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IAEA International Atomic Energy Agency

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Conference on Research Frontiers in Ultra-Cold Atoms

4 - 8 May 2009

Emergence of turbulence in an oscillating Bose-Einstein condensate

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Emergence of “turbulence” in a Bose-Einstein condensate: excitation by external oscillation

BEC project:

Theory :

E.R.F Ramos
M. Caracanhas

Outside Collaborators:
G. Roati (Italy)
V. Yukalov (Russia)

V. S. Bagnato

University of São Paulo

São Carlos

Brazil

www.cepof.ifsc.usp.br

Experiment :

K.M.F. Magalhães
E.A.L. Henn
J.A. Seman
R. Shiozaki
C. CasteloBranco
P. Castilho
P. Tavares

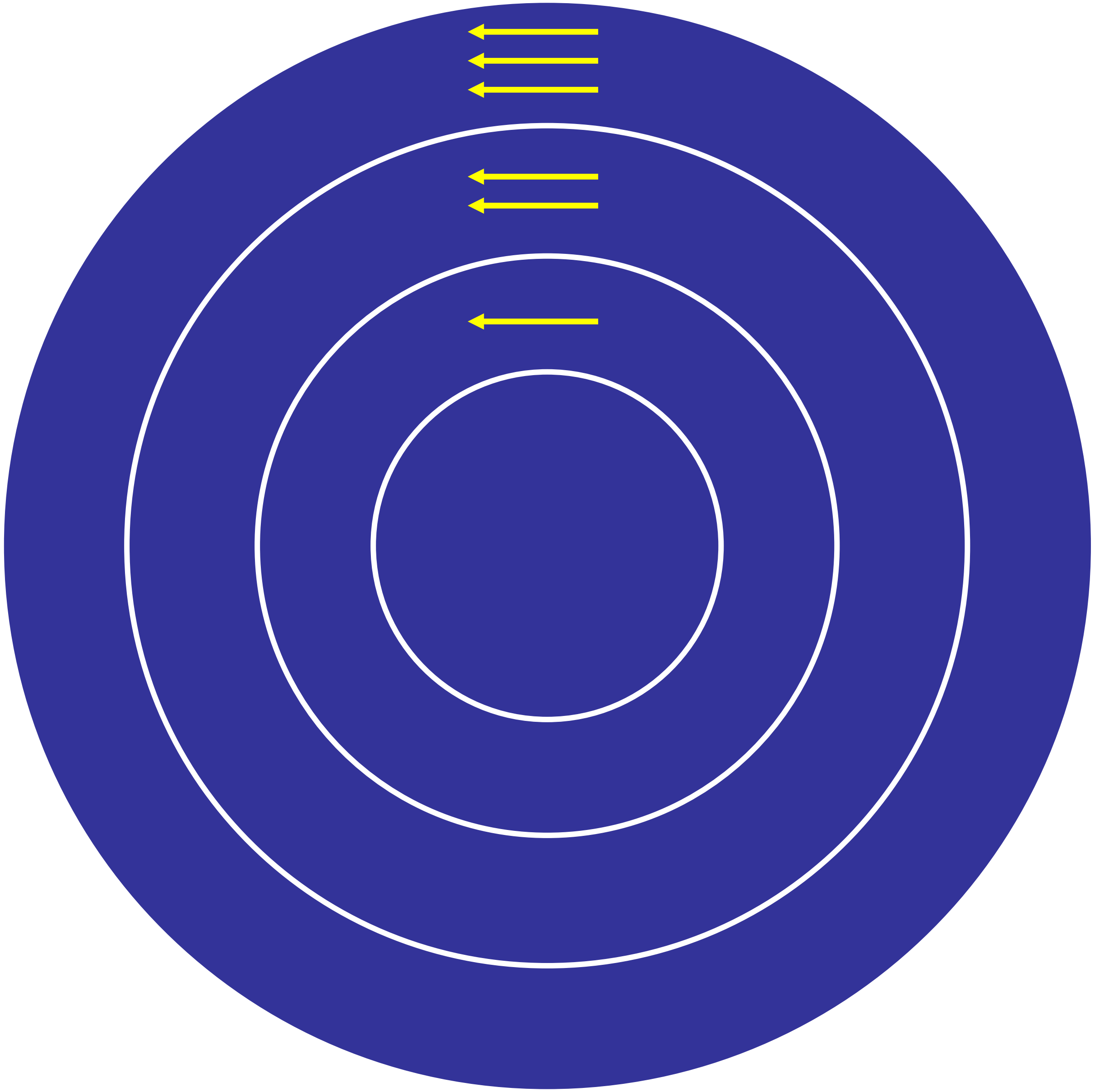
Trapped Bose Condensate and superfluidity

Investigation of Scissors Mode (rotation of the cloud around the symmetry axis)

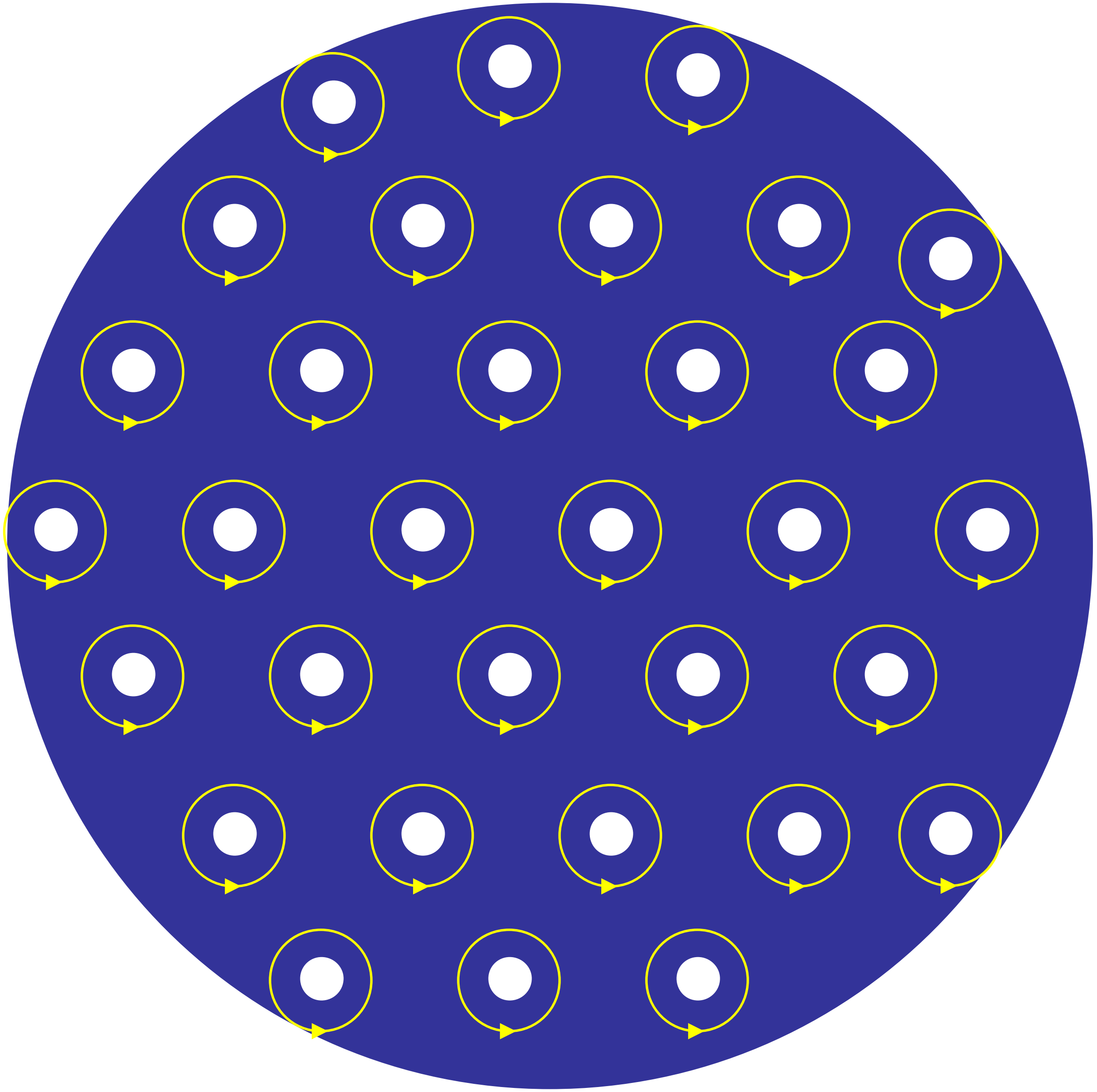
(proposed) Trento – Phys. Rev. Lett. 83,4452(1999)

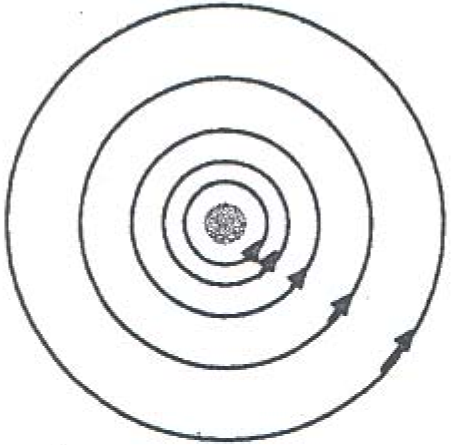
(experiment) Oxford – Phys. Rev. Lett. 84,2056(2000) and Phys. Rev. Lett. 86,3938(2001)

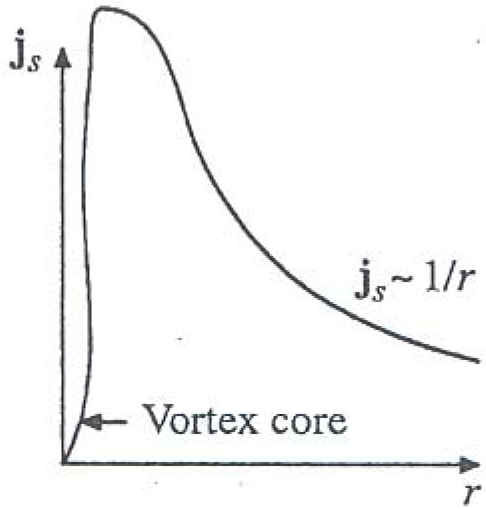
Introducing rotation to the cloud



Vortex structure





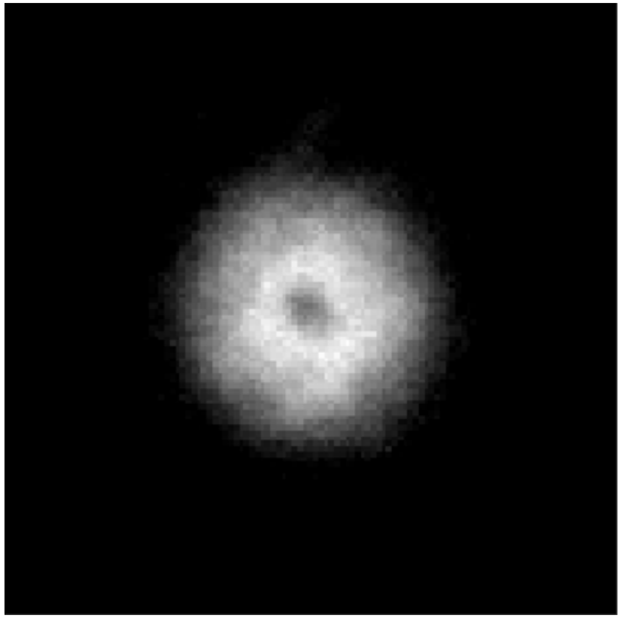


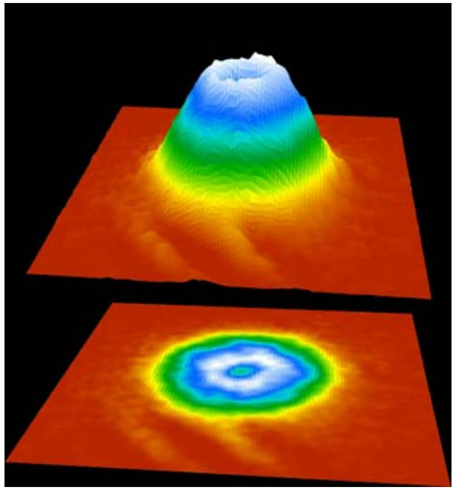
Healing length = $(8\pi \rho a)^{-1/2}$

Can be macroscopic ~ 1 micron

Vortex

After time-of-flight expansion:

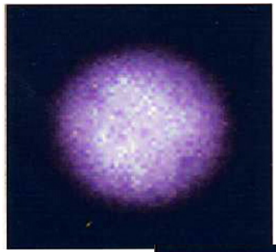


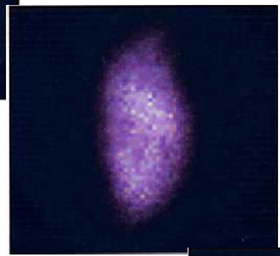
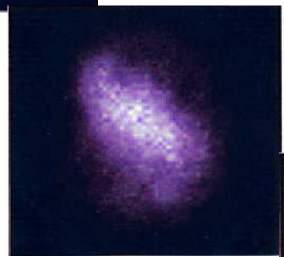


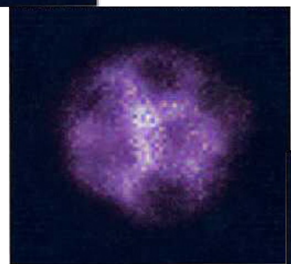
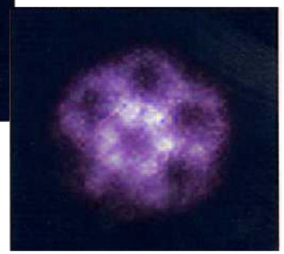
J.DALIBARD

Steps during the formation of vortices by rotating the cloud

Snapshots of the BEC after turning on the rotation



K.W.Madison *et.al*., PRL **86** , 4443 (2001)

There are many studies of vortices in BECs

- Measuring angular momentum – PRL85(2000)
- Nucleation by instabilities in the rotation
  PRL 86 (2001)
- Phase measurement – PRA 64 (2001)
- Dynamics of single vortex line and observation of Kelvin modes – PRL90(2003)
- Lattices – many

How are the vortices formed and how is the dynamics?

- Many experiments and many theoretical papers
- Tsubota’s group : PRA 65(2002), PRA 71(2005)
- Fetter – Rev. Mod. Phys (2008) and reference there in..
- Dalibard’s group – Theory and experiment
- Gardiner’s group – Theory
- Recent: Anderson – Nature(2008); PRL(2007)
- Etc..

Are there more things to be done related to vortices in BEC?

