A dipolar quantum gas with supersolid properties

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Quantum Simulations of Insulators and Conductors

First proposals

QUANTUM THEORY OF DEFECTS IN CRYSTALS

A. F. ANDREEV and I. M. LIFSHITZ

Institute of Physical Problems, U.S.S.R. Academy of Sciences

Submitted January 15, 1969

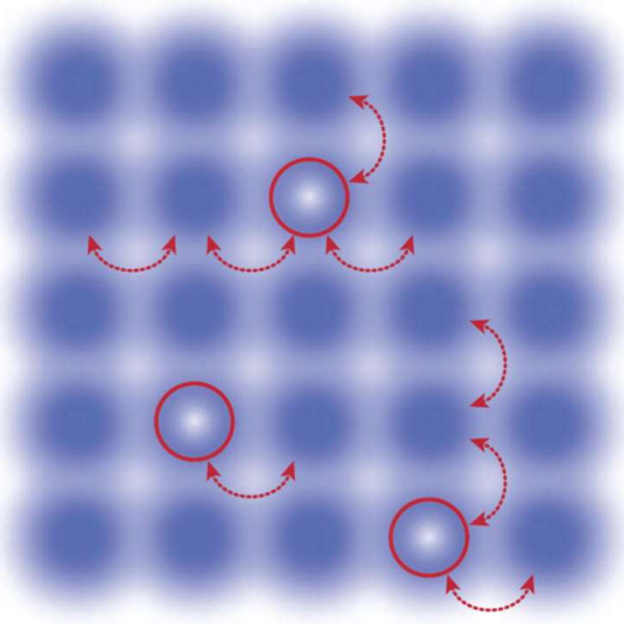
Zh. Eksp. Teor. Fiz. **56**, 2057–2068 (June, 1969)

At sufficiently low temperatures localized defects or impurities change into excitations that move practically freely through a crystal. As a result instead of the ordinary diffusion of defects, there arises a flow of a liquid consisting of "defectons" and "impuritons." It is shown that at absolute zero in crystals with a large amplitude of the zero-point oscillations (for example, in crystals of the solid helium type) zero-point defectons may exist, as a result of which the number of sites of an ideal crystal lattice may not coincide with the number of atoms. The thermodynamic and acoustic properties of crystals containing zero-point defectons are discussed. Such a crystal is neither a solid nor a liquid. Two kinds of motion are possible in it; one possesses the properties of motion in an elastic solid, the second possesses the properties of motion in a liquid. Under certain conditions the "liquid" type of crystal motion possesses the property of superfluidity. Similar effects should also be observed in quasiequilibrium states containing a given number of defectons.

Also:

E. P. Gross, Phys. Rev. 106, 161 (1957)
D.J. Thouless, Ann. Phys, 52, 403 (1969)
G.V. Chester, Phys. Rev. 2, 161 (1970)
A.J. Leggett, Phys. Rev. Lett. 25, 1543 (1970)

First proposals



The large **zero-point motion** in solid He allows the atoms to exchange their positions:

$$\Lambda = \frac{h}{a\sqrt{m\epsilon}} > 1$$

a: interatomic distance
ϵ: interaction energy

Atom vacancies in ^{4}He (defectons) can move, form a Bose-Einstein condensate and give rise to a superfluid mass transport.

The energy cost of creating a vacancy is fully compensated by the decrease of kinetic energy due to delocalization.

First proposals

VOLUME 25, NUMBER 22 PHYSICAL REVIEW LETTERS 30 NOVEMBER 1970

Can a Solid Be "Superfluid"?

A. J. Leggett
School of Mathematical and Physical Sciences, University of Sussex, Falmer, Brighton, Sussex, England
(Received 15 September 1970)

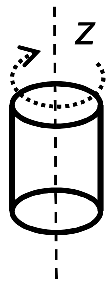
It is suggested that the property of nonclassical rotational inertia possessed by superfluid liquid helium may be shared by some solids. In particular, nonclassical rotational inertia very probably occurs if the solid is Bose-condensed as recently proposed by Chester. Anomalous macroscopic effects are then predicted. However, the associated superfluid fraction is shown to be very small (probably $\lesssim 10^{-4}$) even at $T = 0$, so that these effects could well have been missed. Direct tests are proposed.

Superfluids have a single wavefunction:

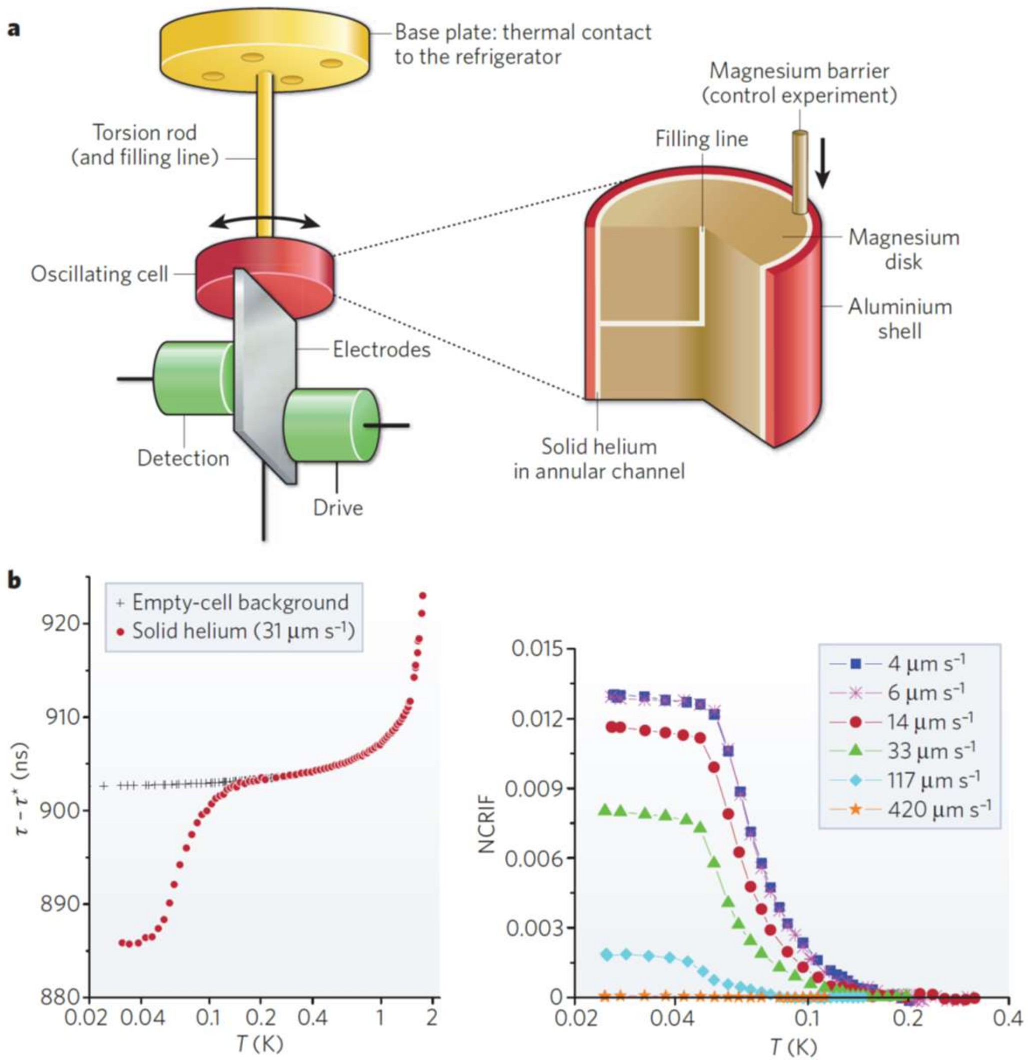
$$\Psi_0(r) = |\Psi_0(r)| e^{i\varphi(r)}$$

and the velocity is the gradient of the phase, $v = (\hbar/m)\nabla\varphi$, so it is irrotational ($\nabla \times v$=0). As a consequence, the moment of inertia of a cylindrically symmetric superfluid is zero:

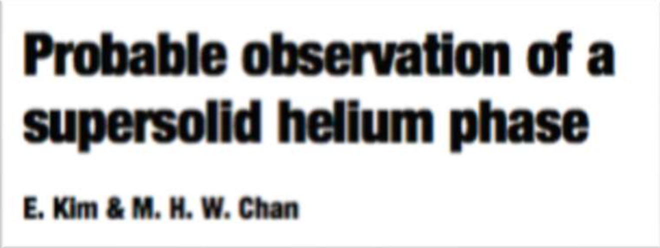
$$I = I_{rig} \frac{\langle x^2 - y^2 \rangle}{\langle x^2 + y^2 \rangle}$$



The search in solid helium



Nature 427, 225 (2004)



Probable observation of a supersolid helium phase

E. Kim & M. H. W. Chan

Torsion oscillator:

$$\tau = 2\pi\sqrt{I/K}$$

τ: oscillation period
I: moment of inertia
K: elastic constant

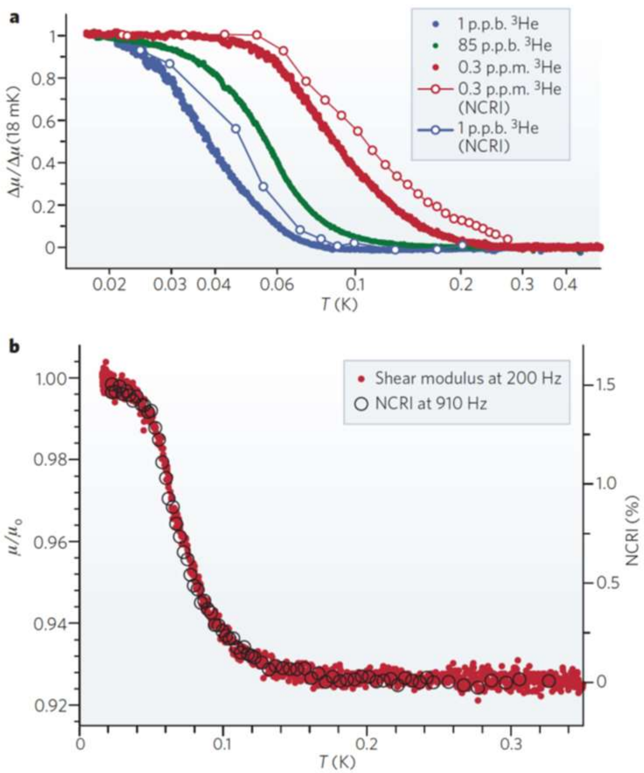
Review: S. Balibar, Nature 464, 176 (2010).

The search in solid helium

Problem: the energy cost in creating vacancies is very large (10 K): the fraction of vacancies at 100 mK must be pratically zero!

Other possible explanations for supersolidity in He:

- Lattice dislocations
- ^{3}He impurities (naturally 10^{-7})

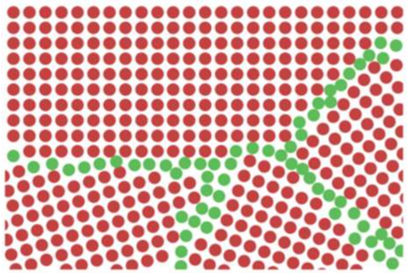


Review: S. Balibar, Nature 464, 176 (2010)

Problem: the change of period might be explained with a change of the elastic constant!

$$\tau = 2\pi\sqrt{I/K}$$

Dislocations change state when lowering the temperature and the crystal stiffens.

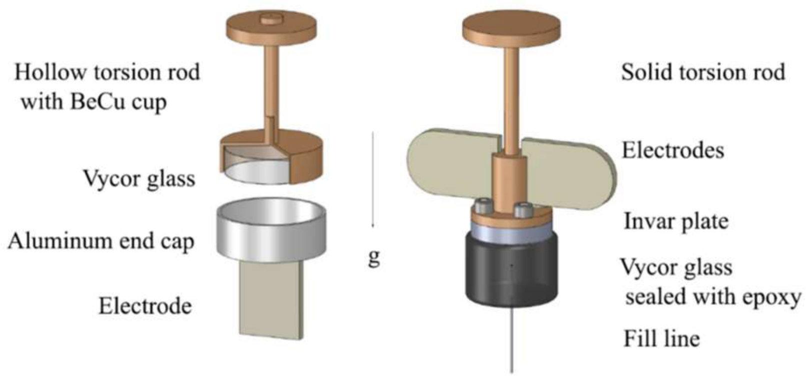


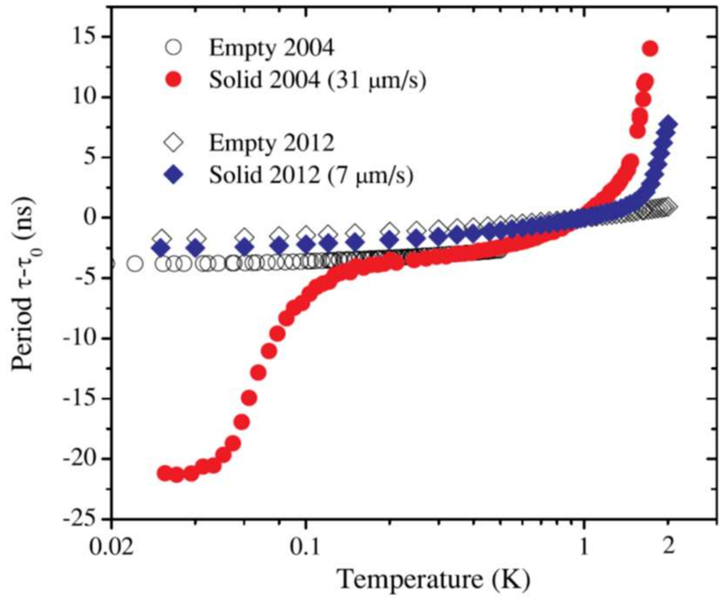
The search in solid helium

Phys. Rev. Lett. 109, 155301 (2012)

Absence of Supersolidity in Solid Helium in Porous Vycor Glass

Duk Y. Kim and Moses H. W. Chan*
Department of Physics, Pennsylvania State University, University Park, Pennsylvania 16802, USA
(Received 24 July 2012; published 8 October 2012)





No reduction of the moment of inertia if bulk solid He is excluded. This contradicts the orginal experiment!

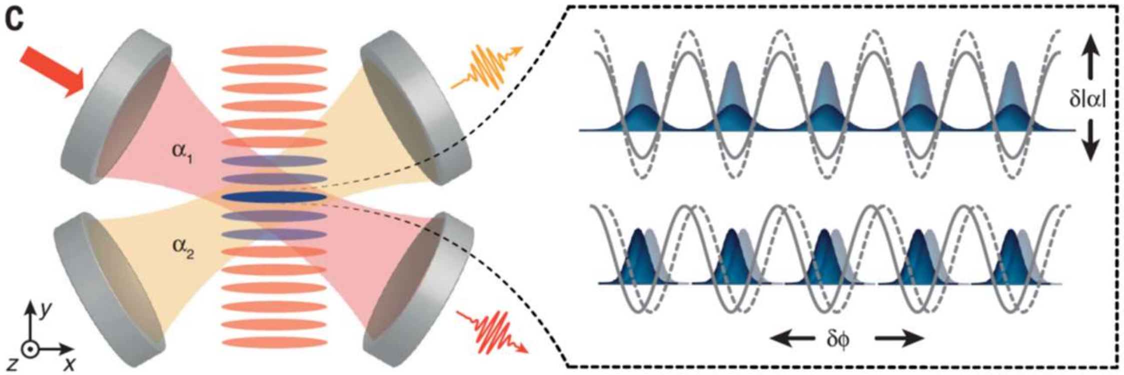
More refined experiments still do not exclude supersolidity: J. D. Reppy et al., PNAS 3203 (2016).

