Rotating Bose-Einstein condensates

and Quantum Vortices

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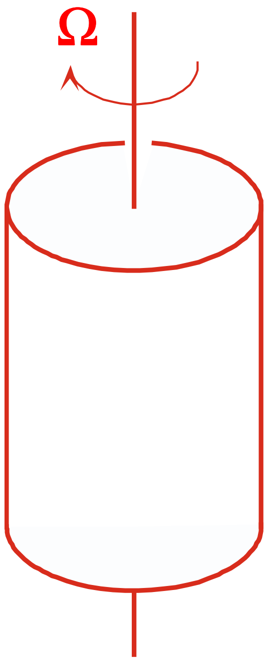
Vortices in a rotating quantum fluid



In a condensate $\psi(\vec{r}) = \sqrt{\rho(\vec{r})}\ e^{iS(\vec{r})}$

the velocity $\vec{v} = \frac{\hbar}{m}\vec{\nabla}S$ is such that $\int \vec{v}\,.\,d\vec{r} = \frac{nh}{m}$

incompatible with rigid body rotation $\vec{v} = \vec{\Omega}\times\vec{r}$

Liquid superfluid helium

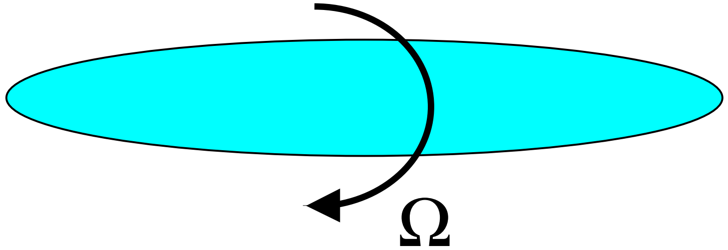
Below a critical rotation Ω_c, no motion at all

Above Ω_c, apparition of singular lines on which the density is zero and around which the circulation of the velocity is quantized

Onsager - Feynman

Dynamics of a rotating Bose gas

Bose-Einstein condensate trapped in a harmonic potential
with transverse frequency $\omega_\perp$



The gas is stirred with a "spoon" rotating at frequency Ω

vortex nucleation

Single vortex preparation:
what is the shape of a single vortex line?

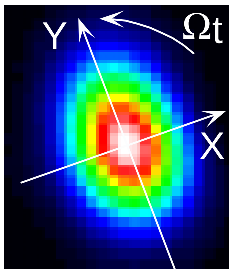
Single vortex dynamics: Kelvin modes of the line

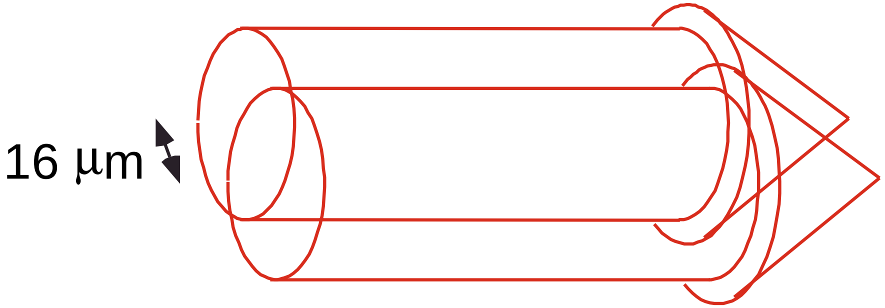
1.

