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The High Density Polariton Phase in Semiconductor Microcavities

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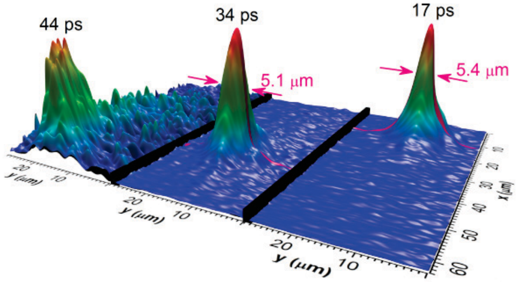
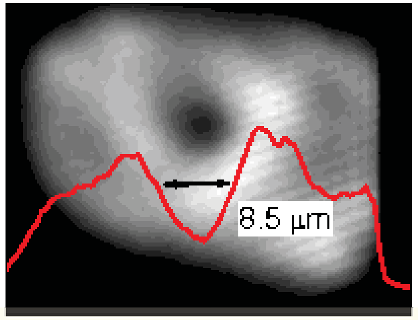
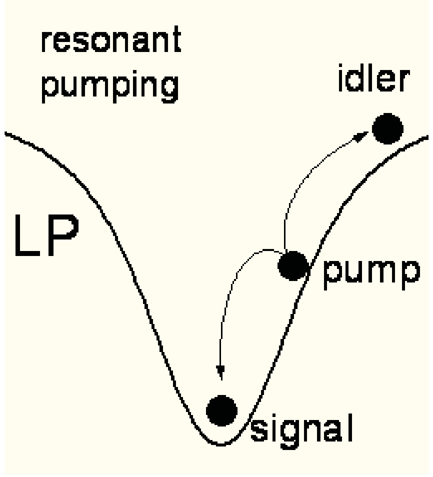
The High Density Polariton Phase in Semiconductor Microcavities

M S Skolnick, University of Sheffield

1. **Introduction to microcavity physics**
2. **Condensation in non-equilibrium system**
3. **Coexisting condensates**
4. **Imprinted vortices and healing length**
5. Bright solitons
6. **Summary**







The University Of Sheffield.

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MARIE CURIE ACTIONS

Acknowledgements

Experiments: D N Krizhanovskii, M Sich, A P D Love, R A Bradley, K Guda, D Sarkar, D Sanvitto, L Vina (Madrid), K G Lagoudakis, B Deveaud (EPFL)

Theory D M Whittaker, M Wouters (EPFL, Antwerp)

Growth J S Roberts, R Hey, K Biermann (PDI), R Andre (Grenoble)

Periodic potential : P V Santos, E Cerda, Paul Drude Institute Berlin

Solitons: D V Skryabin, A V Gorbach, R Hartley (University of Bath)

Stevenson et al, Phys Rev Lett ***85****, 3680, 2000* *(OPO)*

Krizhanovskii et al, Phys Rev Lett ***97****, 097402, 2006* *(coherence, OPO)*

Love et al, Phys Rev Lett ***101****, 067404, 2008* *(coherence, BEC)*

Krizhanovskii et al, Phys. Rev. B ***80****, 045317, 2009* *(coexisting condensates)*

Krizhanovskii et al, Phys Rev Lett ***104****, 126402, 2010* *(vortices)*

Cerda et al, Phys Rev Lett ***105****, 116402 (2010)* *(surface acoustic waves)*

Semiconductor Microcavity

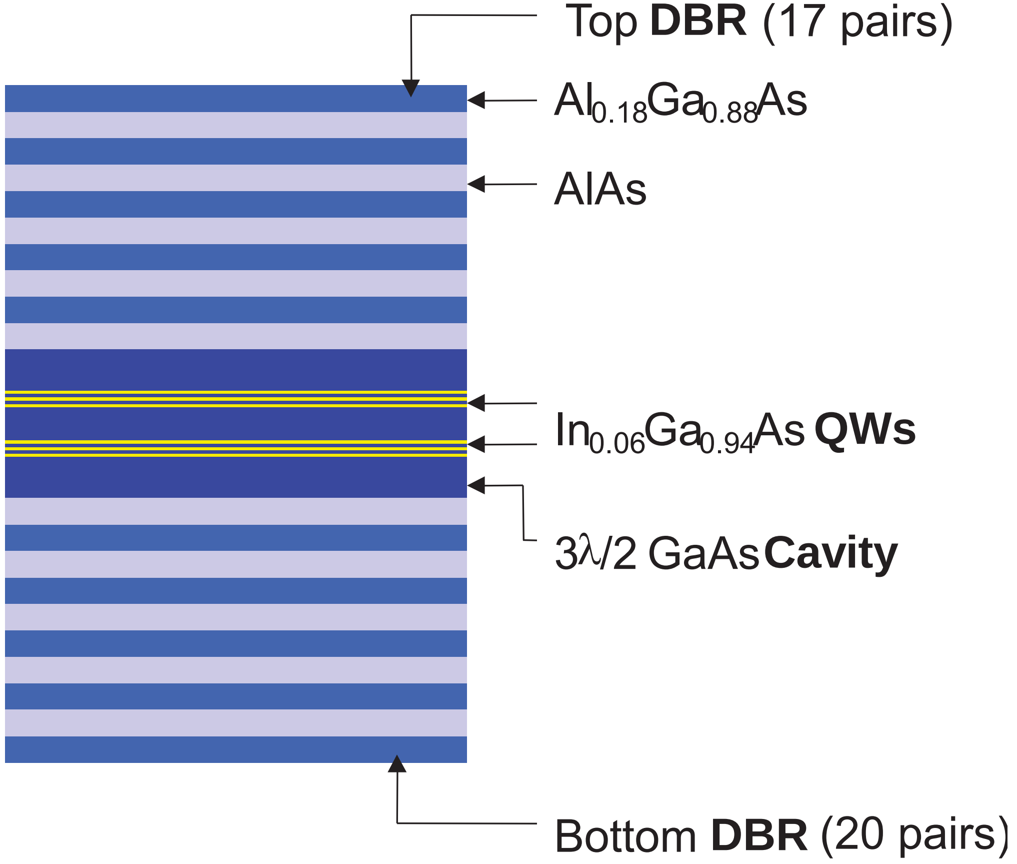
Fabry-Perot cavity with distributed Bragg reflector (DBR) mirrors).
One dimensional photonic structure

High reflectivity mirrors surrounding cavity

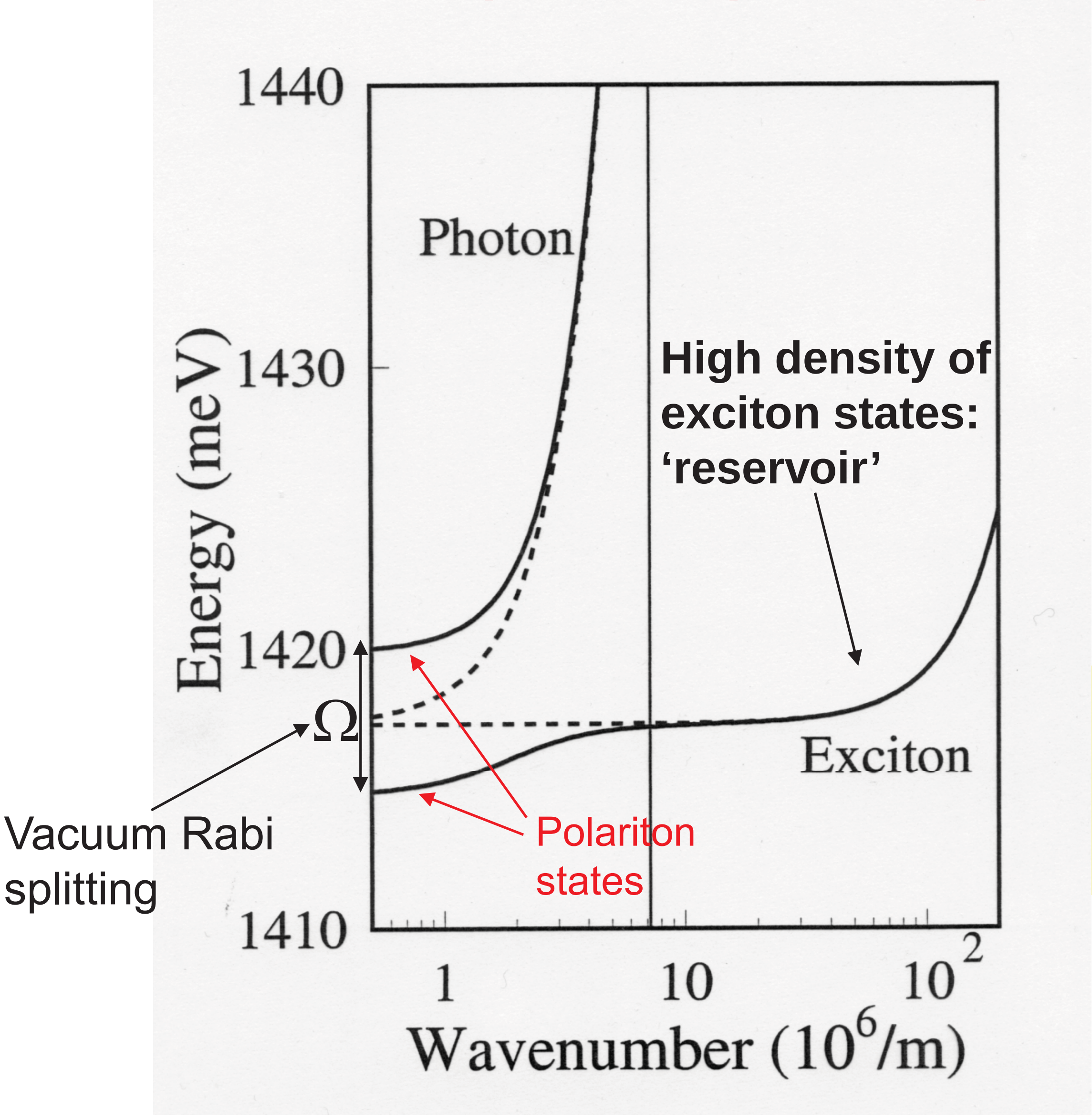
Quantisation of both optical field and excitons

Designed to be close to resonance

Similar structures to vertical cavity surface emitting lasers



Polariton dispersion (exciton-photon coupled modes)



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 ~ 6-15meV in GaAs based structures

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

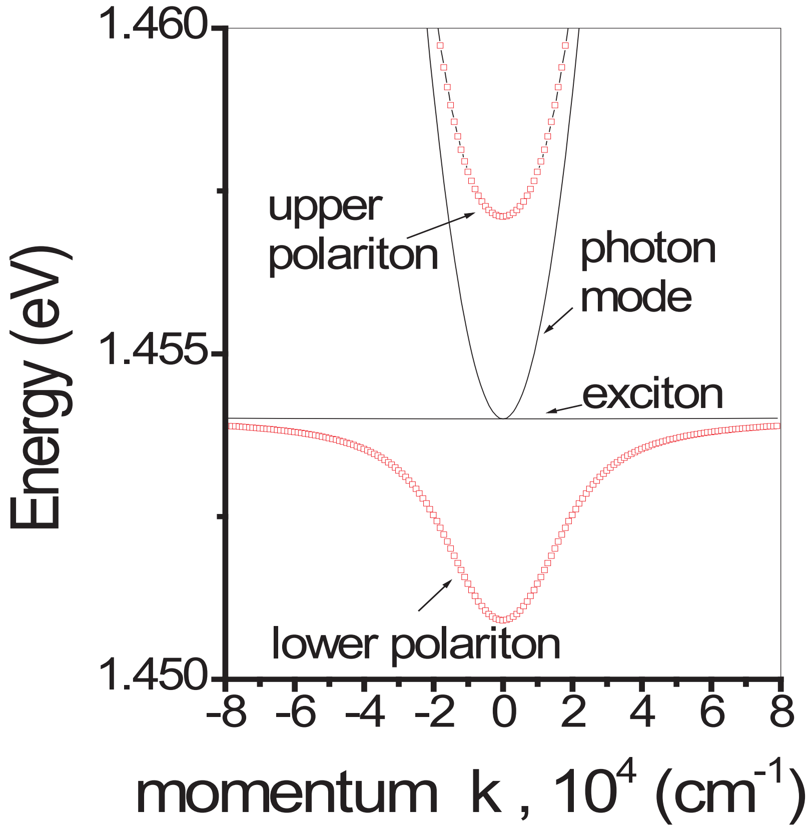
Strong Coupling

Energy exchanged between exciton and electromagnetic field

Photon emitted and then re-absorbed. Reversible process.

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

Lower Polariton Branch

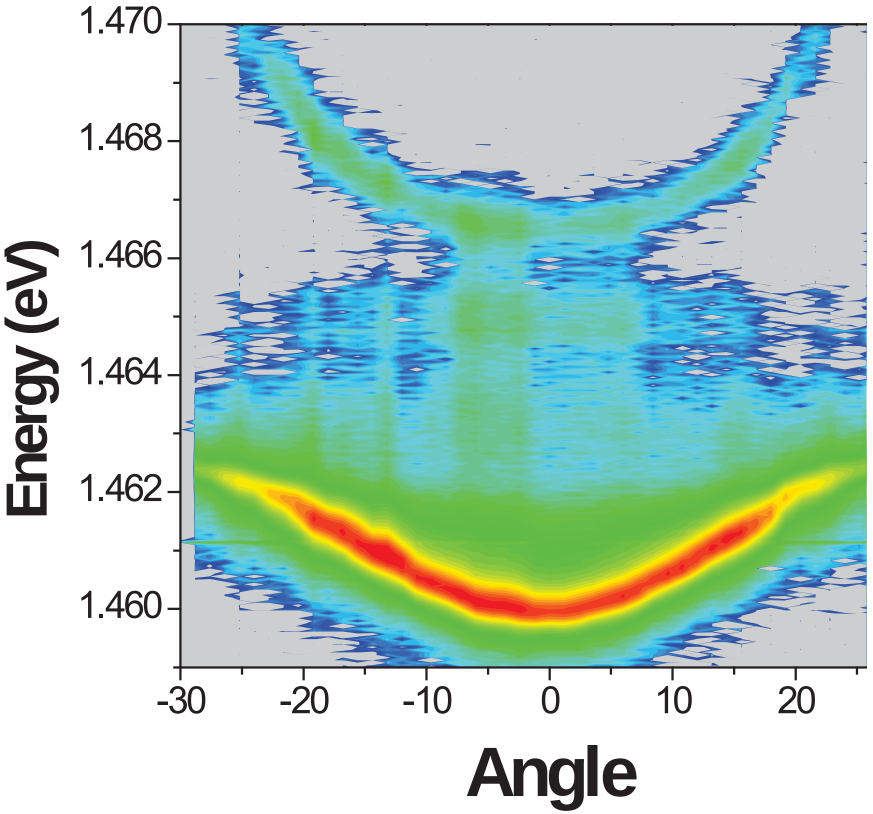


- m_{pol} ~10^{-4} times the electron mass
- High transition temperature $T_c \propto m^{-1}$
- Low density of states
- Can achieve macroscopic occupation
- Bosonic quasi-particles, scattering stimulated by final state occupation
- Strong non-linearities
- Point of inflection

