Ultracold quantum gases: a window on quantum materials

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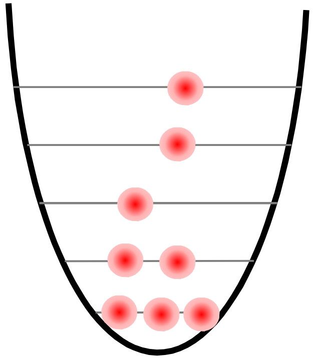
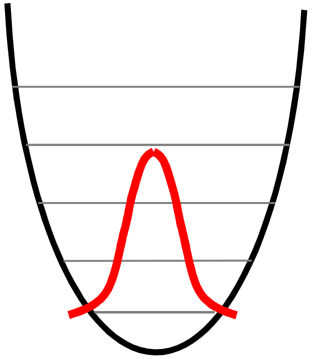
LoT 2019, Firenze 15/4/2019

Quantum degeneracy: bosons



T>Tc

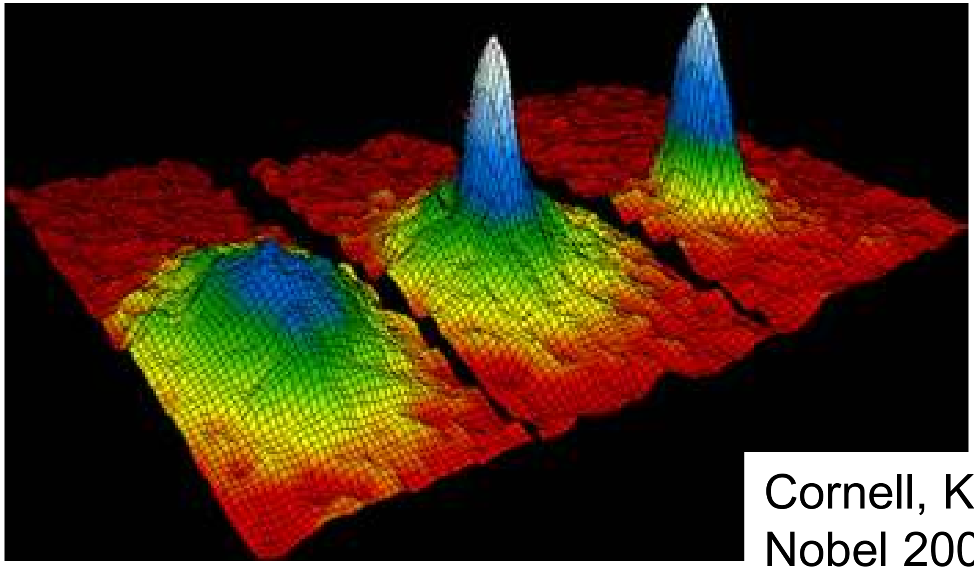


T<Tc

$$f(E) = \frac{1}{e^{\beta(E-\mu)} - 1}$$

$$\beta = (k_{\mathrm{B}}T)^{-1}$$

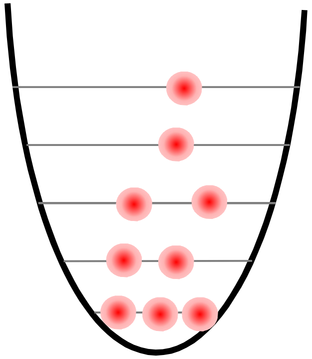
$$T_c = \frac{\hbar\omega_{\mathrm{ho}}}{k_{\mathrm{B}}}\left(\frac{N}{\zeta(3)}\right)^{\frac{1}{3}} \sim 0.94\frac{\hbar\omega_{\mathrm{ho}}}{k_{\mathrm{B}}}N^{\frac{1}{3}}$$



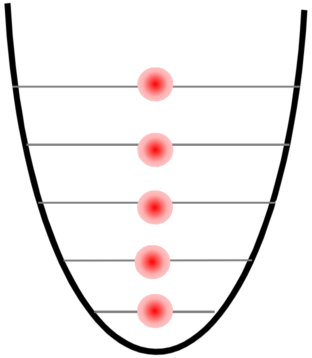
Cornell, Ketterle, Wieman
Nobel 2001

Quantum degeneracy: fermions

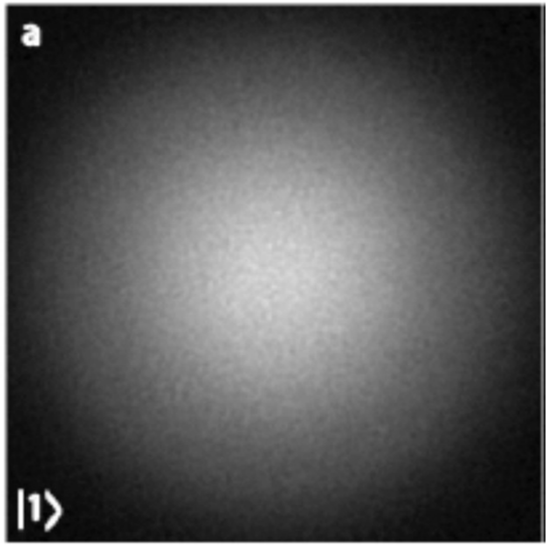
T>>Tc

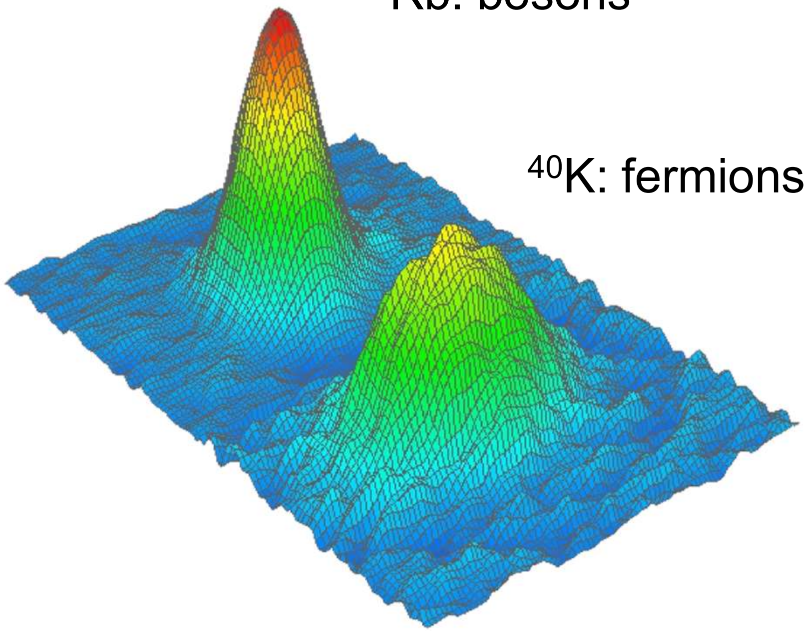


T≈0



$$f(E) = \frac{1}{e^{\beta(E-\mu)} + 1}$$





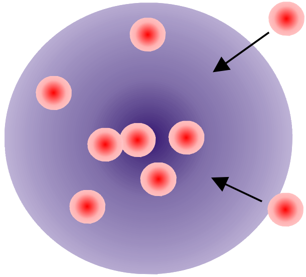
^{87}Rb: bosons

^{40}K: fermions

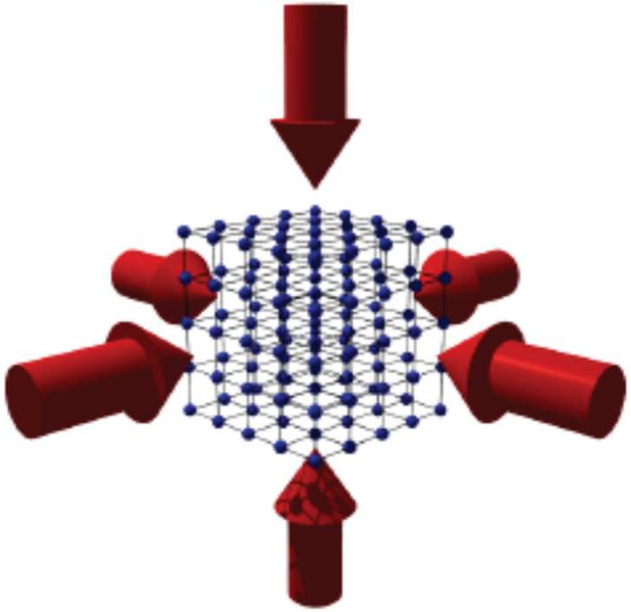
G. Modugno et al. Science 294,1320 (2001)

