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Università della Calabria 17/21 Settembre 2018

SYNTHETIC GAUGE FIELDS IN ULTRACOLD ATOMIC GASES

Sandro Stringari

Università di Trento

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BEC

CNR-INO

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- **At low temperature all the systems existing in nature (with the exception of liquid Helium) undergo a transition to the crystal phase.**
- **Atomic gases are available in conditions of metastability and quantum degeneracy only if their density is extremely small to avoid crystallization. This sets challenging conditions for density** $(10^{13} - 10^{15}\, cm^{-3}$ **) and temperaure (** $10^{-6} - 10^{-8} K$**)**

- Bose-Einstein condensation in atomic gases has been a long sought goal for decades before 1995.

- At low temperature all the systems existing in nature (with the exception of liquid Helium) undergo a transition to the **crystal phase**.
- Atomic gases are available in conditions of metastability and quantum degeneracy only if their density is extremely small to avoid crystallization. This sets **challenging conditions for density** $(10^{13} - 10^{15} cm^{-3})$ and **temperaure** ($10^{-6} - 10^{-8} K$)

- After the first realization of Bose-Einstein condensation in alkali atoms in 1995 the experimental and theoretical activities in the field of **ultracold atomic gases have grown in an impressive way**, giving rise to a well established new field of research of fundamental interest for the investigation of **quantum phenomena**

-Some major achievements of ultra-cold atomic physics

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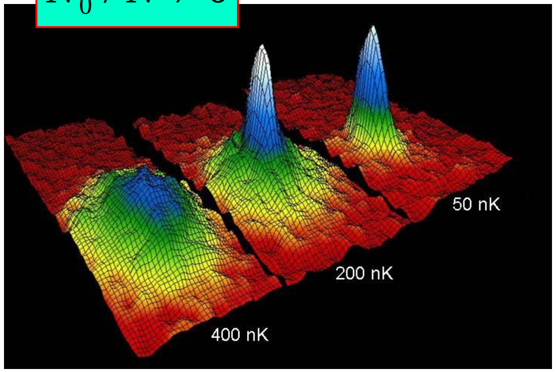
$N_0 / N \neq 0$



1995

(Jila+MIT)

Macroscopic occupation of sp state (Bose-Einstein condensation)

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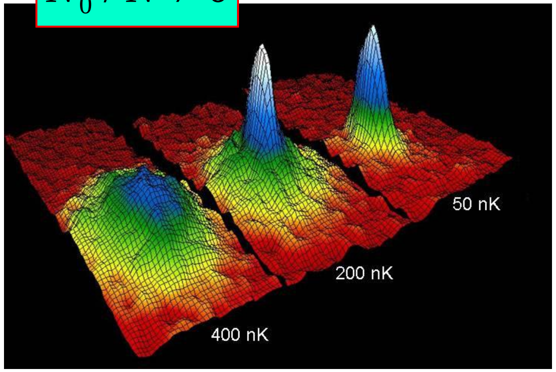

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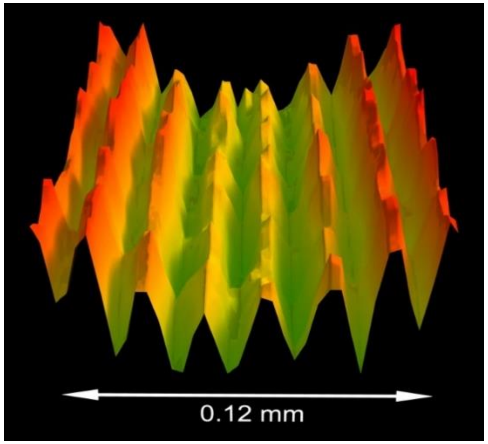
Interference and quantum coherence



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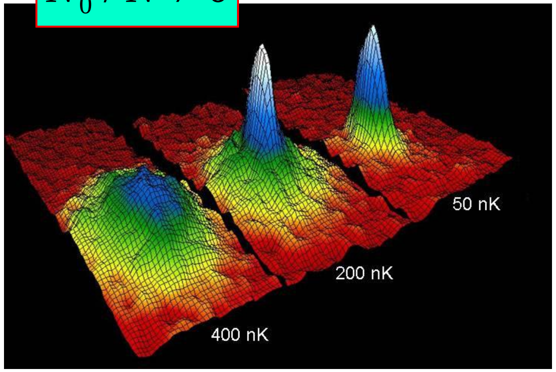

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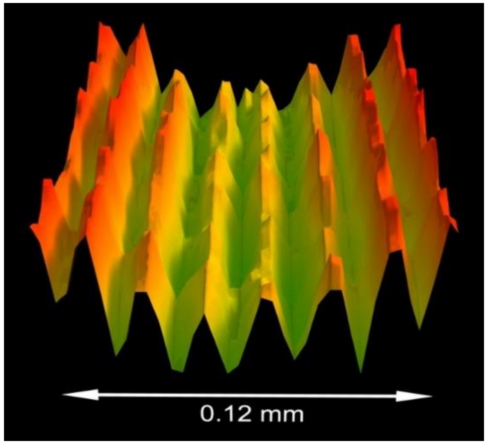
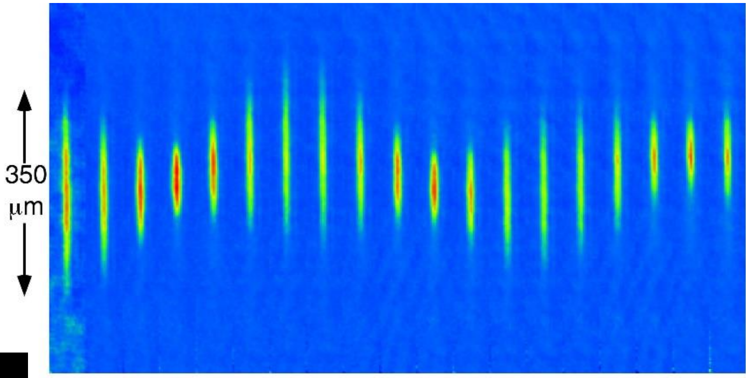
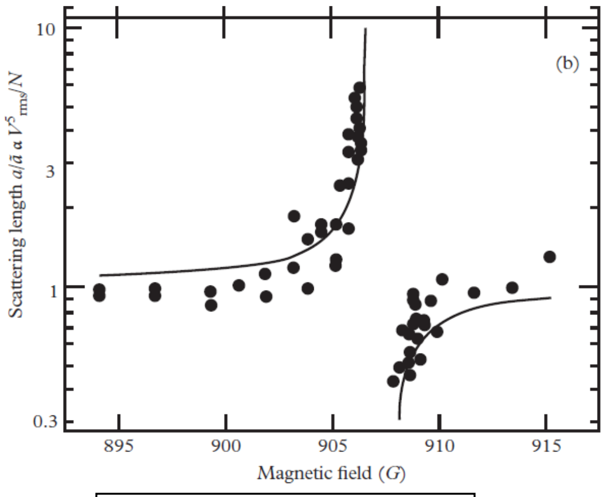




5 milliseconds per frame

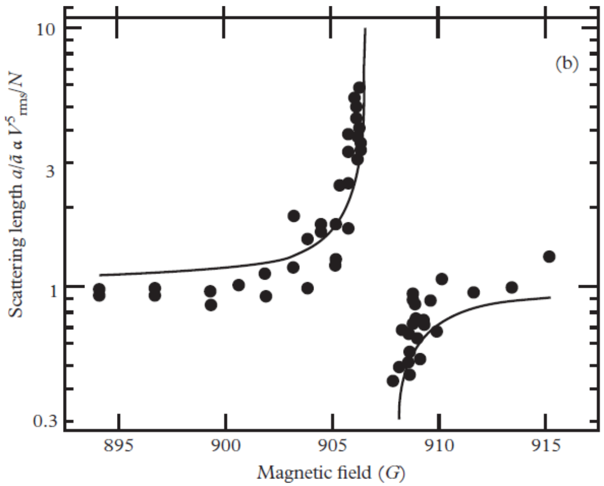
1996
(MIT)

Collective oscillations



1999
(MIT)

Feshbach resonances and tuning of scattering length



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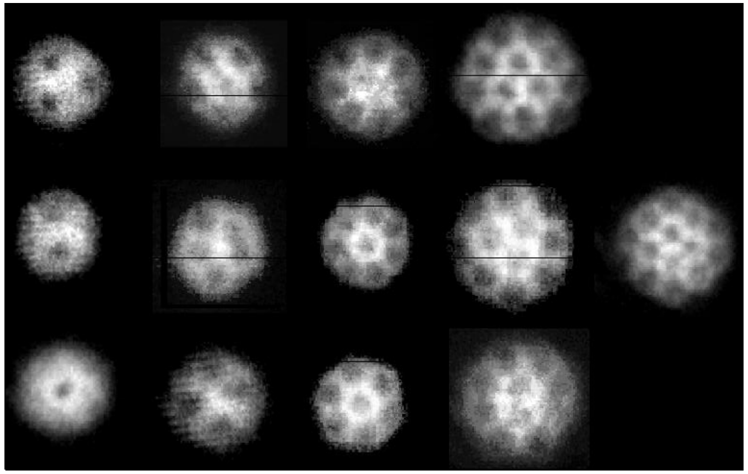
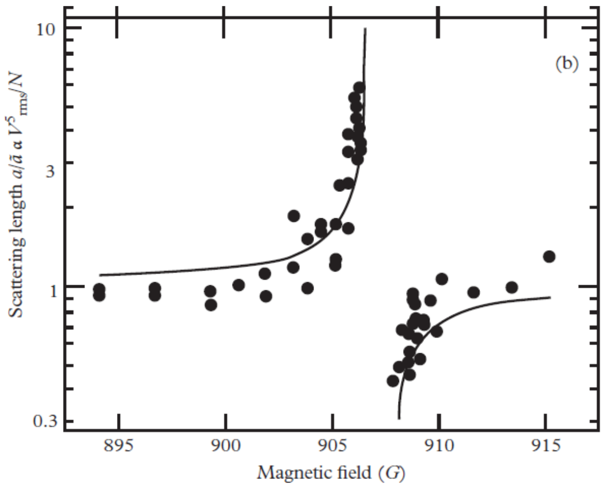
Quantized vortices in BEC





