Some recent developments in Polariton Bose-Einstein Condensation

4th Workshop on QST @ TungHai University

September 10, 2009

Chung-Hsien Chou
Department of Physics,
National Cheng Kung University
Physics division,
National Center for Theoretical Sciences

Outline

I. Introduction to microcavity polariton

II. Bose-Einstein condensation of exciton polaritons

III. Quantized vortices in an exciton-polariton condensate

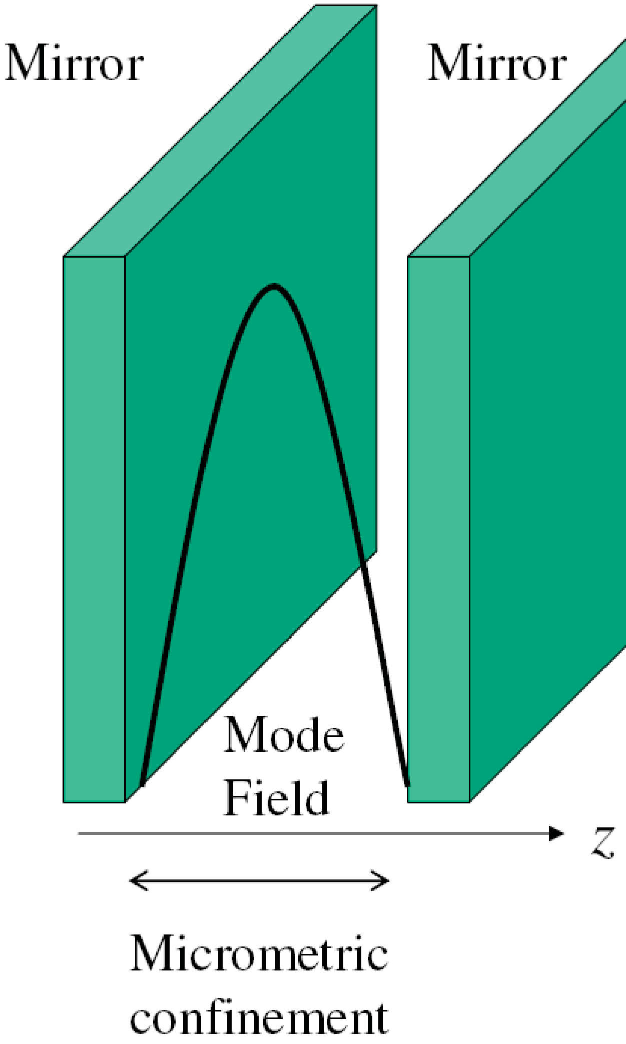
IV. Collective fluid dynamics of a polariton condensate

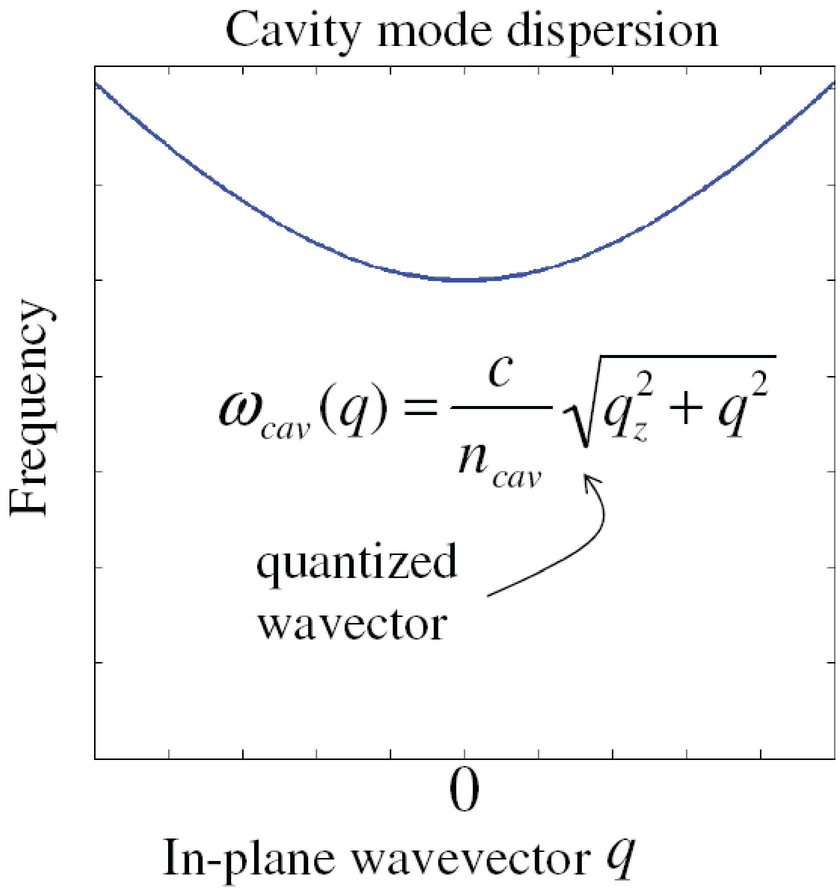
V. Some theoretical approaches

VI. Summary and some open issues

I. Introduction to microcavity polaritons

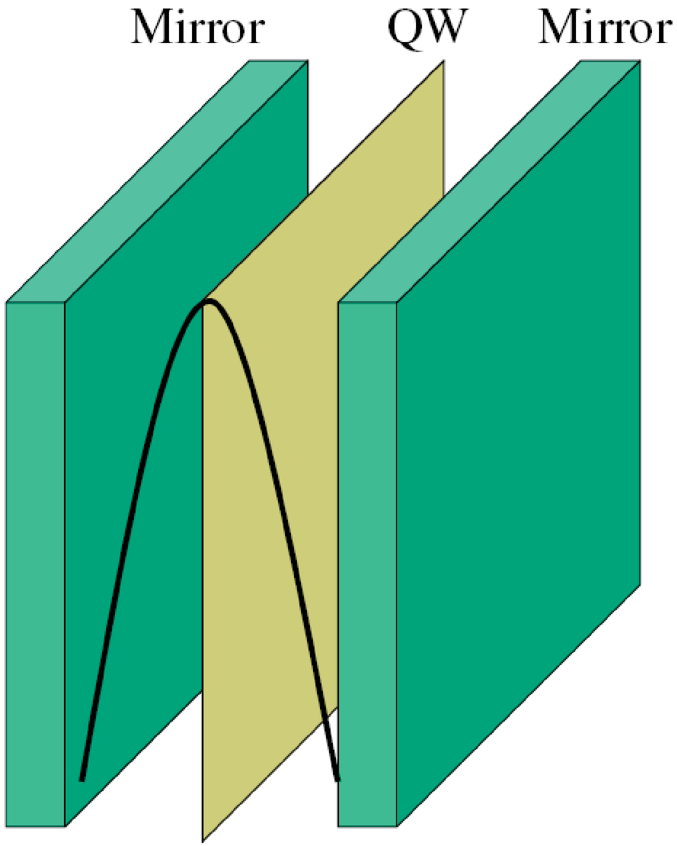
2D photons in planar microcavities





$$\omega_{cav}(q) = \frac{c}{n_{cav}} \sqrt{q_z^2 + q^2}$$

Light-matter interaction in a cavity



$$\left| \sim \right\rangle \Leftrightarrow \left| QW\, exc. \right\rangle$$

STRONG COUPLING

$$\left| \sim \right\rangle \Leftrightarrow \left| QW\, exc. \right\rangle$$

HYBRID EXCITATIONS
=
CAVITY POLARITONS
=
HALF-LIGHT HALF-MATTER
EXCITATIONS

Second quantization Hamiltonian

$$H = H_0 + H_{\text{int}}$$

$$H_0 = \sum_q \hbar\omega_{cav}(k)\, a^+_{\vec{k}} a_{\vec{k}} + \sum_q \hbar\omega_{exc}(k)\, b^+_{\vec{k}} b_{\vec{k}}$$

$$H_{\text{int}} = \sum_{\vec{k}} \hbar\Omega_0\, a^+_{\vec{k}} b_{\vec{k}} + \sum_{\vec{k}} \hbar\Omega_0\, b^+_{\vec{k}} a_{\vec{k}}$$

Photon emission

Photon absorption

- In-plane wavevector is conserved
- Different in-plane wavevectors are decoupled

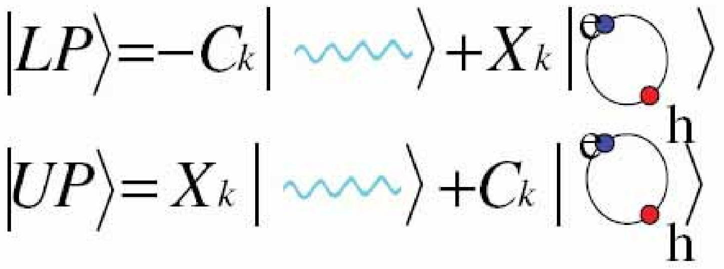
Cavity polariton states and operators

$$p^{+}_{1,\vec{k}} = -C_k\, a^{+}_{\vec{k}} + X_k\, b^{+}_{\vec{k}}$$
$$p^{+}_{2,\vec{k}} = X_k a^{+}_{\vec{k}} + C_k b^{+}_{\vec{k}}$$

$$M = \begin{pmatrix} \omega_{cav}(k) & \Omega_0 \\ \Omega_0 & \omega_{exc}(k) \end{pmatrix}$$

$$\Downarrow$$

$$\boxed{H_0 + H_{\text{int}} = \sum_{\vec{k}} \hbar\omega_{LP}(k)\; p^{+}_{1,\vec{k}} p_{1,\vec{k}} + \sum_{\vec{k}} \hbar\omega_{UP}(k)\; p^{+}_{2,\vec{k}} p_{2,\vec{k}}}$$

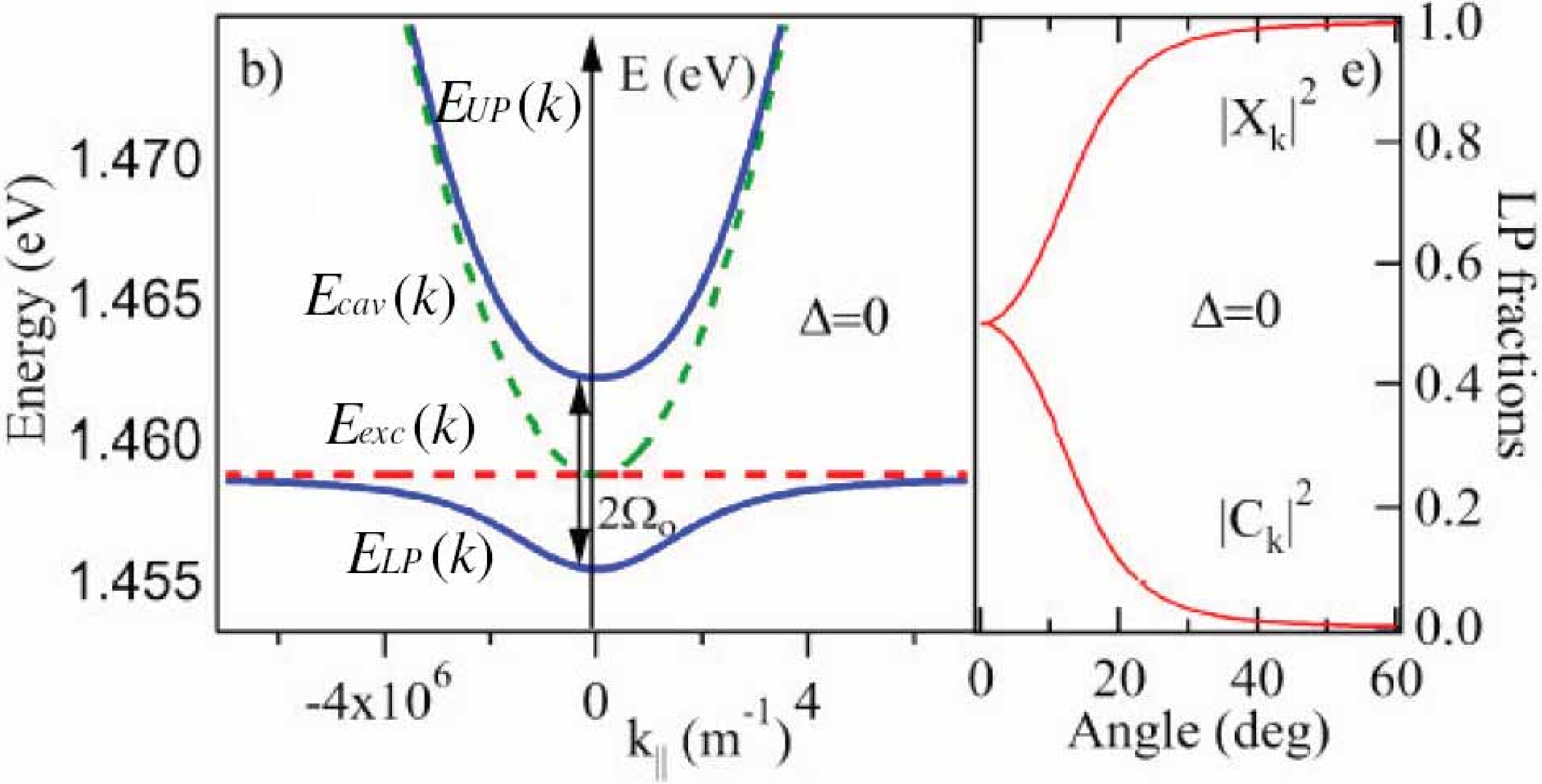


$$|LP\rangle = -C_k|\sim\sim\sim\rangle + X_k|\bigcirc\rangle$$
$$|UP\rangle = X_k|\sim\sim\sim\rangle + C_k|\bigcirc\rangle$$

