Manipulating Polariton Condensates on a Chip

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14.7.12

Acknowledgements

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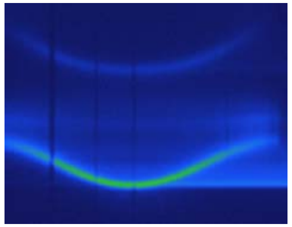
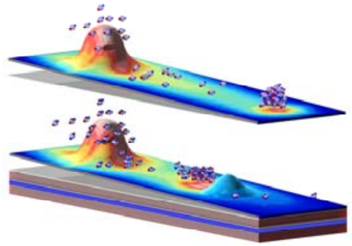
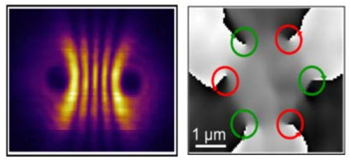
Outline

- Polariton lasing in high finesse microcavities
  - threshold temperature dependence (strong vs weak)

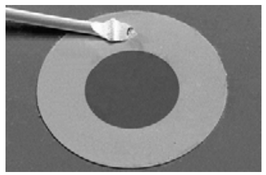


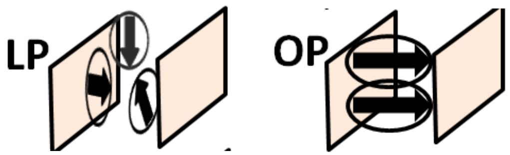
- Electrical and optical manipulation of polariton condensates on a chip
  - polariton condensate transistor
  - interactions between independent condensates
  - electrical control of polariton condensate



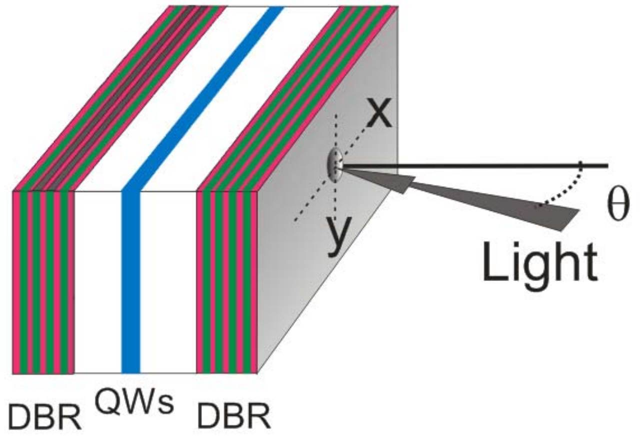


- Dipolaritons: dipole oriented polaritons
  - control of quantum tunneling with light





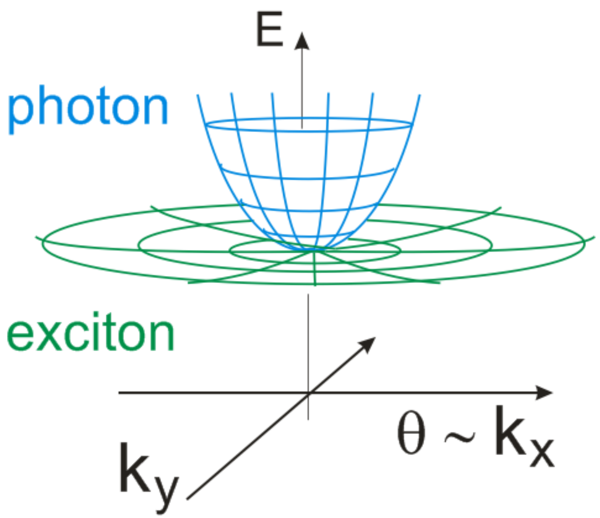
Strong Coupling Regime in Semiconductor Microcavity



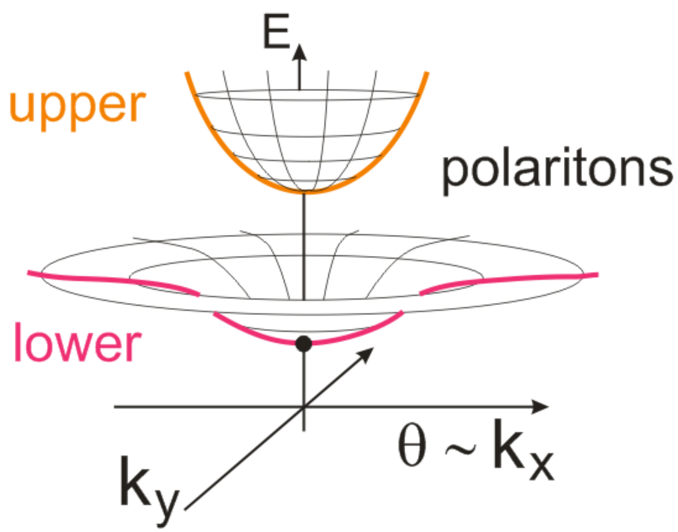
- Strongly modified dispersion relations
  new properties
- small polariton mass $m_{pol} \approx 10^{-4} m_e$

$$E_{photon} = \frac{\hbar c}{n_c}\sqrt{\left(\frac{2\pi}{L_c}\right)^2 + k_{//}^2}$$

$$E_{ex}(k_{II}) = E(0) + \frac{\hbar^2 k_{//}^2}{2M_{exciton}}$$



Strong Coupling Regime



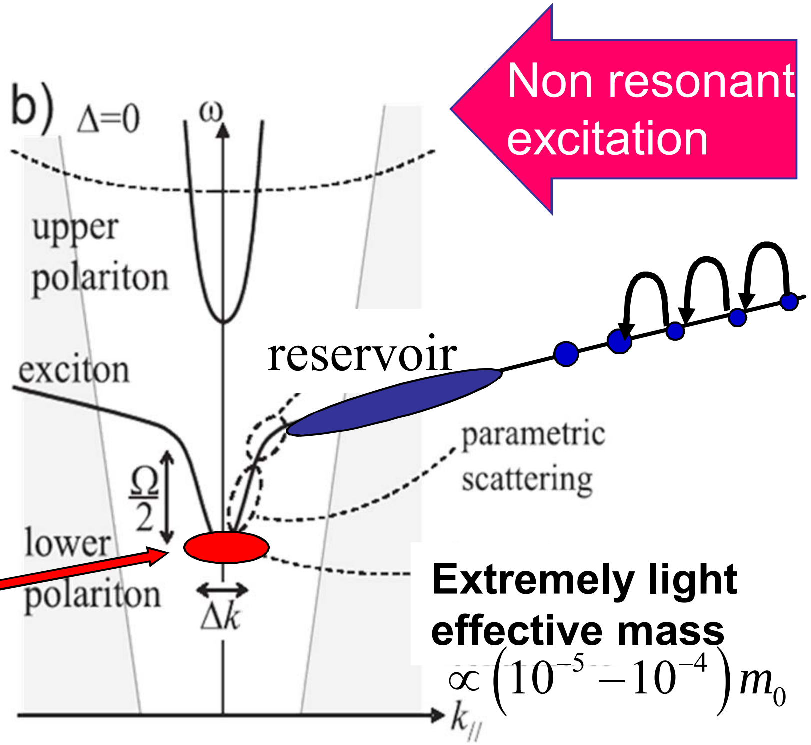
C. Weisbuch et al., Phys. Rev. Lett. 69, 3314 (1992)

Bose-Condensation and Concept of Polariton Lasing

Imamoglu et al., PRA 53, 4250 (1996)

Bosonic character of cavity polaritons could be used to create an exciton-polariton condensate that would emit coherent laser-like light.

Polariton condensate

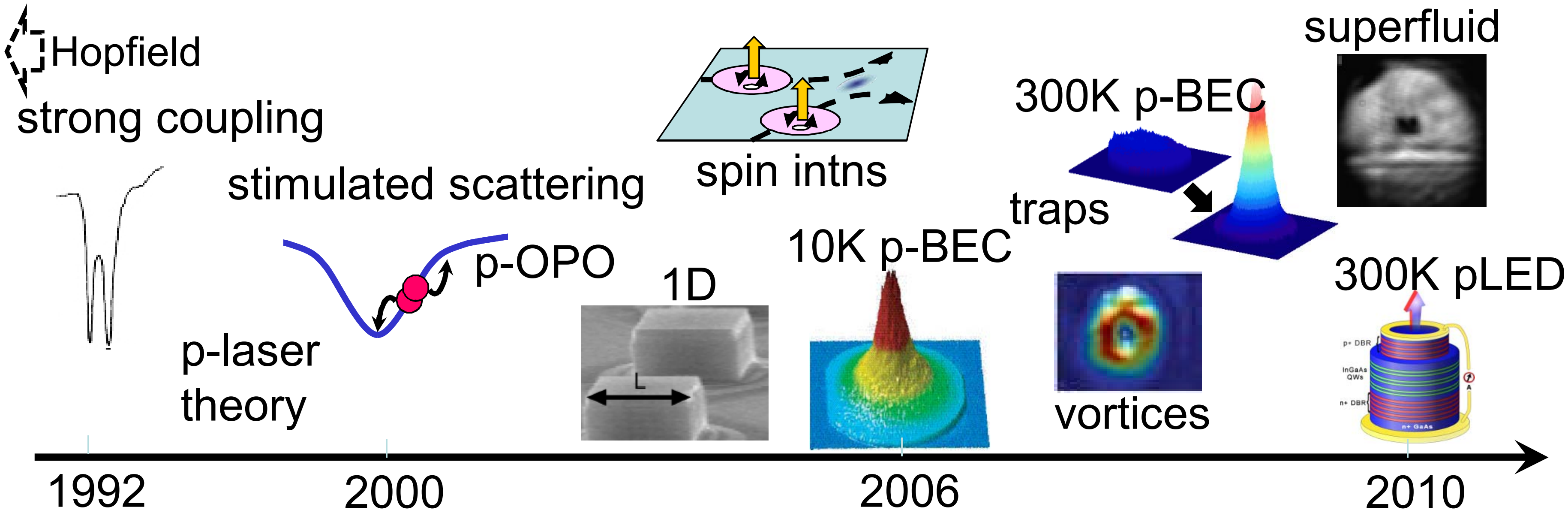


Polaritons accumulate in the lowest energy state by bosonic final state stimulation.

The coherence of the condensate builds up from an incoherent equilibrium reservoir and the BEC phase transition takes place.

The condensate emits spontaneously coherent light without necesity for population inversion

Polaritonics



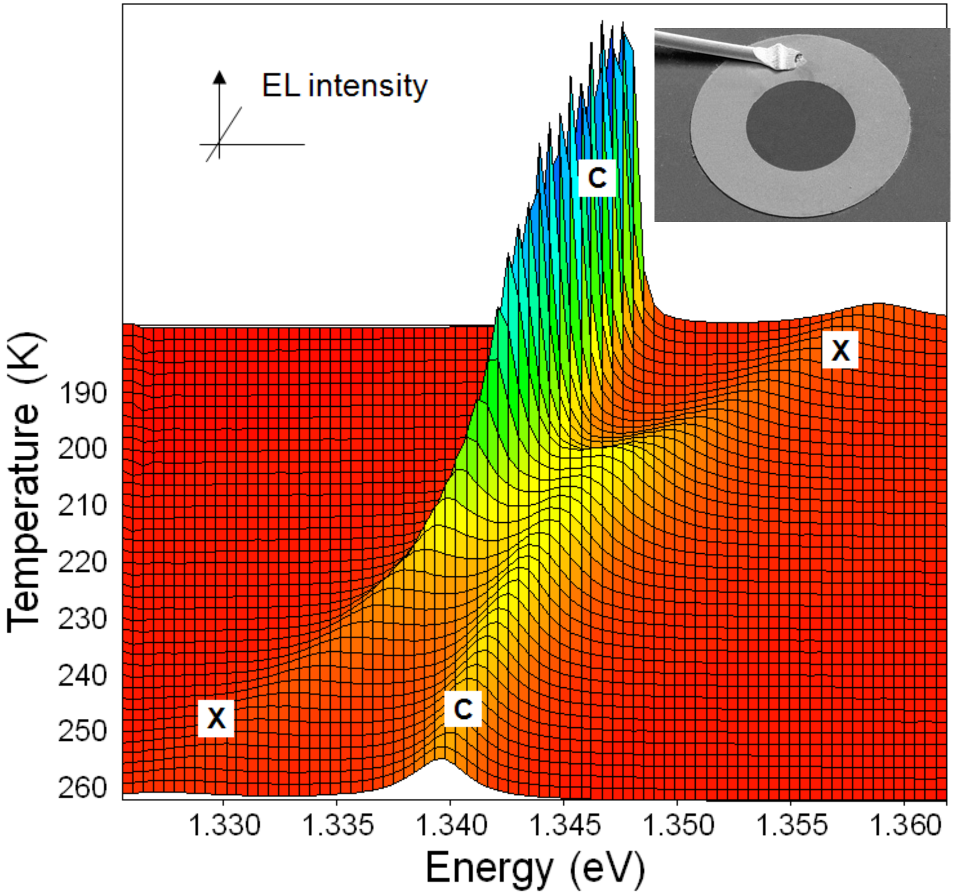
From a device perspective:

- Near speed of light lateral transport
- Light effective mass
- Condensate regime readily available on a chip even at RT

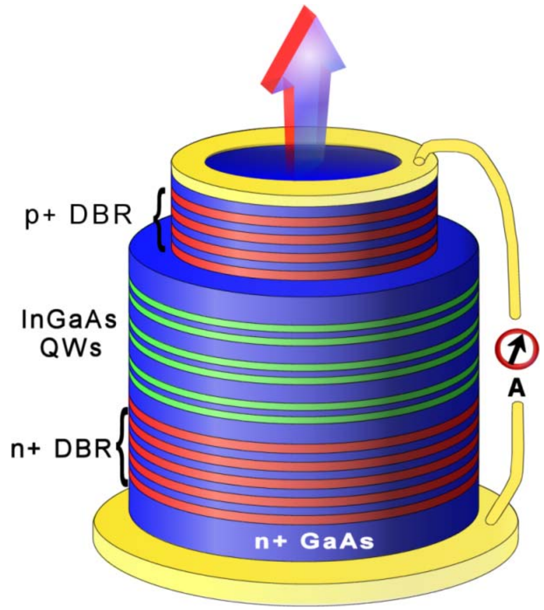
New directions: electrically driven polariton devices

Room temperature Polariton LED

Emission collected normal to the device



- Clear anticrossing observed
- Direct emission from exciton polariton states

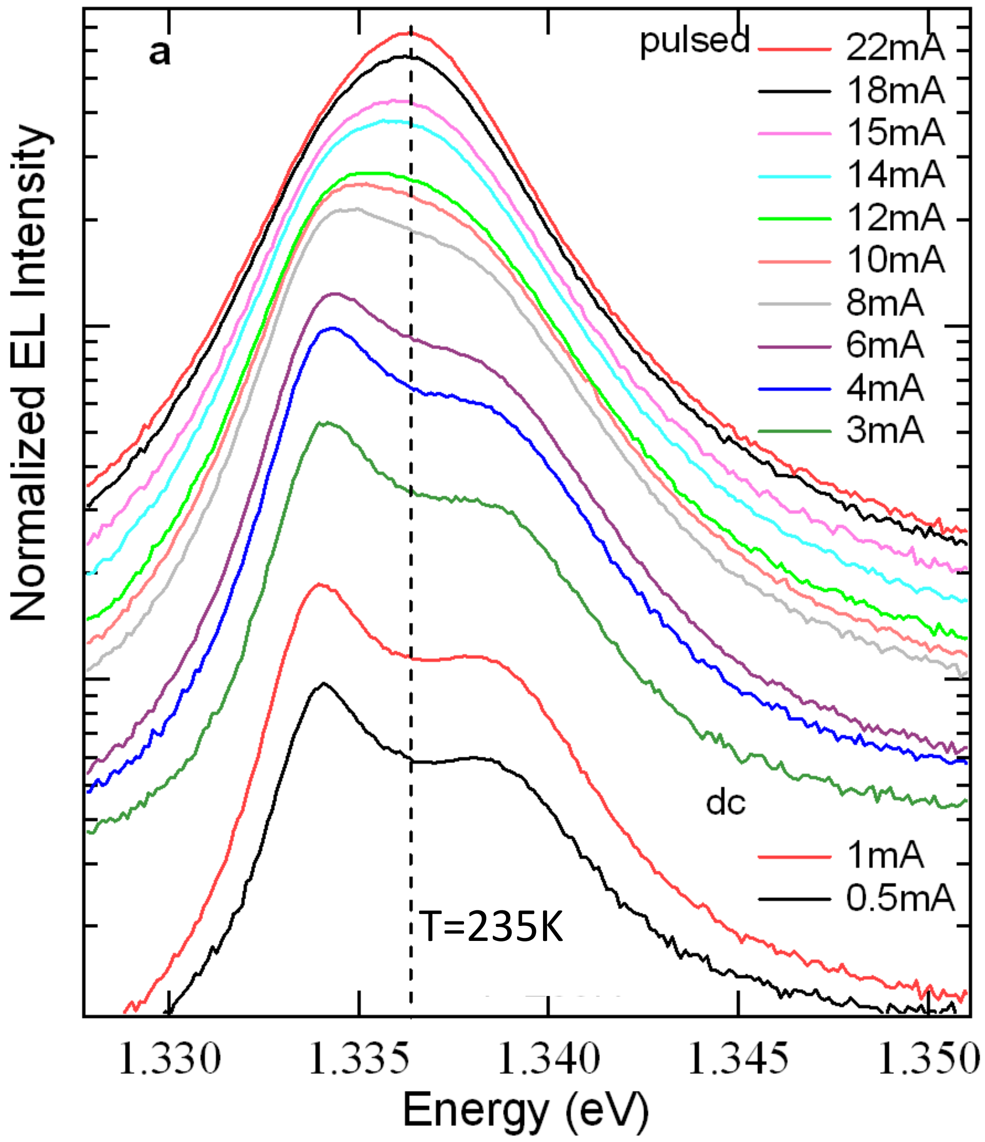


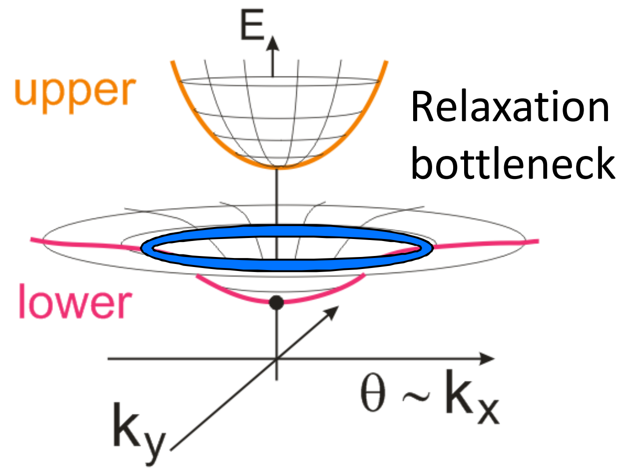
•Rabi splitting of 4.4meV at 219 K

Transport driven device

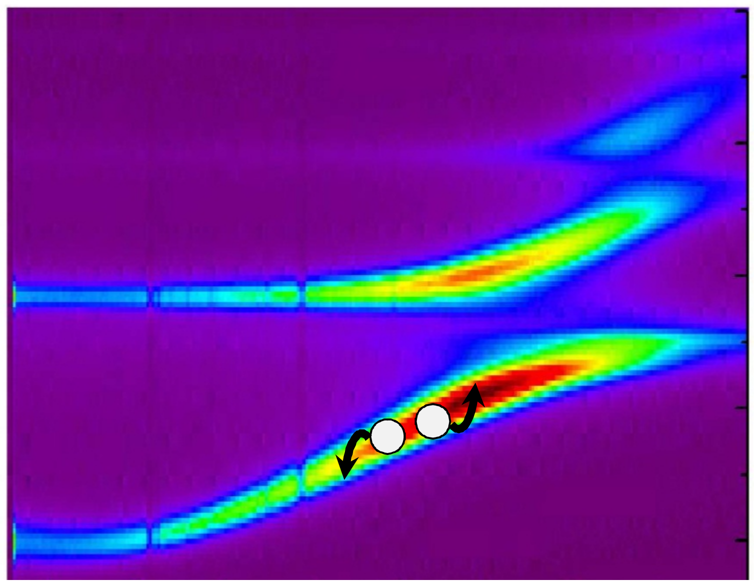
S. Tsintzos *et al.*, *Nature 453, 372* (2008)

Collapse of Strong Coupling Regime at High Densities



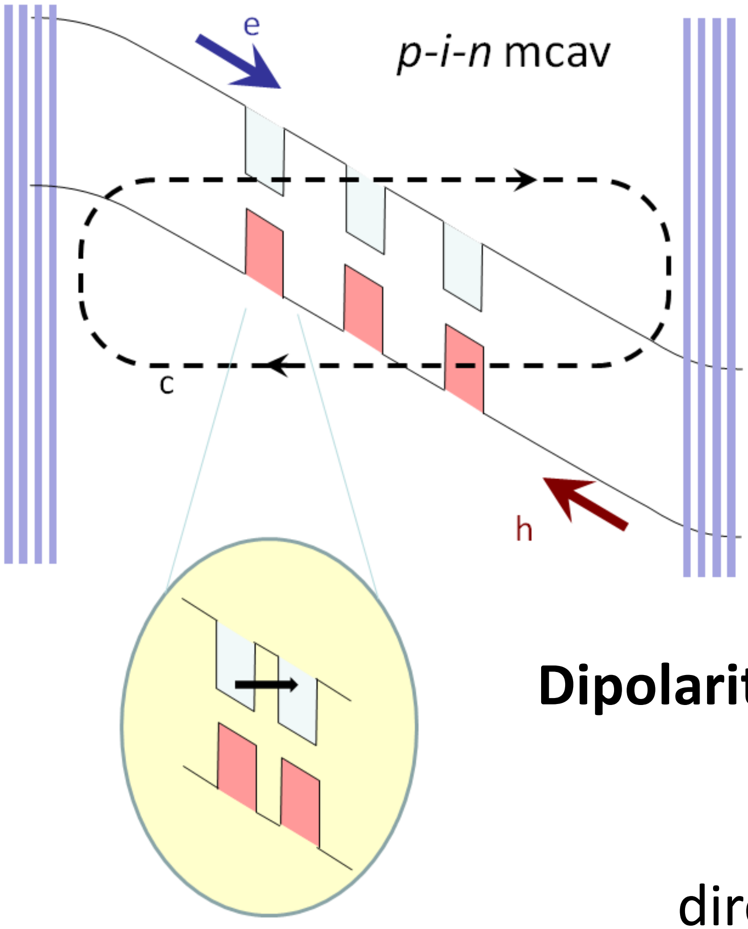


Relaxation on lower branch governed by polariton-polariton interactions (dipole-dipole)



