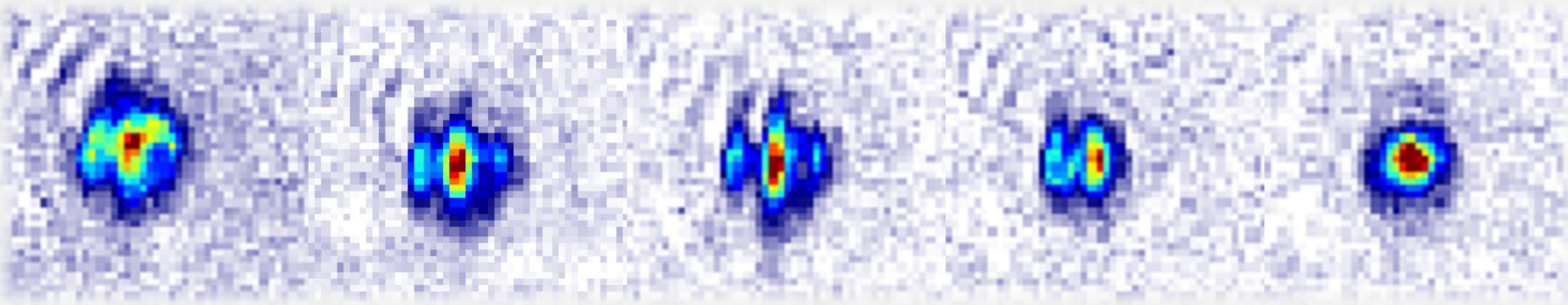

Study of a dipolar quantum gas with supersolid properties

Carlo Gabbanini

INO-CNR, sezione di Pisa

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Outline

- Discovery of the supersolid: a phase-coherent, density-modulated regime. [*PRL 122, 130405 (2019)*]

- Evidence of the simultaneous breaking of two symmetries from the bifurcation of the lowest compressional mode. [*Nature 574, 382 (2019)*]

- In progress: investigation of non-classical rotational inertia and superfluid fraction.

Proposal

PHYSICAL REVIEW A VOLUME 2, NUMBER 1 JULY 1970

Speculations on Bose-Einstein Condensation and Quantum Crystals*

G. V. Chester
Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14850
(Received 13 May 1969)

It is shown, by almost rigorous arguments, that there exist many-body states of a system of interacting bosons which exhibit both crystalline order and Bose-Einstein condensation into the zero-momentum eigenstate of the single-particle density matrix. The implications of this result are discussed in relation to theories of superfluidity and the nature of quantum crystals.

also: E. P. Gross, Phys. Rev. 106, 161 (1957); A.F. Andreev, I.M. Lifshitz, JEPT 29 (1969); G.V. Chester, Phys. Rev. 2, 161 (1970); A.J. Leggett, Phys. Rev. Lett. 25, 1543 (1970); …

Supersolid He?

Lack of unambiguous experimental observation

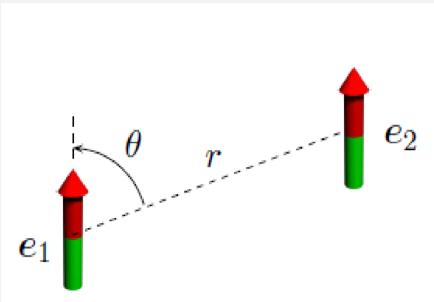
Balibar, The enigma of supersolidity. Nature 464, 176 (2010)
Kim and Chan, Absence of supersolidity in solid helium in porous Vycor glass. Phys. Rev. Lett. 109, 155301 (2012).

Supersolids in quantum gases?

Gaseous Bose-Einstein condensates (**superfluidity**) +
engineered "long-range" interactions (**density modulation**)

Proposals based on:

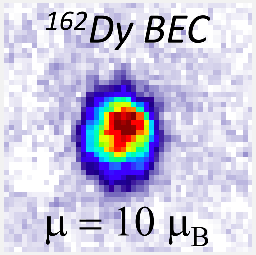
- spin-orbit coupled atoms (observed in J.R. Li et al, Nature 543 (2017))
- atoms in optical cavities (observed in J. Leonard et al, Nature 543 (2017))
- **strongly dipolar atoms**



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

Contact interaction

Dipolar interaction

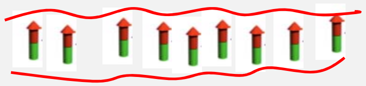


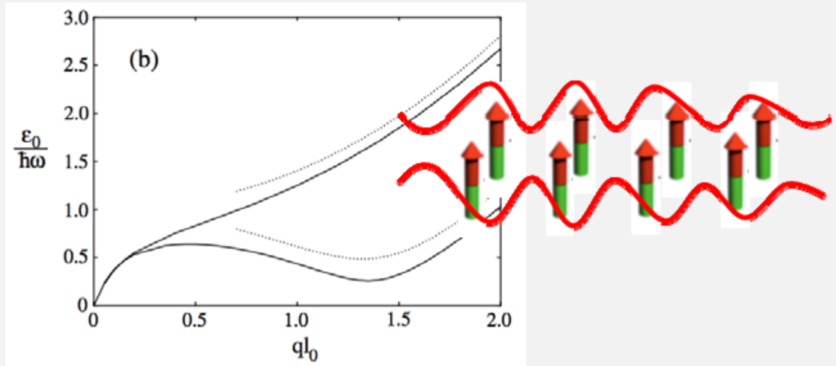
$$a_{dd} = \frac{m\mu_0\mu^2}{12\pi\hbar^2} \approx 130 a_0$$

$$\epsilon_{dd} = a_{dd}/\ a_s$$

Dipolar quantum gases: rotons and droplets

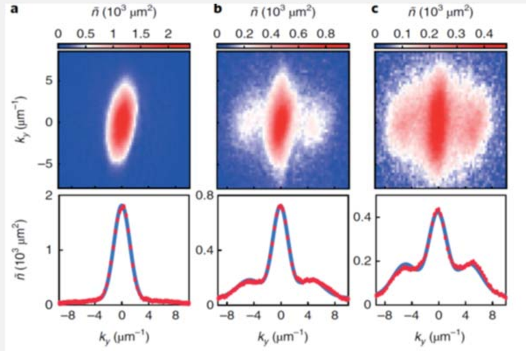
In a confined geometry, the excitation spectrum presents a roton minimum.

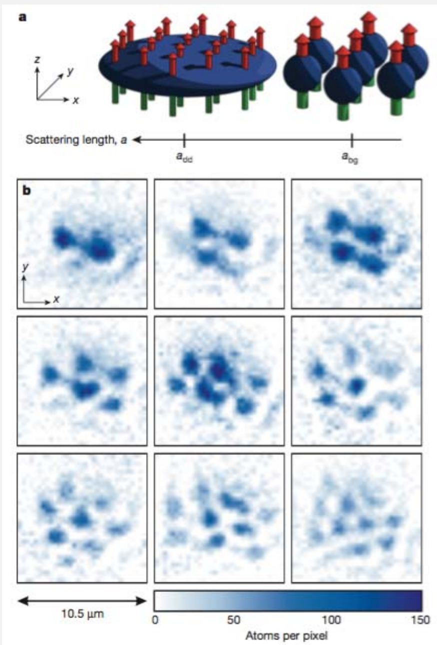




L. Santos et al., PRL 90 (2003)

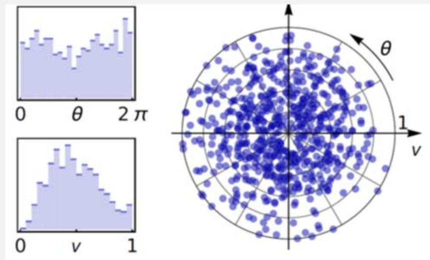
Experiment: L. Chomaz et al., Nat. Phys. 14, 442 (2018) (Innsbruck + Hannover); D. Petter et al. Phys. Rev. Lett. 122, 183401 (2019) (Innsbruck).





Quantum fluctuations stabilize attractive self-bound droplets.

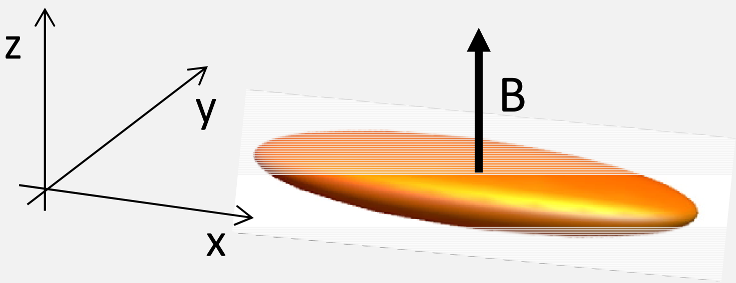
Stuttgart: H. Kadau et al., Nature 530, 194 (2016); I. Ferrier-Barbut et al., Phys. Rev. Lett. 116, 215301 (2016); M. Wenzel et al., Phys. Rev. A 96, 053630 (2017).



Our intuition

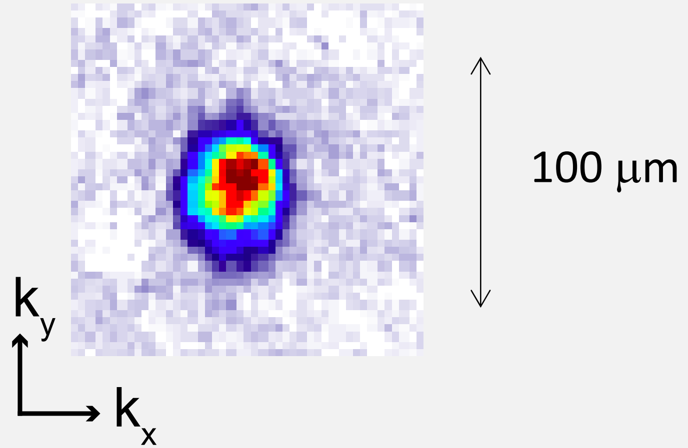
Combining the roton instability with a strongly dipolar system (Dy atoms), one might reach a regime of **overlapping “unbound droplets”**, realizing a supersolid.