YES

Turbulence like in superfluid He

PRESENTATION

OUTLINE

1 - INTRODUCTION

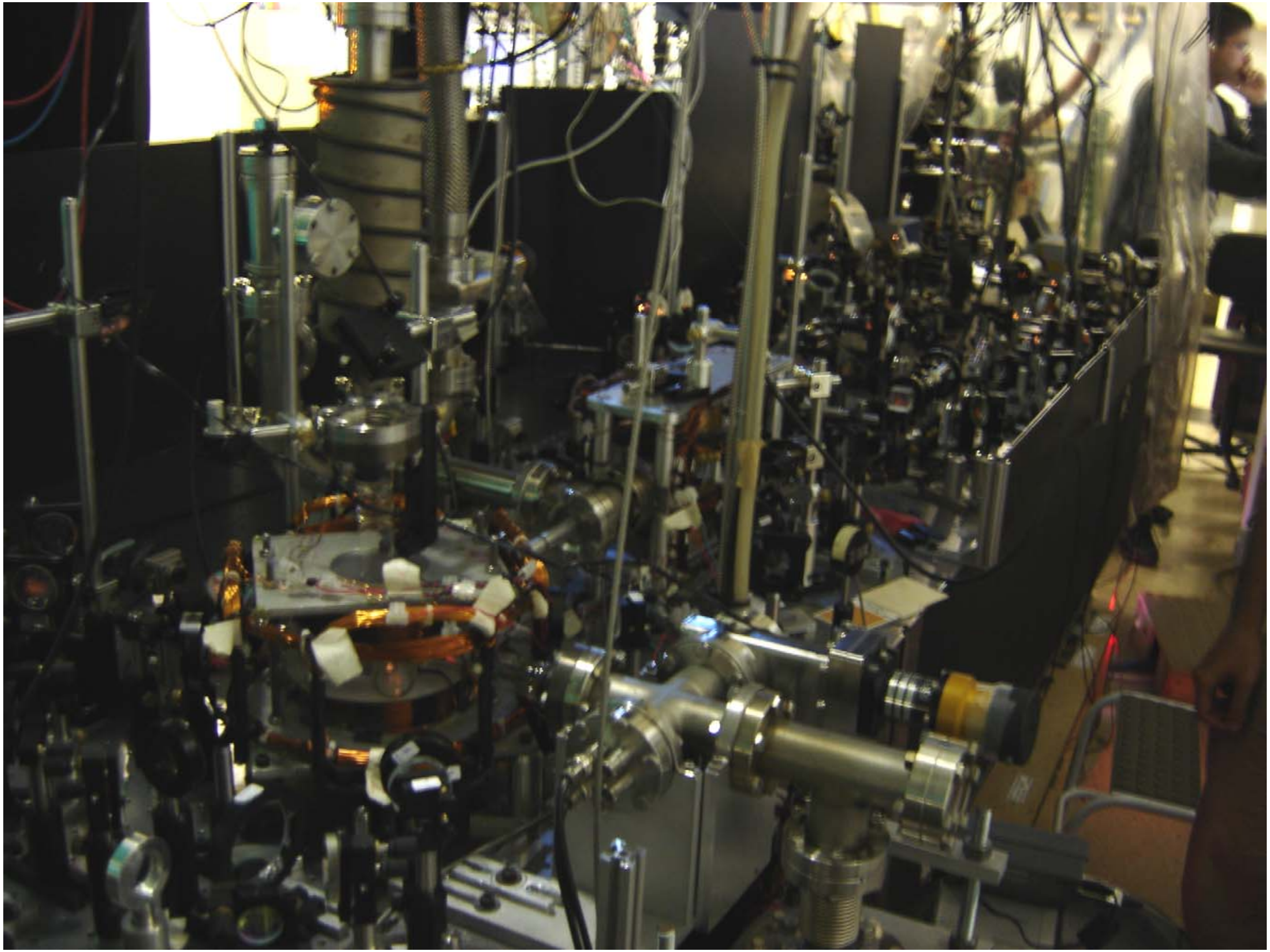
2 - VORTICES FORMED BY OSCILLATIONS

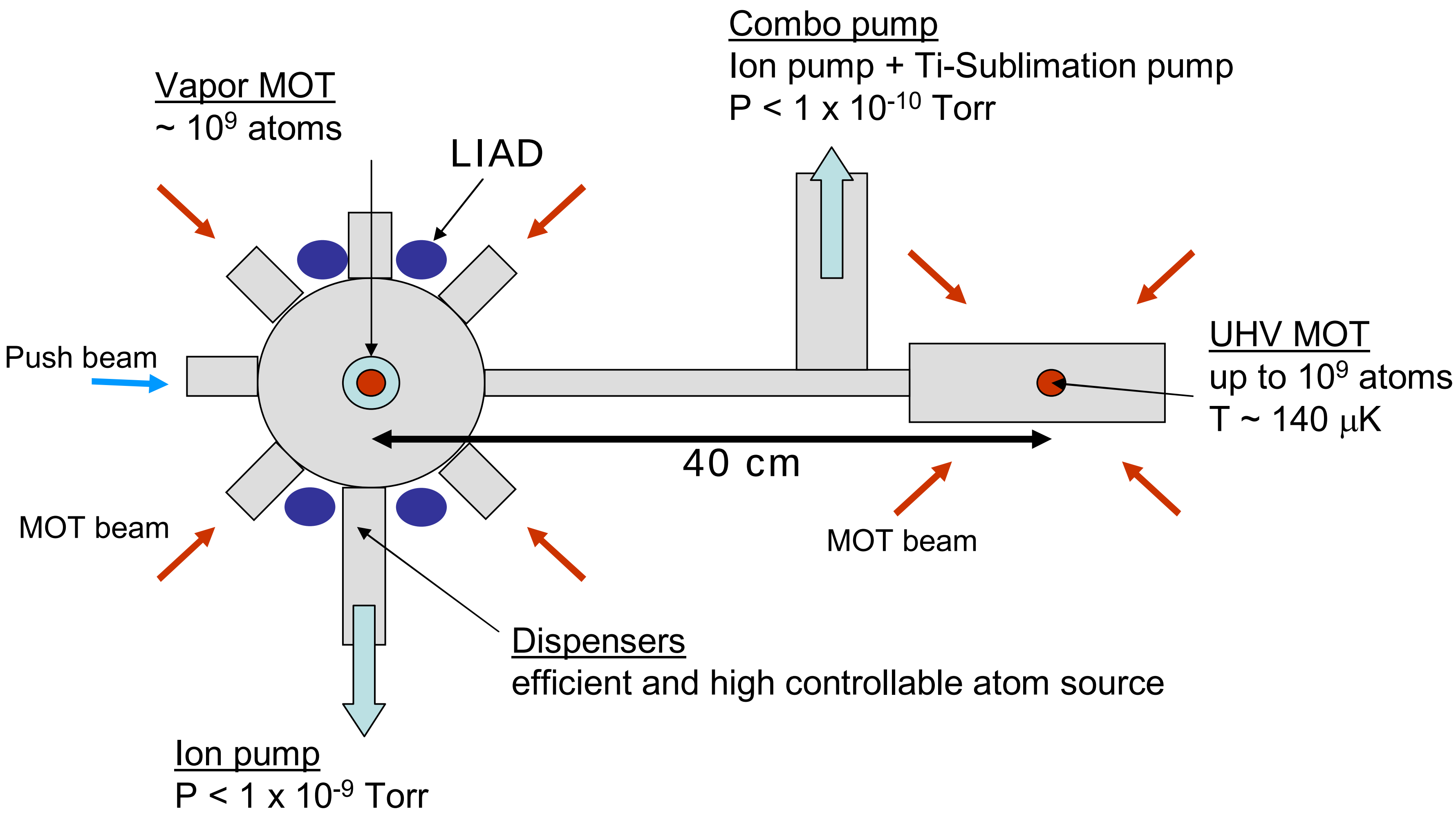
3 – CLUSTERS OF VORTICES: TRIPOLE

4 - EMERGENCE OF VORTICES TANGLE – "TURBULENCE ? "

5 - FRAGMENTATION

BEC OF Rb

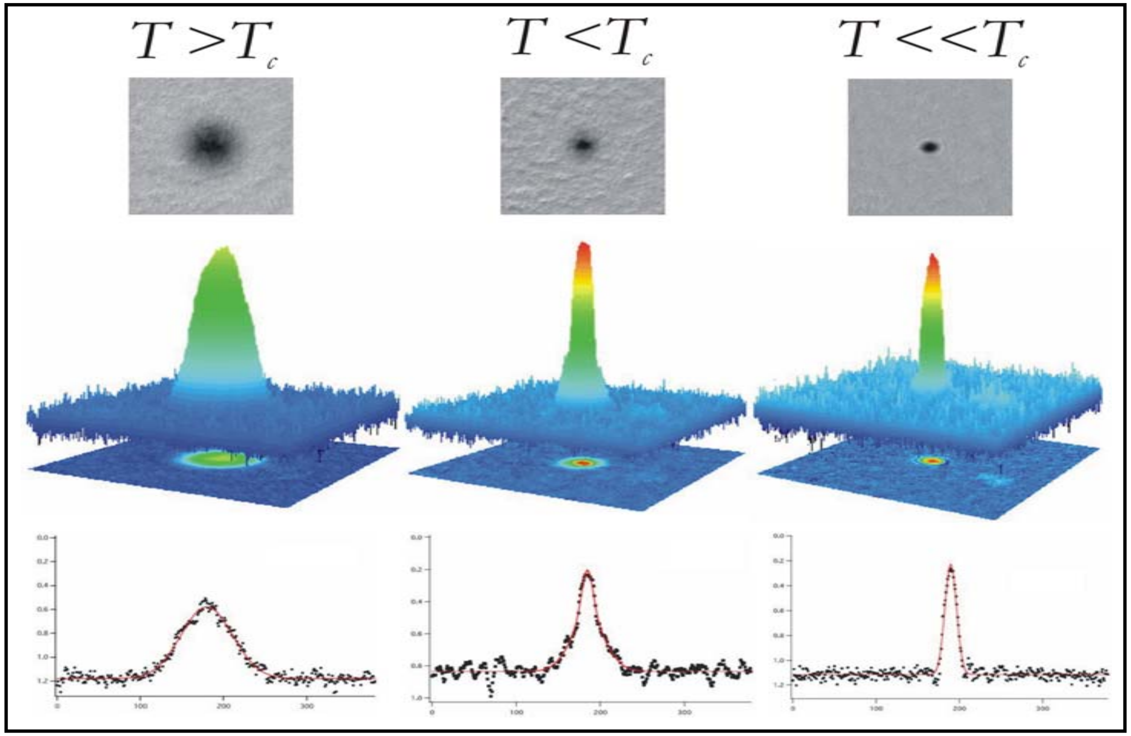


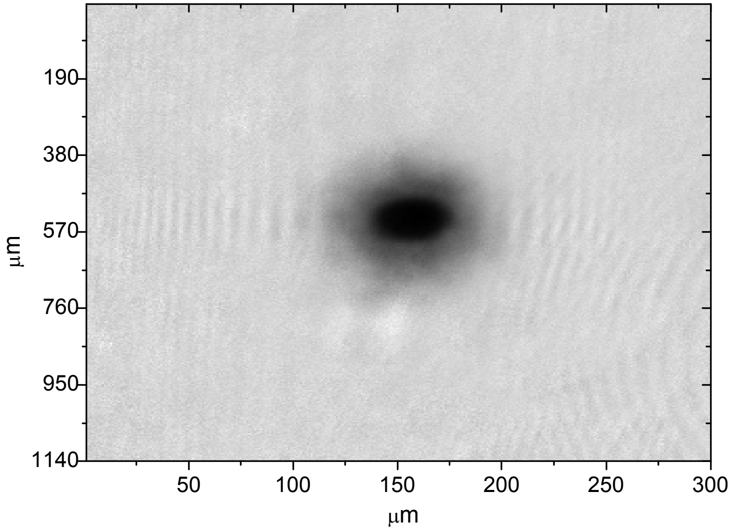


Combo pump
Ion pump + Ti-Sublimation pump
P < 1 x 10^-10 Torr
Vapor MOT
~ 10^9 atoms
LIAD
Push beam
UHV MOT
up to 10^9 atoms
T ~ 140 μK
40 cm
MOT beam
MOT beam
Dispensers
efficient and high controllable atom source
Ion pump
P < 1 x 10^-9 Torr

OUTCOME: 1 to 3 x 10^5 condensate Atoms

T ~ 80 to 200 nK



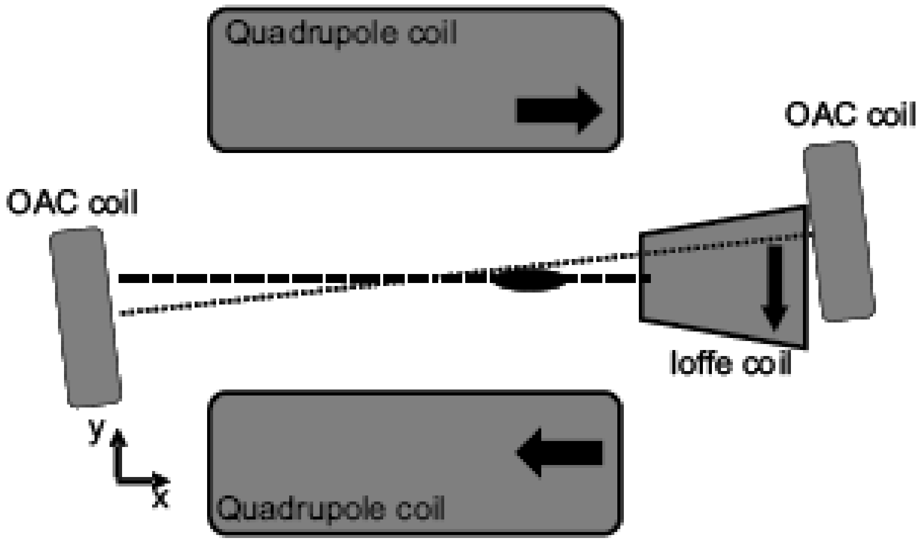


Frequencies: $\omega_x = 2\pi \cdot 23$ Hz $\omega_y = \omega_z = 2\pi \cdot 210$ Hz

EXCITATION BY EXTERNAL OSCILLATION

POSSIBILITY TO EXCITE VORTICES OF BOTH SIGNS:

VORTEX AND ANTI-VORTEX



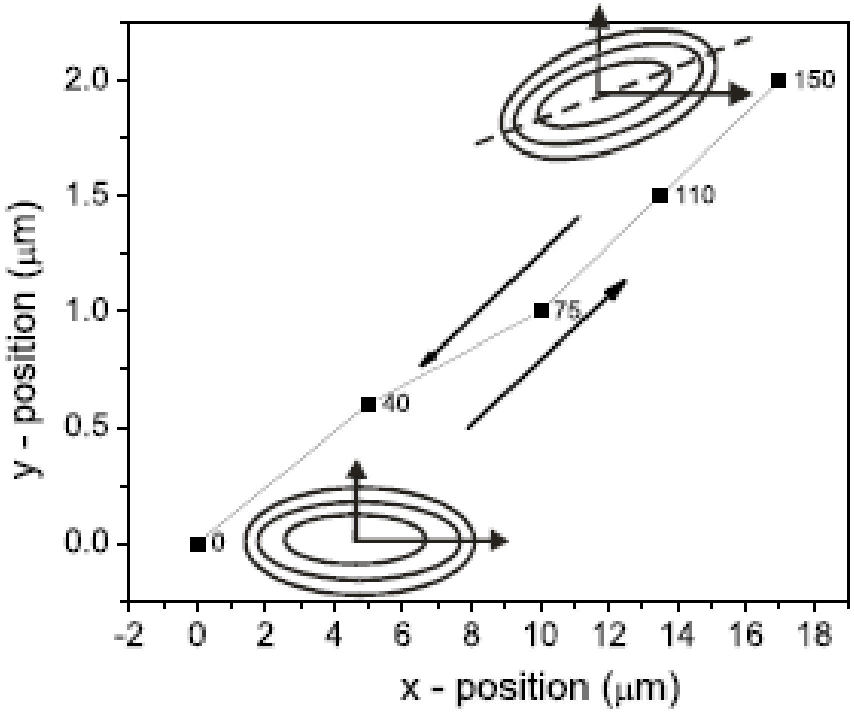
Max add field : 190 mG/cm

Frequency : 0 to 400 Hz

Displacement

Rotation

Deformation of the potential

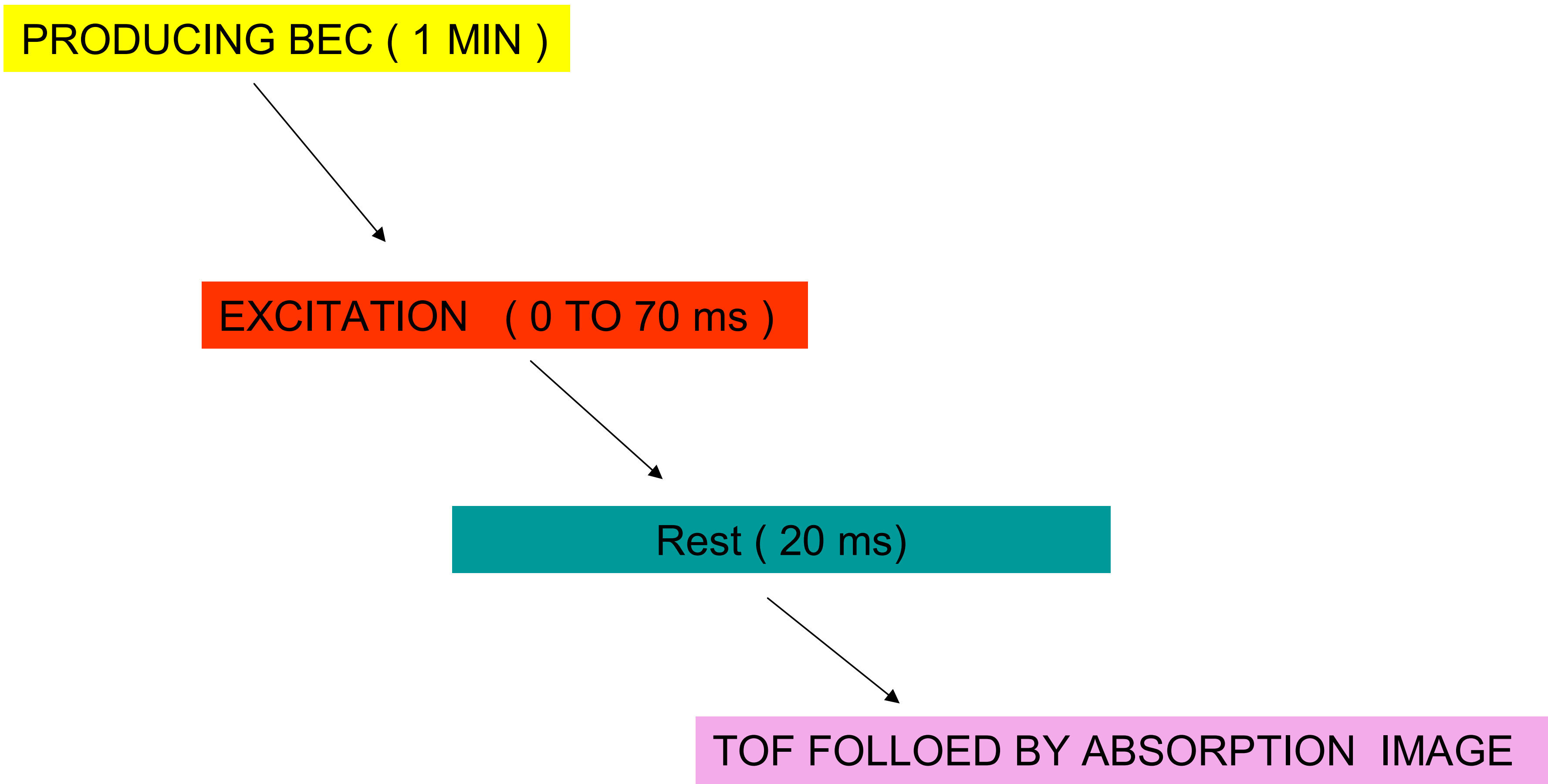


Larger amplitude of oscillation implies in:

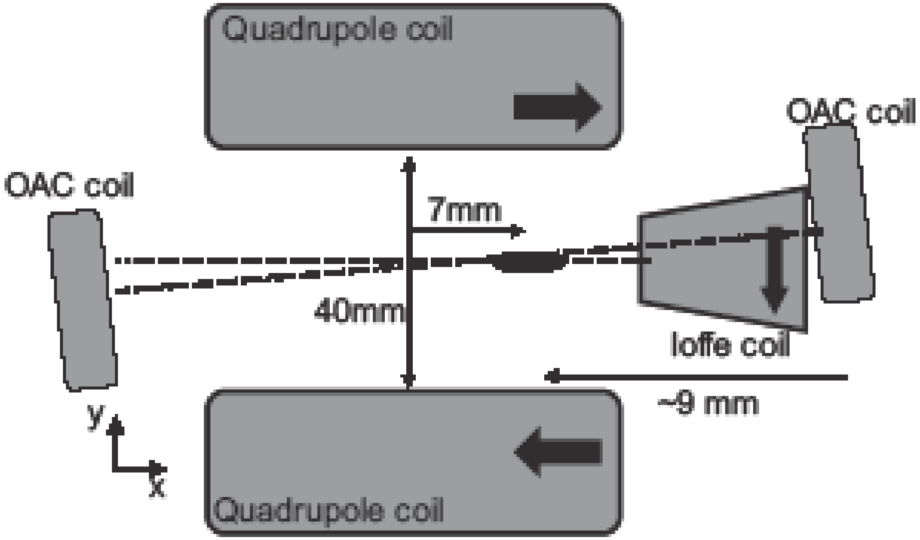
-Larger displacement

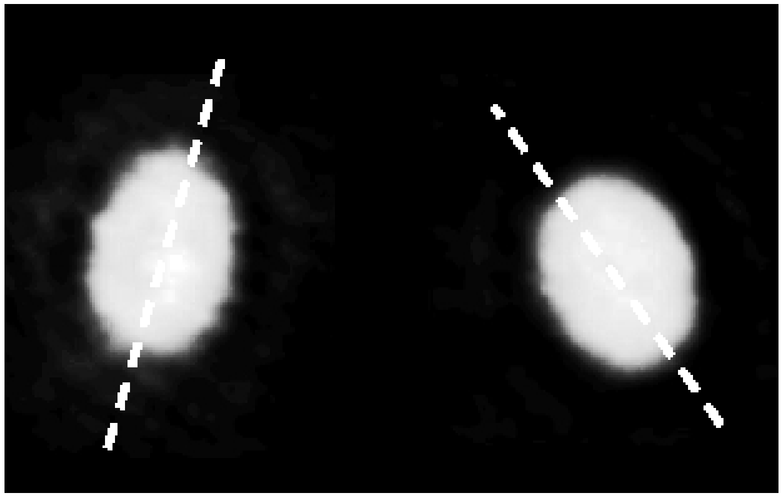
-Larger deformation of the potential

-Higher acceleration in the rotation


PRODUCING BEC (1 MIN)
EXCITATION (0 TO 70 ms)
Rest (20 ms)
TOF FOLLOED BY ABSORPTION IMAGE

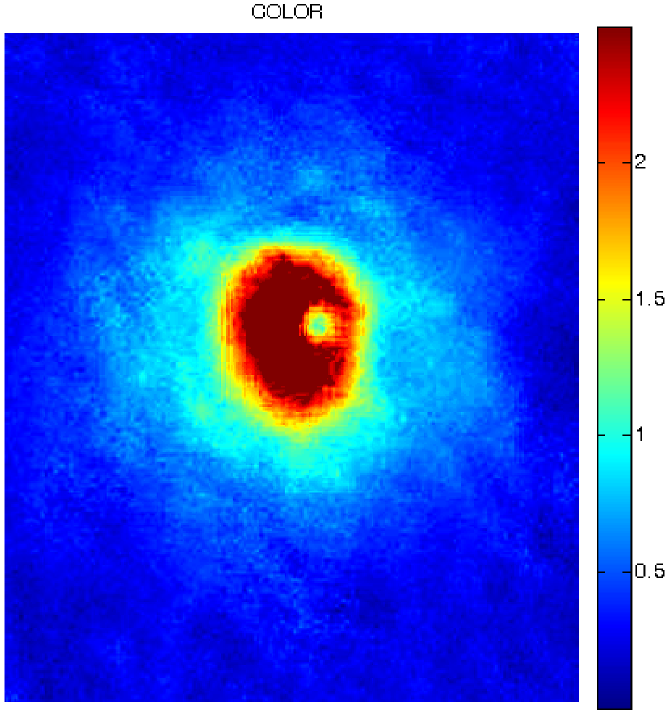
Small amplitudes and/or small times of excitation

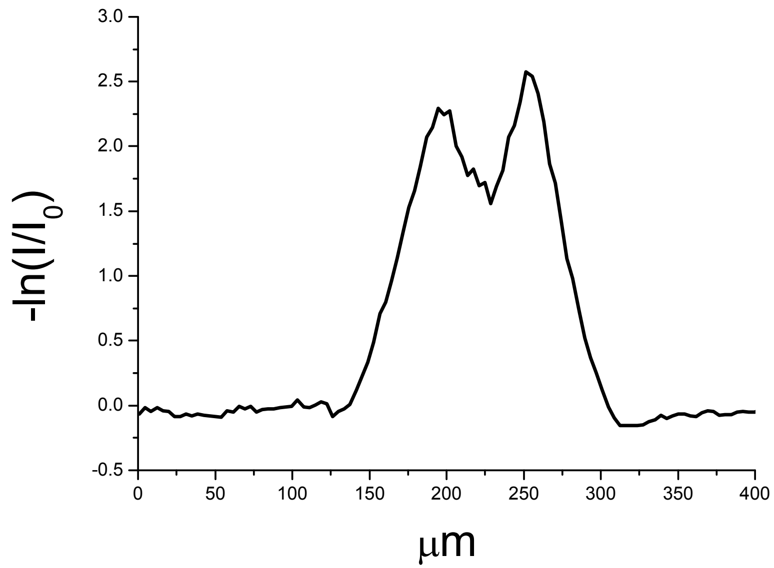




Oscillatory banding

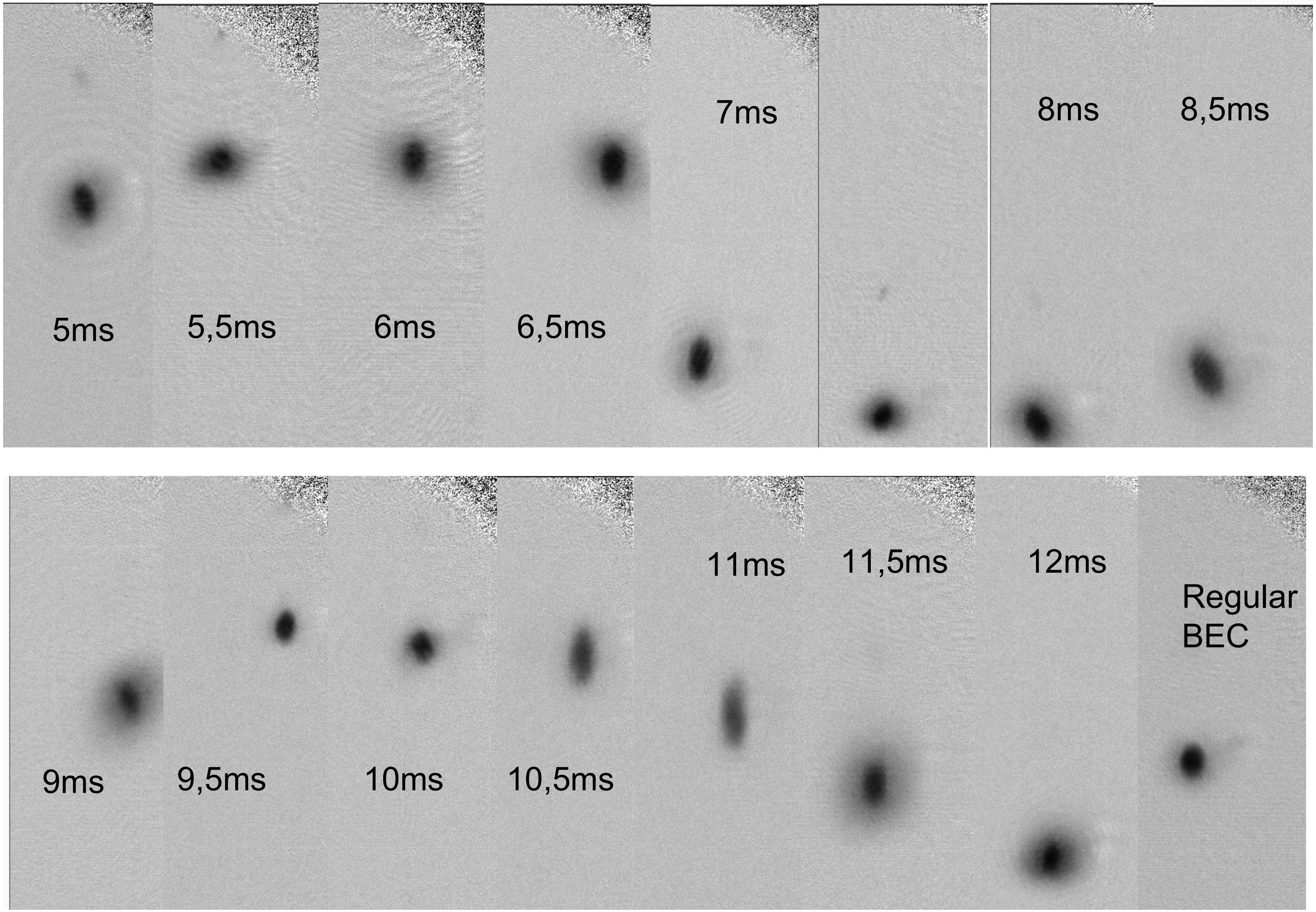
Equivalent to oscillations generated by sudden rotations → Scissors Mode





NEXT STEP AFTER BANDING AXIS IS THE OBSERVATION OF A DEEP IN THE ABSORPTION→ VORTEX

QUADRUPOLE and dipole EXCITATION

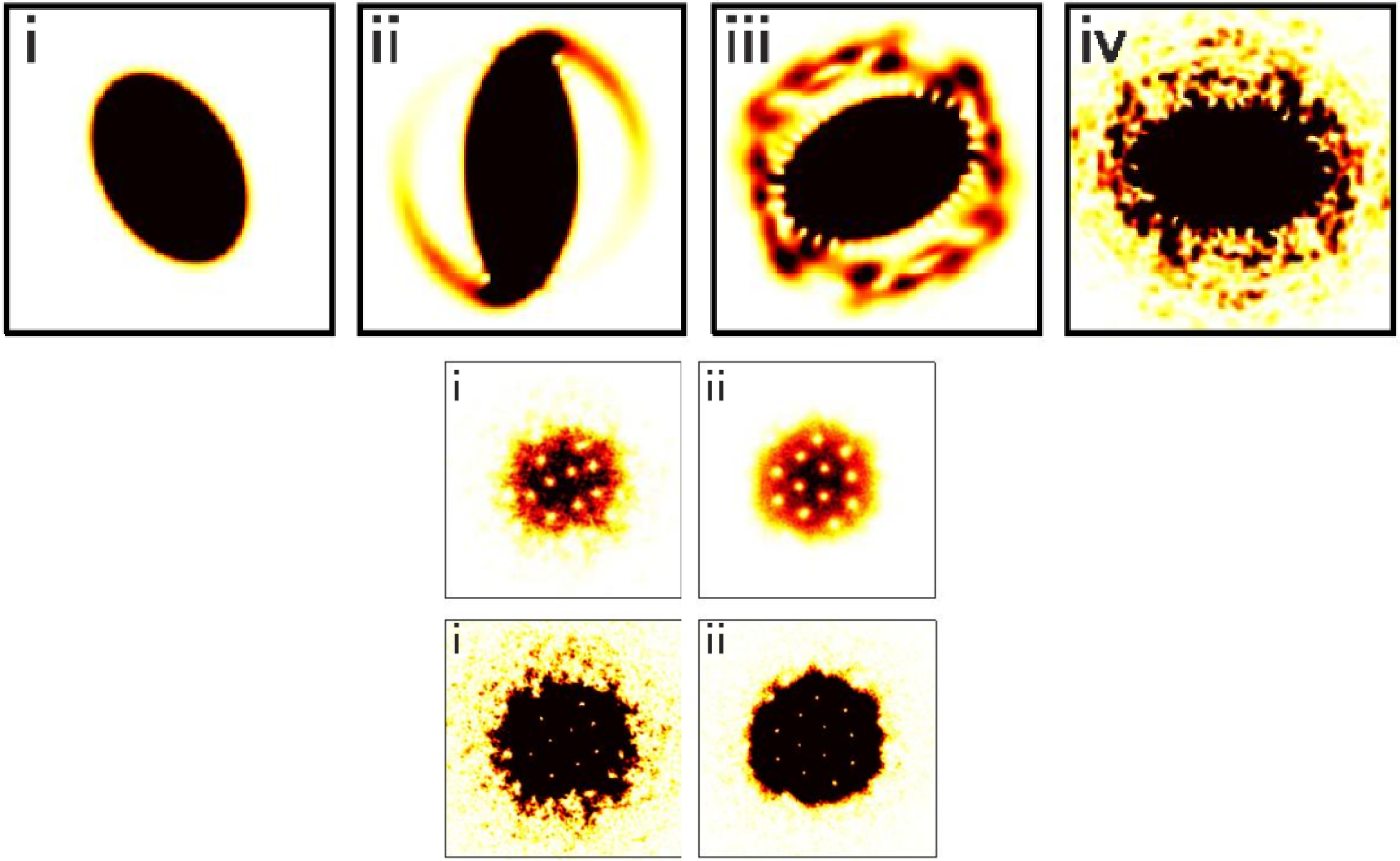


Parker- Adams PRL95(2005) – Stirring BEC

1 – Quadrupolar mode breaks down, ejecting energetic atoms to form an outer cloud

