Spontaneous creation and dynamics of vortices in Bose-Einstein condensates

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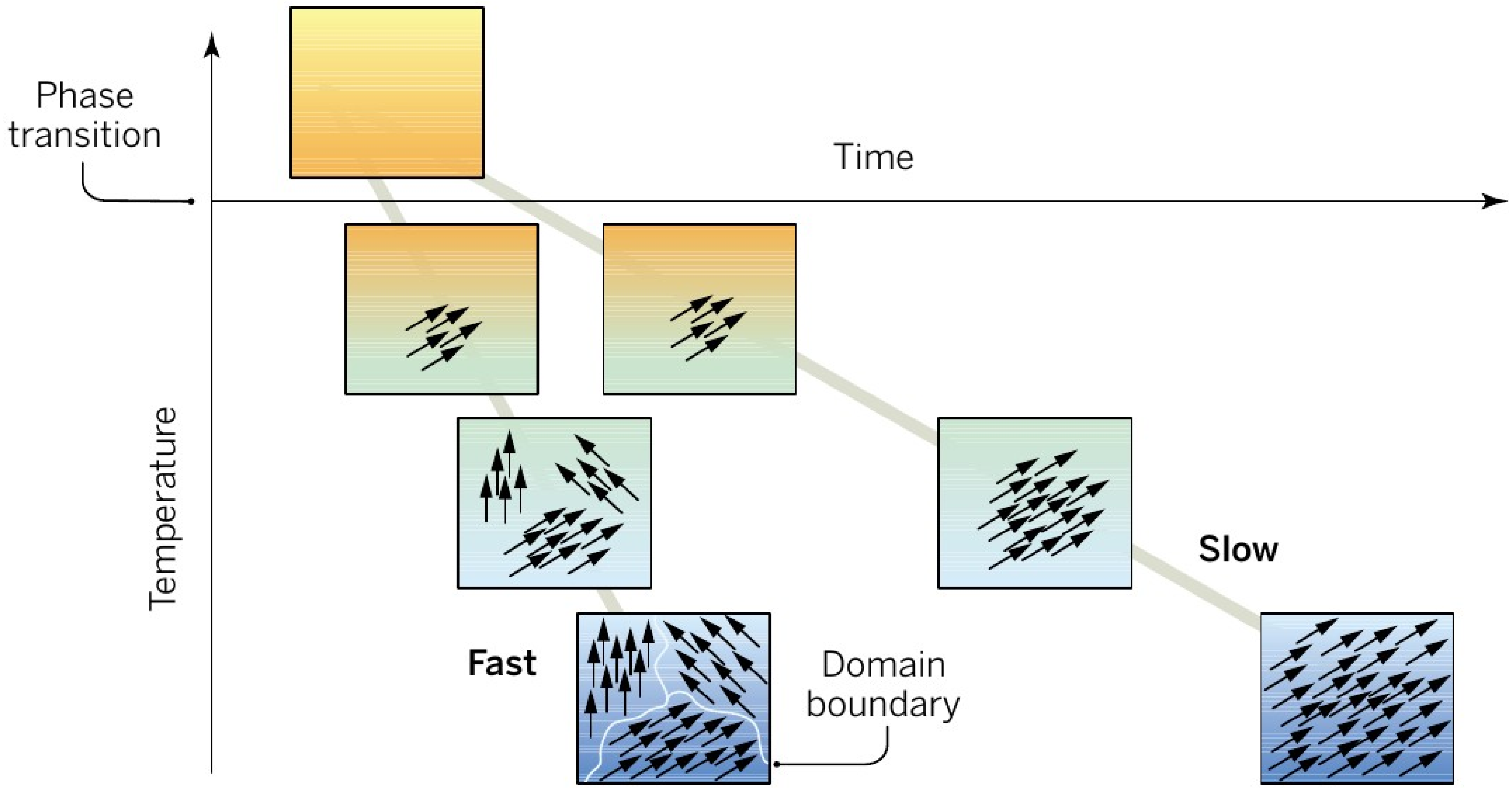
Journées GdR Atomes Froids et IFRAF
École Normale Supérieur, Paris
5 November 2015

outline

- Introduction to the Kibble-Zurek mechanism
- Creating defects in Bose condensates via the Kibble-Zurek mechanism
- Defect's characterization
- Dynamics & interactions

the Kibble-Zurek mechanism



- Second-order phase transitions
- Finite rate crossing
- Spontaneous and stochastic production of defects

the Kibble-Zurek mechanism

Power-law scaling

coherence length

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

relaxation time

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

reduced parameter:

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

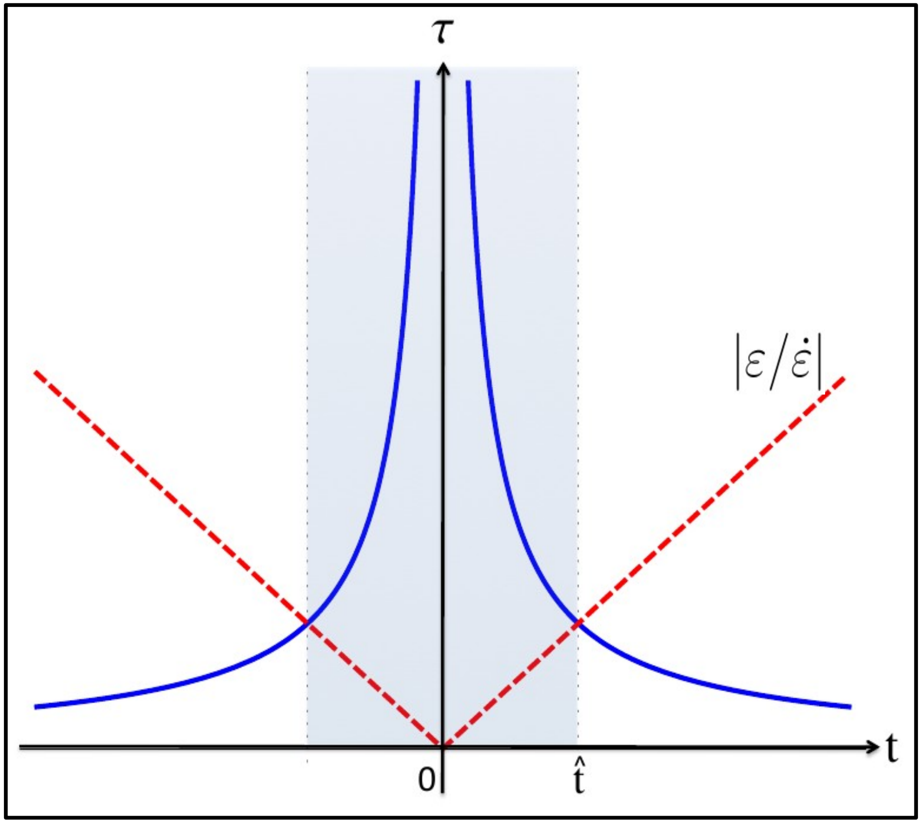
Case of linear quench

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

time to the transition

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

ADIABATIC -- IMPULSE -- ADIABATIC



"freezing time"

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

domain size

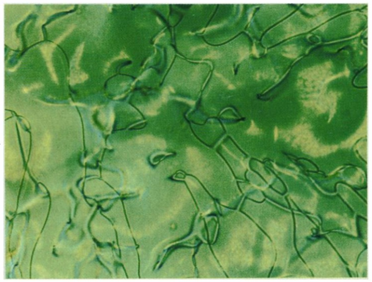
$$\hat{\xi} = \xi(\hat{t}) = \xi_0 \left(\frac{\tau_Q}{\tau_0}\right)^{\frac{\nu}{1+z\nu}}$$

density of defects

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

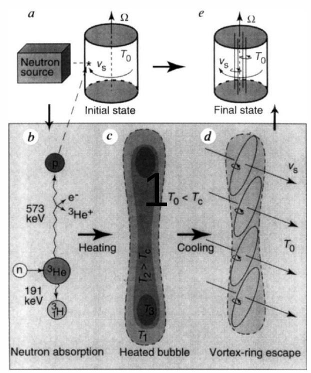
A. del Campo, W. H. Zurek, Int. J. Mod. Phys. A **29**, 1430018 (2014)

Liquid crystals: isotropic/nematic



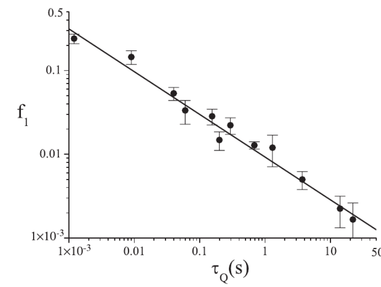
I. Chuang et al. (1991)

Liquid ^{3}He: normal/SF



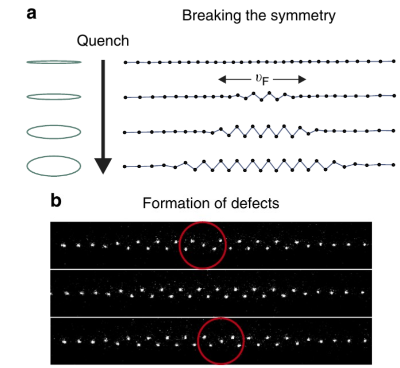
C. Bauerle et al. (1996)
V.M.H Ruutu et al. (1996)

annular Josephson junctions



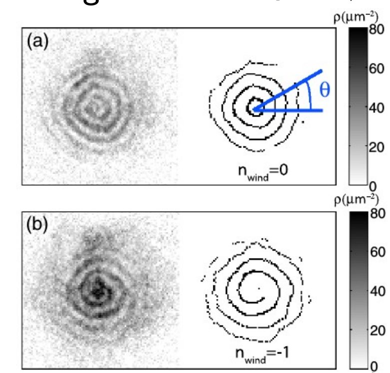
R. Monaco et al. (2009)

1D ion crystals: linear/zig-zag



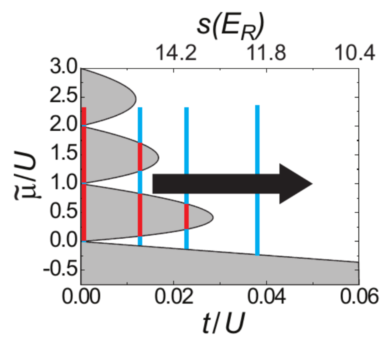
S. Ulm et al. (2013)
K. Pyka et al. (2013)

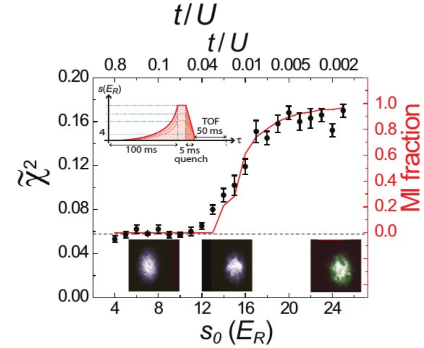
Bose gases: thermal/BEC, D < 3



L. Corman et al. (2014)

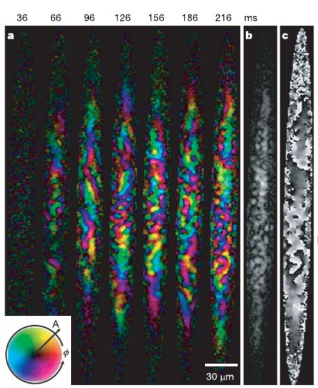
T=0 Bose gases: Mott/SF





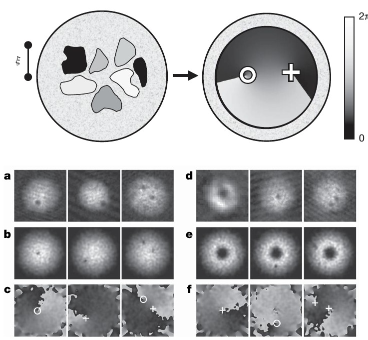
D. Chen et al. (2011)
S. Braun et al. (2014)

Bose gases: ferromagnetic



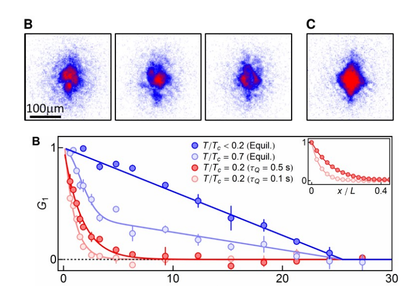
L. E. Sadler et al. (2006)

Bose gases: thermal/BEC



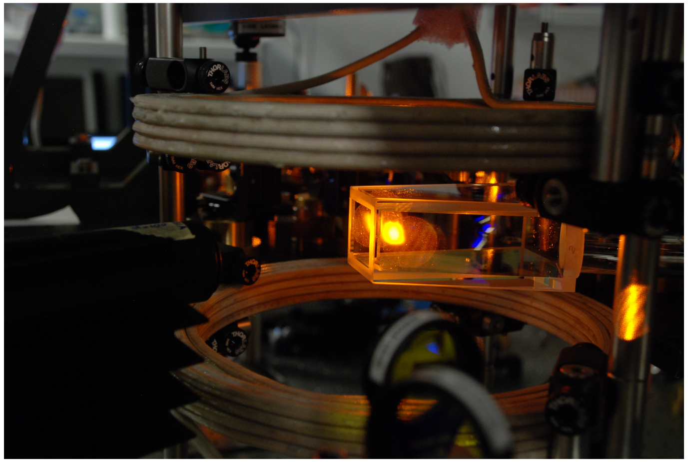
C.N. Weiler et al. (2008)

Hom. Bose gases: thermal/BEC

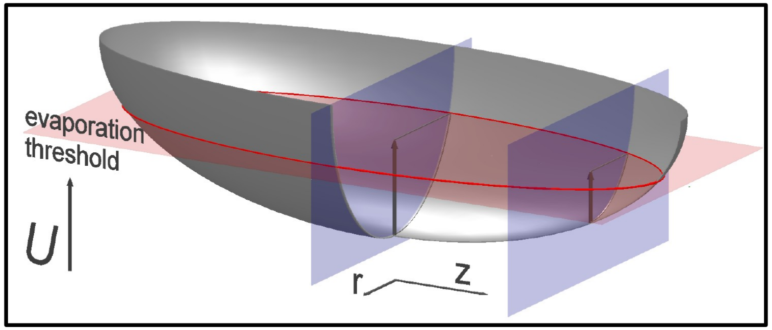


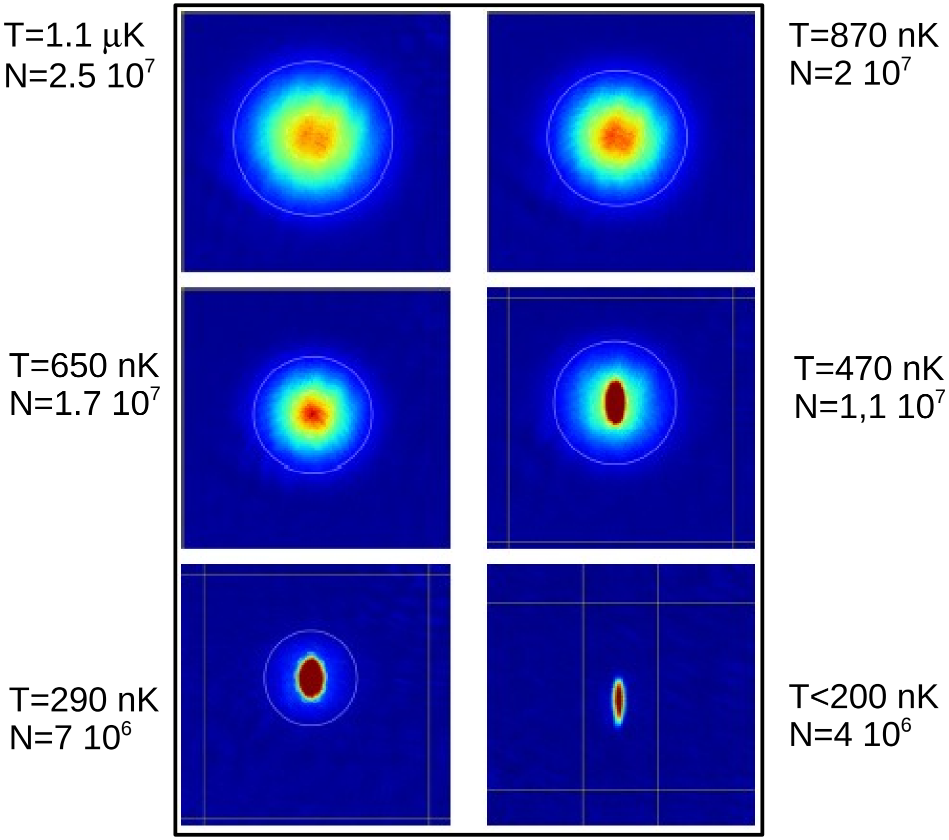
N. Navon et al. (2015)