Weak, anisotropic harmonic trapping (radii 2-15 μm)



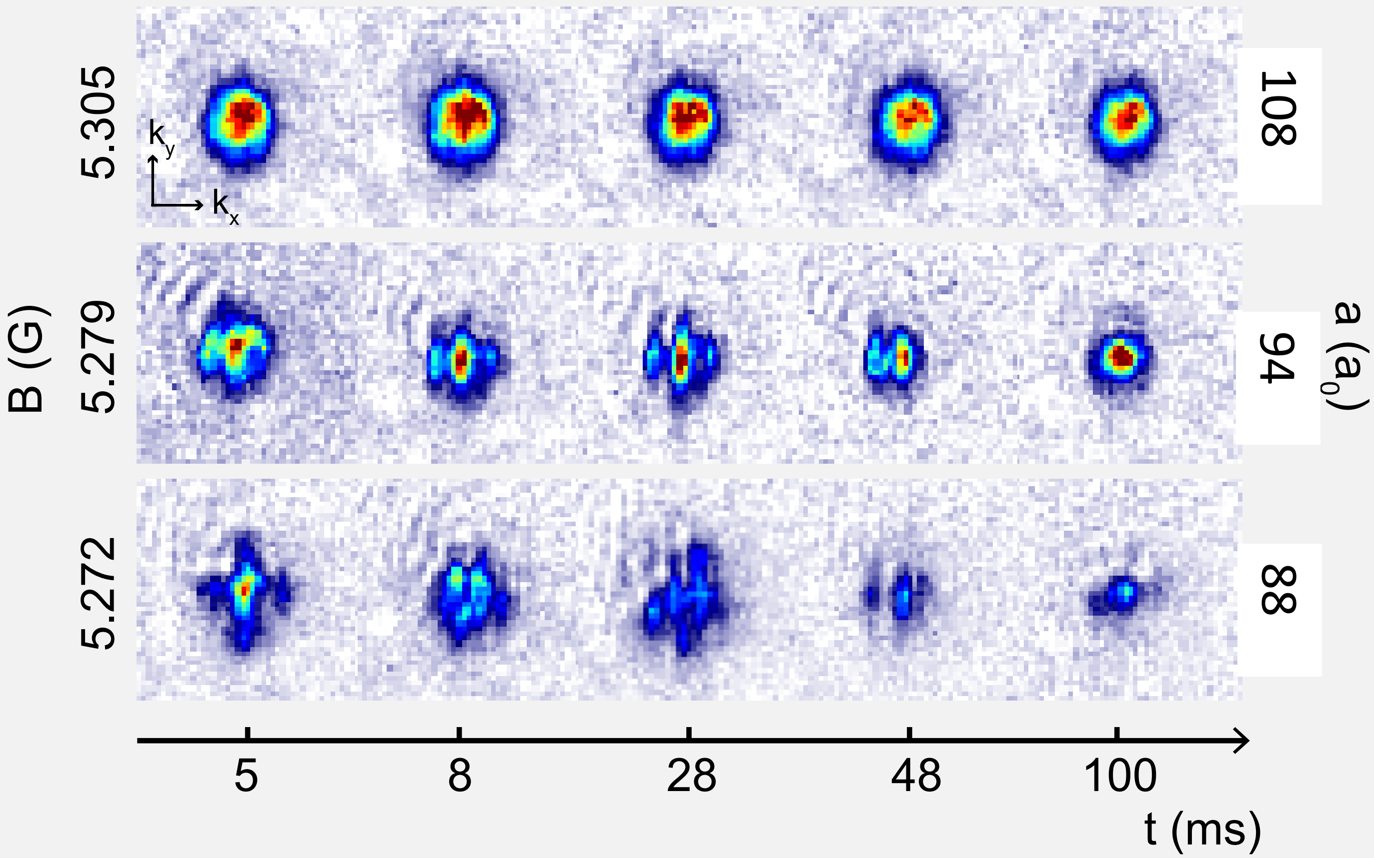
$\omega_{x,y,z}$ = 2π (18, 53, 81) Hz

Detection in momentum space (after free expansion)



Experimental observations

Slow tuning of the contact scattering length beyond the instability point.



Stable BEC

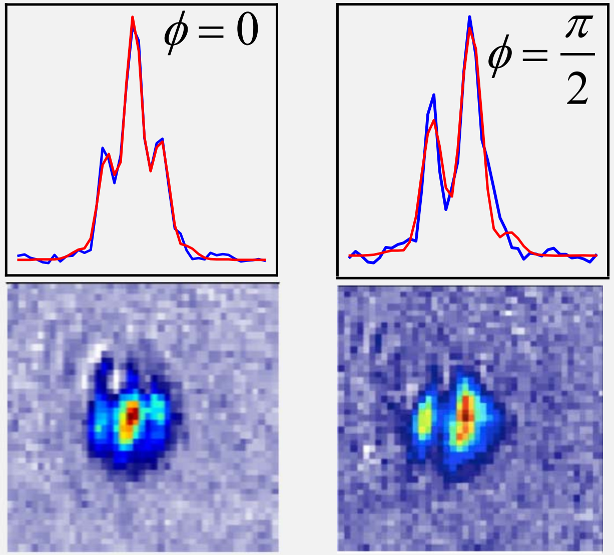
Coherent stripes

Incoherent droplets

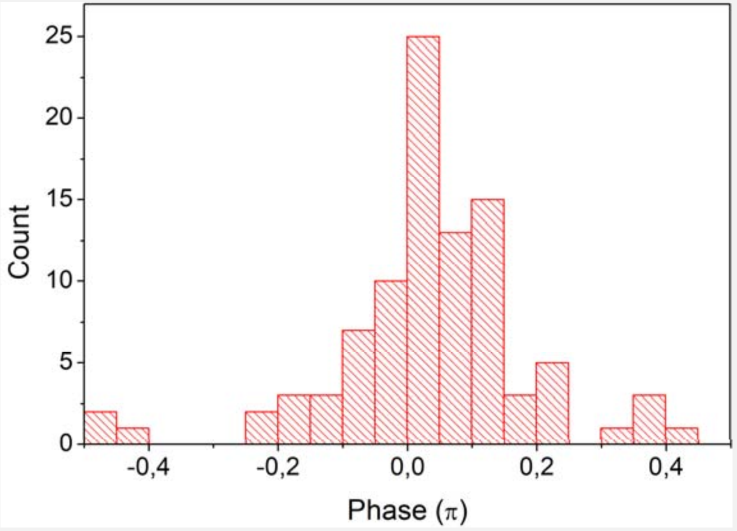
L. Tanzi et al., PRL 122, 130405 (2019)

Phase coherence

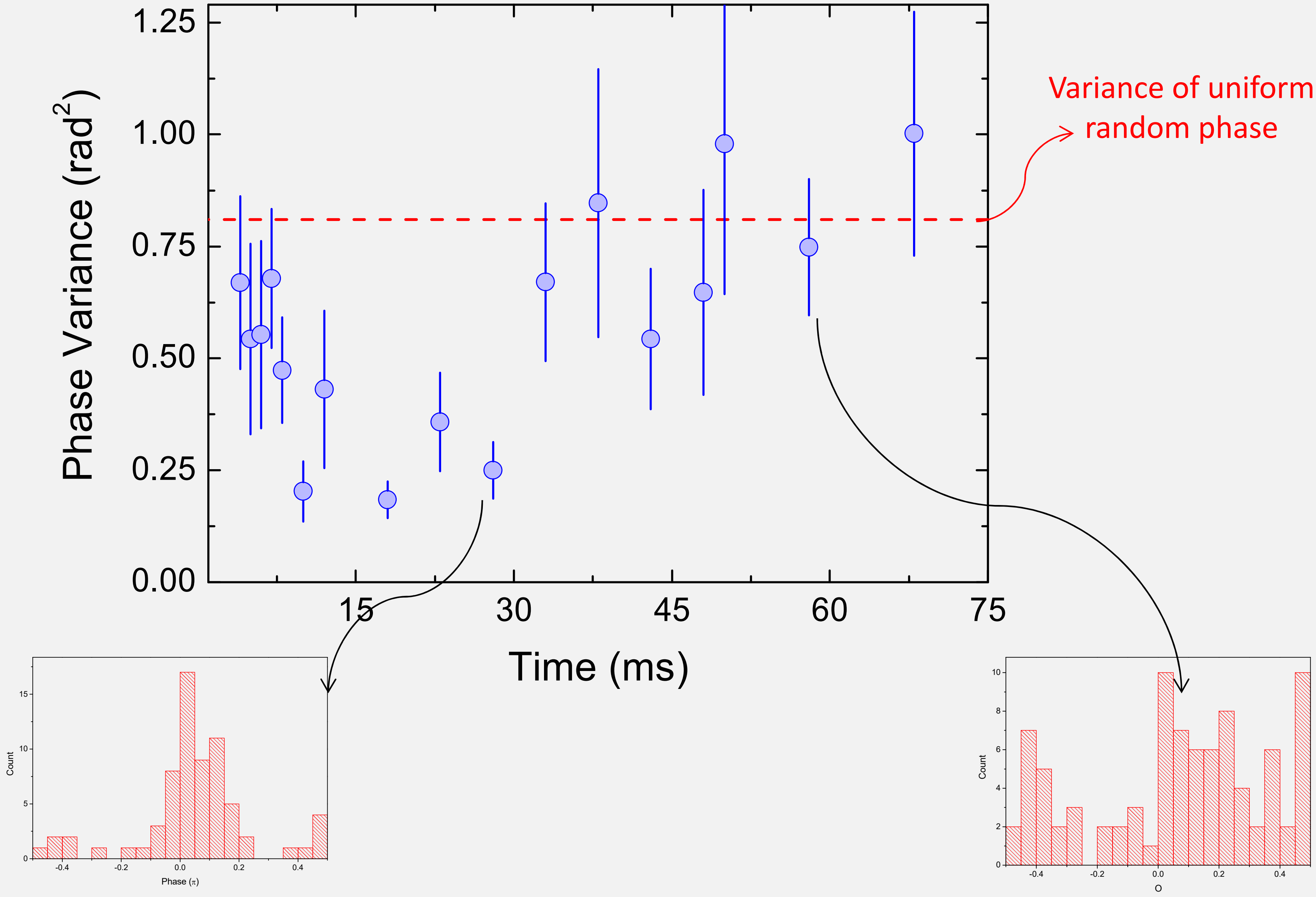
$$\tilde{n}(k) = A_0 e^{\frac{-k^2}{2\sigma^2}} \left[1 + A_1 \cos^2\left(\frac{\pi k}{k_{rot}} + \phi\right)\right]$$



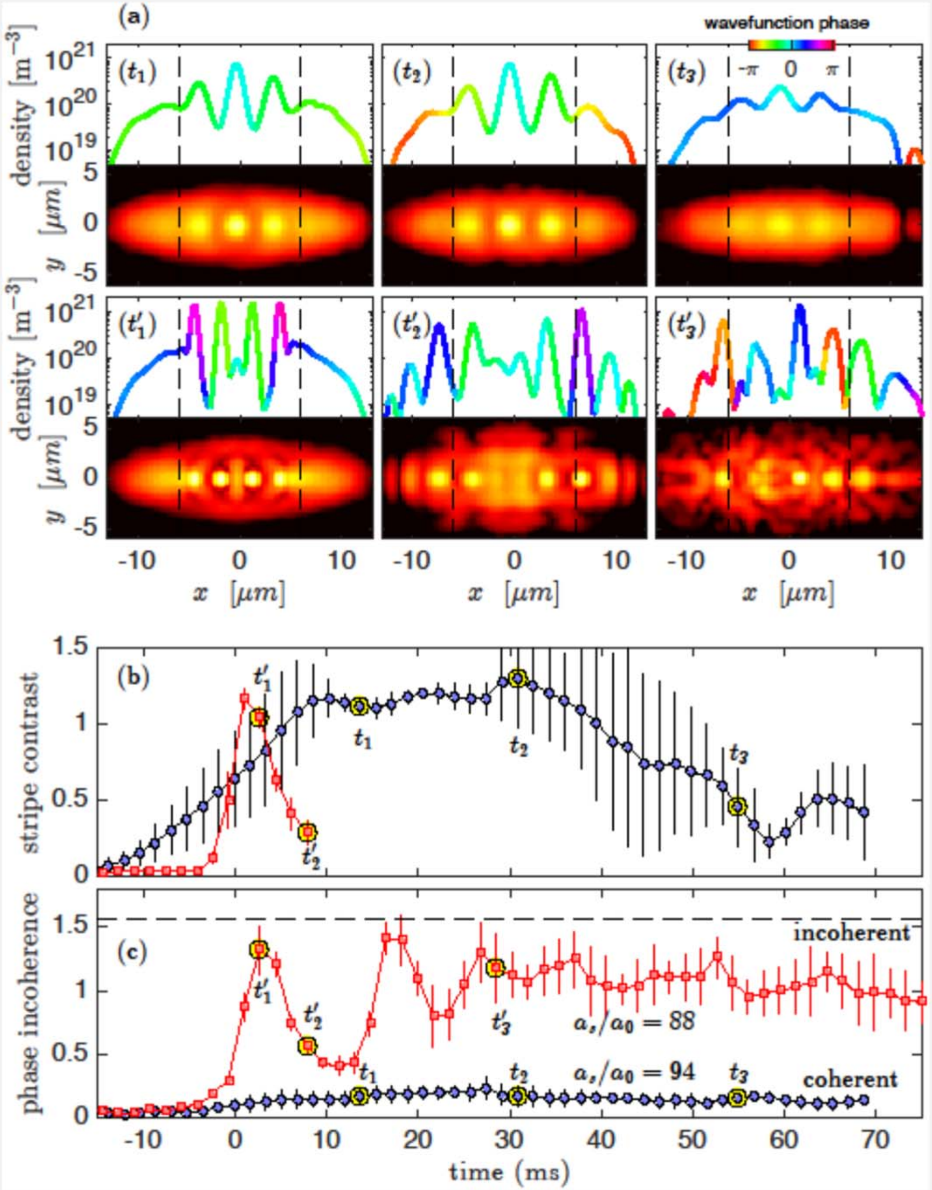
Large statistics
(> 50 images)



