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The macroscopically polariton state in semiconductor microcavities

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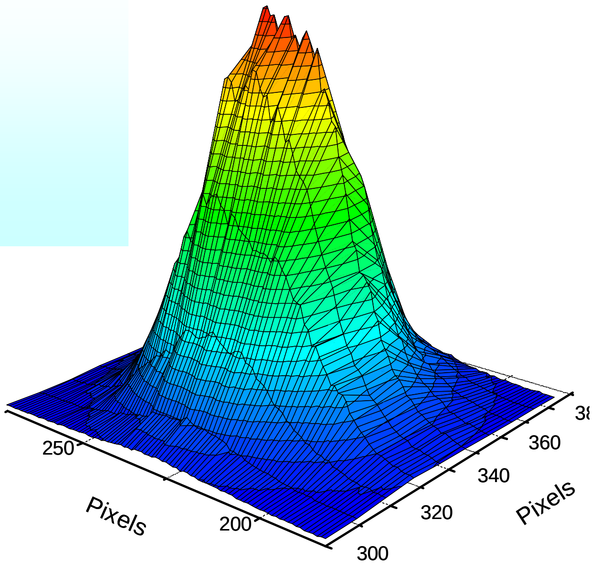
The Macroscopically Polariton State in Semiconductor Microcavities

M S Skolnick, University of Sheffield

1. Introduction to microcavity physics
2. **Bosonic properties**
3. **Coherence of macroscopically occupied state**
4. **Effects of interactions**
5. Summary



RTN *Clermont II*

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Acknowledgements

Experiments: D N Krizhanovskii, D Sanvitto, A P D Love, S Ceccarelli

Theory D M Whittaker

Growth J S Roberts

*Sanvitto et al Phys Rev **B73**, 241308, 2006*

*Krizhanovskii et al, Phys Rev Lett **97**, 097402, 2006*

Krizhanovskii et al 2007

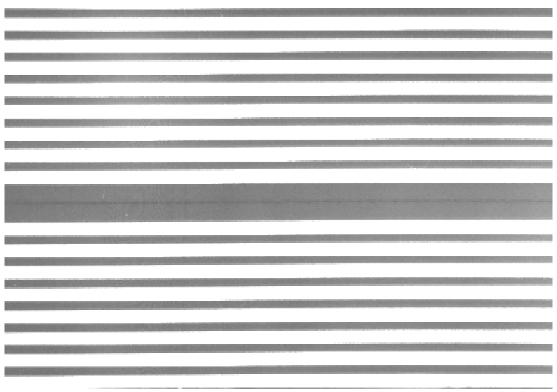
Semiconductor Microcavity

Fabry-Perot cavity with distributed Bragg reflector (DBR) mirrors).
One dimensional photonic structure

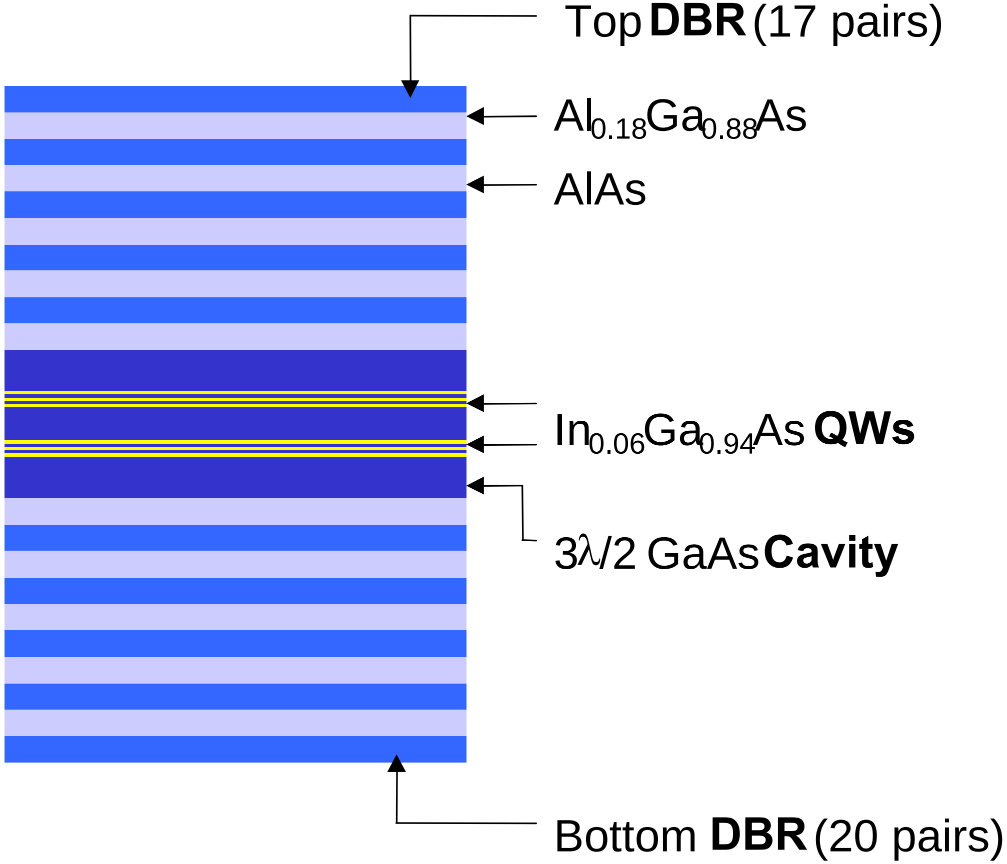
High reflectivity mirrors surrounding cavity

Quantisation of both optical field and excitons

Designed to be close to resonance

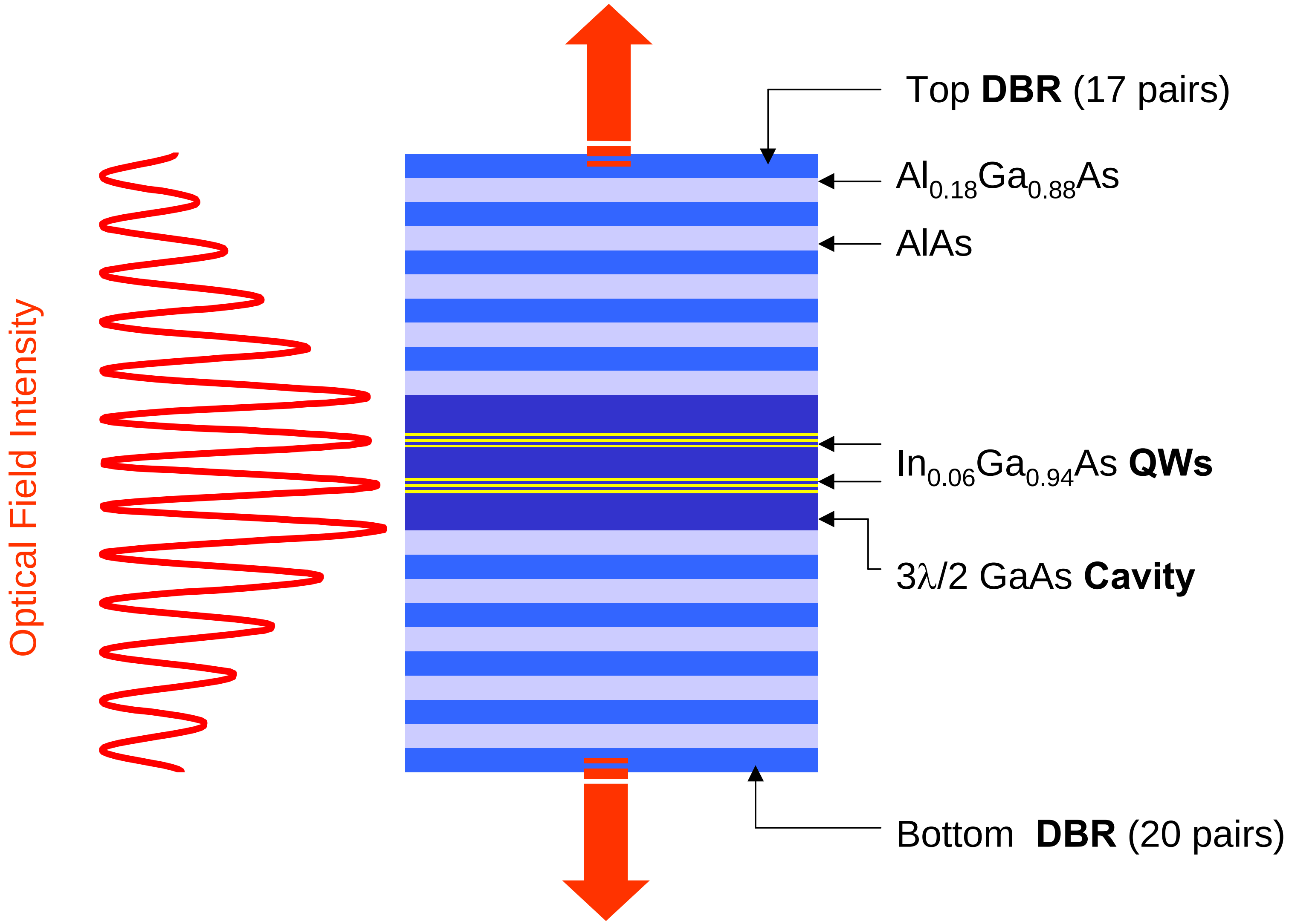


TEM cross section



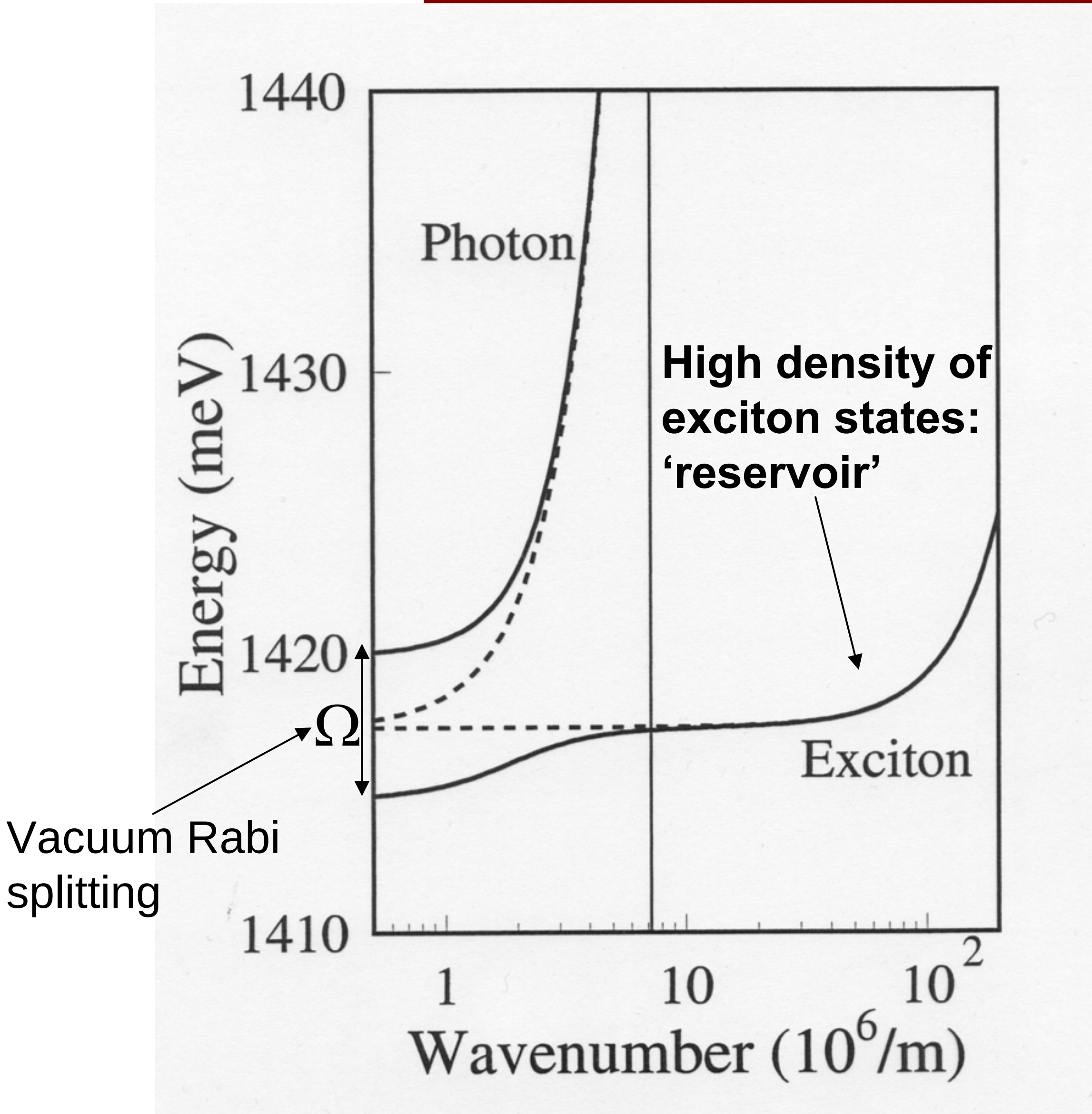
Field enhanced in cavity, but note penetration into DBR mirrors

Similar structures to vertical cavity lasers



QWs at antinodes of optical field

Cavity-polariton dispersion



Photon dispersion near parabolic

$$\omega = \frac{c}{n}\sqrt{k_x^2 + k_y^2 + \left(N\frac{2\pi}{2L}\right)^2}$$

k_z quantised

- Exciton-photon Strong coupling occurs at relatively small $k<10^5\ cm^{-1}$

Ω ~ 6meV in GaAs based structures

First report, Weisbuch, Arakawa et al PRL 69, 3314, 1992

Strong Coupling

Energy exchanged between exciton and electromagnetic field

Photon emitted and then re-absorbed. Reversible process.