- **Injection density at 22mA ~ 10^{10} pol/cm^2**

Electrically pumped polariton lasers



new challenges:

- strong coupling in high finesse doped microcavities structures

- injection bypassing relaxation bottleneck

- control of polariton dispersions and scatterings

Dipolariton approach: weakly-coupled double quantum wells

⬇

direct control of polariton dipole

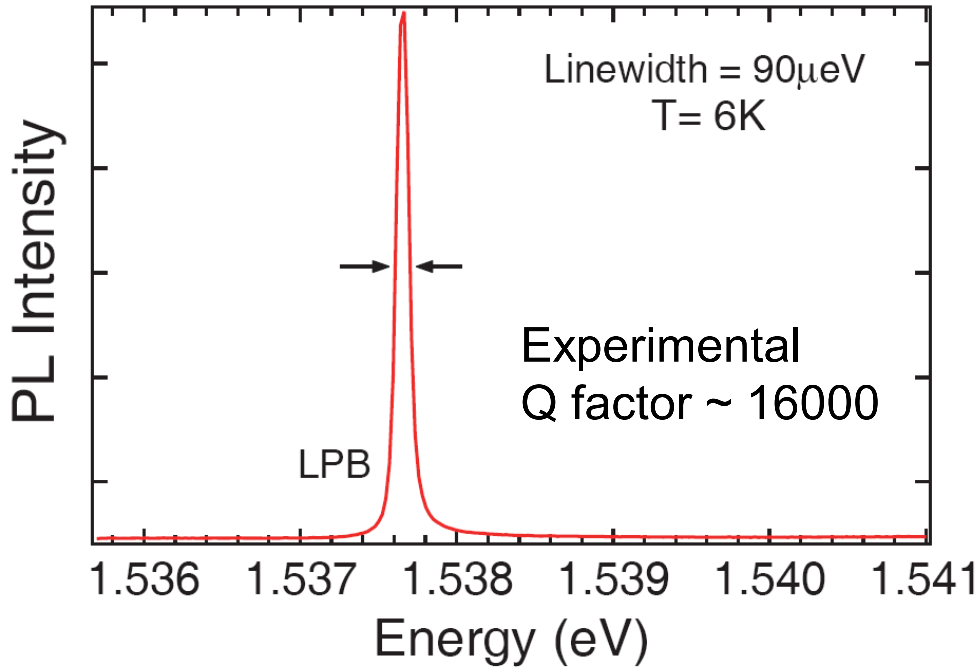
$$H_{PP}^{eff} = \frac{1}{2} \sum_{k,k',q} \frac{a_B^2}{A} V_{k,k',q}^{PP} \hat{p}_{k+q}^{+} \hat{p}_{k'-q}^{+} \hat{p}_{k} \hat{p}_{k'}$$

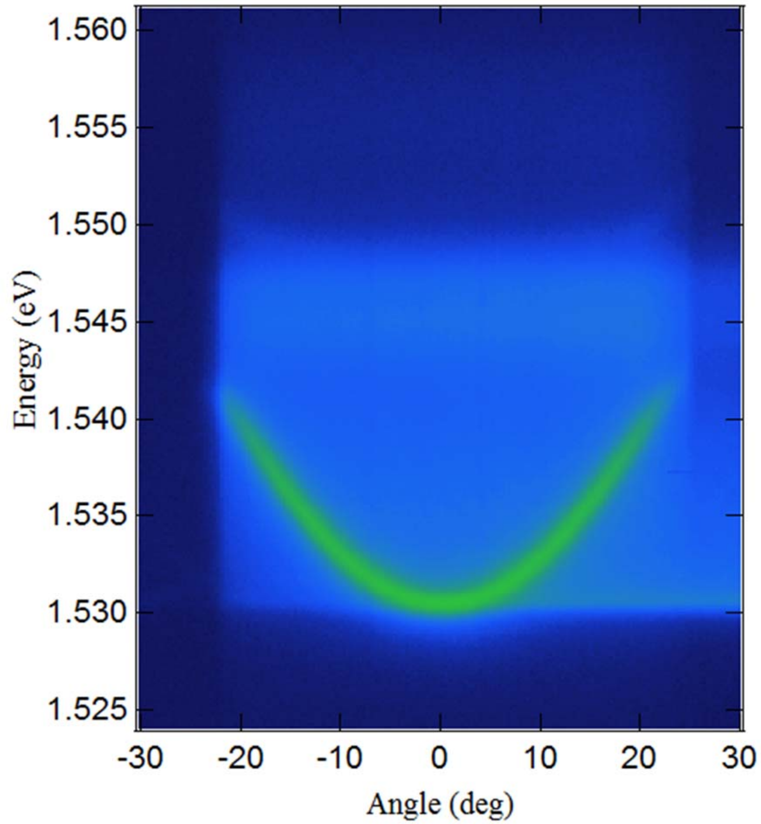
dipole-dipole

P. Cristofolini *et al.,* Science 336, 704 (2012)   G. Christmann APL 98, 081111 (2011)

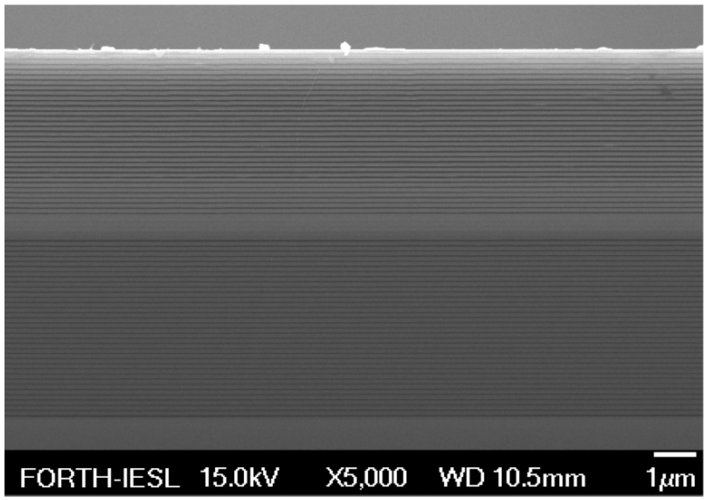
Temperature Dependence of Lasing Threshold in high finesse GaAs microcavities

High finesse GaAs microcavity

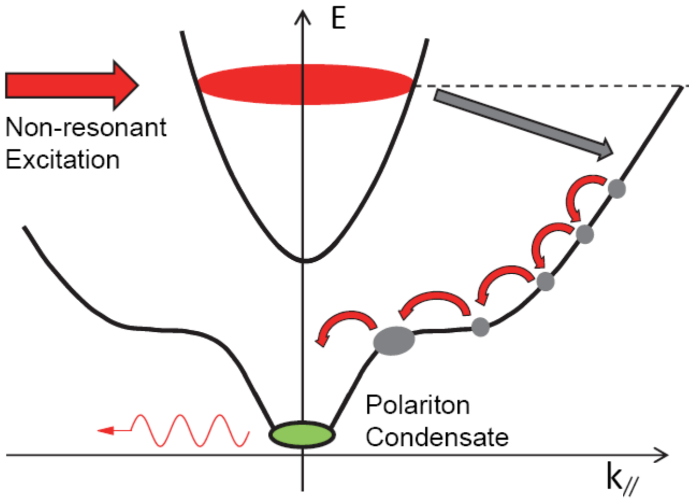


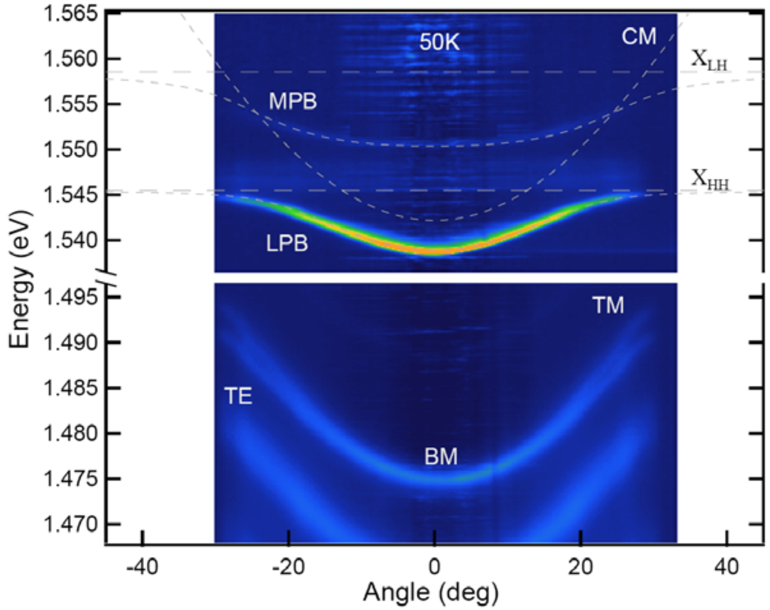


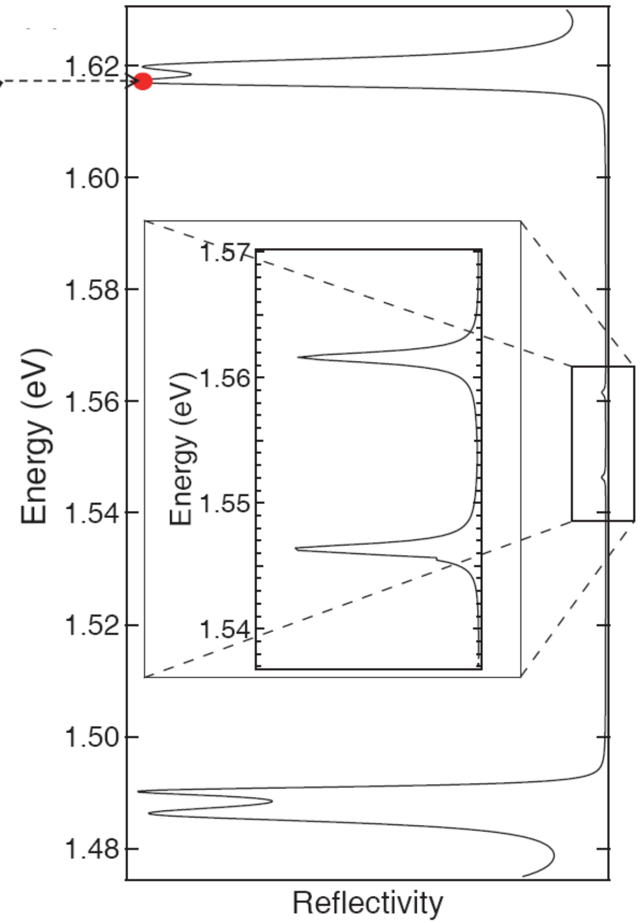
Modeled Q factor ~ 20000



Non-resonant optical excitation

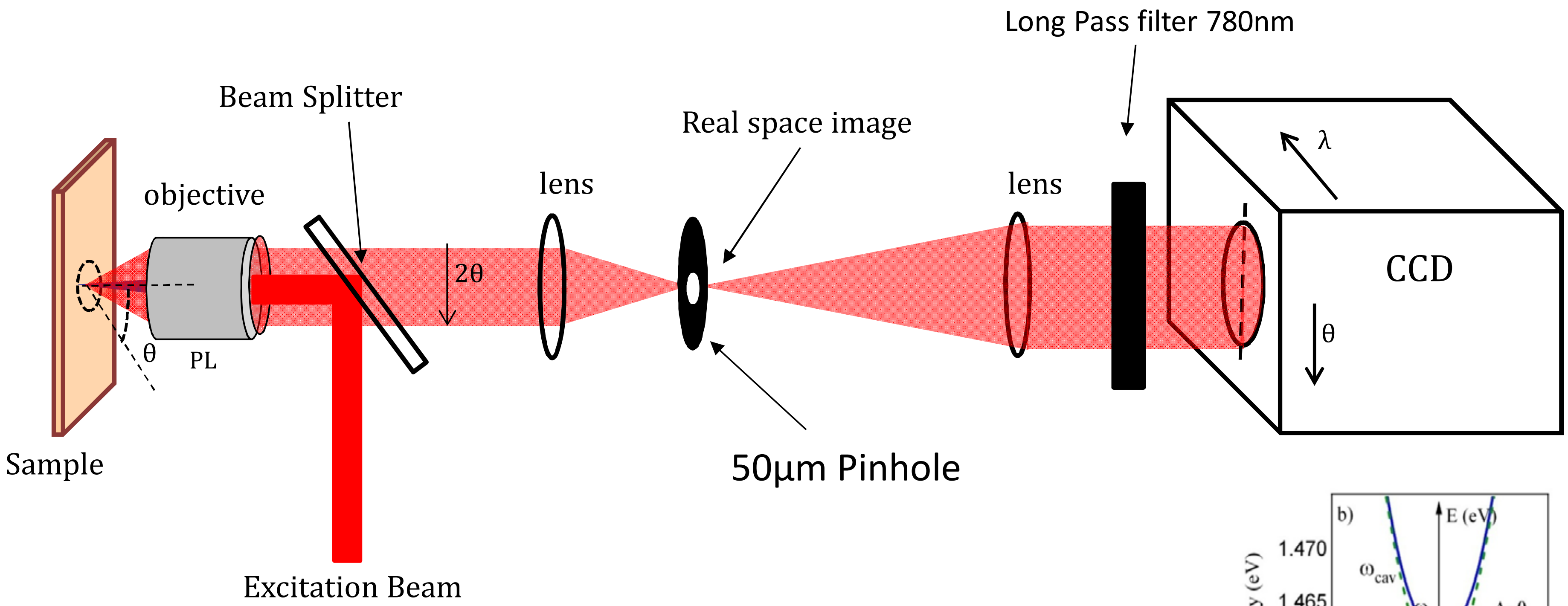


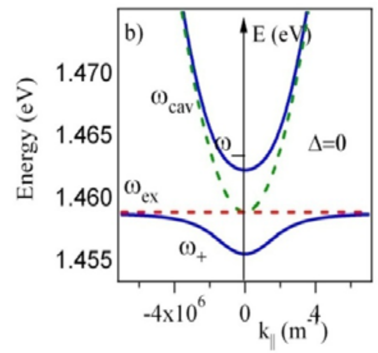




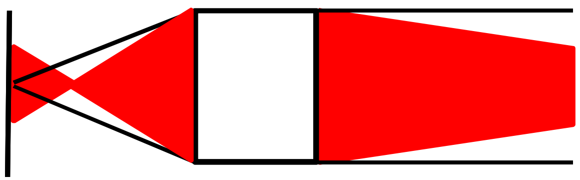
- Rabi splitting of 9.2meV at 50K
- Reflectivity dips relatively small

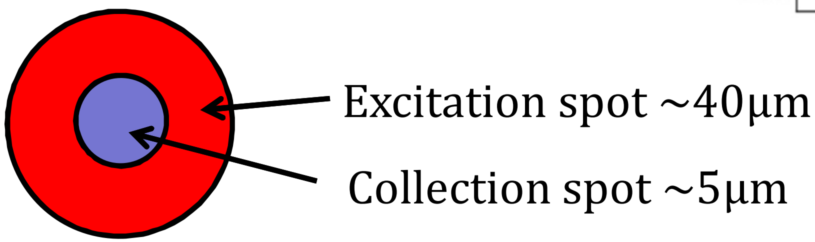
PL imaging Setup





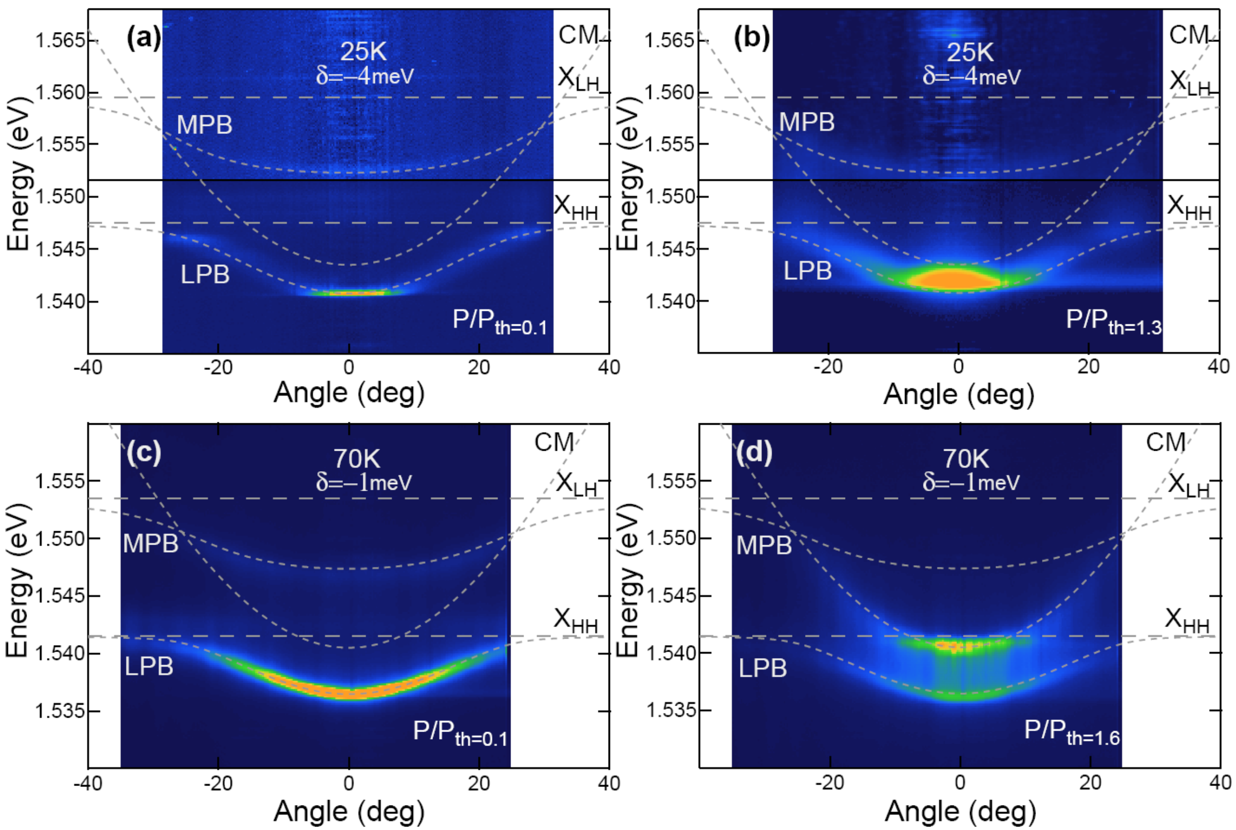
Collection of light from a very small part of excited area

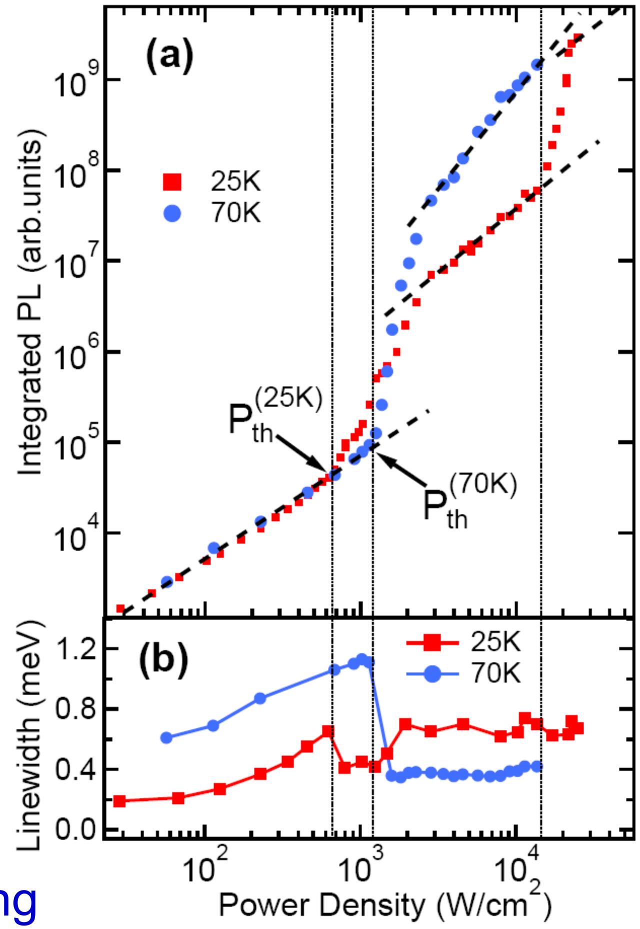




GaAs Polariton Laser 25K vs 70K

- Nonresonant optical pumping above stopband





- Lowest Threshold at 25K ~ 6.5mW strong coupling
  at 70K ~ 13mW weak coupling
- Lasing threshold only **doubles** between polariton laser at 25K and photon laser at 70K

