Part3:Superfluidity:

Flow via obstacles, Persistent Currents & Quantised Vortices

Marzena Szymanska

Collaborators

Theory

F. M. Marchetti

E. Cancellieri

C. Tejedor

D. Whittaker

Experiment

D. Sanvitto, G. Tosi, L. Viña,

D. Krizhanovskii, M. Skolnick

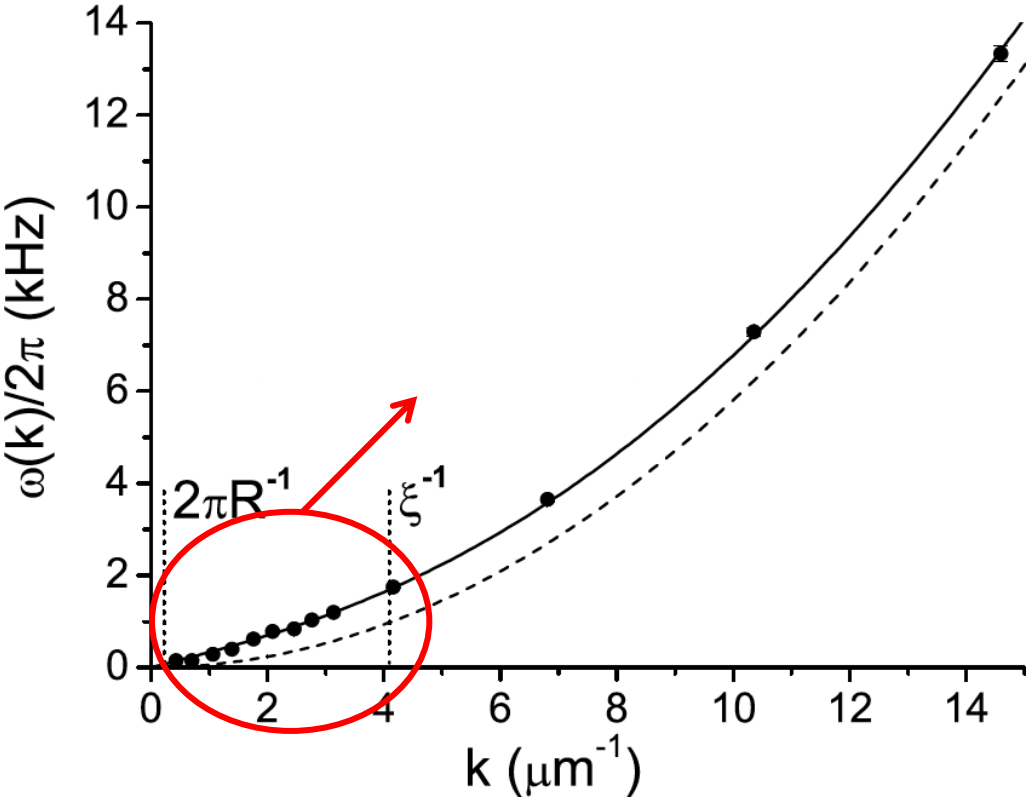
L. Marrucci, A. Lemaître, J. Bloch

Superfluidity in equilibrium systems

SUPERFLUID CHECKLIST

	Landau criterion	frictionless flow	quantised vortices	metastable persistent flow
^{4}He/cold atoms BEC	✓	✓	✓	✓

$$v_c = \min_k \frac{\epsilon(\mathbf{k})}{k}$$



[Steinhauer *et al.* PRL (2002)]

Superfluidity in equilibrium systems

SUPERFLUID CHECKLIST

	Landau criterion	frictionless flow	quantised vortices	metastable persistent flow
^{4}He/cold atoms BEC	✓	✓	✓	✓

$$v_c = \min_k \frac{\epsilon(\mathbf{k})}{k}$$

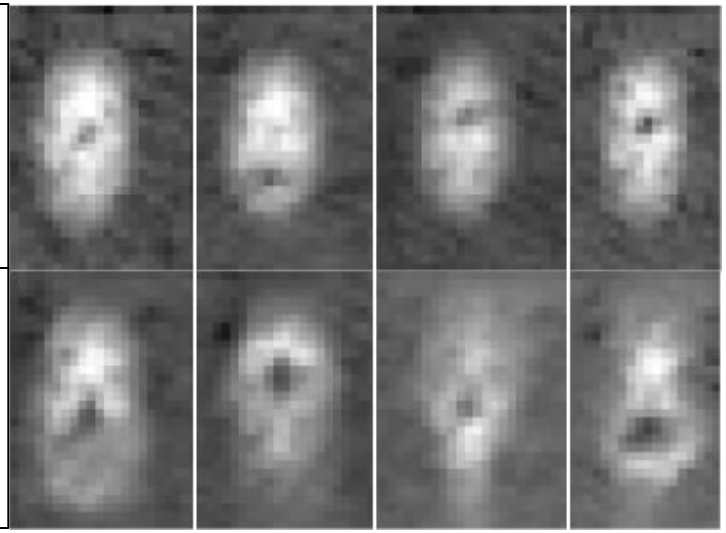
Frictionless flow via macroscopic defect in the fluid

no drag force

$v < v_c$

drag force

$v > v_c$



[Onofrio *et al.*, *PRL* (2000)]

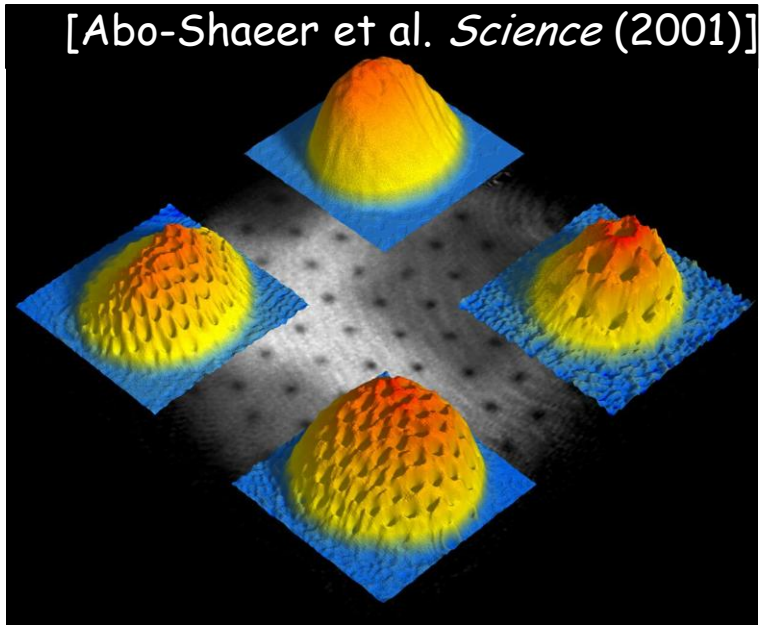
Superfluidity in equilibrium systems

SUPERFLUID CHECKLIST

	Landau criterion	frictionless flow	quantised vortices	metastable persistent flow
^{4}He/cold atoms BEC	✓	✓	✓	✓

$$\oint \mathbf{v}_s \cdot d\mathbf{l} = 2\pi \frac{\hbar}{m} (0, \pm 1, \dots)$$

ground state is flowless &
vortices need external driving

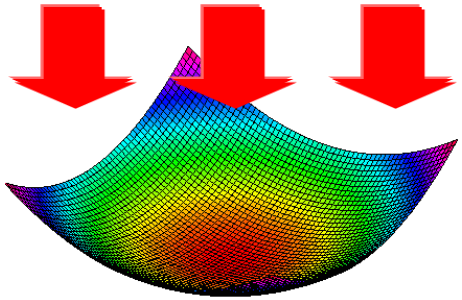


Superfluidity in equilibrium systems

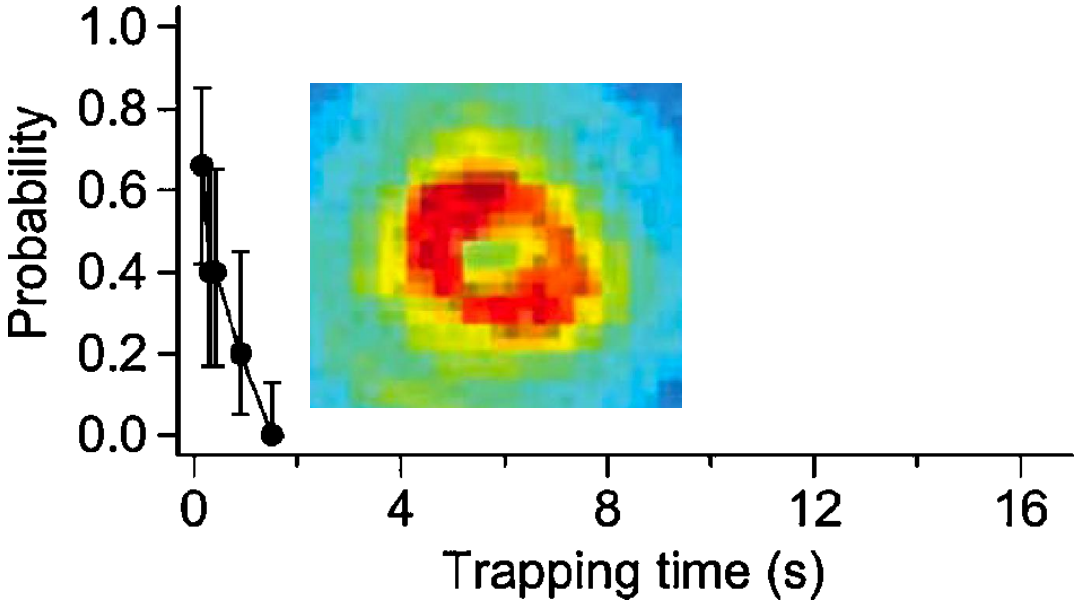
SUPERFLUID CHECKLIST

	Landau criterion	frictionless flow	quantised vortices	metastable persistent flow
^{4}He/cold atoms BEC	✓	✓	✓	✓

