The supersolid phase of matter

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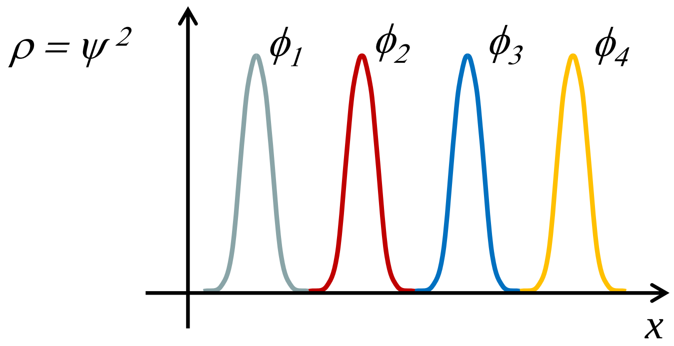
HORIZON 2020

Quantum Simulations of Insulators and Conductors

European Laboratory for Non-Linear Spectroscopy

INO-CNR Istituto Nazionale di Ottica

What is a supersolid?



Crystals: particles are localized in lattice sites

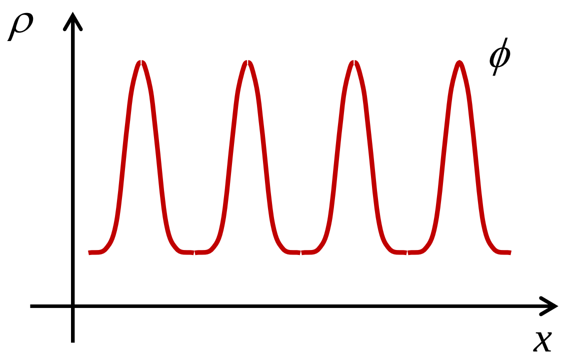
⇓

stiffness (nonzero rigidity) and
plasticity (nonzero stress to produce permanent deformations)

Superfluids: particles are undistinguishable and uniformly delocalized

⇓

supercurrents (zero viscosity) and
absence of stiffness (zero rigidity)



Supersolids: coexistence of the two states above, due to interaction effects (no external lattice).

⇓

???

Seminal work

EUGENE P. GROSS
1926–1991

Phys. Rev. 106, 161 (1957)

Unified Theory of Interacting Bosons

EUGENE P. GROSS
Brandeis University, Waltham, Massachusetts
(Received January 25, 1957)

RECENT work has contributed to the understanding of properties of helium II. Yet there is room for a unified theoretical approach to the problem of interacting bosons for both solid and liquid states.

Microscopic Theory of Superconductivity*

J. BARDEEN, L. N. COOPER, AND J. R. SCHRIEFFER
Department of Physics, University of Illinois, Urbana, Illinois
(Received February 18, 1957)

SINCE the discovery of the isotope effect, it has been known that superconductivity arises from the interaction between electrons and lattice vibrations, but it has proved difficult to construct an adequate theory based on this concept. As has been shown by

The Hamiltonian of identical bosons with the two body interaction potential $V(x)$ … governs the motion of a classical wave field.

There is always a solution of uniform density

$\psi(x) = \left(\frac{N}{L^3}\right)^{1/2}$ with energy $E = \frac{N}{L^3}\int V(x) d^3x$ …

but if $V(x)$ is negative in some region of space, there may be other solutions, such as periodic solutions with lower E than for the uniform solution.

Two sound sound modes

SOVIET PHYSICS JETP VOLUME 29, NUMBER 6 DECEMBER 1969

QUANTUM THEORY OF DEFECTS IN CRYSTALS

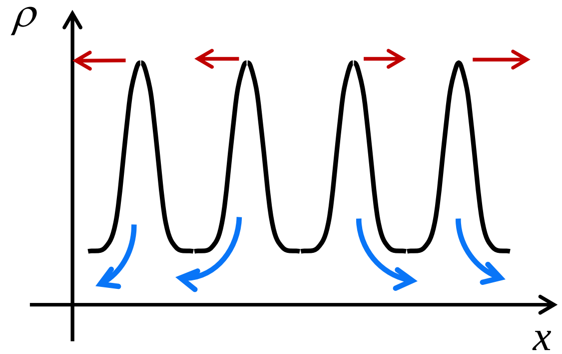
A. F. ANDREEV and I. M. LIFSHITZ

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.



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.

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

Can a supersolid pass through a capillar without friction?

Non classical rotational inertia

Nobel 2003

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.

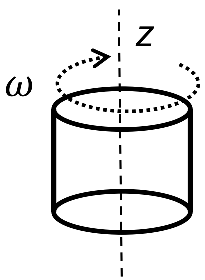
In supersolids, the density modulation reduces the superfluid behavior:

$$I = (1 - f_s)\, I_c$$

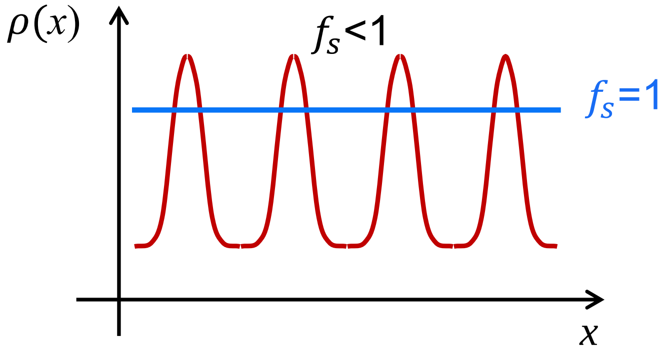
Superfluids: macroscopic wavefunction

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

$v = (\hbar/m)\nabla\varphi$ implies irrotationality, $\nabla \times v = 0$.



$$L = I\omega = 0$$



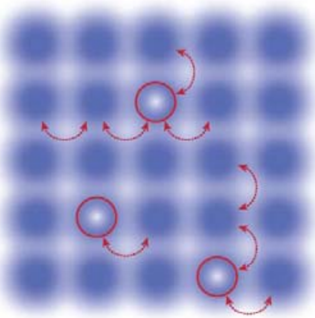
Is solid helium a supersolid?

PHYSICAL REVIEW A VOLUME 2, NUMBER 1 JULY 1970

Speculations on Bose-Einstein Condensation and Quantum Crystals*

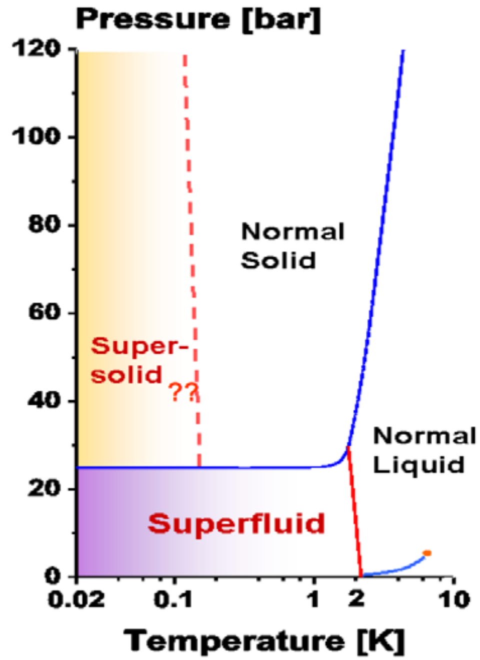
G. V. Chester
Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14850
(Received 13 May 1969)

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.



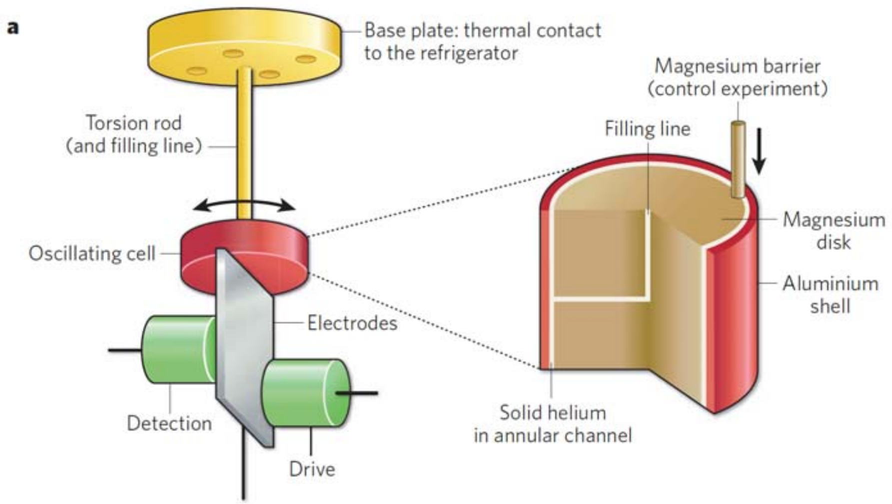
The large zero-point motion in a solid of light bosonic atoms allows the atoms to exchange their positions.

Bose-Einsten condensate of "defectons"



Reviews: Balibar, Nature 464, 176 (2010); Chan, Hallock, Reatto, J. Low. Temp. Phys. 172, 317 (2013).

Experiments on solid helium



Resonant period of the torsion oscillator:

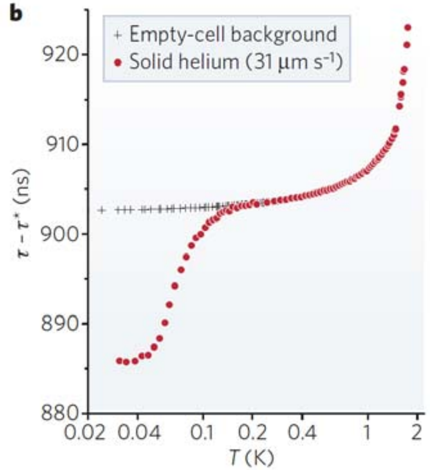
$$\tau = 2\pi\sqrt{I/K}$$

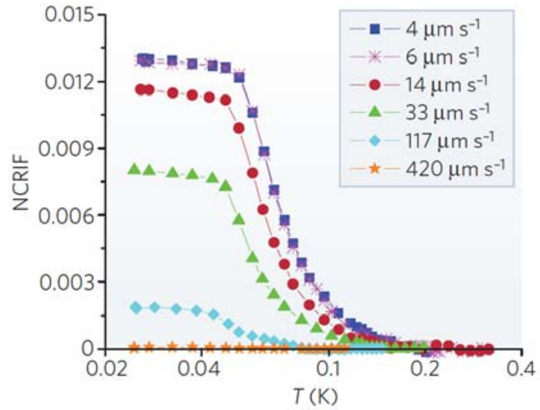
τ: oscillation period
I: moment of inertia
K: elastic constant

E. Kim and M. H. W. Chan, Probable observation of a supersolid helium phase, Nature 427, 225 (2004)

$$I = (1 - f_s)\, I_c$$

large $f_s \sim 10^{-2}$, in disagreement with Leggett predictions (10^{-4})





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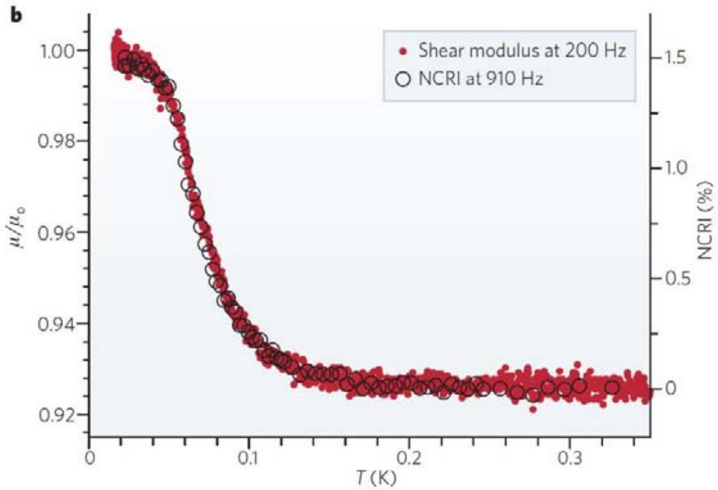
Experiments on solid helium

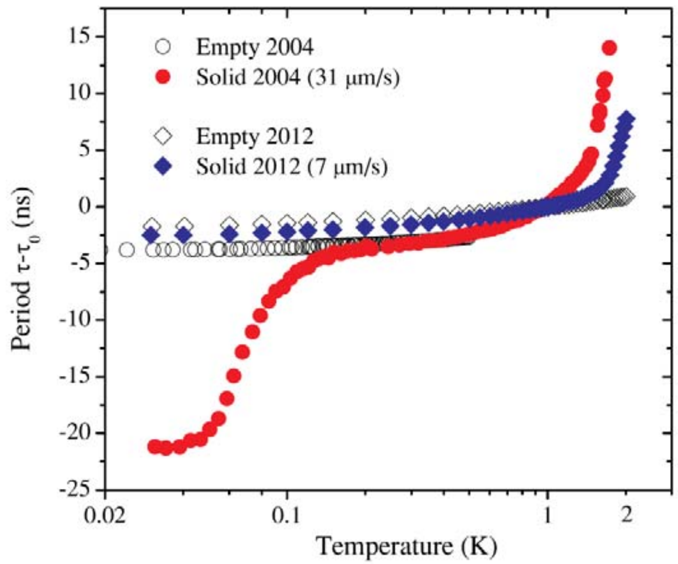


Problem: the change of period might be explained with a change of the elastic constant of He.

