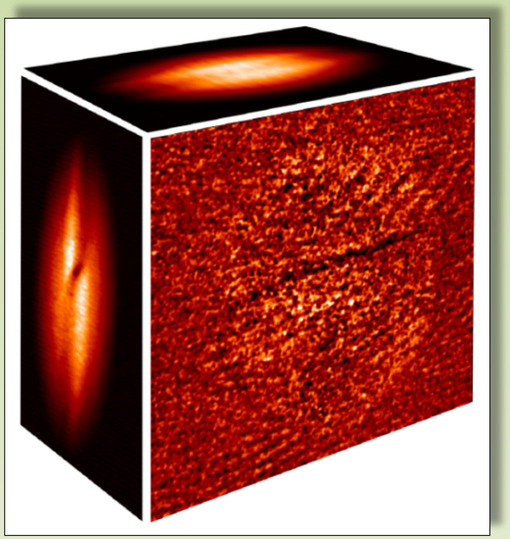
Creation and characterization of defects in a BEC of Sodium atoms



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Theoretical support

BEC

INO-CNR
Istituto Nazionale di Ottica

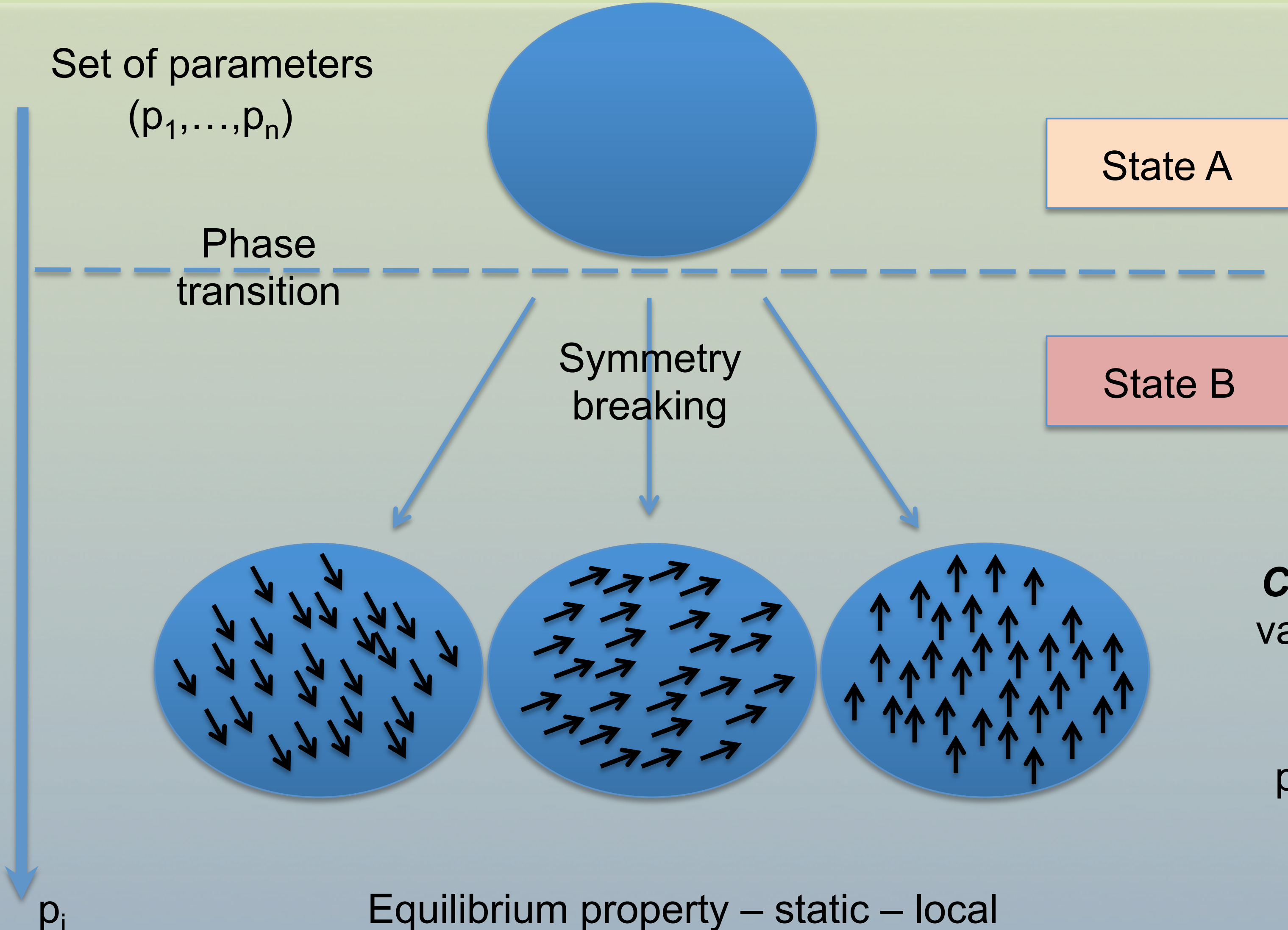
Università degli Studi di Trento

Provincia Autonoma di Trento

EXS2014 – 29 October 2014

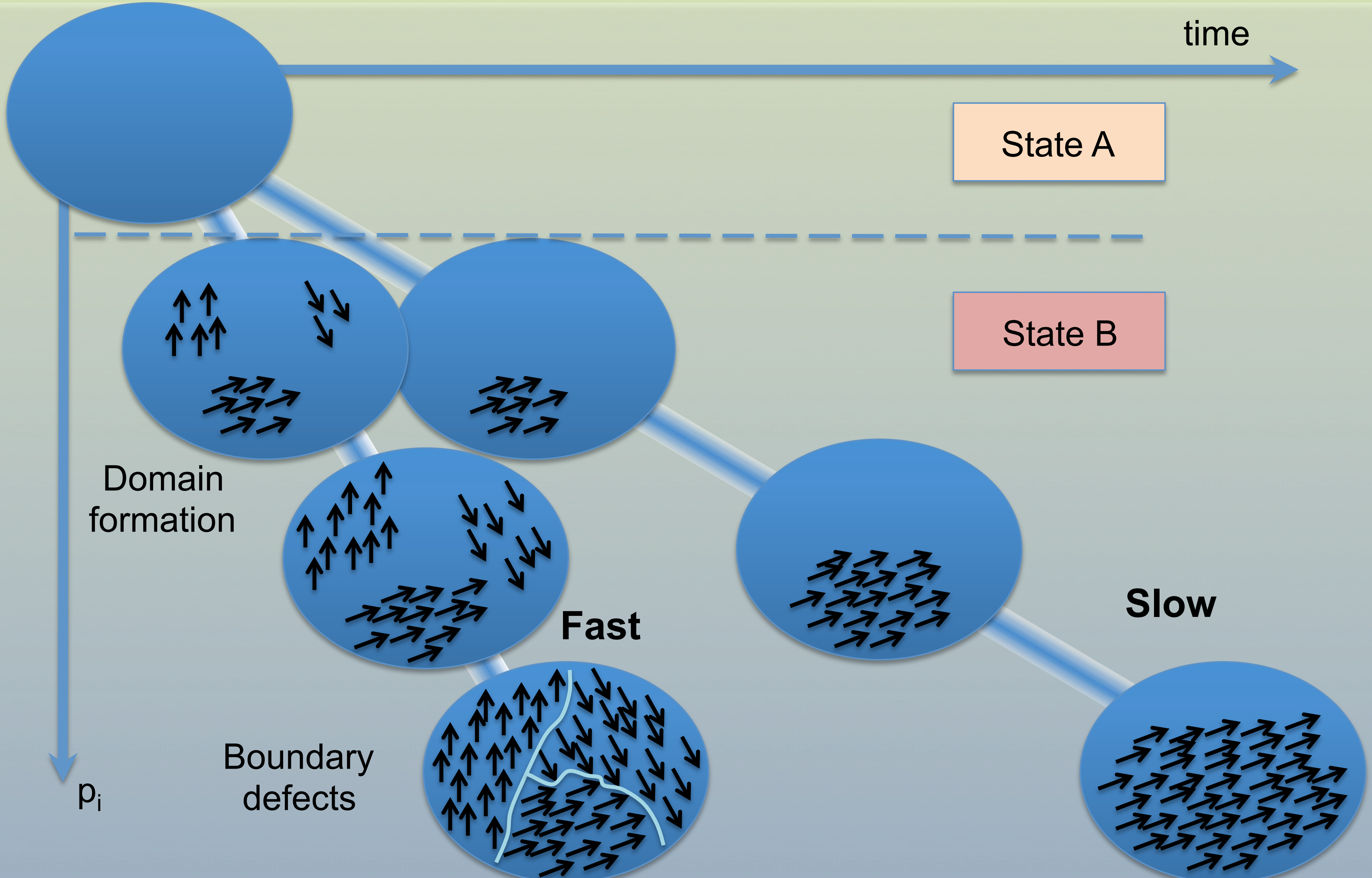
- Phase transitions and Kibble-Zurek mechanism
- Observation of KZM in elongated BEC
- Observation of solitonic vortices in elongated BEC

Phase transitions involving an order parameter



Choice of a value for the newborn order parameter

Equilibrium property – static – local


time
State A
State B
Domain formation
Fast
Slow
Boundary defects
p_i

Kibble-Zurek mechanism

- Spontaneous creation of defects
- 2nd order phase transition
- finite rate crossing

Control parameter

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

Linear quench

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

Coherence length

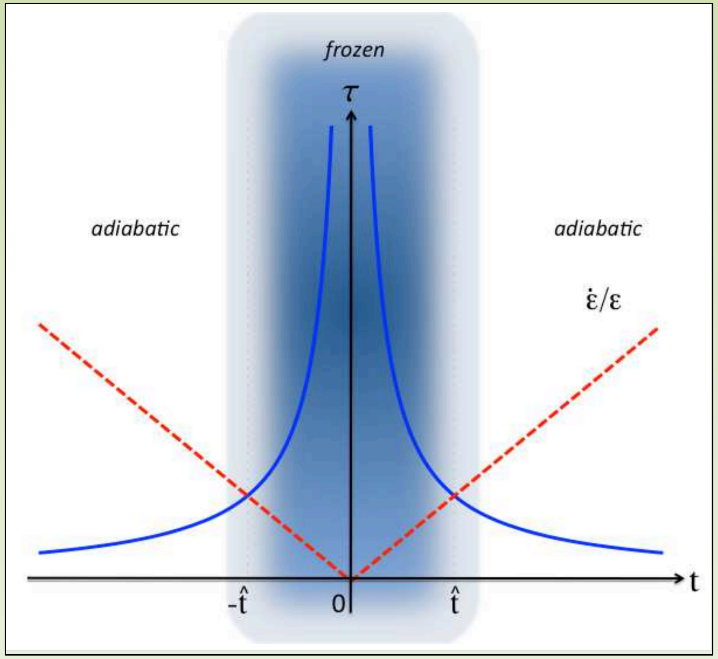
$$\xi(t) = \frac{\xi_0}{|\varepsilon(t)|^{\nu}}$$

Relaxation time

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

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

ν,z: critical exponents



Freeze-out time

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

Domain size

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

Kibble-Zurek mechanism

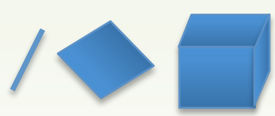
- Spontaneous creation of defects
- 2nd order phase transition
- finite rate crossing

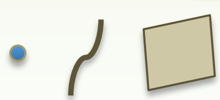
Main prediction: defect density

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

Power-law scaling

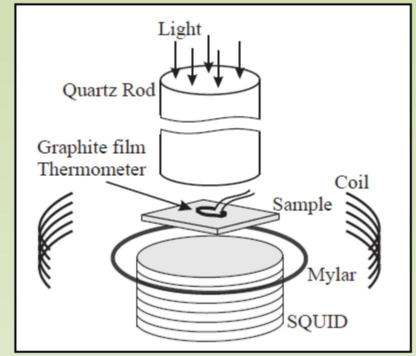
ν,z: critical exponents

D: system dimension 

d: defect dimension 

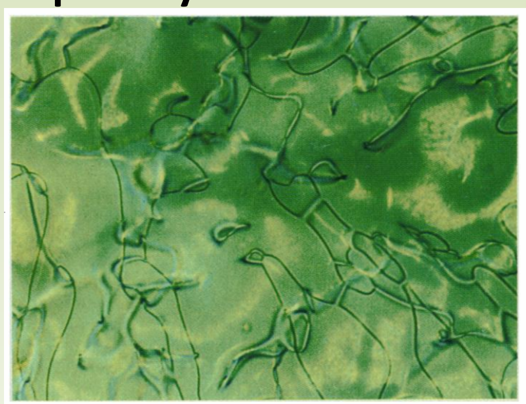
Cosmology

Superconducting films



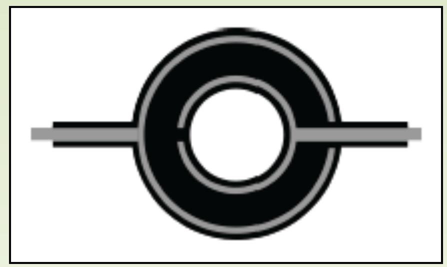
Carmi *et al.*, PRB **60**, 7595 (1999)