Gauss-Laguerre beam rotating drive



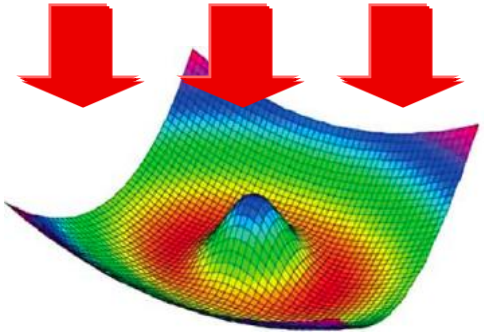
[Ryu *et al. PRL* (2007)]



Superfluidity in equilibrium systems

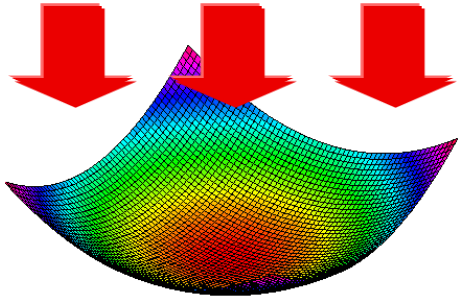
SUPERFLUID CHECKLIST

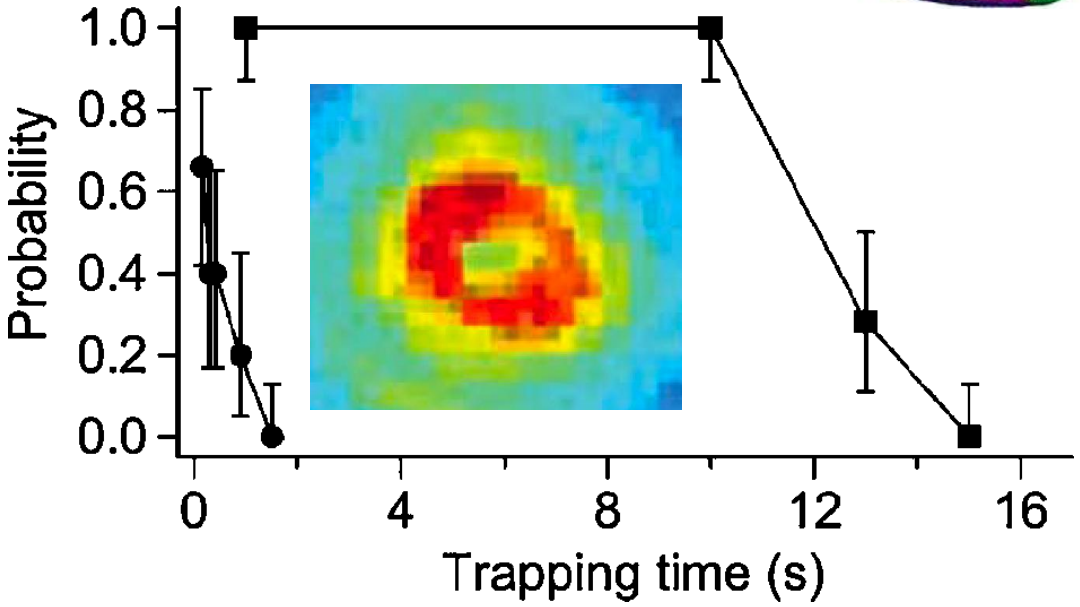
	Landau criterion	frictionless flow	quantised vortices	metastable persistent flow
^{4}He/cold atoms BEC	✓	✓	✓	✓



[Ryu *et al. PRL* (2007)]

Gauss-Laguerre beam rotating drive

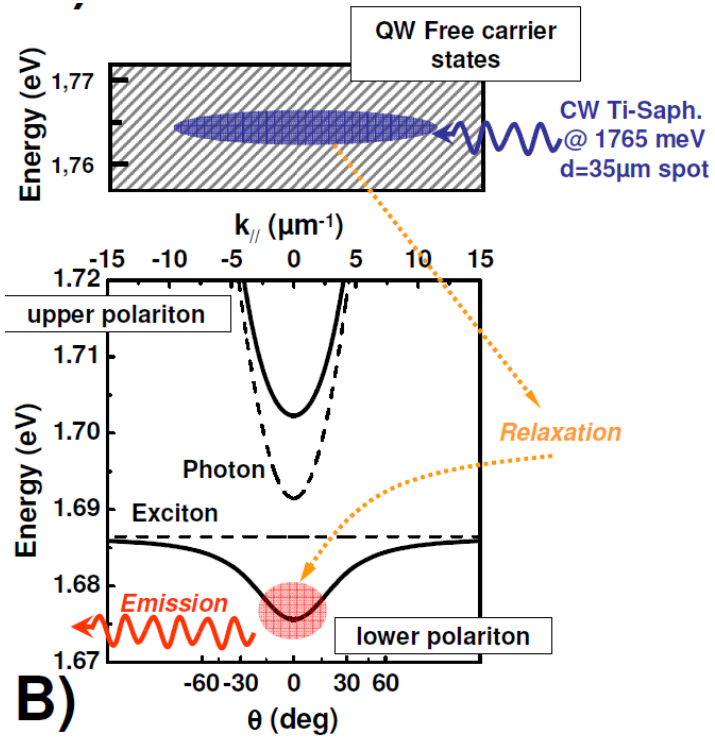




Superfluidity out of equilibrium

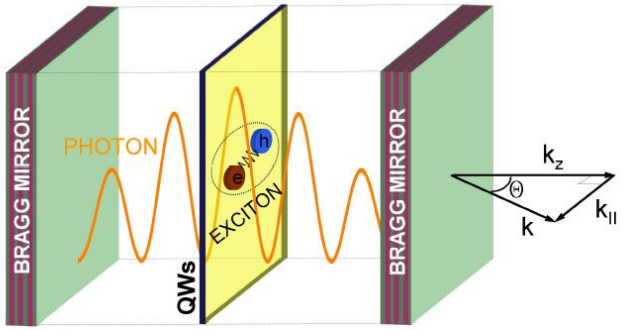
SUPERFLUID CHECKLIST

	Landau criterion	frictionless flow	quantised vortices	metastable persistent flow
^{4}He/cold atoms BEC	✓	✓	✓	✓
polariton condensates (incoherent pump)	?	?	?	?



polariton lifetime

$$\tau_{LP} \sim 2\text{ps}$$



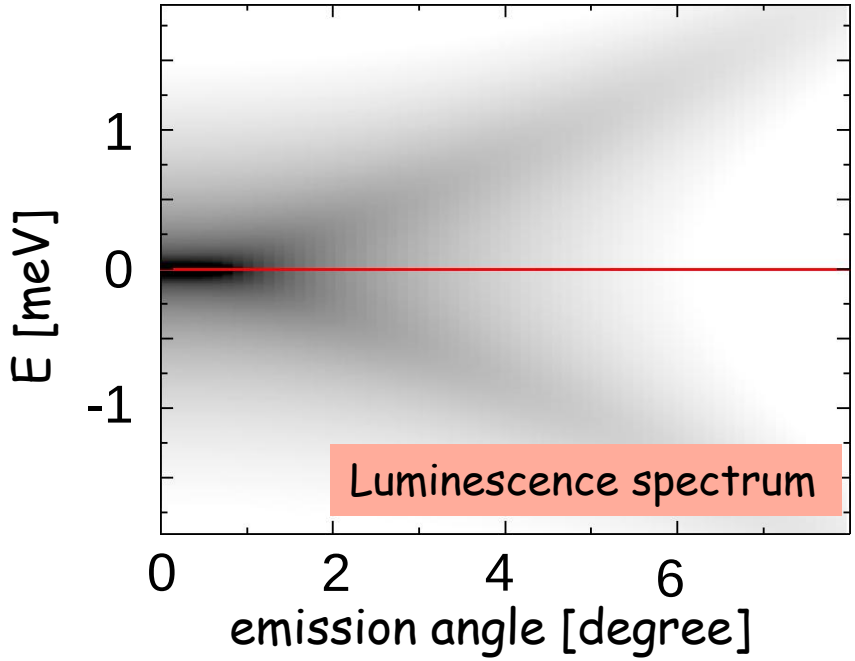
Superfluidity out of equilibrium

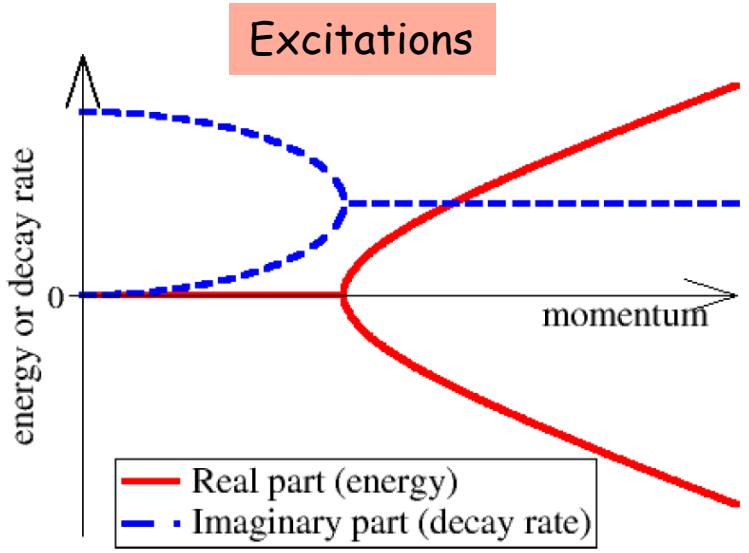
SUPERFLUID CHECKLIST

	Landau criterion	frictionless flow	quantised vortices	metastable persistent flow
^{4}He/cold atoms BEC	✓	✓	✓	✓
polariton condensates (incoherent pump)	×	?	?	?

