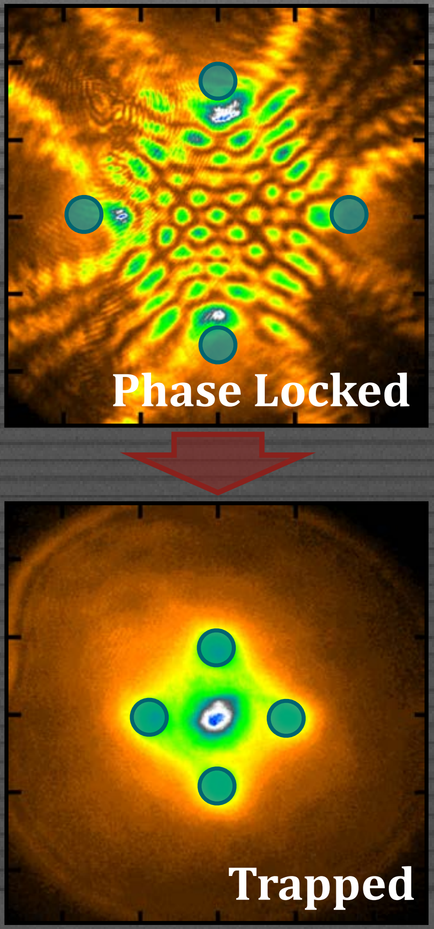
Optical Manipulation of Polariton Condensates

Pavlos G. Savvidis
University of Crete, FORTH-IESL

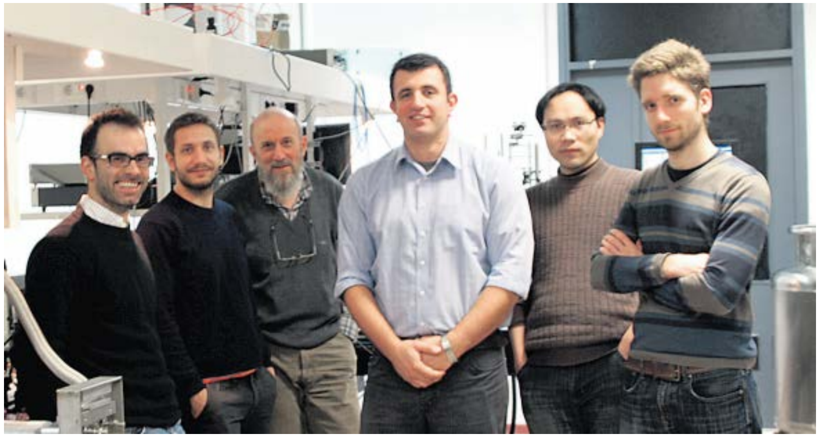


Peterhoff
21.06.13

Acknowledgements

Department of Materials Science / IESL-FORTH

Dr. Simos Tsintzos
Dr. Peter Eldridge
PhD Panos Tsotsis
PhD Tingge Gao



IESL-FORTH

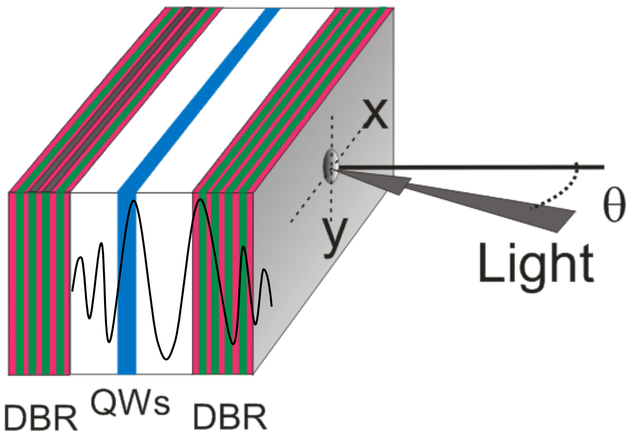
Z. Hatzopoulos *MBE*

Collaboration

J. Baumberg
N. Berloff
G. Christmann
G. Tosi
P. Cristofolini

UNIVERSITY OF CAMBRIDGE

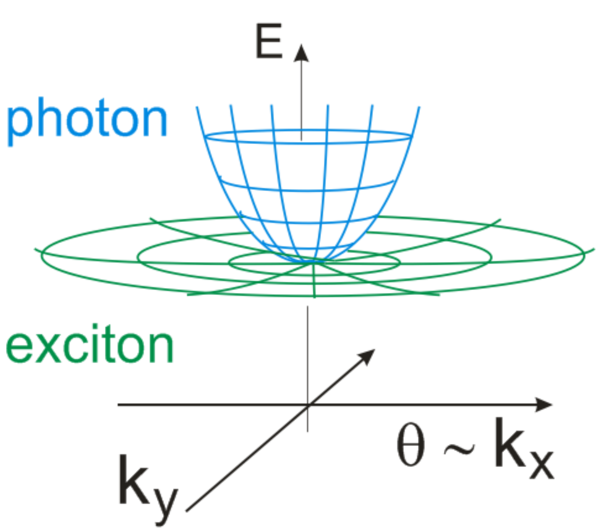
Strong Coupling Regime in Semiconductor Microcavity



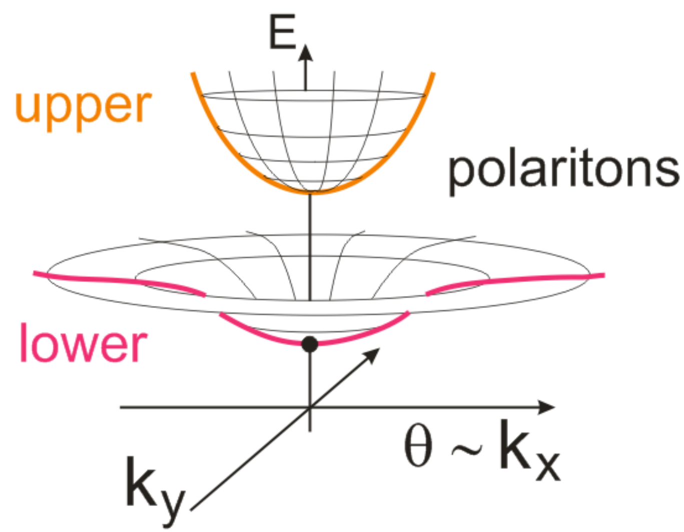
- Polaritons directly accessible by shining light on MC
- Strongly modified dispersion relations
  reduced density of states near $k_{//}=0$
- small polariton mass $m_{pol} \approx 10^{-4} m_e$
- strong non-linearities → χ^3 (exciton component)

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

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

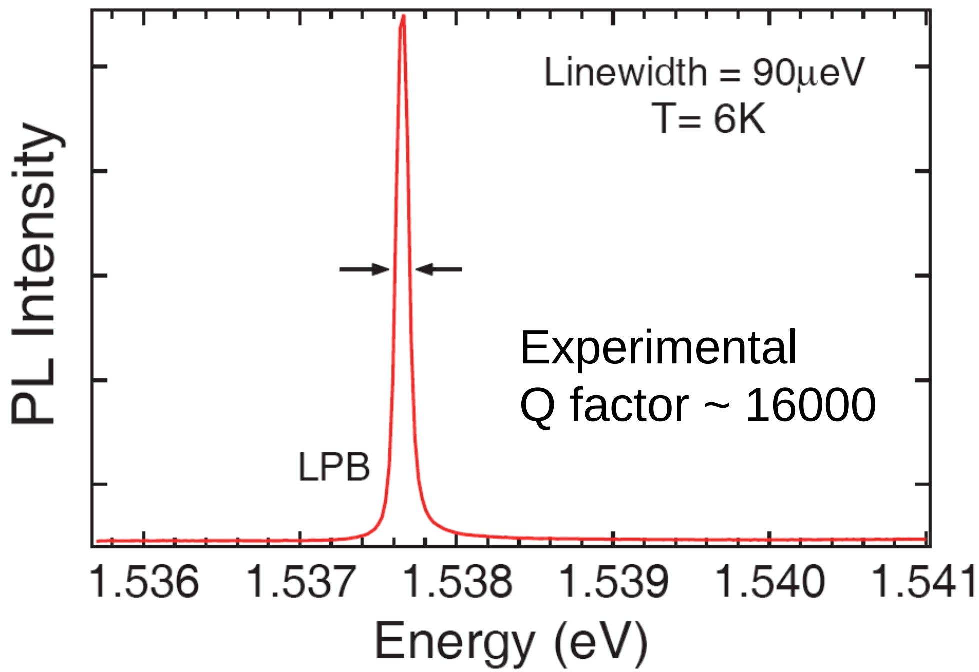


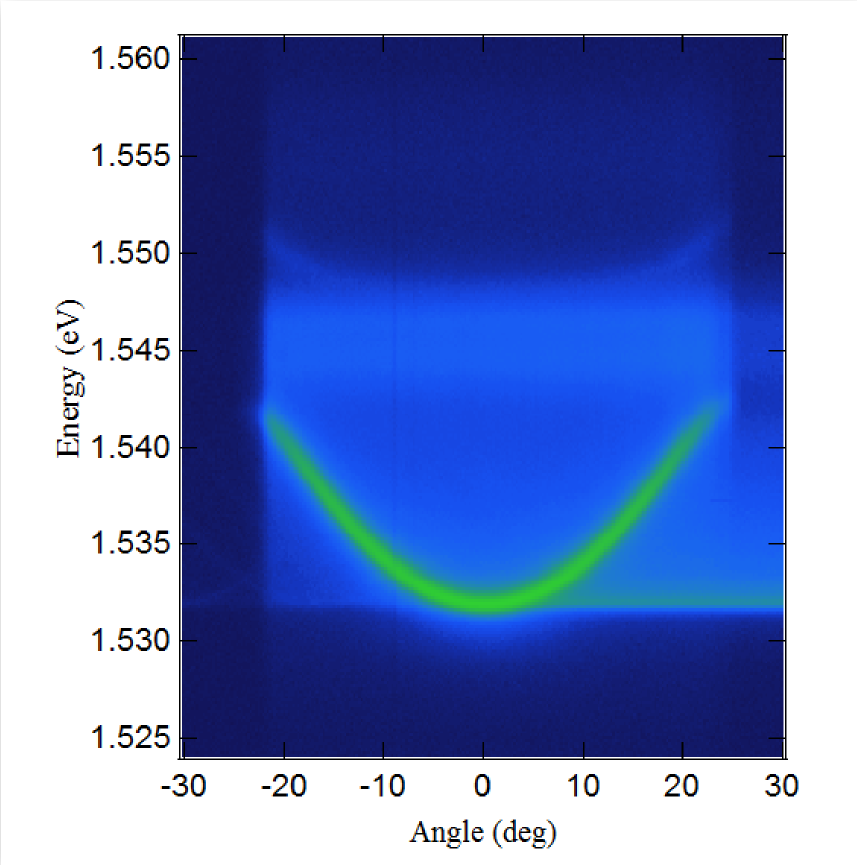
Strong Coupling Regime



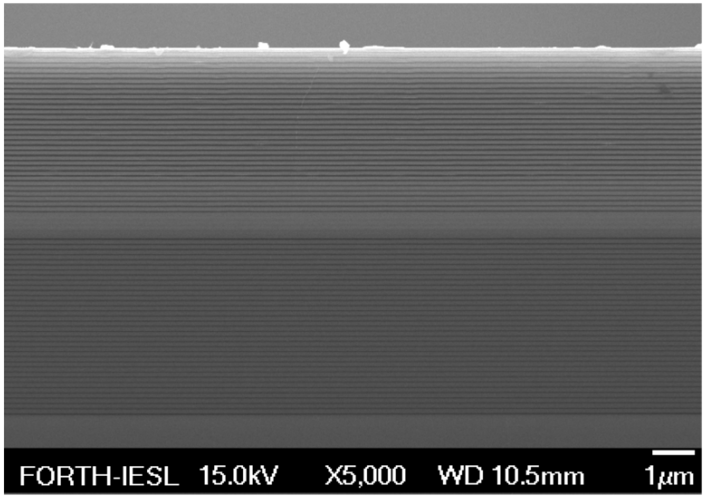
C. Weisbuch et al., Phys. Rev. Lett. 69, 3314 (1992)

High finesse GaAs microcavity





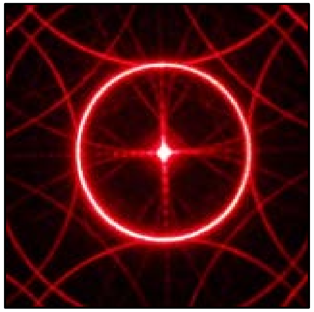
Modeled Q factor ~ 20000



Setup

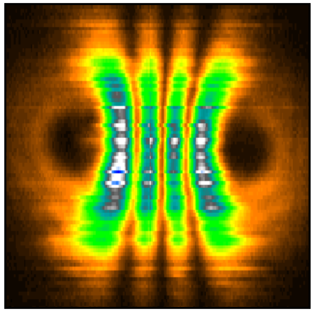
Sample:

- High quality 5/2 λ microcavity (Q < 16.000, τ > 7ps)
- 4 x 3 GaAs quantum wells, 9 meV Rabi splitting
- Cryogenics: kept at T ≈ 10 K



Excitation:

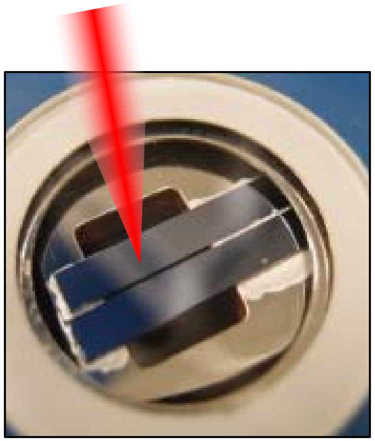
- Single mode Ti-Sapphire laser, λ = 755 nm (non-res.)
- Shaped by Phase modulation with spatial light modulator

