Test

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

FNSNF FONDS NATIONAL SUISSE DE LA RECHERCHE SCIENTIFIQUE

quantum photonics National Centre of Competence in Research

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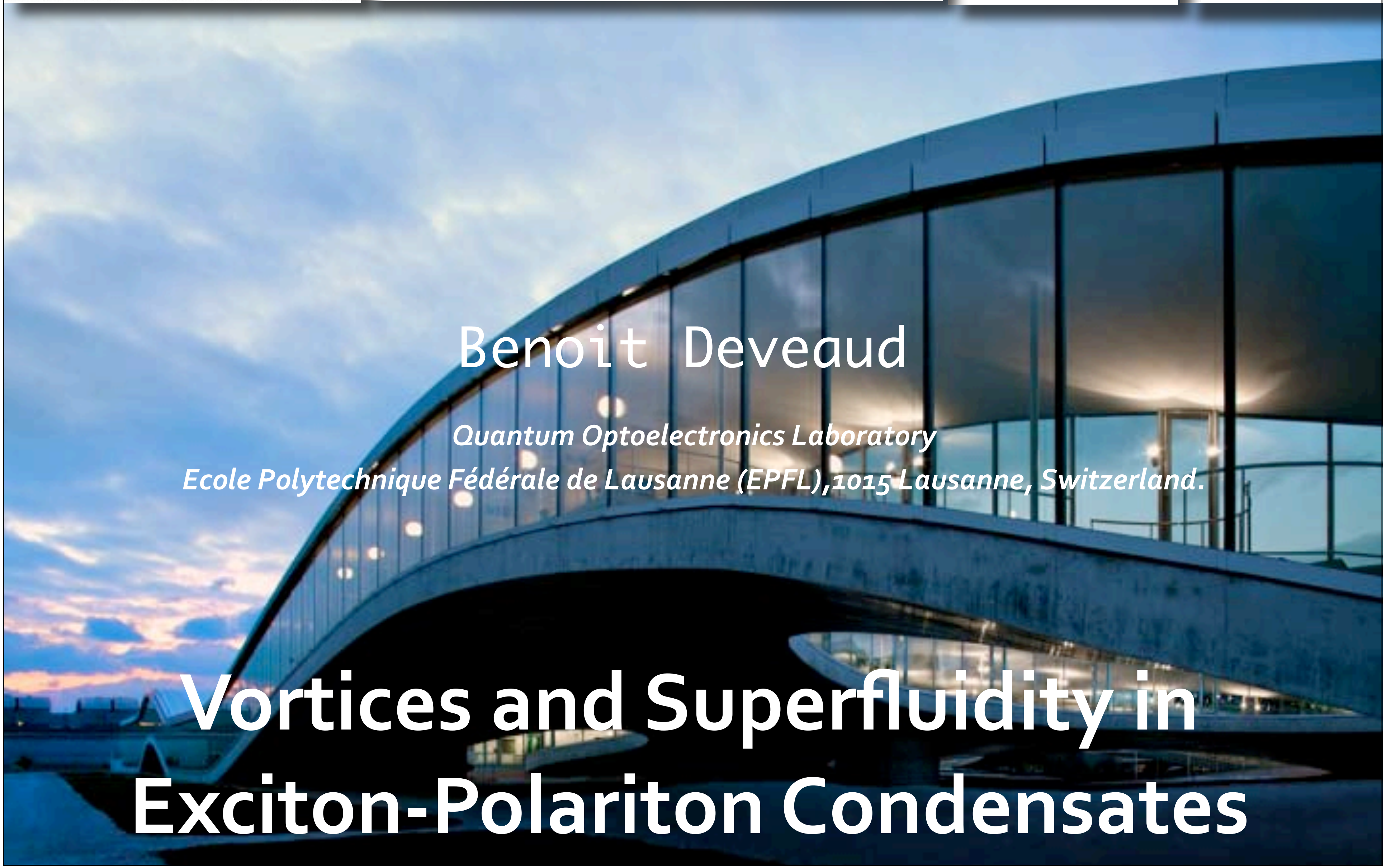


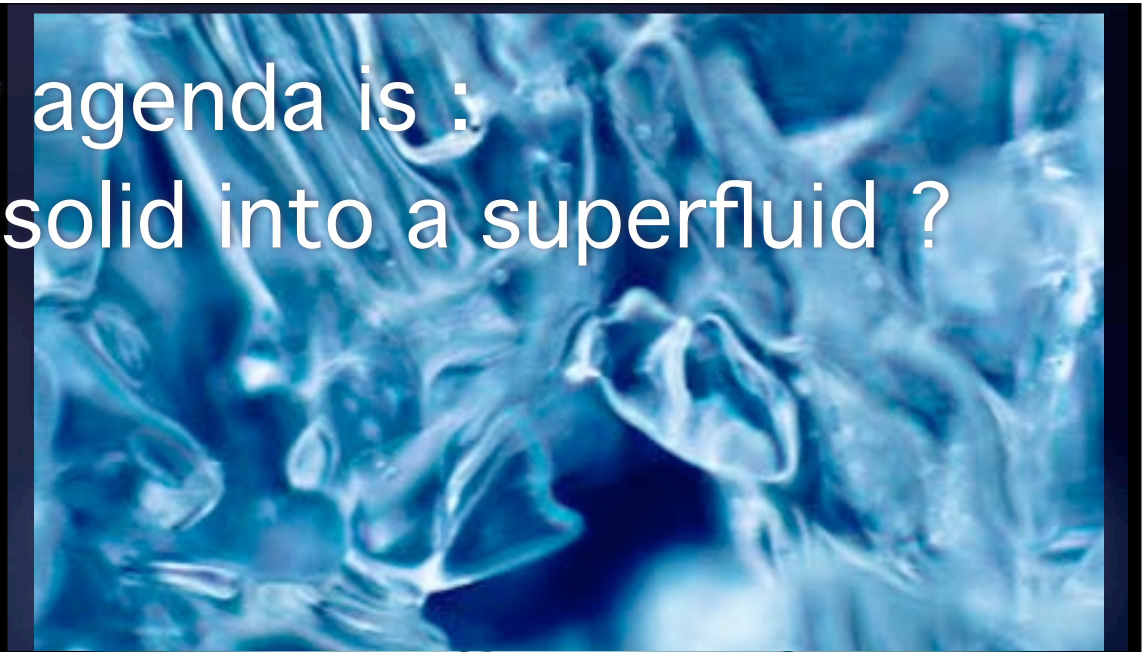
Benoit Deveaud

Quantum Optoelectronics Laboratory

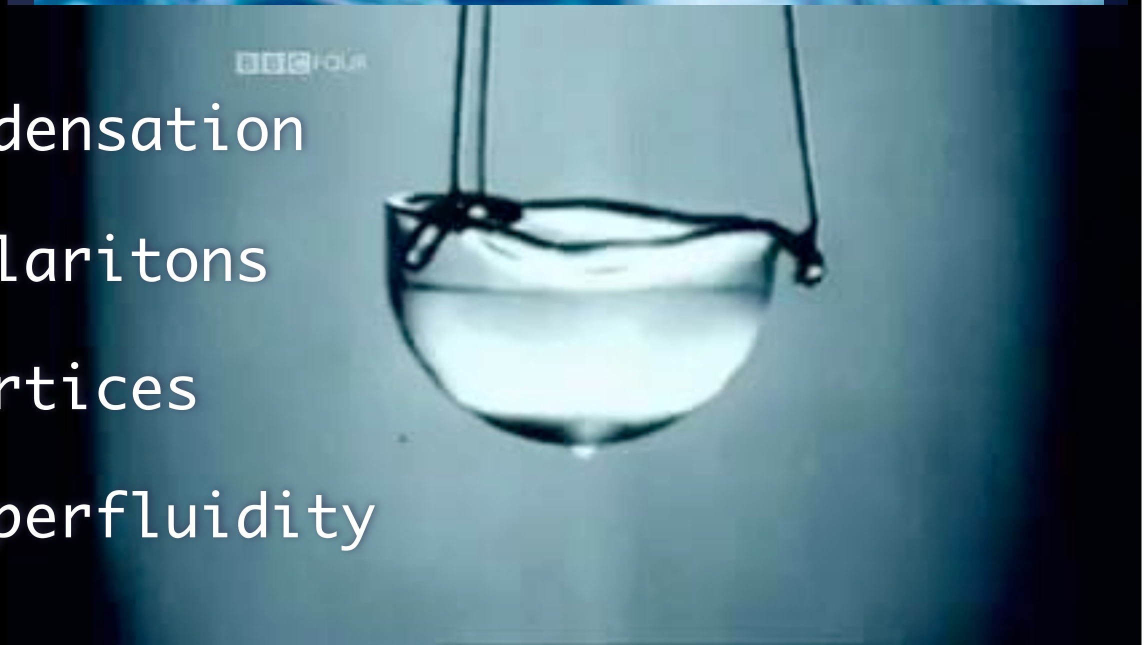
Ecole Polytechnique Fédérale de Lausanne (EPFL),1015 Lausanne, Switzerland.

Vortices and Superfluidity in Exciton-Polariton Condensates

My agenda is :
How to turn a solid into a superfluid ?



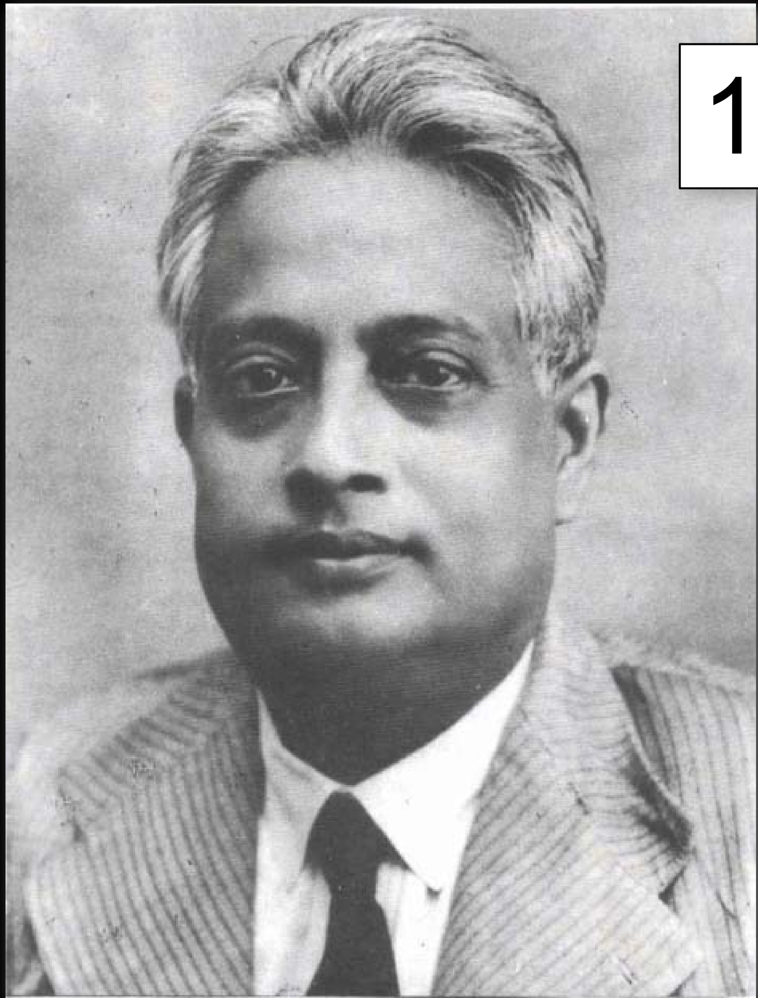
- Bose Einstein condensation
- A few words on polaritons
- Polaritons and vortices
- Polaritons and superfluidity
- What's next?



Superfluid Helium

Bose Einstein condensation

1924



Satyendra Nath Bose

Albert Einstein

The fifth state of matter

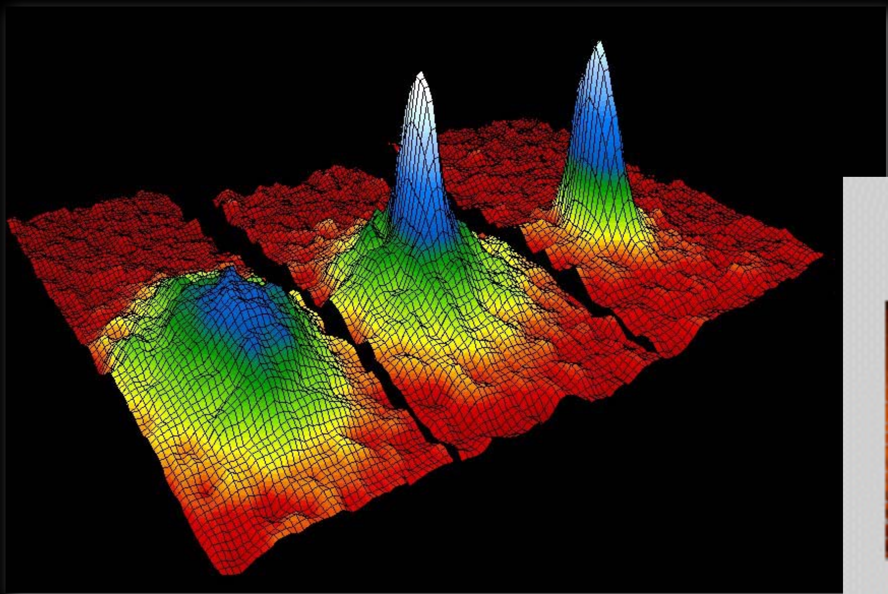
- Integer spin particles,
  - ex. He Atoms
- Low enough temperature,
  - Less than 1 μK for Rubidium
- High enough density
- All atoms in the same quantum state
- Amazing properties.

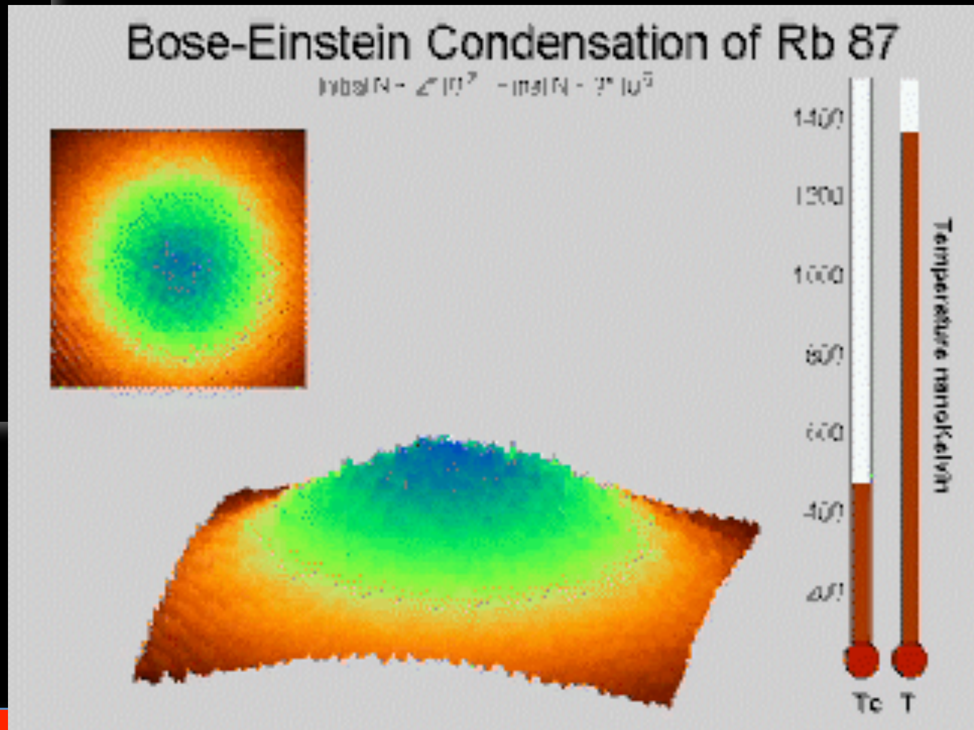
It took 70 years to observe what Bose & Einstein foresaw

It does not matter how slowly you go so long as you do not stop.

Confucius 孔子

Bose Einstein condensation of Rubidium atoms





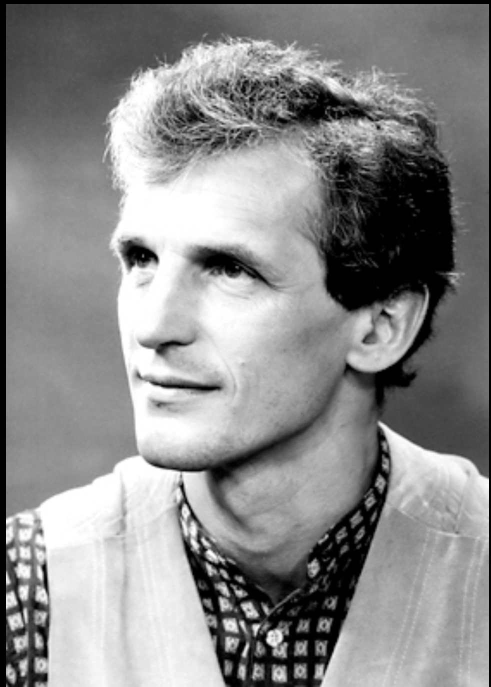
- Observation of speed distribution

Science

Cornell et al. Science **269**, 198 (1995)

Physics Nobel prize 2001

Eric Cornell



Wolfgang Ketterle

Carl Wieman

"for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates".

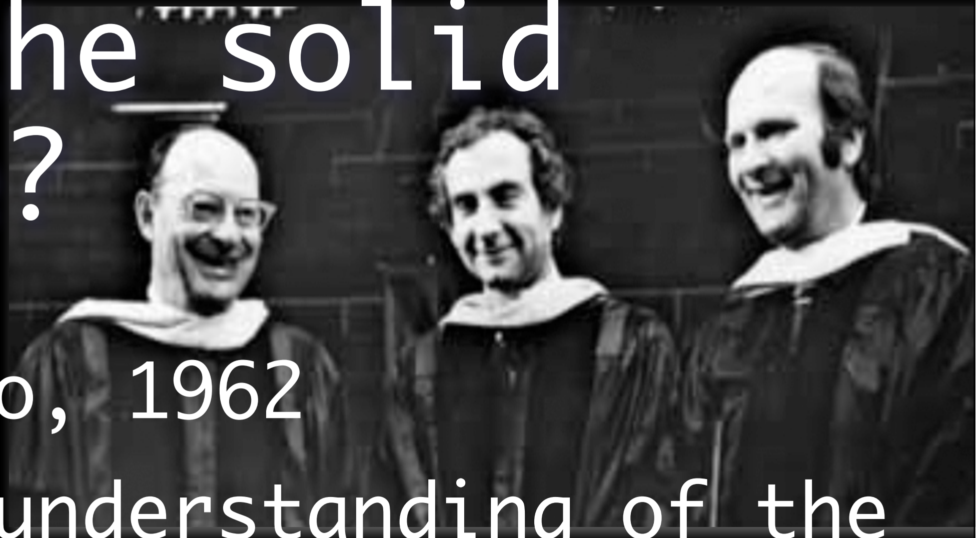
Nobelprize.org
The Official Web Site of the Nobel Prize

Cold atoms are great !

but

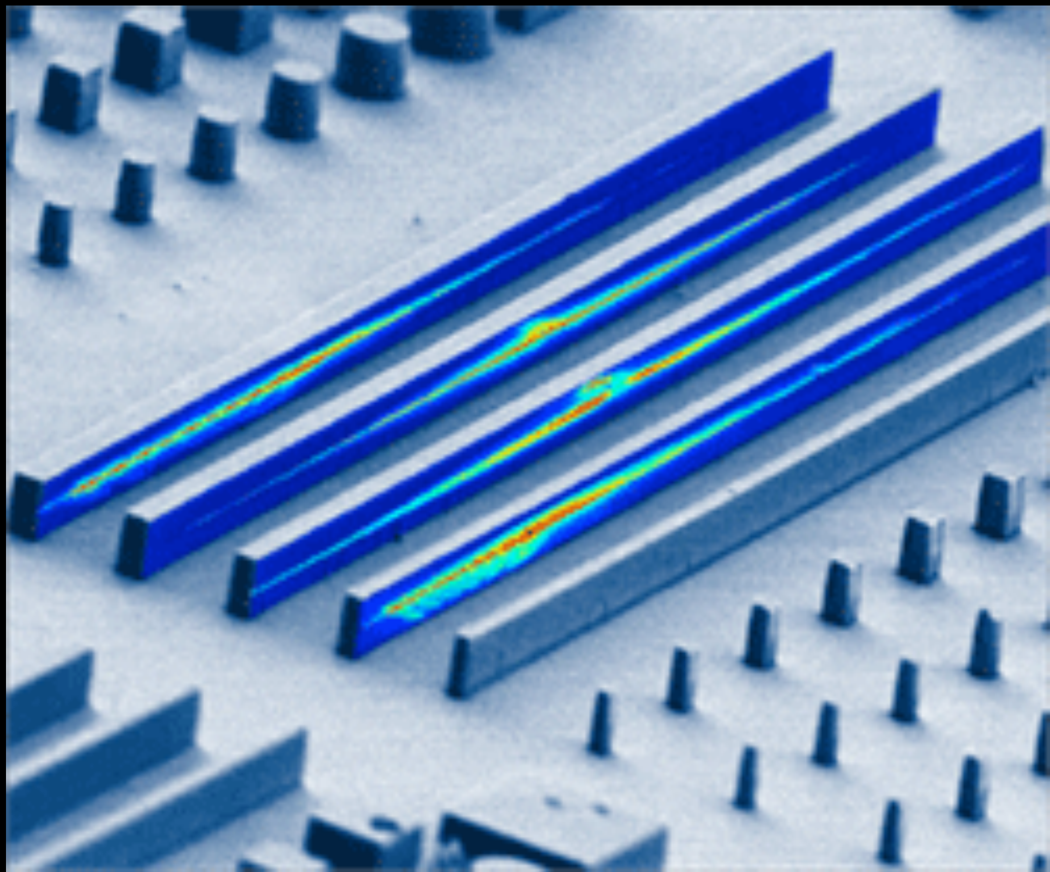
Somewhat complex

Why not in the solid state?



