New possibilities with long-lifetime microcavity polaritons

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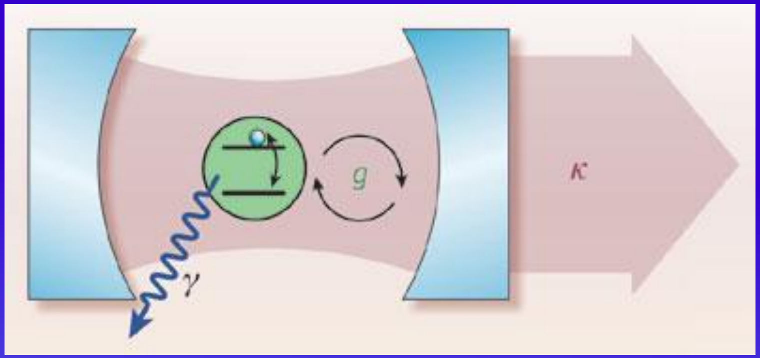
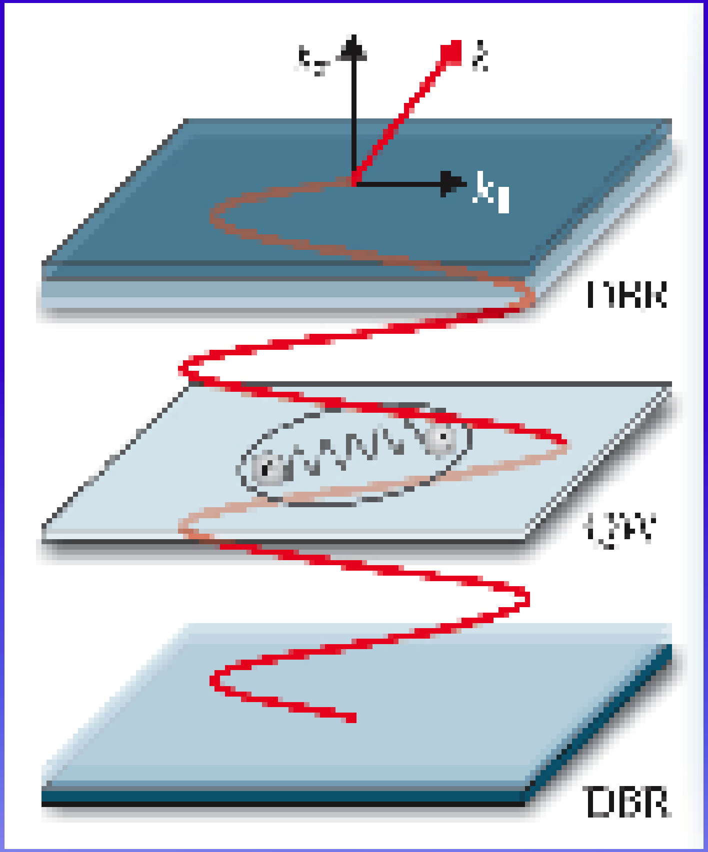
Strong coupling in a cavity



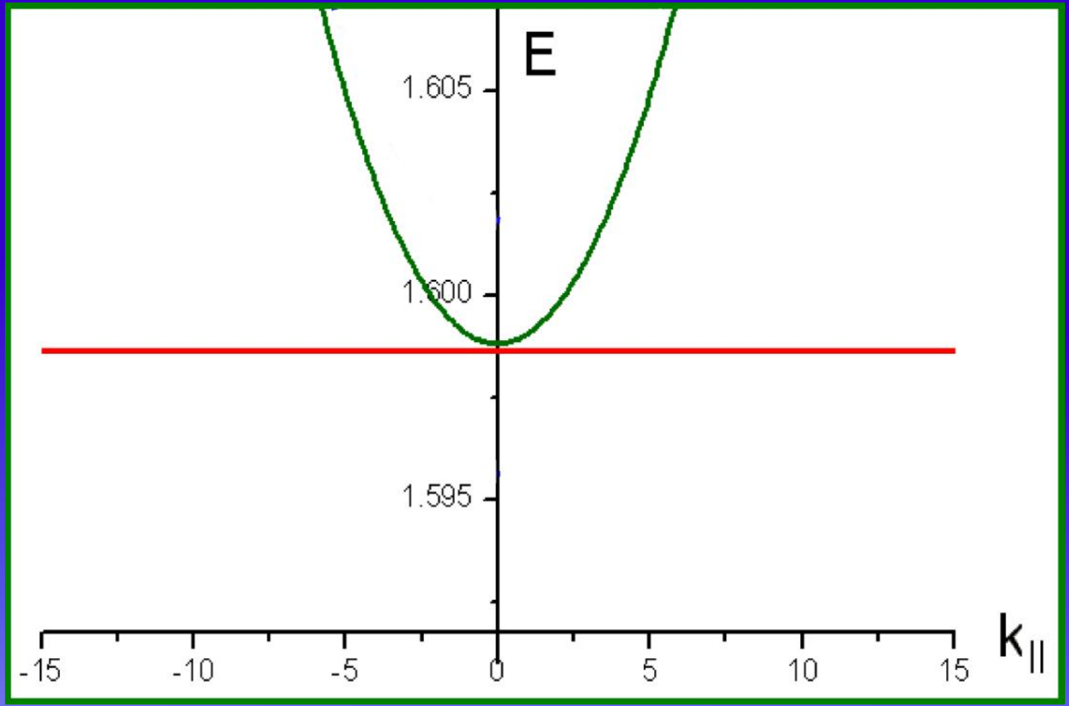


solid: maximum density of oscillators
coupling energy = $g\sqrt{N}$
where N is the number of atoms

tradeoff: disorder

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

exciton

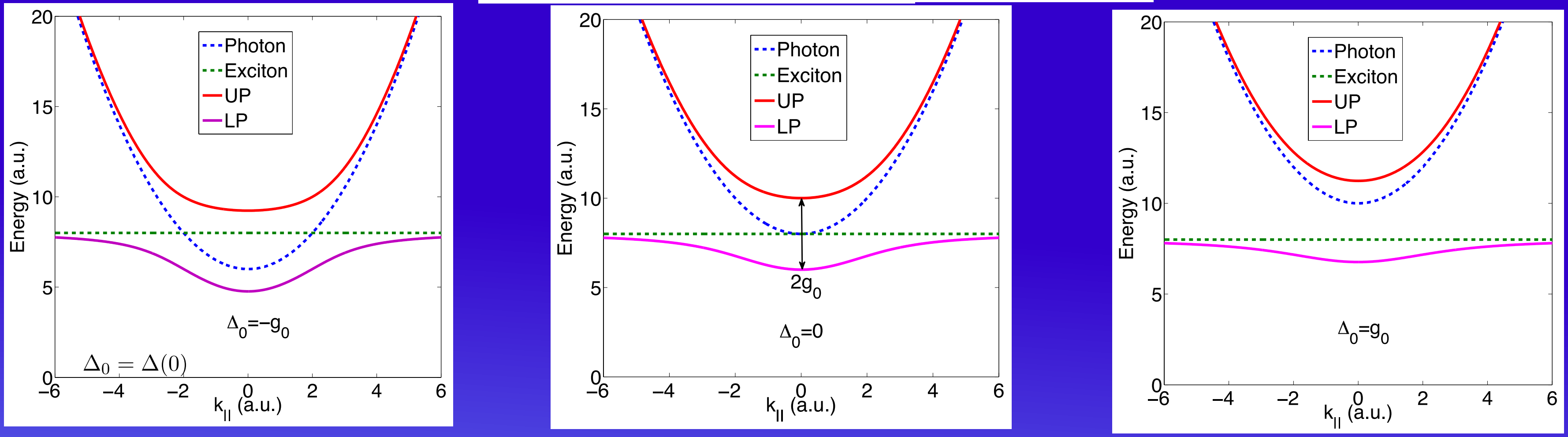


Mixing leads to "upper polariton" (UP) and "lower polariton" (LP)

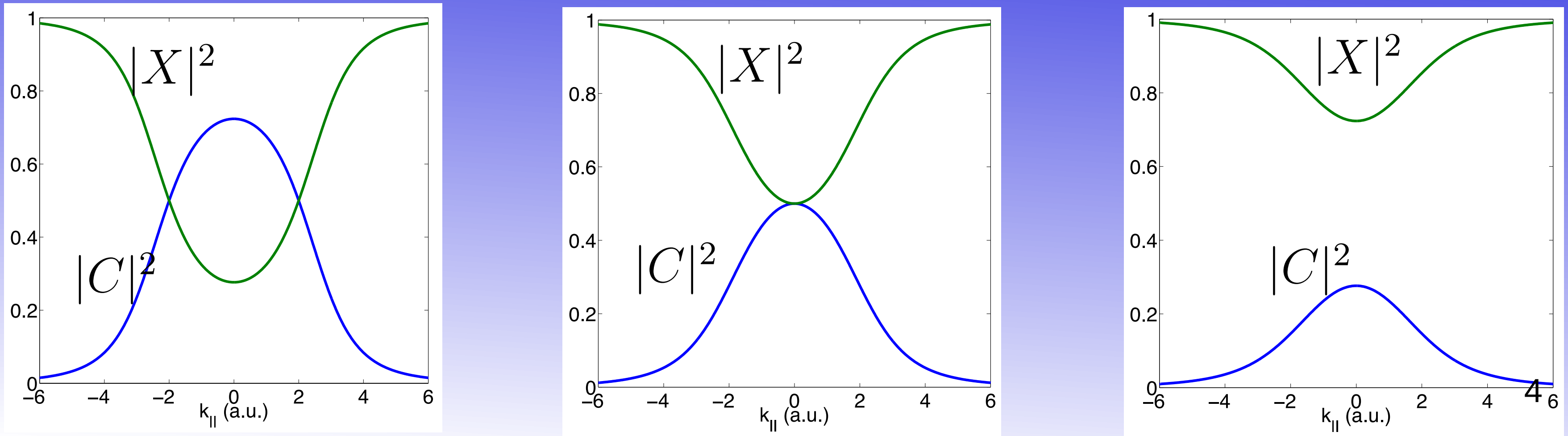
LP effective mass ~ $10^{-4}\, m_e$

Polariton properties vs. detuning

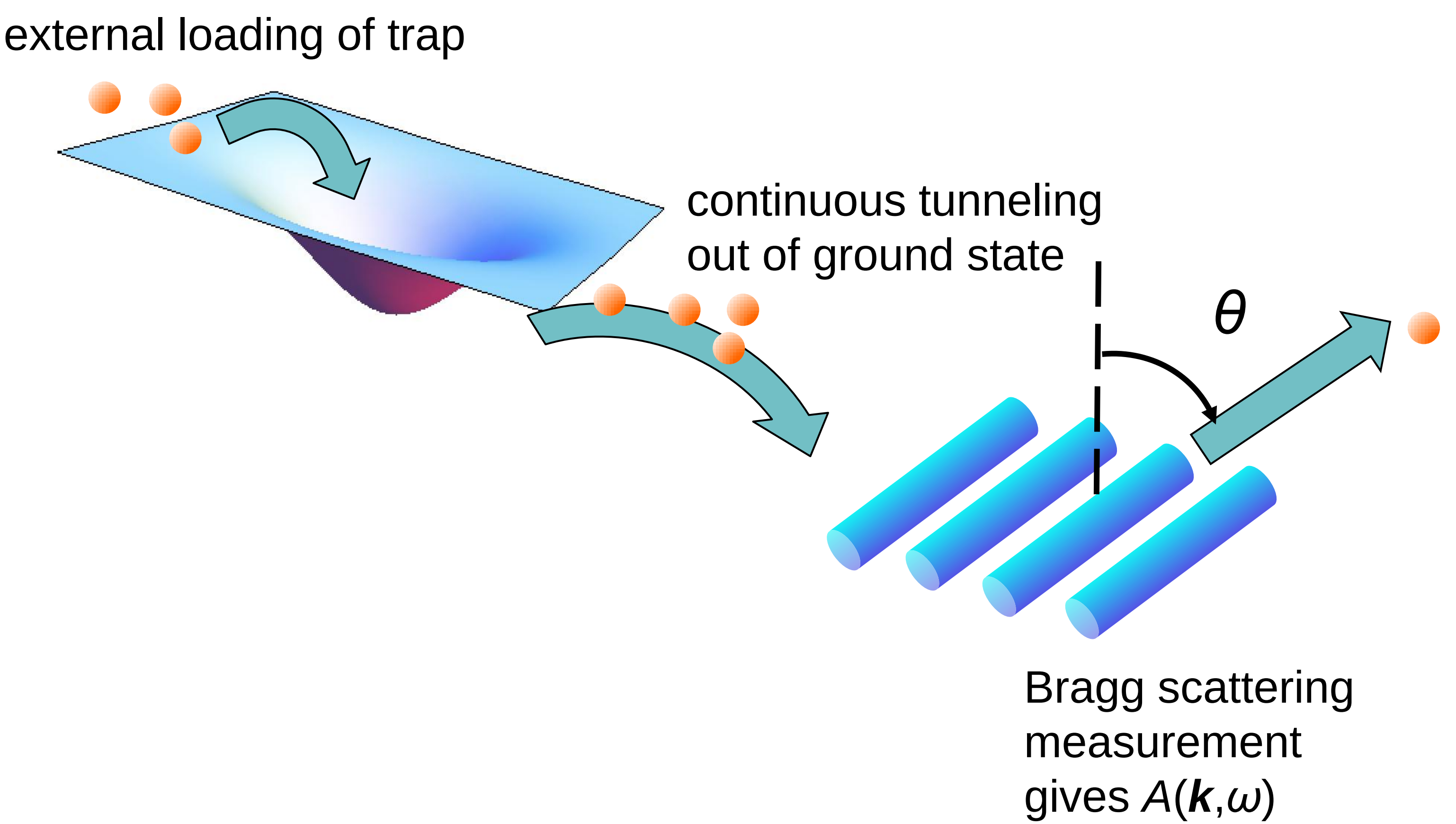
$$\Delta_0 = E_{ph}(0) - E_{ex}(0)$$



For LP, $|C|^2$ = photon fraction, $|X|^2$ = exciton fraction.



A thought experiment:



This is exactly how cavity polariton ("heavy photon") condensates are monitored: photons in (pumping), equilibration, tunneling out through the mirrors, spectroscopy.

Lifetime of microcavity polariton systems

leakage out of mirrors: intrinsic cavity photon lifetime
early samples: ~ 1 ps

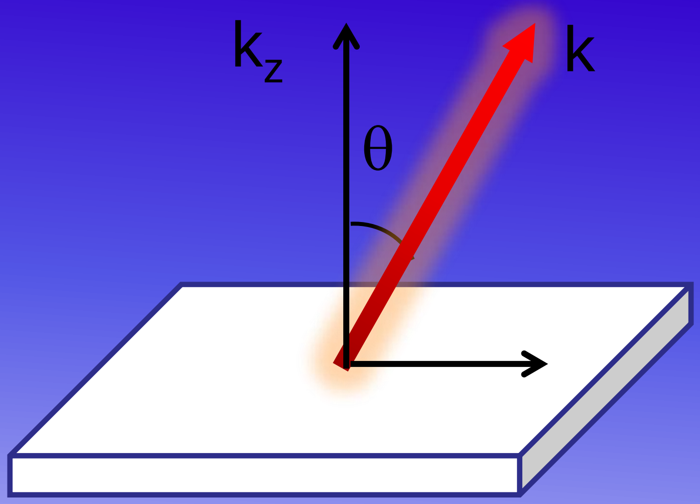
Baumberg, Bloch: ~ 10 ps

Snoke/Pfeiffer: 135 ps

Polariton lifetime is longer than this:
Twice the photon lifetime at resonance.
$\rightarrow \infty$ in excitonic limit.