$|C_k|^2 =$ Photonic fraction of the LP mode

$|X_k|^2 =$ Excitonic fraction of the LP mode

In-plane dispersion of the polariton modes



- The effective mass of polaritons is very small
- The Lower Polariton (LP) dispersion is strongly non-parabolic

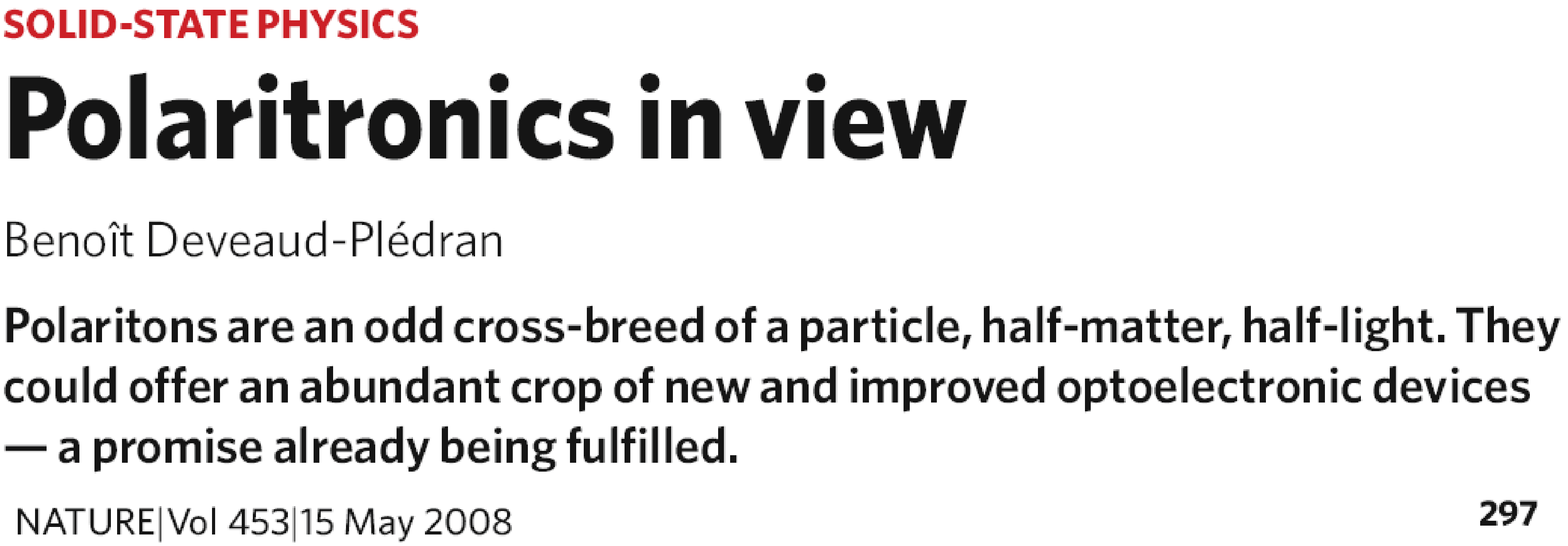
Useful properties

- Light effective mass $\sim 5 \times 10^{-5} \mathrm{m_e}$
- Lifetime in the picosecond range
- They have large de Broglie wavelengths of around 1 micrometer
- They might be stable at room temperature
- They are good bosons (can be parametrically amplifed)

Laser

Bose-Einstein Condensation

Applications of microcavity polaritons



SOLID-STATE PHYSICS

Polaritronics in view

Benoît Deveaud-Plédran

Polaritons are an odd cross-breed of a particle, half-matter, half-light. They could offer an abundant crop of new and improved optoelectronic devices — a promise already being fulfilled.

NATURE|Vol 453|15 May 2008 **297**

Single-photon emitters

Lasers

Light-emitting diodes

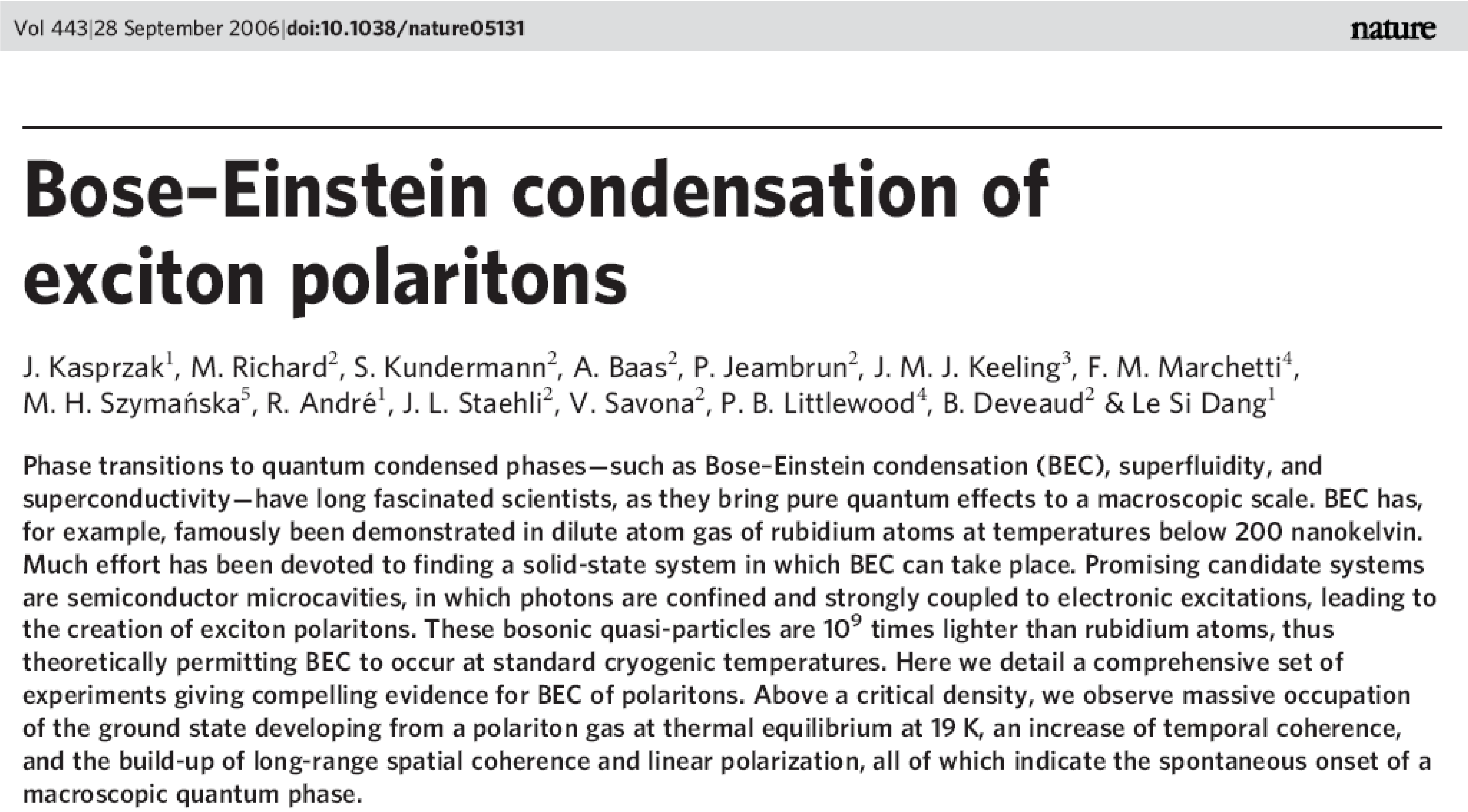
Photodetectors

Optical switches

Types of condensates

	Strongly interacting	Weakly interacting
Free atoms	Helium	Trapped atoms
Electronic quasiparticles in solid	Superconductors	Excitonic condensates

Ⅱ. Bose-Einstein condensation of exciton polaritons



Vol 443|28 September 2006|**doi:10.1038/nature05131** nature

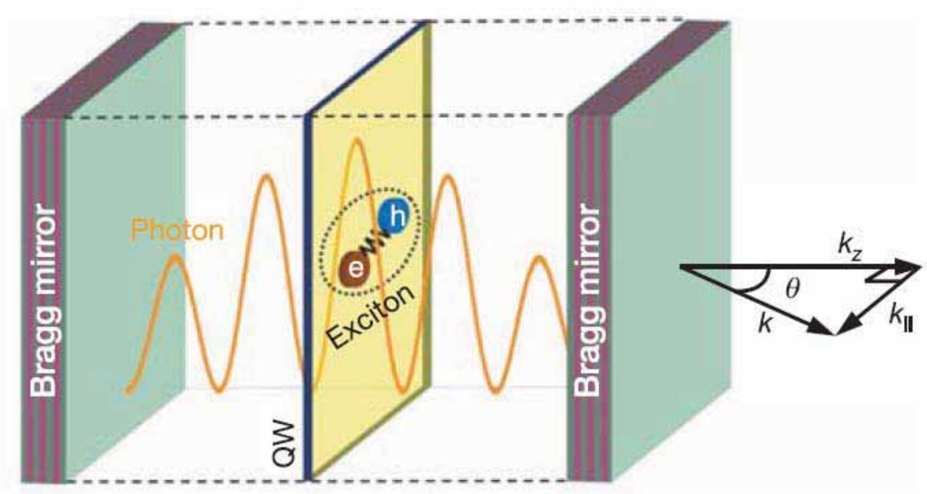
Bose–Einstein condensation of exciton polaritons

J. Kasprzak[1], M. Richard[2], S. Kundermann[2], A. Baas[2], P. Jeambrun[2], J. M. J. Keeling[3], F. M. Marchetti[4], M. H. Szymańska[5], R. André[1], J. L. Staehli[2], V. Savona[2], P. B. Littlewood[4], B. Deveaud[2] & Le Si Dang[1]