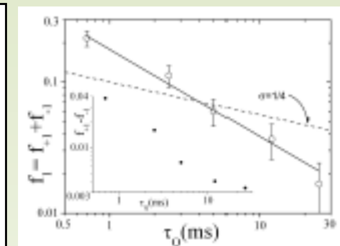
Liquid crystals



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

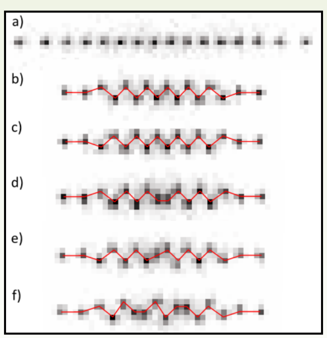
Superconducting rings

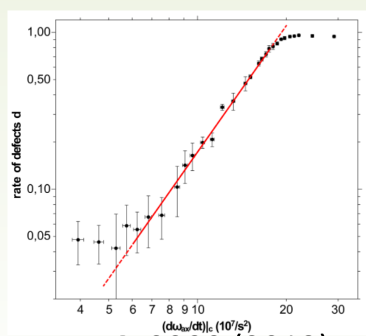




Monaco *et al.*, PRB **80**, 180501 (2009)

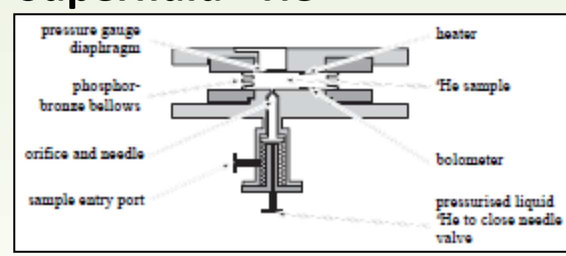
Ion chains





Ulm *et al.*, Nature Commun. **4**, 2290 (2013)

Superfluid ^{3}He

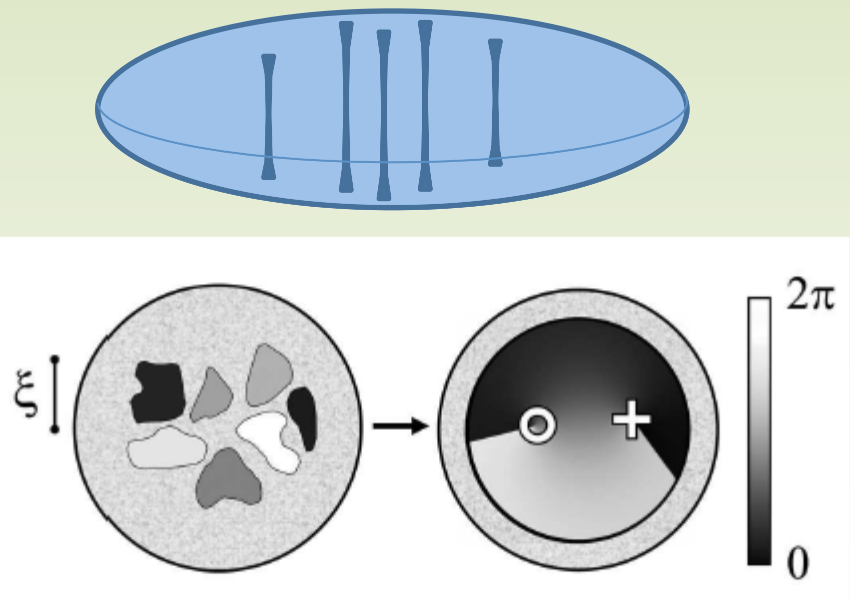


Dodd *et al.*, PRL **81**, 3703 (1998)

KZM in atomic BECs:

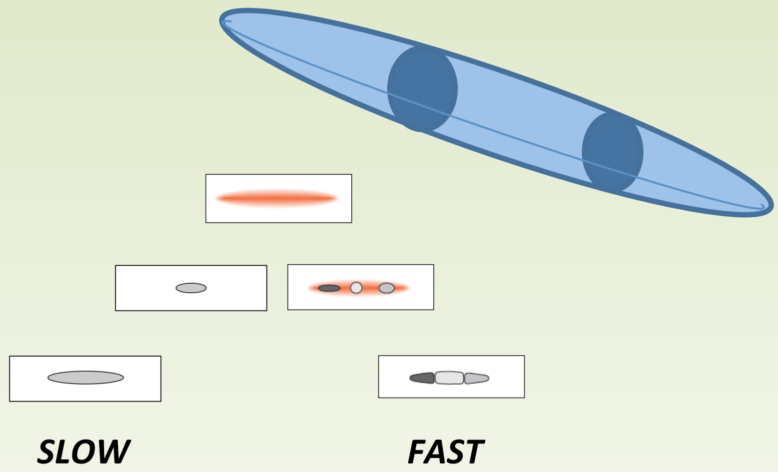
Second-order phase transition;
Order parameter (complex macroscopic wave function);
Temperature quenches.

Pancake-shape → **VORTICES**



Weiler *et al.*, Nature **455**, 948 (2008)

Cigar-shape → **SOLITONS (?)**

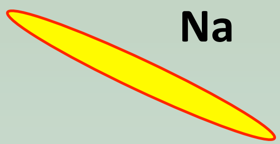


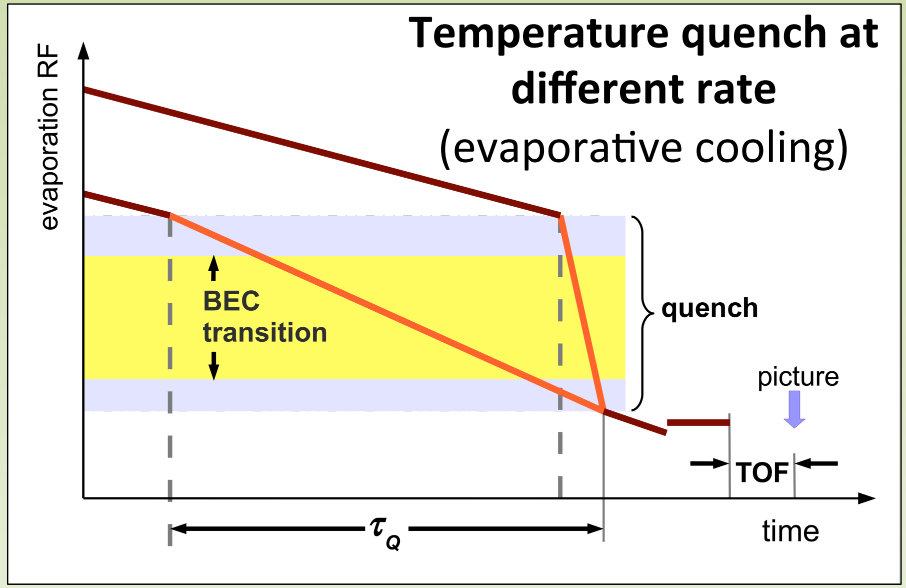
Lamporesi *et al.*, Nature Physics **9**, 656 (2013)

