Non-equilibrium and non-harmonic BECs

Zoran Hadzibabic

University of Cambridge

doctors:

Rob Smith

Scott Beattie

esquires:

Stuart Moulder

Alex Gaunt

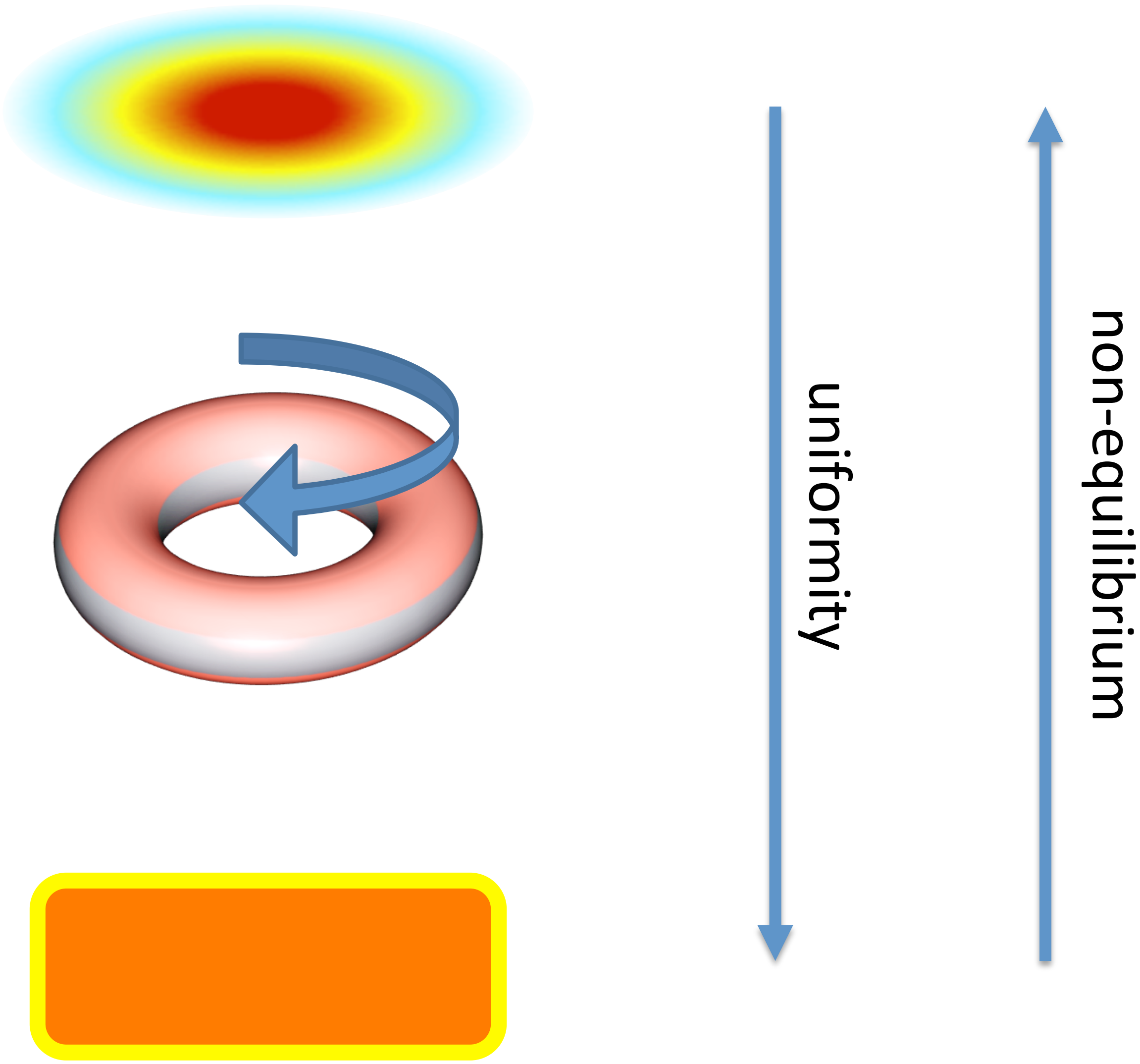
Richard Fletcher

Igor Gotlibovych

Tobias Schmidutz

Paris, February 2013

Outline of the talk

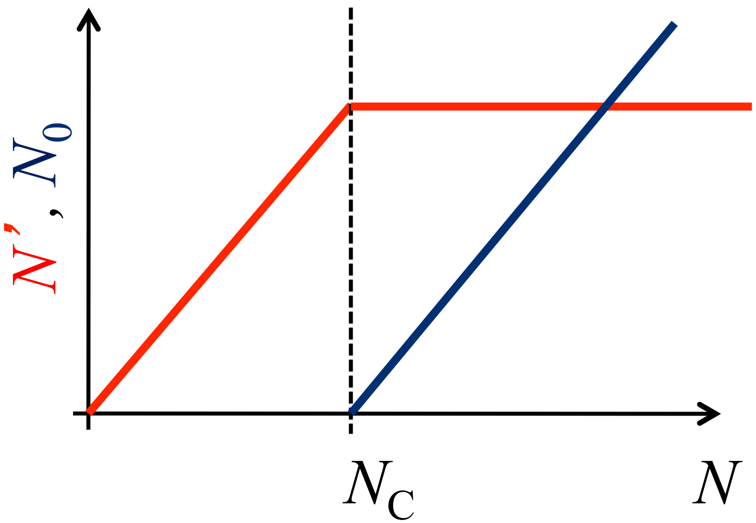


1

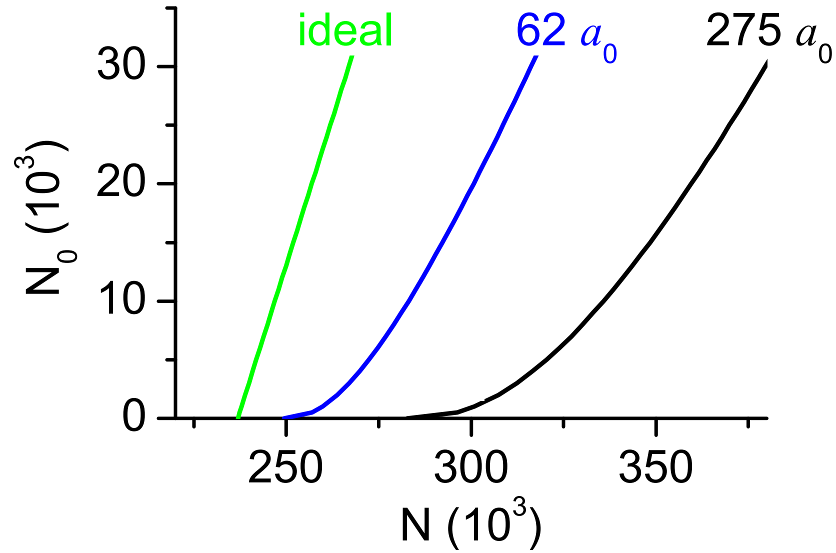
A superheated Bose-condensed gas

Equilibrium BEC summary

Einstein:



Trapped interacting gas:



Equation of state:

(close to the critical point)

$$N = \underbrace{N_c + S_0 N_0^{2/5}}_{N'} + N_0$$

N. Tammuz *et al.*, PRL **106**, 230401 (2011)

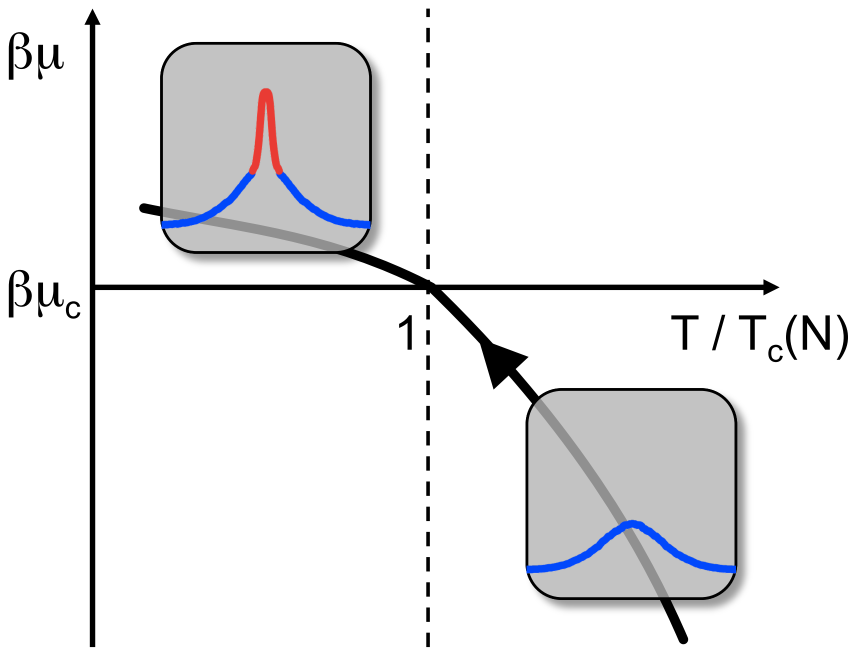
R.P. Smith *et al.*, PRL **106**, 250403 (2011)

R.P. Smith *et al.*, PRL **107**, 190403 (2011)

Review:
R.P. Smith & Z.H., arXiv:1203.2063

A superheated Bose-condensed gas

in equilibrium:



superheated:

BEC present for $T > T_C$
(or equivalently $N < N_C$)

Non-equilibrium stalling of a phase transition:

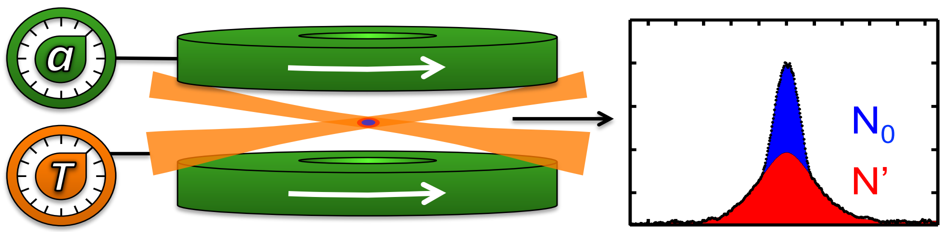
1st order (boiling of water) – absence of nucleation centers (energetics)
2nd order (BEC) – purely dynamical

Non-equilibrium experiments

Harmonically trapped ^{39}K gas, broad Feshbach resonance at 402 G

scattering length *a*

temperature *T*



momentum distribution in TOF

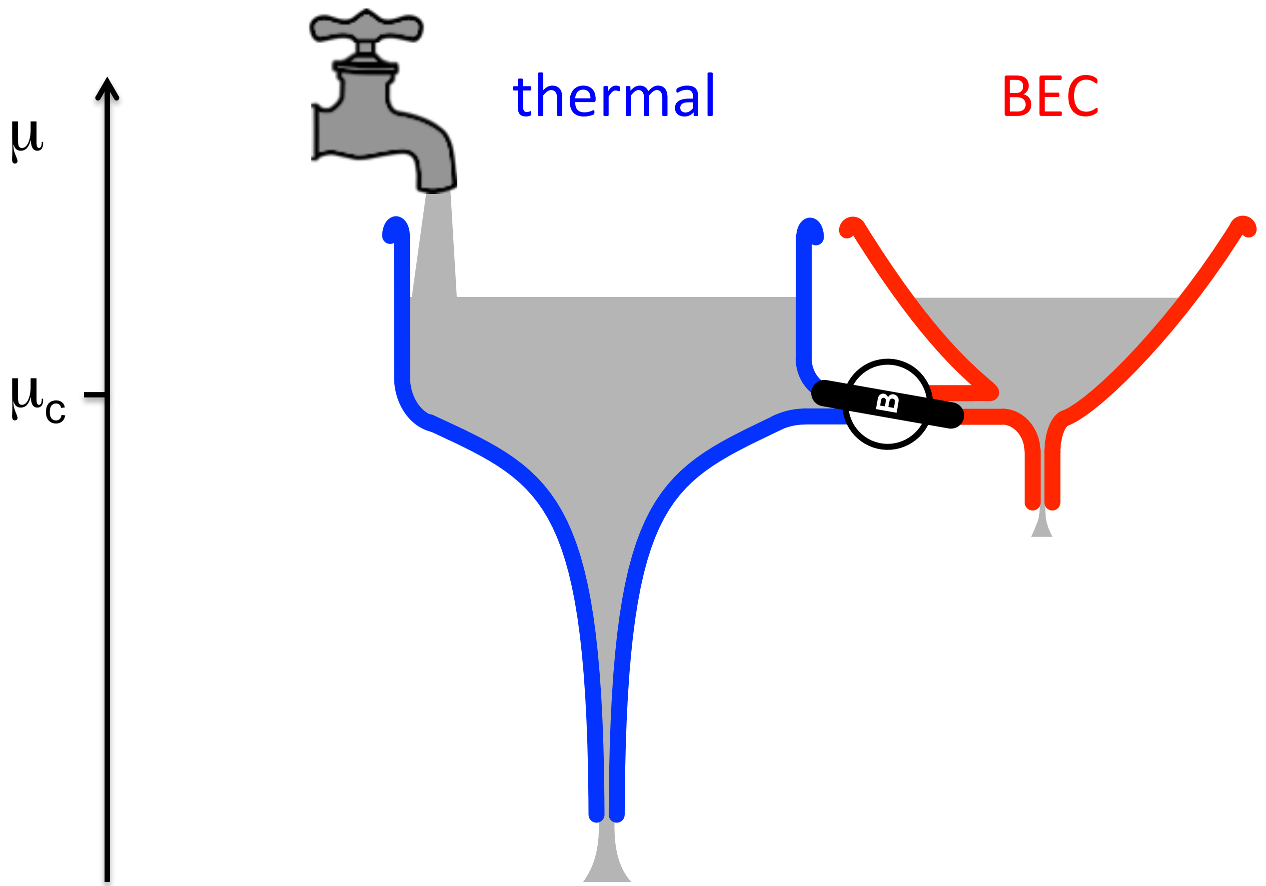
Two kinds:

(1) "transient" – quench something, look "quickly" (eventually new equilibrium)

R.P. Smith *et al.*, PRL **109**, 105301 (2012)

(2) "intrinsic" – non-equilibrium evolution

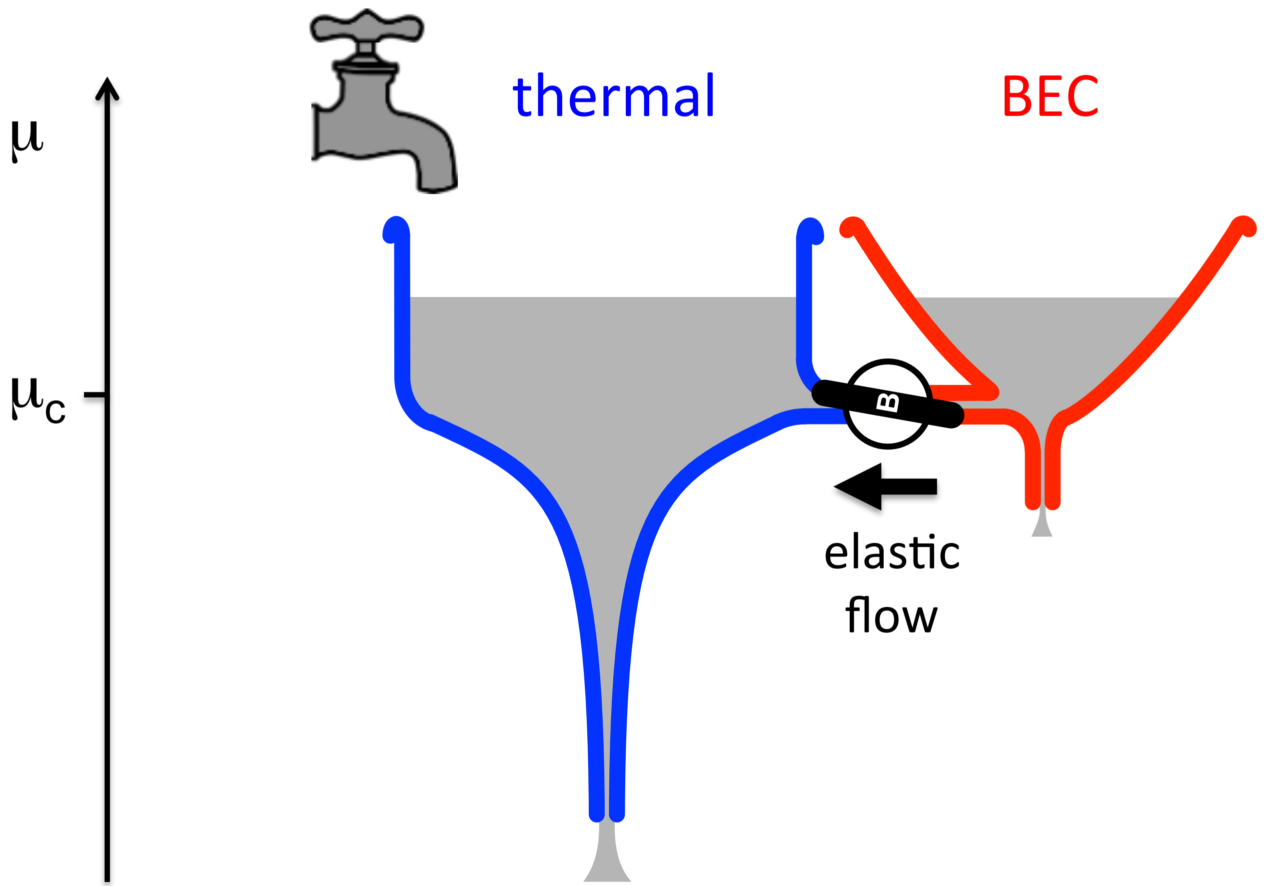
A (crude) classical analogue



Preparing a BEC…

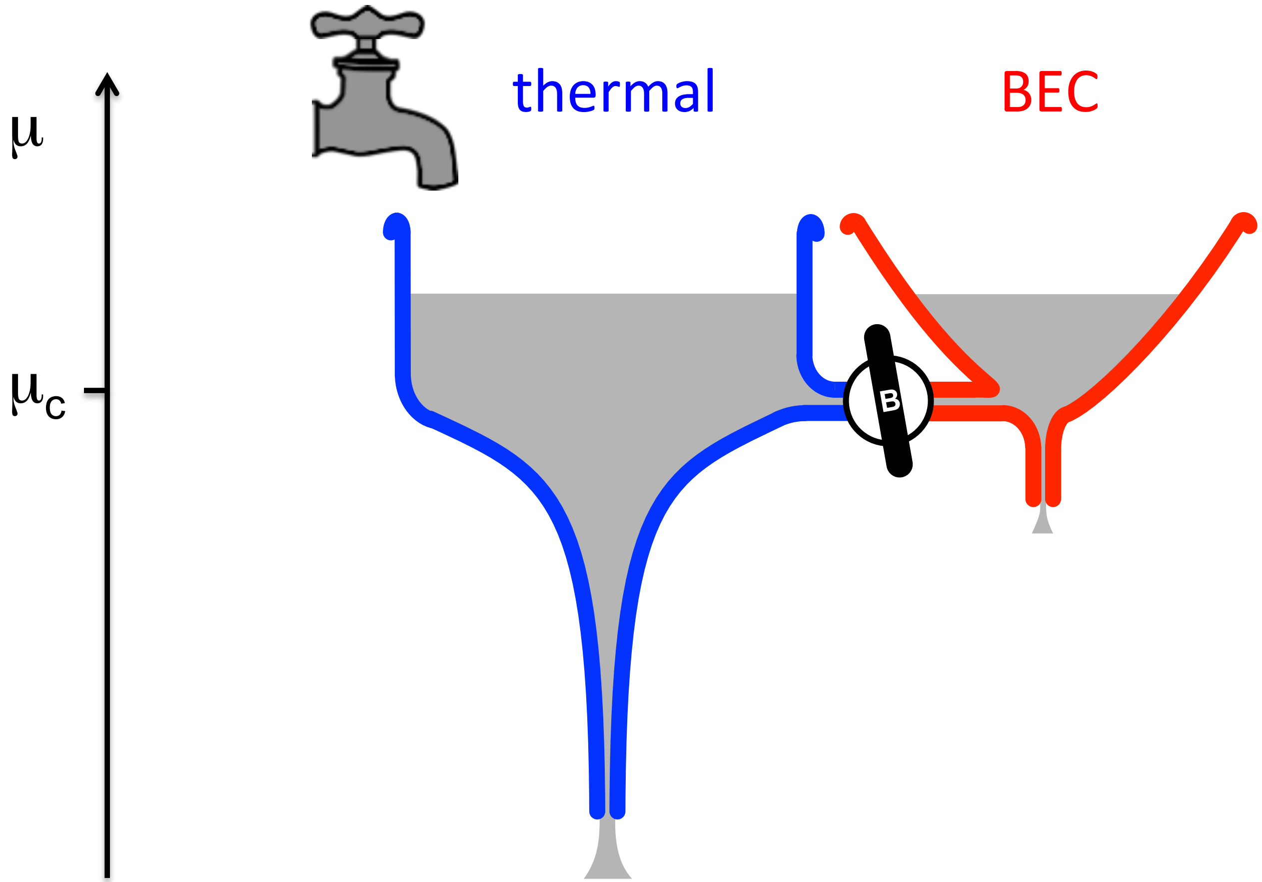
Shape of the vessels – the equation of state

A (crude) classical analogue



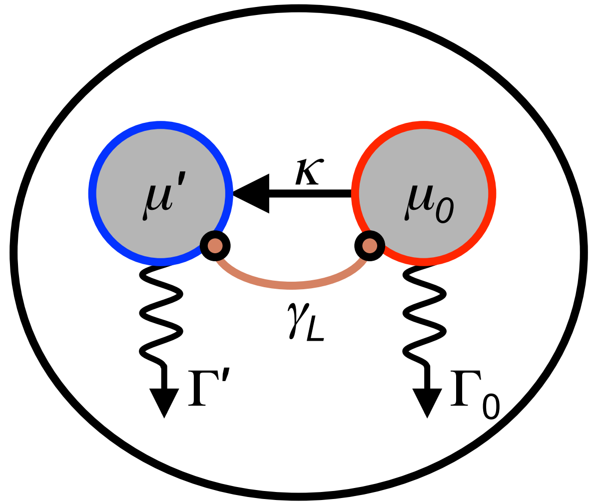
Decay…

Basic idea



Superheating…

(Better) Two-component picture



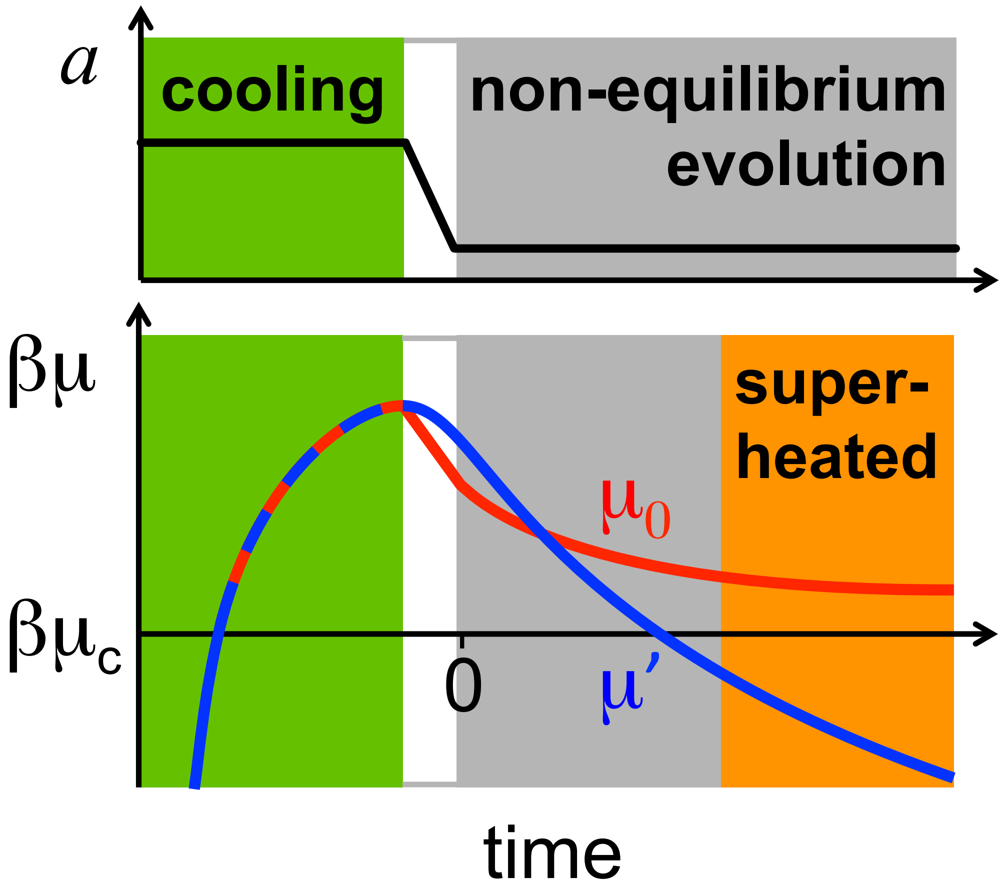
In (full) equilibrium:

$$\mu' = \mu_0 = \mu^{\rm eq}$$

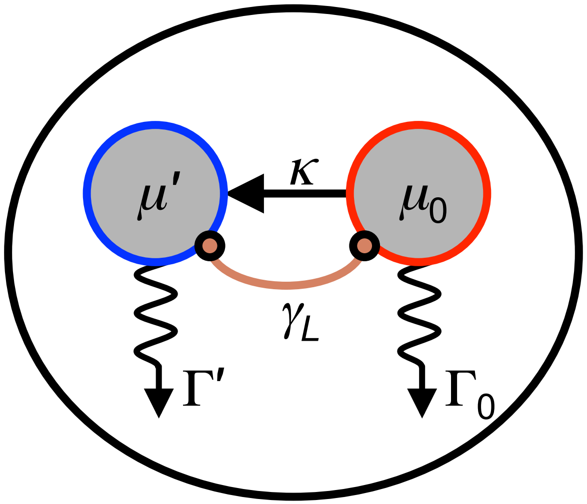
"Kinetic" equilibrium: Landau damping $\gamma_L \sim \sqrt{a}$

"Phase" equilibrium: elastic scattering $\kappa \sim a^2$

Experimental sequence



Equilibrium calculations



total
N, E
always defined
(extensive)

