Evidence of superfluidity in a supersolid under rotation

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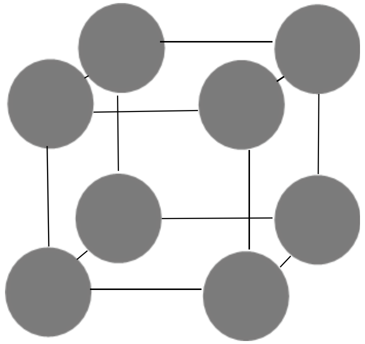
Supersolid state of matter

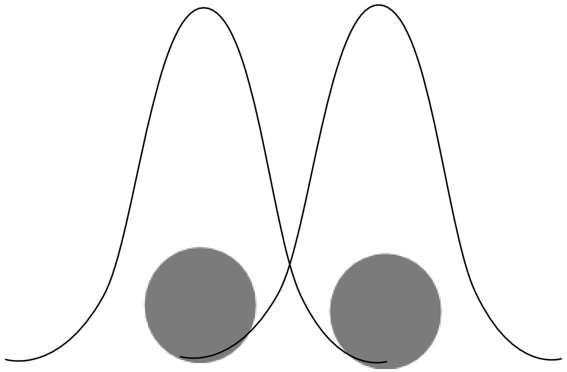
- Classical solid



Crystalline order

Macroscopic consequence: rigidity of the crystal

- Superfluid



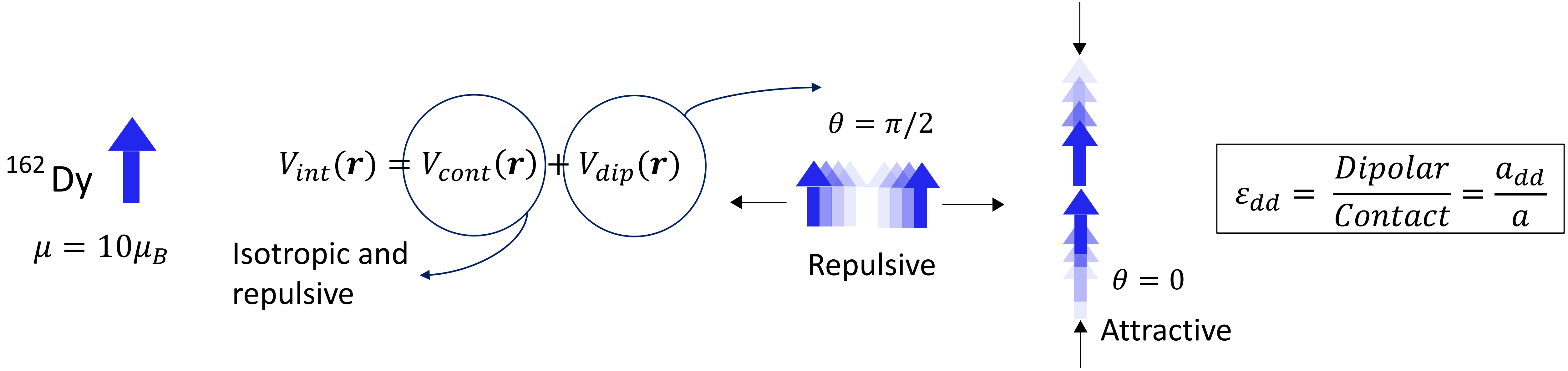
Coherent wave function

Macroscopic consequences: metastibility of supercurrents, reduced moment of inertia

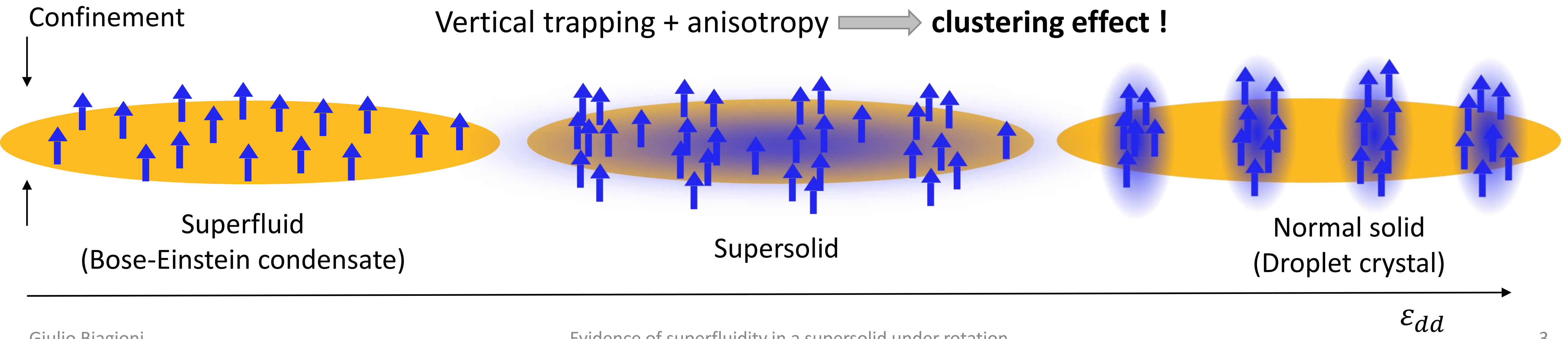
- Supersolid

Both kinds of order
Macroscopic consequences: ?

