A supersolid body with whirling quantum tornadoes

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Nature 635, 327–331 (2024)

Condensed Matter - Quantum Gases

- At the speed of a fighter aircraft, rare earth metals evaporate and spit out of an oven. The gas is then slowed almost to a stop by a combination of lasers and magnetic pulses, making it colder than space. The gas's about 50,000 atoms become one state and lose their individual identities. Finally, little tornadoes emerge, pirouetting in the darkness, with a twist of the ambient magnetic field.
- The physicist Francesca Ferlaino and her colleagues at the University of Innsbruck spent three years trying to capture images of these quantum-scale vortices in action. They have finally confirmed the long-sought signature of an exotic phase of matter known as a supersolid by publishing images of the vortices in a publication.

Observation of vortices in a dipolar supersolid,
E. Casotti et. al, Nature, **635**, *327-331 (2024)*

Certain liquids' atoms will interact across greater distances if you make them cold and sparse enough, eventually joining together to form a single, enormous wave that moves flawlessly and frictionlessly. Russian and Canadian physicists made the initial discovery of these so-called superfluids in helium in 1937.

- *Viscosity of Liquid Helium below the λ-Point,*
  P. Kapitza, Nature, **141**, *74 (1938)*
- *Flow of Liquid Helium II,*
  J. F. Allen and A. D. Misener, Nature, **141**, *75 (1938)*

- Since its prediction in 1957, condensed matter physicists have been captivated by the supersolid, a paradoxical form of matter that is both the stiffest of solids and the flowiest of fluids.
  - *Unified Theory of Interacting Bosons,*
    E. P. Gross, Phys. Rev., **106**, *161 (1957)*
- For decades, physicists argued about the possibility of this strange superfluid-solid hybrid.
  - *Can a Solid Be "Superfluid"?,*
    A. J. Leggett, Phys. Rev. Lett, **25**, *1543 (1970)*
- After initially announcing a discovery in 2004, researchers later withdrew their claim.
  - *Absence of Supersolidity in Solid Helium in Porous Vycor Glass,*
    Duk Y. Kim and Moses H. W. Chan, Phys. Rev. Lett, **109**, *155301 (2012)*

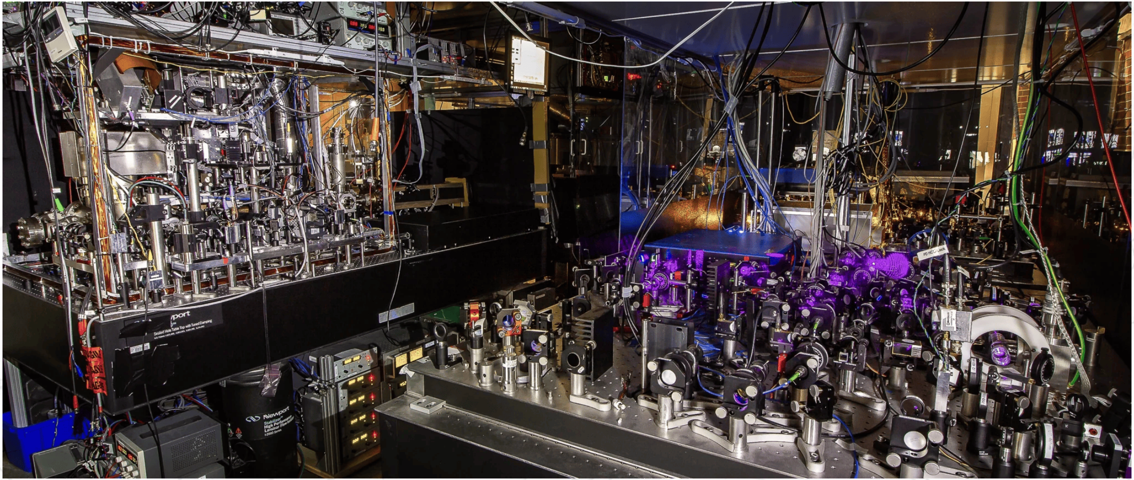
When teams from Stuttgart, Florence, and Innsbruck discovered encouraging signs of supersolidity in one-dimensional systems in 2017 and 2019, there were new surges in activity.

