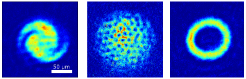
A fast rotating superfluid on a curved surface



Romain Dubessy & BEC group

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

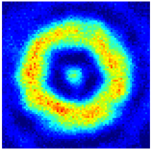
26ème Congrès de la SFP - 3–7 Juillet 2023
MC16 – Fluides classiques et quantiques hors équilibre

Dynamics of quantum gases: superfluidity

Specific dynamical properties

Quantum gases with weak repulsive interactions are **superfluid**.
Superfluidity is a dynamic property with subtle effects.

- absence of viscosity, leading to persistent currents in a circular guide



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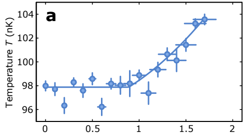

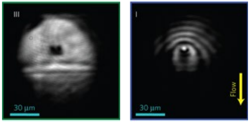

$v < v_c$ $v > v_c$

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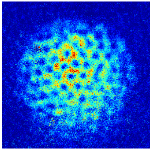

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In this talk: a superfluid rotating in a **bubble** trap.

Physics in a bubble

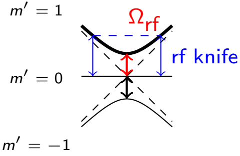
rf-induced adiabatic potentials — the dressed quadrupole trap

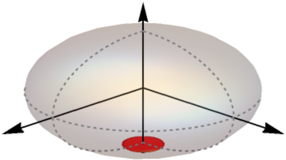
Adiabatic potentials for rf-dressed atoms

Ingredients: inhomogeneous B field + strong rf field, coupling Ω_{rf}

Here: quadrupole field, magnetic gradient b'

- local B and rf fields: atomic spin follows adiabatically a local eigenstate
- local eigenenergy acts as a potential
- atoms are strongly confined to a resonant isomagnetic surface $\mu B(\boldsymbol{r}) = \hbar\omega$
- smooth surface potentials
- cooling with an rf knife.





For a quadrupole field: ellipsoidal isomagnetic surface

$x^2 + y^2 + 4z^2 = r_0^2$ with $r_0 \propto \omega/b'$.

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

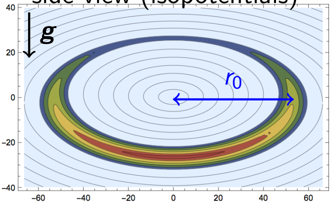
Trapping atoms on a surface

A smooth two-dimensional trap

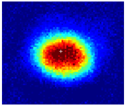
$$\omega_z \propto \frac{b'}{\sqrt{\Omega_{\rm rf}}} \sim 1\ \text{kHz}$$

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

side view (isopotentials)

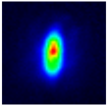


top view



in situ

side view



tof

- very flat $\omega_z \gg \omega_{x,y}$
- 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

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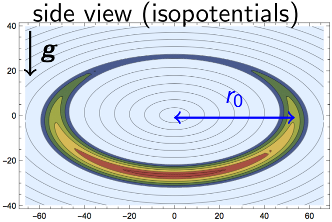

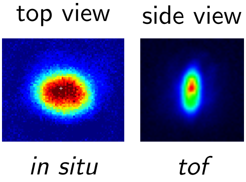

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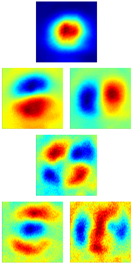
- anisotropic ($\eta \neq 1$) for linear horizontal polarization
- geometry can be modified dynamically
- ideal for the study of the 2D trapped gas dynamics



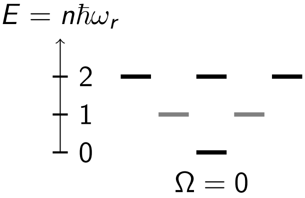
[Dubessy NJP 2014]

Why rotations ?

