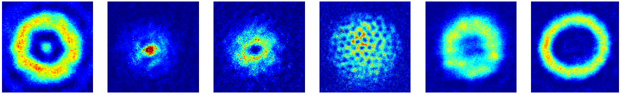
Dynamical ring formed by a superfluid rotating at supersonic speed



Hélène Perrin

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Sorbonne Paris Cité, Villetaneuse, France

Atomtronics — Benasque, May 2019

Outline

Bose-Einstein condensation and superfluidity
A subtle link

Superfluidity is a dynamic property with subtle effects.

- critical velocity v_c for excitation (Landau criterion) $\Rightarrow$ no viscosity

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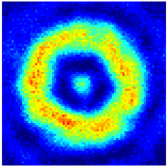

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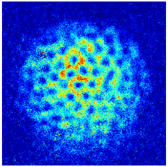

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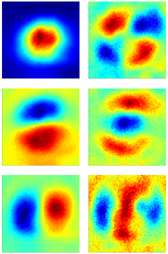

collective modes revealed by PCA [NJP 2014]

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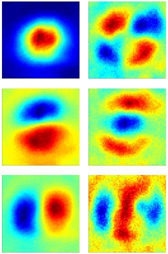
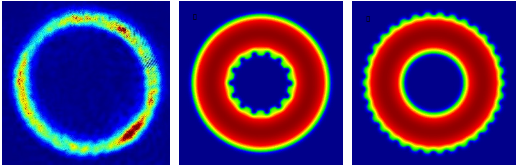


collective modes revealed by PCA [NJP 2014]

In this talk: superfluid rotating in **rings** and **bubbles**.

Annular quantum gases

Annular quantum gases for superfluid dynamics



The ring: basic atomic circuit for quantum transport
Persistent currents and circulation quantization

wave function (analogue to the order parameter in superconductivity):

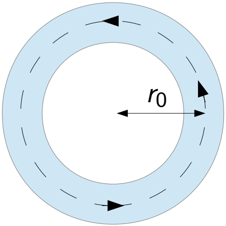
$\psi(r,\theta) = \sqrt{n(r)}\, e^{i\varphi}$

velocity of the flow $v = \frac{\hbar}{M}\nabla\varphi$

ψ is singly valued:

$$\psi(r,\theta) = f(r)\, e^{i\ell\theta}, \quad \ell \in \mathbb{Z}$$

$$\Rightarrow \mathcal{C} = \oint v \cdot ds = \ell \frac{h}{M}, \quad \ell \in \mathbb{Z}$$



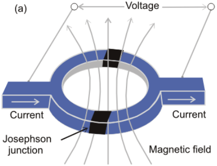
circulation is quantized

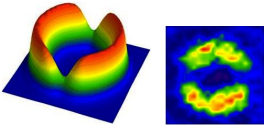
Momentum distribution (Fourier transform) is $|J_\ell(kr_0)|^2$ for non interacting 1D gas.

Analogy with a SQUID

Summary

SQUID	Annular quantum gas
order parameter $\Delta(r)$	wave function $\psi(r)$
pair current	flow
voltage V	chemical potential μ
magnetic field	gauge field (e.g. rotation)
magnetic flux (h/e)	circulation (h/M)
Josephson junction	bosonic junction (barrier)
observable: current	observable: density / winding ℓ





Ryu et al. PRL 2013 [LANL]

Experimental implementation
rf-induced adiabatic potentials – the dressed quadrupole trap

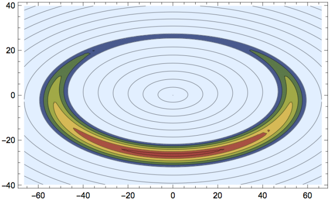
Adiabatic potentials for rf-dressed atoms: dressed quadrupole trap

[see Barry Garraway's talk and reviews Garraway/Perrin: JPB+Advances]

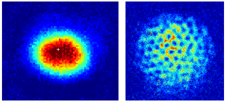
Atoms are confined to an isomagnetic surface of a quadrupole field.

- smooth potentials (magnetic fields with large coils)
- strong confinement to the surface: $\omega_\perp \sim 2\pi \times 1 - 2$ kHz
- geometry (r_0, xy-anisotropy) can be fine-tuned dynamically
- temperature adjusted with a (weak) rf knife (30 – 200 nK)

side view (isopotentials):



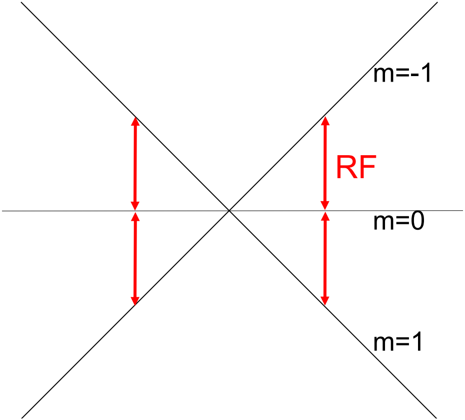
top-view:
a [2D] quantum gas



rf-induced adiabatic potentials

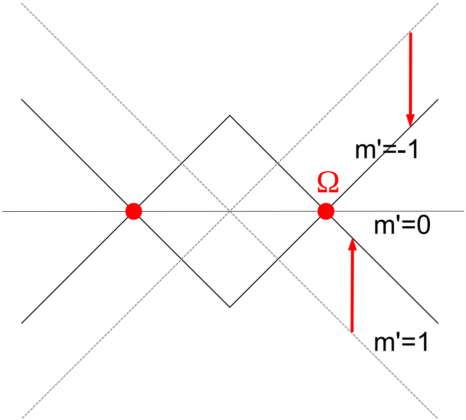
Dressing the atoms

Spin states in a quadrupole field coupled through a rf field...



rf-induced adiabatic potentials
Dressing the atoms

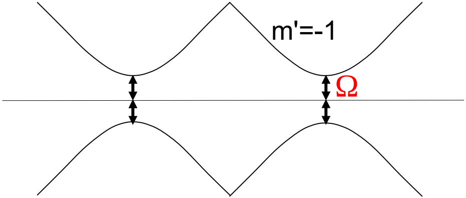
...in the dressed states basis...



rf-induced adiabatic potentials

rf-induced adiabatic potentials

...trap minima at the resonant points = isomagnetic surface.