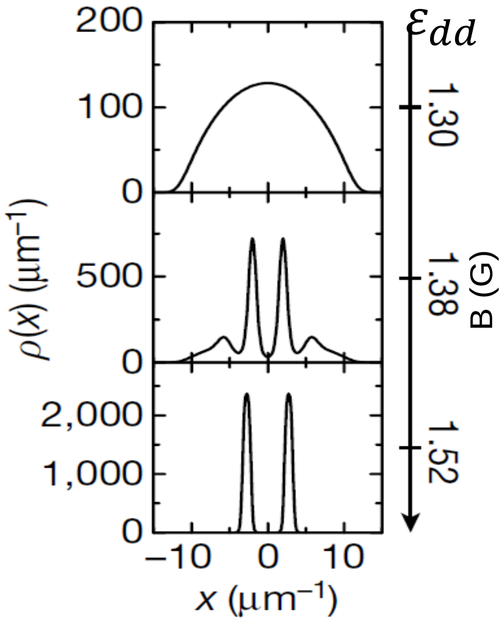
Our dipolar supersolid

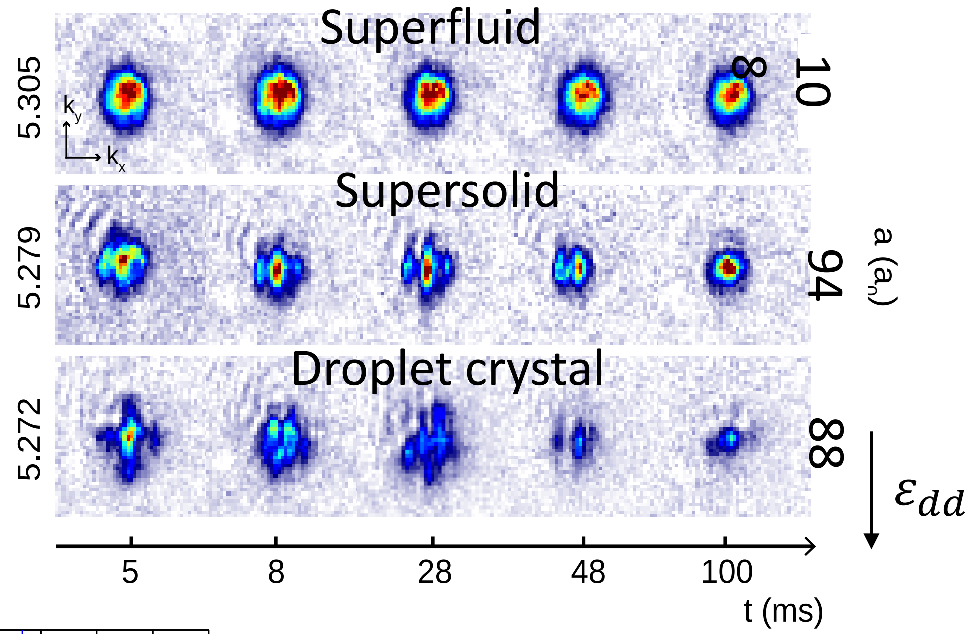


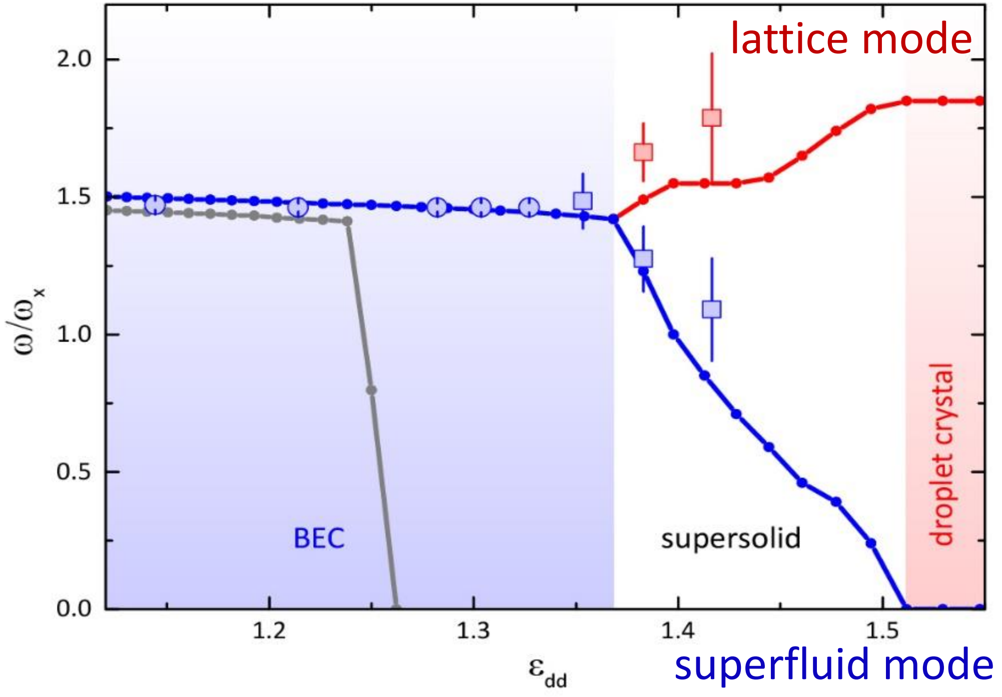
Vertical trapping + anisotropy ⇒ **clustering effect !**

