Supersonic rotation of a superfluid: a long-lived dynamical ring

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Superfluid rotation...

★ Superfluid (SF) ⇒ **macroscopic wavefunction** $\psi_0(\mathbf{r}) = \sqrt{\rho(\mathbf{r})}e^{i\theta(\mathbf{r})}$

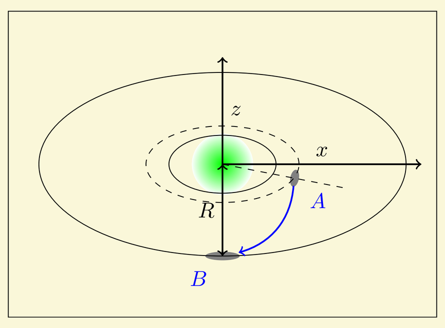
★ **Irrotational velocity field** $\mathbf{v}(\mathbf{r}) = \frac{\hbar}{m}\nabla\theta$ defined for $\rho \neq 0$.

★ **Quantized circulation** $\oint_C \mathbf{v}\cdot d\mathbf{r} = n\frac{h}{m}$ nonzero around singular density regions : vortices.

Rotating SF : N_v vortices of circulation $\frac{h}{m}$ ⇒ $\langle L_z\rangle / N_{at} = N_v\hbar$

Large number of vortices : $\nabla\times\boldsymbol{v} = 2\boldsymbol{\Omega}$ ⇒ **solid-body rotation** at angular frequency $\boldsymbol{\Omega}$.

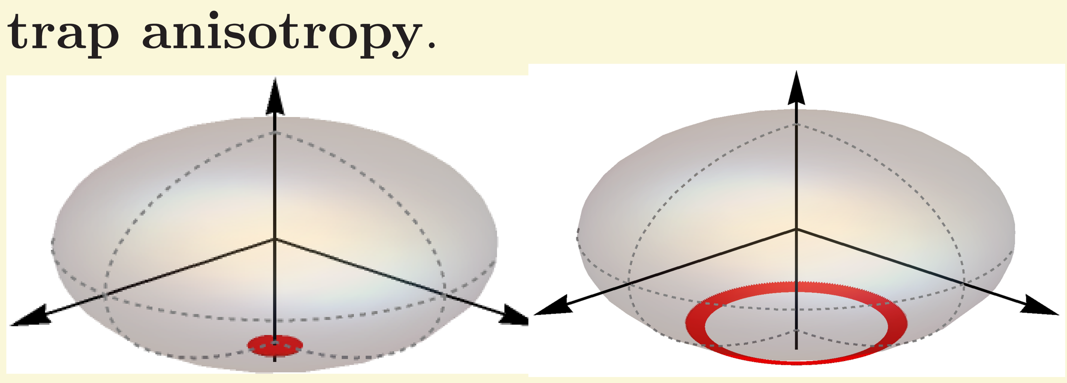
A smooth bubble trap [1]



^{87}Rb BEC produced by an **optically plugged quadrupole trap**.
Transfer to a bubble-shaped **radio-frequency** (rf) **dressed trap** ⇒ 2.5×10^5 atoms pure BEC with $\mu = 1.8\,$kHz.

Trap frequencies :
$\nu_z = 356.5(2)\,$Hz
$\nu_r = 33.70(4)\,$Hz

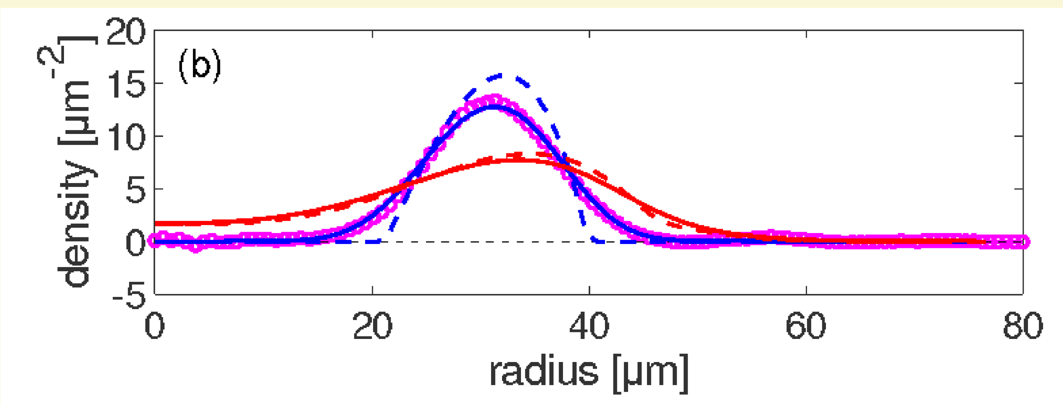
The cloud is set into rotation by a **rotating trap anisotropy**.