- Blatt & Moskalenko, 1962
- Follows from the understanding of the BCS superconductors,
- The idea is to use composite bosons in solids
- This changes the mass of the involved quasi-particles by as much as 10’000
- This should allow to reach reasonable temperatures,

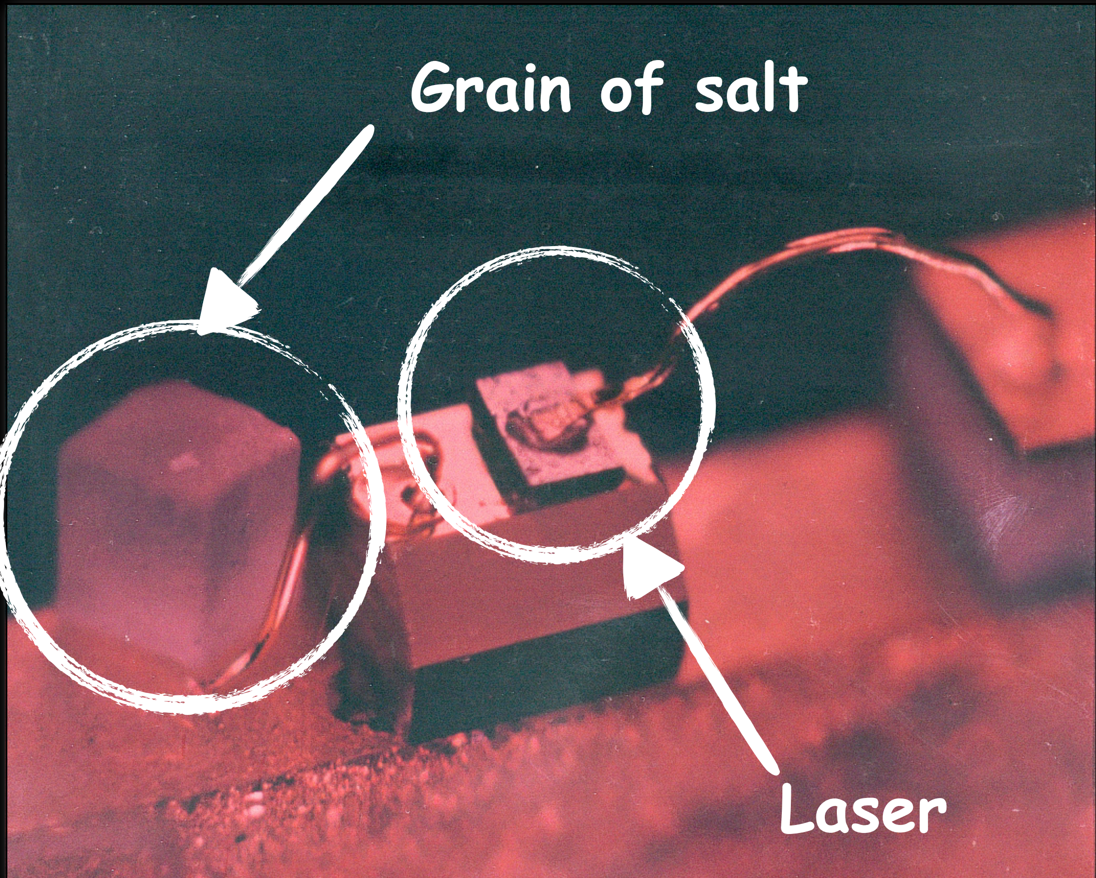
We use polaritons



CNRS Press, 2010, Courtesy Jacqueline Bloch

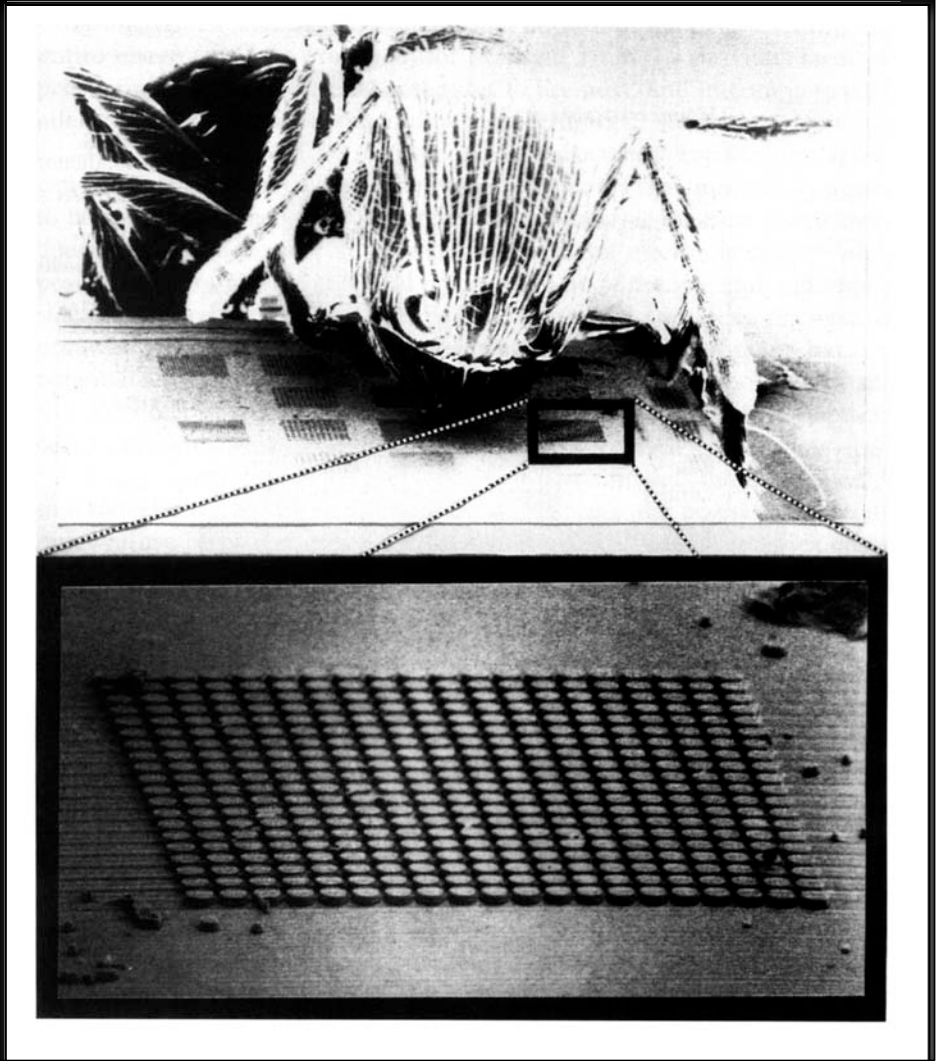
Origin of the idea?

- By chance
- Lets take a semi-conductor laser
- And try to improve it

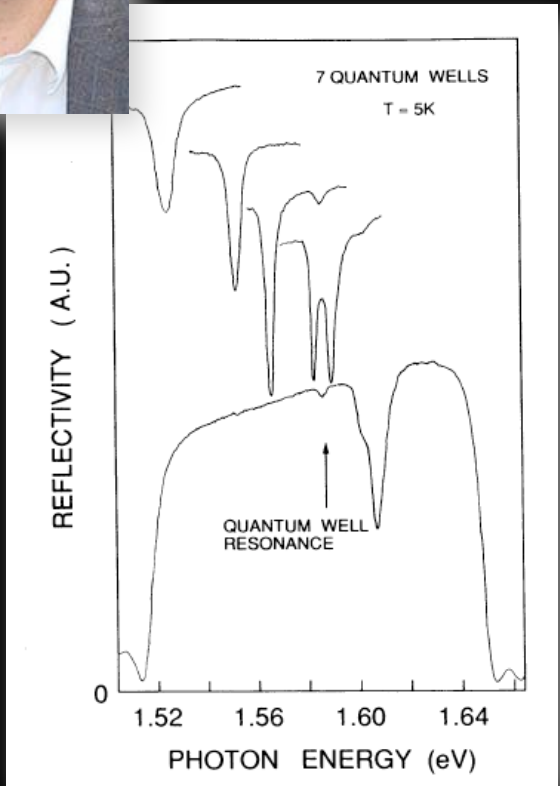


Vertical cavity surface emiting laser : VCSEL

- We increase the reflectivity of the mirors up to 99,99%
- Use of BDR mirors
- Very small laser
- Microcavity polariton



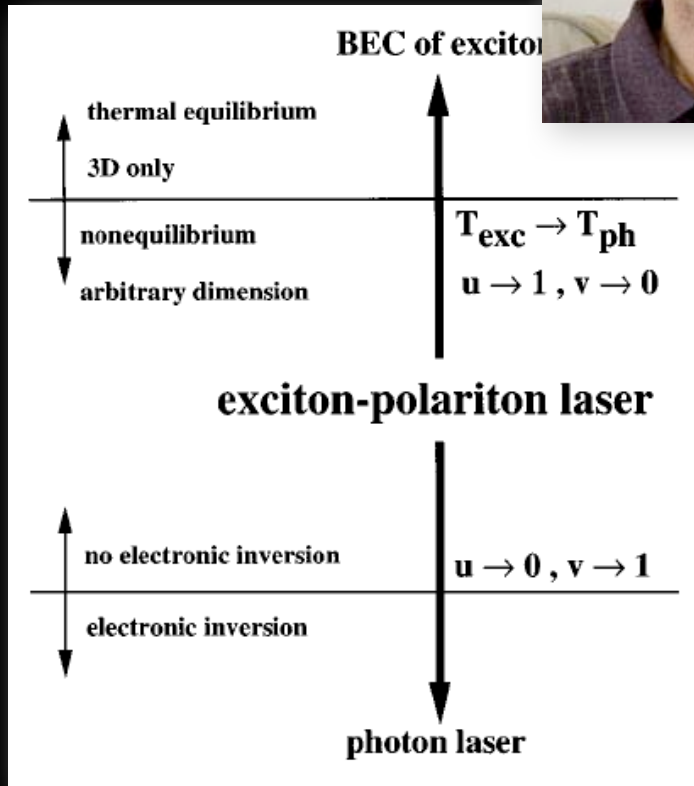
Claude Weisbuch



PRL, 69, 3314 (1992)

UC SANTA BARBARA
engineering and the sciences

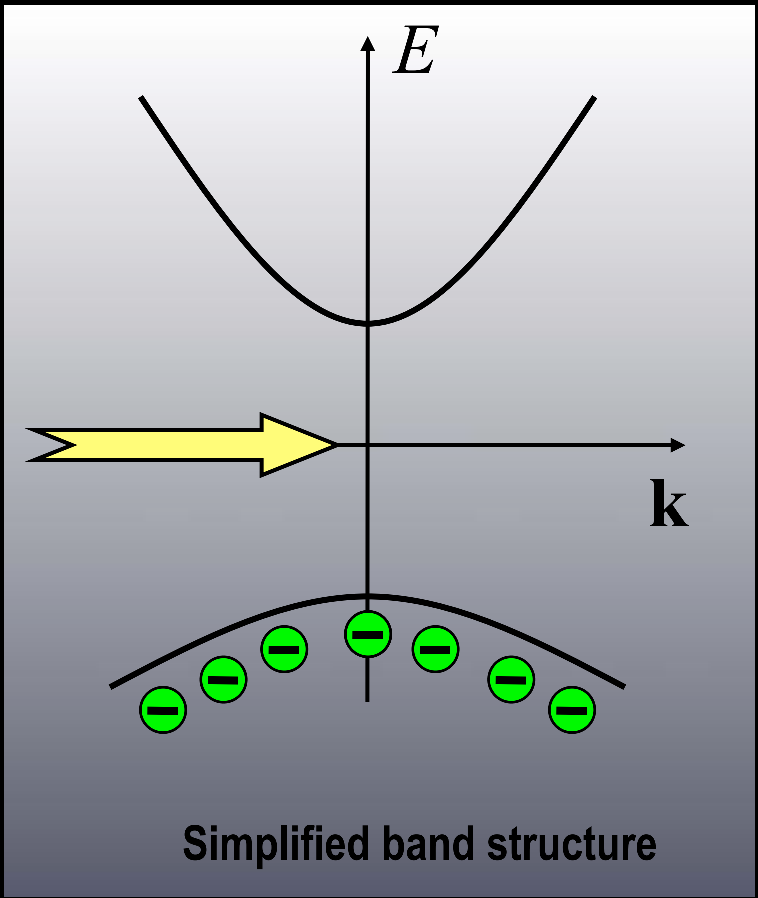
Atac Imamoglu

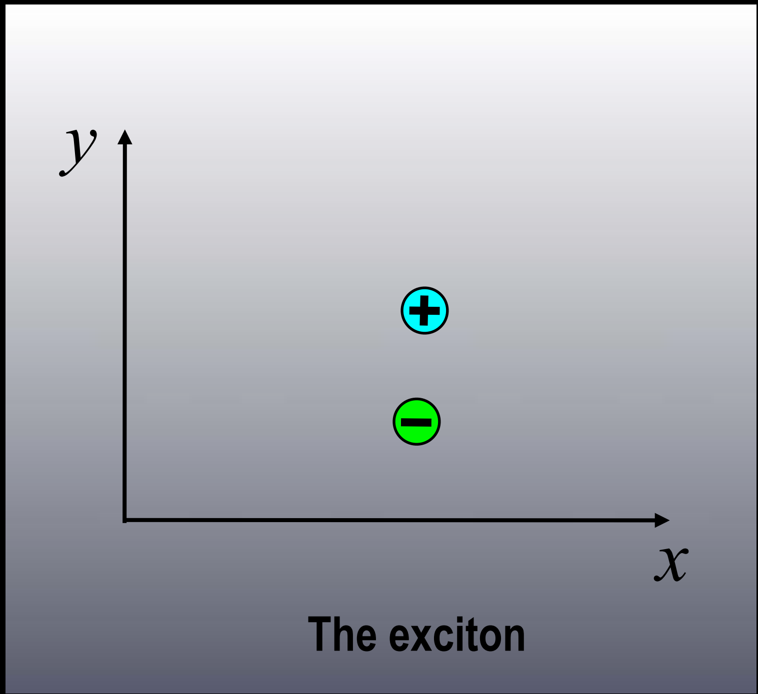


PRA, 53, 4250 (1996)

ETH
Eidgenössische
Technische Hochschule
Zürich

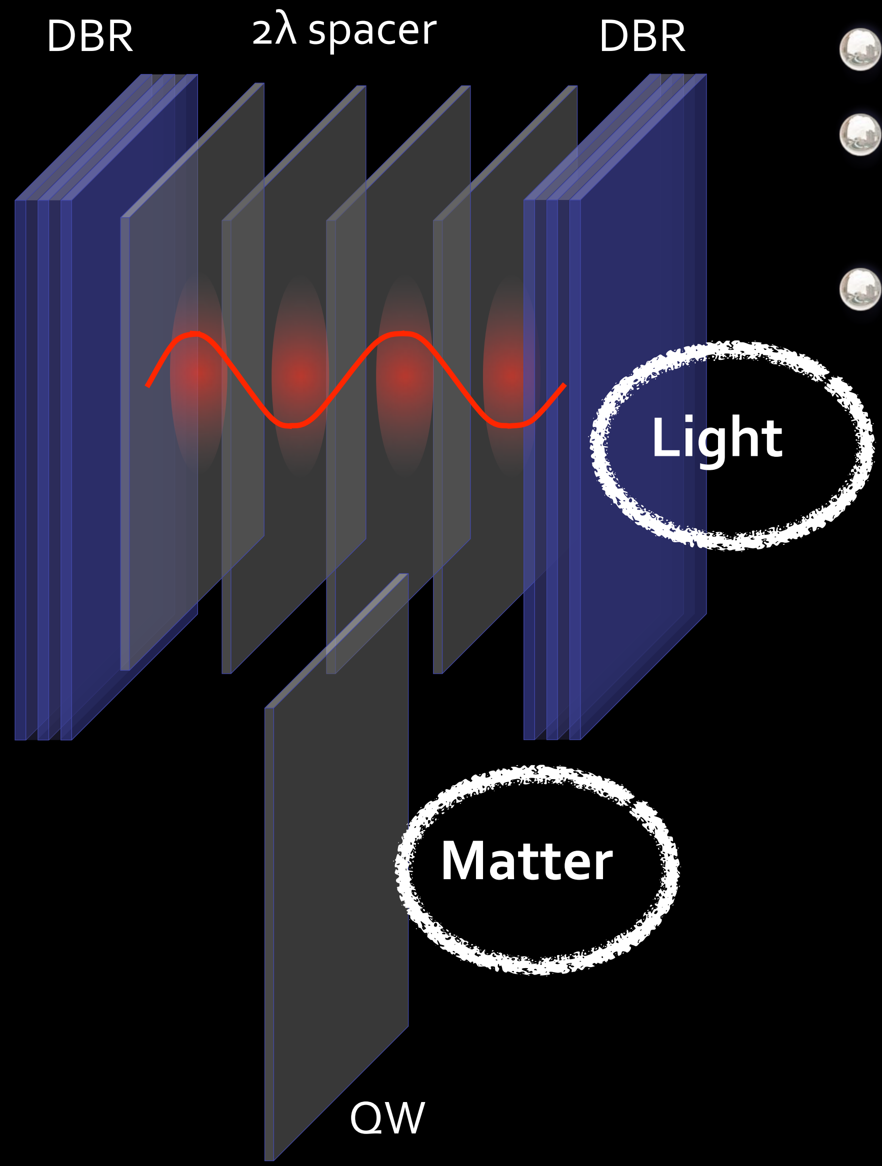
Exciton in a semiconductor



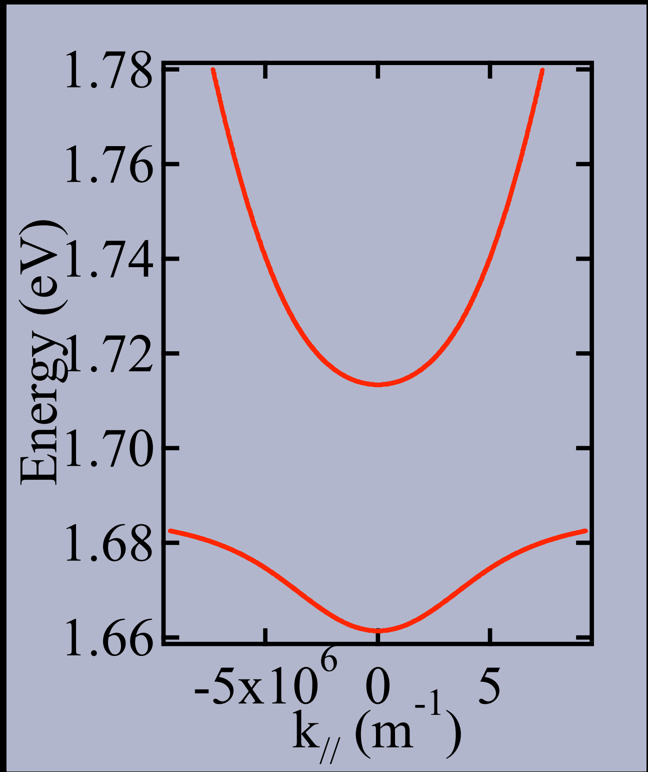


The exciton is a boson
With a mass = 0,1 m_e

Semiconductor microcavities

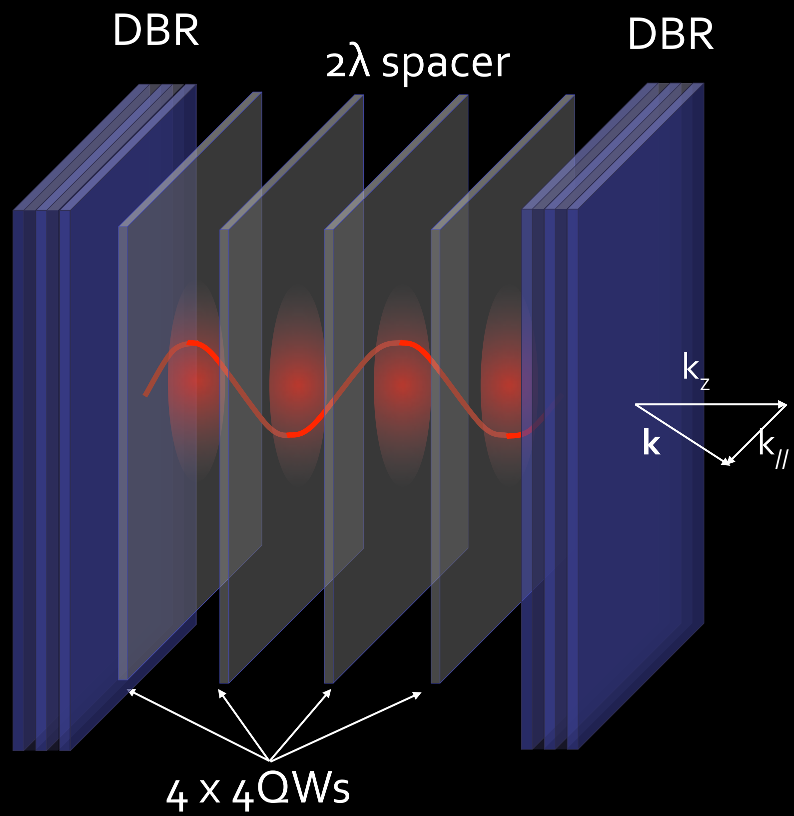


- Matter – light coupling
- New eigenstates : polaritons
- «Magic» quasiparticles



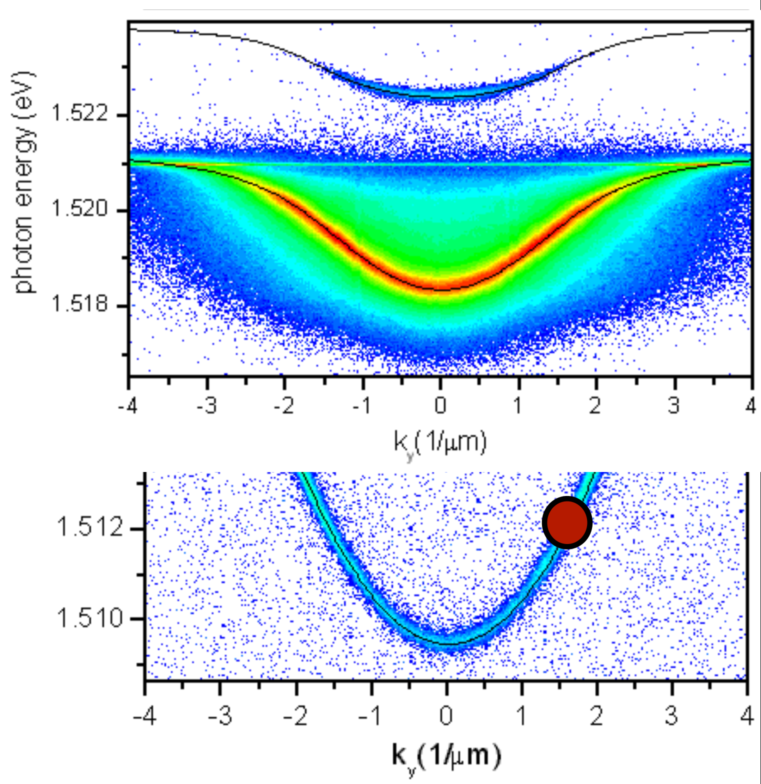
Microcavity polaritons: Half light / half matter particles

- Bosonic particles with a very small mass
- The emitted direction is given by the in-plane momentum
- From the emitted light, we get
- Energy, momentum, polarization
- Coherence and noise properties



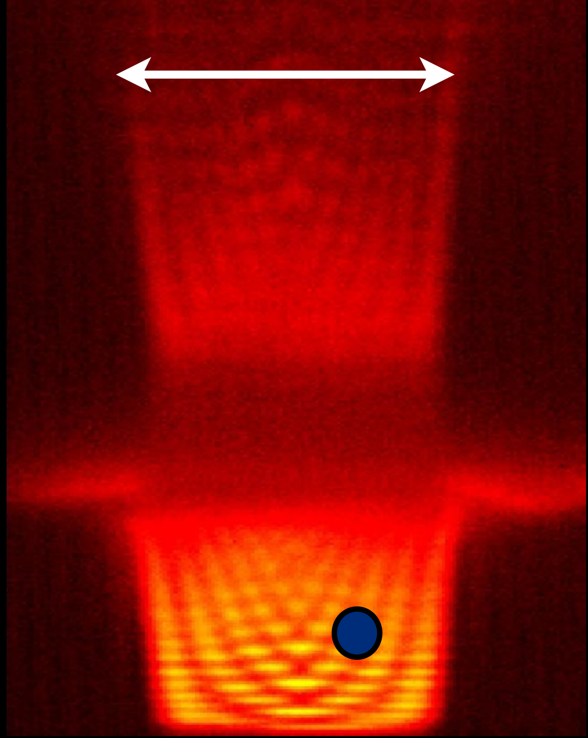
Direct access to the polariton both in k-space & real space