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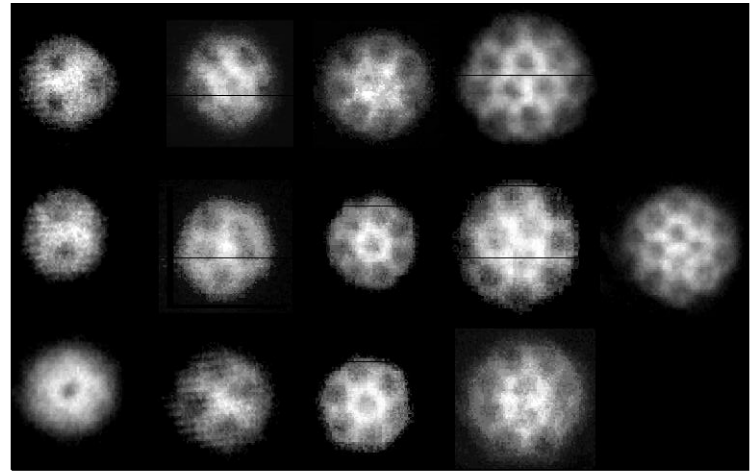
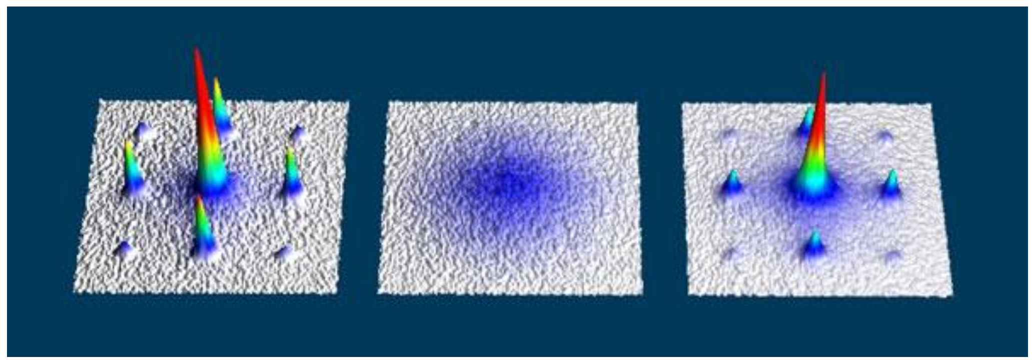
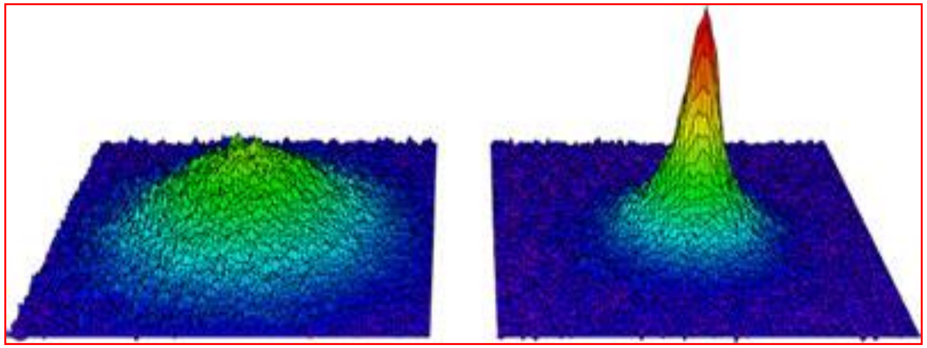




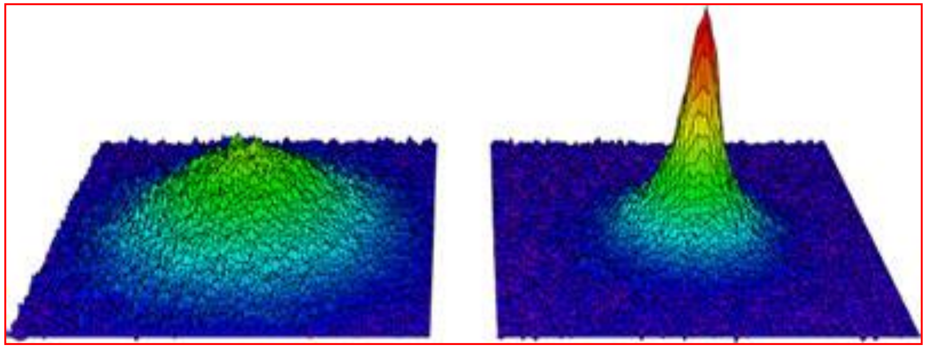
2001
(MPI Munich)

Superfluid-insulator transition



2003
(JILA-ENS-Innsbruck)

BEC of molecules emerging from Fermi see



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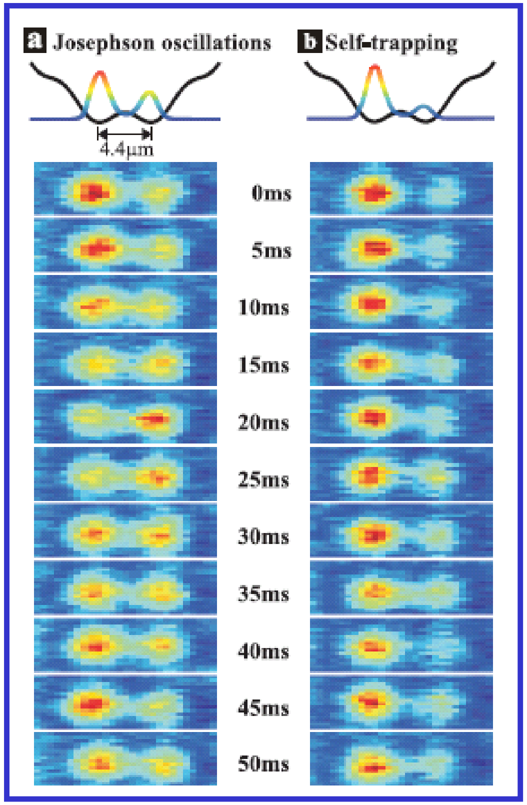
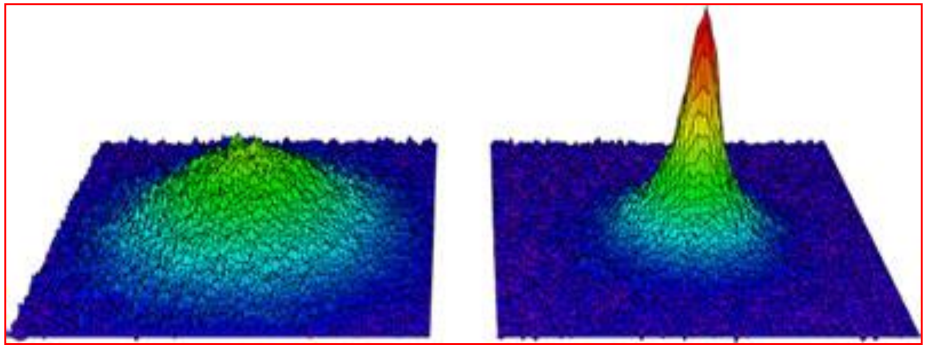


2004
(Heidelberg)

Josephson oscillation



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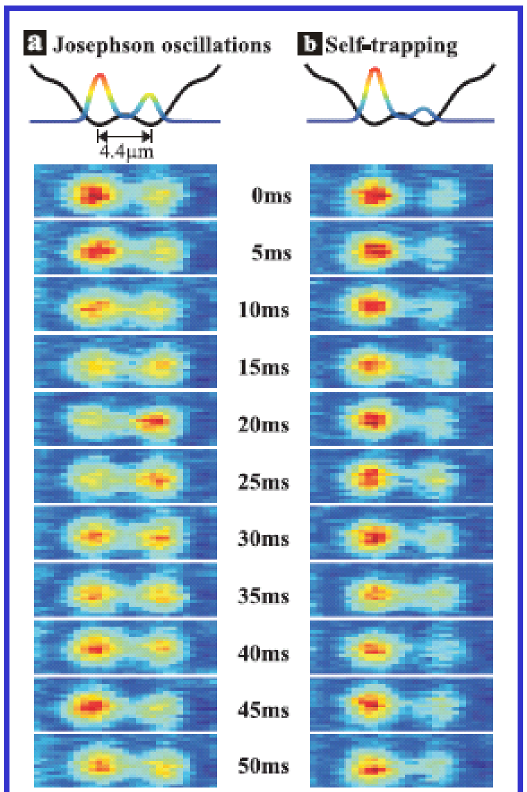

