The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2023-25

Workshop on Topics in Quantum Turbulence

16 - 20 March 2009

Oscillating Bose Condensates: Generation of Vortices and Evidence for Turbulence

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Vortices, clusters of vortices and evidences of turbulence in an oscillating BEC

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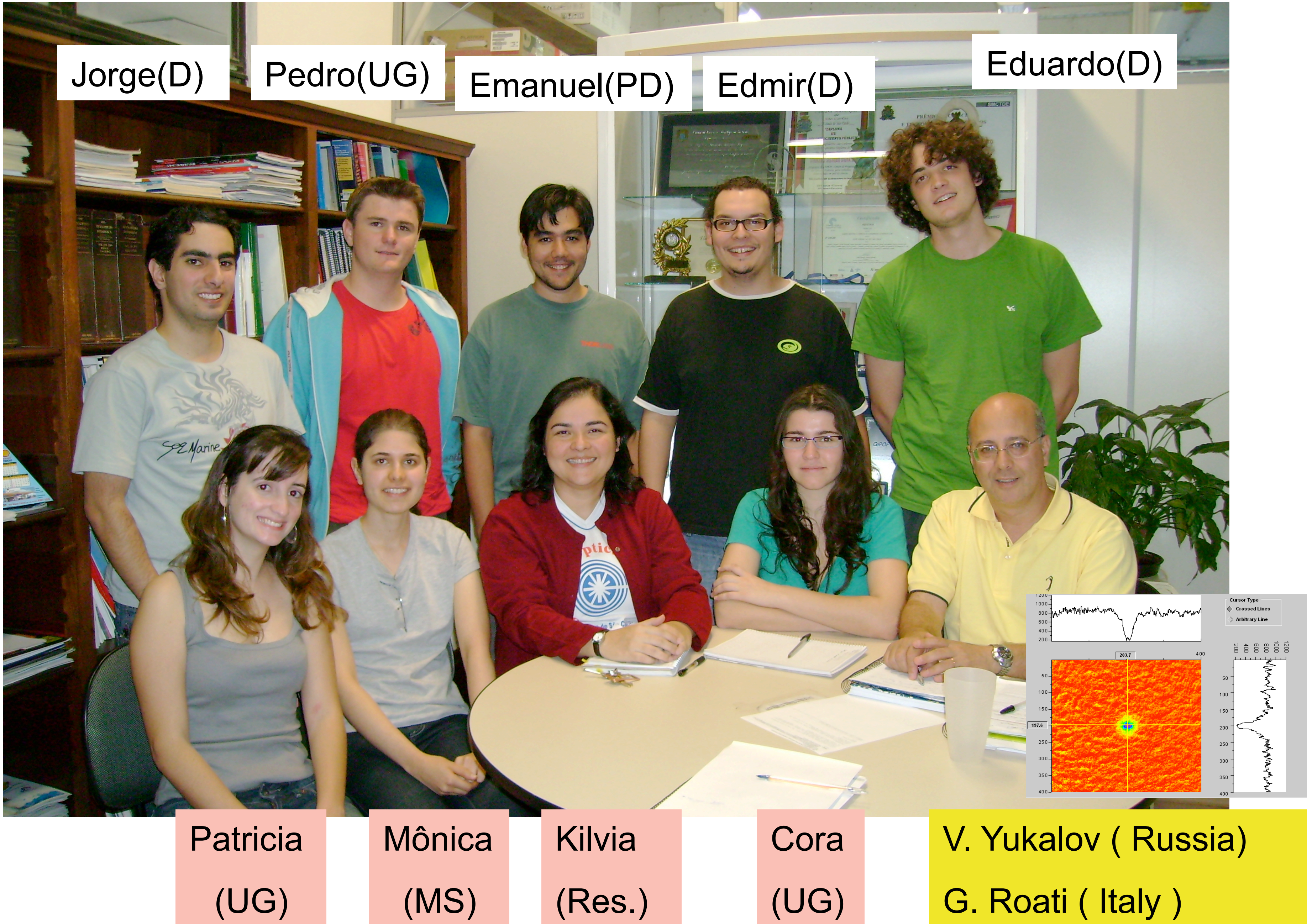
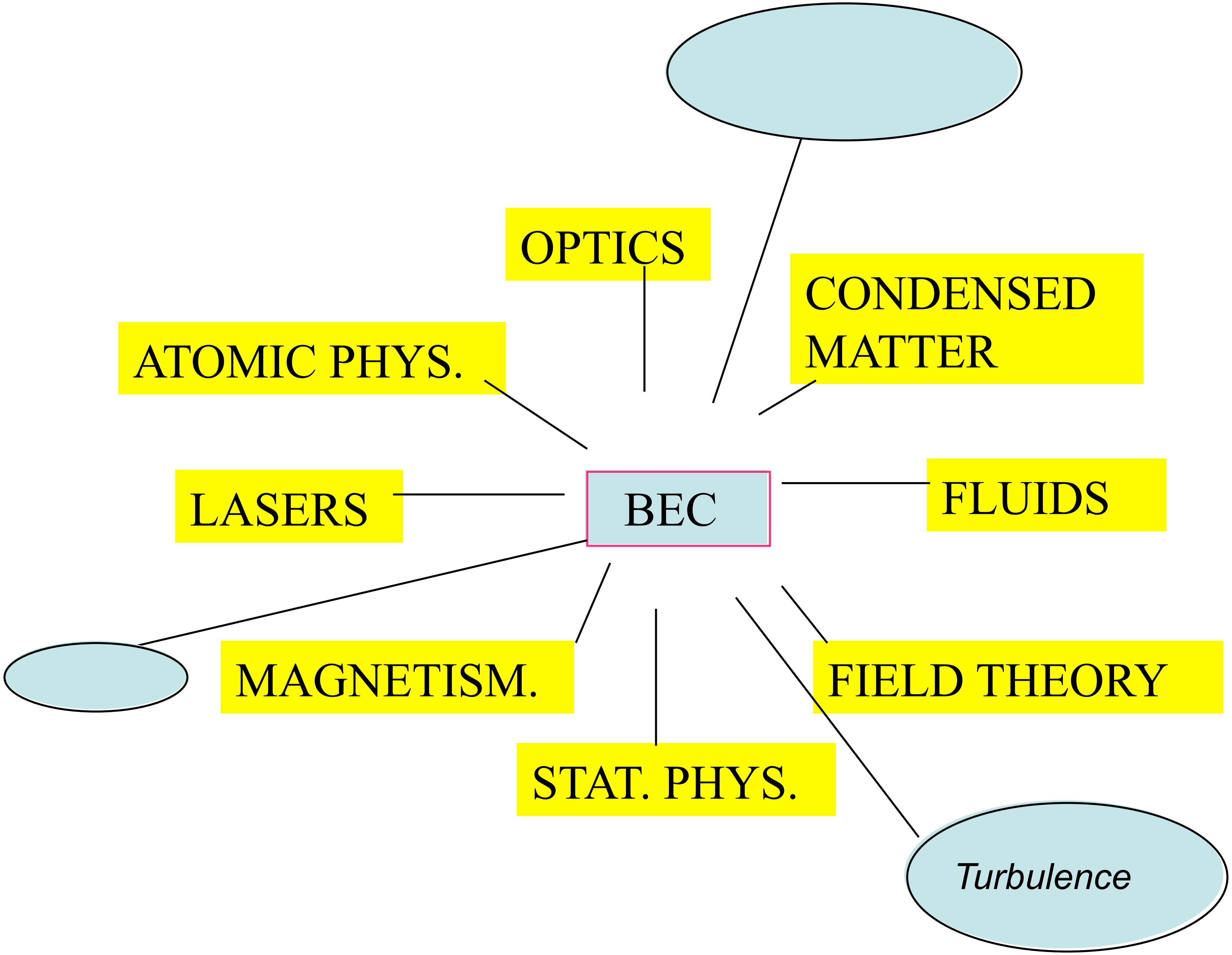
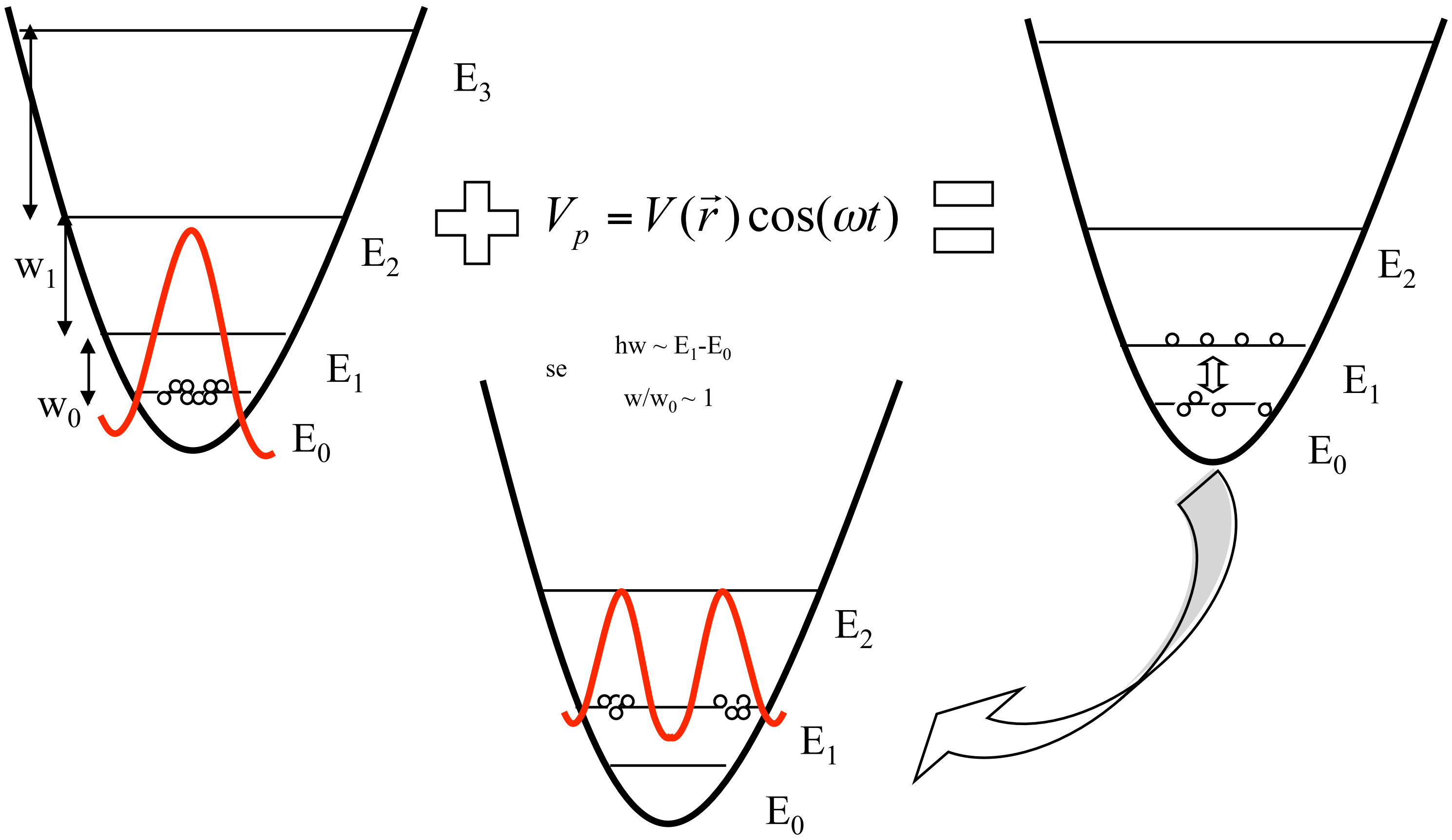
BEC - LABORATORY




