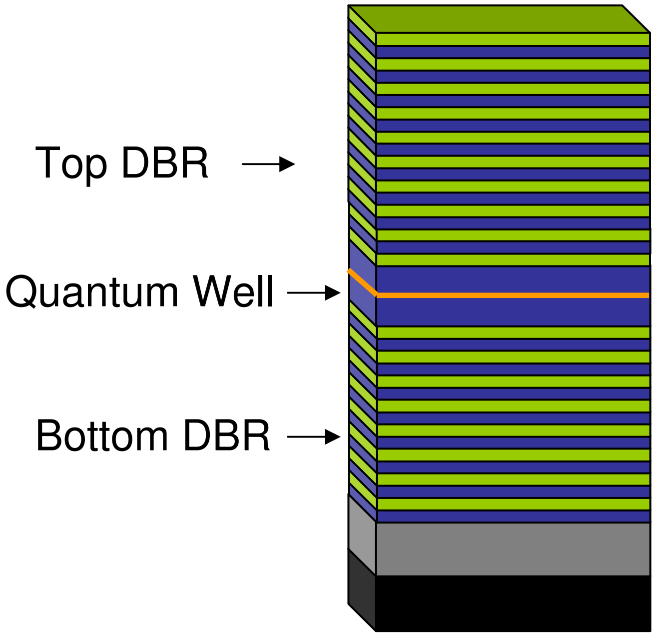
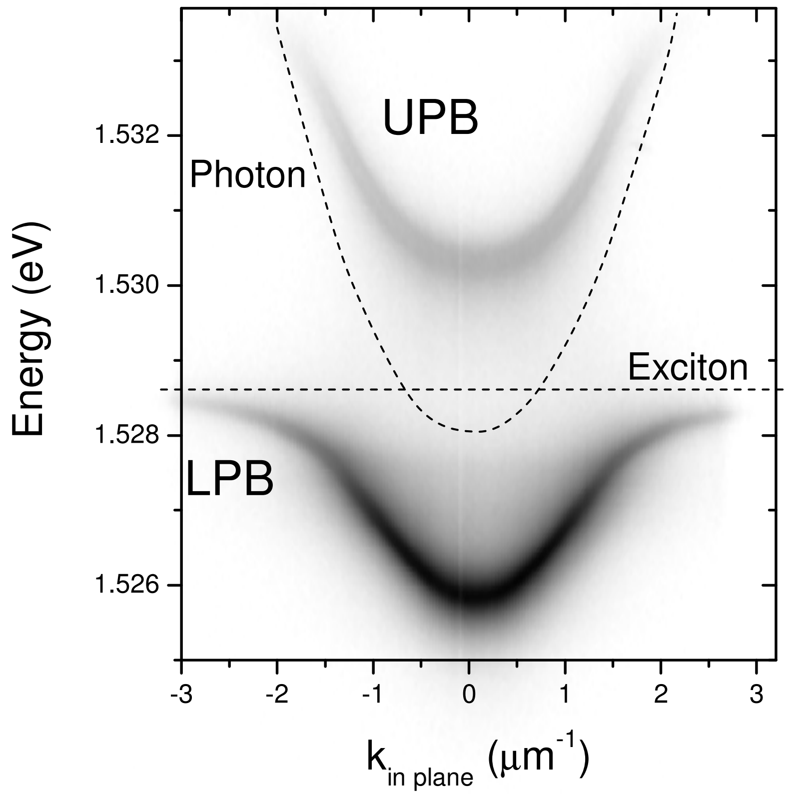
Lattices of quantized vortices in polaritons fluids

Alberto Bramati

Laboratoire Kastler Brossel
Physique quantique et applications

Microcavity Polaritons



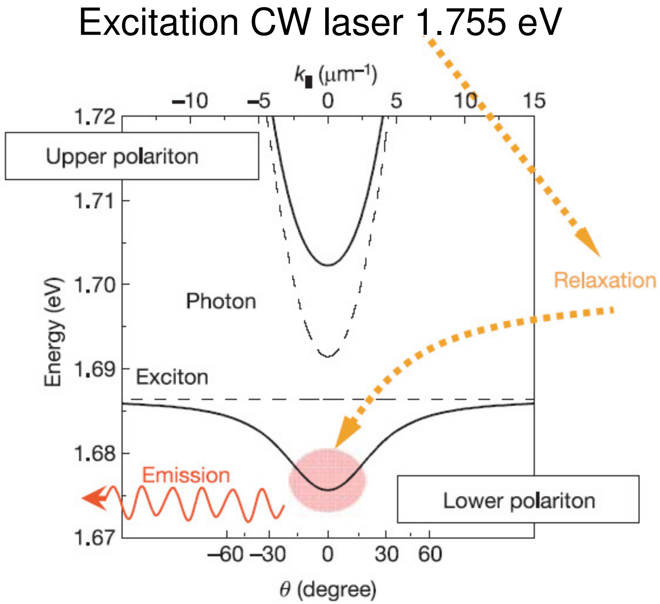


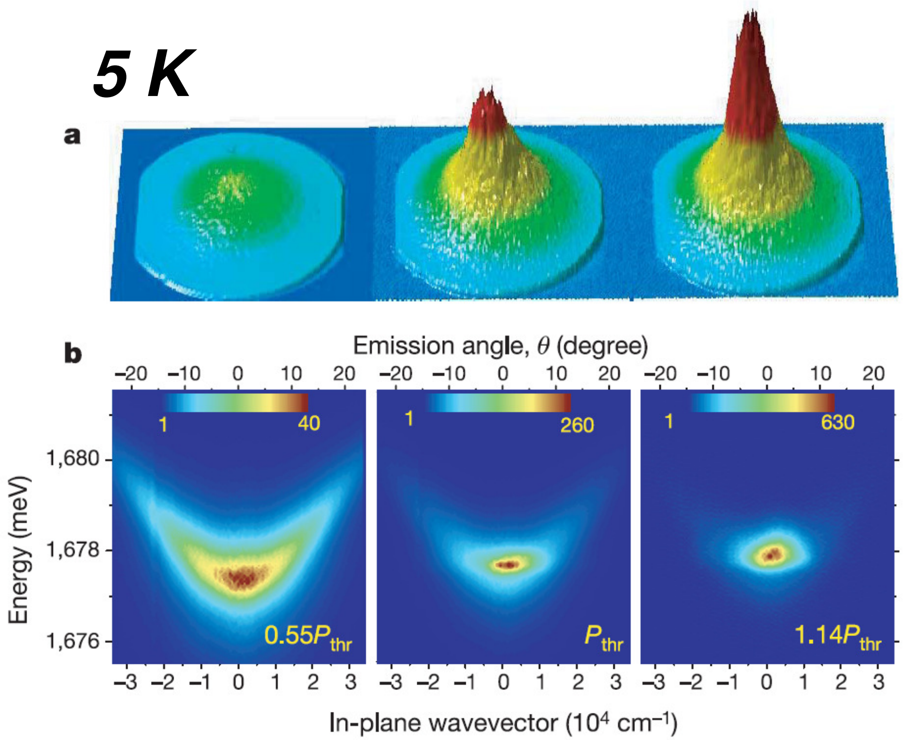
Polaritons: half-light half matter states coming from strong coupling between excitons and photons

Polaritons are weakly interacting composite bosons

An ideal system to study out of equilibrium quantum fluids

Bose Einstein condensation of polaritons



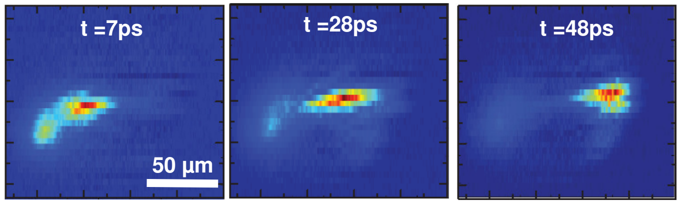


- **2D system**
- Out of equilibrium system **:**
  - Creation and recombination (polariton life time ~5 ps)

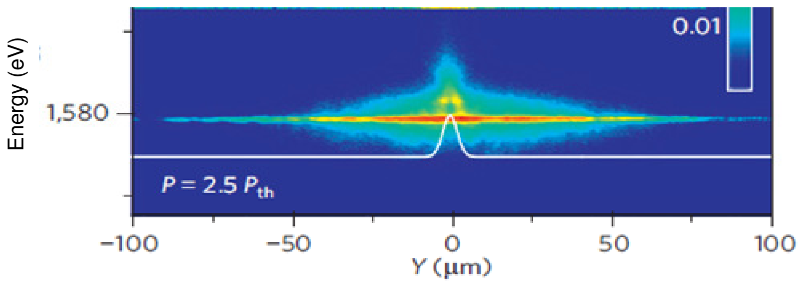
Kasprzak *et al.* Nature*,* **443**, 409 (2006)

Boson quantum fluids: polaritons

Coherent propagation

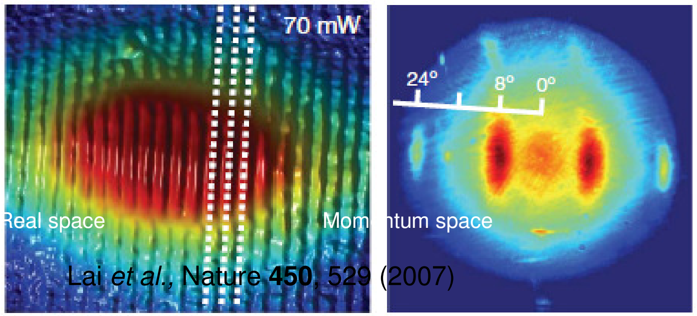


Amo *et al.,* Nature **457**, 295 (2009)