[Wouters & Carusotto, PRL (2007)]

[Szymanska *et al.*, PRL (2006)]



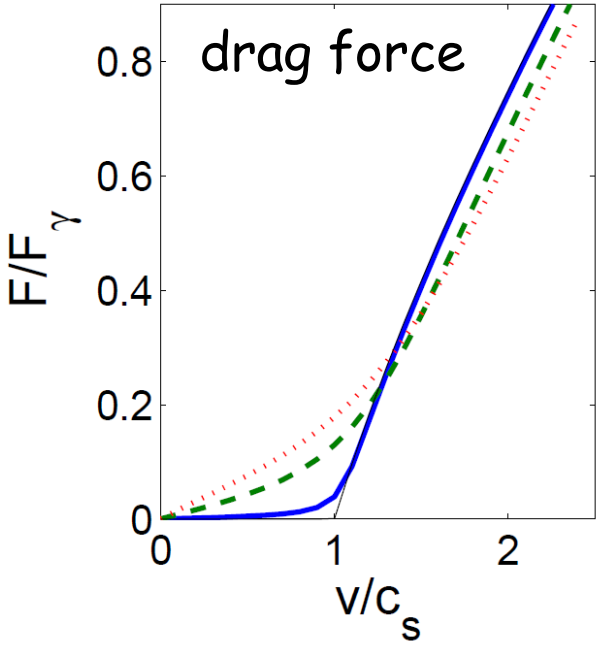


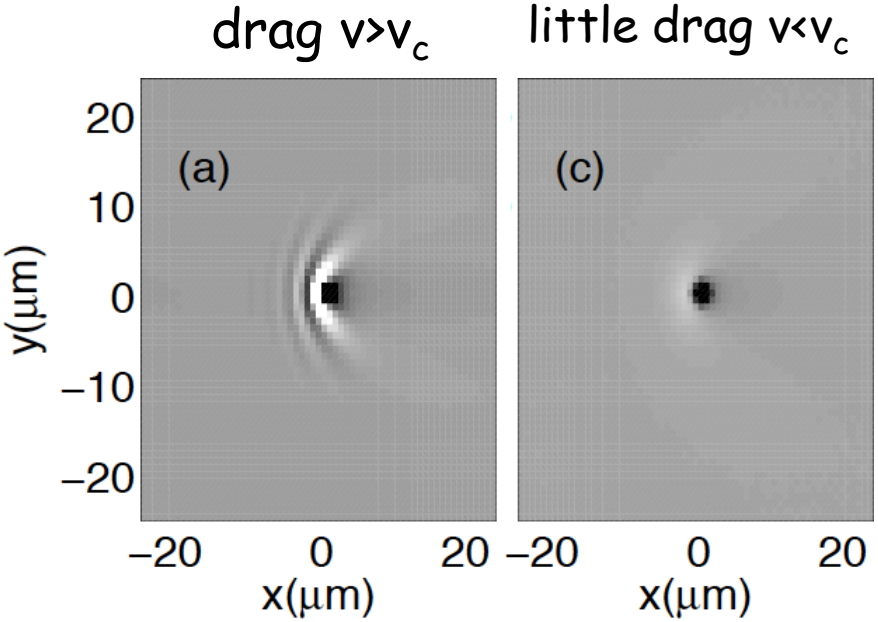
Superfluidity out of equilibrium

SUPERFLUID CHECKLIST

	Landau criterion	frictionless flow	quantised vortices	metastable persistent flow
^{4}He/cold atoms BEC	✓	✓	✓	✓
polariton condensates (incoherent pump)	✗	✓?	?	?

Frictionless flow ?





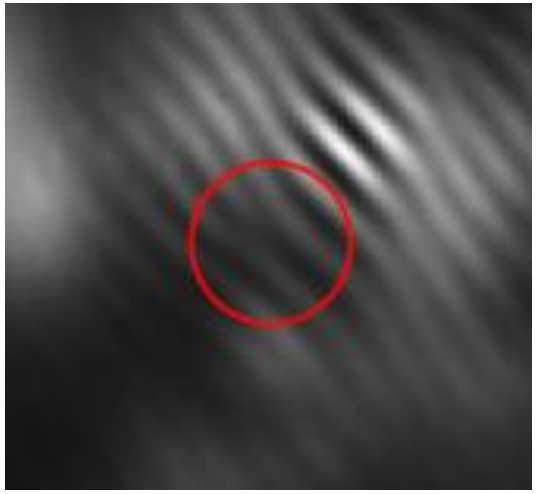
[Wouters & Carussotto, arxiv (2010)]

Superfluidity out of equilibrium

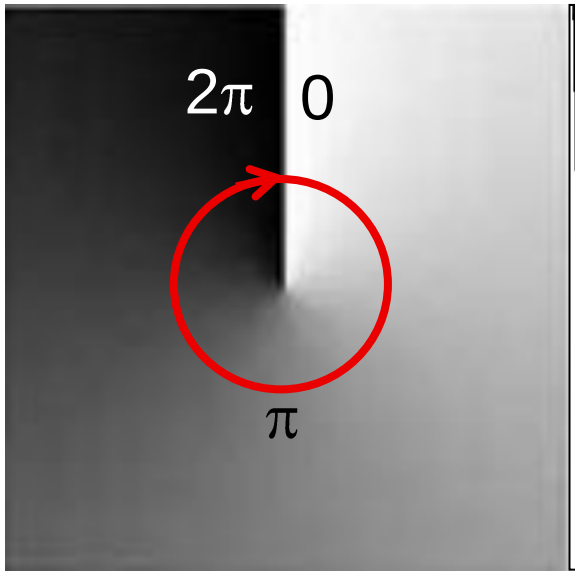
SUPERFLUID CHECKLIST

	Landau criterion	frictionless flow	quantised vortices	metastable persistent flow
^{4}He/cold atoms BEC	✓	✓	✓	✓
polariton condensates (incoherent pump)	✗	✓?	✓	?

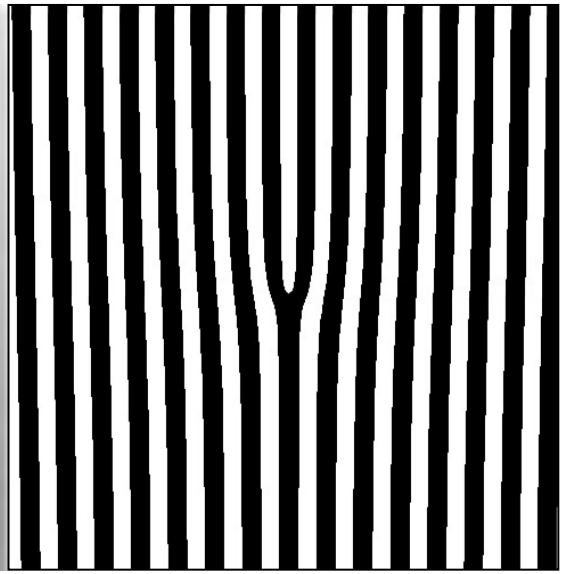
Ground state with a vortex pined by disorder



vortex m=1 phase



interference

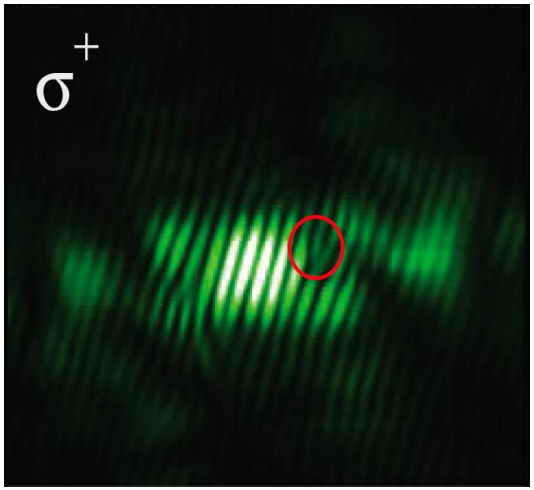


[Lagoudakis *et al. Nature Phys* (2008)]

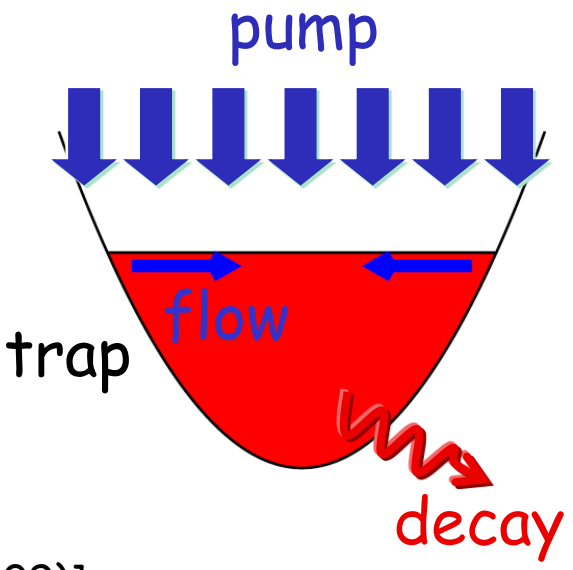
Superfluidity out of equilibrium

SUPERFLUID CHECKLIST

	Landau criterion	frictionless flow	quantised vortices	metastable persistent flow
^{4}He/cold atoms BEC	✓	✓	✓	✓
polariton condensates (incoherent pump)	✗	✓?	✓ no-SF	?



[Lagoudakis *et al. Science* (2009)]

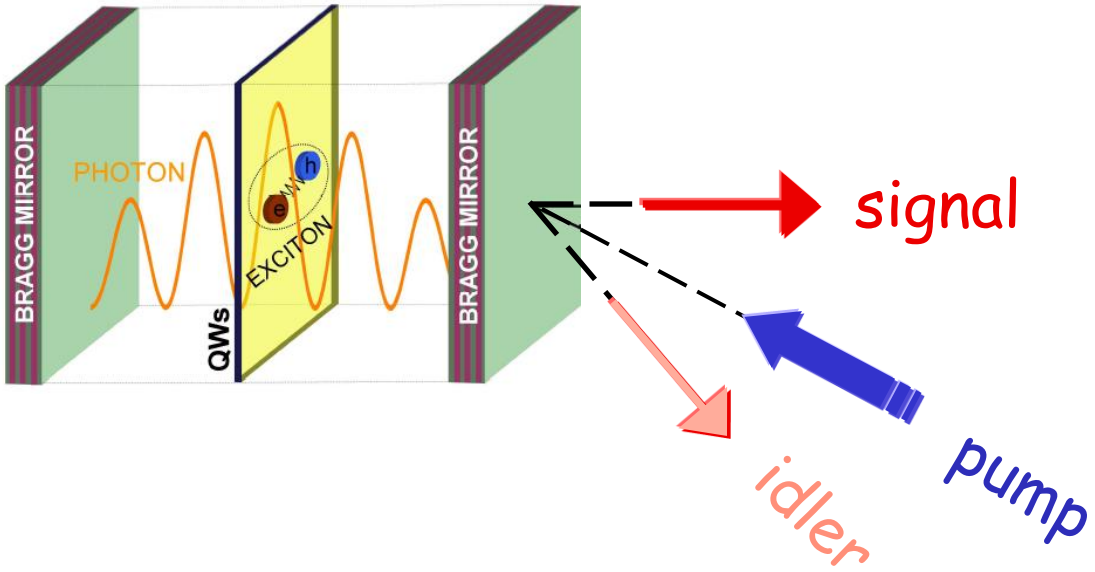


[Keeling & Berloff *PRL* (2008)]