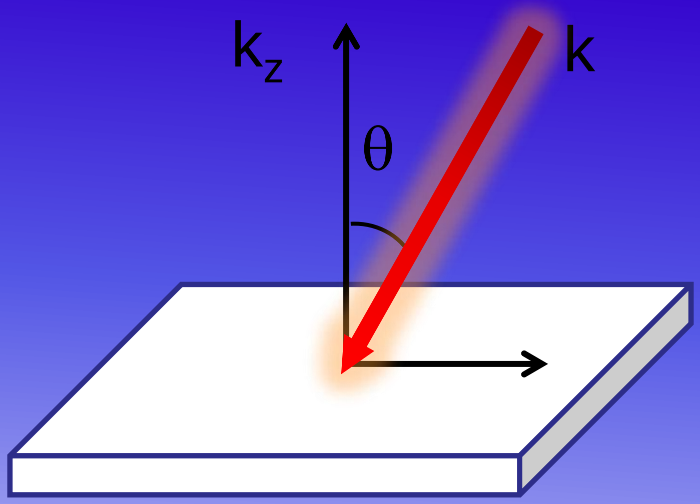
Typical experiment: collisional thermalization time ~ 5-10 ps
In new samples, lifetime is ~ 300 ps.

Angle-resolved photon emission data give momentum distribution



We can therefore image the gas in both <u>real</u> space and <u>momentum</u> space as data.

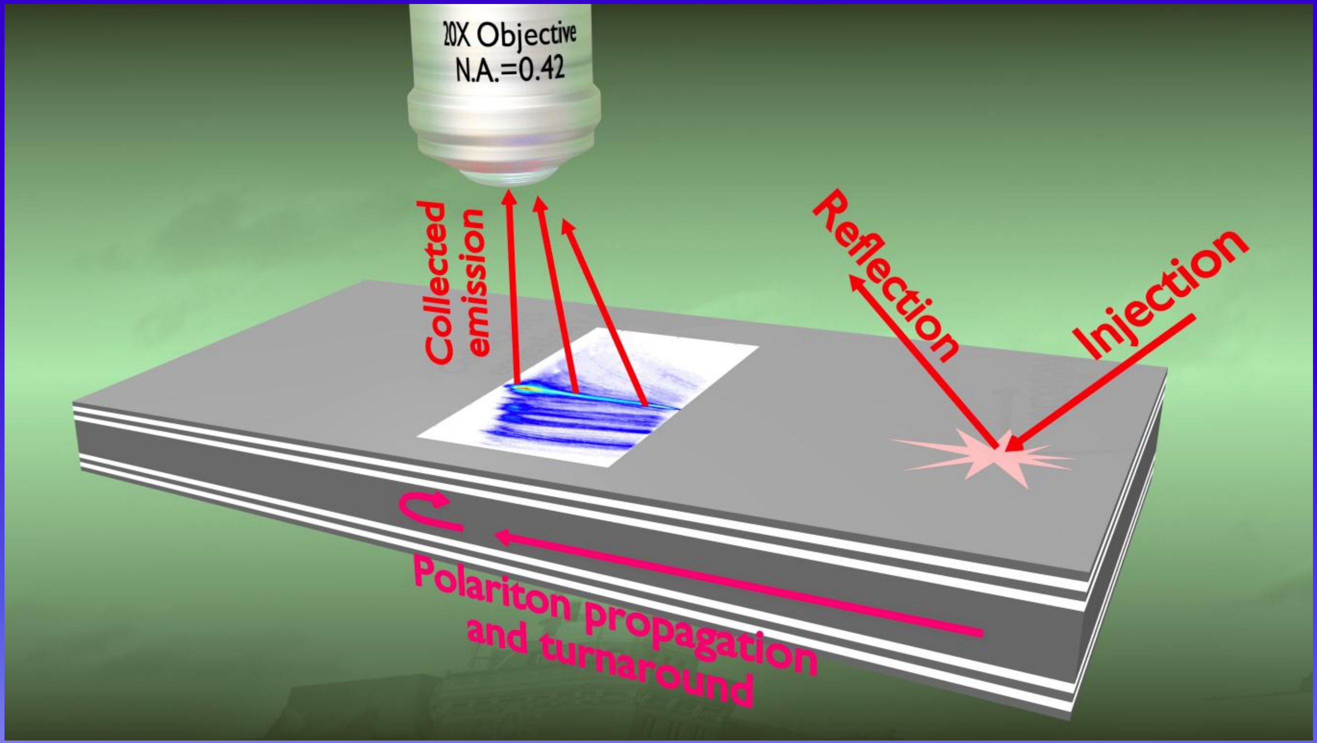
Angle-resolved photon emission data give momentum distribution

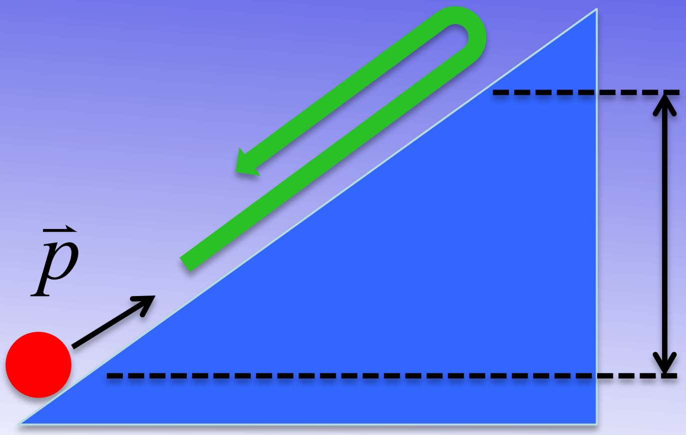


This process also works *backward*: we can inject polaritons at a specific momentum and location.

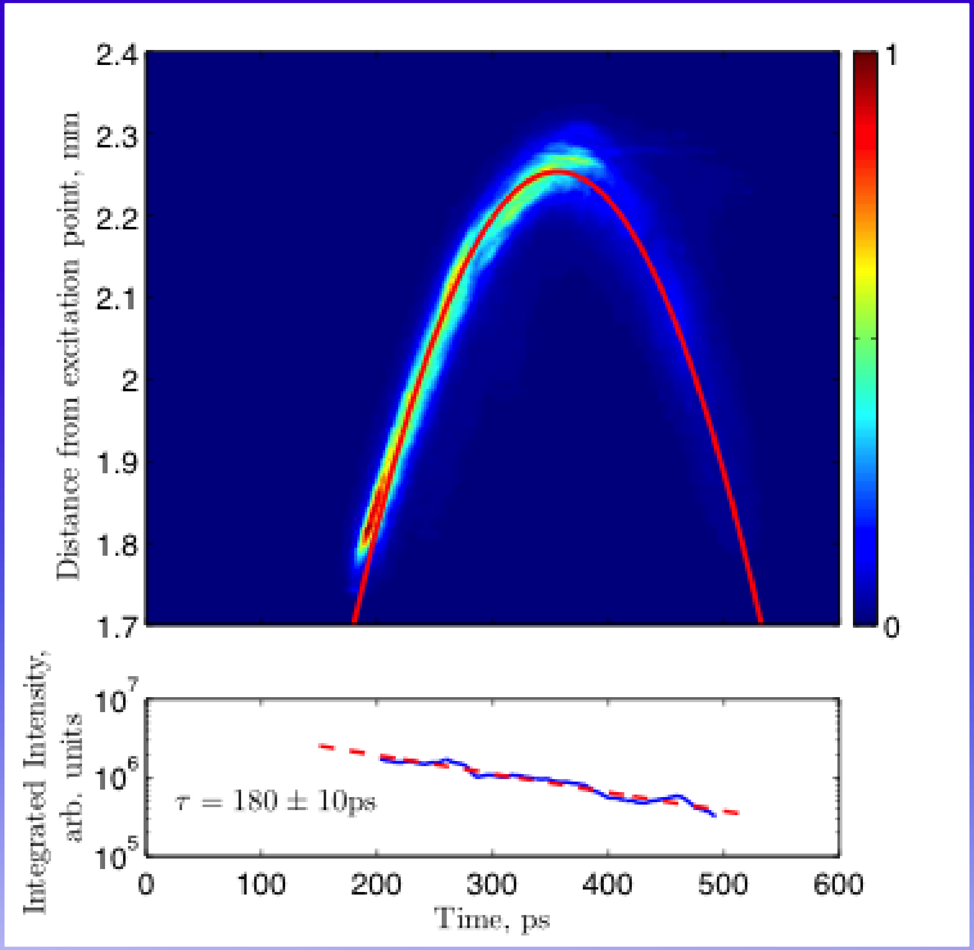
Direct resonant injection:

angle of injection gives in-plane *p*





Time resolved data: ballistic motion

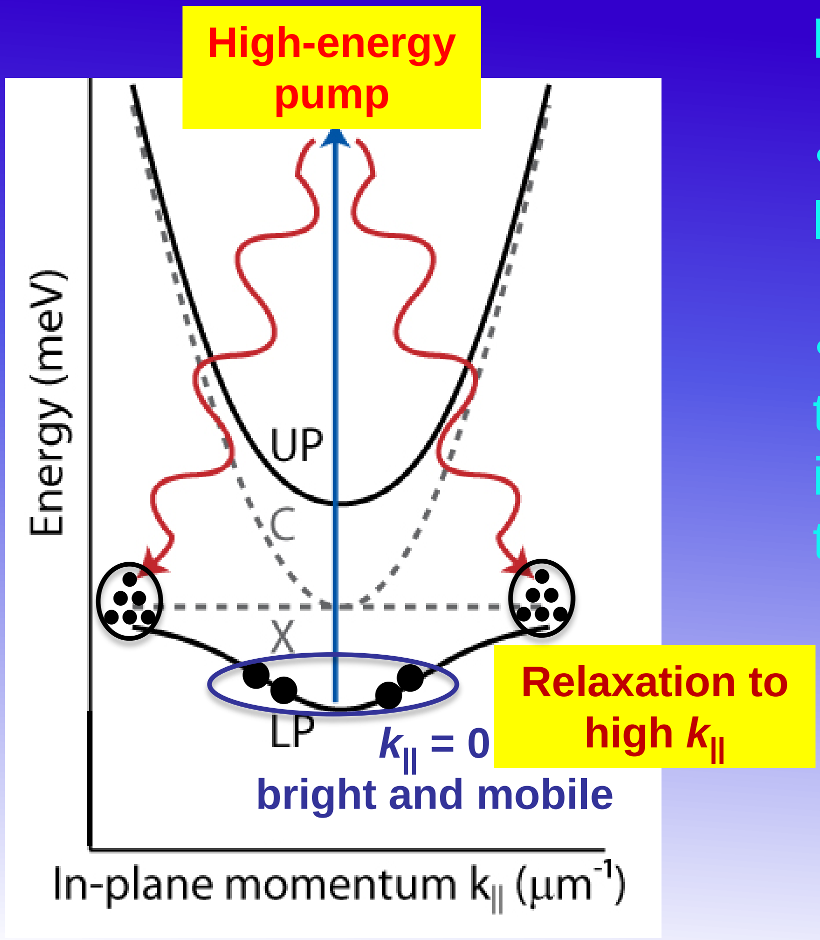


"gravity for photons"

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

long lifetime: 180 ps
-- corresponds to Q ~ $3x10^5$

“Exciton cloud” potential



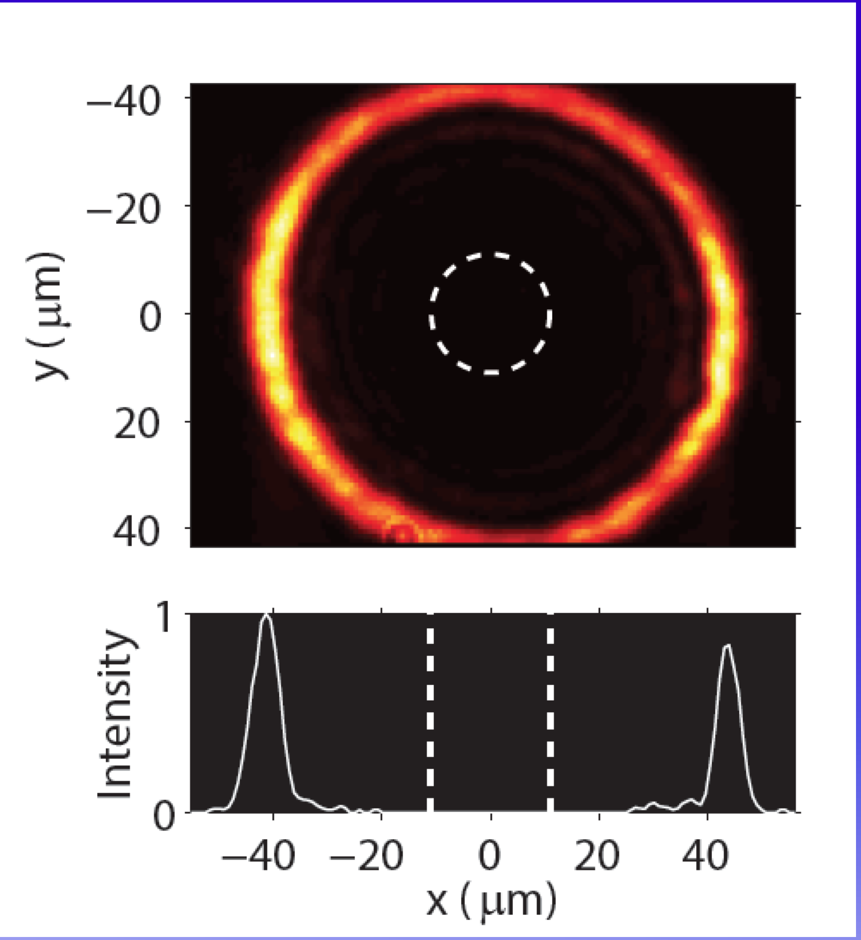
- excitons are 10^4 more massive than the polaritons. They move very little, so that collisions of polaritons with excitons are nearly elastic– a static barrier as seen by polaritons

- 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

laser in ring focus:
ring trap

no excitons in
the middle



Spatially-resolved photoluminescence (PL) measurement:

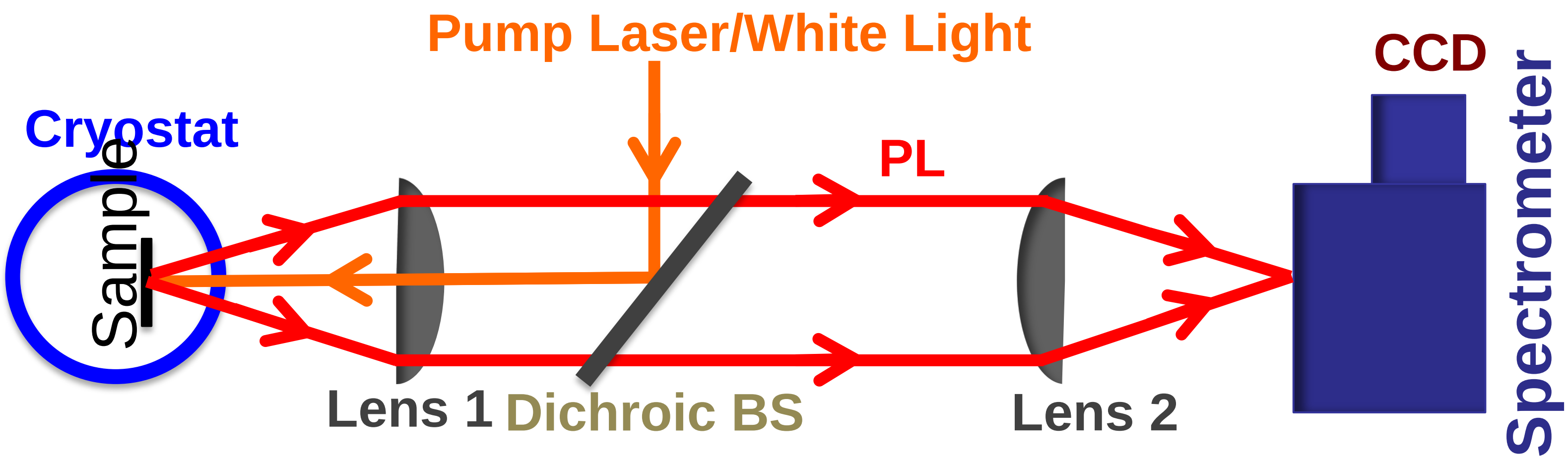
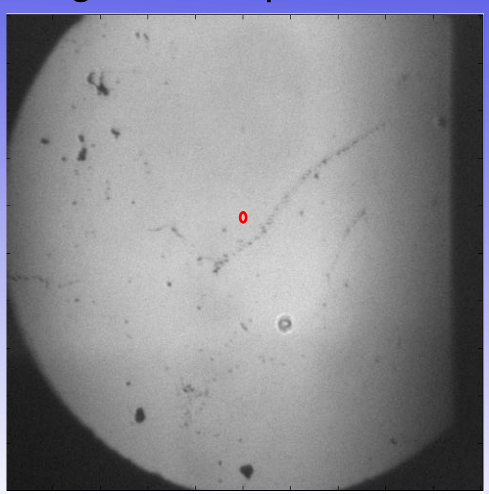
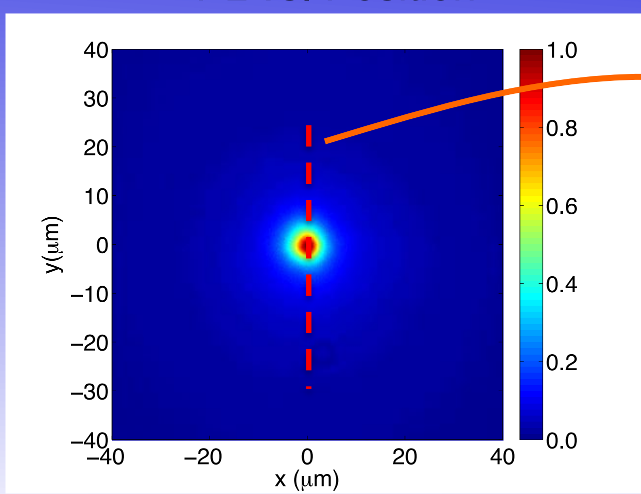