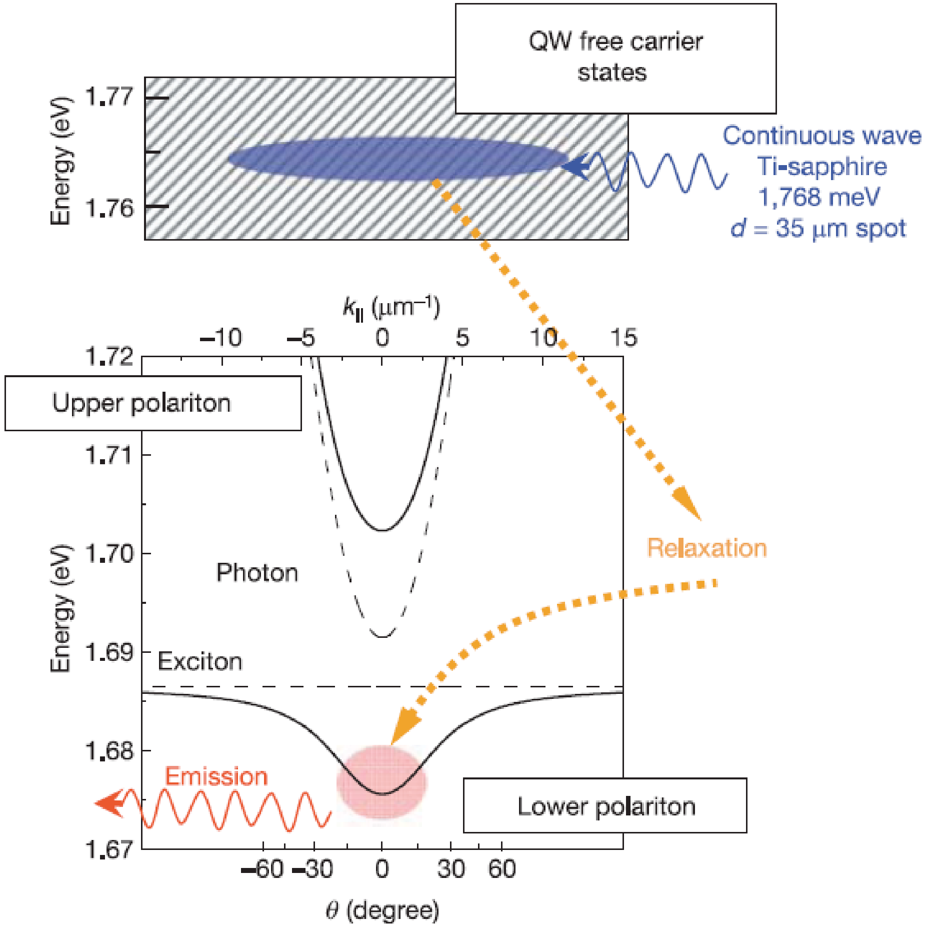
Phase transitions to quantum condensed phases—such as Bose–Einstein condensation (BEC), superfluidity, and superconductivity—have long fascinated scientists, as they bring pure quantum effects to a macroscopic scale. BEC has, for example, famously been demonstrated in dilute atom gas of rubidium atoms at temperatures below 200 nanokelvin. Much effort has been devoted to finding a solid-state system in which BEC can take place. Promising candidate systems are semiconductor microcavities, in which photons are confined and strongly coupled to electronic excitations, leading to the creation of exciton polaritons. These bosonic quasi-particles are 10^9 times lighter than rubidium atoms, thus theoretically permitting BEC to occur at standard cryogenic temperatures. Here we detail a comprehensive set of experiments giving compelling evidence for BEC of polaritons. Above a critical density, we observe massive occupation of the ground state developing from a polariton gas at thermal equilibrium at 19 K, an increase of temporal coherence, and the build-up of long-range spatial coherence and linear polarization, all of which indicate the spontaneous onset of a macroscopic quantum phase.

Microcavity diagram and energy dispersion

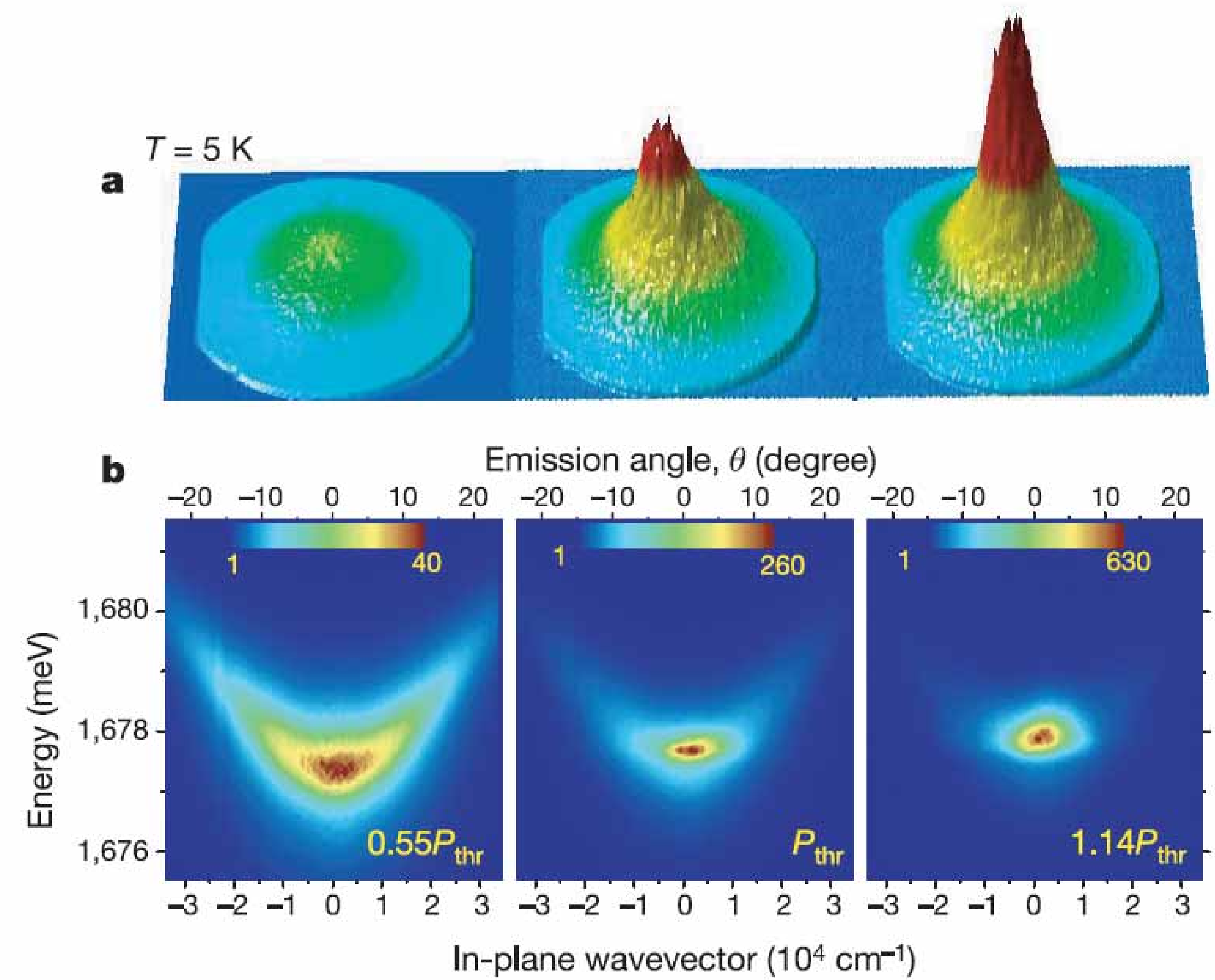
CdTe/CdMgTe microcavity



$$k_{\|} = (E/\hbar c)\sin\theta$$

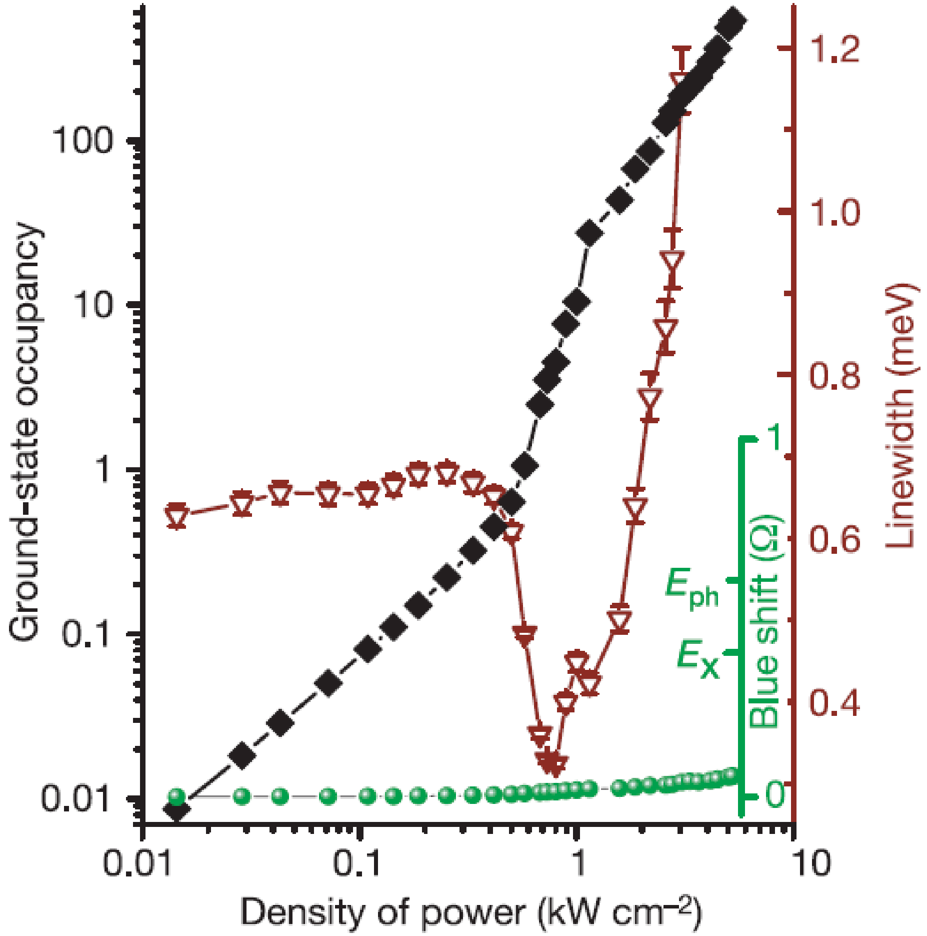


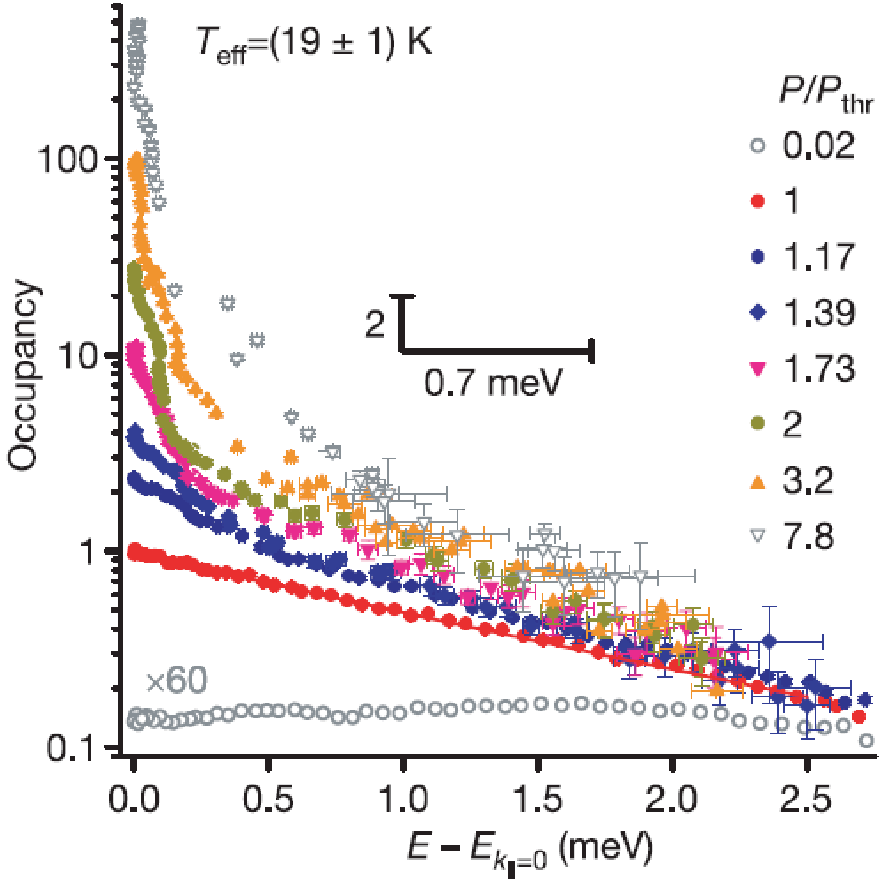
Far-field emission measured at 5K for three excitation intensities