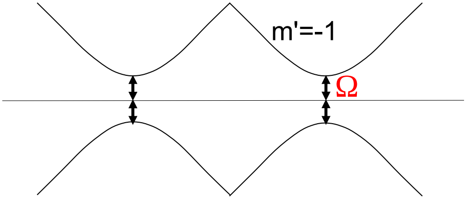


See talk by Barry Garraway

rf-induced adiabatic potentials

rf-induced adiabatic potentials

isomagnetic surfaces: ellipsoids with $r_0 \propto \frac{\omega_{\rm rf}}{b'}$



$$\omega_z \propto \frac{b'}{\sqrt{\Omega}} \sim 350\ \text{Hz-2 kHz} \qquad \omega_x, \omega_y \propto \sqrt{\frac{g}{r_0}} \sim 20\text{-}50\ \text{Hz}$$

in-plane anisotropy $\eta = \frac{\omega_x}{\omega_y}$ controlled through rf polarization

NB: $\eta = 1$ with a circular rf polarization

rf-induced adiabatic potentials

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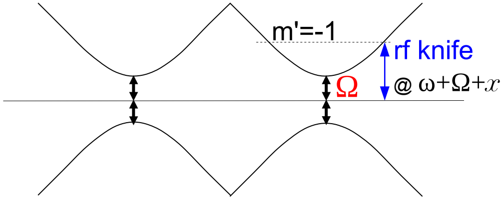

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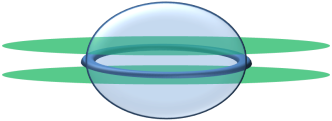
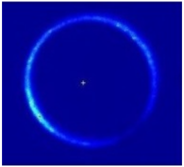
temperature T controlled with a rf knife at $\omega_{\rm rf} + \Omega_{\rm rf} + \omega_{\rm cut}$

Typical figures: $\omega_{\rm rf} = 300$ kHz / $\Omega_{\rm rf} = 50$ kHz / $\omega_{\rm cut} = 10$ kHz

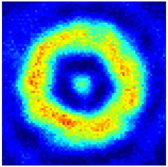
Building a ring trap for superfluid dynamics
How to obtain a ring trap?

'rf bubble' + vertical optical trap = widely tunable ring trap





$r_0 = 125\ \mu\text{m}$



$r_0 = 20\ \mu\text{m}$

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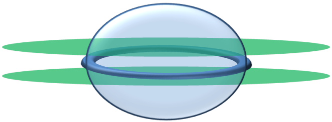

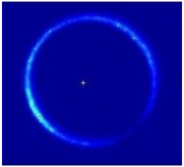

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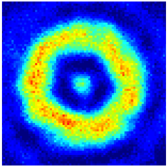
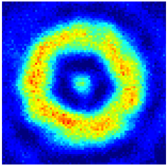
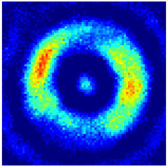


$r_0 = 20\ \mu$m

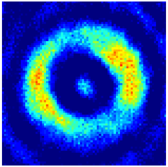
Control of anisotropic trap depth with the rf polarization:



circular



linear at $+\theta_0$



linear at $-\theta_0$

[Morizot/Perrin/Garraway 2006, Heathcote/Foot 2008]

Setting the cloud into rotation

Strategy: realize the Hamiltonian in a frame rotating at Ω:

$$H = H_0 - \Omega L_z.$$

For Ω large enough, states with $\ell \neq 0$ are favoured.

A quadrupole deformation:

ⒸDécors fins

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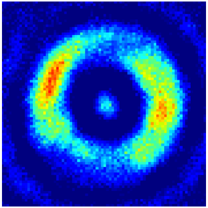
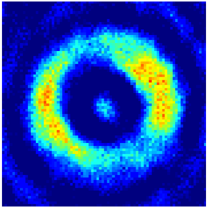


t



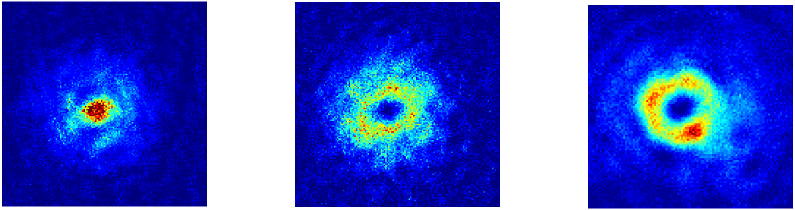
$t + dt$

N.B. Alternative strategy: phase imprinting, see Mark Baker's talk.

Observation of a metastable flow

Observe the gas after a time of flight ⇒ momentum distribution, related to initial phase gradients ⇒ measure phase winding.

$\Omega = 0$ $\Omega > 0$ increasing Ω



The hole in the center is due to destructive interference: $J_\ell(kr_0)$.
Its size increases with ℓ.
⇒ evidence of superfluid persistent current in the ring.
Lifetime = several seconds.

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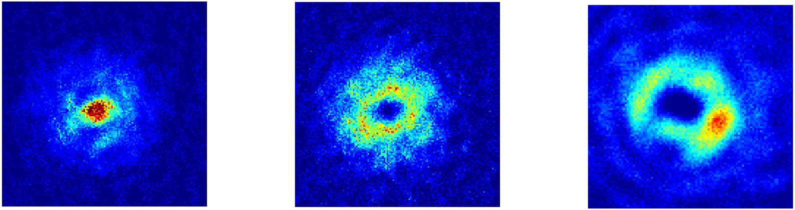

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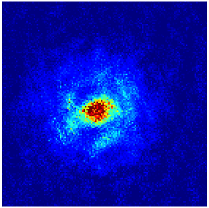

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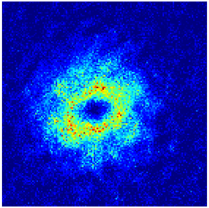
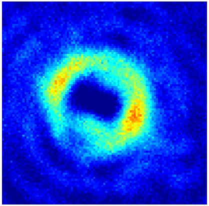


increasing Ω



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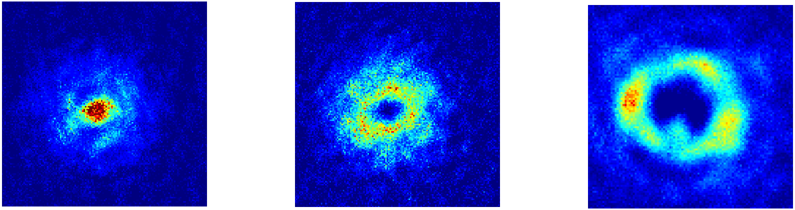

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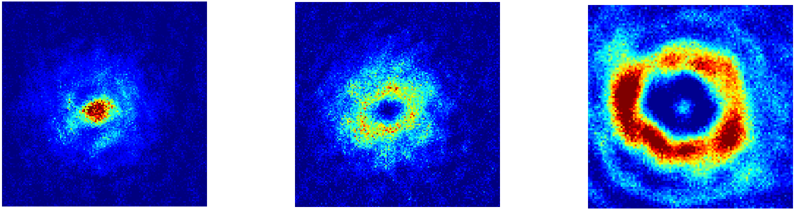

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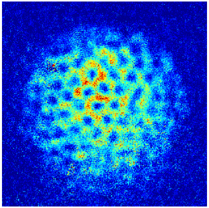
Fast rotation in a bubble trap

Fast rotation in a bubble trap



faster and faster. . .

