

Quantum gases in bubble traps

Romain Dubessy

CIML group, PIIM Laboratory, Aix-Marseille University
collaboration with: BEC group, LPL, Université Sorbonne-Paris Nord

Frontiers in ultracold quantum gases
10 – 12 June 2026 – Menorca



Motivation: why studying quantum gases bubbles ?

Bubble (physics)

Article [Talk](#)

From Wikipedia, the free encyclopedia

A **bubble** is a **globule** of a **gas** substance in a liquid. In the opposite case, a globule of a liquid in a gas, is called a **drop**.^[1]

among other examples:



A soap **bubble** is a **closed surface** separating two volumes of air. It exists because of *surface tension*.

The atmosphere is also a closed surface!



What would happen with a **superfluid** atmosphere ?

- ⇒ Unfortunately quantum gases are usually not *liquids*: no surface tension!
- ⇒ However we can trap them on two-dimensional surfaces...

See L. Chomaz's talk to discover the surprising properties of quantum liquids

- 1) Brief introduction to quantum gases
- 2) How to make a bubble trap ?
- 3) Superfluid dynamics on a curved surface

R. Dubessy & H. Perrin, *Quantum gases in bubble traps*, *AVS Quantum Sci.* **7**, 010501 (2025)

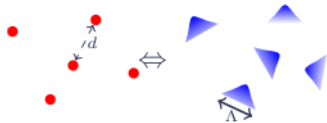
A. Tononi & L. Salasnich, *Shell-shaped atomic gases*, *Physics Reports* **1072** 1 (2024)

N. Lundblad & et al., *Perspective on quantum bubbles in microgravity*, *Quantum Sci. Technol.* **8**, 024003 (2023)

Brief introduction to quantum gases

What are ultra-cold atoms ?

Quantum mechanics:
particles behave as **waves**.



De Broglie (1923)

$$n \sim \frac{1}{d^3} \quad \Lambda = \frac{h}{\sqrt{2\pi M k_B T}}$$

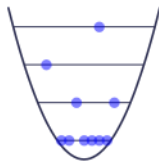
Need a trap and advanced cooling techniques



Cornell, Ketterle & Wieman (Nobel 2001)

R. Dubessy

Quantum statistics:
bosons accumulate in
the lowest energy level



$$n\Lambda^3 > 2.61$$

- ⇒ laser cooling
- ⇒ magnetic / optical traps
- ⇒ evaporation



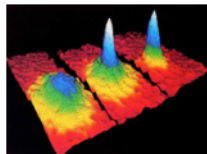
Bose & Einstein (1925)



Chu, Cohen-Tannoudji & Phillips (Nobel 1997)

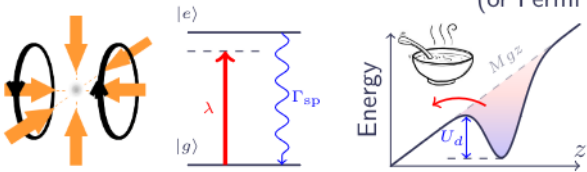
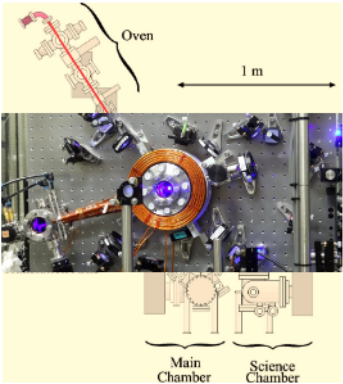
First BEC achieved in 1995
Sodium & Rubidium
Giant matter wave

Since then: Li, H, He, K, Cs, Cr, Yb, Ca, Sr, Dy, Er, molecules, ...
including **degenerate Fermi gases** "Fermi sea"



How to produce ultra-cold gases ?

Path: MOT \Rightarrow optical molasses \Rightarrow conservative trap \Rightarrow evaporative cooling to BEC (or Fermi sea)



Stage	$n \text{ (cm}^{-3}\text{)}$	$v \text{ or } T$	$\text{PSD} = n\Lambda^3$
Oven @400 K	10^{13}	350 m/s	10^{-14}
Slowed beam	10^7	40 m/s	10^{-18}
MOT	10^{10}	150 μK	10^{-7}
c-MOT	10^{11}	300 μK	4×10^{-7}
Molasses	10^{11}	10 μK	6×10^{-5}
Conservative trap	10^{11}	500 μK	2×10^{-7}
BEC / Fermi sea	3×10^{13}	<500 nK	2.61