2- Turbulent cloud containing vortices is formed with a Kolmogorov energy spectrum

3- Dissipation and crystallization



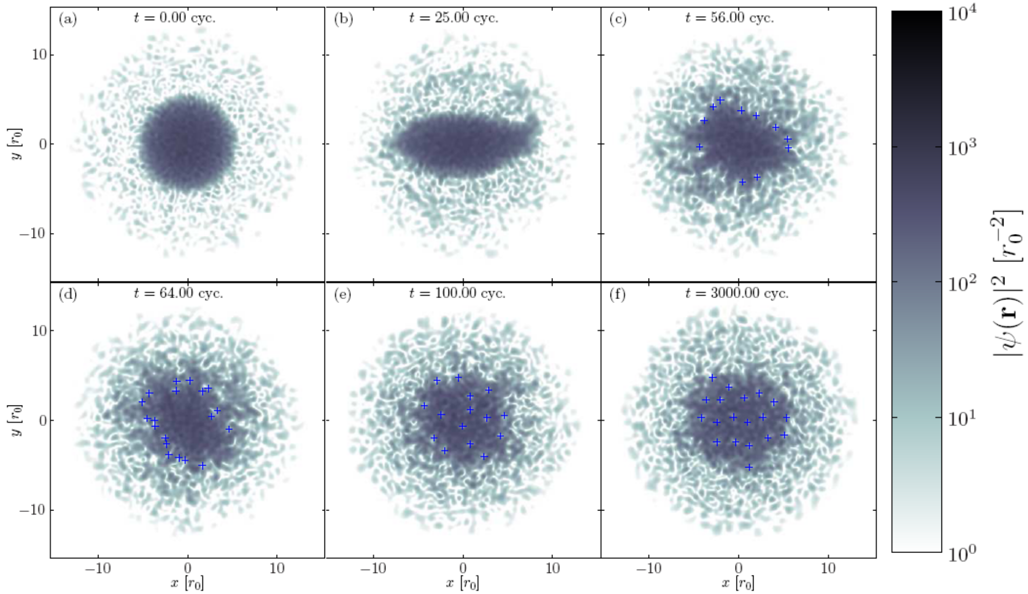
Gardiner et al – arXiv:0808.3553v2

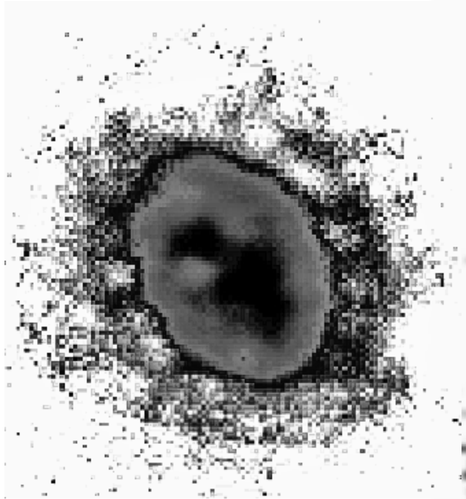
Quadrupole oscillations generate a thermal cloud

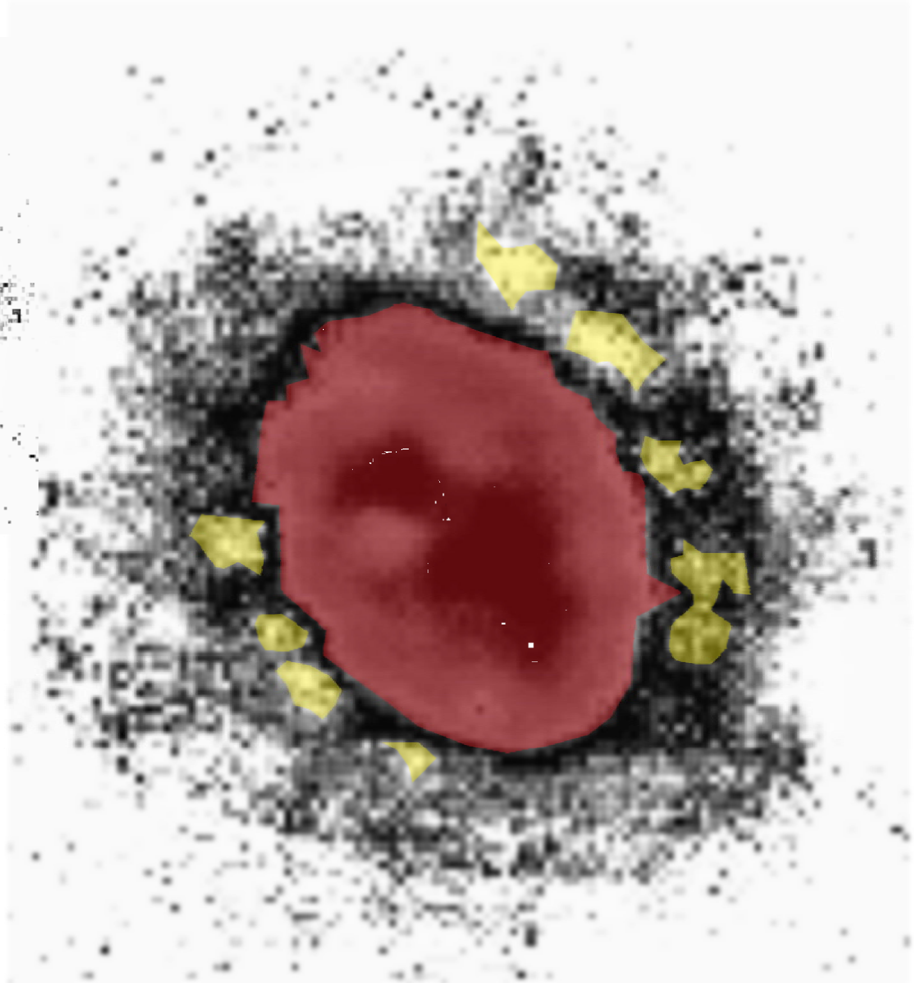
Surface oscillations in the BEC grow in magnitude, such oscillations are unstable in the presence of the thermal cloud

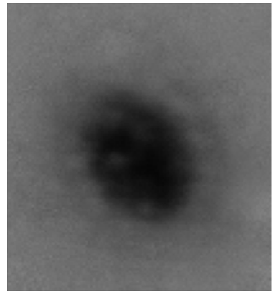
Vortices are nucleated and penetrate into the edges of the condensate

Form a lattice







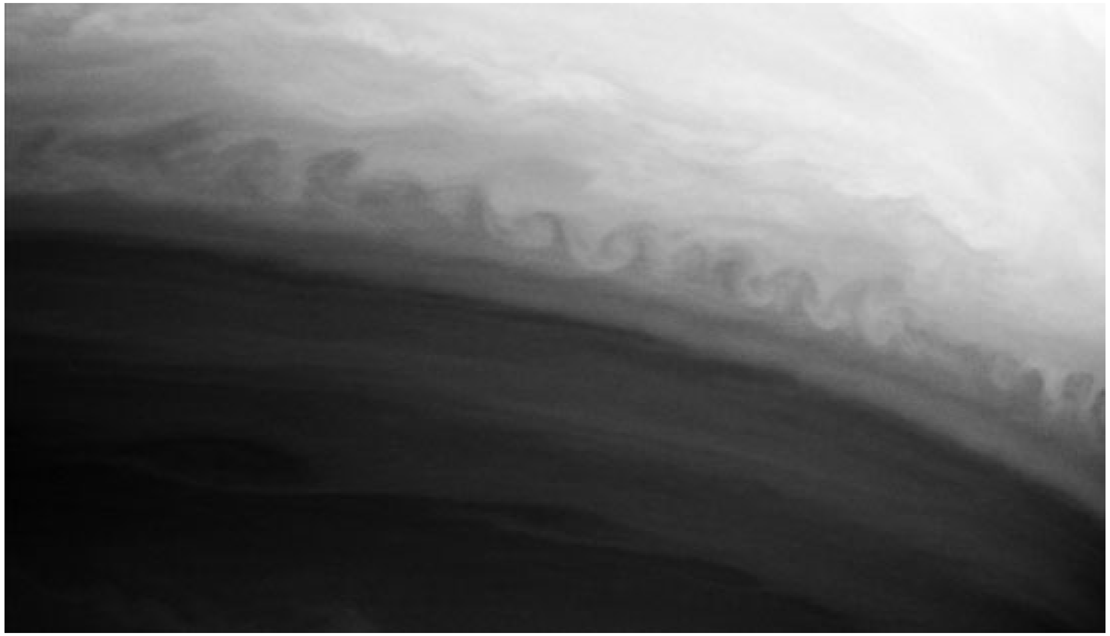


- Injection of vortices from the interface to the quantum fluid

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).

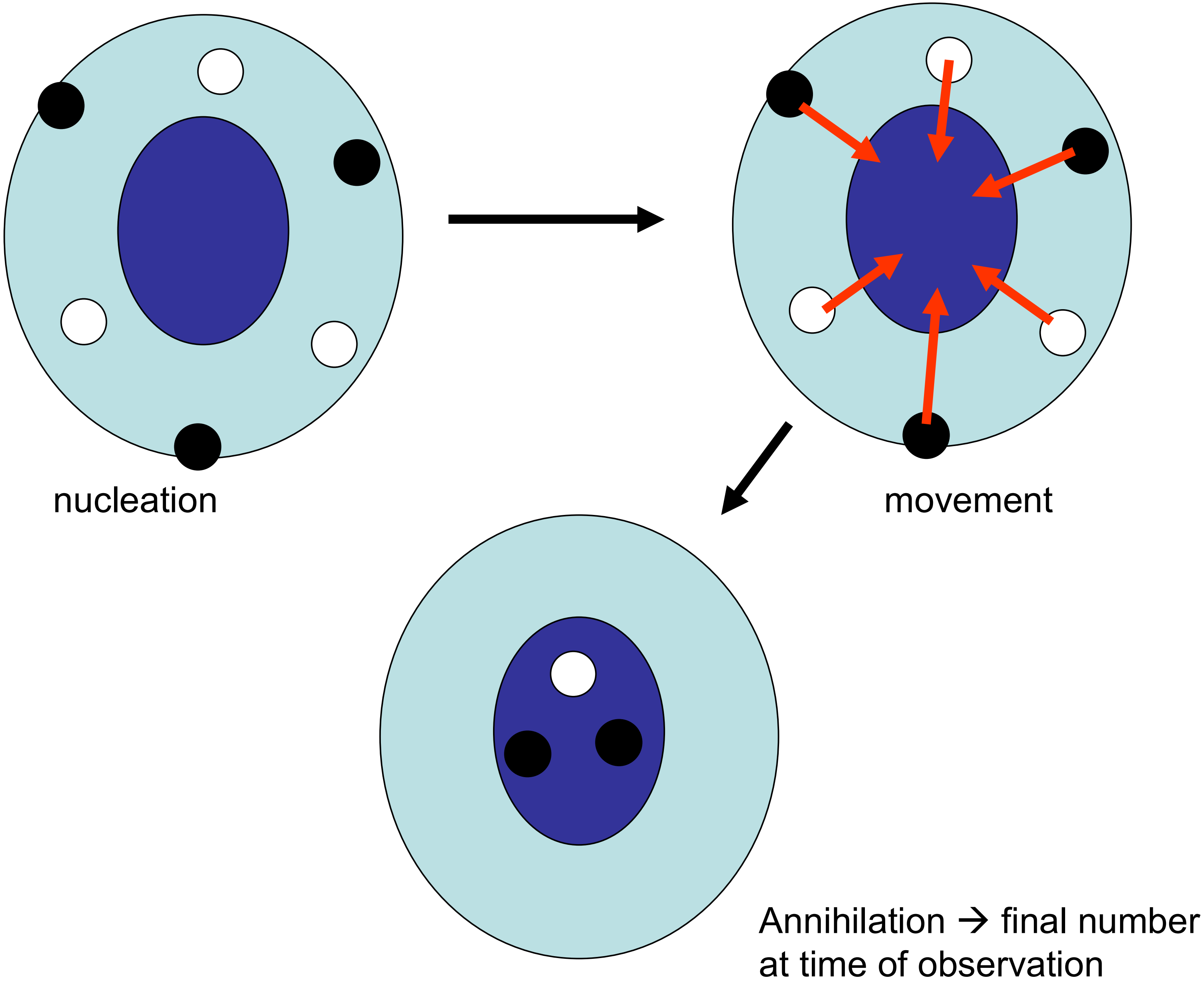
Kelvin type Instability

- At the interface between two fluids with sufficient difference in velocity
- Generation of vortices



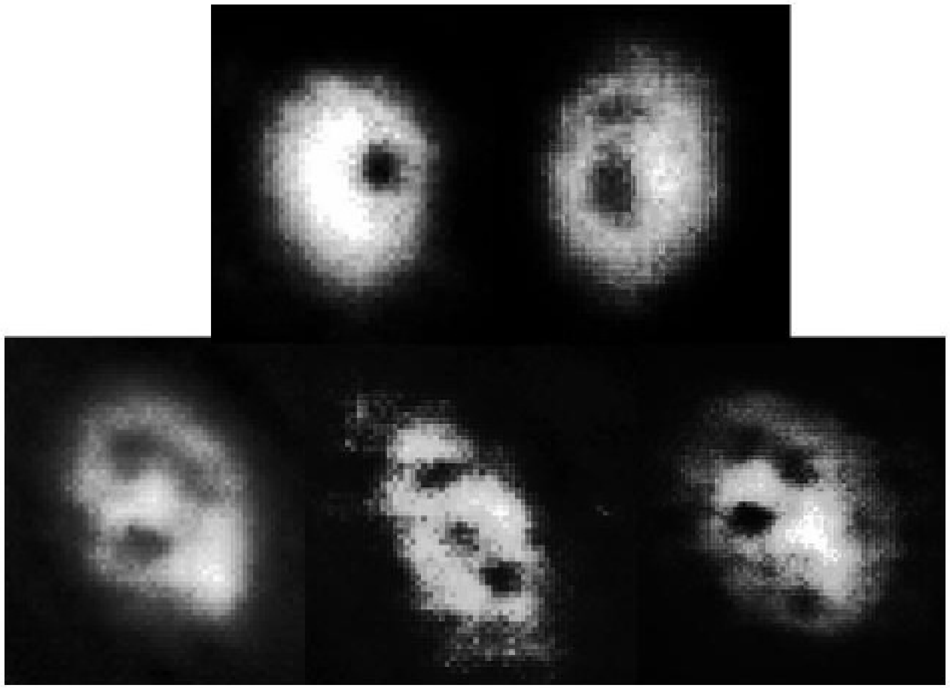
Planet Saturn, interface between two layers of atmosphere.

