Quantum simulation with atomic Bose-Einstein condensates: from cosmology to color confinement

Gabriele Ferrari

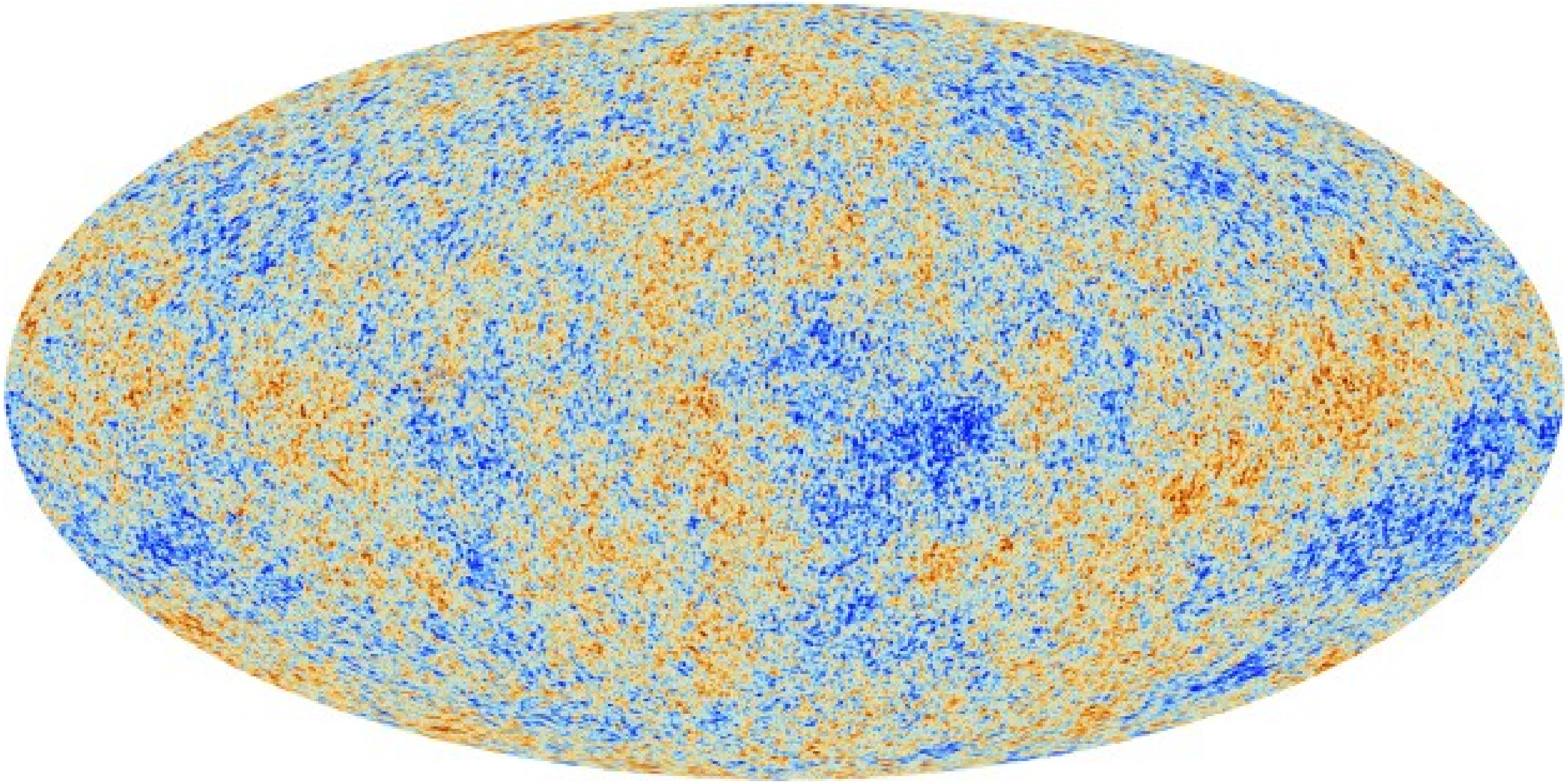
INO-CNR BEC Center, TIFPA-INFN and
Dipartimento di Fisica, Università di Trento

What Next, 6 maggio 2015

outline

- Defects in BECs
- Defect creation mechanism
- Dynamics and interactions
- Simulation of color confinement with ultracold atoms

Satellite: Planck
Depicts: Cosmic Microwave Background

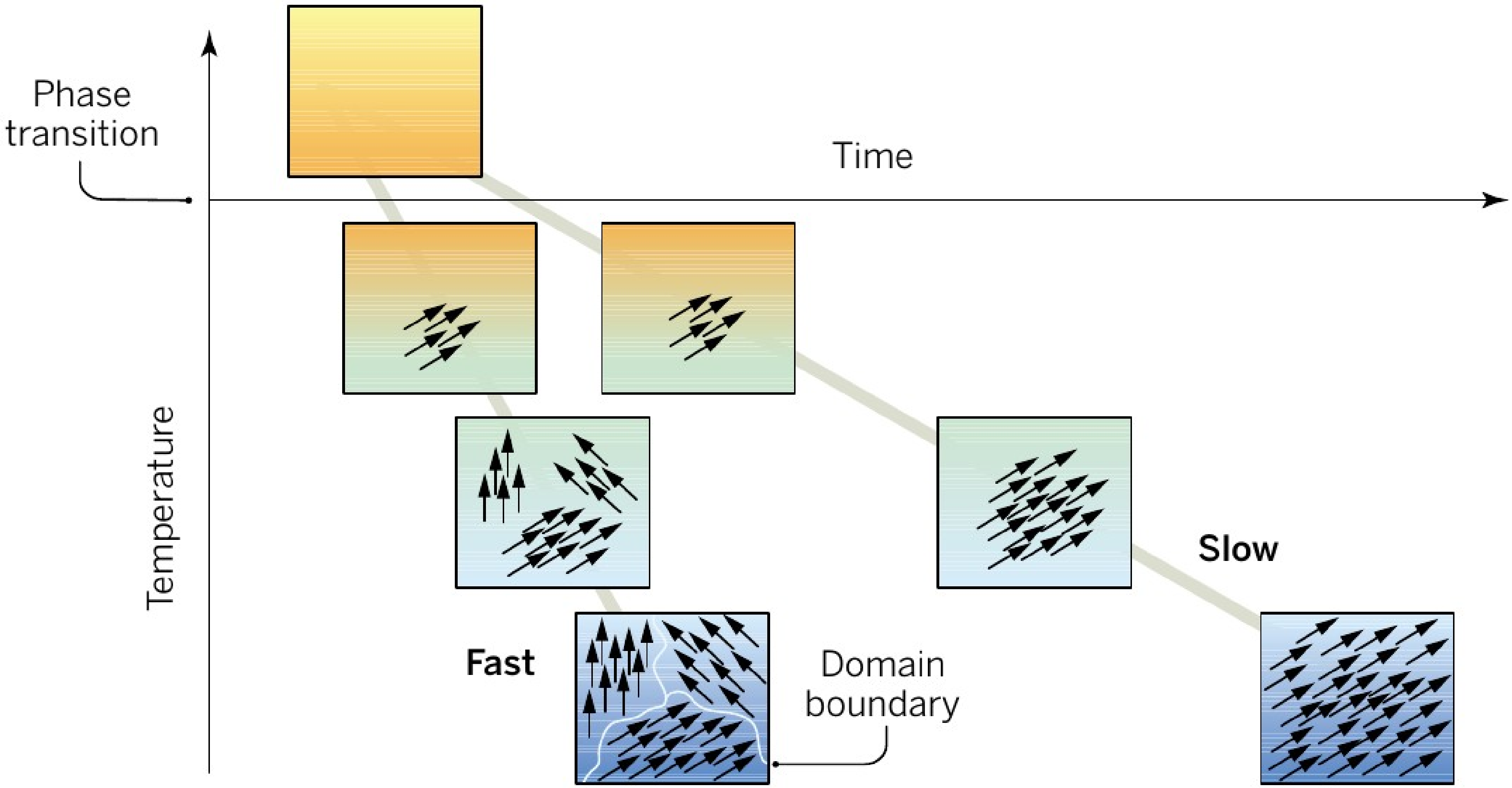


T. W. B. Kibble, J. Phys. A **9**, 1387 (1976)

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

the Kibble-Zurek mechanism

In a second-order phase transition crossed at a finite rate, the order parameter is chosen locally within domains, defects spontaneously create at the domain boundaries



G. F., Science **347**, 127 (2015)

the Kibble-Zurek mechanism

Power-law scaling

ADIABATIC -- IMPULSE -- ADIABATIC

coherence length

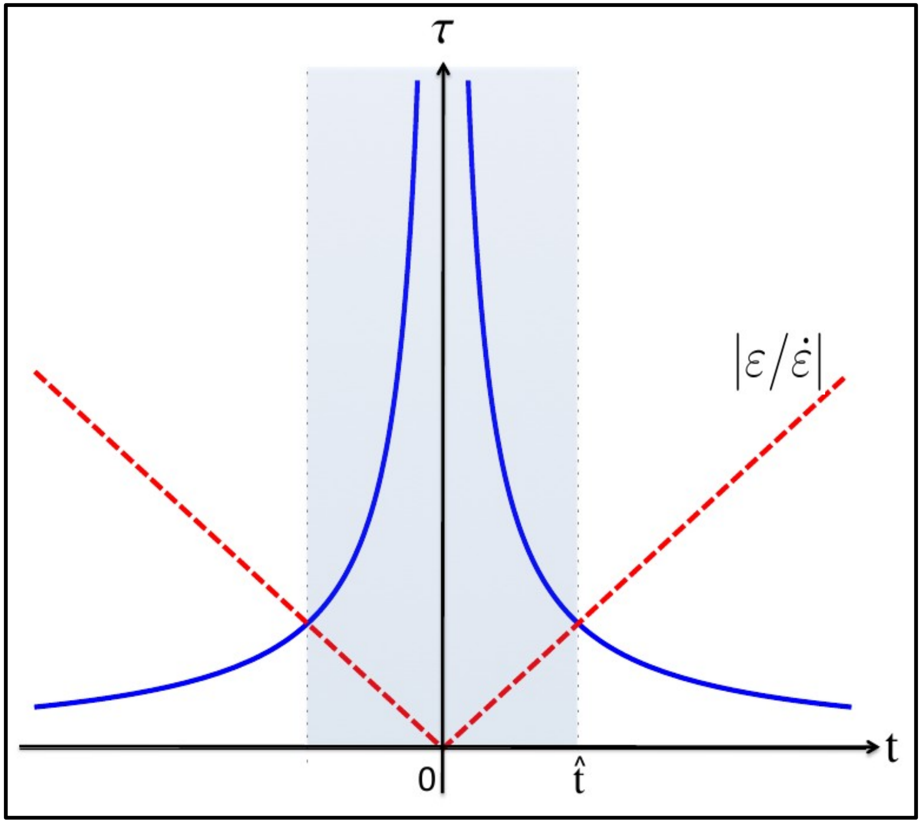
$$\xi(t) = \frac{\xi_0}{|\varepsilon(t)|^\nu}$$

relaxation time

$$\tau(t) = \frac{\tau_0}{|\varepsilon(t)|^{z\nu}}$$

reduced parameter:

$$\varepsilon = \frac{\lambda_c - \lambda}{\lambda_c}$$



Case of linear quench

$$\varepsilon(t) = t/\tau_Q$$

time to the transition

$$\tau(t) \approx |\varepsilon/\dot{\varepsilon}|$$

"freezing time"

$$\hat{t} \sim \left(\tau_0 \tau_Q^{z\nu}\right)^{\frac{1}{1+z\nu}}$$

domain size

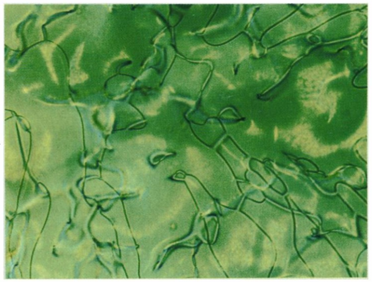
$$\hat{\xi} = \xi(\hat{t}) = \xi_0 \left(\frac{\tau_Q}{\tau_0}\right)^{\frac{\nu}{1+z\nu}}$$

density of defects

$$d \sim \hat{\xi}^{-D}$$

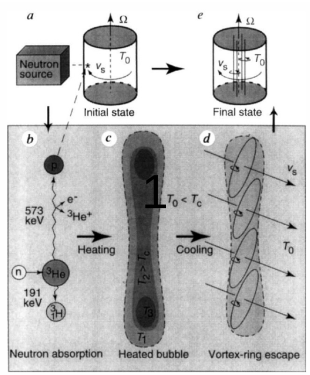
A. del Campo, W. H. Zurek, Int. J. Mod. Phys. A **29**, 1430018 (2014)

Liquid crystals: isotropic/nematic



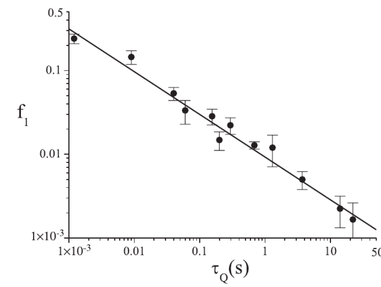
I. Chuang et al. (1991)

Liquid ^{3}He: normal/SF



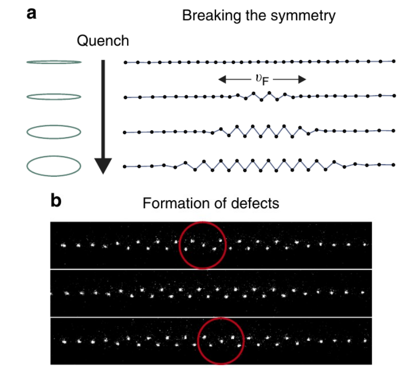
C. Bauerle et al. (1996)
V.M.H Ruutu et al. (1996)

annular Josephson junctions



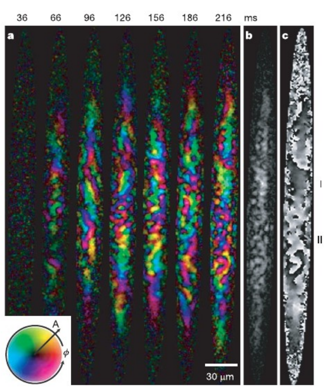
R. Monaco et al. (2009)

1D ion crystals: linear/zig-zag



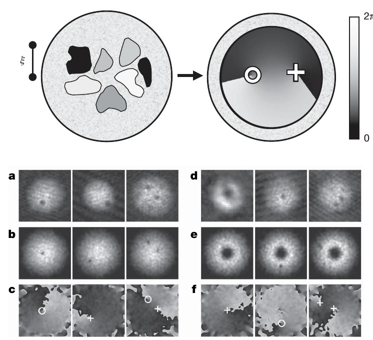
S. Ulm et al. (2013)
K. Pyka et al. (2013)

