195309 (2018)

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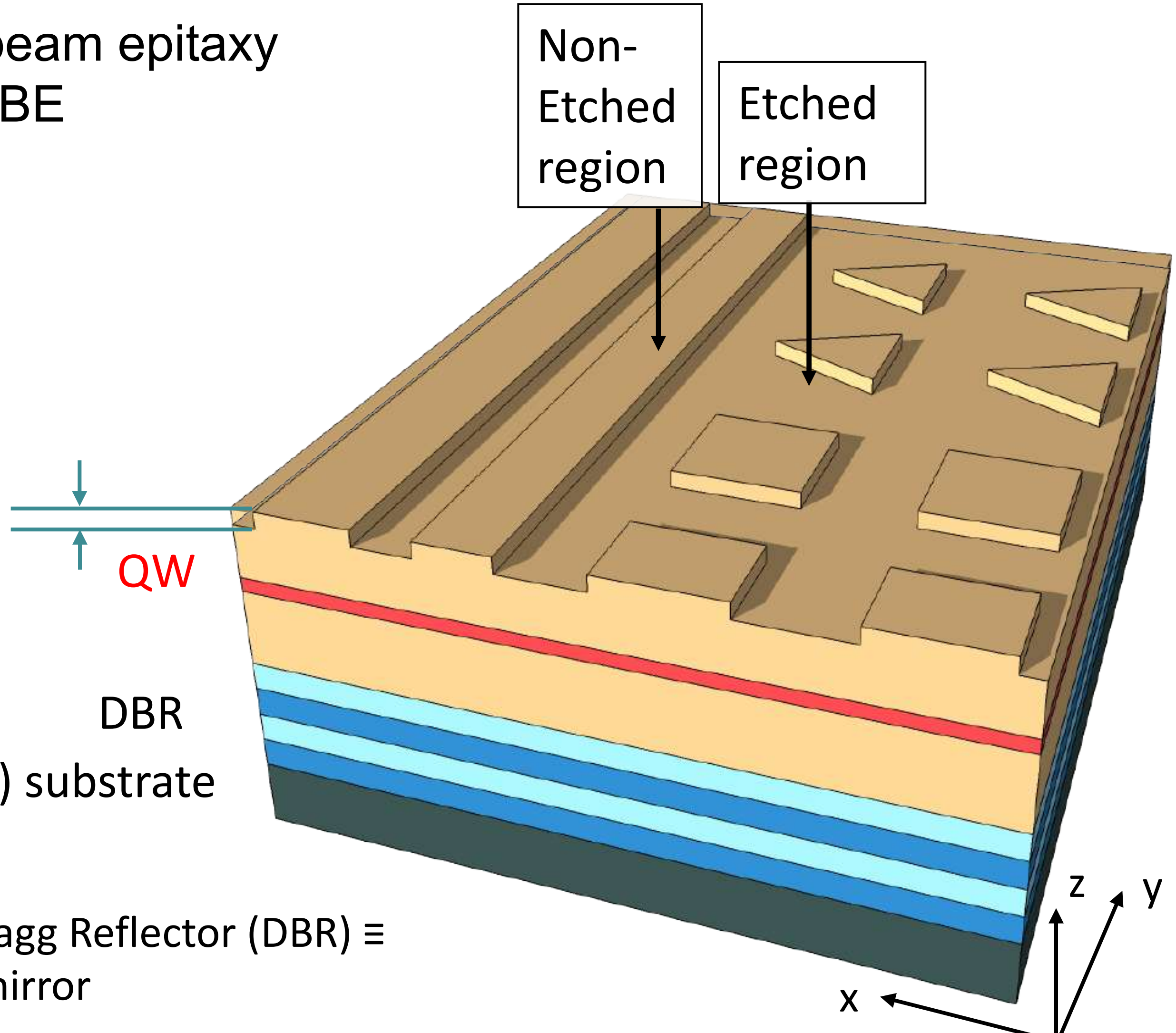

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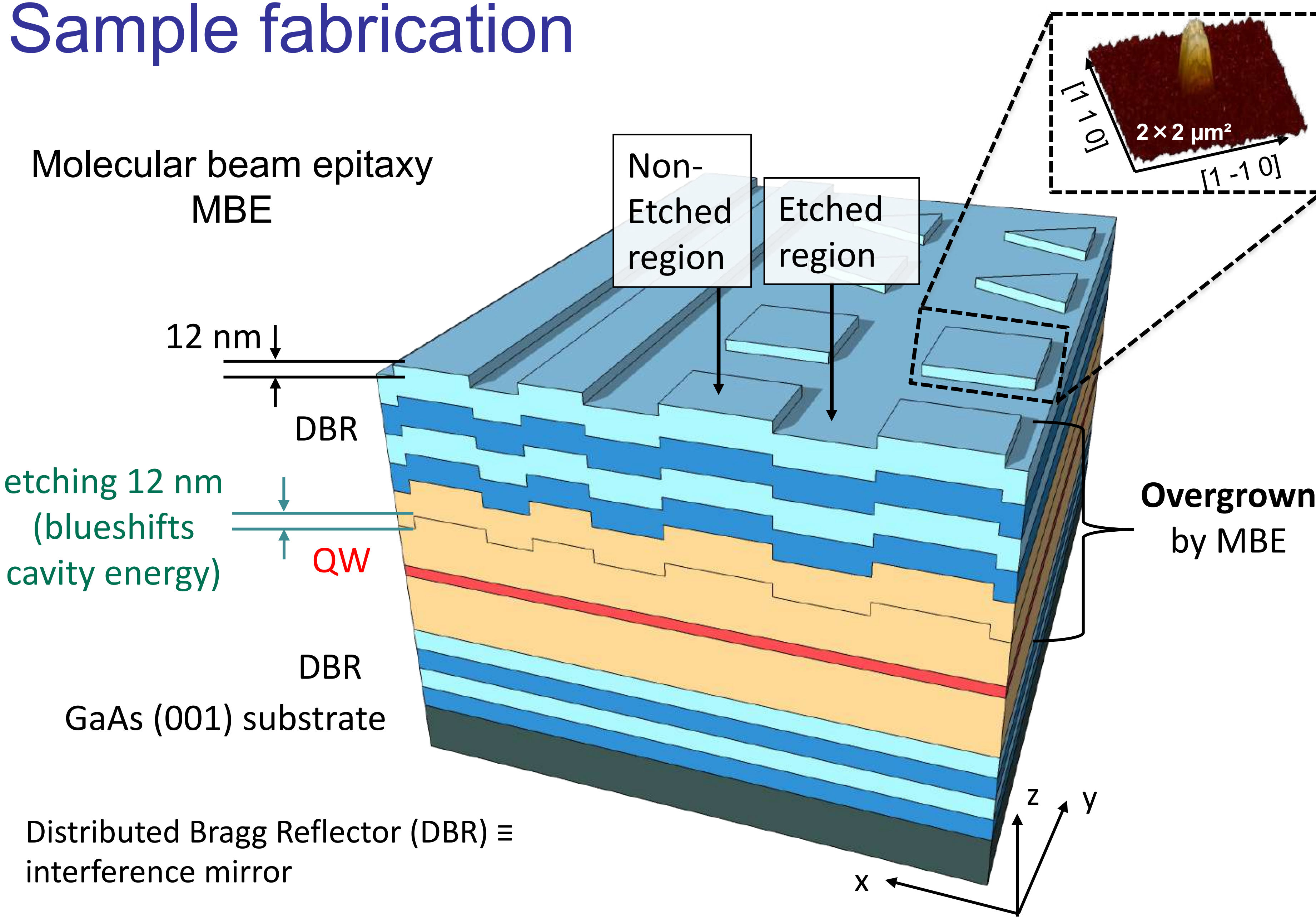