Reliable production of a single vortex

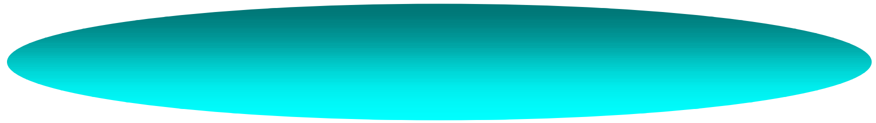
The laser stirrer for a gaseous BEC

Use of a laser spoon to stir the condensate and produce vortices:
ENS group, Phys. Rev. Lett. **84**, 806 (2000)





Magnetically trapped
Rb condensate



stirring laser

$$\omega_\perp / 2\pi = 97 \text{ Hz}$$
$$\omega_z / 2\pi = 12 \text{ Hz}$$
$$N \quad 5\ 10^5 \text{ atoms}$$

small rotating perturbation
of the magnetic potential
(a few %)

$$\Omega \quad \frac{\omega_\perp}{\sqrt{2}}$$ quadrupole resonance

(also at MIT,Boulder,Oxford)

Diagnostic of the rotating quantum gas

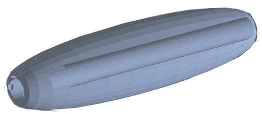
A single vortex is not visible *in situ*

$$\xi = \frac{1}{\sqrt{8\pi\rho\, a}} = 0.2\,\mu\mathrm{m}$$

$\rho = 2\ \ 10^{14}\ \mathrm{cm}^{-3}$

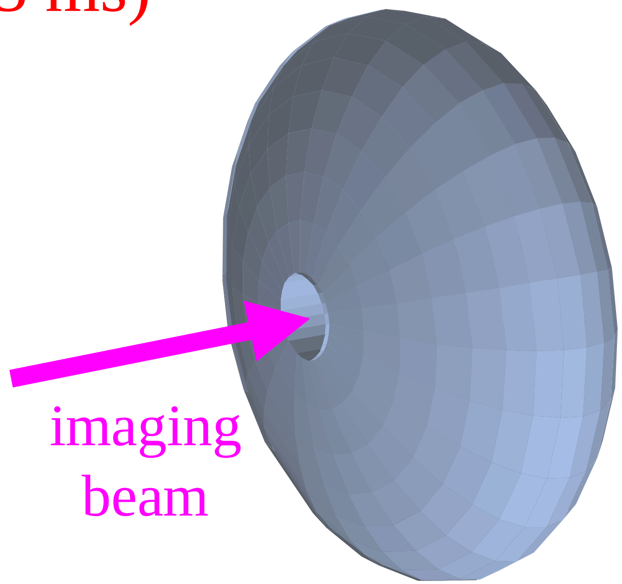
$a = 5.5\ \mathrm{nm}$

Time of flight analysis (25 ms)



