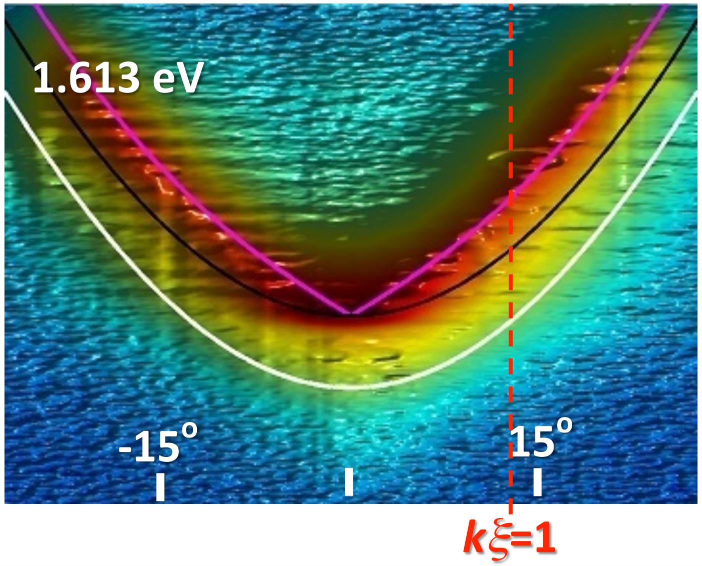
Bogoliubov Excitation Spectrum in Exciton-Polariton Condensates
- Nambu-Goldstone Modes
in Two-Dimensional Open-Dissipative Systems -♪



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Higgs Modes in Condensed Matter and Quantum Gases
(Yukawa Institute of Theoretical Physics (YITP), Kyoto University, June 24, 2014)♪

Outline

- Berezinskii-Kosterlitz-Thouless (BKT) transition in 2D systems
- Free vortices to vortex-anitvortex bound-pairs
- Power-law decay of the correlation functions as the evidence for BKT phase
- Modification of Bogoliubov excitation spectrum with gain and loss
- Observation of Bologiubov excitation spectrum, quasi-superfluidity and sound velocity

Berezinskii-Kosterlitz-Thouless (BKT) Phase Transition

V. L. Berezinskii, Sov. Phys. JETP34, 1144 (1972)
J. M. Kosterlitz and D. J. Thouless J. Phys. C6, 1181 (1973)

There is no long-range-order in uniform 2D system (Hohenberg-Mermin-Wagner Theorem).

The energy cost of a quantized vortex in a 3D superfluid is macroscopic, so that thermal excitation of quantized vortices is not possible in a 3D superfluid. However, it is possible in a 2D superfluid. Creation of quantized vortices is thermodynamically profitable if the free energy would be decreased by the appearance of entropy.

$$F = E_v - TS < 0$$

$$\pi \rho_{2s} \left(\frac{\hbar^2}{m} \right) ln \left(\frac{R}{\xi} \right)$$

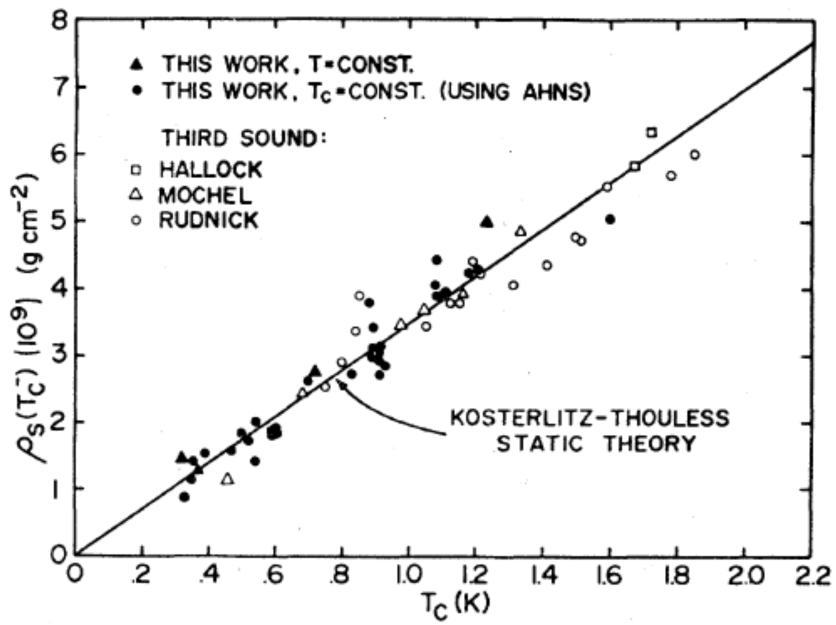
: energy cost per vortex

$$k_B ln \frac{R^2}{\xi^2}$$

: entropy per vortex

ρ_{2S}: 2D superfluid mass density

ξ: healing length (vortex size)



Phase Space Density $n_s \lambda_T^2 < 4$

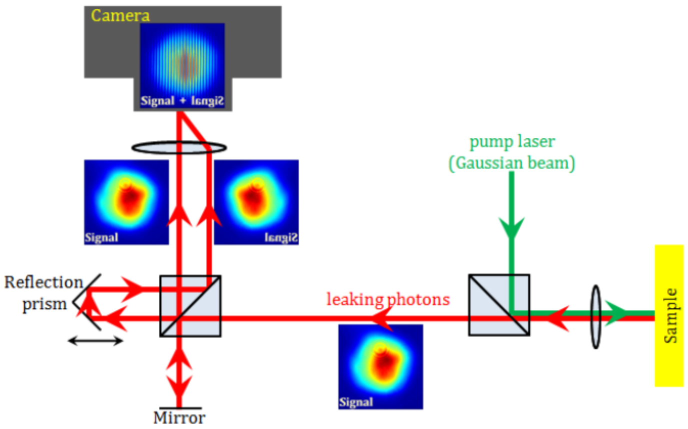
Thermal length $\lambda_T = \left(2\pi\hbar^2 / mk_B T\right)^{1/2}$

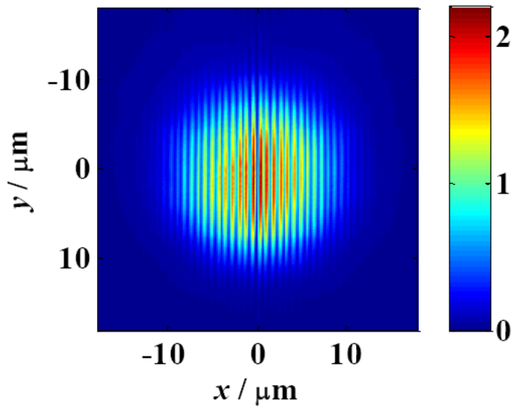
At $n_s \lambda_T^2 > 4$, an anti-vortex and vortex bound-pair is formed.

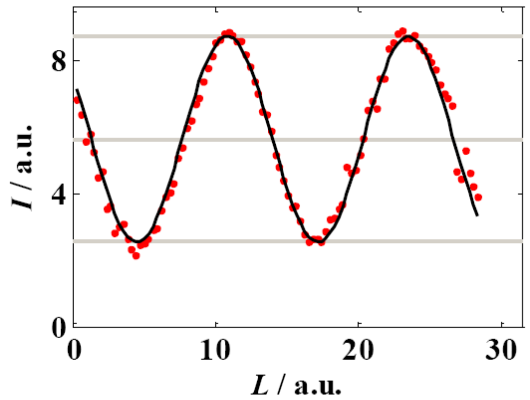
Global phase stabilization

D.J. Bishop and J.D. Reppy, Phys. Rev. B22, 5171 (1980)

Simultaneous Measurements of Phase and Fringe Visibility Maps in Exciton-Polariton Condensates







Michelson interferometer with right angle prism and flat mirror

Superposition of original and inverted near field images with a constant phase slope

Simultaneous measurement of the phase and the fringe visibility

Measured interferogram for one specific path-length difference L at a pump power above condensation threshold

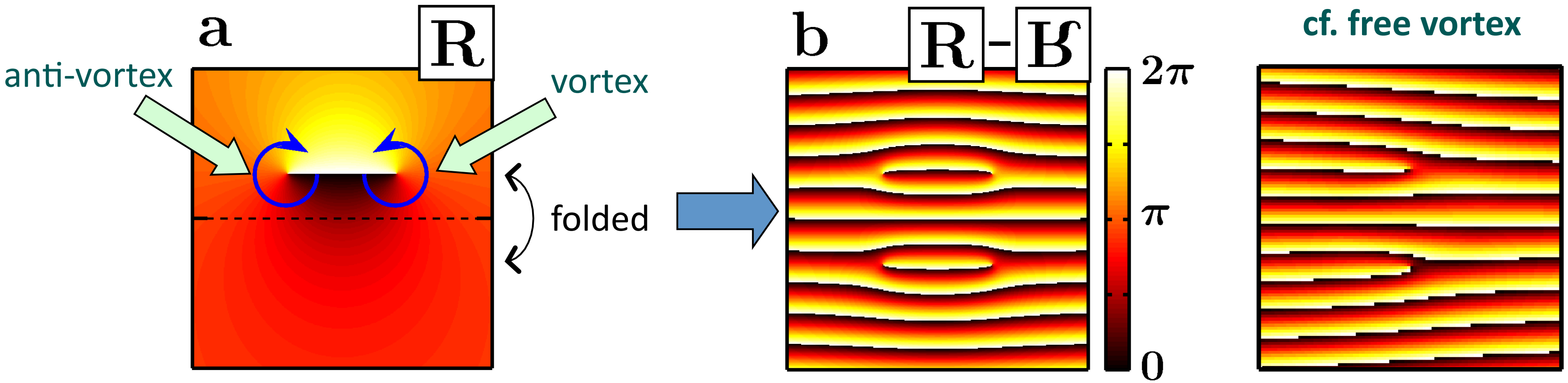
Fringe visibility measurement at a single pixel point

$$I(L) = B + A\sin(kL - \varphi_0)$$

Phase φ_0 and fringe visibility $g^{(1)}(\Delta x) = A/B$ maps in a whole spot can be measured simultaneously.