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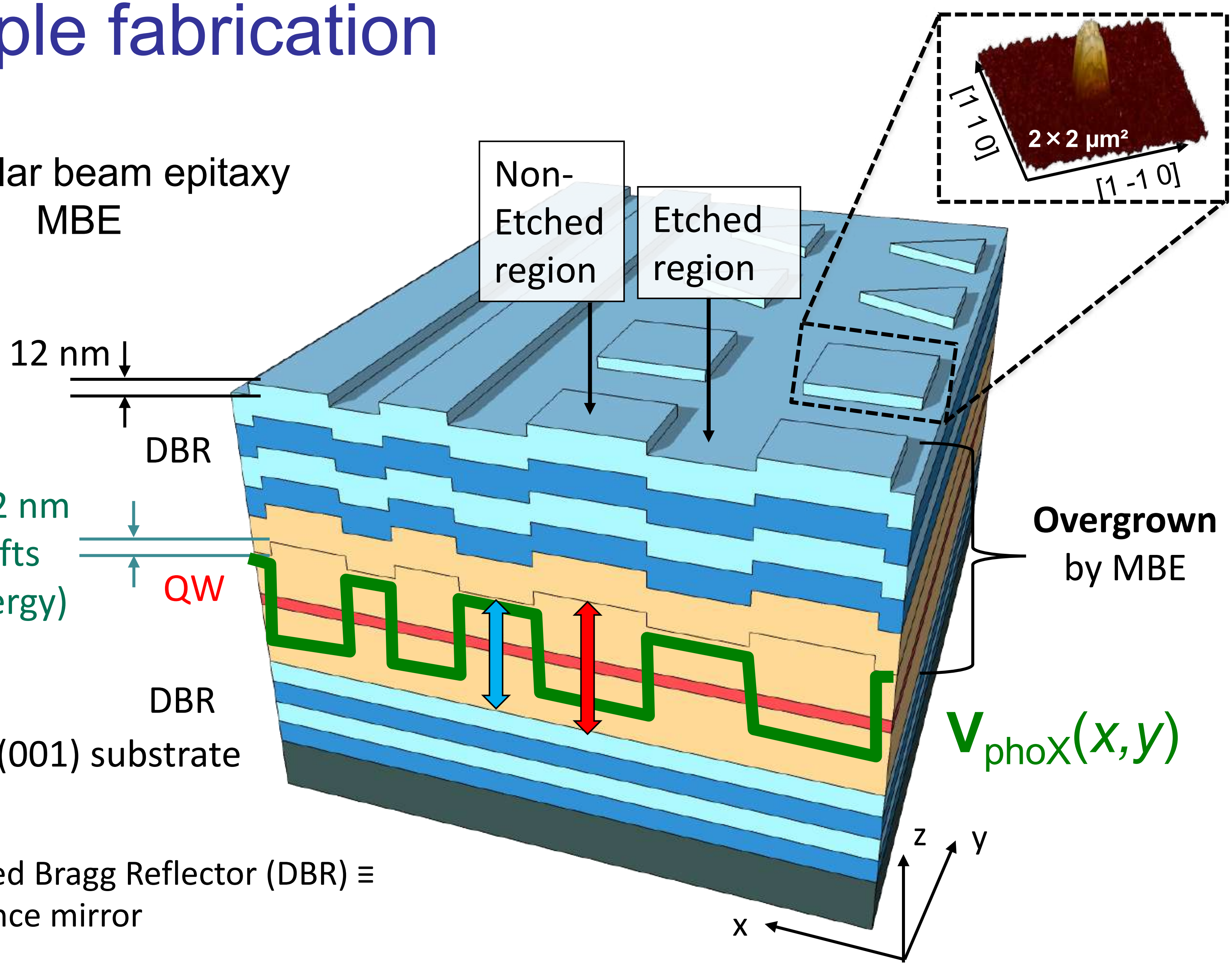

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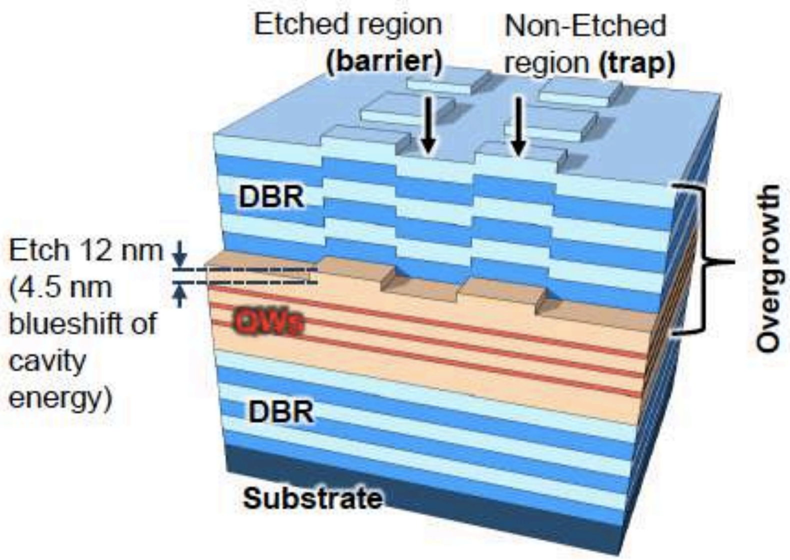
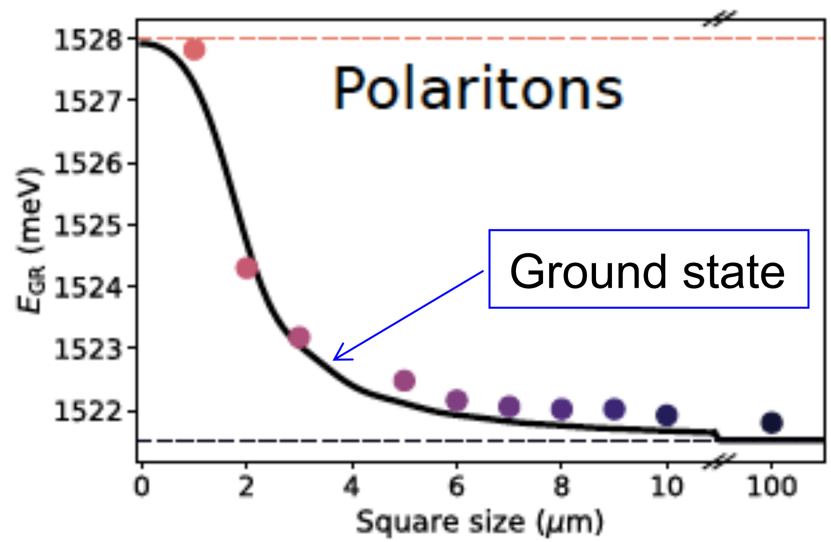
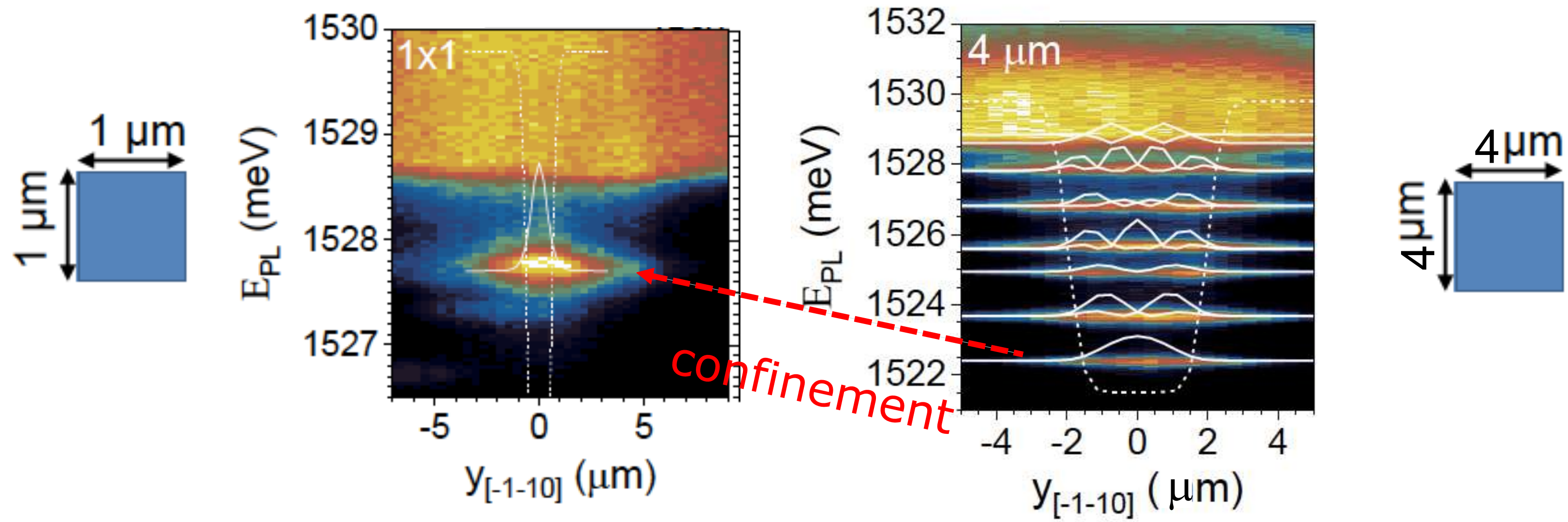
Polaritons in single traps