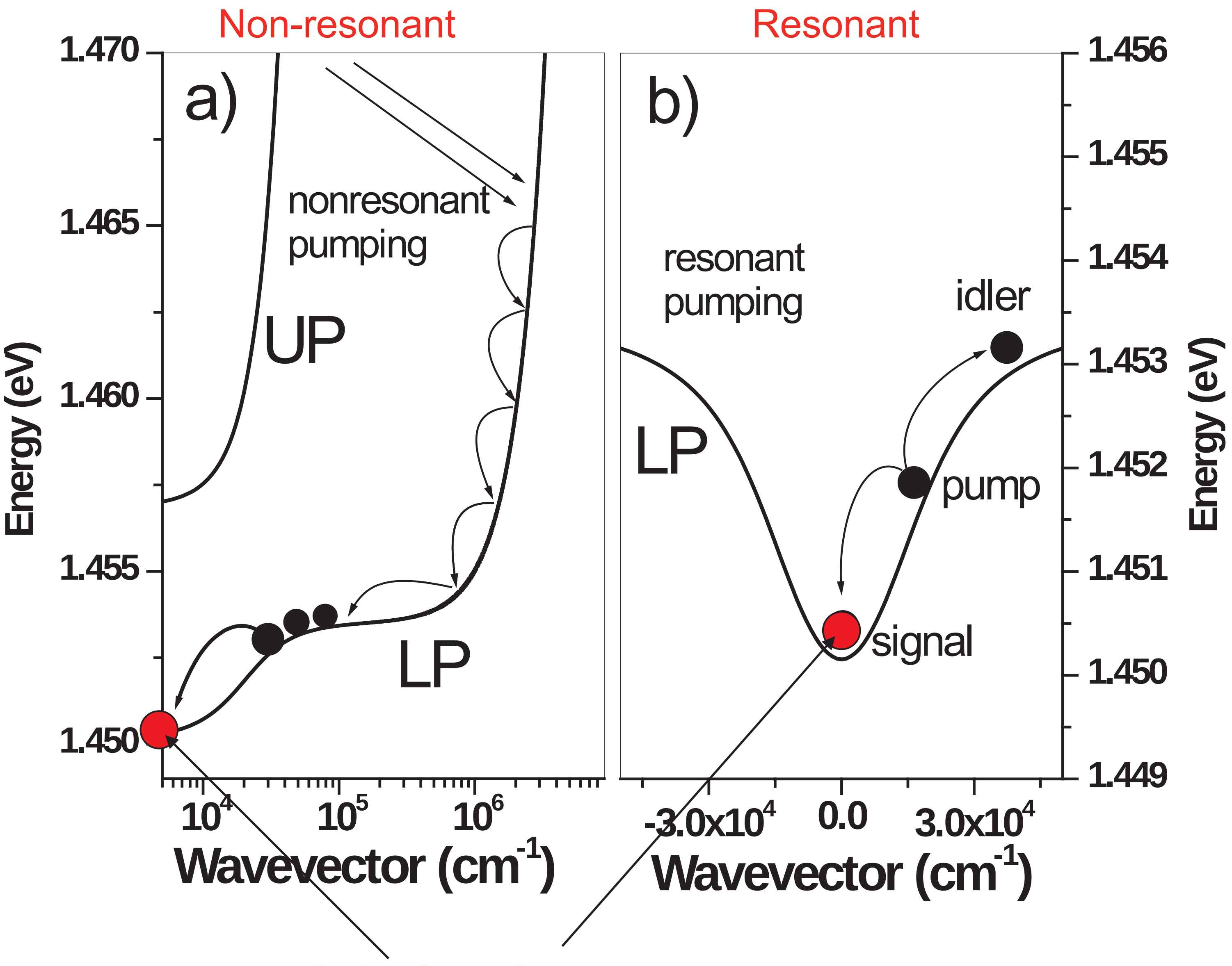
Below Threshold, Non-Resonant Excitation

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

Access to phase, amplitude and coherence of condensate



Creation of Macroscopically Occupied, Condensed State



High density state

Stimulated scattering into macroscopically occupied state

Final state stimulation of scattering.

In laser, particles in final state are photons. Give rise to stimulated emission

- Condensate is non-equilibrium
- Maintained by balance between pumping and losses
- Macroscopic wavefunction – extended spatial and temporal coherence (~50µm, 500psec)
- Described by generalized Gross-Pitaevski equation with pumping and loss*
- Some similarities to laser, but scattering process is stimulated

Wouters PRL 99, 140402, 2007, Keeling PRL 100, 250401, 2008

Gross-Pitaevskii equation with pumping and loss (M Wouters)

Pumping

Loss

$$i\hbar\frac{\partial\psi(\mathbf{r})}{\partial t}=\left\{E_0-\frac{\hbar^2}{2m}\nabla_{\mathbf{r}}^2+\frac{i\hbar}{2}\left[R[n_R(\mathbf{r})]-\gamma_c\right]+V_{ext}(\mathbf{r})\right.$$

External potential

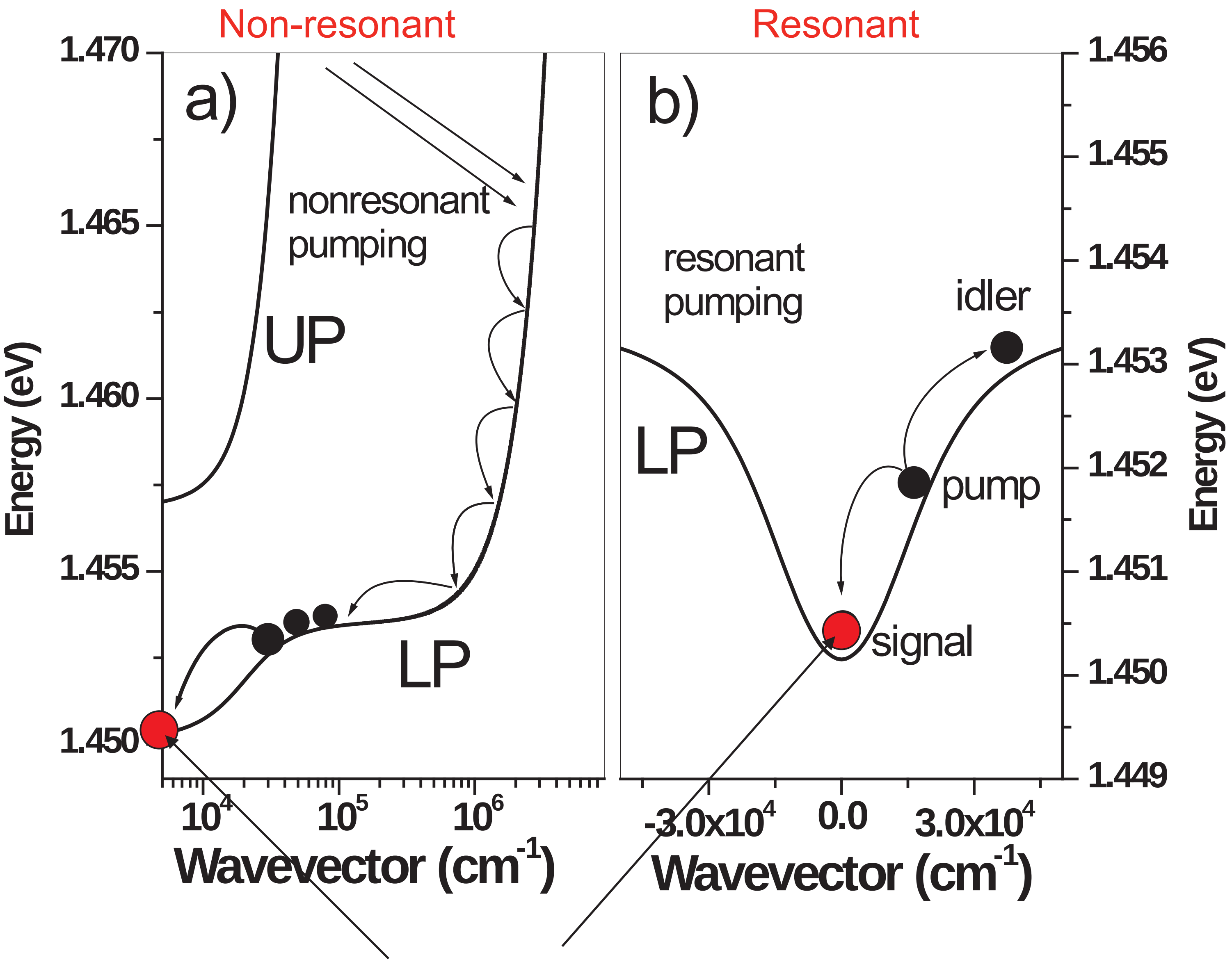
$$\left.+\hbar g\left|\psi(\mathbf{r})\right|^2+V_R(\mathbf{r})\right\}\psi(\mathbf{r}),$$

Interactions

See e.g. Wouters and Carusotto, PRL 99, 140402, 2007

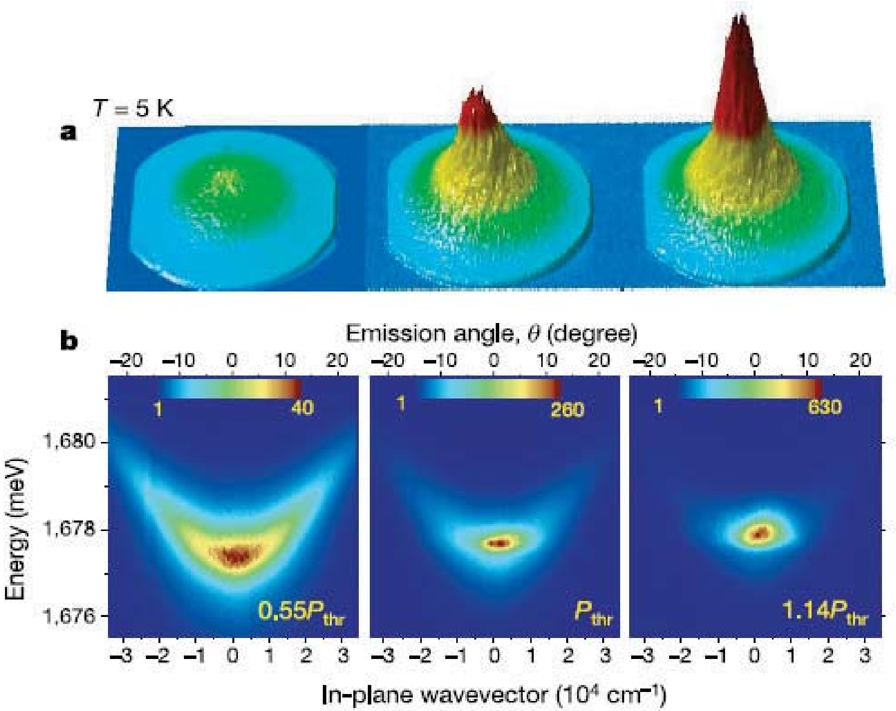
Keeling and Berloff, Contemporary Physics 52, 131, 2011

Creation of Macroscopically Occupied, Condensed State



High density state

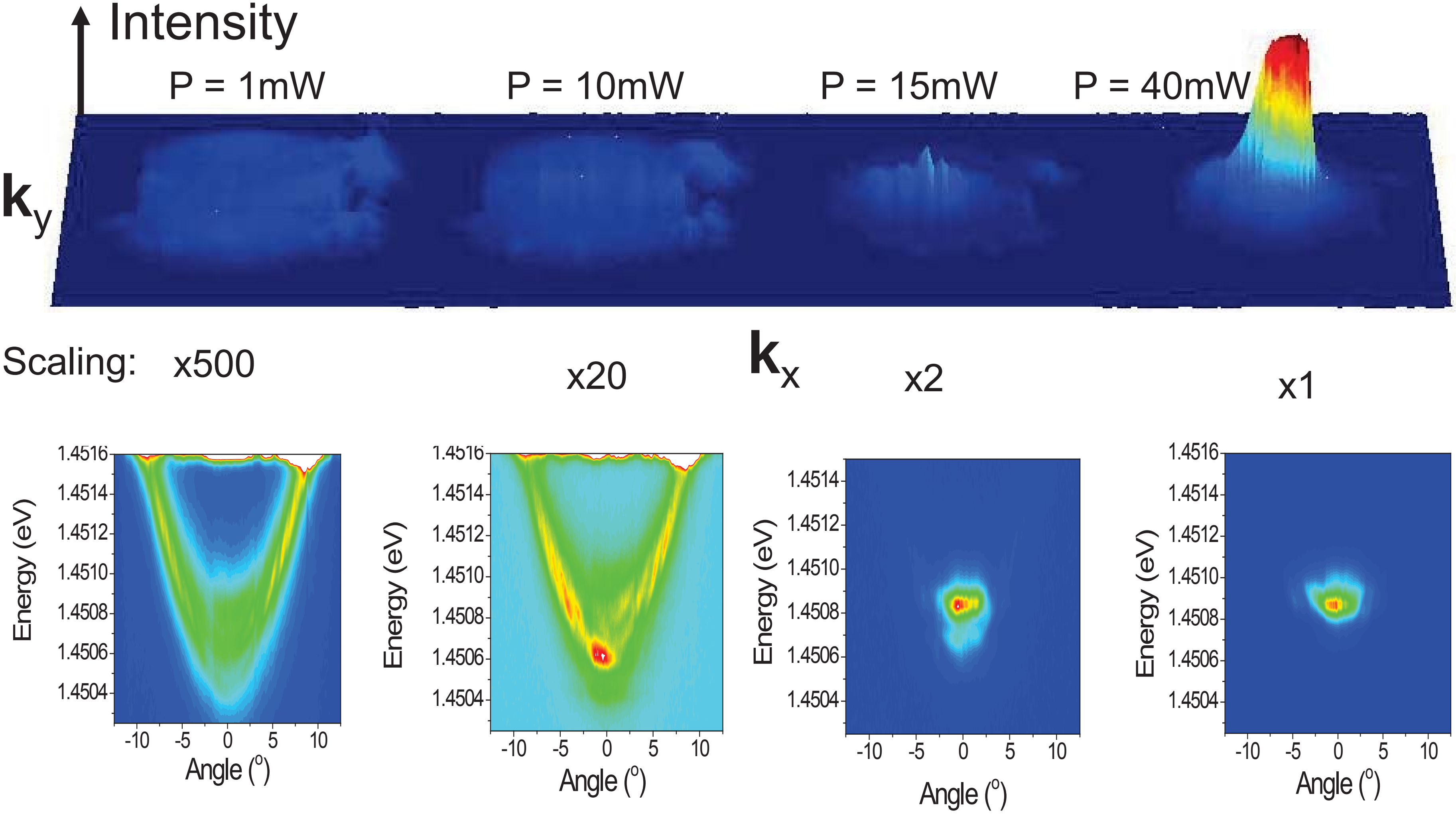
Non-resonant excitation



Kasprzak et al, Nature (2006)