+/- 40° emission angle



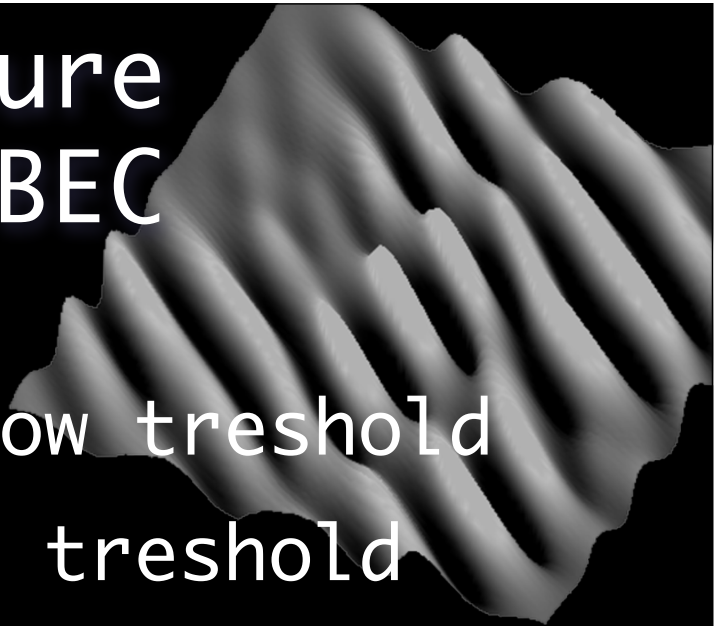
Reciprocal space
Courtesy W. Langbein

20 µm polariton trap



Confined polaritons
Courtesy G. Nardin

What should we measure to claim polariton BEC

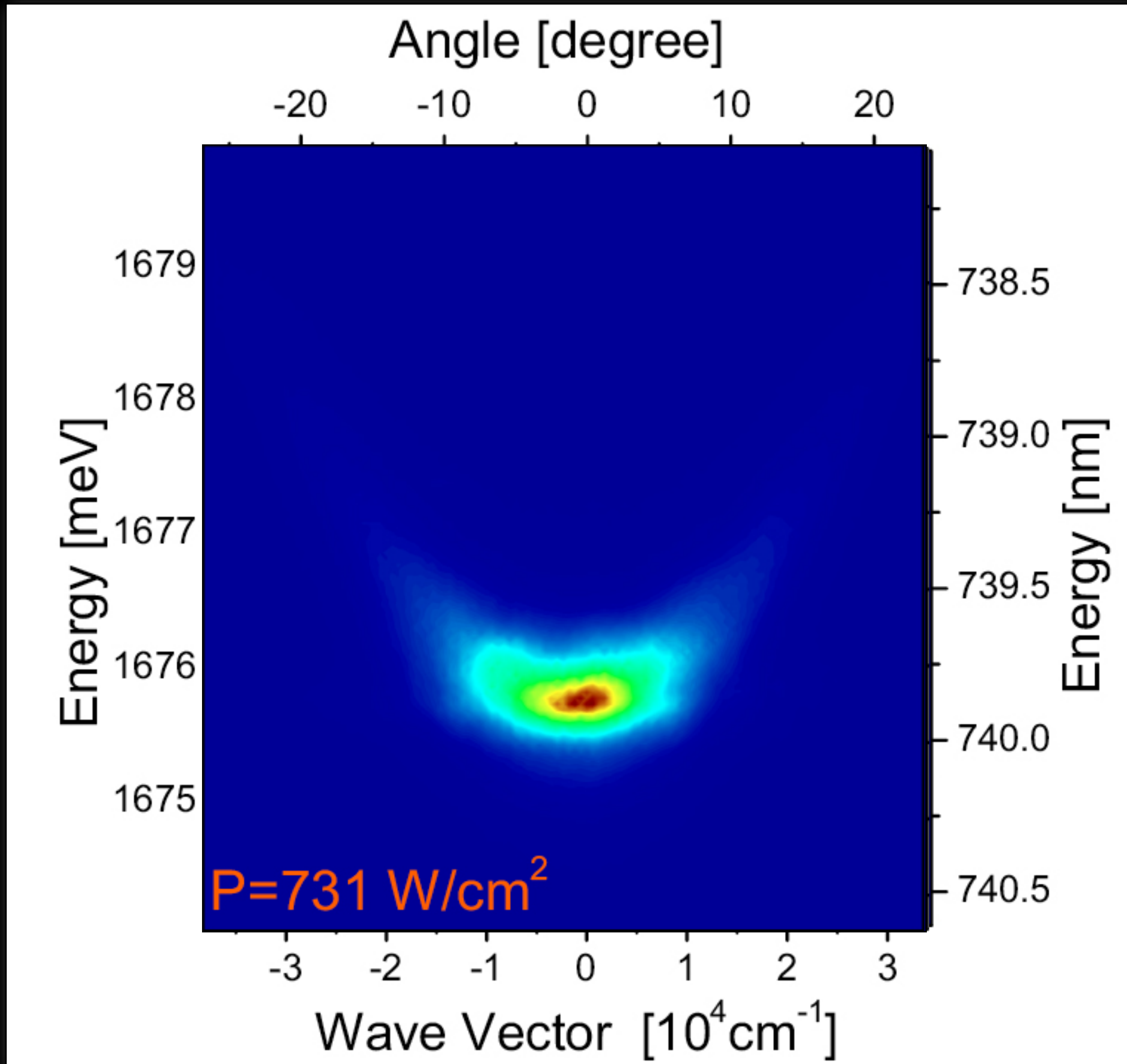


- Thermal equilibrium below treshold
- Bose distribution above treshold
- Clear threshold with line narrowing,
- Increase of the temporal coherence,
- For a number of polariton/state =1
- Second order coherence from 2 to 1
- Spontaneous polarization
- Long range spatial coherence

BEC smoking gun

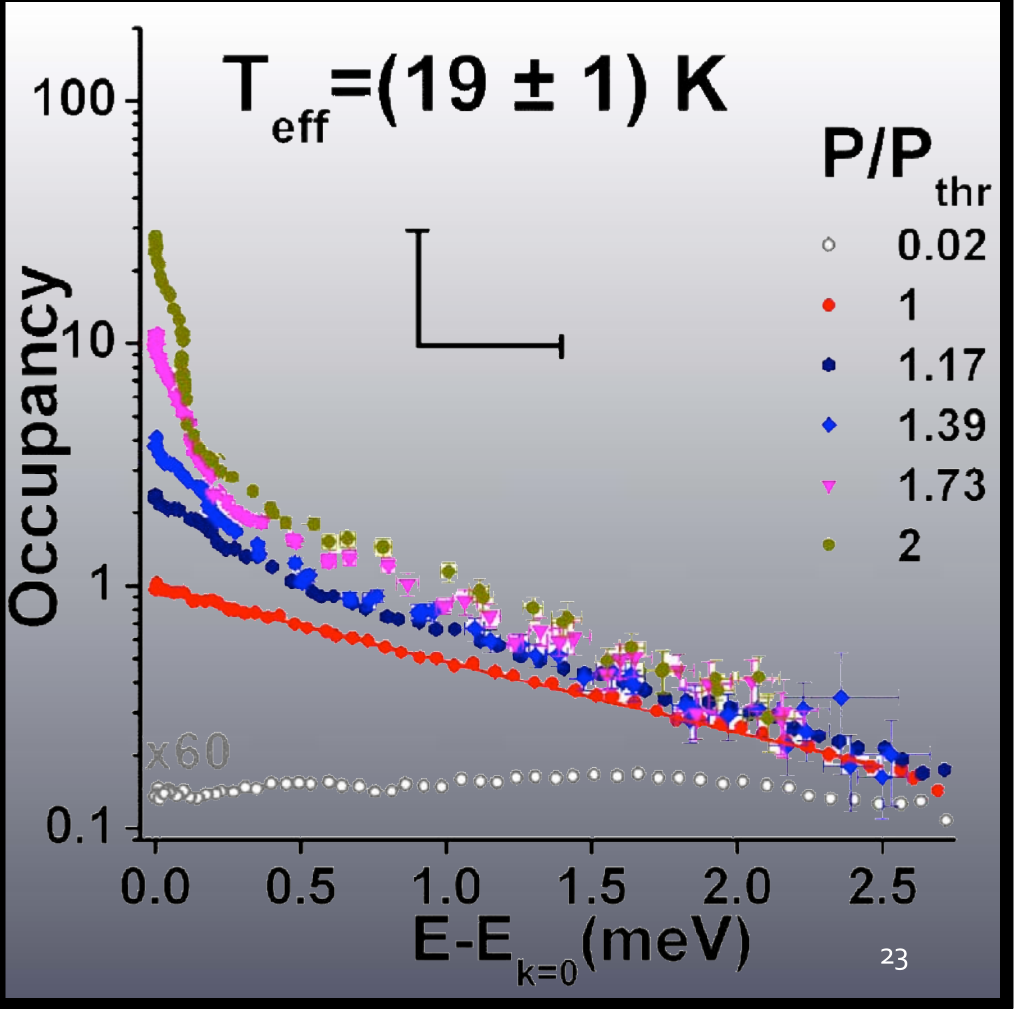
Long Range Spatial Ordering

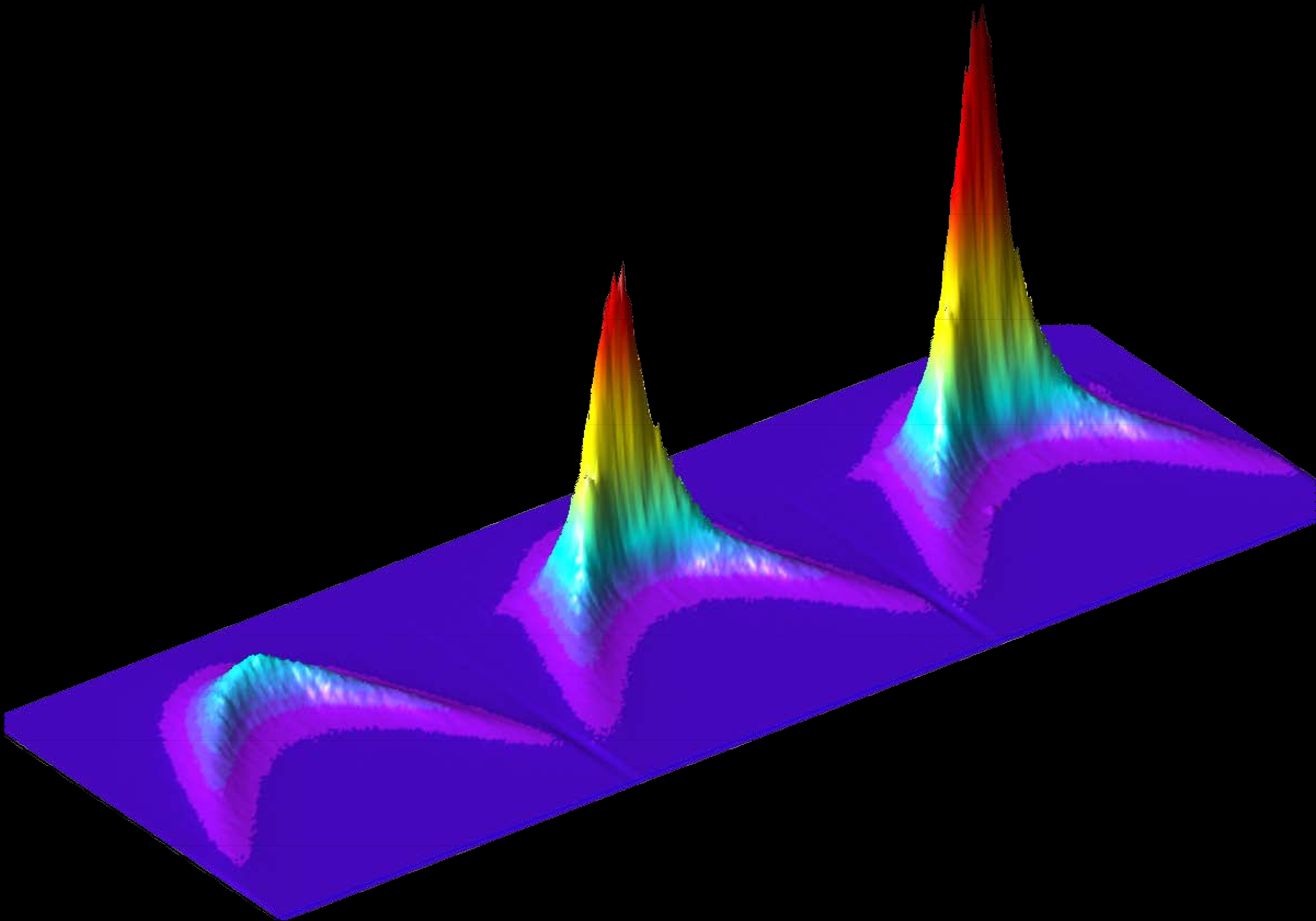
Polariton condensation



From Boltzmann to Bose distribution

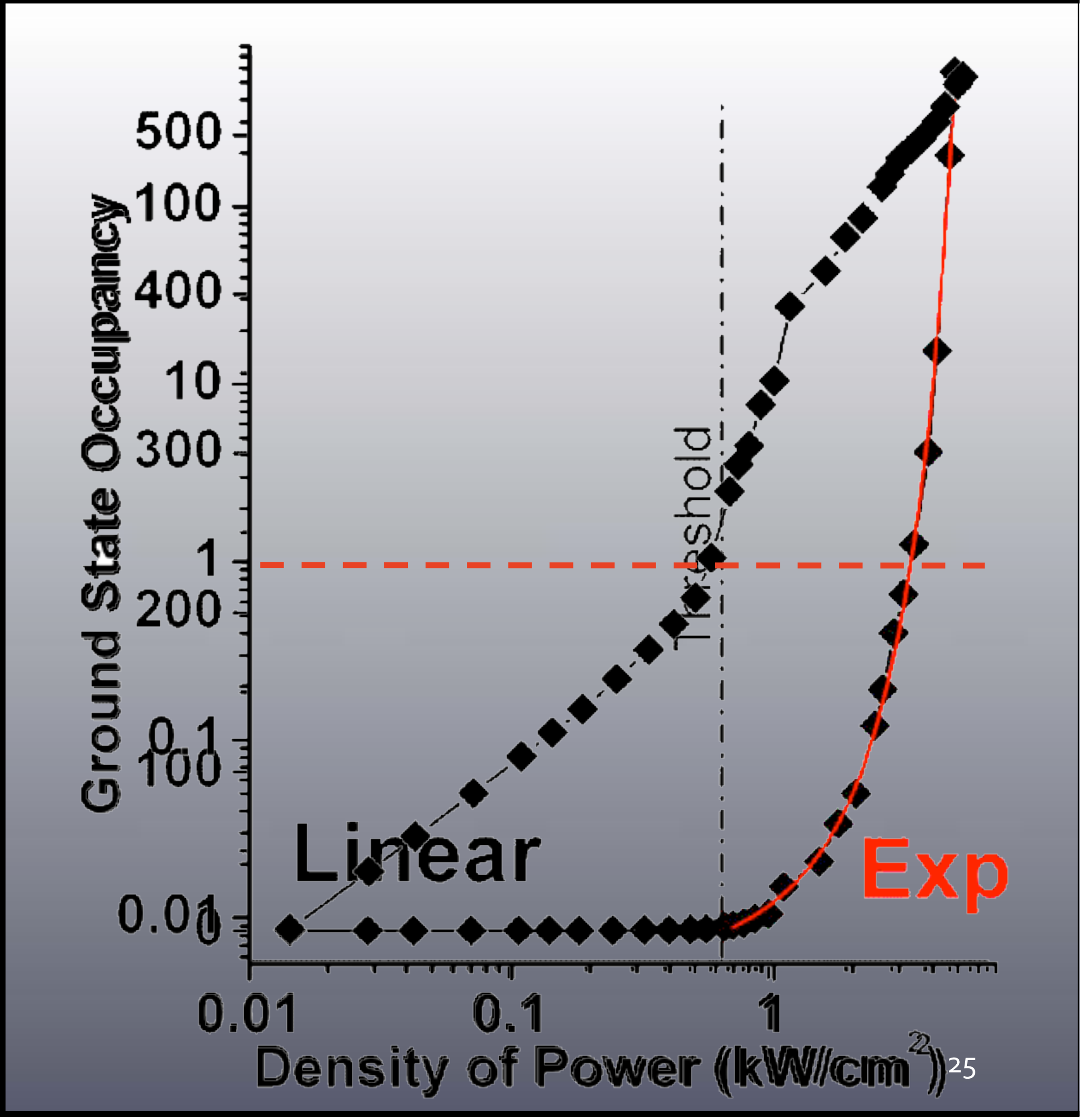
- Bolzmann ditribution below treshold
- Bose distribution above
- Threshold for nb polaritons =1





Clear condensation threshold

- Linear then quadratic increase below threshold
- Exponential increase above threshold
- Threshold for polariton occupation = 1



Interferences between 2 condensates

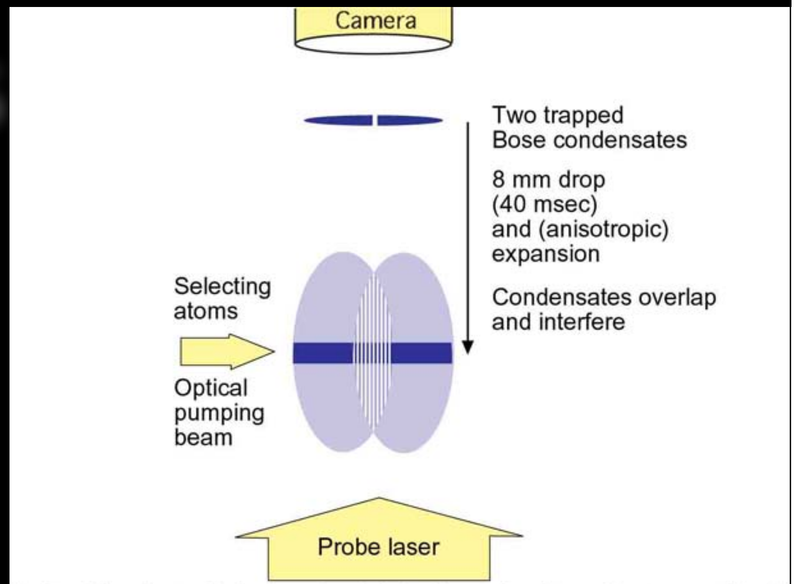
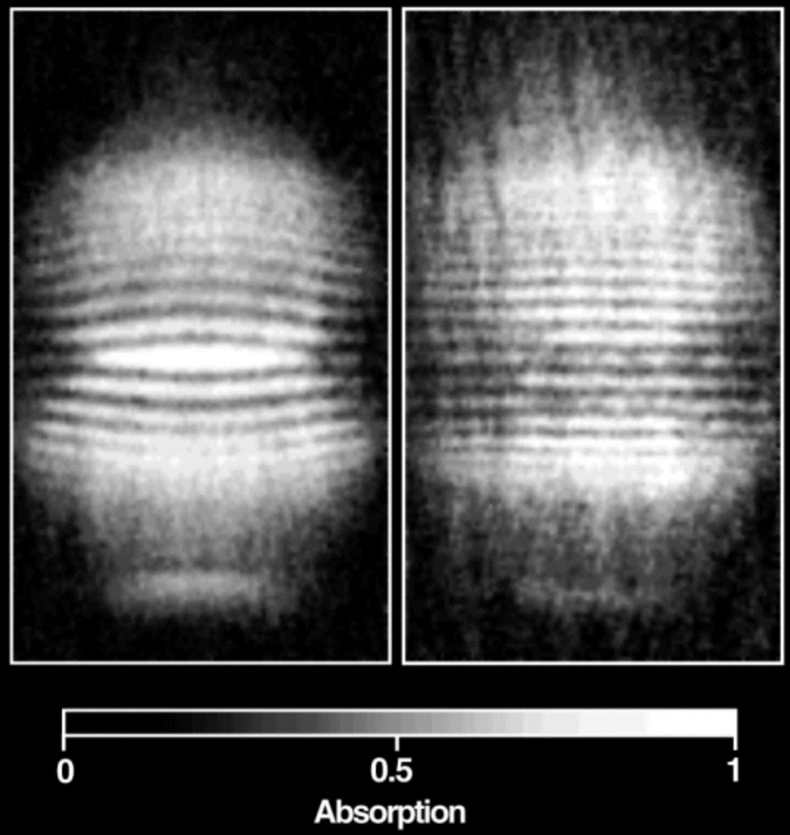


Fig. 27. – Schematic setup for the observation of the interference of two Bose condensates, created in a do well potential. The two condensates were separated by a laser beam which exerted a repulsive force on atoms. After switching off the trap, the condensates were accelerated by gravity, expanded ballistically, overlapped. In the overlap region, a high-contrast interference pattern was observed by using absorption imag An additional laser beam selected a thin layer of atoms by optically pumping them into the initial state for absorption probe. This tomographic method prevented blurring of the interference pattern due to integra along the probe laser beam.

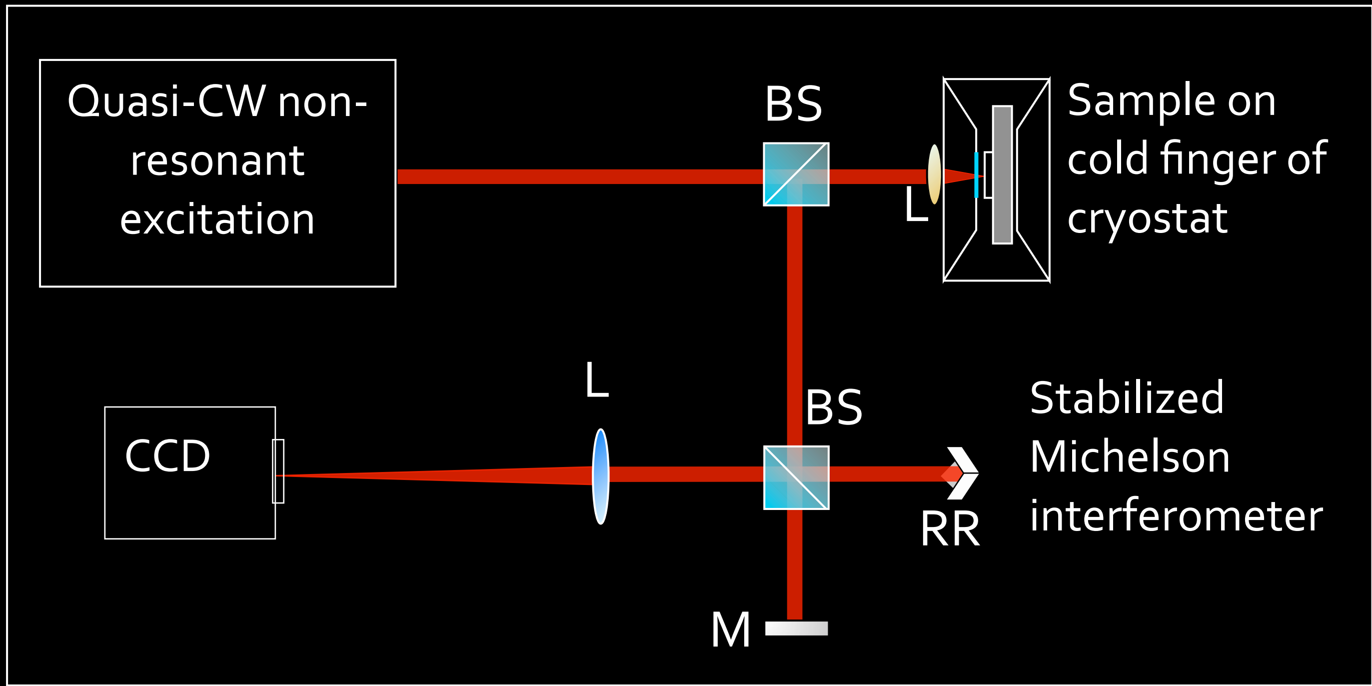


Ketterle et al, 2001

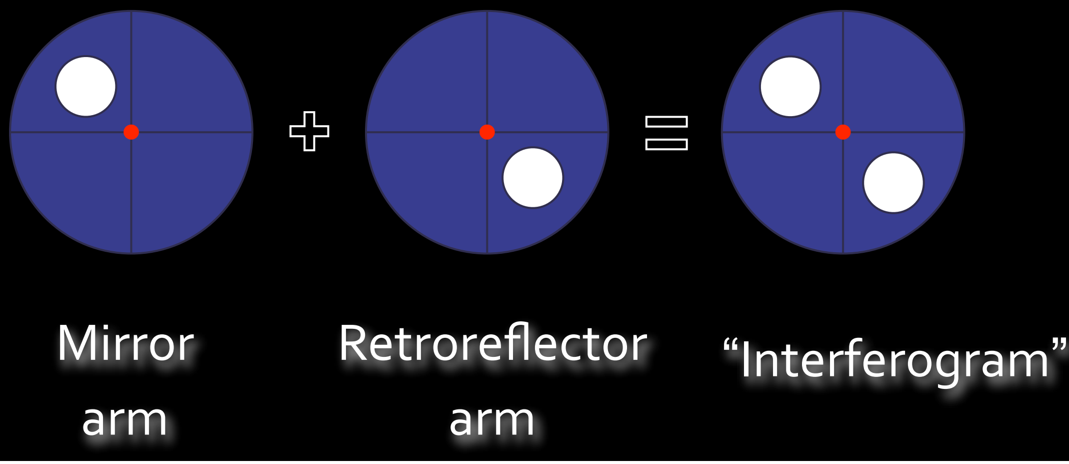
- Interferences between matter waves
- 1+1 atom = nothing ???

