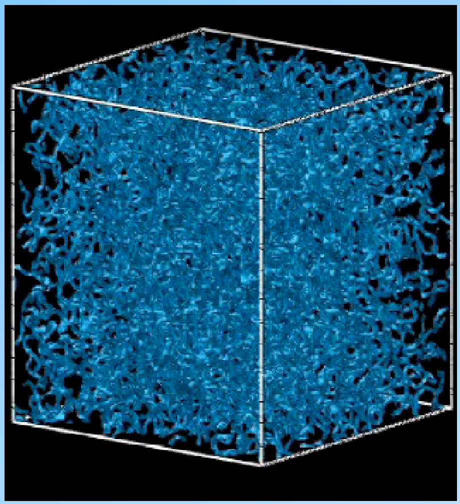
Quantum Turbulence

-Today and Tomorrow-



Makoto TSUBOTA
Department of Physics,
Osaka City University, Japan

Review article: M. Tsubota, J. Phys. Soc. Jpn. 77, 111006(2008)
Progress in Low Temperature Physics, vol.16 (Elsevier, 2008), eds. W. P. Halperin and M. Tsubota

A03 Bose Superfluids and Quantized Vortices

Studies of physics of quantized vortices and “new” superfluid turbulence

M. Tsubota, T. Hata, H. Yano

Public participation: M. Machida, D. Takahashi

Superfluidity of atomic gases with internal degrees of freedom

M. Ueda, T. Hirano, H. Saito, S. Tojo, Y. Kawaguchi

Public participation: Y. Kato

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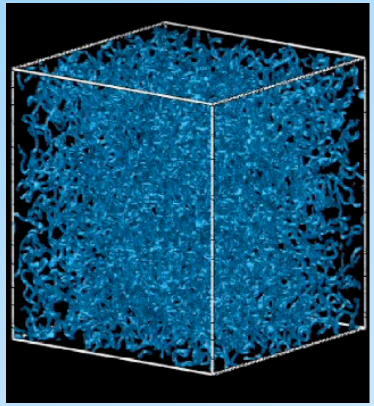


1. Why do we study quantum turbulence(QT)?
2. Quantum turbulence: today
   ～Outputs of A03 Tsubota's group～
3. Quantum turbulence: tomorrow

1. Why do we study quantum turbulence (QT)?

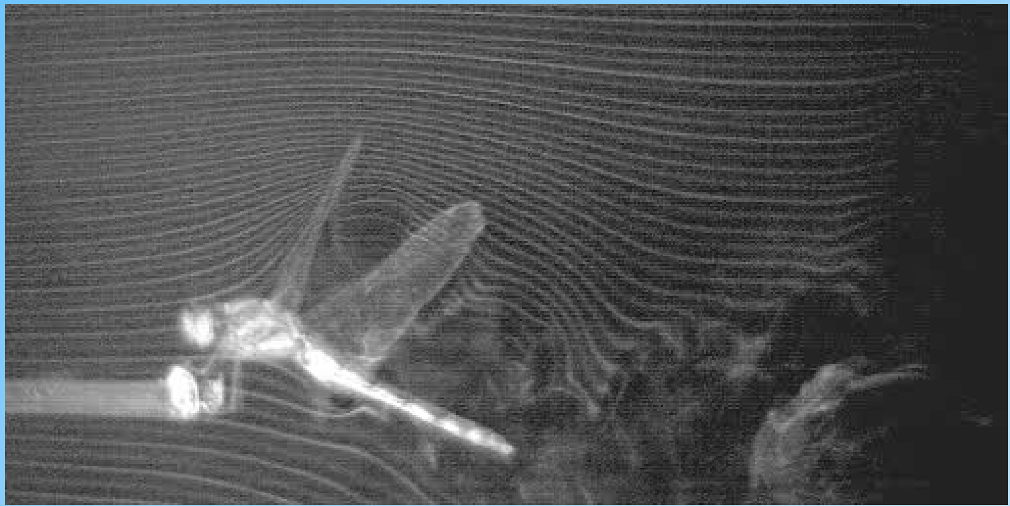
Leonardo Da Vinci (1452-1519)

"turbulence" is a physical problem that is common to many fields, that is very old, and that has not been solved. by R. Feynman

乱流は古典物理学の最終問題の一つである。

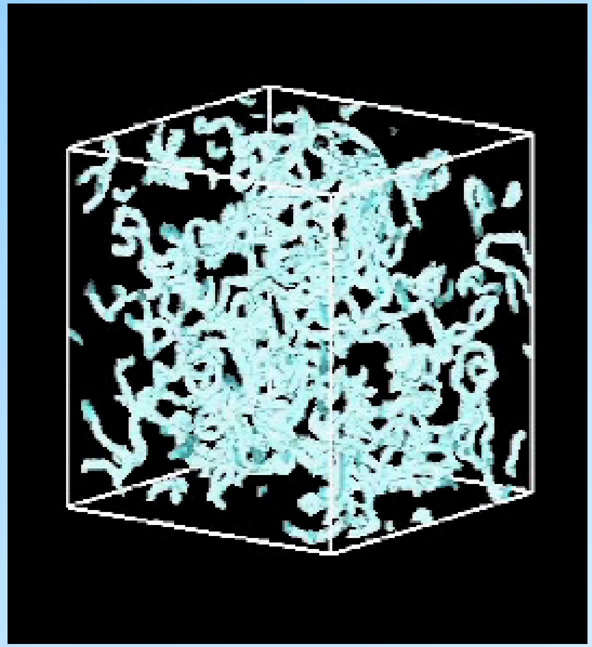
Classical Turbulence (CT) vs. Quantum Turbulence (QT)

Classical turbulence



QT is much simpler than CT, because each element of turbulence is definite and clear.

Quantum turbulence



Motion of vortex cores

- Quantized vortices are stable topological defects.
- Each vortex has the exactly same circulation.
- Circulation is conserved.

Our understanding of nature has been developed through *reductionism* (要素還元主義).

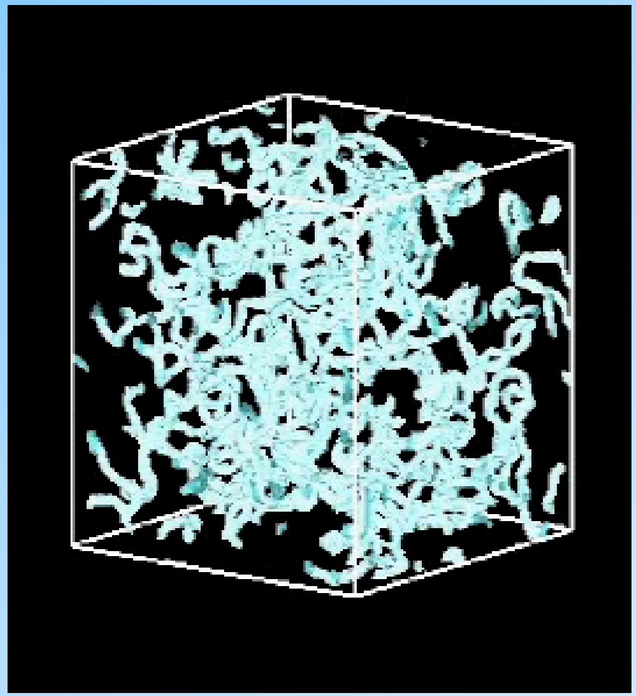
Solid-state physics has developed through *reductionism*, especially with the help of quantum mechanics in the 20’th century.

How about fluid physics? The status is still in its infancy.

Why?

- Lack of translational symmetry
- Many degrees of freedom
- *Reductionism* is not available. *etc.*

Reductionism is available in quantum hydrodynamics (quantum turbulence).



The study of QT can make a breakthrough to the great mystery of nature (turbulence).

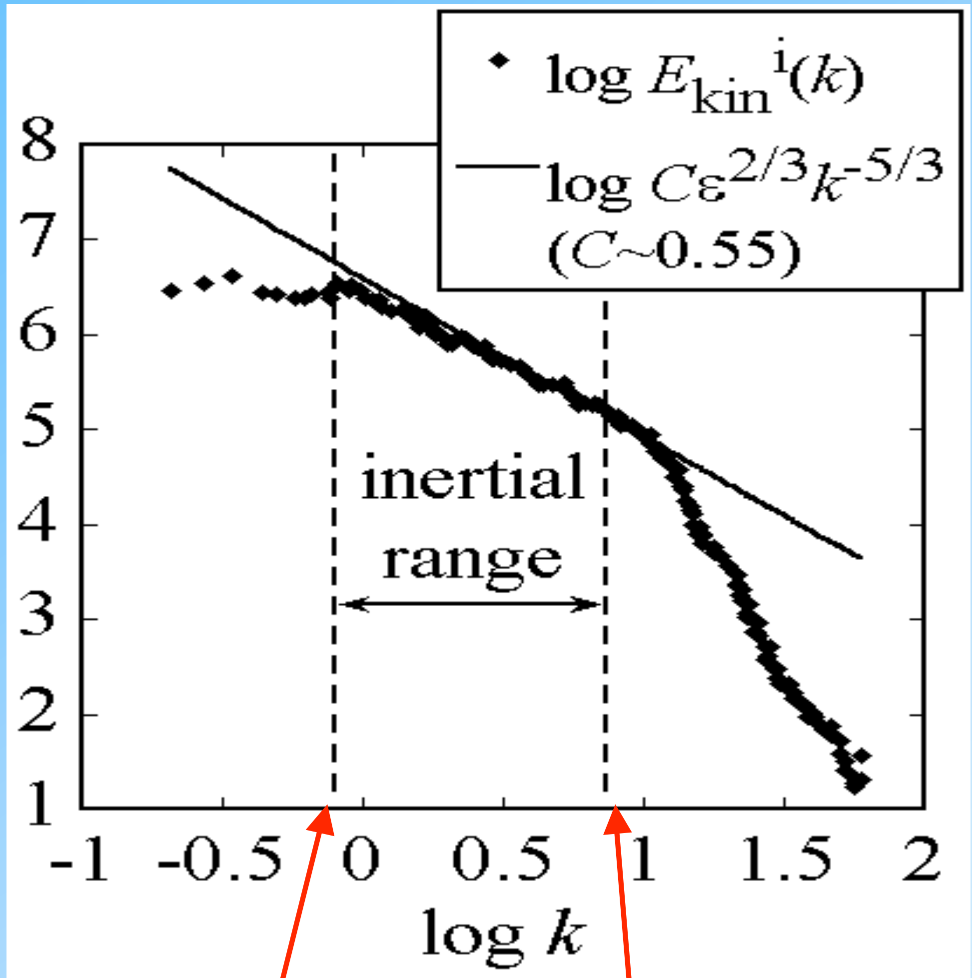
Motivation of “superclean” low temperature physics

	He, Cold atoms	High Tc cuprates
Condensed matter physics	Simple and clean systems Topics may be exhausted.	Neither simple nor clean systems Not exhausted.
Stage for general physics	ex. Quantum turbulence Quantum computer Analogy with cosmology Not exhausted.	?

2. Quantum turbulence: today　～Outputs of A03 Tsubota's group～

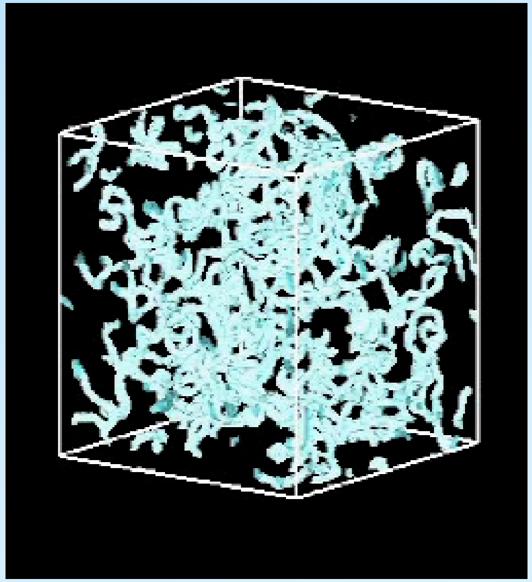
M. Kobayashi and MT, PRL 94, 065302 (2005), JPSJ 74, 3248 (2005)

We confirmed for the first time the Kolmogorov law from the Gross-Pitaevskii model.