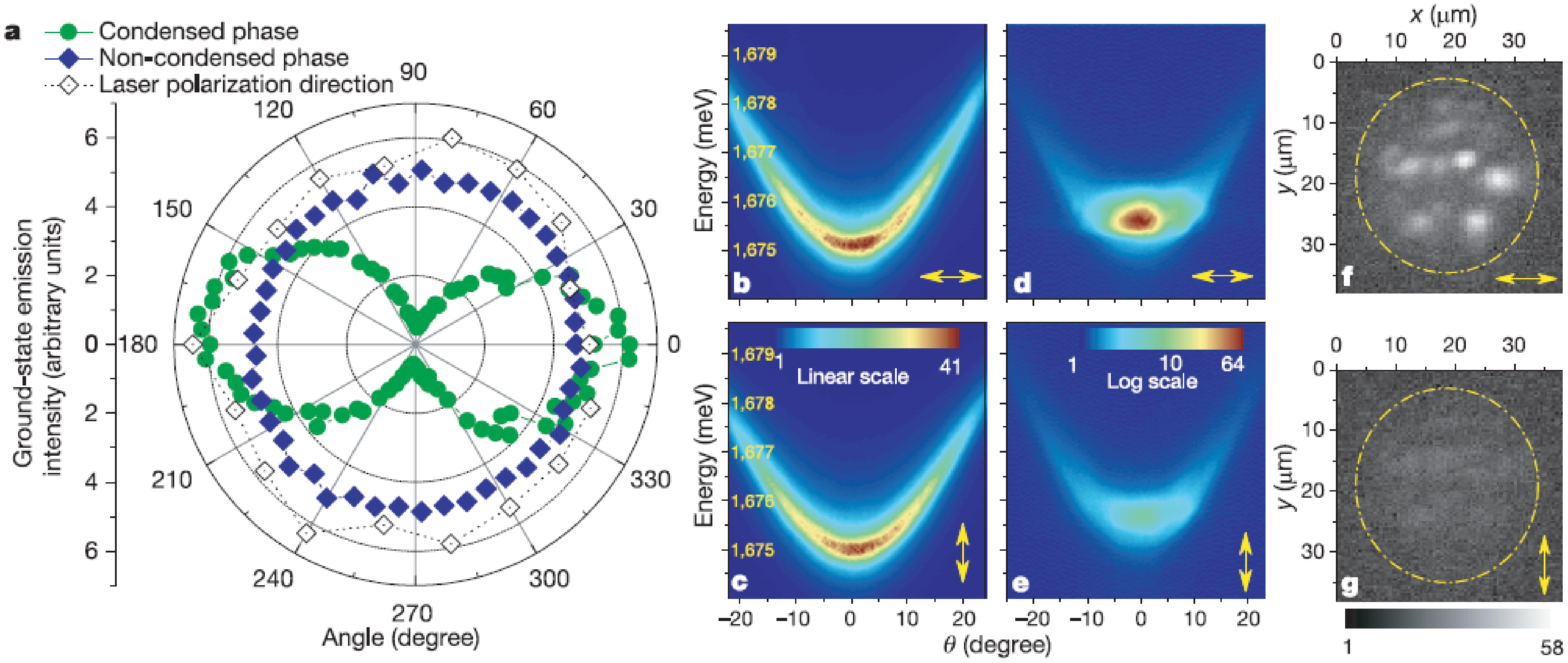
$$P_{\mathrm{thr}} = 1.67\,\mathrm{kW\,cm^{-2}}$$

Polariton occupancy measured at 5K

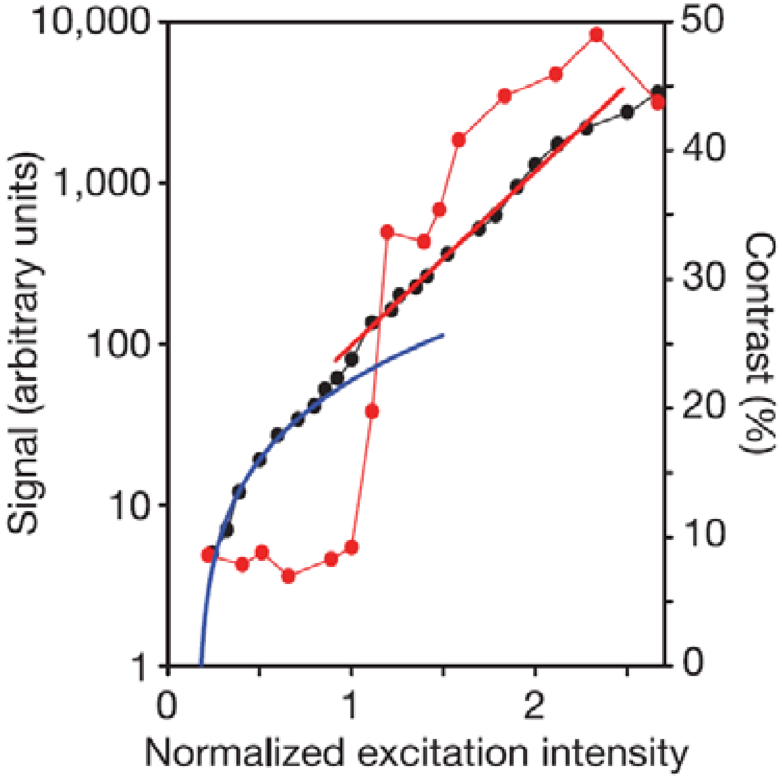


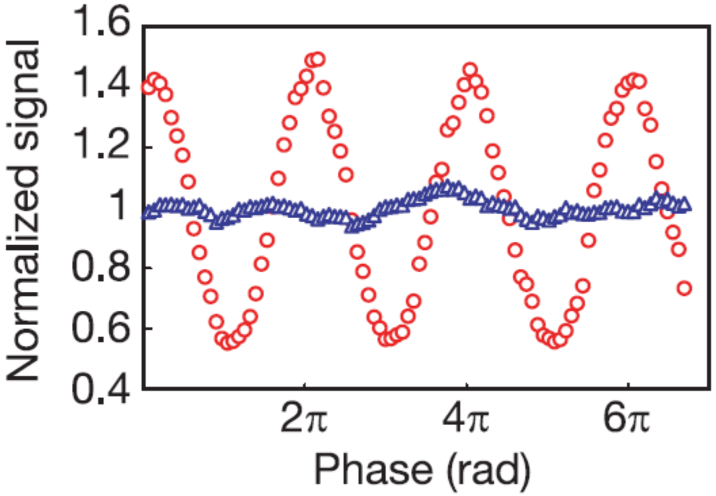


Polarization properties of the polariton emission



Spatial correlation measurements using a Michelson interferometer

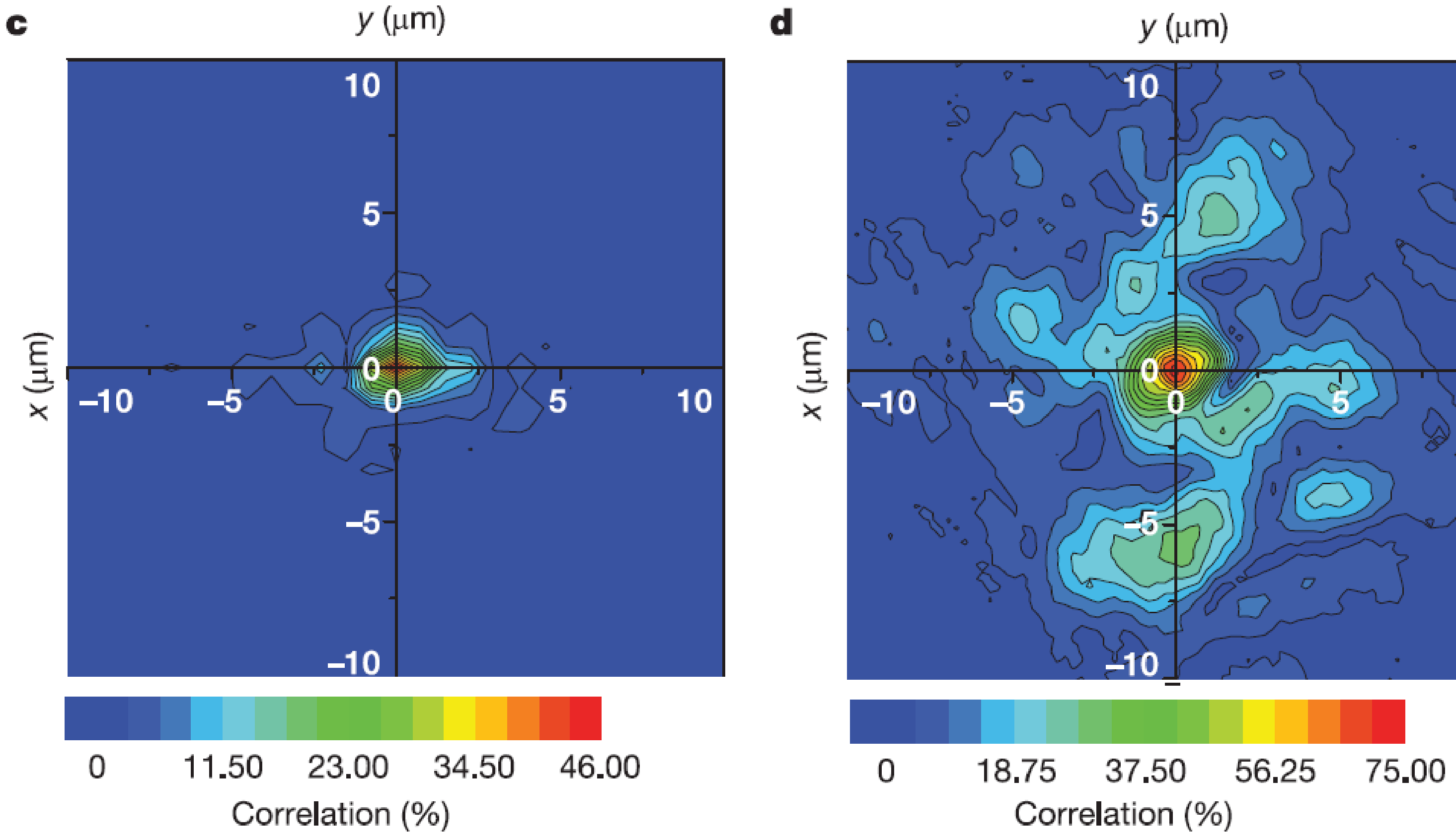




$$g^{(1)}(\mathbf{r},\mathbf{r}') = \frac{\langle E^{\star}(\mathbf{r})E(\mathbf{r}')\rangle}{\langle E^{\star}(\mathbf{r})\rangle\langle E(\mathbf{r}')\rangle}$$

$$C(\mathbf{r},\mathbf{d}) = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{2\sqrt{I(\mathbf{r})I(\mathbf{r}+\mathbf{d})}}{I(\mathbf{r}) + I(\mathbf{r}+\mathbf{d})} g^{(1)}(\mathbf{r},\mathbf{r}+\mathbf{d})$$

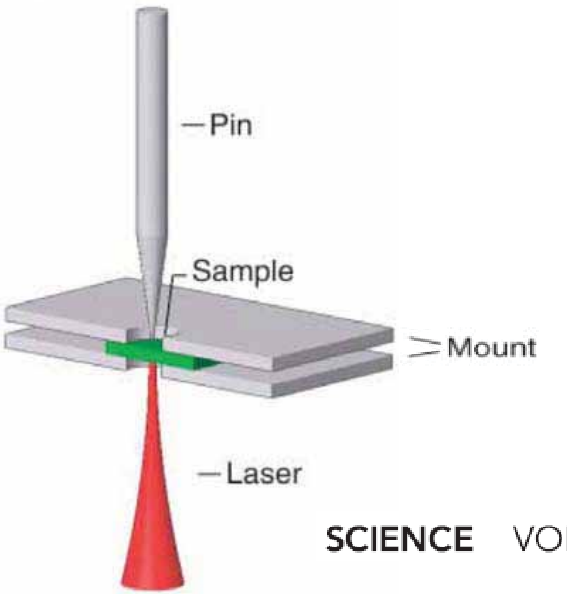
Measurement of spatial coherence



Bose-Einstein Condensation of Microcavity Polaritons in a Trap

R. Balili,[1] V. Hartwell,[1] D. Snoke,[1]* L. Pfeiffer,[2] K. West[2]

We have created polaritons in a harmonic potential trap analogous to atoms in optical traps. The trap can be loaded by creating polaritons 50 micrometers from its center that are allowed to drift into the trap. When the density of polaritons exceeds a critical threshold, we observe a number of signatures of Bose-Einstein condensation: spectral and spatial narrowing, a peak at zero momentum in the momentum distribution, first-order coherence, and spontaneous linear polarization of the light emission. The polaritons, which are eigenstates of the light-matter system in a microcavity, remain in the strong coupling regime while going through this dynamical phase transition.