OPTICS
CONDENSED MATTER
ATOMIC PHYS.
LASERS
BEC
FLUIDS
MAGNETISM.
FIELD THEORY
STAT. PHYS.
Turbulence

Our initial goal :

Coherent population transfer between two trapped states

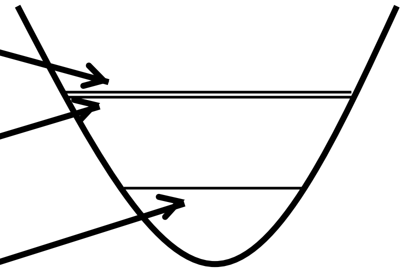


But we forgot the vortices !!!!!!!!!!

$$x\ \exp(-r^2/(2a_0^2)) \longleftrightarrow n_x = 1,\ n_y = 0$$

$$y\ \exp(-r^2/(2a_0^2)) \longleftrightarrow n_x = 0,\ n_y = 1$$

$$\exp(-r^2/(2a_0^2)) \longleftrightarrow n_x = n_y = 0$$



combination $|1_x, 0_y\rangle + i|0_x, 1_y\rangle$

Wave function: $(x + iy)\, e^{-r^2/(2a_0^2)} \quad = r\, e^{i\varphi}\, e^{-r^2/(2a_0^2)}$