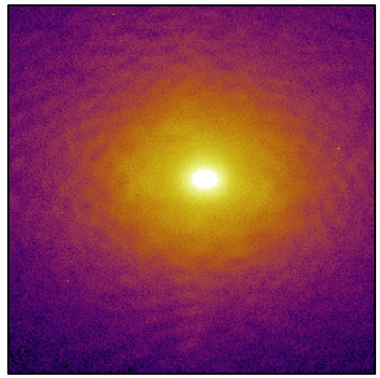


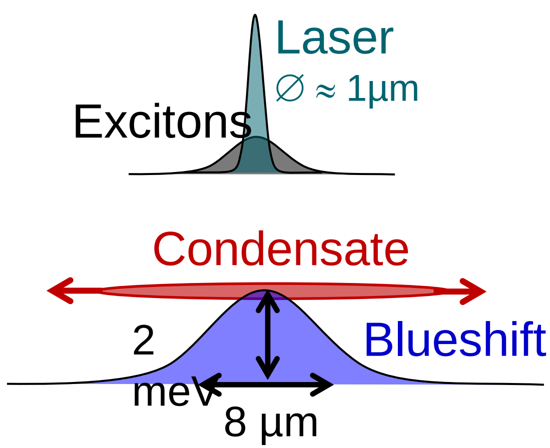
Detection:

- Real & k-space imaging
- Energy-resolved tomography
- Interferometric phase measurement

Blueshift Potential







High Density of Excitons

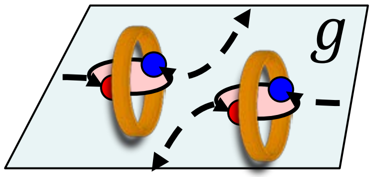
↓

Repulsive Interaction
“Blueshift Hill”

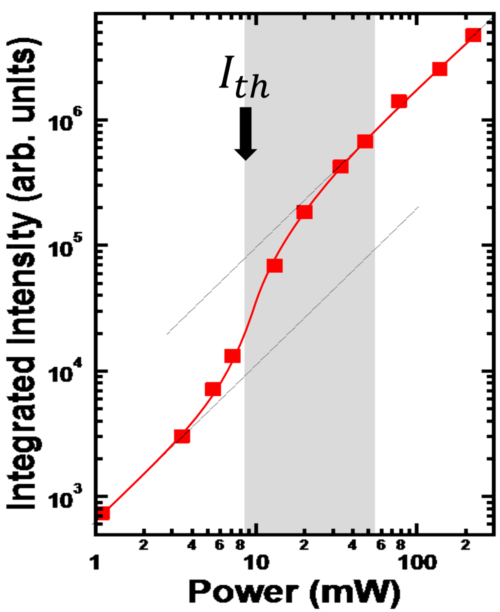
↓

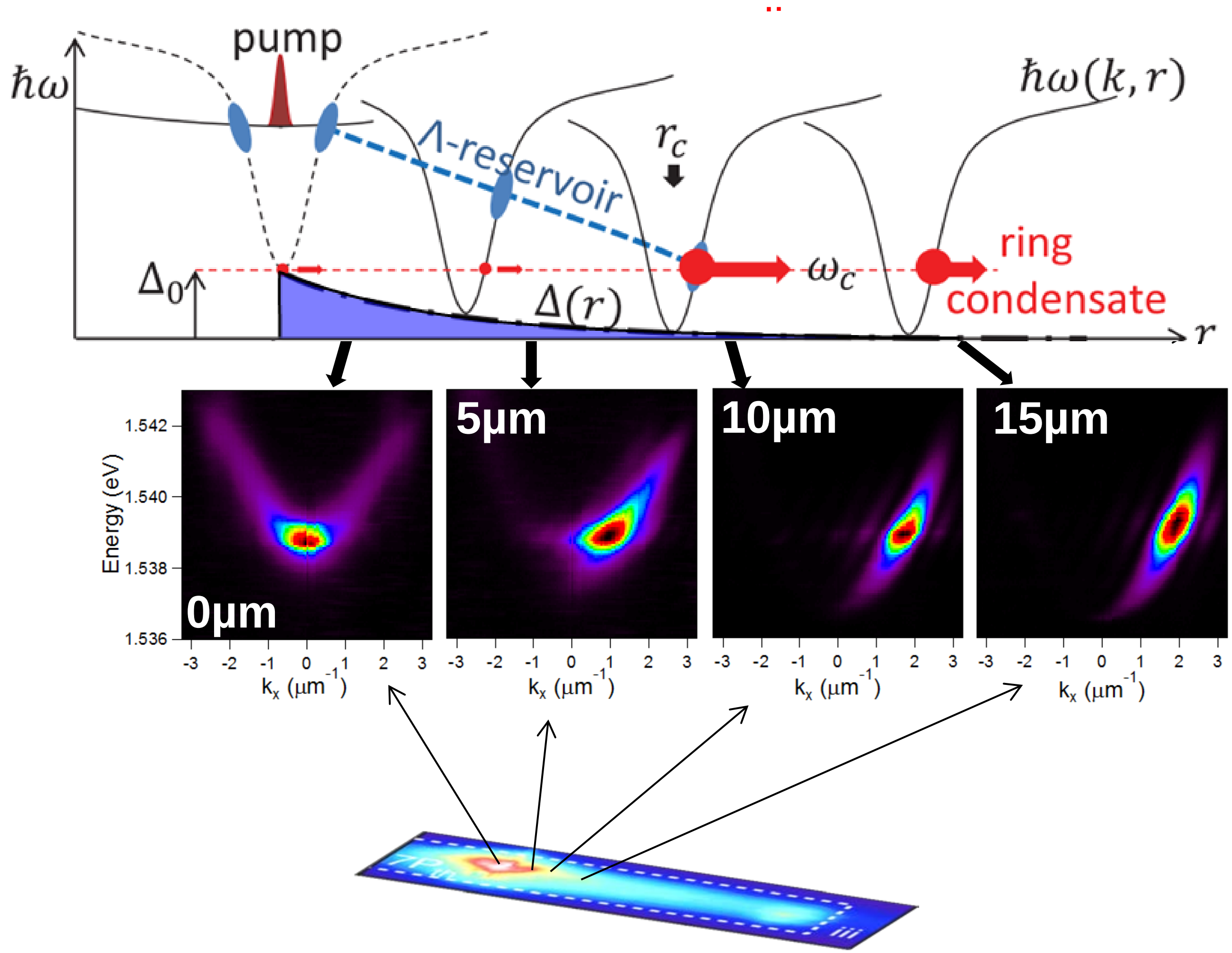
Radially Accelerated
Polariton Flow

Ballistic Condensate Ejection



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

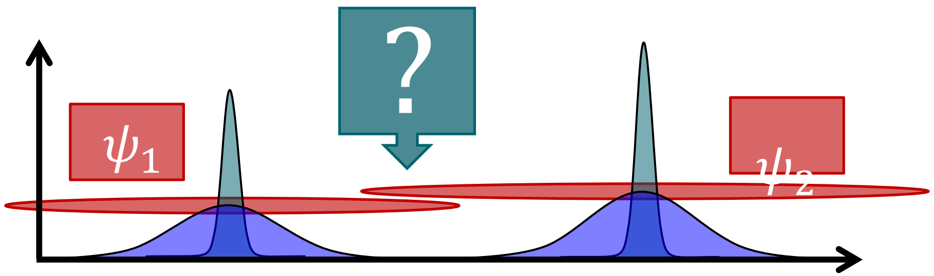




- Condensate fed by relaxing reservoir polaritons
- Condensate remains at same energy --> fully coherent

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

Phase Locked Condensates



Mode Locking

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

Phase Locking

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

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

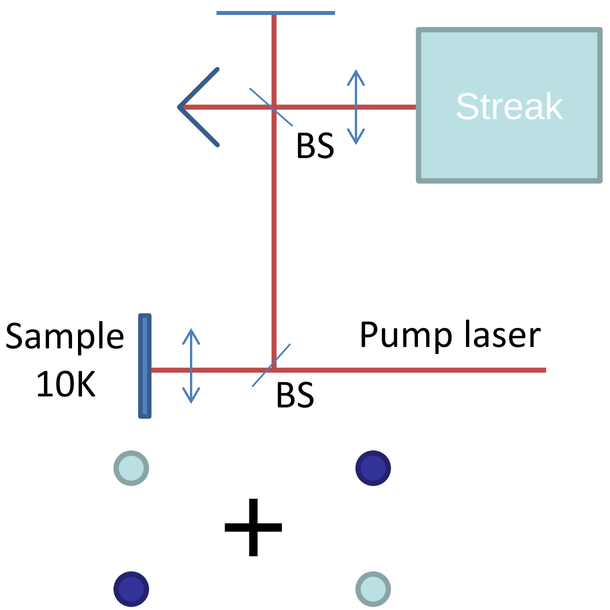
Damped Pendulum

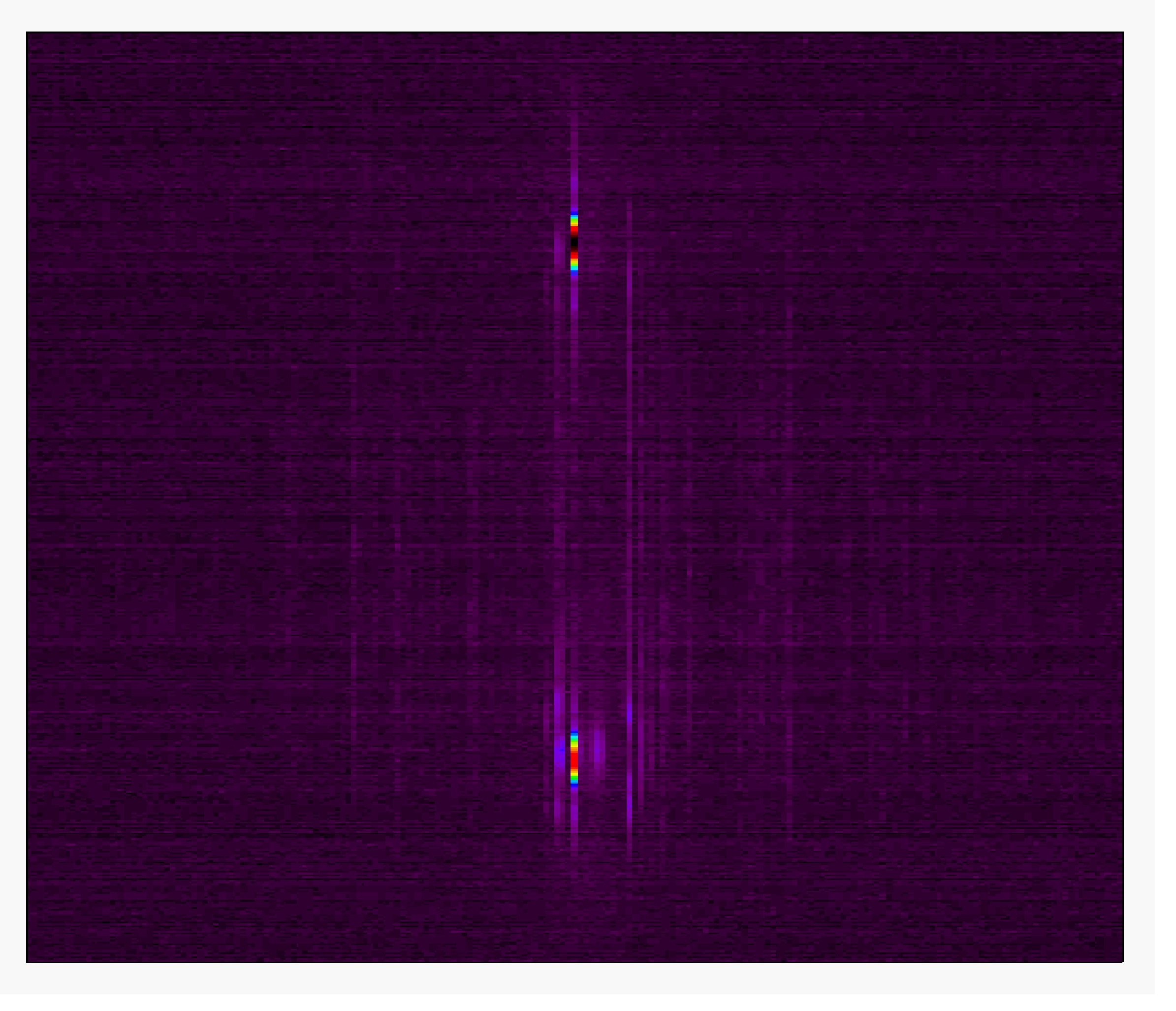
Trapping Transition: PRL **110,** 186403 (2013)