Wertz *et al.,* Nature Phys. **6**, 860 (2010)

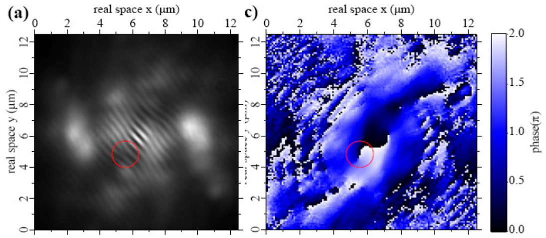
Long-range order phases



Lai *et al.,* Nature **450**, 529 (2007)

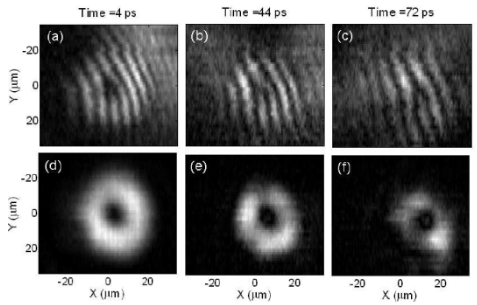
Carusotto&Ciuti, Rev. Mod. Phys.85, 299 (2013)

Vortex and half vortex



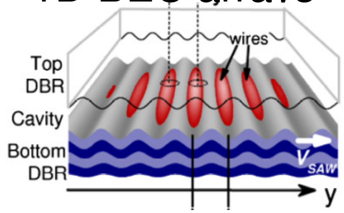
Lagoudakis *et al.*, Nature Phys. **4**, 706 (2008), and Science 326, 974 (2009)
Nardin *et al.*, arXiv:1001.0846v3
Krizhanovskii *et al.*, PRL **104**, 126402 (2010)
Roumpos et al., Nature Phys. **7**, 129 (2010)

Persistent currents



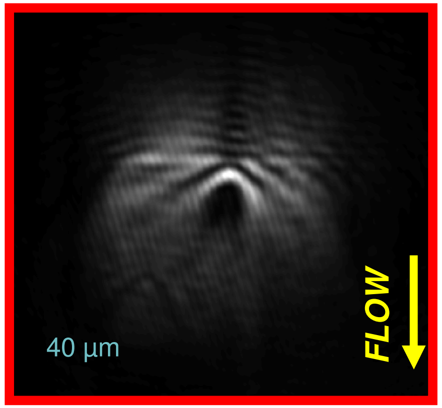
Sanvitto *et al.*, Nature Phys. **6**, 527 (2010)

1D BEC arrays

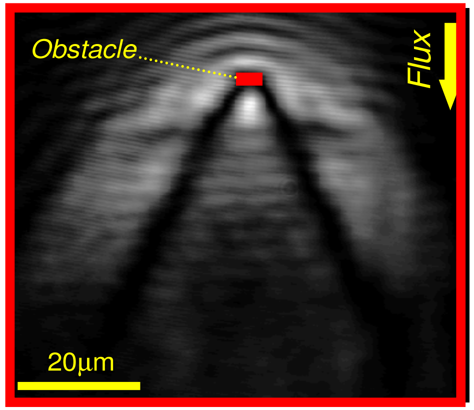


Cerda-Méndez *et al.*, PRL **105**, 116402 (2010)

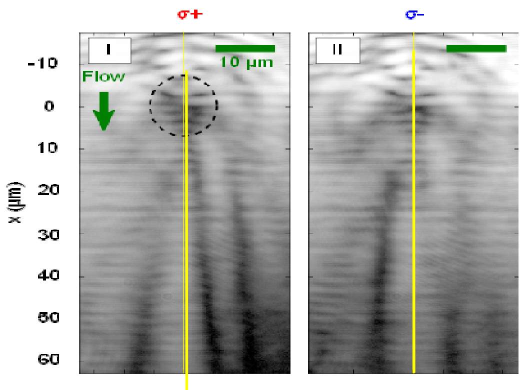
Hydrodynamics of polariton quantum fluids



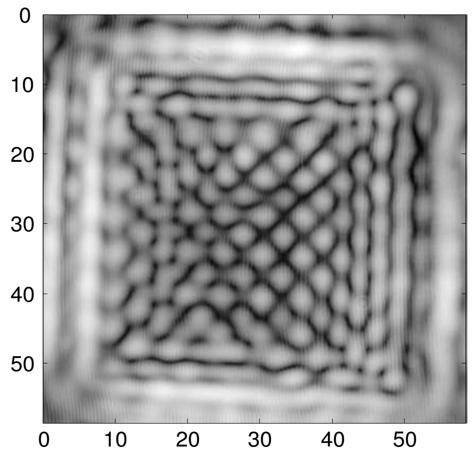
Superfluidity and Cerenkov waves
(*Nature Physics 2009*)



Dark solitons and vortices
(*Science 2011, Nature Photonics 2011*)



Half solitons in spinor quantum fluids
(*Nature Physics 2012*)



Vortex-antivortex lattices in optical traps
(Phys. Rev. B *2014*)

Wave equation for polaritons

Evolution of polaritons in the presence of laser excitation, exciton-exciton interaction and of a defect

$$i\hbar\frac{\partial\psi(\mathbf{x},t)}{\partial t} = \left[E_{LP} - \frac{i\gamma}{2} + V_{\text{def}}(\mathbf{x}) + g|\psi(\mathbf{x},t)|^2\right]\psi(\mathbf{x},t)$$

lower polariton energy

defect

pol-pol interaction

$$+ F_p e^{i(\mathbf{k_p x} - \omega_p t)} e^{(\mathbf{x}-\mathbf{x_0})^2/2\delta_{\mathbf{x}}^2}$$

CW pump laser

Gross-Pitaevskii equation

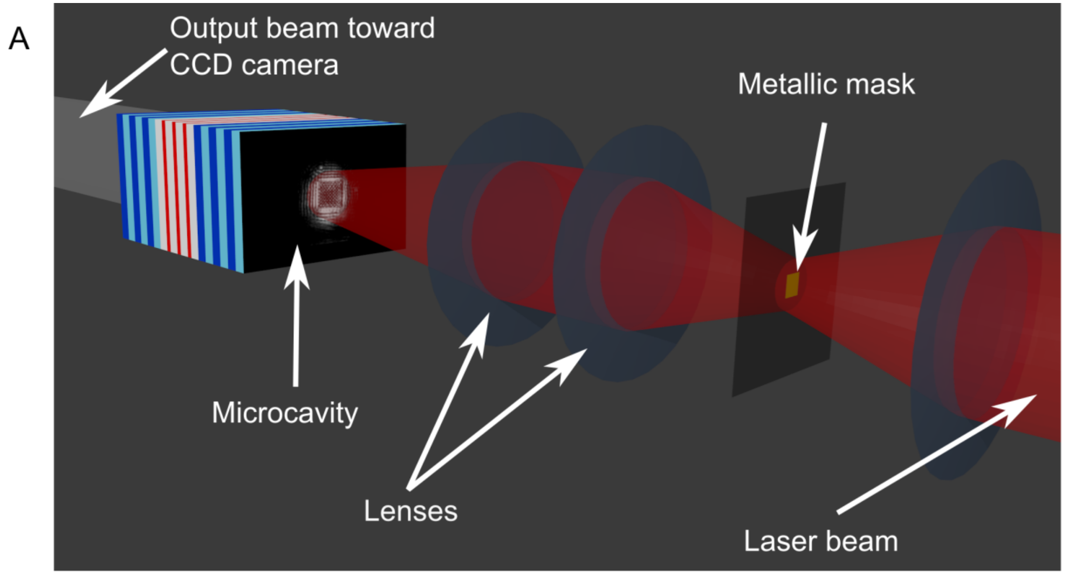
Outline

- Vortex-Antivortex lattices
- Net angular momentum injection: same sign vortex patterns
- Conclusion