vortex with a charge +1

EXPLORATORY PRESENTATION

OUTLINE

1 - GENERAL CONSIDERATIONS

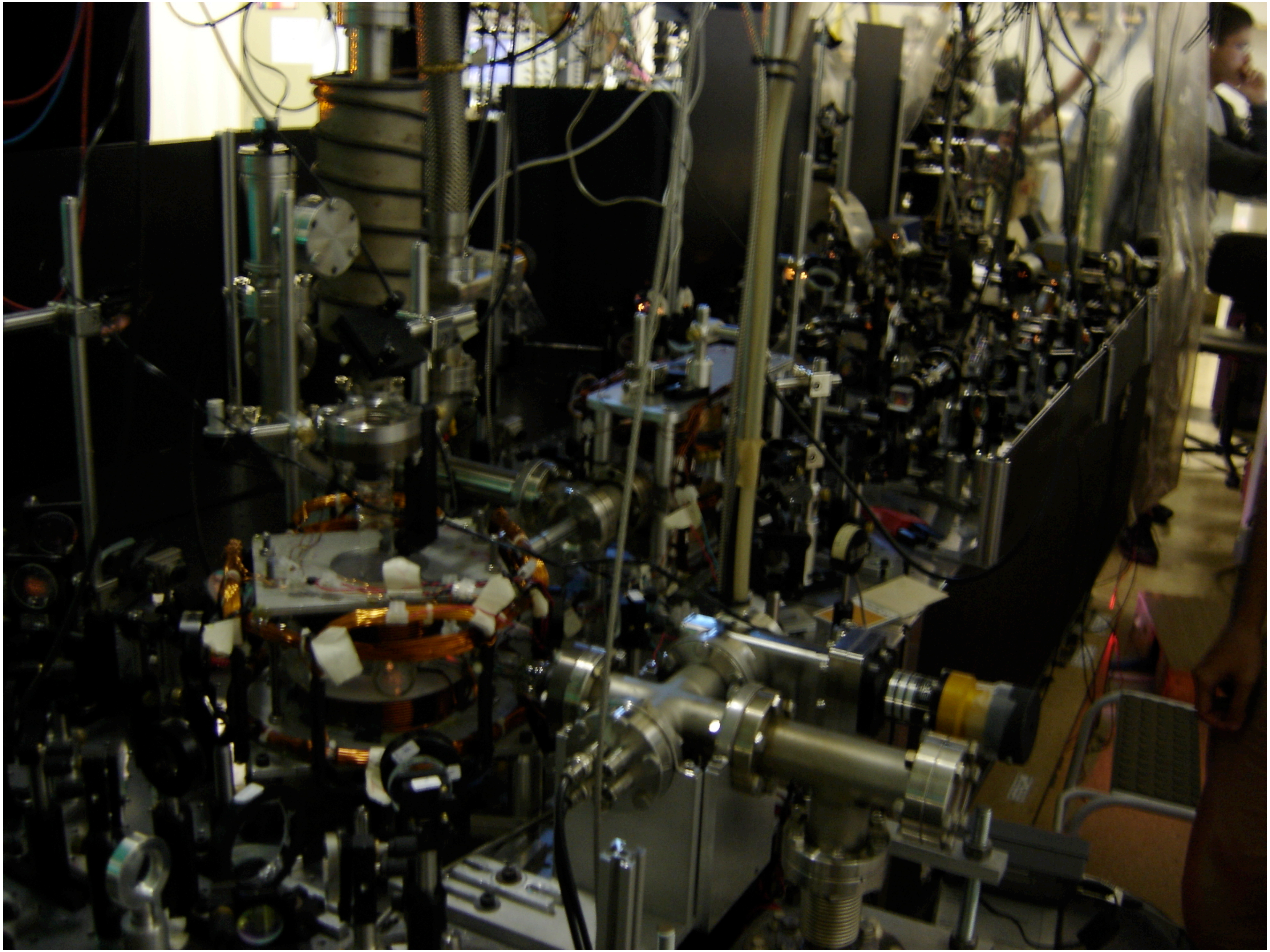
2 - VORTICES FORMED BY OSCILLATIONS

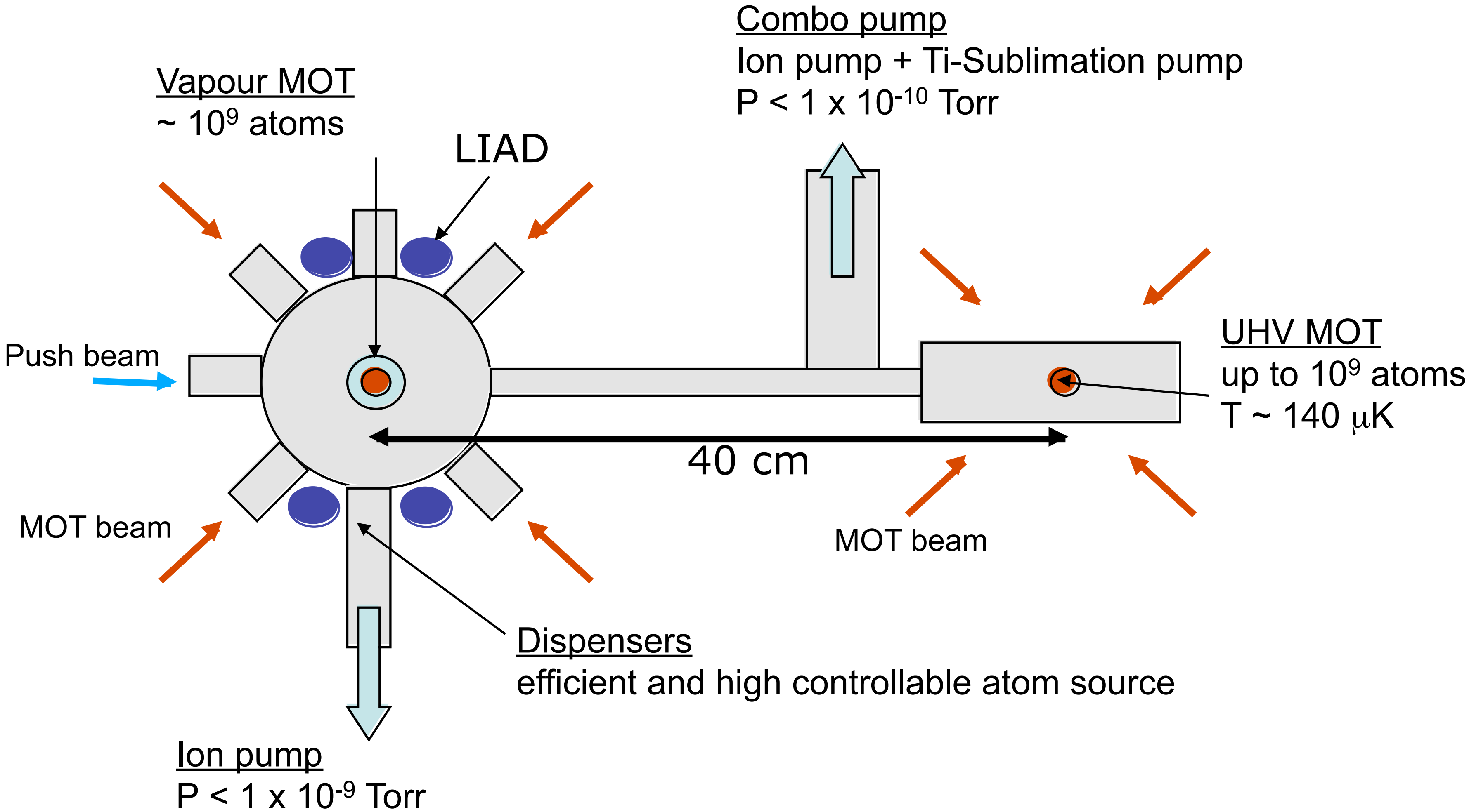
3 - ROUTE TO TURBULENCE

4 - CLUSTERS OF VORTICES: TRIPOLES

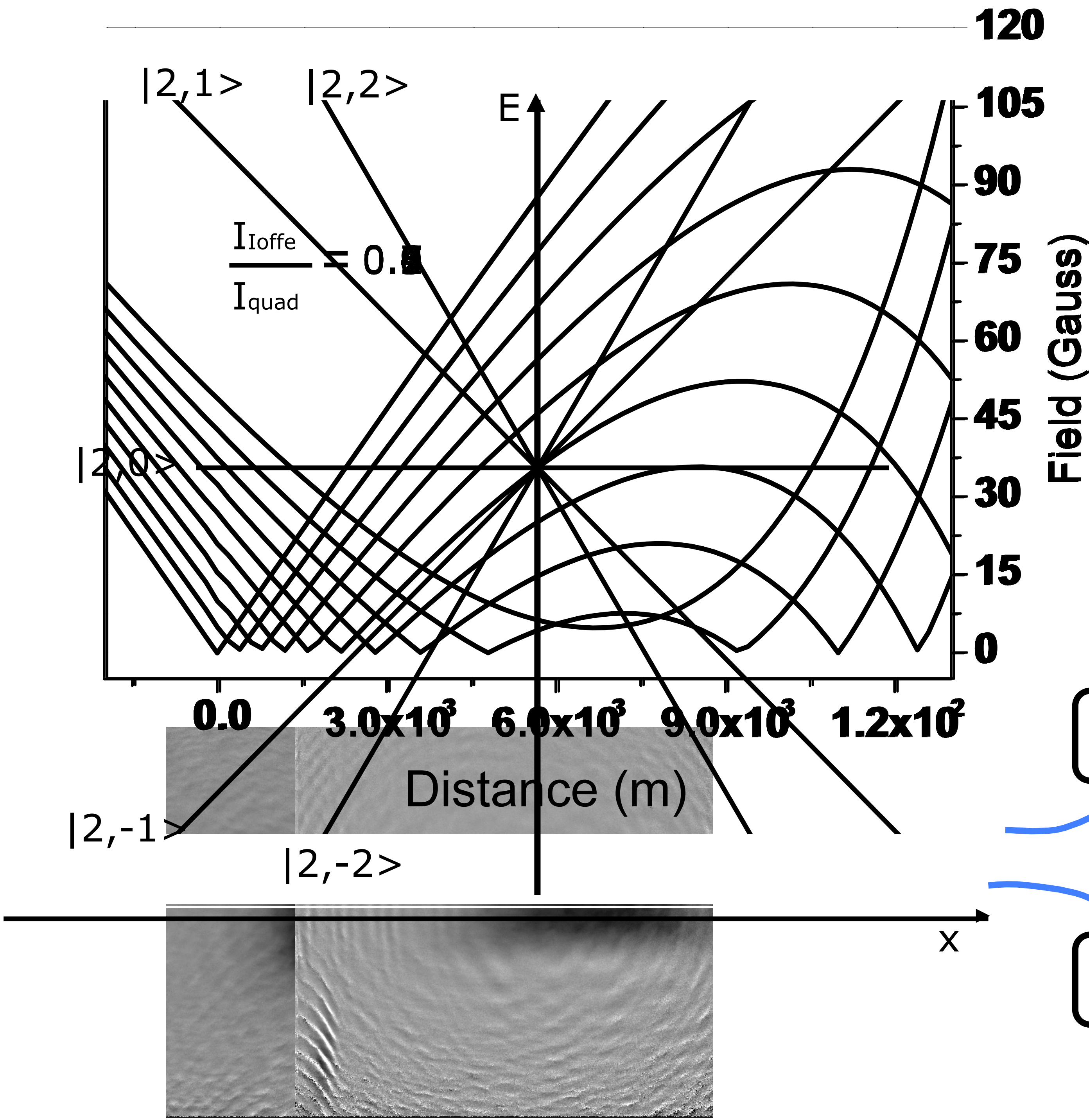
5 - FRAGMENTATION

BEC OF Rb

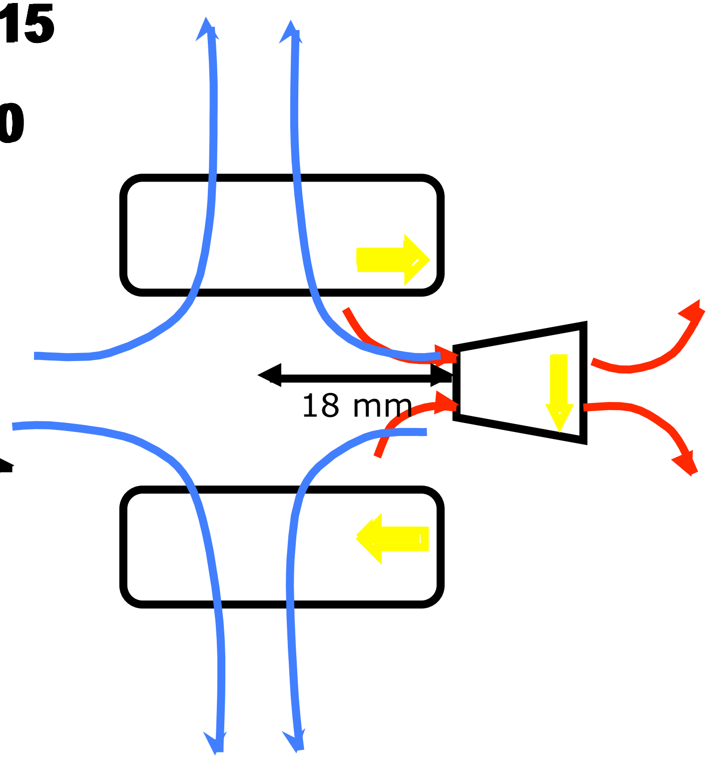




Combo pump
Ion pump + Ti-Sublimation pump
P < 1 x 10-10 Torr
Vapour MOT
~ 109 atoms
LIAD
Push beam
UHV MOT
up to 109 atoms
T ~ 140 μK
40 cm
MOT beam
MOT beam
Dispensers
efficient and high controllable atom source
Ion pump
P < 1 x 10-9 Torr


|2,1>
|2,2>
E
$\frac{I_{Ioffe}}{I_{quad}} = 0.$
|2,0>
|2,-1>
|2,-2>
x
120
105
90
75
60
45
30
15
0
Field (Gauss)
0.0
3.0x10
6.0x10
9.0x10
1.2x10
Distance (m)

QUIC Trap


18 mm

Temporal Sequence

- A full run of the BEC experiment takes 1min

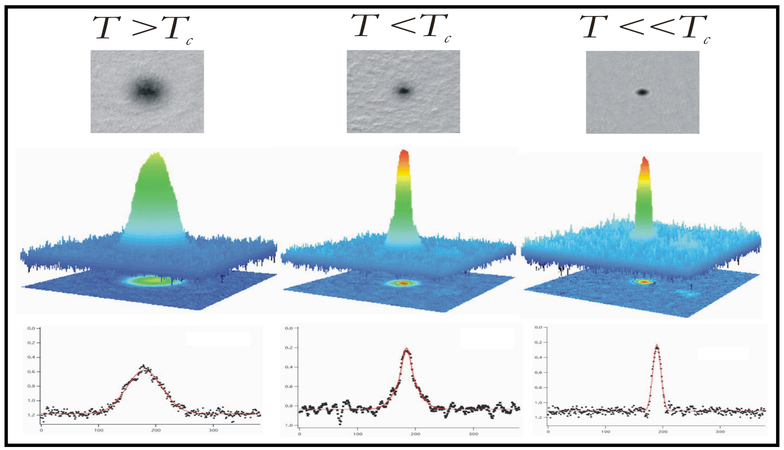
- The first 35s are just for 2nd MOT loading

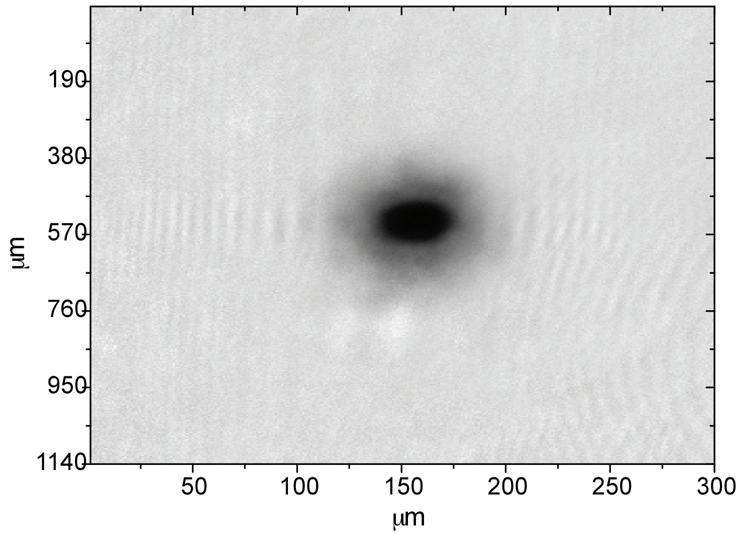
- The last 24s are for magnetic trapping and evaporation, which takes itself 22s

- The link between these two parts is due to a group of 5 processes that take a total of 10ms

OUTCOME: 3 to 8 10^5 condensate Atoms

T ~ 80 to 200 nK





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)

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

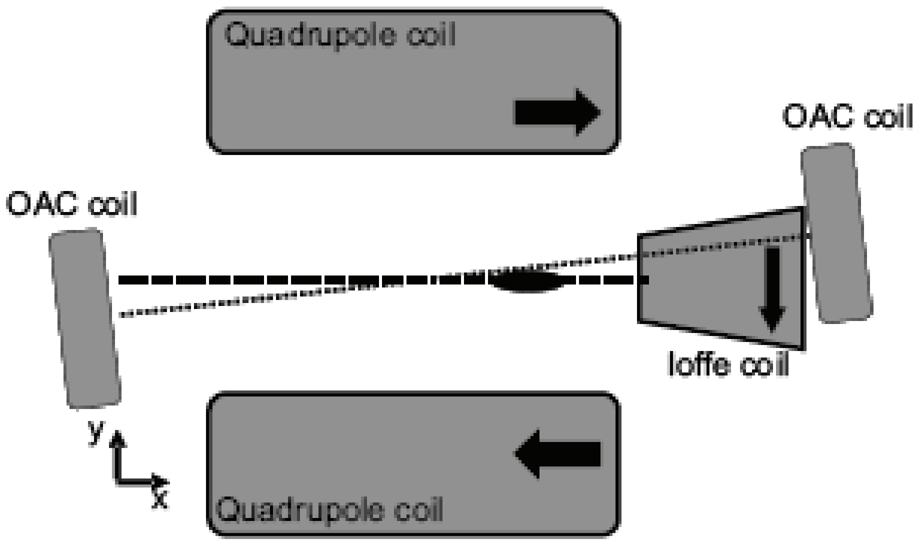
How are the vortices formed and how is the dynamics?