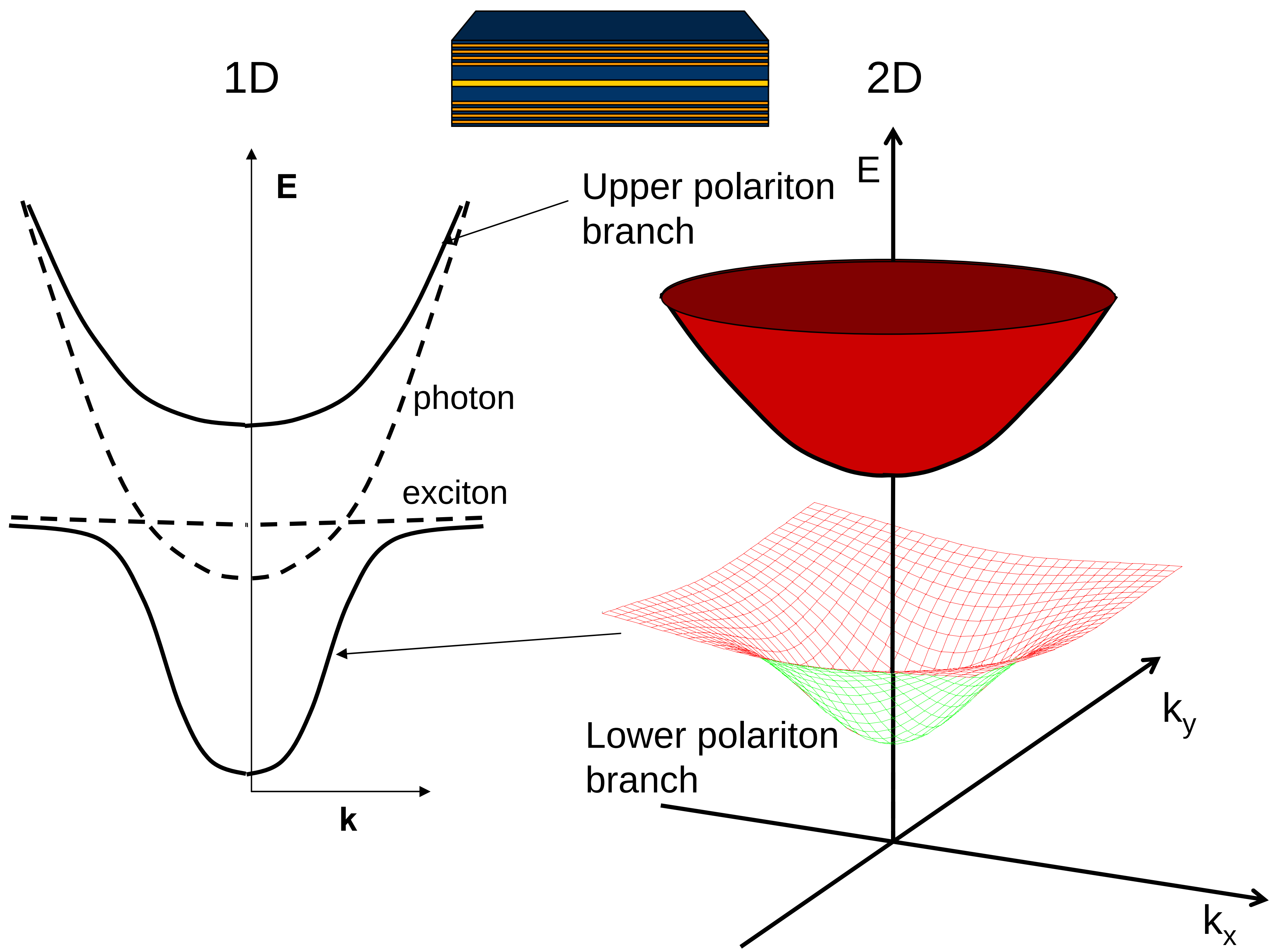
Vacuum Rabi splitting (normal mode coupling strength)

$$\Omega \propto \sqrt{fN/l_{eff}}$$

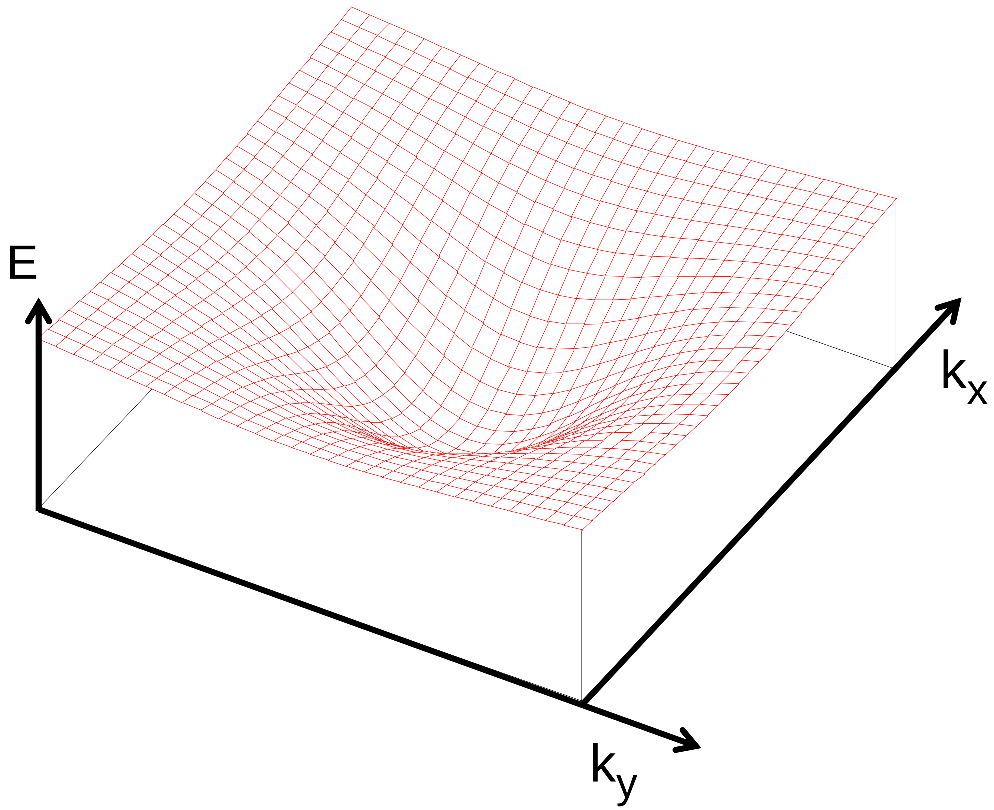
f oscillator strength, N number of quantum wells, L effective length of cavity

Both excitons and photons confined in vertical direction, unconfined in-plane

Strong coupling occurs for each point in *k*-space (*k* good quantum number)


1D
2D
E
Upper polariton
branch
E
photon
exciton
k
Lower polariton
branch
k_y
k_x

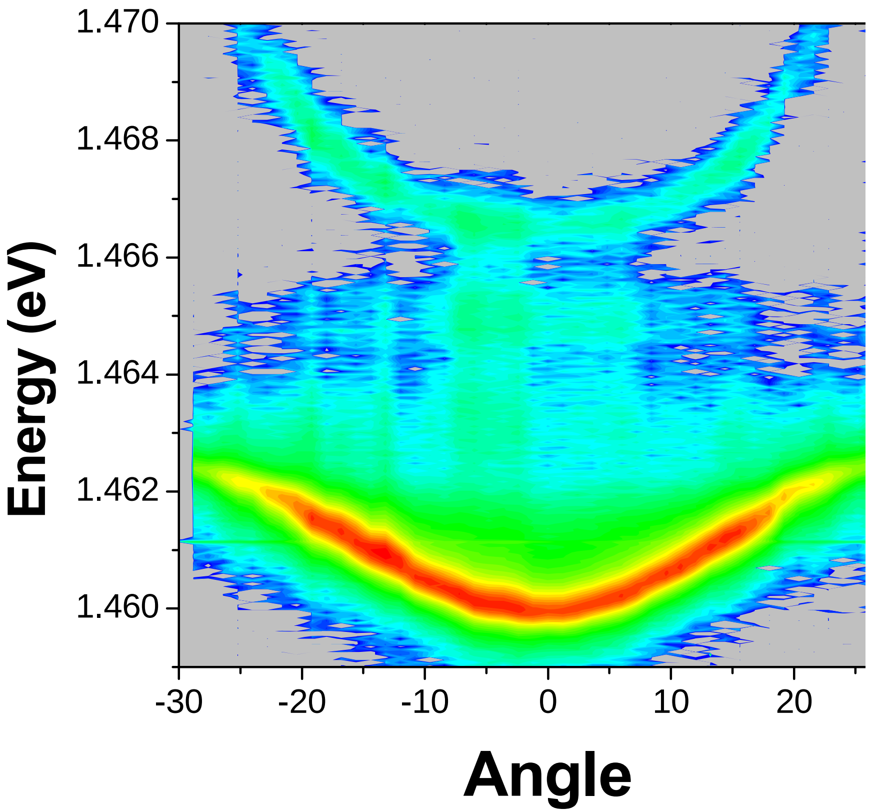
Lower Polariton Branch



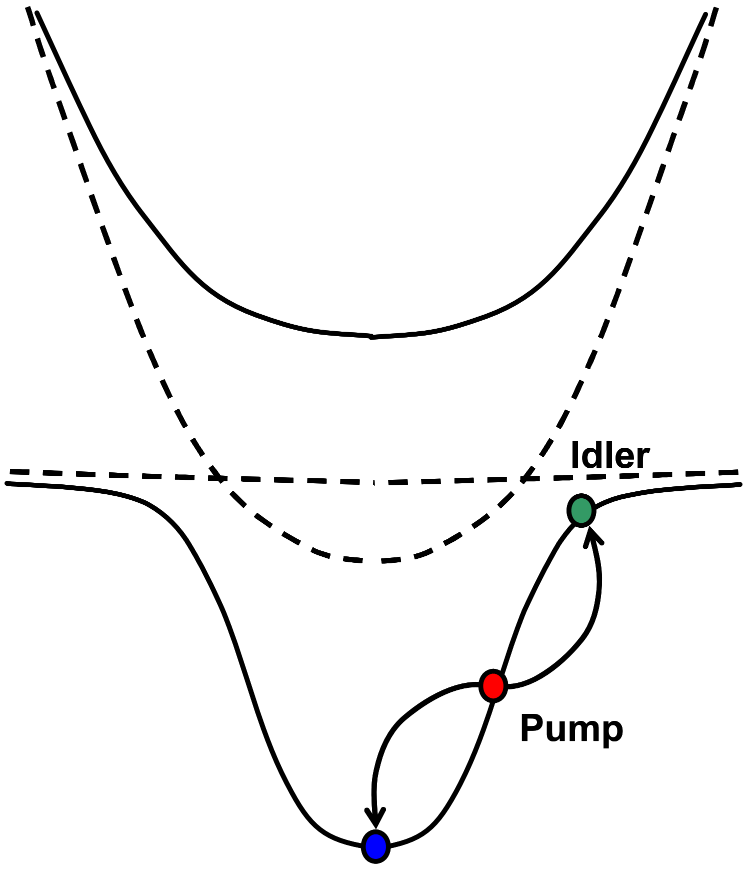
- 10^{-5} times the exciton mass
- Low density of states
- Can achieve macroscopic occupation
- Bosonic quasi-particles, scattering stimulated by final state occupation
- Possibility of Bose condensation. Dynamic equilibrium

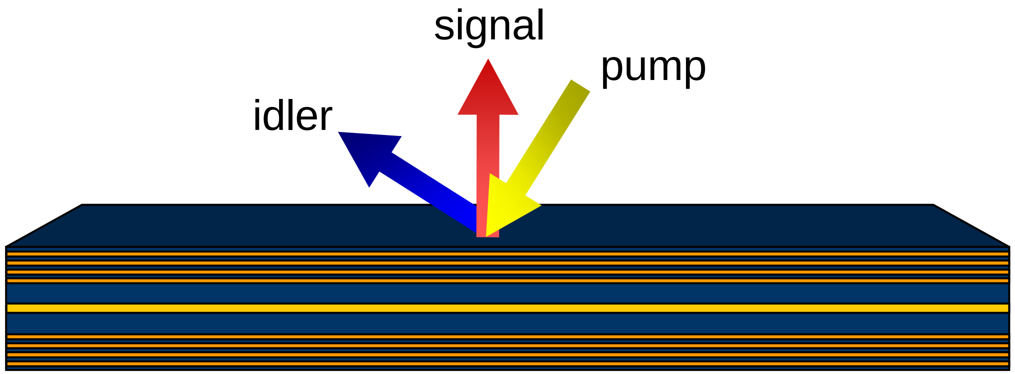
Below Threshold, Non-Resonant Excitation

Direct correspondence between external angle and in-plane k-vector – can inject and detect polariton populations



The Optical Parametric Oscillator
Stimulated polariton scattering, resonant excitation,





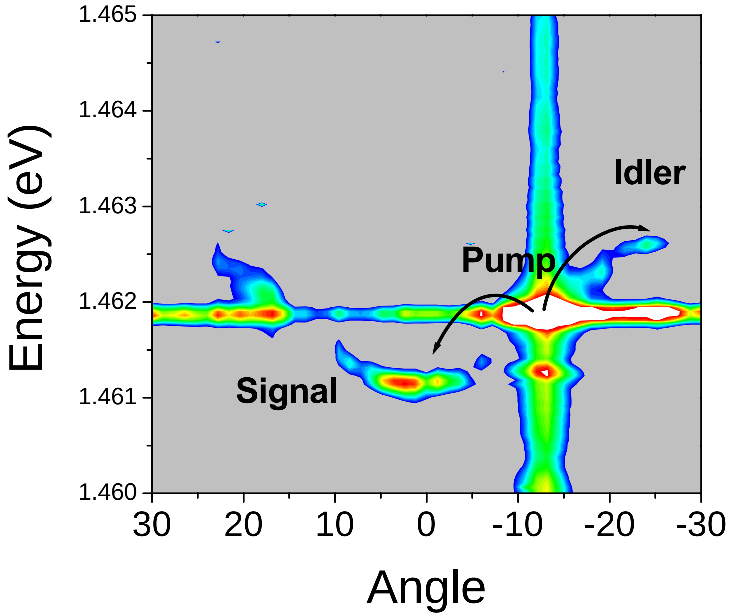
optical parametric oscillator, conservation of energy and wavevector (return to at end)

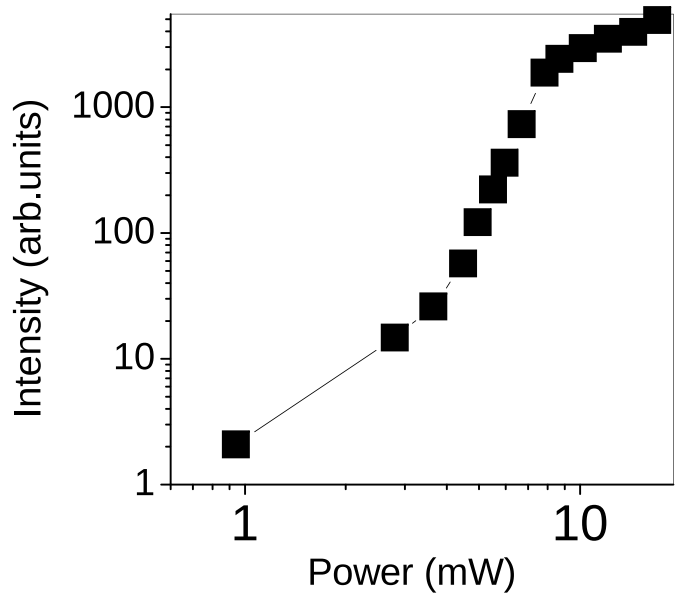
Stevenson et al PRL. **85**, 3680, (2000), Baumberg et al PRB62, R16247, 2000

Tartakovskii PR B **62**, R13298 (2000)

Butté et al PR **B68,** 115325, 2003

Houdré et al PRL 2000, Messin et al, PRL **87**, 127403, 2001, A Baas et al, PR **B70**, 161307, 2004