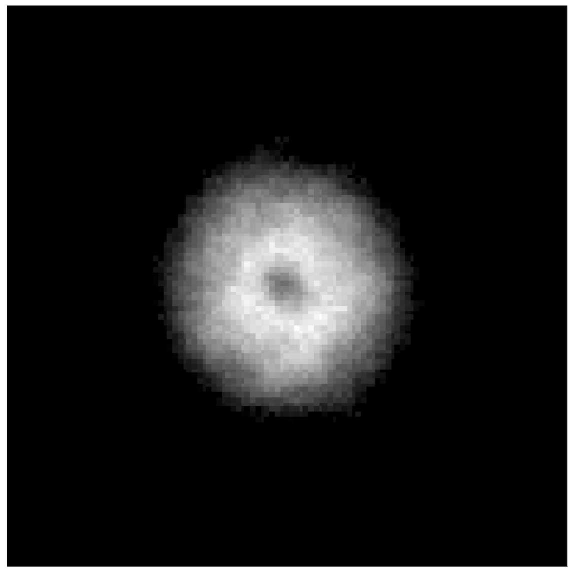
diameter 6 µm

x 40



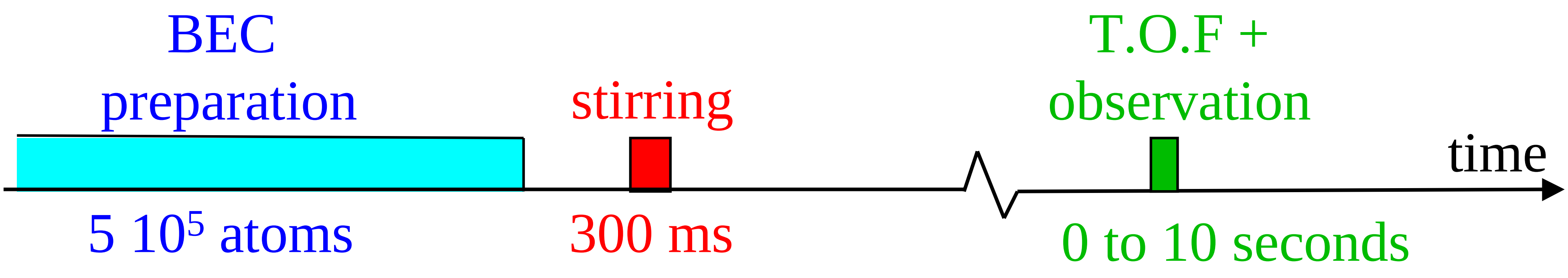
vortex core 8 µm

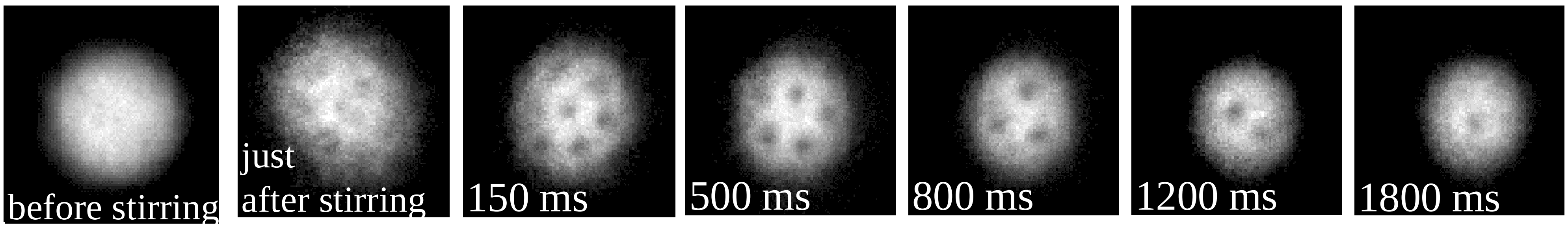
diameter 240 µm



Reliable preparation of a single vortex

Nucleation of a small vortex array which rapidly decays in a single, well-centered vortex





Different time scales for the decay of the array and of the last vortex (also at MIT)

2.