Optical potentials

AC polarizability: mean force on atoms by a laser beam



$$U_{trap}(x) = -\frac{\alpha}{2\varepsilon_0 c}\frac{2P}{\pi w_0^2} e^{\frac{-2x^2}{w_0^2}}$$



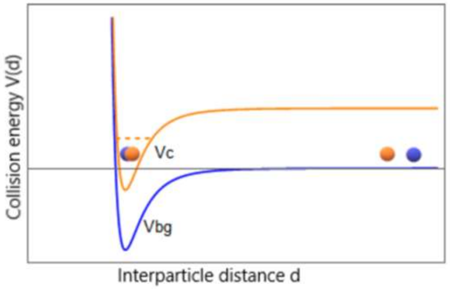
Interference between laser beams creates perfectly sinusoidal potentials

Optical lattices and low-D systems

Interactions

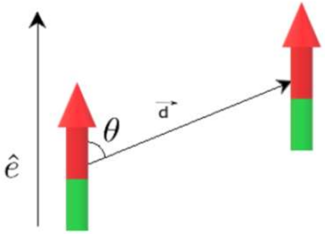
A dilute atomic gas: $\rho \approx 10^{12-14}$ cm^{-3} (1 Torr at room T: $\rho \approx 10^{13}$ cm^{-3})

Van der Waals short-range interaction:



$$\begin{aligned} U_{\mathrm{int}}(r-r') &= g\delta(r-r') \\ g &= \frac{4\pi\hbar^2 a_s}{m} \end{aligned}$$

Dipole-dipole long-range interaction:

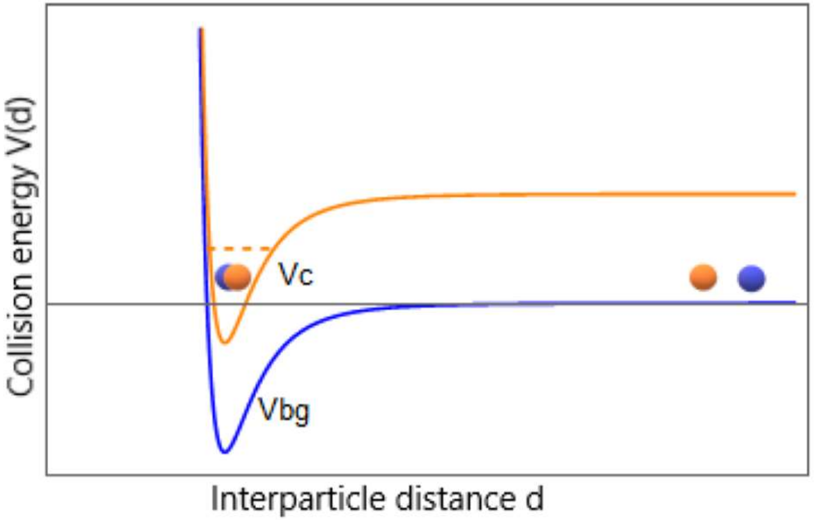


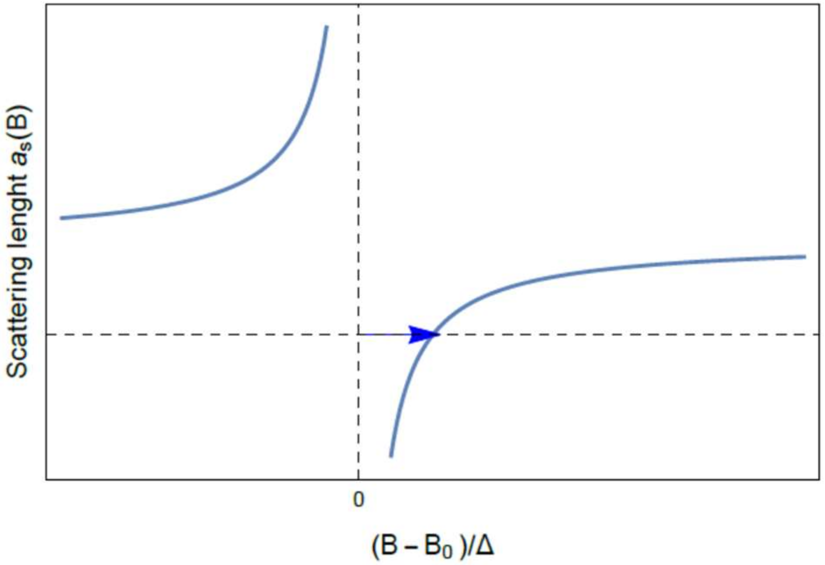
$$U_{dd} = \frac{C_{dd}}{4\pi}\frac{1-3\cos^2\theta}{d^3} \qquad C_{dd} = \mu_0\mu_{\mathrm{m}}^2$$

Weaker interactions: quantum fluctuations, three-body interactions, …

Light-engineered interactions: spin-orbit coupling, infinite-range coupling, …

Interaction control: Feshbach resonances

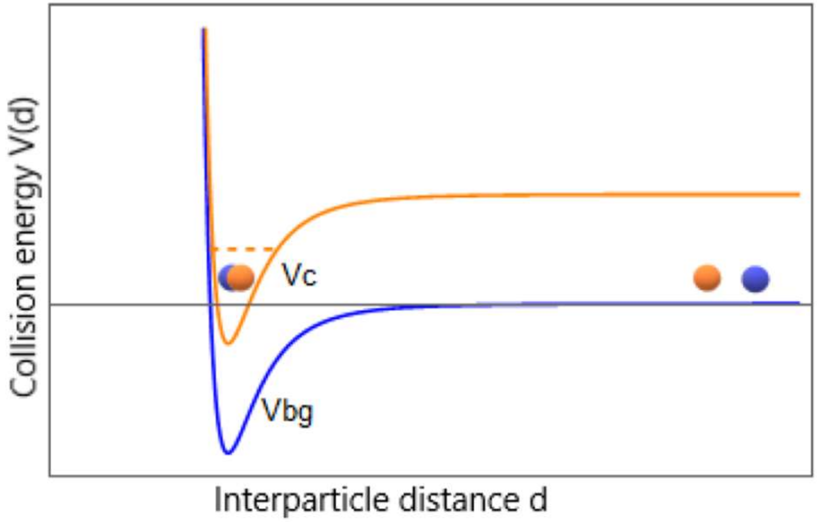


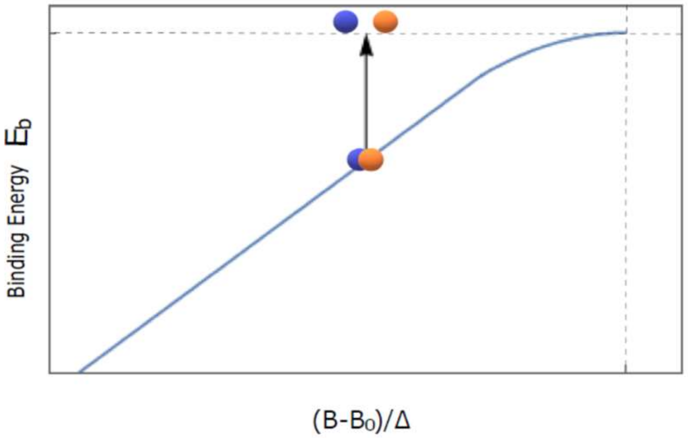


Full control on the scattering length!