Our system

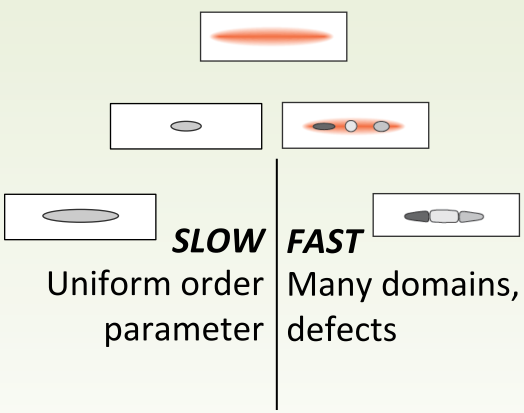
Elongated 3D harmonic trap

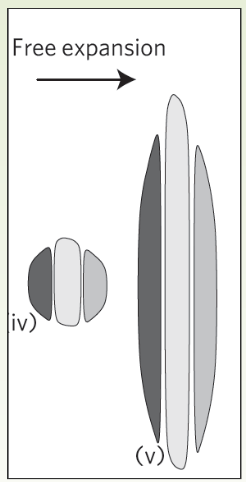
> 10^7 atoms
ν_x = 13 Hz
ν_r = 130 Hz



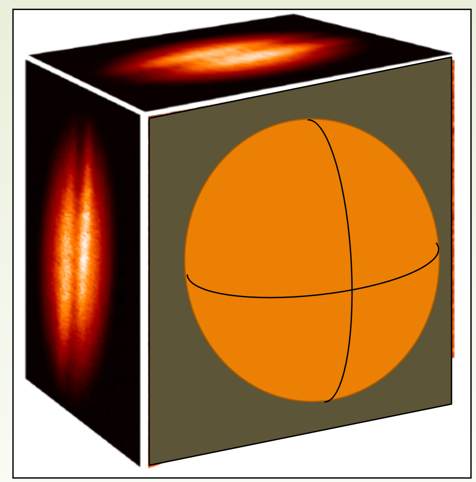


Detection

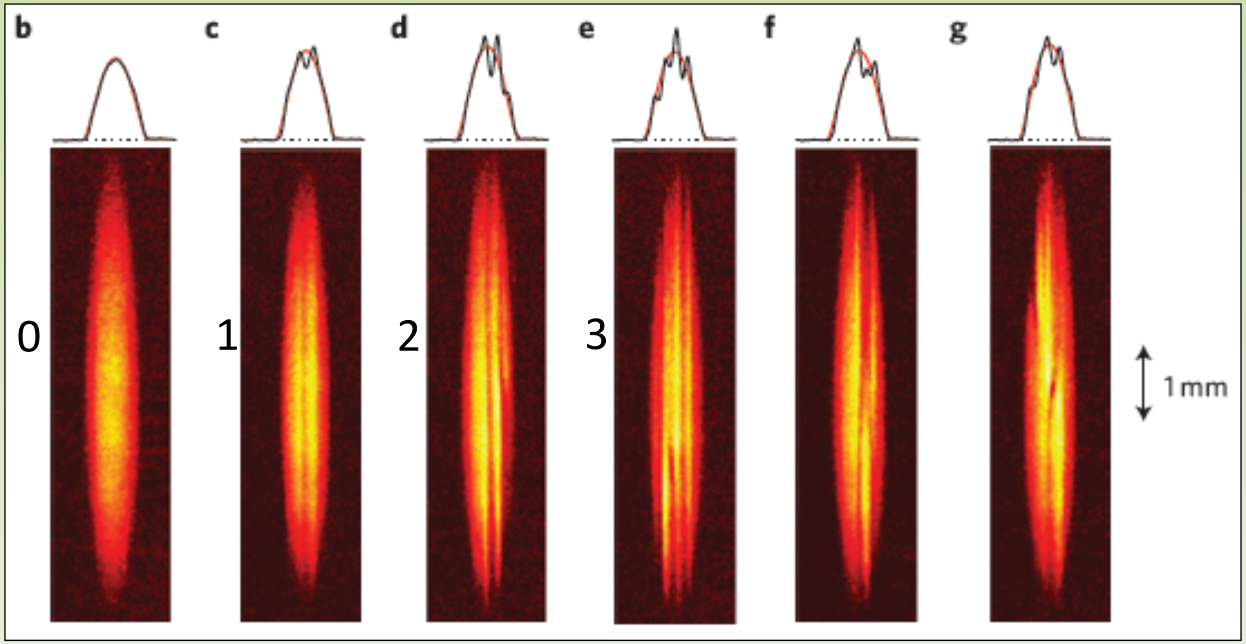




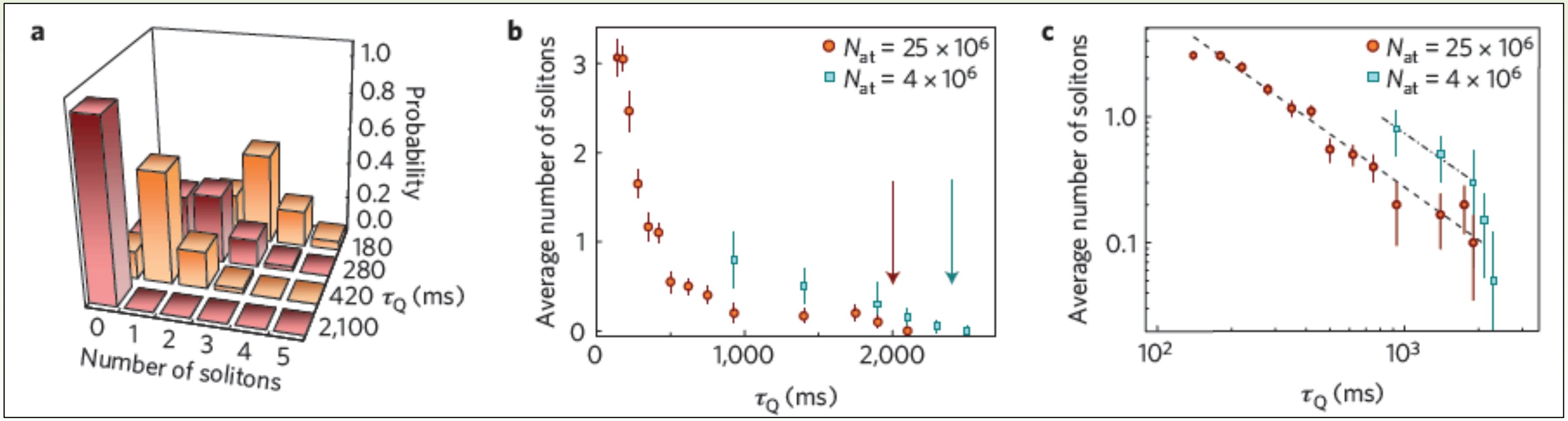
We see planar defects

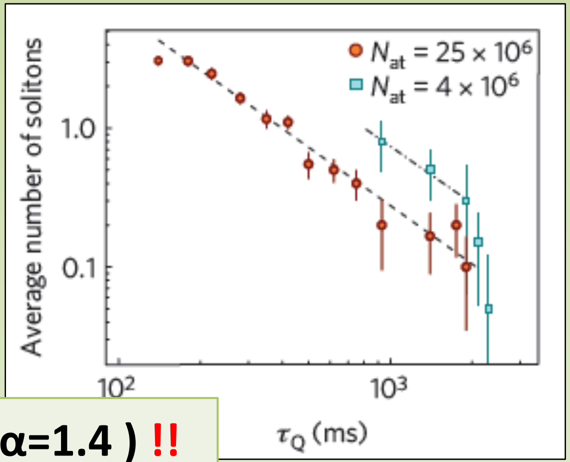


From slow ramps to fast ramps, the number of defects grows



Average number of defects vs. quench time



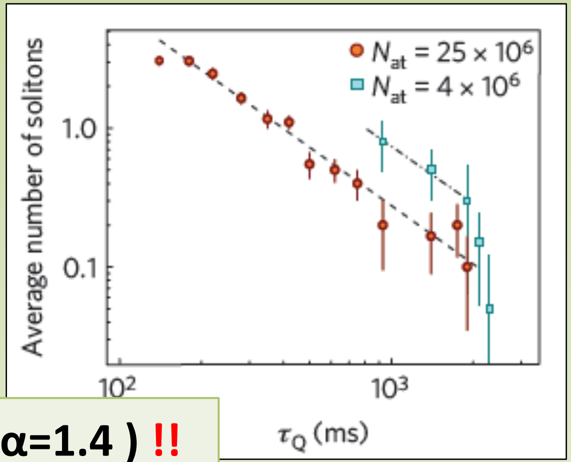


KZM prediction: $$N_s \propto \tau_Q^{-\alpha}$$

Power-law scaling (α=1.4) !!

Observation of KZM in elongated BEC

KZM prediction: $$N_s \propto \tau_Q^{-\alpha}$$



Power-law scaling (α=1.4) !!

(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 $(\nu = \frac{2}{3}, z = \frac{3}{2})$	$\frac{2}{3}$	$\frac{7}{3}$	$\frac{3}{2}$

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

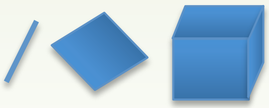
(D-d)=1

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

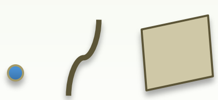
Zurek, PRL **102**, 105702 (2009)

ν,z: critical exponents

D: system dimension

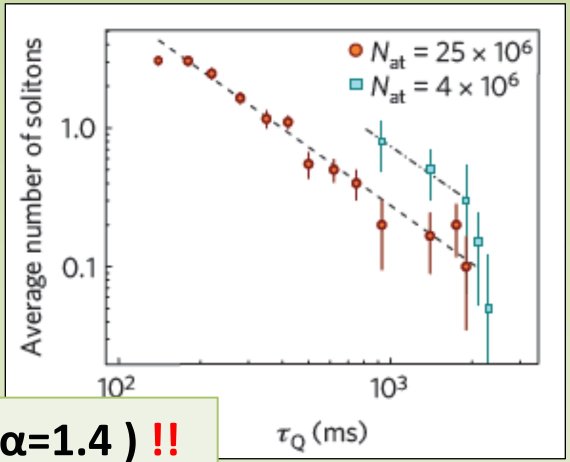


d: defect dimension

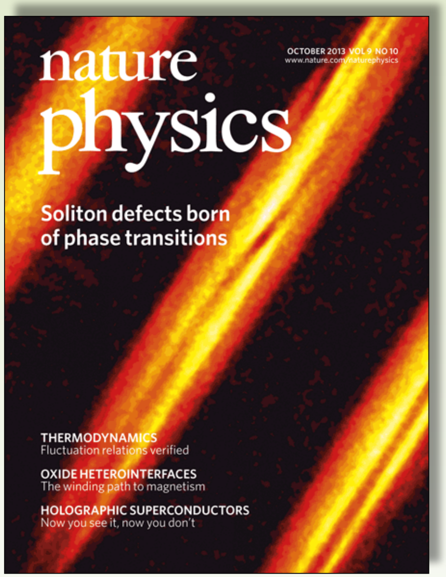


Homog. KZM: [Tc , T]
Inhomog. KZM: [Tc(x) , T]
Our system: [Tc(x) , T (x)]

KZM prediction: $$N_s \propto \tau_Q^{-\alpha}$$

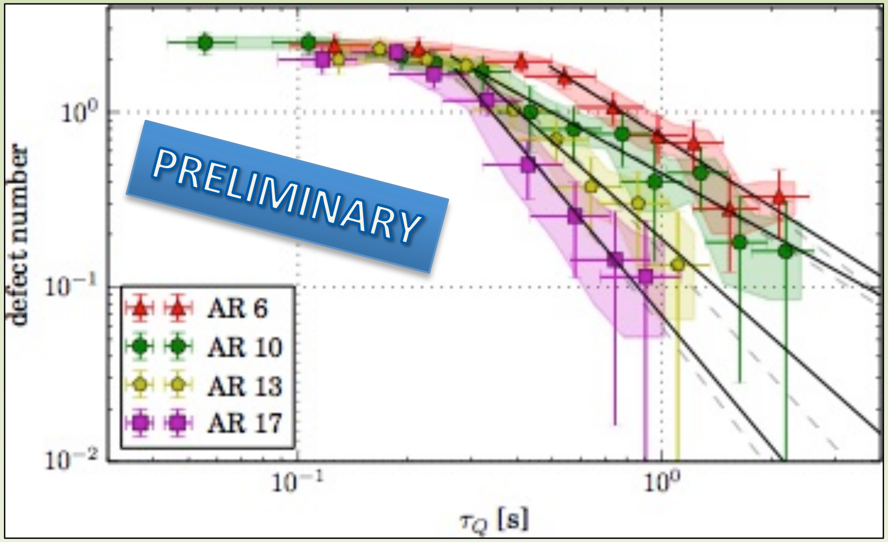


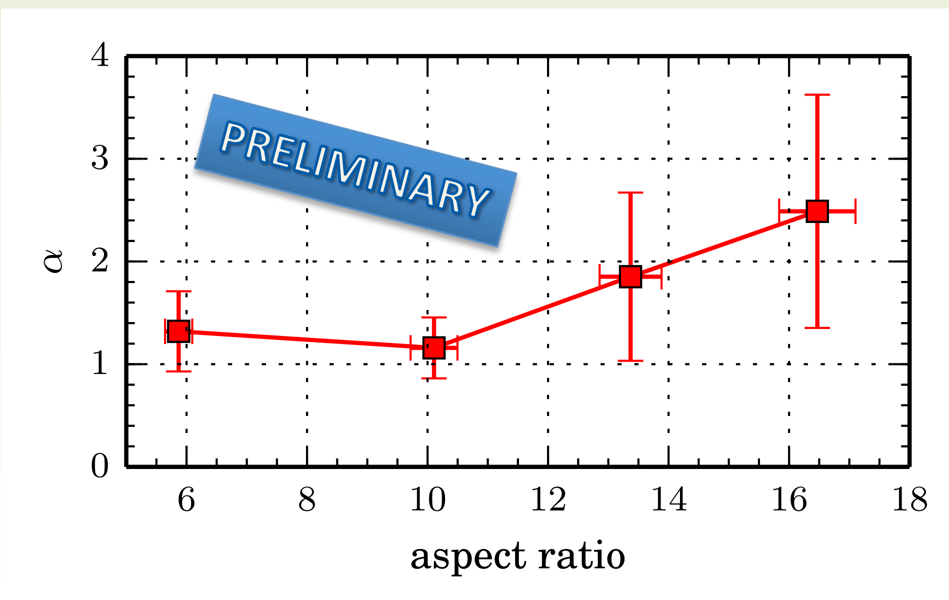
Power-law scaling (α=1.4) !!

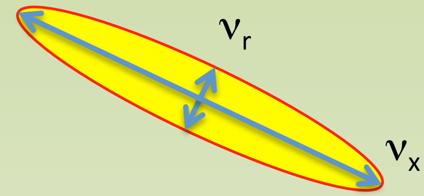


Lamporesi *et al.*, Nature Physics **9**, 656 (2013)

New measurements for different values of aspect ratio



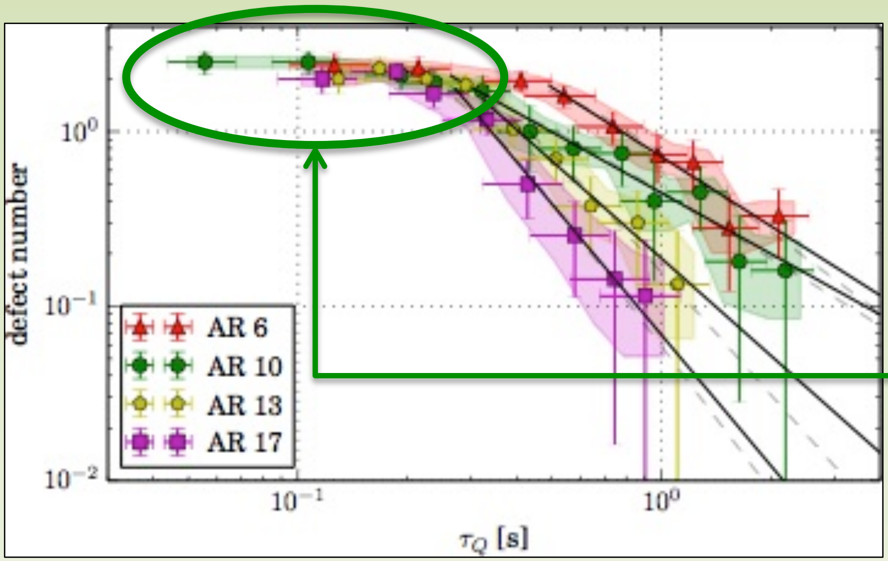


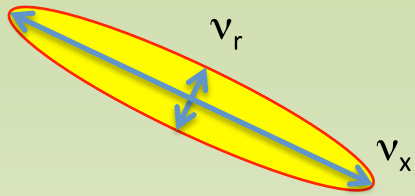


Aspect ratio = ν_r / ν_x

Two open issues (under investigation):