- 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..

Oscillatory Quadrupolar external excitation

POSSIBILITY TO EXCITE VORTICES OF BOTH SIGNS:

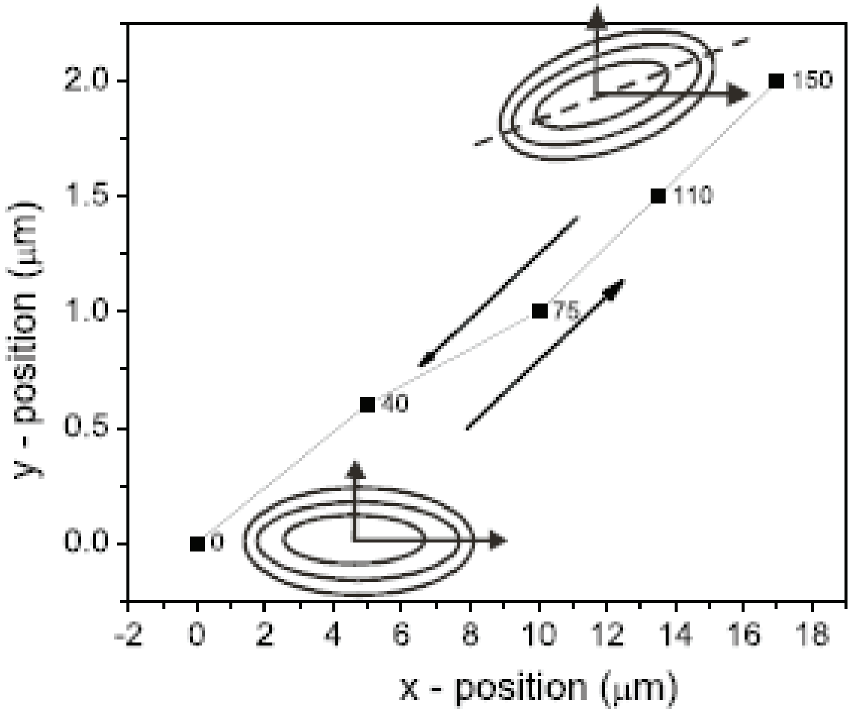
VORTEX AND ANTI-VORTEX



Displacement

Rotation

Deformation of the potential



Larger amplitude of oscillation:

-Larger displacement

-Larger deformation of the potential

-Higher acceleration in the rotation

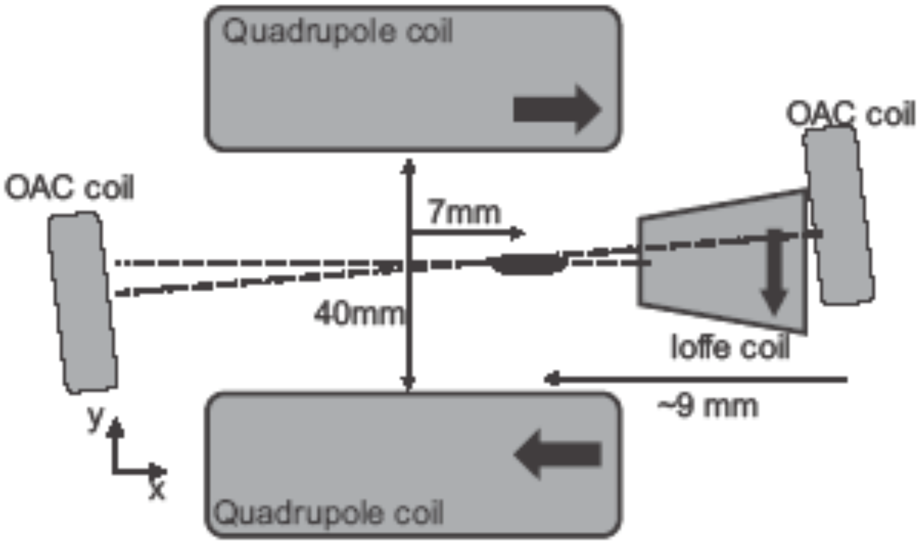
PRODUCING BEC (1 MIN)

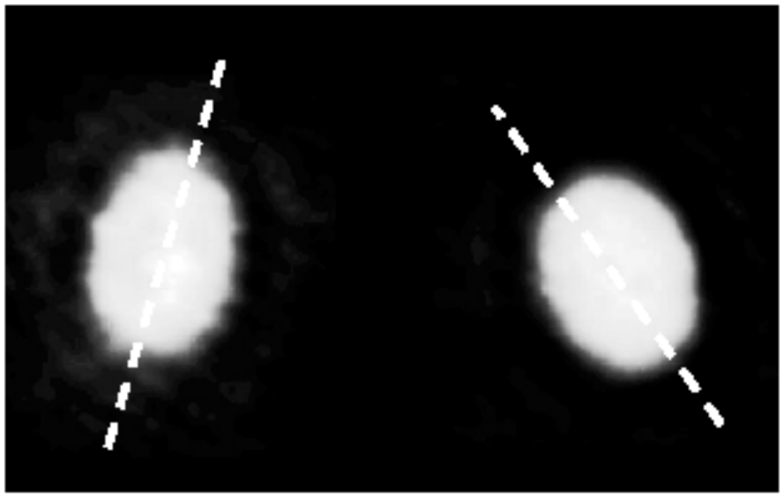
EXCITATION (0 TO 70 ms)

Rest(20 ms)

TOF FOLLOED BY ABSORPTION IMAGE

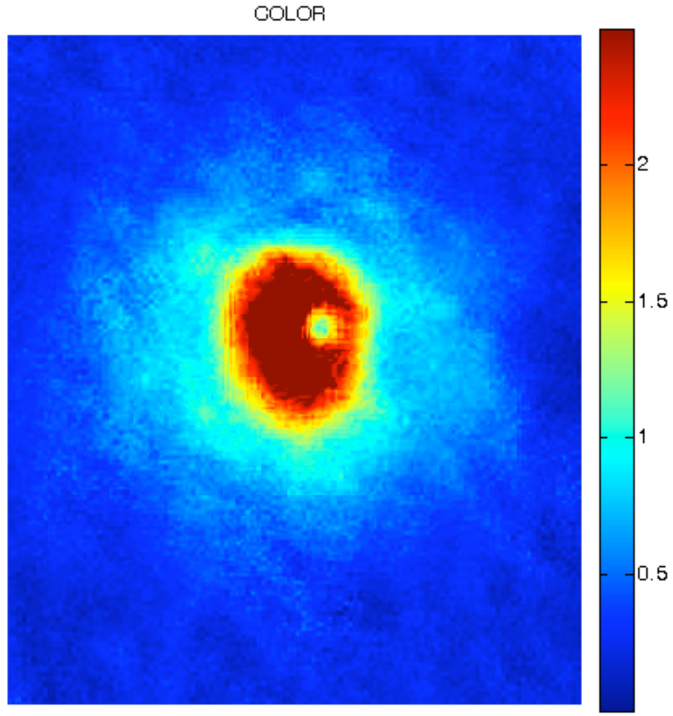
Small amplitudes and/or small times of excitation

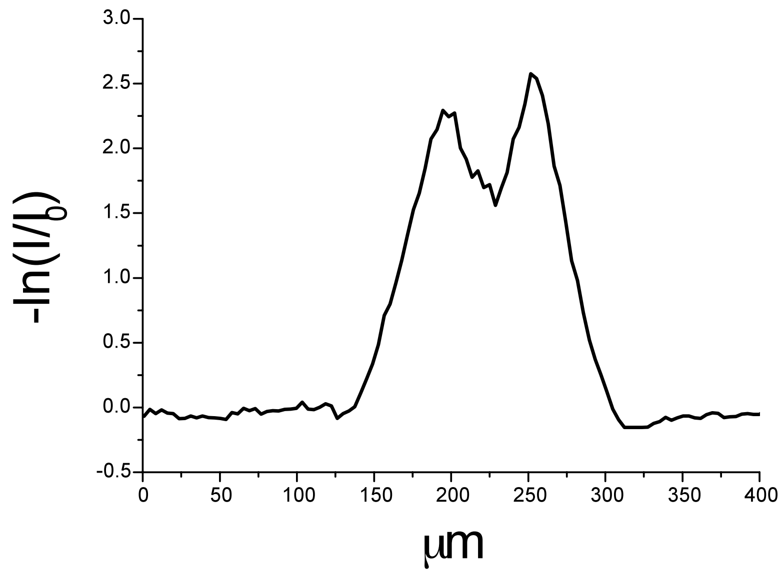




Oscillatory banding

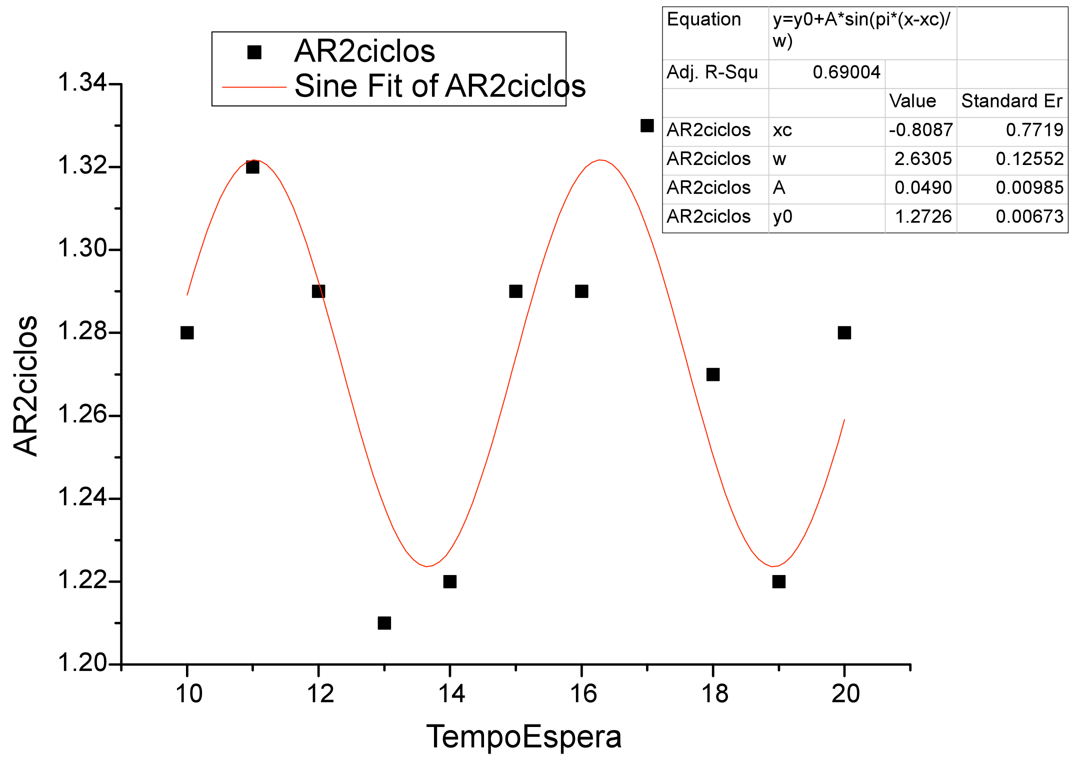
Equivalent to oscillations generated by sudden rotations → Scissors Mode