Creation of optically controlled traps for polaritons

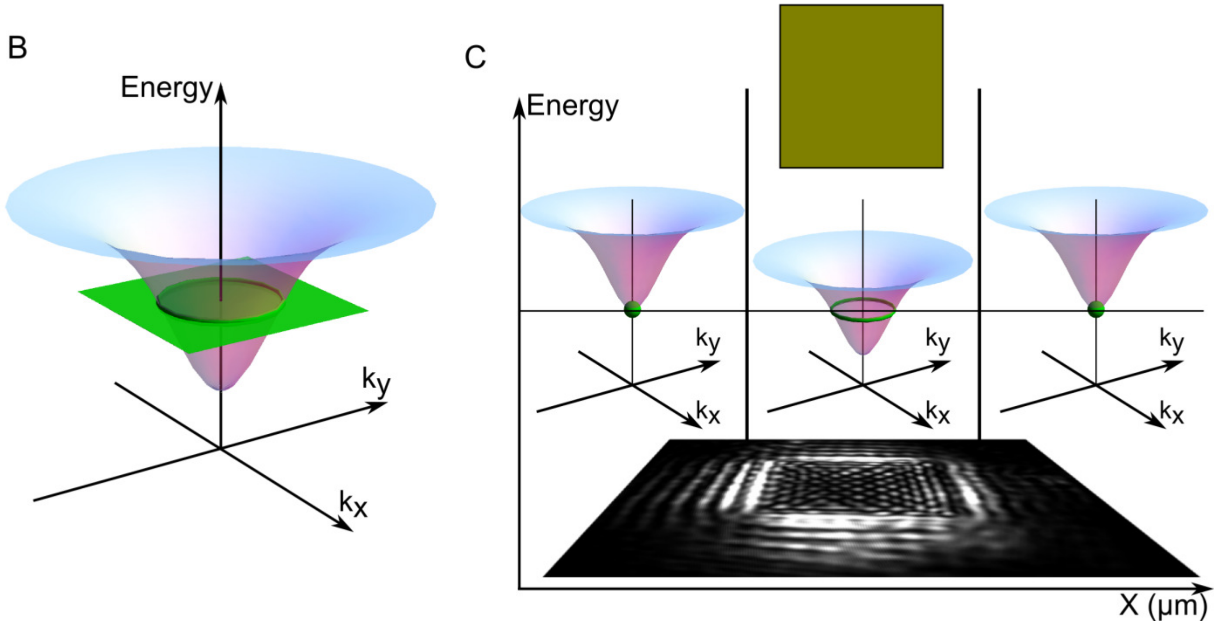
Polariton trap

A mask is put in the center of the beam and imaged on the microcavity



Outside the mask: high polariton density

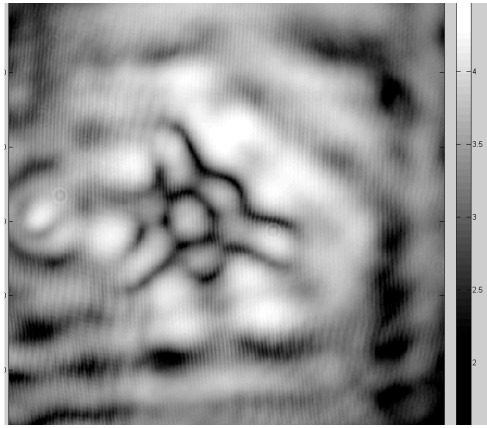
Inside the mask: low polariton density

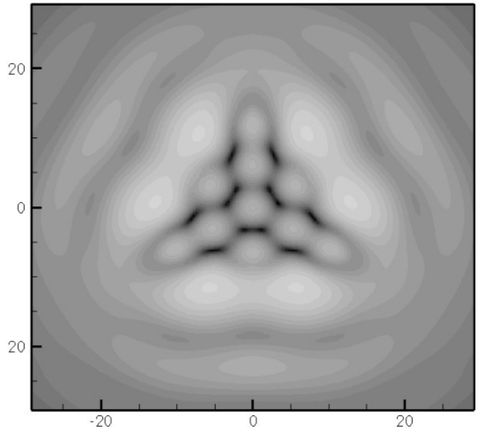


Vortex-antivortex lattices in optical traps

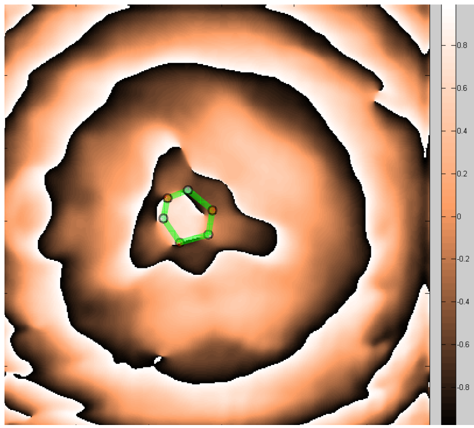
Small triangular trap

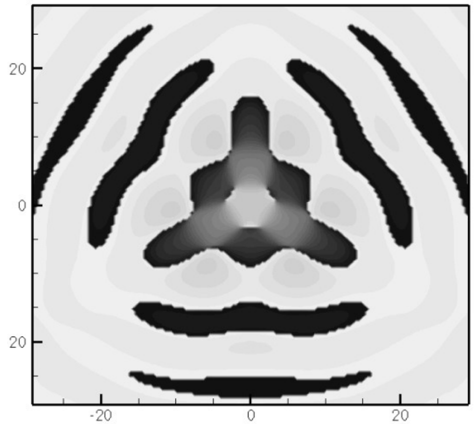
Experiment **Theory**





Polariton density



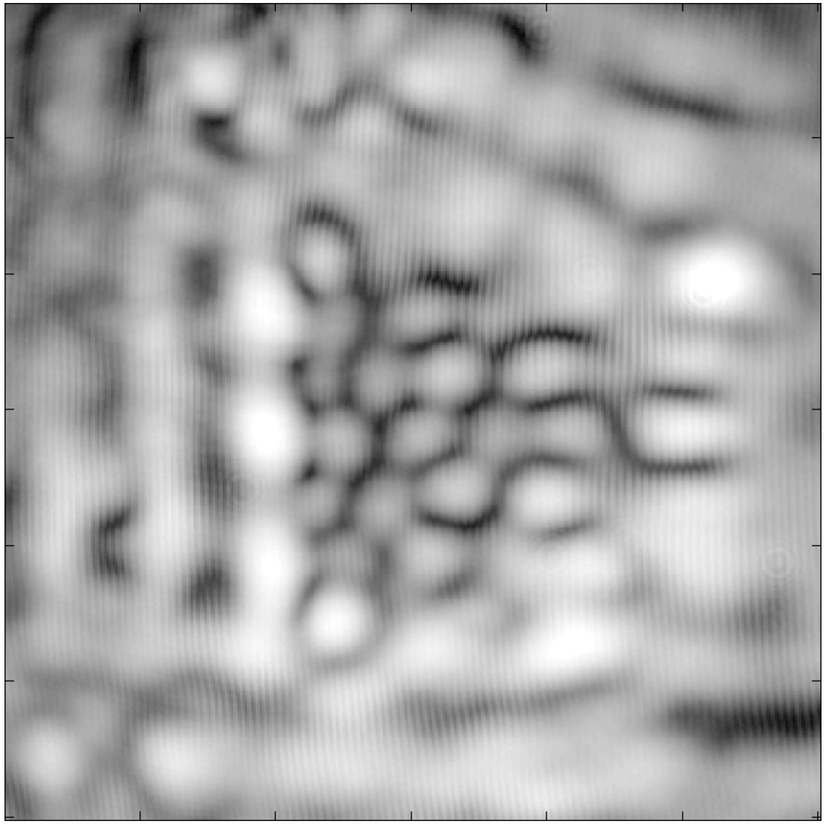


Phase

Lattice shape fixed by the trap geometry

Vortex-antivortex lattices in optical traps

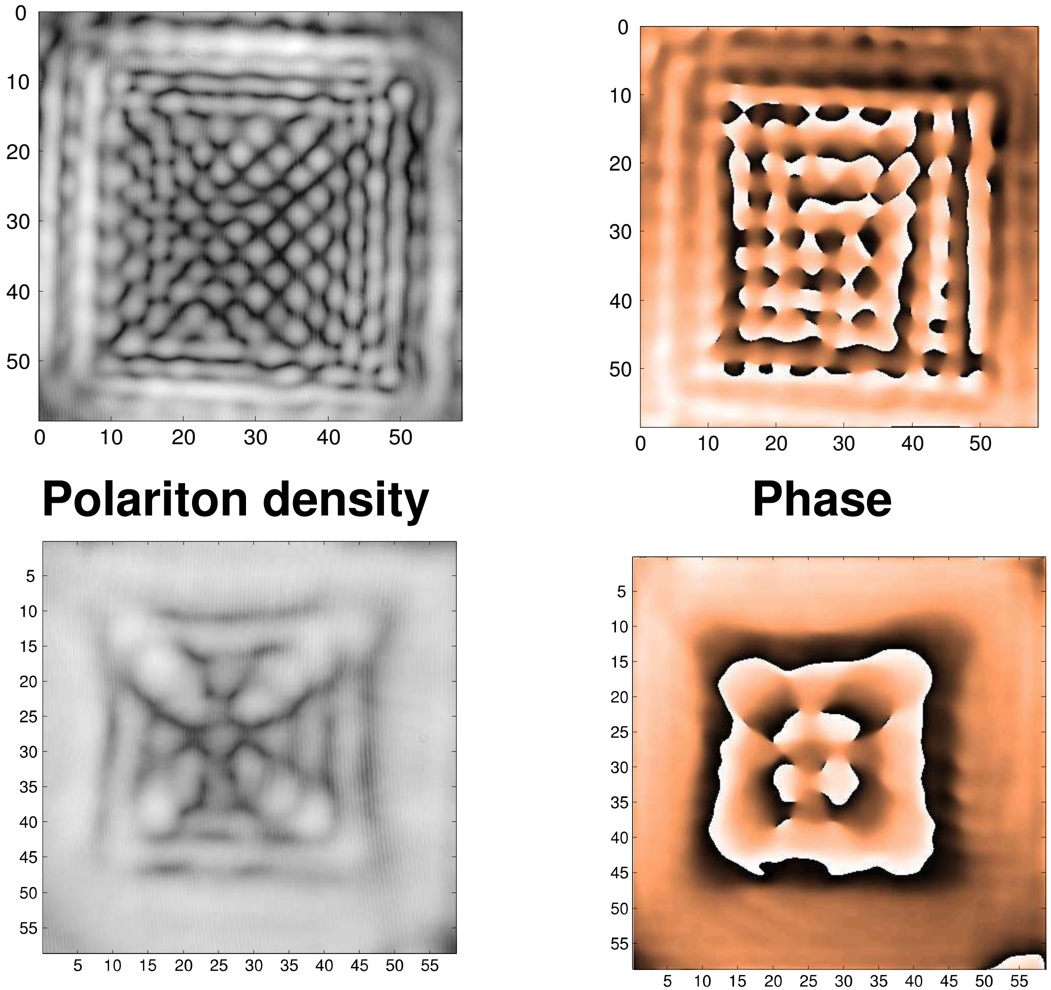
Increasing the size of the trap, a larger number of hexagonal unit cells is formed