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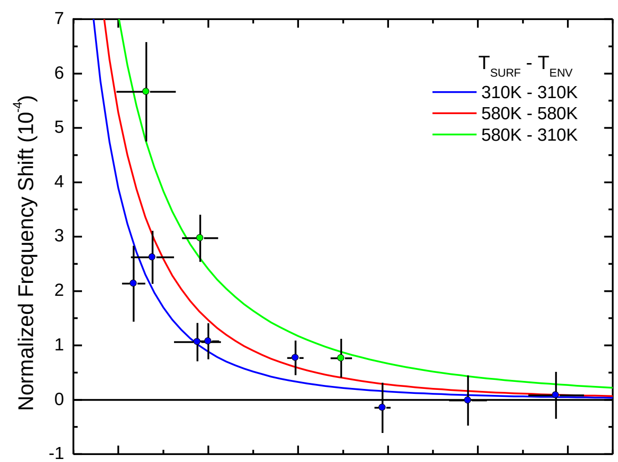
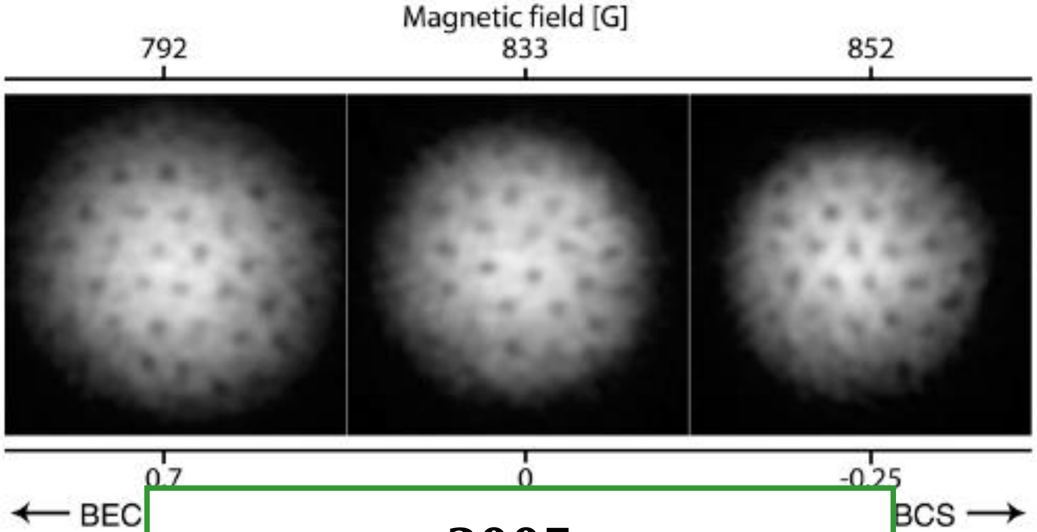


2004

(JILA)

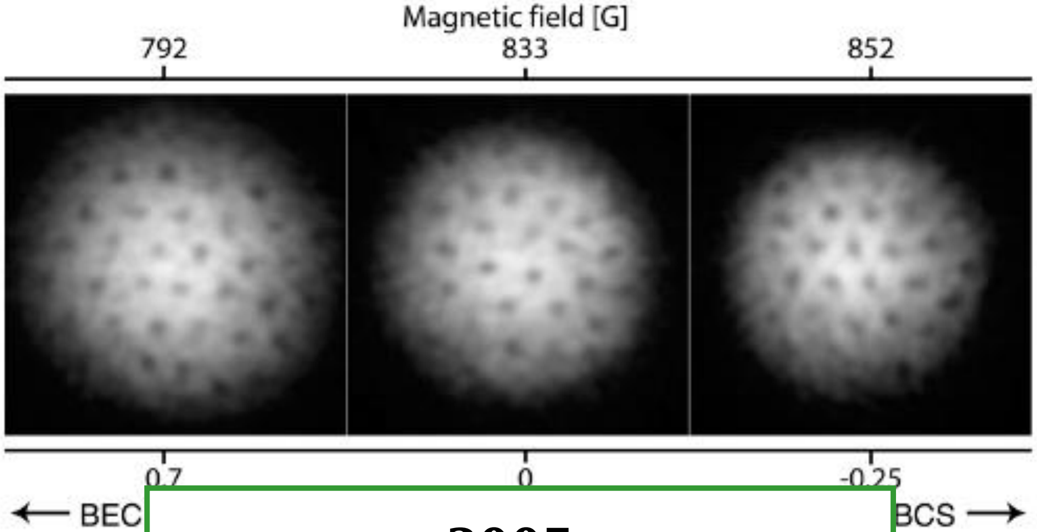
Temperature dependence of Casimir-Polder force



2005

(MIT)

Vortices in a Fermi superfluid



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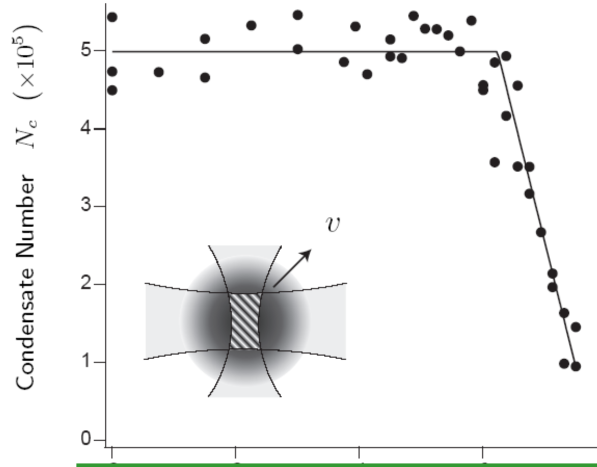
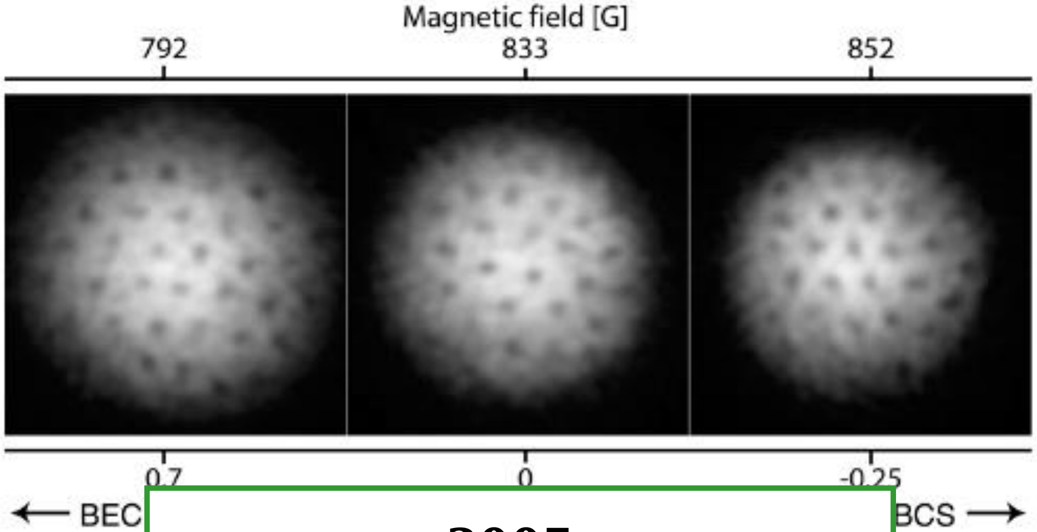


2007

(MIT)

Absence of viscosity in the unitary Fermi superfluid



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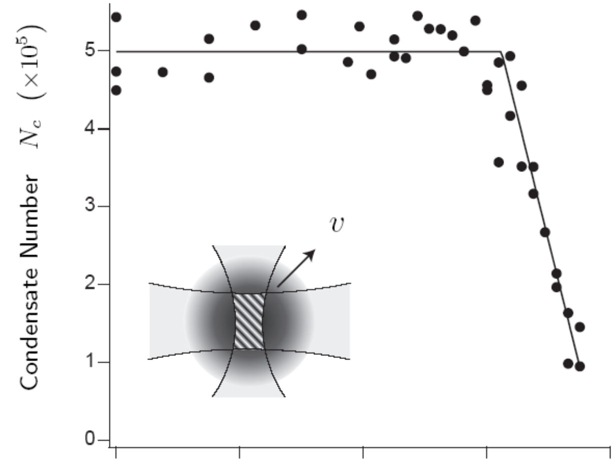

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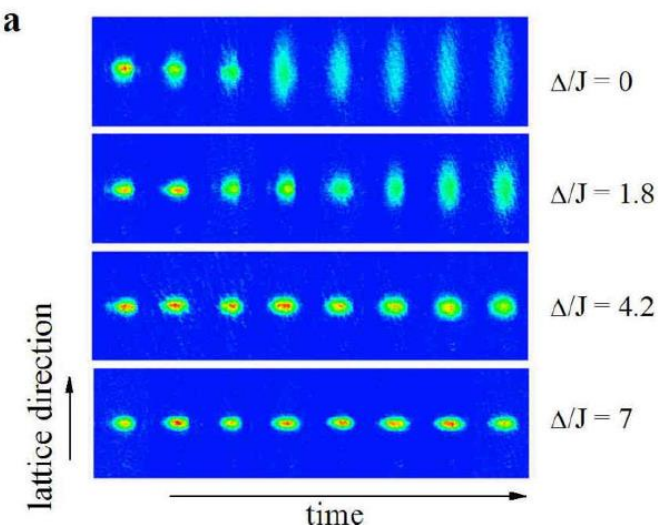
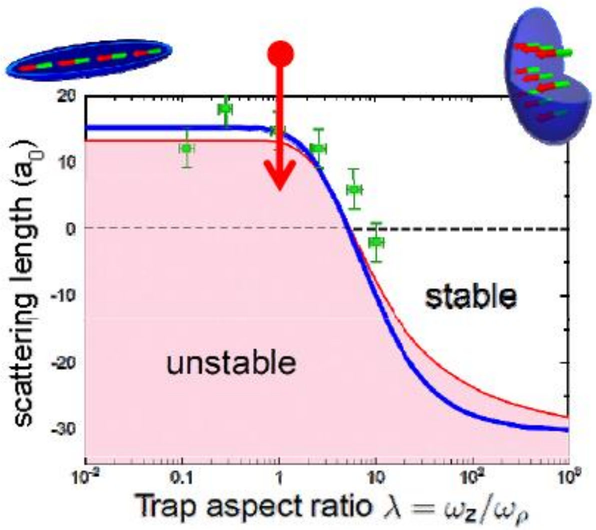