Measurement of spatial coherence

- Setup:



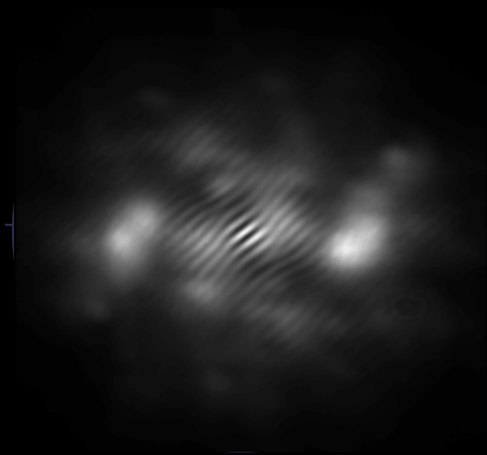
- Principle:



Measurement of spatial coherence
Principle

+

=

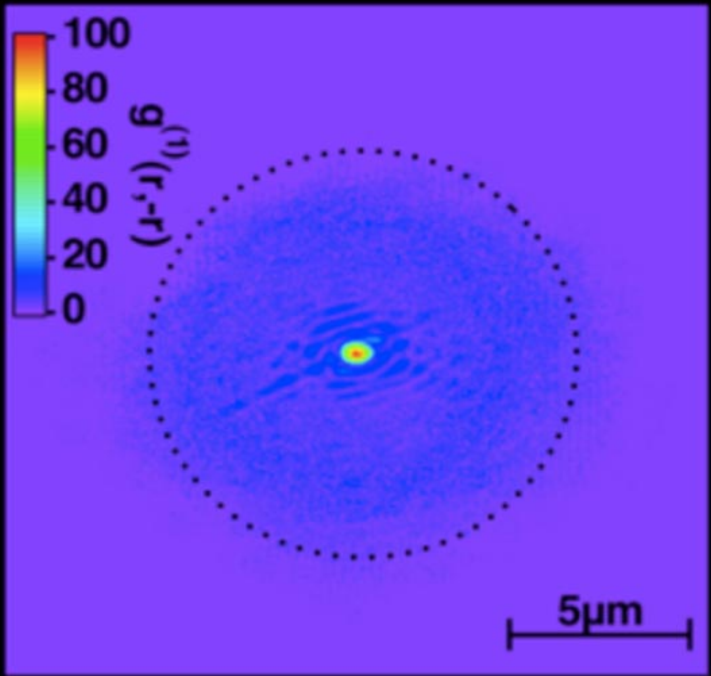


Mirror arm

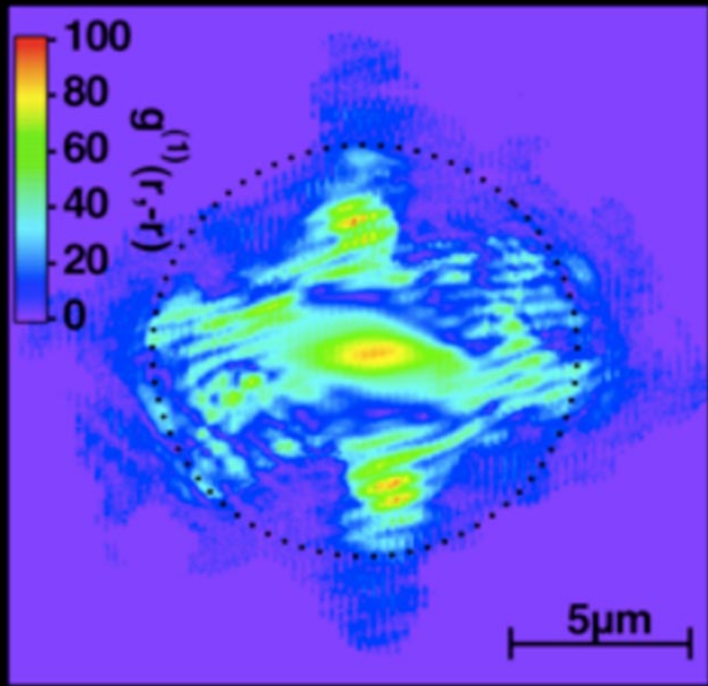
Retroreflector arm

“Interferogram”

Build-up of longe range order



Below threshold,
De Broglie WL of the polariton



Above threshold,
Long range ordering

nature International weekly journal of science

Kazprzak et al. Nature 2006

Superfluidity and vortices

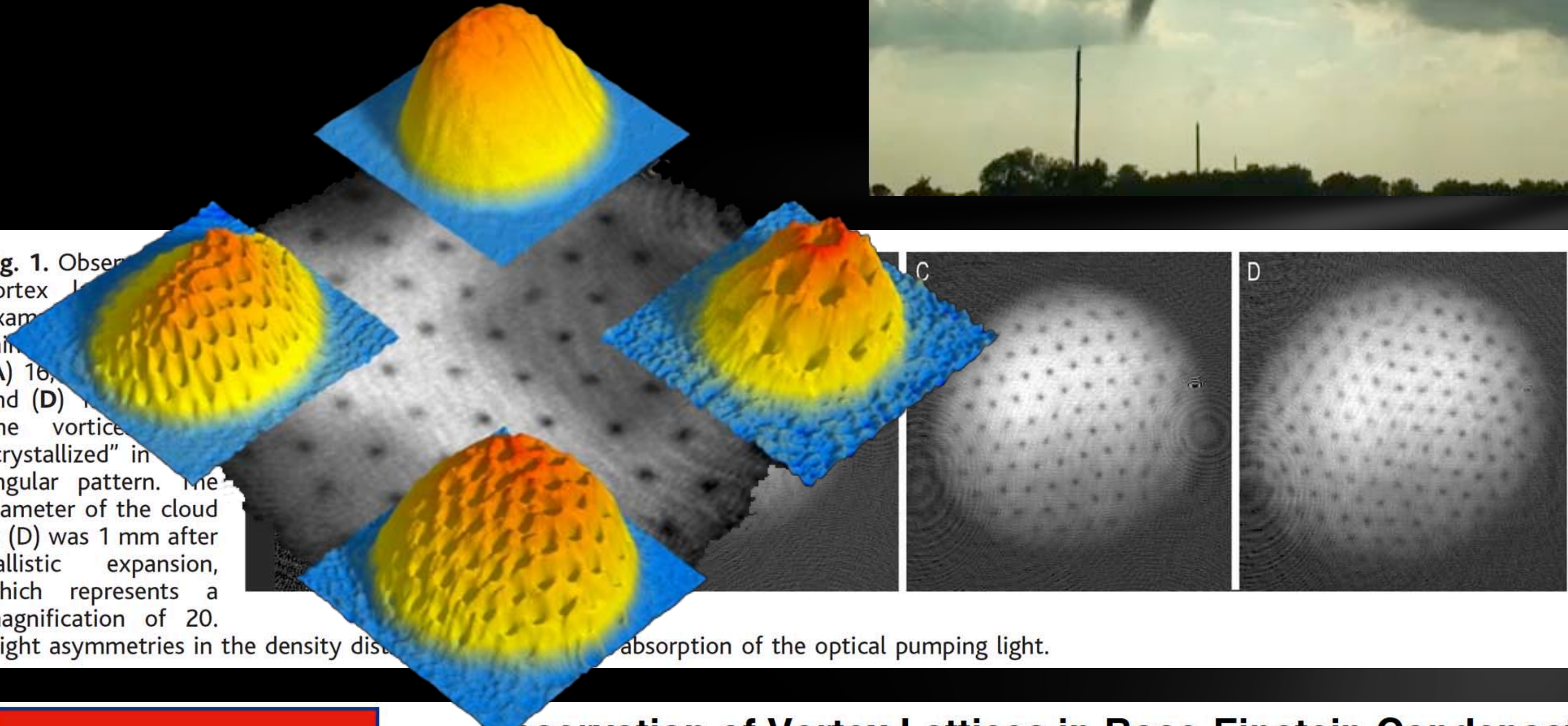


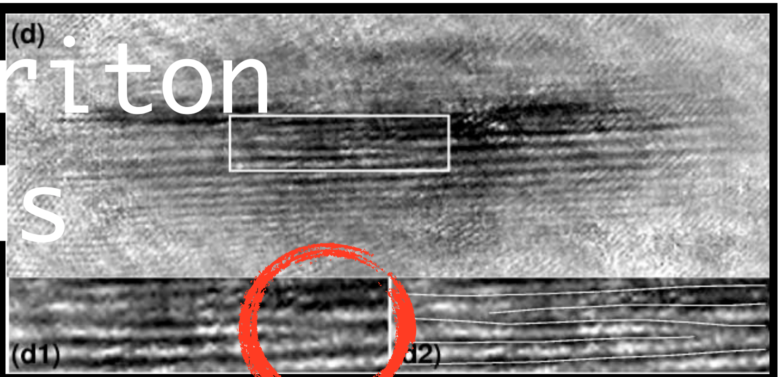
Fig. 1. Obser... vortex ... exam... tai... (**A**) 16... and (**D**) ... The vortice... "crystallized" in ... angular pattern. The diameter of the cloud in (D) was 1 mm after ballistic expansion, which represents a magnification of 20. Slight asymmetries in the density dis... absorption of the optical pumping light.

Science AAAS

Observation of Vortex Lattices in Bose-Einstein Condensates

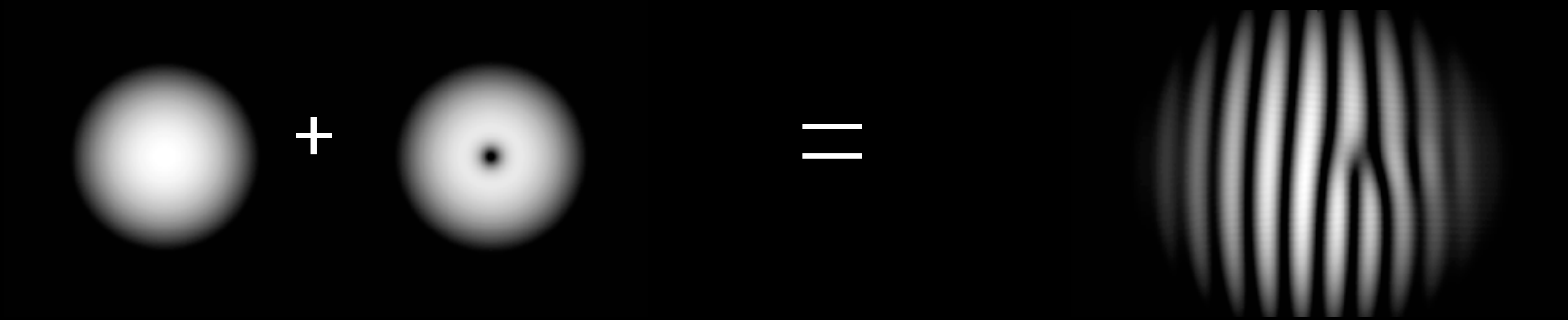
J. R. Abo-Shaeer *et al.*
Science **292**, 476 (2001);
DOI: 10.1126/science.1060182

Vortices in Polariton quantum fluids



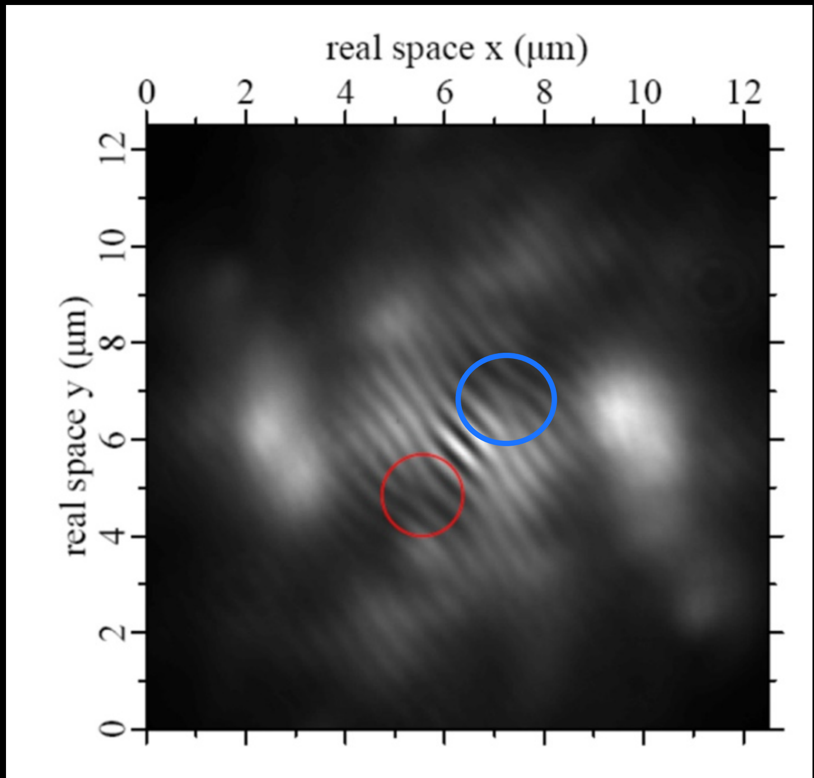
Ketterle et al, PRL , 87 (2001)

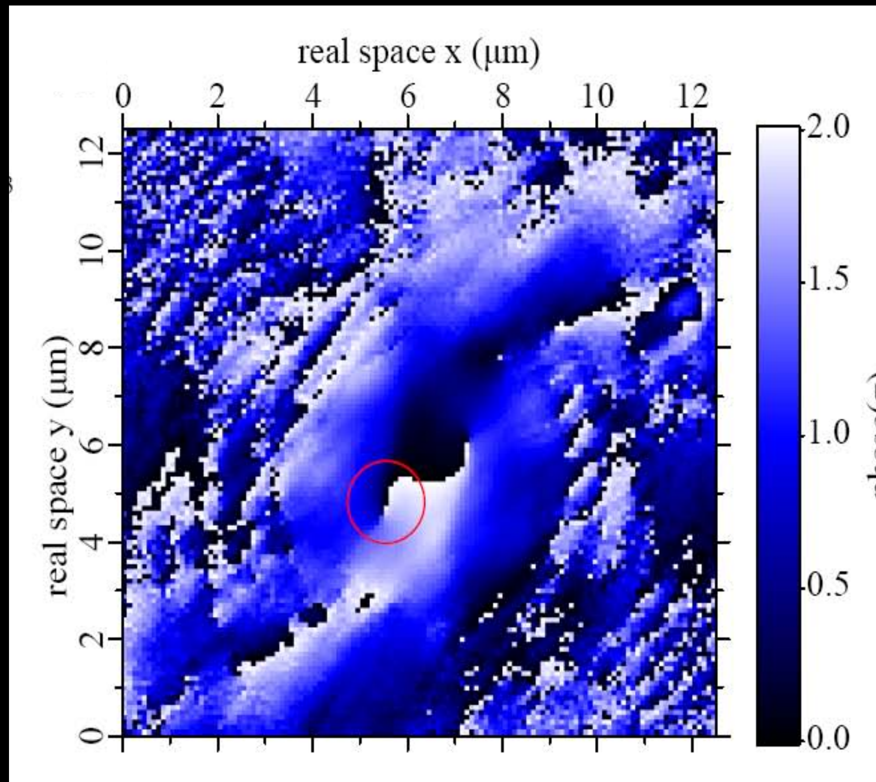
- We should observe a phase change by 2π and a density minimum at the core



- Michelson interferometry
- Forklike dislocation in interference pattern
- Phase may be retrieved through off axis FT

Observation of vortices from interferogram



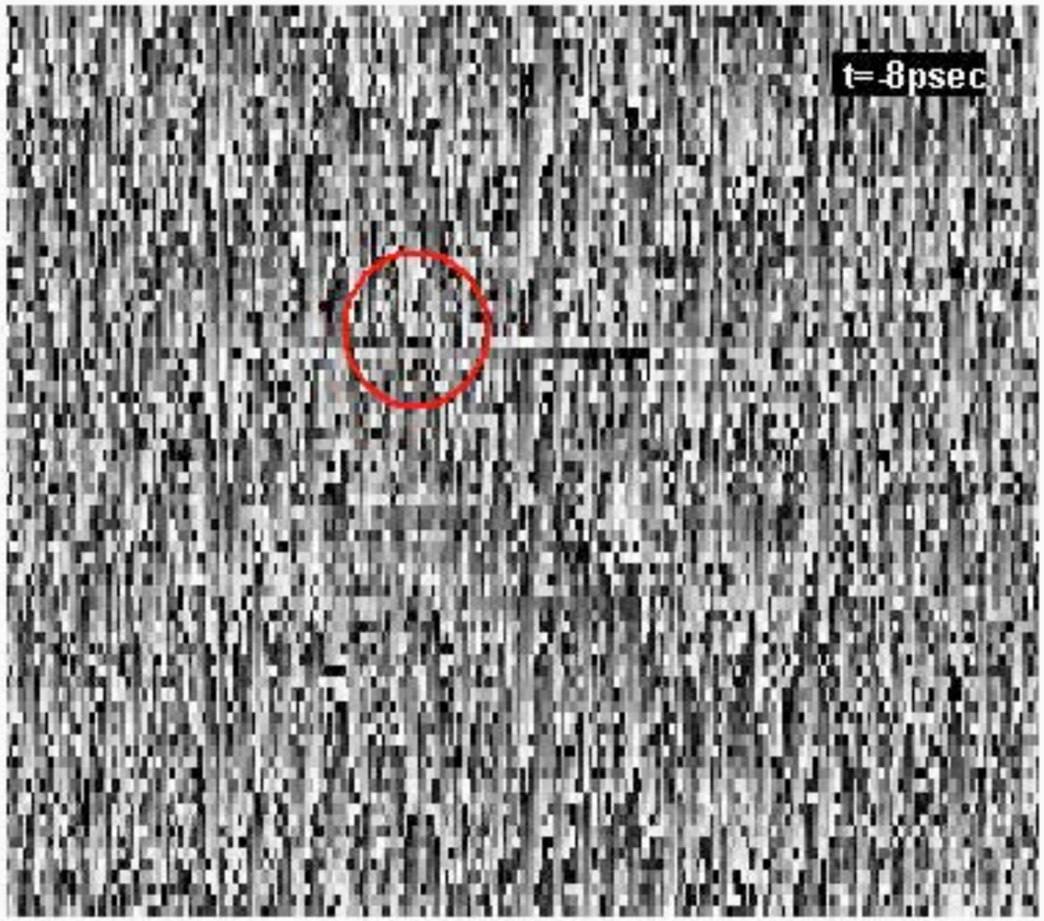


nature physics

Lagoudakis et al., 2008

Dynamics of pinning

- Pulsed non resonant excitation
- Temporally resolved real space data
- Please note the time scale
- Background removed
- Phase map

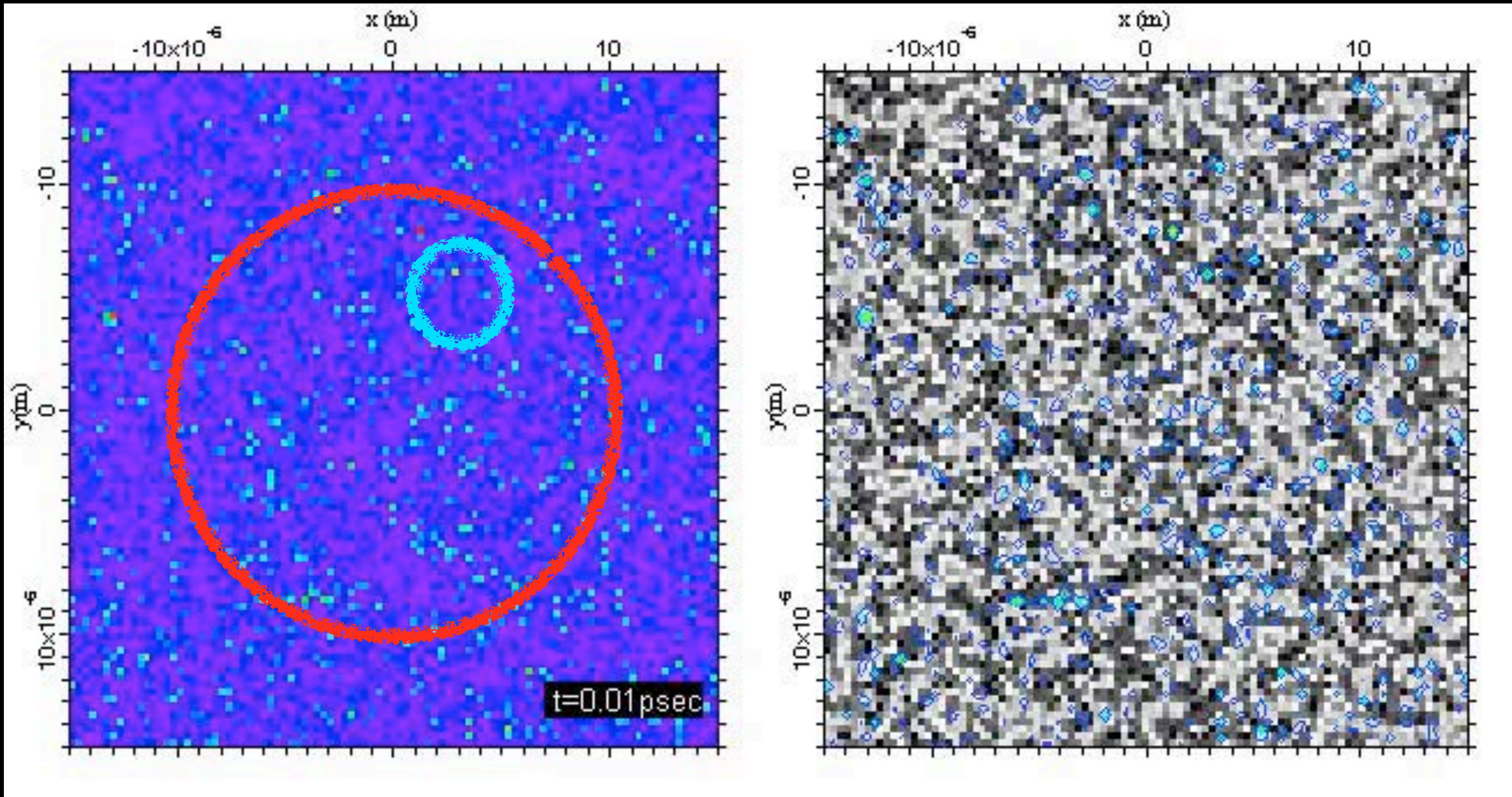


Physical Review Letters
moving physics forward

Reconstructed Time resolved Real space interferences

Lagoudakis et al., PRL 105, 120403 (2010)

Kibble-Zurek mechanism

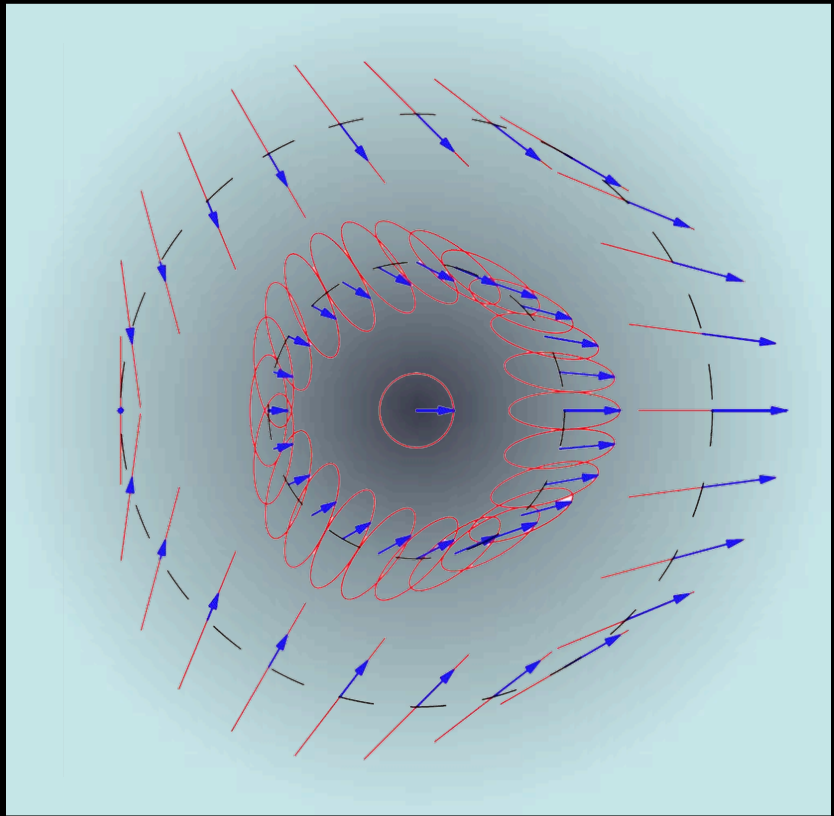


- Gross-Pitaevskii Eq., + Exciton reservoir
- With only one deffect (blue circle)

Half vortices in spinor quantum fluids

- Linear polarization
- Polaritons carry a spin
- New vortical entities
- Phase change by π
- Polarization rotation by π

- Circular polarization
- Vortex in one circular polarization,
- not in the other one



How would a half vortex look like?