Rotation and vortices

Rotation of a trapped superfluid

A superfluid cannot rotate like a solid body. Instead, it supports vortices with a zero of density.

A centered vortex has an orbital angular momentum $\hbar$. The number of vortices at a rotation frequency Ω in the steady state is set by the ground state of

$$H_{\mathrm{rot}} = H_0 - \Omega L_z.$$

Vortices lower the energy in the rotating frame through the term $-\Omega L_z$.

Rotation and vortices

Rotation of a trapped superfluid

Using $L_z = (xp_y - yp_x)$, the hamiltonian can be recast as

$$H_{\rm rot} = \frac{(p - q\mathcal{A})^2}{2M} + V(r) - \frac{1}{2}M\Omega^2 r^2$$

where $q\mathcal{A} = 2M\Omega(-y\mathbf{e}_x + x\mathbf{e}_y)$.

- Analogy with a charged particle q in a uniform magnetic field $\mathcal{B} = \nabla \times \mathcal{A} \propto \Omega$.
- Effective potential shallowed by centrifugal potential:

$$V_{\rm eff}(r) = V(r) - \frac{1}{2}M\Omega^2 r^2$$

In a harmonic trap, $V_{\rm eff}(r) = \frac{1}{2}M\omega_r'^2 r^2$ with $\omega_r'^2 = \omega_r^2 - \Omega^2$.

Fast rotation in an harmonic trap

Lowest Landau level

Energy levels of a 2D non interating trapped atomic [electron] gas with rotation Ω [magnetic field $\mathcal{B}$]:

$3\hbar\omega_r$	—		—		—		—
$2\hbar\omega_r$		—		—		—	
$\hbar\omega_r$			—		—		
0				—			

$m = -3 \ldots \quad m = 0 \ldots \quad m = 3$

$$\Omega = 0$$

Fast rotation in an harmonic trap

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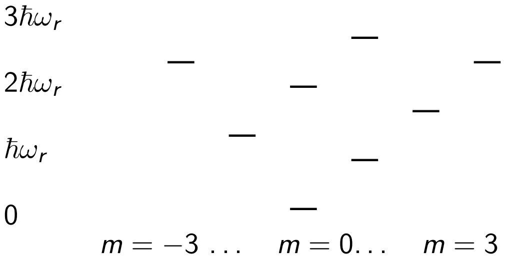

$$\Omega = 0.2\ \omega_r$$

Fast rotation in an harmonic trap

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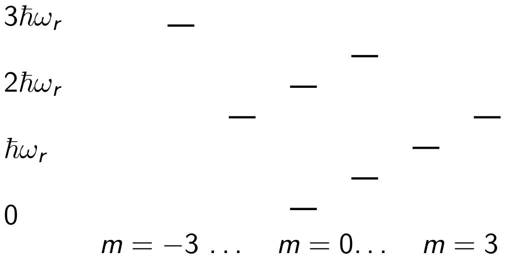
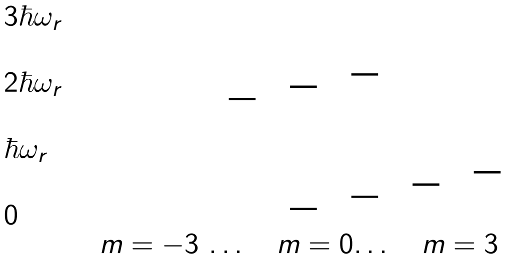


$$\Omega = 0.5\ \omega_r$$

Fast rotation in an harmonic trap

Lowest Landau level

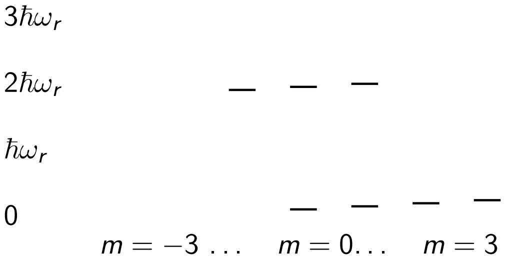
Energy levels of a 2D non interating trapped atomic [electron] gas with rotation Ω [magnetic field $\mathcal{B}$]:



$$\Omega = 0.8\ \omega_r$$

Fast rotation in an harmonic trap
Lowest Landau level

Energy levels of a 2D non interating trapped atomic [electron] gas with rotation Ω [magnetic field $\mathcal{B}$]:



$$\Omega = 0.95\ \omega_r$$

Fast rotation in an harmonic trap

Lowest Landau level

Energy levels of a 2D non interating trapped atomic [electron] gas with rotation Ω [magnetic field $\mathcal{B}$]:

$2\hbar\omega_r$

LLL

Degenerate ground state

$$\Omega \sim \omega_r, \quad N_{\text{vor}} \sim N_{\text{at}}$$

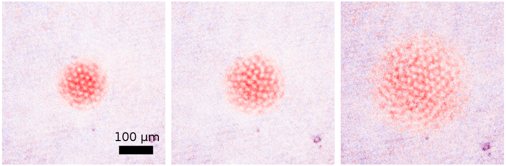
$\Rightarrow$ exploring quantum Hall effect with neutral atoms?

Vortex lattice

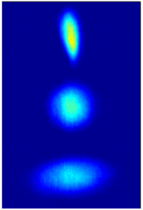
Increasing the rotation frequency

Mind the centrifugal force! ${\omega'_r}^2 = \omega_r^2 - \Omega^2$ vanishes for $\Omega \sim \omega_r$

Absorption images after TOF expansion:



$\Omega = 0.7\ \omega_r$ $\Omega = 0.75\ \omega_r$ $\Omega = 0.8\ \omega_r$



side view

$\Omega = 0$

$\Omega > 0$

$\Omega \nearrow$

The gas spreads as the number of vortices increases.

N.B. The scaling $R_{\rm TOF} \simeq \Omega t_{\rm TOF} \times R_{\rm TF}$ is one possible way to measure the rotation frequency or angular momentum per particle (see Piero Naldesi's talk).

QHE requires $\Omega \sim \omega \Rightarrow$ atoms will escape!