New measurements for different values of aspect ratio

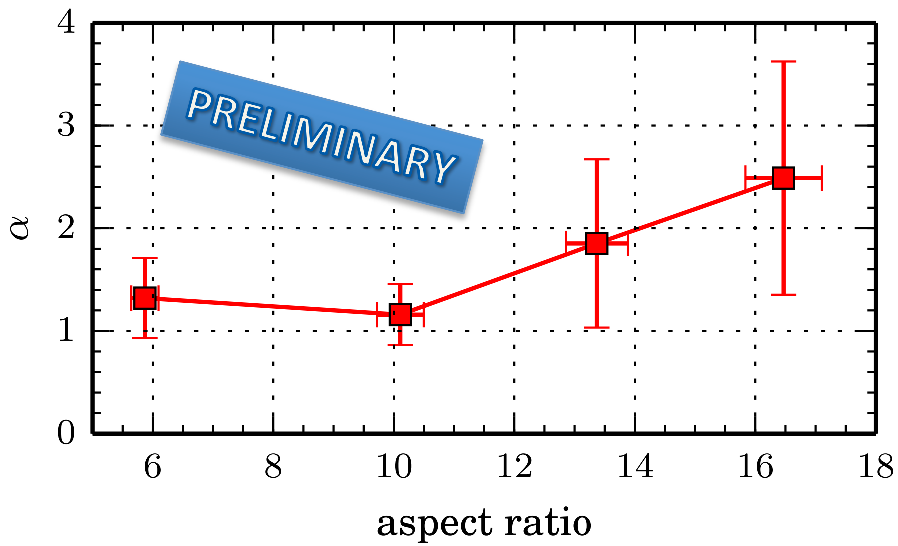




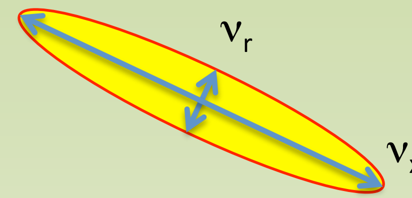
Aspect ratio = ν_r / ν_x

Two open issues (under investigation):

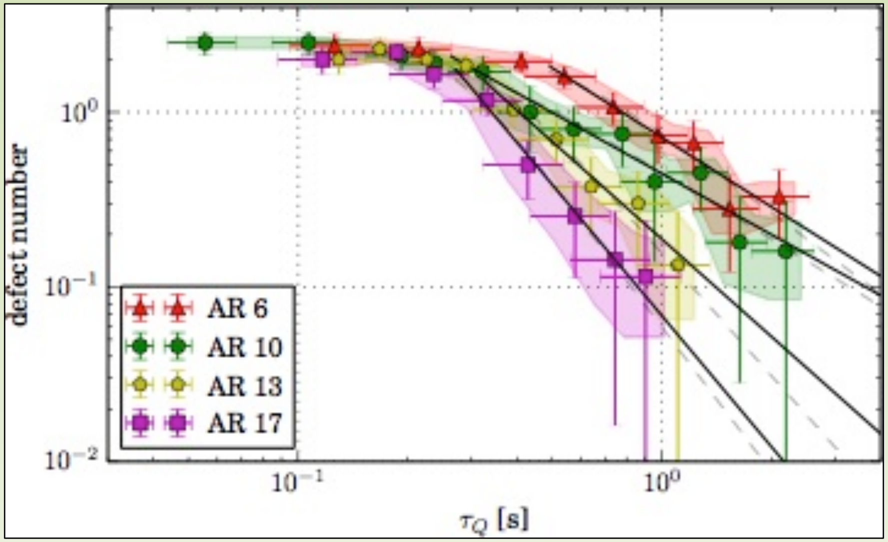
- Origin of the universal plateau at fast quenches



New measurements for different values of aspect ratio

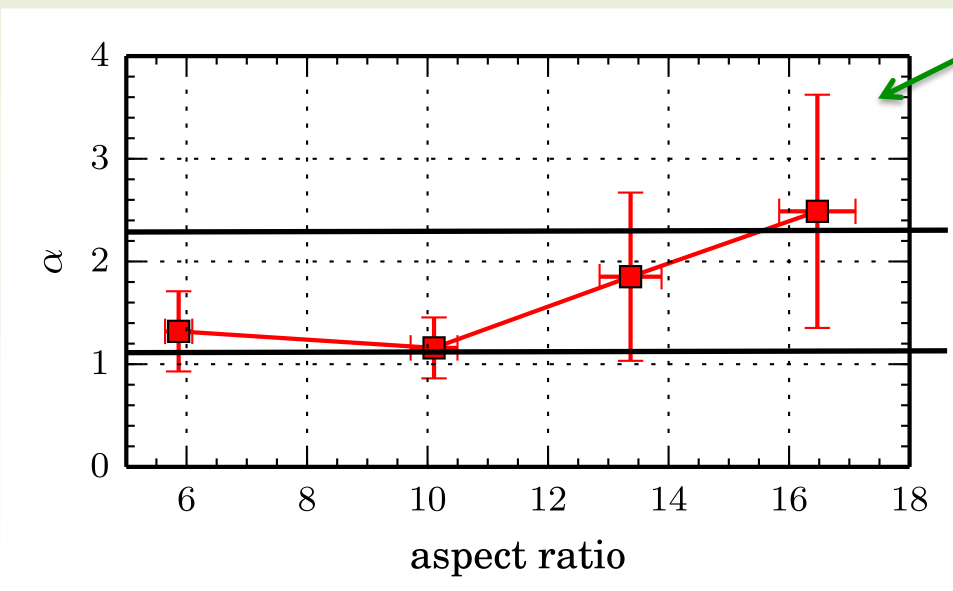


Aspect ratio = ν_r / ν_x



Two open issues (under investigation):

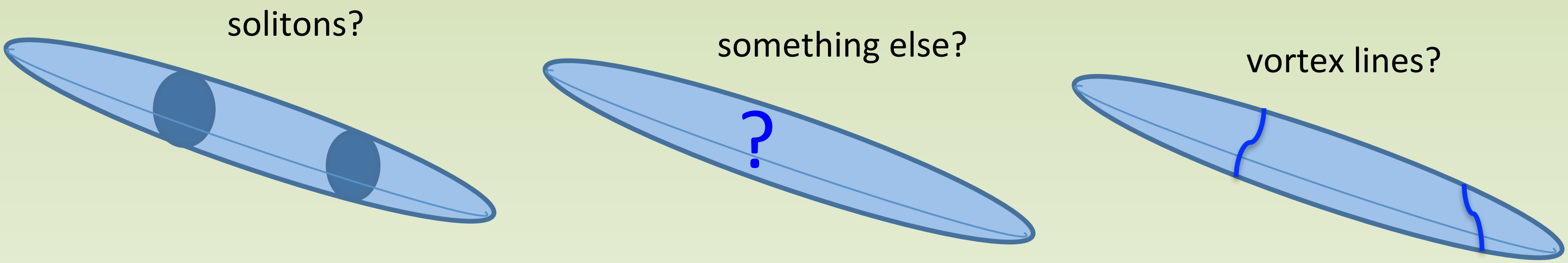
- Origin of the universal plateau at fast quenches
- Dependence of α on aspect ratio



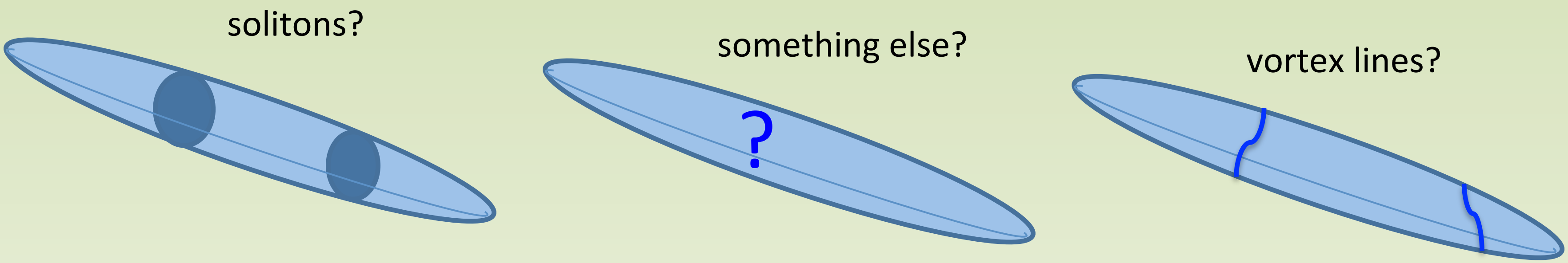
7/3 : KZM for vortex line in a 3D BEC

7/6 : KZM for soliton planes in a 3D BEC

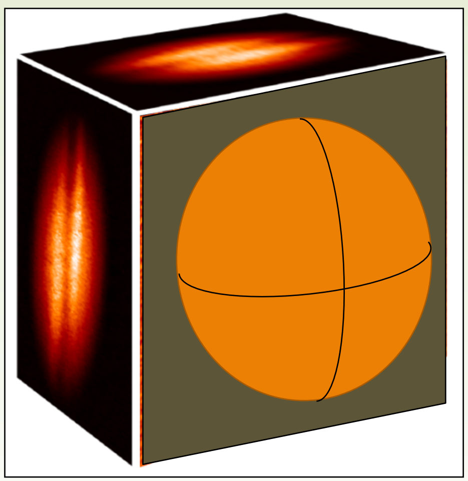
Crucial question: what are these defects?



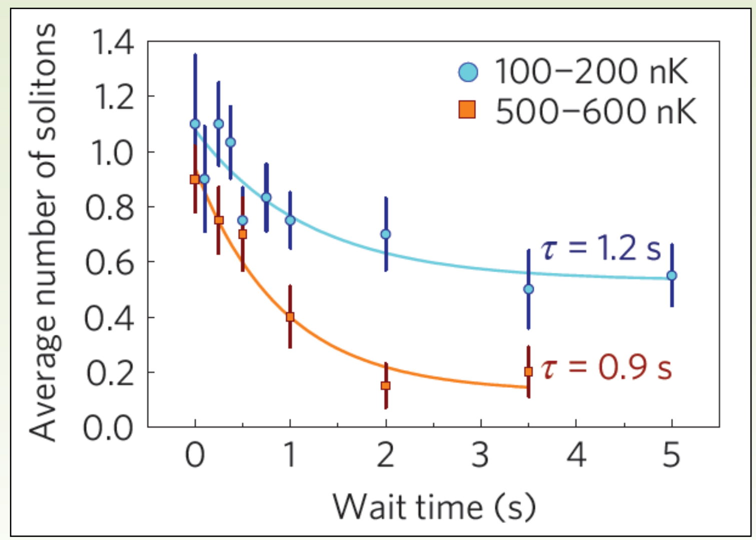
Crucial question: what are these defects?



In favor of solitons:
planar structure



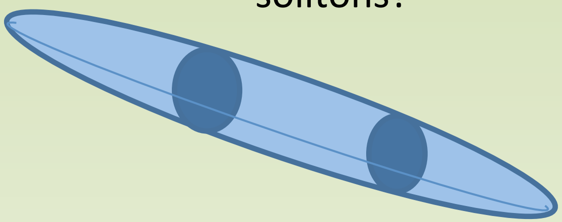
Against solitons: very long life time



See also Yefsah *et al.*, Nature **499**, 426 (2013), for fermions

Crucial question: what are these defects?

solitons?



In favor of solitons:
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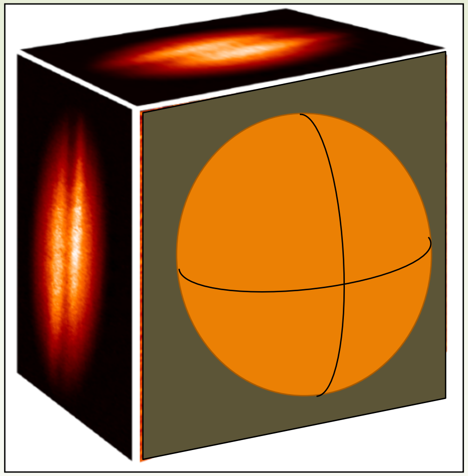
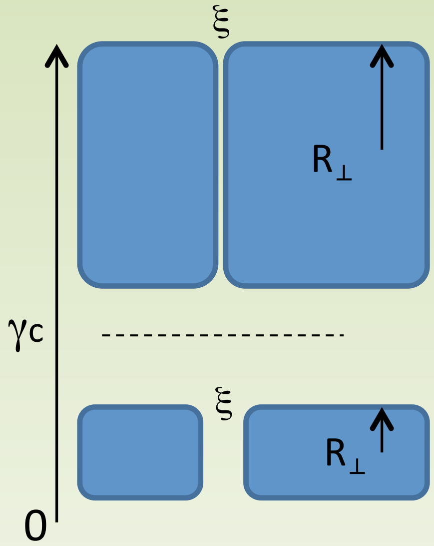


$\gamma > 30$

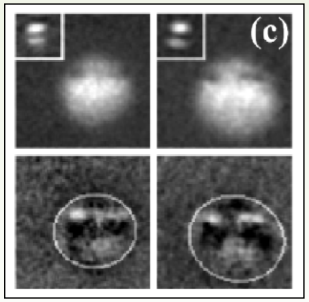
Solitons are expected to be **unstable**
THERMALLY (due to thermal dissipation)
DYNAMICALLY (due to snake instabilities)

Key parameter:

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



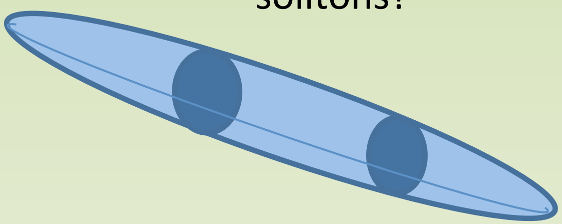
… and to decay into **vortex rings** or other excitations.