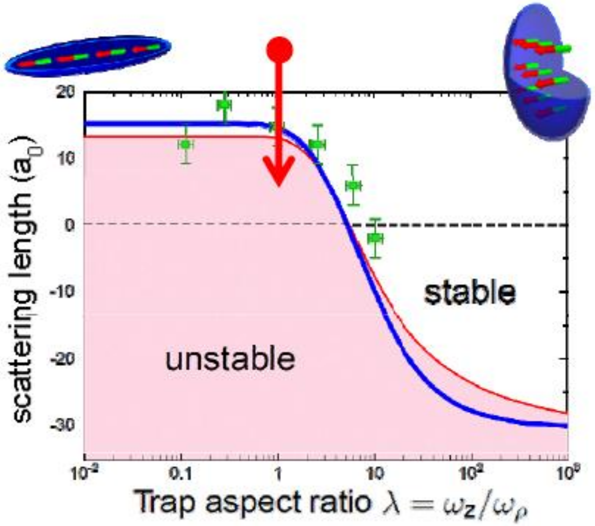
2008
(Florence-Palaiseau)

Anderson localization



2008
(Stuttgart)

Dipolar gases
(anisotropy and
long range)



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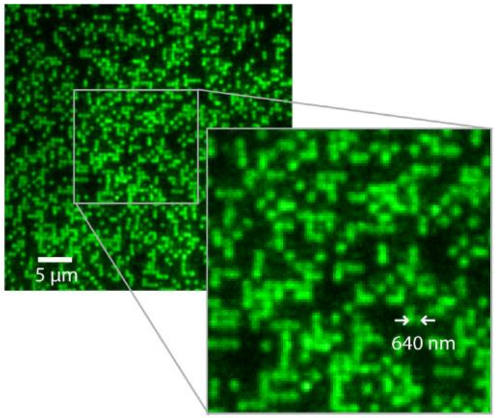
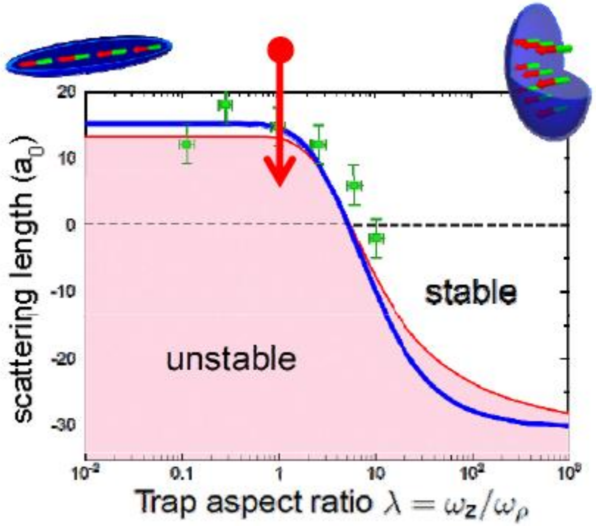


2009
(Harvard)

Quantum gas microscope



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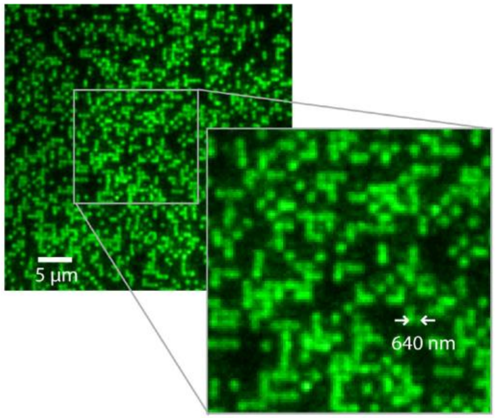

2009
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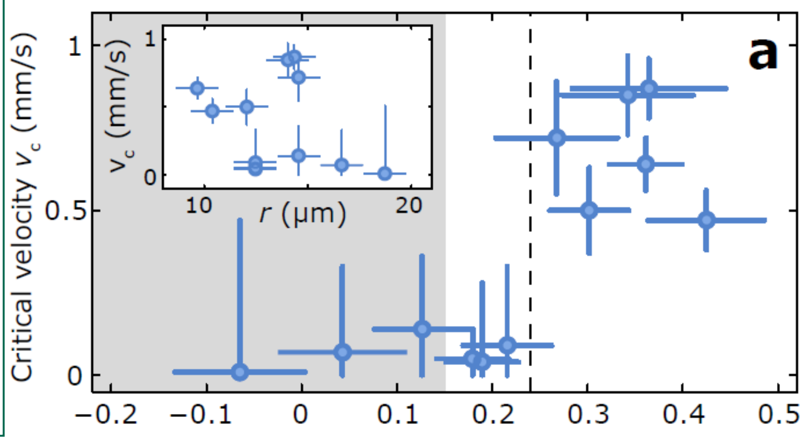
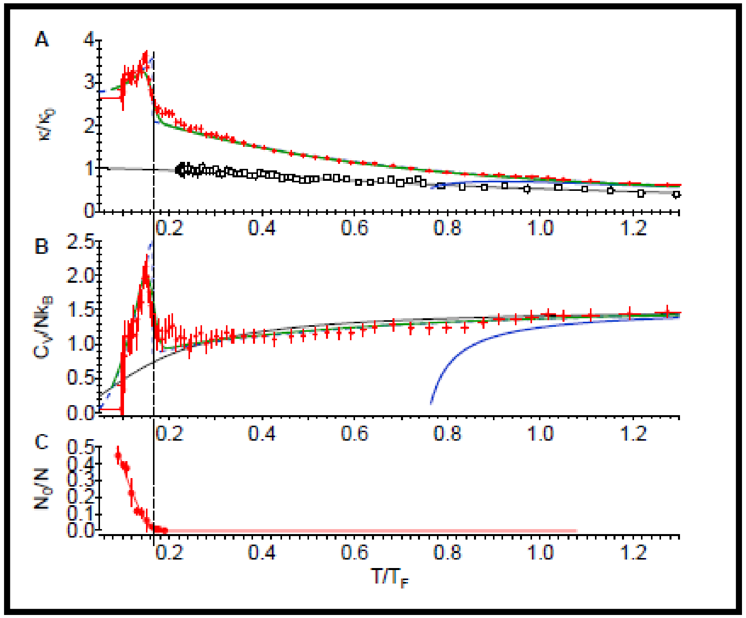
Quantum gas microscope

2012
(ENS)

BKT transition in 2D Bose gas

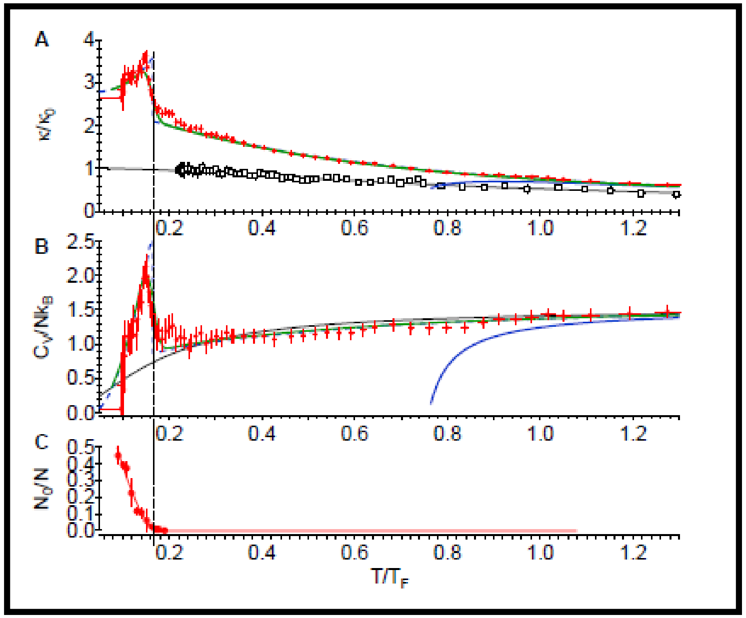




2012

(MIT)

