Quantum Turbulence in BEC overview and new perspectives

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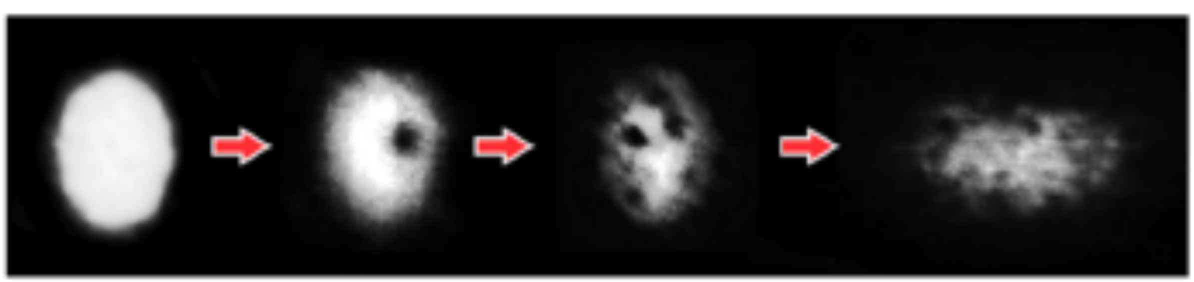
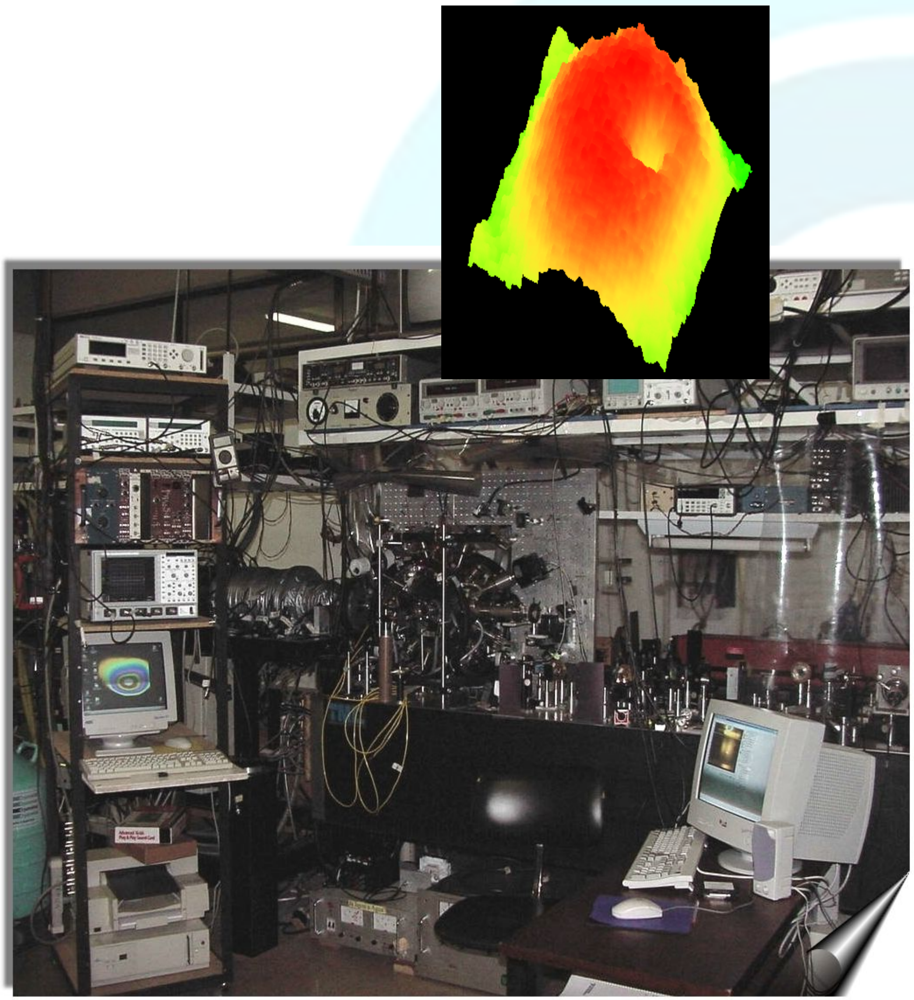
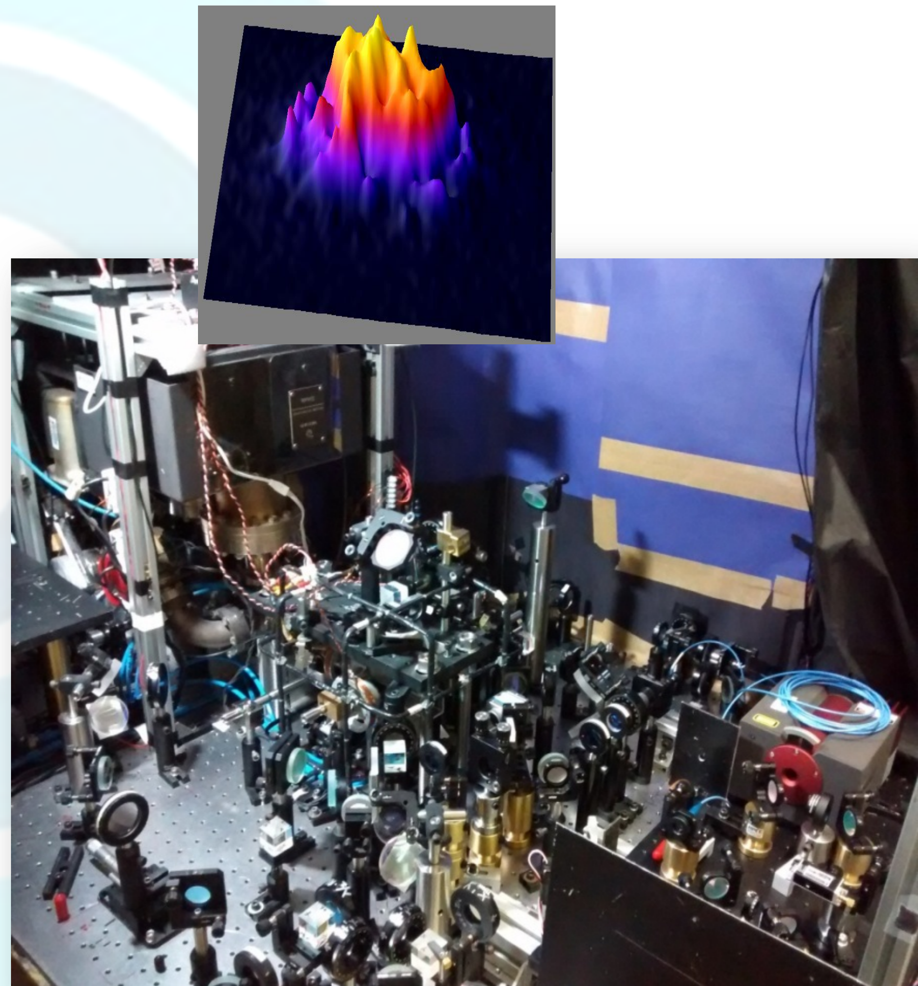


Turbulence is all around us

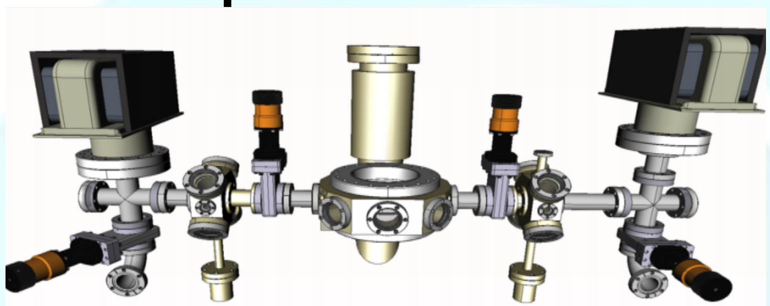
Quantum turbulence in superfluids



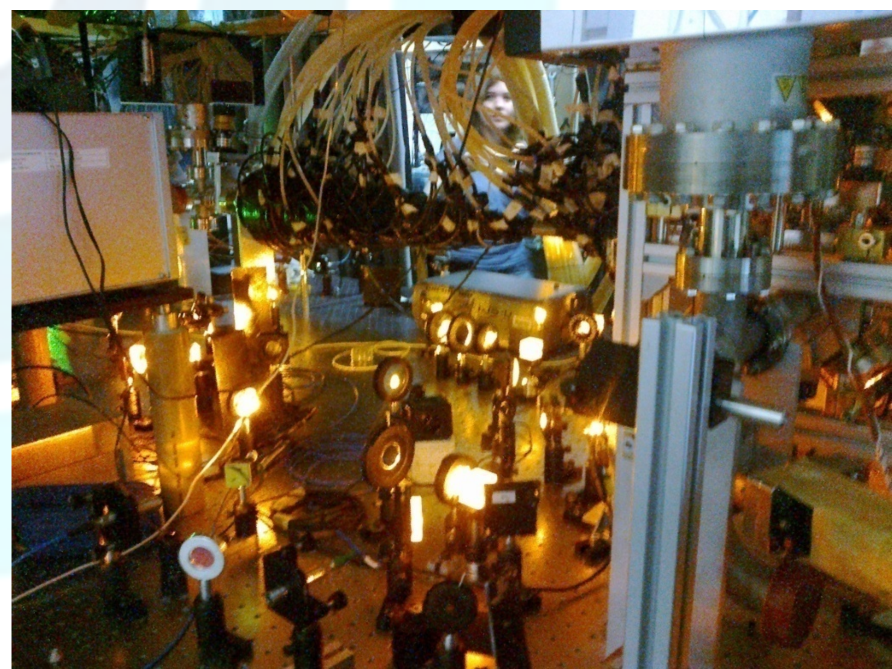


Na/K BEC Mixture

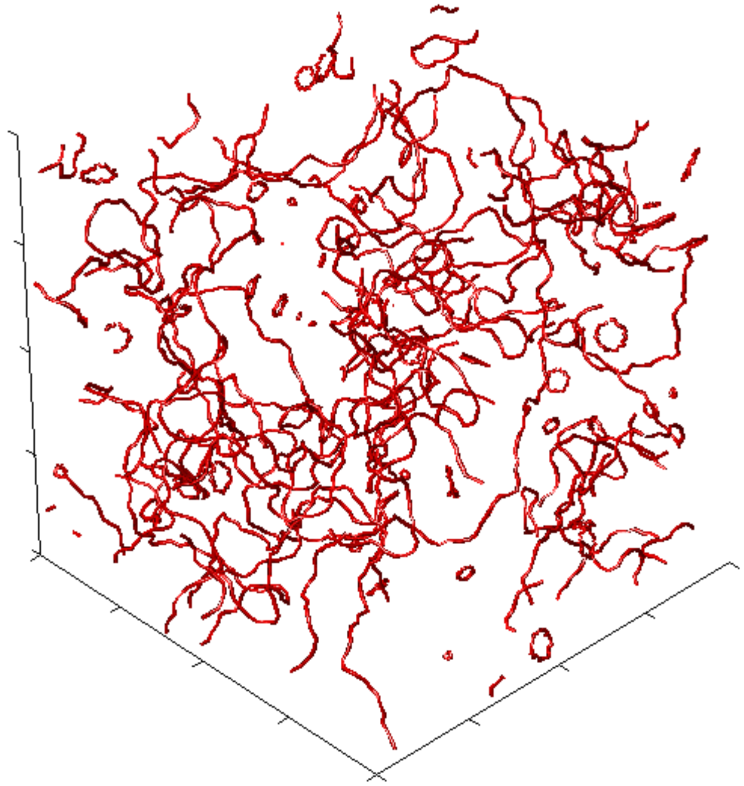
Mixture of two superfluids

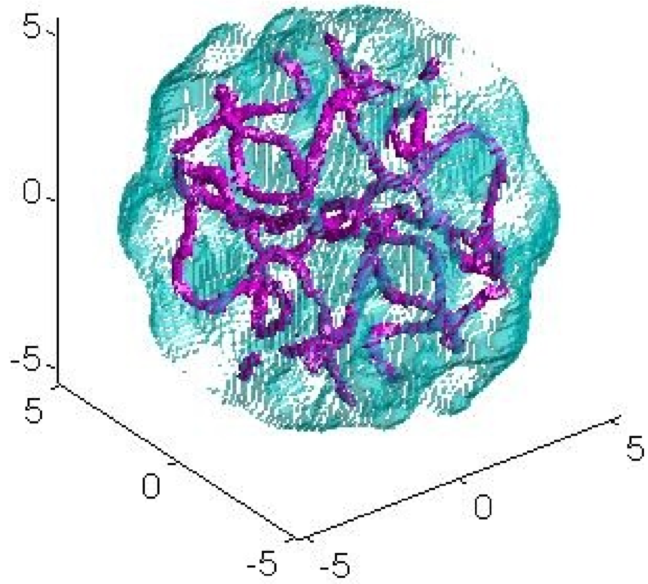


K source



Idea of turbulent regime in superfluids





1955: **Feynman** proposed that “superfluid turbulence” consists of a tangle of quantized vortices.

(1) Circulation

$$\oint \mathbf{v}_s \cdot d\mathbf{s} = \kappa n$$

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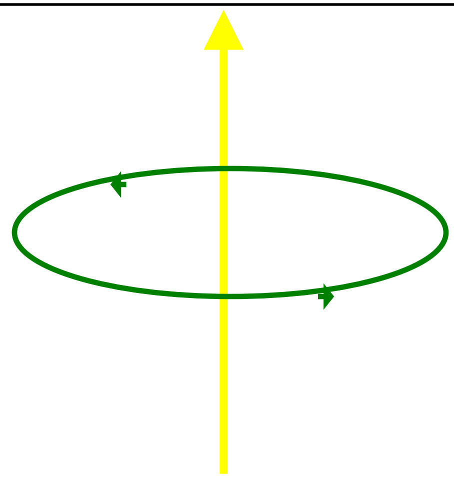
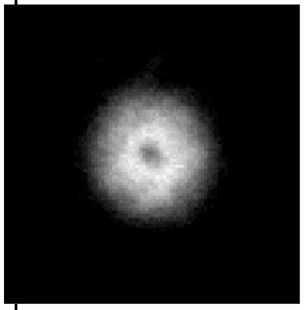


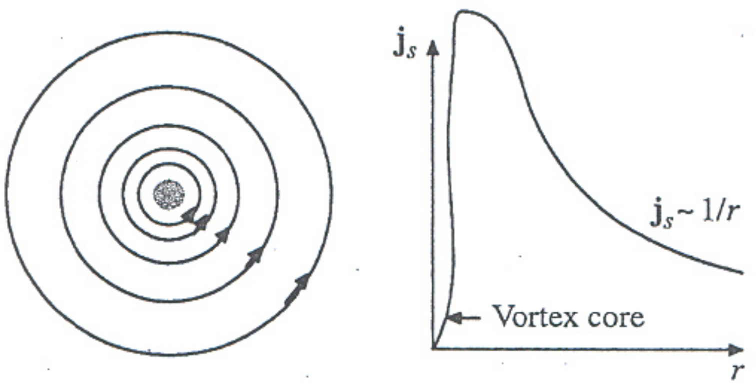
$$\kappa = h/m$$

Stability => n = 1

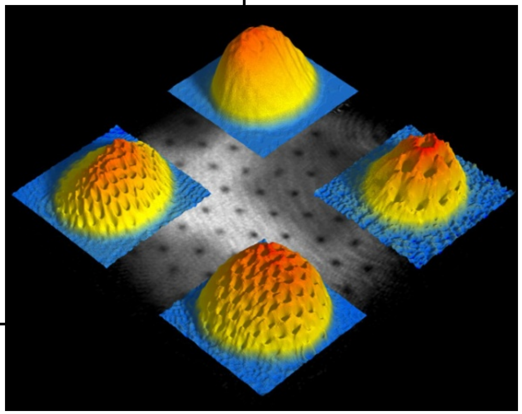


ENS

(2)core size is very small.

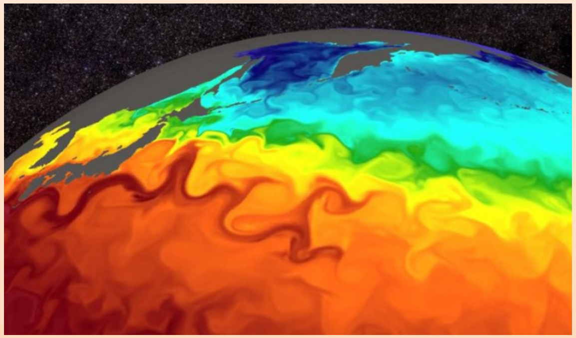


Healing length = $(8\pi \rho a)^{-1/2}$



MIT

Classical Turbulence



Eddies produced by flow

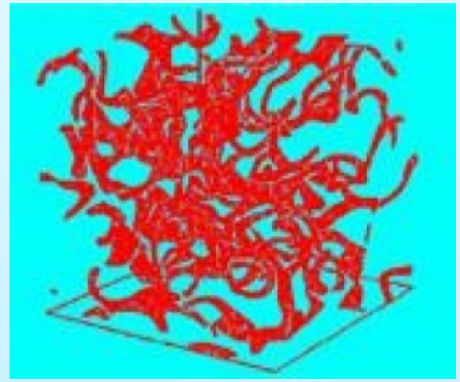
Many values of vorticities

Flux lines crossing

Cascade of energy

Viscous dissipation at small scales

Quantum turbulence



Quantum vortices – single vorticity

Tangle configurations

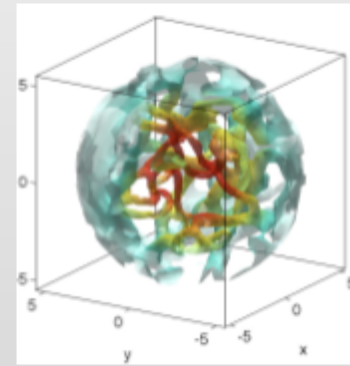
Reconnection

Large number of vortices

Small core

Many decades of scale

QT in BEC



Fine size

Finite number of vortices

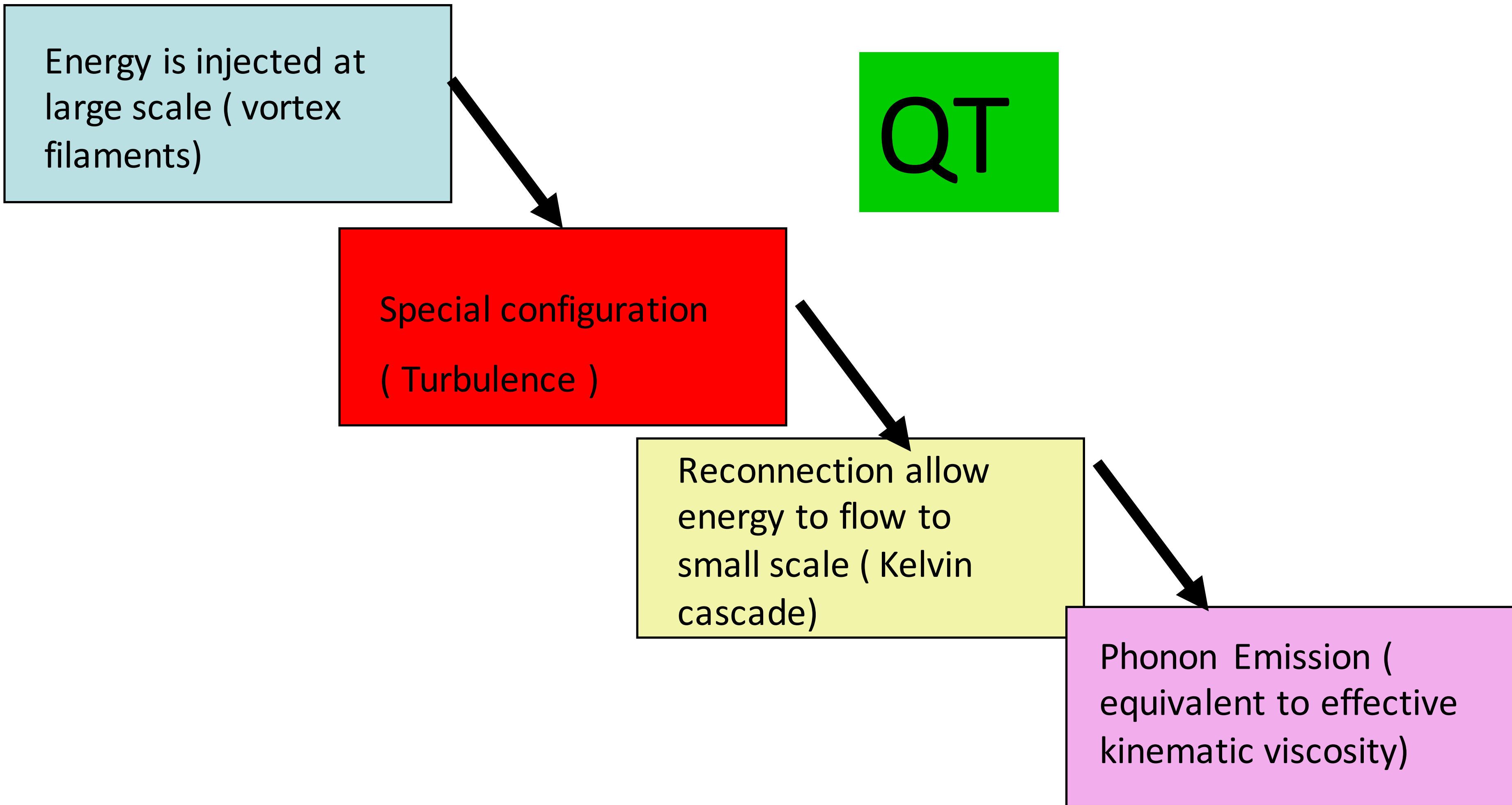
Reconnection

Large Core

Few decades of scale

-In comparison with many other areas, our knowledge and understanding of Turbulence (classical and quantum) is primitive

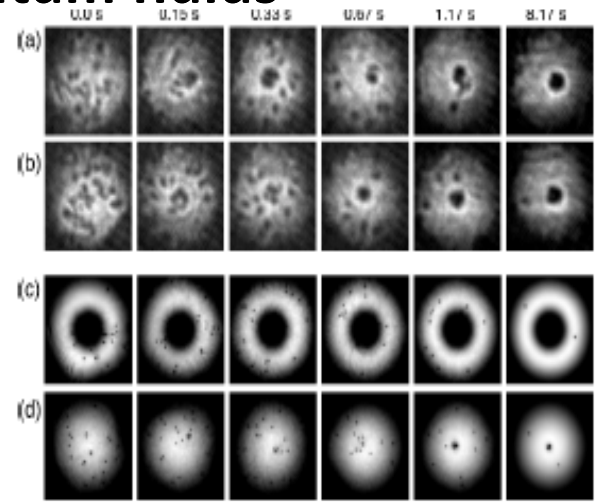
-The topic is placed as a challenges for present decade



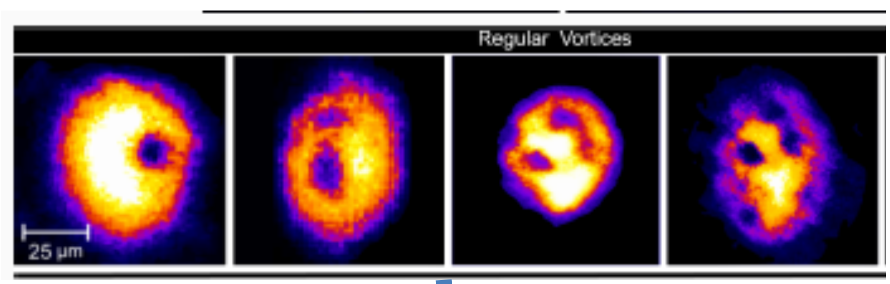
Investigations involving 2D quantum fluids

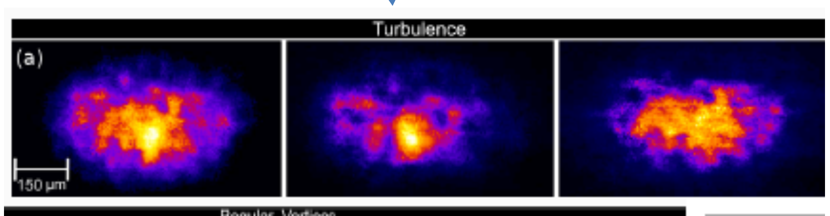
2D: Anderson's group, Arizona:

- Highly oblate condensate: aspect ratio $\omega_z/\omega_\perp \sim 11 \rightarrow$ 2D vortex dynamics.
- Gaussian laser beam directed through the trap centre $\rightarrow$ annular trap.
- Centre of the harmonic trap moves in a circle $\rightarrow$ small scale forcing induced, vortices nucleated.



