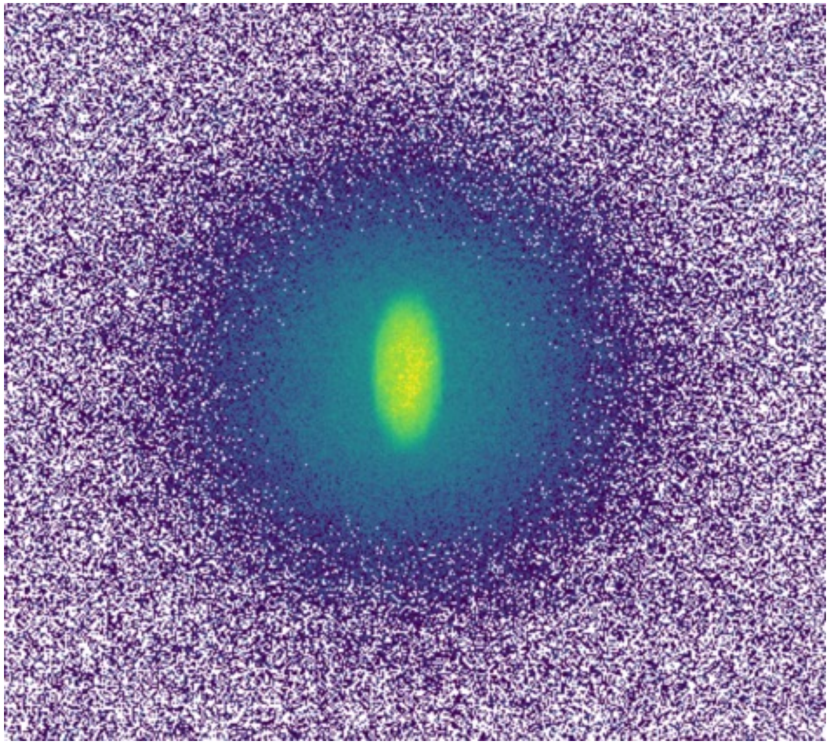
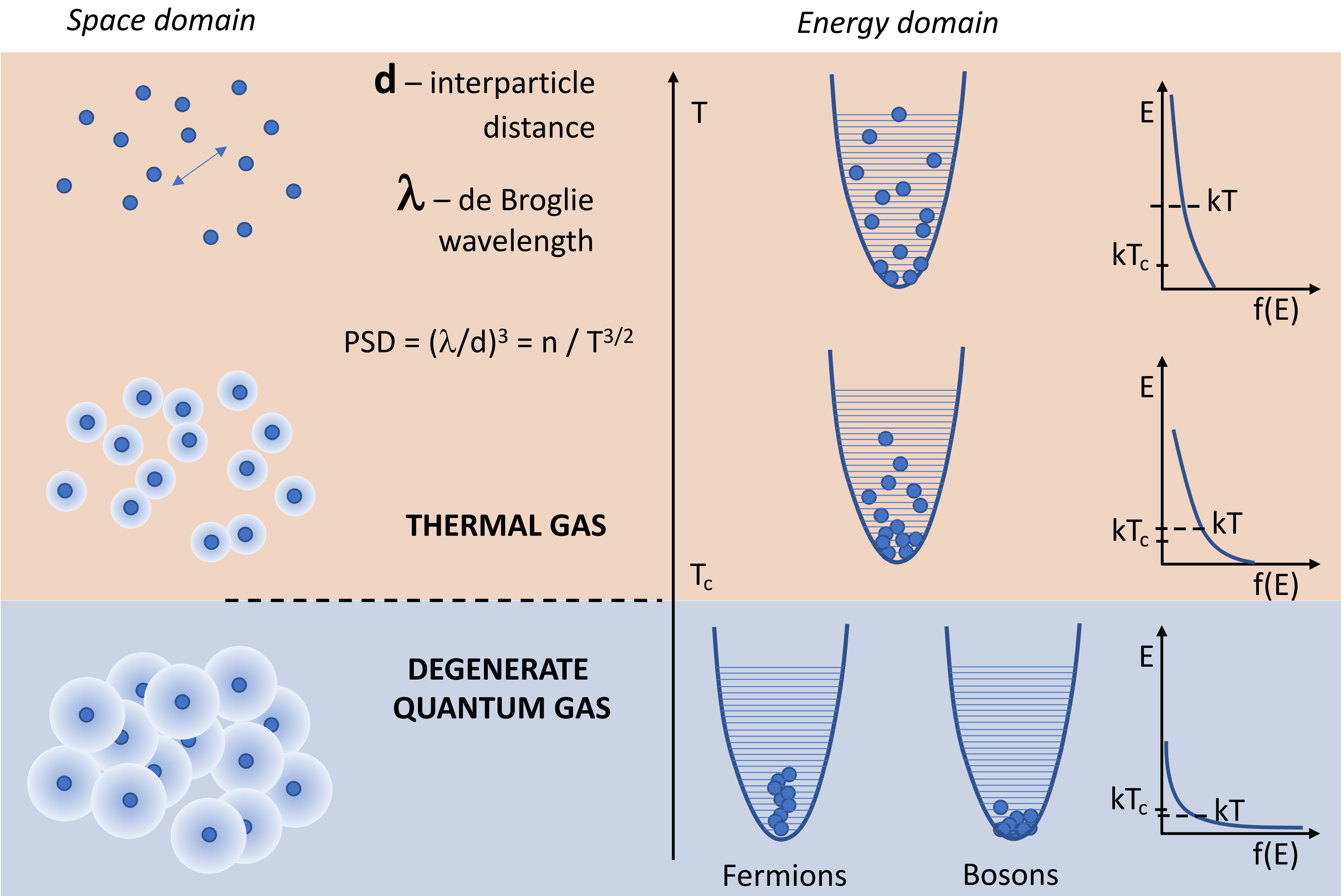


BASIC EXPERIMENTS ON **B**ose - **E**instein **C**ondensates

Giacomo Lamporesi
Pitaevskii BEC Center
CNR-INO / University of Trento
Italy

BEC
CNR-INO ISTITUTO NAZIONALE DI OTTICA CONSIGLIO NAZIONALE DELLE RICERCHE
UNIVERSITÀ DI TRENTO
PROVINCIA AUTONOMA DI TRENTO

BEC



Space domain
Energy domain
d – interparticle distance
λ – de Broglie wavelength
PSD = (λ/d)³ = n / T^3/2
THERMAL GAS
DEGENERATE QUANTUM GAS
T
Tc
E
kT
kTc
f(E)
Fermions
Bosons