Phase coherence



Theoretical simulations



Coherent regime

Incoherent regime

Numerical simulations at finite T with LHY term and 3-body losses by R.Bisset and L.Santos (Hannover)

Strong interest by the scientific community

PHYSICAL REVIEW LETTERS

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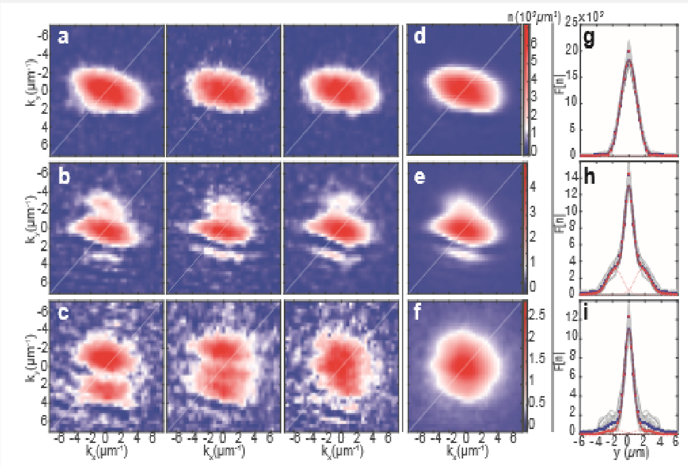
Observation of a Dipolar Quantum Gas with Metastable Supersolid Properties

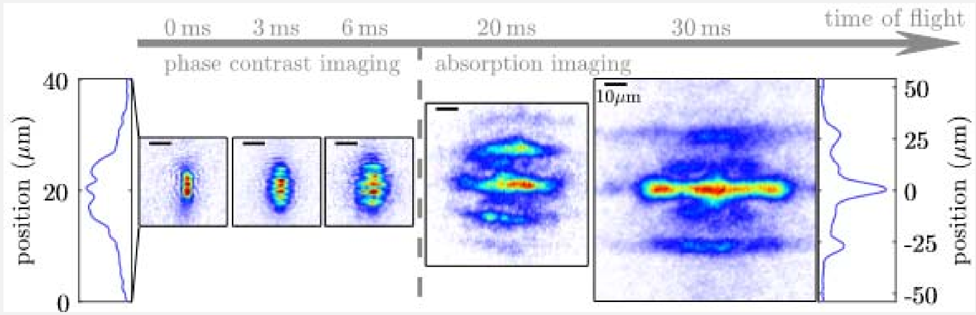
L. Tanzi, E. Lucioni, F. Famà, J. Catani, A. Fioretti, C. Gabbanini, R. N. Bisset, L. Santos, and G. Modugno

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

Physics See Viewpoint: Dipolar Quantum Gases go Supersolid



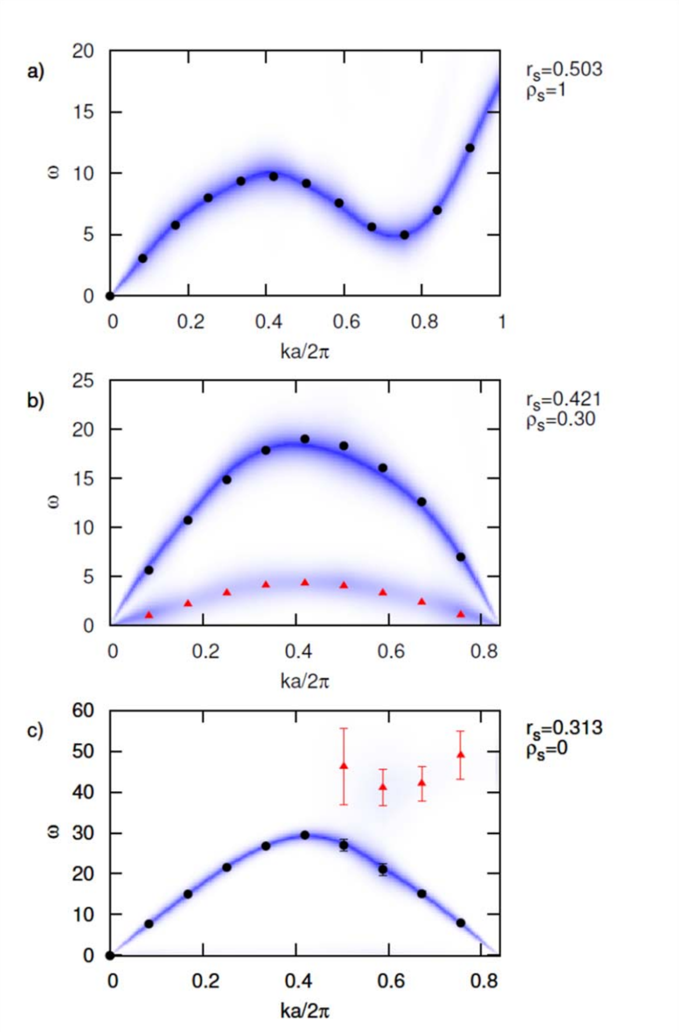
L. Chomaz et al., *Long-lived and transient supersolid behaviors in dipolar quantum gases,* Phys. Rev. X 9, 021012 (2019).



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

Symmetry breaking and Goldstone modes

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).

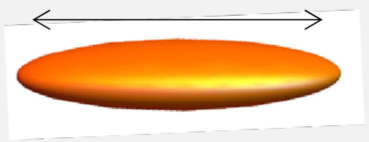
Trapped system: normal modes

How to observe symmetry breaking in a trapped system?

Phonon wavelengths are bound by the system size.
Momentum and sound velocity are not well defined in a non-homogeneous system.

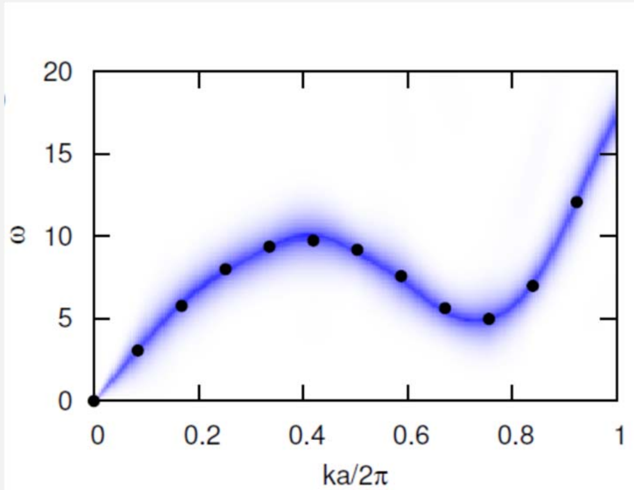
Answer:
Phonons can be mapped to the **compressional modes** of the system.
The lowest achievable energy at finite momentum is lifted.

l_x



$$k_{min} \sim 1/l_x$$

$$\mu = \frac{1}{2} m\, \omega_x^2\, l_x^2$$



$$\omega_{min} = v_s\, k_{min} = \sqrt{\mu/m l_x^2} \quad \Rightarrow \quad \omega_{min} \sim \omega_x$$

Normal modes

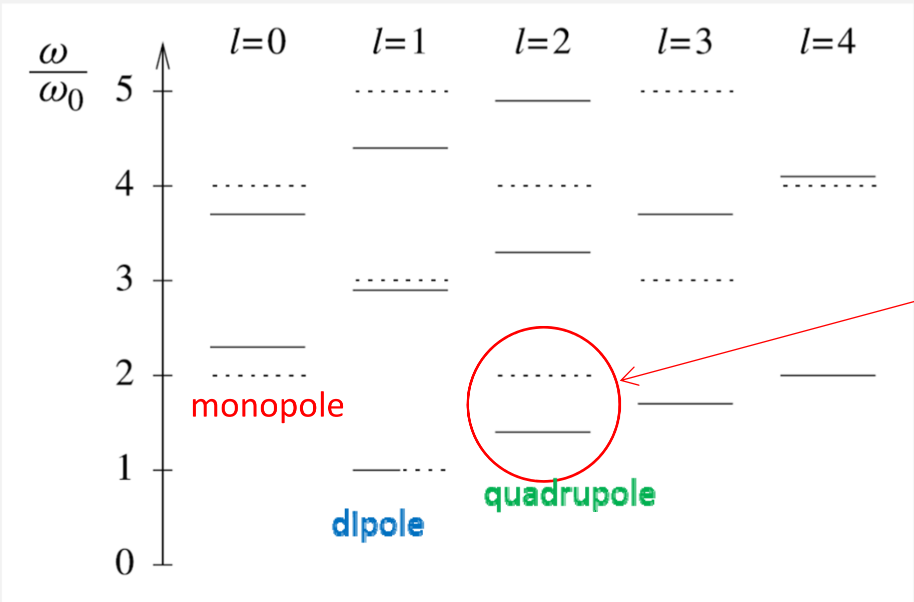
BEC in the Thomas-Fermi regime: hydrodynamic equations for an ideal liquid.

$$\psi_0 = |\psi_0| e^{iS(t)}$$

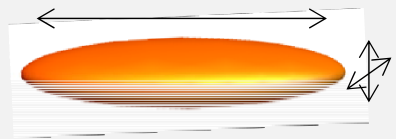
$$\frac{\partial n}{\partial t} + \boldsymbol{\nabla} \cdot (n\mathbf{v}) = 0$$