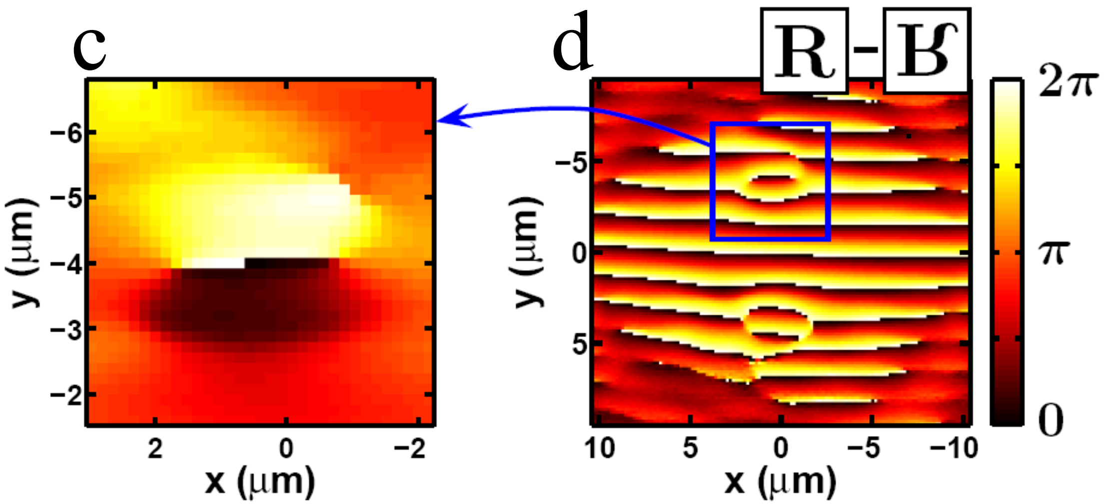
Observation of a Vortex-Antivortex Bound Pair

Phase distribution (Theory) Interference pattern (Theory)



The phase rotations of 2π and - 2π , associated with a vortex and antivortex, cancel out by forming a bound pair.

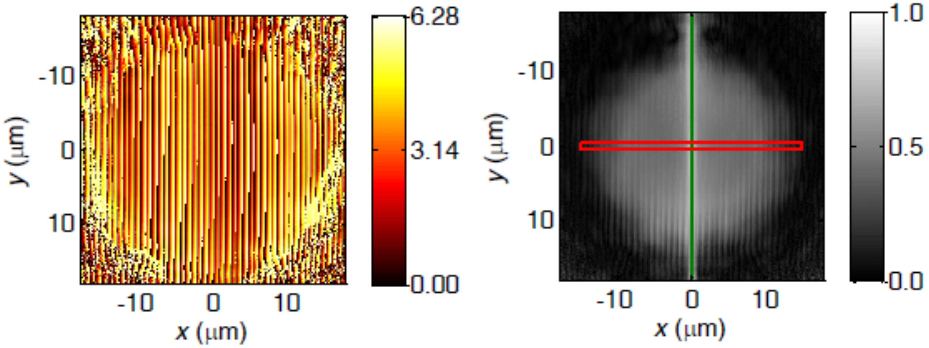
Phase distribution (Experiment) Interference pattern (Experiment)



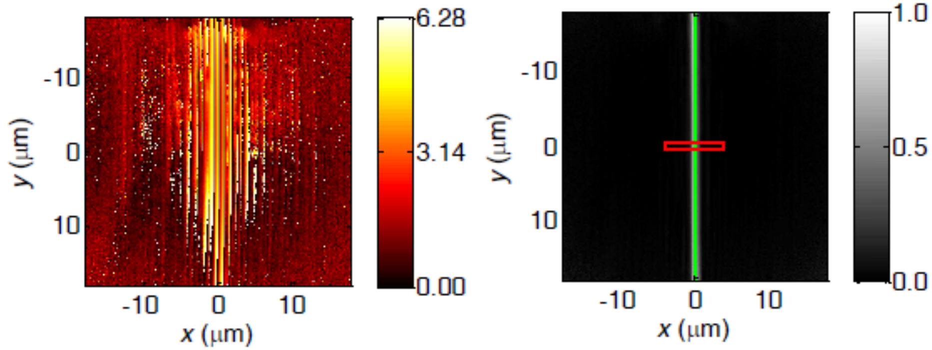
G. Roumpos et al., Nature Physics 7, 126 (2011)

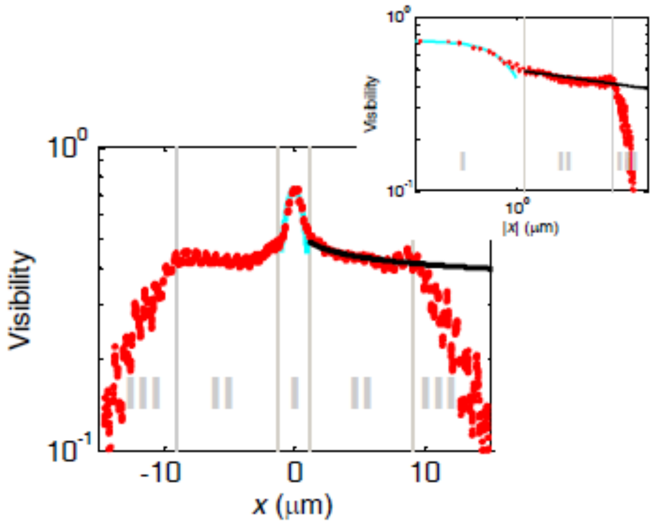
Measured Visibilities at Different Pump Powers: From Gaussian to Power-law Decay

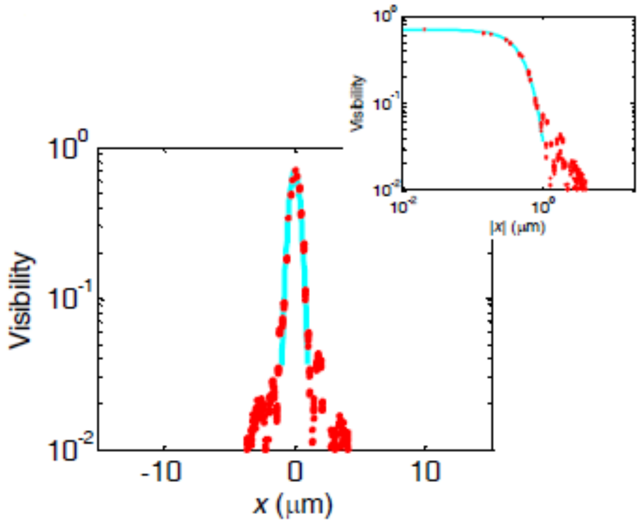
Above threshold density (14 mW)



Below threshold density (2 mW)



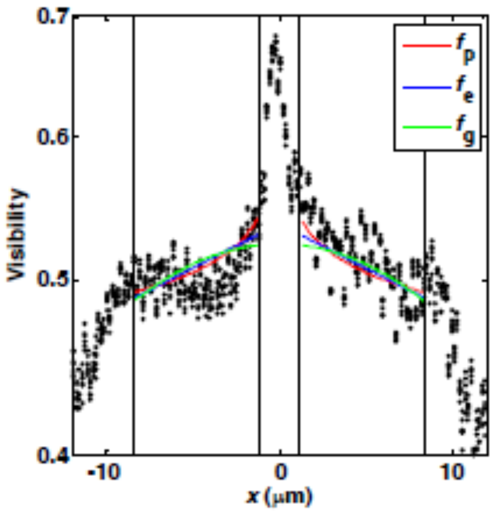




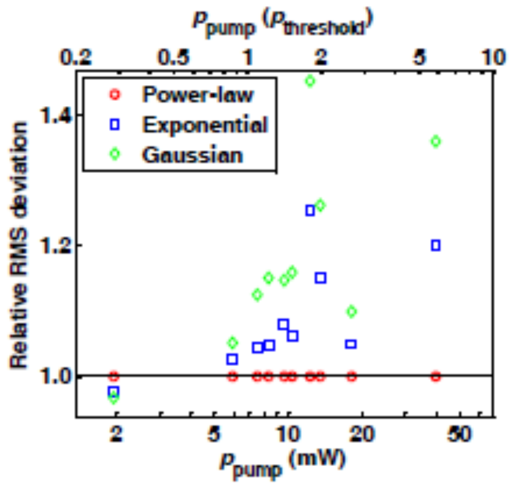
G. Roumpos et al., PNAS 109, 6467 (2012)