- *Supersolid formation in a quantum gas breaking a continuous translational symmetry, J. Léonard et. al,* Nature, **543**, *87-90 (2017)*
- *A stripe phase with supersolid properties in spin-orbit-coupled Bose-Einstein condensates, Jun-Ru Li et. al,* Nature, **543**, *91-94 (2017)*
- *Transient Supersolid Properties in an Array of Dipolar Quantum Droplets, F. Böttcher et. al,* Phys. Rev. X, **9**, *011051 (2019)*
- *Observation of a Dipolar Quantum Gas with Metastable Supersolid Properties, L. Tanzi et. al,* Phys. Rev. Lett., **122**, *130405 (2019)*
- *Long-Lived and Transient Supersolid Behaviors in Dipolar Quantum Gases, L. Chomaz at. al,* Phys. Rev. X, **9**, *021012 (2019)*

Dysprosium and erbium atom gasses, which are naturally magnetic enough to function as tiny bar magnets, were the first materials the groups used. When a magnetic field was applied, the atoms spontaneously gathered into clusters that were uniformly spaced apart, creating a crystalline lattice. The atoms then spontaneously oscillated as a single coherent wave with all the characteristics of a superfluid when the temperature and density were reduced due to interactions between them.

The “two competing natures” of the supersolid were glimpsed in the 2019 trials. Since then, it has tested it for many predicted qualities and expanded from supersolid from one dimension to two.

- *Two-dimensional supersolidity in a dipolar quantum gas,*
  M. A. Norcia et. al, Nature, **596**, *357-361 (2021)*
- *Can Angular Oscillations Probe Superfluidity in Dipolar Supersolids?,*
  M. A. Norcia et. al, Phys. Rev. Lett., **129**, *040403 (2022)*
- *Compressibility and speeds of sound across the superfluid-to-supersolid phase transition of an elongated dipolar gas,*
  P. B. Blakie et. al, Phys. Rev. Research, **5**, *033161 (2023)*



The laboratory of Francesca Ferlaino at the University of Innsbruck.

Creation and robustness of quantized vortices in a dipolar supersolid when crossing the superfluid-to-supersolid transition,
M. Šindik et. al, Phys. Rev. A, **106**, *L061303 (2022)*

- Their supersolid was simulated on a computer to simulate the effects of a comparable substance within a rotating neutron star. They suggested that these faults would momentarily accelerate the neutron star's rotation, producing a glitch.

    - *Glitches in Rotating Supersolids,*
      E. Poli et. al, Phys. Rev. Lett., **131**, *223401 (2023)*

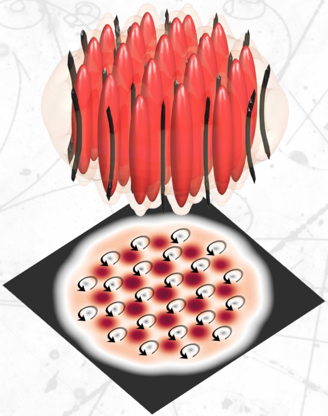
- An assessment of neutron star laboratory analogs conducted a few years prior.

    - *Neutron stars in the laboratory,*
      V. Graber et. al, IJMP D, **26**, *1730015 (2017)*

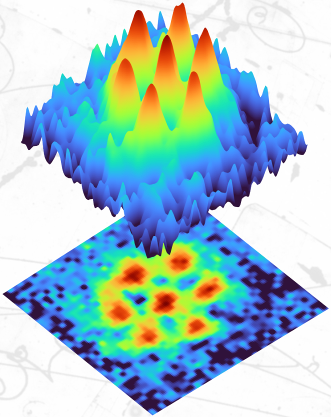
- These investigations aim to unravel additional unusual phases of matter, like high-temperature superconductors, where vortices are anticipated to be crucial.

    - *Vortices in high-temperature superconductors,*
      G. Blatter et. al, Rev. Mod. Phys., **66**, *1125 (1994)*