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

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



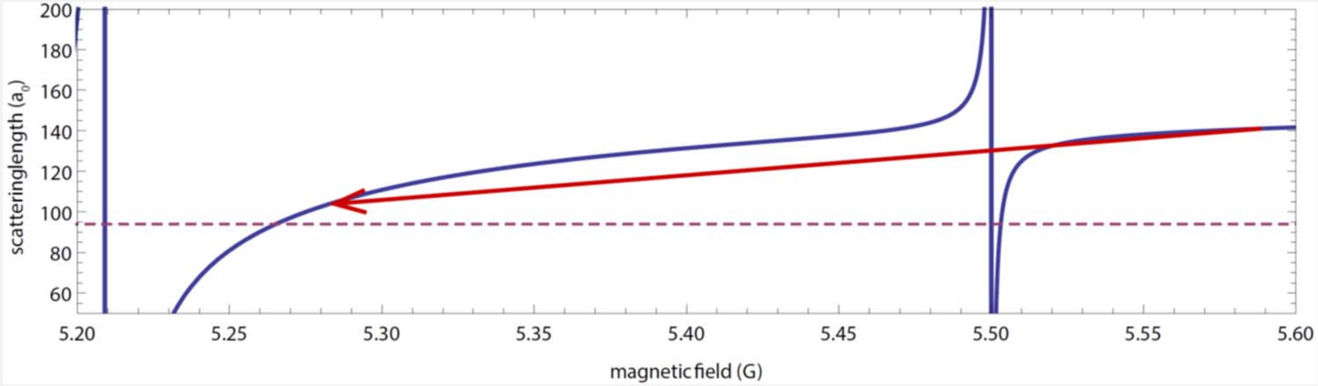
axial breathing mode



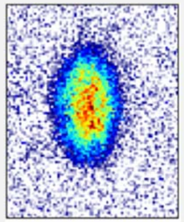
$$\omega_{BEC} = \sqrt{5/2}\,\omega_x$$

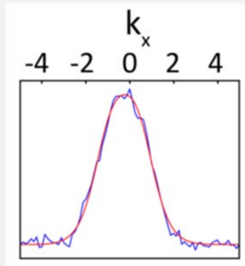
Experiment: axial breathing mode in the BEC regime

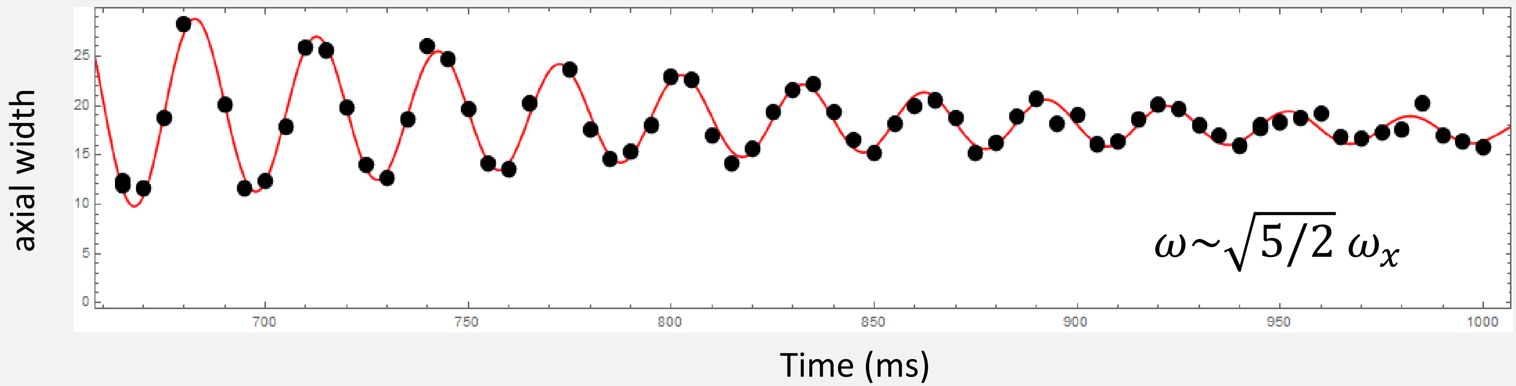
Quench of the scattering length through Feshbach resonances



Observable: second moment along x

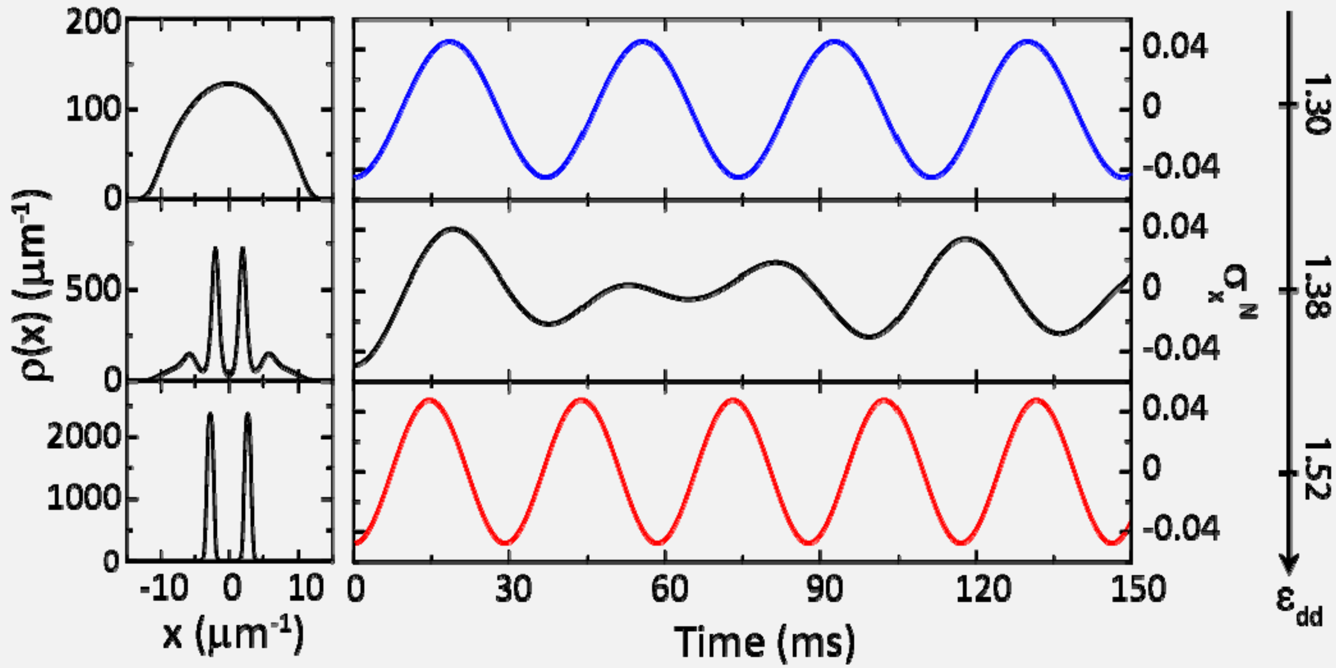






Theory: axial breathing mode in the SS regime

Numerical simulations at T=0 and no losses:

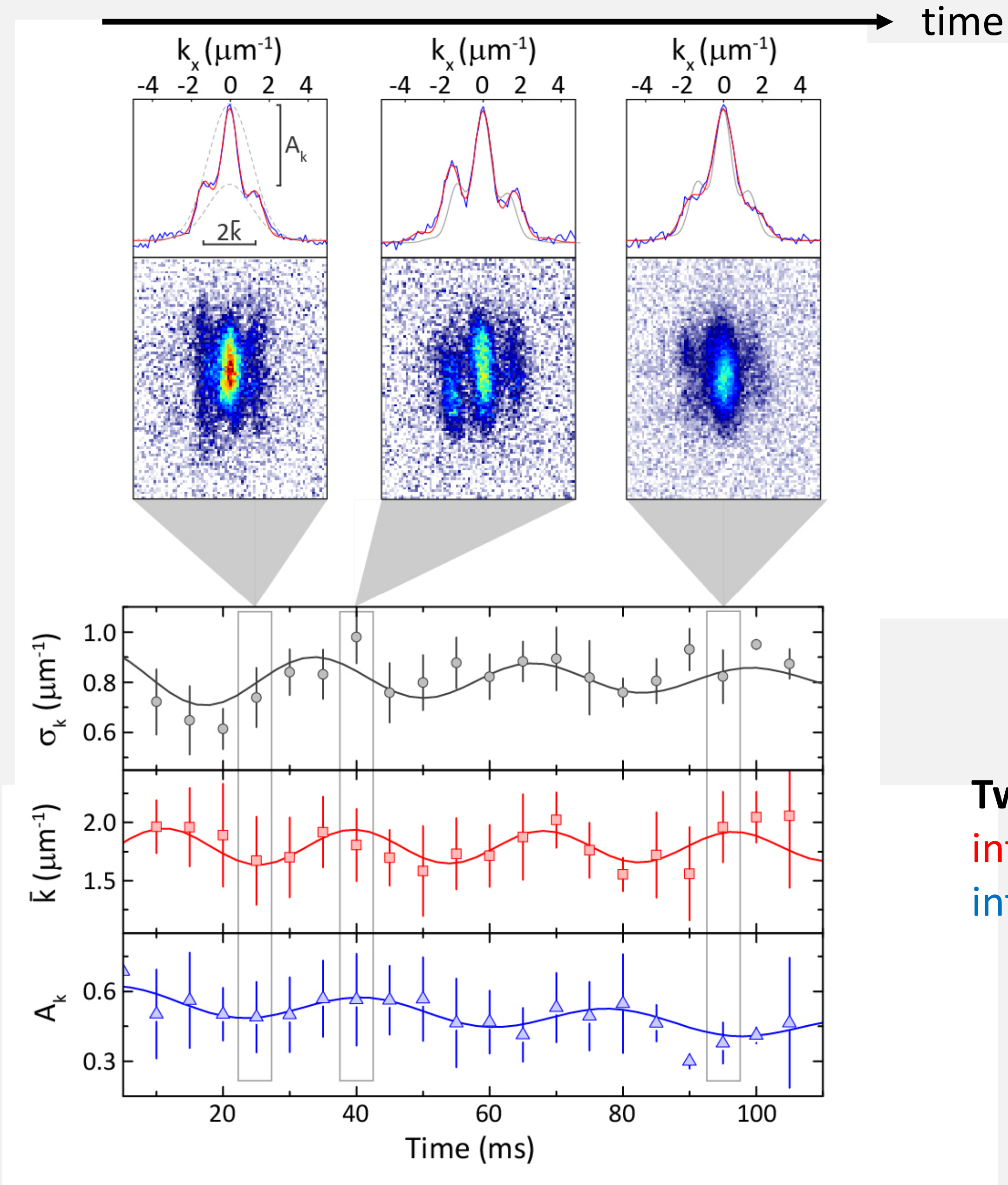


Beating of the axial breathing mode in the supersolid!

Due to the coupling of the two sound modes, the beating is visible only for very small amplitudes (<5%).

