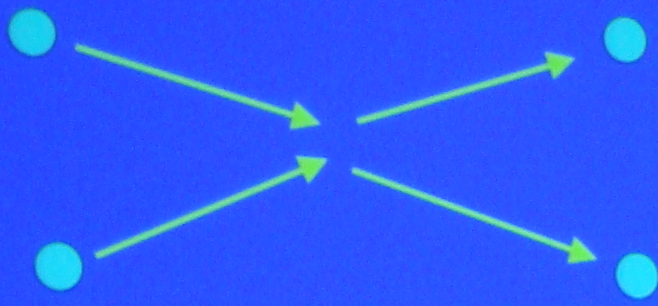
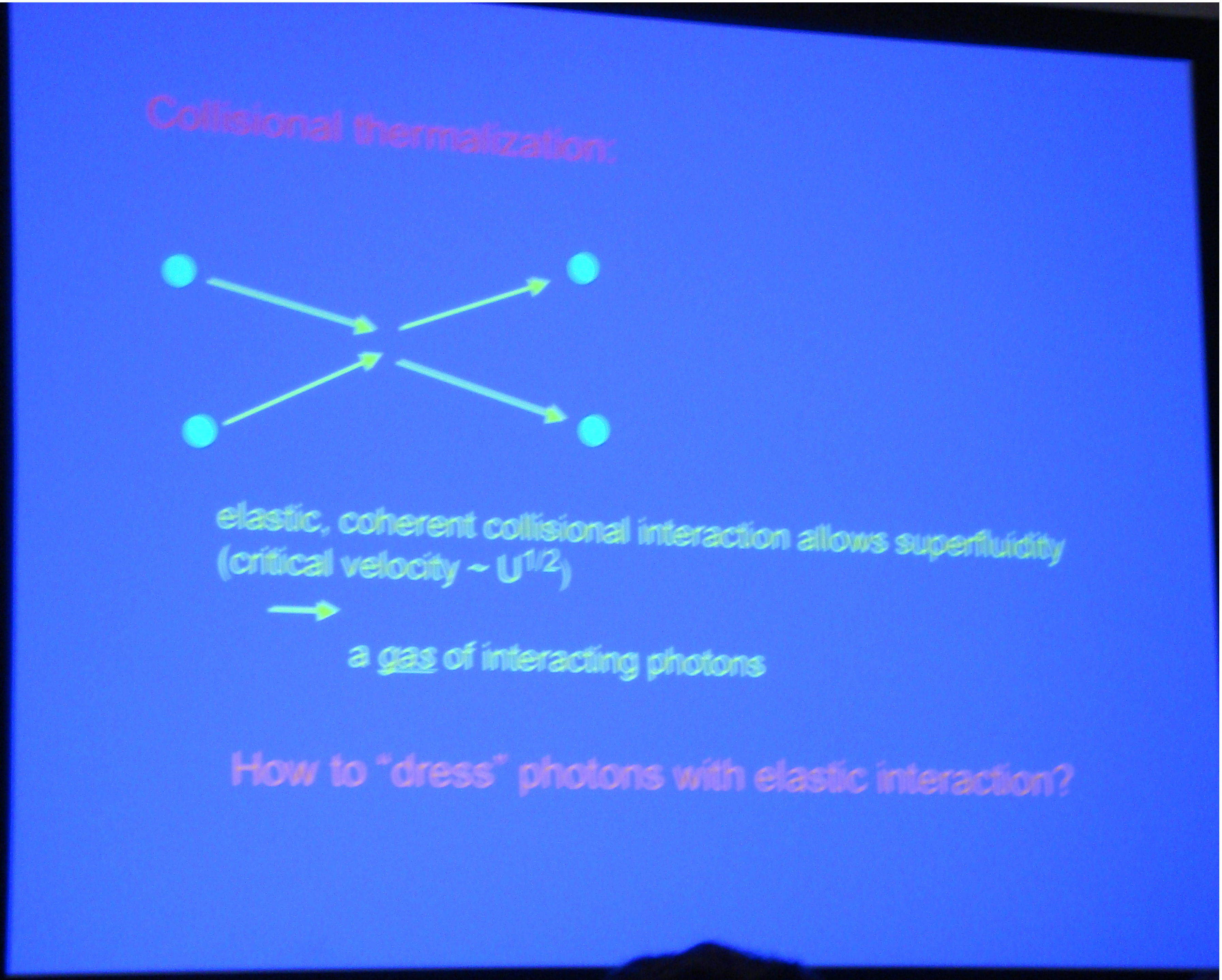
Collisional thermalization:



elastic, coherent collisional interaction allows superfluidity
(critical velocity ~ $U^{1/2}$)

→

a *gas* of interacting photons



Collisional thermalization:

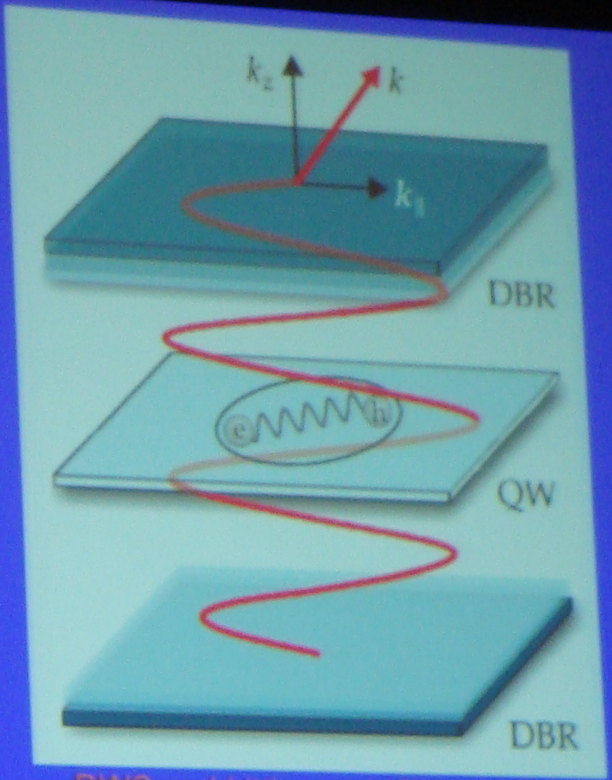
elastic, coherent collisional interaction allows superfluidity (critical velocity ~ $U^{1/2}$)

→

a gas of interacting photons

How to "dress" photons with elastic interaction?

Cavity Polaritons



DWS and Littlewood, *Physics Today*, August 2010.

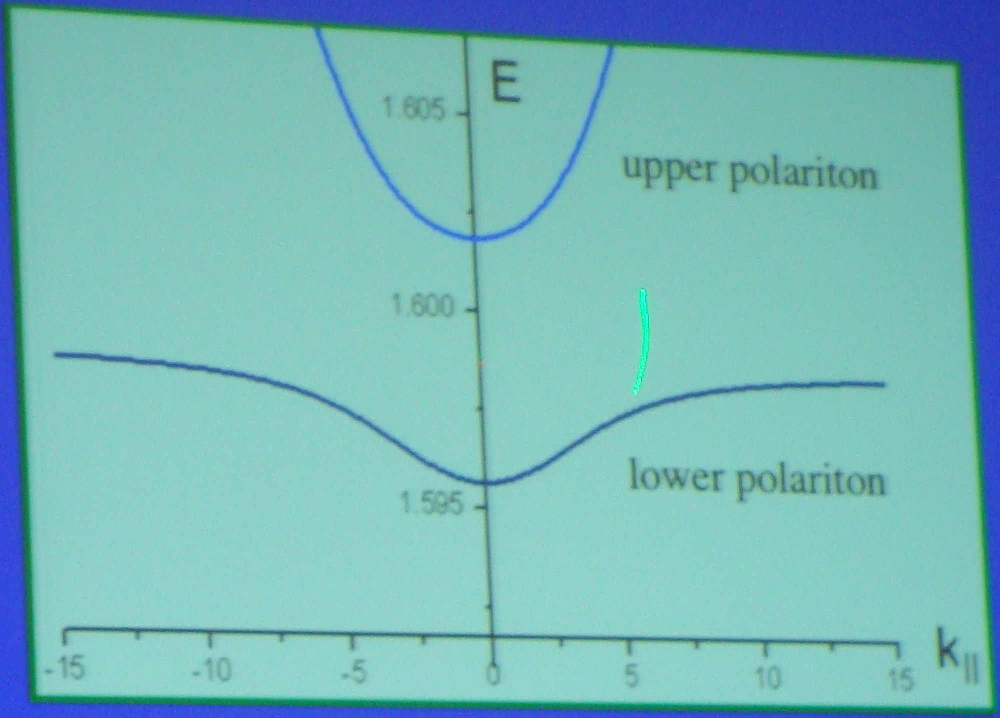
cavity photon:

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

quantum well exciton:

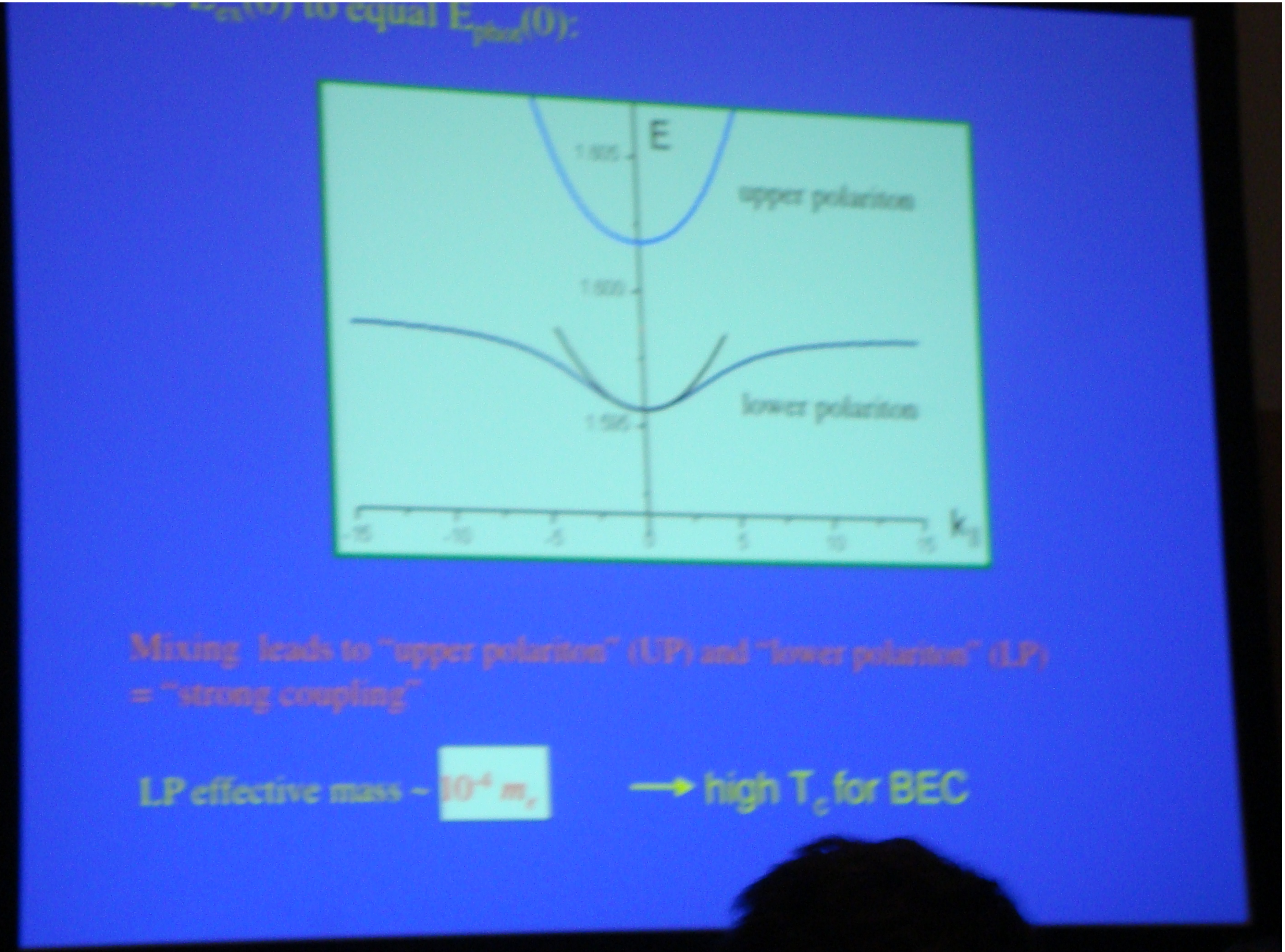
$$E = E_{gap} - \Delta_{bind} + \frac{h^2 N^2}{2m_r(2L)^2} + \frac{\hbar^2 k_{||}^2}{2m} \quad \approx \text{const. near } k_{||}=0$$