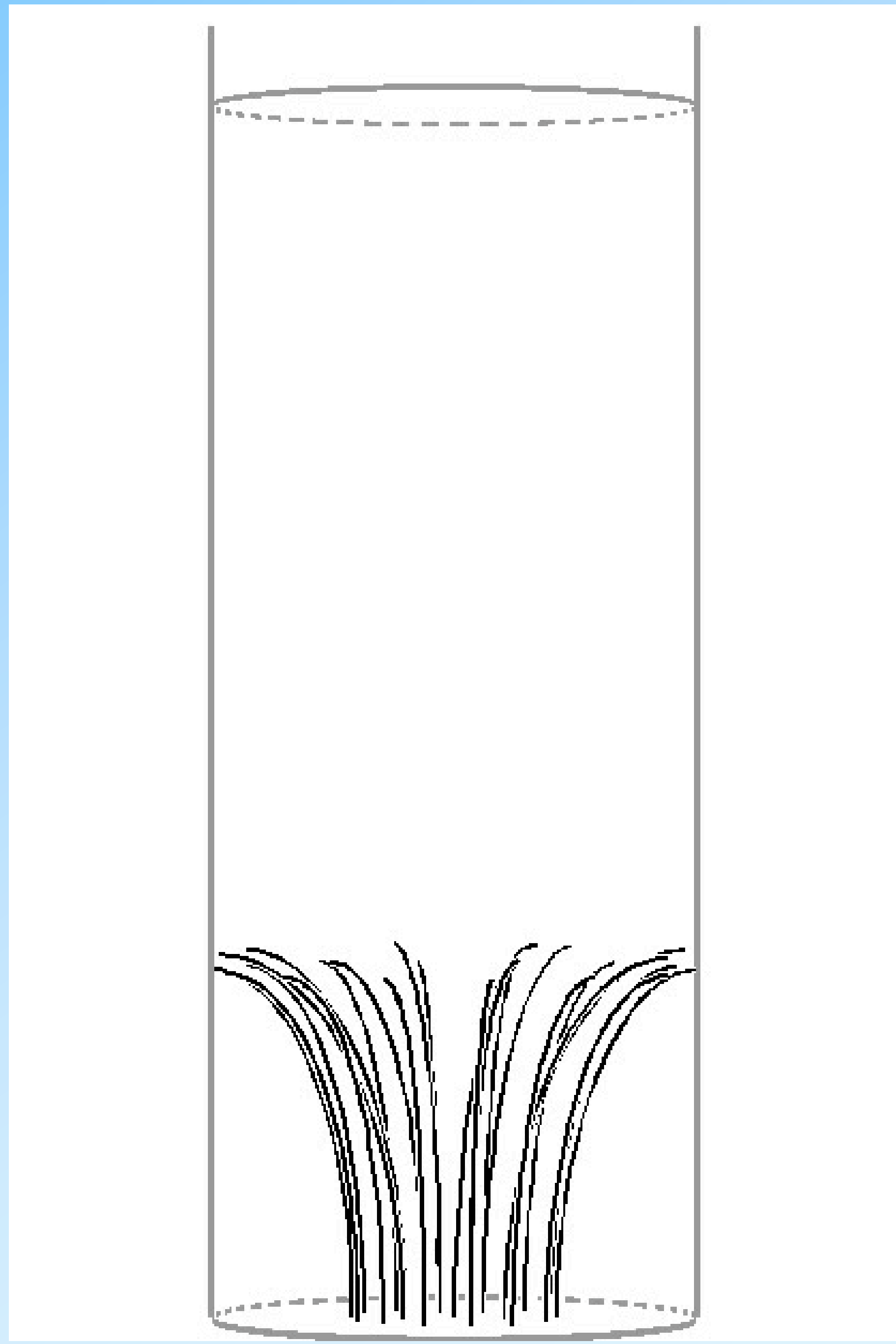
$2\pi / X_0$　　$2\pi / \xi$

Quantum turbulence is found to express the essence of classical turbulence!



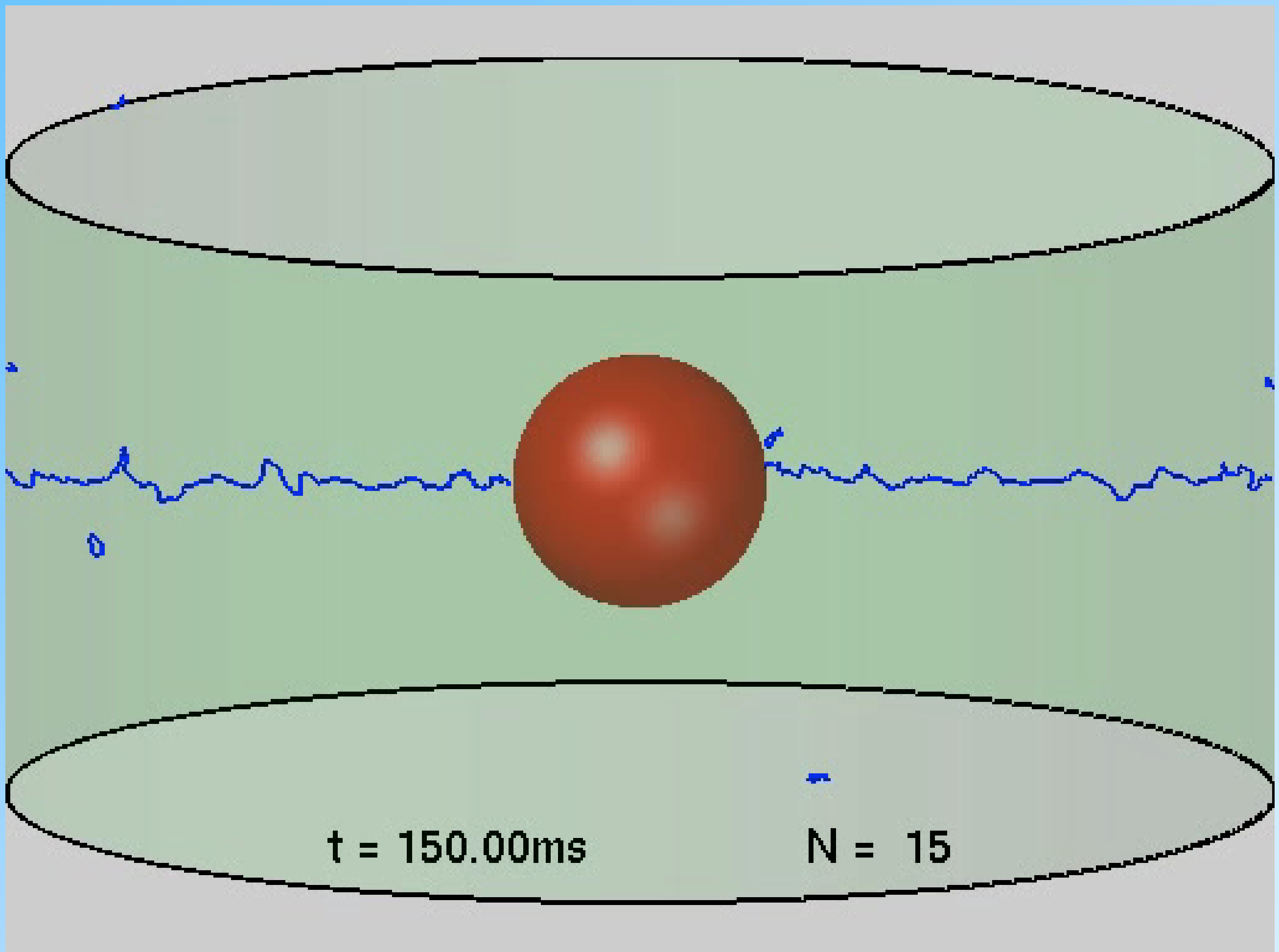
V.B.Eltsov, A.P.Finne, R.Hänninen, J.Kopu, M.Krusius, MT and E.V.Thuneberg, PRL 96, 215302 (2006)

We discovered twisted vortex state in ^{3}He-B theoretically, numerically and experimentally.



R. Hänninen, MT, W.F. Vinen, PRB **75**, 064502 (2007)

How remnant vortices develop to a tangle under AC flow



R=100 μm

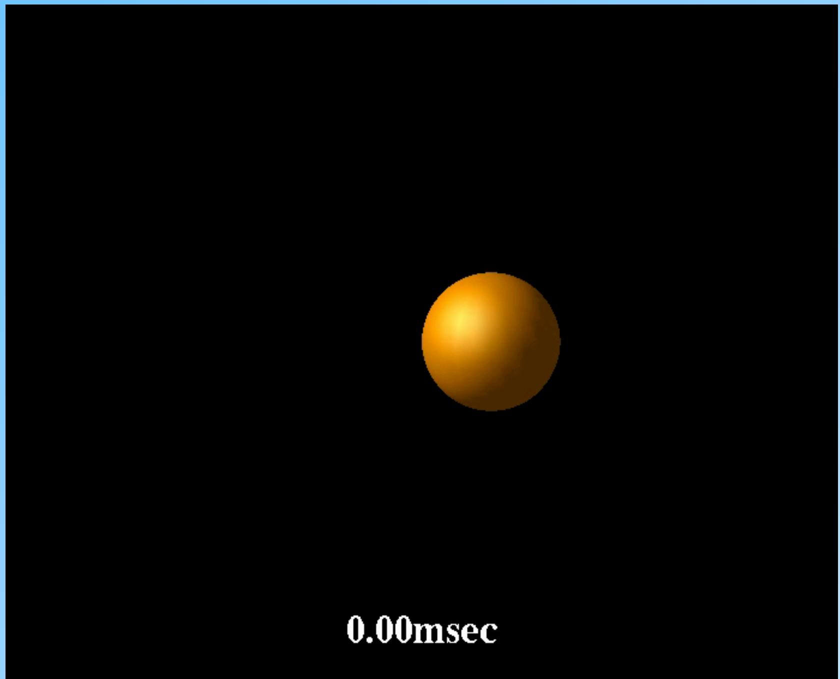
ω=200 Hz

V=150 mm/s

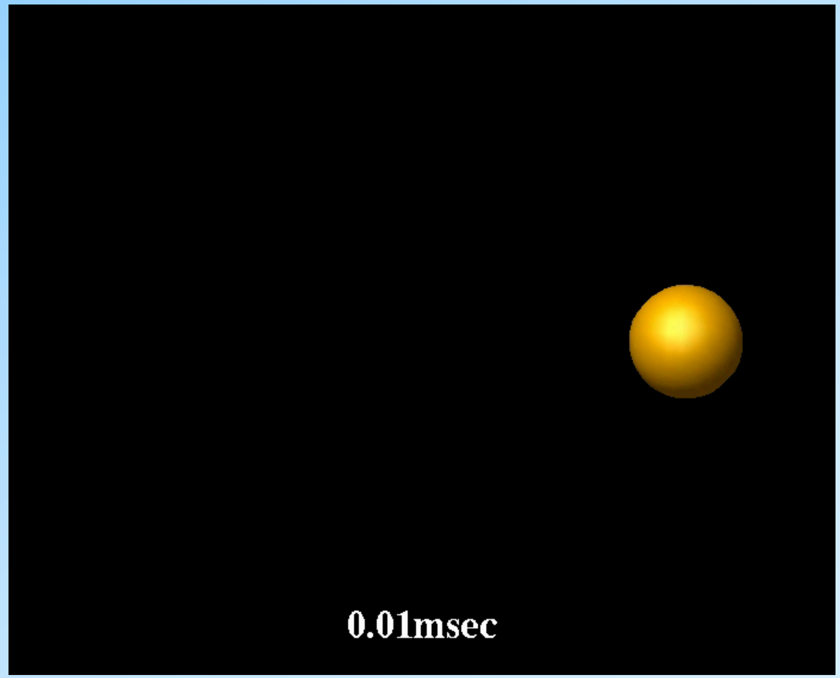
a. Kelvin waves form on the bridged vortex line.
b. Vortex rings nucleate by reconnection.
c. Turbulence develops.

R. Goto, S. Fujiyama, H. Yano, Y. Nago, N. Hashimoto, K. Obara, O. Ishikawa, MT, T. Hata, PRL 100, 045301(2008)

We found the transition to QT by seed vortex rings.



30mm/s

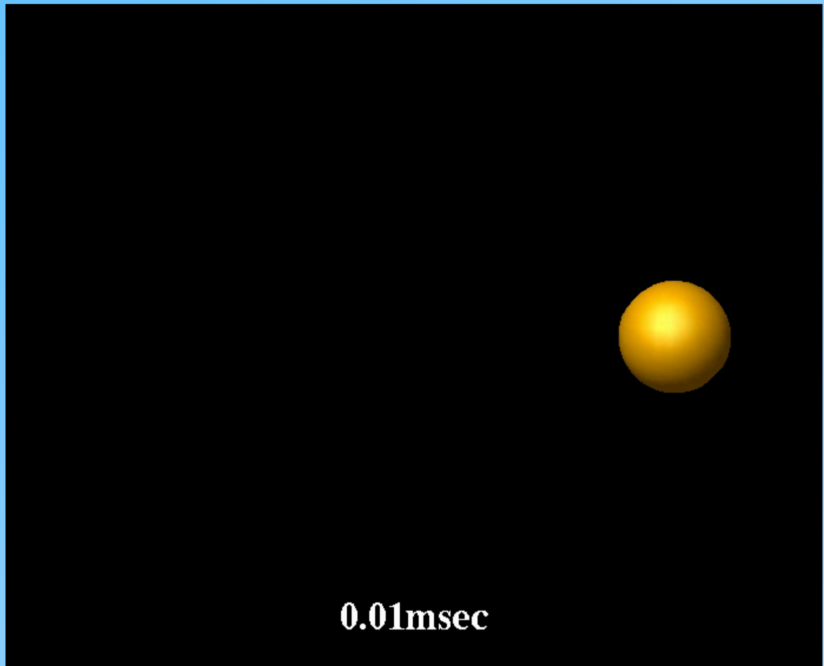


137 mm/s

Parameters for the sphere : Radius 3μm, Frequency 1590 Hz

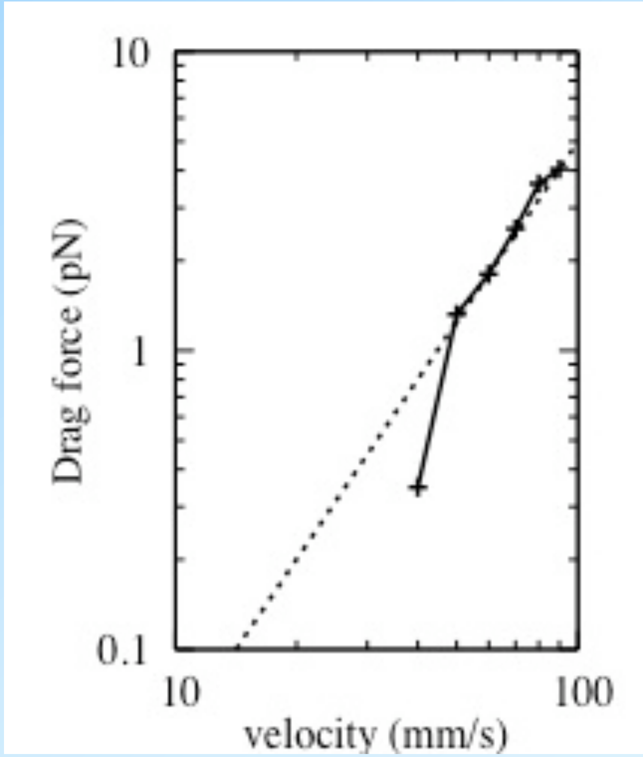
S. Fujiyama and MT, PRB79, 094513(2009)

→ P-2 S. Fujiyama



We obtained the drag force proportional to v^2.