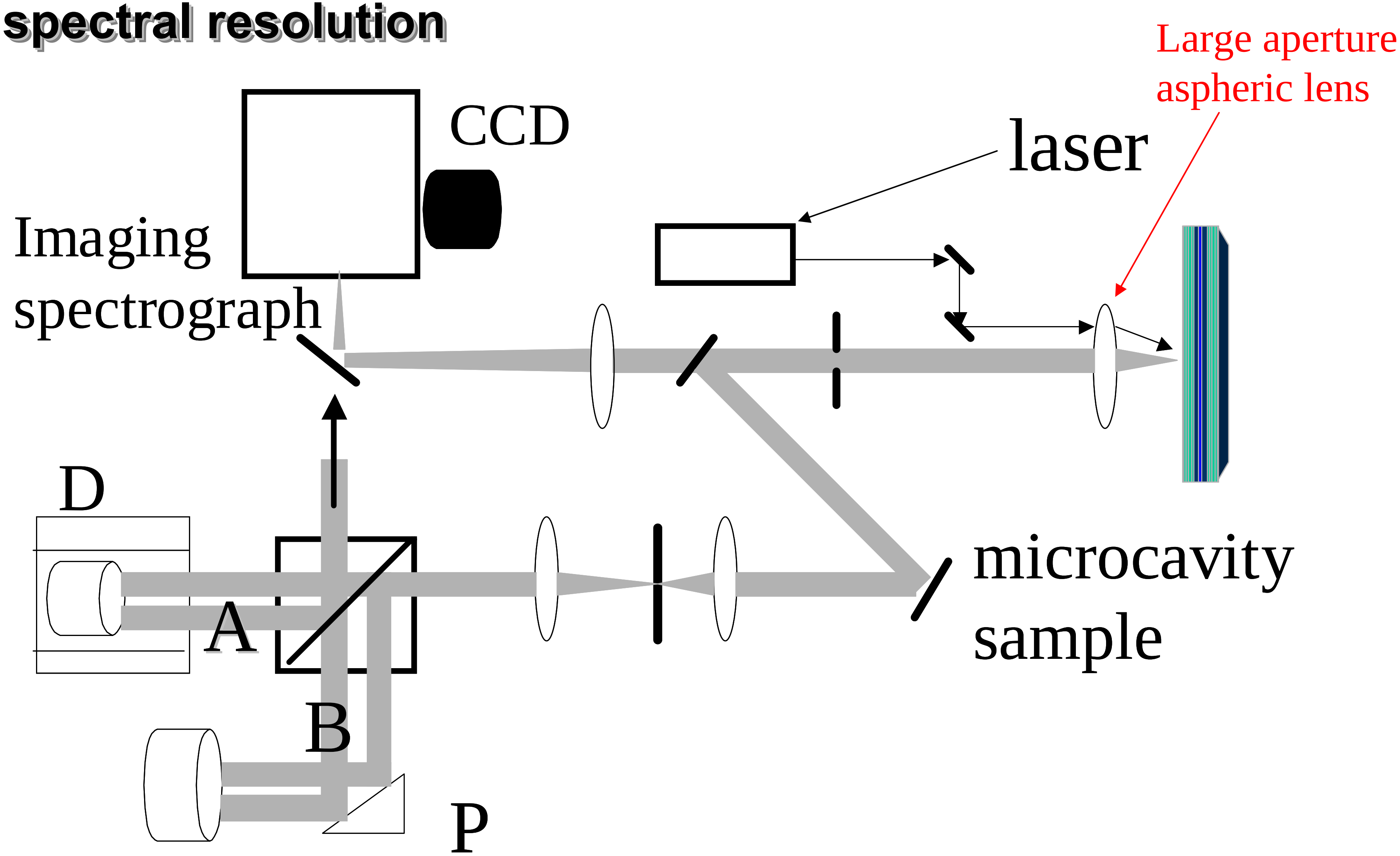


- Scattering of pump polaritons to signal and idler states at k=0 and k=2k_p.

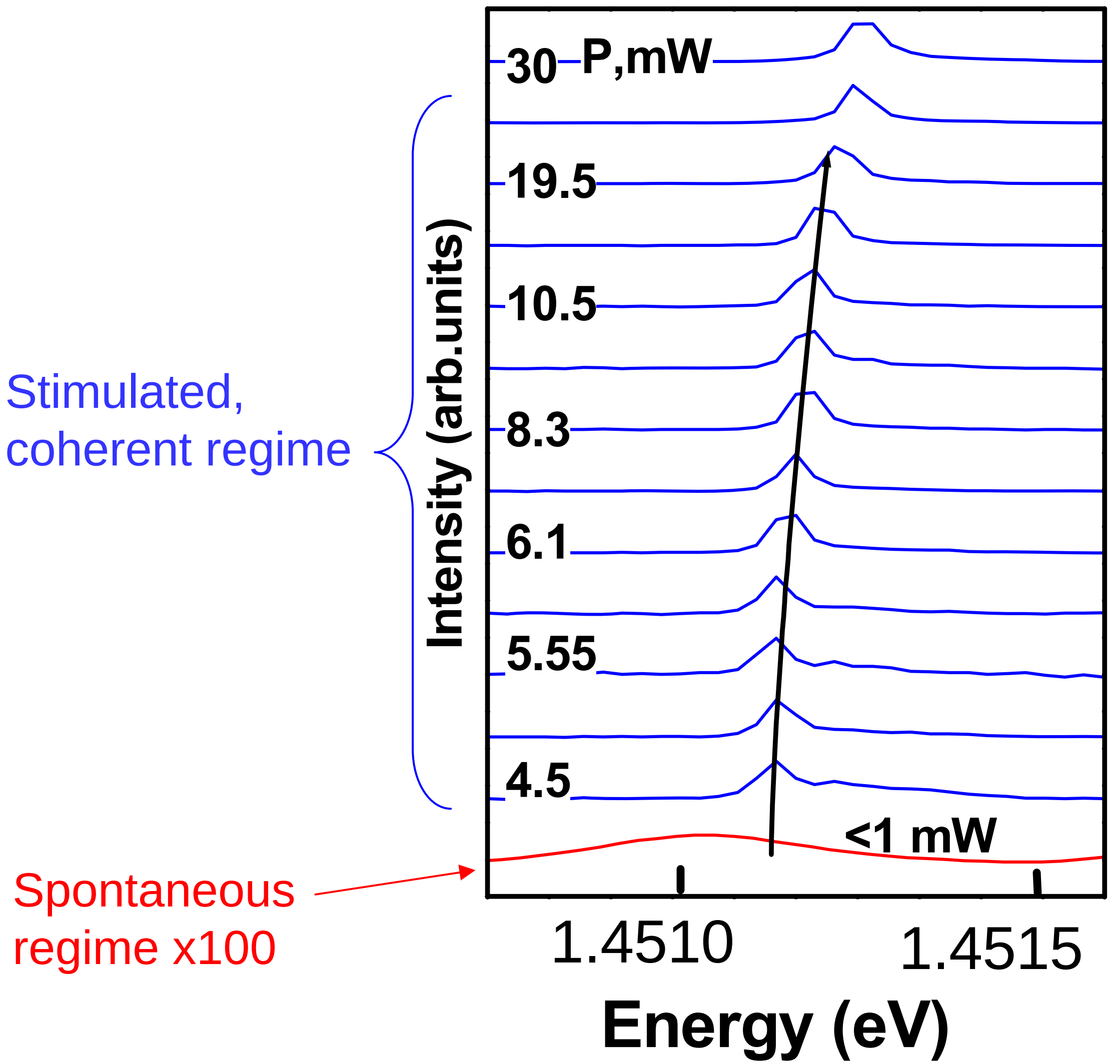
- Clear threshold, stimulated by final state occupation. Coherent regime.

- Creation of macroscopically occupied states – state occupancy 100 - 1000

Experimental set-up for studies with spatial and spectral resolution



Normalised k=0 emission as a function of excitation power (single mode spectra)



- As threshold is crossed – marked narrowing, onset of coherence
- Blue shift due to polariton-polariton interactions

Ciuti et al,

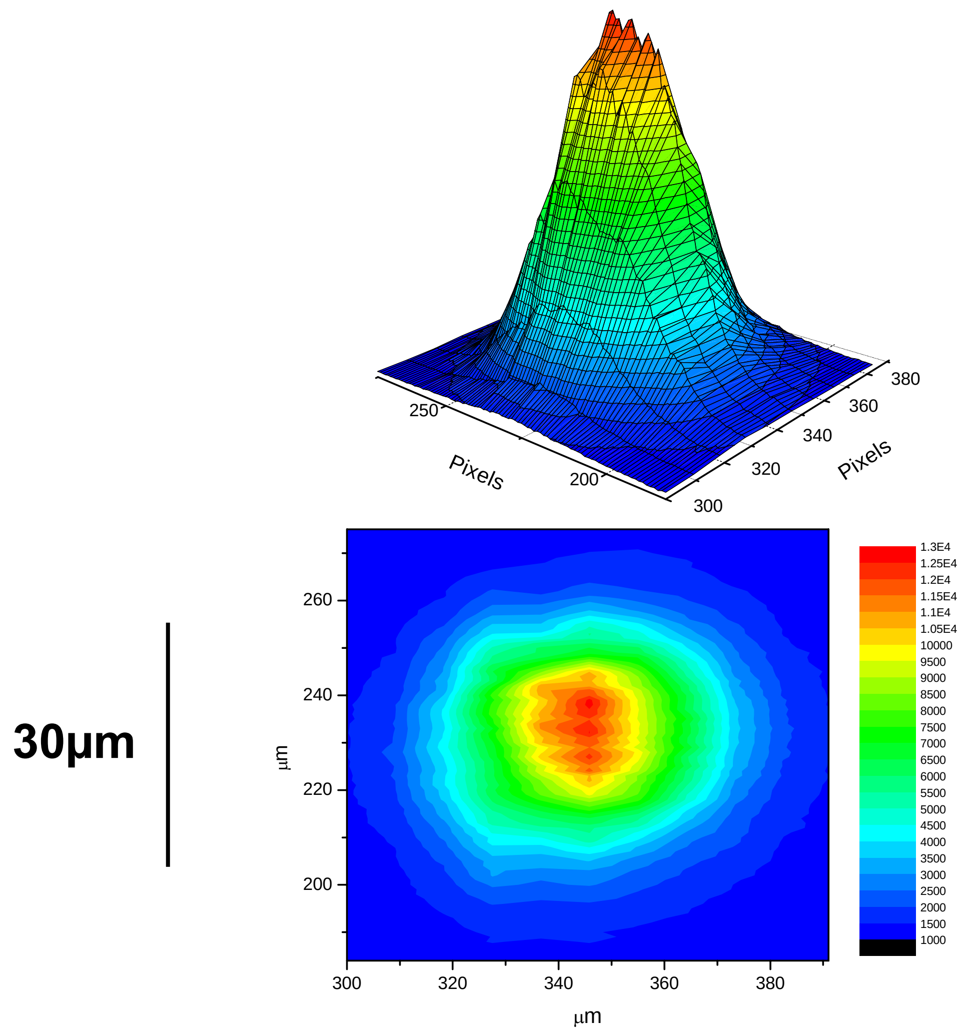
PR B62, R4825, 2000, B63, 041303(R) (2001),

Whittaker et al

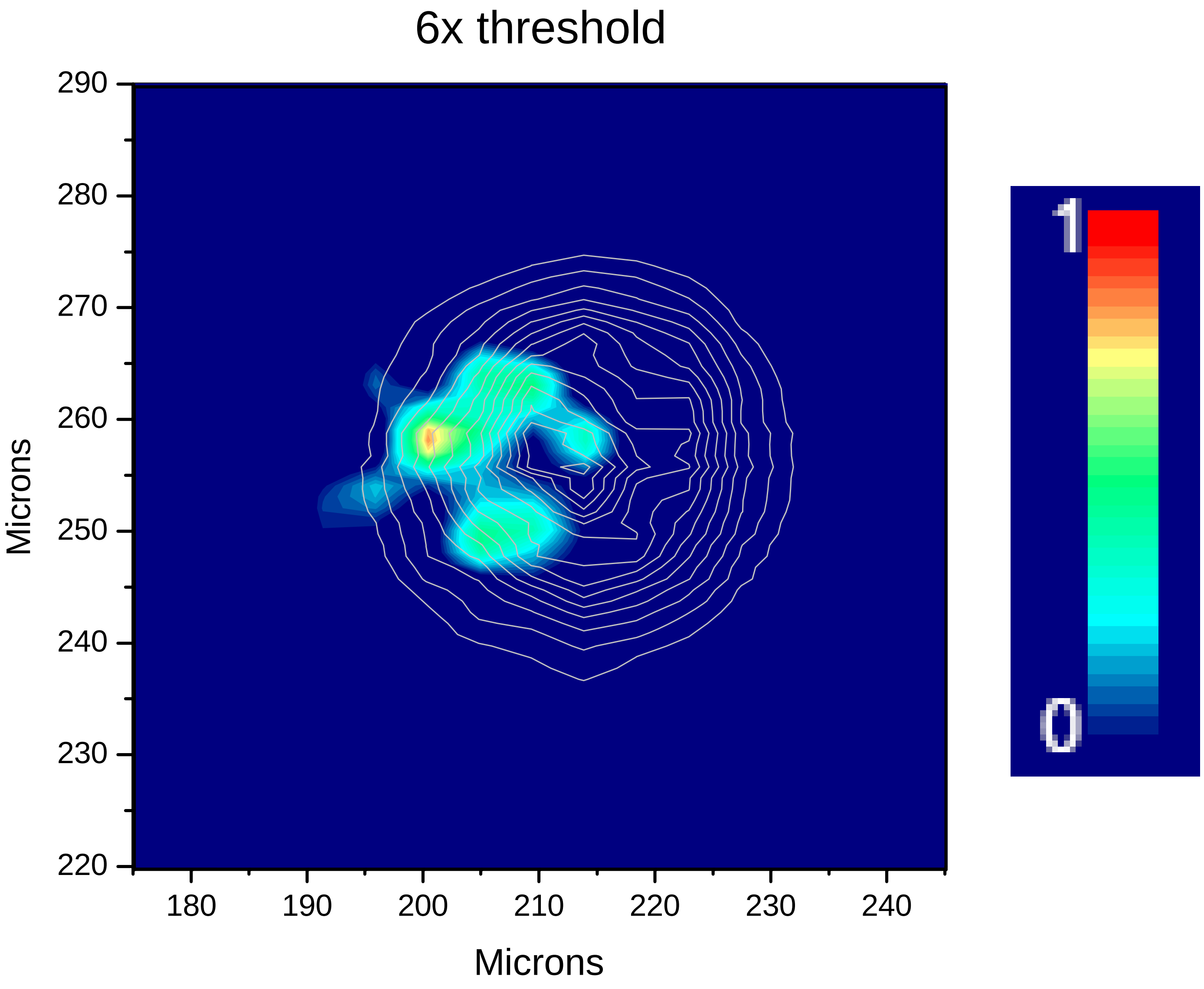
D M Whittaker Phys. Rev. B63, 193305 (2001)