Fitting Different Functions to the Visibility

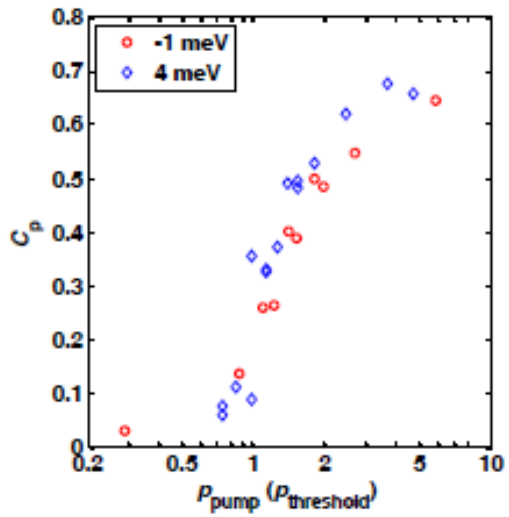
Correlation function



RMS deviations



Fractional superfluid



root-mean-square (RMS) deviation:

$$D_i = \left[\sum_{n=1}^{N} [f_i(x_n) - V_n]^2 / N \right]^{1/2}$$

fitting functions

experimental data

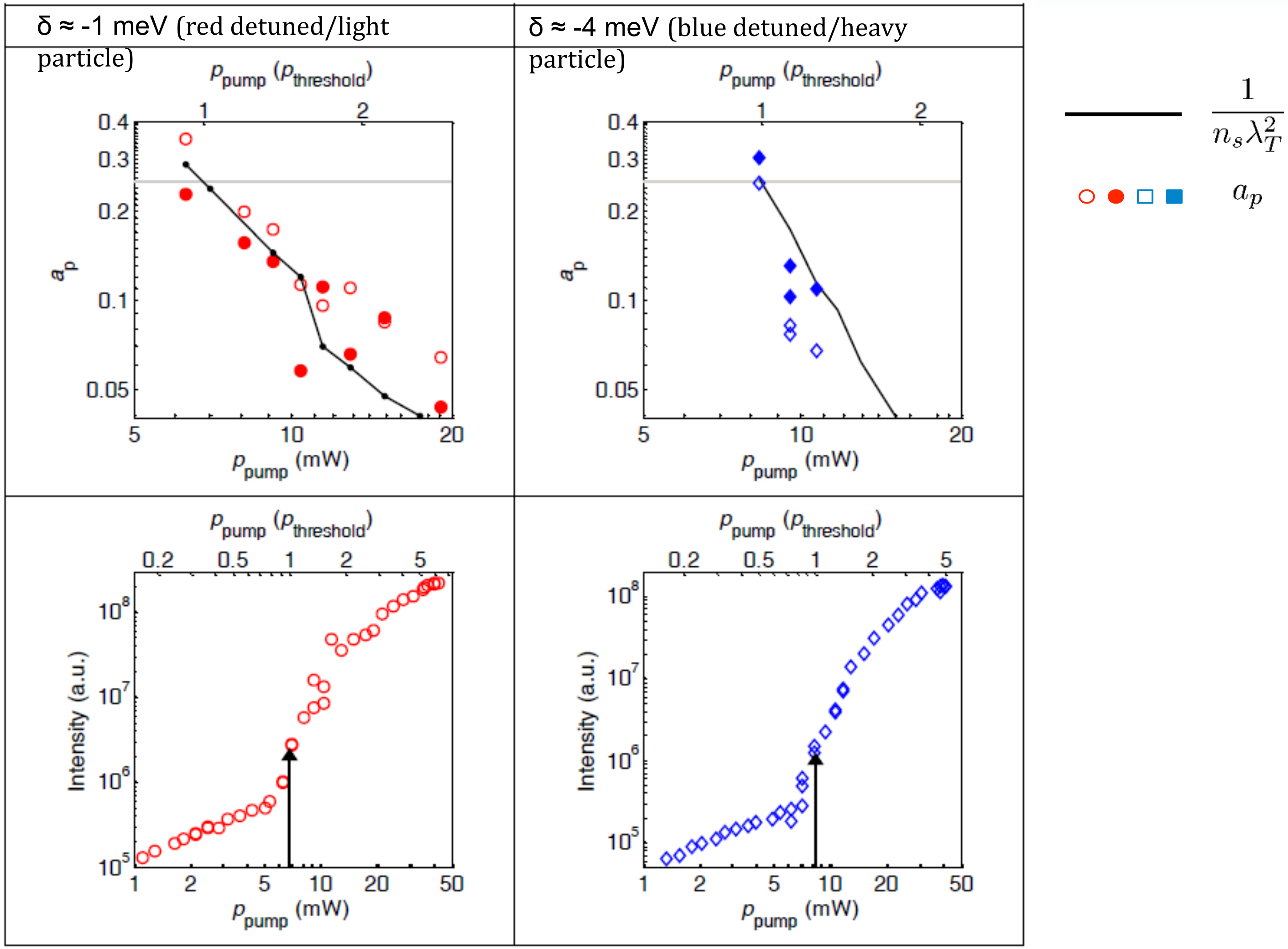
$$i \in \{p, e, g\}$$

power-law decay : $f_p(x) = c_p |x/\mu m|^{-a_p}$

exponential decay: $f_e(x) = c_e \, exp(-a_e |x/\mu m|)$

Gaussian decay: $f_g(x) = c_g \, exp[-a_g (x/\mu m)^2]$

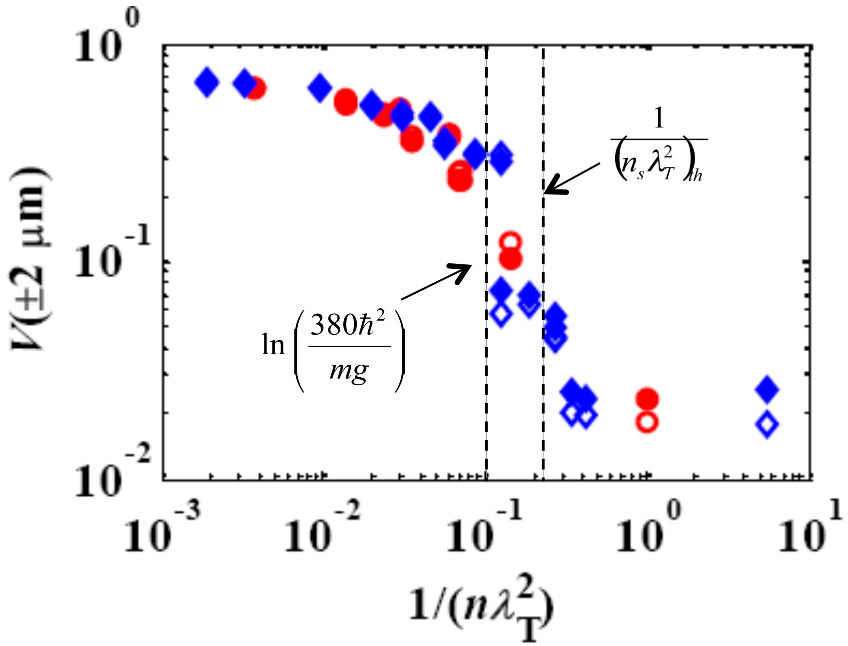
Pump-Power Dependence of Exponent a_p

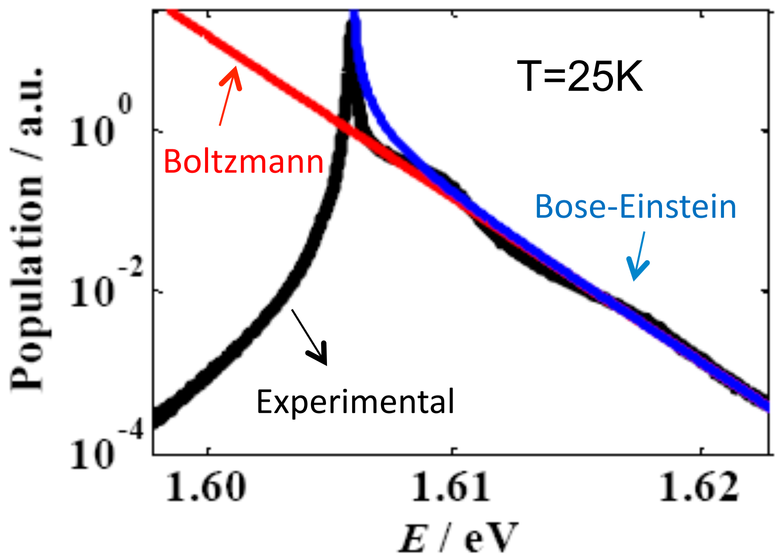


➔ exponent a_p and inverse phase space density $1/n_s\lambda_T^2$ decrease with increasing pump power (as expected)