Rabi Splitting vs Density

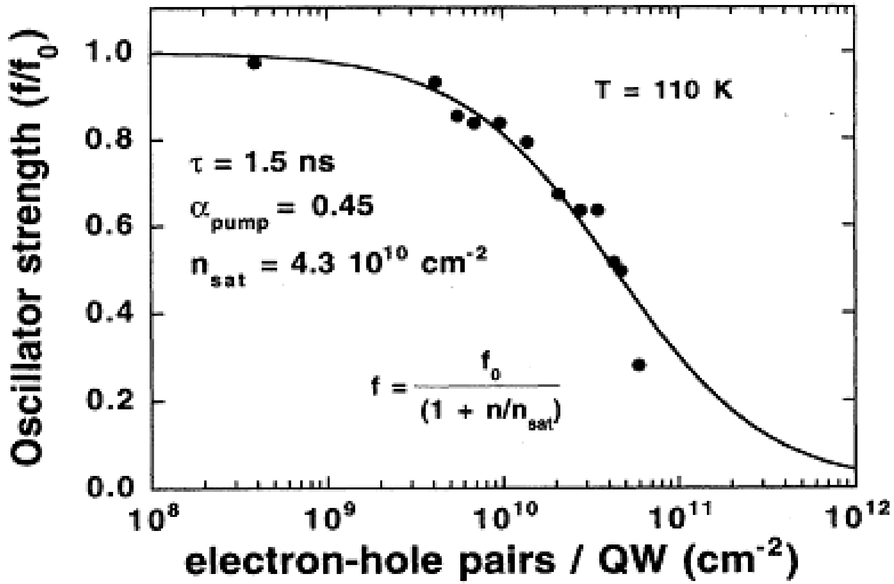
$$\Omega = \sqrt{4V^2 - (\gamma_X - \gamma_C)^2}$$

f : exciton oscillator strength
n : carrier density
n_{sat}: saturation density

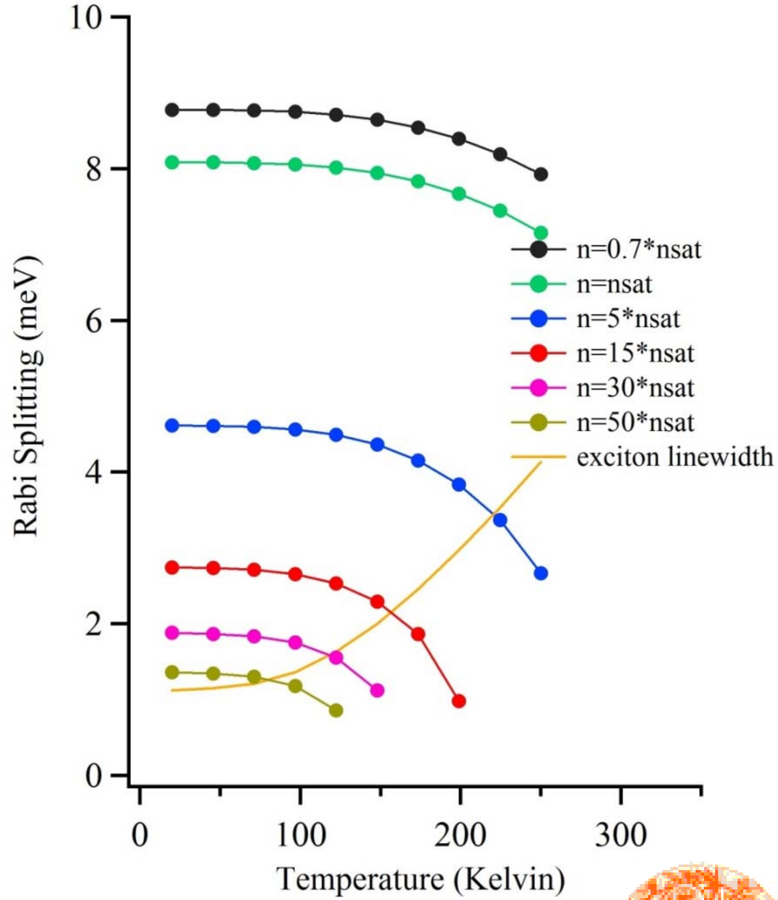
$$\hbar V = \hbar\sqrt{\frac{1+\sqrt{R}}{\sqrt{R}}\frac{c\Gamma_0}{n_{cav}L_{eff}}}$$

$$f = \frac{f_0}{1+\frac{n}{n_{sat}}}$$

$$\Gamma_0 = \frac{e^2}{4\varepsilon_0 n_{cav} m_0 c}\frac{f}{S}$$



(PRB , M. Ilegems)



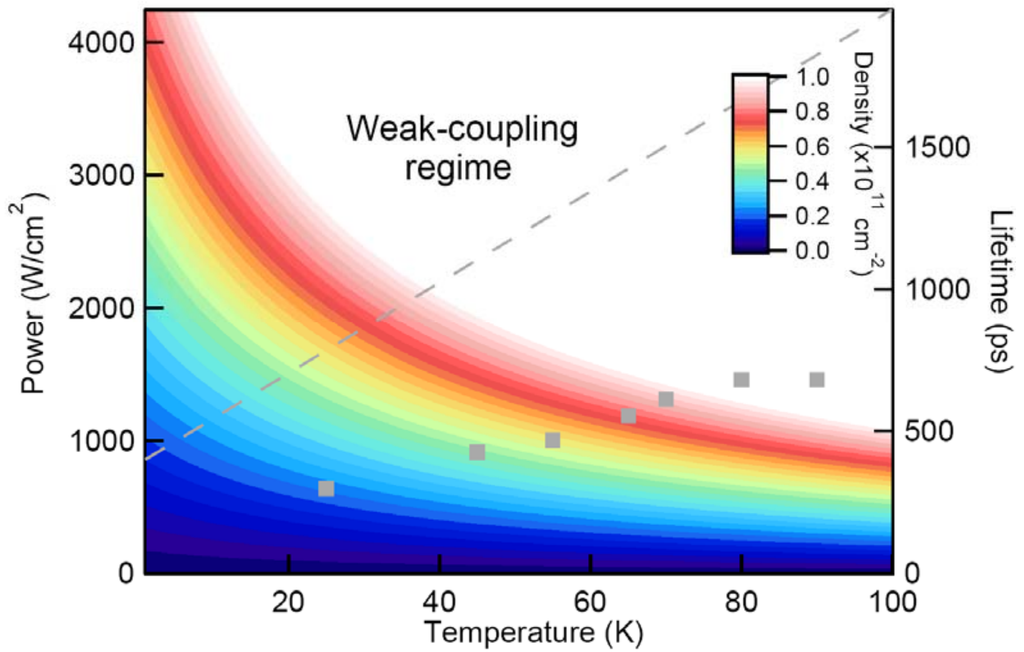
Crossover from Strong to Weak coupling Lasing

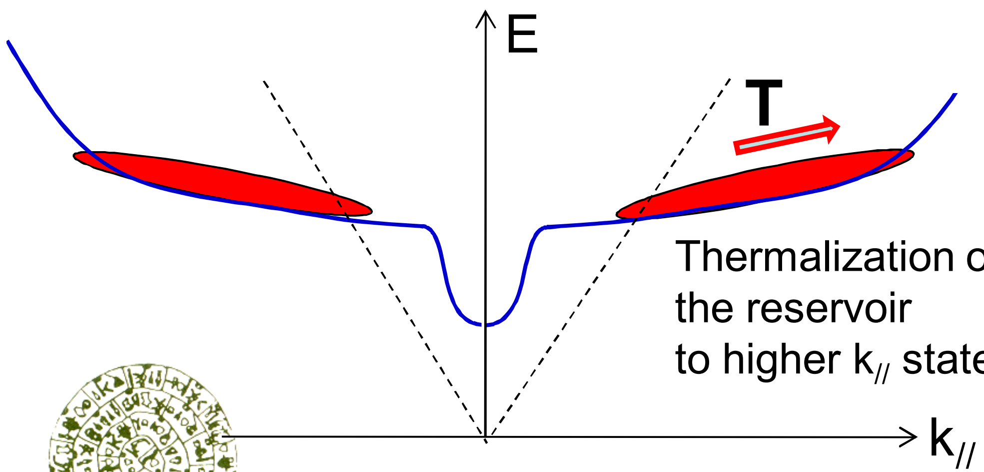
$$\frac{dN}{dt} = g - \frac{N}{\tau} \Rightarrow N = g \cdot \tau \quad \text{(steady state)}$$

↑ pump

Exciton lifetime τ increases with temperature (PRB M.Gurioli, V. Savona)

• For same pumping rate carrier density increases dramatically with increasing T





Thermalization of the reservoir to higher $k_{//}$ states

P. Tsotsis et al., New Journal of Physics **14**, 023060 (2012)

Polariton Condensate Transistor Switch

Polariton Condensate Transistor Switch

Motivation: Although photonic circuits have been proposed, a viable optical analogue to an electronic transistor has yet to be identified as switching and operating powers of these devices are typically high

Common perception: In the future, charged carriers have to be replaced by information carriers that do not suffer from scattering, capacitance and resistivity effects

Approach: Polaritons being hybrid photonic and electronic states offer natural bridge between these two systems

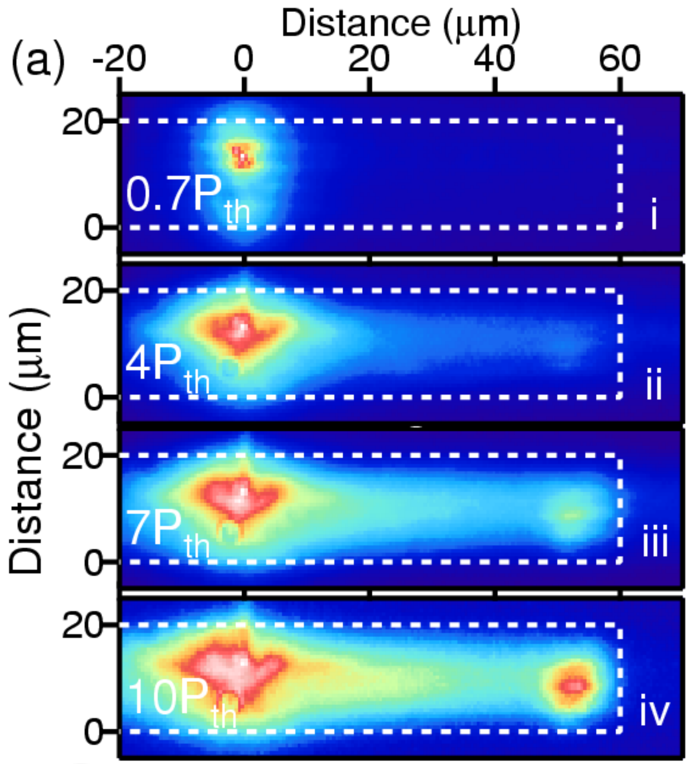
Excitonic component allows them to interact strongly giving rise to the nonlinear functionality enjoyed by electrons

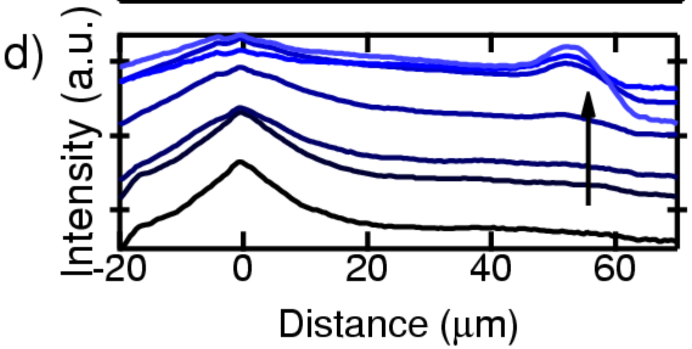
Photonic component restricts their dephasing allowing them to carry information with minimal data loss and high speed

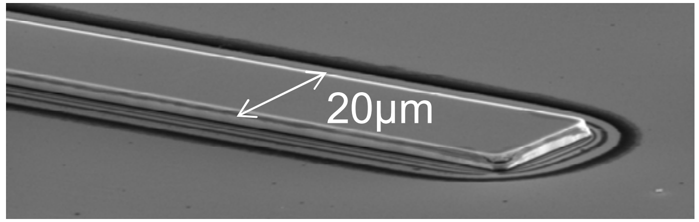
Macroscopic quantum properties of polariton condensates make them ideal candidates for use in quantum information devices and all optical circuits

Gao et al.,PRB 85, 235102 (2012)
D.Ballarini et al. arXiv:1201.4071 (2012)
D.Sanvitto *et al.* Nature Photon. 5, 610 (2011)
E.Wertz *et al.* Nature Phys 6, 860 (2010)

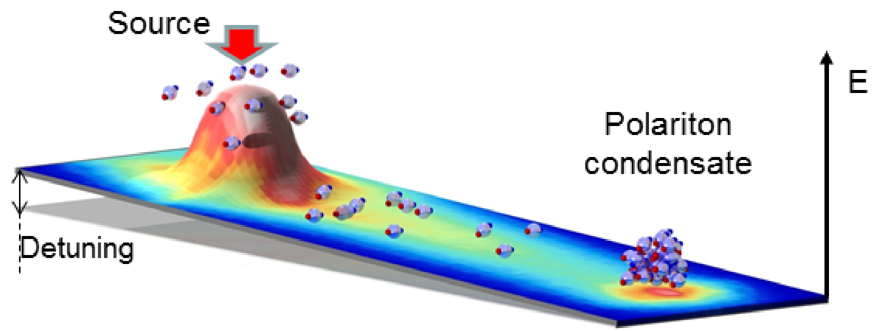
Generating Polariton Condensate Flow



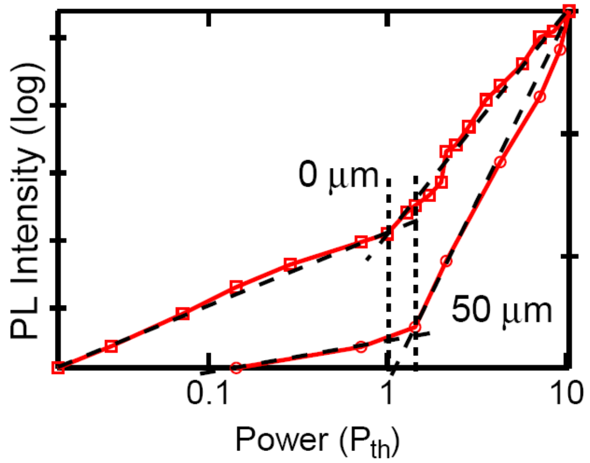




Only top DBR is etched

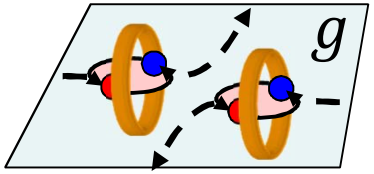


- Polariton condensate forming at the ridge end

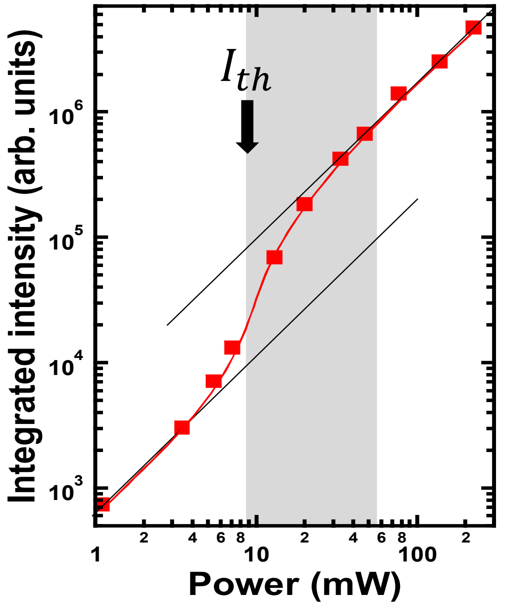


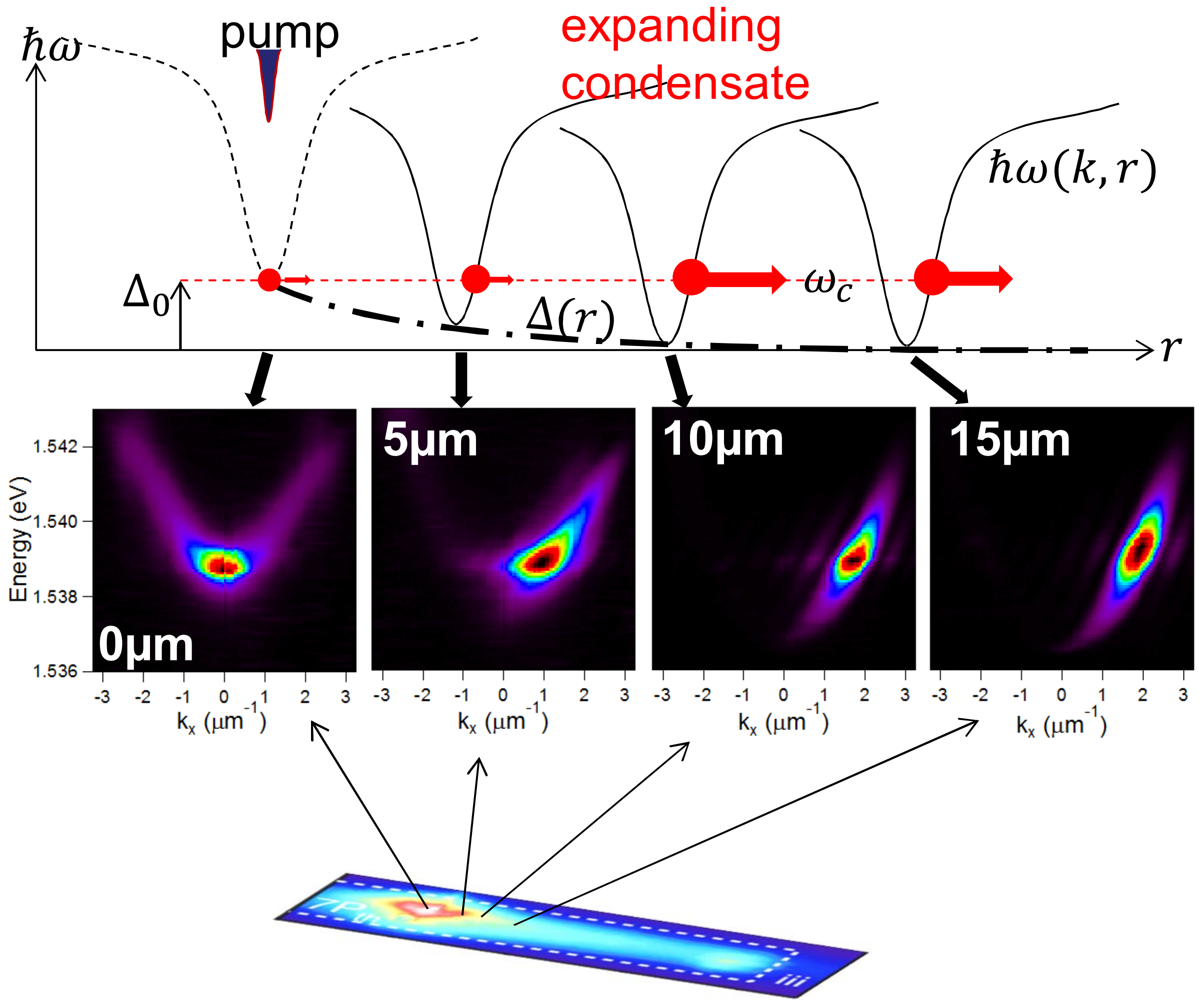
- Local pump induced blueshift and lateral confinement forces polariton flow along the ridge

Ballistic Condensate Ejection



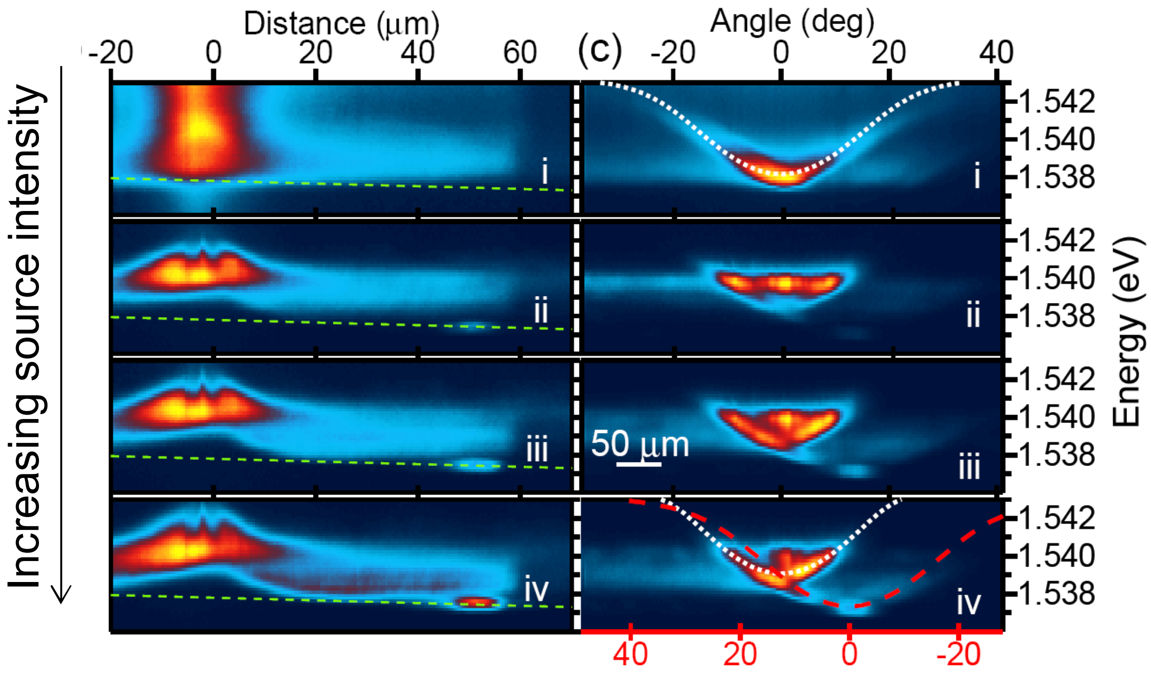
- blue shift at pump
  $V_{max} = g|\psi|^2$
- polaritons expand
  along the ridge