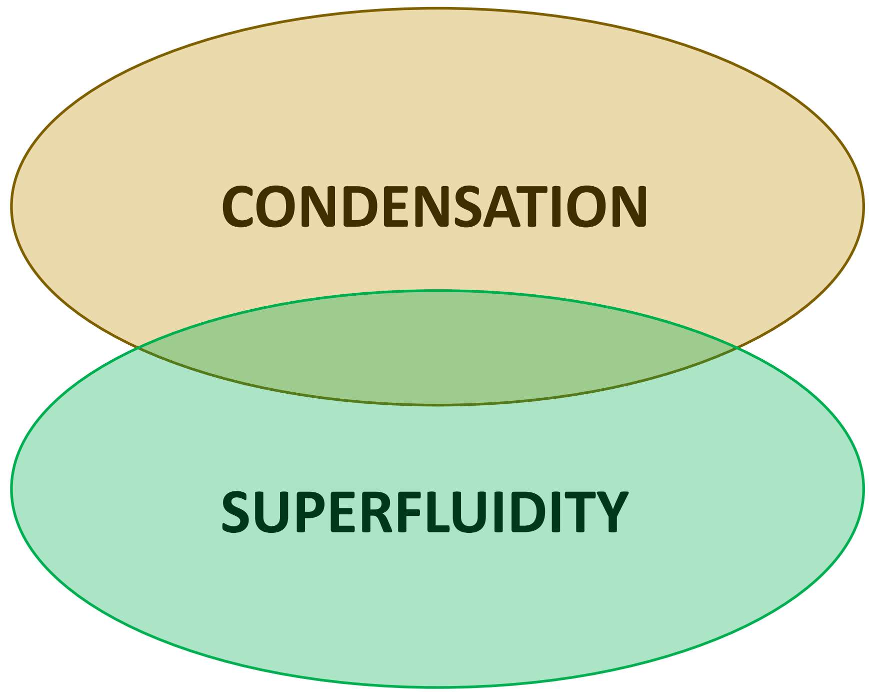
Condensation and superfluidity

Macroscopic occupation of the ground state

Peaked momentum distribution

Long-range coherence

Ideal gases

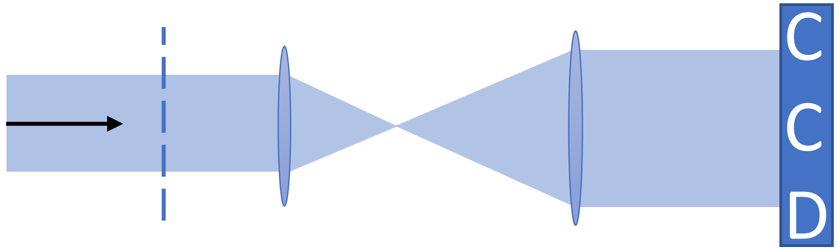


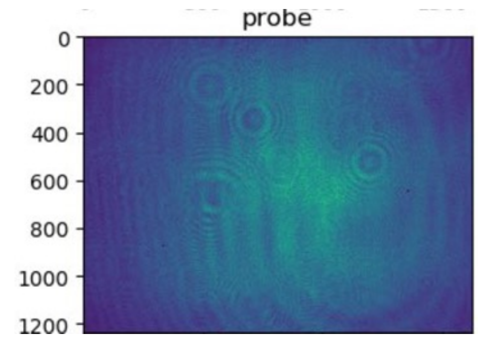
Absence of viscosity

Existence of quantized vortices

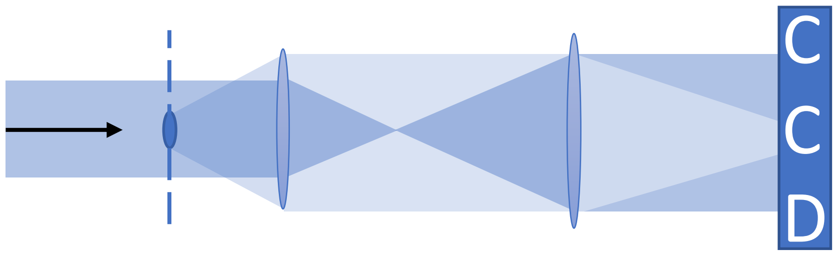
Interacting
Gases in low Dim

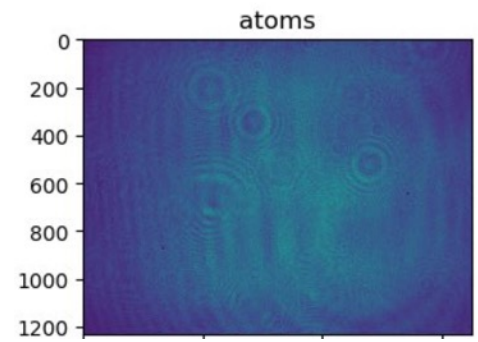
Detection - Imaging





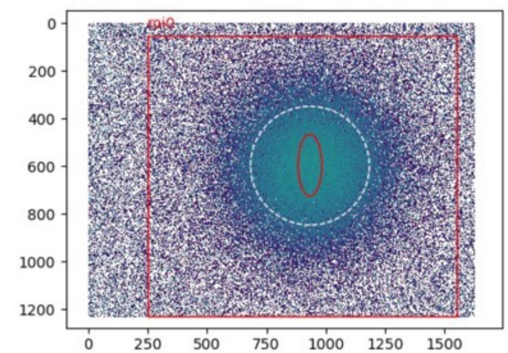
$I_0(y,z)$





$I(y,z)$

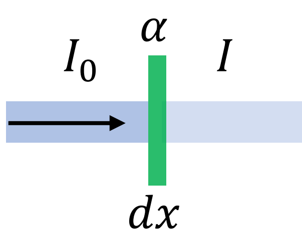
Absorption imaging



$n(y,z)$

Lambert-Beer law

$$dI = -\alpha\, I dx$$



$n(y)$

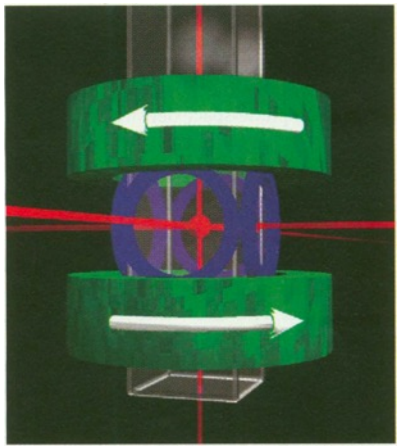
$$ln\left(\frac{I_0}{I}\right) = \int \alpha(x)dx = \sigma_0 \int n(x,y,z)dx = \sigma_0\, n(y,z)$$

First observations: 1995

Laser cooling → Evaporative cooling → ... BEC

(→ Manuele's talk)

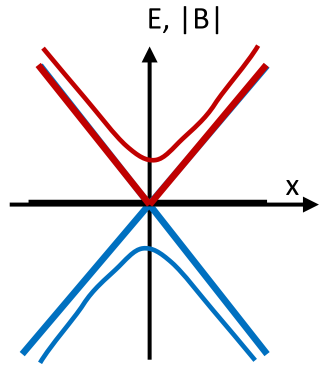
Cornell-Wieman
(JILA, Boulder, Colorado)

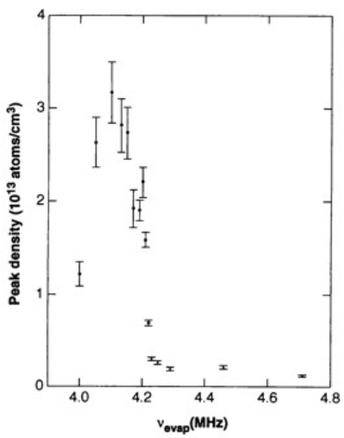


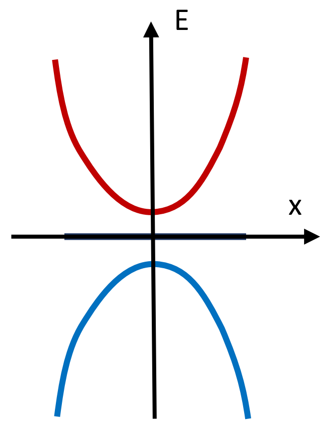
^{87}Rb

TOP trap

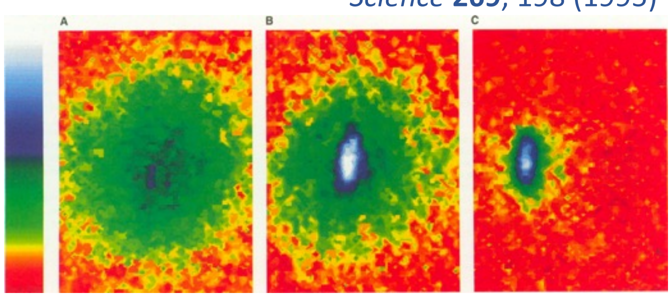
(Quadrupole
+rotating bias)







Science **269**, 198 (1995)

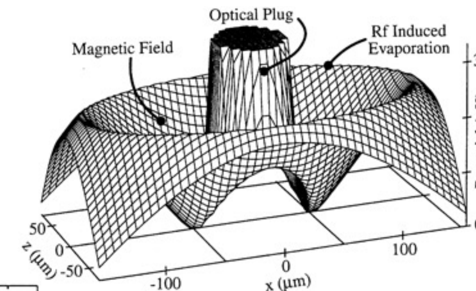


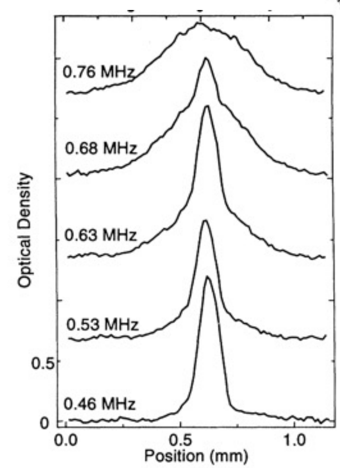
Bimodal distribution
after free expansion

Proof of BEC

Ketterle
(MIT, Boston, Massachussetts)

^{23}Na

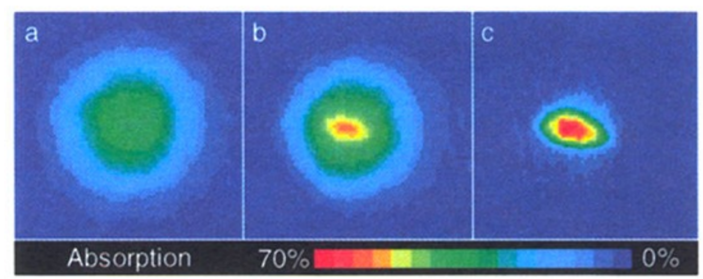




Optically plugged
magnetic trap

(Quadrupole
+repulsive laser)

PRL **76**, 3969 (1995)



Gross-Pitaevskii equation *(→ Russell's talk)*

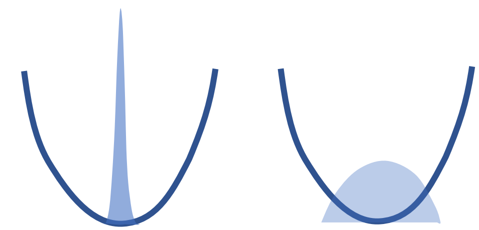
$$\left(-\frac{\hbar^2}{2m}\boldsymbol{\nabla}^2 + V(\boldsymbol{r}) + g|\psi(\boldsymbol{r},t)|^2\right)\psi(\boldsymbol{r},t) = i\hbar\frac{\partial}{\partial t}\psi(\boldsymbol{r},t)$$

Kinetic energy

External potential

Interactions

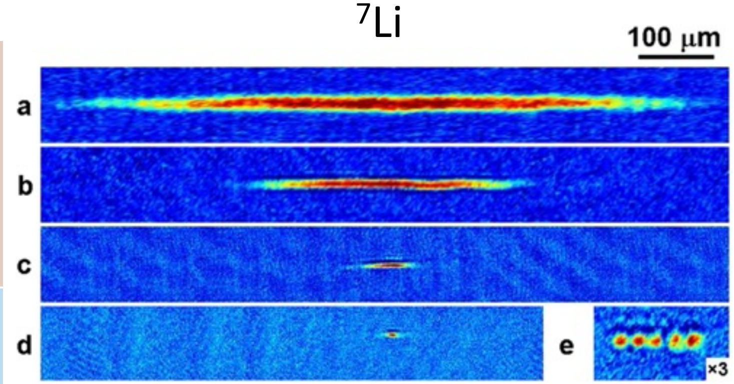
Tunable interactions
(→ Alessandro's talk)



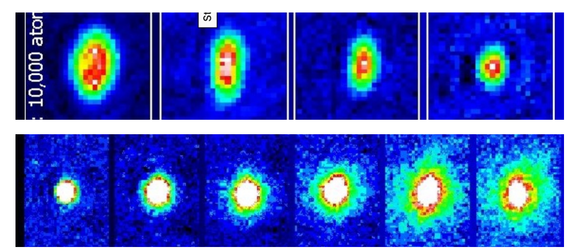
In 3D…

$g > 0$	Repulsive interactions (stable)	BEC of weakly-interacting particles
$g = 0$	No interactions	Ideal BEC
$g < 0$	Attractive interactions (collapse)	«Bose nova»

^{7}Li



PRL **102**, 090402 (2009)