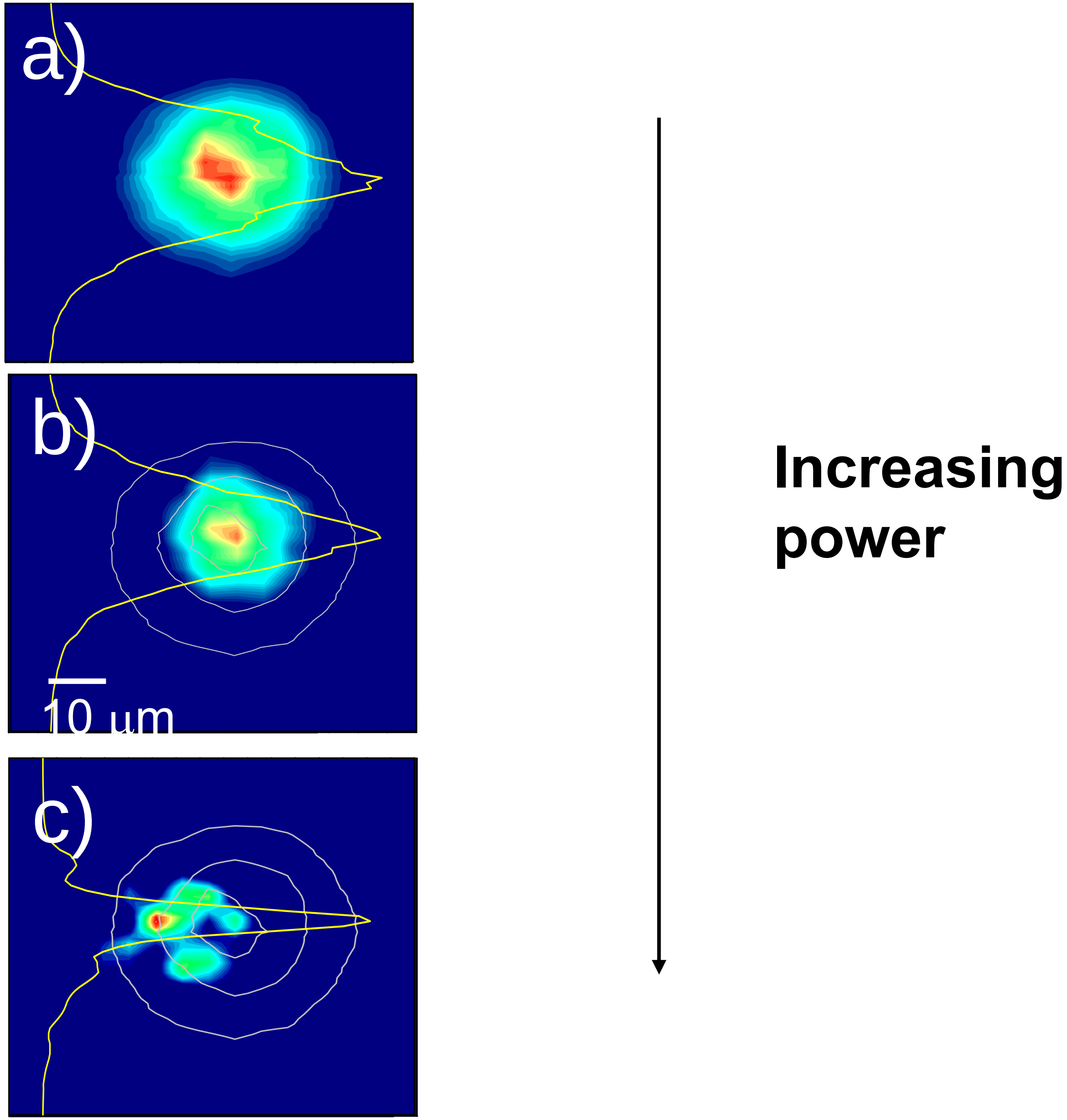
Spatially resolved polariton images

Below threshold

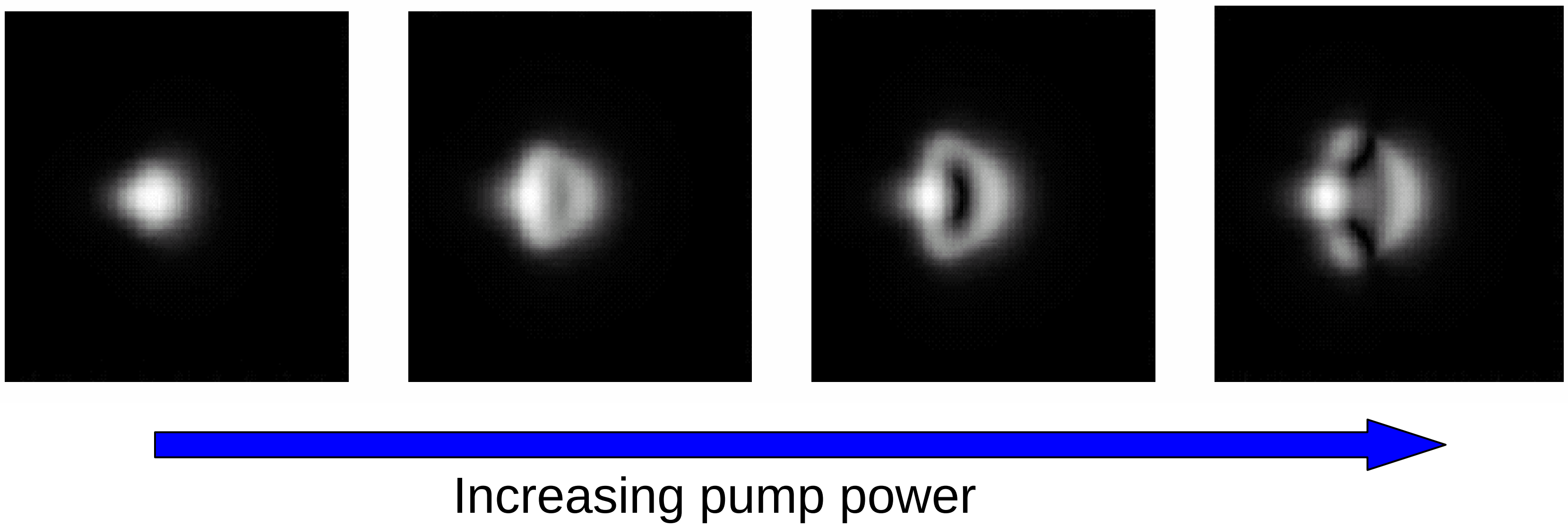


Spatial distribution of the signal




a)
b)
10 μm
c)
Increasing
power

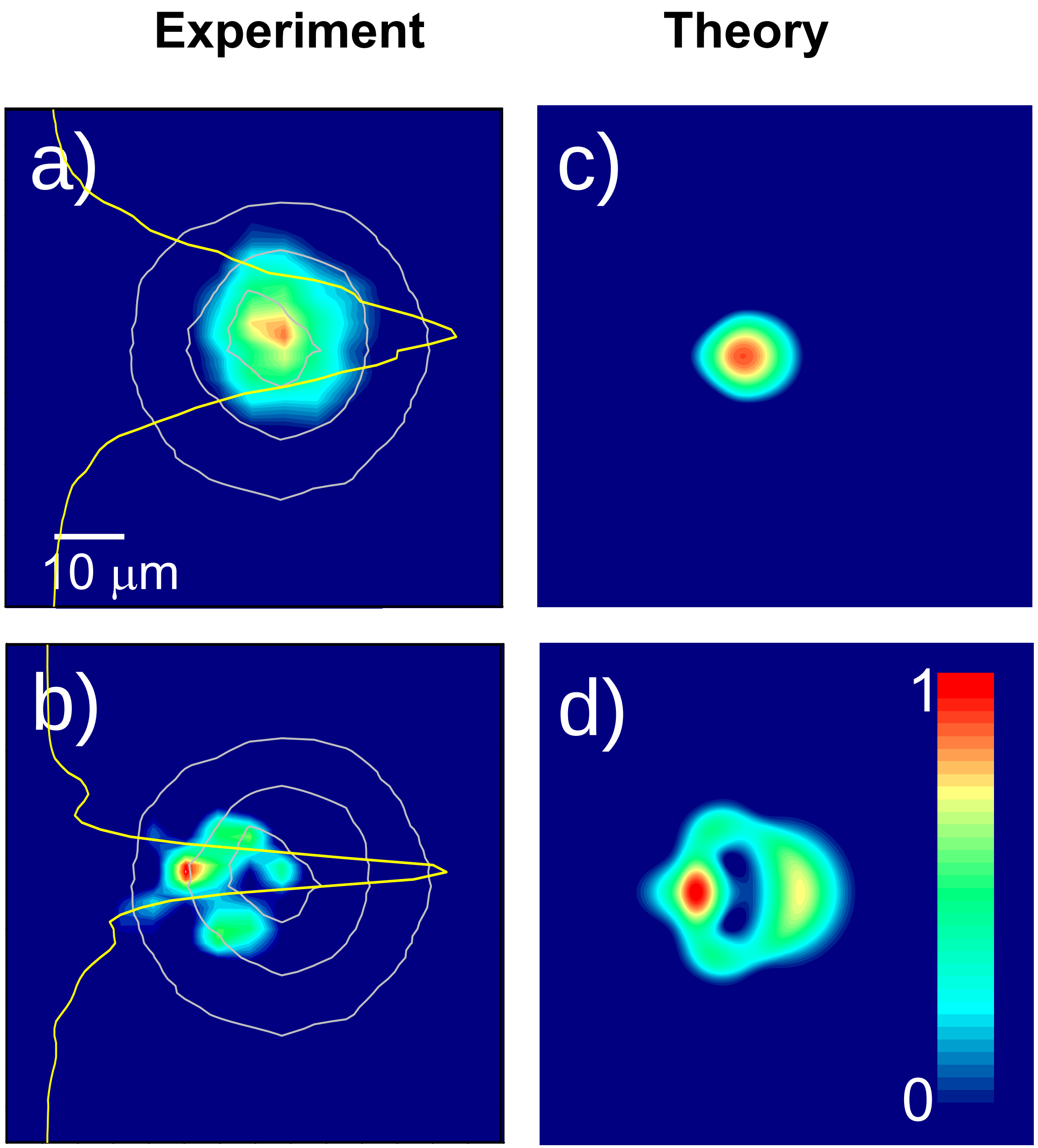
Theory: Spatial evolution of the signal state



- **Depletion in centre of beam due to blue shift**

D M Whittaker Phys. Stat. Sol. (c) 2, 733 (2005),Sanvitto, *Phys Rev* ***B73, 241308, 2006***

A Baas et al, PR **B70**, 161307, 2004, PR **A69**, 023809, 2004



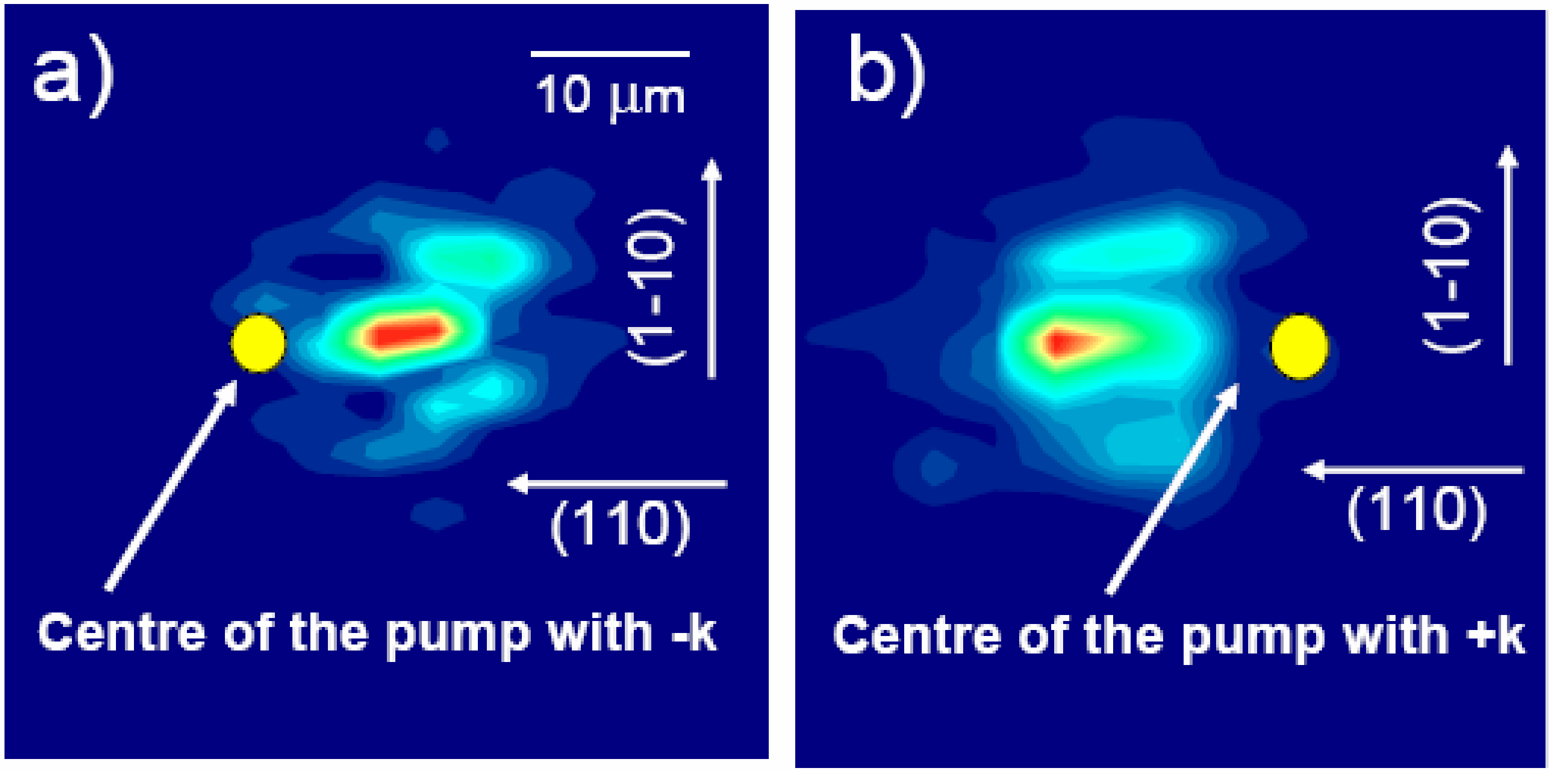
Similarities between theory and experiment:

Depletion around pump spot

Shift along direction of pump

But strong localisation experimentally

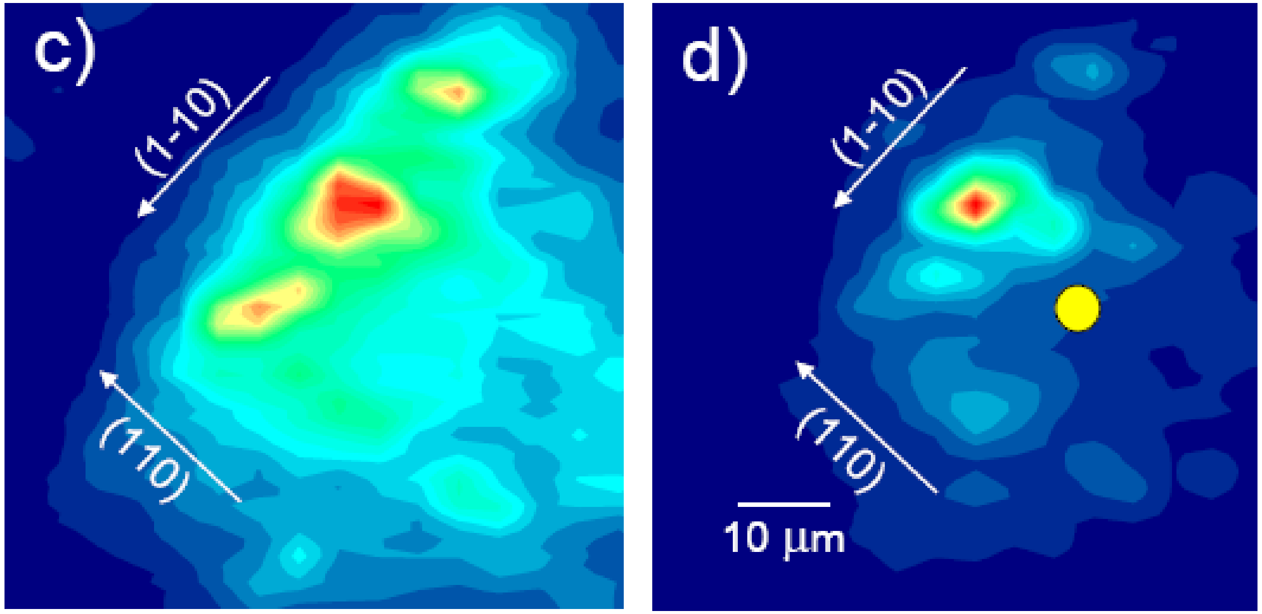
Another region on the sample, larger spot size