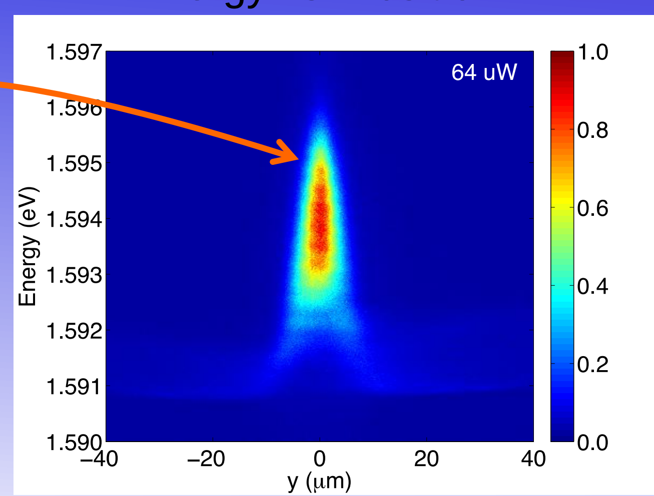
Image of Sample Surface



PL vs. Position

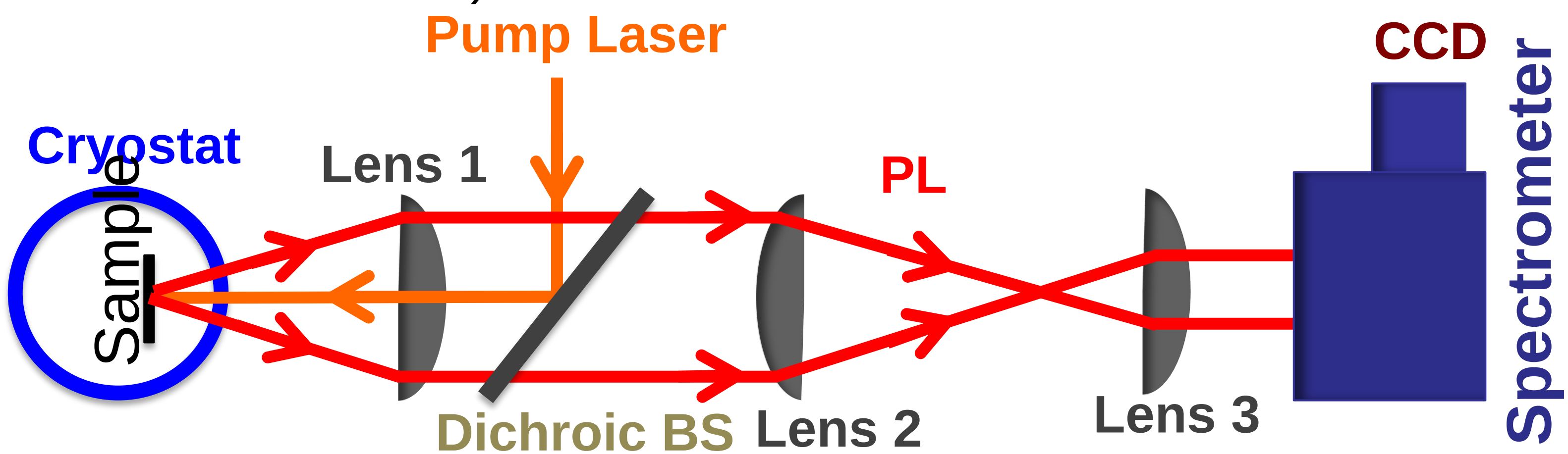


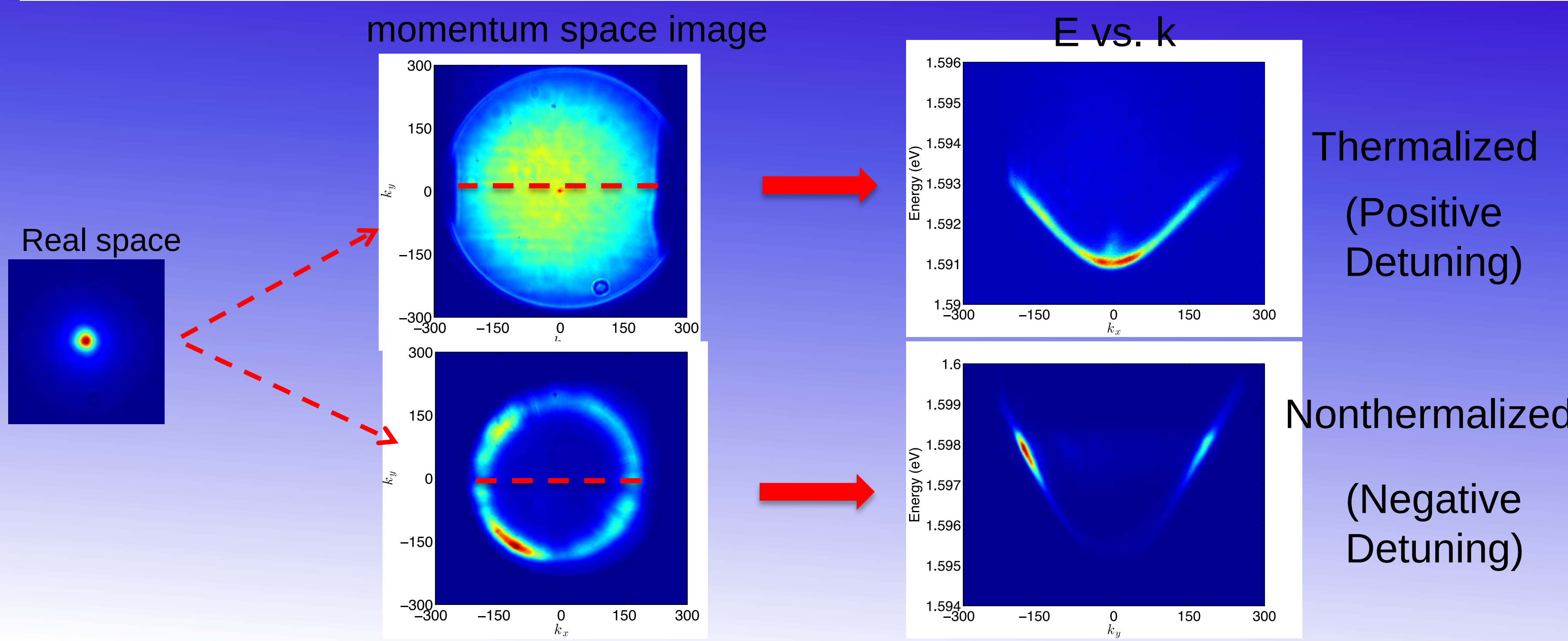
Energy vs. Position



Angle-resolved photoluminescence (PL) measurement:

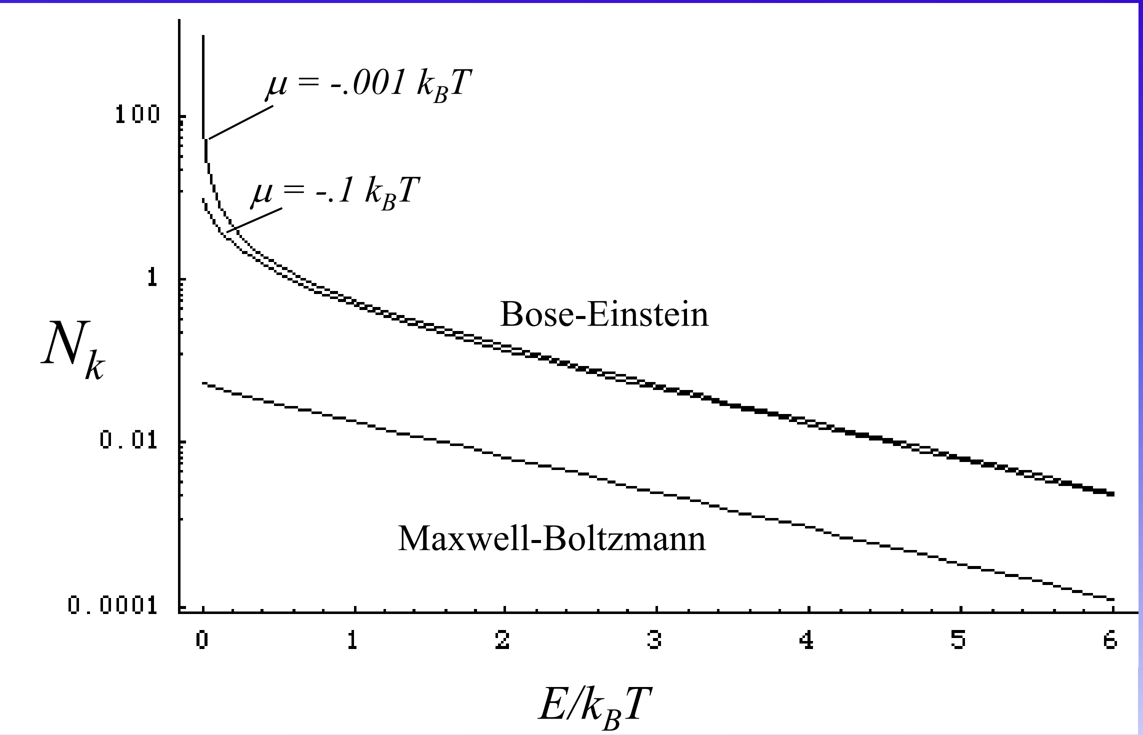
(momentum distribution)





Ideal equilibrium Bose-Einstein distribution

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

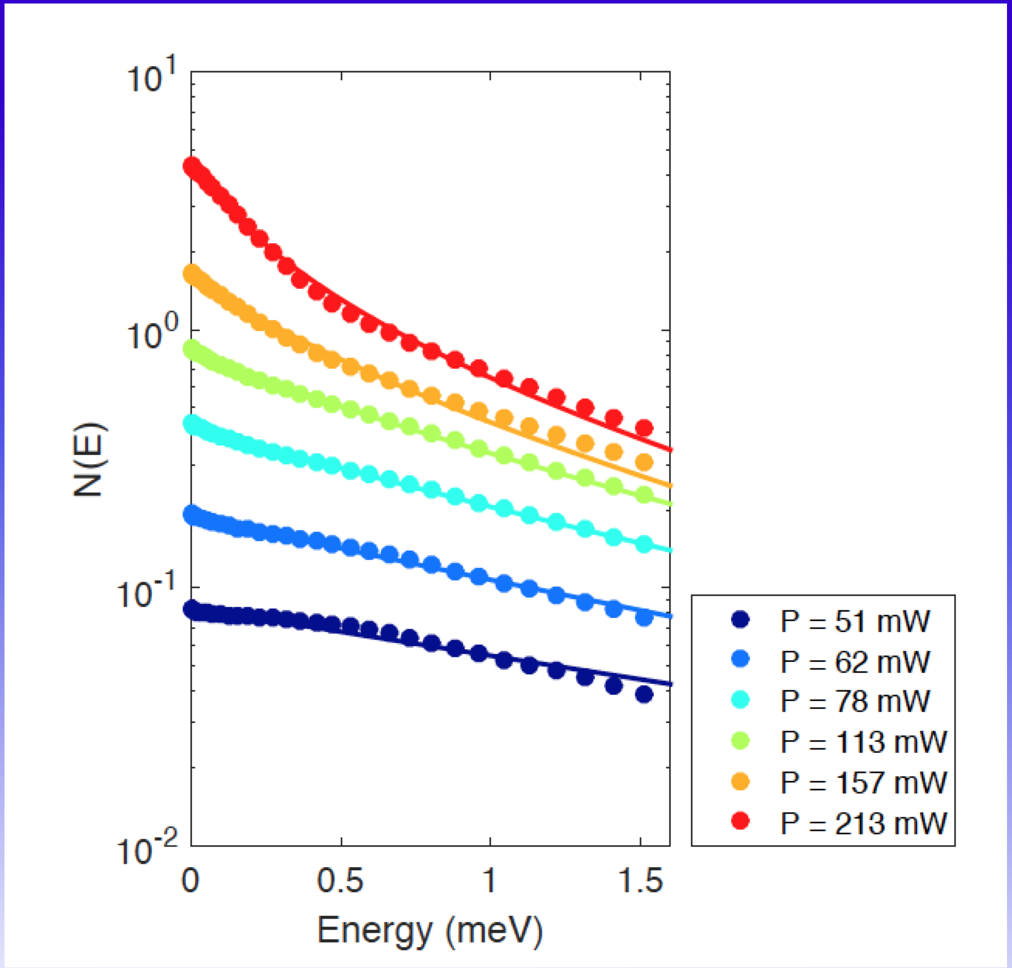


Thermalization of polaritons

Fit density agrees within 10% of pure photon counting!

recall at threshold:

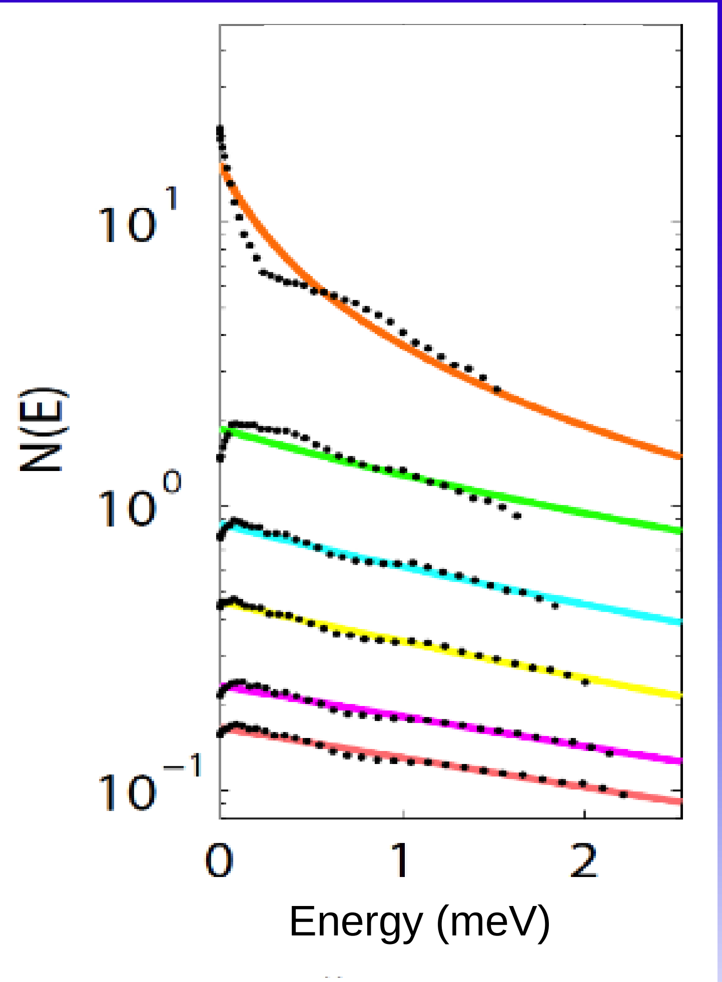
$$\lambda = h / \sqrt{2mk_B T} \sim r_s$$



solid lines: fit to equilibrium Bose-Einstein distribution *(with same overall collection-efficiency multiplier for all)*