MIT, 2006, Rubidium

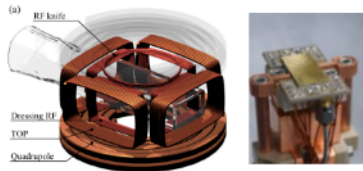
[Ketterle et al., *Making, probing and understanding BECs* (1999)]

Examples of traps for ultra-cold atoms

Magnetic traps

$$V(\mathbf{r}) = -\langle \hat{\boldsymbol{\mu}} \cdot \mathbf{B}(\mathbf{r}) \rangle \propto |\mathbf{B}(\mathbf{r})|$$

⇒ trap near a local minimum of B-field

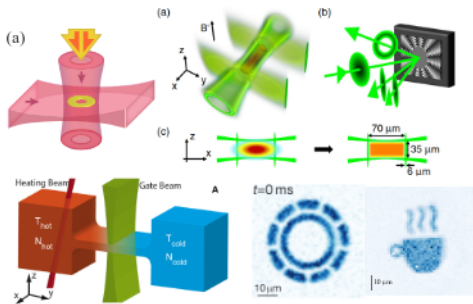


$$V(\mathbf{r}) = \frac{M}{2} (\omega_x^2 x^2 + \omega_y^2 y^2 + \omega_z^2 z^2)$$

Optical traps

$$V(\mathbf{r}) = -\langle \hat{\mathbf{d}} \cdot \mathbf{E}(\mathbf{r}) \rangle \propto I(\mathbf{r})$$

⇒ trap near local extrema of intensity



pros

- ⇒ easy & stable
- ⇒ extremely smooth

[Oxford, Paris, ...]

R. Dubessy

cons

- ⇒ large scale only
- ⇒ bulky

pros

- ⇒ highly versatile
- ⇒ uniform

cons

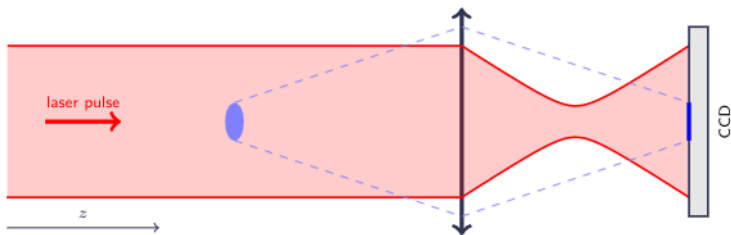
- ⇒ heating & stability
- ⇒ rugosity

[NIST, Cambridge, Zurich, Paris, ...]

Frontiers in ultracold quantum gases

7 / 30

How to probe quantum gases ?



Record the *shadow* of the cloud on the camera.

⇒ in situ

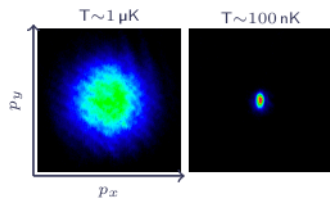
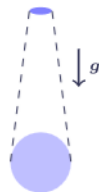
⇒ after a time-of-flight

mapping: $\mathbf{r} = \mathbf{r}_0 + \mathbf{v}t \Rightarrow$ access to momentum distribution.

$$n_{2D}(x, y) = \int dz n(\mathbf{r})$$

Thermal gas: $\Delta p_x = \Delta p_y = \sqrt{Mk_B T}$

Condensate: $\Delta p_x = \frac{\hbar}{2\Delta x} \neq \Delta p_y$



Superfluid properties ?

Quantum fluids are superfluids:

- ⇒ no viscosity
- ⇒ irrotational flow

critical velocity v_c
quantum vortices

simple model: **nonlinear** Schrödinger equation

$$i\hbar \frac{\partial \psi}{\partial t} = \left(-\frac{\hbar^2 \nabla^2}{2M} + V(\mathbf{r}, t) + g|\psi|^2 - \mu \right) \psi$$

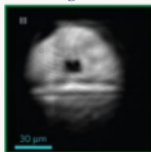
Classical fluid



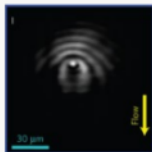
Wikimedia: wake of a boat

Quantum fluid

$v < v_c$



$v > v_c$

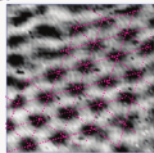
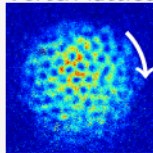


[Amo et al., Nat. Phys. (2009)]

No wake for $v < v_c$!