Note [110] ordering, plus disorder

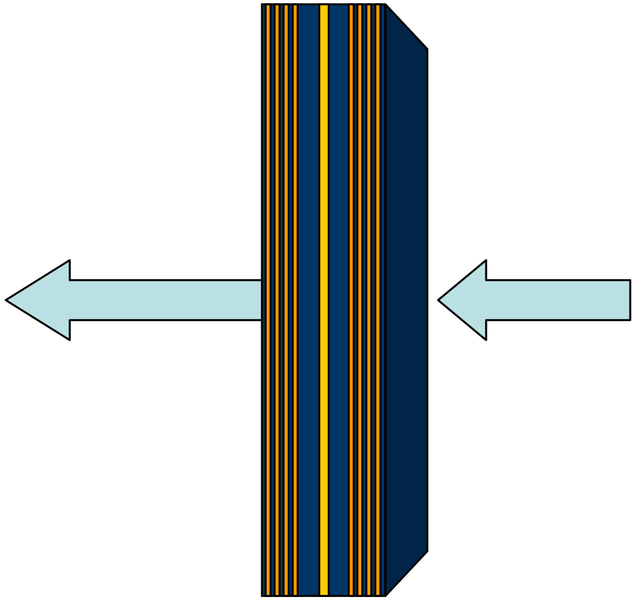
Shift parallel to pump beam, as predicted

Sample rotated by 45 degrees

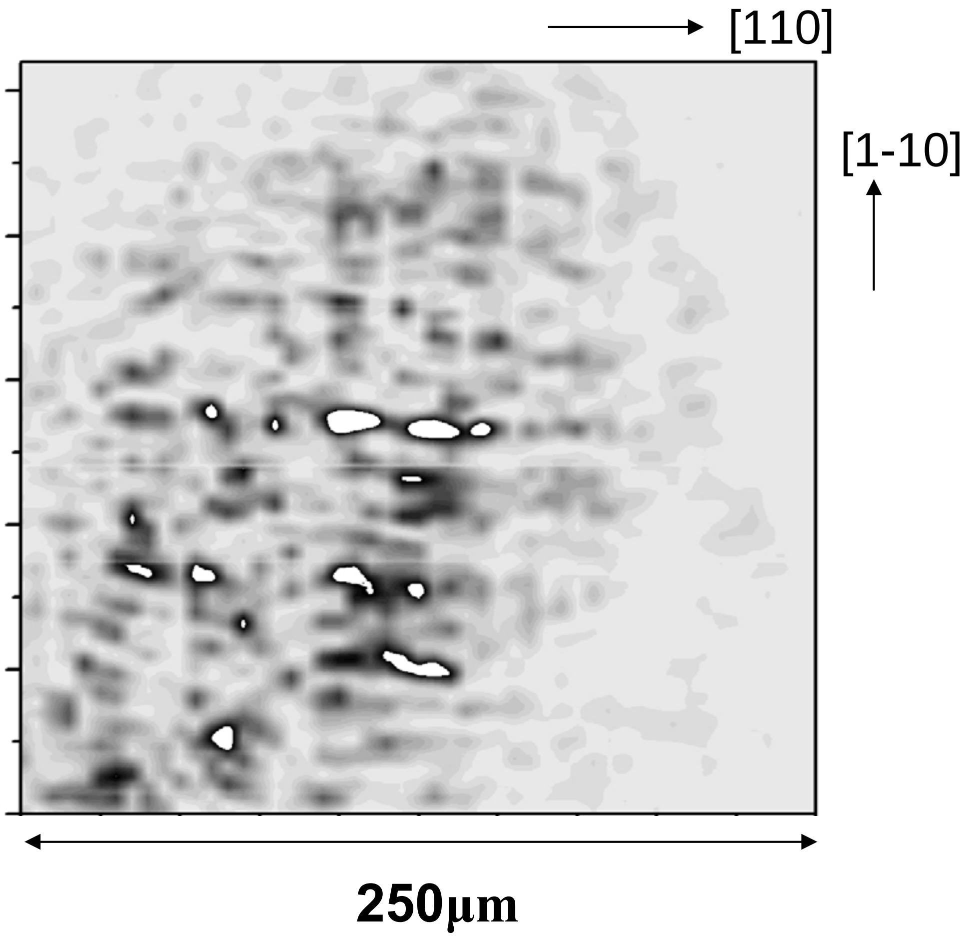


Supports (110) ordering

Origin of Spatial Patterning: Imaging in the Linear Regime in Transmission



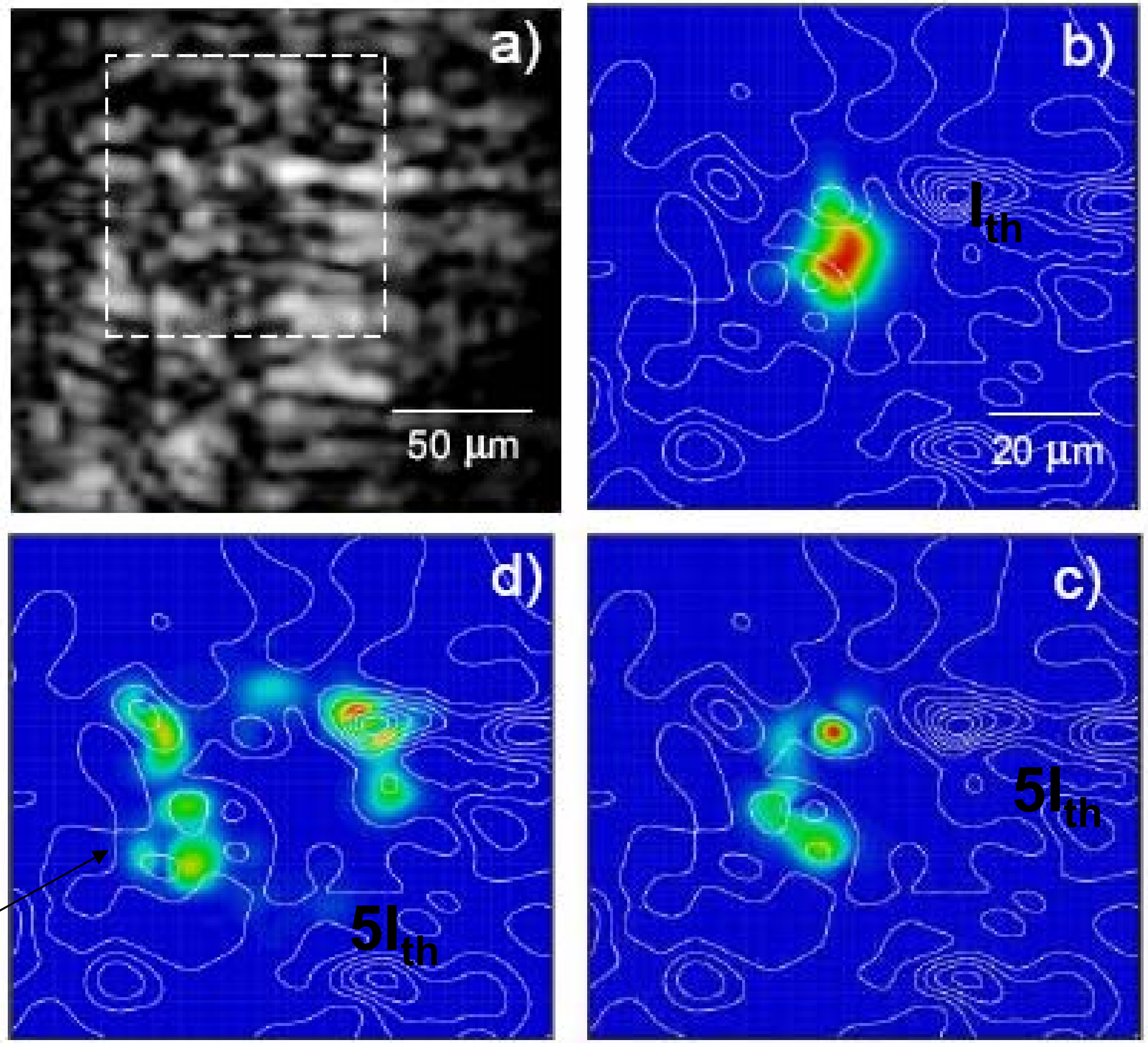
Laser in resonance with lower polariton branch



See also W Langbein, ICPS2002, Houdre PRB Gurioli PRB 64, 165309, 2004 for evidence for (110) potential in MBE material

Deduce: photonic Potential (fluctuations 5-10μm length scale, 2-300 μeV depth), partial (110) ordering

Simulations using the real photonic potential:
Good qualitative agreement with experiment



Maxima at positions of optimum phase matching

Larger spot:

Ring plus ordering

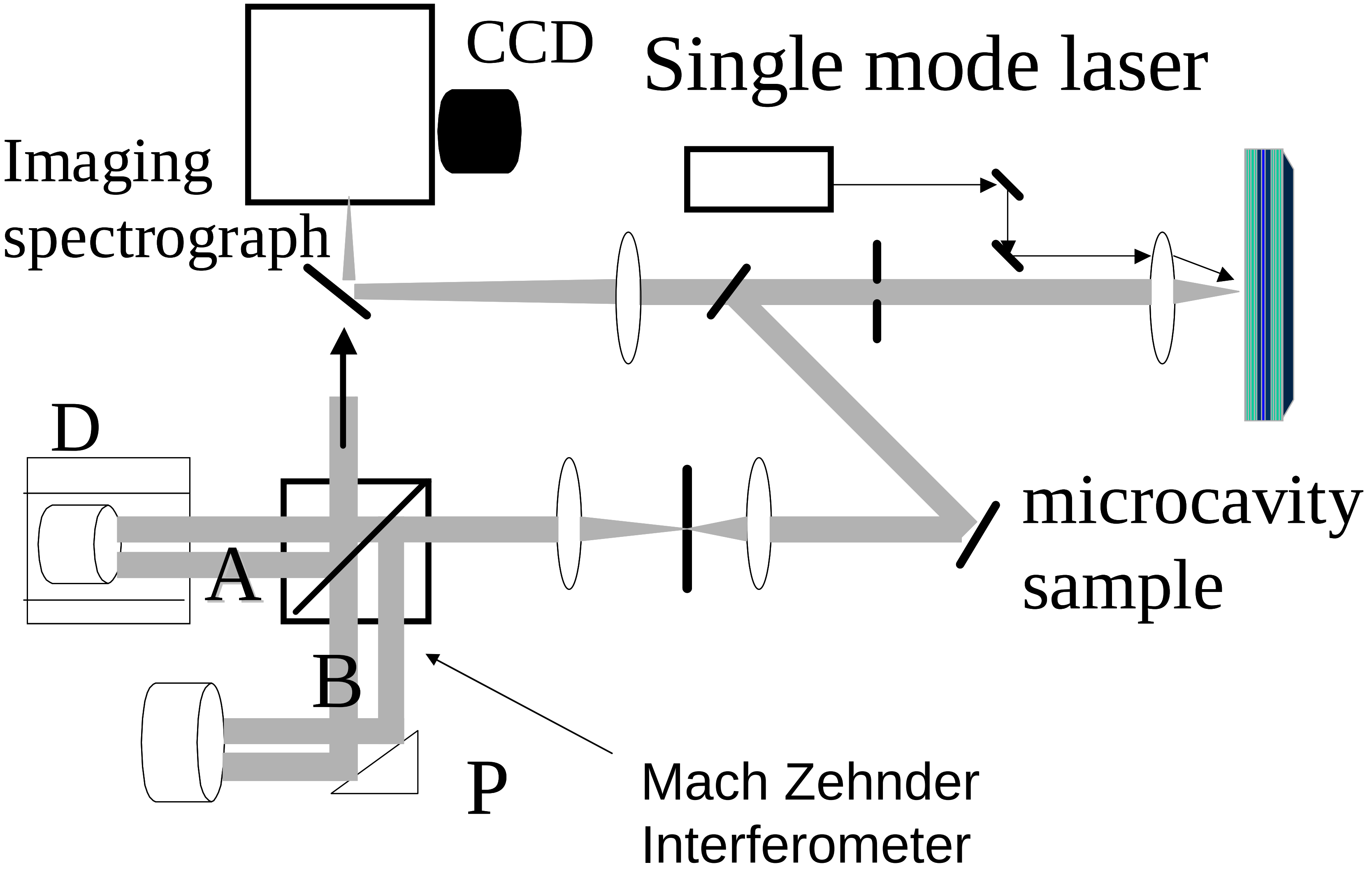
Mode Structure and Coherence

Effects of Interactions 1

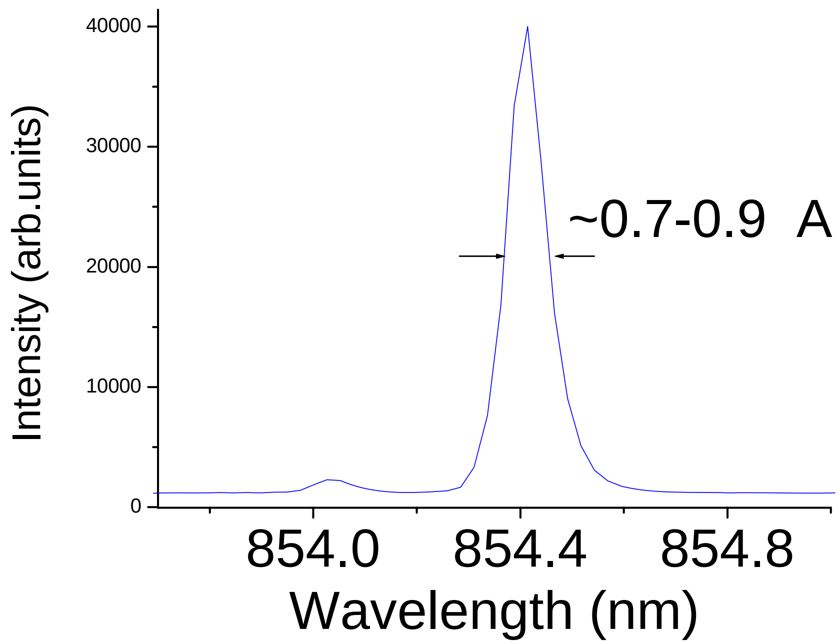
*Krizhanovskii et al, Phys Rev Lett **97**, 097402, 2006*

