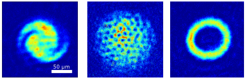
A two-dimensional superfluid on a curved surface

from supersonic rotation to gravity compensation



Romain Dubessy & BEC group

Laboratoire de physique des lasers, CNRS UMR 7538
Université Sorbonne Paris Nord, Villetaneuse, France

Prospects of Quantum Bubble Physics - April 6-7 2022

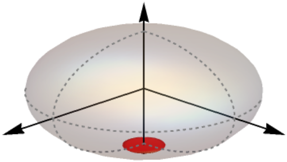
Physics in a bubble

the dressed quadrupole trap

Adiabatic potentials for rf-dressed atoms

Atoms are confined to an isomagnetic surface of a quadrupole field.

- local B and rf fields: atomic spin follows adiabatically a local eigenstate
- strong confinement to the surface
- smooth surface potentials

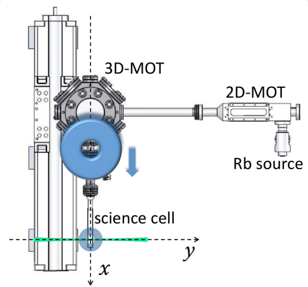


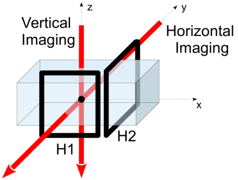
[reviews Garraway/Perrin 2016 & 2017]

This talk: quasi 2D superfluid on the surface of the bubble trap

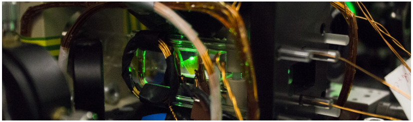
The Rb experiment at Villetaneuse

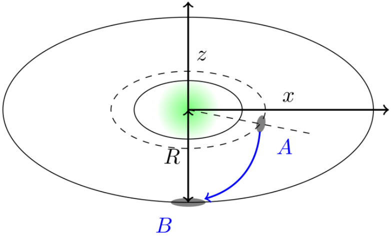
From a plugged quadrupole trap to an adiabatic potential





lifetime up to 120 s





[Dubessy PRA 2012, Merloti NJP 2013]

The Rb experiment at Villetaneuse

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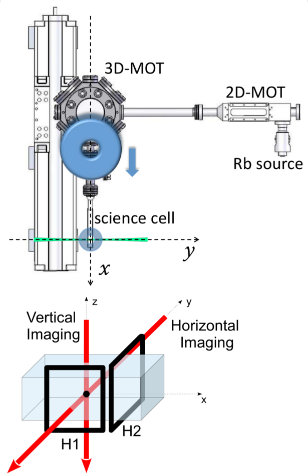

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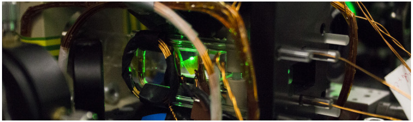
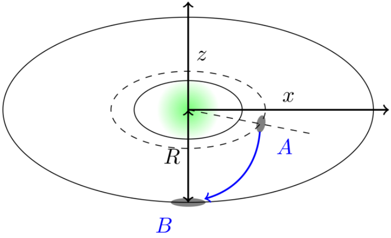
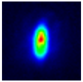






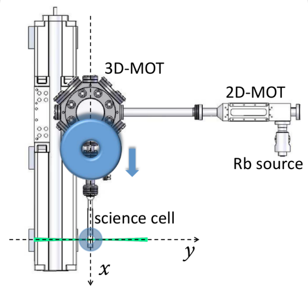
$N_{\mathrm{bec}} \sim 2 \times 10^5$

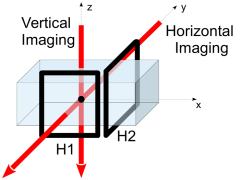
$T \sim 100\ \mathrm{nK}$

[Dubessy PRA 2012, Merloti NJP 2013]

The Rb experiment at Villetaneuse

From a plugged quadrupole trap to an adiabatic potential





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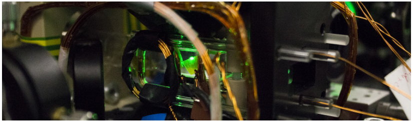