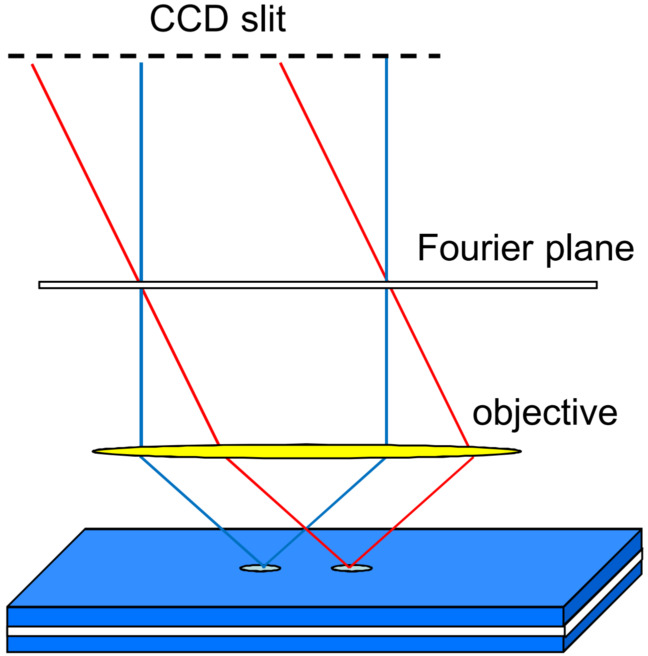


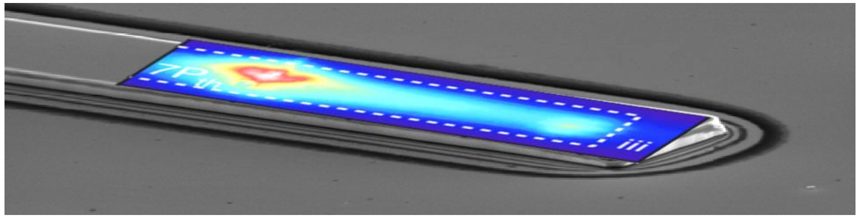
G. Christmann *et al.*, Phys. Rev. B 85, 235303 (2012)

Polariton Condensate Built-up



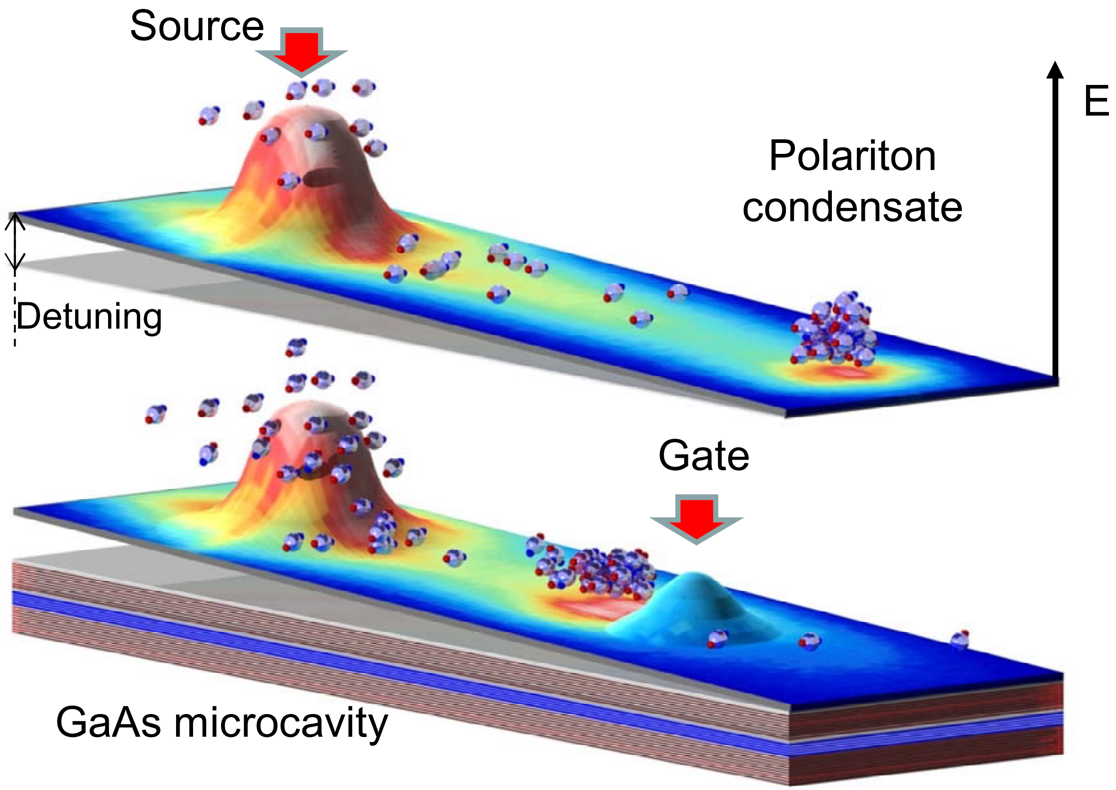
- spatially separated and angle resolved emission





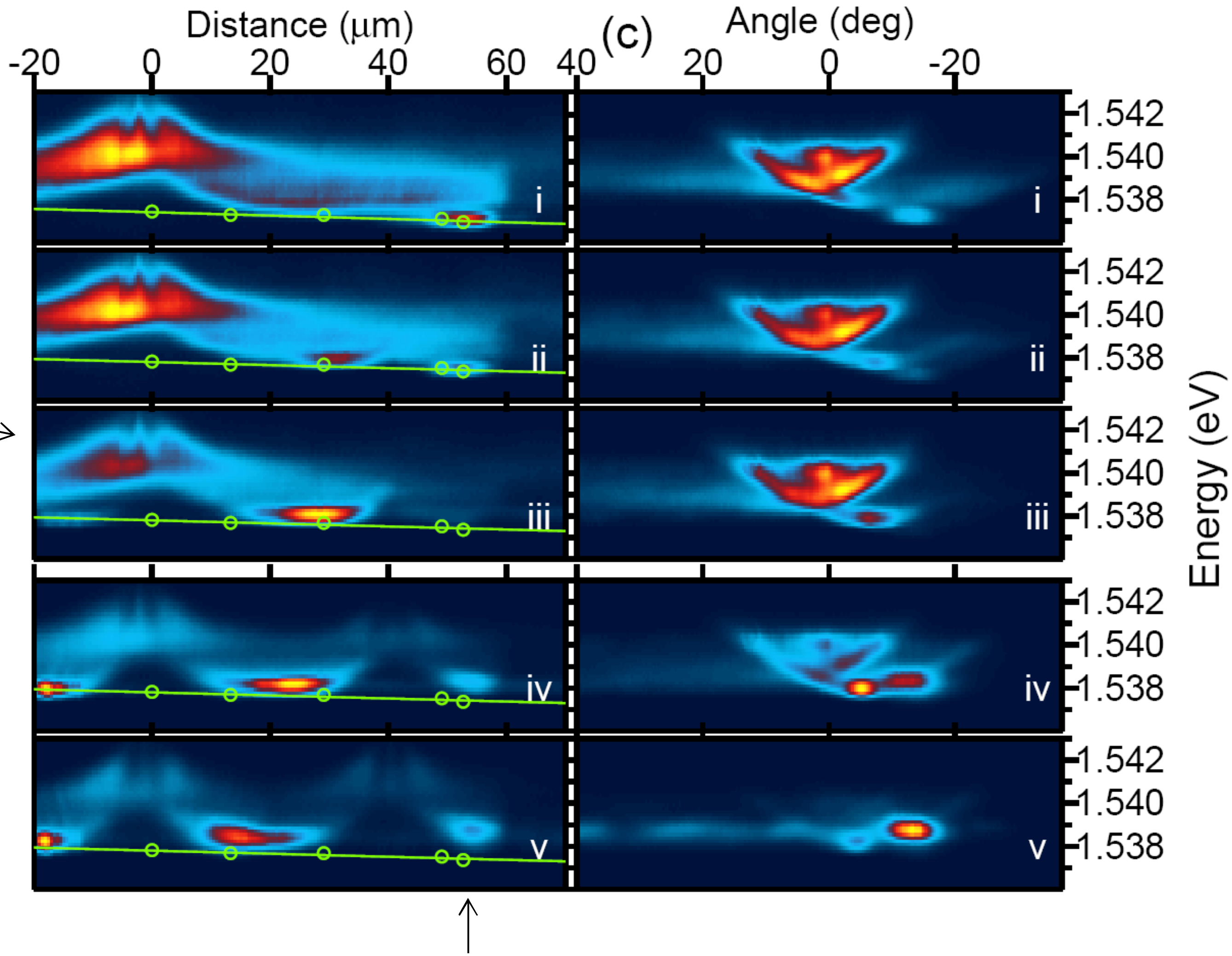
- Ballistic transport of polaritons
- Polaritons flow and relax in the direction of negative detuning
- Condensate forming at the ridge end

Polariton Condensate Transistor Switch



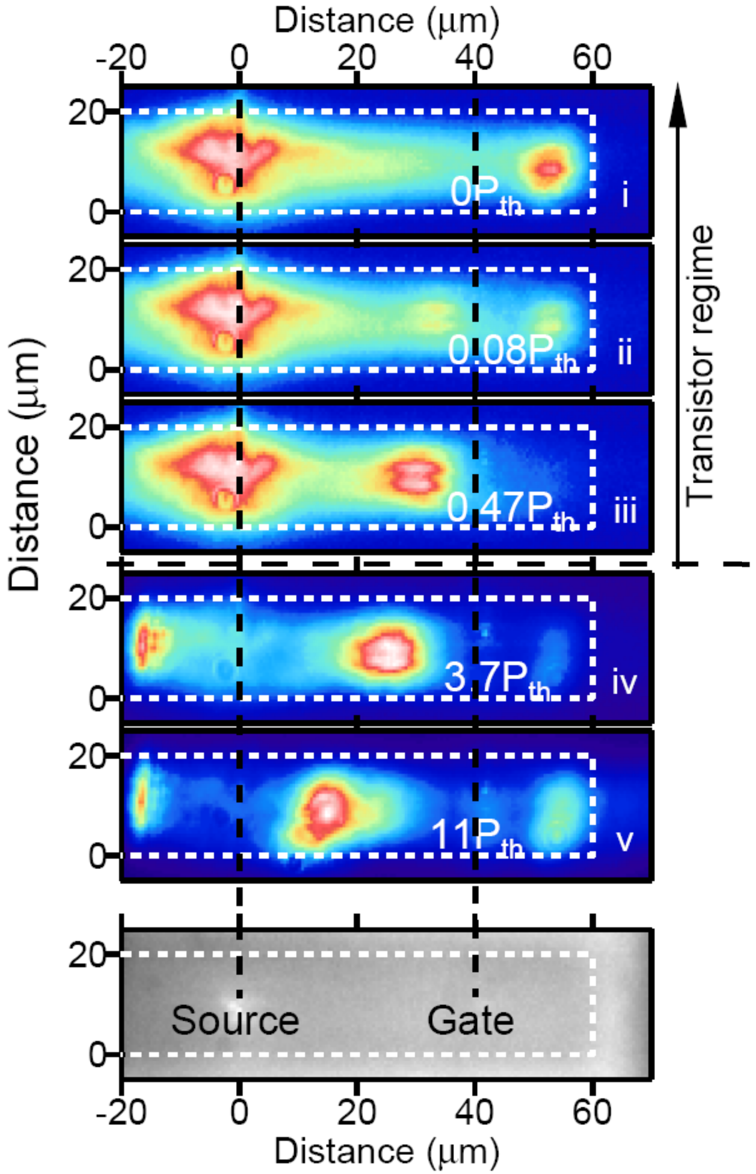
- Polariton propagation is controlled using a second weaker beam that gates the polariton flux by modifying the energy landscape

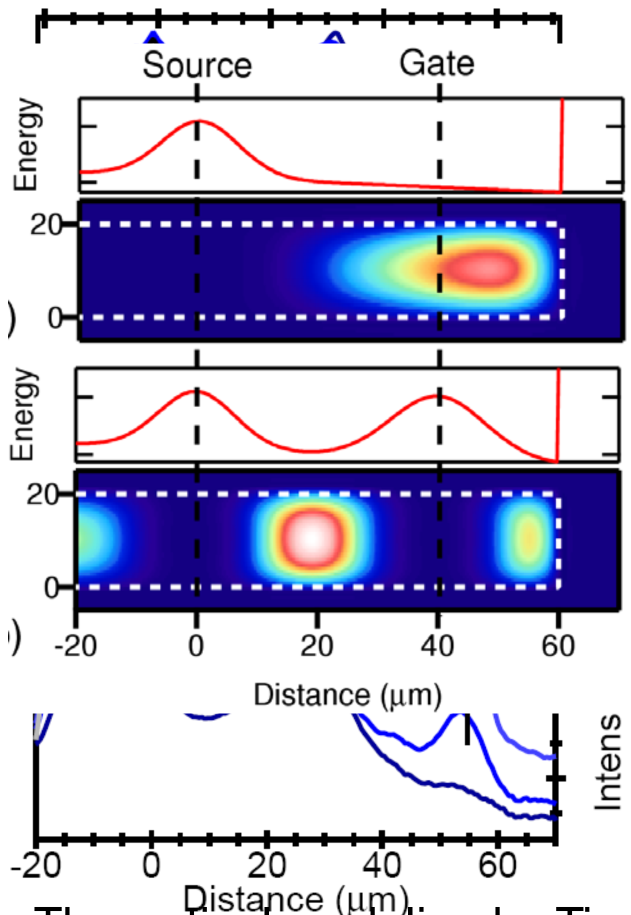
Gating Polariton Condensate Flow



- Gate beam power 20 times weaker than source
- Second condensate appears between source and gate at higher gate powers
- At higher powers gate re-pumps the condensate at the ridge end

Gating Polariton Condensate Flow





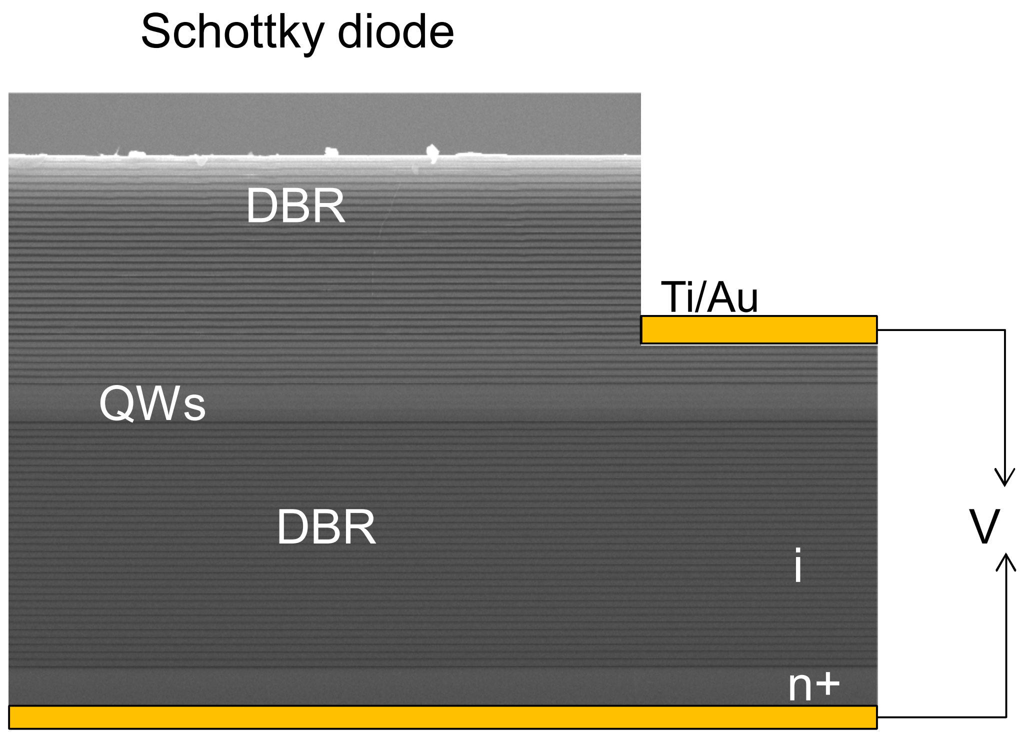
Theoretical modeling by Tim Liew

- gating efficiency up to 90% is demonstrated

Electrical and optical control of polariton condensates

Is electric gating of transistor feasible ?

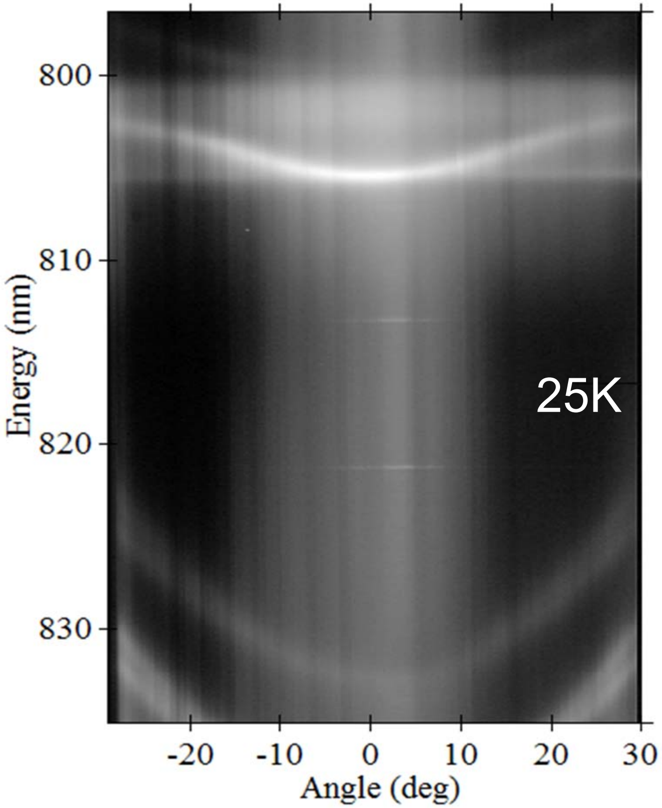
Electrical control of polariton dispersions



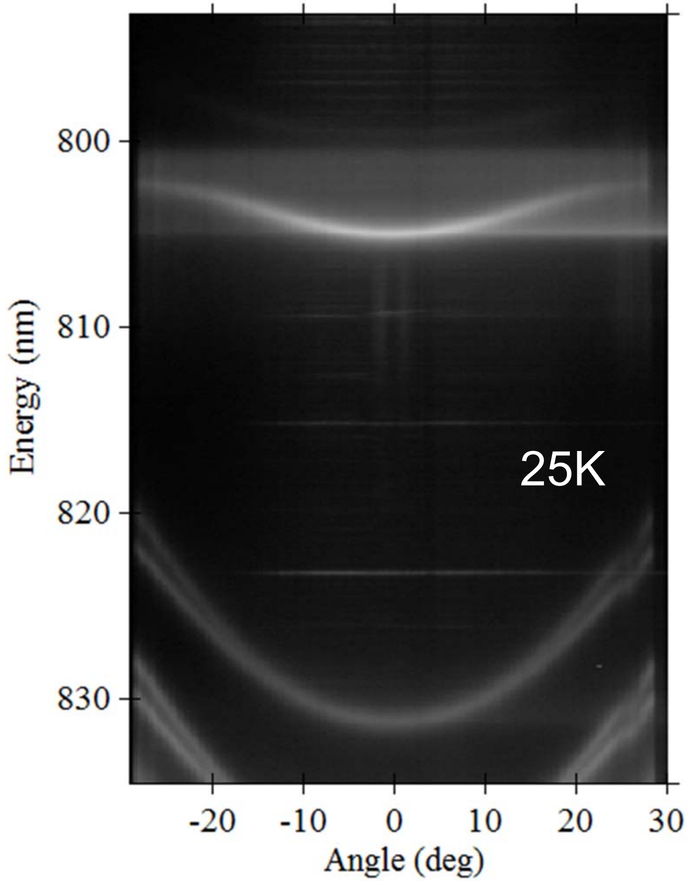
- Application of electric field to the QW tunes the exciton energy through QCSE
- Reduction in exciton oscillator strength & Rabi splitting have to be considered