experimental setup in Trento



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

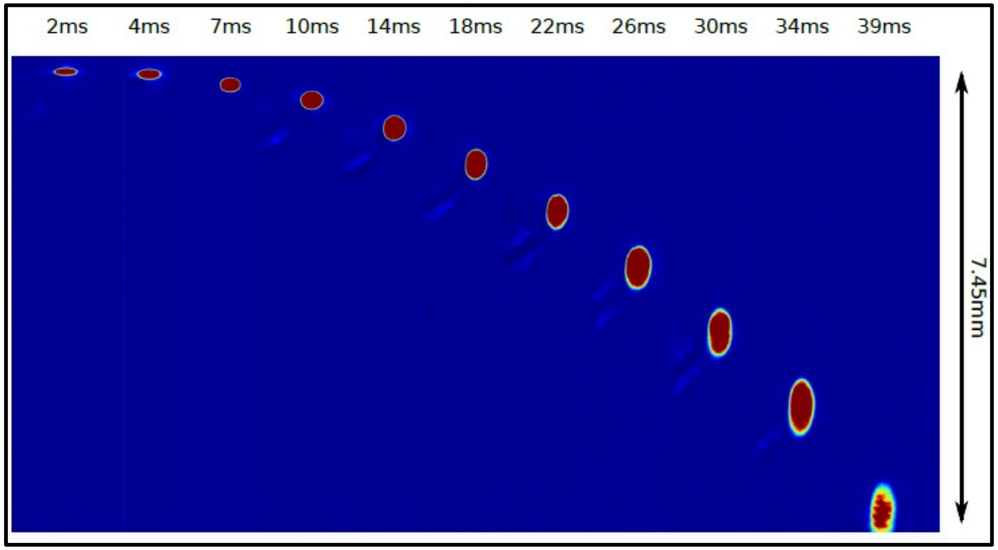




ToF expansion of a BEC

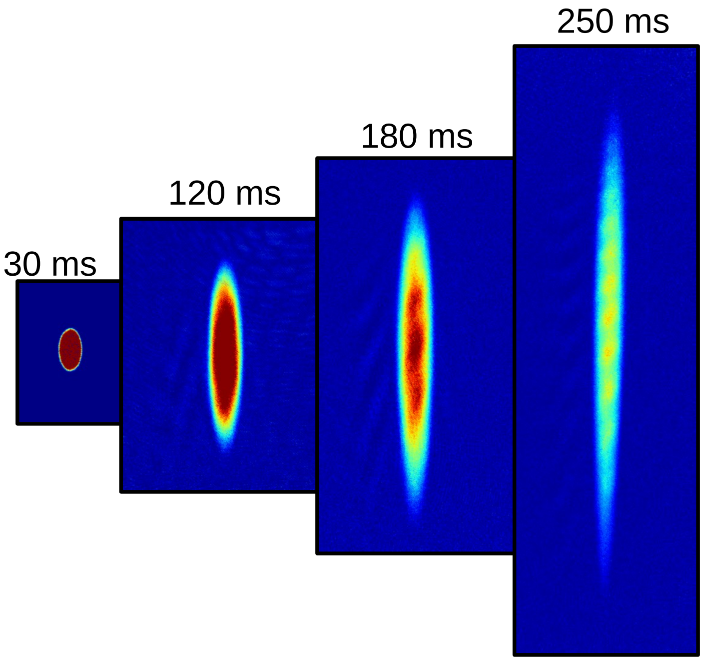
expansion time limited to ~ 40 ms

due to the gravity fall



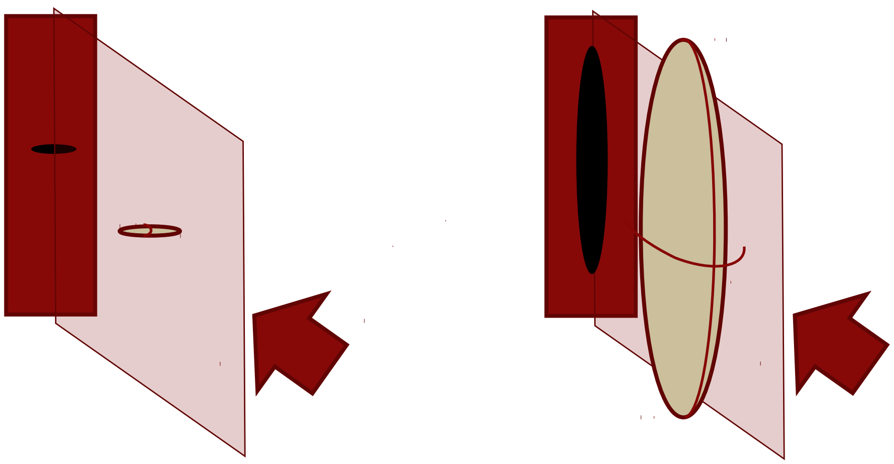
magnetic levitation against the gravity

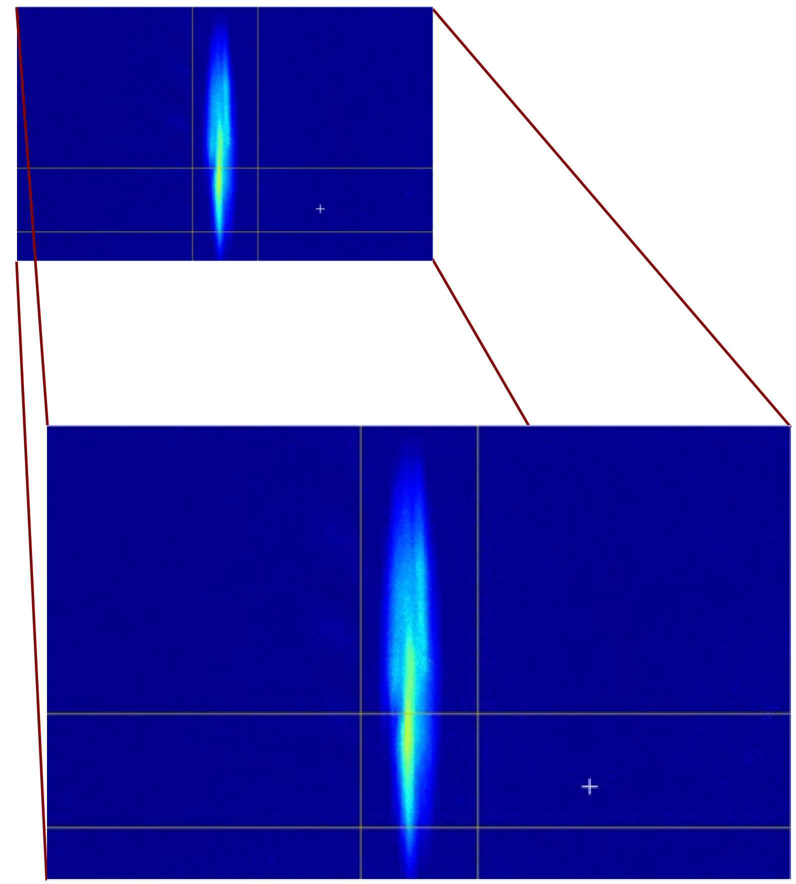
to increase the expansion time



ToF expansion of a BEC

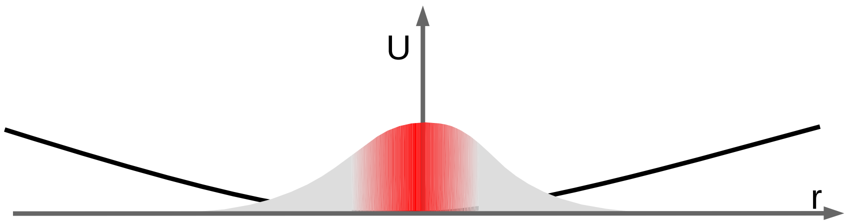
In trap after expansion

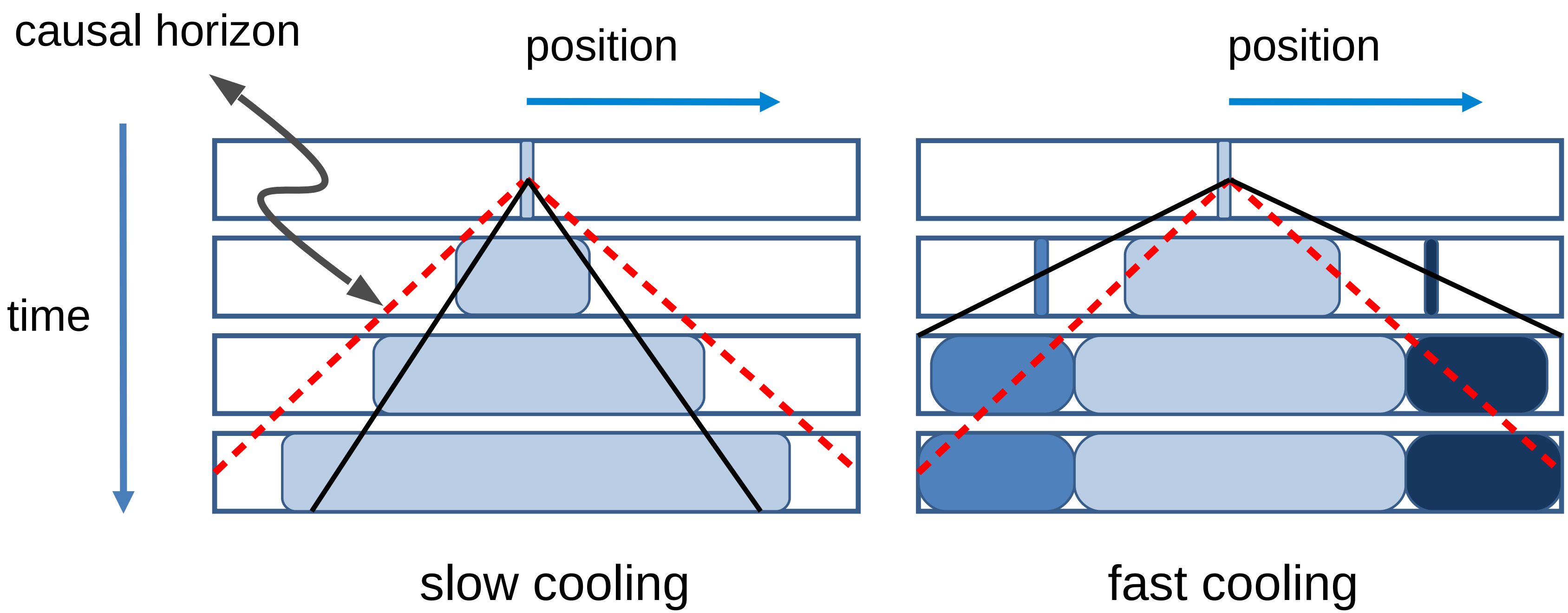




Key observation: the number of defects strongly depends on the rate at which the BEC transition is crossed **!!**

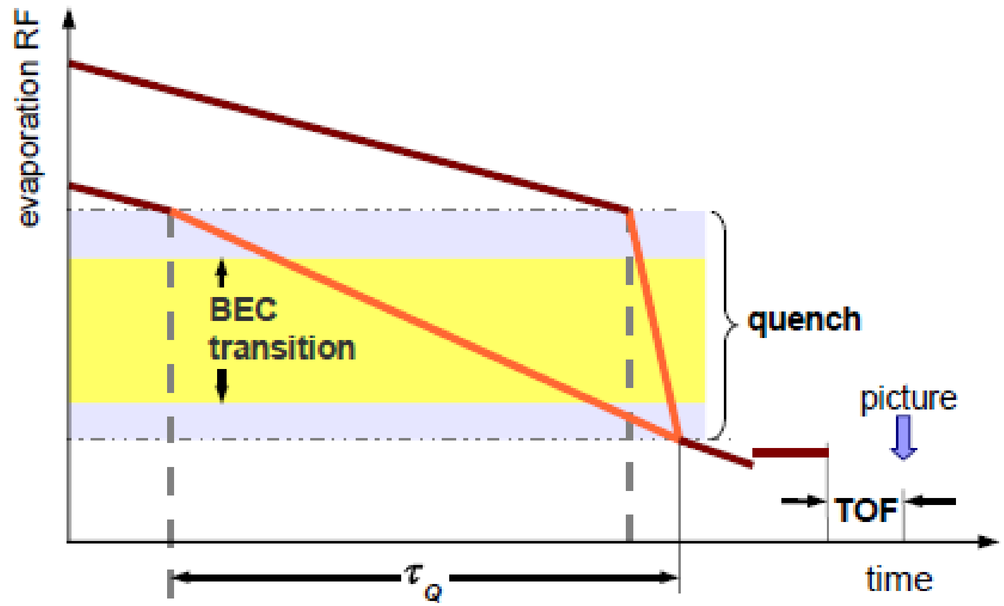
Generating solitons via the Kibble-Zurek mechanism