Bose gases: ferromagnetic



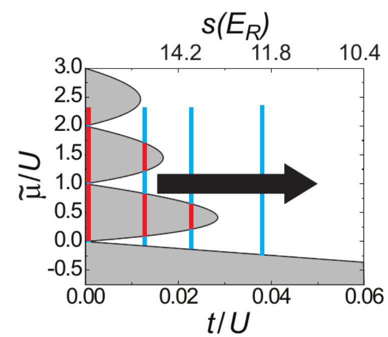
L. E. Sadler et al. (2006)

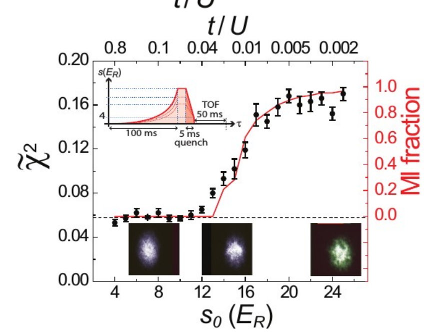
Bose gases: thermal/BEC



C.N. Weiler et al. (2008)

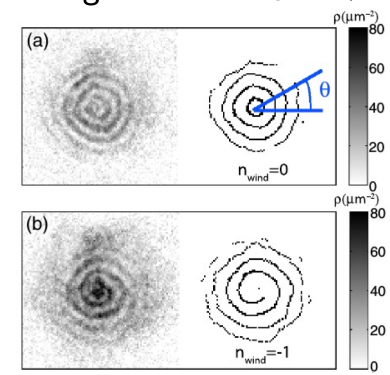
T=0 Bose gases: Mott/SF





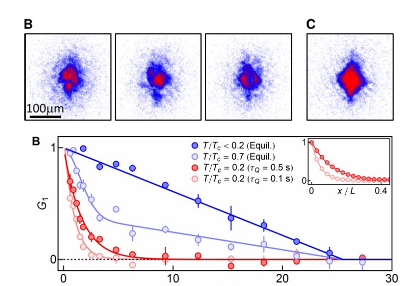
D. Chen et al. (2011)
S. Braun et al. (2014)

Bose gases: thermal/BEC, D < 3



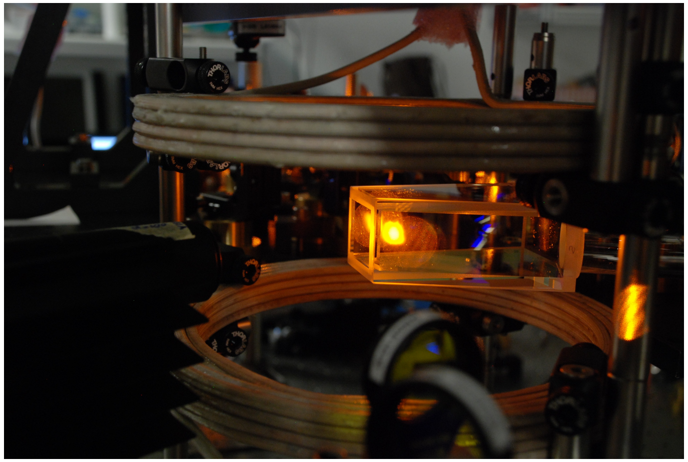
L. Corman et al. (2014)

Hom. Bose gases: thermal/BEC

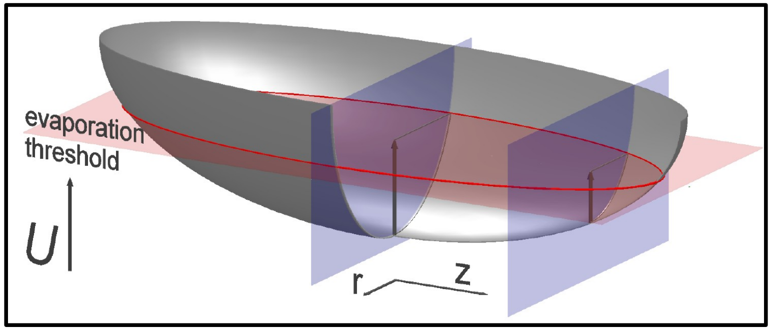


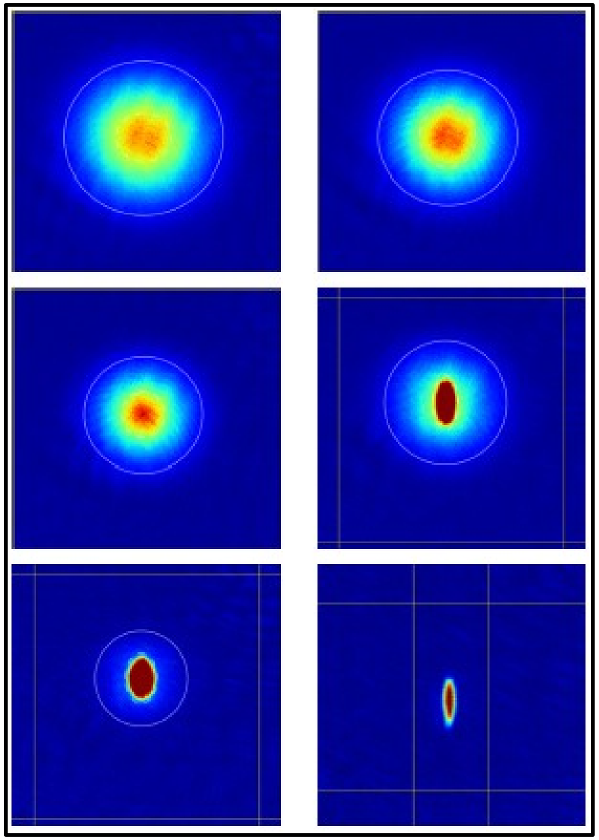
N. Navon et al. (2014)