Lambda transition in superfluid Fermi gas



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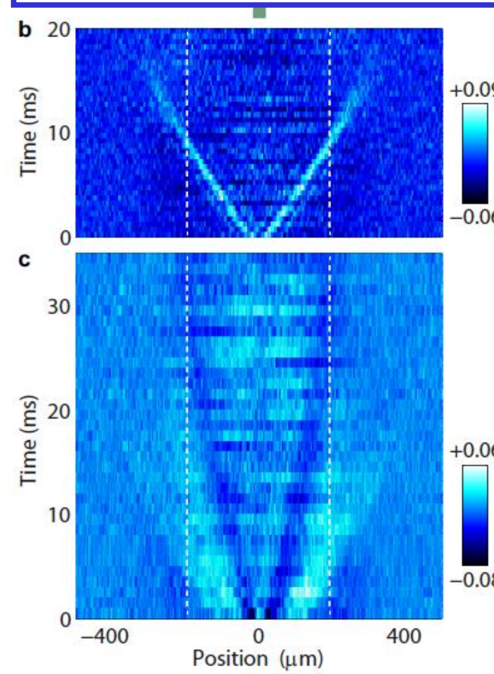
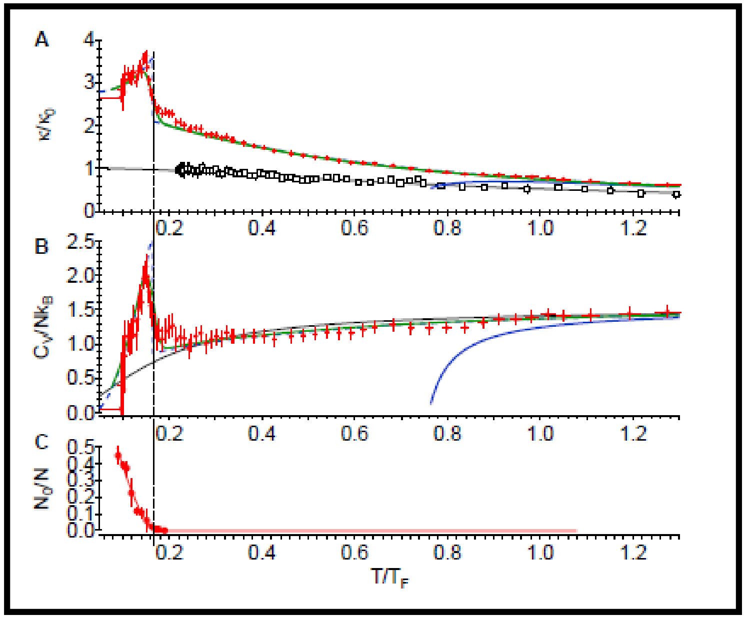
Lambda transition in superfluid Fermi gas

2013
(Innsbruck)

Propagation of second sound in a Fermi superfluid





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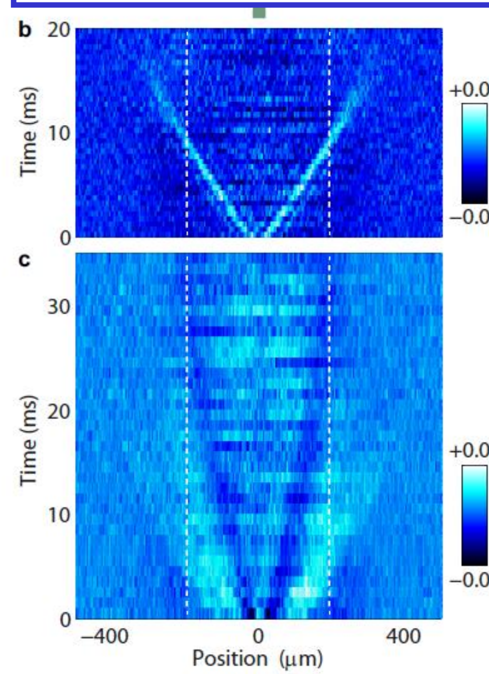
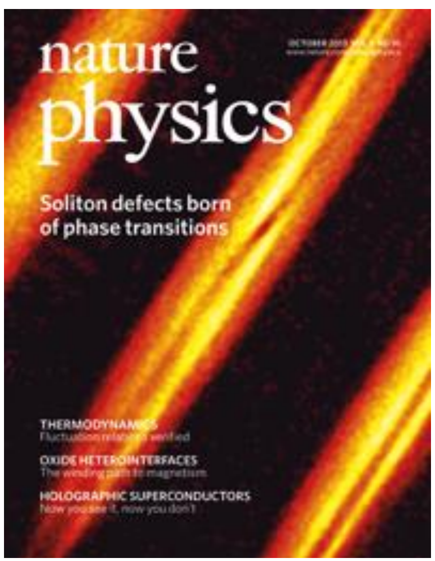




2013
(Trento)

Kibble Zurek generation of quantum defects

Atoms are **neutral objects** and are **not sensitive to Lorentz force** which in charged systems is at the basis of important many-body phenomena (ex: Quantum Hall effect)

It is now possible to **create artificial gauge fields** which simulate in neutral systems the effect of a magnetic field on a charged particle

For a recent review see

Jean Dalibard:
Introduction to the physics of artifical gauge fields

[Proceedings of the International School of Physics "Enrico Fermi" of July 2014, "Quantum matter at ultralow temperatures“]

In the presence of a magnetic field the kinetic energy of a charged particle can be written as

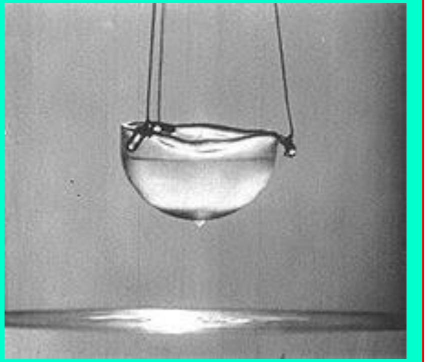
$$H = \frac{(\vec{p} - e\vec{A})^2}{2m}$$

Where p is canonical momentum operator. In the case of a uniform magnetic field oriented along the z-direction one has $A_y = Bx\,, A_x = A_z = 0$ (Landau gauge)

Can we produce similar Hamiltonians employing neutral atoms and explore the effects at the many-body level

The simplest example:

Rotating a trapped gas

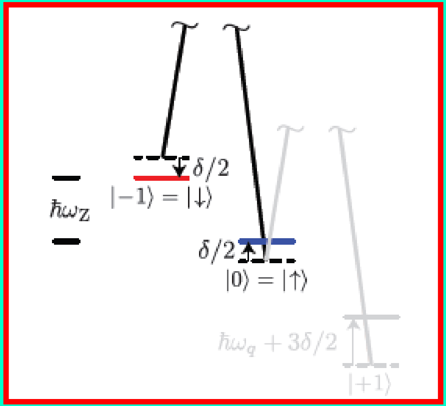


Analogy with bucket
experiment of superfluid Helium

A more advanced example:

Spin-orbit coupling

Raman transitions between
two hyperfine states



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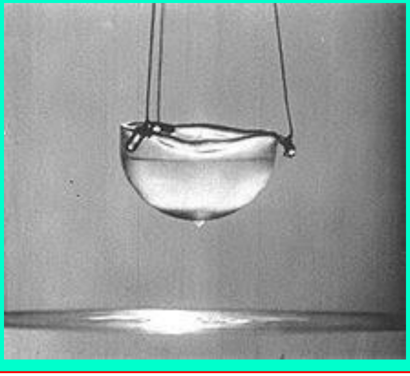


Analogy with bucket experiment of superfluid Helium

This approach takes advantage of the similarity between the **magnetic Lorentz force** and the **Coriolis force** which appears in the rotating frame.

In practice one confines the gas in an isotopic harmonic trap and adds a slightly deformed potential which rotates at angular velocity Ω. The system is expected to thermalize in the rotating frame where the Hamiltonian takes the form:

$$\boxed{H = \frac{\vec{p}^{\,2}}{2m} + \frac{1}{2} m\omega_{ho}^2 \vec{r}^{\,2} - \Omega L_z}$$

with $L_z = xp_y - yp_x$

In rotating frame the Hamiltonian can be also written as

$$H = \frac{(\vec{p} - e\vec{A})^2}{2m} + \frac{1}{2} m\omega_{ho}^2 r^2 + V_{centrif.}$$

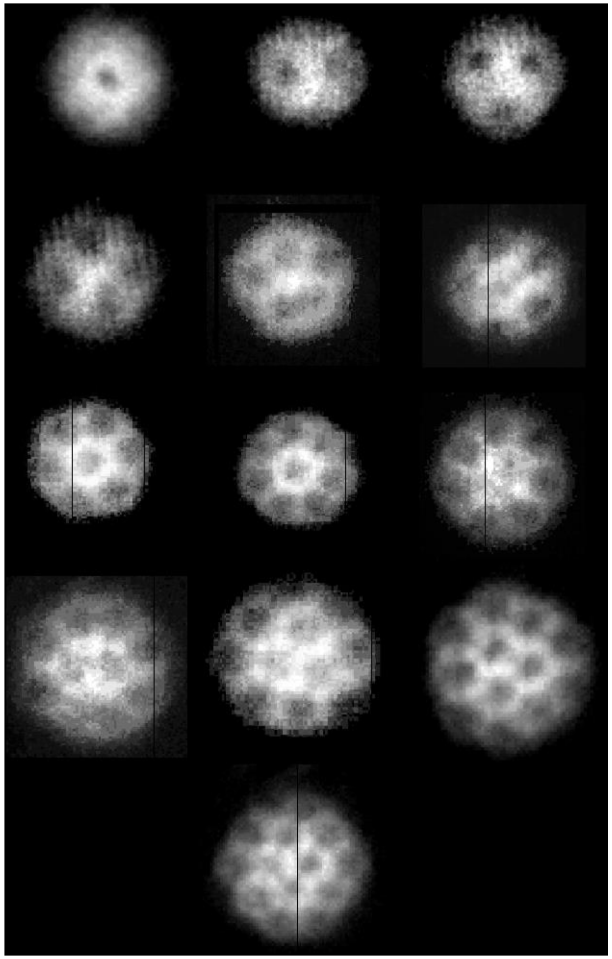
with $$e\vec{A} = m\Omega(x\vec{j} - y\vec{i})$$

$$V_{centrif.} = -\frac{1}{2} m\Omega^2 (x^2 + y^2)$$

The rotation then gives rise to an **effective gauge field** of magnetic-type with the additional presence of a **centrifugal term**.