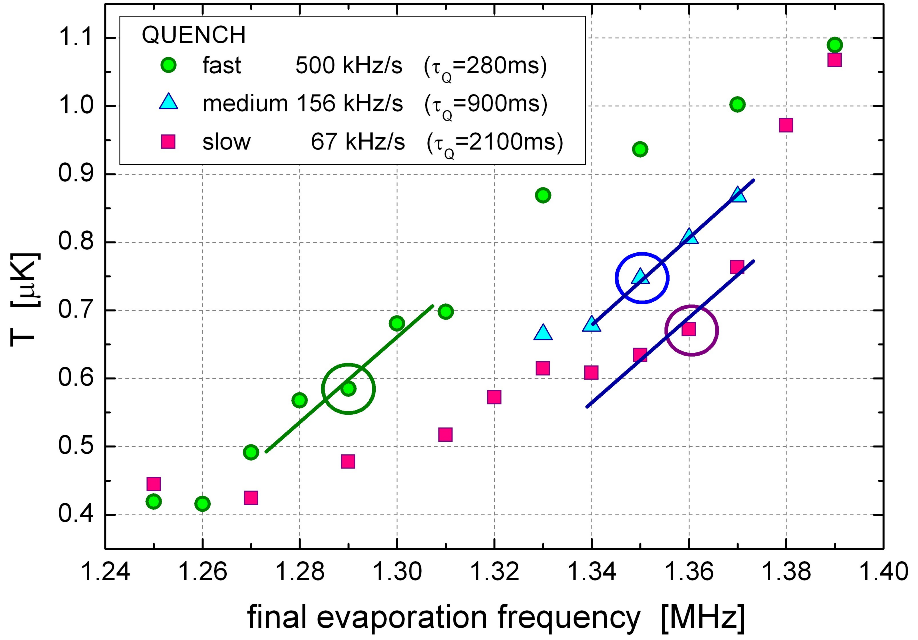


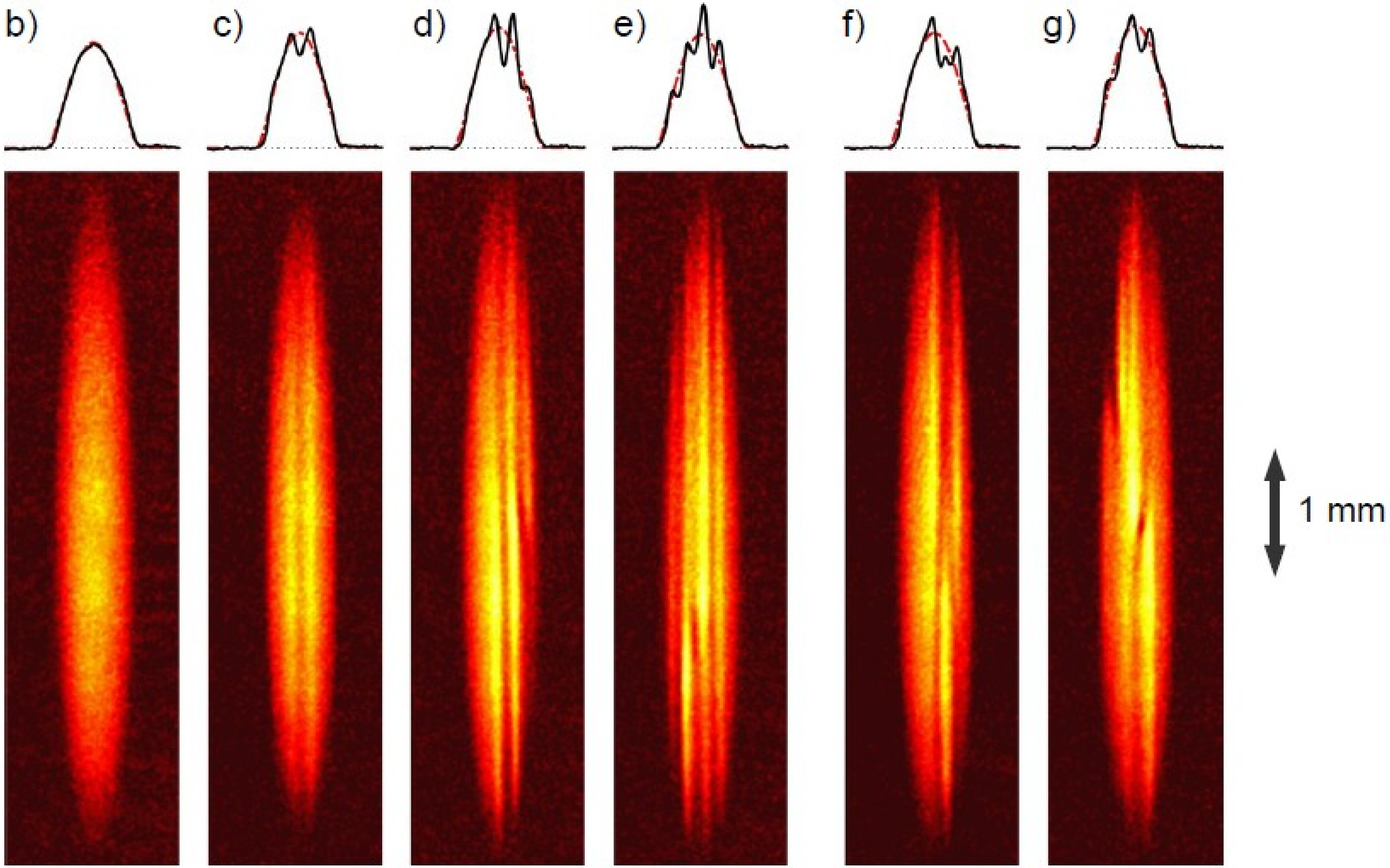
W. H. Zurek, PRL 102, 105702 (2009)

Check: change the cooling/quench time.



temperature VS evapoation thershold

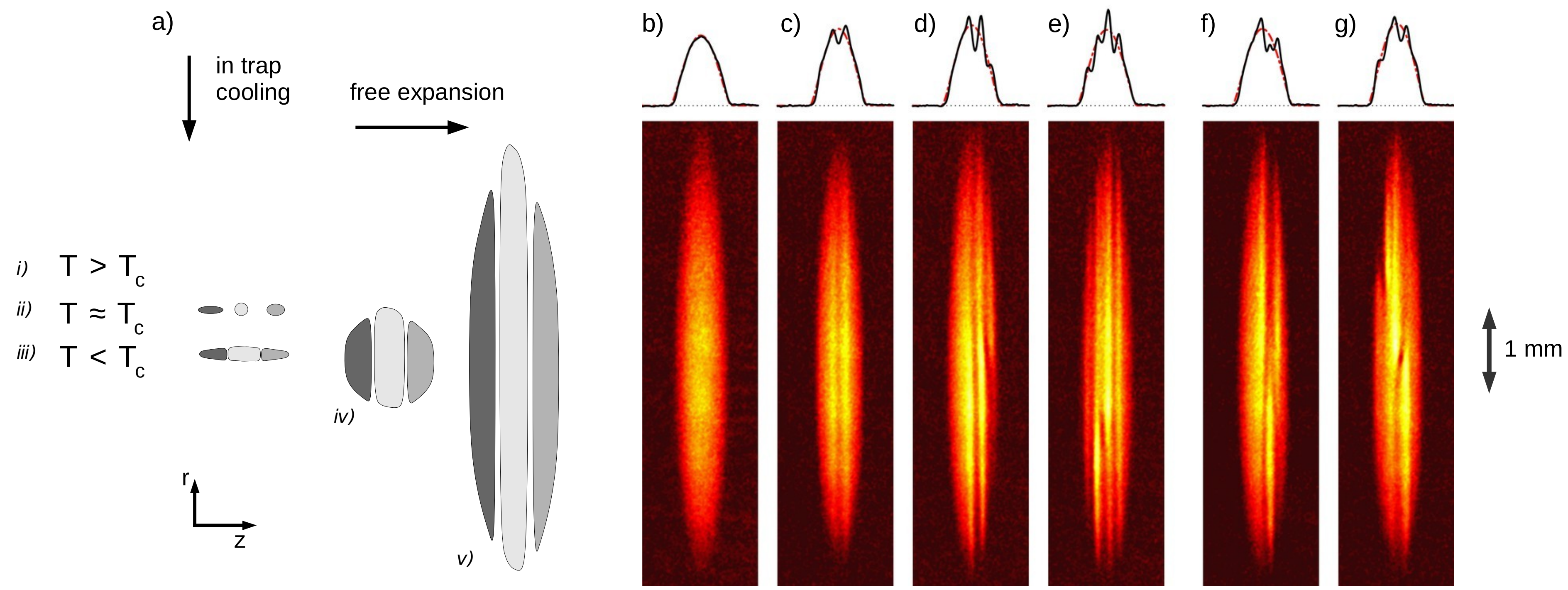




slow cooling

fast cooling

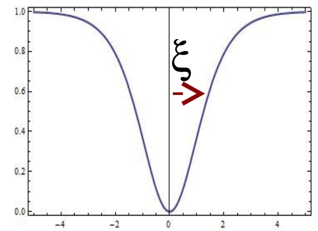
guess: these are gray solitons spontaneously nucleated at the BEC transition by the Kibble-Zurek mechanism (KZM) **!!**

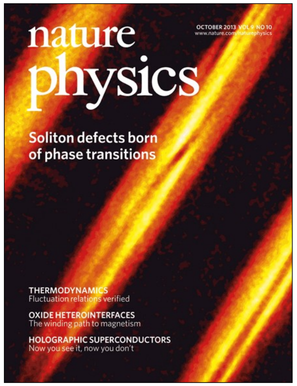


imaging resolution: 10 μm

soliton width in trap: ξ(0) = 200-250 nm

width after TOF: ξ(180 ms) = 50-100 μm





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

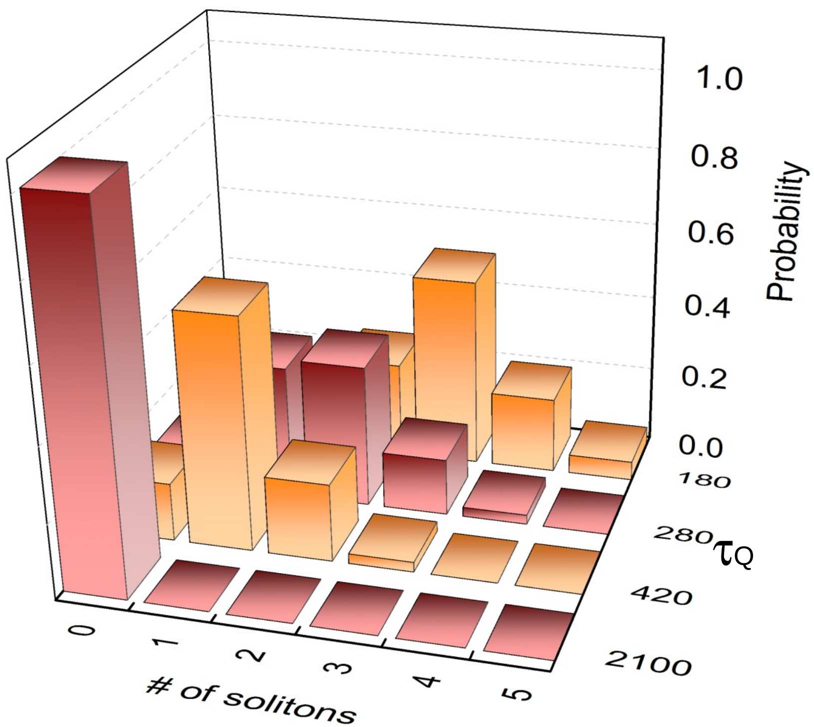
Measurement of the KZ α coefficient

the number of defects is expected to follow a power-law as a function of the quench time (fixed size of the system)

$$N_s \mu \ \tau_Q^{-\alpha}$$

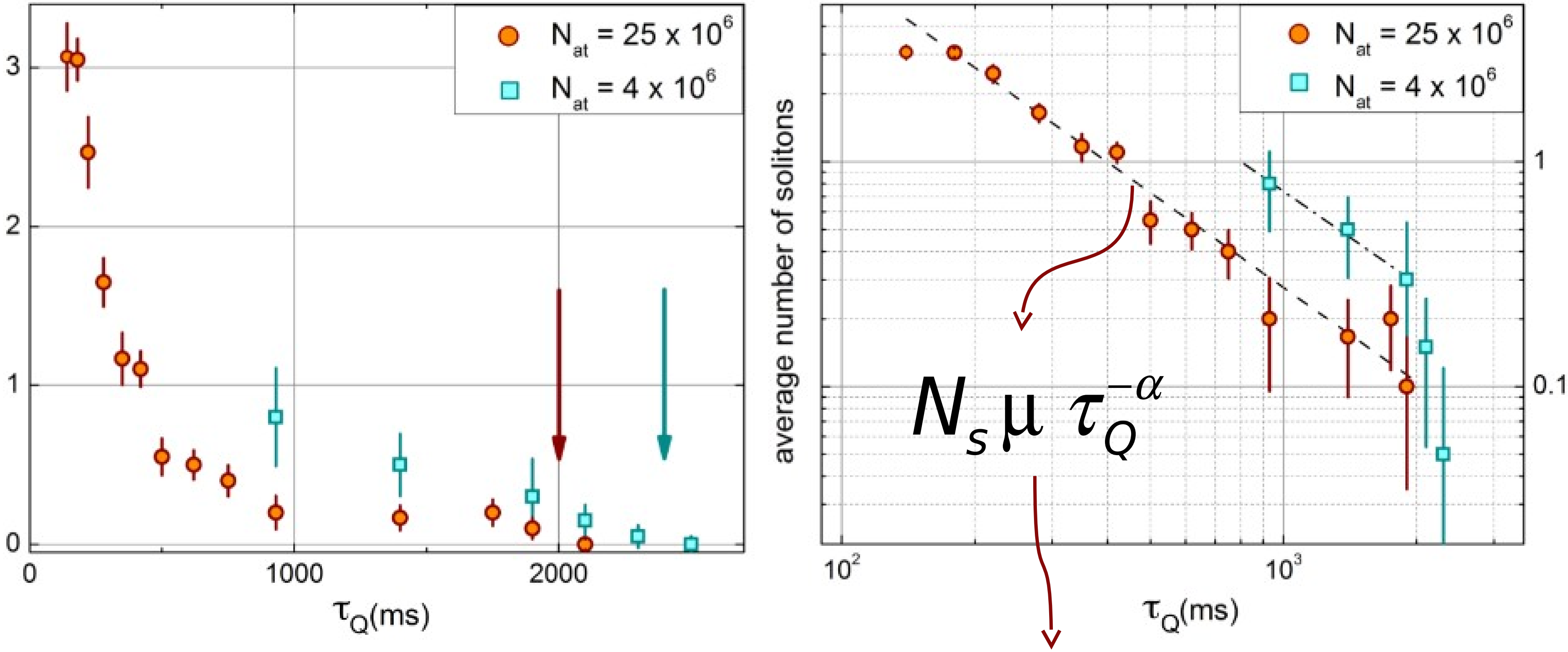
where α is determined by the critical exponents of the phase transition.

W. H. Zurek
PRL 102, 105702 (2009)



OK, we can count our solitons !

Measurement of the KZ α coefficient



$$N_s \mu\ \tau_Q^{-\alpha}$$

$\alpha = 1.4$

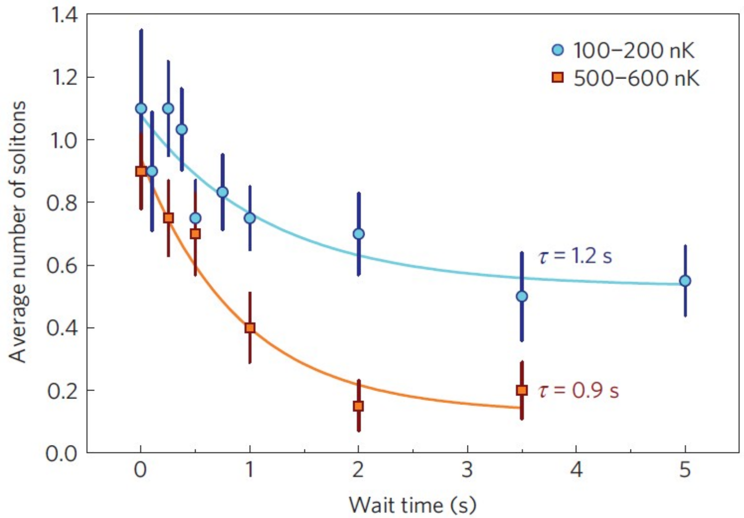
to compare with the available theoretical prediction (Zurek 2009)

1D, homogeneous temperature

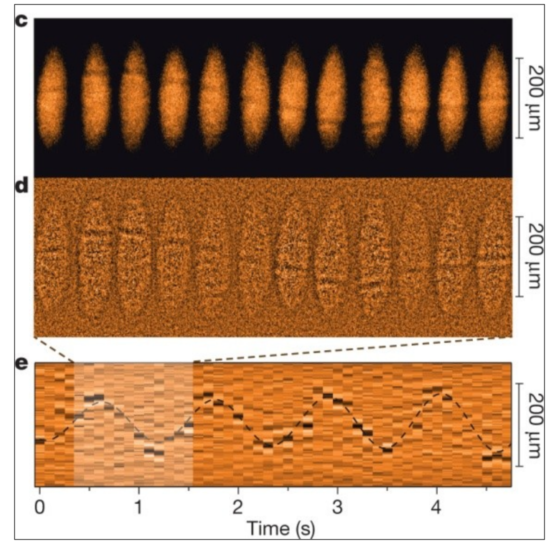
$\alpha = 7/6 \sim 1.17$

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

The lifetime puzzle



(also in DFG at MIT)



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

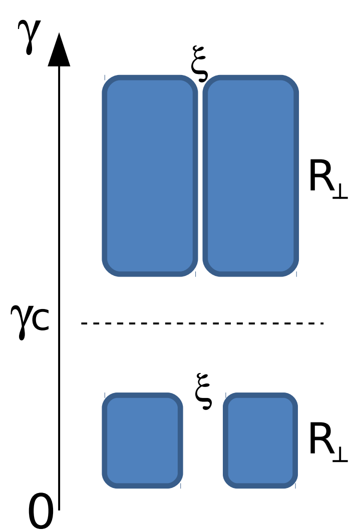
Solitons are expected to be **unstable**

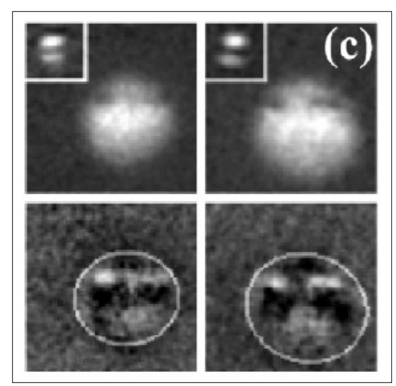
THERMALLY (unless at T=0)

DYNAMICALLY (due to snake instabilities)