We generate vortices of both signs



EVOLUTION WITH AMPLITUDE AND TIME OF EXCITATION

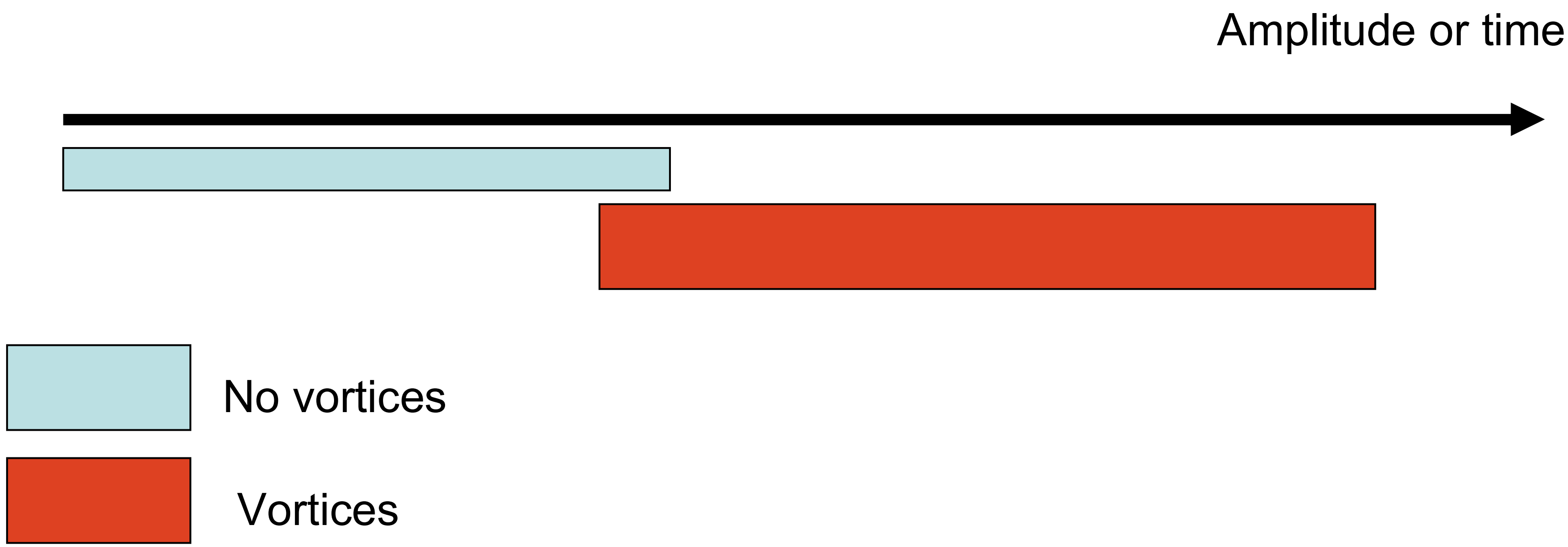
large shot-to-shot fluctuation



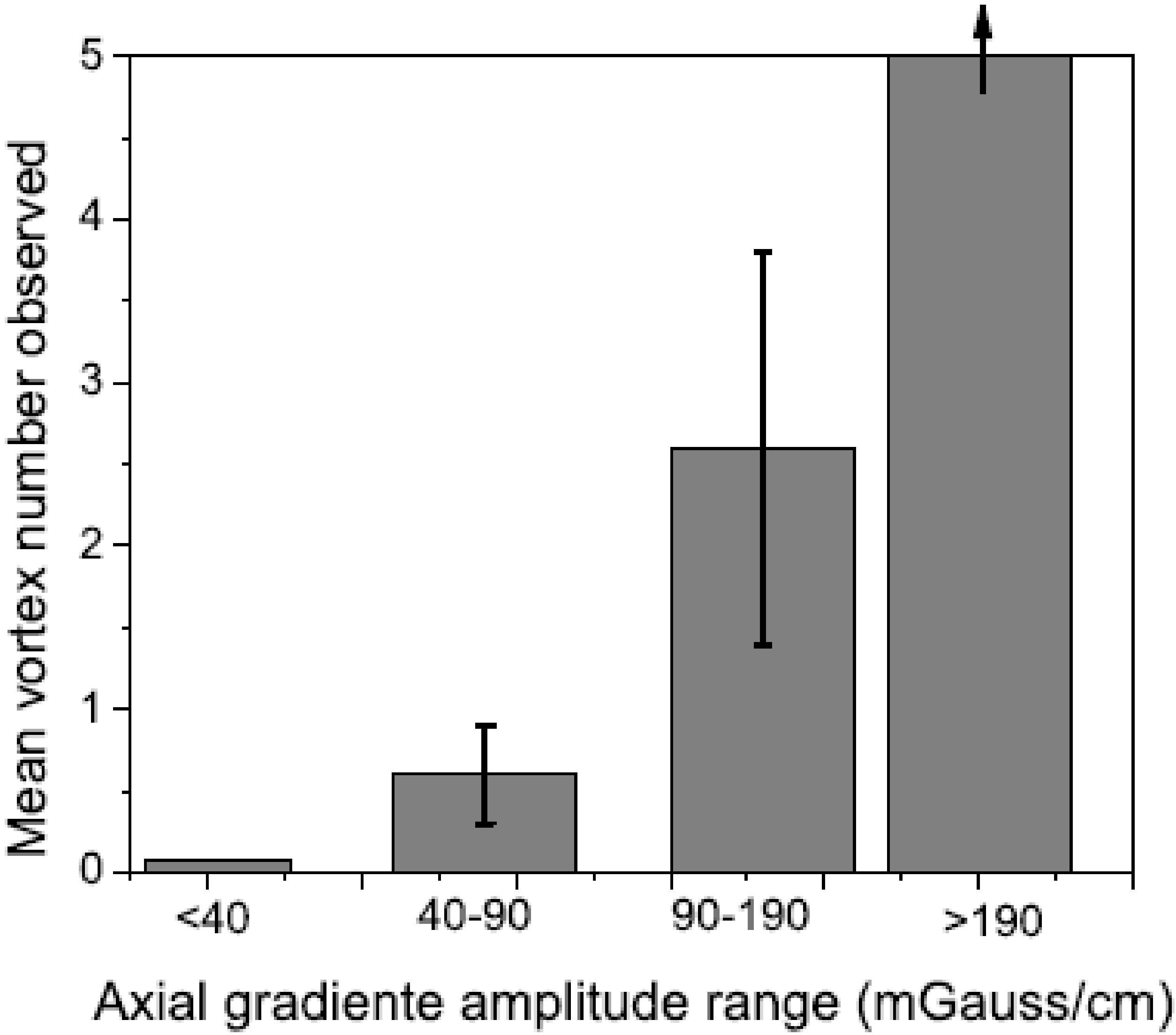
Similar core → equivalent circulation

Phys. Rev. A 79, 043618 (2009)

Fixing frequency → varying amplitude and time of excitation



Fixed time of excitation – 20 ms, TOF 15 ms, 200Hz



VORTEX CLUSTERS

IN A MIXTURE OF VORTEX-ANTIVORTEX: IS POSSIBLE THE FORMATION OF CLUSTERS OF VORTICES

THEORY (Mottonen et al – PRA 71,033626(2005)) PREDICTS THAT:

-DIPOLE AND QUADRUPOLE ARE ENERGETICALLY AND DYNAMICALLY UNSTAMBLE

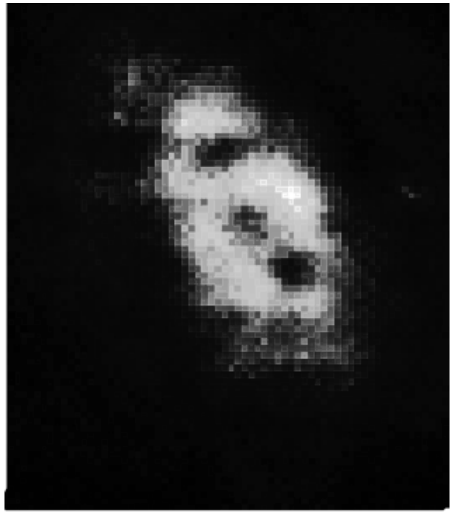
-TRIPOLE IS METASTABLE IN A STRONG INTERACTING TRAP

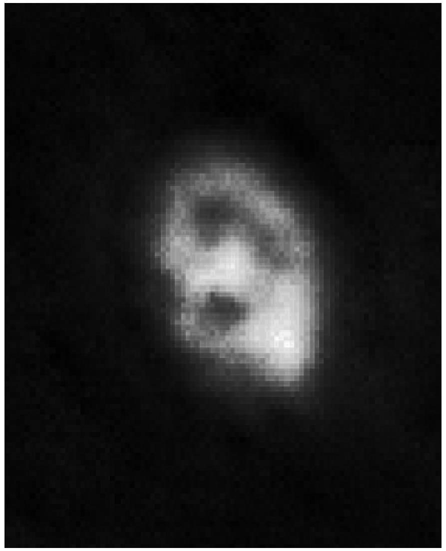
$g \sim N\, a/l > 108$ l= oscillator length

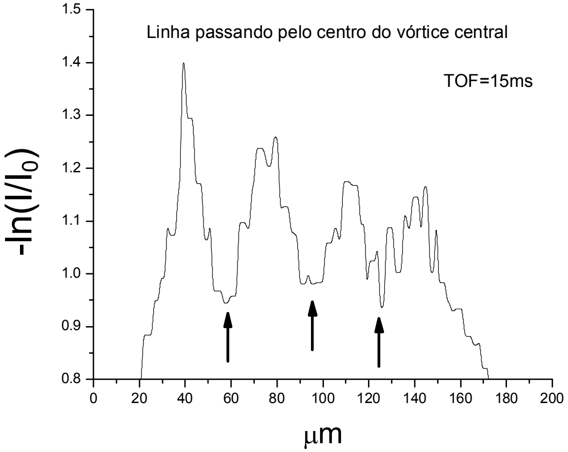
For us $g \sim 500 \rightarrow$ correct g for Metastable tripole

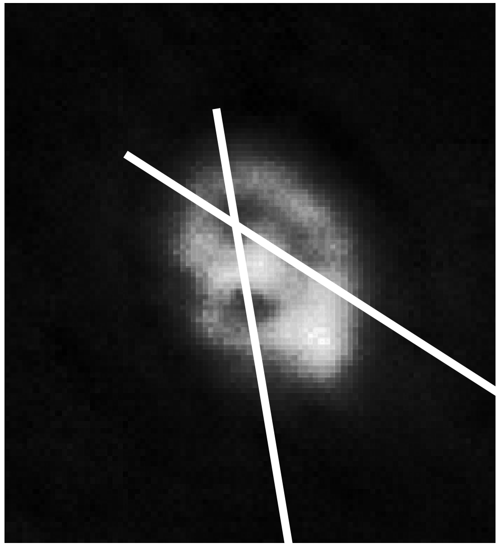
The only clear regularity we observe for a few vortices formed were when a three vortices configuration was observed

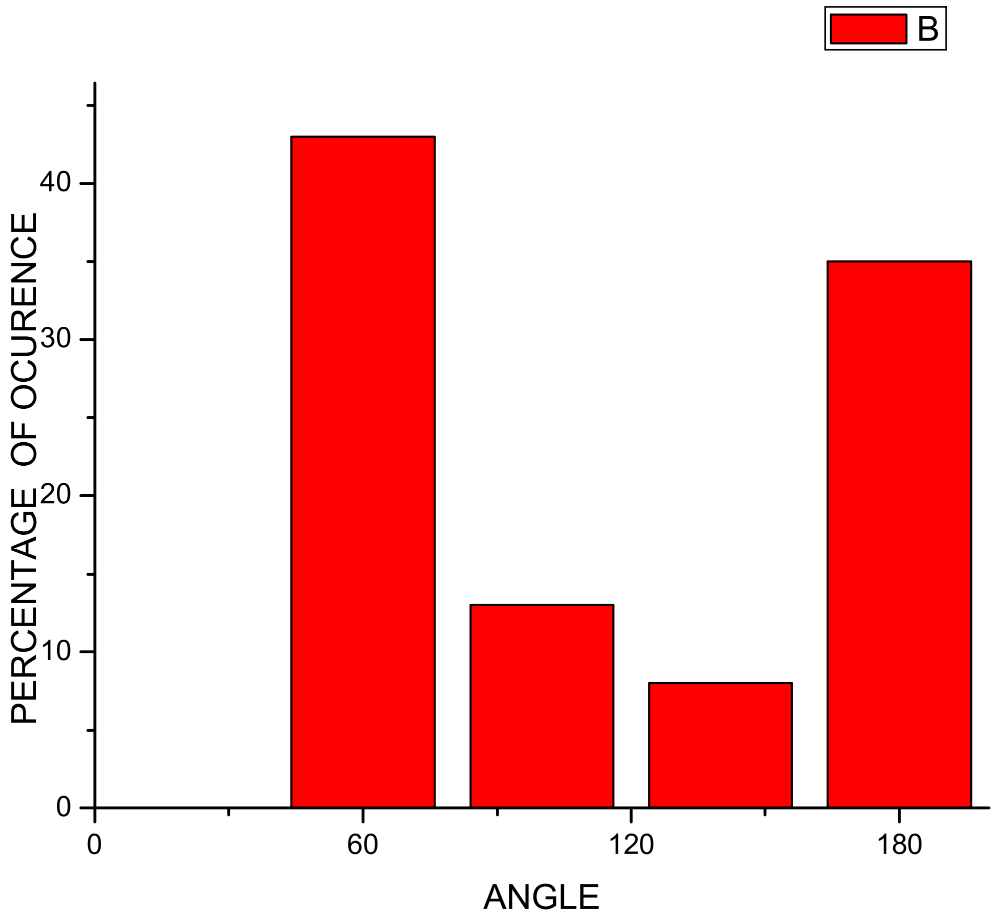
3 vortices stable configurations
From experimental observations , appears to be the only stable structure within the parameters of the experiment
(time of excitation, time of resting, amplitude)







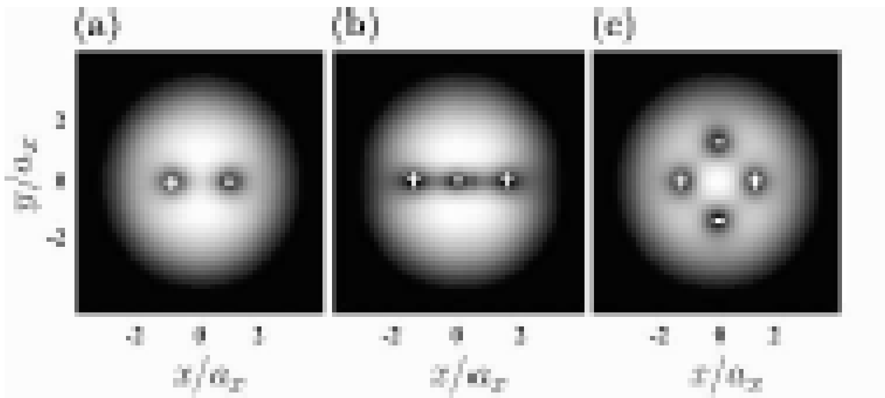




56 observations of
3 vortices

Stability and dynamics of vortex clusters in nonrotated Bose-Einstein condensates

