Optical and Electrical Manipulation of Polariton Condensates on a Chip

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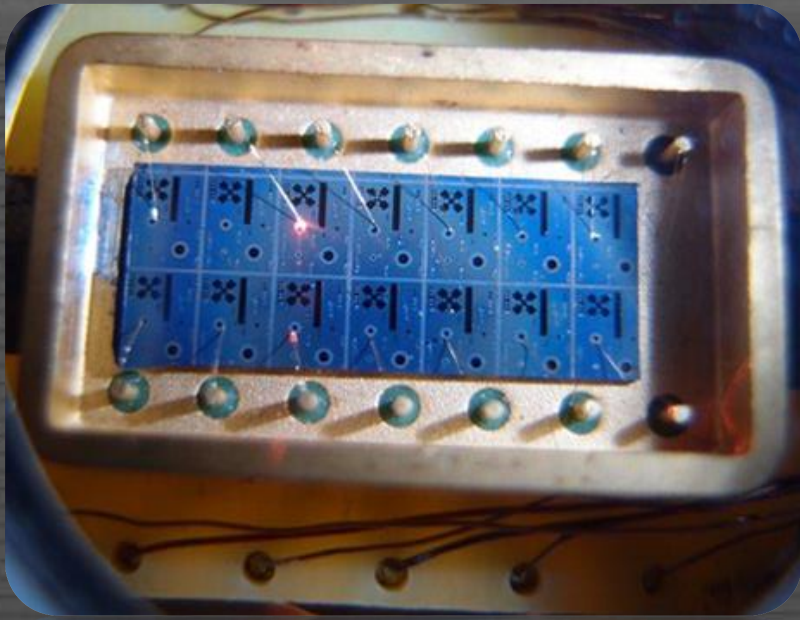

Maratea
02.09.13

Acknowledgements

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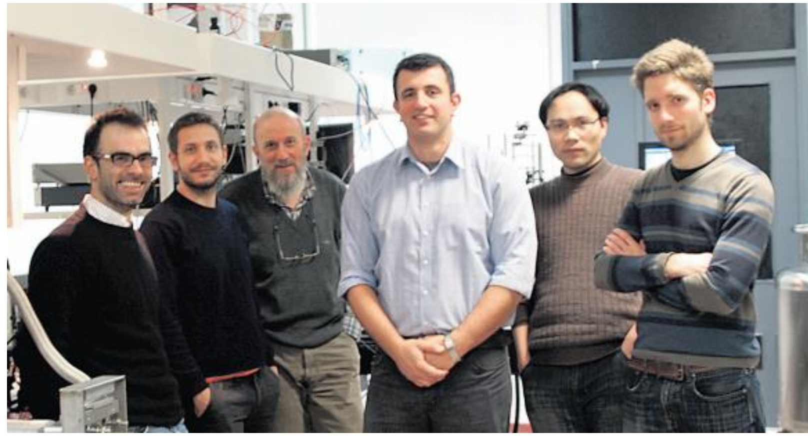
Pavlos G Savvidis
Dr. Peter Eldridge
Dr. Simos Tsintzos
PhD Panos Tsotsis
PhD Tingge Gao
PhD Pramod Sharma
PhD Kostas Daskalakis



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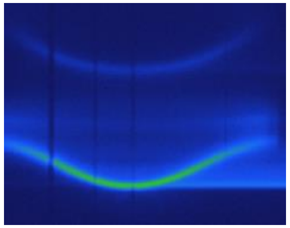
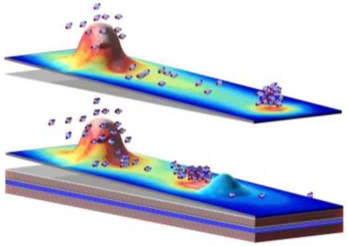
Outline

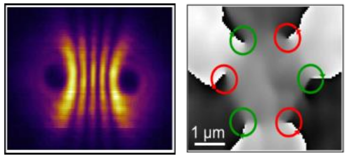
- New generation of semiconductor lasers operating in the so called strong light-matter coupling regime



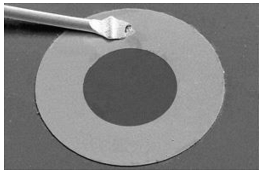
- Electrical and optical manipulation of polariton condensates on a chip

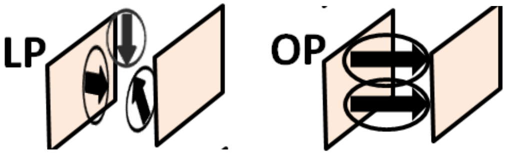


  - polariton condensate transistor
  - interactions between independent condensates
  - electrical control of polariton condensate



- Dipolaritons: dipole oriented polaritons
  - control of quantum tunneling
  - enhance nonlinearities





The History of Semiconductor Lasers

The concept of the semiconductor laser diode proposed by Basov in 1959
N. G. Basov, B. M. Vul and M. Popov
Soviet JETP, 37(**1959)**

First GaAs *laser diode* demonstrated by Robert N. Hall in 1962.

Pulsed operation at liquid nitrogen temperatures (77 K)

Bulk

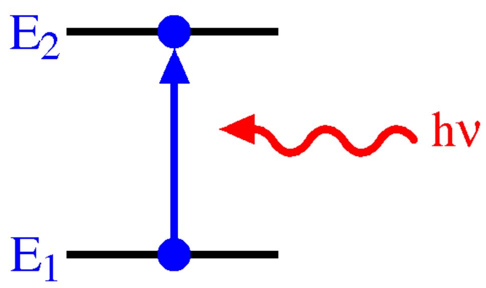
Electronic confinement in heterostructures

In 1970, Zhores Alferov, Izuo Hayashi and Morton Panish independently developed CW laser diodes at room temperature

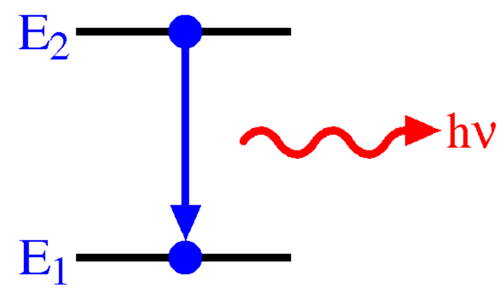
- the laser disc player, introduced in 1978, was the first successful consumer product to include a laser

Fundamental Optical Processes Involved in Operation of Semiconductor Lasers

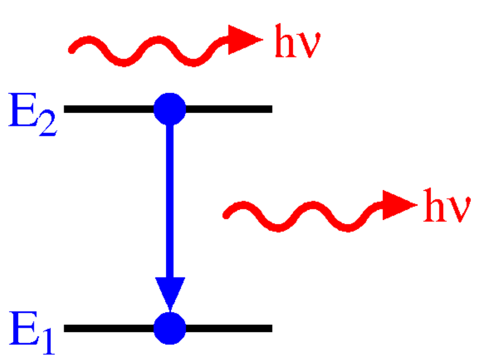
Absorption

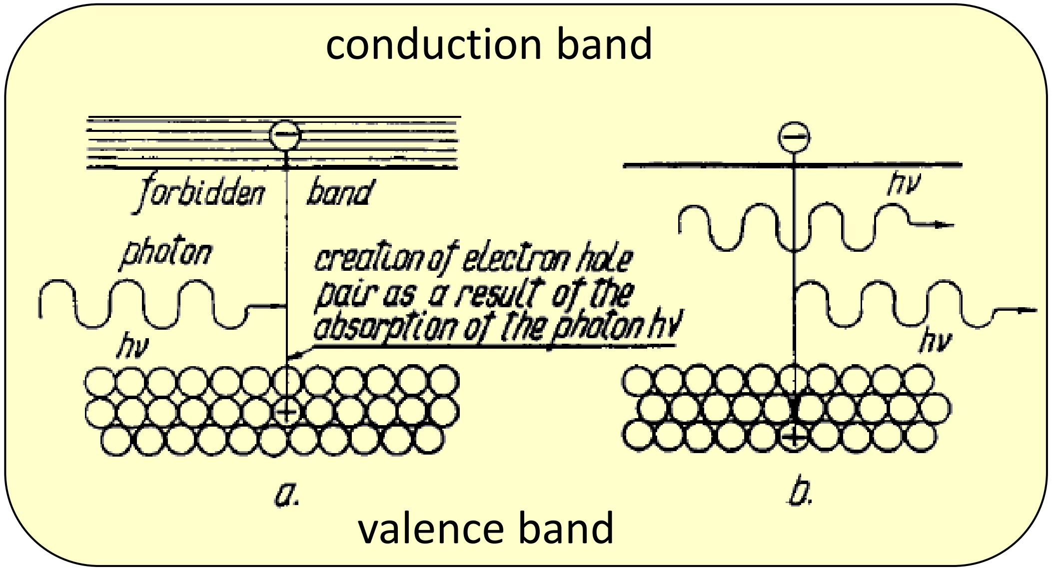


Spontaneous emission



Stimulated Emission





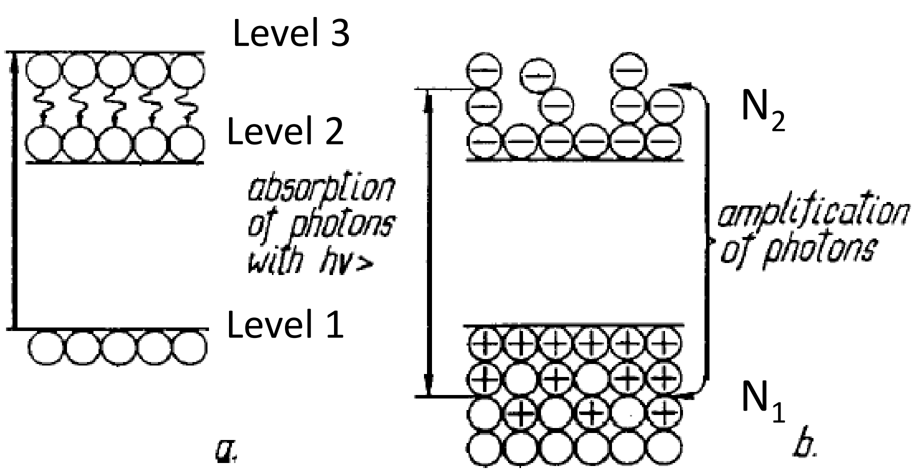
Semiconductors

Negative Temperature & Population Inversion Lasing

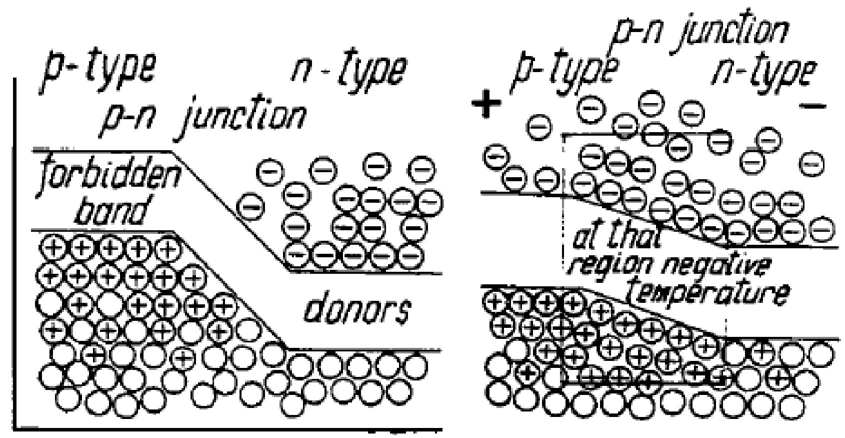
To achieve non-equilibrium conditions, an indirect method of populating the excited state must be used.

Three-level laser energy diagram

Basov Nobel Lecture



Atoms **Semiconductors**

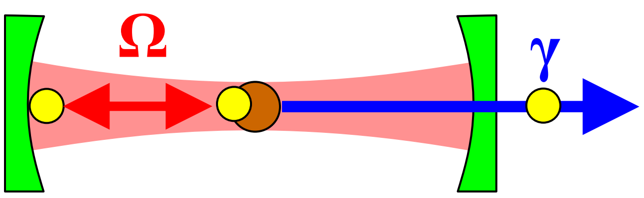


p-n junction in the external electrical field

- Population inversion when ($N_2 > N_1$) → optical amplification at the frequency ω_{21}
- At least half the population of atoms must be excited from the ground state
  - to get population inversion laser medium must be very strongly pumped

This makes three-level lasers rather inefficient.

Weak Coupling Regime



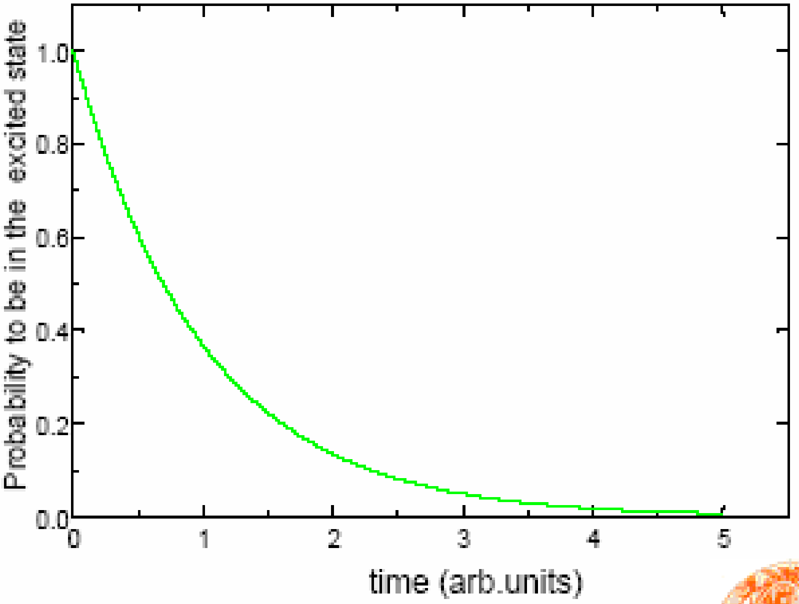
γ: loss channel (e.g. imperfect mirror)

Ω coupling strength between optical transition of the material and the resonance photon mode

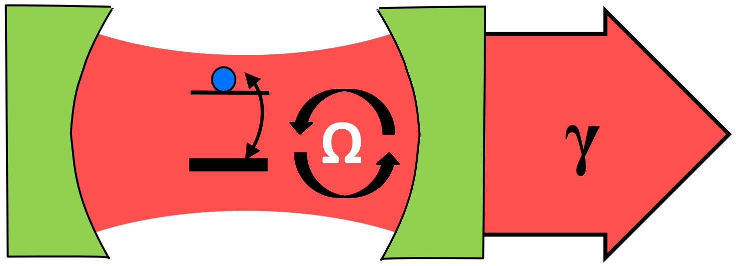
Weak Coupling Regime (γ>>Ω) :

emitted photon leaves the resonator (after some reflections) no reabsorption

⇒ Spontaneous Emission is irreversible



Strong Coupling Regime



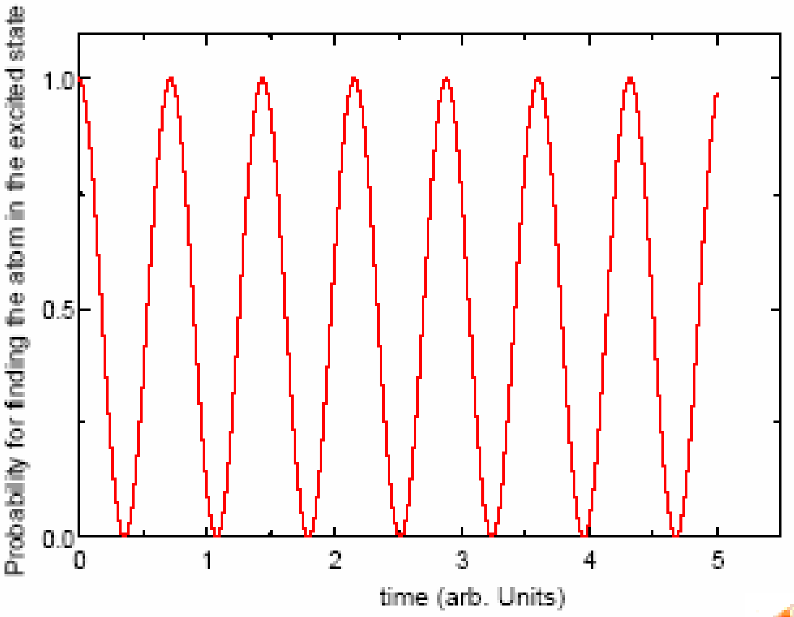
γ: loss channel

Ω coupling strength between optical transition of the material and the resonance photon mode

Strong Coupling Regime (Ω>>γ) :

emitted photon will be reabsorbed before it leaves the cavity

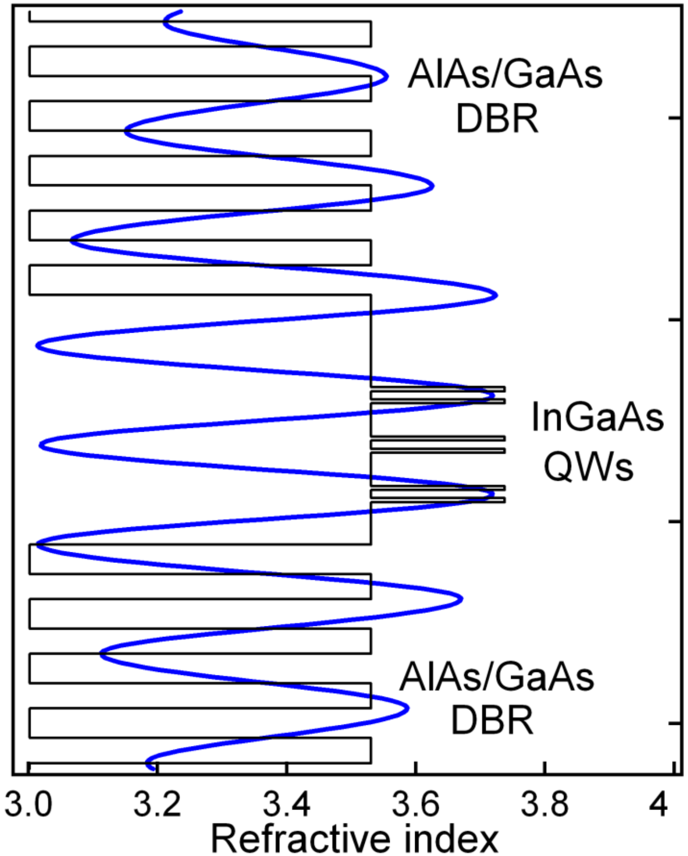
⇒ **Spontaneous Emission is a reversible process**



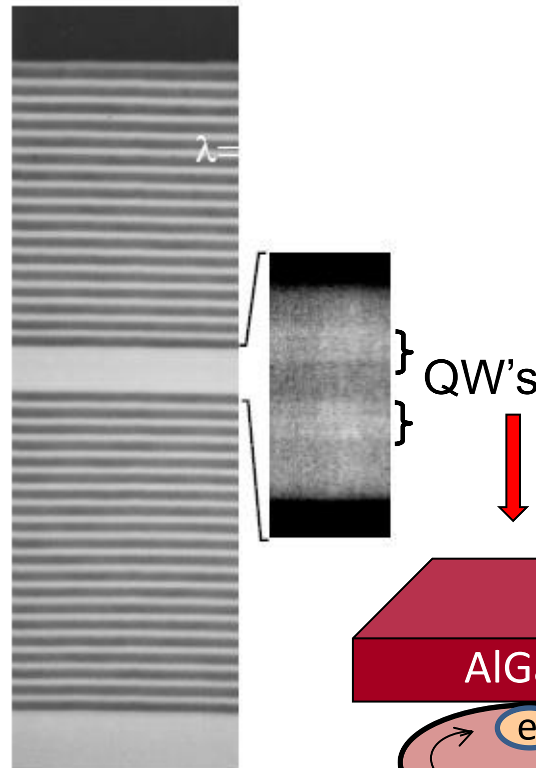
Monolithic Semiconductor Microcavity

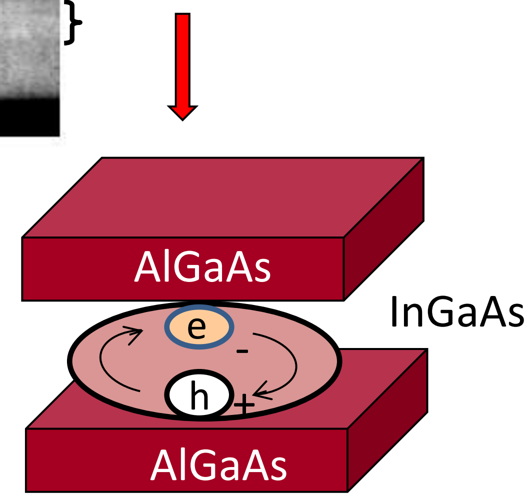
Top DBR Mirror

Bottom DBR Mirror



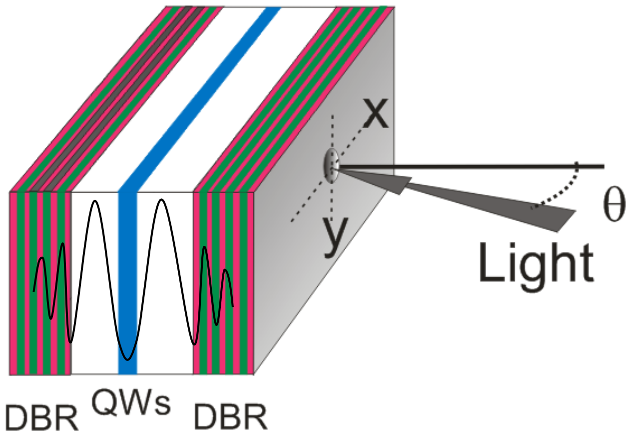
- QWs placed at the E-field maxima





- Combine electronic and photonic confinement in the same structure

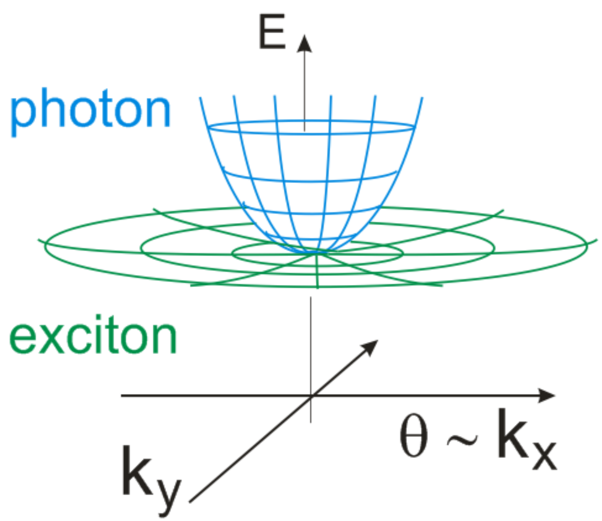
Strong Coupling Regime in Semiconductor Microcavity



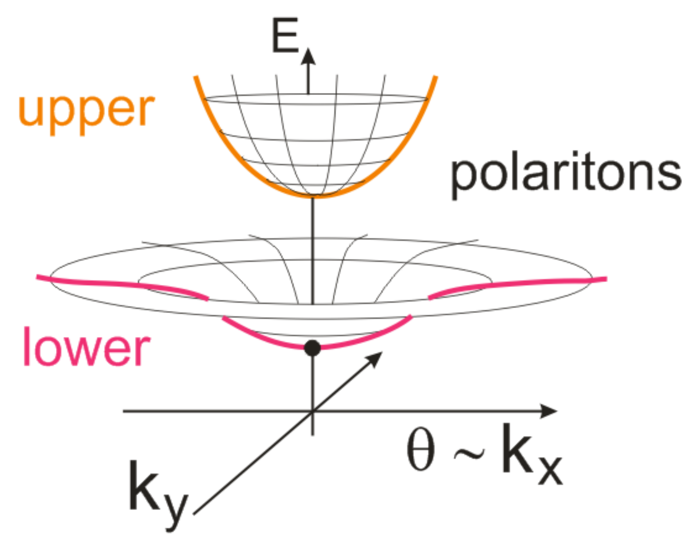
- Strongly modified dispersion relations
  reduced density of states near $k_{//}=0$
- small polariton mass $m_{pol} \approx 10^{-4} m_e$
- strong non-linearities → χ^3 (exciton component)

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

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

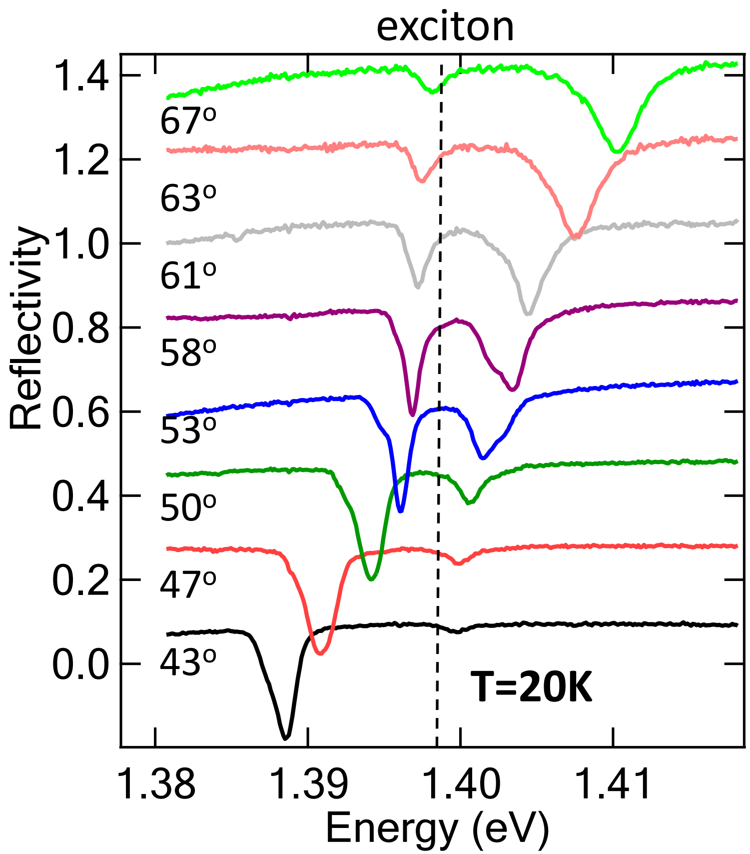


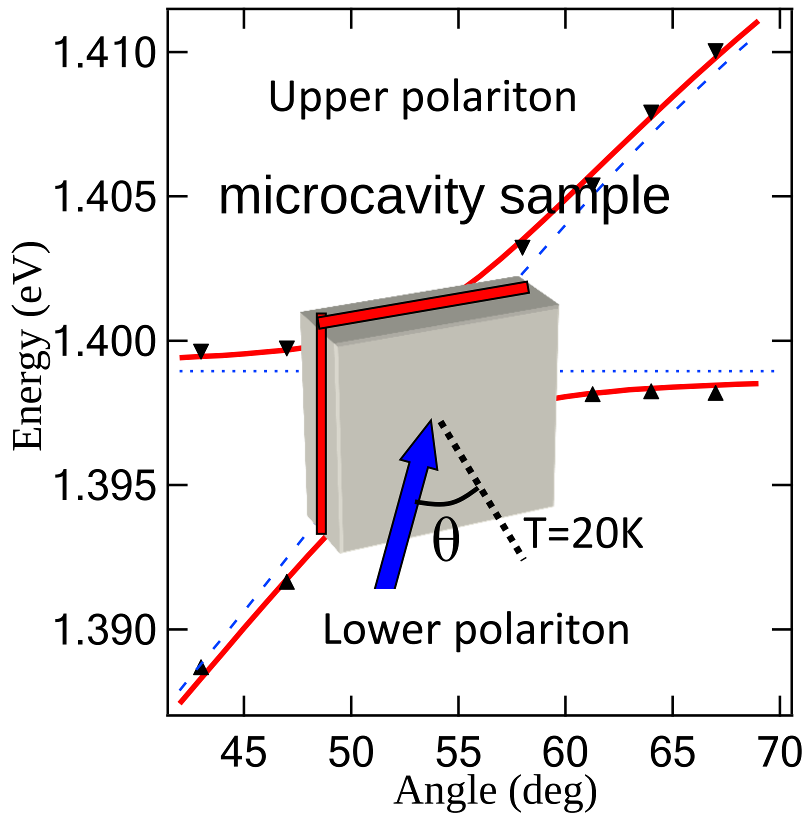
Strong Coupling Regime



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

Polariton Dispersions in the strong coupling regime





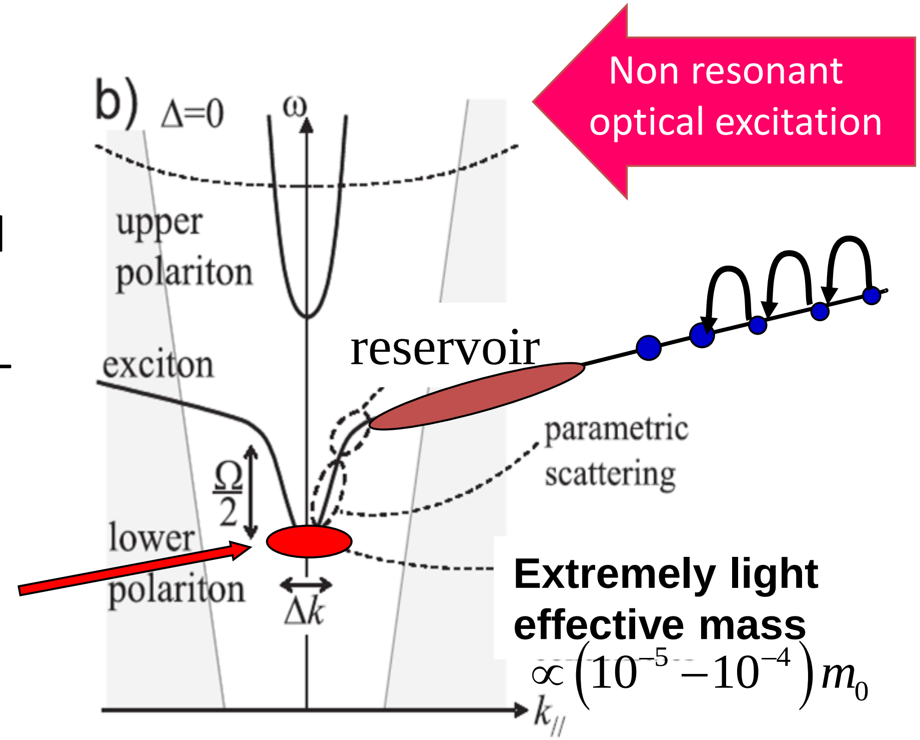
- reflectivity probes allowed states in the system
- characteristic anticrossing behaviour with Rabi splitting of 4.8meV

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



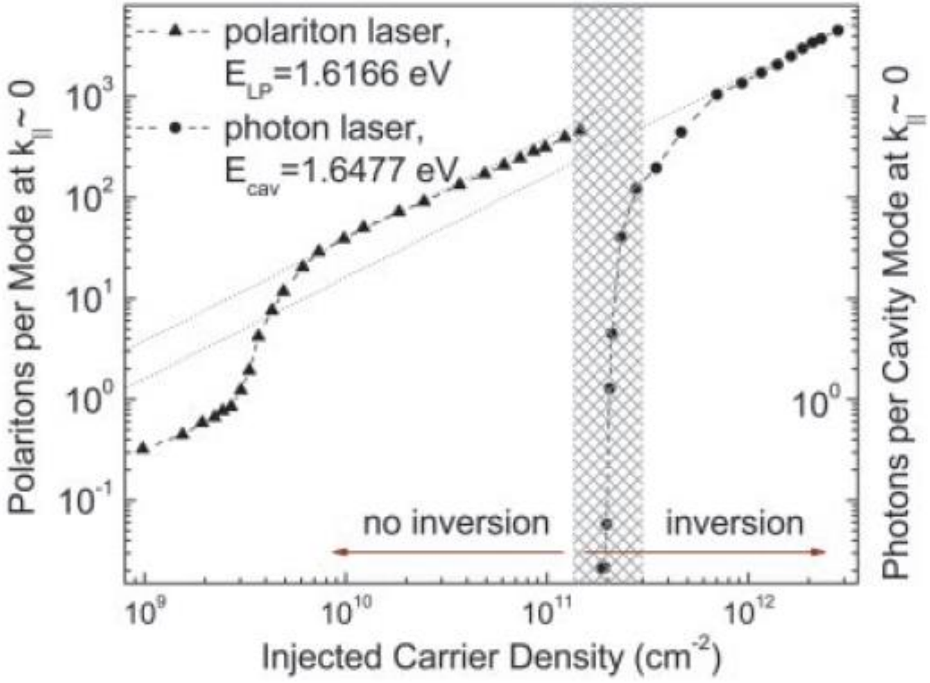
Polaritons accumulate in the lowest energy state by bosonic final state stimulation.