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

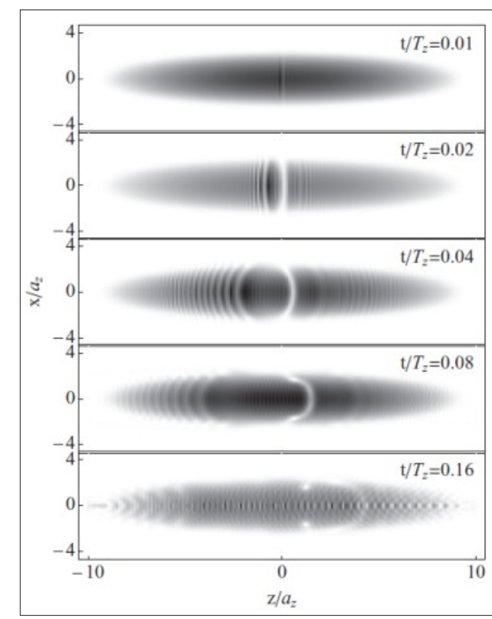
$$\gamma = \frac{\mu}{\hbar\omega_\perp} = \frac{R_\perp}{2\xi}$$



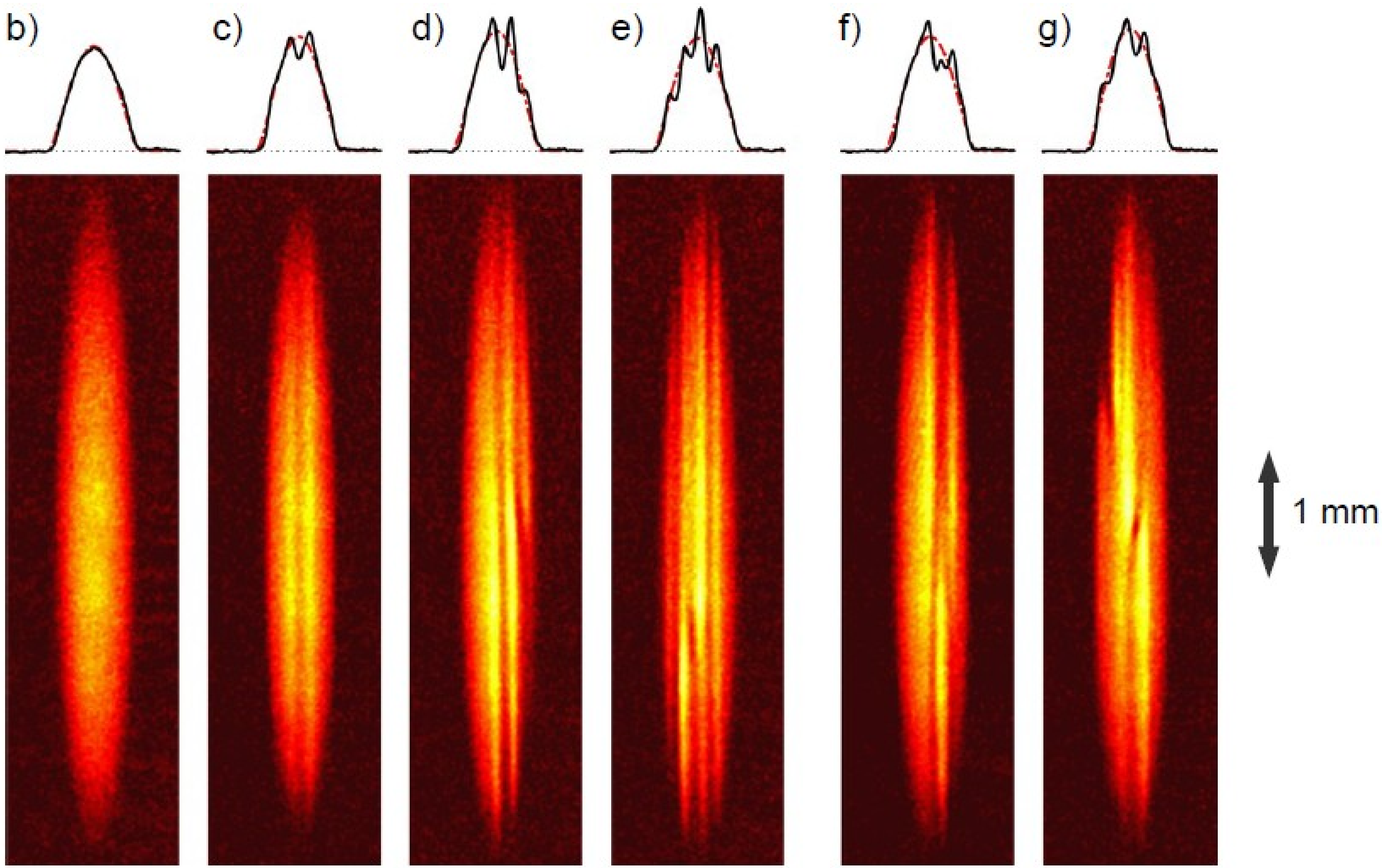


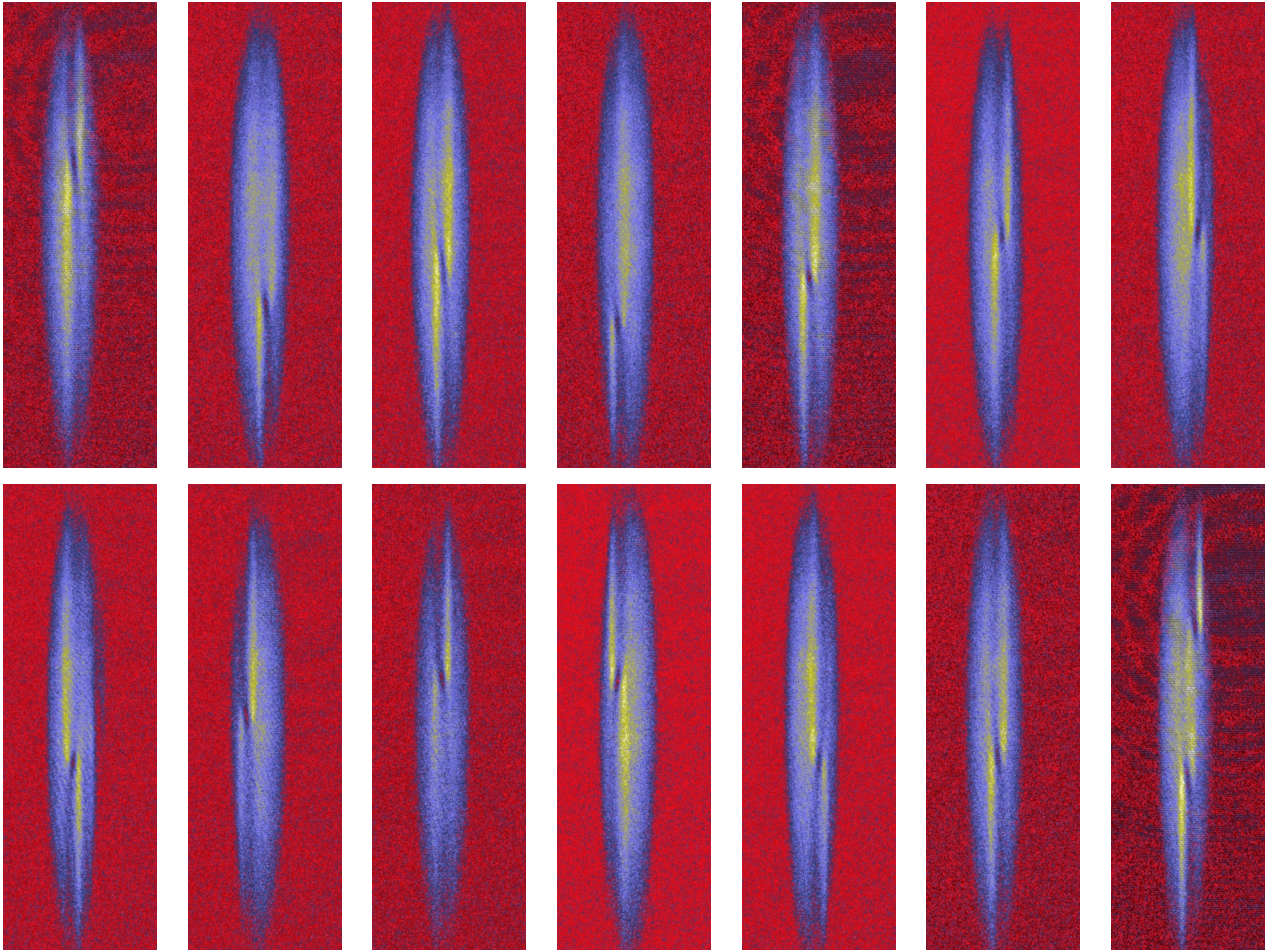
spherical BEC (JILA)

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



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

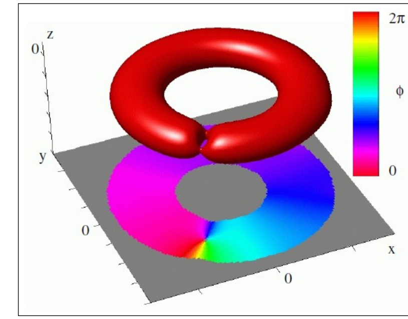

b)
c)
d)
e)
f)
g)
1 mm



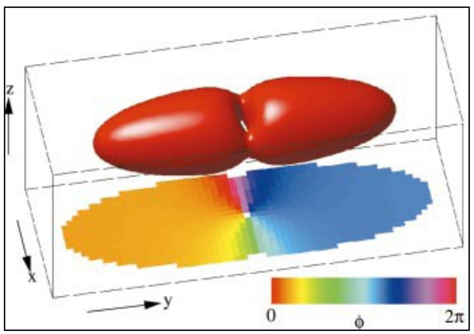
Solitonic vortices

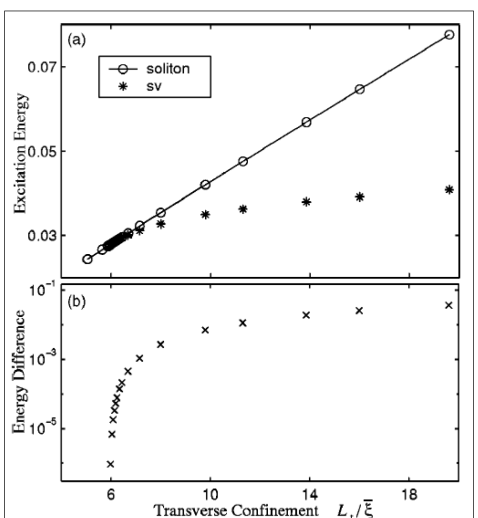
Vortex oriented perpendicularly to the axis of an axisymmetric elongated trap.

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



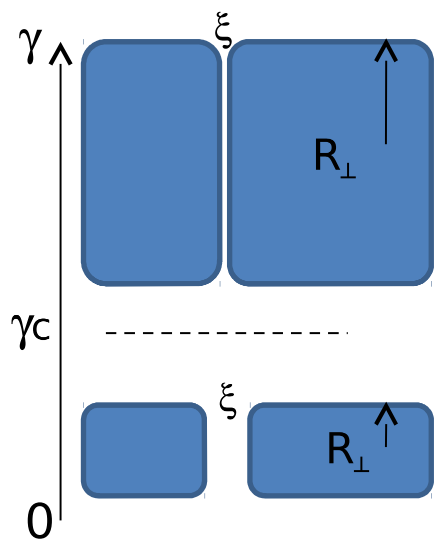
Brand *et al*., JPB **34**, L113 (2001)

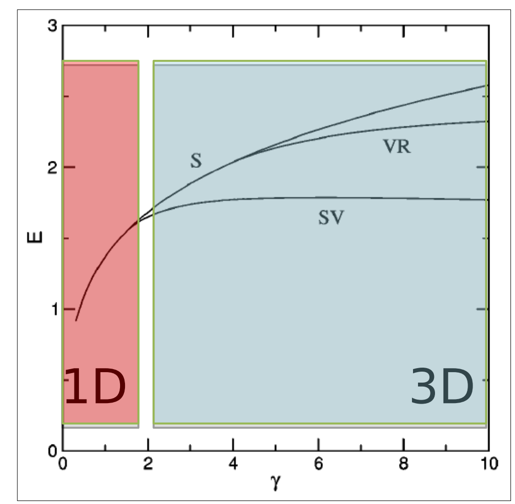




Brand *et al*., PRA **65**, 043612 (2002)

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

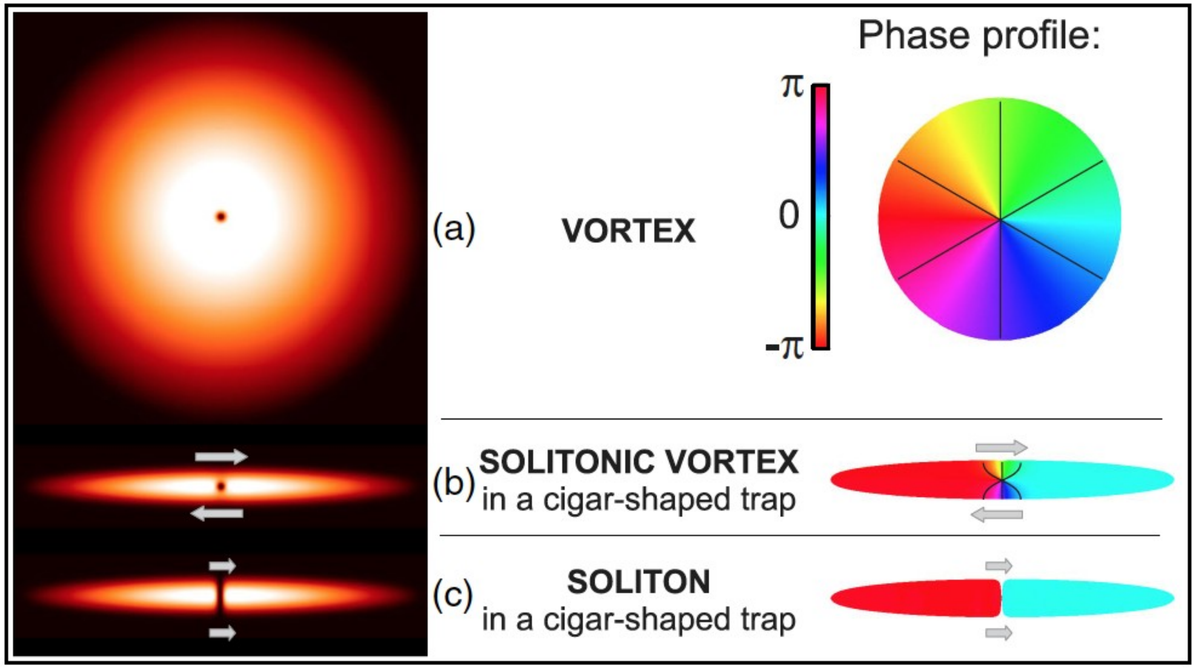




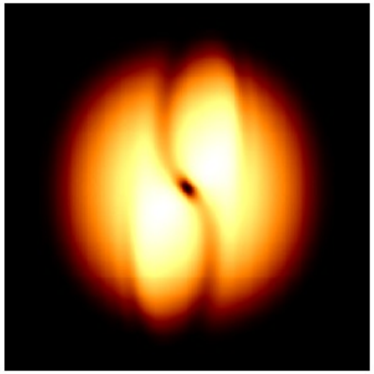
Komineas *et al*., PRA **68**, 043617 (2003)