Supersolids in quantum gases

gaseous Bose-Einstein condensates (**superfluidity**)
+
long-range interactions (**density modulation**)

Proposals for:

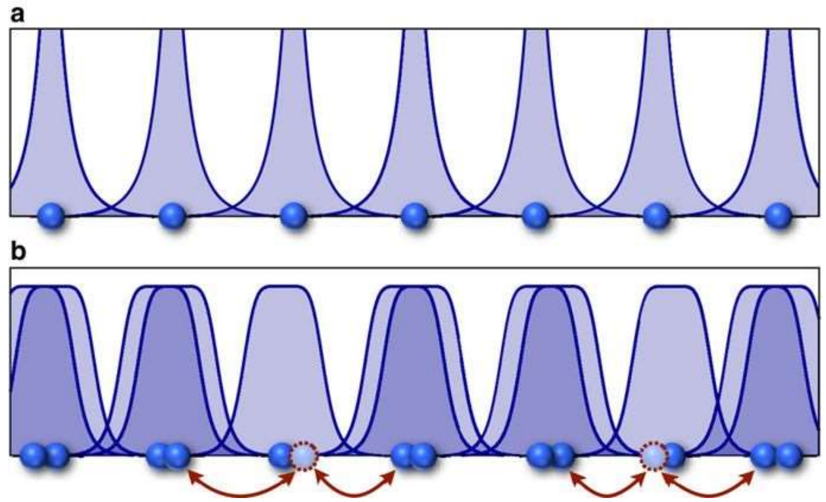
- Rydberg atoms with soft-core interactions
- strongly dipolar atoms
- spin-orbit coupled atoms (J.R. Li et al., Nature 543 (2017))
- atoms in optical cavities (J. Leonard et al., Nature 543 (2017))

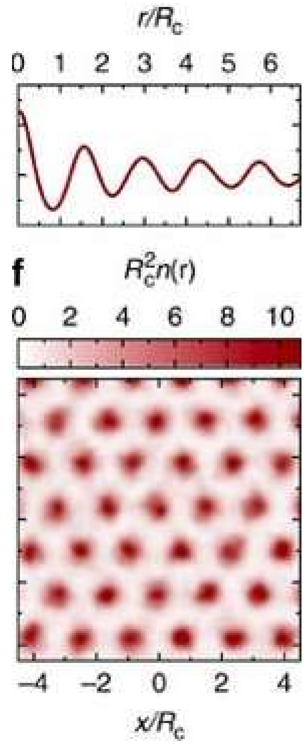


Light-coupled supersolids are perfectly stiff: the supersolid is not compressible.

Supersolids in quantum gases

Bosons with soft-core interactions



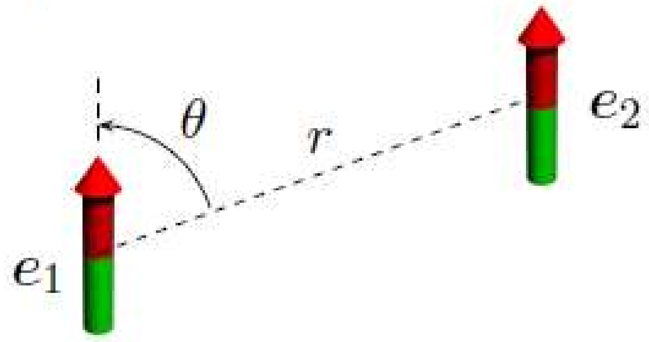


The key ingredient to establish superfluidity is to employ N-atom clusters and not single atoms:

Bosonic enhancement increases the strength of the phase links by (N+1).

F. Cinti et al, Nature Comm. 5, 3235 (2014).

Dipolar quantum gases



$$U(r) = \frac{4\pi\hbar^2}{m} a\,\delta(r) + \frac{\mu_0 \mu^2}{4\pi} \frac{1 - 3\cos^2\vartheta}{r^3}$$

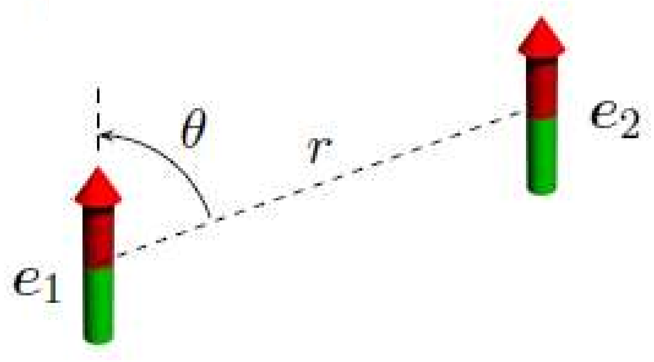
Contact interaction:
Short-range
Isotropic

Dipole-dipole interaction
Long-range
Anisotropic

Repulsive

Attractive

Dipolar quantum gases



$$U(r)=\frac{4\pi\hbar^2}{m}a\delta(r)+\frac{\mu_0\mu^2}{4\pi}\frac{1-3\cos^2\vartheta}{r^3}$$

Contact interaction:
Short-range
Isotropic

Dipole-dipole interaction
Long-range
Anisotropic

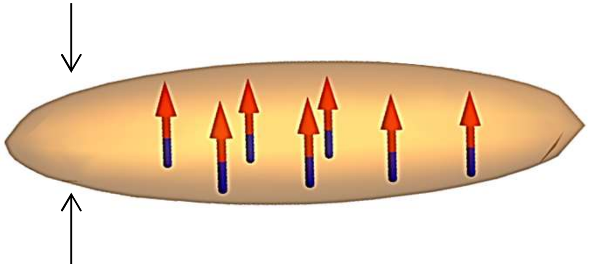
Dy atoms: $\mu=10\ \mu_B$

$a_s \approx 160 a_0$

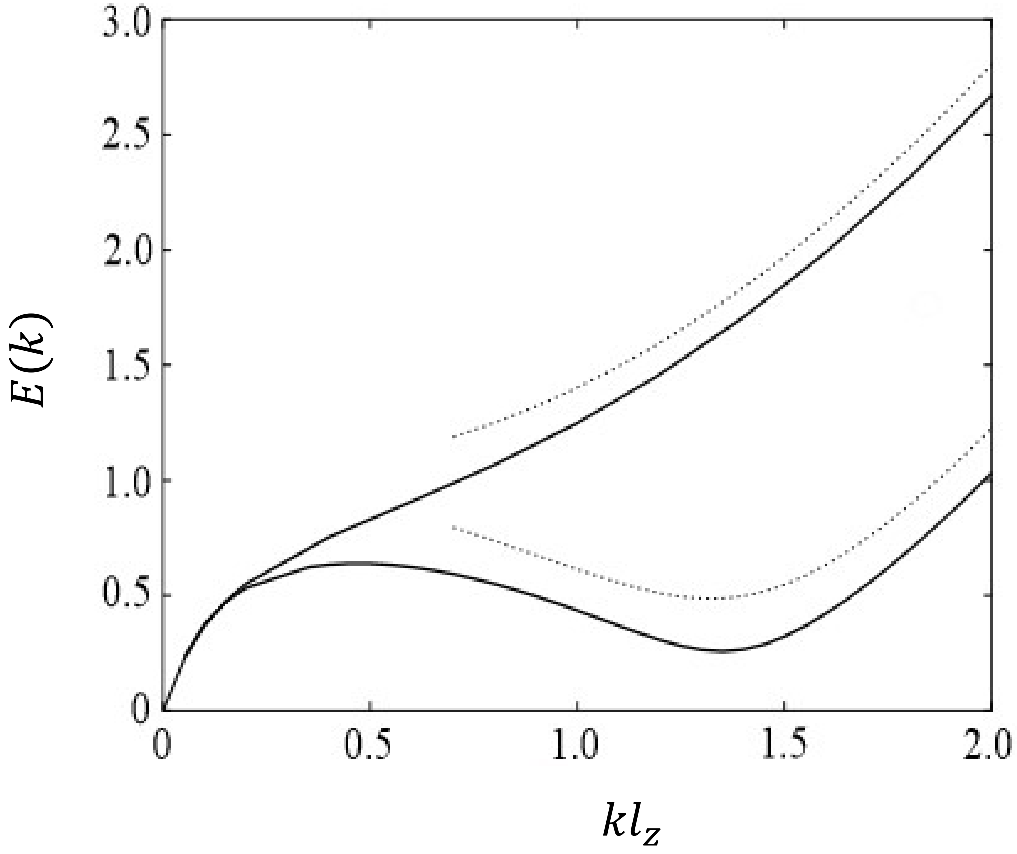
$$a_{dd}=\frac{m\mu_0\mu^2}{12\pi\hbar^2}\approx 130 a_0$$

Excitation spectrum in an elongated trap

$l_z = \sqrt{\hbar/m\omega}$



Mean-field picture (quantum fluctuations are neglected)



L. Santos, G. V. Shlyapnikov, and M. Lewenstein, Roton-Maxon spectrum and stability of trapped dipolar Bose-Einstein condensates, Phys. Rev. Lett. 90, 250403 (2003).

Excitation spectrum in an elongated trap

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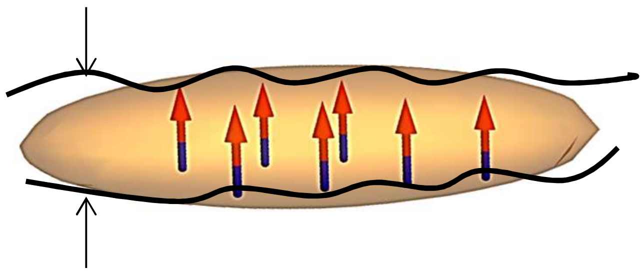
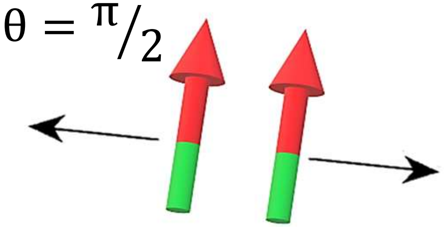
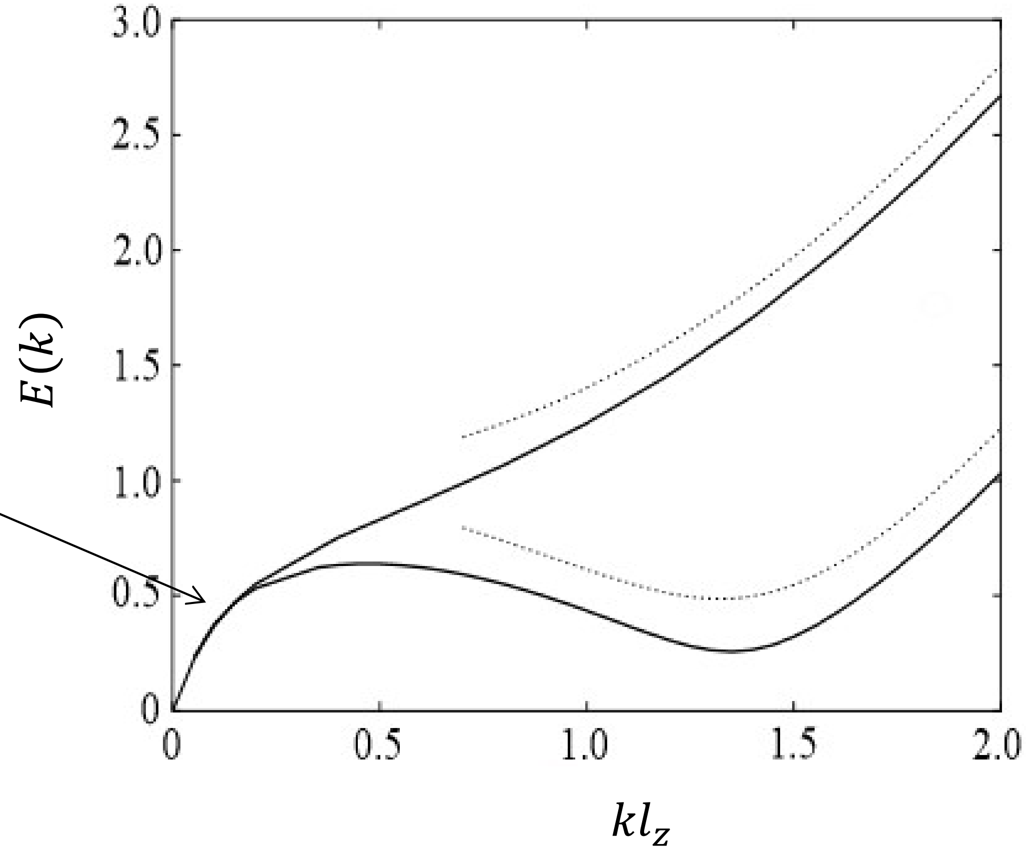


phonons

$\theta = {}^{\pi}/_{2}$



Mean-field picture (quantum fluctuations are neglected)



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Excitation spectrum in an elongated trap

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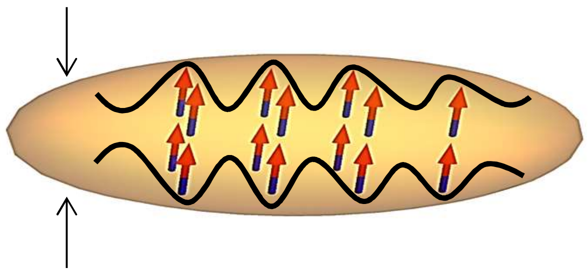
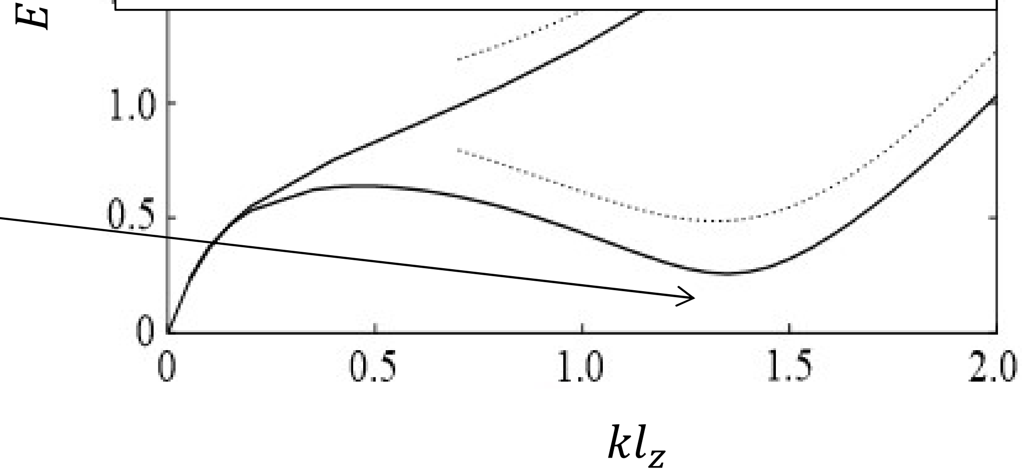


$\theta = 0$

rotons

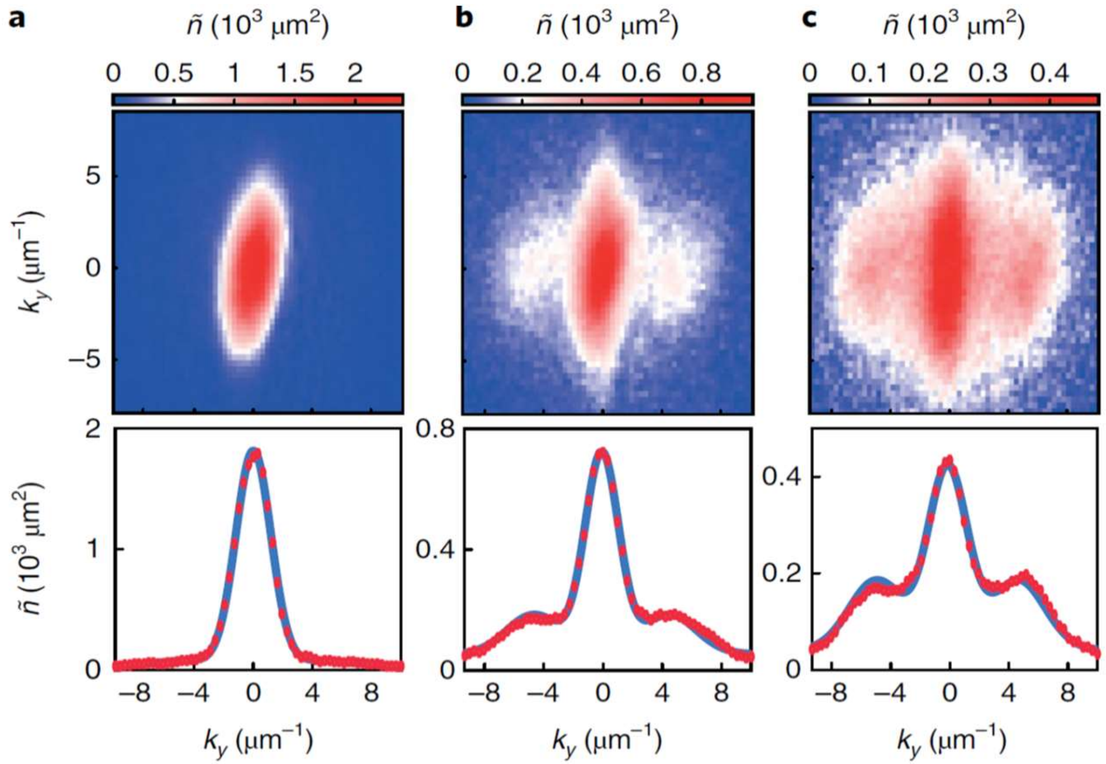


The roton gap can be changed by simply tuning the scattering length (no need to change pressure as in He).