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 necessity for population inversion

New Physics & Applications

• Strong-coupling provides a new insight into a number of very interesting fundamental physical processes and applications



Polaritons are Bosons

- Bose condensation
- stimulated scattering

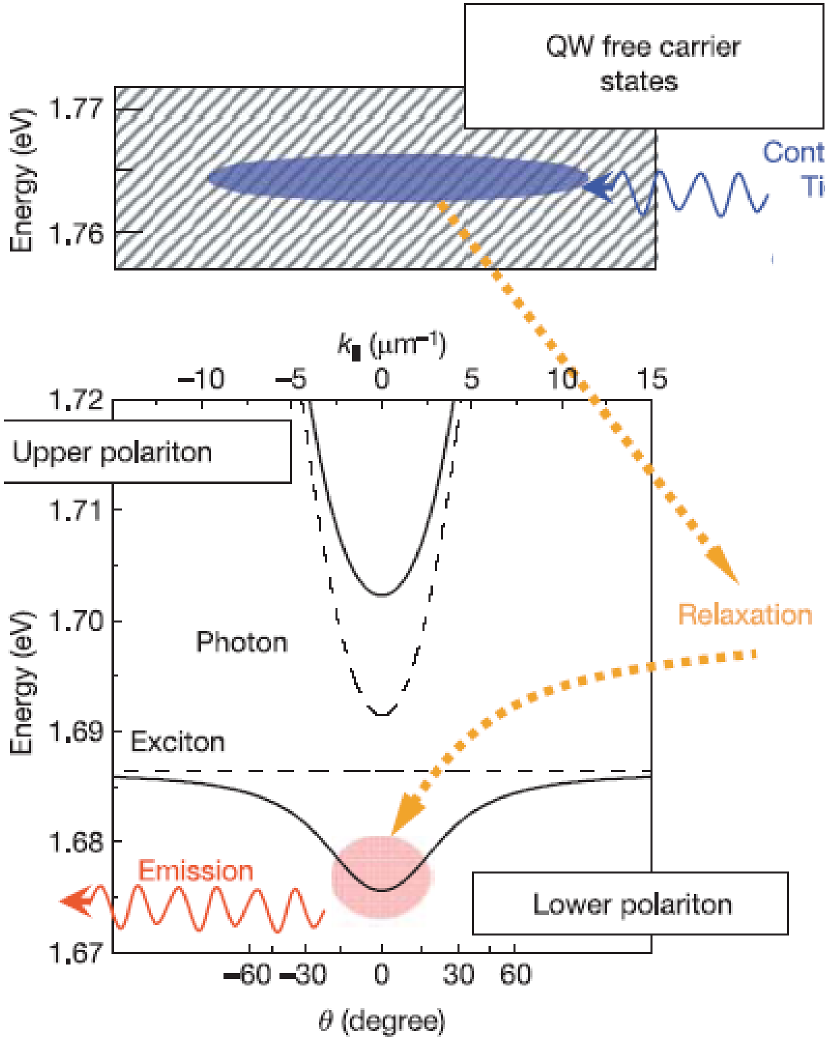
Polariton vs Photon Laser

Deng, et al. Natl. Acad. Sci. 15318 (2003)

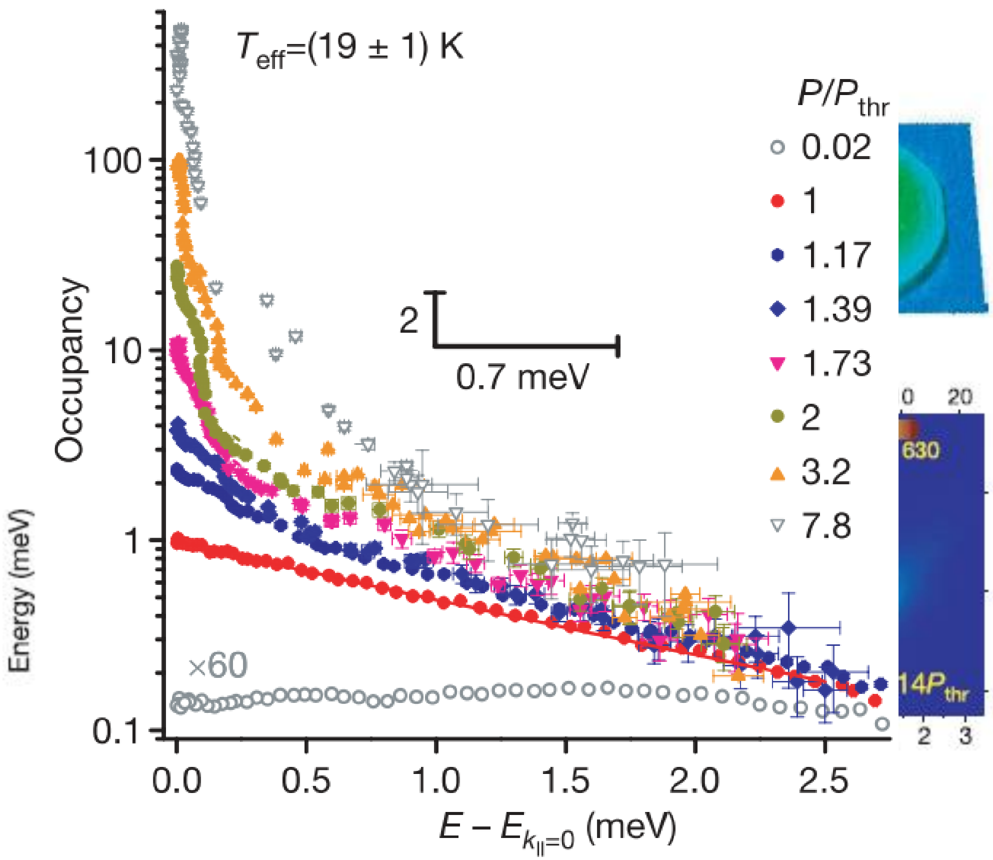
- ultralow threshold polariton lasers
- all optical switches, transistors and amplifiers

Polariton Condensation in CdTe/CdMnTe MC

J. Kasprzak et al. *Nature* **443, 409** (2006)

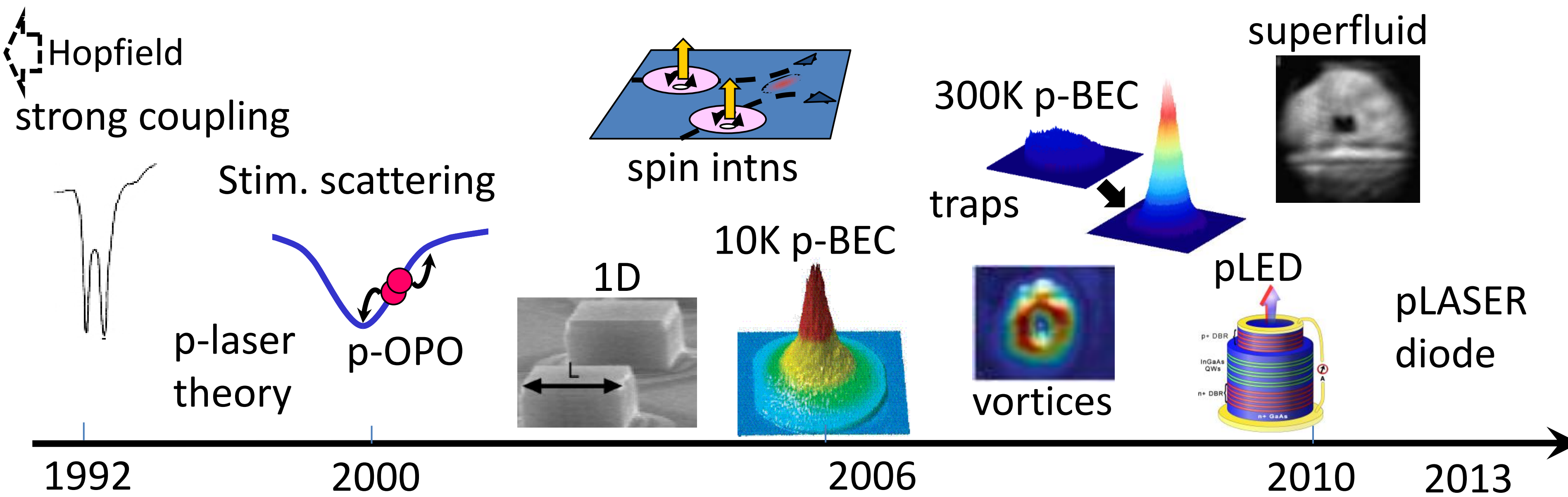


Narrowing of the momentum distribution



- **polaritons 10^9 times lighter than Rubidium atoms**
- **observation of polariton BEC at cryogenic temperature is possible**

Polaritonics



From a device perspective:

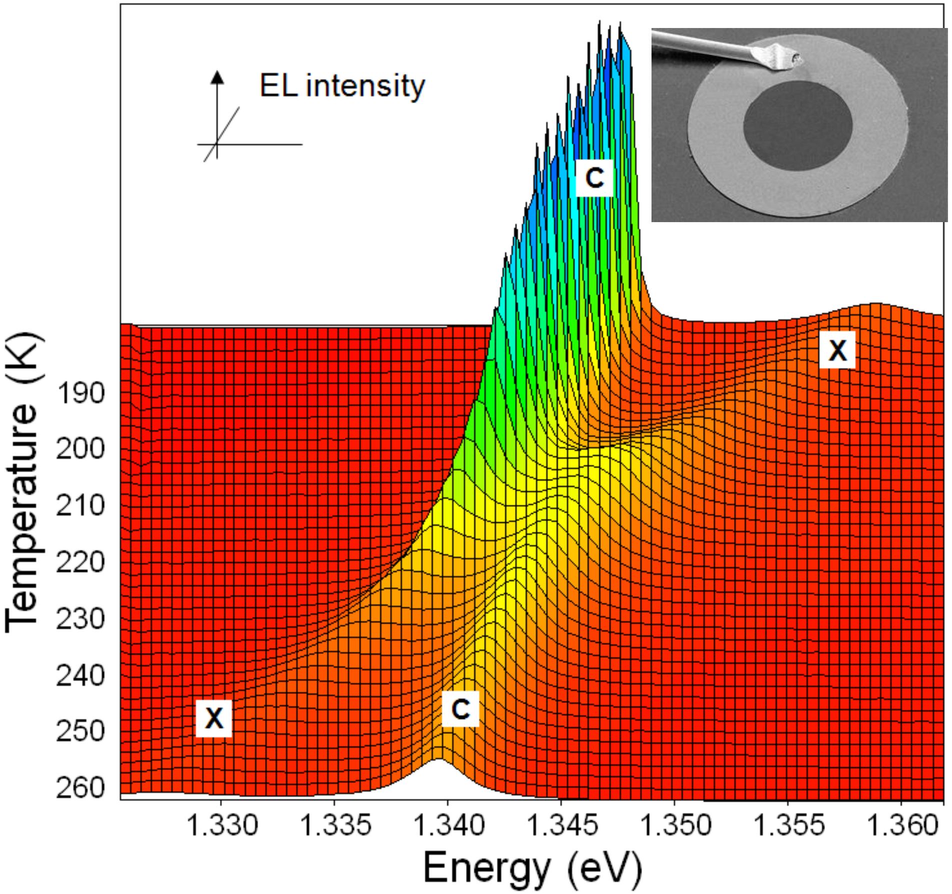
- Near speed of light lateral transport
- Light effective mass
- Condensate regime readily available on a chip even at RT

New directions: electrically driven polariton devices

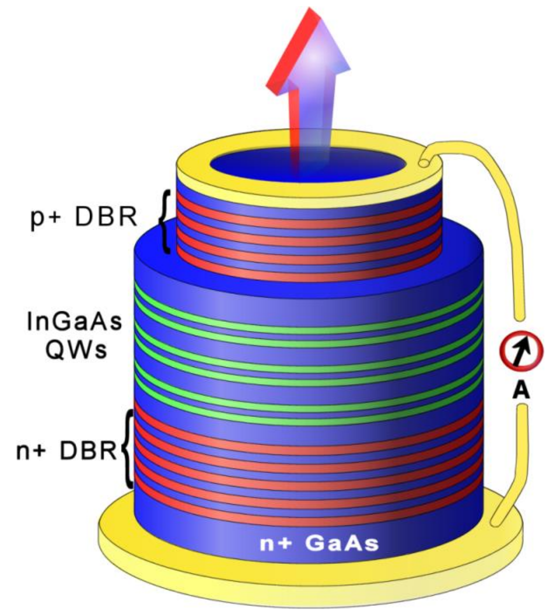
Polariton based Devices
“Polaritonics”

Room temperature Polariton LED

Emission collected normal to the device



- Clear anticrossing observed
- Direct emission from exciton polariton states



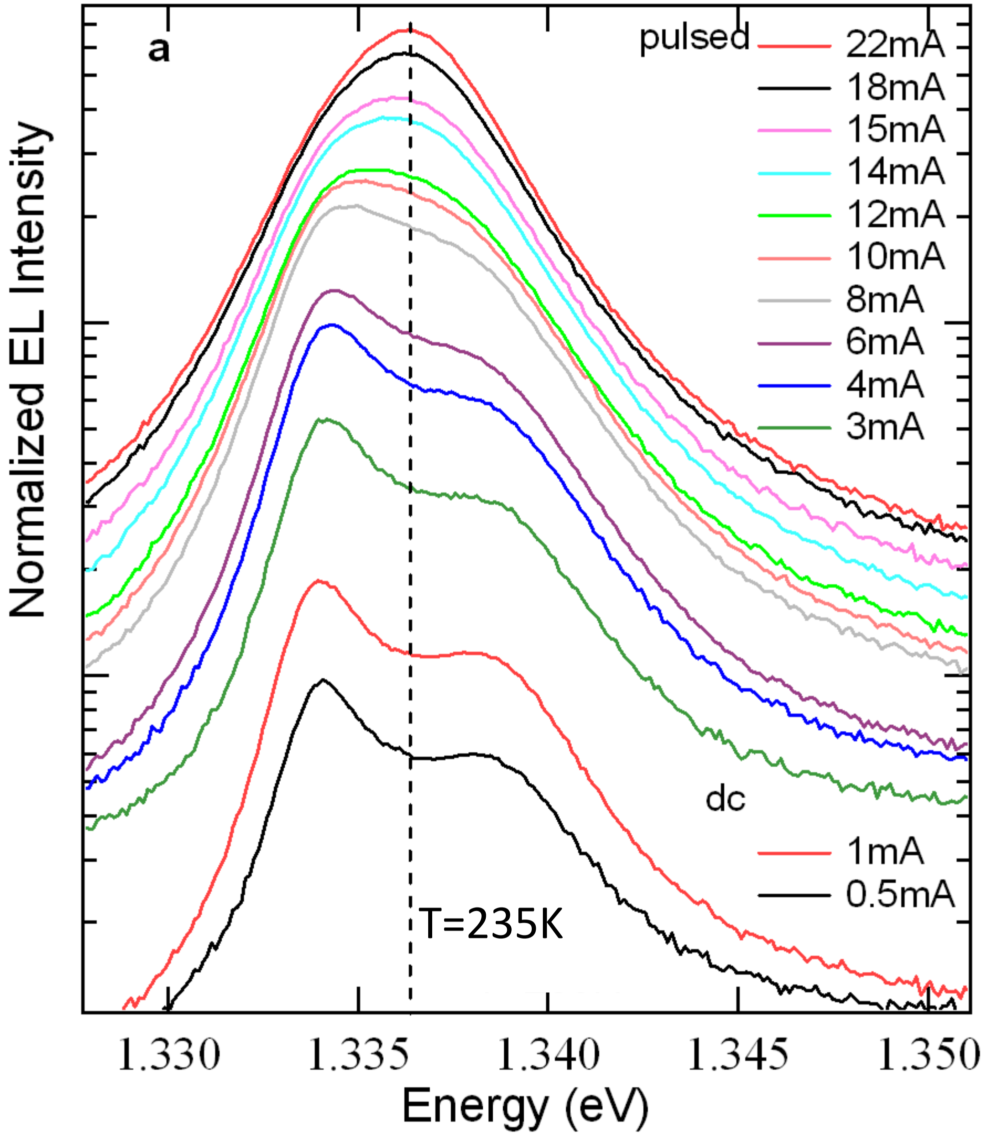
•Rabi splitting of 4.4meV at 219 K

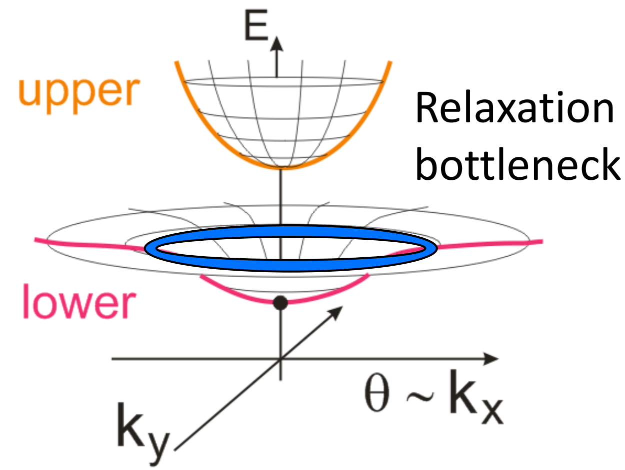
Transport driven device

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

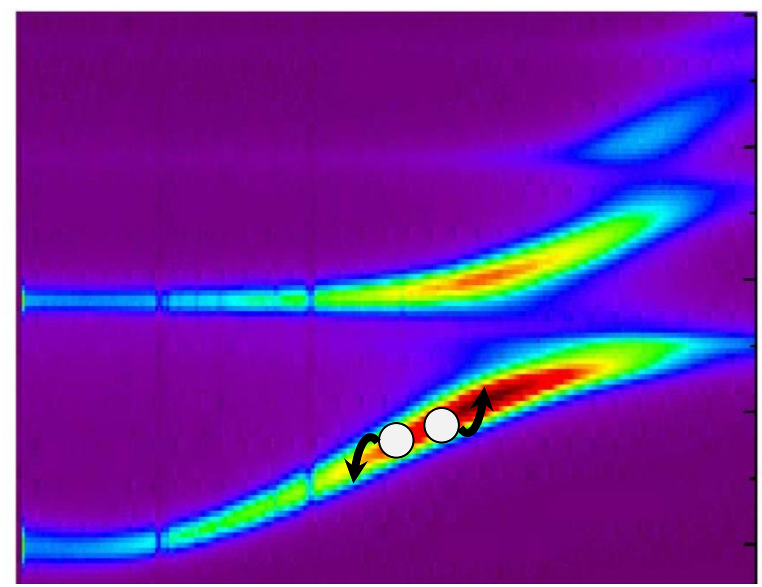
N. Pelekanos

Collapse of Strong Coupling Regime at High Densities



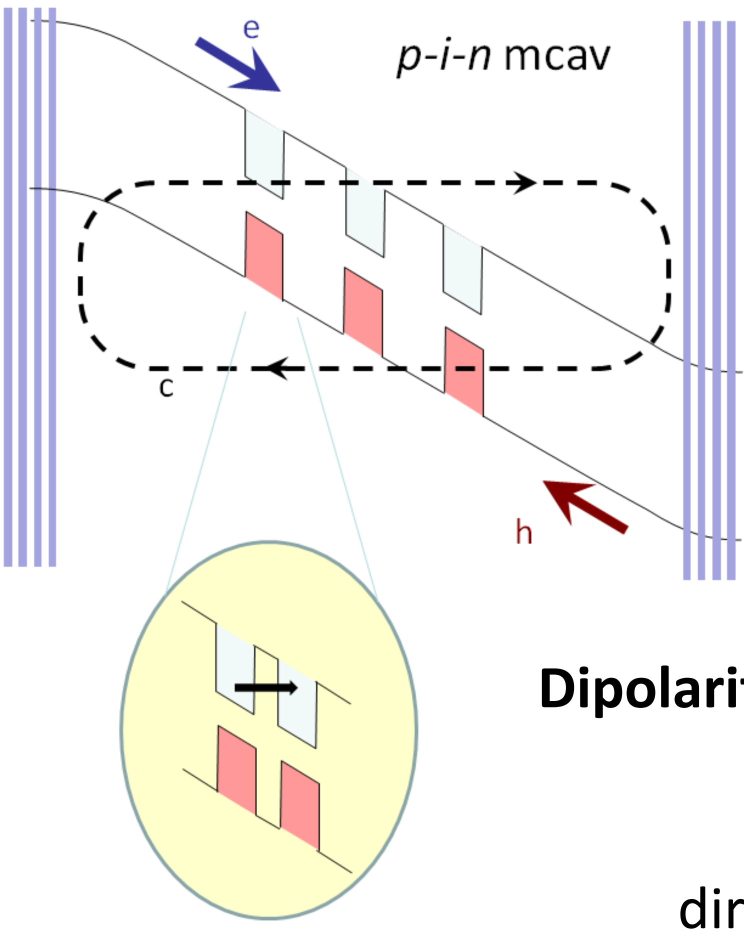


Relaxation on lower branch governed by polariton-polariton interactions (dipole-dipole)



- **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

⬇

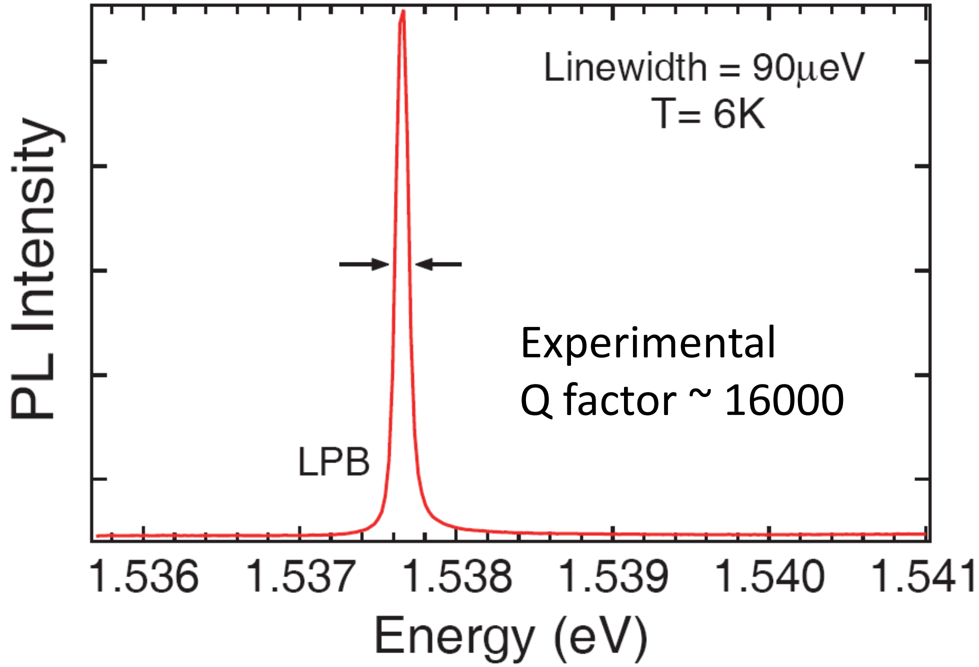
direct control of polariton dipole

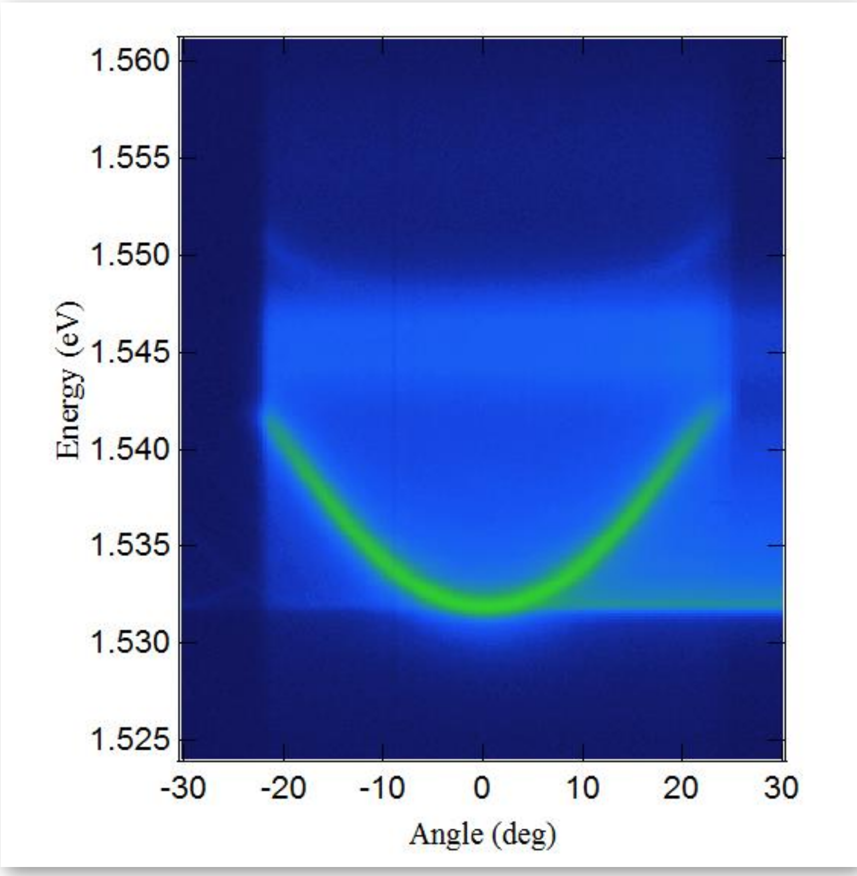
$$H_{PP}^{eff} = \frac{1}{2}\sum_{k,k',q}\frac{a_B^2}{A}V_{k,k',q}^{PP}\hat{p}_{k+q}^{+}\hat{p}_{k'-q}^{+}\hat{p}_{k}\hat{p}_{k'}$$

dipole-dipole

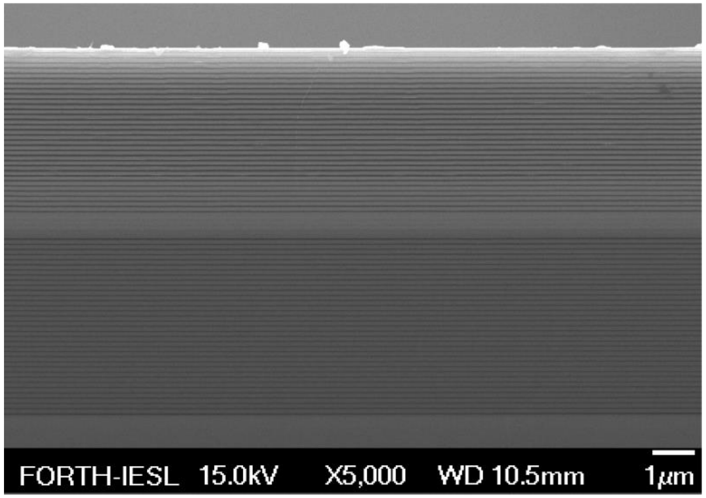
P. Cristofolini *et al.*, Science 336, 704 (2012)   G. Christmann APL 98, 081111 (2011)

High finesse GaAs microcavity

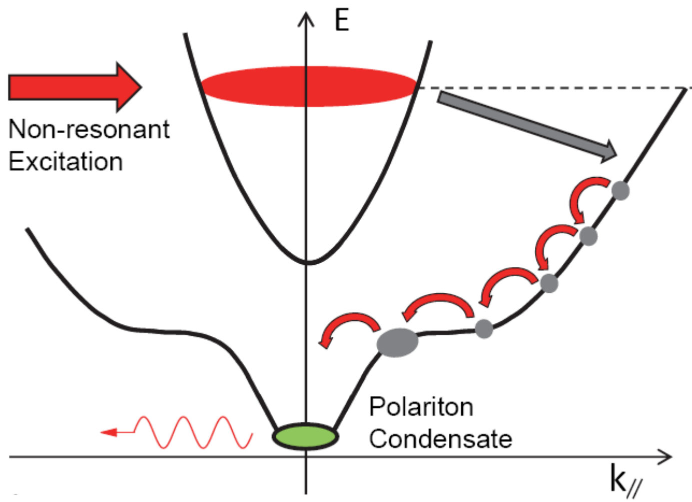


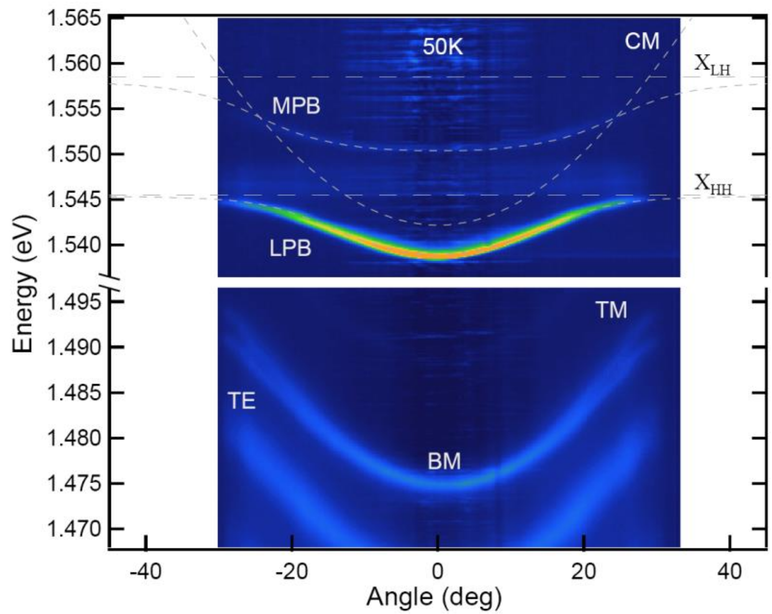


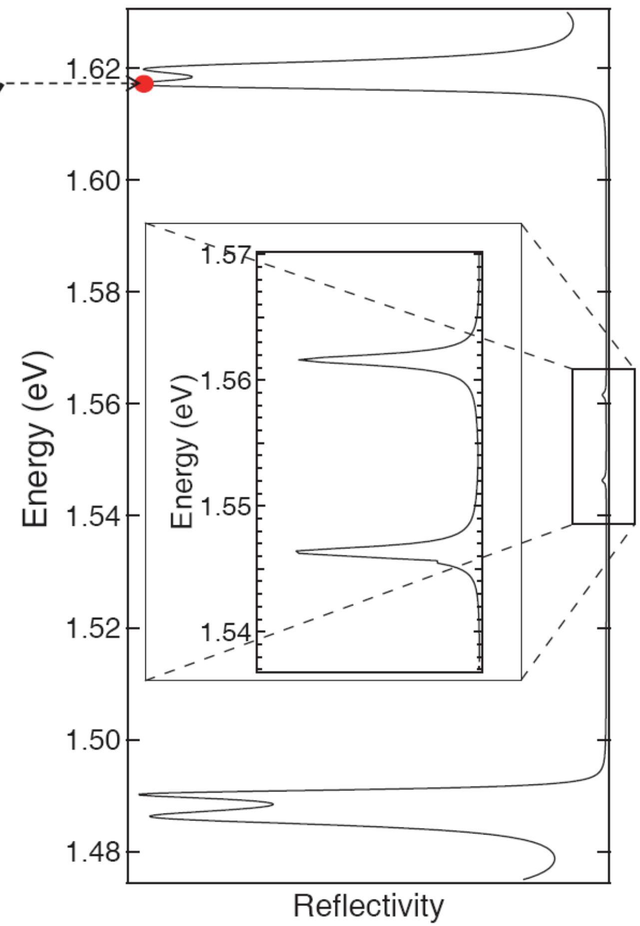
Modeled Q factor ~ 20000



Non-resonant optical excitation

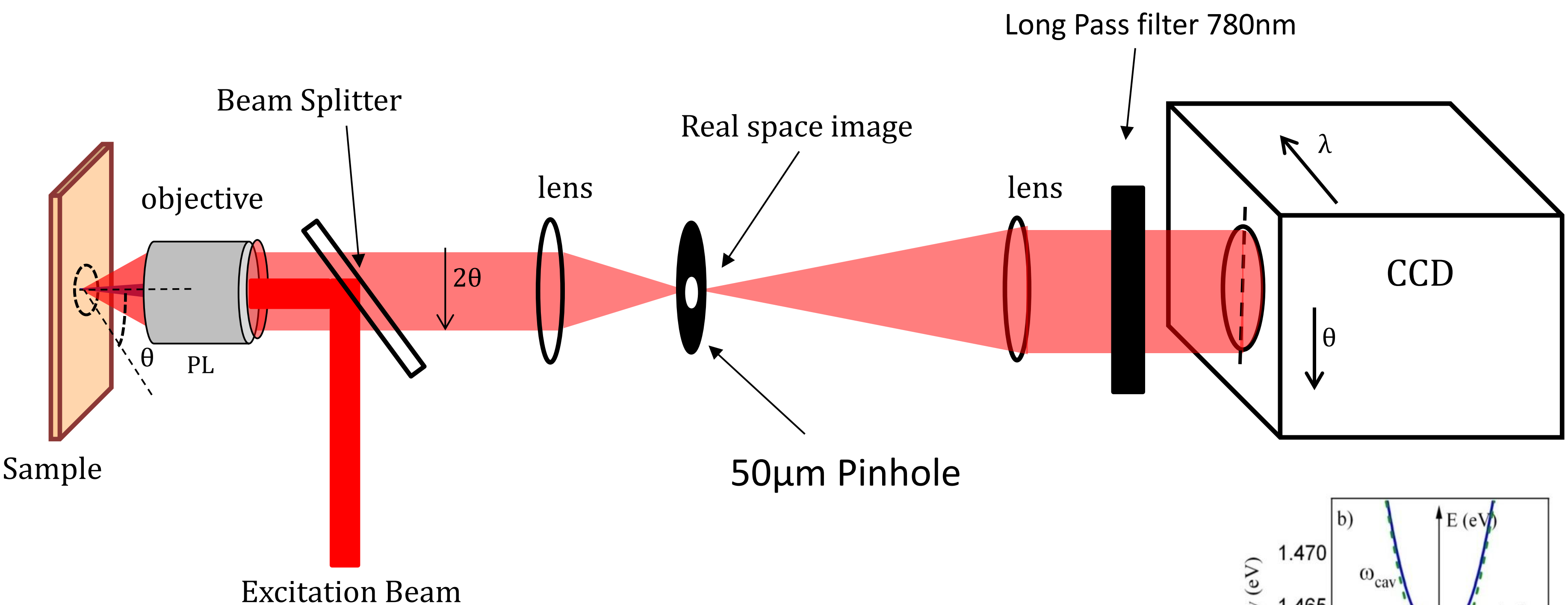


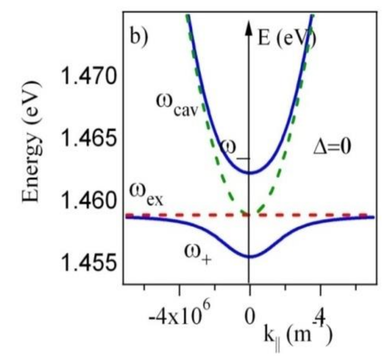




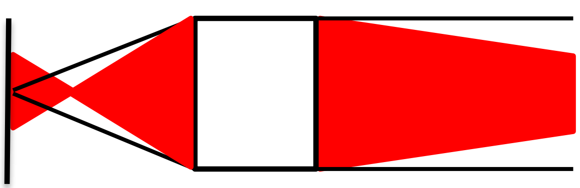
- Rabi splitting of 9.2meV at 50K
- Reflectivity dips relatively small