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



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

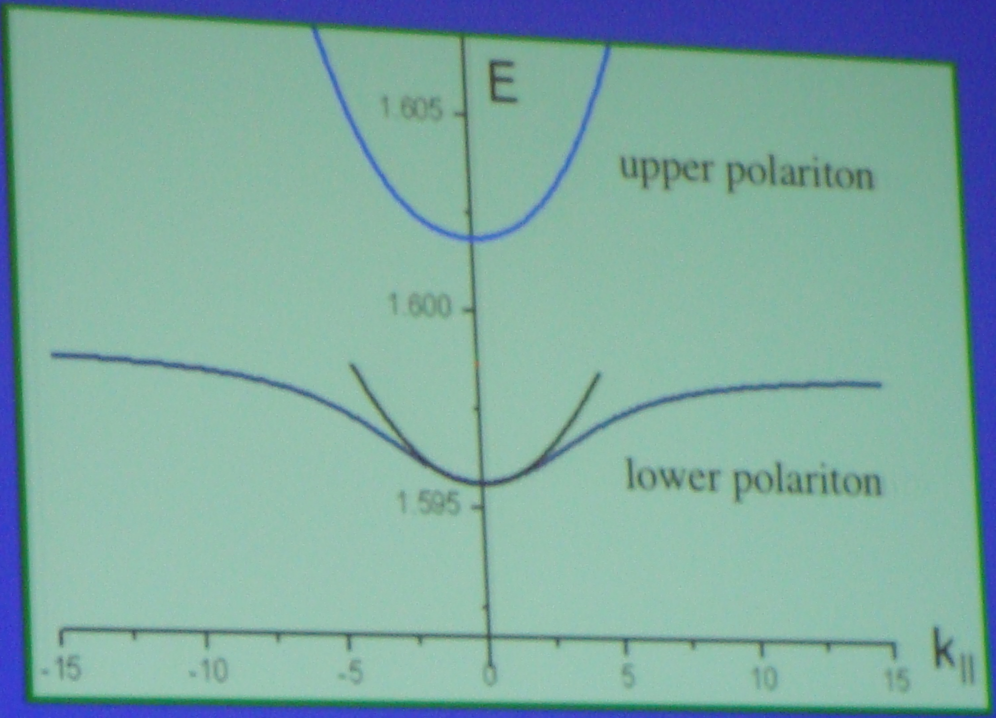
$E_{ex}(0)$ to equal $E_{phot}(0)$:



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

LP effective mass ~ $\boxed{10^{-4}\,m_e}$ → high T_c for BEC

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



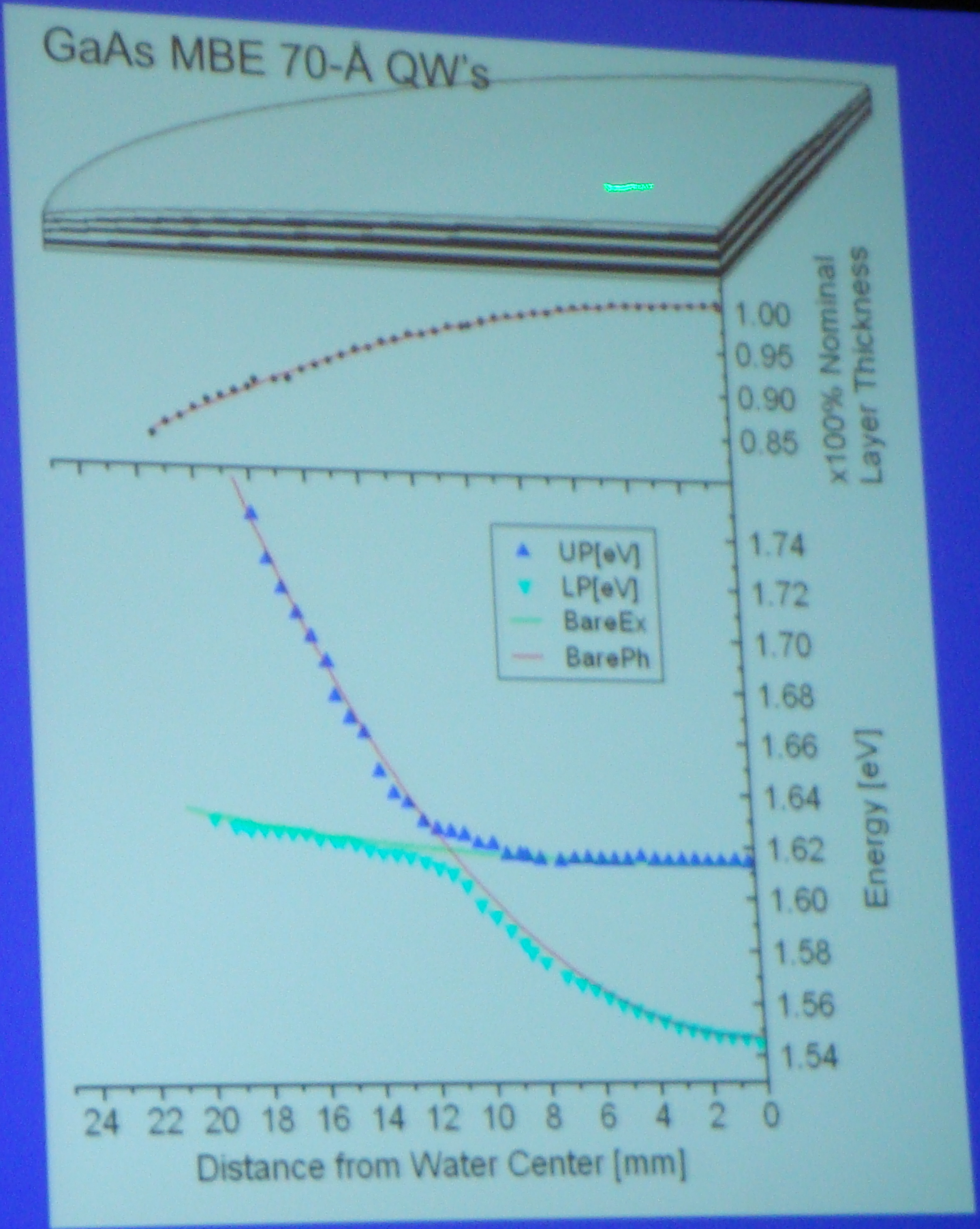
Mixing leads to "upper polariton" (UP) and "lower polariton" (LP) = "strong coupling"

LP effective mass ~ $10^{-4}\, m_e$ → high T_c for BEC

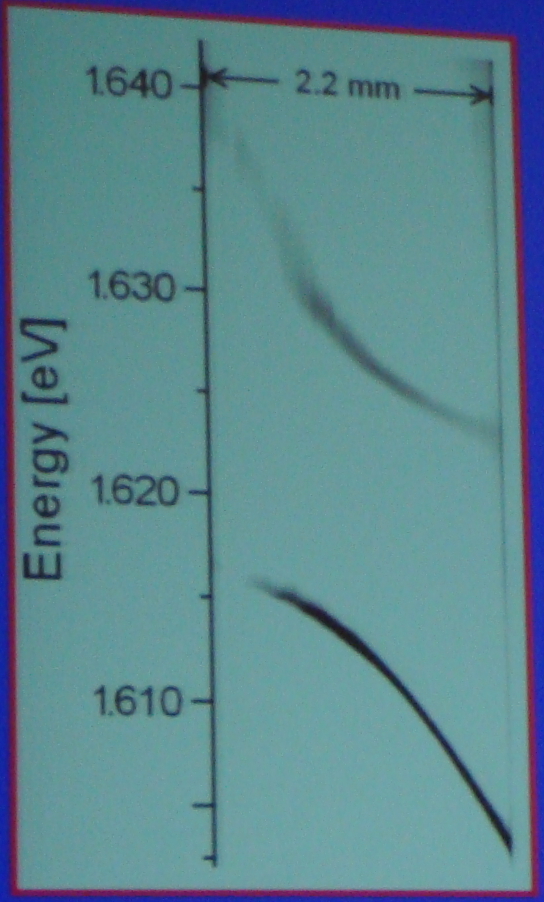
Particle-particle interaction ~ hard core with radius a_B of exciton

Typical wafer properties

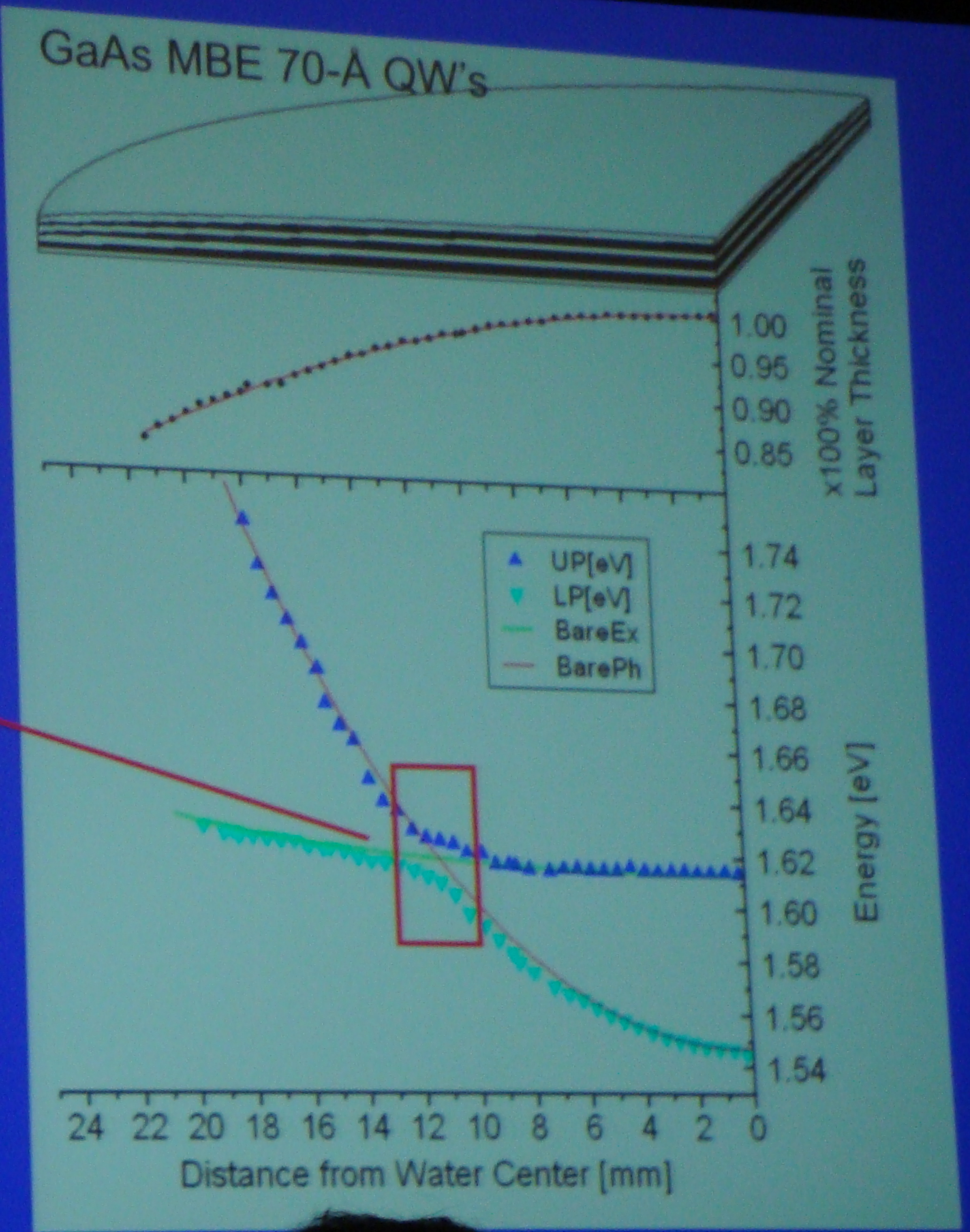
- Wedge in the layer thickness
- Cavity photon shifts in energy due layer thickness