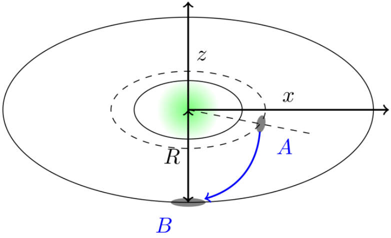

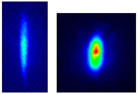

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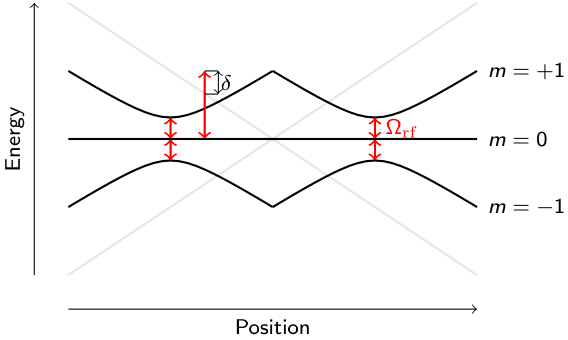
[Dubessy PRA 2012, Merloti NJP 2013]

The dressed quadrupole trap

Dressing the spin states

quadrupole field: $\boldsymbol{B}_0 = b'(x\boldsymbol{e}_x + y\boldsymbol{e}_y - 2z\boldsymbol{e}_z)$ & rf photons



Follow the spin states: ^{87}Rb $F = 1$

- bare basis
- to dressed states
- find level crossings
- rf coupling lifts degeneracy

Adiabatic potential: $V = \hbar\sqrt{\delta(\boldsymbol{r})^2 + \Omega_{\mathrm{rf}}(\boldsymbol{r})^2}$ (RWA)

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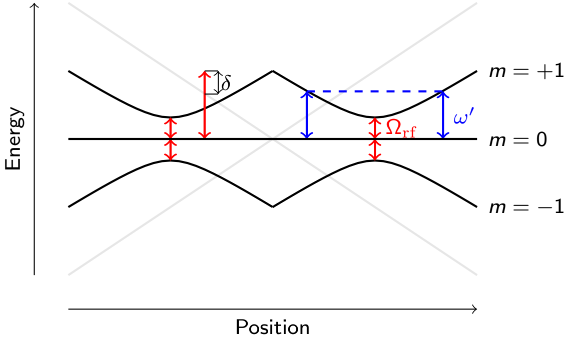

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Further control the trap with additional rf fields.

Trapping atoms on a surface

A smooth two-dimensional trap

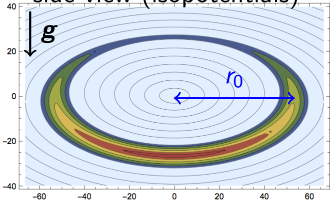
$\Omega_{\rm rf} \sim$ 50-100 kHz

$\omega_z \propto \dfrac{b'}{\sqrt{\Omega_{\rm rf}}} \sim$ 0.3-2 kHz

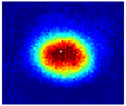
$\omega_x, \omega_y \propto \sqrt{\dfrac{g}{r_0}} \sim$ 20-50 Hz

$r_0 \propto \omega_{\rm rf}/b' \sim$ 20-200 μm

side view (isopotentials)

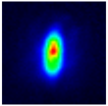


top view



in situ

side view



tof

- very flat $\omega_z \gg \omega_{x,y}$
- in-plane anisotropy $\eta = \dfrac{\omega_x}{\omega_y}$ controlled through rf polarization:
- rotationally invariant $(\eta = 1)$ for a σ^+ polarization along z
- anisotropic $(\eta \neq 1)$ for linear horizontal polarization

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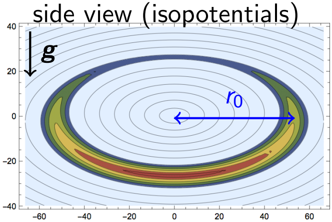