(Output energy)-(Input energy)
= (Work by sphere)



Parameters for the sphere

Radius 3μm

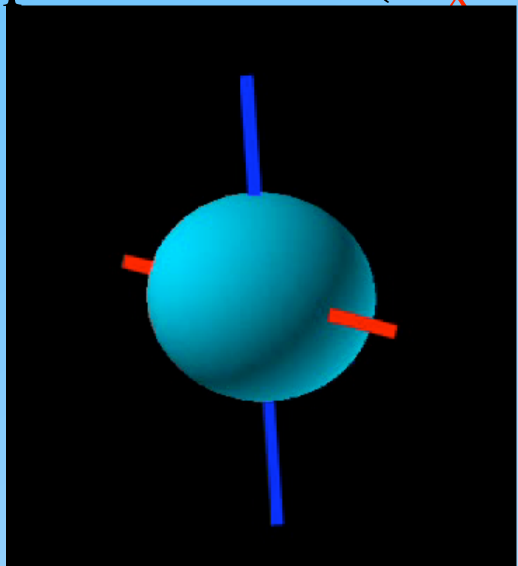
Frequency 1590 Hz

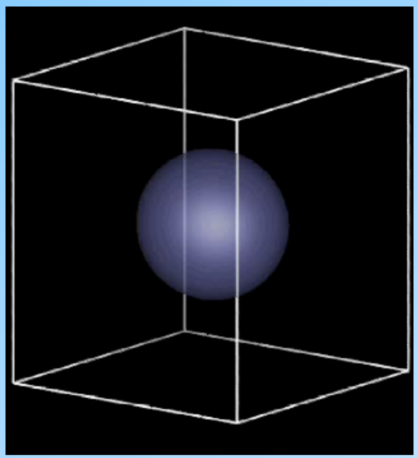
Velocity 137 mm/s

Classical analogue in AC turbulence

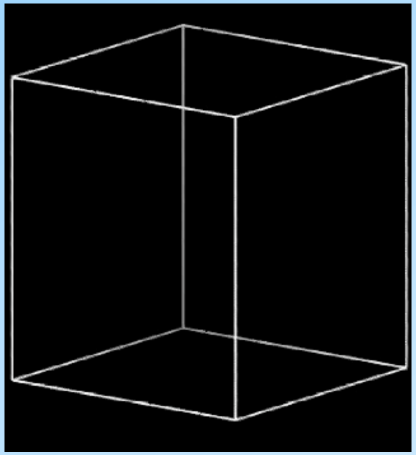
M. Kobayashi and MT, PRA76, 045603(2007)

Two precessions ($\omega_x \times \omega_z$)



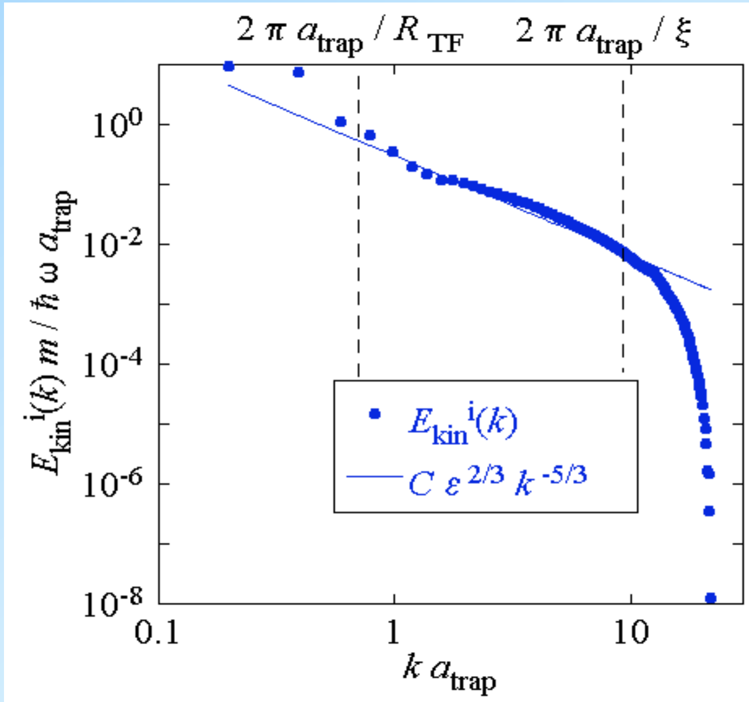


Condensate density



Quantized vortices

We showed how to make QT in a trapped BEC and obtained the energy spectrum consistent with the Kolmogorov law.

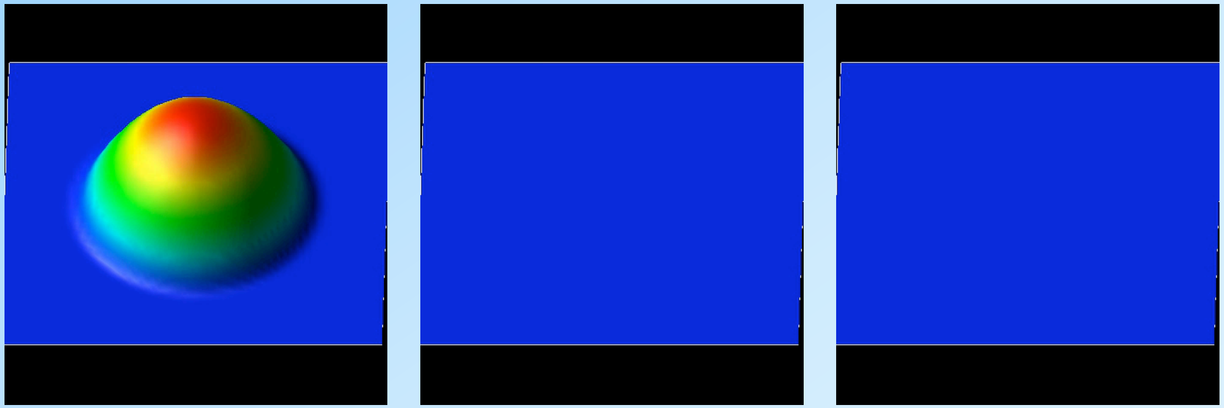


M. Yasunaga and MT, PRL 101, 220401 (2008)

→ O-26 M. Yasunaga

We studied Magnetic Resonance in spinor BECs. The spin-echo is strongly effected by the phase separation of the multi-components.

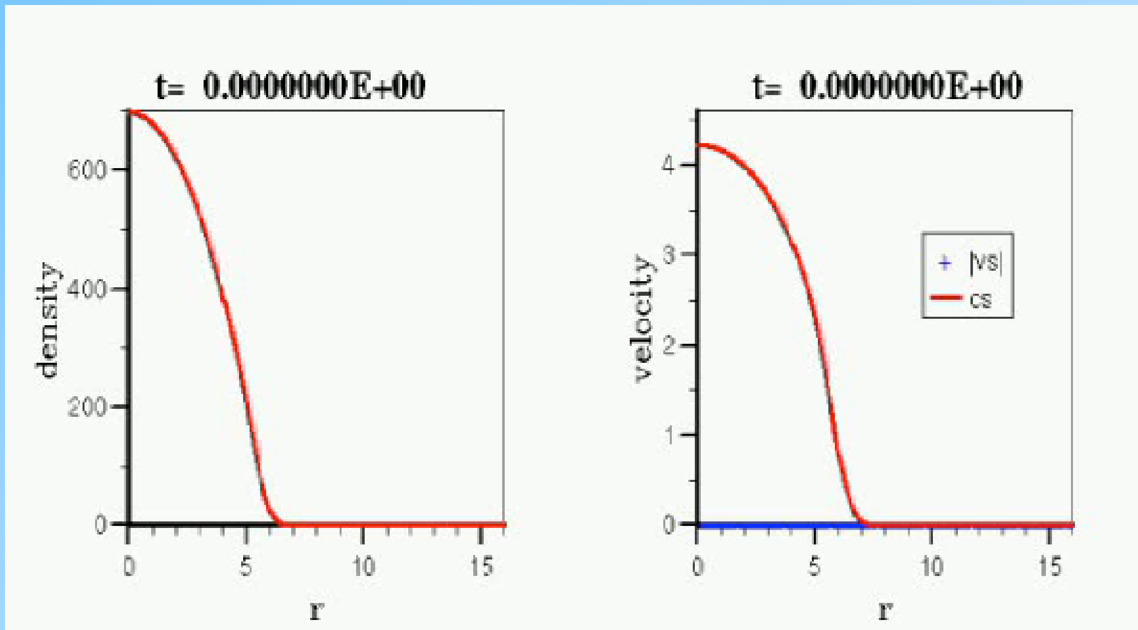
$|\Psi_1|^2$ $|\Psi_0|^2$ $|\Psi_{-1}|^2$



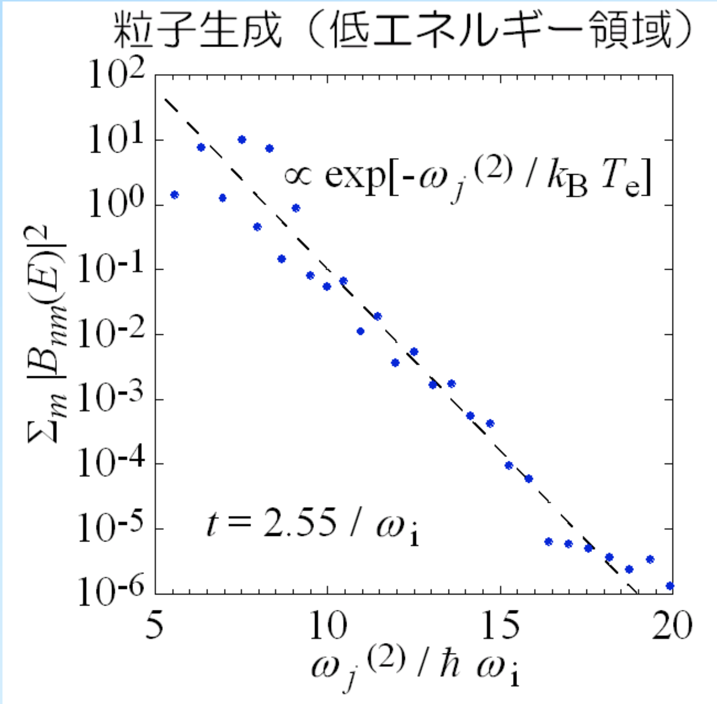
Y. Kurita, M. Kobayashi, T. Morinari, MT and H. Ishihara, PRA79, 043616(2009)

We studied spacetime analog of BEC. An oscillating BEC radiates excitations which obey the Boltzman distribution.

Solution of the GP equation



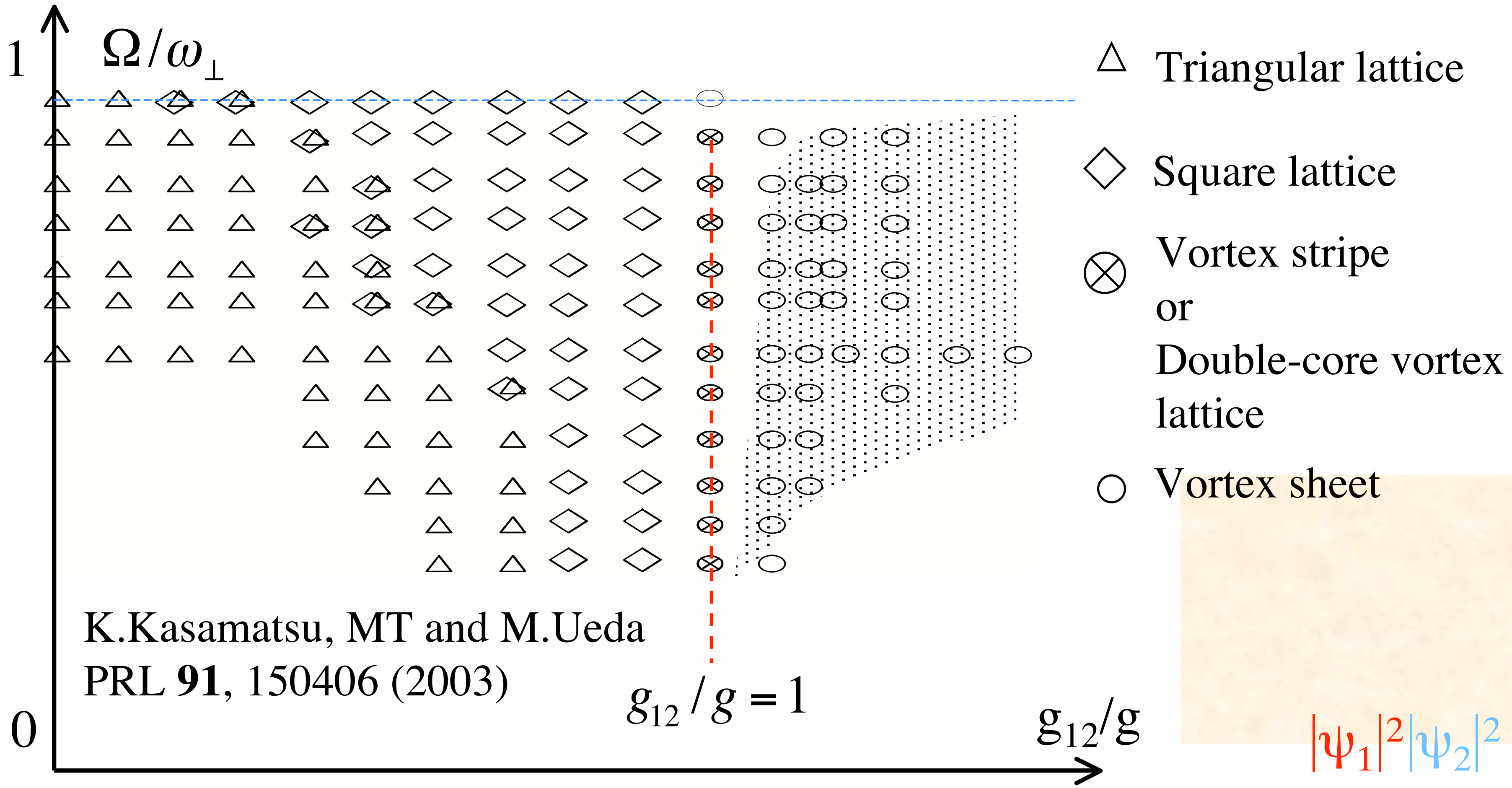
Spectrum of the particles



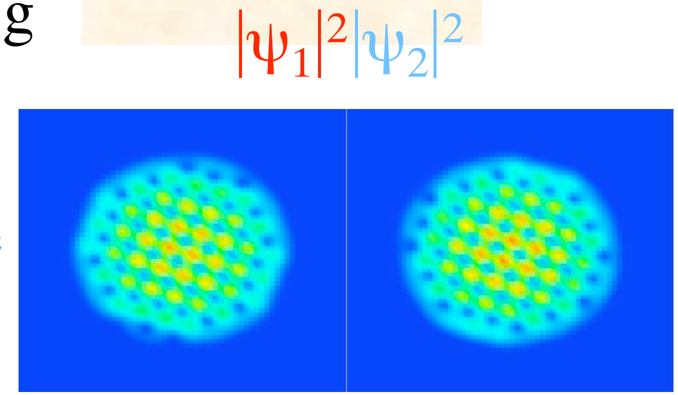
cf. Hawking radiation

K. Kasamatsu and MT, PRA79, 023606(2009)

We revealed vortex sheet in rotating two-component BECs.