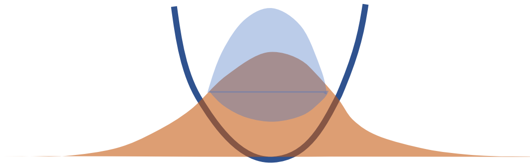


^{85}Rb

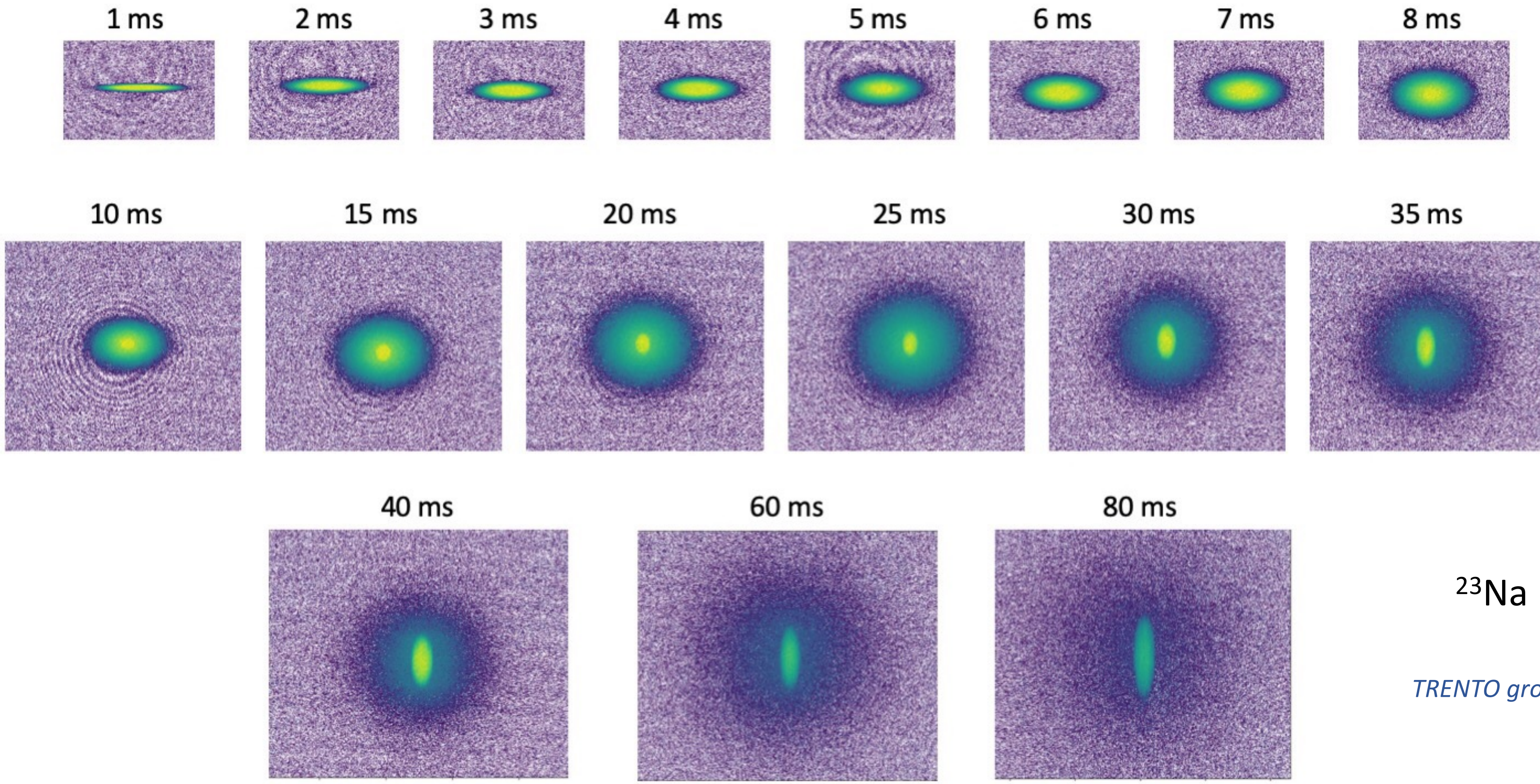
JILA group

Free expansion

Elongated harmonic trap



Short expansion:
-high optical density
-small features
-hard to distinguish the two components



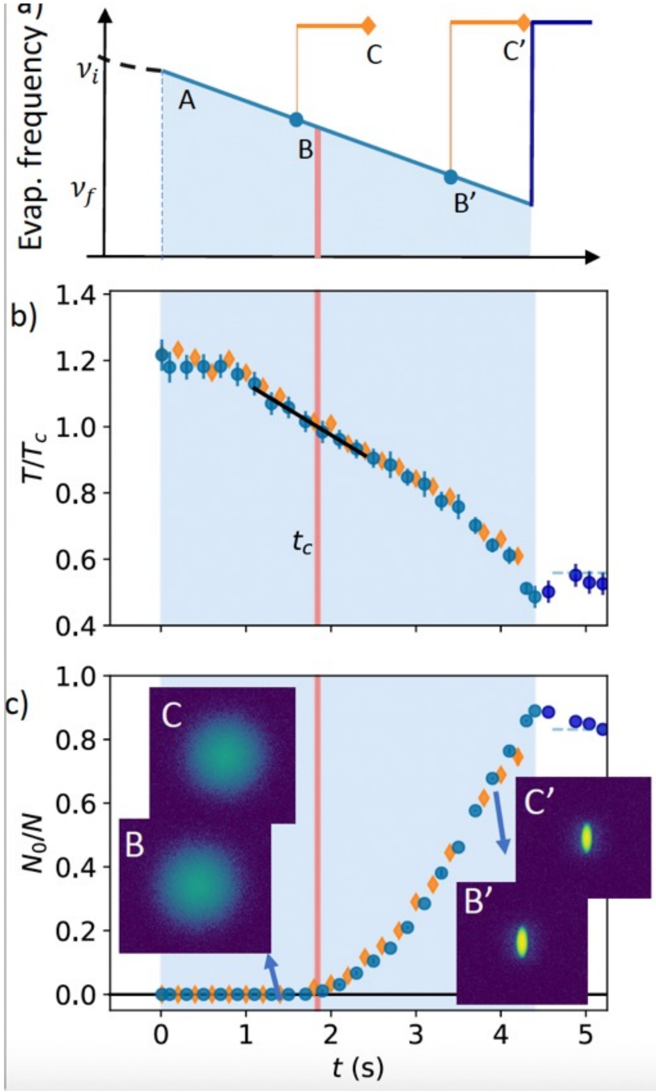
^{23}Na

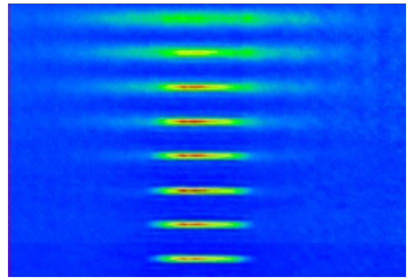
TRENTO group

Long expansion:
-Thermal component tends to n(k) (temperature measurement)
-BEC expansion is domiunated by interactions (Aspect ratio inversion)

Condensate fraction

Cooling across the transition





Science **273**, 84 (1996)

$$kT_c = 0.94\hbar\omega\, N^{1/3}$$

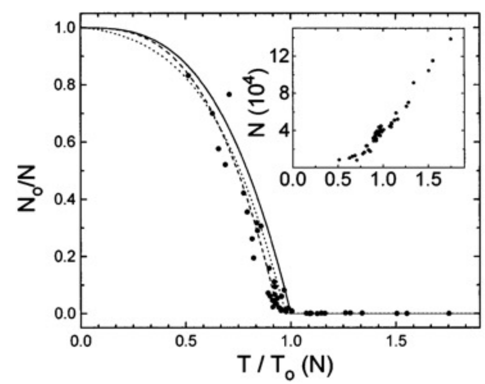
BEC wave function

$$\Psi(\boldsymbol{r}) = \sqrt{n(\boldsymbol{r})}\, e^{-i\varphi(\boldsymbol{r})}$$

Symmetry breaking

Growth of the order parameter

$$\frac{N_0}{N} = 1 - \left(\frac{T}{T_c}\right)^3$$



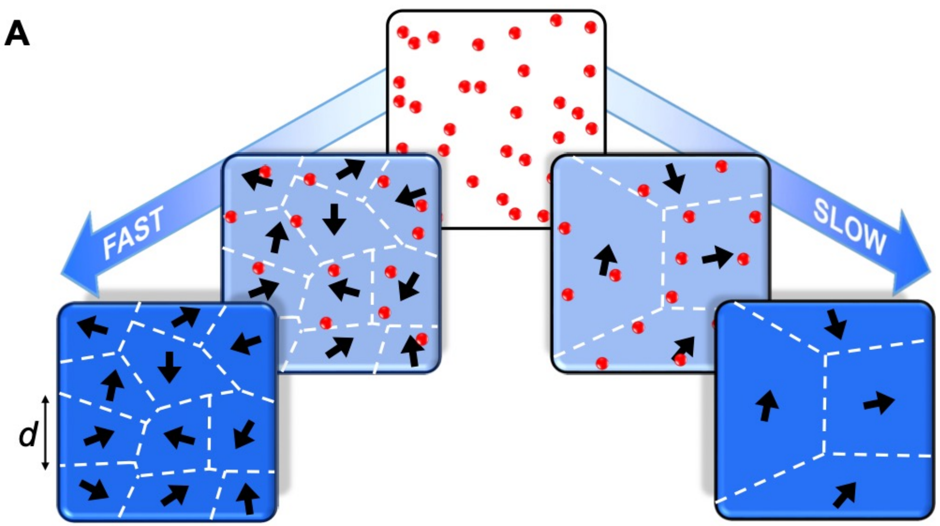
PRL **77**, 4984 (1996)

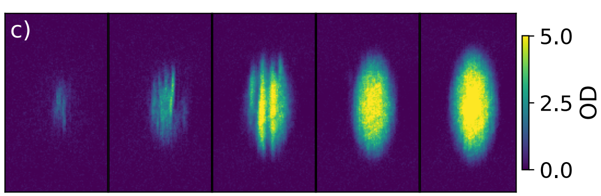
Condensate formation

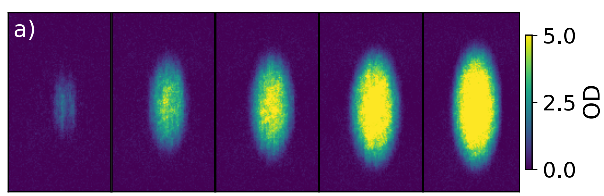
$$\Psi(\boldsymbol{r}) = \sqrt{n(\boldsymbol{r})}\, e^{-i\varphi(\boldsymbol{r})}$$

Symmetry breaking

Local choice of the order parameter





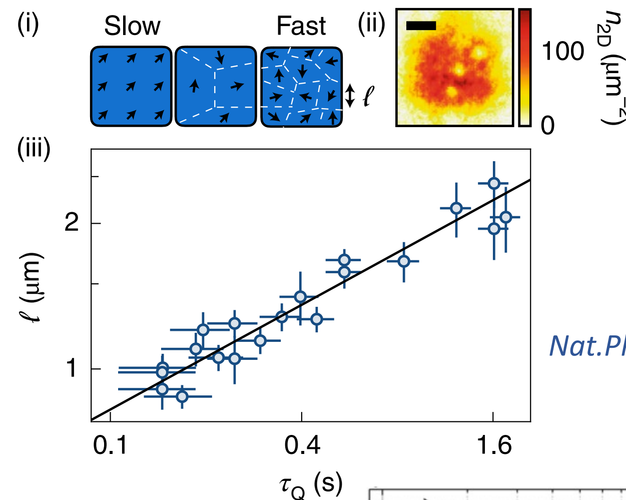


PRA **105**, 033316 *(2022)*

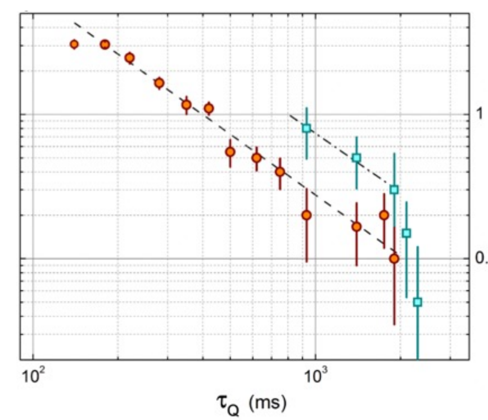
BEC: second order phase transition
(symmetry breaking)