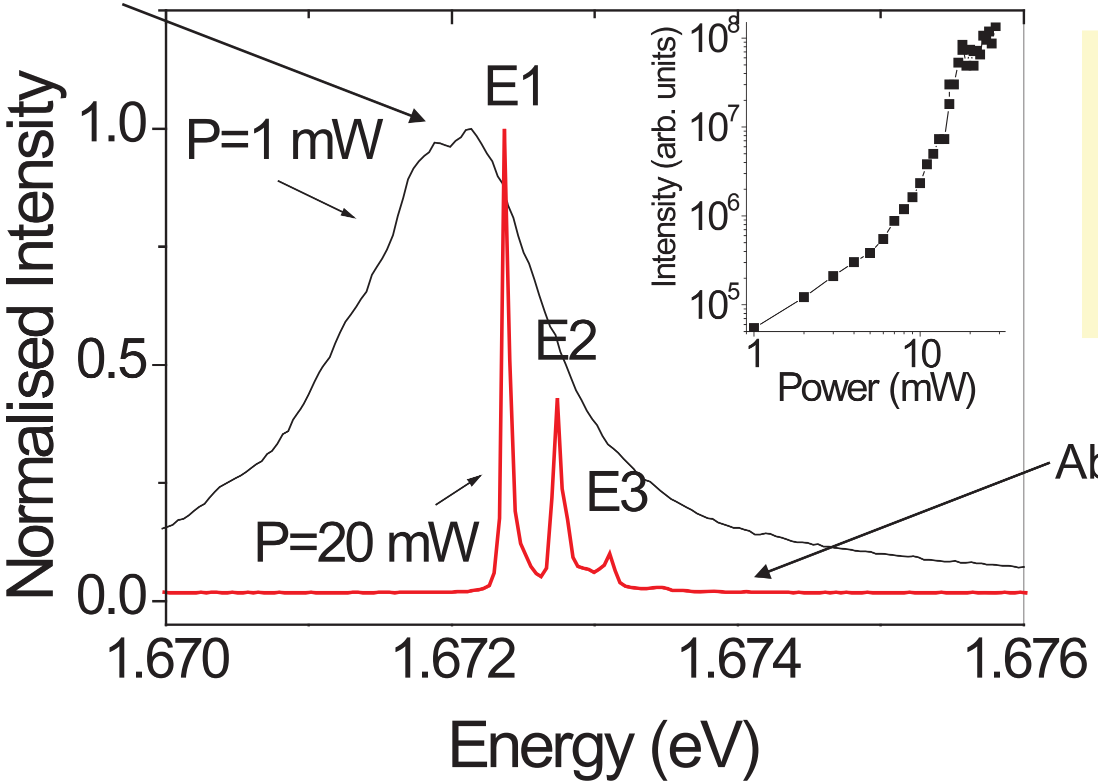
Linear polarisation?

Non-resonant excitation Stevenson, MSS et al PRL 85, 3680, 2000



Increasing power →

Emission spectra: non resonant excitation, CdTe cavities, photonic disorder



Below Threshold

Above Threshold

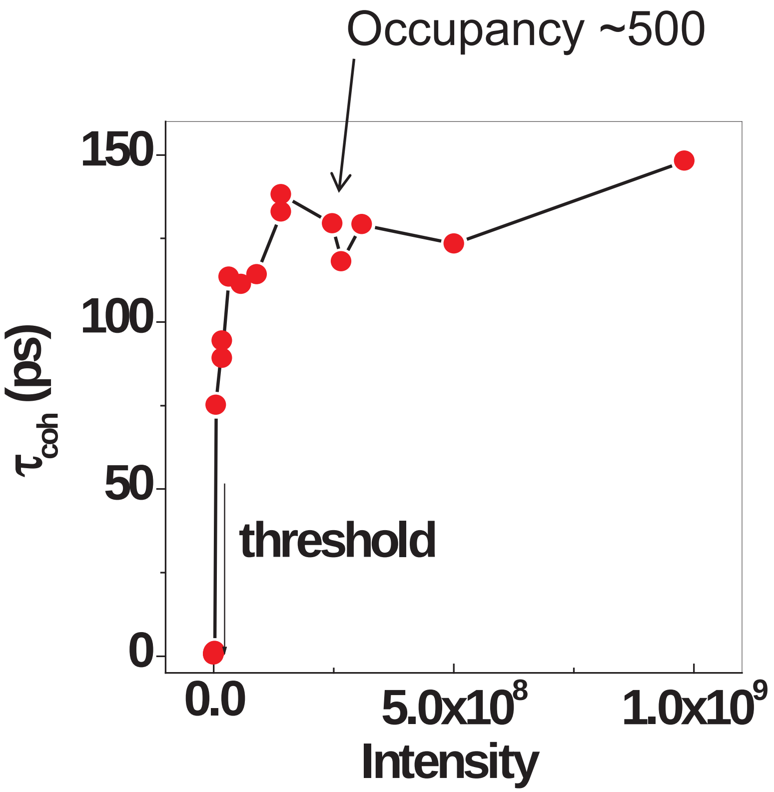
Clear threshold behaviour for all modes

Blue-shift ~0.5meV

Due to interactions

Two orders of magnitude narrowing from below to above threshold
– characteristic of formation of state with long temporal coherence
– macroscopic occupancy

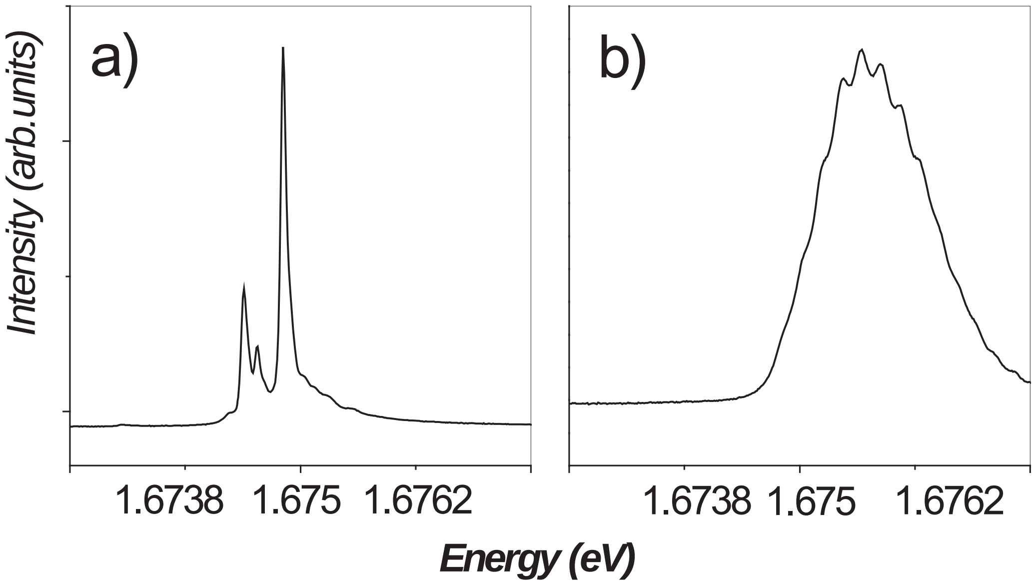
Long Temporal Coherence



- Coherence time increases as function of number of particles in the condensate and then saturates at 120-150 ps
- Limited by interactions
- Very similar behaviour to resonant excitation (PRL ***97***, *097402, 2006)*

- Longest 1nsec (for OPO)

Key to observation of true condensate properties: ‘noise free’ excitation source



Noise free laser:
BEC emission consists of sharp peaks, linewidth ~ 10 μeV
Coherence time ~100-500ps

Multimode laser:
Linewidth of BEC emission ~ 0.1-0.5 meV

Love, Krizhanovskii et al PRL ***101**, 067404, 2008*

Multimode Ti:S laser: mode spacing 250MHz, nsec timescale fluctuations

Modulates reservoir on this timescale (ns relaxation dynamics).

Blue shift due to interaction with reservoir: ~1meV

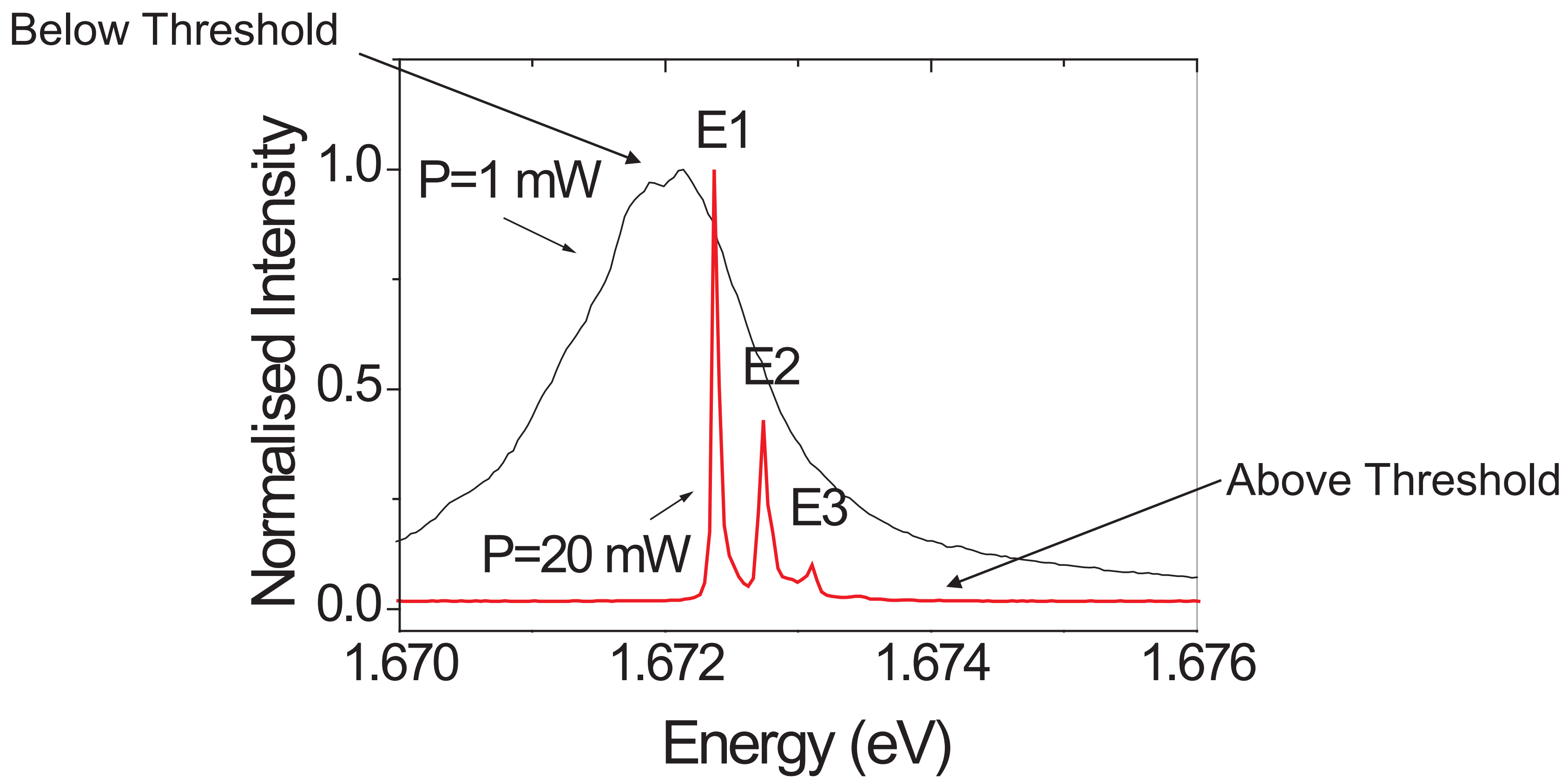
Fluctuations in peak position on same timescale

Broadening of ~0.2meV, obscures true condensate properties

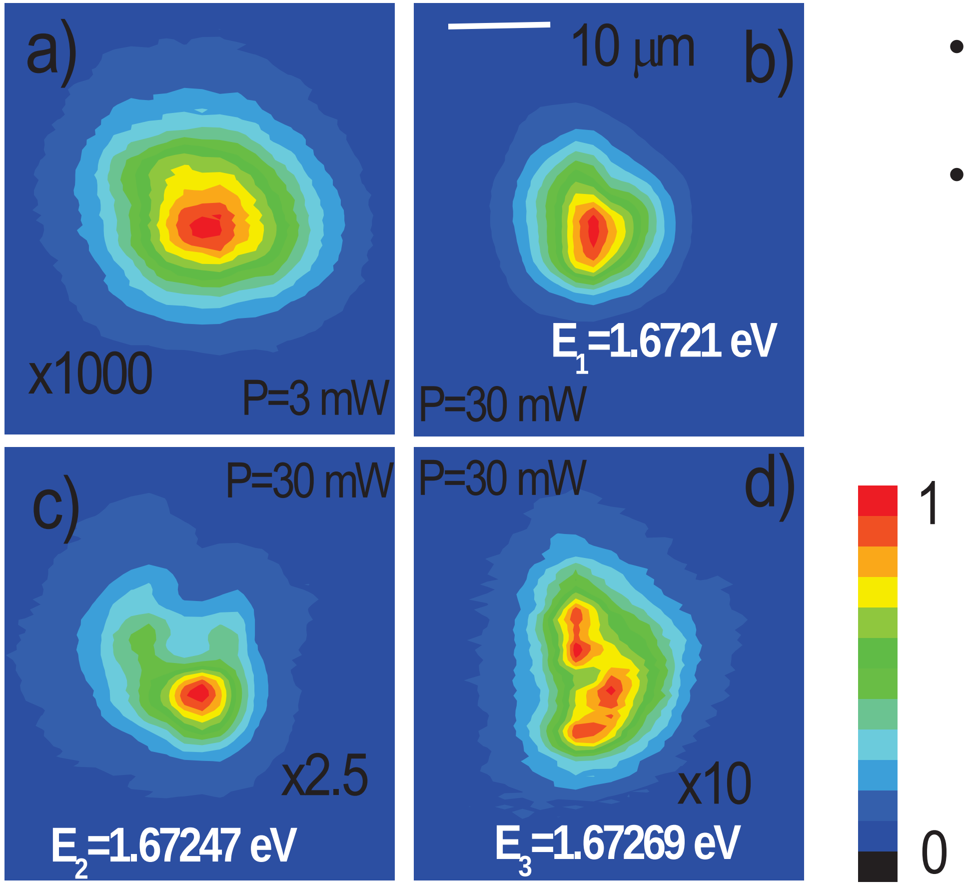
Single mode laser

Eliminates extrinsic broadening. Essential to observe true condensate properties

Coherence time 100-500ps, limited by interactions


Below Threshold
E1
P=1 mW
E2
E3
P=20 mW
Above Threshold
Normalised Intensity
1.0
0.5
0.0
1.670
1.672
1.674
1.676
Energy (eV)