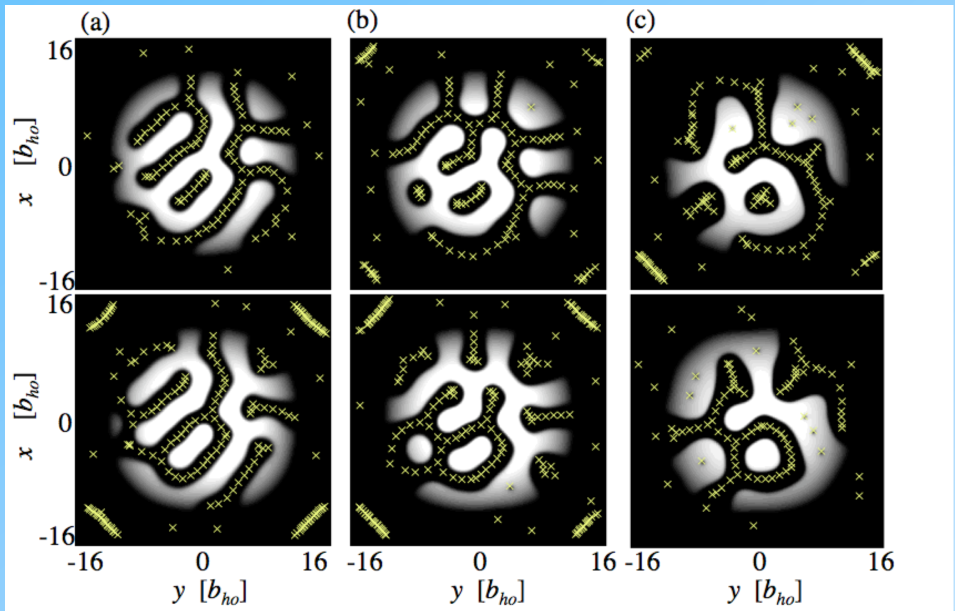
g_{12}: Interaction between two components



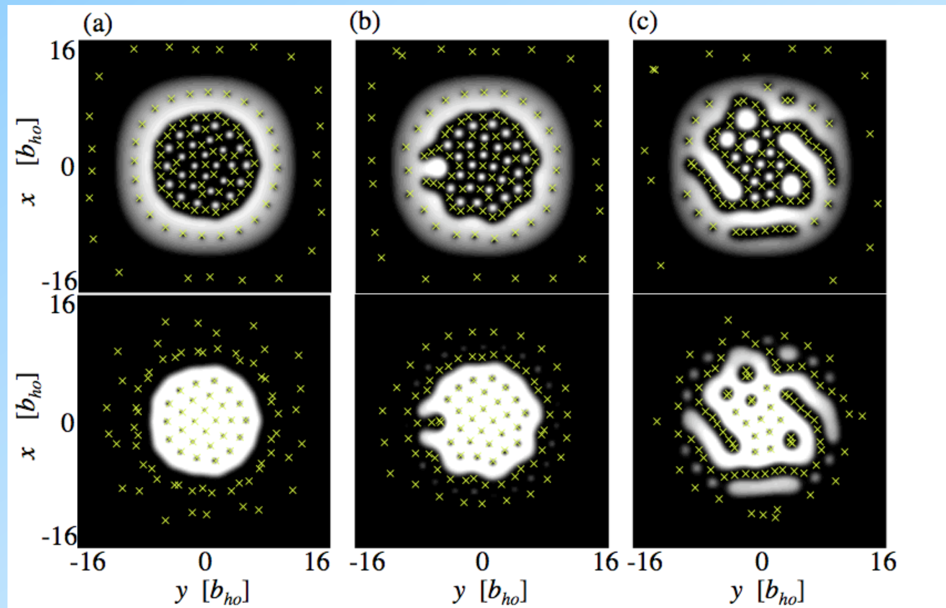
Square lattice

K. Kasamatsu and MT, PRA79, 023606(2009)

We revealed vortex sheet in rotating two-component BECs.



Density profile for g_{12}/g= 1.5 (a), 2.0 (b) and 3.0 (c).



Imbalanced case with g_{12}/g= 1.1, u_1=4000, and u_2=3000 (a), 3500 (b) and 3900 (c).

3. Quantum turbulence: tomorrow

3-1. Leggett Nobel lecture

3-2. Recent interesting topics

- 3-2-1. Experiments of QT in trapped BECs (Bagnato)
- 3-2-2. Dynamics of charged vortices and tangles in superfluid helium (Golov)
- 3-2-3. Question for the Kibble-Zurek problem (Bunkov)

SUPERFLUID 3-He: THE EARLY DAYS AS SEEN BY A THEORIST

Nobel Lecture, December 8, 2003

by

ANTHONY J. LEGGETT

University of Illinois, Department of Physics, 1110 West Green Street, Urbana, Ijl 61801-3080, USA.

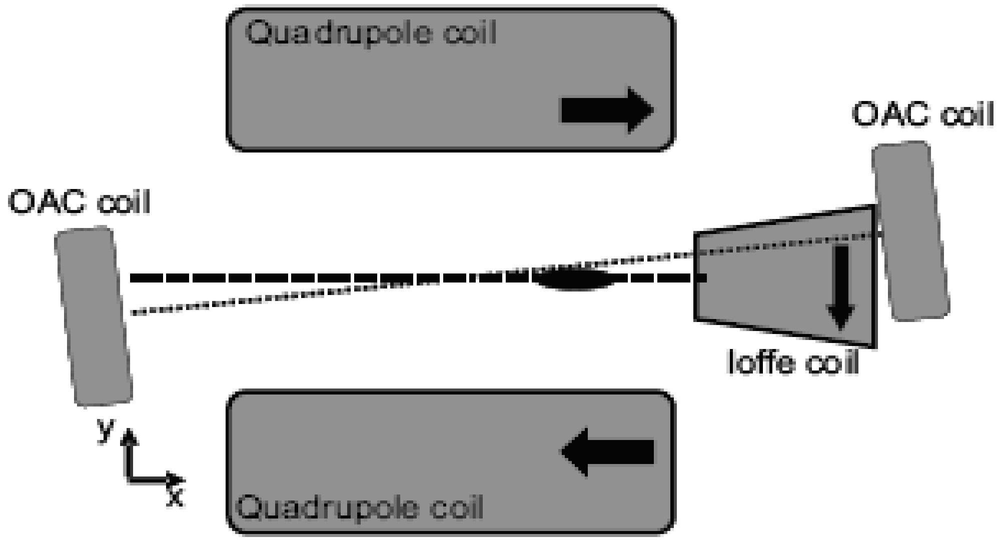
3. Quantum turbulence: tomorrow 3-1. Leggett Nobel lecture

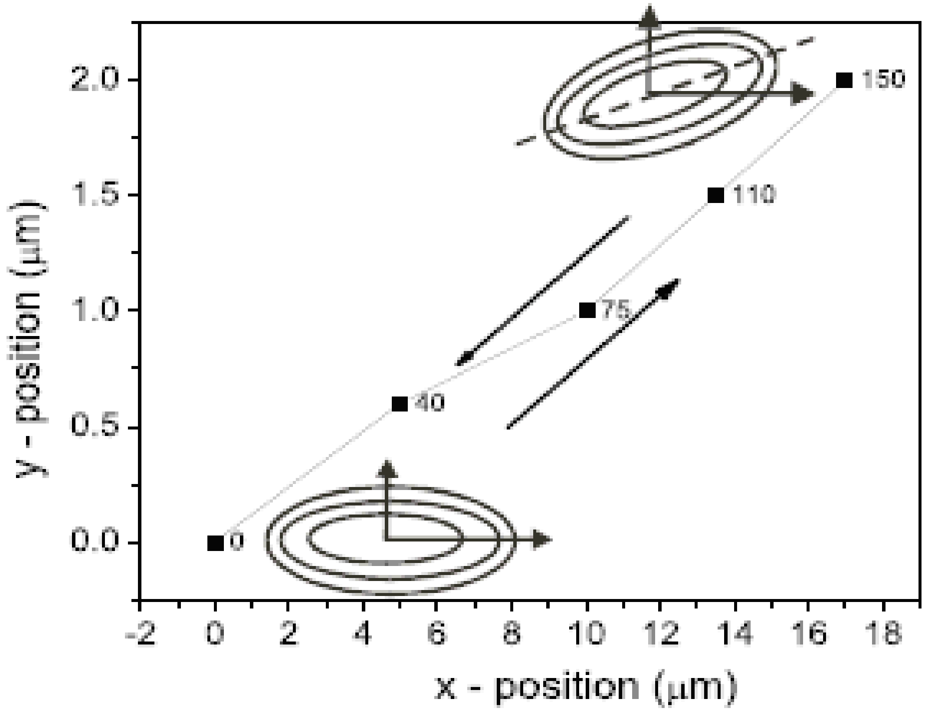
If we take a broader view, however, and content ourselves with indirect applications, the picture is much rosier. With the arguable exception of the "fractional quantum Hall" systems discovered ten years later, the superfluid phases of liquid ^{3}He are probably the most sophisticated physical systems of which we can claim a quantitative understanding, showing a subtlety of correlation unprecedented in all of known physics; and the lessons learned from them have been very widely applied elsewhere, both in condensed matter physics (for example to the cuprate superconductors, which like ^{3}He are believed to form Cooper pairs in an "exotic " (non-s-wave) pairing state), and in particle physics and cosmology; indeed, whole books(e.g., ref. [37]) have been written on the analogies between various phenomena known experimentally to occur in superfluid ^{3}He and some postulated in particle physics and/or the cosmology of the early universe. A second area in which the uniquely rich structure of the order parameter (pair wave function) of superfluid ^{3}He has had fruitful consequences is in studies of chaos and turbulence, and particularly of the way in which topological defects in the order parameter are generated in quenching through a phase transition (a process which is in fact frequently regarded as a model for processes believed to occur in the early universe).

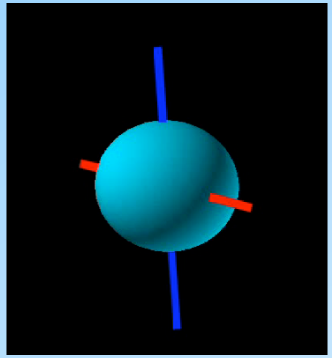
3-2-1. Experiments of QT in trapped BECs (Bagnato)

E.A.L. Henn, J.A.Seman, G. Roati, K. M.F. Magalhaes and V. S. Bagnato, arXiv:0904.2564