Kibble-Zurek mechanism

Formation of **domains**
Power-law scaling between
domain size and cooling rate

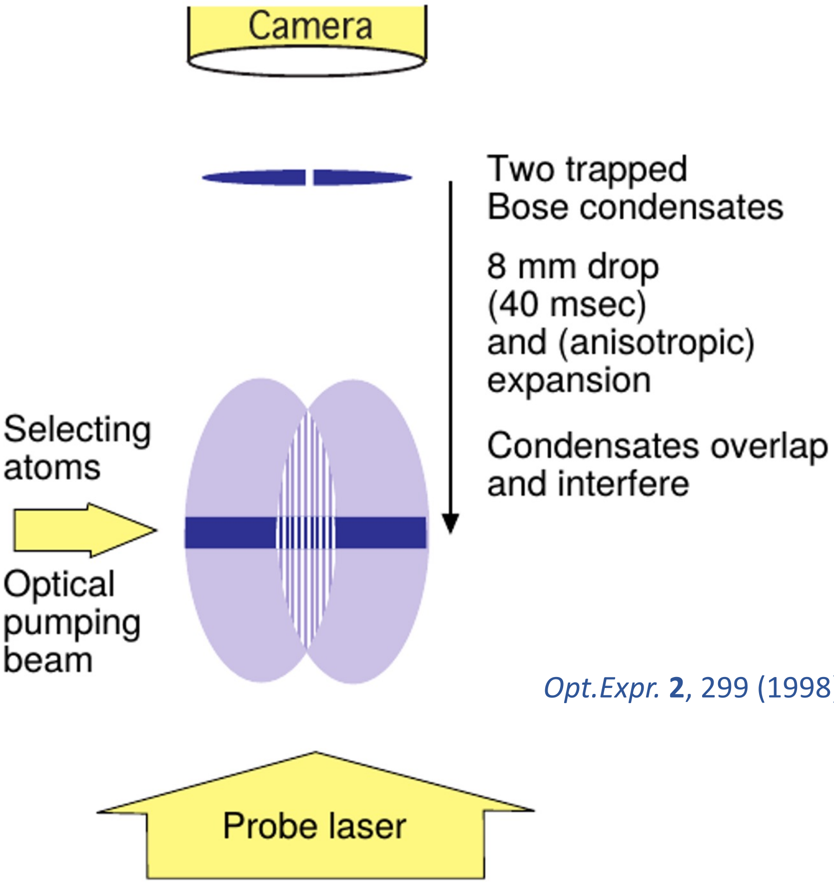


Nat.Phys. **17**, 1334 (2021)

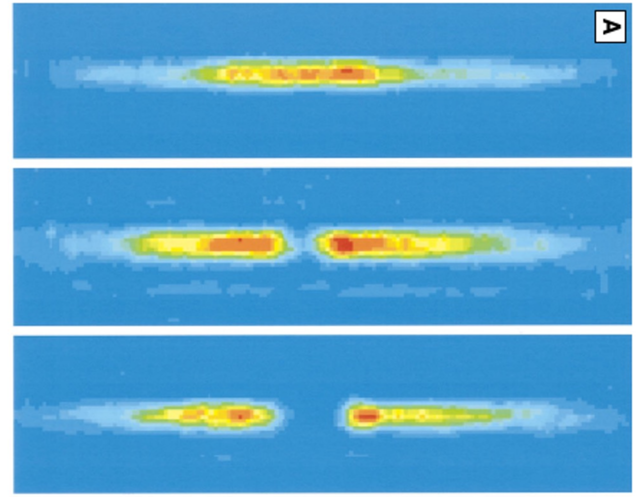


Nat.Phys. **9**, 656 (2013)

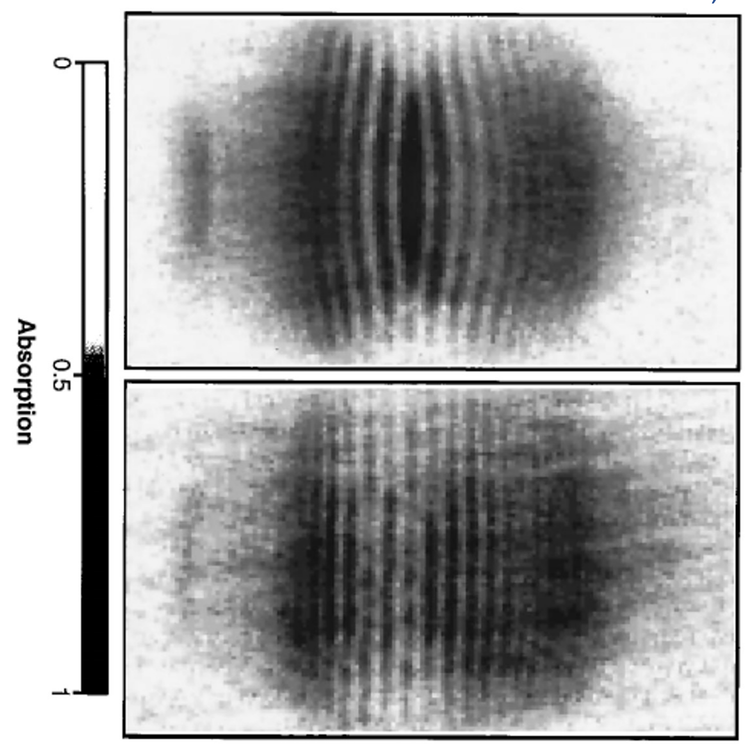
Long-range coherence



Opt.Expr. **2**, 299 (1998)

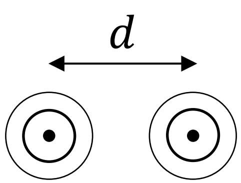


Science **275**, 637 (1997)



Proof of BEC

$$p = mv = \frac{h}{\lambda}$$

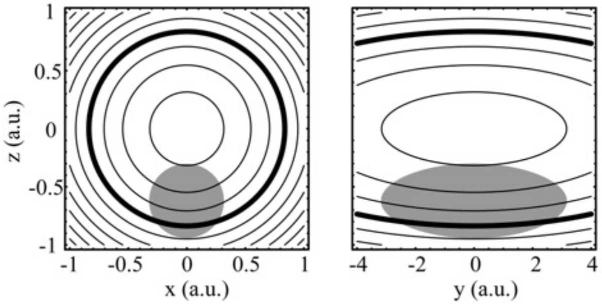


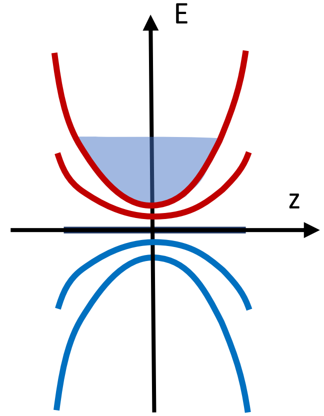
$$m\frac{d}{t} = \frac{h}{\lambda}$$

$$\lambda = \frac{ht}{md}$$

Long-range coherence

Magnetic trap

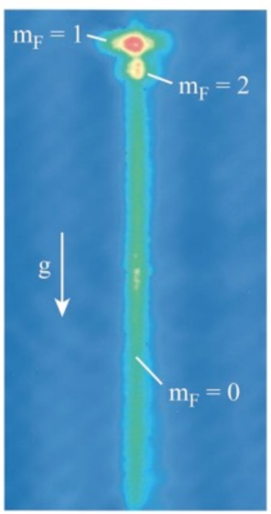




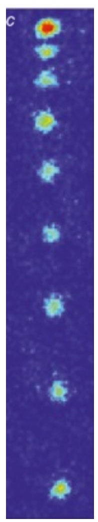
Atom laser

Proof of BEC

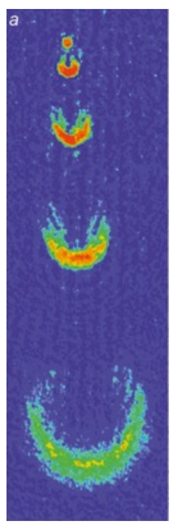
Interference between two CW coherent sources



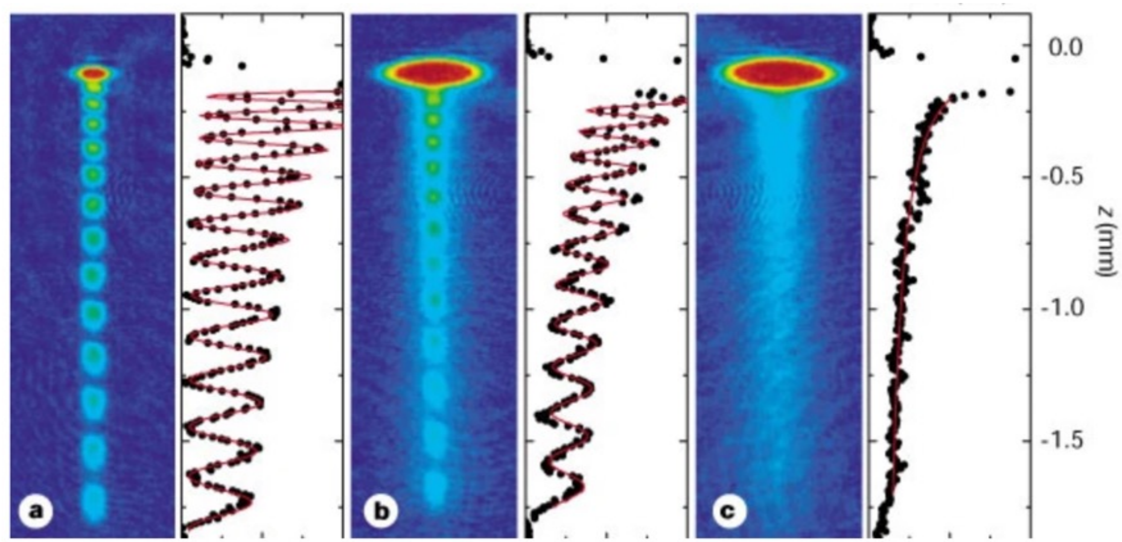
CW



pulsed



Interaction effects



Temperature effects on laser coherence

PRL **82**, 3008 (1999)

PRL **78**, 582 (1997)