$\Omega = 0$ $\quad$ $\Omega = 1.06\omega_r$

Ring profile analysis

$\mu < \hbar\omega_z$ ⇒ **quasi-2D regime** ⇒ **Berezinskii-Kosterlitz-Thouless** superfluid transition.



Magenta: Radial density profile at $t = 35\,$s
Blue: Fit with Thomas-Fermi profile at zero temperature.
Red: Density profile at critical temperature of the **BKT** transition.
Dash line: without taking account the optical resolution $4\,\mu$m
⇒ **superfluid 2D quasi-condensate**.

References

References

[1] K. Merloti, *et al.* A two-dimensional quantum gas in a magnetic trap. *NJP*, **15** 033007 (2013).

[2] A. Fetter, *et al.* Rapid rotation of a Bose-Einstein condensate in a harmonic plus quartic trap. Phys. Rev. A, **71**, 013605 (2005).

[3] Y. Guo, *et al.* Supersonic rotation of a superluid : a long-lived dynamical ring. Phys. Rev. Lett, **124**, 025301 (2020)
(Editors'suggestion, Featured in a Synopsis in Physics)

...for a trapped BEC

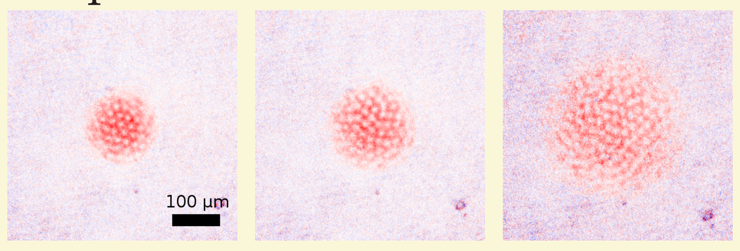
Hamiltonian in the rotating frame at Ω : $H_{\rm rot} = H_0 - \boldsymbol{\Omega} L_z$ with $L_z = (xp_y - yp_x)$

$$\Rightarrow H_{\rm rot} = \frac{(p - q\mathcal{A})^2}{2M} + V(r) - \frac{1}{2}\mathbf{M\Omega^2 r^2} \text{ where } q\mathcal{A} = 2M\boldsymbol{\Omega}(-y\mathbf{e}_x + x\mathbf{e}_y).$$

⇒ Effective **centrifugal potential** $V_{\rm eff}(r) = V(r) - \frac{1}{2}M\Omega^2 r^2$.

Harmonic trap

$V_{\rm eff}(r) = \frac{1}{2}M\omega_r'^2 r^2$ with $\omega_r'^2 = \omega_r^2 - \Omega^2$
For $\Omega \simeq \omega_r$ analogous to free charge q in $\boldsymbol{B} = \nabla\times\boldsymbol{\mathcal{A}} \propto \boldsymbol{\Omega}$.
Description in terms of **Landau levels** ⇒ quantum Hall effect with neutral atoms?



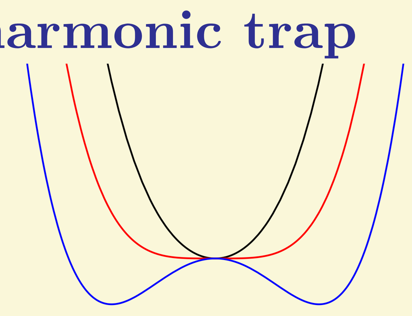
$0.7\ \omega_r$ $\quad$ $0.75\ \omega_r$ $\quad$ $0.8\ \omega_r$

$\Omega \longrightarrow \omega_r$: **vanishing trapping frequency**

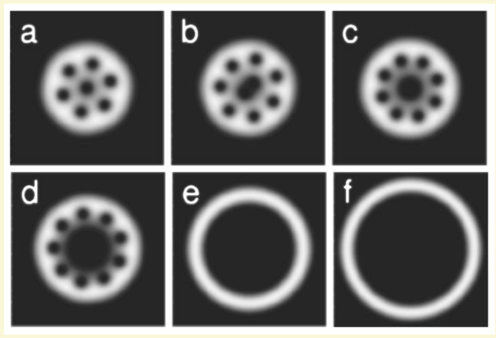
To preserve confinement : anharmonic potential.