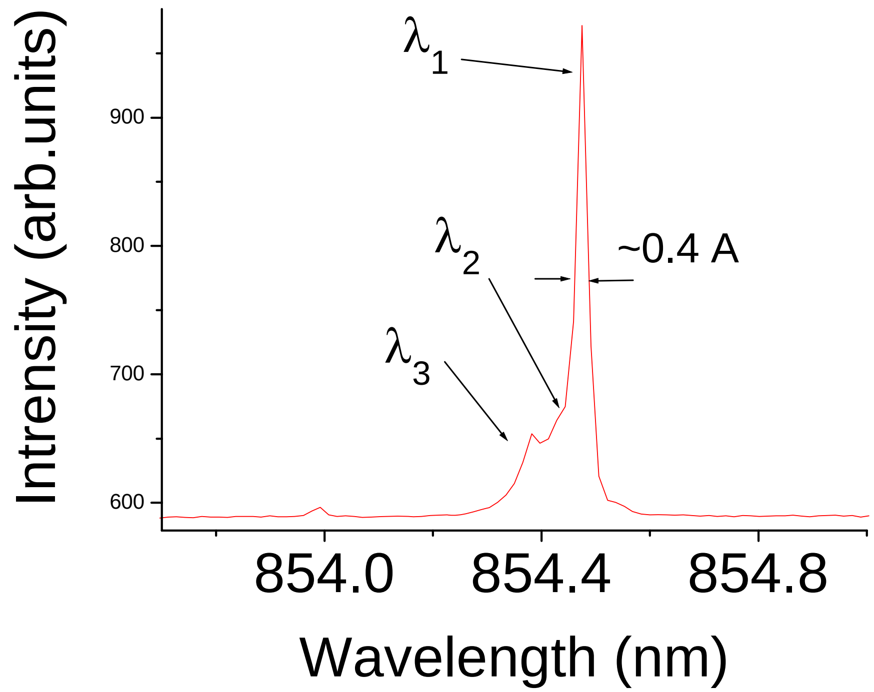
*See also Baas et al PRL **96**, 176401, 2006*

Experimental set-up for spatially & spectrally resolved images



Spectral structure

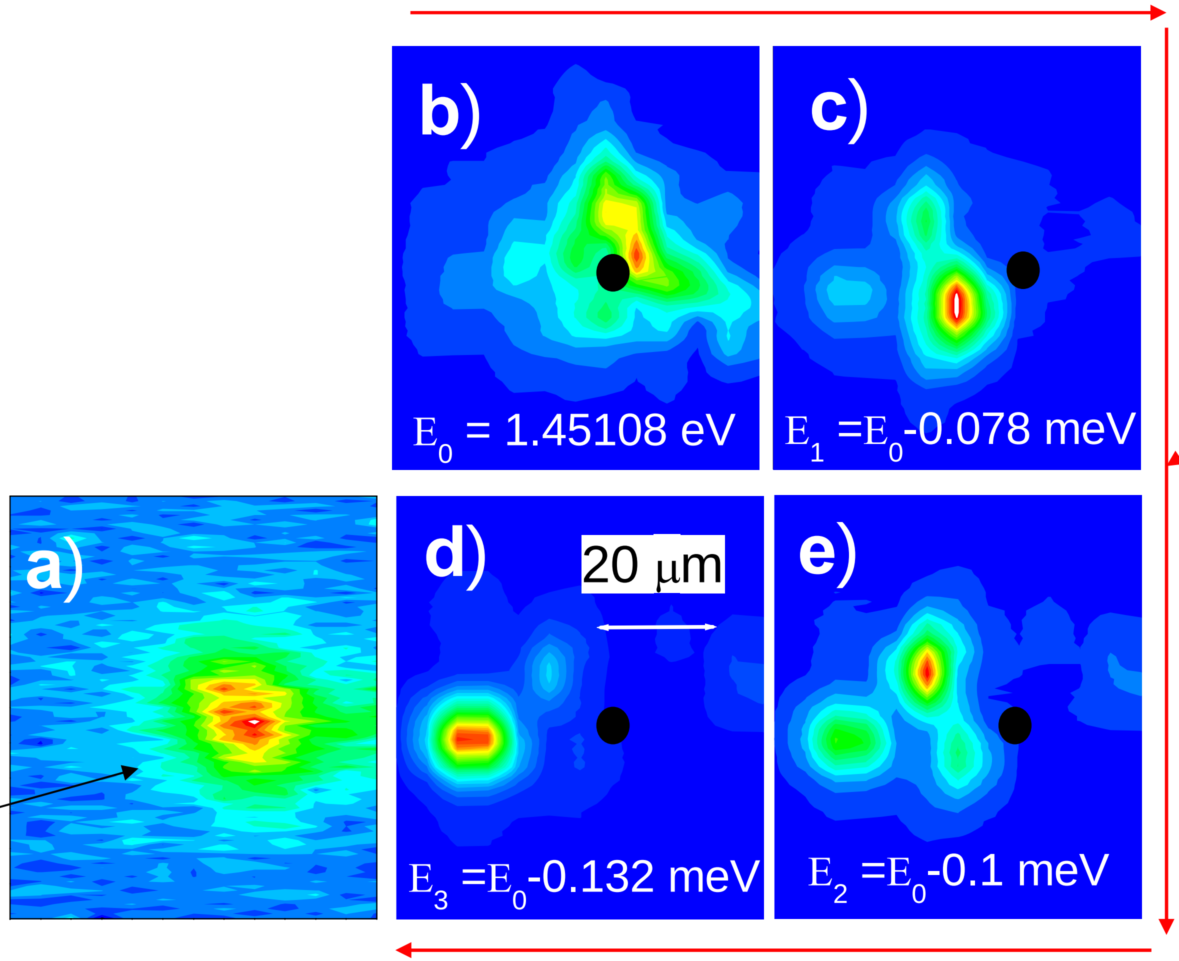




Excitation with
multimode Ti-Sapphire laser

Excitation with single mode
diode laser. Linewidth
resolution limited

Spectrally Resolved OPO Images at P ~ 10 P_{thr}

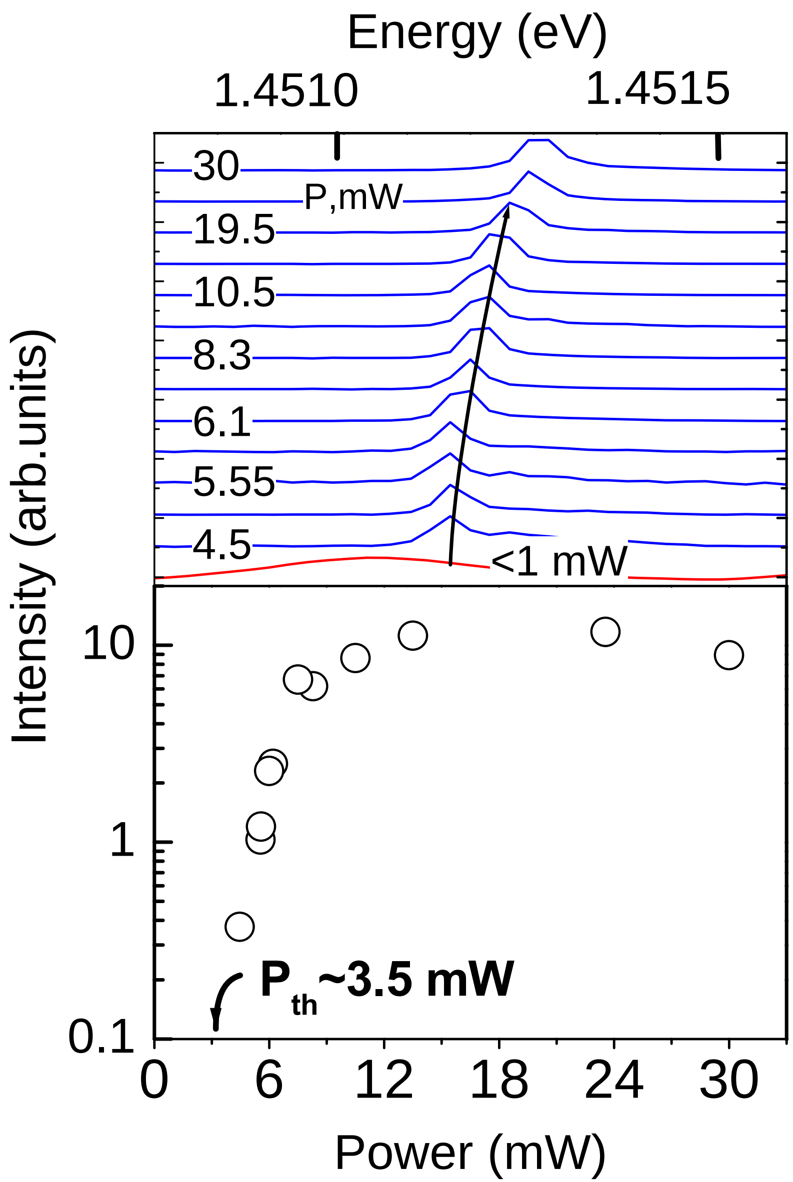


Decreasing energy, less blue shift

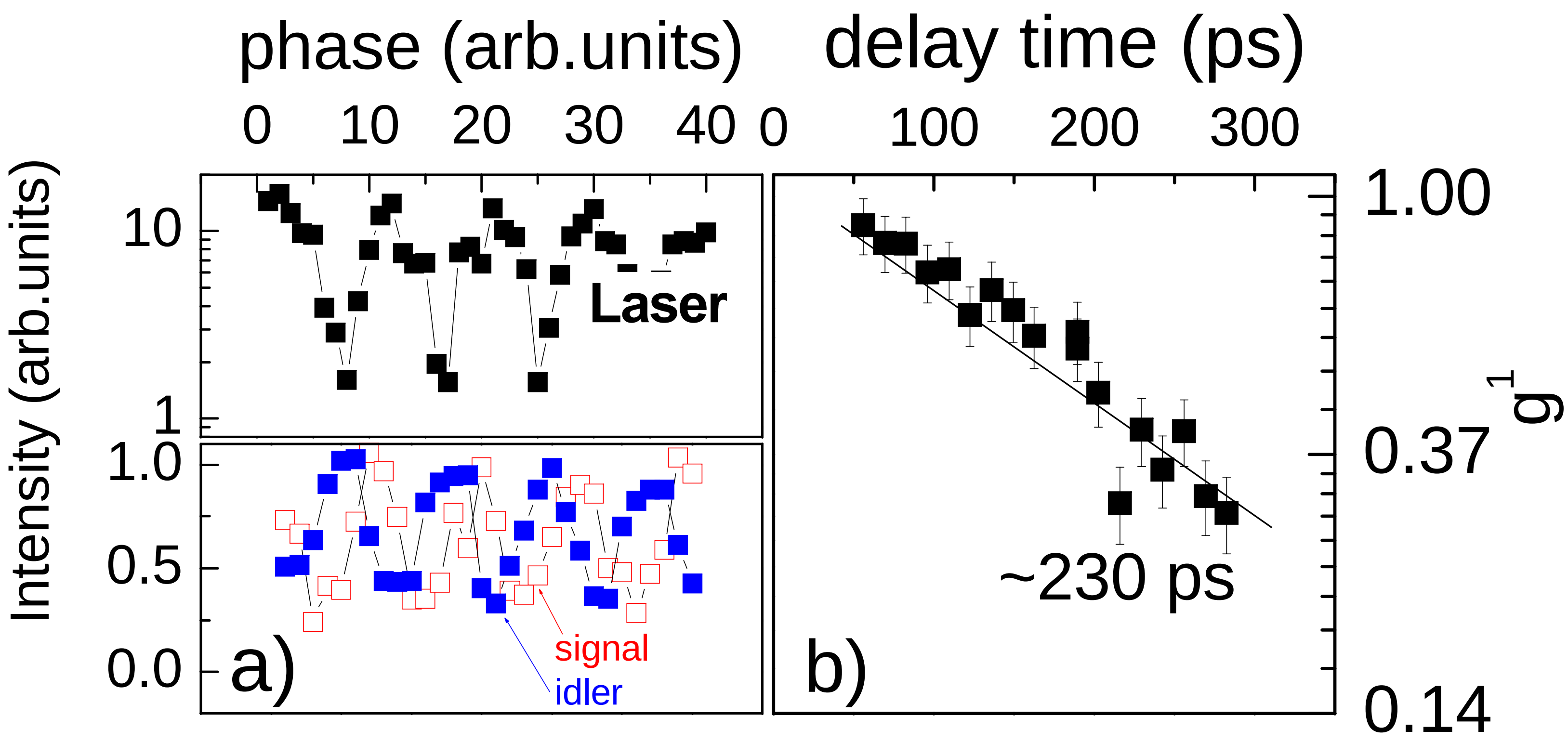
Below threshold

Mode energy decreases with distance from pump spot – decreasing blue shift, since lower density

Single mode spectra as a function of power



Measure Coherence Time Using Mach-Zehnder Interferometer



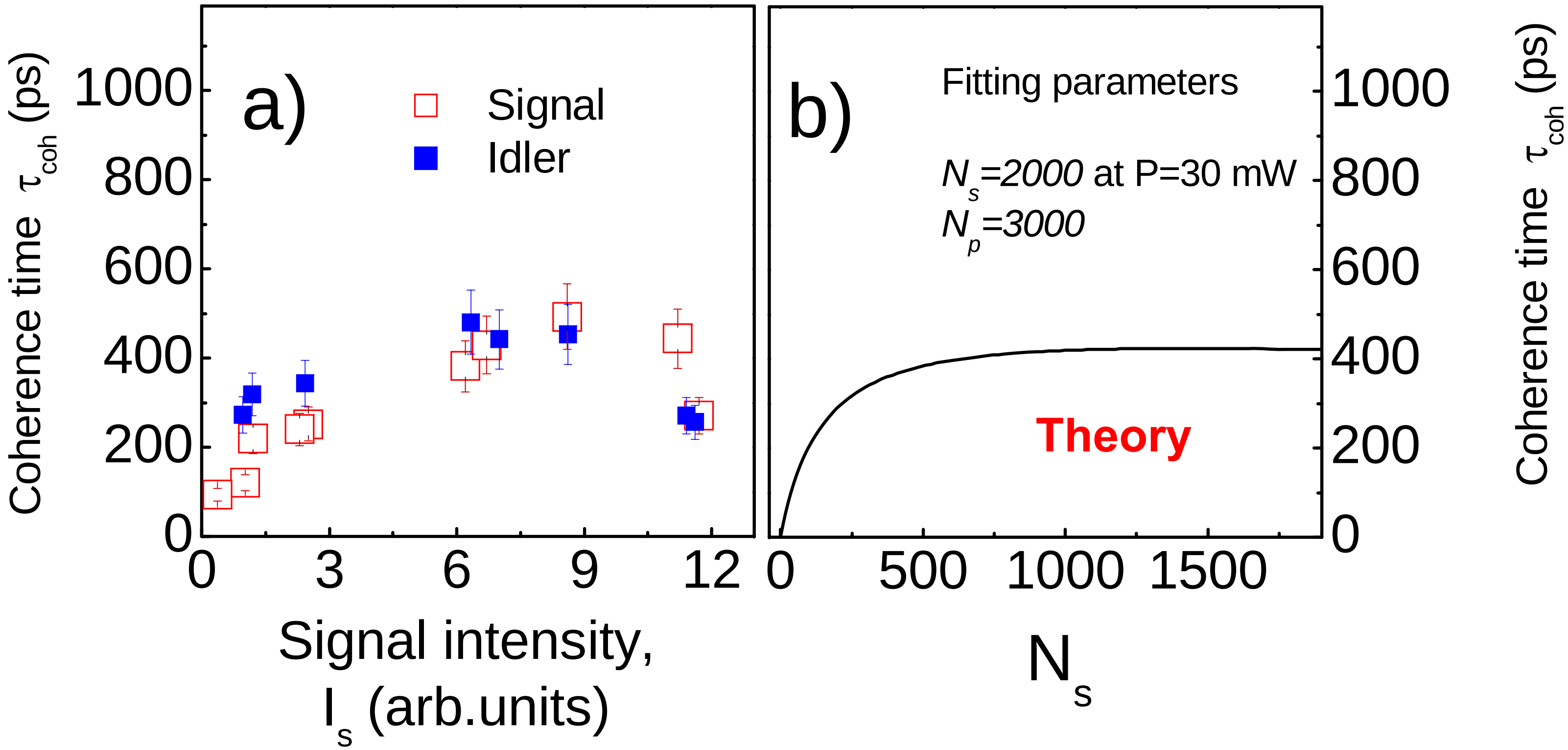
First order correlation function (visibility of interference fringes)