See for example: C. Chin, et al., Rev. Mod. Phys. 82, 1225 (2010)

Interaction control: Feshbach resonances

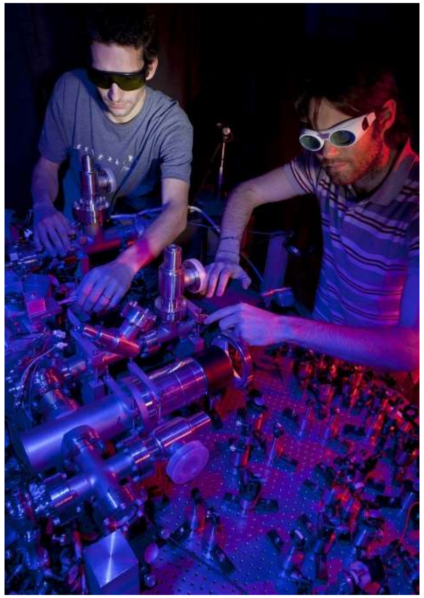




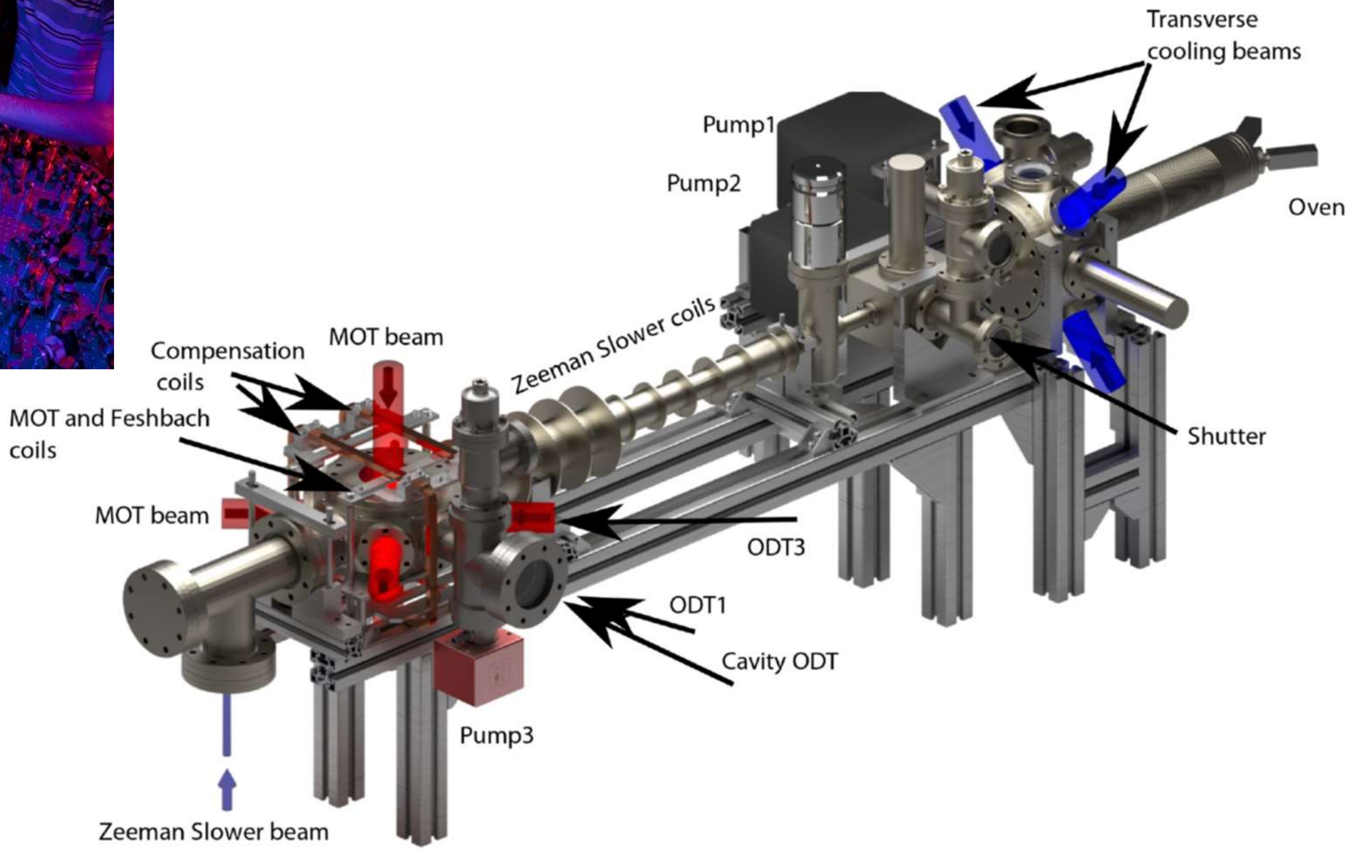
Pairs of atoms can be associated into molecules!

See for example: C. Chin, et al., Rev. Mod. Phys. 82, 1225 (2010)

