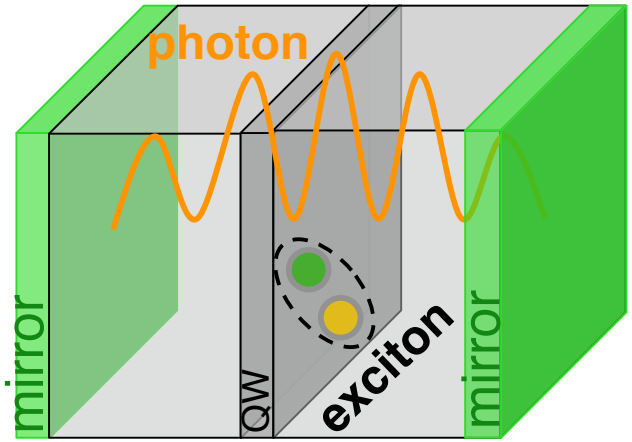
Persistent Quantised Currents in a Polariton Superfluid

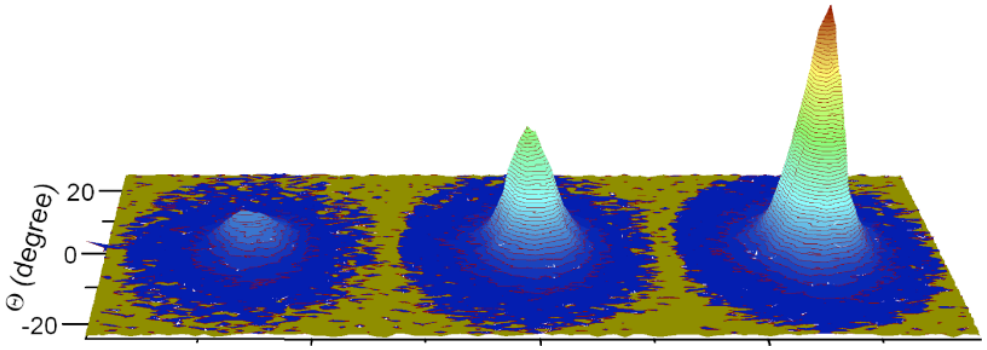
Francesca M. Marchetti

Microcavity polariton condensates

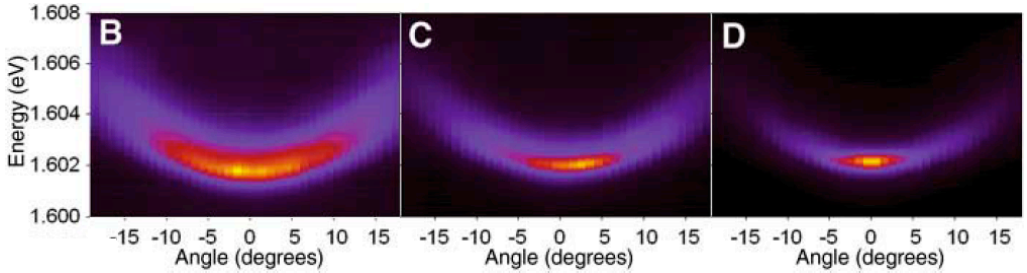
- non-equilibrium (short lifetime)

does the observation of vortices in a polariton condensate imply superfluid behaviour?

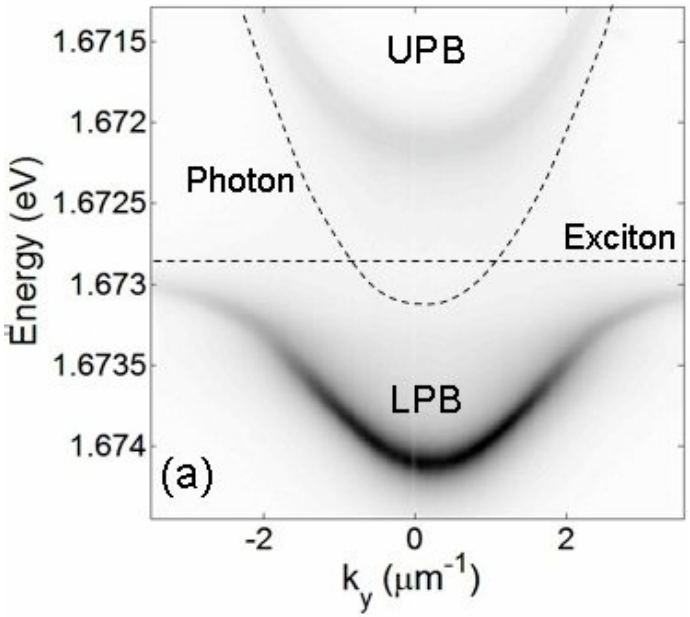




[Kasprzak *et al. Nature* (2006)]



[Balili *et al. Science* (2007)]



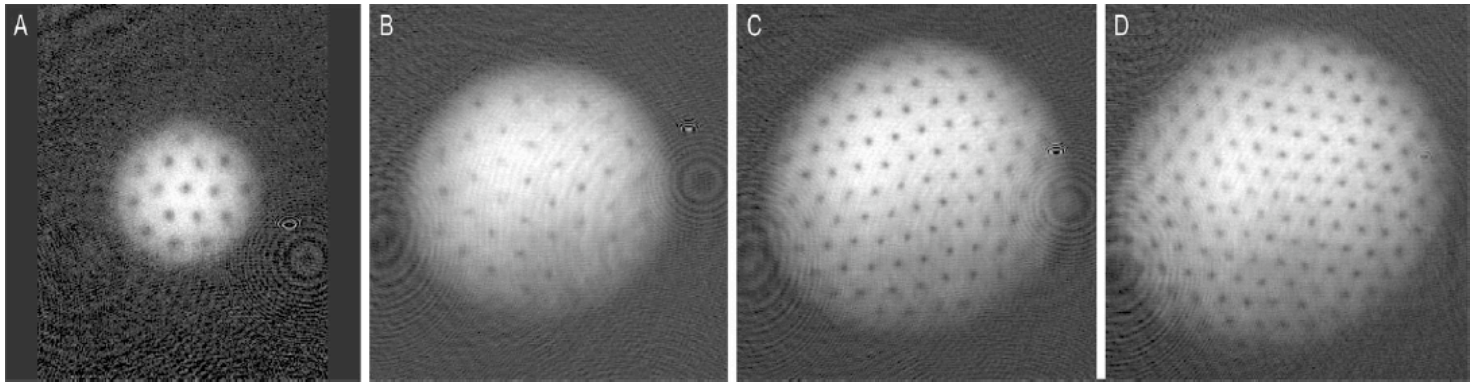
Equilibrium superfluids

- equilibrium (non-rotating) condensates:
  the ground state is flowless & vortex solutions are metastable (unless in toroidal traps)