Anharmonic trap

$\Omega = 0$
$\Omega = \omega_r$
$\Omega = 1.15\ \omega_r$



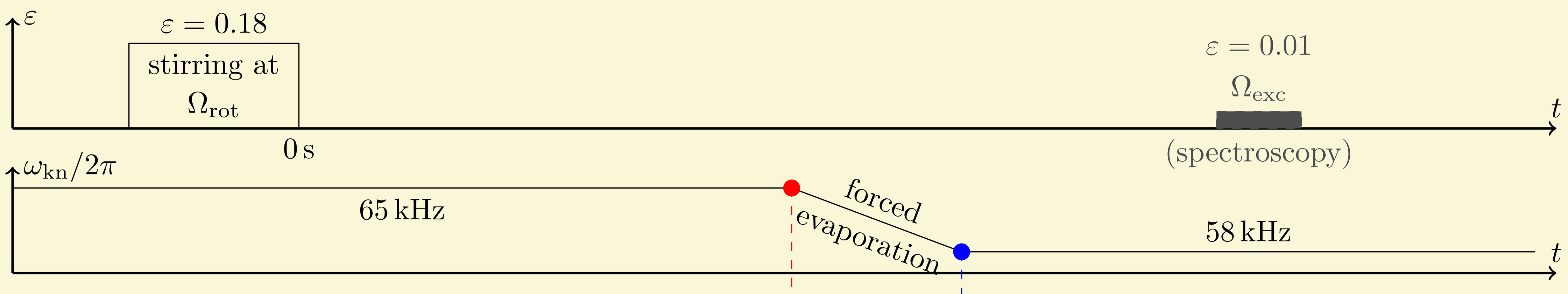
$\Omega > \omega_r$: **dynamical ring**.
Vortices in the bulk + topologically protected multi-charged vortex in the center [2].

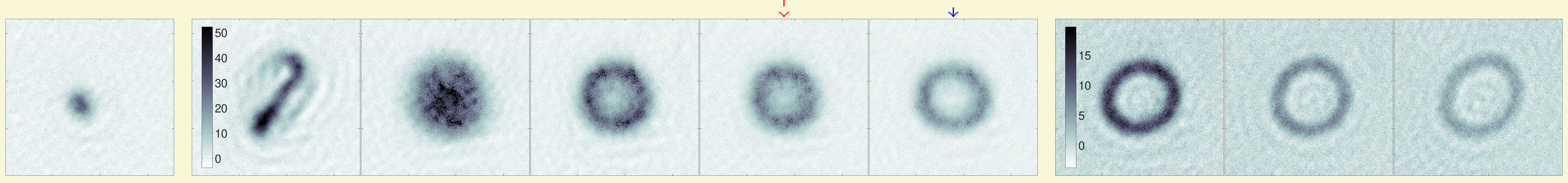


Our anharmonic trap : a bubble trap!

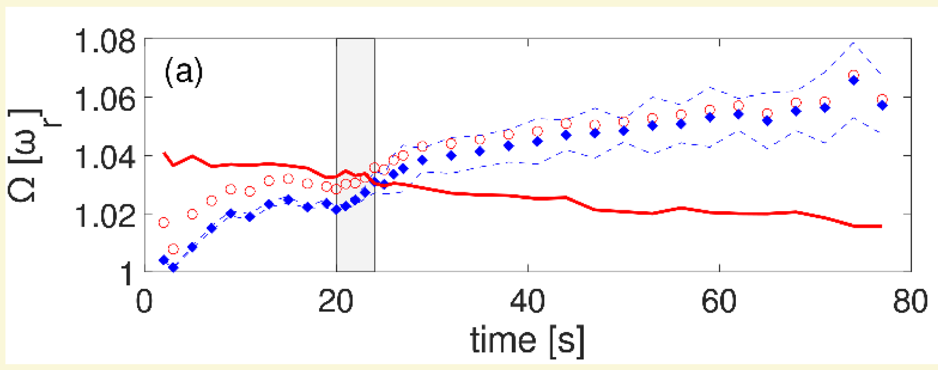
From a connected SF to a dynamical ring [3]

Principle of the experiment : **trap deformation** of anisotropy $\varepsilon = \frac{\omega_x^2 - \omega_y^2}{2\omega_r^2}$ is rotated at $\nu_{\rm rot} = 31\,$Hz for 11 half-turns. The excited cloud **evolves freely** in the rotationally invariant trap, with an **rf-knife** setting the trap depth.