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

Experimental observations



An **axial breathing mode** is spontaneously excited at the instability

Oscillation amplitude: 10%

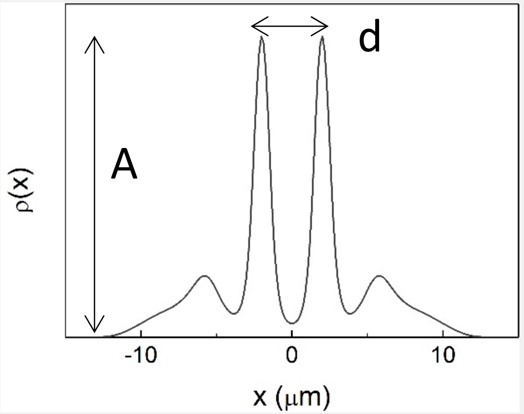
Two different frequencies for

interference period ω=1.66(10) ω_x

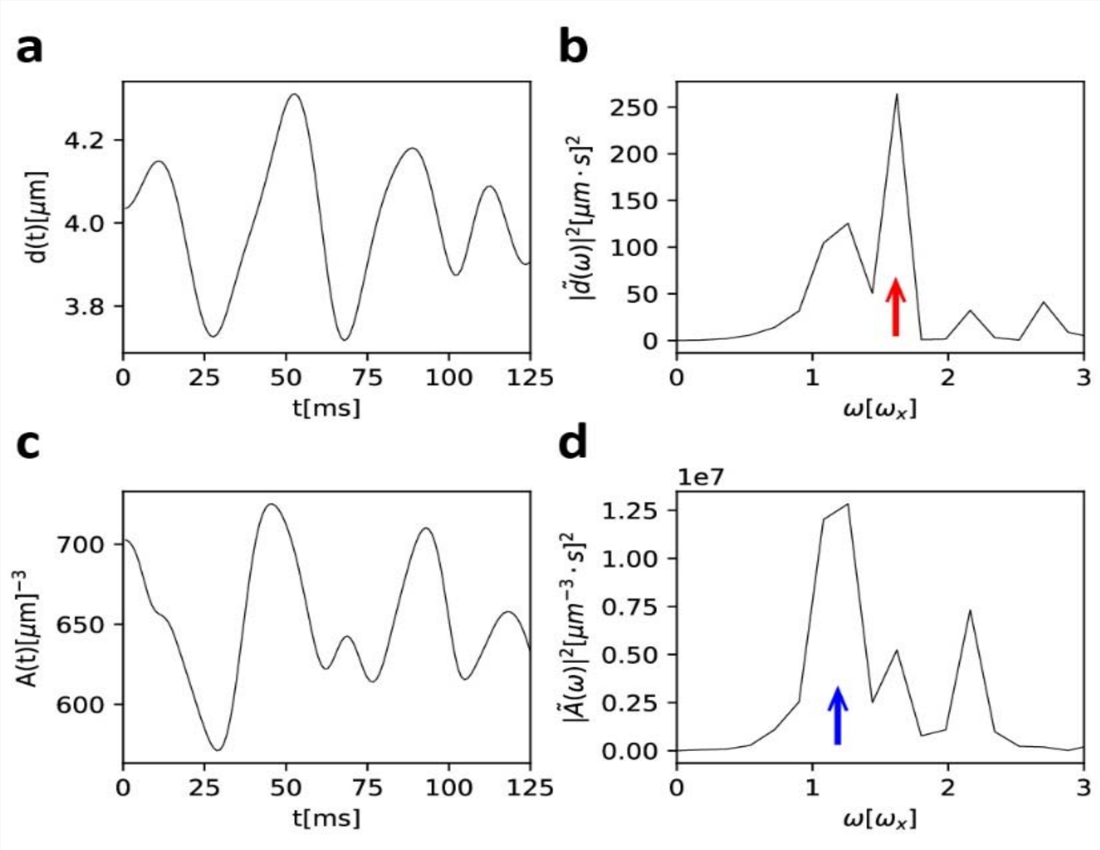
interference depth ω=1.27(12) ω_x

L. Tanzi et al, *Nature 574, 382 (2019*)

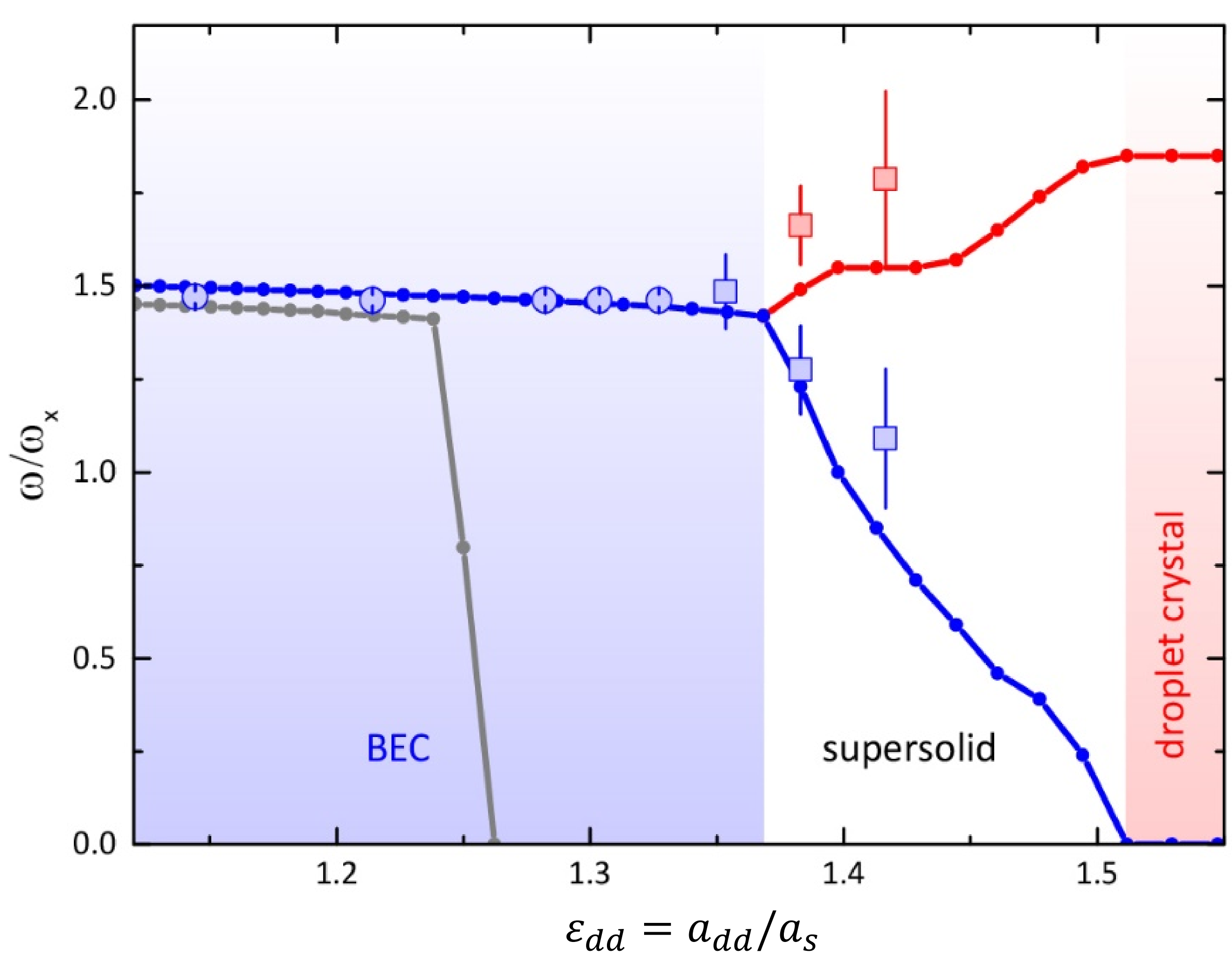
Theory: nature of the modes



Theory confirms that the two modes are coupled differently to the lattice spacing and lattice depth



Symmetry breaking in a supersolid



L. Tanzi, S. Roccuzzo et al., Supersolid symmetry breaking from compressional oscillations in a dipolar quantum gas, *Nature* *574*, *382 (2019)*

Complementary experiments in Stuttgart (Nature *574*, *386 (2019)*) and Innsbruck (Phys. Rev. Lett. 123, 050402).

Nonclassical rotational inertia in supersolids

VOLUME 25, NUMBER 22 PHYSICAL REVIEW LETTERS 30 NOVEMBER 1970

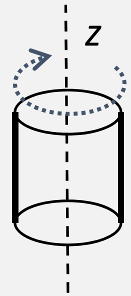
Can a Solid Be "Superfluid"?

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.

Due to irrotationality, the moment of inertia of a cylindrically symmetric superfluid is 0.

→ Torsional oscillator measurements in solid He



The momentum of inertia defines the superfluid fraction:

$$I = (1 - f_S)\, I_{rig}$$

Leggett finds that independently from the shape of the density ($\rho_0 = \rho V/N$):

$$f_S = \left(\int dx\, \frac{1}{\rho_0(x)}\right)^{-1}$$

1 for standard SF -> $f_S = 1$

≈ 0 at the edge of the Brillouin zone for a SS -> $f_S < 1$

Scissors mode: theory

VOLUME 83, NUMBER 22 PHYSICAL REVIEW LETTERS 29 NOVEMBER 1999

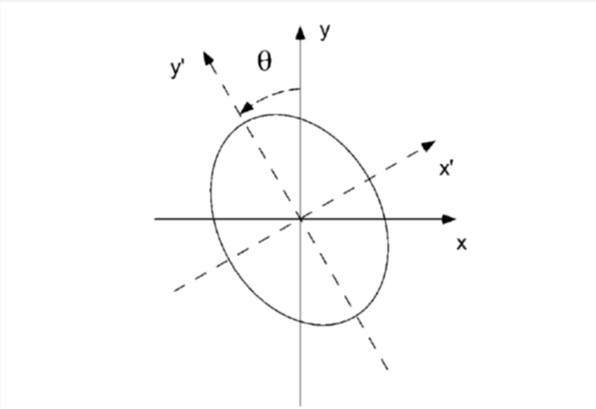
Scissors Mode and Superfluidity of a Trapped Bose-Einstein Condensed Gas

D. Guéry-Odelin and S. Stringari

Dipartimento di Fisica, Università di Trento, and Istituto Nazionale per la Fisica della Materia, I-38050 Povo, Italy

(Received 16 July 1999)

We investigate the oscillation of a dilute atomic gas generated by a sudden rotation of the confining trap (scissors mode). This oscillation reveals the effects of superfluidity exhibited by a Bose-Einstein condensate. The scissors mode is also investigated in a classical gas above T_c in various collisional regimes. The crucial difference with respect to the superfluid case arises from the occurrence of low frequency components, which are responsible for the rigid value of the moment of inertia. Different experimental procedures to excite the scissors mode are discussed.



Angular oscillations, linear response theory:

$$\frac{I}{I_{rig}} = \frac{\left(\omega_y^2 - \omega_x^2\right)^2}{\omega_{sc}^4}$$

- Similar to the torsion oscillator, but now each atom is suspended to a «torsion spring», so the mass distribution cancels out!
- In a BEC: $\omega_{sc}^4 = \left(\omega_y^2 + \omega_x^2\right)^2$
- In fact, for a nondipolar BEC in an elliptic geometry: $\frac{I}{I_{rig}} = \epsilon^2 = \frac{\left(\omega_y^2 - \omega_x^2\right)^2}{\left(\omega_y^2 + \omega_x^2\right)^2}$

Experimental observation by Maragò et al., PRL 84, 2056 (2000)

The objective

Measure the **scissor frequency.** Combine Stringari's and Leggett's theory results to obtain the **nonclassical rotational inertia** and **superfluid fraction** of the dipolar supersolid:

- moment of inertia from the scissors mode frequency

$$\frac{I}{I_{rig}} = \epsilon' \; \frac{\left(\omega_y^2 - \omega_x^2\right)}{\omega_{sc}^2}$$

with $\epsilon' = \frac{<y^2-x^2>}{<x^2+y^2>}$

- superfluid fraction from the moment of inertia

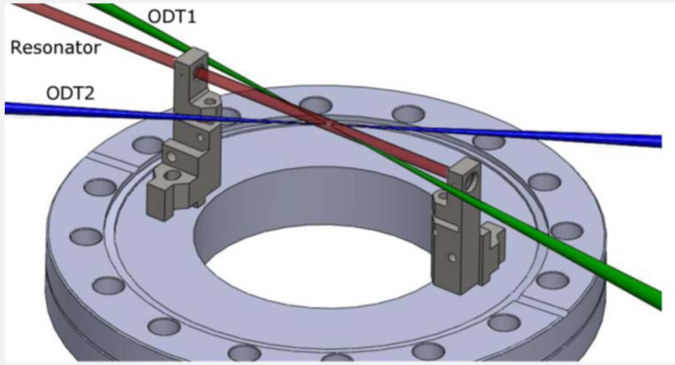
$$f_S = \frac{1-\frac{I}{I_{rig}}}{1-\epsilon'^2}$$

- the measured ρ_s from the oscillations can be compared to that expected from the density modulation

$$f_S = \left(\int dx \, \frac{1}{\rho_0(x)}\right)^{-1}$$

Scissors mode: experiment

The x-y scissors mode (in the plane perpendicular to B) can be excited by a quench of the strength of two optical traps.