The shape of a single vortex line

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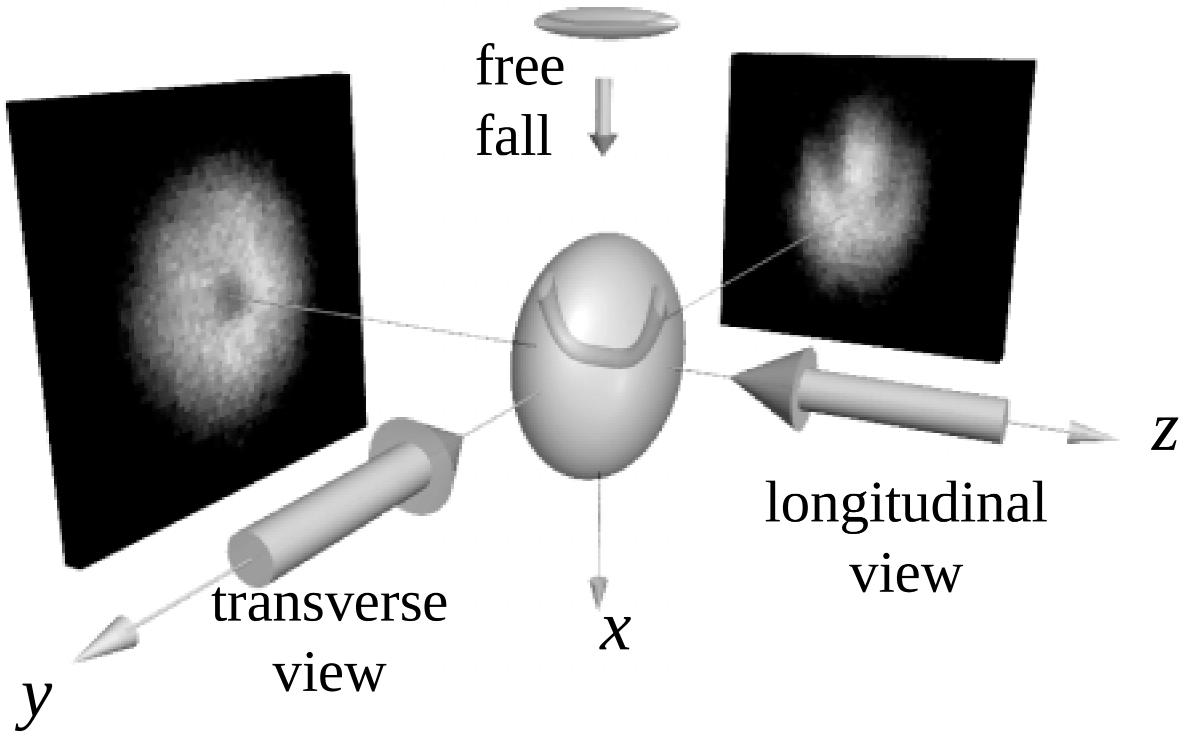
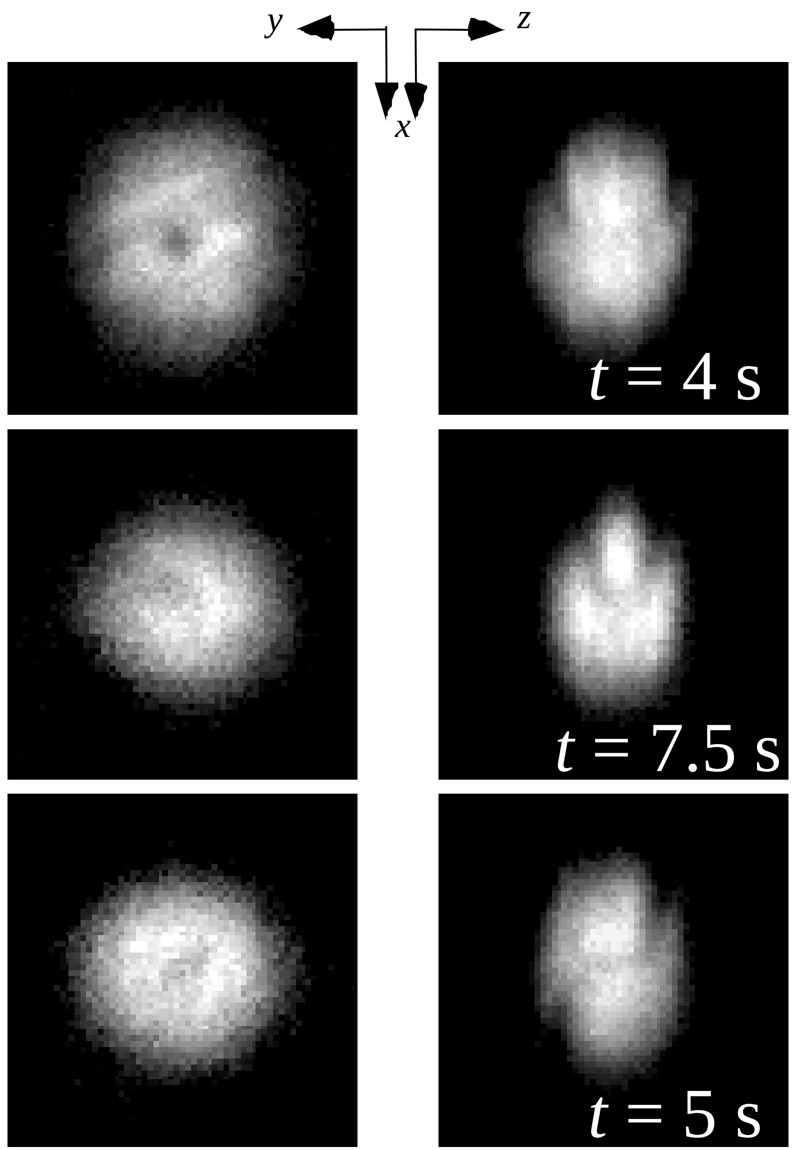
cond-mat/0206511