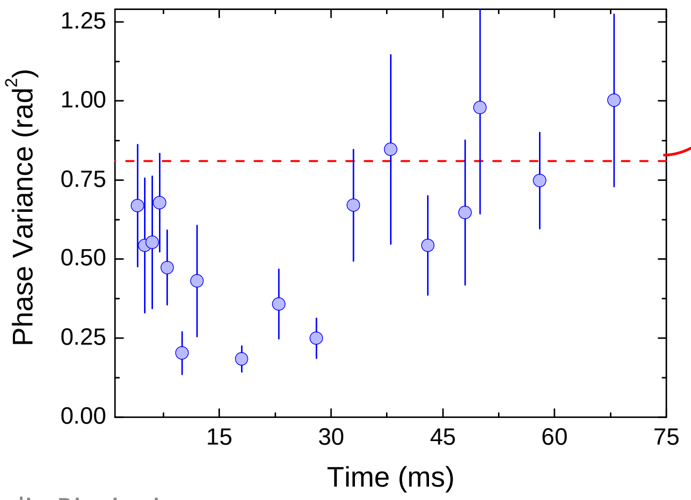


Our dipolar supersolid









Variance of uniform random phase

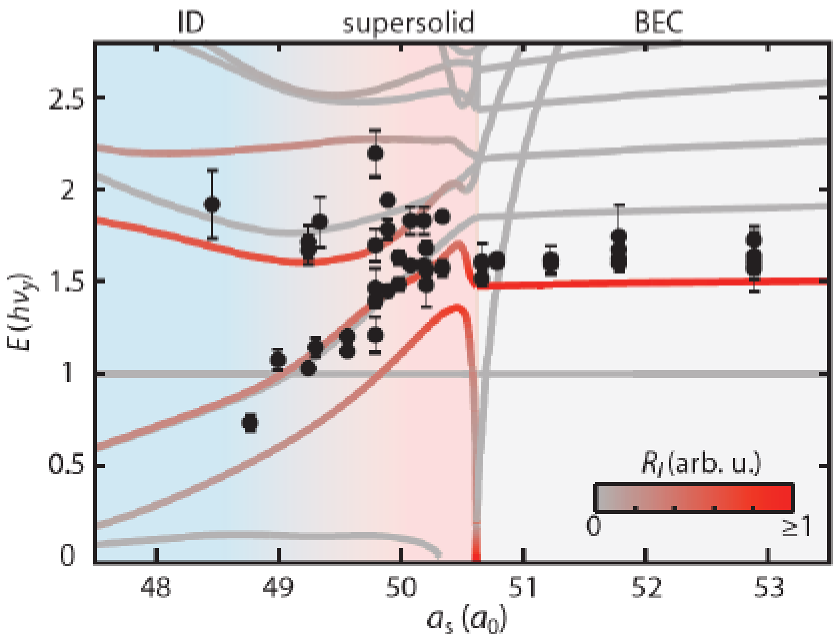
L. Tanzi et al., Phys. Rev. Lett., 122, 130405 (2019)

Evidence for double symmetry breaking

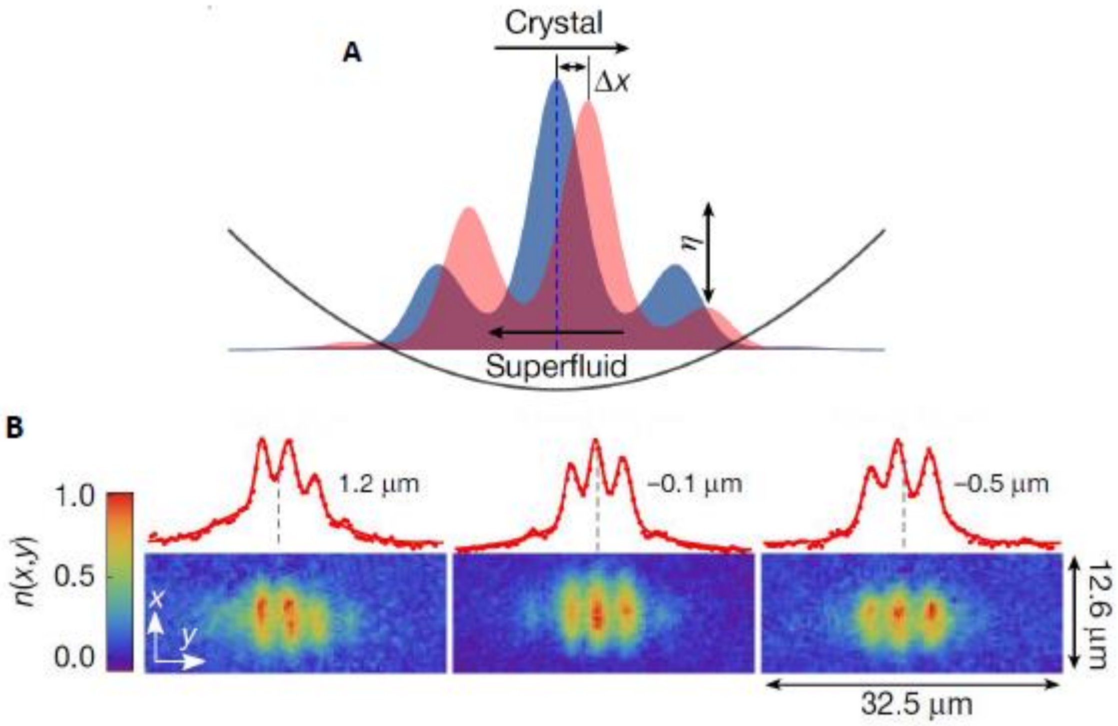
L. Tanzi et al., Nature, 574, 774 (2020)