Quantum Hall effect with atoms

ideal 2D trapped rotating atomic gas $\leftrightarrow$ 2D electron gas with a uniform magnetic field

$$H = \hbar\omega_r \left(\hat{a}_x^\dagger \hat{a}_x + \hat{a}_y^\dagger \hat{a}_y \right) - \Omega \hat{L}_z$$



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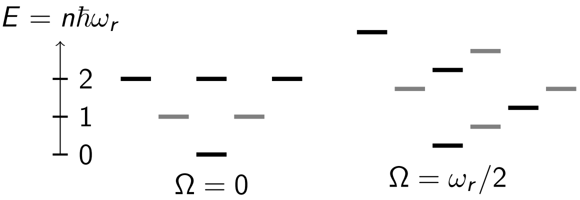

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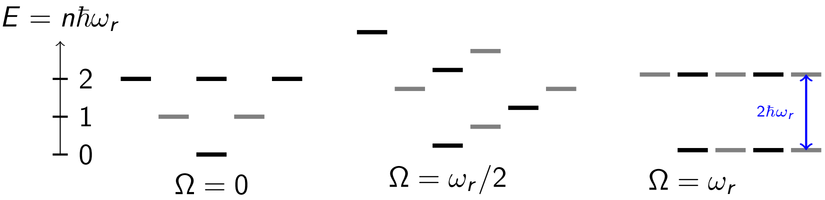


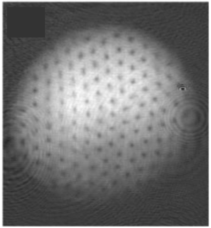
- Landau level structure $\Rightarrow$ highly degenerate groundstate

[Fetter RMP 2009, Fletcher Science 2021 & gauge fields: Chalopin Nat. Phys. 2020]

- Small energy gap $\Rightarrow$ increased role of temperature

Vortex crystals

Low energy modes & melting transition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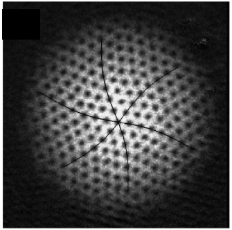
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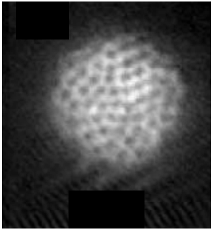
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never observed in BEC !

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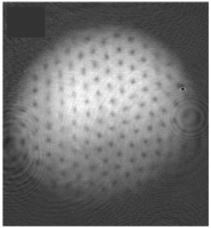
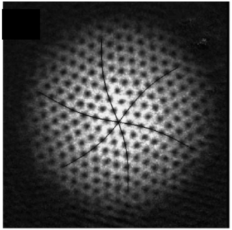


[Abo-Shaeer Science 2001]
$\omega_r / \omega_z = 4.2$



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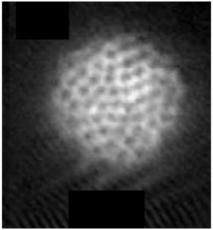
1.6



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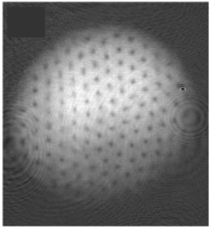

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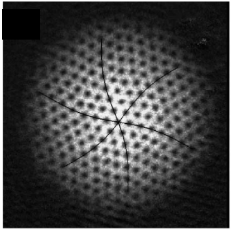

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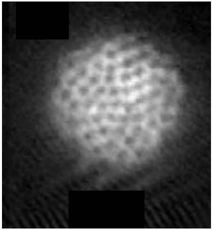
1.6 $T_m/T_c \sim 0.78$



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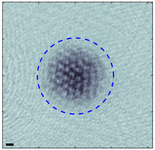
To lower T_m/T_c: decrease $\omega_r/\omega_z \Rightarrow$ go 2D ! bubble: $\omega_r/\omega_z \leq 0.1$

Vortex lattice in fast rotating bubble trap

A first quick look

- Start from a a degenerate cloud at rest at the bottom of the bubble, $\omega_r = 2\pi \times 34$ Hz
- Induce an in-plane elliptic deformation rf polarization $V(r) = M\omega_r^2/2 \times [(1-\epsilon)x'^2 + (1+\epsilon)y'^2] + \dots$
- Rotate the trap main axes x', y' at frequency Ω_{rot}
- Restore the rotationally invariant trap

Increasing $\Omega_{\mathrm{rot}}\dots$



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

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

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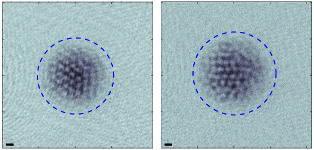

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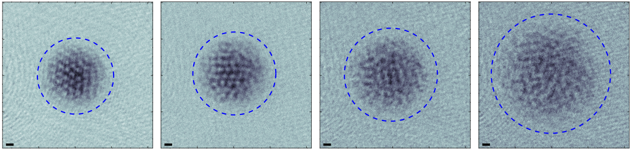
Increasing $\Omega_{\rm rot}$... disordered lattice...