Observation of the complete vortex line

Simultaneous longitudinal and transverse imaging





similar transverse imaging developed
in Boulder and Oxford for a vortex array

A single vortex line is generally not straight...

U shaped or N shaped

Why is a single vortex line curved?

Precursor: for cigar shaped condensates, anomalous modes of the state with one straight vortex (Fetter-Svidzinsky 2000, Feder *et al.*)

Garcia-Ripoll & Perez-Garcia (2001)

symmetry breaking effect, which occurs even for $\varepsilon=0$

See also Aftalion *et al.* (2001)

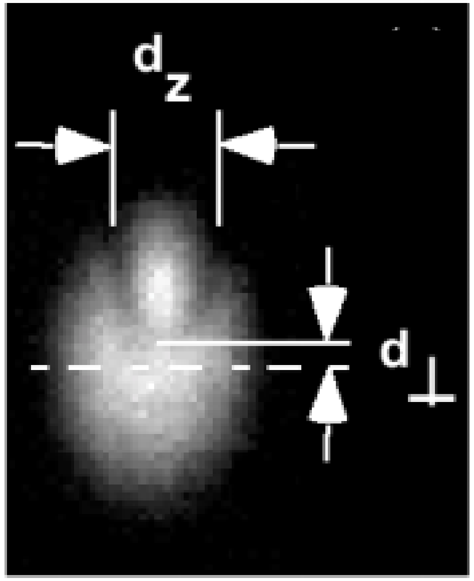
Modugno,Pricoupenko,Castin (2002)

Interpretation in terms of a series of 2D problems

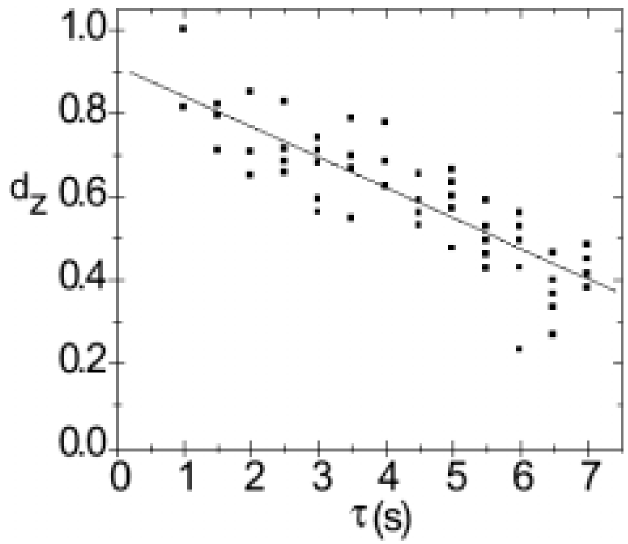
The decay of a vortex line

The trap is not perfectly axisymmetric...