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

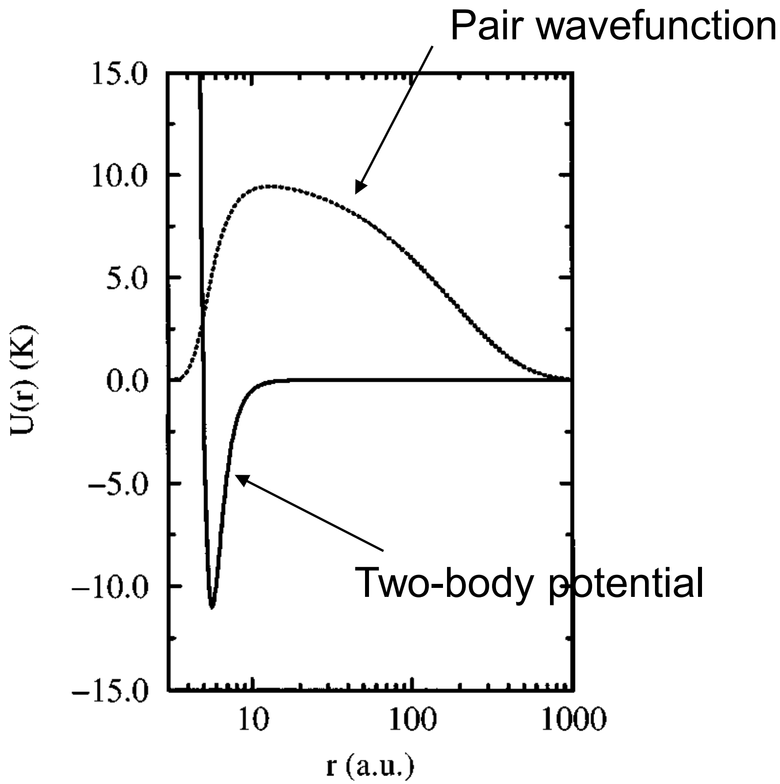
Dislocations change state when lowering the temperature, and the crystal stiffens (*K* increases).

J. Day, J. Beamish, Low-temperature shear modulus changes in solid ^{4}He and connection to supersolidity, Nature 450, 853 (2007).



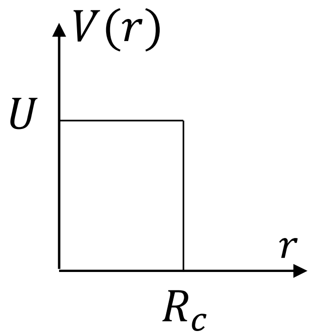
D. Y. Kim and M. H. W. Chan, Absence of supersolidity in solid helium in porous Vycor glass, Phys. Rev. Lett. 109, 155301 (2012).

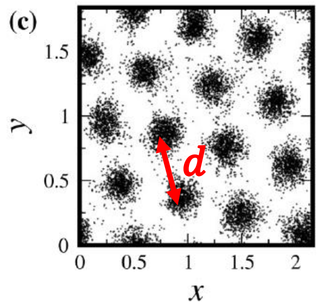
From single particle to cluster supersolids



Helium has a hard-core interaction potential.
There is space only for one particle.
Particles exchange relies only on kinetic energy.

Soft-core interaction potentials allow supersolids with more than one particle per site.



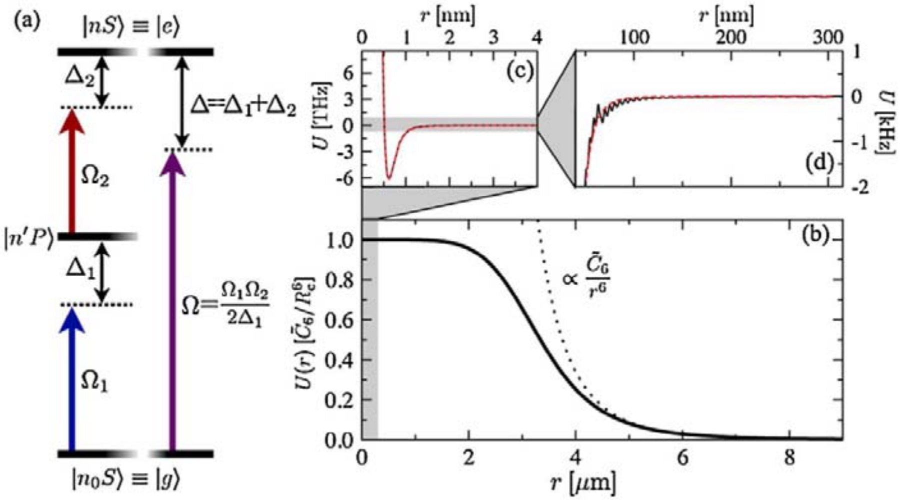


- finite energy cost for multiple occupation of a site
- repulsion between sites, lattice constant $d \approx R_c$
- phase transitions by tuning the interaction strength U

Y. Pomeau and S. Rica, dynamics of a model of a supersolid, Phys. Rev. Lett. 72, 2426 (1994)

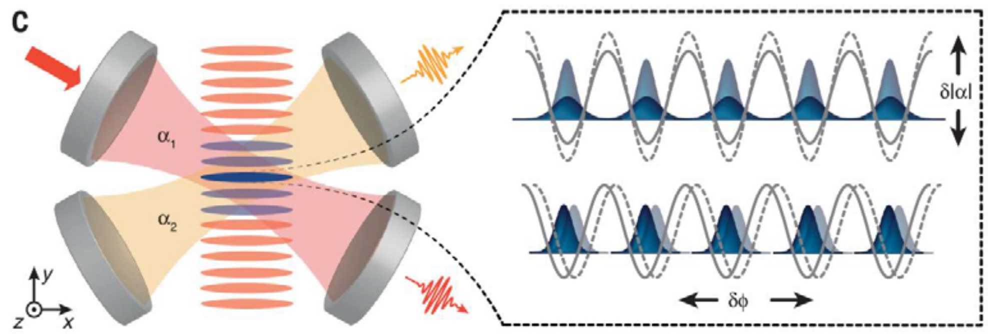
Searching cluster supersolids

Weak dressing of Rydberg levels in a Bose-Einstein condensate.



N. Helkel et al., 3D roton excitations and supersolid formation in Rydberg-excited Bose-Einstein condensates, Phys. Rev. Lett. 104, 195302 (2010).

Infinite range interactions for a BEC in optical cavities.



J. Léonard et al., Monitoring and manipulating Higgs and Goldstone modes in a supersolid quantum gas, Science 358, 1415 (2017).

Similarly for BECs with light-induced spin-orbit coupling.

J. R. Li et al., A stripe phase with supersolid properties in spin–orbit-coupled Bose–Einstein condensates, Nature 543 (2017)

Supersolid phase in Bose-Einstein condensates of magnetic atoms

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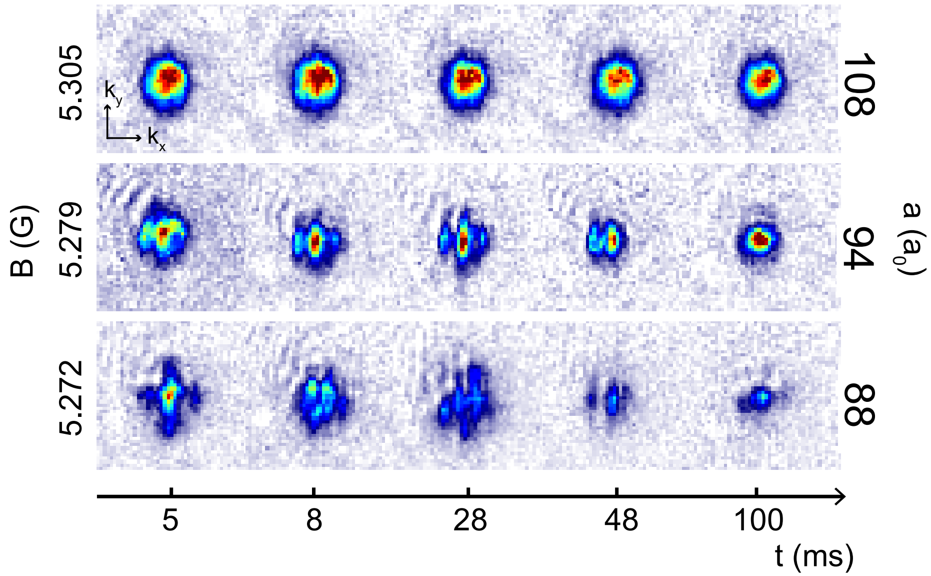
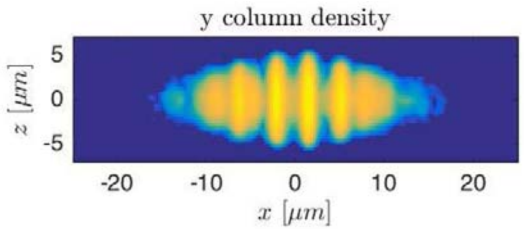
Observation of a Dipolar Quantum Gas with Metastable Supersolid Properties

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

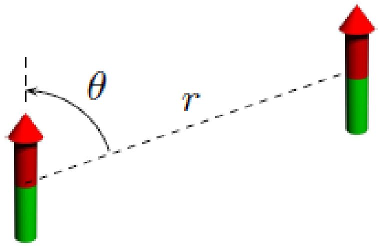
Physics See Viewpoint: Dipolar Quantum Gases go Supersolid





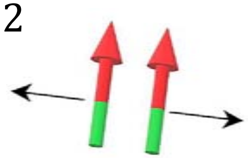
Interactions in dipolar BECs

Interaction between two polarized magnetic dipoles:



Attractive
$\theta = 0$

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



van der Waals   dipole-dipole

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

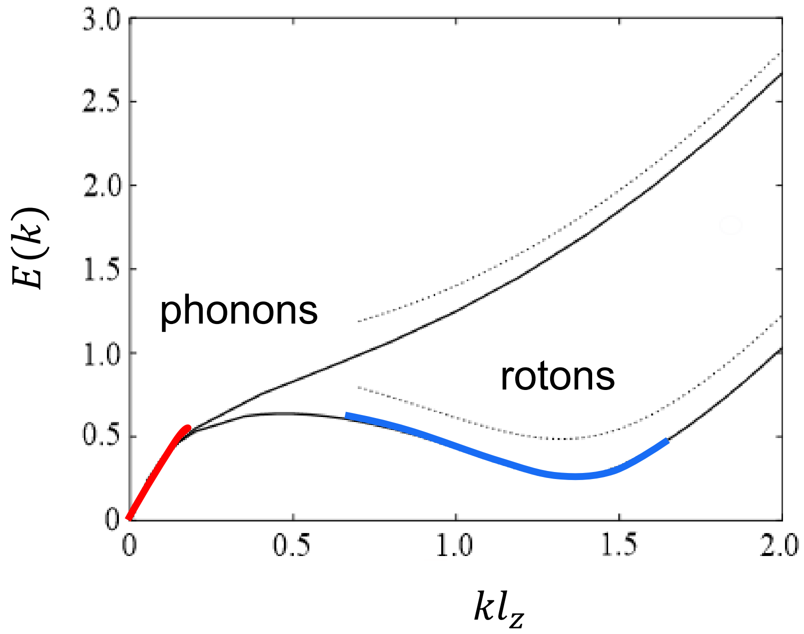
a_s contact scattering length

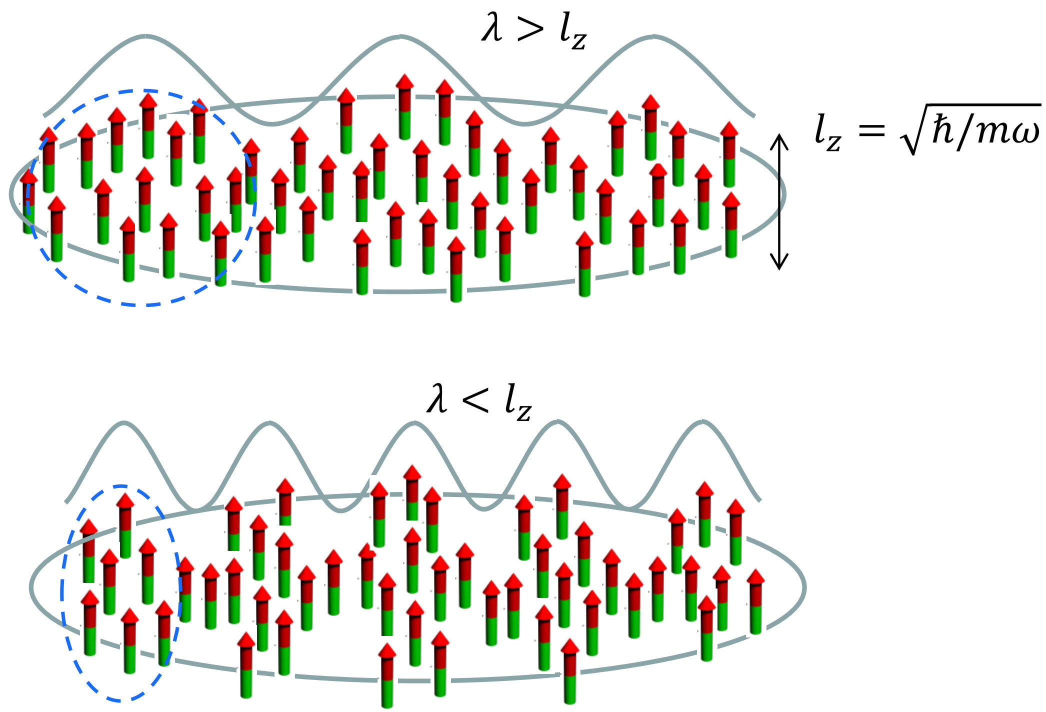
Tuneable (Feshbach resonance)

$a_{dd} = \frac{m\mu_0\mu^2}{12\,\pi\hbar^2}$ dipolar length

Fixed.

Excitation spectrum of dipolar BECs



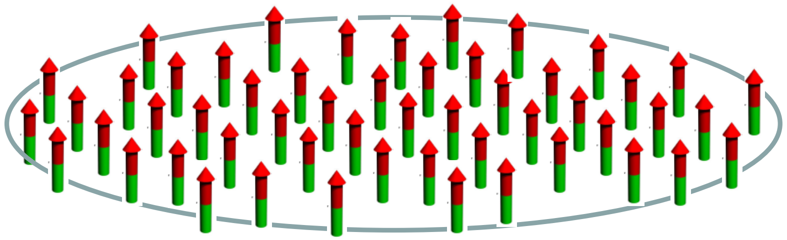


L. Santos, G. V. Shlyapnikov, and M. Lewenstein, Roton-Maxon spectrum and stability of trapped dipolar Bose-Einstein condensates, Phys. Rev. Lett. 90, 250403 (2003).

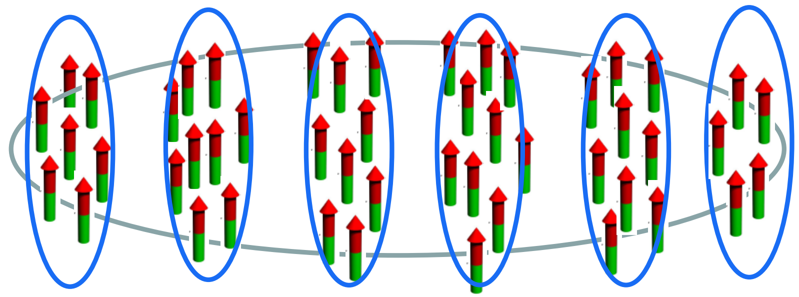
Phase diagram

dipolar int. / contact int.

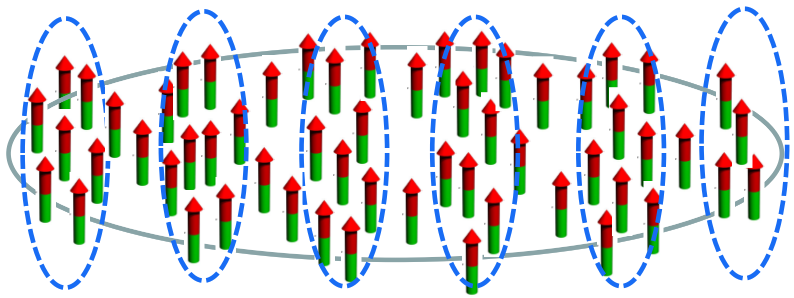
BEC: superfluid, follows hydrodynamic equations as an ideal liquid



Droplet crystal: normal solid of self-bound droplets (individually superfluid)

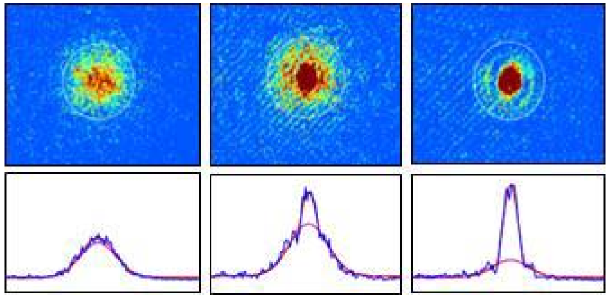


Supersolid?