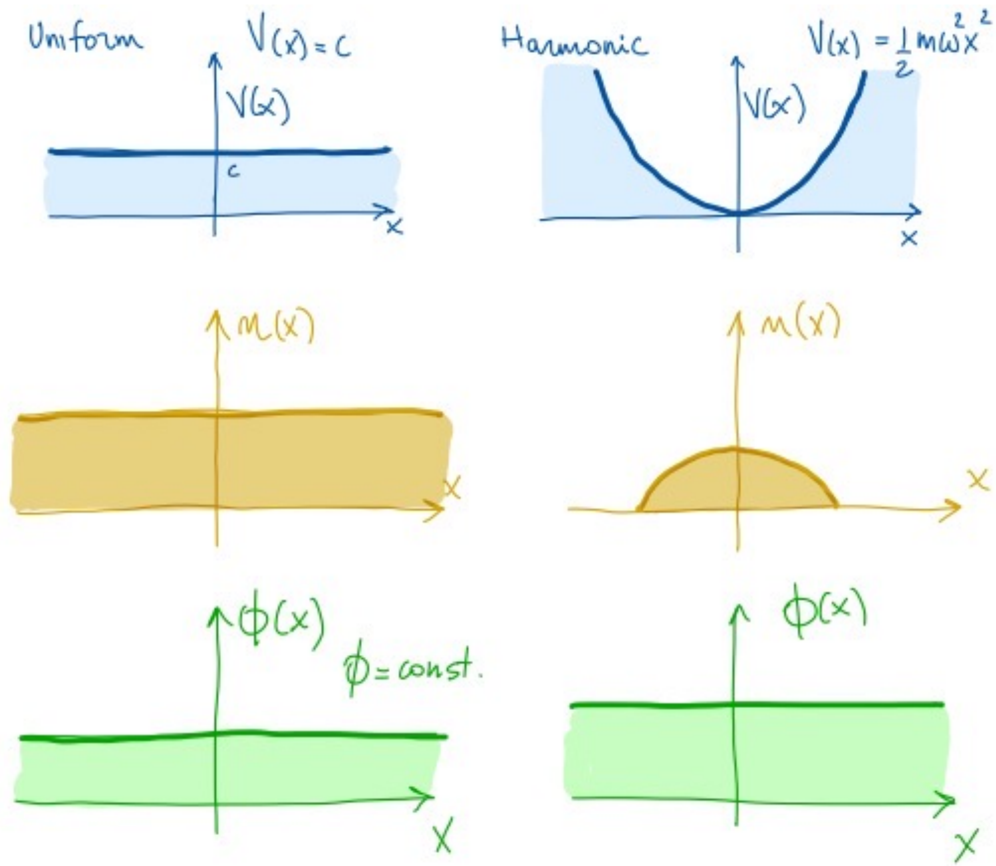
Nature **403**, 6766 (2000)

Gross-Pitaevskii equation

$$\left(-\frac{\hbar^2}{2m}\boldsymbol{\nabla}^2 + V(\boldsymbol{r}) + g|\psi(\boldsymbol{r},t)|^2\right)\psi(\boldsymbol{r},t) = i\hbar\frac{\partial}{\partial t}\psi(\boldsymbol{r},t)$$

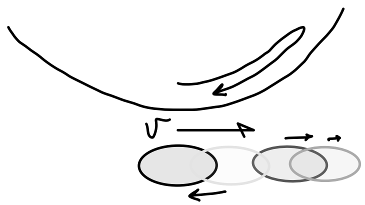
$$\Psi(\boldsymbol{r}) = \sqrt{n(\boldsymbol{r})}\, e^{-i\varphi(\boldsymbol{r})}$$

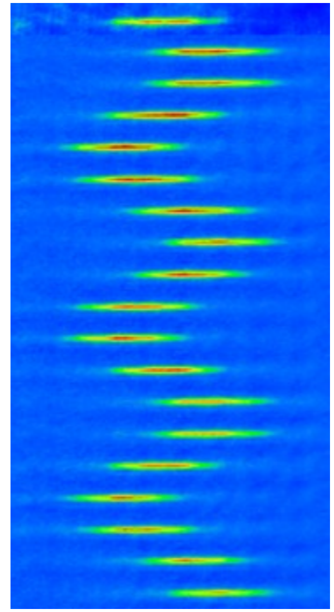
$$\boldsymbol{v} = \frac{\hbar}{m}\,\boldsymbol{\nabla}\varphi$$



Collective modes

Dipole mode





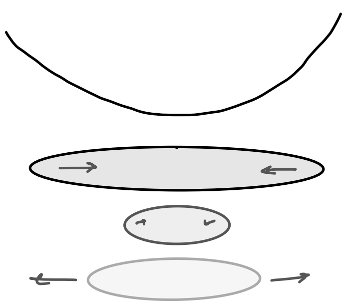
Thermal

ω_x damped

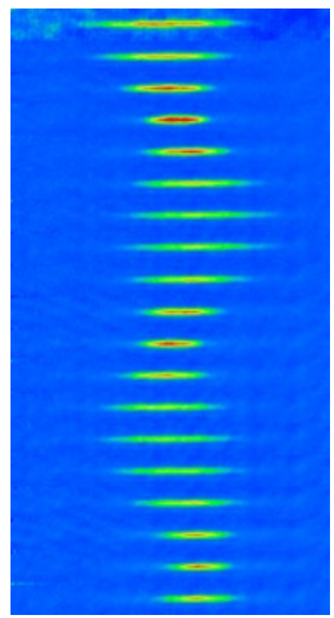
BEC

ω_x undamped
(absence of viscosity)

Proof of SF



Quadrupole mode



Thermal

$2\omega_x$

BEC

$\sqrt{5/2}\ \omega_x$

collective modes
(hydrodynamic nature,
reduced compressibility)

Localized solitary wave
Stable solution of the 1D GPE
Balance between nonlinearity and dispersion

Dark soliton | **Grey soliton**

v = 0 | v ≠ 0

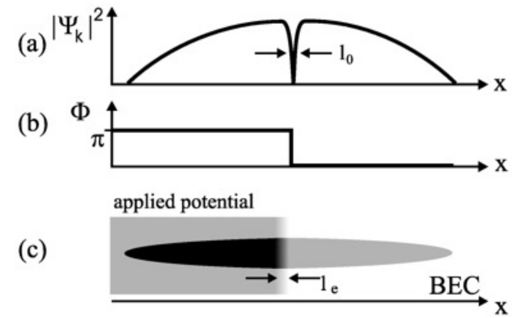
$$n(x) = |\psi(x)|^2 = n_0 \tanh^2\left(\frac{x}{\sqrt{2}\,\xi}\right)$$

$$n_v(x,t) = n_{min} + (n_0 - n_{min}) \tanh^2\left(\frac{x - vt}{\sqrt{2}\,\xi_v}\right)$$

Slow solitons: (deep, narrow, π phase jump)

Fast solitons: (small depletion, wide, small Δϕ)

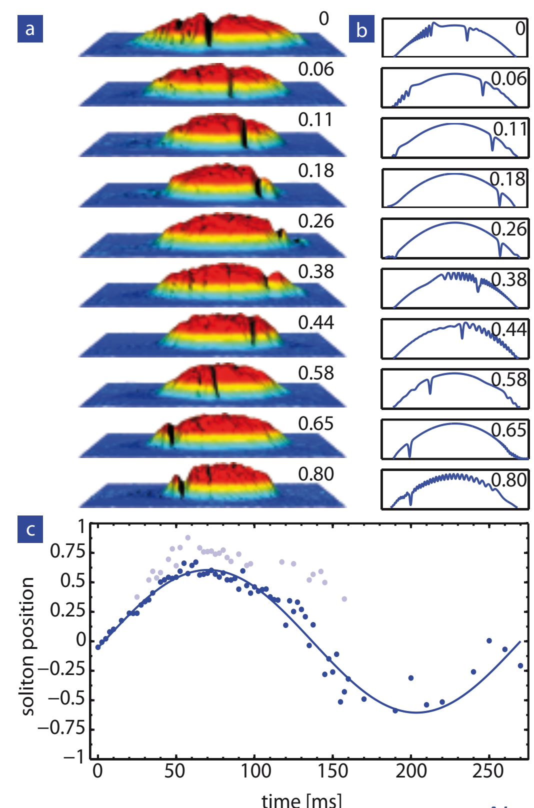
Phase imprinting



$$\Delta\varphi = \frac{U\,\Delta t}{\hbar}$$

PRL **83**, 5198 (1999)

Soliton dynamics

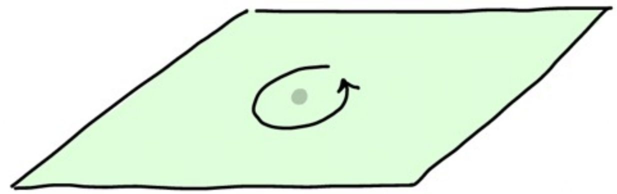


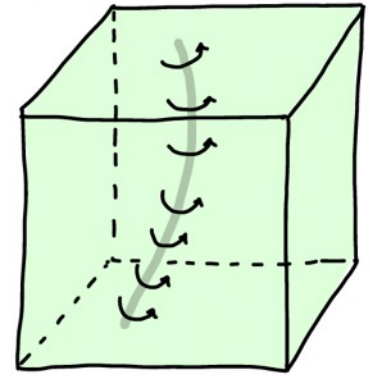
Nat.Phys. **4**, 496 (2008)

Quantized vortices

Singlevaluedness of the wavefuncton → phase windings of n2π on a closed line

$$\Psi(\boldsymbol{r}) = \sqrt{n(\boldsymbol{r})}\, e^{-i\varphi(\boldsymbol{r})}$$

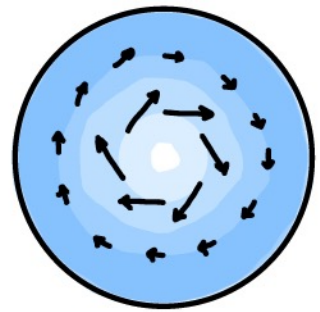




$$\boldsymbol{v} = \frac{\hbar}{m} \boldsymbol{\nabla}\varphi$$

$$v = \frac{l\, h}{2\pi\, m} \frac{1}{r}$$

→ Density depletion at the vortex core

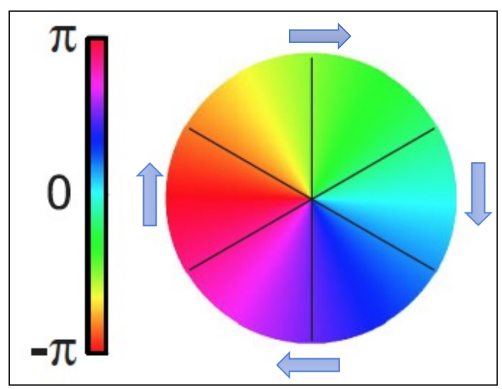


$\boldsymbol{v}$(x,y)

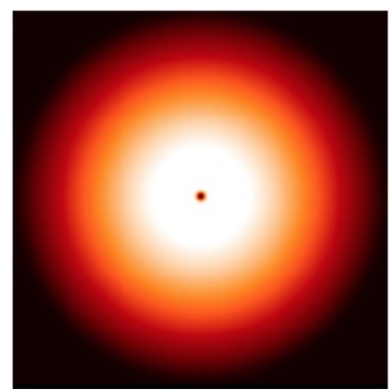
$$\Gamma = \oint \boldsymbol{v}.\boldsymbol{dl} = 2\pi\, l\, \frac{\hbar}{m}$$

Quantization of the circulation

φ(x,y)



n(x,y)