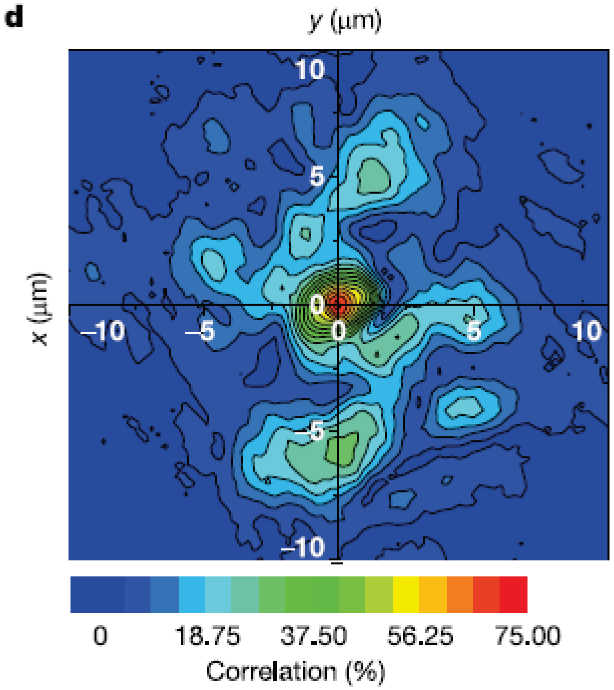
Real Space Images



- Size of laser spot ~15 μm
- 3 modes the same as on previous slide
- Above threshold:
  - Size of the modes ~10-15 μm
  - Separation between modes ~ 2 μm. Strong overlapping
  - Localisation due to fluctuations in photonic potential
  - Coexisting condensates
  - Consequence of non-equilibrium character (lifetime ~5ps)

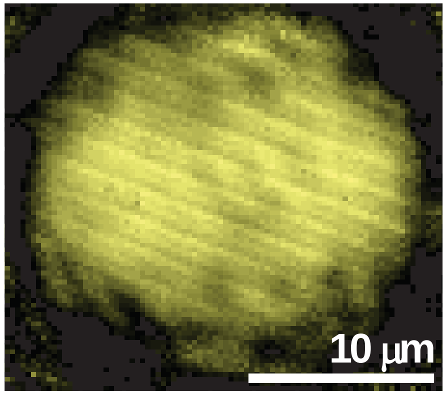
Extended spatial coherence – further evidence for macrosopic occupancy (first order correlation function)

Strong photonic disorder (CdTe)



Kasprzak et al, Nature (2006)

Uniform sample (GaAs)



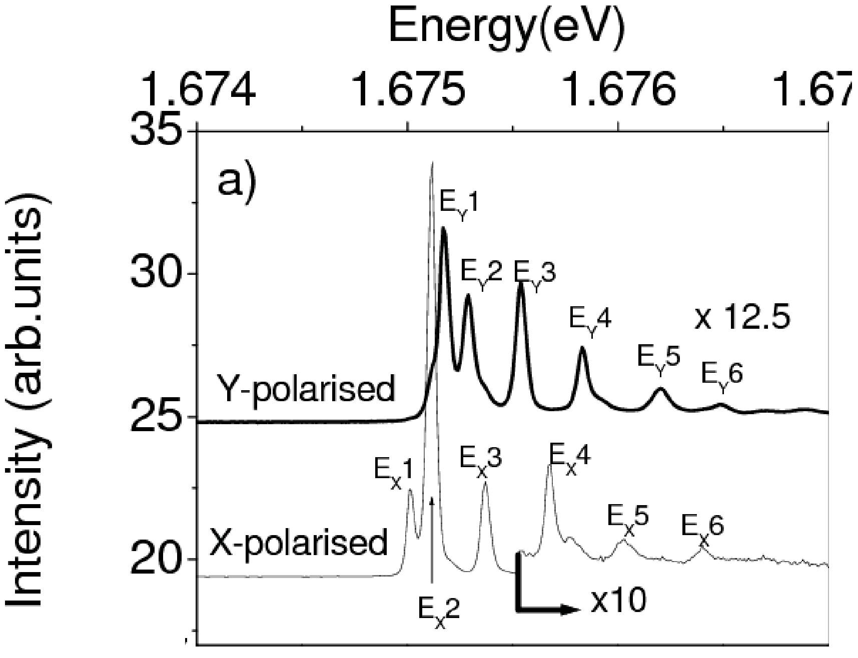
Cerda, DNK, MSS et al ***105**, 116402 (2010)*

First order spatial correlation function, $g^1(-r,+r)$ obtained by interfering image and inverted image

$$g^{(1)}(\mathbf{r},\mathbf{r}') = \frac{\langle E^*(\mathbf{r})E(\mathbf{r}')\rangle}{\langle E^*(\mathbf{r})\rangle\langle E(\mathbf{r}')\rangle}$$

Energy and momentum space imaging, comparison with theory

D N Krizhanovskii, K G Lagoudakis, B Deveaud, M Wouters,
MSS *et al, Phys Rev B* ***80****, 045317, 2009*



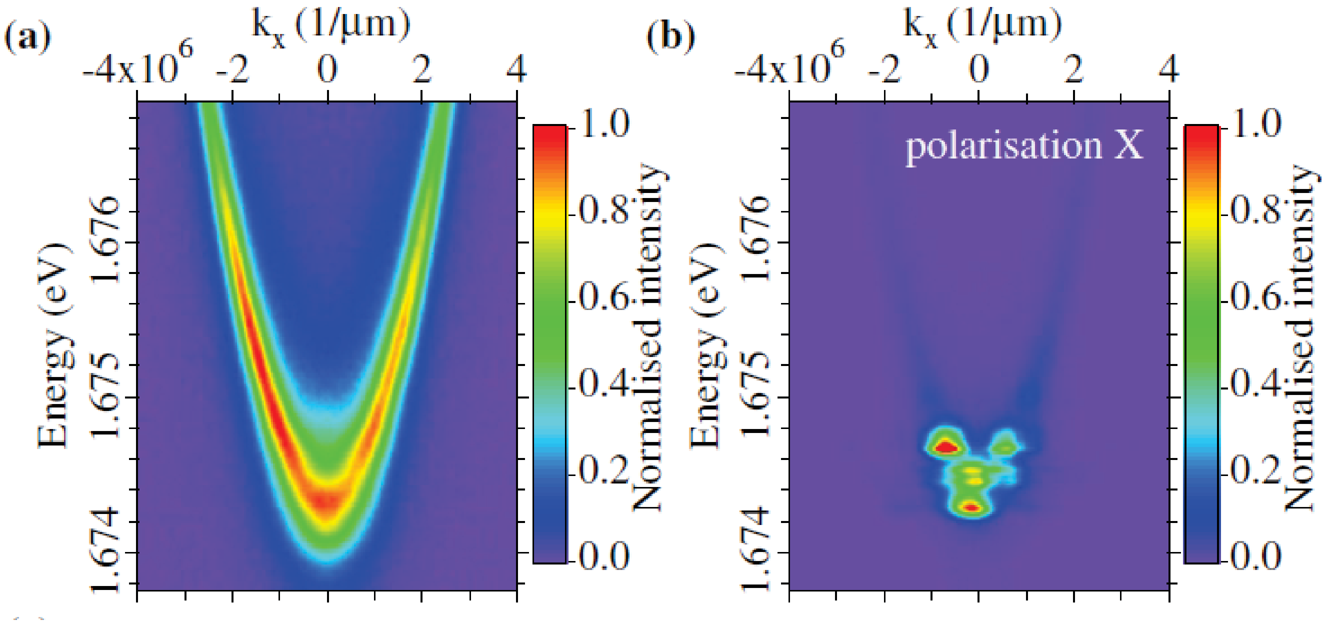
Co-existing condensates: characteristic of non-equilibrium character

Small splitting between X and Y modes

In-plane birefringence

But spatial patterns very similar

Energy versus momentum



Below threshold

Above threshold

Images in momentum space

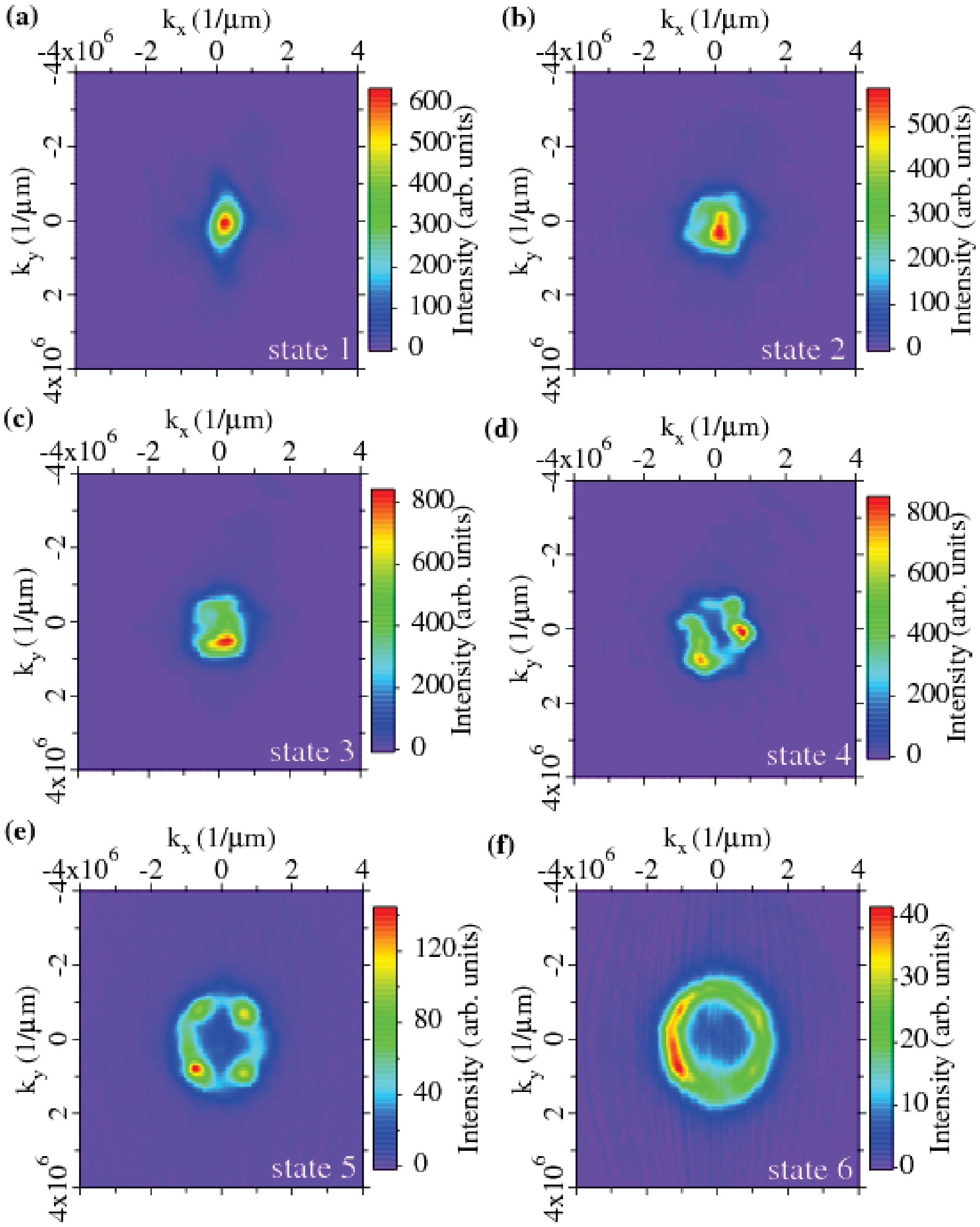
Lower energy states close to k = 0

Higher energy modes at higher k

Lie on rings of finite k

Absence of inversion symmetry, *k* to –*k*

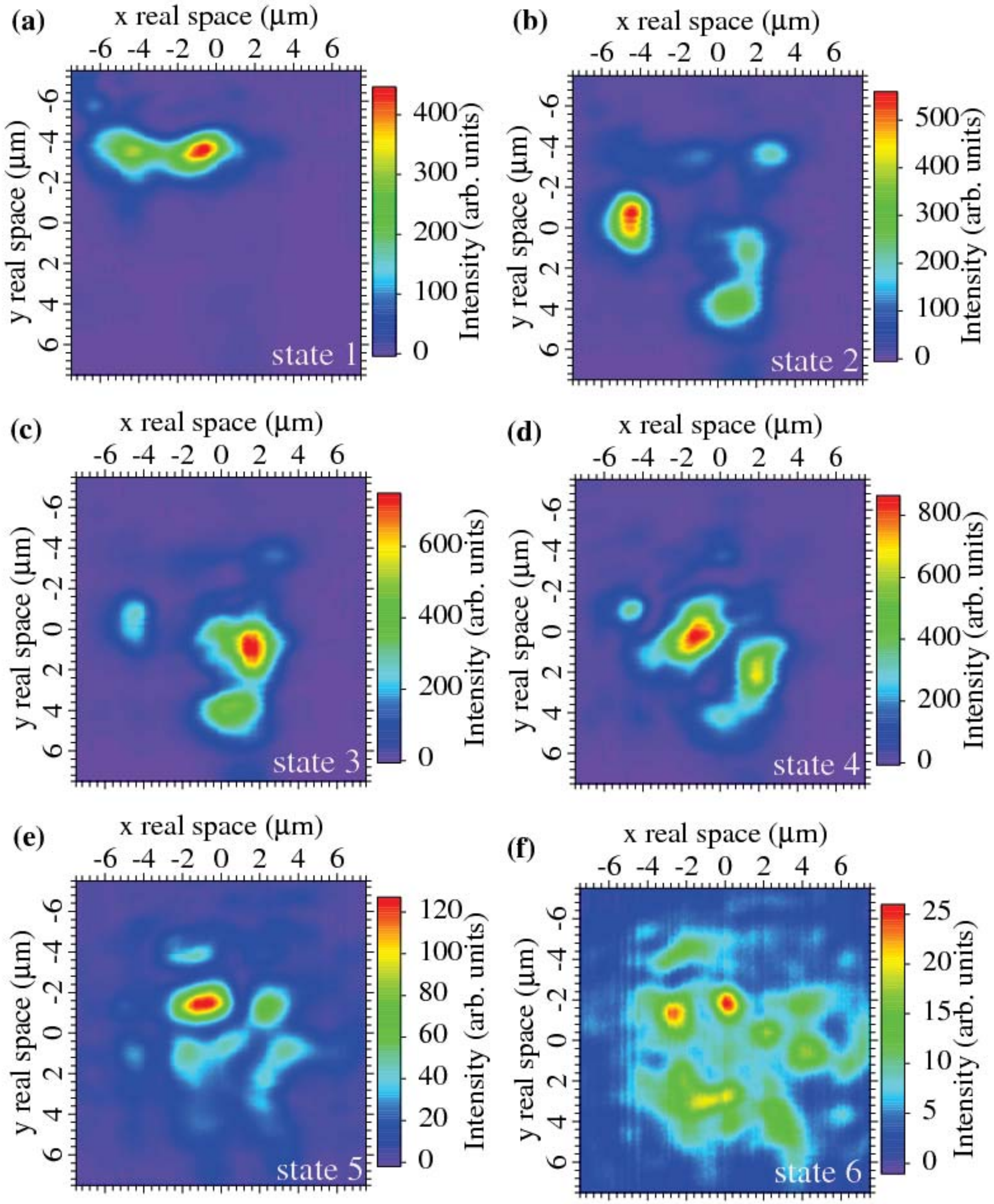
Some evidence for coherent back-scattering?