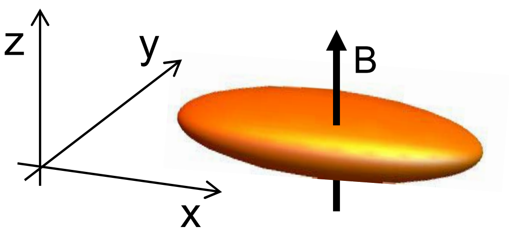


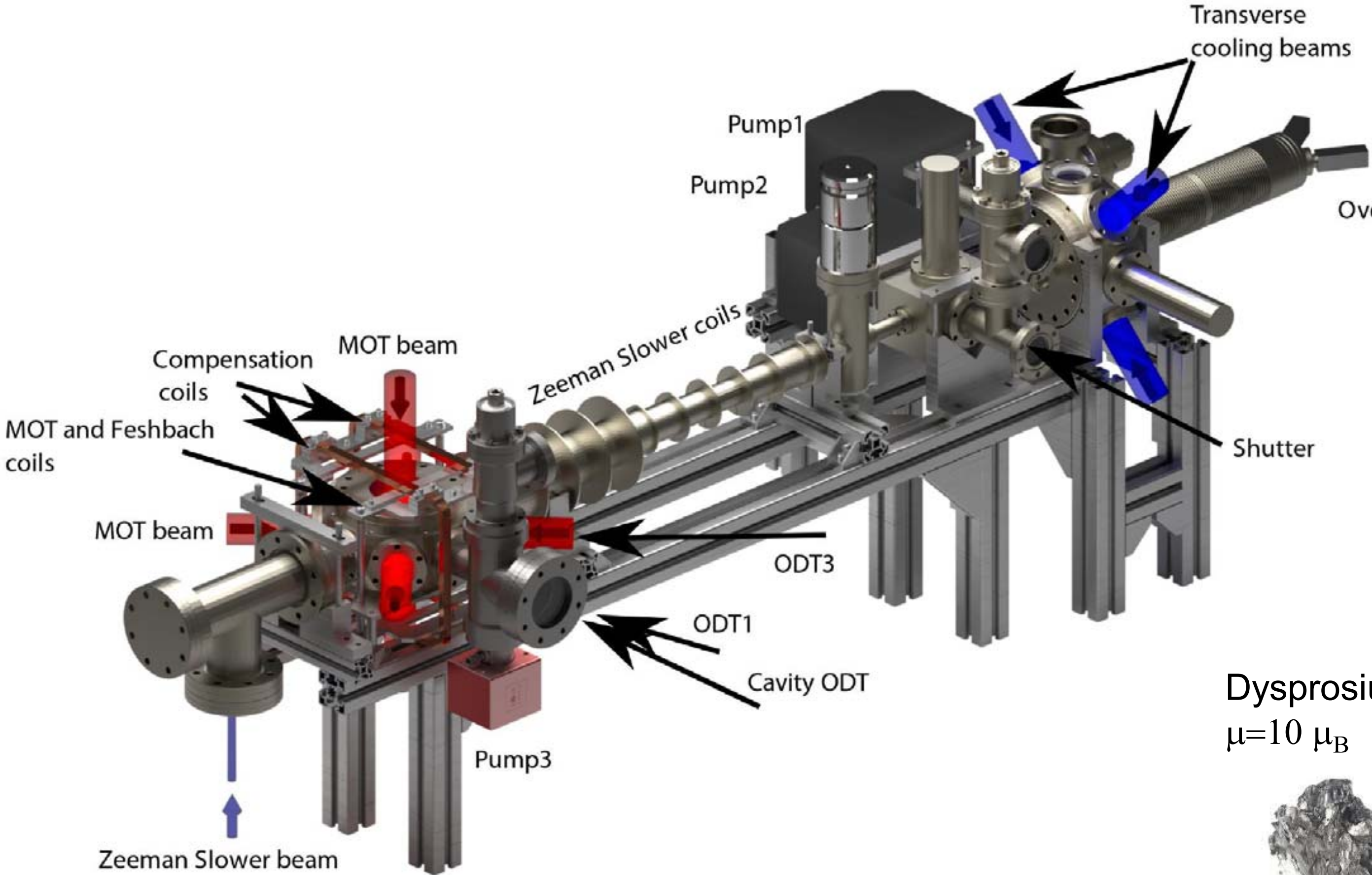
Experimental methods for dipolar BECs

Typical BECs: N= 5×10^4 , T<50 nK



Anisotropic optical trap





Dysprosium Lab CNR – INO, Pisa

Dysprosium:
$\mu=10\ \mu_B$

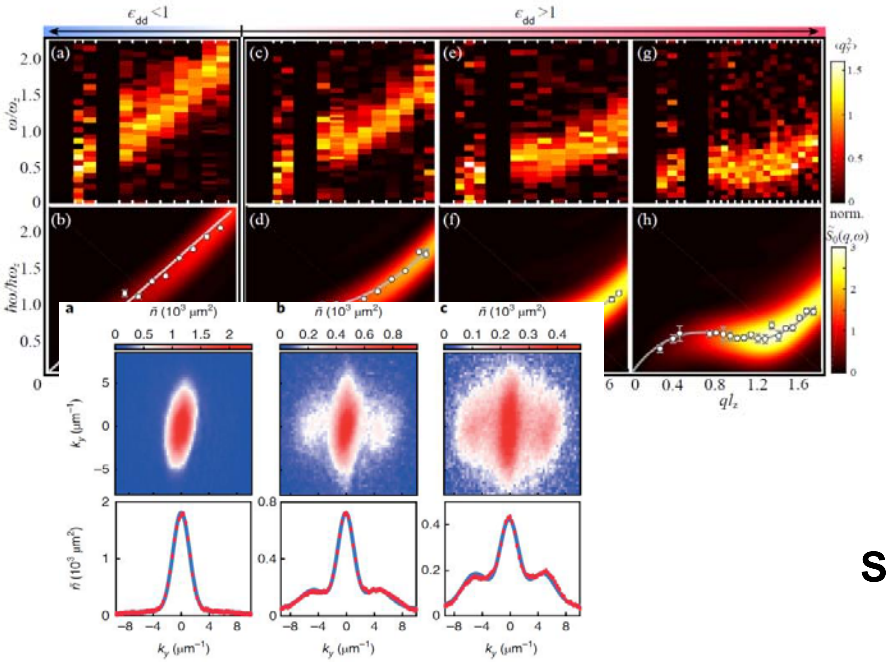
Melting point:
1680 K

Phase diagram

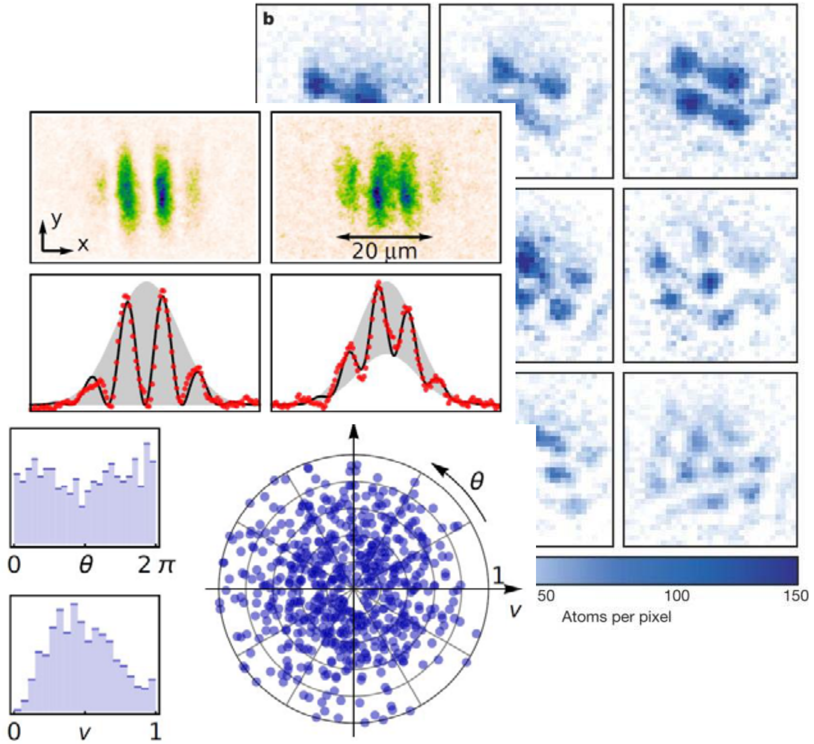
dipolar int. / contact int.

BEC (superfluid)

Droplet crystal (solid)



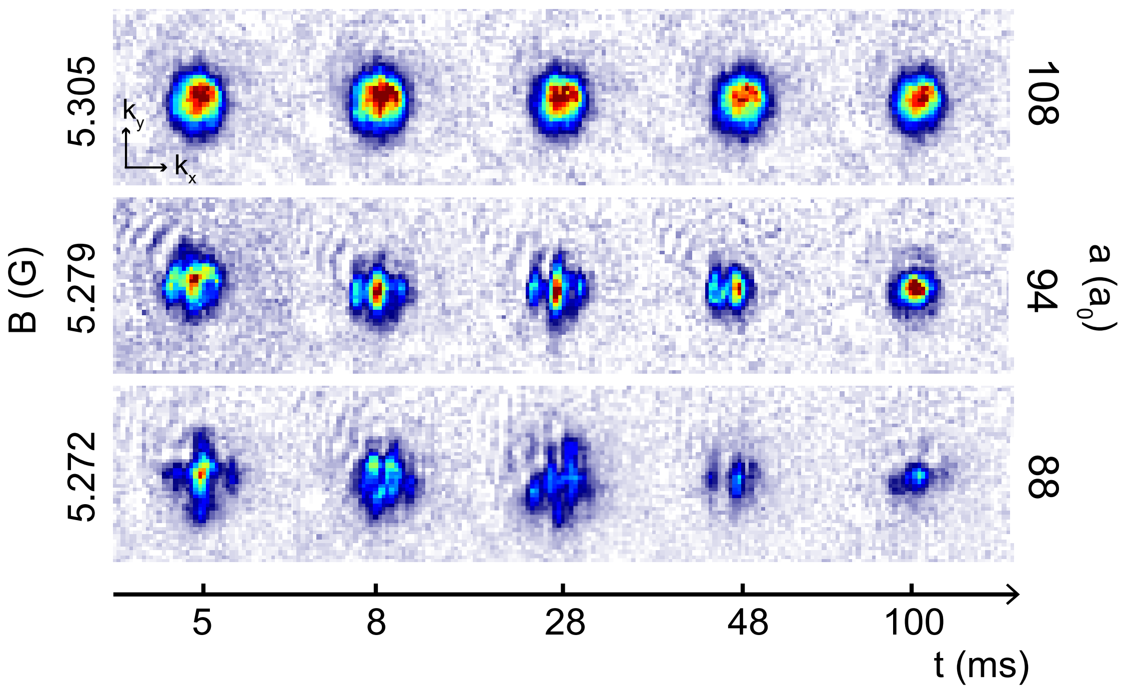
Supersolid?



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

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).

Observation of a coherent density-modulated regime

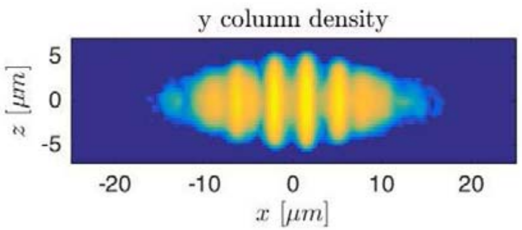


Stable BEC

Coherent regime
(supersolid)

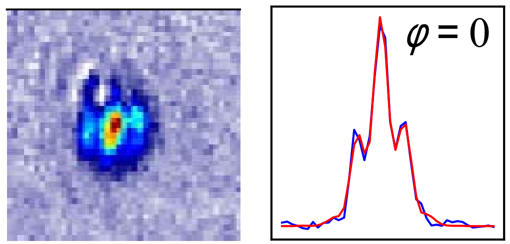
Incoherent regime
(droplet crystal)

Theory: spatial distribution



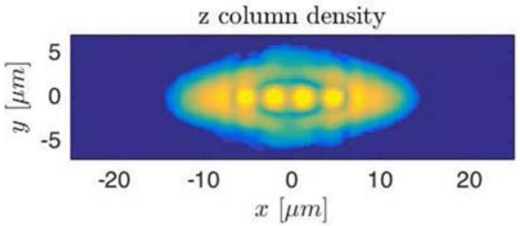
3-4 lattice sites,
10^4 atoms per site

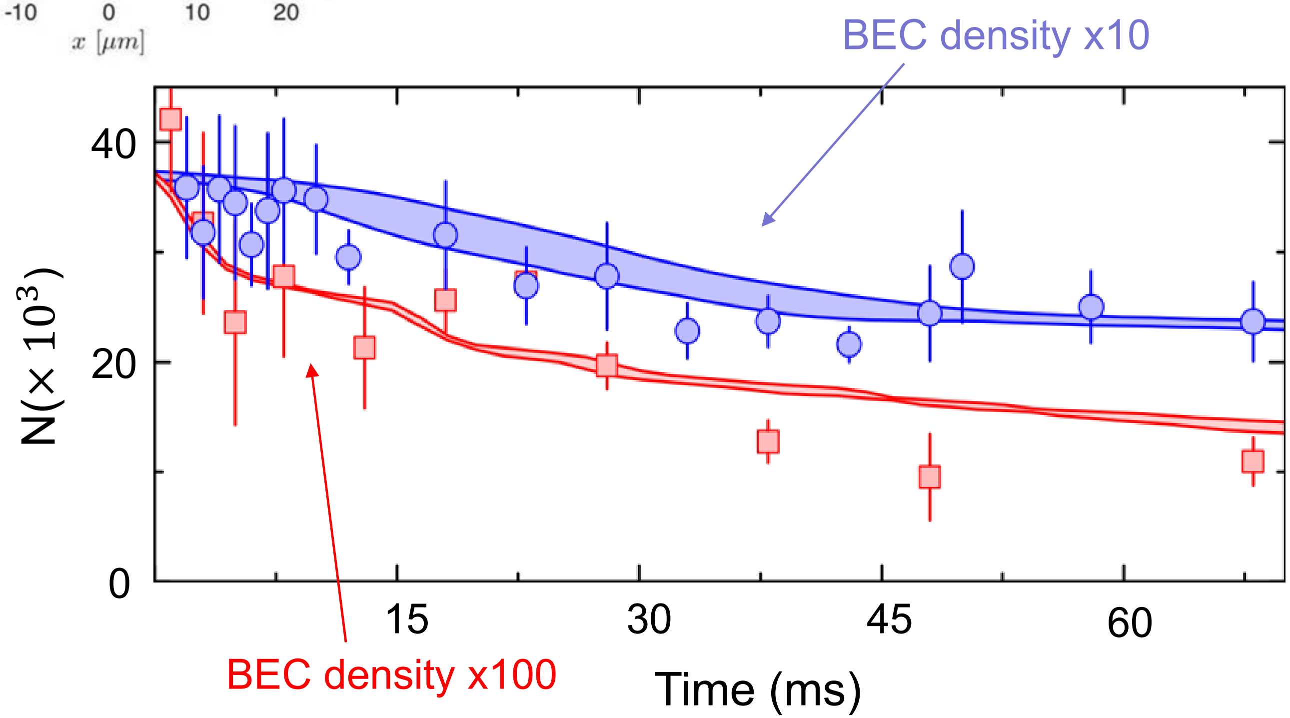
Experiment: momentum distribution
(double-slit interference)



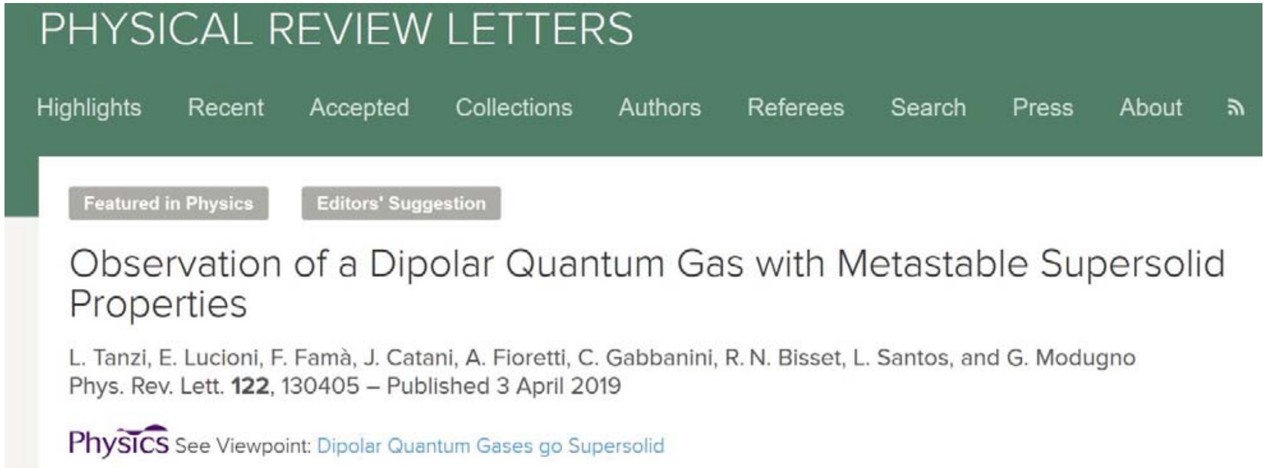
Finite lifetime

Atomic gases decay via formation of molecules.