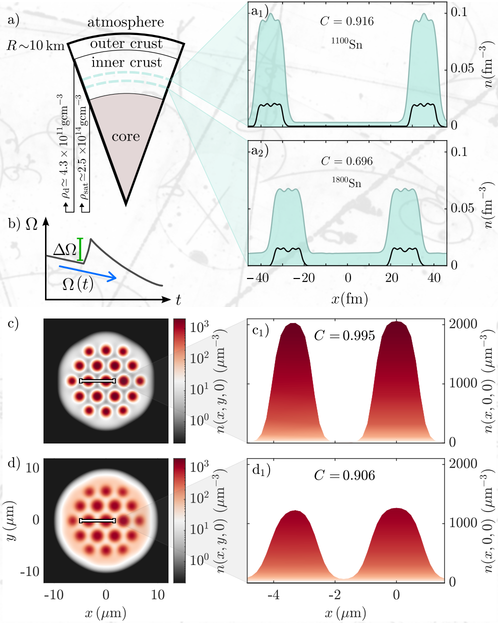
Theoretical simulation



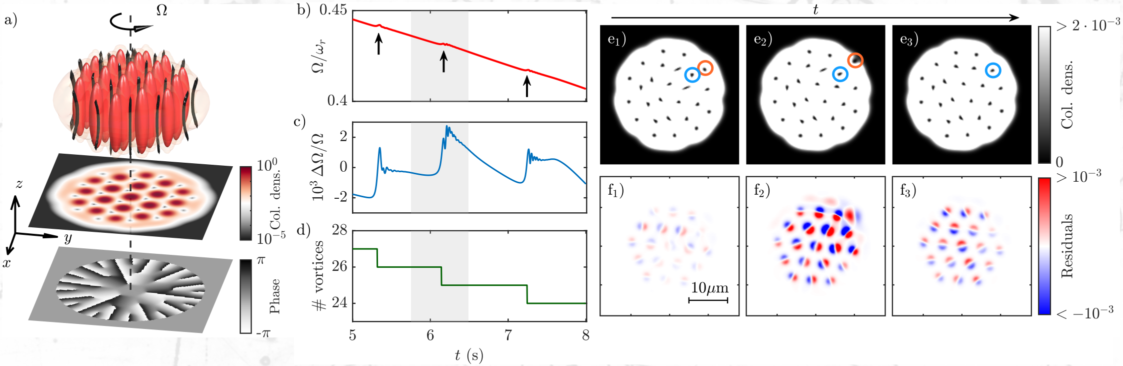
Experimental data



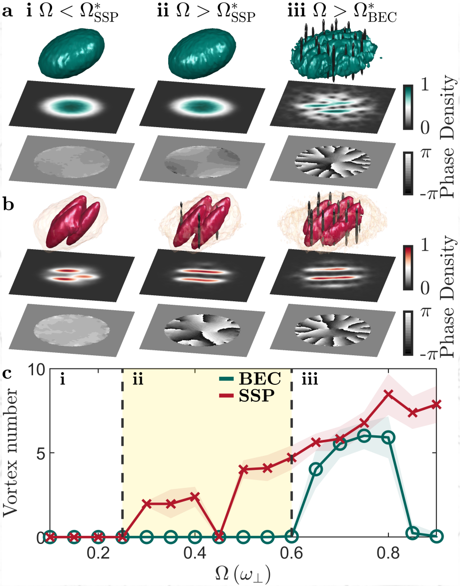
In these 2D density maps (and 3D reconstructions) of of the dysprosium atoms in a supersolid, dense clumps of atoms take on a crystalline arrangement while quantum vortices form in the space between.