Cluster supersolid with $\sim 3-4$ droplets and $\sim 10^4$ atoms per droplet

Related works



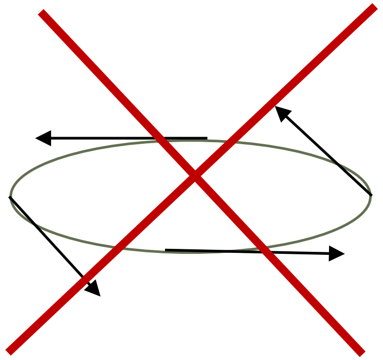
G. Natale et al., Phys. Rev. Lett. 123, 050402 (2019)
Innsbruck



M. Guo et al., Nature 574, 386 (2019)
Stuttgart

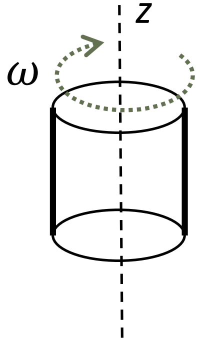
Superfluids under rotation

- Macroscopic wavefunction $\Psi_0(r) = |\Psi_0(r)|e^{i\varphi(r)}$
- $\vec{v} = \frac{\hbar}{m}\nabla\varphi \Rightarrow \nabla \wedge \vec{v}=0 \Rightarrow \oint \vec{v} \cdot d\vec{l} = 0 \Rightarrow$ classical irrotational hydrodynamics



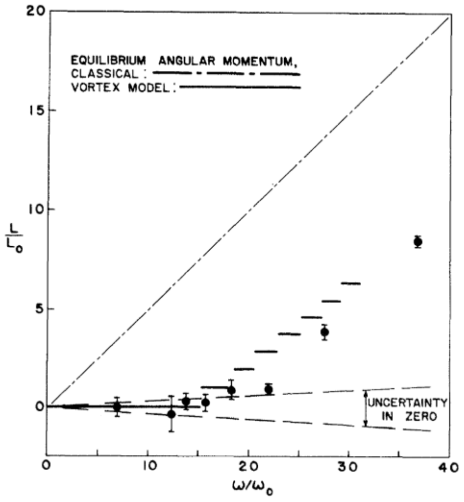
$\vec{v} = \omega R\hat{\theta}$

- Reduced moment of inertia $\Rightarrow I = (1 - f_s)I_c$ (in a cylindrical geometry)
- Normally, $f_s \to 1$ for $T \to 0 \Rightarrow I = 0$
- No angular momentum is acquired from the container when $\omega \to 0$



$< L >= I\omega$

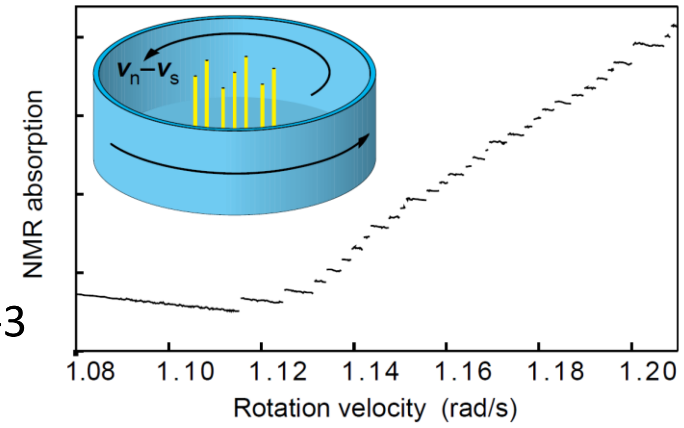
Superfluids under rotation

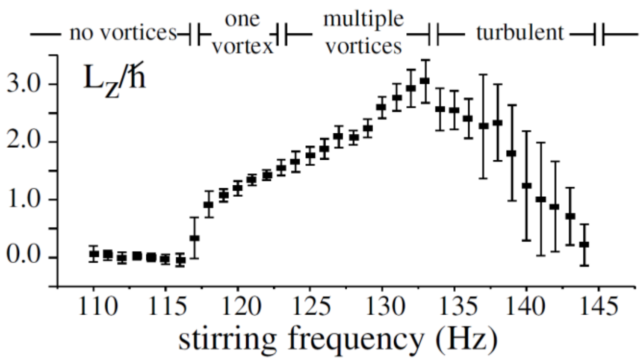


Helium-4 (1967)

Hess-Fairbank

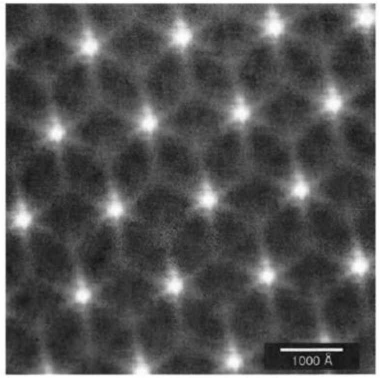
Helium-3 (1982)





BECs (2000)

related Meissner effect in superconductors



Leggett's argument: can a solid be superfluid?

