Superfluids of Light: Bose-Einstein Condensation of Polaritons

David Snoke
University of Pittsburgh
Burcu Ozden
Shouvik Mukherjee
David Myers
Jonathan Beaumarriage

Experimental Collaborators:
L. Pfeiffer, K. West, Princeton
K. Nelson, Y. Sun, Y. Yoon, MIT

Theory collaborators:
Allan MacDonald, Xie Ming, U.Texas
Andrew Daley, Rosaria Lena, U. Strathclyde

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Outline

1. Review of Bose-Einstein condensation

2. What is a polariton?

3. Review of results with short-lifetime polaritons

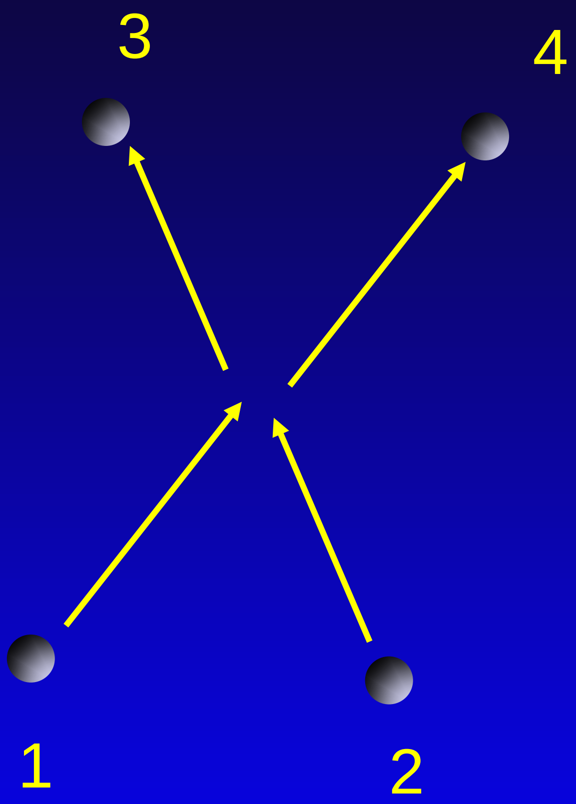
4. New results with long-lifetime polaritons

1. Review of Bose-Einstein Condensation

entire universe

	fermions	bosons
spin	1/2, 3/2, ...	0, 1, 2, ...
transition rate	$\Gamma_{i\to f} \propto 1\text{-}N_f$ *(Pauli exclusion)*	$\Gamma_{i\to f} \propto 1+N_f$ *(Stimulated transitions)*
examples	electrons, protons	photons, phonons

detailed balance in equilibrium



forward scattering rate:

$$\langle M \rangle^2 N_1 N_2 (1 \pm N_3)(1 \pm N_4)$$

reverse scattering rate:

$$\langle M \rangle^2 N_3 N_4 (1 \pm N_1)(1 \pm N_2)$$

balance:

$$N_1 N_2 (1 \pm N_3)(1 \pm N_4) = N_3 N_4 (1 \pm N_1)(1 \pm N_2)$$

only solution for *N*(*E*) is

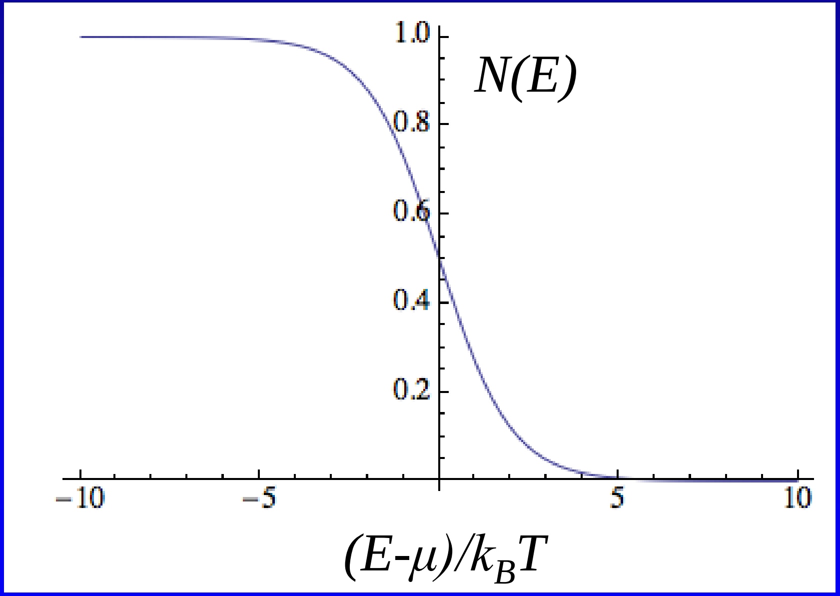
$$N(E) = \frac{1}{e^{\beta E + \alpha} \mp 1}$$

$$N(E) = \frac{1}{e^{(E-\mu)/kT} \mp 1}$$

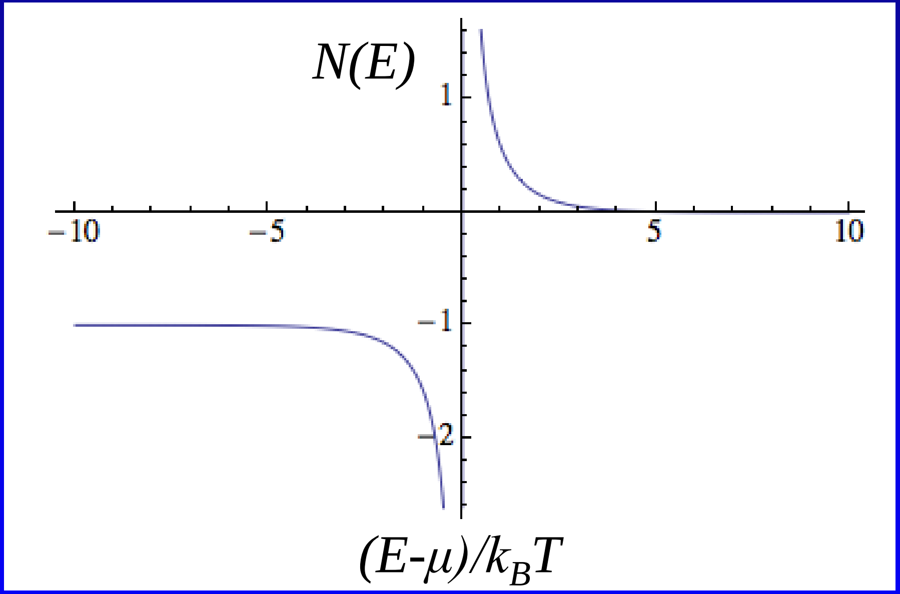
+ “Fermi-Dirac”

\- “Bose-Einstein”

Fermi-Dirac



Bose-Einstein

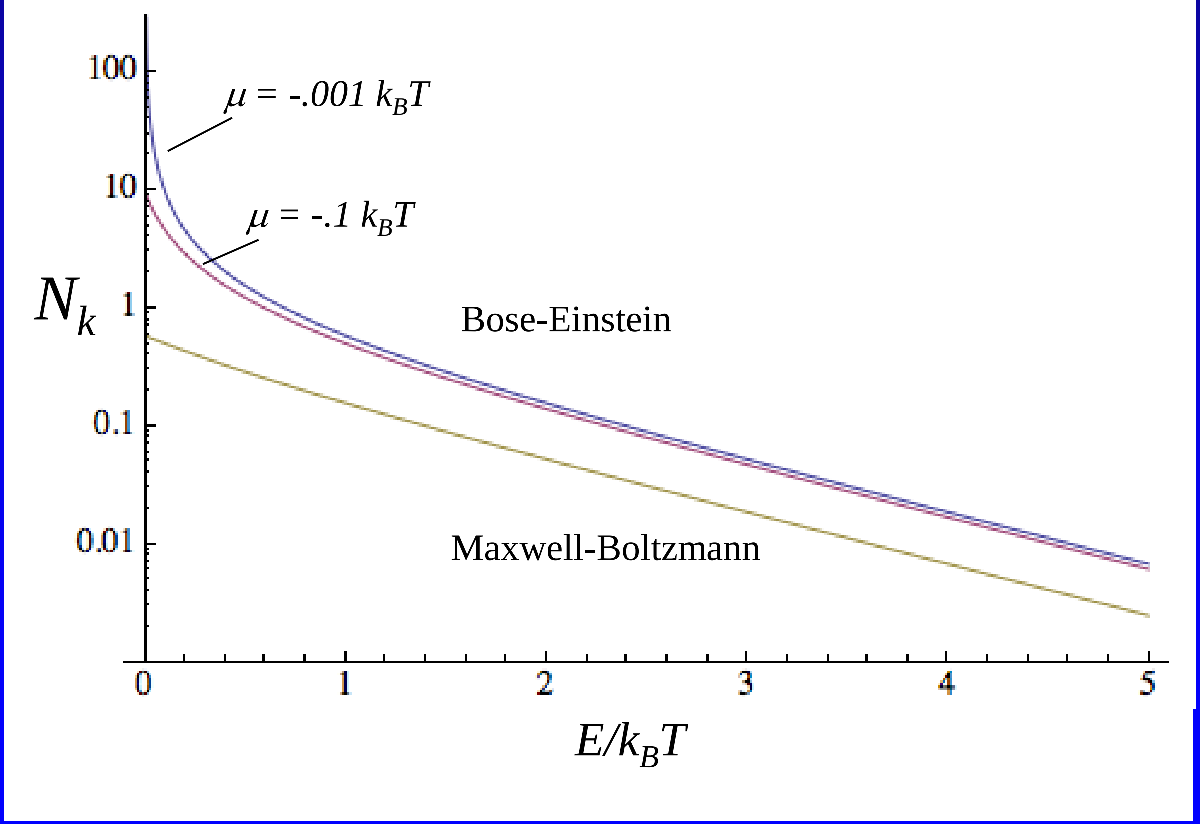


$$N_k = \frac{1}{e^{(E_k - \mu)/k_B T} - 1}$$

approaches $e^{-E/kT}$ when $\mu \ll E_0$

Ideal equilibrium Bose-Einstein distribution

what happens when $\mu = E_0$?



Macroscopic occupation of ground state!

collection of particles act as a *single wave*
= *“coherent state”*

Not unusual for “driven” boson systems
e.g. coherent EM wave (radio)
or coherent sound wave (loudspeaker)

but here occurs by spontaneous symmetry breaking.

Imagine that we can do the following

Start with photons, which are good bosons, and give them

- a) mass
- b) interactions
- c) number conservation, with only weak decay within their thermalization time

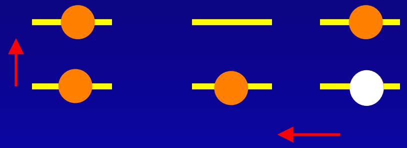
Their behavior will obey the same equations as atomic condensates, with a few alterations:

1) terms for weak generation and decay

2) direct measurement of wave function amplitude in light which leaks out of the system

2. What is a polariton?

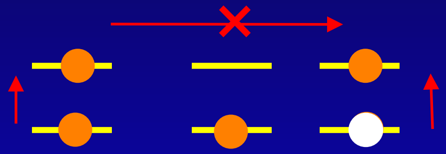
Start with a set of two-level quantum oscillators:



excitation is mobile: an “exciton”

2. What is a polariton?

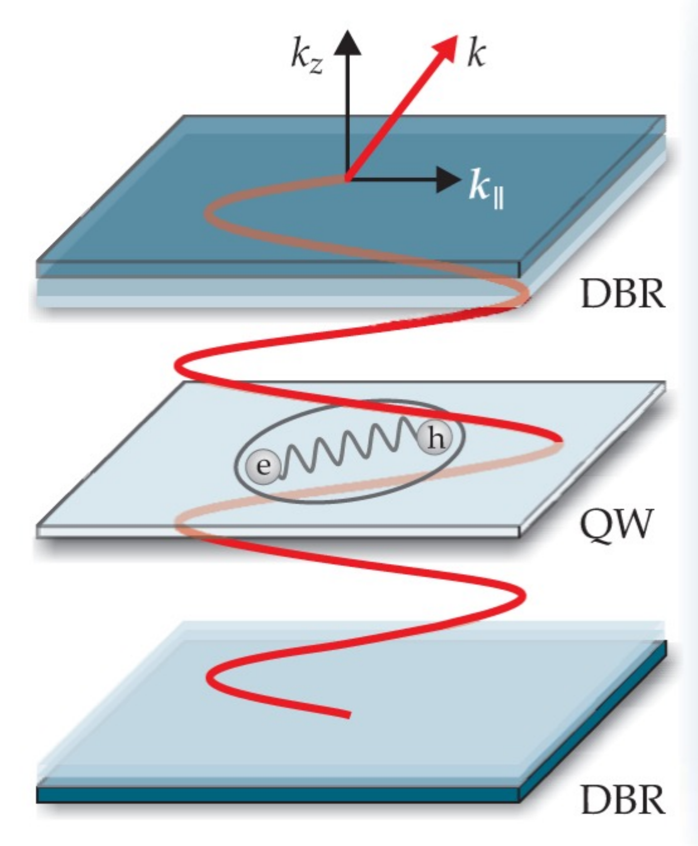
Two excitations:



hard-core repulsion of excitons

Polaritons in a Cavity

mix photon states
with a two-level excitation
(exciton)



cavity photon:

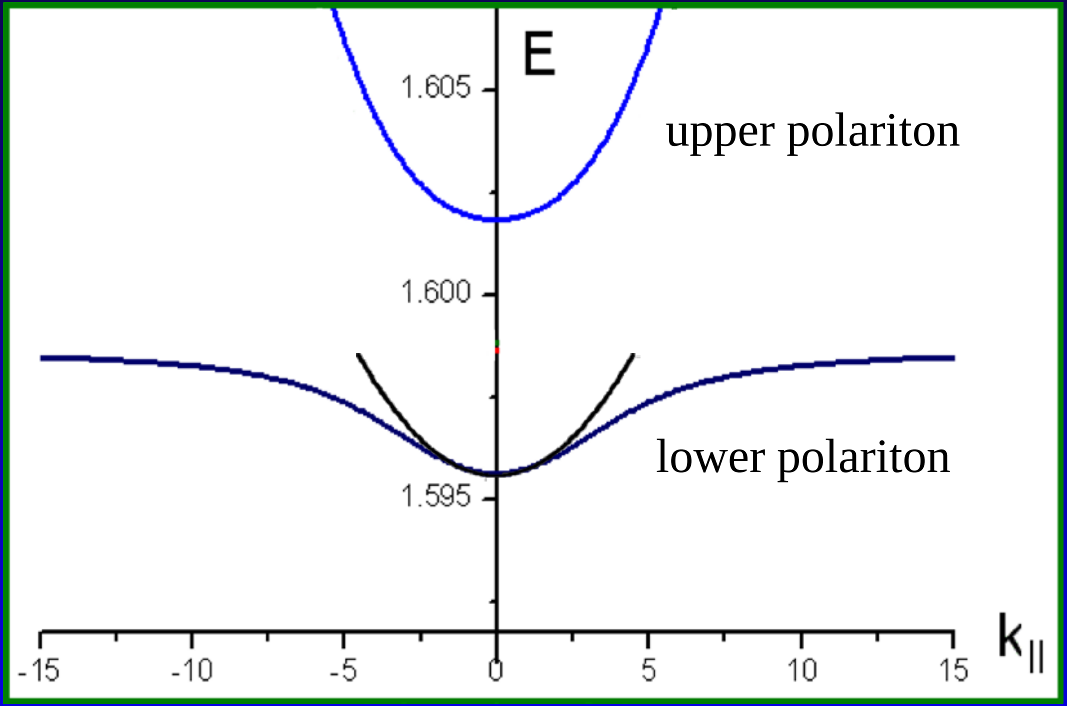
$$E = \hbar c \sqrt{k_z^2 + k_\parallel^2} = \hbar c \sqrt{(\pi/L) k_z^2 + k_\parallel^2}$$

quantum well exciton:

$$E = E_{gap} - \Delta_{bind} + \frac{h^2 N^2}{2m_r(2L)^2} + \frac{h^2 k_\parallel^2}{2m}$$

≈ const. near $k_\parallel = 0$

Tune $E_{ex}(0)$ to equal $E_{phot}(0)$:



Mixing leads to “upper polariton” (UP) and “lower polariton” (LP)

LP effective mass ~ $\boxed{10^{-4}\, m_e}$

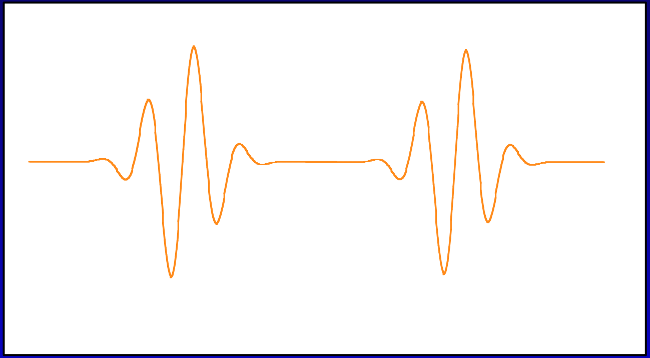
By mixing with exciton states, we have an *interacting*, light-mass boson gas.