$\Omega_{\rm rot}/(2\pi) = 20$ Hz 21 Hz 24.5 Hz 28.5 Hz

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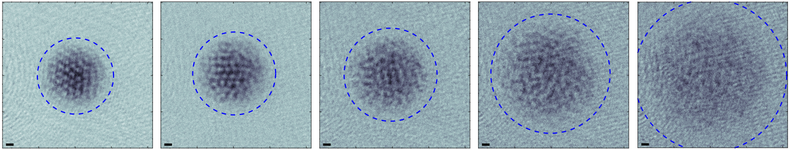
Increasing Ω_{rot}... disordered lattice... melting ?



$\Omega_{\mathrm{rot}}/(2\pi) = 20$ Hz | 21 Hz | 24.5 Hz | 28.5 Hz | 30 Hz

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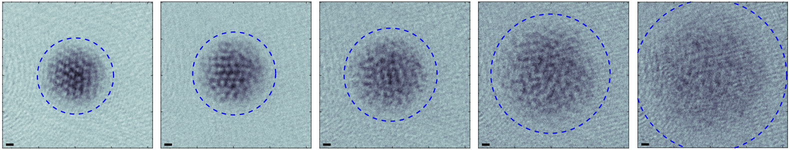

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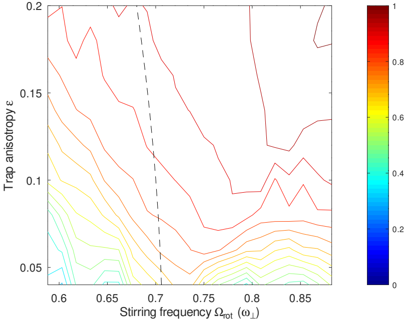
We need to measure N, Ω, T and compare to $T_m(N, \Omega)$...

Rotation control

Stirring and evaporating



Effective rotation Ω/ω_r

with post-stirring rf ramp 80 $\rightarrow$ 60 *kHz*

- allows to reach $\Omega \sim \omega_r$
- at constant $T \sim 18$ nK

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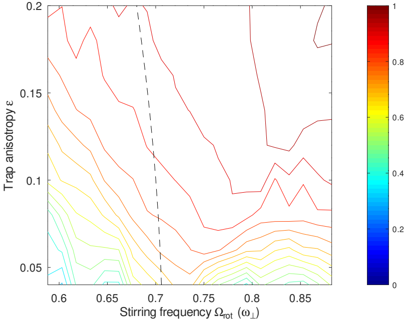
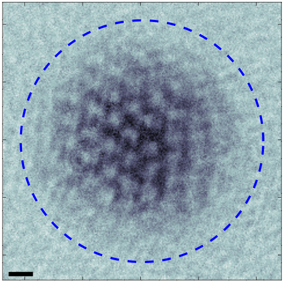


Counting vortices

- top view, 27 ms tof



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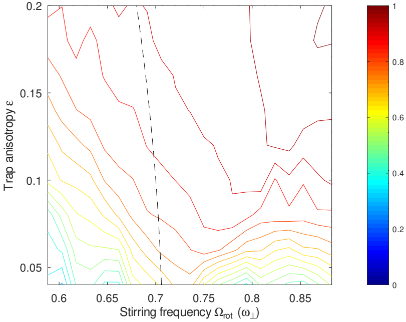
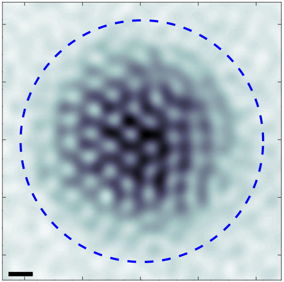


Counting vortices

- top view, 27 ms tof
- enhance visibility



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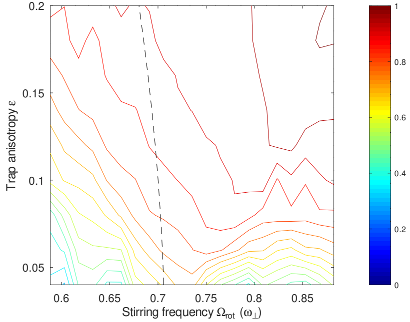