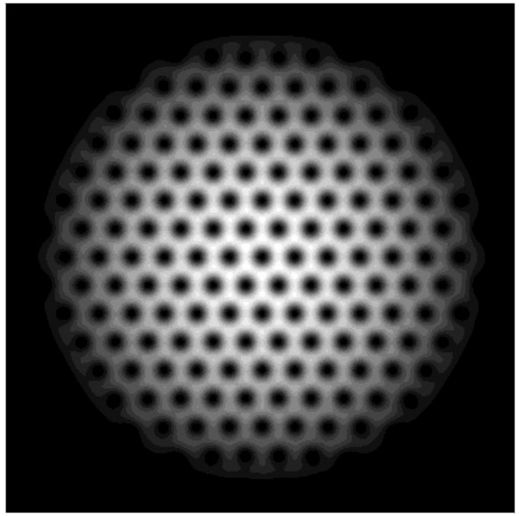


Quantized vortices

Increasing the total angular momentum

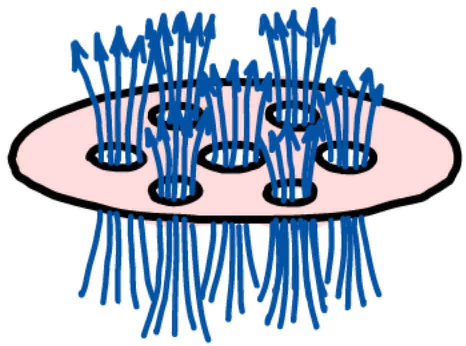
Multiply quantized vortices are not stable → decay into separated singly quantized vortices

Fast rotation: Abrikosov lattice



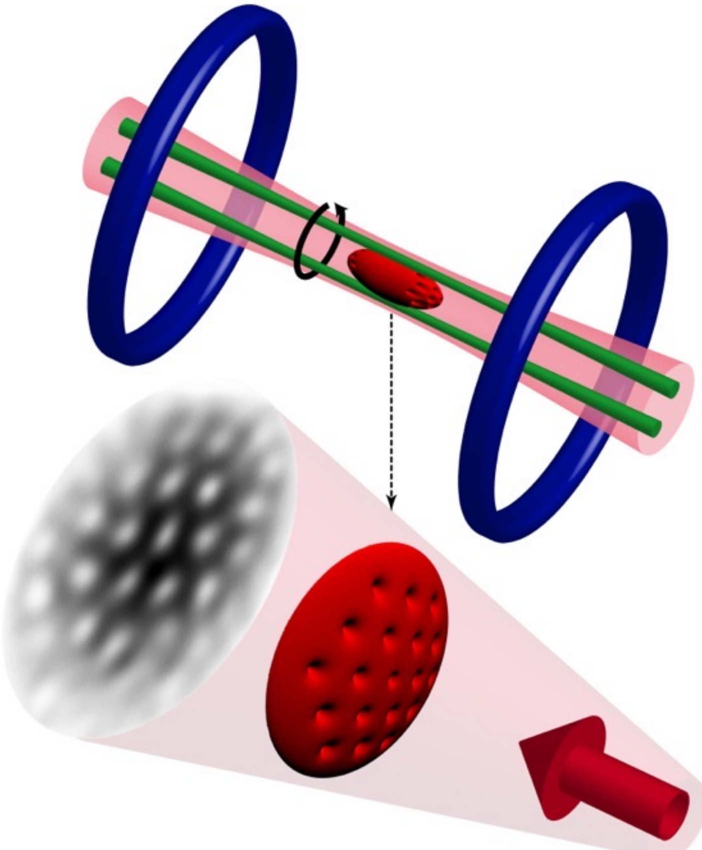
$$n_v = 2\Omega m/h$$

Analogy SUPERFLUIDS - SUPERCONDUCTORS:

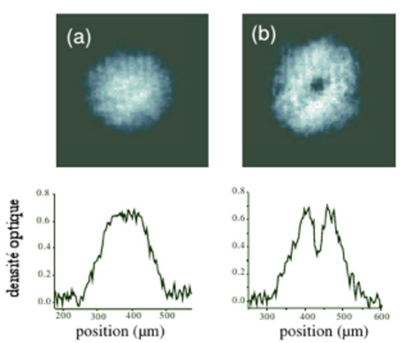


- Neutral atoms + rotation (**L** . **Ω**)
- Charged particles + magnetic field (**S** . **B**)

Quantized vortices – ROTATION

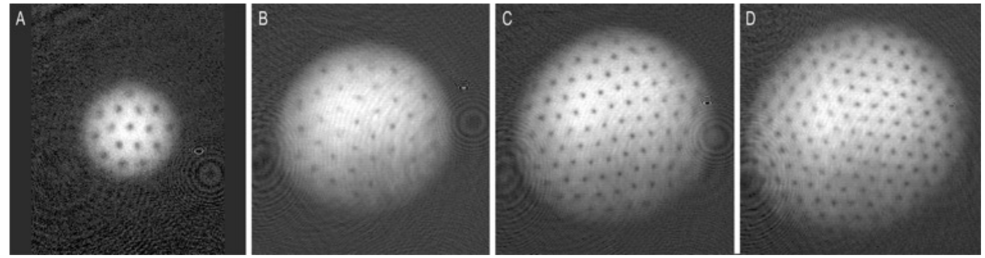


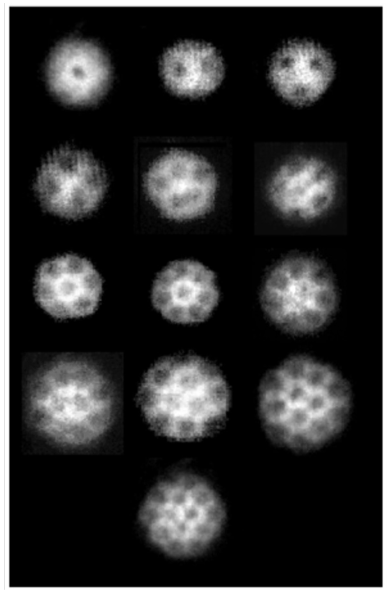
PRL **84**, 806 (2000)



JILA group

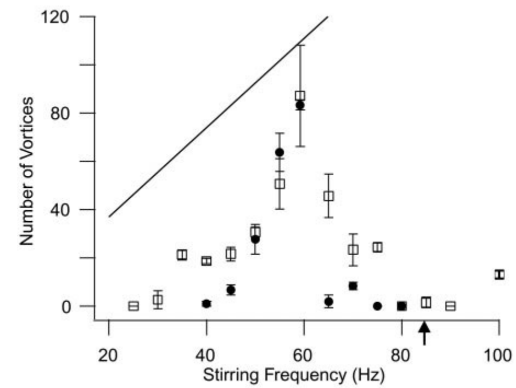
Large L, all vortices with the same sign



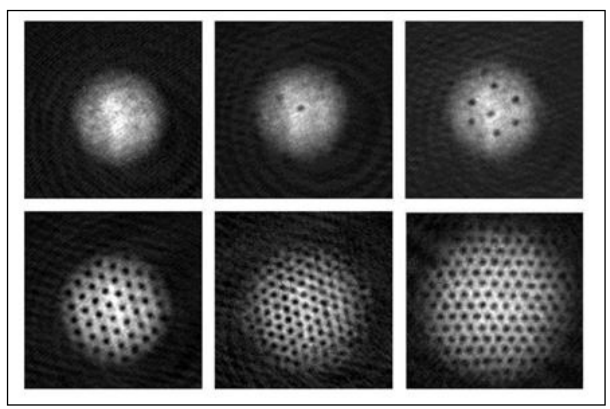


Proof of SF

Science **292**, 476 (2001)



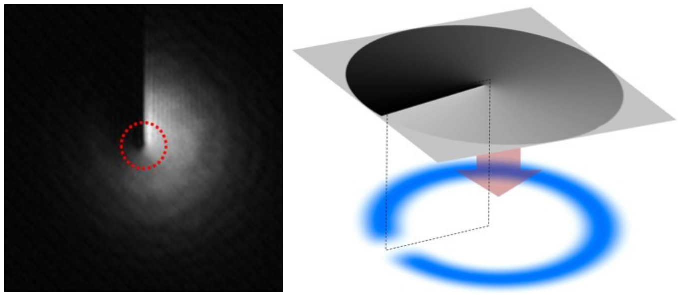
PRL **84**, 806 (2000)



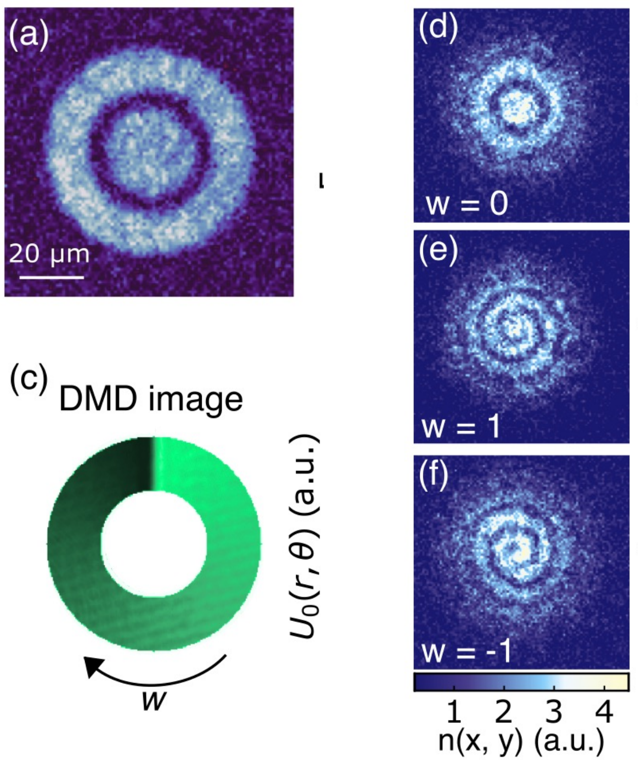
Deform symmetric potential
Rotating the deformation excites surface modes that let vortices enter from the outside