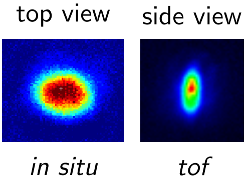

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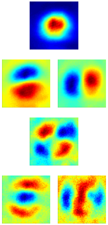
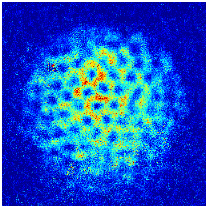
- in-plane anisotropy $\eta = \frac{\omega_x}{\omega_y}$ controlled through rf polarization:
- rotationally invariant ($\eta = 1$) for a σ^+ polarization along z
- anisotropic ($\eta \neq 1$) for linear horizontal polarization
- geometry can be modified dynamically
- ideal for the study of the 2D trapped gas dynamics

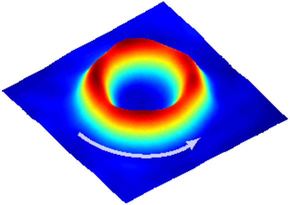


[Dubessy NJP 2014]

Fast rotation in a bubble trap

Fast rotation in a bubble trap

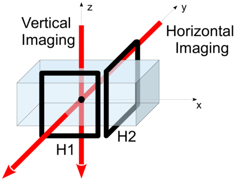


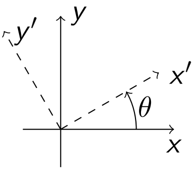


[Guo et al. PRL **124**, 025301 (2020)]

How to rotate ?

Using a quadrupolar deformation





- use a weakly elliptic rf polarization
- angle & amplitude are fully controlled

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

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

- couple to the BEC quadrupole mode
- resonant coupling for:

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

[Chevy PRL 2000, Abo-Shaeer Science 2001]

Other methods:

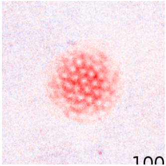
[Schweikhard PRL 2004, Kang PRA 2015, Sherlock 2011, Gildemesiter PRA 2012, Navez NJP 2016, ...]

First attempts at rotating a quasi 2D Bose gas

Increasing the stirring frequency

Vortex lattice. . .

24 Hz



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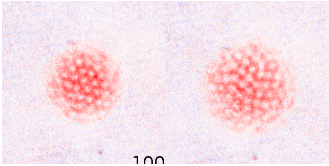

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Vortex lattice. . . disordered lattice. . .

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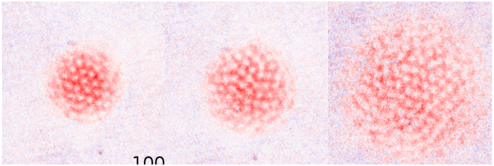

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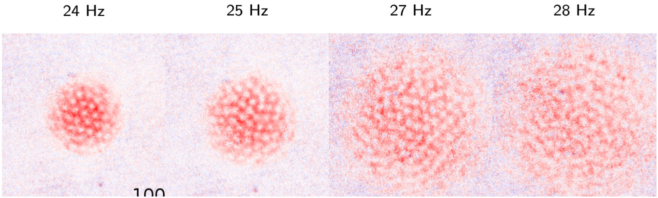

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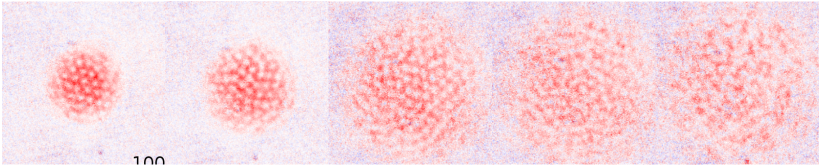

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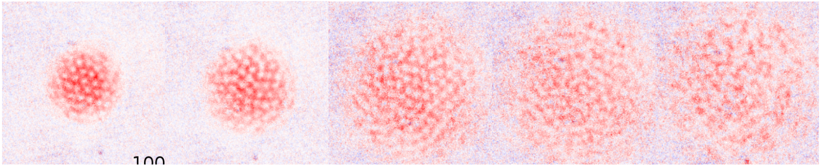
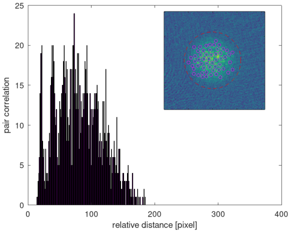




- possible melting of the vortex lattice

  pair correlations: crystal $\rightarrow$ liquid

- can we reach higher rotations ?

  centrifugal force cancels

  the harmonic trapping!