Transient supersolid properties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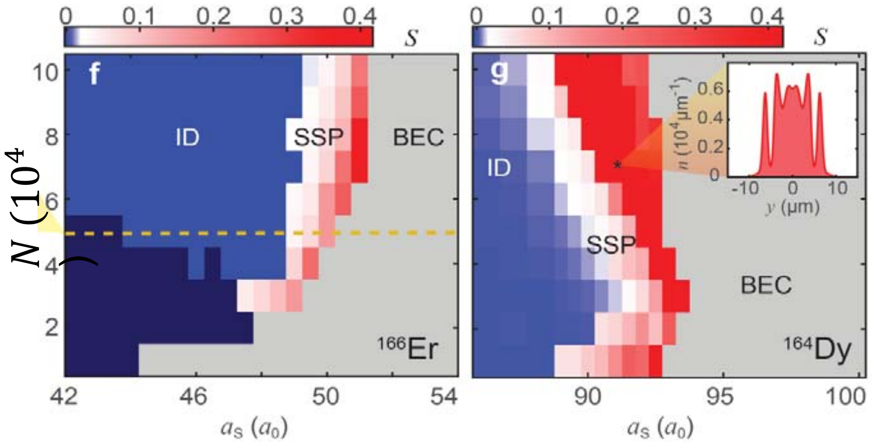
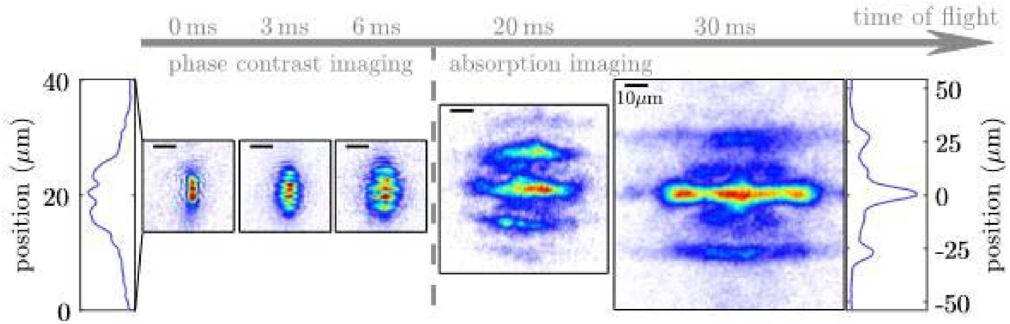


Innsbruck: L. Chomaz et al., Long-lived and transient supersolid behaviors in dipolar quantum gases, Phys. Rev. X 9, 021012 (2019).

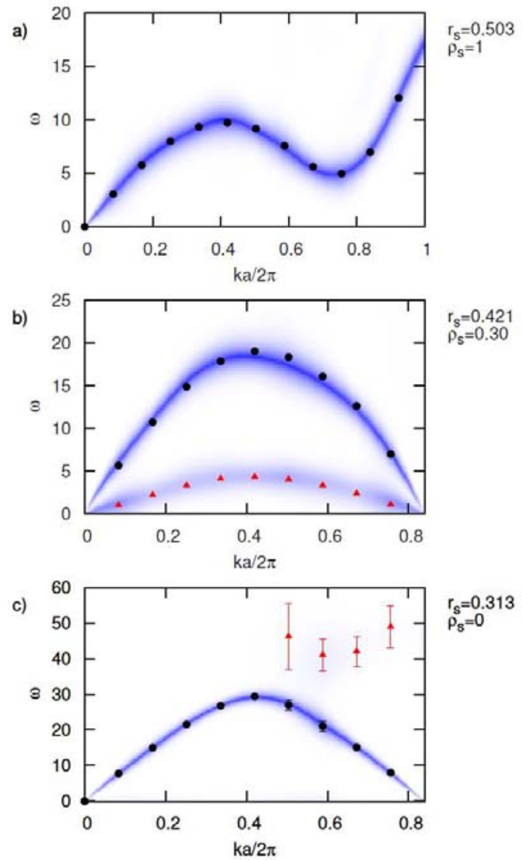


Stuttgart: F. Böttcher et al, Transient supersolid properties in an array of dipolar quantum droplets, Phys. Rev. X 9, 011051 (2019).

Spontaneous breaking of two symmetries

Symmetry breaking and Goldstone modes

Modern treatment of sound modes: a gapless Goldstone mode arises each time that an underlying continuous symmetry is spontaneously broken.



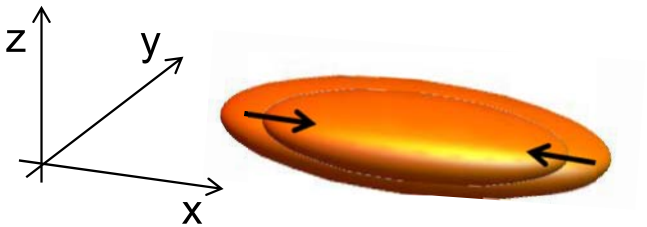
Superfluid: gauge symmetry (phase invariance)

Supersolid: gauge symmetry and translational symmetry

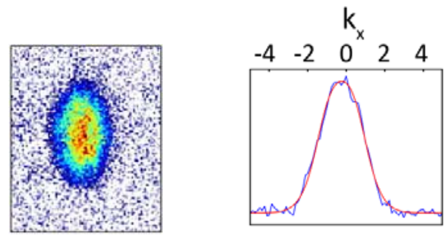
Solid: translational symmetry

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

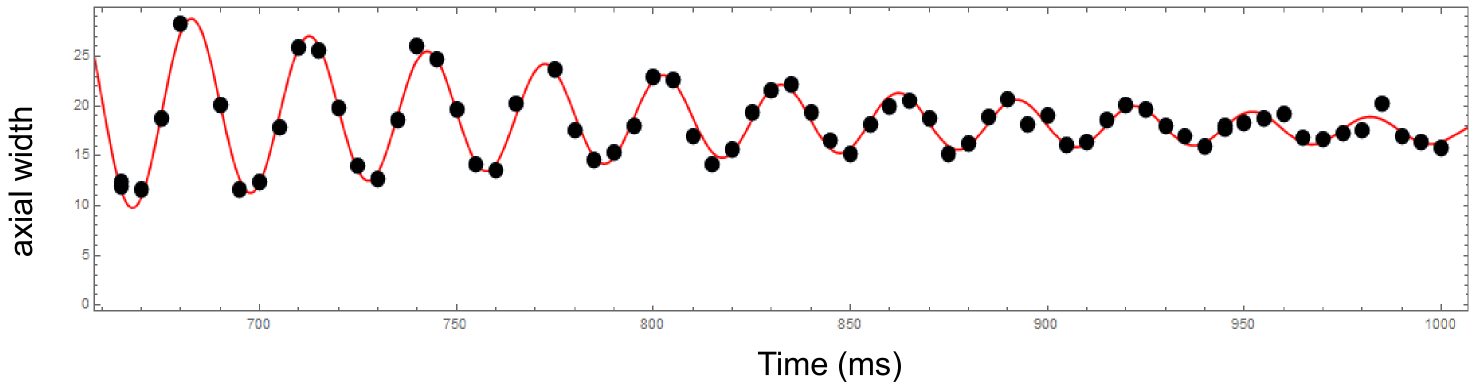
Superfluid regime



Quench of a_s through Feshbach resonances excites the axial breathing mode.



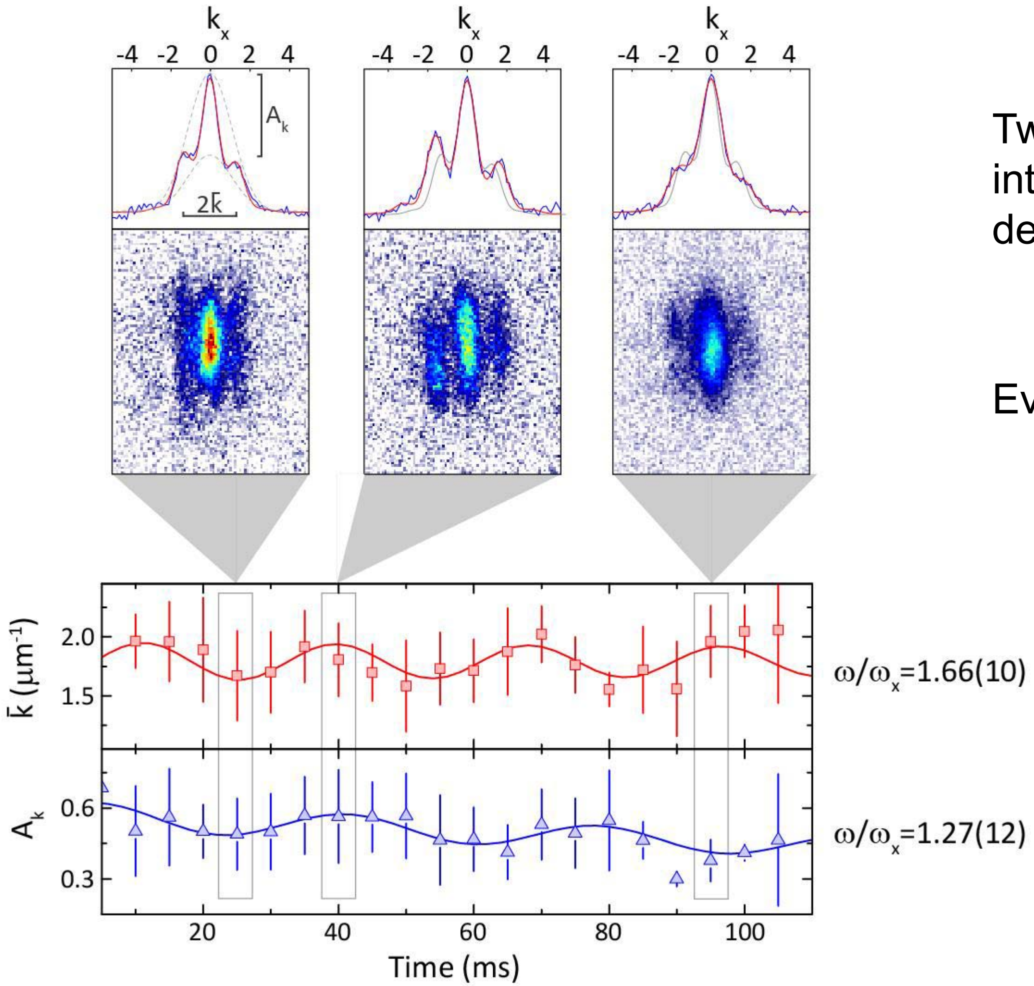
Observable: second moment along x



Frequencies can be measured with relatively high accuracy

$$\omega \sim \sqrt{5/2}\, \omega_x$$

Symmetry breaking in a supersolid



Two different frequencies for the interference period and interference depth.