3D Turbulence





In terms of QT, BEC of trapped atoms goes beyond superfluid Helium

- Small number of vortices
- Smaller range of intervortex spacing
- Possibility to control vortex lines
- 1D,2D,3D
- Homogeneous and non-homogeneous
- Adjustment of intrinsic atomic properties
- Large range of densities
- Mixtures
- MORE………

Sequence of works

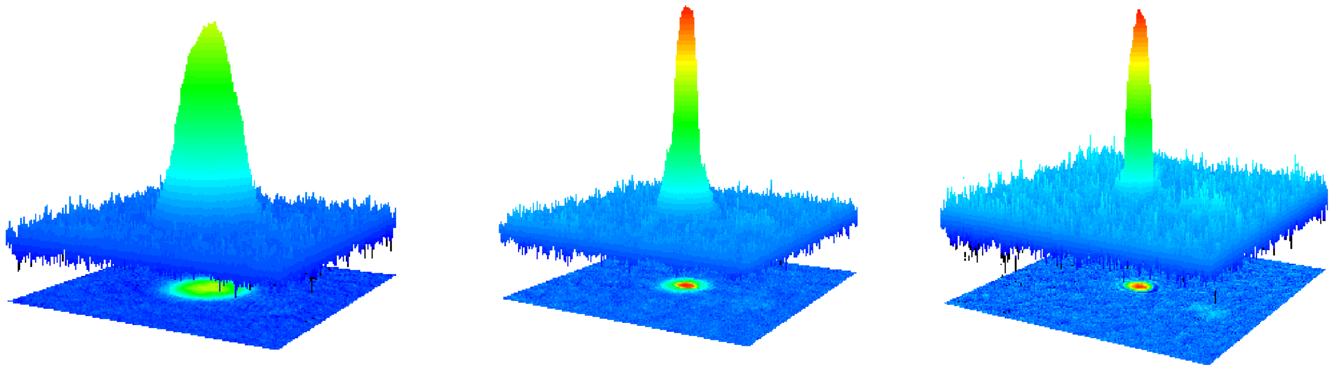
2009

- GENERATION OF VORTICES
- FORMATIONS OF VORTICES CLUSTERS
- EMERGENCE OF TURBULENCE
- SELF-SIMILAR EXPANSION
- DIAGRAM OF EXCITATIONS
- FINITE SIZE EFFECT
- GRANULATION
- MODEL FOR SELF-SIMILAR EXPANSION
- SECOND SOUND EXCITATION (COUNTER FLOW)
- KINETIC ENERGY SPECTRUM
- HIGHLY CHARGED VORTEX
- ESPONTANEOUS GENERATION OF QT
- DYNAMICAL STABILITY OF HIGLY CHARGED VORTEX
- MATTER WAVE ASPECT - SPECKLES

2016

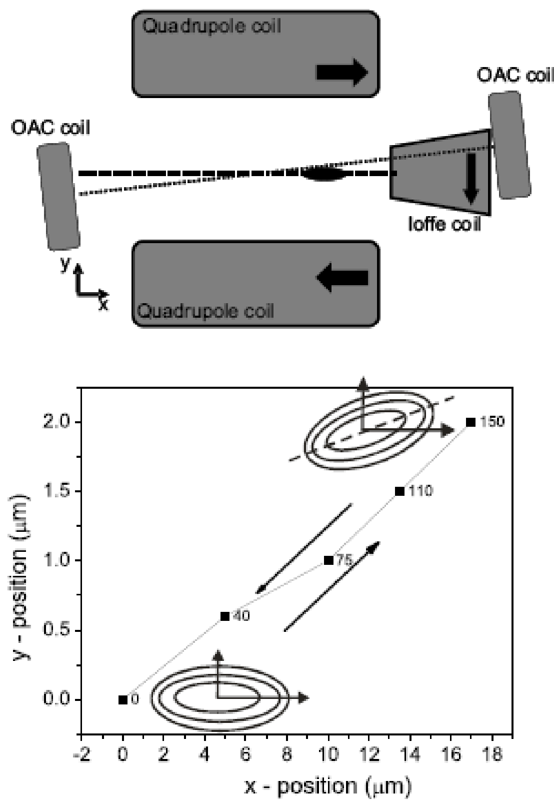
http://cepof.ifsc.usp.br

1

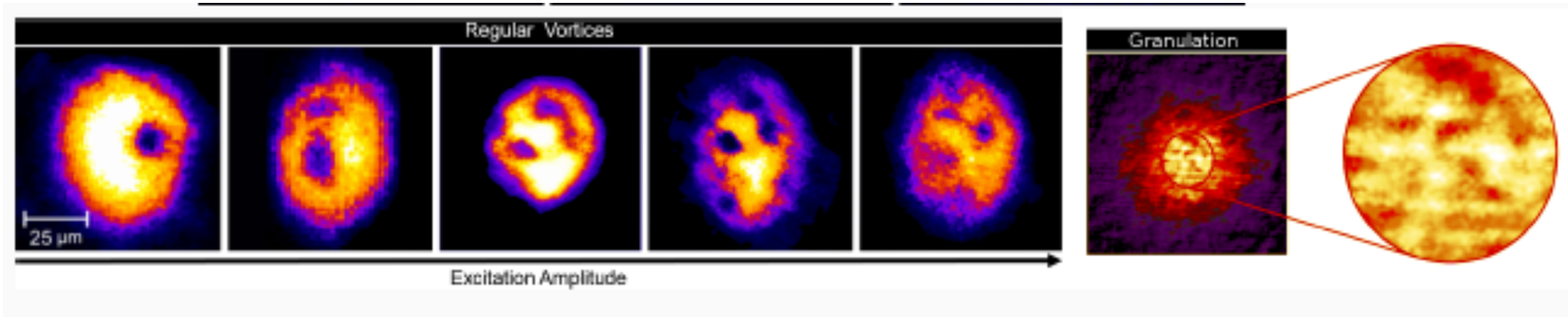


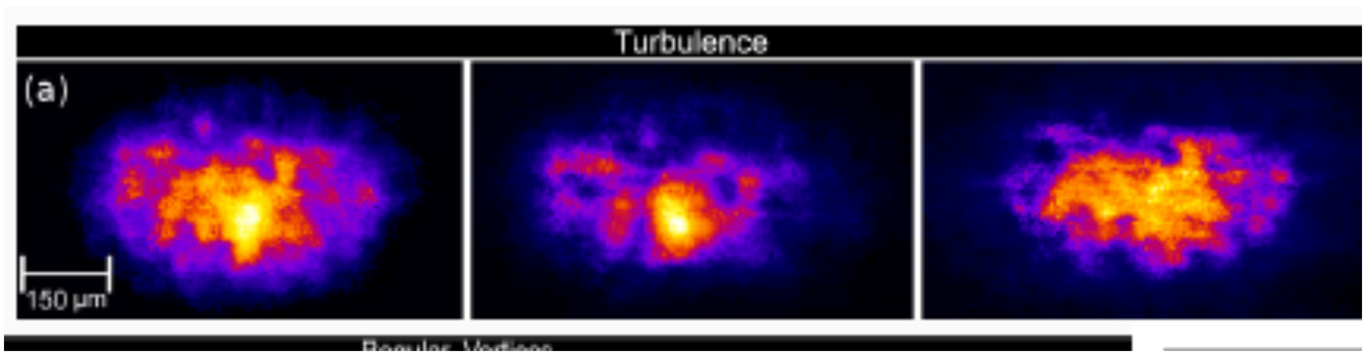
$T > T_c$ $T < T_c$ $T << T_c$

2

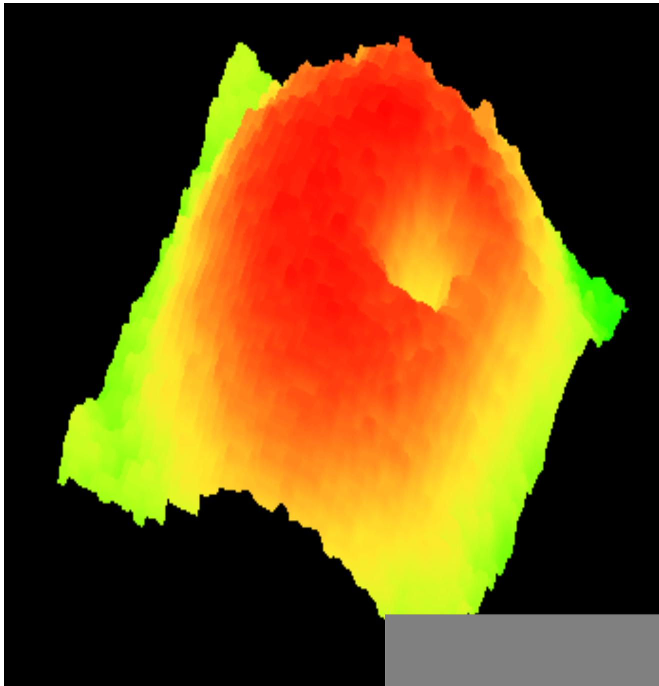


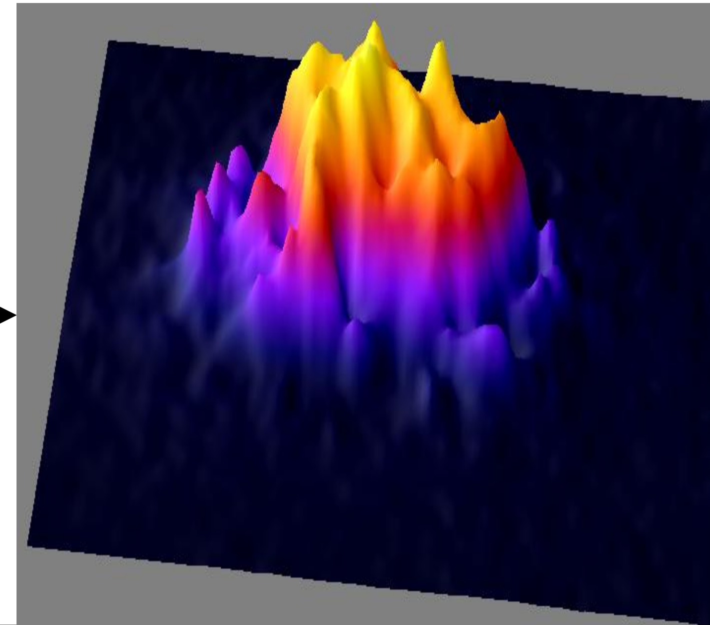
Atomic washing machine
(excitation by shaking)

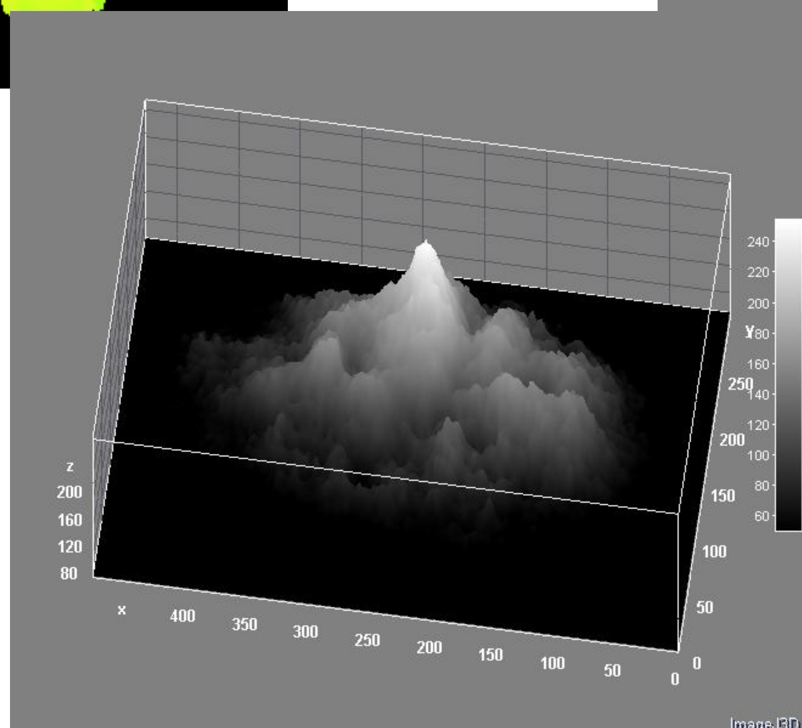

Regular Vortices
25 µm
Excitation Amplitude
Granulation


Turbulence
(a)
150 µm

Turbulent cloud







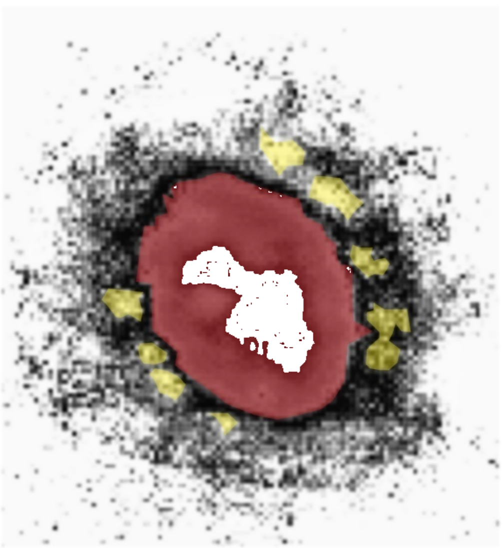
Complete list of publications:

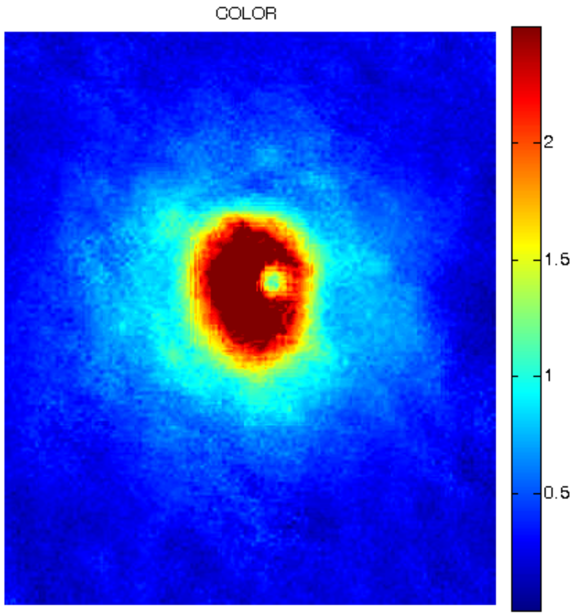
http:// cepof.ifsc.usp.br

(publications – atomic physics)

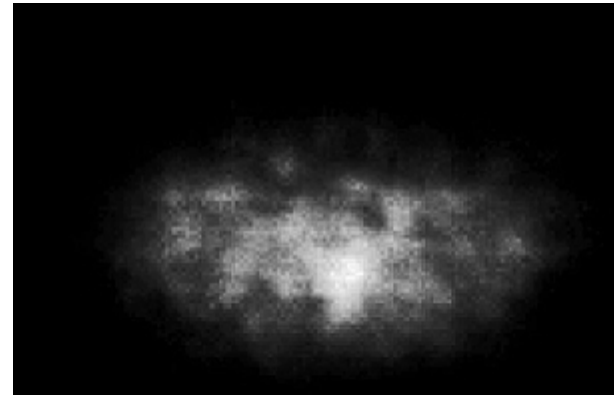
Vortex formation

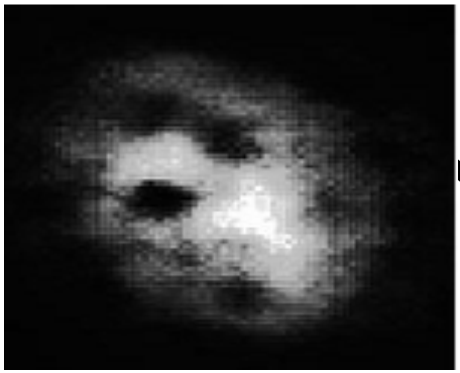
COLLECTIVE MODES

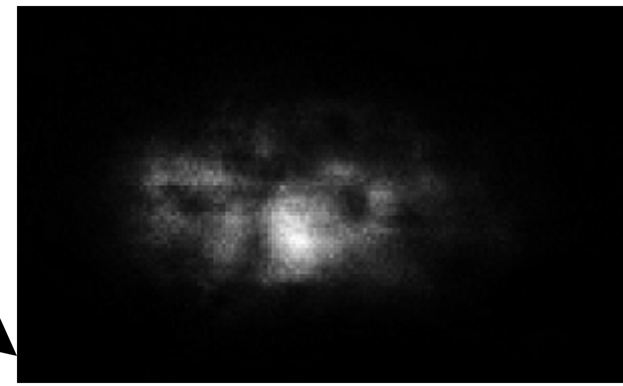




Increasing amplitude or time of excitation:
Explosion and proliferation of many vortices but no regular pattern and hard to count





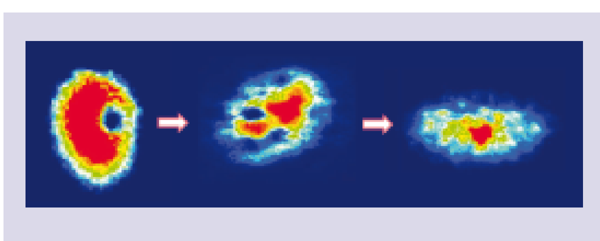


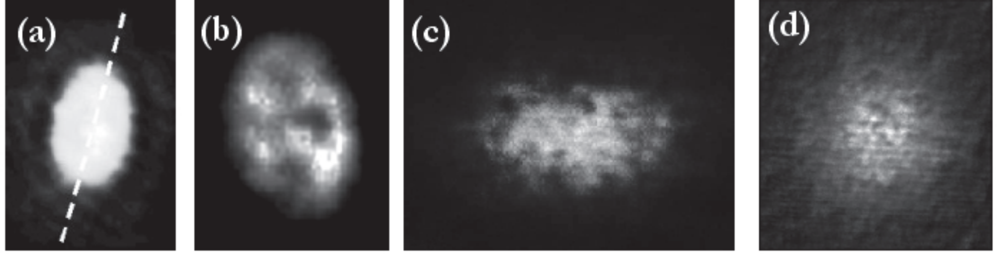
Vortices to tangle vortices

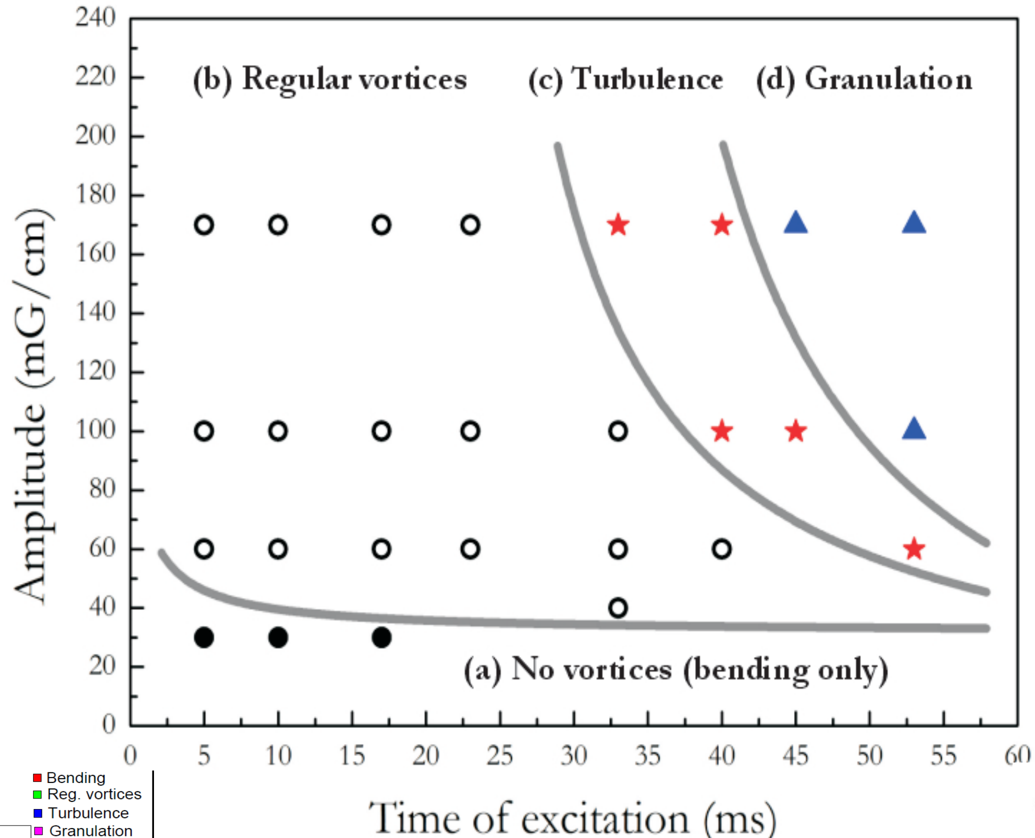
"TURBULENCE"

NON REGULAR – MANY POSITIONS

ORIENTATIONS AND LENGTH




(a)
(b)
(c)
(d)


(b) Regular vortices
(c) Turbulence
(d) Granulation
(a) No vortices (bending only)
Amplitude (mG/cm)
Time of excitation (ms)