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

superfluidity ⟺ vortices

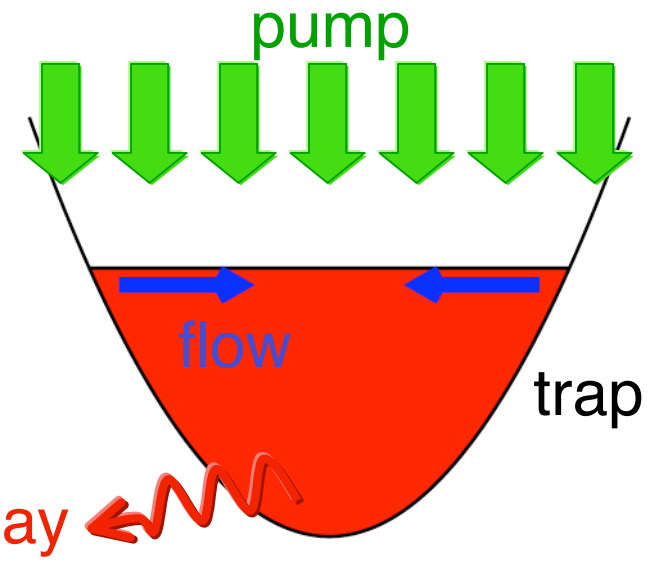
Atomic BEC

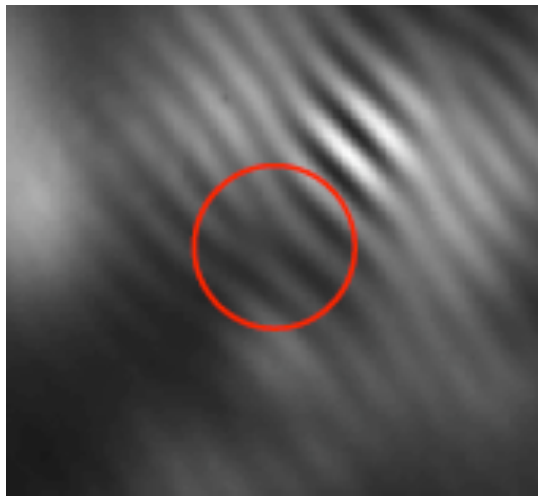


[Abo-Shaeer *et al. Science* (2001)]

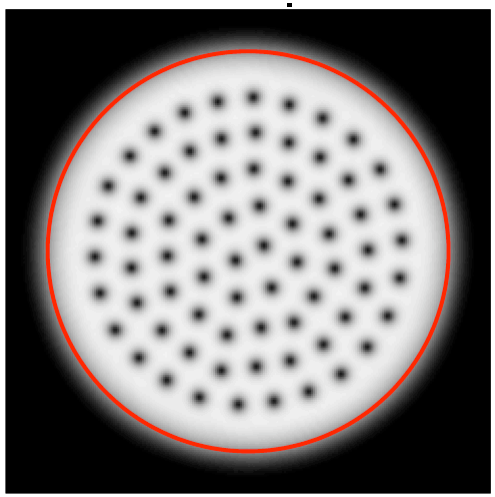
Polariton condensates: flowing groundstate

- driven-dissipative system
- pump&decay in a trapped polariton condensate: flow
- instability to spontaneous formation of vortices





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

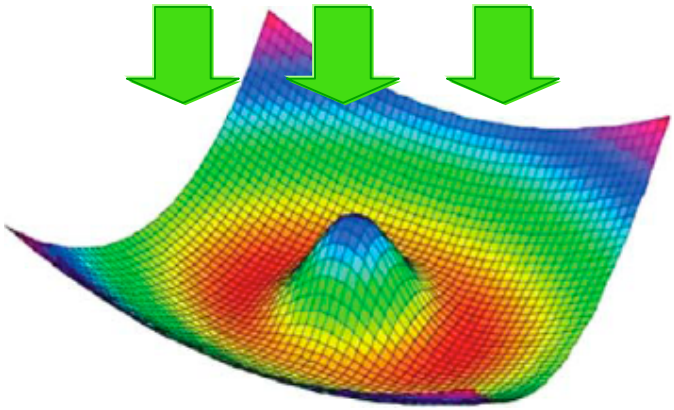


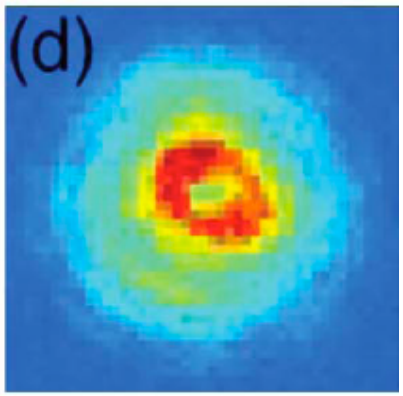
[Keeling&Berloff *PRL* (2008)]

Persistent flow

- Proposed experiment:
  - External creation of a vortex
    (rotating drive: pulsed probe carrying a vortex)
  - Does the vortex persist in absence of the rotating drive?
- Atomic BEC

Gaussian Laguerre Beam
(vortex)



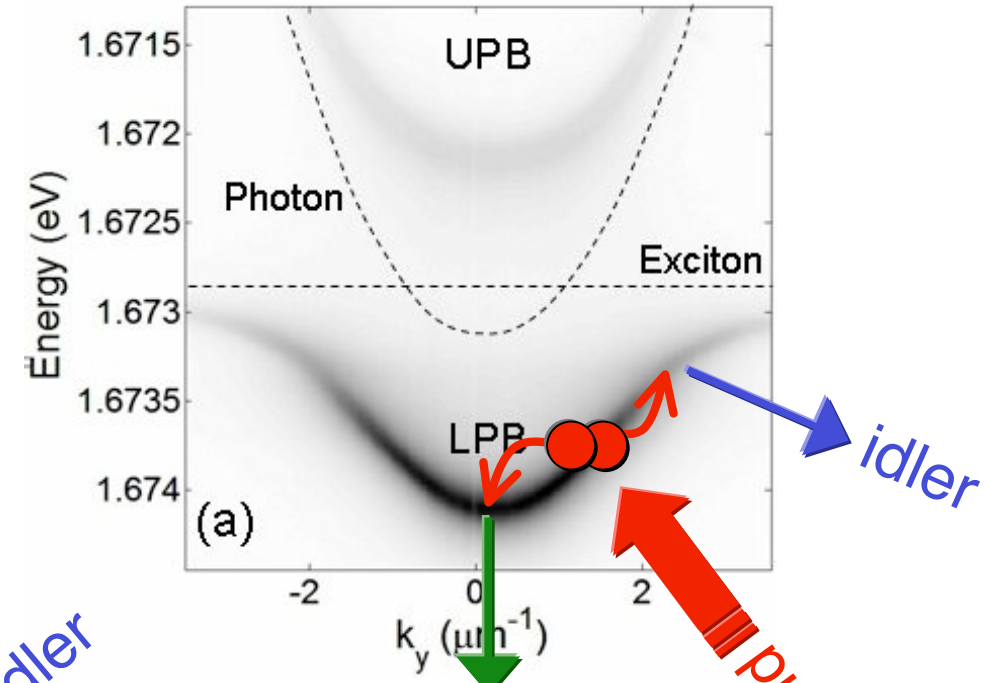


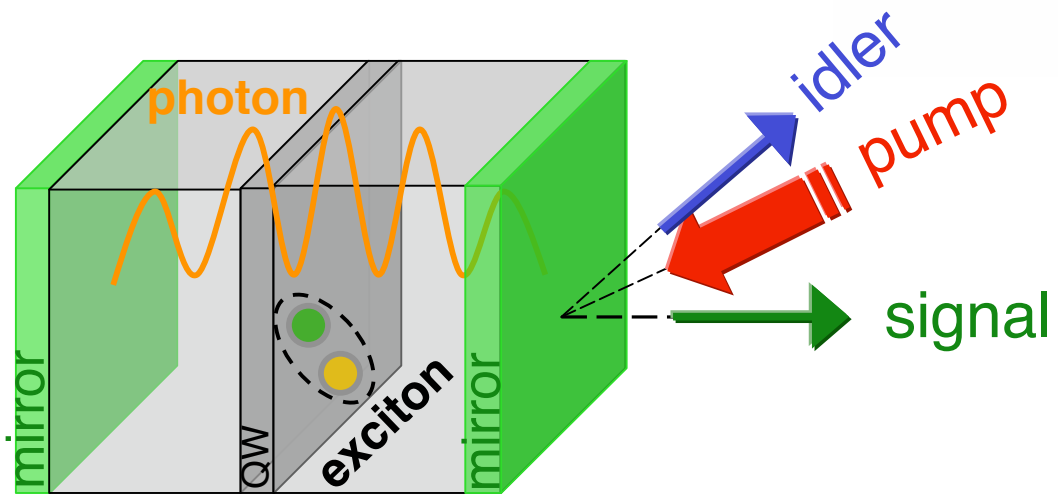
vortex lifetime 10s
(condensate
lifetime 15s)