General condition for quantum effects to be important:

$$r \sim \lambda_{dB}$$

$$n^{-1/d} \sim h/\sqrt{mk_BT}$$

$$T \sim \frac{h^2 n^{2/d}}{m}$$



$\Rightarrow$ superfluid at *low T* or *high density*

$\Rightarrow$ light mass means *high* T_c

(typical T ~ 10-20 K, room temperature possible)

Methods of Controlling the Potential Energy Felt by Microcavity Polaritons

Two general approaches:

1) shift exciton level

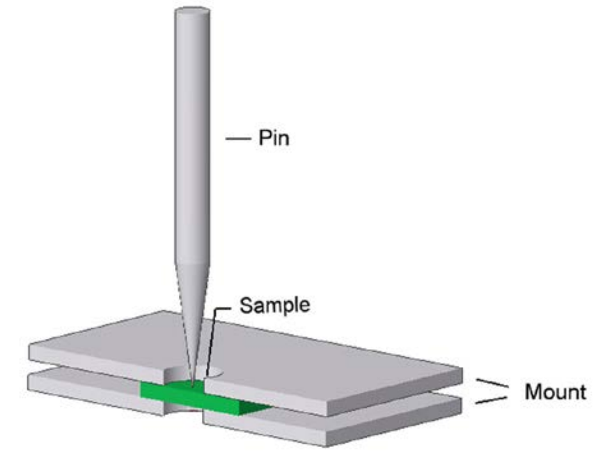
- shift bare exciton energy using stress
- shift exciton energy by mean-field potential of exciton cloud
- shift exciton energy by AC Stark effect

2) shift photon level

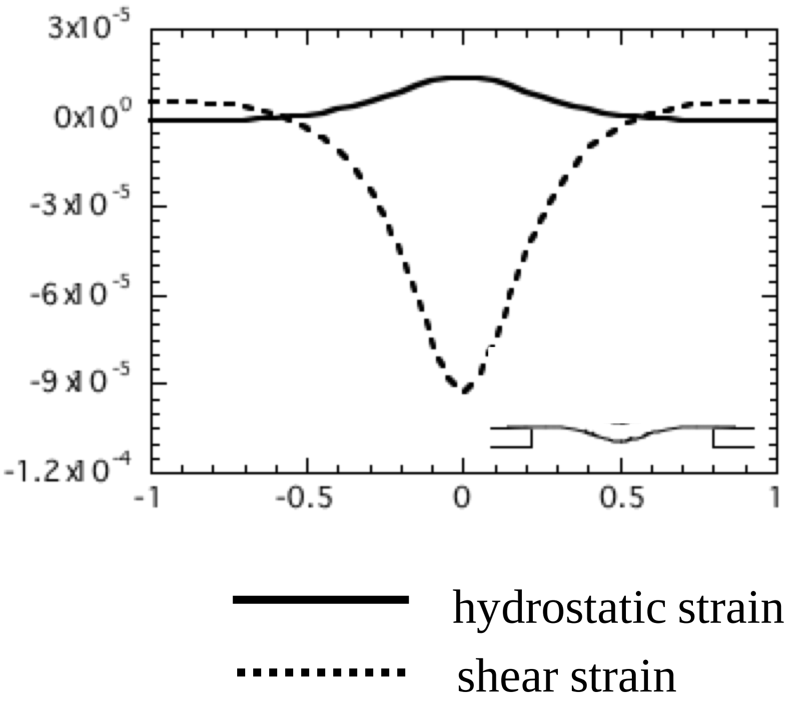
- change cavity width
- change cavity Q

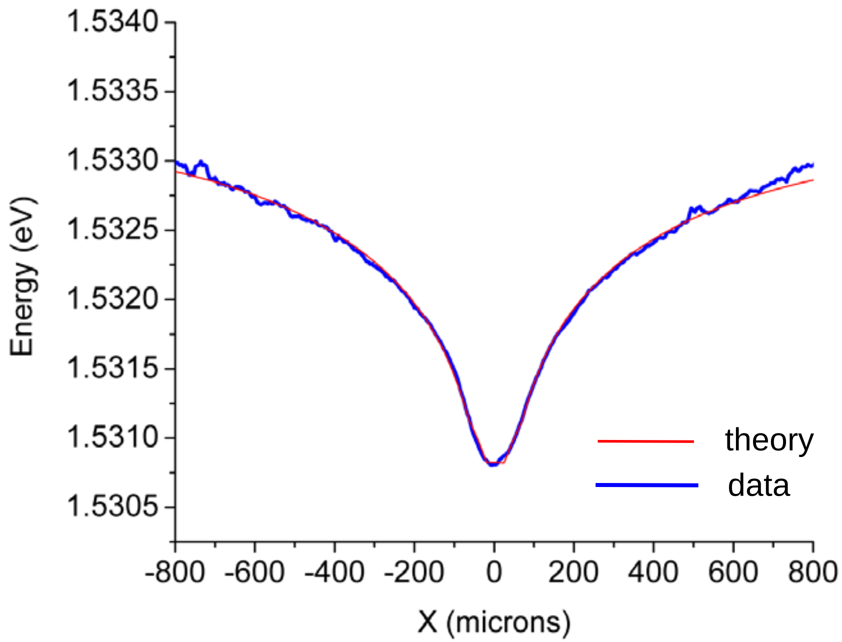
Using Stress to Shift Exciton Energy:

Bending free-standing sample gives hydrostatic expansion:



finite-element analysis of stress

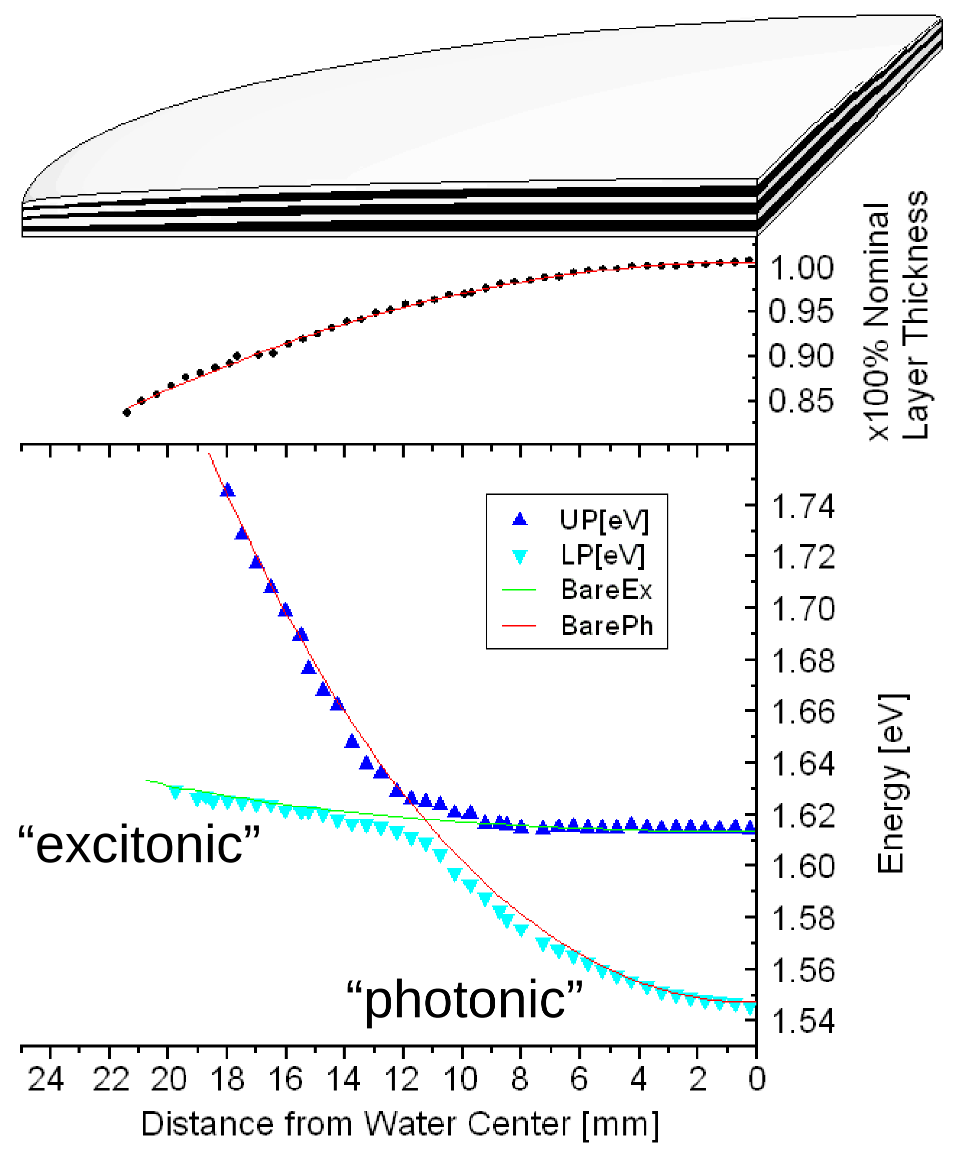




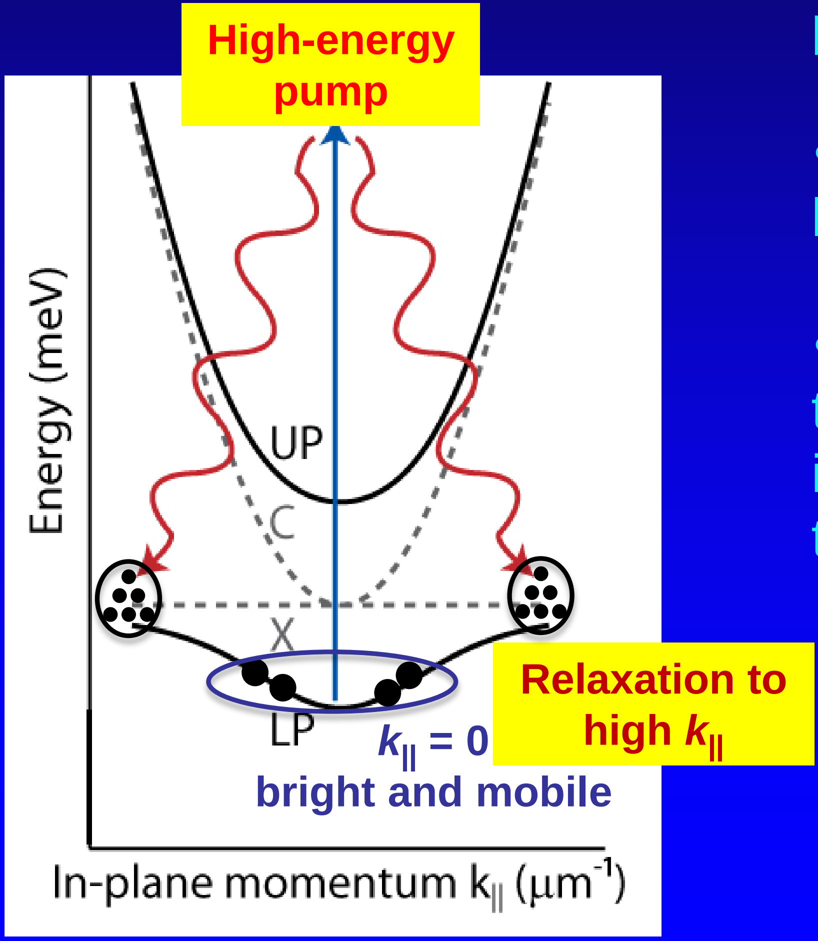
bare excitons in a single quantum well

Photon energy shift by cavity wedge:

crossing of photon and exciton energies gives "photonic" and "excitonic" sides for lower polariton



“Exciton cloud” potential



High-energy pump

Relaxation to high $k_{||}$

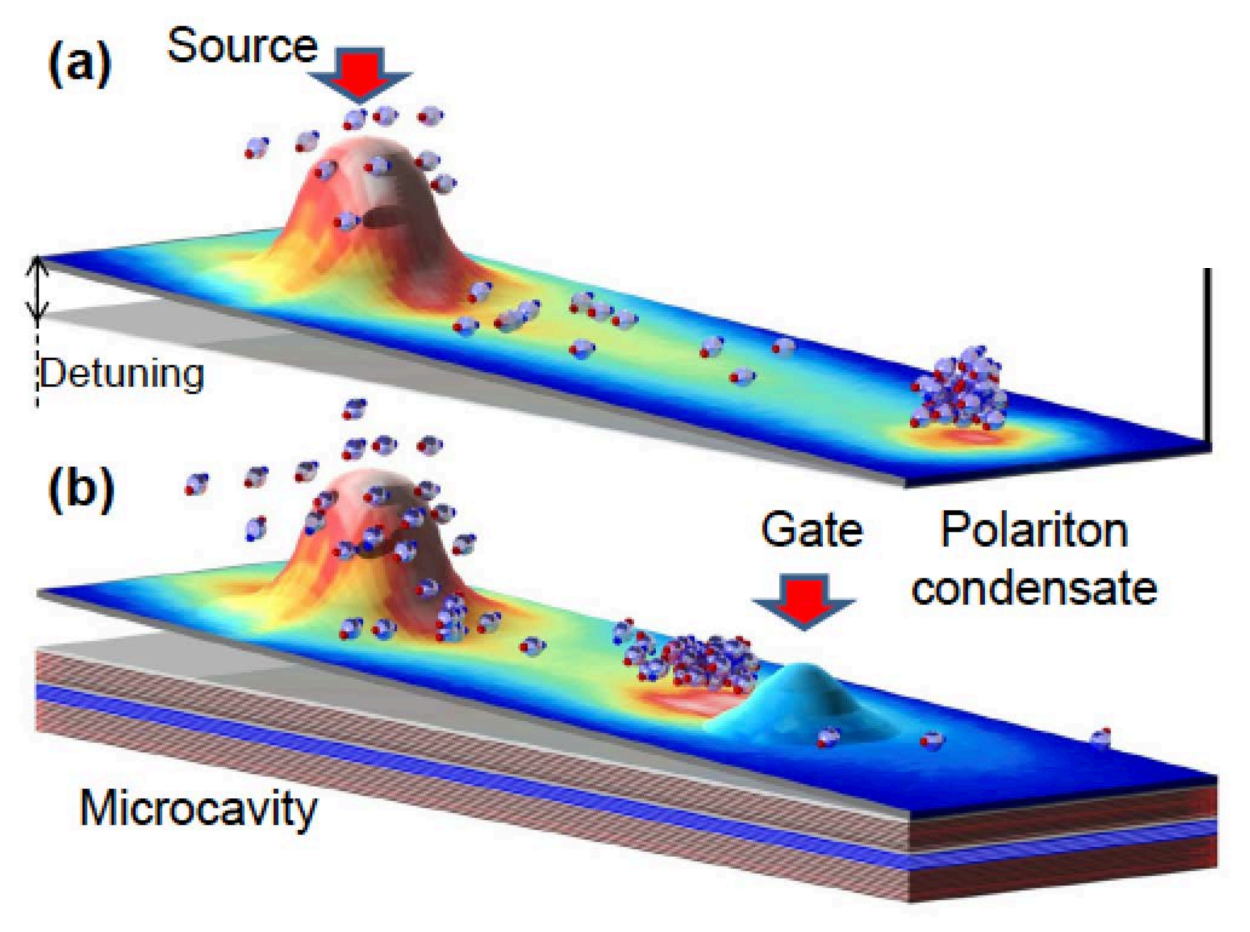
$k_{||} = 0$ bright and mobile

- excitons are 10^4 more massive than the polaritons. They move very little, so that collisions of polaritons with excitons are nearly elastic– a static barrier as seen by polaritons

- position and height controlled directly by laser

- disadvantage: polaritons are created at the same place by conversion of polaritons into excitons. Potential energy cannot be tuned independently of polariton density