Buildup of Coherence and Phase Locking

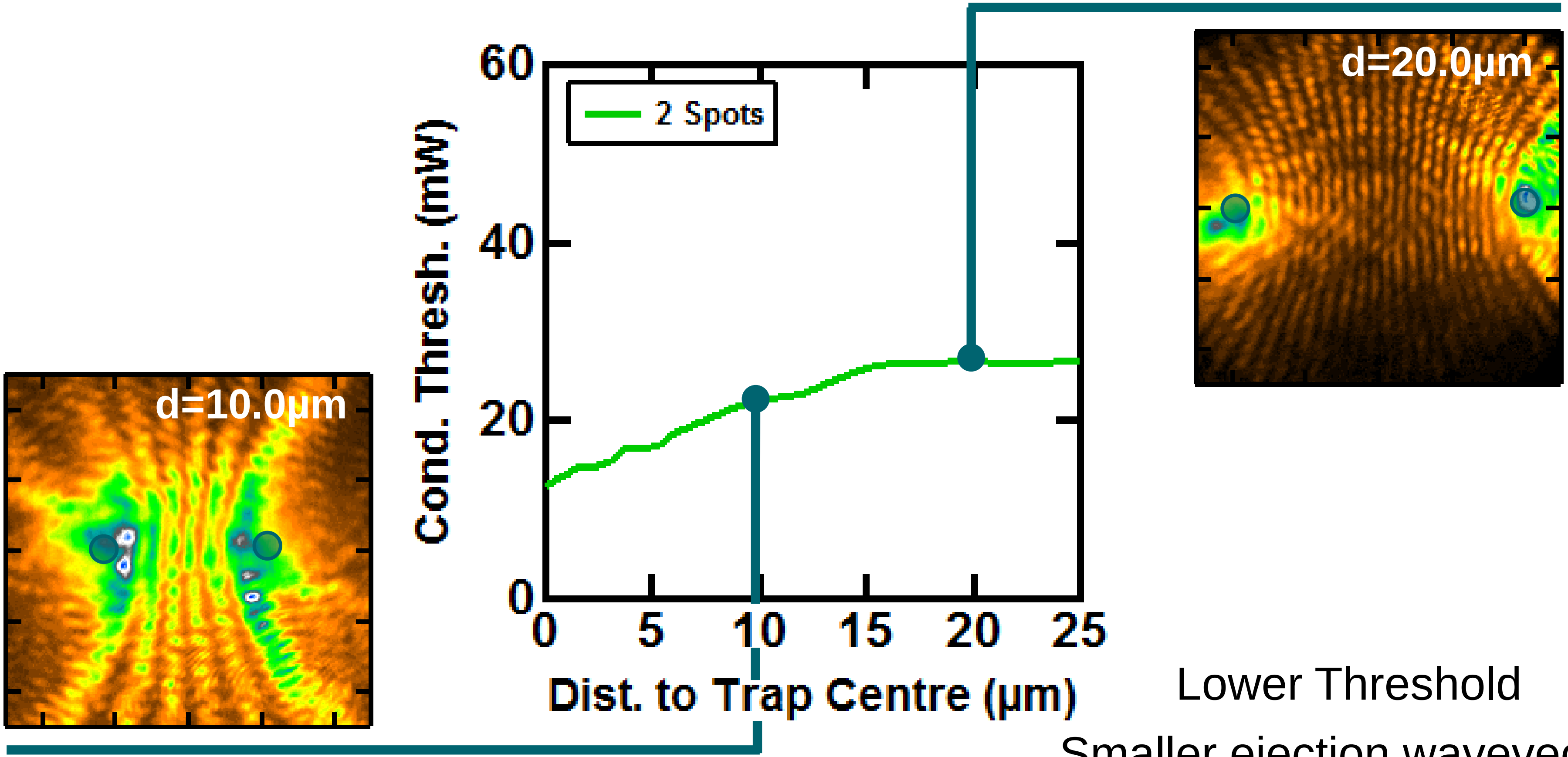
Time resolved measurement & interferometry

Pulsed excitation, interference of one condensate with the other





N = 2: Cooperative Effect

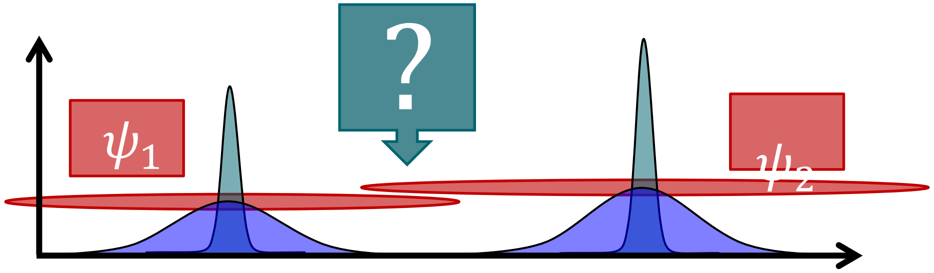


Lower Threshold

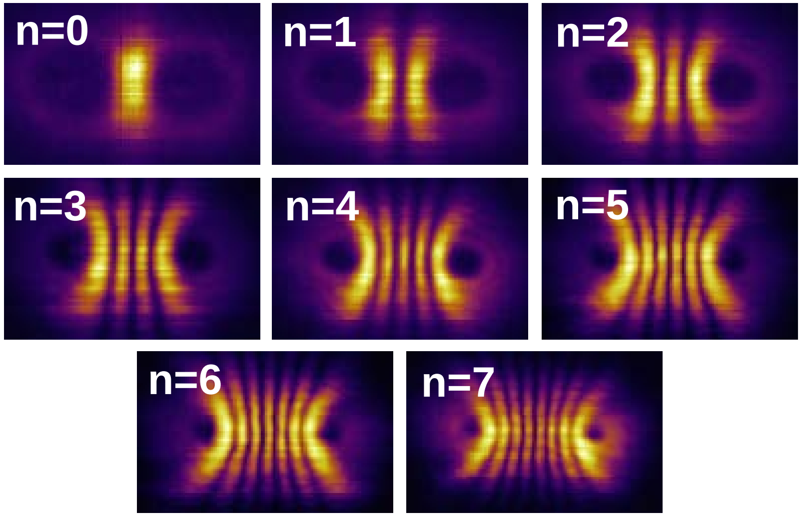
Smaller ejection wavevector

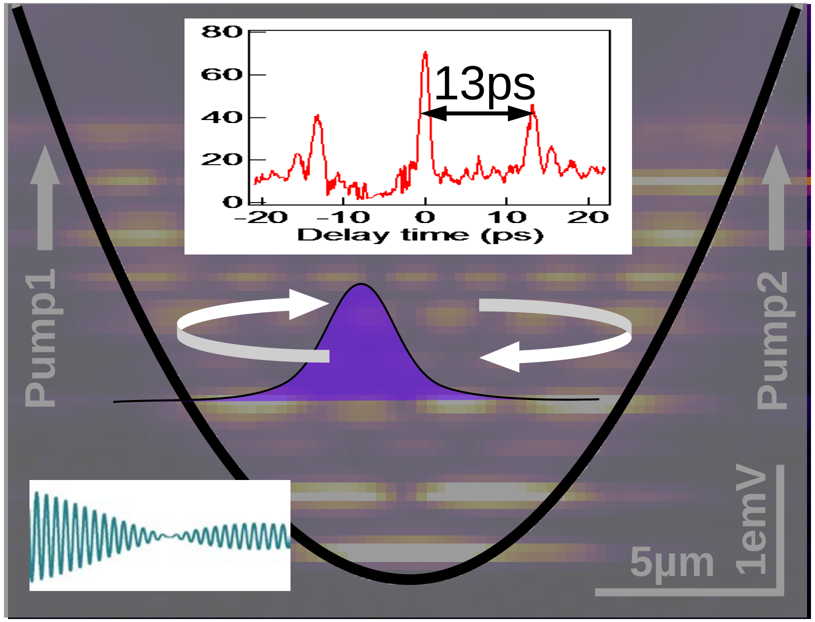
Larger Interference fringes

N=2: 2D Quantum Oscillator



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





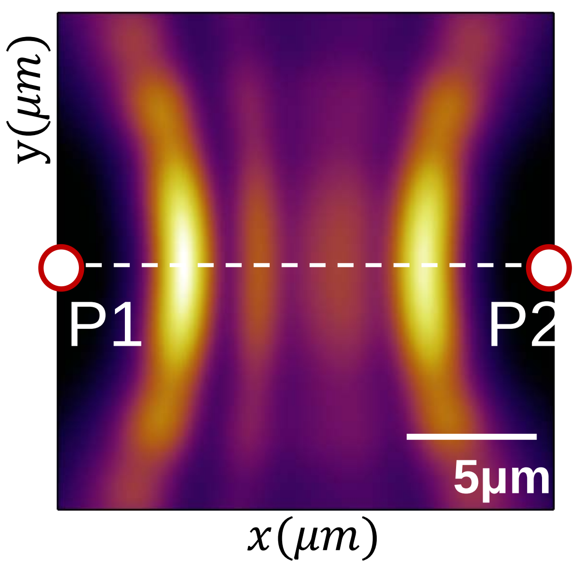
Condensate theory

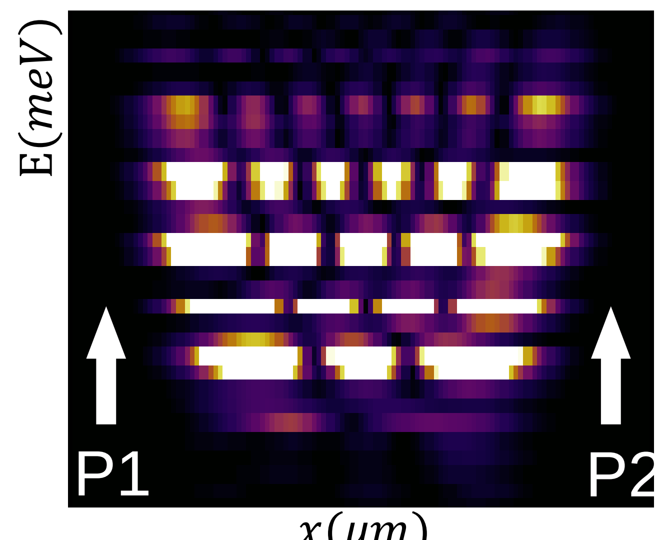
- complex Ginzburg-Landau equation (cGL)

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

- reservoir dynamics

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

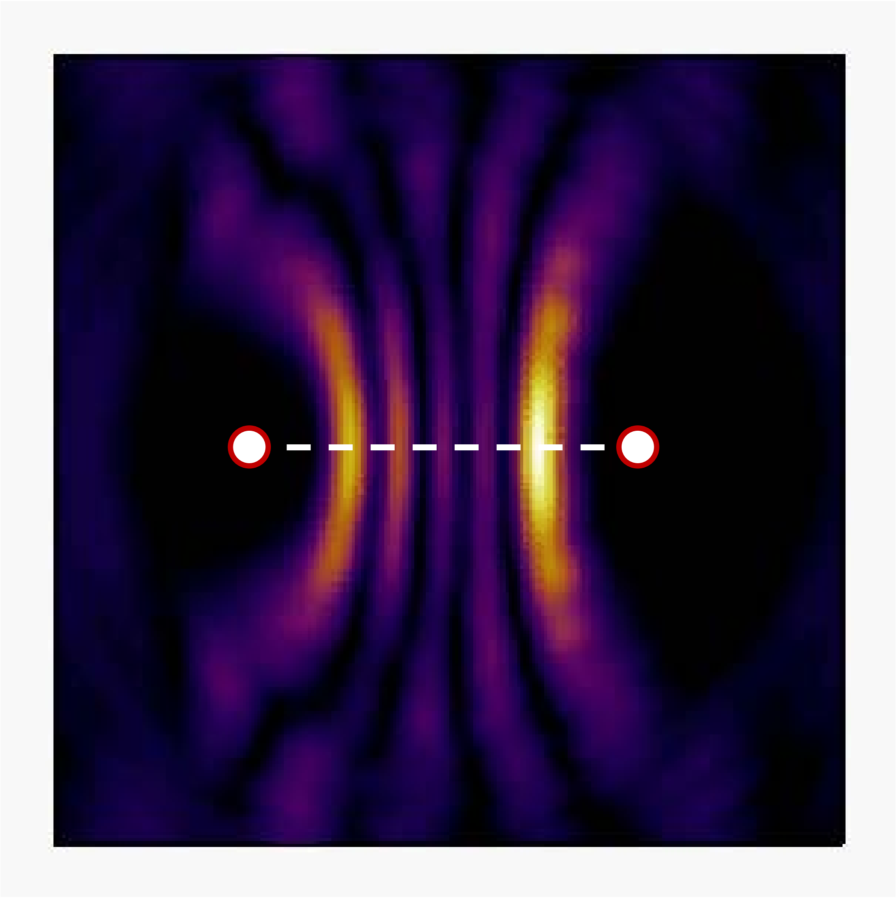


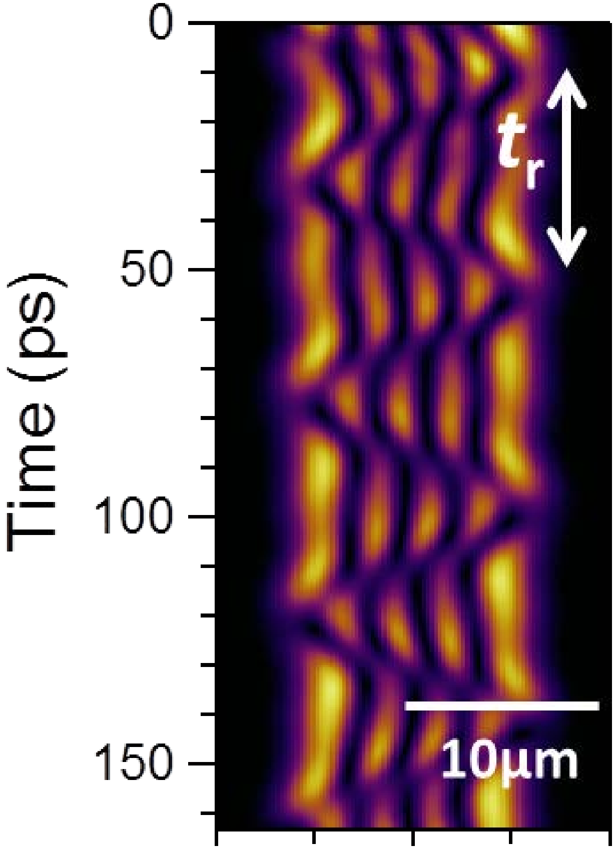


N. Berloff

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

Simulation results

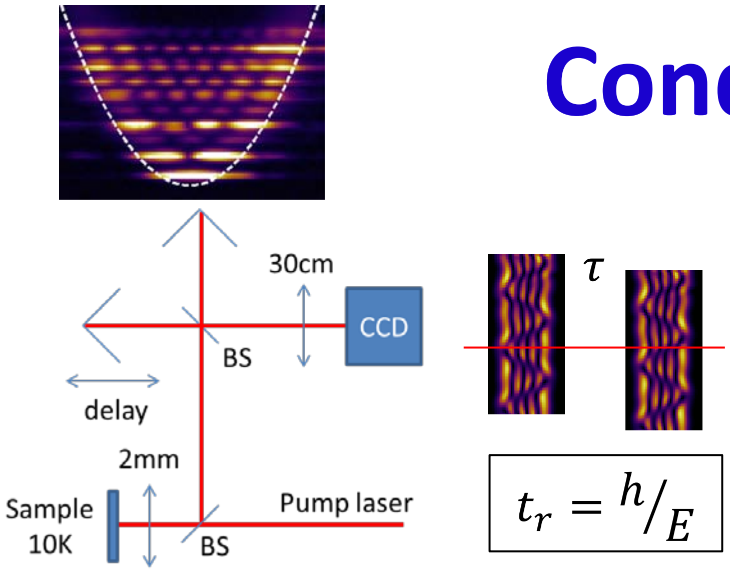




Resembles oscillating dark-solitons

How to measure?