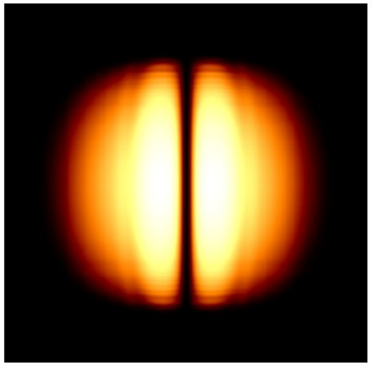
Solitonic vortices

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



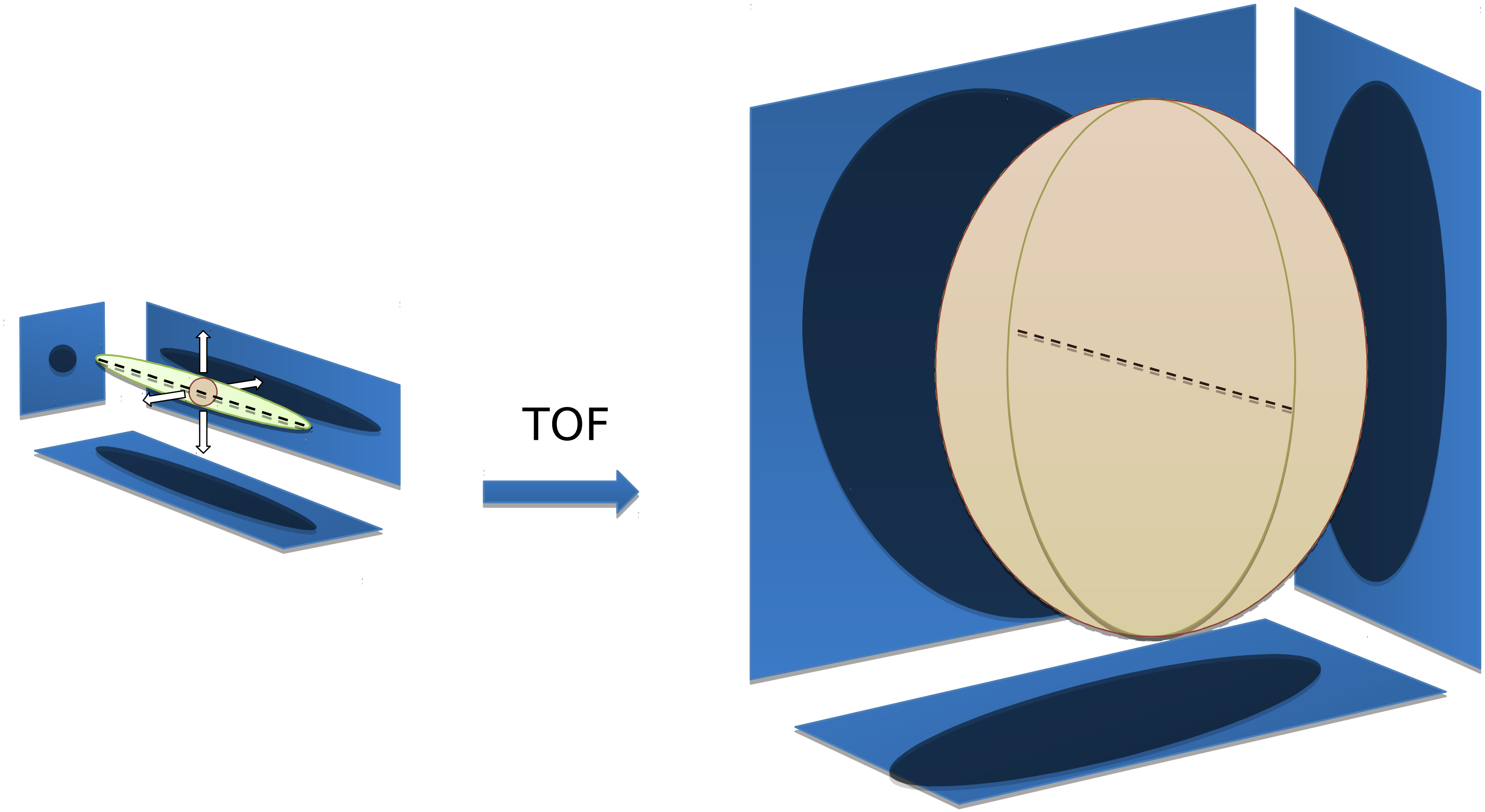
<u>Asymmetric twist</u>





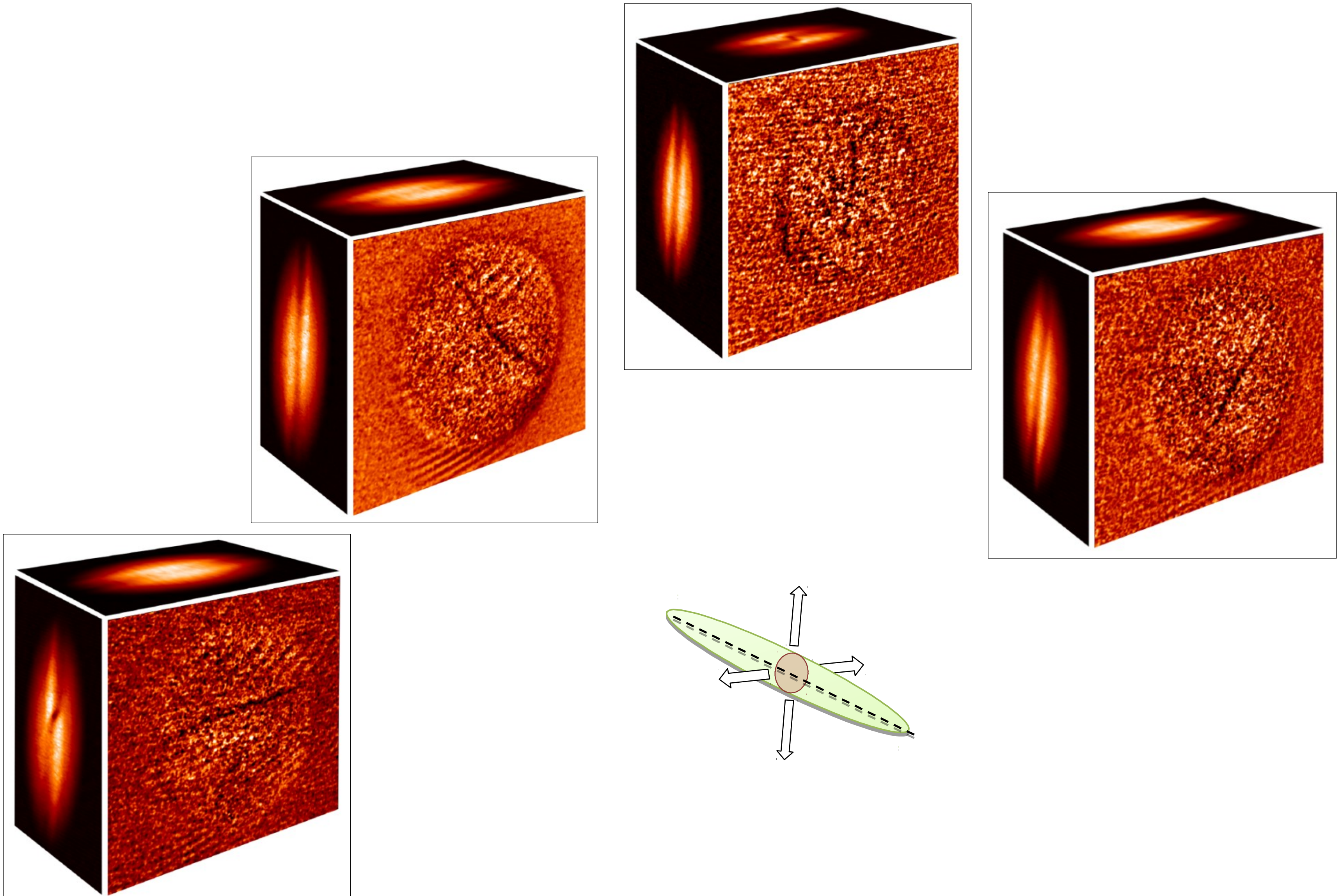
M. Tylutki *et al*., EPJ-ST **224**, 577 (2015)

Solitonic vortices



Random orientation

Triaxial absorption imaging after long TOF



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

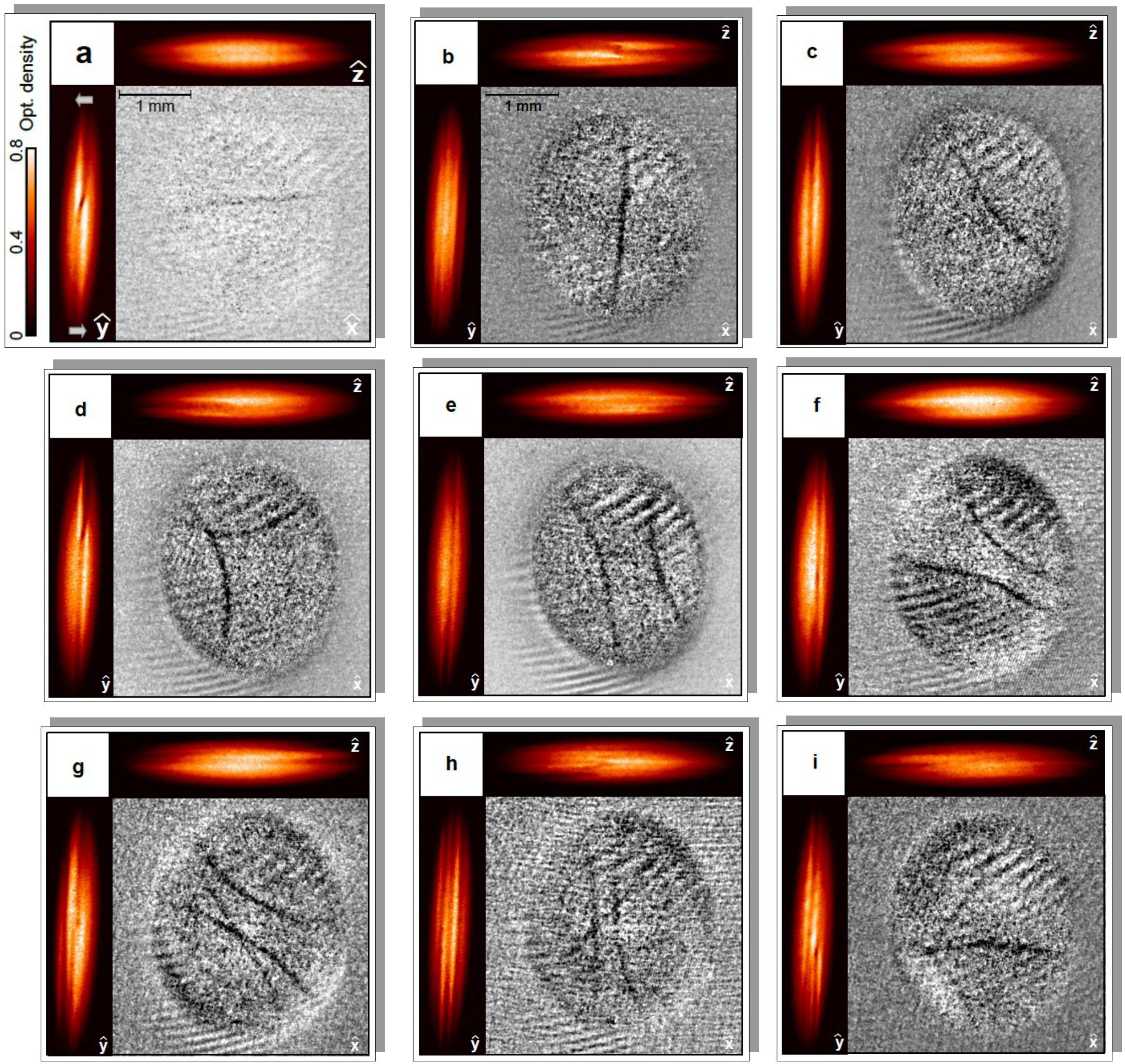
M. J. H. Ku *et al.*, PRL **113**, 065301 (2014)

Random number

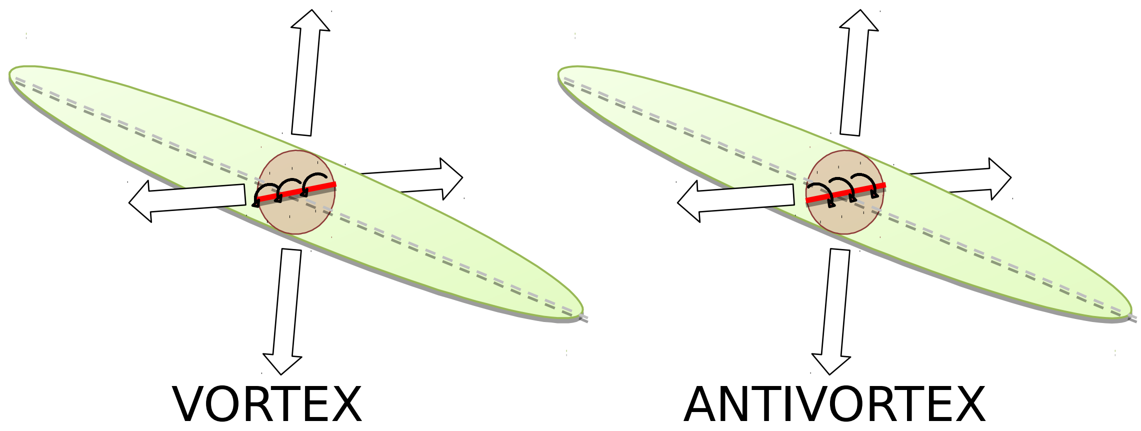
1

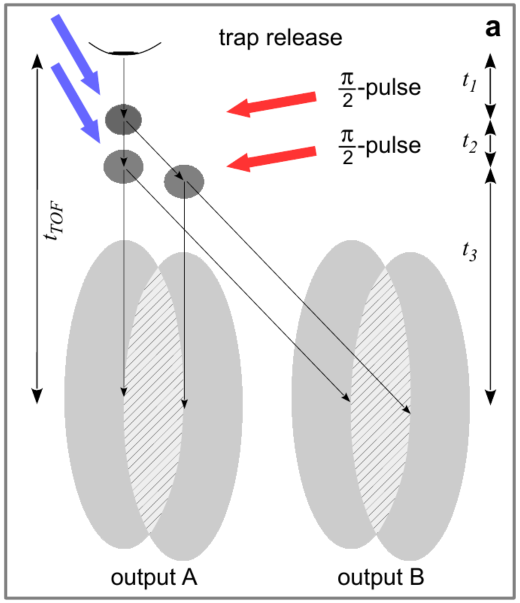
2

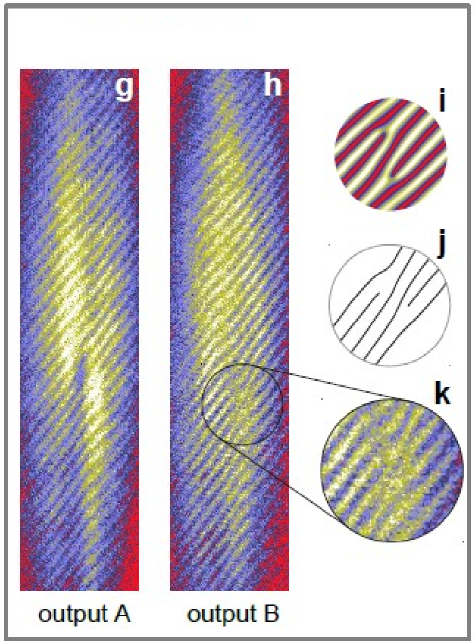
3

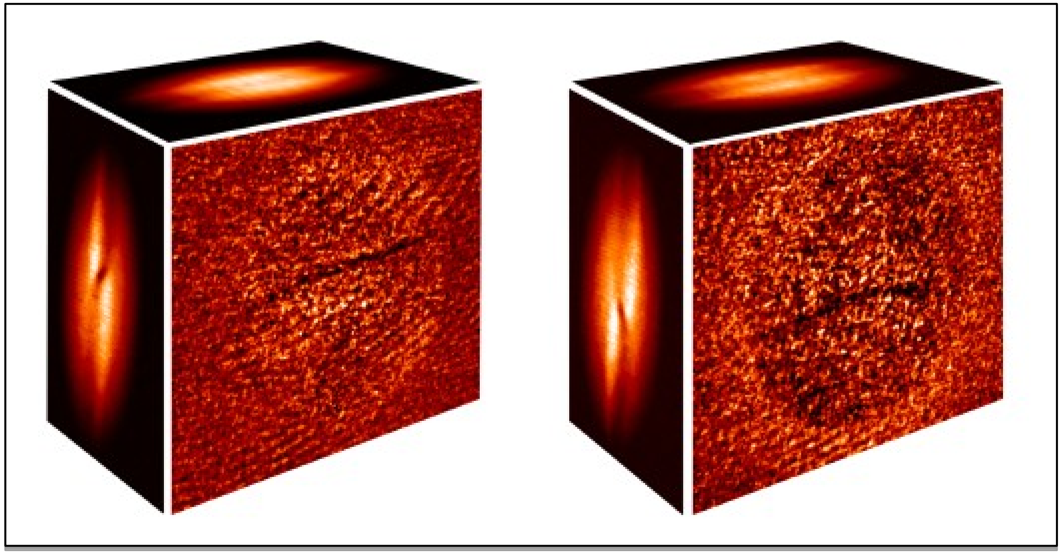


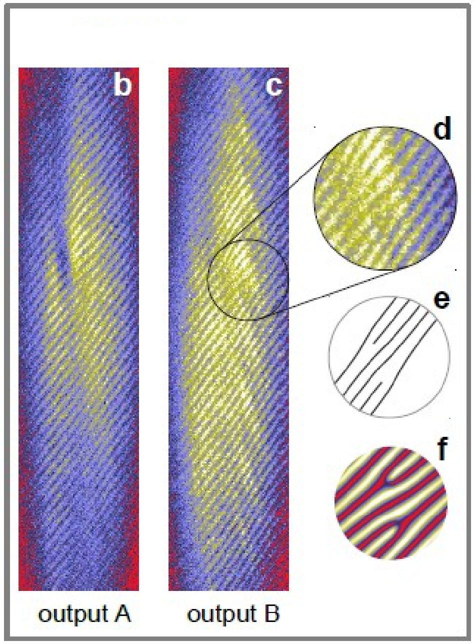
Random circulation









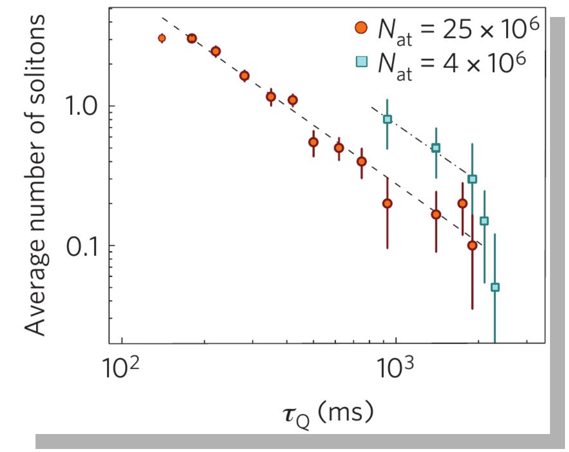


homodyne detection of the phase pattern by interfering two copies of the condensate