Control of polariton flow by laser-generated barriers



Christmann, Savvidis, and Baumberg, 2015

3. Review of results with short-lifetime polaritons

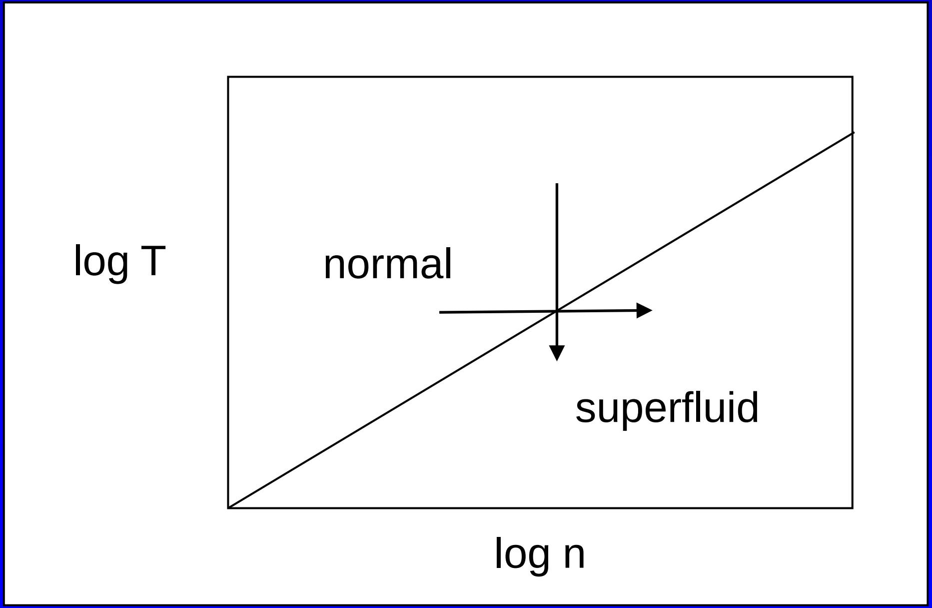
($\tau \sim 5$ ps)

Recall: Critical threshold for quantum coherence

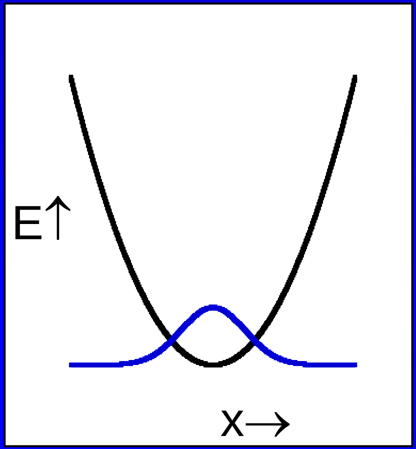
$$r \sim \lambda_{dB}$$

$$n^{-1/d} \sim h/\sqrt{mk_BT}$$

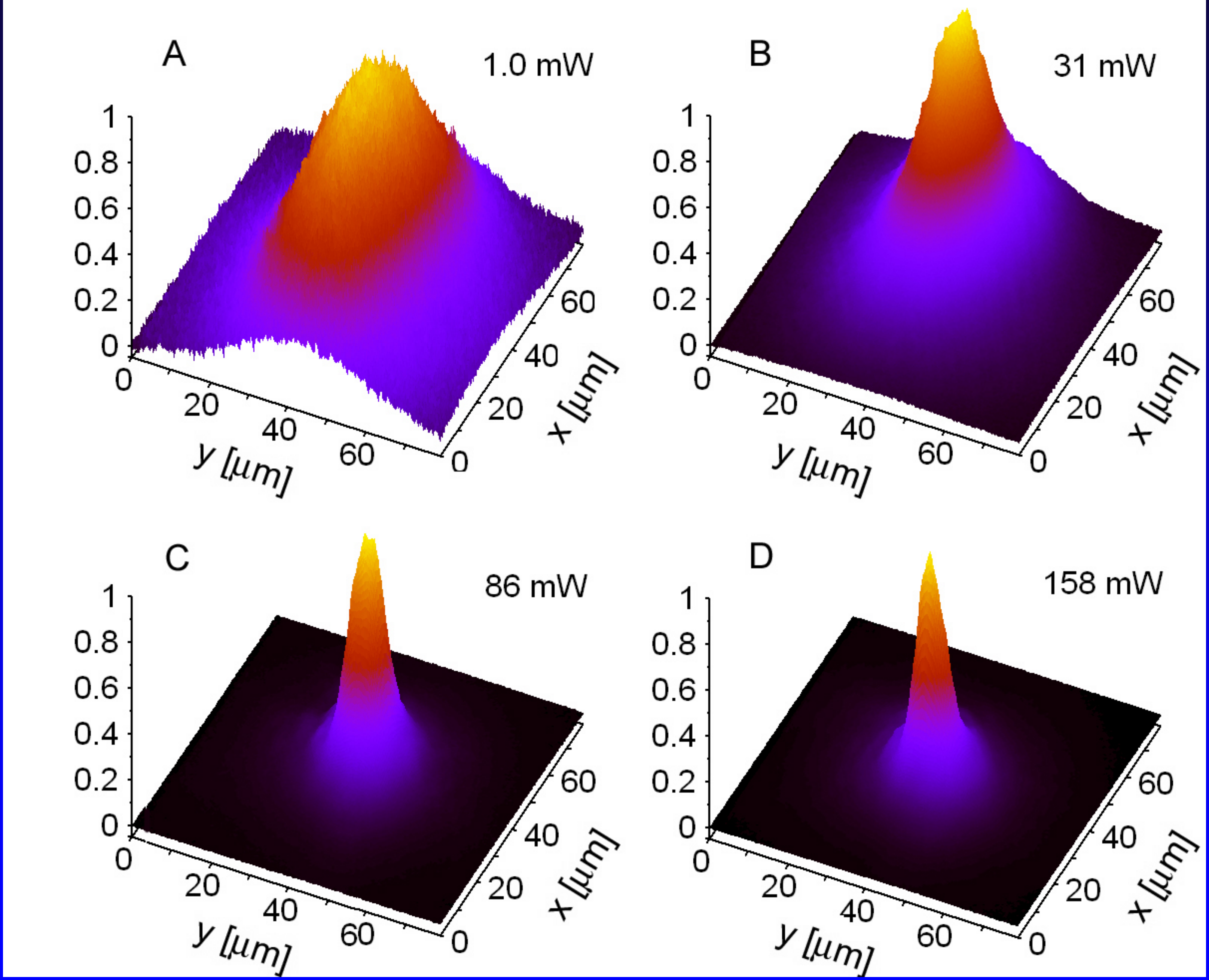
⇒ superfluid at *low T* or *high density*



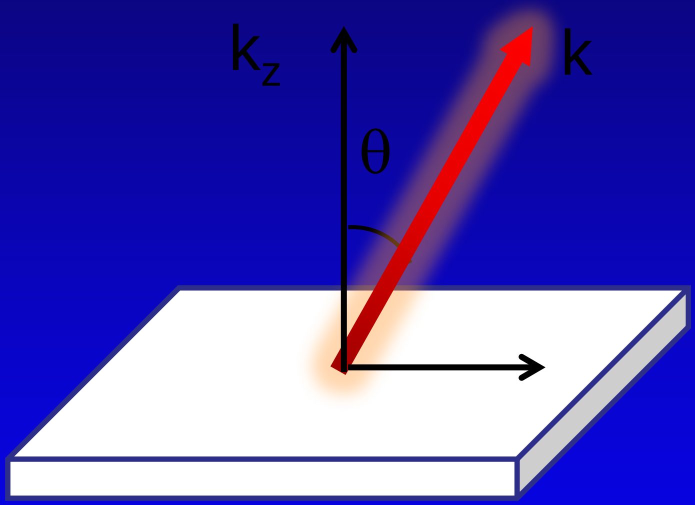
trap implies *spatial* condensation



Spatial profiles of polaritons in a harmonic potential trap

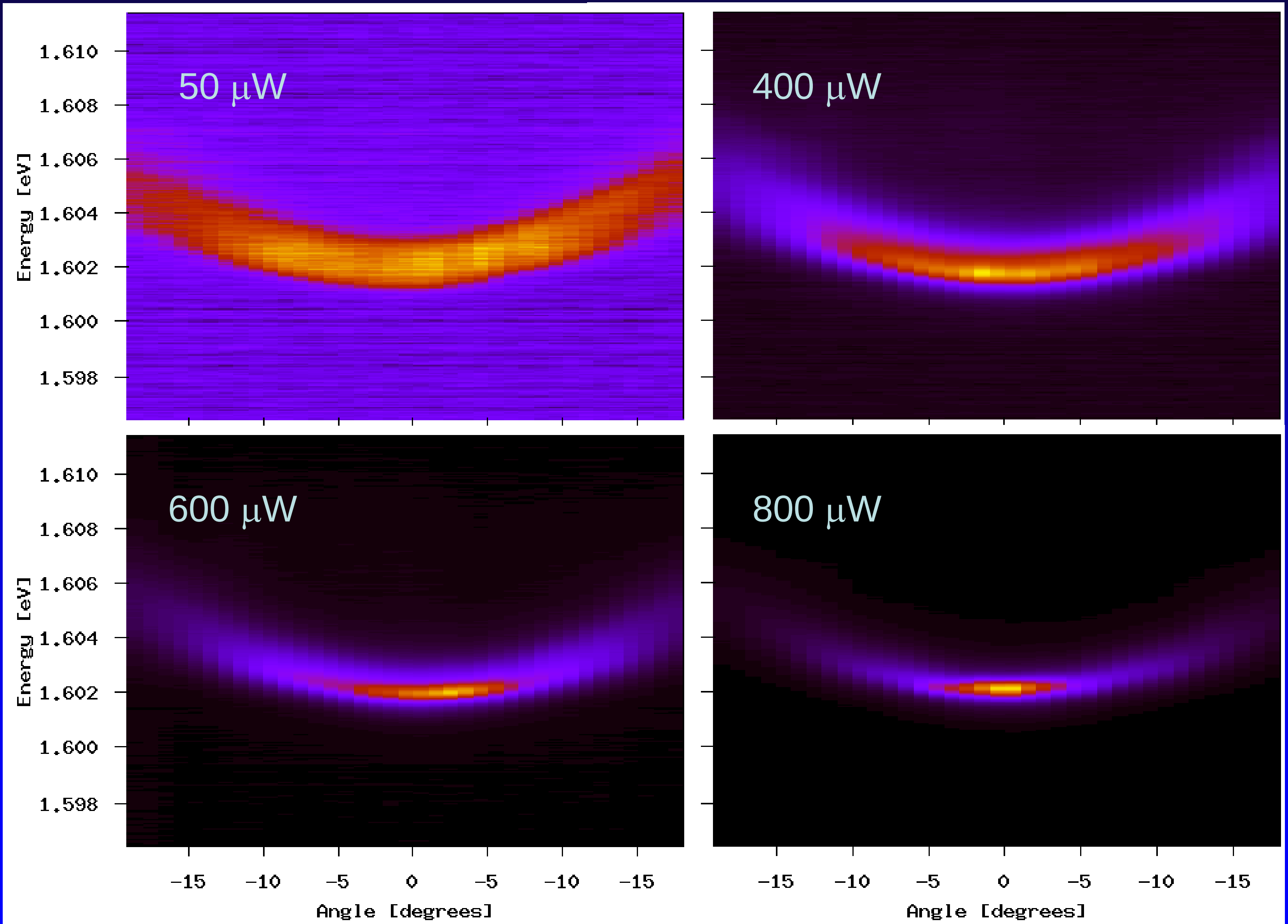


Angle-resolved photon emission data give momentum distribution



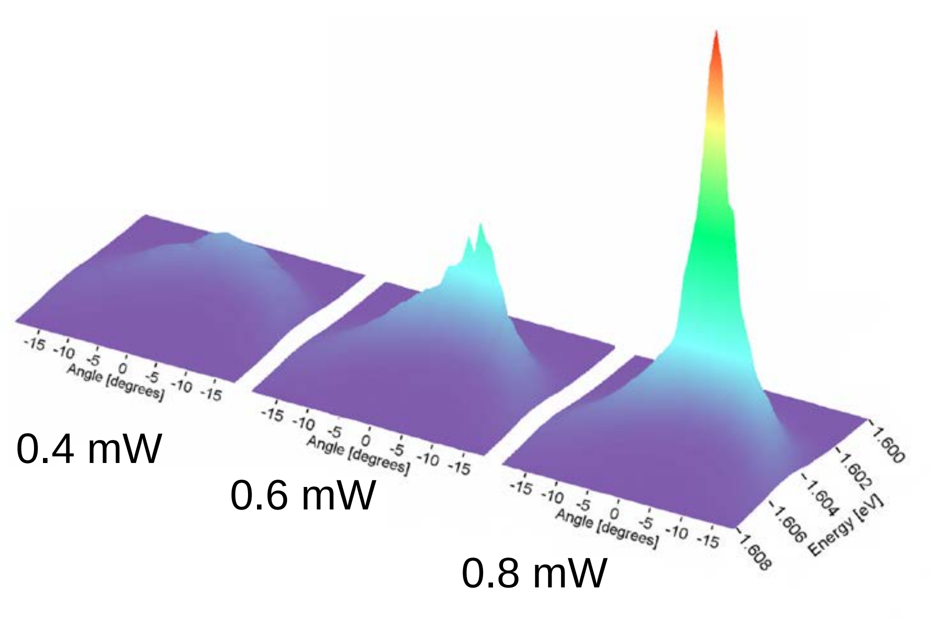
We can therefore image the gas in both real space
and momentum space as data.

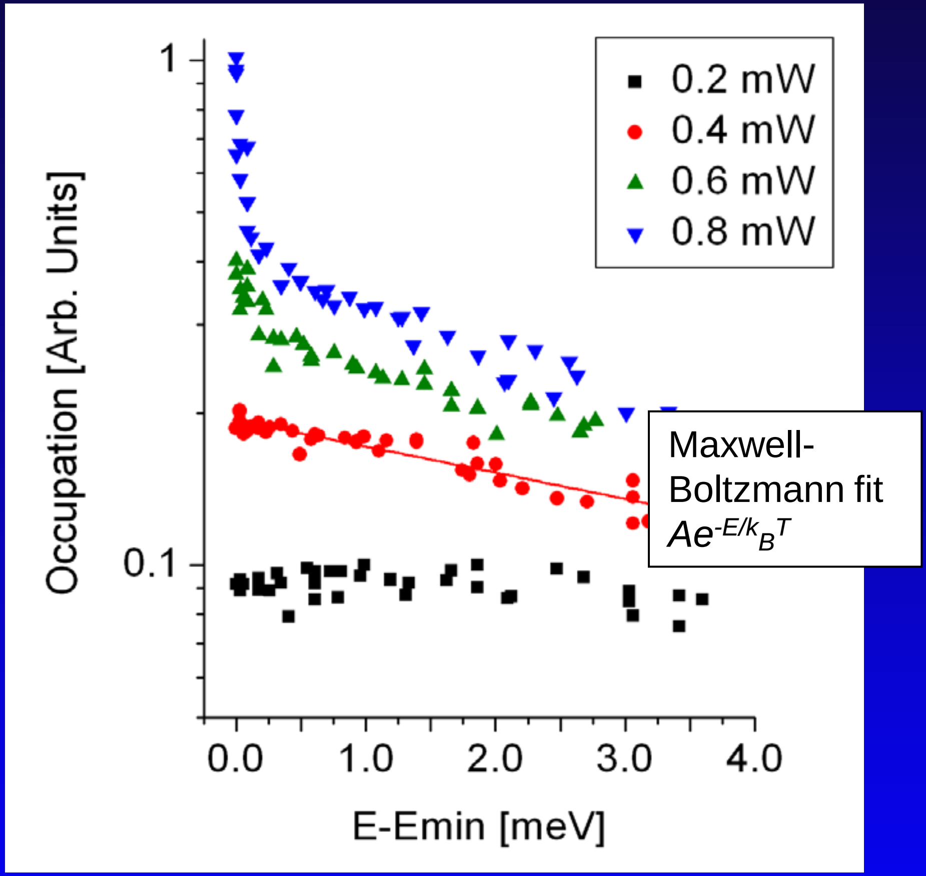
Momentum-resolved luminescence spectra: short lifetime
(cavity lifetime ~ 1 ps, average lifetime ~ 10 ps)



R. Balili et al., Science **316**, 1007 (2007)

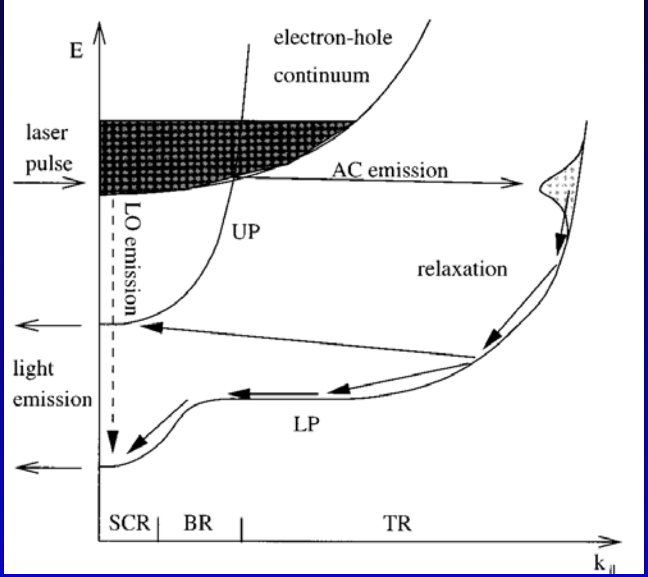
“Bimodal” momentum distribution of polaritons





2006-2007 data actually a *nonequilibrium* condensate—
Peaking due to Bose statistics, but excited states not in equilibrium.