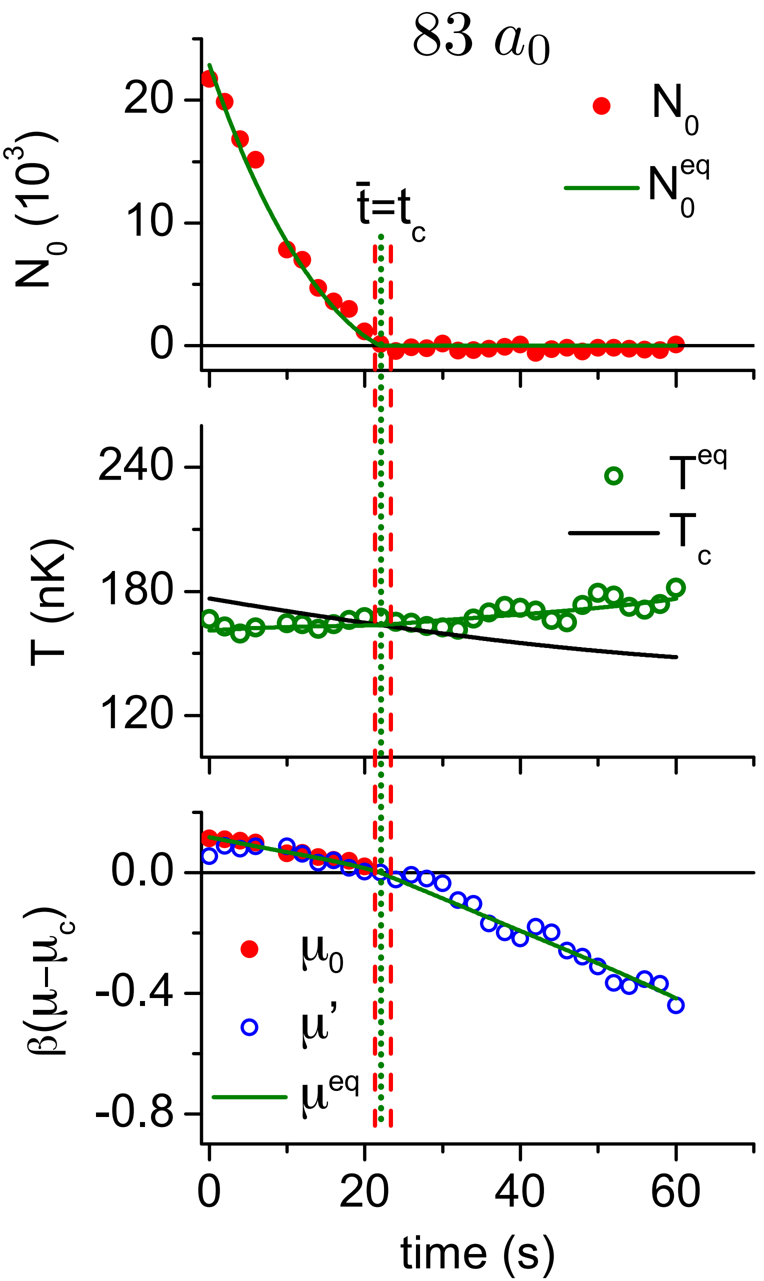
$$N, E \rightarrow N_0^{\mathrm{eq}}, \mu^{\mathrm{eq}}, T^{\mathrm{eq}}$$

(intensive)

$$N' \rightarrow \mu', \quad N_0 \rightarrow \mu_0$$

Fit T^f to thermal wings

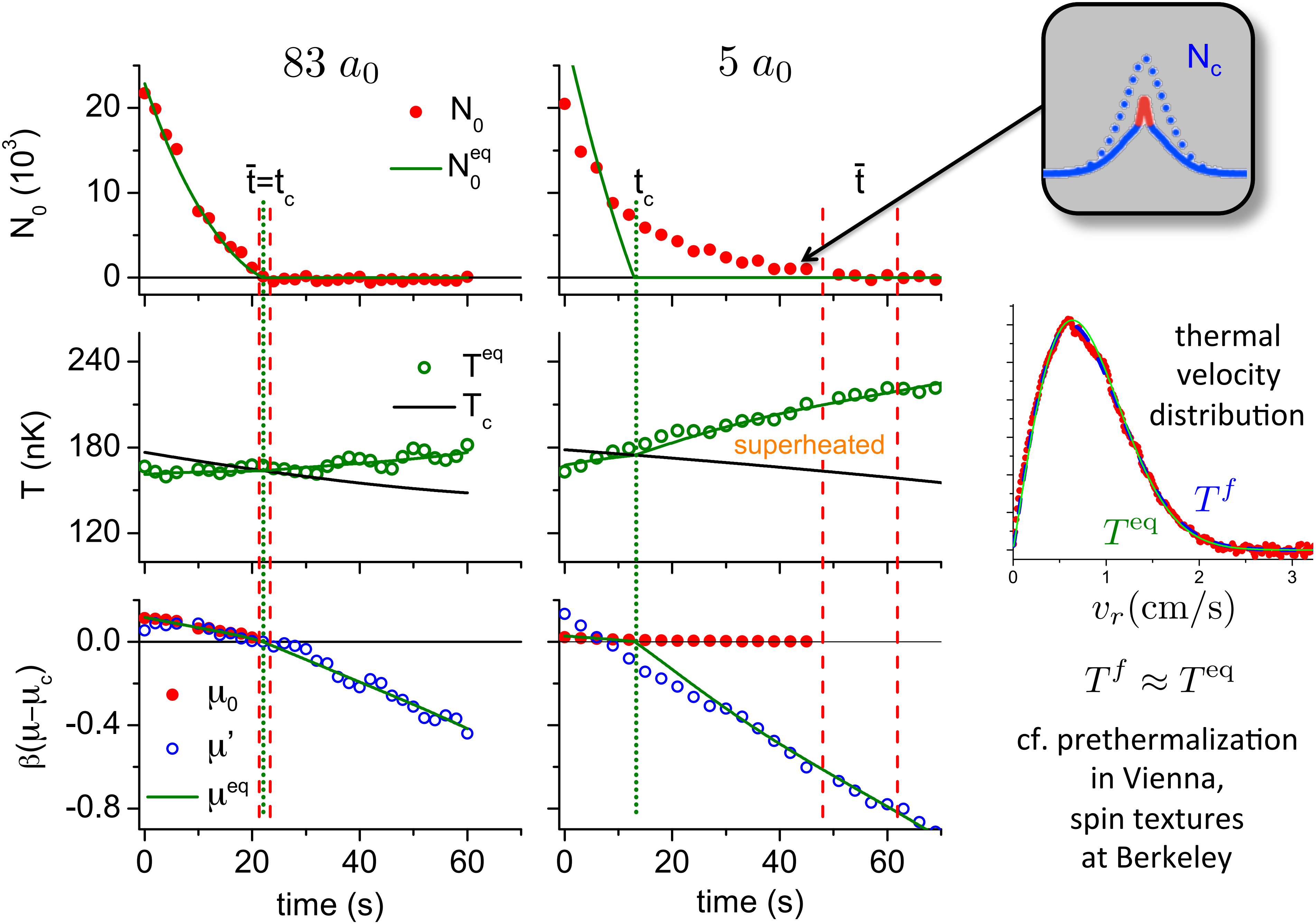
Equilibrium evolution



t_c - when the BEC should die

$\bar{t}$ - when it actually dies

Superheating

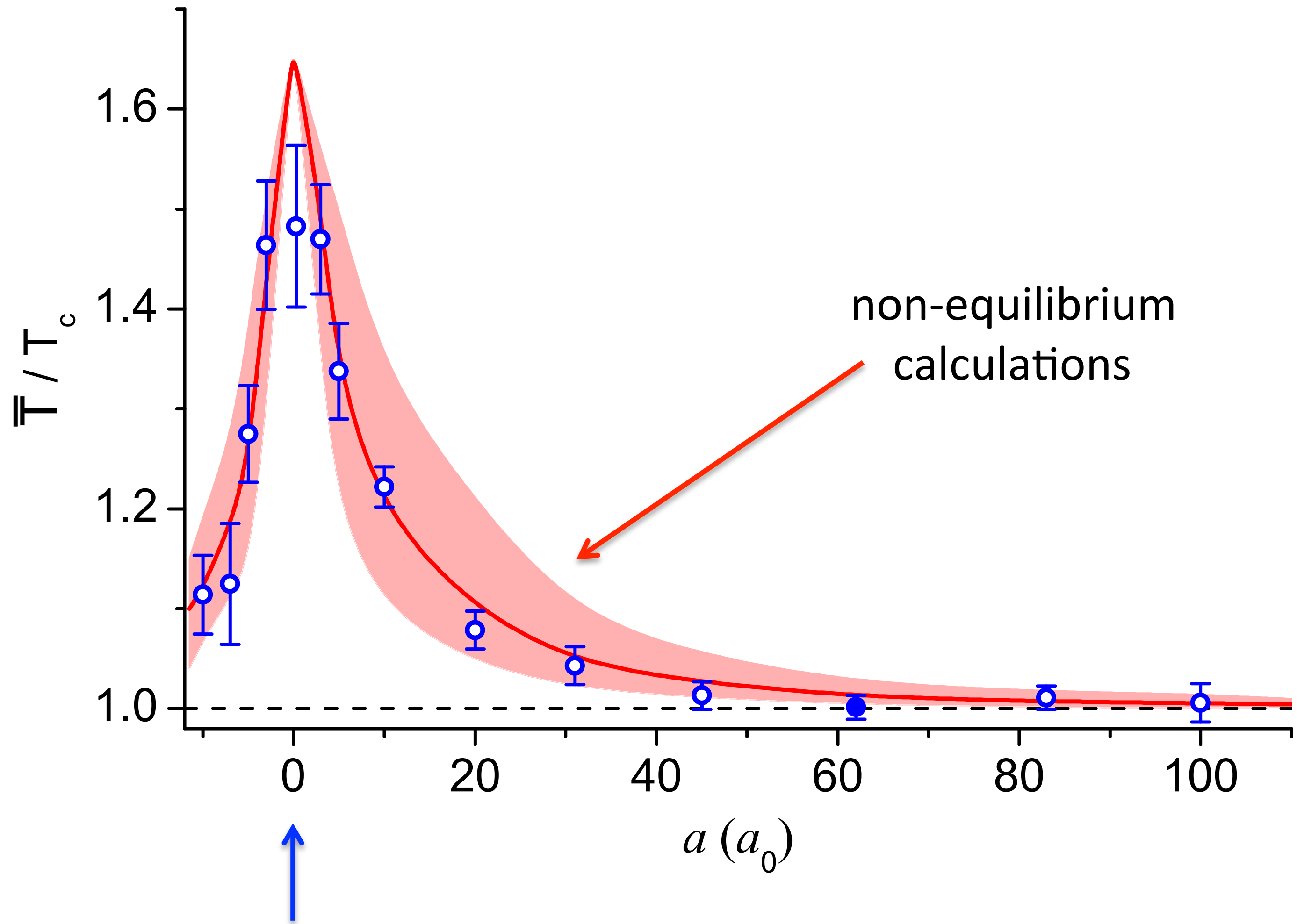


$T^f \approx T^{eq}$

cf. prethermalization
in Vienna,
spin textures
at Berkeley

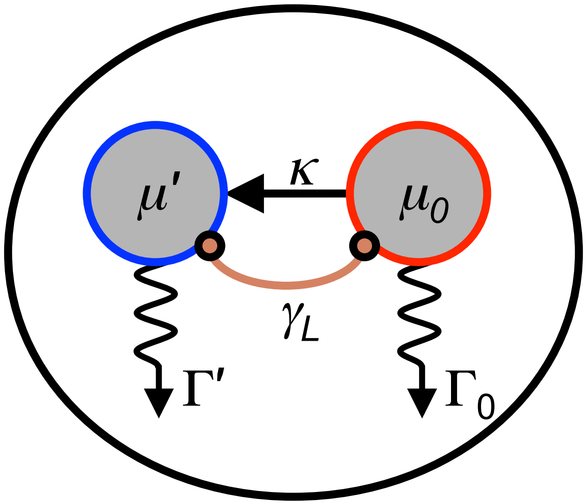
Limits of superheating

$$\bar{T} \equiv T(t = \bar{t})$$



like water at 280 ^{0}C

Non-equilibrium calculations

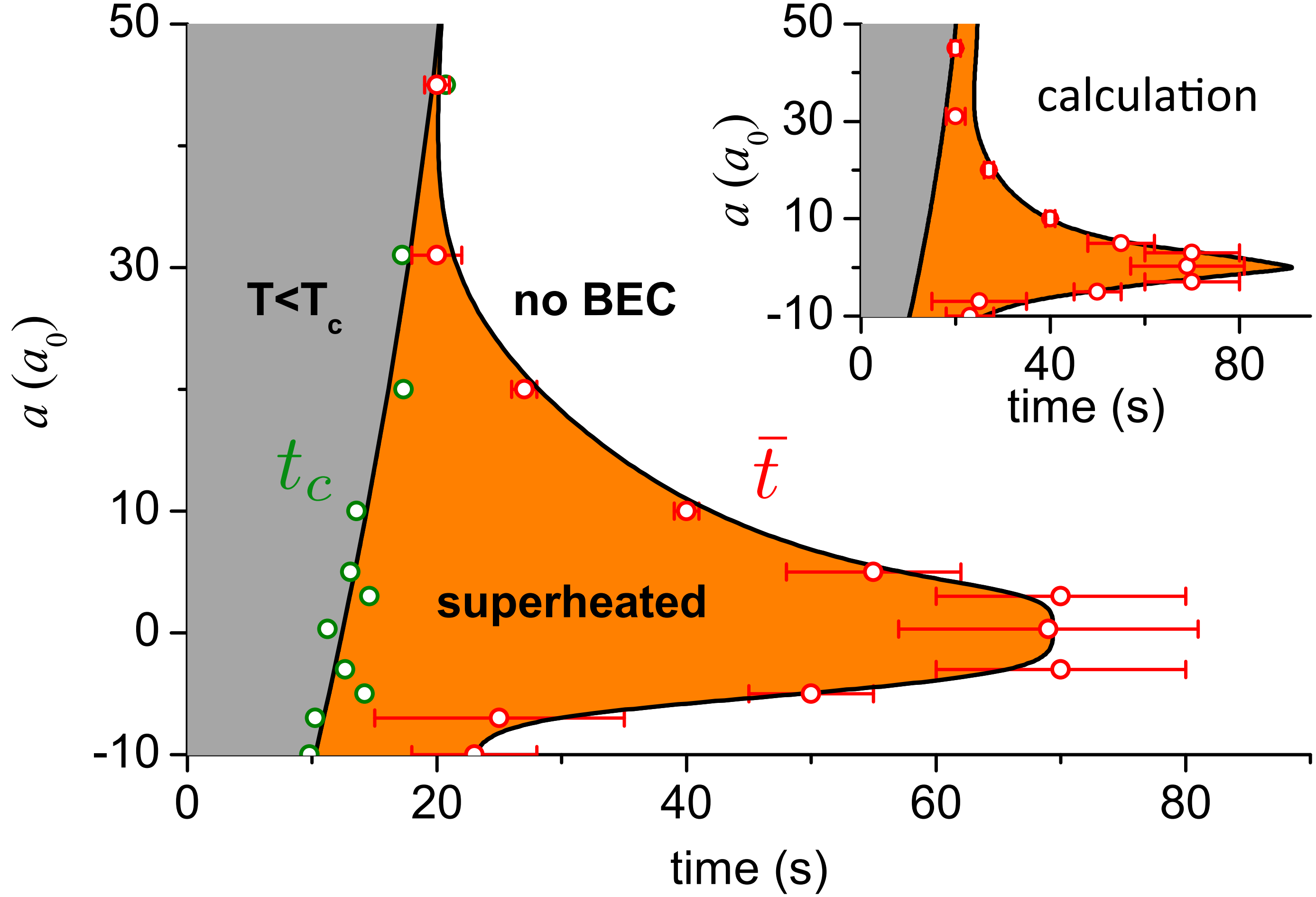


$$\dot{N}_0 = -\kappa - \Gamma_0 N_0$$

$$\kappa = A\gamma_{\rm el} N_0 \left[e^{\beta(\mu_0 - \mu_c)} - e^{\beta(\mu' - \mu_c)} \right]$$