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

During oscillations there are excitation of collective Quadrupoleoscillations

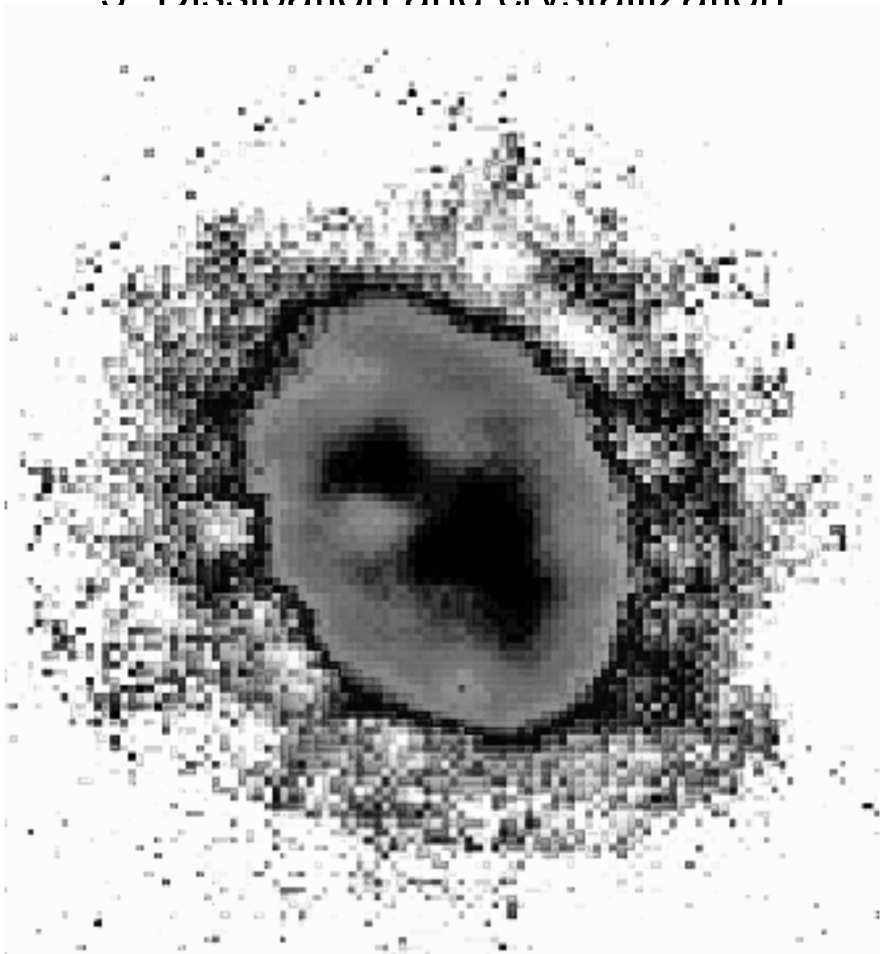


Parker- Adams PRL95(2005) – Stirring BEC

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

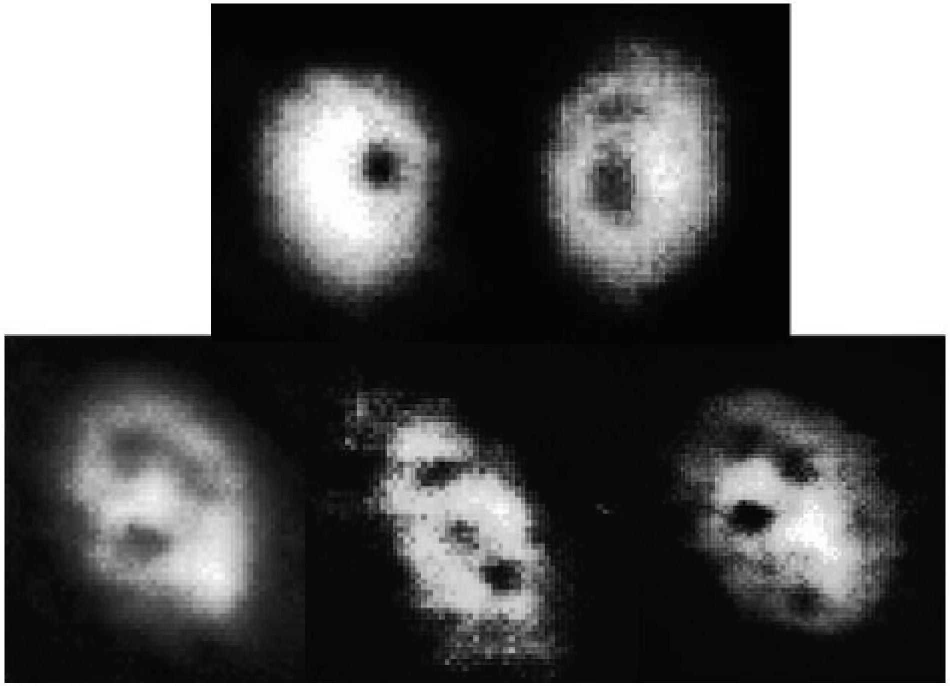
2- Turbulent cloud containing vortices is formed with a Kolmogorov energy spectrum

3- Dissipation and crystallization

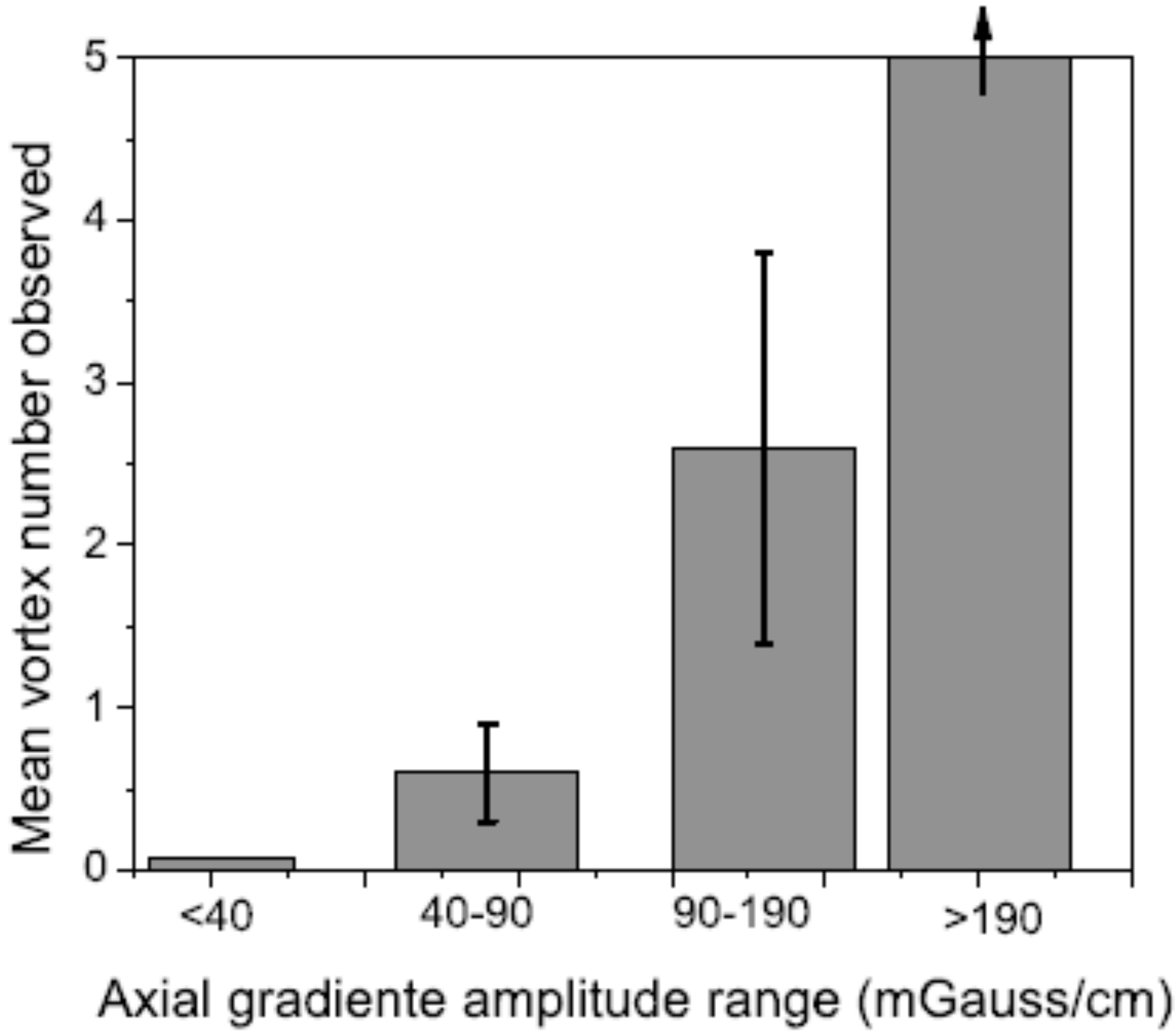


EVOLUTION WITH AMPLITUDE AND TIME OF EXCITATION

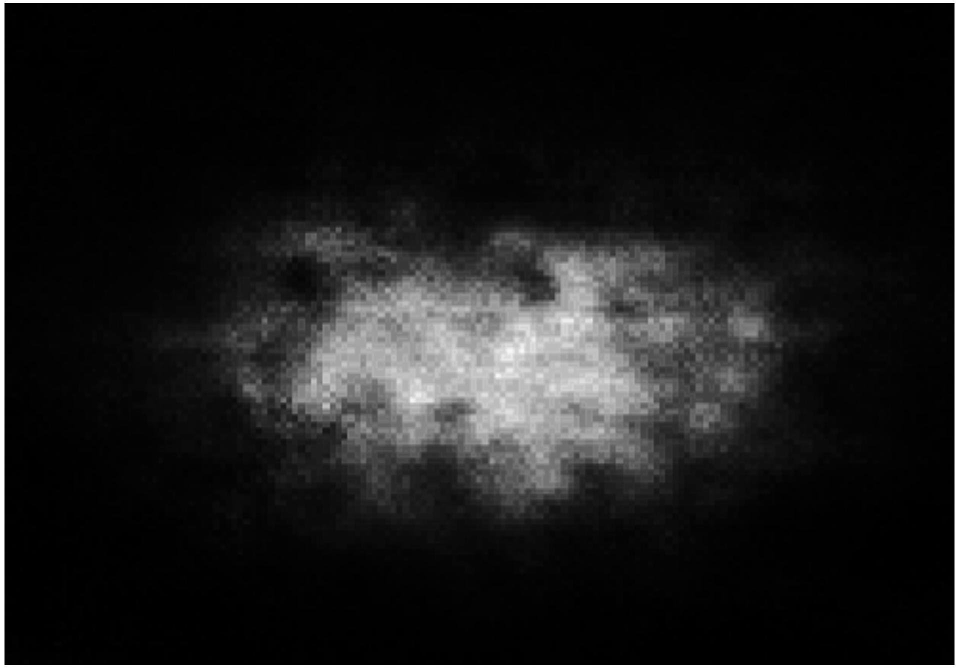
There are a large shot-to-shot fluctuation