What happens when the roton gap is nulled?

L. Santos, G. V. Shlyapnikov, and M. Lewenstein, Roton-Maxon spectrum and stability of trapped dipolar Bose-Einstein condensates, Phys. Rev. Lett. 90, 250403 (2003).

Rotonic instability



Spontaneous population of the roton mode: transient density modulation (picture shows the momentum distribution), unclear what happens at long times.

What happens then? Does the system collapse?

Innsbruck, Er atoms (7 μ_B): L. Chomaz et al., Nat. Phys. 14, 442 (2018).
Attempt in Firenze, K atoms (1 μ_B): M. Fattori, et al., Phys. Rev. Lett. 101, 190405 (2008).

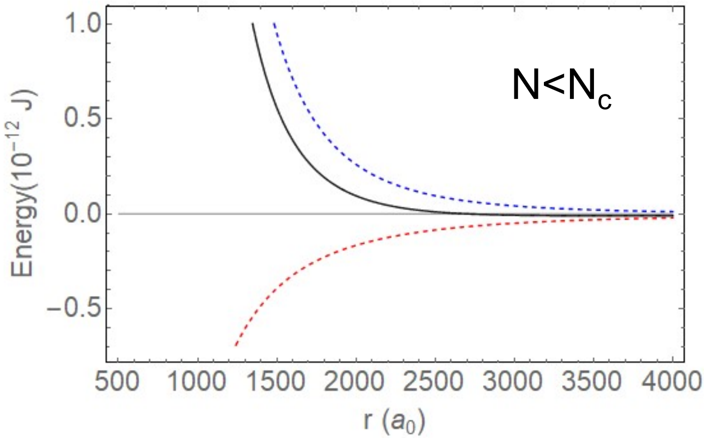
Quantum fluctuations

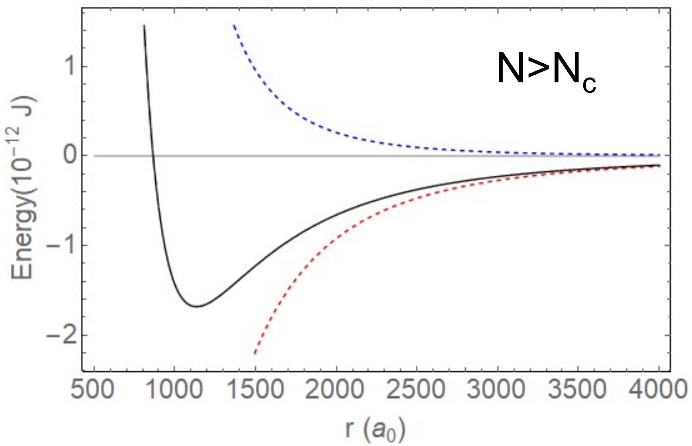
Quantum fluctuations lead to quantum depletion of the BEC and to an energy shift, due to the Lee-Huang-Yang energy term:

$$\frac{E_{\mathrm{int}}}{V} = \frac{gn^2}{2} + E_{dd} + \frac{32 g a^{3/2}}{3\sqrt{\pi}}\left(1 + \frac{3a_{dd}^2}{2a^2}\right) n^{5/2}$$

MF<0 LHY > 0

Energy vs interatomic distance





T. D. Lee, K. Huang, and C. N. Yang, Phys. Rev. 106, 1135 (1957)

Quantum droplets

Ultradilute Quantum Droplets

A new class of quantum mechanical liquids is stabilized by an elegant mechanism that allows them to exist despite being orders of magnitude thinner than air.

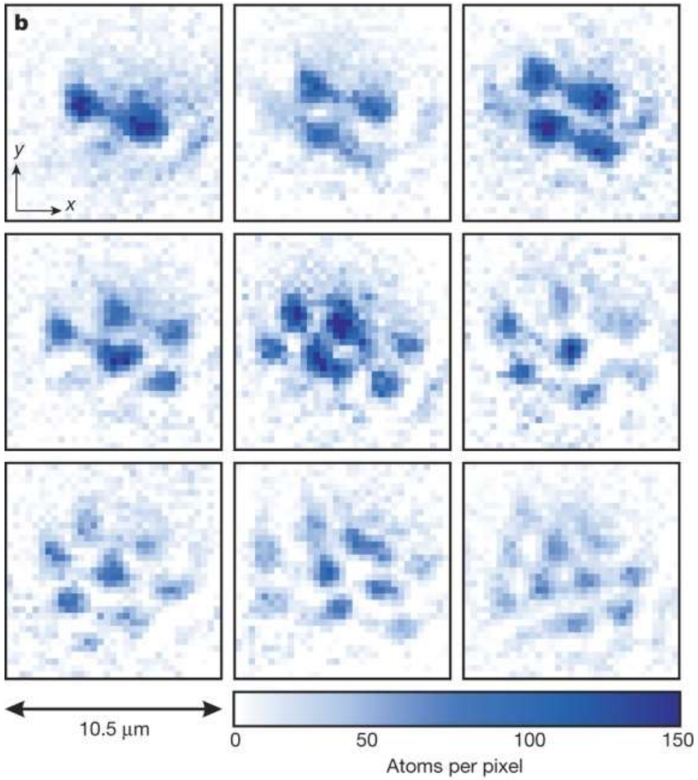
Igor Ferrier-Barbut

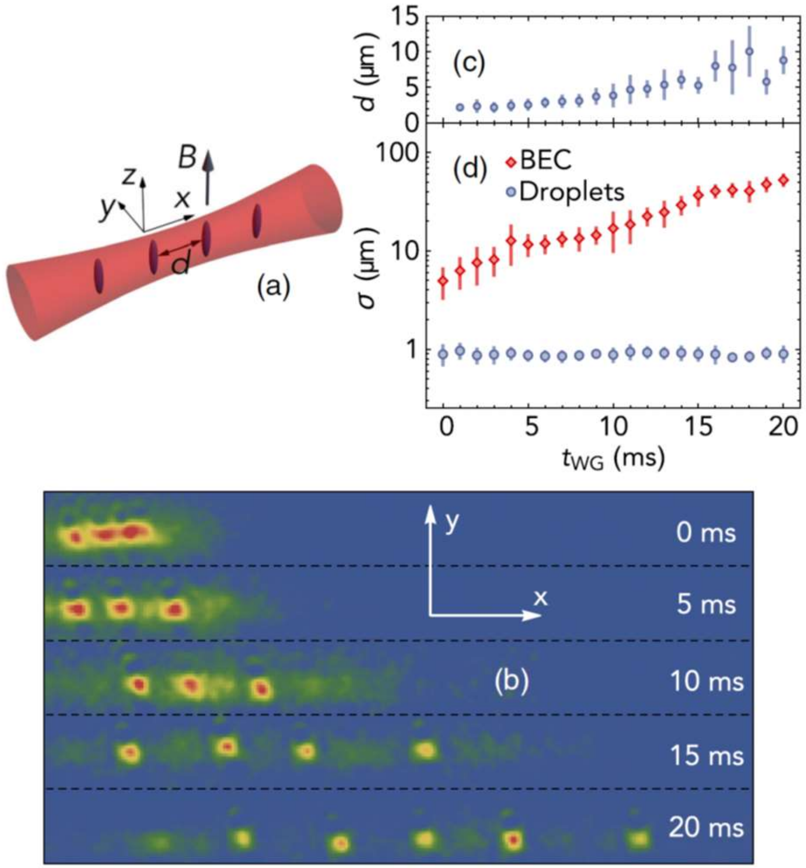
In his PhD thesis from 1873, Johannes van der Waals devised a theoretical framework to describe the gas and liquid phases of a molecular ensemble and the phase transition from one to the other. That work resulted in the celebrated equation of state bearing his name. To this day, the van der Waals theory is still the prevailing picture in most physicists' minds to explain the emergence of the liquid state. It asserts that the liquid state arises at high densities from an equilibrium between attractive interatomic forces and short-range repulsion. Now, a new type of liquid has emerged in ultracold, extremely dilute atomic systems for which the van der Waals model does not predict a liquid phase.

I. Ferrier-Barbut et al., Physics Today, April 2019.
Theoretical proposal by D. S. Petrov – Phys. Rev. Lett. 115, 155302 (2015).

Quantum droplets

Dipolar repulsion: periodic arrays of small, strongly-bound droplets.



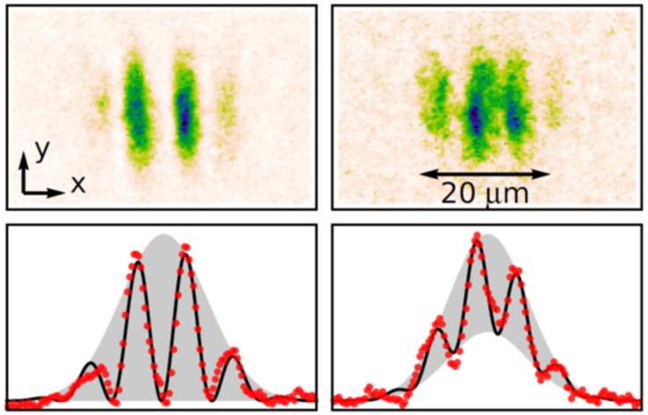


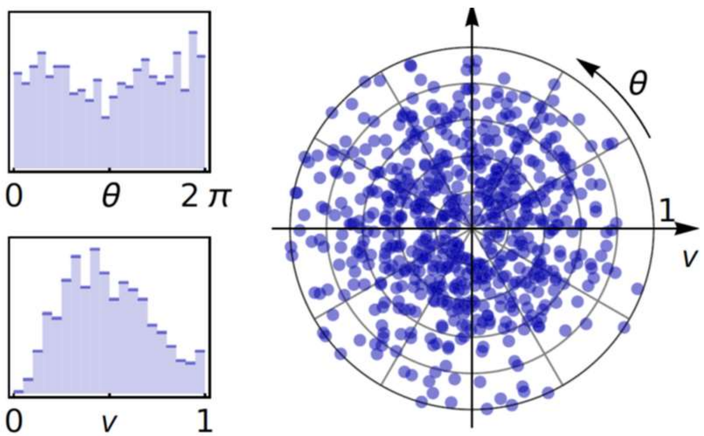
Stuttgart, Dy atoms (10 μ_B): H. Kadau et al., Nature 530, 194 (2016); I. Ferrier-Barbut et al., Phys. Rev. Lett. 116, 215301 (2016).

Quantum droplets

Unfortunately, the tunneling between droplets is very small, due to the strong repulsion between droplets.

No coherence!



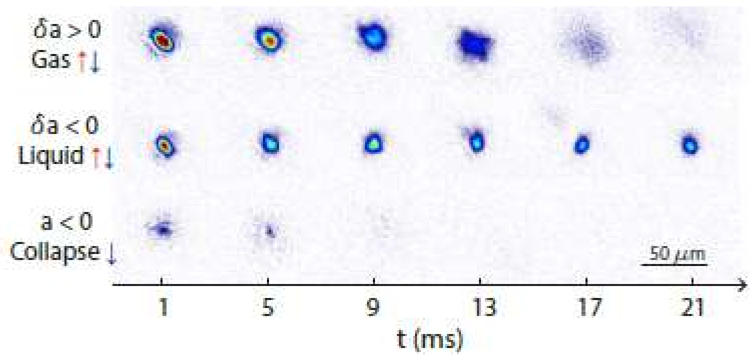


Interference of matter waves.

Stuttgart, Dy atoms (10 μ_B): M. Wenzel et al., Phys. Rev. A 96, 053630 (2017).