III. Quantized vortices in an exciton-polariton condensate

Quantized vortices in an exciton–polariton condensate

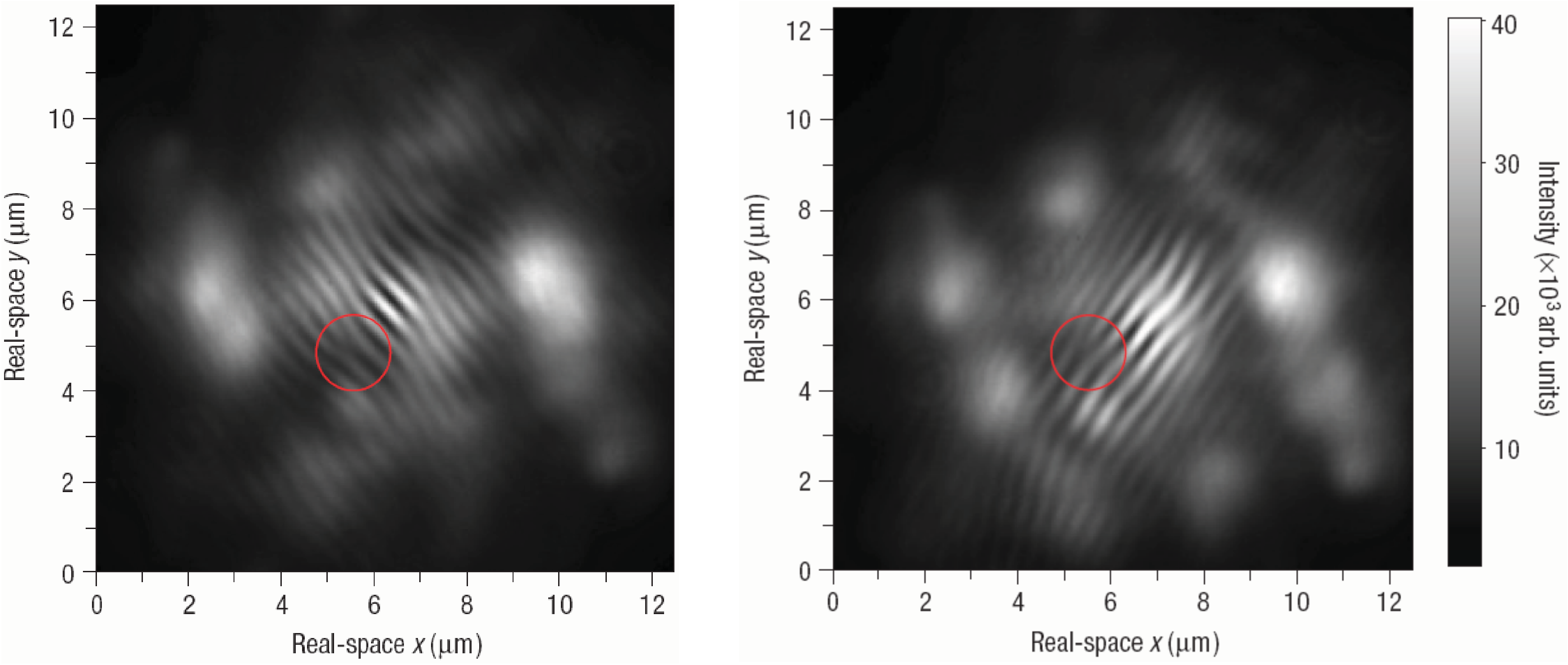
K. G. LAGOUDAKIS[1]*, M. WOUTERS[2]*†, M. RICHARD[1], A. BAAS[1], I. CARUSOTTO[3], R. ANDRÉ[4], LE SI DANG[4] AND B. DEVEAUD-PLÉDRAN[1]

[1] IPEQ, Ecole Polytechnique Fédérale de Lausanne(EPFL), Station 3, 1015 Lausanne, Switzerland
[2] ITP, Ecole Polytechnique Fédérale de Lausanne(EPFL), Station 3, 1015 Lausanne, Switzerland
[3] INFM-CNR BEC and Dipartimento di Fisica, Universita di Trento, via Sommarive 14, 38050 Povo (Trento), Italy
[4] Institut Néel, CNRS, 25 Avenue des Martyrs, 38042 Grenoble, France
†Previously: TFVS, Universiteit Antwerpen, Universiteitsplein 1, 2610 Antwerpen, Belgium
*e-mail: konstantinos.lagoudakis@epfl.ch; michiel.wouters@epfl.ch

Published online: 10 August 2008; doi:10.1038/nphys1051

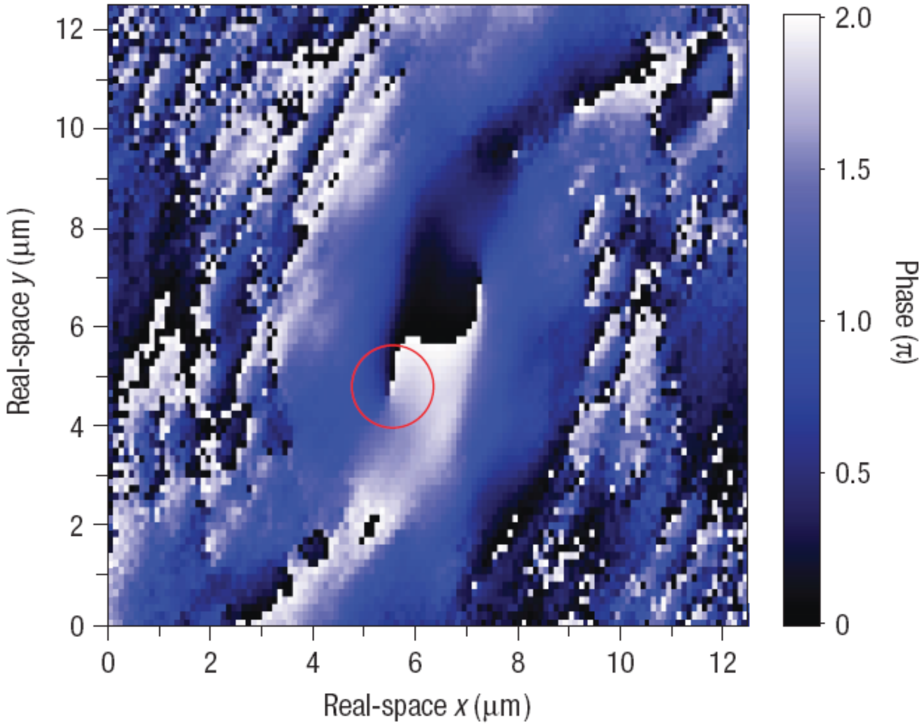
Interferogram with vortex

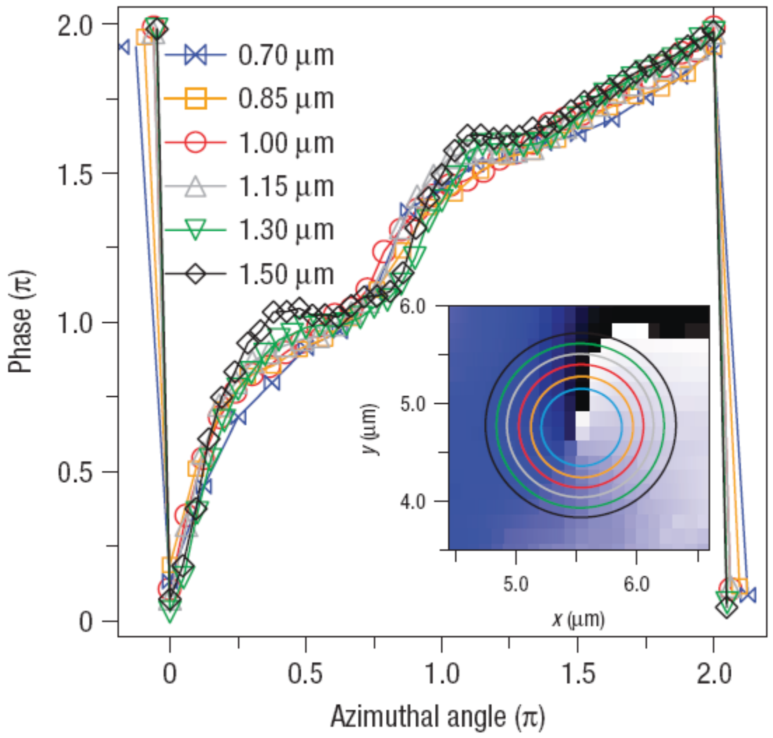
- 2 π phase shift is verified by monitoring dislocation while changing the orientation of fringes
- A forklike dislocation is seen for all fringe orientations



Extraction of phase from interferogram

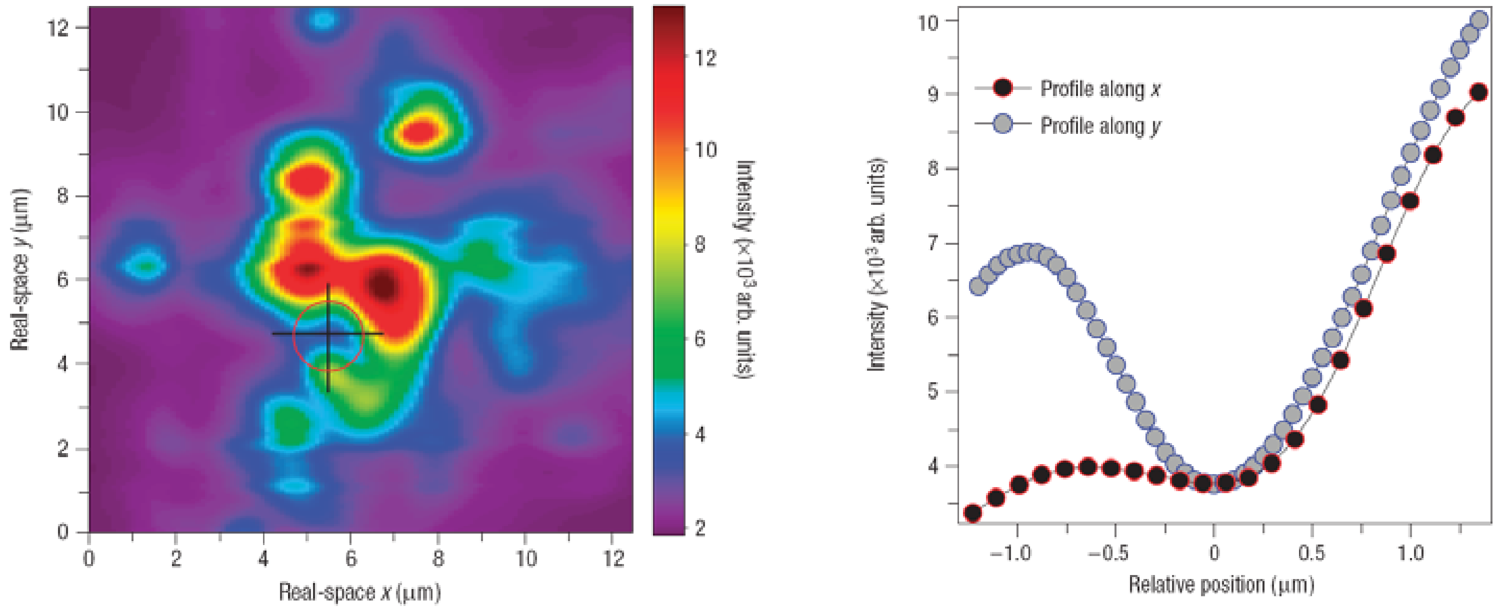
- Application of fringes: key features for extraction of phase
- The dislocation indeed gives a 2 π winding of the phase