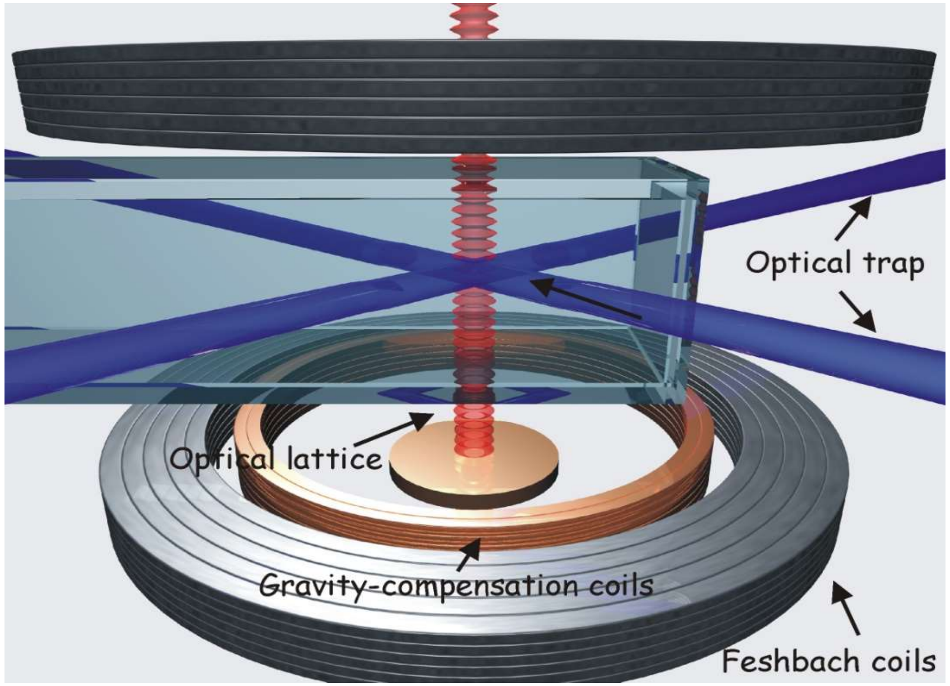
Quantum gas machines



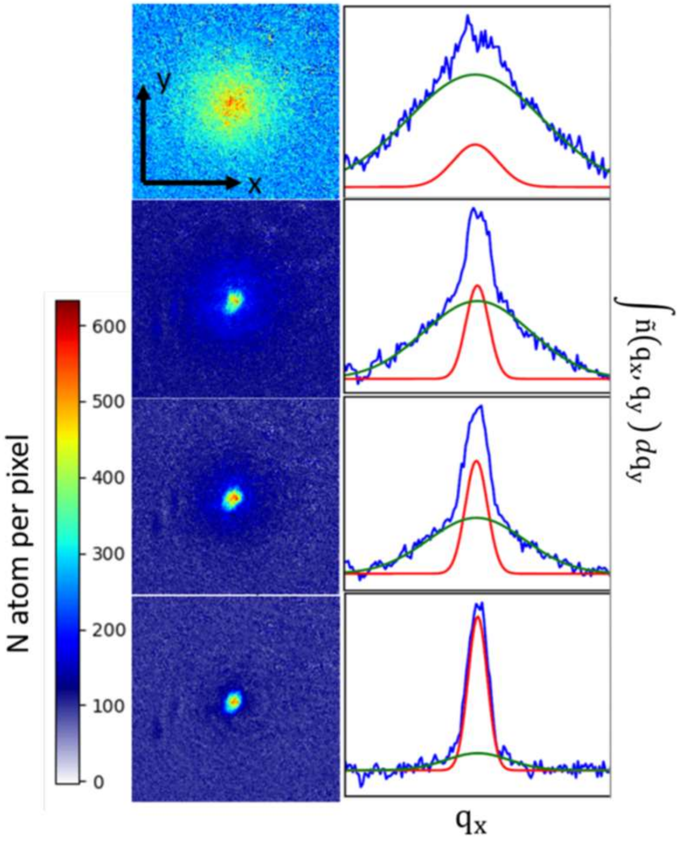
See the LENS group website:
http://quantumgases.lens.unifi.it/



Quantum gas machines



BEC transition



The first 10 years: Superfluidity

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

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

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

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

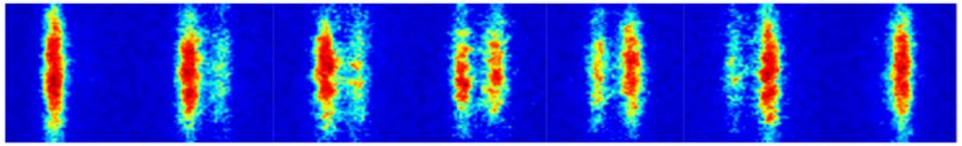
$$\frac{\partial \mathbf{v}}{\partial t} = -\frac{1}{mn}\boldsymbol{\nabla}p - \boldsymbol{\nabla}\left(\frac{v^2}{2}\right) + \frac{1}{m}\boldsymbol{\nabla}\left(\frac{\hbar^2}{2m\sqrt{n}}\nabla^2\sqrt{n}\right) - \frac{1}{m}\boldsymbol{\nabla}V.$$

BECs are superfluid!

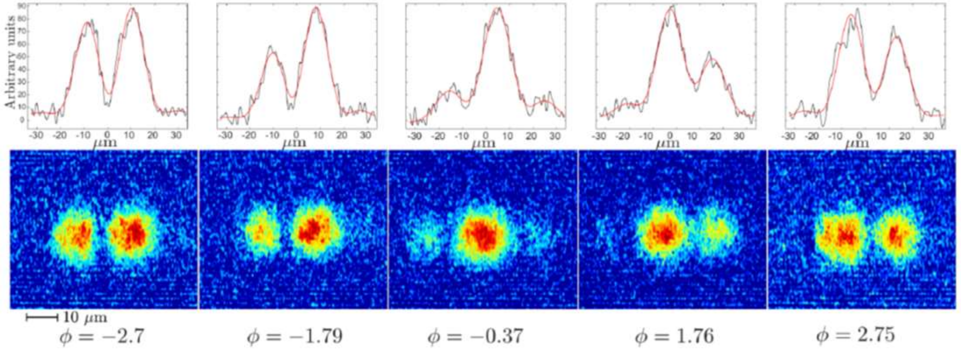
Flow without dissipation, irrotationality, quantized vortices, …

Matter-wave interference

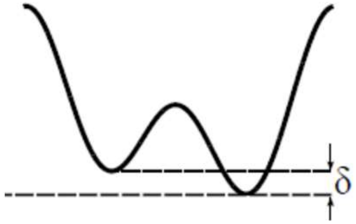
Real space

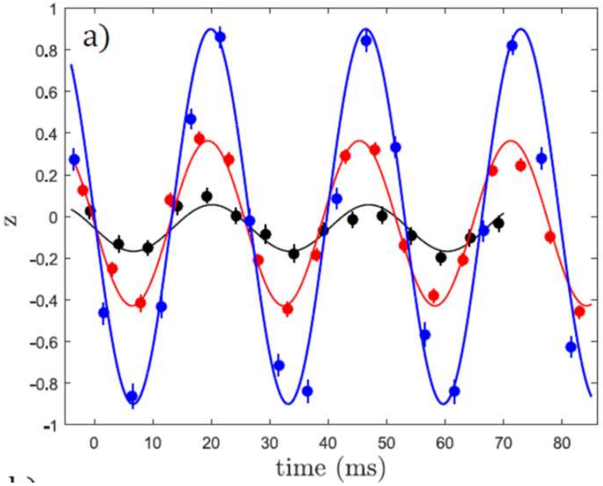


Momentum space



Double-well trap

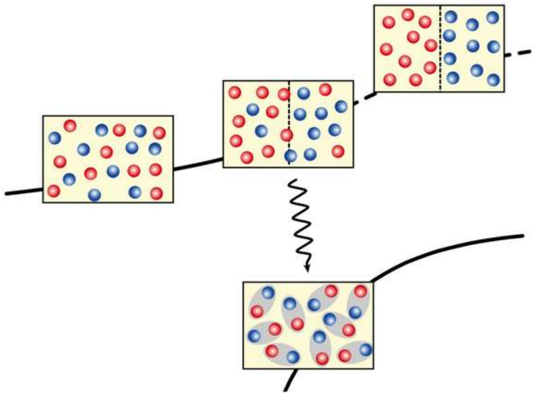




Interferometric force measurements, quantum-enhanced sensitivity, Schroedinger cats, …

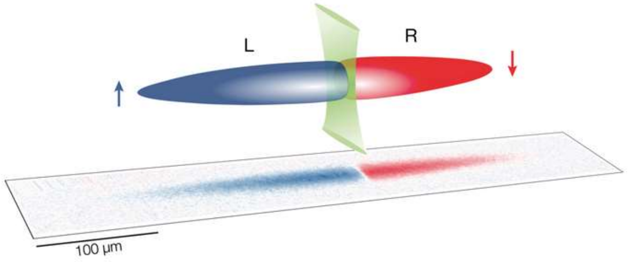
K team @LENS

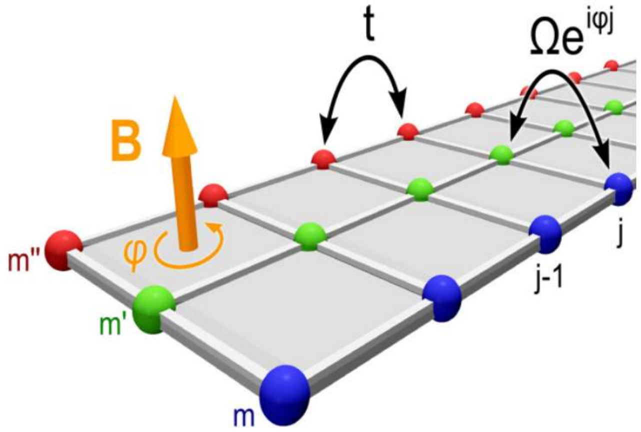
Condensed-matter phenomena



Fundamental phenomena in quantum ferromagnets, fermionic Josephson junctions, …

Li team @LENS

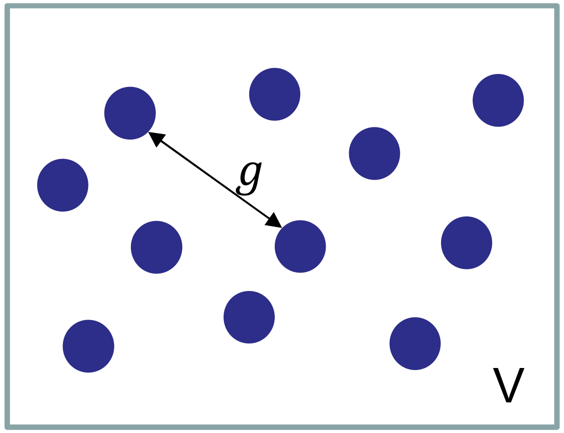




Quantum Hall physics in synthetic dimensions

Yb team @LENS

Quantum fluctuations in dilute Bose-Einstein condensates



$g = 4\pi\hbar^2 a/m$,
a = collisional scattering length

na^3<< 1 → LHY negligible

$$\frac{E_{int}}{V} = \boxed{\frac{gn^2}{2}}\left(1 + \boxed{\frac{128}{15\sqrt{\pi}}\sqrt{na^3}} + \cdots\right)$$