[see also Bretin PRL 2004, Schweikhard PRL 2004]

Anharmonic trap

Fighting the centrifugal force

To restore the trapping potential, add a quartic term to $V(r)$:

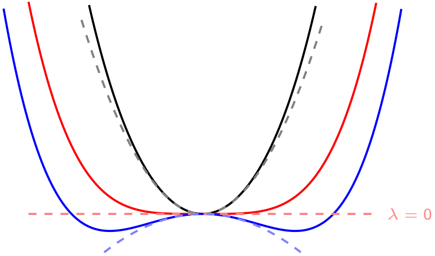
$$V_{\text{eff}}(r) = \frac{m}{2}(\omega_r^2 - \Omega^2)r^2 + \lambda r^4.$$

[Dalibard PRL 2004]

$\Omega = 0$

$\Omega = \omega_r$

$\Omega = 1.15\ \omega_r$



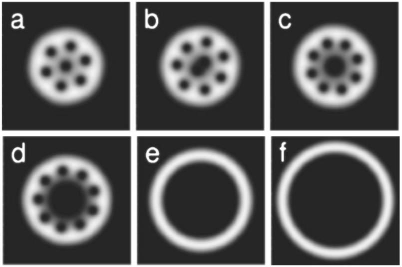
$\Rightarrow$ the bubble trap has higher order terms.

Theoretical predictions

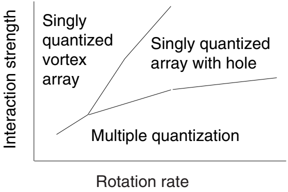
Rotating beyond the trapping frequency

Giant vortex in a harmonic + quartic trap:

vortex lattice



dynamical ring



giant vortex

[Fetter 2005, Kavoulakis / Baym 2003]

(A. White's talk for a shell geometry)

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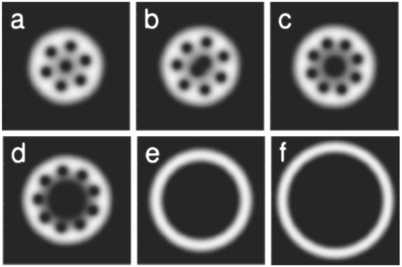

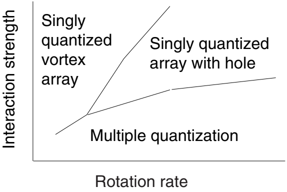

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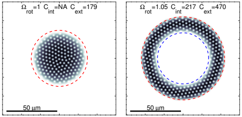
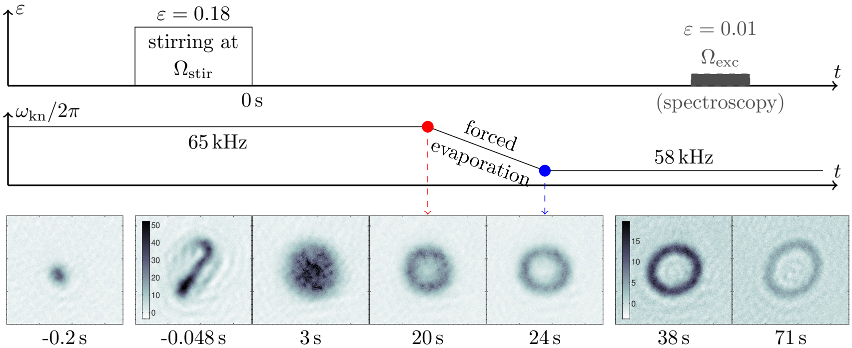