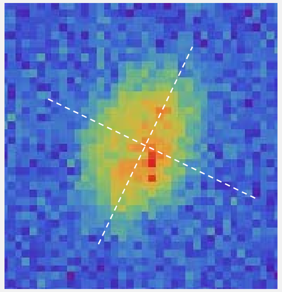
Since the deviation between SF and SS behaviour depends on the fraction of system which contributes to the NCRI, proportional to (1-ϵ'^2), we choose a more symmetric geometry to observe a large deviation in the measure of I/I_{rig}:

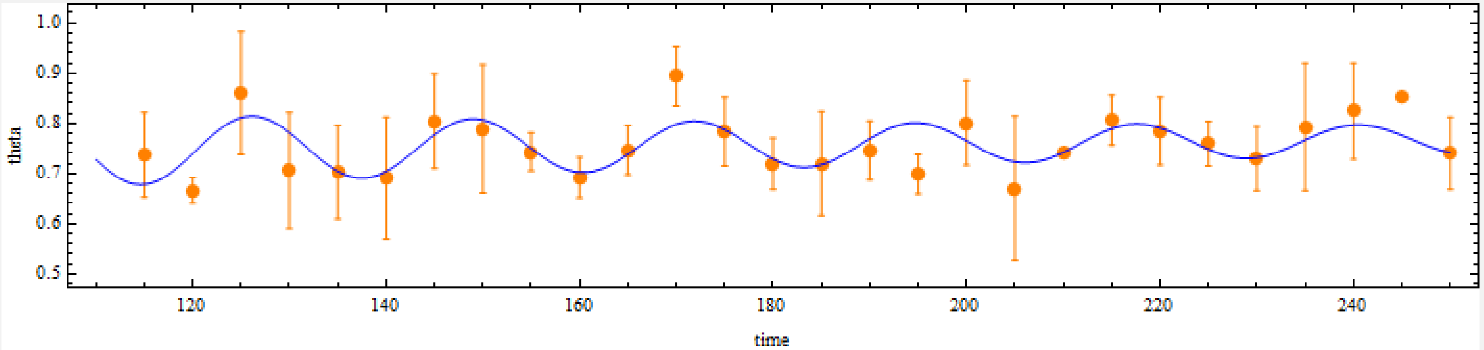
$$\omega_x \approx 20 \text{ Hz} \qquad \omega_y \approx 40 \text{ Hz}$$

Scissors mode: BEC regime

BEC regime: $\omega_{sc} = 2\pi \times 43.7\ (1.1)\ \text{Hz} \approx \sqrt{\omega_y^2 + \omega_x^2}$

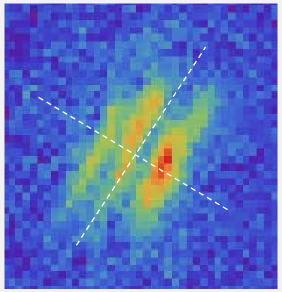
preliminary data

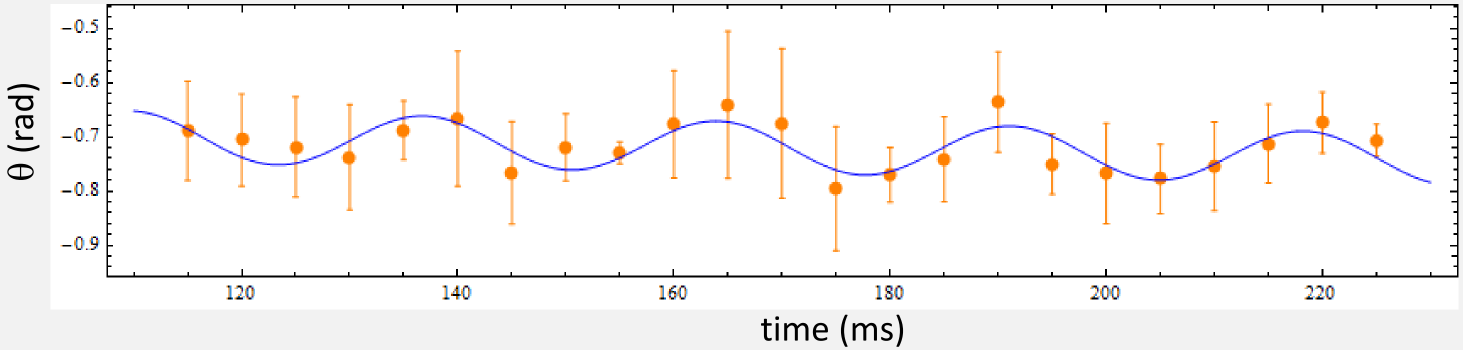




The angle evolution is determined with a 2D fit

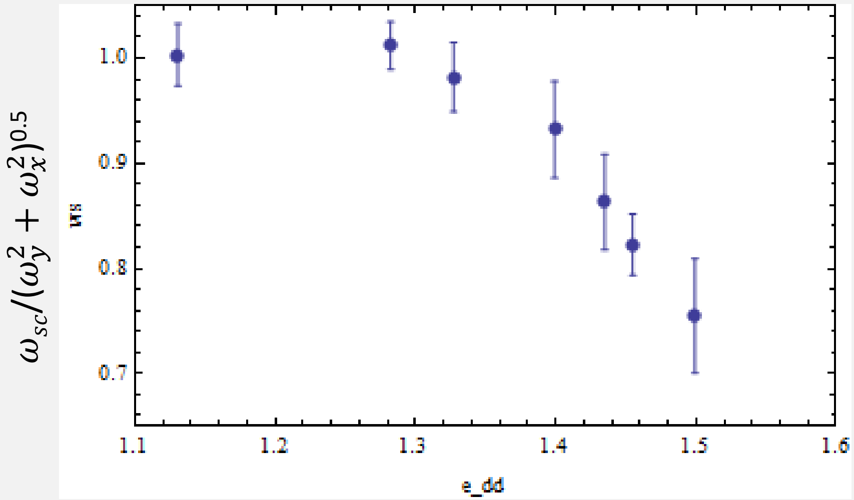
Supersolid regime: $\omega_{sc} = 2\pi \times 36\ (6)\ \text{Hz} \approx 0.8\sqrt{\omega_y^2 + \omega_x^2}$





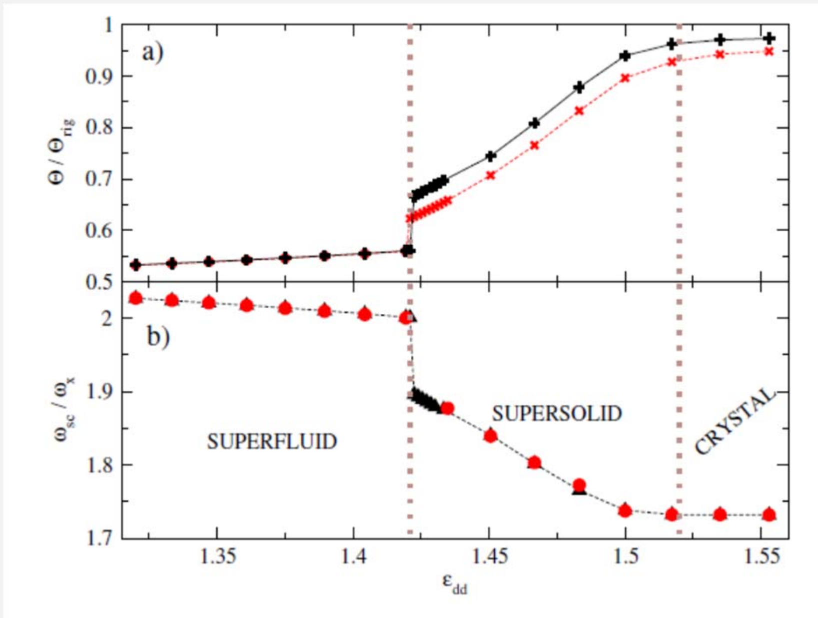
Superfluid fraction from scissors frequency

preliminary data



$f_s \approx 50\%$

Theor. paper by Trento group, S.M.Roccuzzo et al arXiv:1910.08513v1

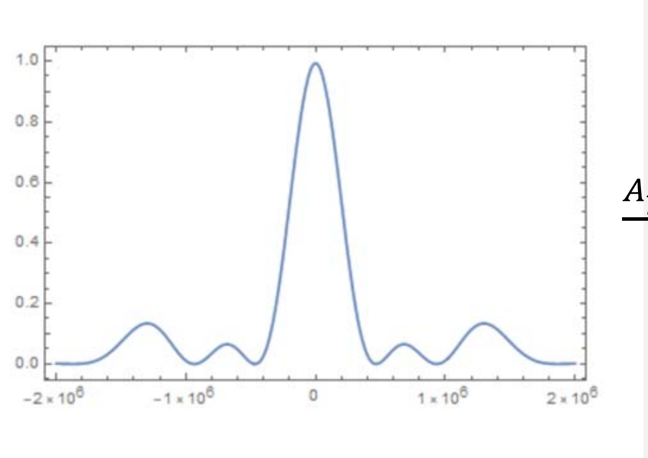


Superfluid fraction from density distribution

We can qualitatively reconstruct the in-trap density distribution from the time-of-flight distributions (assuming no distortion at the release from the trap).