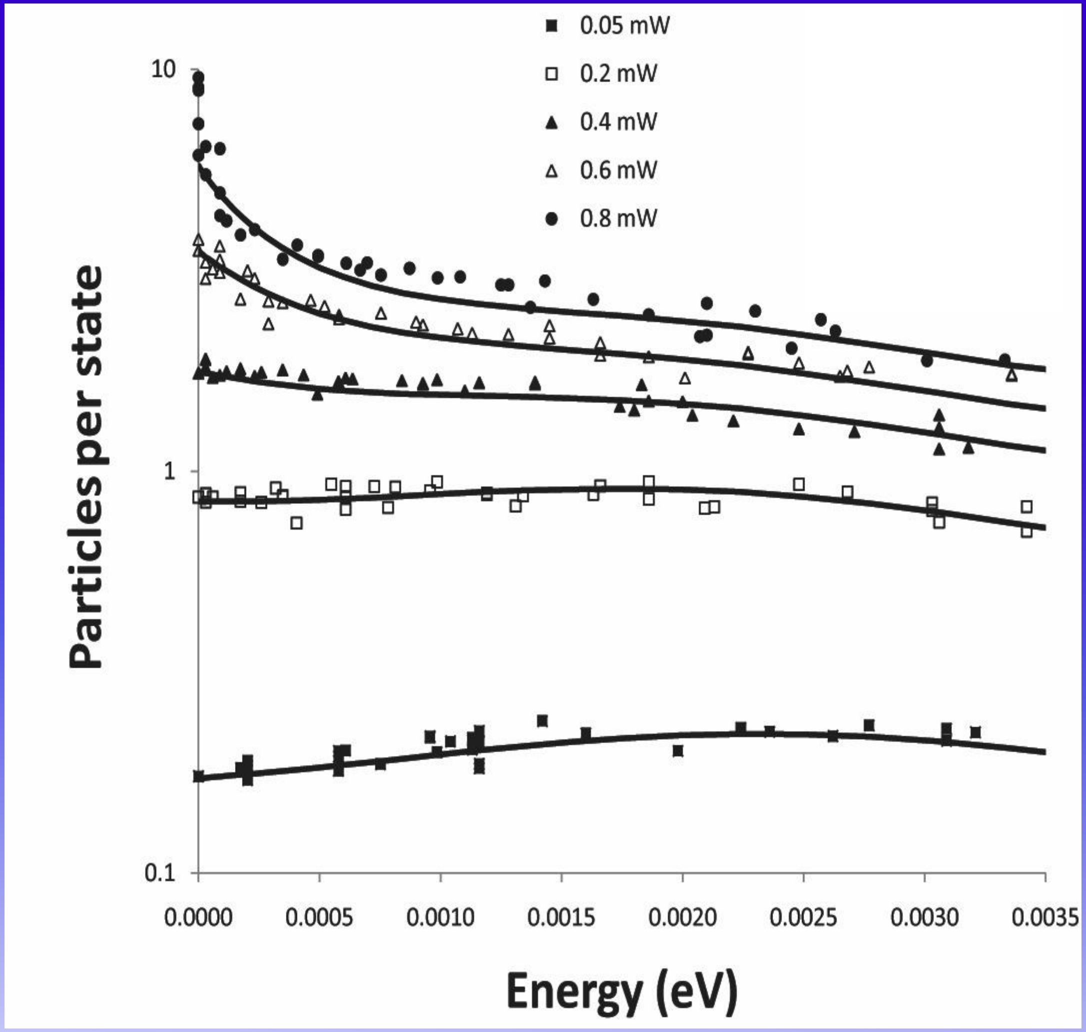
non-thermal distributions:
too weakly interacting

Photon-like detuning (weak interactions)



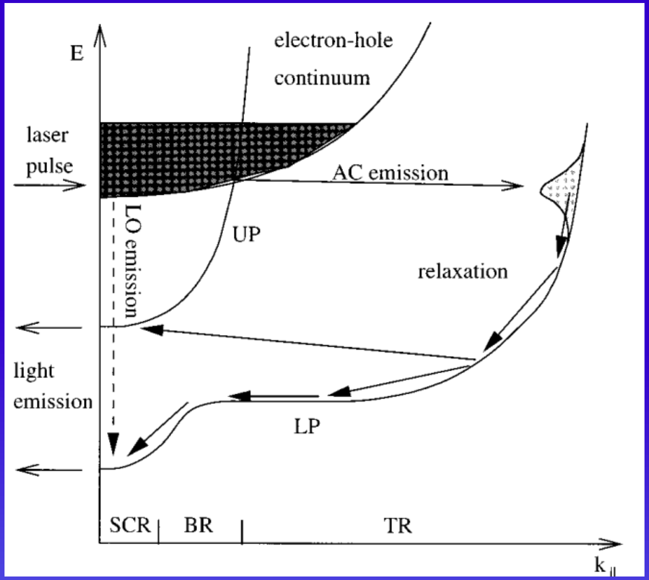
dashed lines:
best Bose-Einstein fit

Intermediate case: short lifetime polaritons, quasi-thermalization



V. Hartwell and D. Snoke, PRB **82**, 075307 (2010).

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).

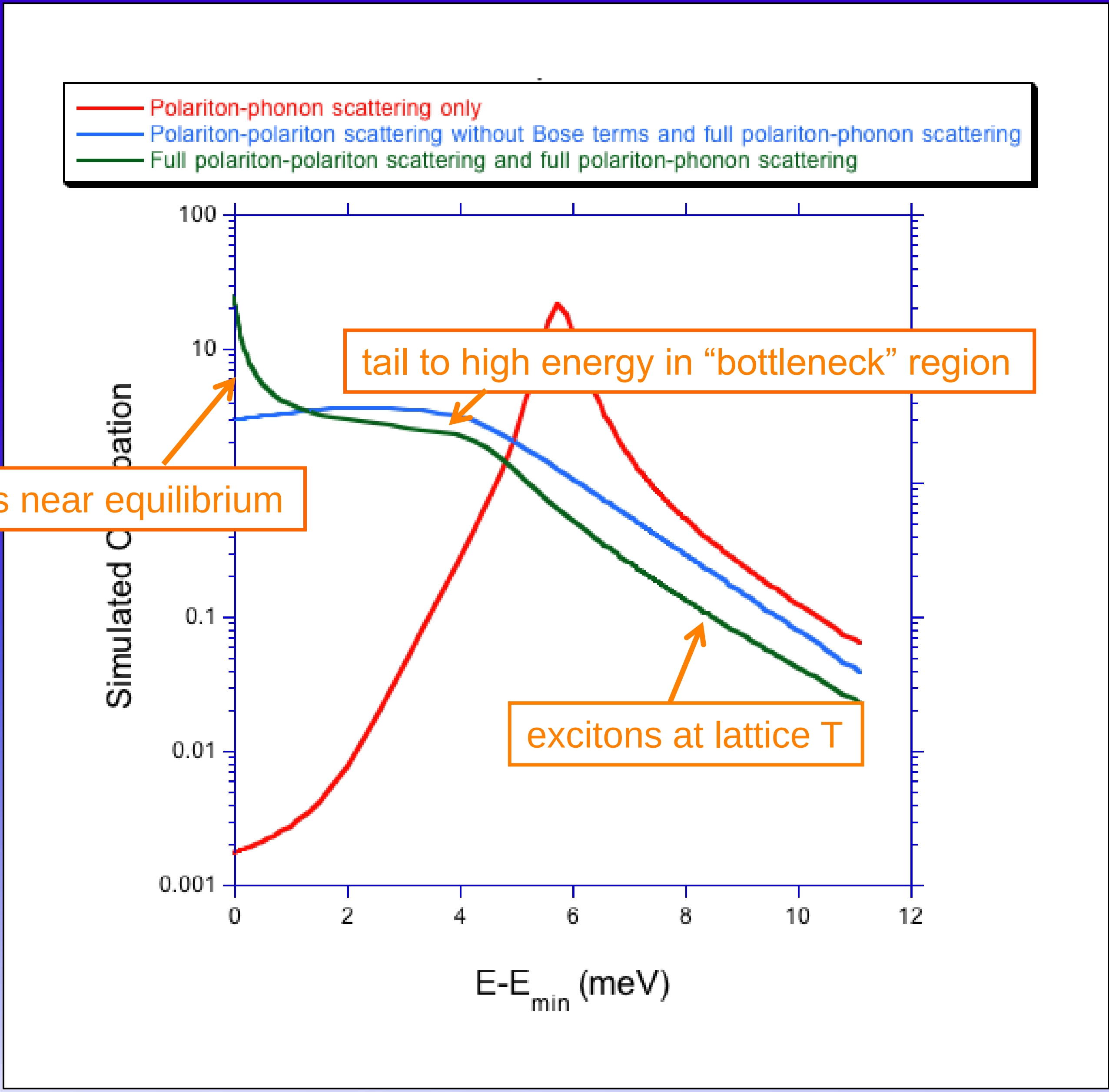
Sarchi and Savona, Solid State Comm **144**, 371 (2007).

$$\frac{\partial n(\vec{k}_1)}{\partial t} = \frac{2\pi}{\hbar} \sum_{\vec{k}_2 \vec{k}_{1'}} M^2(|\vec{k}_1 - \vec{k}_{1'}|) n(\vec{k}_1) n(\vec{k}_2)[1 + n(\vec{k}_{1'})][1 + n(\vec{k}_{2'})] \delta(E_1 + E_2 - E_{1'} - E_{2'})$$

Include polariton-phonon, polariton-electron, and polariton-polariton scattering.

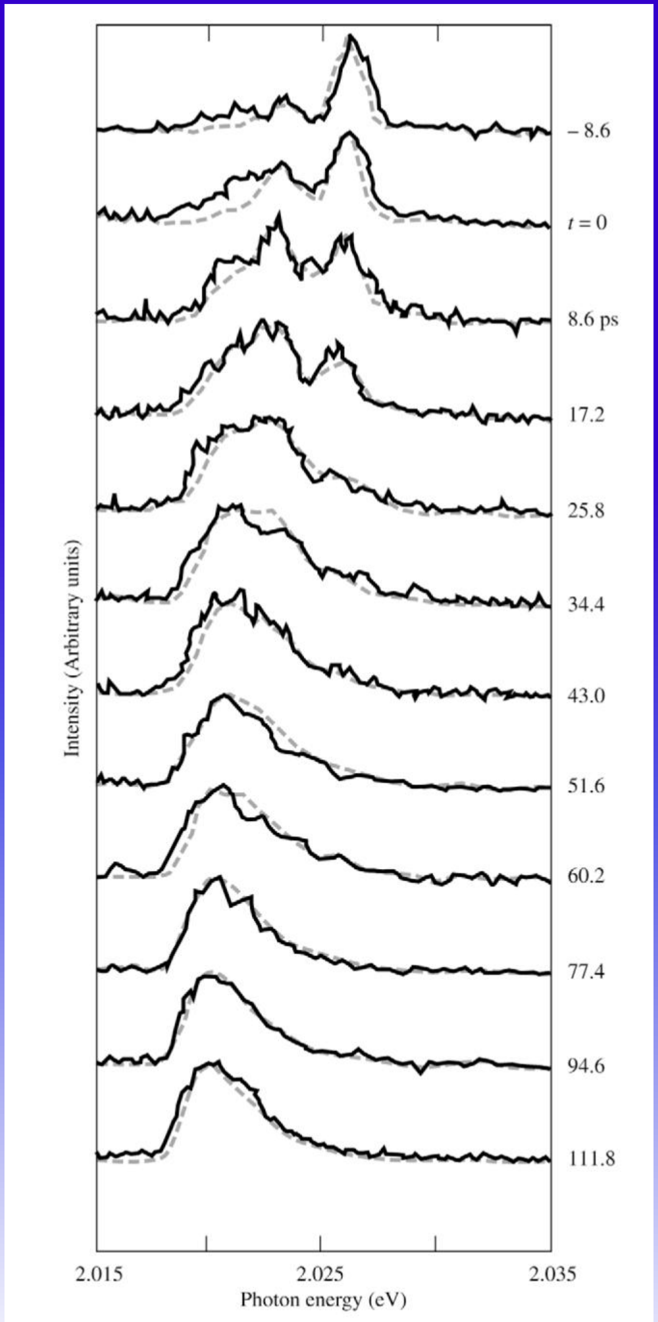
Our approach: Treat entire lower band (polariton $\rightarrow$ exciton) as continuum. Iterate time-resolved equations until equilibrium.

Numerical steady-state solution for occupation number



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

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



comparison of experiment
to theory, for exciton-phonon
scattering in bulk

(ultrafast exciton optics experiments
on picosecond time scale)

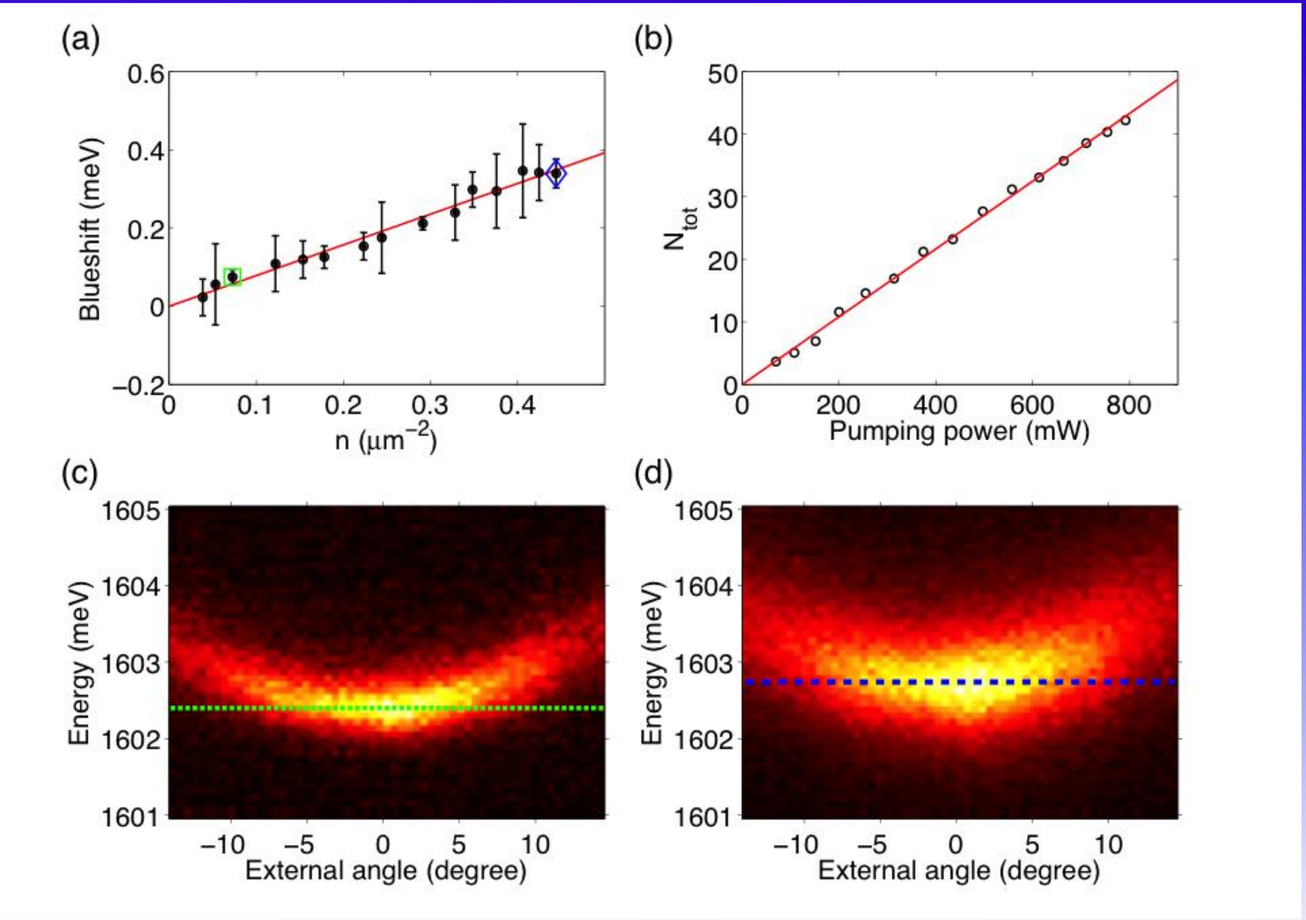
Snoke, Braun, Cardona, PRB (1992)