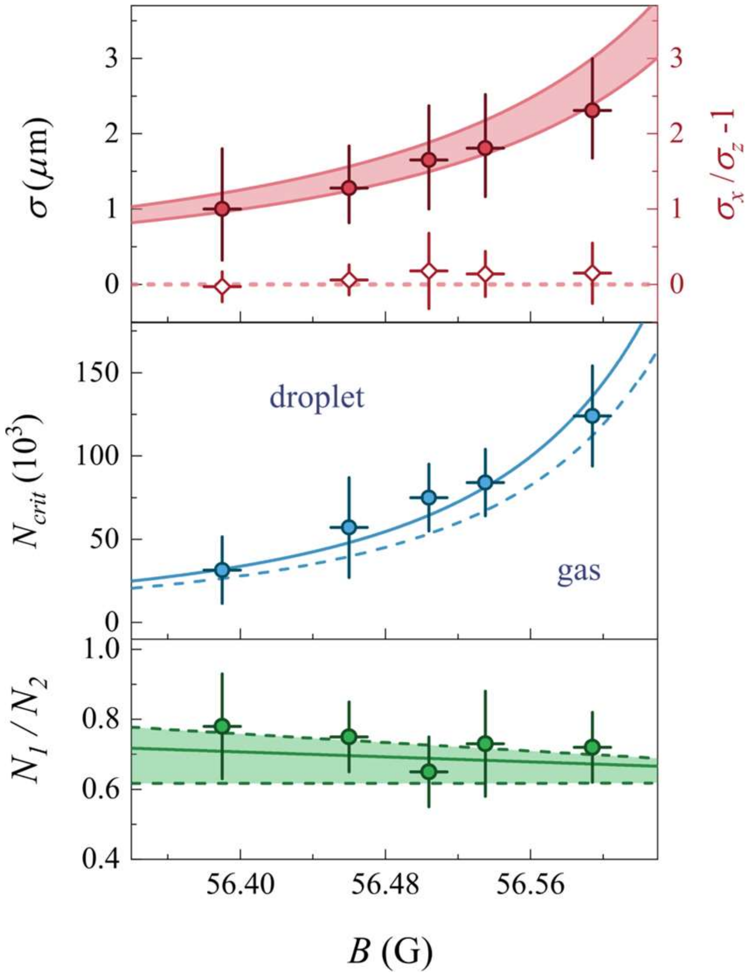
Quantum droplets in Bose-Bose mixtures

Barcelona, K atoms



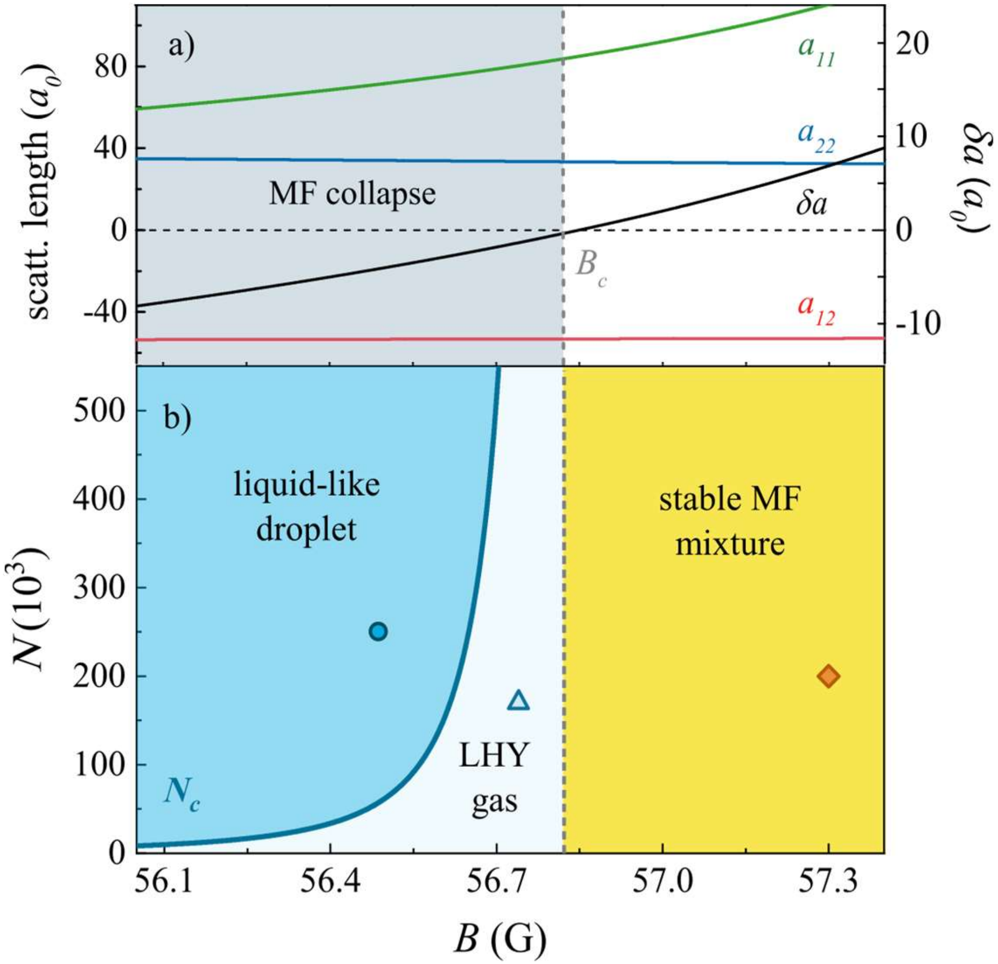
C. R. Cabrera, L. Tanzi, J. Sanz, B. Naylor, P. Thomas, P. Cheiney, and L. Tarruell, Science 359, 301 (2018)

Firenze, K atoms



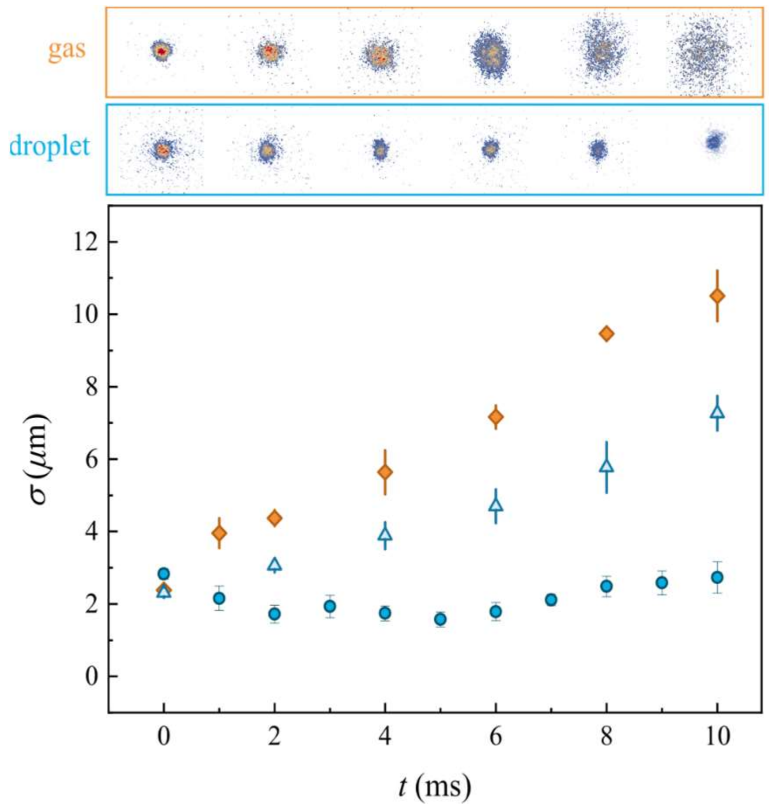
G. Semeghini et al., M. Fattori, Phys. Rev. Lett. 120, 235301 (2018)

Quantum droplets in Bose-Bose mixtures



Broad regime of weak binding

Firenze, K atoms



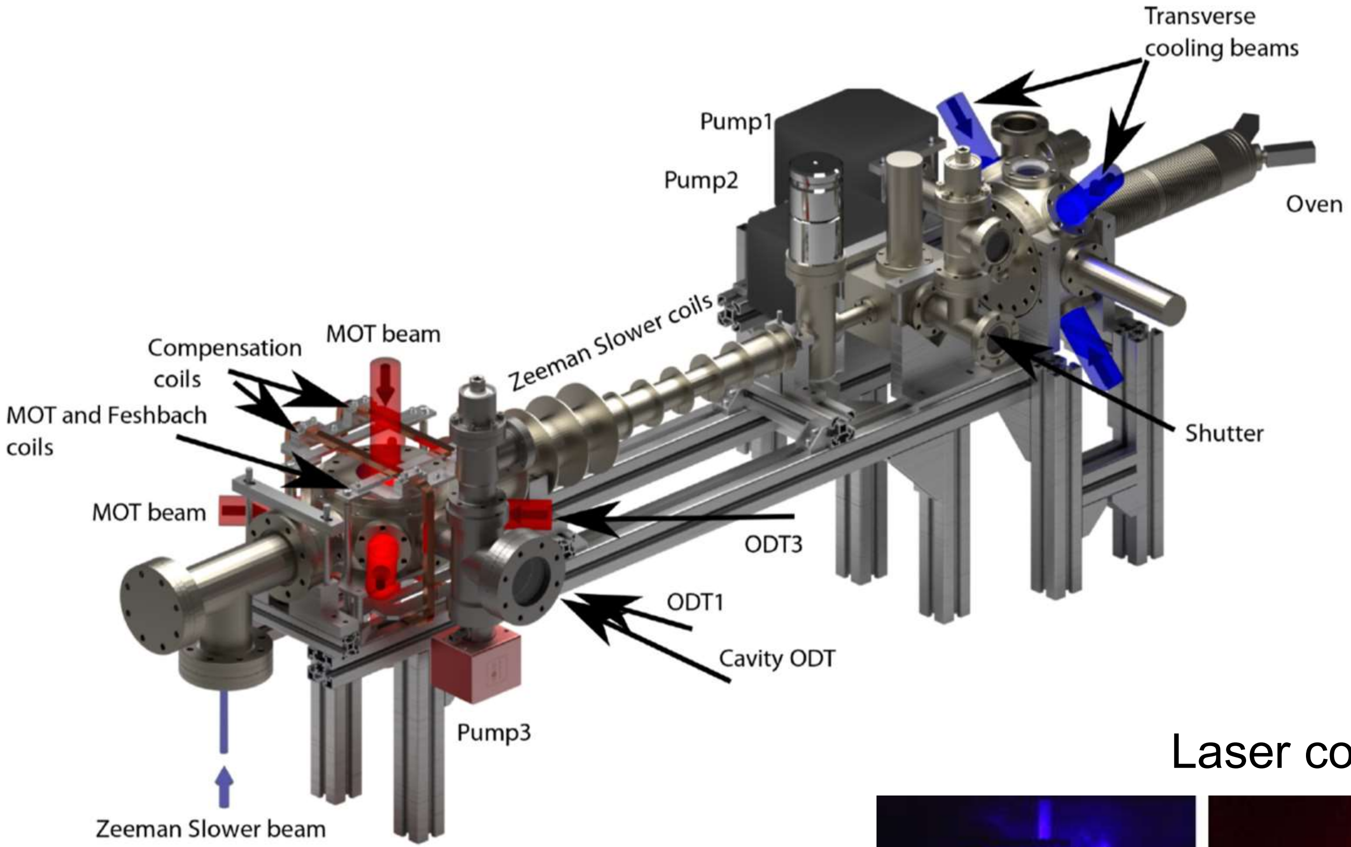
G. Semeghini et al., M. Fattori,
Phys. Rev. Lett. 120, 235301 (2018)

Our strategy

Combining the roton instability with a strongly dipolar system (Dy), can we reach a regime of **overlapping weakly bound droplets**?

Does that realize a **supersolid** system?

The experiment



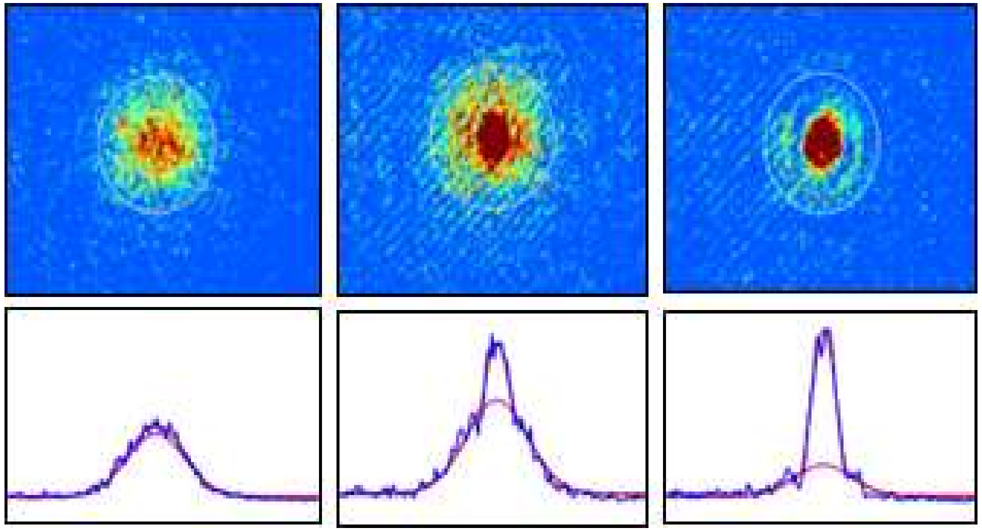
Dysprosium:
$\mu = 10\ \mu_B$

Melting point:
1680 K

Laser cooling:

Condensation temperature:
100 nK

Dy Bose-Einstein condensate



Typical condensates:

N= 5x10^4 , T<50 nK

BEC transition: breaking of gauge symmetry.

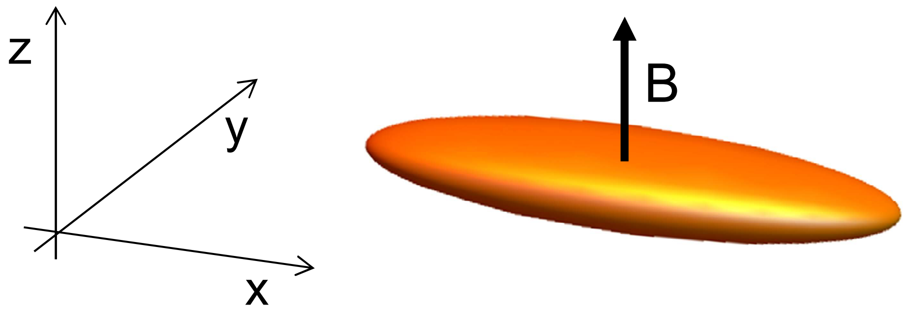
Order parameter:

$$\Psi_0(r) = |\Psi_0(r)| e^{i\varphi(r)}$$

E. Lucioni, et al. Phys. Rev. A 97, 060701(R) (2018).

The experiment

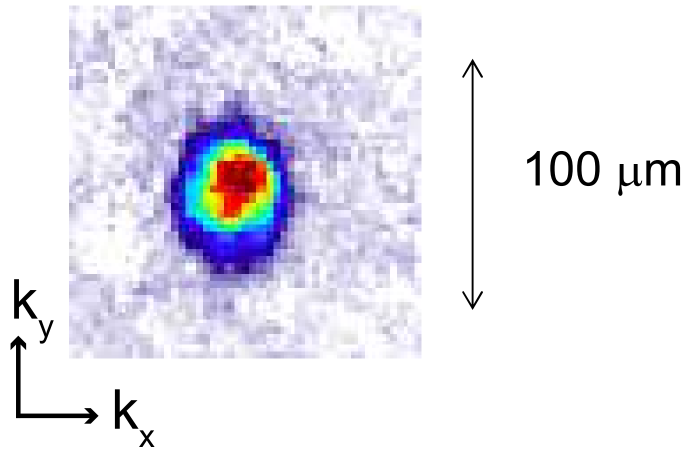
Geometry of the BEC in the harmonic trap