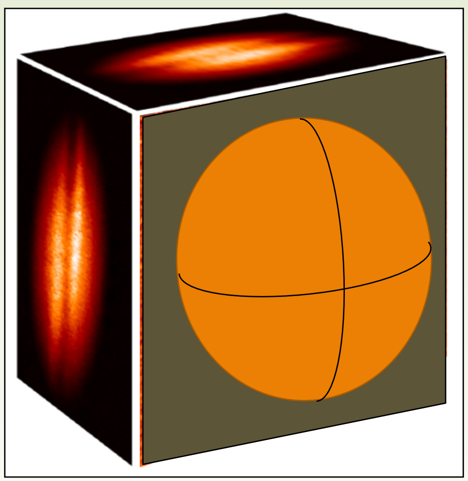
spherical BEC (JILA)
Anderson *et al.*,
PRL **86** 2926 (2001)

Crucial question: what are these defects?

solitons?

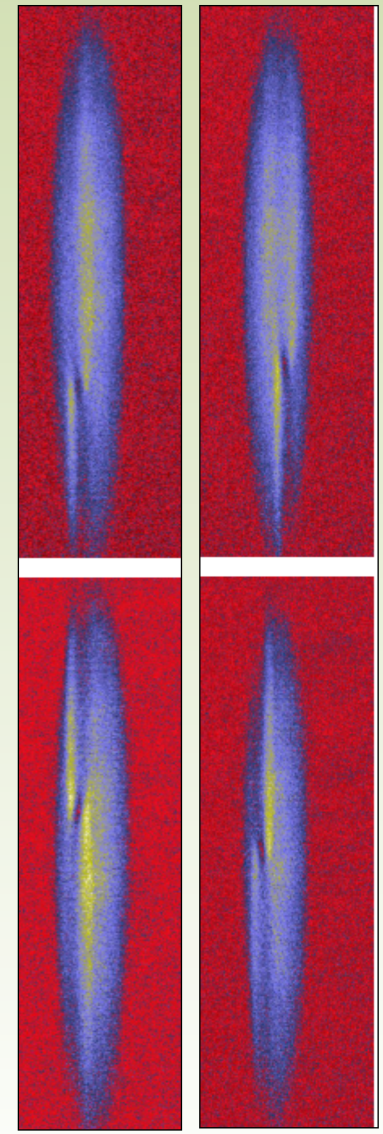


In favor of solitons:
planar structure



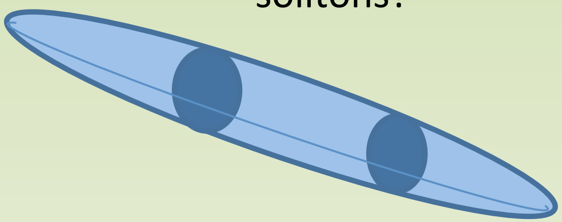
$\gamma > 30$

Note: we often observe **point-like density minima** associated with a **twist** of the planar density depletion (after expansion)

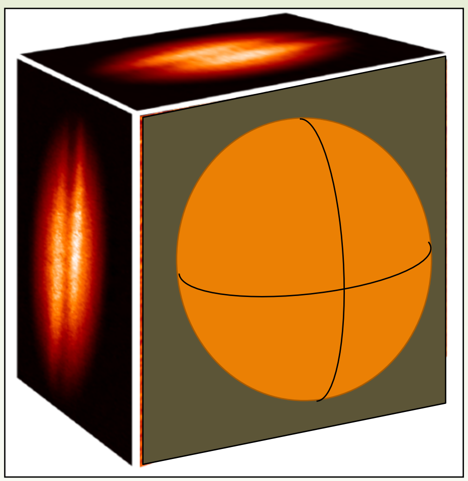


Crucial question: what are these defects?

solitons?



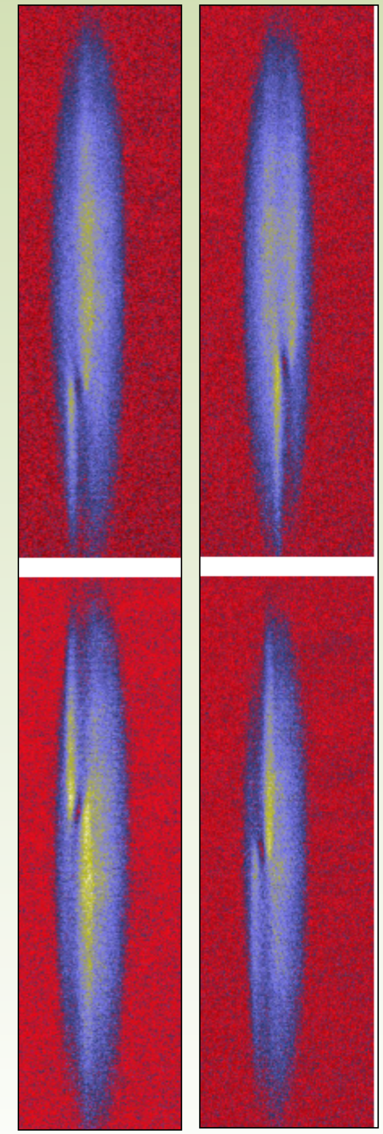
In favor of solitons:
planar structure



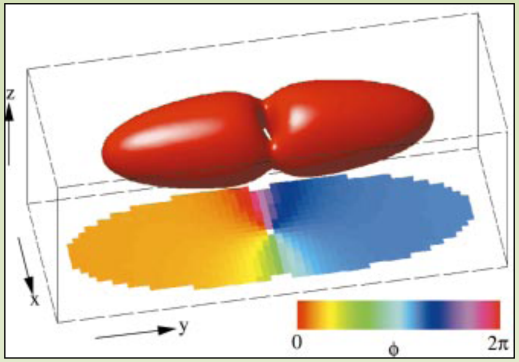
$\gamma > 30$

Note: we often observe **point-like density minima** associated with a **twist** of the planar density depletion (after expansion)

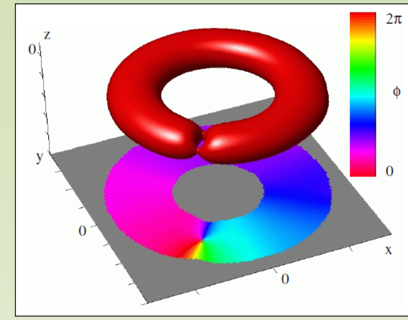
Solitonic vortices ?



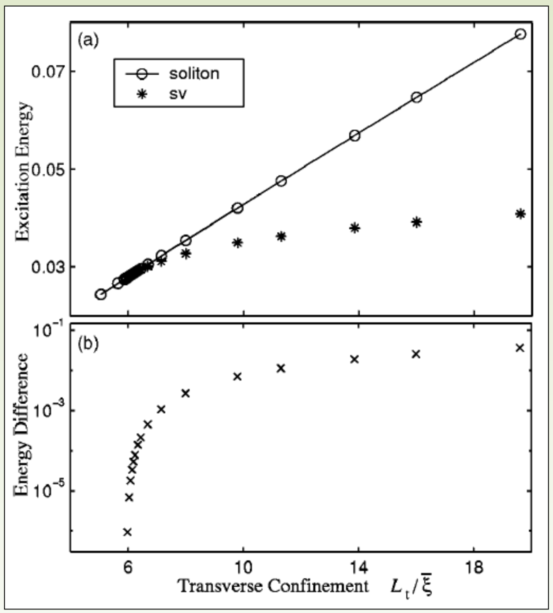
Solitonic Vortex: vortex oriented perpendicularly to the axis of an axisymmetric elongated trap.



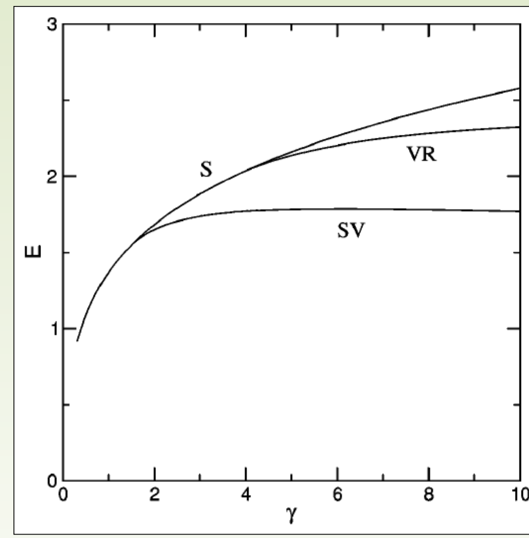
- *Quantized vorticity*
- *Anisotropic phase pattern*
- *Planar density depletion*



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



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



above. The predicted decay of the band soliton into a single SV has not been seen, or predicted, before and should be easily observable with current experimental techniques.

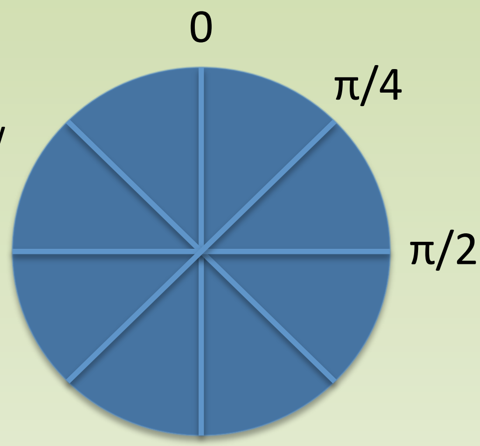
Brand *et al.*, PRA **65**, 043612 (2002)

spherical trap. On the other hand, it is curious that the predicted solitonic vortex has not yet been seen in experiment.

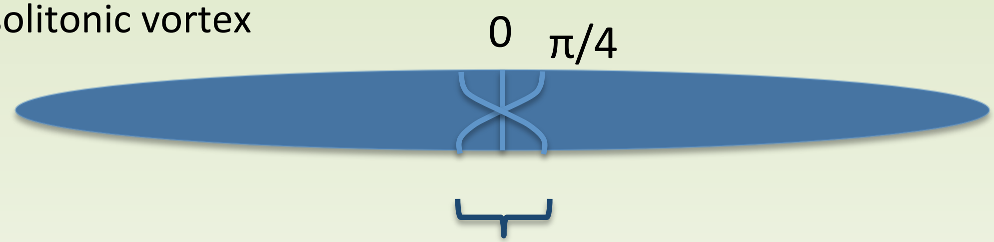
Komineas *et al.*, PRA **68**, 043617 (2003)