transverse view



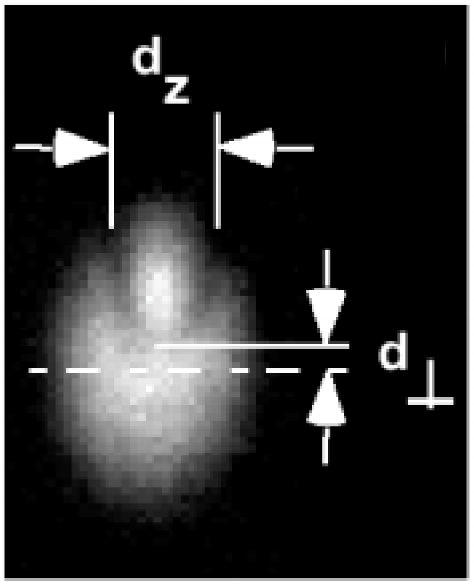
We normalize d_z by the length of the condensate

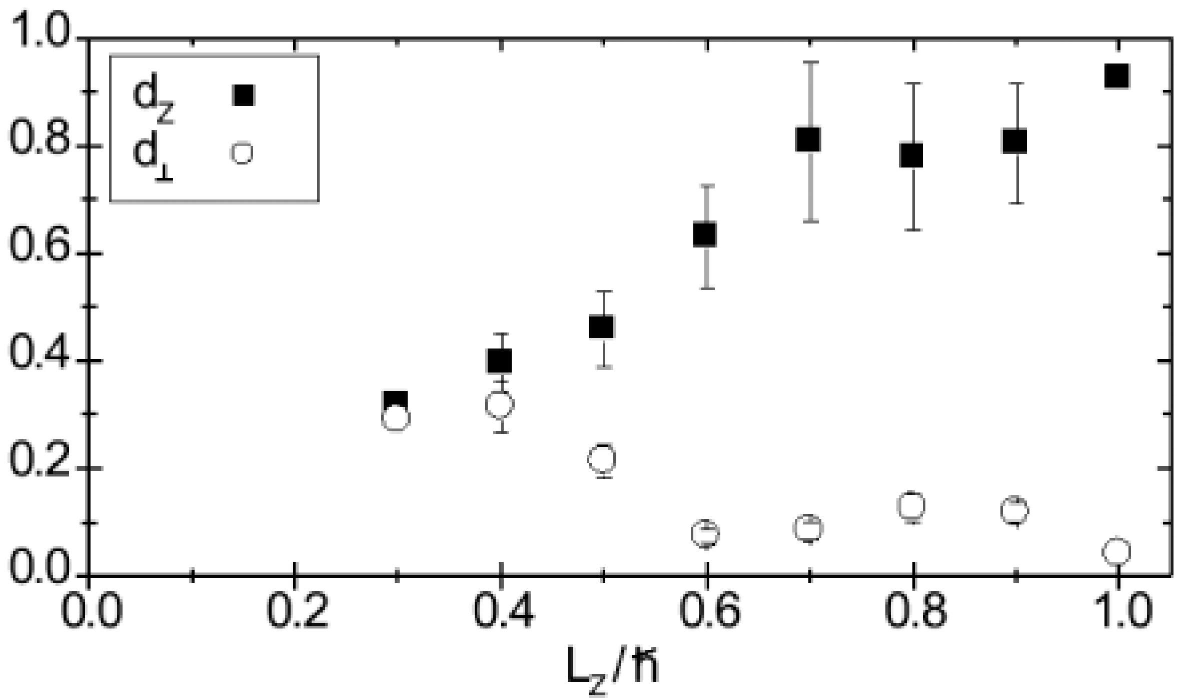


Relation between the shape of the vortex line and the angular momentum

Measurement of the angular momentum using the frequency of the two quadrupole modes $m = \pm 2$

Theory: Zambelli and Stringari, PRL **81**, 1754 (1998)
Exp. for a well centered vortex: ENS group, PRL **85**, 2223 (2000)





3.