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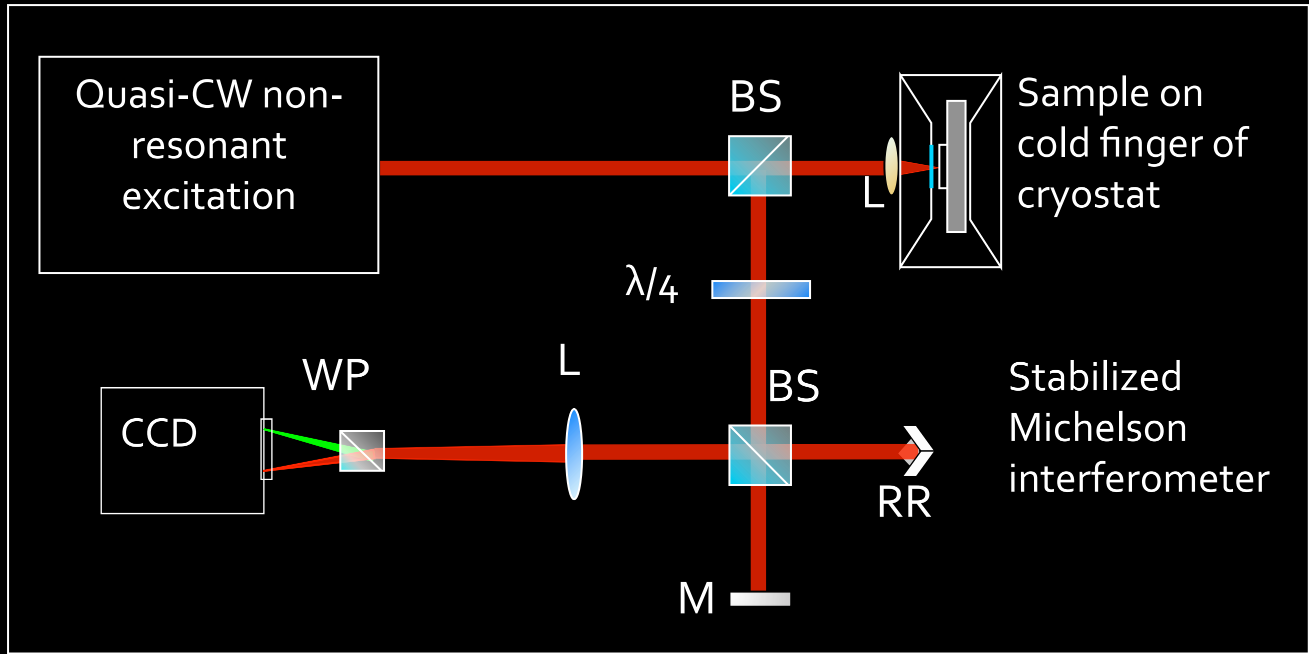
moving physics forward

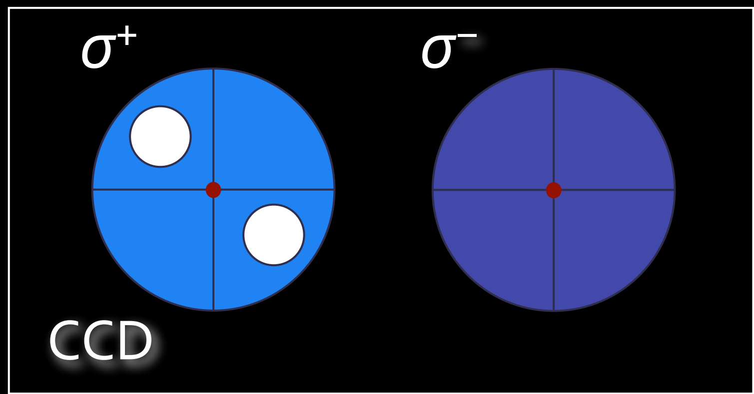
Yuri Rubo, *Phys. Rev. Lett.*, 99 (2007)

Simultaneous measurement in σ^+ and σ^-

- **Setup:**

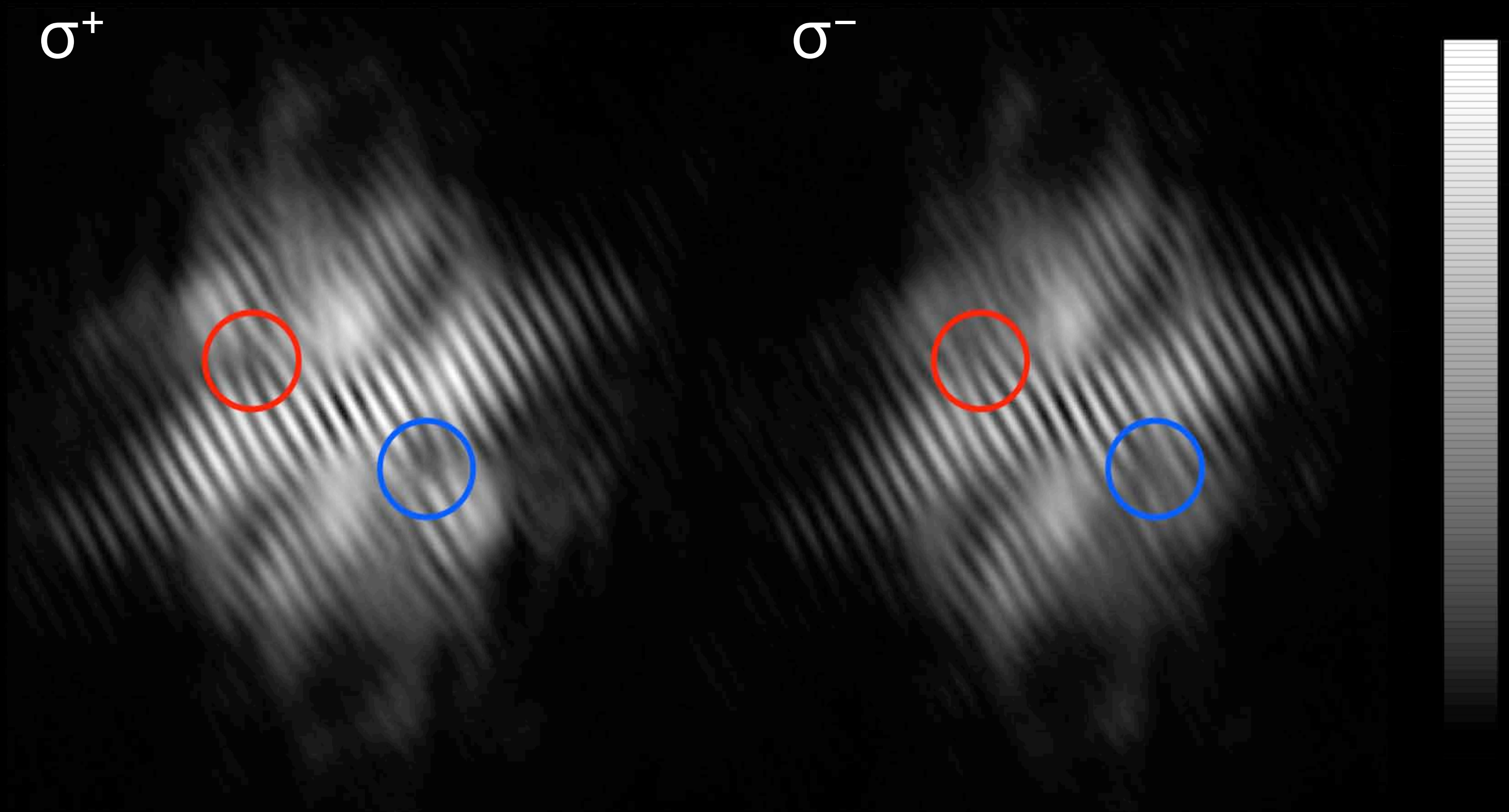


- **Principle:**



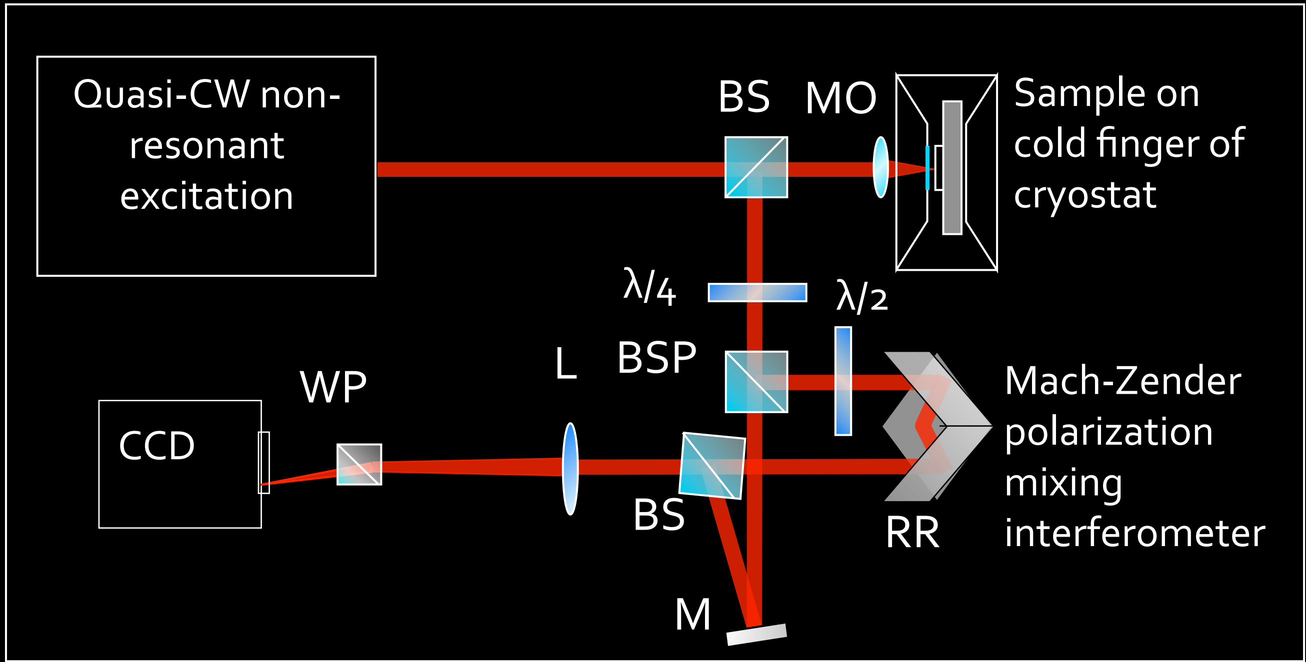
Half vortices in circular polarization

- Interferograms (raw data)

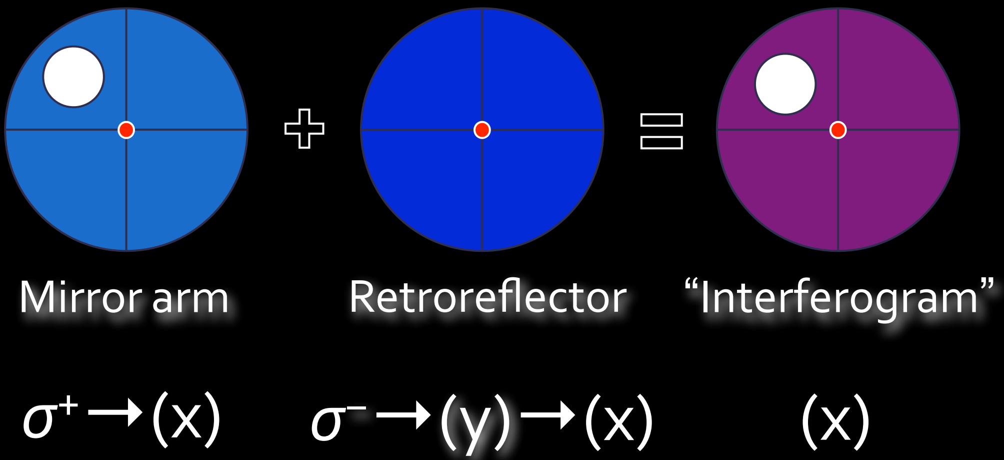


σ^+ - σ^- coherence through Polarization mixing

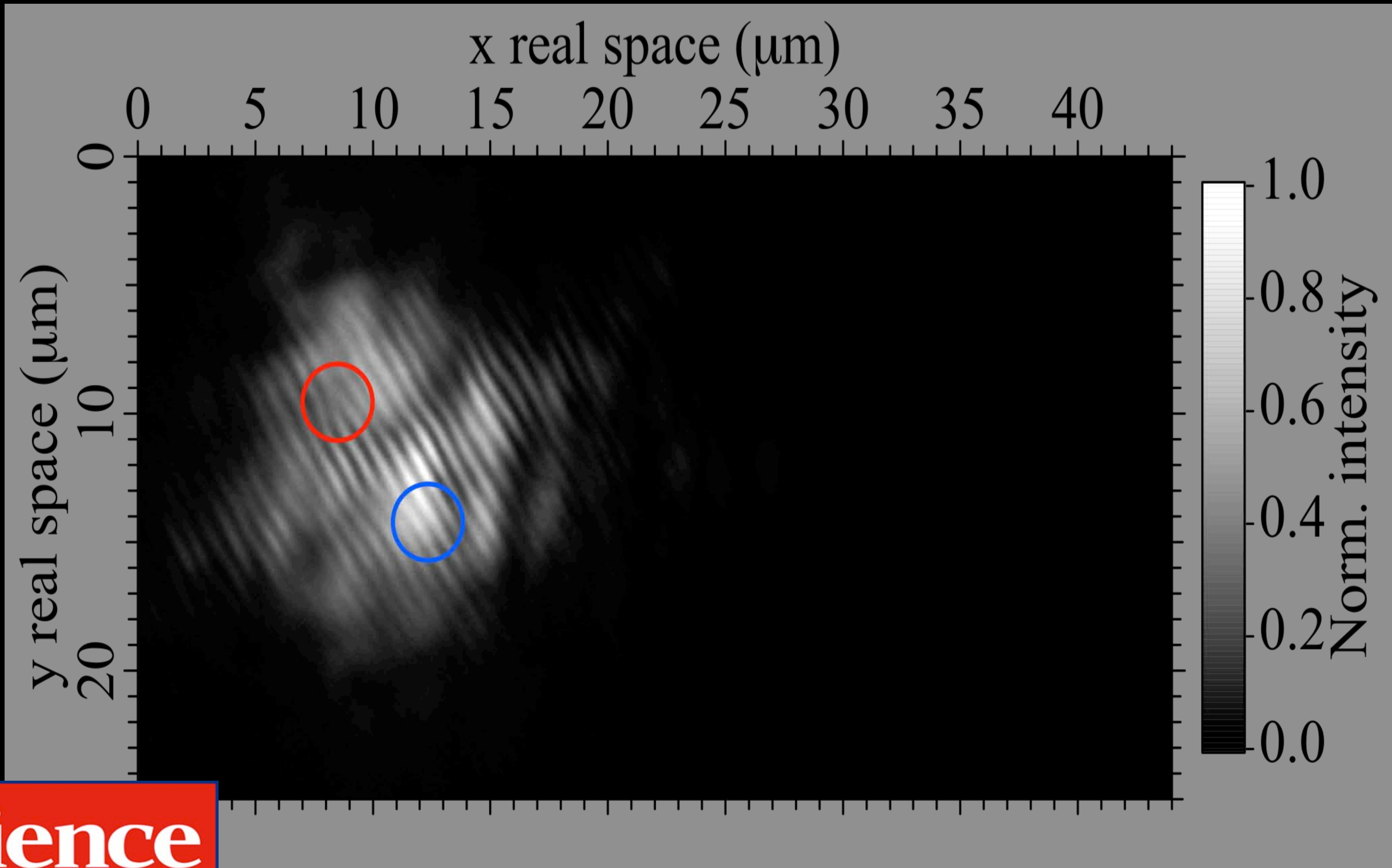
- Setup:



- Principle:

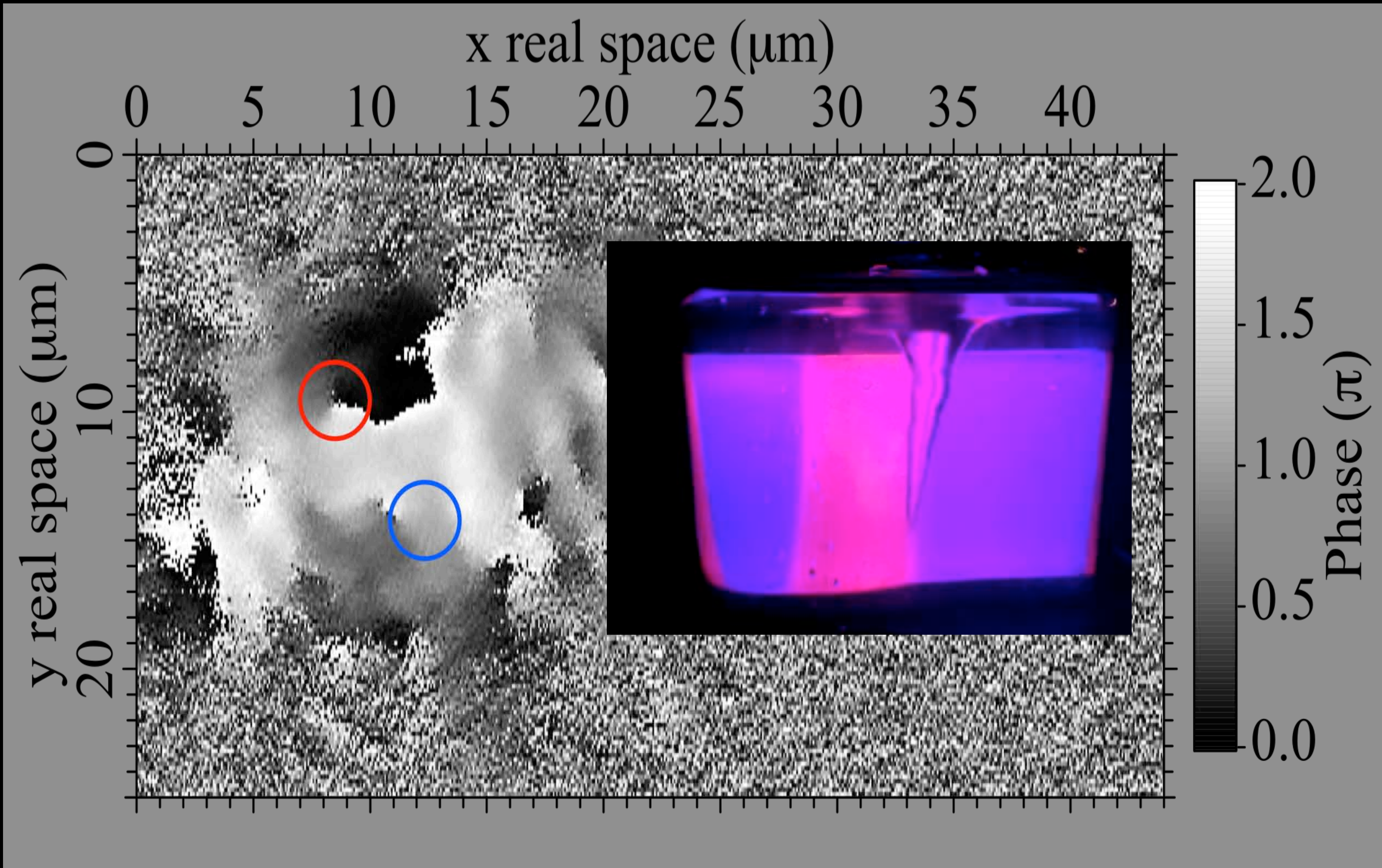


Half vortex with polarisation mixing interference



Lagoudakis et al., Science **326**, 974 (2009)

Phase map

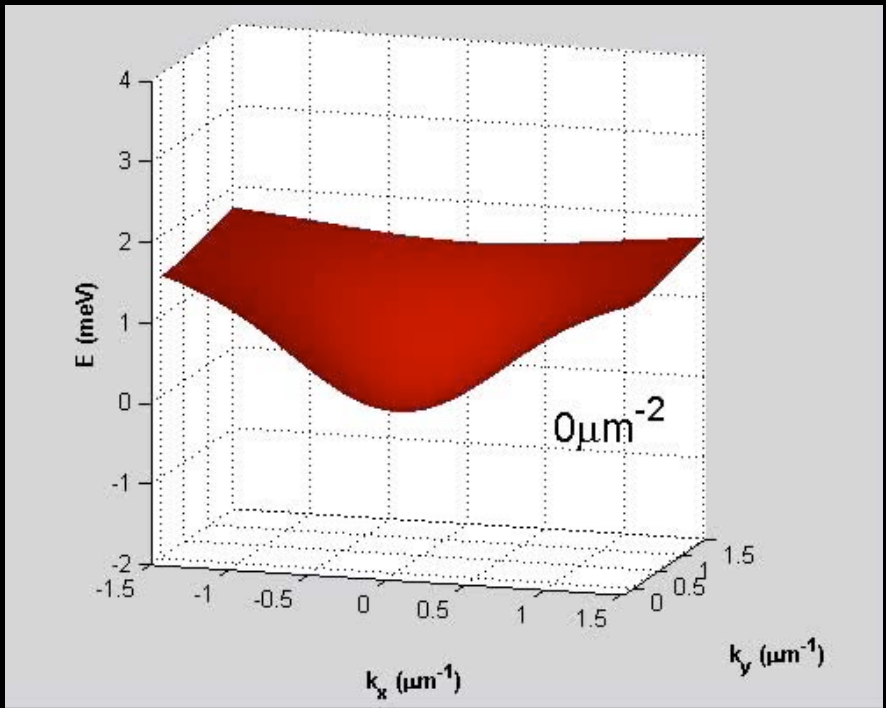


x real space (μm)
0
5
10
15
20
25
30
35
40
y real space (μm)
0
10
20
2.0
1.5
1.0
0.5
0.0
Phase (π)