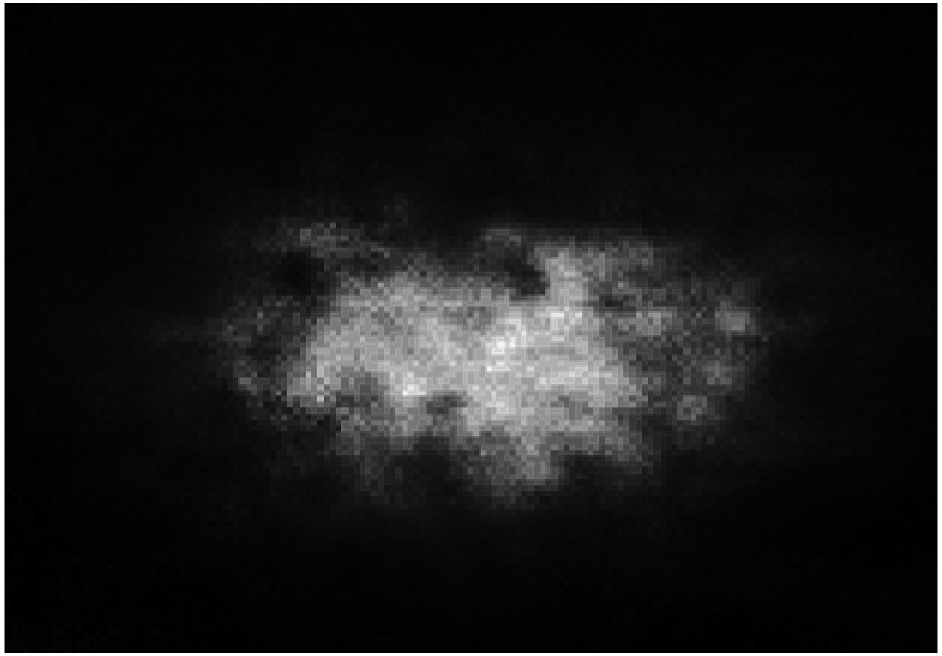
V. Pietilä,[1] M. Möttönen,[1,2] T. Isoshima,[3] J. A. M. Huhtamäki,[1] and S. M. M. Virtanen[1]
[1]*Laboratory of Physics, Helsinki University of Technology, P.O. Box 4100, FI-02015 TKK, Finland*
[2]*Low Temperature Laboratory, Helsinki University of Technology, P.O. Box 3500, FI-02015 TKK, Finland*
[3]*Department of Physics, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan*
(Dated: February 6, 2008)

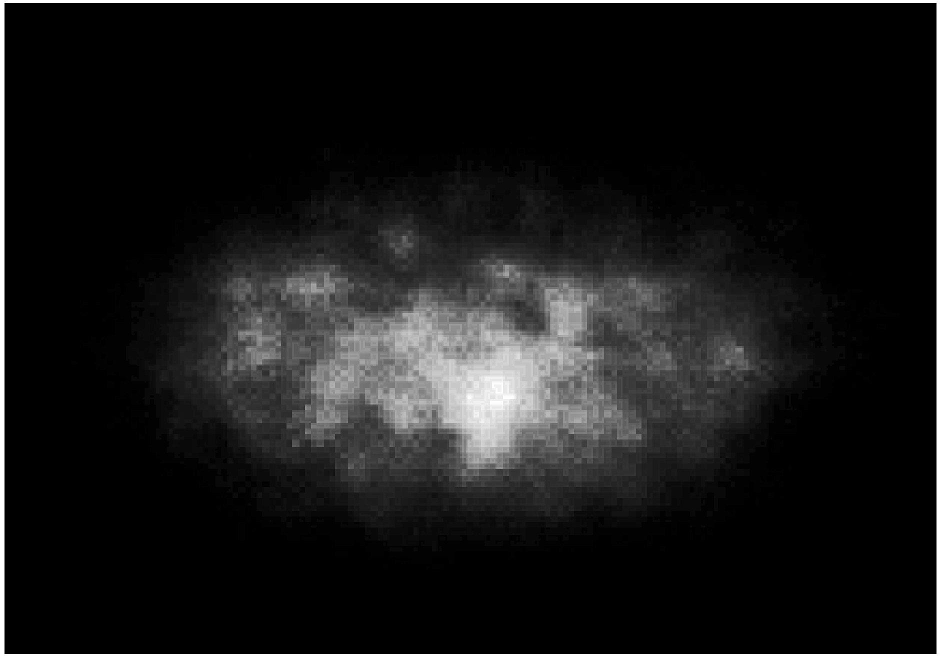


M. Haque and collaborators : Phys. Rev. A 77, 053610(2008) - Dipoles

Increasing amplitude or time of excitation:

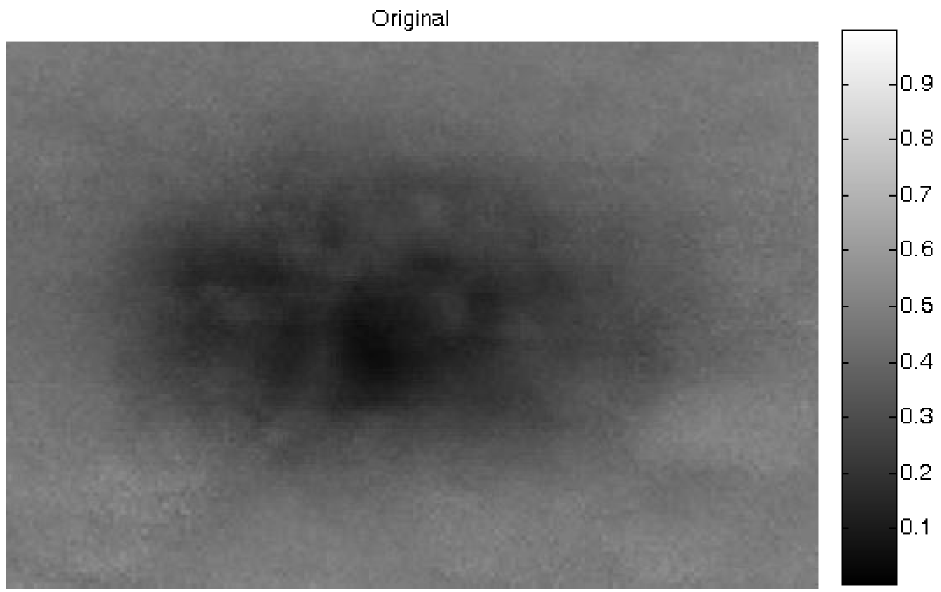
Explosion → proliferation of many vortices but no regular patern

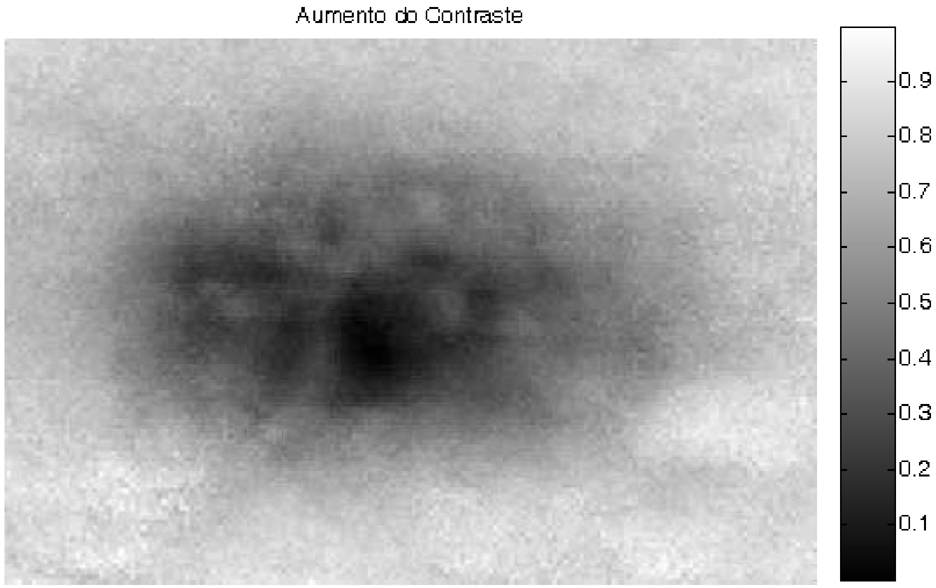




Changing in the behavior of free expansion

NON REGULAR – MANY POSITIONS, ORIENTATIONS AND LENGTH

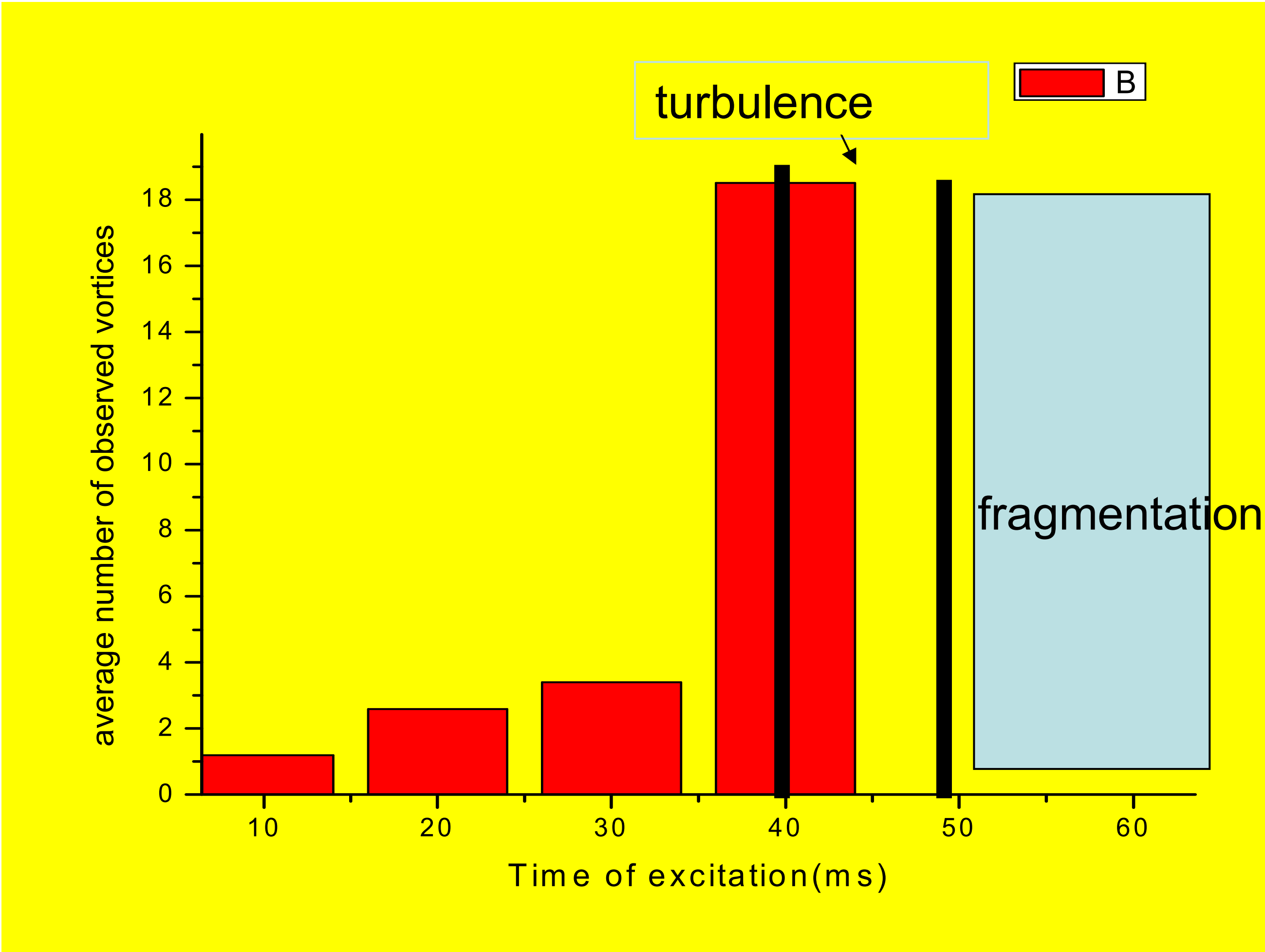




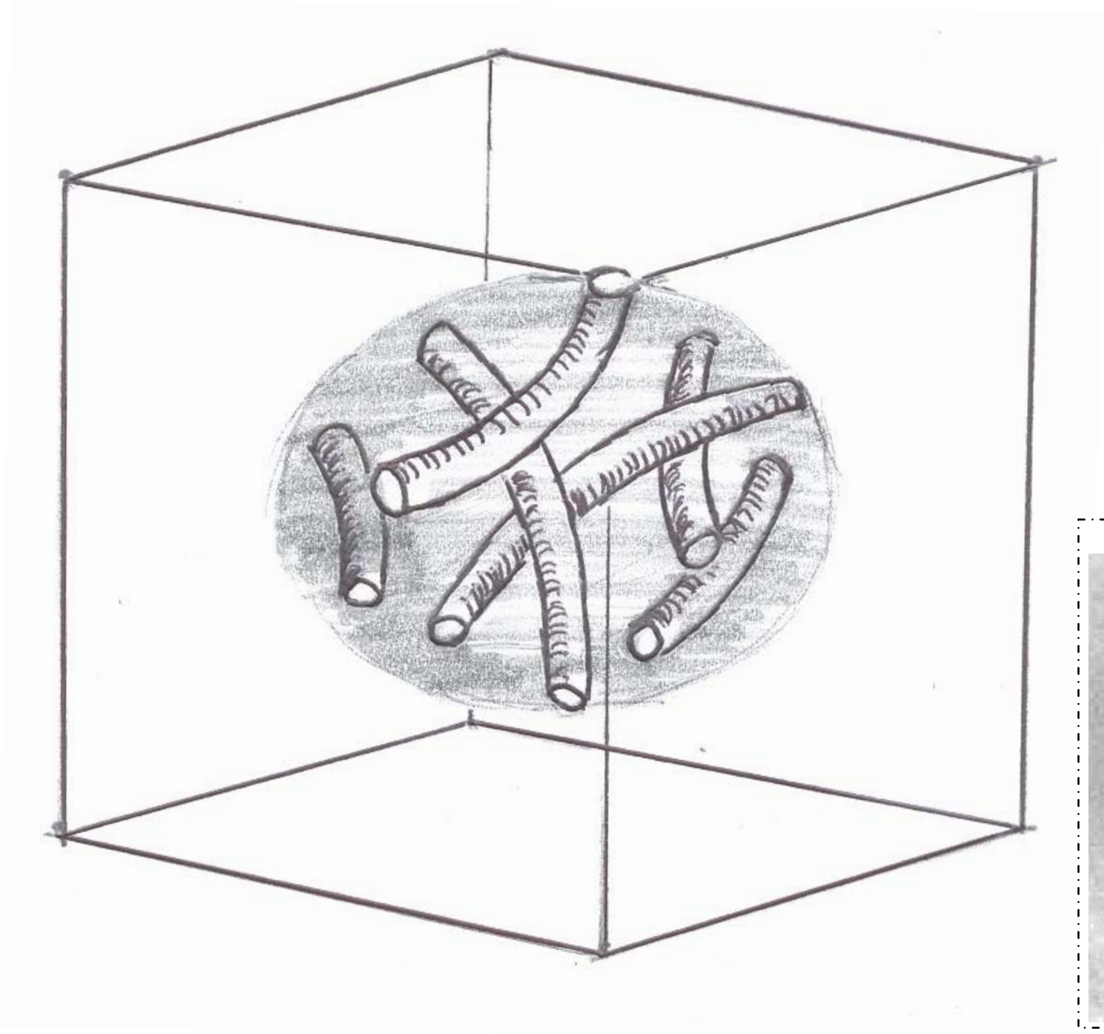
Characteristics of turbulence

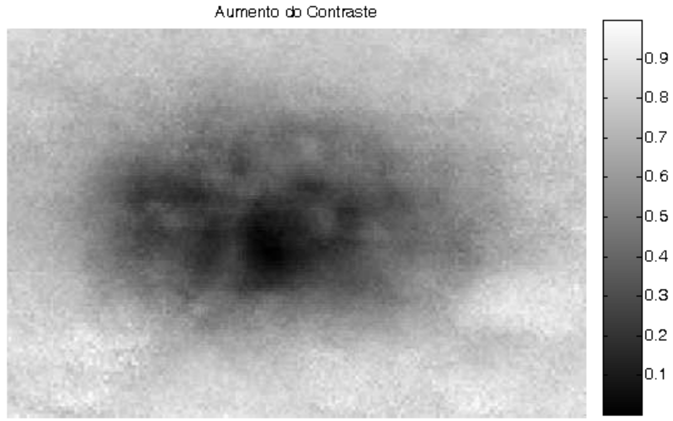
Average Numbers of vortices as a function of excitation time