Also supersolids are described by a macroscopic wavefunction $\Psi_0(r) = |\Psi_0(r)| e^{i\varphi(r)}$

The density modulation appears in the form of the superfluid fraction:

$I = (1 - f_s) I_c$ with $f_s \leq \left(\int dx / \bar{\rho}(x) \right)^{-1}$

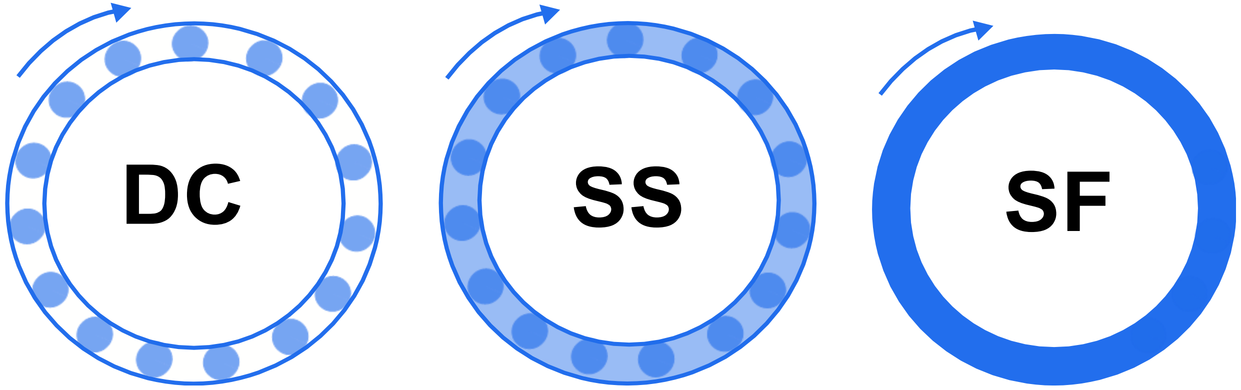
so that $0 < I < I_c$ at $T = 0$

NCRI (Non Classical Rotational Inertia)

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)

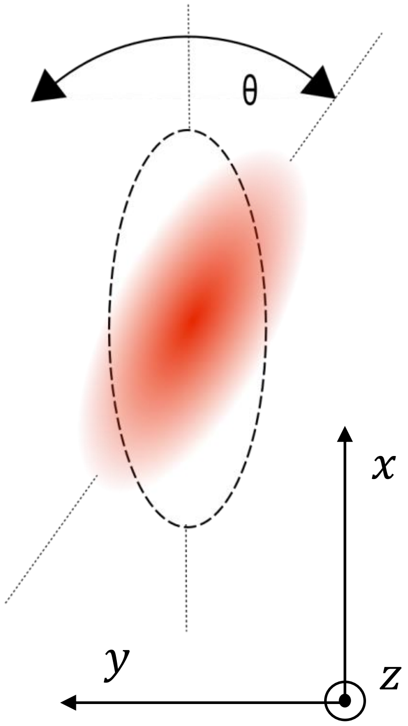


$I = I_c$ $0 < I < I_c$ $I = 0$

The scissors mode

How to probe the moment of inertia of our small and non-homogenous system?

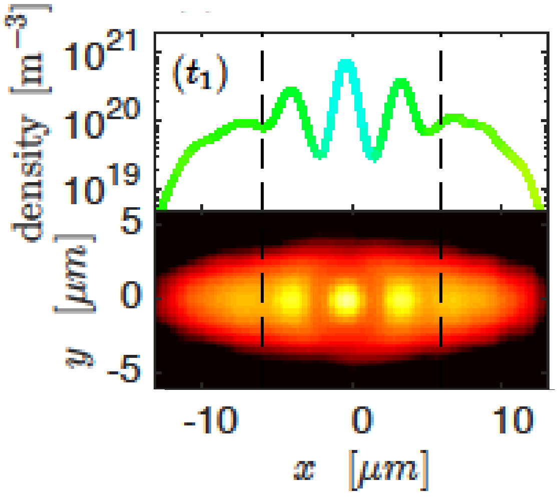
We employ a collective mode of the trapped condensate: the scissors mode



In the small-angle limit:

$$\theta(t) = \vartheta_0 \sin(\omega_{sc} t)$$

$$\omega_{sc} = \sqrt{\omega_x^2 + \omega_y^2}$$



Experiments with non-dipolar BECs: O.M. Maragò et al., Phys. Rev. Lett. **84**, 2056-2019 (2000)