Superfluidity and Bogoliubov excitations

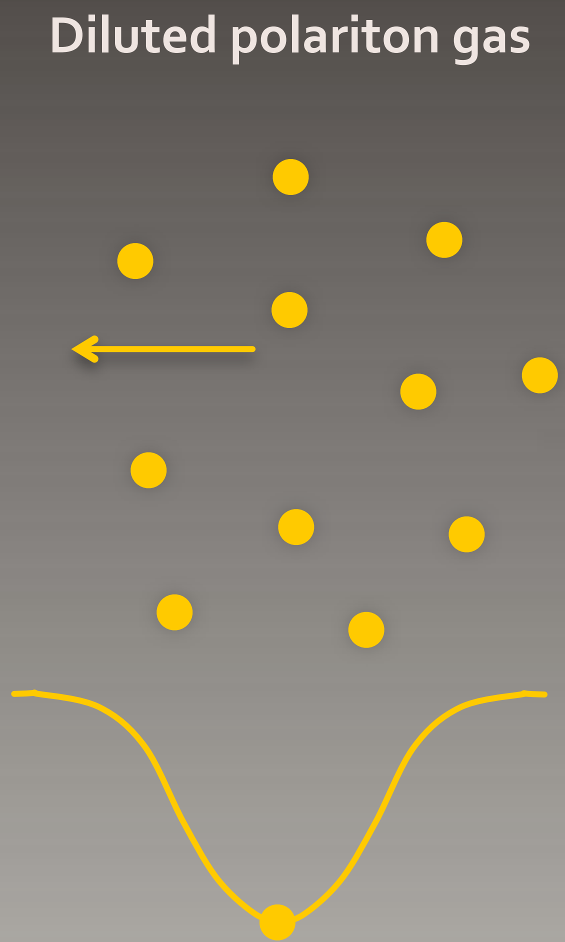
- Consequences of superfluidity
  - Linearization of the dispersion
  - Appearance of a ghost branch

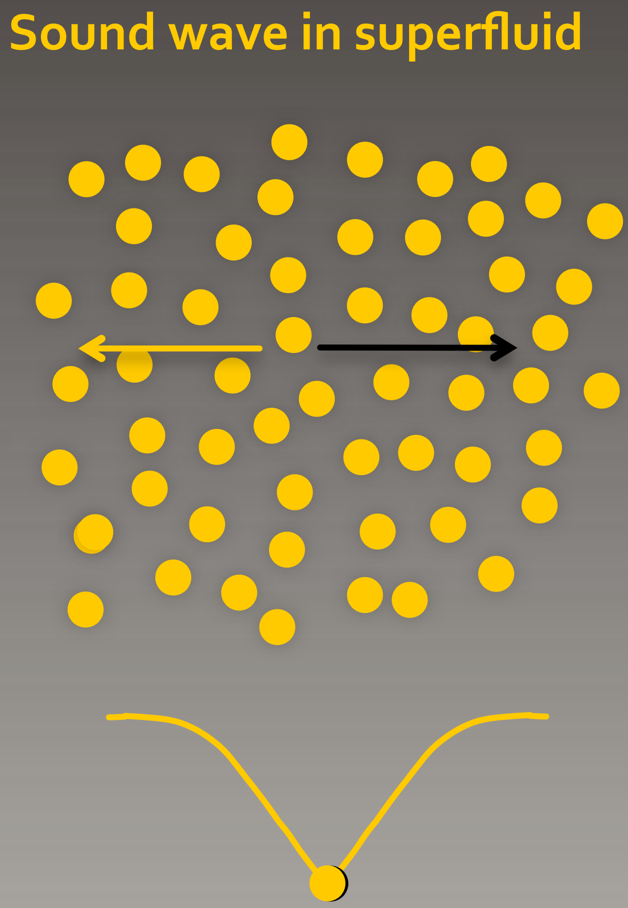
Superfluid Helium fountain



N. N. Bogoliubov.
On the theory of superfluidity.
J. Phys. (USSR), (1947)

Naive picture of the ghost branch

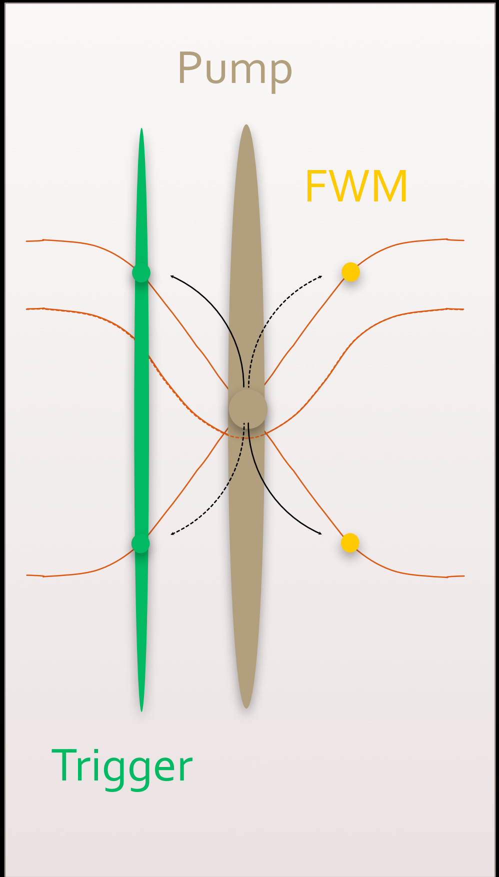




Particle-hole superposition

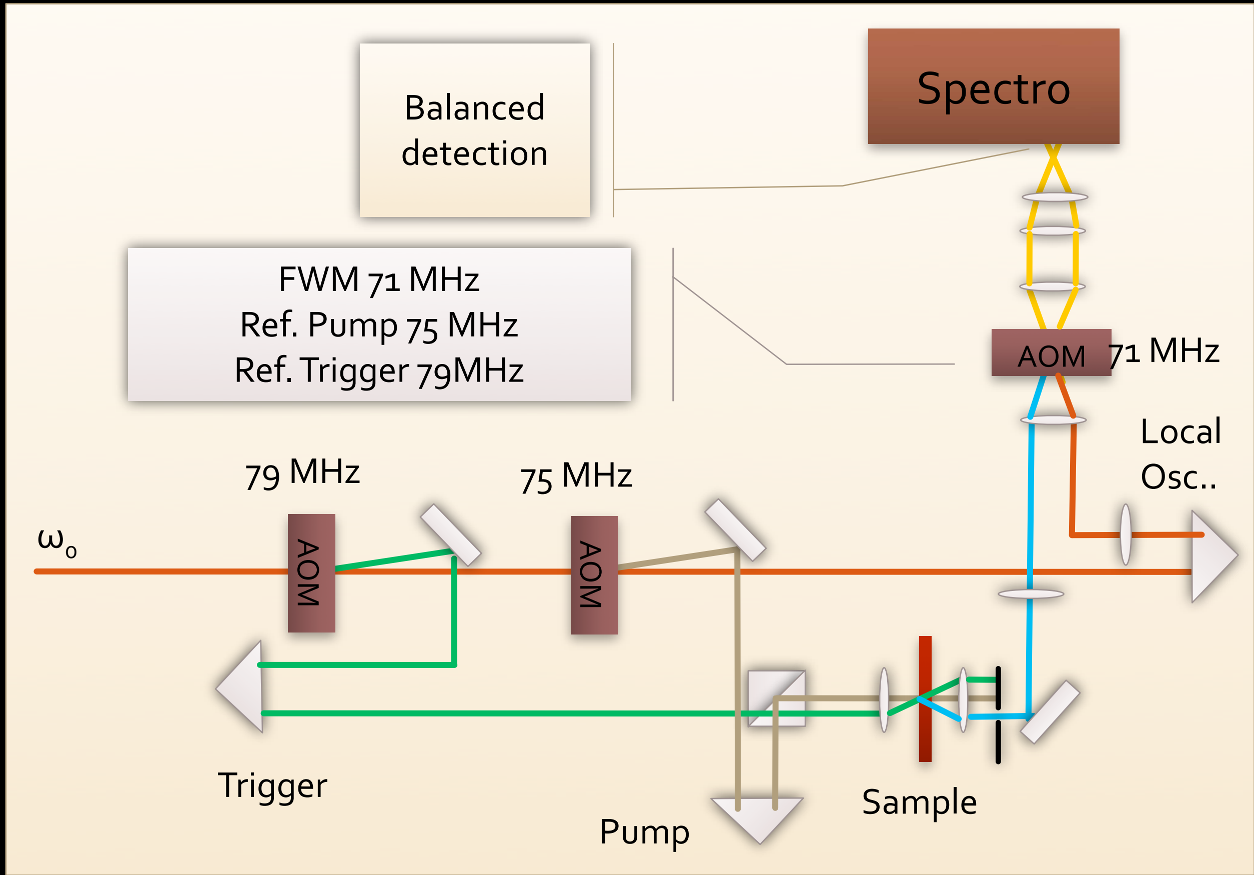
Coherent excitation

Pulsed resonant excitation



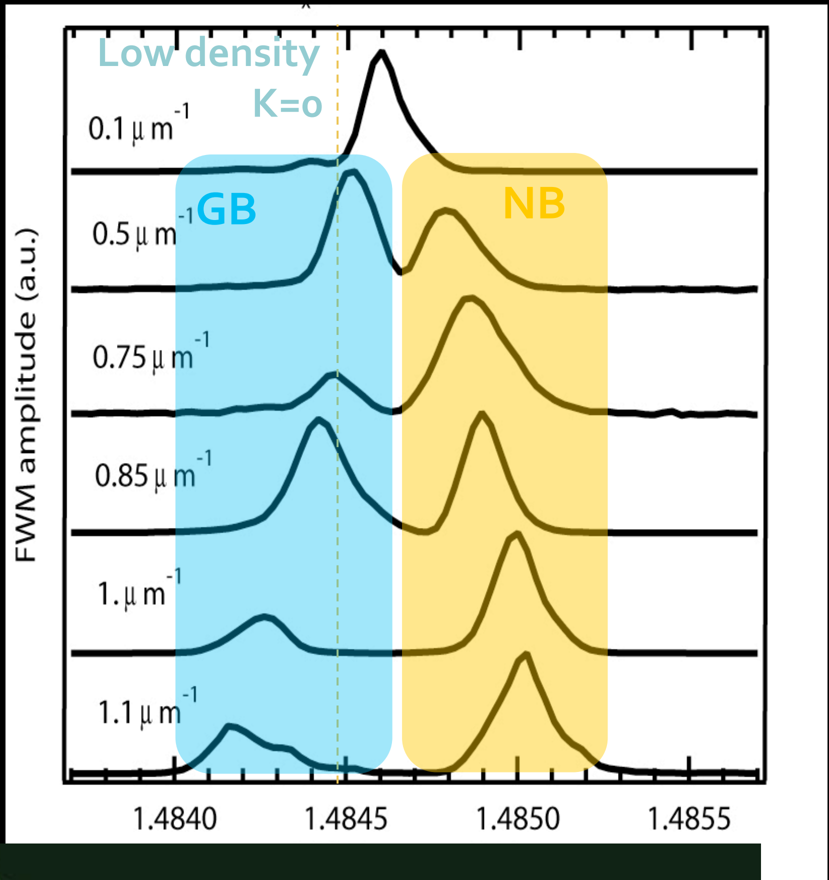
Spectral interferometry

Energy selection

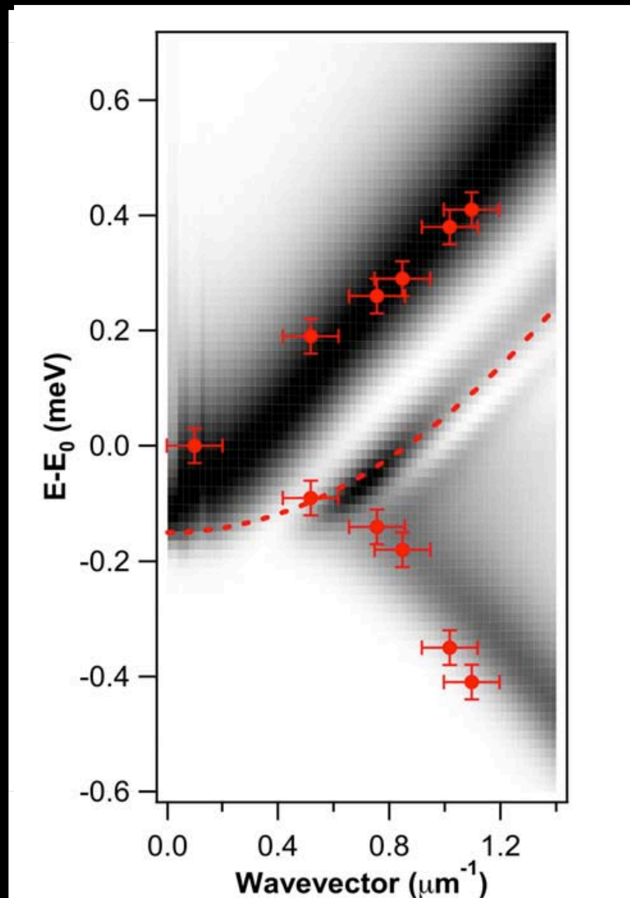


Polariton Ghost Branch

Normal & ghost branch



Damping of polariton density!



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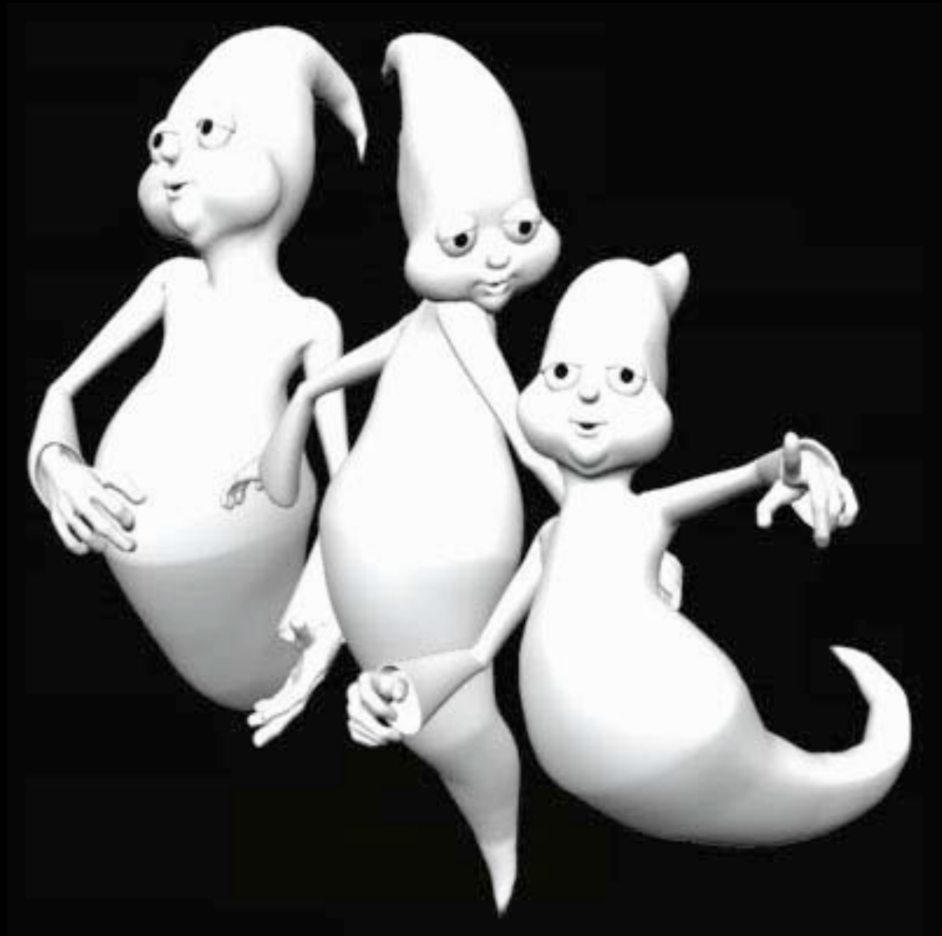
Kohnle et al, *Phys. Rev. Lett.* (2011)

How to observe superfluidity?
not only Ghosts



PRL 105, 020602 (2010) PHYSICAL REVIEW LETTERS week ending 9 JULY 2010

Superfluidity and Critical Velocities in Nonequilibrium Bose-Einstein Condensates

Michiel Wouters[1] and Iacopo Carusotto[2]

Polariton flow

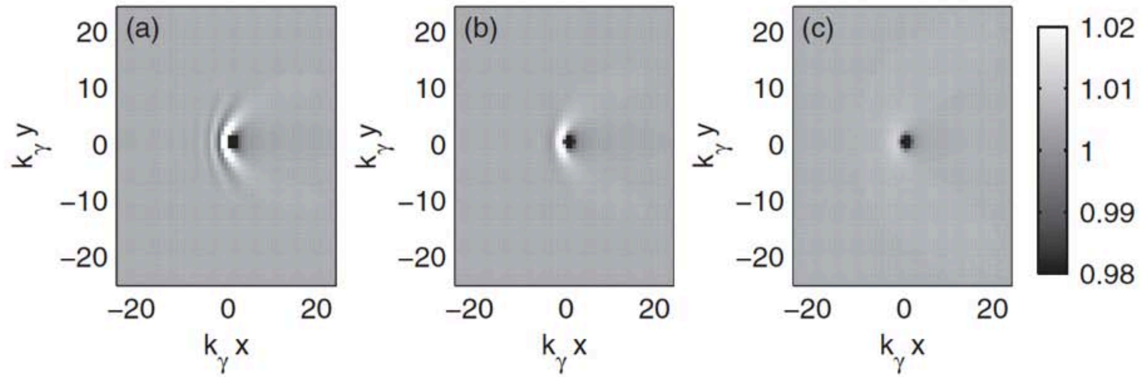


FIG. 3. Density perturbation created in a moving condensate by a stationary weak defect for three values of the condensate velocity $v/c_s = 1.5, 1, 0.4$ across the critical value for superfluidity. Parameters: $n_c g/\gamma = n_c r/\gamma = 1$, $\Omega_K/\gamma = 50$.

Physical Review Letters
moving physics forward

Wouters et al, Phys. Rev. Lett. 2010

nature physics
LETTERS
PUBLISHED ONLINE: 20 SEPTEMBER 2009 | DOI: 10.1038/NPHYS1364

Superfluidity of polaritons in semiconductor microcavities

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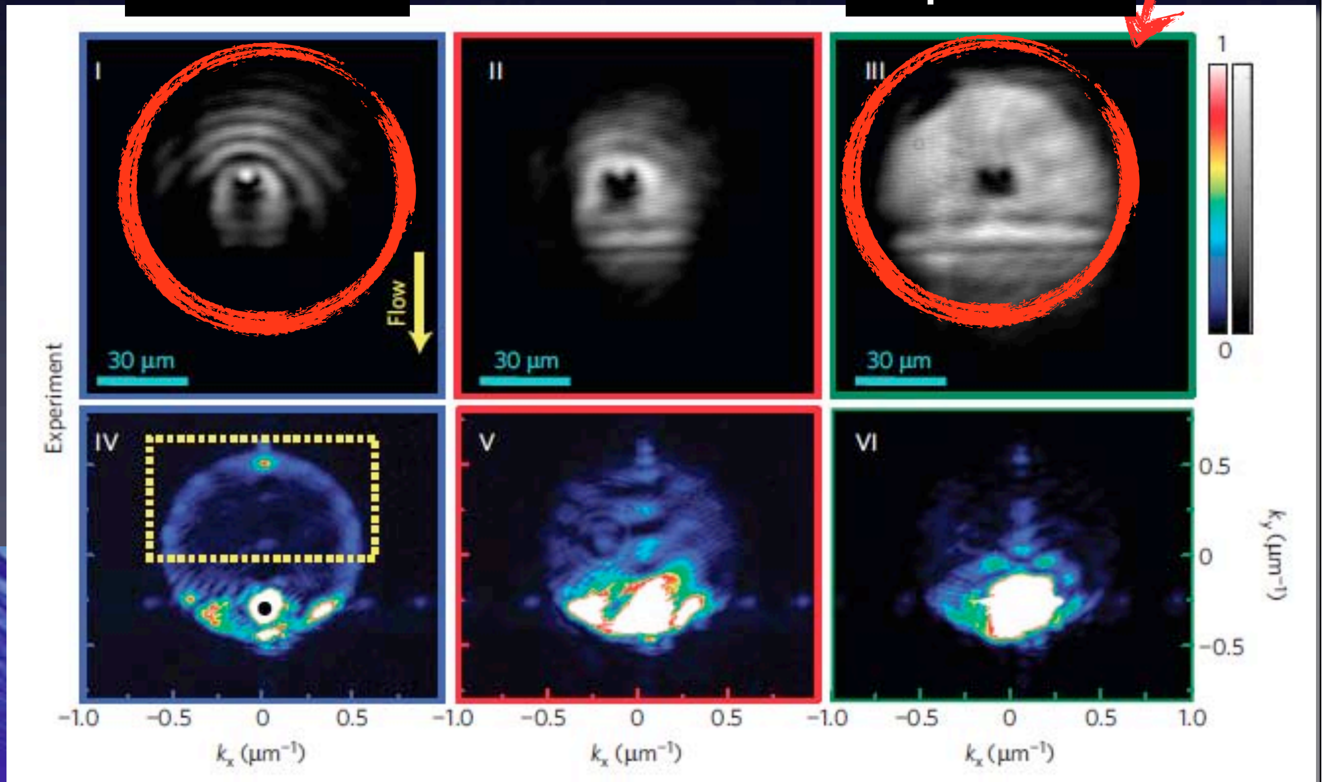
cw laser

Polariton density : sound speed

Polariton flow

Cerenkov

Superfluid



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Theoretical Background

Gross-Pitaevskii equation:

$$i\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m} \nabla^2 \psi + V\psi + g\,|\psi|^2\,\psi - i\frac{\gamma}{2}\psi + |F_p| e^{i(\omega_p t - k_p r)}$$

External Potential: Obstacle

Dissipative Term

Pulsed Excitation

Relevant terms for Quantum Hydrodynamics :

$$v_{flow} = \frac{\hbar k_{\parallel}}{m}$$

- Controlled by the injection moment
- Accessed experimentally from the polariton phase