Superfluidity out of equilibrium

SUPERFLUID CHECKLIST

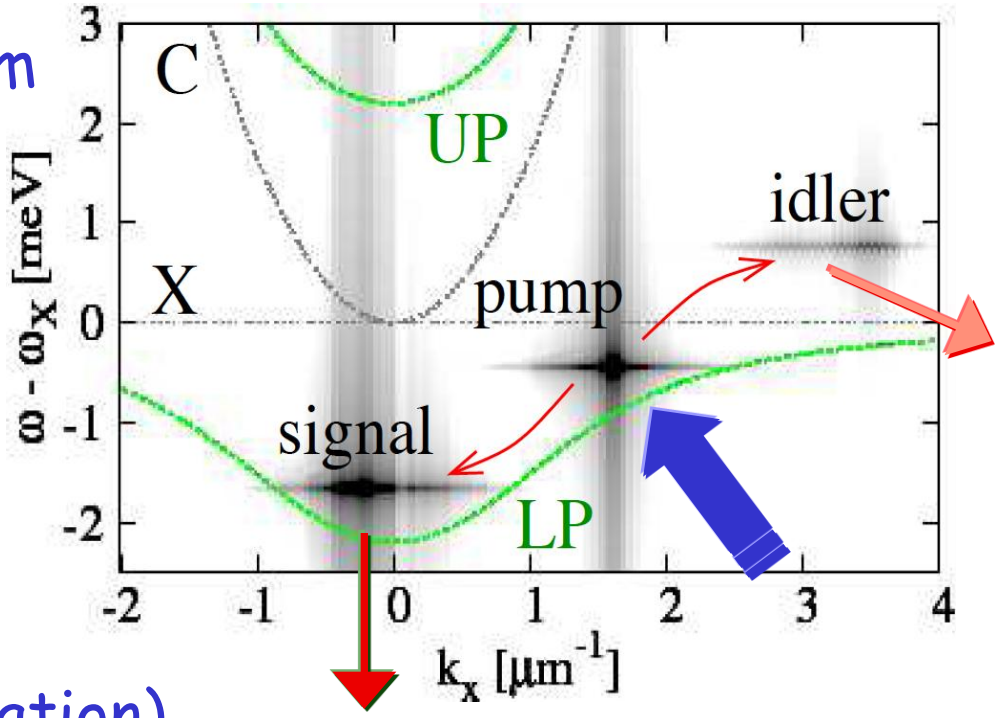
	Landau criterion	frictionless flow	quantised vortices	metastable persistent flow
^{4}He/cold atoms BEC	✓	✓	✓	✓
polariton condensates (incoherent pump)	✗	✓?	✓ no-SF	?
polariton condensates (parametrical pump)	?	?	?	?



Optical parametric oscillator (OPO)

✓Stimulated scattering from pump to signal and idler

✓ Pump threshold



✓ U(1) symmetry (phase rotation)

$$2\varphi_p = \varphi_s + \varphi_i$$

✓ U(1) spontaneous symmetry breaking:
gapless and diffusive Goldstone mode

[Wouters & Carusotto *PRA* (2007)]

Optical parametric oscillator (OPO)

SUPERFLUID CHECKLIST

	Landau criterion	frictionless flow	quantised vortices	metastable persistent flow
^{4}He/cold atoms BEC	✓	✓	✓	✓
polariton condensates (incoherent pump)	✗	✓?	✓ no-SF	?
polariton condensates (parametrical pump)	✗	?	?	?

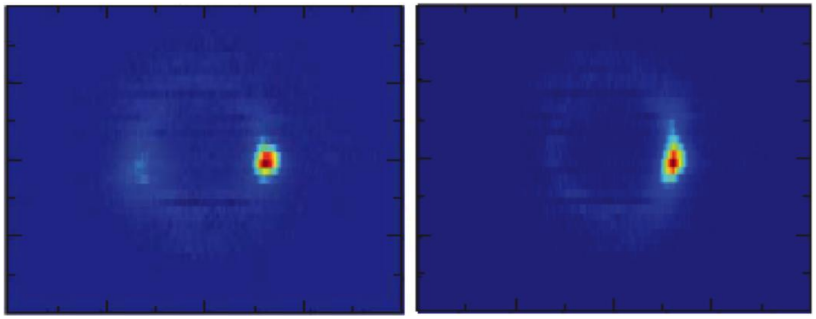
Optical parametric oscillator (OPO)

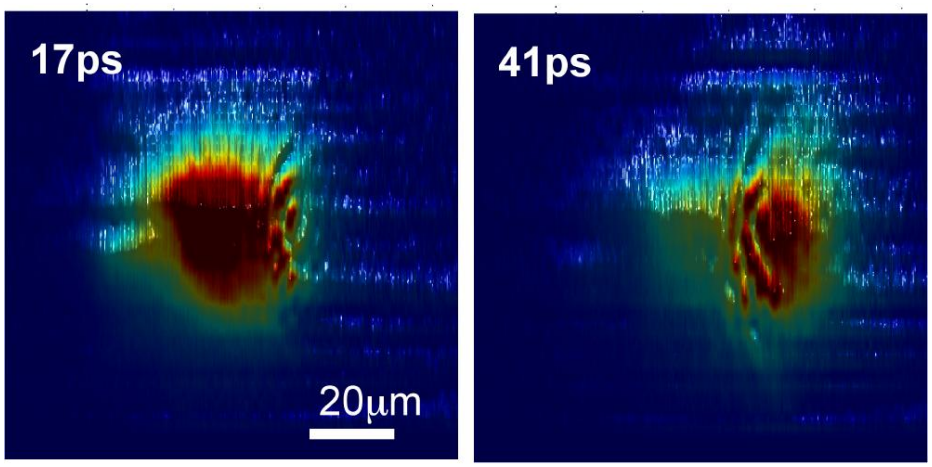
SUPERFLUID CHECKLIST

	Landau criterion	frictionless flow	quantised vortices	metastable persistent flow
^{4}He/cold atoms BEC	✓	✓	✓	✓
polariton condensates (incoherent pump)	✗	✓?	✓ no-SF	?
polariton condensates (parametrical pump)	✗	✓	?	?

Above OPO threshold

Frictionless flow
(no scattering in momentum)





[Amo *et al. Nature* (2009)]

Theoretical Model

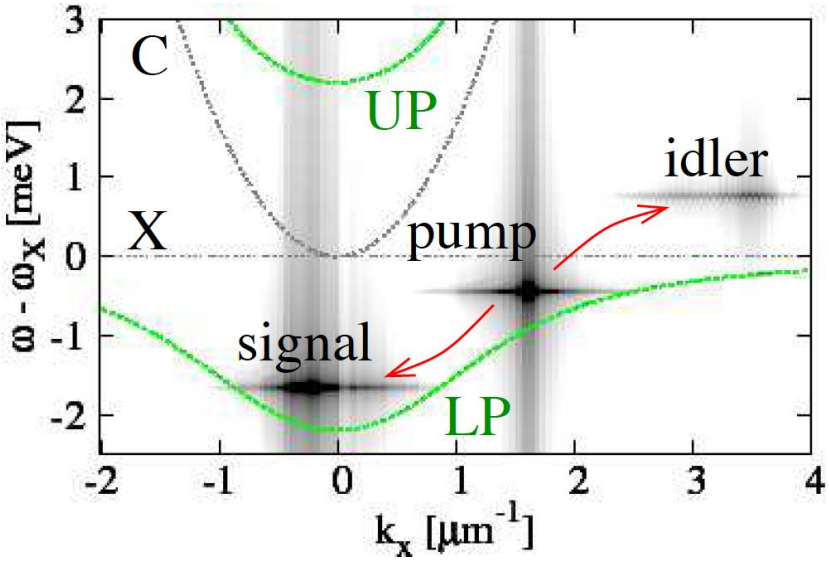
Gross-Pitaevskii equation with pump & decay

$$i\partial_t \begin{pmatrix} \psi_X \\ \psi_C \end{pmatrix} = \begin{pmatrix} \omega_X - i\kappa_X + g_X|\psi_X|^2 & \Omega_R/2 \\ \Omega_R/2 & \omega_C - i\kappa_C \end{pmatrix} \begin{pmatrix} \psi_X \\ \psi_C \end{pmatrix} + \begin{pmatrix} 0 \\ F_p + F_{pb} \end{pmatrix}$$

- coupling
- interaction
- decay
- cw pump (OPO)

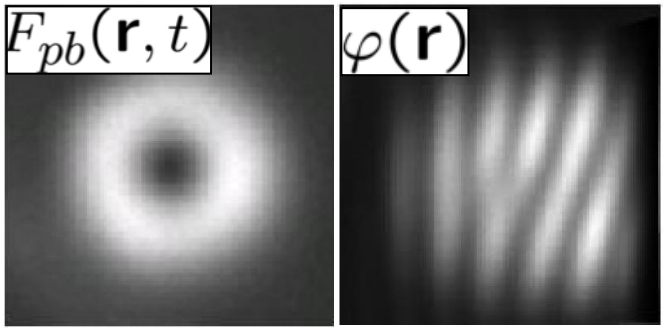
$$F_p(\mathbf{r},t) = \mathcal{F}_p(\mathrm{r}) e^{i(\mathbf{k}_p \cdot \mathbf{r} - \omega_p t)}$$