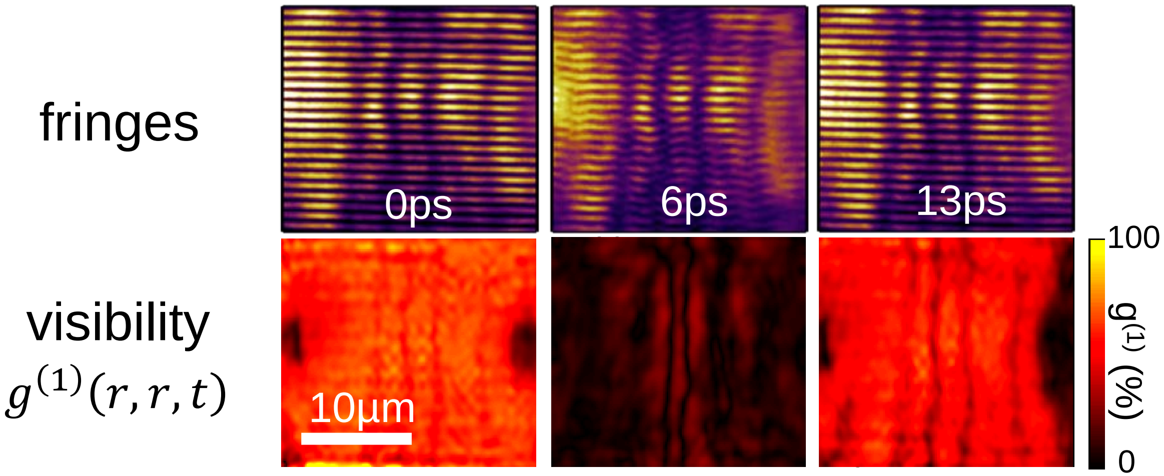
Condensate dynamics

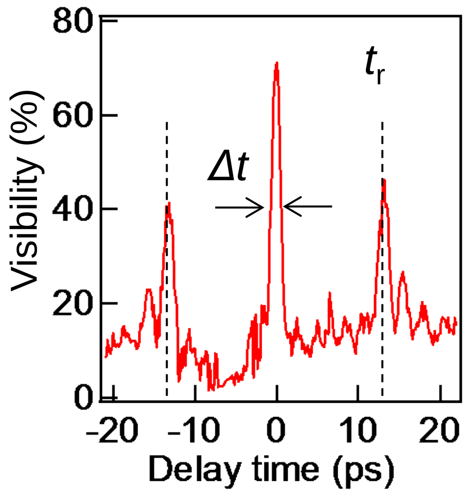


$$t_r = h/E$$

- modelocking condensates

nonlinear optics
cf: ultrafast lasers, supercontinuum generation

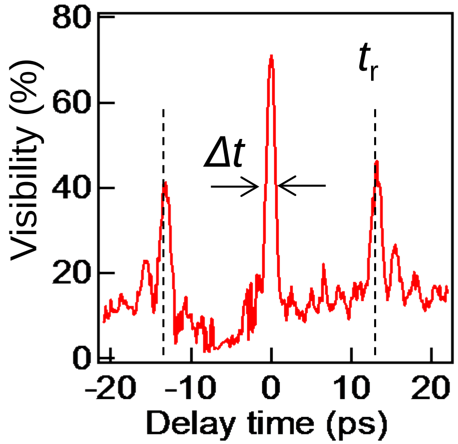




- self-interference every round trip time (exact match)
- all the simple harmonic oscillator levels are phase coherent

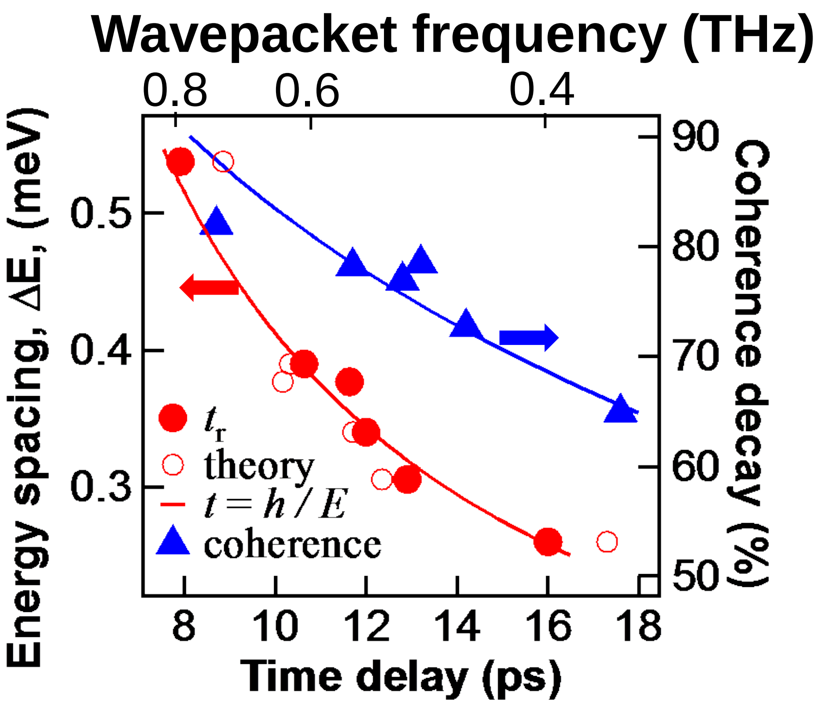
Nature Physics **8**, 190–194 (2012)

Tuneable oscillator



temporal width $\Delta t \simeq t_r / n_{SHO}$
set by number of SHO states (n_{SHO}=10)

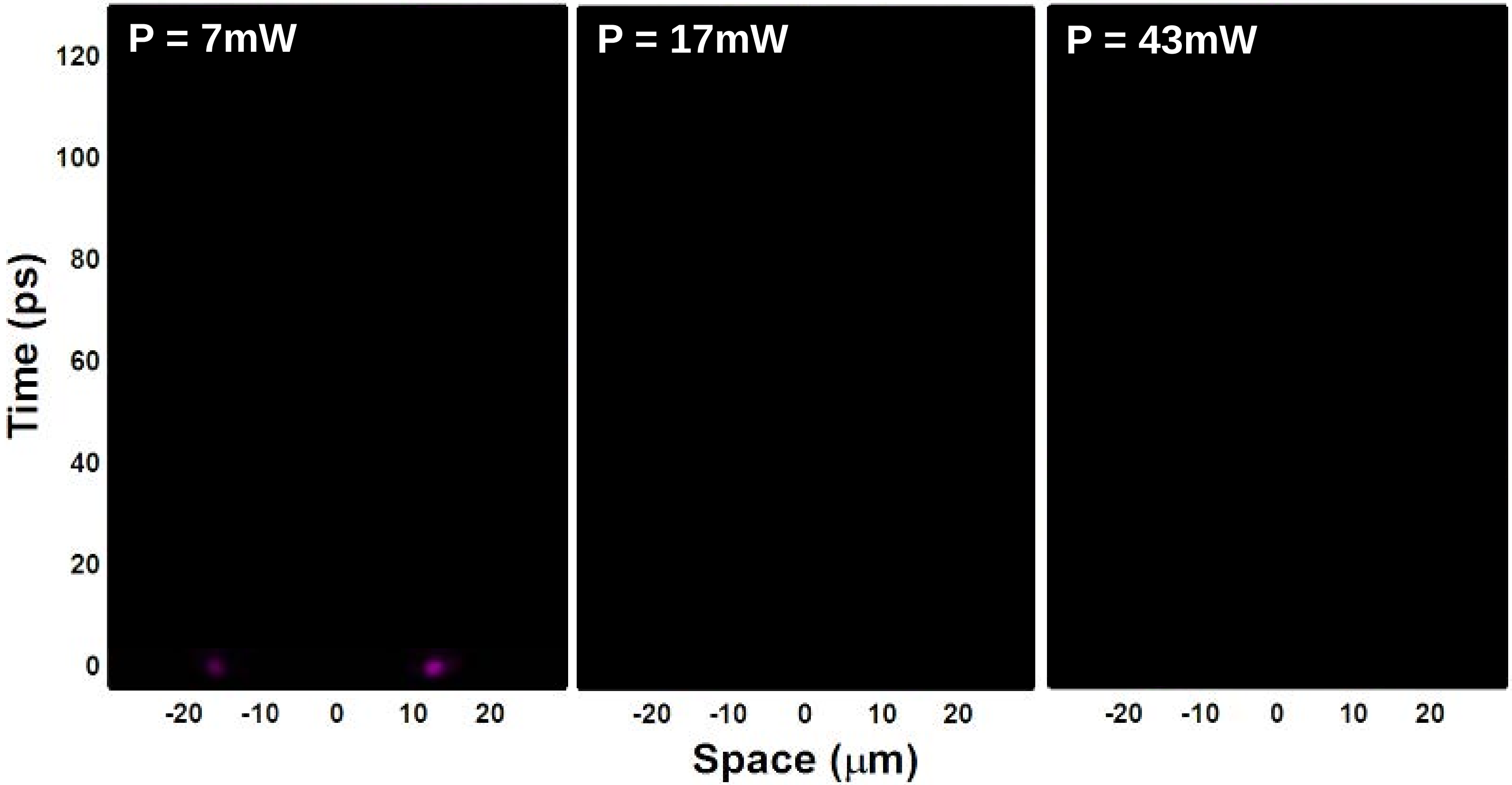
$$t_r = \pi L \sqrt{\frac{m^*}{2(g|\psi|^2 + \hbar R_R N)}}$$



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

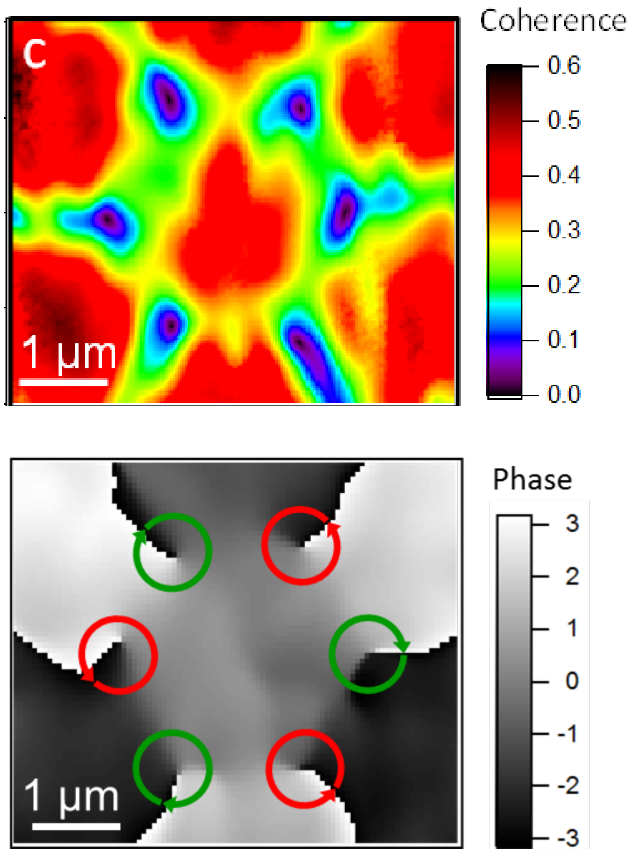
Bright Wavepacket

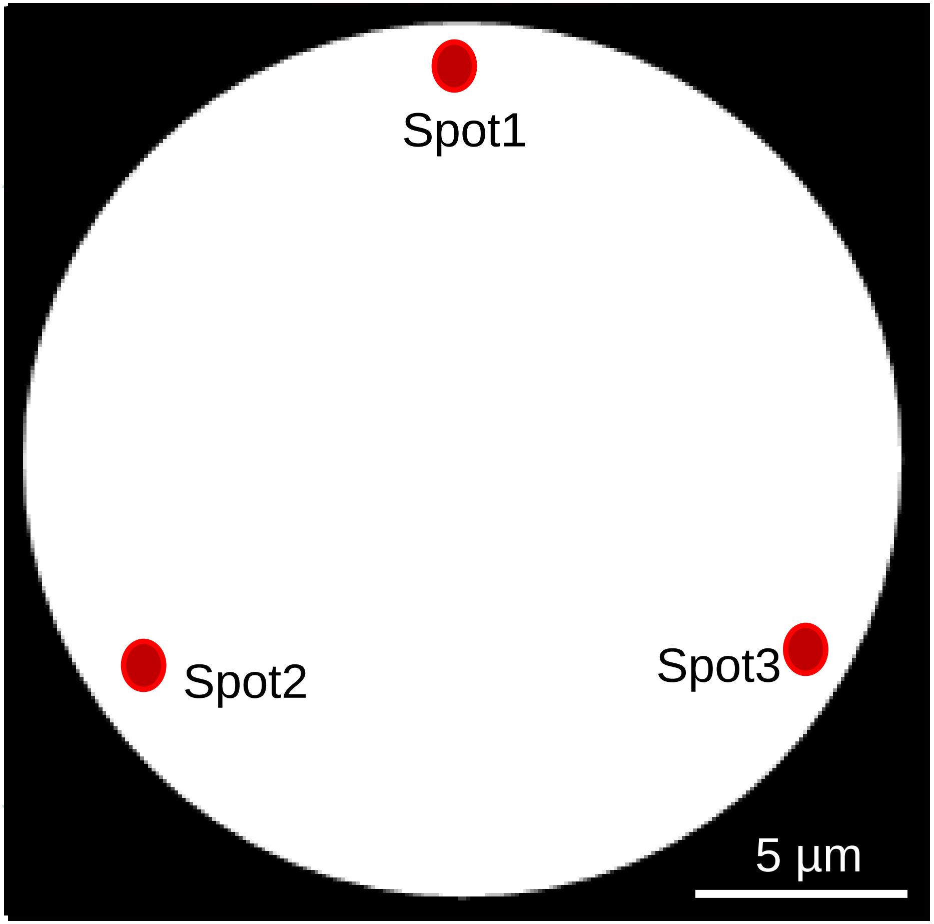
Time resolved phase locking of polariton cond. In prep.