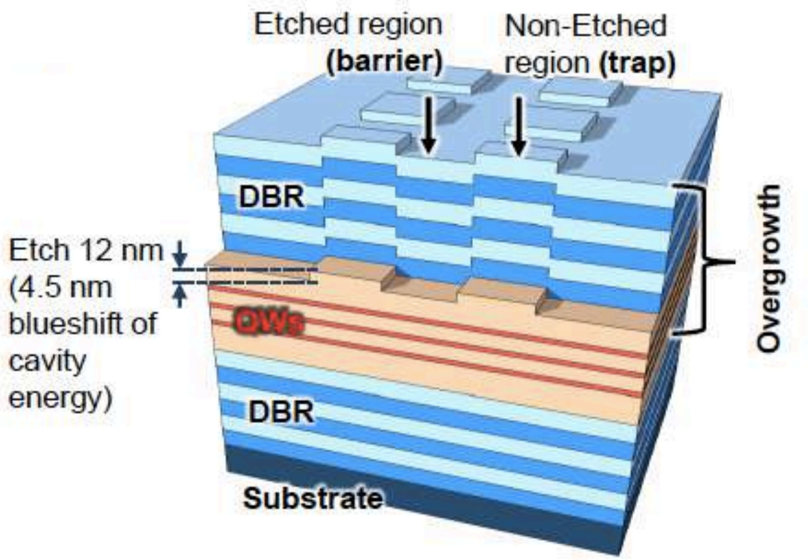


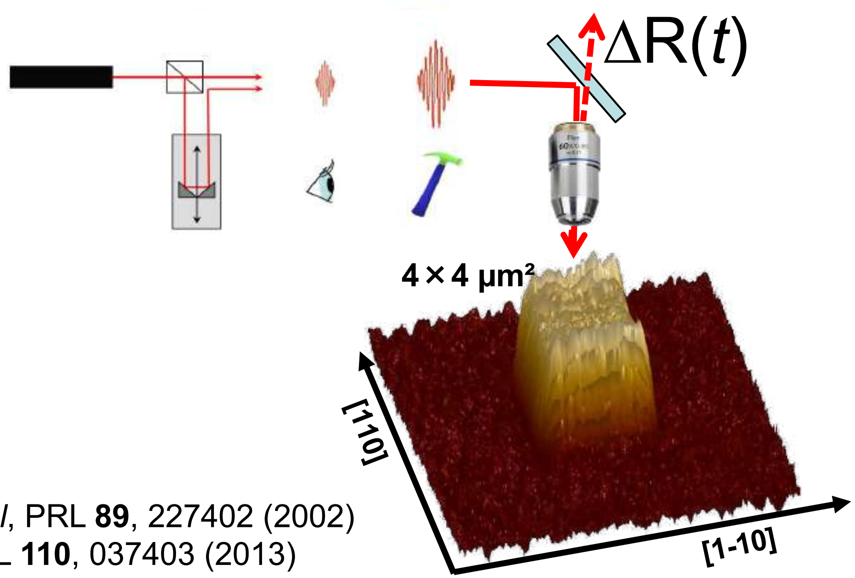


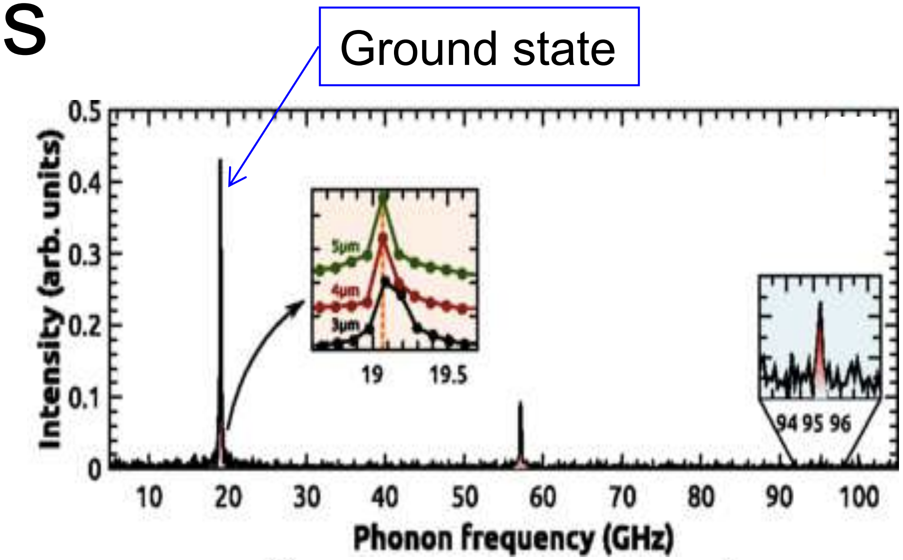


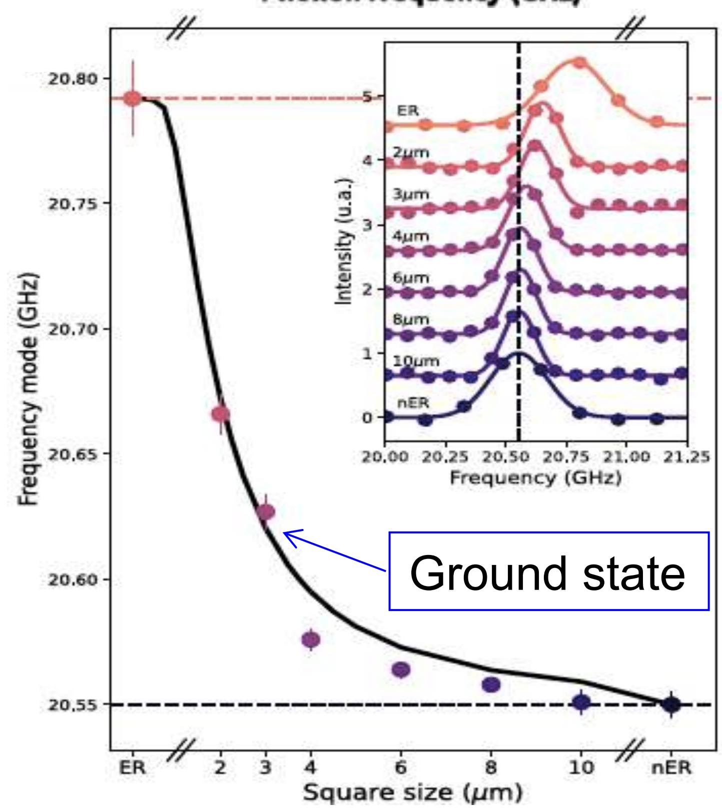
A. Kuznetsov *et al*, PRB **97**, 195309 (2018)

Phonons in single traps



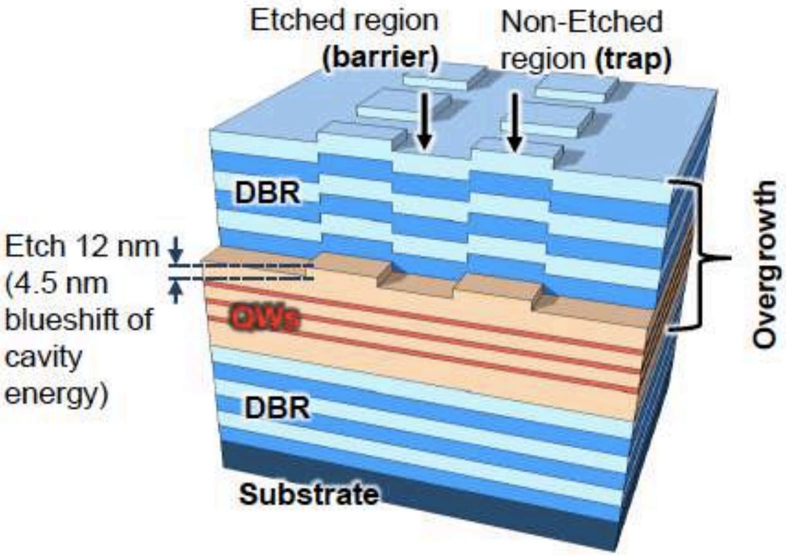




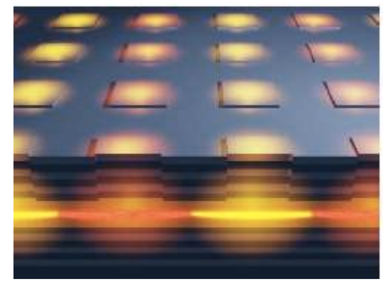


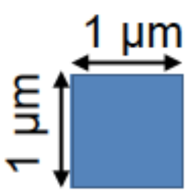