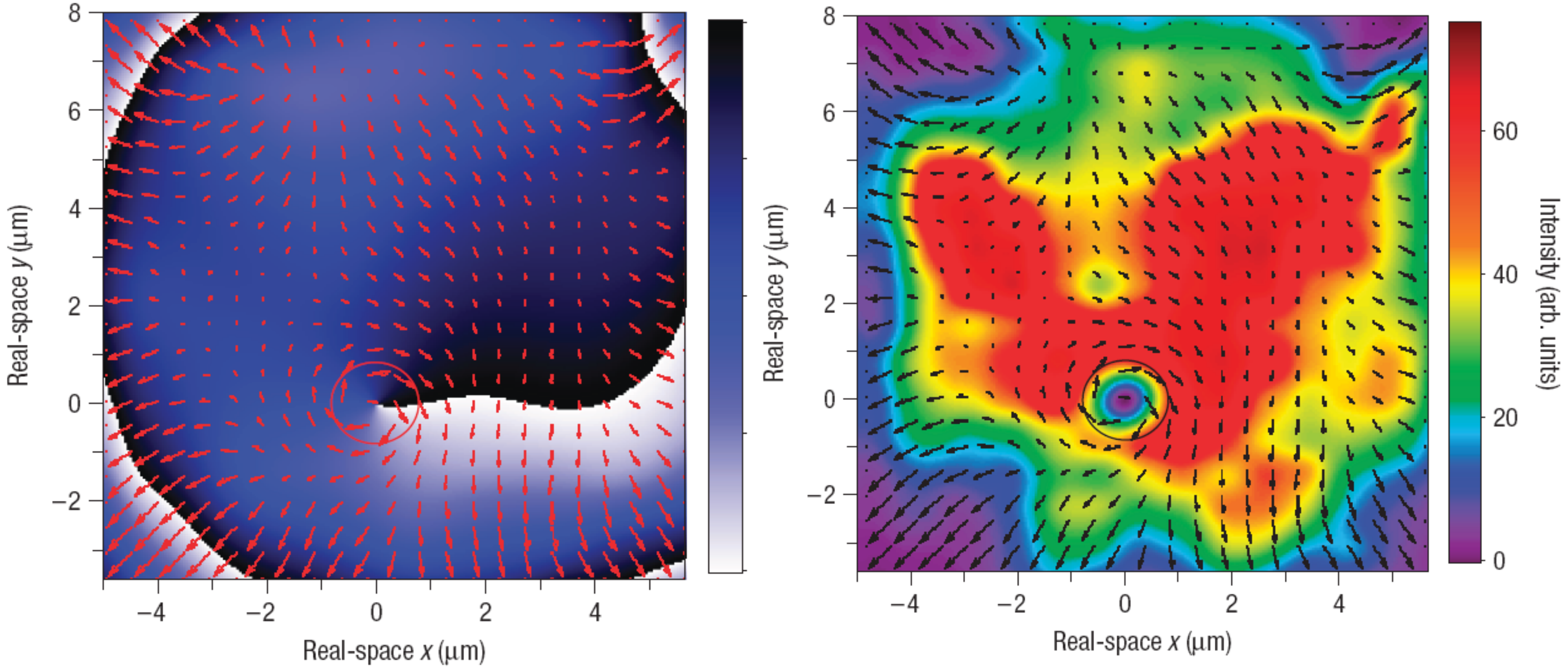
Real-space polariton population at the vortex region

- Vortex is located at a region of reduced density
- Both x and y directions have local minimum



- Vortices are hence identified in a polariton condensate: Both characteristics are demonstrated

Phase and density distribution from the mean field theory



$$i\frac{\partial}{\partial t}\psi(\mathbf{r},t) = \left\{-\frac{\hbar\nabla^2}{2m}+V_d(\mathbf{r})-\frac{i}{2}[\gamma_c-R(n_{\mathrm{R}}(\mathbf{r},t))]+g|\psi(\mathbf{r},t)|^2+g_{\mathrm{R}}n_{\mathrm{R}}(\mathbf{r},t)\right\}\psi(\mathbf{r},t)$$

IV. Collective fluid dynamics of a polariton condensate

Vol 457|15 January 2009|**doi:10.1038/nature07640** nature

LETTERS

Collective fluid dynamics of a polariton condensate in a semiconductor microcavity

A. Amo[1], D. Sanvitto[1], F. P. Laussy[2], D. Ballarini[1], E. del Valle[2], M. D. Martin[1], A. Lemaître[3], J. Bloch[3], D. N. Krizhanovskii[4], M. S. Skolnick[4], C. Tejedor[2] & L. Viña[1]

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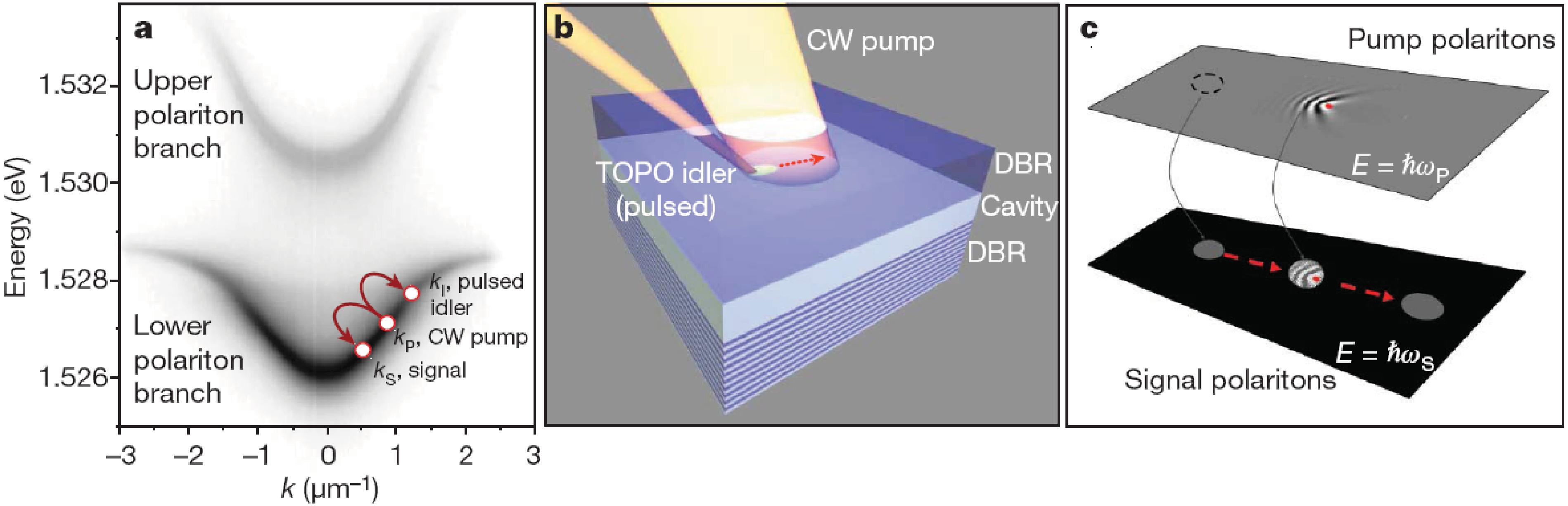
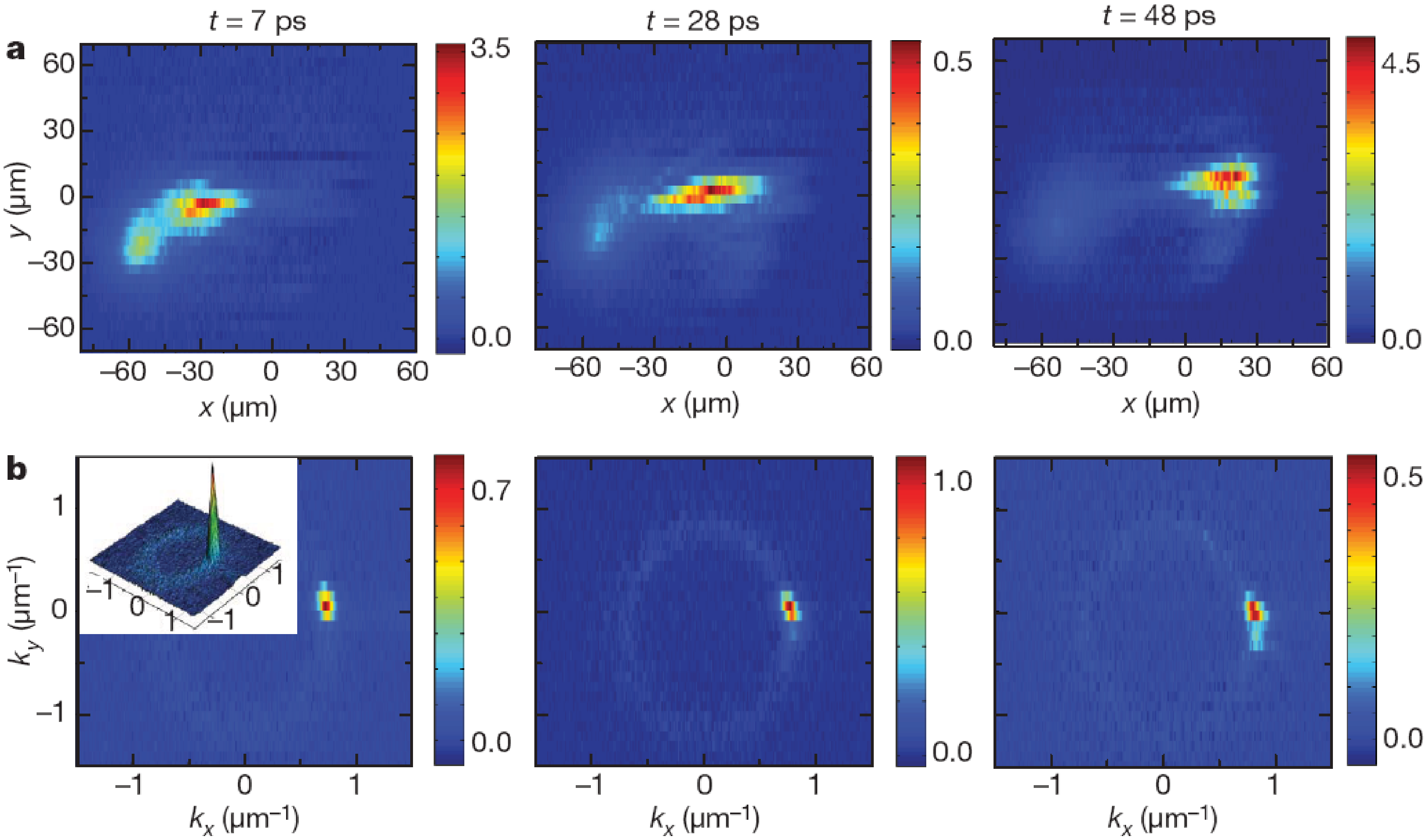
[1]Departamento Física de Materiales, [2]Departamento Física Teórica de la Materia Condensada, Universidad Autonóma de Madrid, 28049 Madrid, Spain. [3]LPN/CNRS, Route de Nozay, 91460 Marcoussis, France. [4]Department of Physics & Astronomy, University of Sheffield, Sheffield S3 7RH, UK.