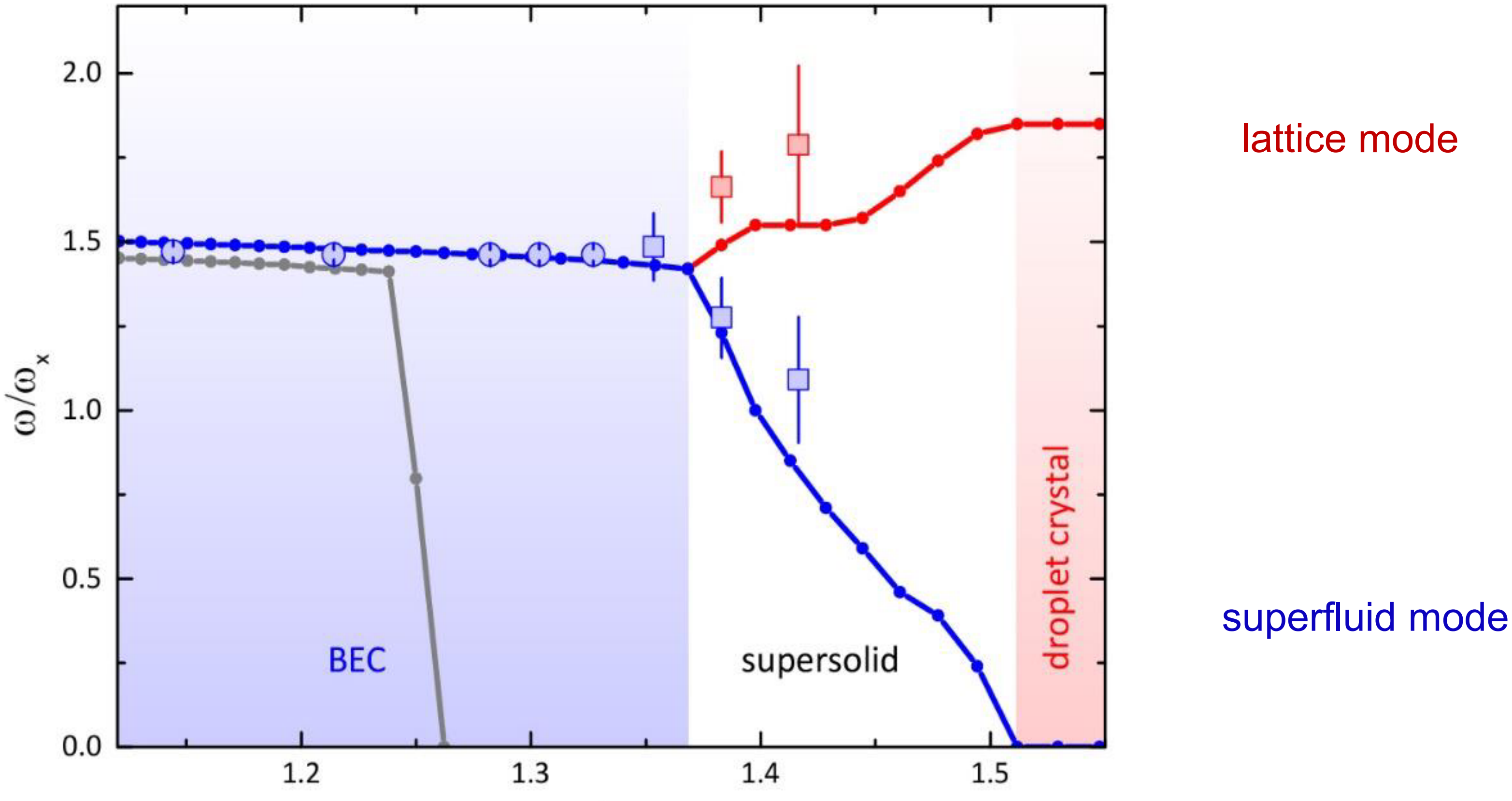
Evidence of the lattice compressibility!

lattice mode

superfluid mode

Symmetry breaking in a supersolid

Two quantum phase transitions tuning a single parameter!



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

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

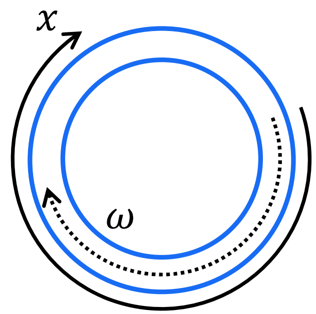
Superfluidity from non-classical rotational inertia

Rotation of supersolids

VOLUME 25, NUMBER 22 PHYSICAL REVIEW LETTERS 30 NOVEMBER 1970

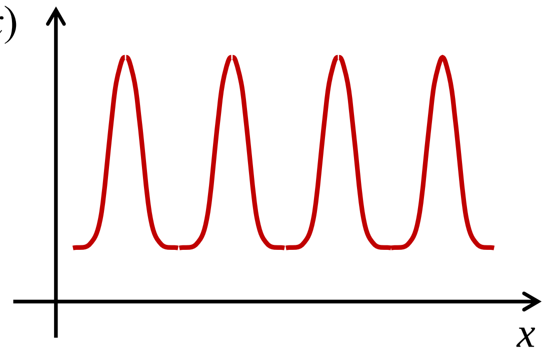
Can a Solid Be "Superfluid"?

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



Density modulation $\Rightarrow$ local phase variation,
kinetic energy contribution to the free energy:

$\frac{\hbar^2}{2m}\int (\nabla\varphi)^2 \rho(\vec{r}) d\vec{r}$ with $\varphi(x) = \int_0^x dx' / \bar{\rho}(x')$

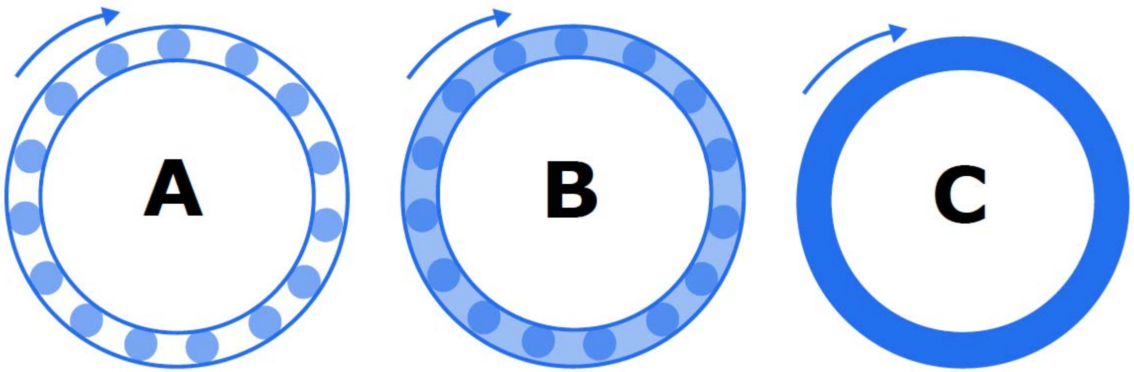


Reduced superfluid behavior under rotation: $I = (1 - f_s)\, I_c$

Superfluid fraction: $f_s \simeq \left(\int dx / \bar{\rho}(x) \right)^{-1}$

Rotation of supersolids

Intuitive explanation

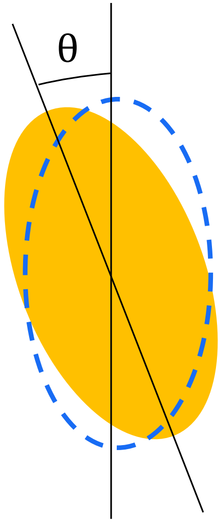


A: normal solid
B: supersolid
C: homogeneous superfluid

Caveat: Leggett’s approach is one-dimensional and does not consider the superfluidity of individual lattice sites …

Giulio Biagioni, Master Thesis, Università di Firenze (2020).

Rotations in an anisotropic trap: scissors mode



Trapped superfluids: small-angle rotational oscillation in the harmonic trap.

In nuclear physics: relative oscillation of neutrons and protons

Moment of inertia from oscillation frequency, similar to torsion oscillators:

$$I = I_c \alpha\, \beta\, \frac{(\omega_x^2 + \omega_y^2)}{\omega_{sc}^2}$$

Geometrical factors:

$$\alpha = (\omega_y^2 - \omega_x^2)/(\omega_x^2 + \omega_y^2)$$

$$\beta = \langle y^2 - x^2 \rangle / \langle y^2 + x^2 \rangle$$

VOLUME 83, NUMBER 22 PHYSICAL REVIEW LETTERS 29 NOVEMBER 1999

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

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(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.

VOLUME 84, NUMBER 10 PHYSICAL REVIEW LETTERS 6 MARCH 2000

Observation of the Scissors Mode and Evidence for Superfluidity of a Trapped Bose-Einstein Condensed Gas

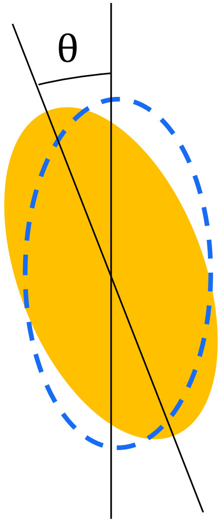
O. M. Maragò, S. A. Hopkins, J. Arlt, E. Hodby, G. Hechenblaikner, and C. J. Foot

Clarendon Laboratory, Department of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom

(Received 18 October 1999)

We report the observation of the scissors mode of a Bose-Einstein condensed gas of ^{87}Rb atoms in a magnetic trap, which gives direct evidence of superfluidity in this system. The scissors mode of oscillation is excited by a sudden rotation of the anisotropic trapping potential. For a gas above T_c (normal fluid) we detect the occurrence of oscillations at two frequencies, with the lower frequency corresponding to the rigid body value of the moment of inertia. Well below T_c the condensate oscillates at a single frequency, without damping, as expected for a superfluid.

Rotations in an anisotropic trap: scissors mode



Trapped superfluids : small-angle rotational oscillation in the harmonic trap.

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Geometrical factors:

$$\alpha = (\omega_y^2 - \omega_x^2)/(\omega_x^2 + \omega_y^2)$$

$$\beta = \langle y^2 - x^2 \rangle / \langle y^2 + x^2 \rangle$$

For a supersolid:

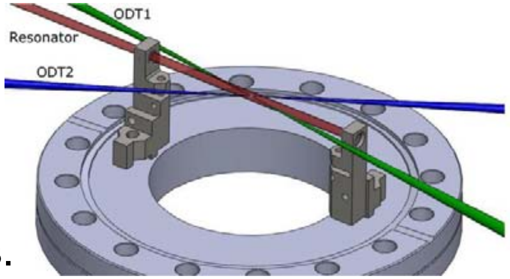
- Same results for the moment of inertia
- Modified definition of the superfluid fraction, due to the deviation from cylindrical symmetry:

$$I = (1 - f_s) I_c + f_s \, \beta^2 I_c$$

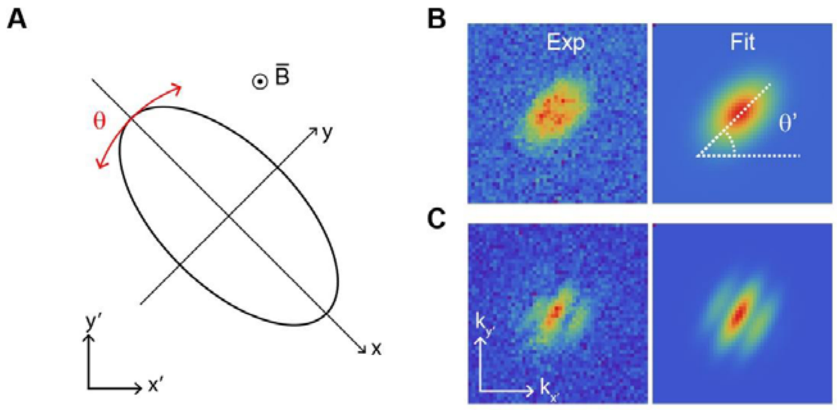
A.L. Fetter, Vortex nucleation in deformed rotating cylinders. J. Low Temp. Phys. 16, 533 (1974).

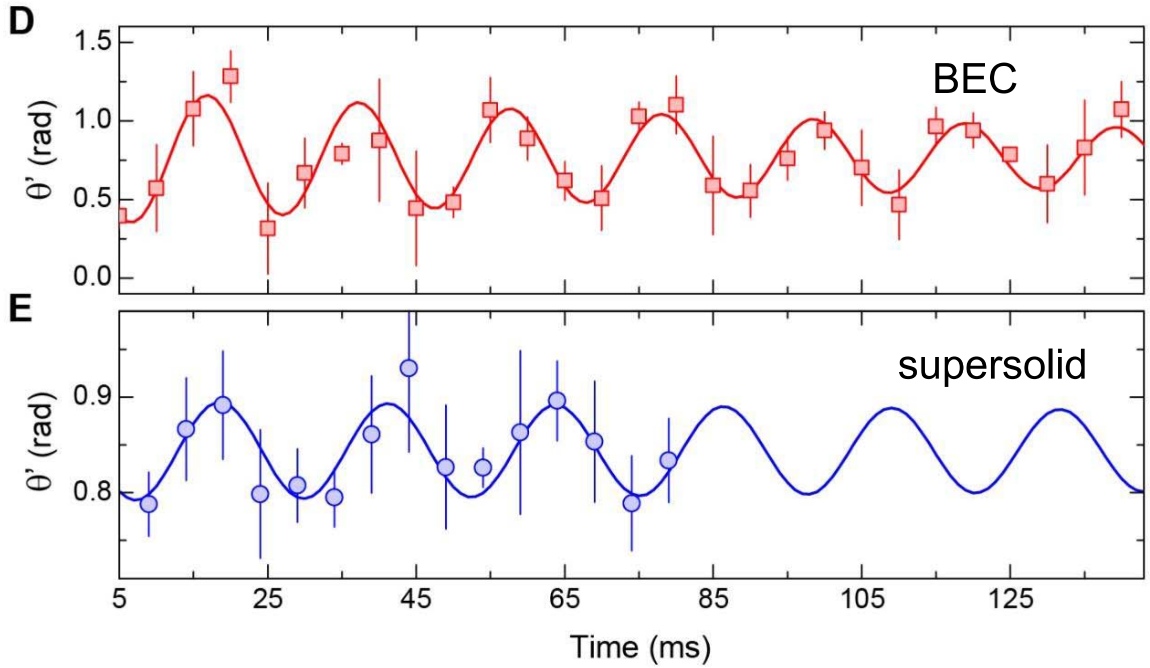
Experimental techniques

The scissors mode is excited by a quench of the strength of the optical traps.