GP simulation for our trap

Creating a dynamical ring

Spin-up evaporation mechanism



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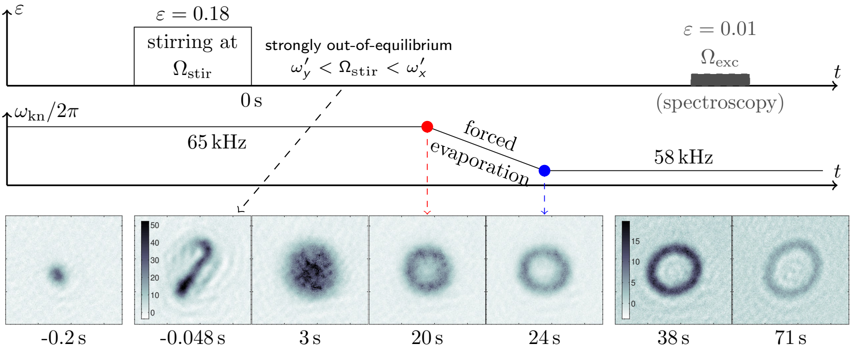

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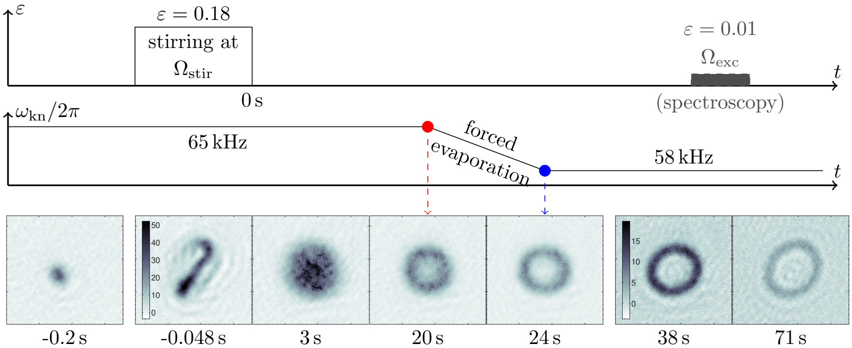
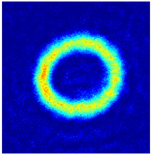
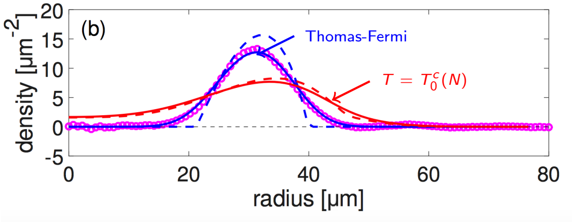


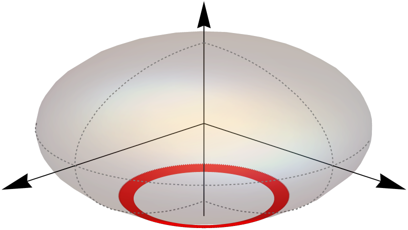
Acceleration of the rotation, full depletion of the center.
(atoms are removed selectively at the center)

A thin ring sustained by its dynamics

Observation of a annular quantum gas stabilized by rotation



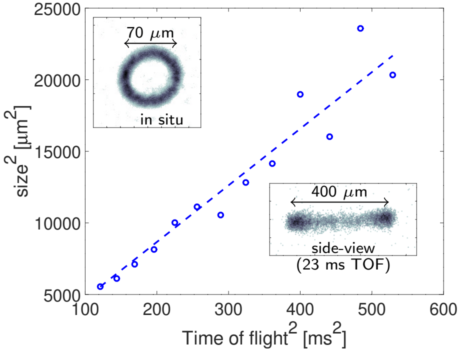




- analysis of the radial profile
  $\Rightarrow$ Thomas-Fermi profile
- what is different from all other rings ?