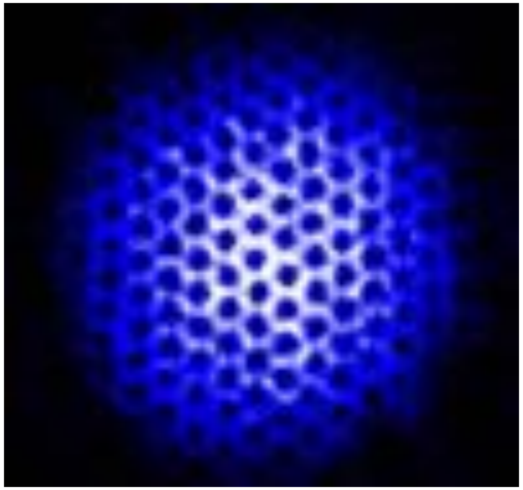
The centrifugal term contrasts the confinement provided by the harmonic trap and sets a limit to the available values of angular velocity

For sufficiently large angular velocity the **gauge field**, applied to a Bose-Einstein condensed gas, causes the appearence of **quantized vortices**

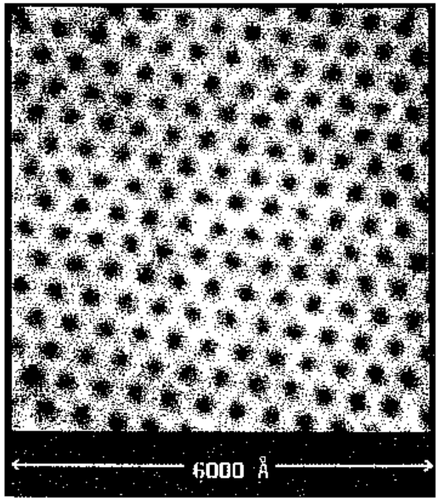


Quantized vortices obtained by rotating the confining trap at different angular velocities (ENS, 2000)

At higher angular velocity one can nucleate more vortices which form a **triangular lattice**
(similar to **Abrikosov** lattice in superconductors)



Vortex lattice created in a rotating
Bose-Einstein condensate
MIT, Jila (2001-2002)



STM image of vortex lattice in superconductor
(Bell Lab 1989)

The density of vortices is fixed by the angular velocity according to

$$n_v = \frac{N_v}{V} = \frac{m}{\pi\hbar}\Omega$$

If $N_v << N$ the system can be described by mean field regime (Gross-Pitaevskii theory)

If $N_v \approx N$ one enters the **Quantum Hall Regime** (so far inacessible in rotating Bose-Einstein condensates)

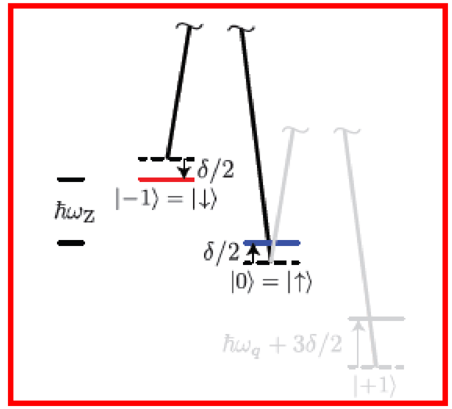
Look for alternative methods to generate gauge fields

A more advanced example of generation of artificial gauge fields:

Spin-orbit coupling

Simplest realization of spin-orbit coupling in a binary mixture (s=1/2) of Bose-Einstein condensates (Spielman, Nist, 2009)

Two detuned and **polarized** laser beams + non linear Zeeman field provide Raman transitions between two spin states, giving rise to new s.p. Hamitonian



$$h_0^{lab} = \frac{\vec{p}^{\,2}}{2m} + \frac{\hbar\Omega}{2}\sigma_x \cos(2k_0 x - \Delta\omega_L t) + \hbar\frac{\Omega}{2}\sigma_y \sin(2k_0 x - \Delta\omega_L t) - \hbar\frac{\omega_Z}{2}\sigma_z$$

The Hamiltonian is invariant with respect to **helicoidal (skew) translation** (**continuous** symmetry)

$$e^{id(p_x - k_0\sigma_z)}$$

Rigid **translation** plus **rotation** in **spin space**

Unitary transformation $e^{i\Theta\sigma_z/2}$ with $\Theta = 2k_0 x - \Delta\omega_L t$

transforms h_0^{lab}

into **translationally invariant**, **time independent** spin-orbit Hamiltonian

$$h_0 = \frac{1}{2m}[\left(p_x - k_0\sigma_z\right)^2 + p_\perp^2] + \frac{1}{2}\hbar\Omega\sigma_x + \frac{1}{2}\hbar\delta\sigma_z$$

$p_x = -i\hbar\partial_x$ is canonical momentum

k_0 is laser wave vector difference

Ω is strength of Raman coupling

$\delta = \Delta\omega_L - \omega_Z$ is effective Zeeman field

Spin orbit Hamiltonian is **translationally invariant**.

However it breaks

- **Galilean** invariance

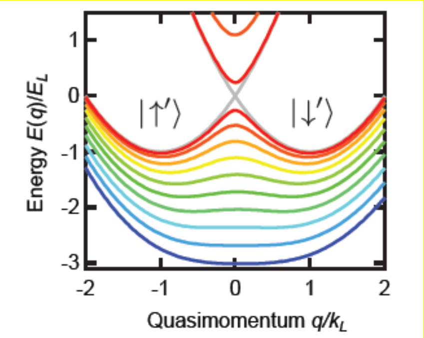
as well as

- **Parity** &**Time Reversal**

physical momentum (and physical velocity) equal to

$$P_x = mv_x = (p_x - k_0\sigma_z)$$

Single particle spin-orbit Hamiltonian is characterized by a novel
two band structure



- **Novel many-body physics** caused by the profound modification of the single particle Hamiltonian and by the presence of a **spin dependent gauge field**

- Many properties of the **ground state** as well as of the **excited states** are now investigated both theoretically and experimentally.

Different strategies to realize novel quantum phases

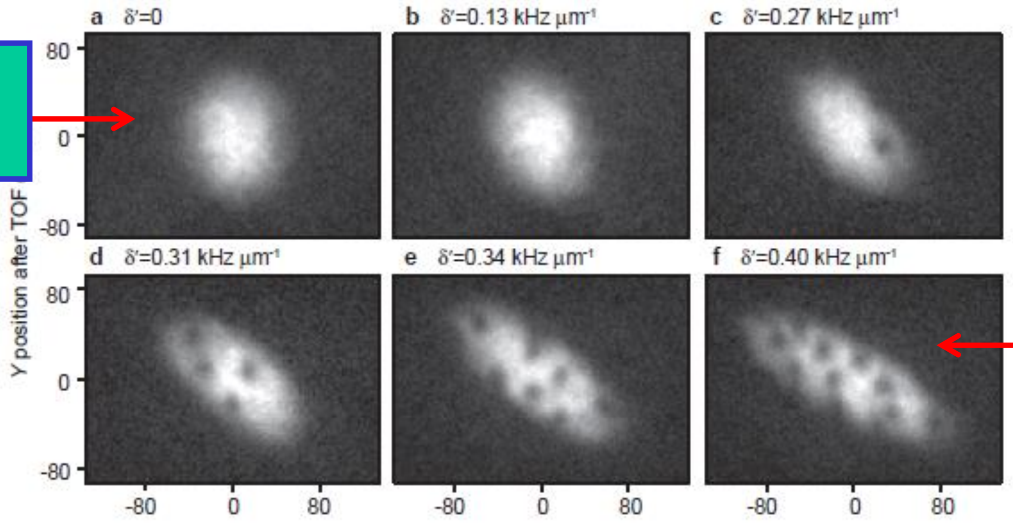
- **First strategy** (Lin et al., Nature 2009).
  Spatially dependent detuning ($\delta(y)$) in strong Raman coupling ($\Omega >> k_0^2$) regime yields position dependent vector potential

$$h_0 = \frac{1}{2m^*}\left(p_x - A_x(y)\right)^2$$

and **effective Lorentz force in neutral atoms.**

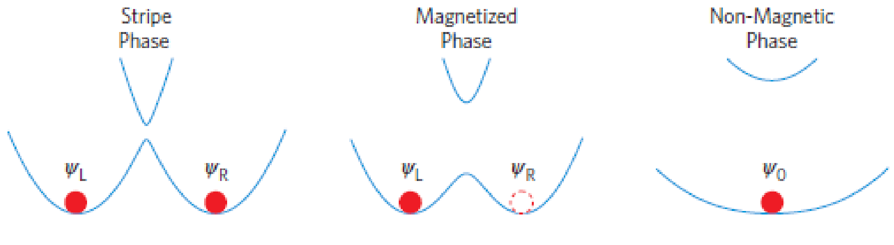
This causes the appearence of quantized vortices (**no need to rotate the confining trap**)

No y-dependence
In detuning



strong
y-dependence
In detuning

Second strategy (Lin et al. Nature 2011). At small Raman coupling lowest band exhibits **two degenerate minima** which can host a BEC.
As a function of coupling one predicts different phases



Order parameter in the new phases

I) Stripe phase

$$\Psi = \sqrt{\frac{N}{2V}}\left[\begin{pmatrix}\cos\theta \\ -\sin\theta\end{pmatrix}e^{ik_1x} + \begin{pmatrix}\sin\theta \\ -\cos\theta\end{pmatrix}e^{-ik_1x}\right]$$