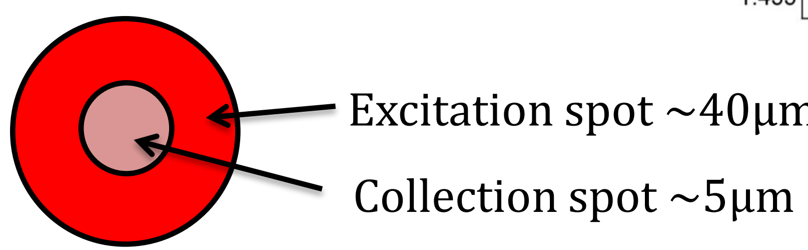
PL imaging Setup





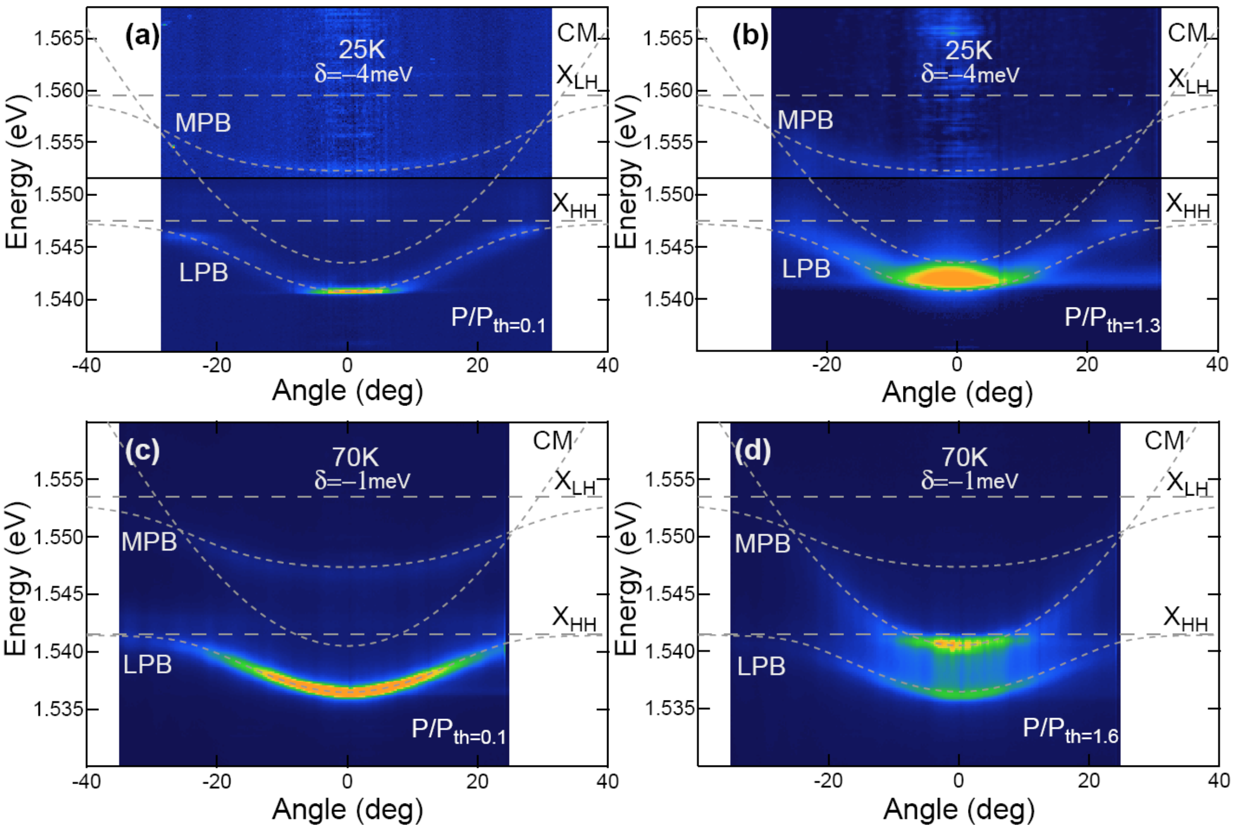
Collection of light from a very small part of excited area

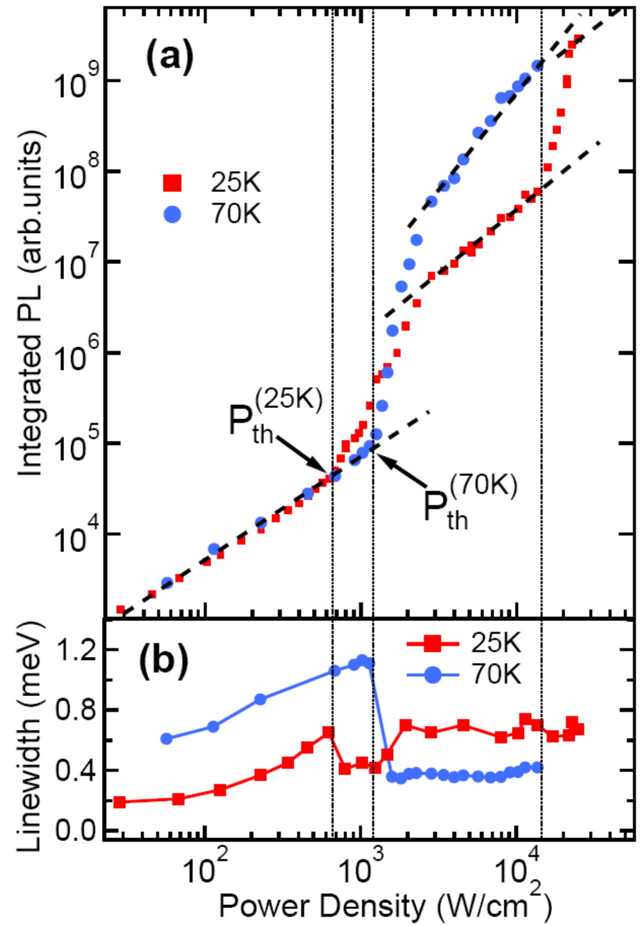




GaAs Polariton Laser 25K vs 70K

- 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

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

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

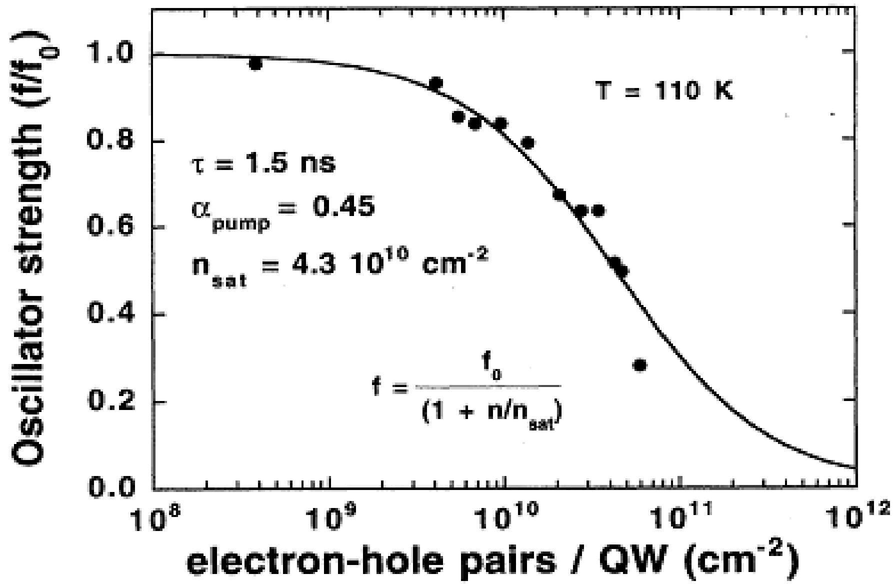
$$\Gamma_0 = \frac{e^2}{4\varepsilon_0 n_{cav} m_0 c} \frac{f}{S}$$

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

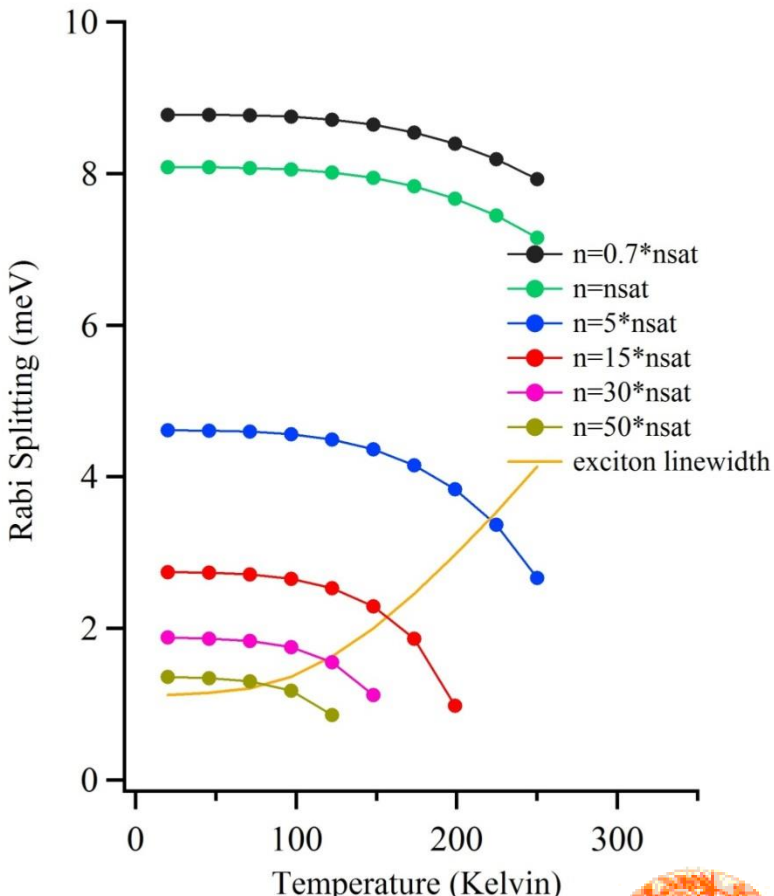
f : exciton oscillator strength

n : carrier density

n_{sat}: saturation density



(PRB , M. Ilegems)

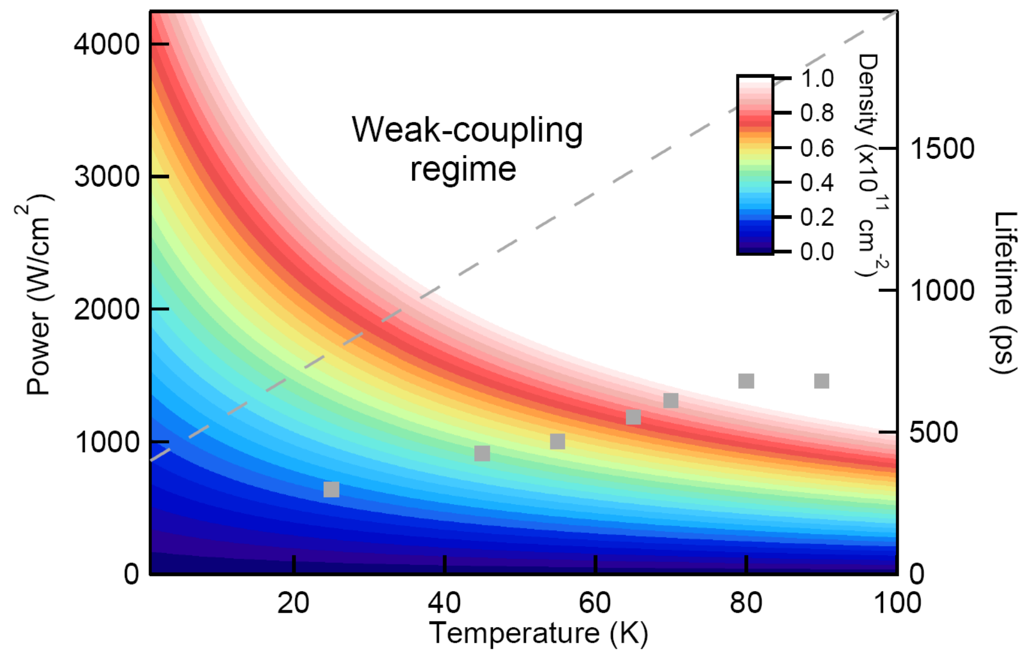


Crossover from Strong to Weak coupling Lasing

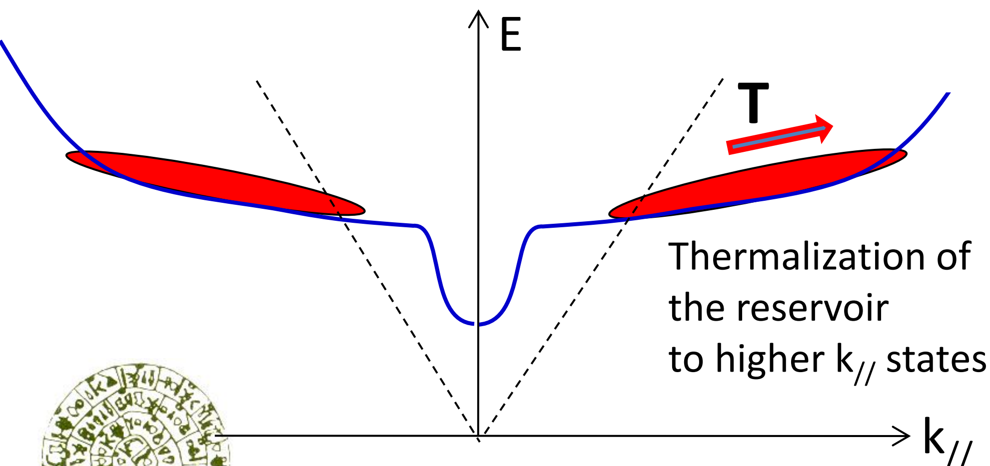
$$\frac{dN}{dt} = g - \frac{N}{\tau} \Rightarrow N = g \cdot \tau \quad \text{(steady state)}$$

↑ pump

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



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



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

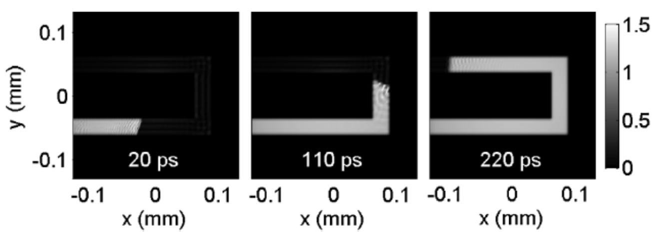
Polaritonic Circuits

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

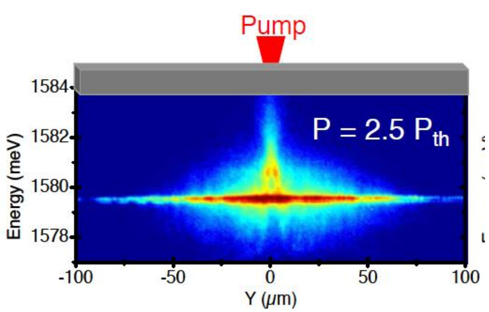
Approach: Polaritons being hybrid photonic and electronic states offer natural bridge between these two systems

- 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

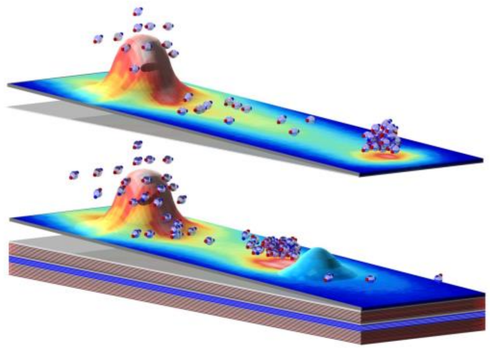
Macroscopic quantum properties of polariton condensates make them ideal candidates for use in quantum information devices and all optical circuits



Liew PRL **101,** 016402 (2008)



Wertz , Nature Phys **6,** 860 (2010)

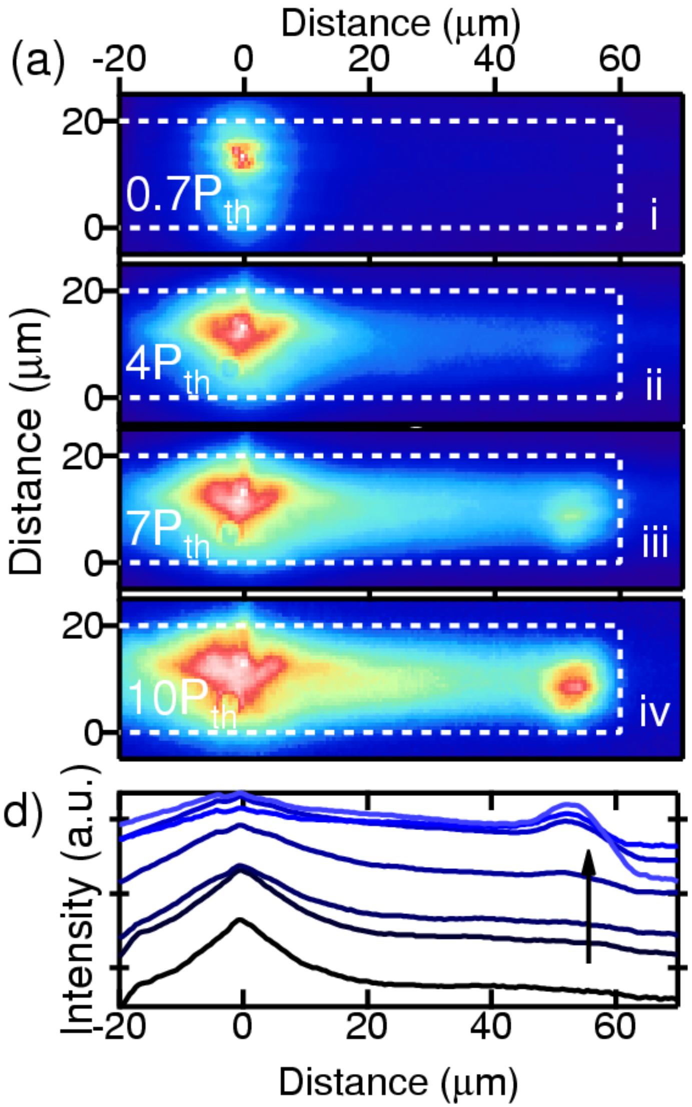


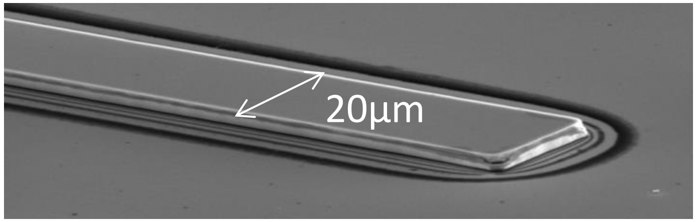
Amo et al., Nature Phot. **4**, 361 (2010).

Ballarini et al., Nat Comm. **4**, 1778 (2013).

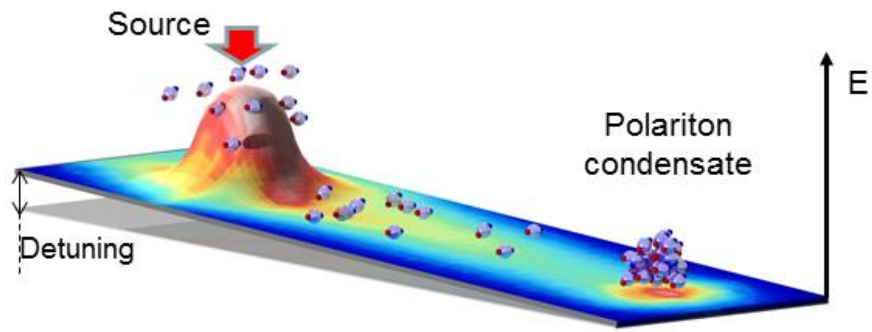
Gao, Phys. Rev. B **85**, 235102 (2012)

Generating Polariton Condensate Flow

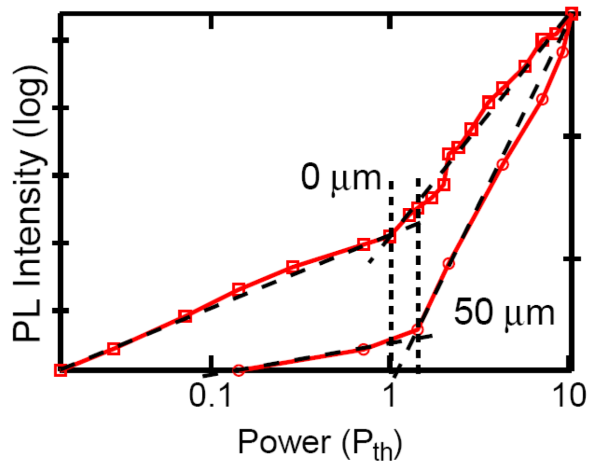




Only top DBR is etched

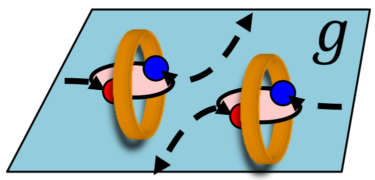


- Polariton condensate forming at the ridge end

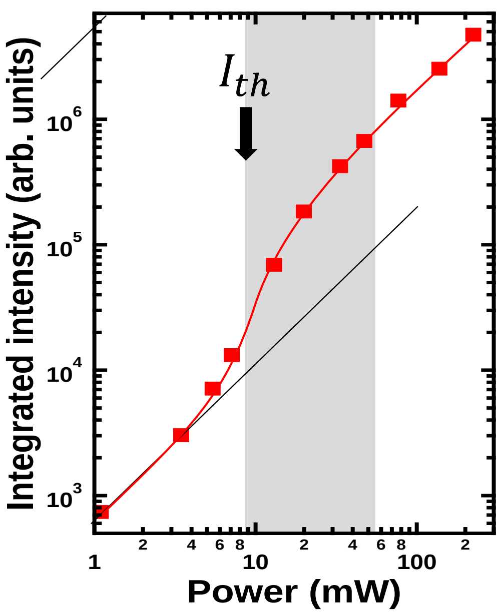


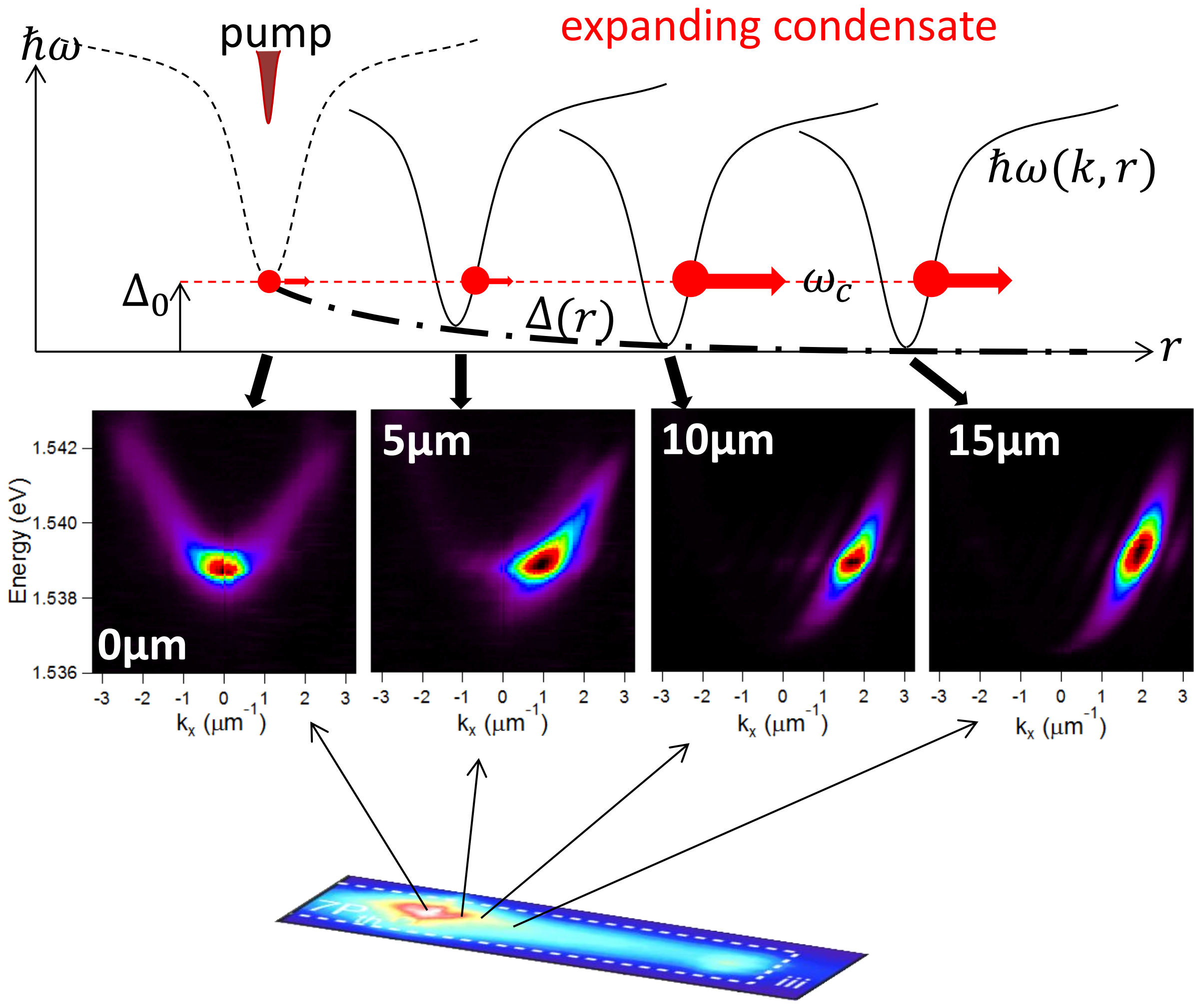
- Local pump induced blueshift and lateral confinement forces polariton flow along the ridge

Ballistic Condensate Ejection



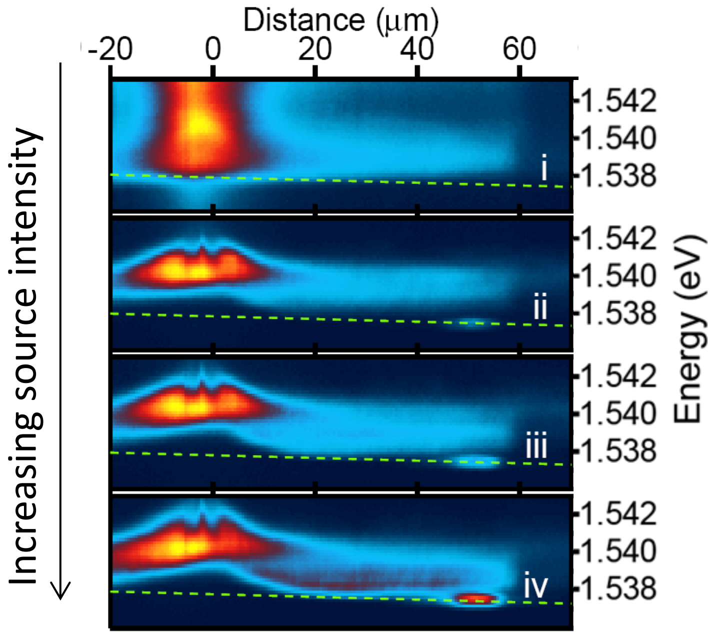
- blue shift at pump
  $V_{max} = g|\psi|^2$
- polaritons expand along the ridge



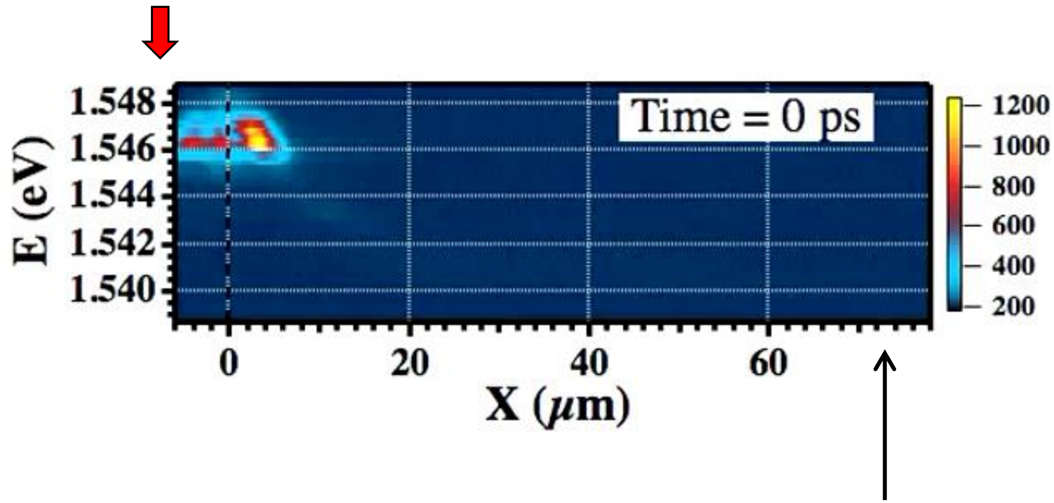


G. Christmann *et al.*, Phys. Rev. B 85, 235303 (2012)

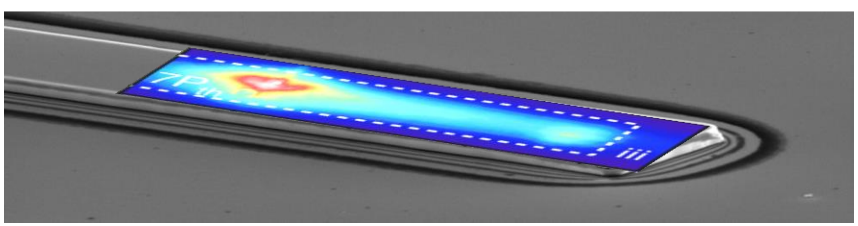
Polariton Condensate Dynamics



Pump pulse



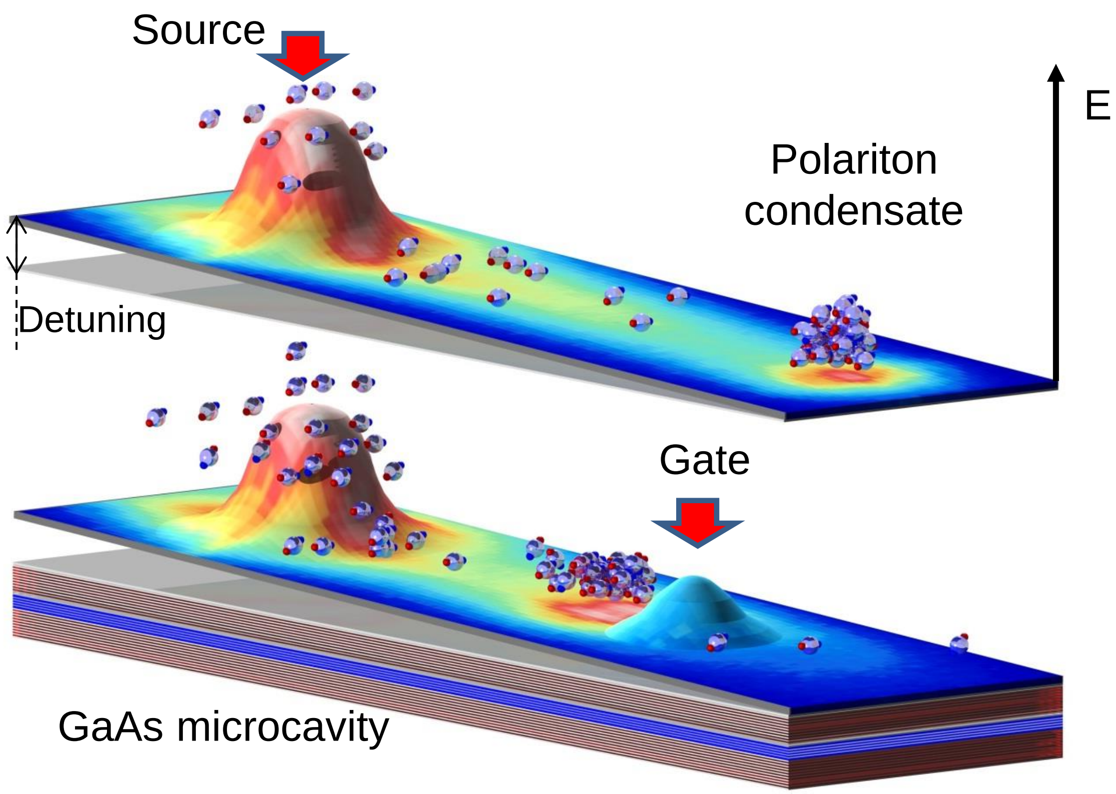
Build-up of polariton condensate at ridge end



Anton et al., Appl. Phys. Lett. 101, 261116 (2012)