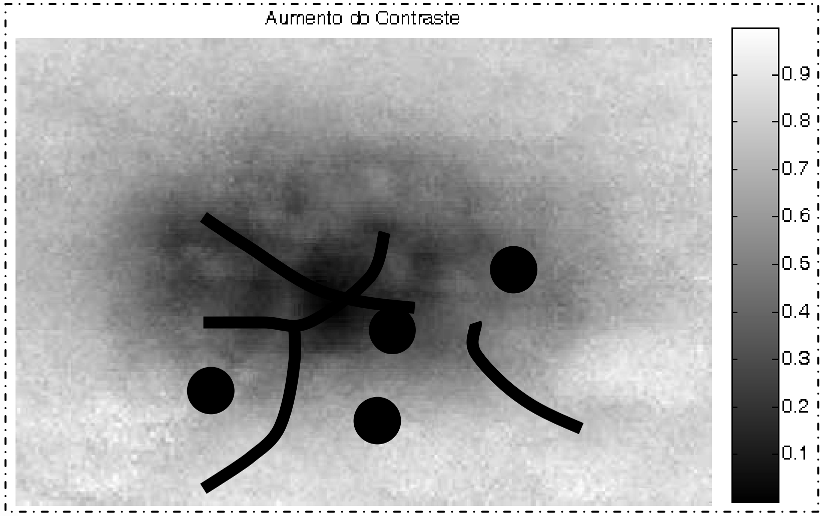
Excitation frequency : 200Hz, Amplitude 250 mV



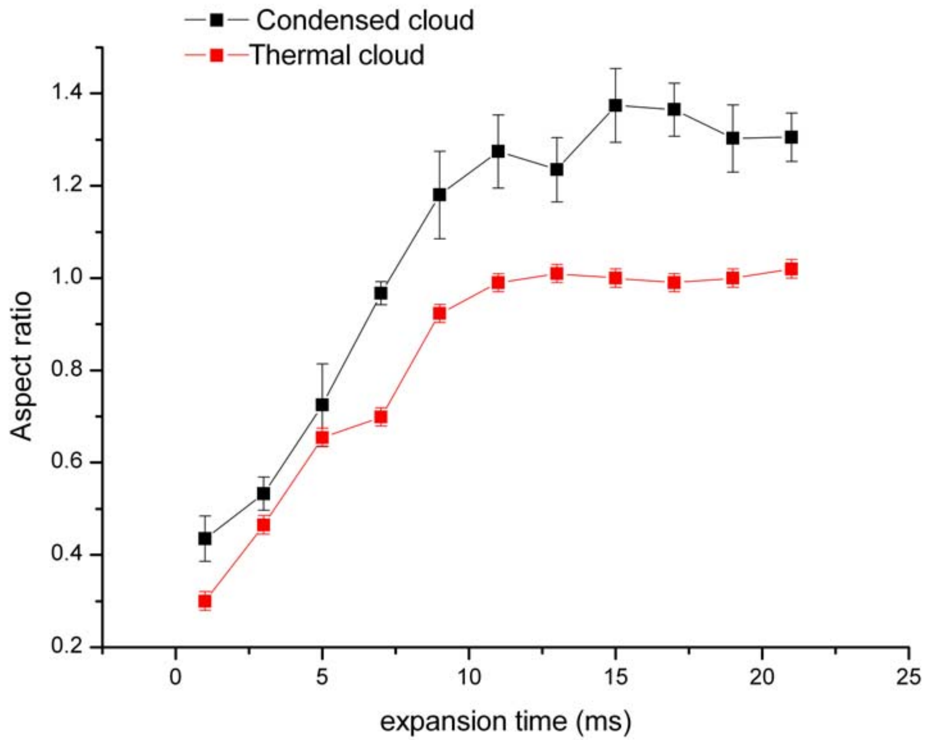
Tangle vortices region

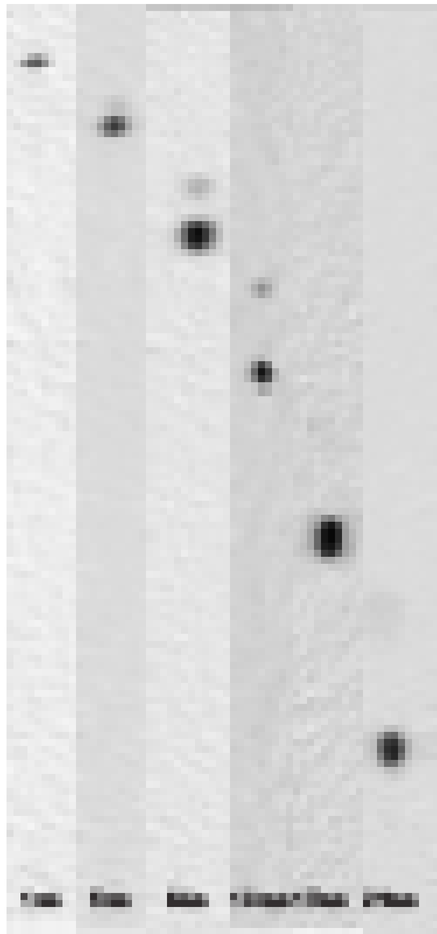




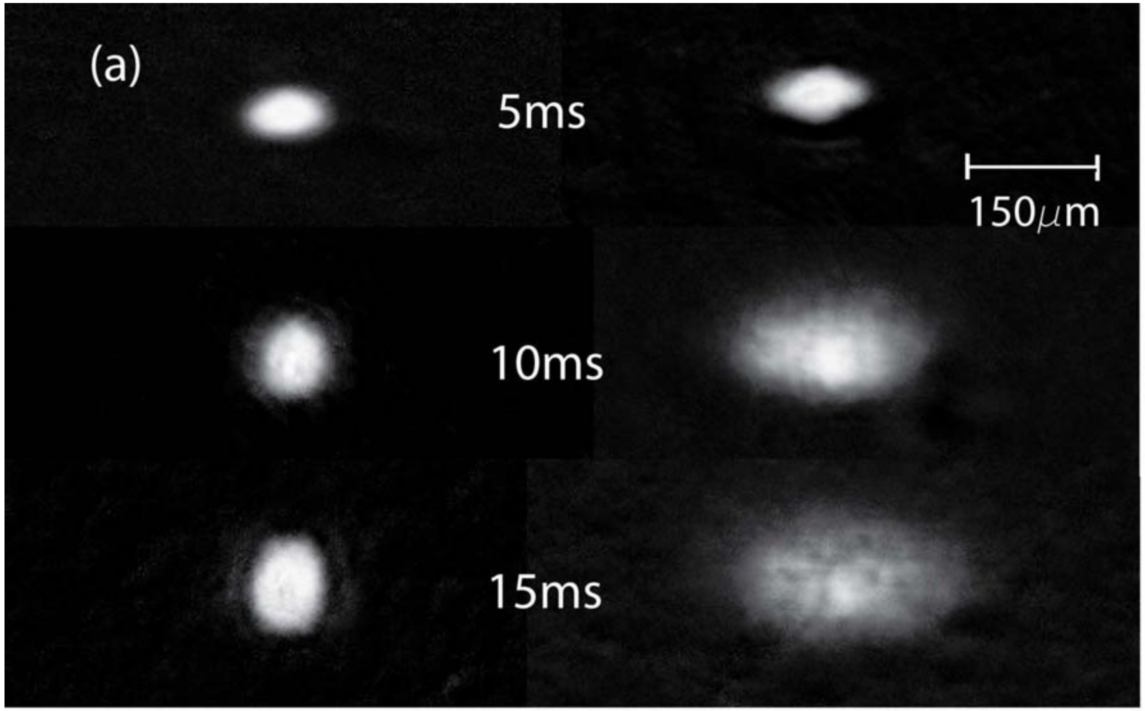


Observation of aspect ratio inversion of the quantum cloud- energy conversion

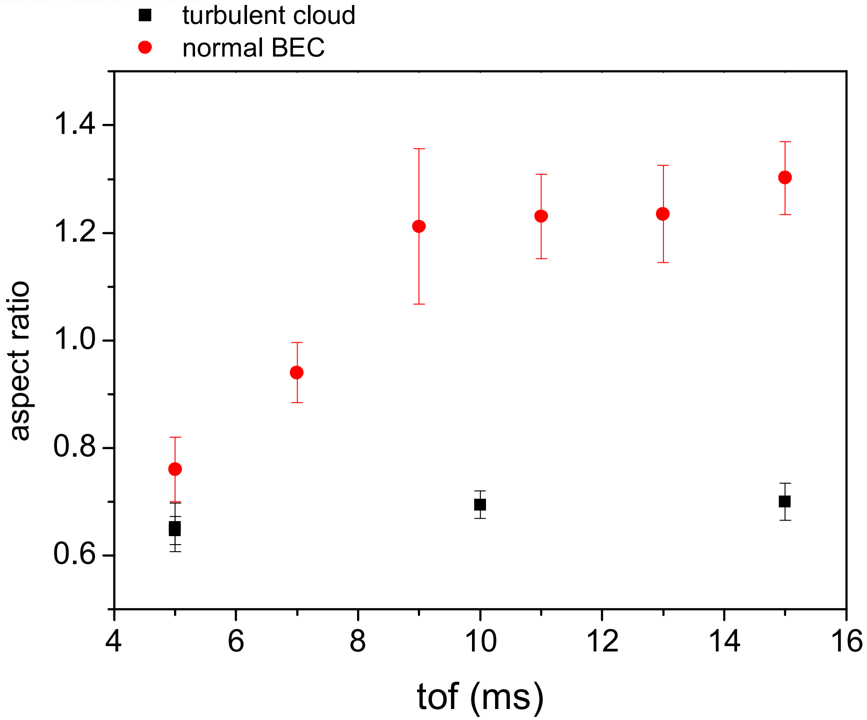




For a large number of vortices, the inversion is not observed



Non usual hydrodynamic behavior during expansion



Arxiv: 0904.2564

ANALYSIS OF ROTATING CLOUDS → CHANGE IN BEHAVIOR DURING EXPANSION

Phys. Rev. Lett. 88,070405(2002)

(Edwards, Clark, Pedri, Pitaevskii and Stringari)

Phys. Rev. Lett. 88,070406 (Hechenblaikner, Hodby, Hopkins, Marago and Foot)

- “ ….since the instantaneous moment of inertia is them proportional to the asymmetry of the cross section…”
- “ …. Preventing the released condensate from attaining a circular cross section..”

Clear the presence of angular momentum affects the expansion

The absence of inversion in the ratio may be an indicative of Turbulence . That would be a new effect in the atomic quantum fluid.

How we explain the formation of tangle vortices?

- EXCITATION IN AT LEAST TWO PLANS
- ENOUGH AMPLITUDE TO TRANSFER MANY UNITS OF ANGULAR MOMENT
- Two axis of oscillations (not equivalent)
- Tangle vortices (Feyman)
- When the vortices become tangle, the flow has a strong random element, varying rapidly from point to point (lost of inversion)

PHYSICAL REVIEW A 76, 045603 (2007)

Quantum turbulence in a trapped Bose-Einstein condensate

Michikazu Kobayashi and Makoto Tsubota
Department of Physics, Osaka City University, Sumiyoshi-Ku, Osaka 558-8585, Japan
(Received 16 March 2007; published 31 October 2007)

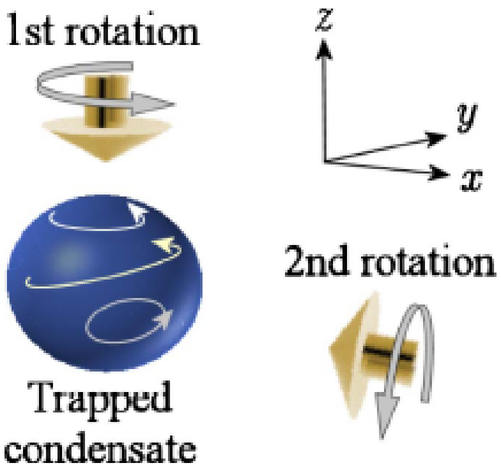


FIG. 1. (Color online). Schematic sketch of the rotation. The first rotation is applied along the z axis and the second rotation is applied along the x axis.

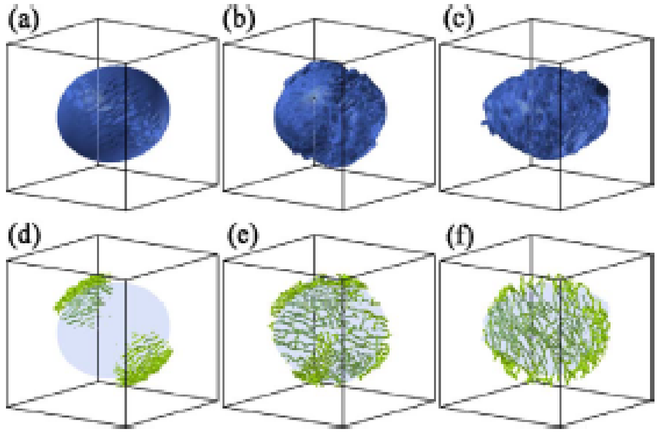
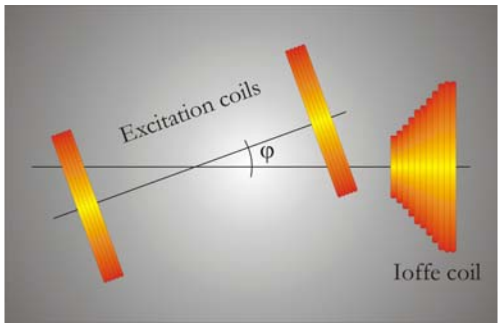
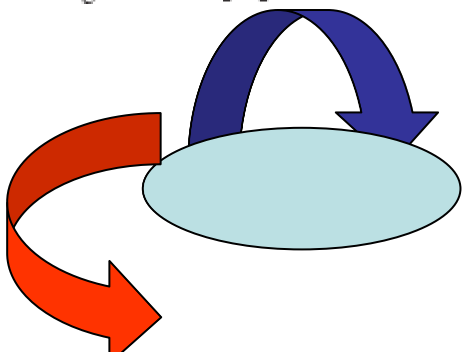
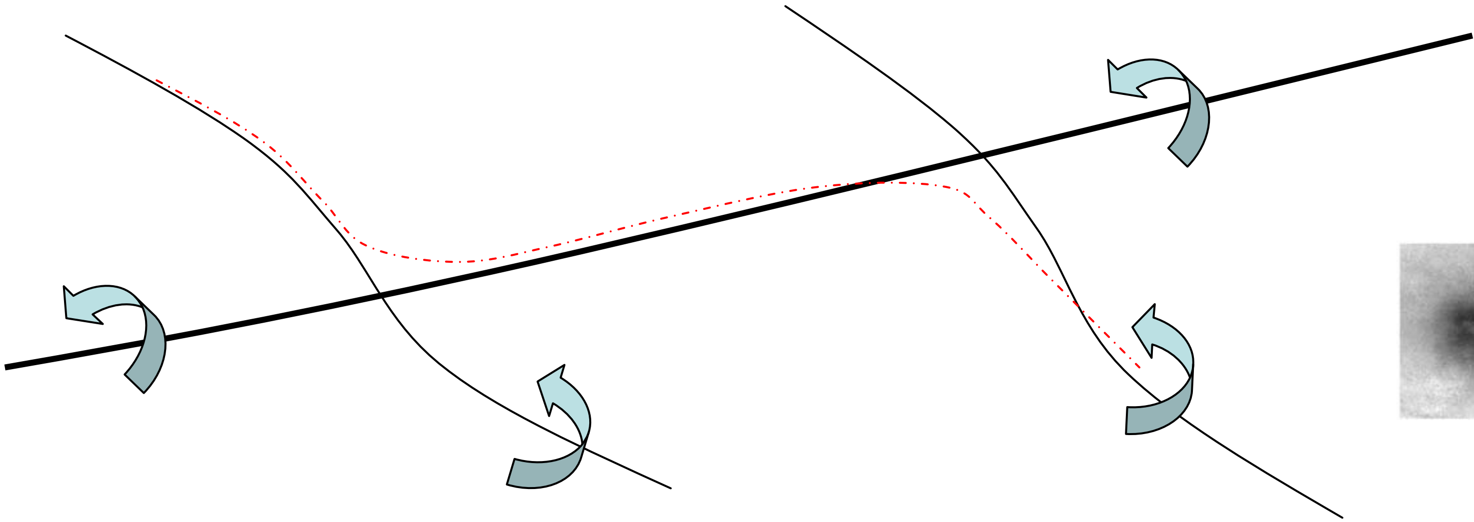