M. Trigo *et al*, PRL **89**, 227402 (2002)
AF *et al*, PRL **110**, 037403 (2013)
A. Anguiano *et al*, PRL **118**, 263901 (2017)
D. Chafatinos *et al*, Nat. Comm. **14**, 3485 (2023)

Polaritons in lattices of traps

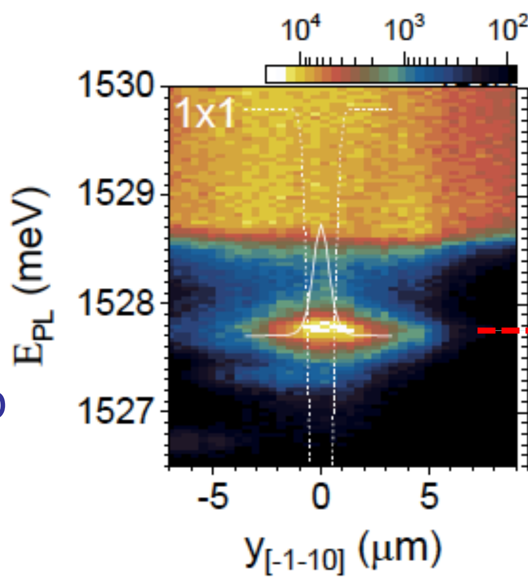


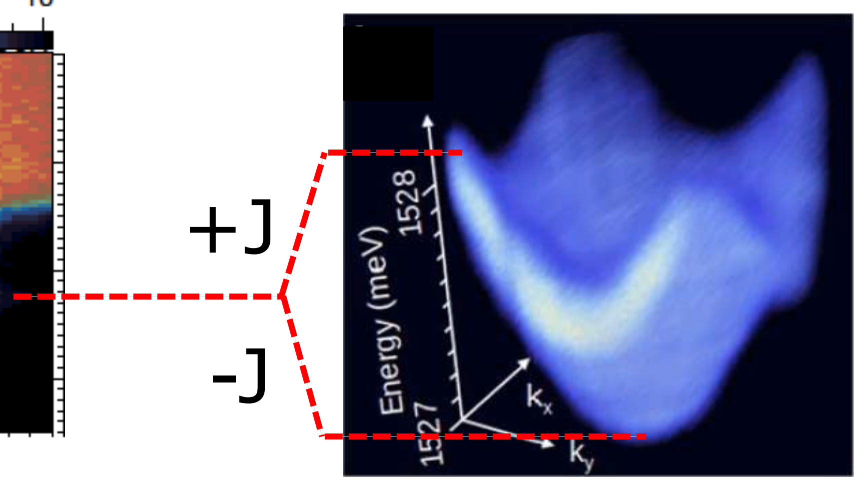
Array of 1μm traps
with intersite coupling J