II) Plane wave phase

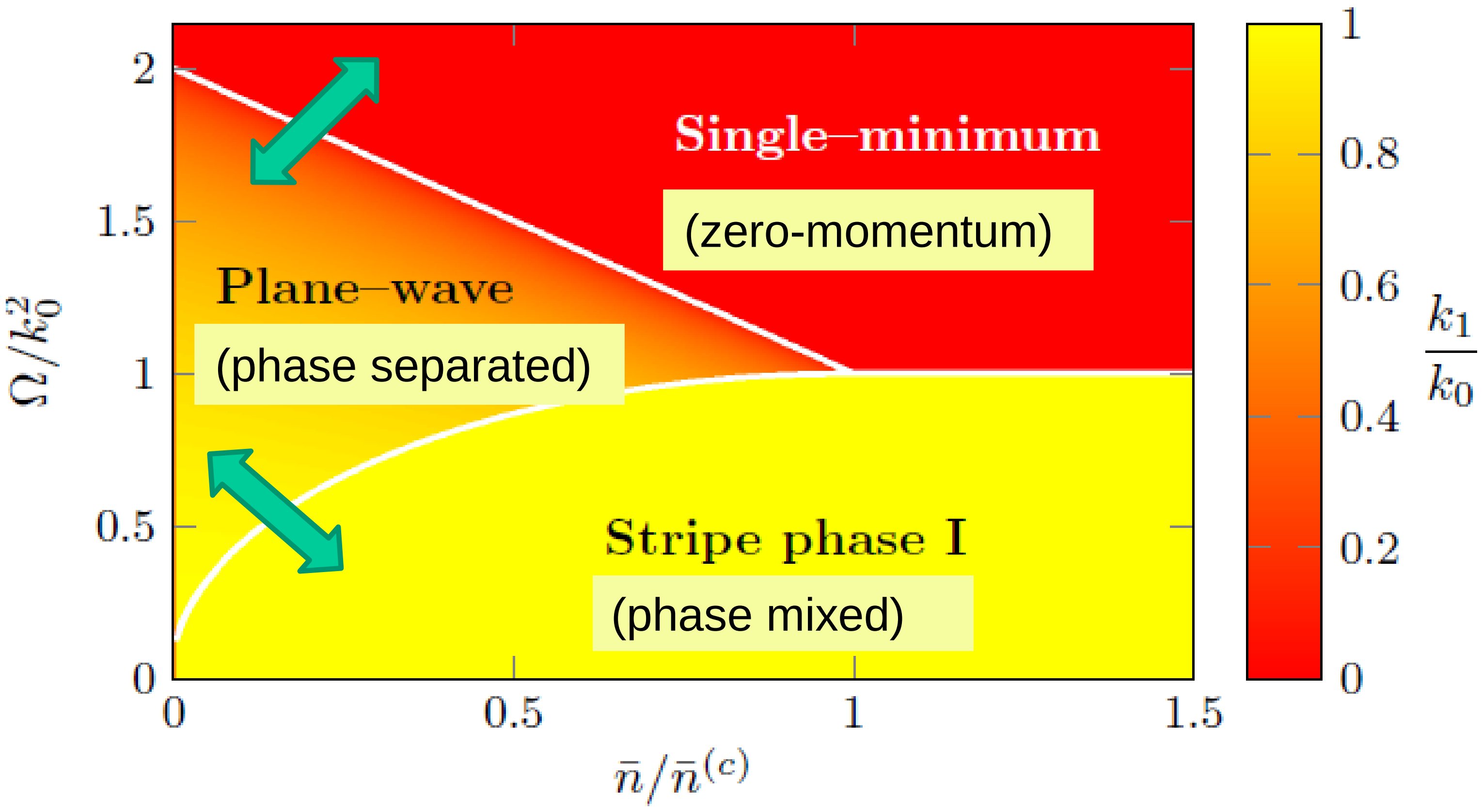
$$\Psi = \sqrt{\frac{N}{2V}}\begin{pmatrix}\sin\theta \\ -\cos\theta\end{pmatrix}e^{-ik_1x}$$

$$<\sigma_z>=\frac{k_1}{k_0}$$

III) Zero momentum phase

$$\Psi = \sqrt{\frac{N}{V}}\begin{pmatrix}1 \\ -1\end{pmatrix}$$

New quantum phases (T=0)



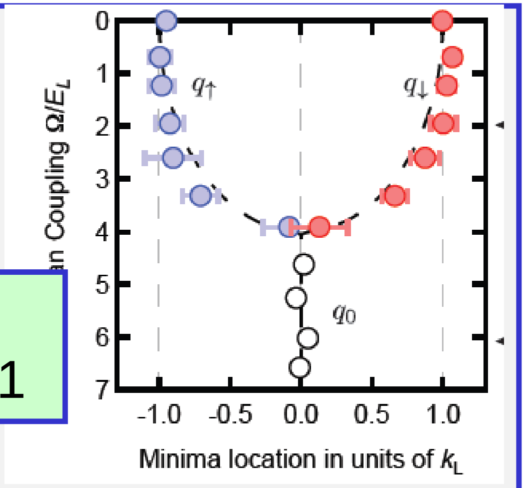
Plane wave-Single minimum phase transition

Transition is **second order**.
It has been observed
at the predicted value

$$\Omega = \Omega_c \approx 2k_0^2$$

of the Raman coupling

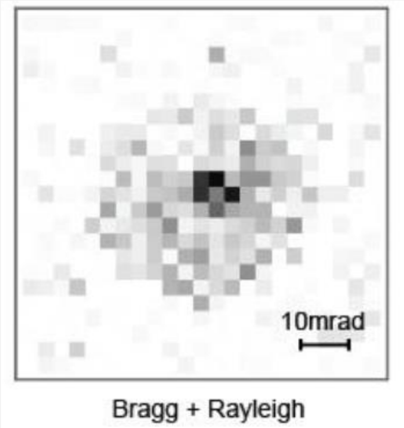
Lin et al.,
Nature 2011



Plane wave-Stripe phase transition

Transition is **first order**.

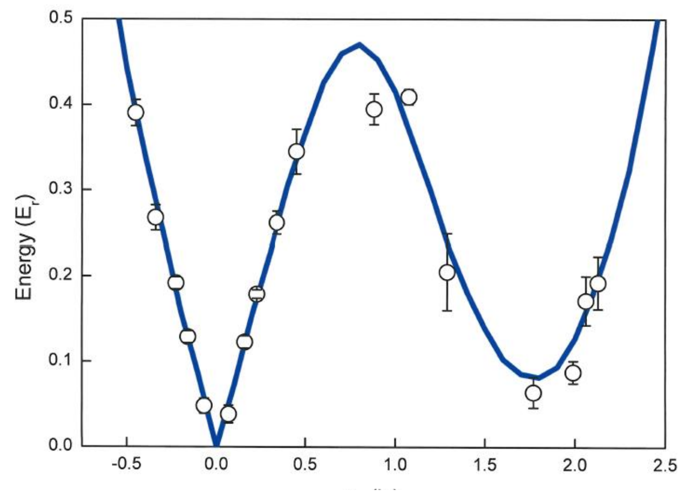
First experimental evidence of stripe phase has become recently available via Bragg scattering (MIT 2017)



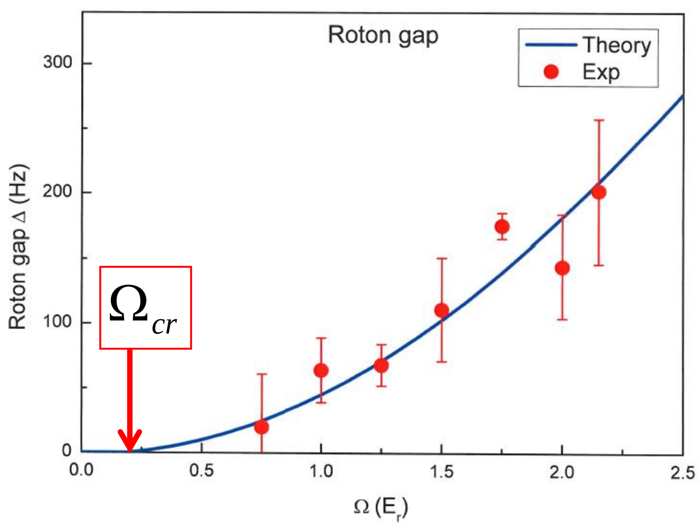
Spin-orbit coupling has **important** consequences on the **dynamic** and **superfluid behavior** of a Bose-Einstein condensate

At small Raman coupling, near the transition to the stripe phase a **roton** structure emerges in the excitation spectrum

Exp: Si-Cong Ji et al., PRL 114, 105301 (2015)
Theory: Martone et al., PRA 86, 063621 (2012)



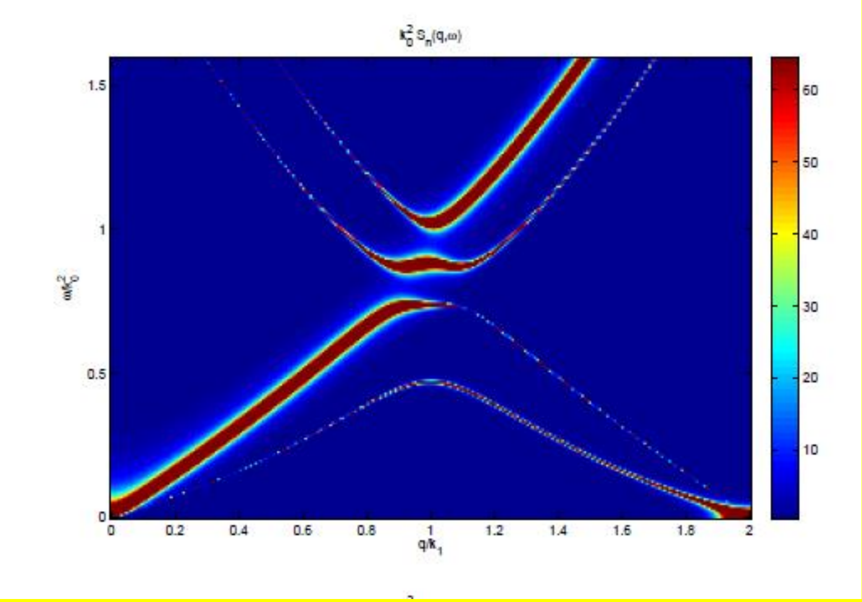
$\omega(q) \neq \omega(-q)$ consequence of violation of **parity** and **time reversal** symmetry