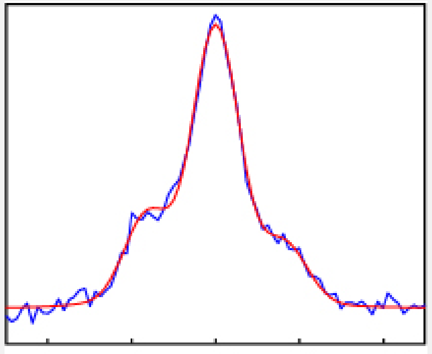
simulated

$\rho_0(k_x)$

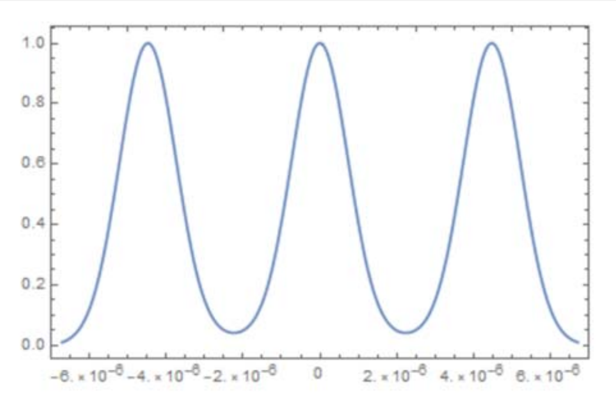


$\frac{A_{peak}}{A_c} = 0.2$

experimental



$\rho_0(x)$



$\longrightarrow$ $f_s = \left(\int dx \frac{1}{\rho_0(x)}\right)^{-1} \approx 30\%$

same order of magnitude

preliminary data, analysis in progress

Conclusions and outlook

Evidence of a phase-coherent, density modulated phase with two broken symmetries confirms the supersolid nature of the observed phase.

In progress: first measurements of nonclassical rotational inertia and superfluid fraction

Other manifestations of superfluidity:

- Existence of a critical velocity
- Existence of quantized vortices

Towards a «solid-state supersolid»:

- Homogeneous and larger systems.
- 2D systems.

The Dy-lab group

A.Fioretti
C.Gabbanini

L.Tanzi
G.Modugno

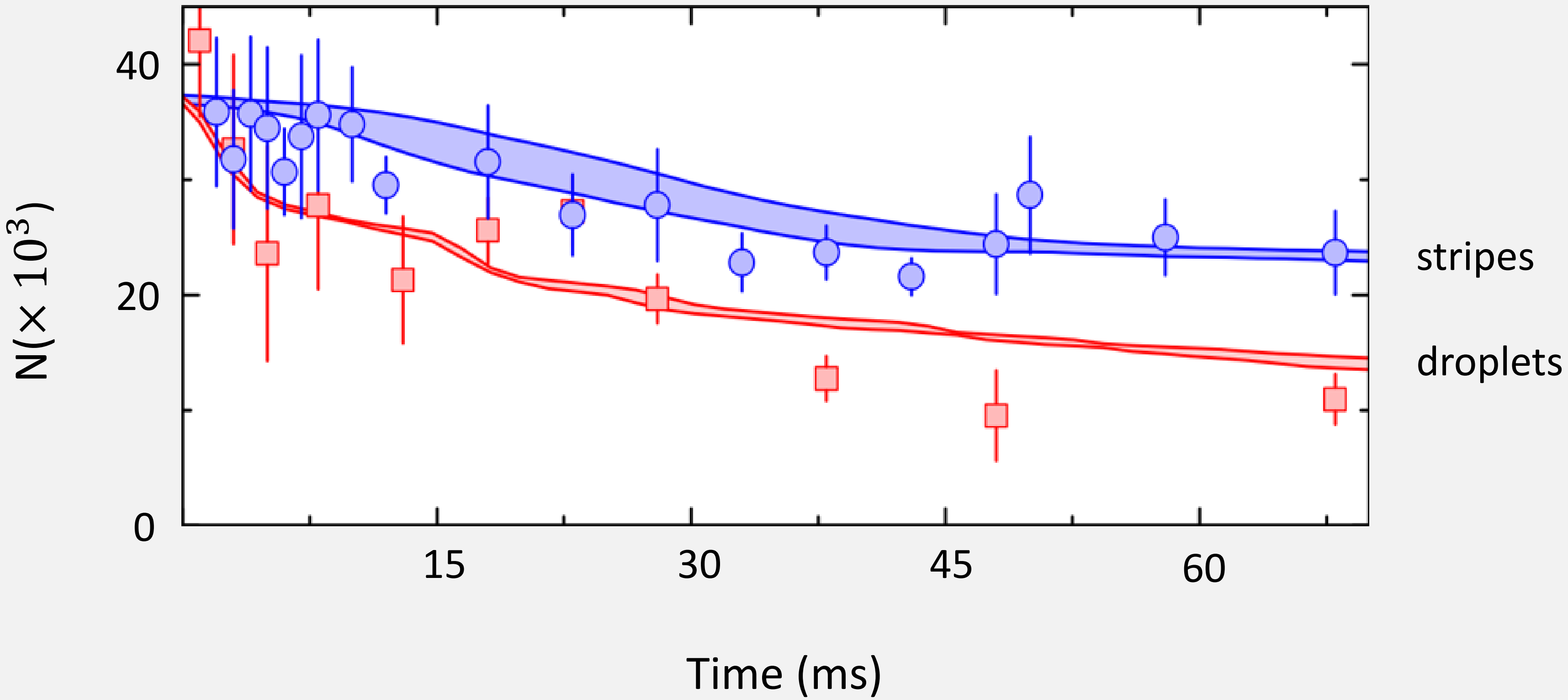
J.Maloberti, G.Biagioni Master Students

Previous members: F.Famà, E.Lucioni

Theory by:
R.Bisset, L. Santos (Hannover)
A. Recati, S.Roccuzzo, S. Stringari (Trento)

Inelastic decay

Atom-number decay due to three-body recombination



Sound modes and symmetry breaking

QUANTUM THEORY OF DEFECTS IN CRYSTALS

A. F. ANDREEV and I. M. LIFSHITZ

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

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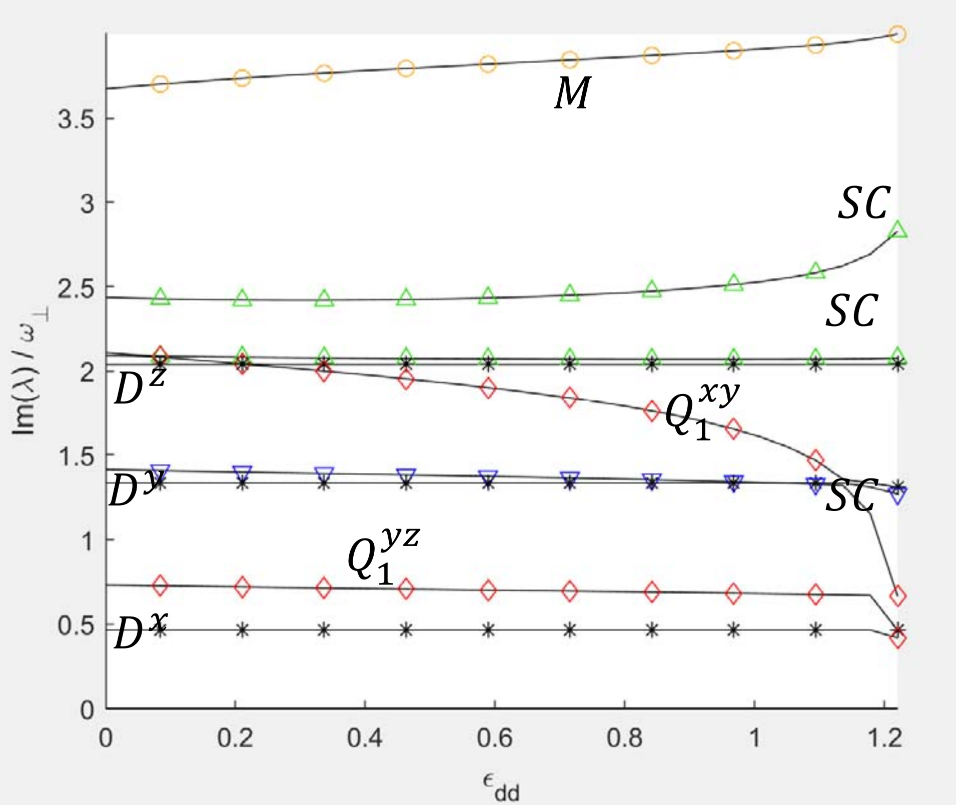
At sufficiently low temperatures localized defects or impurities change into excitations that move practically freely through a crystal. As a result instead of the ordinary diffusion of defects, there arises a flow of a liquid consisting of "defectons" and "impuritons." It is shown that at absolute zero 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.

… we obtain an equation for the acoustic vibrations of a crystal … and oscillations of the crystal density with fixed lattice sites…

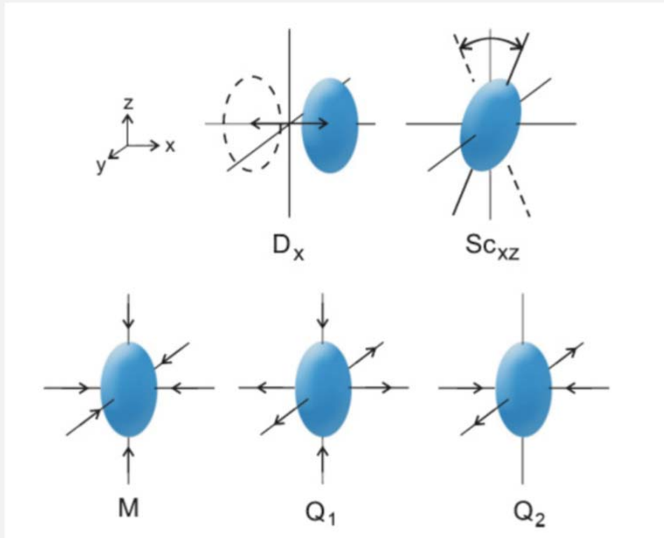
Normal modes in a dipolar BEC

Lowest-lying normal modes from the hydrodynamic equations (without LHY):

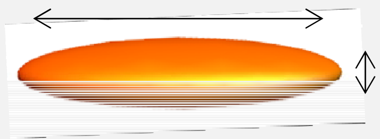
van Bijnen et al, Phys. Rev. A 82, 033612 (2010)