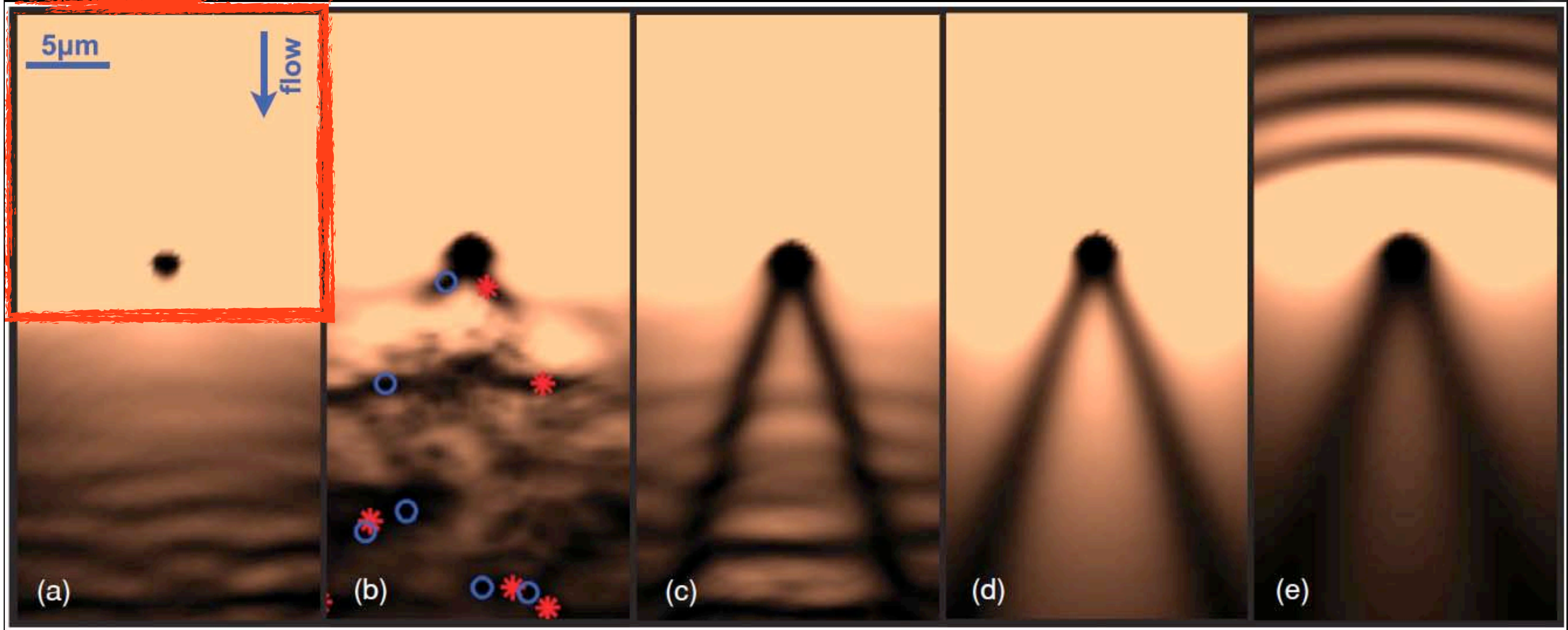
$$c_s = \sqrt{\frac{g|\psi|^2}{m}}$$

- Controlled by the pump power
- Estimated experimentally from polariton emission

Hydrodynamics of polariton fluids

Fluid speed

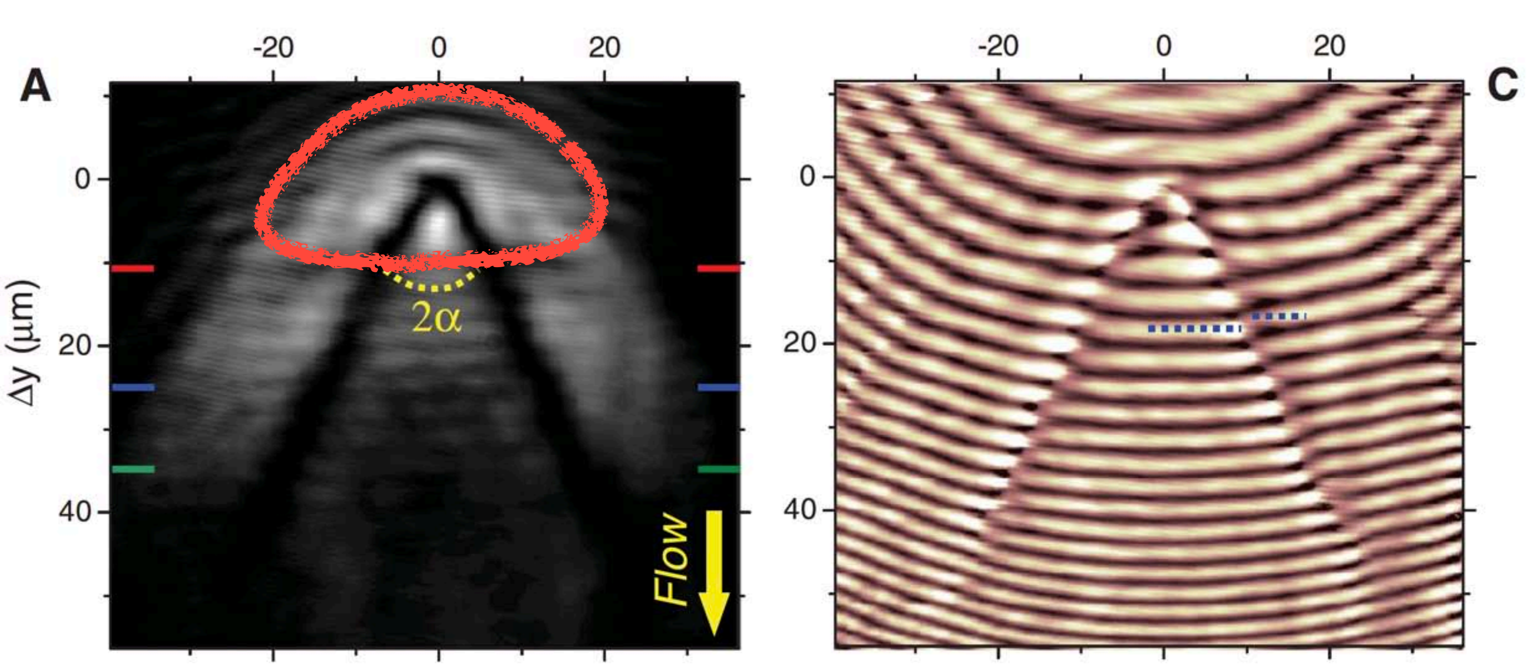
Laser spot



Physical Review B
condensed matter and materials physics

Pigeon et al, PRB, 83, 144513 (2011)

Dark solitons in polariton fluids



Polariton Superfluids Reveal Quantum Hydrodynamic Solitons
A. Amo *et al.*
Science **332**, 1167 (2011);
DOI: 10.1126/science.1202307

What are Solitons?

Solitary waves on River Dordogne in France

- Solitary waves which propagate maintaining their shapes
- Solutions of nonlinear equations

$$i\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m} \nabla^2 \psi + V\psi + g|\psi|^2 \psi$$

- Result from the compensation between the dispersive and interaction terms

Repulsive interaction $g > 0$ ⟹ DARK SOLITONS

Turbulence in quantum fluids

SUPERFLUID

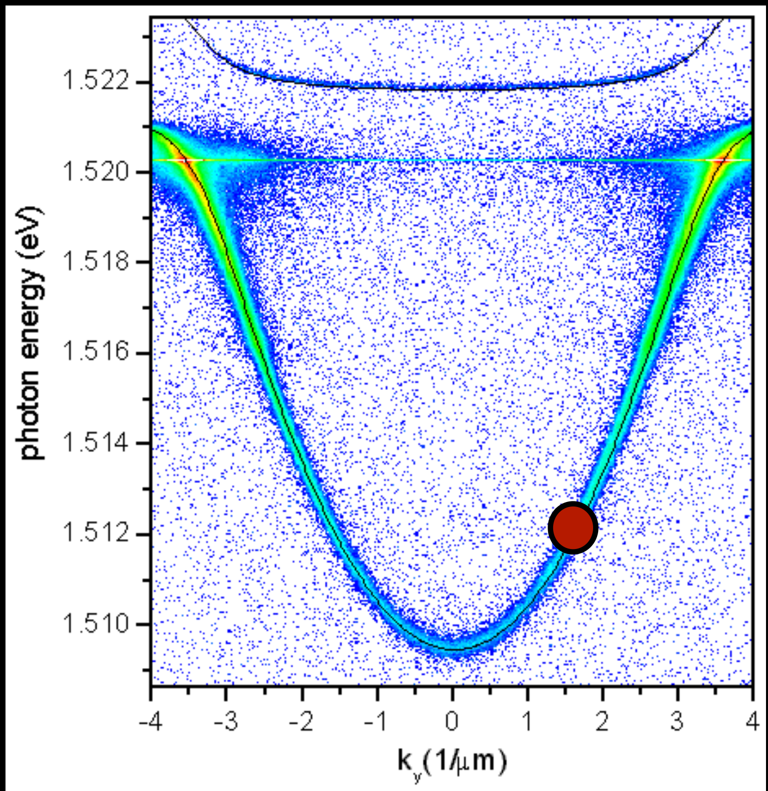
Drag force
+
Nucleation of
vortex pairs

Cerenkov

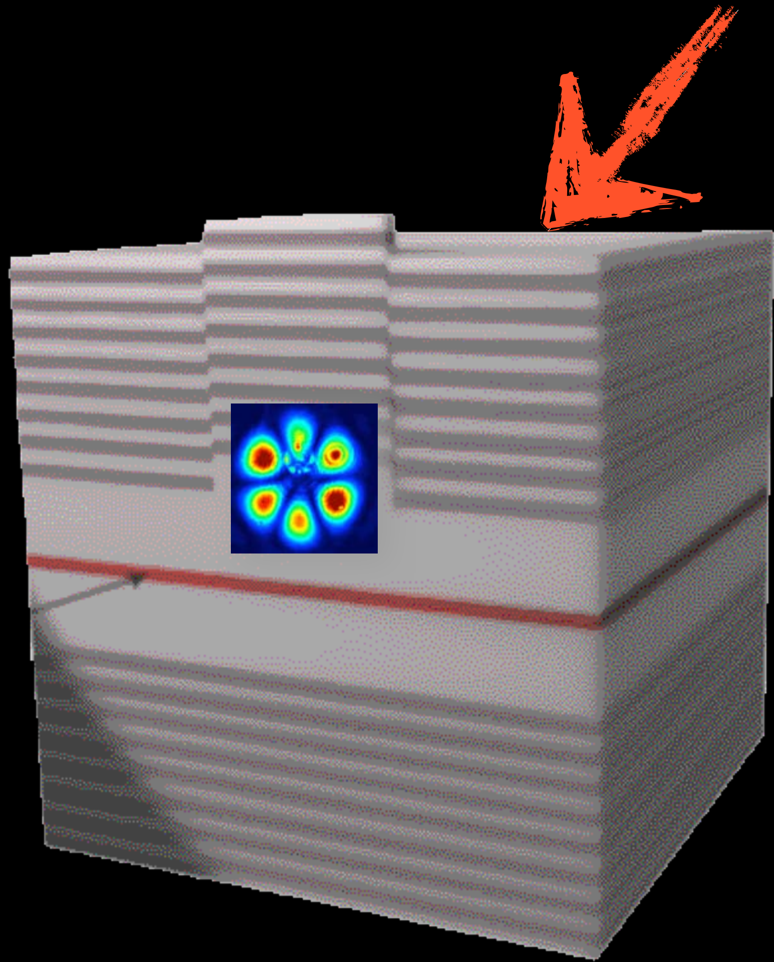
Sound speed c_s

Fluid velocity

How do we probe this dynamically?



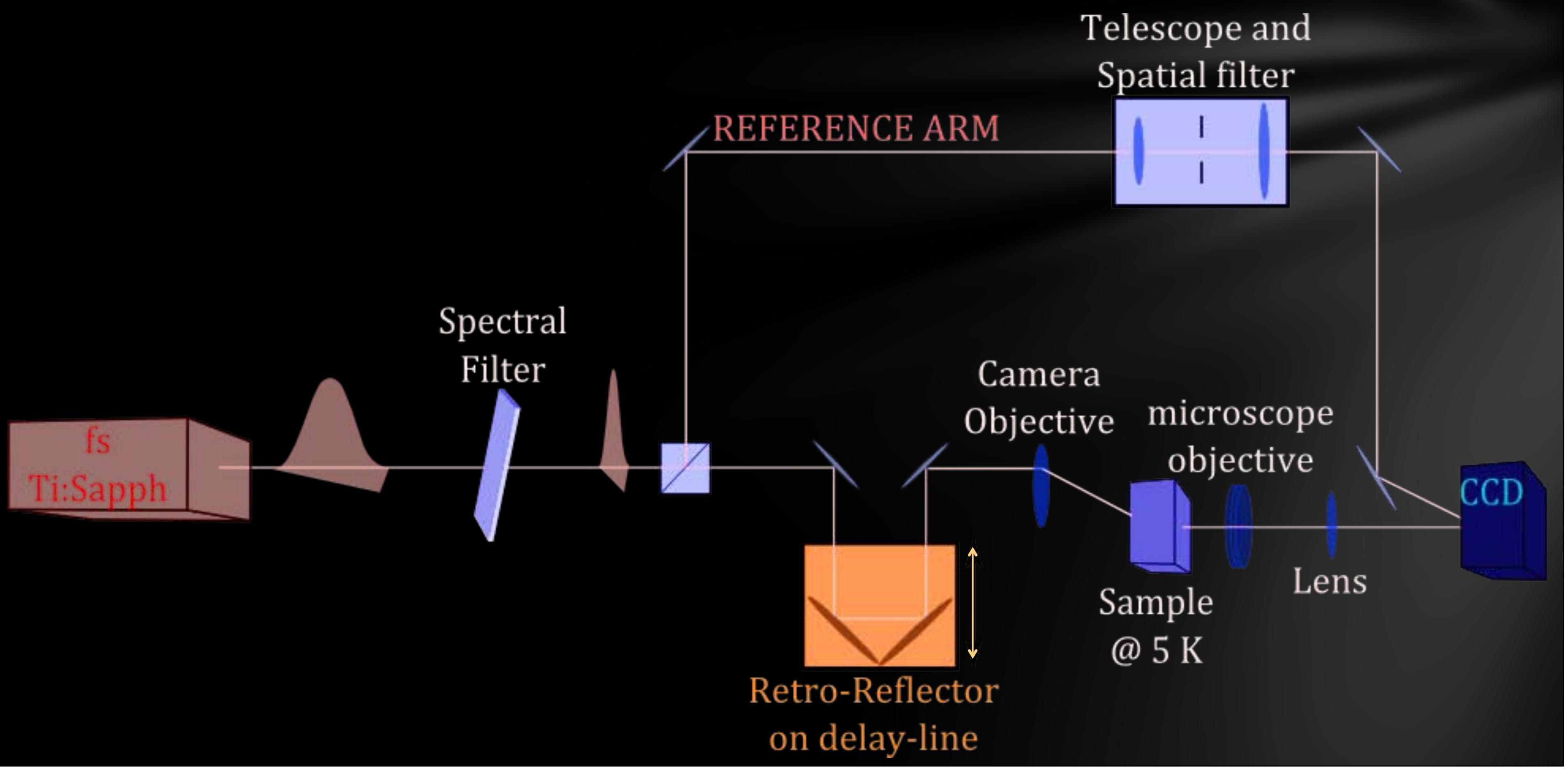
We excite the fluid at
a given wavevector



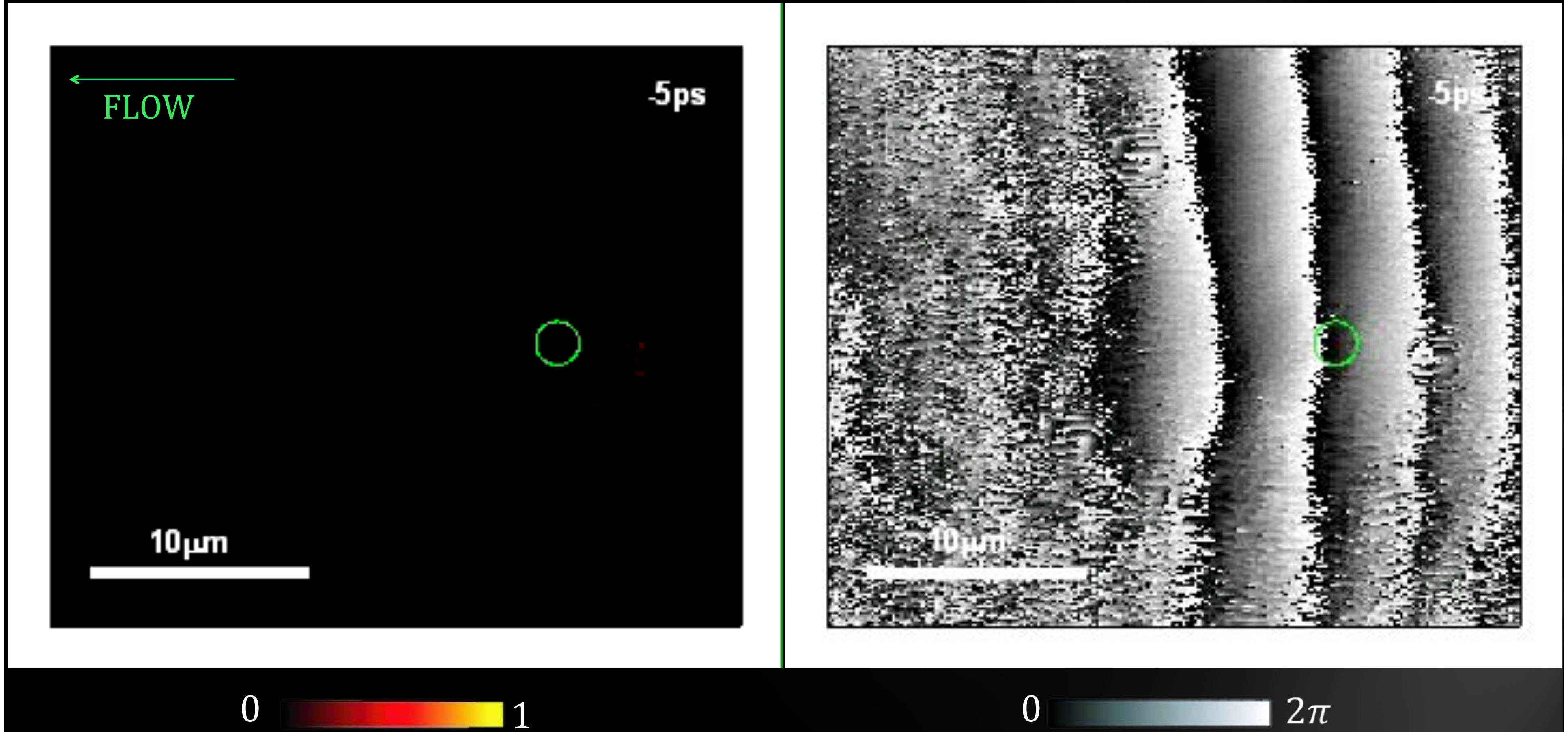
And send the fluid
Against an obstacle

Experimental Setup : Homodyne detection

- Resonant Pulsed Excitation, momentum control
- Mach-Zehnder Interferometer : Phase and time imaging



Vortex Pairs in the wake of an obstacle



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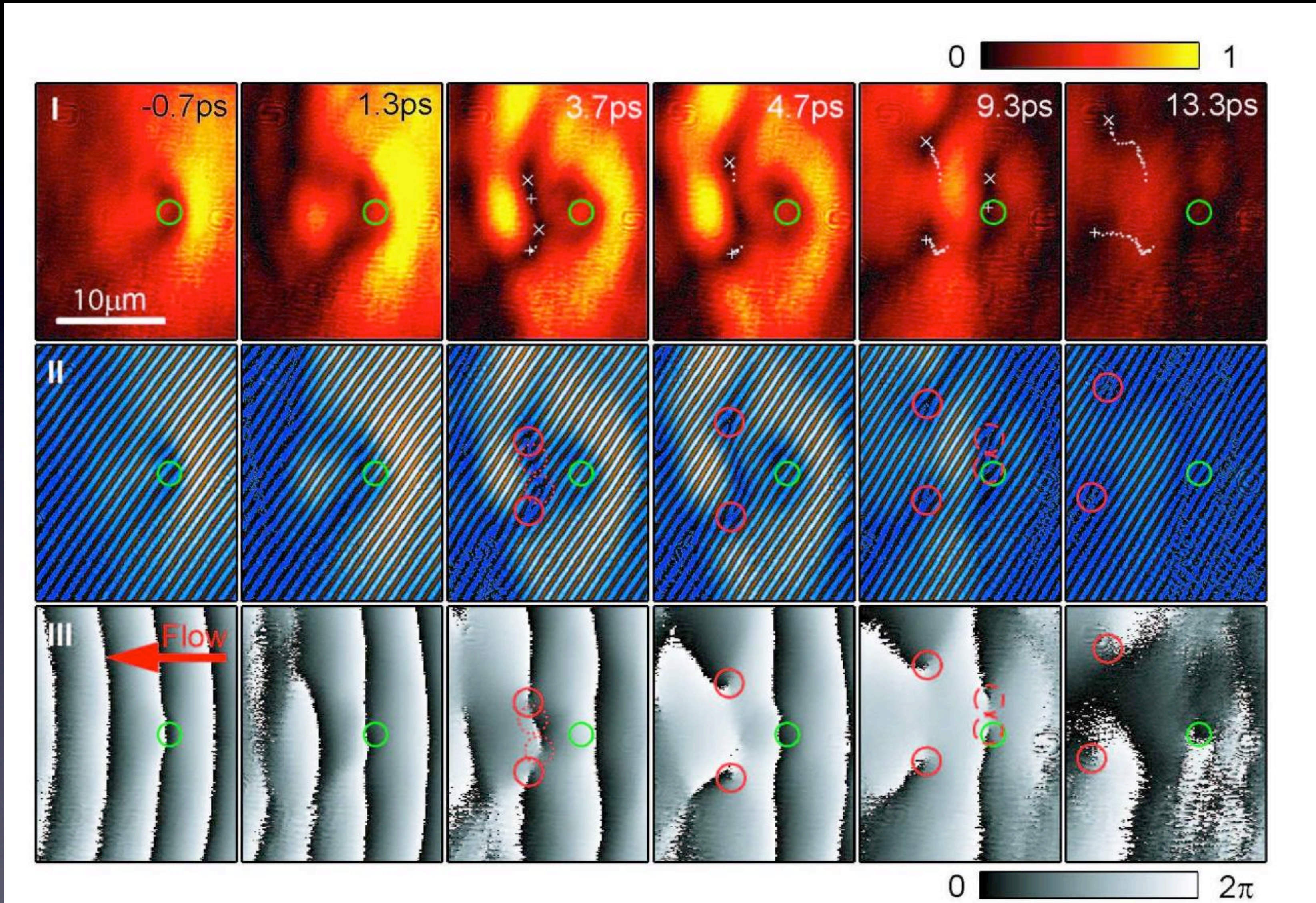
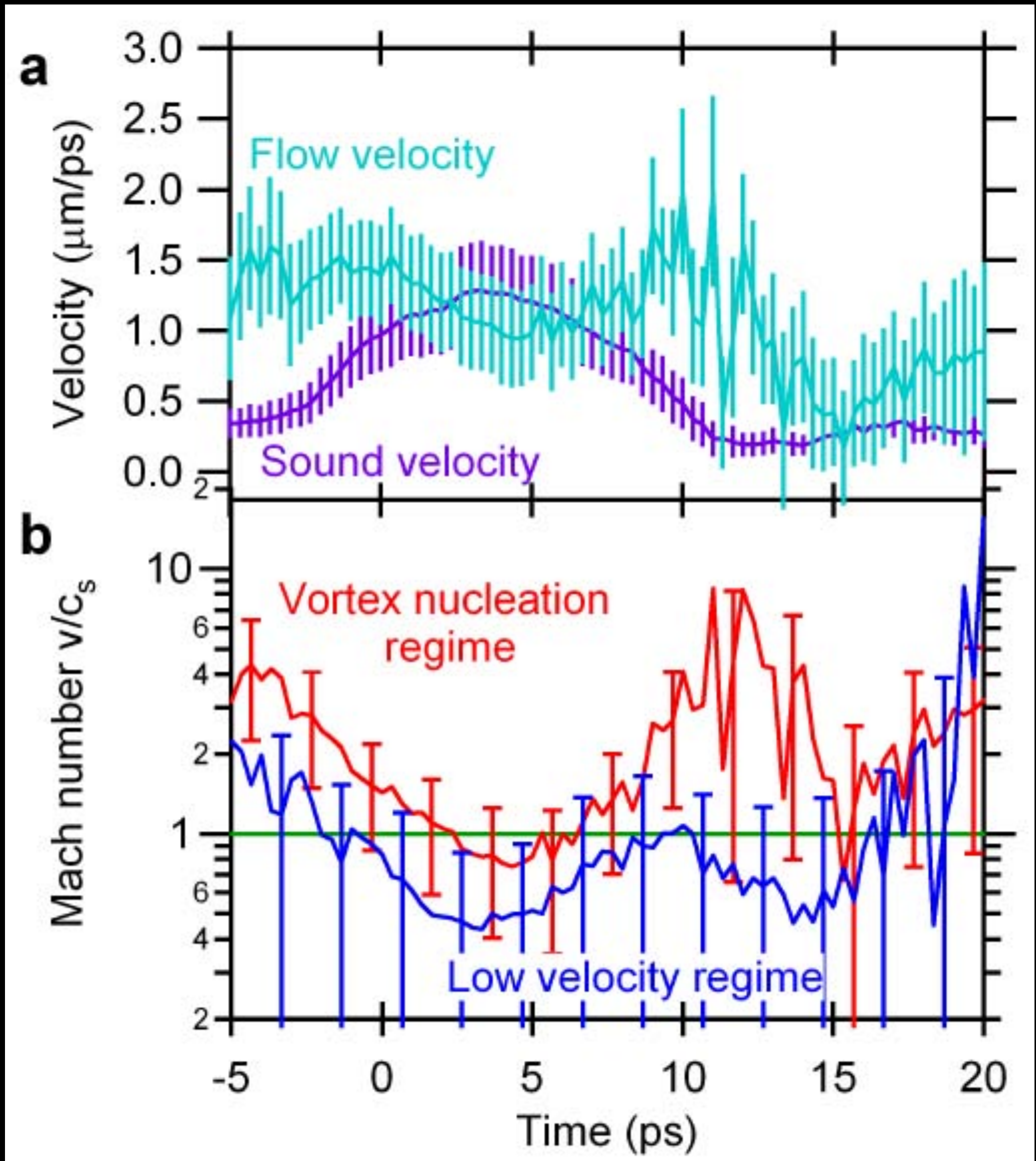
G. Nardin, G. Grosso *et al*, Nature Physics 7, 635–641 (2011)