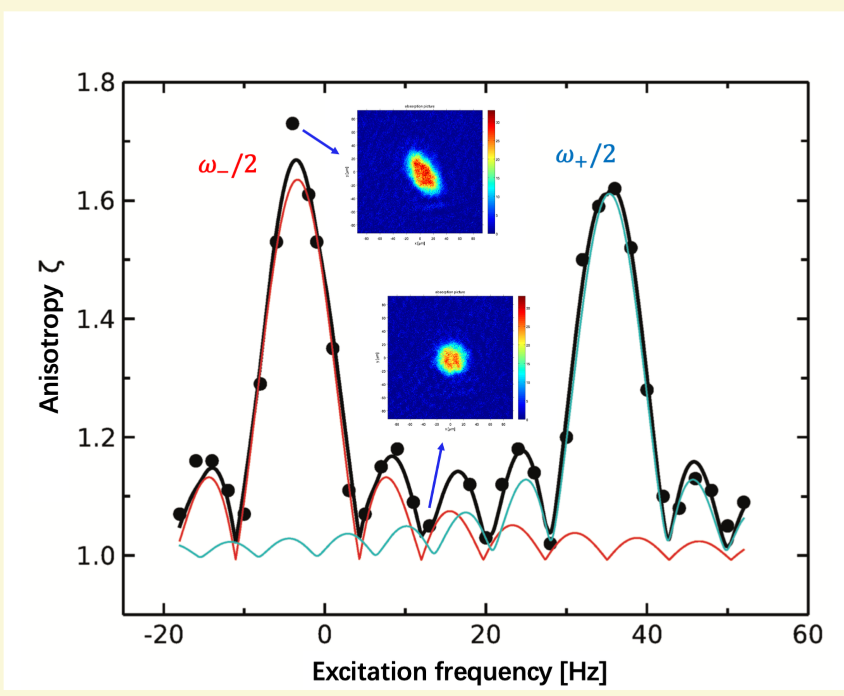


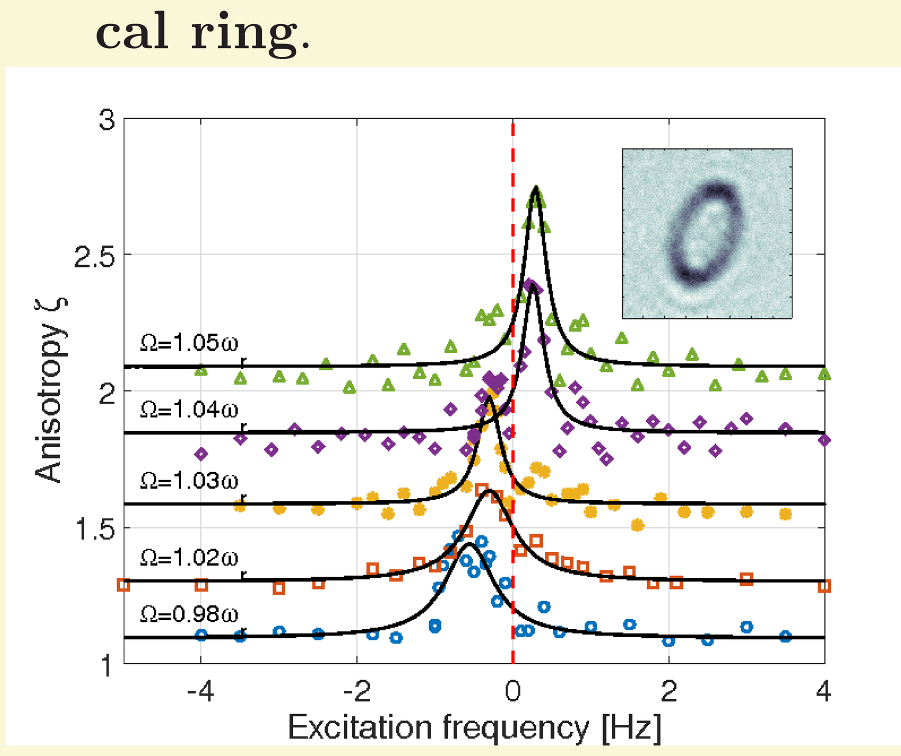


-0.2 s $\quad$ -0.048 s $\quad$ 3 s $\quad$ 15 s $\quad$ 20 s $\quad$ 24 s $\quad$ 38 s $\quad$ 50 s $\quad$ 71 s



Rotation acceleration due to **spin-up evaporation** from the rf-knife. **Forced evaporation** to cross the hole-formation rotation rate.
For $\Omega \sim 1.05\ \omega_\perp$ ⇒ $v = 7.4 \pm 0.3$ mm/s
Local peak speed of sound: $c = 0.4 \pm 0.03$ mm/s
⇒ $\mathbf{v \sim 18 \pm 2\ c}$ and $\boldsymbol{\langle L_z\rangle / N_{at} = 337 \pm 25\hbar}$
⇒ **supersonic high angular momentum dynamical ring**.





Collective mode spectroscopy: the mode $m = -2$ resonant excitation changes sign and co-rotates with the atomic flow
⇒ not predicted by diffuse vorticity hydrodynamic predictions.

Conclusion and perspective

- **First experimental realization** of a superfluid dynamical ring, rotating over a minute at more than ten times the speed of sound.
- **Supersonic rotation** ⇒ how would a localized defect dissipate superfluidity?
- Towards the **giant vortex** regime ⇒ accessible for an atom number of 400 atoms.
- Experimental evidence of **weakly damped collective quadrupole modes**.
- Observed frequency of the low frequency mode **does not agree with hydrodynamic calculations** ⇒ need more refined theoretical models ?