Interaction blue shift

mean-field theory:

$$\Delta E_k = g\sum_{k'}\langle a_k^+ a_{k'}^+ a_{k'} a_k\rangle \sim gN^2$$

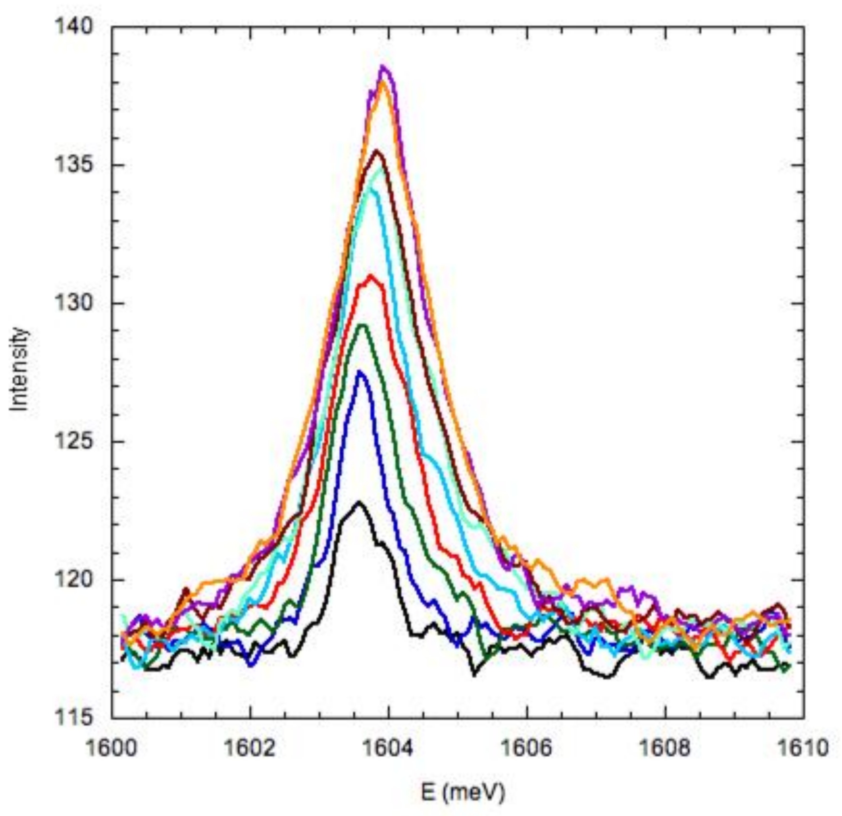
$$\frac{\Delta E_k}{N} \sim gN$$



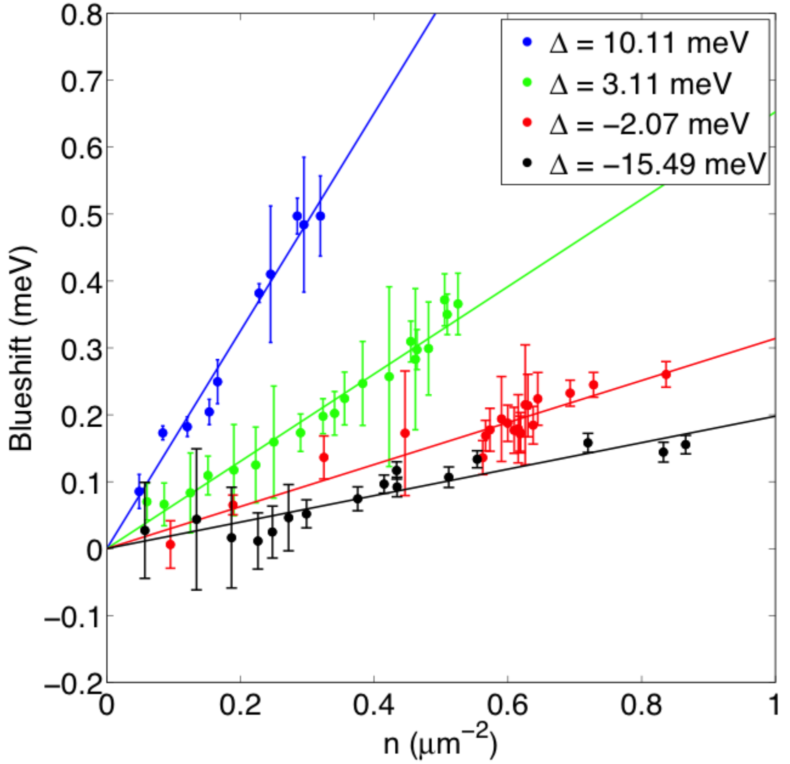
(In general, the spectral shift gives the real self-energy and the spectral width gives the imaginary self-energy.)

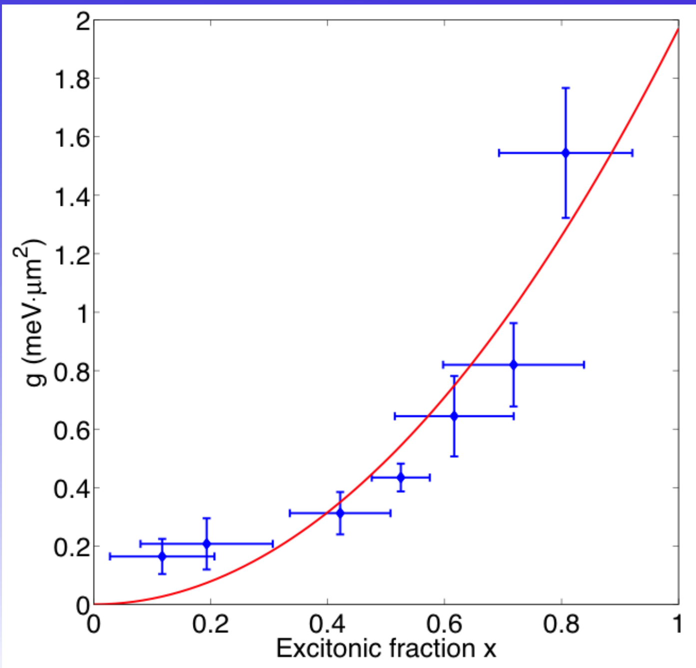
Non-normalized data (excitonic detuning)

Lorentzian shape
at high density
indicates homogeneous
(collisional) broadening



Interaction strength is tunable via exciton fraction



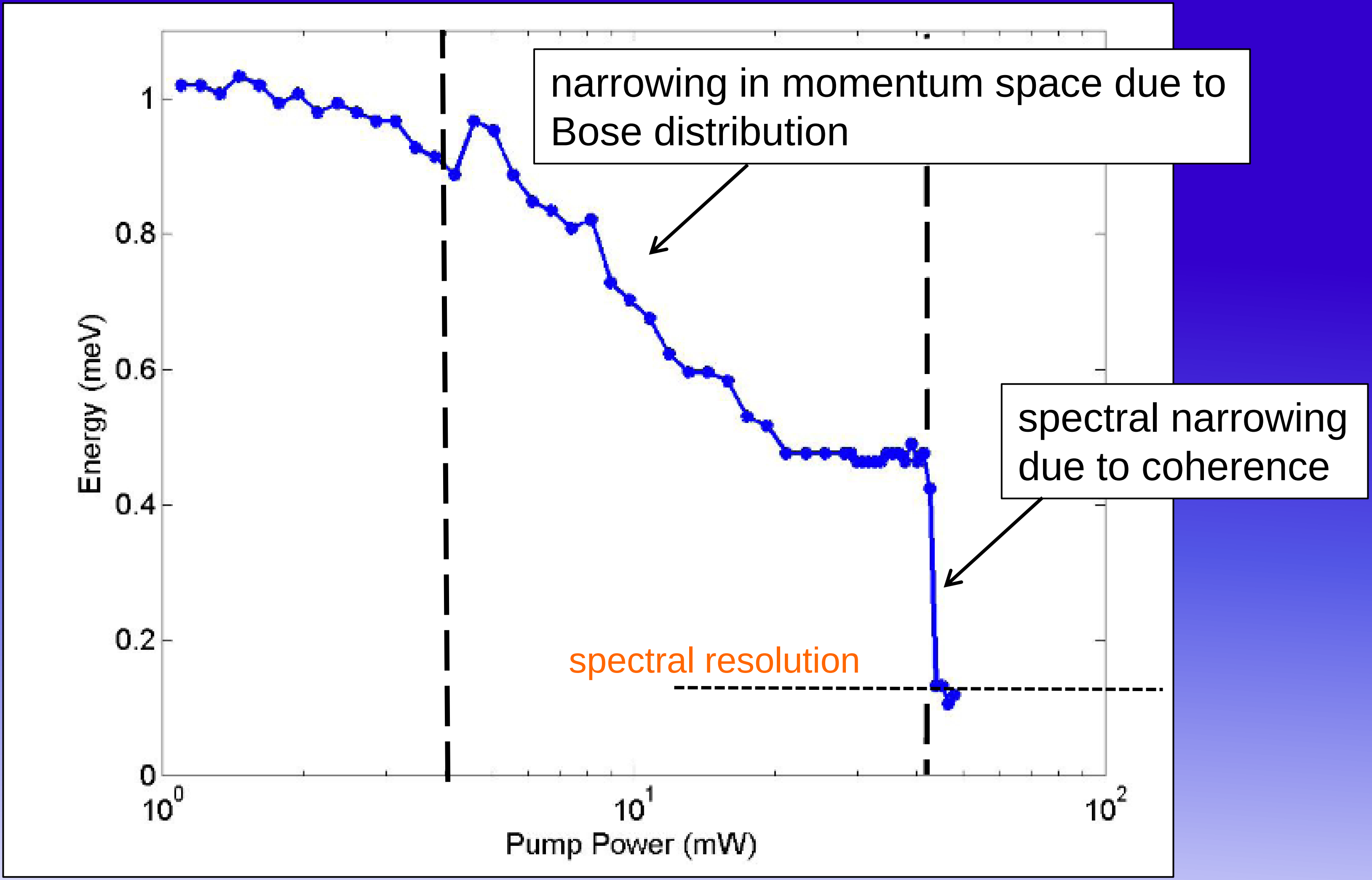


measured value is 100 times stronger than theoretical prediction!

$$\gamma = g/(\hbar^2/2m) \sim 0.1 - 1$$

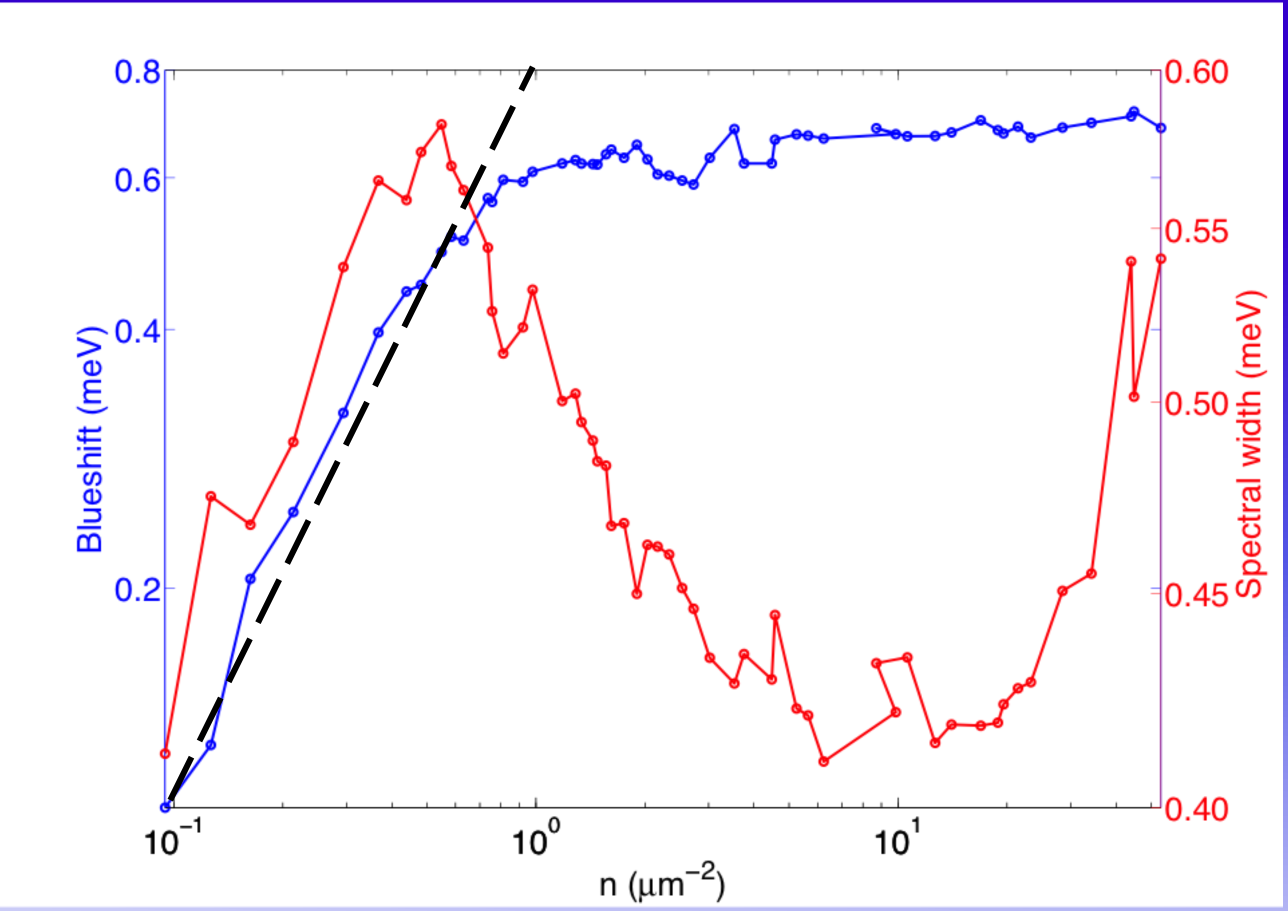
Spectral narrowing at condensation

typical spectral width vs. pump power



Nelson et al., PRX **3**, 041015 (2013)