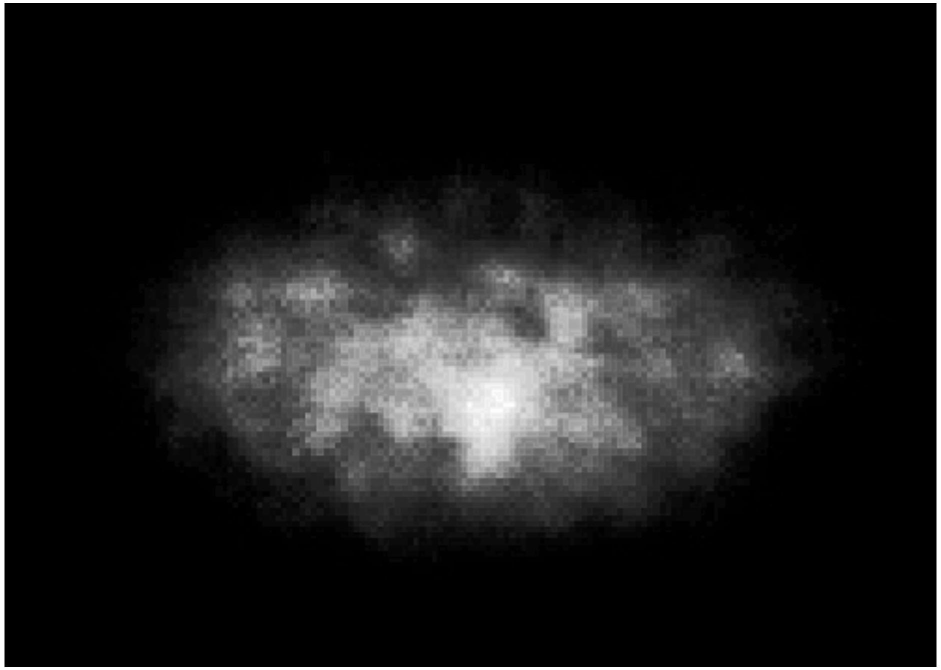


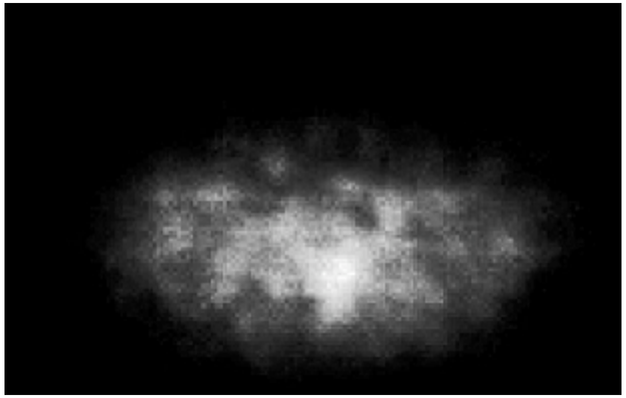
Fixed time of excitation – 20 ms



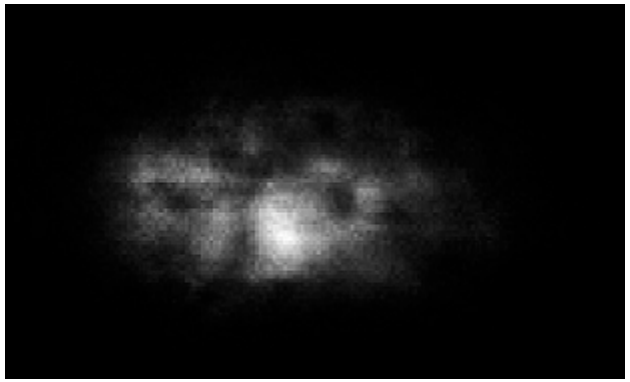
Explosion point → proliferation of many vortices → turbulence