Vortex-antivortex lattices in optical traps

Low density

High density



Effects of the interactions (Hivet et al, PRB 2014)

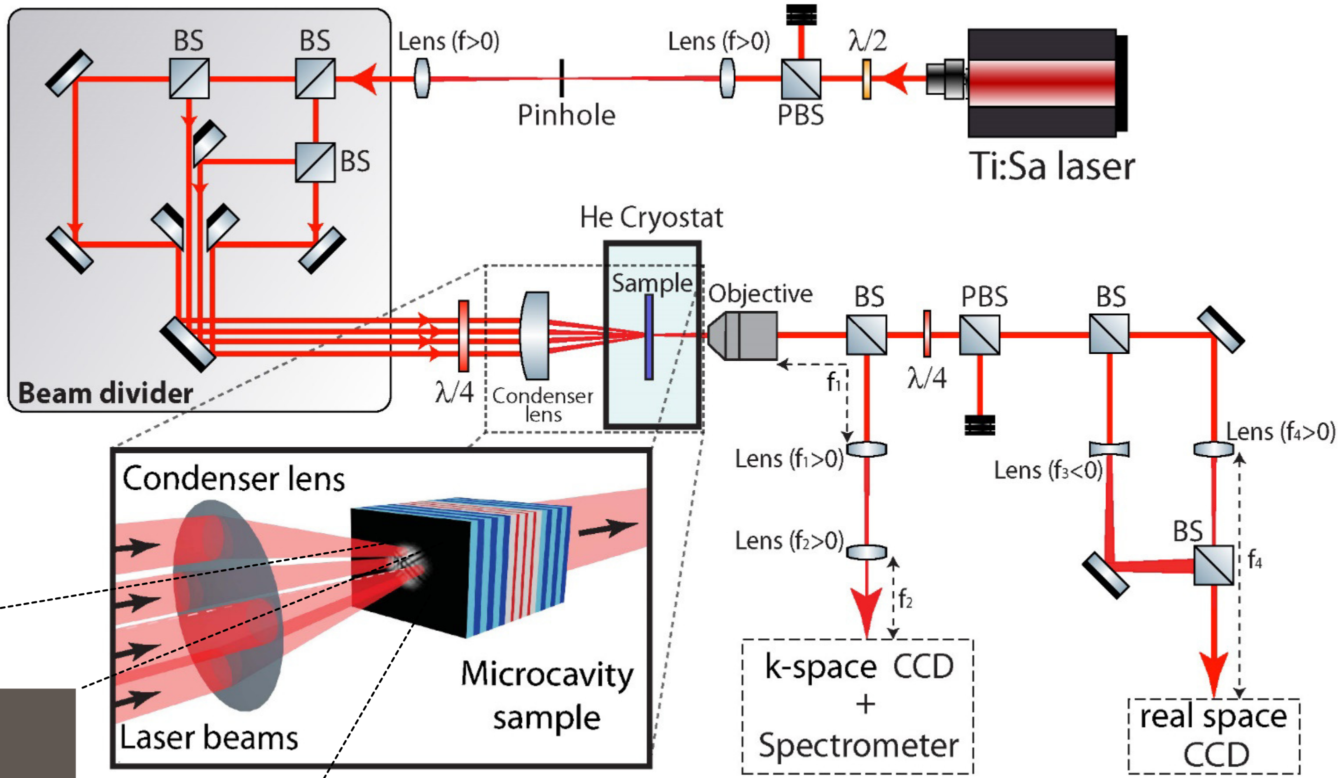
Mask method: limitations

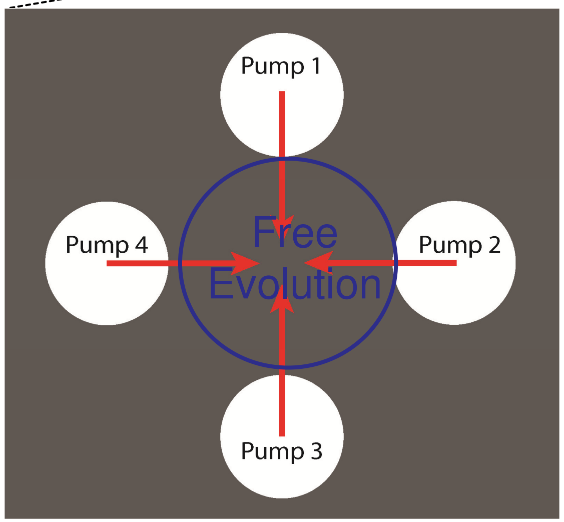
- **The metallic mask induces strong intensity losses**
- **Study of very high density regime is prevented**

➡ A new method, based on a multi-beam approach, is developed

Four-fluids setup

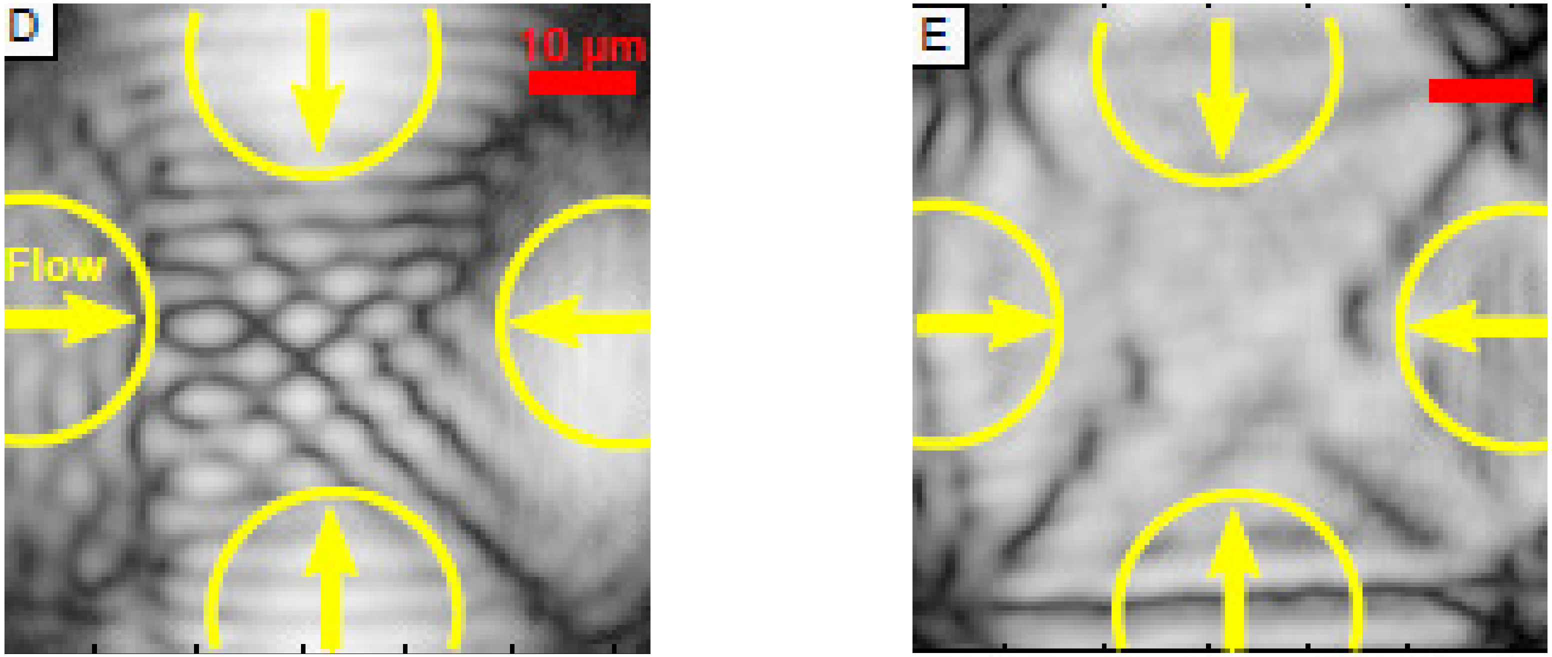
- No angular momentum
- Vortex-antivortex pairs
- Study of the effect of interactions





- Square geometry
- Four converging coherent fluids
- Detection in real space, k-space, energy