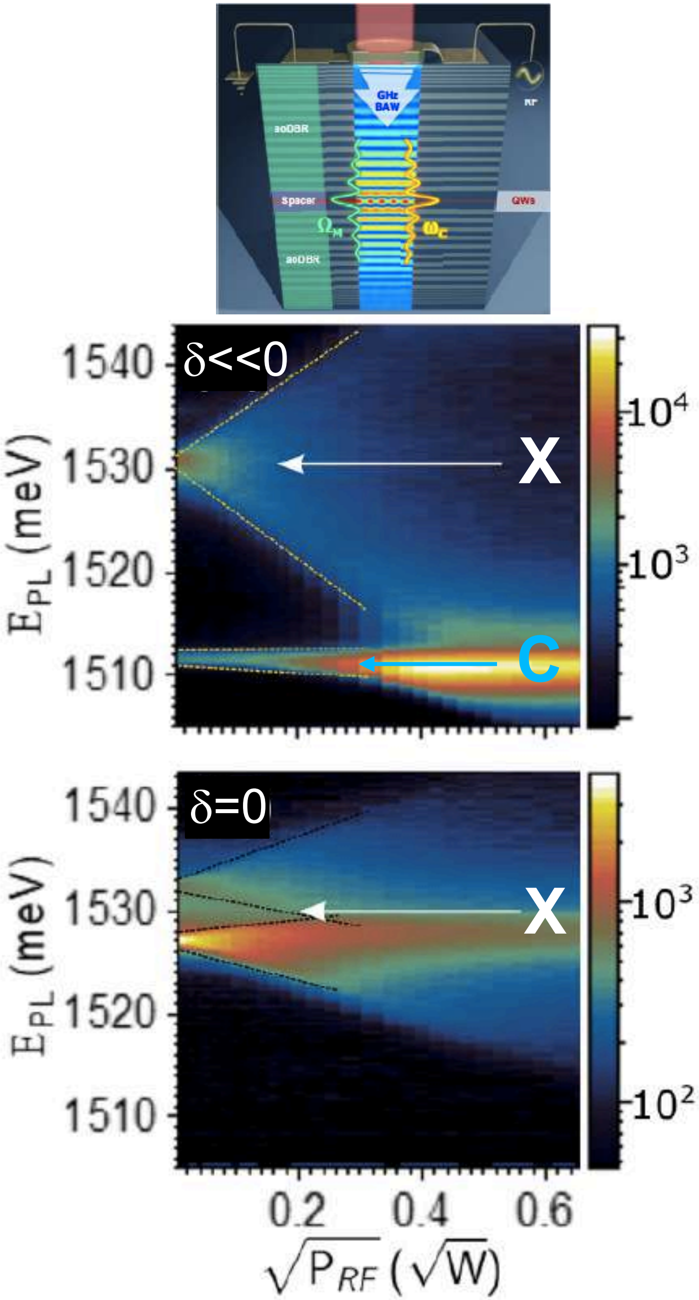
Single trap





A. Kuznetsov *et al*, PRB **97**, 195309 (2018)

The OM coupling: RF driving



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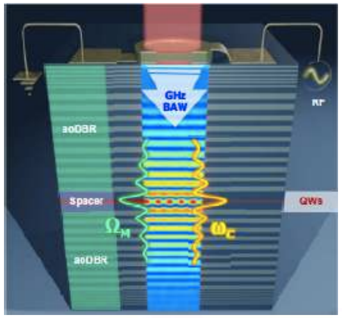
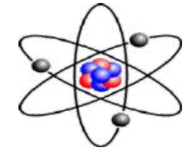
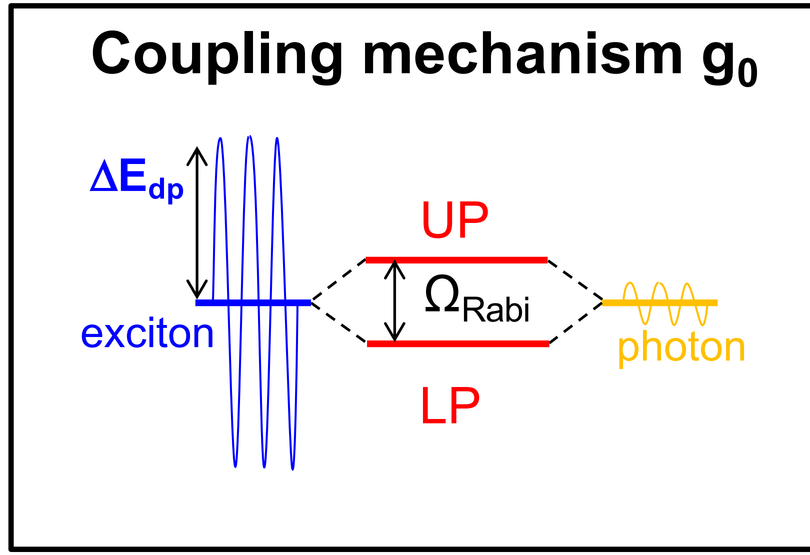


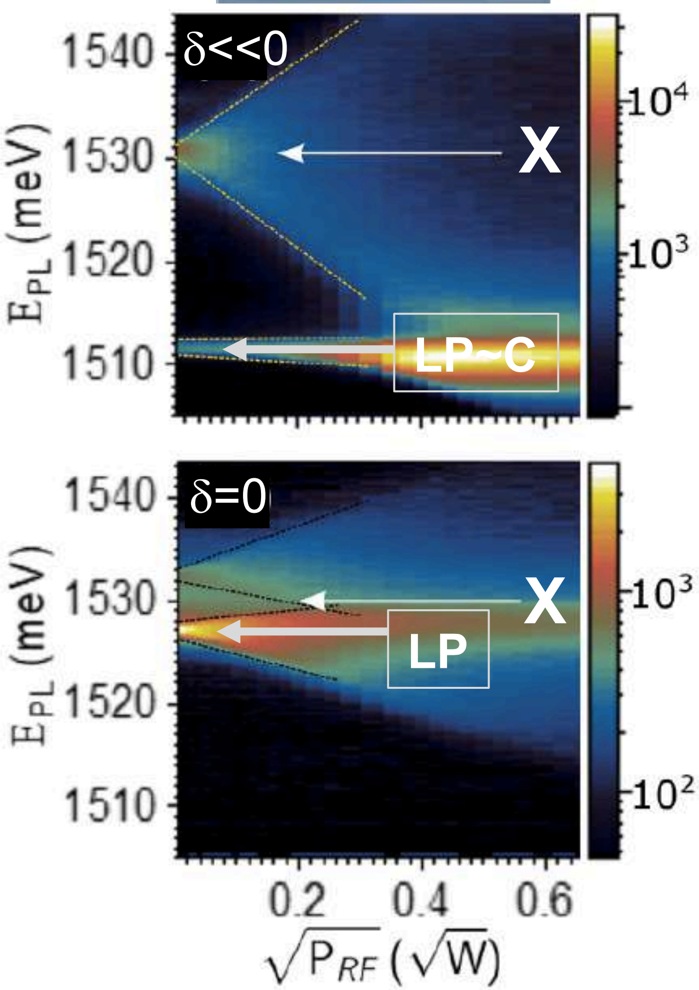
$\Psi = \alpha$  $+ \beta$ 



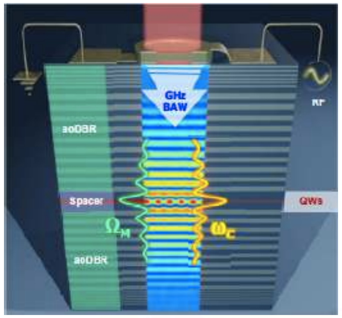
$$g_0 = S_c\, g_0^{RP} + S_x\, g_0^{DP}$$