A supersonic flow

Measuring the rotation from time-of-flight expansion



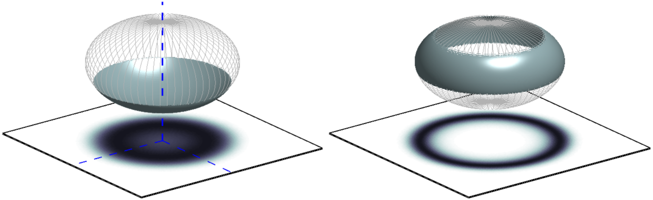
- size^2 scales as t^2_{TOF} (ballistic expansion)
- fit gives: $\Omega \sim 1.05\omega_r$, i.e. $v = 7.4$ mm/s
- peak density $n_0 \sim 15\ \mu\mathrm{m}^{-2}$ $\Rightarrow c_0 = 0.4$ mm/s

A degenerate gaz flowing at Mach 18 !

[see also Pandey Nature 2019] (and W. von Klitzing's talk)

Compensating gravity in a quadrupole dress trap

Compensating gravity in a bubble trap

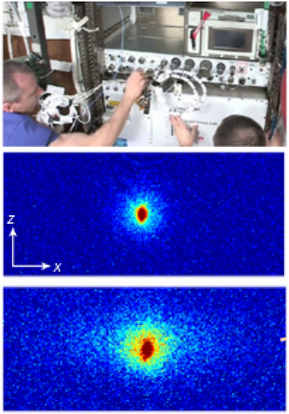


[Guo et al. arXiv:2105.12981 (2021)]

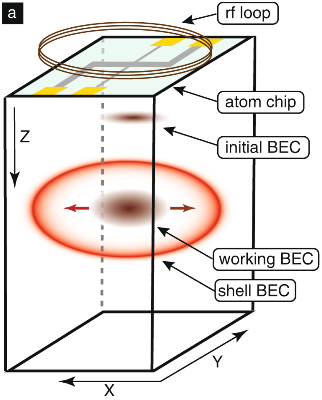
Physics in a bubble

BEC in the ISS

A BEC machine on board the ISS!



[Aveline Nature 2020]



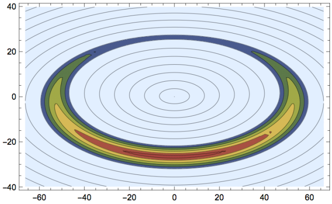
[Lundblad npj Microgravity 2019]

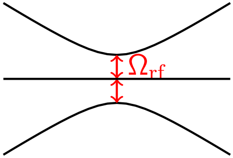
[Sun PRA 2018, Bereta Am. J. Phys. 2019, Tononi PRL 2019 & PRL 2020, Móller NJP 2020, Bereta PRA 2021]

Gravity compensation

Doing bubbles on Earth?

Can't we look for this physics on Earth?





On the shell ($\delta = 0$):

$V = \hbar\Omega_{\mathrm{rf}} + Mgz$

Fighting gravity?

Gravity compensation

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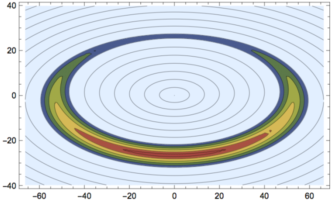

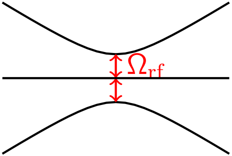

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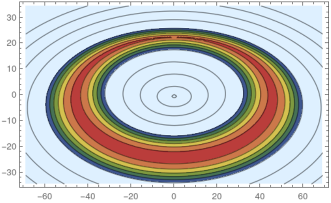
$V = \hbar\Omega_{\rm rf} + Mgz$

Fighting gravity?

- for the choice of a σ^+ rf:

$$\Omega_{\rm rf} = \Omega_0 \left(\frac{1}{2} - \frac{z}{r_0} \right)$$

- effective "anti-gravity" force

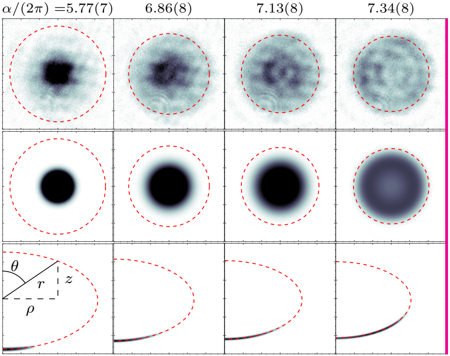


for $\hbar\Omega_0 = Mgr_0$

Pushing the atoms upwards

Experimental results

- Increasing gradient b' i.e. reducing r_0
- Experiment (top view) vs GP ground state (top / side views)