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

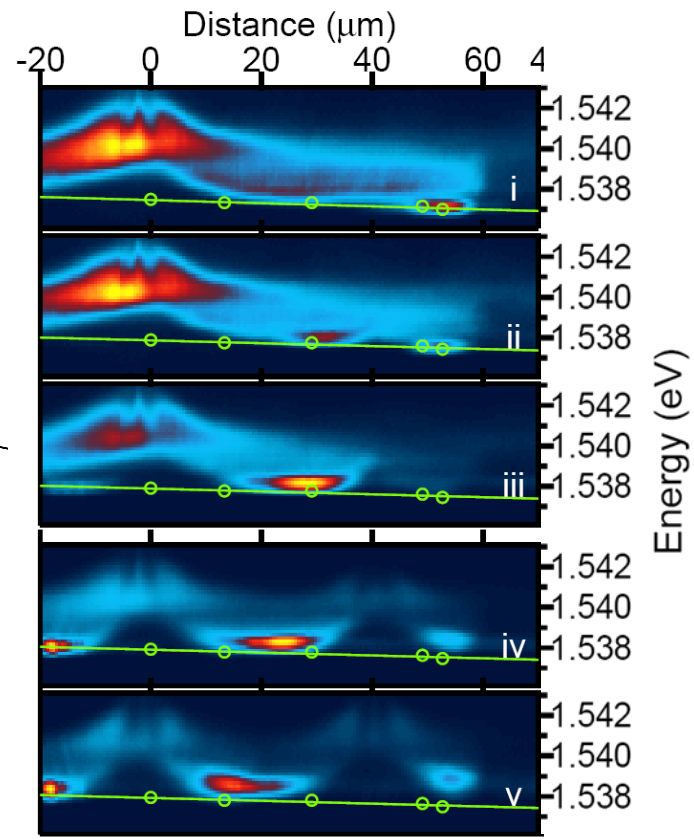
Polariton Condensate Transistor Switch

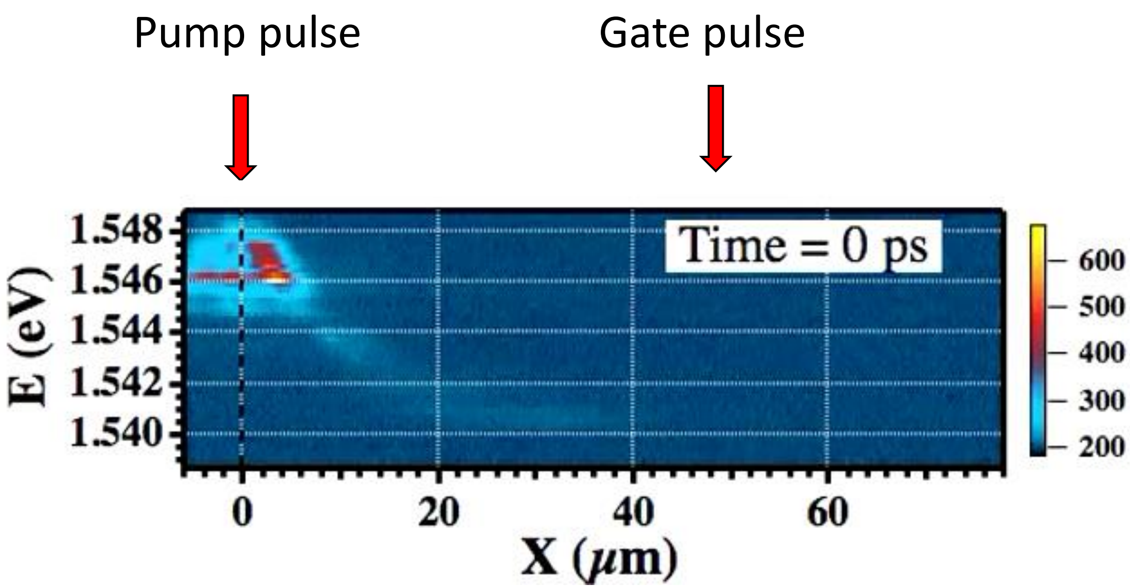


- Polariton propagation is controlled using a second weaker beam that gates the polariton flux by modifying the energy landscape

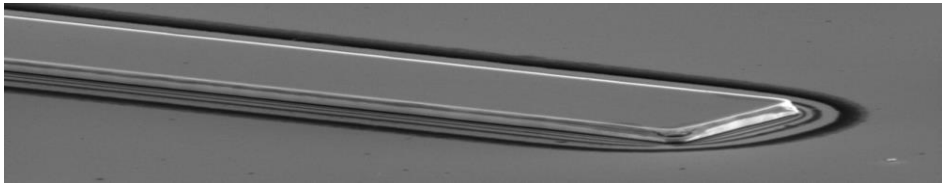
Gao, Phys. Rev. B **85**, 235102 (2012)

Gating Polariton Condensate Flow





90% gating of the polariton condensate flow

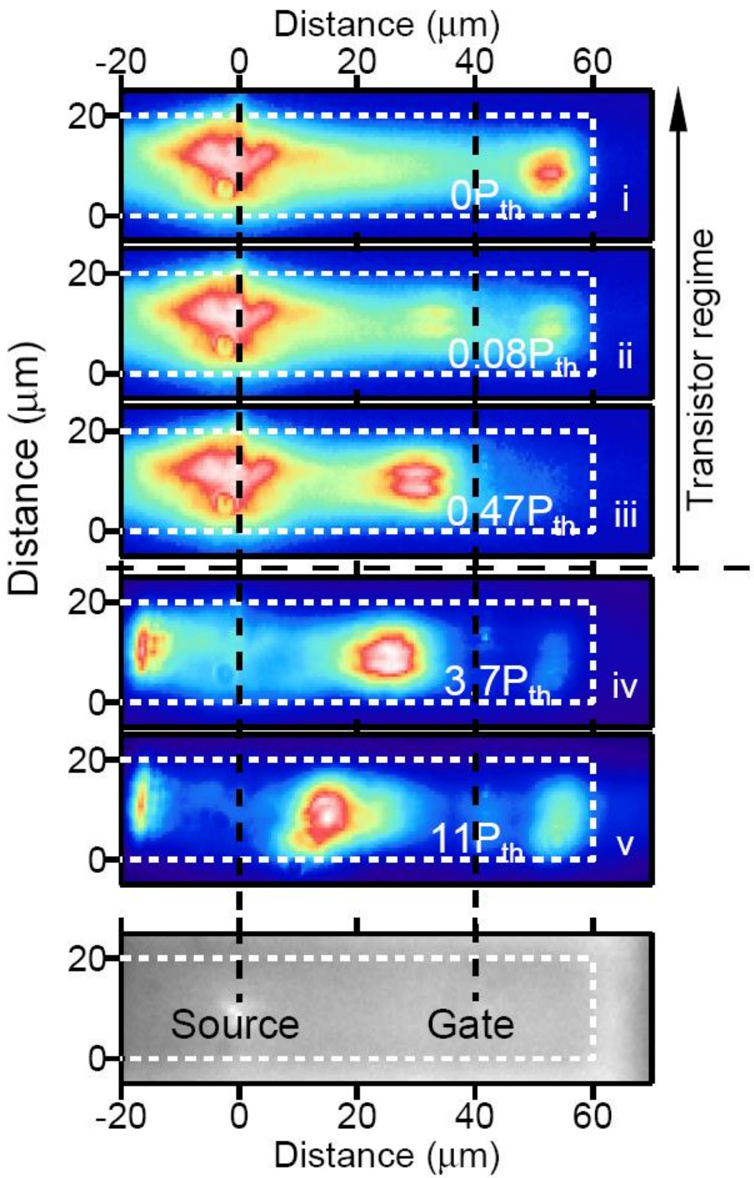


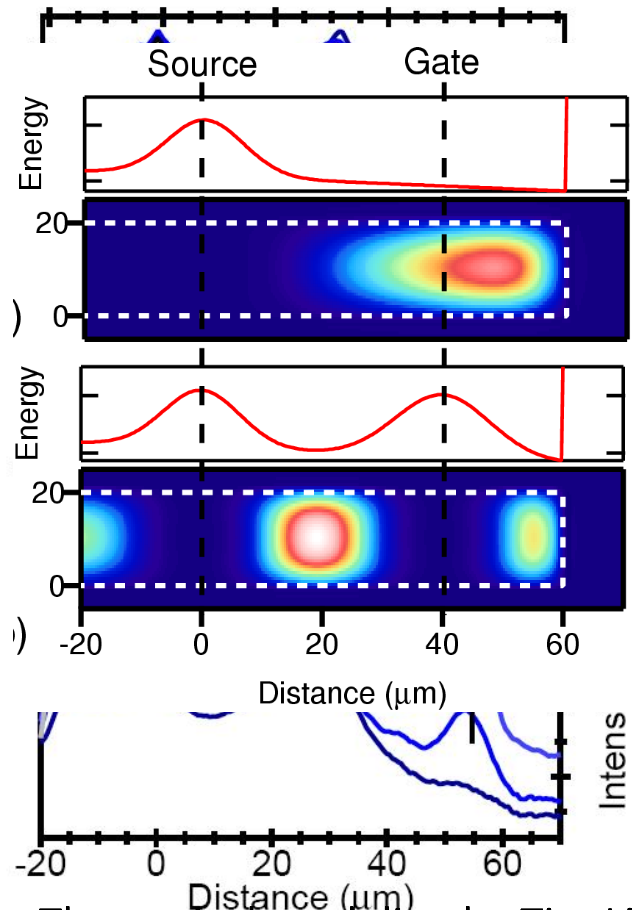
- Gate beam power 20 times weaker than source
- Second condensate appears between source and gate at higher gate powers

Gao, Phys. Rev. B **85**, 235102 (2012)

Anton et al., Appl. Phys. Lett. 101, 261116 (2012)

Gating Polariton Condensate Flow



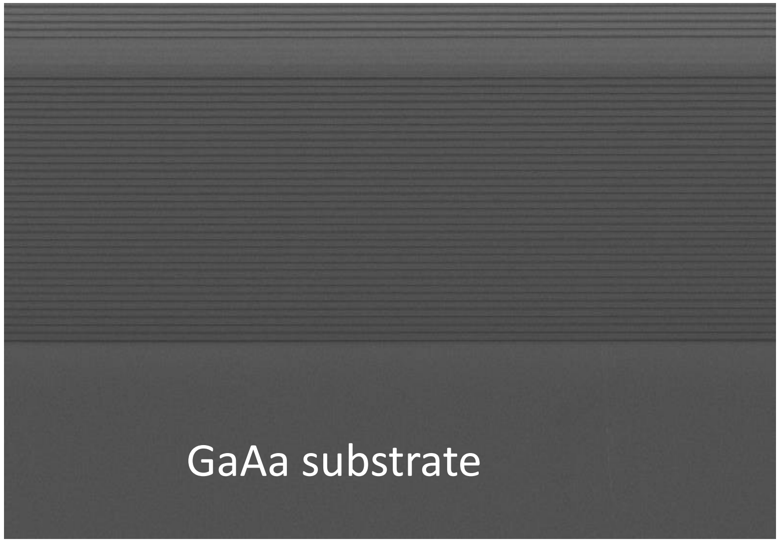


Theoretical modeling by Tim Liew

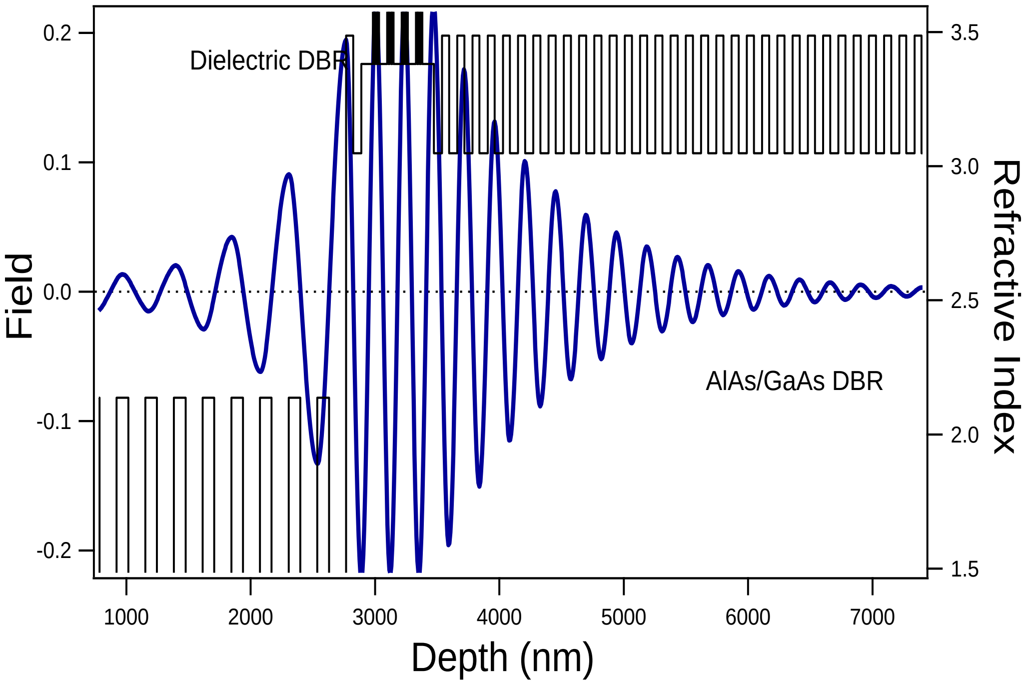
- gating efficiency up to 90% is demonstrated

High Q hybrid GaAs/dielectric microcavity

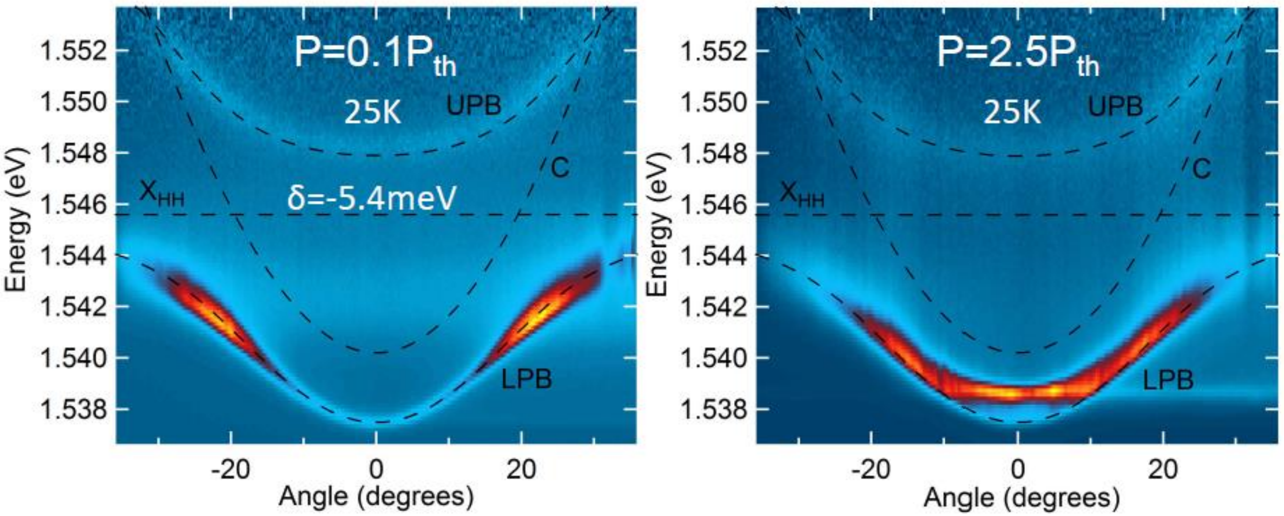
- Dielectric DBR mirrors in hybrid microcavity
- Allows precise control of electrical contact close to the cavity

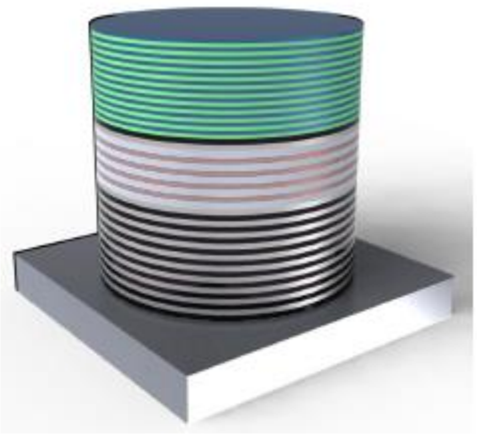


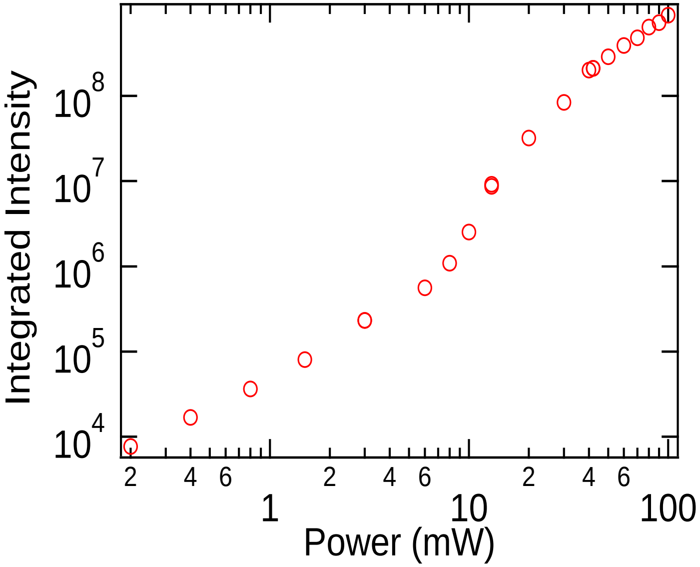
Half microcavity structure



Polariton Lasing in Hybrid Microcavities



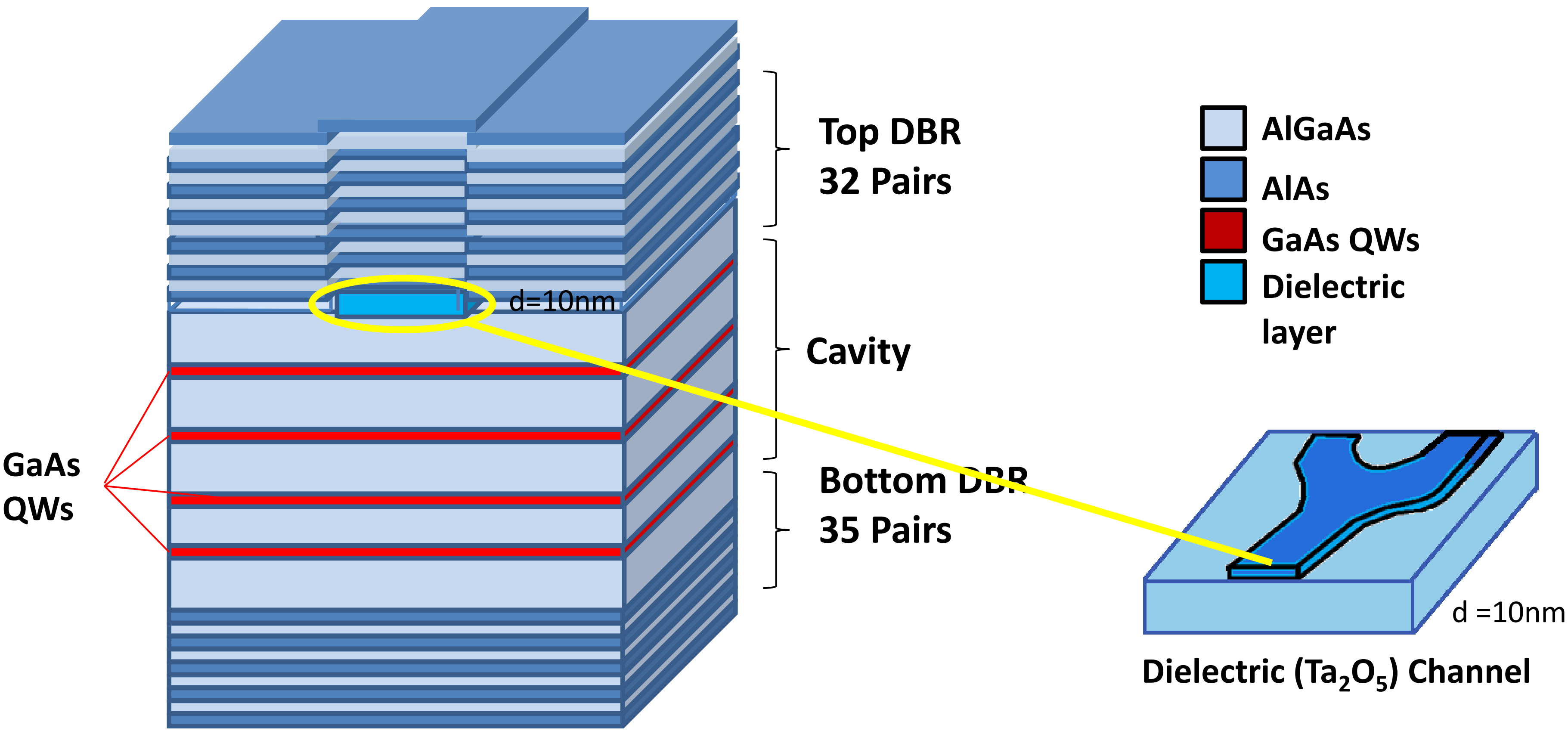




- Observation of the formation of a polariton condensate
- Contacts can be easily deposited close to the cavity region

Writing Polariton Circuits with dielectric Channels

- Dielectric DBR mirrors in hybrid microcavity
- polariton confinement in dielectric channels
- Allows precise control of electrical contact close to the cavity

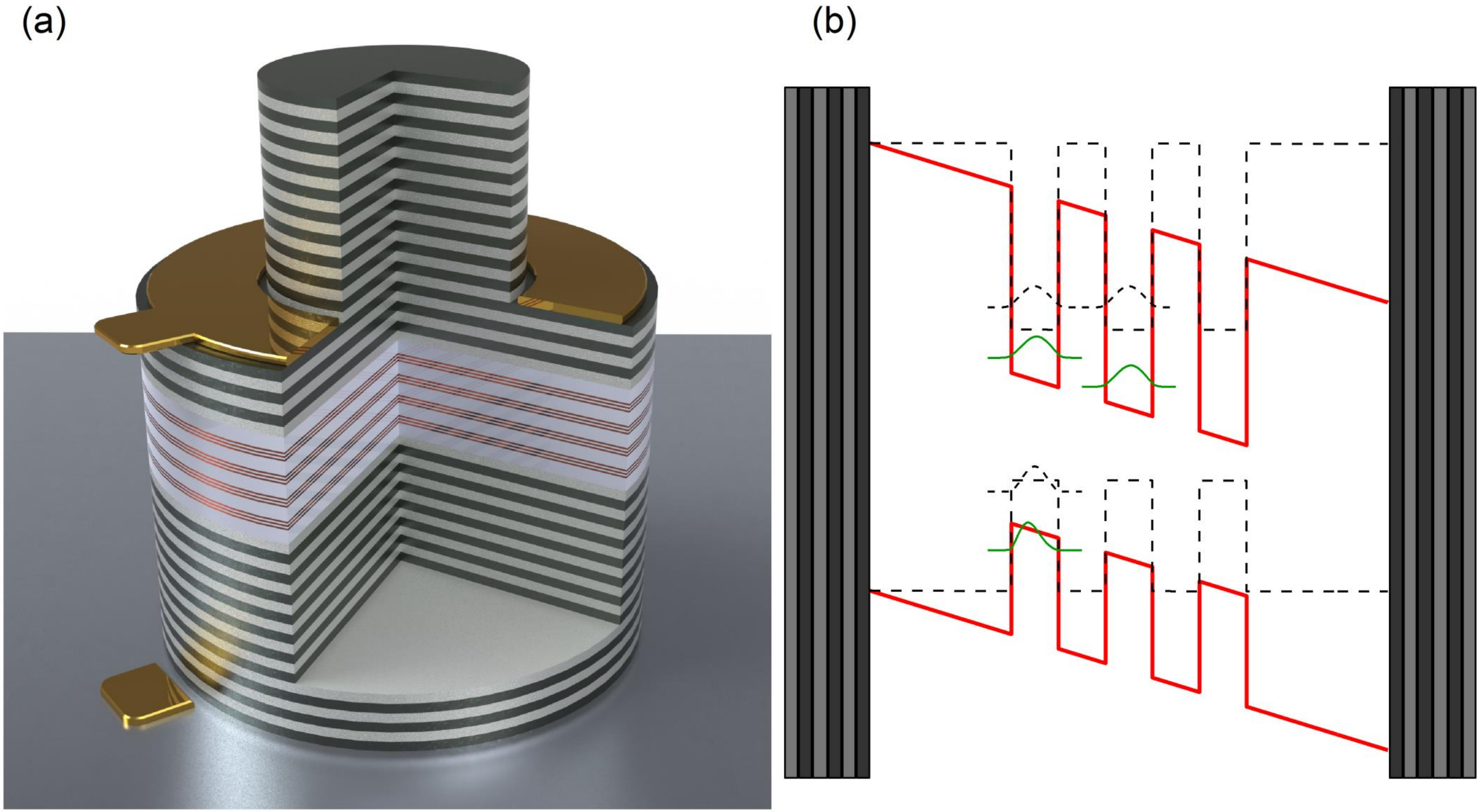


Dielectric (Ta_2O_5) Channel

Electrical and optical control of polariton condensates

Is electric gating of transistor feasible ?

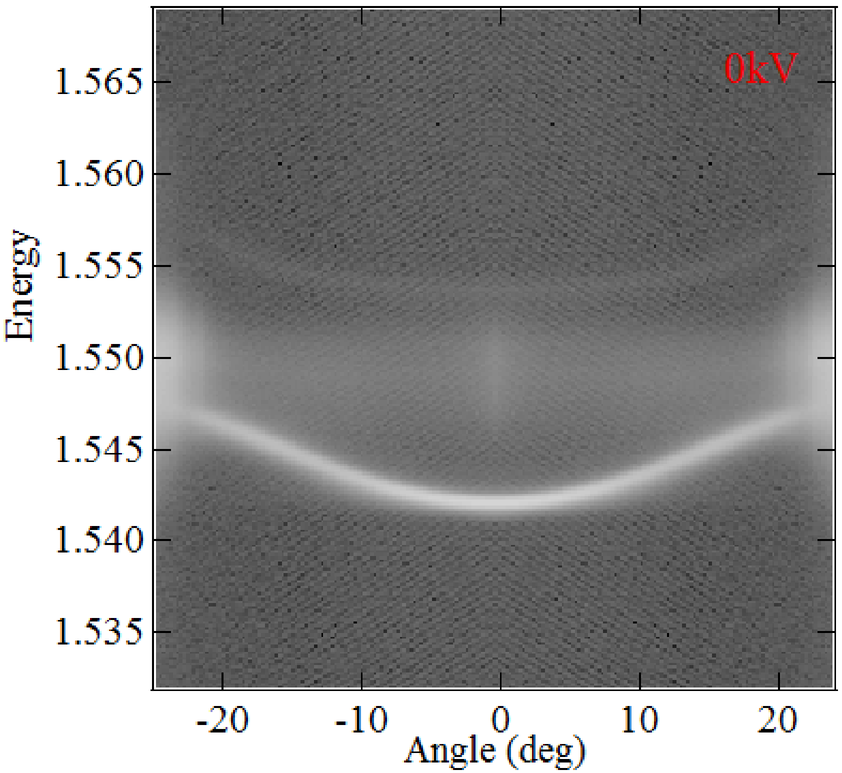
Electrical control of a polariton condensate



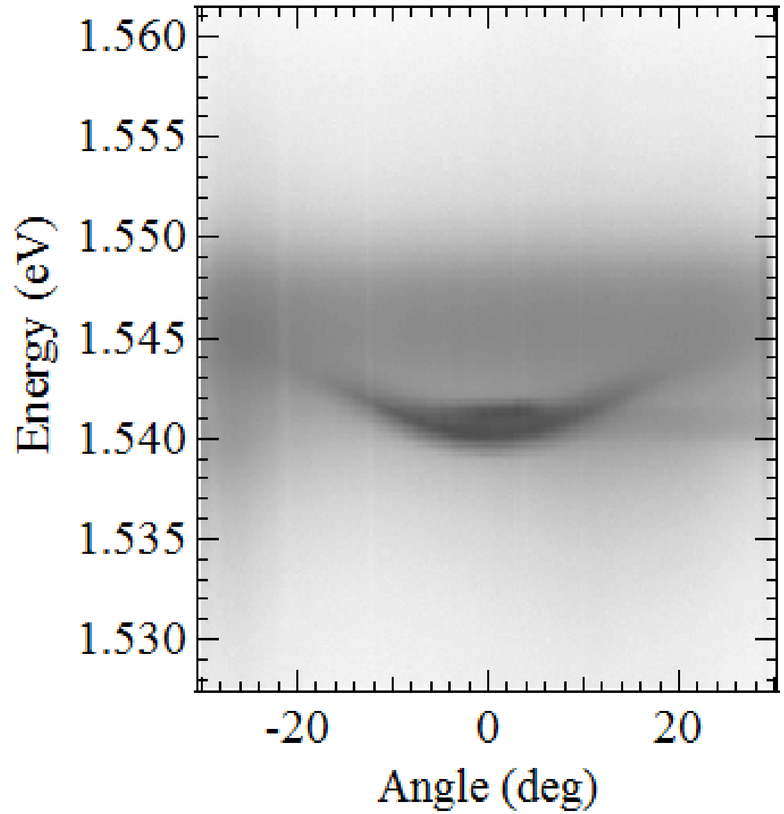
- AlGaAs/GaAs quantum wells- 10nm well , 10nm barrier

Linear and non-linear regimes

Below Threshold

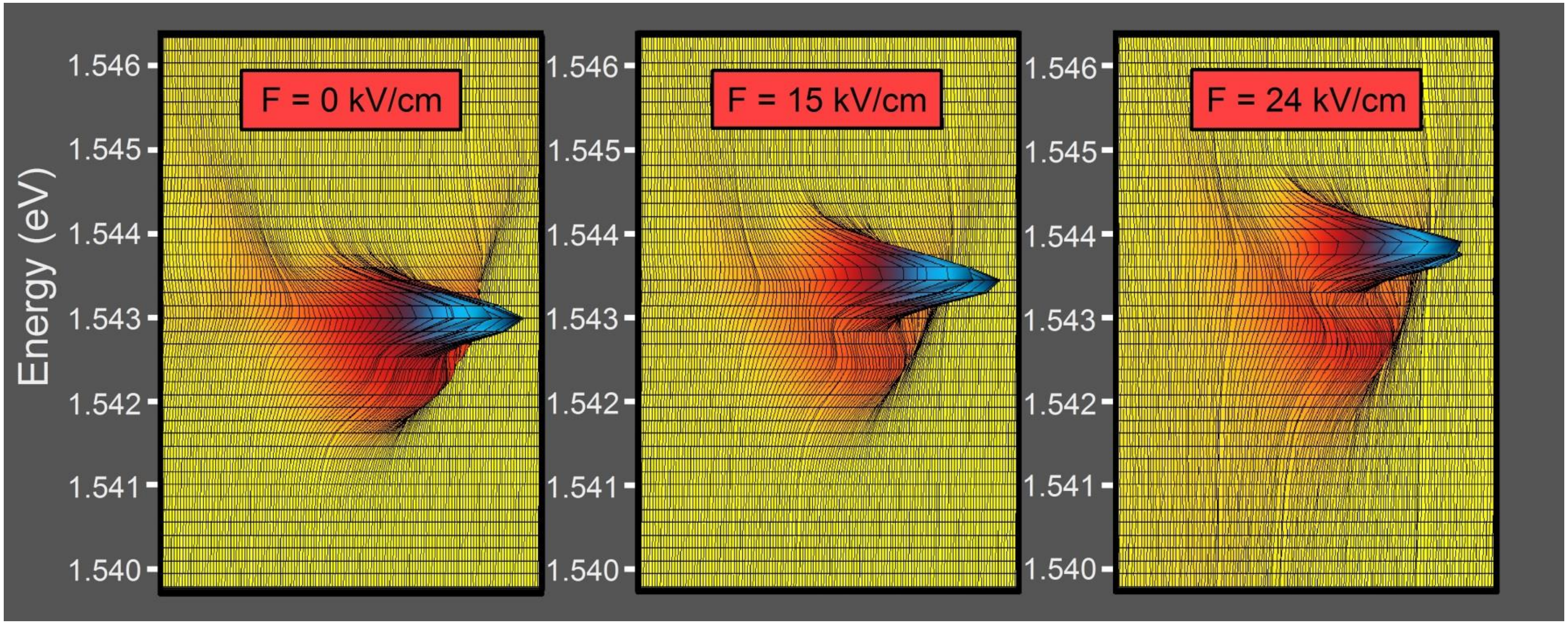


Above Threshold



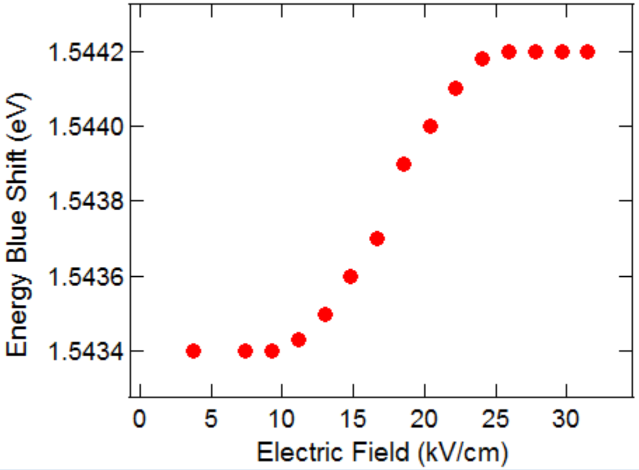
Electric field tuning of a polariton condensate