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

Optical parametric oscillator (OPO)

- scattering from pump to signal and idler (bosonic final state stimulation)
- pump threshold





New non-equilibrium superfluid phase

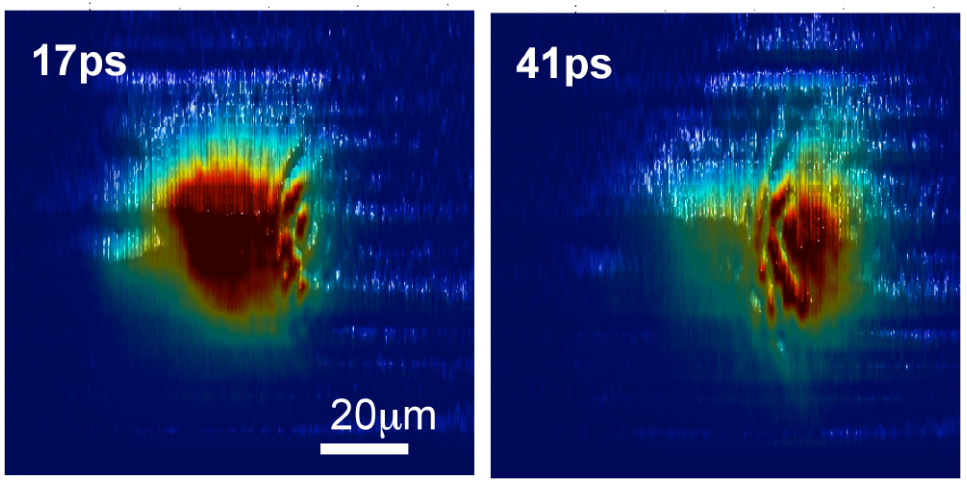
- Landau criterion
- U(1) spontanous symmetry breaking

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

&Goldstone mode

[Wouters&Carusotto *PRA* (2007)]

- Frictionless flow



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

[Keeling&Berloff *Nature* News&Views (2009)]

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

New non-equilibrium superfluid phase

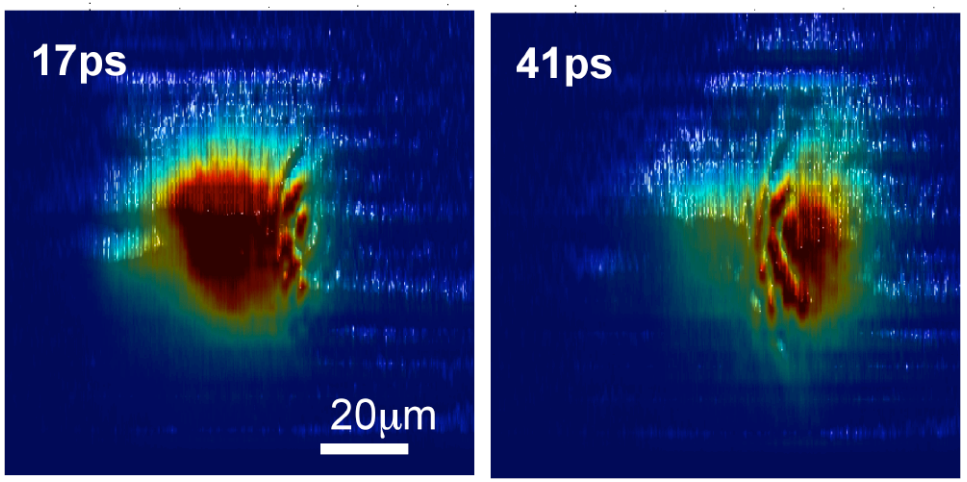
- Landau criterion
- U(1) spontanous symmetry breaking

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

&Goldstone mode

[Wouters&Carusotto *PRA* (2007)]

- Frictionless flow

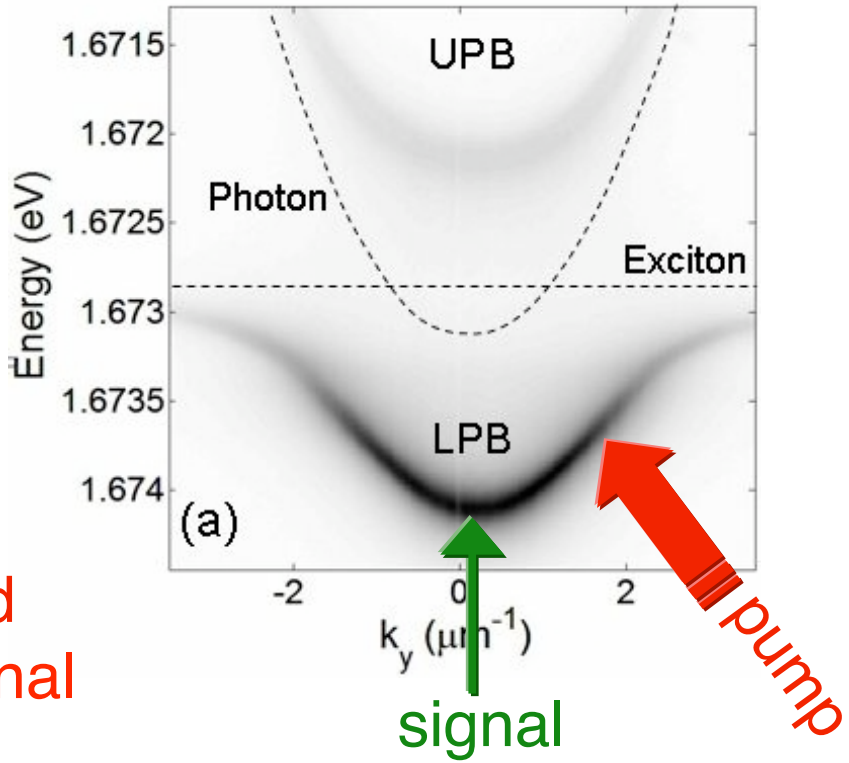


[Amo *et al. Nature* (2009)]

[Keeling&Berloff *Nature* News&Views (2009)]

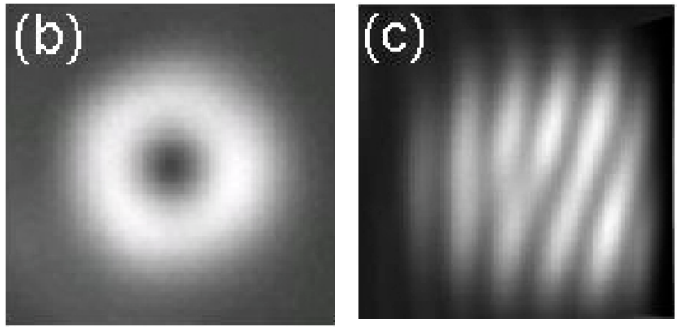
SUPERFLUID CHECKLIST	quantised vortices	Landau criterion	metastable persistent flow	equilibrium
^{4}He/cold atoms BEC	✓	✓	✓	✓
…				
polariton condensates (incoherent pump)	✓?	✗	?	✗
polariton condensates (parametrical pump)	?	✓	?	✗

Triggering OPO with a vortex state



- triggering vortex: pulsed probe resonant with signal

$$F_{pb}(\mathbf{r},t) \simeq f_{pb}|\mathbf{r}|^m e^{-\frac{\mathbf{r}^2}{2\sigma_{pb}^2}} e^{im\varphi} \times e^{-\frac{t^2}{2\sigma_t^2}} e^{i(\mathbf{k}_{pb}\cdot\mathbf{r}-\omega_{pb}t)}$$