$\psi_C(\omega,\mathrm{k})$

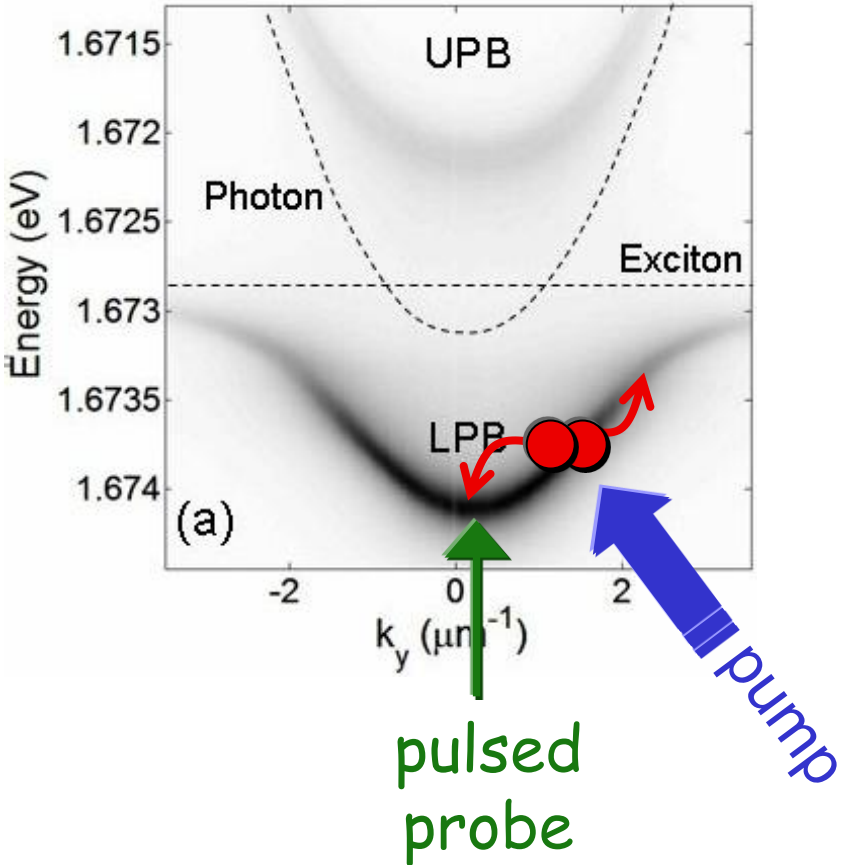


Persistent flow after a "rotating drive" pulse?

Gauss-Laguerre pulse - stirring the polariton superfluid for a short (2ps) time

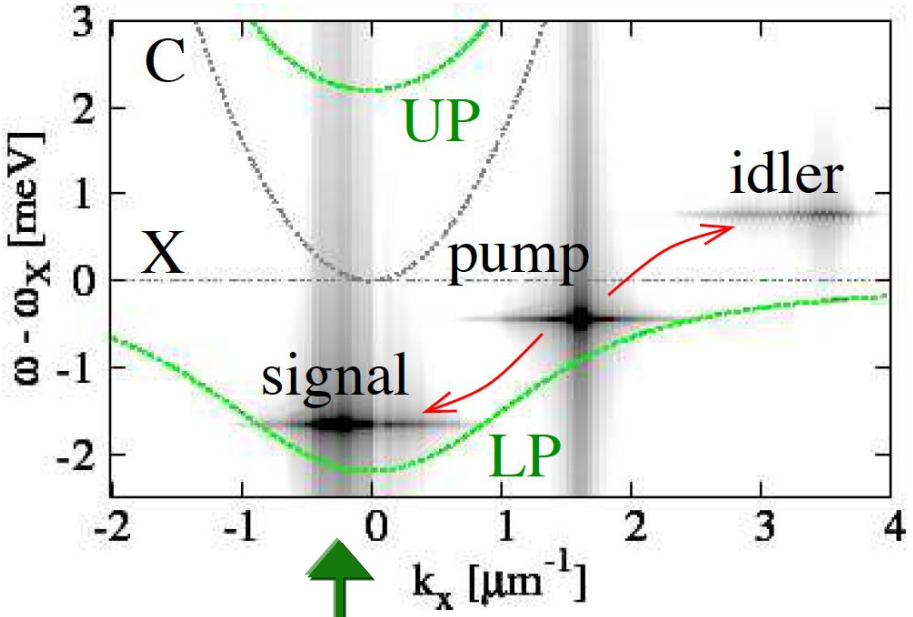


$$F_{pb}(\mathbf{r},t) = \mathcal{F}_{pb}(\mathbf{r})e^{i\varphi(\mathbf{r})}e^{-\frac{t^2}{2\sigma_t^2}}e^{i(\mathbf{k}_s\cdot\mathbf{r}-\omega_s t)}$$