The scissors mode

Useful link with the moment of inertia

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

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

Trap deformation

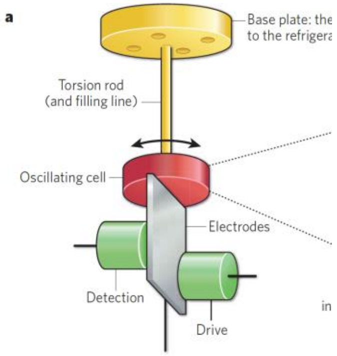
$\beta = \langle x^2 - y^2 \rangle / \langle x^2 + y^2 \rangle$

Cloud deformation

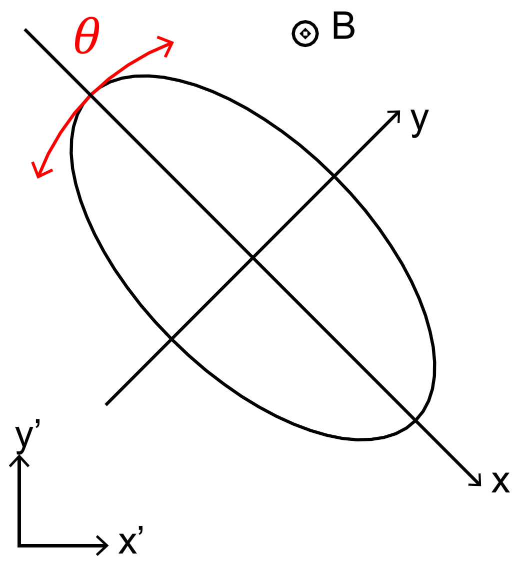
D. Guéry-Odelin and S. Stringari, Phys. Rev. Lett. **83**, 4452-4455 (1999)