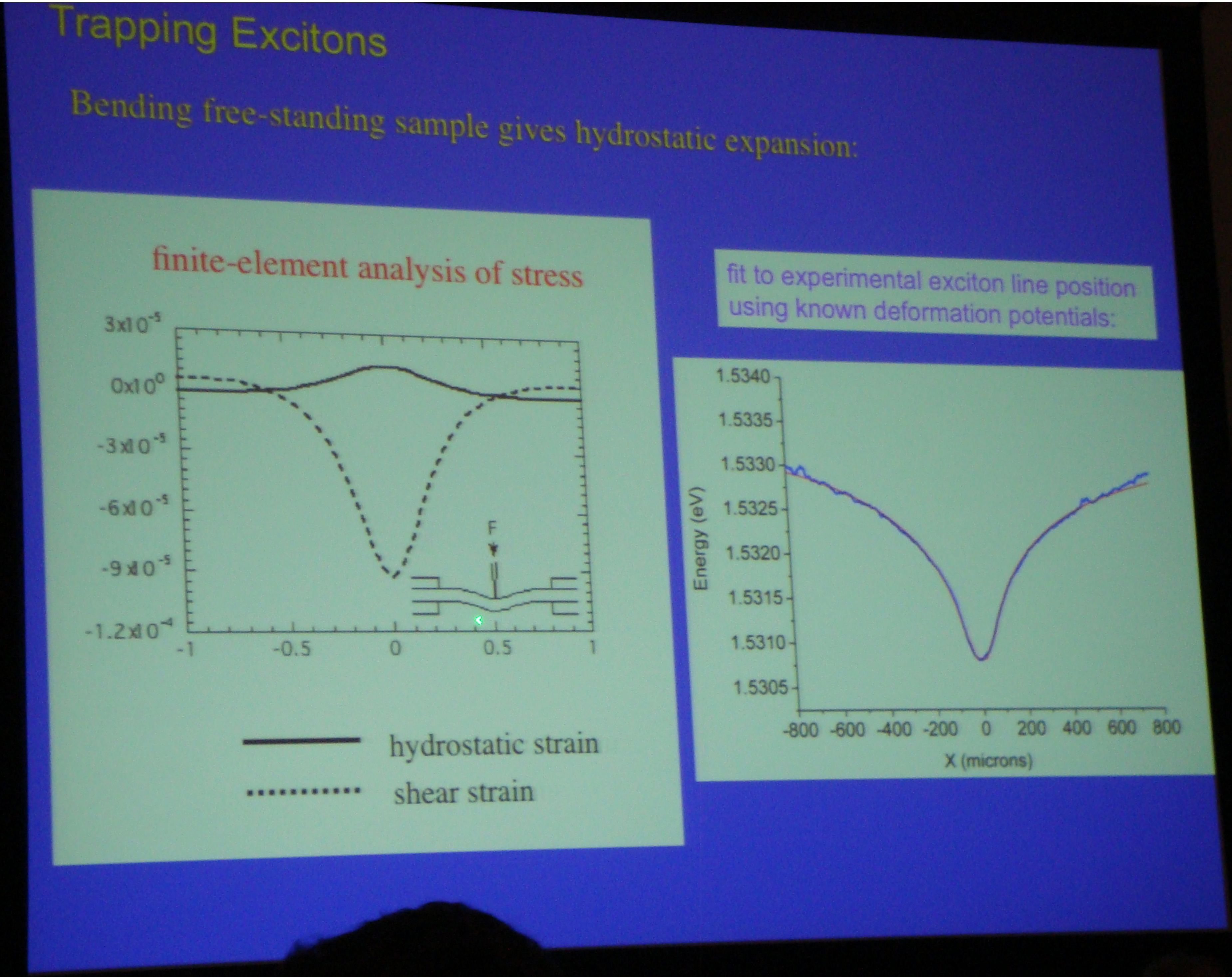


Typical wafer properties



Reflectivity spectrum around point of strong coupling





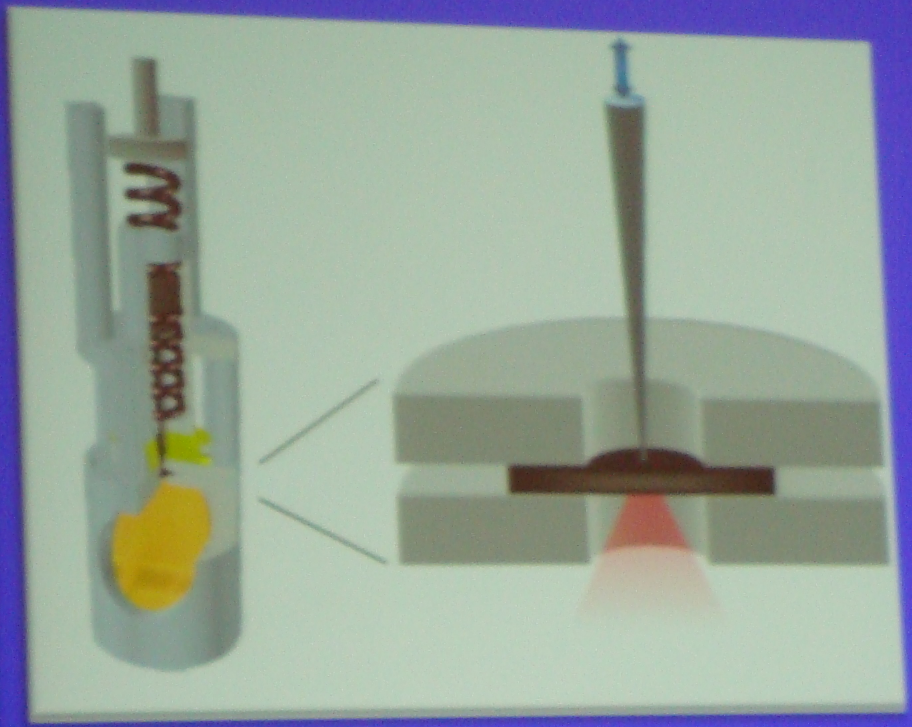
Trapping Excitons

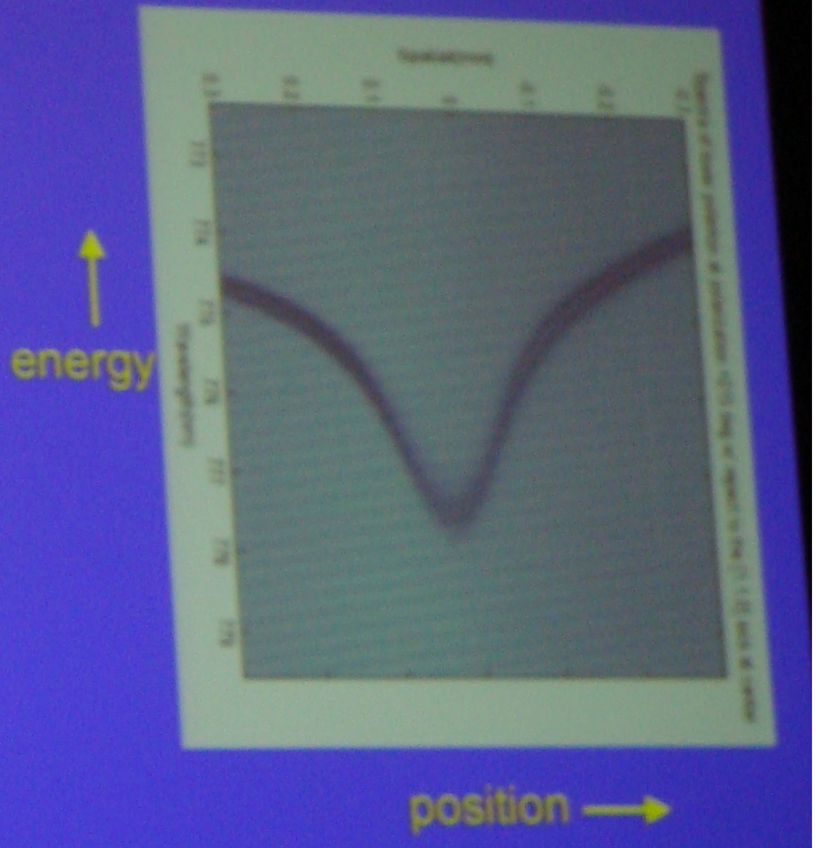
Bending free-standing sample gives hydrostatic expansion:

finite-element analysis of stress

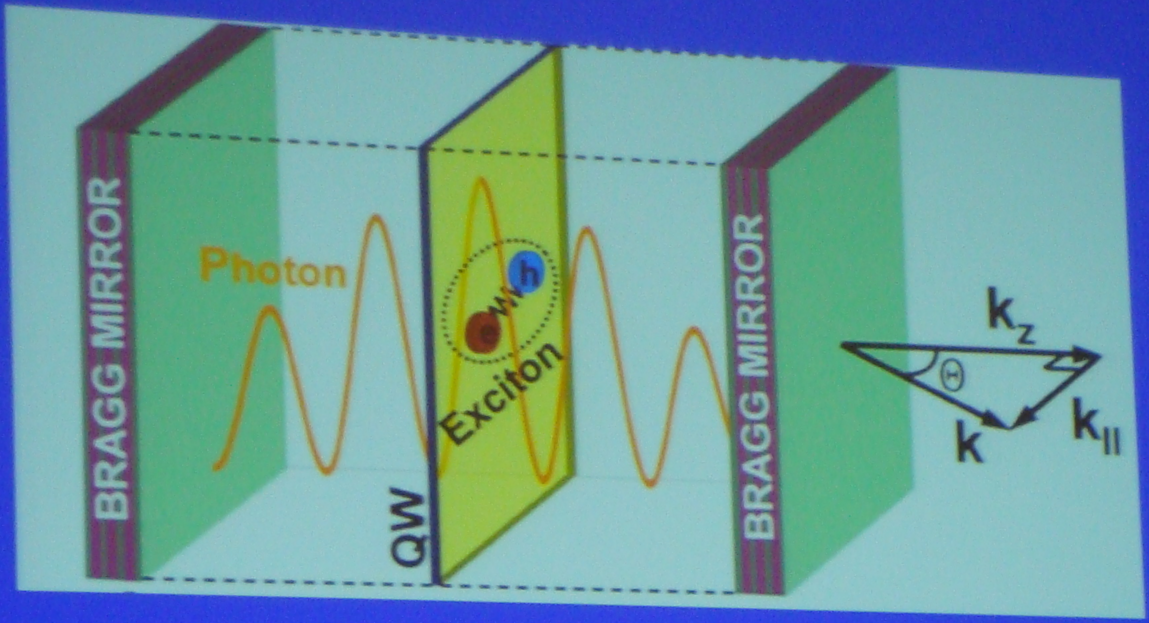
fit to experimental exciton line position using known deformation potentials:

Experimental trapping of polaritons using stress

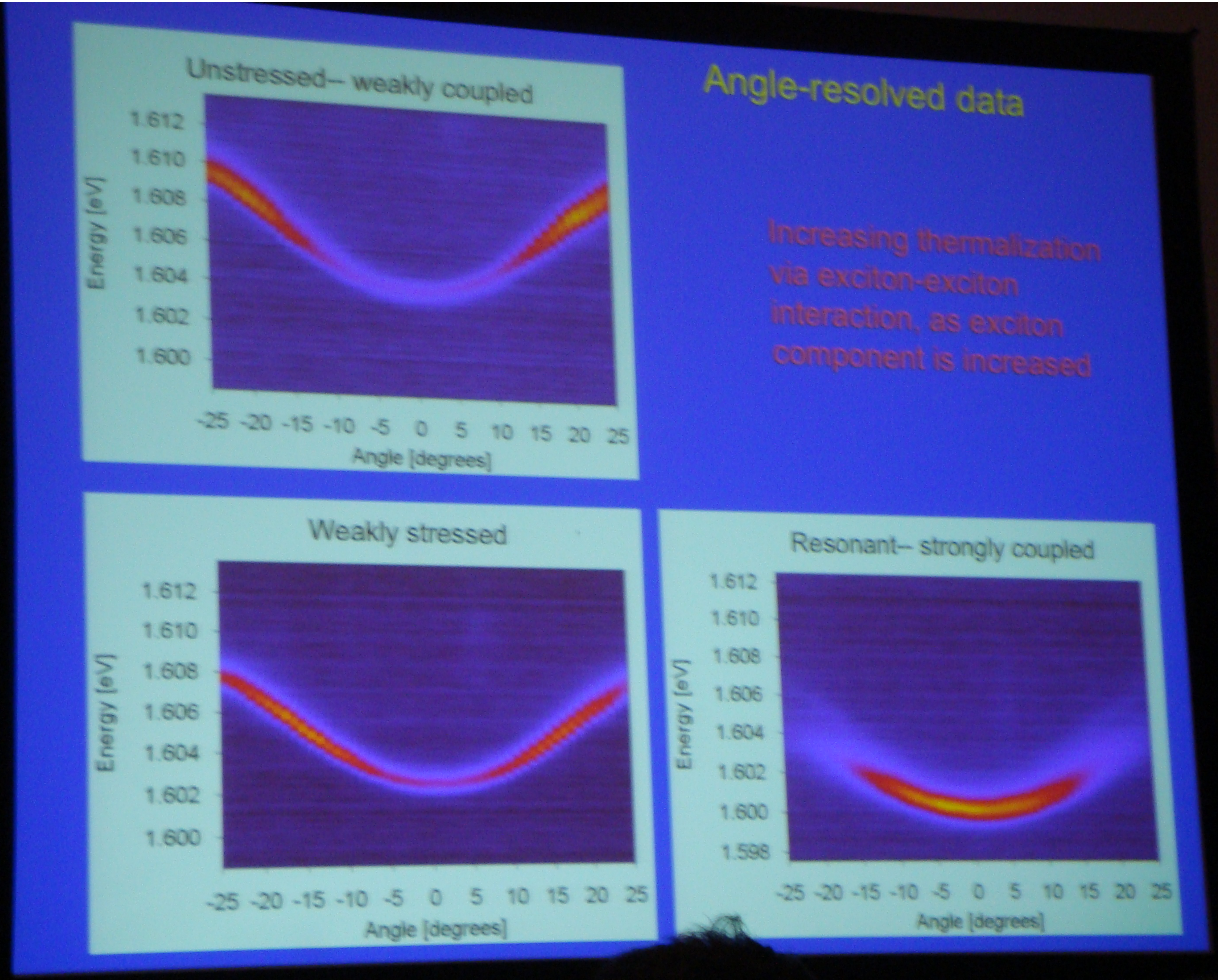




Angle-resolved data gives momentum distribution



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



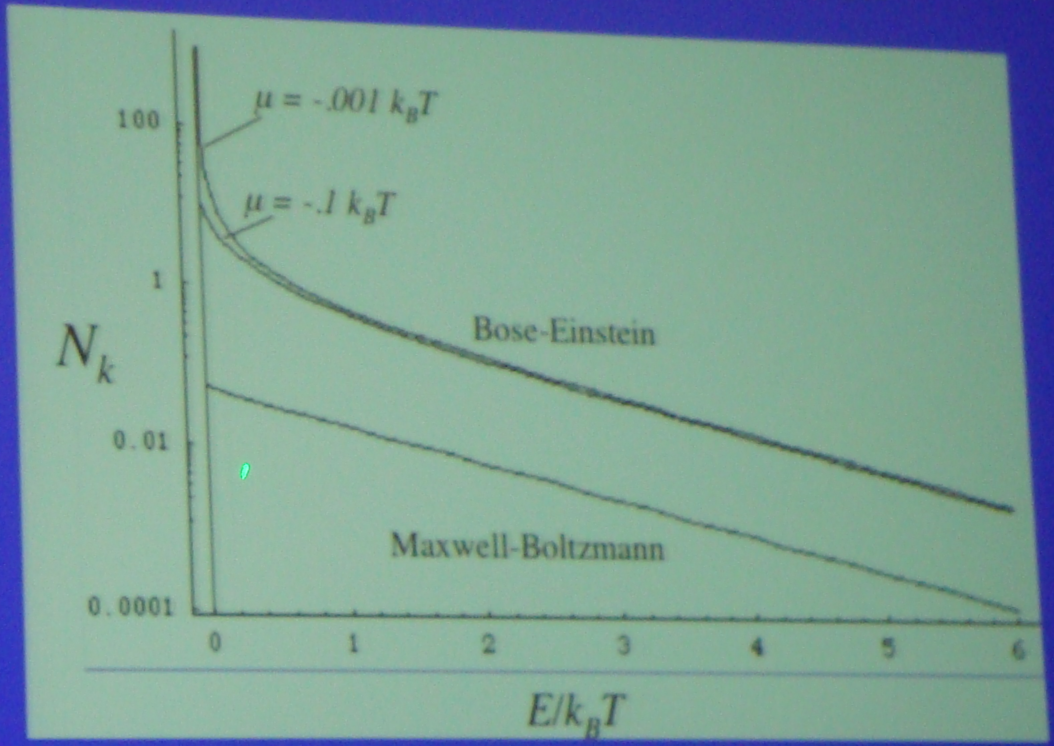
Angle-resolved data

Increasing thermalization via exciton-exciton interaction, as exciton component is increased