1. QT was realized in an oscillating BEC.
2. The BEC cloud expands isotropically when turbulence appears.







Displacement

Rotation

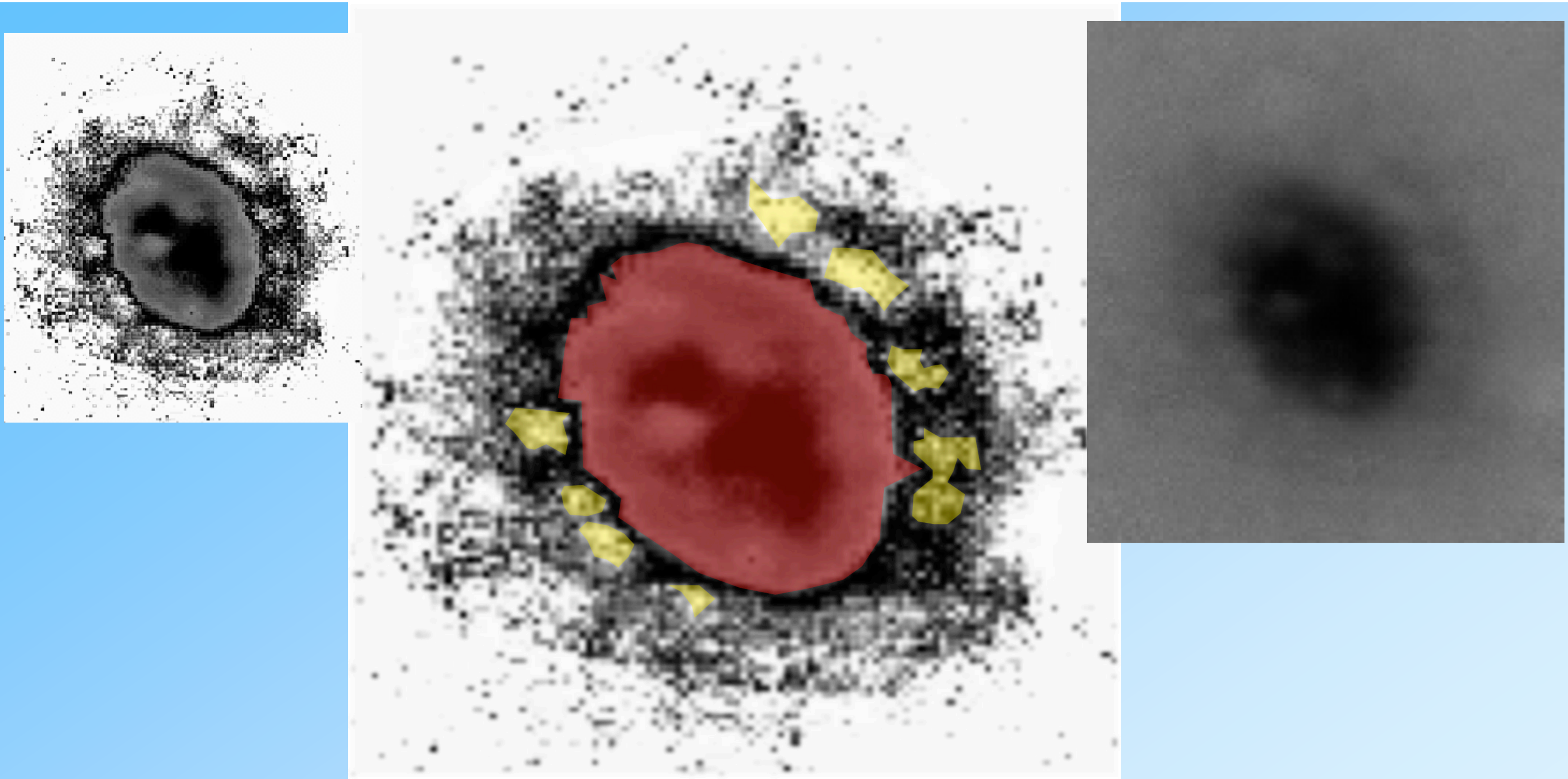
Deformation of the potential

Larger amplitude of oscillation:

-Larger displacement

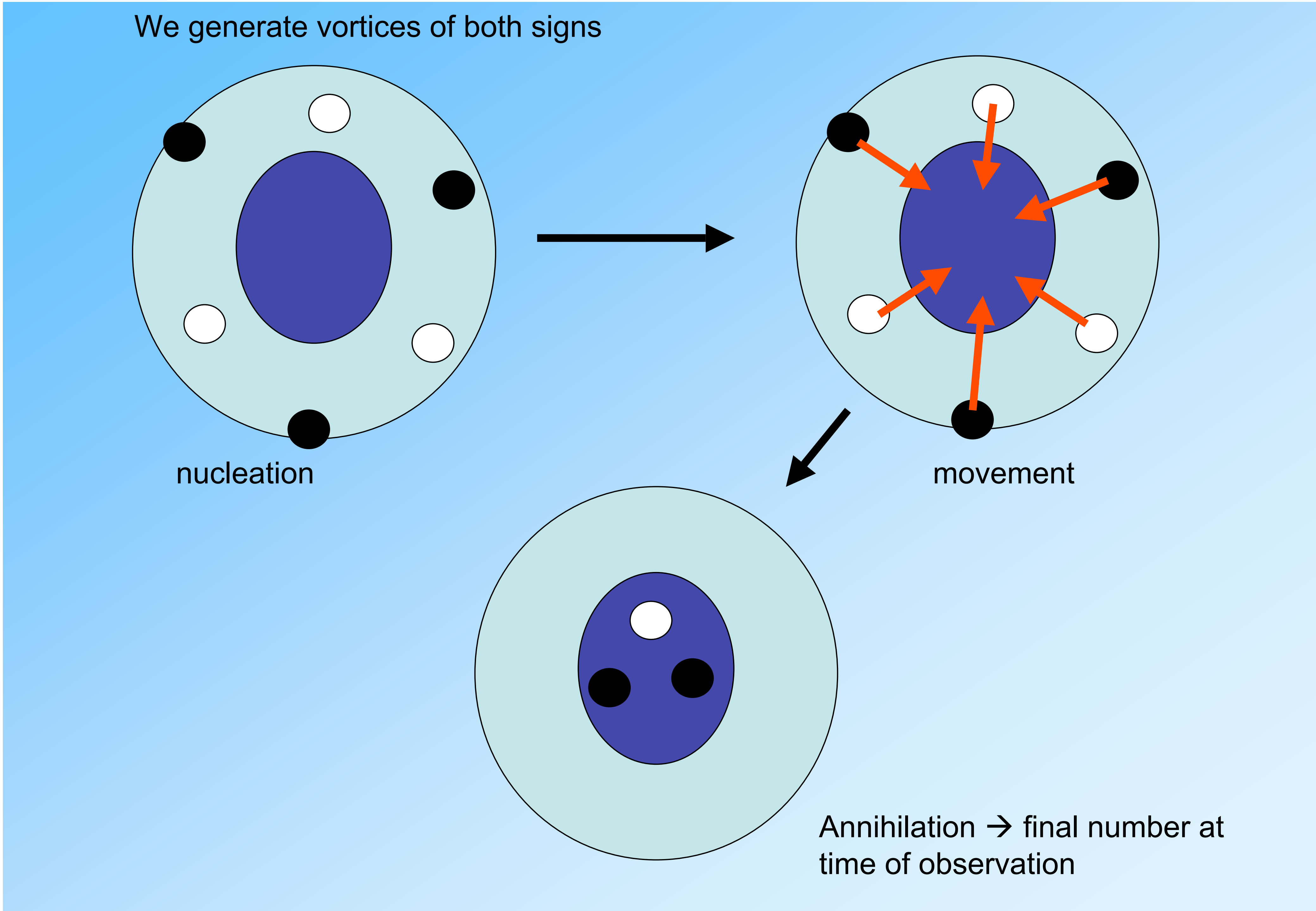
-Larger deformation of the potential

-Higher acceleration in the rotation



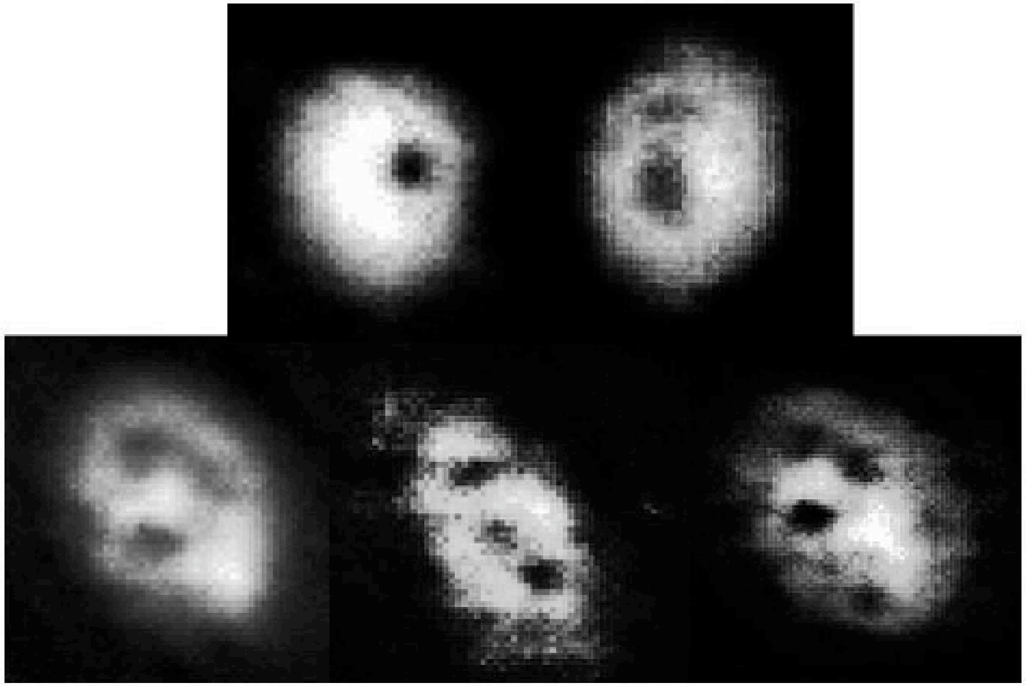
- Injection of vortices from the interface to the quantum fluid

First observation of an individual vortices forming at the edge and migrating to the interior , when rotating the BEC, was done by C. Foot’s group in Oxford – PRL88,(2002).

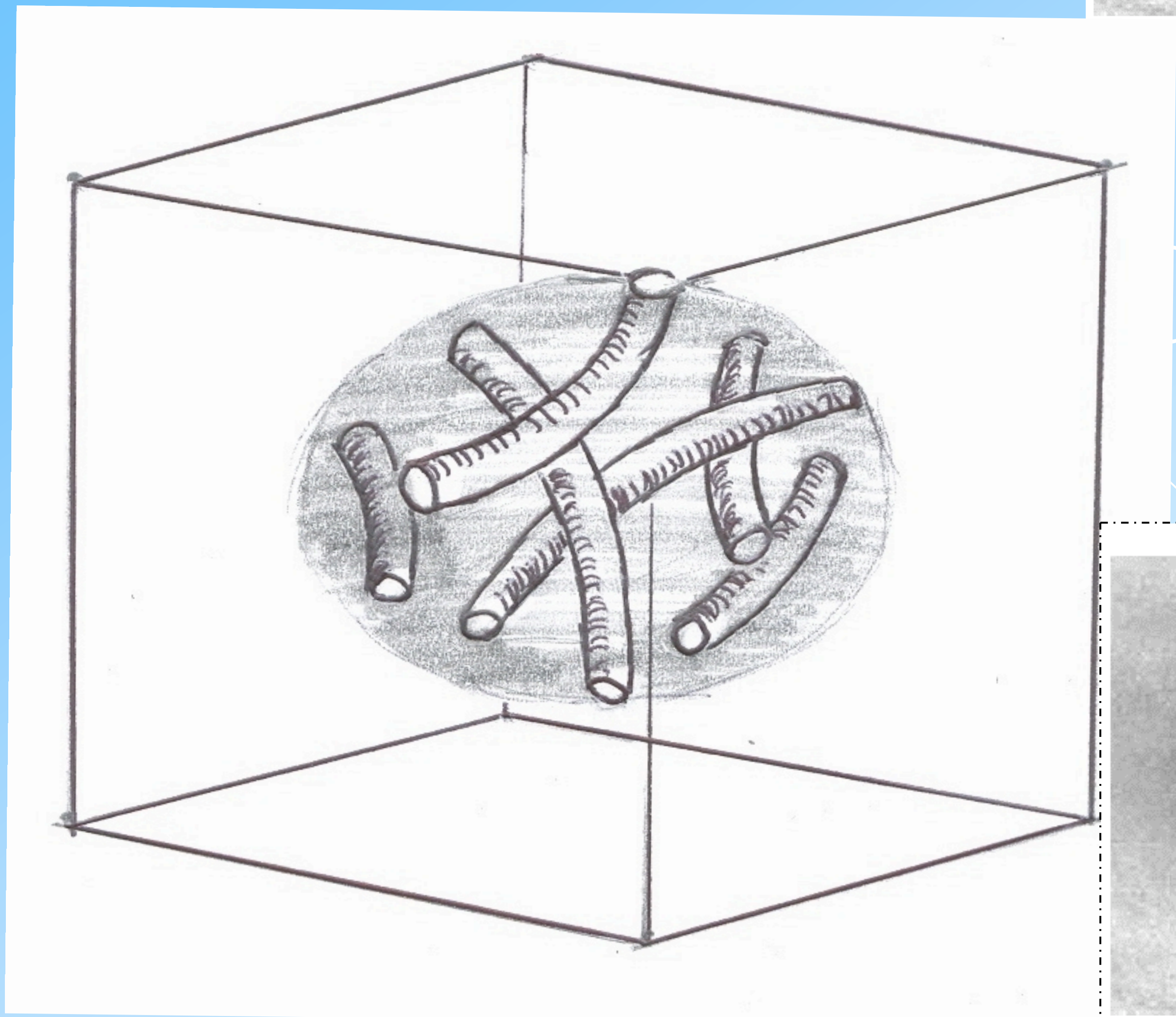

We generate vortices of both signs
nucleation
movement
Annihilation → final number at
time of observation

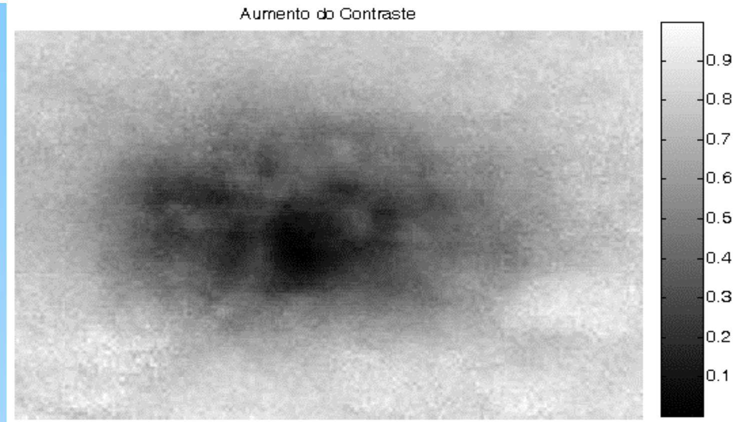
EVOLUTION WITH AMPLITUDE AND TIME OF EXCITATION