Vortex-Antivortex Annihilation



No vortices in the trap

Low density regime

High density regime

Merging of a vortex-antivortex pair

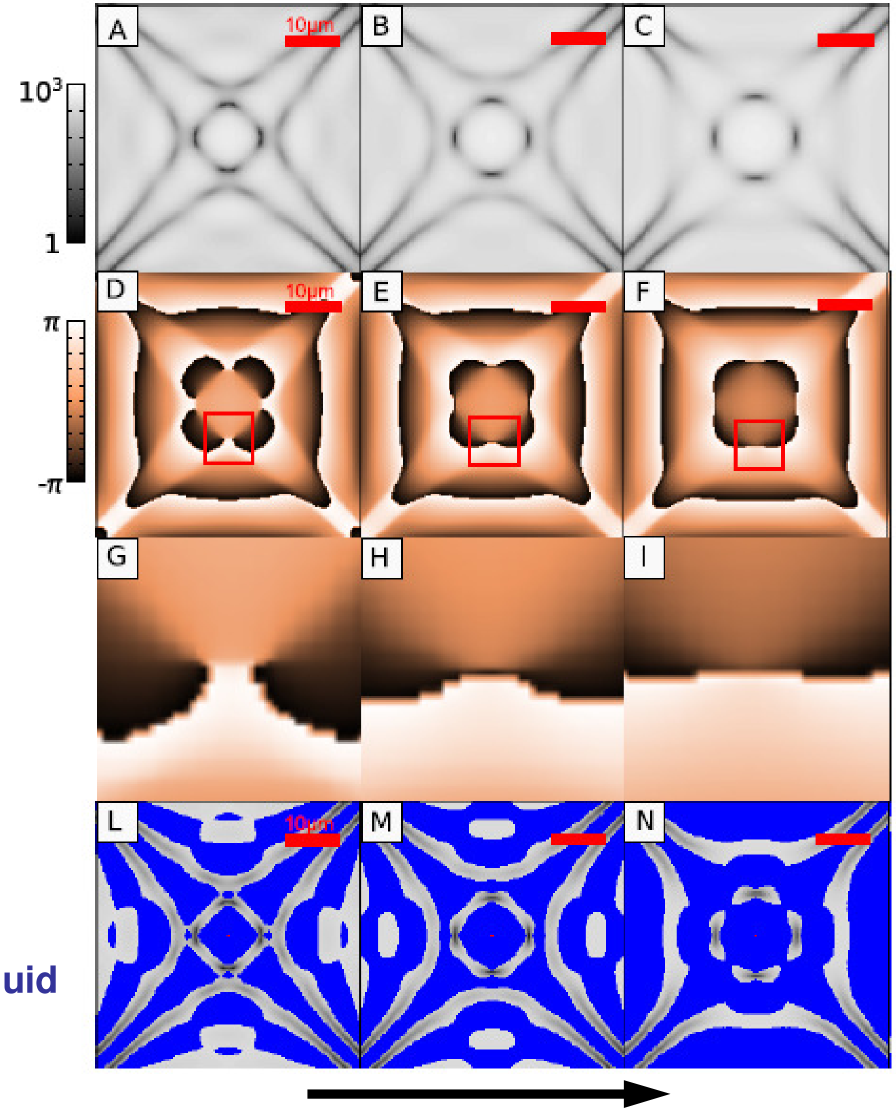
Polariton density

Polariton phase

Zoom of the red square region

Mach charts;

blue regions=subsonic fluid



Polariton density

Simulations:

Vortex-antivortex pairs can exist only in supersonic regions of the quantum fluid

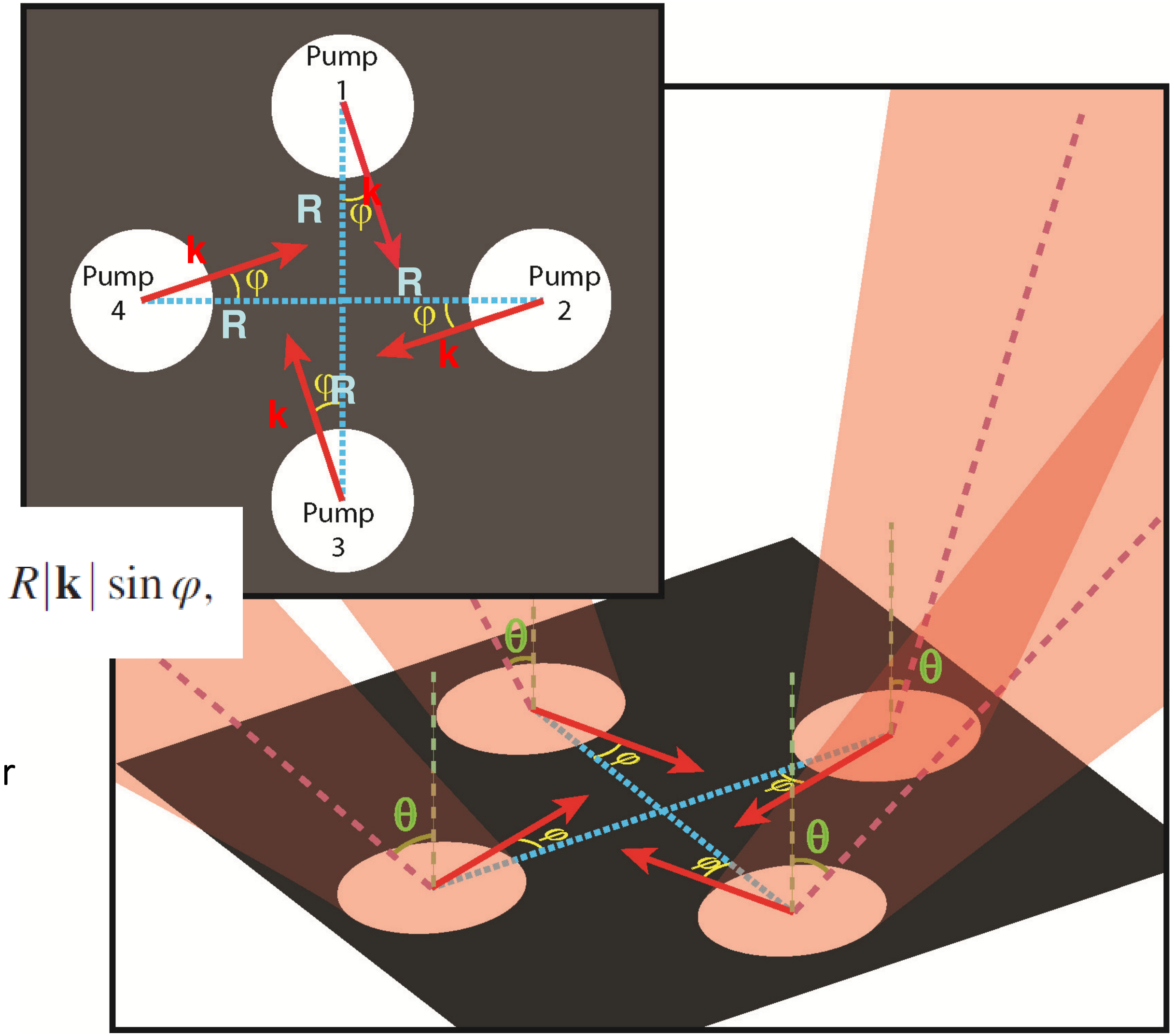
(Cancellieri et al, PRB 2014)

Injection of angular momentum: same sign vortices?

“Stirring” polaritons

- « Four pumps » setup
- The fluids are not directed toward the center
- They inject a classical angular momentum:

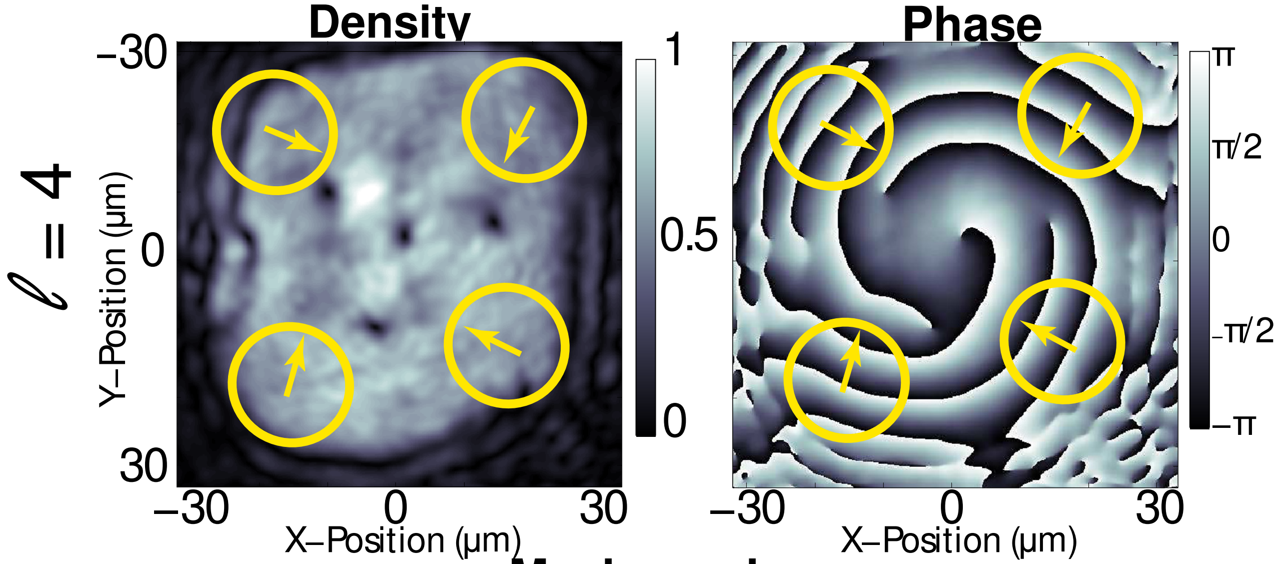
$$\frac{L}{\hbar} = \frac{1}{N} \iint dxdy F^*(\mathbf{r}) \hat{L}_z F(\mathbf{r}) = R|\mathbf{k}| \sin\varphi,$$