Mean-field (MF) energy

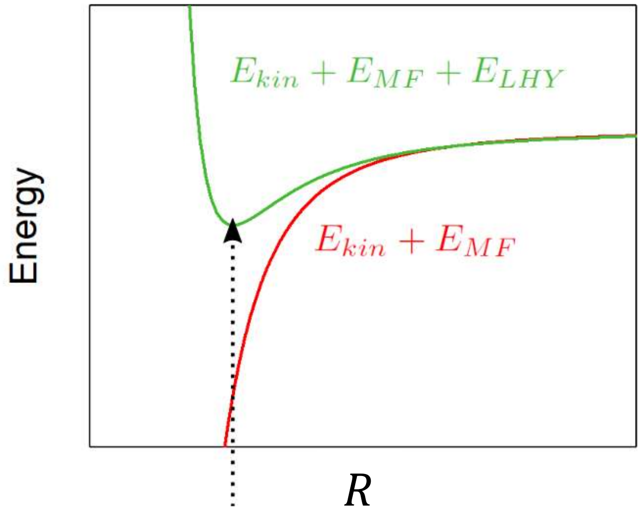
Lee-Huang-Yang (LHY) correction

The LHY term can become much larger in «two-component» systems:

- **Two-component quantum mixtures**
- **Strongly dipolar quantum gases**

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

Quantum droplets in Bose-Bose mixtures



minimum energy at a finite $R \propto N^{\frac{1}{3}}$

$$E_{kin} \propto \frac{N}{R^2}$$

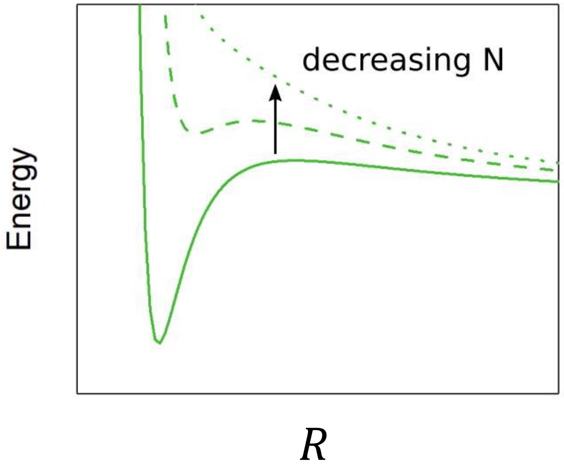
$$E_{MF} \propto -\frac{N^2}{R^3}$$

$$E_{LHY} \propto \frac{N^{\frac{5}{2}}}{R^{\frac{9}{2}}}$$

Liquid-like behavior:

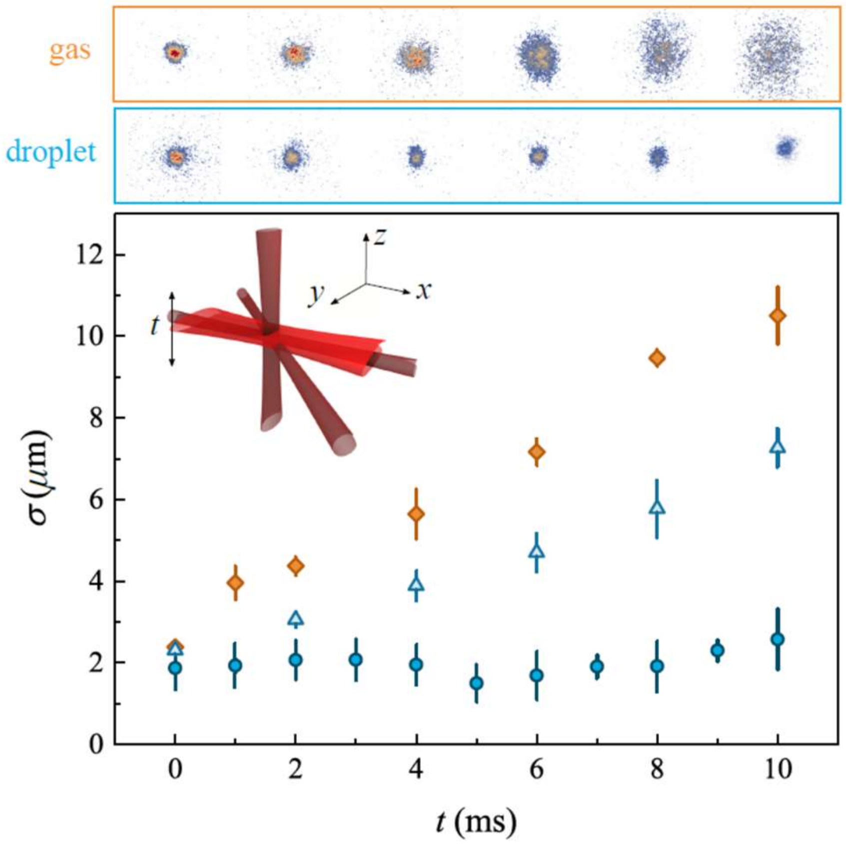
- self-bound
- weak compressibility

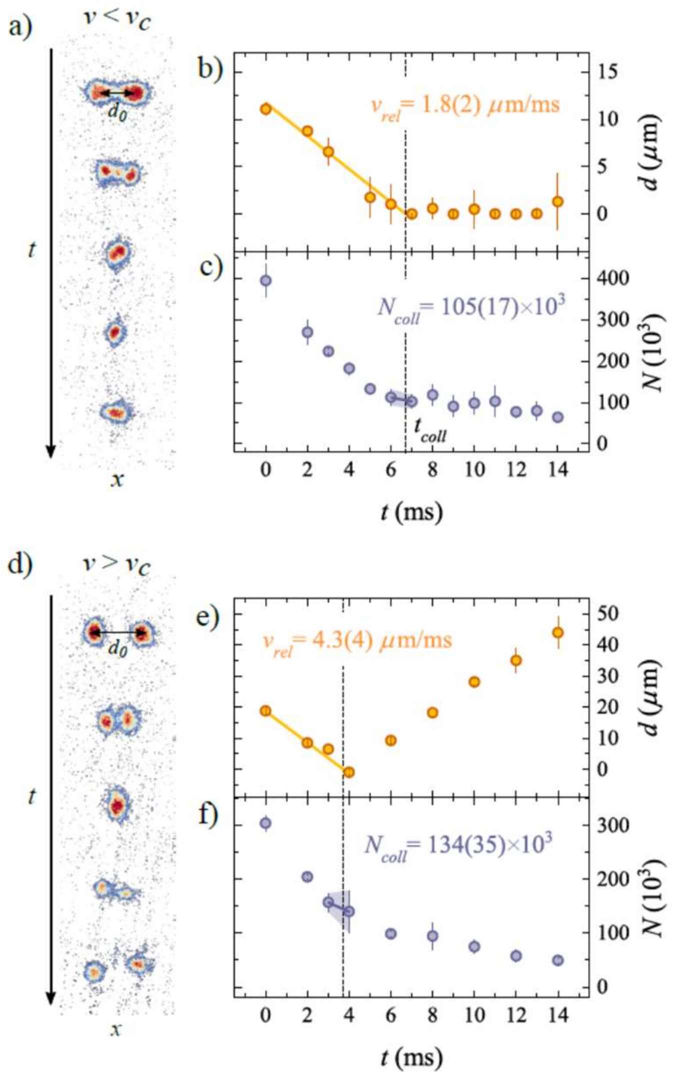
critical atom number



Theoretical proposal by D. S. Petrov – Phys. Rev. Lett. 115, 155302 (2015).