Anharmonic trap
Fighting the centrifugal force

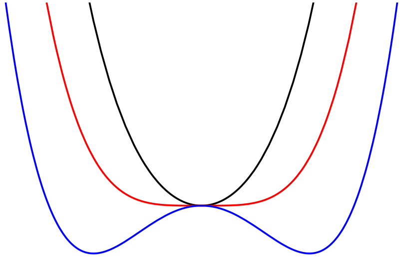
To restore the trapping potential, add a quartic term to $V(r)$:
[Cornell & Dalibard groups, Phys. Rev. Lett. 92, 040404 & 050403 (2004)]

$$V(r) = \frac{1}{2}M\omega_r^2 r^2 + \lambda r^4 \Rightarrow V_{\text{eff}}(r) = \frac{1}{2}M(\omega_r^2 - \Omega^2)r^2 + \lambda r^4$$

$\Omega = 0$

$\Omega = \omega_r$

$\Omega = 1.15\ \omega_r$



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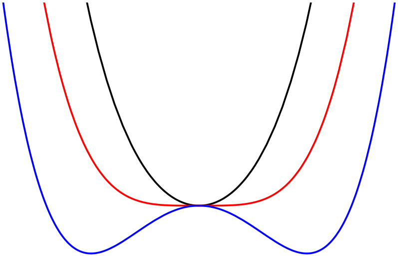
$\Omega = \omega_r$

$\Omega = 1.15\ \omega_r$



Even better than the quartic trap: the bubble trap!

Experimental implementation

rf-induced adiabatic potentials – the dressed quadrupole trap

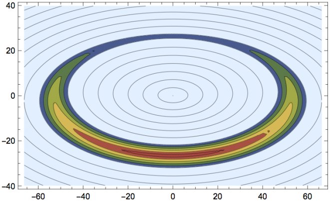
Adiabatic potentials for rf-dressed atoms: dressed quadrupole trap

[reviews Garraway/Perrin: JPB 2016 and Adv.At.Mol.Opt.Phys. 2017]

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

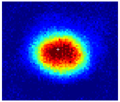
- smooth potentials (magnetic fields with large coils)
- strong confinement to the surface: $\omega_\perp \sim 2\pi \times 1 - 2$ kHz
- geometry (r_0, xy-anisotropy) can be fine-tuned dynamically
- temperature adjusted with a (weak) rf knife (30 – 200 nK)

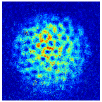
side view (isopotentials):



top-view:

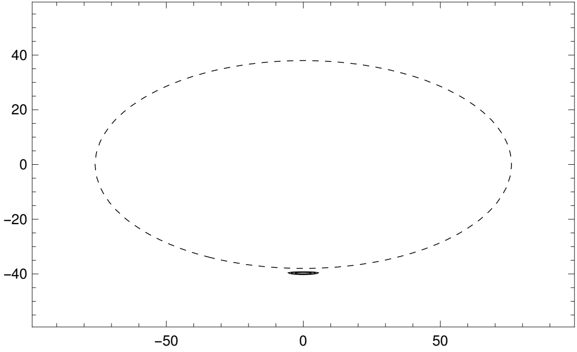
a [2D] quantum gas





The rotating bubble
Potential in the rotating frame

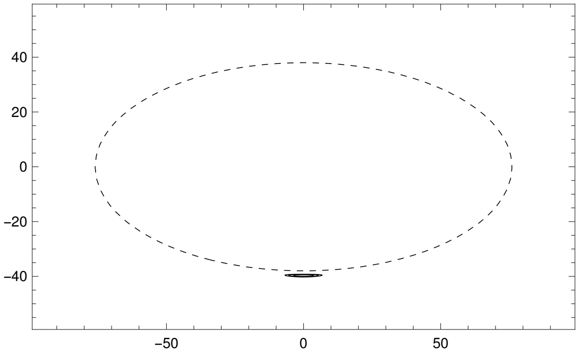
Trap minimum in the rotating bubble, $\omega_r = 2\pi \times 34$ Hz:



$\Omega = 0$

The rotating bubble
Potential in the rotating frame

Trap minimum in the rotating bubble, $\omega_r = 2\pi \times 34$ Hz:

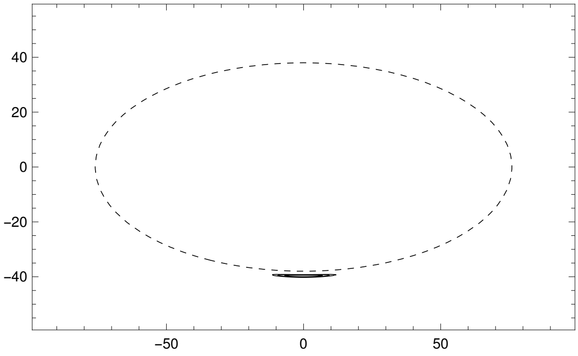


$$\Omega = 2\pi \times 20 \text{ Hz}$$

The rotating bubble

Potential in the rotating frame

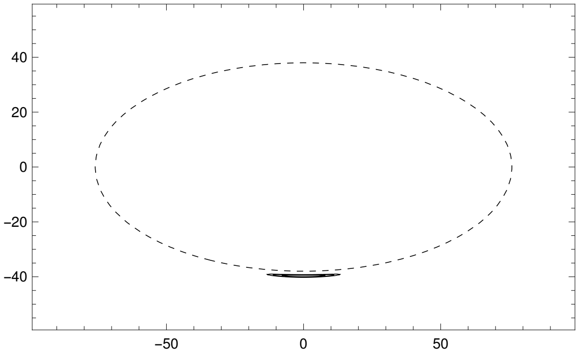
Trap minimum in the rotating bubble, $\omega_r = 2\pi \times 34$ Hz:



$$\Omega = 2\pi \times 30 \text{ Hz}$$

The rotating bubble
Potential in the rotating frame

Trap minimum in the rotating bubble, $\omega_r = 2\pi \times 34$ Hz:

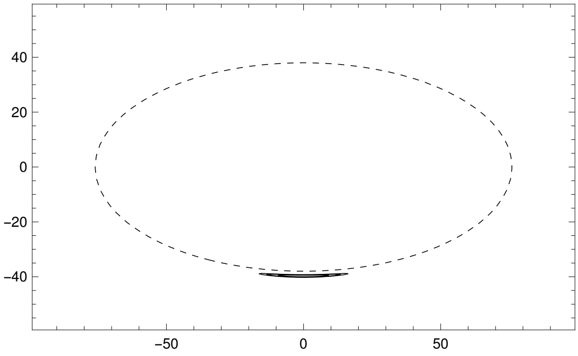


$$\Omega = 2\pi \times 31 \text{ Hz}$$

The rotating bubble

Potential in the rotating frame

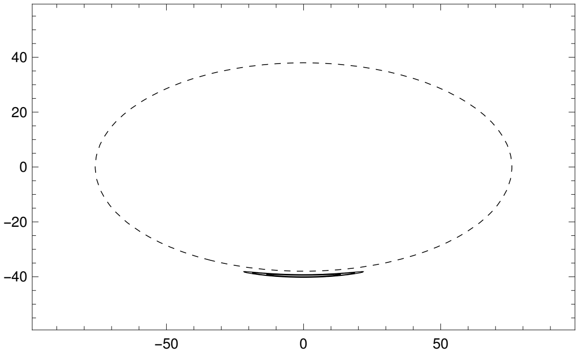
Trap minimum in the rotating bubble, $\omega_r = 2\pi \times 34$ Hz:



$$\Omega = 2\pi \times 32 \text{ Hz}$$

The rotating bubble
Potential in the rotating frame

Trap minimum in the rotating bubble, $\omega_r = 2\pi \times 34$ Hz:

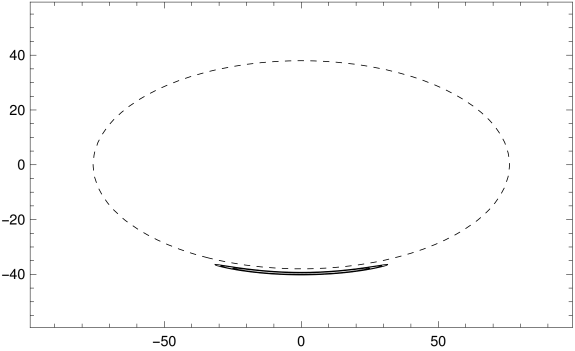


$$\Omega = 2\pi \times 33 \text{ Hz}$$

The rotating bubble

Potential in the rotating frame

Trap minimum in the rotating bubble, $\omega_r = 2\pi \times 34$ Hz:

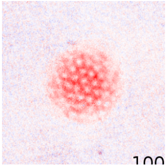


$$\Omega = 2\pi \times 34 \text{ Hz}$$

Vortex lattice in fast rotating trap

Increasing rotation frequency Ω...

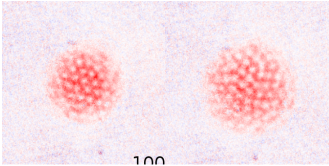
24 Hz



Vortex lattice in fast rotating trap

Increasing rotation frequency Ω. . .

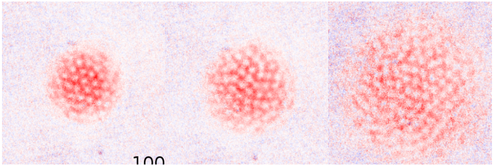
24 Hz 25 Hz



Vortex lattice in fast rotating trap

Increasing rotation frequency Ω...

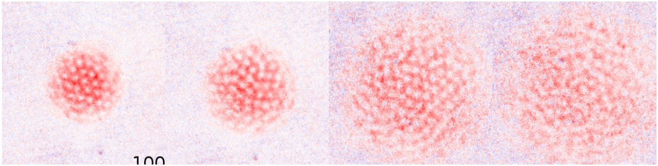
24 Hz 25 Hz 27 Hz



Vortex lattice in fast rotating trap

Increasing rotation frequency Ω... disordered lattice...

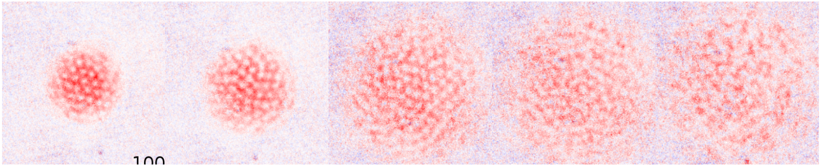
24 Hz 25 Hz 27 Hz 28 Hz



Vortex lattice in fast rotating trap

Increasing rotation frequency Ω... disordered lattice... melting!

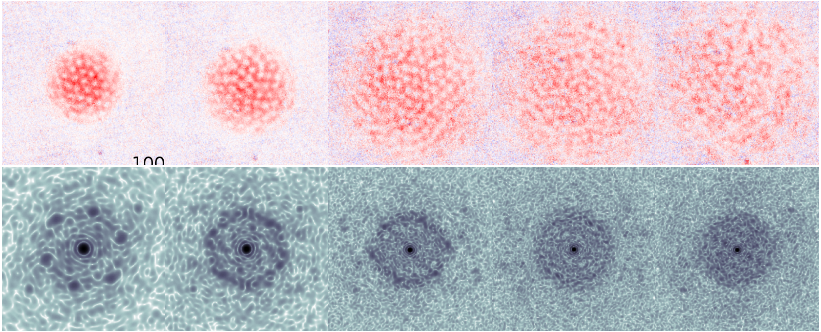
24 Hz 25 Hz 27 Hz 28 Hz 30 Hz



Vortex lattice in fast rotating trap

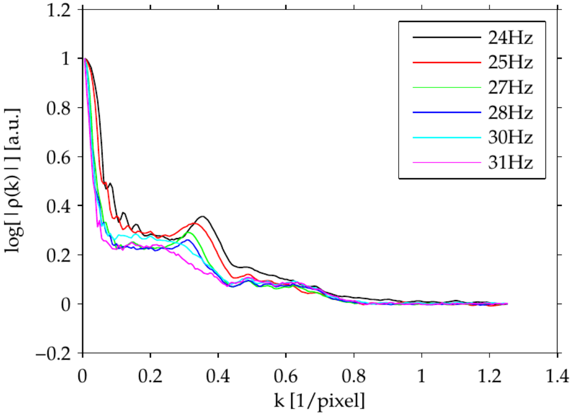
Increasing rotation frequency Ω. . . disordered lattice. . . melting!

24 Hz 25 Hz 27 Hz 28 Hz 30 Hz



FFT analysis: 6 peaks for ordered vortex lattice, disappear as the lattice melts.

FFT analysis
Average over azimuthal angle



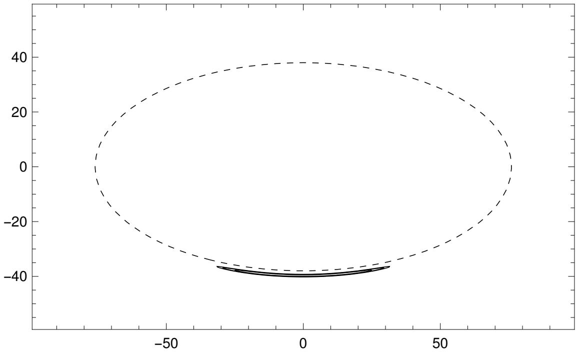
Vortex lattice disorder: signature of phase fluctuations in 2D gases at finite temperature

[Matveenko S.I.,and Shlyapnikov, Phys. Rev. A 83, 033604 (2011)]