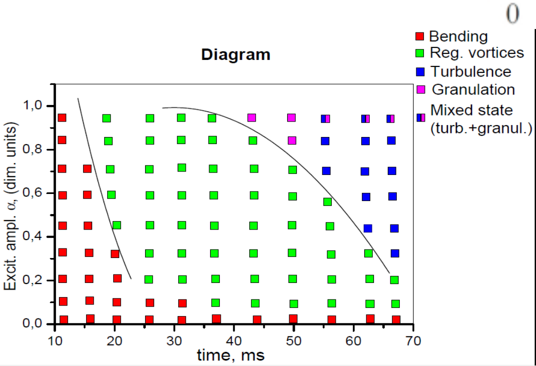


Diagram
Bending
Reg. vortices
Turbulence
Granulation
Mixed state
(turb.+granul.)
Excit. ampl. α, (dim. units)
time, ms

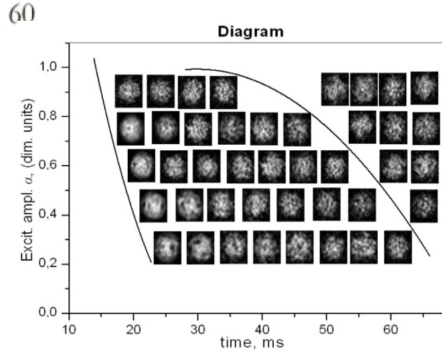
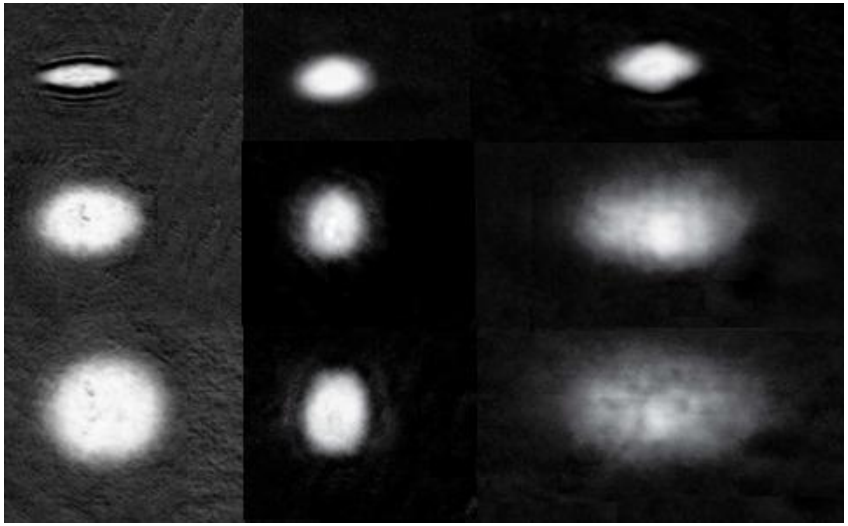
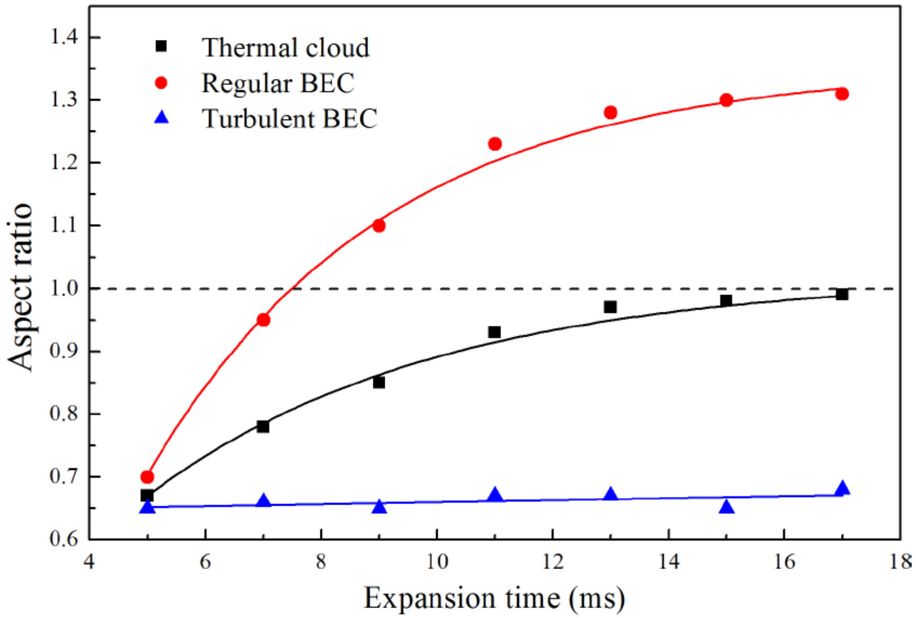


Diagram
Excit. ampl. α, (dim. units)
time, ms

Cloud expansion

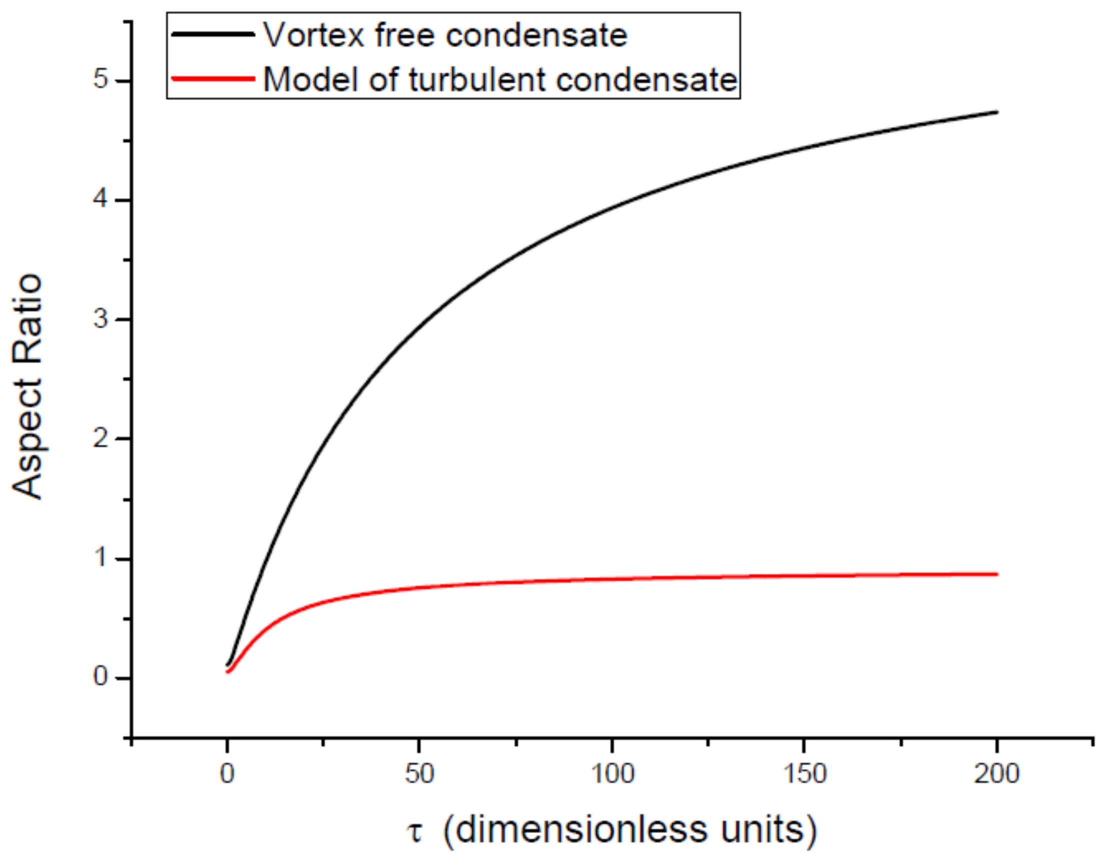


Thermal BEC Turbulent

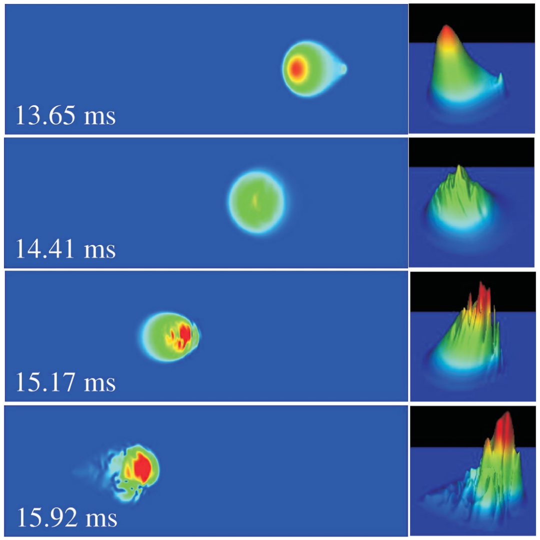


M. Caracanhas · A. L. Fetter · G. A. Baym · S. R. Muniz · V. S. Bagnato

Self-similar expansion of a turbulent Bose-Einstein condensate: a generalized hydrodynamic model



Simulation by Tsubota, Kasamatsu and Kobayashi - Japan



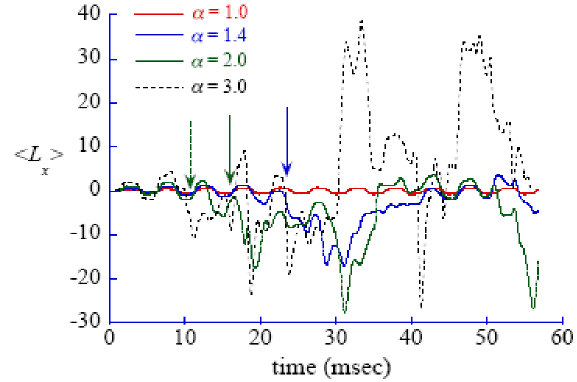


FIG. 5: The time development of the mean angular momentum per atom for $\gamma = 0.02$ and α=1.0, 1.4, 2.0, 3.0. The onset time of vortex nucleation is indicated by arrows.

$$(i-\gamma)\frac{\Omega}{\omega_r}\frac{\partial\Psi}{\partial t} = \left[-\frac{\nabla^2}{2} - \mu + \frac{1}{2}\left(\frac{\omega_x^2}{\omega_r^2}x^2 + y^2\right) + u_{2\mathrm{D}}|\Psi|^2 - \Omega_z \sin t \cdot L_z\right]\Psi$$

Kibble–Zurek mechanism (KZM)

KZM characterizes the spontaneous formation of defects in the process of system equilibration from an initial strongly nonequilibrium symmetric state to an equilibrium state with broken symmetry

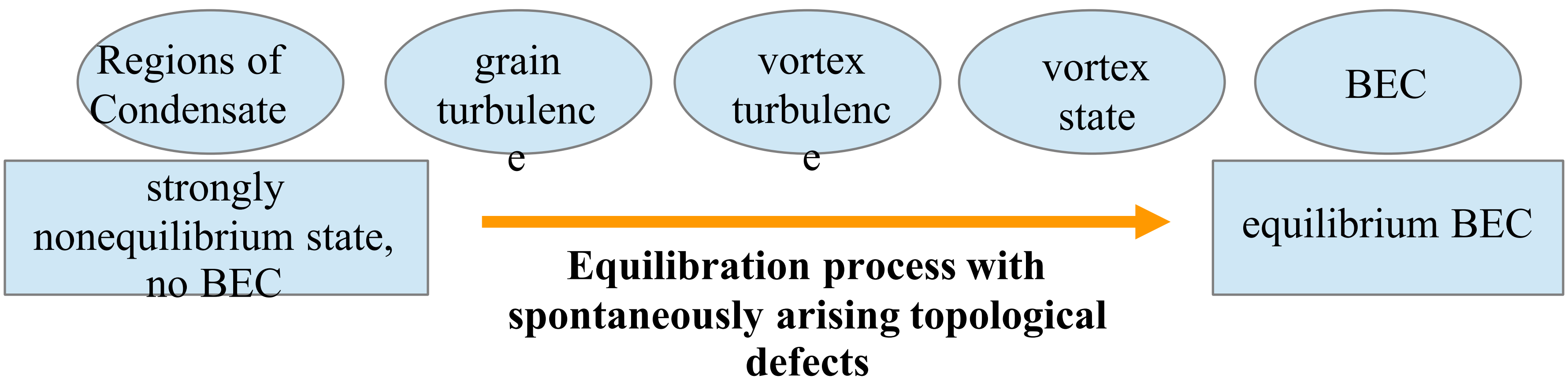
T.W.B. Kibble, J. Phys. A 9 (1976) 1387,

W.H. Zurek, Nature 317 (1985) 505

Experimentally observed in:

- **ion crystals**
- **superconducting films**
- **superfluid He-3 and He-4,**
- **trapped Bose–Einstein condensate**

KZM in Bose-Einstein condensate



E. Levich, V. Yakhot, Phys. Rev. B 15 (1977) 243

Physics Letters A 379 (2015) 1366–1371

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Realization of inverse Kibble–Zurek scenario with trapped Bose gases

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ARTICLE INFO

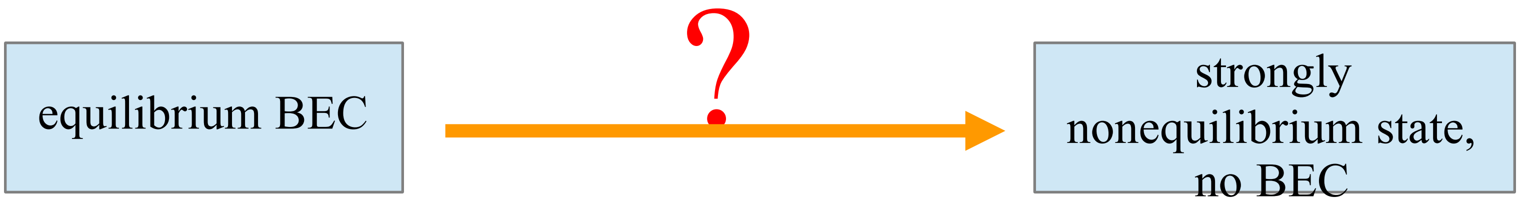
Article history:
Received 8 February 2015
Accepted 18 February 2015
Available online 23 February 2015
Communicated by V.M. Agranovich

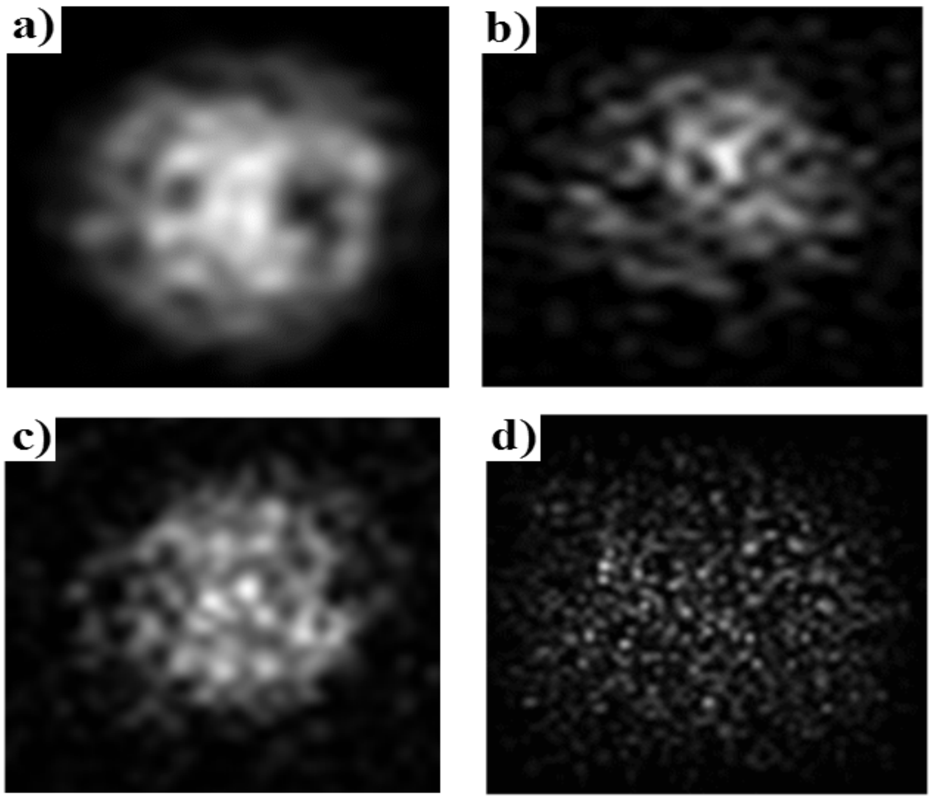
Keywords:
Nonequilibrium Bose gas
Quantum vortices
Vortex turbulence
Grain turbulence
Wave turbulence
Inverse Kibble–Zurek scenario

ABSTRACT

We show that there exists the *inverse Kibble–Zurek scenario*, when we start with an equilibrium system with broken symmetry and, by imposing perturbations, transform it to a strongly nonequilibrium symmetric state through the sequence of states with spontaneously arising topological defects. We demonstrate the inverse Kibble–Zurek scenario both experimentally, by perturbing the Bose–Einstein condensate of trapped ^{87}Rb atoms, and also by accomplishing numerical simulations for the same setup as in the experiment, the experimental and numerical results being in good agreement with each other.

Could we realise a inverse KZ scenario in trapped BEC?





The sequence of nonequilibrium states (the density cross-sections) realized in modeling of BEC under external perturbation:

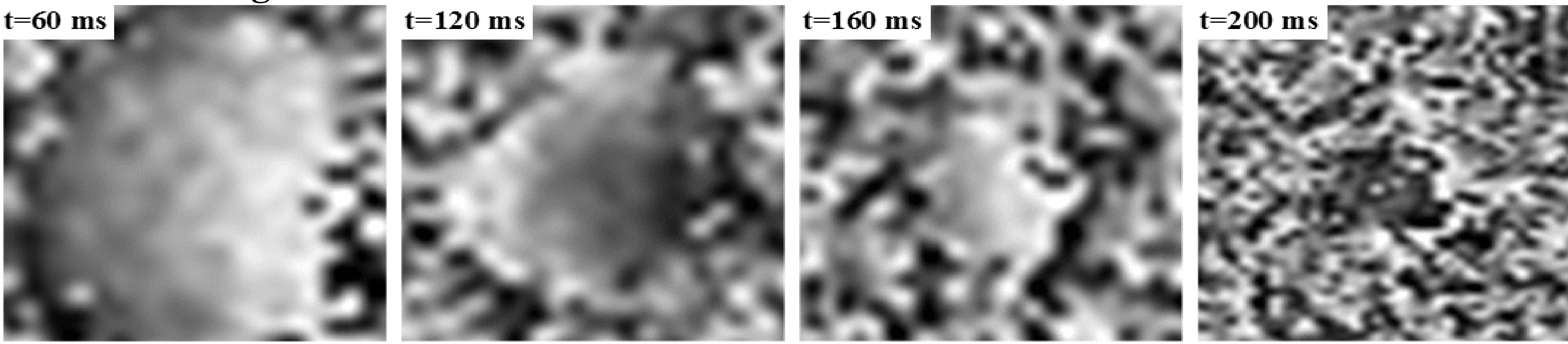
a) vortex state
b) vortex turbulence
c) grain turbulence
d) wave turbulence

The results of simulation are in a perfect agreement with the experiment!

...and some more info

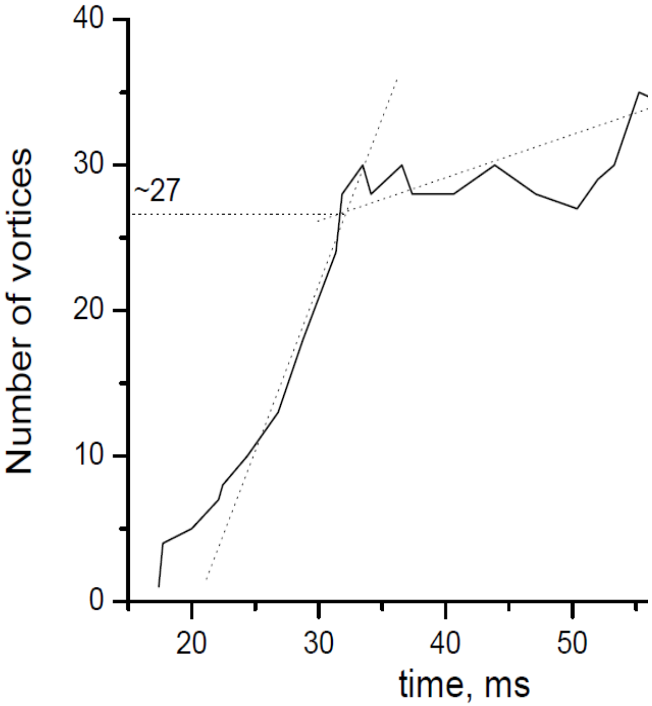
The sequence of snapshots of system phase at consecutive moments of time:

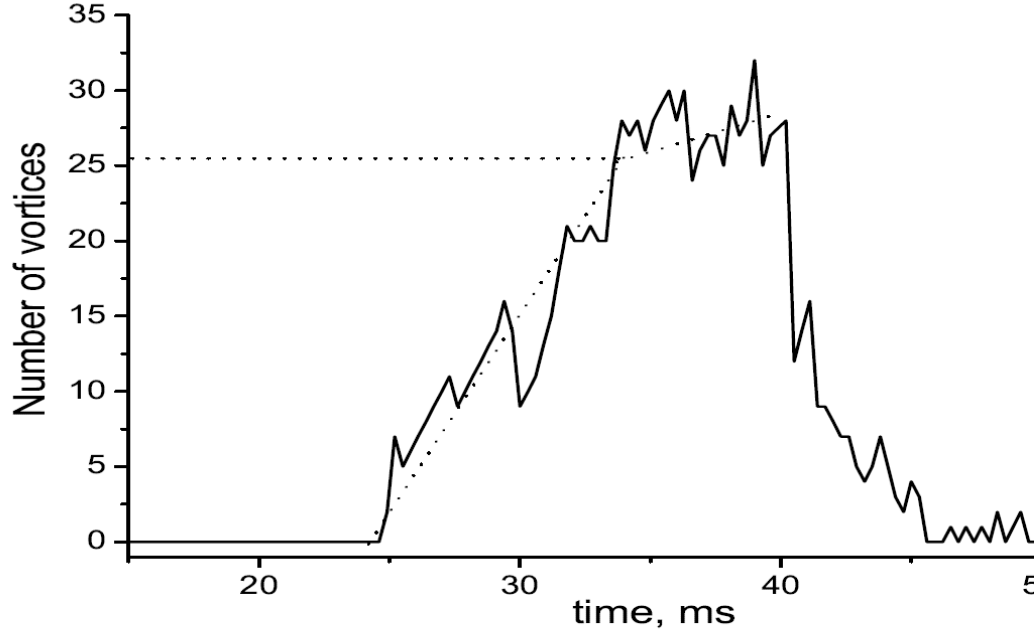
grain turbulence **wave turbulence**



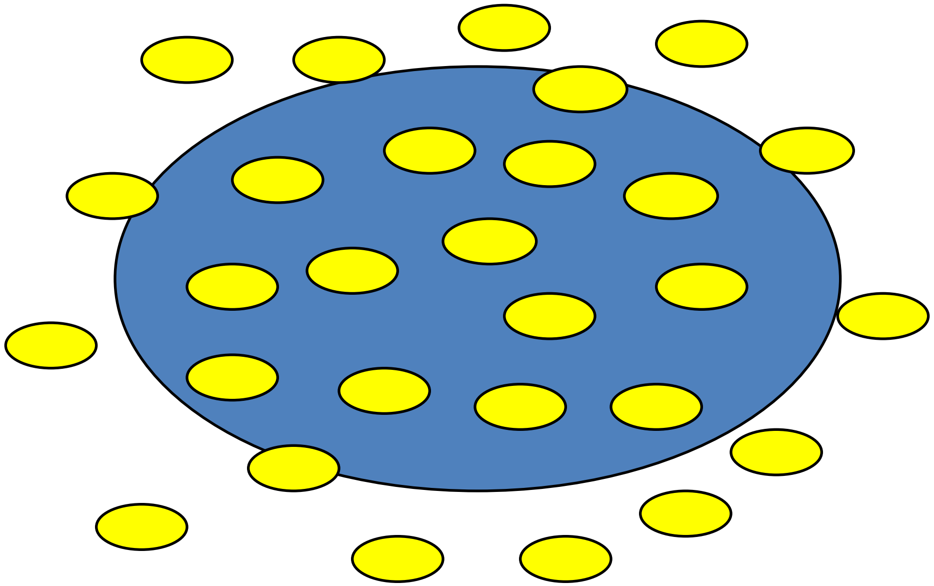
equilibrium Bose-condensed state → **a state with almost destroyed coherence**

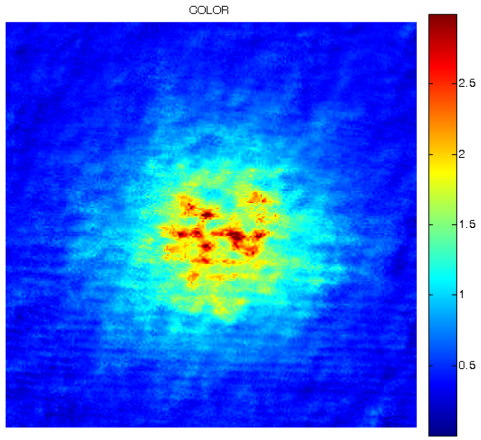
Opposite Kibble-Zurek mechanism order!