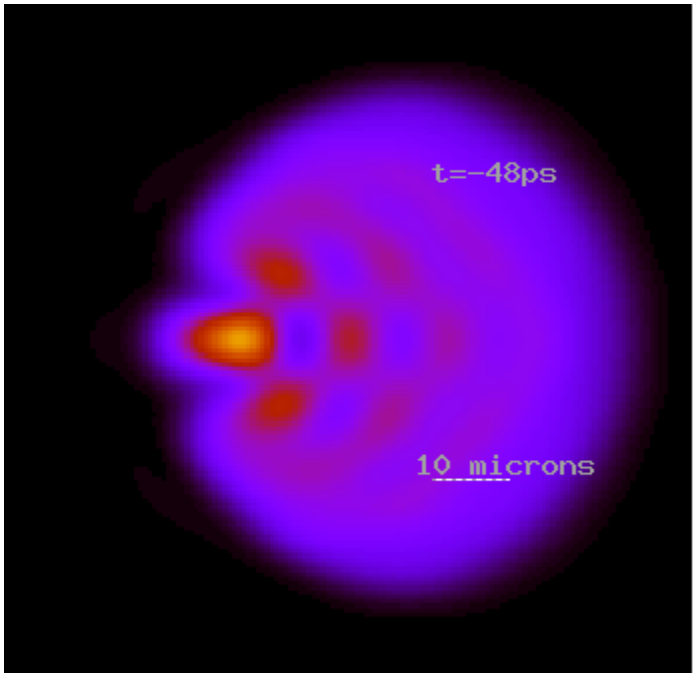


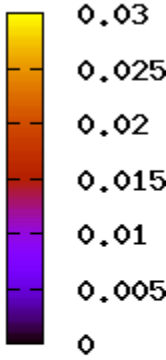
Metastable persistent vortices

Vortex imprinting into signal (&idler) for strong enough probe



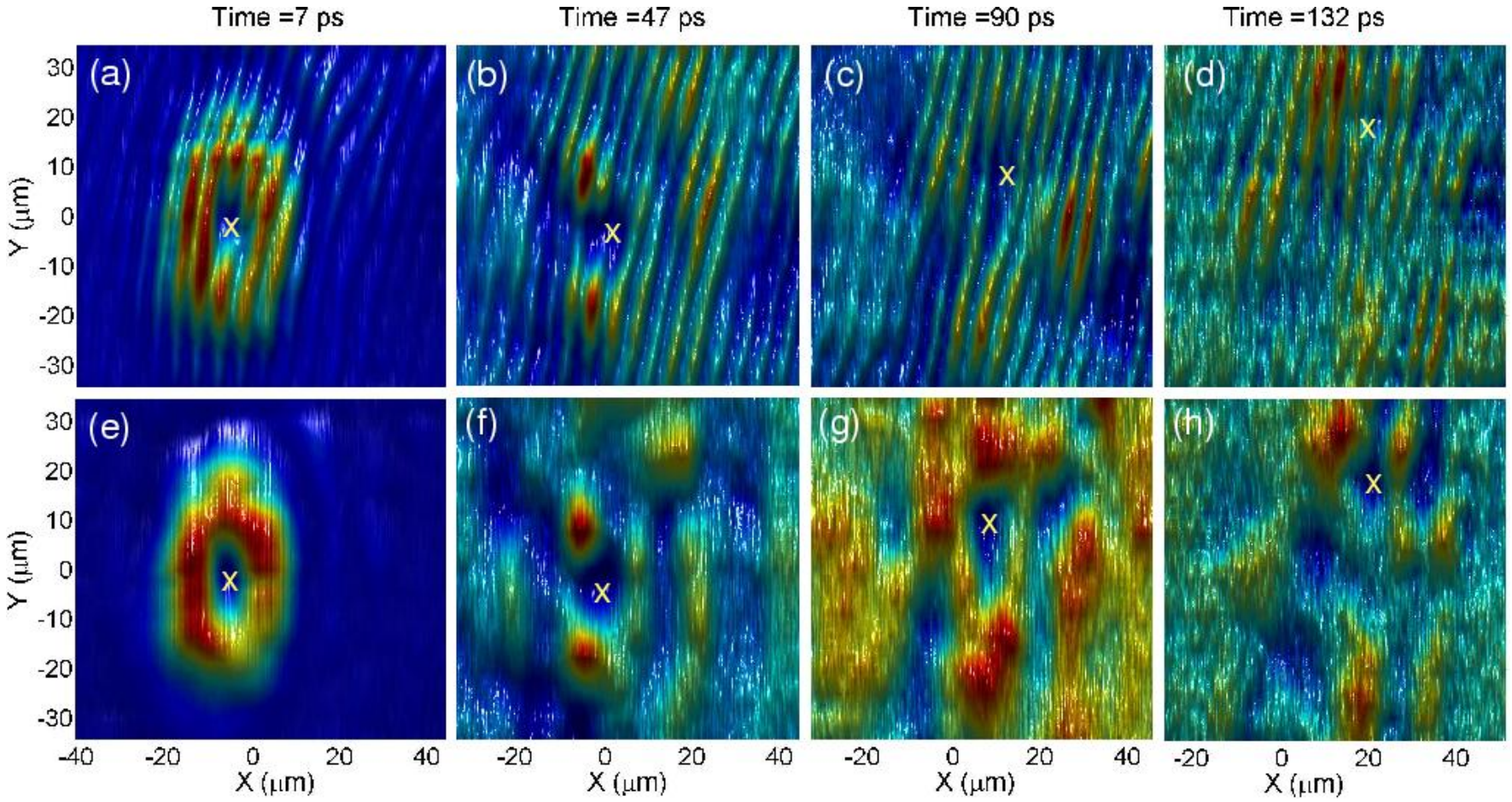
pulsed probe





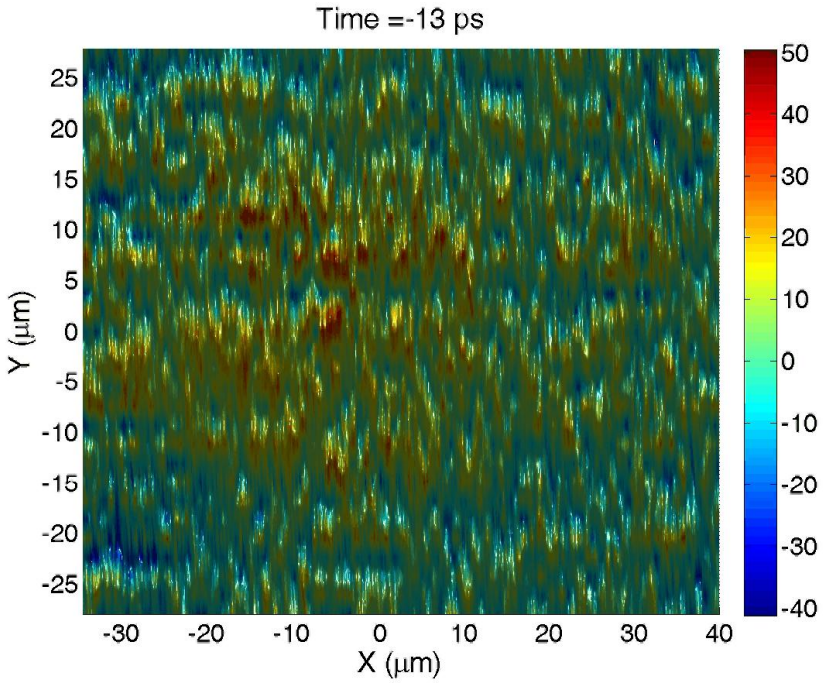
[Sanvitto, Marchetti, Szymanska *et al.*, Nature Phys. (2010) (arxiv/0907.2371)]
[Marchetti, Szymanska *et al. PRL* (2010), arxiv/1003.5111]

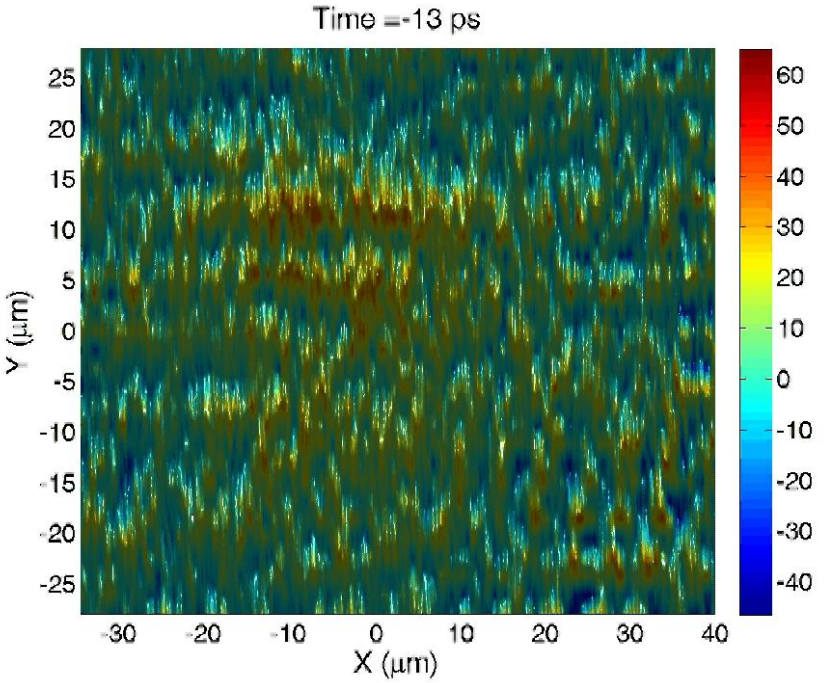
Metastable persistent vortices



[Sanvitto, Marchetti, Szymanska *et al.*, Nature Phys. (arxiv/0907.2371) 2010]

Metastable persistent vortices





[Sanvitto, Marchetti, Szymanska *et al.*, Nature Phys. (arxiv/0907.2371)]

Optical parametric oscillator (OPO)

SUPERFLUID CHECKLIST

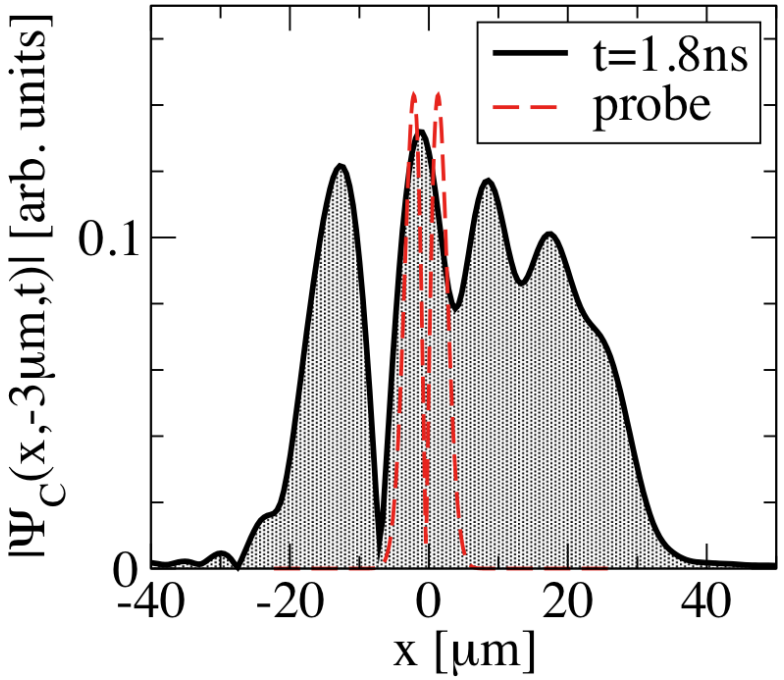
	Landau criterion	frictionless flow	quantised vortices	metastable persistent flow
^{4}He/cold atoms BEC	✓	✓	✓	✓
polariton condensates (incoherent pump)	✗	✓?	✓ no-SF	?
polariton condensates (parametrical pump)	✗	✓	?	✓

Vortex healing length

Independent on probe size, but on OPO properties only

$$\xi \propto \left(m_C g_X \sqrt{n_s n_i}\right)^{-1/2}$$

[Marchetti, Szymanska *et al.*, arxiv/1003.5111

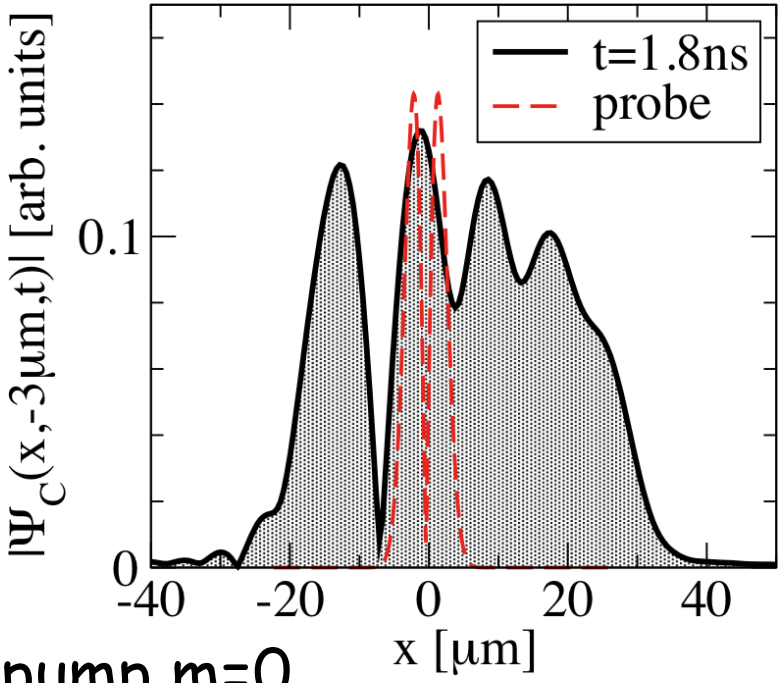


Vortex healing length

Independent on probe size, but on OPO properties only

$$\xi \propto \left(m_C g_X \sqrt{n_s n_i}\right)^{-1/2}$$

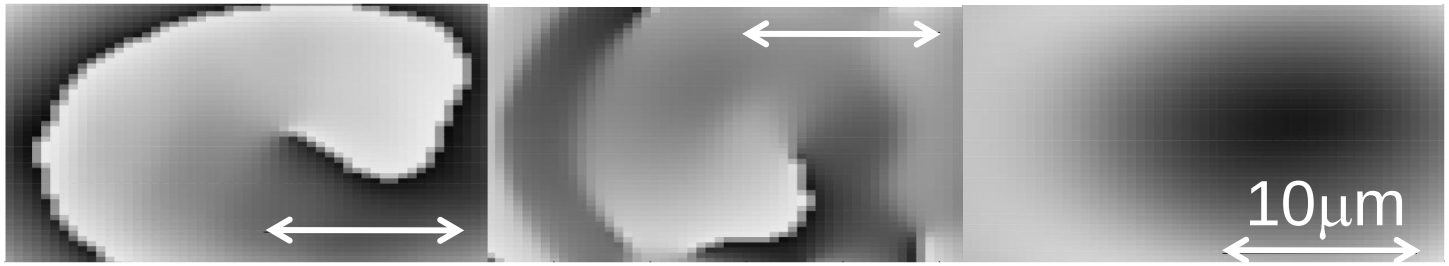
[Marchetti, Szymanska *et al.*, PRL (2010) arxiv/1003.5111]