The rotating bubble

Rotating beyond the trapping frequency

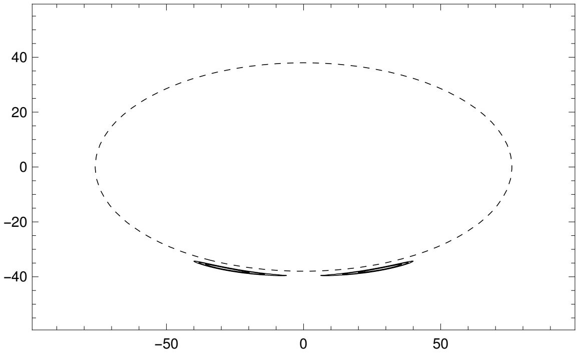
What if we rotate beyond $\omega_r = 2\pi \times 34$ Hz?



$$\Omega = 2\pi \times 34 \text{ Hz}$$

The rotating bubble
Rotating beyond the trapping frequency

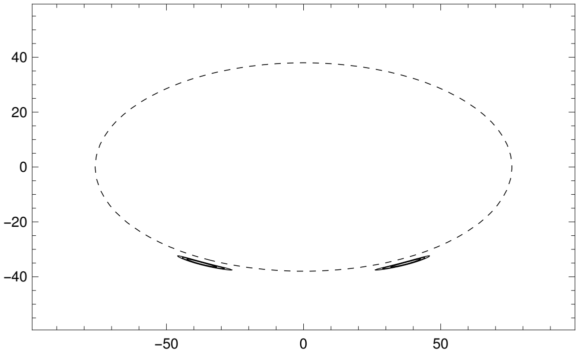
Trap minimum in the rotating bubble, $\omega_r = 2\pi \times 34$ Hz:



$\Omega = 2\pi \times 35$ Hz

The rotating bubble
Rotating beyond the trapping frequency

Trap minimum in the rotating bubble, $\omega_r = 2\pi \times 34$ Hz:

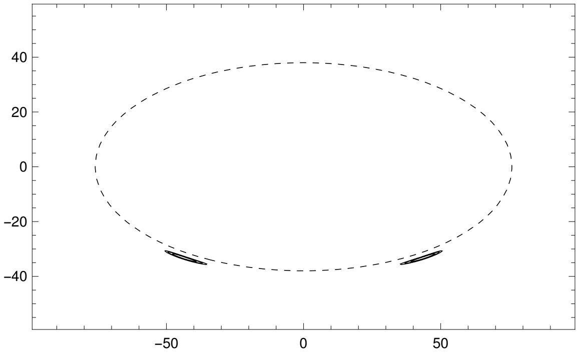


$\Omega = 2\pi \times 36$ Hz

The rotating bubble

Rotating beyond the trapping frequency

Trap minimum in the rotating bubble, $\omega_r = 2\pi \times 34$ Hz:

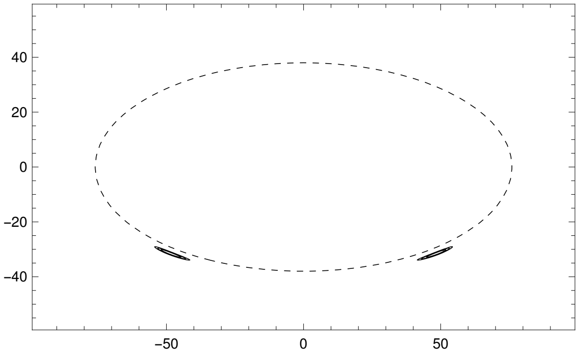


$\Omega = 2\pi \times 37$ Hz

The rotating bubble

Rotating beyond the trapping frequency

Trap minimum in the rotating bubble, $\omega_r = 2\pi \times 34$ Hz:

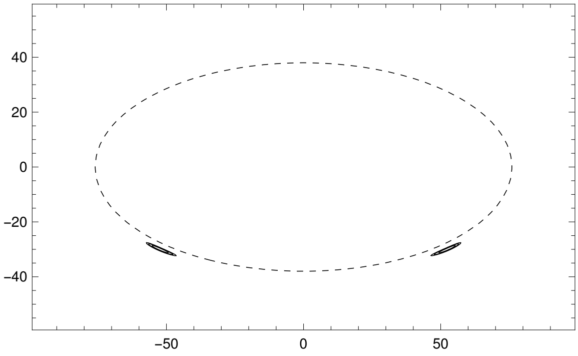


$\Omega = 2\pi \times 38$ Hz

The rotating bubble

Rotating beyond the trapping frequency

Trap minimum in the rotating bubble, $\omega_r = 2\pi \times 34$ Hz:

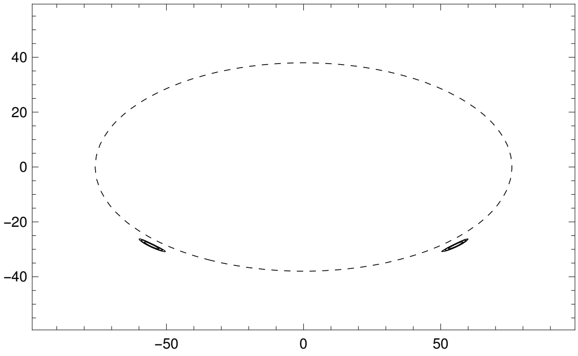


$\Omega = 2\pi \times 39$ Hz

The rotating bubble

Rotating beyond the trapping frequency

Trap minimum in the rotating bubble, $\omega_r = 2\pi \times 34$ Hz:

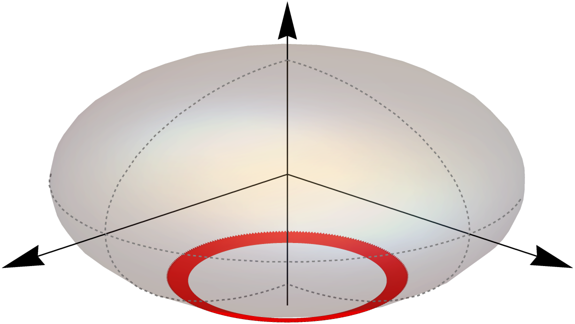


$\Omega = 2\pi \times 40$ Hz

The rotating bubble

Rotating beyond the trapping frequency

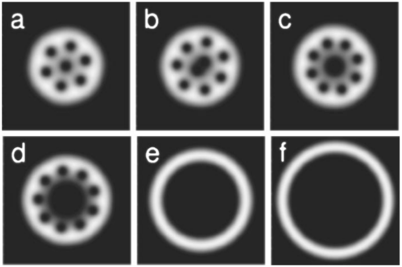
Trap minimum in the rotating bubble, $\omega_r = 2\pi \times 34$ Hz:



$\Omega = 2\pi \times 35.8$ Hz

Theoretical predictions
Rotating beyond the trapping frequency

Giant vortex in a harmonic + quartic trap:

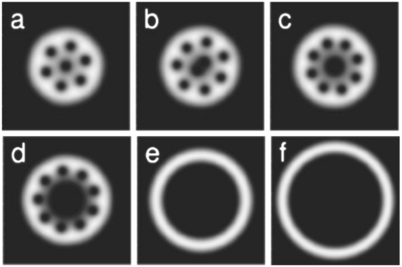


[Fetter 2005]

Theoretical predictions

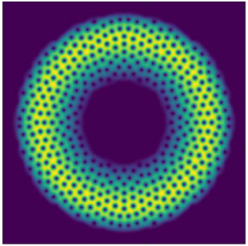
Rotating beyond the trapping frequency

Giant vortex in a harmonic + quartic trap:

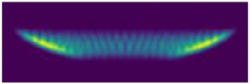


[Fetter 2005]

Ground state in the rotating bubble (numerical GPE)



top view

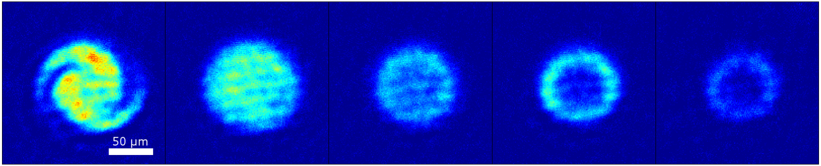


side view

The dynamical ring: hole formation

Observation of a annular quantum gas stabilized by rotation

Stirring frequency: 31 Hz *in situ* pictures



100 ms 1 s 4 s 10 s 20 s

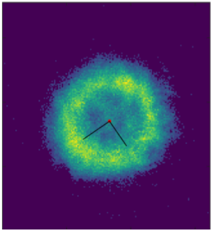
waiting time *after* the stirring phase

- spontaneous hole formation: $\Omega_{\rm rot} > \omega_\perp > \Omega_{\rm stir}$
- stable up to $\sim$ 60 s

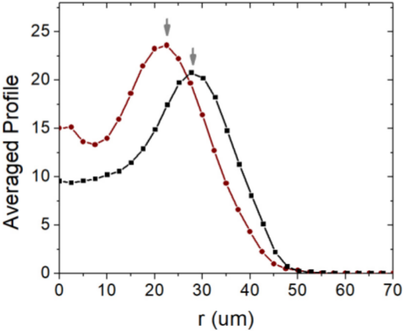
equilibrium configuration

Cooling further

A hole starts forming, but can we do better?



azimuthal averaging

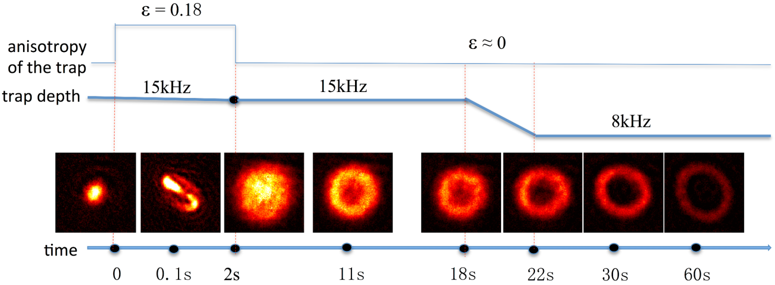


Cut in the dynamical ring formed at ~ 20 s.

Cooling further

A hole starts forming, but can we do better?

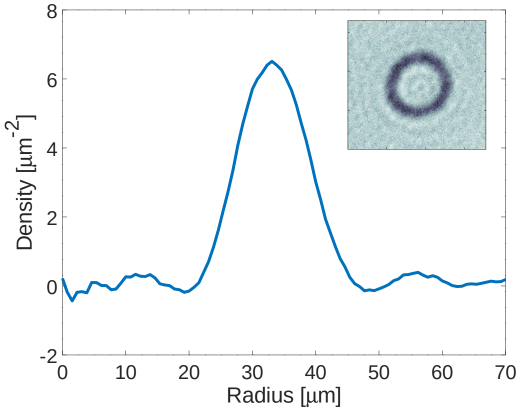
Yes! After further rf evaporative cooling.



Acceleration of the rotation, full depletion of the center.

A thin ring sustained by its dynamics
Observation of a annular quantum gas stabilized by rotation

radial profile (azimuthal average)



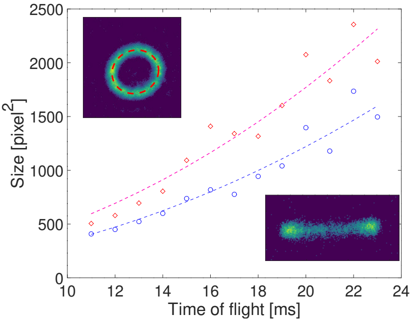
Acceleration of the rotation, full depletion of the center.

The dynamical ring: measurement of rotation

Method 1: scaling = size in the horizontal plane after TOF:
$R_{\mathrm{TOF}} \simeq \Omega t_{\mathrm{TOF}} \times R_{\mathrm{TF}}$

Method 2: in-situ profile, especially once the ring is formed
$\Omega = \omega_\perp \sqrt{1 + 2\lambda r_0^2 / a_r^2}$

[Also: spectro of quadrupole modes]



Result: $\Omega \sim 1.05\ \omega_\perp$ i.e. $v = 7.4 \pm 0.3$ mm/s
local peak speed of sound: $c = 0.4 \pm 0.03$ mm/s $\Rightarrow v \sim 18 \pm 2\ c$!

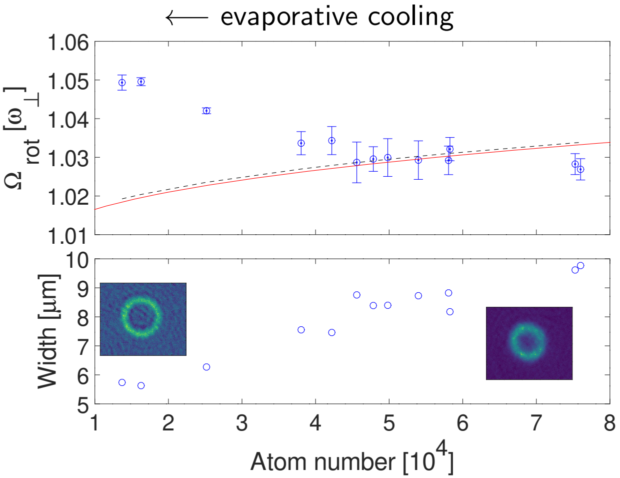
Corresponding angular momentum per particle $\langle L_z \rangle = 337 \pm 25\hbar$

A degenerate gas flowing at Mach 18... [Guo et al. arXiv:1907.01795]

See also Wolf von Klitzing's talk.

Acceleration of the rotation during cooling

Preliminary results



L_z increases during evaporation, where does it come from?