Resonance $\omega/\sqrt{2}$
Max rotation ω

Phase mask
- Critical phase jump
- Low definition at the core



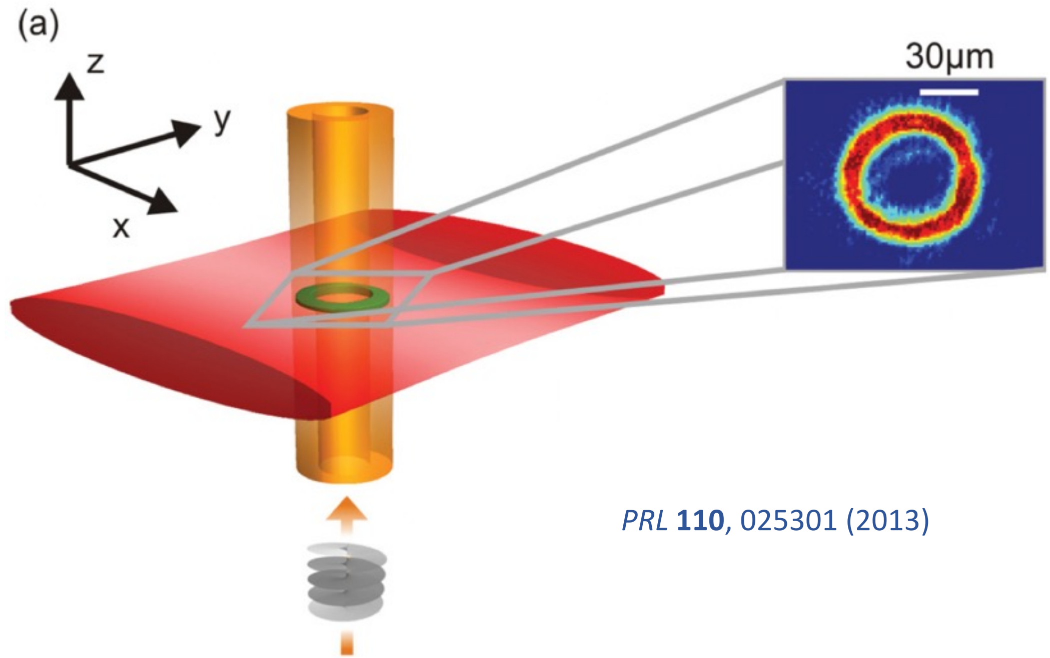
PRA **97**, 043615 (2018)



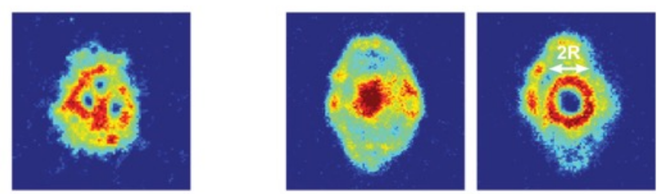
PRX **12**, 041037 (2022)

Well definite **L**

Laguerre-Gauss beam

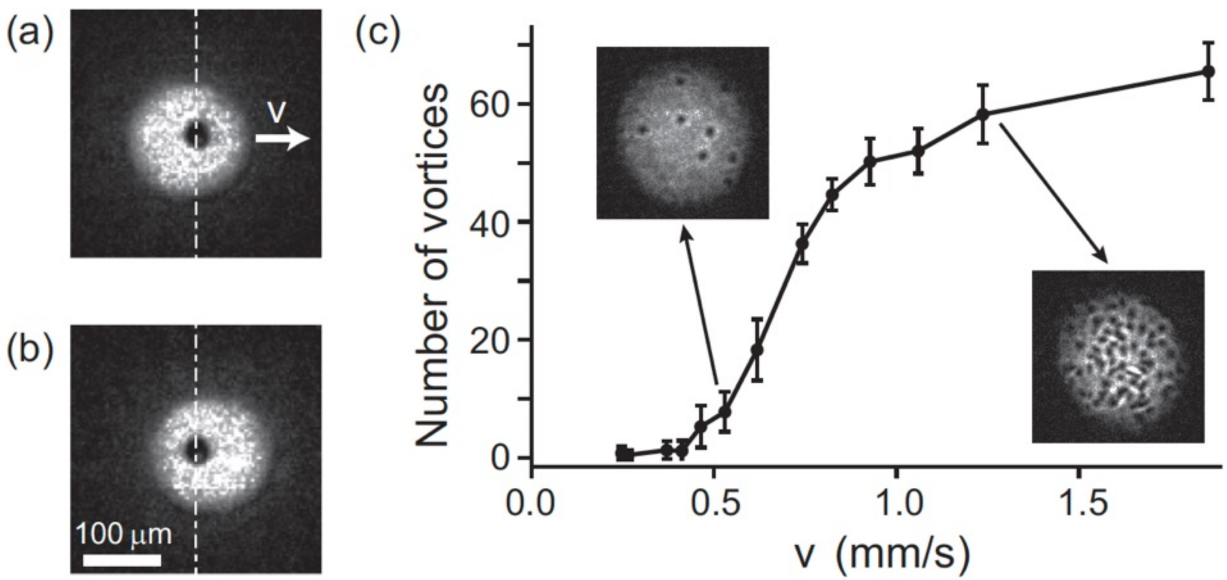


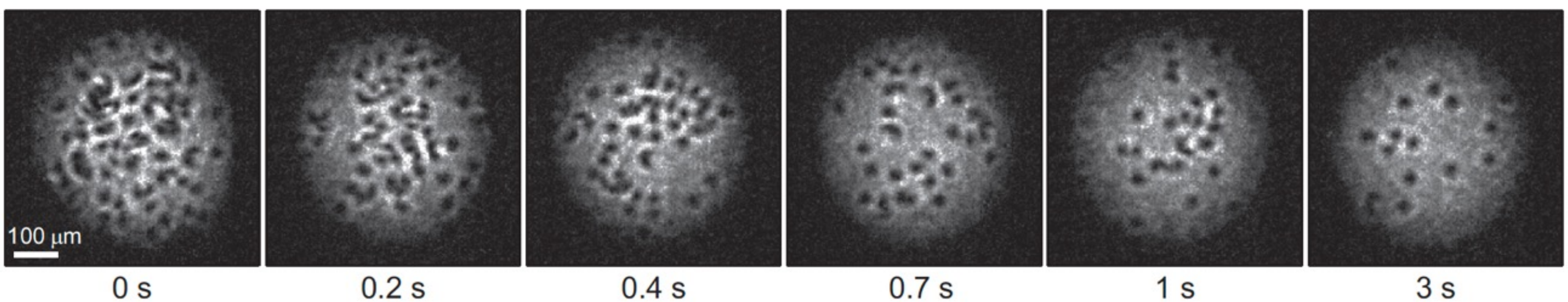
PRL **110**, 025301 (2013)



Quantized vortices – MECHANICAL TURBULENCE

No net angular momentum



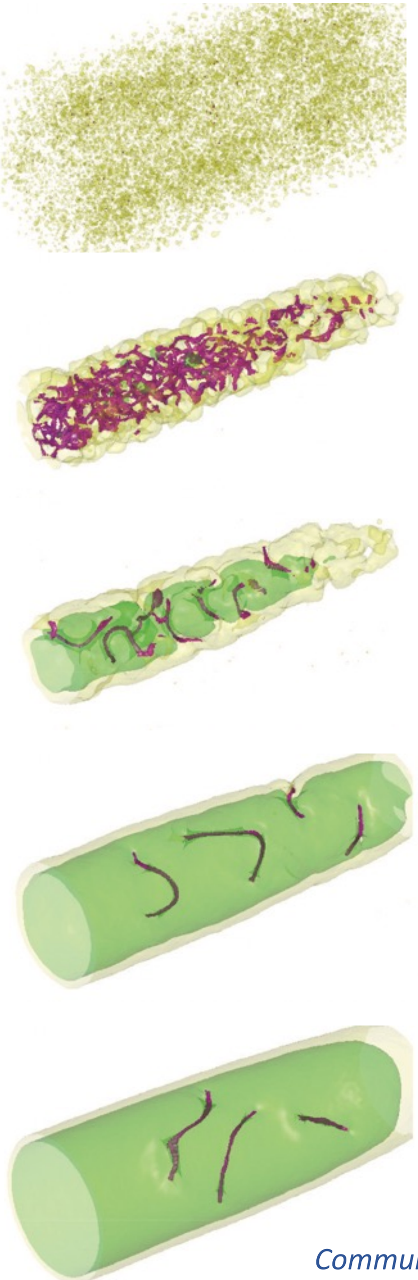


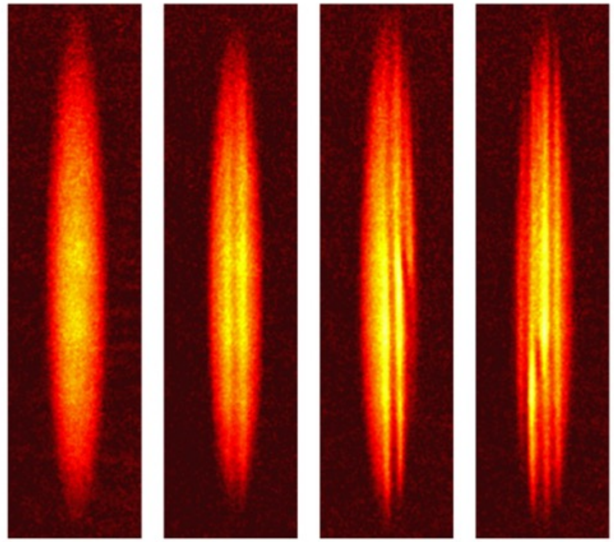
PRA **90**, 063627 (2014)

Quantized vortices – KIBBLE-ZUREK TURBULENCE

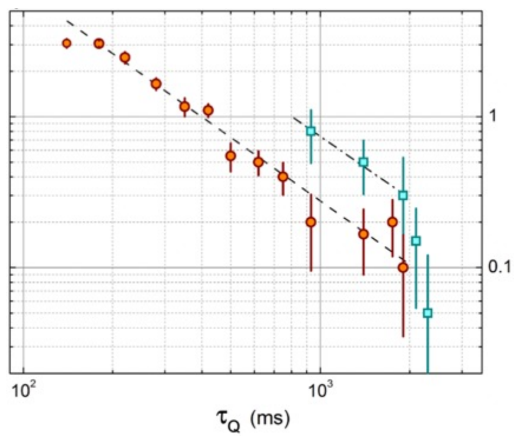
No net angular momentum

Kibble-Zurek mechanism

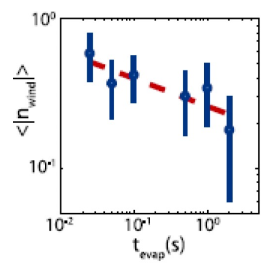


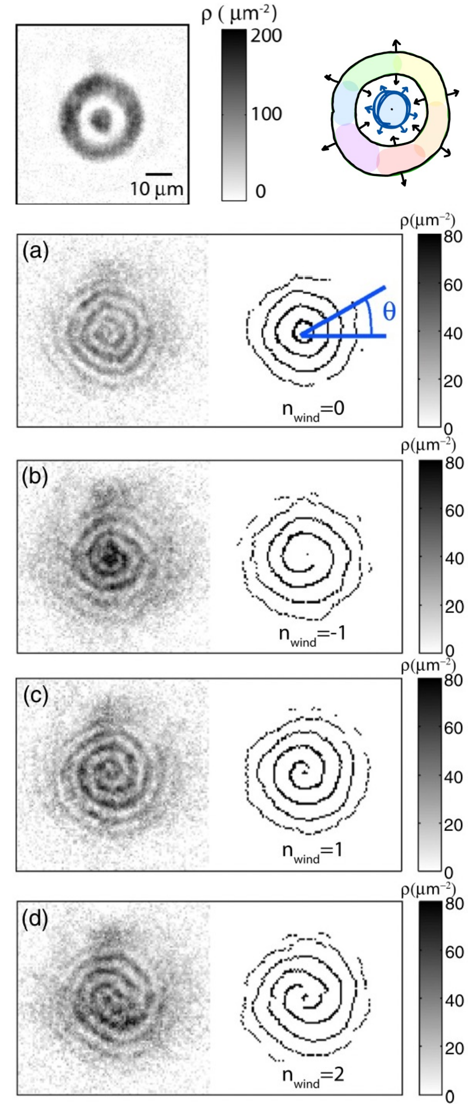


Nat.Phys. **9**, 656 (2013)