➔ a_p =0.25 achieved at just above quantum degeneracy threshold

Fractional Superfluid Density





Fractional superfluid:

$$V(\Delta x = \xi) \sim \frac{n_s}{n}$$

Effective Temperature:

$$\frac{1}{n\lambda_T^2} \sim \left(\frac{2\pi m_{eff} k_B}{n\hbar^2}\right) T$$

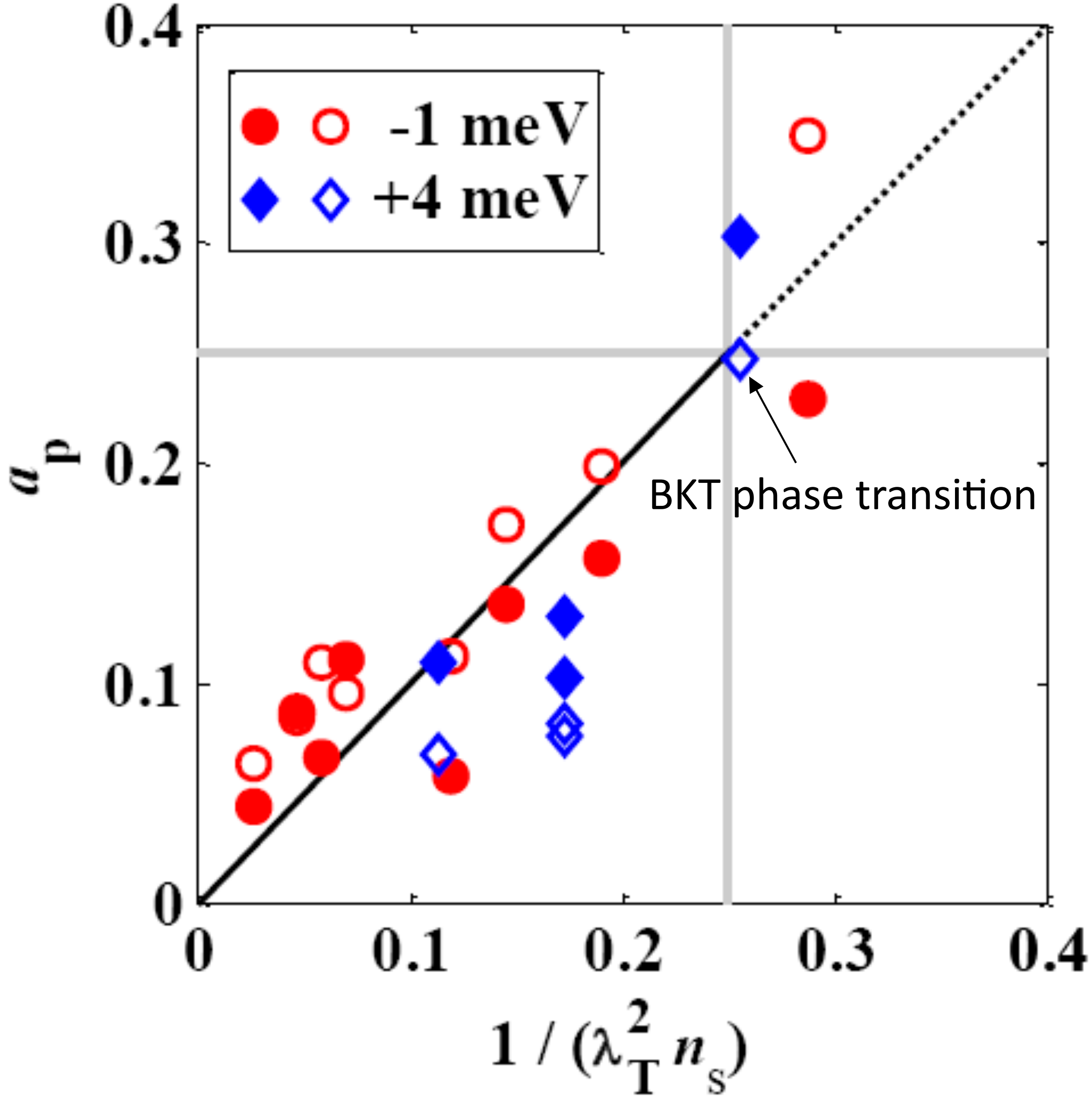
$$\Downarrow$$

BKT threshold

$$\frac{1}{(n_s\lambda_T^2)_{th}} \geq \frac{1}{(n\lambda_T^2)_{th}} \geq \ln\left(\frac{380\hbar^2}{mg}\right)$$

Z. Hadzibabic and J. Dalibard,
Rivista del Nuovo Cimento 34, 389 (2011)

Power-Law Decay Exponent



BKT Theory:

$$g^{(1)}(r) = \frac{n_s}{n}\left(\frac{\xi}{\Delta x}\right)^{a_p}$$

$$a_p = \frac{1}{n_s \lambda_T^2}$$

W. H. Nitsche
(Ph. D. Dissertation, June 2014)

Modified Bogoliubov Excitation Spectrum

Open-dissipative Gross-Pitaevskii equation

External potential
Stimulated scattering gain
Condensate-reservoir interaction

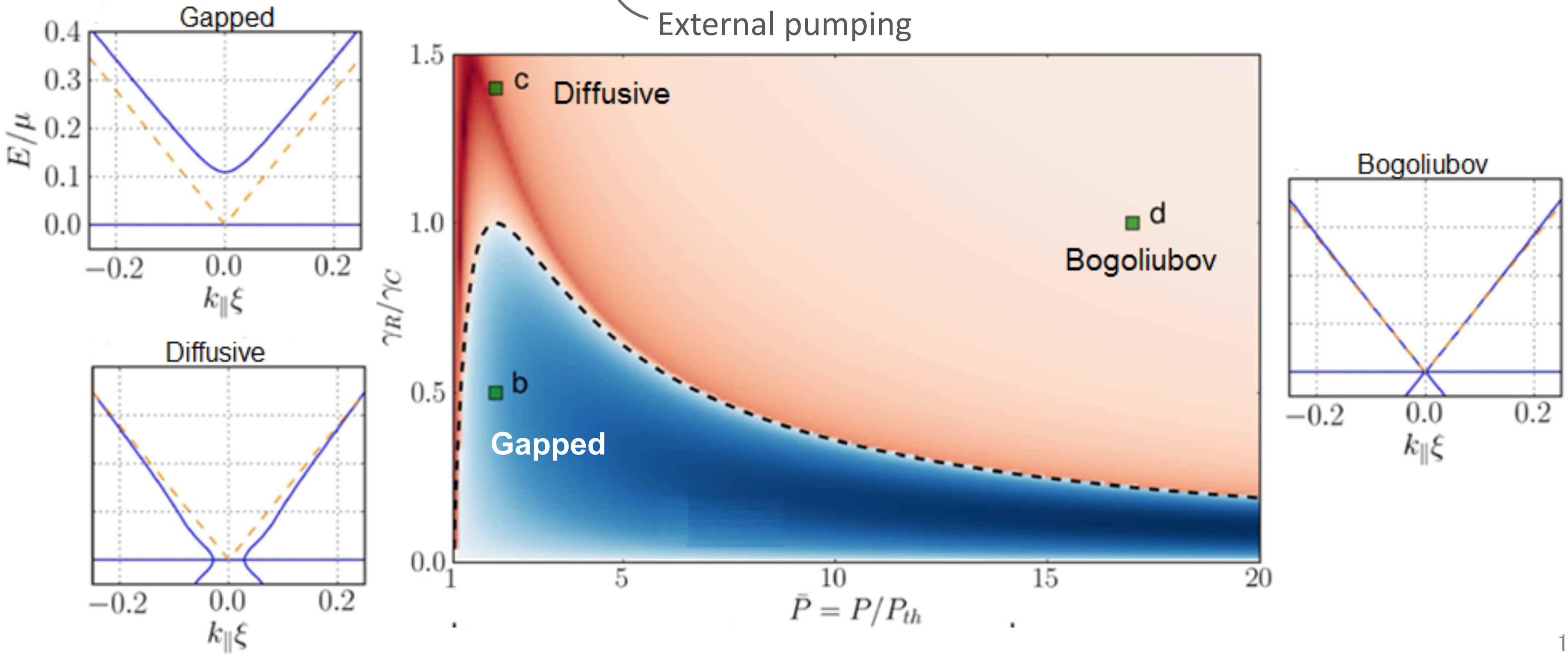
$$i\hbar\frac{\partial\psi(\mathbf{r},t)}{\partial t} = \left(-\frac{\hbar^2\nabla^2}{2m} + V_{ext}(\mathbf{r}) - \frac{i\hbar}{2}\left[\,\gamma_C - R(n_R(\mathbf{r},t))\,\right] + g_C|\psi(\mathbf{r},t)|^2 + g_R n_R(\mathbf{r},t)\right)\psi(r,t)$$