- Corresponding real space images, for each mode

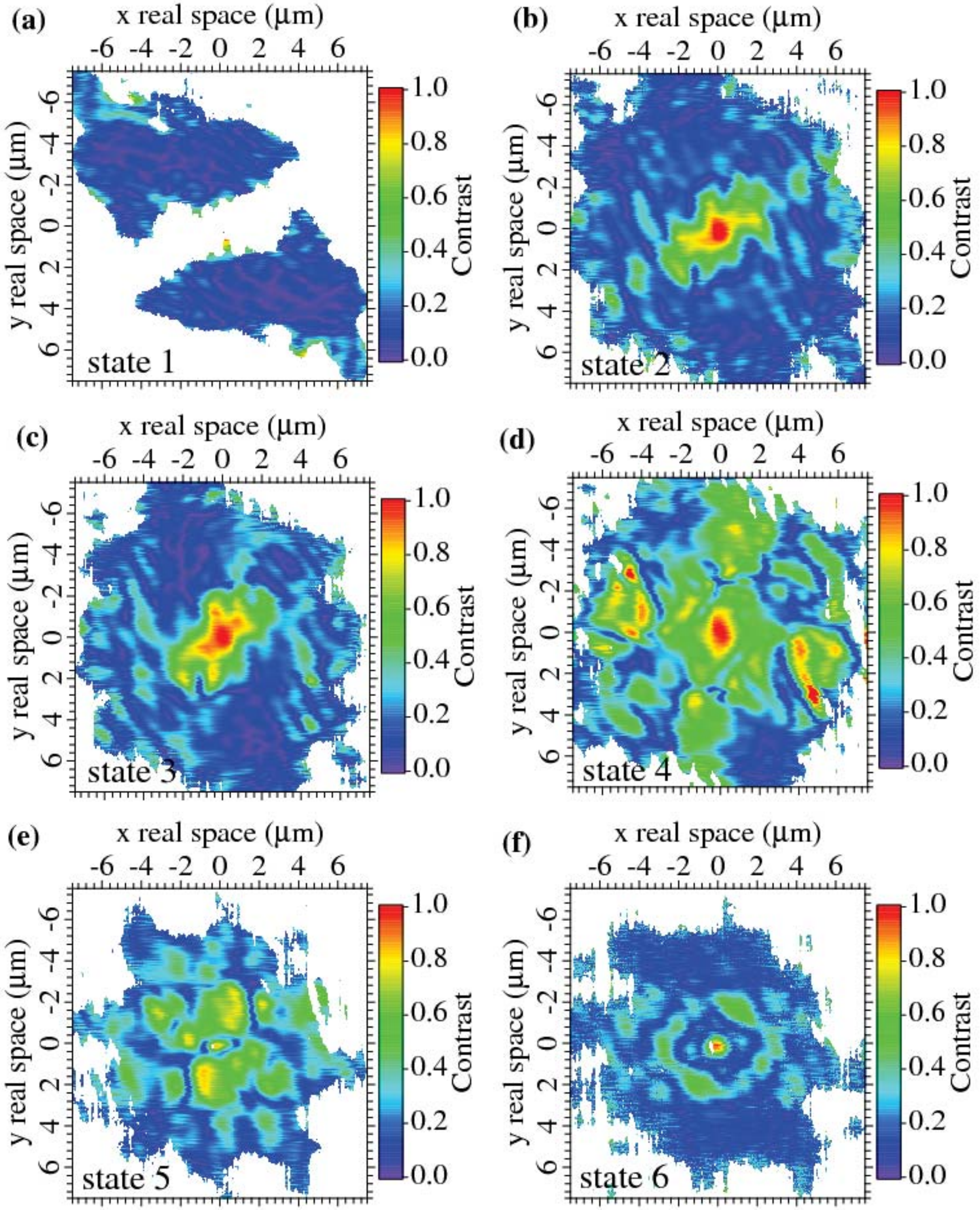
- Increasing delocalisation with energy

- But strong overlapping of modes

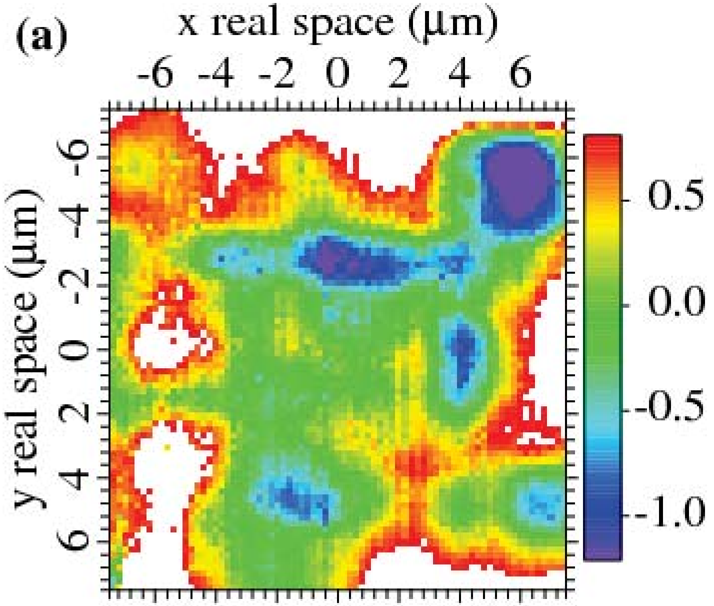


First order correlation functions

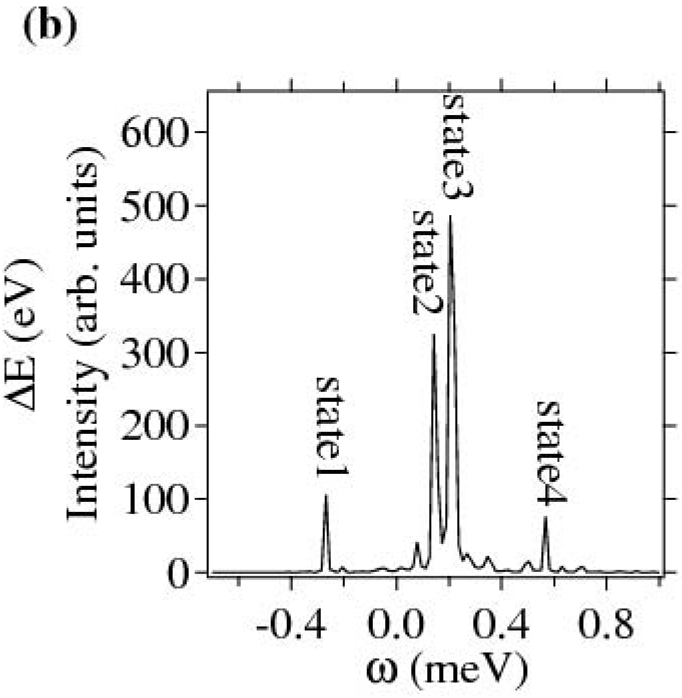
Long range coherence for all modes



Modelling: Michiel Wouters



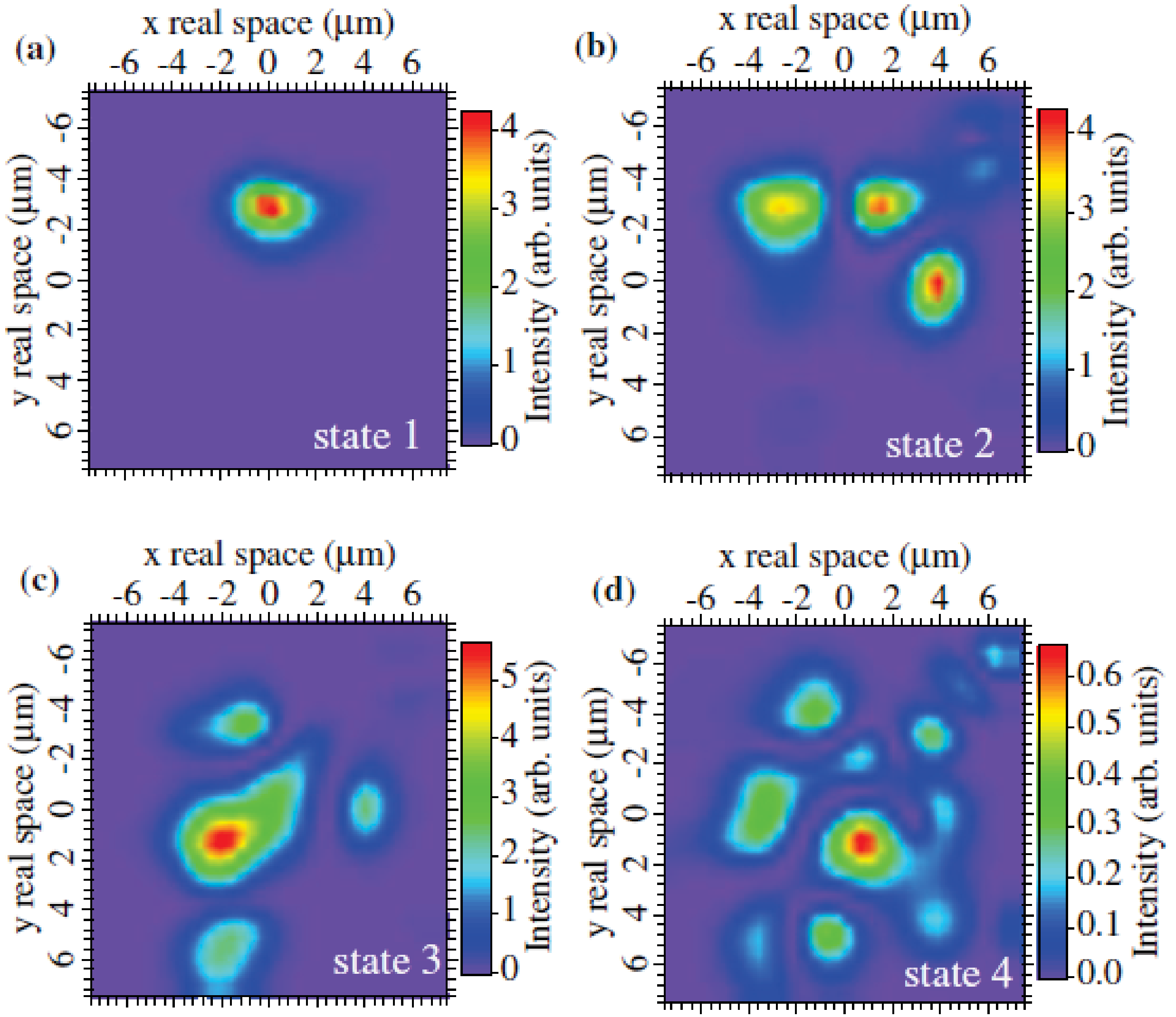
Disorder potential



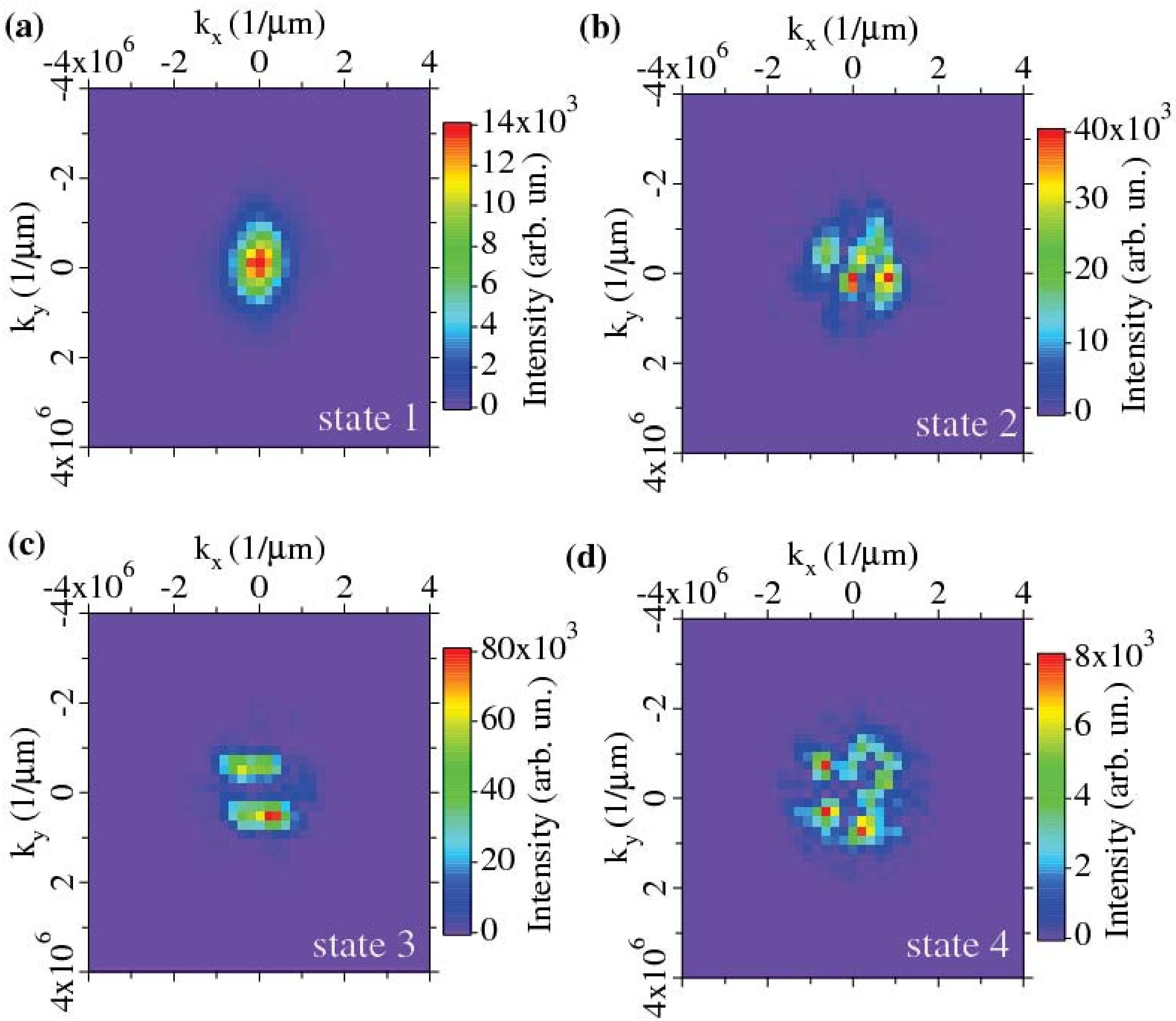
Multi-modes reproduced: disorder potential stronger than blue shifts (Wouters PRB 77, 121302, 2008, Baas PRL 100, 170401, 2008)

Calculated real space distributions of modes

Good qualitative agreement with experiment



- **Calculated momentum space distributions**
- Lowest states localised at k = 0
- Higher states ring-like
- Inversion symmetry lacking
- Linear Schrödinger equation is real → k, -k symmetry
- Non-linear dynamics defines condensate modes