(generally: $v_c \leq v_{\text{sound}}$)

Vortex lattices:



rotating superfluid, LPL

superconductor

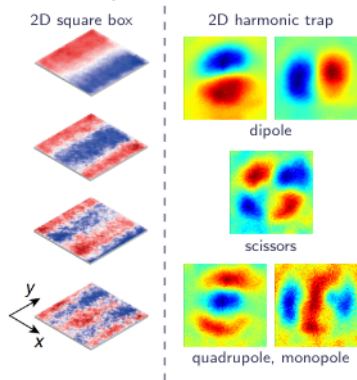
[Guillamón et al., Nat. Phys. (2009)]

quantized vorticity

Superfluid flow **without dissipation** (for $v \leq v_c$)
Rotating superfluid is analogous to a **superconductor**

Experiments with superfluids

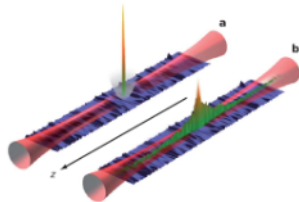
Small amplitude waves



(low energy excitation spectrum)

[Galka et al., PRL (2022), Dubessy et al., NJP (2014)]

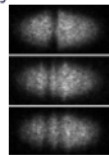
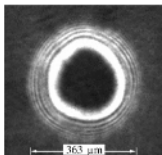
Anderson localization



[Billy et al., Nature (2008)]

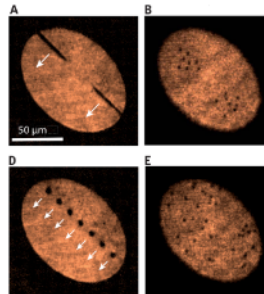
Dispersive shock waves

& grey solitons



[Hoefer et al., PRA (2006), Burger et al., PRL (1999)]

Vortex turbulence



[Gauthier et al., Science (2019)]

How to make a bubble trap ?

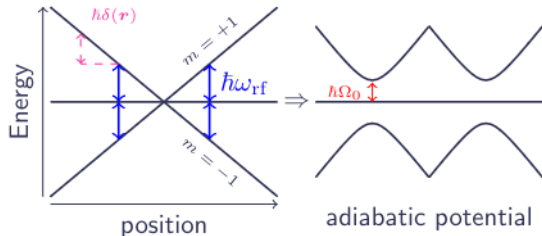
Two-Dimensional Atom Trapping in Field-Induced Adiabatic Potentials

O. Zobay and B.M. Garraway

Sussex Centre for Optical and Atomic Physics, University of Sussex, Brighton BN1 9QH, United Kingdom
(Received 8 March 2000; revised manuscript received 20 October 2000)

We show how to create a novel two-dimensional trap for ultracold atoms from a conventional magnetic trap. We achieve this by utilizing rf-induced adiabatic potentials to enhance the trapping potential in one direction. We demonstrate the loading process and discuss the experimental conditions under which it might be possible to prepare a 2D Bose condensate. A scheme for the preparation of coherent matter-wave bubbles is also discussed.

Example for a spin 1 atom:



Key ideas

- \Rightarrow static magnetic trap $B_0(\mathbf{r})$
- \Rightarrow rf field $B_{\text{rf}} \cos \omega_{\text{rf}} t$
- \Rightarrow avoided crossing $\hbar\Omega_0$

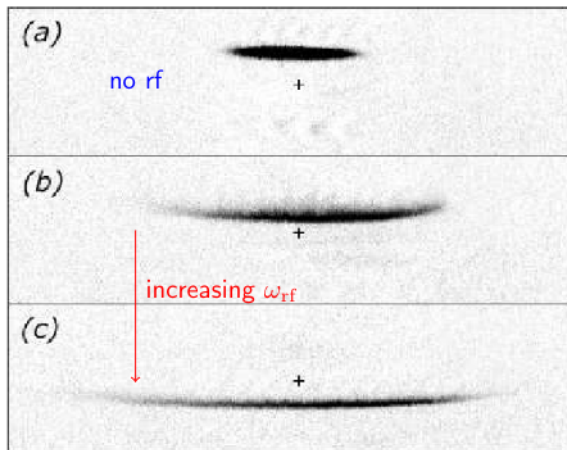
$$V(\mathbf{r}) = \hbar \sqrt{\delta(\mathbf{r})^2 + \Omega_0^2}$$

The atoms are trapped on the resonant **isomagnetic surface**

$$\delta(\mathbf{r}) = 0 \Leftrightarrow \hbar\omega_{\text{rf}} = g\mu_B |\mathbf{B}_0(\mathbf{r})|.$$

Early implementation

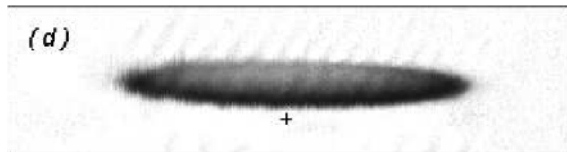
About 10^6 Rb atoms at $5\ \mu\text{K}$ loaded in the adiabatic potential.