Condensate loss
Condensate interaction

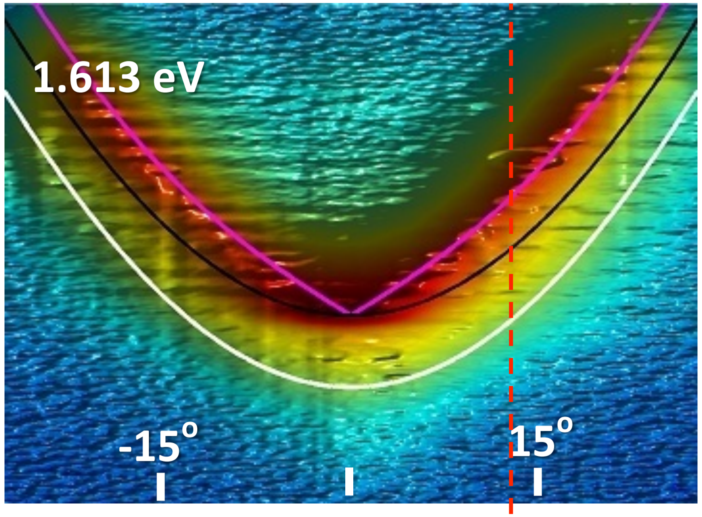
Reservoir population

$$\frac{\partial}{\partial t}n_R(r,t) = P_L(r,t) - \gamma_R n_R(r,t) - R\big(n_R(r,t)\big)|\psi(r,t)|^2$$

External pumping



Bogoliubov Excitation Spectrum

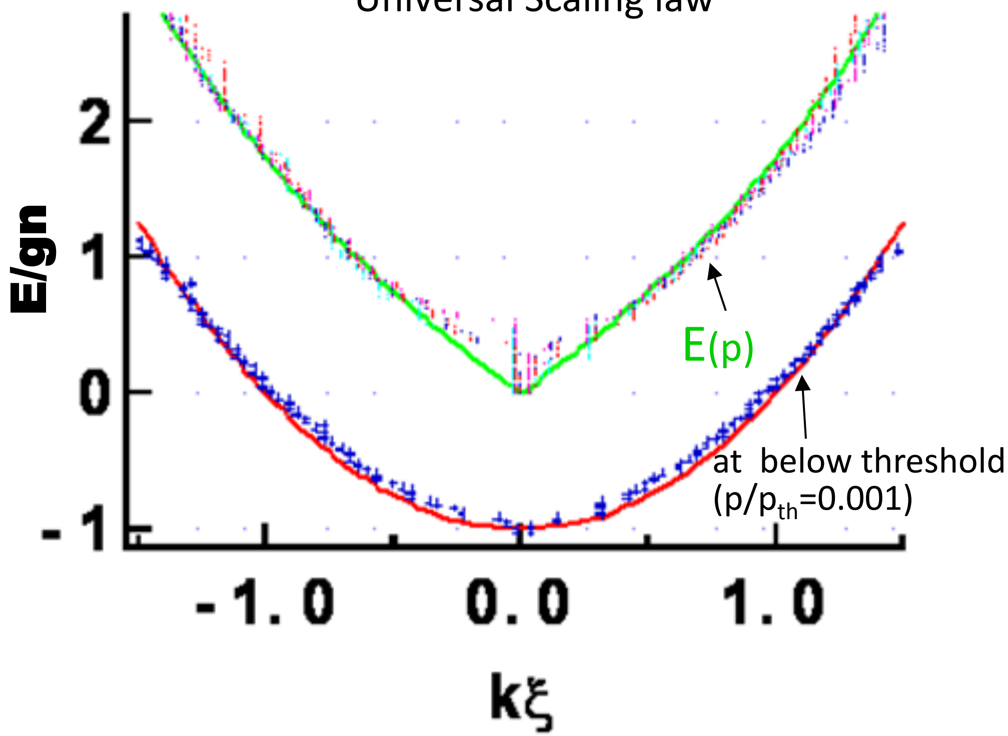


Free particle dispersion (black)

$$E(p) = \frac{p^2}{2m}$$

Bogoliubov dispersion (pink)

$$E(p) = \left[\left(\frac{p^2}{2m}\right)^2 + \frac{gn}{m}p^2\right]^{1/2} \begin{array}{l} \nearrow cp \text{ (small p)} \\ \searrow \frac{p^2}{2m} + gn \text{ (large p)} \end{array}$$



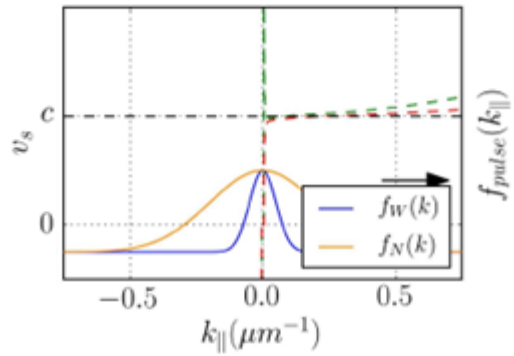
- **A:** D=1.41 (meV)
- **B:** D=0.82 (meV)
- **C:** D=4.2 (meV)
- **D:** D=-0.23 (meV)

Sound velocity $c = \sqrt{\frac{gn}{m}} \sim 10^8 \mathrm{cm/s}$ **(c~1cm/s for atomic BEC)**

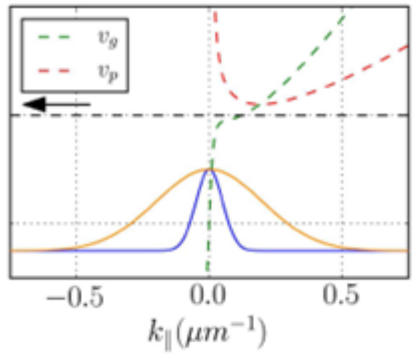
S. Utsunomiya et al., Nature Physics 4, 700 (2008)