Only signal & idler carry a vortex

$$2\varphi_p = \varphi_s + \varphi_i$$
$$0 = +1 - 1$$

signal m=-1 idler m=+1 pump m=0



Vortex healing length

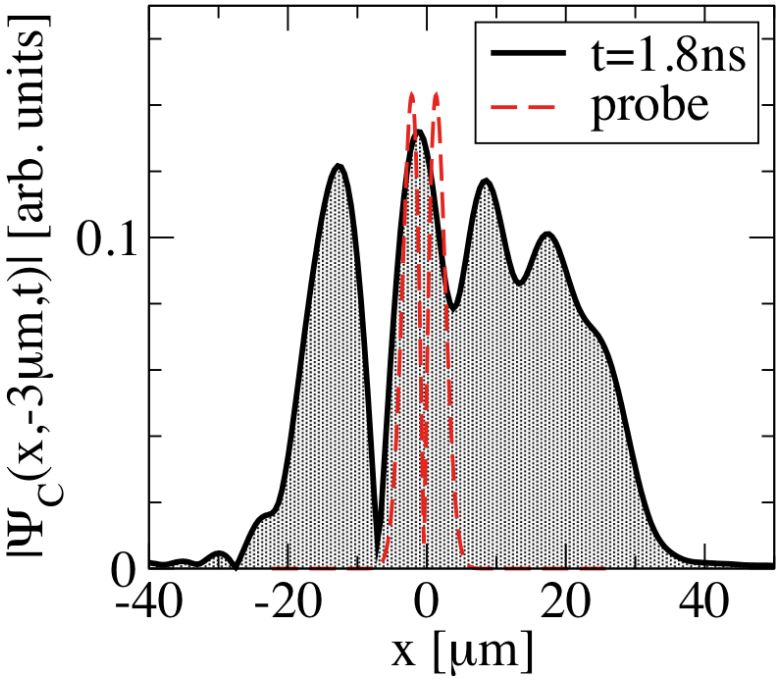
Independent on probe size, but on OPO properties only

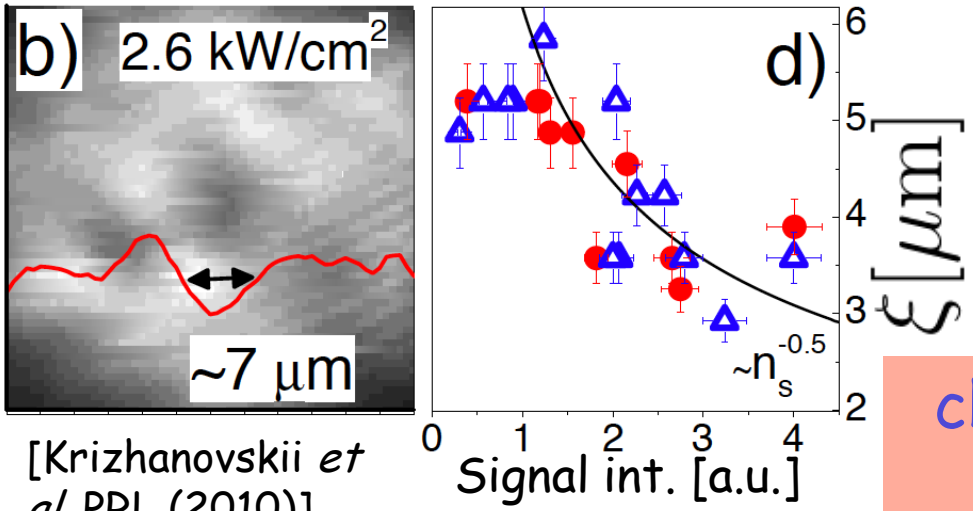
$$\xi \propto \left(m_C g_X \sqrt{n_s n_i}\right)^{-1/2}$$

Only signal & idler carry a vortex

$$2\varphi_p = \varphi_s + \varphi_i$$
$$0 = +1 - 1$$

[Marchetti, Szymanska *et al.*, PRL (2010) arxiv/1003.5111]





[Krizhanovskii *et al.* PRL (2010)]

checked by weak continuous-wave imprinting beam

Optical parametric oscillator (OPO)

SUPERFLUID CHECKLIST

	Landau criterion	frictionless flow	quantised vortices	metastable persistent flow
^{4}He/cold atoms BEC	✓	✓	✓	✓
polariton condensates (incoherent pump)	✗	✓?	✓ no-SF	?
polariton condensates (parametrical pump)	✗	✓	✓	✓
polariton condensates (coherent pump)	✓	?	?	?

Below OPO threshold

✓ No spontaneous symmetry breaking but…

Landau criterion satisfied

[Ciuti & Carusotto *PRA* (2007)]

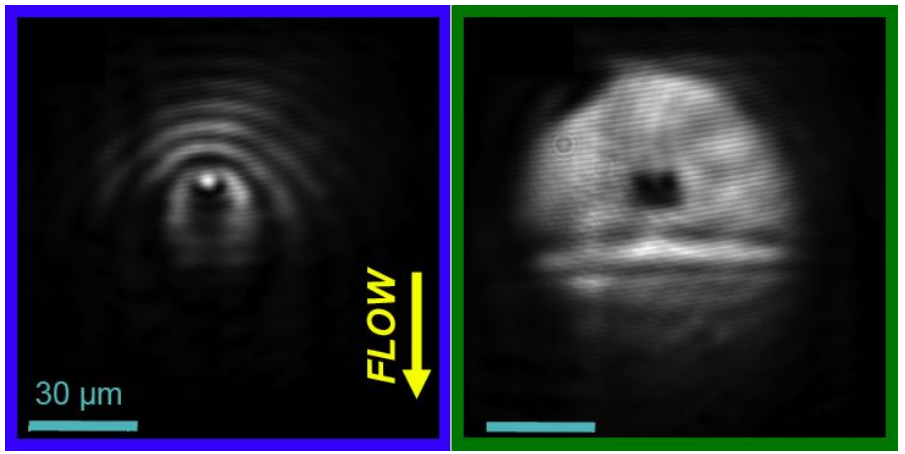
Optical parametric oscillator (OPO)

SUPERFLUID CHECKLIST

	Landau criterion	frictionless flow	quantised vortices	metastable persistent flow
^{4}He/cold atoms BEC	✓	✓	✓	✓
polariton condensates (incoherent pump)	✗	✓?	✓ no-SF	?
polariton condensates (parametrical pump)	✗	✓	✓	✓
polariton condensates (coherent pump)	✓	✓	✗	?

Below OPO threshold

- ✓ Frictionless flow below critical flow velocity
- ✓ Phase fixed by the pump thus no vortices



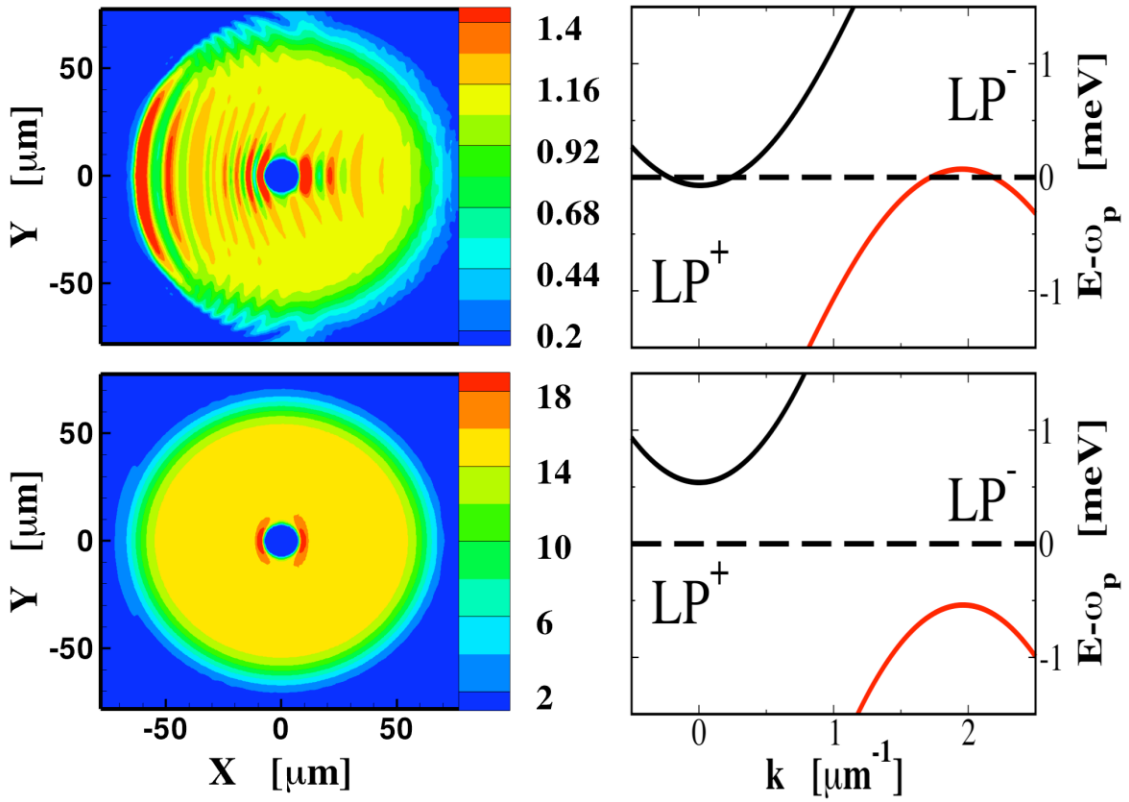
[Amo *et al. Nature Phys* (2009)]

Frictionless flow of the OPO

Gross-Pitaevskii equation with pump & decay

$$i\partial_t \begin{pmatrix} \psi_X \\ \psi_C \end{pmatrix} = \begin{pmatrix} \omega_X - i\kappa_X + g_X|\psi_X|^2 & \Omega_R/2 \\ \Omega_R/2 & \omega_C - i\kappa_C \end{pmatrix} \begin{pmatrix} \psi_X \\ \psi_C \end{pmatrix} + \begin{pmatrix} 0 \\ F_p + F_{pb} \end{pmatrix}$$

$$F_n(\mathbf{r},t) = \mathcal{F}_p(\mathrm{r}) e^{i(\mathbf{k}_p\cdot\mathbf{r}-\omega_p t)}$$