Quantum droplets in Bose-Bose mixtures



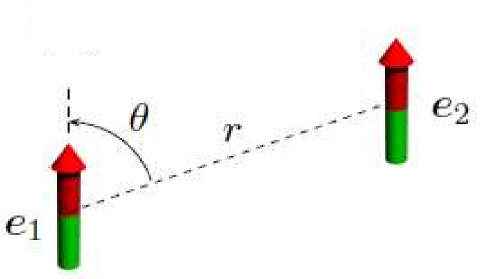


K team @LENS

G. Semeghini et al, Phys. Rev. Lett. 120, 235301 (2018);
G. Semeghini et al, Phys. Rev. Lett. 122, 090401 (2019).

Bose gas with dipolar interaction

Dipole-dipole interaction:



$$U_{dd}(r) = \frac{\mu_0\mu^2}{4\pi}\frac{1-3\ \cos^2\vartheta}{r^3}$$

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

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

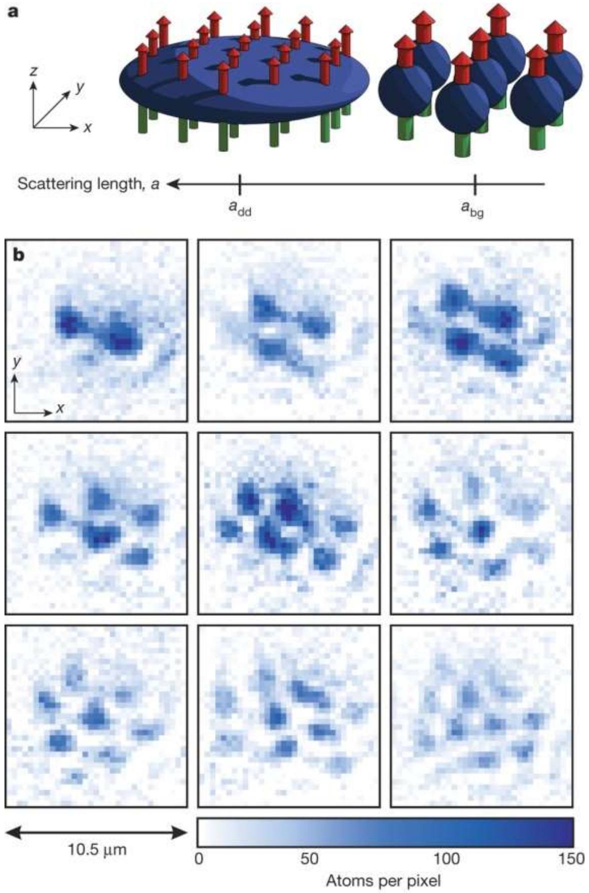
LHY >0

Depends on the geometry, can be negative

Erbium:	μ=7 μ_B	$a_{dd} \approx 70 a_0$
Dysprosium:	μ=10 μ_B	$a_{dd} \approx 140\ a_0$

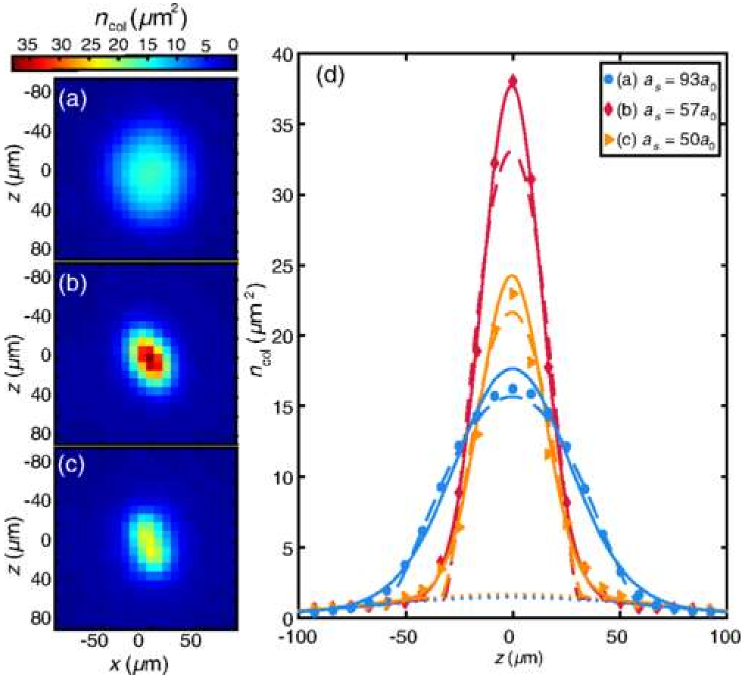
Quantum droplets in dipolar systems

Dy atoms, Stuttgart group



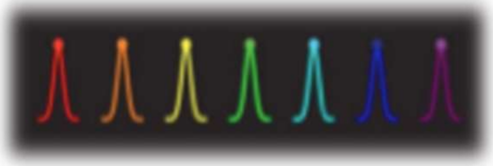
H. Kadau et al., *Nature* 530, 194 (2016); M. Schmitt et al., *Nature* 539, 259 (2016); I. Ferrier-Barbut et al., *Phys. Rev. Lett.* 116, 215301 (2016); ...

Er atoms, Innsbruck group

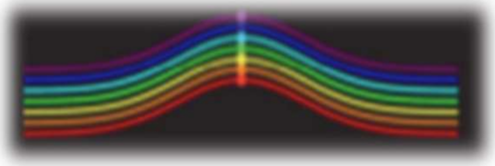


L. Chomaz et al., *Phys. Rev. X* 6, 041039 (2016)

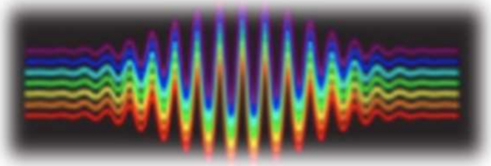
A supersolid phase in dipolar systems?



Solid

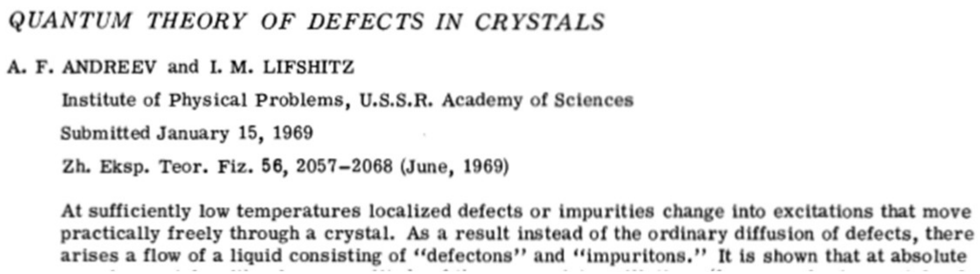


Superfluid



Supersolid

Supersolids in brief:
superfluids with an interaction-induced crystalline structure.



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

Helium: E. Kim, and M. H. W. Chan, *Nature*, 427, 6971 (2004); D. Y. Kim, and M. H. W. Chan, *Phys. Rev. Lett.*, 109, 155301 (2012).