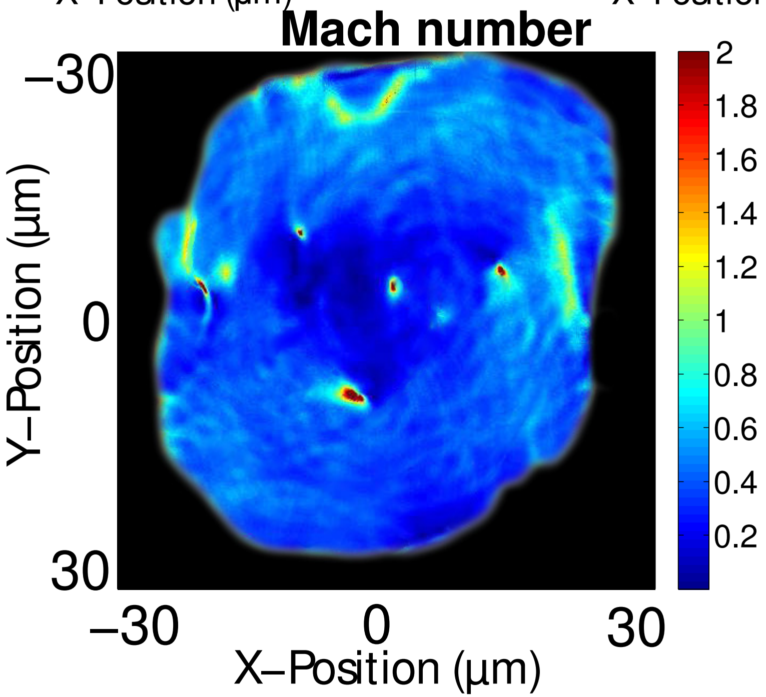
- R is the pump distance to the center
- k is the polariton wave-vector amplitude
- φ is the (in-plane) azimuthal angle

(Boulier et al, PRL 2016)

Nonlinear regime



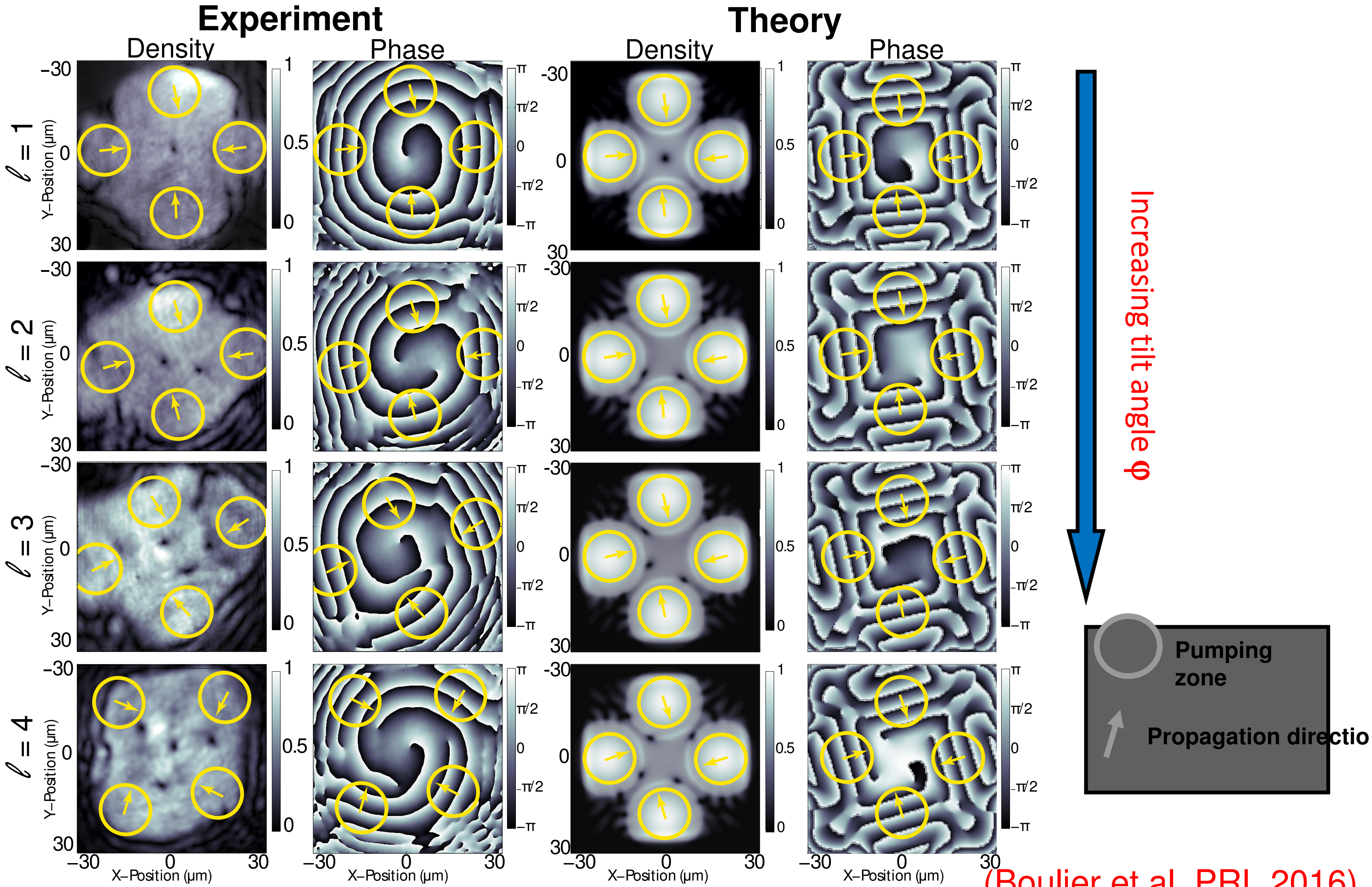
- 4 elementary vortices are observed
- The fluid is subsonic, except inside the vortices



The Mach number $M = \dfrac{v_{fluid}}{v_{sound}}$

diverges at the vortex cores

Nonlinear regime



(Boulier et al, PRL 2016)

Four pumps method: Summary

Counter-propagating beams: vortex-antivortex lattices, merging of vortex-antivortex pairs in supefluid regime

Tilting the pumps injects angular momentum in the system

• Response of the system: in the superfluid regime, a pattern of same-sign vortices is formed

Main Limitation

•The number of injected vortices is limited (up to five in our set up)

➡ A new method, based on phase imprinting allows to increase the number of vortices

Single rotating pump

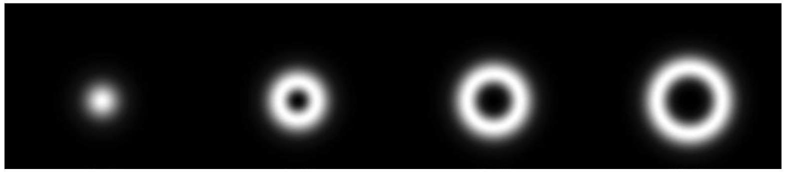
We now use a Laguerre-Gaussian beam

– Cylindrical-symmetric modes

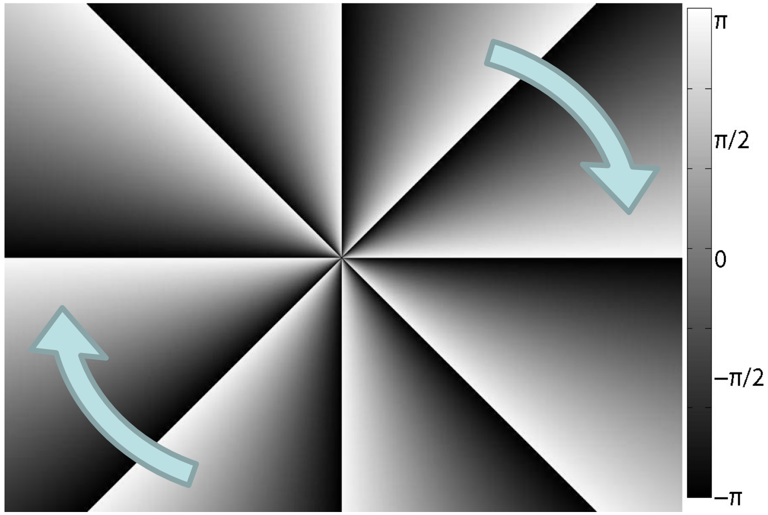
– Ring profile

– Carrying a Orbital Angular momentum (vortex with topological charge l)

$$u_p^\ell(r,\phi) \propto r^\ell L_p^\ell(2r^2/w^2)\, e^{-r^2/w^2}\; e^{-i\ell\phi}$$