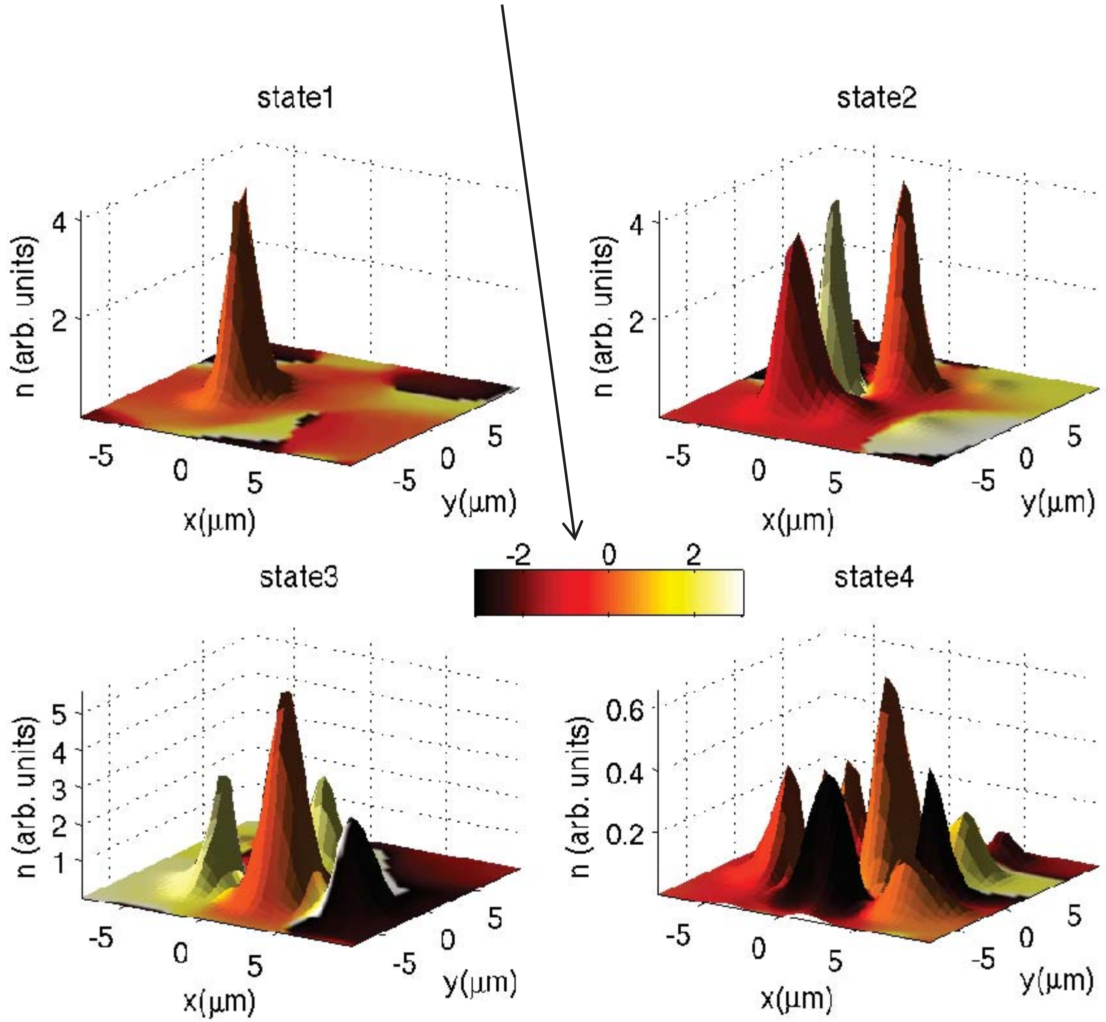
Calculated phase and mode intensity

Large differences in phase between maxima (~π), → k non-zero condensation

k_{ring} ~ 1/(spatial separation)

Phase differences lead to currents connecting different regions.

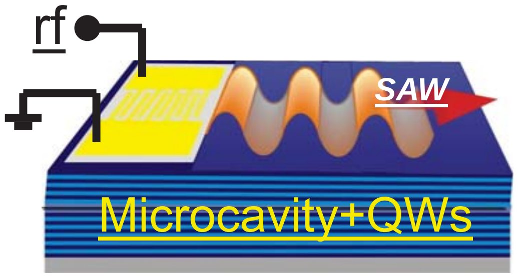
Frequency locking

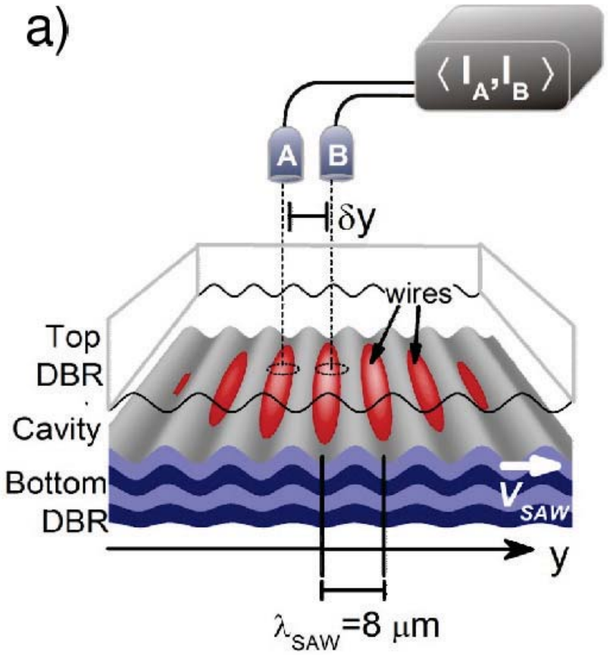


Phase scale

Periodic potential superimposed on uniform condensate

Use surface acoustic waves

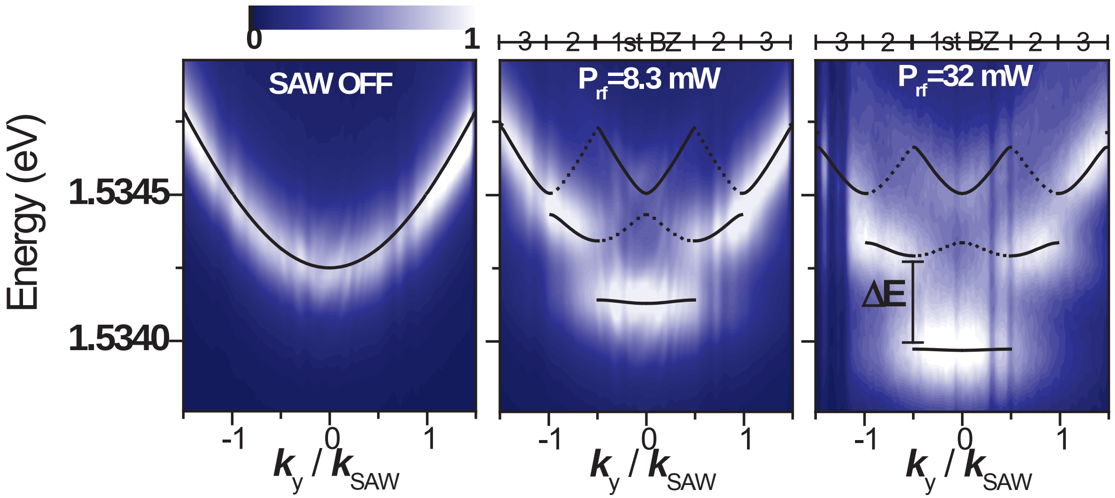




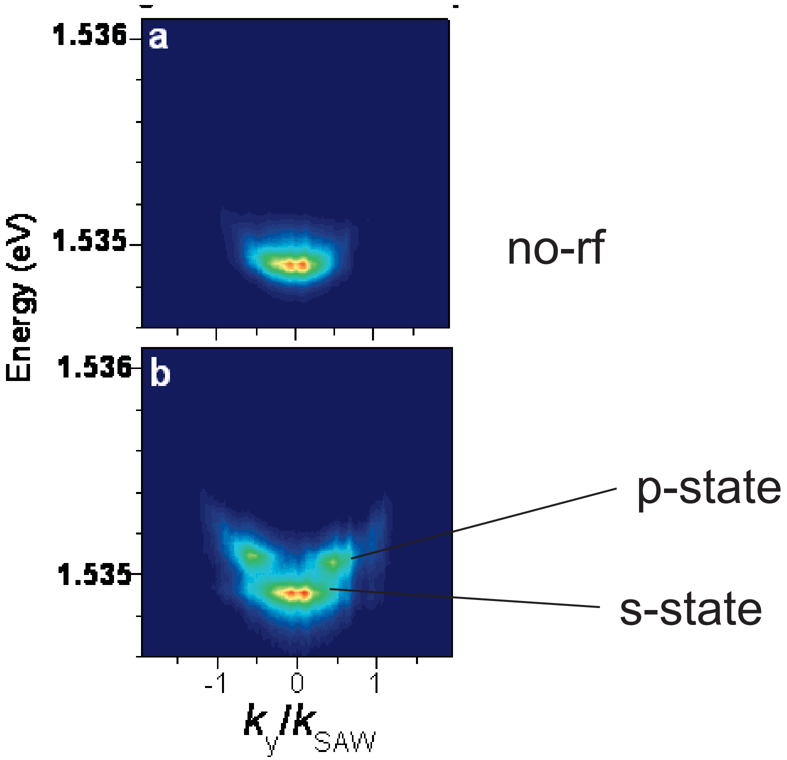
Phys Rev Lett 105, 116402 (2010)

Modification of band structure (linear regime, below threshold)

- Surface acoustic wave creates periodic potential (highly perfect periodicity)
- Formation of mini-Brillouin zones and minigaps (0.1 - 0.2meV)
- Polariton confinement in real space



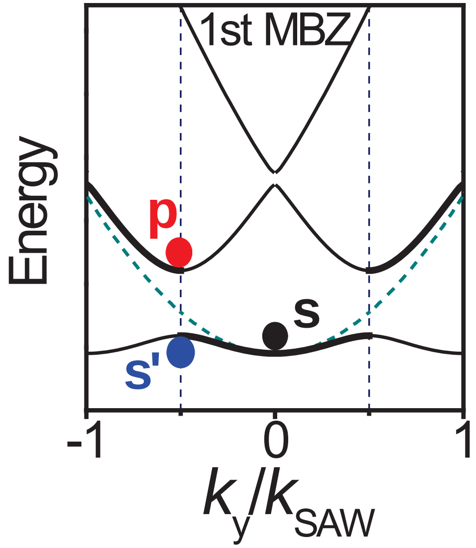
Non-resonantly excited polariton condensate in periodic potential



no-rf

p-state

s-state

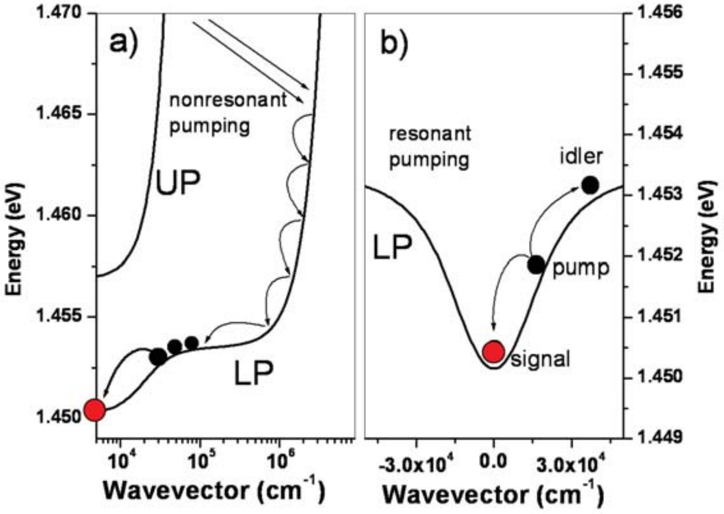


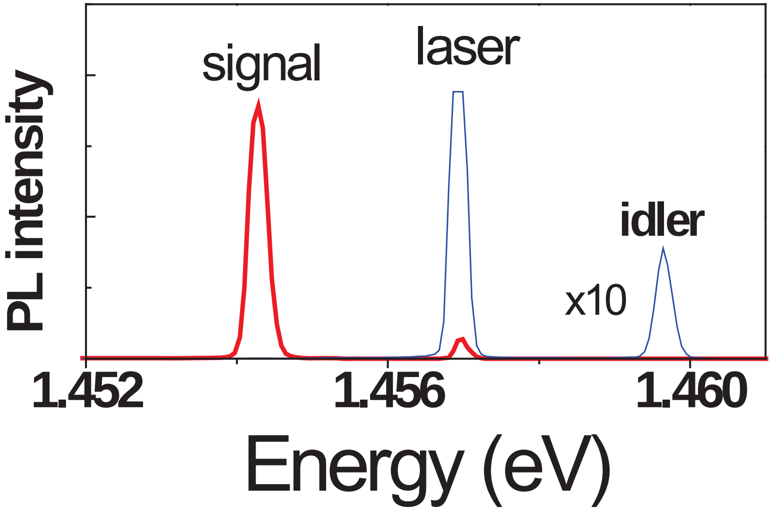
Coexisting condensates again observed

Lai, Yamamoto, fixed potential, Nature 450, 529, 2007

Back to resonant excitation

Stevenson PRL 86, 3680, 2000





$$E_{signal} + E_{idler} = 2E_{pump}$$

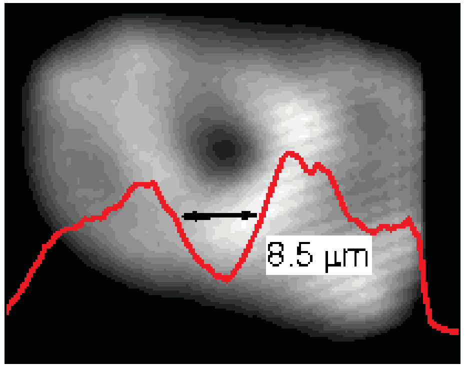
$$k_{signal} + k_{idler} = 2k_{pump}$$

Signal phase independent of that of pump

Very similar properties to that of non-resonantly excited BEC

Imprinting of Vortices on Polariton Condensates

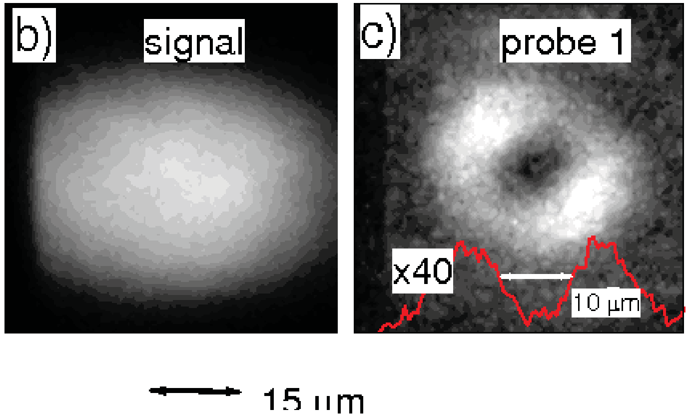
PRL ***104**, 126402, 2010* , Krizhanovskii, Whittaker, Sanvitto, Vina, MSS et al
Nature Physics 6, 527, 2010 Time resolved