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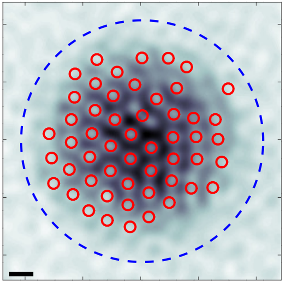
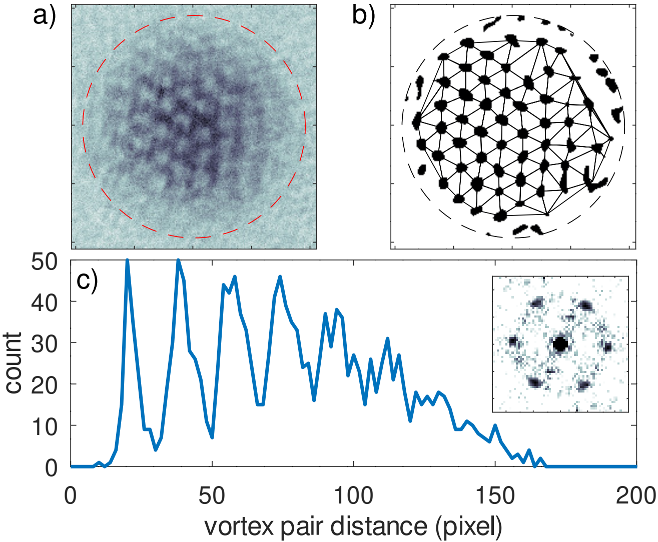
Counting vortices

- top view, 27 ms tof
- enhance visibility
- detect positive curvature



Quantitative study of the vortex lattice

Vortex-vortex correlations



Thermal melting of the vortex lattice ?

Studying a quasi-2D crystal

quasi 2D rotating Bose gas $T_m \leq 0.23 T_{BKT}$ [Gifford PRA 2008]

upper bound on melting temperature

(computed using low energy modes of the crystal lattice & KTHNY theory)

studied in many systems: supraconductors, colloids, ... [Gasser ChemPhysChem 2010]

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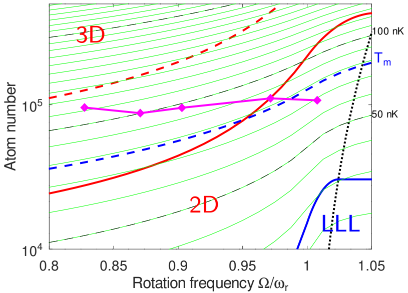
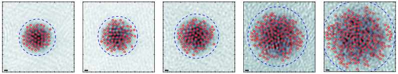
What is T_{BKT} ?

semi-classical + LDA + $\mathcal{D}_c$ from QMC





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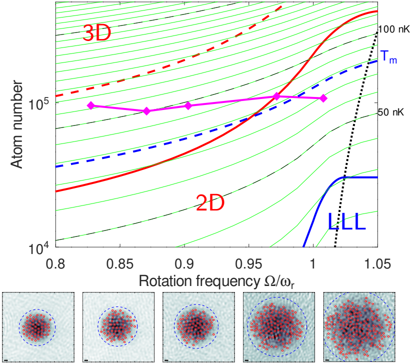
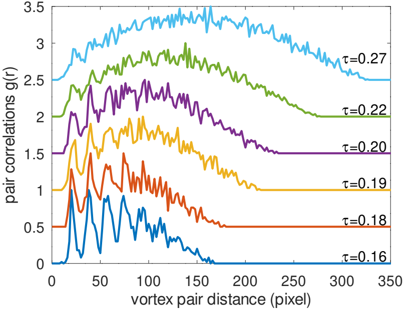
What is T_{BKT} ?

semi-classical + LDA + $\mathcal{D}_c$ from QMC





- Remember: rf-knife sets the temperature $T \simeq 18$ nK, $\tau = T/T_{BKT}$
- Qualitative agreement: change in $g(r)$ as T/T_m varies.

Can we rotate even faster ?