Multiple spot excitation

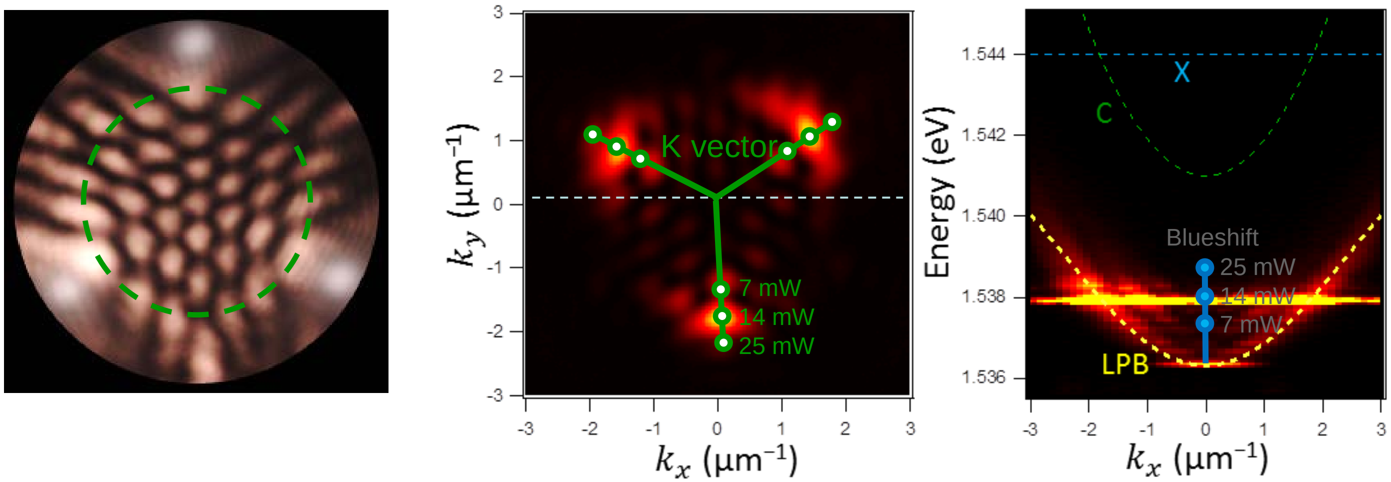
Vortex lattices

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

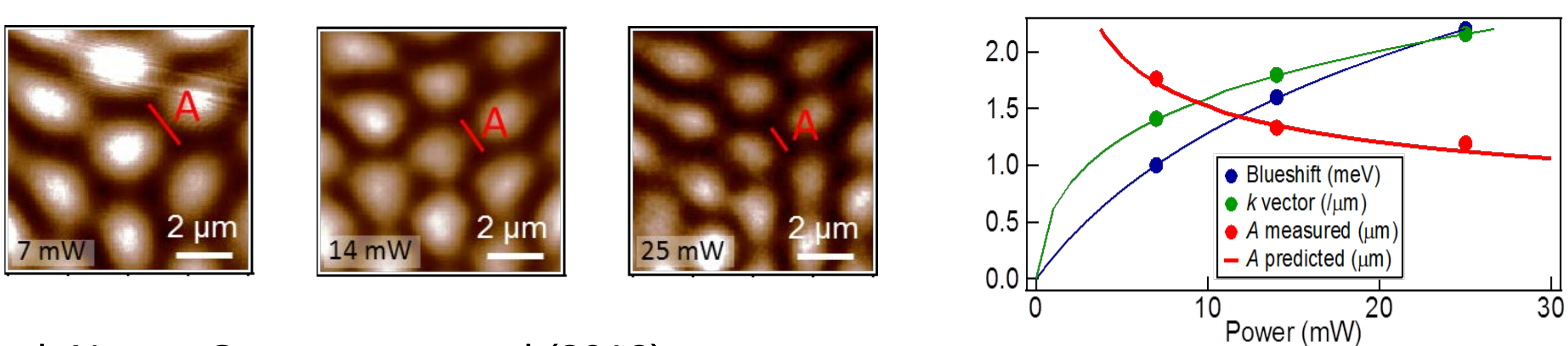




Stretching the lattice

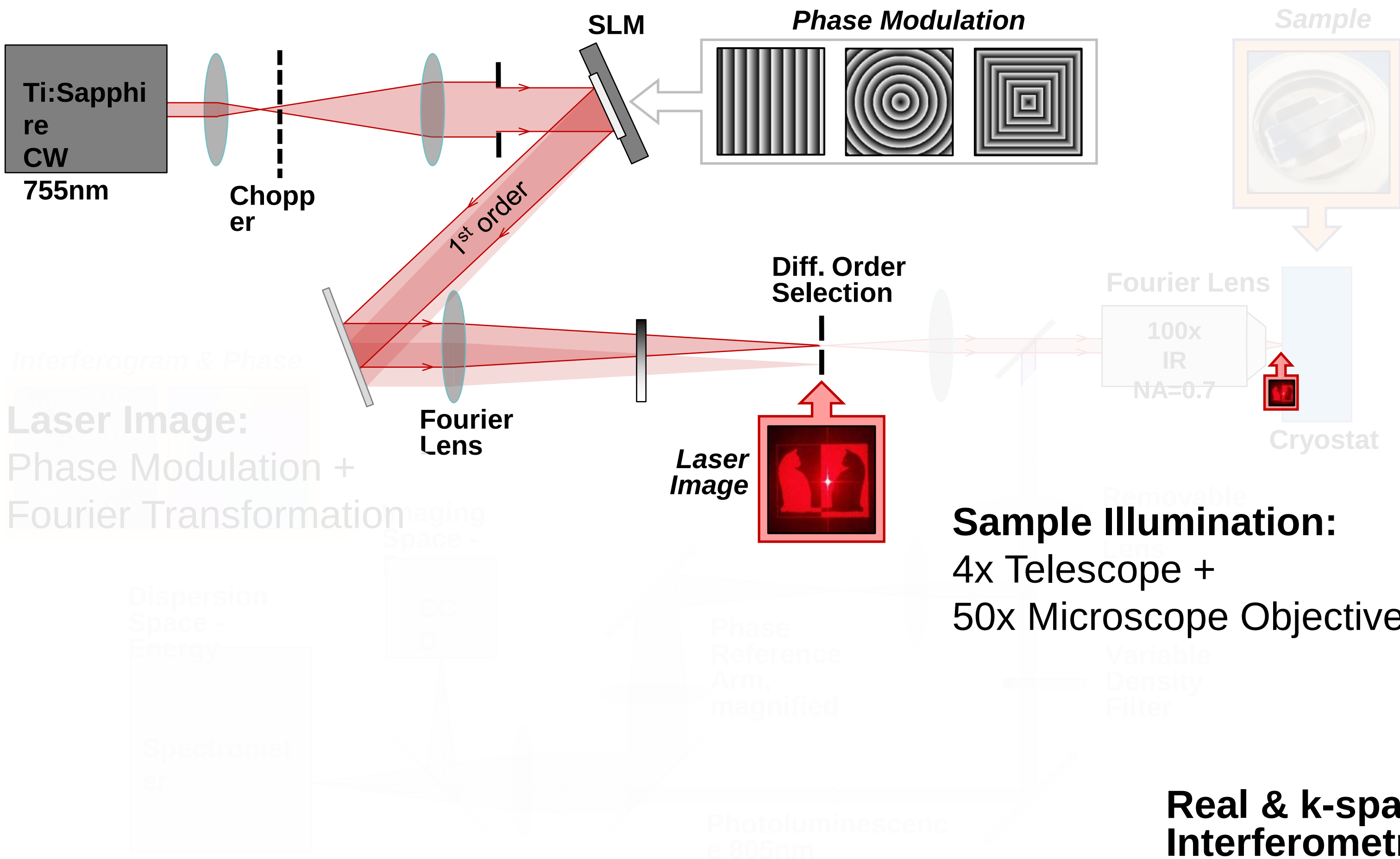


- Vortices formed by a linear superposition of 3 waves outflowing from each spot.
- Average distance between neighbouring vortices: $A = 4\pi/(3k\sqrt{3})$
- Outflow momentum dependent on power: $k(r) = K[\omega_c - \Delta(r)]$



G. Tosi, Nature Comm., accepted (2012)

Setup

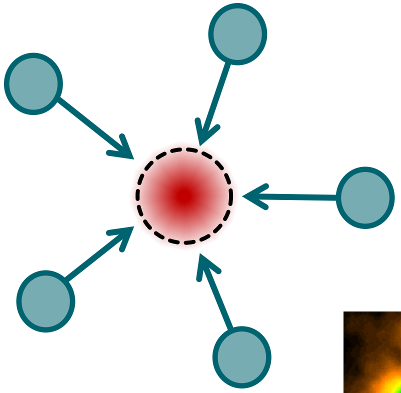


Sample Illumination:
4x Telescope +
50x Microscope Objective

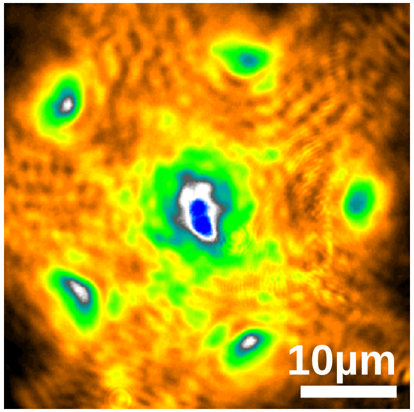
Real & k-space Interferometry

Flow Control

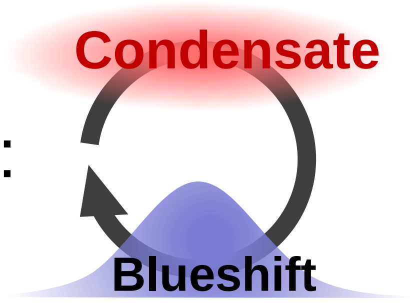
- Design optical potential by non-resonant laser excitation



- Blueshift gradient <--> main flow direction



- Very non-linear system: condensate shapes its own potential

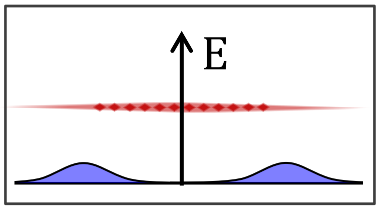


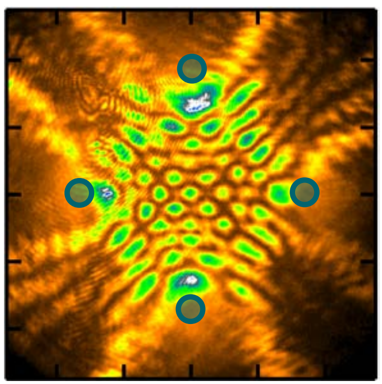
$$i\hbar\partial_t\psi = \dots + V(\boldsymbol{r})\psi + g|\psi|^2\psi$$

Phase Transition

Phase Locked <--> **Trapped**

Pumps far apart — Pumps Close Together





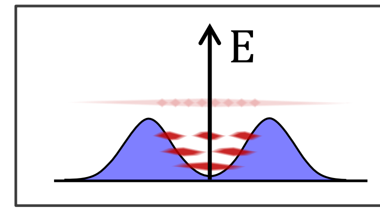
Single Energy

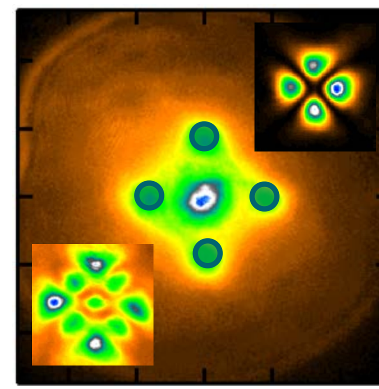
Physics:

Vortex Lattice — Q. Oscillator

Condensation:

At pump — Centre



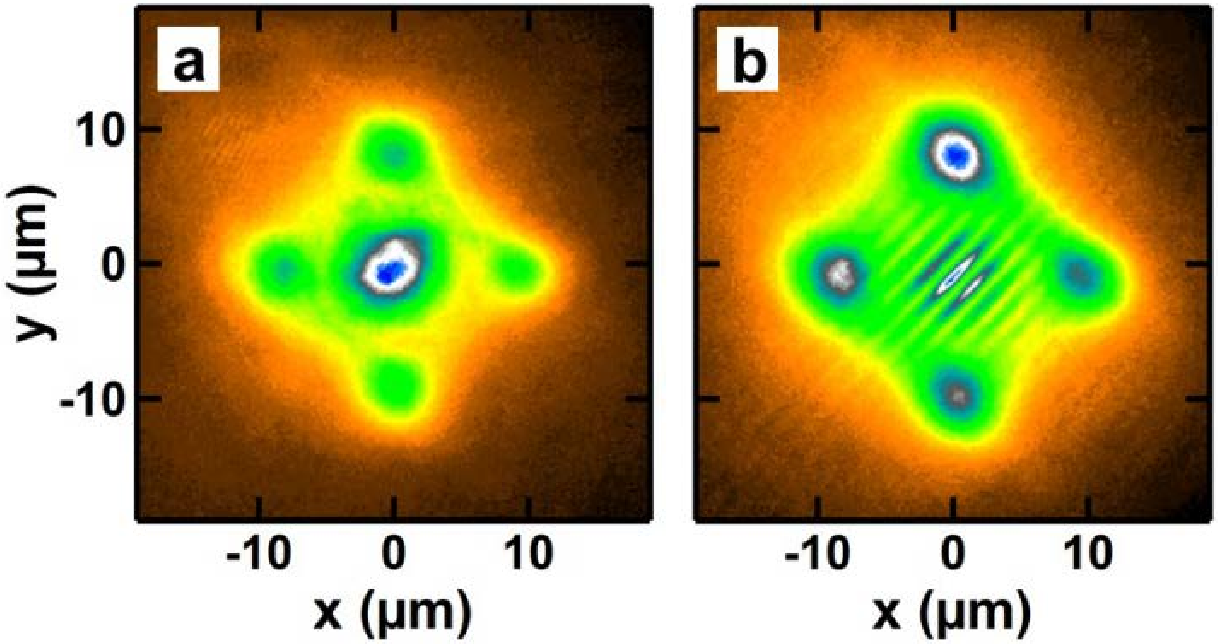


Condensation Threshold?