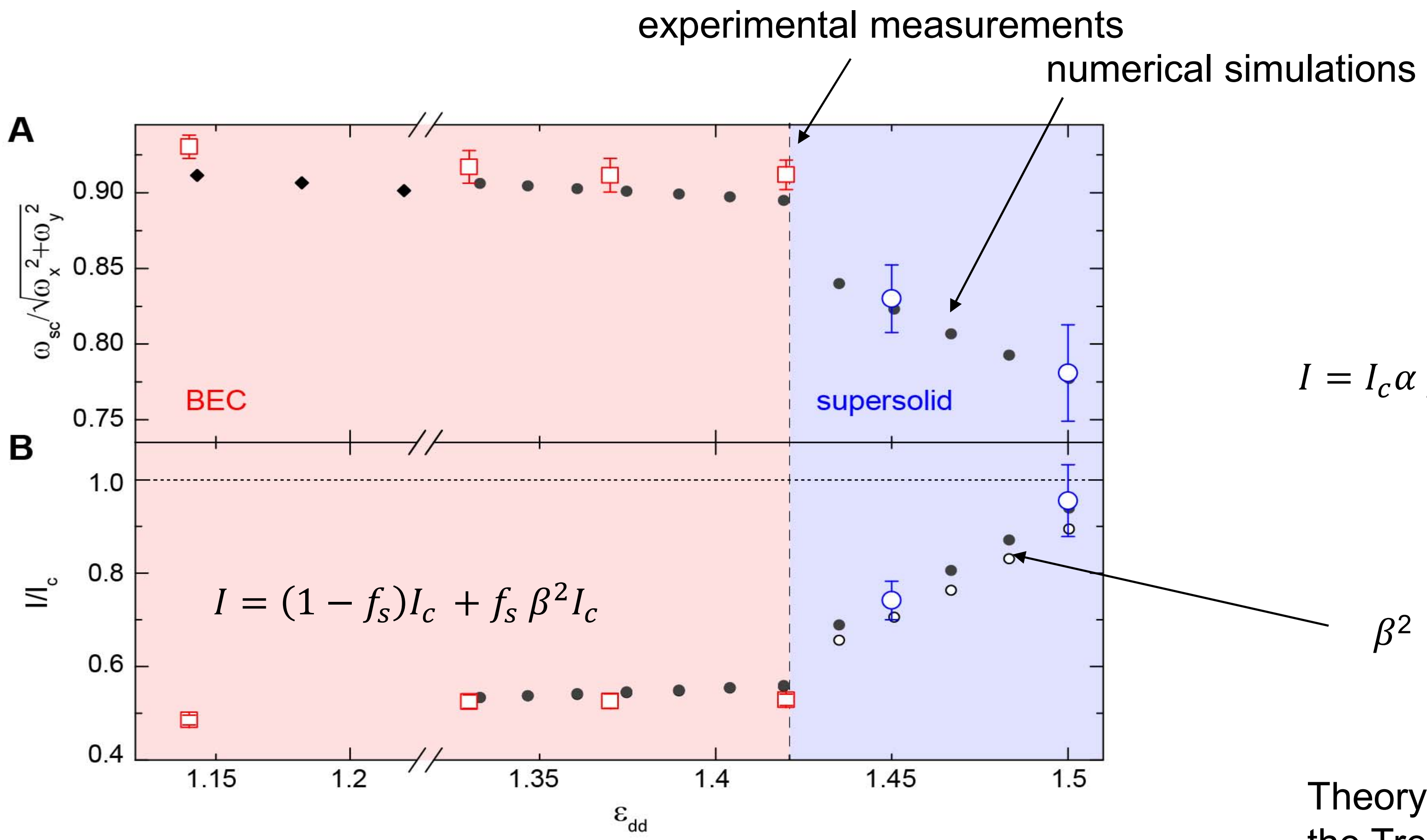


Single mode oscillation in both BEC and supersolid regimes, with different frequencies





Scissors frequency and moment of inertia

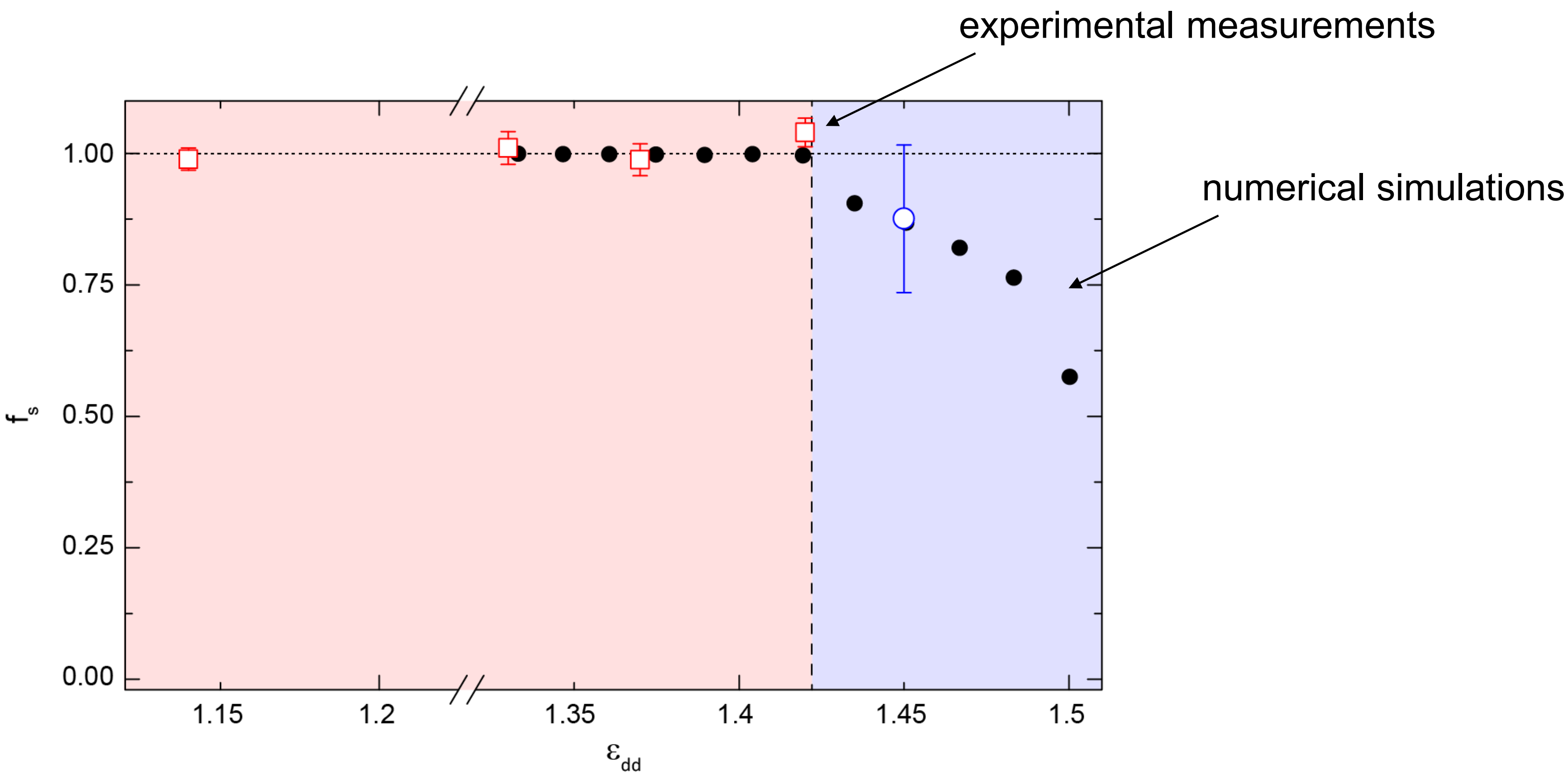


$$I = I_c \alpha\, \beta\, \frac{(\omega_x^2 + \omega_y^2)}{\omega_{sc}^2}$$

Theory, including β, by the Trento group.

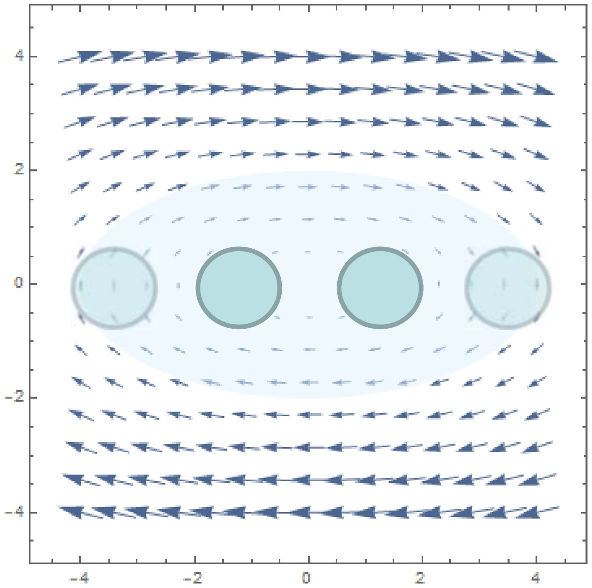
L. Tanzi et al. Evidence of superfluidity in a dipolar supersolid from non-classical rotational inertia, arXiv:1912.01910, submitted to Science.
S. Roccuzzo, A Gallemi, S. Stringari, A. Recati, Rotating a supersolid dipolar gas, Phys. Rev. Lett. 124, 045702 (2020).