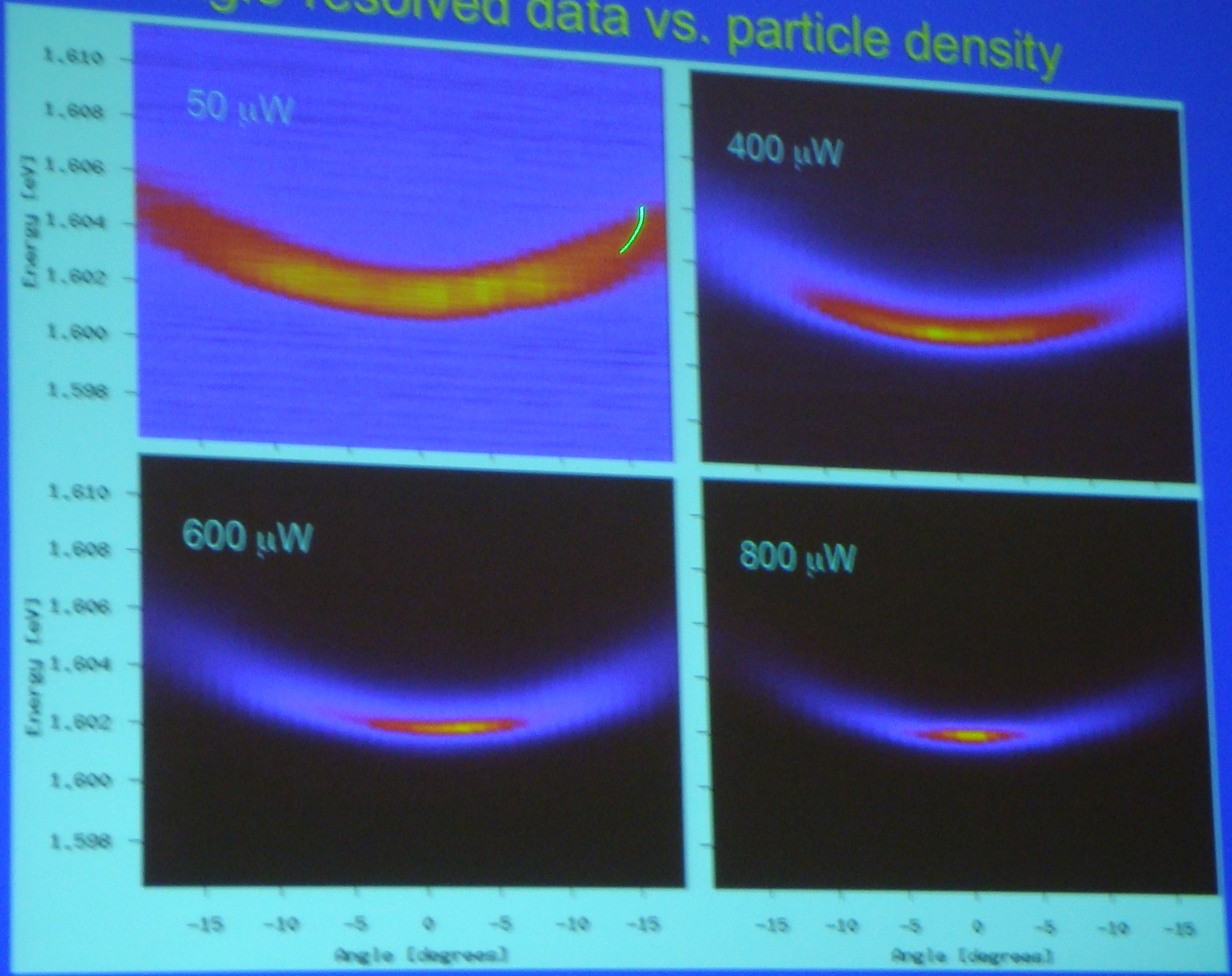
II. Review of Bose Condensation Experiments

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

Ideal equilibrium Bose-Einstein distribution

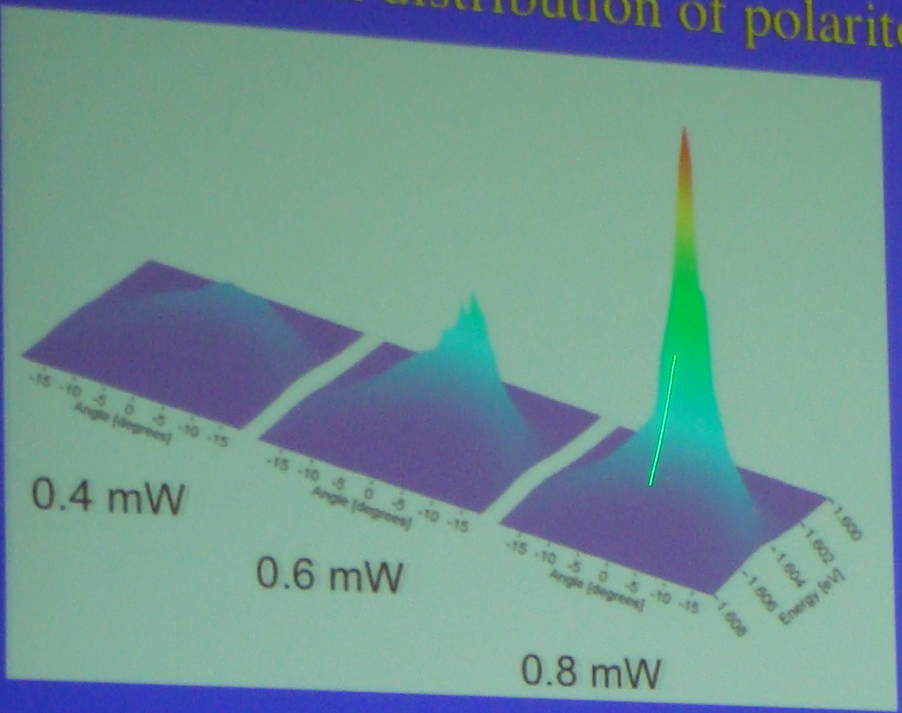


Angle-resolved data vs. particle density

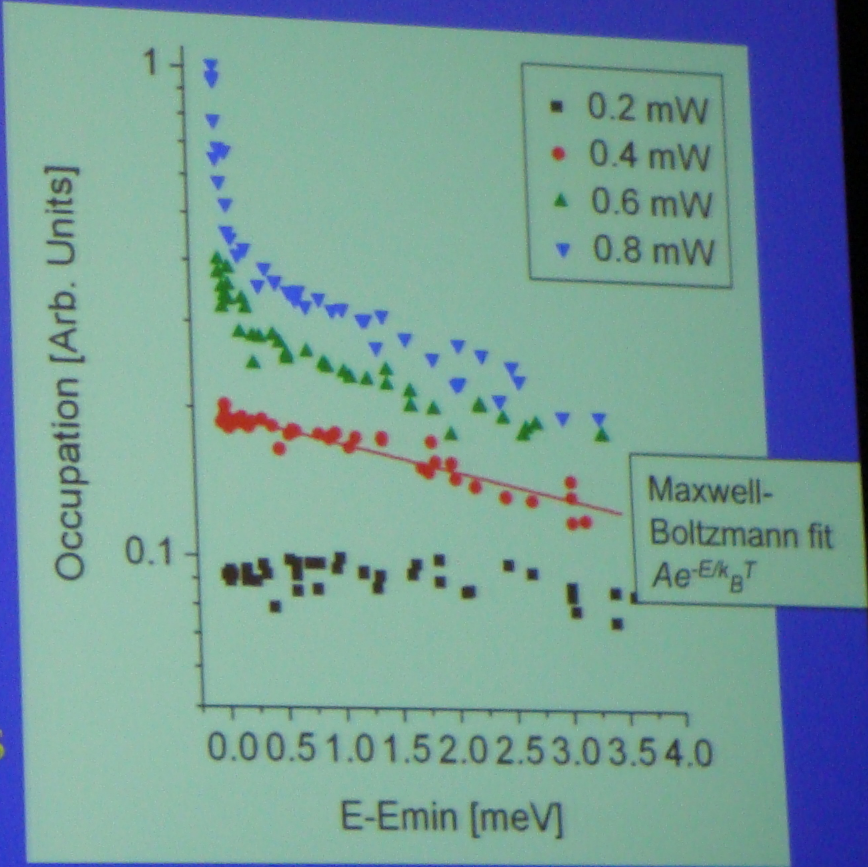


R. Balili et al., Science **316**, 1007 (2007)

Momentum distribution of polaritons

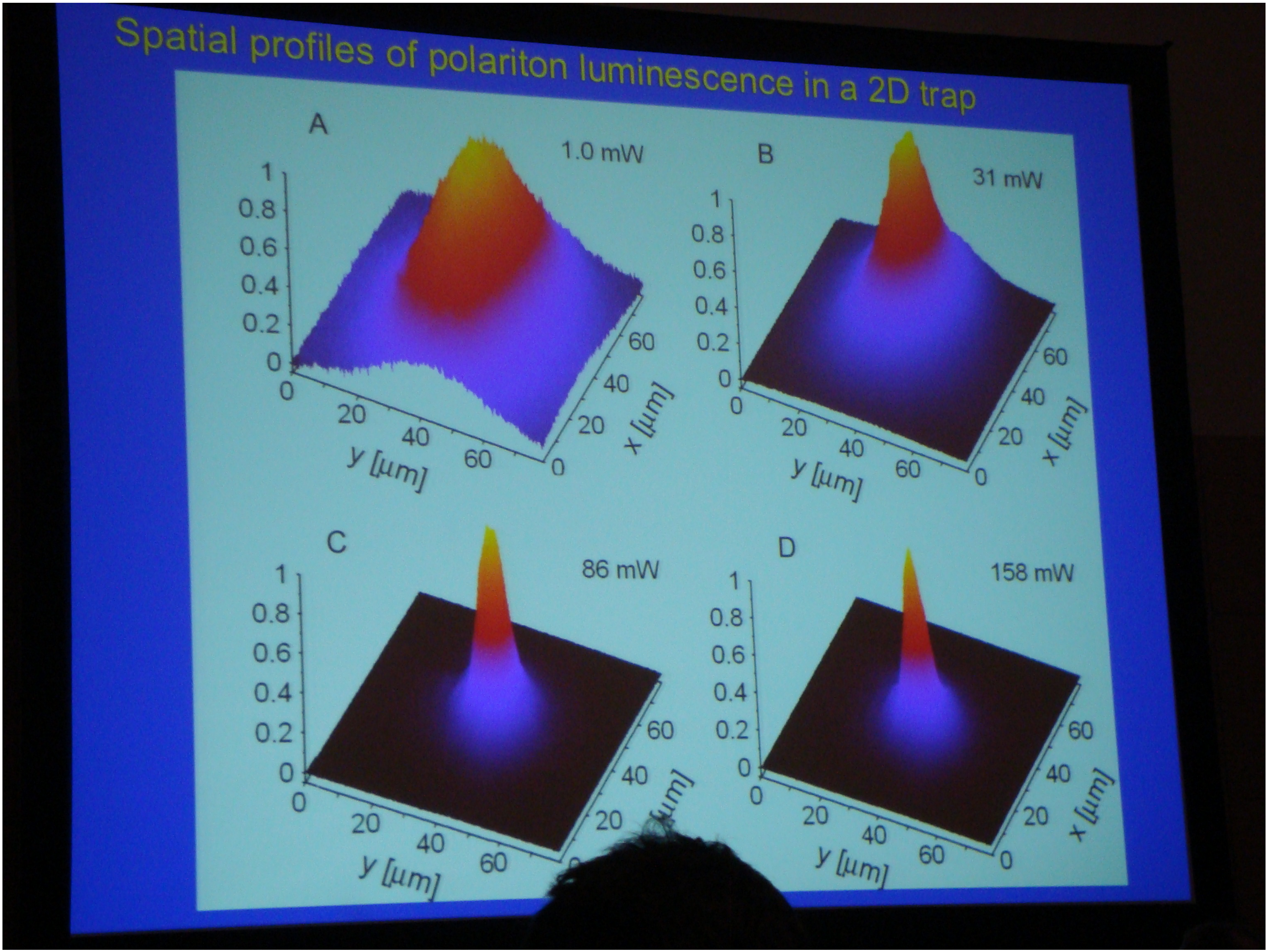


Energy distribution of polaritons



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

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



Spatial profiles of polariton luminescence in a 2D trap

Other recent experiments:

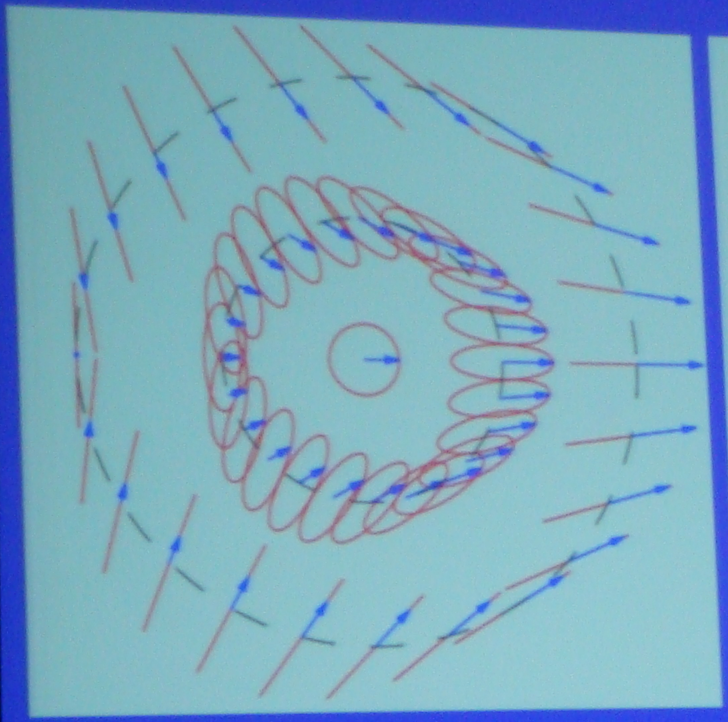
- quantized vortices
- superfluid soliton motion, suppression of scattering
- spontaneous symmetry breaking (polarization)
- first- and second-order coherence
- spatial phase locking of two condensates
- onset time of coherence
- BEC in microtraps with discrete states
- Bogoliubov linear branches
- Trapping in periodic lattices

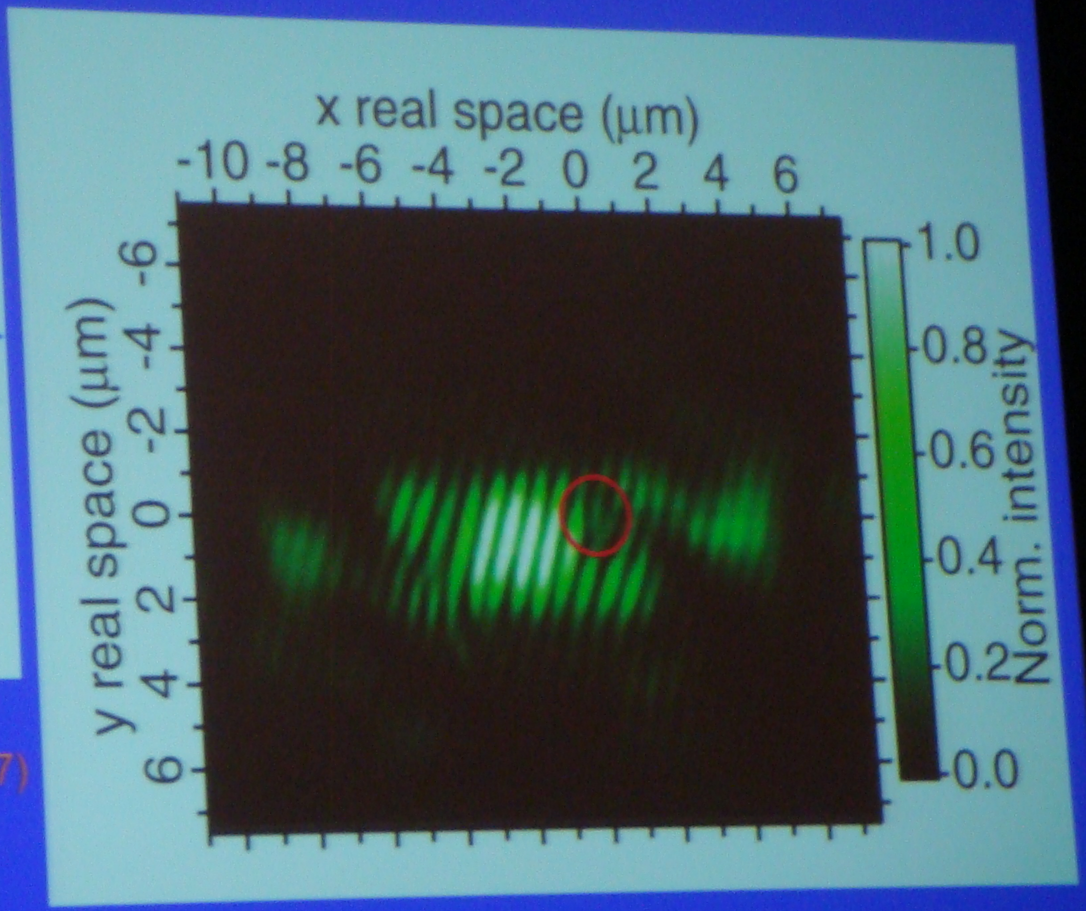
...applications in optical communications (nonlinear modulation, low-threshold lasing, cw OPO, optical spin-Hall effect, etc.)

... room temperature polaritons possible with organics, GaN

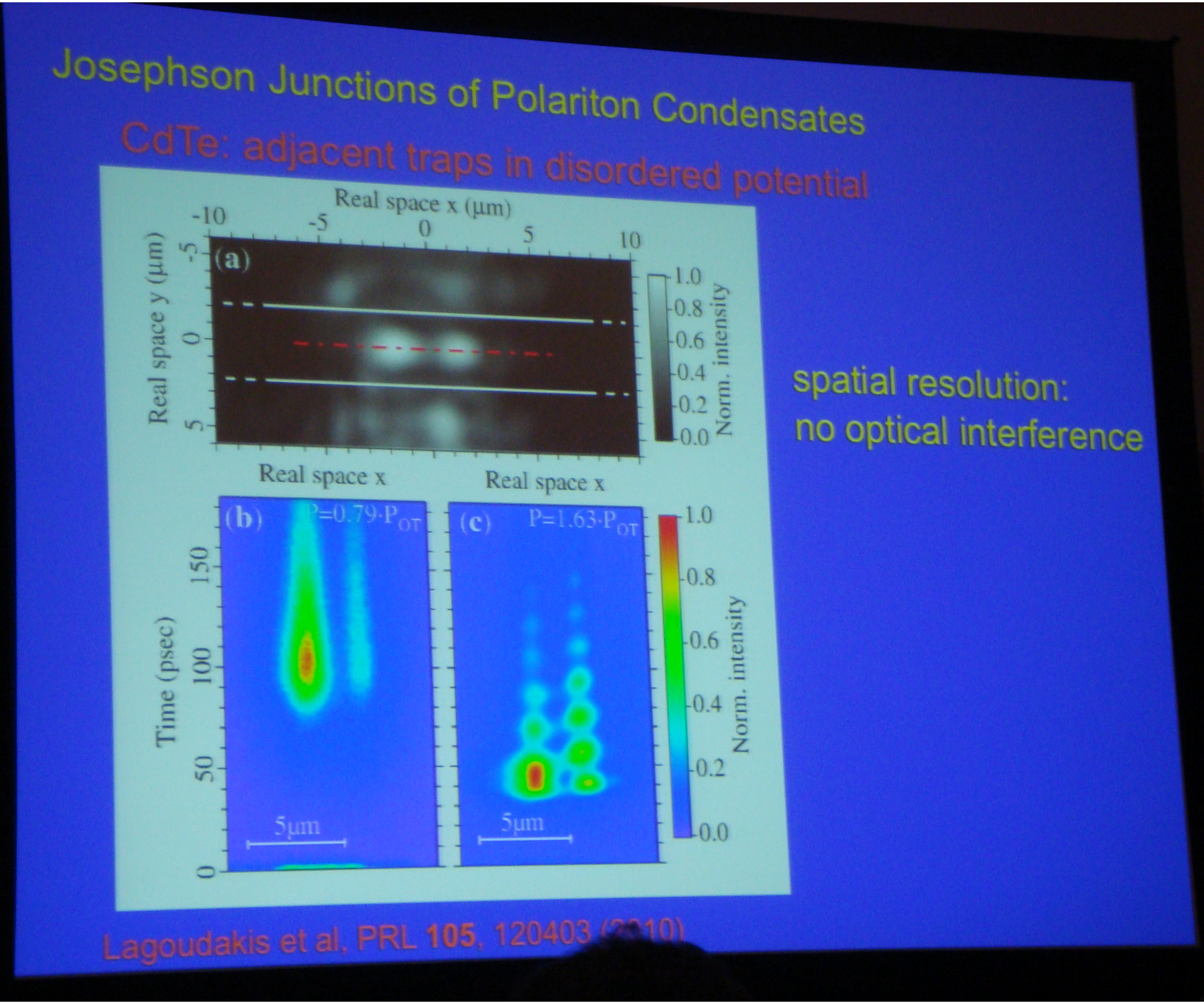
Spin vortices:

microcavity polaritons are a *spin-1*, *two-state* system
"half vortices": polarization and phase each rotate by π


Y.G. Rubo, PRL **99**, 106401 (2007)



Lagoudakis et al., Science **326**, 974 (2009)



Josephson Junctions of Polariton Condensates

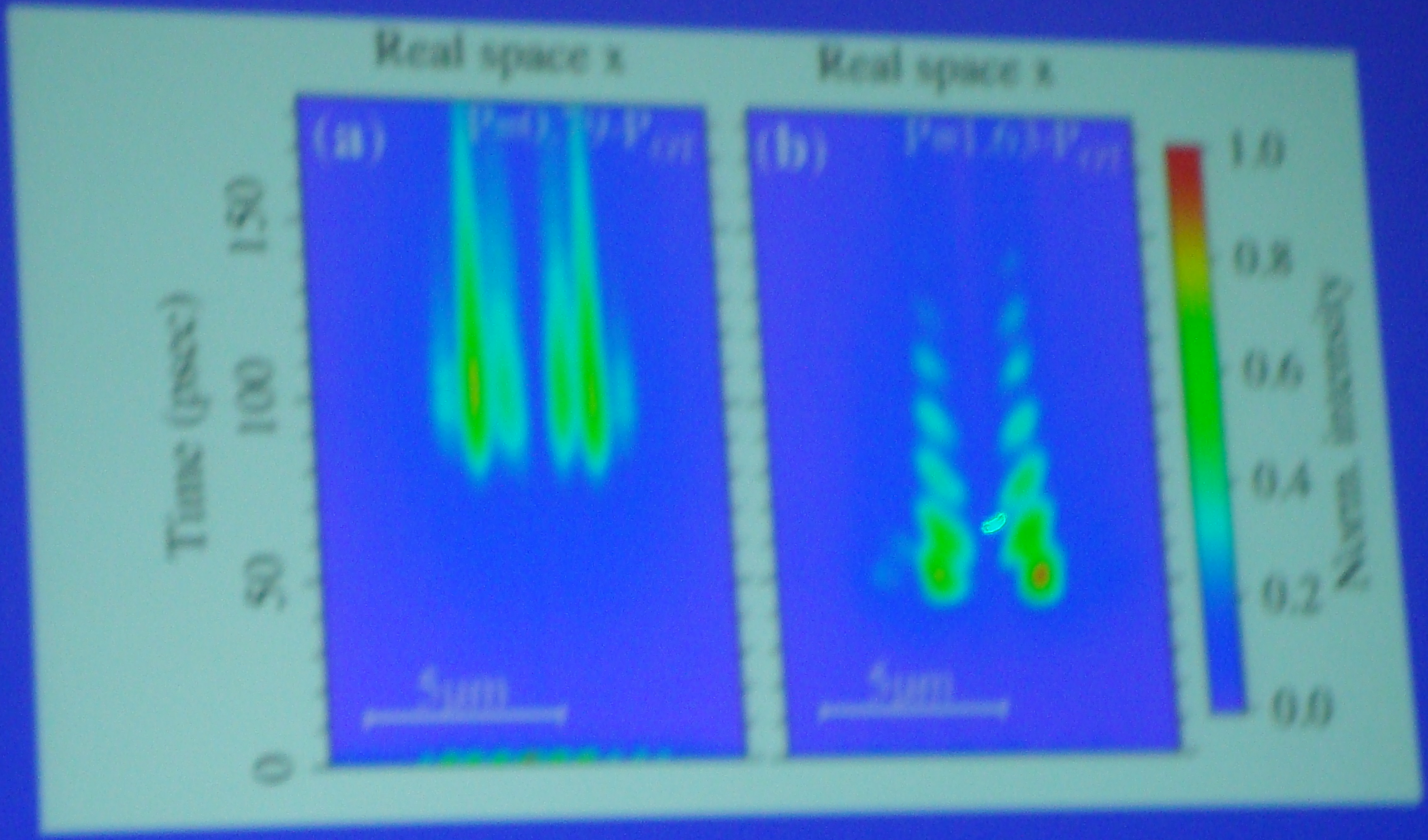
CdTe: adjacent traps in disordered potential