Non-linear regime



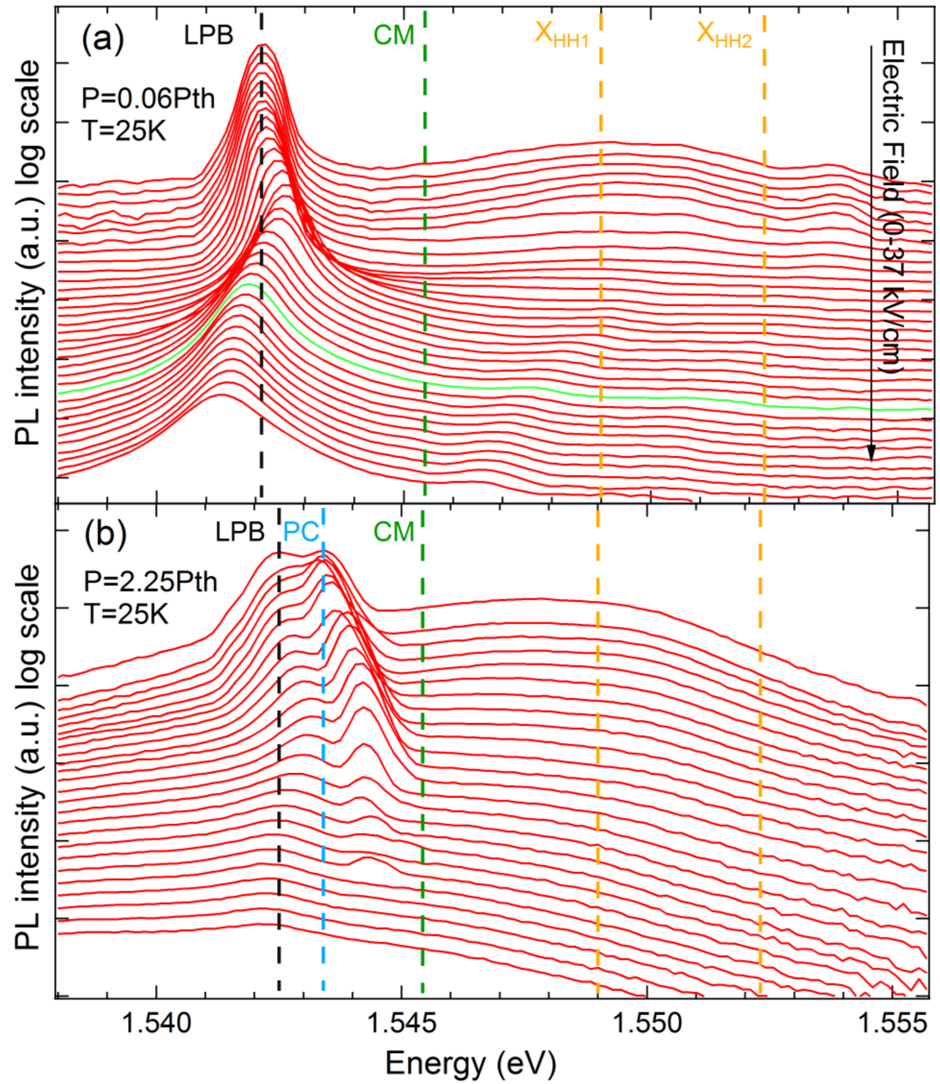
- Blueshift 0.8meV

- Larger Rabi splitting should allow larger tuning



Linear and non-linear regimes

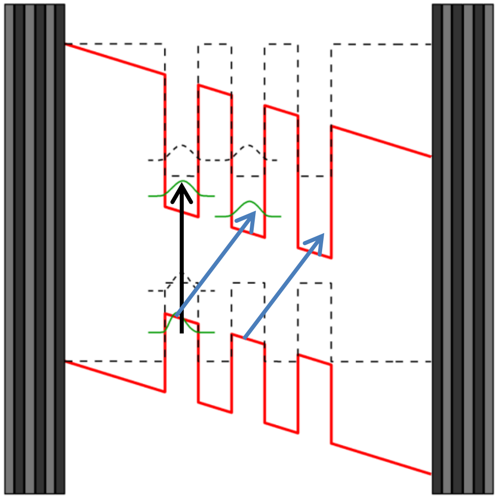
- Linear regime
  - Small fields-blueshift
  - Large fields-redshift
- Non-linear regime
  - Small fields- blueshift
  - Large fields- Emission quenching
- Interpretation
  - Reduction in oscillator strength
  - Quantum confined Stark Effect
  - Contribution of indirect exciton

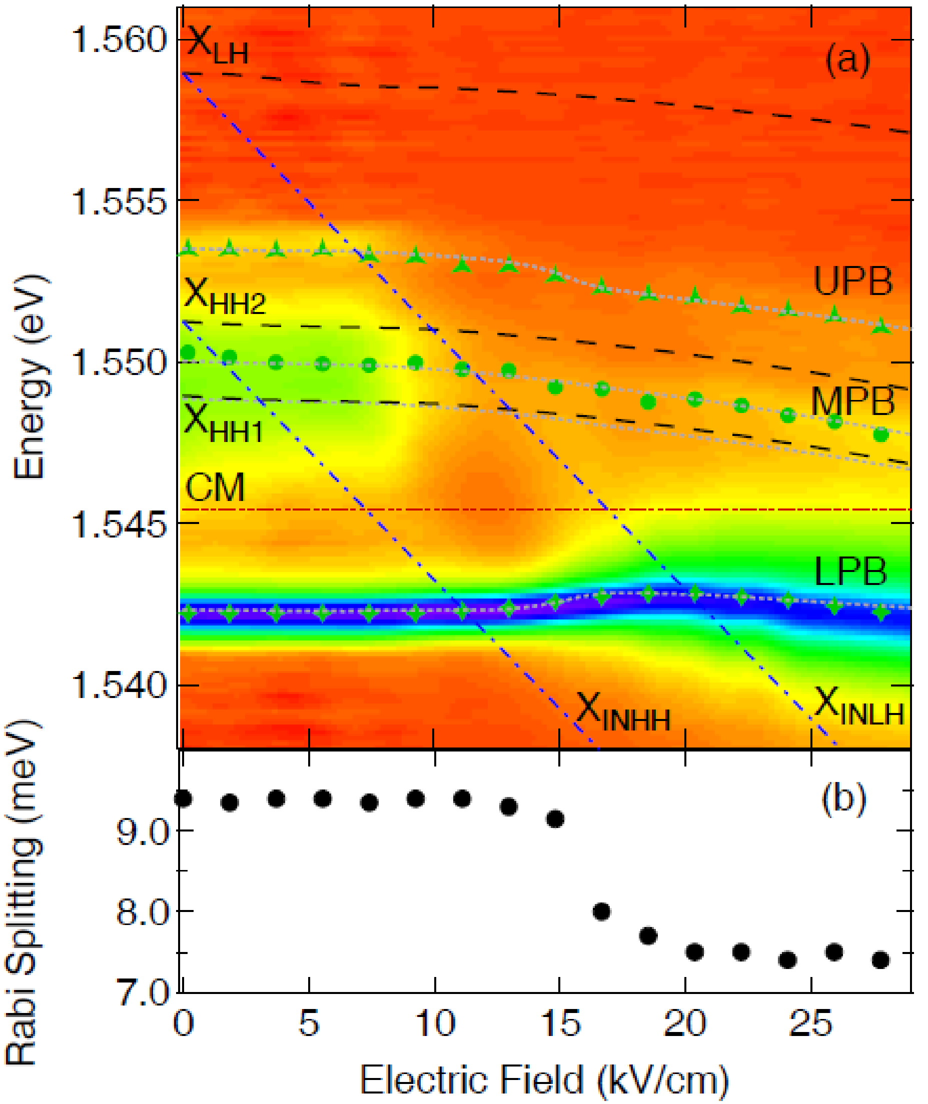


Electric field tuning of a polariton condensate

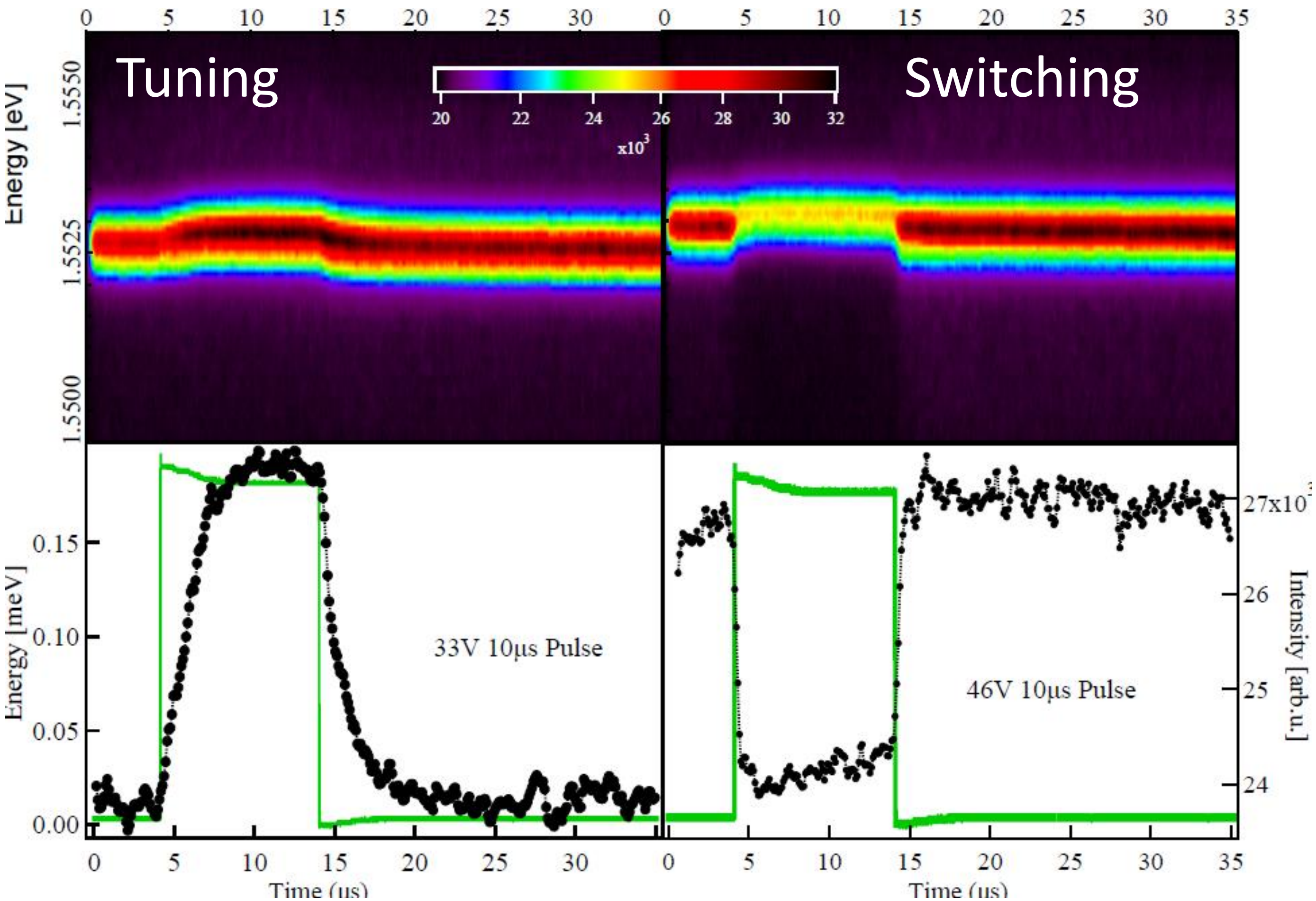
Linear Regime

- Origin of blueshift under investigation
  - Indirect exciton





Dynamical Response

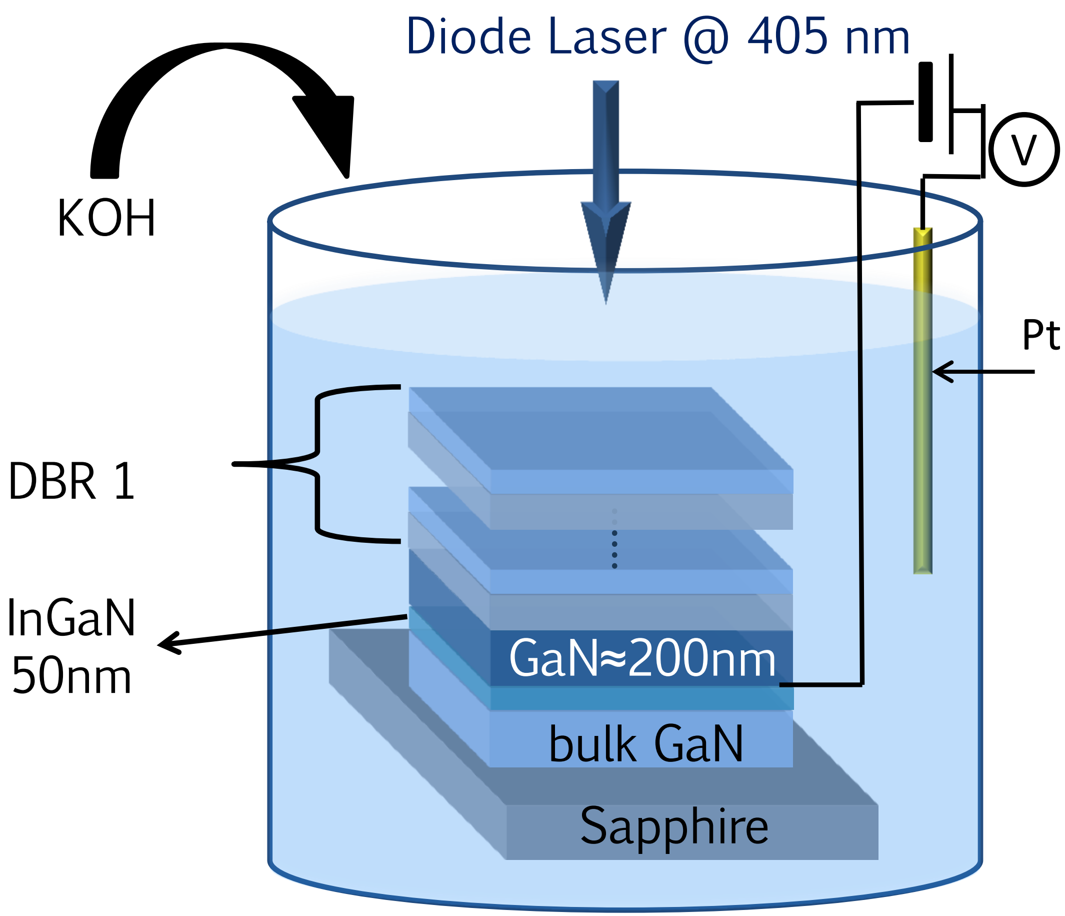


In collaboration with Southampton
P. G. Lagoudakis

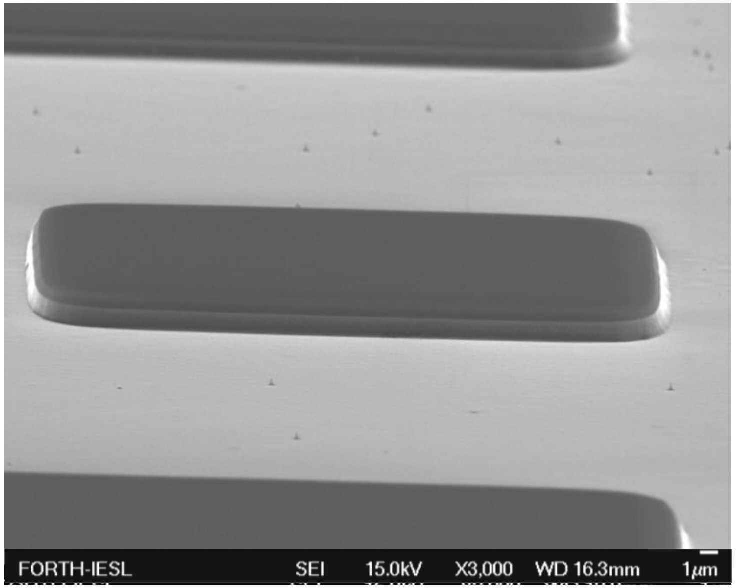
- Different modulation regimes are possible
- Voltage dependent response may indicate screening effects

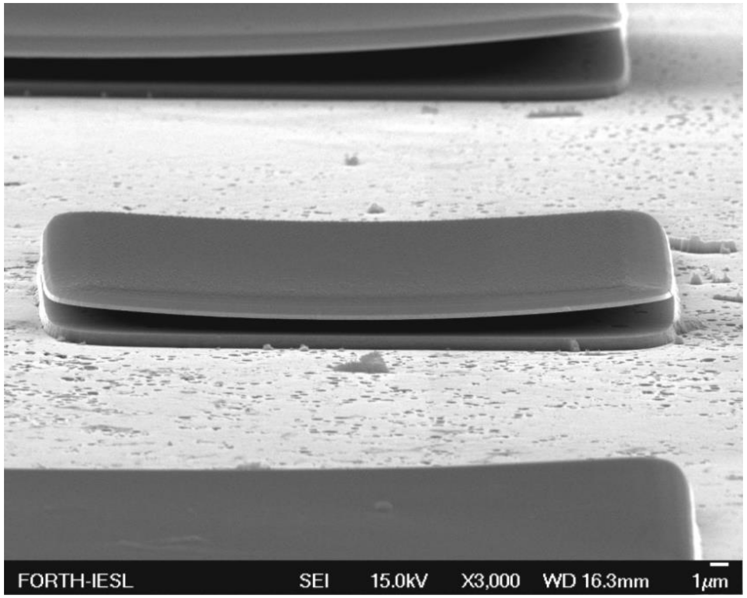
Polariton Lasing in GaN
At room temparature

All-Dielectric mirror GaN microcavity

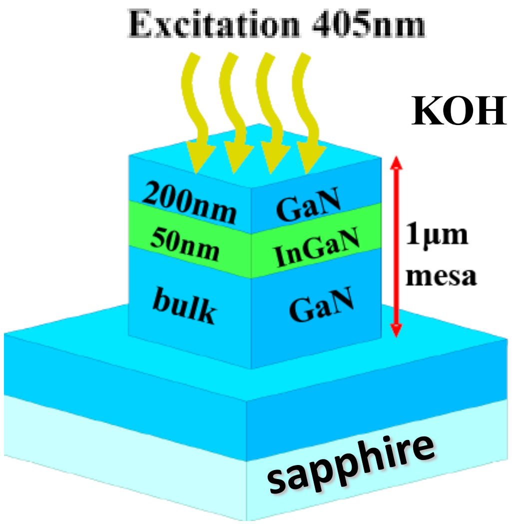


Mesa formation by
Reactive Ion Etching (40μm × 40μm x 1μm)

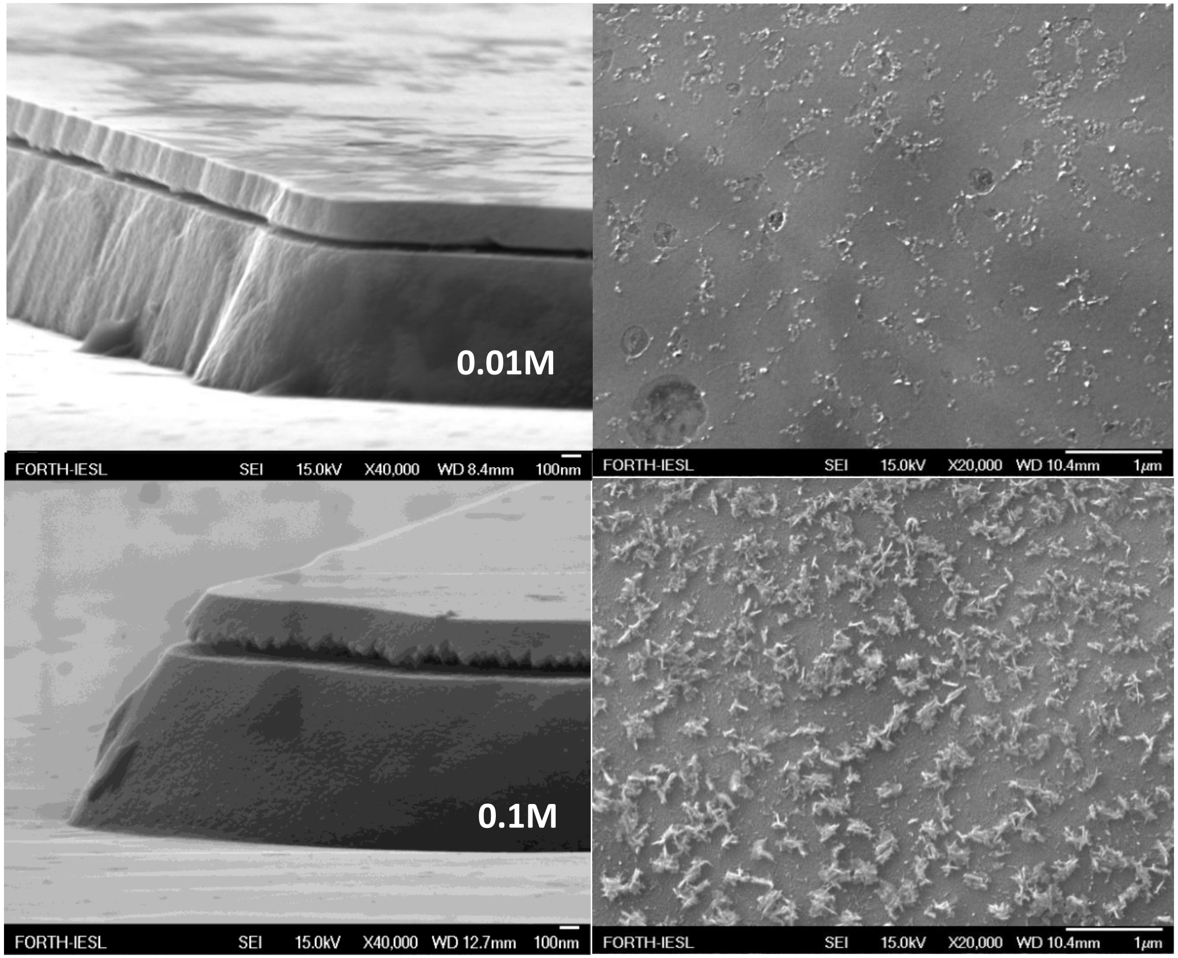


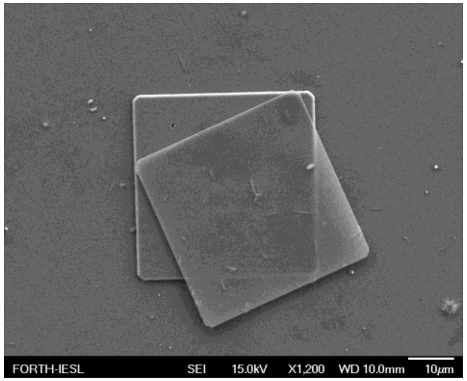


Freestanding GaN membranes by Lateral Etching of InGaN



- Optical quality GaN membranes

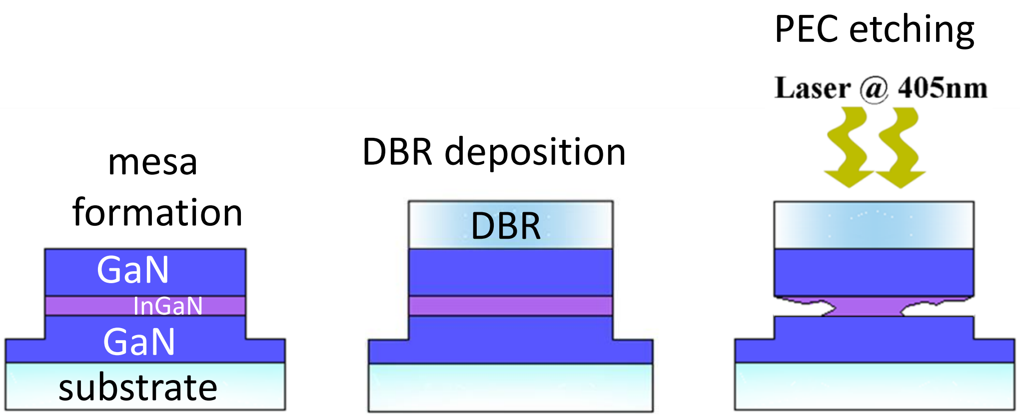


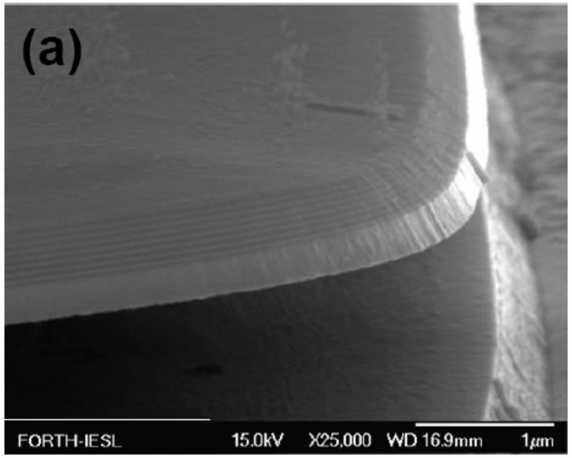


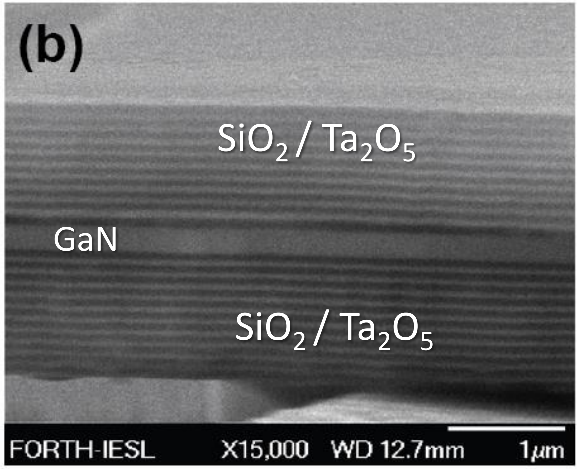
Trichas et. al, APL **94**,173505 (2009)

Trichas *et al.* APL **98**, 221101 (2011)

Bragg Luminescence in All Dielectric Microcavity



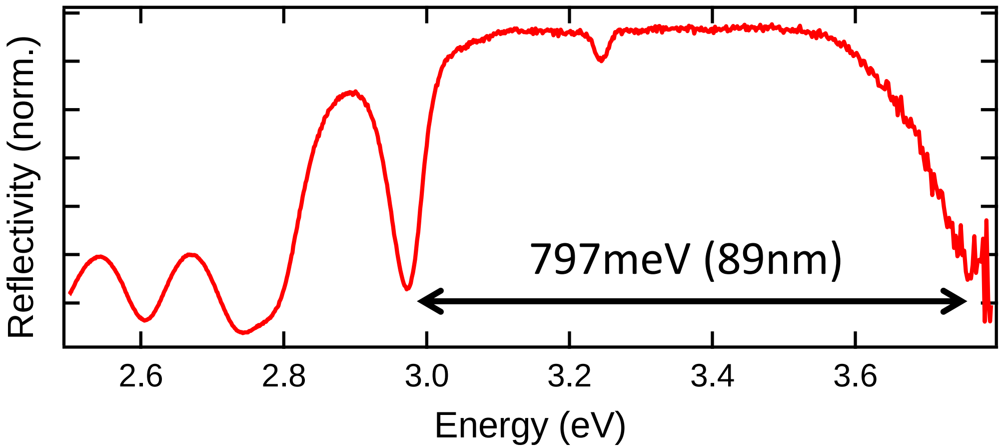


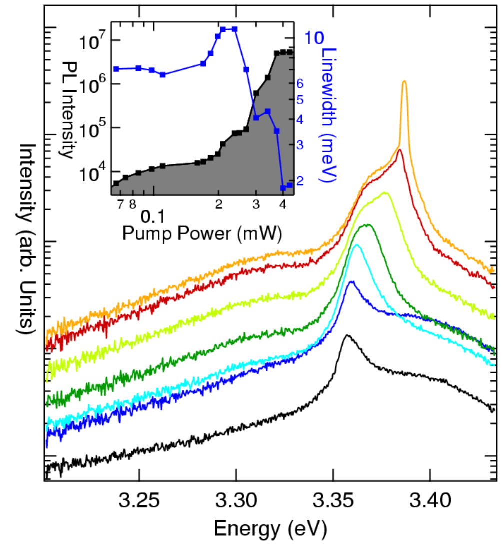


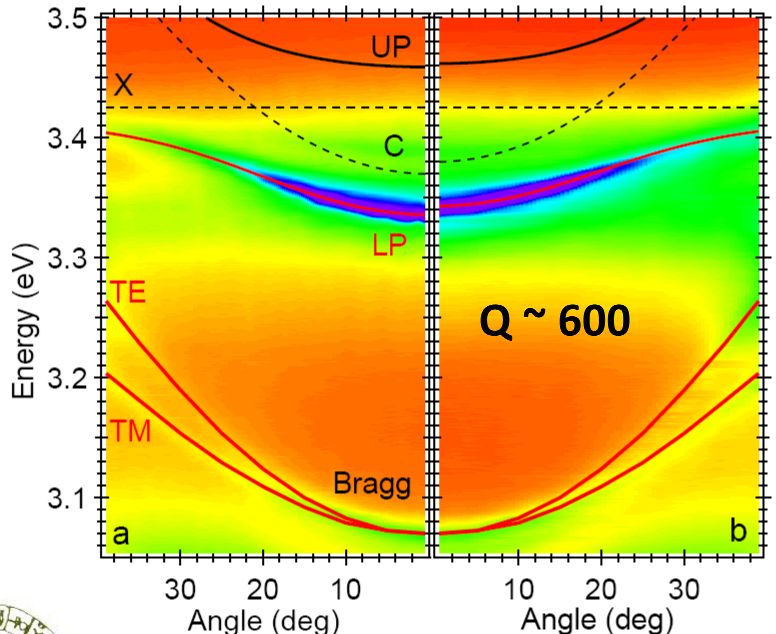
SEM of the free standing GaN membrane/DBR

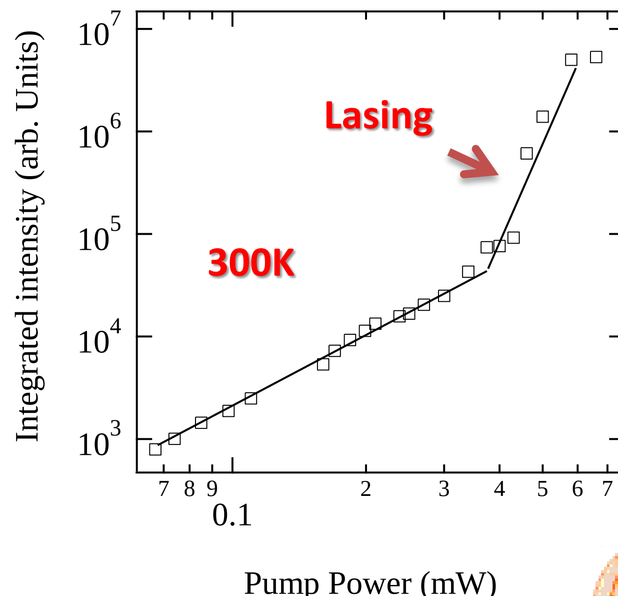
E. Trichas, Appl. Phys. Lett. 98, 221101 (2011)

Room temperature GaN based polariton laser





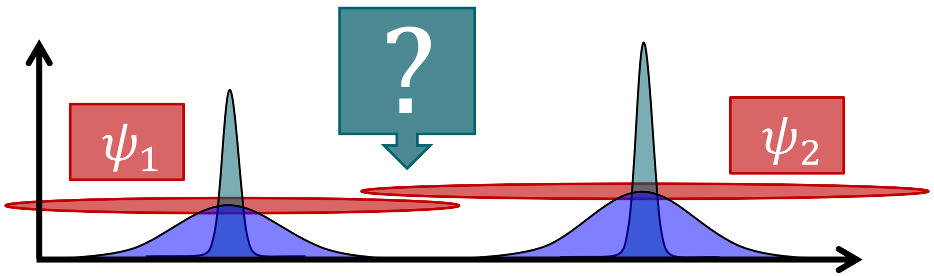




Appl. Phys. Lett. 102, 101113 (2013)

Interacting polariton condensates

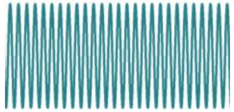
Phase Locked Condensates



Mode Locking

$$\psi = \sqrt{\rho} \cdot e^{-i\left(\frac{Et}{\hbar} + \varphi\right)}$$

Phase Locking



$$\theta = (E_2 - E_1)t/\hbar \rightarrow 0$$

$$\ddot{\theta} + 2\alpha\dot{\theta} = 4\tilde{g}J\frac{\alpha}{\sigma}\sin(\theta)$$

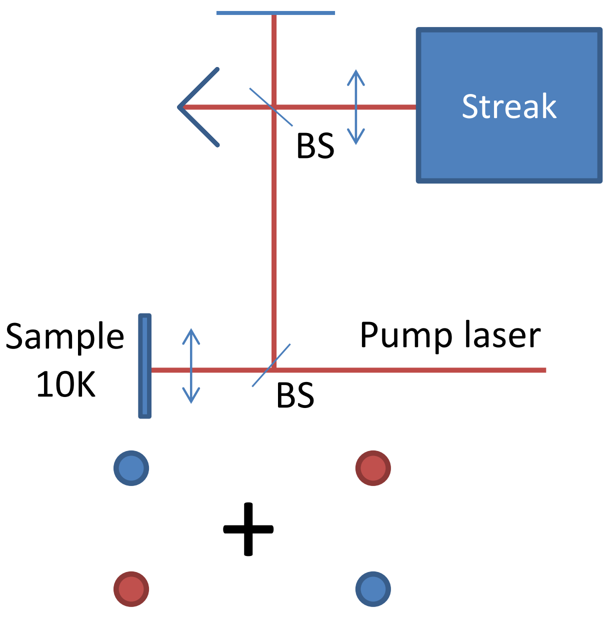
Damped Pendulum

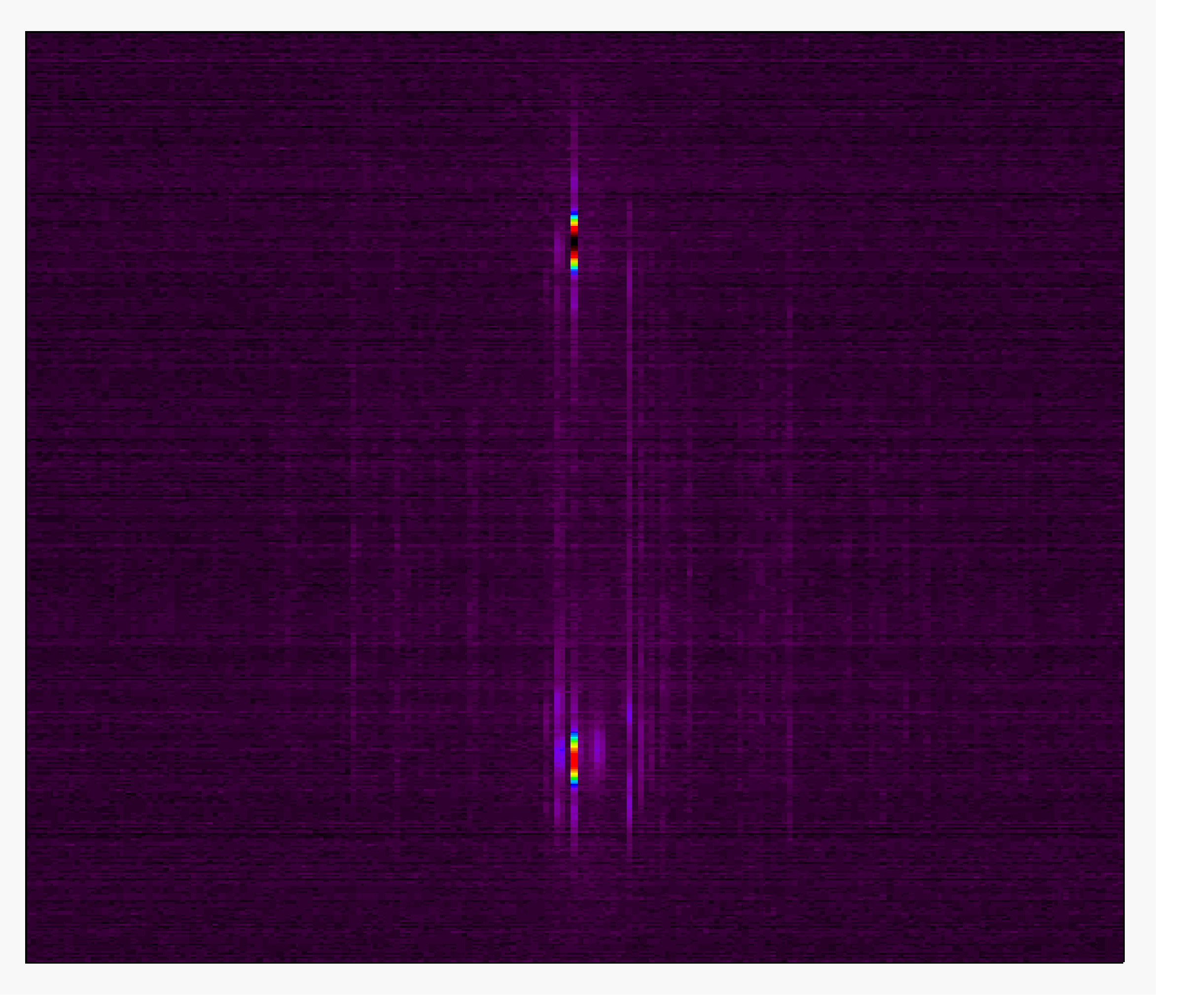
Trapping Transition: PRL **110,** 186403 (2013)