$$\varepsilon_{dd} = a_{dd}/a_s$$



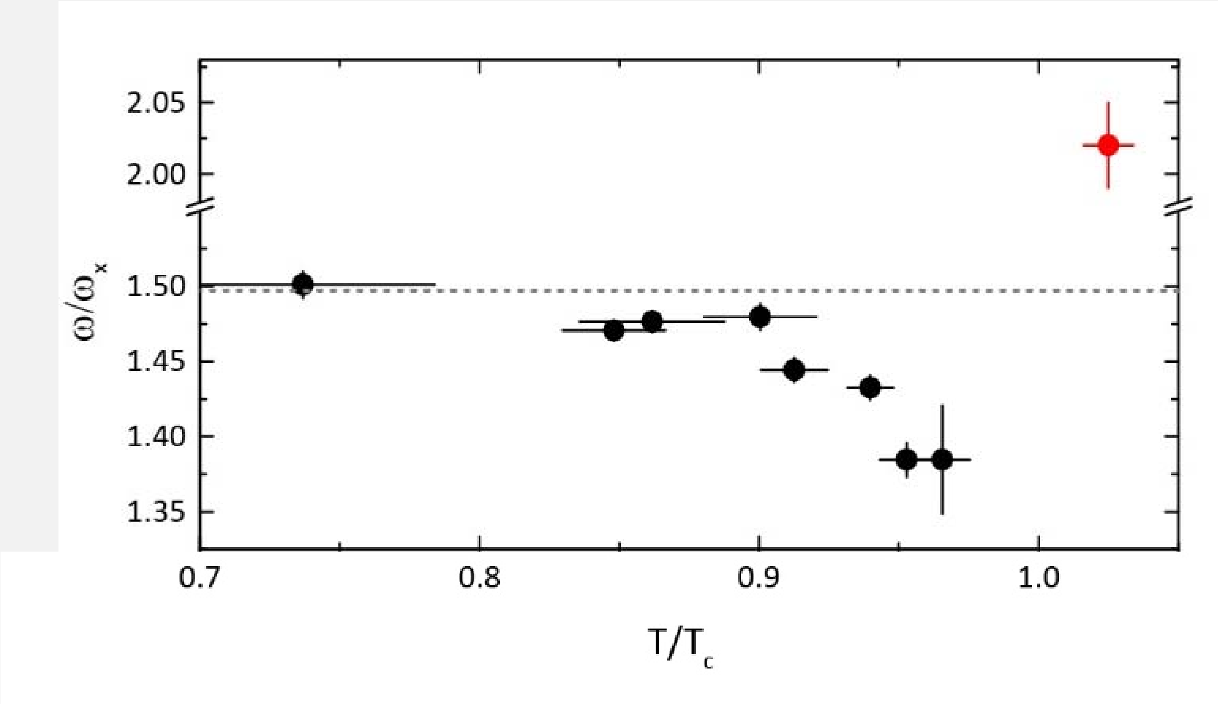
Axial breathing mode



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

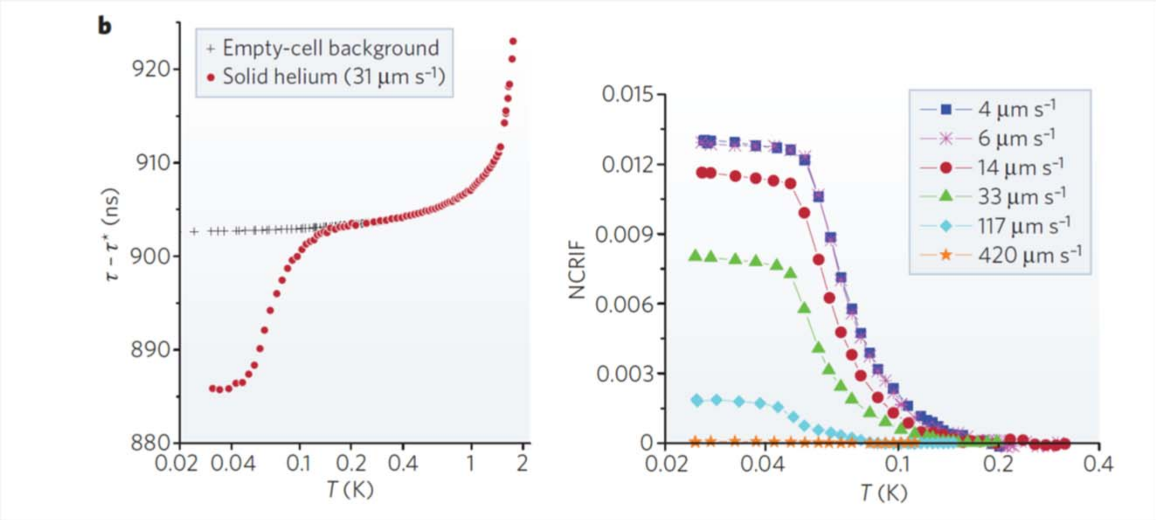
Experiment: BEC regime

Superfluid symmetry breaking: the axial breathing mode frequency is very different from that of a classical gas.



The frequency shift of the BEC mode is a well known effect due to interaction with the thermal component.

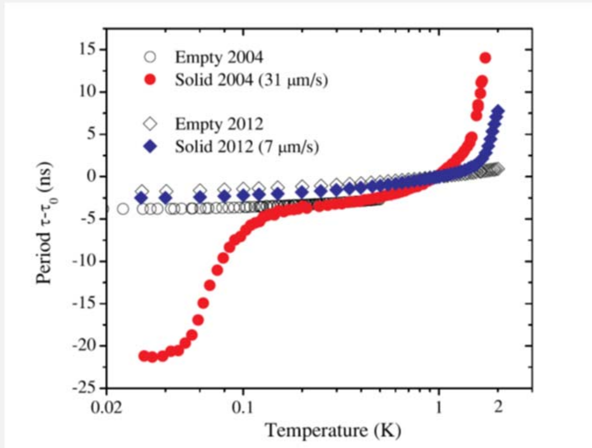
Torsional oscillator measurements on solid He



Reduction of the moment of inertia: supersolidity!!!

Supersolid fraction is tiny.

Probable observation of a supersolid Helium phase, Kim and Chan, Nature 427, 225 (2004).



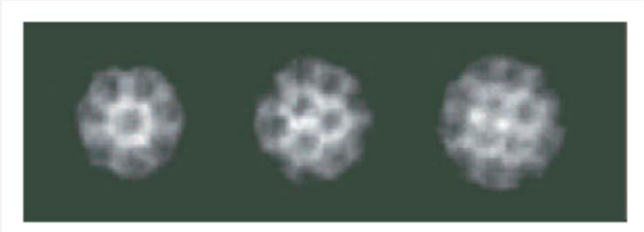
When considering the elastic deformations of He under rotation no NCRI is observed!

Absence of superfluidity of solid Helium in porous Vycor glass, Kim and Chan, Phys. Rev. Lett. 109, 155301 (2012); Review: Balibar, Nature 464, 176 (2010); Torsion oscillator theory: Maris and Balibar, J. Low Temp. Phys. 162, 12 (2011).

Rotating BECs

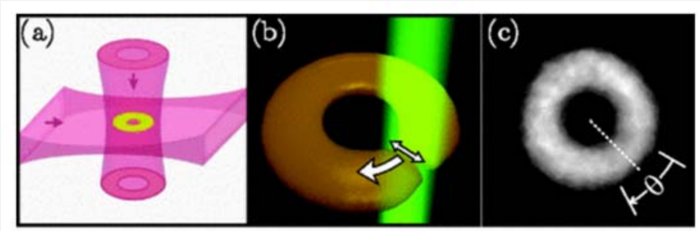
Rotating BECs is also possible:

Rotating harmonic traps



Phys. Rev. Lett. 84, 806 (2000), …

Toroidal traps



Phys. Rev. Lett. 110, 025302 (2013), …

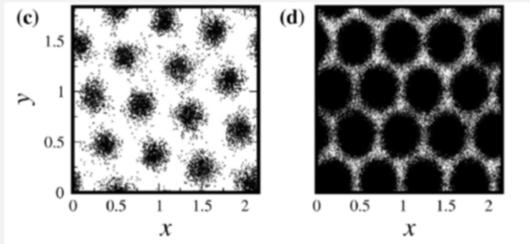
… but a much simpler alternative exists: the scissors mode

Supersolids in superfluid quantum gases?

Gaseous Bose-Einstein condensates (**superfluidity**) +
Engineered "long-range" interactions (**density modulation**)

Cluster supersolids benefit from
bosonic enhancement

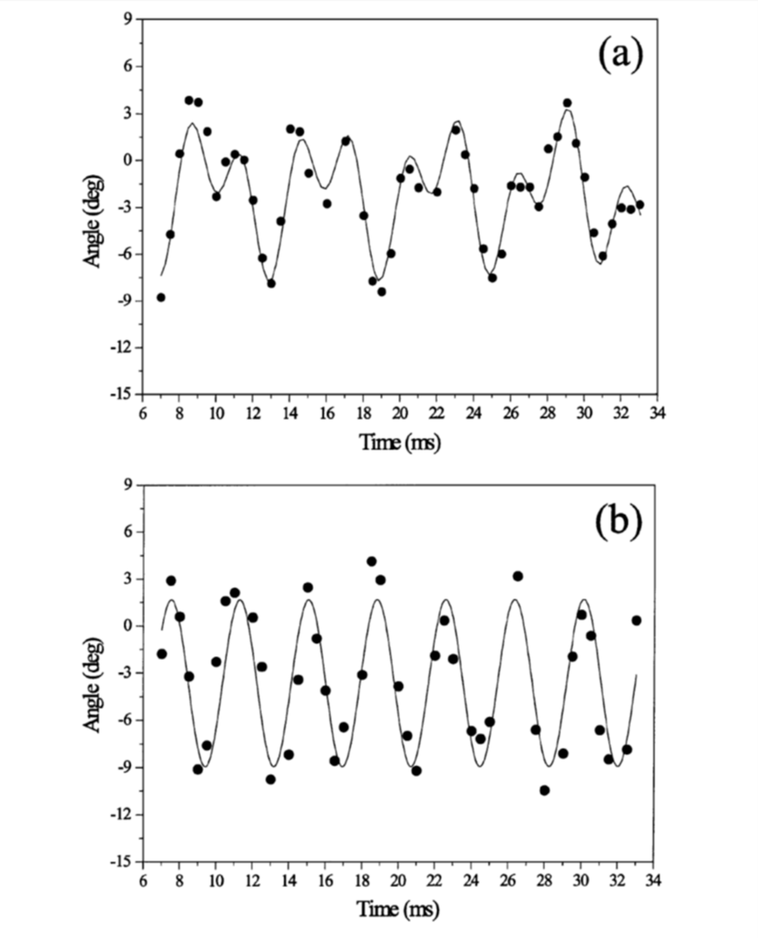
Pomerau and Rica, Phys. Rev. Lett. 72, 2426 (1994)



Proposals based on:

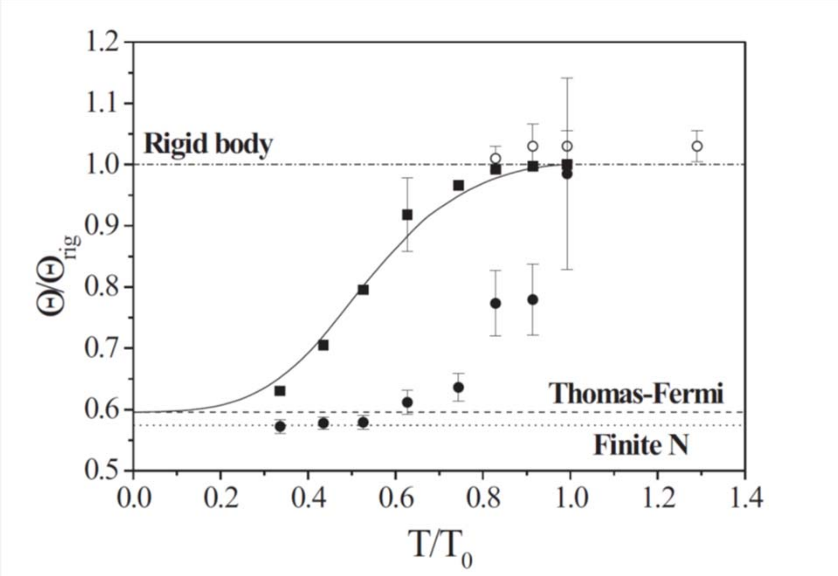
- Rydberg atoms with soft-core interactions
- spin-orbit coupled atoms (observed in J.R. Li et al., Nature 543 (2017))
- atoms in optical cavities (observed in J. Leonard et al., Nature 543 (2017))
- **strongly dipolar atoms**

Scissors mode: experiment



The scissors mode of a classical gas (a) and a BEC (b) are qualitatively different.

The BEC is fully superfluid (ρ_s/ρ = 1), so the "superfluid fraction" changes only because of the thermal component at T>0.



Observation of the scissors mode and evidence of superfluidity of a trapped BEC, Maragò et al., Phys. Rev. Lett. 84, 2056 (2000).