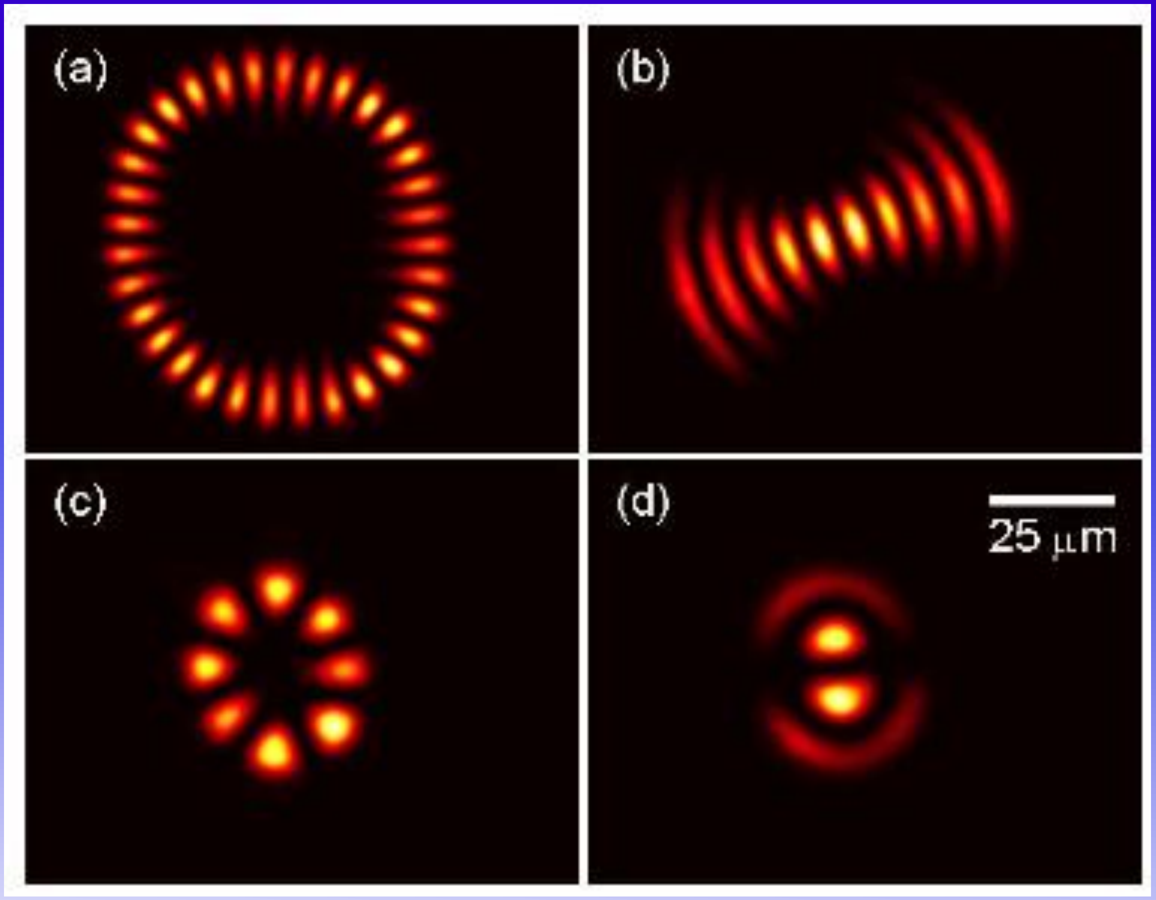
Blue shift saturates at condensation threshold:



polariton number (not pump power) ⟶

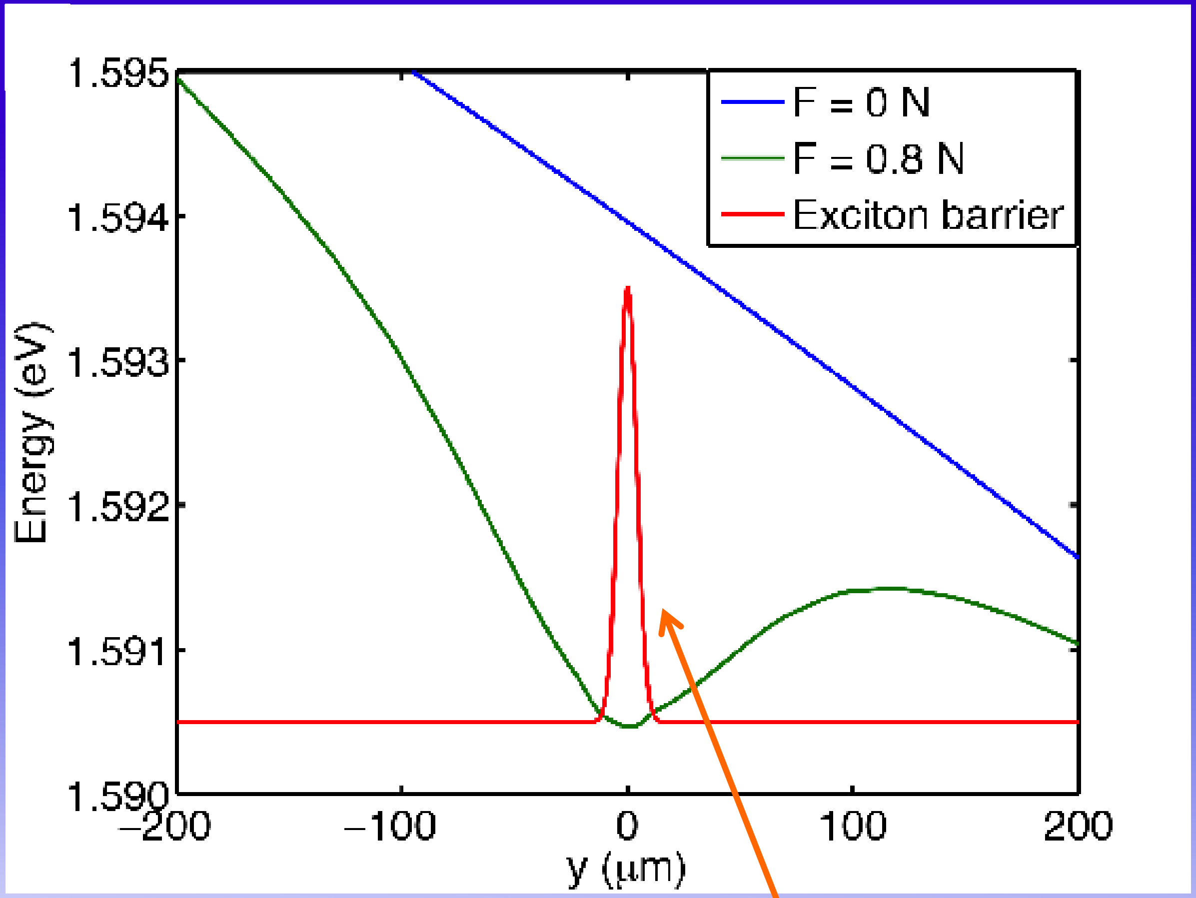
Reduce interaction strength: less thermalization

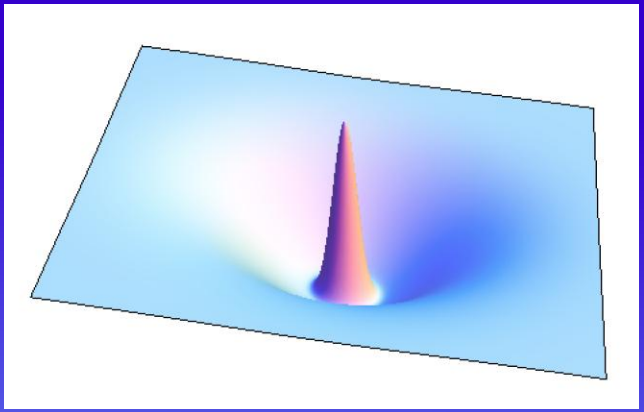
Confined higher-order coherent modes in the trap



(collaboration with MIT Nelson group, Princeton Tureci theory group)

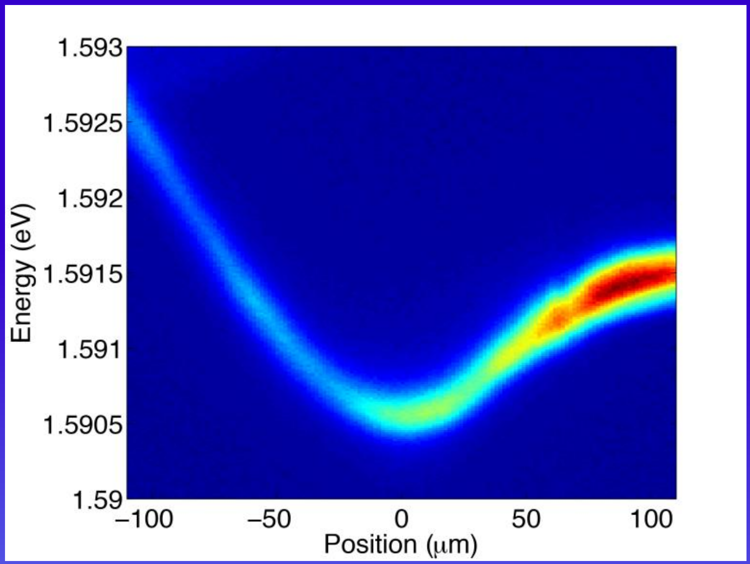
Polariton ring trap



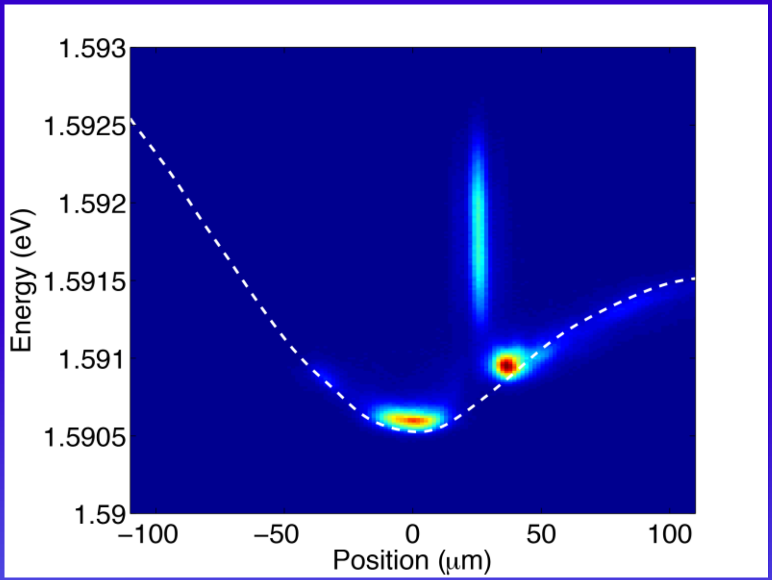


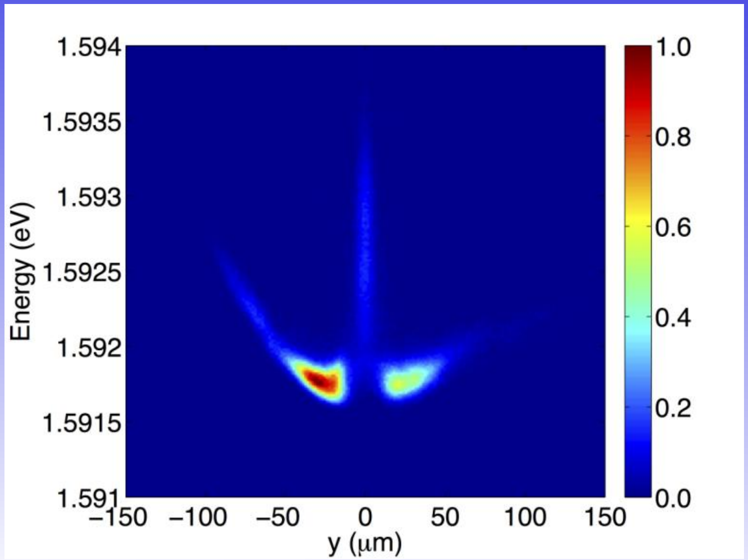
laser-generated barrier (exciton cloud)

Defocused laser



Focused laser, to side



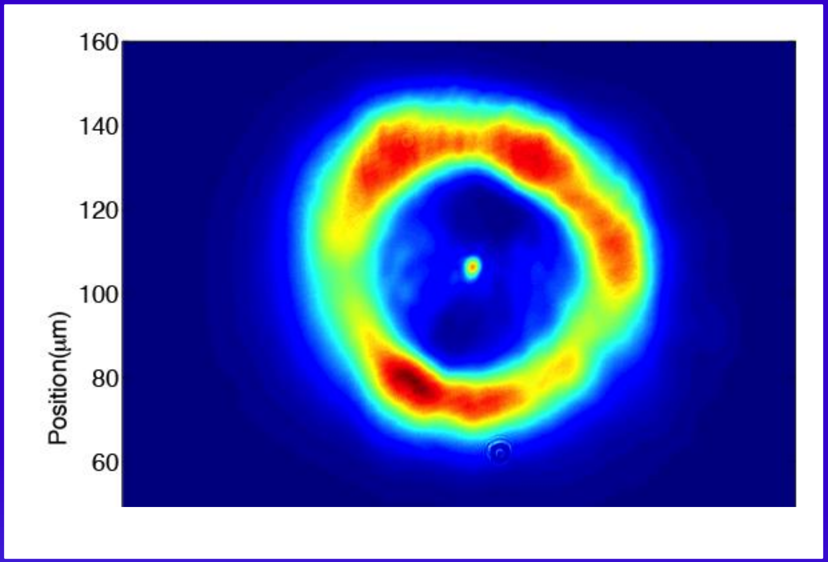


Focused laser, center

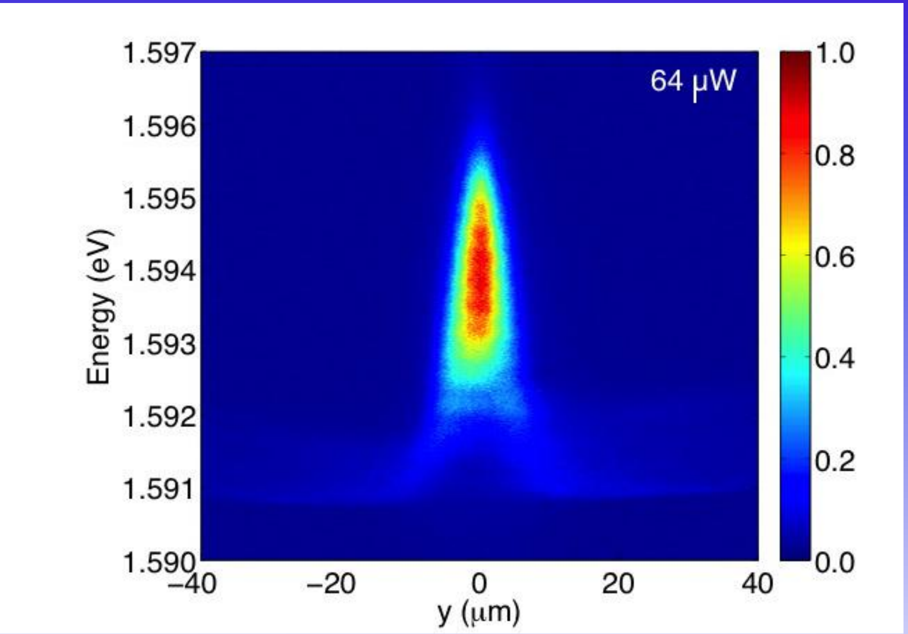
G. Liu et al., PNAS **112**, 2676 (2015)