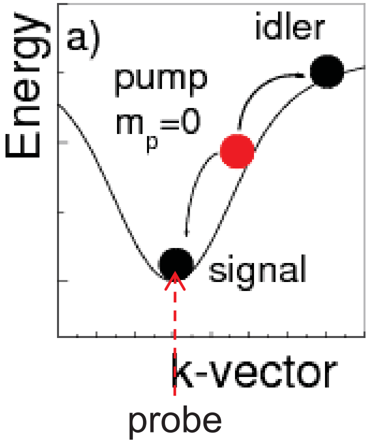


Characterised by core where density goes to zero and quantised winding of phase around the core

Characteristic of condensate, but also of optical beams carrying finite orbital angular momentum

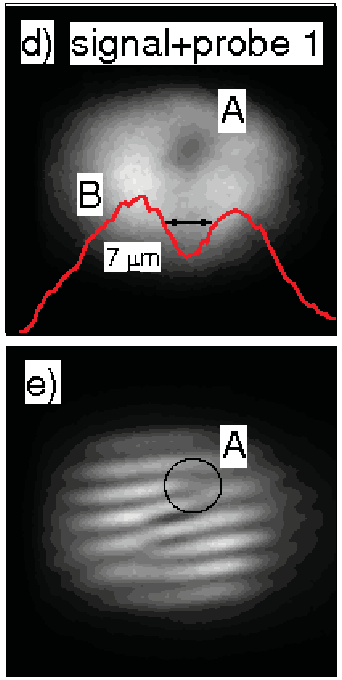
Imprinting of vortices using weak light beams with finite angular momentum





Use of very weak probe carrying vortex with orbital angular momentum M=1 resonant with the signal (Gauss-Laguerre beam)

Uniform sample

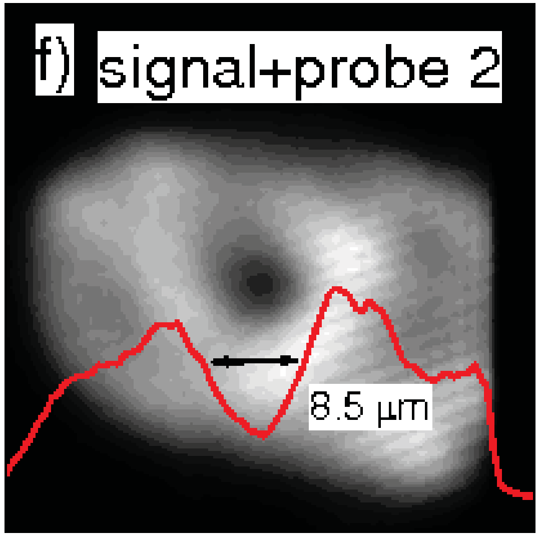


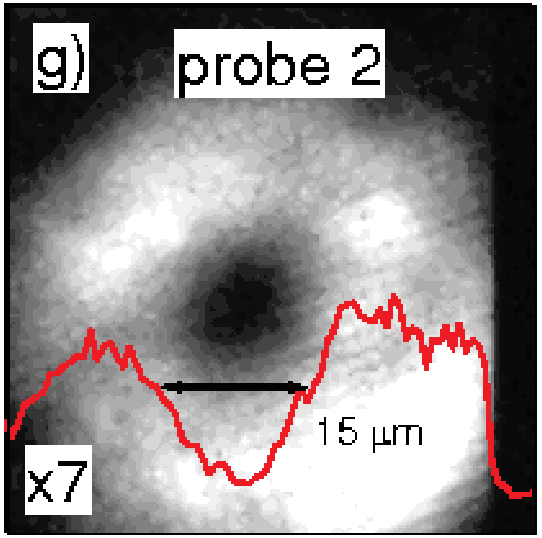
Vortex is imprinted on the signal, phase of the signal locked to that of very weak probe

Without probe, phase of signal is random

Fork-like dislocation in signal self-interference pattern shows quantised 2π phase variation

Vortex core size is intrinsic property of condensate



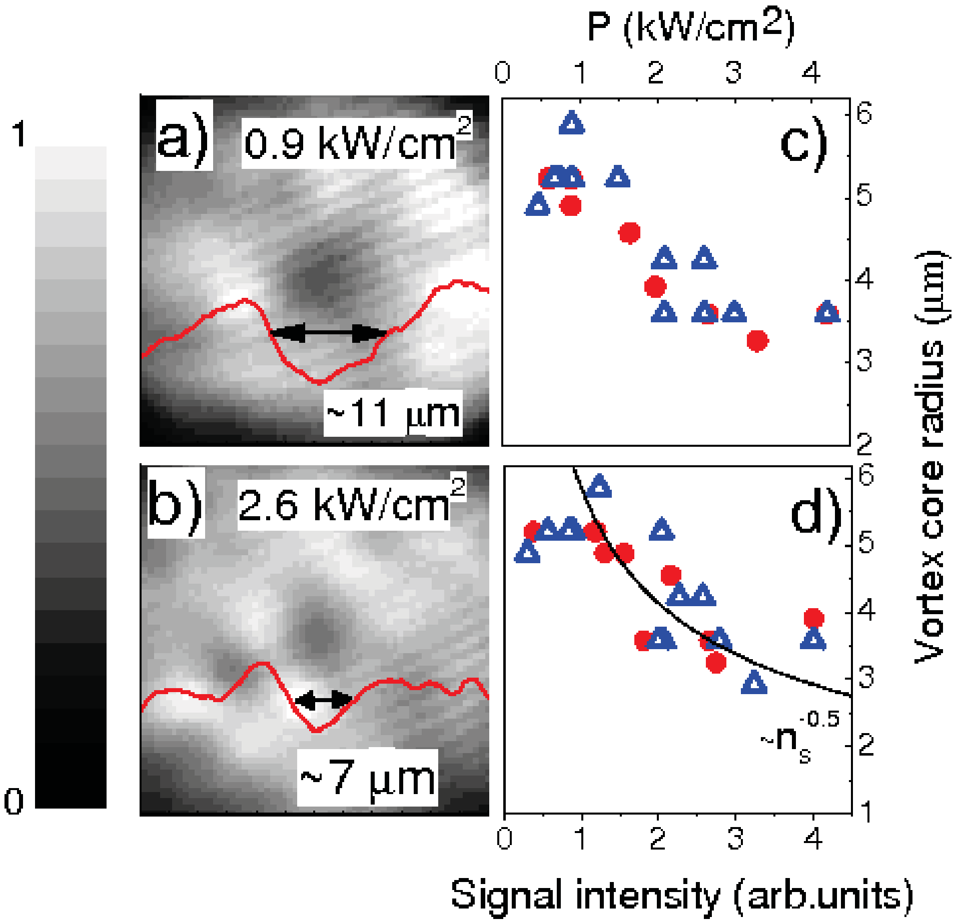


Vortex diameter created in the signal is not determined by the spatial size of the probe.

Using imprinting beams of 10 or 15µm leads to polariton vortices of same diameter (~8µm)

Interactions produce a natural size for the vortex determined by the strength of the interactions

Vortex size: interactions and particle density



Kinetic term is compensated by the interaction term (the blue shift), which determines the natural vortex size (healing length) ξ:

$$\frac{\hbar^2\pi^2}{2M_c\xi^2} \sim E_{shift} = k\sqrt{n_s n_i}$$

Kinetic energy *Interaction energy*

Healing length

$$\xi = \frac{\hbar}{\left(2\alpha M_c \kappa \sqrt{n_s n_i}\right)^{\frac{1}{2}}}$$

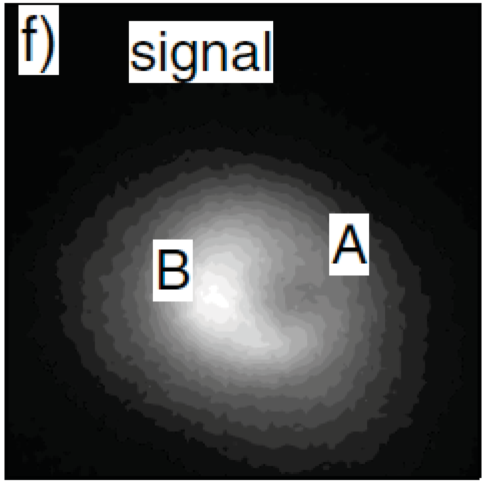
Since n_s is proportional to n_i, expect vortex radius proportional to $n_s^{-1/2}$, as observed

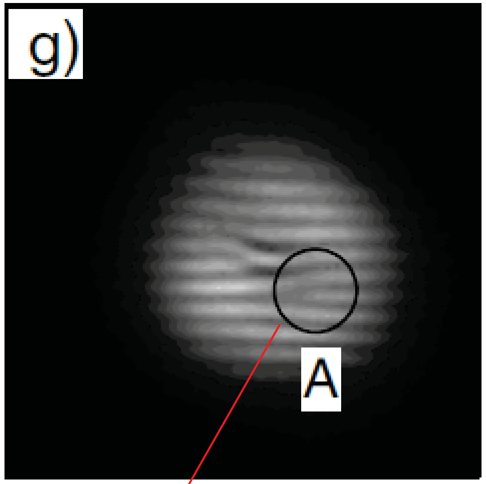
	Atom BEC (3D)	Polariton condensate (2D)
Mass	10^5 m_e	$5\text{x}10^{-5}$ m_e
Density	$\sim 10^{14}$ cm^{-3}	$\sim 10^9 - 10^{10}$ cm^{-2}
Interactions $\sim \kappa N$	10^{-7} meV	0.1 meV
Healing length	0.1 μm	10 μm

- Very small polariton effective mass leads to large healing lengths, (partly compensated by interactions)
- Vortices in polariton system can thus be measured in situ
- Vortices in atomic BEC are measured after expansion (usually)

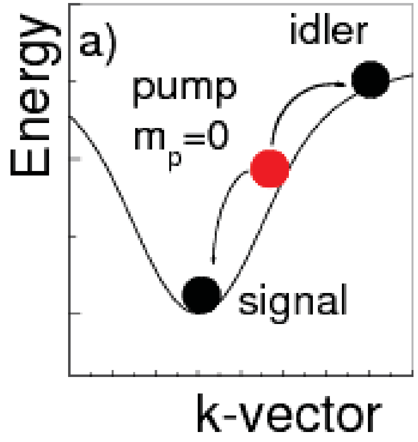
Signal/idler Vortex- Antivortex pair

m=+1 beam at k-idler





m_s = -1 vortex



Expect creation of signal vortex corresponds to creation of signal/idler vortex anti-vortex pair, with opposite angular momenta

Conservation of orbital angular momentum $2m_p=m_s + m_i$

But difficult to observe idler directly, since weak

Instead create vortex at idler with m_s = +1

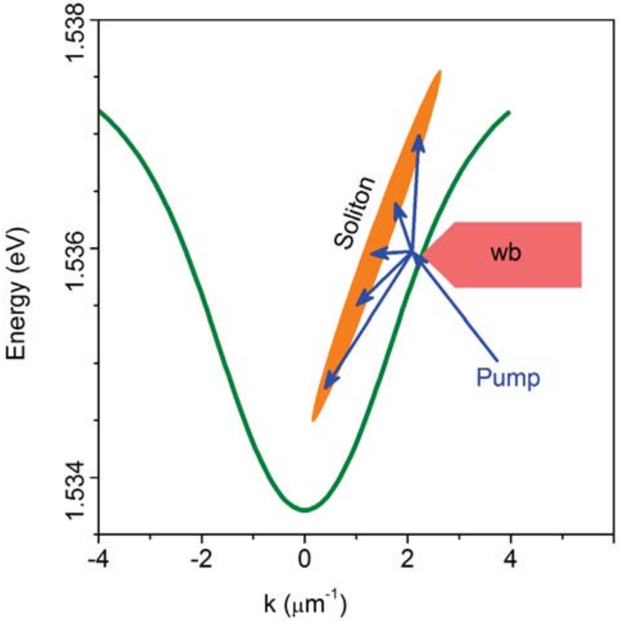
Signal anti-vortex with m_s = -1 is seen.

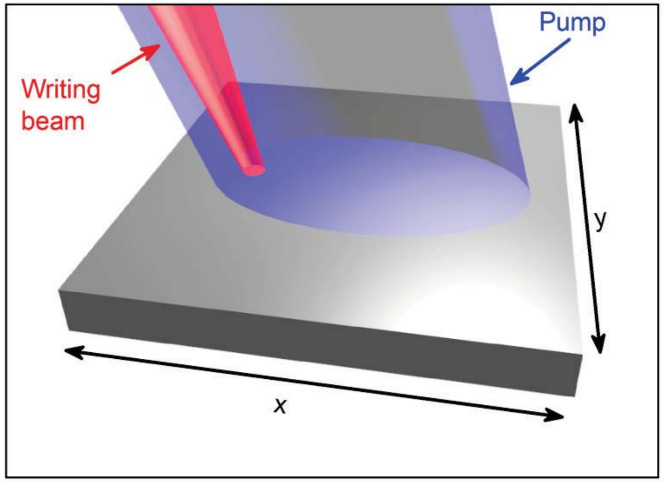
Bright Polariton Solitons (matter-wave solitons) M Sich, D N Krizhanovskii, D V Skryabin, A V Gorbach, R Hartley (University of Bath)

Polariton-polariton interactions repulsive → spreading of wavepackets

Compensated by negative effective mass above point of inflection (anomalous dispersion)

Leads to non-spreading wavepackets → bright solitons





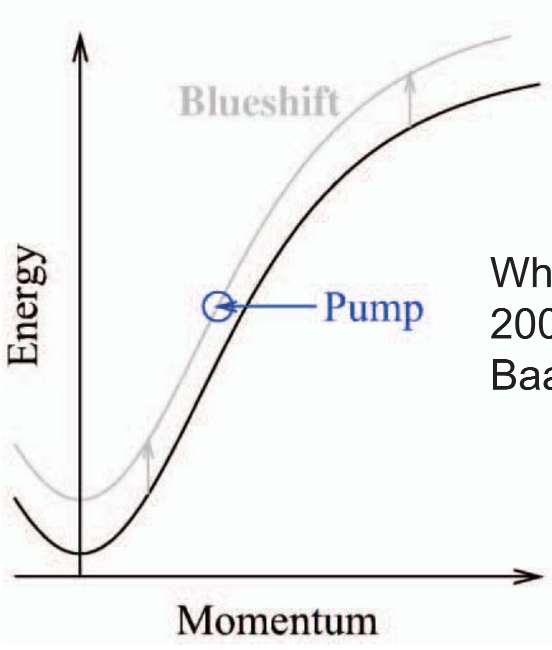
Cold atoms e.g. Strecker et al, Nature 417, 150, 2002, Kaykovich et al, Science 296, 1290, 2002
Photonic lattices Fleischer et al, Nature 422, 147, 2003