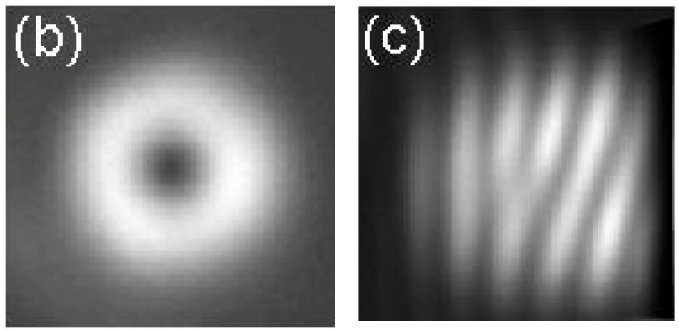
Dynamics of the triggered OPO

- Gross-Pitaevskii equation with pump & decay

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

- coupling
- interaction
- decay
- resonant cw pump (OPO) $F_p(\mathbf{r},t) = f_p e^{-\frac{\mathbf{r}^2}{2\sigma_p^2}} e^{i(\mathbf{k}_p\cdot\mathbf{r}-\omega_p t)}$
- triggering vortex: pulsed probe resonant with signal

$$F_{pb}(\mathbf{r},t) \simeq f_{pb}|\mathbf{r}|^m e^{-\frac{\mathbf{r}^2}{2\sigma_{pb}^2}} e^{im\varphi} \times e^{-\frac{t^2}{2\sigma_t^2}} e^{i(\mathbf{k}_{pb}\cdot\mathbf{r}-\omega_{pb}t)}$$



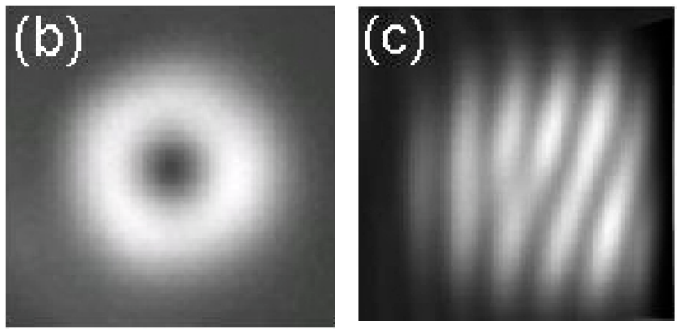
Dynamics of the triggered OPO

- Gross-Pitaevskii equation with pump & decay

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

- coupling
- interaction
- decay
- resonant cw pump (OPO) $F_p(\mathbf{r},t) = f_p e^{-\frac{\mathbf{r}^2}{2\sigma_p^2}} e^{i(\mathbf{k}_p\cdot\mathbf{r}-\omega_p t)}$
- triggering vortex: pulsed probe resonant with signal

$$F_{pb}(\mathbf{r},t) \simeq f_{pb}|\mathbf{r}|^m e^{-\frac{\mathbf{r}^2}{2\sigma_{pb}^2}} e^{im\varphi} \times e^{-\frac{t^2}{2\sigma_t^2}} e^{i(\mathbf{k}_{pb}\cdot\mathbf{r}-\omega_{pb}t)}$$



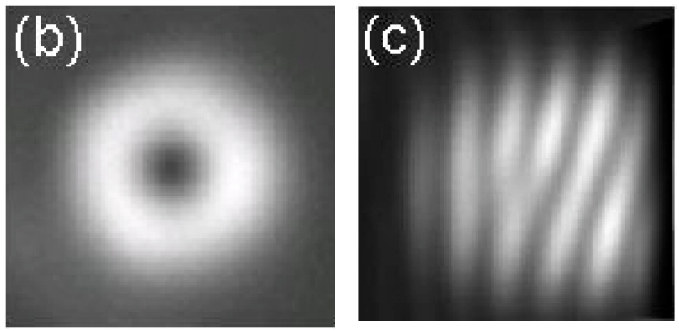
Dynamics of the triggered OPO

- Gross-Pitaevskii equation with pump & decay

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

- coupling
- interaction
- decay
- resonant cw pump (OPO) $F_p(\mathbf{r},t) = f_p e^{-\frac{\mathbf{r}^2}{2\sigma_p^2}} e^{i(\mathbf{k}_p\cdot\mathbf{r}-\omega_p t)}$
- triggering vortex: pulsed probe resonant with signal

$$F_{pb}(\mathbf{r},t) \simeq f_{pb}|\mathbf{r}|^m e^{-\frac{\mathbf{r}^2}{2\sigma_{pb}^2}} e^{im\varphi} \times e^{-\frac{t^2}{2\sigma_t^2}} e^{i(\mathbf{k}_{pb}\cdot\mathbf{r}-\omega_{pb}t)}$$



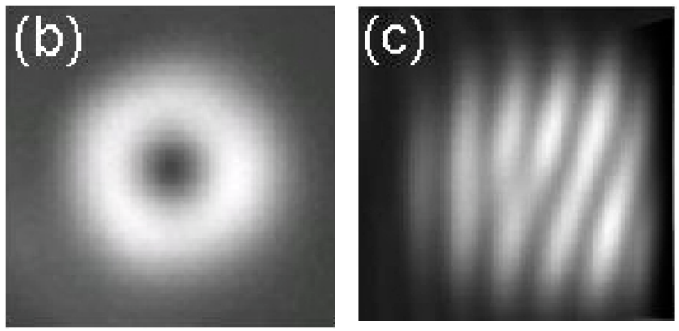
Dynamics of the triggered OPO

- Gross-Pitaevskii equation with pump & decay

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

  - coupling
  - interaction
  - decay
  - resonant cw pump (OPO) $F_p(\mathbf{r},t) = f_p e^{-\frac{\mathbf{r}^2}{2\sigma_p^2}} e^{i(\mathbf{k}_p\cdot\mathbf{r}-\omega_p t)}$
  - triggering vortex: pulsed probe resonant with signal

$$F_{pb}(\mathbf{r},t) \simeq f_{pb}|\mathbf{r}|^m e^{-\frac{\mathbf{r}^2}{2\sigma_{pb}^2}} e^{im\varphi} \times e^{-\frac{t^2}{2\sigma_t^2}} e^{i(\mathbf{k}_{pb}\cdot\mathbf{r}-\omega_{pb}t)}$$



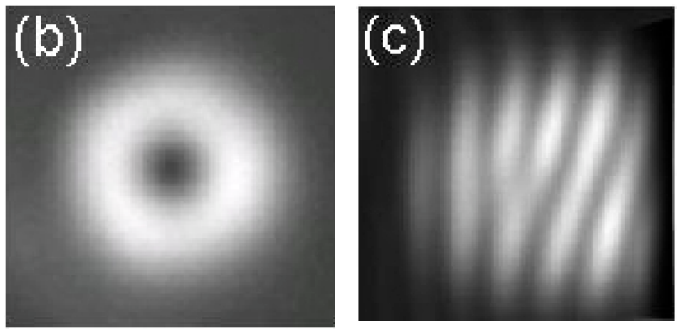
Dynamics of the triggered OPO

- Gross-Pitaevskii equation with pump & decay

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

  - coupling
  - interaction
  - decay
  - resonant cw pump (OPO) $F_p(\mathbf{r},t) = f_p e^{-\frac{\mathbf{r}^2}{2\sigma_p^2}} e^{i(\mathbf{k}_p\cdot\mathbf{r}-\omega_p t)}$
  - triggering vortex: pulsed probe resonant with signal

$$F_{pb}(\mathbf{r},t) \simeq f_{pb}|\mathbf{r}|^m e^{-\frac{\mathbf{r}^2}{2\sigma_{pb}^2}} e^{im\varphi} \times e^{-\frac{t^2}{2\sigma_t^2}} e^{i(\mathbf{k}_{pb}\cdot\mathbf{r}-\omega_{pb}t)}$$