ring condensate in the trap

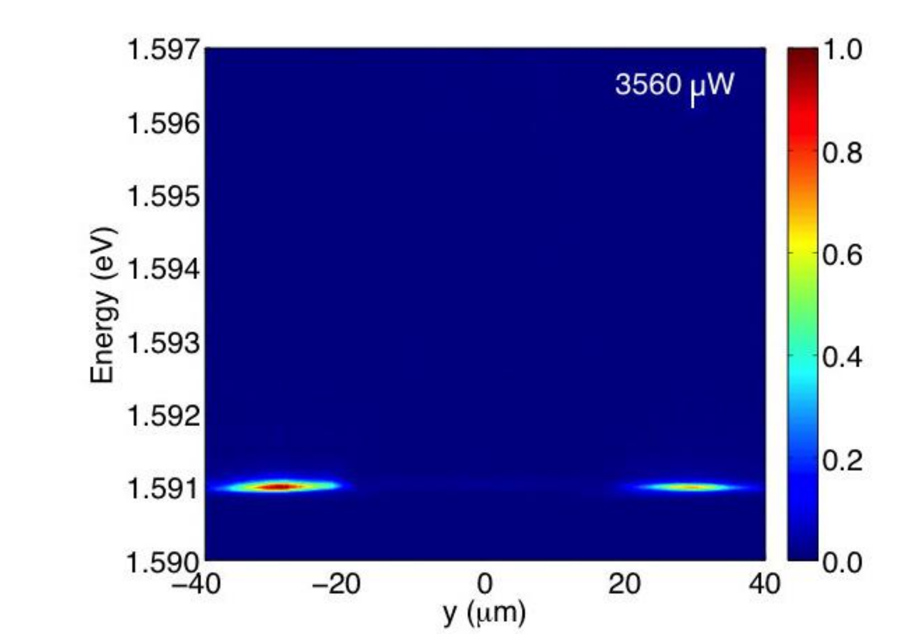
spatial image



energy spectra



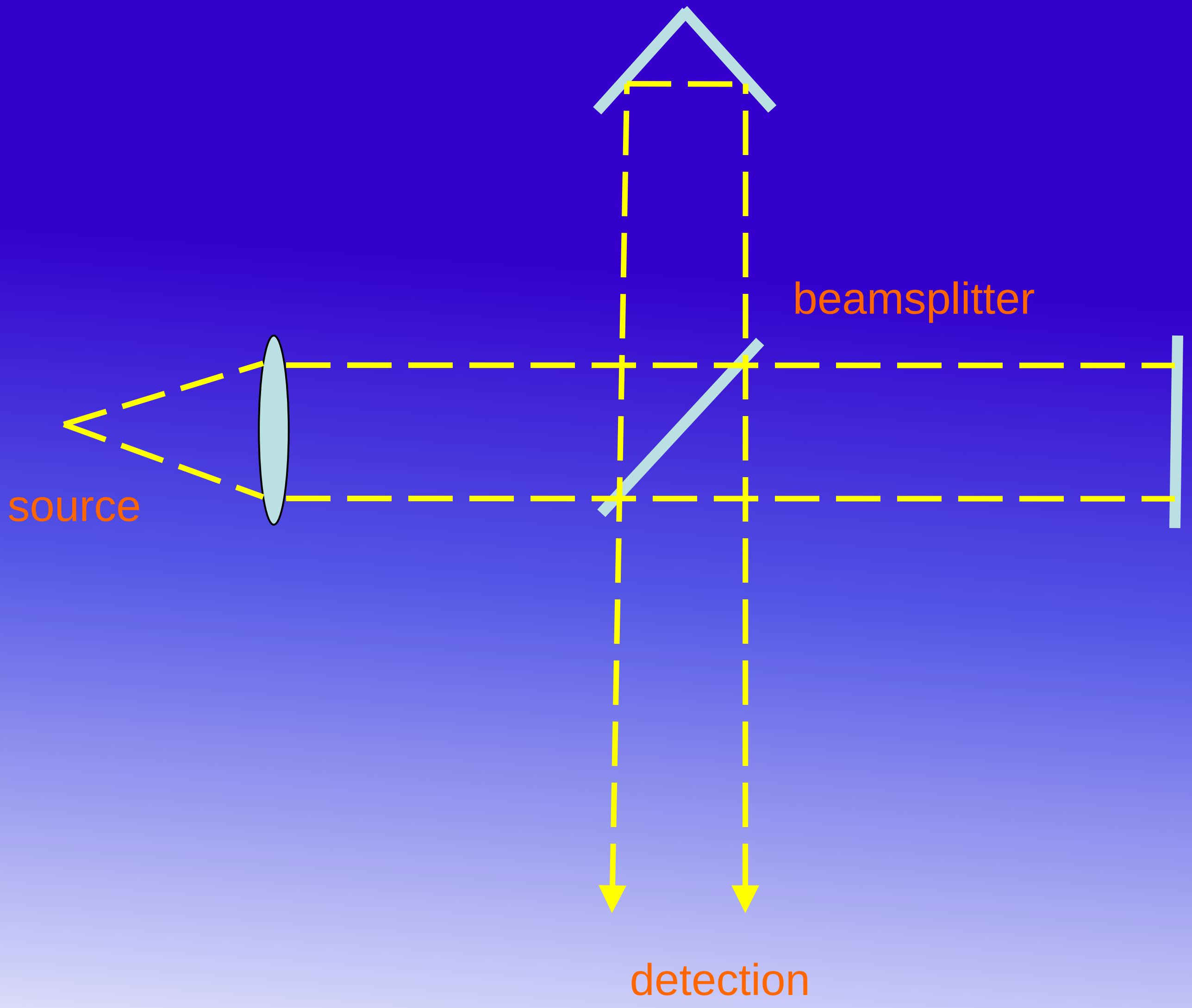
no condensate



condensate

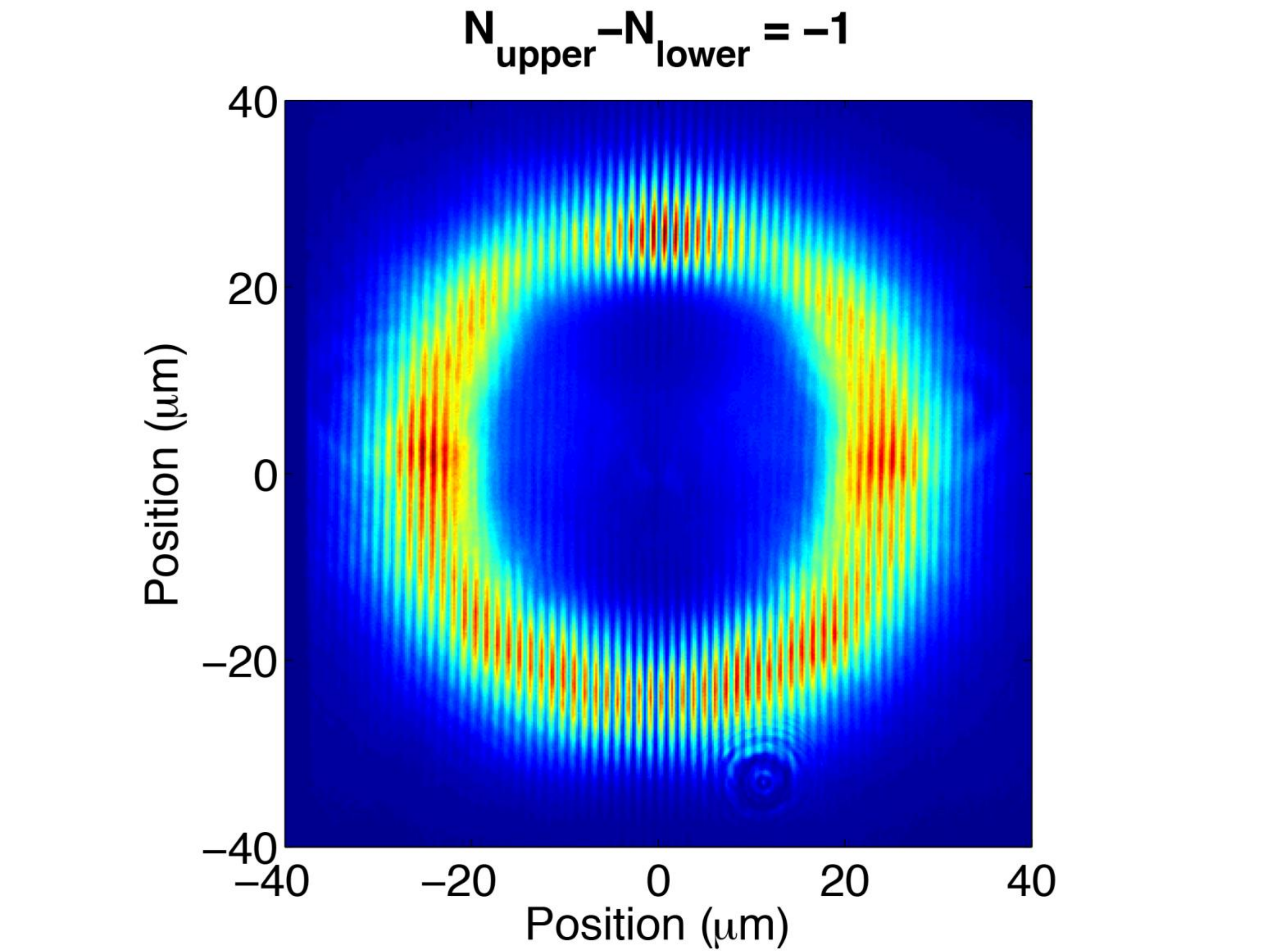
G. Liu et al., PNAS **112**, 2676 (2015)

Direct measure of coherence properties

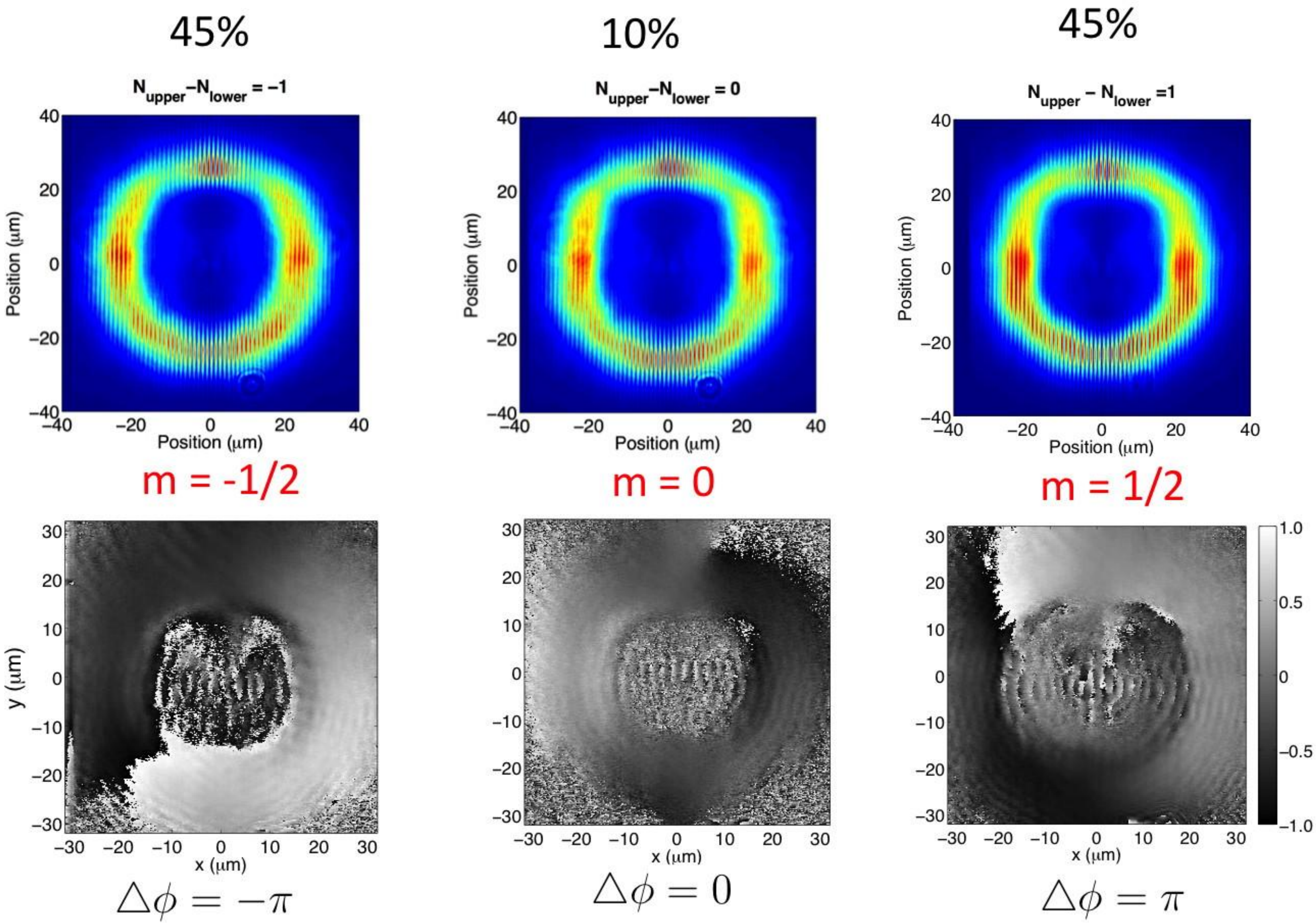


Michelson interferometer with flip of x-axis

Interference patterns- fork in interference shows vorticity



G. Liu et al., PNAS **112**, 2676 (2015)



phase maps extracted from fringe patterns

Half-quantum circulation of polariton condensate

The polariton gas is spinor fluid: the wave function has two polarization components;

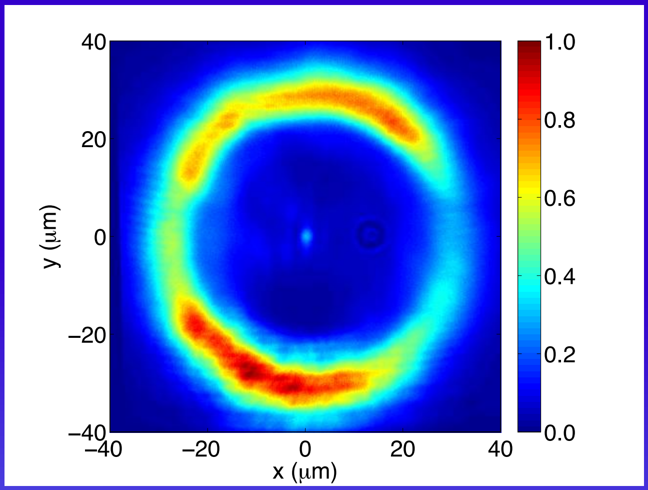
$$\psi(\vec{r}) = \{\psi_x(\vec{r}), \psi_y(\vec{r})\} = \sqrt{\rho(\vec{r})}e^{i\theta(\vec{r})}\{cos(\eta), sin(\eta)\}$$

2π phase continuity condition made up by π phase change of flow, plus π rotation of polarization

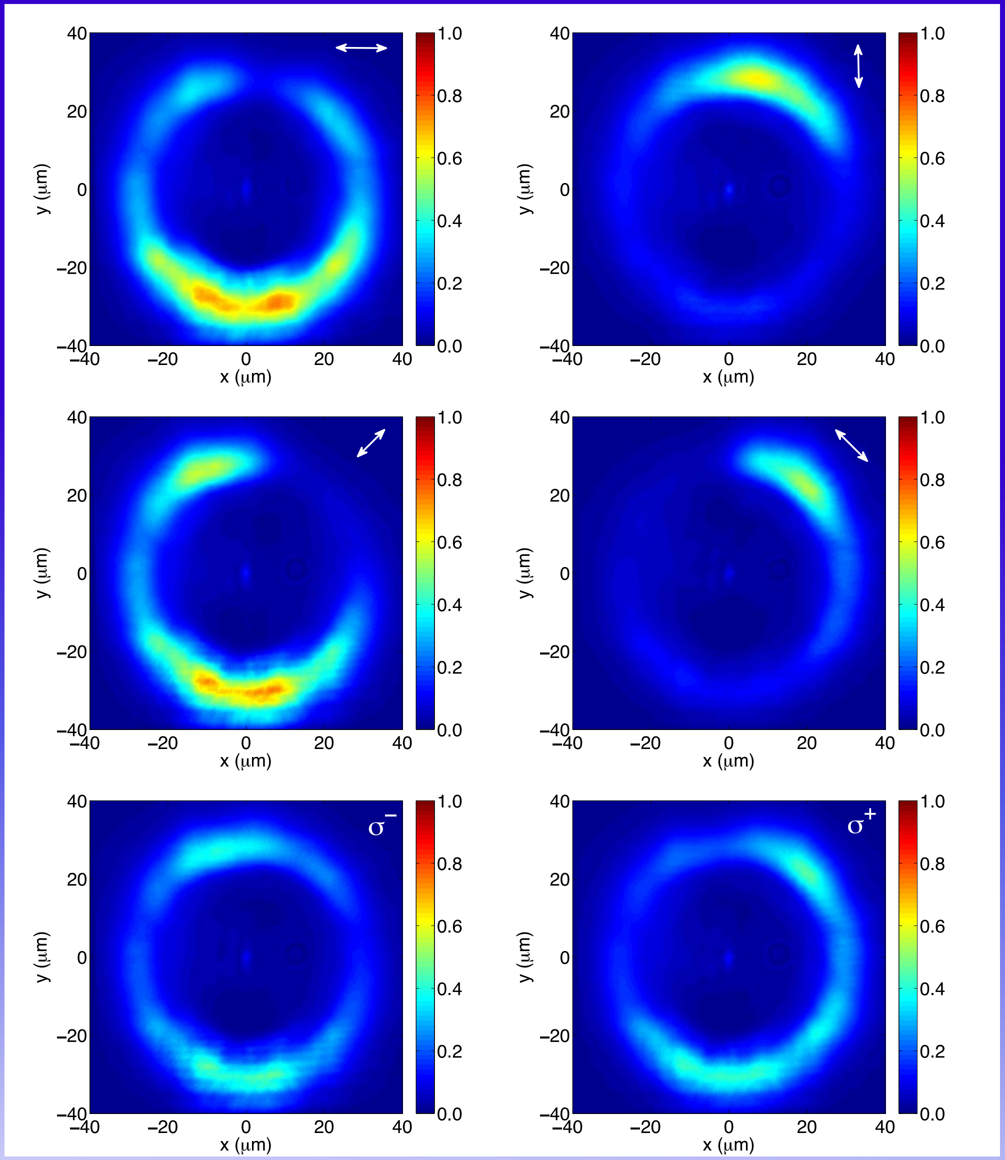
Y. Rubo, Phys. Rev. Lett. **99**, 106401 (2007)
M. C. Cross and W. F. Brinkman, J. Low Temp. Phys. **27**, (1976).