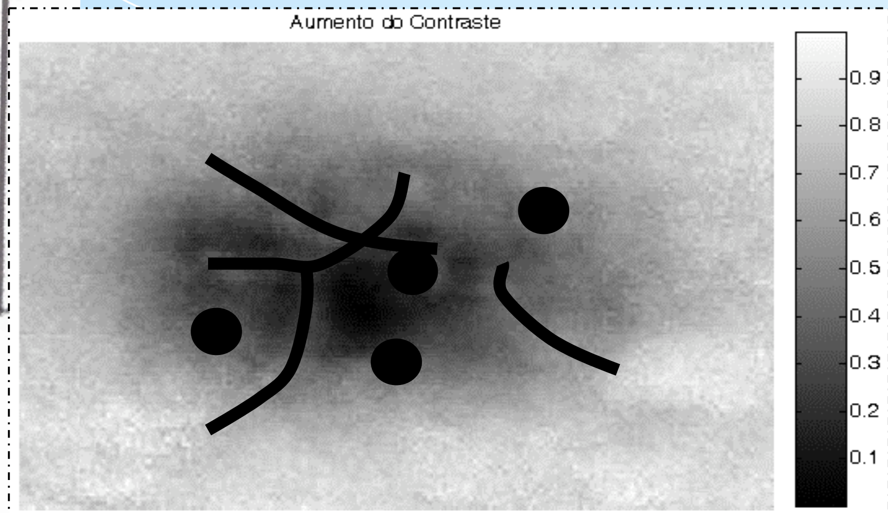
There are a large shot-to-shot fluctuation

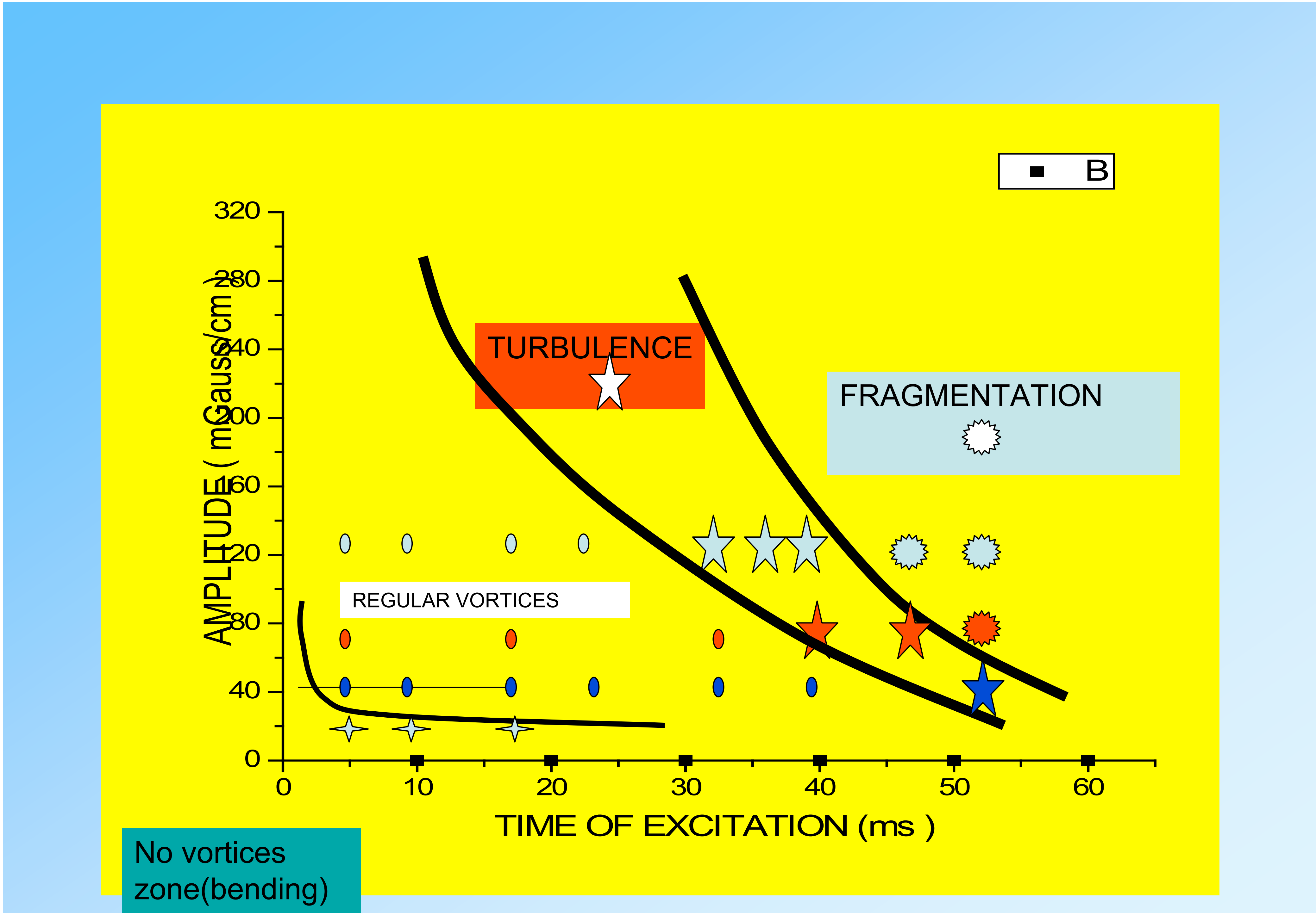


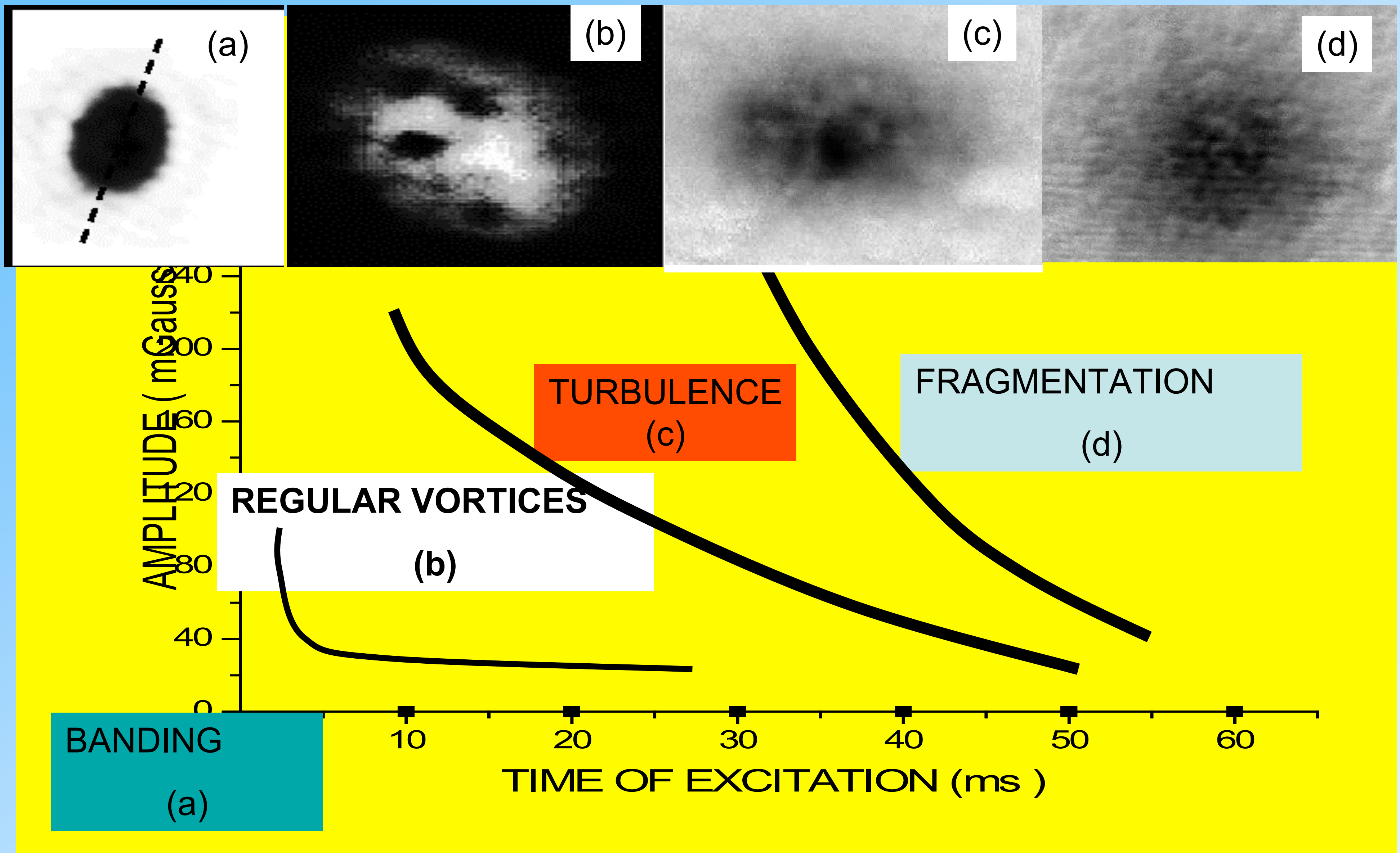
Tangle vortices



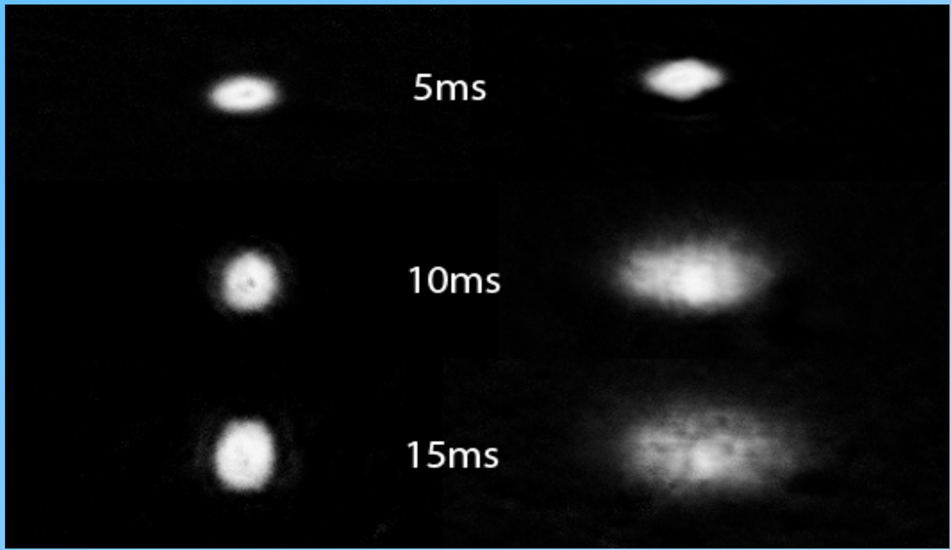


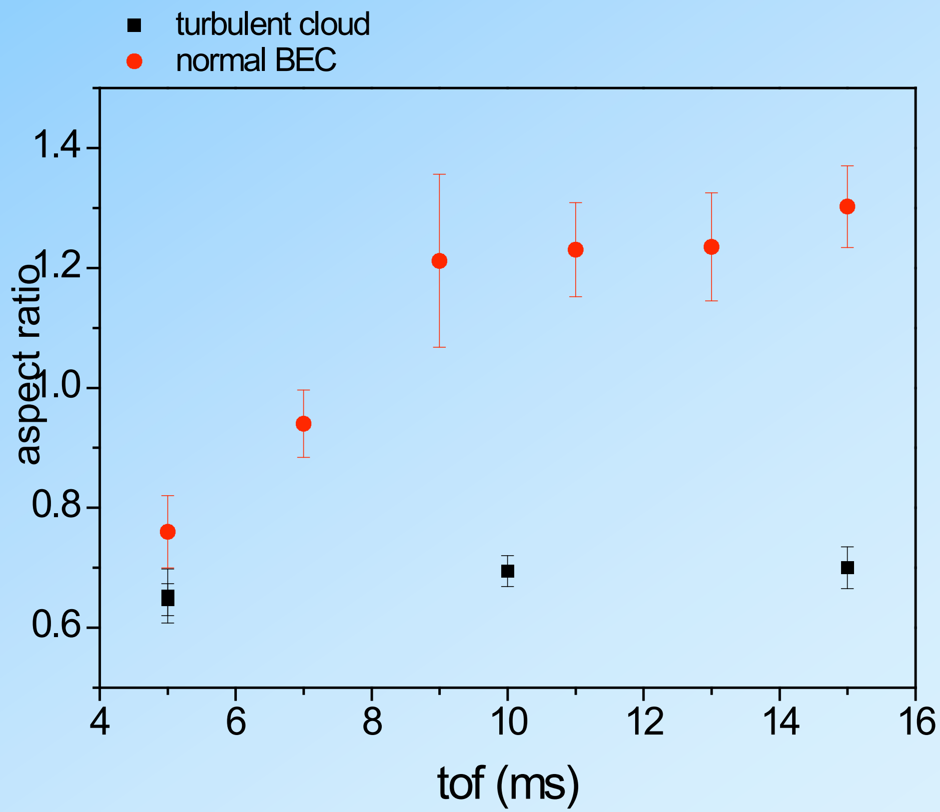



B
TURBULENCE
FRAGMENTATION
REGULAR VORTICES
AMPLITUDE (mGauss/cm)
320
280
240
200
160
120
80
40
0
0
10
20
30
40
50
60
TIME OF EXCITATION (ms)
No vortices
zone(bending)



(a)
(b)
(c)
(d)
AMPLITUDE (mGauss)
240
200
160
120
80
40
0
TURBULENCE
(c)
FRAGMENTATION
(d)
REGULAR VORTICES
(b)
BANDING
(a)
10
20
30
40
50
60
TIME OF EXCITATION (ms)



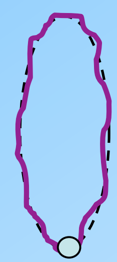


Turbulent cloud expands keeping the aspect ratio!