experimental setup in Trento

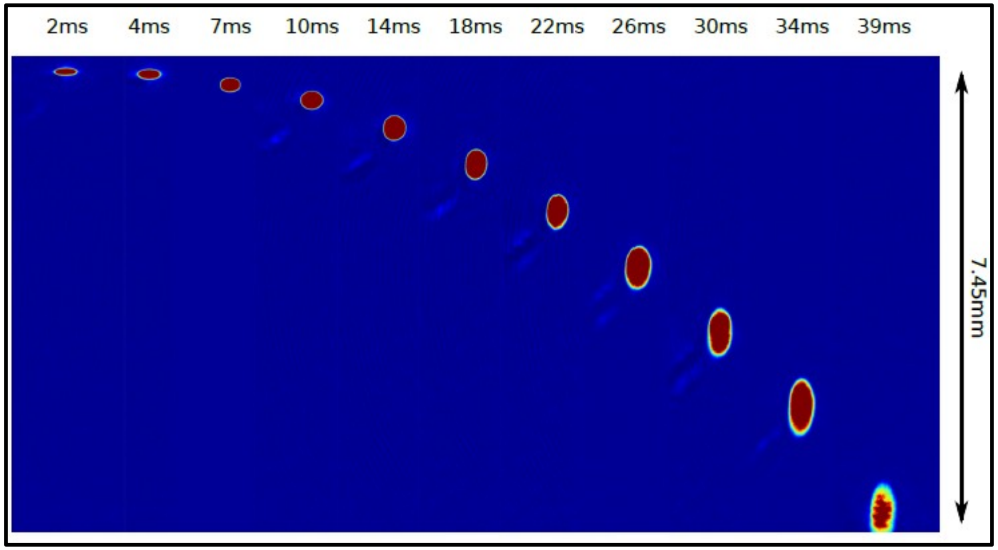


G. Lamporesi *et al.*,
Rev. Sci. Instrum. **84**, 063102 (2013)



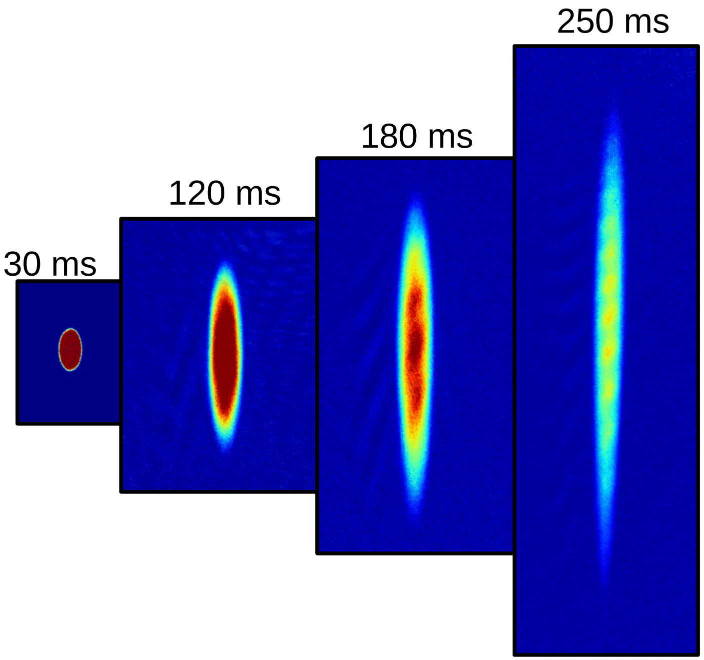


ToF expansion of a BEC



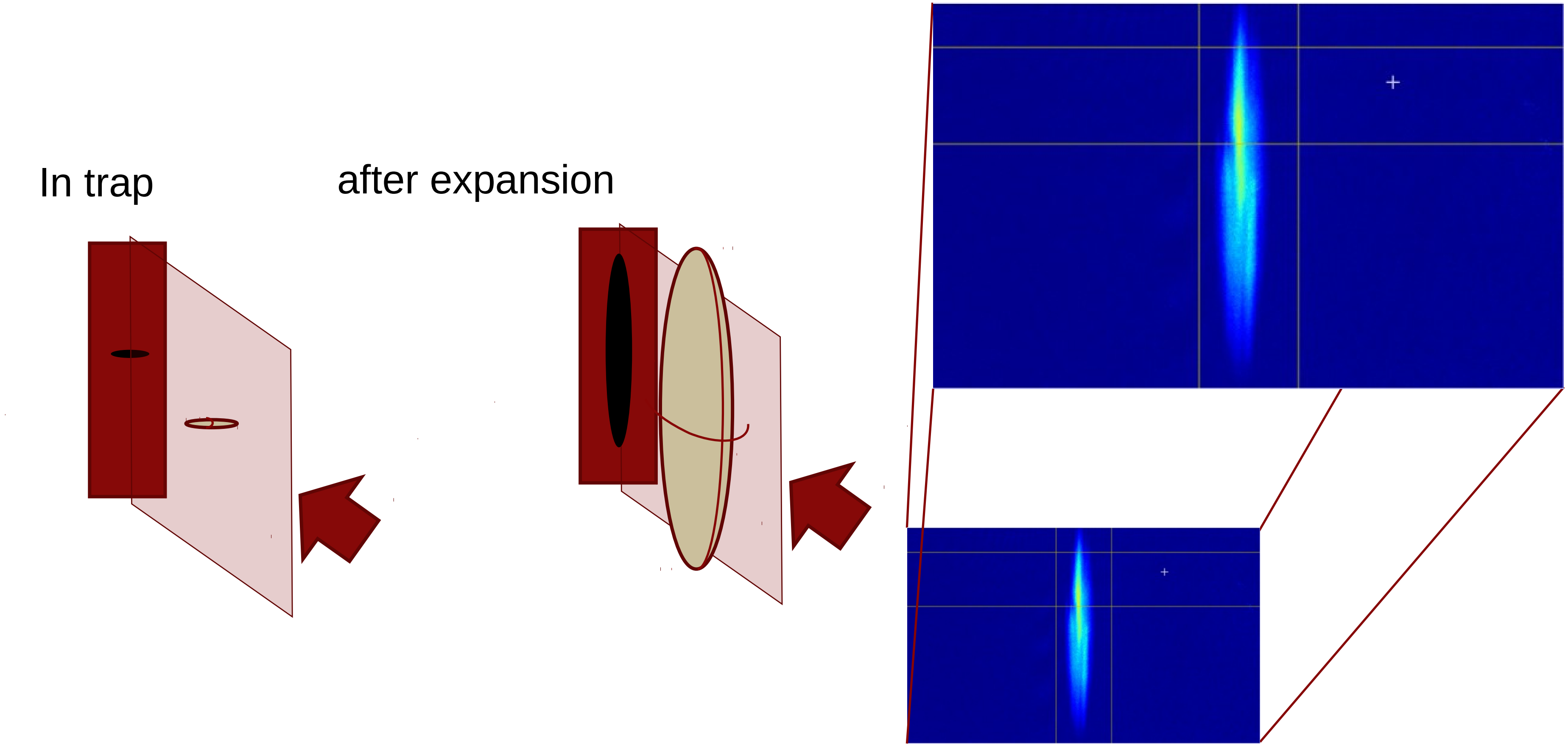
expansion time limited to ~ 40 ms

due to the gravity fall



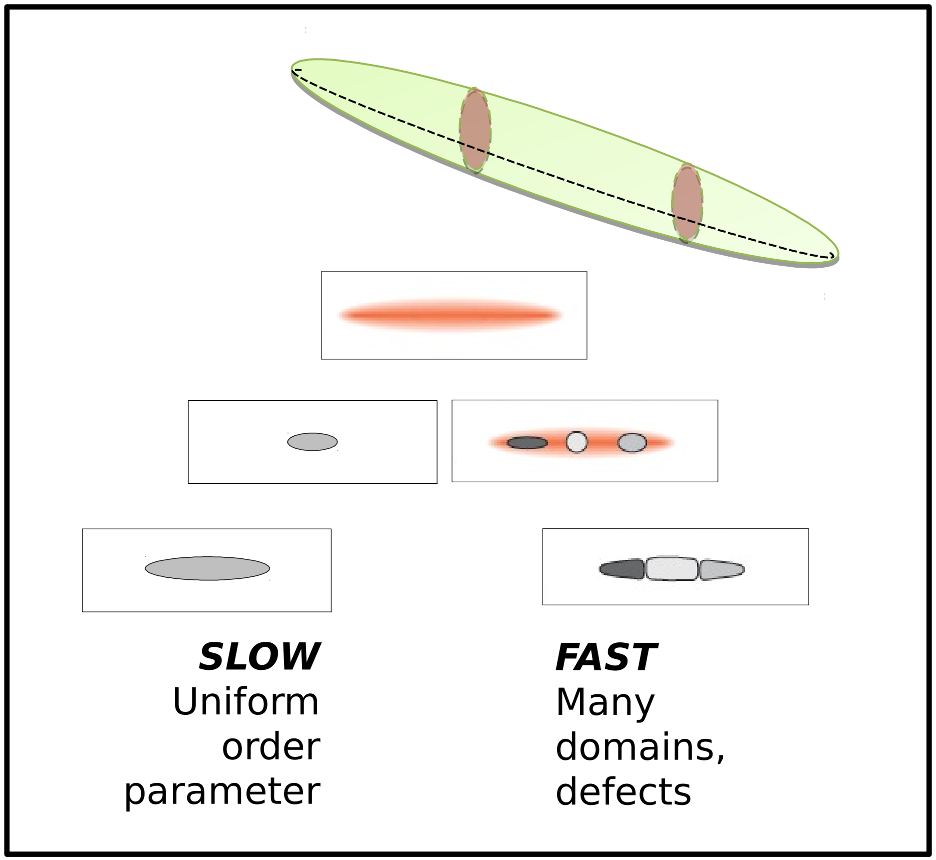
magnetic levitation against the gravity

to increase the expansion time



In trap
after expansion

Defect creation

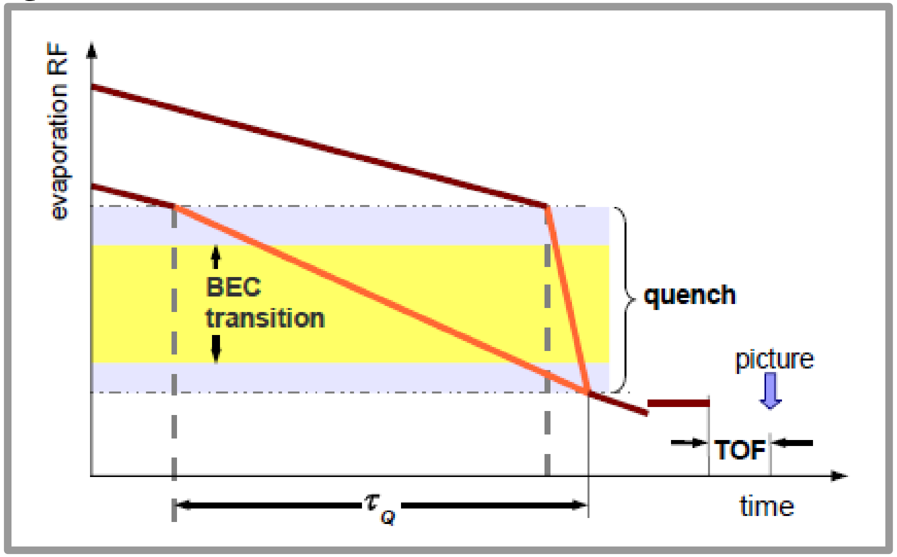


Cigar-shaped Na BEC
130 Hz x 13 Hz
N= 20 millions at Tc

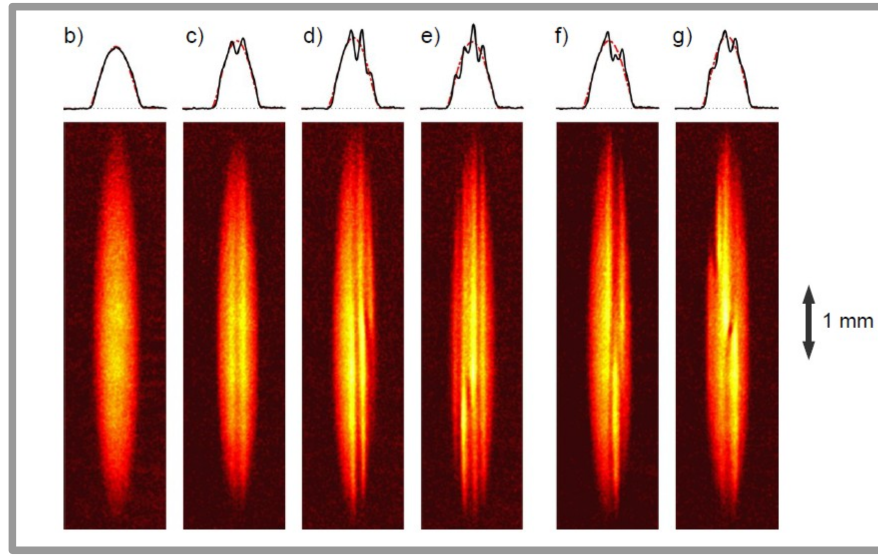
Most likely **SOLITONS** are formed

Observation of the KZ mechanism

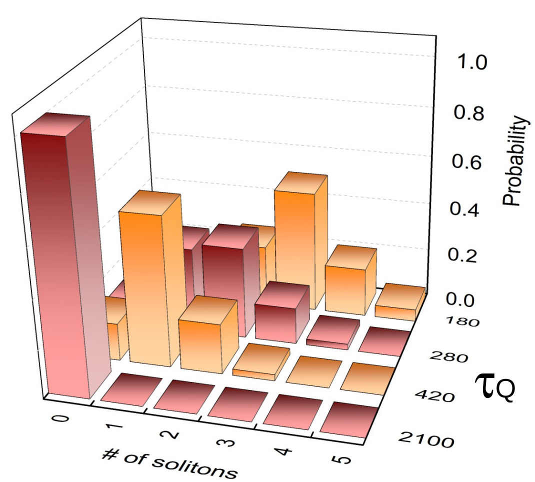
Quench



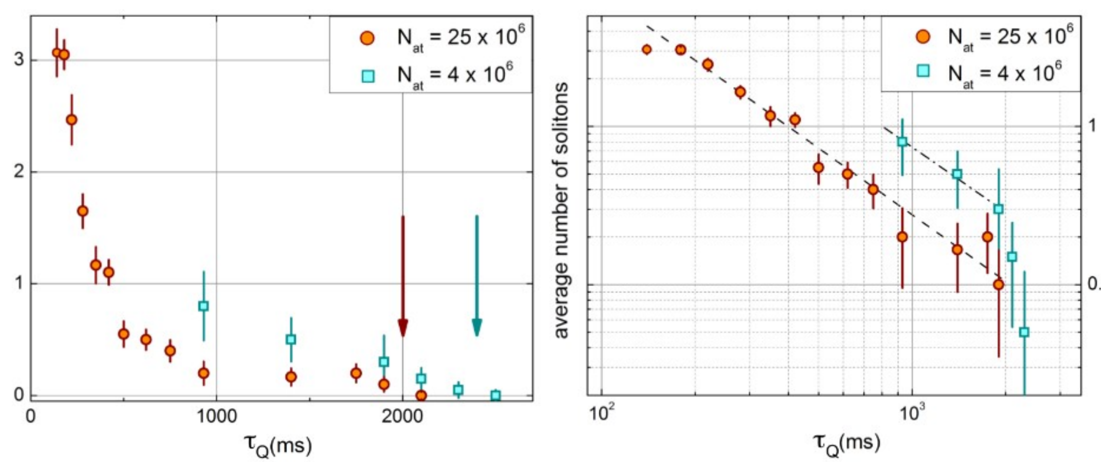
Defect detection



Statistics

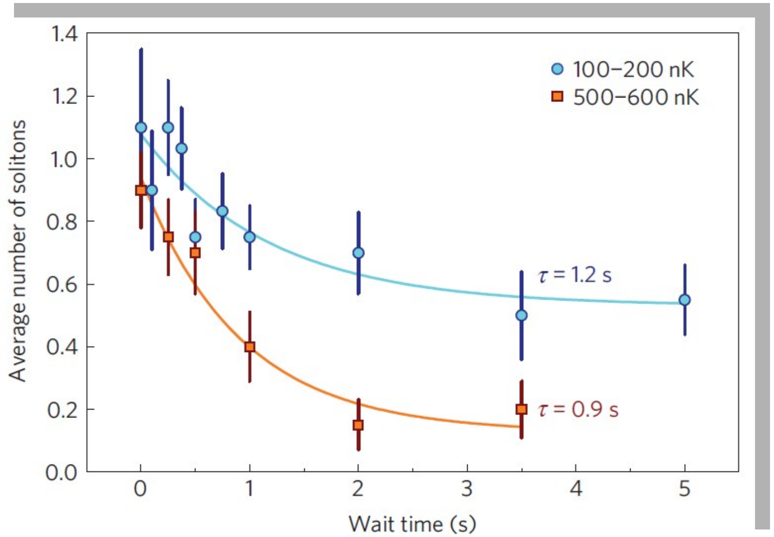


Power-law scaling (α=1.4)

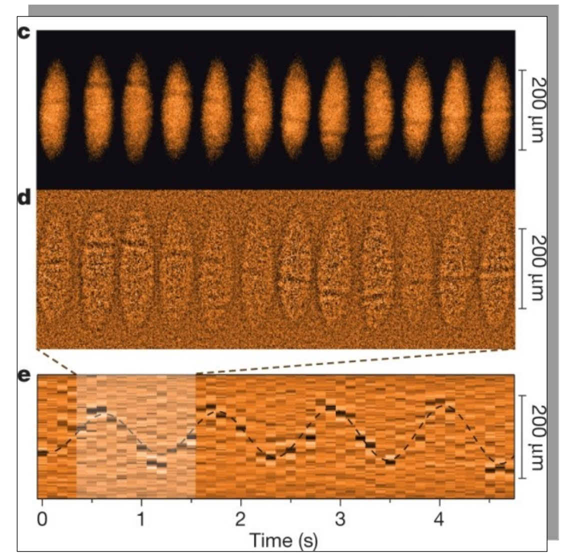


G. Lamporesi *et al.*, Nat Phys **9**, 656 (2013)

The lifetime puzzle



(also in DFG at MIT)



Yefsah *et al.*,
Nature **499**, 426 (2013)

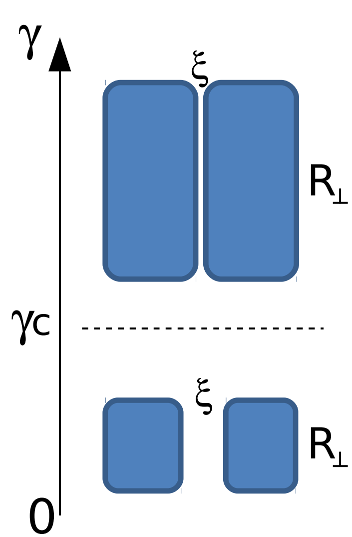
Solitons are expected to be **unstable**

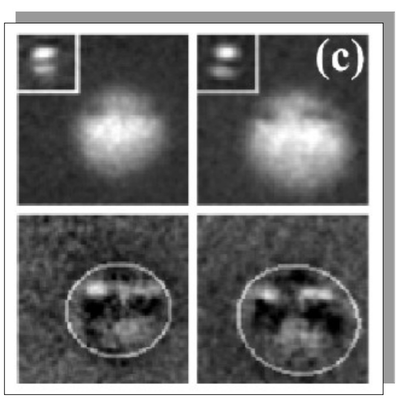
THERMALLY (unless at T=0)

DYNAMICALLY (due to snake instabilities)

... and to decay into **vortex rings**

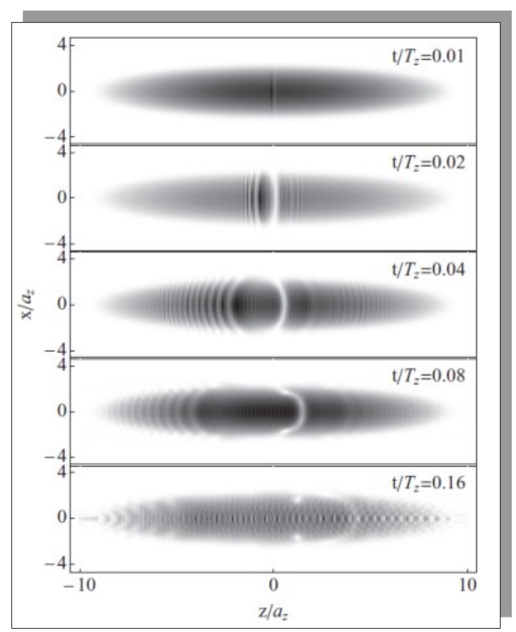
$$\gamma = \frac{\mu}{\hbar\omega_\perp} = \frac{R_\perp}{2\xi}$$



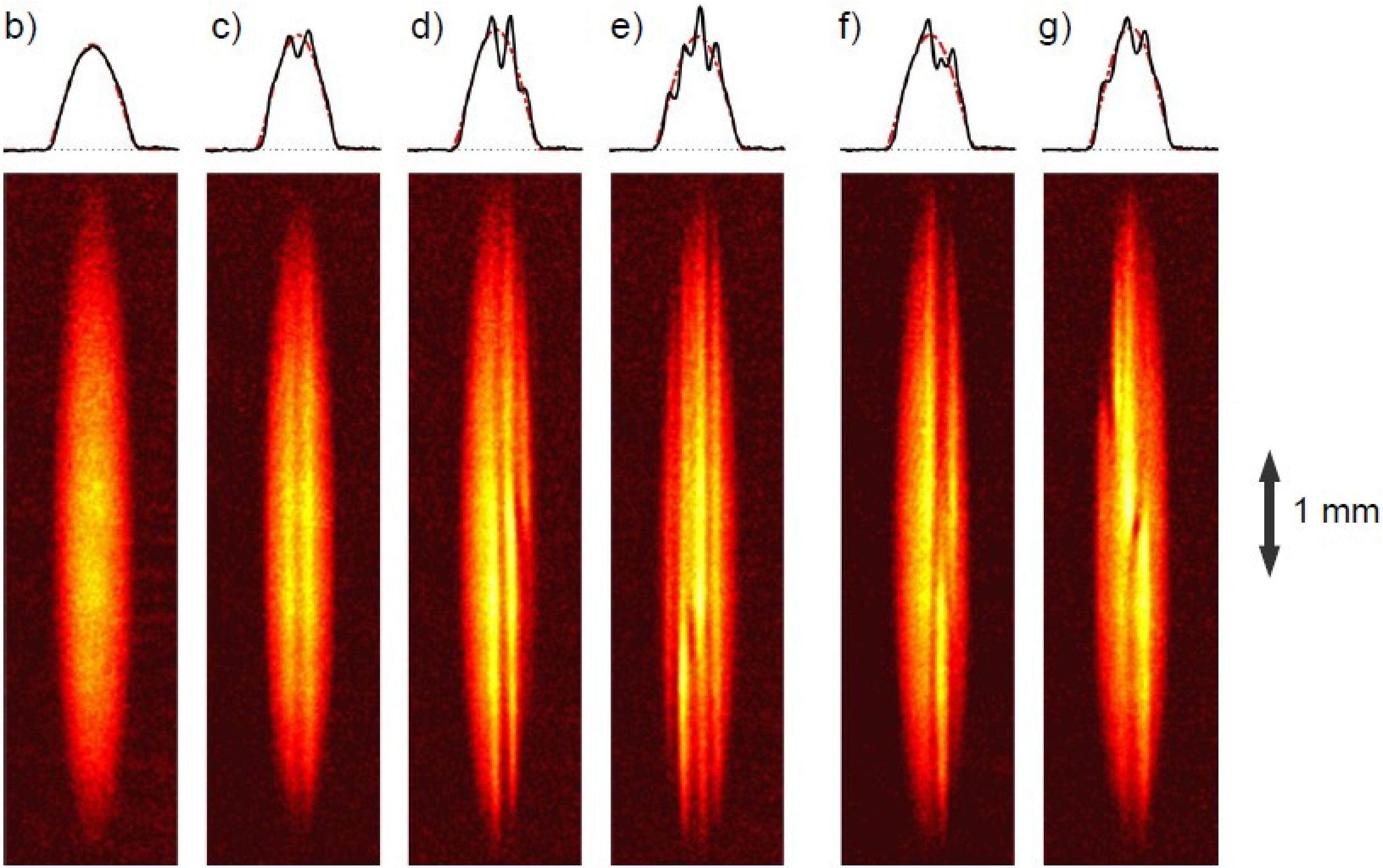


spherical BEC (JILA)