$$g^1(\tau_d) = \langle E(t)E(t+\tau_d) \rangle = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

$$g^1(\tau_d) \rightarrow \tau_{coherence}$$

Temporal Coherence Time

Variation of Coherence Time With Occupancy of State

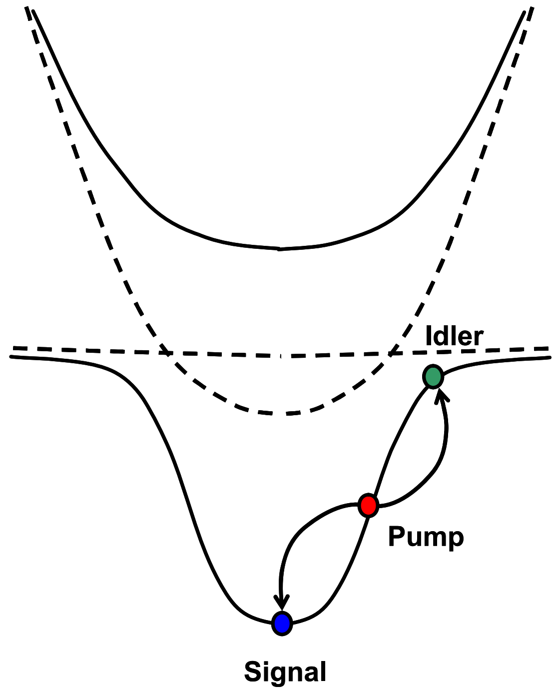


- Initial rapid increase, followed by near saturation at ~500psec (~2μeV) $\tau_{coh} \propto 1/\Delta E$
- More than an order of magnitude shorter than that of pump
- Contrast with laser where coherence time increases linearly (non-interacting particles)

The blue shift (arises from polariton-polariton interactions)

$$E_s^{blue} \sim \chi^3 \left(\frac{\gamma_i}{(\gamma_i + \gamma_s)} (N_s - N_i \frac{\gamma_s |X_i|^4}{\gamma_i |X_s|^4}) + \frac{2}{(\gamma_i + \gamma_s)} (\gamma_i |X_s|^2 - \gamma_s |X_i|^2) N_p \right)$$

- Depends on populations at signal, pump and idler states, N_s, N_p, N_i



Estimation of coherence time

- Number fluctuations in macroscopically occupied state
- Give rise to energy fluctuations in blue shift, and hence line broadening
- Limit coherence time

Assume Poissonian number fluctuations $\delta N_s = N_s^{0.5}$

$$1/\tau_{coh} = 1/\left(\tau_{sp} * N_s\right) + \chi^3 \sqrt{\left(\frac{\gamma_i}{\gamma_i + \gamma_s}\right)^2 N_s + \frac{4}{\left(\gamma_i + \gamma_s\right)^2} (\gamma_i |X_s|^2 - \gamma_s |X_i|^2)^2 N_p}$$

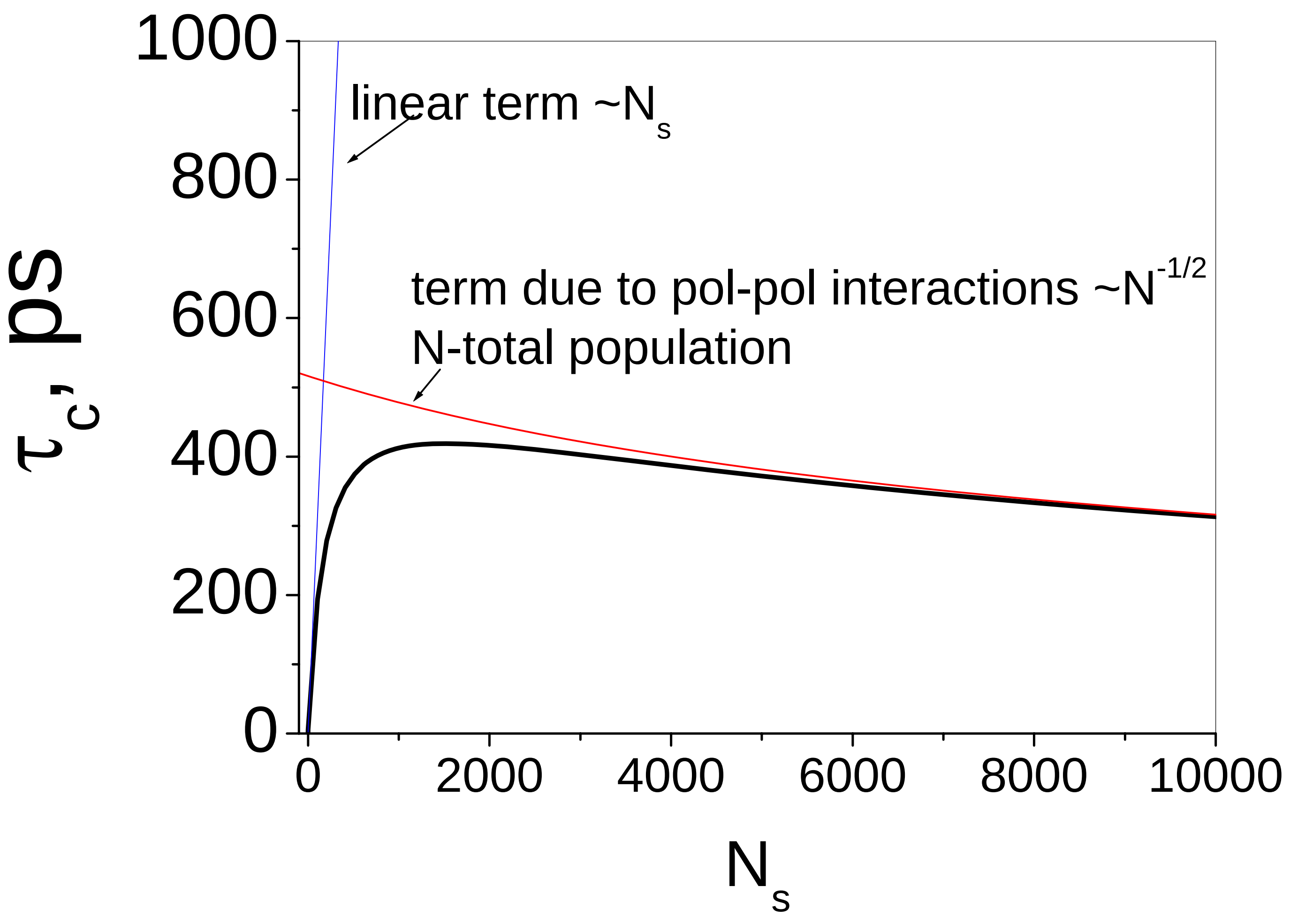
Non-interacting term. Ratio of stimulated to spontaneous particles

Interaction term, polariton-polariton interactions

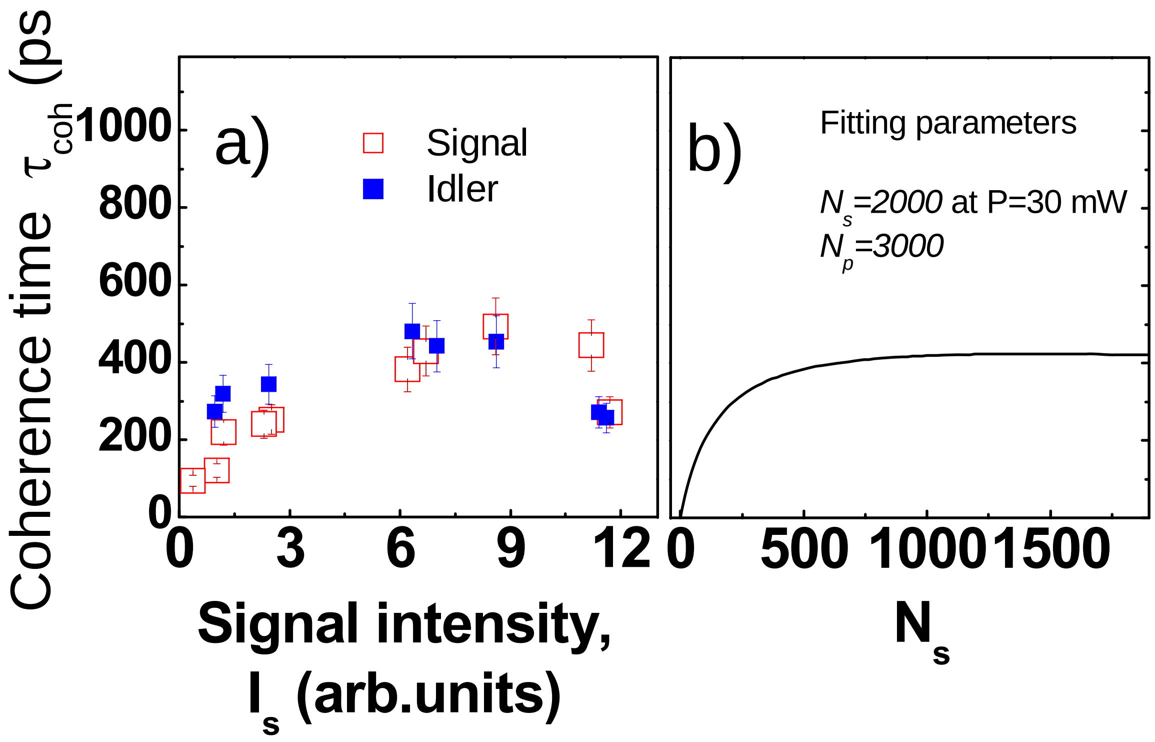
Coherence time increases with N. As in laser

$$\tau_{coh} \propto 1/\Delta E$$

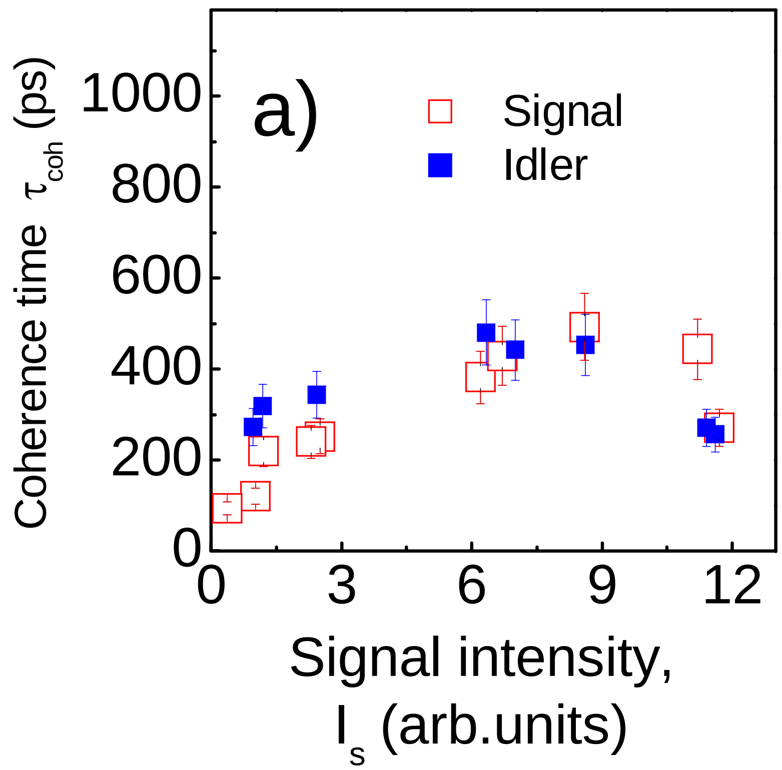
Contribution of two terms to coherence



- Using above (simple) theory, predict coherence time of ~500psec for state occupancy of ~1000
- Good agreement with experiment
- Overall form of variation with occupancy also reproduced
- Evidence for role of polariton-polariton interactions in determining the temporal coherence
- Interactions also limit the spatial coherence



Coherence Times of Signal and Idler



- Very similar coherence times for signal and idler
- Surprising?