Number of vortices
time, ms
~27
0
10
20
30
40
20
30
40
50

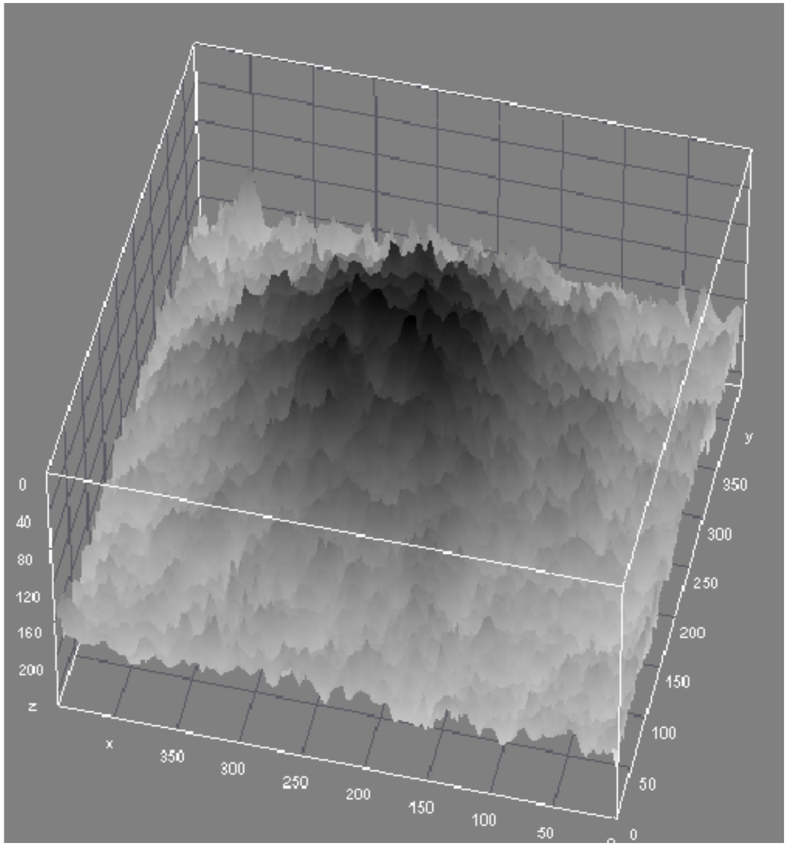

Number of vortices
time, ms
0
5
10
15
20
25
30
35
20
30
40
50

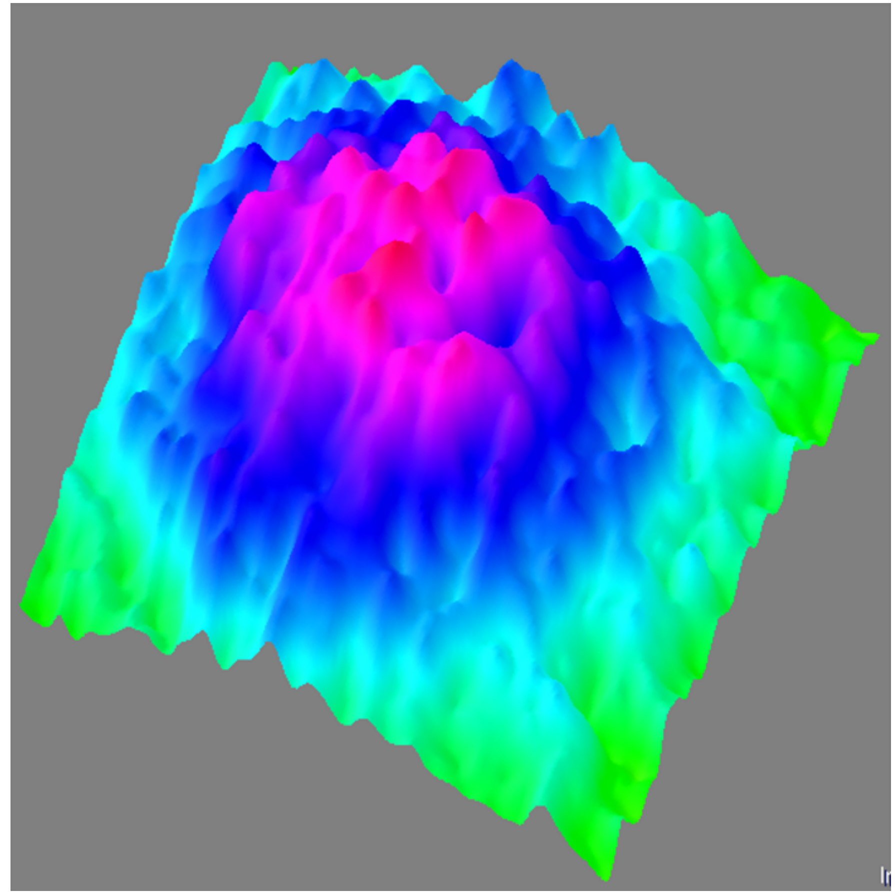
Granulation

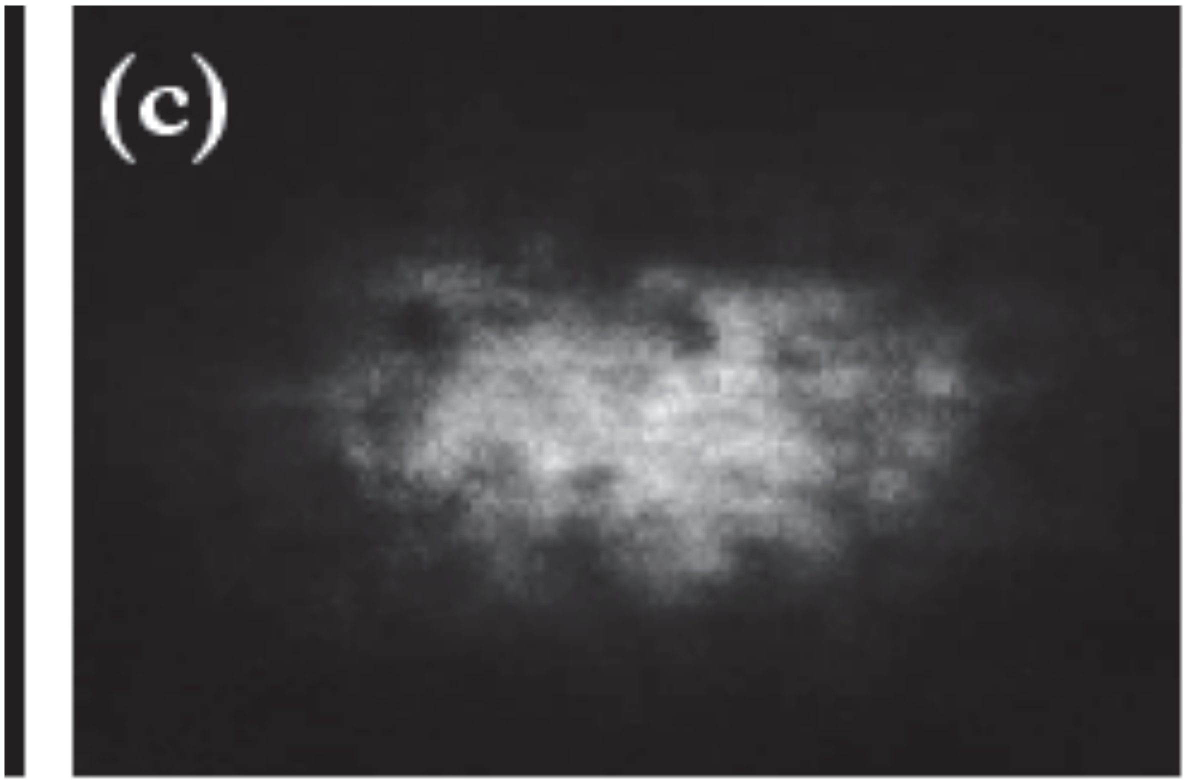




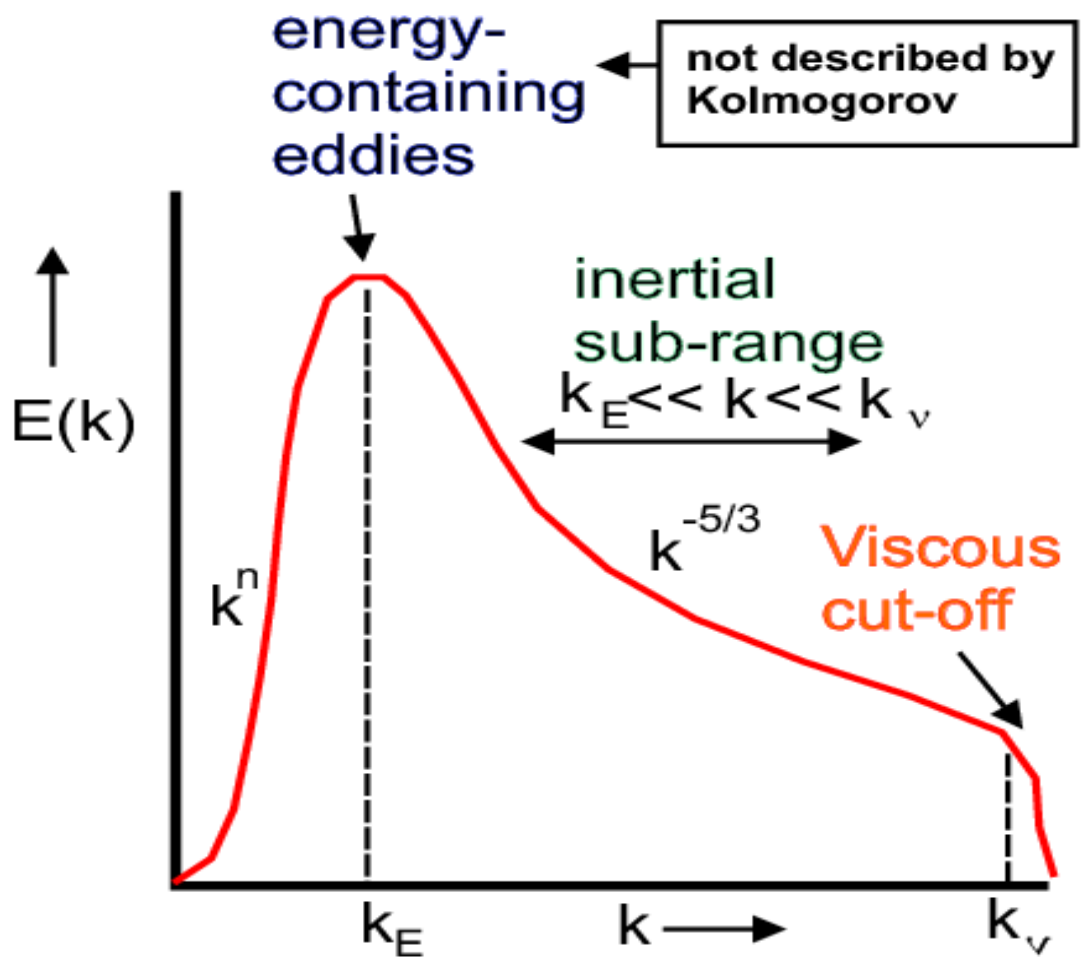
HIGH DENSITY FLUCTUATIONS


0
40
80
120
160
200
z
x
350
300
250
200
150
100
50
y
350
300
250
200
150
100
50
0

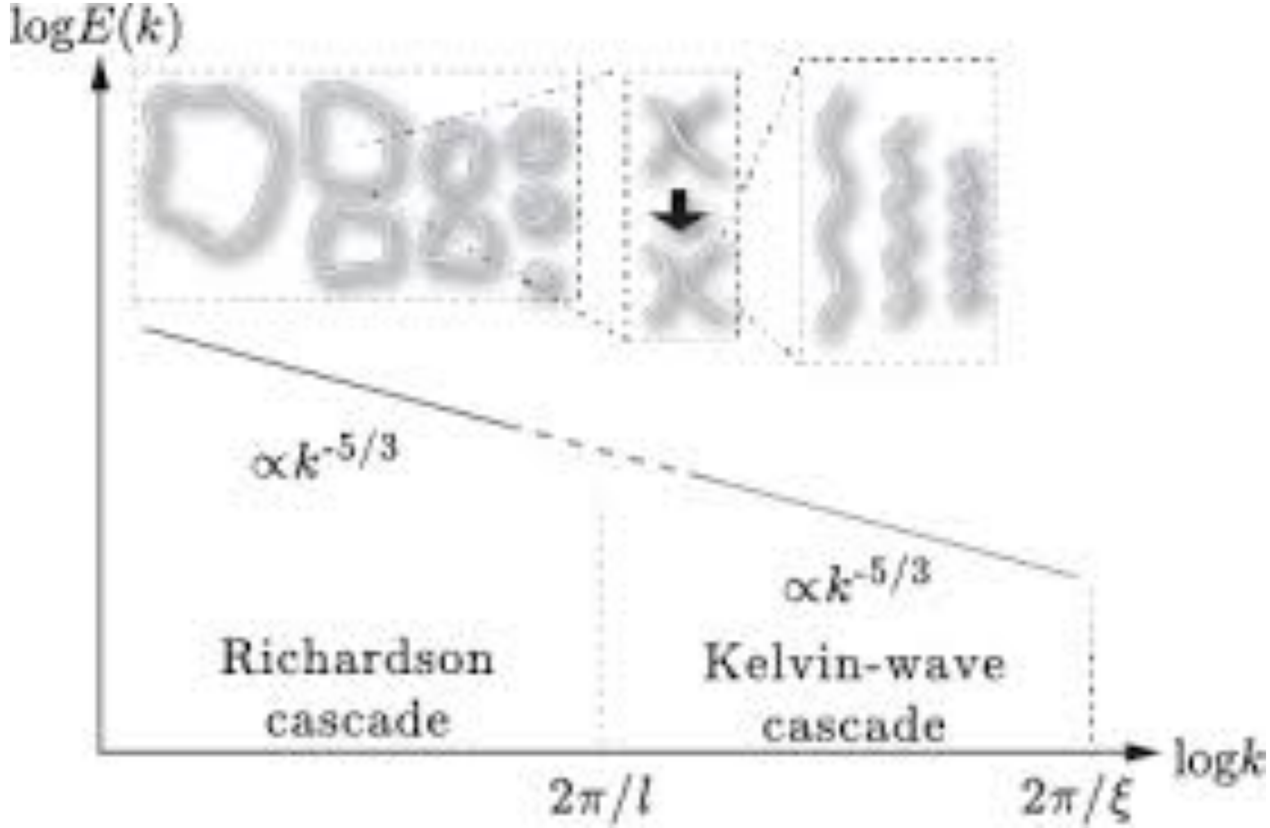




Collective modes are frozen

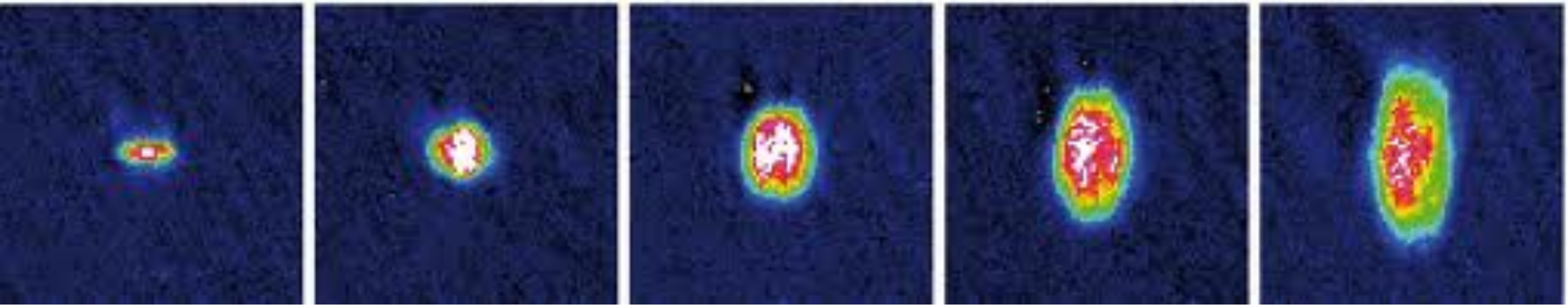


Kolmogorov: In the inertial sub-range, no dissipation and local interactions

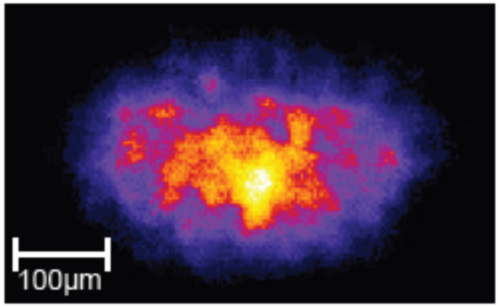


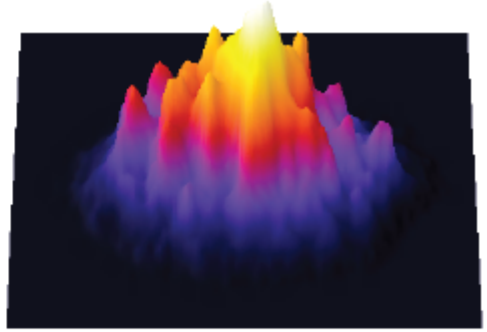
$\log E(k)$
$\propto k^{-5/3}$
$\propto k^{-5/3}$
Richardson
cascade
Kelvin-wave
cascade
$\log k$
$2\pi/l$
$2\pi/\xi$

HOW TO OBTAIN n (k) in a trapped superfluid?