Polarization profile

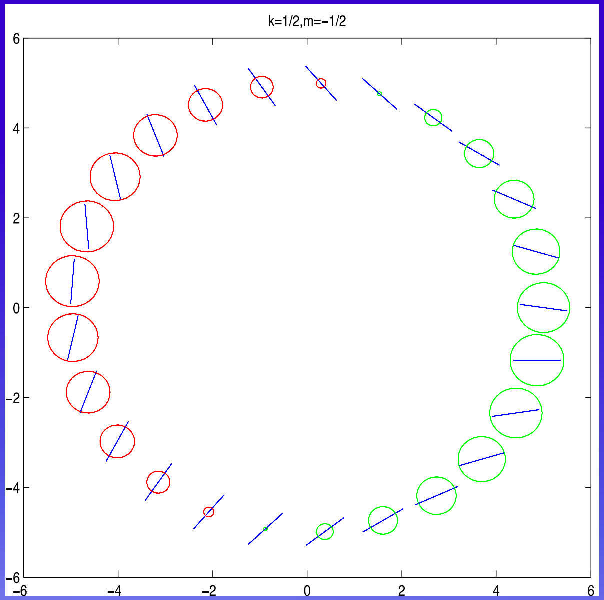
No polarizer



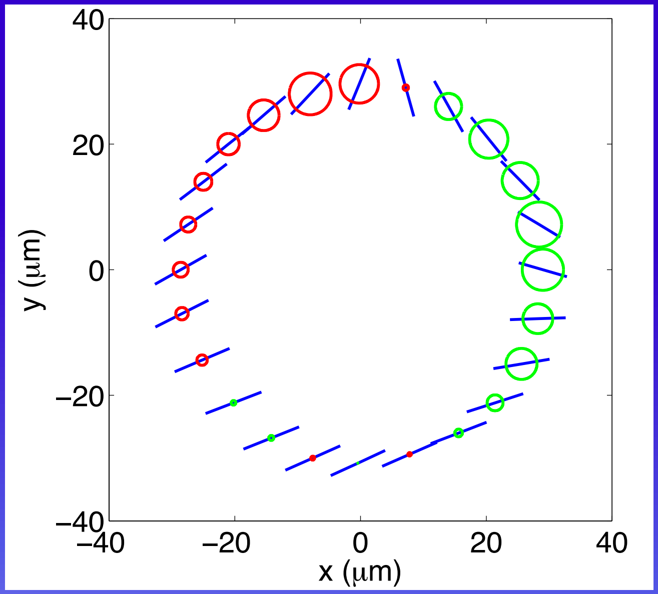
polarization resolved images



Polarization map consistent with half quantum circulation:



Theory



Experiment

Wave function that reproduces our experiment result (A. Daley):

$$\vec{\psi}_{k,m}(\theta) = \sqrt{n(\theta)}e^{im\theta}\left[f\begin{pmatrix}\cos(k\theta)\\ \sin(k\theta)\end{pmatrix} + i\,\mathrm{sgn}(km)\sqrt{1-f^2}\begin{pmatrix}\sin(k\theta)\\ \cos(k\theta)\end{pmatrix}\right]$$

What's the difference from a laser?

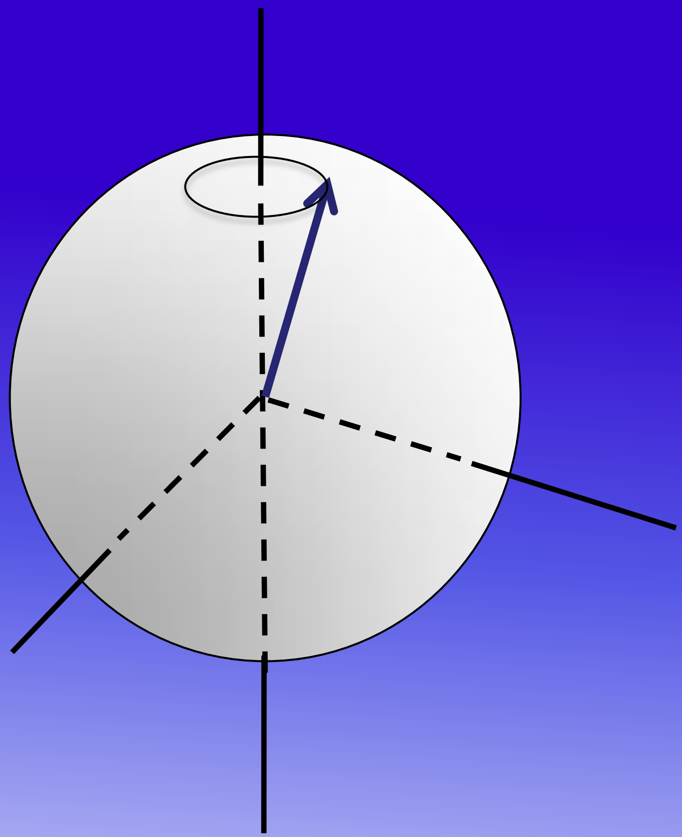
- superficially, looks similar: mirrors, optical pumping, coherent light emission

- strong coupling gives strong nonlinearity, which gives strong inter-mode coupling in continuum of modes

- inter-mode coupling (thermalization of modes), rather than gain, stabilizes the state:

  no need for inversion, and in fact, inversion destroys the condensate!

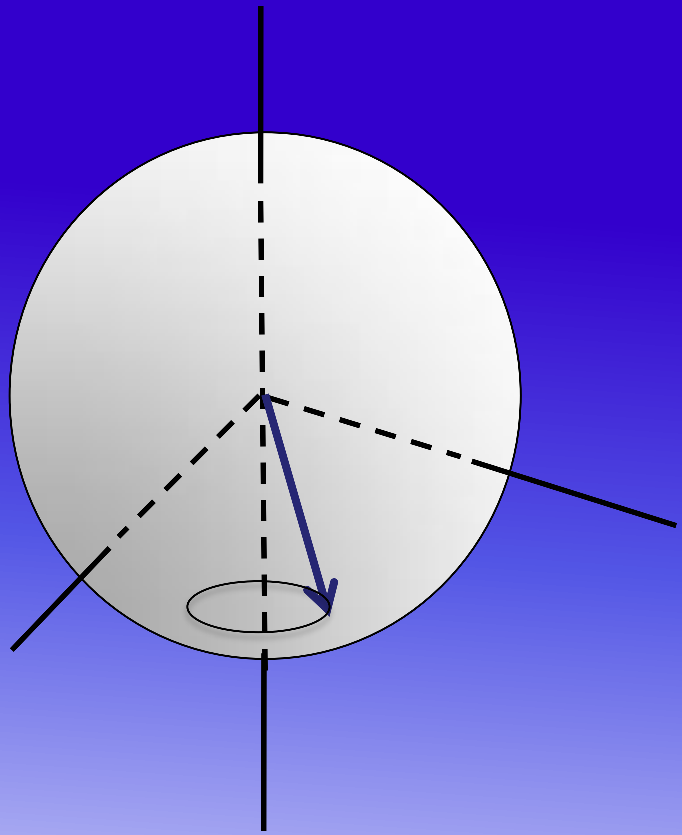
Bloch sphere picture



standard laser with inversion

spontaneous symmetry breaking
gives exact phase of oscillation

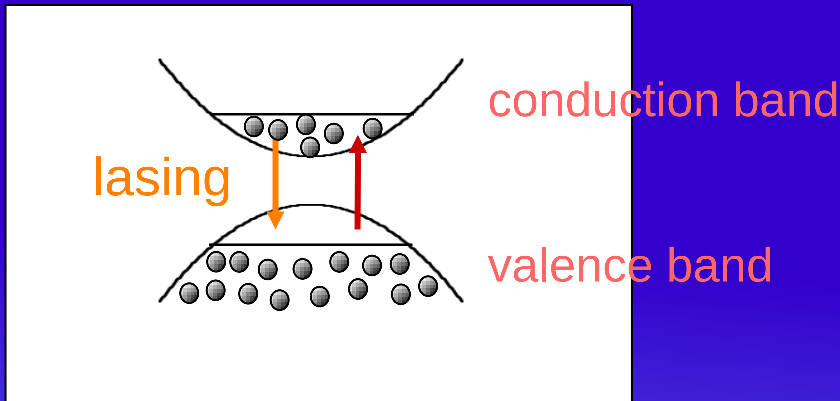
Bloch sphere picture



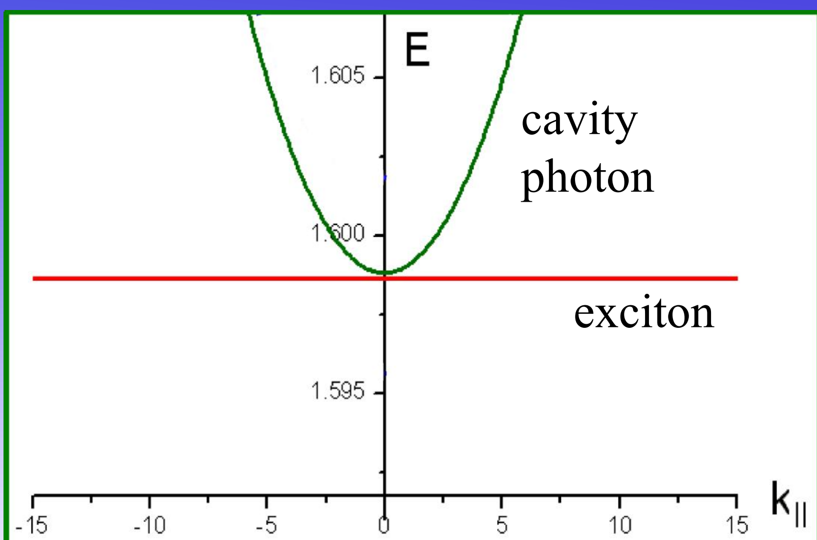
polariton condensate

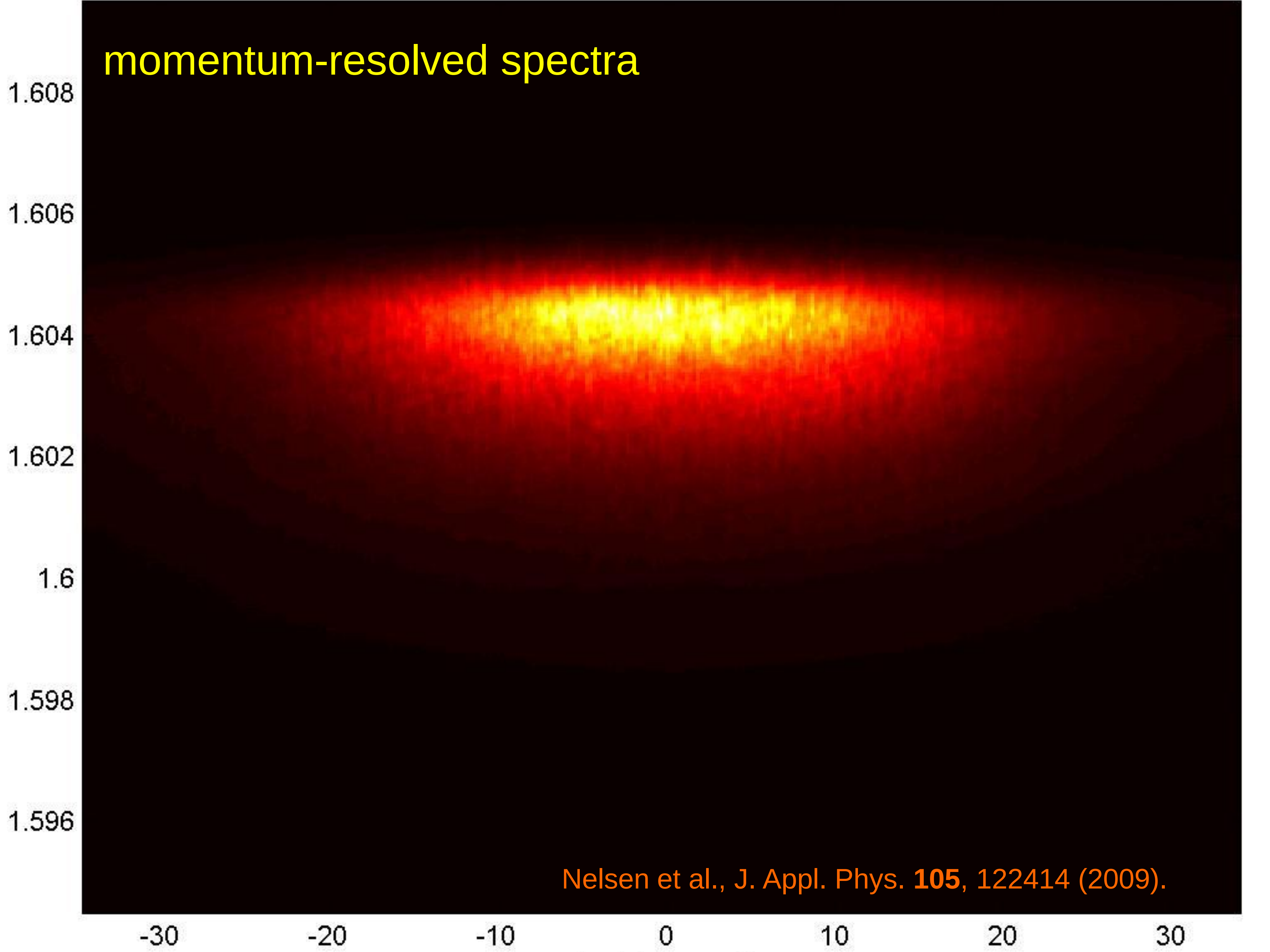
coherent oscillation without inversion

Transition between polariton BEC and lasing



Weak coupling turns off Rabi splitting




momentum-resolved spectra
1.608
1.606
1.604
1.602
1.6
1.598
1.596
-30
-20
-10
0
10
20
30
Nelsen et al., J. Appl. Phys. 105, 122414 (2009).

Conclusions

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

- We have many ways now to control the potential: ring traps, lattices, wires, etc.

- Long-distance propagation is now possible, allowing macroscopic coherent effects

- We can move between nonequilibrium behavior and nearly-equilibrated by tuning the interactions

Can move from weakly interacting to strongly interacting regimes