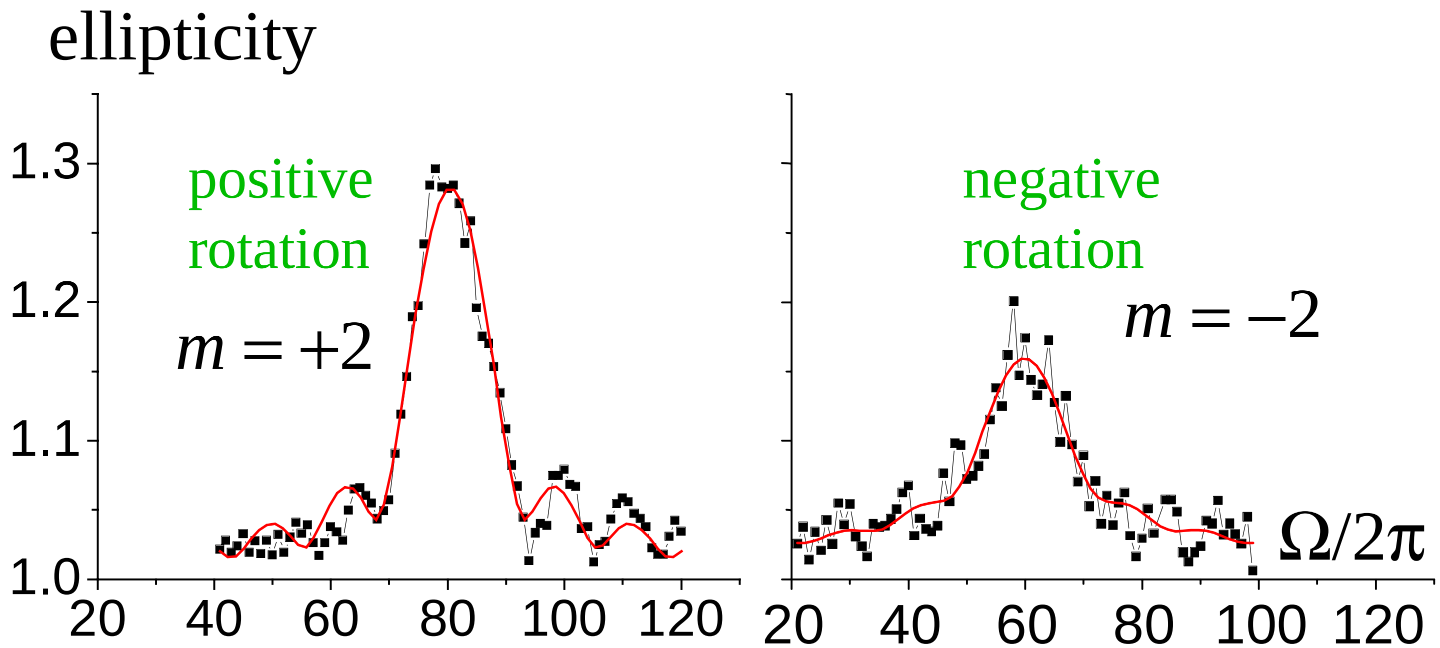
Excitations of a single vortex line: the Kelvin mode

Quadrupole excitation of a condensate with a single vortex line

$$\frac{\omega_\perp}{2\pi} = 97\,\text{Hz}$$

excitation (40 ms)
of the *m*=+2 or *m*=-2
quadrupole mode
by the stirring laser
$\Omega/2\pi$=20 ... 130 Hz

T.O.F. and
detection of
the transverse
ellipticity



center + : 80.5 Hz
center - : 59.9 Hz

→ angular
momentum h
(also in Boulder)

lifetime + : 42 ms
lifetime - : 18 ms

Possible explanation (s) for the rapid decay of the *m* = -2 mode

- After the vortex nucleation phase, the uncondensed part is rotating in the positive sense, as the vortex itself.