Bistability needed for soliton formation

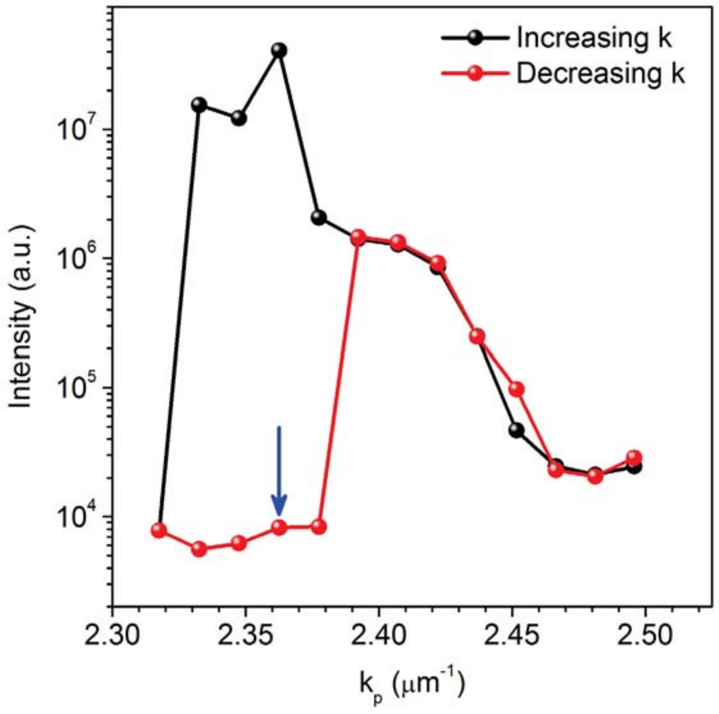
- Arises from polariton-polariton blue shift

- System held on lower branch by large pump spot

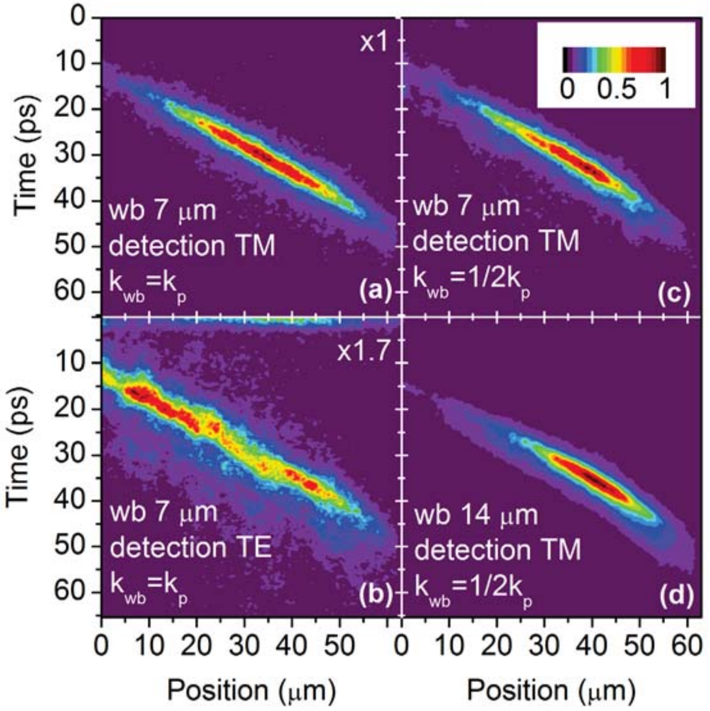
- Writing beam excites soliton → excites large range of k-vectors, corresponding to localisation in real space

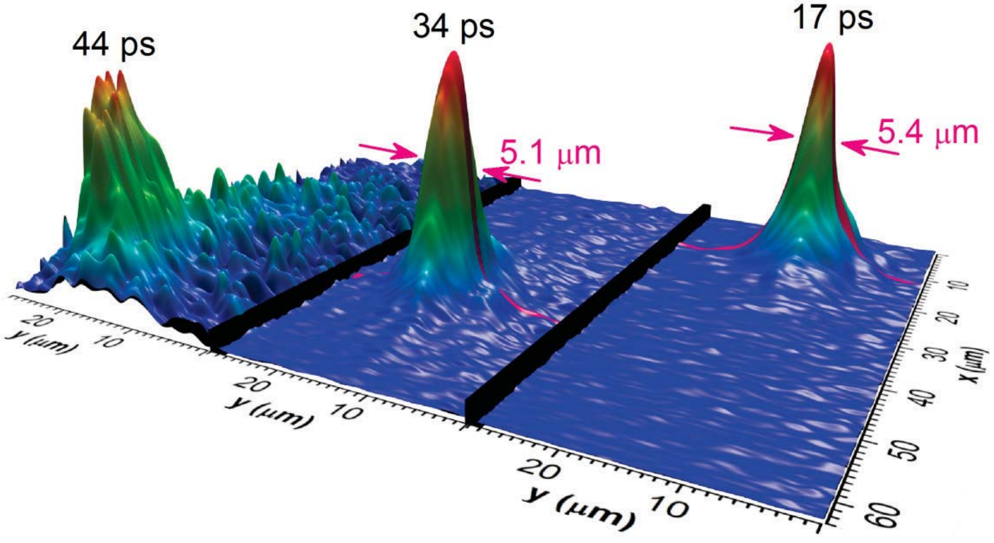


Whittaker
2001, 2005
Baas 2004



Non-spreading soliton propagation





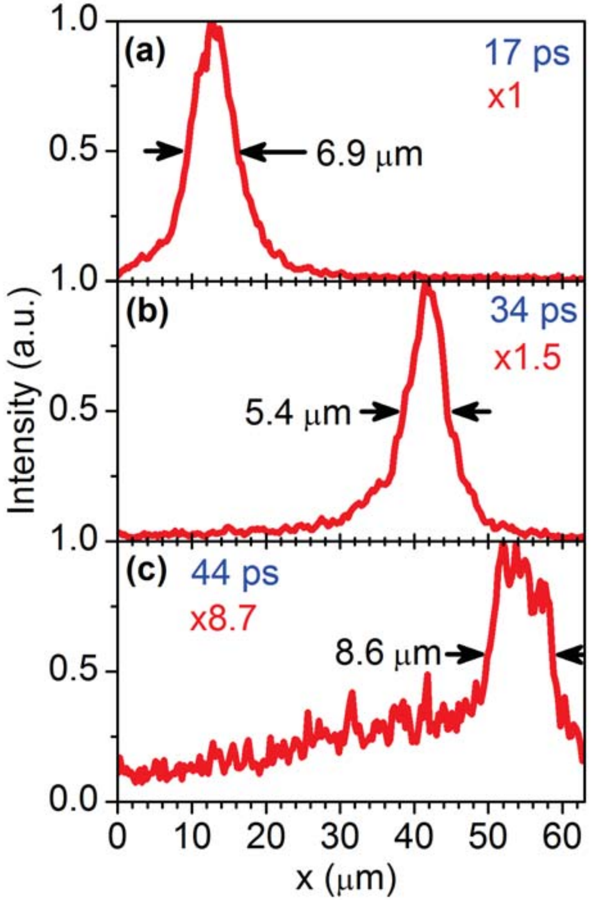
100-1000 particles

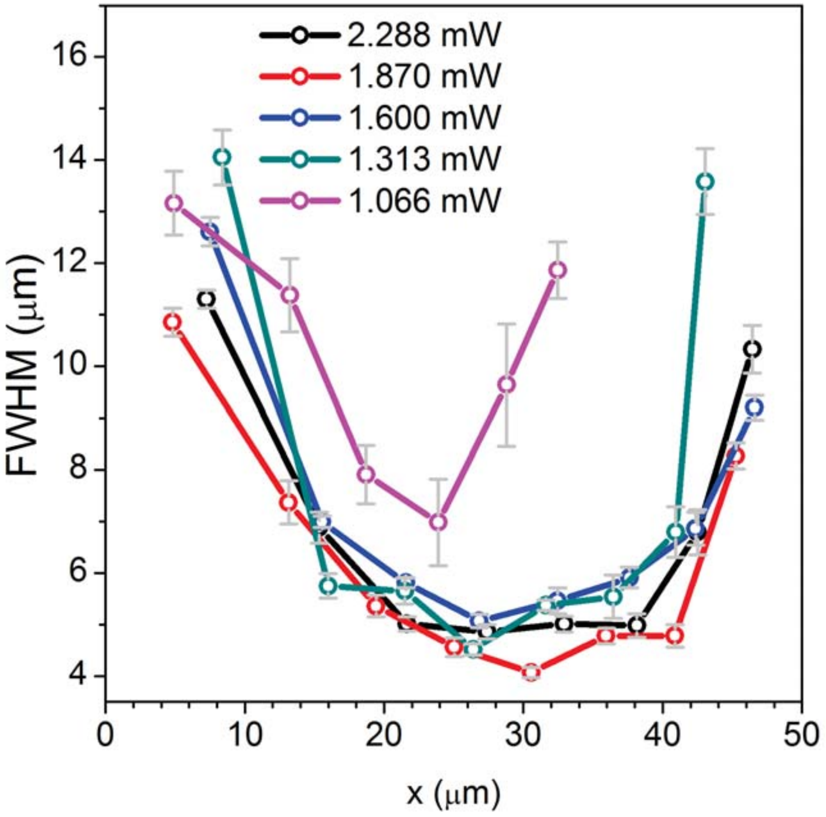
High propagation speeds ~2 x 10^6 m/s

ps writing times

Size determined by healing length of quantum fluid 2-5μm

Focussing and propagation





Writing beam
powers

Shows initial focussing

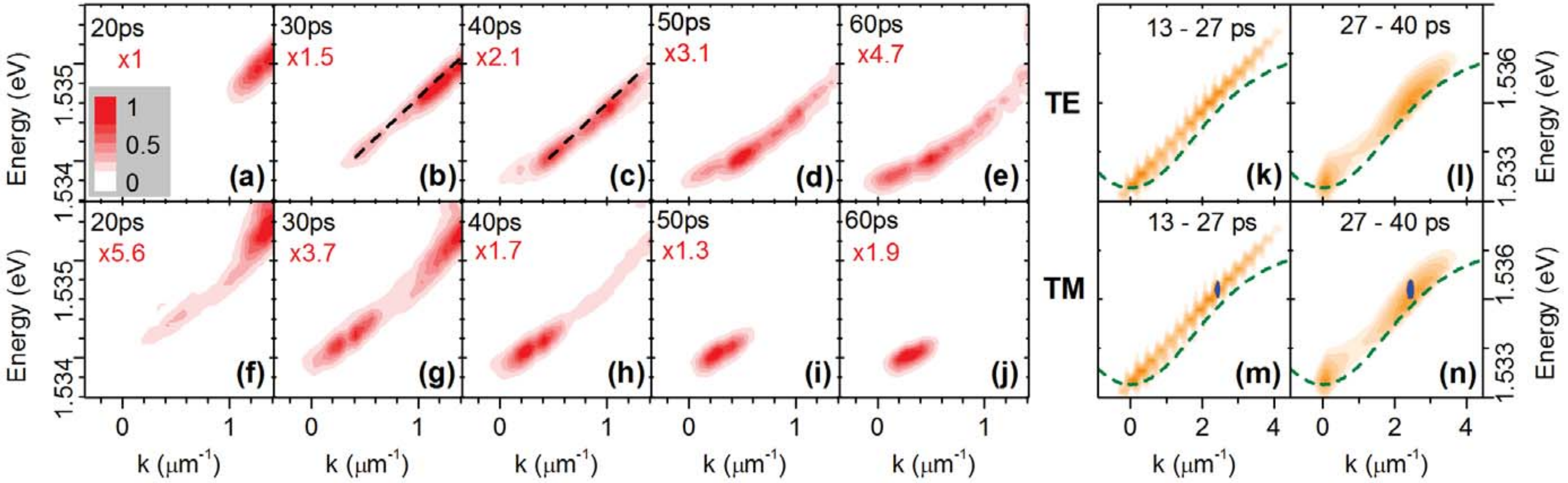
Then constant size

Threshold writing beam power

Energy versus momentum dispersion

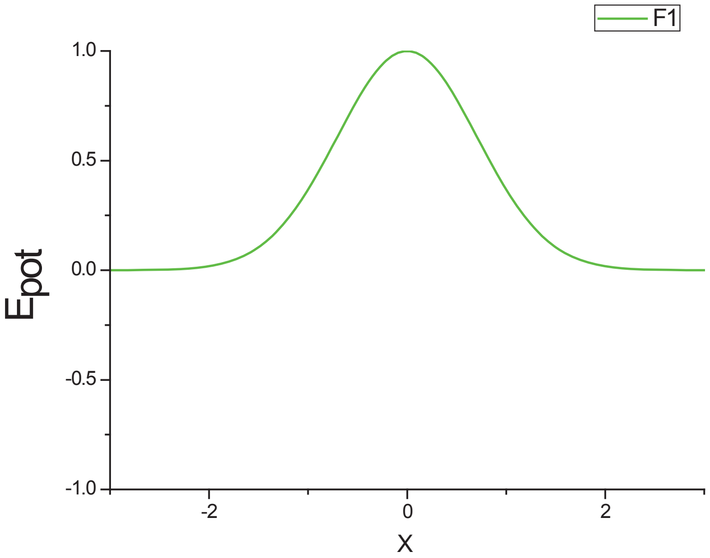
Large spread in *k* as expected. Contrast with condensate.

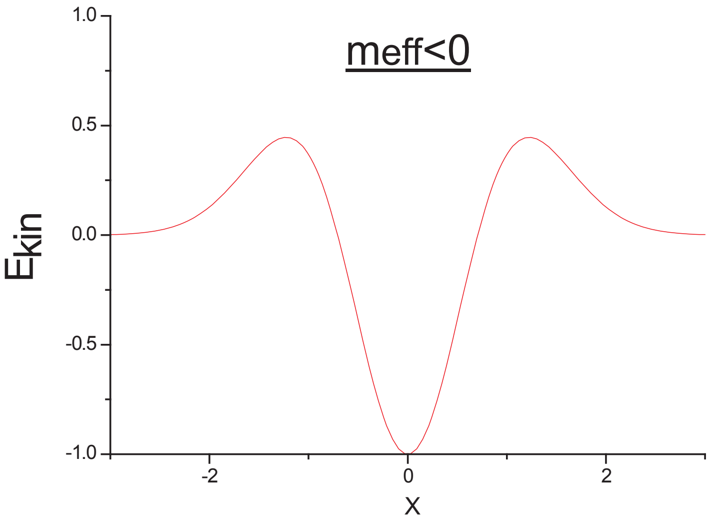
Near linear dispersion



experiment

theory





$$E_{pot} = \kappa \left| \psi(x) \right|^2$$

$$E_{kin} = \frac{-\hbar^2}{2m_{eff}} \frac{\partial^2}{\partial x^2} \psi(x)$$

In soliton regime $E = E_{pot}(x) + E_{kin}(x) = const$

hence $\frac{\partial E}{\partial x}(x) = 0 \Rightarrow$ The wavepacket is nondispersive and forms a soliton

Summary

1. Condensate in solid state system
2. Non-equilibrium character
3. Coexisting condensates in modulated systems
4. Role of interactions, bistability, vortices, solitons