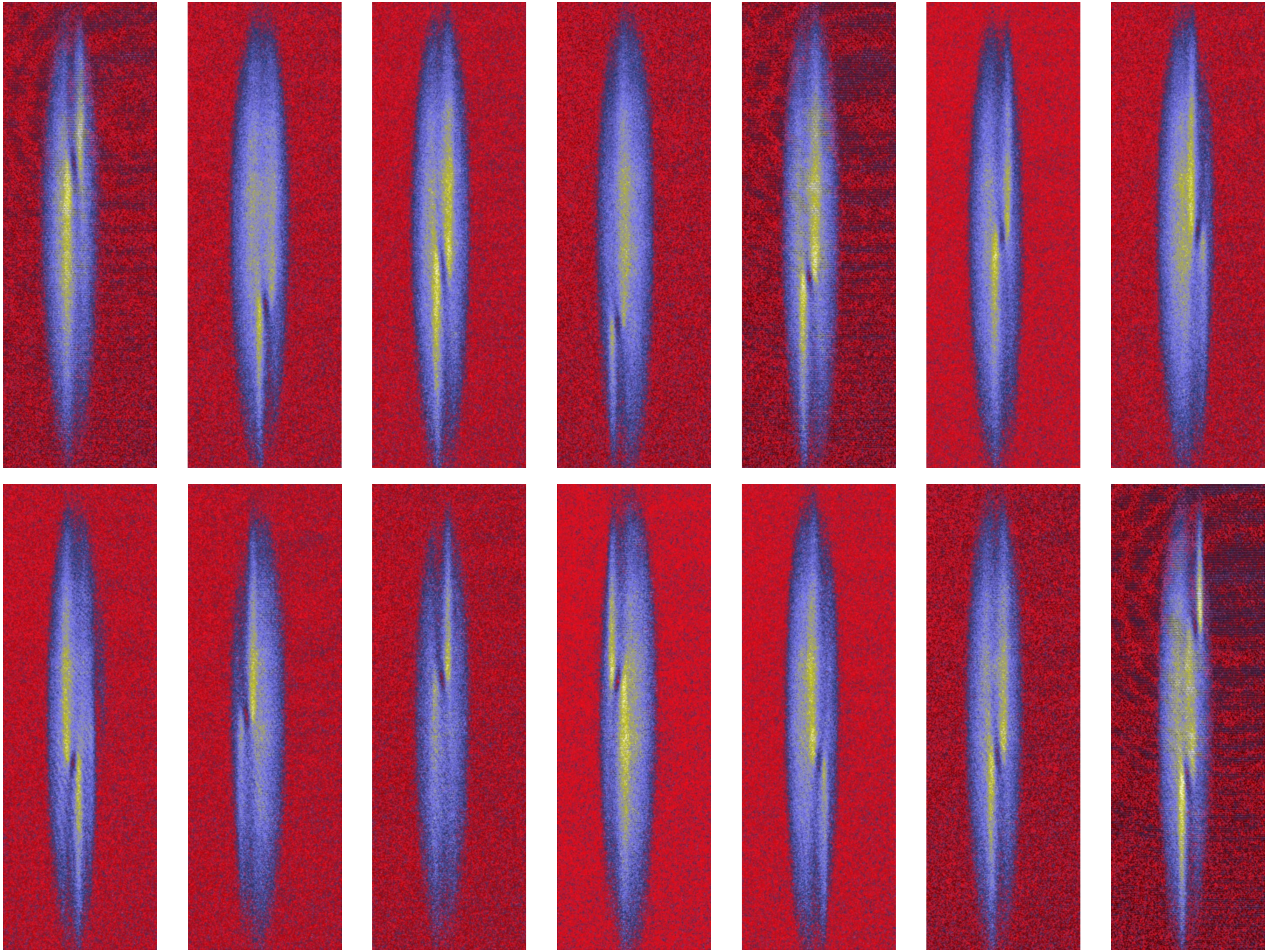
Anderson *et al.*,
PRL **86** 2926 (2001)



Reichl *et al.*,
PRA **88**, 053626 (2013)



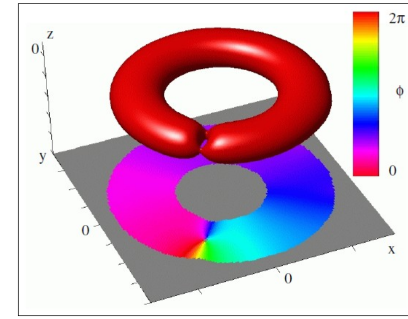
b)
c)
d)
e)
f)
g)
1 mm



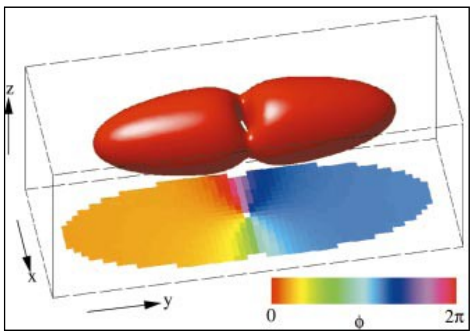
Solitonic vortices

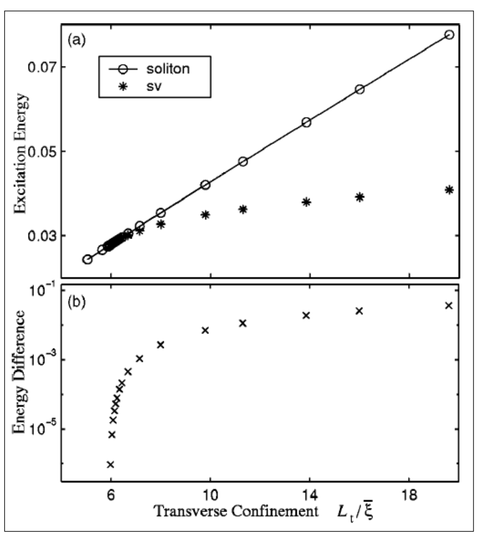
Vortex oriented perpendicularly to the axis of an axisymmetric elongated trap.

- *Quantized vorticity*
- *Anisotropic phase pattern*
- *Planar density depletion*



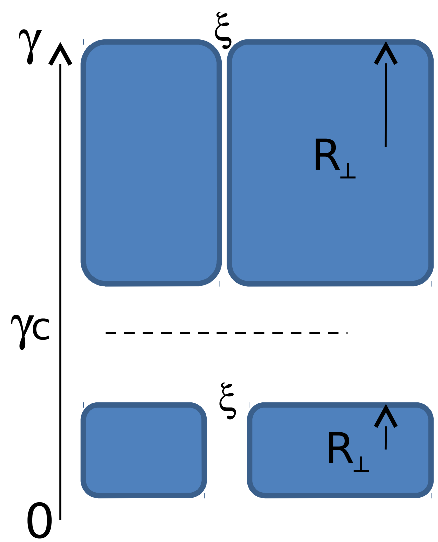
Brand *et al.*, JPB **34**, L113 (2001)

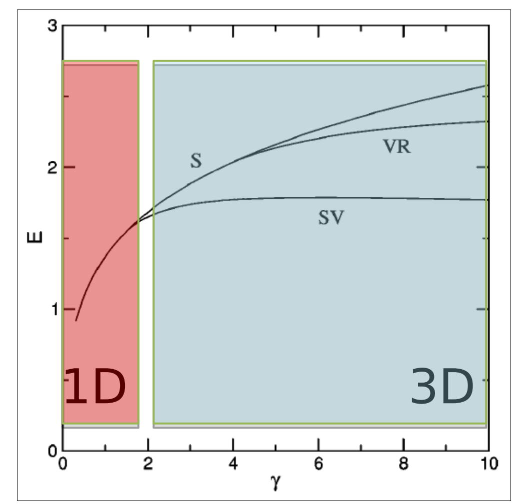




Brand *et al.*, PRA **65**, 043612 (2002)

$$\gamma = \frac{\mu}{\hbar\omega_\perp} = \frac{R_\perp}{2\xi}$$

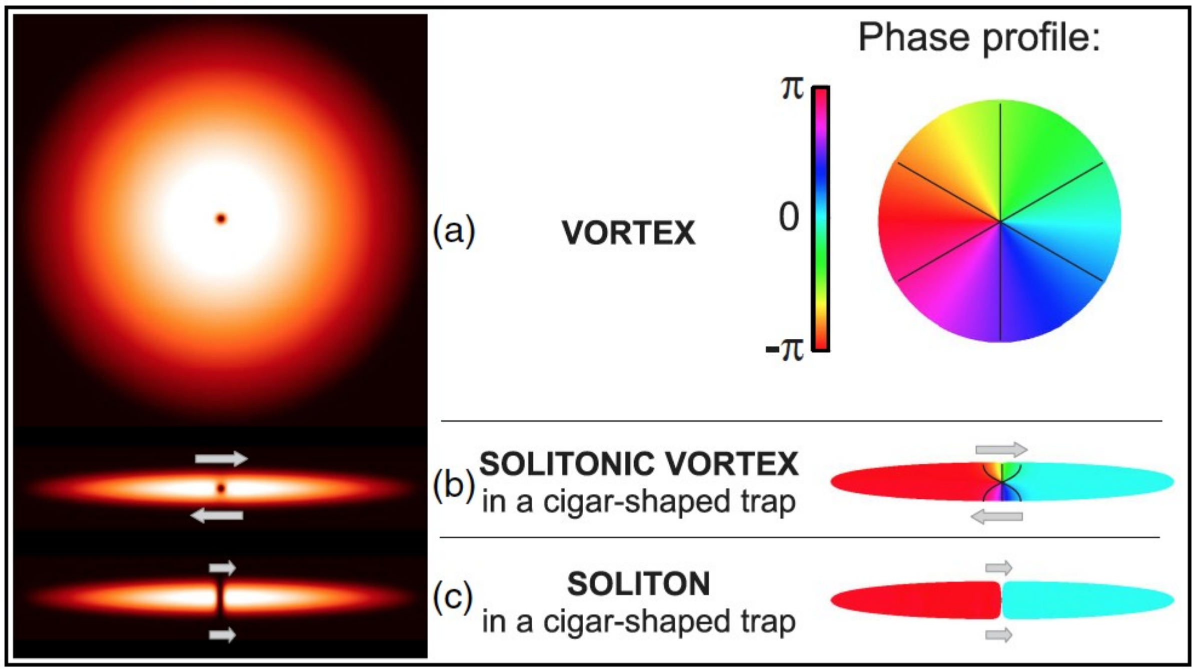




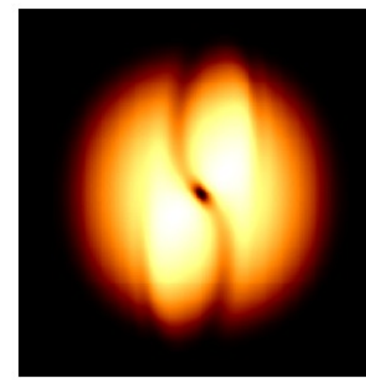
Komineas *et al.*, PRA **68**, 043617 (2003)