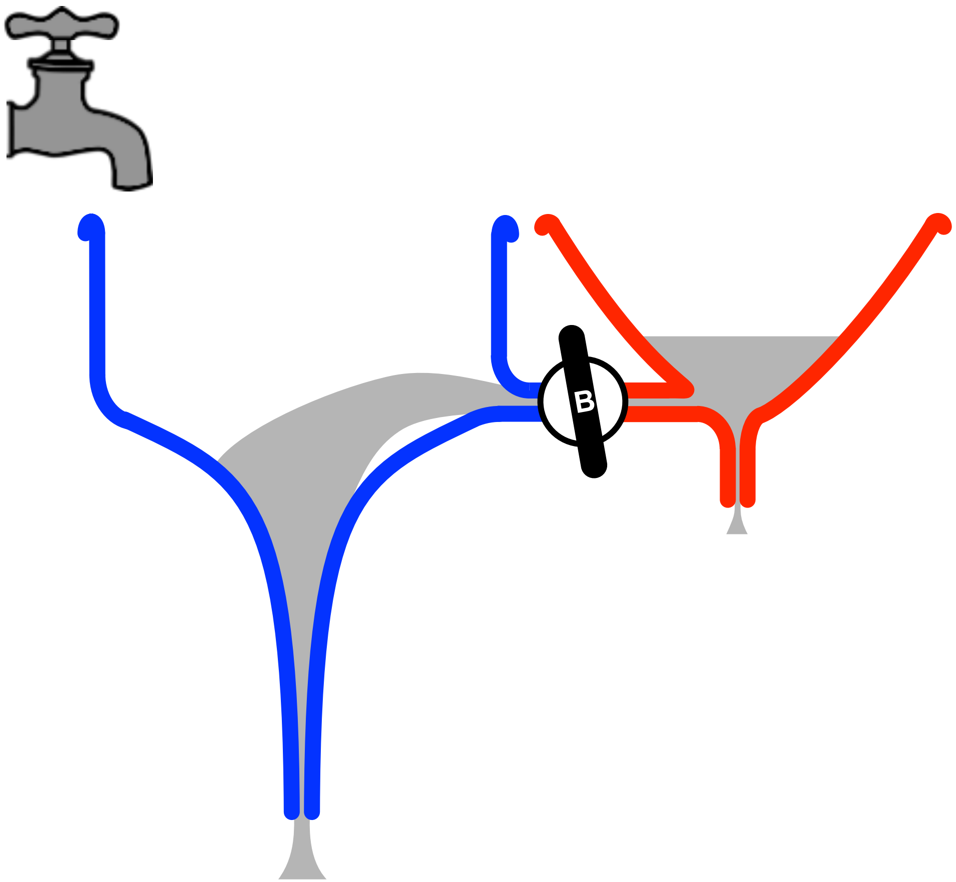
C.W. Gardiner, P. Zoller, R.J. Ballagh, M.J. Davis,
PRL **79**, 1793 (1997)

Temporal phase diagram

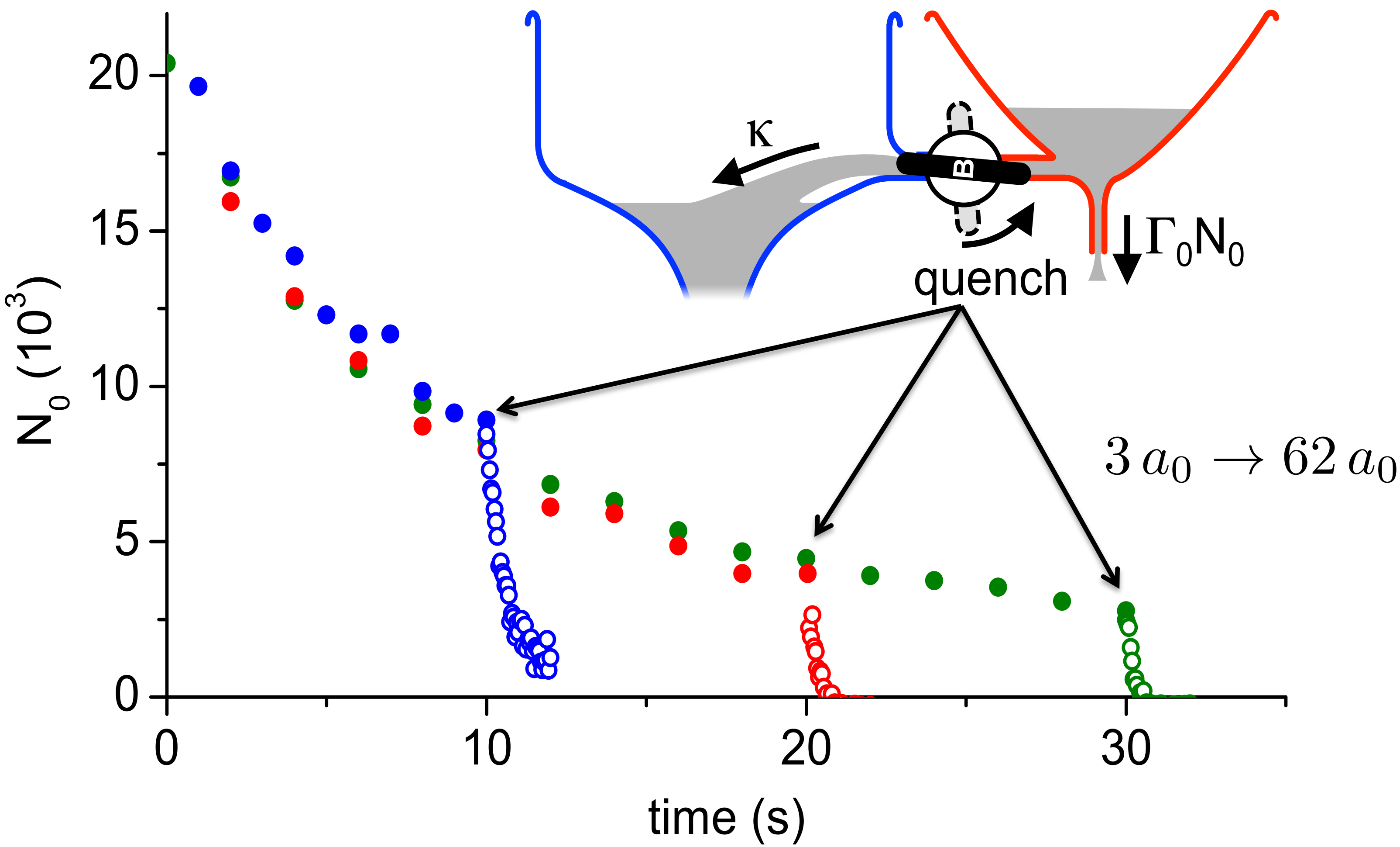


A. L. Gaunt, R. J. Fletcher, R.P. Smith, and Z. H. , arXiv:1212.5833

Sprinkling in a bit of salt...



Sprinkling in a bit of salt...



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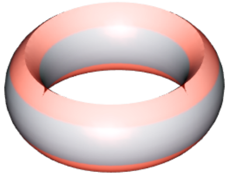
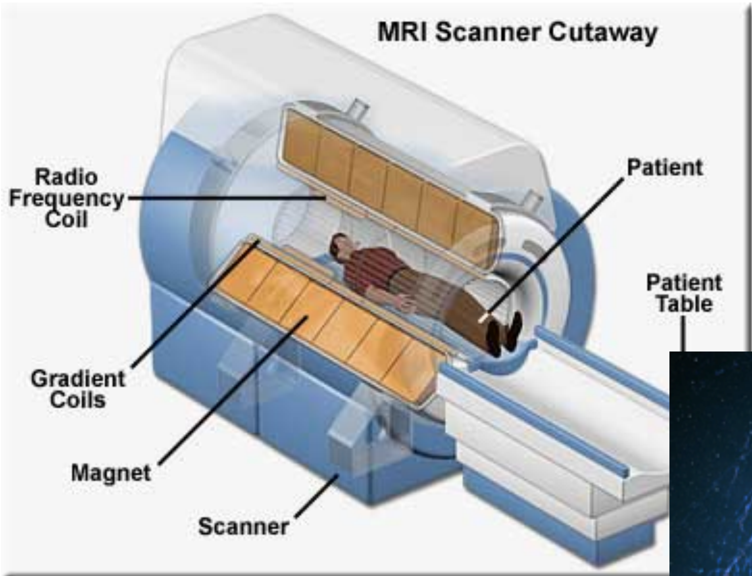
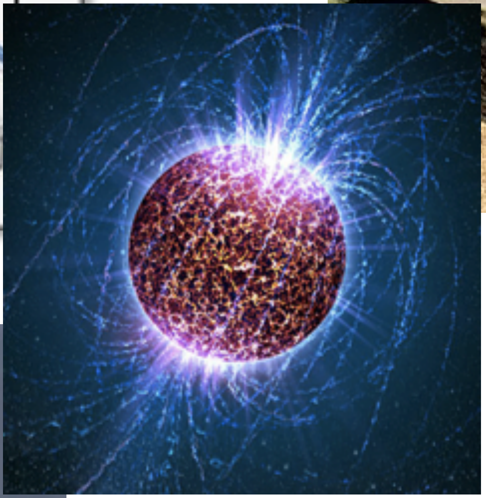
Persistent currents in a toroidal BEC

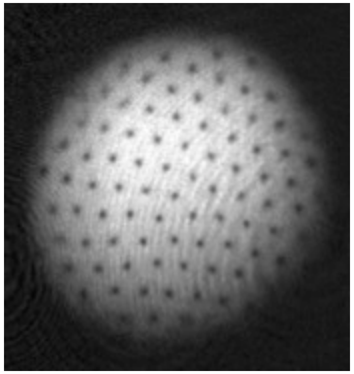






Superfluidity in atomic BECs

Simply connected geometry since 1999:



Critical velocity – MIT (Ketterle)

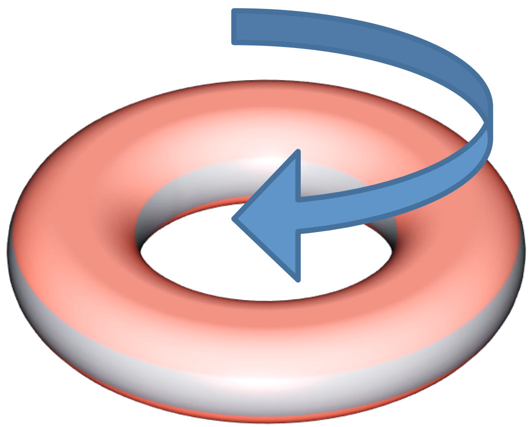
Quantized vortices – JILA (Cornell), ENS (Dalibard), MIT (Ketterle)….

Persistent currents (in a ring/torus):

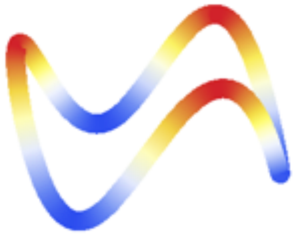
Pioneering work at NIST (Phillips/Helmerson/Campbell)
10s in 2007, 40s in 2011…

Other ring traps: Berkeley, Oxford, Paris, LANL, Strathclyde…

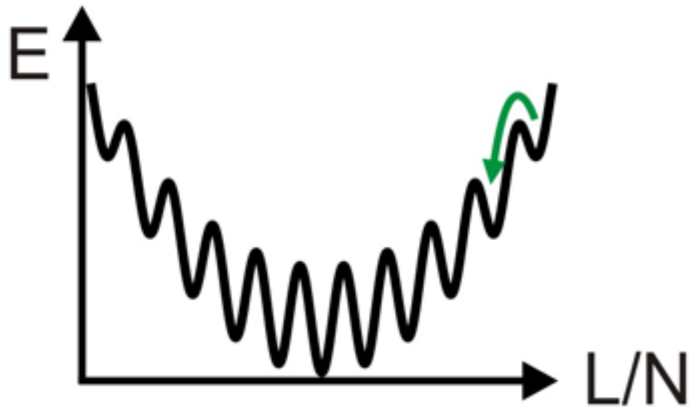
Why persistent?