Signal, Idler Coherence

- Signal and idler coherence times are the same over wide range of occupancy
- Temporal coherence is property of OPO coupled system, not of signal or idler separately
- Strong idler scattering affects coherence of signal as well as that of idler (pump, signal and idler are coupled)

- Phase and energy fluctuations of signal and idler are anti-correlated
- Hence equal temporal coherence times
- Not related to that of pump laser

$$\phi_s + \phi_i - 2\phi_p = 0 \qquad \phi_s + \phi_i = 2\phi_p$$

$$E_s + E_i - 2E_p = 0 \qquad E_s + E_i = 2E_p$$

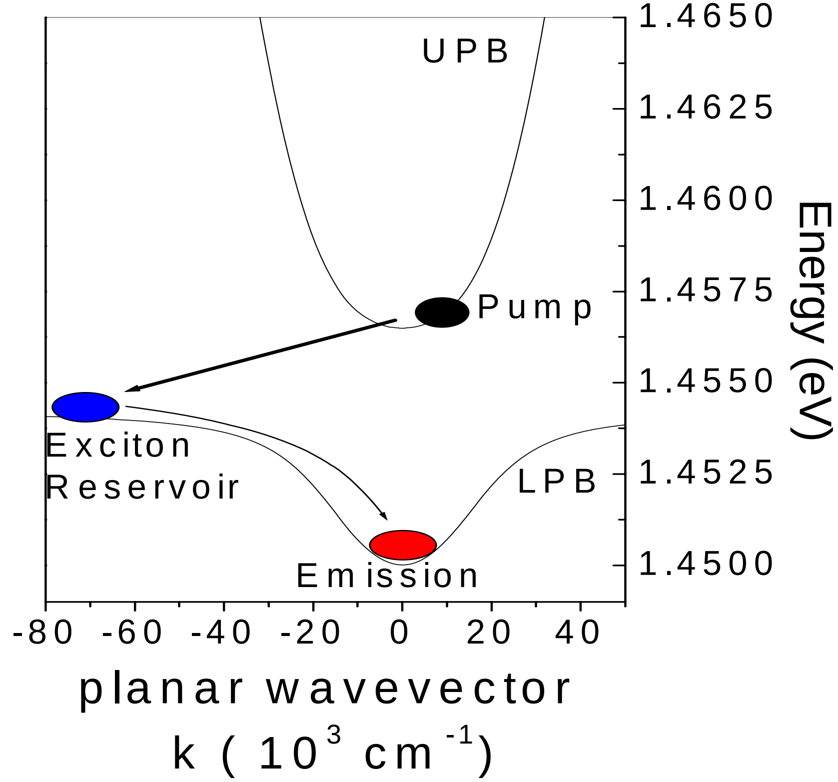
Effects of Interactions 2

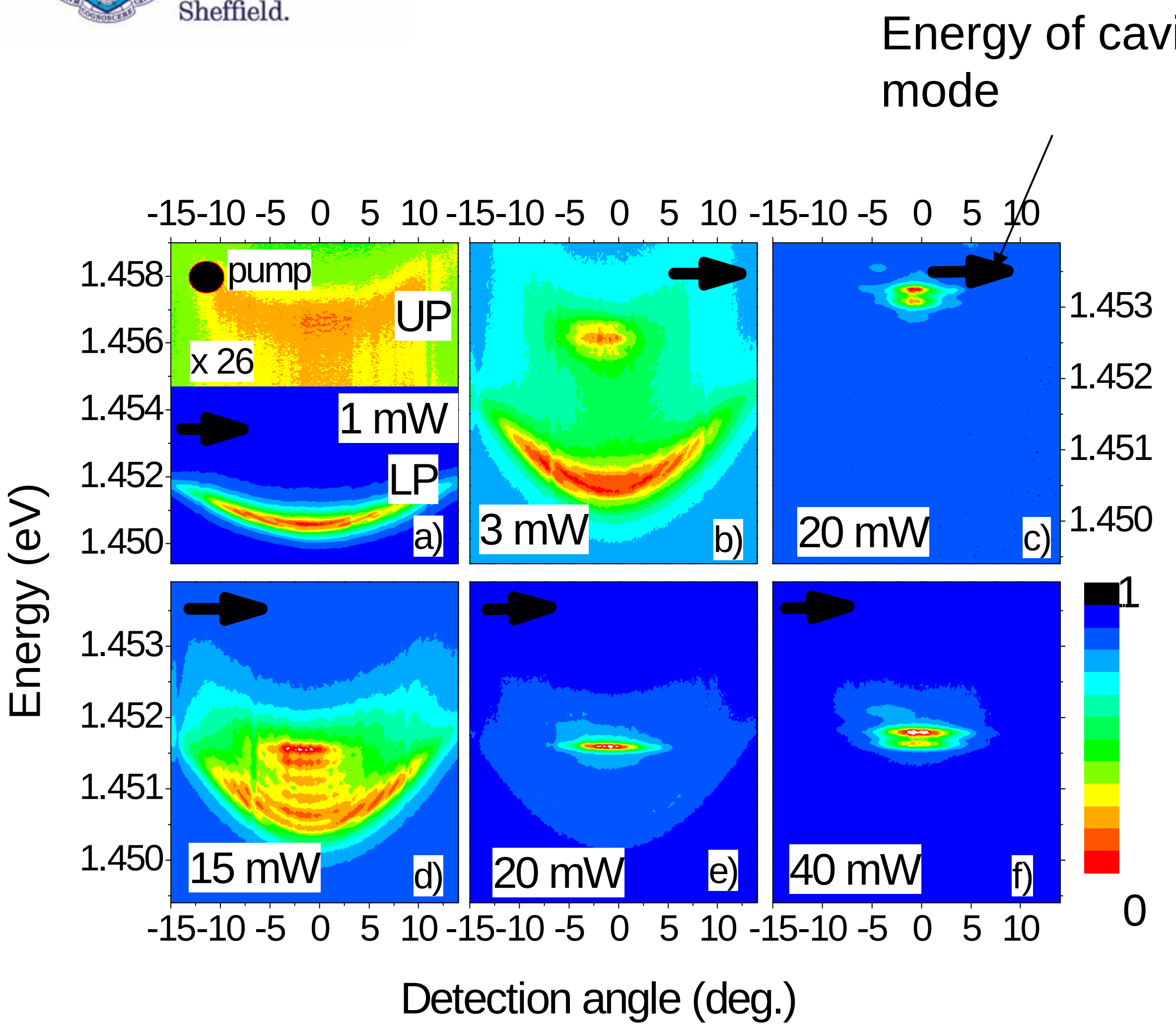
Resonant excitation into Upper Polariton Branch

Equivalent to non-resonant excitation

Occupation of non-equilibrium condensate

Importance of reservoir



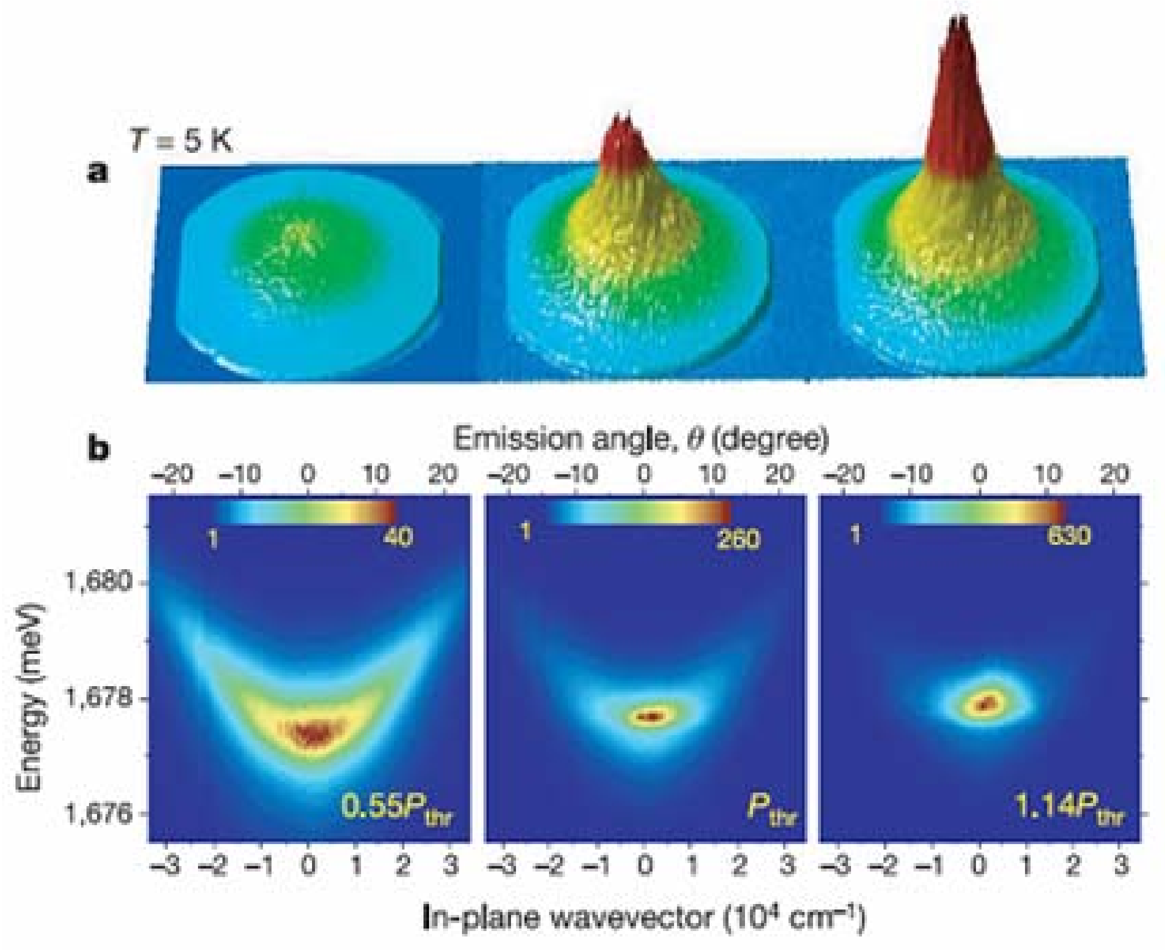


Excitation above GaAs band gap: Weak coupling

Resonant excitation into UP branch: Strong coupling

Coherent emission in strong coupling regime is observed

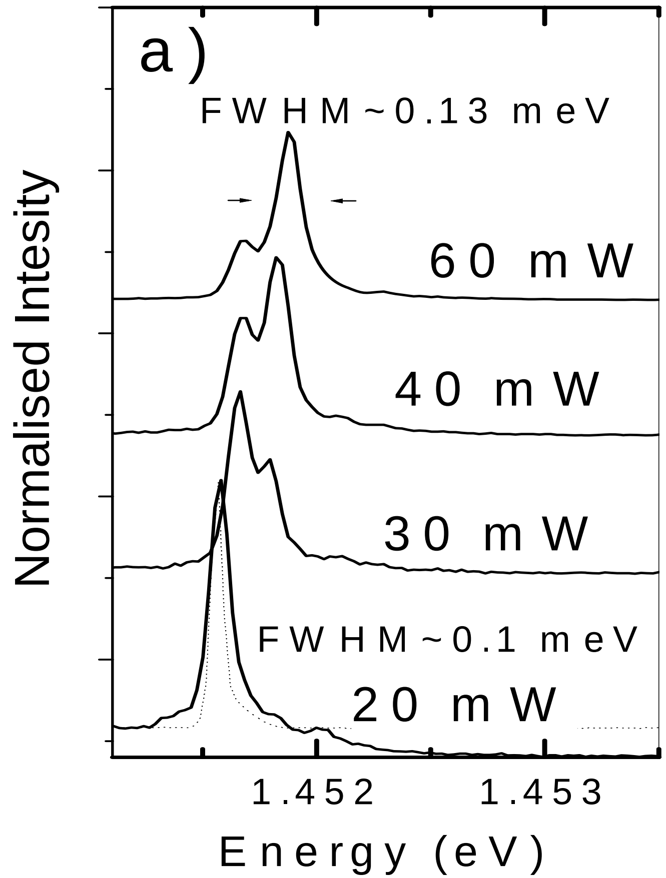
Non-equilibrium condensate, occupancy ~500



Kasprzak et al, Nature 443, 409 (2006)

II-VI Microcavities

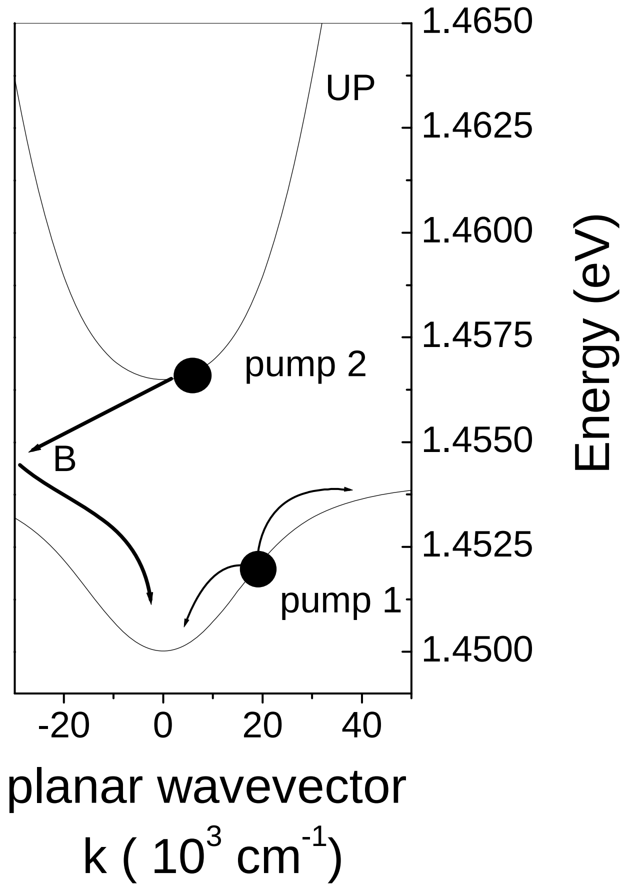
Coherence of stimulated emission



Coherence time is 10-20 ps due to strong exciton-polariton interactions (was 500psec for excitation into lower branch)

Marked interaction between condensed polaritons at k=0 and excitons in 'reservoir'

Effect of Interactions 3: population of of exciton reservoir on the coherence of occupied state

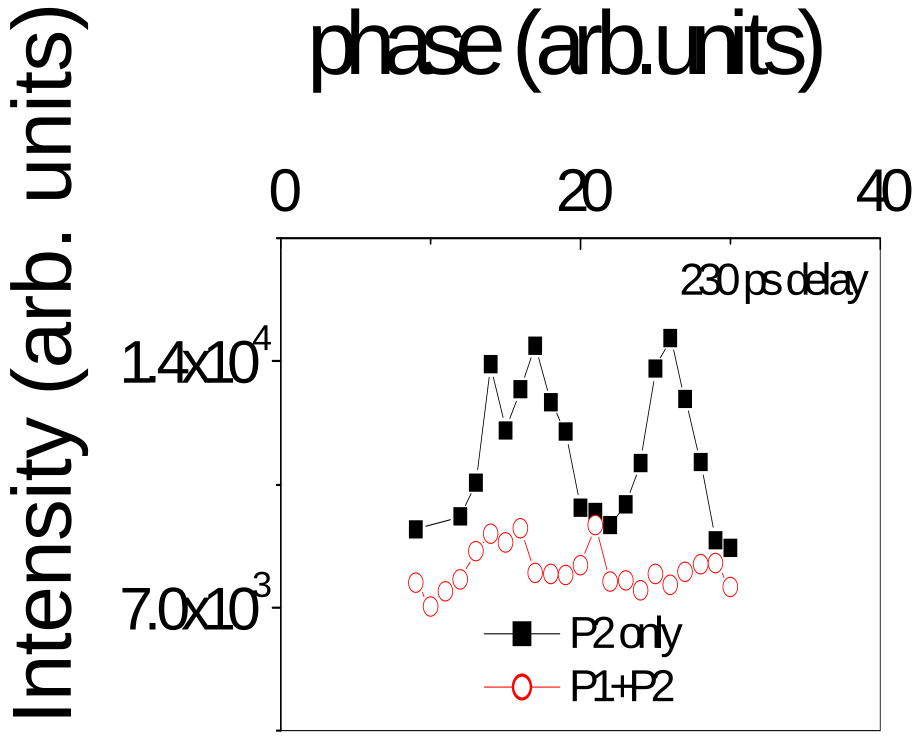


Pump 1: excitation into lower branch
Creates high density phase

Pump 2: weak optical excitation
=> population of exciton reservoir

Two – beam experiment

- **Pump 2:** coherence time ~180ps
- **Pump 1 + Pump 2**: coherence time of reduced to ~70ps due to strong interactions with the reservoir excitons



Summary

1. Spatial properties need to be understood to study fundamental properties of macrosopically occupied states
2. Interactions determine coherence properties
3. Limited spatial coherence
4. Coherence times much longer for resonant excitation. Better isolated system in resonant case?
5. Strong role of interactions