Experimental configuration of the TOPO



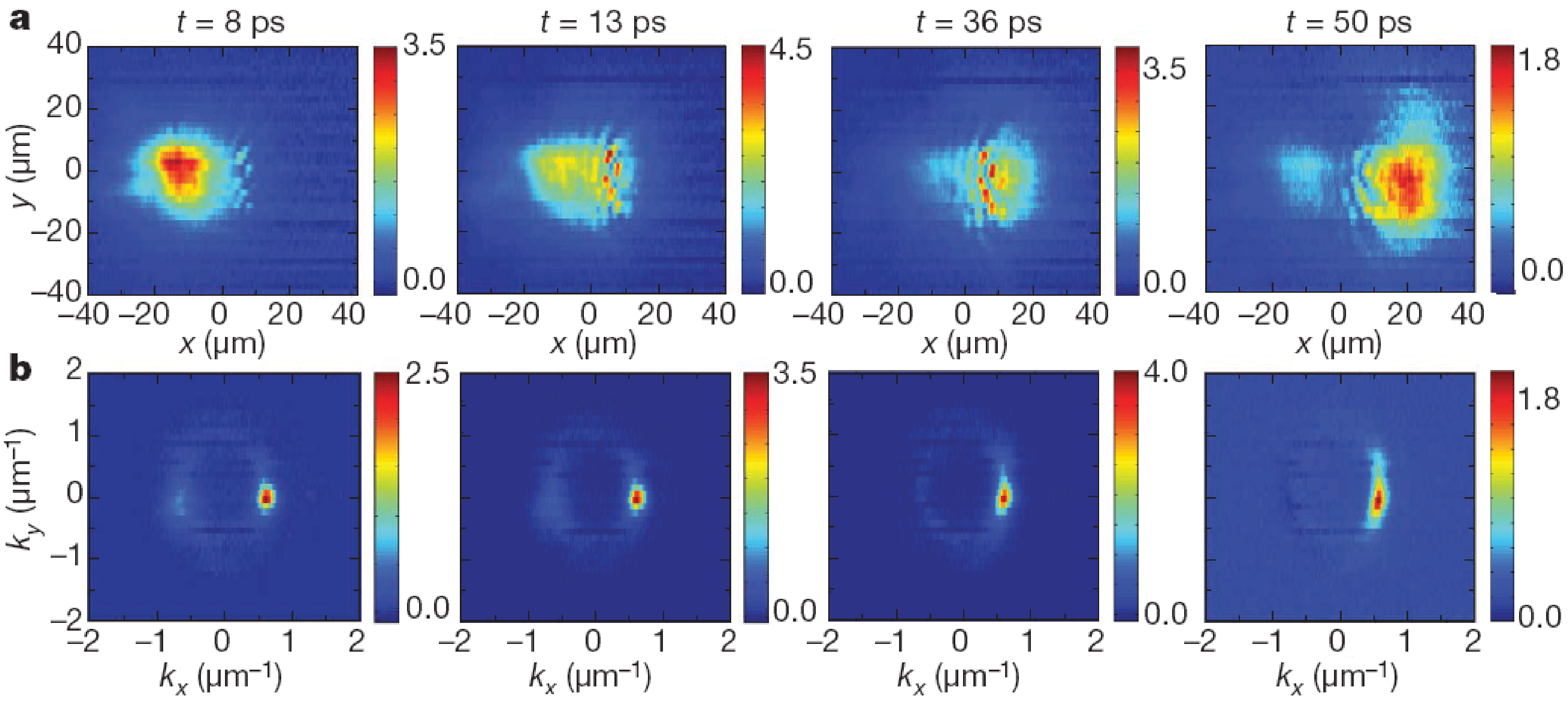
$$2k_P = k_S + k_I \qquad 2E_P = E_S + E_I$$

Free movement of a polariton droplet



$$v_g = 1.2 \times 10^6 \,\mathrm{m\,s}^{-1}$$

Images of a polariton droplet colliding against native defects



$$v_g = 0.9 \times 10^6 \, \mathrm{m\,s}^{-1}$$

Some issues

- The momentum distribution measured in the experiments never fits an equilibrium B-E distribution
    - High-energy “reservoir” of excitons
    - A “bottleneck” region
    - Low-energy polariton ststes
  - ◆ Each of three regions has a different characteristic temperature
- Intrinsic non-equilibrium
- Despite the incomplete equilibrium, so many of the canonical telltales of condensation can still be observed in polariton condensates

V. Some theoretical approaches

PRL **96,** 230602 (2006) PHYSICAL REVIEW LETTERS week ending 16 JUNE 2006

Nonequilibrium Quantum Condensation in an Incoherently Pumped Dissipative System

M. H. Szymańska,[1] J. Keeling,[2] and P. B. Littlewood[3]
[1]*Clarendon Laboratory, Department of Physics, University of Oxford, Parks Road, Oxford, OX1 3PU, United Kingdom*
[2]*Department of Physics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA*
[3]*Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3 0HE, United Kingdom*
(Received 5 March 2006; published 12 June 2006)

We study spontaneous quantum coherence in an out of an equilibrium system, coupled to multiple baths describing pumping and decay. For a range of parameters describing coupling to, and occupation of the baths, a stable steady-state condensed solution exists. The presence of pumping and decay significantly modifies the spectra of phase fluctuations, leading to correlation functions that differ both from an isolated condensate and from a laser.

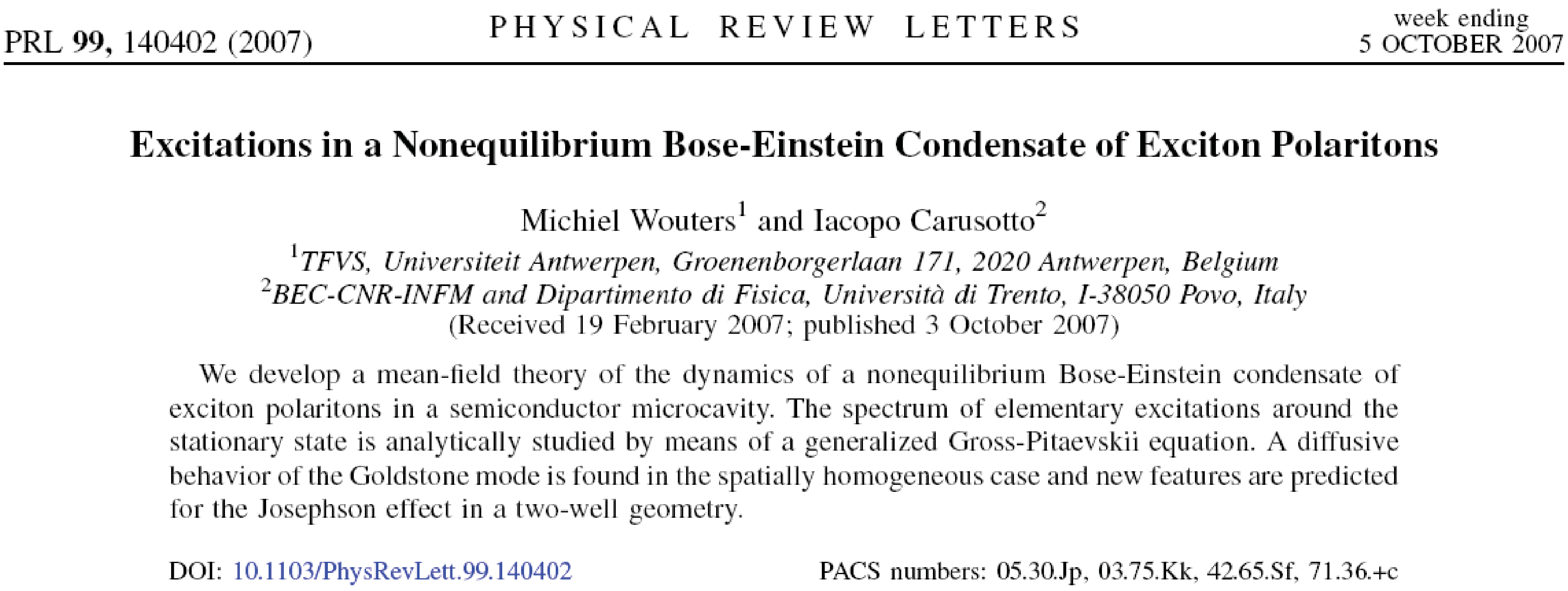
DOI: 10.1103/PhysRevLett.96.230602 PACS numbers: 05.70.Ln, 03.75.Gg, 03.75.Kk, 42.50.Fx

$$\hat{H} = \hat{H}_{\text{sys}} + \hat{H}_{\text{sys,bath}} + \hat{H}_{\text{bath}}$$

$$\hat{H}_{\text{sys}} = \sum_{\alpha} \epsilon_{\alpha}(b^{\dagger}_{\alpha} b_{\alpha} - a^{\dagger}_{\alpha} a_{\alpha}) + \sum_{\mathbf{p}} \omega_{\mathbf{p}} \psi^{\dagger}_{\mathbf{p}} \psi_{\mathbf{p}} + \frac{1}{\sqrt{L^2}} \sum_{\alpha} \sum_{\mathbf{p}} (g_{\alpha,\mathbf{p}} \psi_{\mathbf{p}} b^{\dagger}_{\alpha} a_{\alpha} + \text{H.c.})$$

$$\hat{H}_{\text{sys,bath}} = \sum_{\alpha,k} \Gamma^{a}_{\alpha,k}(a^{\dagger}_{\alpha} A_{k} + \text{H.c.}) + \Gamma^{b}_{\alpha,k}(b^{\dagger}_{\alpha} B_{k} + \text{H.c.}) + \sum_{\mathbf{p},k} \zeta_{\mathbf{p},k}(\psi^{\dagger}_{\mathbf{p}} \Psi_{k} + \text{H.c.})$$

$$\hat{H}_{\text{bath}} = \sum_{k} \omega^{\Gamma^{a}}_{k} A^{\dagger}_{k} A_{k} + \sum_{k} \omega^{\Gamma^{b}}_{k} B^{\dagger}_{k} B_{k} + \sum_{k} \omega^{\zeta}_{k} \Psi^{\dagger}_{k} \Psi_{k}$$


PRL **99,** 140402 (2007) PHYSICAL REVIEW LETTERS week ending 5 OCTOBER 2007

Excitations in a Nonequilibrium Bose-Einstein Condensate of Exciton Polaritons

Michiel Wouters[1] and Iacopo Carusotto[2]

[1]*TFVS, Universiteit Antwerpen, Groenenborgerlaan 171, 2020 Antwerpen, Belgium*
[2]*BEC-CNR-INFM and Dipartimento di Fisica, Università di Trento, I-38050 Povo, Italy*

(Received 19 February 2007; published 3 October 2007)

We develop a mean-field theory of the dynamics of a nonequilibrium Bose-Einstein condensate of exciton polaritons in a semiconductor microcavity. The spectrum of elementary excitations around the stationary state is analytically studied by means of a generalized Gross-Pitaevskii equation. A diffusive behavior of the Goldstone mode is found in the spatially homogeneous case and new features are predicted for the Josephson effect in a two-well geometry.

DOI: 10.1103/PhysRevLett.99.140402 PACS numbers: 05.30.Jp, 03.75.Kk, 42.65.Sf, 71.36.+c

$$i\frac{\partial\psi}{\partial t}=\left\{-\frac{\hbar\nabla^2}{2m_{\mathrm{LP}}}+\frac{i}{2}[R(n_R)-\gamma]+g|\psi|^2+2\tilde{g}n_R\right\}\psi$$

$$\frac{\partial n_R}{\partial t}=P-\gamma_R n_R-R(n_R)|\psi(\mathbf{r})|^2+D\nabla^2 n_R$$

PRL **100,** 250401 (2008) PHYSICAL REVIEW LETTERS week ending 27 JUNE 2008

Spontaneous Rotating Vortex Lattices in a Pumped Decaying Condensate

Jonathan Keeling[1] and Natalia G. Berloff[2]

[1]*Cavendish Laboratory, University of Cambridge, J.J. Thomson Avenue, Cambridge CB3 0HE, United Kingdom*
[2]*Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge, CB3 0WA, United Kingdom*

(Received 18 June 2007; revised manuscript received 19 February 2008; published 23 June 2008)

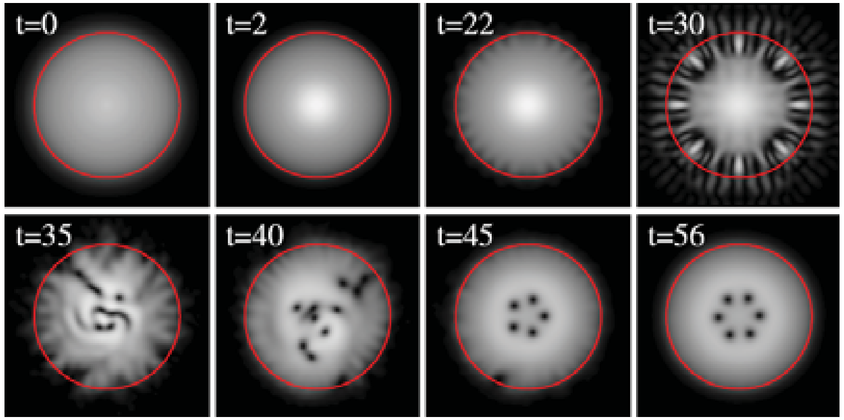
Injection and decay of particles in an inhomogeneous quantum condensate can significantly change its behavior. We model trapped, pumped, decaying condensates by a complex Gross-Pitaevskii equation and analyze the density and currents in the steady state. With homogeneous pumping, rotationally symmetric solutions are unstable. Stability may be restored by a finite pumping spot. However if the pumping spot is larger than the Thomas-Fermi cloud radius, then rotationally symmetric solutions are replaced by solutions with spontaneous arrays of vortices. These vortex arrays arise without any rotation of the trap, spontaneously breaking rotational symmetry.