Buildup of Coherence and Phase Locking

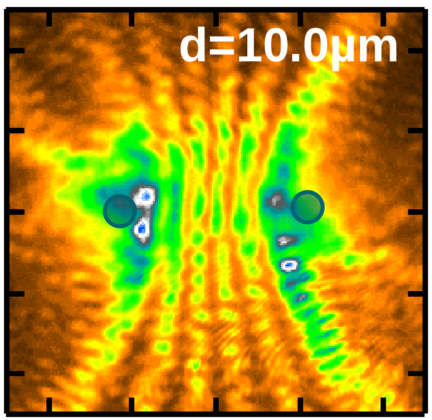
Time resolved measurement & interferometry

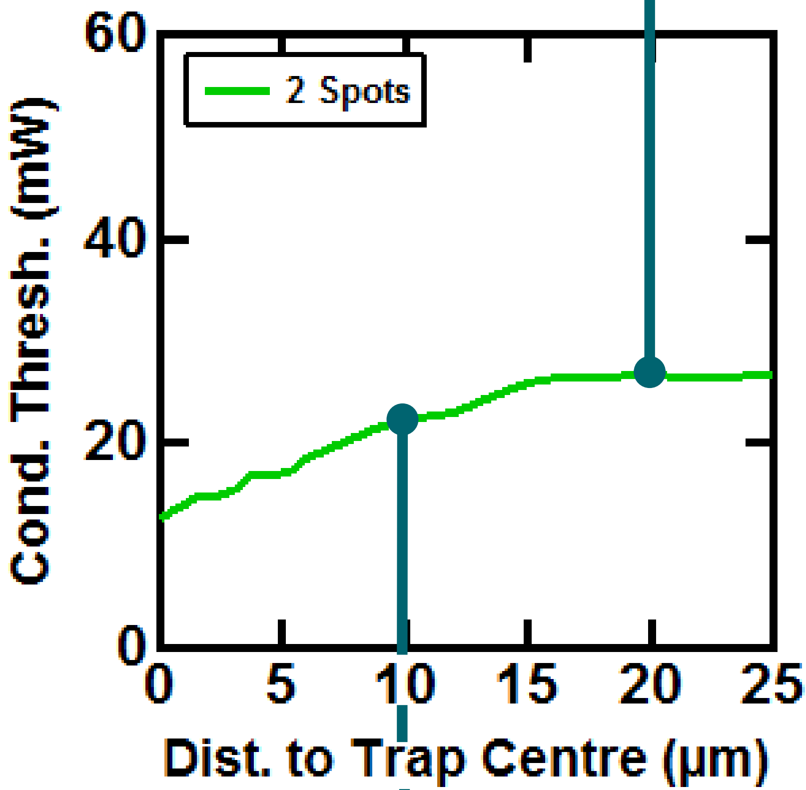
Pulsed excitation, interference of one condensate with the other

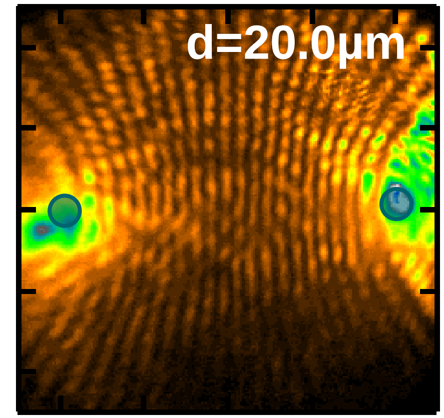




N = 2: Cooperative Effect







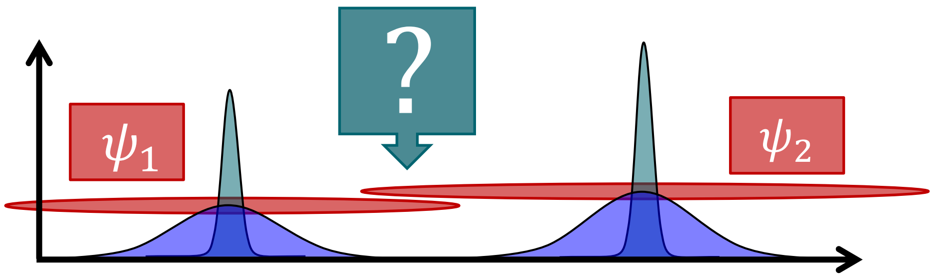
Lower Threshold

Smaller ejection wavevector

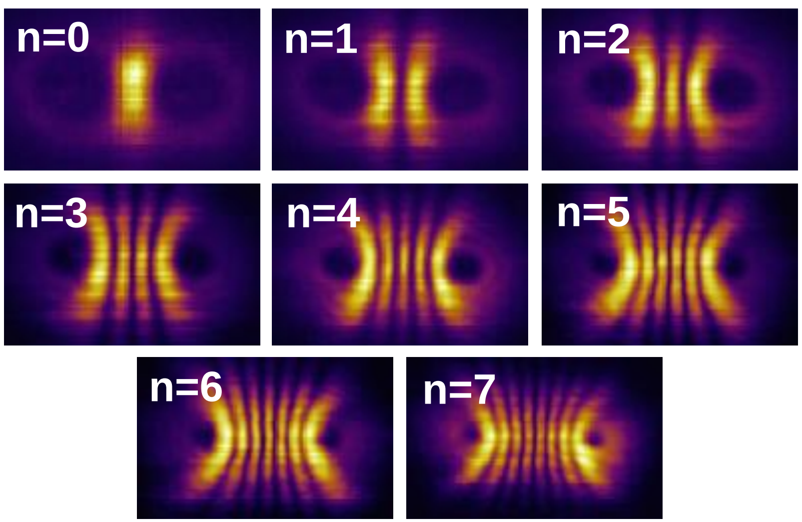
Larger Interference fringes

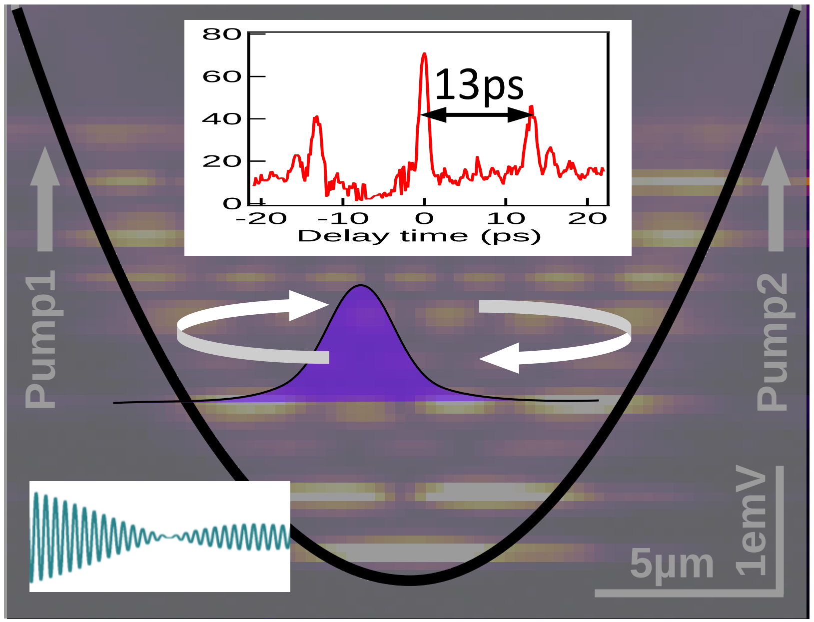
Trapping Transition: PRL **110,** 186403 (2013)

N=2: 2D Quantum Oscillator



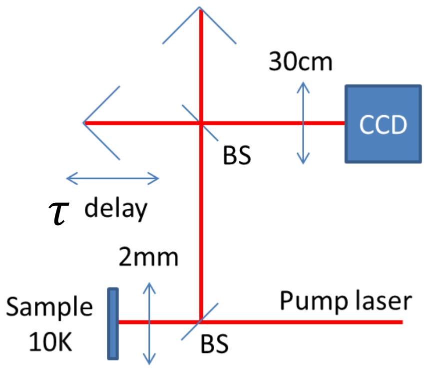
$$\psi = \sqrt{\rho} \cdot e^{-\frac{iEt}{\hbar}+\varphi}$$

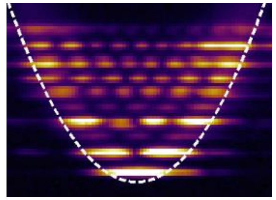




2D Polariton Oscillator: Nature Physics **8**, 190–194 (2012)

Condensate dynamics

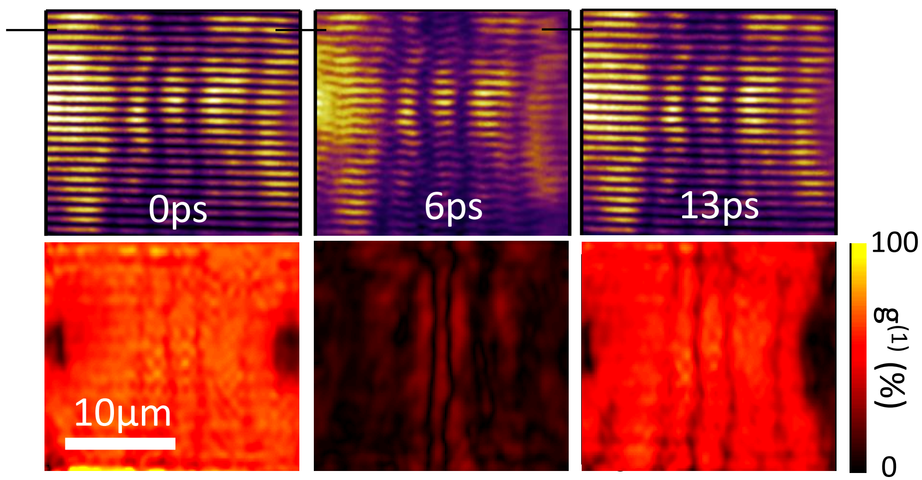


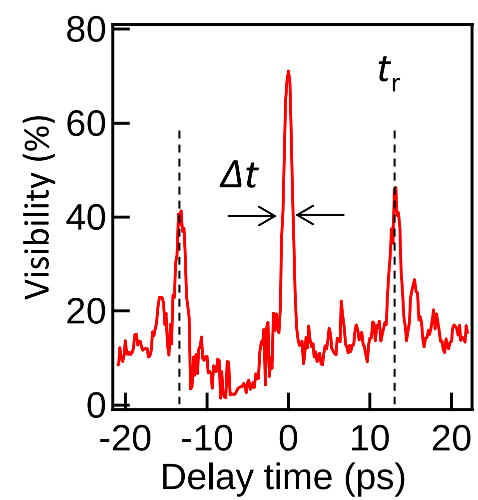


$$t_r = h/E$$

- modelocking condensates

nonlinear optics
cf: ultrafast lasers, supercontinuum generation

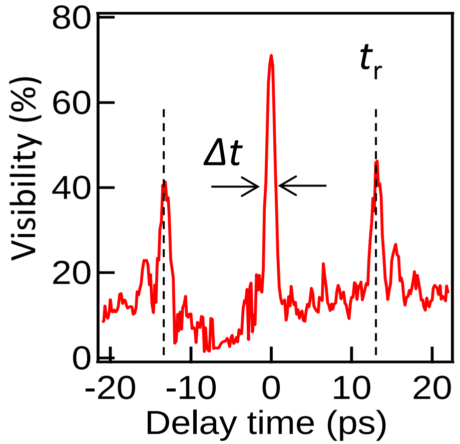




- self-interference every round trip time (exact match)
- all the simple harmonic oscillator levels are phase coherent

Nature Physics **8**, 190–194 (2012)

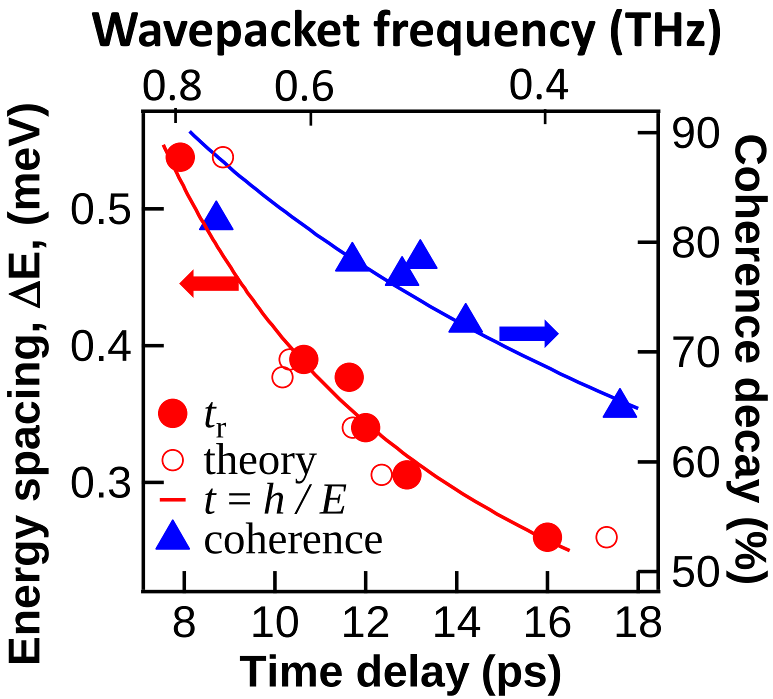
Tuneable oscillator



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

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

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



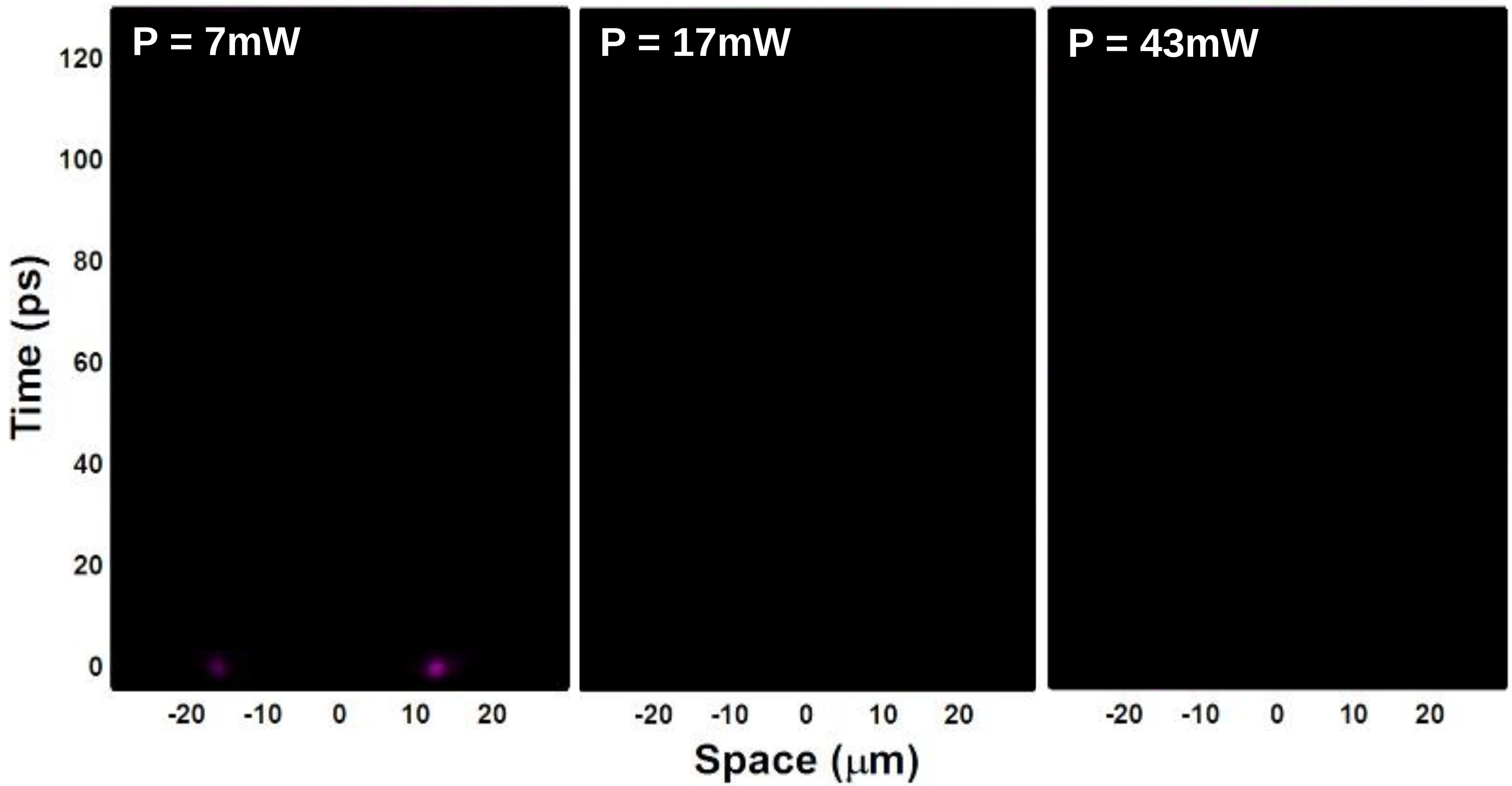
wavepacket revival is not perfect

decays over 40ps

due to coherent wavepacket

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

N=2: Ultrafast dynamics



Interference of Condensates

Dark Wavepacket

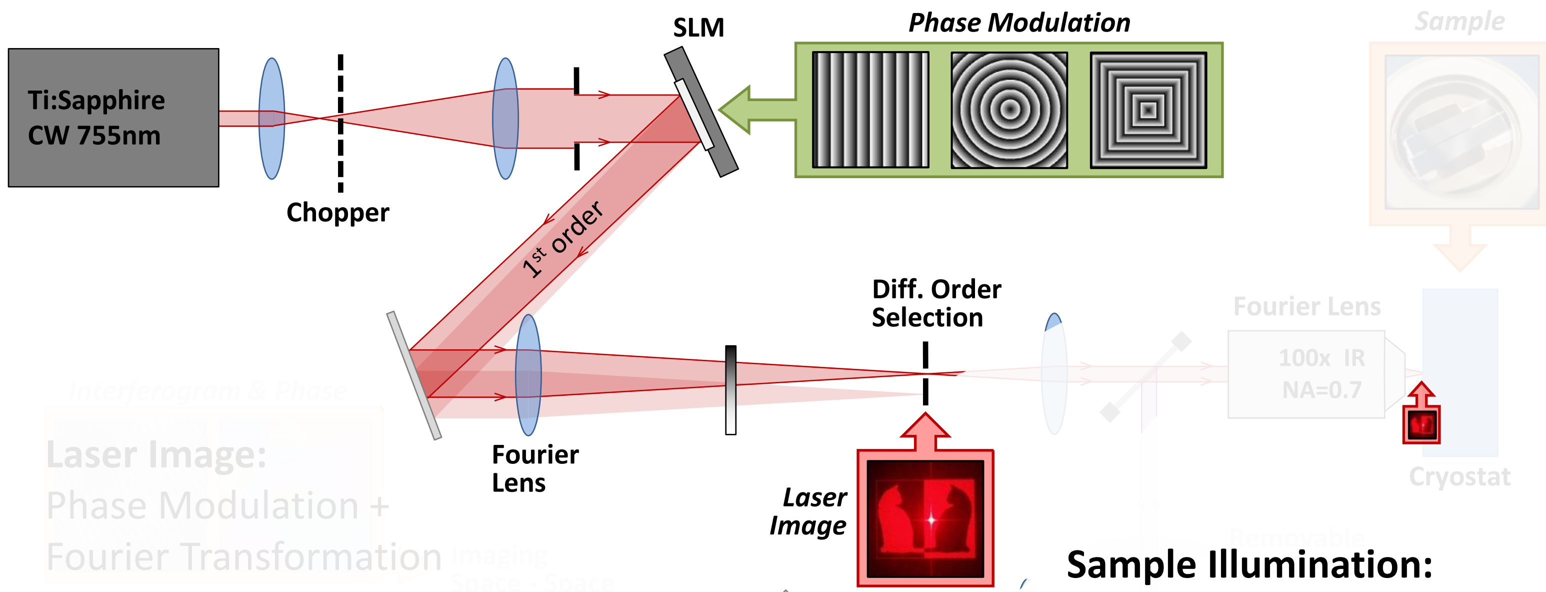
Bright Wavepacket

Time resolved phase locking of polariton cond. In prep.

Multi-spot Excitation: N=2

Multiple spot excitation

Setup

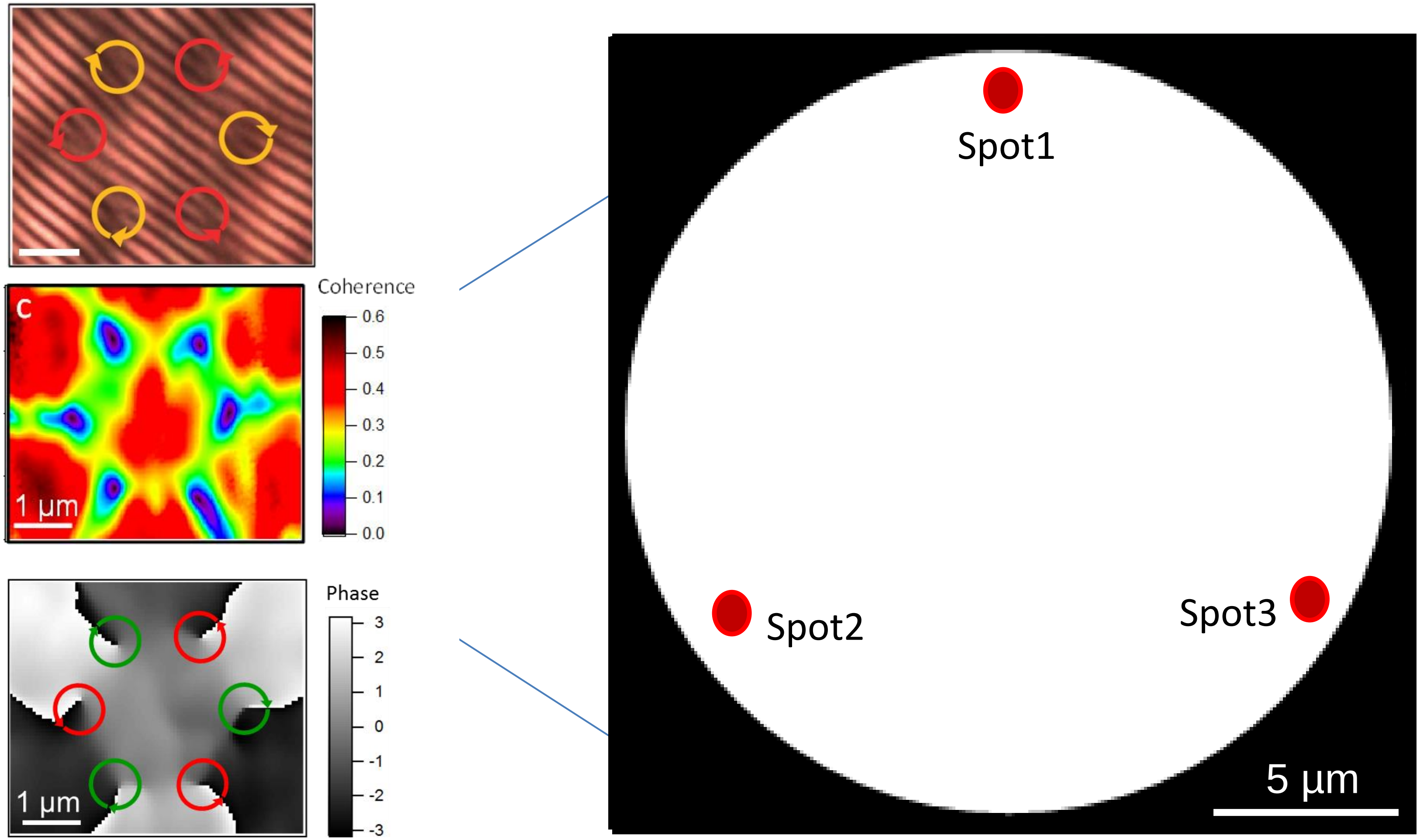


Sample Illumination:
4x Telescope +
50x Microscope Objective

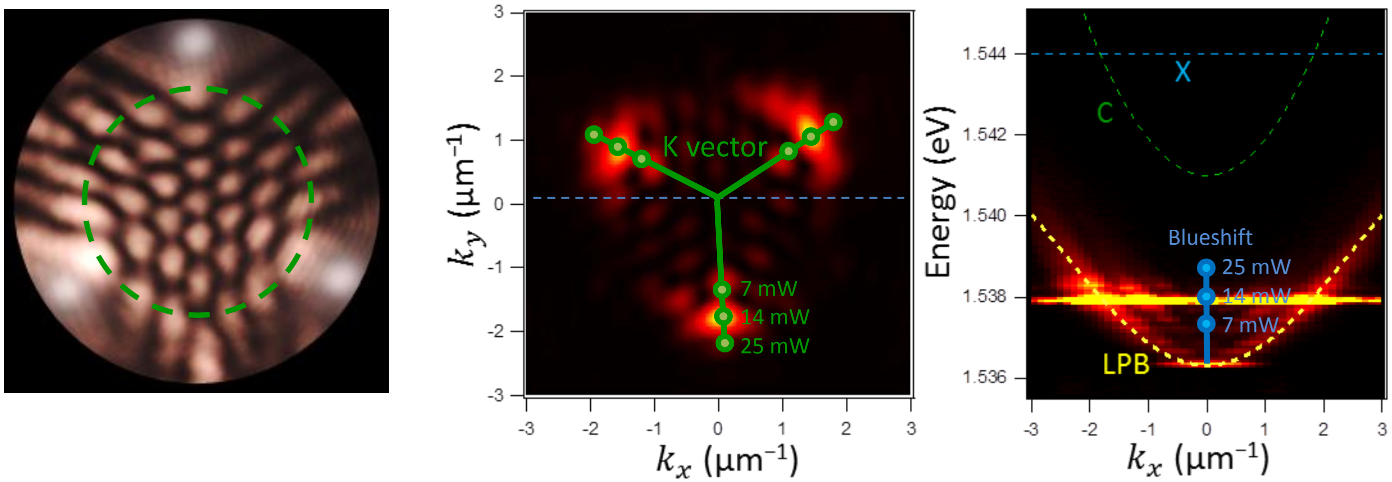
Real & k-space
Interferometry

Vortex lattices

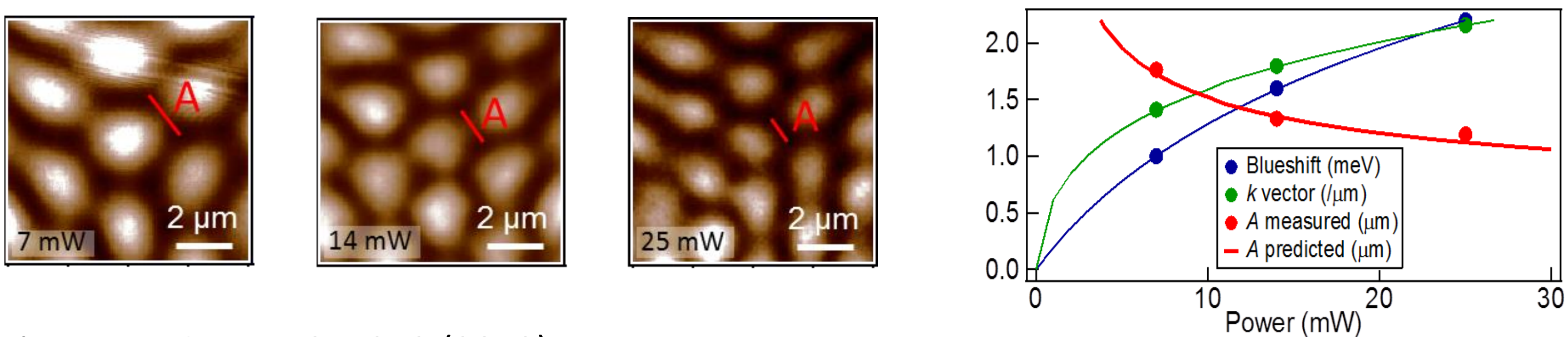
- honeycomb lattice of up to 100 vortices and anti-vortices



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: $k(r) = K[\omega_c - \Delta(r)]$

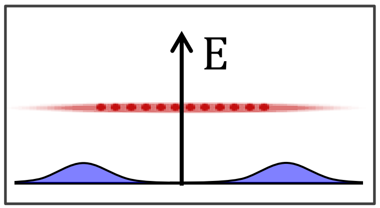


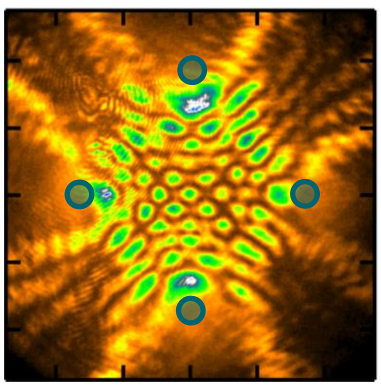
G. Tosi, Nature Comm. 3, 1243 (2012)

Phase Transition

Phase Locked <--> **Trapped**

Pumps far apart — Pumps Close Together





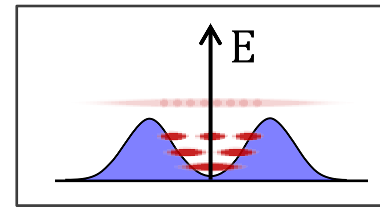
Single Energy

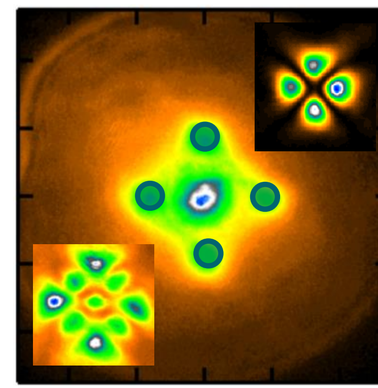
Physics:

Vortex Lattice — Q. Oscillator

Condensation:

At pump — Centre





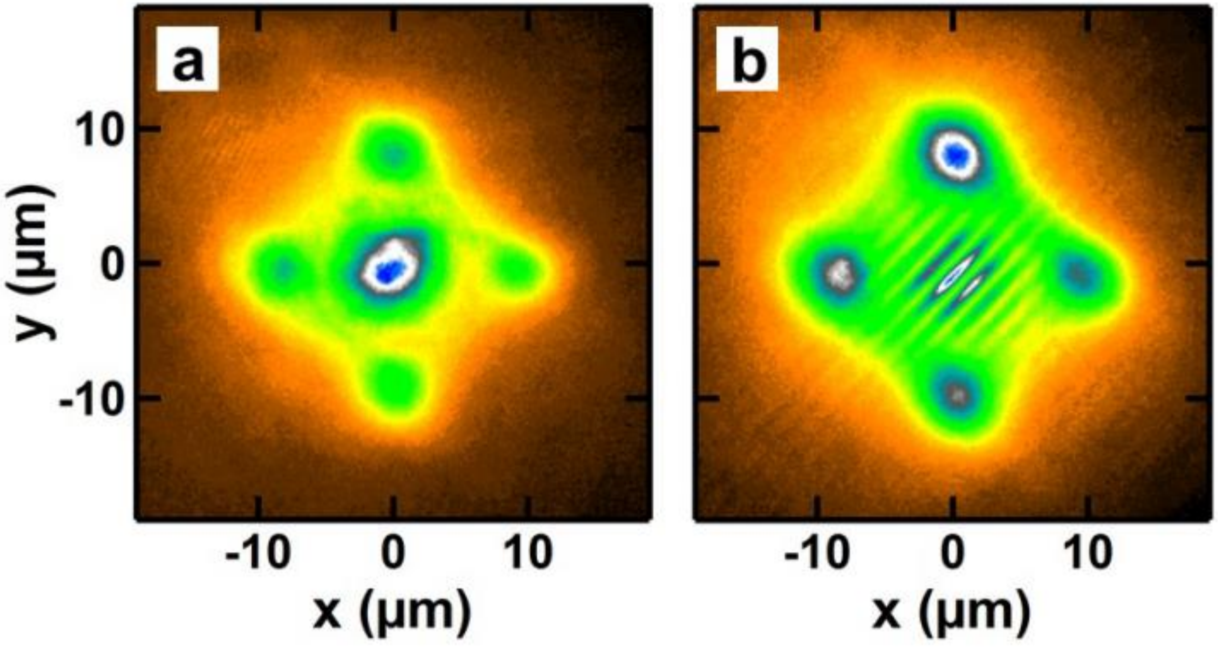
Condensation Threshold?