spatial resolution:
no optical interference

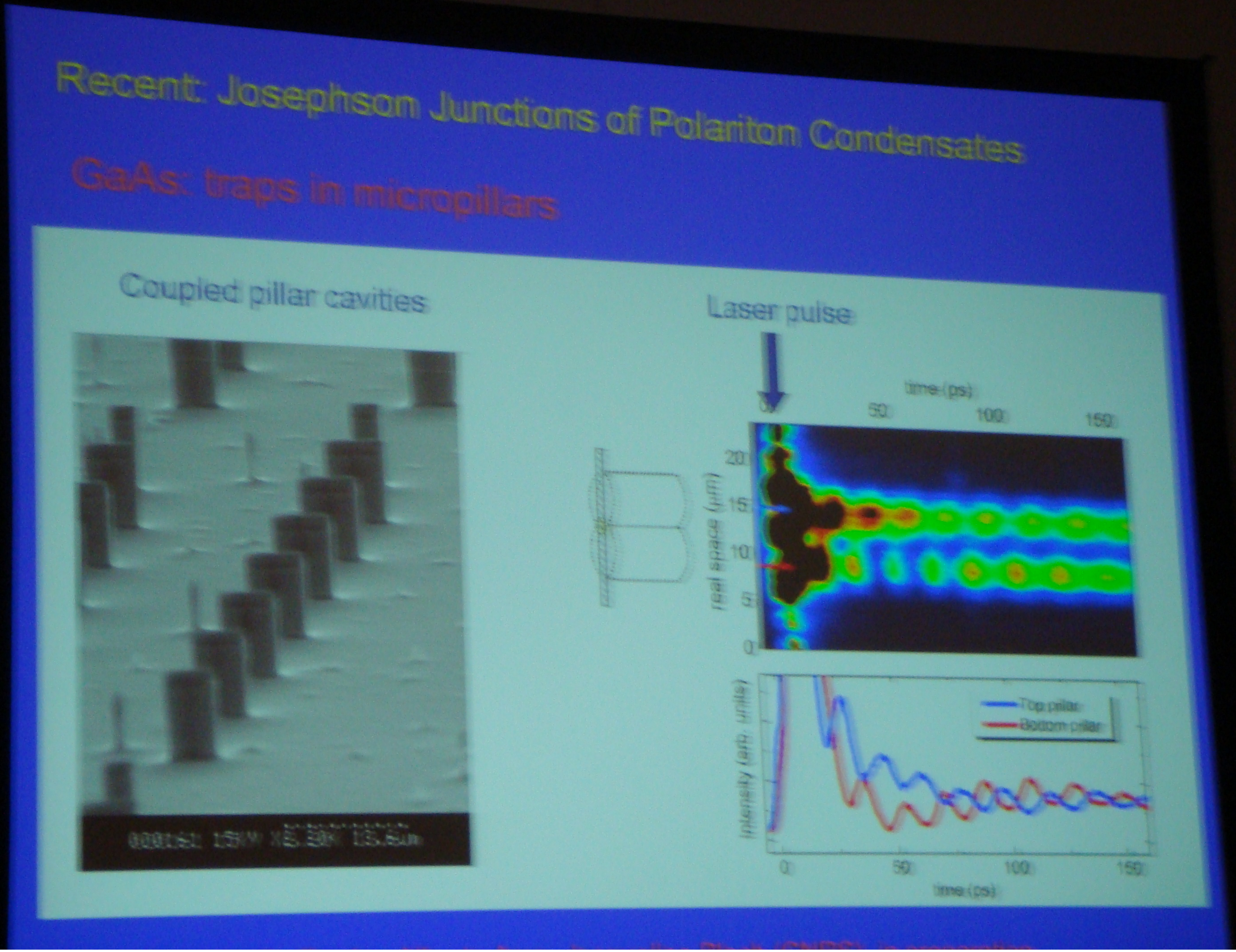
Lagoudakis et al, PRL **105**, 120403 (2010)

Recent: Josephson Junctions of Polariton Condensates

phase winding



PRL 105, 120403 (2010)



Recent: Josephson Junctions of Polariton Condensates

GaAs: traps in micropillars

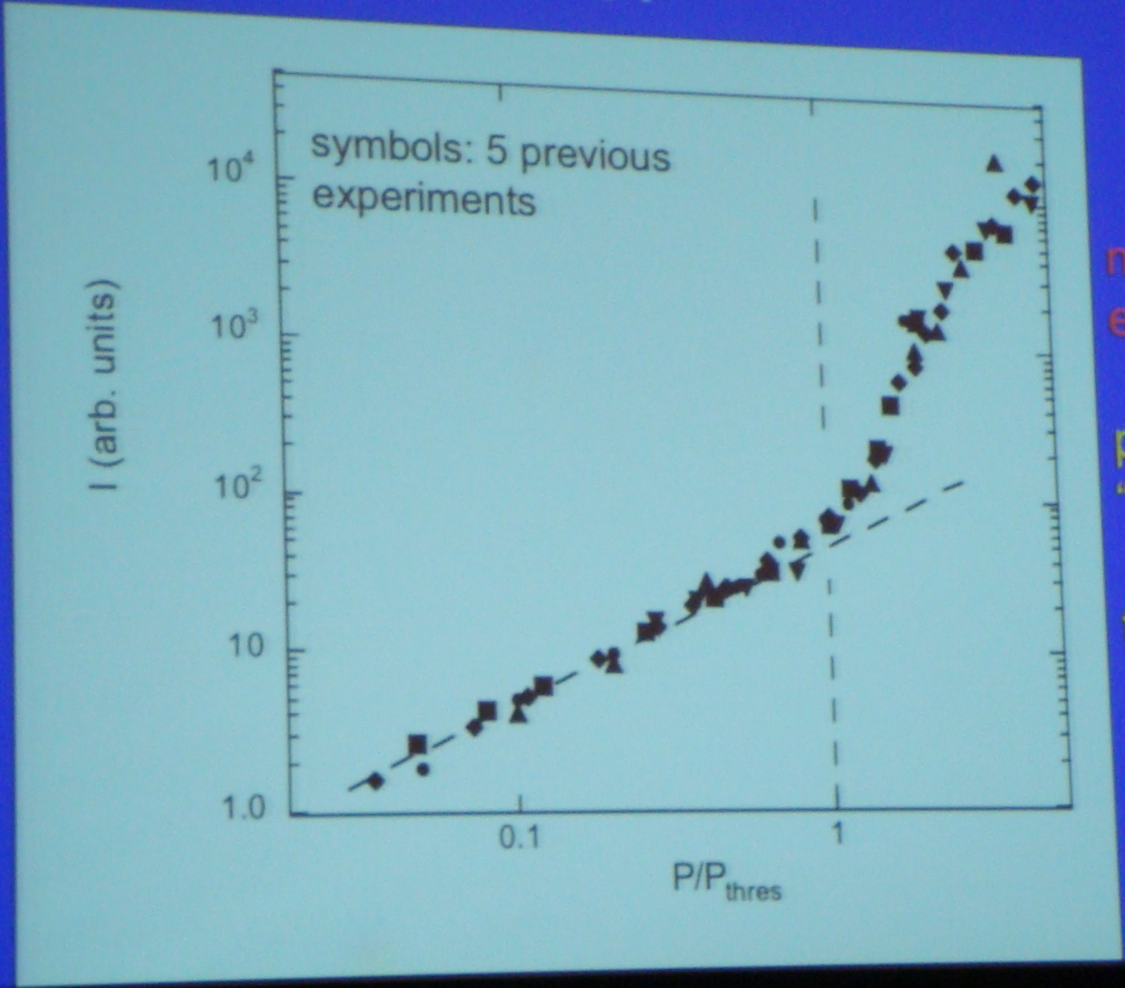
Coupled pillar cavities

Laser pulse

III. New Results with Long-Lifetime Polaritons

Threshold-type behavior seen in earlier experiments:

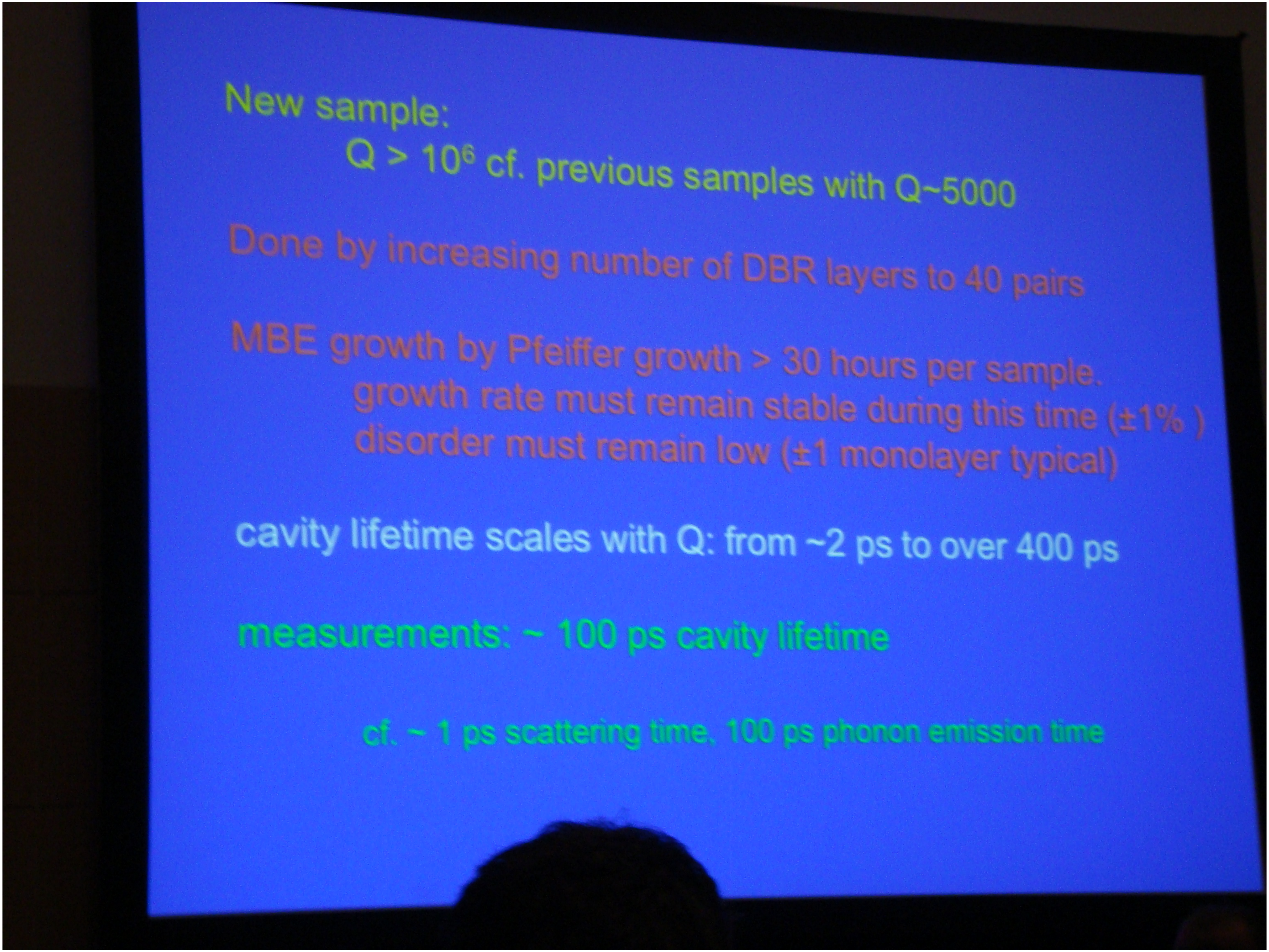
Luminescence intensity
at $k_{\parallel}=0$ vs. pump power



nearly universal curve in all experiments up to now

phase transition is "smeared".

finite lifetime < 15 ps



New sample:

$Q > 10^6$ cf. previous samples with Q~5000

Done by increasing number of DBR layers to 40 pairs

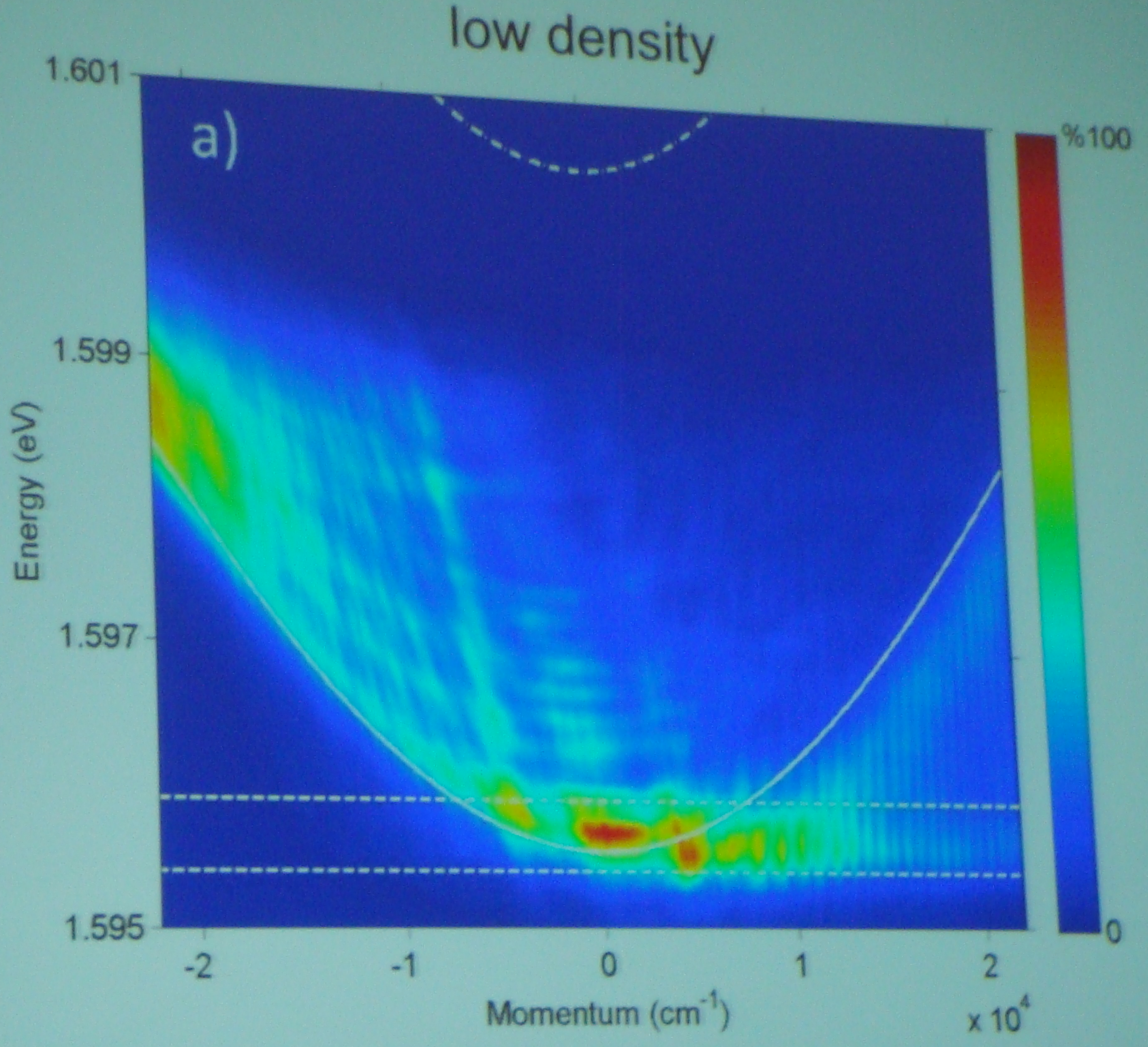
MBE growth by Pfeiffer growth > 30 hours per sample.
growth rate must remain stable during this time (±1%)
disorder must remain low (±1 monolayer typical)

cavity lifetime scales with Q: from ~2 ps to over 400 ps

measurements: ~ 100 ps cavity lifetime

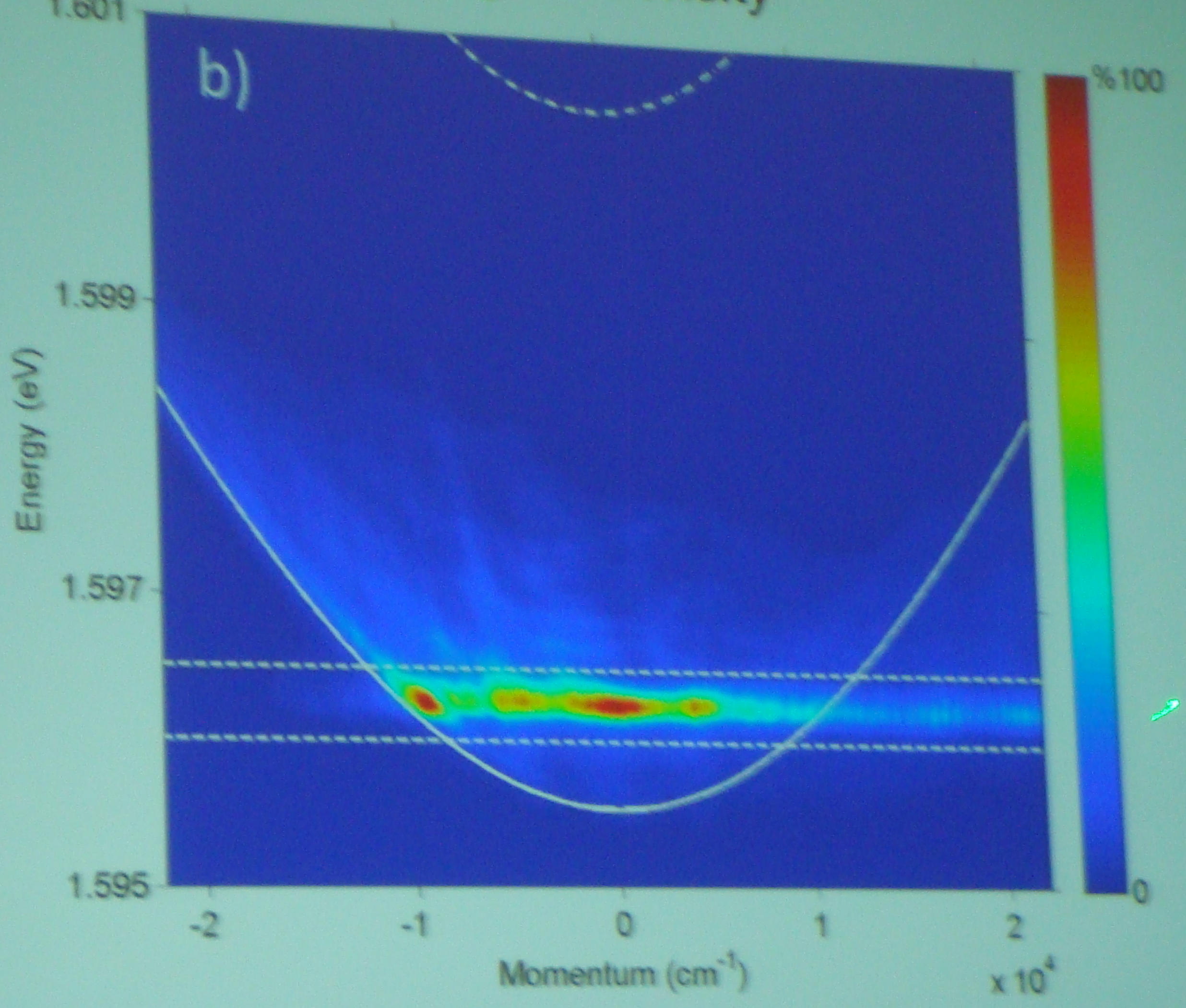
cf. ~ 1 ps scattering time, 100 ps phonon emission time