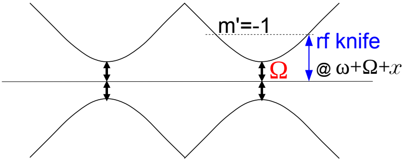
'Spin-up' evaporation
A local effect of the rf-knife

rf-coupling of the dressing field varies with the height on the bubble:

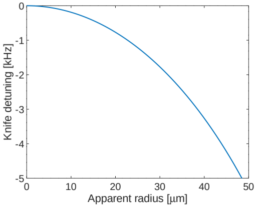
$$\Omega_{\rm rf}(z) \propto (1 - 2z/r_0)$$

Distance between dressed states larger at the bottom $\Rightarrow$ weak rf-knife is more efficient at small radii

reminder: effect of knife:



local trap depth:

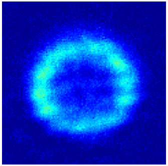


Shift of the rf-knife frequency as a function of the dynamical ring radius.

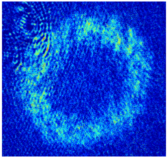
The dynamical ring

Observation of a annular quantum gas stabilized by rotation

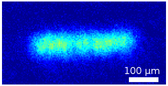
- Formation of a dynamical ring, stabilized by rotation, lifetime > 20 s



- 2D gas with phase fluctuations visible after TOF (top view)

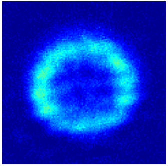


- Fast rotation, very cold sample (no thermal fraction visible after TOF, side view)

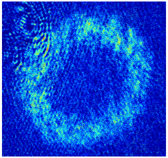


The dynamical ring

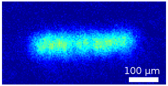
Observation of a annular quantum gas stabilized by rotation



- Formation of a dynamical ring, stabilized by rotation, lifetime > 20 s



- 2D gas with phase fluctuations visible after TOF (top view)



- Fast rotation, very cold sample (no thermal fraction visible after TOF, side view)

Ongoing work: probe the low energy excitations of the dynamical ring (quadrupole mode)

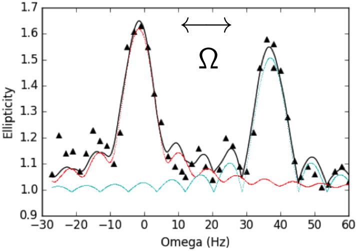
Quadrupole modes spectroscopy
Preliminary results

Quadrupole mode spectroscopy: rotate a very small anisotropy for time τ and record cloud anisotropy

$\rightarrow$ used to determine the rotation frequency Ω:

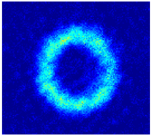
$\Omega_{+2} - \Omega_{-2} = 2\Omega \quad \tau = 60$ ms

$\Omega_{-2} \sim 0$ for $\Omega \sim \omega_\perp$

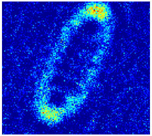


This low frequency mode is also present in the dynamical ring

[Cozzini & Stringari 2006]



non resonant



resonant

Quadrupole modes spectroscopy
Preliminary results

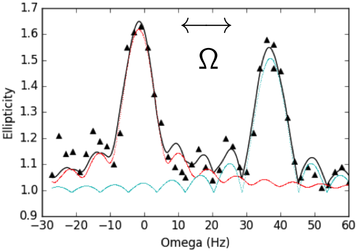
Quadrupole mode spectroscopy: rotate a very small anisotropy for time τ and record cloud anisotropy

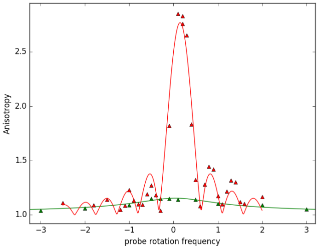
$\rightarrow$ used to determine the rotation frequency Ω:
$\Omega_{+2} - \Omega_{-2} = 2\Omega \quad \tau = 60$ ms

$\Omega_{-2} \sim 0$ for $\Omega \sim \omega_\perp$

This low frequency mode is also present in the dynamical ring
$\tau = 1$ s $\rightarrow$ very narrow linewidth!

[Cozzini & Stringari 2006]
[Guo et al. arXiv:1907.01795]

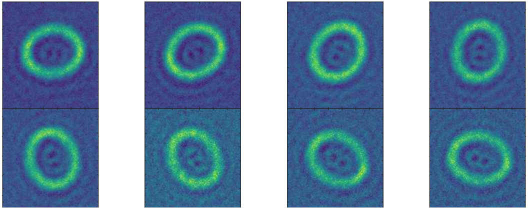




Quadrupole modes spectroscopy

Preliminary results

Follow the rotating cloud

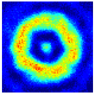


rotation frequency ~ 0.15 Hz
in the direction of the flow

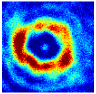
Summary & prospects

(1) **Annular gas**: Develop experimental tools for quantum simulation of mesoscopic SC systems with quantum gases

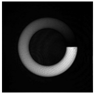
- Towards atomtronic circuits: ring trap. . .



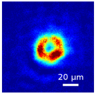
- . . . sustaining a persistent current. . .



- . . . produced by rotation or a phase imprinting. . .



- . . . in the presence of local barriers



Summary & prospects

Outlook / ring: a quantum simulator with a complete toolbox for modeling mesoscopic physics.
Example: look for phase slips of a circulation state in the 1D limit in the presence of a potential barrier (Juan Polo's talk).

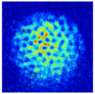
Challenges:

- Keep temperature low enough
- Beyond weak links: realize tunnel junctions (narrow barrier)
- Entangle circulation states: towards N00N states
- Go 1D, increase interactions, add a lattice: many-body mesoscopic physics

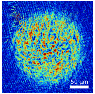
Summary & prospects

(2) **Bubble trap**: a very smooth and tunable trap to study the collective modes and fast rotations

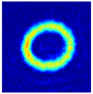
- Observation of vortex lattices



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



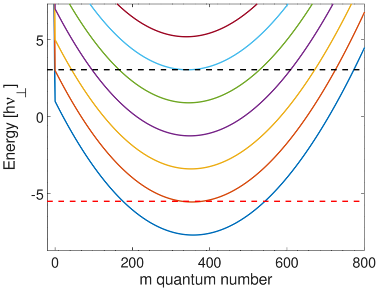
- Formation of a long-lived dynamical ring flowing at Mach 18 for tens of second for $\Omega > \omega_r$



Summary & prospects

Outlook / fast rotation: reaching the lowest Landau level.

Fig: Single particle spectrum in the rotating bubble trap



Challenges:

- Keep temperature low enough – again
- Understand vortex lattive melting in the 2D gas
- Explore the excitation spectrum

Acknowledgments

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