Problem: the gravity pulls down the atoms

$$V(\mathbf{r}) = \hbar\sqrt{\delta(\mathbf{r})^2 + \Omega_0^2} + Mgz$$

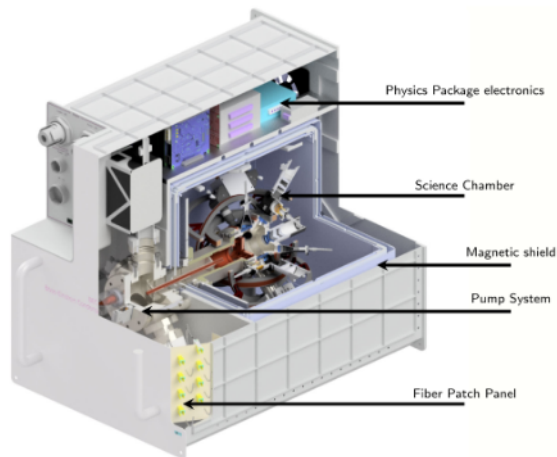
One solution: overcome gravitational potential with kinetic energy.



Adiabatic potential loaded with thermal atoms at $35\ \mu\text{K}$

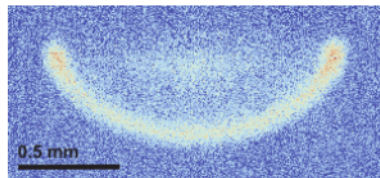
The straightforward solution: remove gravity

Gravity pulls the atoms to the bottom of the bubble \Rightarrow go to micro-gravity



[Frye et al., EPJ Quant. Tech. (2021)]

The international space station hosts a **compact** ultracold atom laboratory.



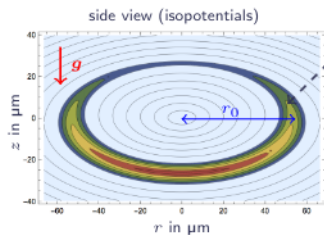
\Rightarrow ultracold thermal atoms (100 nK)

\Rightarrow loaded in an adiabatic potential

limited to an hemisphere
by magnetic field in-homogeneities

[Carollo et al., Nature (2022)]

Gravity compensation on earth



ellipsoid shape

$$\ell^2 = r^2 + 4z^2 \simeq r_0^2$$

inhomogeneous coupling

$$\Omega(\mathbf{r}) = \frac{\Omega}{2} \left(1 - \frac{2z}{\ell}\right)$$

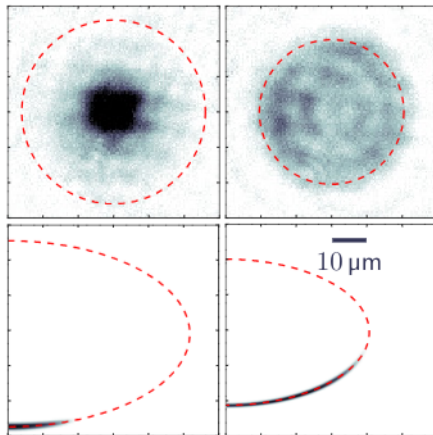
$$V(\mathbf{r}) = \hbar\sqrt{\delta(\mathbf{r})^2 + \Omega(\mathbf{r})^2} + Mgz$$

On the resonant surface $\ell = r_0 \Leftrightarrow \delta(\mathbf{r}) = 0$:

$$V(\mathbf{r}) = \frac{\hbar\Omega}{2} + \left(Mg - \frac{\hbar\Omega}{r_0}\right)z$$

[Guo et al., NJP (2022)]

Gravity can be compensated by varying the bubble radius r_0 !