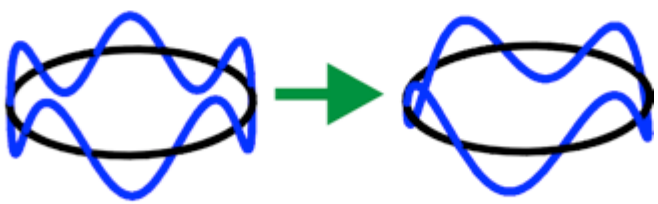


$$\Psi = \Psi(r, z)e^{iq\varphi}$$

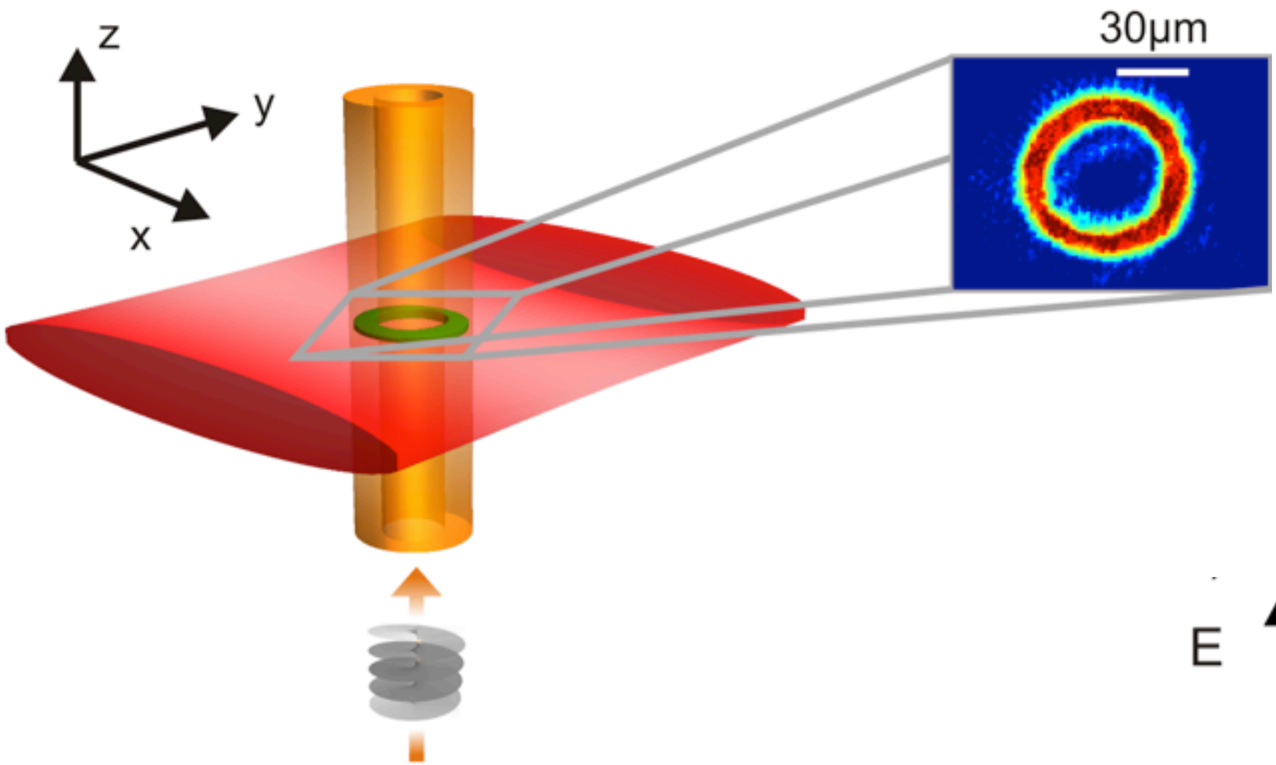


q=3



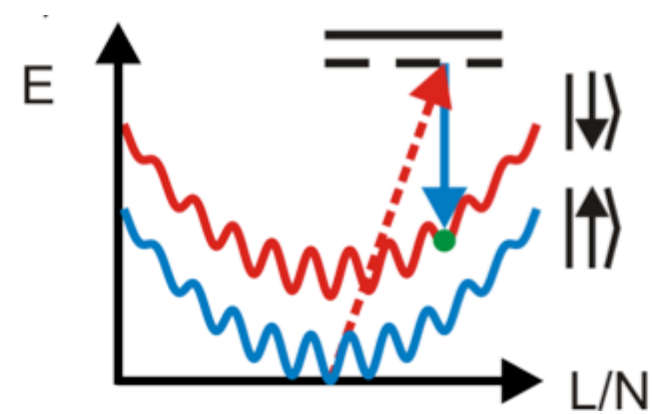


Preparing a persistent current



LG^{ℓ} beam

Each photon $\ell\hbar$ of angular momentum

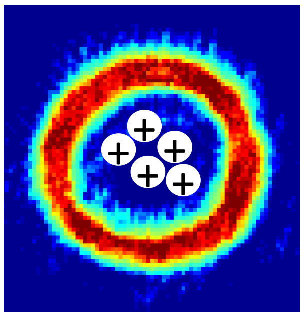


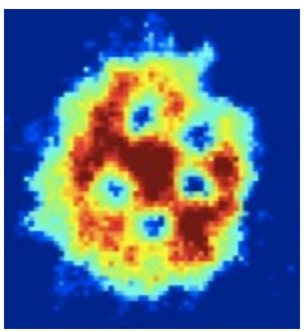
S. Moulder, S. Beattie, R.P. Smith, N. Tammuz, and ZH, PRA **86**, 013629 (2012)

See also: M.F. Andersen *et al.*, PRL **97**, 170406 (2006)

Detecting the supercurrent

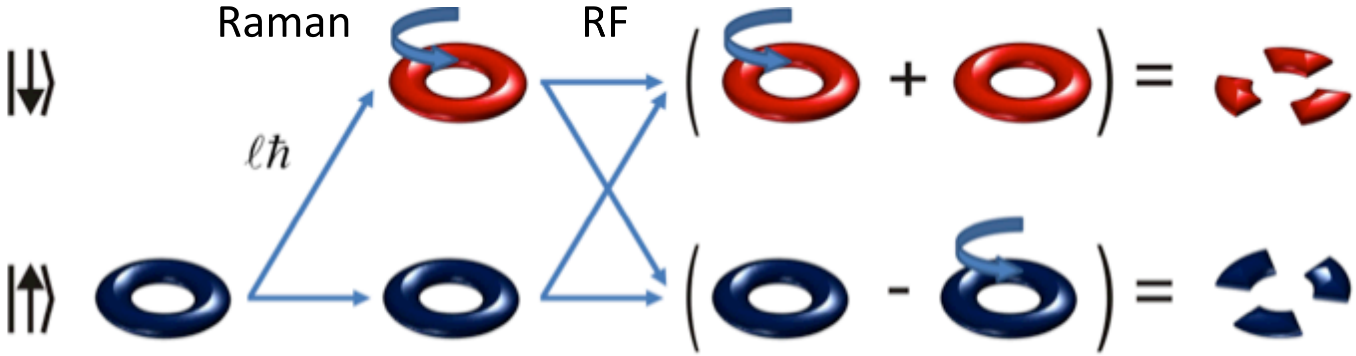
1 vorticity

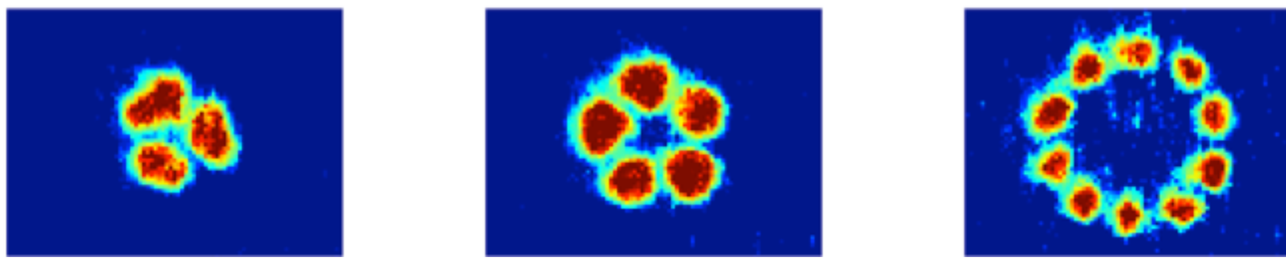




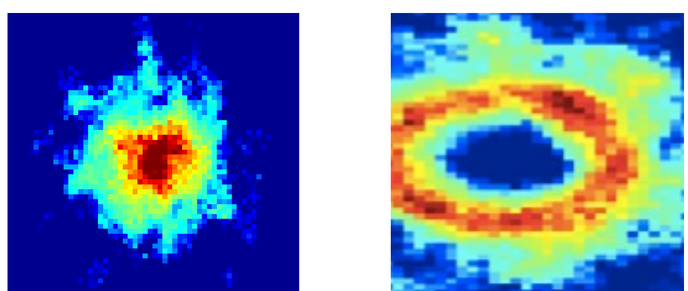
2 phase winding - interferometry

S. Moulder et al.,
PRA **86**, 013629 (2012)





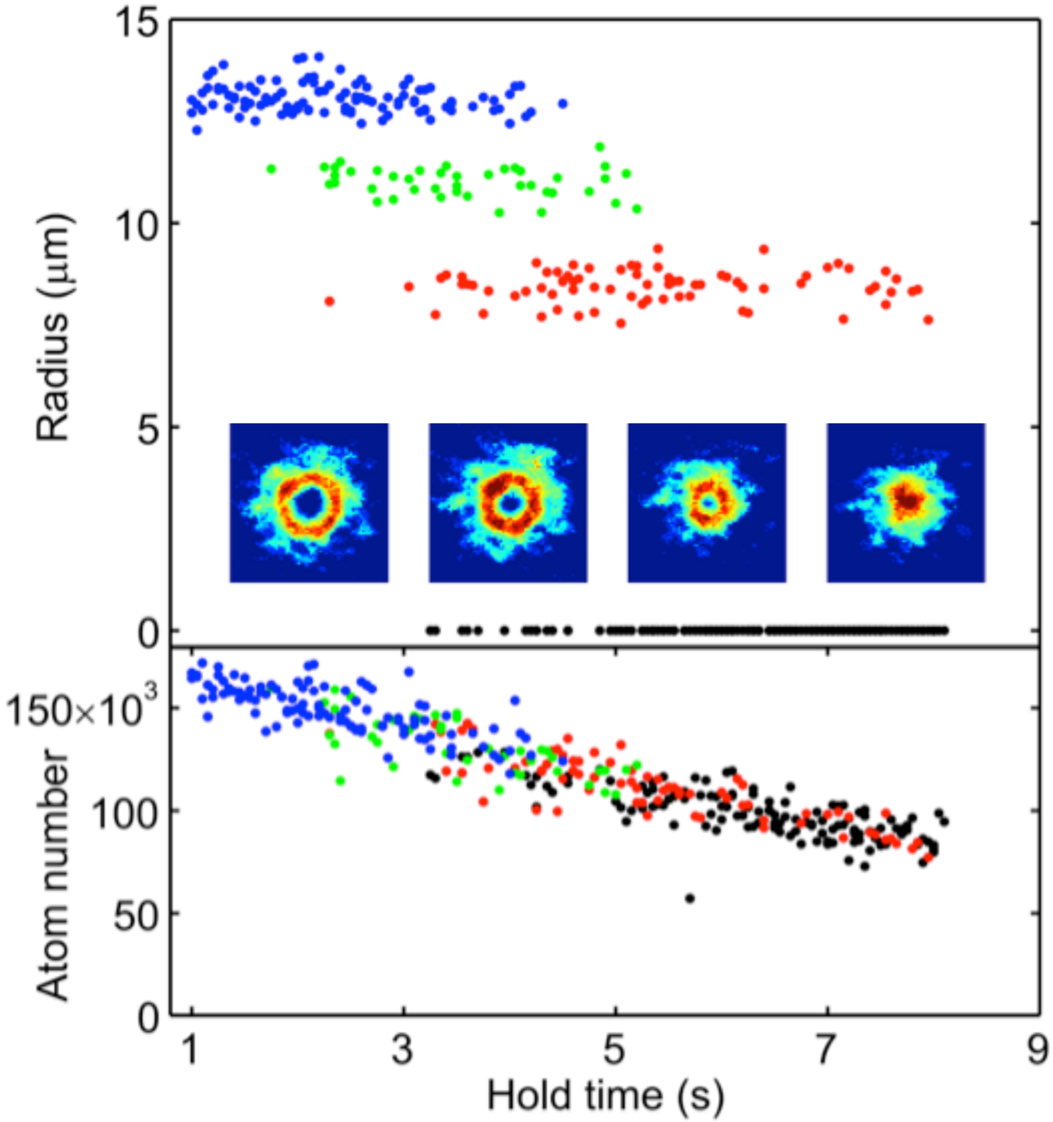
3 angular momentum – centrifugal barrier in TOF