Kinetic simulations of polariton equilibration



Tassone, *et al* , Phys Rev B **56**, 7554 (1997).

Tassone and Yamamoto, Phys Rev B **59**, 10830 (1999).

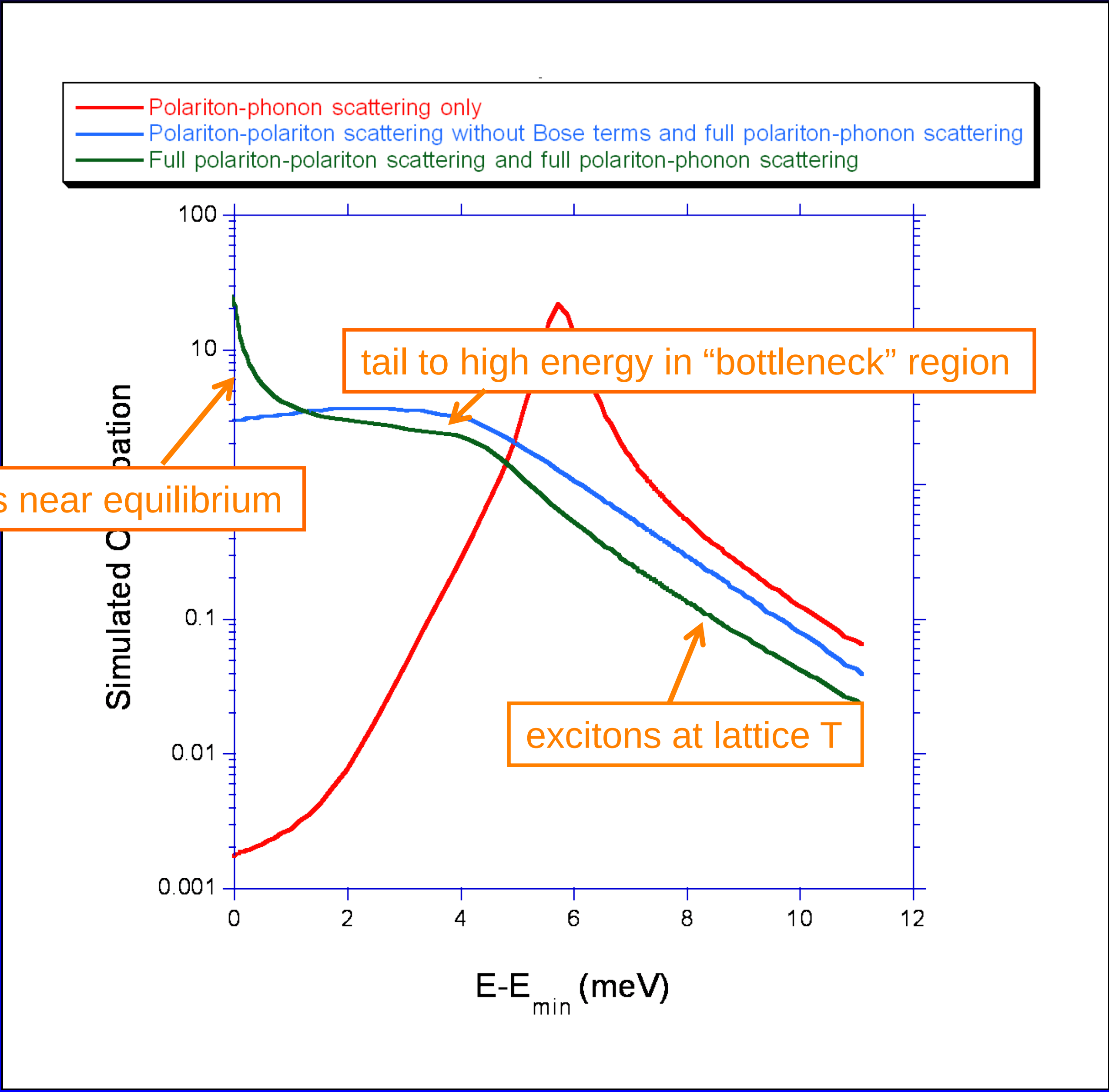
Porras et al., Phys. Rev. B **66**, 085304 (2002).

Haug et al., Phys Rev B **72,** 085301 (2005).

Sarchi and Savona, Solid State Comm **144**, 371 (2007).

$$\frac{d\langle \hat{N}_k\rangle}{dt} = \frac{2\pi}{\hbar}\left(\frac{V}{(2\pi)^3}\right)^2 \frac{1}{2}\int d^3k_1\, d^3k_2\, |U_D \pm U_E|^2\,\delta(E_{k_1}+E_{k_2}-E_k-E_{k'})$$
$$\times\left[\langle \hat{N}_{k_1}\rangle\langle \hat{N}_{k_2}\rangle(1\pm\langle\hat{N}_k\rangle)(1\pm\langle\hat{N}_{k'}\rangle) - \langle\hat{N}_k\rangle\langle\hat{N}_{k'}\rangle(1\pm\langle\hat{N}_{k_1}\rangle)(1\pm\langle\hat{N}_{k_2}\rangle)\right]$$

Numerical steady-state solution for occupation number



tail to high energy in “bottleneck” region

polaritons near equilibrium

excitons at lattice T

phonon emission
is so weak that particles
are essentially
isolated from the lattice

V. Hartwell, Ph.D. thesis (2008); PRB **82**, 075307 (2010)

4. New results with long-lifetime polaritons

($\tau \sim 300$ ps)

Super sample:

Q > 300,000

cf. previous samples with Q~5000

Done by using DBR mirrors with 40 layers

MBE growth by Pfeiffer growth > 30 hours per sample.

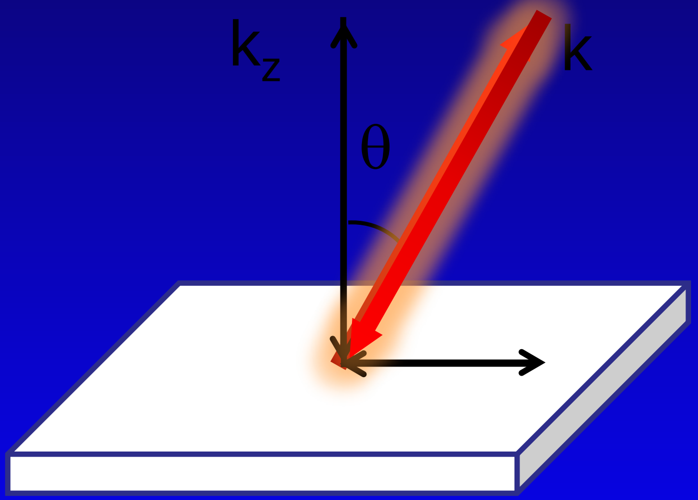
growth rate must remain stable during this time (±1%)

disorder must remain low (±1 monolayer typical)

cavity lifetime scales with *Q*: from ~2 ps to over 200 ps

polariton lifetime is longer: decay rate is proportional to photon fraction

Recall generalized Snell’s law: In-plane momentum must match between polariton and external photon.

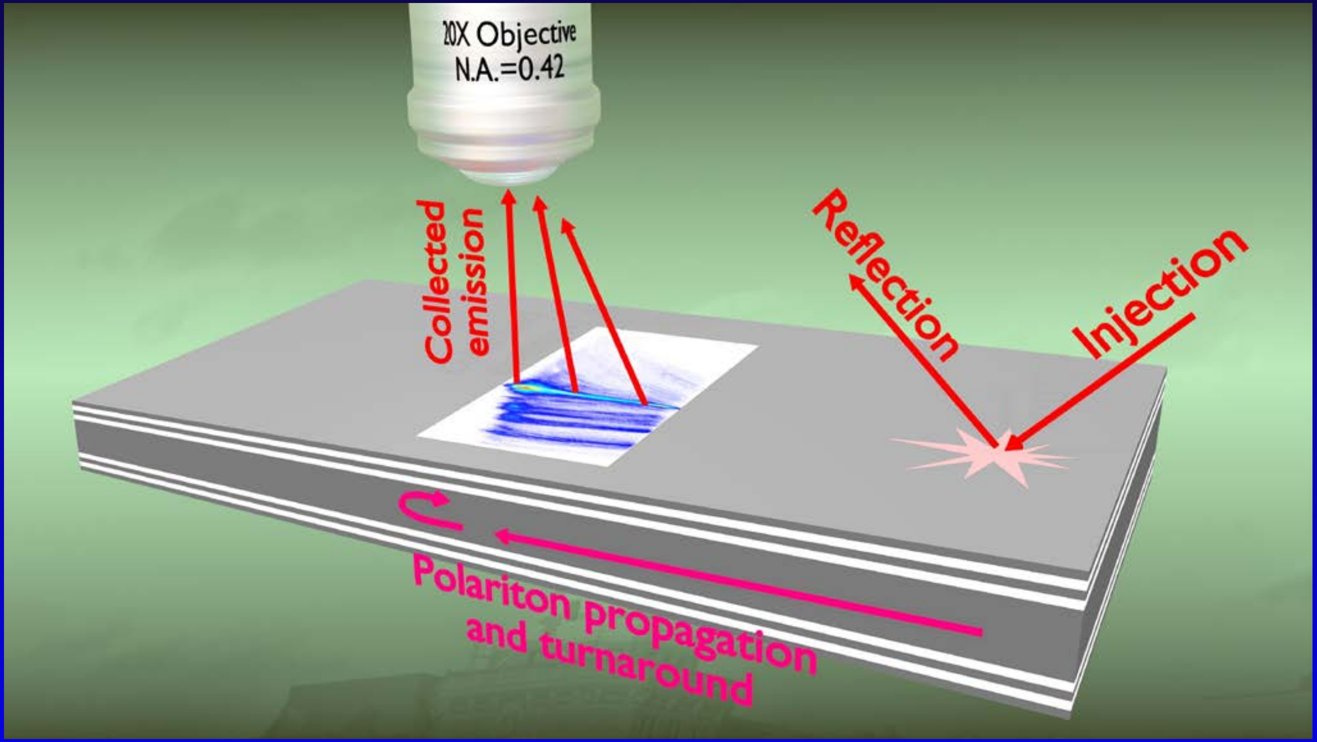


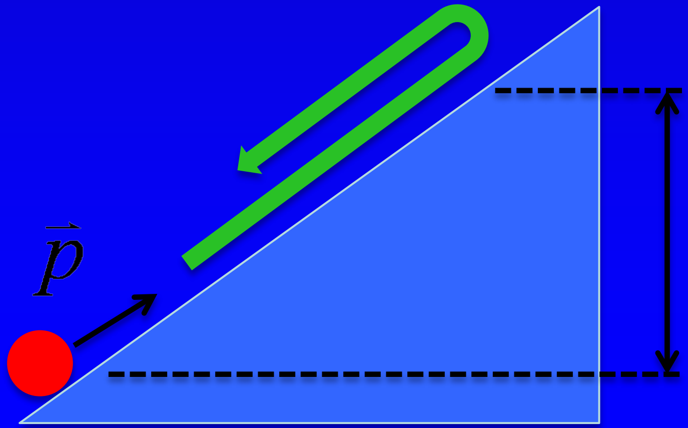
We can therefore image the gas in both real space
and momentum space as data.

We can also *inject* polaritons with a specific momentum.

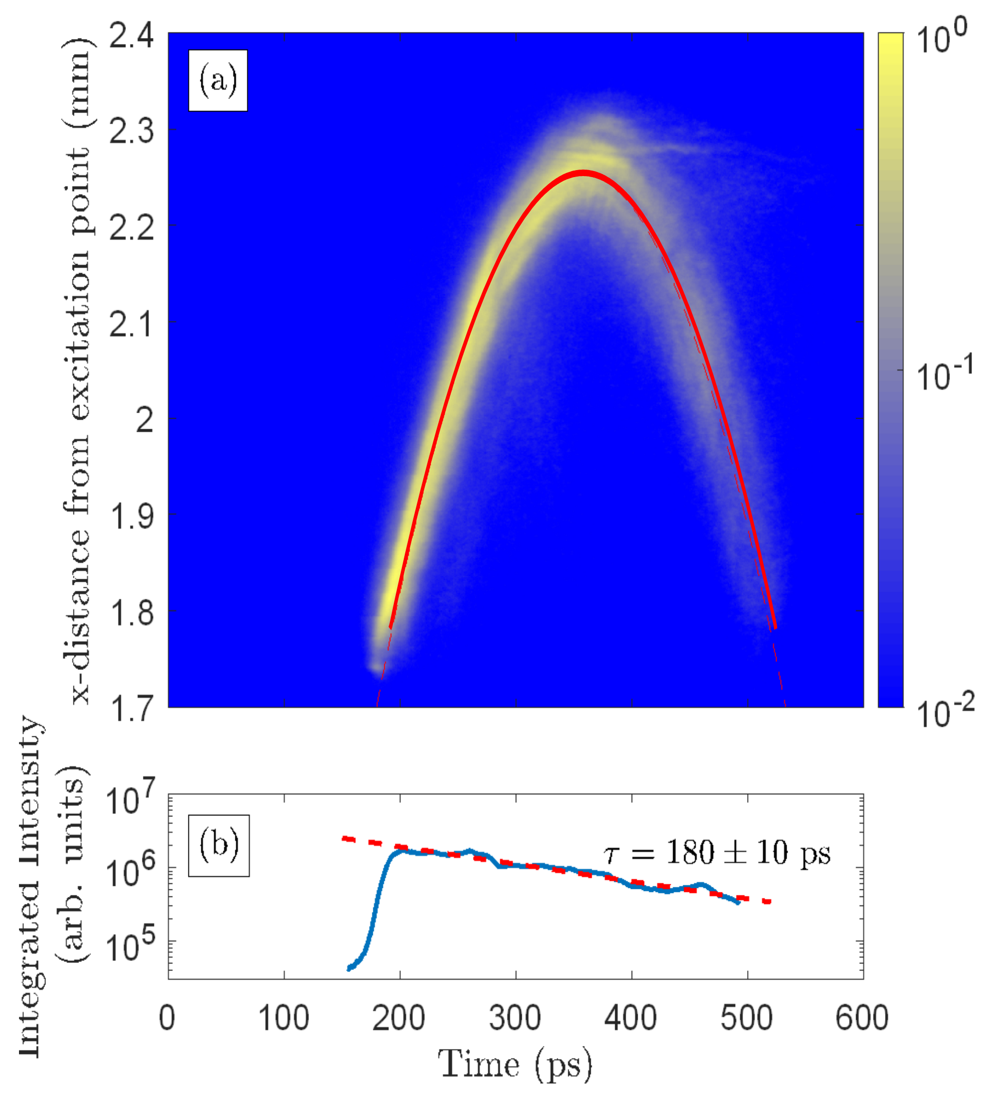
Direct resonant injection:

angle of injection gives in-plane p





M. Steger et al., Optica **2**, 1 (2015)

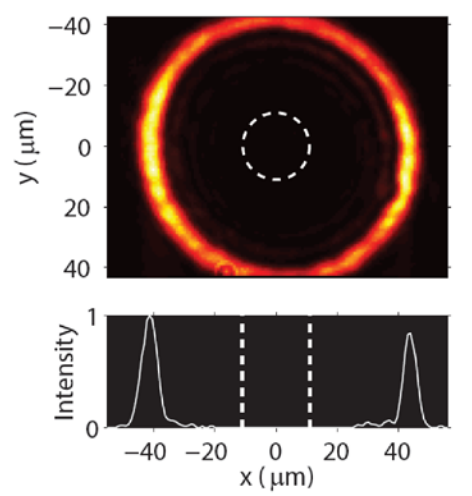


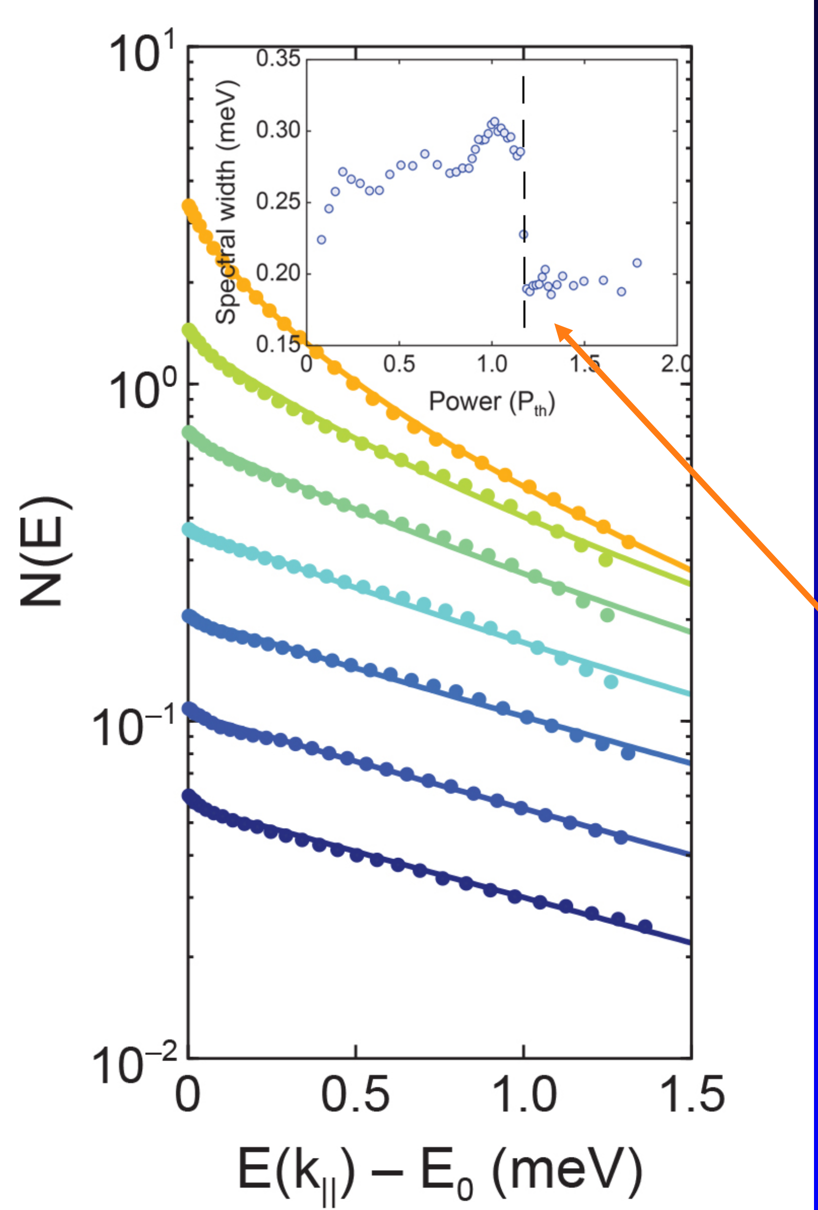
The quality of our samples
is shown by these measurements:
> 200 ps lifetime, > 2 mm transport

Time-resolved
polariton motion
in a potential gradient

“slow reflection”

Equilibrium distributions of polaritons in laser trap in long lifetime samples





overall height is *not* a free parameter: fixed by *μ.*

$$N(E) = \frac{1}{e^{(E-\mu)/kT} - 1}$$

Spectral width drops sharply at BEC transition (spontaneous coherence)

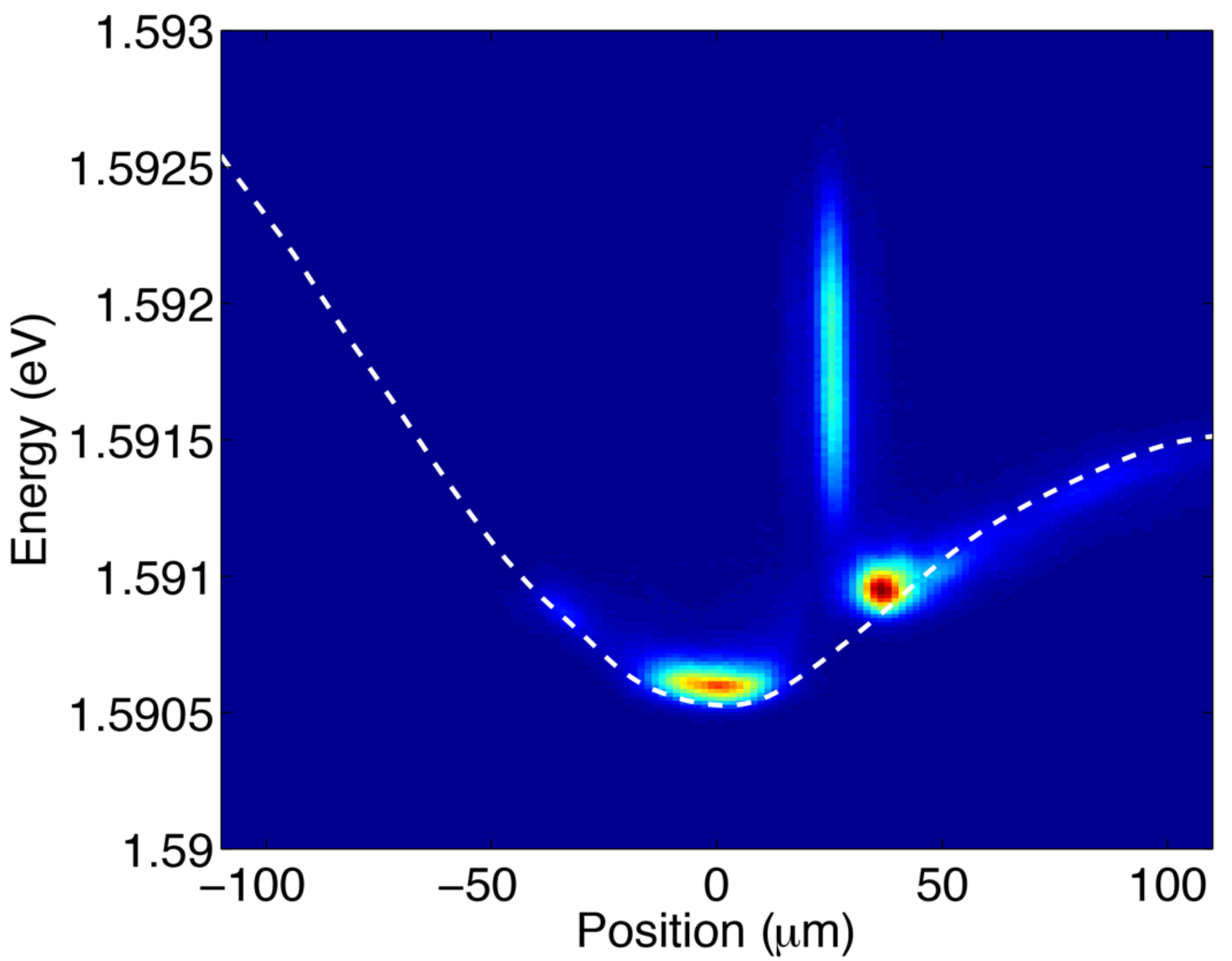
Maxwell-Boltzmann at low density Ae^{-E/k_BT}

Y. Sun, et al., PRL **118**, 016602 (2017).

Making a ring trap

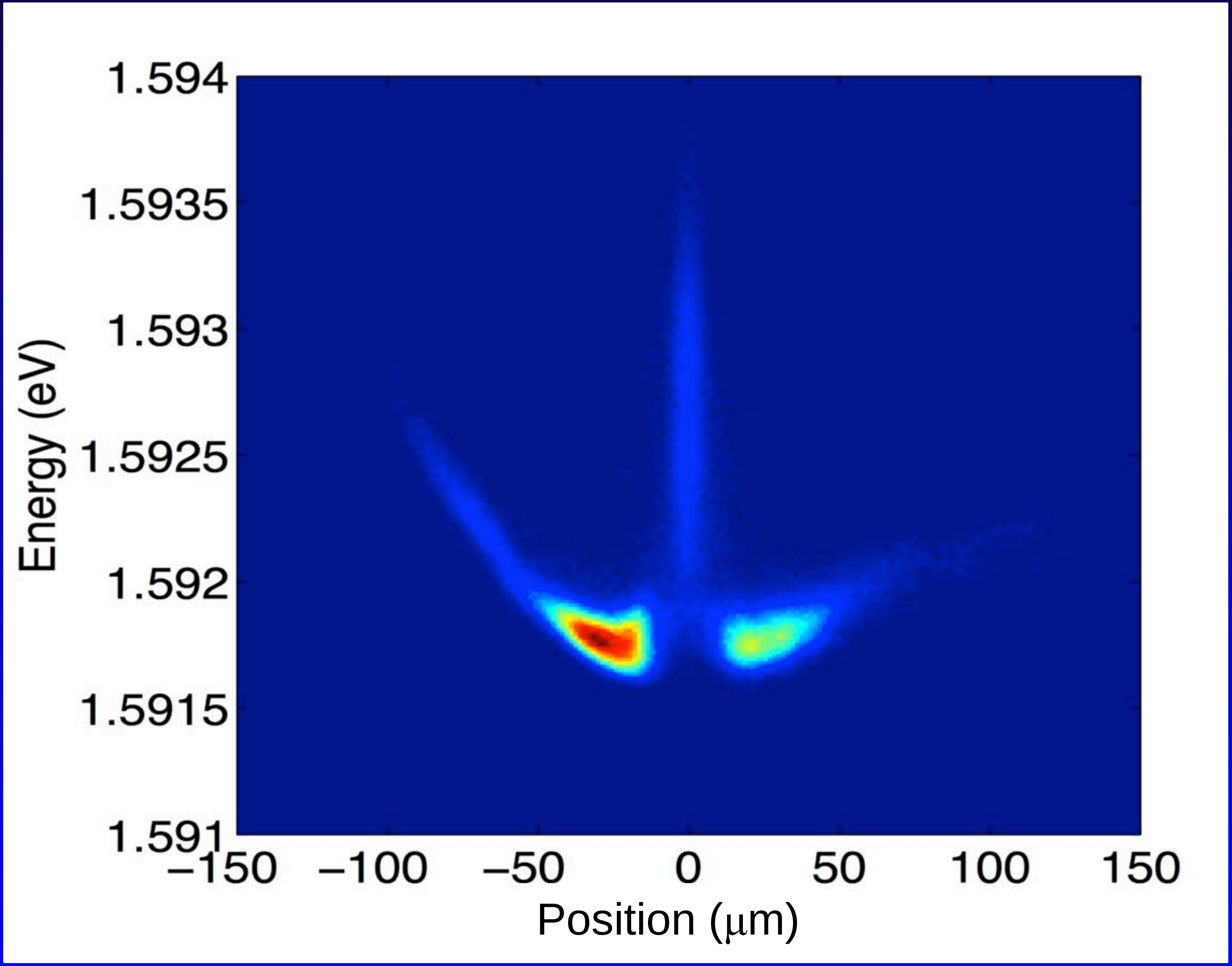
defocused laser

focused laser, to side



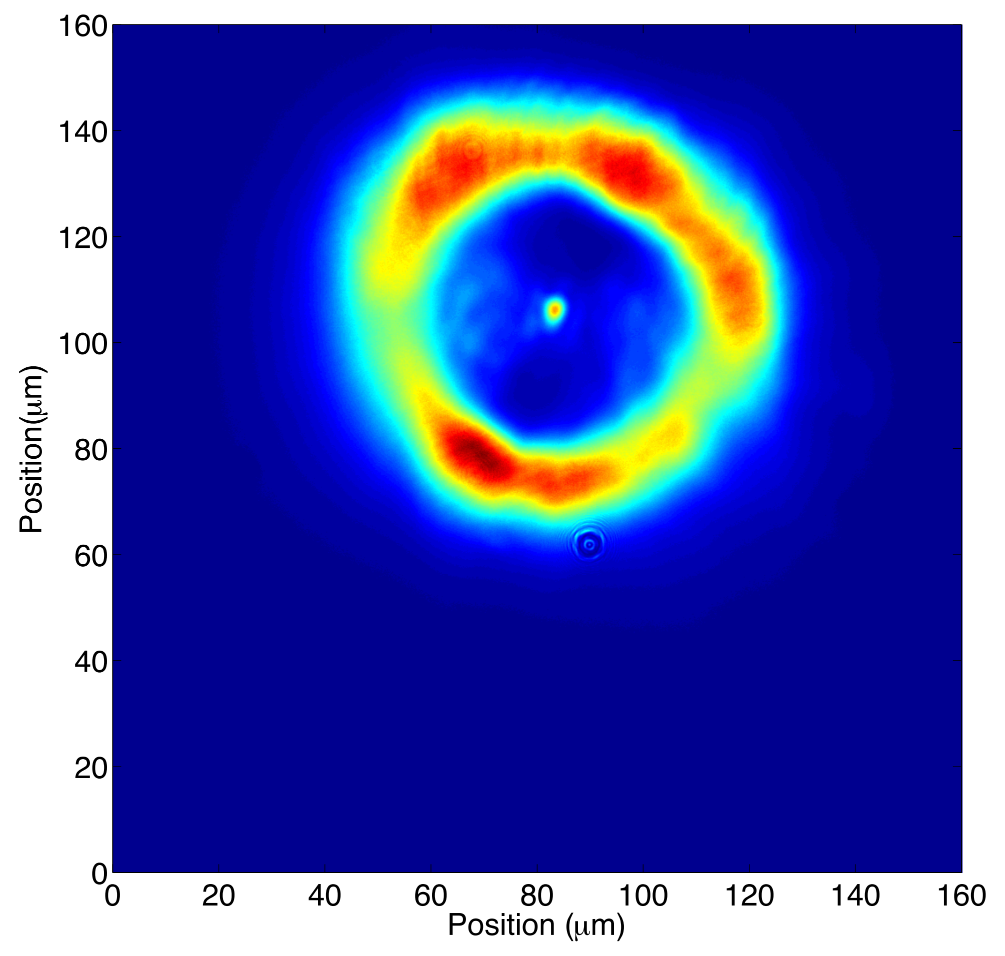
Making a ring trap

focused laser, in center

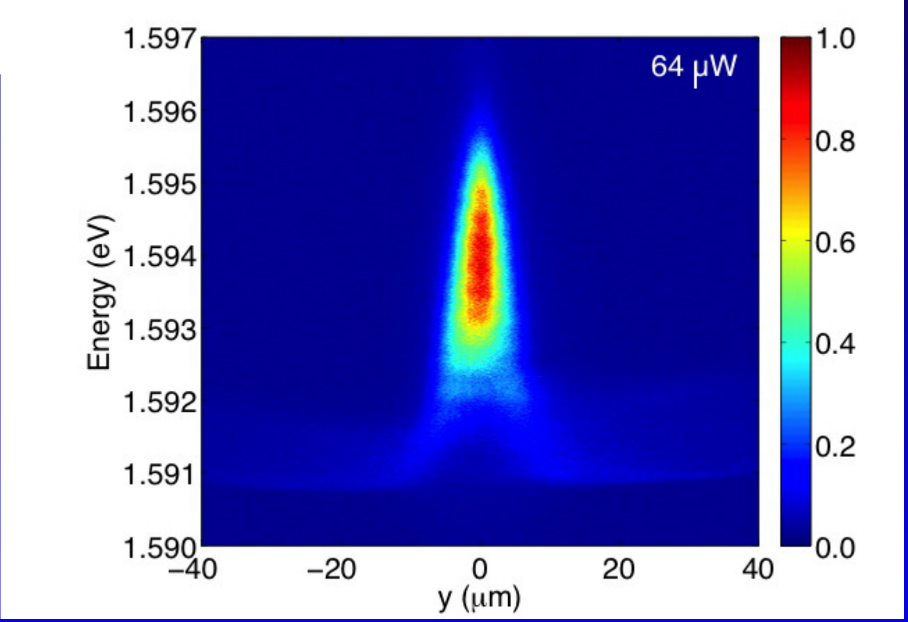


2D spatial image

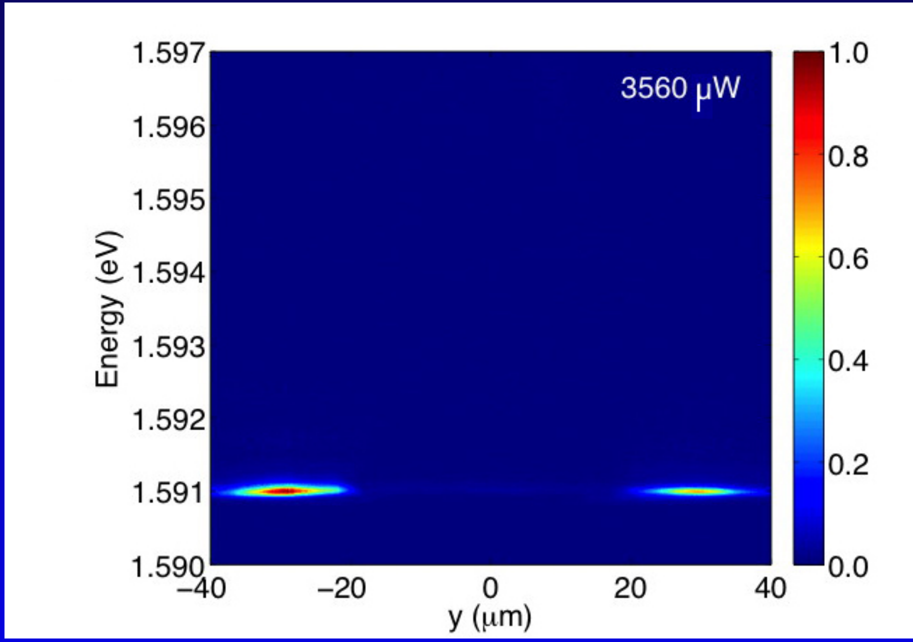
below
above
threshold



spectral narrowing in ring:

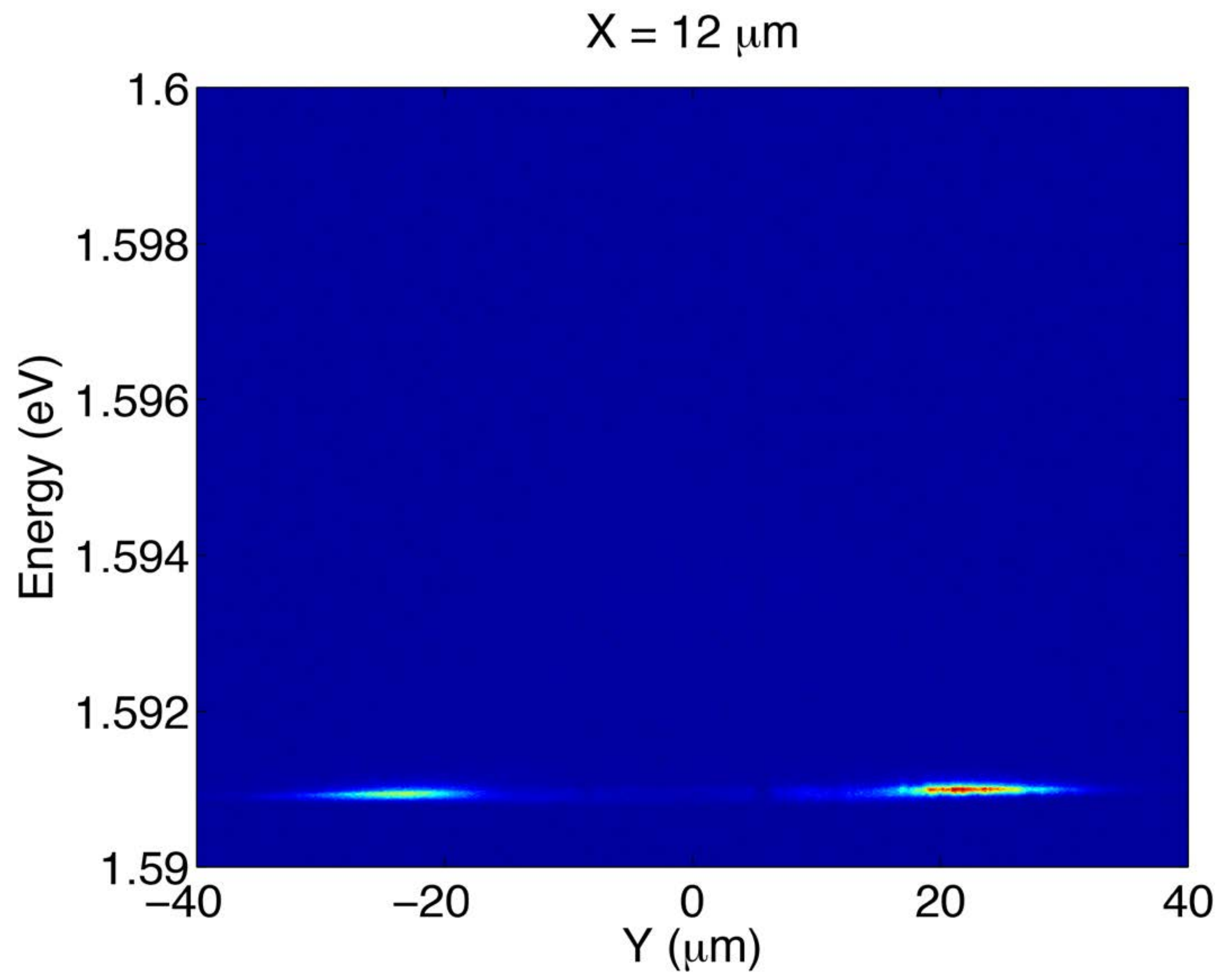


below threshold

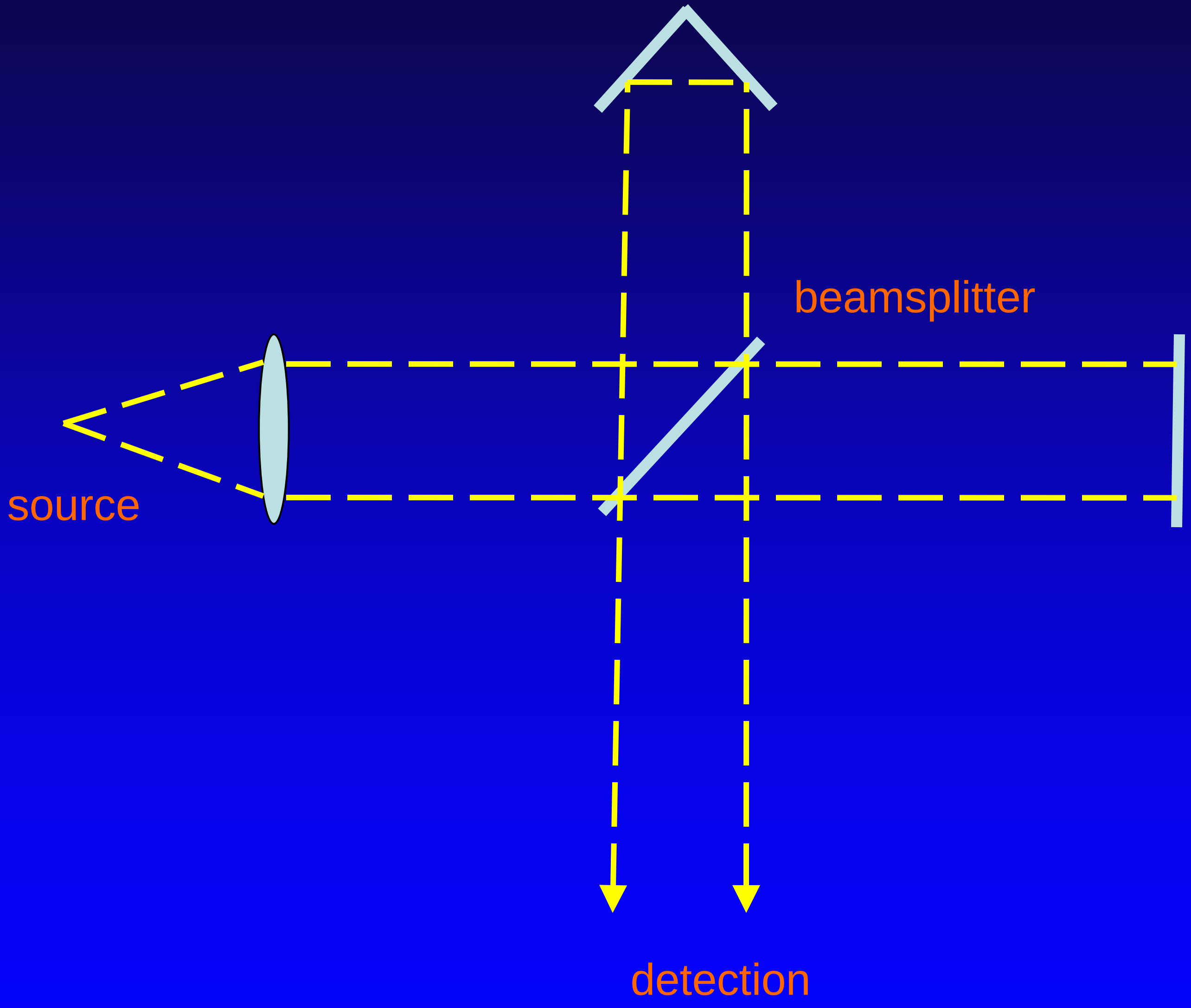


above threshold

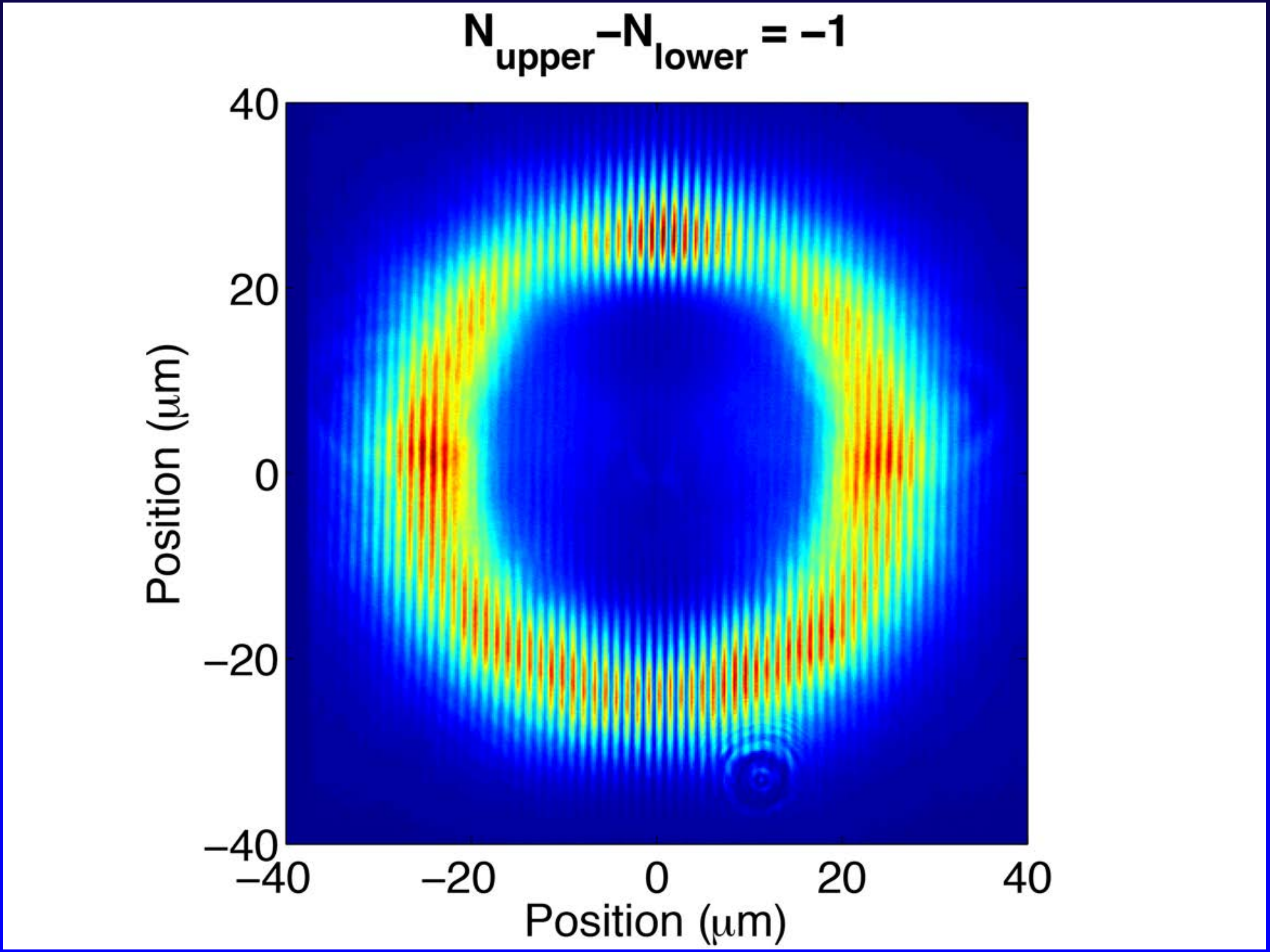
Energy spectrum of ring condensate



Michelson interferometer with flip of x-axis

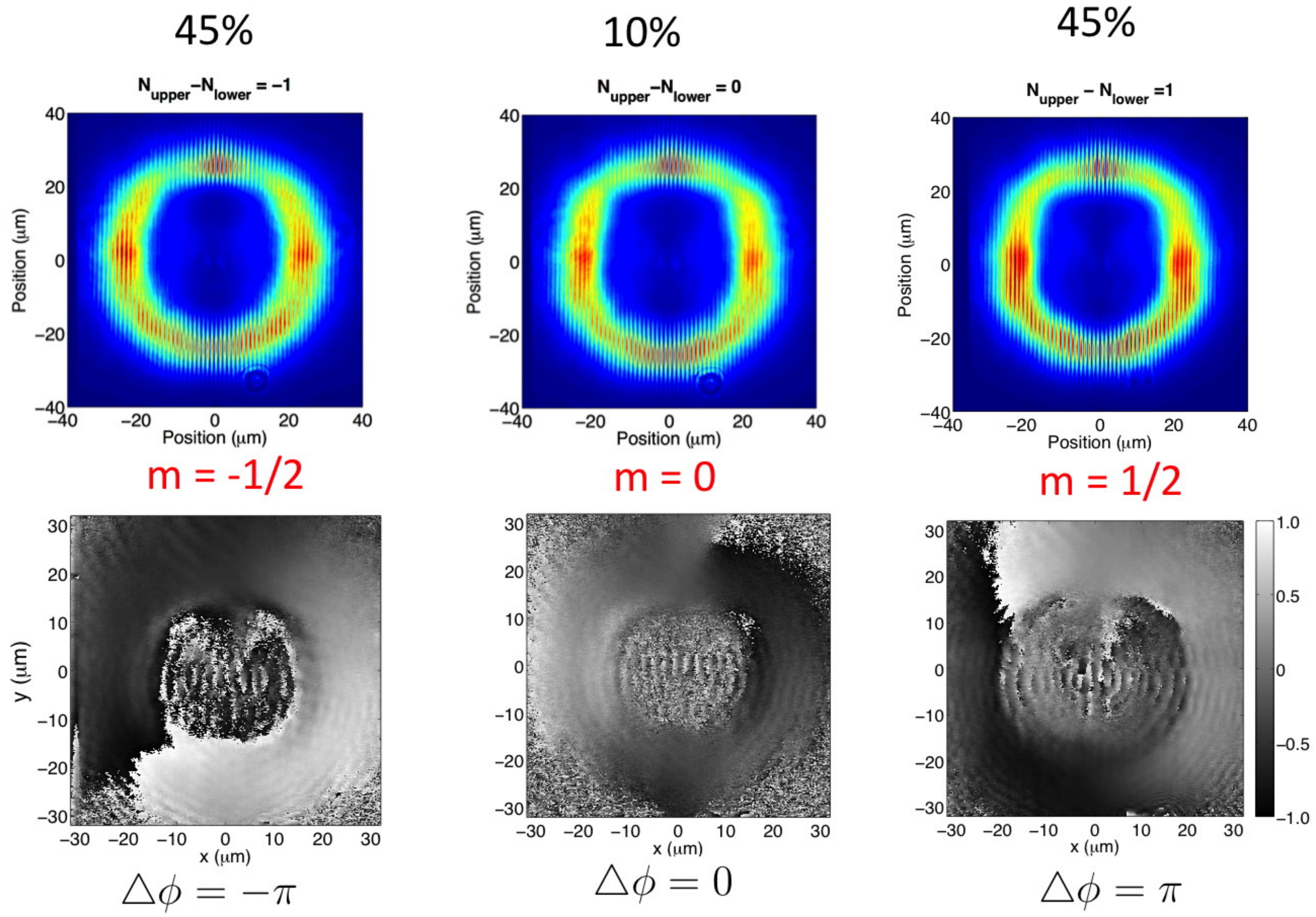


Interference patterns- fork in interference shows vorticity



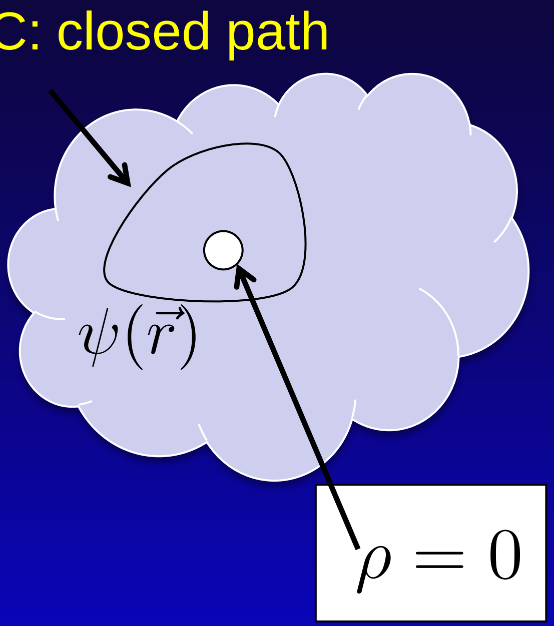
This is a persistent circulating current. Coherence time > 25 μs