Fighting the centrifugal force

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

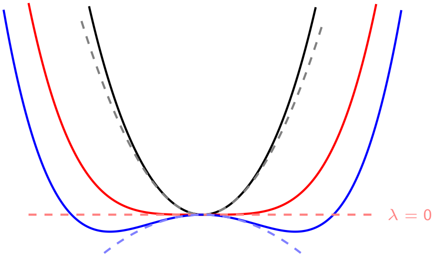
$$V_{\text{eff}}(r) = \frac{M}{2}(\omega_r^2 - \Omega^2)r^2 + \lambda r^4.$$

[Bretin PRL 2004]

$\Omega = 0$

$\Omega = \omega_r$

$\Omega = 1.15\ \omega_r$



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

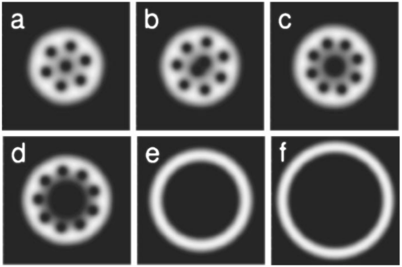
Theoretical predictions

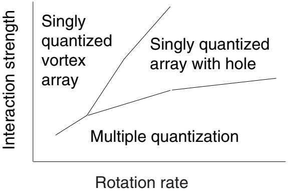
Rotating beyond the trapping frequency

Giant vortex in a harmonic + quartic trap:

vortex lattice

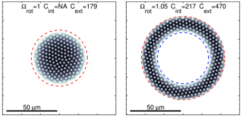
dynamical ring





giant vortex

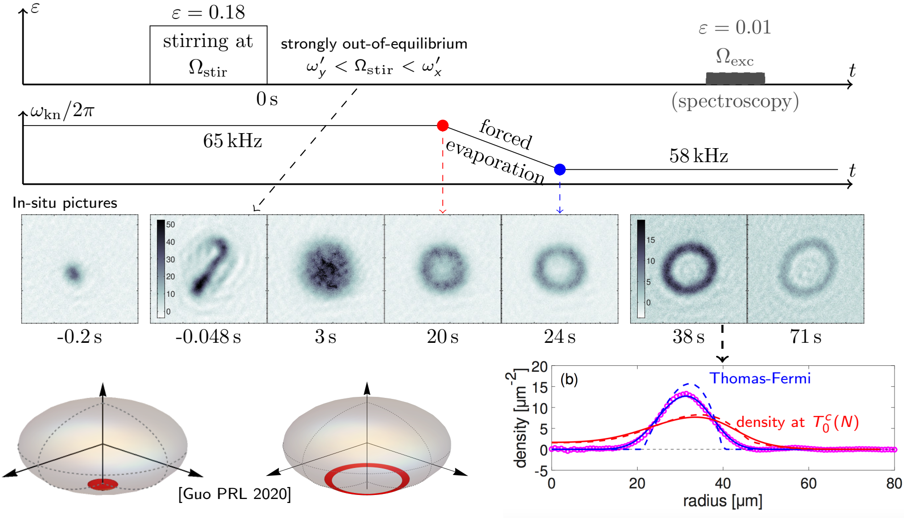
[Kavoulakis NJP 2003, Fetter PRA 2005]



GP simulation for the bubble
(quartic approximation)

Creating a dynamical ring

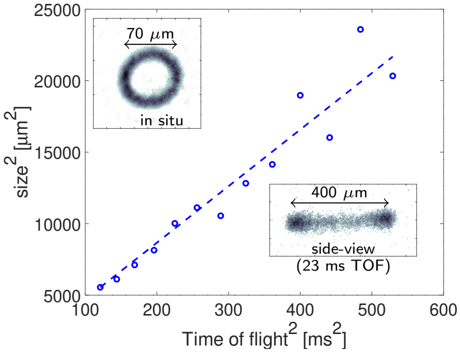
Using the spin-up evaporation



[Guo PRL 2020]

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 !

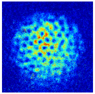
[see also Pandey Nature 2019]

Summary & prospects

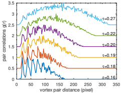
Fast rotations on a shell

A very smooth and tunable shell trap to study fast rotations

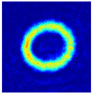
- Fine control of the effective rotation



- 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 — obstacle in a supersonic flow

$\Rightarrow$ test the melting scenario (KTHNY) — loss of orientational order

$\Rightarrow$ play with the curvature in the rotating frame — β effect

Thanks for your attention !

The BEC group at Villetaneuse

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