Electrical control of polariton dispersions

side contact

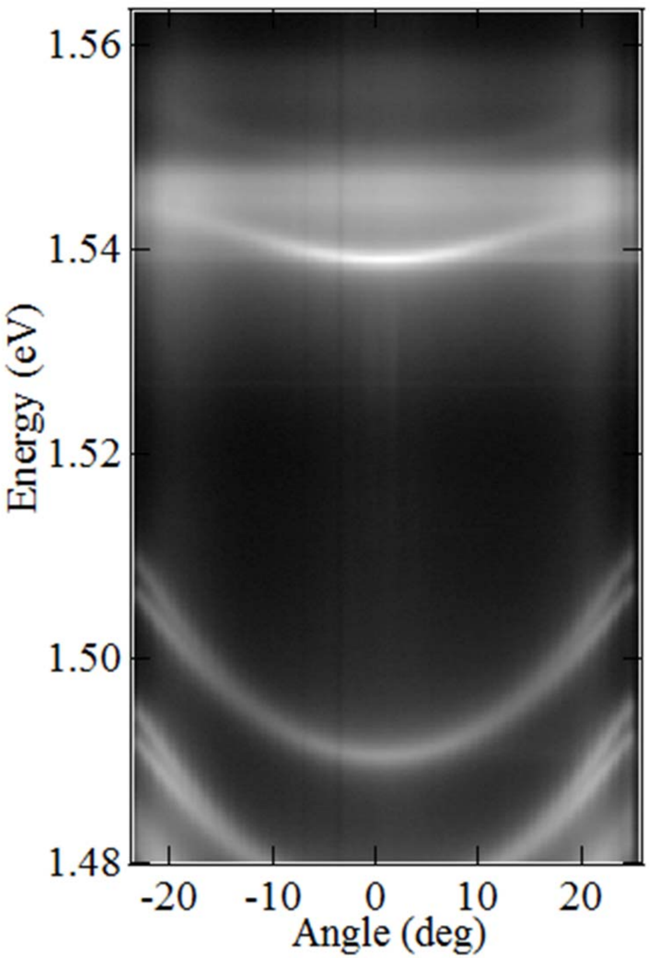


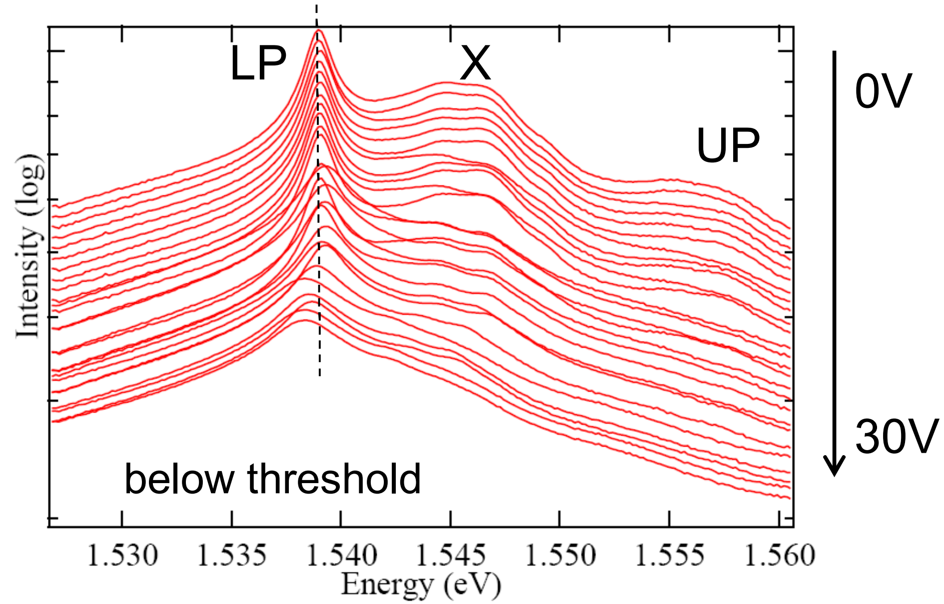
top contact

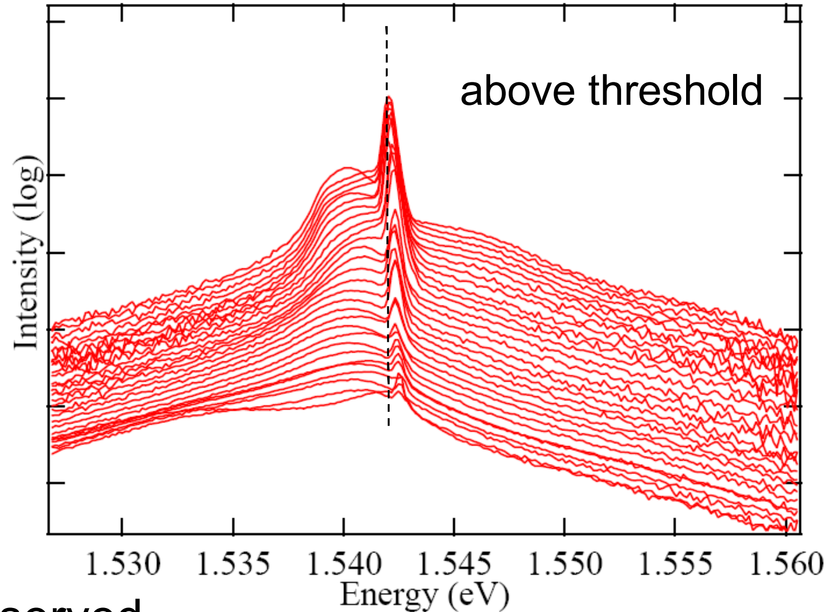


- Clear tuning of the lower polariton branch energy
- Schottky diode allows local spatial field to be applied

Control of polariton dispersions in nonlinear regime

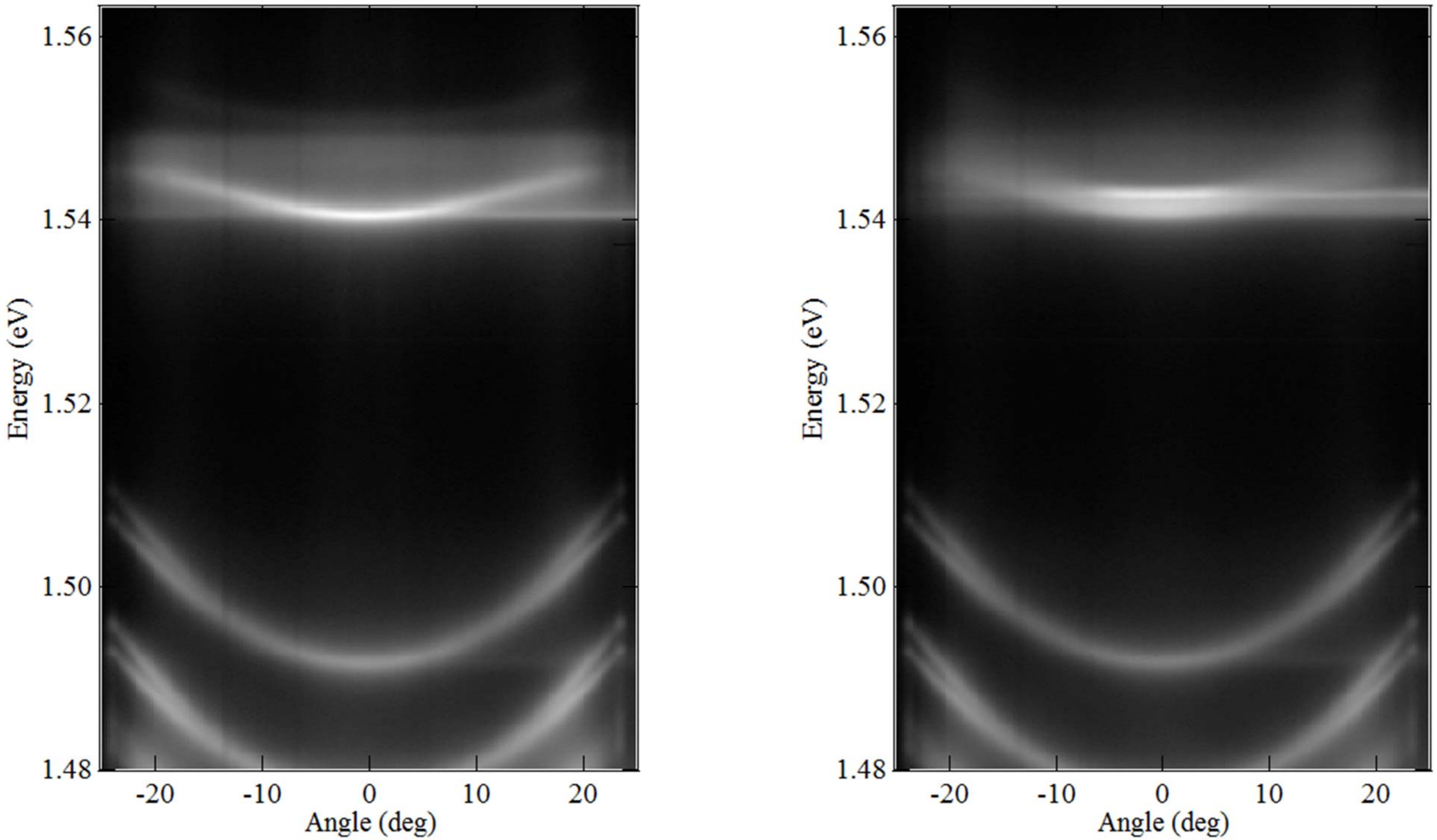






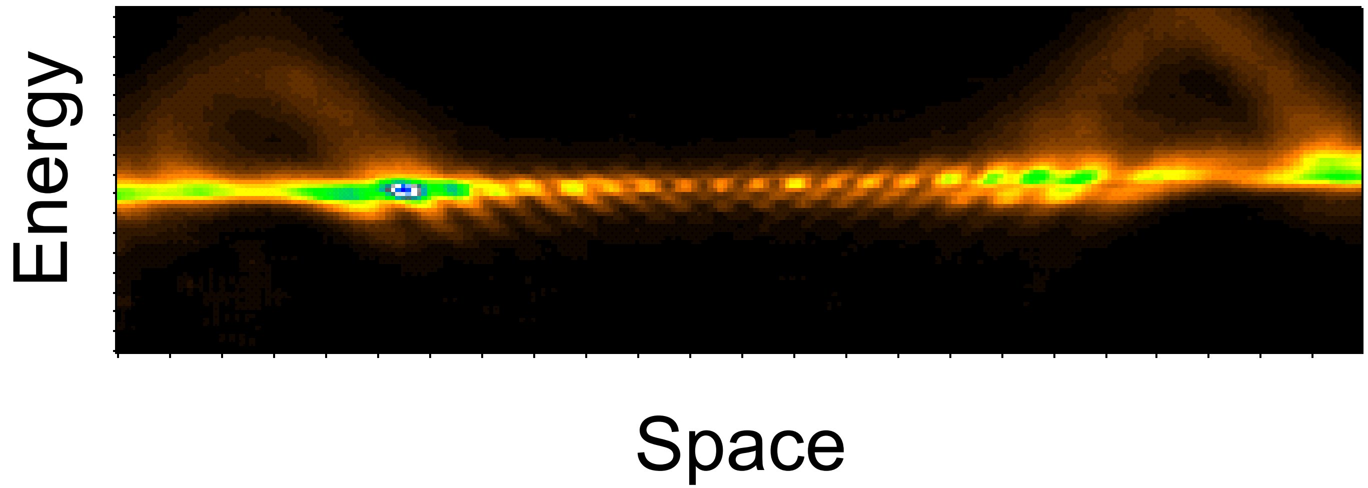
- electric tuning of the lasing energy observed

Control of polariton dispersions in nonlinear regime



Interactions Between Condensates

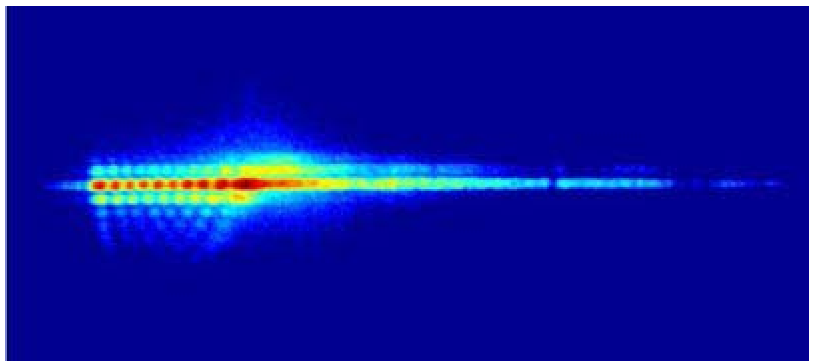
- Can we make two independent condensates interact on a chip?
- What happens if we launch two condensates against each other



LETTERS
PUBLISHED ONLINE: 29 AUGUST 2010 | DOI: 10.1038/NPHYS1750
nature physics

Spontaneous formation and optical manipulation of extended polariton condensates

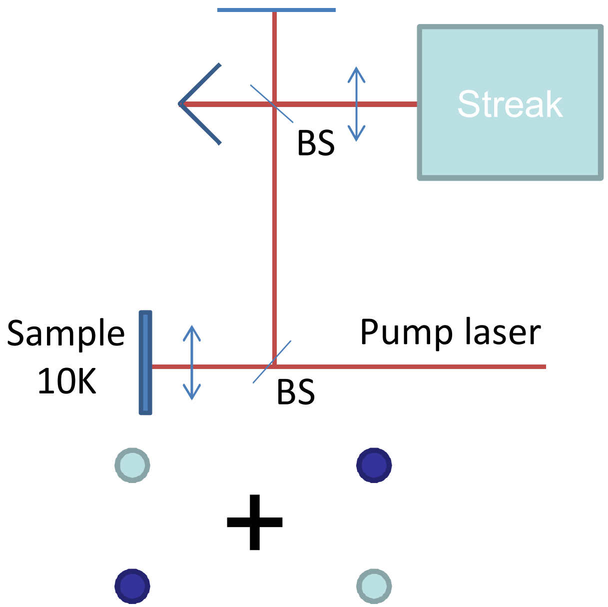
E. Wertz[1], L. Ferrier[1], D. D. Solnyshkov[2], R. Johne[2], D. Sanvitto[3], A. Lemaître[1], I. Sagnes[1], R. Grousson[4], A. V. Kavokin[5], P. Senellart[1], G. Malpuech[2] and J. Bloch[1]*

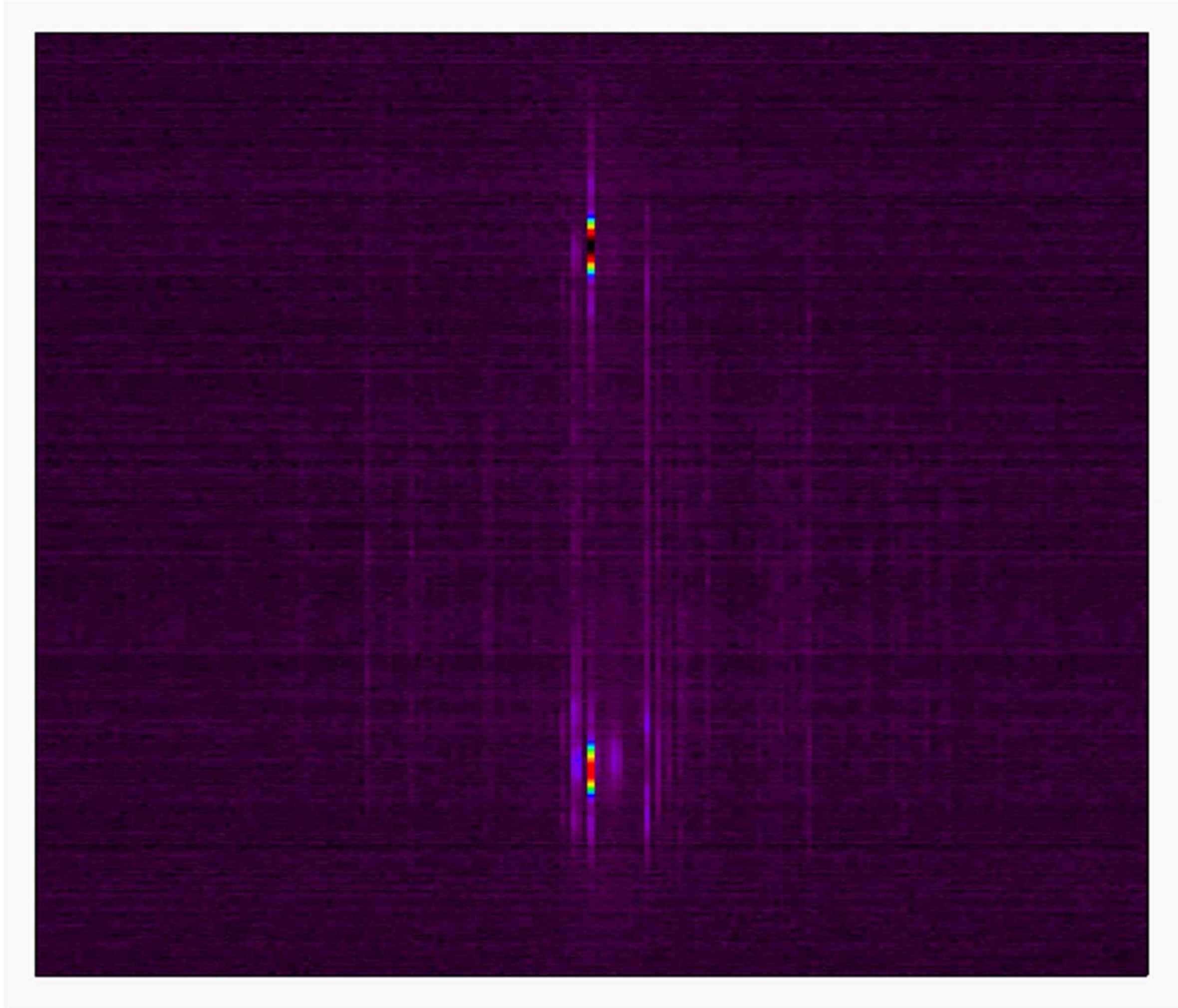


Buildup of Coherence and Phase Locking

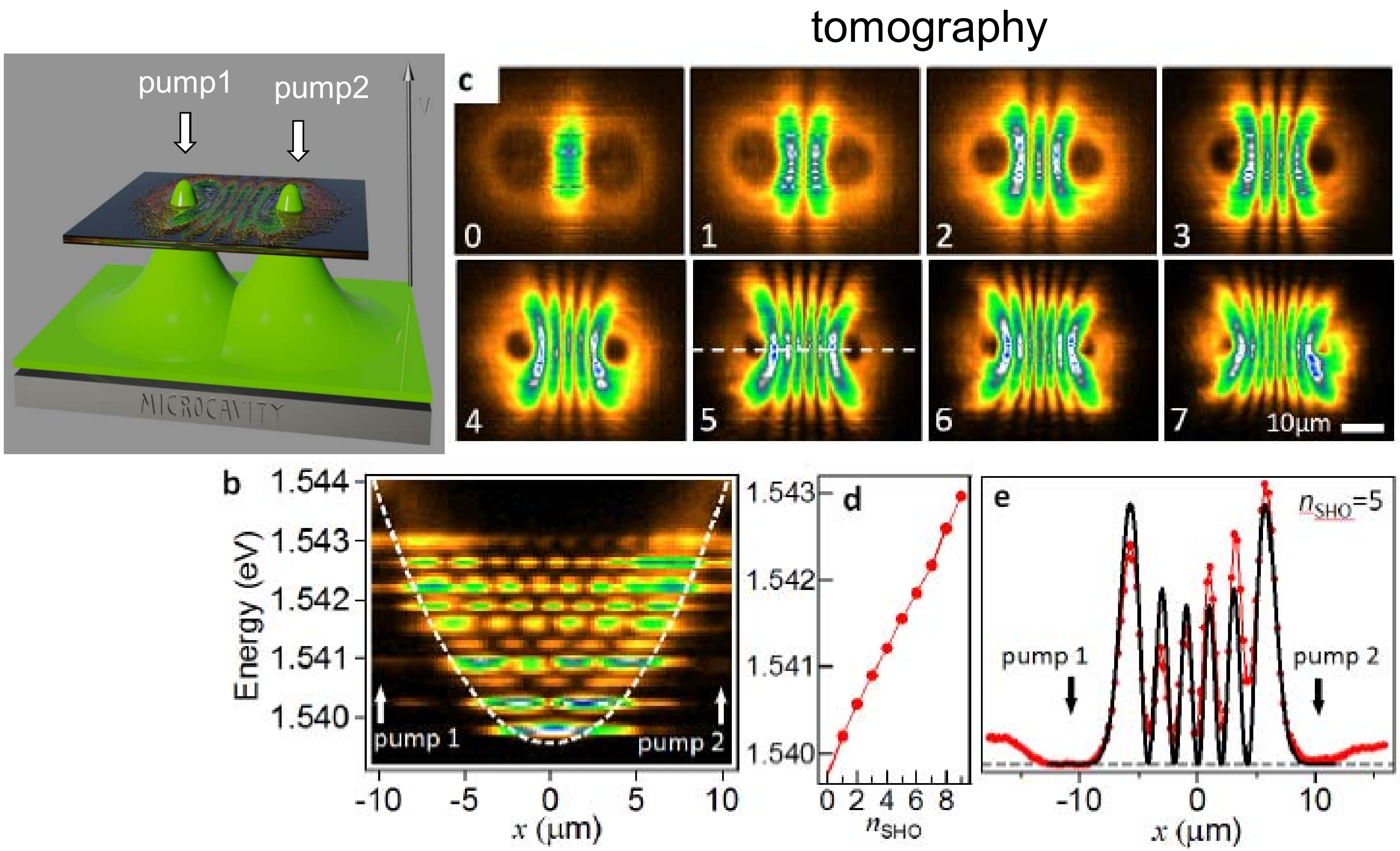
Time resolved measurement & interferometry

Pulsed excitation, interference of one with the other





Polariton condensates in a parabolic optical trap



- equal spaced energies SHO wavefunctions
- harmonic potential - quantum pendulum

G. Tosi et al. Nature Physics 8, 190 (2012)

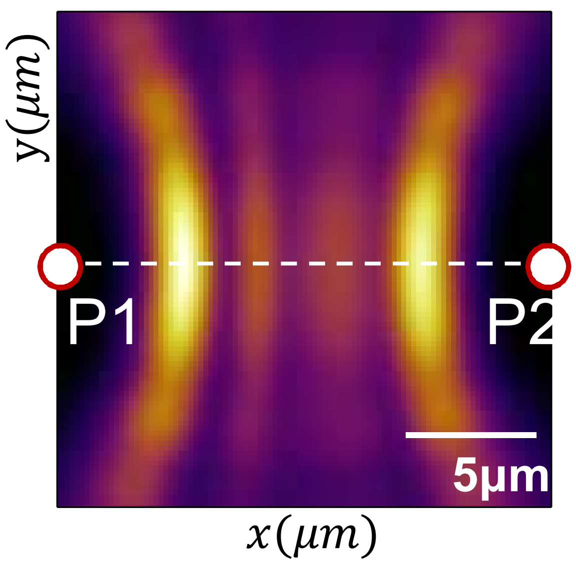
Condensate theory

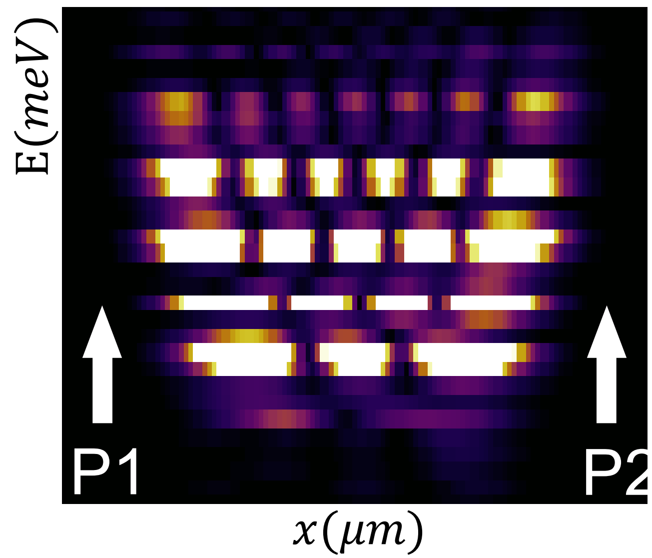
- complex Ginzburg-Landau equation (cGL)

$$i\hbar\partial_t\psi = [E(i\nabla) + \overbrace{g|\psi|^2 + \hbar R_R N(\mathbf{r},t)}^{\text{polariton potential}}]\psi + i[\overbrace{\tfrac{\hbar}{2}R_R N(\mathbf{r},t)}^{\text{reservoir pump}} - \underbrace{i\hbar\eta N\partial_t}_{\text{relaxation}} - \overbrace{\Gamma_C}^{\text{decay}}]\psi$$