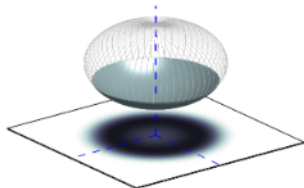
quantum gas on a curved surface

The challenges for adiabatic potentials

Loading a shell-shaped adiabatic potential requires:

- ⇒ cancelling gravity
- ⇒ nearly **perfect control** of inhomogeneities
- ⇒ ultimate limitation: non uniform curvature

levitation, micro-gravity
very small energy scales
accumulation at the equator



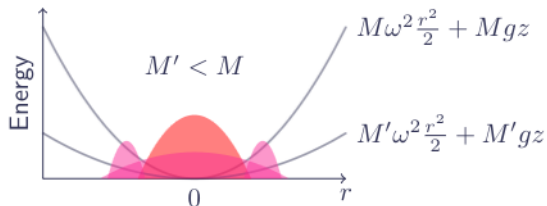
Convenient tool to study **2D quantum gases** & **superfluidity**

(last part of this talk & S. Sunami's talk)

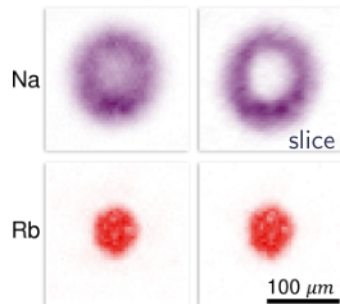
An alternative and successful approach

Key idea: use a mixture of quantum gases, in the **immiscible phase**

[Ho et al., PRL (1996), Pu et al., PRL (1998), Wolf et al., PRA (2022)]



Works for a Na-Rb mixture trapped by $\lambda = 946$ nm lasers.



Requirements

⇒ nearly spherical harmonic trap

(crossed dipole trap)

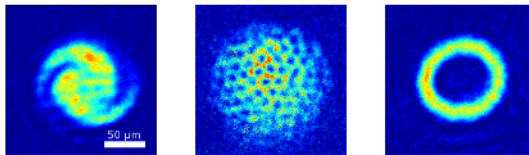
⇒ identical trap frequency for both species

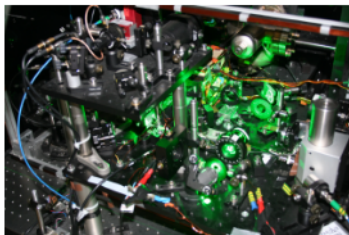
(same gravitational sag)

⇒ immiscible phase: $g_{12}^2 > g_{11}g_{22}$

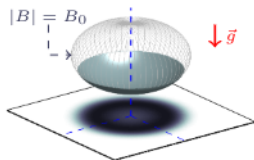
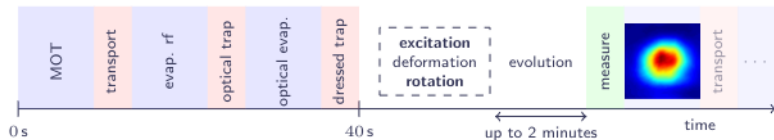
[Jia et al., PRL (2022)]

Superfluid dynamics on a curved surface





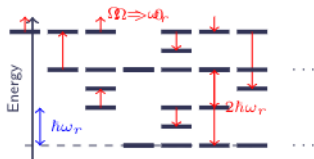
- ⇒ laser cooling to $T \sim 100 \mu\text{K}$
magneto-optical trap
- ⇒ trap the atoms ^{87}Rb
adiabatic potential
- ⇒ reach the **quantum** regime $n\Lambda^3 > 1$
evaporation
 $T \sim 100 \text{ nK}$



Group expertise: control of atoms with rf & magnetic fields

Rotation in a 2D harmonic trap: simulation of quantum Hall physics

See S. Nascimbène's talk for more quantum Hall physics



Landau levels hamiltonian

[Schweikhard et al. PRL (2004),
Fletcher et al. Science (2021)]

When $\Omega = \omega_r$: the centrifugal force
cancels the trapping force
Add a **quartic term** : stabilizes the cloud

$$V(r) = \frac{M\omega_r^2}{2}r^2(1 + \kappa r^2)$$

[Bretin et al. PRL (2004)]



omnium, wikimedia

We may reach the **fast rotation** regime in a bubble trap.

⇒ use a weakly elliptic rf polarization

⇒ angle & amplitude are fully controlled

$$\theta(t) = \Omega_{\text{stir}} t.$$

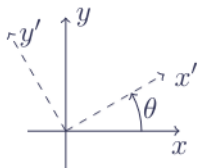
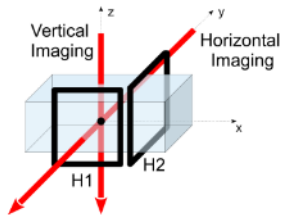
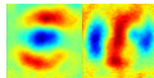
$$V_{\text{trap}} \simeq \frac{M}{2} \omega_r^2 [(1 + \epsilon)x'^2 + (1 - \epsilon)y'^2]$$

⇒ couples to the BEC quadrupole mode

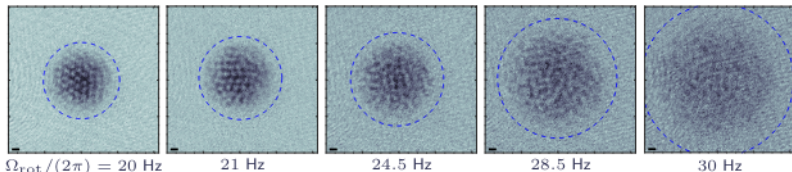
⇒ resonant coupling for:

$$\Omega_{\text{stir}} = \frac{\omega_r}{\sqrt{2}} \simeq 2\pi \times 24 \text{ Hz}$$

[Chevy et al. PRL 2000, Abo-Shaeer et al. Science 2001]



Increasing Ω_{rot} ... **disordered lattice**... **melting** ?