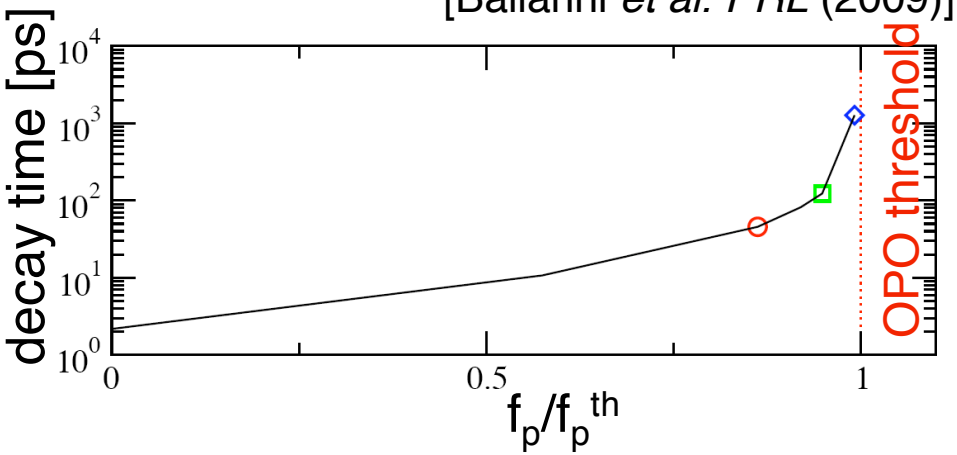


Critical slowing down of dynamics

appearance of a Goldstone mode at threshold

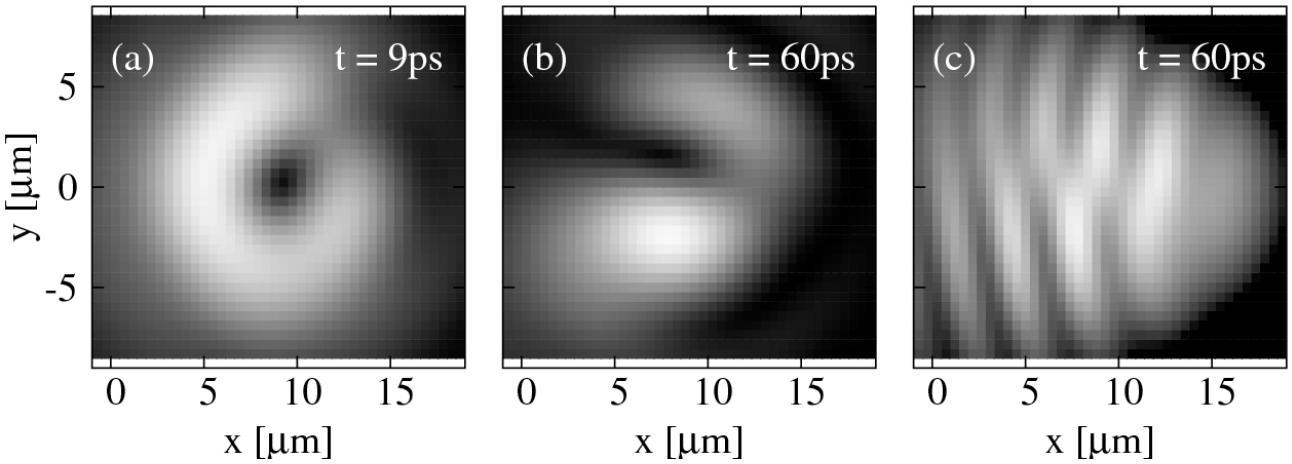
$$2\varphi_p = \varphi_s + \varphi_i$$

[Ballarini *et al. PRL* (2009)]



- Just below threshold for OPO

[Sanvitto *et al. cond-mat/0907.2371*]

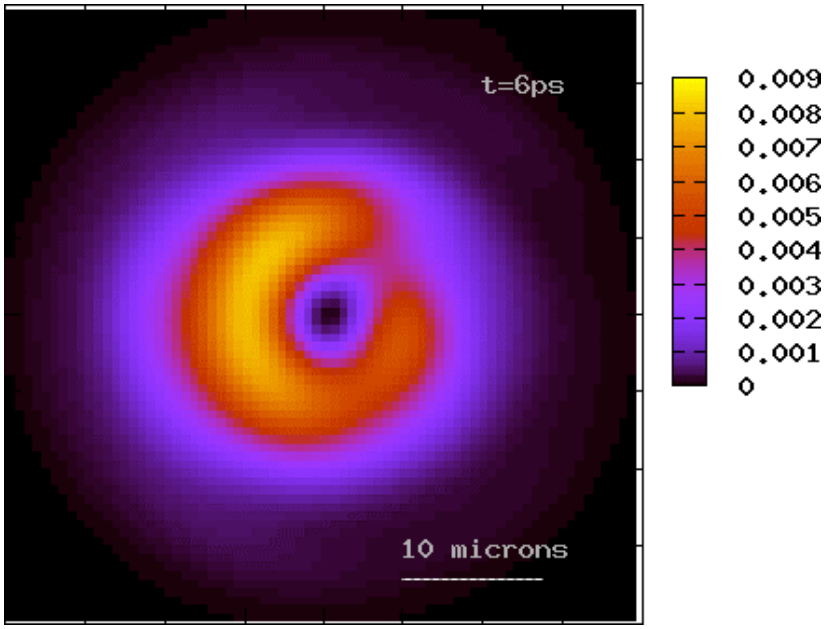


Persistent flow of polaritons

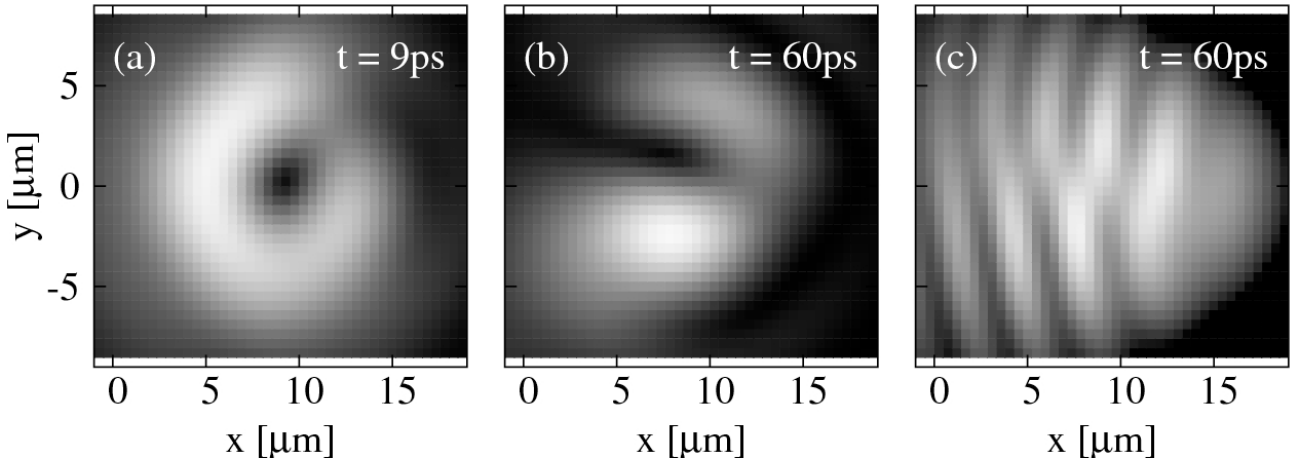
- probe lasts 2ps only
- triggered vortex lasts up to 80ps