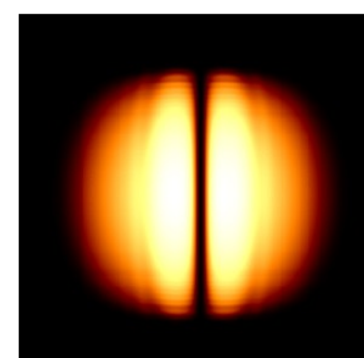
Solitonic vortices

Density in trap ***Phase*** ***Density after free expansion***



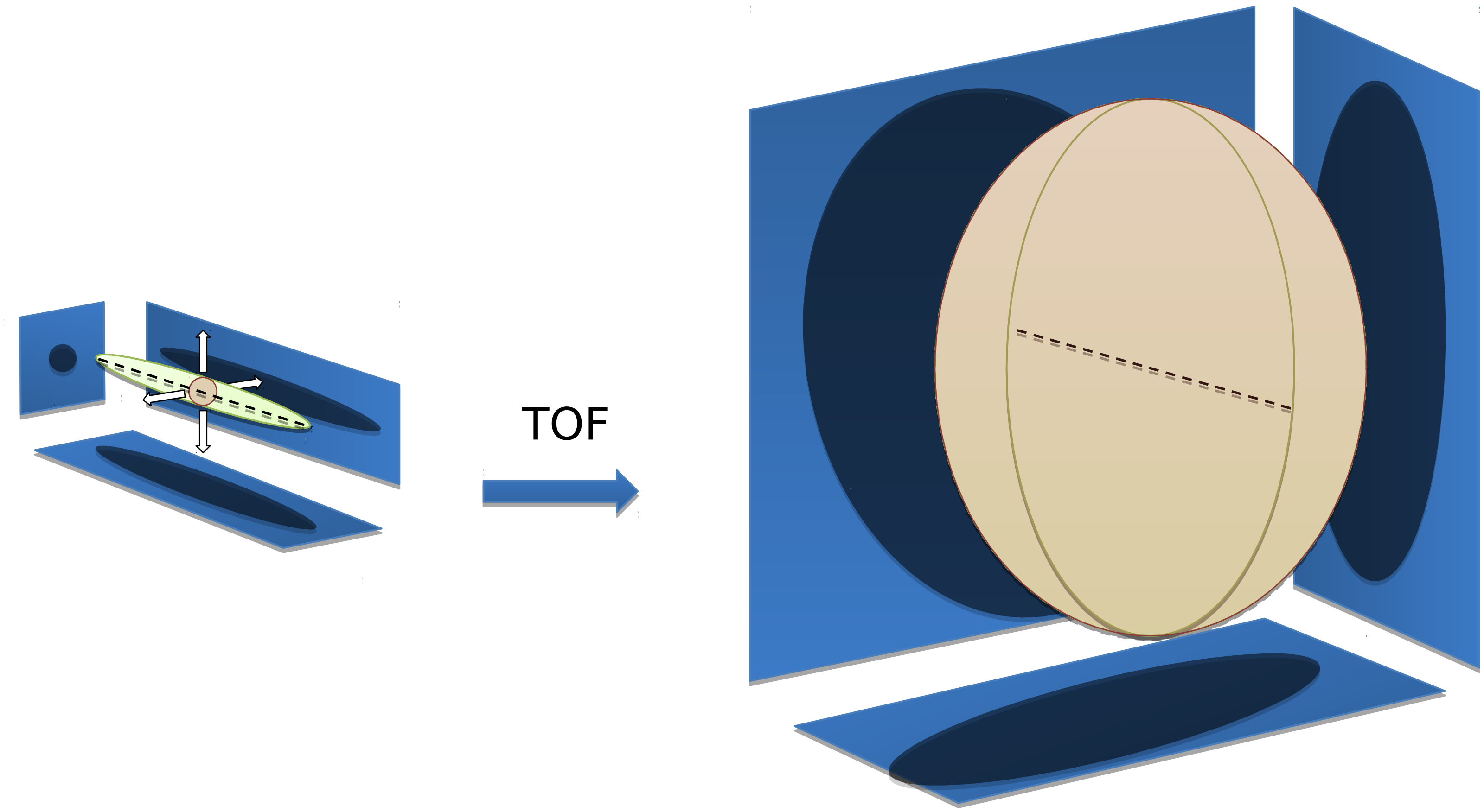
<u>Asymmetric twist</u>





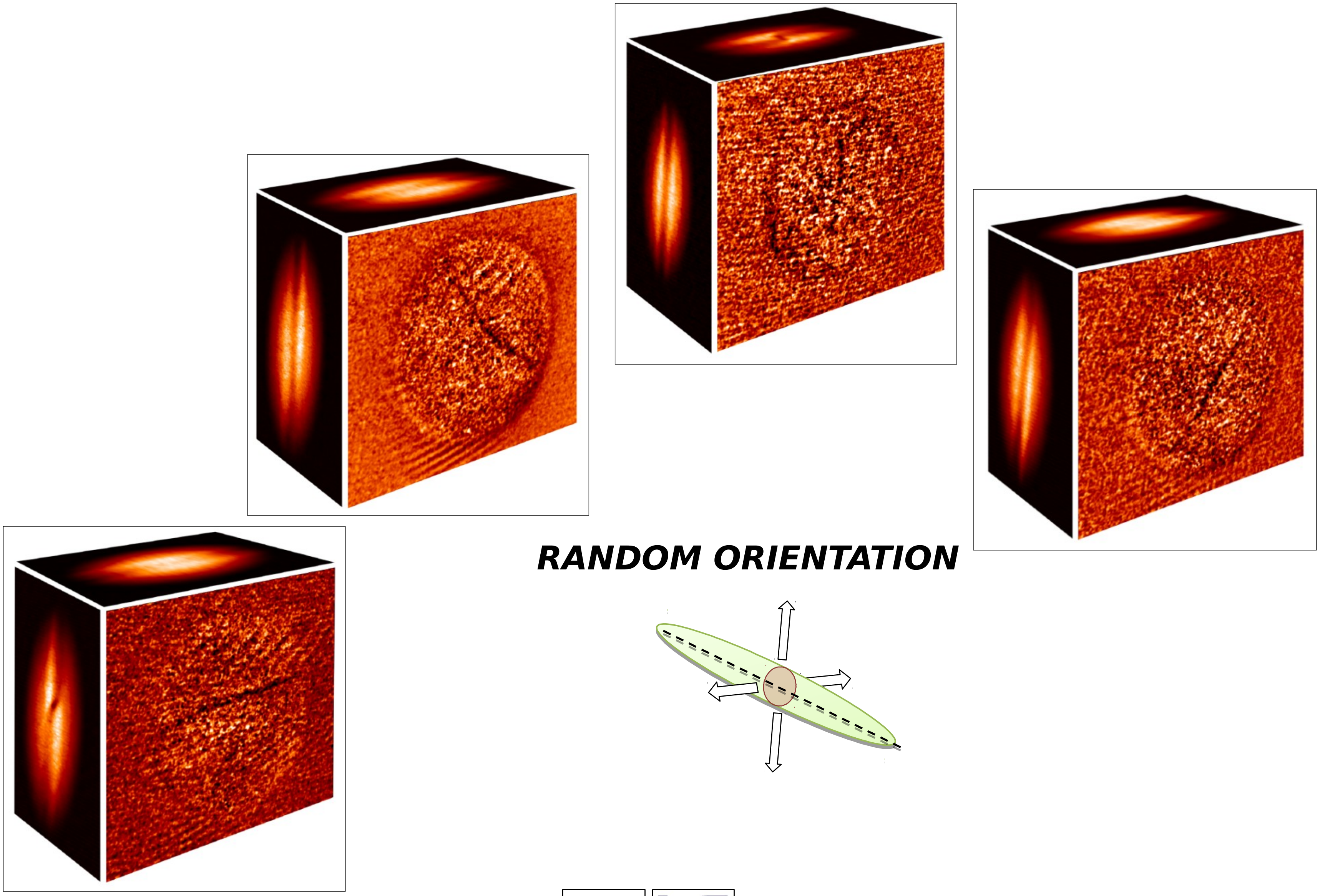
M. Tylutki *et al*., EPJ-ST **224**, 577 (2015)

Solitonic vortices



Solitonic vortices

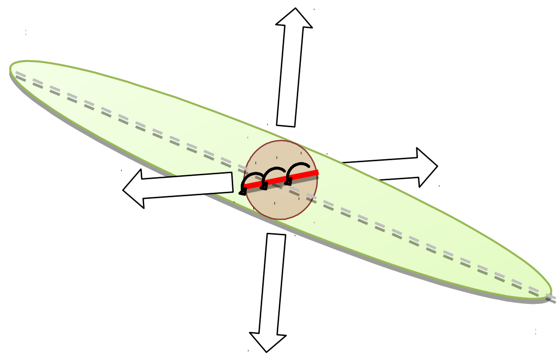
Triaxial absorption imaging after long TOF



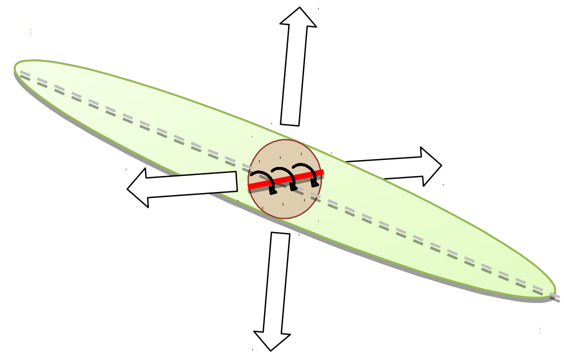
S. Donadello *et al.*, PRL **113**, 065302 (2014)