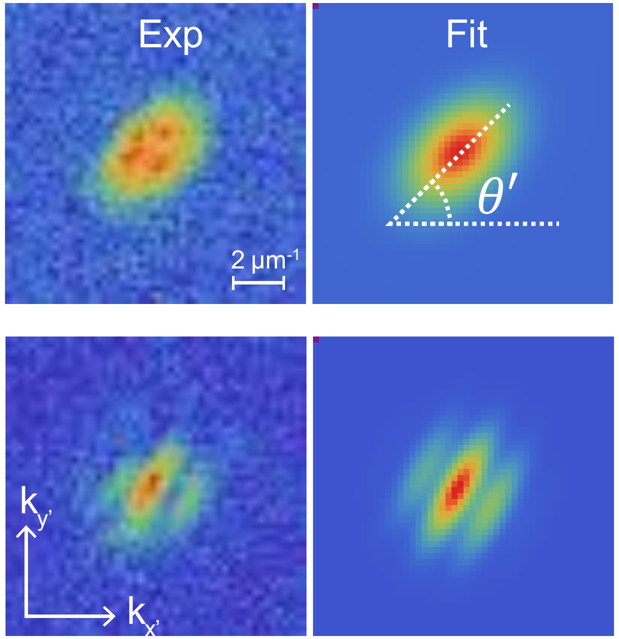
Analogy with torsional oscillators

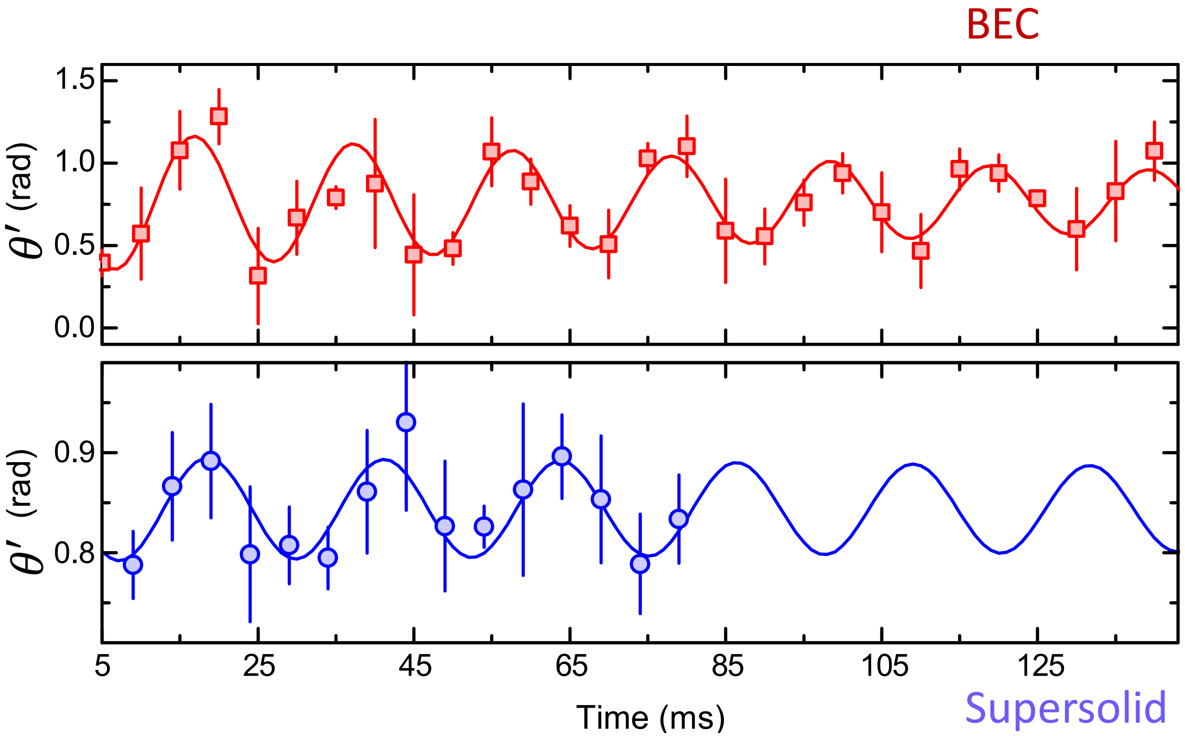
$$I = \frac{K}{\omega_{osc}^2}$$



Scissors oscillation





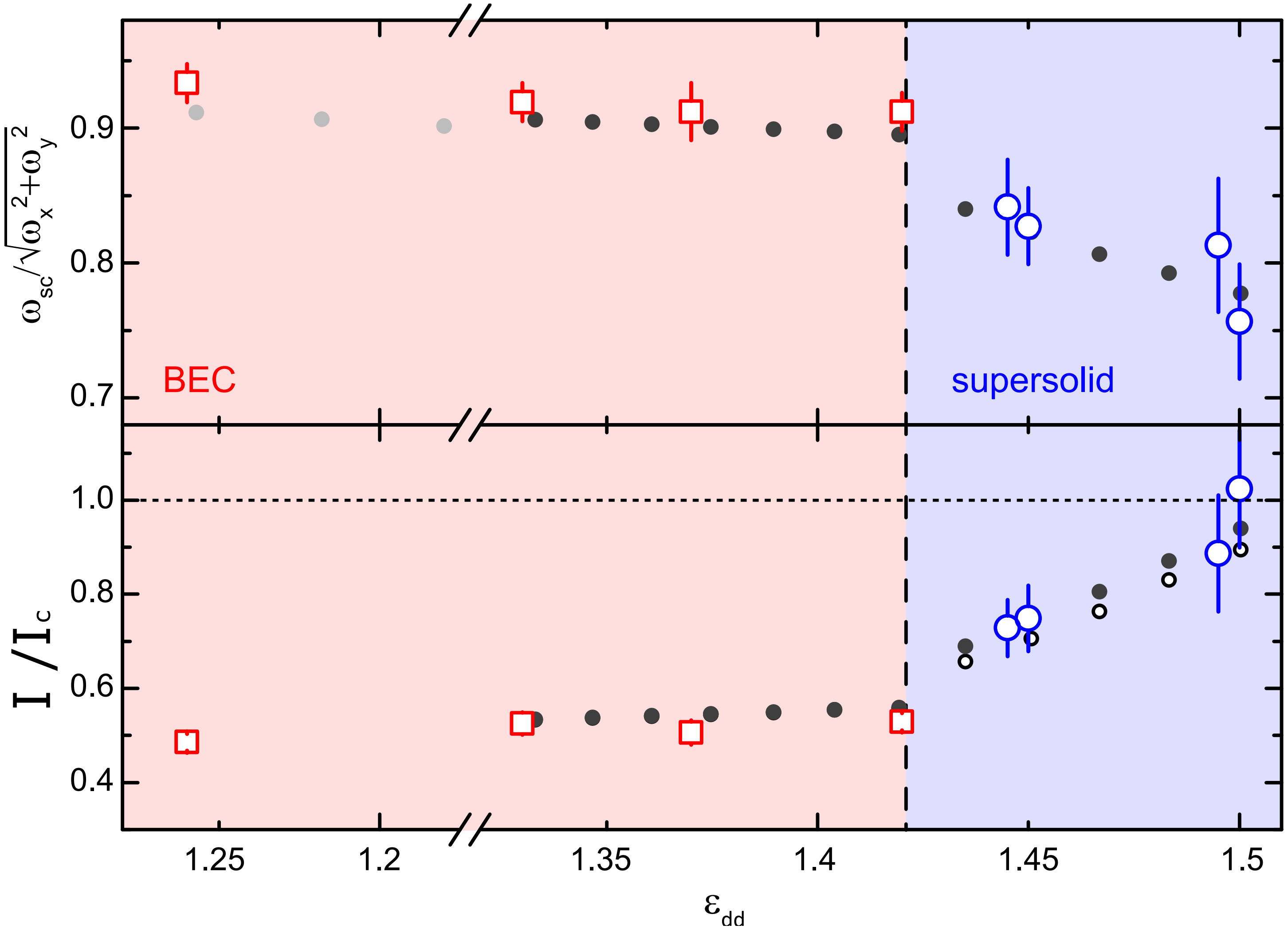


We excite the scissors mode changing temporary the relative power between ODT2 and ODT3..