$\Omega_{\text{rot}}/(2\pi) = 20 \text{ Hz}$

21 Hz

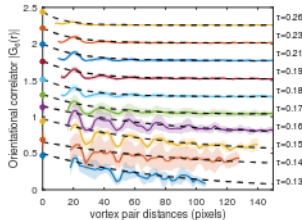
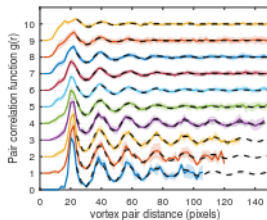
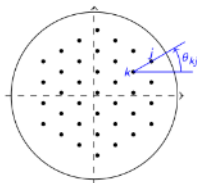
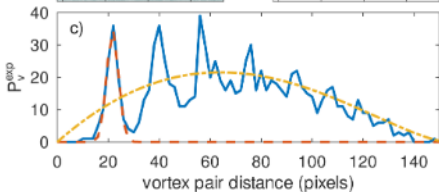
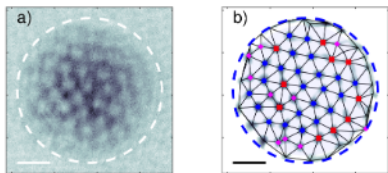
24.5 Hz

28.5 Hz

30 Hz

Blue dashed circle: Thomas-Fermi radius after 27 ms time-of-flight

$\epsilon = 0.18$



Study vortex lattice order:

⇒ pair correlation function decay $g(r)$

⇒ lattice order parameter: $\psi_6(\mathbf{r}_k) = \frac{1}{N_v} \sum_{j=1}^{N_v} e^{i6\theta_{kj}}$

⇒ orientational correlator

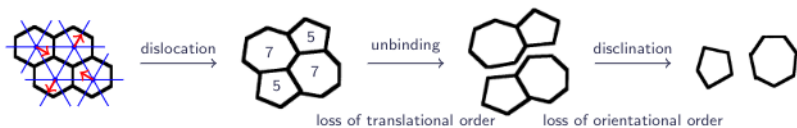
$$G_6(r) = \langle \psi_6(\mathbf{r}_k)^* \psi_6(\mathbf{r}_p) \rangle_{|\mathbf{r}_k - \mathbf{r}_p| \sim r}$$

We evidence a transition from
a **hexatic phase** to a **liquid** (of vortices)

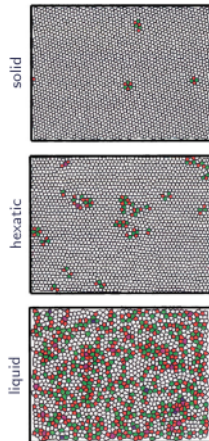
A generic melting scenario in 2D

Prediction of a two-step melting scenario:

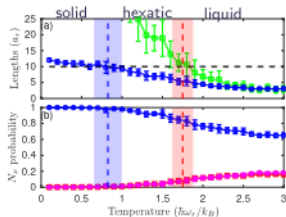
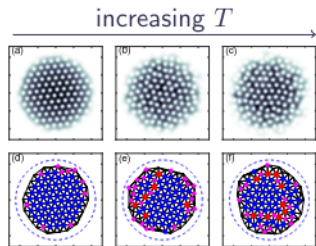
(Kosterlitz-Thouless-Halperin-Nelson-Young)



Observed in colloids:



Study with a **classical field simulation**:



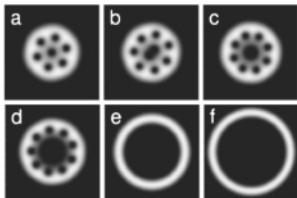
[Bereta et al., accepted in NJP (2026)]

[Marcus & Rice PRE 1997]

Similar results in other type of 2D crystals: type-II supra, dusty plasmas, ...