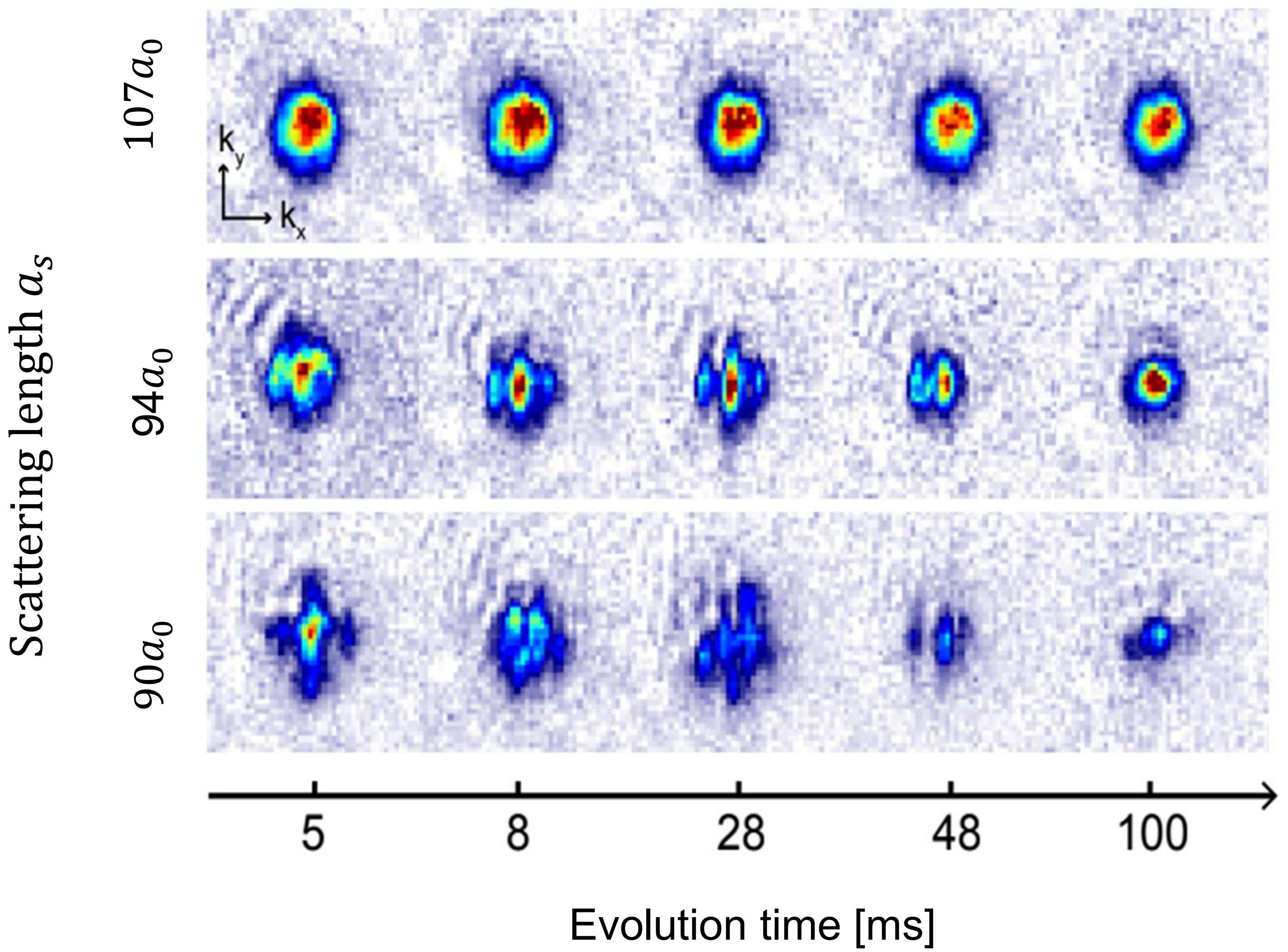
Probably not observable.

Ultracold atoms: J. Léonard, et al., *Nature*, 543, 7643 (2017); J. R. Li *et al.*, *Nature*, 543, 7643 (2017).

Supersolid behavior observed, but only with light assisted interactions.