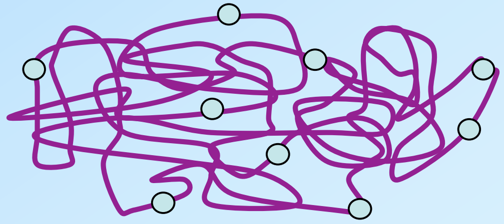
Theoretical and numerical works by our group are now in progress.

Dynamics of charged vortex rings and tangles in the zero temperature limit

P. M. Walmsley, A. I. Golov, P. A. Tompsett, A. A. Levchenko

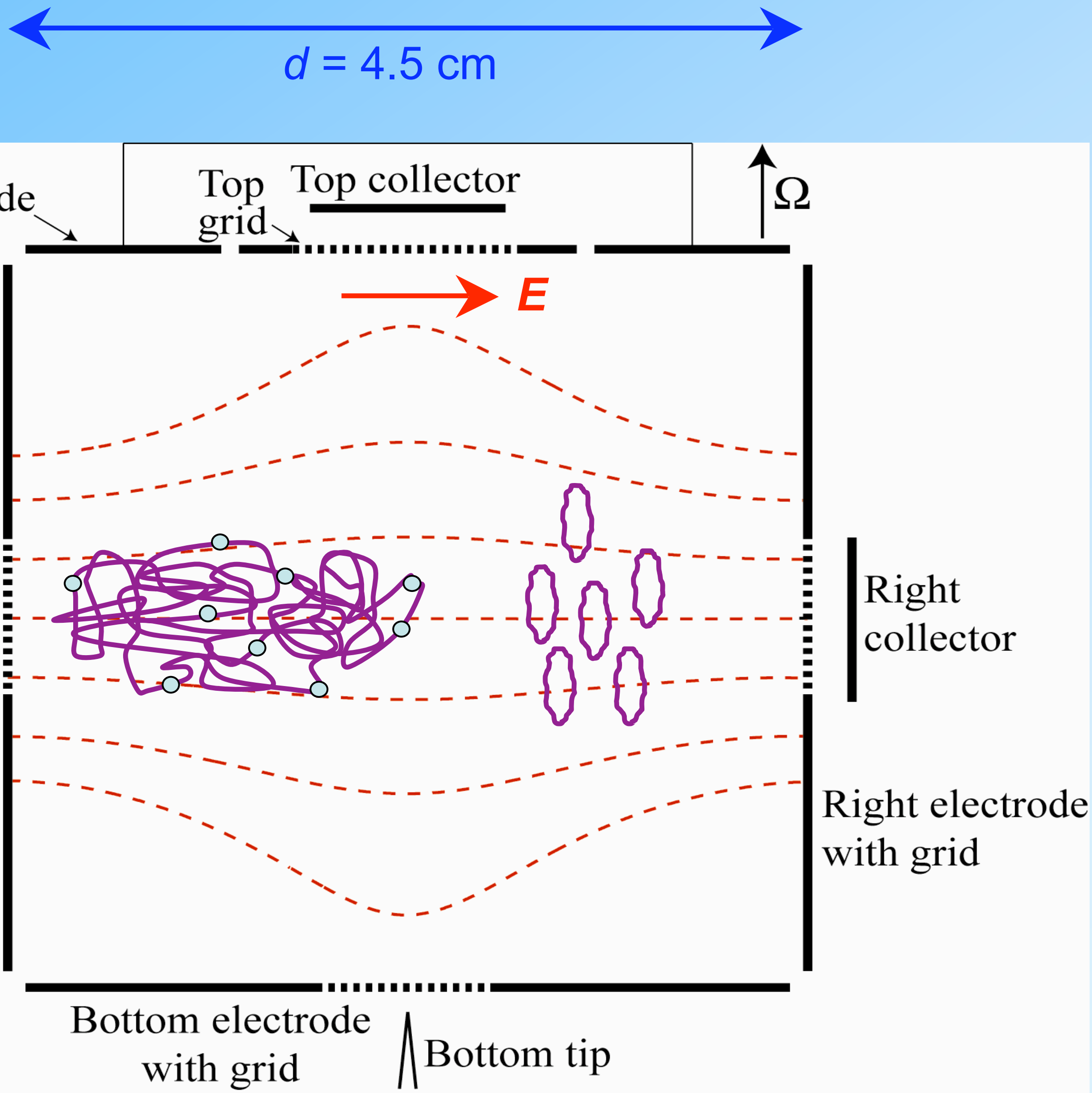


1) Charged vortex rings



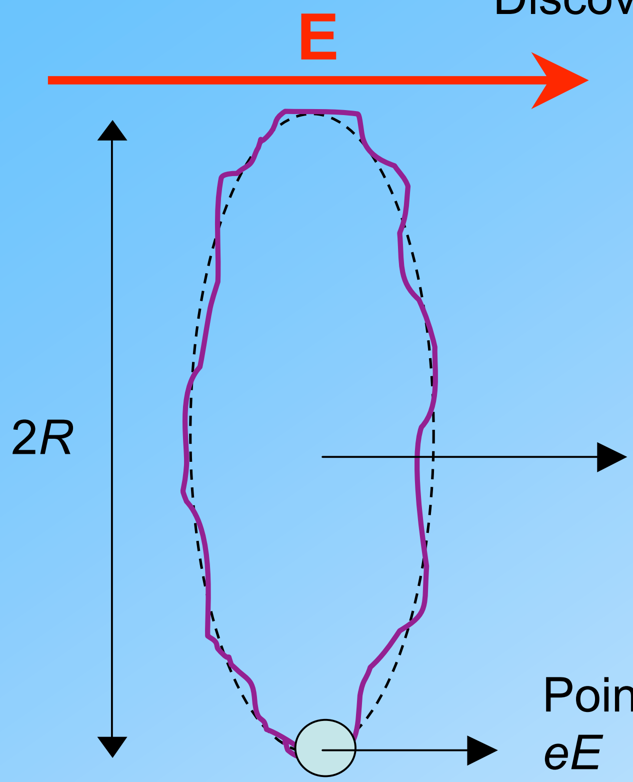
2) Charged vortex tangle

Experimental Cell



Characteristics of Charged Vortex Rings

Discovered by Rayfield and Reif in 1964.



Pulling on the ring with an electric field increases the energy and radius but decreases the velocity of the ring.

Energy: $H_0 = ½ \rho\kappa^2 (\Lambda\text{-}3/2)\, R$

Velocity: $v = \kappa\, (\Lambda\text{-}1/2)/(4\pi\, R)$

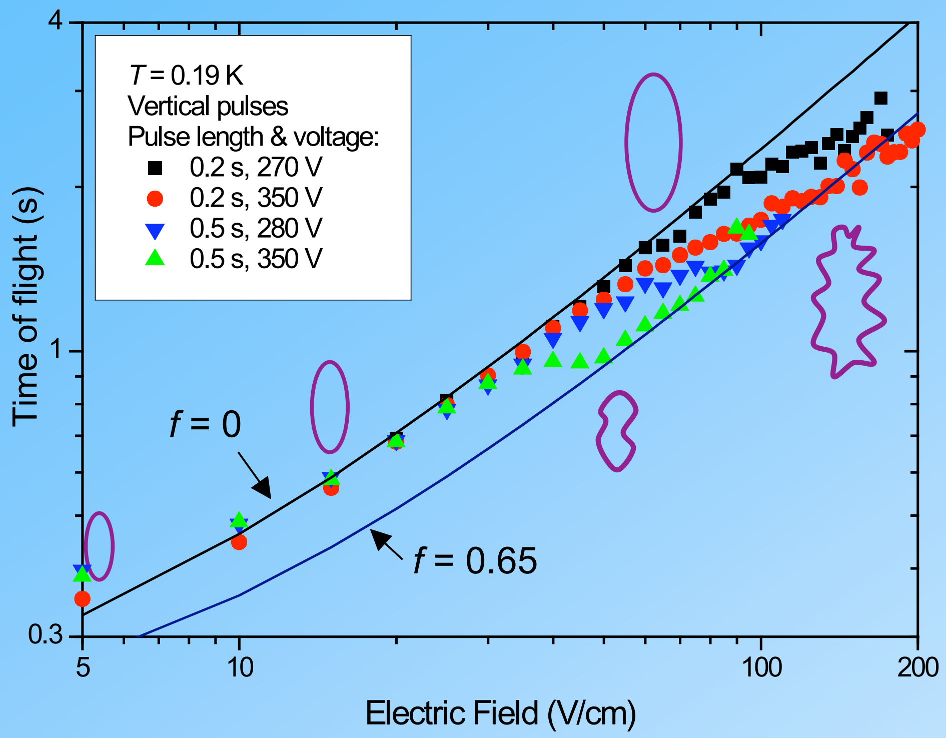
$\Lambda = \ln\, (8R/a_0) \approx 13$

Point force applied via a trapped ion: $F = eE$

Schwarz and Donnelly (1966) showed that the trapping diameter, σ, could found from the attenuation of a beam of CVR's during steady rotation.

$$I = I_0 \exp\, (-2\Omega\sigma d/\kappa) \qquad \text{where } \sigma \sim R.$$

Time of flight vs. Electric field



CVR's arrive faster than expected at high fields, implies losses.

Possible explanations:

- non-linear cascade?
- pinching off of rings?
- accumulation of energy in Kelvin waves (distorted rings)?

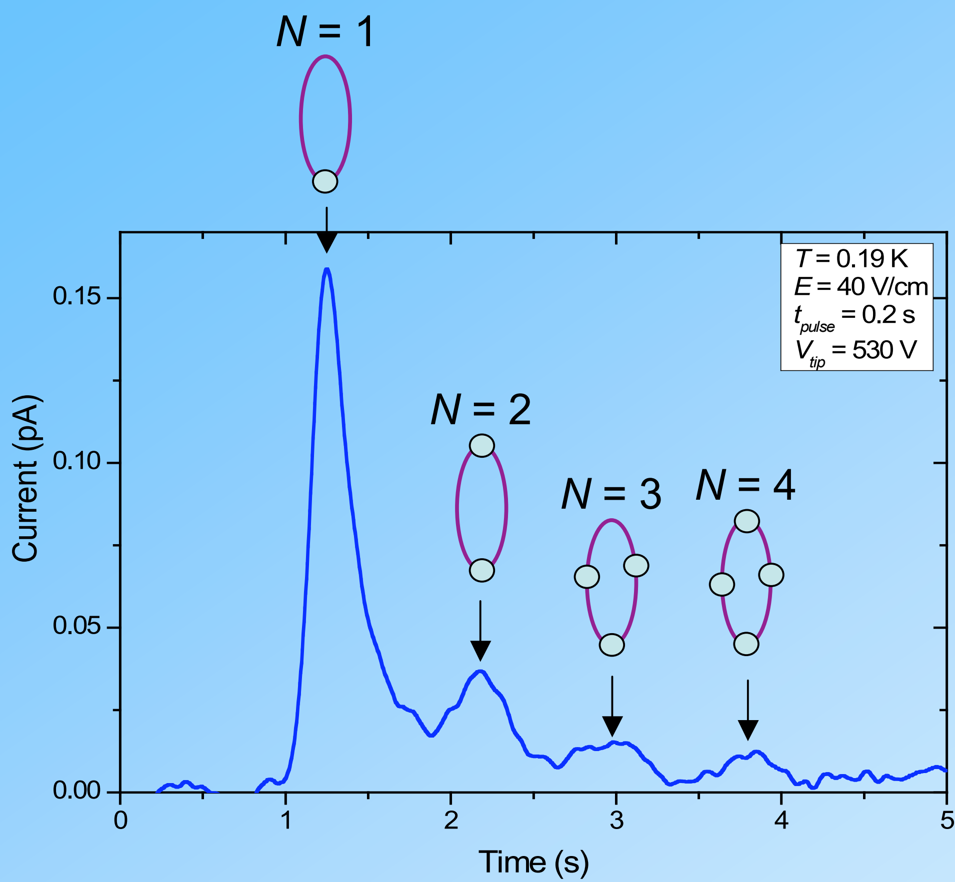
Simple model: some energy goes into Kelvin waves

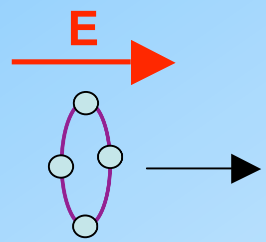
$$e\,E\,v = d/dt\,(H_0) + d/dt\,(H_{KW}) \qquad H_{KW} = f\,H_0$$

Transition to distorted ring state depends upon charge density, then follows f=0.65

Multi-charged Rings

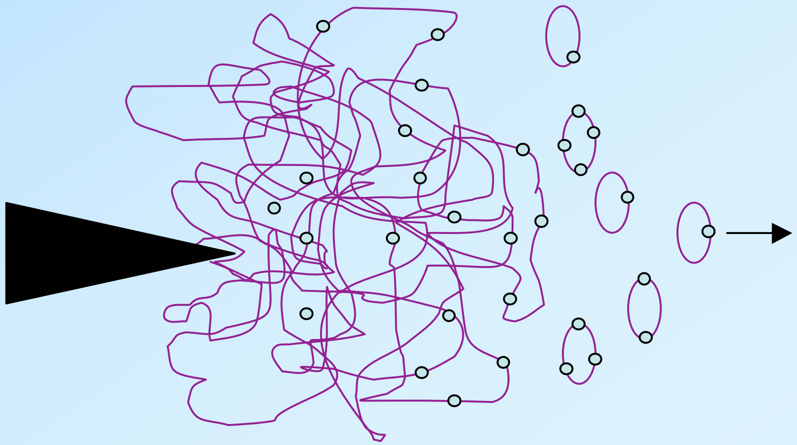
We can observe multi-charged rings with N =1 - 11 ions per ring at low temperatures.