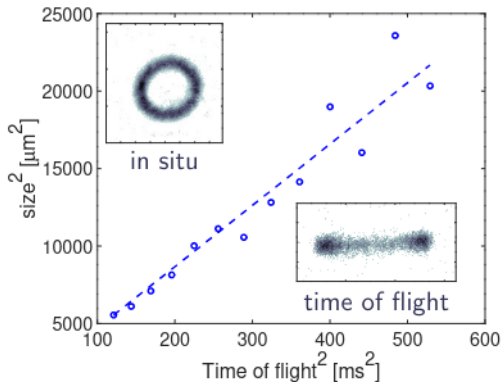
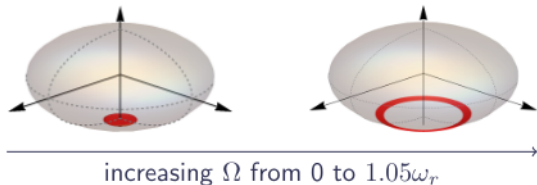
Rotating faster: the dynamical ring regime

In a harmonic plus quartic trap, a transition to a giant vortex is expected for increasing Ω .



[Fetter et al., PRL (2005)]

In the bubble trap we expect a similar feature:

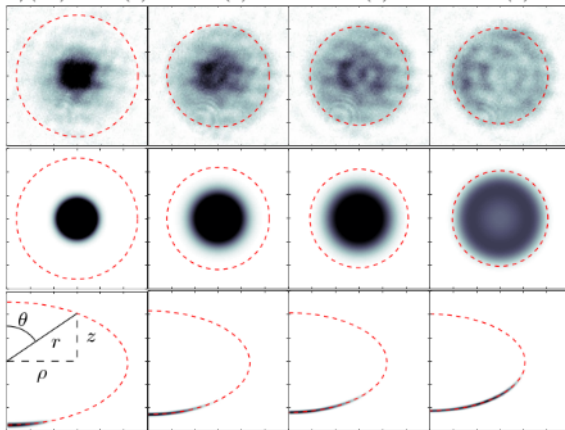


The ballistic expansion gives: $v \simeq 7.4 \text{ mm/s}$
and the peak density $c_0 \simeq 0.4 \text{ mm/s}$
 \Rightarrow a **stable Mach 18 supersonic superfluid**.

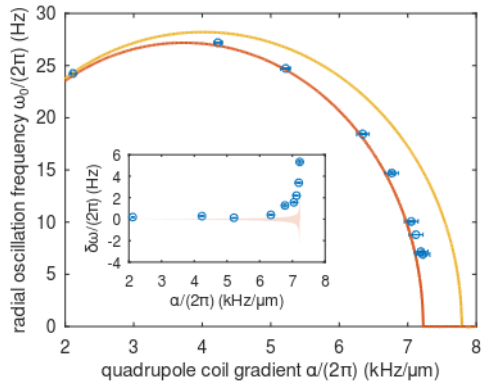
[Guo et al., PRL (2020)]

Reducing $r_0 = \omega_{\text{rf}}/\alpha$ by increasing α .

$\alpha/(2\pi) = 5.77(7)$ 6.86(8) 7.13(8) 7.34(8)

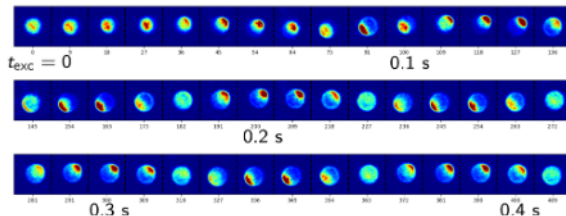
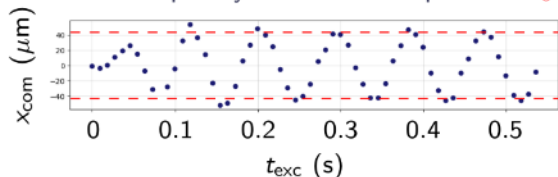


We expect a softening of the center of mass motion as we compensate gravity.



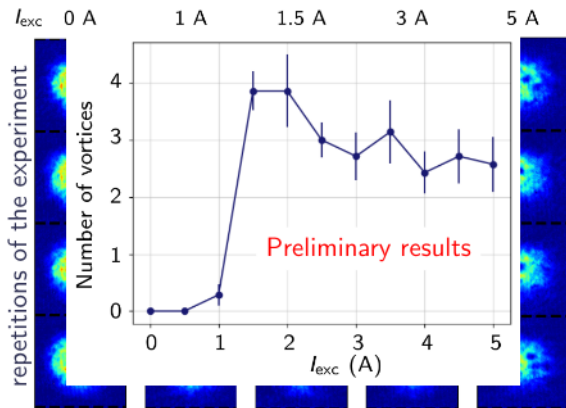
Damping and vortex nucleation

For strong excitation $I_{exc} = 4$ A the center of mass motion quickly reaches the equator $\pm r_0$.