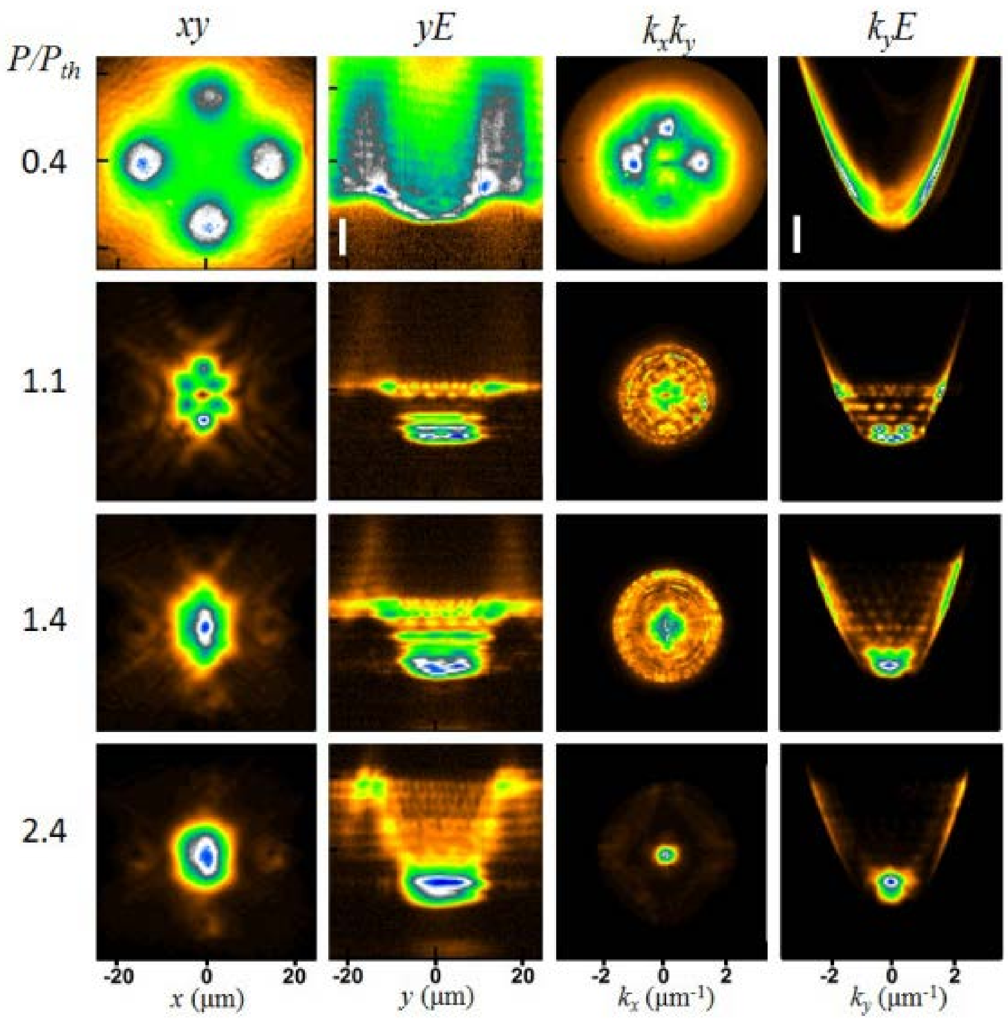
Trapping Transition: PRL **110,** 186403 (2013)
Vortex Lattice: Nature Comm. **3**, 1243 (2012)

Condensation Threshold

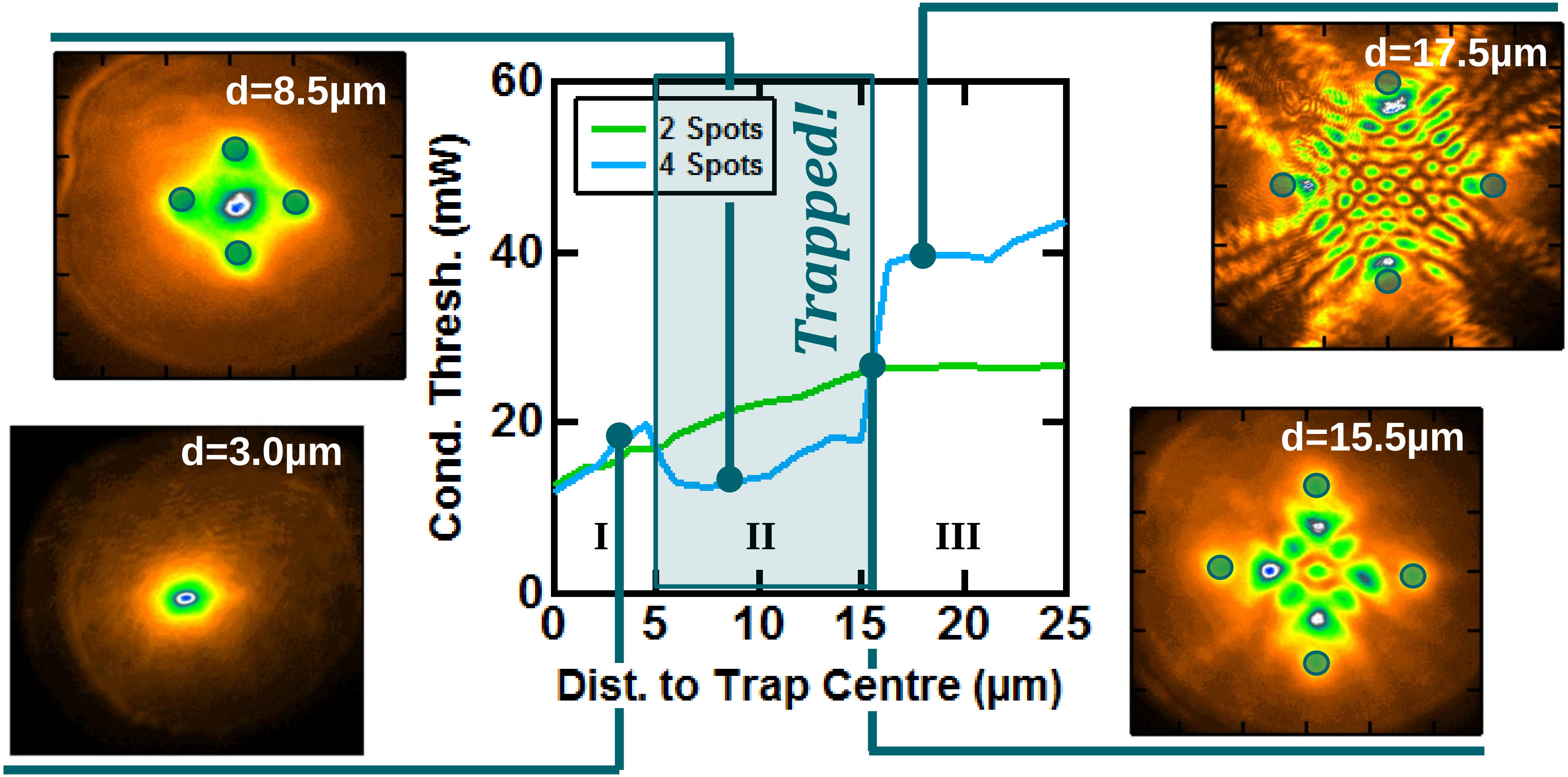
Below Threshold Above Threshold



N ≥ 4: Opt. Trapped Condensates

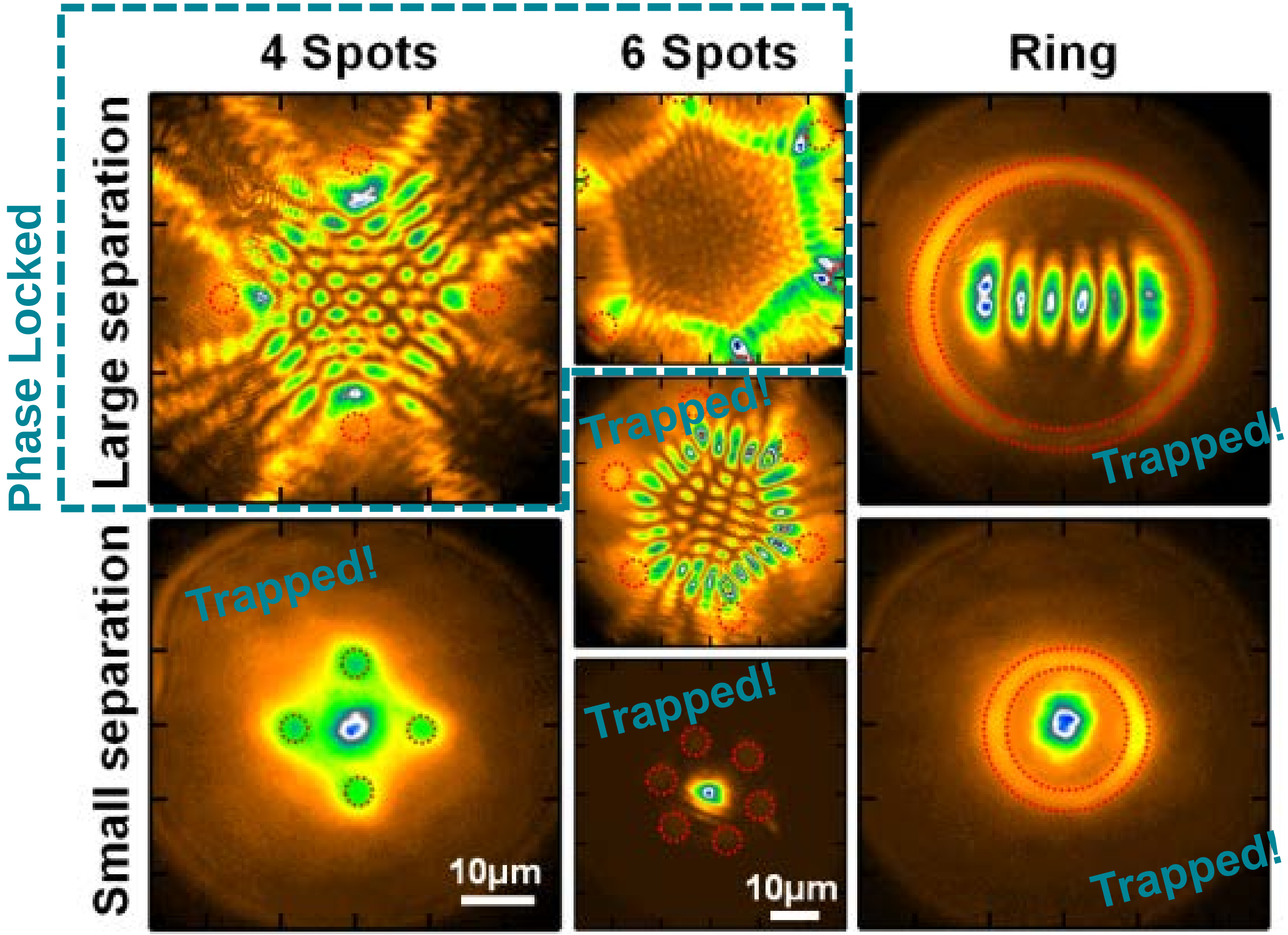


N = 4: Optical Trapping



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

N = 4, 6, 8, ...