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

Scaling exponents

$$n \sim \frac{\hat{\xi}^d}{\hat{\xi}^D} = \frac{1}{{\xi_0}^{D-d}}\left(\frac{\tau_0}{\tau_Q}\right)^{(D-d)\frac{\nu}{1+z\nu}}$$

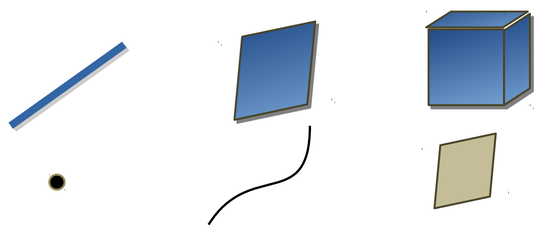


(α=1.4)

ν,z: critical exponents

D: system dimension

d: defect dimension



(D-d)=2

Critical exponents \ Trap	Homogeneous	Harmonic	Toroidal
Arbitrary (ν, z)	$\frac{2\nu}{1+\nu z}$	$\frac{2(1+2\nu)}{1+\nu z}$	$\frac{1+3\nu}{1+\nu z}$
Mean-field theory ($\nu=\frac{1}{2}$, $z=2$)	$\frac{1}{2}$	2	$\frac{5}{4}$
Experiments/F model ($\nu=\frac{2}{3}$, $z=\frac{3}{2}$)	$\frac{2}{3}$	$\frac{7}{3}$	$\frac{3}{2}$

(D-d)=1

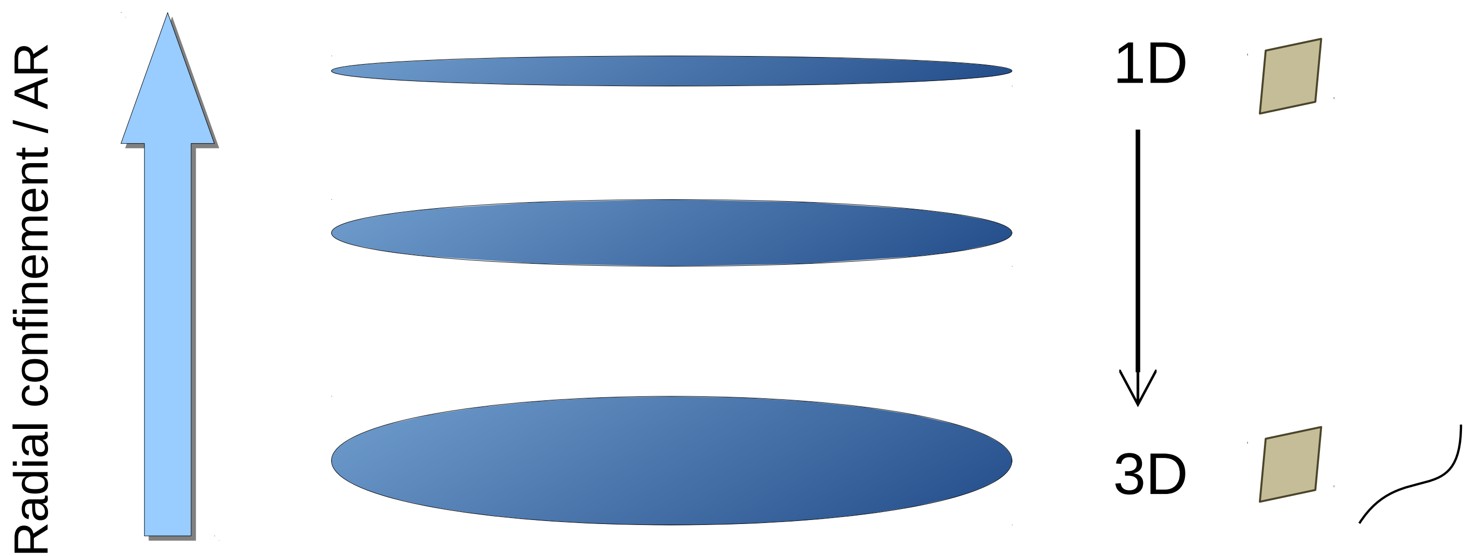
Homog.	Harm.
$\frac{\nu}{1+\nu z}$	$\frac{1+2\nu}{1+\nu z}$
1/4	1
1/3	7/6

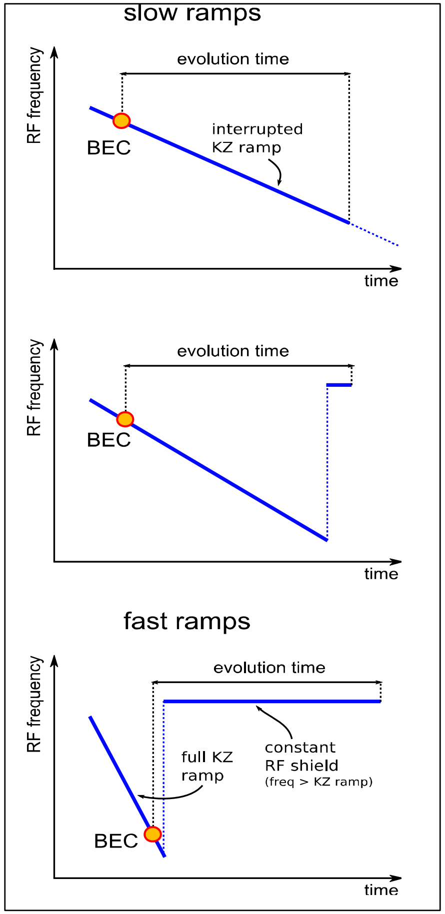
Del Campo *et al.*, NJP **13**, 083022 (2011)

Zurek, PRL **102**, 105702 (2009)

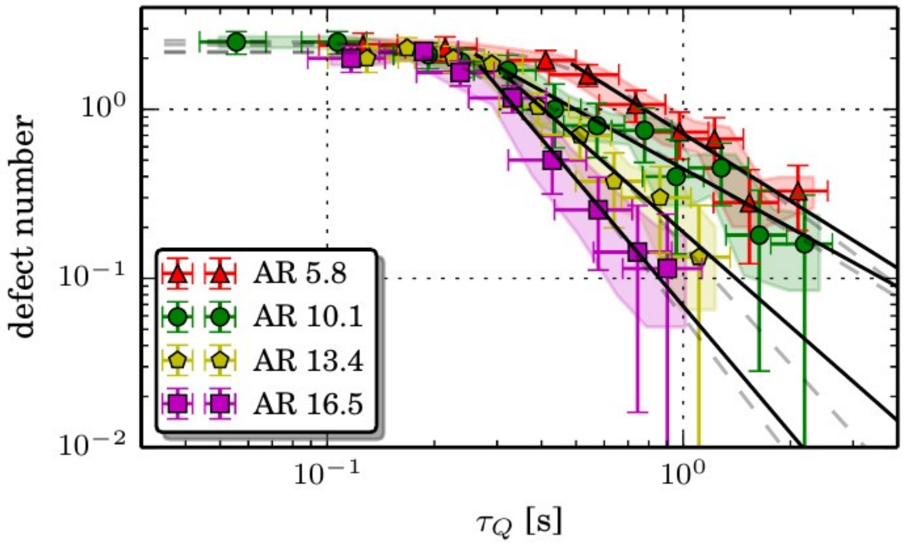
Search for effects on KZ scaling due to geometry of confinement:

- dimensional cross-over
- creation of different types of defects

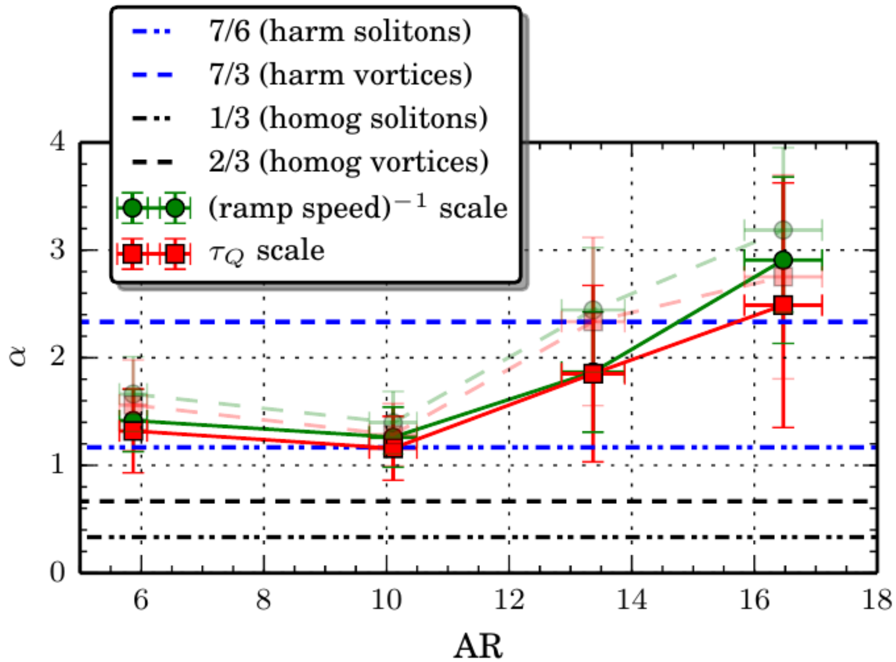




Revised evaporation ramps suppressing the effects of decay of defects preliminary



- power-law scaling for slow ramps
- aspect ratio dependent exponent



- flat plateau for fast ramps
- plateau independent on aspect ratio

	model	α_{homog}	α_{harm}
solitons in 3D or in 1D	MF	1/4	1
$(S - D = 1)$	F-model	1/3	7/6
vortices in 3D	MF	1/2	2
$(S - D = 2)$	F-model	2/3	7/3

Dynamics of quantized vortices

Determine dissipative and transport processes in:

- Superfluid helium
- Superconductors
- Neutron stars

In atomic BECs:

Controllable environment, spatial scale from ξ to tens of ξ, inhomogeneous systems, boundary physics...

BUT

Vortices are produced stochastically and their dynamics cannot be followed through standard destructive absorption imaging