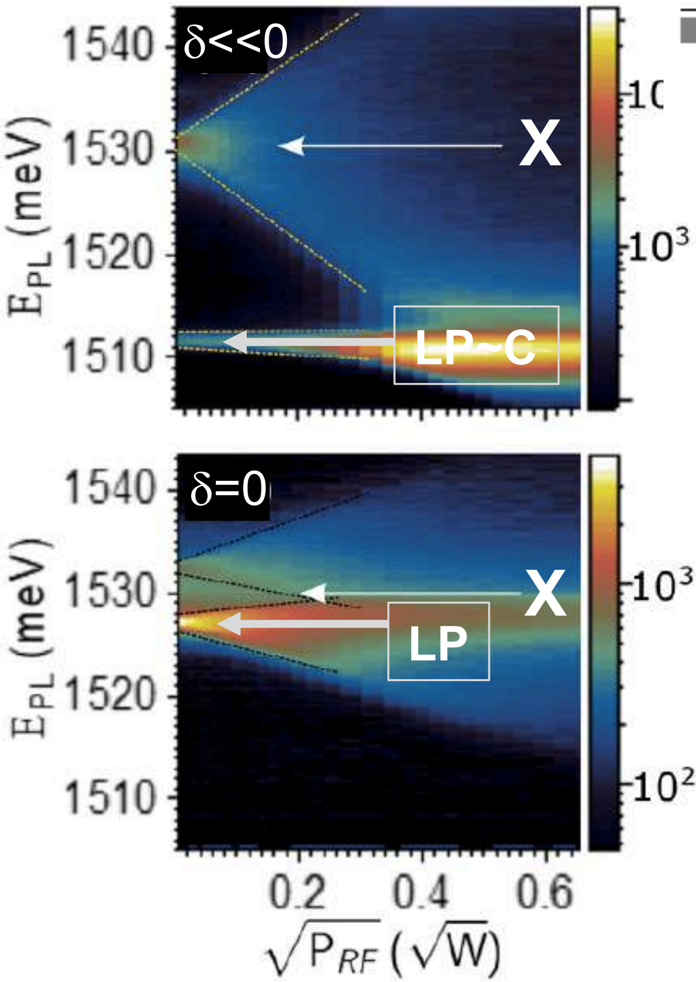
Interface displacement

X-energy displacement



The OM coupling: Modeling





PHYSICAL REVIEW LETTERS 129, 093603 (2022)

Enhanced Cavity Optomechanics with Quantum-Well Exciton Polaritons

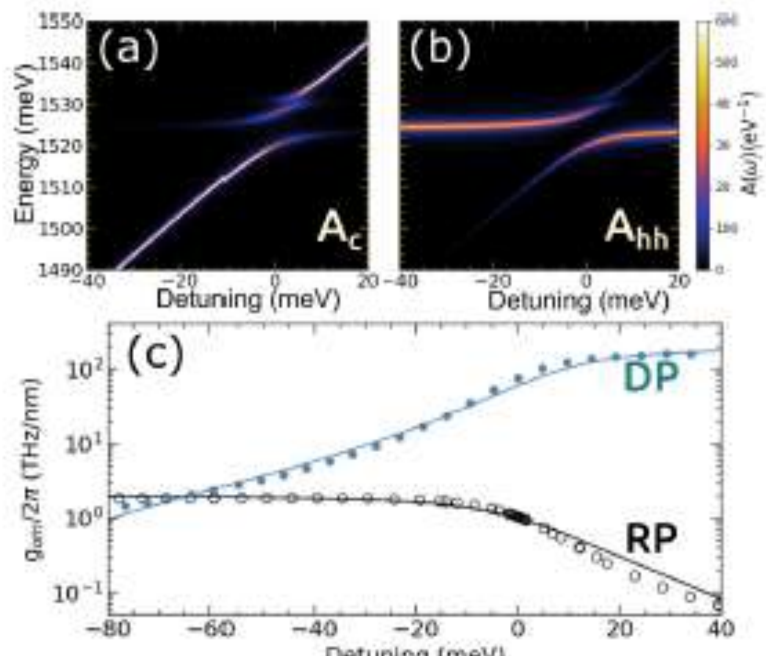
N. Carlon Zambon,[1,*,†,‖] Z. Denis,[2,*,‡] R. De Oliveira,[2] S. Ravets,[1] C. Ciuti,[2] I. Favero,[2] and J. Bloch[1]

PHYSICAL REVIEW RESEARCH 5, L042035 (2023)

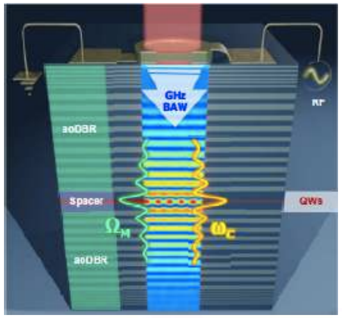
Letter

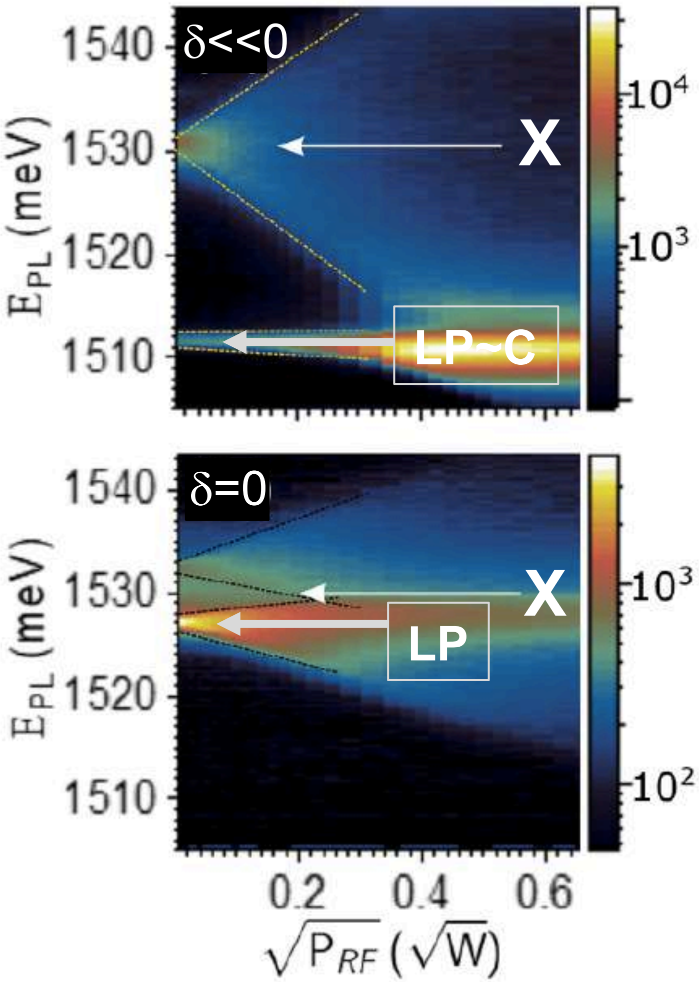
Giant optomechanical coupling and dephasing protection with cavity exciton-polaritons