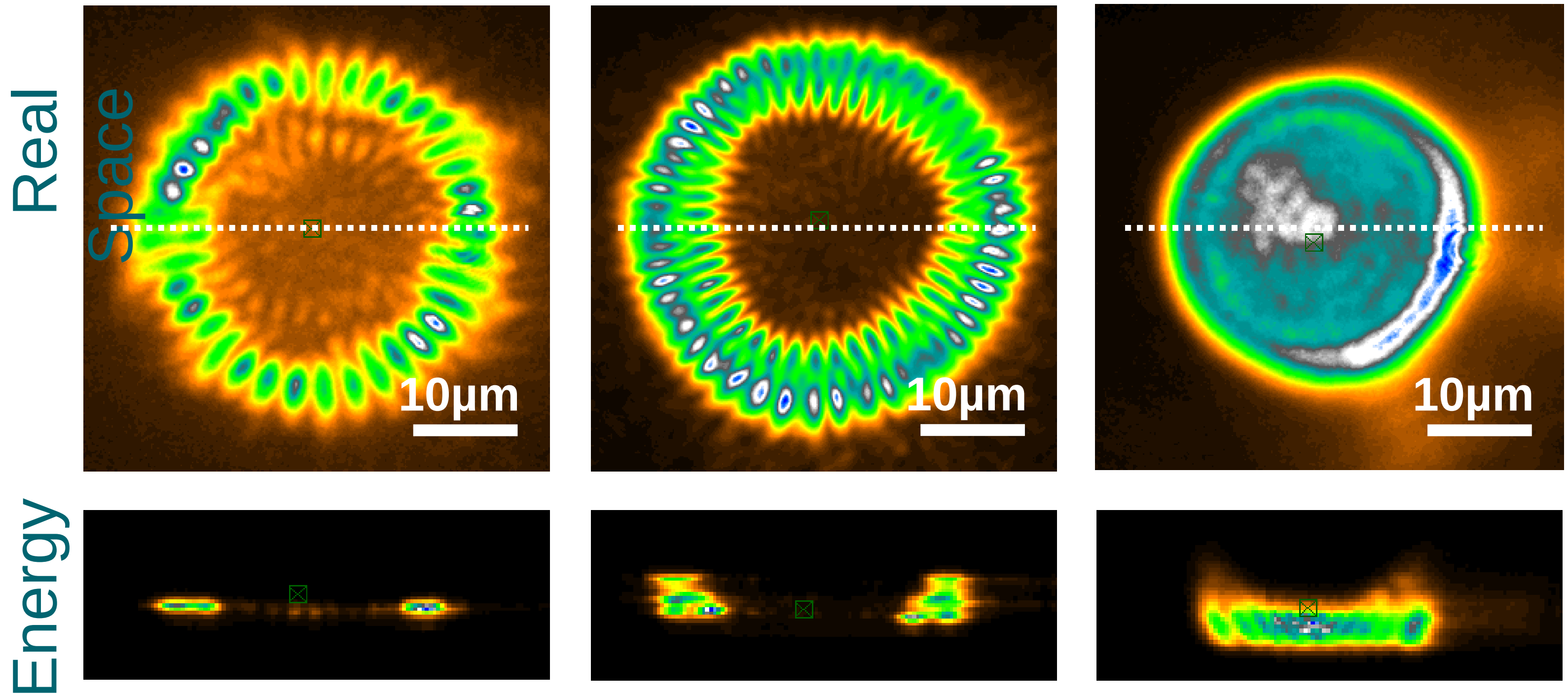


Phase Locked
4 Spots
6 Spots
Ring
Large separation
Small separation
Trapped!
Trapped!
Trapped!
Trapped!
Trapped!
10μm
10μm

Ring Condensates

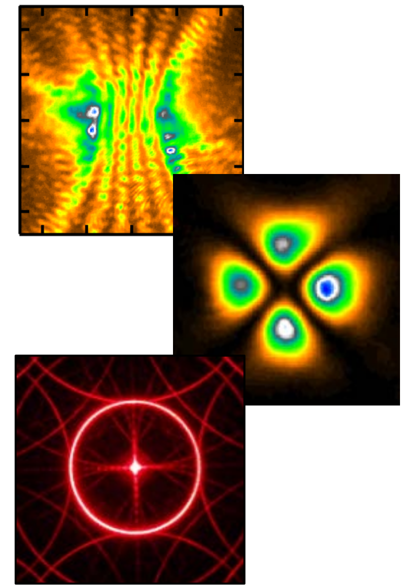
Change Excitation geometry

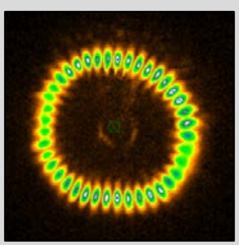
Excitation power

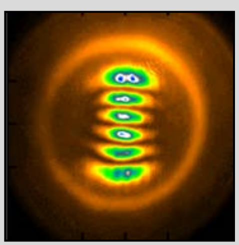


Conclusion

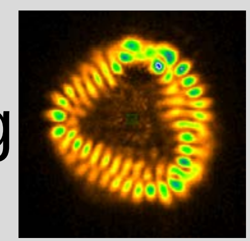
- **Phase-Locking:** Cooperative Effect
- **Phase Transition:** Locked --> Trapped
- **Direct Optical Flow Control + Trapping:**
  SLM + Blueshift

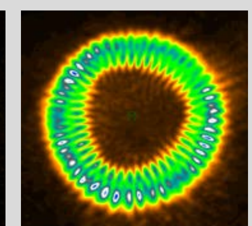






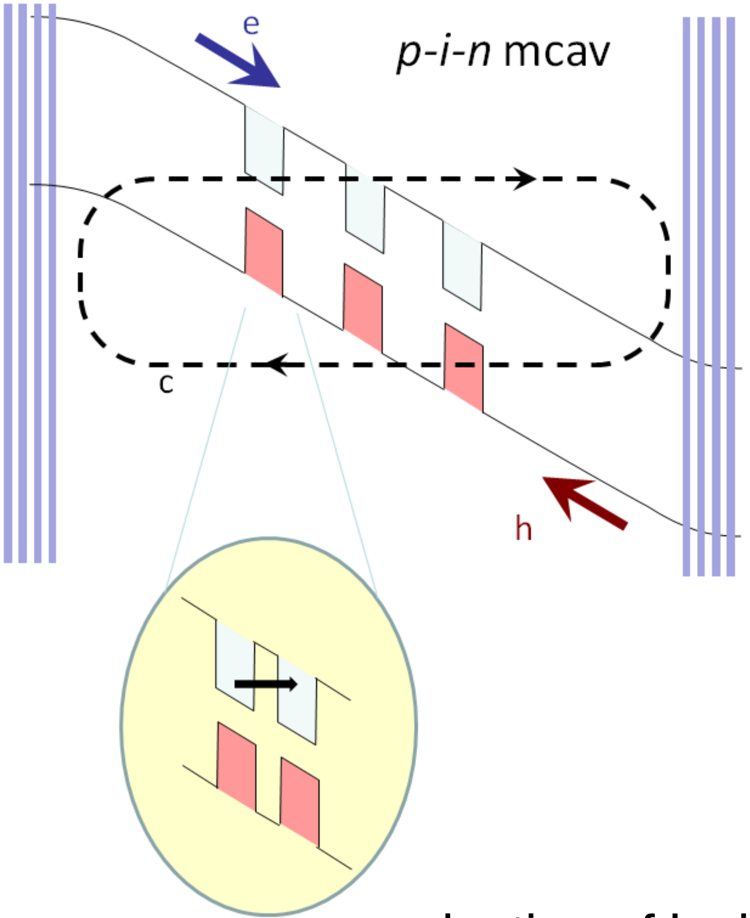
Future:
Explore new exciting pump geometries!





Indirect polaritons: Dipolaritons

Indirect polaritons: Dipolaritons



Dipolariton approach:
weakly-coupled double quantum wells

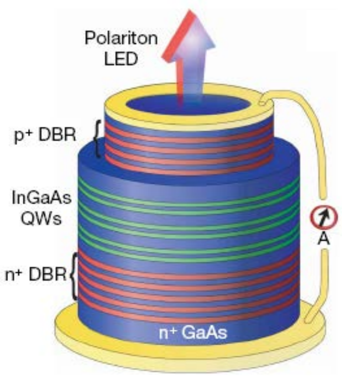
⬇

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

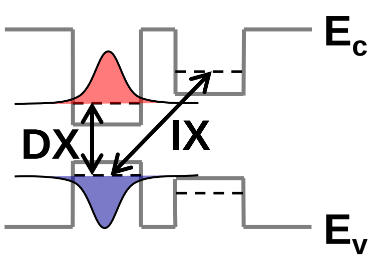
- reduction of lasing threshold
- electrically-pumped polariton lasers and BECs



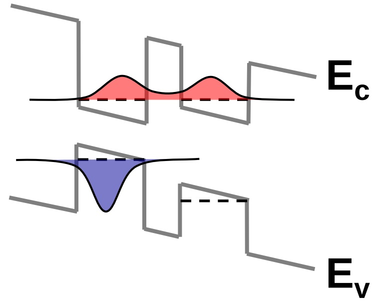
P. Cristofolini *et al.*, Science 336, 704 (2012)   G. Christmann APL 98, 081111 (2011)

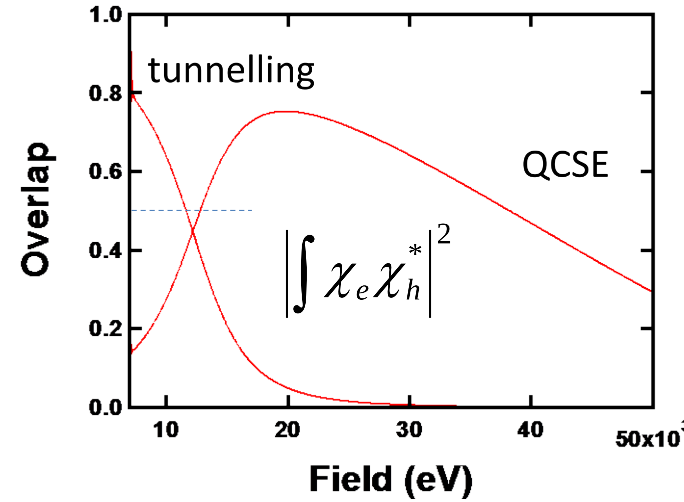
Dipolaritons

electron levels
off resonance

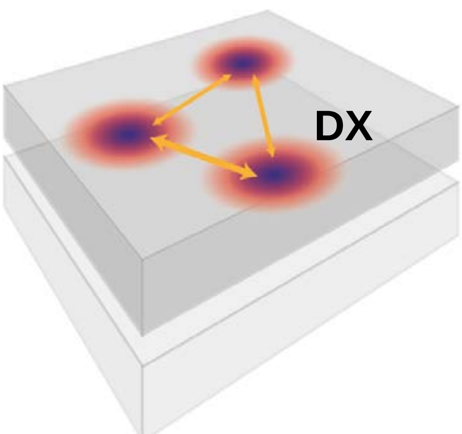


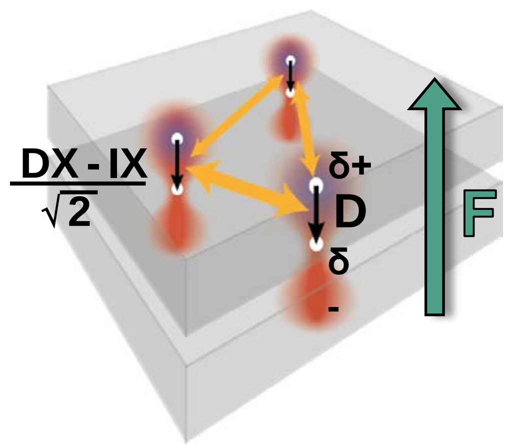
electron levels
at resonance

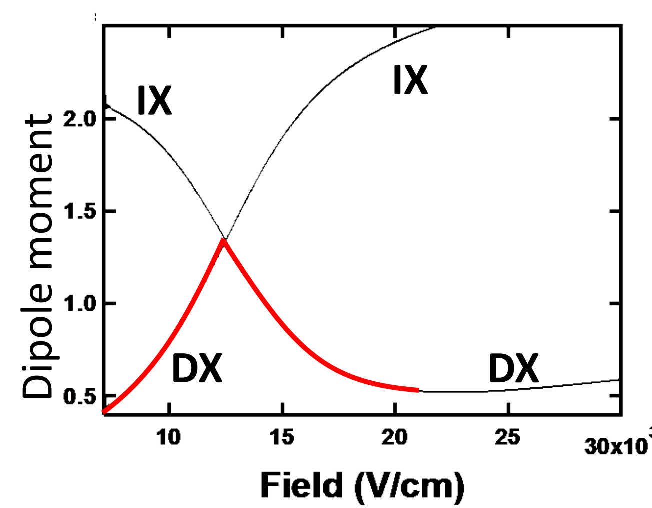




Oscillator strength is kept







Strong dipole moment

"tunnelling off"

↓

direct excitons DX

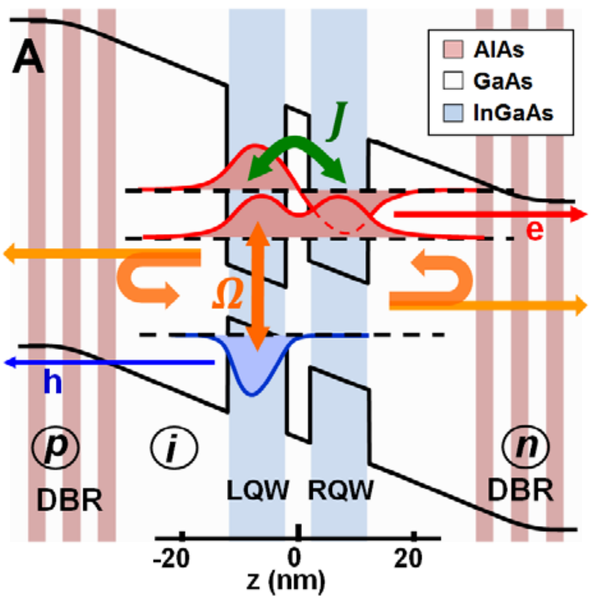
"tunnelling on"

↓

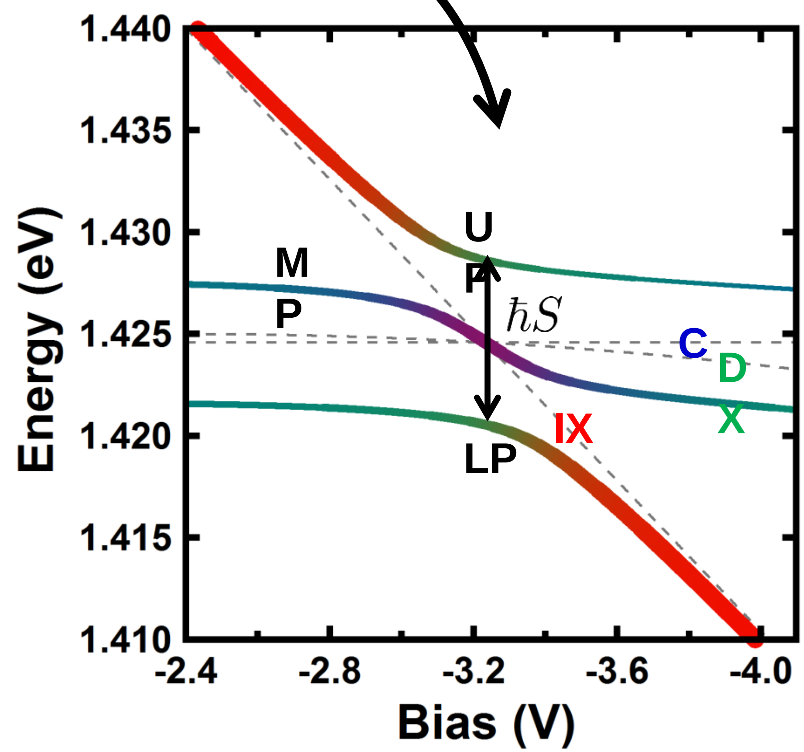
mixed excitons DX±IX, static dipole moment