- reservoir dynamics

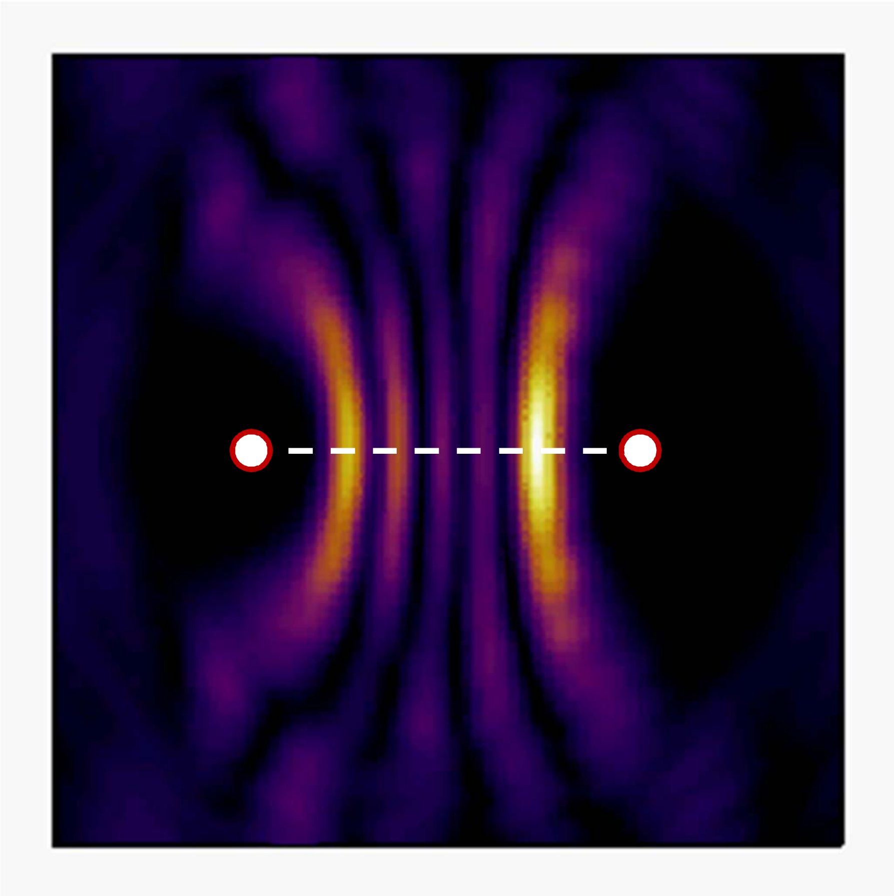
$$\partial_t N(x,t) = -[\underbrace{\Gamma_R}_{\text{decay}} + \overbrace{\beta R_R|\psi(x,t)|^2}^{\text{condensate feed}}]N(x,t) + \underbrace{P(x)}_{\text{laser pump}} + \overbrace{D\nabla^2 N}^{\text{diffusion}}$$

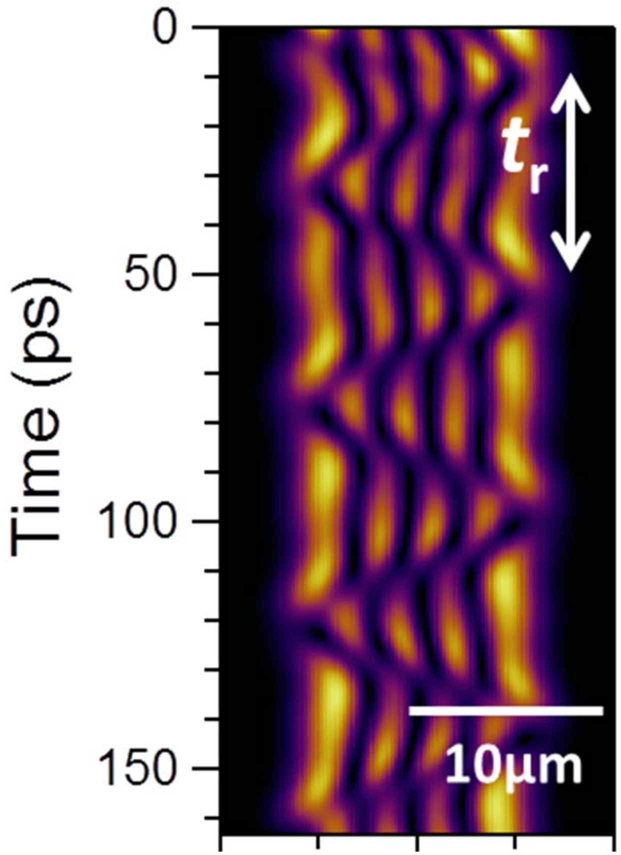




Nature Physics **8**, 190 (2012)

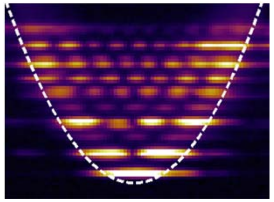
Simulation results



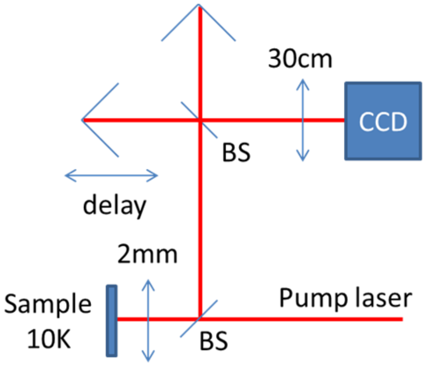


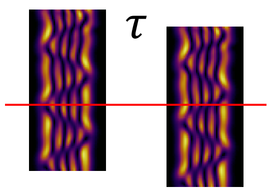
Resembles oscillating dark-solitons

How to measure?



Condensate dynamics





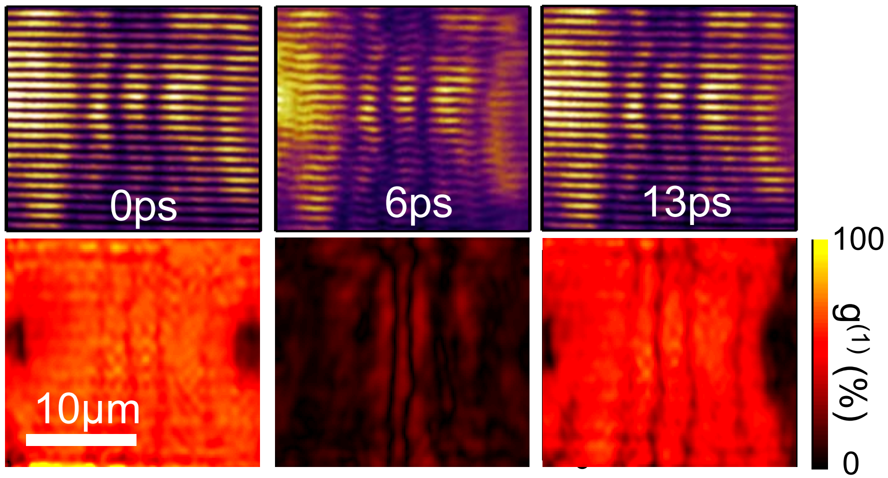
$$t_r = {}^{h}/_{E}$$

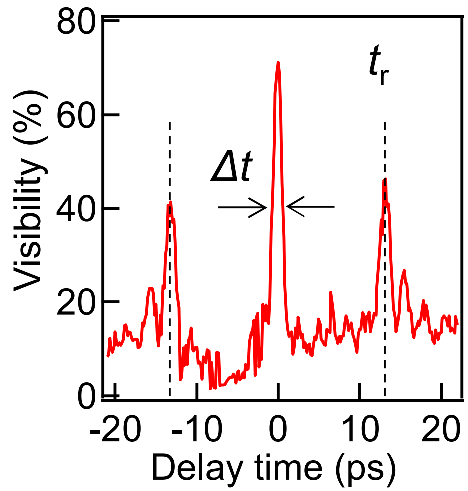
- modelocking condensates

nonlinear optics
cf: ultrafast lasers, supercontinuum generation

fringes

visibility
$g^{(1)}(r,r,t)$

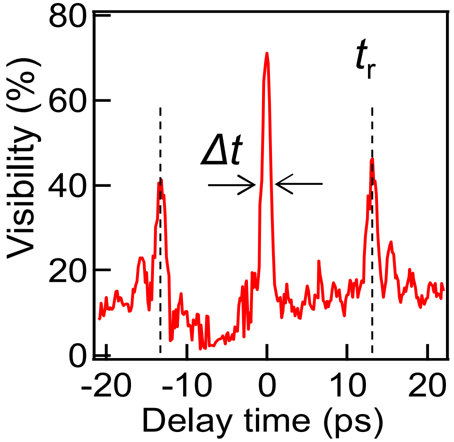




- self-interference every round trip time (exact match)
- all the simple harmonic oscillator levels are phase coherent
- implies **spontaneous** soliton oscillations, not static

Nature Physics **8**, 190–194 (2012)

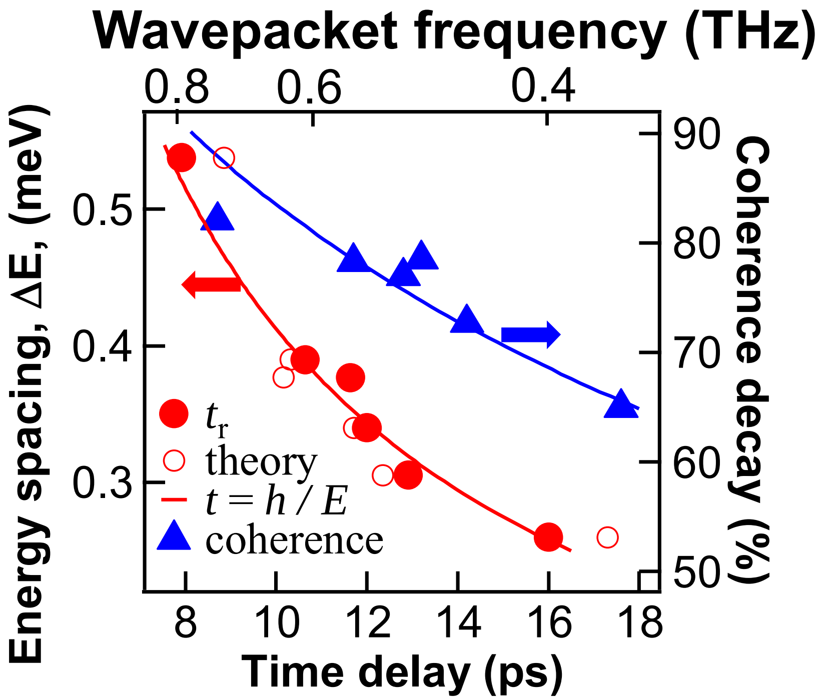
Tuneable oscillator



temporal width $\Delta t \simeq t_r / n_{SHO}$

set by number of SHO states (n_{SHO}=10)