The cloud density is strongly deformed.

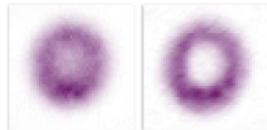
We observe the nucleation of vortices above a critical excitation amplitude



See M. Caracanhas' talk for the role of curvature in vortex dynamics

Summary

- ⇒ quantum gases in bubble traps **have been realized**
- ⇒ adiabatic potentials enable studies on a **smooth curved surface**



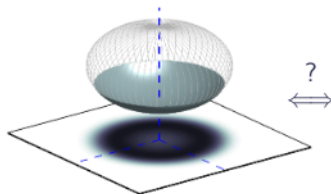
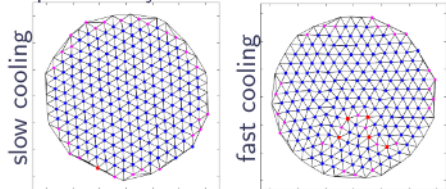
Melting of large vortex lattices

- ⇒ role of curvature ?
- ⇒ 2D to 3D crossover ?
- ⇒ temperature quenches ?

Shaken bubble trap

- ⇒ route to vortex turbulence ?
- ⇒ weak wave turbulence ?
- ⇒ compare to flat 2D superfluids

preliminary classical field simulations



[Gałka et al., PRL (2022)]



Perspectives

Theoreticians have suggested many ideas for quantum gases in bubble traps:

⇒ in a **rotating frame**: point vortex & effective models, vortex lattices, large scale flows, ...

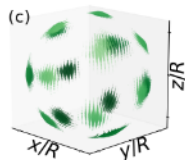
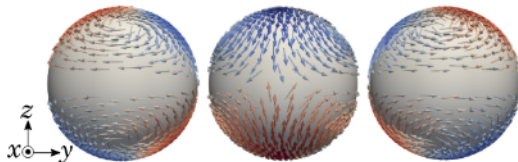
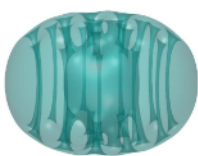
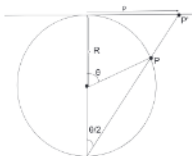
[Bereta et al., PRA (2021), Biral et al., NJP (2024), White, PRA (2024), Saito & Hayashi, JPSJ (2023)]

⇒ changing the **interactions**: Fermi gases, Faraday waves in mixtures, supersolids, ...

[He & Chien, PRA (2023), Brito et al., PRA (2023), Ciardi et al., PRL (2024)]

⇒ out of equilibrium properties (see B. Rhyuo's talk)

[Tononi et al., PRA (2025)]



Efficient routes to **controlled** vortex *nucleation* ?

Recently approved quantum institute: **QuantA**

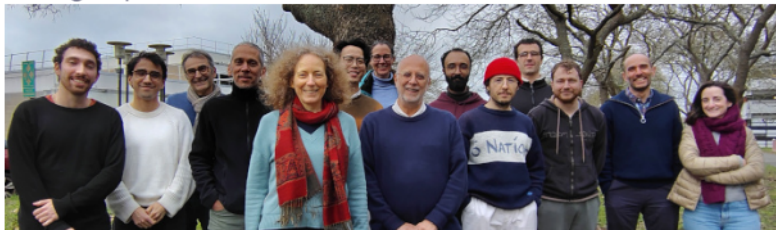


- ⇒ 1.5 M€ funding for 5 years (2026–2030)
- ⇒ interdisciplinary institute
physics, chemistry, mathematics, computer science, ...
- ⇒ PhD & post-docs opportunities
- ⇒ scholarships, visiting professors, summer schools



Thanks

BEC group at LPL & collaborators



From left to right: P. Minarelli, R. Vatré, L. Longchambon, T. Badr, H. Perrin, Z. Yao, S. Cuk, V. Bagnato, P. Diniz, M. Cassus, M. Pesche, B. Mirmand, A. Perrin, P. Castilho.



Y. Guo, S. Bereta, D. Rey, R. Sharma, M. Caracanhas, L. Madeira, M. Tsubota, S. Nazarenko

and thank you for your attention !

Funding

amidex Aix
Marseille
Université

anr FRANCE
2030

QUANTIP Région
Île de France

FAPESP COFECUB

UNIVERSITÉ
SORBONNE
PARIS NORD

cnrs