Observation of solitonic vortices in elongated BEC

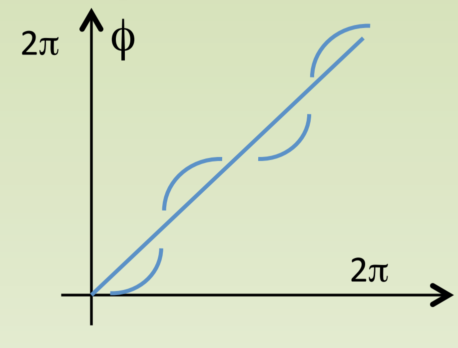
vortex with
isotropic flow



solitonic vortex



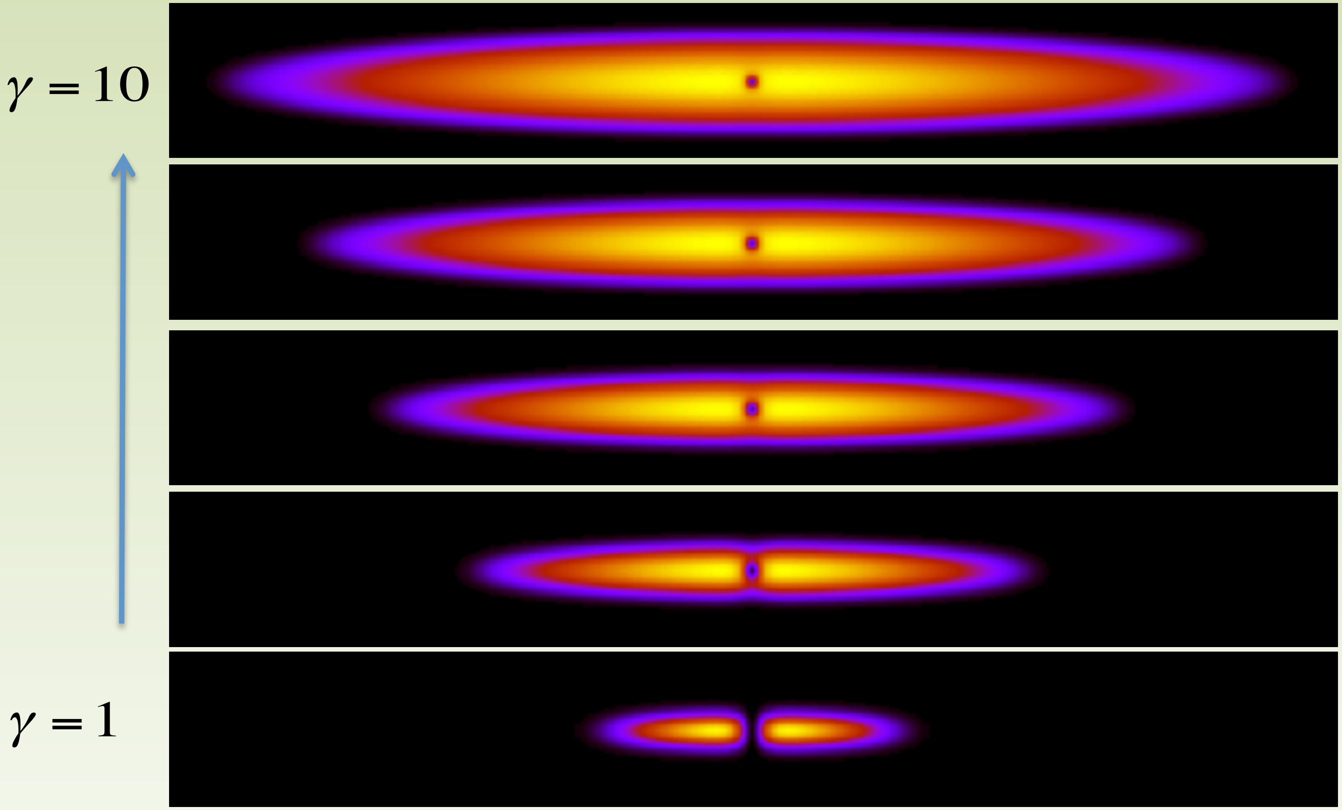
phase of order parameter



angle around the vortex core

large phase gradients in narrow region → high superfluid flow velocity → density depletion to reduce kinetic energy

Numerical simulations:
Solution of Gross-Pitaevskii equation (2D and 3D BECs)

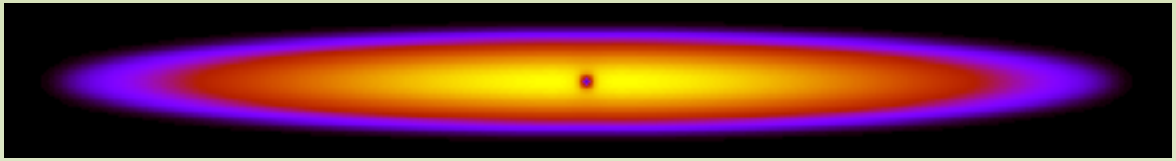


density (in trap)

Observation of solitonic vortices in elongated BEC

Numerical simulations:
Solution of Gross-Pitaevskii equation (2D and 3D BECs)

$\gamma = 10$



density (in trap)

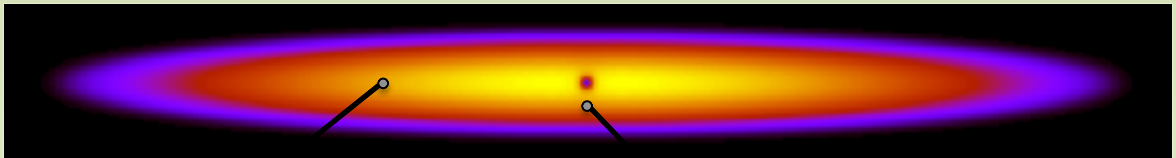
phase (in trap)

Observation of solitonic vortices in elongated BEC

Numerical simulations:

Solution of stationary Gross-Pitaevskii equation (2D and 3D BECs)

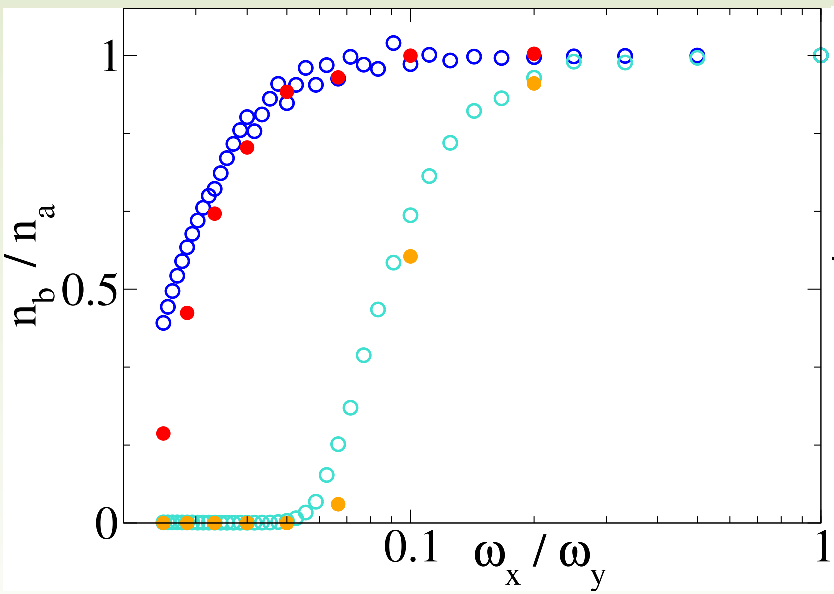
$\gamma = 10$

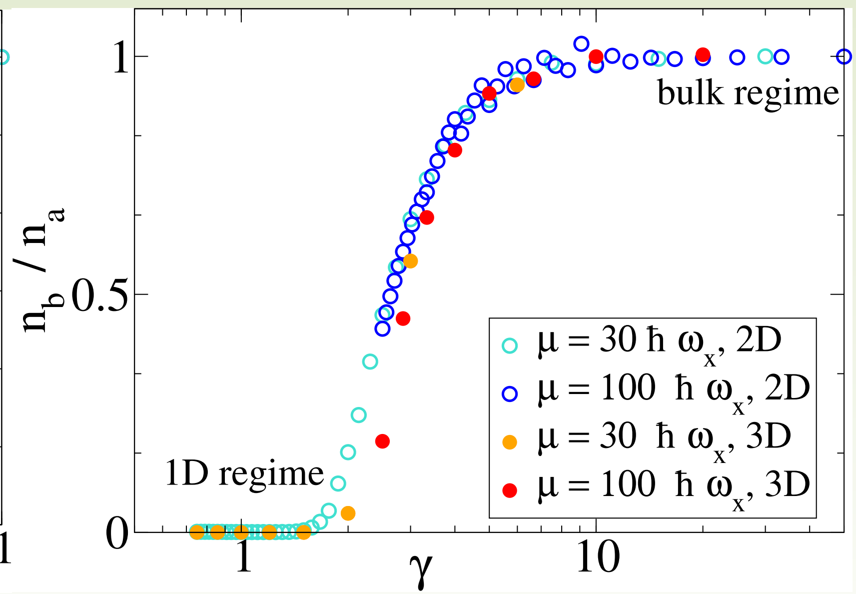


density (in trap)

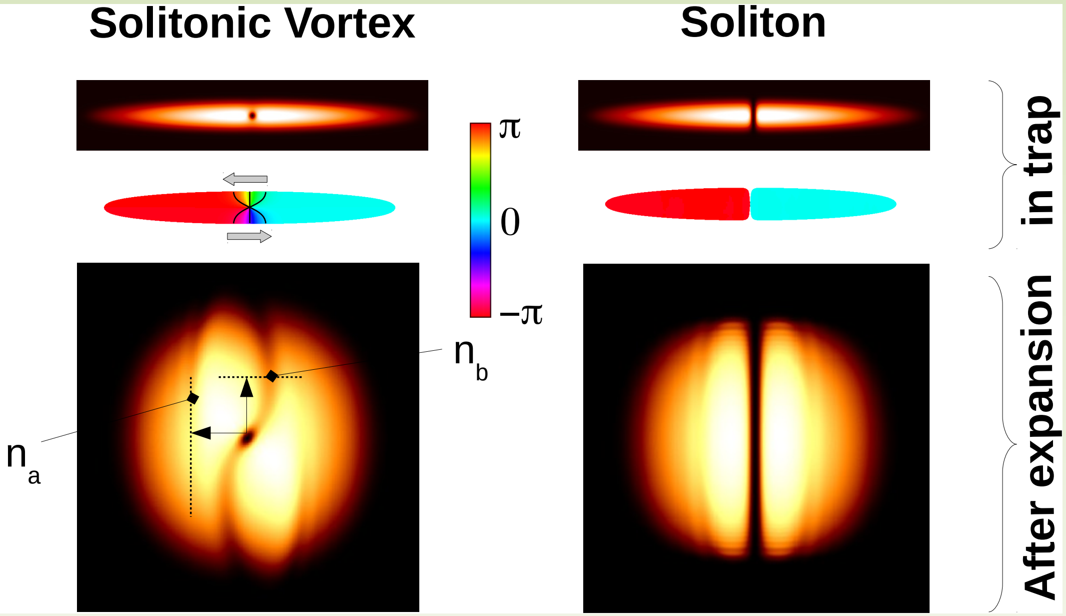
n_a : density along the axis (half a way from center to border)

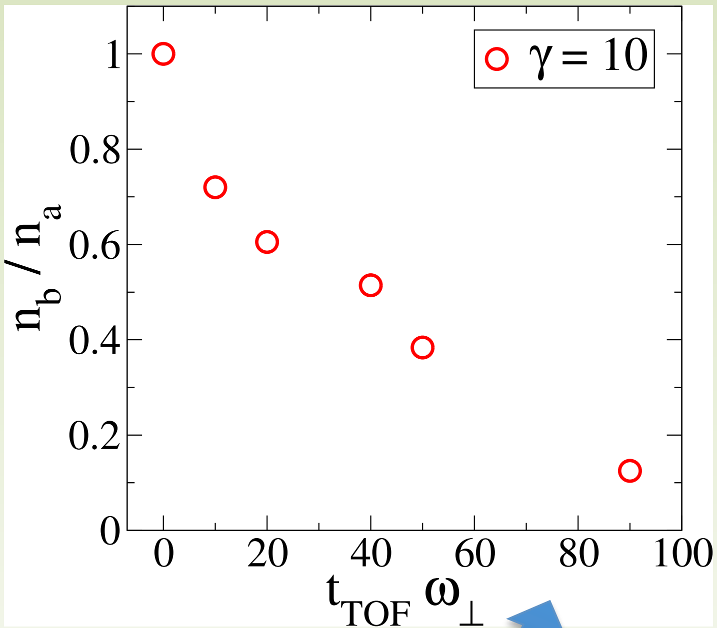
n_b : density in the radial plane (half a way from center to border)





Numerical simulations of **free expansion** (releasing the atoms from the trap): solution of time dependent Gross-Pitaevskii equation





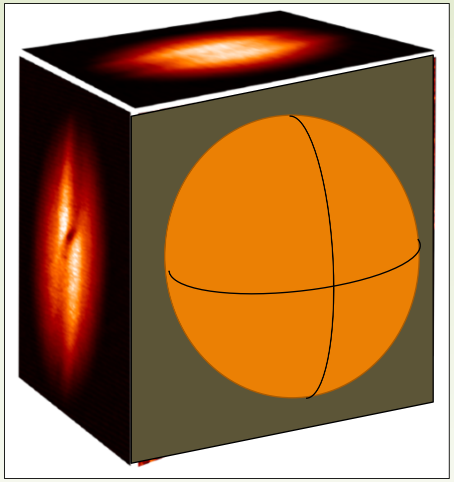
The plane is twisted around the vortex line **!**

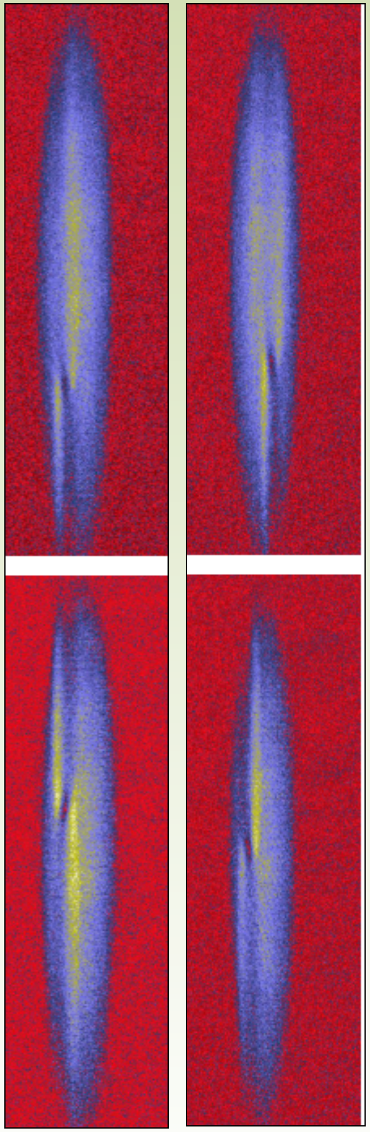
Strong enhancement of density depletion in the plane**!**

Back to the experimental observations:

Long lifetime, planar density depletion, twisted plane around a hole, suggest that defects may be solitonic vortices.