$$t_r = \pi L \sqrt{\frac{m^*}{2(g|\psi|^2 + \hbar R_R N)}}$$



wavepacket revival is not perfect
decays over 40ps

due to coherent wavepacket

- dispersion (SHO spacings)
- decay
- dephasing
- diffusion

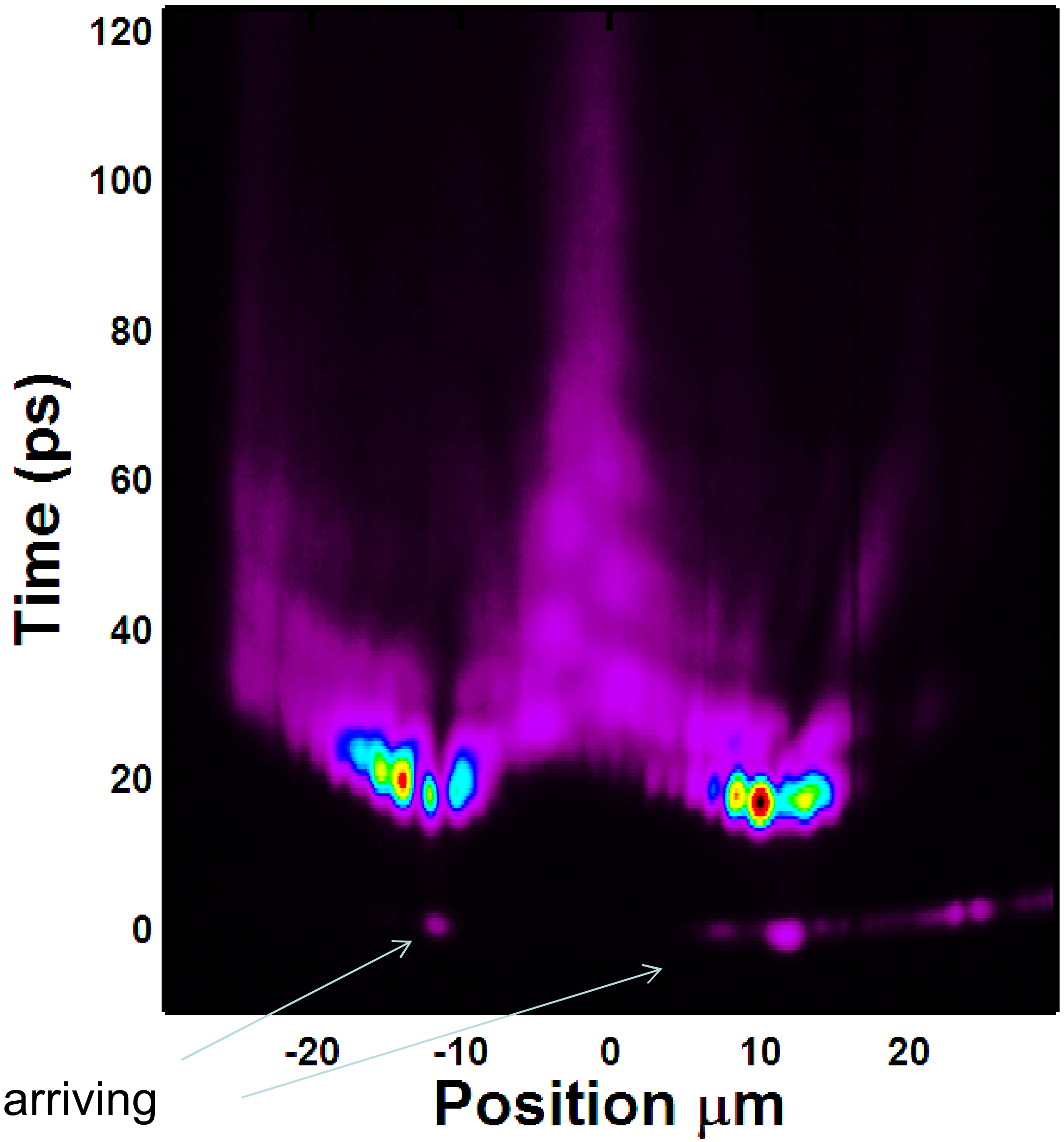
Polariton Quantum Pendulum

Oscillations observed under pulsed excitation regime

2 spots separated by 25 microns

Streak camera measurement

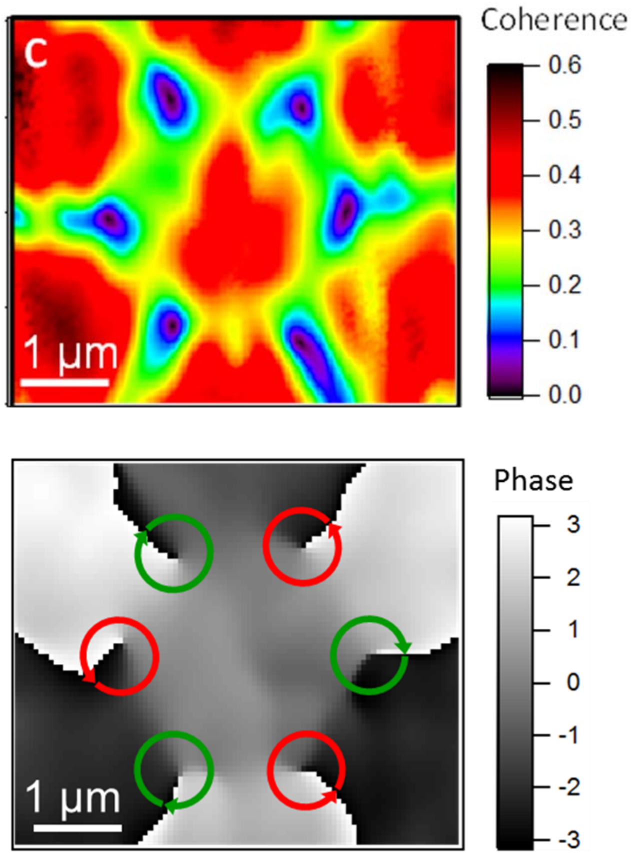
Increasing pump power

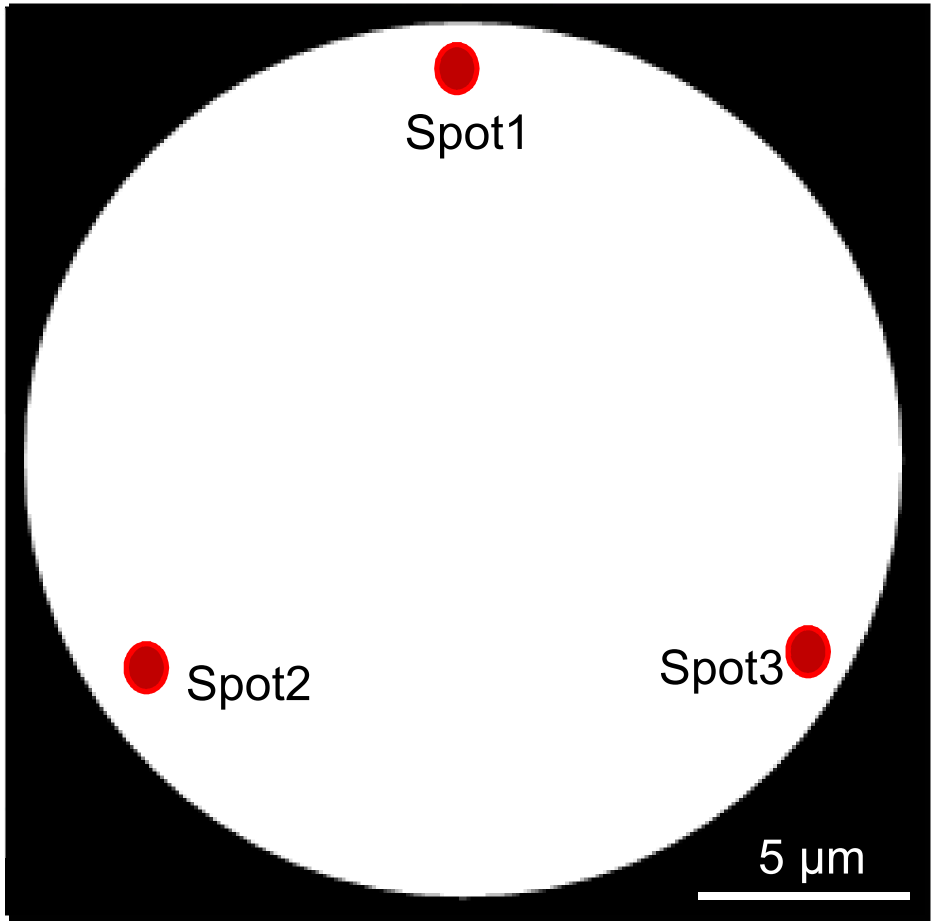


Multiple spot excitation

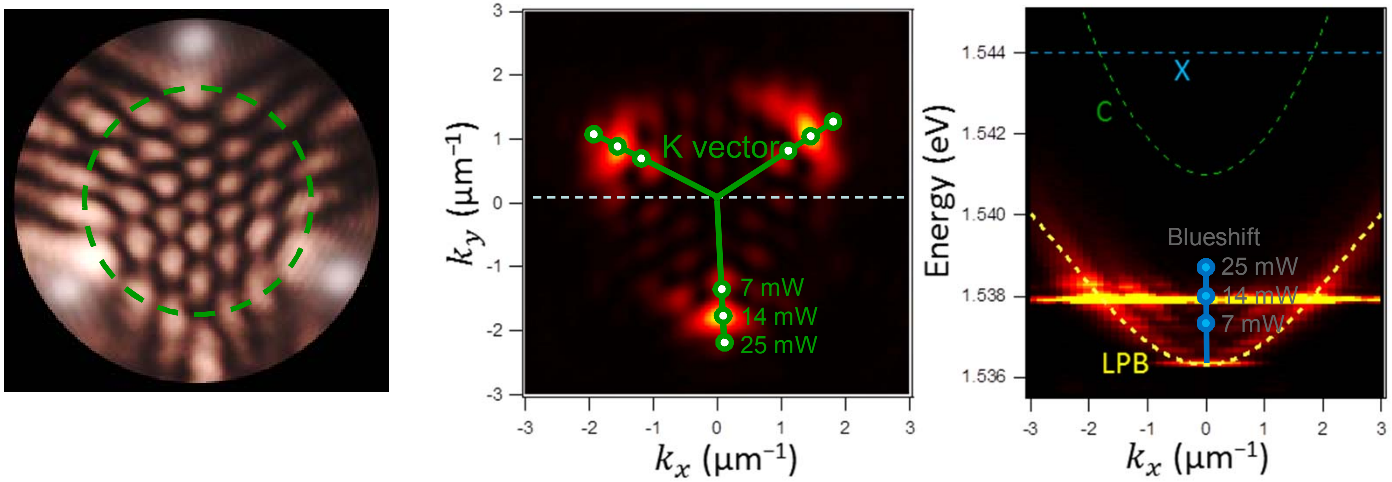
Vortex lattices

- honeycomb lattice of up to 100 vortices and anti-vortices

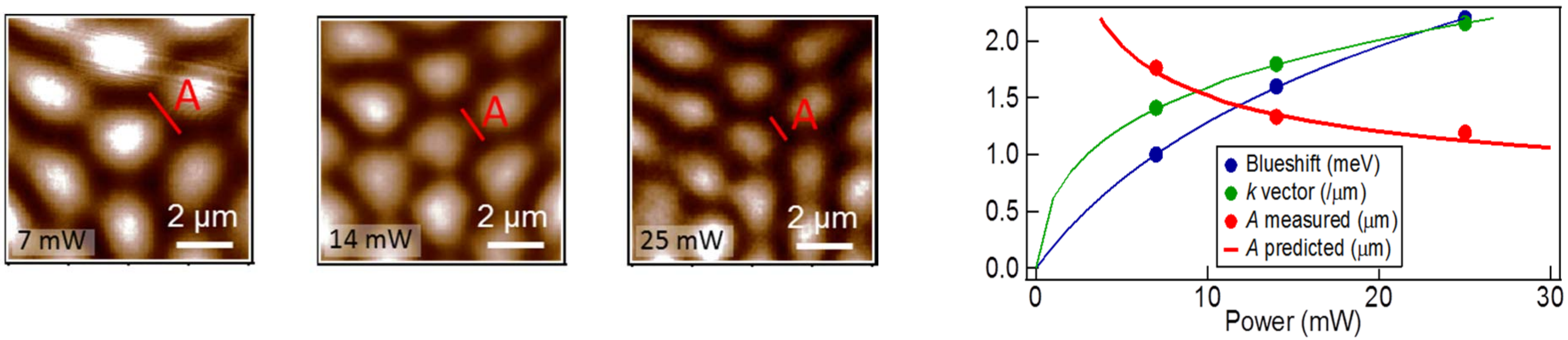




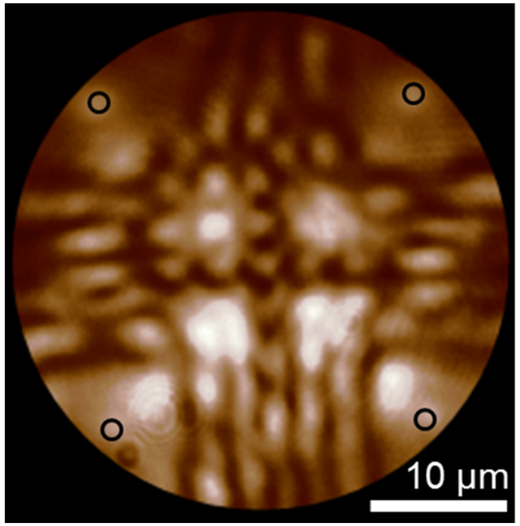
Stretching the lattice



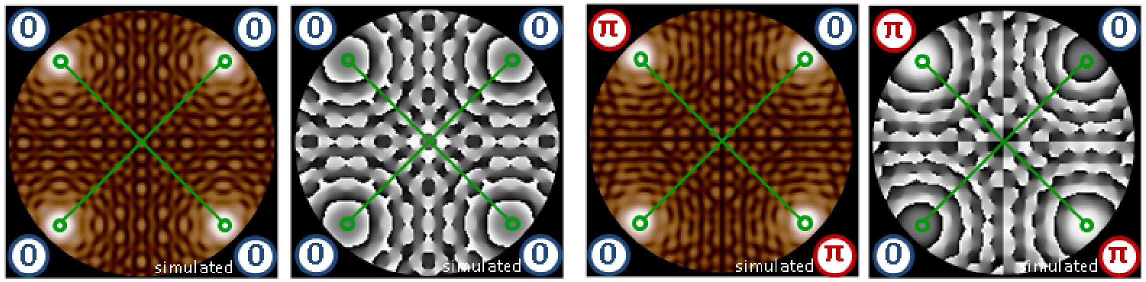
- Vortices formed by a linear superposition of 3 waves outflowing from each spot.
- Average distance between neighbouring vortices: $A = 4\pi/(3k\sqrt{3})$
- Outflow momentum dependent on power: $k(r) = K[\omega_c - \Delta(r)]$



Square lattice

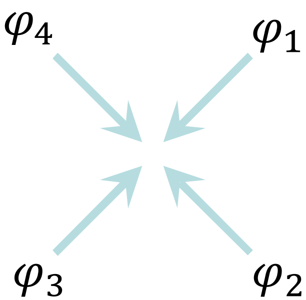


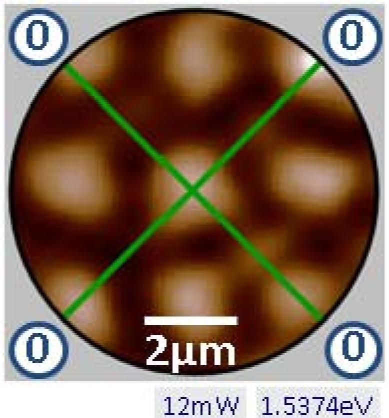
CGL simulations

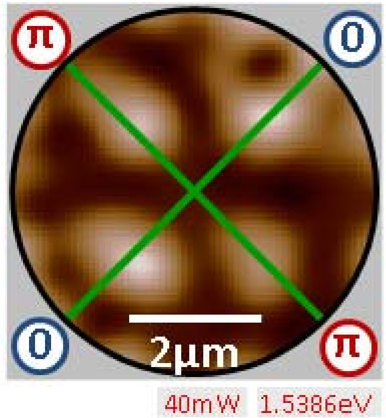


Ferromagnetic like

Antiferromagnetic like

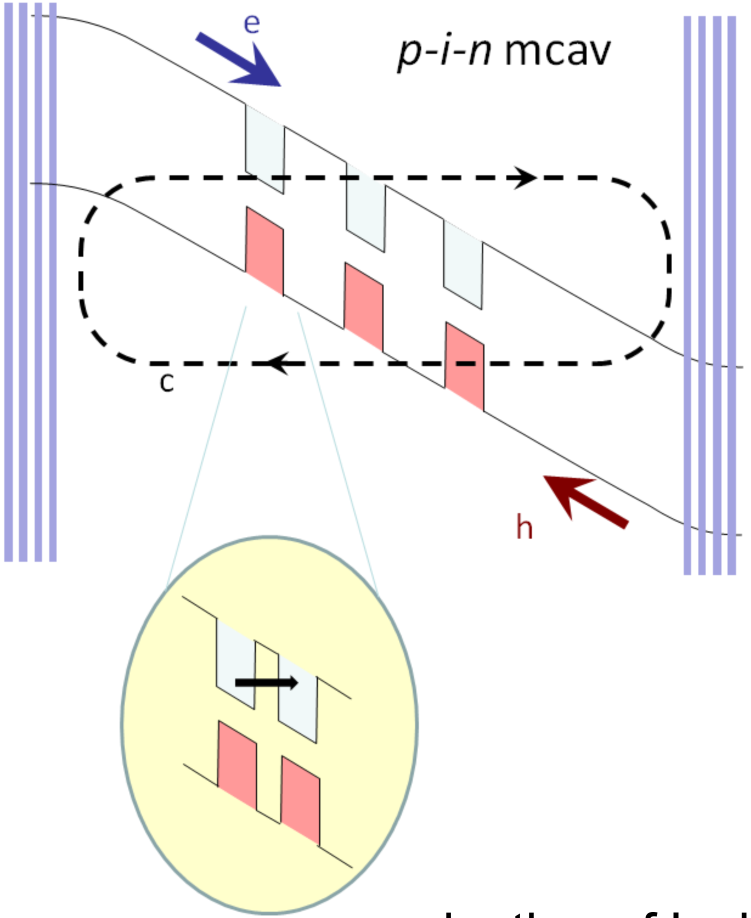






Indirect polaritons: Dipolaritons

Indirect polaritons: Dipolaritons



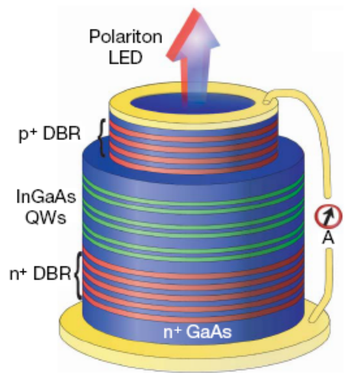
Dipolariton approach:
weakly-coupled double quantum wells

⬇

direct control of polariton dipole

$$H_{PP}^{eff} = \frac{1}{2}\sum_{k,k',q}\frac{a_B^2}{A} V_{k,k',q}^{PP}\hat{p}_{k+q}^{+}\hat{p}_{k'-q}^{+}\hat{p}_{k}\hat{p}_{k'}$$

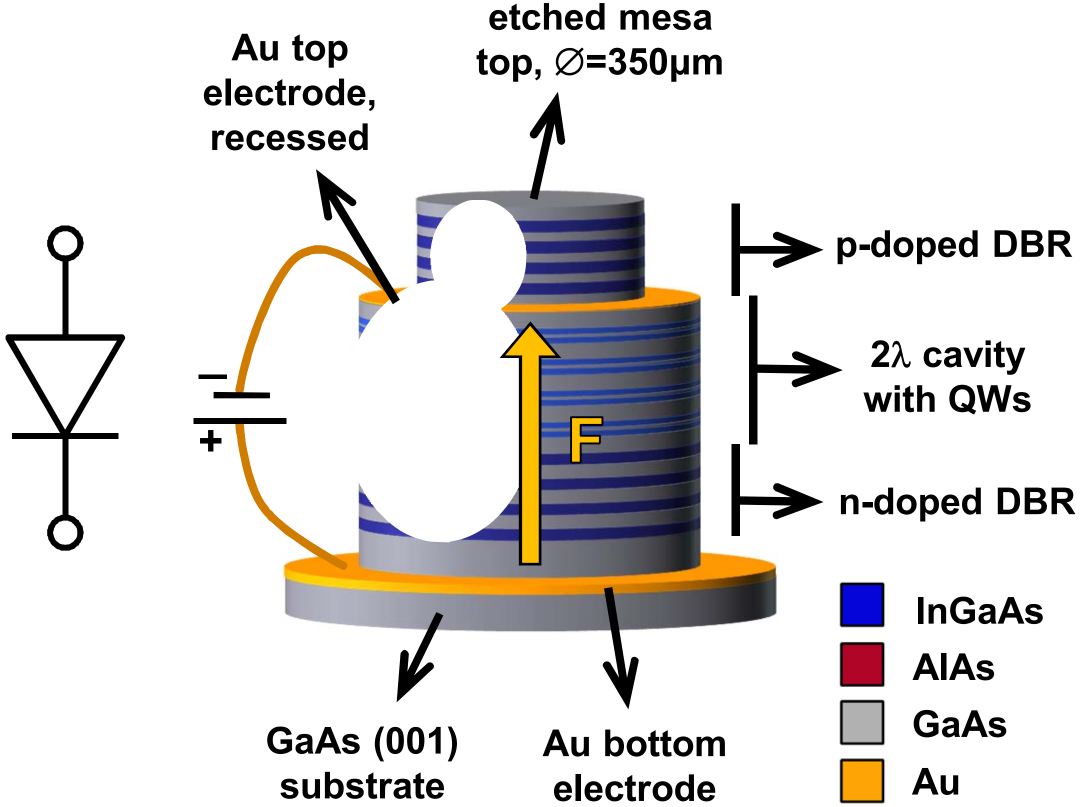
dipole-dipole

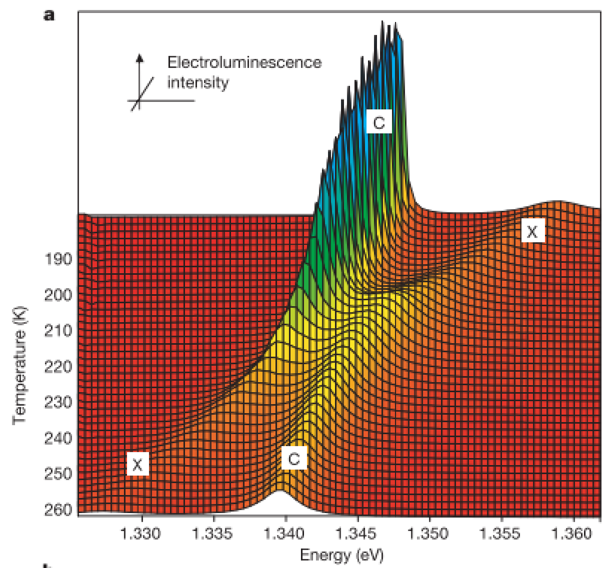


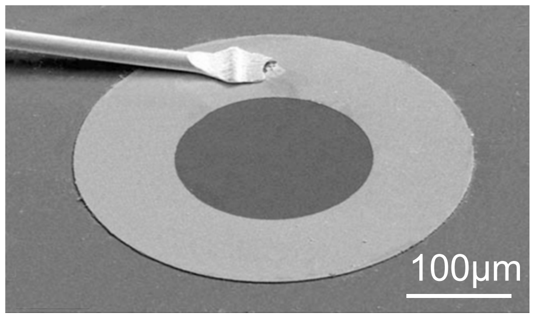
- reduction of lasing threshold
- electrically-pumped polariton lasers and BECs

P. Cristofolini *et al.*, Science 336, 704 (2012) G. Christmann APL 98, 081111 (2011)

Biased samples: Polariton LED structure



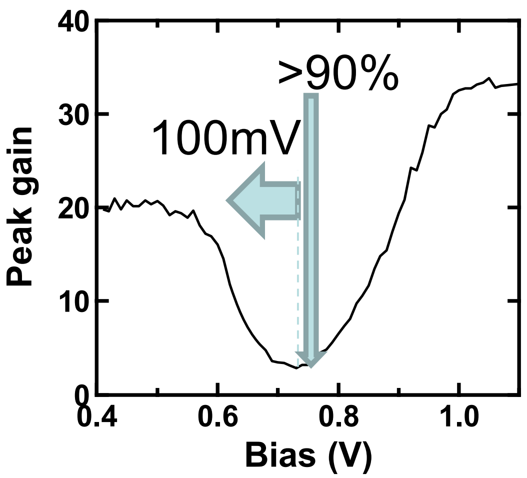


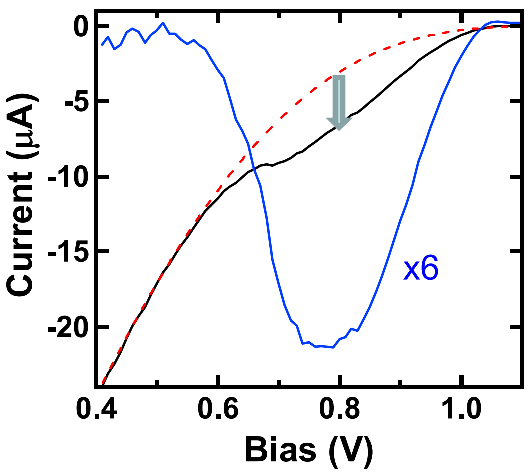


“A GaAs light-emitting diode operating near room temperature”, *Nature* **453**, 372-375 (2008)

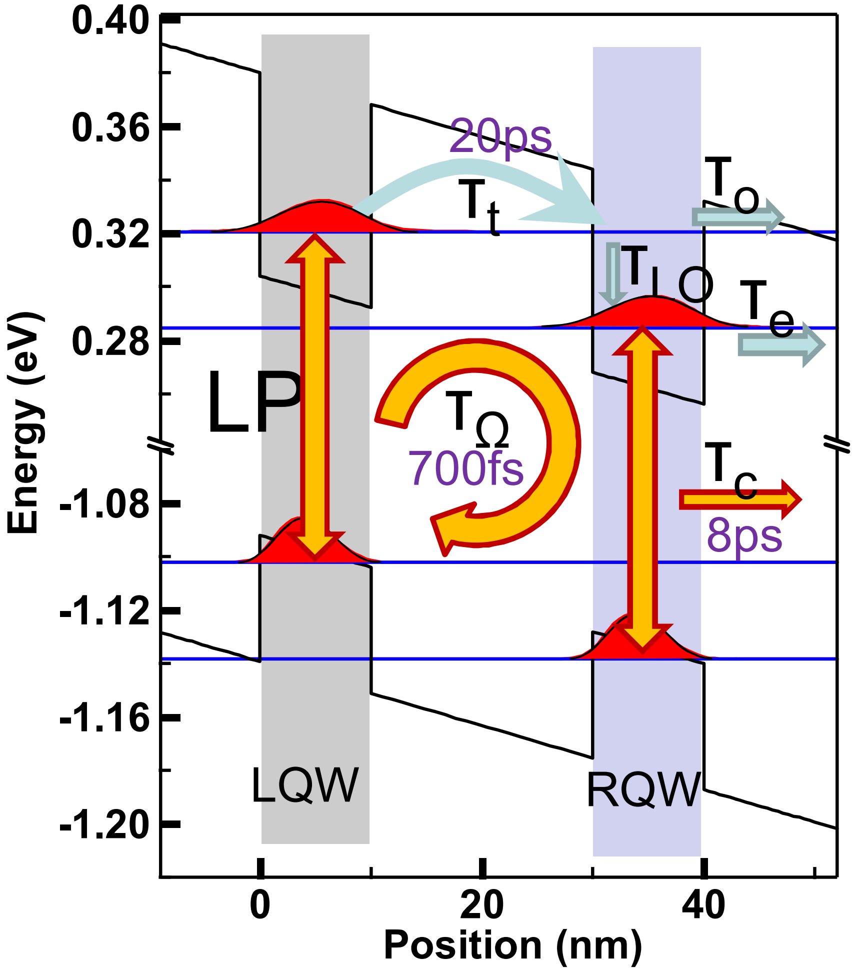
Motivation

sharp dip in gain





extra photocurrent
at same bias

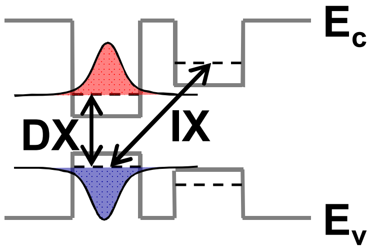


Control of polariton parametric scattering due to LO phonon assisted tunnelling with a double QW microcavity

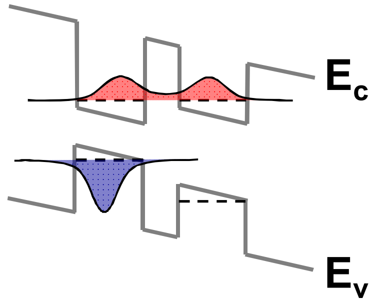
"Control of polariton scattering in resonant-tunneling double-quantum-well semiconductor microcavities", *Phys. Rev. B* **82**, 113308 (2010)

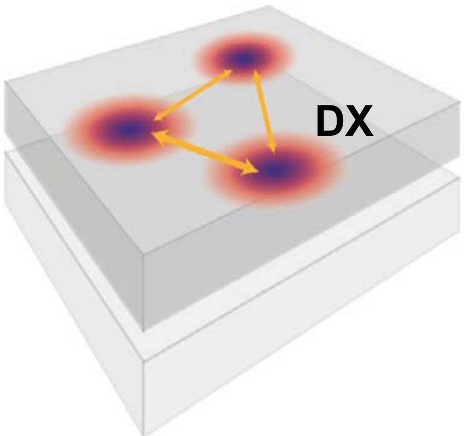
Dipolaritons

electron levels
off resonance



electron levels
at resonance

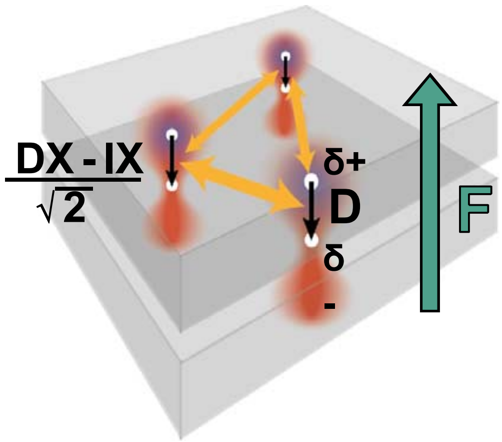




"tunnelling off"

↓

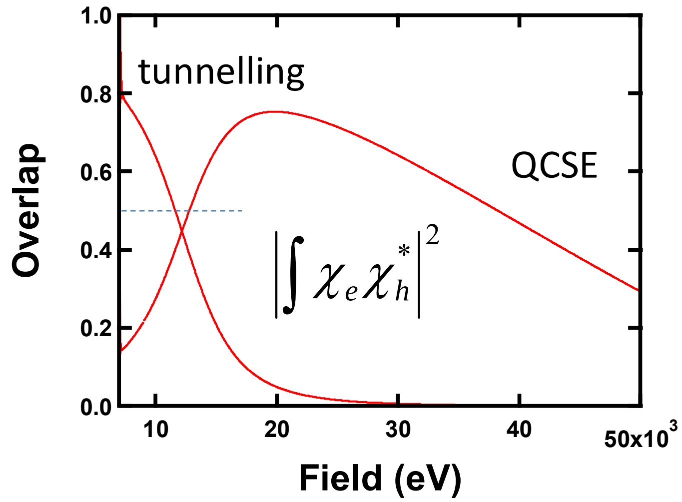
direct excitons
DX



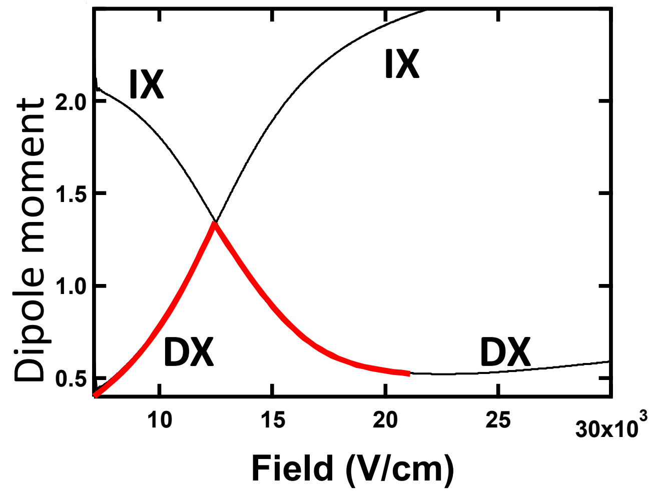
"tunnelling on"