- The vortex lasts for as long as OPO can be sustained

- slow drift



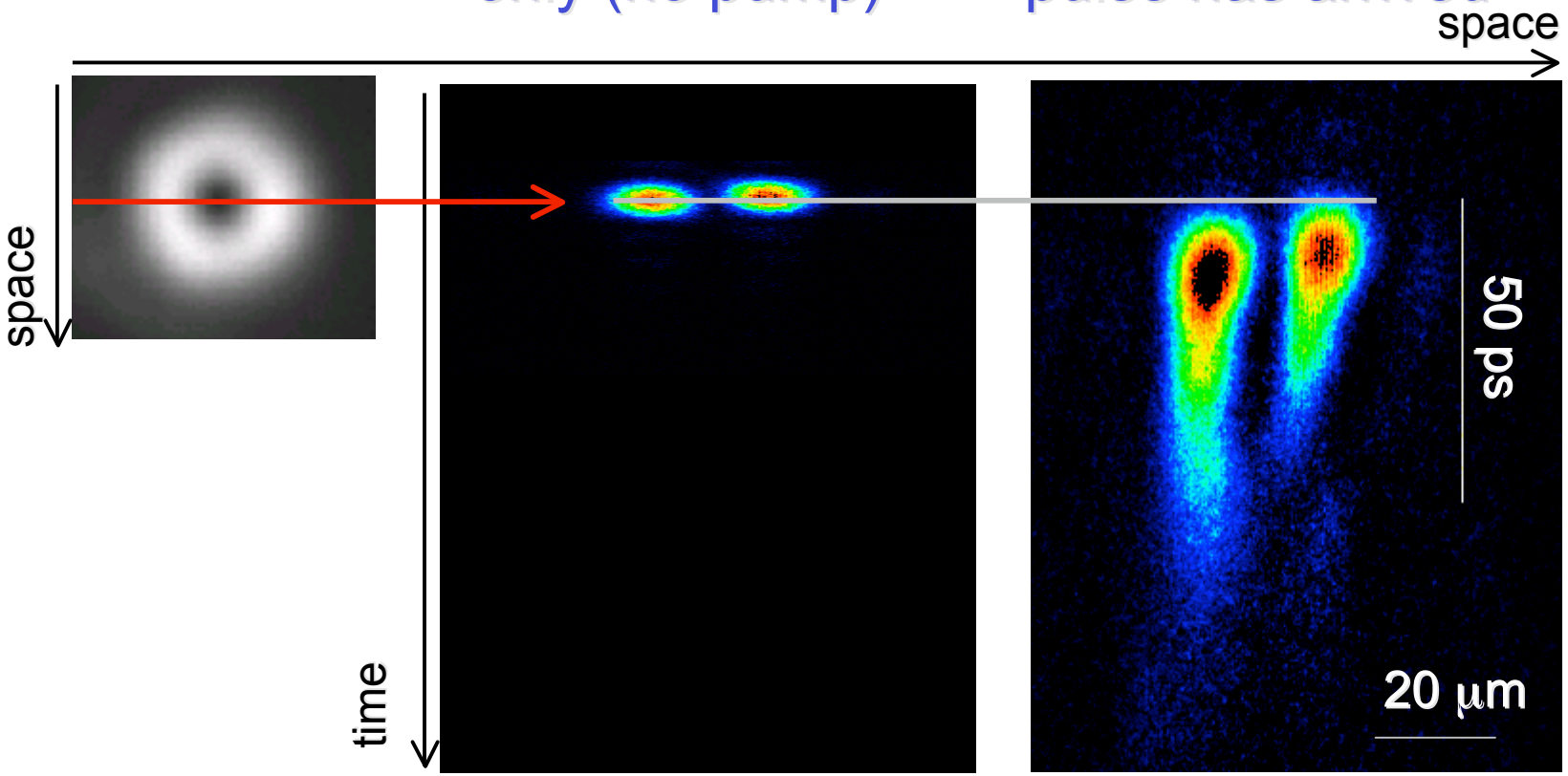
- Just below threshold for OPO



Experiments

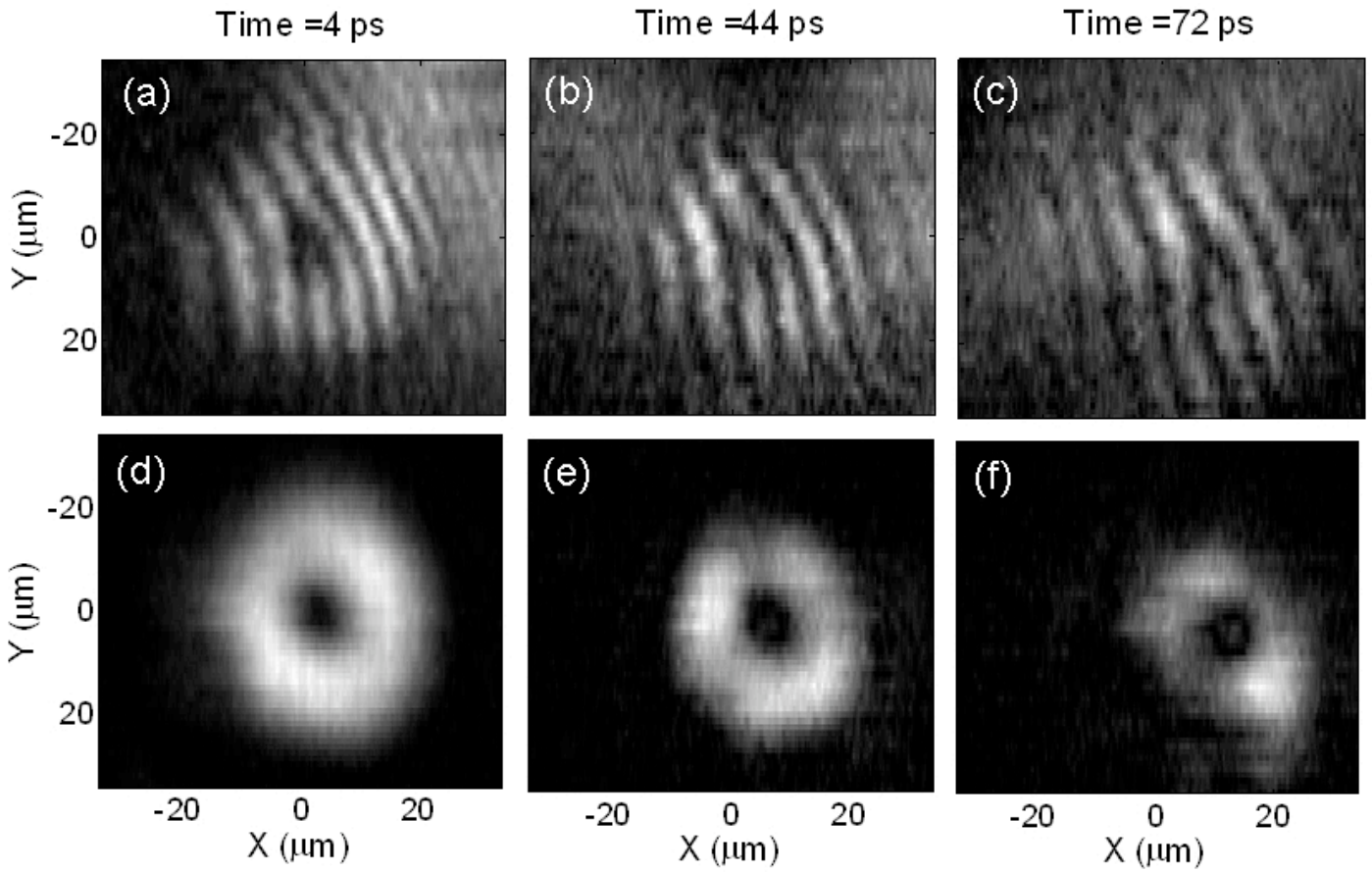
image of the pulsed probe only (no pump)