Defect number





Commun.Phys. **1**, 24 (2018)

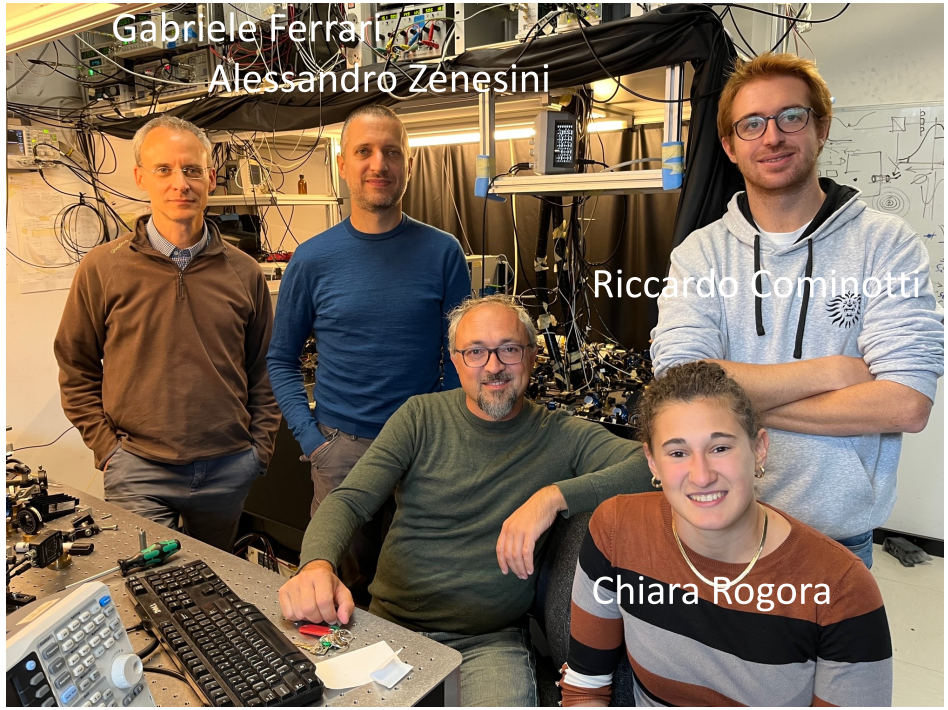
PRL **113**, 135302 (2014)

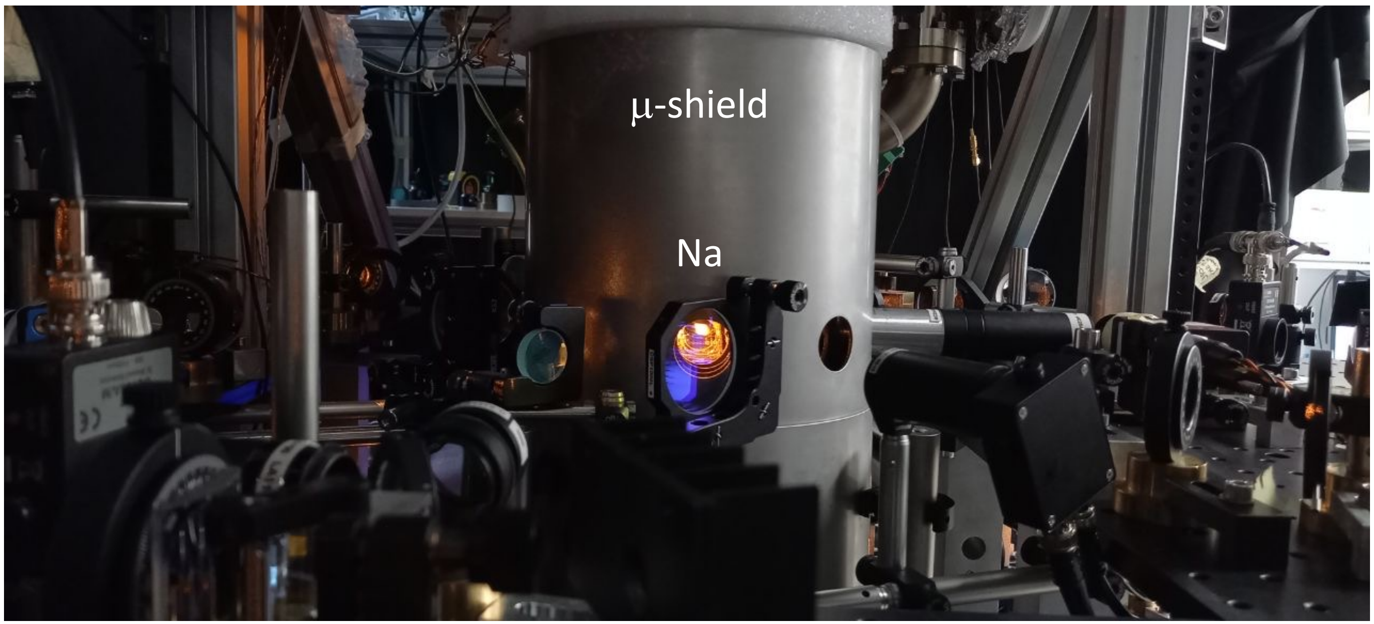
Experiments in **Trento**

Master and **PhD** positions available.
If you're interested… let me know!

https://bec.science.unitn.it

Experimental team:





Theory collaborators in Trento:

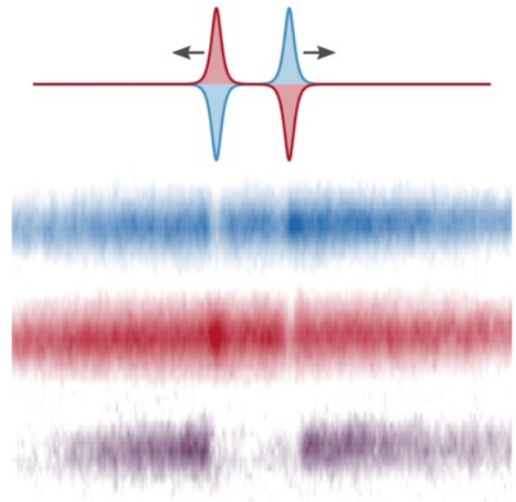
Alessio Recati
Iacopo Carusotto
Anna Berti
Franco Dalfovo
Sandro Stringari

Experiments in **Trento**

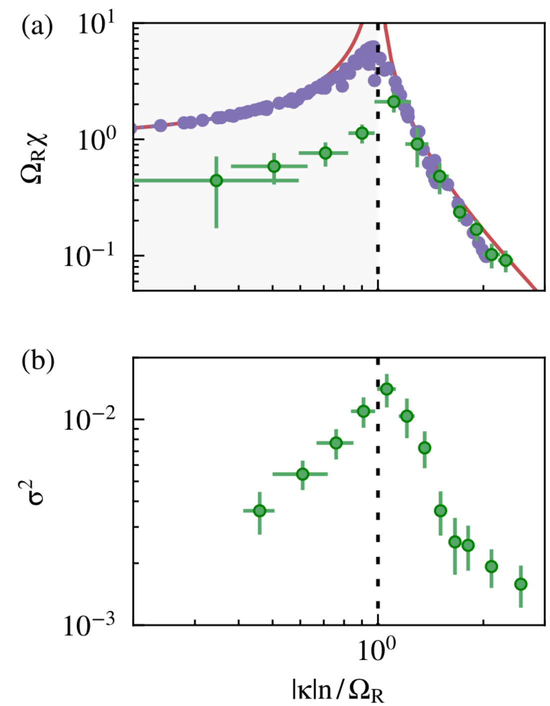
https://bec.science.unitn.it

Main Topic: **Spin mixtures**

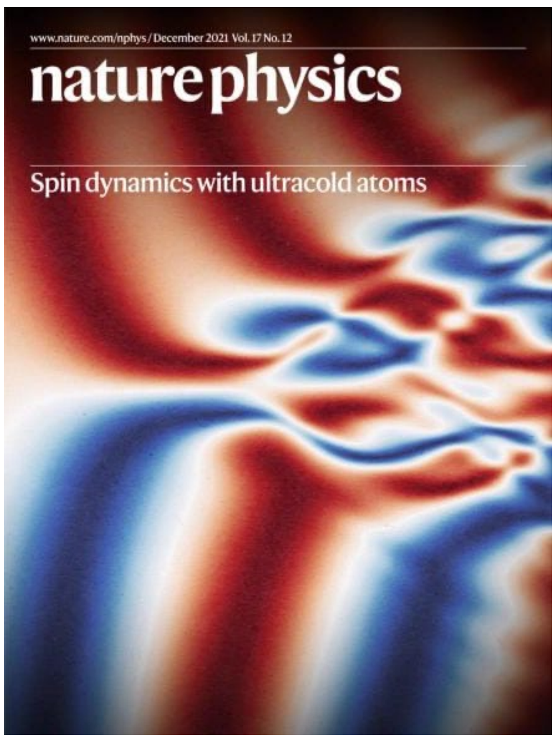
- Observation of magnetic solitons
- Spin dynamics in coherently-coupled mixtures
- Spin Faraday waves
- Simulation of para-ferromagnetic QPT



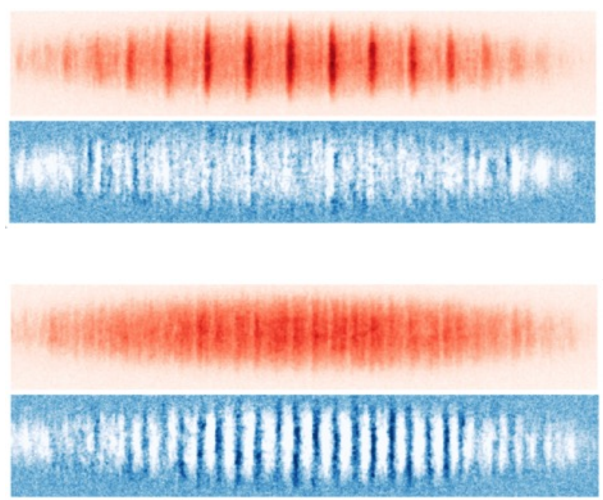
PRL **125**, 030401 (2020)



PRX **13**, 021037 (2023)



Nat. Phys. **17**, 1359 (2021)



PRL **128**, 210401 (2022)