Trapping Transition: PRL **110,** 186403 (2013)

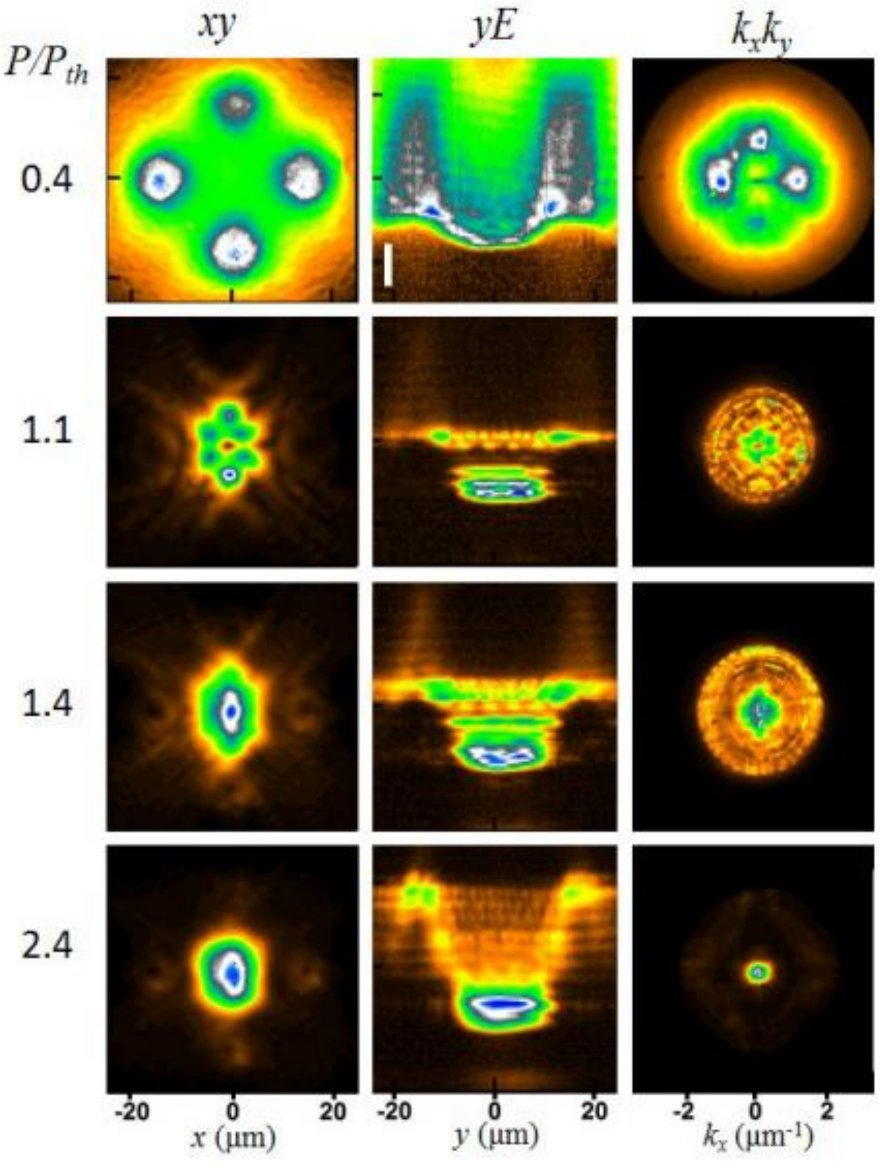
Vortex Lattice: Nature Comm. **3**, 1243 (2012)

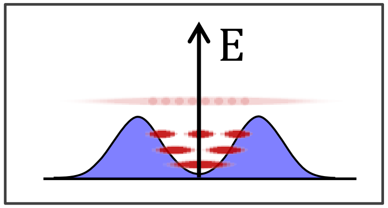
Condensation Threshold

Below Threshold Above Threshold

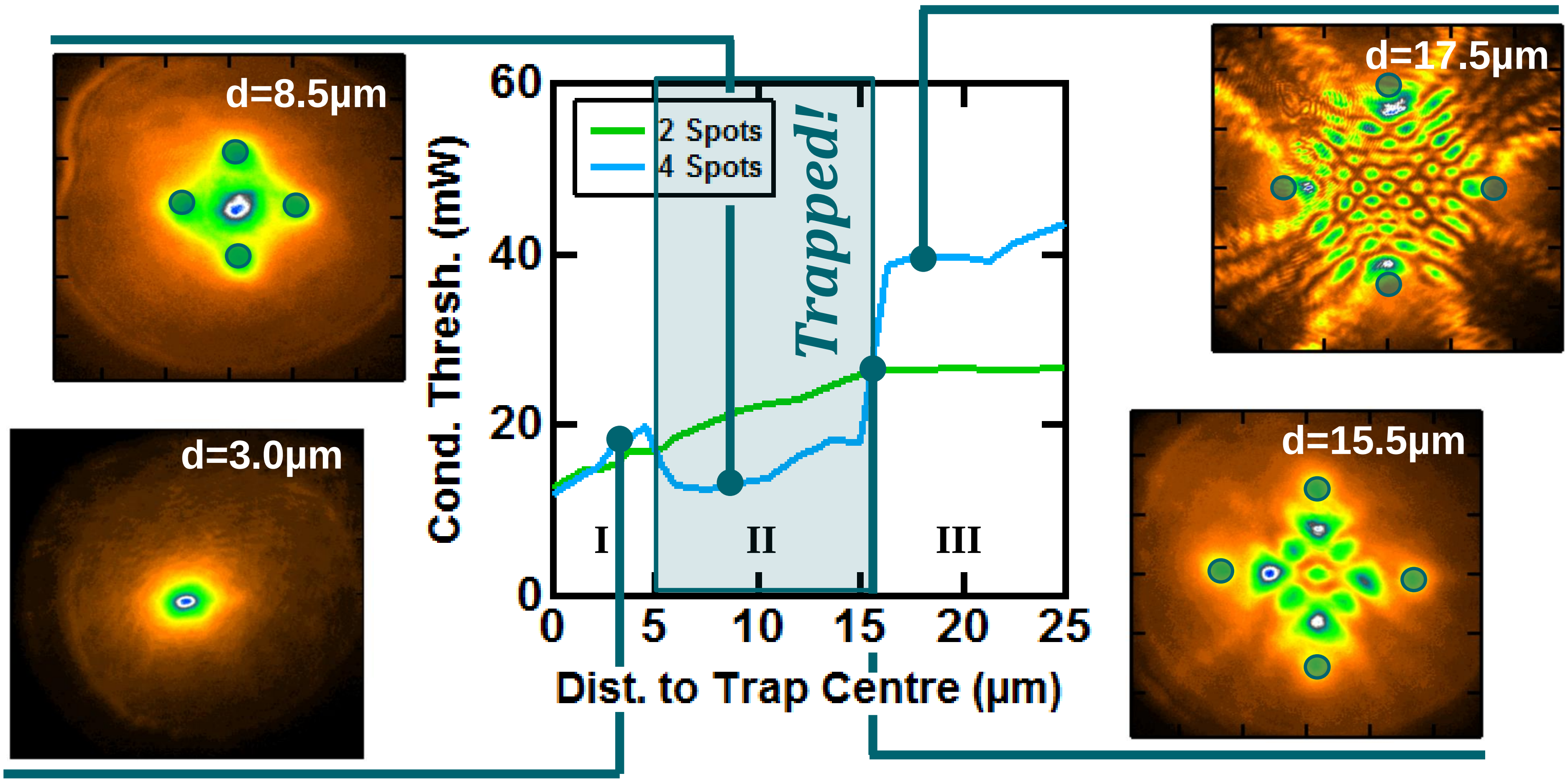


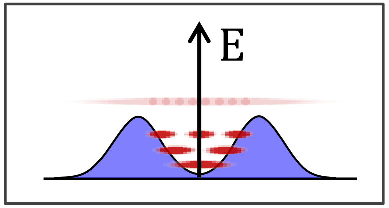
N ≥ 4: Opt. Trapped Condensates





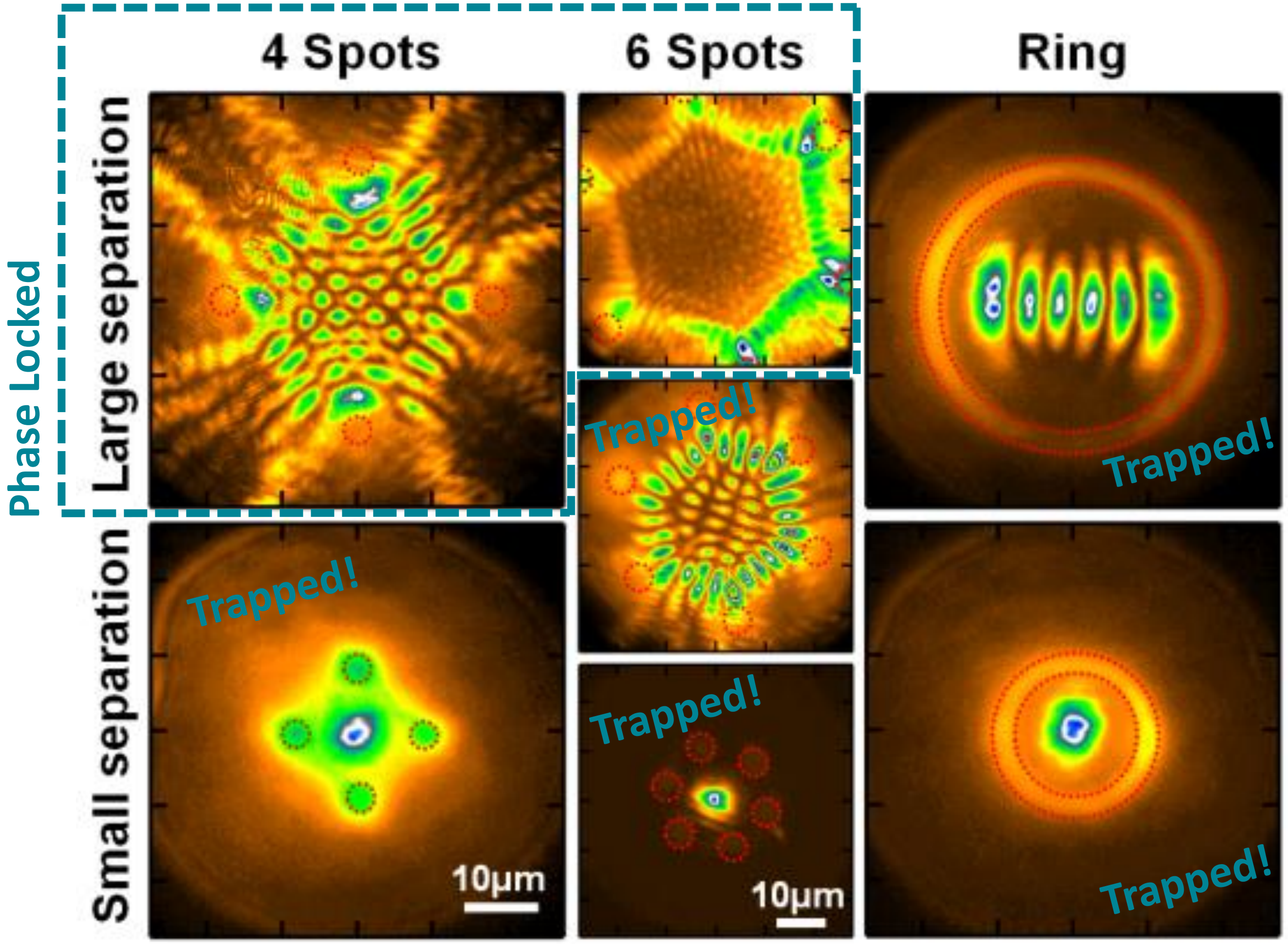
N = 4: Optical Trapping





Trapping Transition: PRL **110,** 186403 (2013)

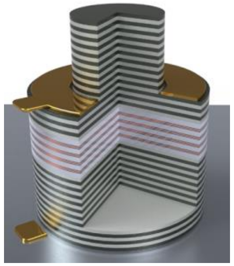
N = 4, 6, 8, ...



Trapping Transition: PRL **110,** 186403 (2013)

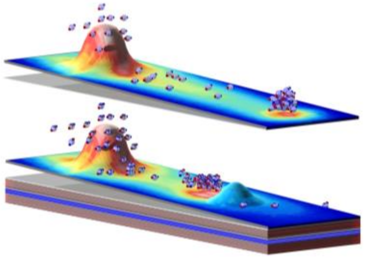
Summary

- Low threshold polariton lasing at 25K



- Electrical and optical manipulation of polariton condensates

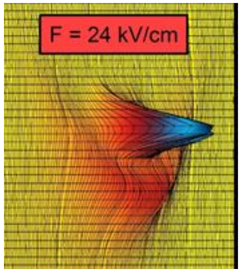
  - propagation of polariton condensates in waveguides
  - polariton condensate transistor
  - electric field tuning of the polariton condensate energy.

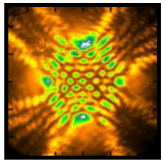


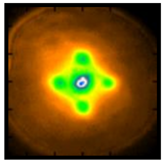
- Interactions between condensates in confining potentials

  polariton condensate pendulum

  phase locked vs trapped polariton condensates





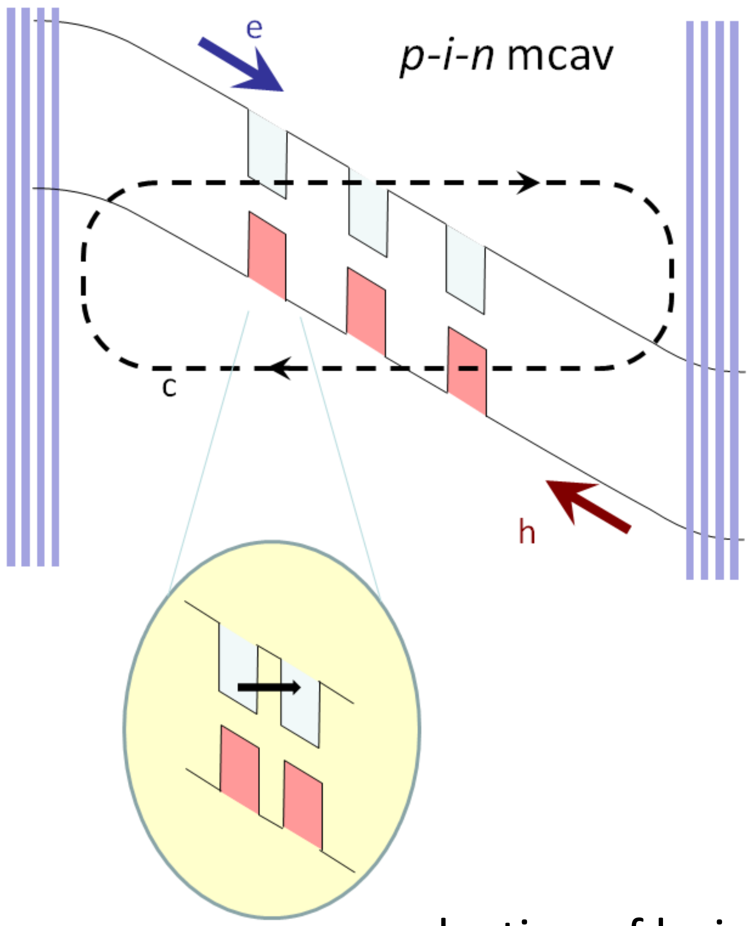


Thank you

Dipole Oriented Polaritons

Oriented polaritons in strongly-coupled <u>asymmetric</u> DQW microcavities

Indirect polaritons: Dipolaritons



Dipolariton approach:
weakly-coupled double quantum wells

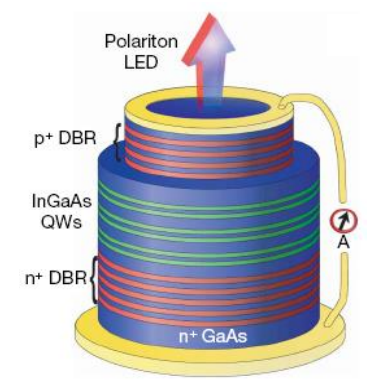
⬇

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

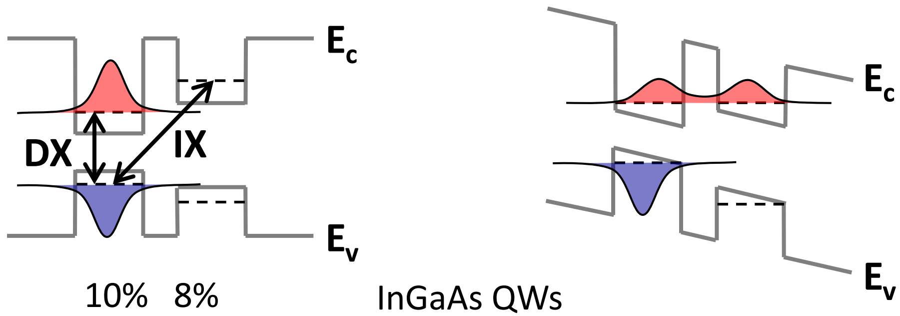


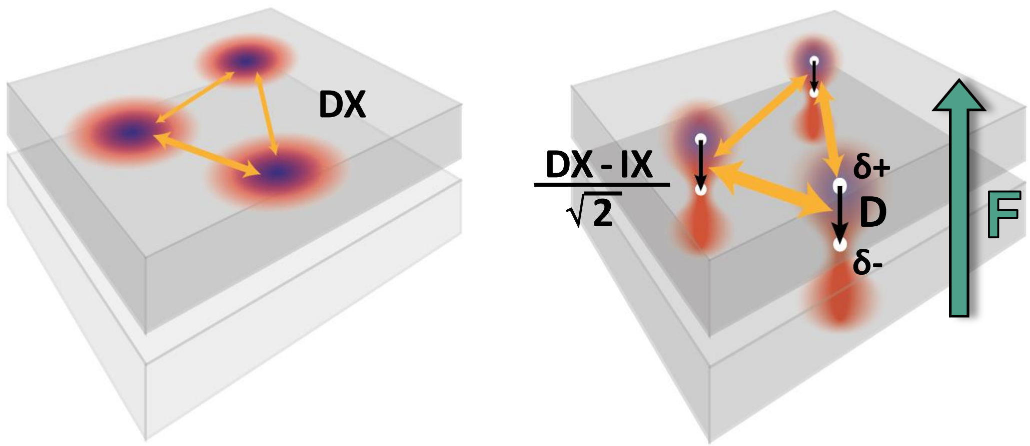
P. Cristofolini *et al.*, Science 336, 704 (2012) G. Christmann APL 98, 081111 (2011)

Dipolaritons

electron levels **off resonance**

electron levels **at resonance**





"tunnelling off"

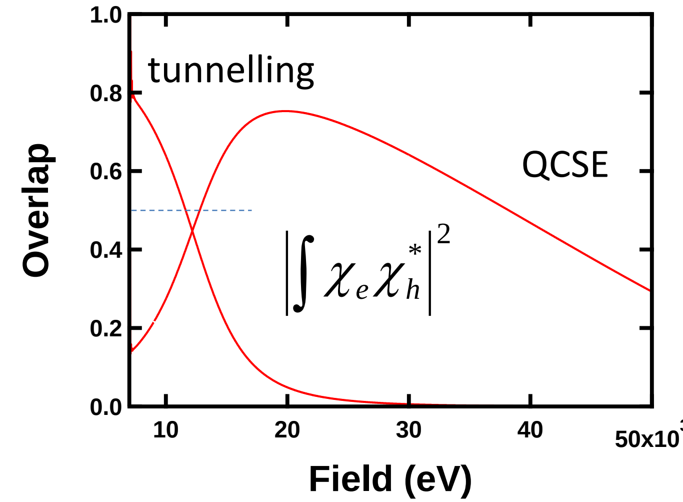
↓

direct excitons DX

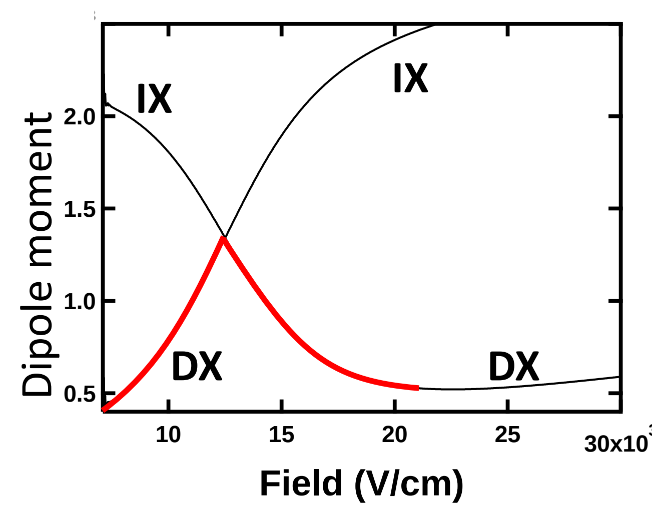
"tunnelling on"

↓

mixed excitons DX±IX, static dipole moment



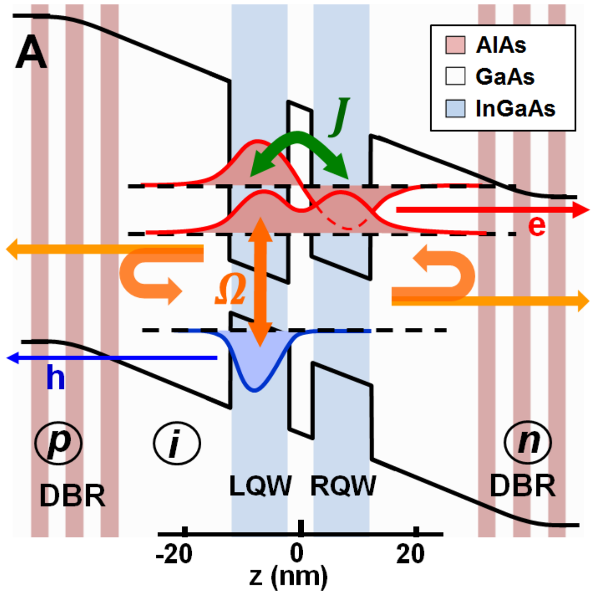
Oscillator strength is kept



Strong dipole moment

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

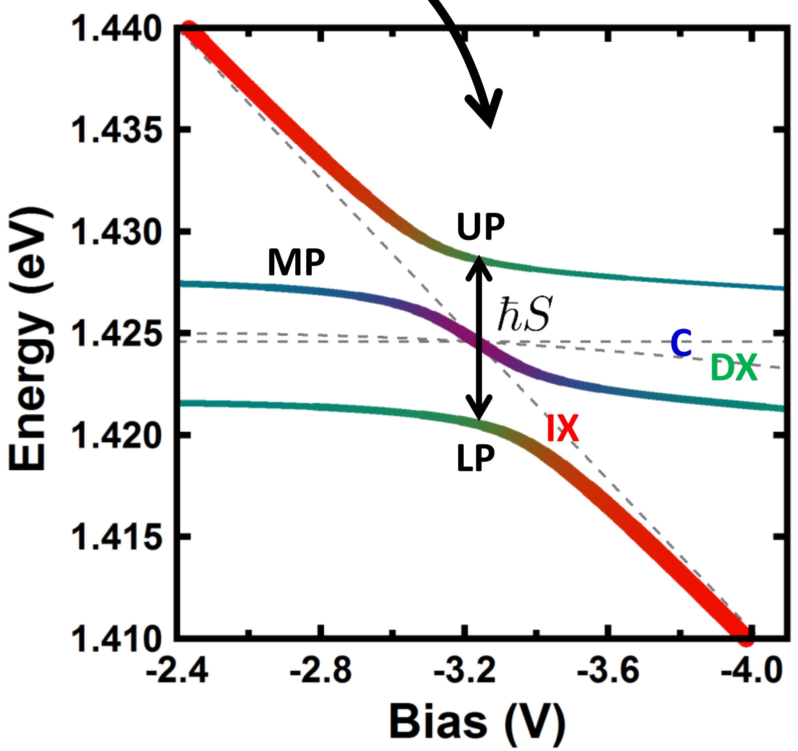
Dipolaritons



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

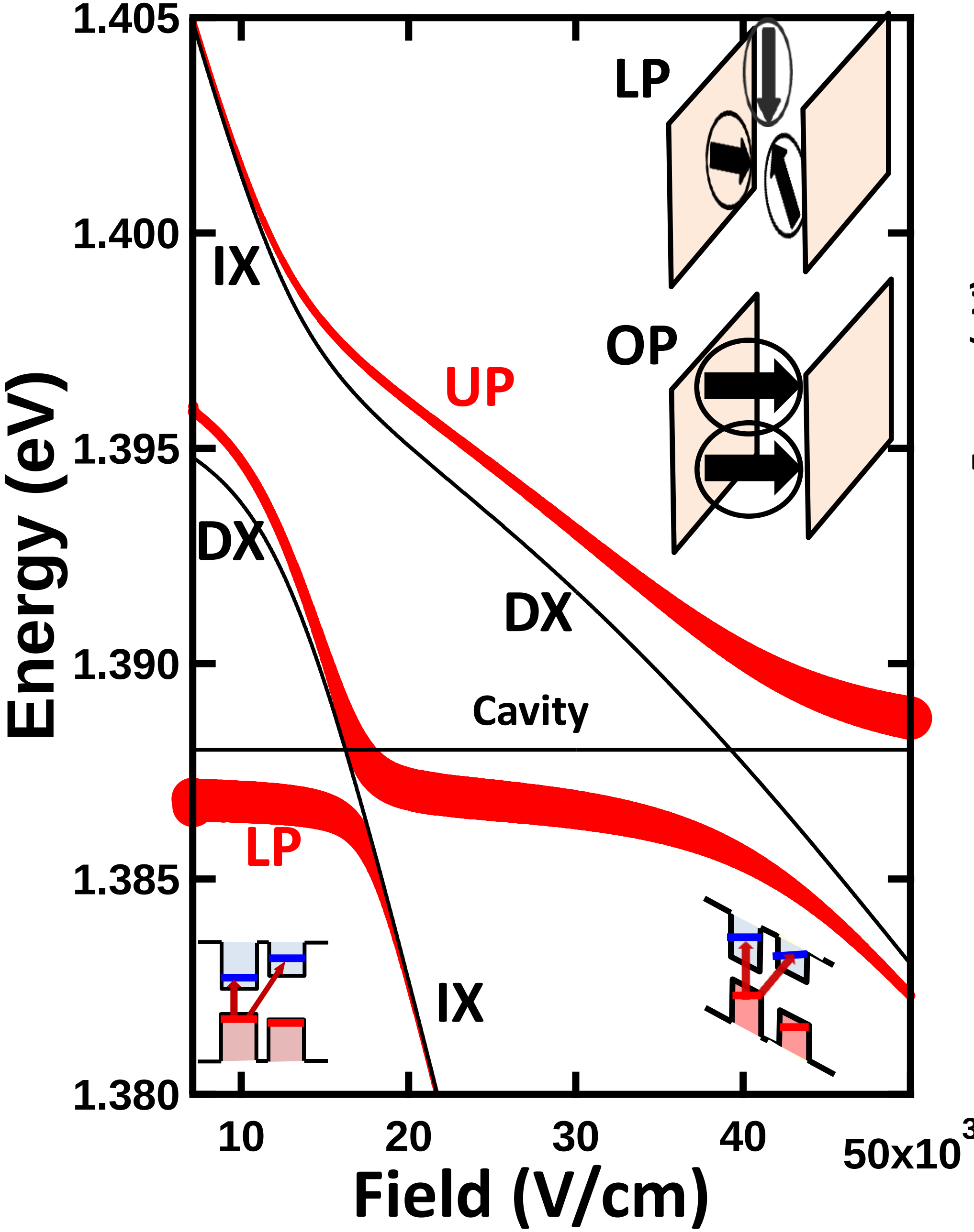
$$H = \begin{pmatrix} E_C & \Omega/2 & 0 \\ \Omega/2 & E_{DX} & J/2 \\ 0 & J/2 & E_{IX} \end{pmatrix}$$

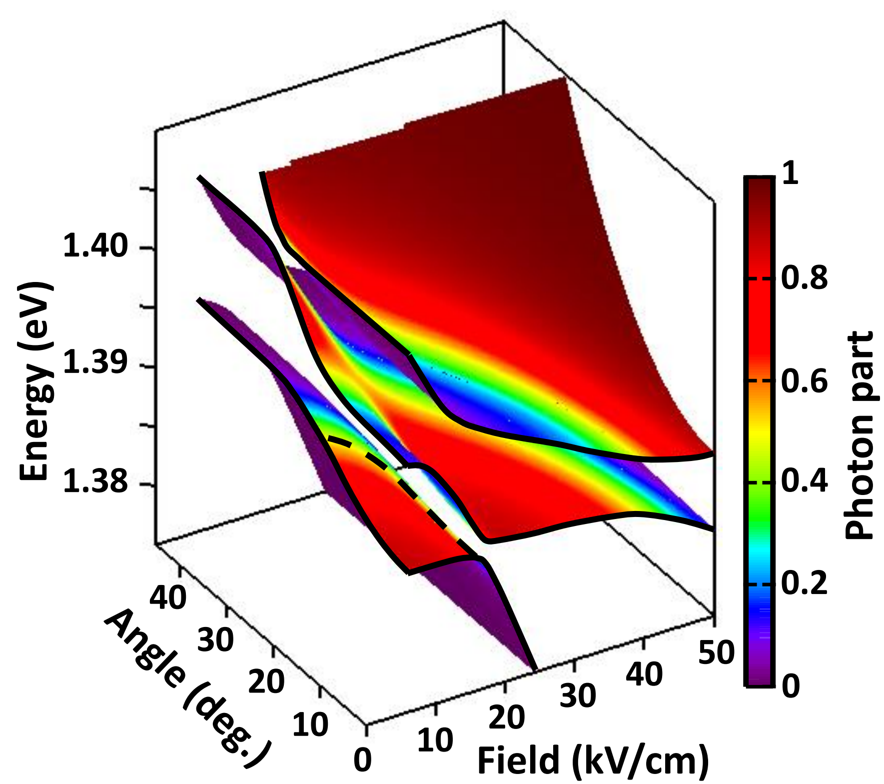
strong coupling



Coupled harmonic oscillator model

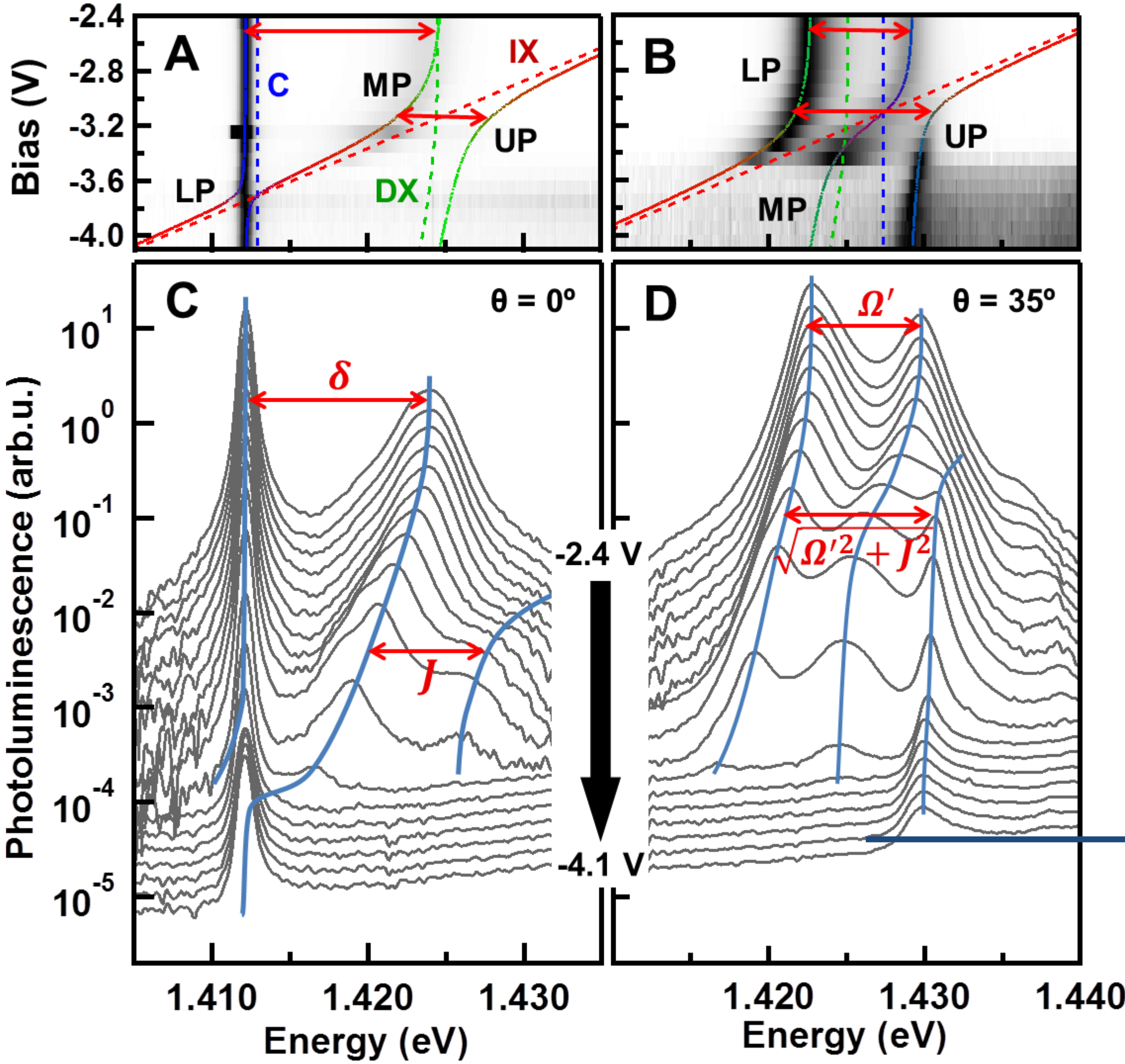
Dipolariton Dispersions





- vertical polariton dipole
- enhanced polariton-polariton coupling

Observation of dipolaritons



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

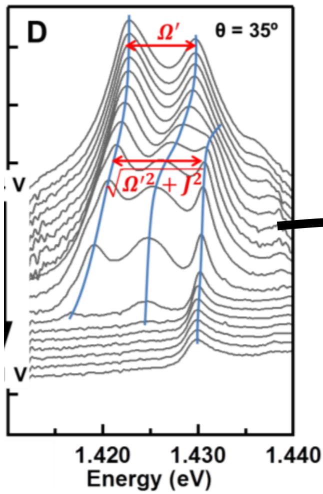
PL is lost because electron tunnel out of the system