Roton gap decreases as Raman coupling is lowered: **onset of crystallization** (**striped** phase)

Striped phase (supersolid phase) results from **spontaneous** breaking of two continuous symmetries: **gauge** and **translational** symmetries

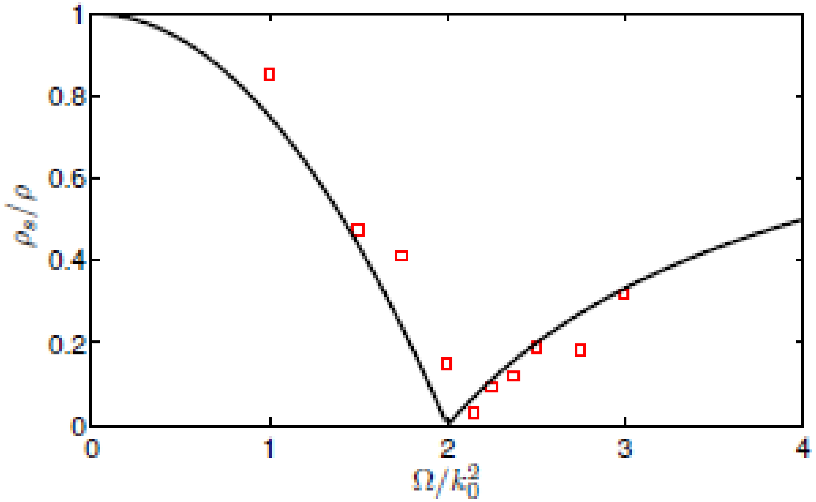
Two Goldstone modes:



- Double band structure in the striped phase of a SO coupled Bose-Einstein condensate (Yun Li et al. PRL 2013)
- No experiments available so far !!

Breaking of **Galilean** invariance caused by spin-orbit coupling has
major consequences on the **superfluid behavior**

Superfluid density as a function of Raman coupling



$$\rho_s = \rho m c^2 \kappa$$

- Superfluidity disappears at the tranistion between plane wave-and single minimum phases

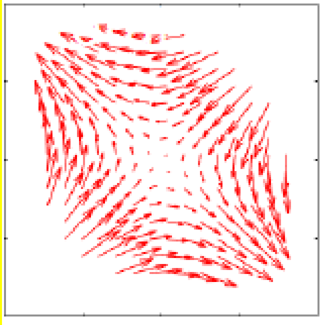
- Full line is prediction of theory (Hong Kong- Trento 2016)

- Exp points are obtained using measured values of sound velocity (Shanghai 2015)

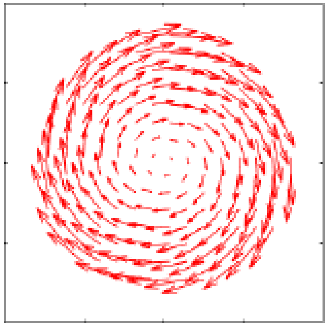
Moment of inertia of a spin-orbit coupled BEC

Can a **BEC rotate** like a **rigid body** ?

$\vec{v} \propto \nabla(xy)$



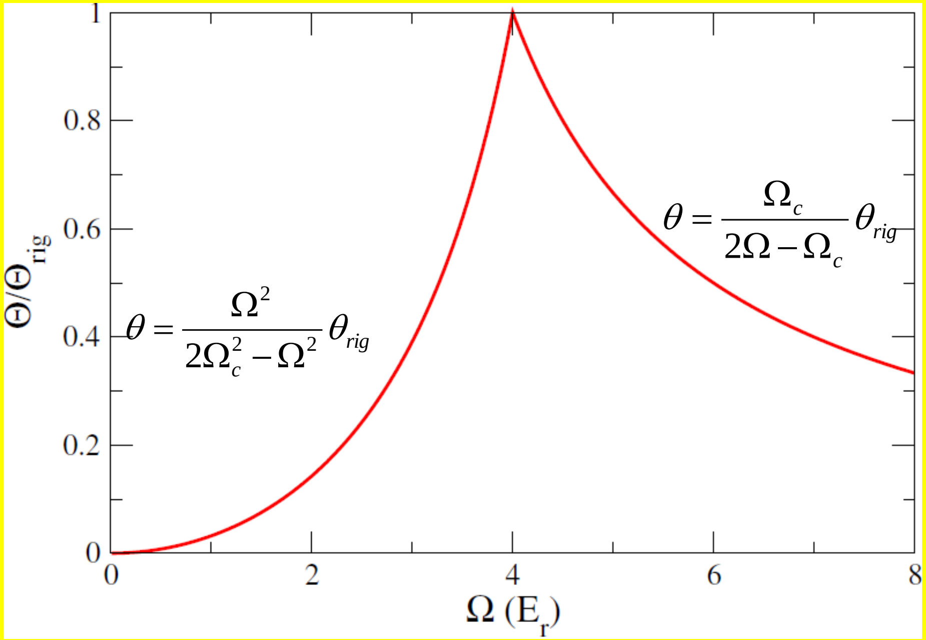
$\vec{v} = \vec{\omega}_{rot} \times \vec{r}$



Superfluid (irrotational) flow

Non superfluid (rigid body) flow

Behavior of moment of inertia
(S.S. PRL 18, 145302 2017)



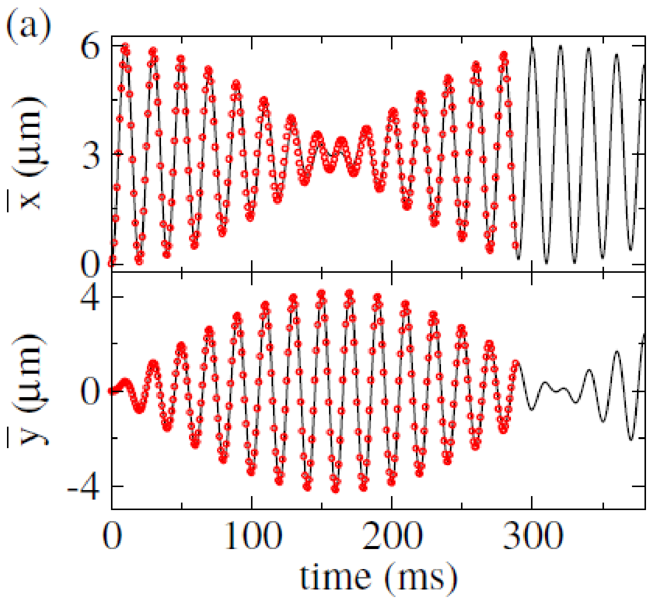
Rigid value $\theta = \theta_{rig}$ at the transition between plane wave and single momentum phase.
Dramatic consequence of spin-orbit coupling

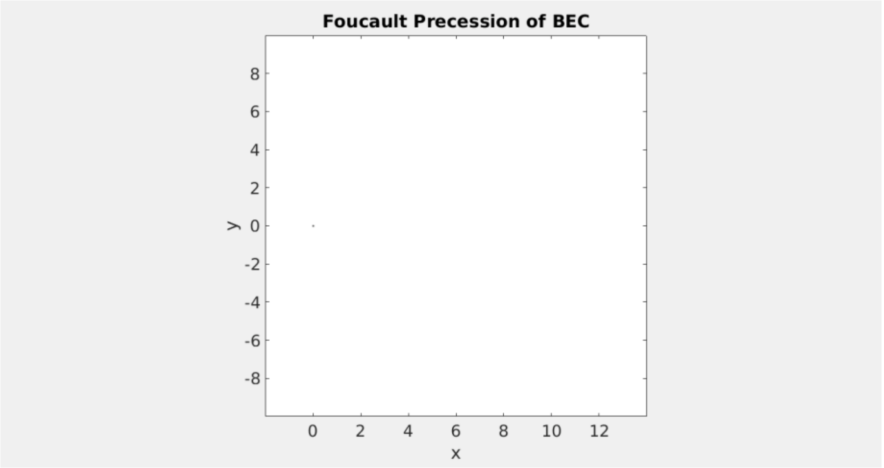
The presence of the artificial gauge field caused
by spin-orbit coupling brings effectively
the quantum system into a **non inertial frame**

Foucault pendulum in a spin-orbit coupled gas

(Chunlei Qu and S.S., PRL 2018)

Precession following the excitation of the dipole mode along x





MAIN CONCLUSION AND PERSPECTIVES

- The investigation of synthetic (artificial) gauge fields is opening **rapidly evolving frontiers** of experimental and theoretical research in cold atomic physics.

- Many other important issues (not addressed in this talk):
  - realization of **2D and 3D** spin orbit coupling
  - Gauge fields in the presence of **optical lattices**
  - **Synthetic dimensions**
  - Superfluidity of **supersolid** matter
  - Synthetic gauge fields in Fermi superfluids
  - **Non Abelian** gauge fields (Rashba Hamiltonian)
  - **Berry's phase**
  - novel **topological properties** of quantum matter
  - etc..

The Trento BEC team

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http://bec.science.unitn.it/