Dispersive Shock Wave and Dark Solution

Bogoliubov spectrum

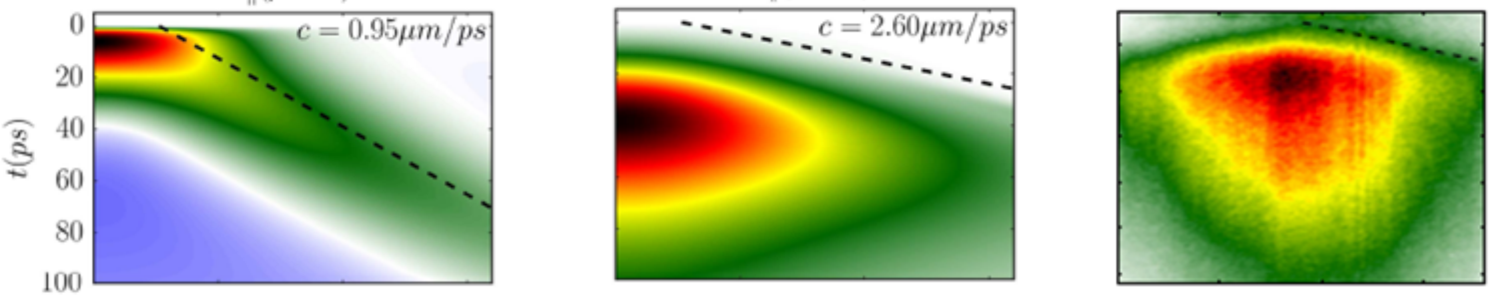


Gapped spectrum

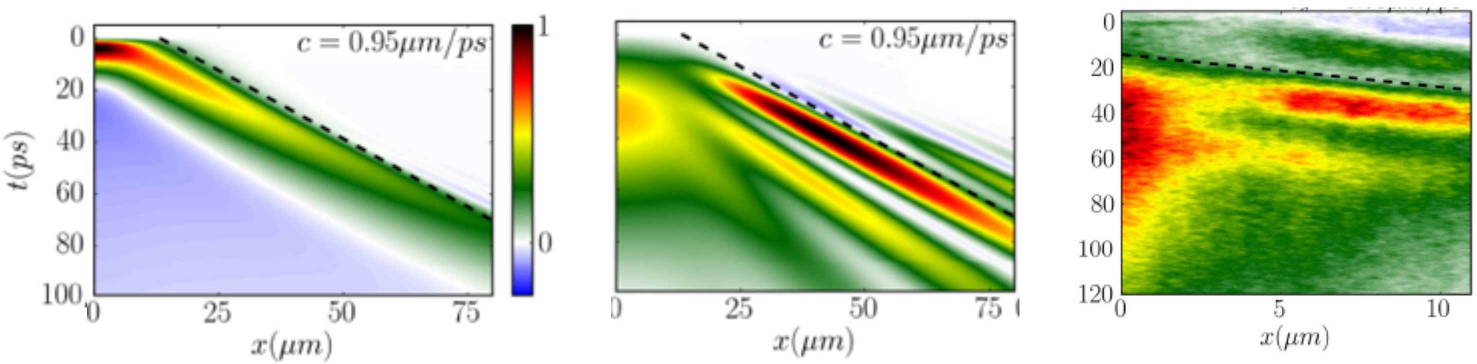


Experimental results suggest a gapped spectrum

Wide pulse

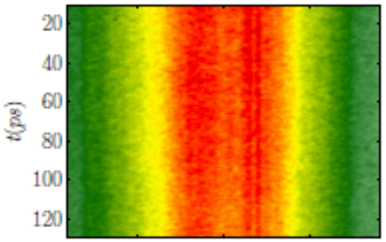


Narrow pulse

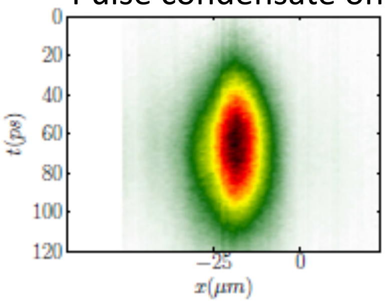


Sound Velocity in Polariton Condensates
ー Wide Spatial Pulse Excitation ー

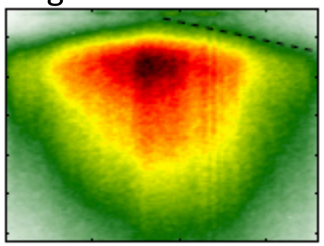
Background cw condensate



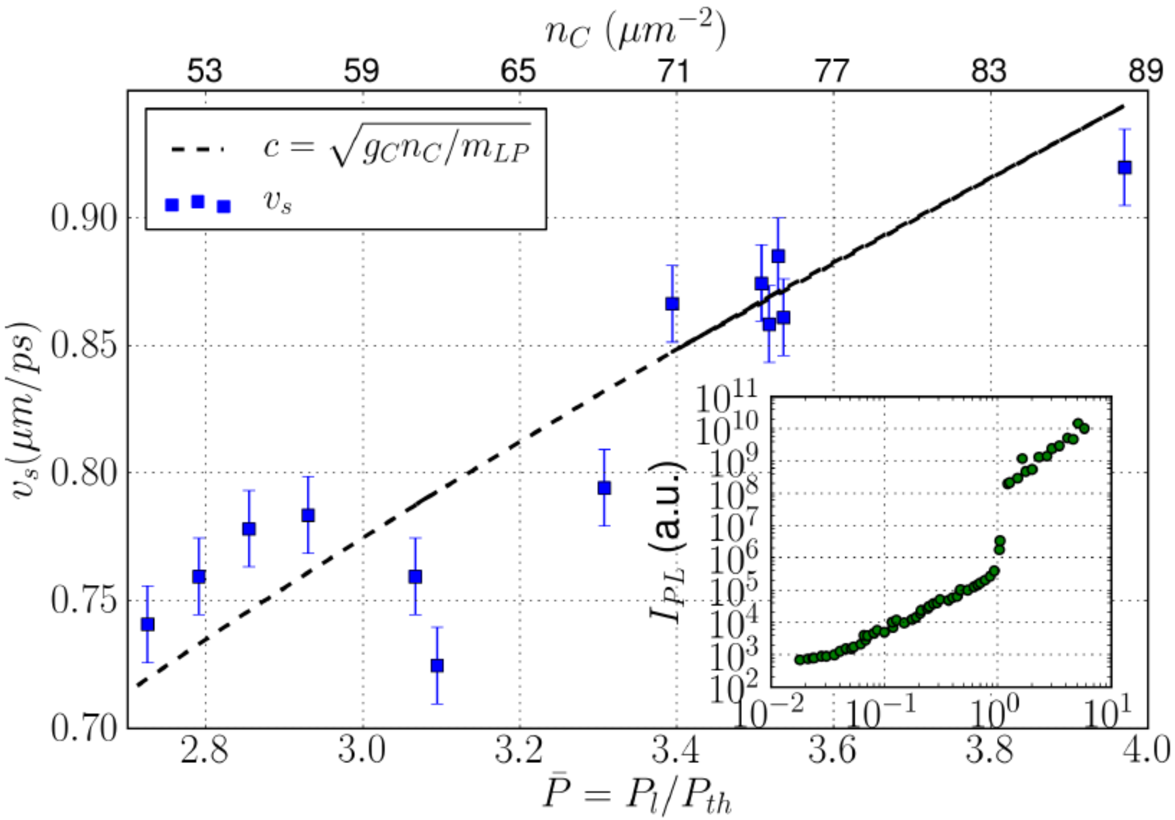
Pulse condensate only



Pulse condensate +
Background cw condensate



⇨ v_s



Superfluid velocity v_s recovers the equilibrium sound velocity $c = \sqrt{\frac{gn}{m}}$

Conclusions

- A vortex-antivortex bound-pair is directly imaged by the phase mapping technique.

- Power-law decay of the correlation function is observed by the visibility mapping technique.

  ⇩

  Support the BKT theory for 2D condensates ($a_p = {}^{1}/_{n_s \lambda_T^2}$)

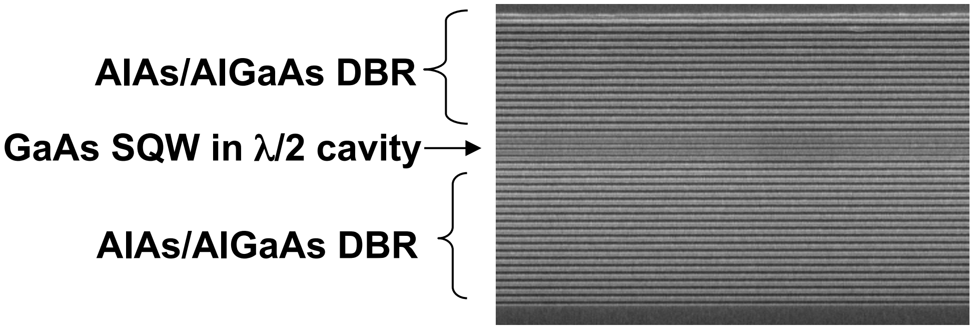
- Modified Bogoliubov (gapped) excitation spectrum is confirmed in E vs. $k_{/\!/}$ dispersion and dispersive shock wave measurements.

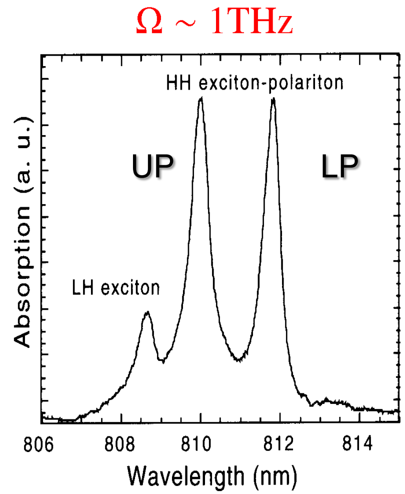
- A sound velocity is measured by the pump-probe technique.

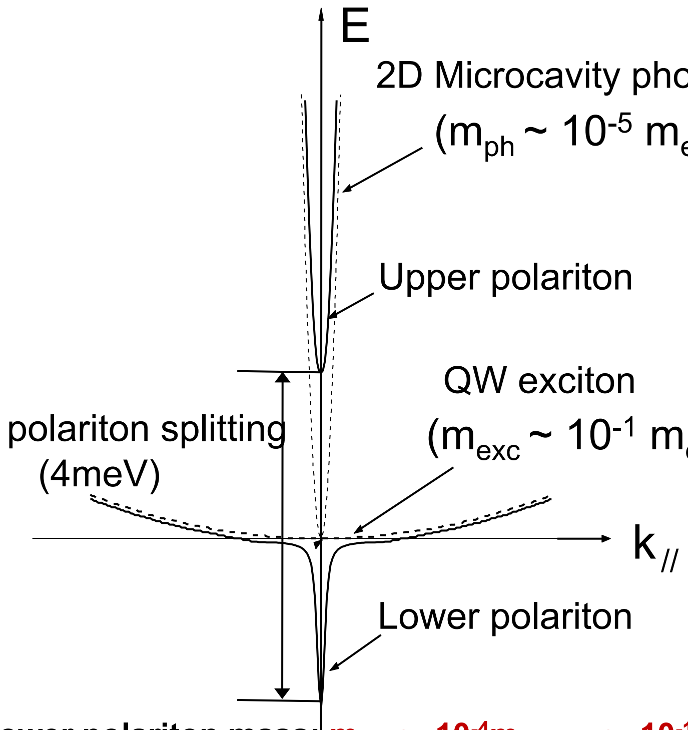
  ⇩

  Support the open-dissipative GP equation

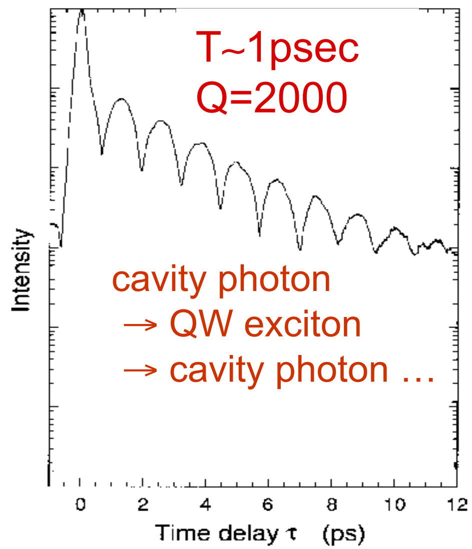
Exciton-Polaritons
ー Dressing Quantum Well Excitons with Microcavity Fields ー