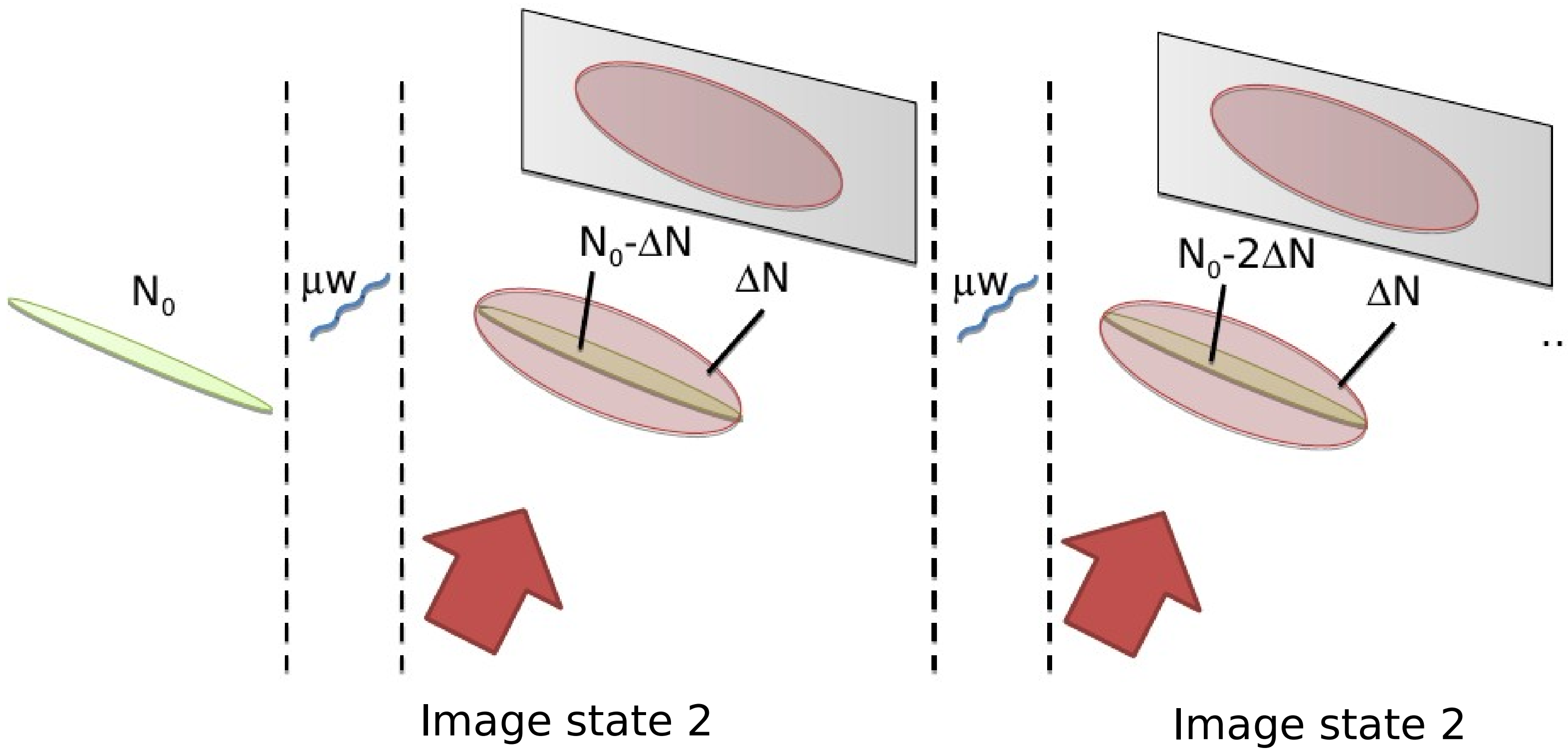
Stroboscopic imaging of defect dynamics

μ–wave pulses extract a small fraction from the BEC

$$|1,-1\rangle \longrightarrow |2,-2\rangle$$

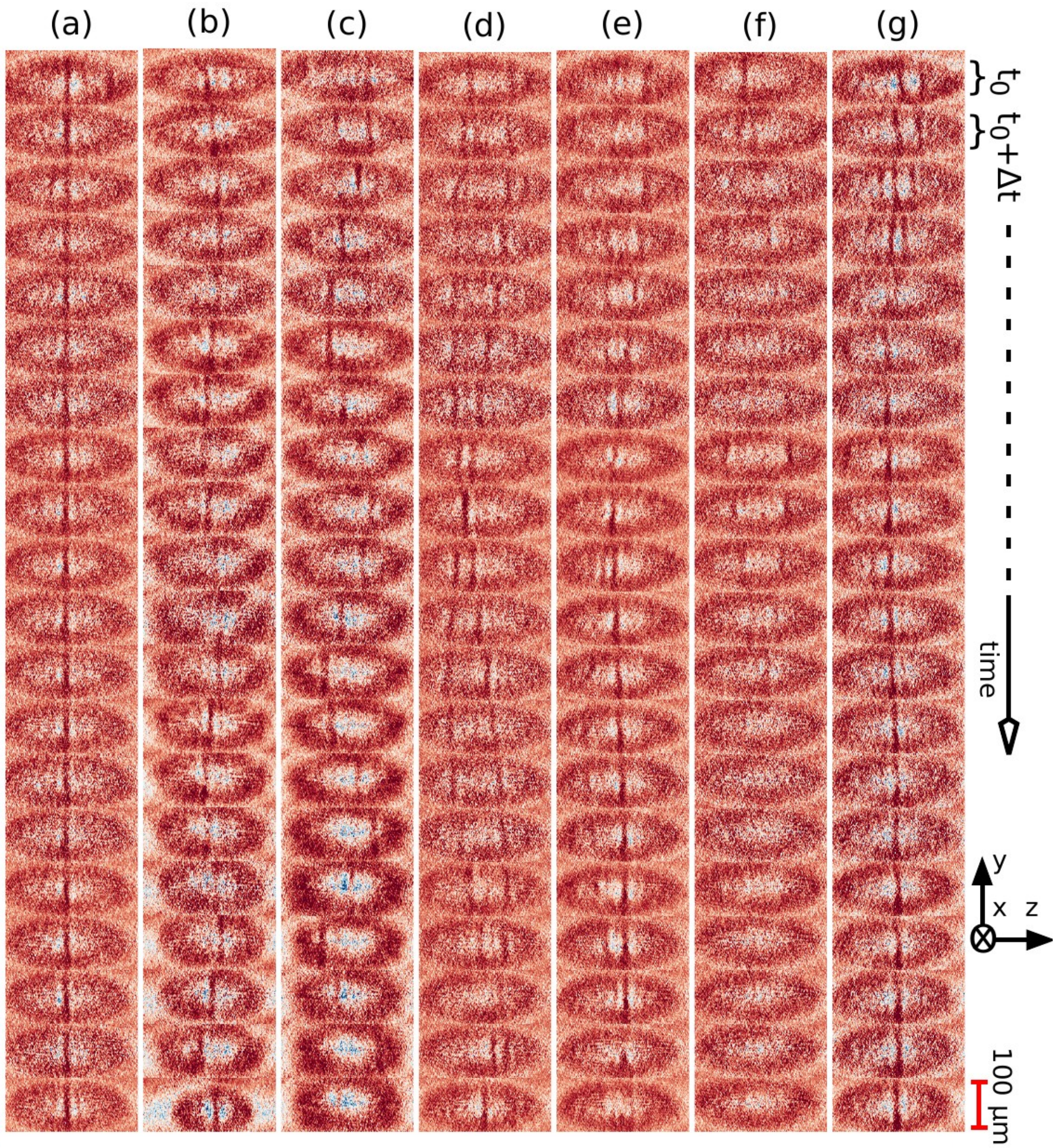
$$\frac{\Delta N}{N_0} \sim 4\%$$

- Initial atom number ~ 10^7
- Magnetic harmonic trap in |1, −1> with $\{\omega_{x,y} = \omega_\perp, \omega_z\}/2\pi = \{131, 13\}$ Hz
- 13 ms expansion in |2, −2> plus RF dressing
- Selective imaging of the output coupled fraction



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

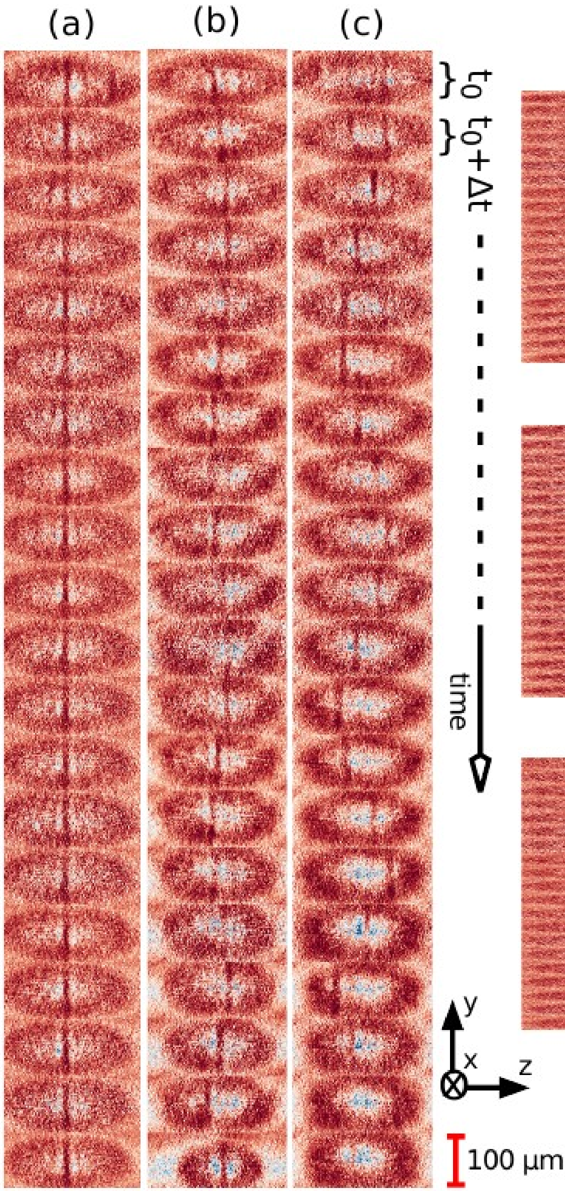
Stroboscopic imaging of defect dynamics



- expansion in the anti-trapped state
- selective imaging of the output coupled fraction
- imaging iterated up to 20 times
- plot residuals from the Thomas-Fermi profile

S. Serafini *et al.*, PRL **115**, 170402 (2015)

Stroboscopic imaging of defect dynamics



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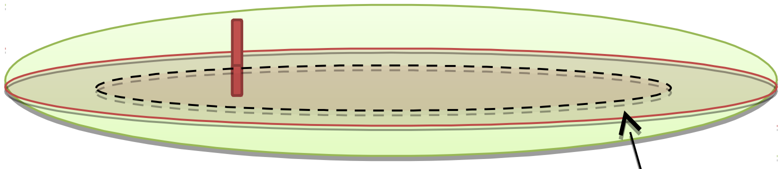
S. Serafini *et al.*, PRL **115**, 170402 (2015)

Vortex dynamics



SINGLE VORTEX DYNAMICS

A straight vortex line is expected to precess in an inhomogeneous non-rotating condensate, following an equipotential elliptical orbit around the center:

$$T_{SV} = \frac{4(1 - r_o^2)\mu}{3\hbar\omega_\perp \ln(R_\perp/\xi)} T_z$$

$$T_z = \frac{2\pi}{\omega_z}$$ axial trapping period

$$r_0 = \frac{z_{max}}{R_z} = \frac{y_{max}}{R_\perp}$$ normalized oscillation amplitude

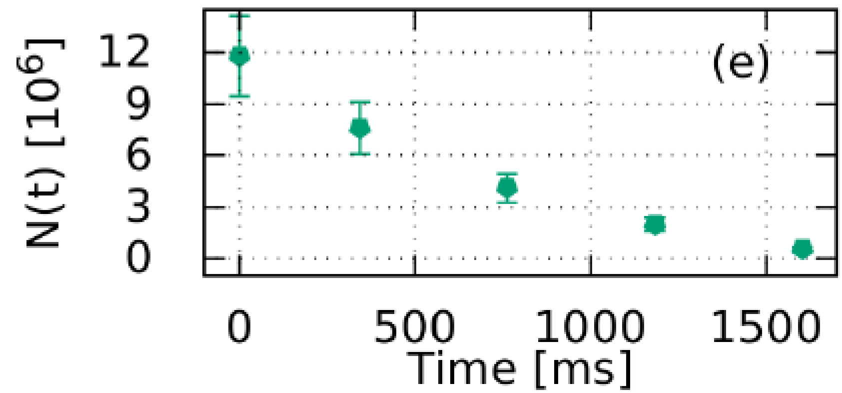
ξ condensate healing length

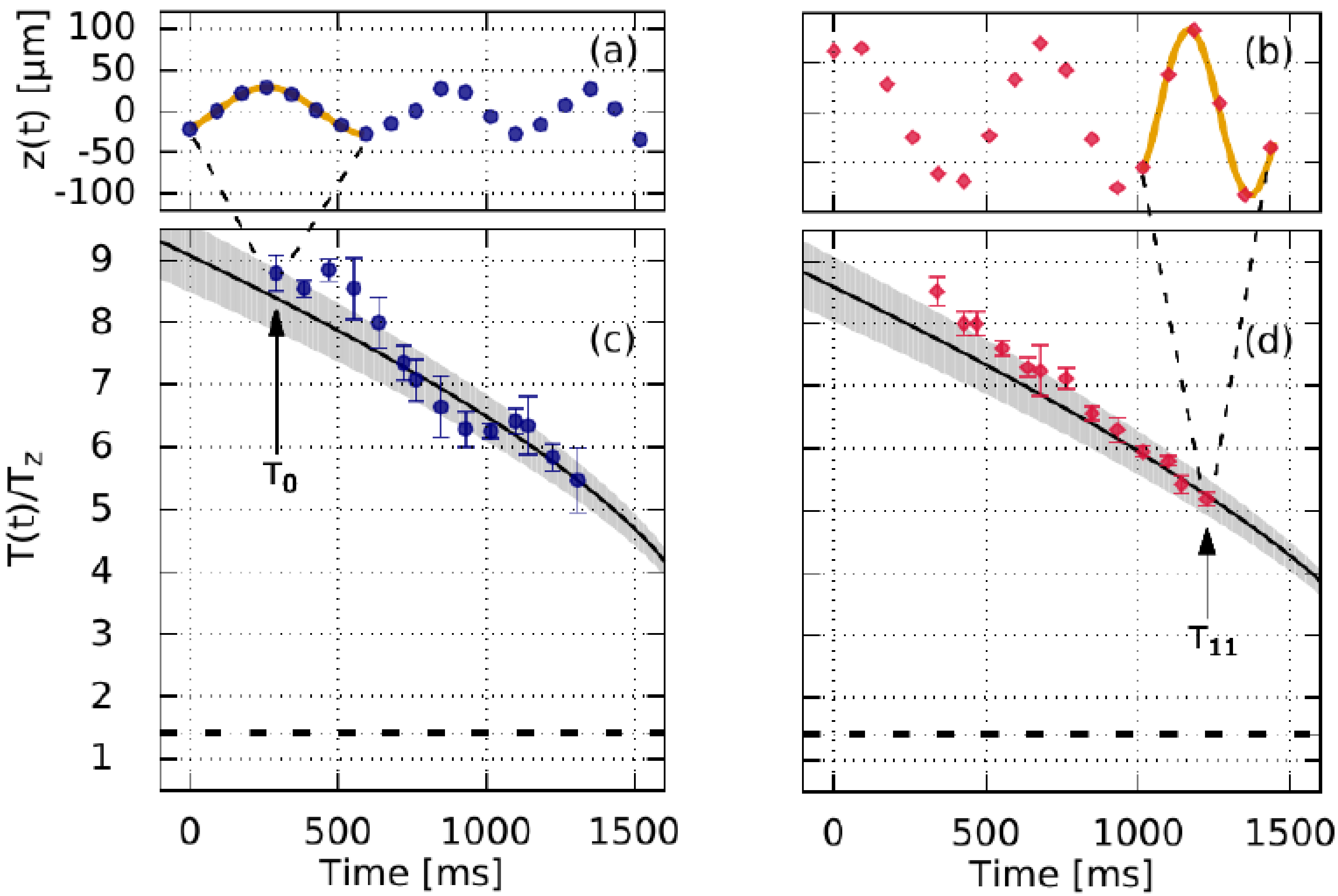
A. L. Fetter and J.-K. Kim, J. Low Temp. Phys. **125**, 239 (2001)

L. P. Pitaevskii, arXiv: 1311.4693 (2013), M. J. H. Ku *et al.*, PRL **113**, 065301 (2014)

Period VS atom number

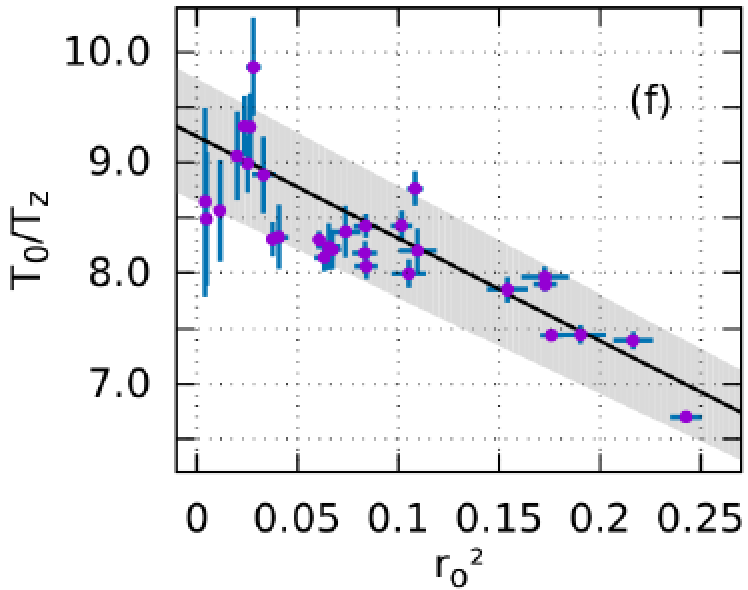
$$T_{SV} \propto \mu \propto N(t)^{2/5}$$

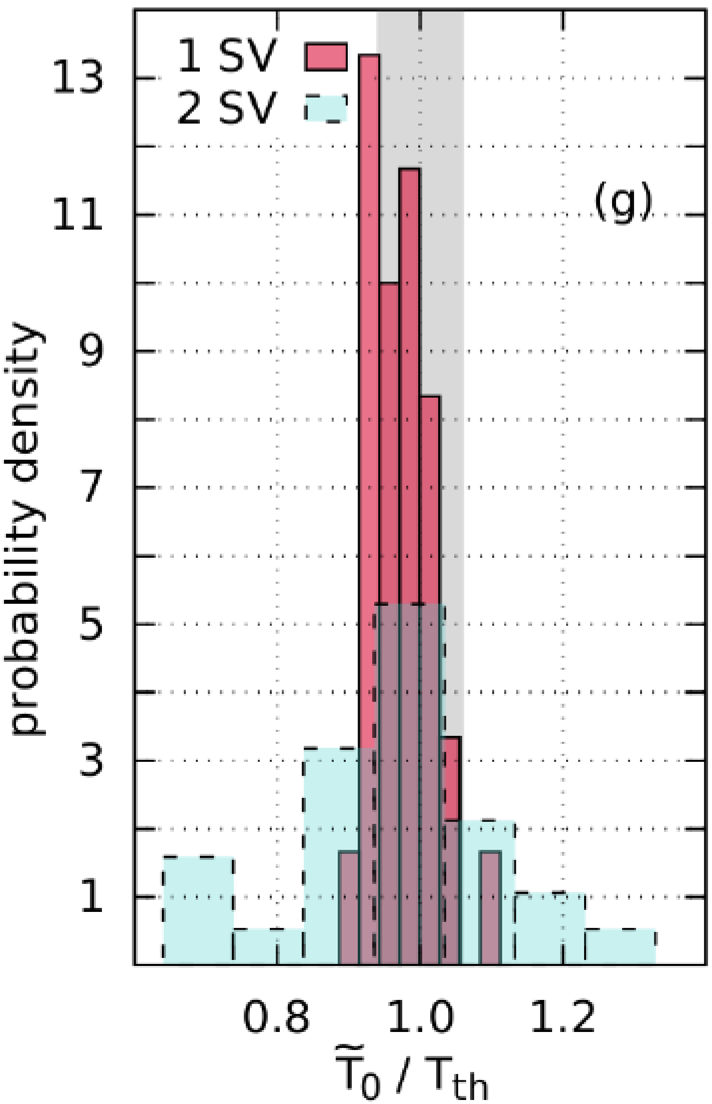




Period VS amplitude of orbit

$$\frac{T_{SV}}{T_z} = \frac{4(1 - r_o^2)\mu}{3\hbar\omega_\perp \ln(R_\perp/\xi)}$$