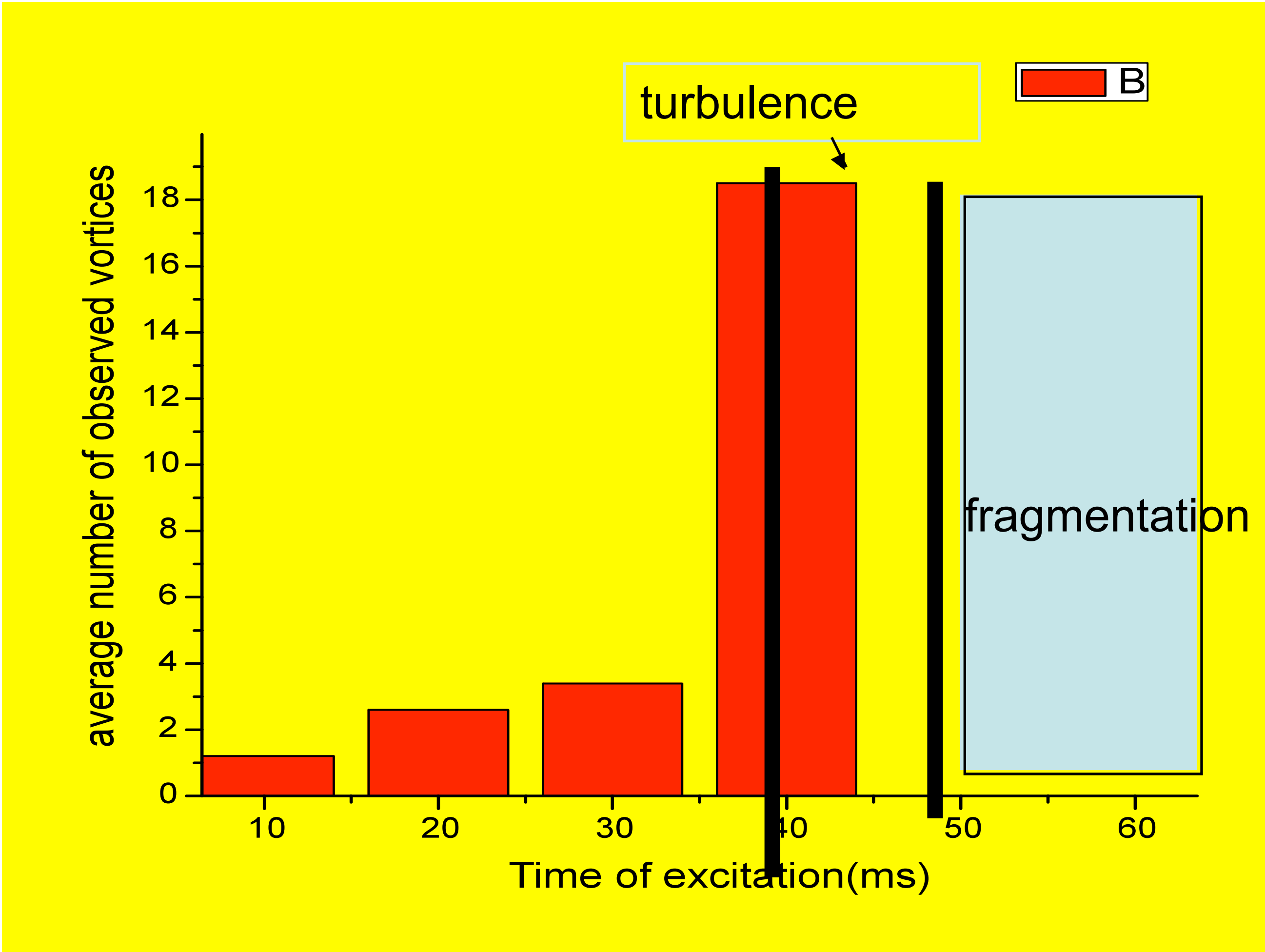


Vortices to tangle vortices

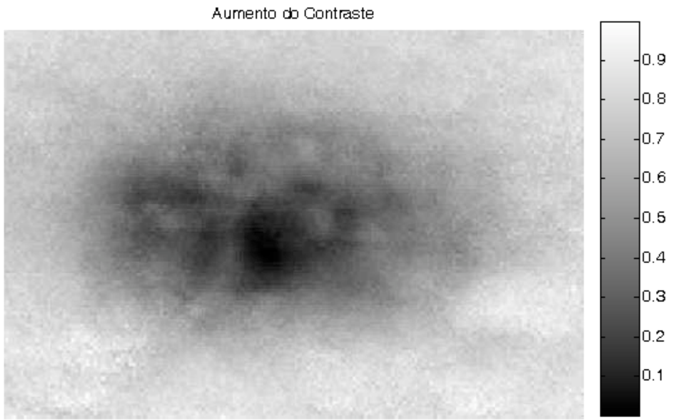


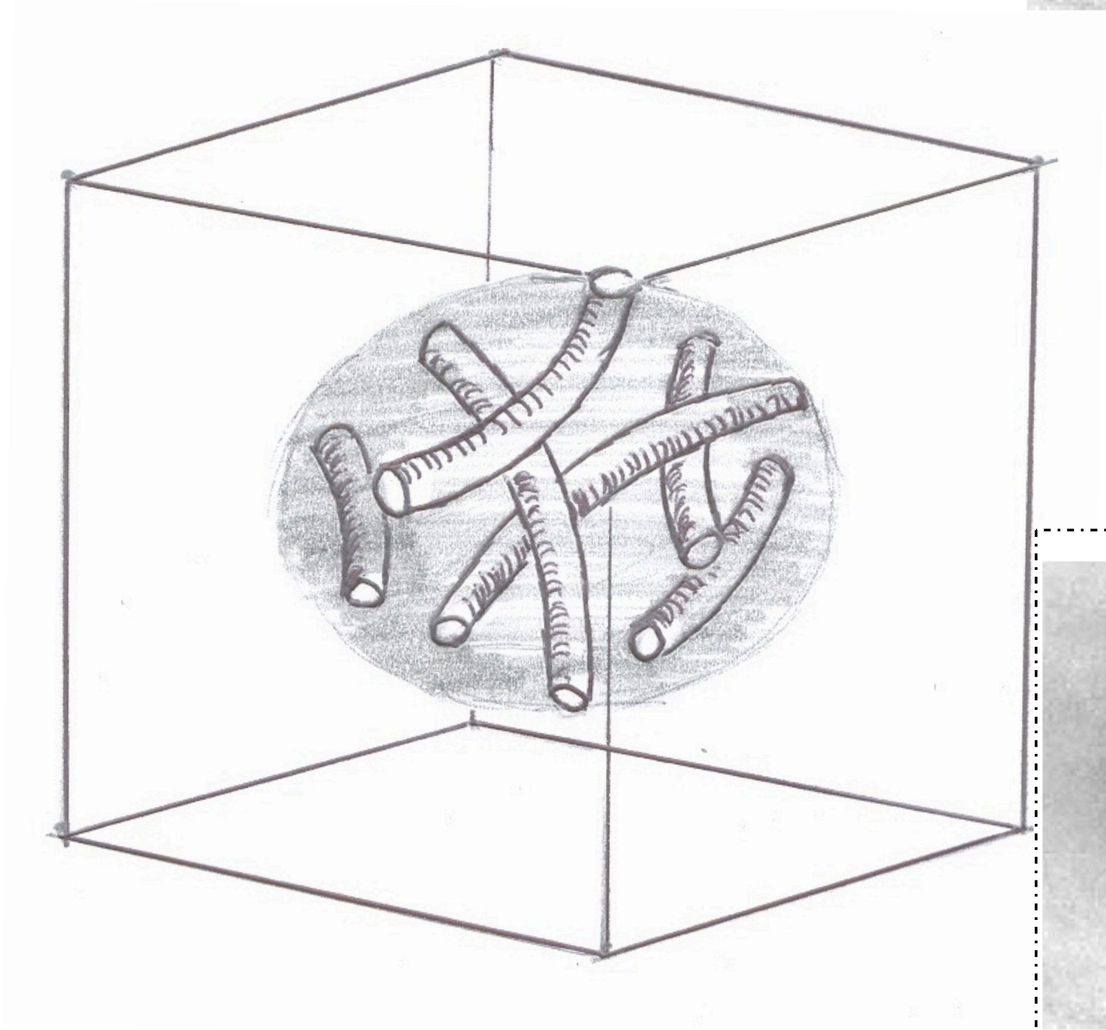
Average Numbers of vortices as a function of excitation time

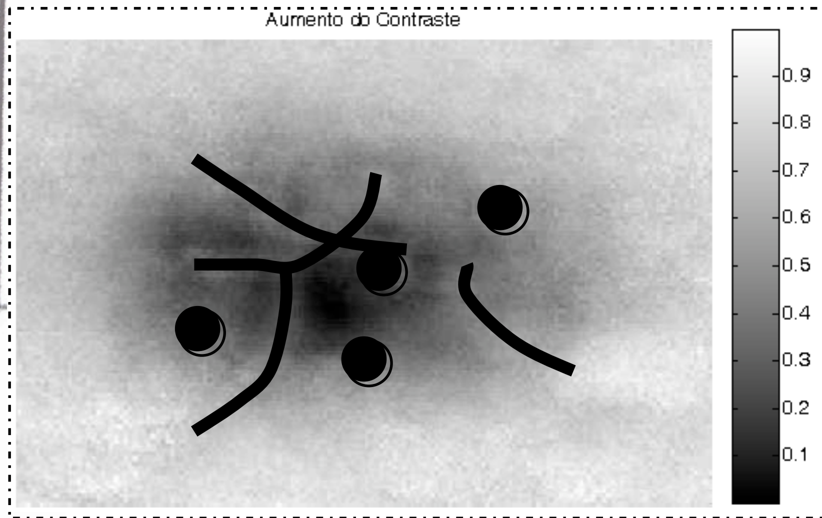
Excitation frequency : 200Hz, Amplitude 250 mV



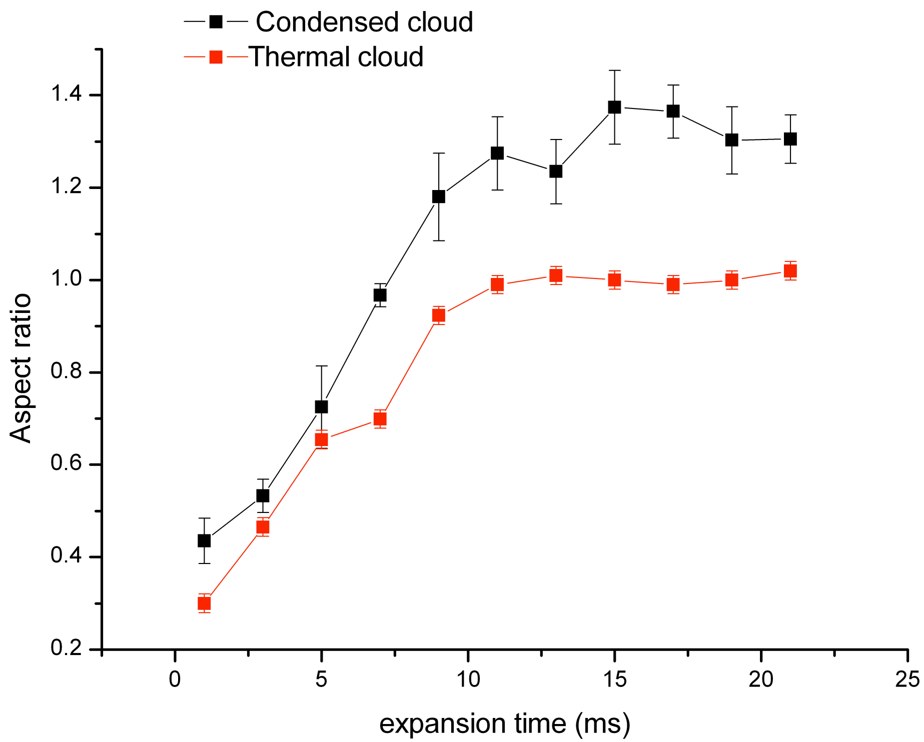
Tangle vortices

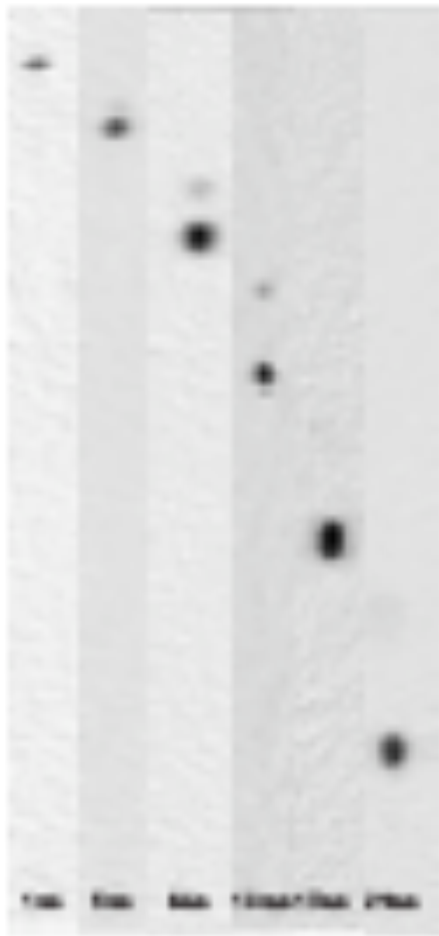




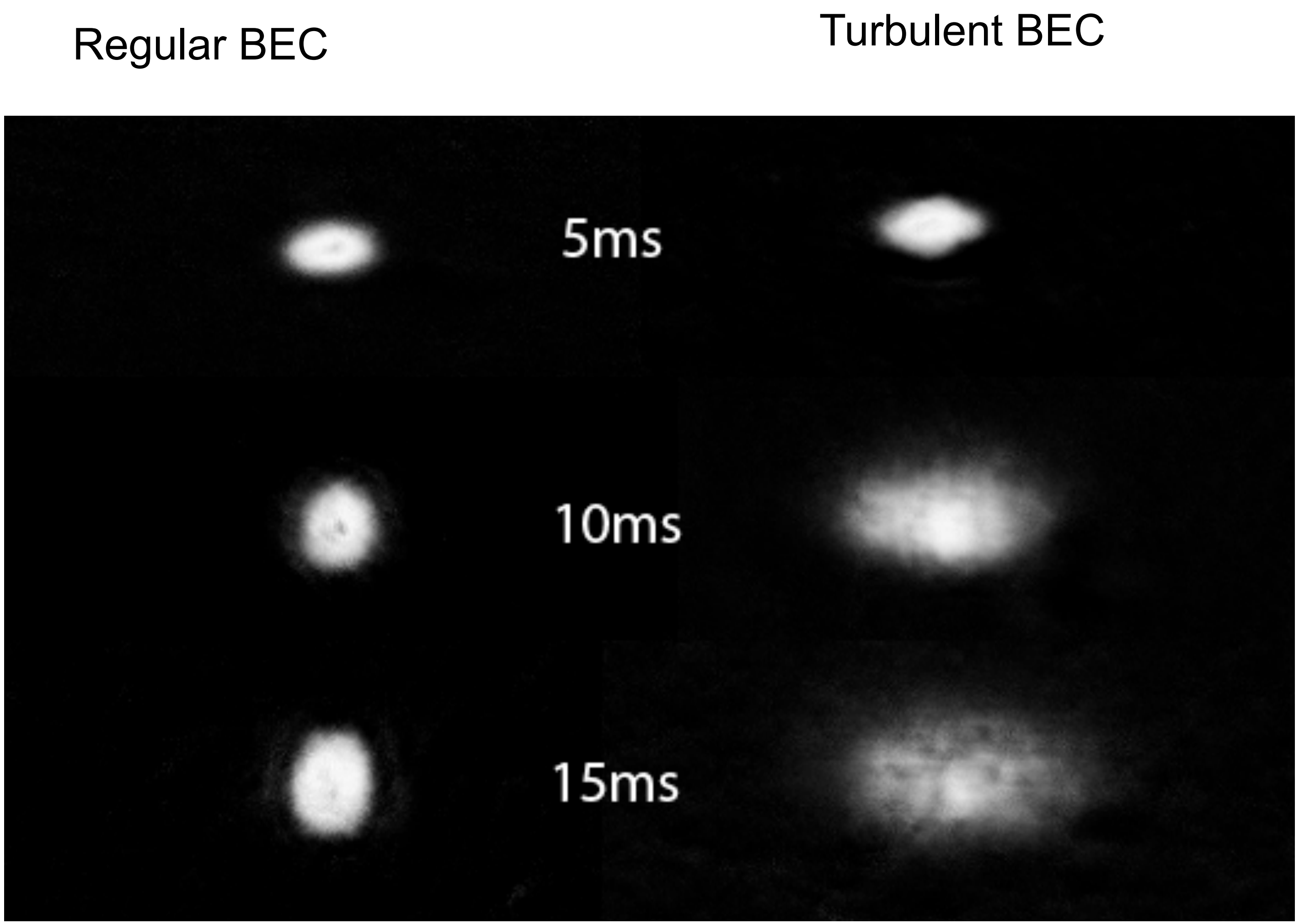


<u>Observation of aspect ratio inversion of the quantum cloud- energy conversion</u>