arXiv: 2306.09698

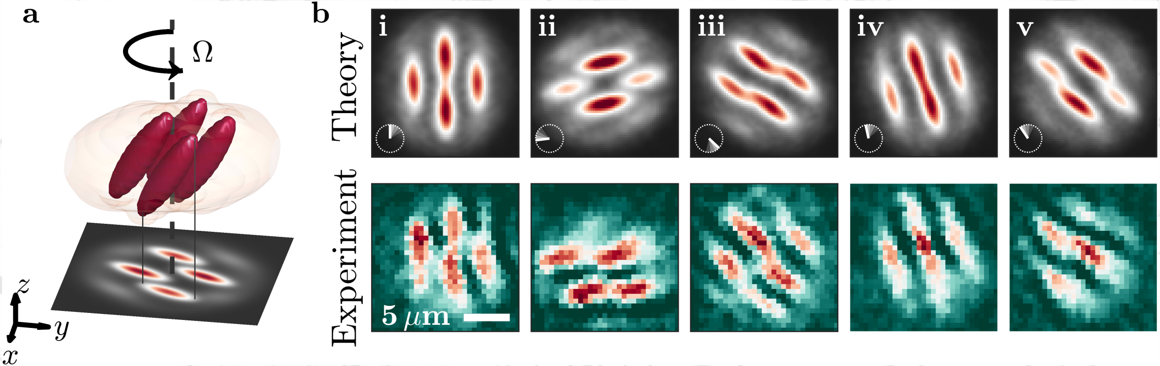


arXiv: 2306.09698

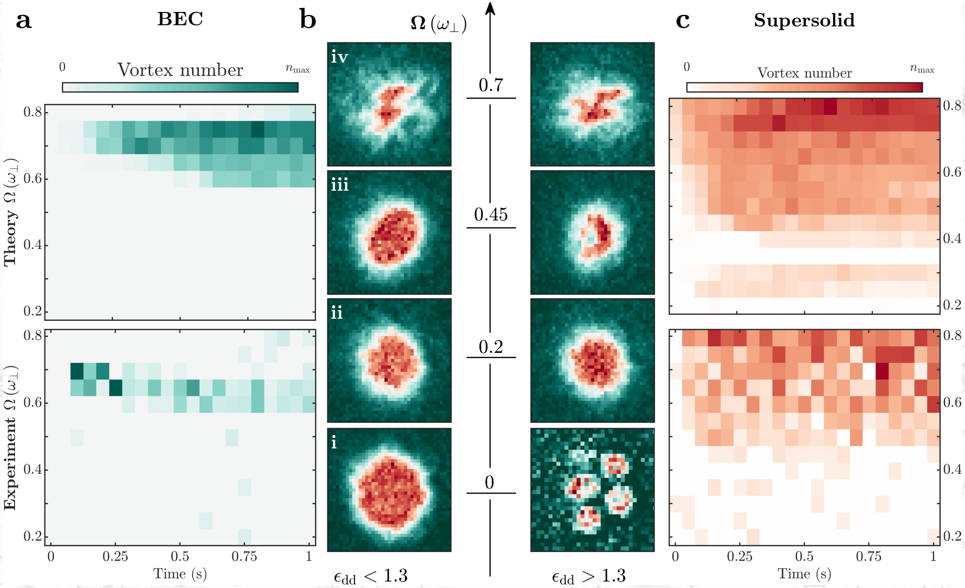


Simulation of vortex nucleation in a supersolid and unmodulated BEC.

arXiv: 2403.18510

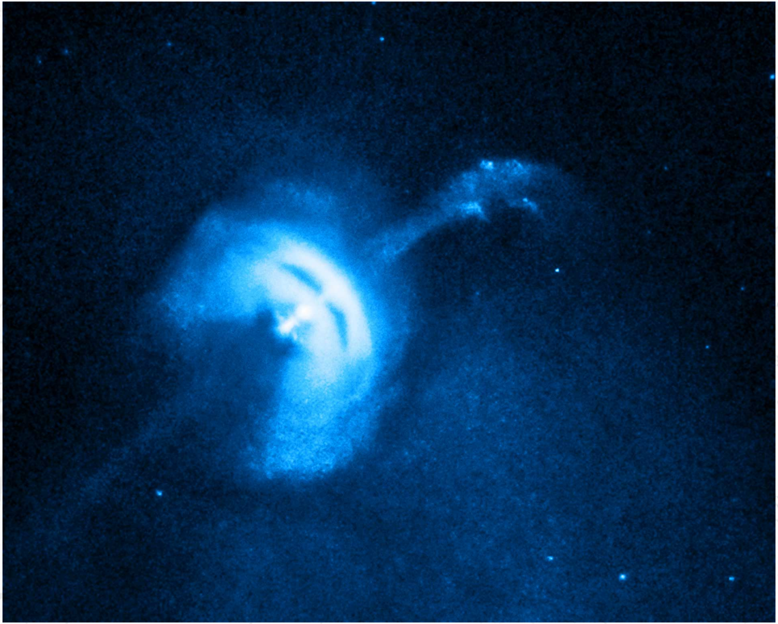


Magnetostirring of a ^{164}Dy dipolar supersolid.
arXiv: 2403.18510



Vortex nucleation in a dipolar supersolid and BEC.

arXiv: 2403.18510



Vela Pulsar

Astronomers had been monitoring the remarkably steady rotation of the Vela pulsar, the magnetic remains of a huge star that burst some 11,000 years ago, at the Instituto Argentino de Radioastronomía. With a regularity that exceeds the greatest clocks that humanity can create, Vela's poles emit radiation beams that flash on Earth eleven times every second as it twirls. However, the star once rotated at a speed of around 2.4 billionths of a second quicker than normal.