signal time resolved 1D image after the pulse has arrived



- above threshold but triggered state different from OPO signal

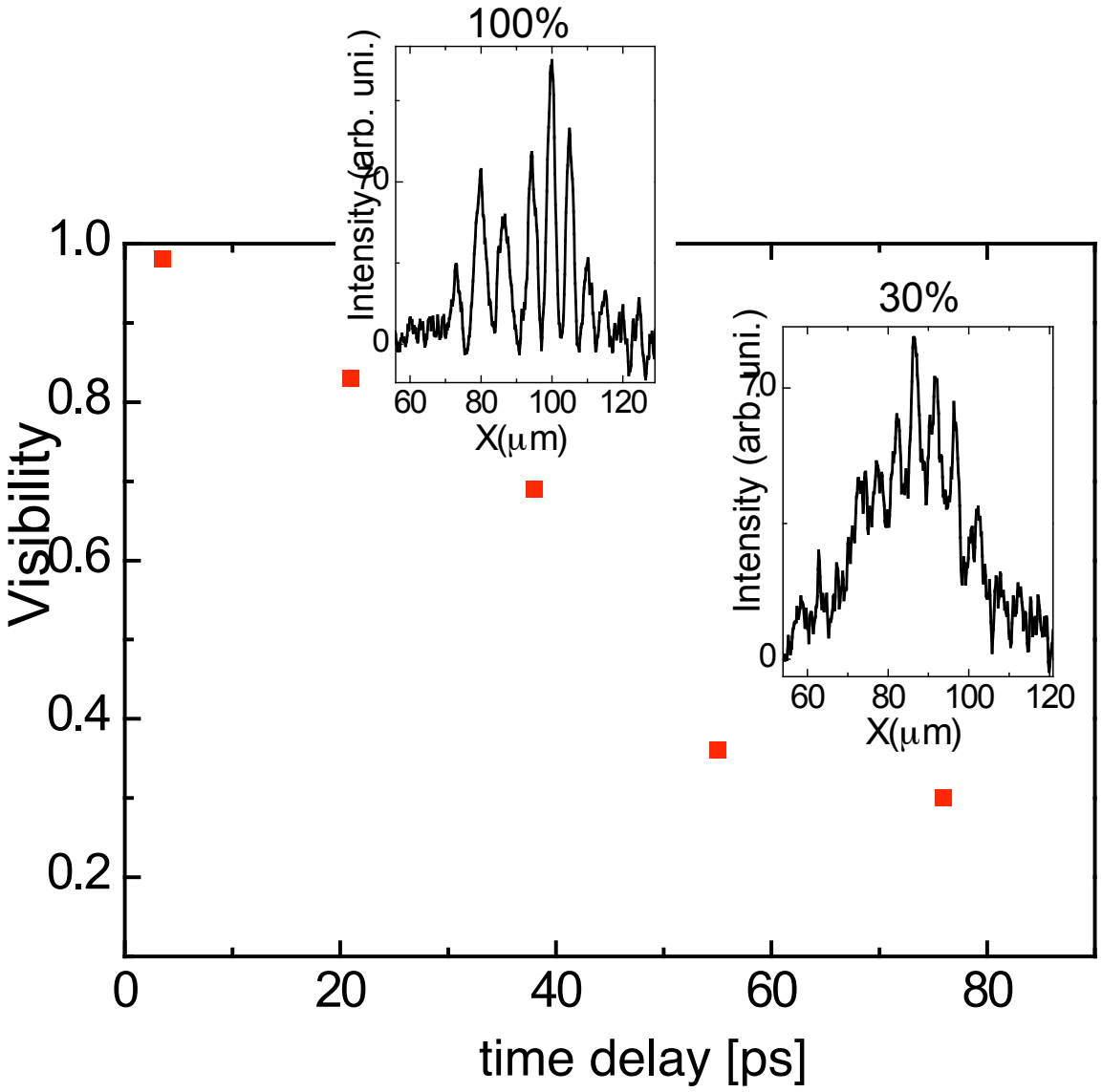
Persistent m=1 vortex

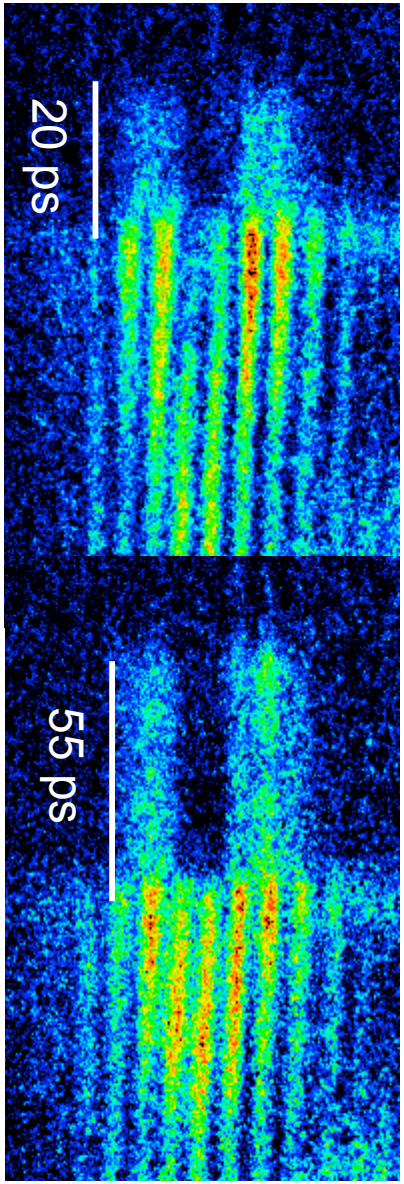


[Sanvitto *et al. cond-mat/0907.2371*]

The vortex lasts for as long as OPO can be sustained (c.f. cold atoms)