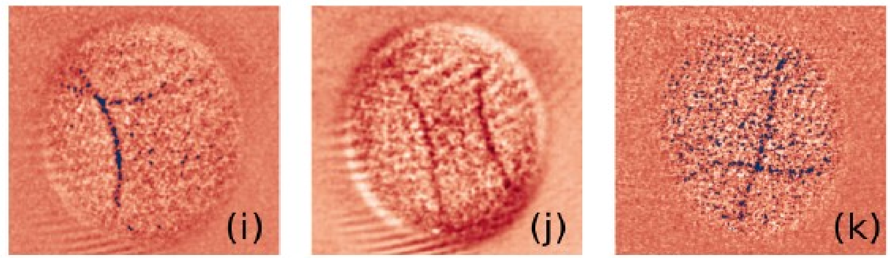


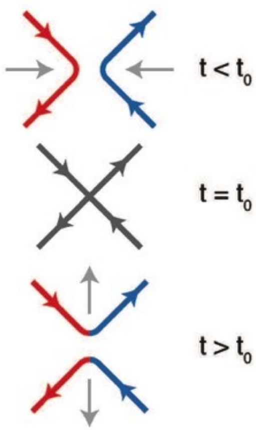


Interaction among vortices

Random orientation of the nodal lines in the radial plane

→ Full 3D vortex interaction

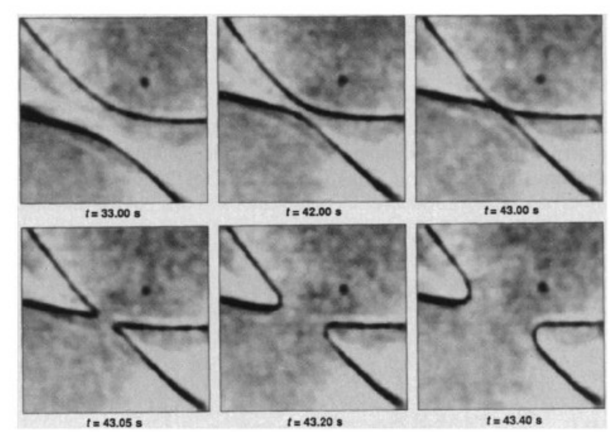




Ideal benchmark for:

- Vortex annihilation
- Vortex decay
- Vortex reconnection

Reconnection in liquid crystals



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

Present simulations:

Vortices are initially at rest

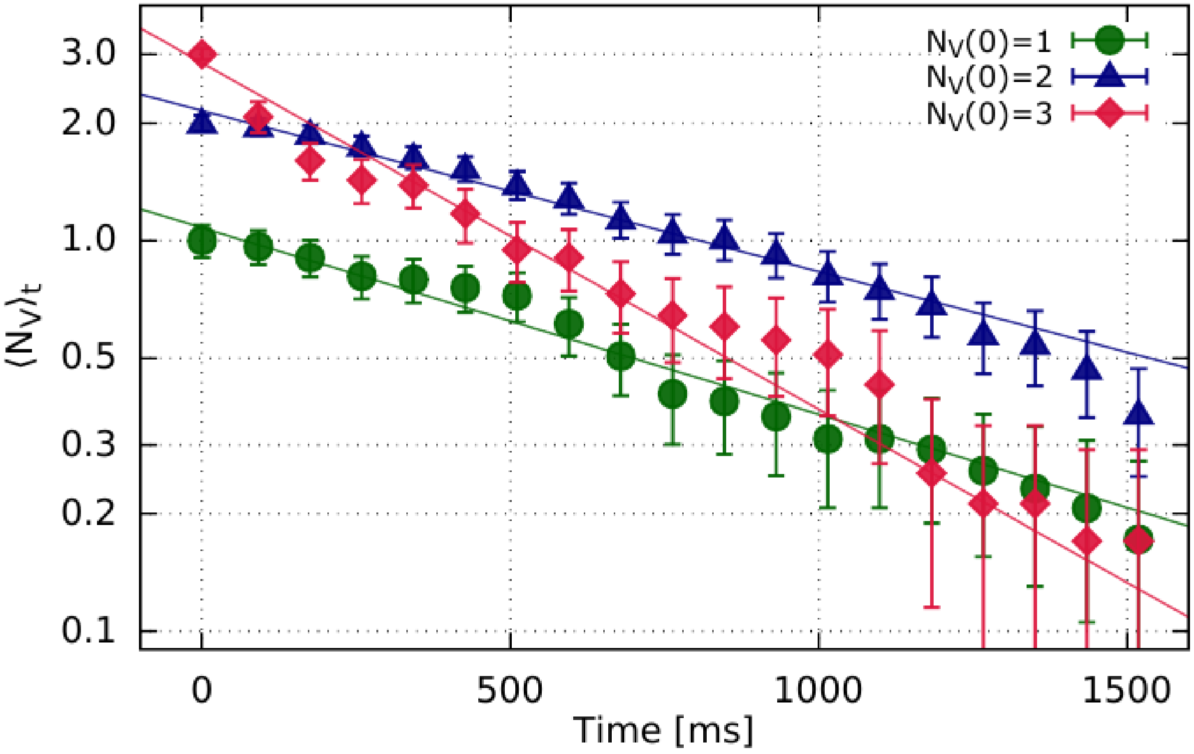
Our experiment:

finite relative momentum

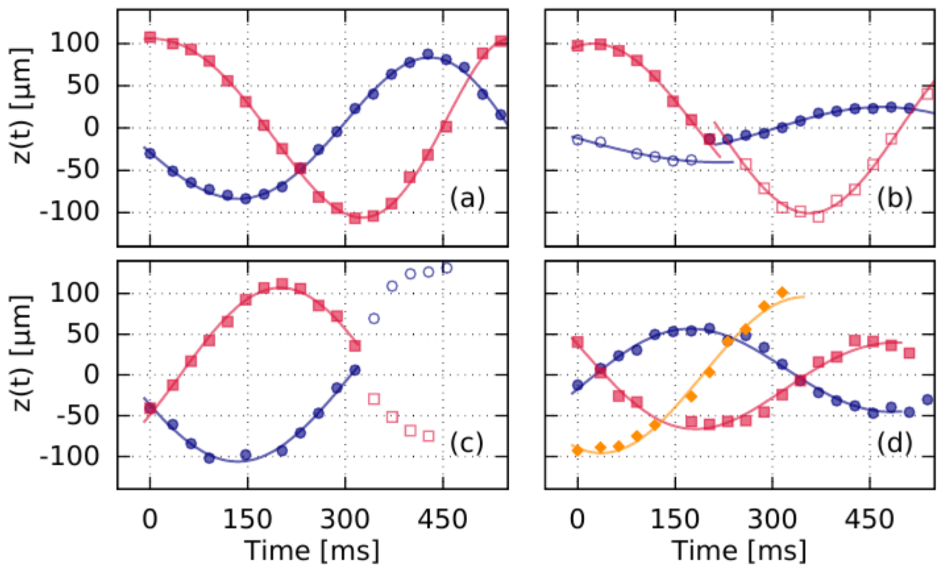
Interaction among vortices: lifetime measurement

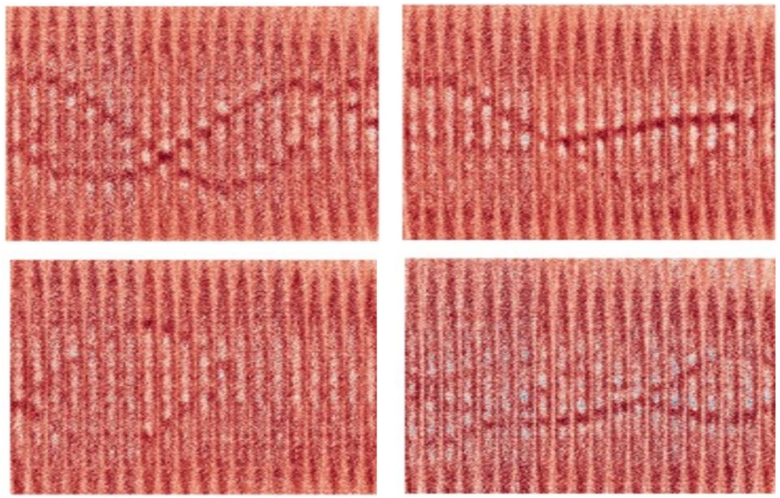
1 or 2 vortices: decay by dissipation with the thermal fraction

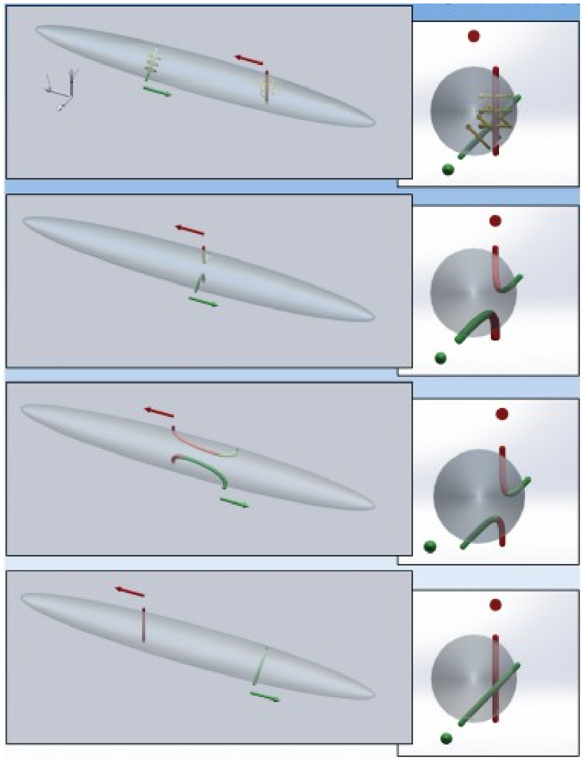
3 vortices: faster decay



Interaction among vortices: phase delays







- Frequently: no visible interactions
- Frequently: change of visibility
- Sometimes: phase shifts
- Seldom: annihilations

Single reconnection energetically expensive due to nodal line stretching.

Possible alternatives:

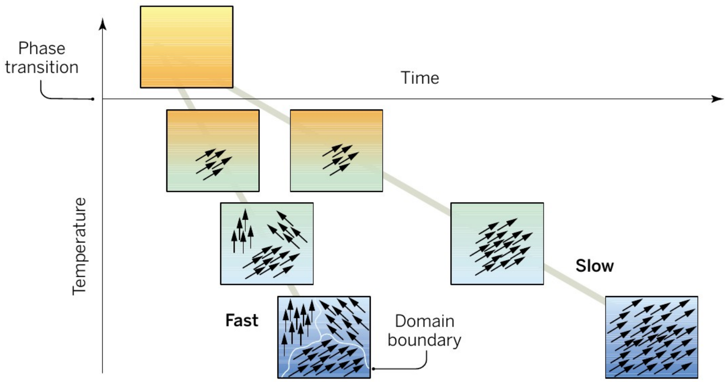
- double reconnection

- rotation of the nodal lines when approaching

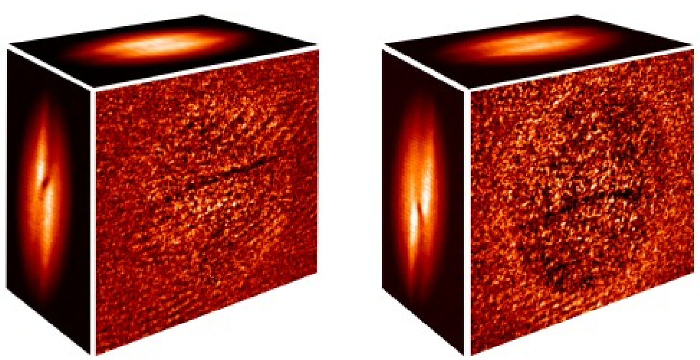
M. V. Berry and M. R. Dennis, Eur. J. Phys. **33**, 723 (2012)

Summary

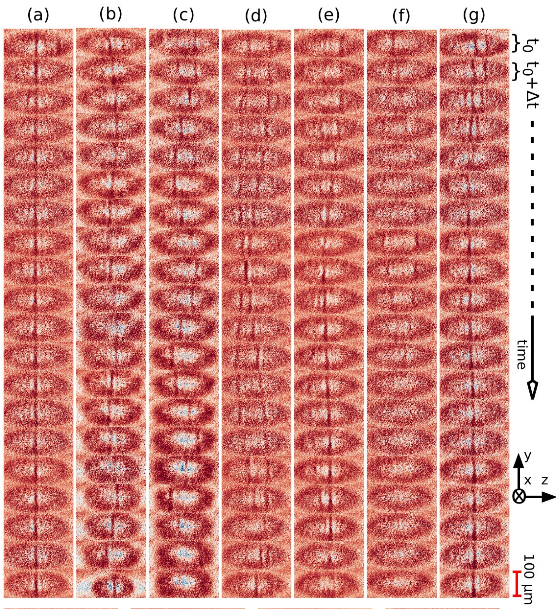
formation



nature



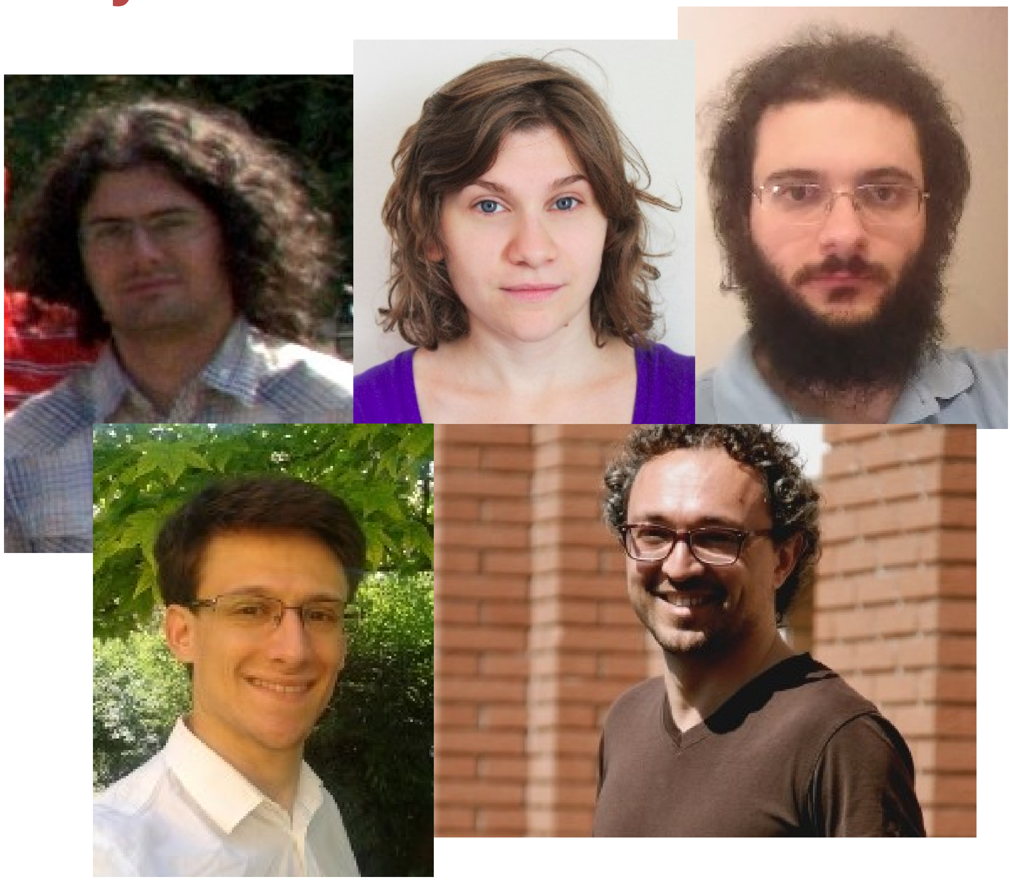
dynamics & interaction



future developments

- investigation of post-quench dynamics after crossing phase transitions
- microscopic study of reconnection mechanisms

Thank you!



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