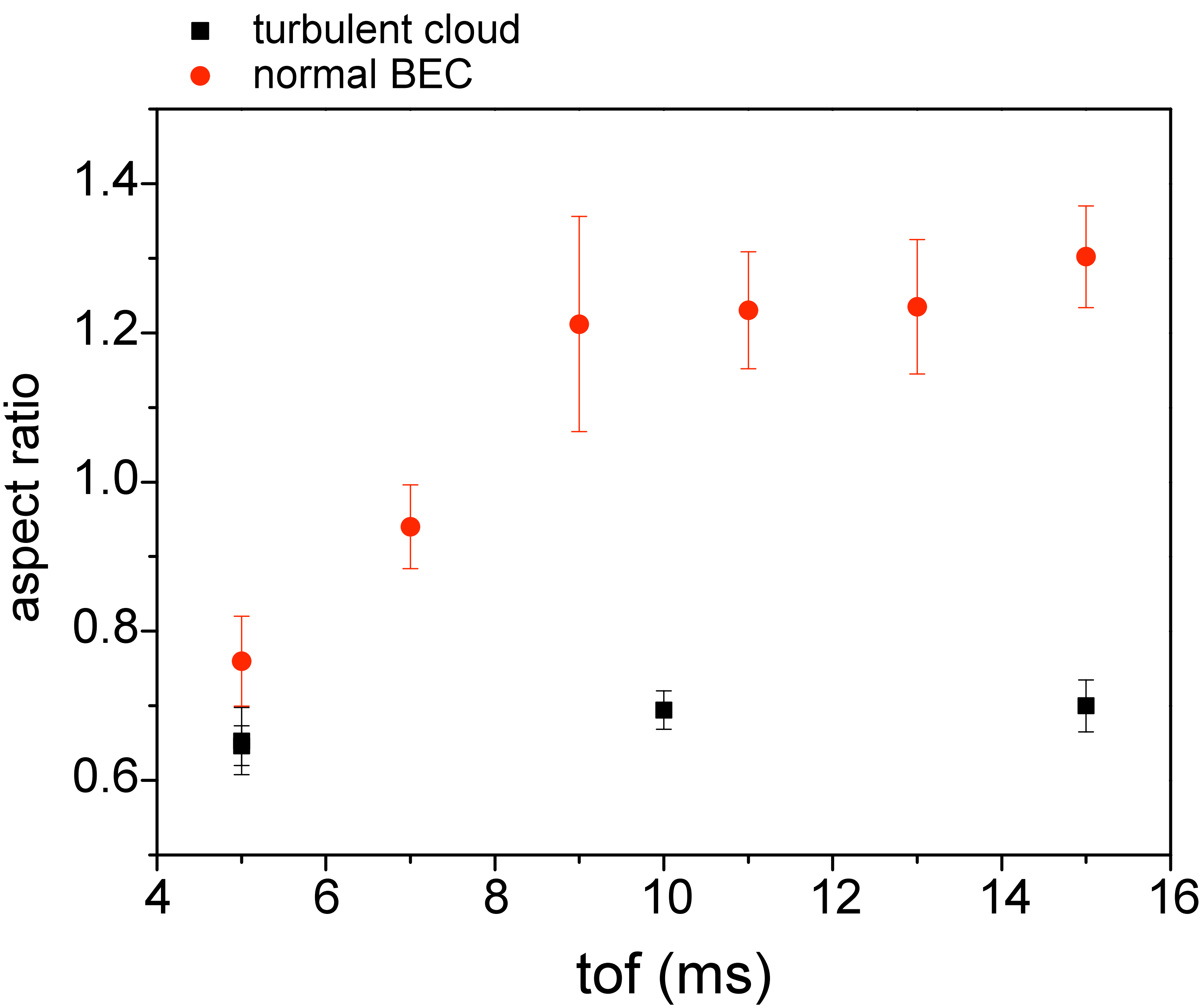




For a large number of vortices (turbulent?), the inversion is not observed



Regular BEC
Turbulent BEC
5ms
10ms
15ms



turbulent cloud
normal BEC
1.4
1.2
1.0
0.8
0.6
aspect ratio
4
6
8
10
12
14
16
tof (ms)

Phys. Rev. Lett. 88,070405(2002)
(Edwards, Clark, Pedri, Pitaevskii and Stringari)

- " ….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 in the quantum atomic fluid, that would be a new effect in the atomic quantum fluid

Route to QUANTUM TURBULENCE

- 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)

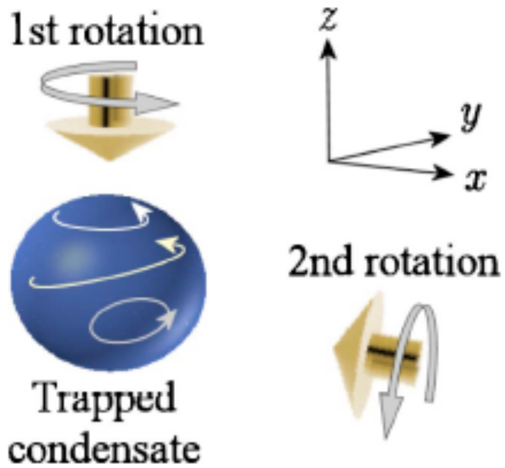


FIG. 1. (Color online). Schematic sketch of the rotation. The first rotation is applied along the z axis and the second rotation is applied along the x axis.

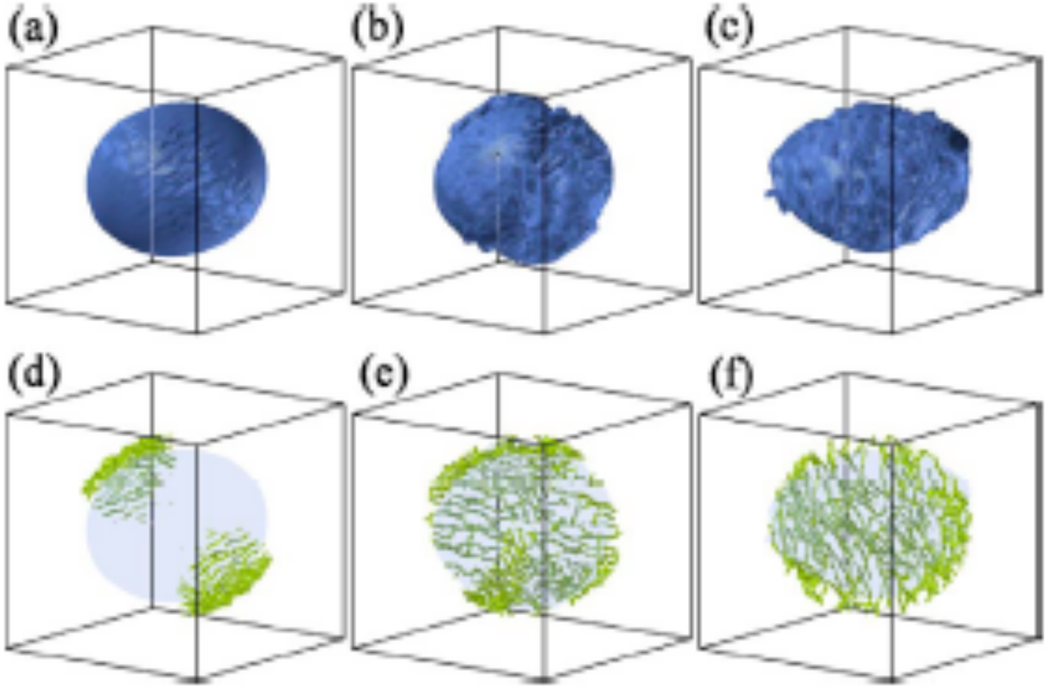
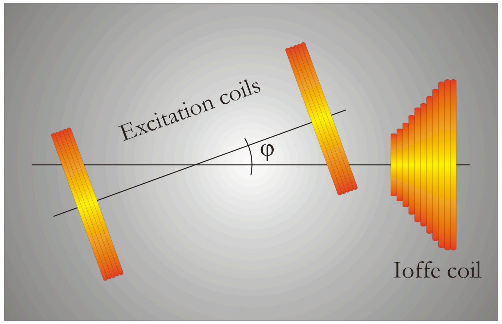
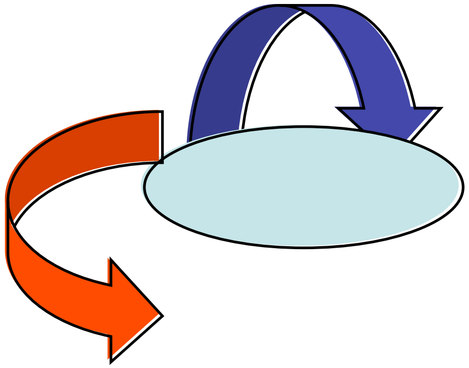


FIG. 4. (Color online). Isosurface plots of 5% of the maximum condensate density (a)–(c) and configuration of quantized vortices inside the Thomas-Fermi radius R_{TF} (d)–(f). (a), (d) $t\omega=10$; (b), (e) $t\omega=50$; (c), (f) $t\omega=300$. The method for identifying vortices in (d)–(f) is the same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


Excitation coils
φ
Ioffe coil



CONCLUSIONS:

- EXCITATION OF VORTICES WITHOUT DIRECT ROTATION
- EVOLUTION TO TANGLE VORTICES – lost of inversion property
- FRAGMENTATION
- CLUSTER OF THREE VORTICES: TWO DIFFERENT SPATIAL STRUCTURES

THANKS