What next?

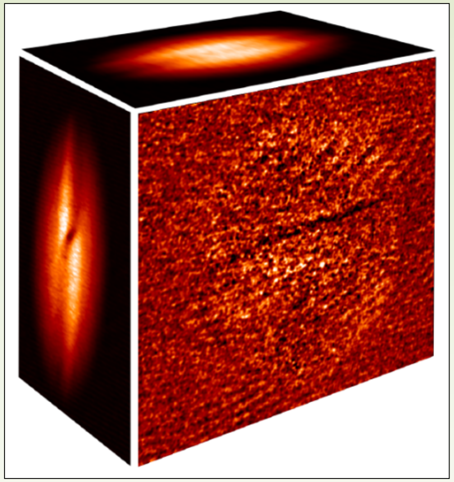




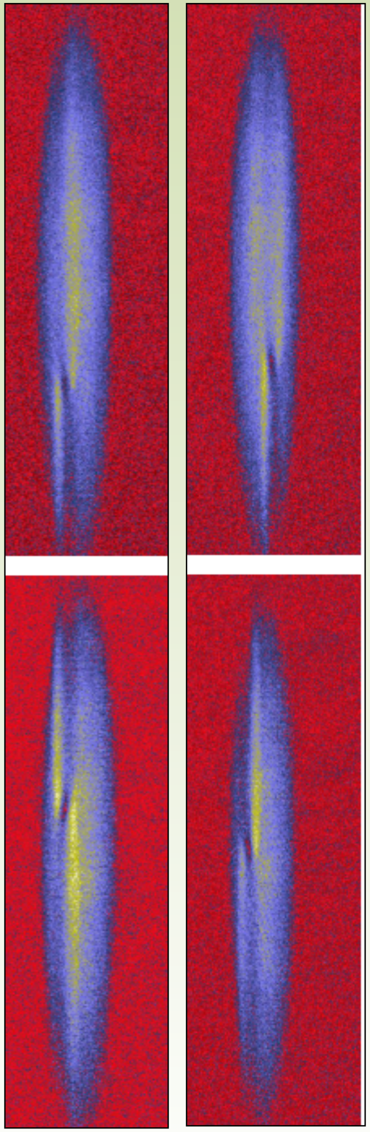
Back to the experimental observations:

Long lifetime, planar density depletion, twisted plane around a hole, suggest that defects may be solitonic vortices.

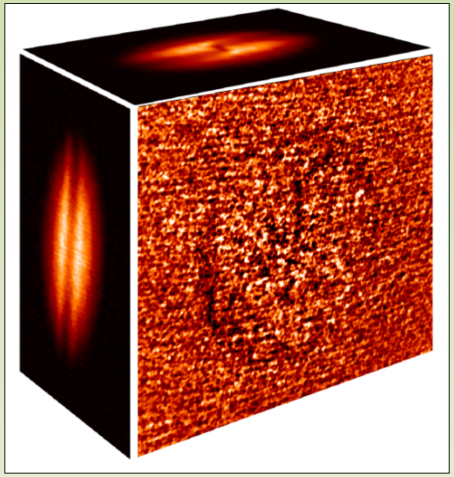
What next?
We add an imaging system also in the third direction

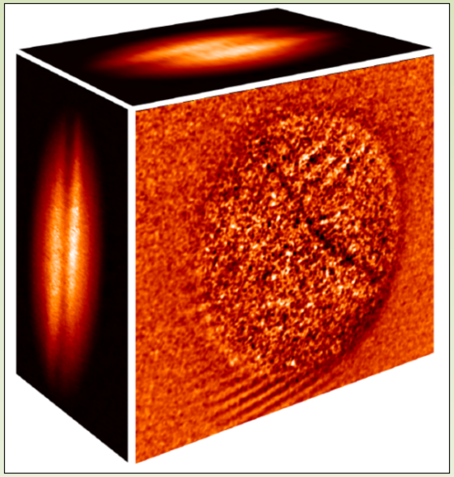


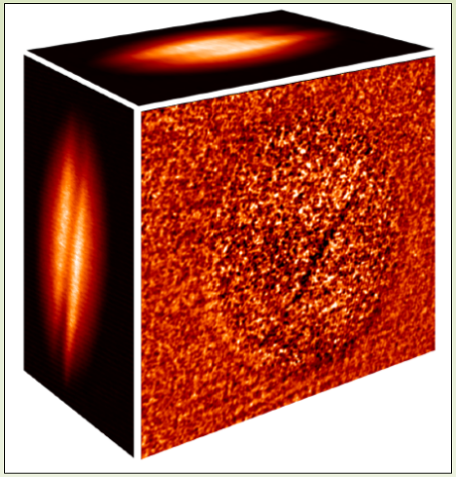
We see the vortex line **!!**

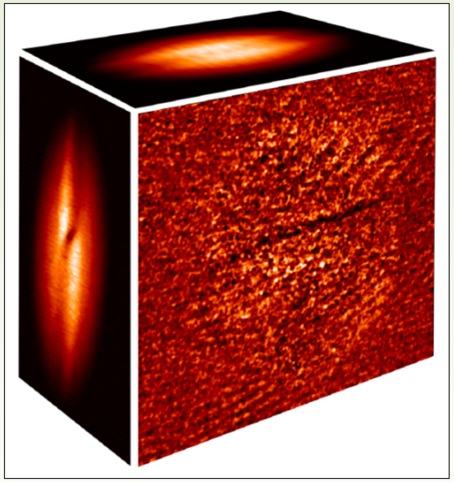


Radial + Axial Imaging (3 axes)





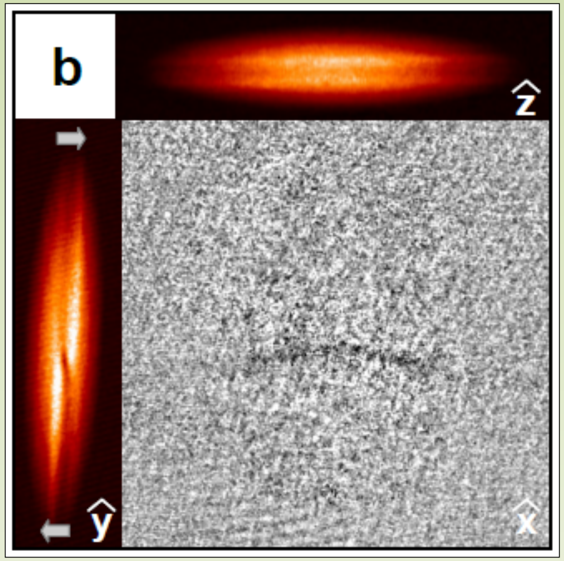


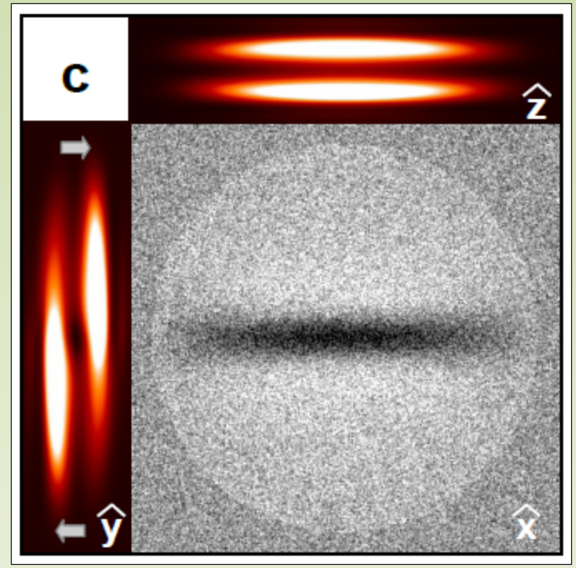


Planar structure (twisted)
+
String across BEC (radial)

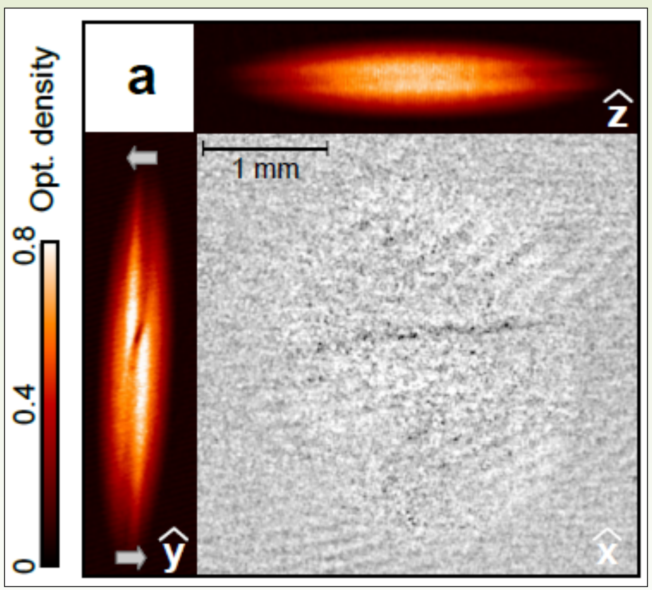
SOLITONIC VORTICES

Experiment
μ_exp = 27 ħω





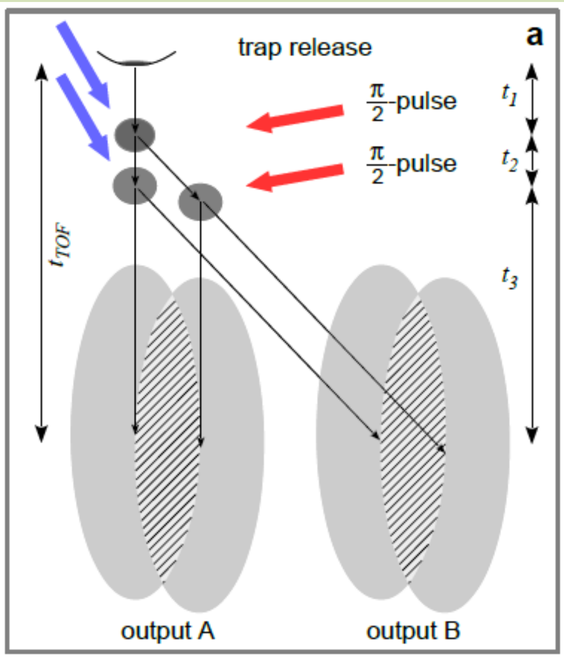
Simulation
μ = μ_exp /3



Vortex and antivortex

Observation of solitonic vortices in elongated BEC

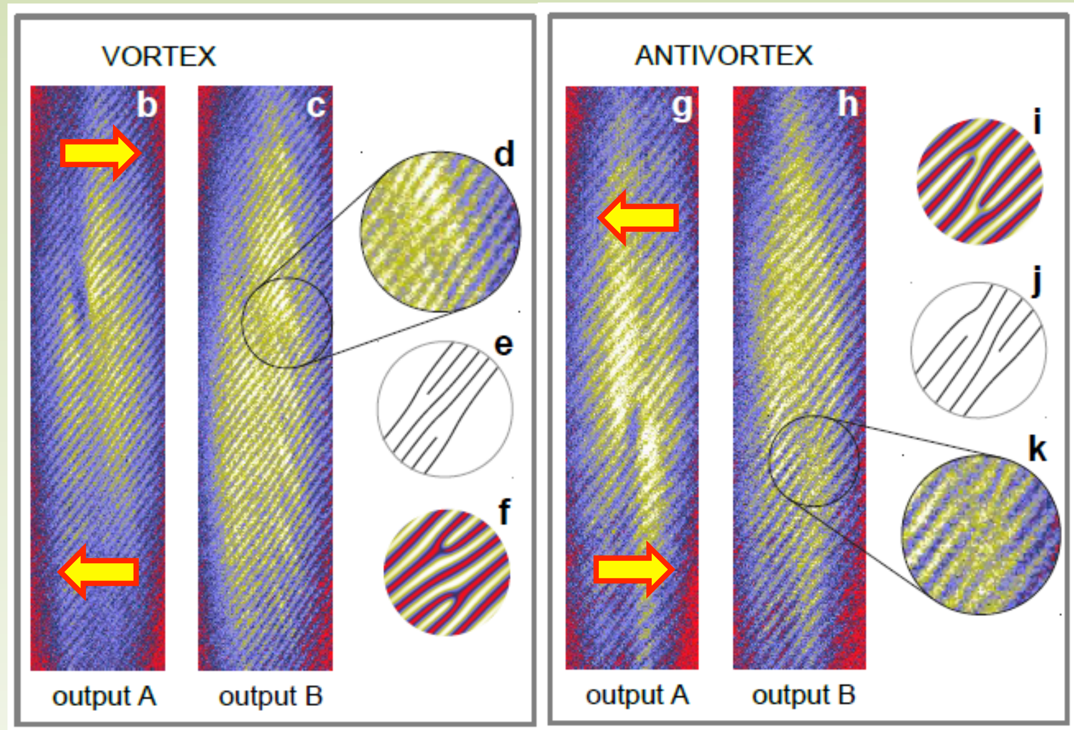
We can directly observe the phase of the quantized vortex by Bragg interferometry