$\omega_{x,y,z}$ = (18, 53, 81) Hz

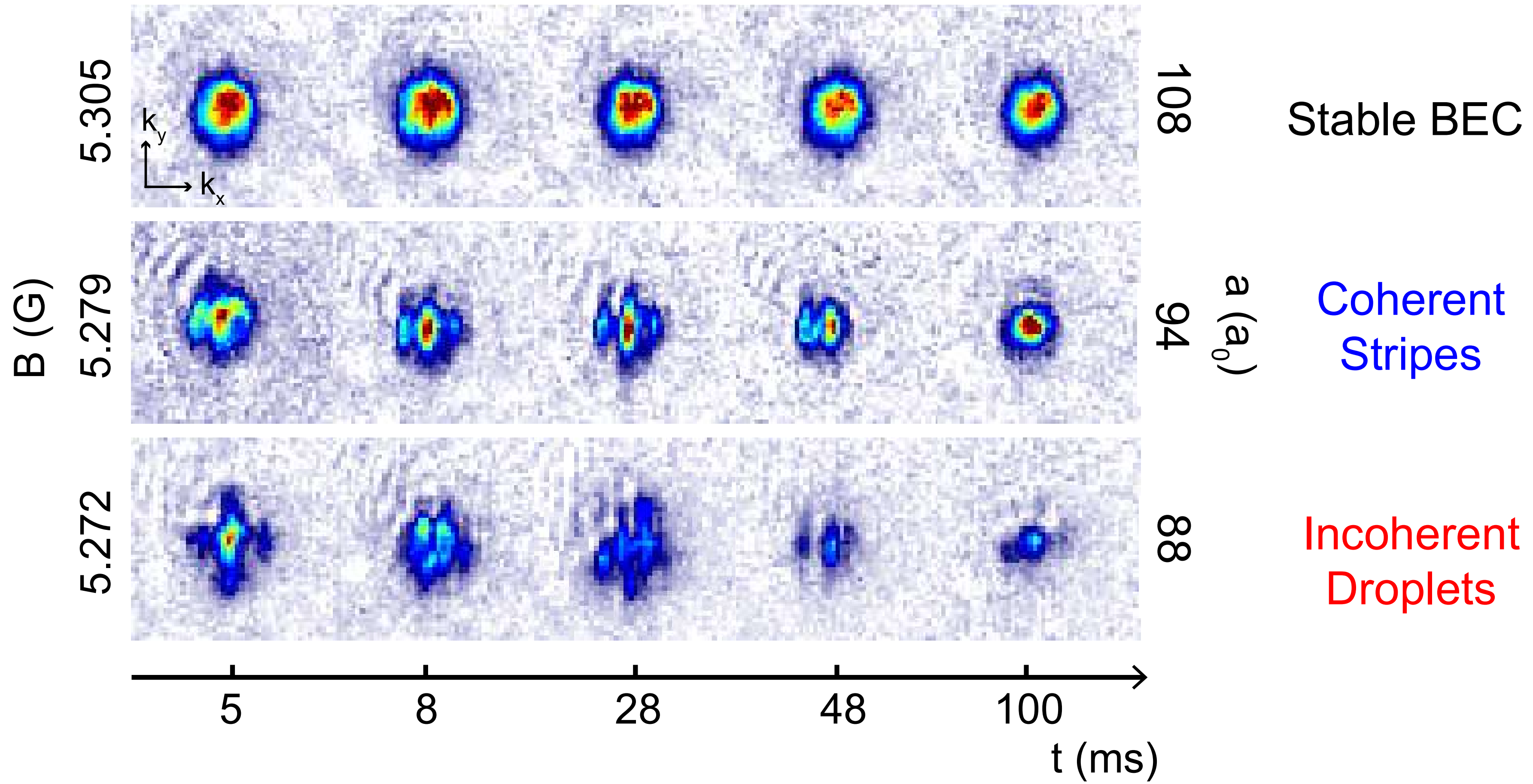
in-trap sizes: 1-10 μm

Detection in momentum space (60 ms of free fall).



Experimental observations

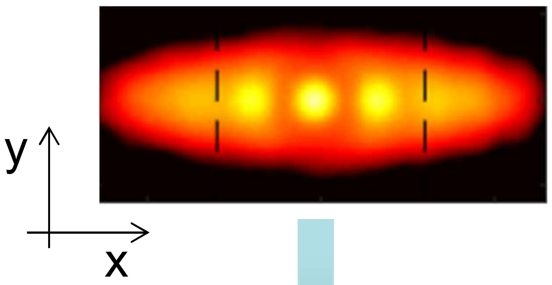
Slow tuning of the contact scattering lenght:



TOF pictures - momentum distribution

L. Tanzi et al., Phys. Rev. Lett. 122, 130405 (2019)

Coherent stripe phase

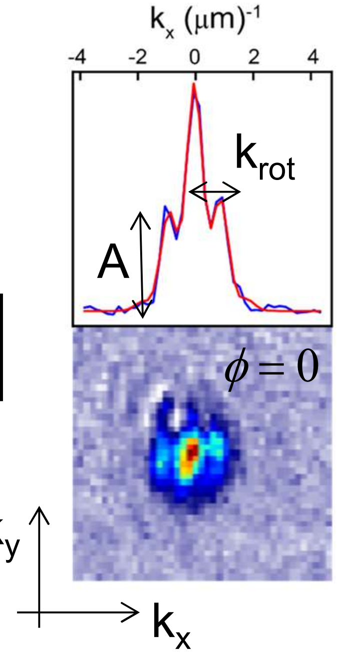


In-situ density distribution

60 ms of free fall

Double slit model:

$$\tilde{n}(k) = Ae^{\frac{-k^2}{2\sigma^2}}\left[1 + A_1 \cos^2\left(\frac{\pi k}{k_{rot}} + \phi\right)\right]$$

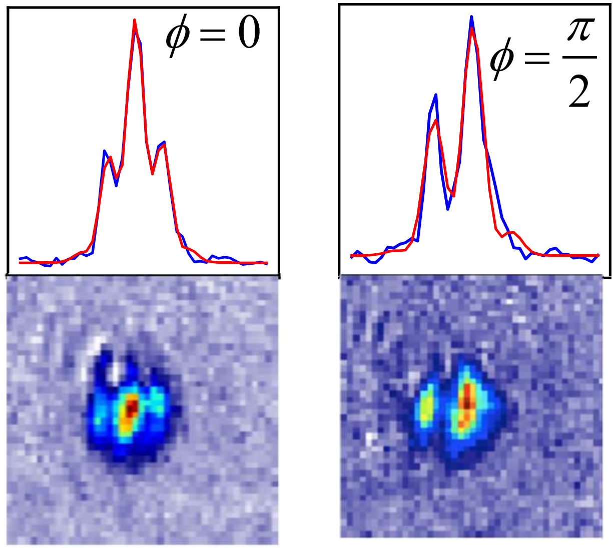


Momentum distribution:
Matter-wave interference

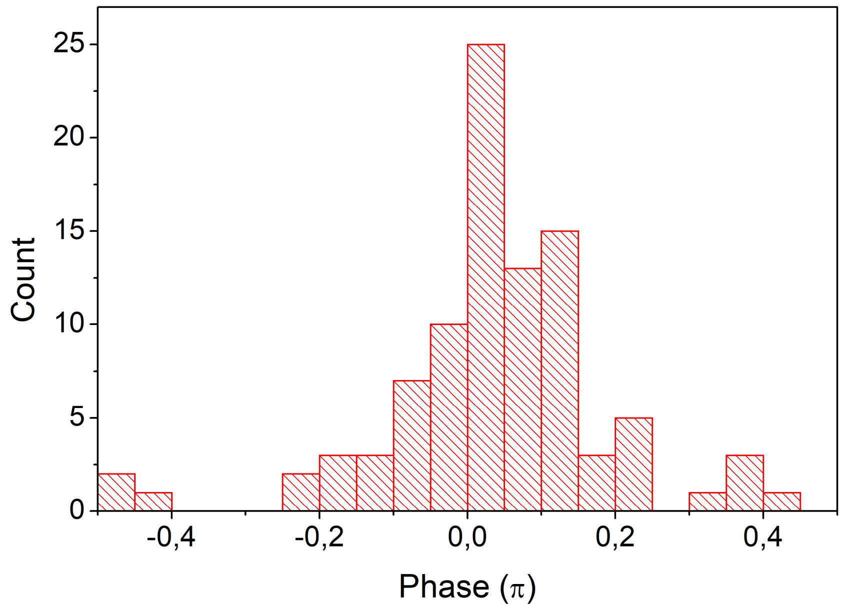
Info about: amplitude, periodicity and phase of the modulation

Coherent stripe phase

$$\tilde{n}(k) = A_0 e^{\frac{-k^2}{2\sigma^2}}\left[1 + A_1 \cos^2\left(\frac{\pi k}{k_{rot}} + \phi\right)\right]$$



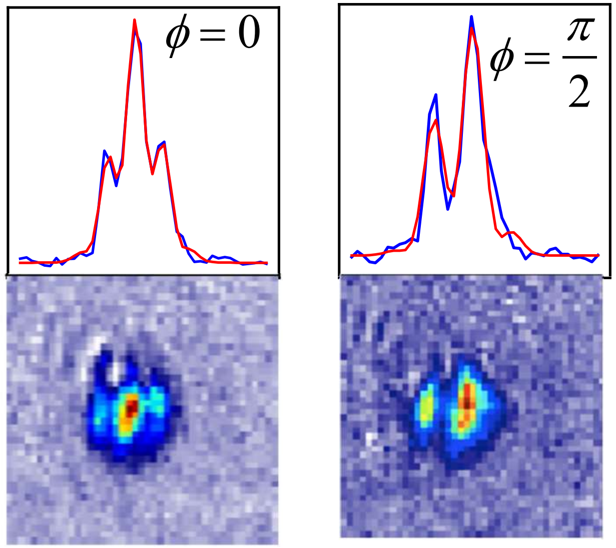
Large statistics
(> 50 images)



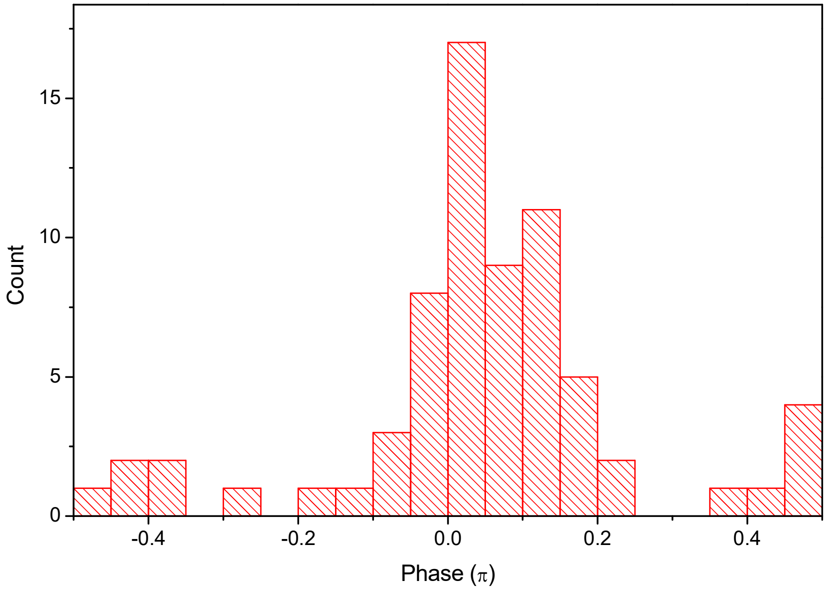
t=18 ms

Coherent stripe phase

$$\tilde{n}(k) = A_0 e^{\frac{-k^2}{2\sigma^2}}\left[1 + A_1 \cos^2\left(\frac{\pi k}{k_{rot}} + \phi\right)\right]$$



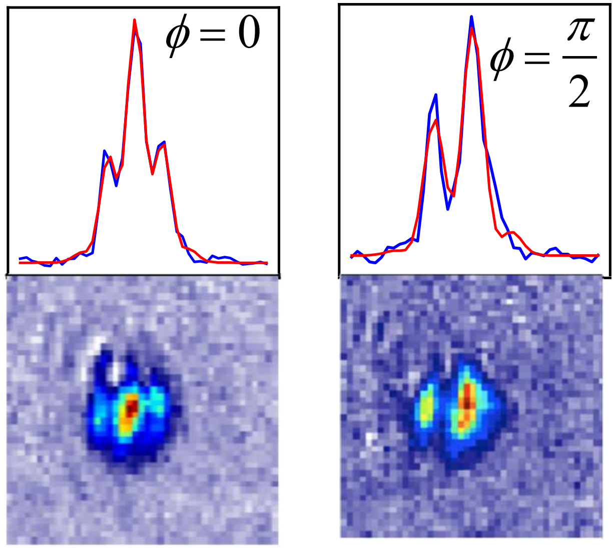
Large statistics
(> 50 images)



t=28 ms

Coherent stripe phase

$$\tilde{n}(k) = A_0 e^{\frac{-k^2}{2\sigma^2}}\left[1 + A_1 \cos^2\left(\frac{\pi k}{k_{rot}} + \phi\right)\right]$$



Large statistics
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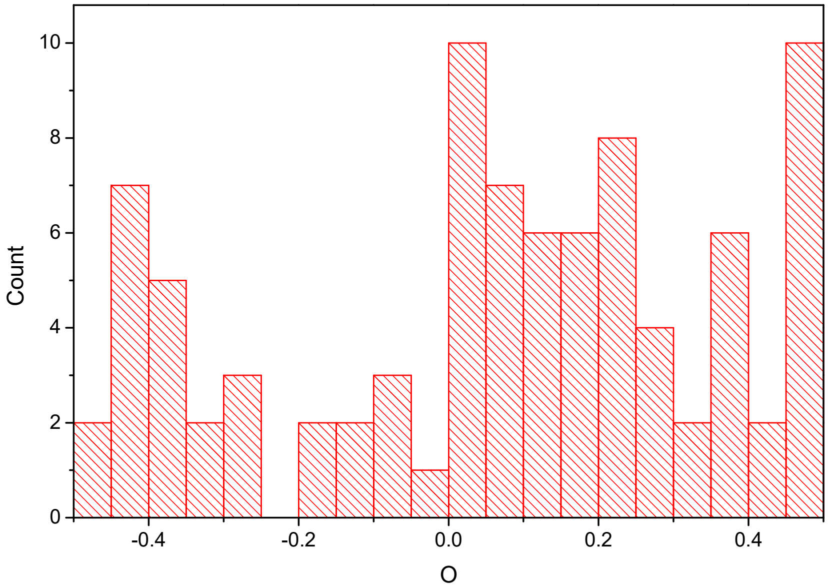
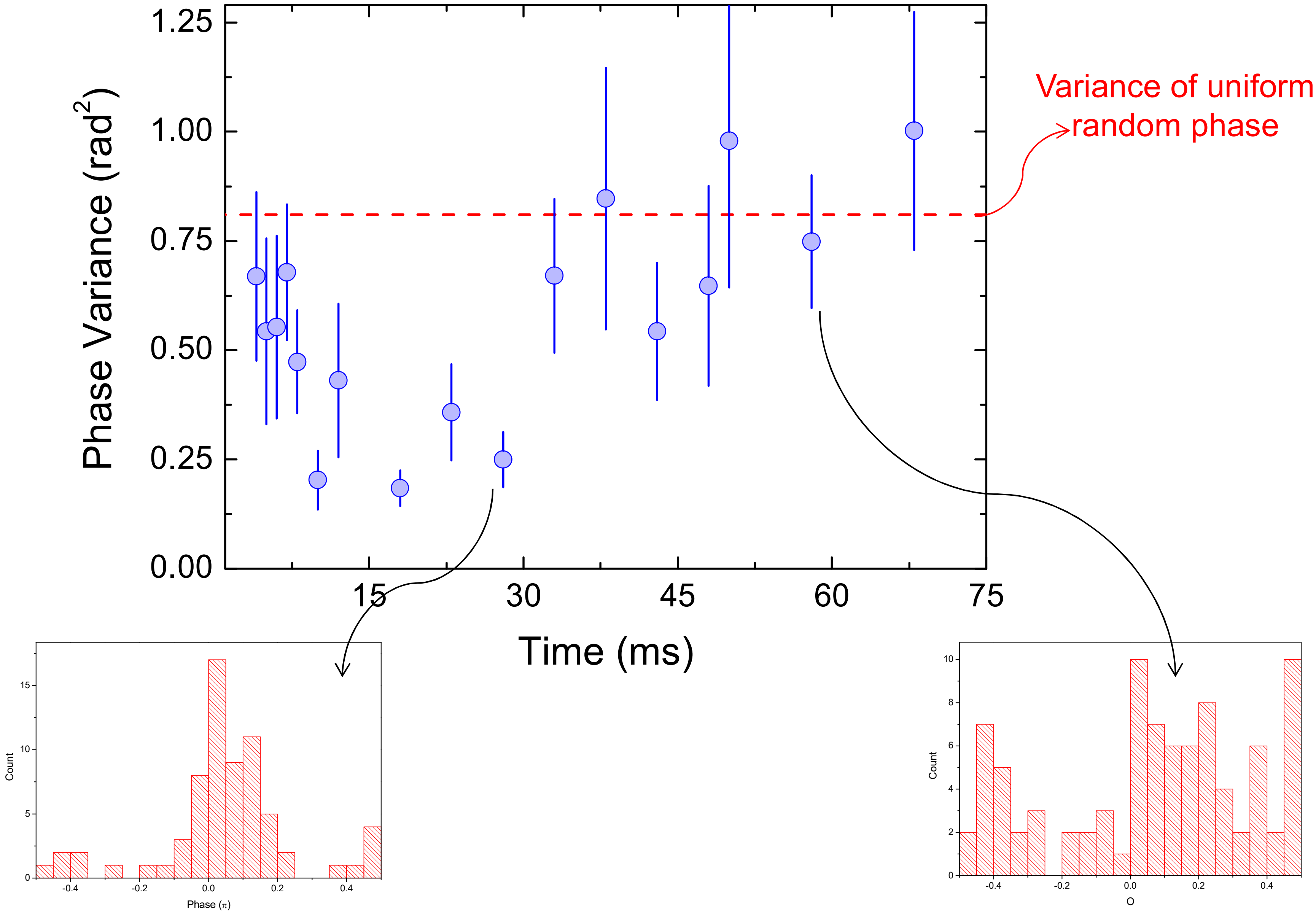