The *m* = -2 mode is more damped than the *m* = +2

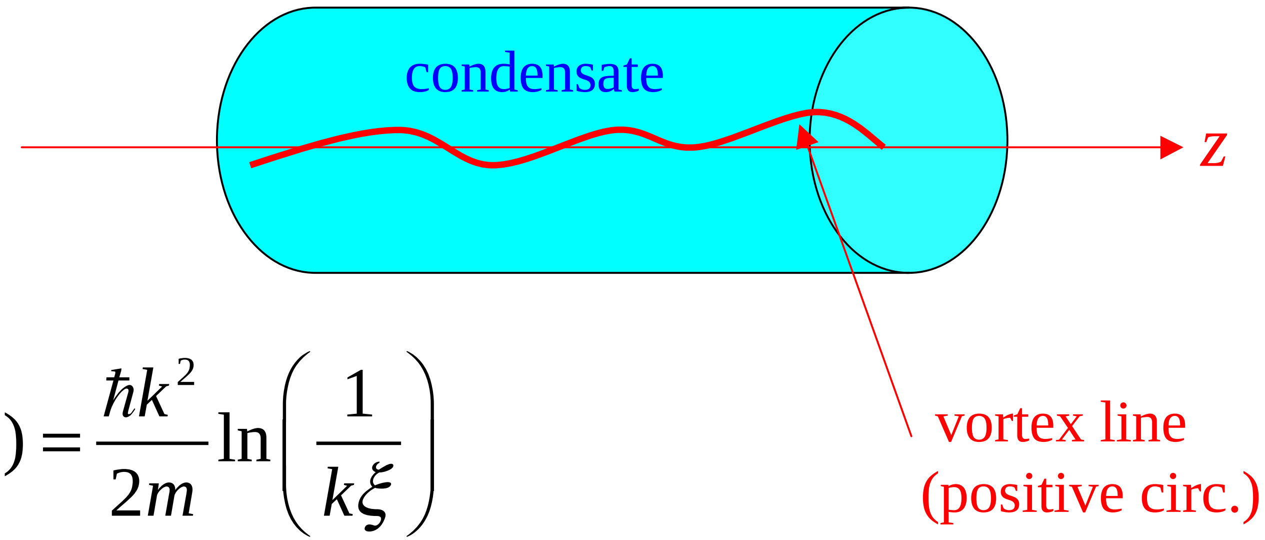
Williams, Zaremba, Jackson, Nikuni, Griffin, P.R.L. 2002

- Conversion of the m=-2 quadrupole mode into a pair of "kelvons"

Excitations of the vortex line

Shlyapnikov, private com.

The Kelvin modes of a vortex line



Wave vector along z : k

Dispersion relation: $\omega(k) = \frac{\hbar k^2}{2m} \ln\left(\frac{1}{k\xi}\right)$

Angular momentum along z : $-\hbar$

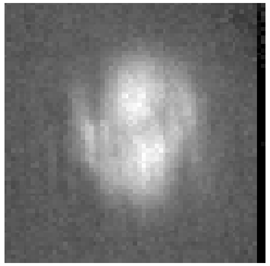
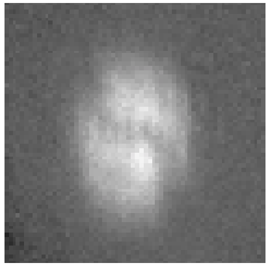
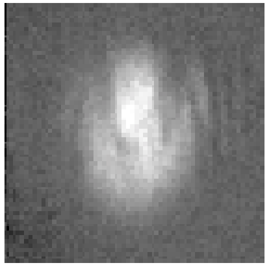
Possible mechanism for the decay of the quadrupole m=-2 mode:

$$\text{Quadrupole, } \omega_{-2} \longrightarrow \text{Kelvon } k, \frac{\omega_{-2}}{2} + \text{Kelvon } -k, \frac{\omega_{-2}}{2}$$

Conclusions

Are the Kelvin modes directly observable?

transverse pictures of the condensate after the excitation of the *m*=-2 mode:

no equivalent "fringes" after excitation of the m=+2 mode

Universal character of vortices as a way to set a macroscopic quantum object into motion:

superfluid liquid helium, (type II) supraconductors, neutron stars

Gaseous BECs offer unique possibilities for a direct observation of these objects and of their dynamics