Solitonic vortices

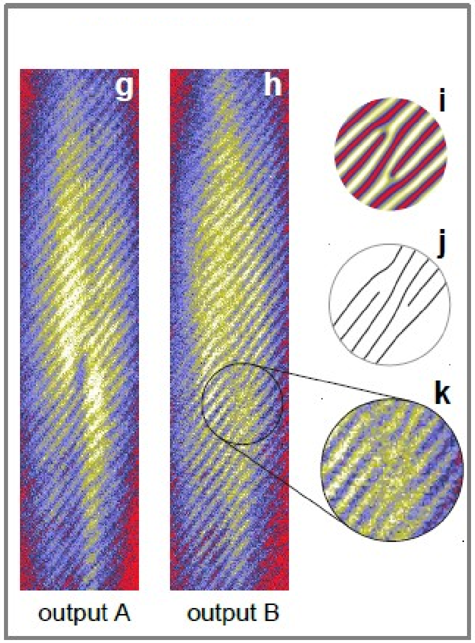
RANDOM SIGN

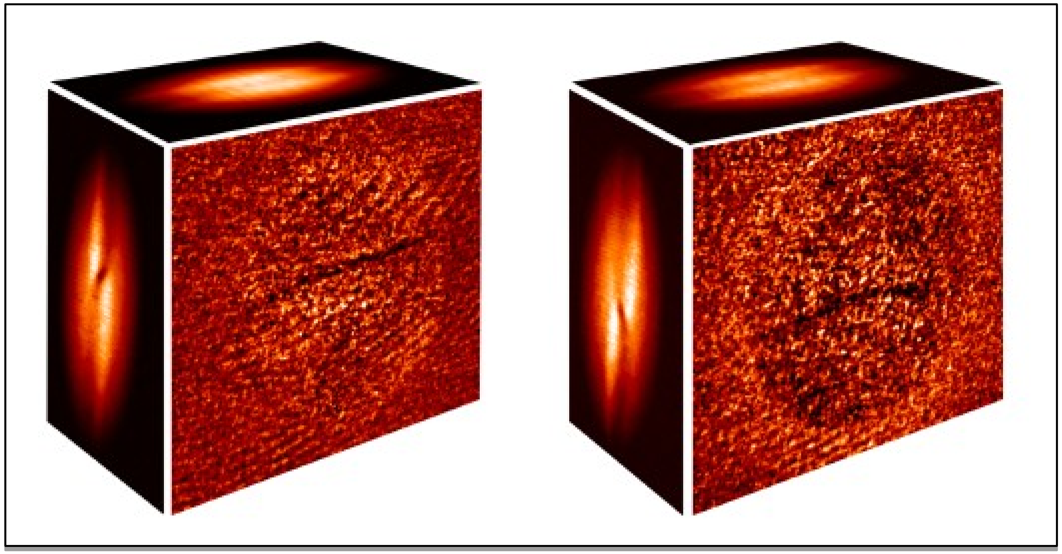


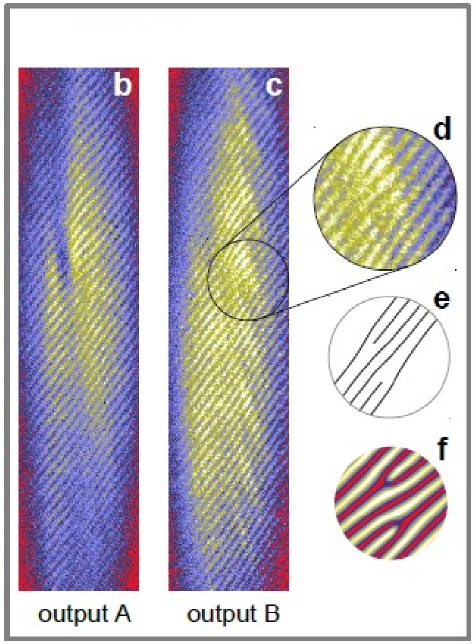
VORTEX



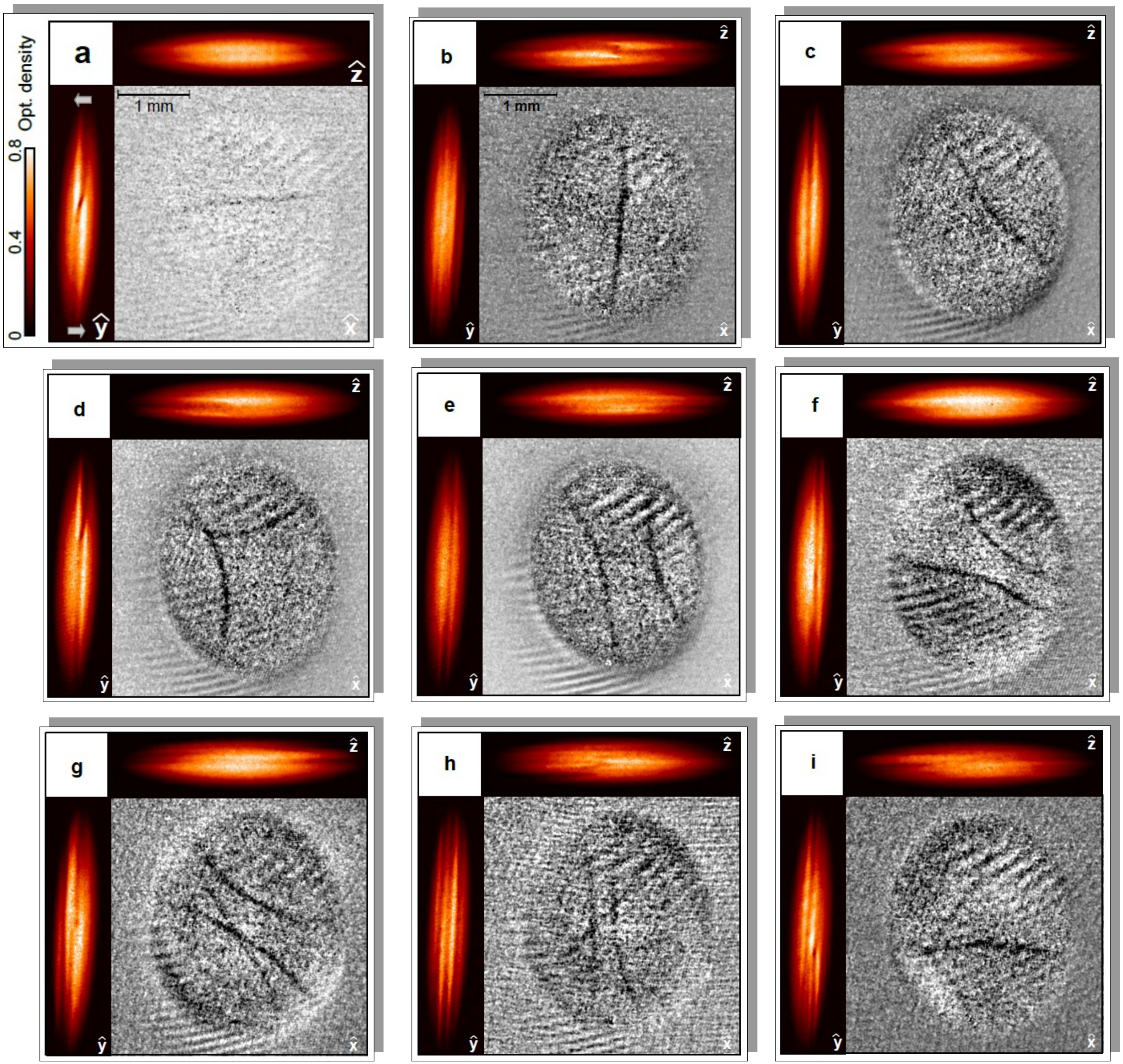
ANTIVORTEX







Solitonic vortices



RANDOM NUMBER

1

2

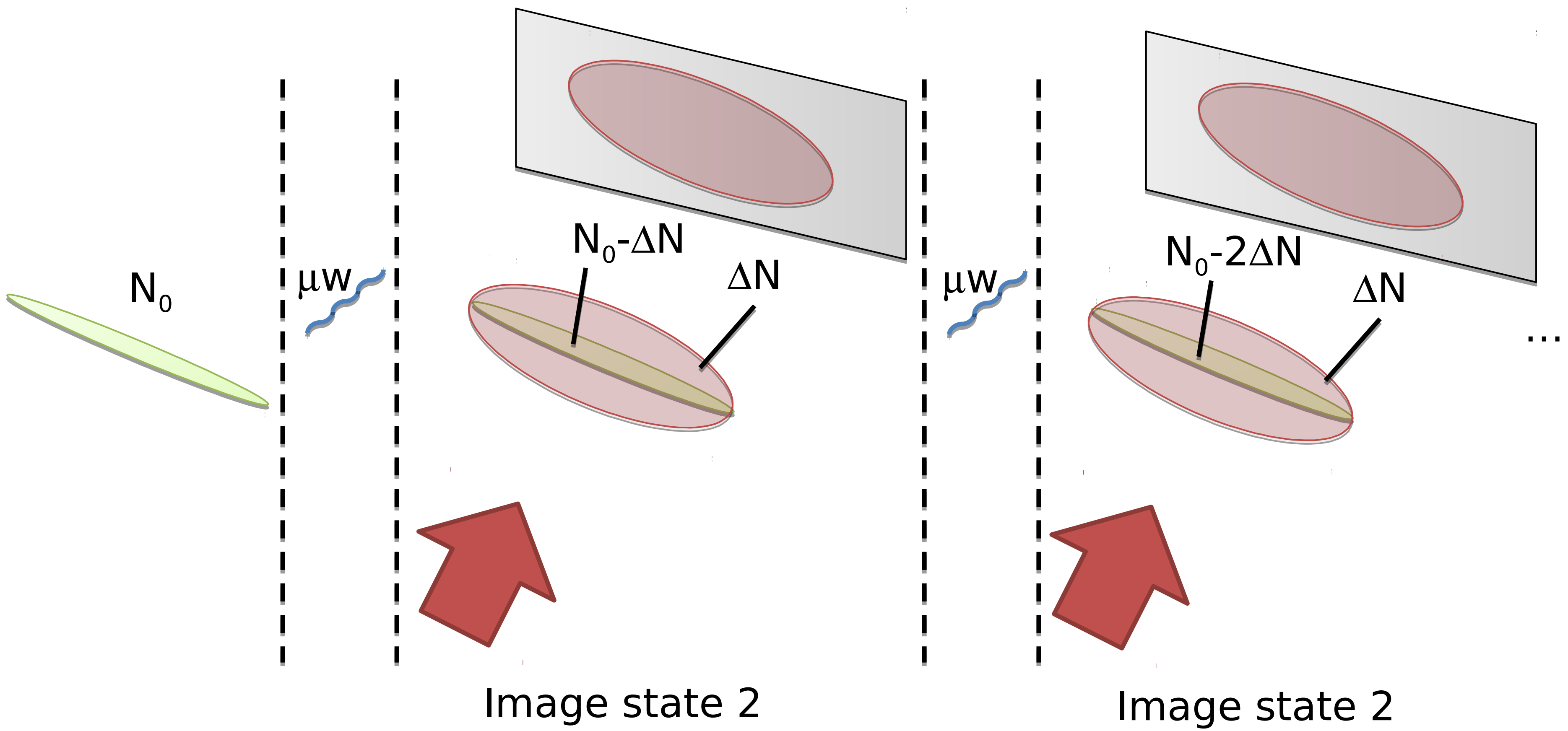
3

Real-time imaging of defect dynamics

Method: Real-time imaging of a small out-coupled fraction

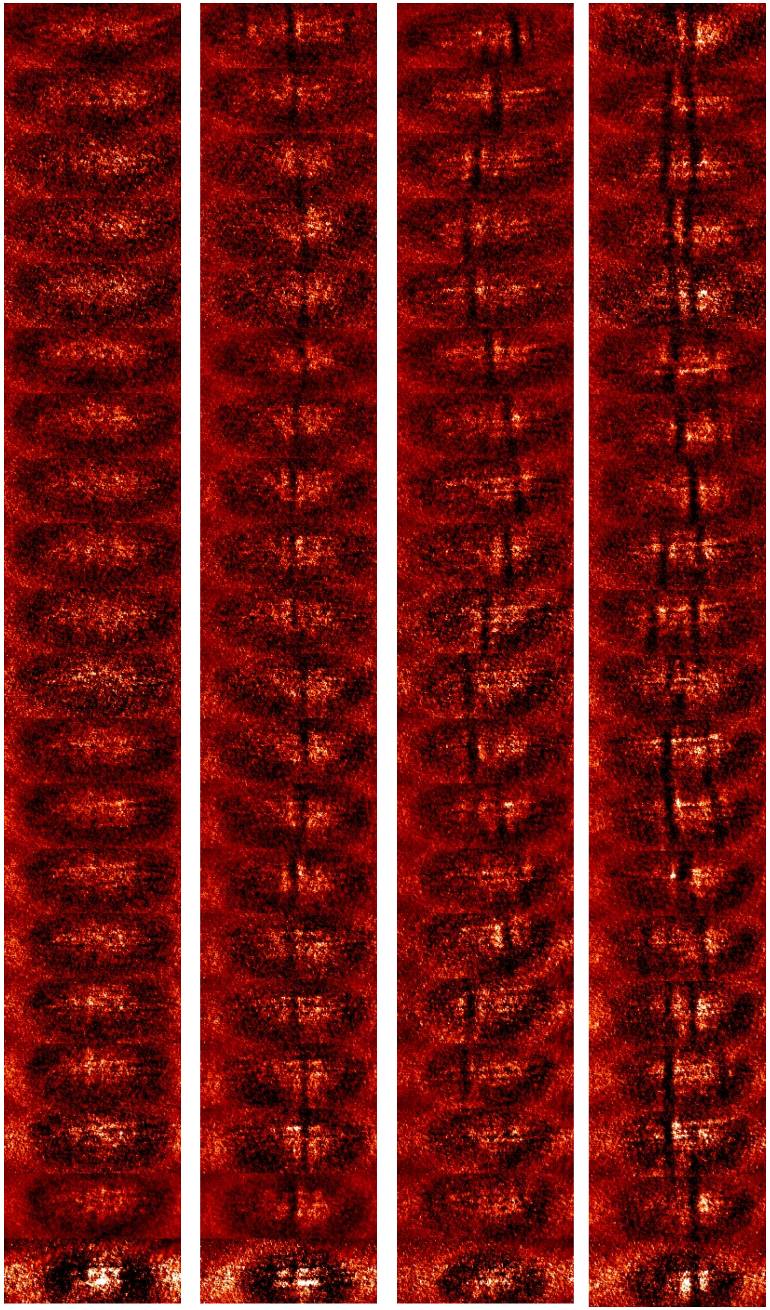
μw pulse $|1,-1\rangle \longrightarrow |2,-2\rangle$ ($\Delta N/N_0$ = 4%)

Antitrapped expansion with optical levitation



D. V. Freilich *et al*., Science **329**, 1182 (2010)

Dynamics of solitonic vortices

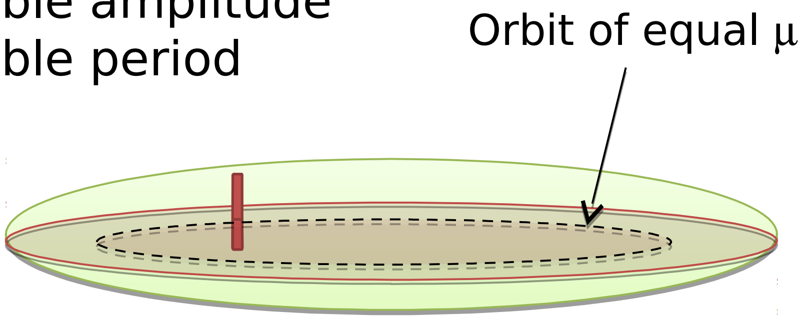


Dynamics of solitonic vortices

SINGLE VORTEX DYNAMICS

Select BEC with 1 vortex
Long sampling time (81 ms (Tz=77 ms))
Period variation with time (check model)

Oscillatory motion
Variable amplitude
Variable period



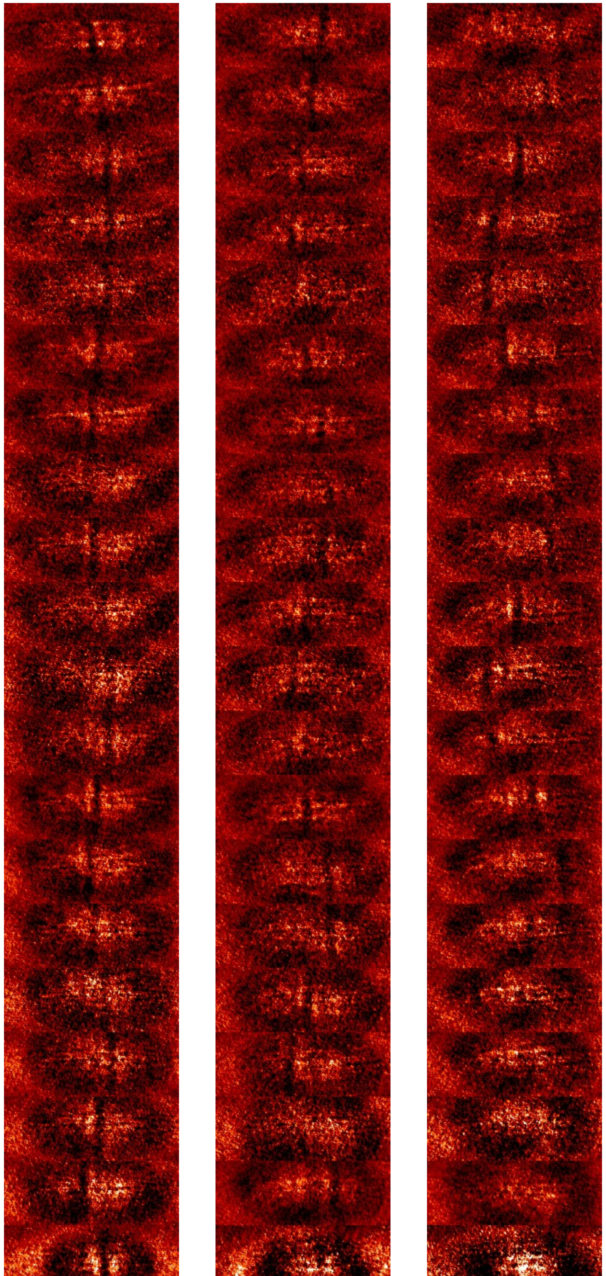
Soliton oscillation period

$$T = \sqrt{2}\ T_z$$

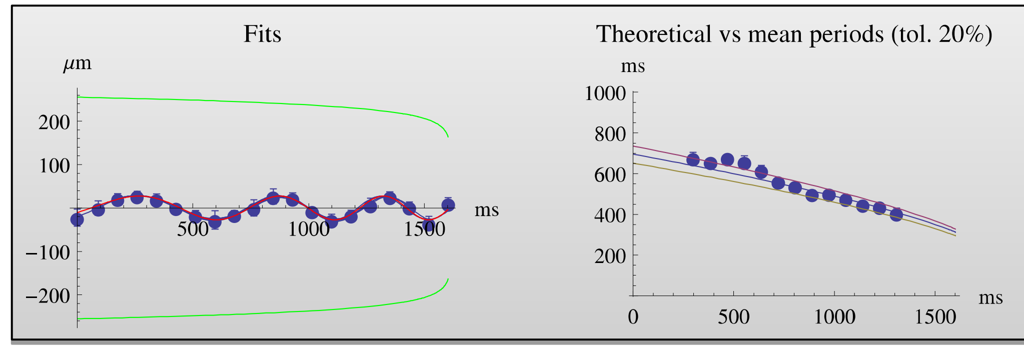
Vortex orbital period

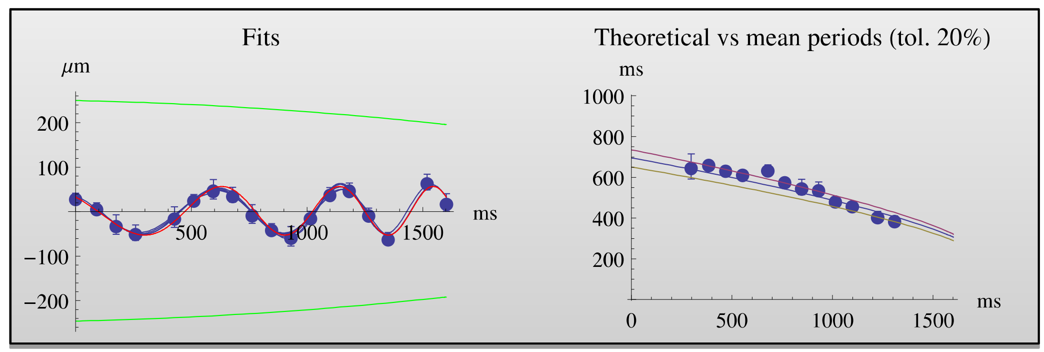
$$T = T_z \frac{4}{3} \frac{\mu_0}{\hbar\omega_\perp}(1 - \frac{A_z^2}{R_z^2})/ln(\frac{2\mu_0}{\hbar\omega_\perp})$$

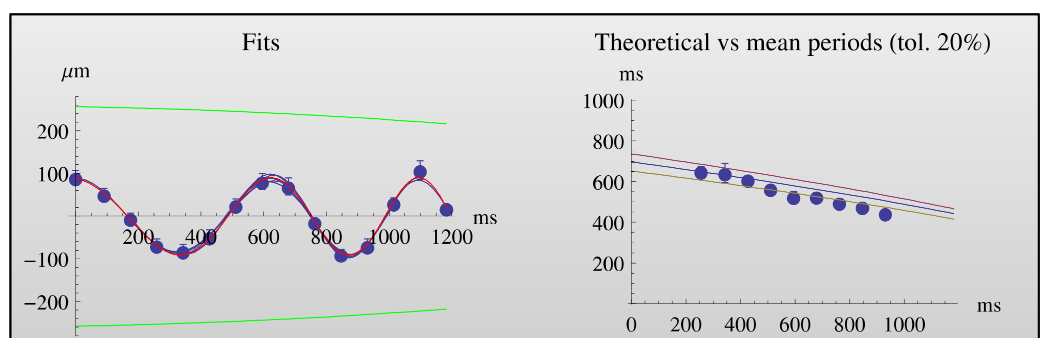
Dynamics of solitonic vortices



$$T = T_z \frac{4}{3}\frac{\mu_0}{\hbar\omega_\perp}(1-\frac{A_z^2}{R_z^2})/ln(\frac{2\mu_0}{\hbar\omega_\perp})$$







Dynamics of solitonic vortices

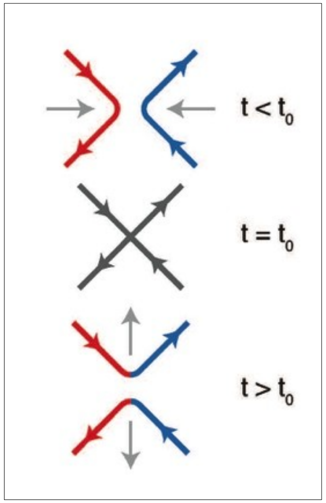
Select BECs with more than 1 vortex
Short sampling time (27 ms (Tz=77 ms))
Observation of phase shifts
Anomalous decay of vortex number

MANY VORTICES DYNAMICS (INTERACTION & DECAY)

- Vortex annihilation
- Vortex decay
- Vortex reconnection (tail exchange)