Supersolid behaviour of a dipolar quantum gas

Dy team @CNR-INO (Pisa) and LENS

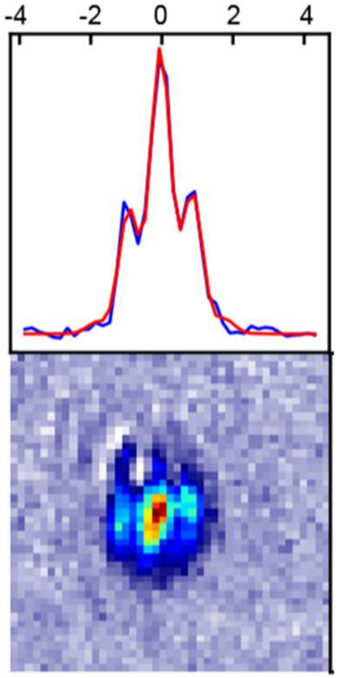


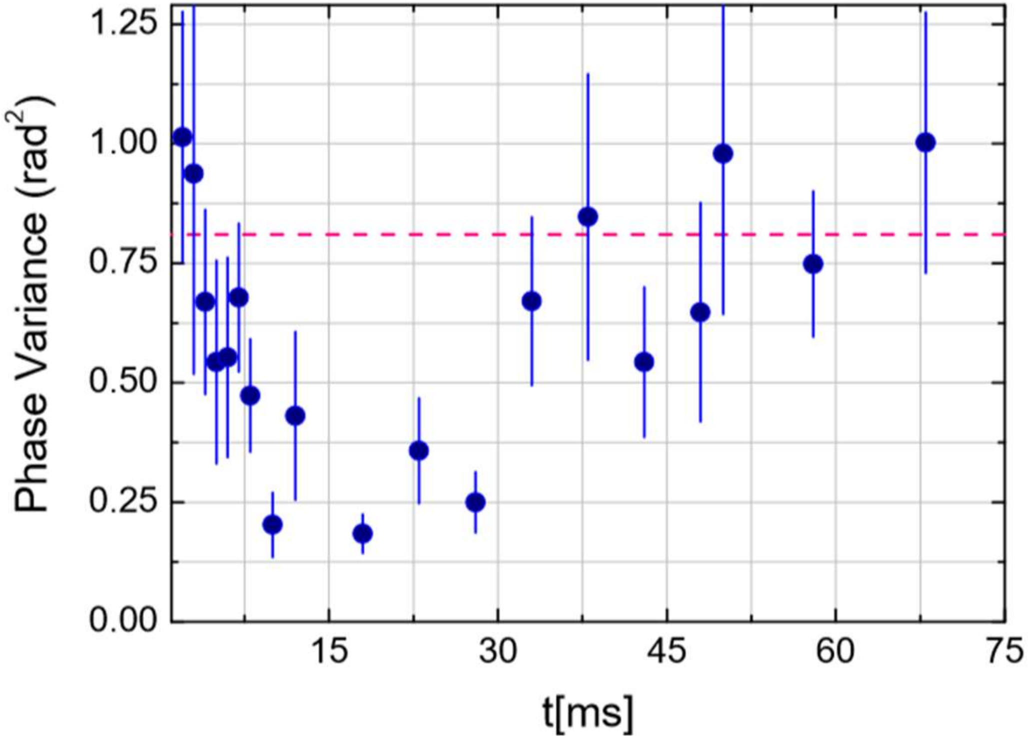
BEC

Coherent
stripe phase

Incoherent
droplets

Supersolid behaviour of a dipolar quantum gas

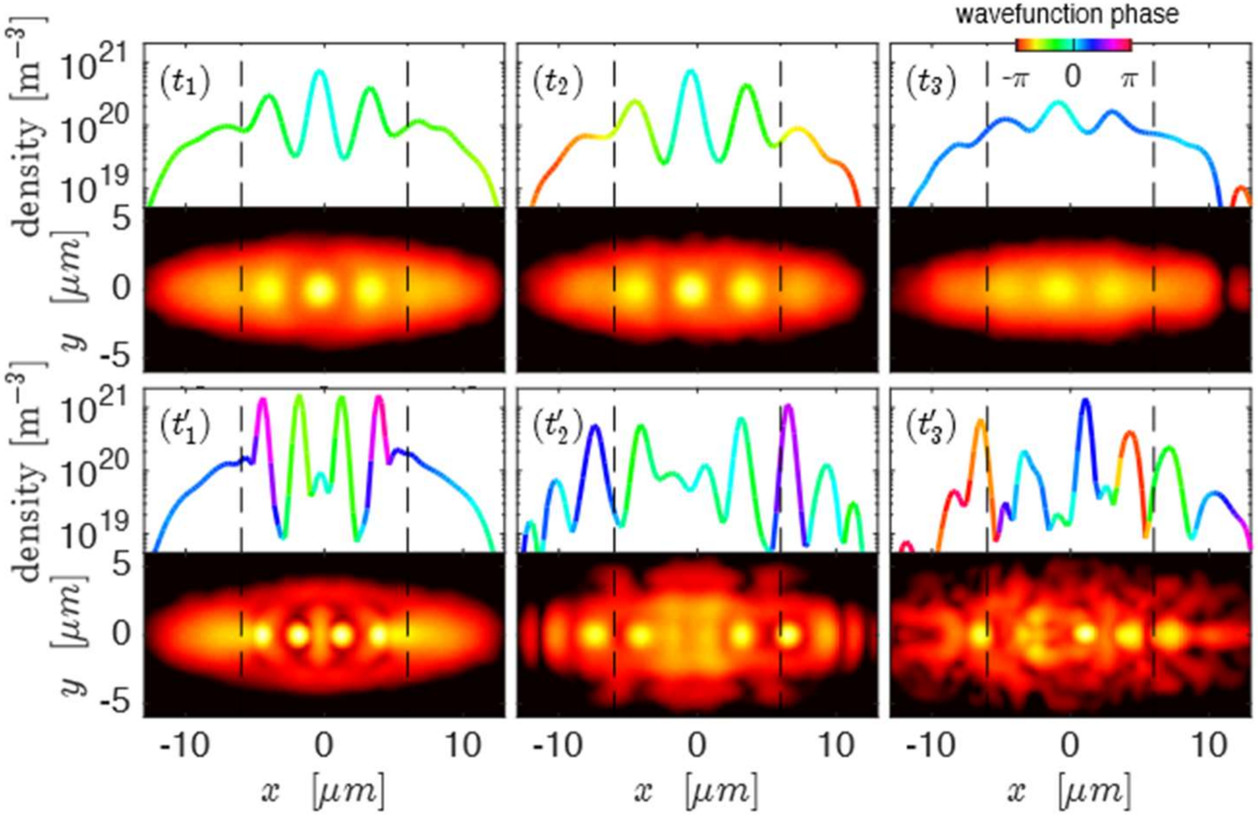




A double-slit analysis shows phase coherence for at least 50 ms.

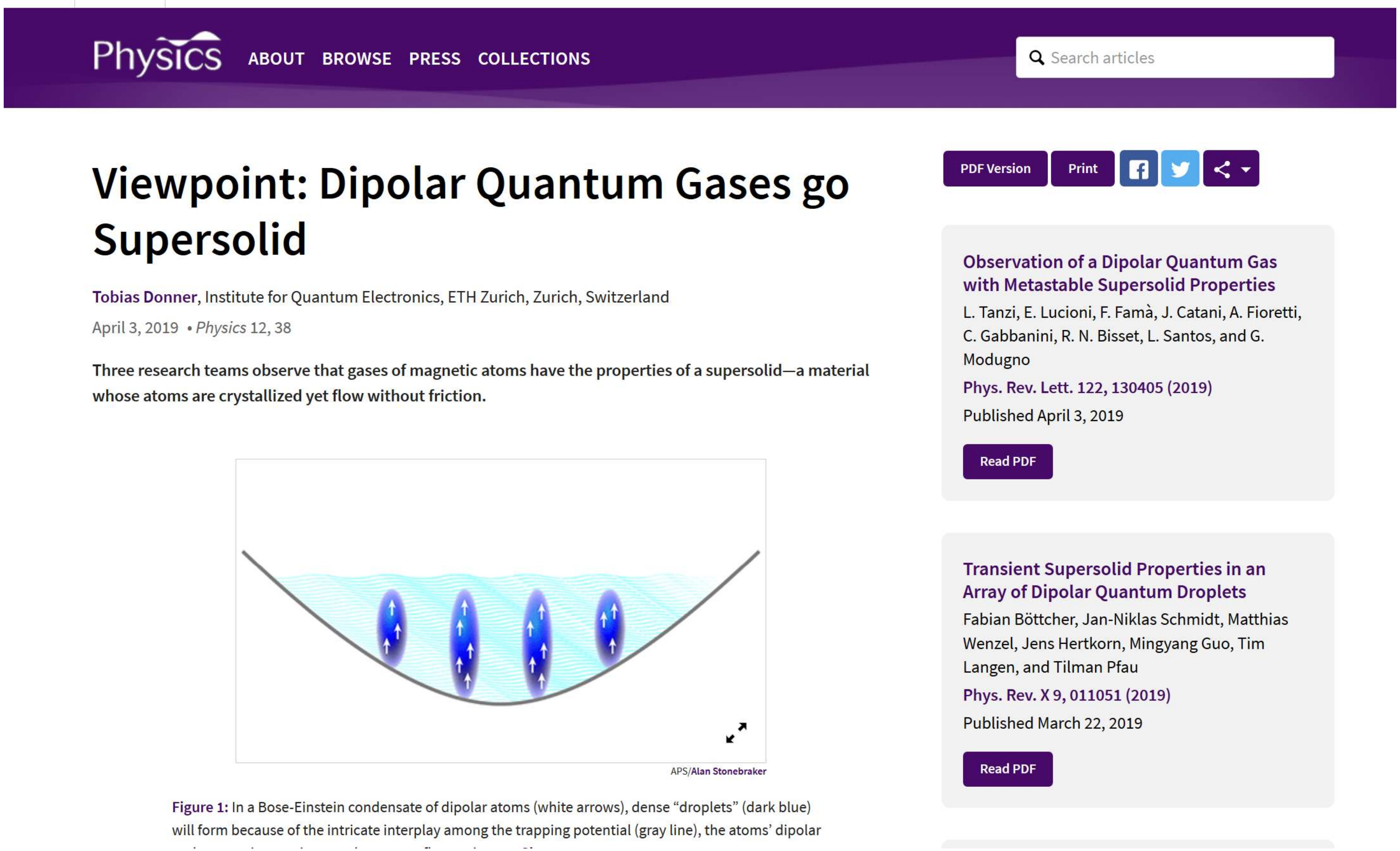
L. Tanzi et al., Phys. Rev. Lett. 122, 130405 (2019)

Supersolid behaviour of a dipolar quantum gas



Theoretical confirmation of the supersolid behavior by the Hannover team (L. Santos and R. Bisset)

Supersolid behaviour of a dipolar quantum gas



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.

APS/Alan Stonebraker

Figure 1: In a Bose-Einstein condensate of dipolar atoms (white arrows), dense "droplets" (dark blue) will form because of the intricate interplay among the trapping potential (gray line), the atoms' dipolar

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 (2019)

Published April 3, 2019

Transient Supersolid Properties in an Array of Dipolar Quantum Droplets

Fabian Böttcher, Jan-Niklas Schmidt, Matthias Wenzel, Jens Hertkorn, Mingyang Guo, Tim Langen, and Tilman Pfau

Phys. Rev. X 9, 011051 (2019)

Published March 22, 2019

A lot of excitement in the scientific community!

Outlook

More than 20 years after their discovery, ultracold quantum gases are still a very exciting field of research.

With relatively simple experiments, we can test fundamental phenomena and create known or exotic quantum materials.

A relatively small international community, with lots of interactions.