l=0 1 2 3



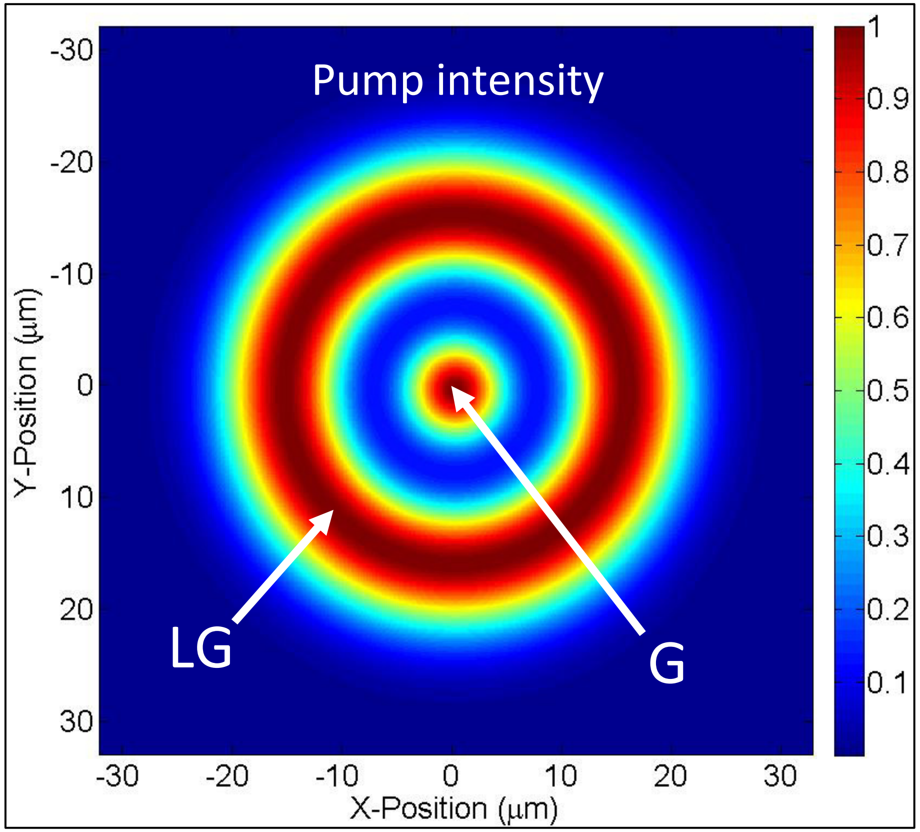
l=8 (phase)

Such a pump creates a rotating ring-shaped polariton fluid

Vortex ring: injection method

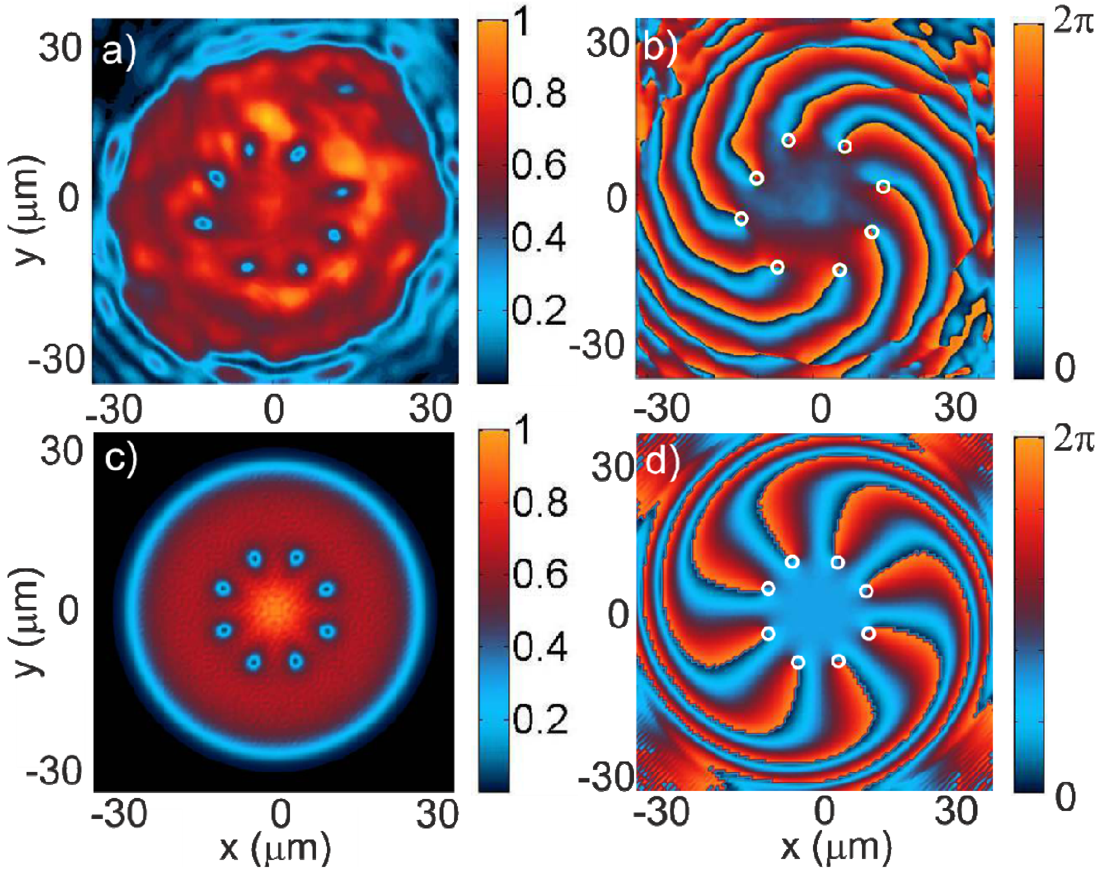
Injection scheme:

- **Gaussian central pump (zero angular momentum)**
- **Laguerre-Gauss beam (*l* = 8)**



Collaboration with Malpuech's group at LASMEA, Clermont-Ferrand

High density regime: Annular vortex chain

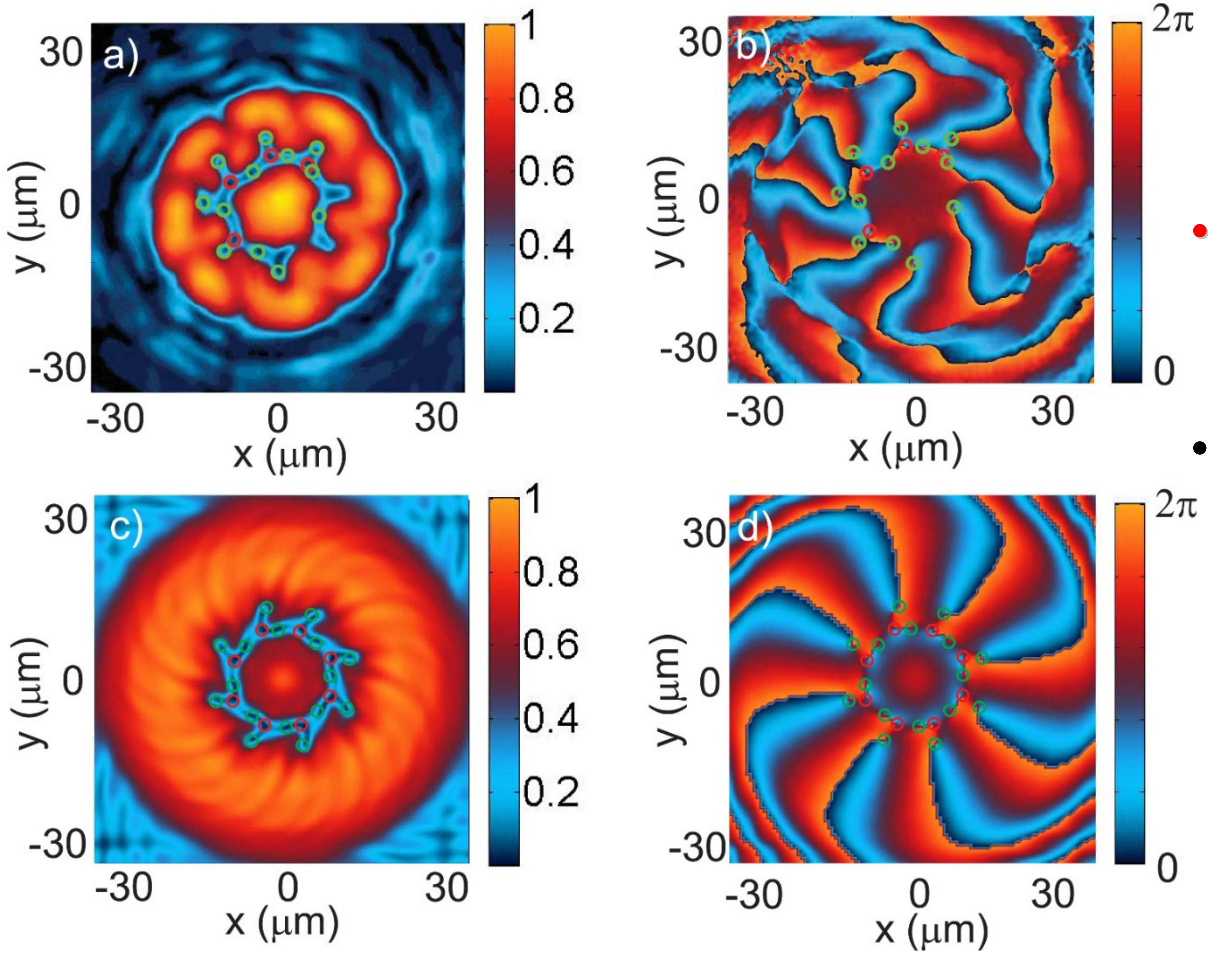


- Injection of **non zero angular momentum:** Laguerre-Gauss beam
- **Control of vortex position** via additional Gaussian beam at the center
- A **chain of same sign** vortices is formed