Temporal coherence of the signal state



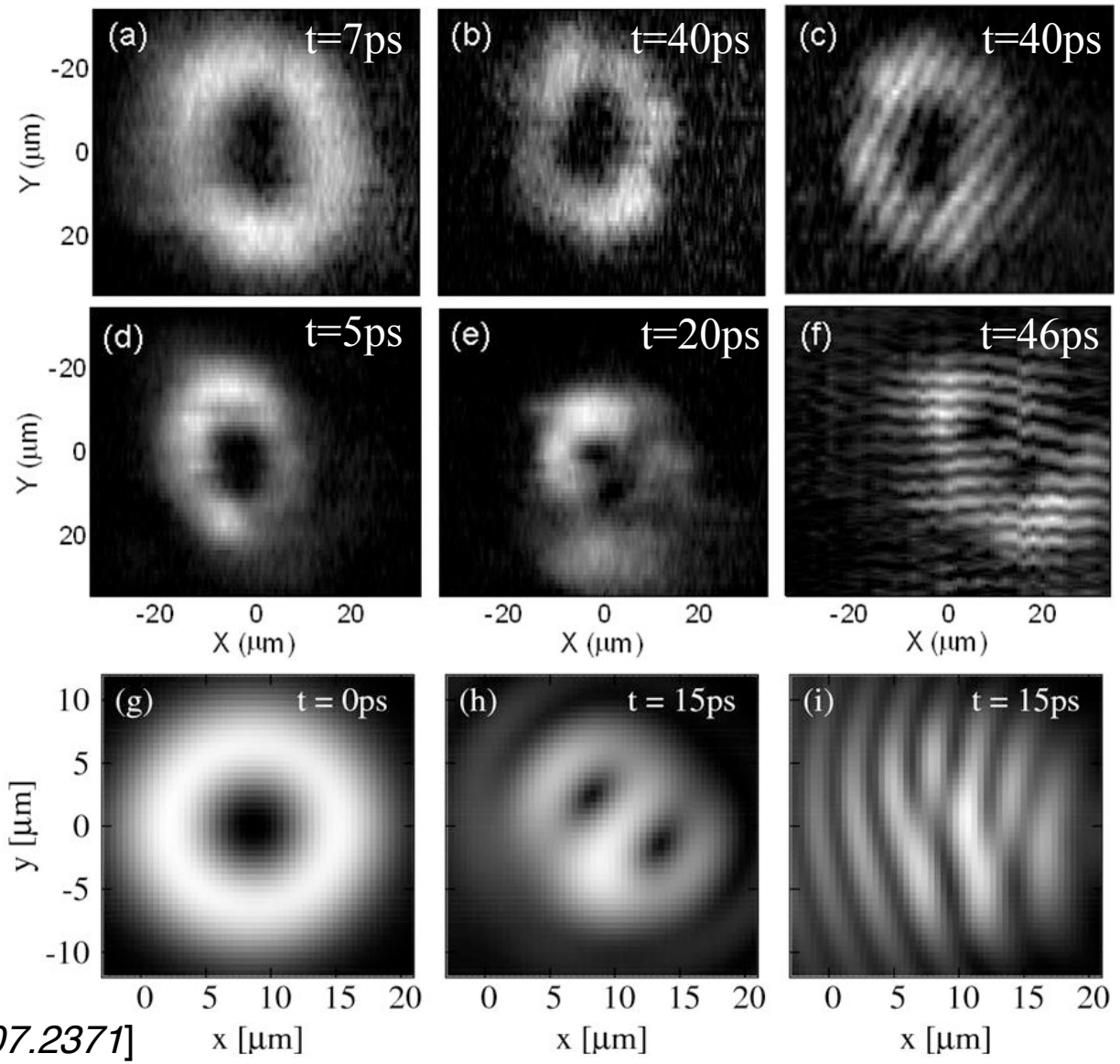


Stability of doubly quantised vortices

experiment
(static signal)

experiment
(moving signal)

theory

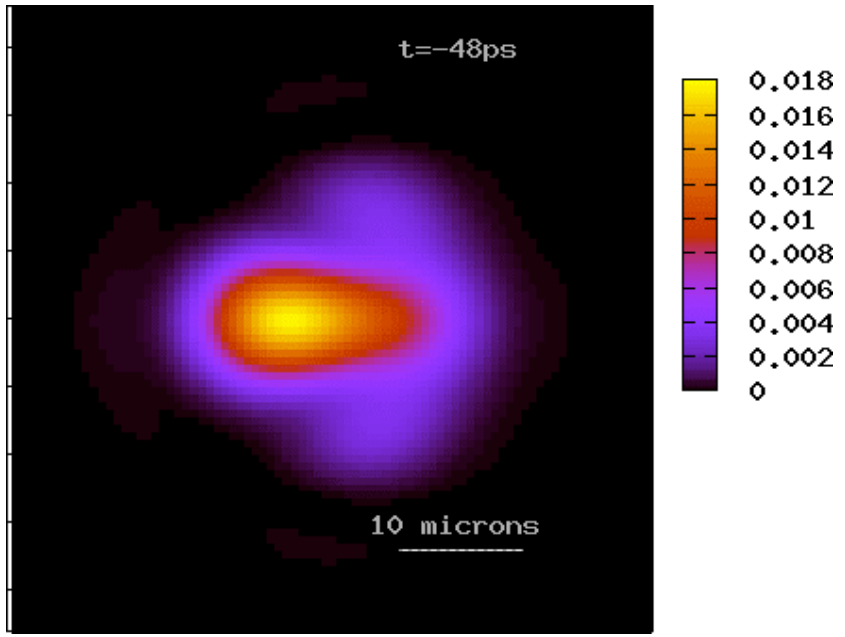


[Sanvitto *et al. cond-mat/0907.2371*]

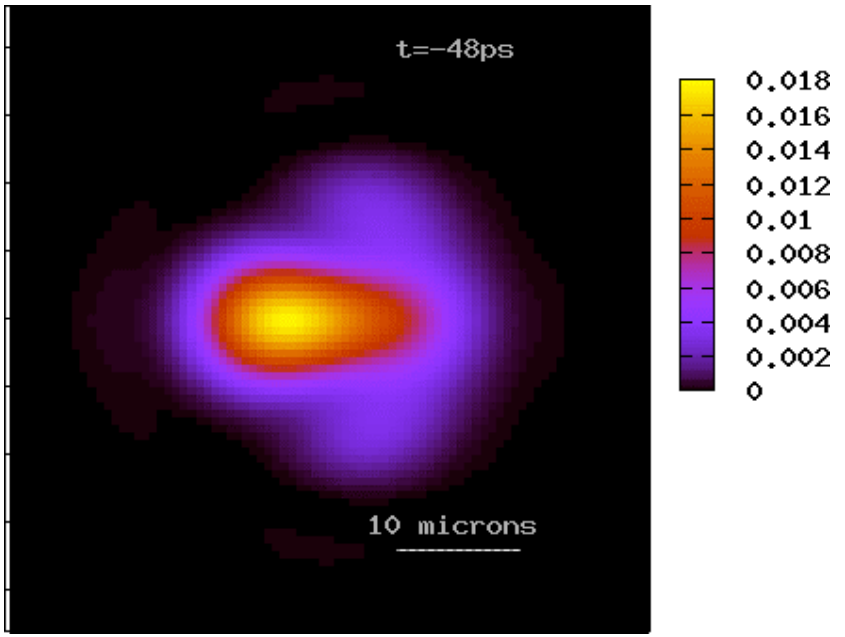
Steady state vortex solutions

- different regime above OPO threshold
- stable steady state vortex solutions may appear in the signal following a transient period after the probe pulse
- stable vortex independent on probe (intensity and size)
- See also: [Whittaker *Superl.&Microstr.* (2007)]
  [Wouters&Savona, arxiv/0904.2966]

weak probe $\sim I_s/5$

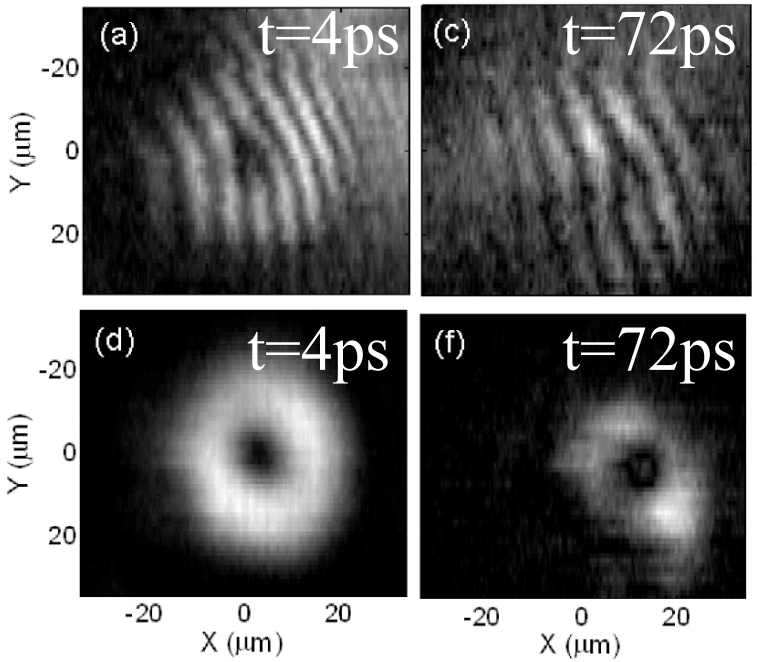


strong probe $\sim 10 I_s\,(f_p = 1.2 f_p^{\mathrm{th}})$



Conclusions

- persistent quantised polariton current in the OPO regime
- stable & unstable doubly quantised vortices
- theory: steady state vortex solutions



SUPERFLUID CHECKLIST		quantised vortices	Landau criterion	metastable persistent flow	equilibrium
	^{4}He/cold atoms BEC	✓	✓	✓	✓
	…				
	polariton condensates (incoherent injected)	✓?	✗	?	✗
	polariton condensates (coherent injected)	✓	✓	✓	✗

Collaboration

- D. Sanvitto, G. Tosi, M. Baudish, C. Tejedor, L. Viña (UAM)
- M. Szymanska (Warwick)
- F. Laussy (Southampton)
- D. Krizhanovskii, M. Skolnick (Sheffield)
- L. Marrucci (Napoli)
- A. Lemaître, J. Bloch (Marcoussis)

Daniele Sanvitto

Marzena Szymanska