Temperature below 30 nK

(Need to take into account imaging resolution $\sim 4\ \mu$m)

Pushing the atoms upwards

Experimental results

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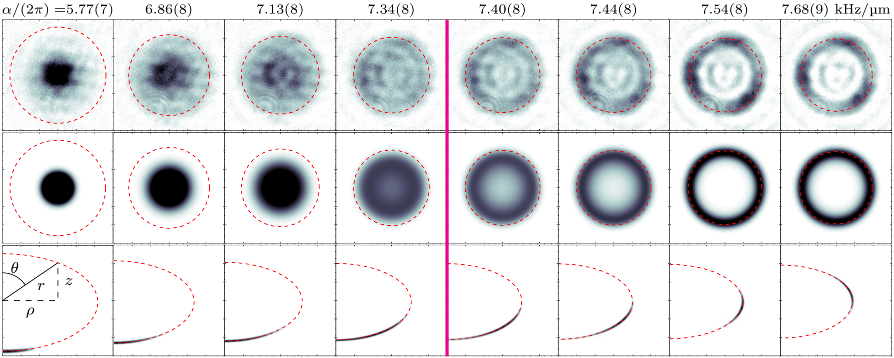


Temperature below 30 nK (Need to take into account imaging resolution $\sim$ 4 μm)

A ring forms! [Guo et al., arXiv:2105.12981]

Why a ring ?

Did we miss something ?

The transverse trapping frequency $\omega_\perp$ is not constant...

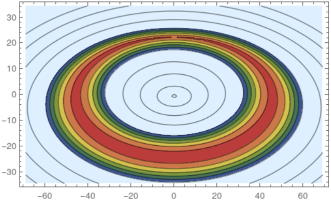
(B. Garraway / N. Móller talks)

$$V = \hbar\Omega_0\left(\frac{1}{2} - \frac{z}{r_0}\right) + Mgz + \frac{\hbar\omega_\perp(z)}{2}$$

(assume the atoms are in the transverse groundstate)

Avoided crossing: $\omega_\perp \sim b'/\sqrt{\Omega_{\rm rf}}$

- $\omega_\perp$ minimal close to the equator
- diverges at the north pole!
  - $\Rightarrow$ repels the atoms from the top

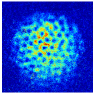


Summary & prospects (I)

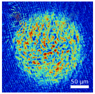
Fast rotations on a shell

A very smooth and tunable shell trap to study fast rotations

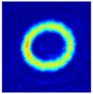
- Observation of vortex lattices



- Vortex lattice melting for $\Omega \sim \omega_r$



- Formation of a long-lived dynamical ring flowing at Mach 18 for tens of second for $\Omega > \omega_r$



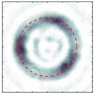
$\Rightarrow$ investigate the decay mechanisms (add an obstacle)
$\Rightarrow$ study the lattice - liquid transition

Summary & prospects (II)

Effect of dimensional reduction on a shell

A novel gravity compensation mechanism

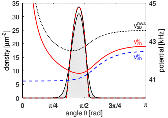
- induces spatial localization (a ring appears)



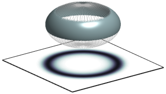
requires a fine tuning of the rf

residual inhomogeneities due to rf gradients

- quantitative agreement requires beyond RWA



- effective potential including zero-point energy



non-separable potential

cannot fill a full bubble... but half of it

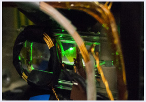
we face similar problems than in the Bubble-CAL experiment

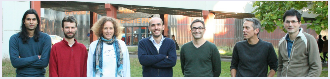
$\Rightarrow$ Combine rotation and gravity compensation to explore vortex physics on a curved surface

The people behind this work

BEC group @ Villetaneuse

H. Perrin





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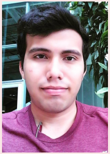

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