k-space resolved data



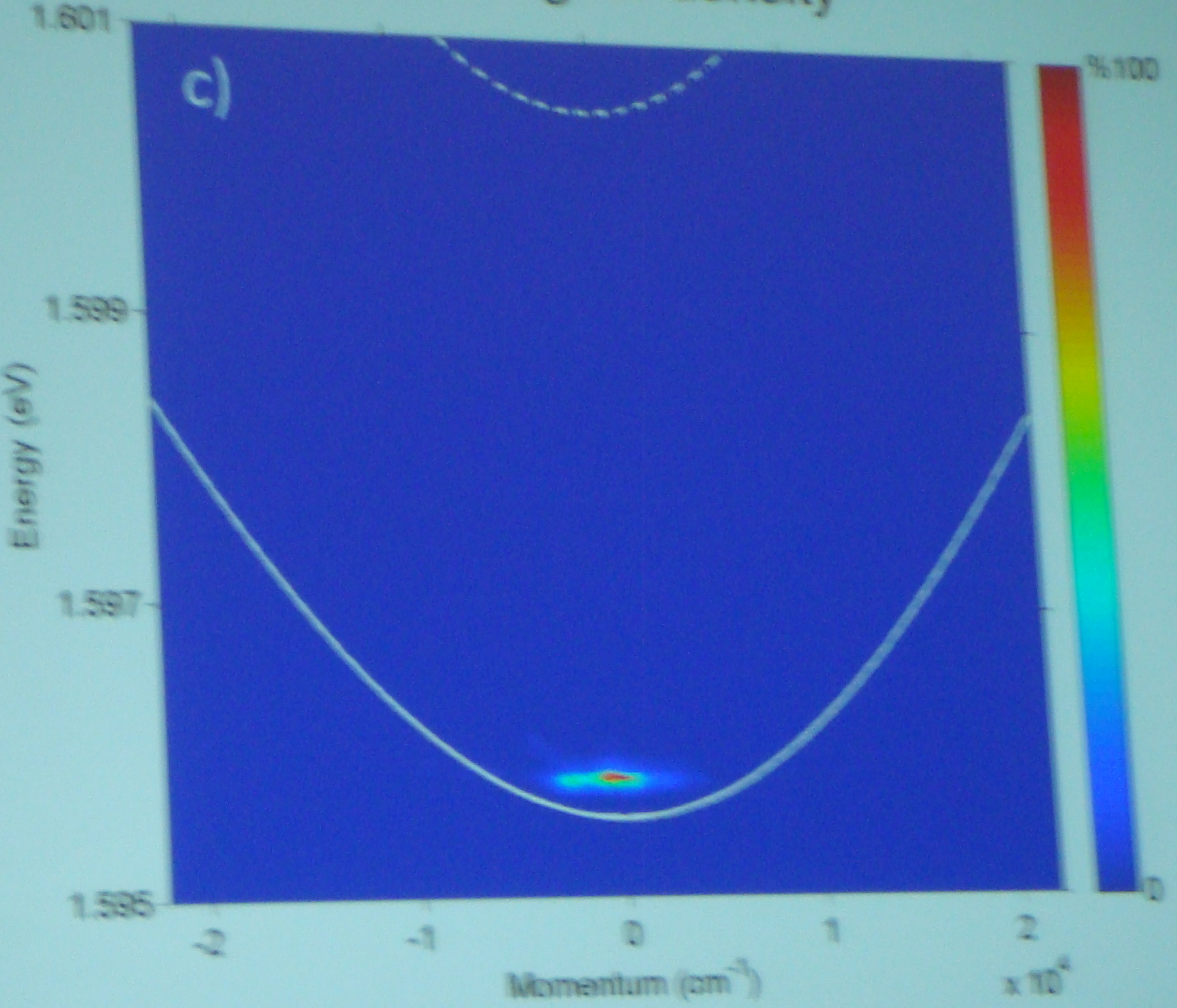
k-space resolved data

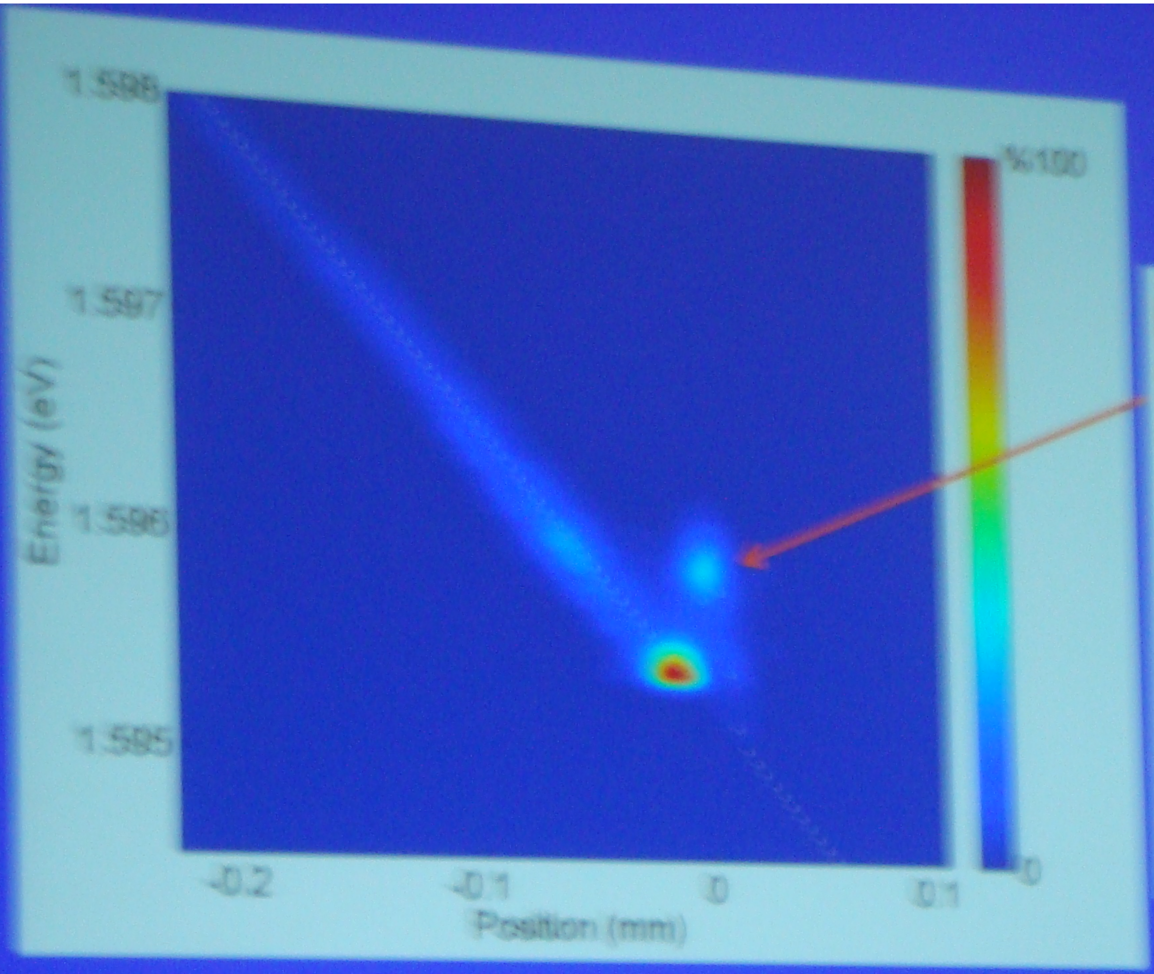
higher density



k-space resolved data

even higher density



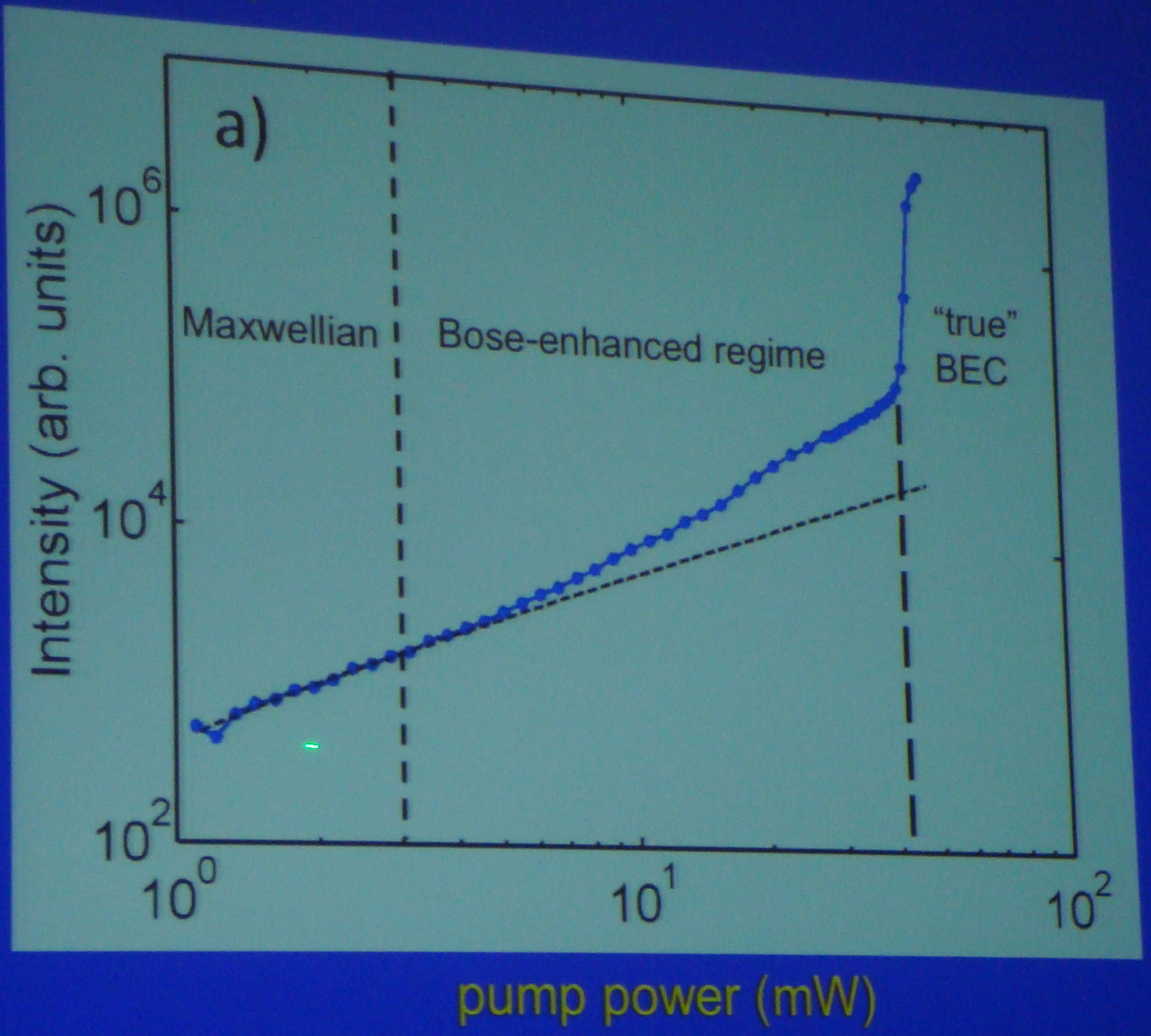


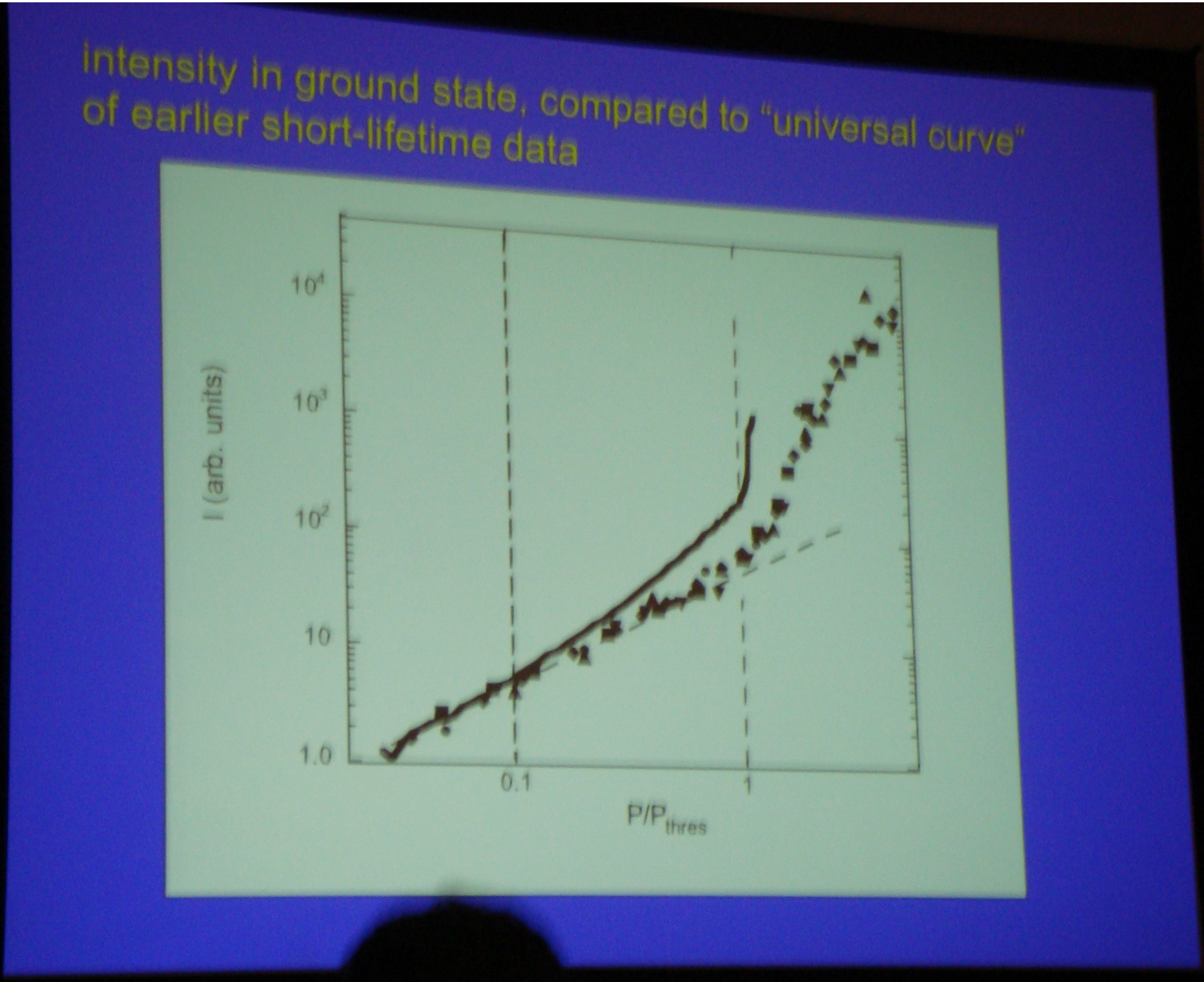
potential barrier created by repulsion of polaritons from "normal" excitons at point of creation

excitons with mass 10^4 higher are effectively a static barrier

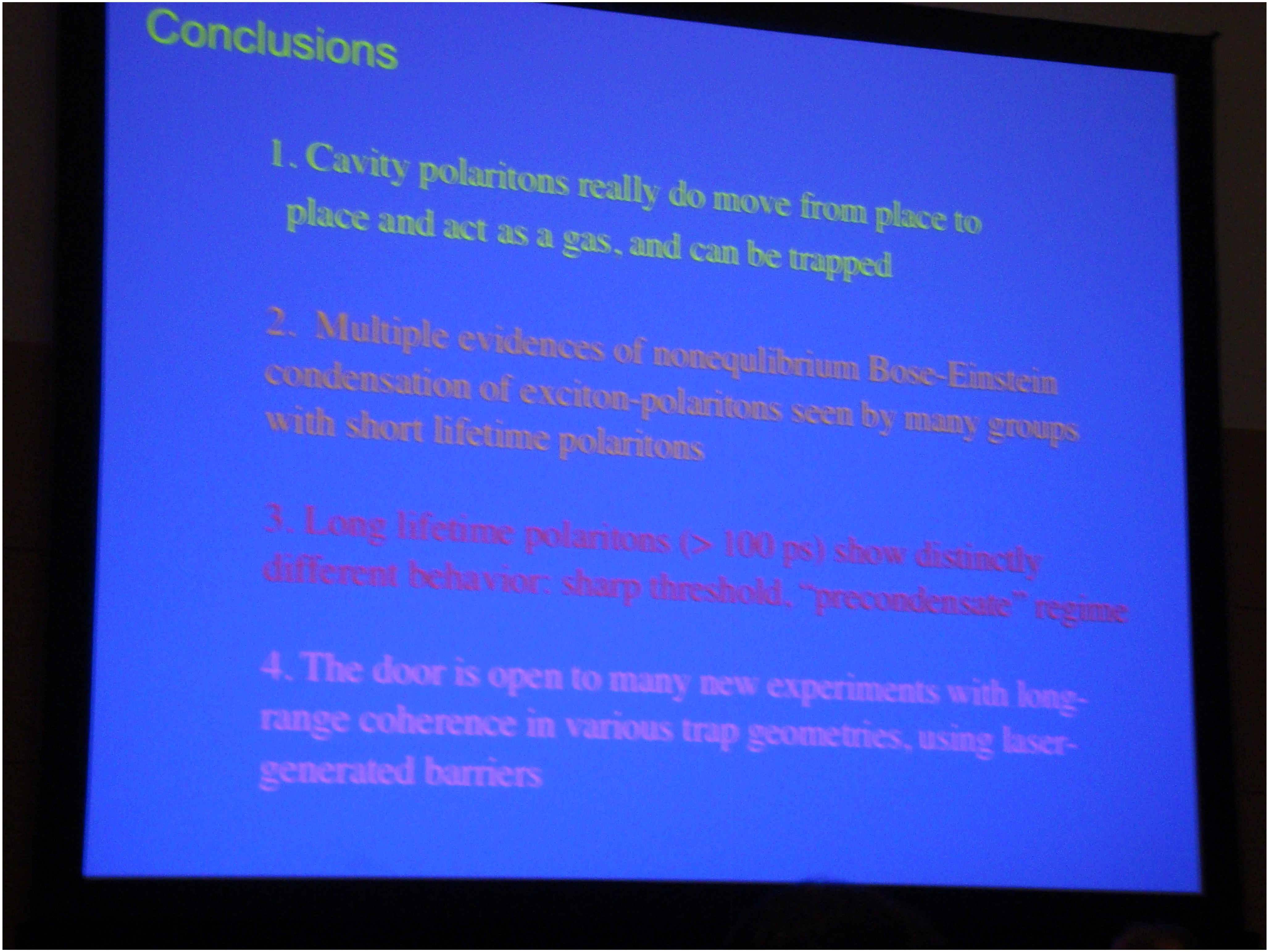
(red shift and spatial shift relative to point of creation shows lasing is not occurring)

Three regimes: classical, Bose-enhanced, and fully coherent (BEC)





intensity in ground state, compared to "universal curve" of earlier short-lifetime data



Conclusions

1. Cavity polaritons really do move from place to place and act as a gas, and can be trapped

2. Multiple evidences of nonequlibrium Bose-Einstein condensation of exciton-polaritons seen by many groups with short lifetime polaritons

3. Long lifetime polaritons (> 100 ps) show distinctly different behavior: sharp threshold, "precondensate" regime

4. The door is open to many new experiments with long-range coherence in various trap geometries, using laser-generated barriers