lower polariton mass: $m_{LP} \sim 10^{-4} m_{exciton} \sim 10^{-10} m_{atom}$

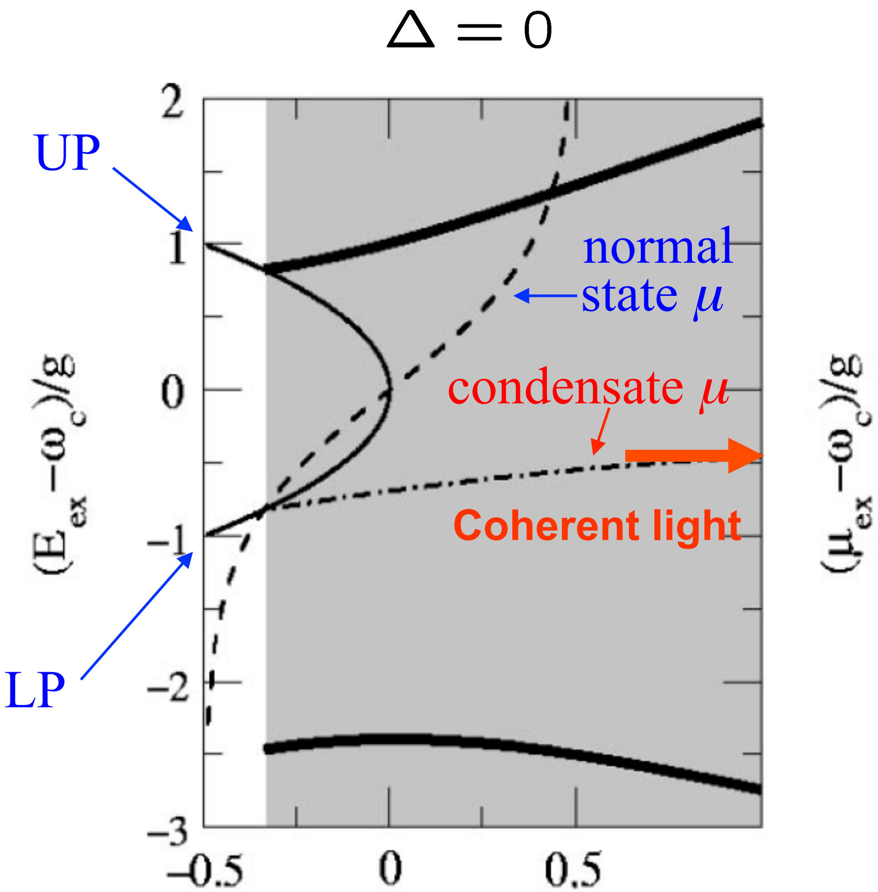


A normal mode splitting ～ 4 (meV)x $\sqrt{N_{QW}}$

number of quantum wells

BCS Crossover in Exciton-Polariton Condensates

Two-level atoms: J. Keeling et al., Phys. Rev. B72, 115320 (2005)



Coherent state cavity field modulates an electronic excitation (e-h pair at Fermi surface)

⇩

Coherent Rabi oscillation with $\omega_{Rabi} = 2g|\lambda|$

⇩

Mollow's triplet-like spectrum

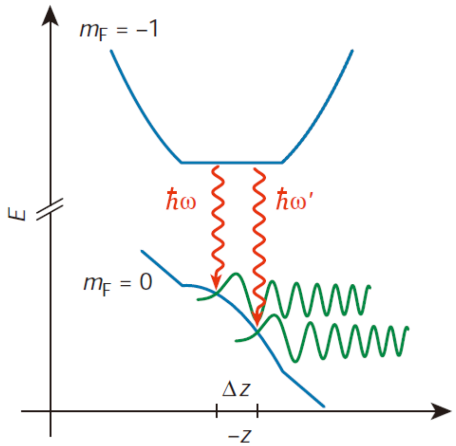
Electron-holes pairing by coherent cavity field rather than Coulomb interaction

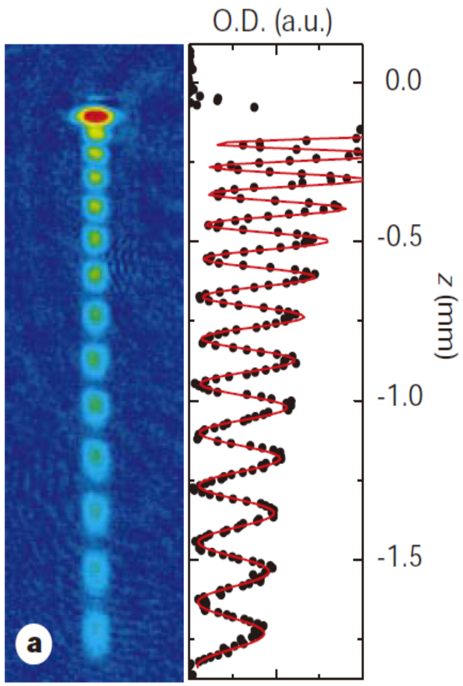
Long Range Order in Three-Dimensional Atomic BEC

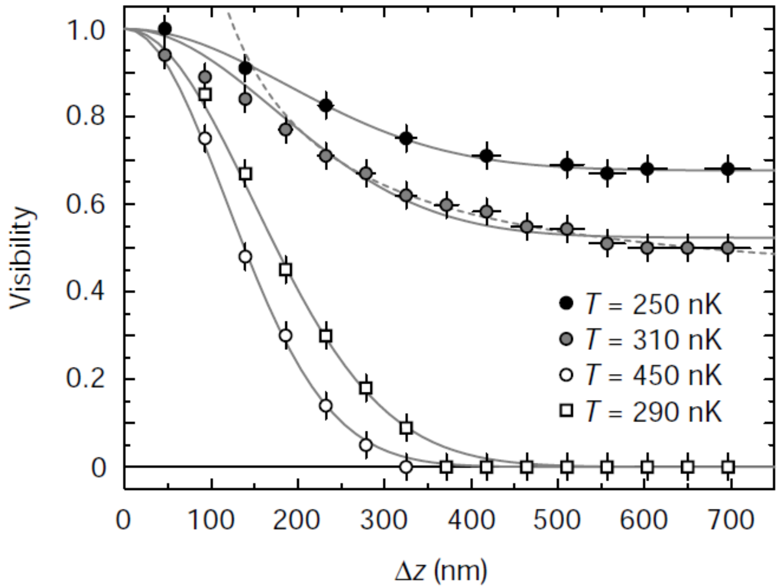
I. Bloch, T. W. Hänsch & T. Esslinger, Nature 403, 166 (2000)

The spatial correlation function decays toward a plateau at large distances.

⇨ Fractional condensate n_o/n is constant in an entire condensate







Quasi-Long Range Order in Two-Dimensional Atomic Gas

Z. Hadzibabic, P. Krüger, M. Cheneau, B. Battelier and J. Dalibard, Nature 441, 1118 (2006)

$$g^{(1)}(r_1 t_1; r_2 t_2) = \frac{\langle \psi^+(r_1,t_1)\psi(r_2,t_2)\rangle}{\sqrt{\langle \psi^+(r_1,t_1)\psi(r_1,t_1)\rangle\langle \psi^+(r_2,t_2)\psi(r_2,t_2)\rangle}}$$

$$g^{(1)}(\Delta x) = \frac{n_s}{n}\left(\frac{\xi}{\Delta x}\right)^{1/n_s\lambda_T^2} = \left(\frac{\lambda_p}{\Delta x}\right)^{a_p}$$

n: particle density

n_s: superfluid density

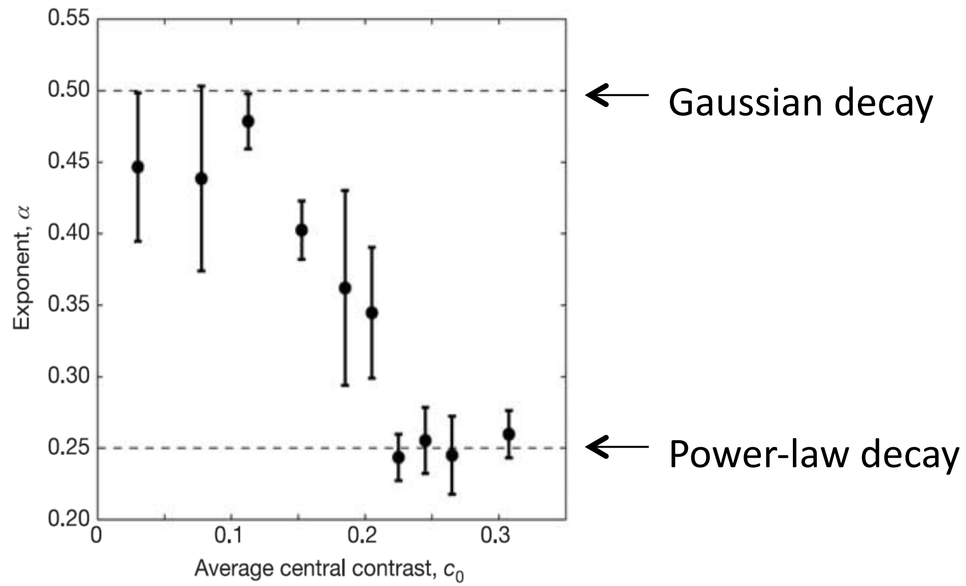
$\xi = \frac{\hbar}{\sqrt{2mgn}}$: healing length