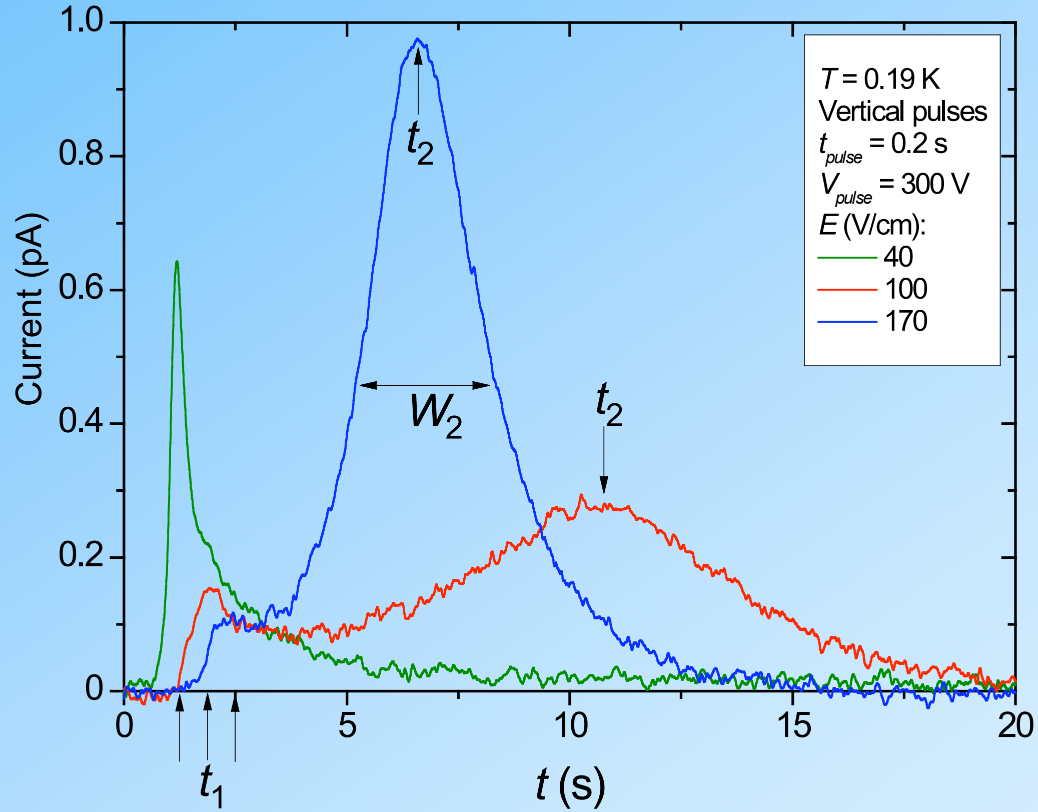
Force: F = e N E
- applied more homogeneously to ring

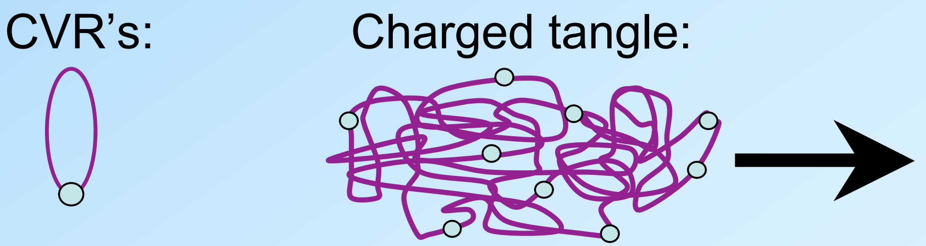
The multi-charged rings are probably produced from the breakup of a dense vortex tangle near the field emission tip.



2) Charged Tangle

At high E, we observe a 2nd peak due to a drifting charge vortex tangle.

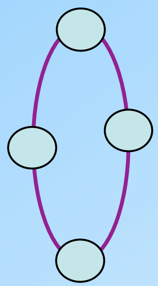


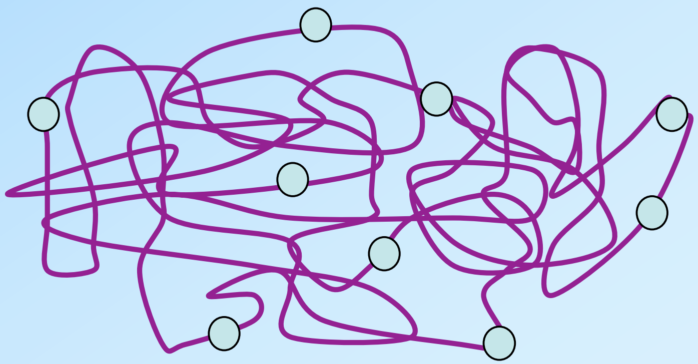


Total force:
$F_2 = Q_2 E$

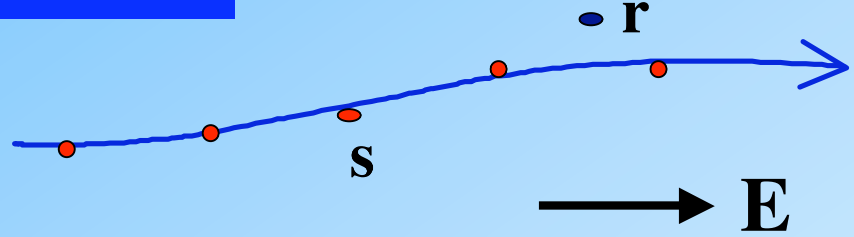
Quantized vortices in superfluid ^{4}He and atomic BECs are electrically neutral. Thus they are not controlled by electric or magnetic field.

However, charged vortices enable us to control and observe them electrically.





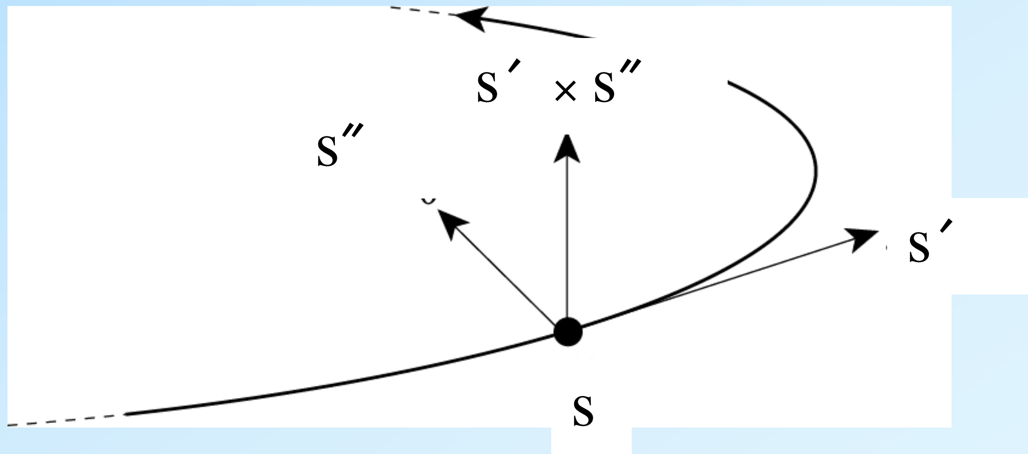
Dynamics of charged quantized vortices



$$\frac{d\mathbf{s}}{dt} = \beta \mathbf{s}' \times \mathbf{s}'' + \frac{\kappa}{4\pi}\int_L' \frac{(\mathbf{s}-\mathbf{r}) \times d\mathbf{s}}{|\mathbf{s}-\mathbf{r}|^3} + \underline{\frac{e}{2R_{\text{ion}}\rho_s\kappa}\mathbf{s}' \times \mathbf{E}}$$

$$\beta = \frac{\kappa}{4\pi}\log\frac{R}{a}$$

The simulation of the dynamics is now in progress.

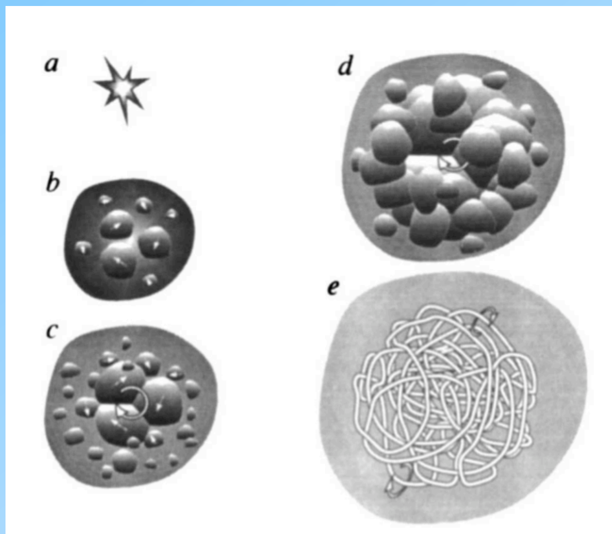


3-2-3. Question for the Kibble-Zurek(KZ) problem (Bunkov)

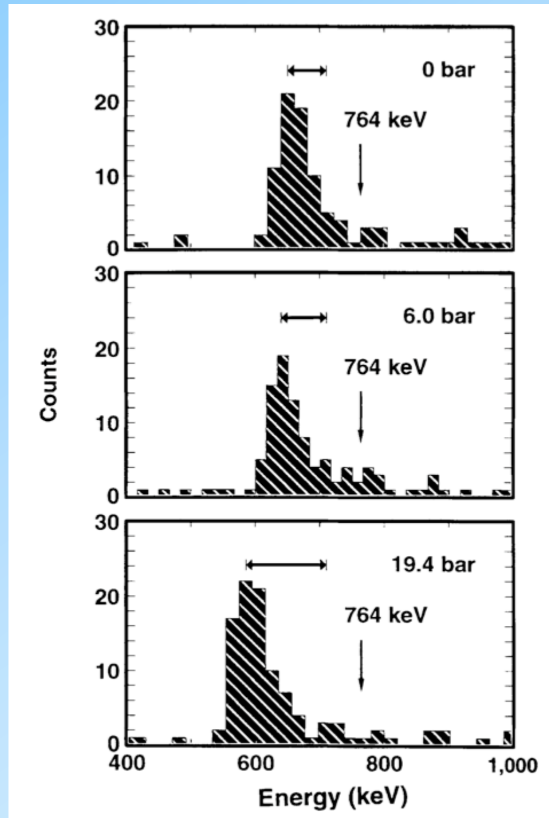
Laboratory simulation of cosmic string formation in the early Universe using superfluid ^3He

C. Bäuerle*, Yu. M. Bunkov*, S. N. Fisher*, H. Godfrin* & G. R. Pickett†

Nature 382, 332(1996)



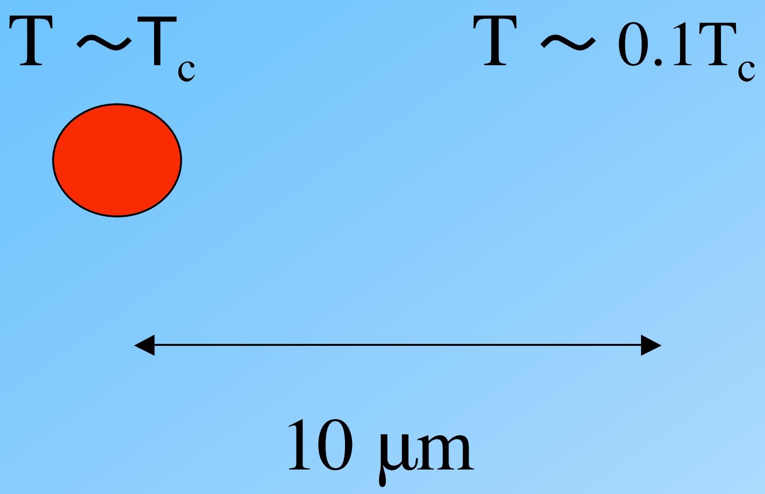
$$n + {}^3He \rightarrow {}^3H + p + 764\ keV$$



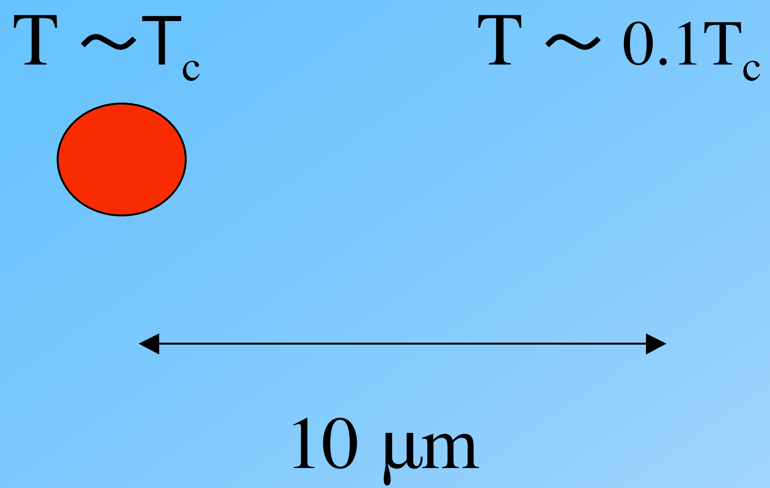
The emitted energy is always less than 764keV. The lost energy should be due to quantized vortices.

Bunkov told me that he is not quantitatively satisfied with this result.

What actually occurs is…..



1. Quantized vortices may be nucleated by the KZ mechanism.
2. Vortices are under the large temperature gradient, thus be amplified by the local strong counterflow.
3. The resulting vortices should be observed.



Quantum hydrodynamics far from equilibrium

Strategy

1. Decide the temperature profile.
2. Consider the vortex dynamics under the temperature gradient.

Contents

1. Why do we study quantum turbulence(QT)?
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3-2-1. Experiments of QT in trapped BECs (Bagnato)

3-2-2. Dynamics of charged vortices and tangles in superfluid helium (Golov)

3-2-3. Question for the Kibble-Zurek problem (Bunkov)

Tomorrow never knows

by Mr. Children