Time dependence on the free expansion





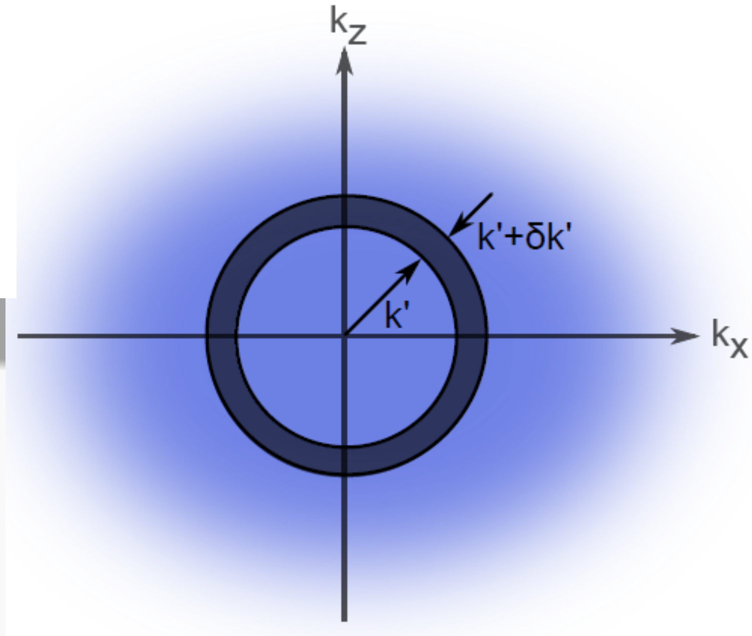
os BEC turbulento

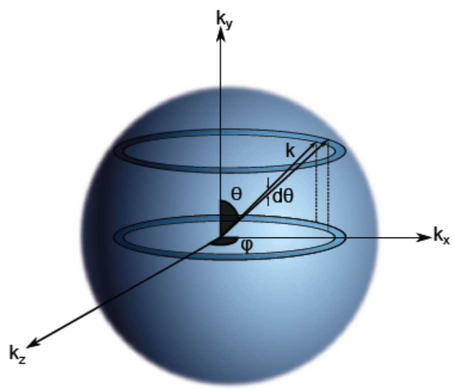
$$R_\rho(0) = 2,65\ \mu\text{m}$$

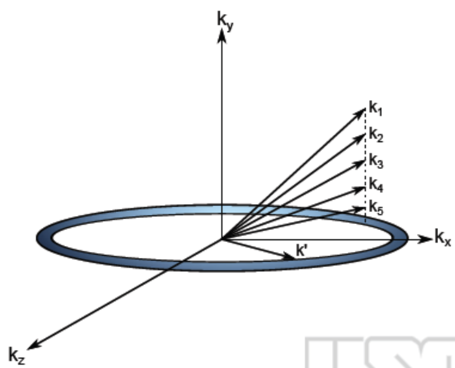
$$R_x(0) = 51,33\ \mu\text{m}$$

$$R_\rho(15) = 60\ \mu\text{m}$$

$$R_x(15) = 105\ \mu\text{m}$$







$$g(k') = 2\pi \int_{k'}^{k'+\delta k'} n'(k')\ k'\ dk'$$

$$\int n'(k')\ k'\ dk' = N$$

$$n'(k') = 2 \int_{k'}^{\infty} \frac{n(k)\, dk}{\sqrt{1 - (\frac{k'}{k})^2}}.$$

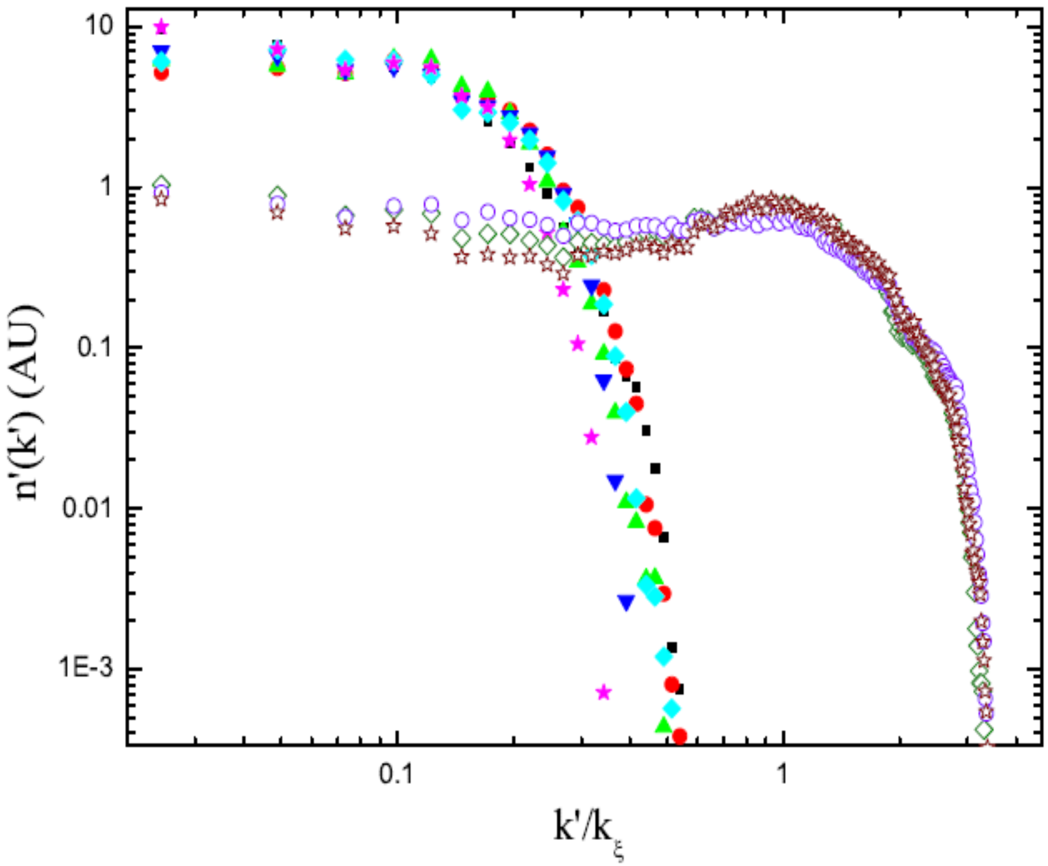
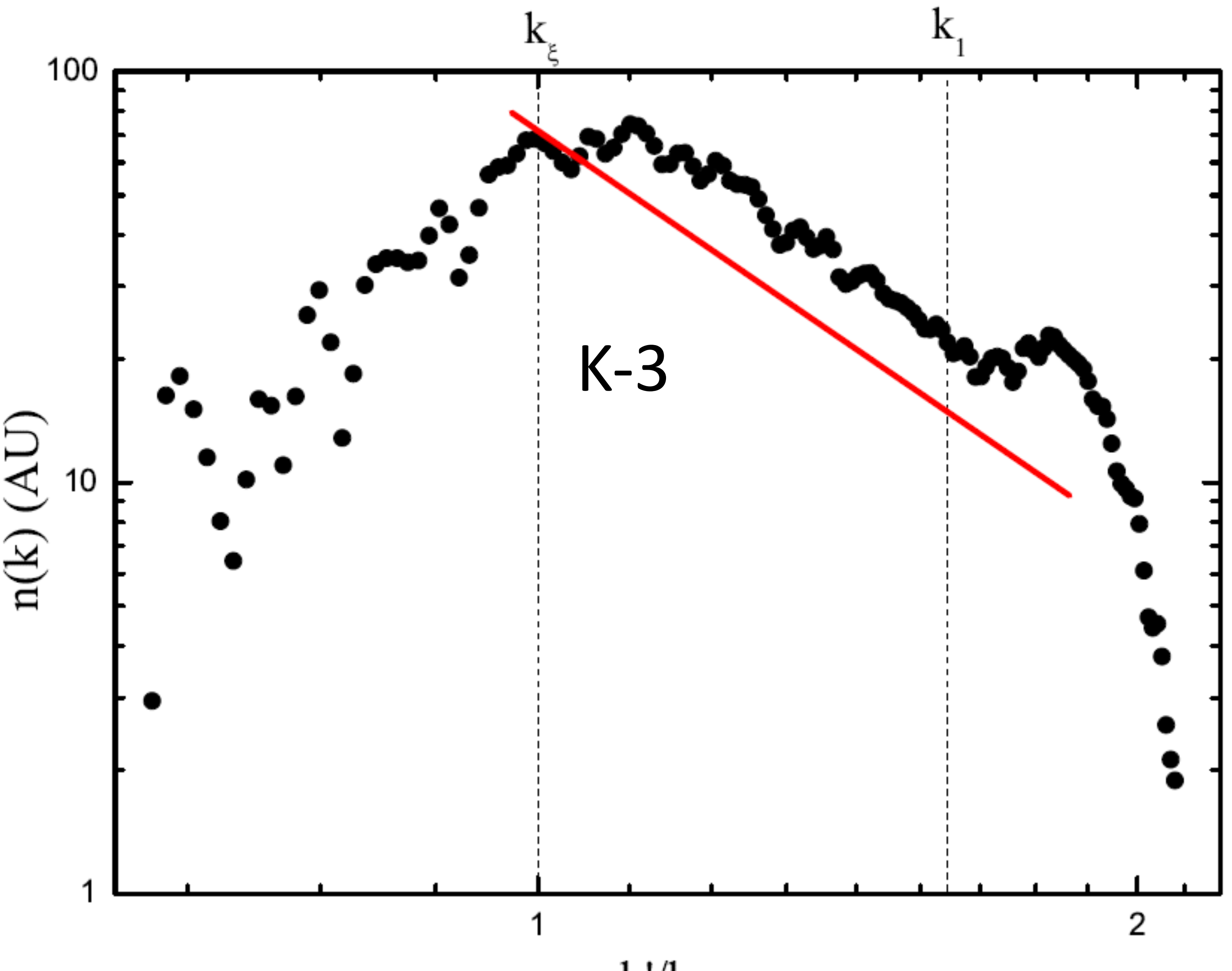
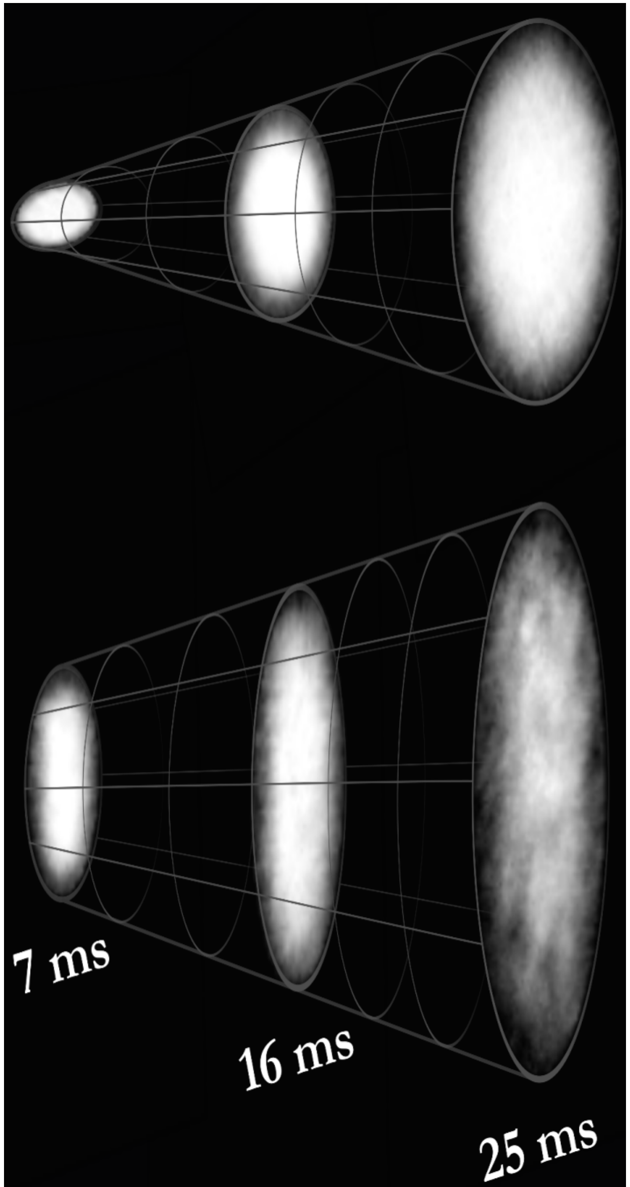


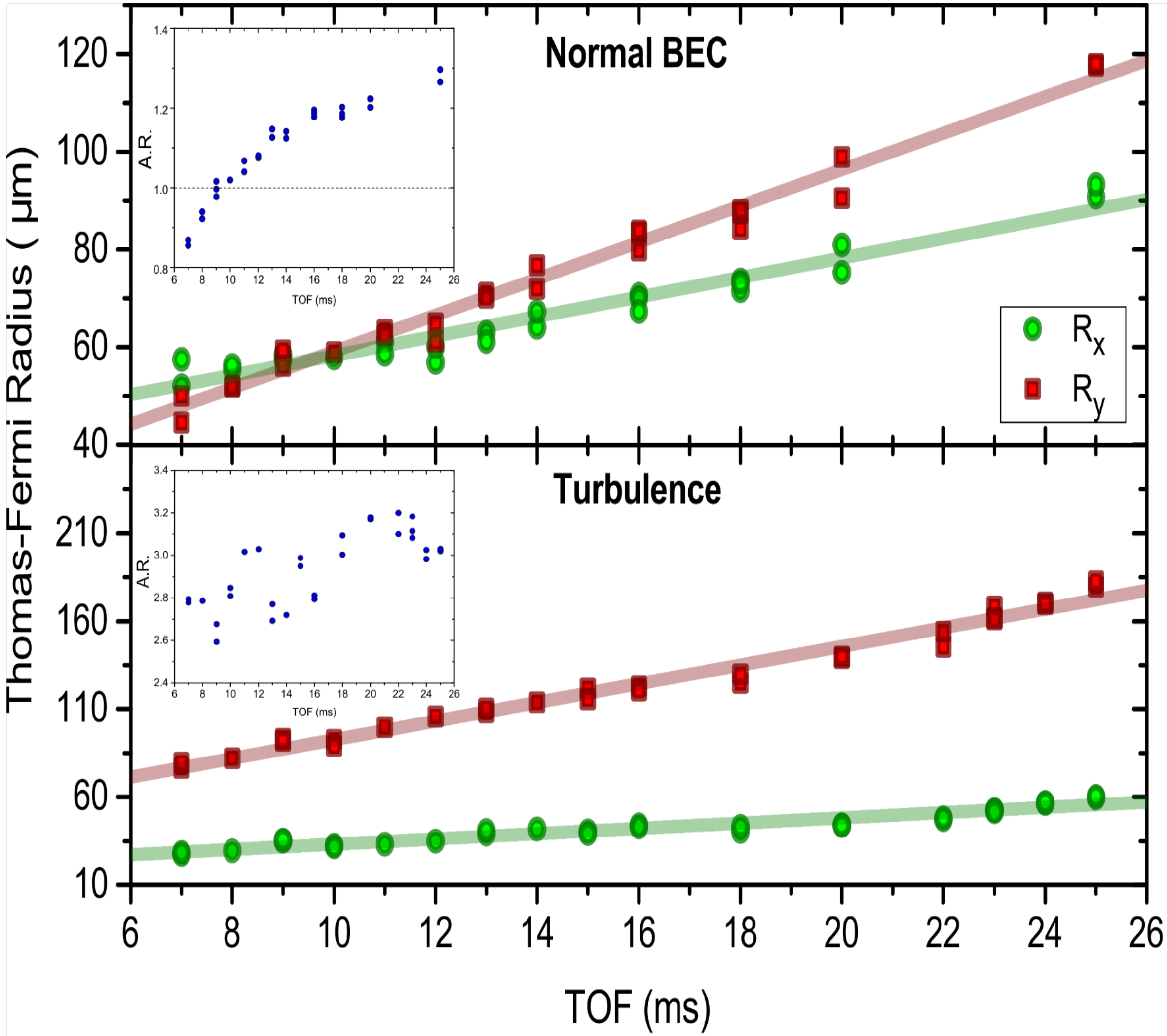
Figure 6: This figure shows the two dimensional projected momentum density, $n'(k')$, on a log-log plot. The Thomas-Fermi and condensates with a low number of vortices are shown in closed symbols. The ■, ●, ▲, ▼, ♦, and ★ symbols represent condensates with 0, 1, 2, 3, 4, and 5 vortices respectively and the open symbols are data from three different realizations of a turbulence. The distinction between the behavior of condensates with energy dominated by internal and kinetic energy are clear from the different behavior.

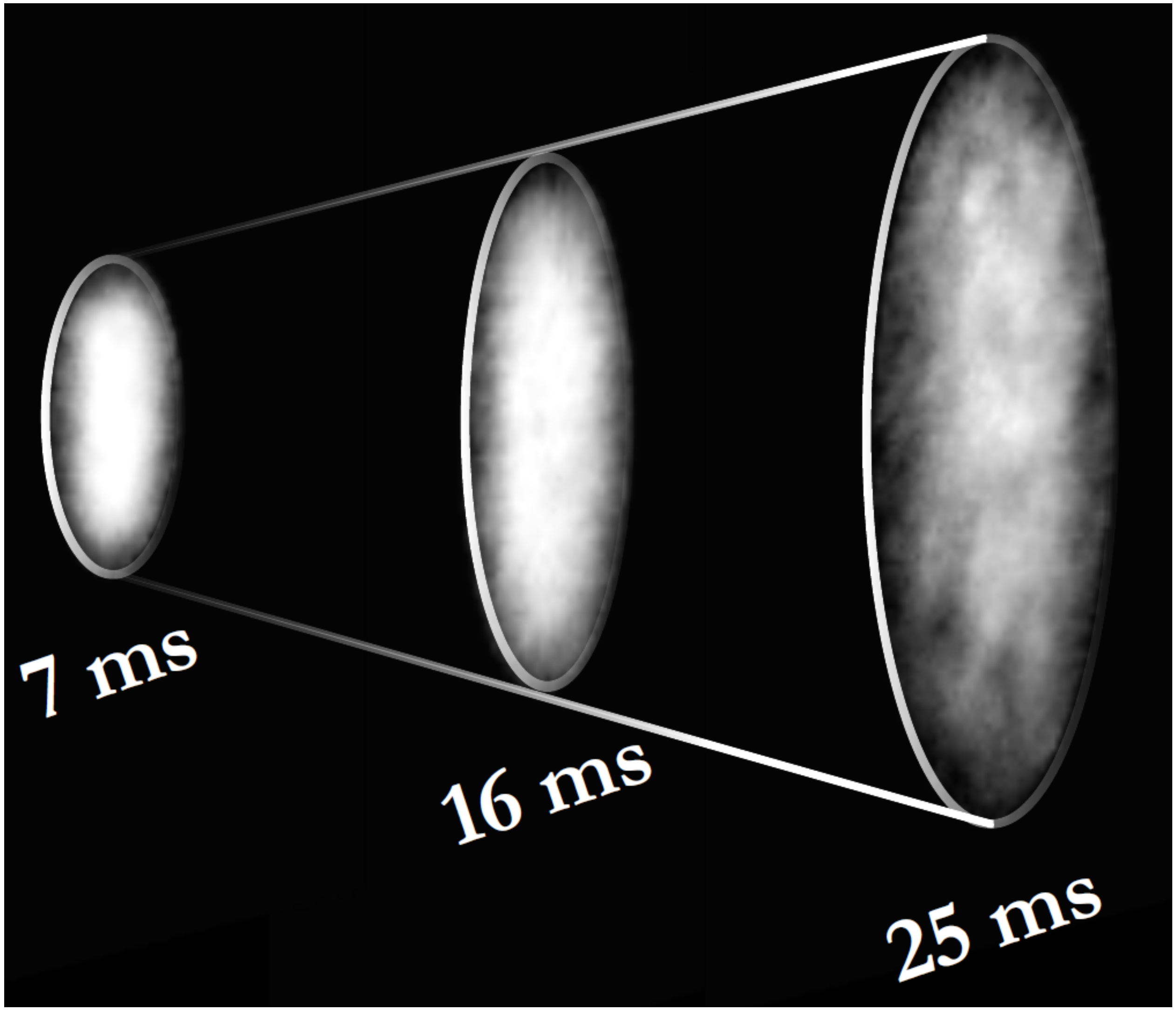


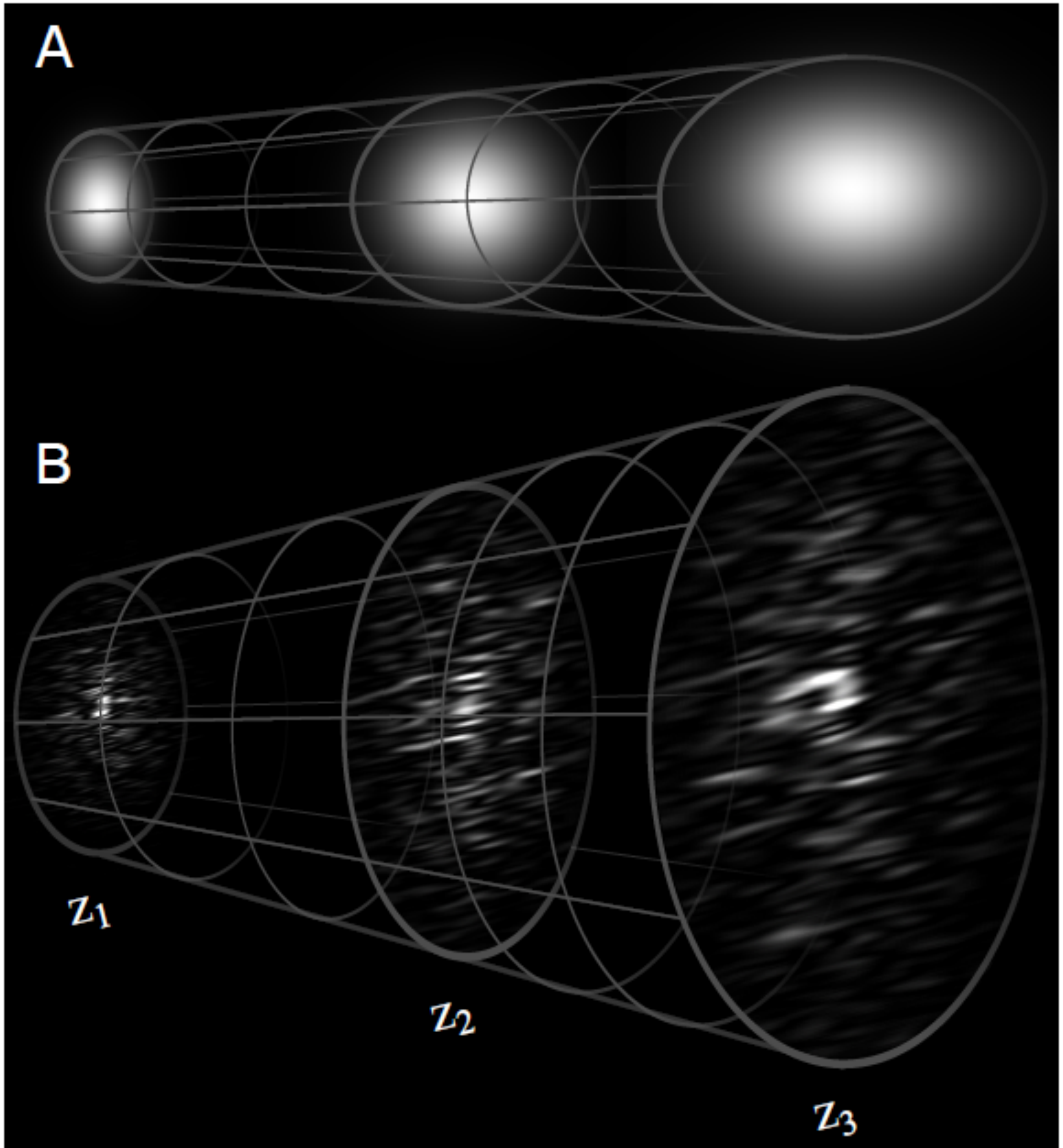
k_ξ
k_1
100
10
1
n(k) (AU)
K-3
1
2

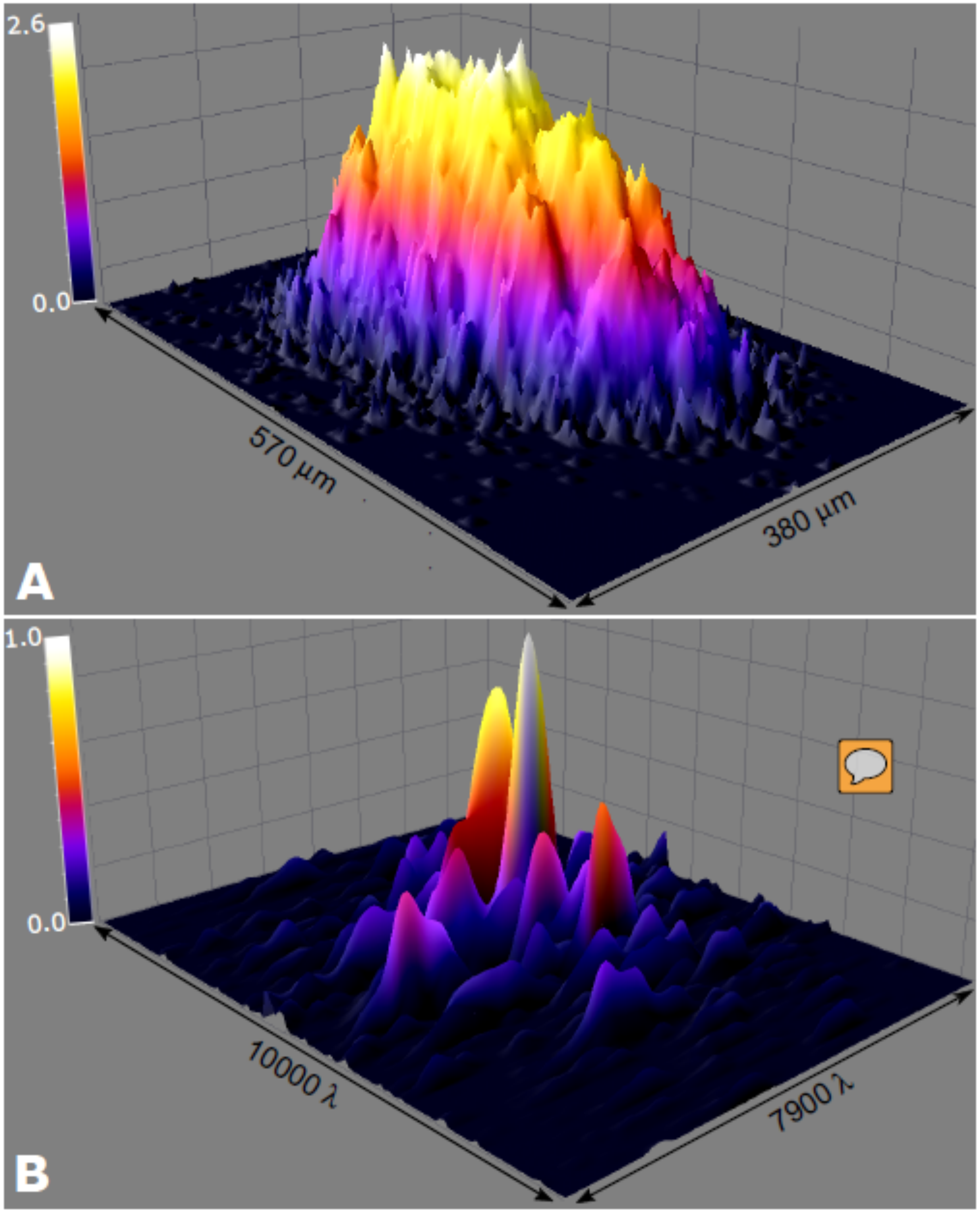
Matter wave expansion:






7 ms
16 ms
25 ms

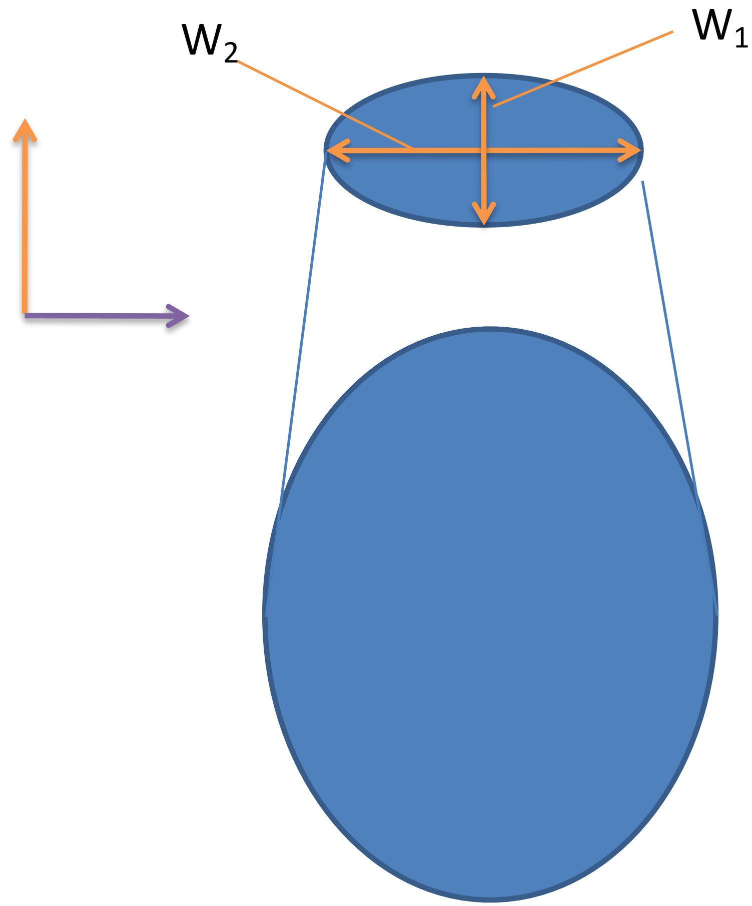

A
B
z_1
z_2
z_3



Comparison between turbulent cloud and speckle beam. 3D column

COHERENT LASER FIELD

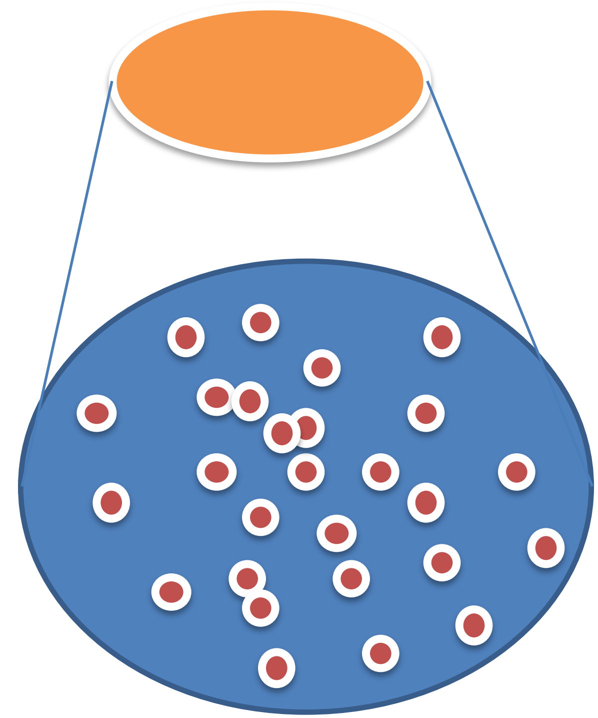
$$\tan\Theta = \frac{\lambda}{w_i}$$



w_i is well determinied in both directions

SPEKLE FIELD

$$\tan\Theta = \frac{\lambda}{l_i}$$



$\tan\Theta = \frac{\lambda}{}$

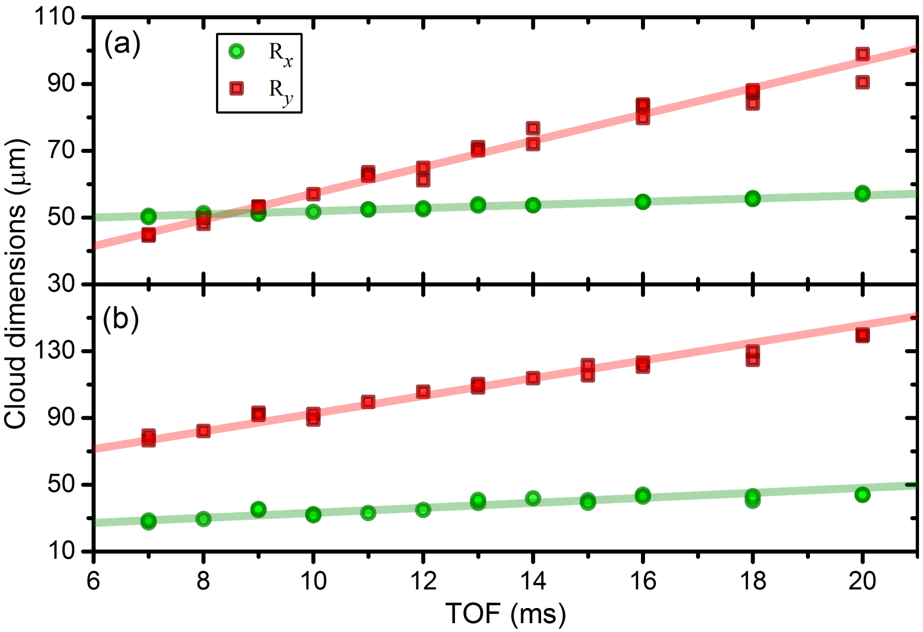
l_i is the **correlation length,** equal in all directions

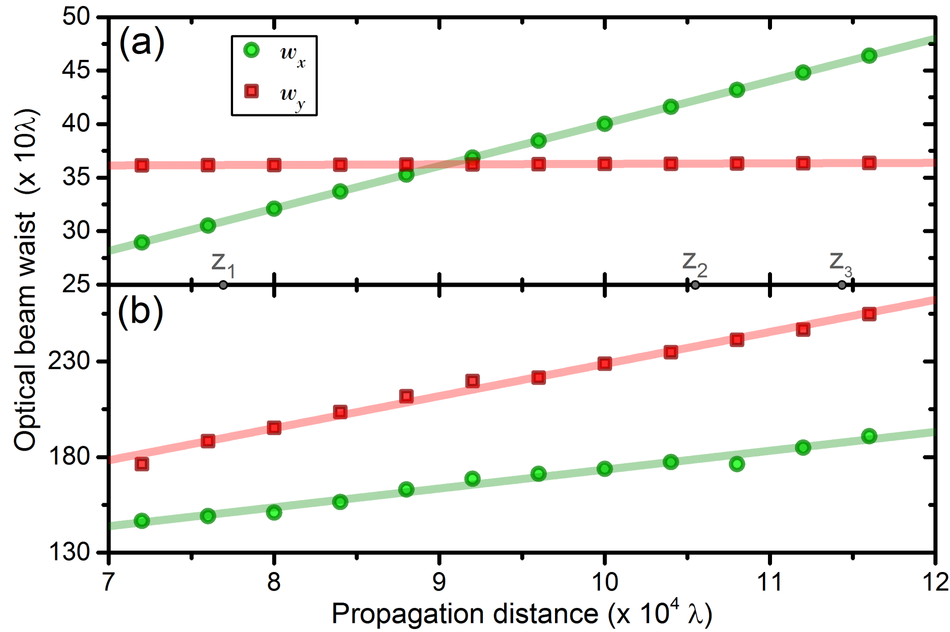
Equivalences in Expansion and Propagation

➢ **Divergence angles:**

$$\tan\theta_i^c = \frac{\lambda}{w_{0i}}$$
$$\tan\theta_i^d = \frac{\lambda}{\ell_i}$$

$\ell_i < w_{0i}$ → $\tan\theta_i^d > \tan\theta_i^c$





$$\dot{R}_x^{\mathrm{BEC}} = 0.47(1)\ \mu\mathrm{m/ms} \qquad \dot{R}_y^{\mathrm{BEC}} = 3.9(1)\ \mu\mathrm{m/ms}$$
$$\dot{R}_x^{\mathrm{Turb}} = 1.5(1)\ \mu\mathrm{m/ms} \qquad \dot{R}_y^{\mathrm{Turb}} = 5.3(2)\ \mu\mathrm{m/ms}$$

$$\dot{w}_x^{\mathrm{Gauss}} = 39.64(2)\times10^{-3} \qquad \dot{w}_y^{\mathrm{Gauss}} = 0.48(1)\times10^{-3}$$
$$\dot{w}_x^{\mathrm{Speckle}} = 0.098(5) \qquad \dot{w}_y^{\mathrm{Speckle}} = 0.167(6)$$

DIVERGENCE DURING PROPAGATION

For the coherent light field **, θ_1 > θ_2 → inversion ratio**

For the speckle field, $l_1 \sim l_2$ **→ , θ_1 ~ θ_2 → self-similar expansion**

$$g_2(\Delta\mathbf{r}) = \frac{\langle I(\mathbf{r}) I(\mathbf{r} + \Delta\mathbf{r})\rangle}{\langle I(\mathbf{r})\rangle\langle I(\mathbf{r} + \Delta\mathbf{r})\rangle}.$$

Optical field → intensity –intensity correlation

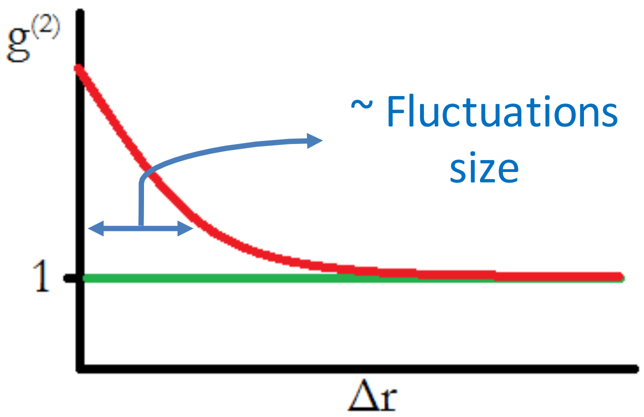
Matter field → density –density correlation

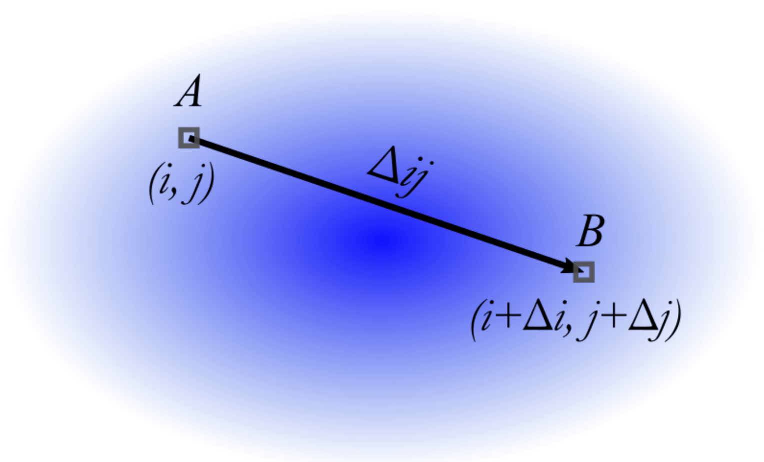
$$g^{(2)}(\Delta r) = \frac{\langle n(r)\ n(r + \Delta r)\rangle}{\langle n(r)\rangle\ \langle n(r + \Delta r)\rangle}$$

Second-order Correlation Function

$$g^{(2)}(\Delta r) = \frac{\langle n(r)\; n(r+\Delta r)\rangle}{\langle n(r)\rangle\,\langle n(r+\Delta r)\rangle}$$

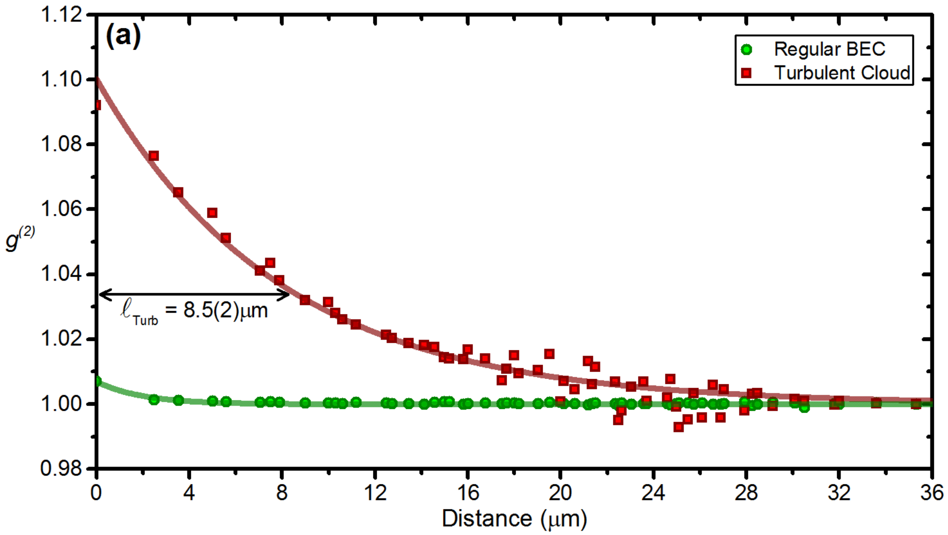
- For coherent state → $g^{(2)}(\Delta r) = 1$
- For disordered state → $g^{(2)}(0) > 1$
  → decay to 1

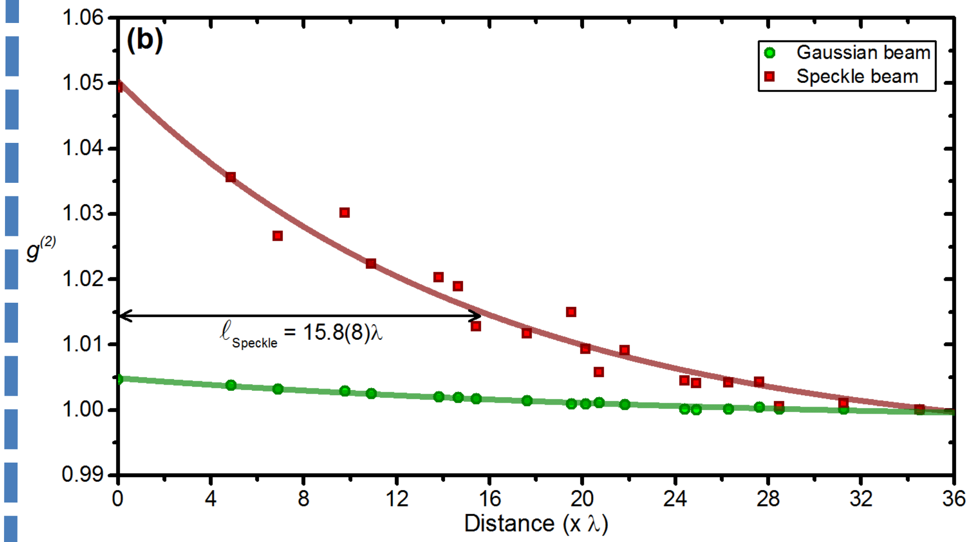




$$g^{(2)}(\Delta ij) = \frac{\langle \mathrm{OD}(i,j)\; \mathrm{OD}(i+\Delta i, j+\Delta j)\rangle_{\Delta ij}}{\langle \mathrm{OD}(i,j)\rangle_{\Delta ij}\,\langle \mathrm{OD}(i+\Delta i, j+\Delta j)\rangle_{\Delta ij}}$$

$g^{(2)}$ for Atomic Cloud and Optical Beam





$R_x = 63(3)\ \mu\text{m} \qquad R_y = 198(6)\ \mu\text{m}$

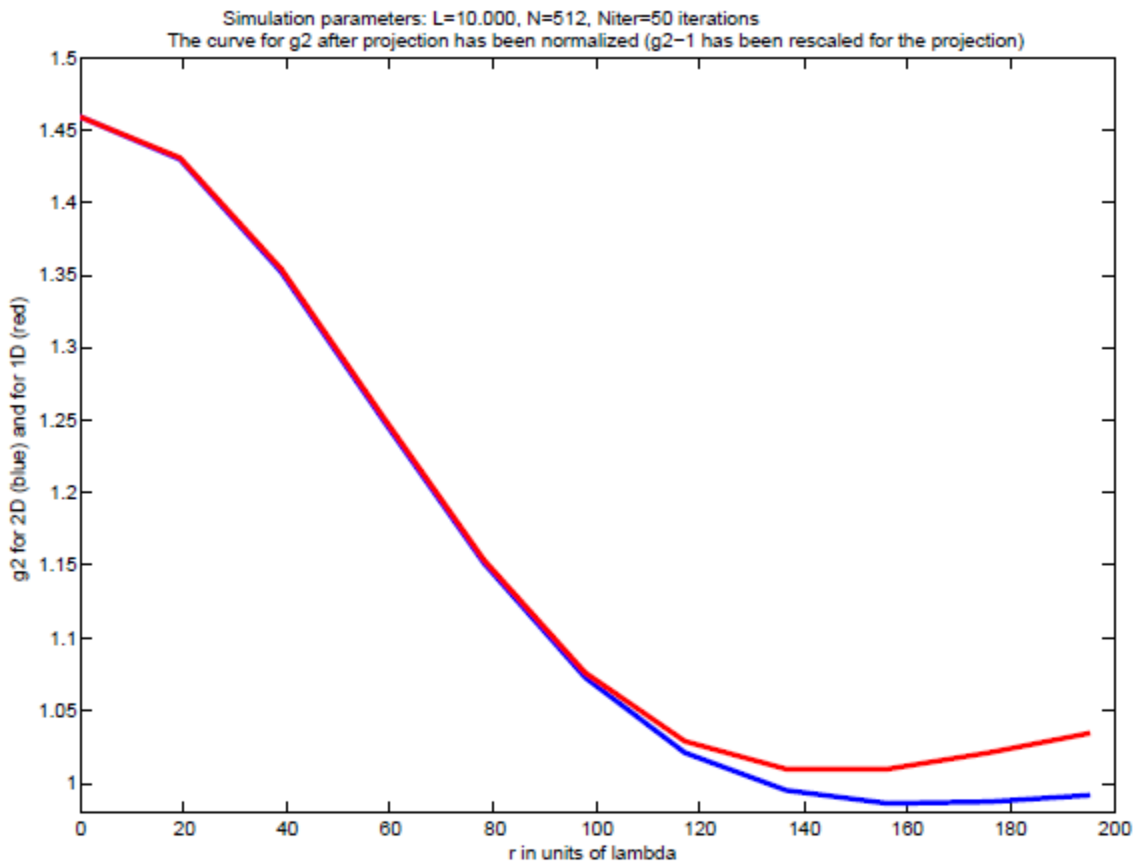
$w_x = 1876\lambda \qquad w_y = 2528\lambda$