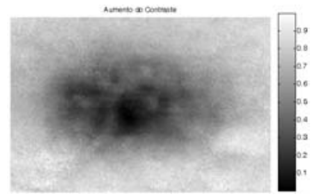
FIG. 4. (Color online). Isosurface plots of 5% of the maximum condensate density (a)–(c) and configuration of quantized vortices inside the Thomas-Fermi radius R_{TF} (d)–(f). (a), (d) $t\omega=10$; (b), (e) $t\omega=50$; (c), (f) $t\omega=300$. The method for identifying vortices in (d)–(f) is the same as that in Fig. 7 in Ref. [15].

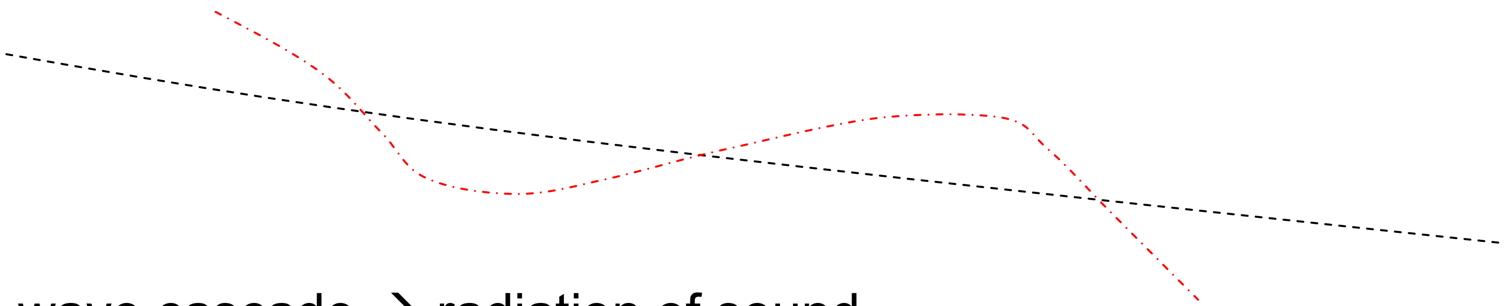




Dissipation in QT
KELVIN WAVES
Vortex breaking and reconnecting







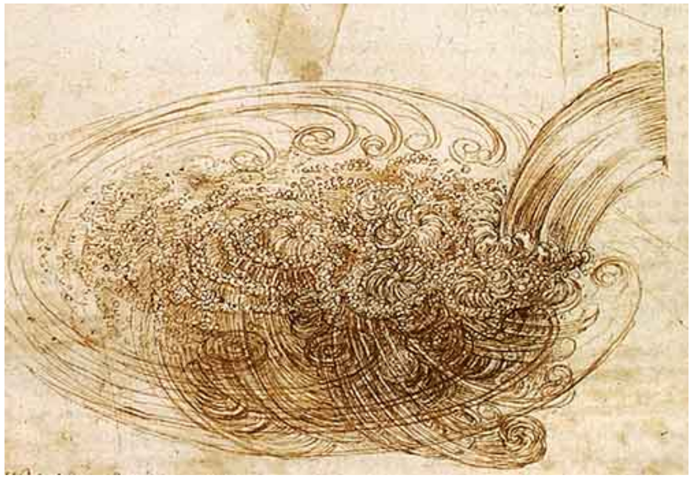
Kelvin wave cascade → radiation of sound

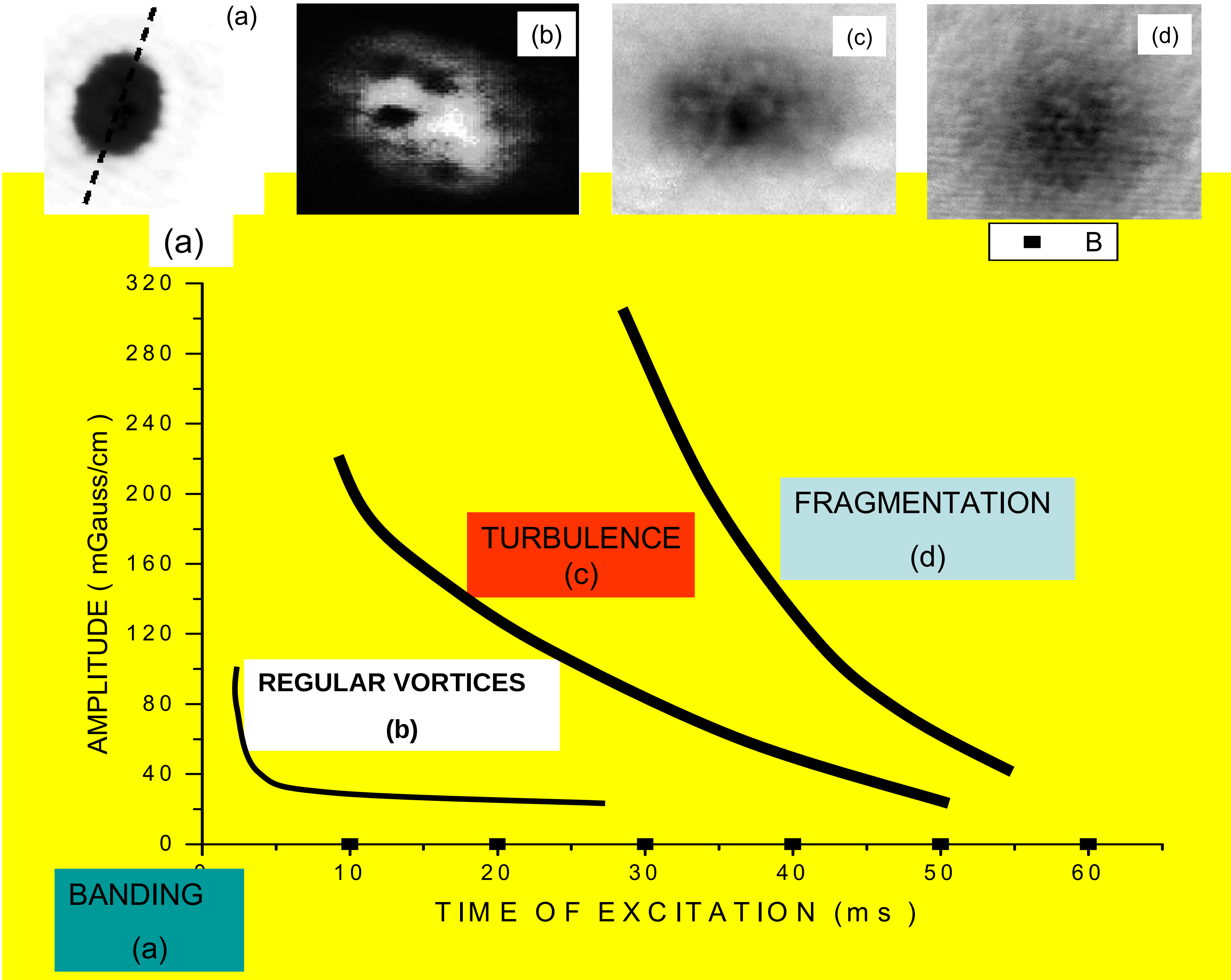
PRESENTLY

- Controlling turbulence in BEC is possible (changing fraction of condensate, changing interaction, etc)

-Kolmogorov spectrum(how to measure in a BEC after expansion?)

-Quantum turbulence - dissipation mechanisms





(a)
(b)
(c)
(d)
(a)
B
320
280
240
200
160
120
80
40
0
AMPLITUDE (mGauss/cm)
0
10
20
30
40
50
60
TIME OF EXCITATION (ms)
REGULAR VORTICES
(b)
TURBULENCE
(c)
FRAGMENTATION
(d)
BANDING
(a)

V.I. Yukalov

Bose systems in spatially random or time-varying potentials

Abstract

Bose systems, subject to the action of external random potentials, are considered. For describing the system properties, under the action of spatially random potentials of arbitrary strength, the stochastic mean-¯eld approximation is employed. When the strength of disorder increases, the extended Bose-Einstein condensate fragments into spatially disconnected regions, forming a granular condensate. Increasing the strength of disorder even more transforms the granular condensate into the normal glass. The in°uence of time-dependent external potentials is also discussed. Fastly varying temporal potentials, to some extent, imitate the action of spatially random potentials. In particular, strong time-alternating potential can induce the appearance of a nonequilibrium granular condensate.

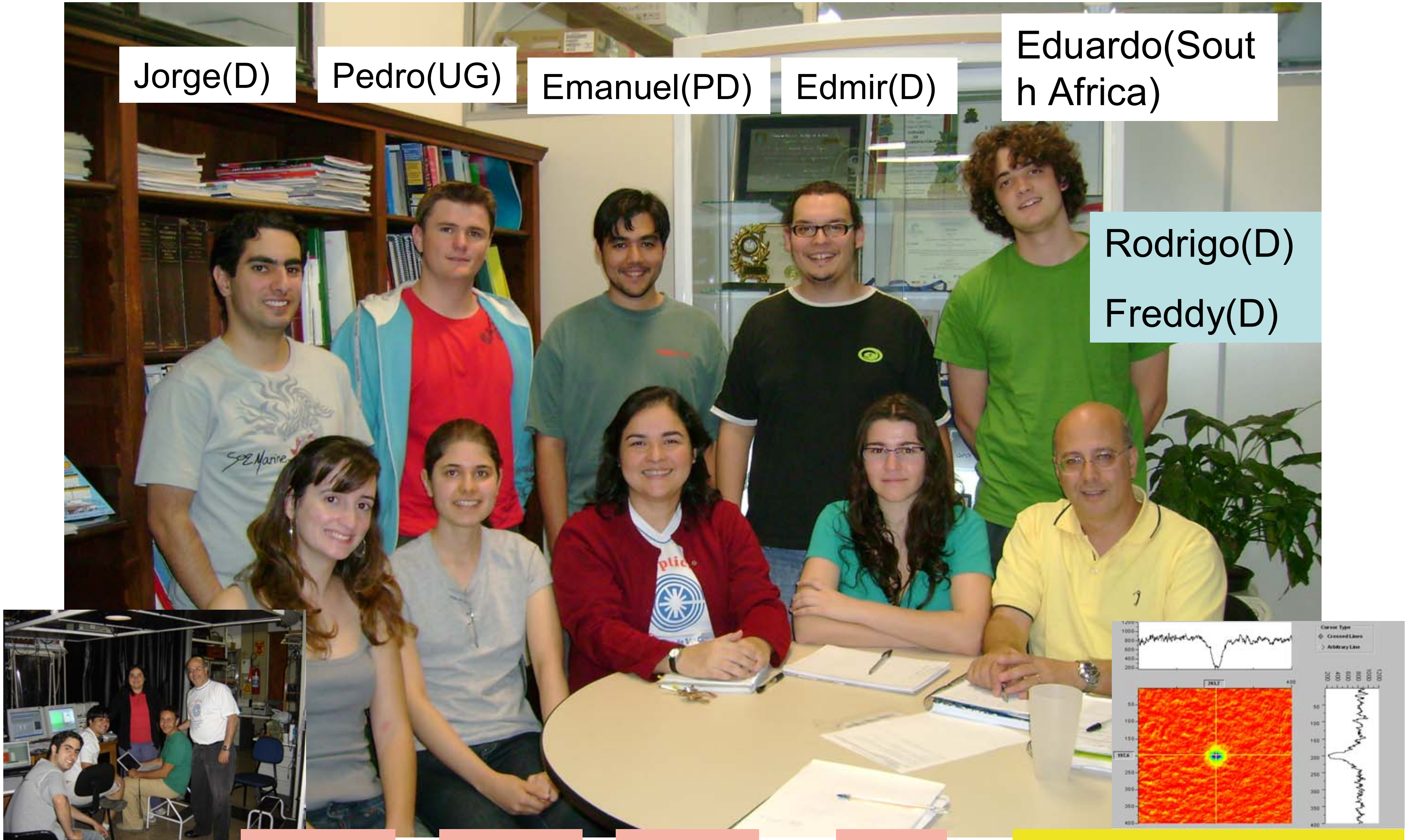
SPECIAL ISSUE OF J. LAS. PHYS.

arXiv:0904.0749

CONCLUSIONS:

- Many observations: tangle vortices(QT), Clusters, new hydrodynamic expansion, fragmentation, evidences of ripplons,…
- BUT
- Much more to do ...

BEC - LABORATORY



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2 POSTDOC POSITIONS IN ATOMIC PHYS.

One faculty position – second semester 2009

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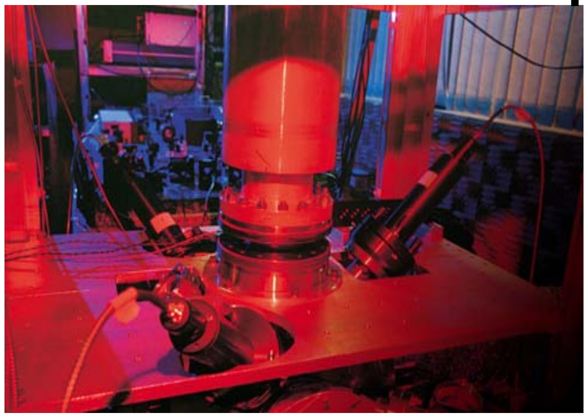




http://www.lasphys.com/workshops/lasphys10

19th INTERNATIONAL LASER PHYSICS WORKSHOP

(Foz do Iguaçu, July 5-9, 2010)

The nineteenth annual International Laser Physics Workshop (LPHYS'10) will be held from July 5 to July 9, 2010, in the Carimã Hotel, Foz do Iguaçu, Brazil. The city of Foz do Iguaçu is situated near the world-famous falls, the Iguazu Falls. That is why the excursion on the Iguazu Falls for participants of LPHYS'10 will be organized by the Local Organizing Committee.

LPHYS'10

THANKS