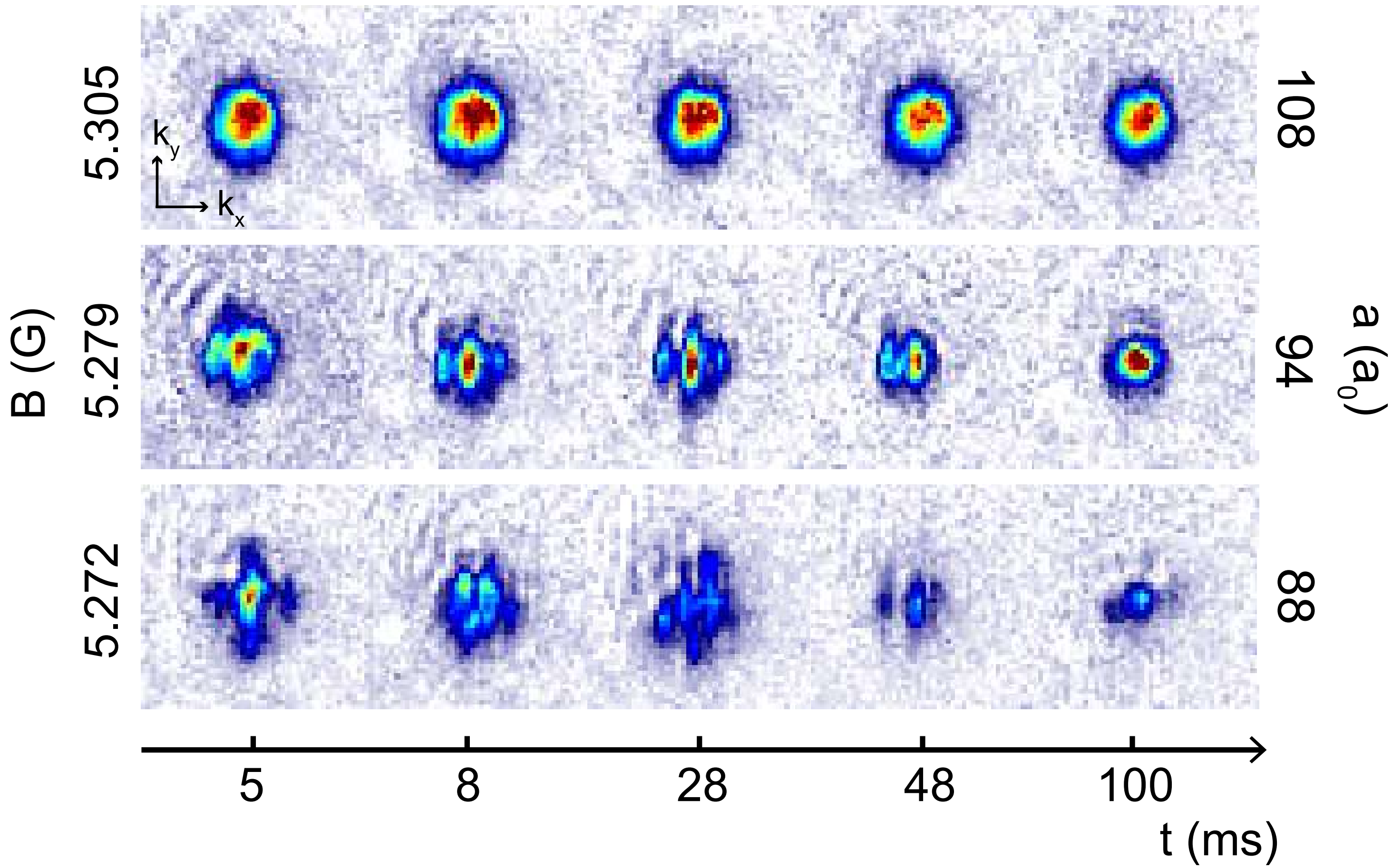
t=68 ms

Coherent stripe phase



Experimental observations

Slow tuning of the contact scattering lenght:



Stable BEC

Coherent Stripes

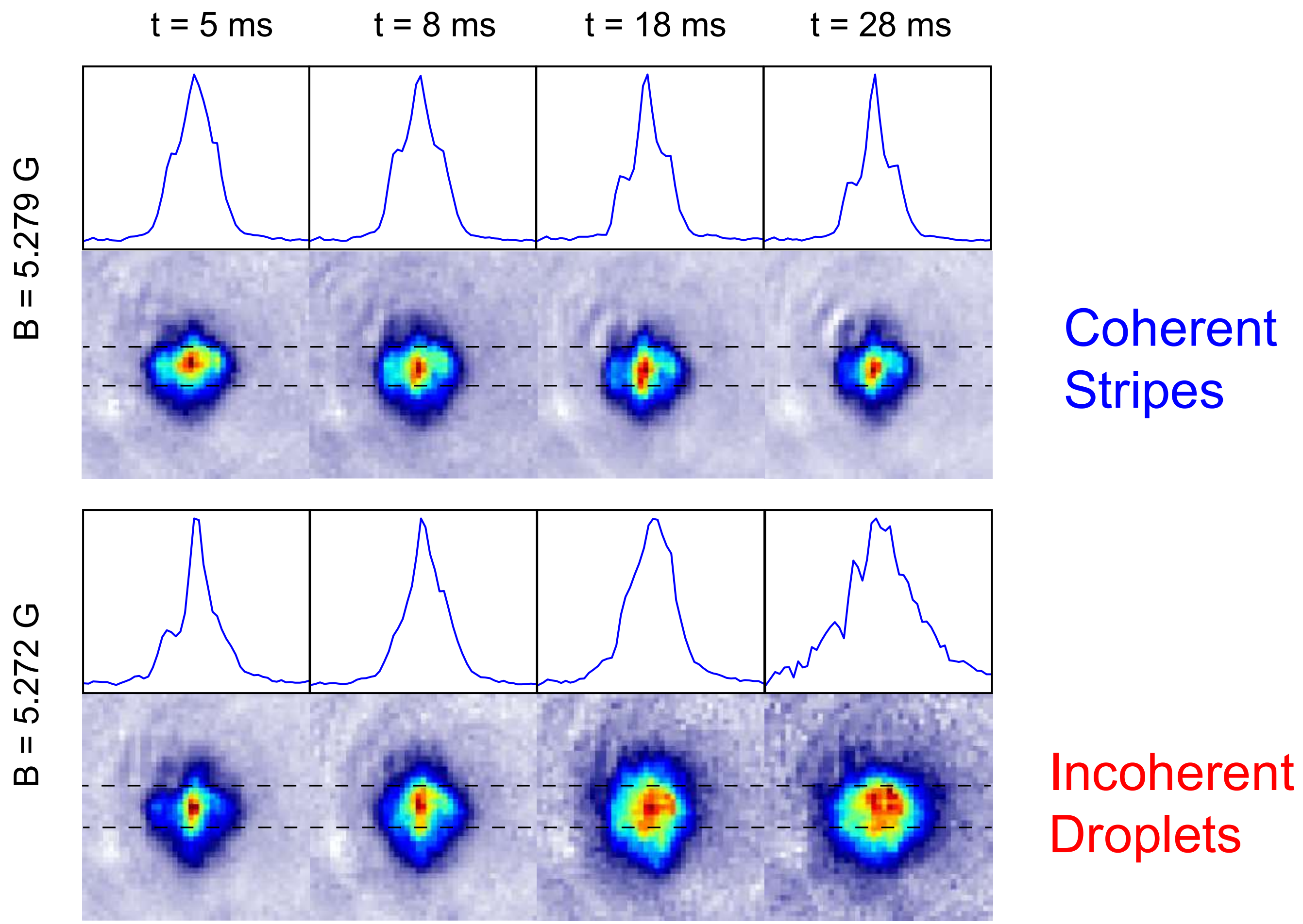
Incoherent Droplets

TOF pictures - momentum distribution

L. Tanzi et al., Phys. Rev. Lett. 122, 130405 (2019)

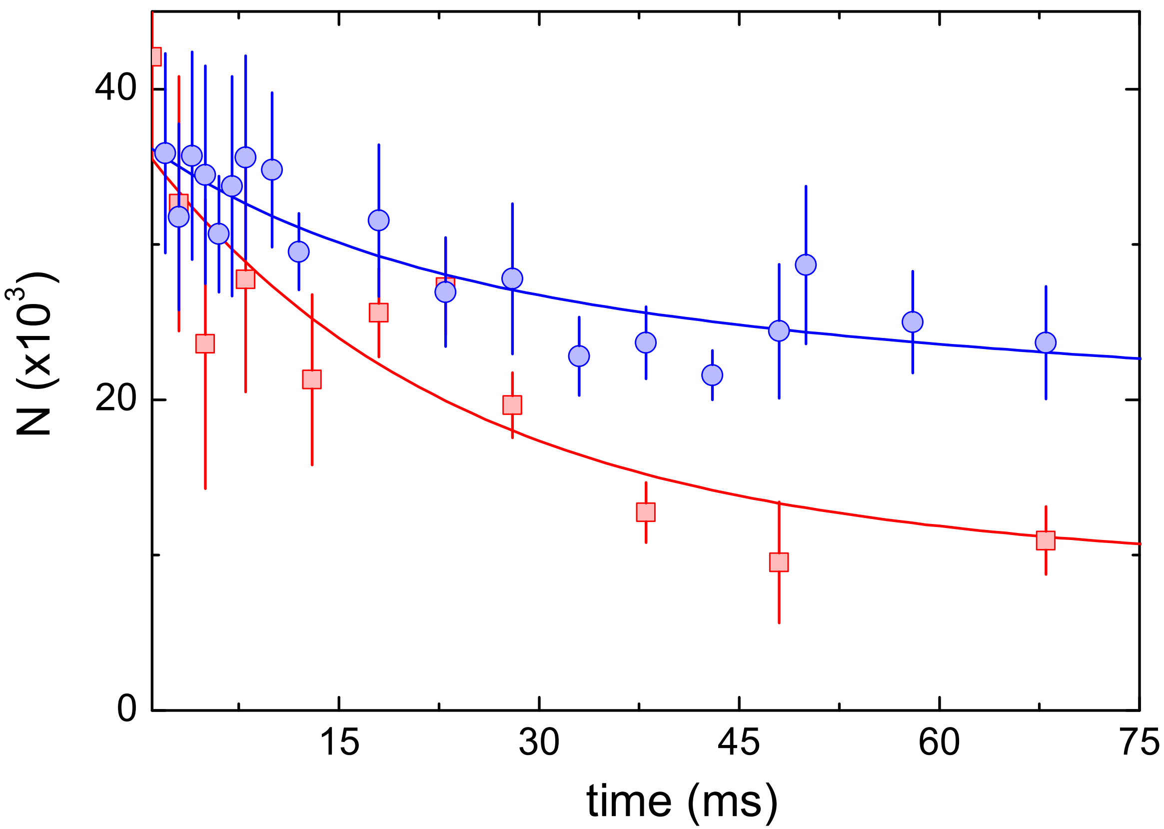
Coherent stripe phase vs droplets

Averaged $n(k_x,k_y)$ over 40-70 images



Three-body recombination

The atomic gas is in a metastable state, and tends to decay towards a real solid.



Recombination rate:

$$\frac{\dot{N}}{N} = -K_3 \langle n^2 \rangle$$

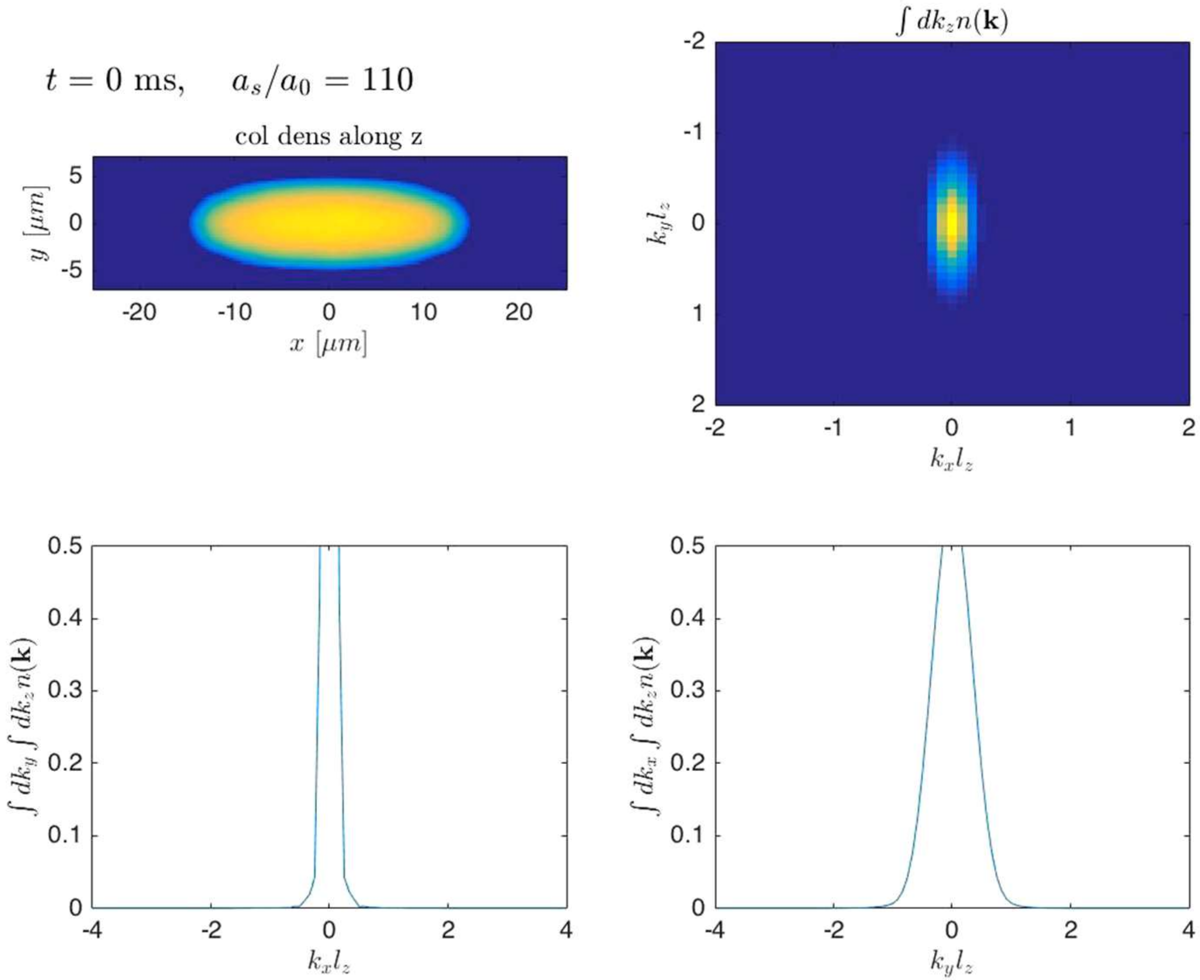
Stripes: τ≈18 ms

Droplets: τ ≈20 ms

Same density: $n \approx 4\times10^{14}$ cm^{-3}

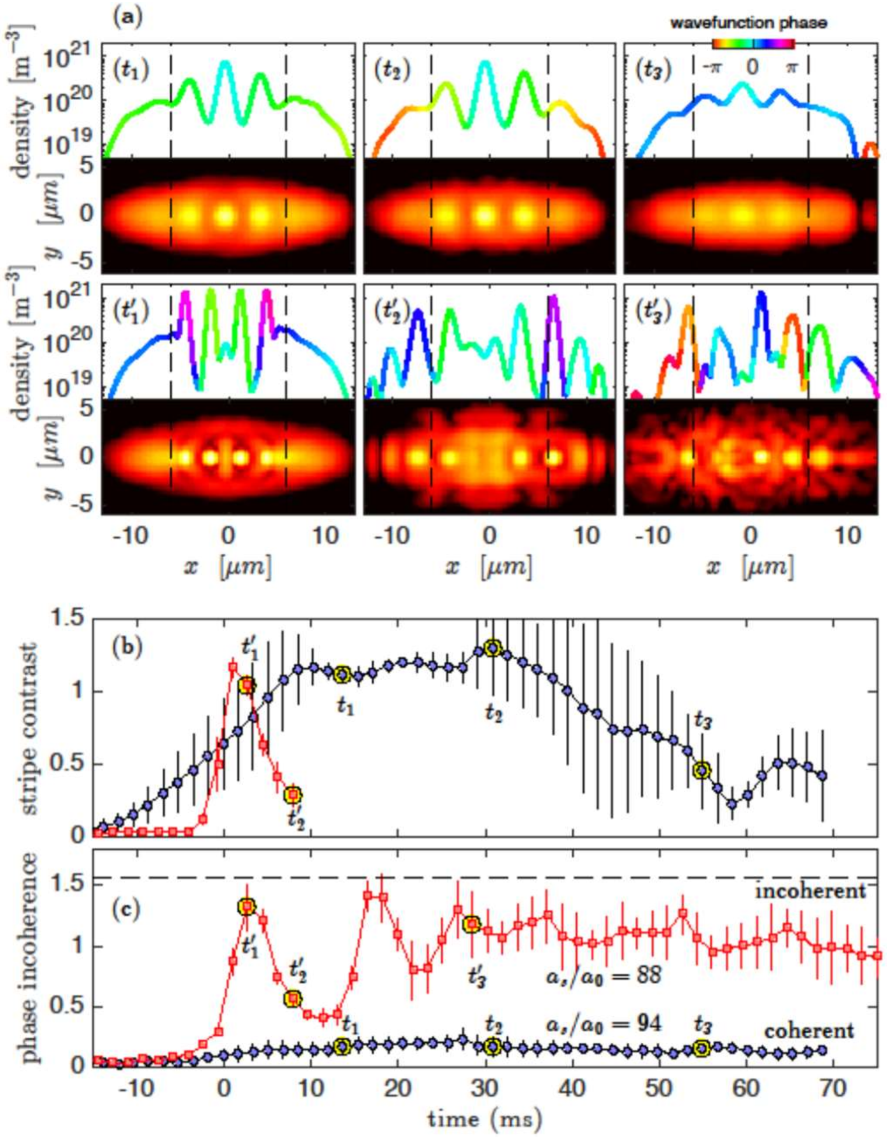
Also stripes are stabilized by quantum fluctuations.

Coherent stripe phase: theory



Numerical simulations by: R.N. Bisset and L. Santos, University of Hannover

Coherent stripe phase: theory



Coherent Stripes

Incoherent Droplets

The theory confirms that the system is supersolid!

(transient, at finite temperature)

Numerical simulations by: R.N. Bisset and L. Santos, University of Hannover

Strong interest by the scientific community

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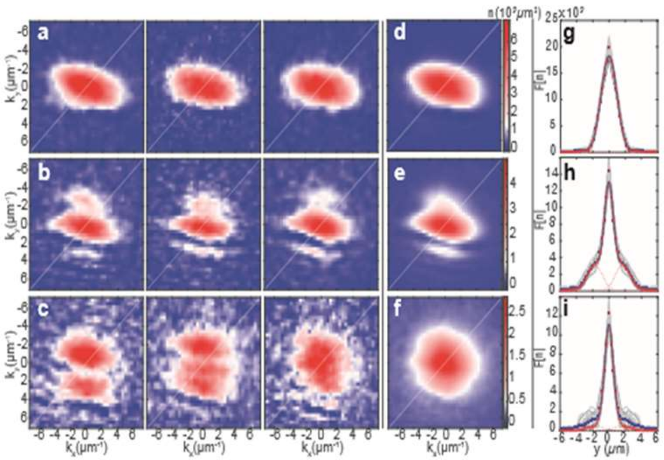
Observation of a Dipolar Quantum Gas with Metastable Supersolid Properties

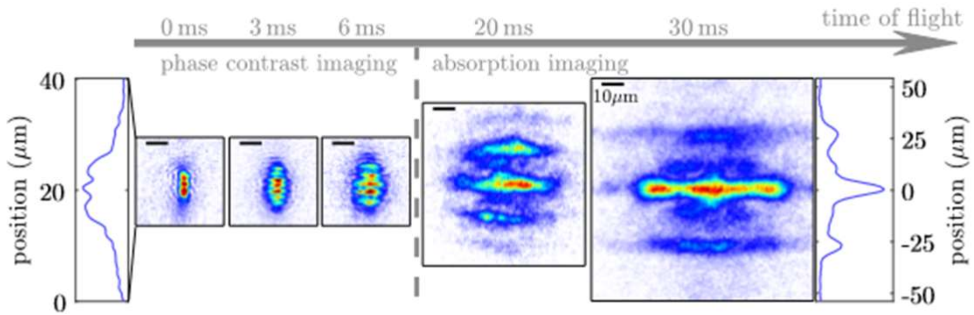
L. Tanzi, E. Lucioni, F. Famà, J. Catani, A. Fioretti, C. Gabbanini, R. N. Bisset, L. Santos, and G. Modugno

Phys. Rev. Lett. **122**, 130405 – Published 3 April 2019

Physics See Viewpoint: Dipolar Quantum Gases go Supersolid



L. Chomaz et al., *Long-lived and transient supersolid behaviors in dipolar quantum gases,* Phys. Rev. X 9, 021012 (2019).



F. Böttcher et al, *Transient supersolid properties in an array of dipolar quantum droplets,* Phys. Rev. X 9, 011051 (2019)

Strong interest by the scientific community

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states of matter

STATES OF MATTER | RESEARCH UPDATE

Supersolid behaviour spotted in dipolar quantum gases

20 Apr 2019

APS physics | Journals | Physics | PhysicsCentral | APS News

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Viewpoint: Dipolar Quantum Gases go Supersolid

Tobias Donner, Institute for Quantum Electronics, ETH Zurich, Zurich, Switzerland

April 3, 2019 • *Physics* 12, 38

Three research teams observe that gases of magnetic atoms have the properties of a supersolid—a material whose atoms are crystallized yet flow without friction.

le Scienze

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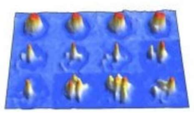
16 aprile 2019

Il supersolido, nuovo stato quantistico della materia



Comunicato stampa - Un team di ricercatori del Cnr e dell'Università di Firenze ha osservato nel laboratorio dell'Istituto nazionale di ottica di Pisa (Cnr-Ino) un nuovo stato della materia: il supersolido. Esso ha la struttura di un solido, le proprietà di un superfluido e si comporta secondo le leggi della meccanica quantistica. Alla ricerca, pubblicata su *Physical Review Letters,* hanno collaborato anche ricercatori dell'Università di Hannover *CNR/Università di Firenze*

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NEWS AND VIEWS · 20 MAY 2019

ATOMIC PHYSICS

Quantum gases show flashes of a supersolid

Supersolids are highly sought-after structures whose atoms can simultaneously support frictionless flow and form a crystal. Hallmarks of a supersolid have now been observed in three experiments that involve quantum gases of dipolar atoms.

LODE POLLET

Sixty years ago, the theoretical physicist Eugene Gross suggested that a substance could have properties of both a solid and

initial excitement[9,10], pure supersolidity is not observed in solid helium-4. However, in this substance, related phenomena such as giant quantum plasticity[11] are measurable and there is mounting evidence of frictionless flow along

Symmetry breaking in a supersolid

SOVIET PHYSICS JETP VOLUME 29, NUMBER 6 DECEMBER 1969

QUANTUM THEORY OF DEFECTS IN CRYSTALS

A. F. ANDREEV and I. M. LIFSHITZ

Institute of Physical Problems, U.S.S.R. Academy of Sciences

Submitted January 15, 1969

Zh. Eksp. Teor. Fiz. 56, 2057–2068 (June, 1969)

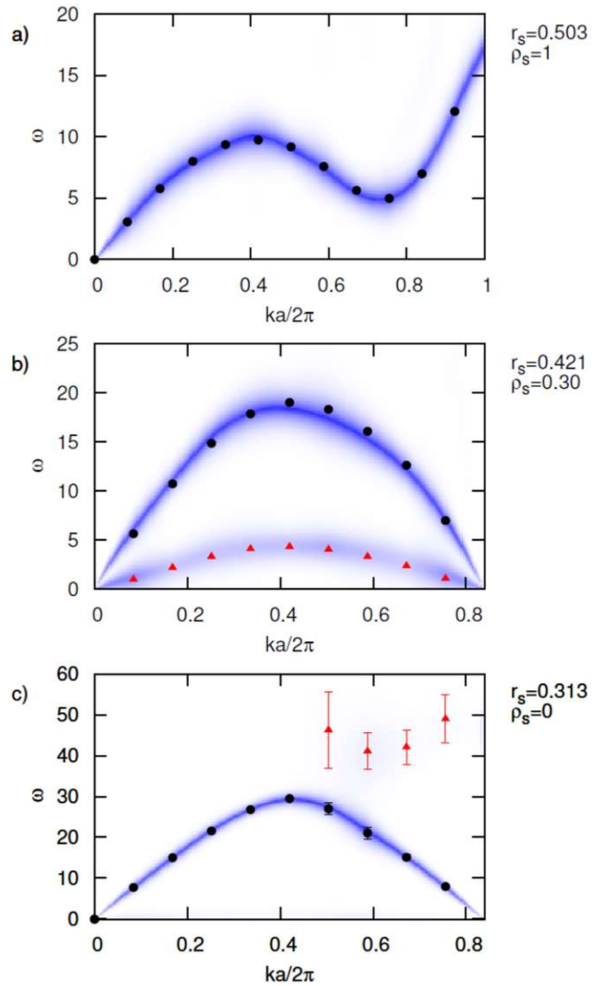
At sufficiently low temperatures localized defects or impurities change into excitations that move practically freely through a crystal. As a result instead of the ordinary diffusion of defects, there arises a flow of a liquid consisting of "defectons" and "impuritons." It is shown that at absolute zero in crystals with a large amplitude of the zero-point oscillations (for example, in crystals of the solid helium type) zero-point defectons may exist, as a result of which the number of sites of an ideal crystal lattice may not coincide with the number of atoms. The thermodynamic and acoustic properties of crystals containing zero-point defectons are discussed. Such a crystal is neither a solid nor a liquid. Two kinds of motion are possible in it; one possesses the properties of motion in an elastic solid, the second possesses the properties of motion in a liquid. Under certain conditions the "liquid" type of crystal motion possesses the property of superfluidity. Similar effects should also be observed in quasiequilibrium states containing a given number of defectons.

Coupled liquid and solid, both are compressible:

two sound velocities are expected, even at zero temperature.

Symmetry breaking in a supersolid

Modern treatment: a **gapless Goldstone mode** arises each time that an underlying **symmetry** is **spontaneously broken**.



Superfluid: gauge symmetry

Supersolid: gauge symmetry and translational symmetry

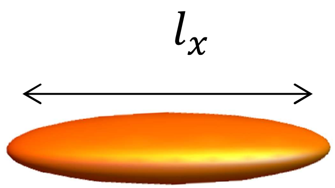
Solid: translational symmetry

S. Saccani, S. Moroni and M. Boninsegni, Excitation spectrum of a supersolid. Phys. Rev. Lett. 108, 175301 (2012).

Normal modes

Question: How to observe symmetry breaking in a trapped gas?

Phonon wavelengths are bound by the system size.
Phonons are no longer defined in a non-homogeneous system.



$$k_{min} = 1/l_x$$

Answer: phonons can be mapped to the normal compressional modes of the system.

Normal modes

The Gross-Pitaevskii equation for a BEC is equivalent to the hydrodynamic equations for an ideal liquid (zero viscosity).

$$\psi_0 = |\psi_0| e^{iS(t)} \qquad i\hbar\frac{\partial}{\partial t}\psi_0(r,t) = \left(-\frac{\hbar^2}{2m}\nabla^2 + V_{\rm ext} + g|\psi_0|^2\right)\psi_0(r,t)$$

$$\frac{\partial n}{\partial t} + \boldsymbol{\nabla}\cdot(n\mathbf{v}) = 0 \qquad \frac{\partial \mathbf{v}}{\partial t} = -\frac{1}{mn}\boldsymbol{\nabla}p - \boldsymbol{\nabla}\left(\frac{v^2}{2}\right) + \frac{1}{m}\boldsymbol{\nabla}\left(\frac{\hbar^2}{2m\sqrt{n}}\nabla^2\sqrt{n}\right) - \frac{1}{m}\boldsymbol{\nabla}V.$$

Normal modes are a direct consequence of the locking of the condensate phase (gauge symmetry breaking).

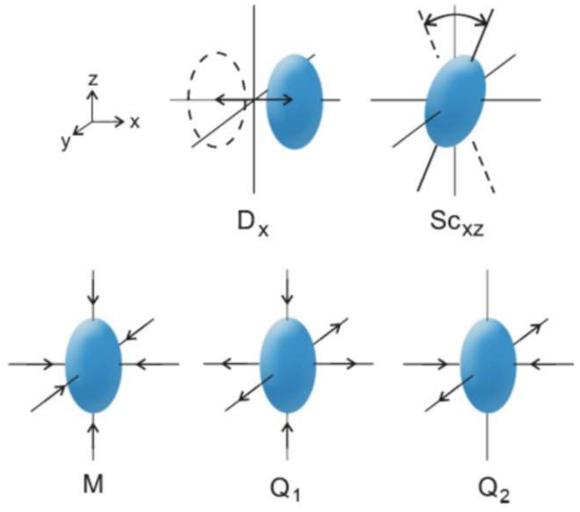


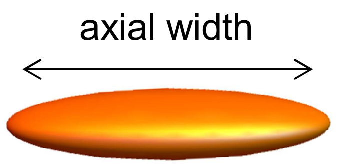
FIG. 1. (Color online) Schematic illustration of the basic collective modes under consideration: the dipole mode D (shown here in the x direction D_x), scissors mode Sc (shown here in x-z plane Sc_{xz}), the monopole mode M, and the quadrupole modes Q_1 and Q_2. These modes are discussed in more detail in Sec. III.