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

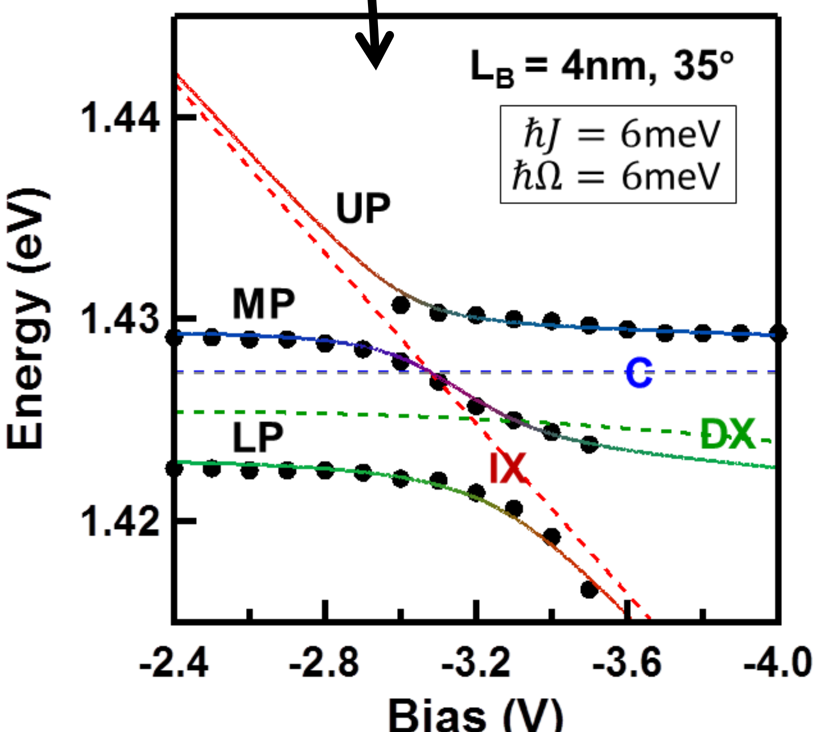


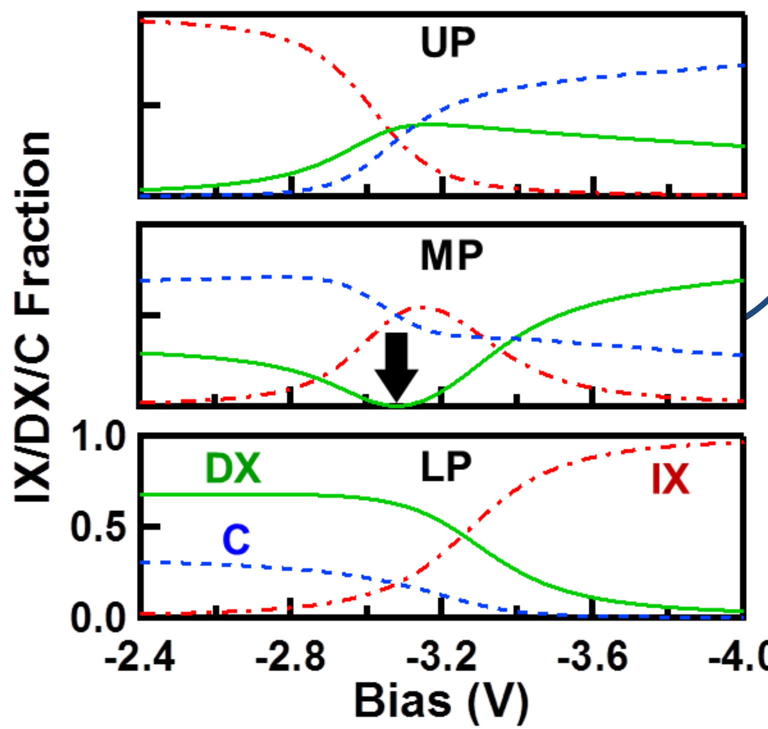
peak extraction +

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

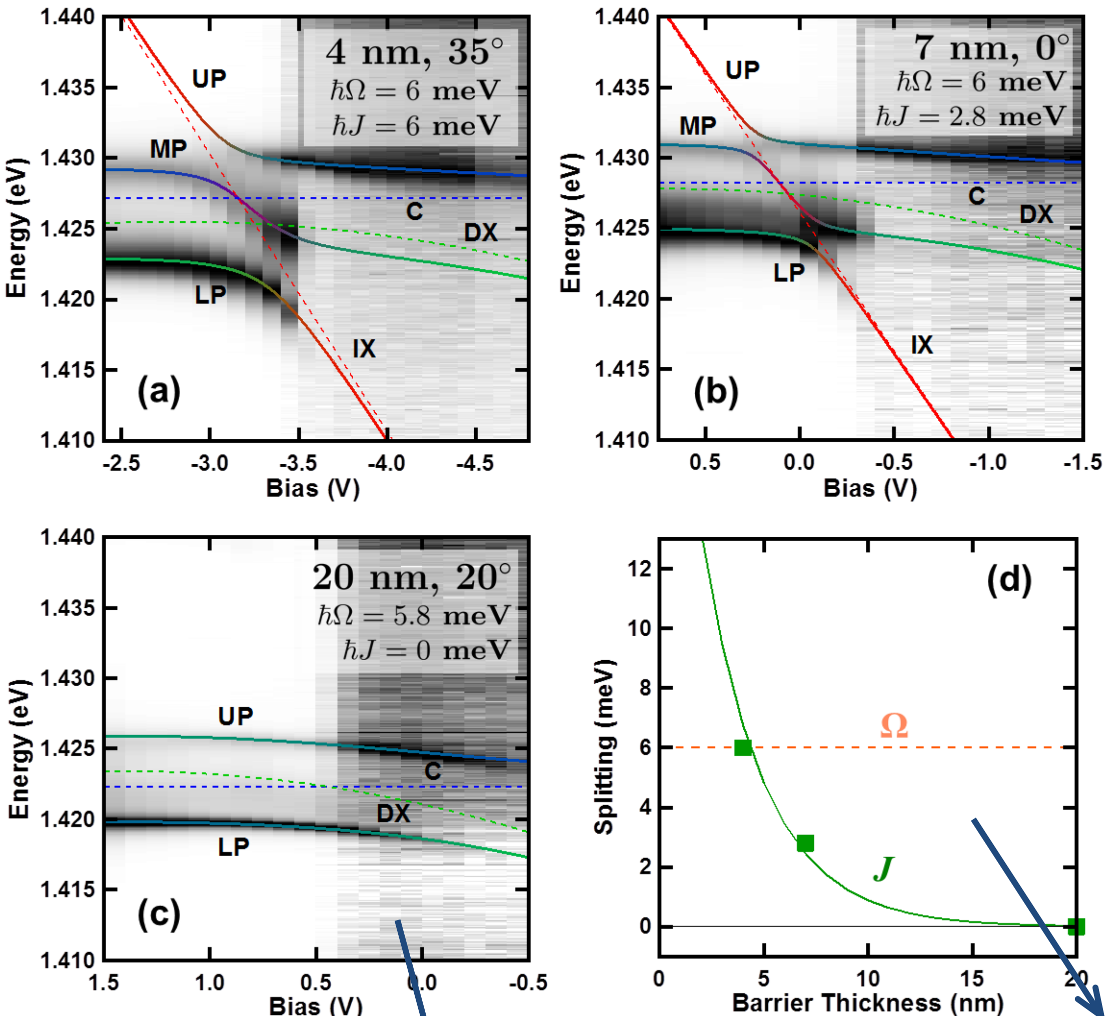
MP – state: no DX!

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





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

Applications of Dipolaritons

Continuous THz lasing from dipolaritons

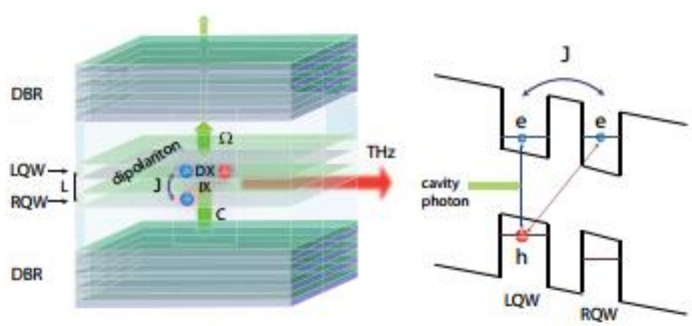
K. Kristinsson,[1] O. Kyriienko,[1,2] T. C. H. Liew,[1] and I. A. Shelykh[1,2]

[1]*Division of Physics and Applied Physics, Nanyang Technological University 637371, Singapore*
[2]*Science Institute, University of Iceland, Dunhagi-3, IS-107, Reykjavik, Iceland*

(Dated: April 5, 2013)

We propose a scheme of continuous tunable THz emission based on dipolaritons — mixtures of strongly interacting cavity photons and direct excitons, where the latter are coupled to indirect excitons via tunnelling. We investigate the property of multistability under continuous wave (CW) pumping, and the stability of the solutions. We establish the conditions of parametric instability, giving rise to oscillations in density between the direct exciton and indirect modes under CW pumping. In this way we achieve continuous and tunable emission in the THz range, in a compact single-crystal device, which is expected to operate at high temperatures. We show that the emission frequency can be tuned in a certain range by varying an applied electric field and pumping conditions. Finally, we demonstrate the dynamic switching between different phases in our system, allowing rapid control of THz radiation.

PACS numbers: 71.36.+c,78.67.Pt,42.65.-k,71.35.Lk

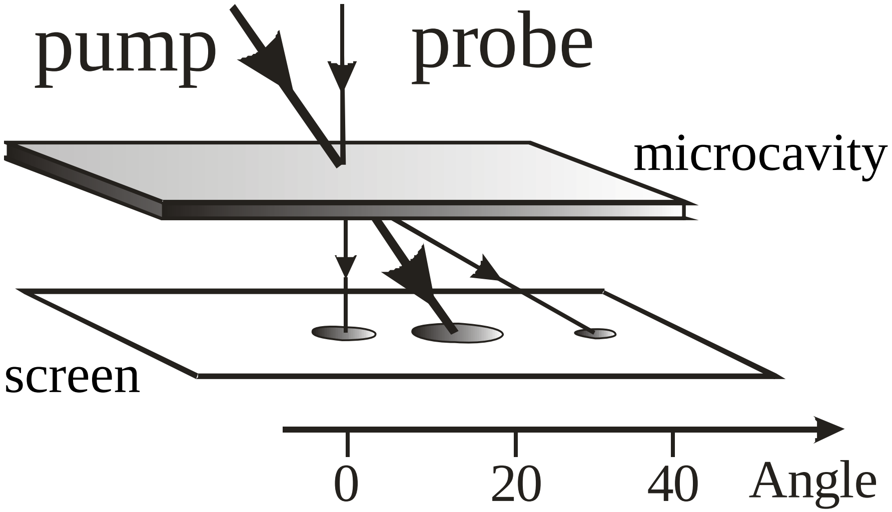


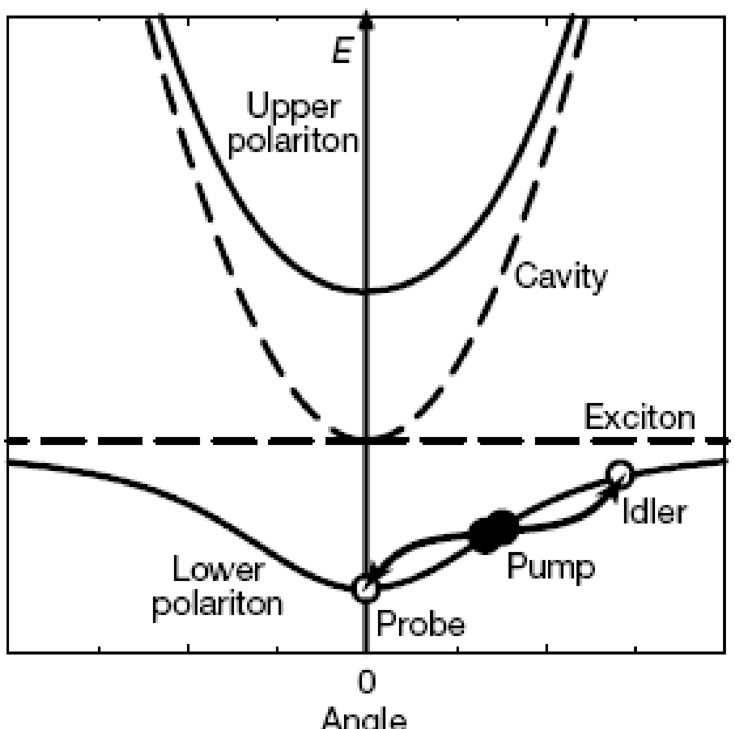
(a) (b)

Nonlinear properties of Tunnelling Polaritons

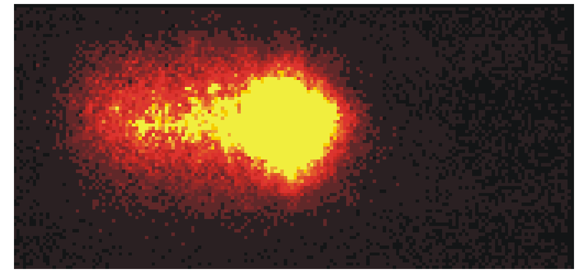
Control of polariton scattering in resonant-tunnelling <u>symmetric</u> DQW semiconductor microcavities

Polariton Parametric Amplification



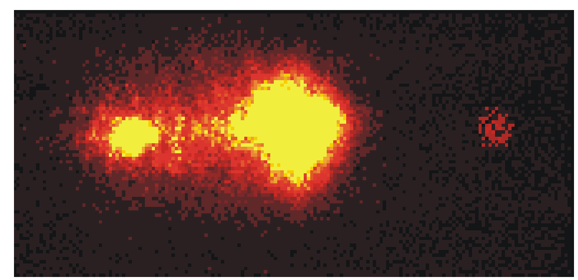


pump only



probe only

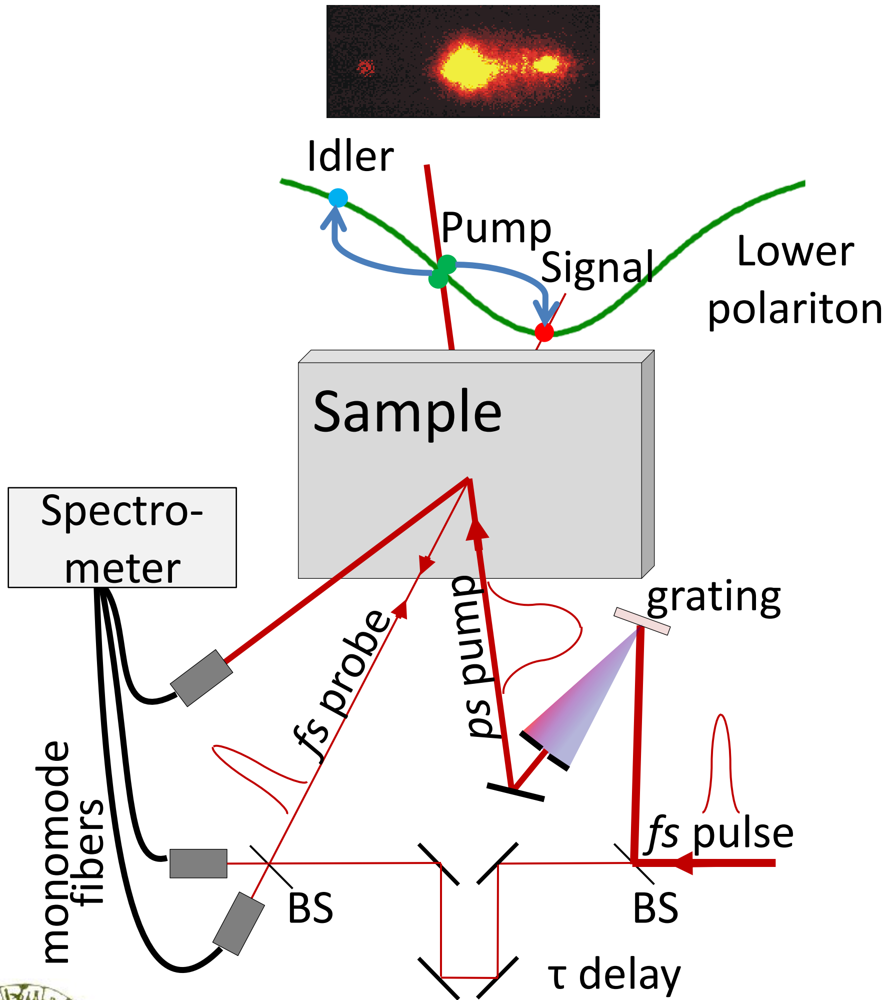
pump & probe



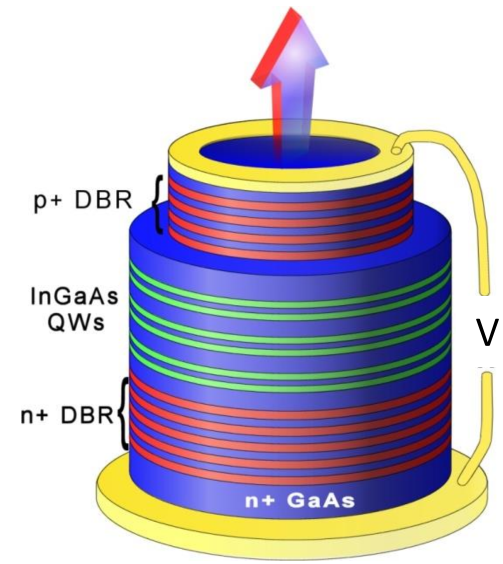
- Stimulated scattering of polaritons
- ultrafast amplification process

Savvidis *et. al.* PRL **84,** 1547 (2000)

Electrical control of parametric amplification



- 100fs OPO regime
- spectrally-filtered pump at θ_m
- monitor probe gain at k=0

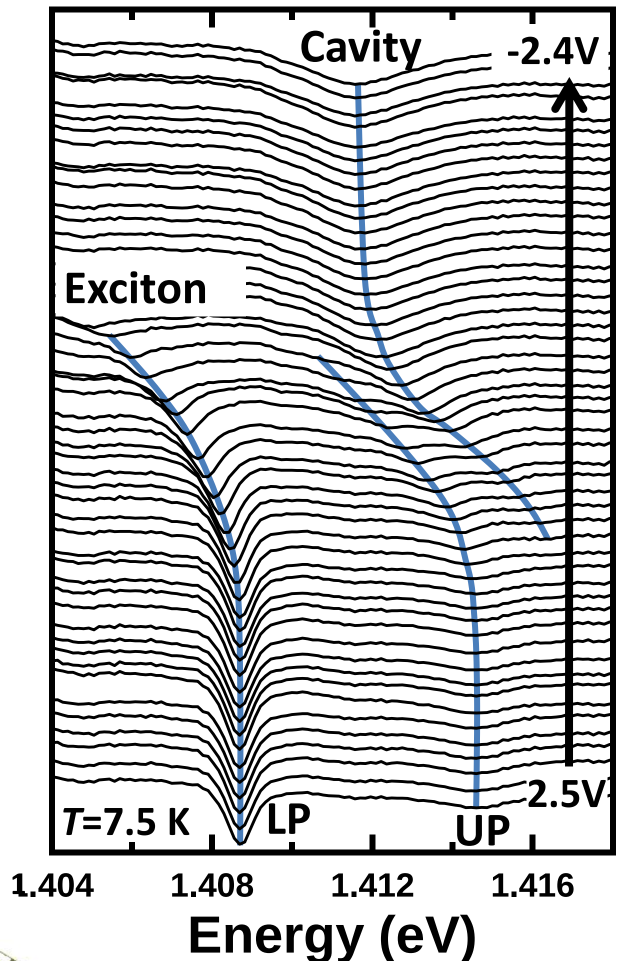


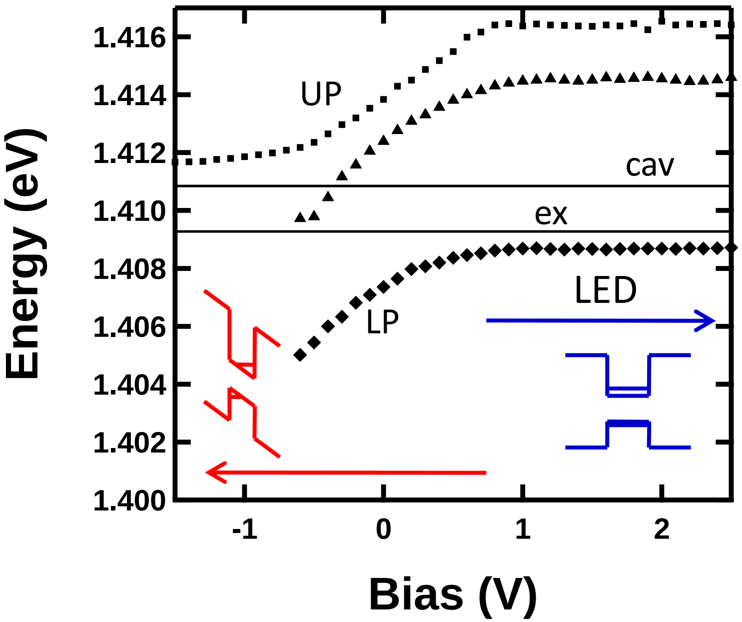
Electrical control: reverse bias

Quantum confined Stark effect

Stark tunable polariton modes

Probe reflectivity

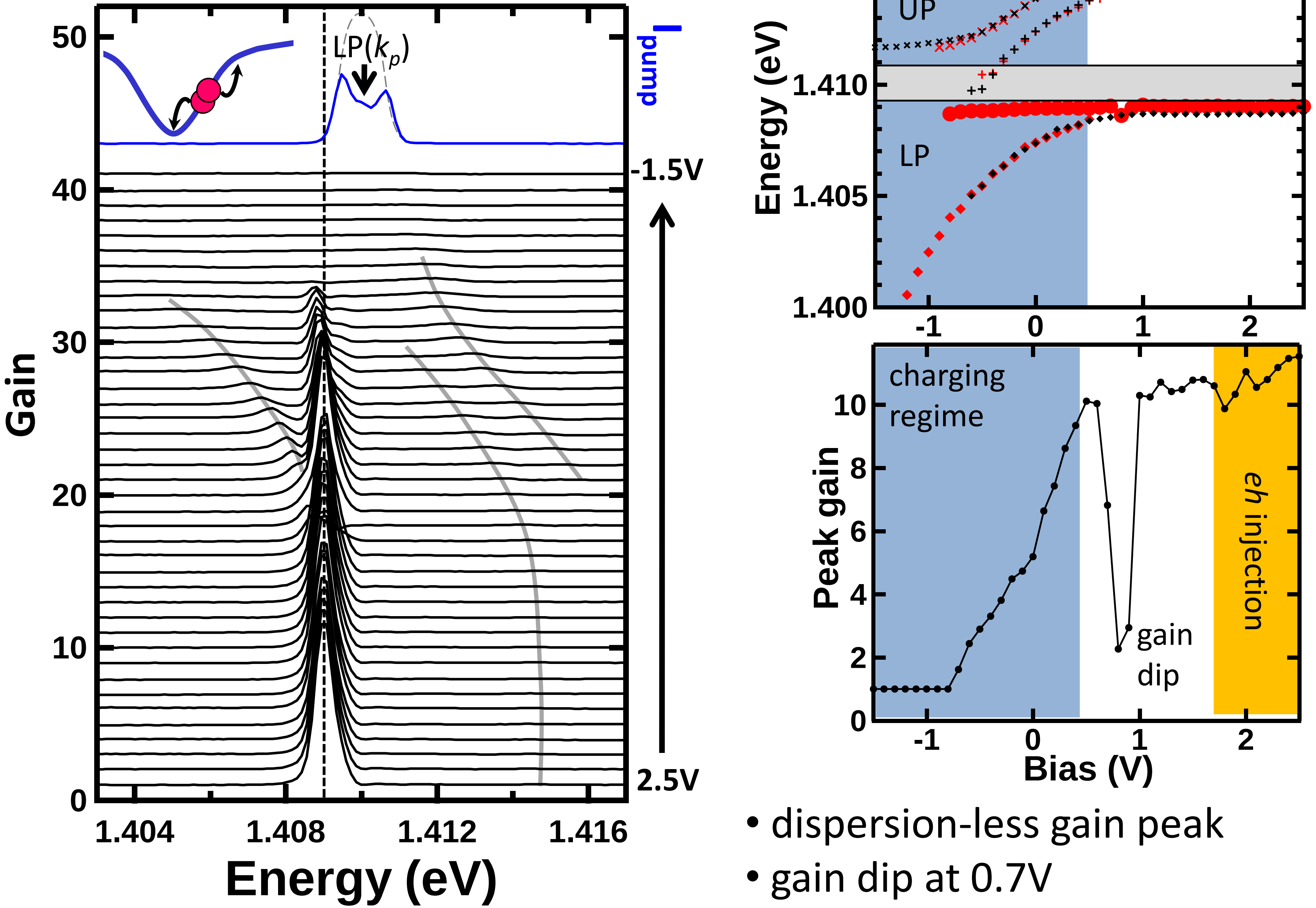




Stark tuning of the excitons

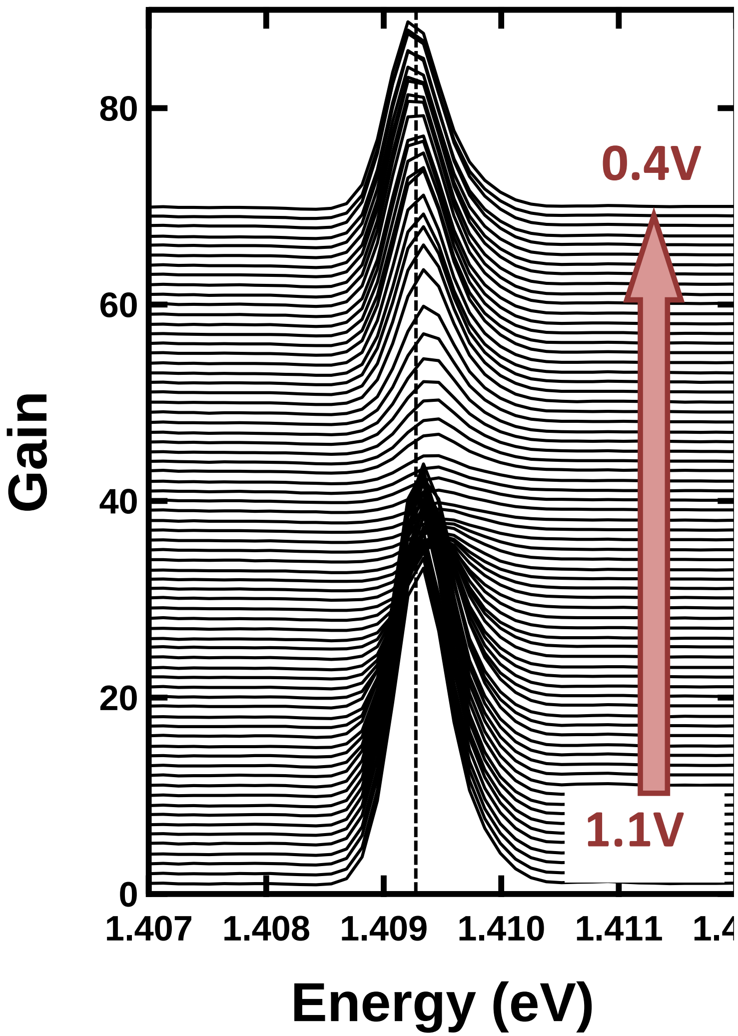
Rabi splitting 6 meV

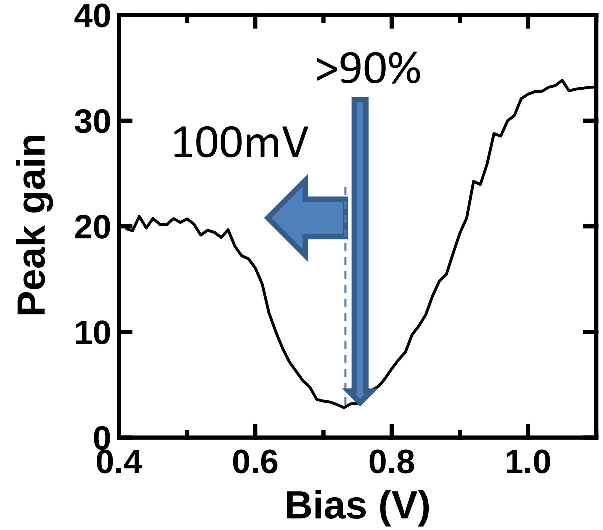
Ultrafast Gain



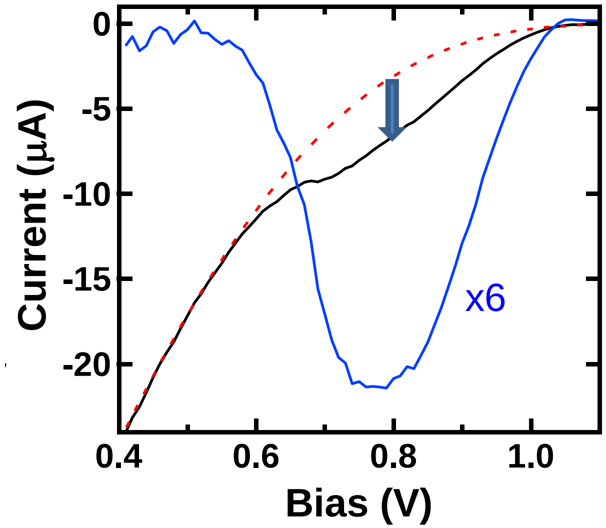
- dispersion-less gain peak
- gain dip at 0.7V

Gain dip





sharp dip in gain

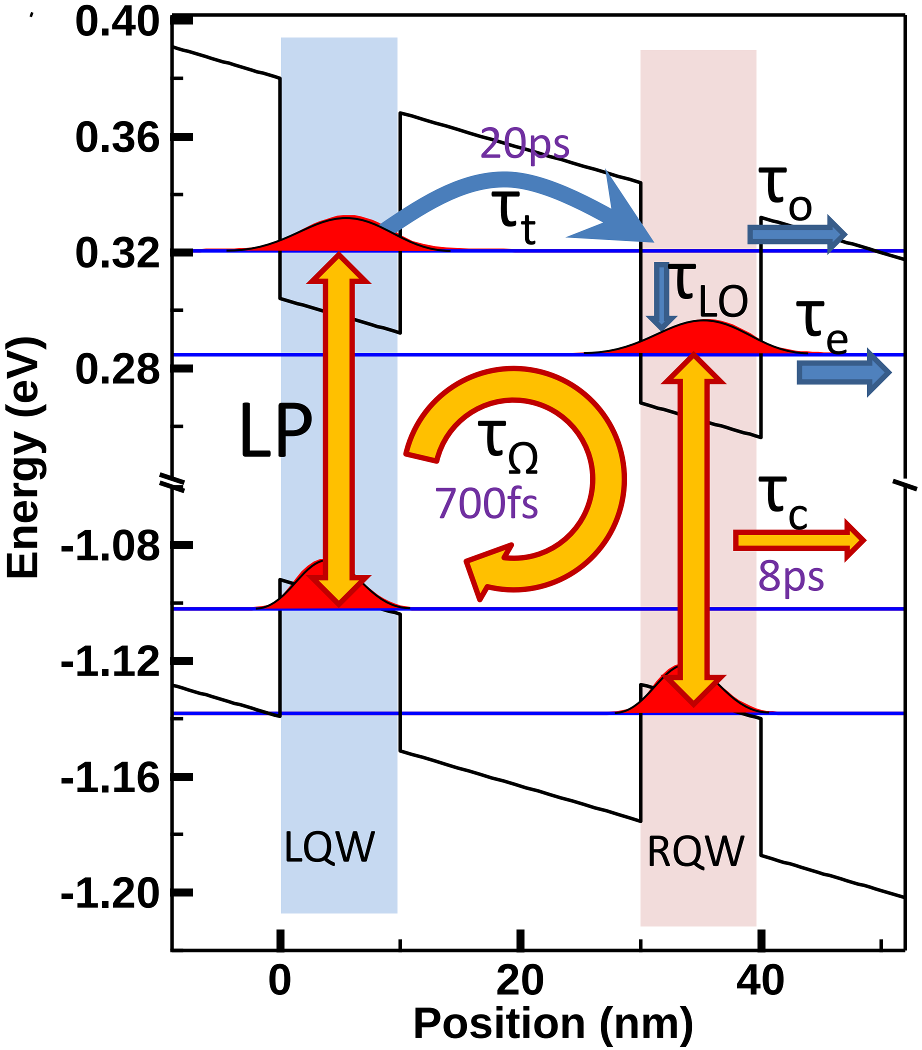


extra photocurrent at same bias

- tunnelling-induced gain quenching

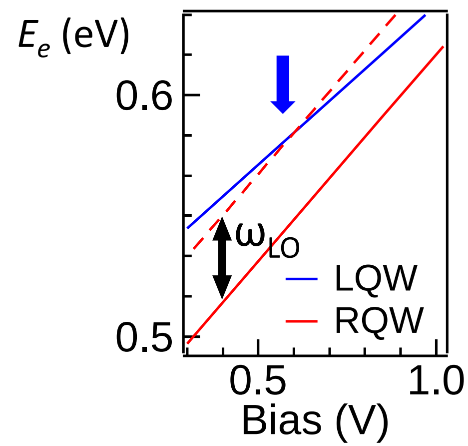
PRB (2010)

Tunnelling in microcavities

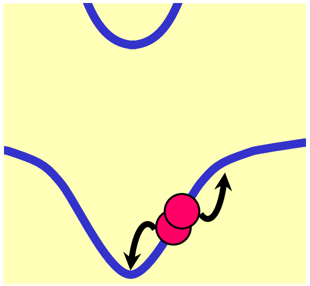


transport competition:

- <u>tunnelling</u> separates *e* and *h*
- <u>Rabi coupling</u>: polaritons redistribute *eh* pairs between QWs



- LO phonon-induced tunnelling 100fs
- carrier escape 180ns, 250fs



- extra e^- population creates extra scattering
- OPO gain very sensitive to damping: phonon vs e^-