t_1 = 20 ms

t_2 = 1.5 ms

t_3 = 98.5 ms



Bragg Pulse	τ = 8 μs I = 12 mW/cm^2

fringe spacing: $$\lambda = \frac{ht_3}{md}$$

- Signature: double dislocation
- Sign of circulation

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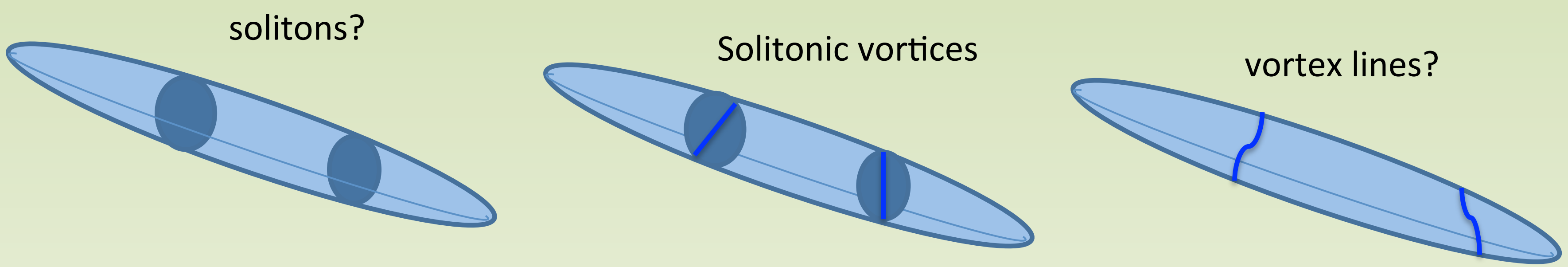
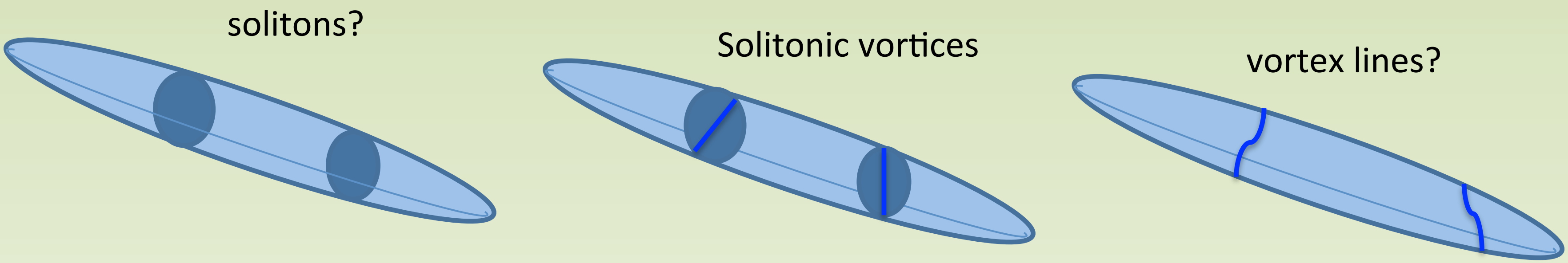
Coming back to the crucial question: what are these defects?



The answer is: we observe solitonic vortices

Coming back to the crucial question: what are these defects?



The answer is: we observe solitonic vortices

The next open question:

Are they the decay products of KZM solitons created at the transition?

Or, are they directly created by KZM at the transition?

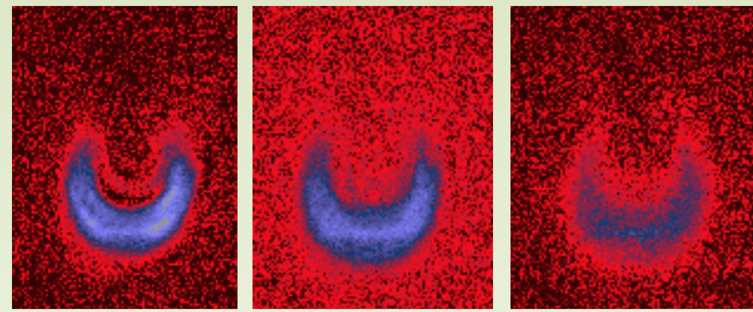
Work in progress

Work in progress

Iterated out-coupling of small fractions af a BEC

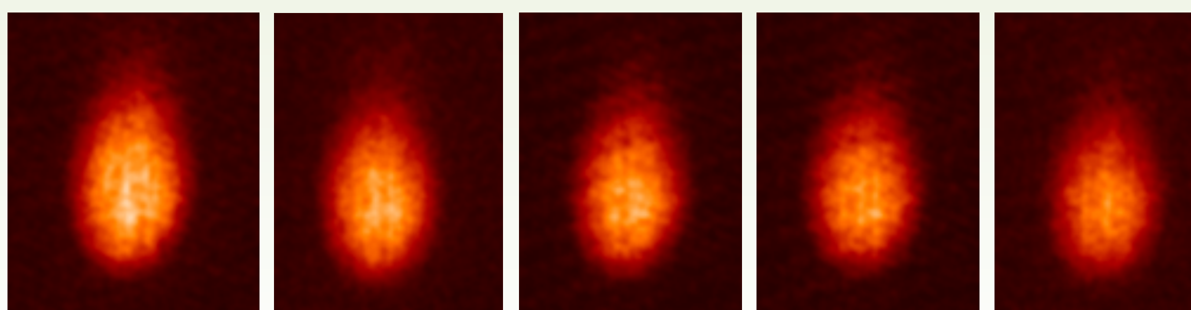
In trap: N= 5 ML atoms in |F=1, mF=-1 >

Outcouple #1: N= 0.4 ML (8 %) atoms to |F=2, mF=0 >
Free expansion
Free fall due to gravity
Move through the trapped BEC
5 ms expansion
Shot every 30 ms



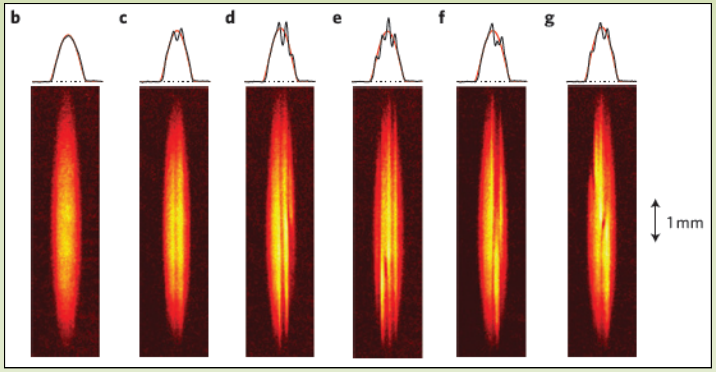
Outcouple #2: N= 0.4 ML (8 %) atoms to |F=2, mF=-2 >
Antitrapping expansion
Fast motion due to gravity+magnetic force
5 ms expansion
Shot every 70 ms

PRELIMINARY

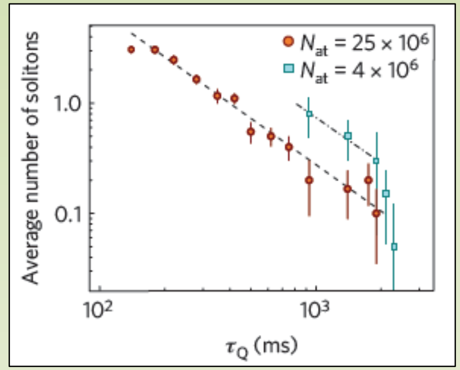


We will add a hold beam to compensate for gravity…

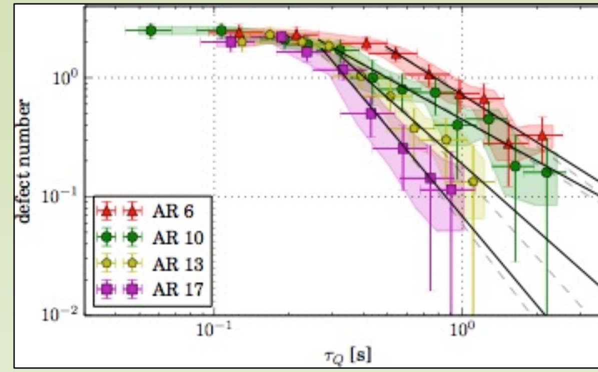
Creation of defects through quenches



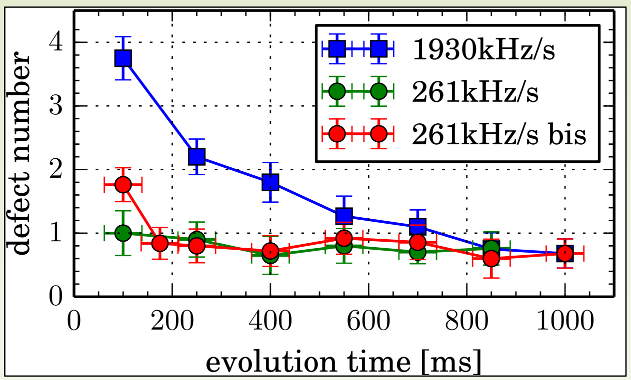
KZM, power-law scaling



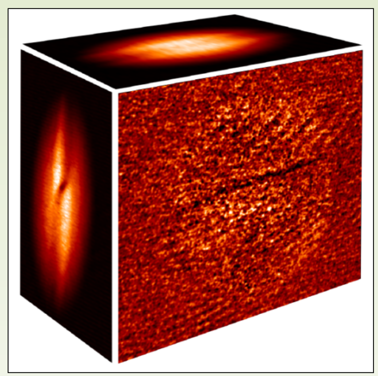
KZM, different geometries

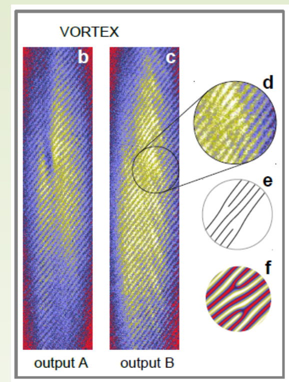


Defect lifetime

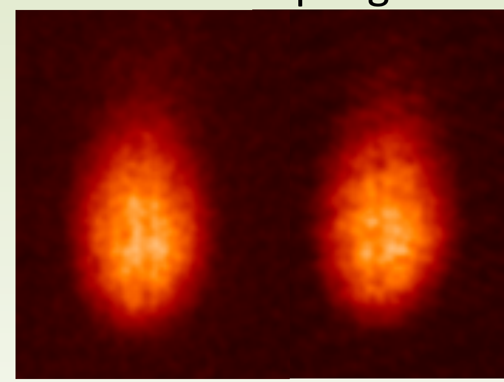


Solitonic vortices





Out-coupling



Lamporesi *et al.*, Nature Physics **9**, 656 (2013) **news & views**

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


Thank you