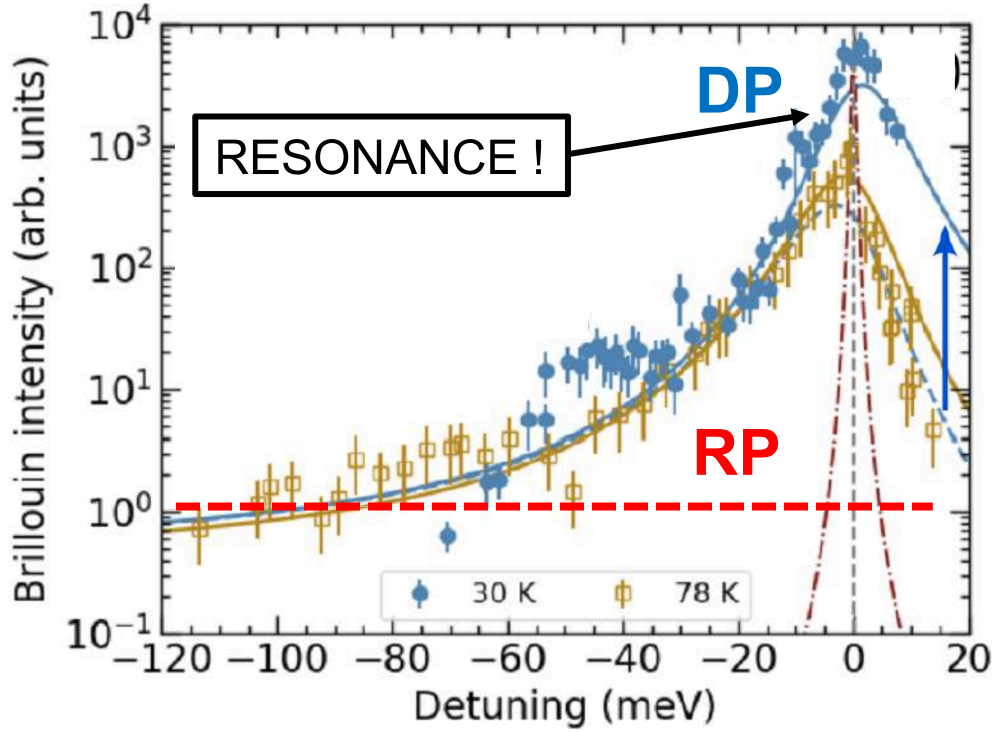
P. Sesin,[1,2] A. S. Kuznetsov,[3] G. Rozas,[1,2] S. Anguiano,[1,2] A. E. Bruchhausen,[1,2] A. Lemaître,[4] K. Biermann,[3] P. V. Santos,[3,*] and A. Fainstein[1,2,†]



The OM coupling: LP Brillouin scattering





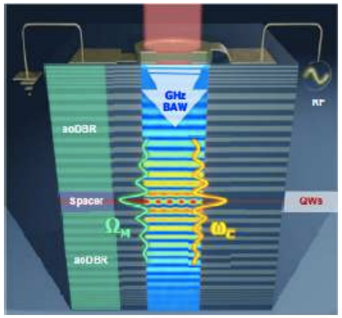


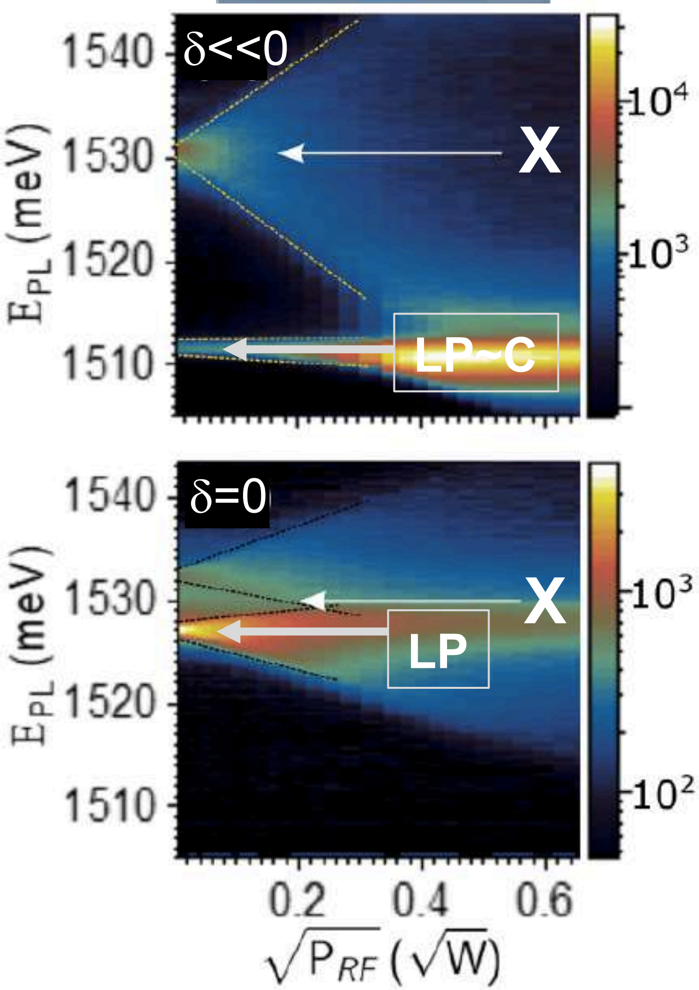
$$g_0 = S_c\, g_0^{RP} + S_x\, g_0^{DP}$$