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

Dipolaritons



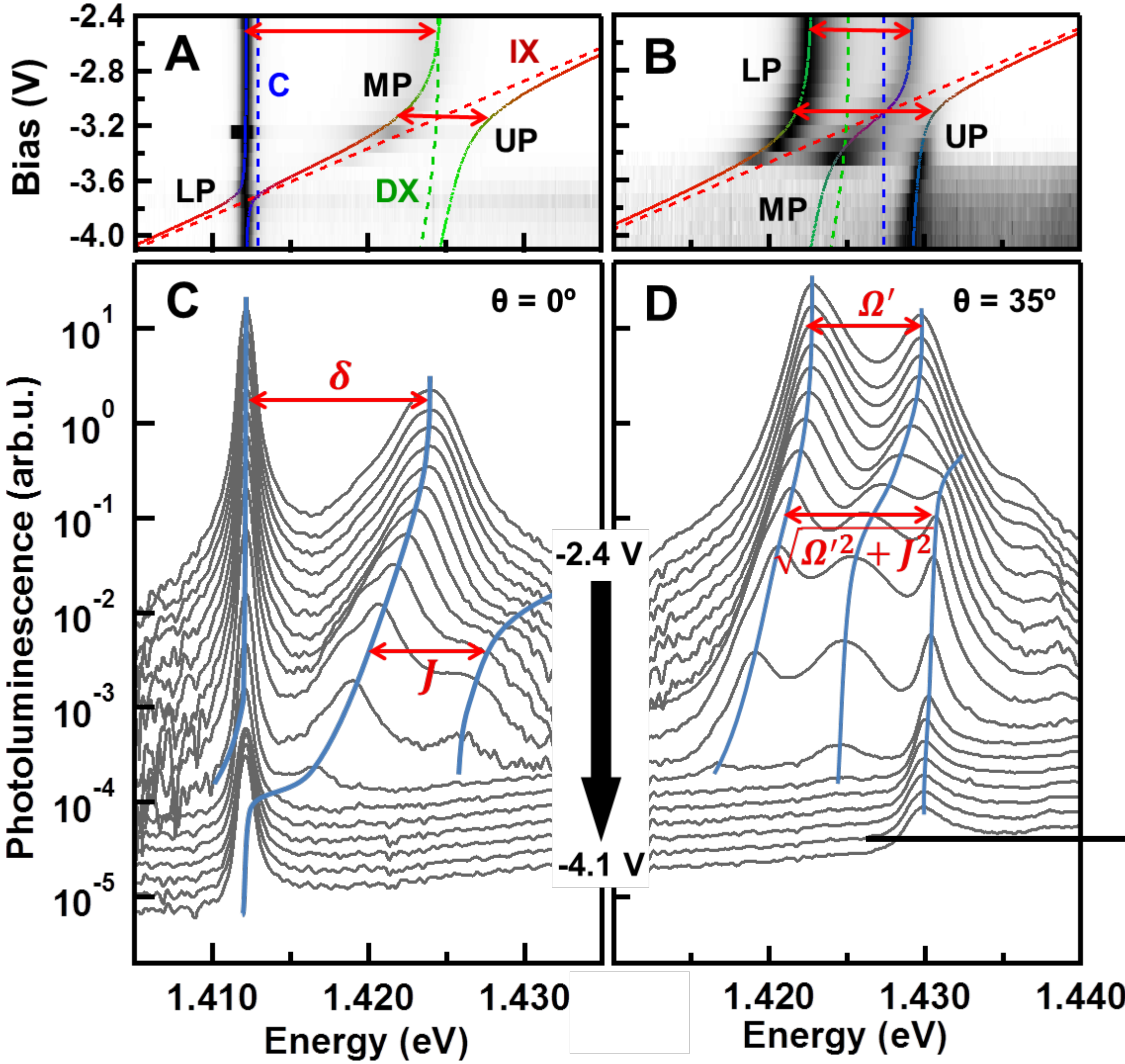
strong coupling



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

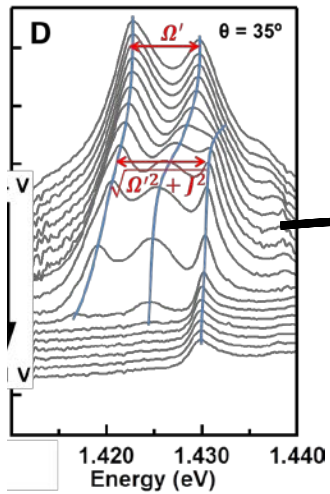
PL is lost because electron tunnel out of the system

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

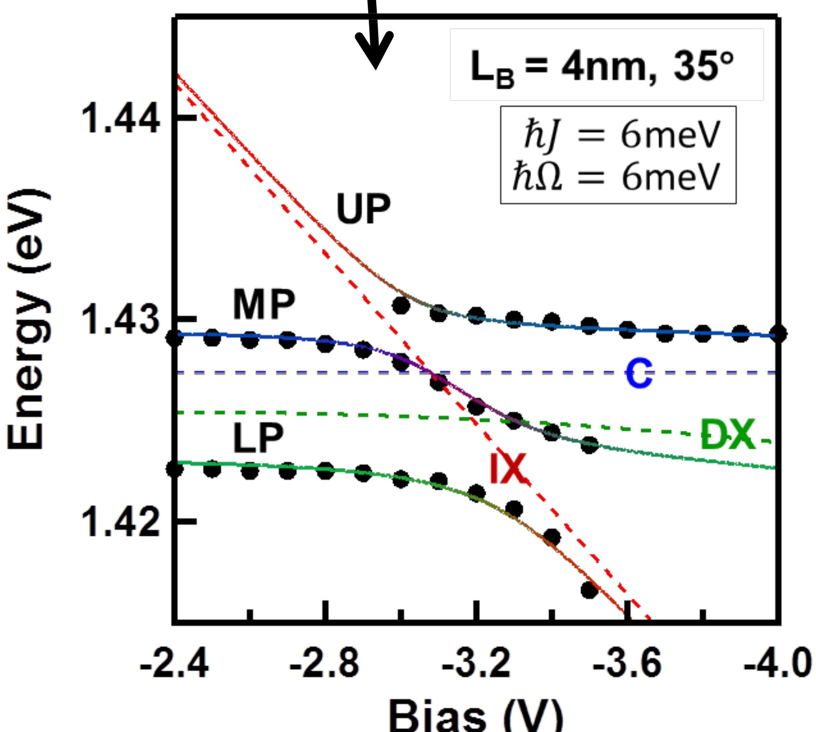


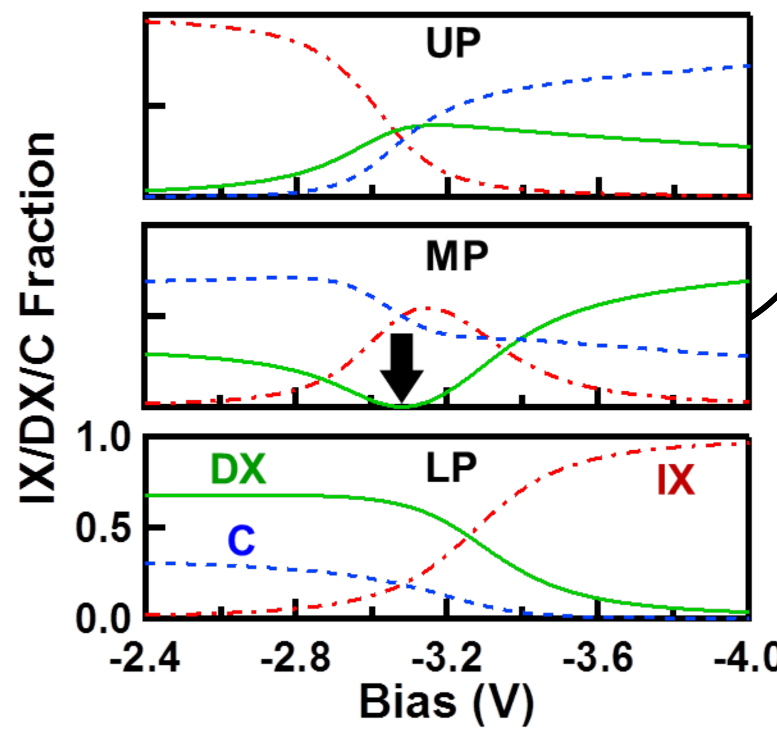
peak extraction
+

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

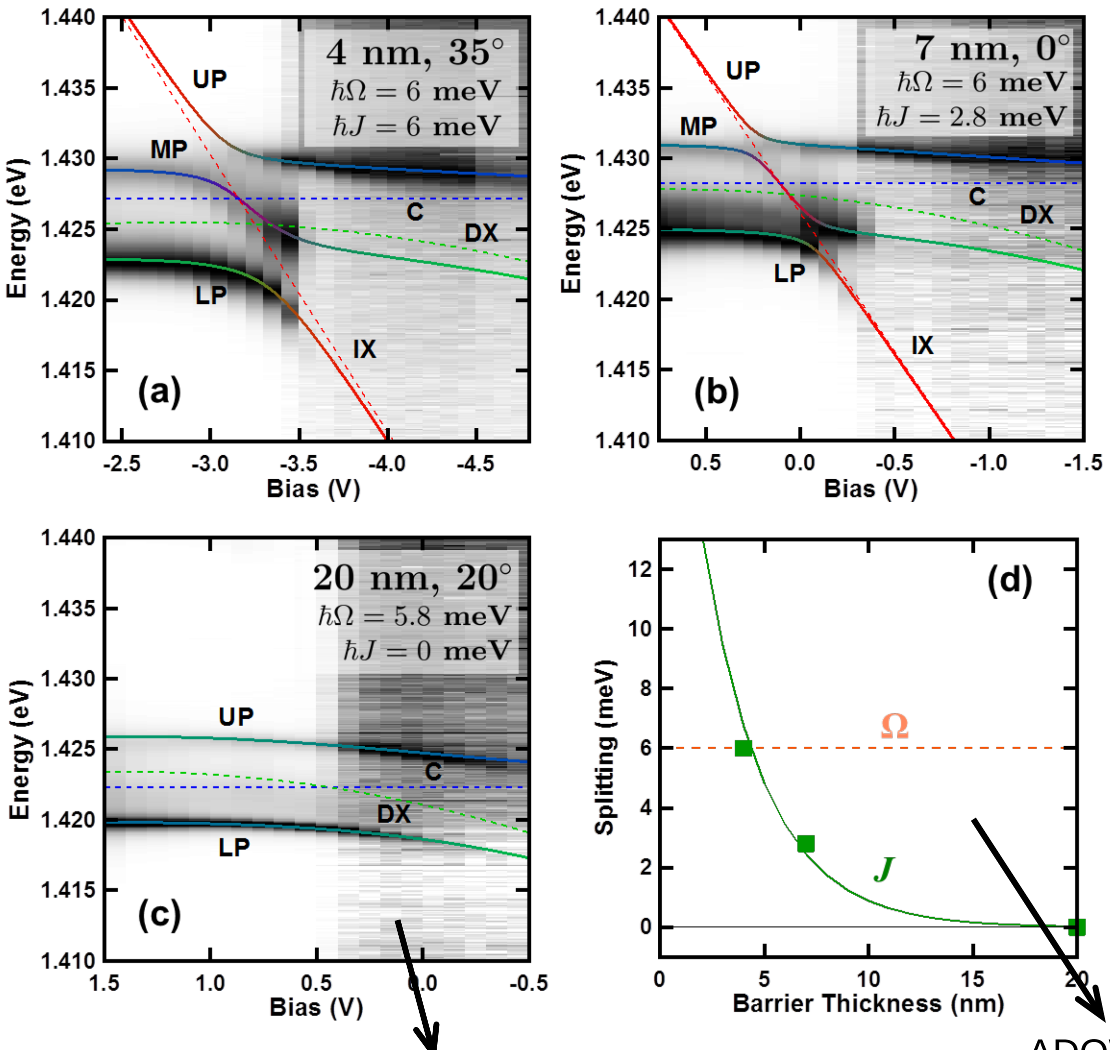
MP – state: no DX!

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





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

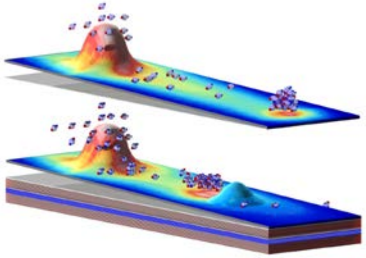
Summary

- Low threshold polariton lasing at 25K and RT in GaN

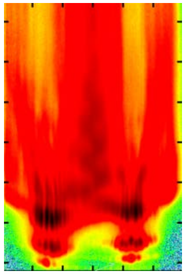
- Electrical and optical manipulation of polariton condensates on a chip

  polariton condensate transistor

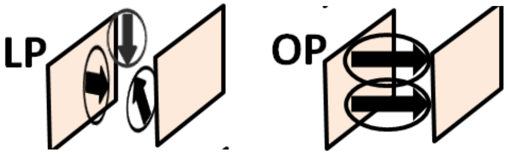
  polariton condensate pendulum



  interactions between condensated in confining potentials



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



Thank you