QUANTUM TURBULENCE

Reconnection in liquid crystals



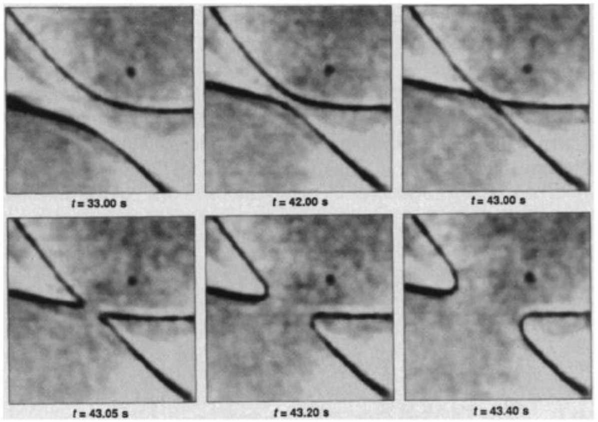
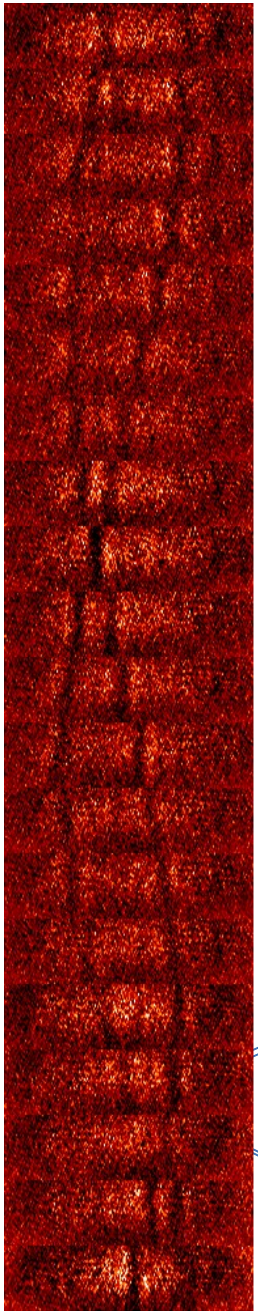
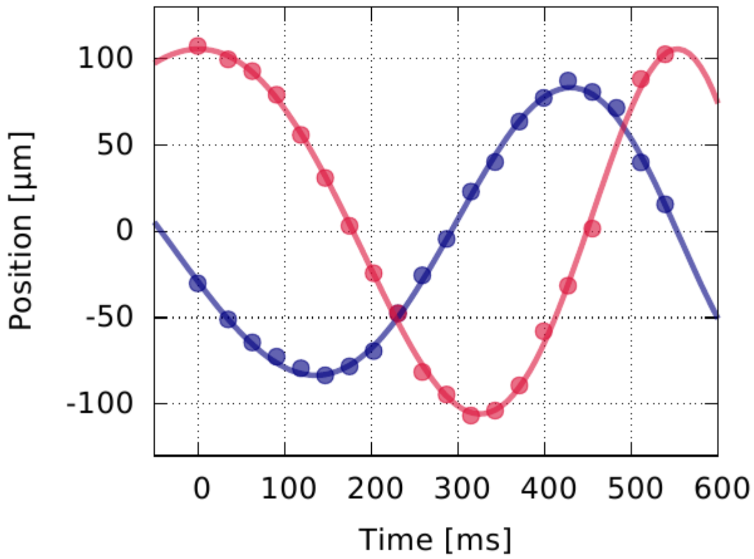


Fig. 1. String intercommutation sequence, showing two type-$\frac{1}{2}$ strings crossing each other and reconnecting the other way. Each picture shows a region 140 μm in width. Note that the two strings lie almost in the same plane—the intercommutation occurs after the strings move toward each other under their mutual attraction.

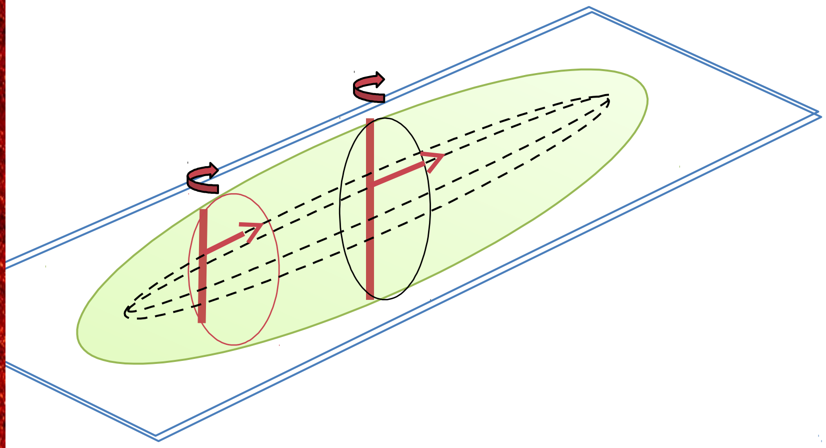
Chuang *et al.*, Science **251**, 1336 (1991)

Dynamics of solitonic vortices

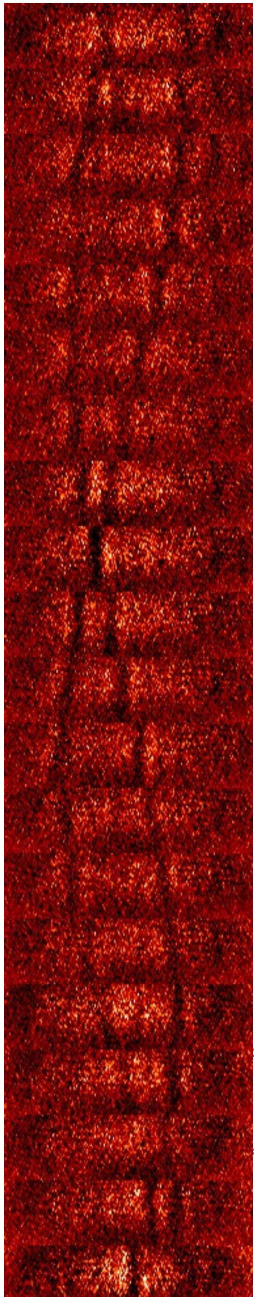


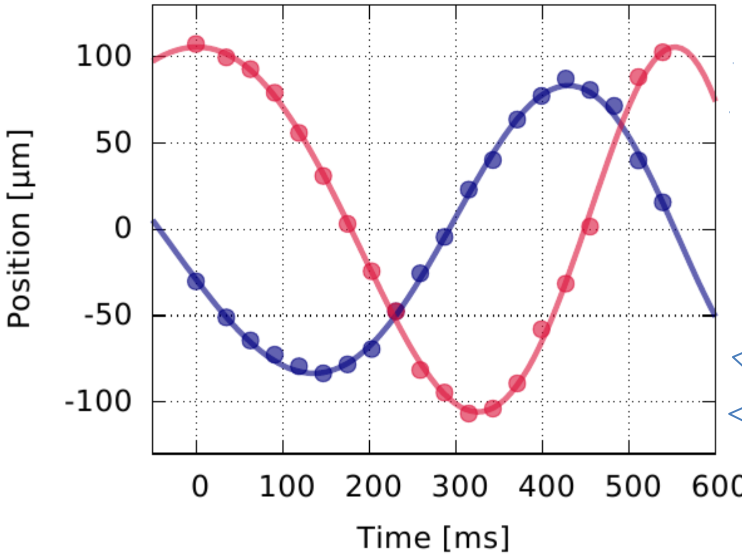


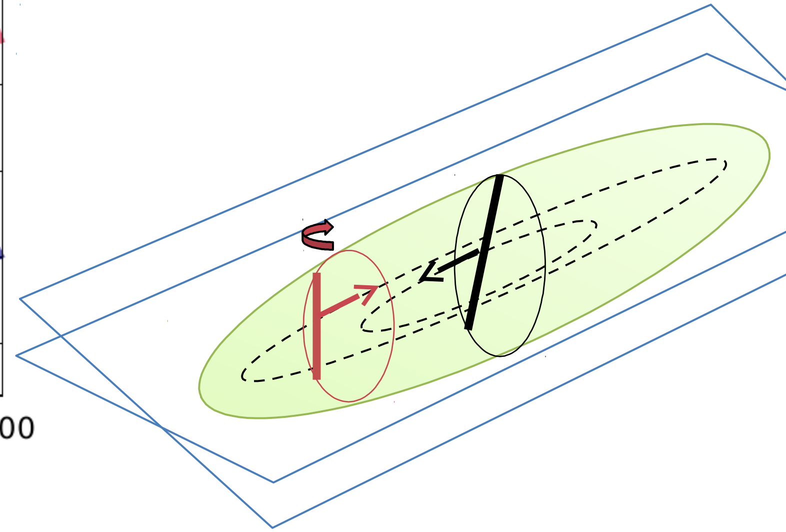
No perturbation at crossing point
No apparent interaction



Dynamics of solitonic vortices

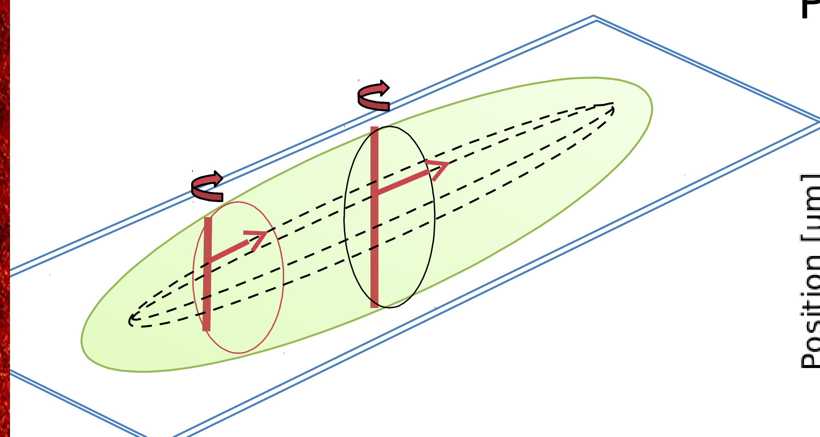


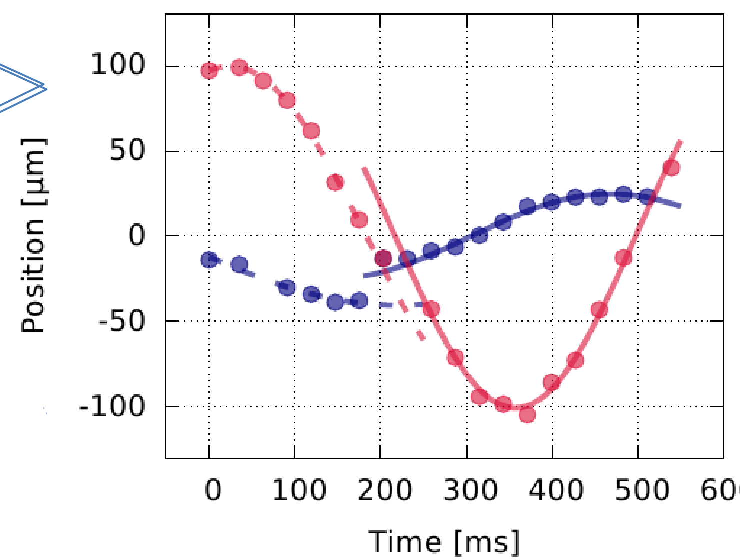


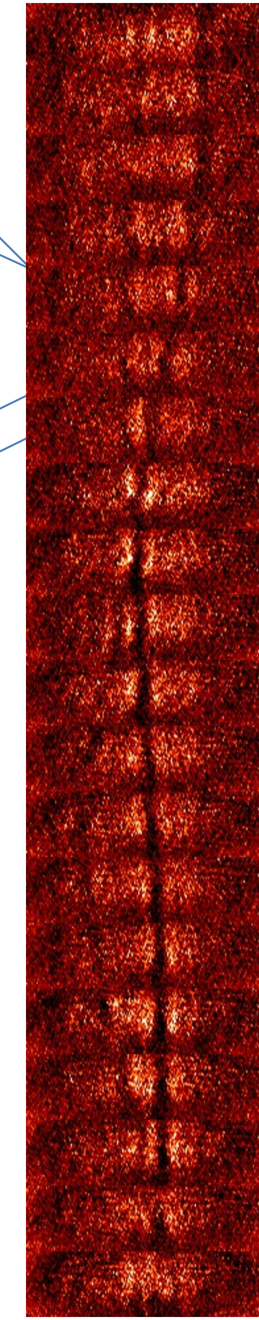


No perturbation at crossing point
No apparent interaction

Perturbation at crossing point
Possible interaction !!







Resonantly coupled spinor BECs

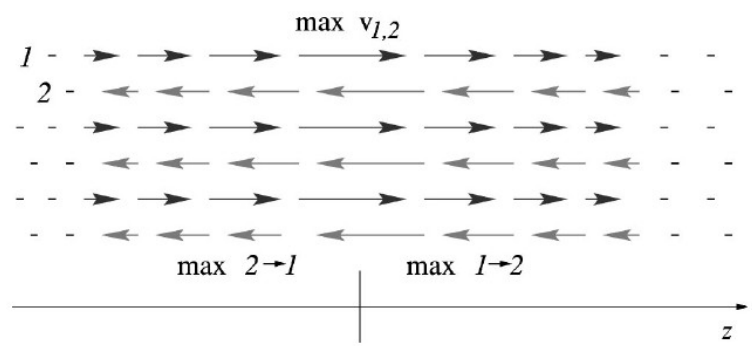
Coherent coupling between two internal states of a spinor BEC

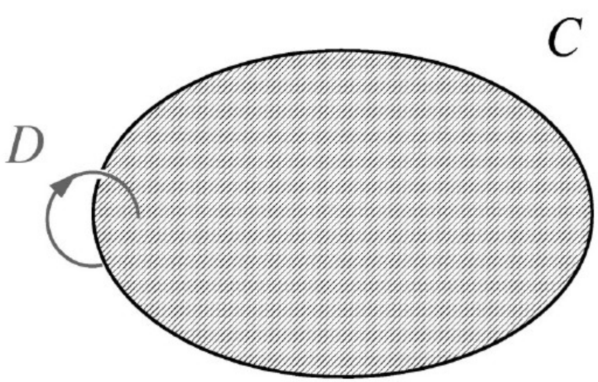
↓

Generation of topological defects (domain walls on the relative phase)

$$E[\varphi_1,\varphi_2]=\int d^3\boldsymbol{x}\left[\frac{\hbar^2}{2m}[n_1(\nabla\varphi_1)^2+n_2(\nabla\varphi_2)^2] -\hbar\Omega\sqrt{n_1 n_2}\cos(\varphi_1-\varphi_2)\right]$$

$$\varphi_A\equiv\varphi_1-\varphi_2=4\arctan e^{kz}, \qquad k^2=\frac{m\Omega}{\hbar}\frac{n}{\sqrt{n_1 n_2}}$$





In a finite-sized 3D geometry ⟶ vortex lines at the domain wall boundaries

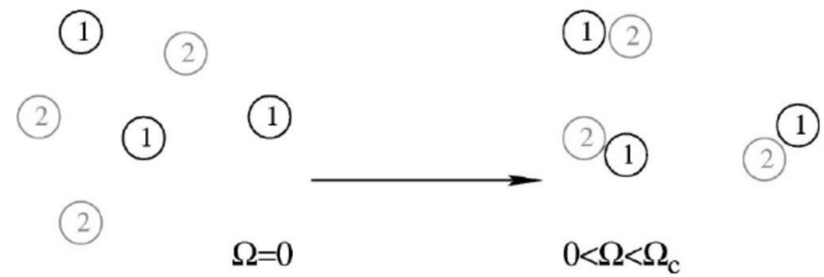
In 2D vortices exsist only as vortex-antivortex bound states with binding force independent on the relative distance

Domain walls of relative phase in two-component BECs
D. T. Son & M. A. Stephanov, Phys. Rev. A 65, 063621 (2002).