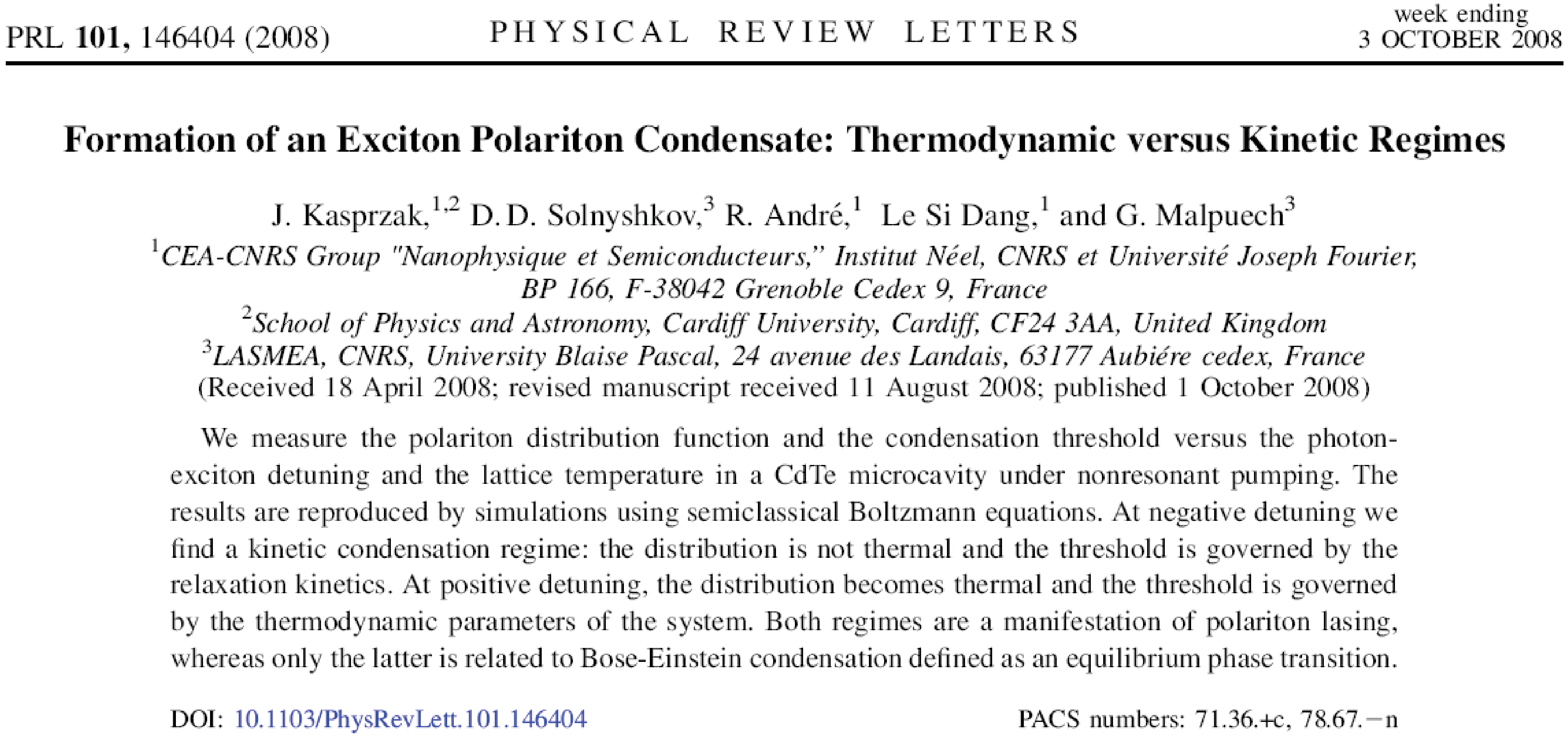
DOI: 10.1103/PhysRevLett.100.250401 PACS numbers: 05.30.Jp, 03.75.Kk, 47.37.+q, 71.36.+c

$$i\hbar\partial_t\psi = \left[-\frac{\hbar^2\nabla^2}{2m} + V(r) + U|\psi|^2 + i(\gamma_{\text{eff}} - \Gamma|\psi|^2)\right]\psi$$

$$\nabla\cdot[\rho(\nabla\phi - \Omega\times\mathbf{r})] = (\alpha\Theta(R-r) - \sigma\rho)\rho,$$

$$\tilde{\mu} = |\nabla\phi - \Omega\times\mathbf{r}|^2 + r^2(1-\Omega^2) + \rho - \frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}.$$





PRL **101,** 146404 (2008) PHYSICAL REVIEW LETTERS week ending 3 OCTOBER 2008

Formation of an Exciton Polariton Condensate: Thermodynamic versus Kinetic Regimes

J. Kasprzak,[1,2] D. D. Solnyshkov,[3] R. André,[1] Le Si Dang,[1] and G. Malpuech[3]
[1]*CEA-CNRS Group "Nanophysique et Semiconducteurs," Institut Néel, CNRS et Université Joseph Fourier, BP 166, F-38042 Grenoble Cedex 9, France*
[2]*School of Physics and Astronomy, Cardiff University, Cardiff, CF24 3AA, United Kingdom*
[3]*LASMEA, CNRS, University Blaise Pascal, 24 avenue des Landais, 63177 Aubiére cedex, France*

(Received 18 April 2008; revised manuscript received 11 August 2008; published 1 October 2008)

We measure the polariton distribution function and the condensation threshold versus the photon-exciton detuning and the lattice temperature in a CdTe microcavity under nonresonant pumping. The results are reproduced by simulations using semiclassical Boltzmann equations. At negative detuning we find a kinetic condensation regime: the distribution is not thermal and the threshold is governed by the relaxation kinetics. At positive detuning, the distribution becomes thermal and the threshold is governed by the thermodynamic parameters of the system. Both regimes are a manifestation of polariton lasing, whereas only the latter is related to Bose-Einstein condensation defined as an equilibrium phase transition.

DOI: 10.1103/PhysRevLett.101.146404 PACS numbers: 71.36.+c, 78.67.−n

VI. Summary and open issues

BEC-like effects that have been observed

- Bimodal momentum-space distribution with a narrow peak at zero momentum
- Long-range off-diagonal order
- Spatial condensation in a macroscopic trap
- Spontaneous symmetry breaking
- Existence of quantized vortices
- Linear Bogoliubov excitation spectrum
- Flow without dispersion

Superfluid behavior

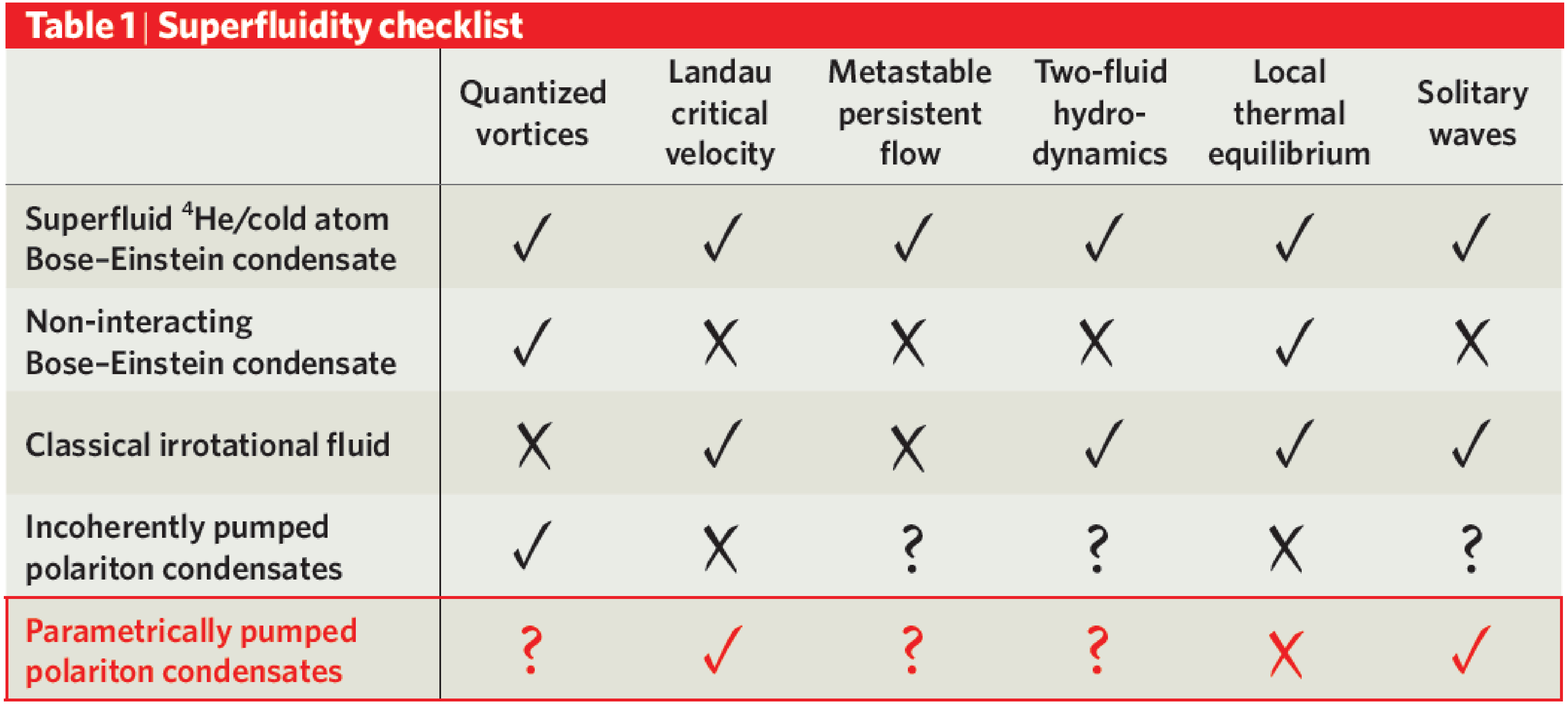


Table 1 | Superfluidity checklist

	Quantized vortices	Landau critical velocity	Metastable persistent flow	Two-fluid hydro-dynamics	Local thermal equilibrium	Solitary waves
Superfluid ^{4}He/cold atom Bose–Einstein condensate	✓	✓	✓	✓	✓	✓
Non-interacting Bose–Einstein condensate	✓	X	X	X	✓	X
Classical irrotational fluid	X	✓	X	✓	✓	✓
Incoherently pumped polariton condensates	✓	X	?	?	X	?
Parametrically pumped polariton condensates	?	✓	?	?	X	✓

Open questions

- What exactly determines the point of breakdown?
- When can we no longer speak of a condensate because the lifetime is too short?
- Which properties of a condensate are robust against non-equilibrium perturbations?
- Polaritons provide a test bed for experimental and theoretical investigations

Thank you for your attention !