S. Stringari, Phys. Rev. Lett. 77, 2360 (1997).

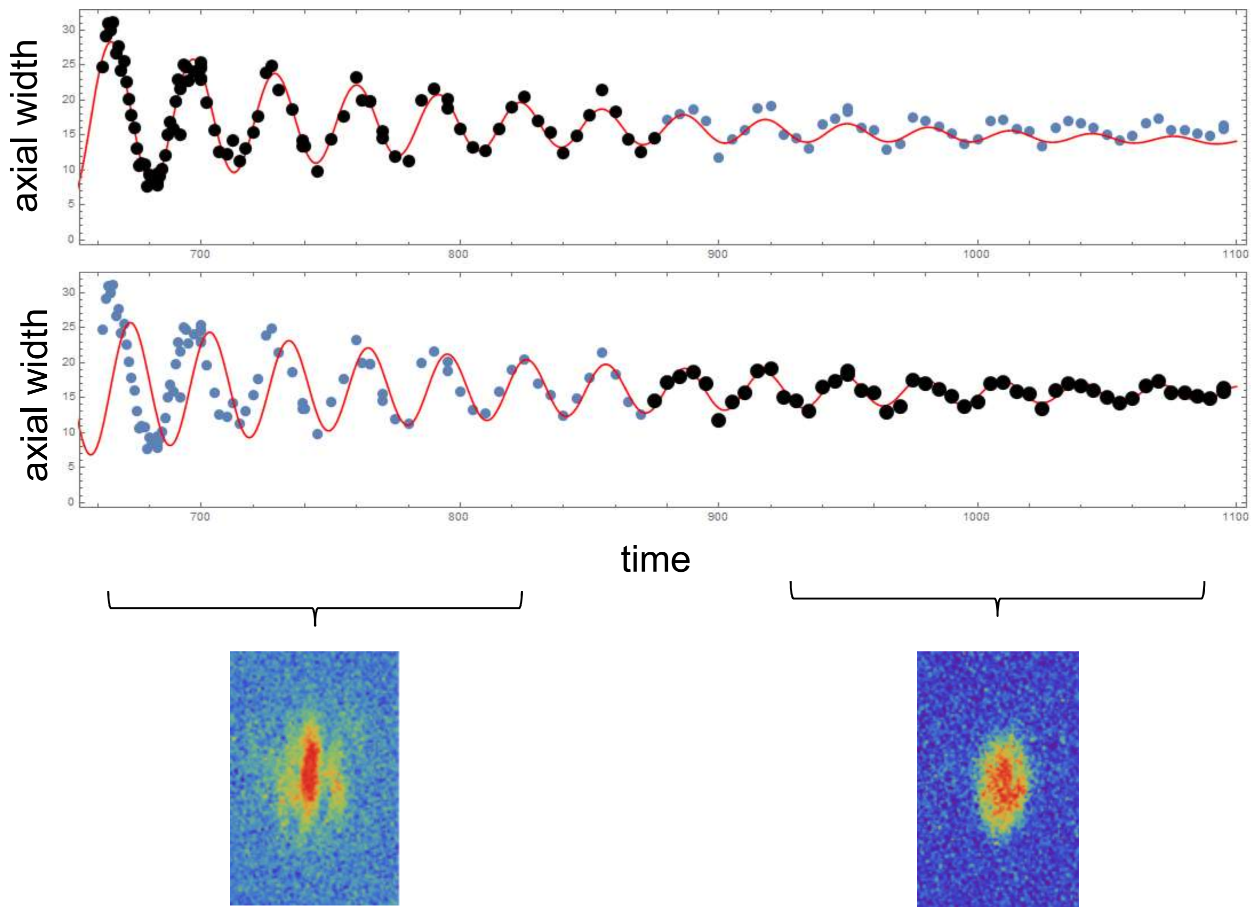
Normal modes

We excite the lowest normal mode (axial breathing mode) by quenching the scattering length.

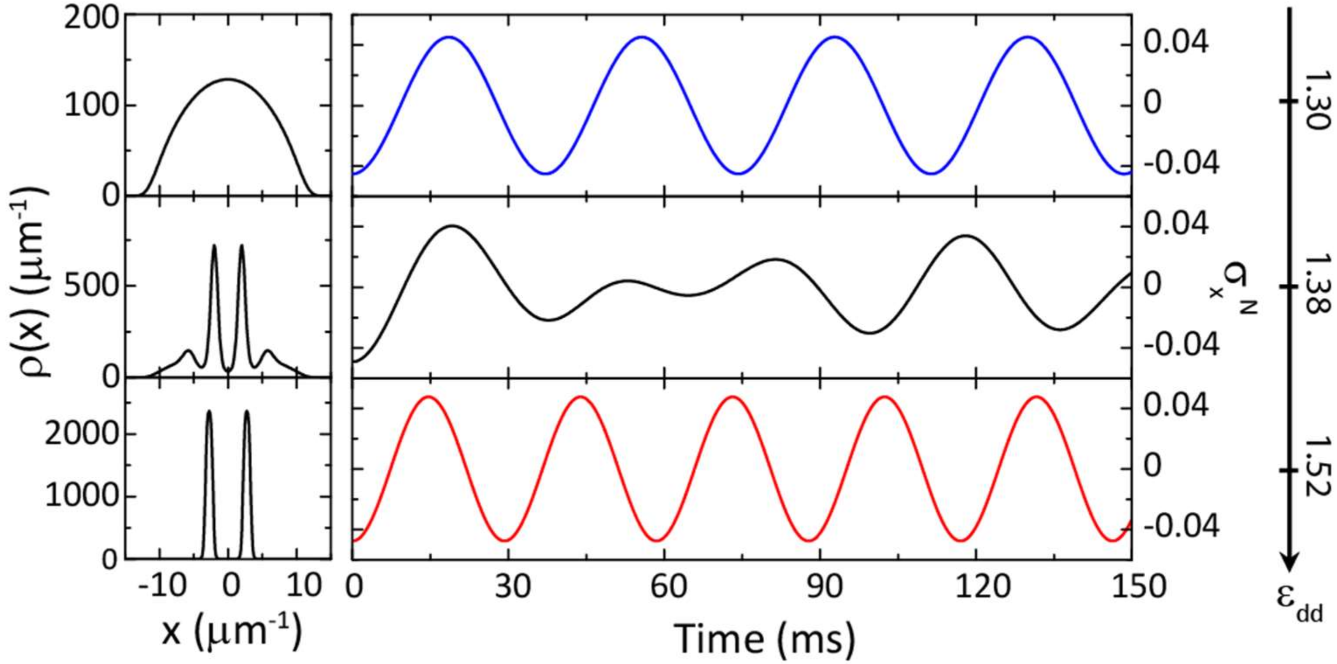
Supersolid regime: **frequency shift** when the stripes are present!



$$\omega_{BEC} = \sqrt{5/2}\,\omega_x$$



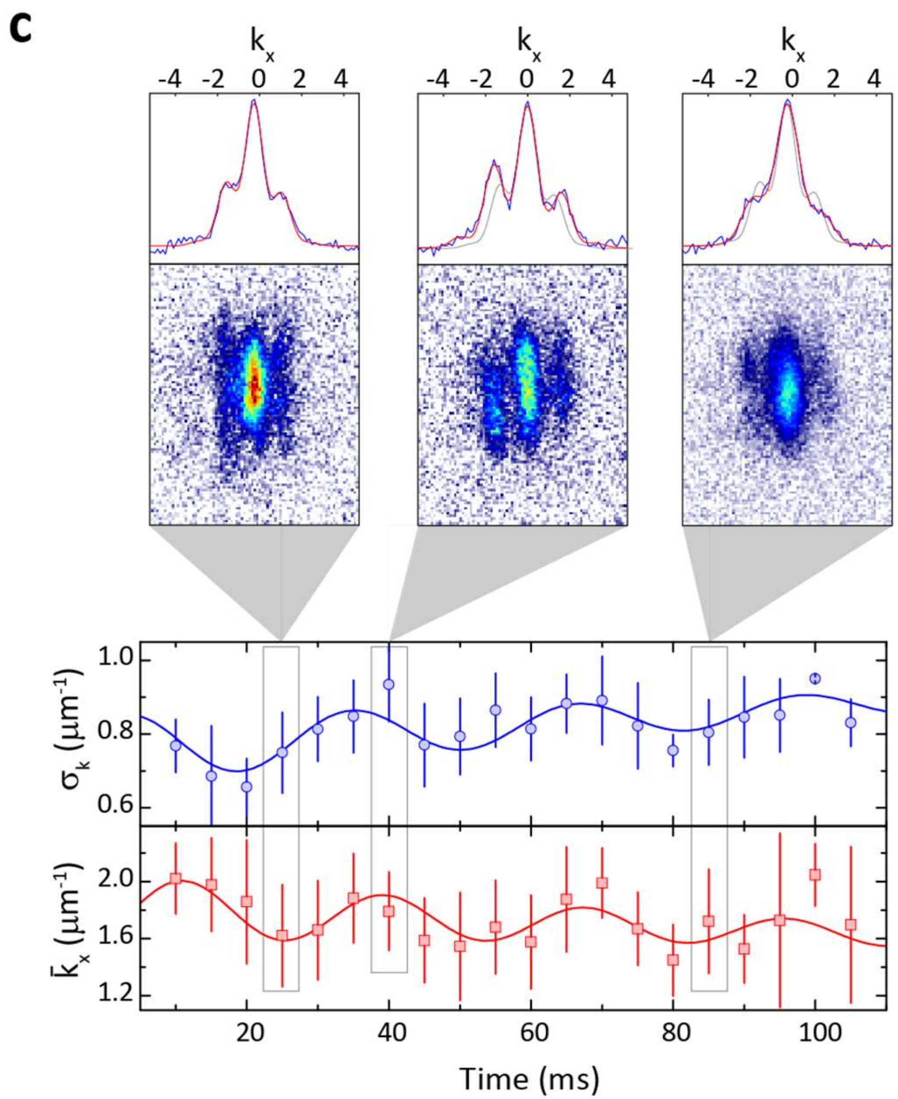
Symmetry breaking in a supersolid



The theory predicts two coupled oscillation modes of the in-trap density.

Theory by S. Roccuzzo, A. Recati and S. Stringari.

Symmetry breaking in a supersolid



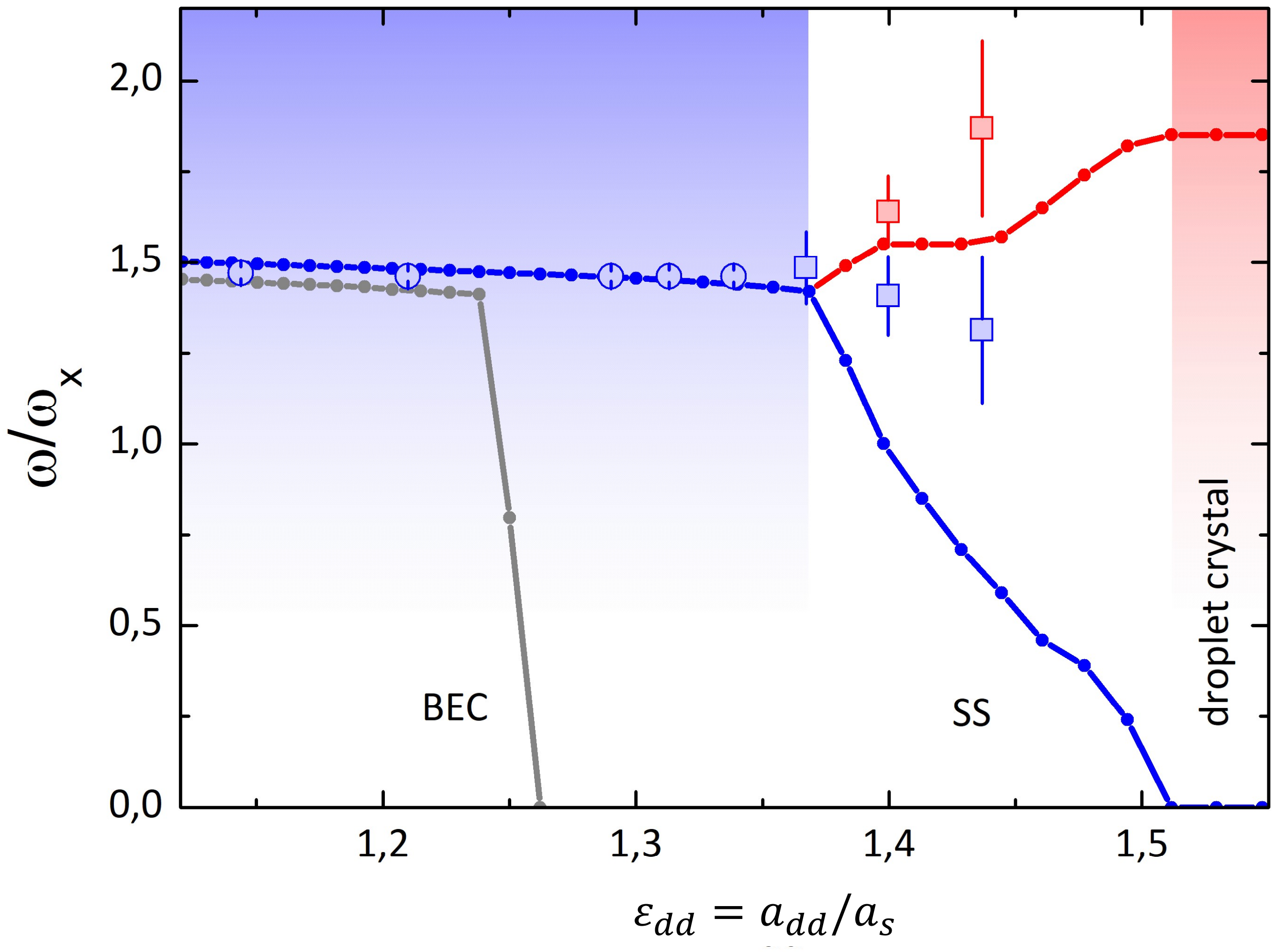
Two different frequencies for the peak spacing and the peak heights.

Two normal modes!

We can study the compression mode of the solid part!!

Symmetry breaking in a supersolid

Phase diagram of the dipolar supersolid from normal modes:



L. Tanzi et al., arXiv:1906.02791. Theory by S. Roccuzzo, A. Recati and S. Stringari.

Conclusions and outlook

Finally, we have a compressible supersolid in the laboratory, available for investigations.

It displays a rich phase diagram. We can use the proven tools of quantum gases to explore its properties.

Quick questions:

- Non-classical moment of inertia: can we study the phenomena searched in solid He?
- Larger systems with smaller periodicity: what is the limit?
- Two-dimensional systems: how does the roton instability and the crystallization develop?
- Two quantum phase transitions: first or second order?
- How do the critical temperature and superfluid fraction of the supersolid evolve across the phase diagram?

Long term dream: use the «atomic quantum simulator» to understand supersolids, and perhaps engineer similar phases in real materials.

The team

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Francesca Famà
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Julian Maloberti

Eleonora Lucioni
Jacopo Catani
Carlo Gabbanini

Theory by: Russell Bisset, Luis Santos (Hannover)
Santo Roccuzzo, Alessio Recati, Sandro Stringari (Trento)

lens European Laboratory for Non-Linear Spectroscopy

erc European Research Council Established by the European Commission

HORIZON 2020

Quantum Simulations of Insulators and Conductors

INO-CNR Istituto Nazionale di Ottica