- **Azimuthal vortex position fixed, radial position free: the ring radius increases with density**
  - Not possible for optical interferences

Boulier et al, Scientific Reports 2015

Phase freedom: Hydrodynamical instabilities



- Hydrodynamical instabilities appear
- Formation of vortex-antivortex pairs inside the ring

Boulier et al, Scientific Reports 2015

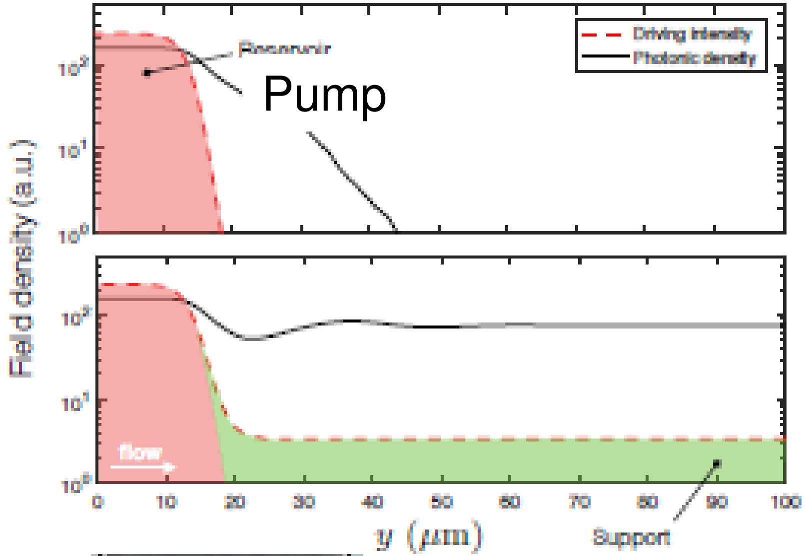
Conclusion

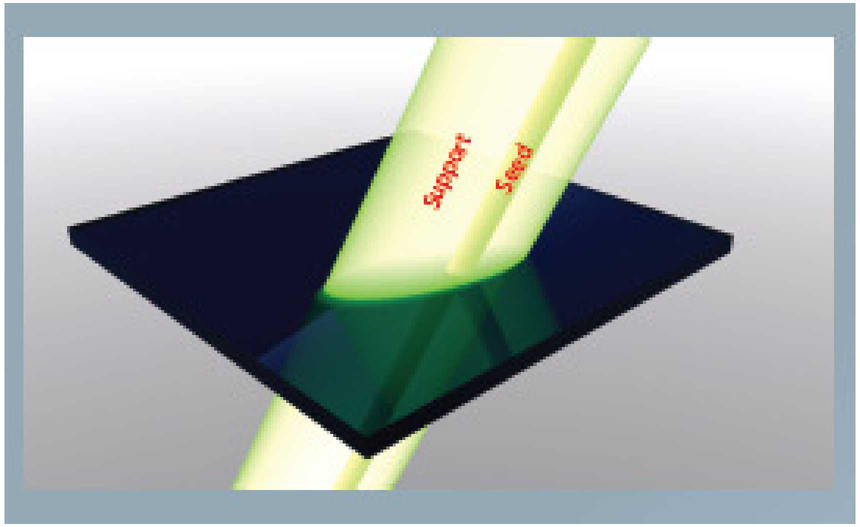
- Successful **injection of a controlled angular momentum** in 2D polariton superfluid

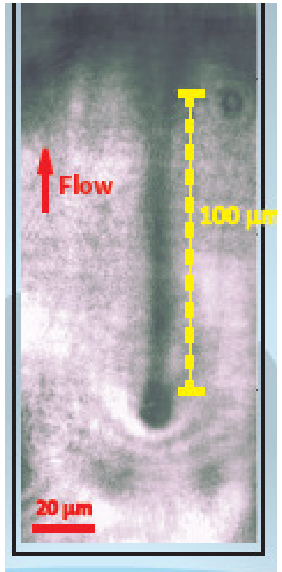
- Observation of multiple **elementary vortices of the same sign,** ordered in a ring

- Polariton phase free to evolve
  - **Quantum hydrodynamics** **dominates** in the high density regime

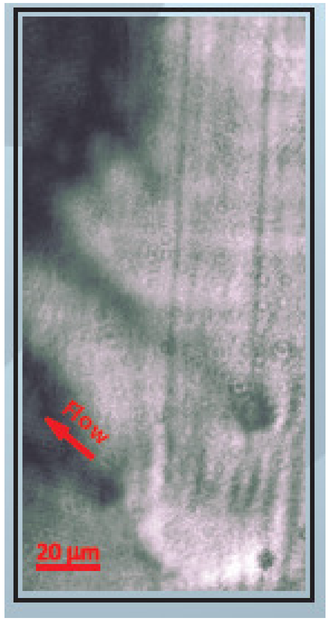
Outlook: Pump and support beam







Extended propagation distance of the topological excitations



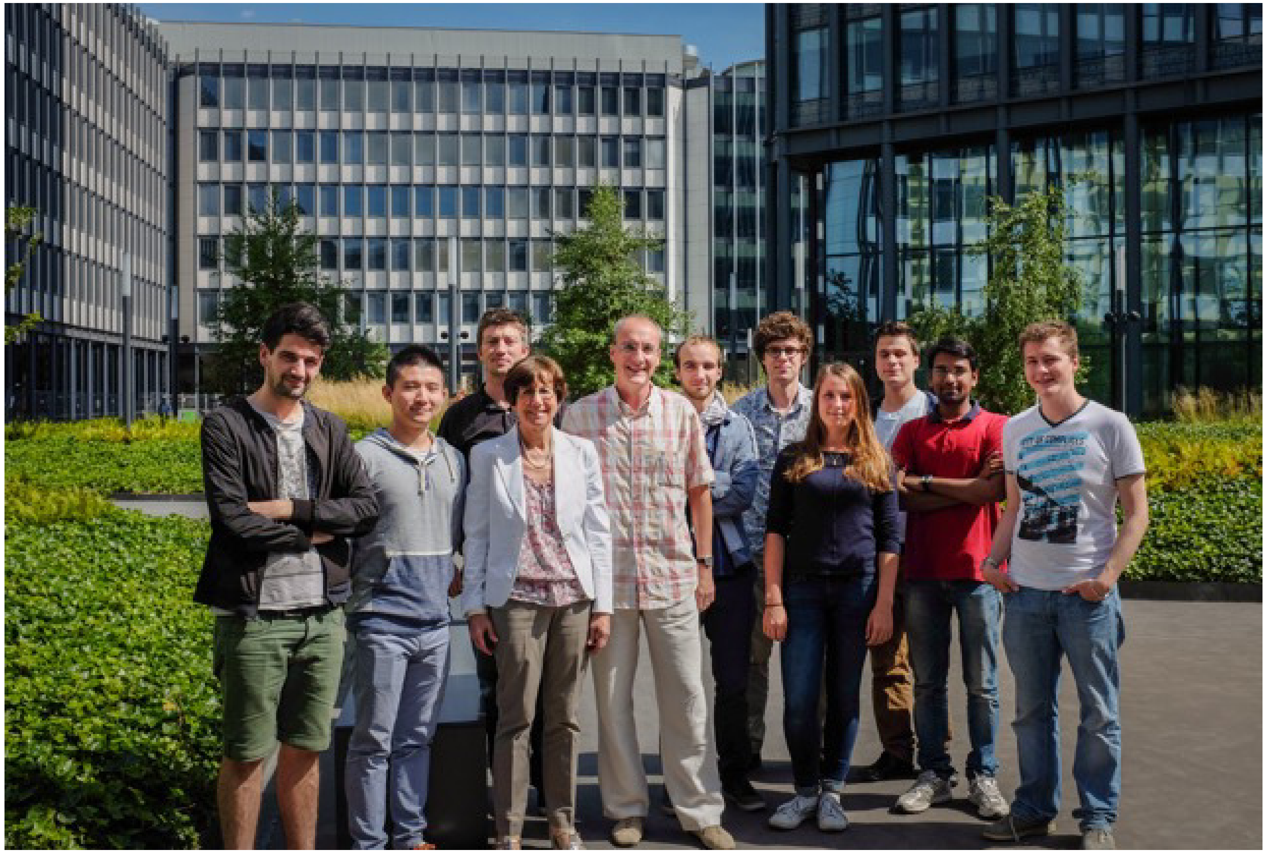
Control of the propagation direction of the topological excitations

Interesting technique to study the interactions between topological excitations

The team

Permanent Staff: **A. Bramati, Q. Glorieux, E. Giacobino**

PhD Students, PostDocs :
T. Boulier, R. Hivet, N. Sangouard, E. Cancellieri, S. Pigeon, G. Lerario



Collaborations

EXPERIMENTS

Lab. C2N

J. Bloch, A. Amo

CNR Lab., Lecce

D. Sanvitto

Lab. LPA, Paris

J.Tignon

EPFL, Lausanne

R. Houdré

THEORY

Lab. MPQ, Paris

C. Ciuti

University of Trento

I. Carusotto

University of Southampton

A. Kavokin

Lab. LASMEA, Clermont Ferrand

G. Malpuech

ÉCOLE DE PHYSIQUE
des HOUCHES

UNIVERSITÉ
Grenoble
Alpes