Superfluid fraction



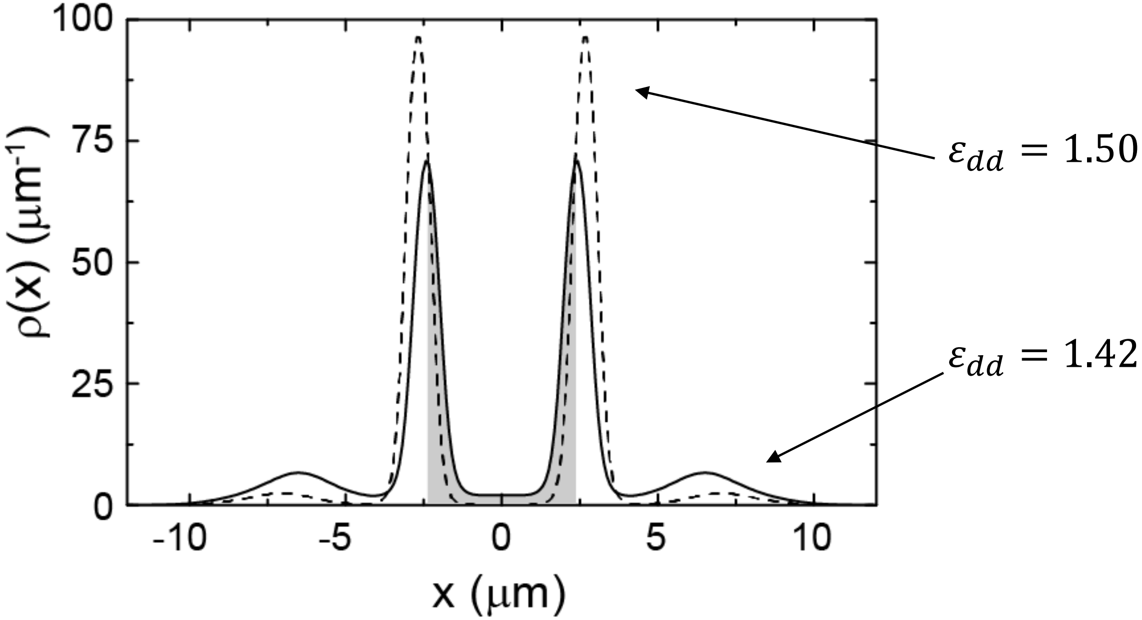
Superfluid fraction: $I = (1 - f_s) I_c + f_s\, \beta^2 I_c \quad \Rightarrow \quad f_s = \frac{1 - \alpha\beta\,(\omega_x^2 + \omega_y^2)/\omega_{sc}^2}{1 - \beta^2}$

Superfluid fraction: Leggett mechanism

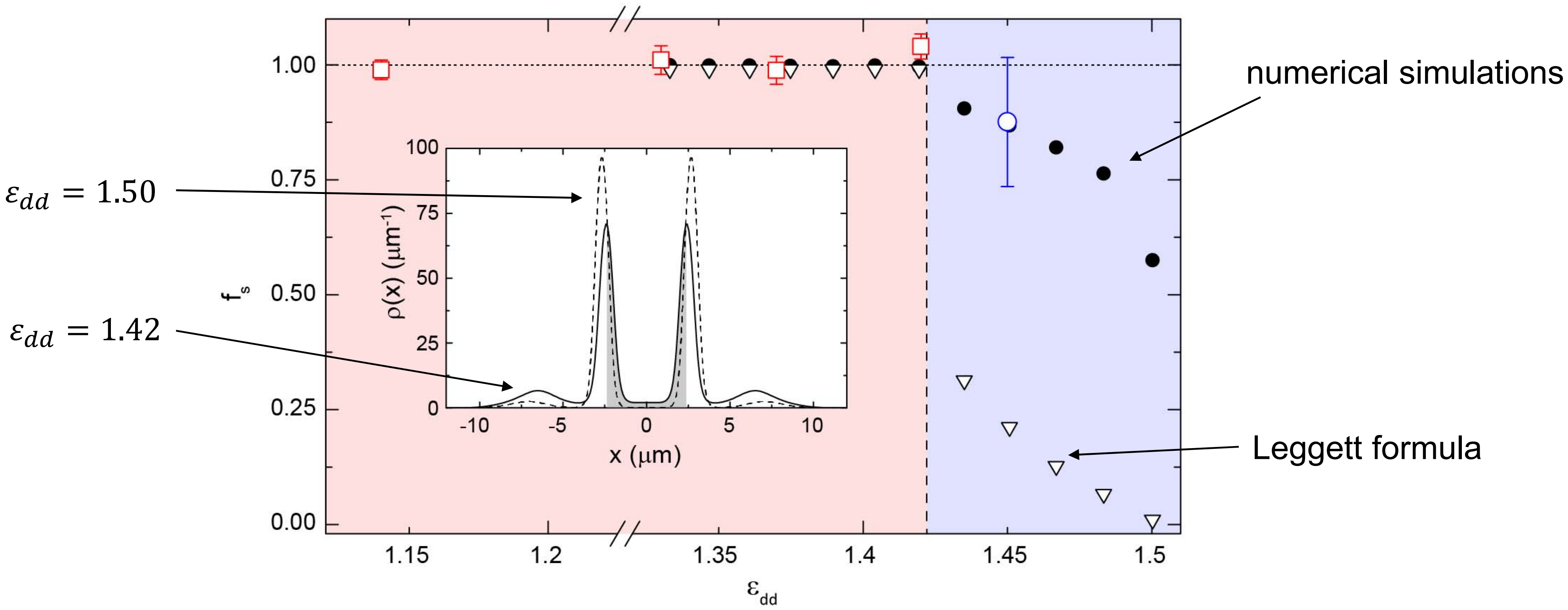


Scissors velocity field
(rotating frame)

Leggett formula: $f_s \leq \left(\int dx / \bar{\rho}(x) \right)^{-1}$



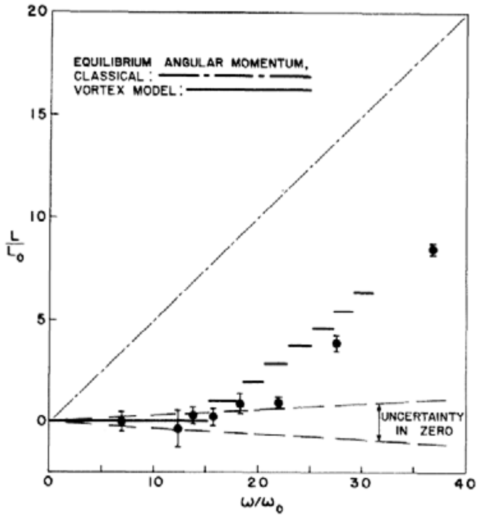
Superfluid fraction: Leggett mechanism



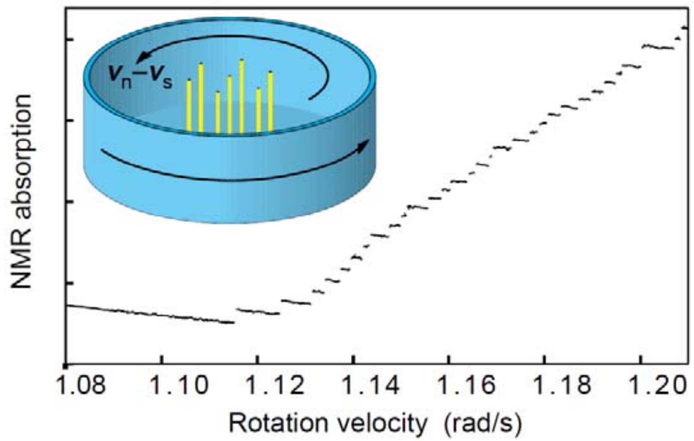
Qualitative agreement with Leggett's 1D prediction: large overlap of neigbouring droplets.
For helium there was a disagreement by 2-3 orders of magnitude.
Disagreement justified by superfluidity of droplets …

Rotation of superfluids

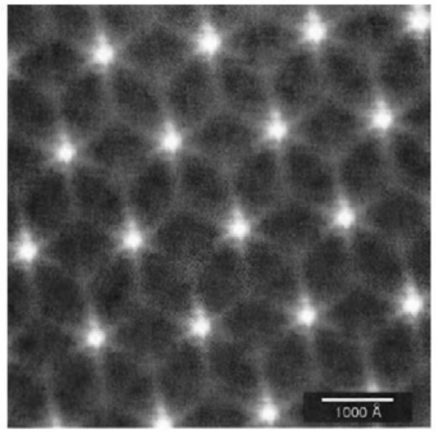
Helium-4 (1967)



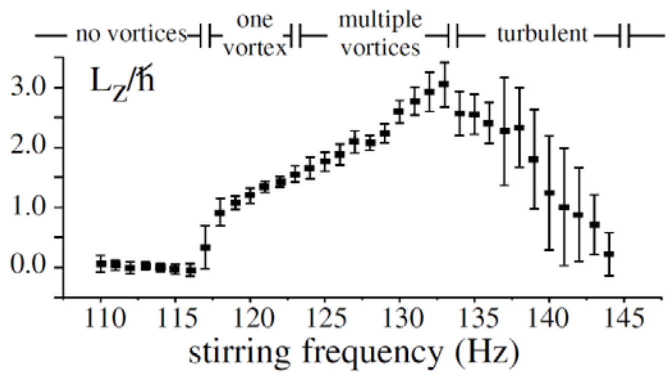
Helium-3 (1982)



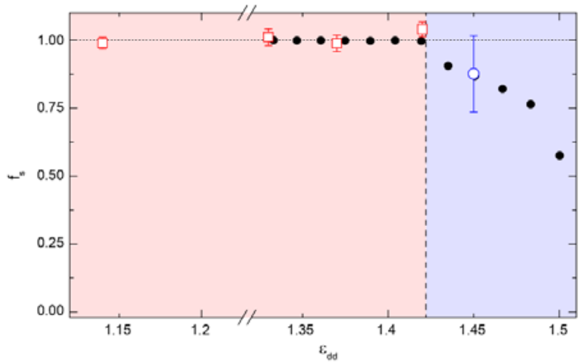
related Meissner effect in superconductors



BECs (2000)



Dipolar supersolid (2020)



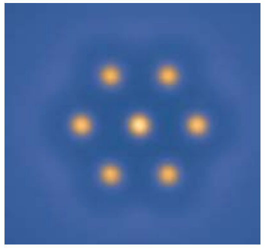
Conclusions and outlook

A quantum gas allows studying a fundamental phase of matter intermediate between a liquid (superfluid) and a solid.

Our minimal supersolid is fully controllable and allows testing fundamental properties developed conceptually more than 50 years ago, using methods from various fields of physics.

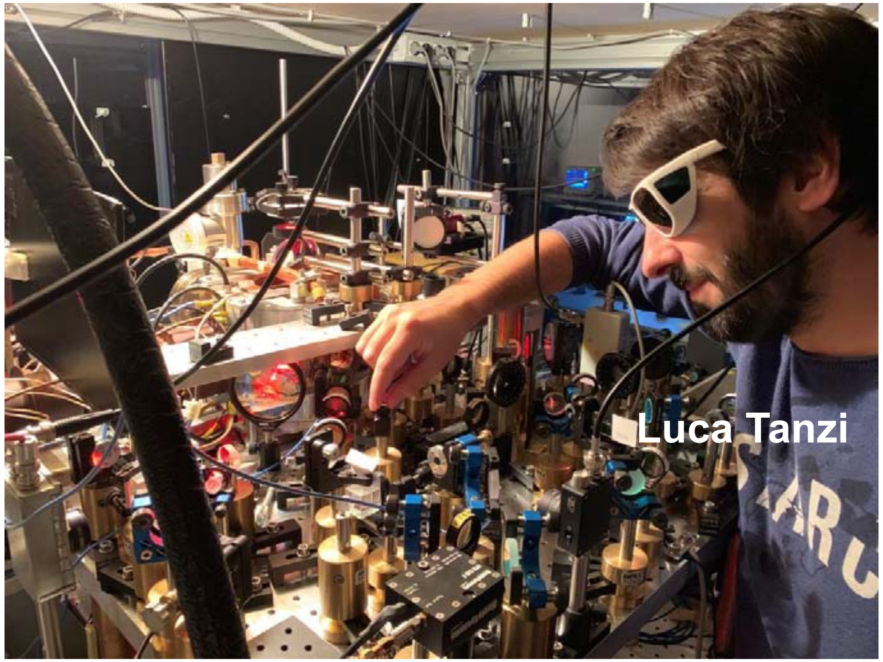
An unknown quantum material. An extreme form of quantum simulations: testing the properties of future materials…

<u>Future goals</u>:



- Realize larger, 2D supersolids
- Measure a sub-unity superfluid fraction.
- Study the formation of vortices (angular momentum per particle $L = \hbar f_s$).
- Characterize the solid properties of the supersolid (rigidity, plasticity).
- Can a supersolid pass through a capillar without friction?
- Josephson effect without a barrier, …
- Supersolids in fermionic matter? (pair-density waves in superconductors)

The team – CNR-INO, sede di Pisa and LENS, Università di Firenze



Former members: Francesca Famà, Julian Maloberti, Eleonora Lucioni, Jacopo Catani

Theory by: Russell Bisset, Luis Santos (Hannover); Alessio Recati, Sandro Stringari (Trento); Michele Modugno (Bilbao); Luca Pezzè, Augusto Smerzi (Firenze); Maria Luisa Chiofalo (Pisa), Adriano Angelone (Trieste) …

http://quantumgases.lens.unifi.it/exp/dy

INO-CNR
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