$\ell_{Turb} = 8.5(2)\ \mu\text{m}$

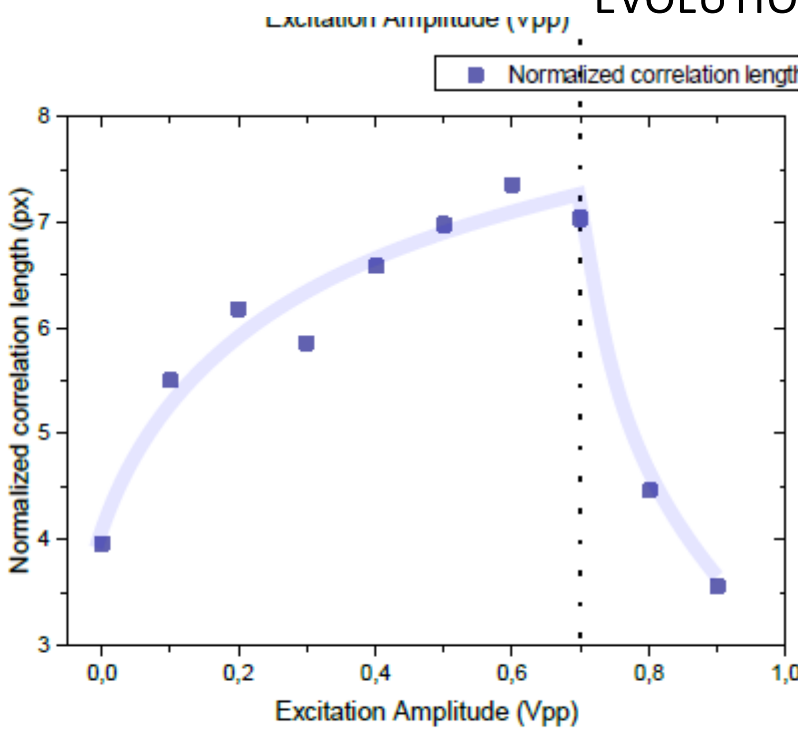
$\ell_{Speckle} = 15.8(8)\lambda$

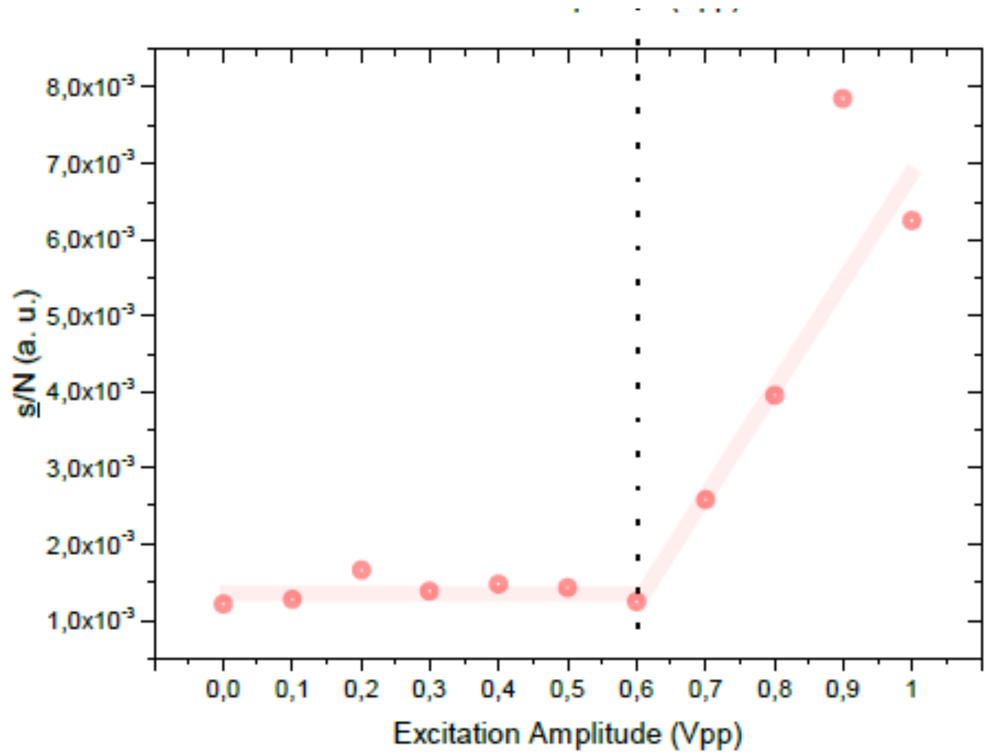
$$\ell_i < w_i$$

SPECKLE FIELD – PROJECTED CORRELATION



EVOLUTION OF THE DISORDER

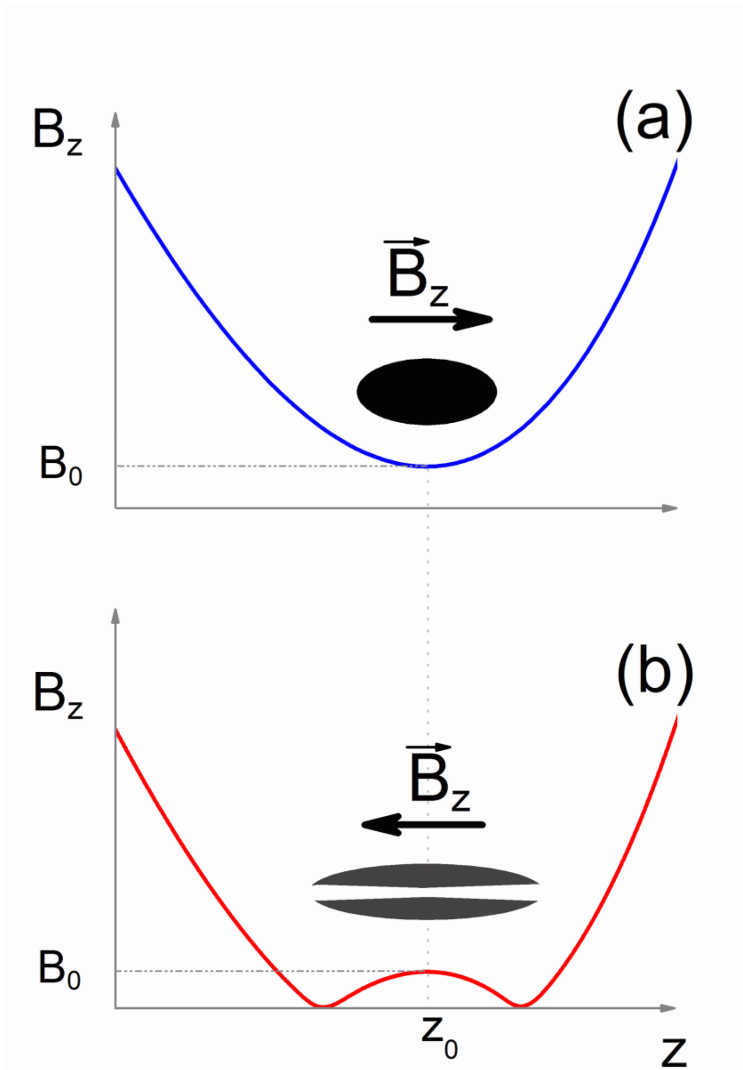


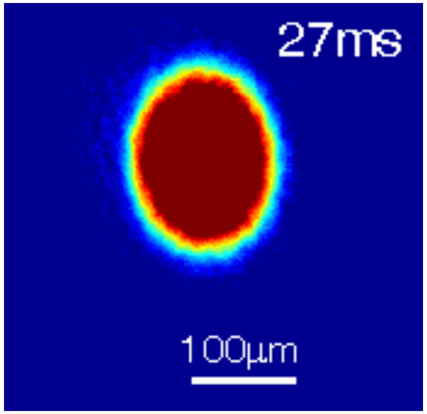


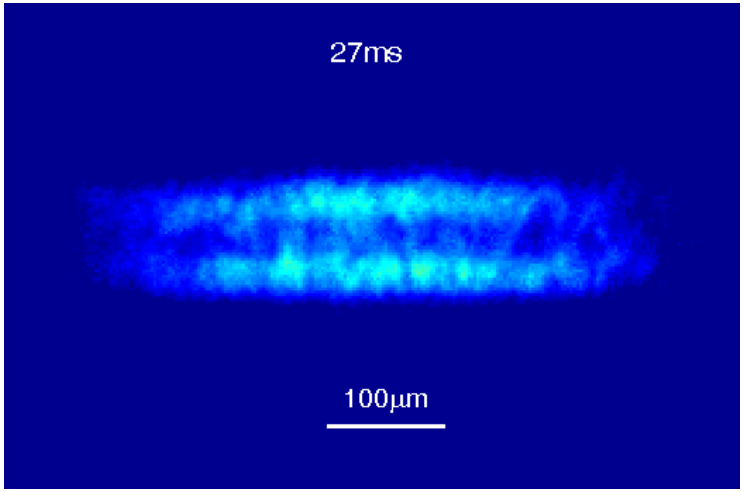
$$S = -k \int n(\vec{r}) \ln n(\vec{r}) d^3 r$$

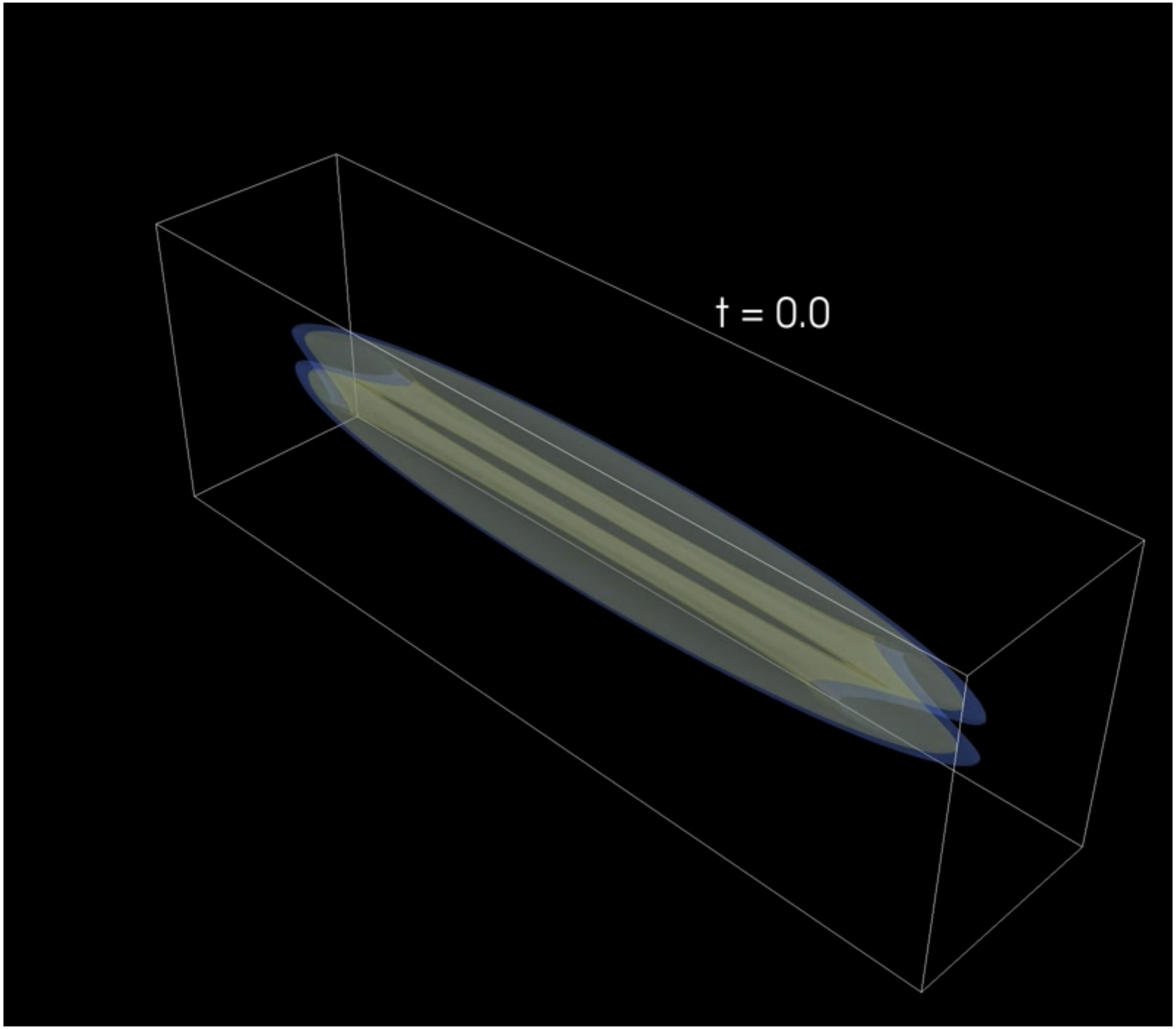
$$\int n(\vec{r}) d^3 r = 1$$

PRODUCTION OF MULTIPLE CHARGED VORTEX



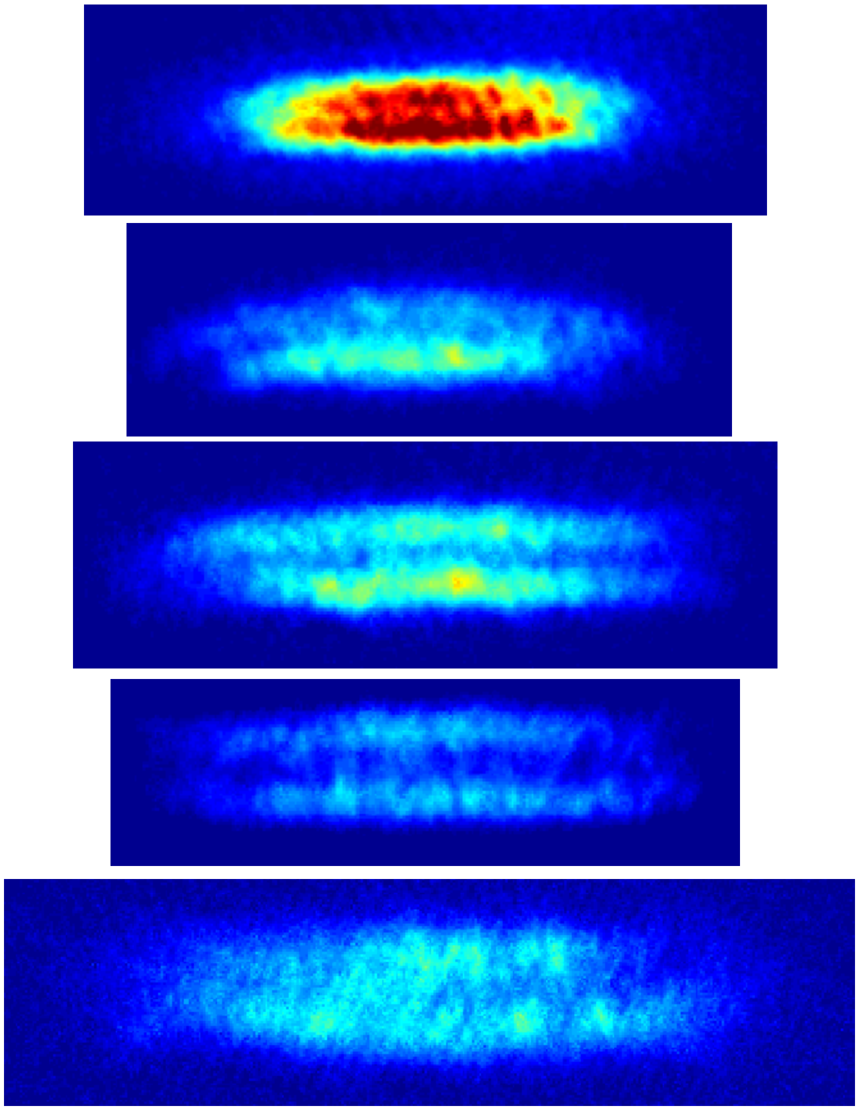


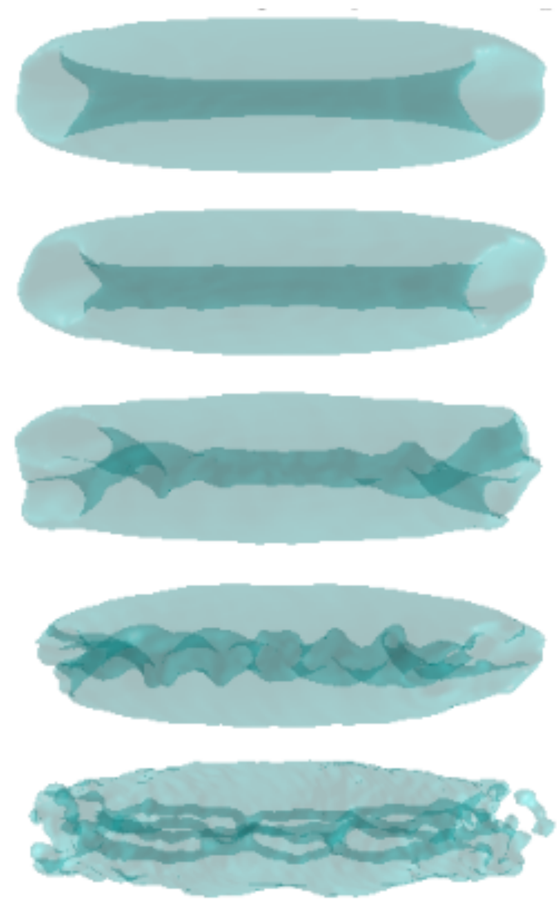




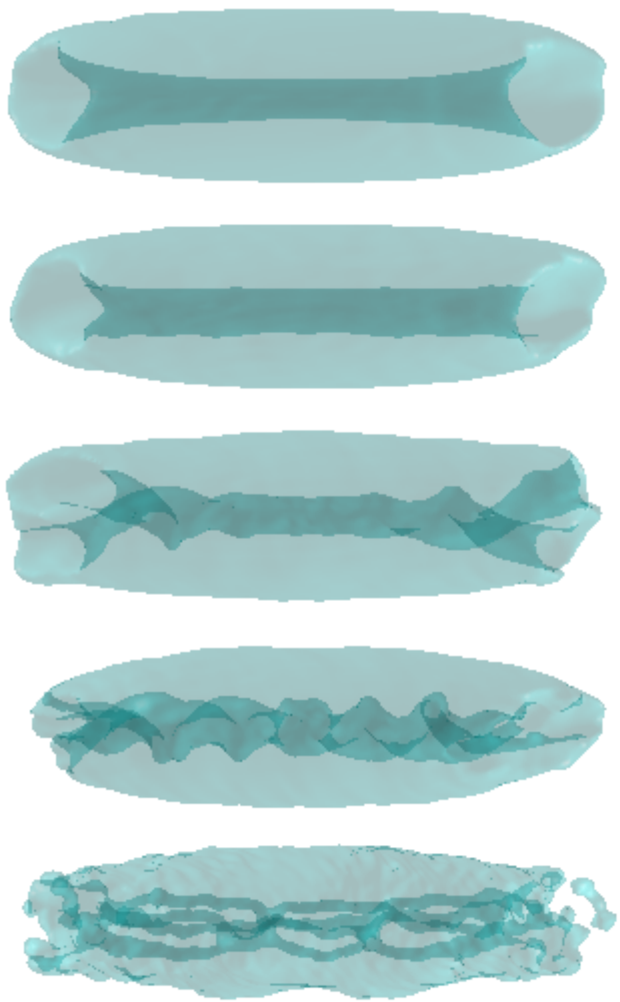
Collaboration: C. Barenghi
PhD of Andre Cidrim

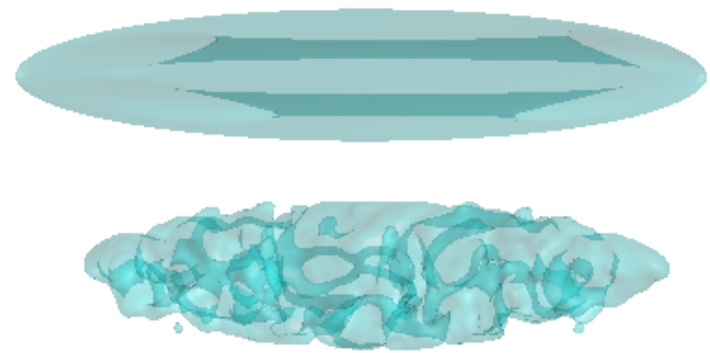
Multicharged vortex: initial results



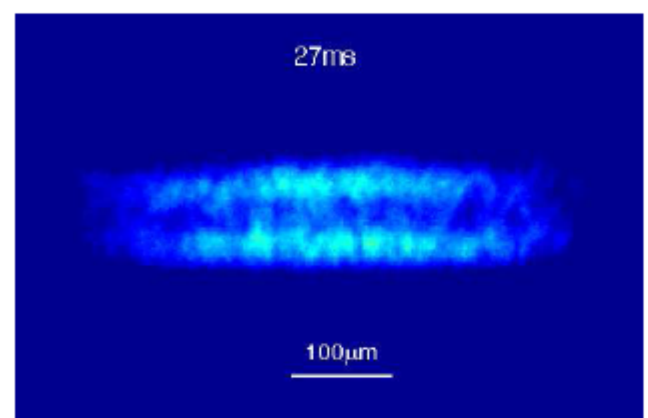


Collaboration:
Newcastle & São Carlos





Twisted Unwinding…:
arXiv:1505.00616



MODULATION OF SCATT. LENGTH

$$a(B) = a_{BG}\left(1 - \frac{\Delta}{B - B_{\infty}}\right),$$

$$\downarrow$$

$$B(t) = B_{av} + \delta B \cos(\Omega t),$$

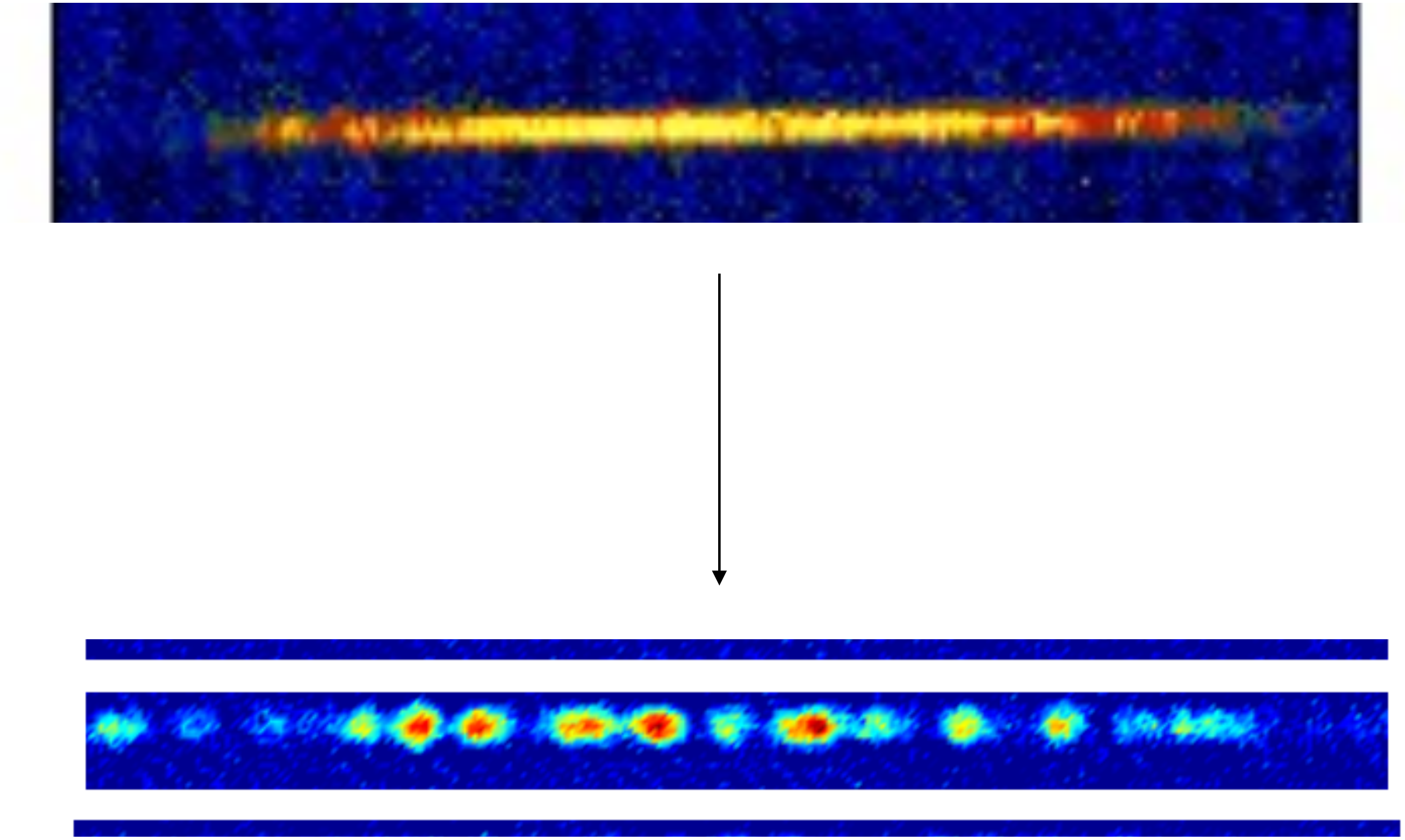
$$\downarrow$$

$$a(t) \simeq a_{av} + \delta a \cos(\Omega t),$$

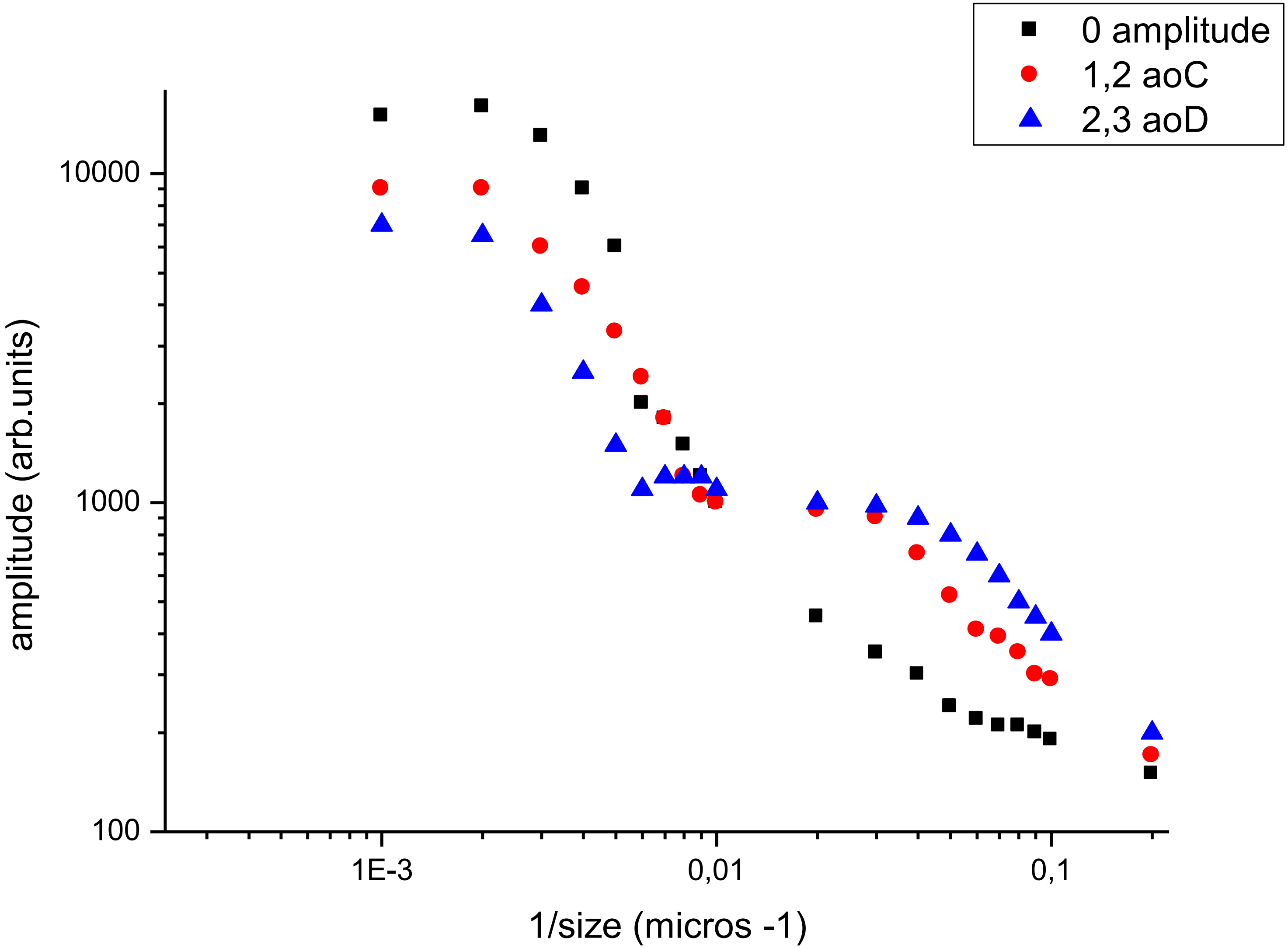
Collaboration with R. Hulet - Texas

- PhysRevA.85.033608(2012)