$\lambda_T = \sqrt{\frac{2\pi\hbar^2}{mk_B T}}$: thermal de Broglie wavelength

$\lambda_p = \xi\left(\frac{n_s}{n}\right)^{n_s\lambda_T^2}$: characteristic length

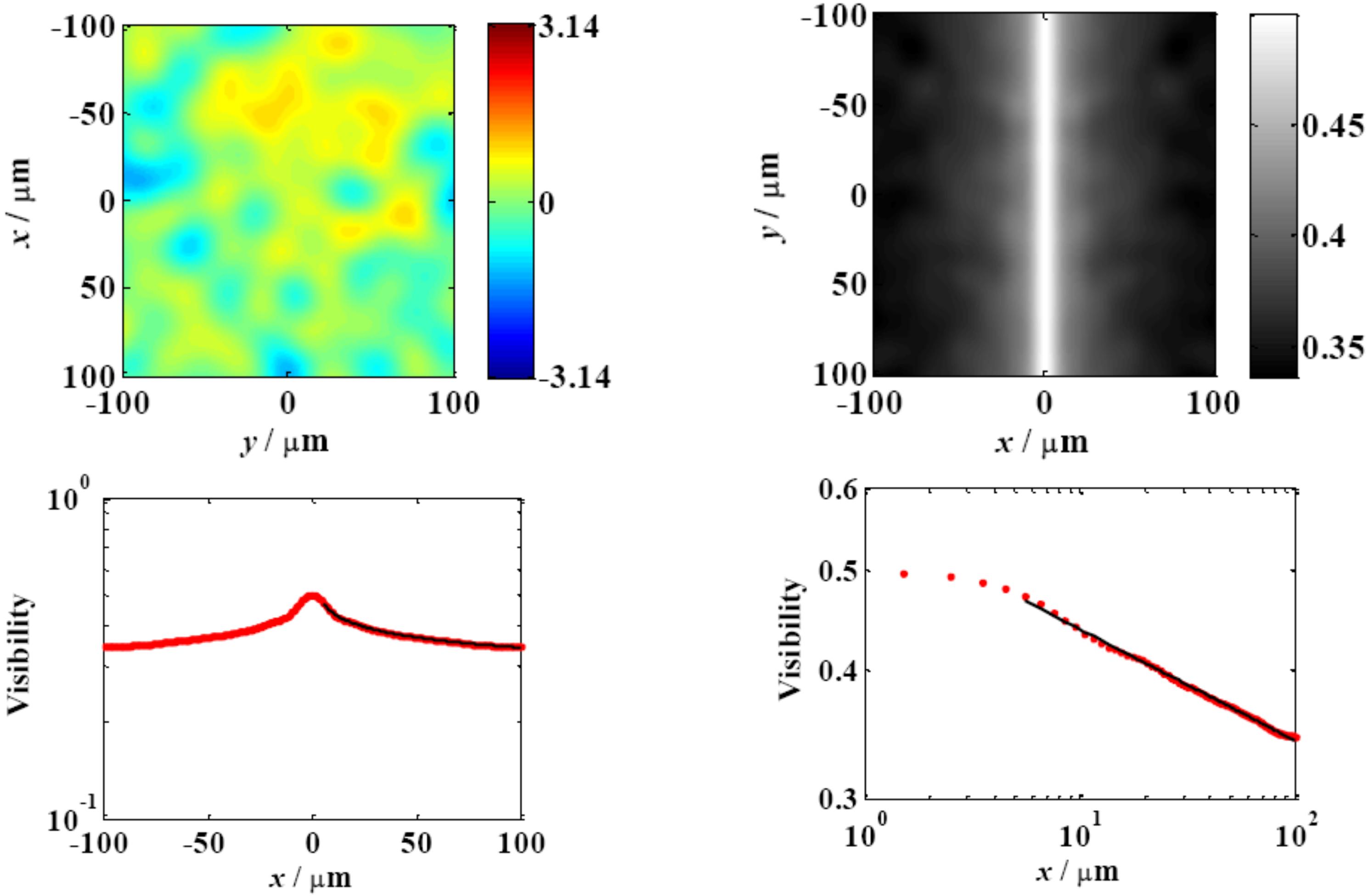
Integrated interference contrast

$$\langle C^2(L_x)\rangle = \frac{1}{L_x}\int dx g_1(x)^2 \propto \left(\frac{1}{L_x}\right)^{2\alpha}$$



Simulated Power-Law Decay

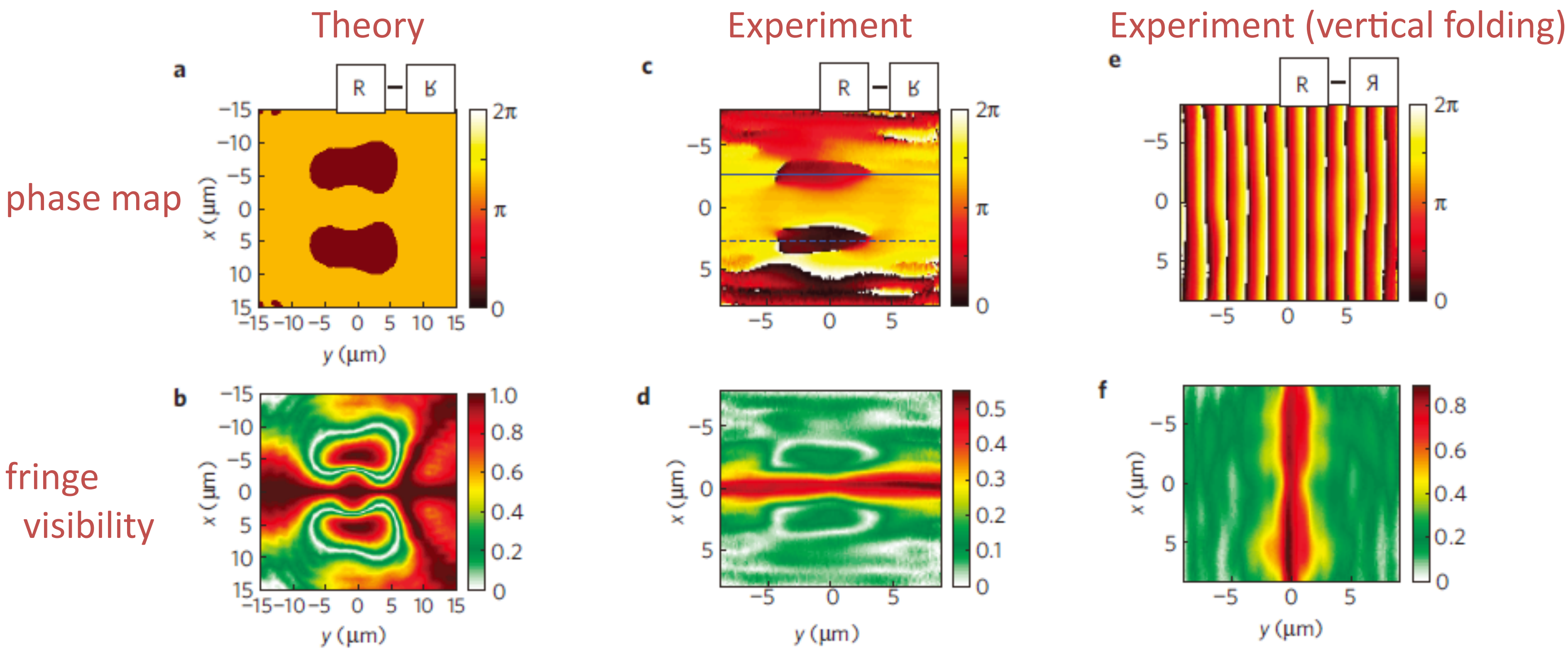
Two-dimensional phonon modes scatter the phase of a polariton condensate



Z. Hadzibabic and J. Dalibard, Rivista del Nuovo Cimento 34, 389 (2011)

Phase Mapping for Switching Vortex-antivortex Pairs (Weak Potential Fluctuation)

- If the vortex and antivortex can flip mutual positions and co-propagate, the areas with π-phase shift are observed, which are surrounded by the minimum fringe visibility.
- If the phase map is folded along the vertical line between vortex and antivortex, the phase rotations associated with the vortex and antivortex cancel out exactly so that no phase defect is observed.



G. Roumpos et al., Nature Physics 7, 126 (2011)

Dispersive Fluid, Dissipative Shock Wave and Superfluid in Three Regimes of Polariton Condesates

Non-resonantly excited two condensates