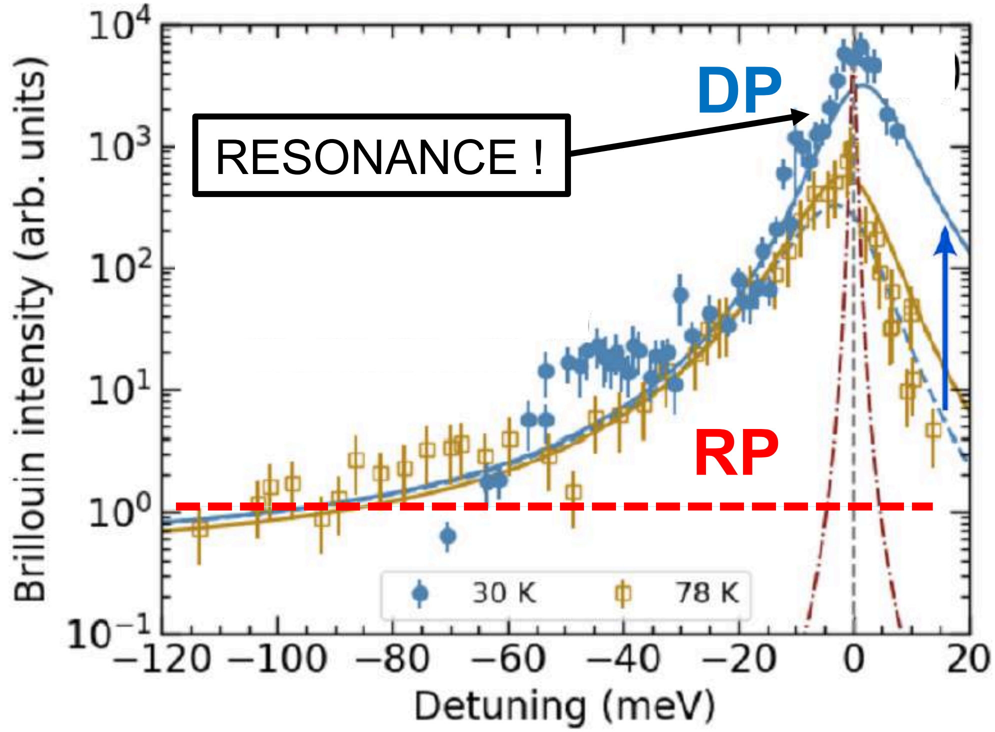
Interface displacement

X-energy displacement

The OM coupling: LP Brillouin scattering



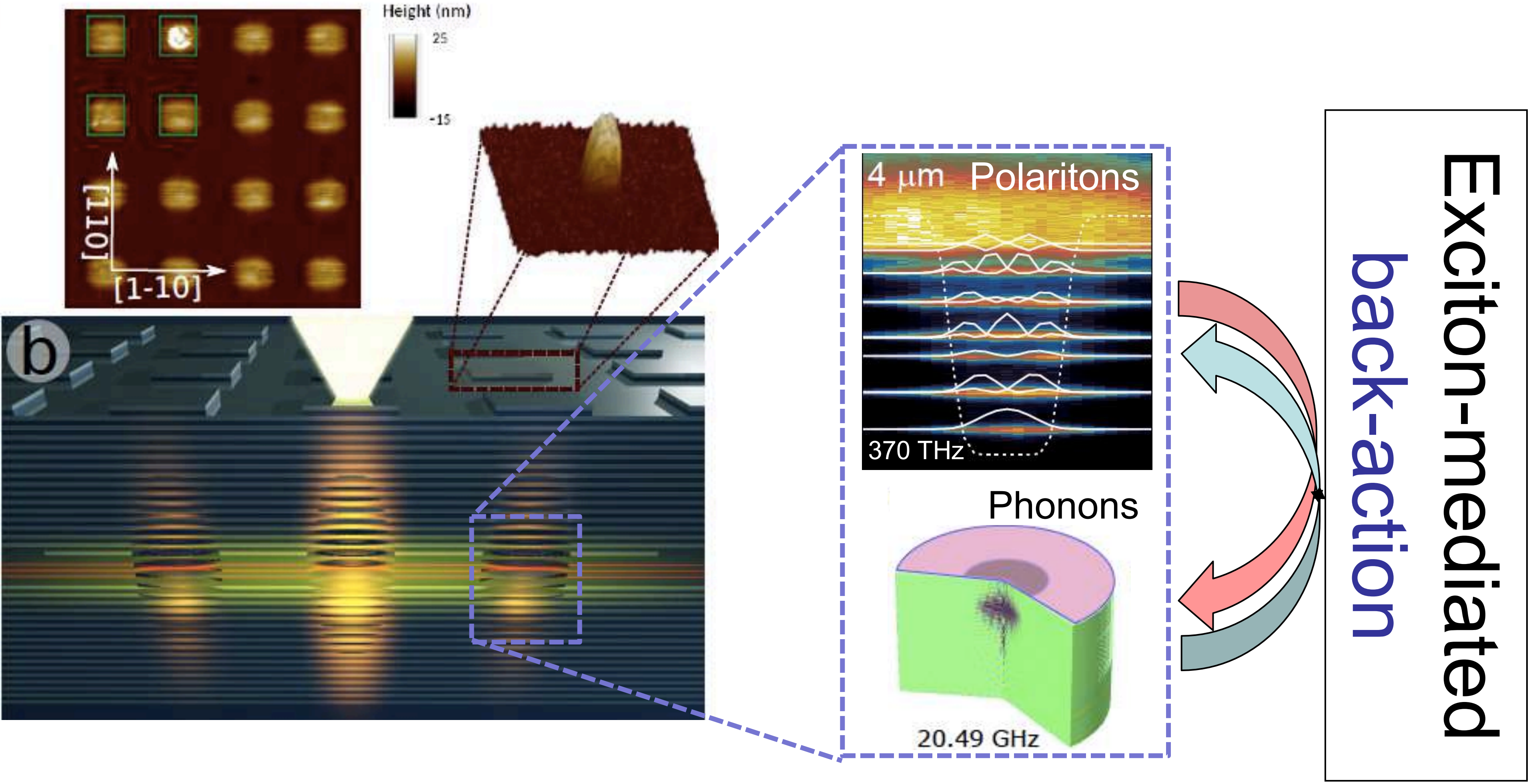




$$g_0 = S_c\, g_0^{RP} + S_x\, g_0^{DP}$$

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

Polaromechanical “Metamaterials”

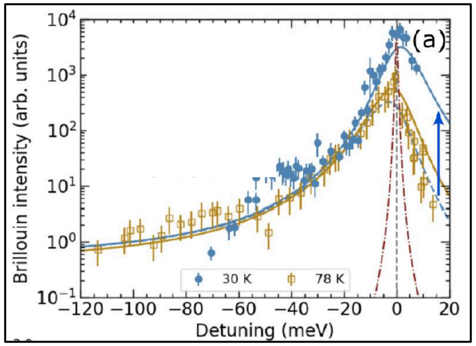


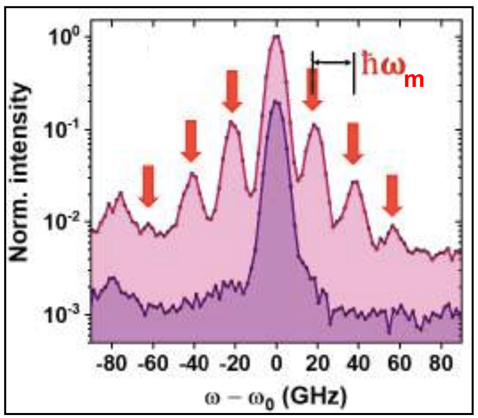
+ exciton-exciton Coulomb interactions

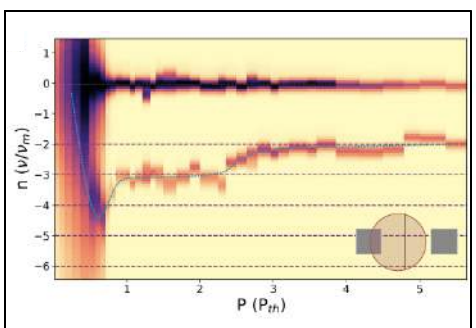
Day #1 wrap-up

- Concept: CQED (polaritons) + cavity optomechanics
- What are these polaritons?: tunable superposition of photon and exciton 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

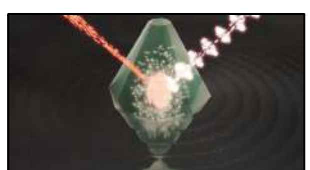
Index







- **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