Vortex nucleation regime



Vortex Pairs Nucleation Conditions



Experimental values of local v and c_s are estimated in the perimeter of the obstacle

MACH NUMBER

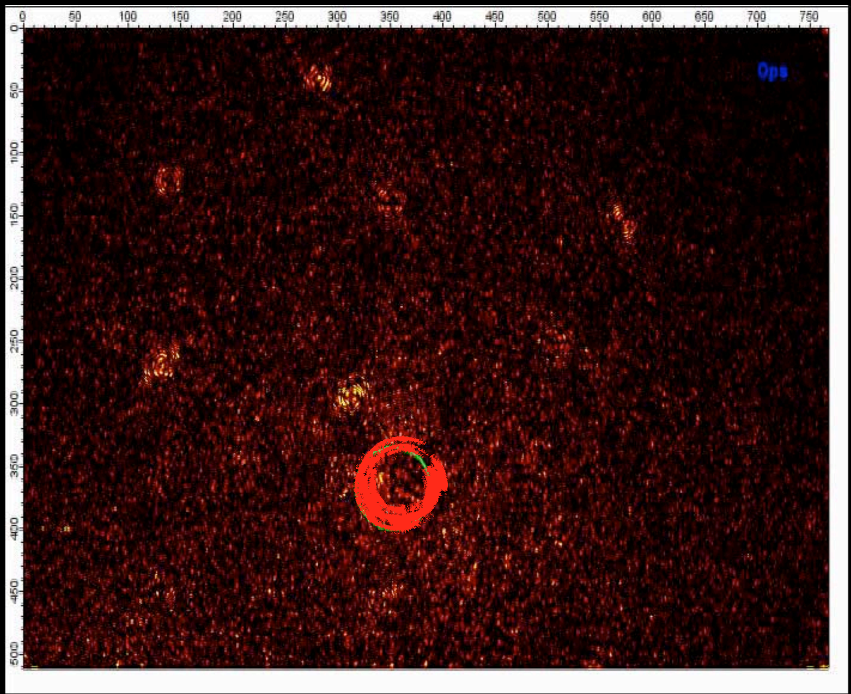
$$v_{flow} = \frac{\hbar k_{\parallel}}{m}$$

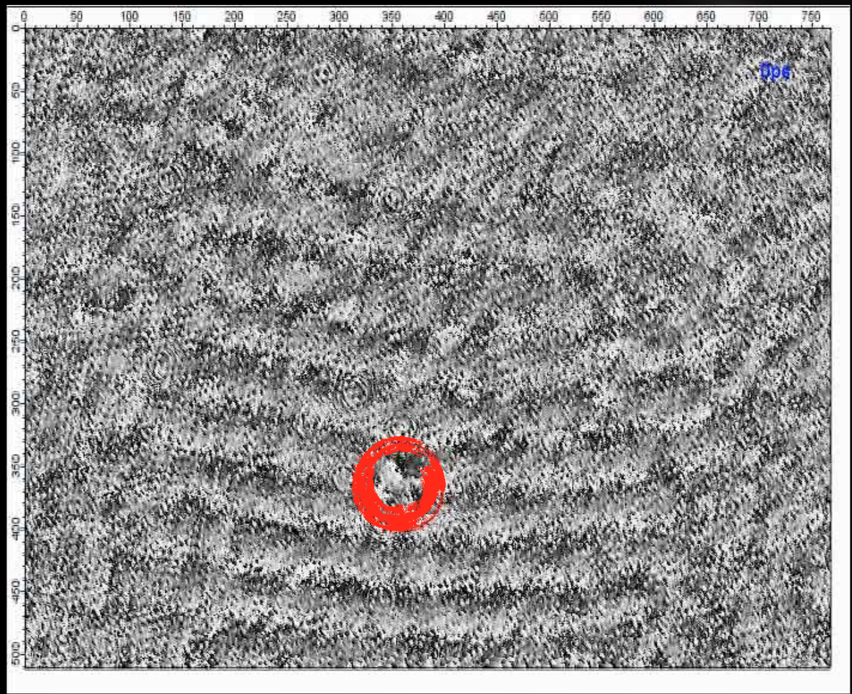
$$c_s = \sqrt{\frac{g|\psi|^2}{m}}$$

$$\Rightarrow M = \frac{v_{flow}}{c_s}$$

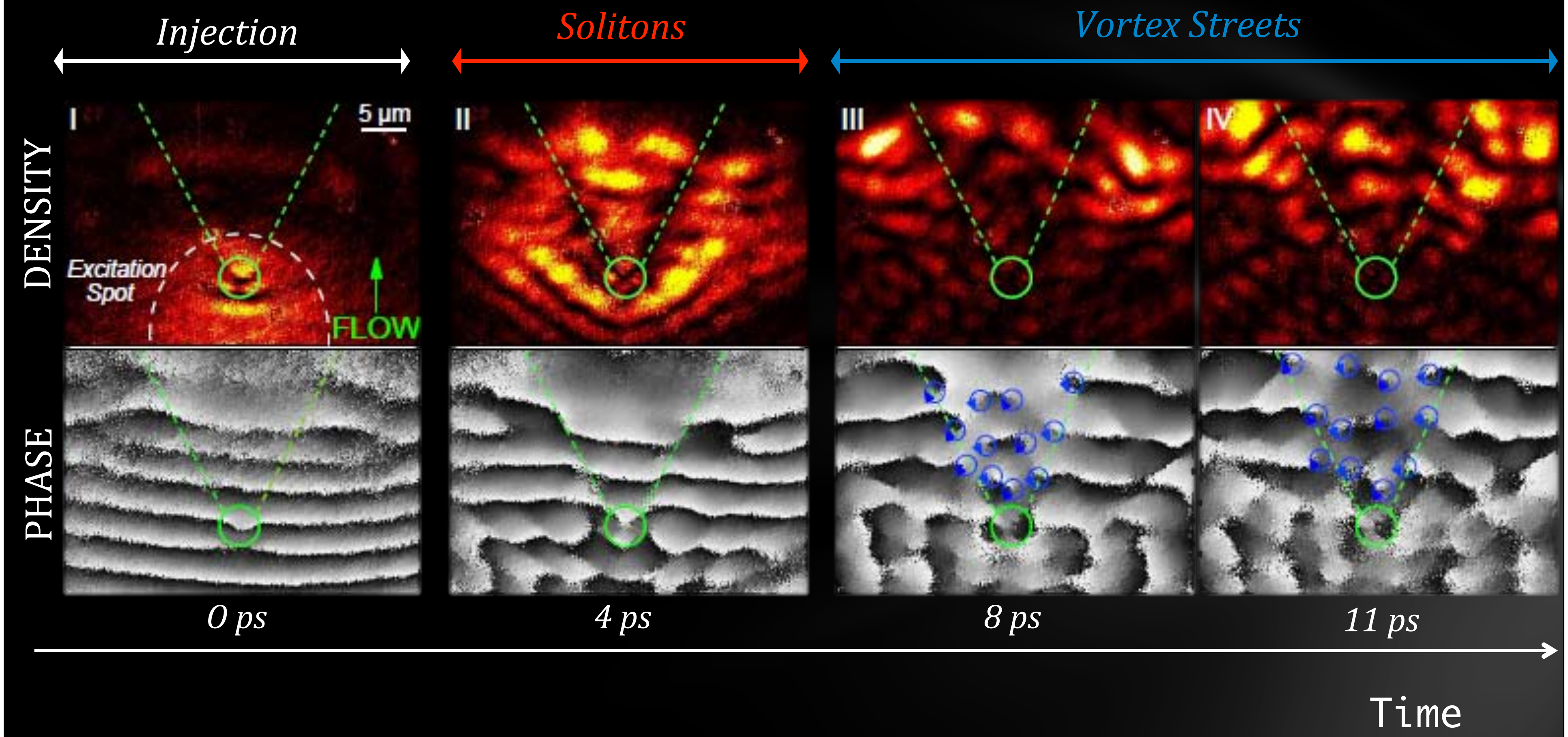
G. Nardin, G. Grosso *et al,* Nature Physics 7, 635–641 (2011)

Dark solitons
in the wake of a 3μm mesa





Discociation of Dark Solitons into vortices



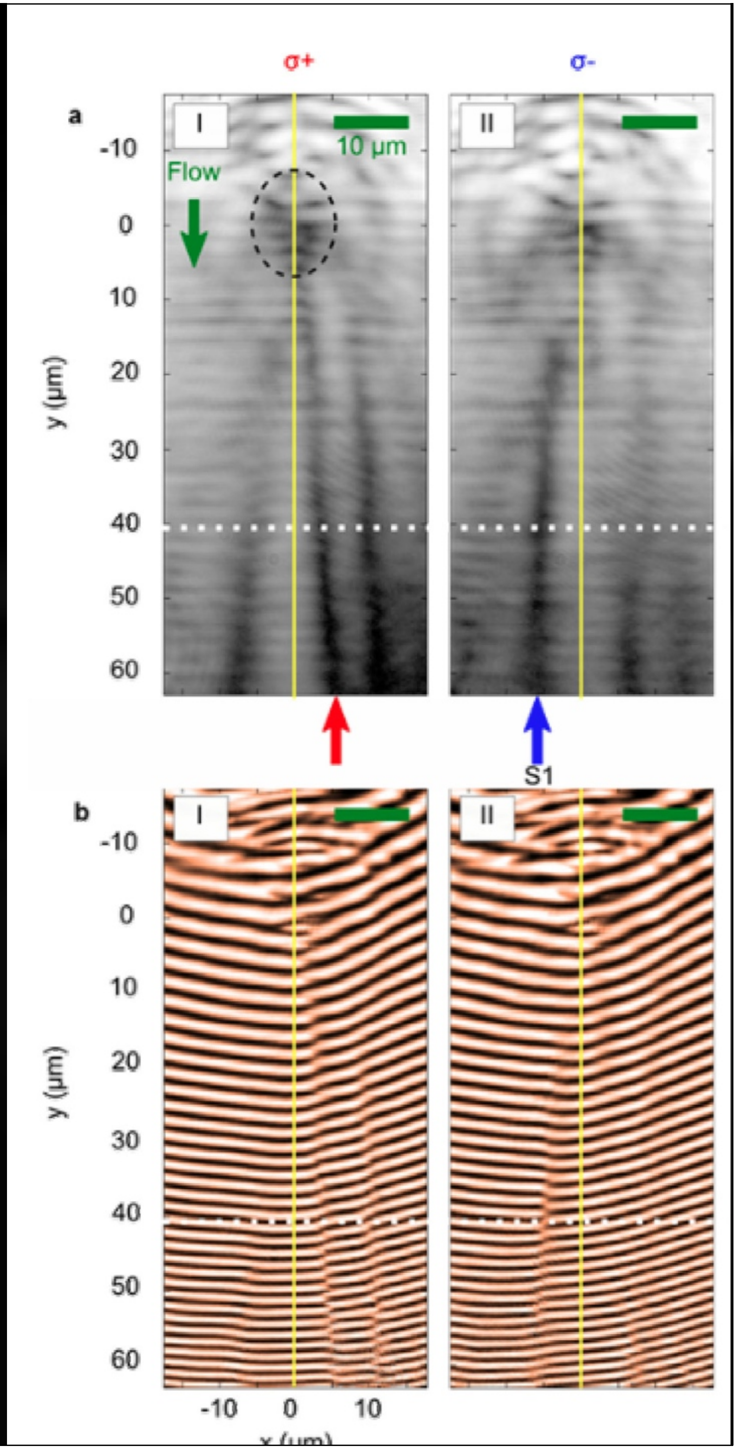
- Characteristic soliton profile along transversal direction
- Width constant during the whole soliton lifetime

Next ?

Many things

For example :

Half solitons

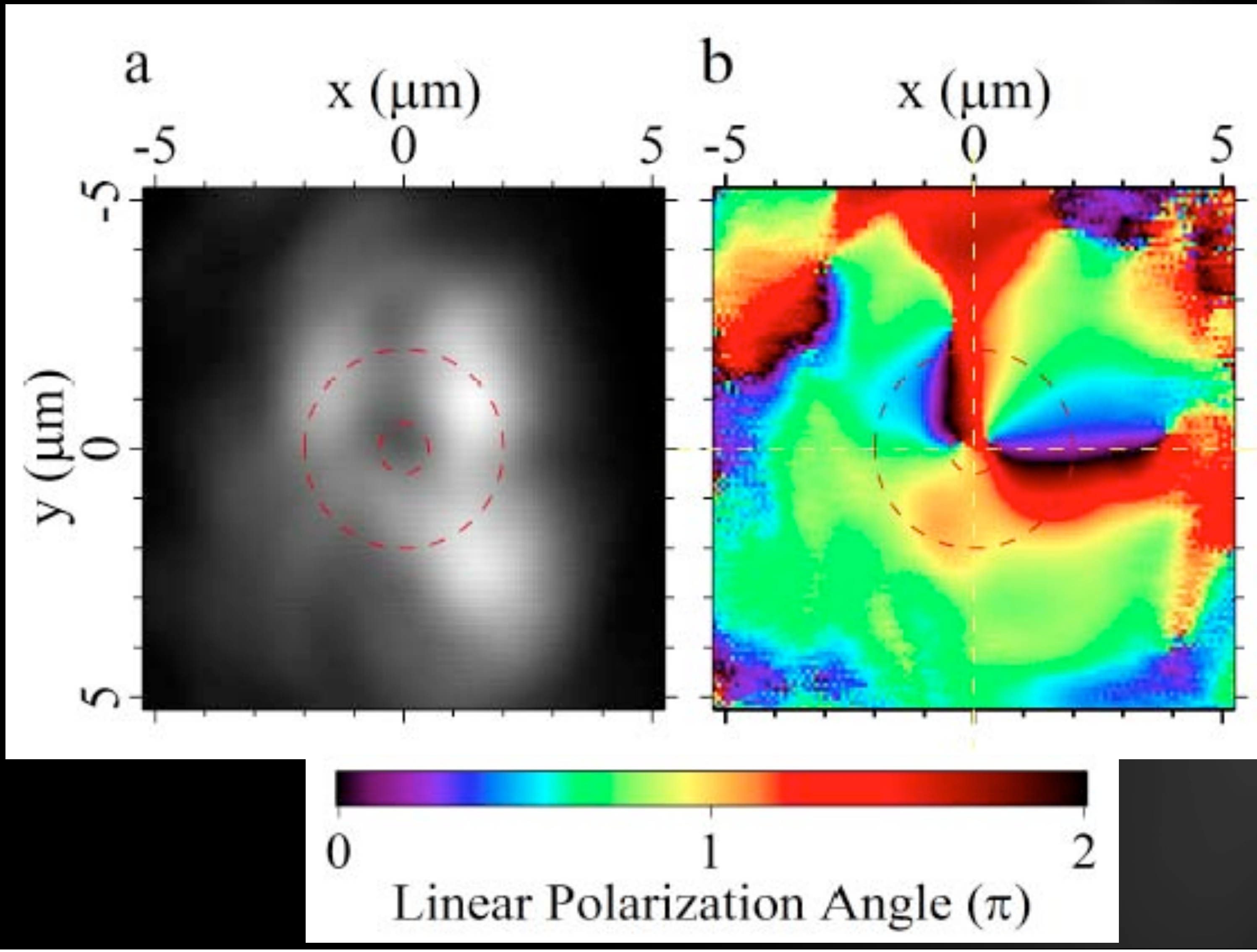


Hivet et al. ArXiv.1204.3564

Dissociation of a quantized vortex into 2 half vortices

Francesco Manni et al, submitted Nature Communications

Spin vortices



The dream team

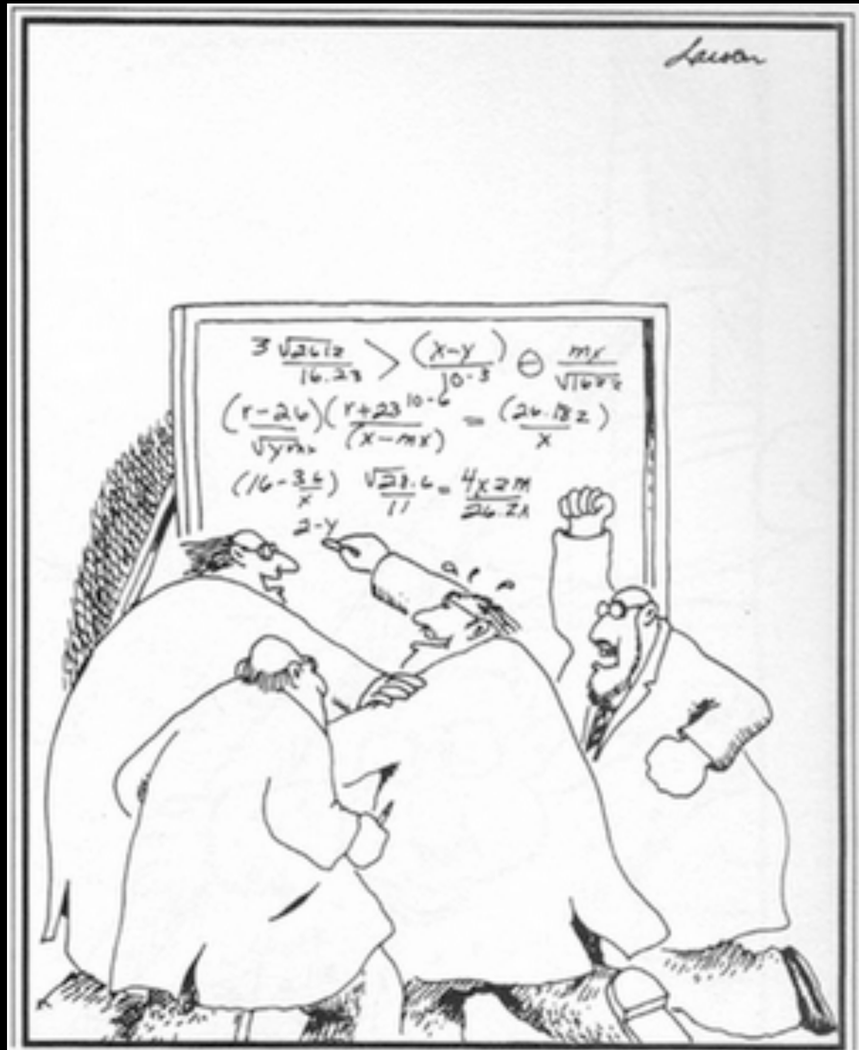
I would to thank our dear theorists

Vincenzo Savona
EPFL

Michiel Wouters
Leuven

Alexei Kavokin
Southampton

Yuri Rubo
Mexico



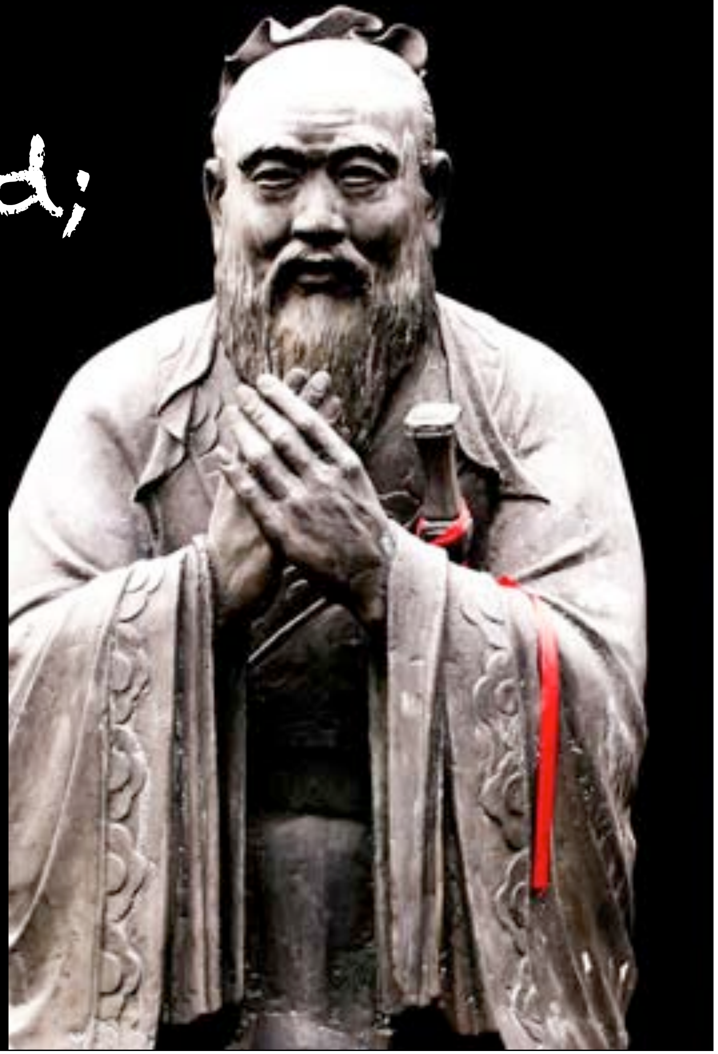
"Go for it, Sidney! You've got it! You've got it! Good hands! Don't choke!"

I leave you with a take home message

"Knowledge is limited; but imagination encircles the world"

Lao Tzu

老子




Thank you / Merci
谢谢