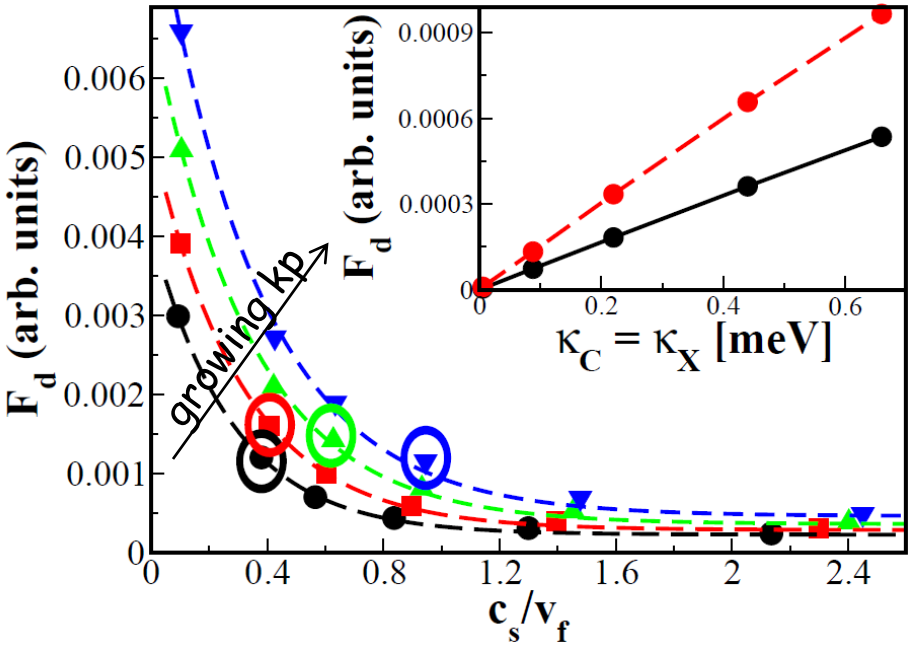
Frictionless flow of the OPO

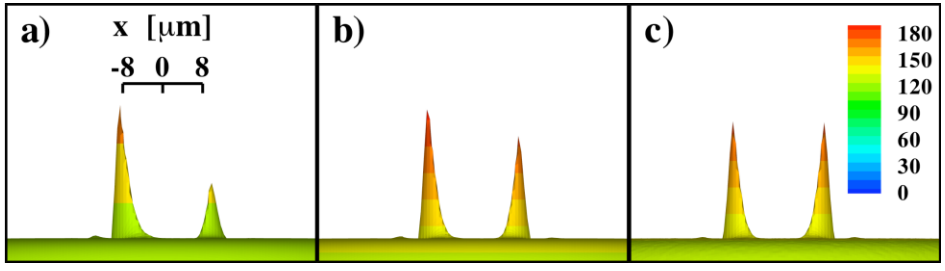
Gross-Pitaevskii equation with pump & decay

$$i\partial_t \begin{pmatrix} \psi_X \\ \psi_C \end{pmatrix} = \begin{pmatrix} \omega_X - i\kappa_X + g_X|\psi_X|^2 & \Omega_R/2 \\ \Omega_R/2 & \omega_C - i\kappa_C \end{pmatrix} \begin{pmatrix} \psi_X \\ \psi_C \end{pmatrix} + \begin{pmatrix} 0 \\ F_p + F_{pb} \end{pmatrix}$$

$$F_p(\mathbf{r},t) = \mathcal{F}_p(\mathrm{r}) e^{i(\mathbf{k}_p\cdot\mathbf{r}-\omega_p t)}$$

Drag force: $$\mathbf{F} = -\frac{1}{\int |\psi_C(\mathbf{r})|^2 \, d^3x} \int |\psi_C(\mathbf{r})|^2 \, \vec{\nabla} \left[V(\mathbf{r})\right] d^3x$$

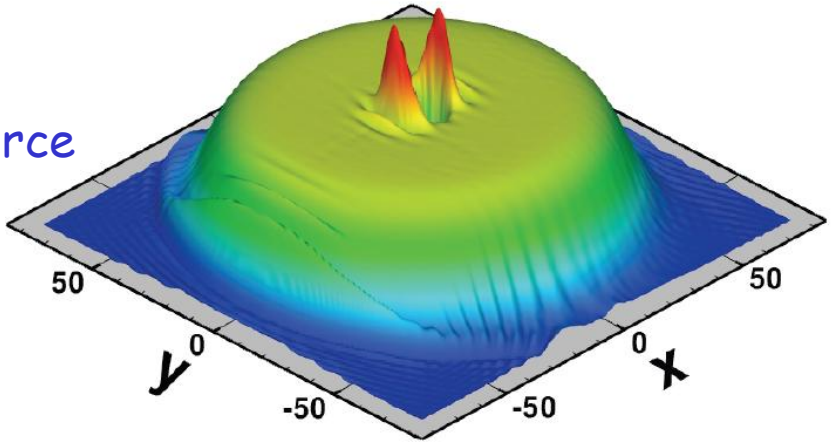




Conclusions

a novel light-matter superfluid out of equilibrium

1. Frictionless flow: almost vanishing drag force



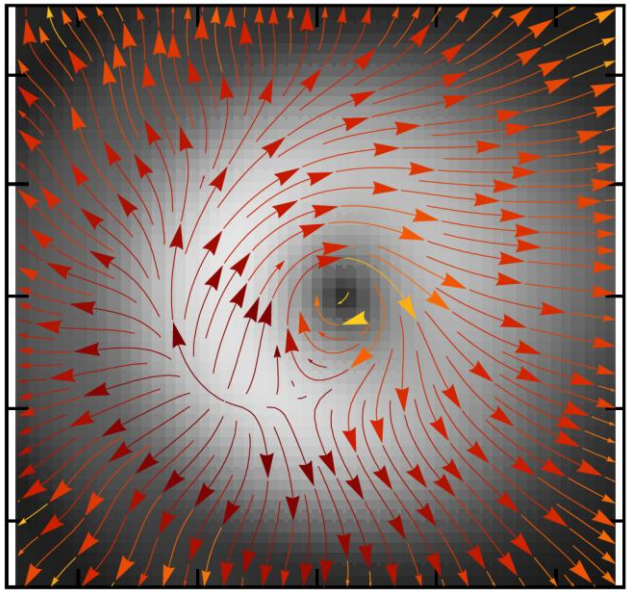
SUPERFLUID CHECKLIST

	Landau criterion	frictionless flow	quantised vortices	metastable persistent flow
^{4}He/cold atoms BEC	✓	✓	✓	✓
polariton condensates (incoherent pump)	✗	✓?	✓ no-SF	?
polariton condensates (parametrical pump)	✗	✓	✓	✓
polariton condensates (coherent pump)	✓	✓	✗	?

Conclusions

a novel light-matter superfluid out of equilibrium

1. Frictionless flow: almost vanishing drag force
2. Persistent currents in the OPO regime
3. Vortex healing length



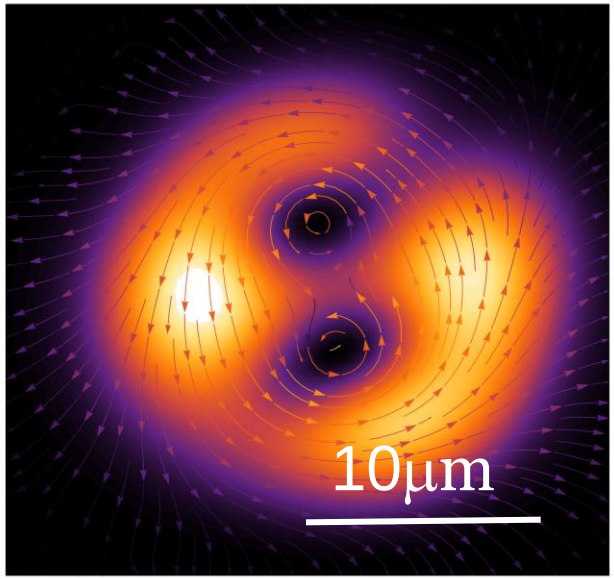
SUPERFLUID CHECKLIST

	Landau criterion	frictionless flow	quantised vortices	metastable persistent flow
^{4}He/cold atoms BEC	✓	✓	✓	✓
polariton condensates (incoherent pump)	✗	✓?	✓ no-SF	?
polariton condensates (parametrical pump)	✗	✓	✓	✓
polariton condensates (coherent pump)	✓	✓	✗	?

Conclusions

a novel light-matter superfluid out of equilibrium

1. Frictionless flow: almost vanishing drag force
2. Persistent currents in the OPO regime
3. Vortex healing length
4. Stable & unstable doubly quantised vortices

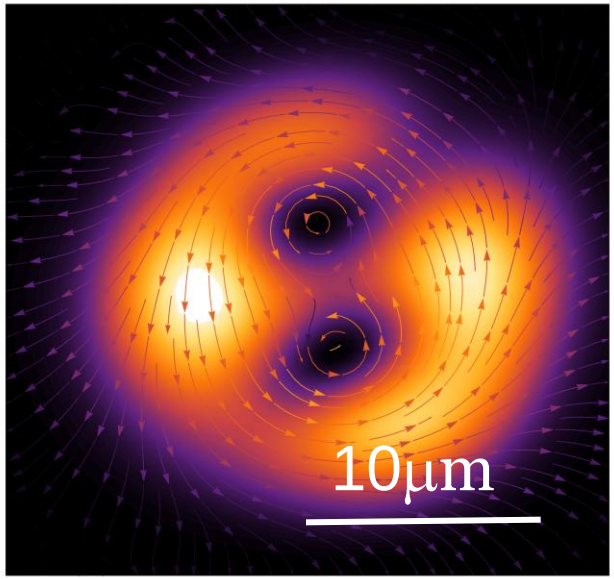


SUPERFLUID CHECKLIST

	Landau criterion	frictionless flow	quantised vortices	metastable persistent flow
^{4}He/cold atoms BEC	✓	✓	✓	✓
polariton condensates (incoherent pump)	✗	✓?	✓ no-SF	?
polariton condensates (parametrical pump)	✗	✓	✓	✓
polariton condensates (coherent pump)	✓	✓	✗	?

Conclusions

a novel light-matter superfluid out of equilibrium



So far experiments and numerical simulations

Analytical theory of non-equilibrium superfluidity still missing!

SUPERFLUID CHECKLIST

	Landau criterion	frictionless flow	quantised vortices	metastable persistent flow
^{4}He/cold atoms BEC	✓	✓	✓	✓
polariton condensates (incoherent pump)	✗	✓?	✓ no-SF	?
polariton condensates (parametrical pump)	✗	✓	✓	✓
polariton condensates (coherent pump)	✓	✓	✗	?