↓

mixed excitons
DX±IX,
static dipole
moment



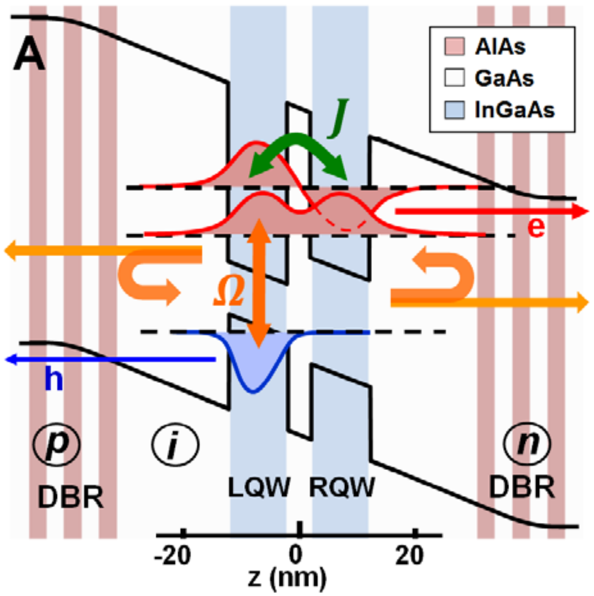
Oscillator strength is kept



Strong dipole moment

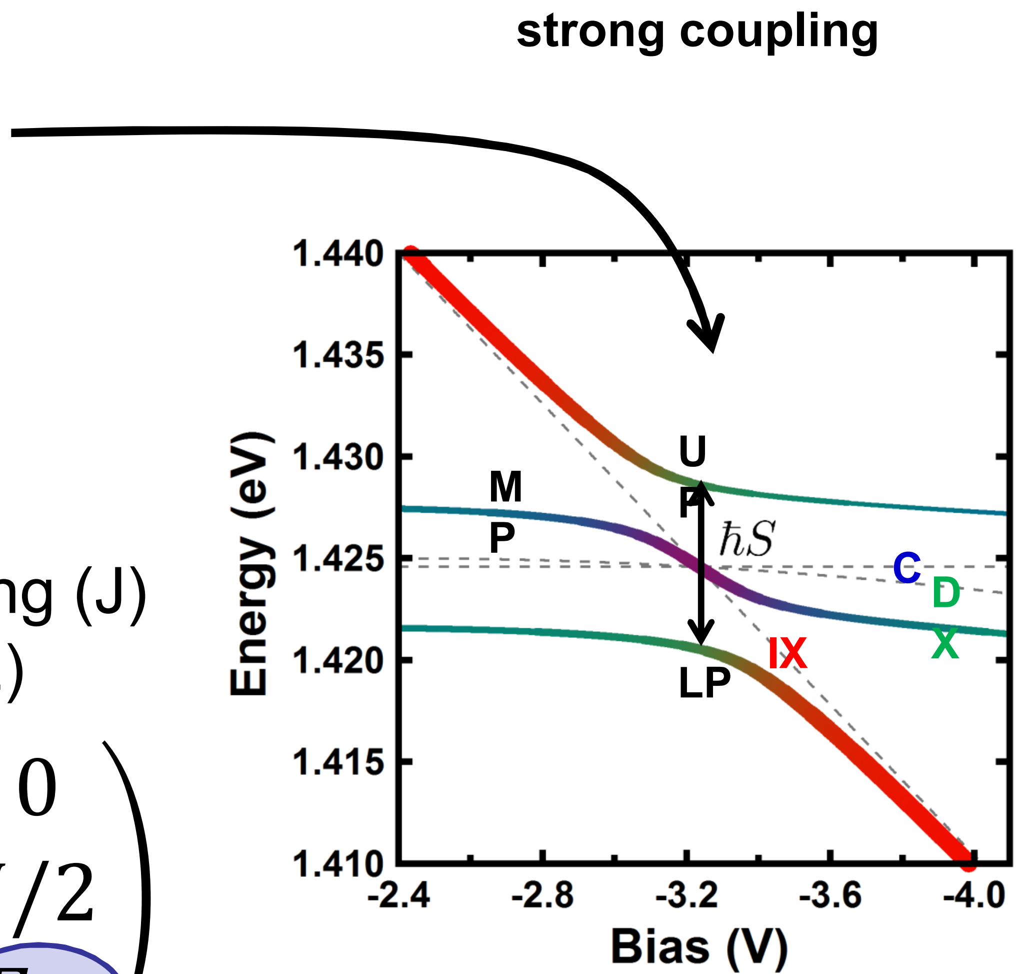
"Oriented polaritons in strongly-coupled asymmetric double quantum well microcavities", Appl. *Phys. Lett.* **98**, 081111 (2011)

Dipolaritons

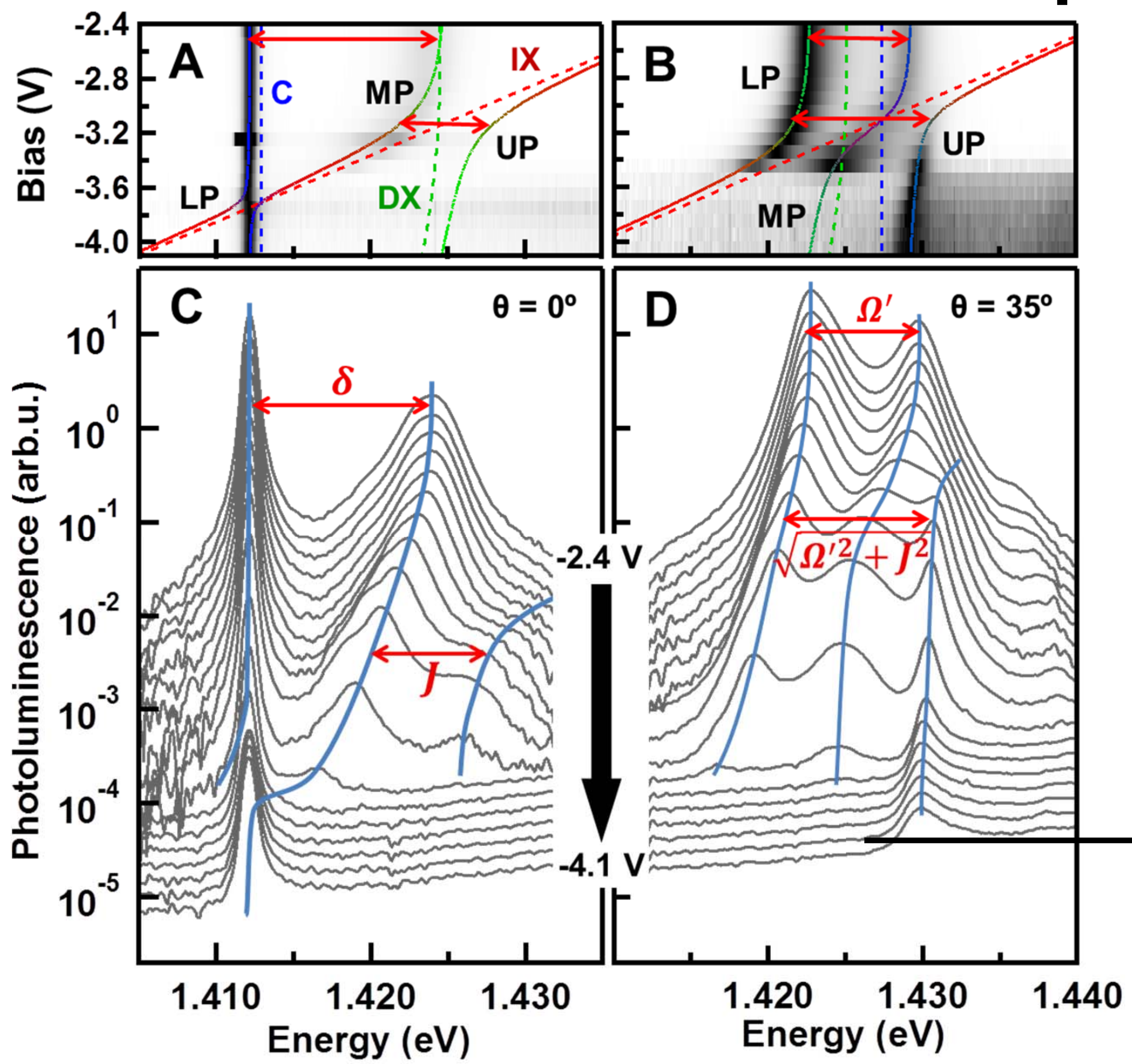


Combining tunnel coupling (J) and Rabi splitting (Ω)

$$H = \begin{pmatrix} E_C & \Omega/2 & 0 \\ \Omega/2 & E_{DX} & J/2 \\ 0 & J/2 & E_{IX} \end{pmatrix}$$



Observation of dipolaritons



Photoluminescence of the the system versus increasing bias for detuned and resonant cavity

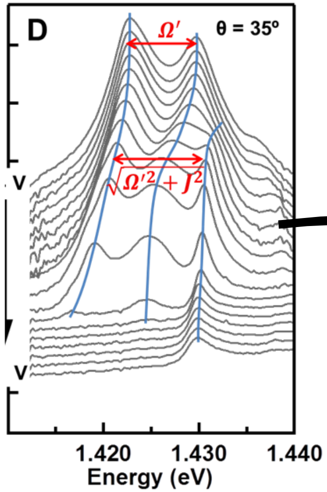
PL is lost because electron tunnel out of the system

tunnel-split excitons, uncoupled cavity

dipolaritons, strong coupling of J and Ω

"Coupling Quantum Tunneling with Cavity Photons"
Science **336**, 704 (2012)

Dipolaritons at resonance

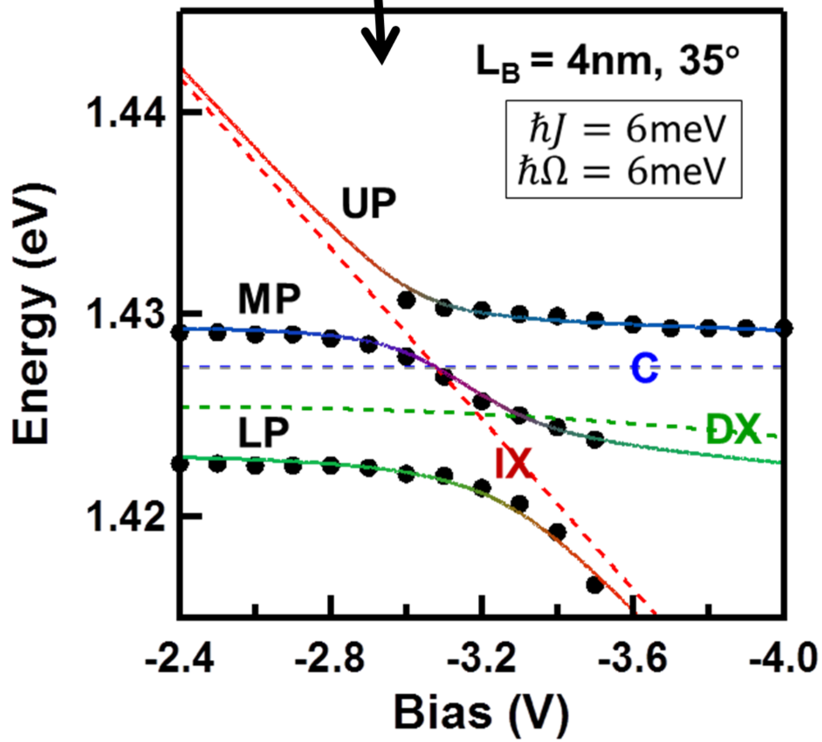


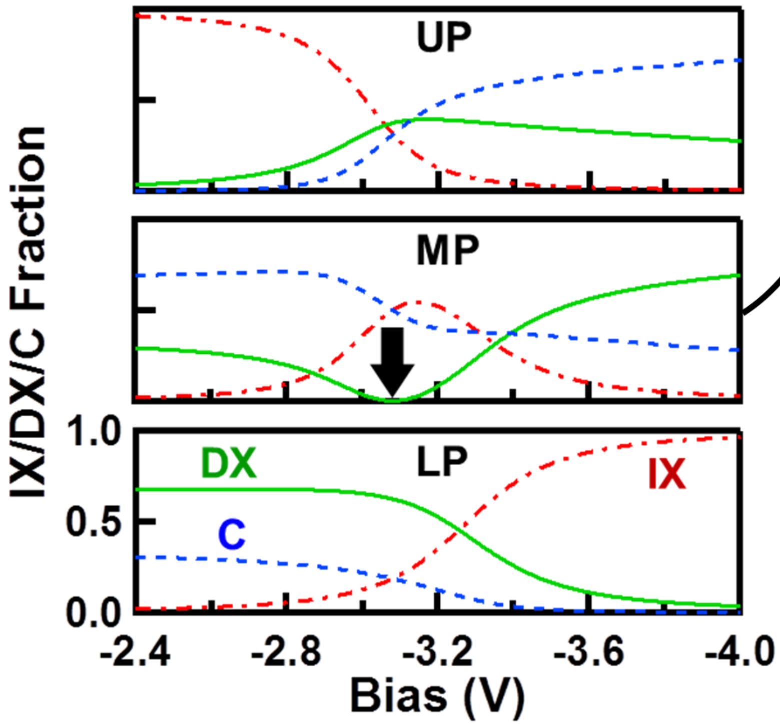
peak extraction
+

$$H = \begin{pmatrix} E_C & \Omega/2 & 0 \\ \Omega/2 & E_{DX} & J/2 \\ 0 & J/2 & E_{IX} \end{pmatrix}$$

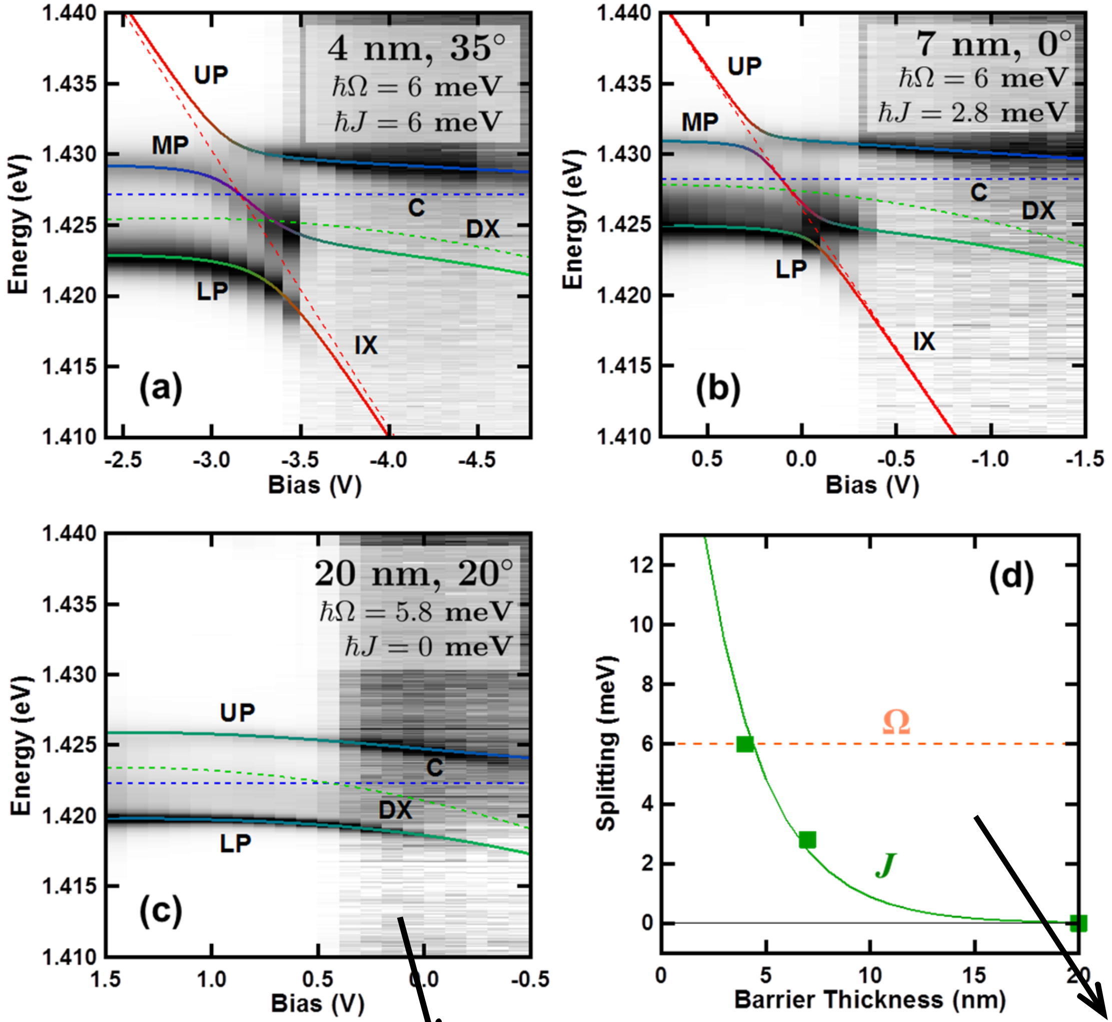
MP – state: no DX!

$$|\mathrm{MP}\rangle = \frac{\Omega|\mathrm{IX}\rangle - J|\mathrm{C}\rangle)}{S}$$





Barrier width dependence



Influence of the **tunnelling barrier thickness** (4,7,20nm) on the bare tunnelling rate *J*

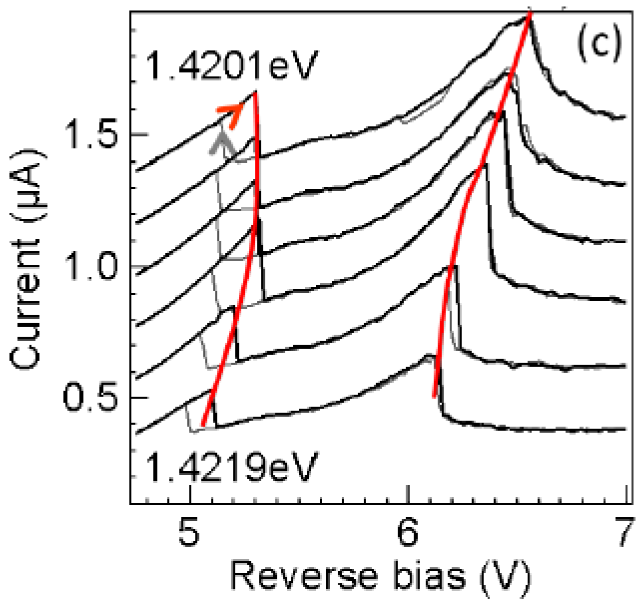
Excellent agreement with solution of the Schrödinger equation for tunnel coupling

no tunnel coupling normal polariton regime

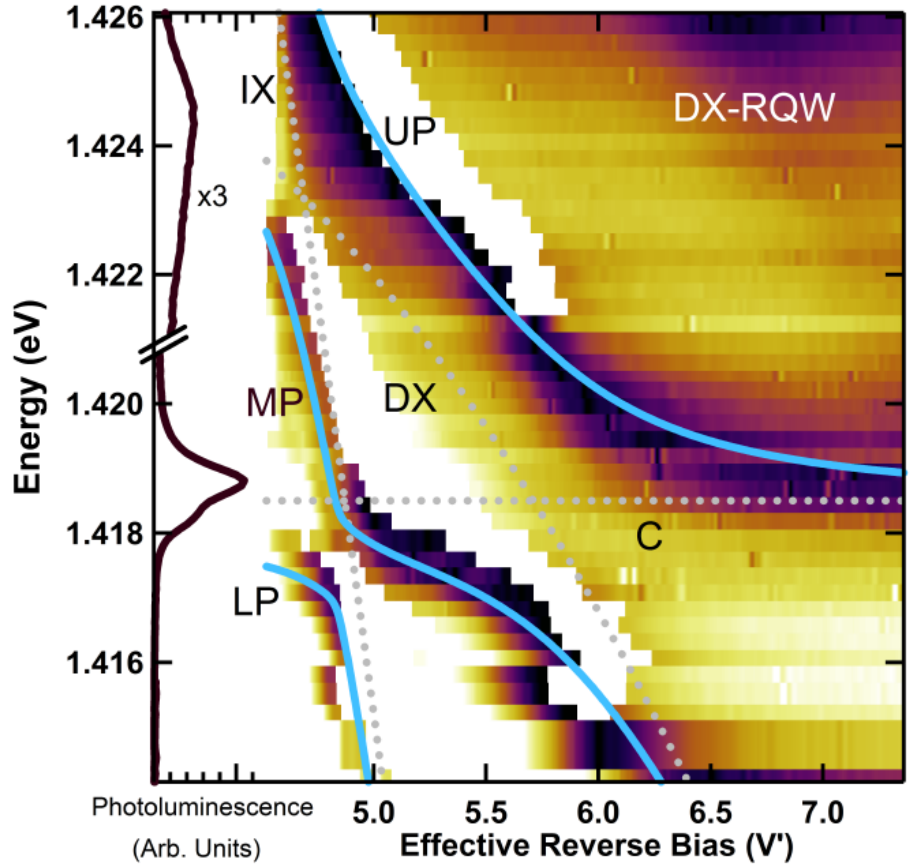
ADQW simulation from solving Schrödinger equation

Observation through photocurrent

Experiment: Tuning laser energy while monitoring photocurrent



Strong coupling observed on photocurrent measurements
Hysteresis observed at resonance positions due to charge build-up



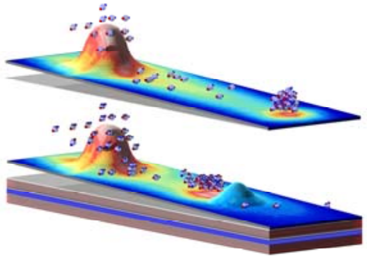
Mapping of the full dispersion curves
Excellent sensitivity on otherwise poorly optically active modes

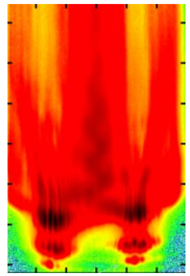
Summary

- lasing threshold at 25K vs 70K (strong vs weak)

- Electrical control of polariton dispersions
  tuning of the condensate energy

- Electrical and optical manipulation of polariton condensates on a chip





polariton condensate transistor

polariton condensate pendulum

Interactions between condensated in confining potentials

- Dipolaritons: Oriented polaritons
  new possibilities for enhancing nonlinear Interactions
  threshold reduction, control of parametric scattering

Thank you