Resonantly coupled spinor BECs

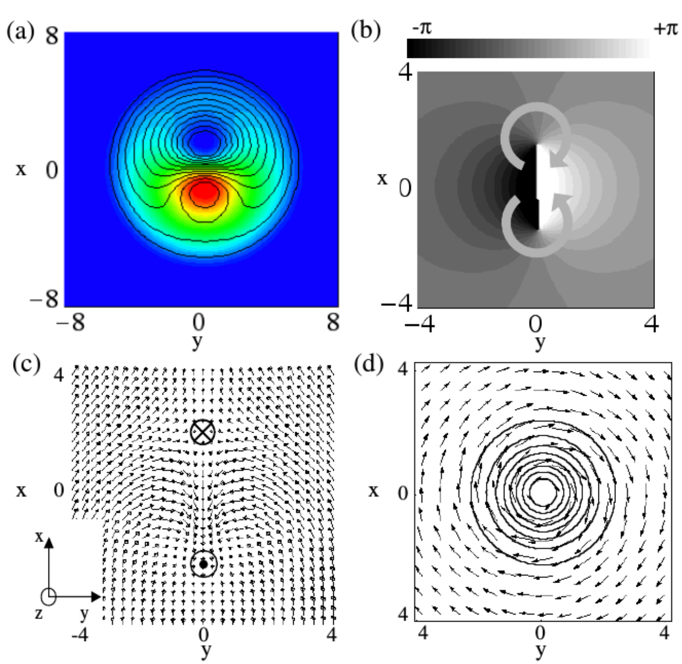
Analogy vortex/antivortex molecule ⟷ $q\bar{q}$ bound state in a meson

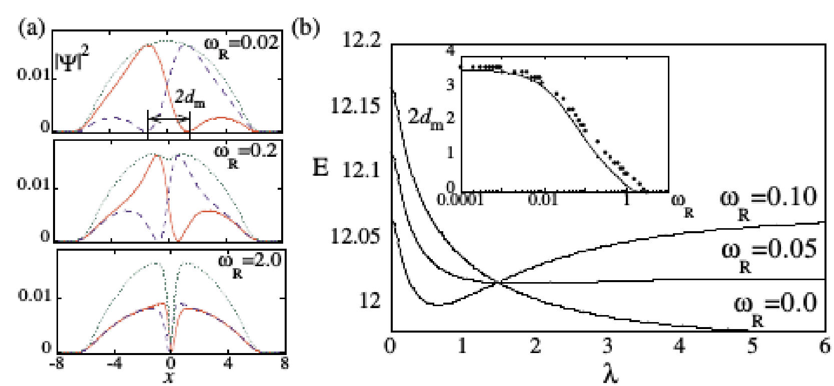
The binding energy of the vortex/antivortex molecule (bound by the domain wall) simulates the attraction between quark and antiquark



Simulation of a string breaking

These vortex/antivortex molecules can be generated by setting the BEC into rotation



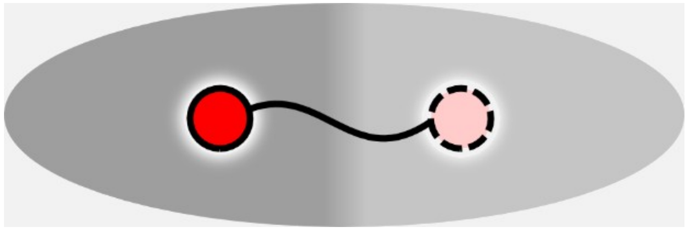


Vortex Molecules in Coherently Coupled Two-Component BECs
K. Kasamatsu *et al.*, PRL **93**, 250406 (2004).

Fundamental Interactions Simulations with quantum gases

Resonantly coupled spinor BECs

Analogy vortex/antivortex molecule ⟷ $q\bar{q}$ bound state in a meson



Realization of a new experimental apparatus, with highly-stabilized magnetic fields (μG), dedicated to the production of spinor ^{23}Na BECs.

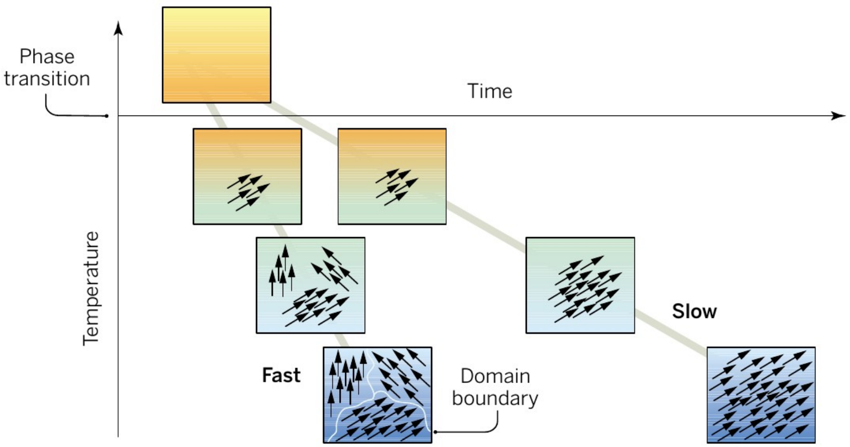
The behavior of the vortex/antivortex molecule will be studied (at equilibrium or dynamically after a quench) as a function of:

- Interactions between particles / density of the gas
- Total angular momentum
- Intensity of the coherent coupling
- External perturbing potentials simulating the breaking of the molecule

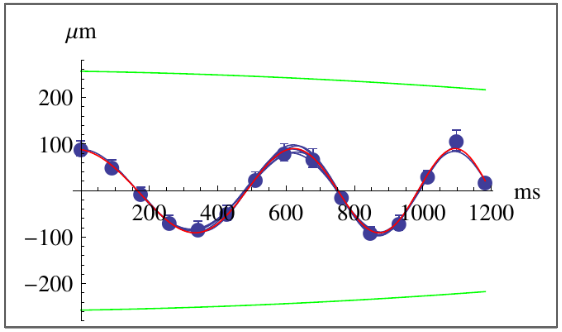
FISħ Fundamental Interactions Simulations with quantum gases

Summary

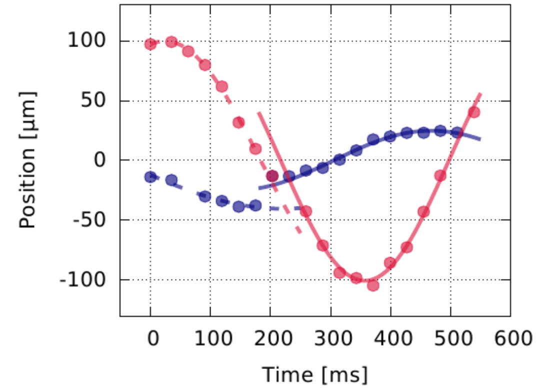
formation



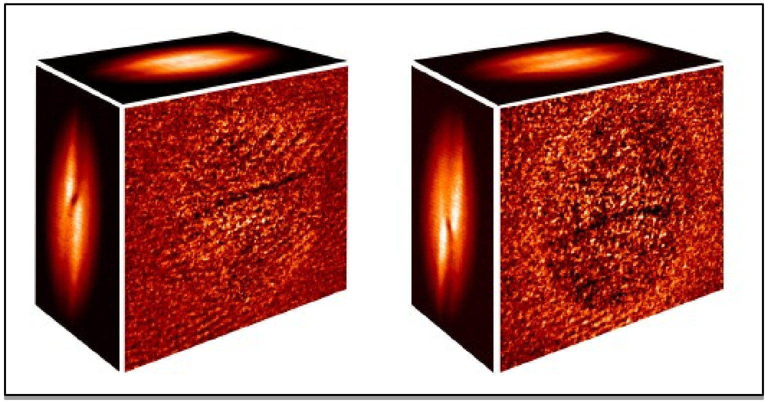
dynamics



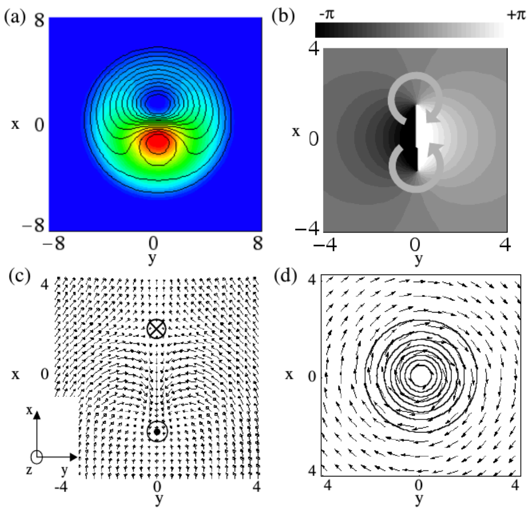
interaction



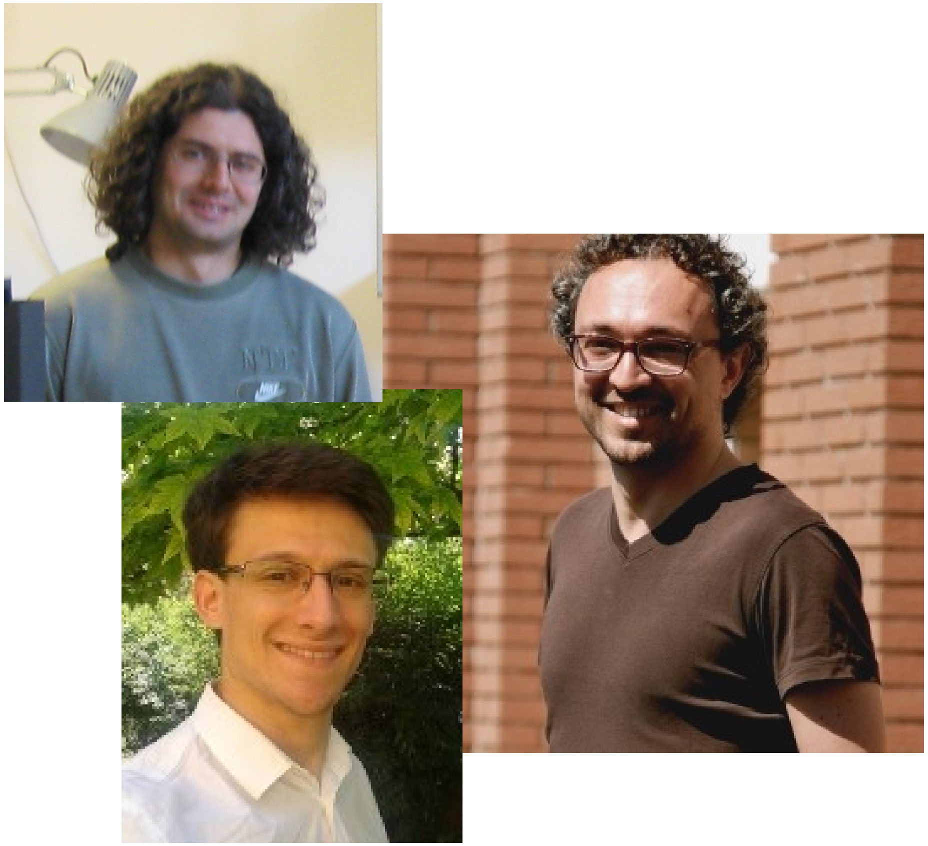
nature

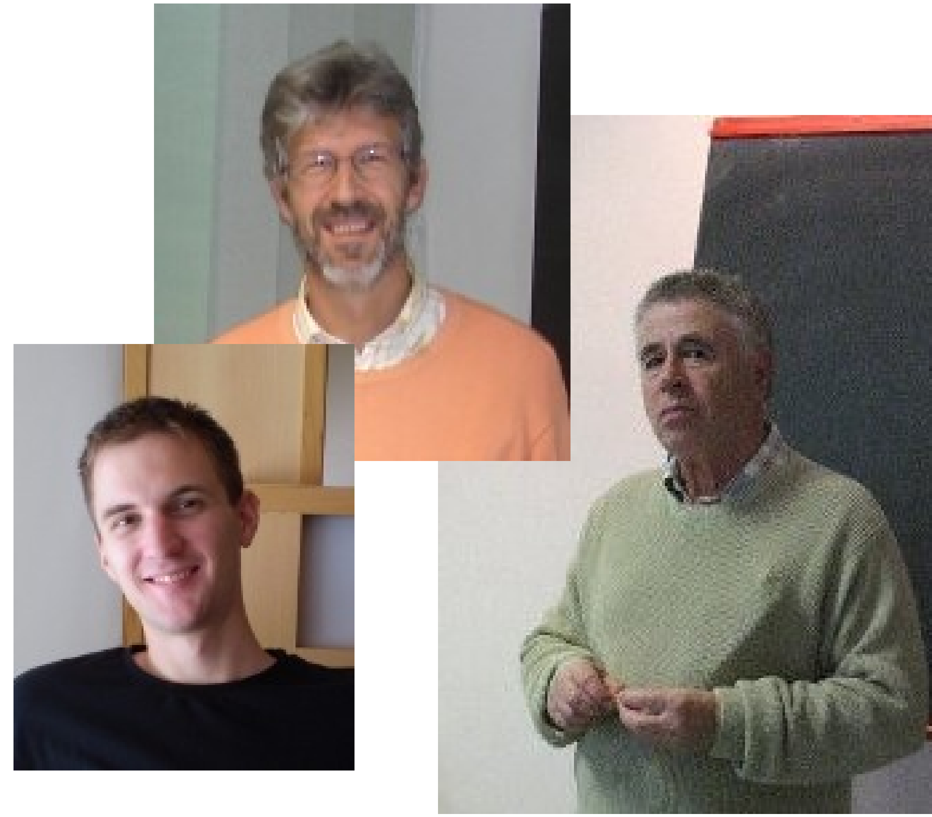


QS of string braking



Thank you!





Simone Serafini
Simone Donadello
Matteo Barbiero
Michele Debortoli
Giacomo Lamporesi

Marek Tylutki
Fabrizio Larcher
Lev Pitaevskii
Franco Dalfovo