.. then we extract the angle at different times with a 2D fit

Single-frequency oscillation in both the BEC and the supersolid regime

Scissors frequencies and moment of inertia



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

$$I_{BEC} < I_{ss} < I_c$$

Reduced moment of inertia ⇒ proof of the superfluid behavior under rotation

L. Tanzi et al., (2019) Preprint: arXiv:1912.01910. Accepted for publication in Science.

Theory, including β, by the Trento group: S. M. Roccuzzo et al., Phys. Rev. Lett., 124:045702 (2020)

Superfluid fraction

Our definition of superfluid fraction for an anisotropic system:

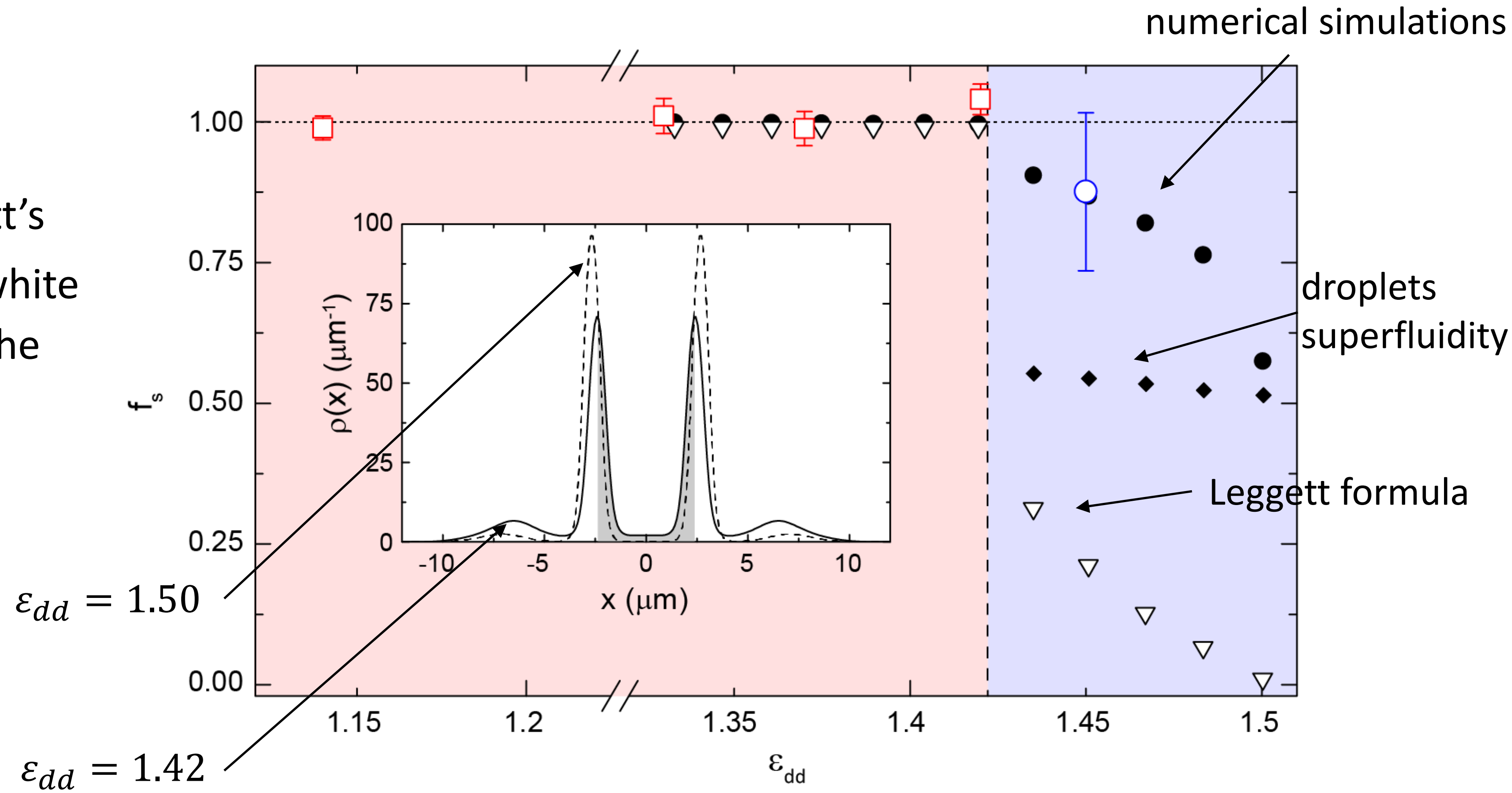
$$I = (1 - f_s)I_c + f_s\beta^2 I_c \Rightarrow \quad f_s = \frac{1-\alpha\beta\,(\omega_x^2+\omega_y^2)/\omega_{sc}^2}{1-\beta^2}$$

$f_s \sim 1$ (cluster supersolid)

Comparison with the 1D Leggett's model: $f_s \leq \left(\int d\,x/\bar{\rho}\,(x)\right)^{-1}$ (white triangles, density profile from the Trento group)

Our experiment: 0.88 ± 0.14
Leggett: 0.25
Droplets superfluidity: 0.50

Helium experiments: ~ 0.01
Leggett: 10^{-4}



Conclusions and outlook

We have demonstrated the superfluid properties of the dipolar supersolid under rotation through a measurement of its moment of inertia.

Next goals:

- Realizing larger, 2D supersolids to detect a sub-unity superfluid fraction, study vortices and measure a finite shear modulus
- Josephson effect without a barrier
- Other types of supersolids with cold atoms (e.g. dipoles in 2D stabilized by 3-body forces, or lattice supersolids)

The team

Current team: Luca Tanzi, Giulio Biagioni, Andrea Fioretti, Giovanni Modugno, Nicolò Antolini, Carlo Gabbanini

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

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) …