phase winding



phase maps extracted from fringe patterns

Standard vortex in quantum fluids



If a system can be described by a macroscopic wave function, for example a condensate,

$$\psi(\vec{r}) = \sqrt{\rho(\vec{r})}e^{i\theta(\vec{r})}$$

then the velocity field at a point where the particle density is nonzero is given by

$$\vec{v}(\vec{r}) = \frac{\hbar}{m}\nabla\theta(\vec{r})$$

Vortex: for a single-valued (coherent) wave function, the phase shift around the path is quantized,

$$\oint_C \vec{v}(\vec{r}) \cdot d\vec{r} = n\frac{h}{m}, \quad n = 0, \pm 1, \pm 2 \cdots$$

$$\Rightarrow \oint_C \nabla\theta(\vec{r}) \cdot d\vec{r} = n \cdot 2\pi$$

implies flux quantization in superconductors

Half vortex of polariton condensate

In a spinor fluid, the wave function has two components; for example, two spin components in the *xy* plane,

$$\psi(\vec{r}) = \{\psi_x(\vec{r}), \psi_y(\vec{r})\} = \sqrt{\rho(\vec{r})}e^{i\theta(\vec{r})}\{cos(\eta), sin(\eta)\}$$

Exciton-polariton is a spinor fluid:
The polariton has angular momentum ±1 projection perpendicular to the 2D plane.

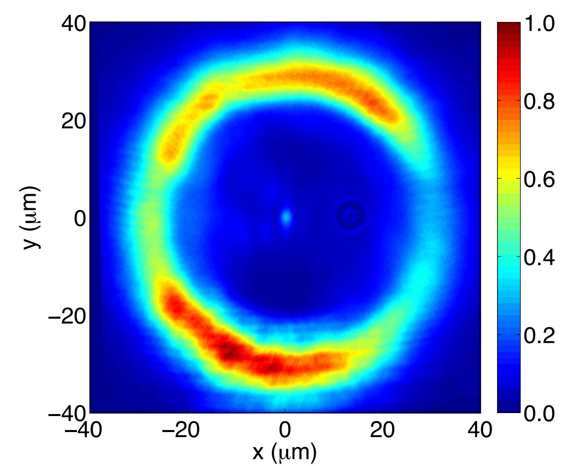
Fractional vortex:

Two rotations involved: phase and spin.
Two quantum numbers (k, m)

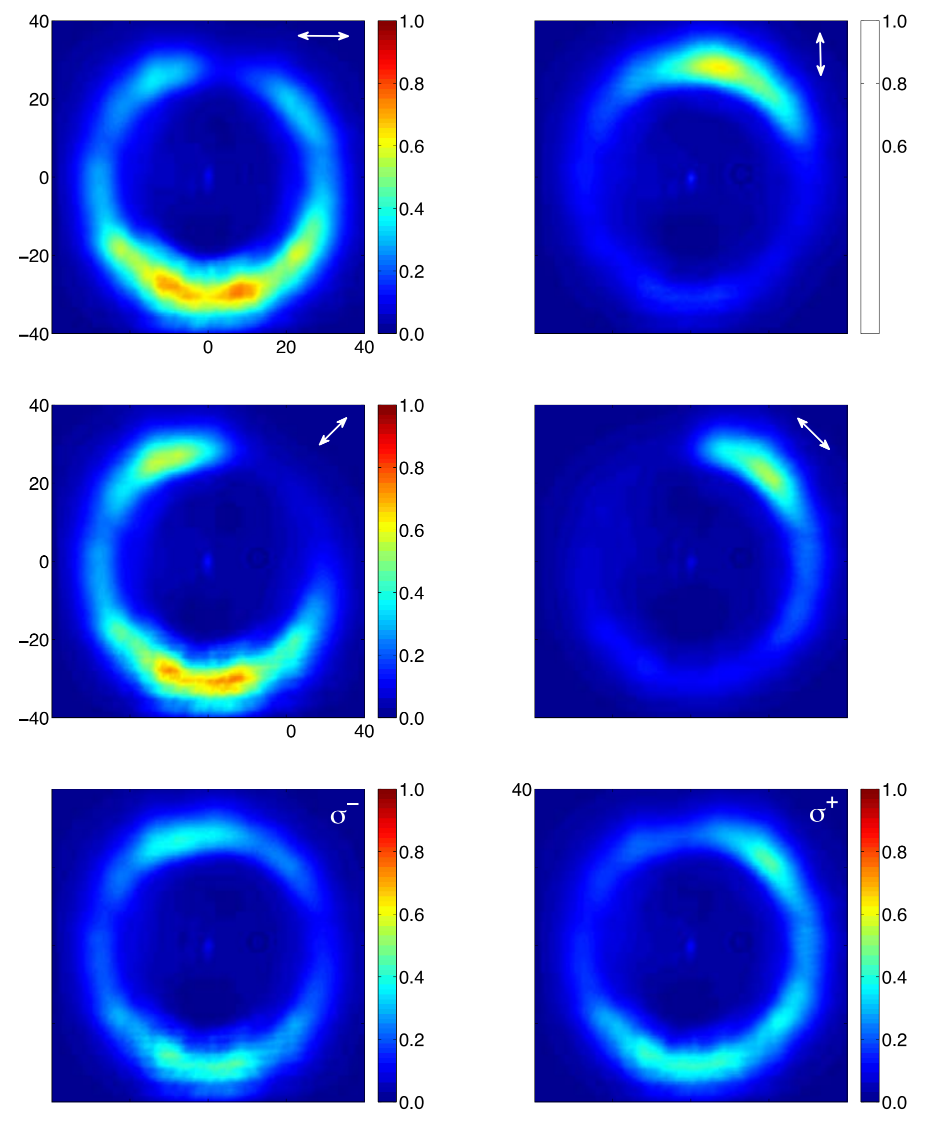
Y. Rubo, Physical Review Letters **99**, 106401 (2007)
M. C. Cross and W. F. Brinkman, J. Low Temperature Physics **27**, (1976).

Polarization profile

No polarizer

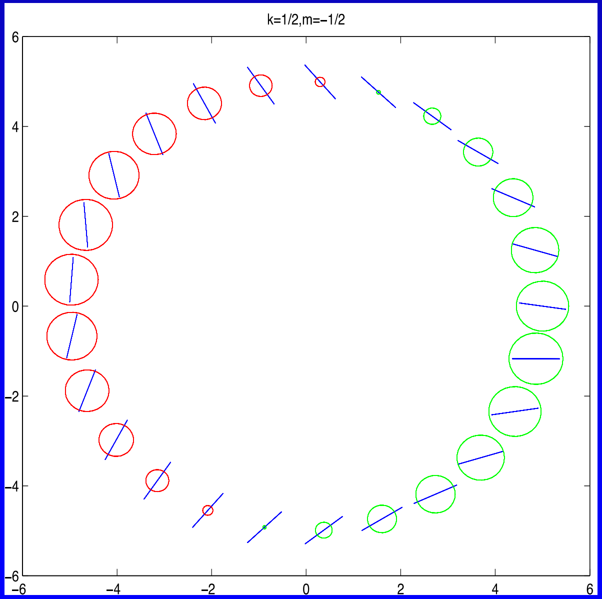


polarization resolved images

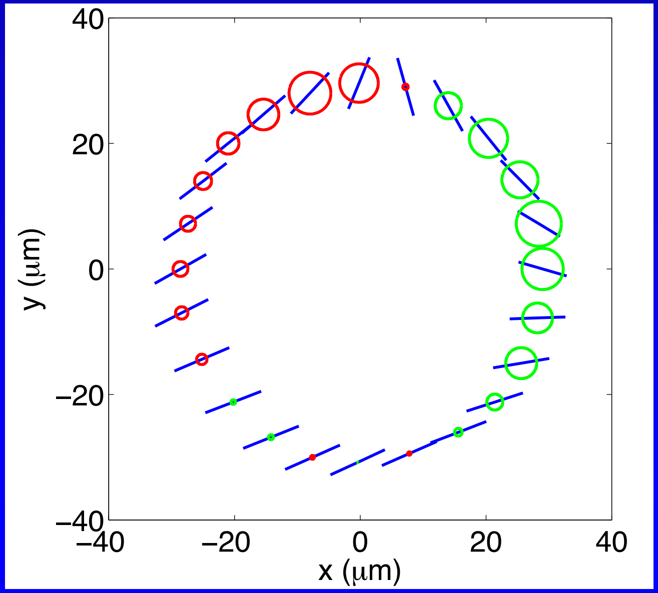


Wave function that reproduces our experiment result:

$n(\theta)$: particle density from experiment

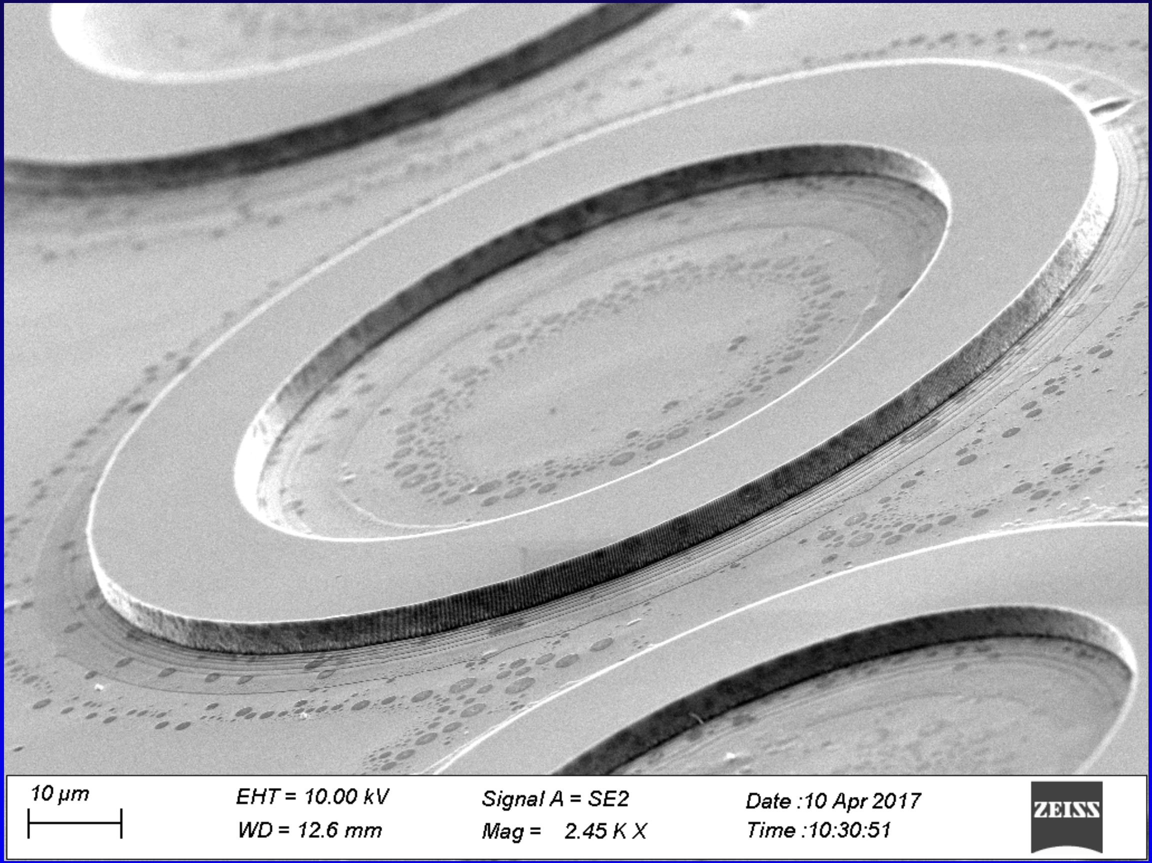


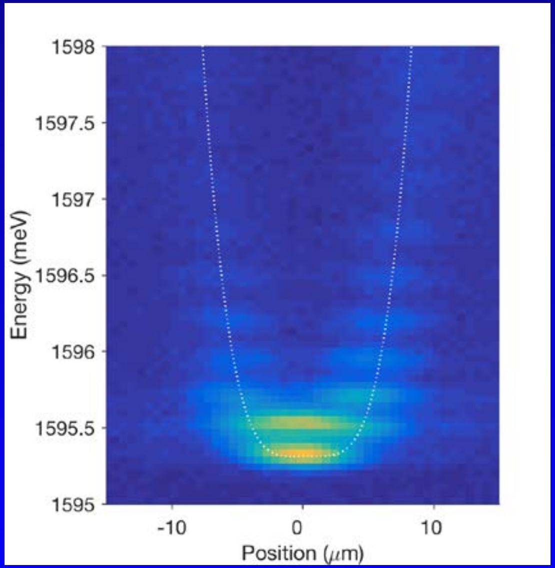
Theory



Experiment

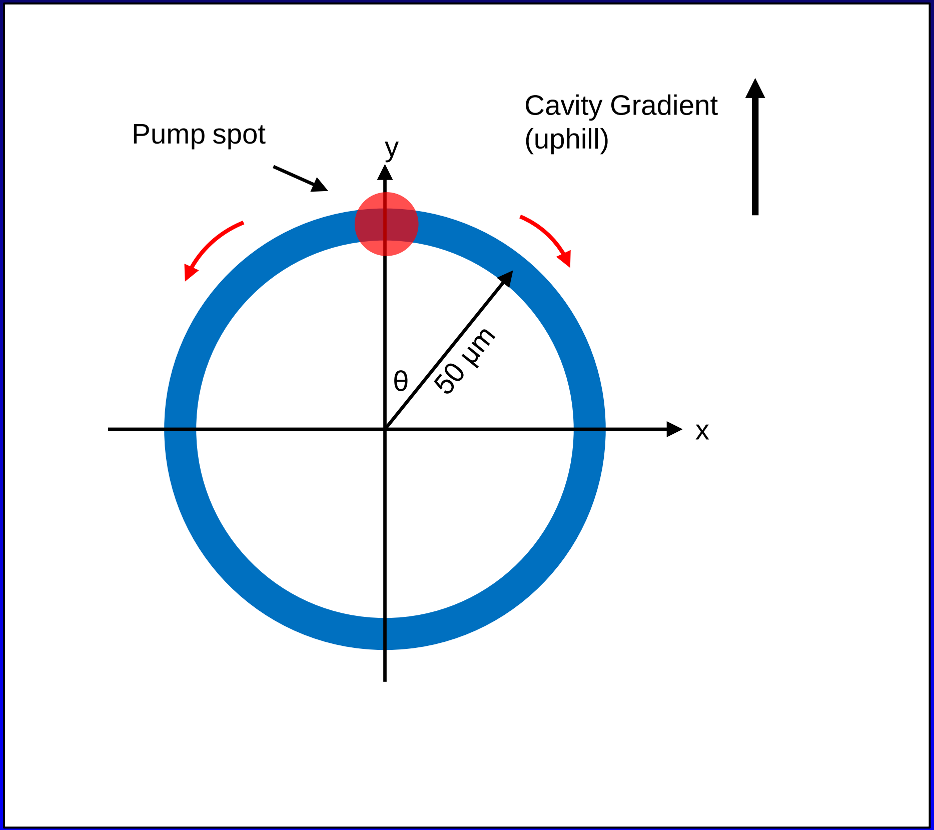
Condensate motion in etched rings



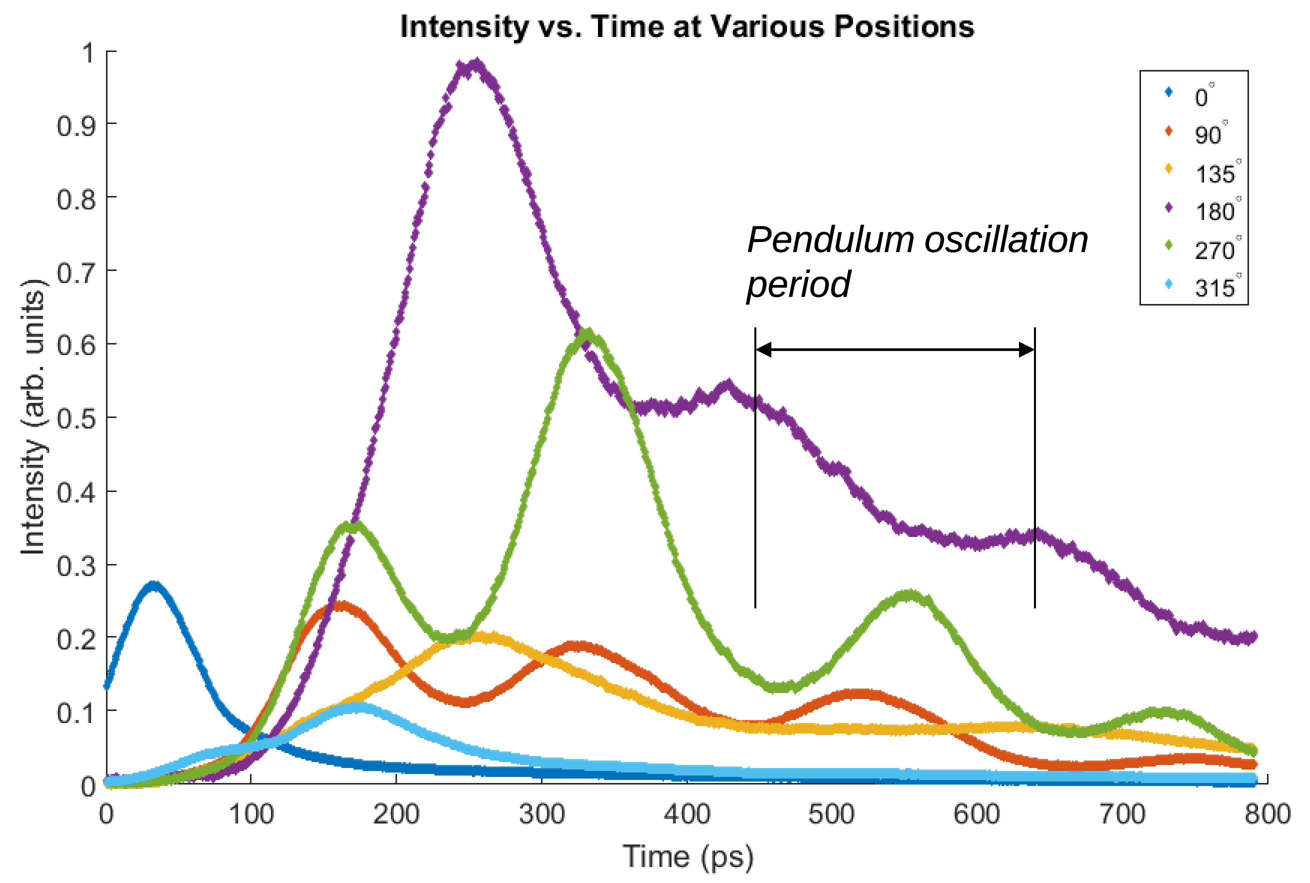


- Typical width (outer – inner radius) ≈ 15 µm
- Typical Center radius = 50 µm

Time-resolved measurements with streak camera and pulsed excitation



Hamiltonian of the system is the same as a rigid pendulum.

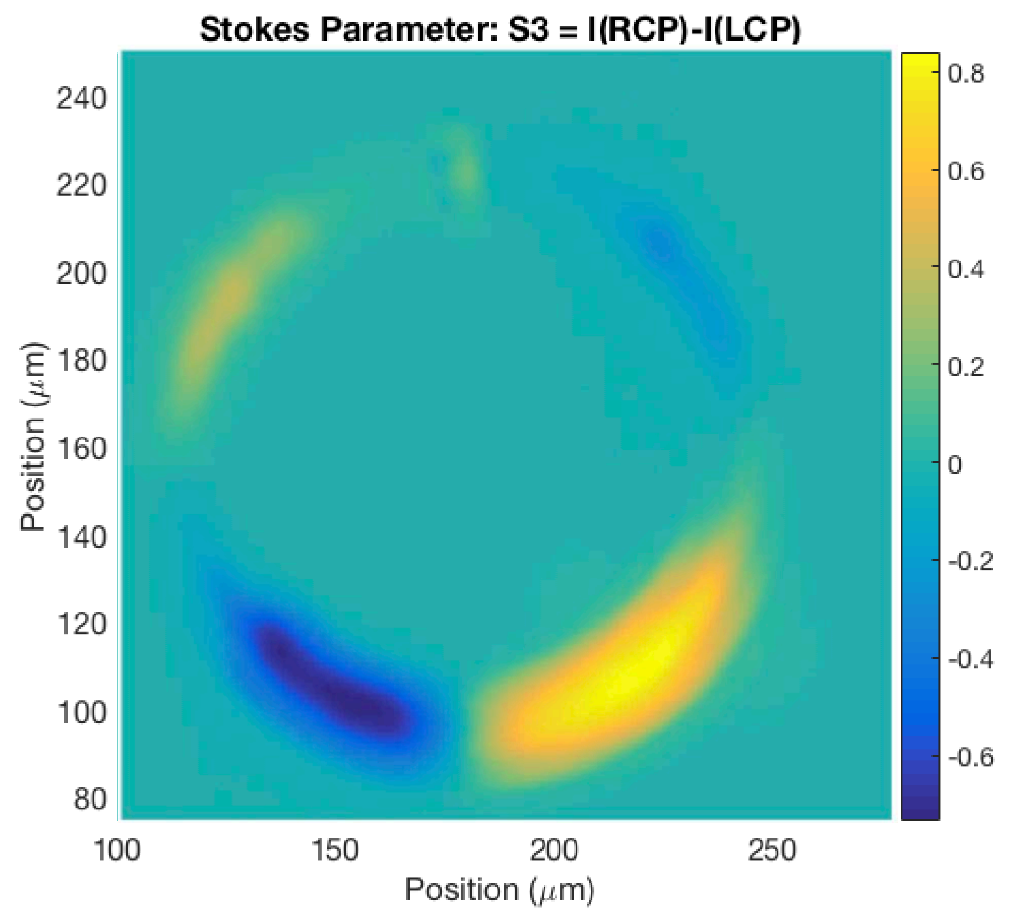


Intensity vs. Time at Various Positions

Pendulum oscillation period

100 µm diameter ring

Time-averaged, polarization-resolved image

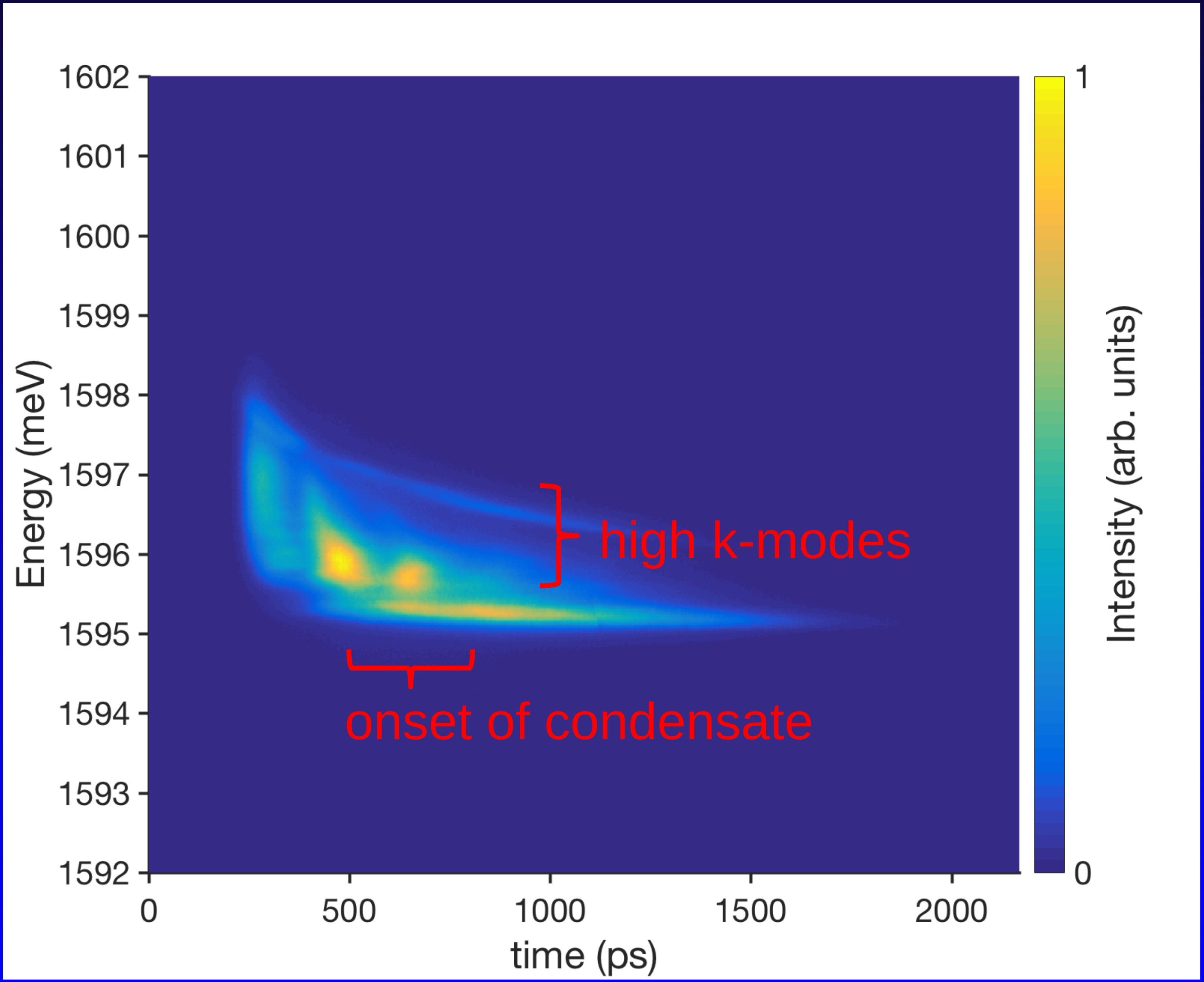


Four-fold symmetry of spin orientations in condensate.

Precession of spin state can occur due to GaAs Hamiltonian which gives effective magnetic field: optical spin-Hall effect

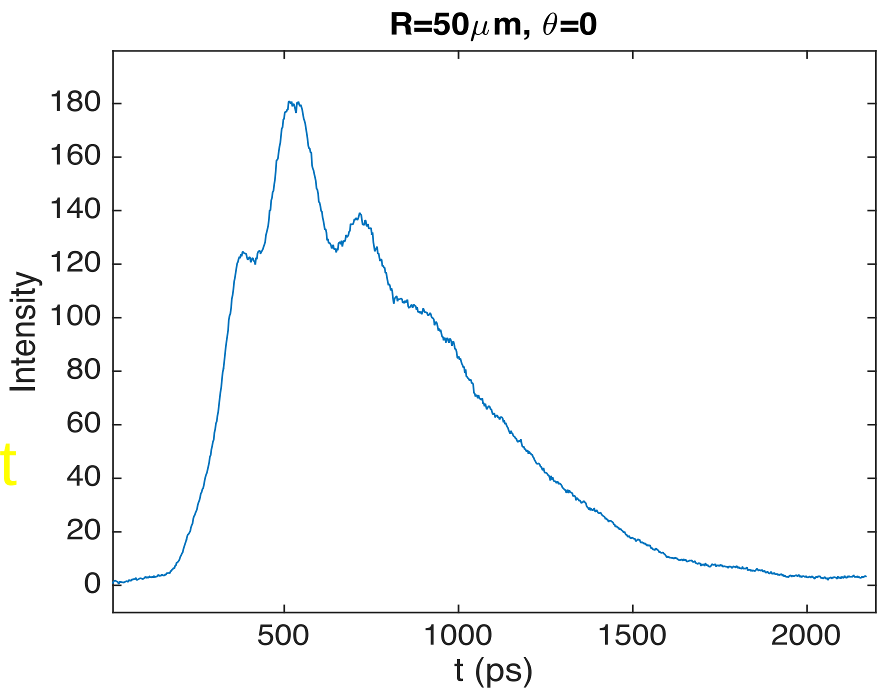
Streak image

(wide
k-collection)

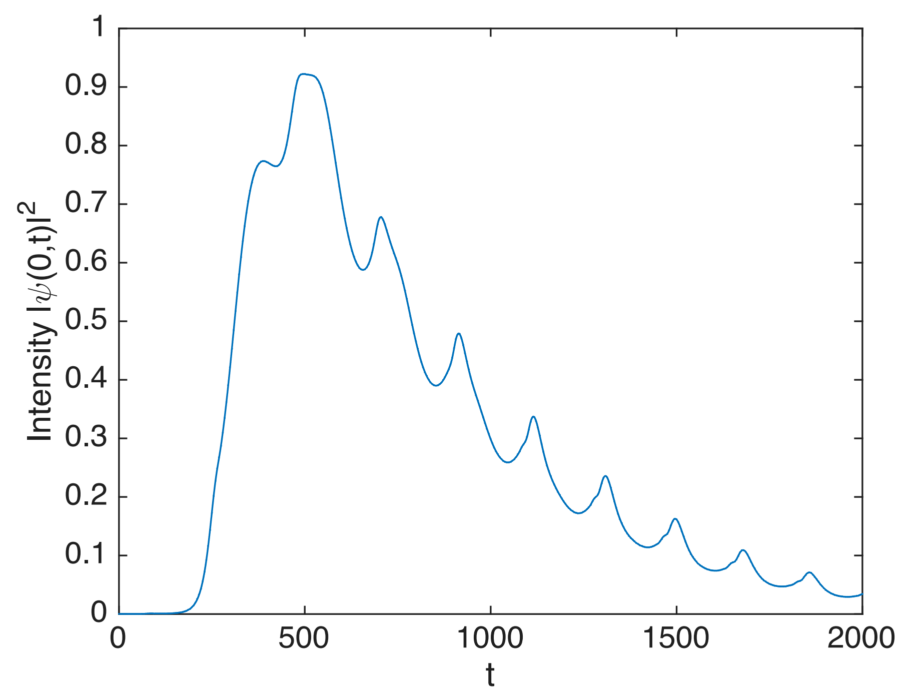


Solution of quasi 1D Gross-Pitaveskii equation
(A. Daley and R. Lena)

experiment



theory



Conclusions

- Polariton BEC is now well established, and is moving toward room temperature

- We have many ways now to control the potential
  - static exciton cloud, static strain, acoustic waves,
  - modulate cavity Q with surface patterning, AC Stark shift

- New long-lifetime samples allow true equilbrum of polariton gas and long-range motion

- Ring trap now possible, with quantized circulation as stable state

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Jonnie Beaumarriage
Adam Grusky
David Myers
Shouvik Mukherjee
Burcu Ozden