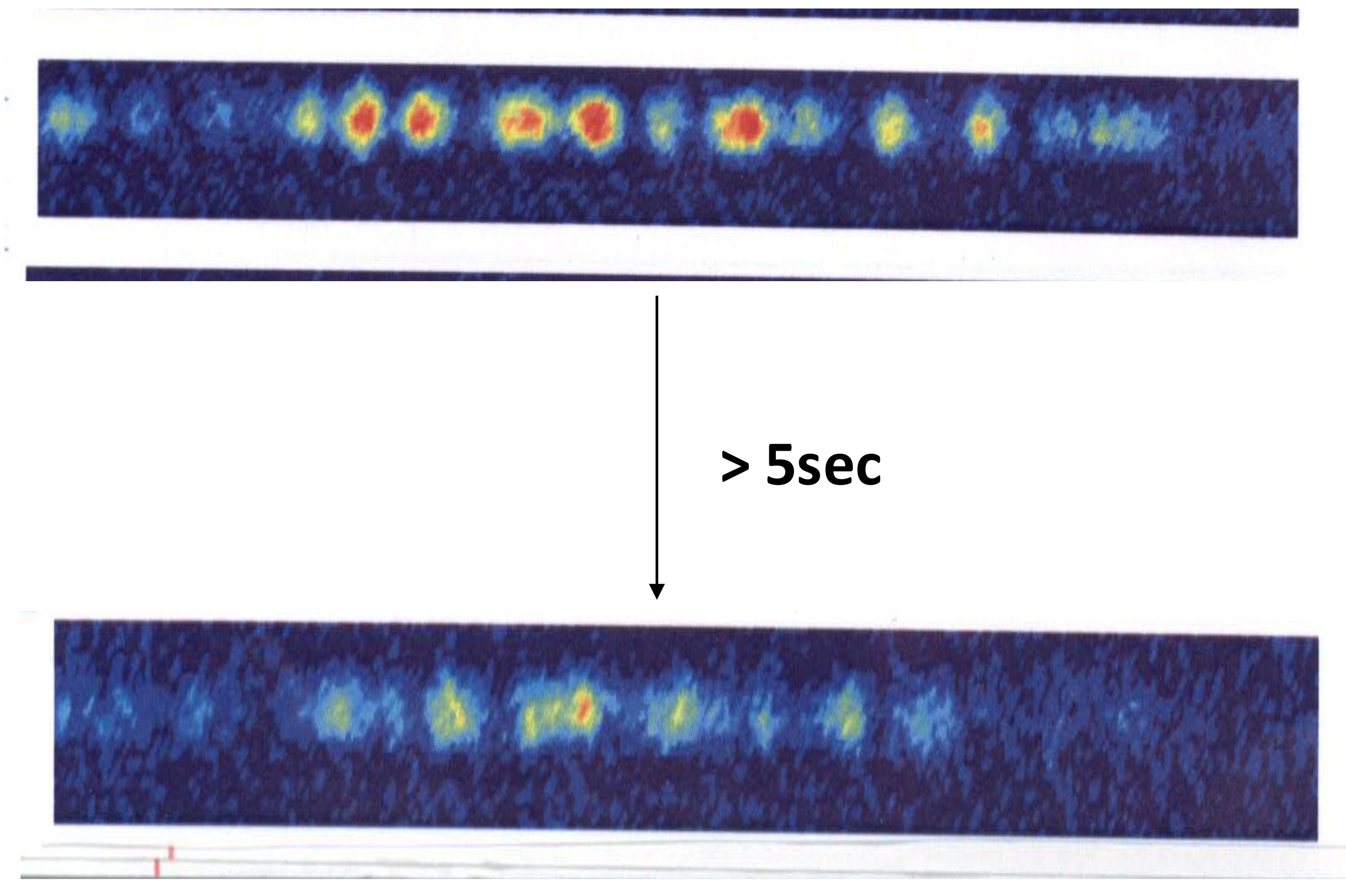
- Higher amplitudes take to “granulation”



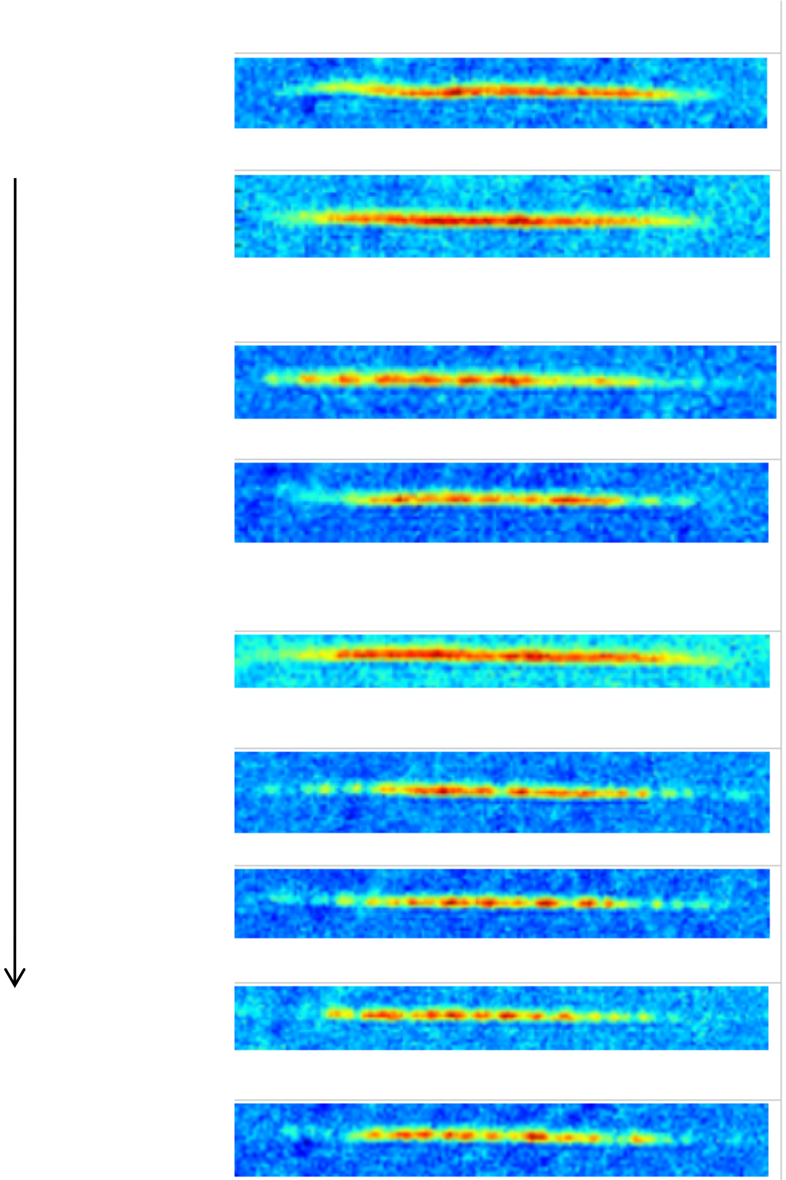
Higher amplitudes → fined size grains

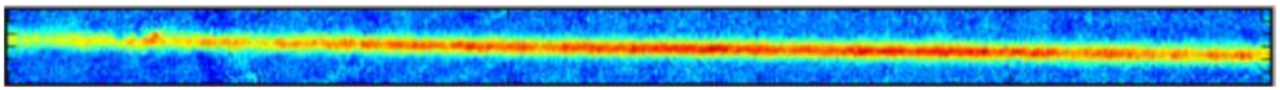


Long living after excitation!!!!

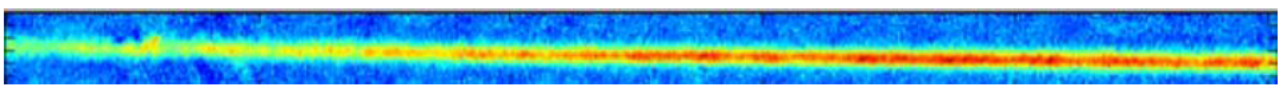


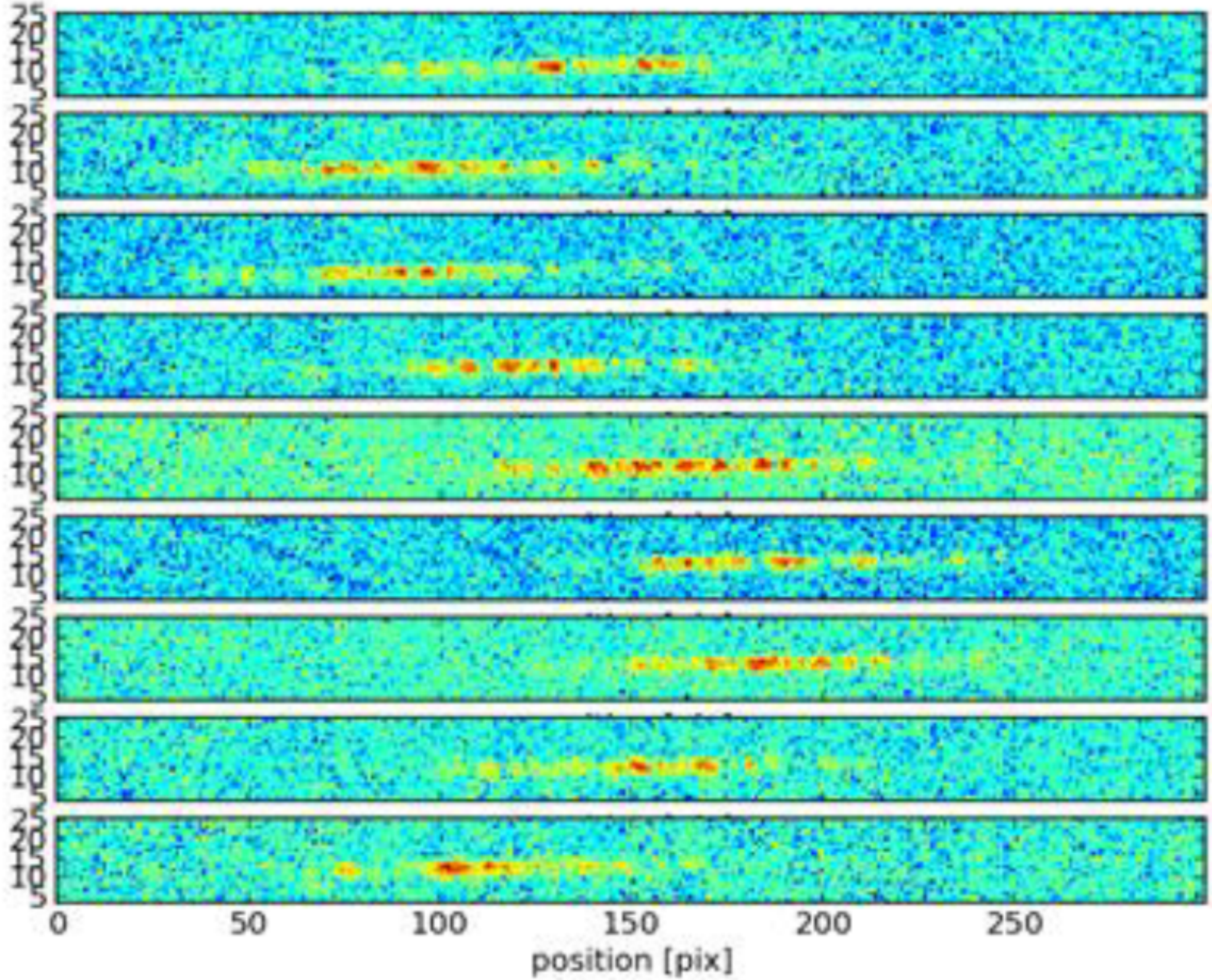
Time of excitation





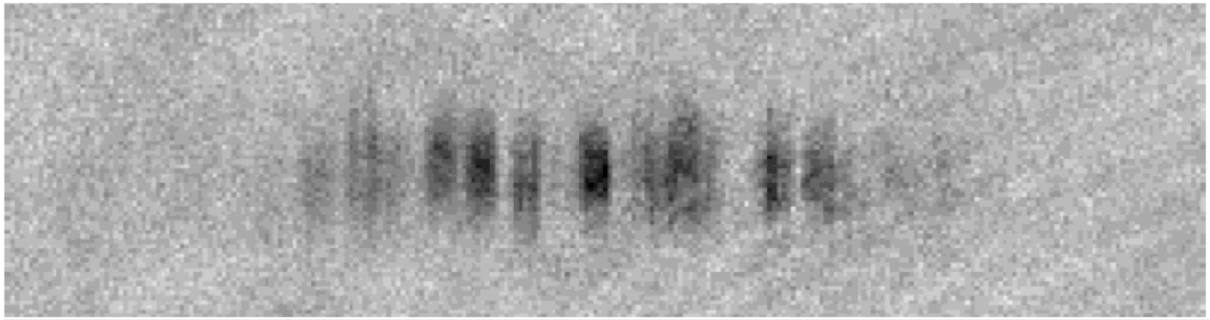
Now what happens when we modulate? Shot number 57788:

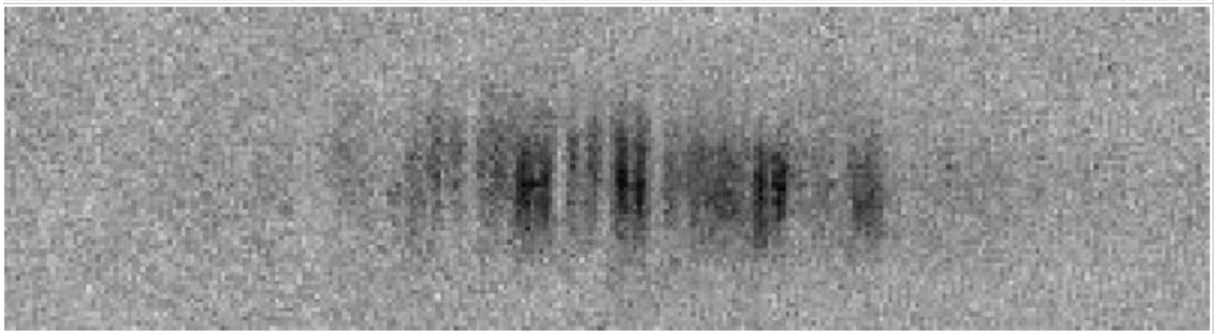


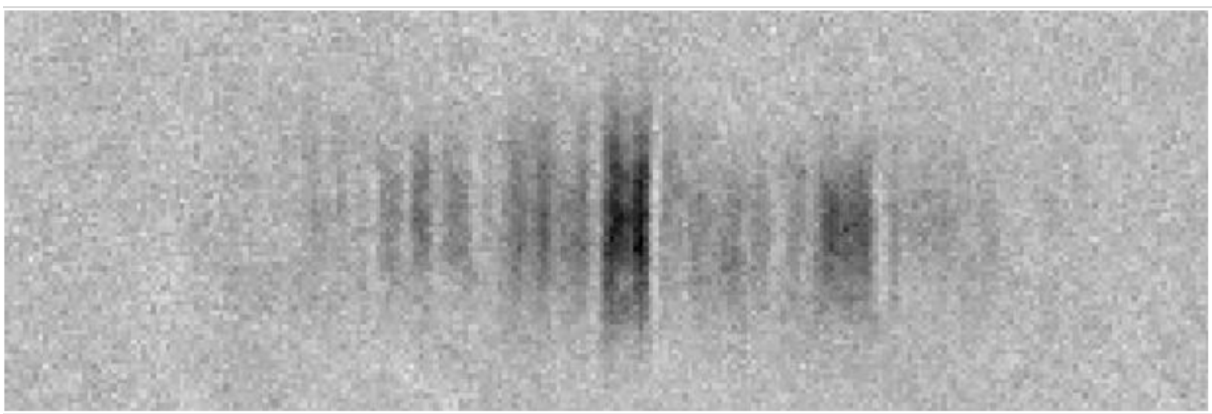


25
20
15
10
5
0
50
100
150
200
250
position [pix]

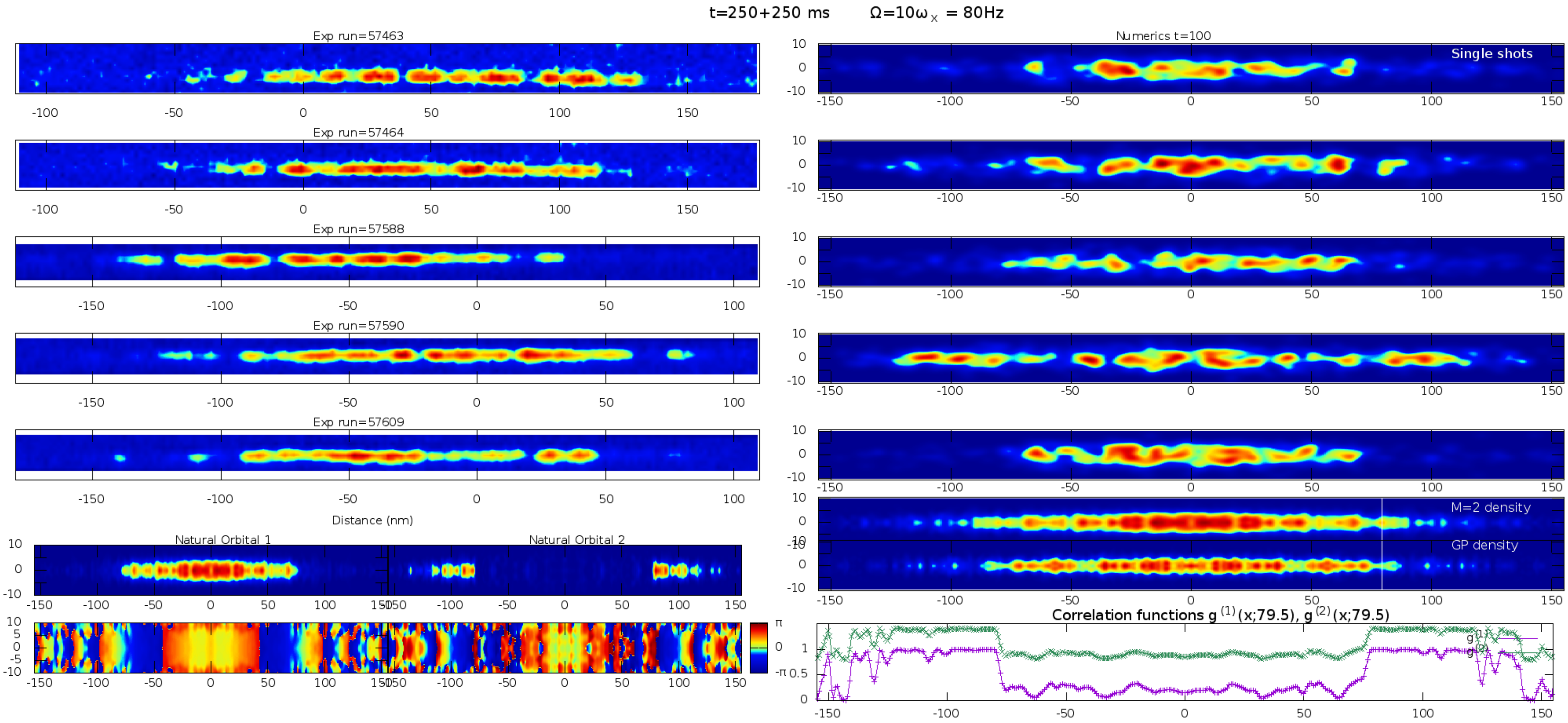
Image







Beyond mean field ……………….



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Quantum turbulence in trapped atomic Bose–Einstein condensates

Marios C. Tsatsos [a,*], Pedro E.S. Tavares [a], André Cidrim [a], Amilson R. Fritsch [a], Mônica A. Caracanhas [a], F. Ednilson A. dos Santos [b], Carlo F. Barenghi [c], Vanderlei S. Bagnato [a]

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