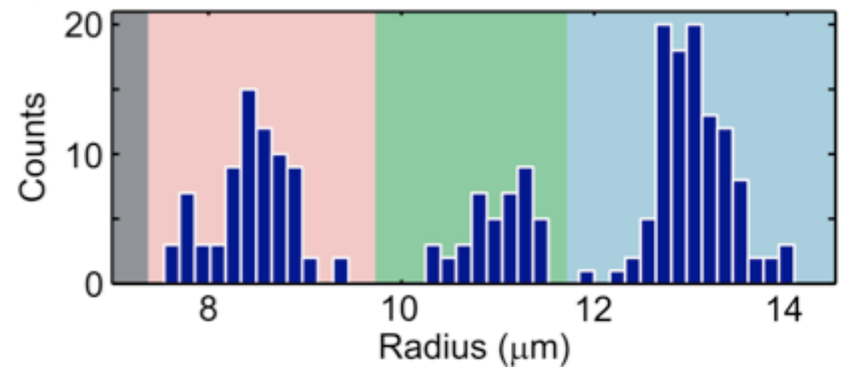


C. Ryu et al.,
PRL **99**, 260401 (2007)

Quantized supercurrent decay

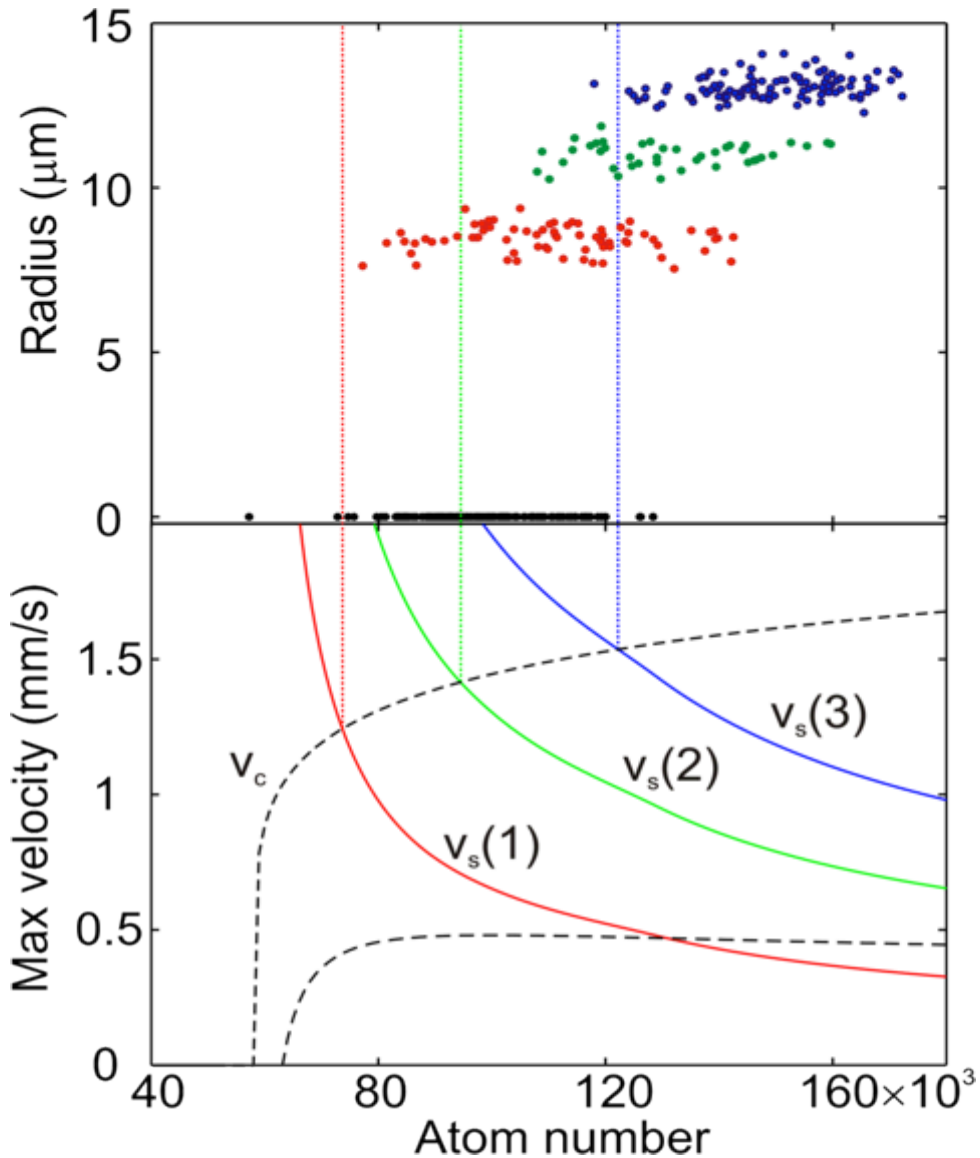
Starting with q = 3 :





S. Moulder et al.,
PRA **86**, 013629 (2012)
Also at NIST: K.C. Wright *et al*., arXiv:1208.3608

Critical velocity



Theory based on:
J.R. Anglin, PRL **87**, 240401 (2001)

No survival for

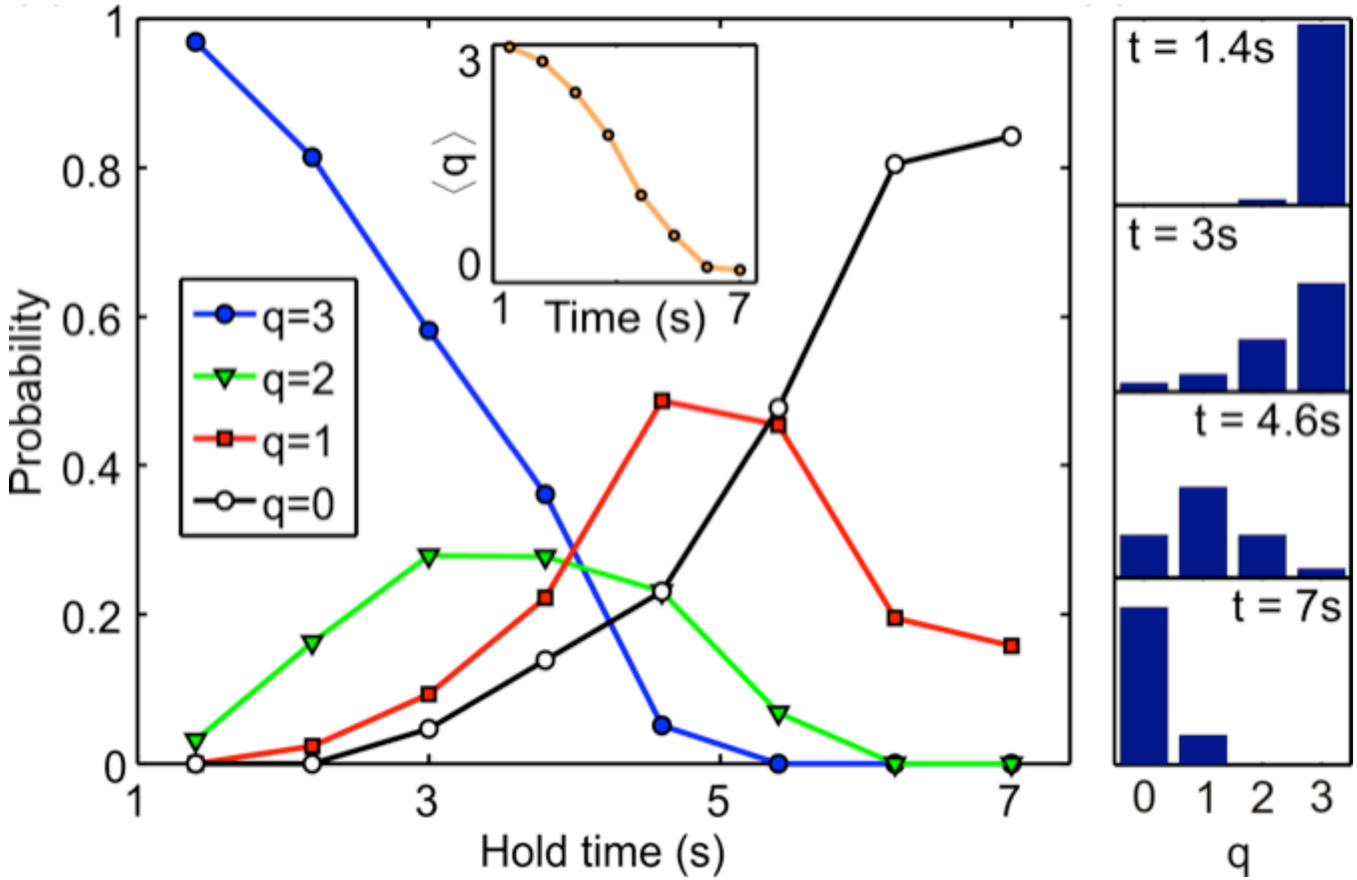
$$v > v_c$$

But also stochastic decay for

$$v < v_c$$

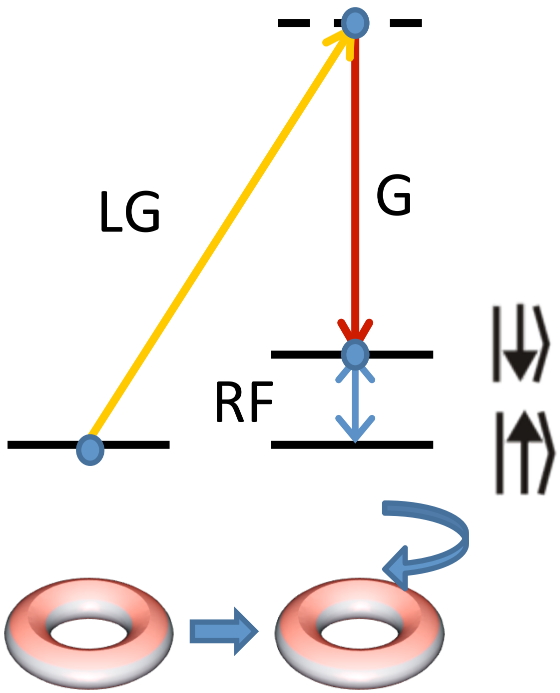
(thermal excitations?)

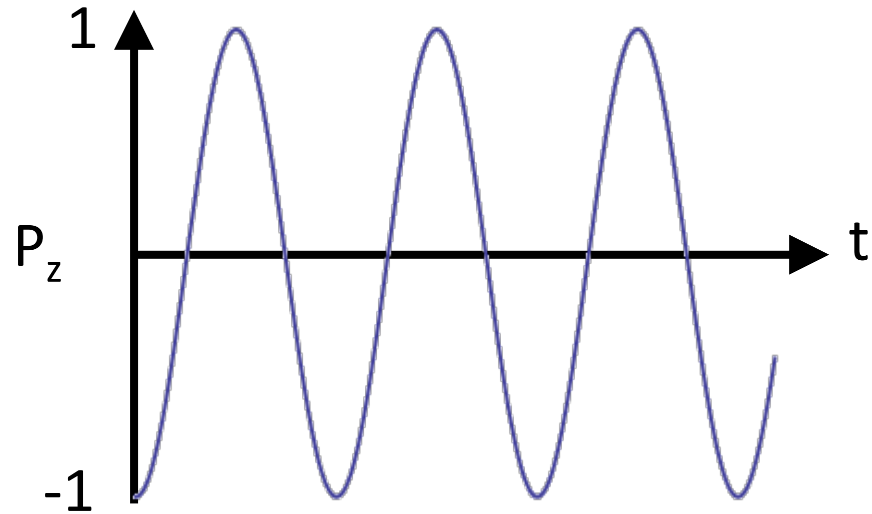
Full counting statistics of phase slips



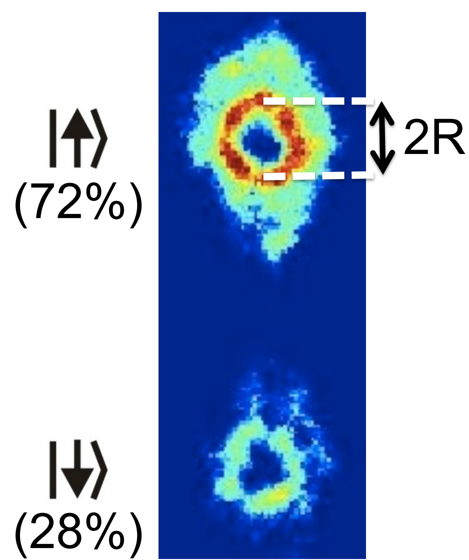
…but no theory yet

Persistent currents in a spinor gas



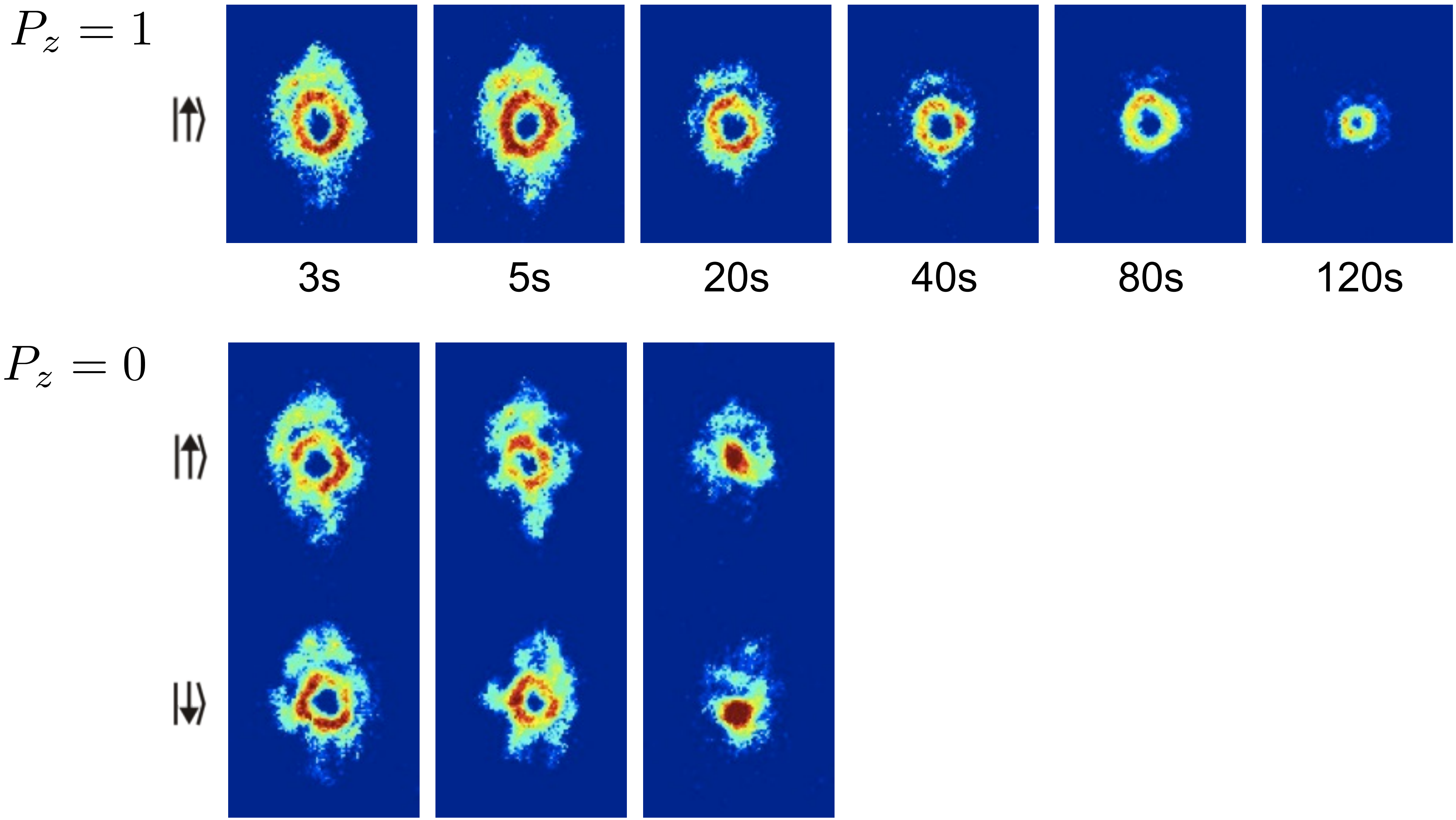


Stern-Gerlach in TOF:



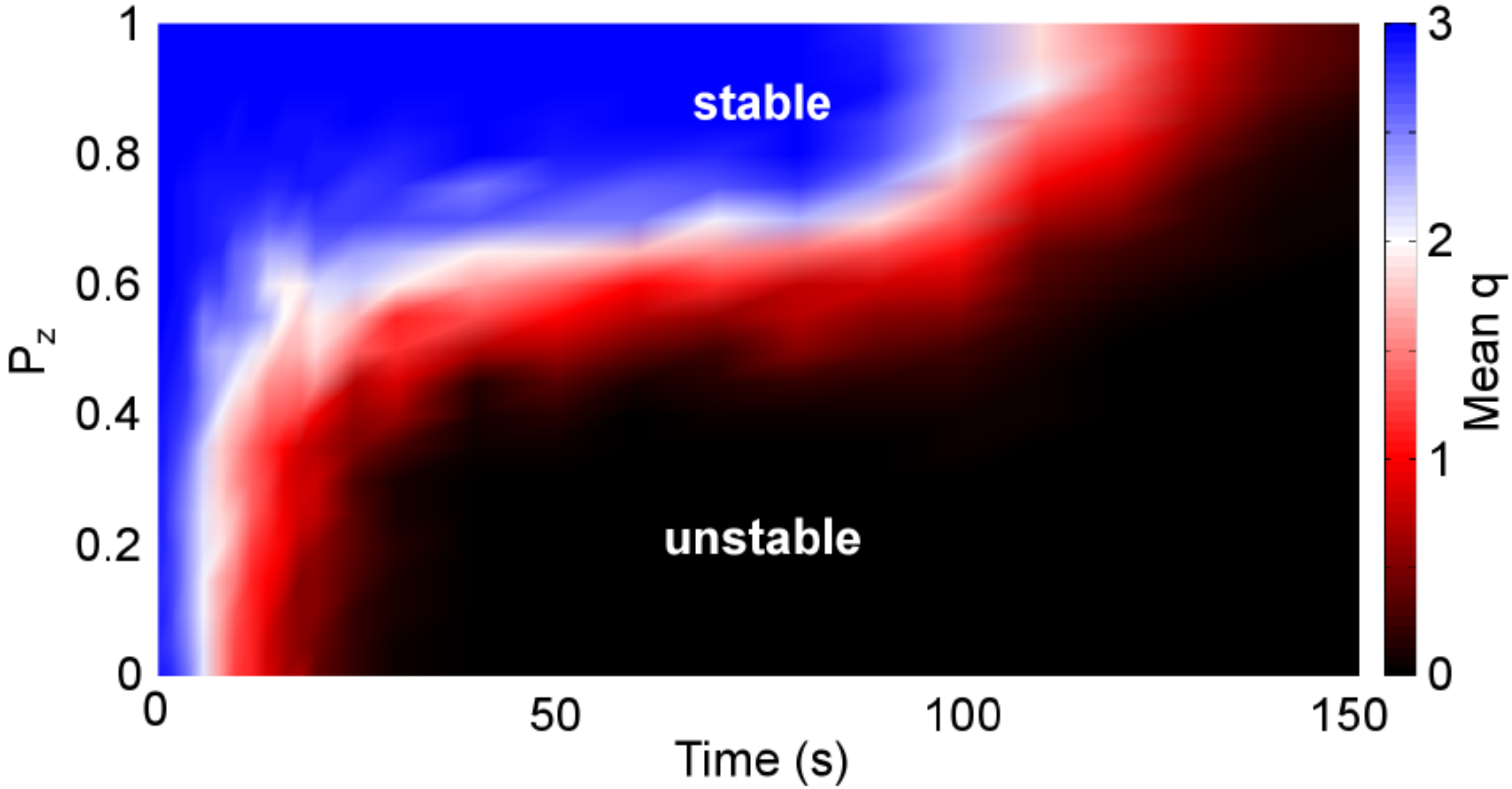
$$P_z = \frac{N_\uparrow - N_\downarrow}{N_\uparrow - N_\downarrow}$$

Single- vs. two-component current



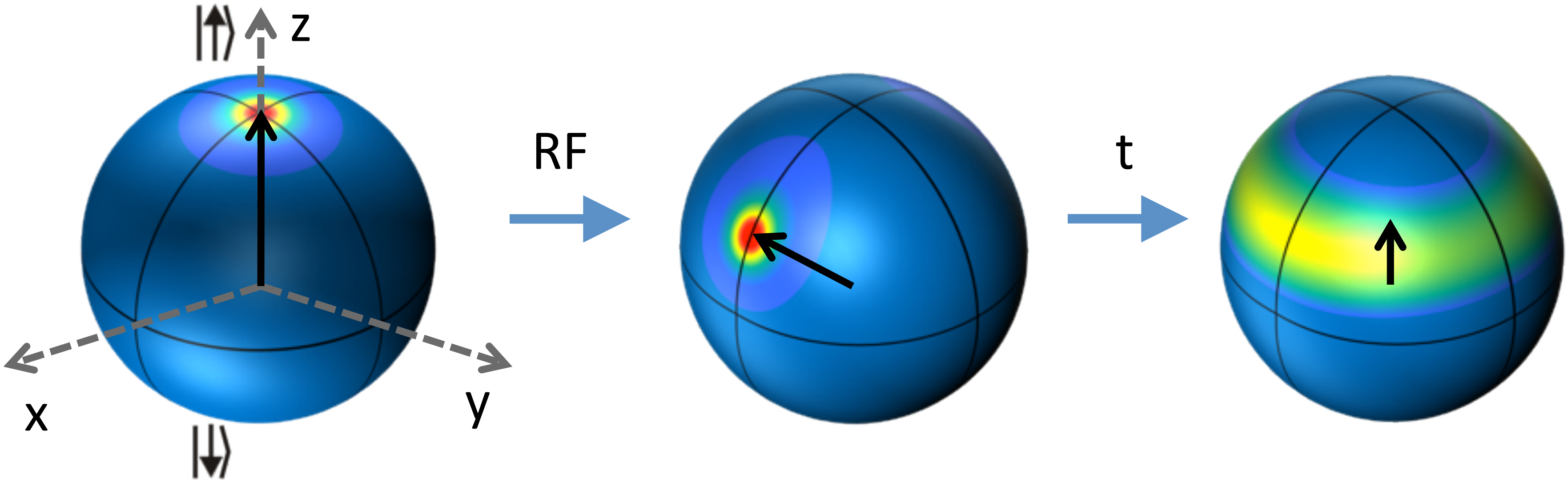
Stability diagram
(sponsored by Pepsi)

~ 1600 measurements of $q(P_z, t)$



Theory: Kavoulakis, Zaremba… but no resolution yet

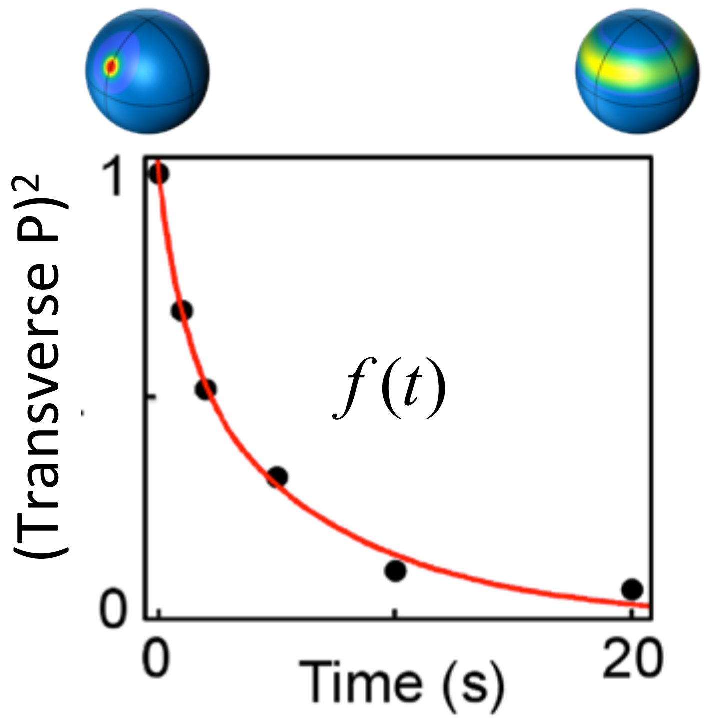
The role of spin coherence



$$\vec{P} = (0, 0, 1) \qquad \vec{P} = (\sqrt{1 - P_z^2}, 0, P_z) \qquad \vec{P} = (0, 0, P_z)$$

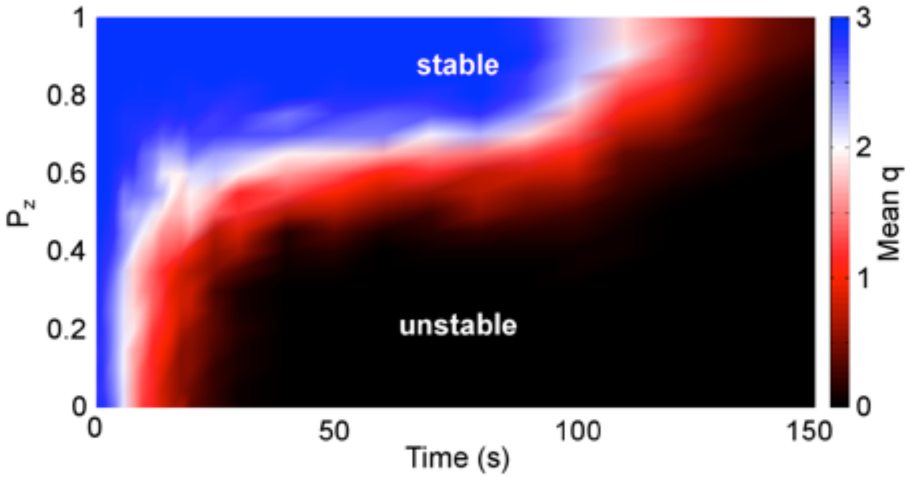
The role of spin coherence

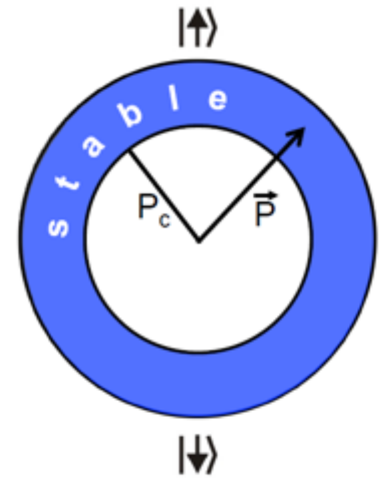
Ramsey:



$$|\vec{P}(t)| = \sqrt{P_z^2 + (1 - P_z^2) f(t)}$$

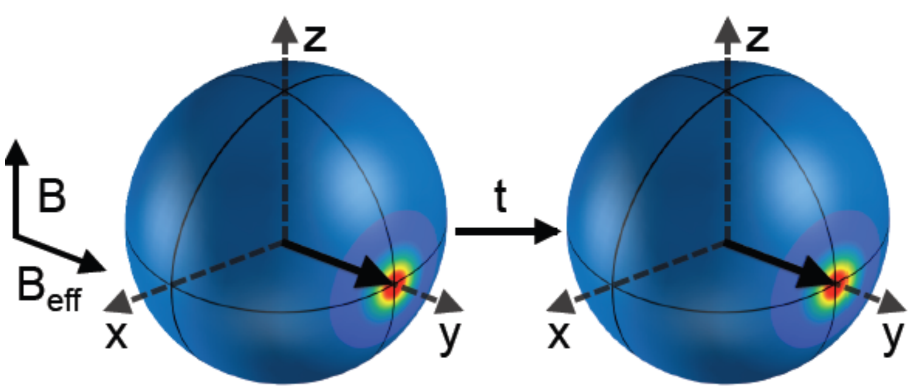
Spin-rotational invariance

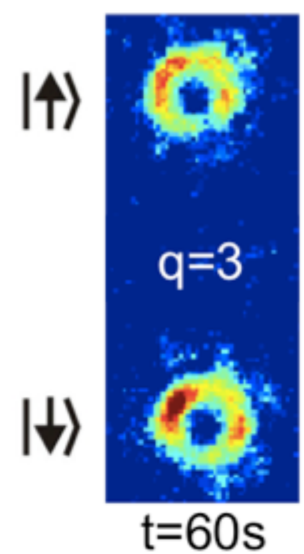




$$P_c = 0.64 \pm 0.01$$

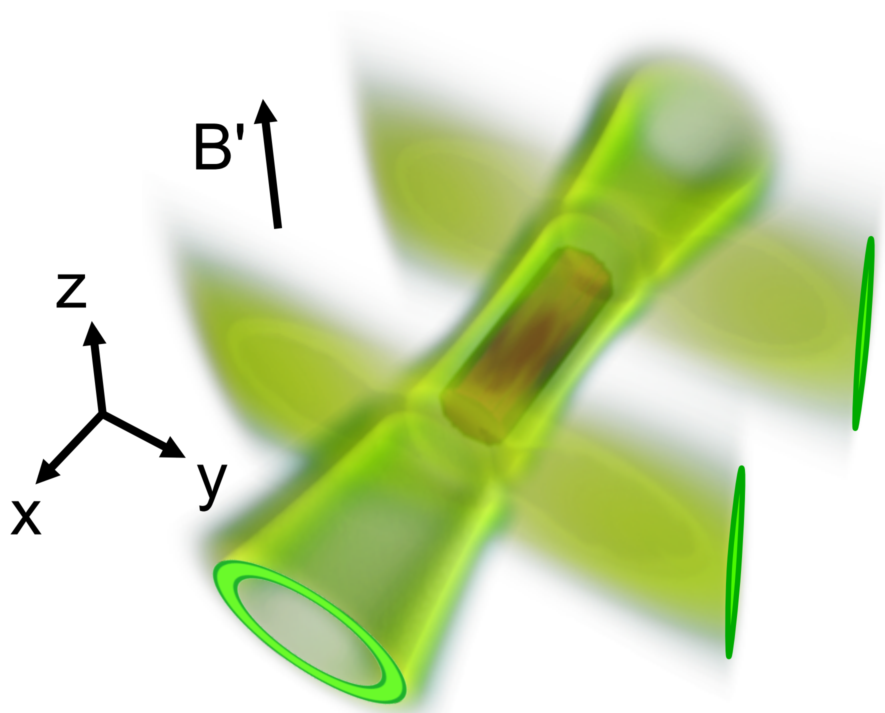
Check by adiabatic RF dressing:



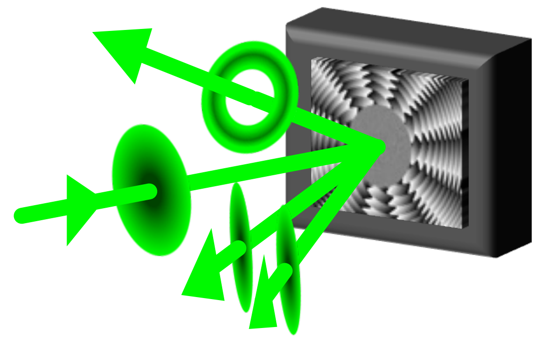


BEC in a (quasi-)uniform potential

- Many-body without LDA (critical behavior, diverging correlation lengths…)
- Strong(er) 2-body interactions with less 3-body decay (unitary Bose gas?)
- Trapped atom interferometry w/ long coherence times
- …

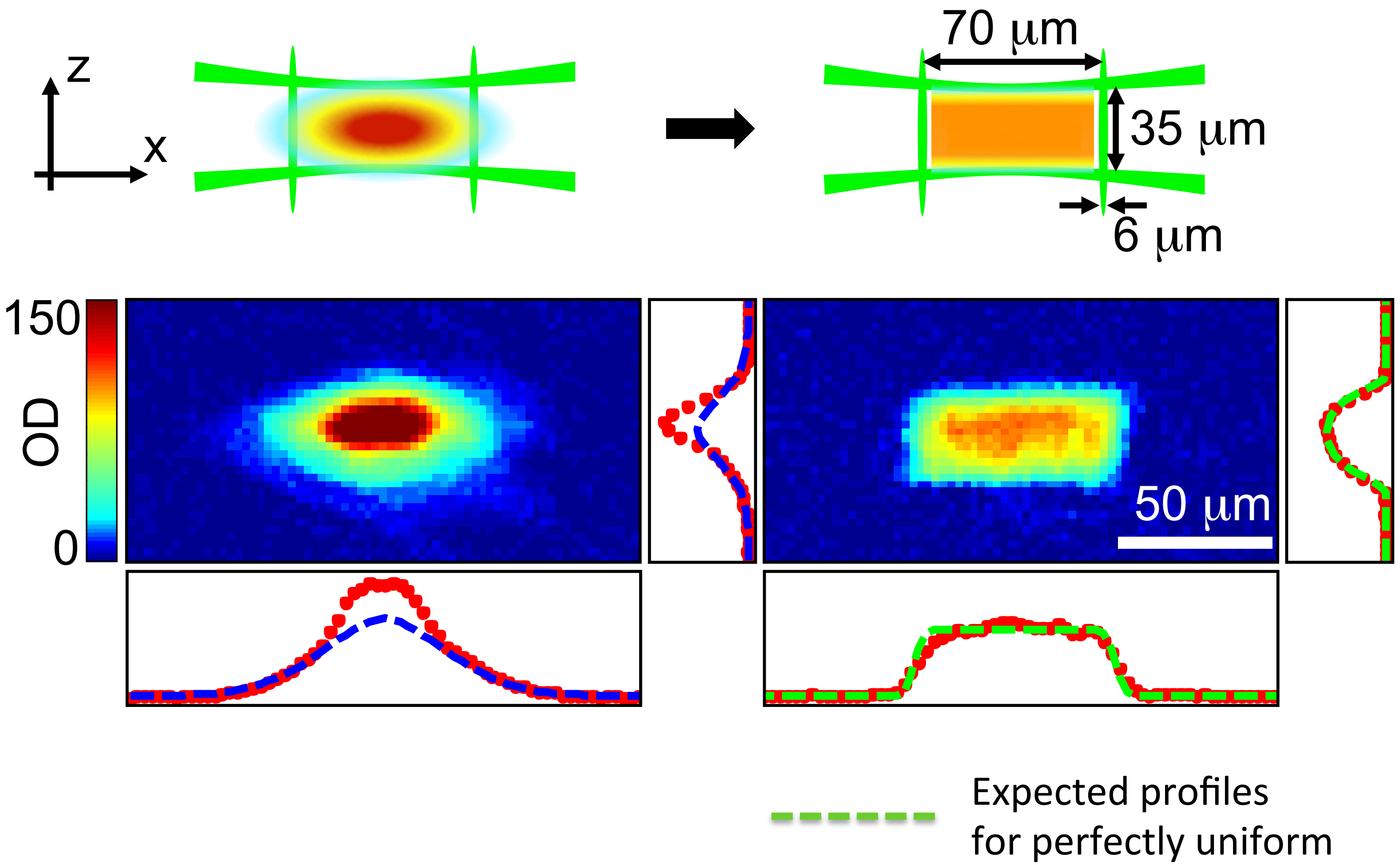


Alex Gaunt's magic:

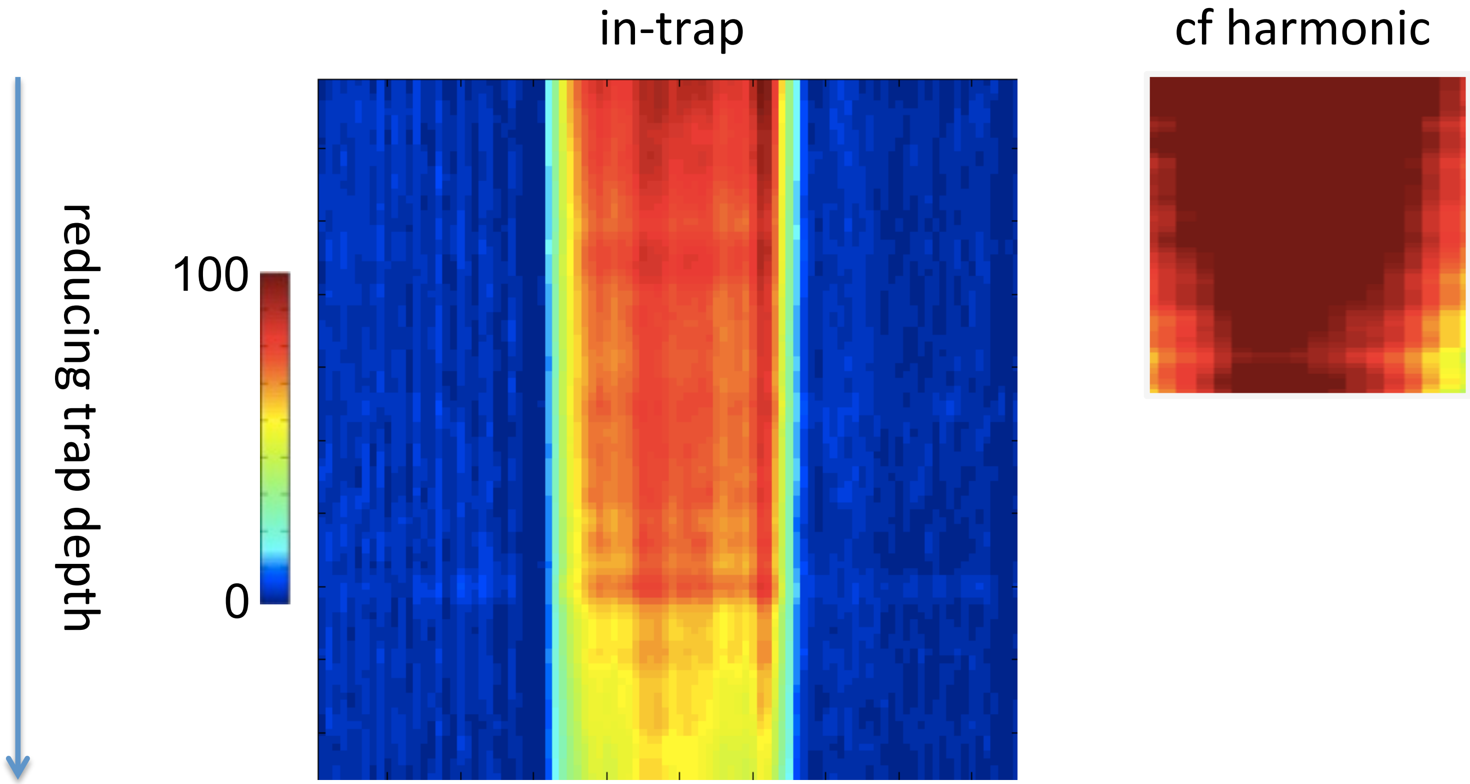


Loading the box

Pre-cool in harmonic trap,
turn on the optical box,
turn off harmonic and gravity (not adiabatic)

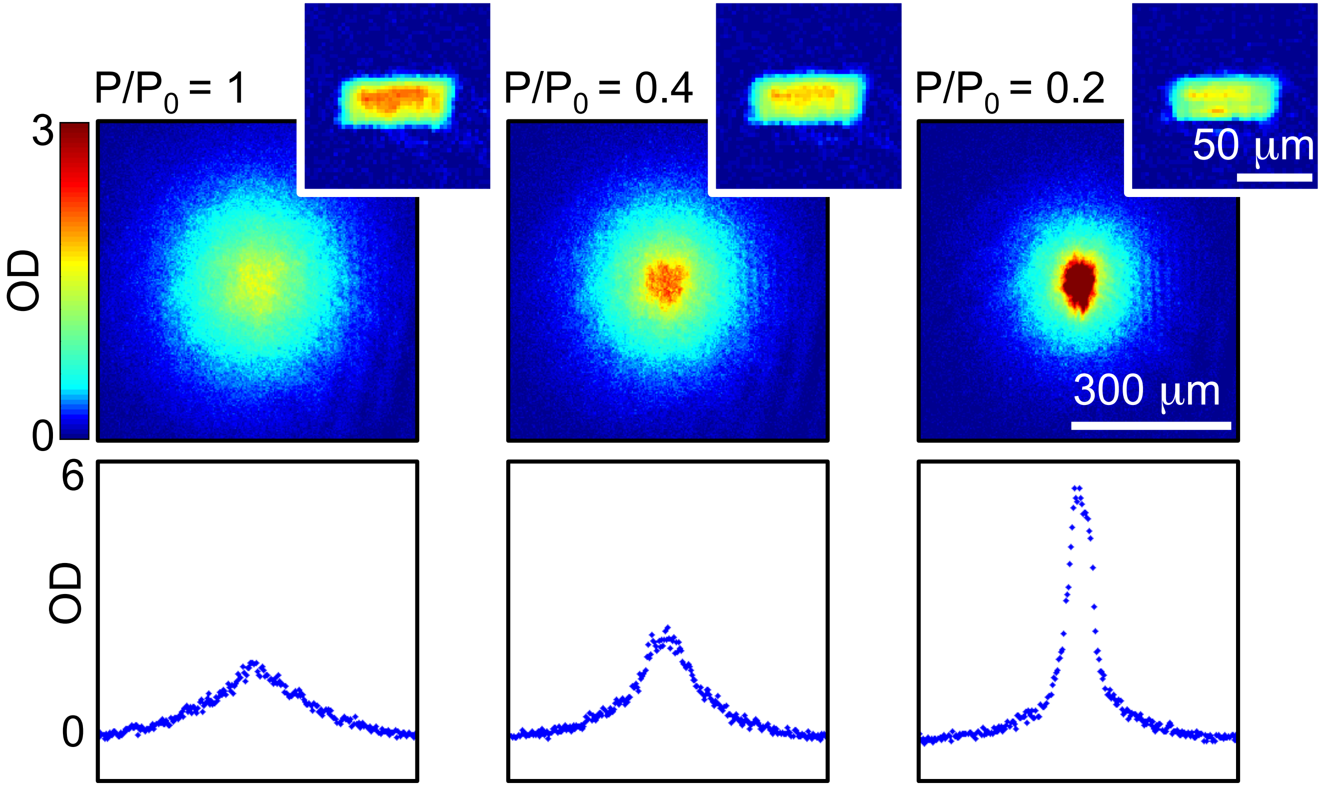


Evaporation in a box



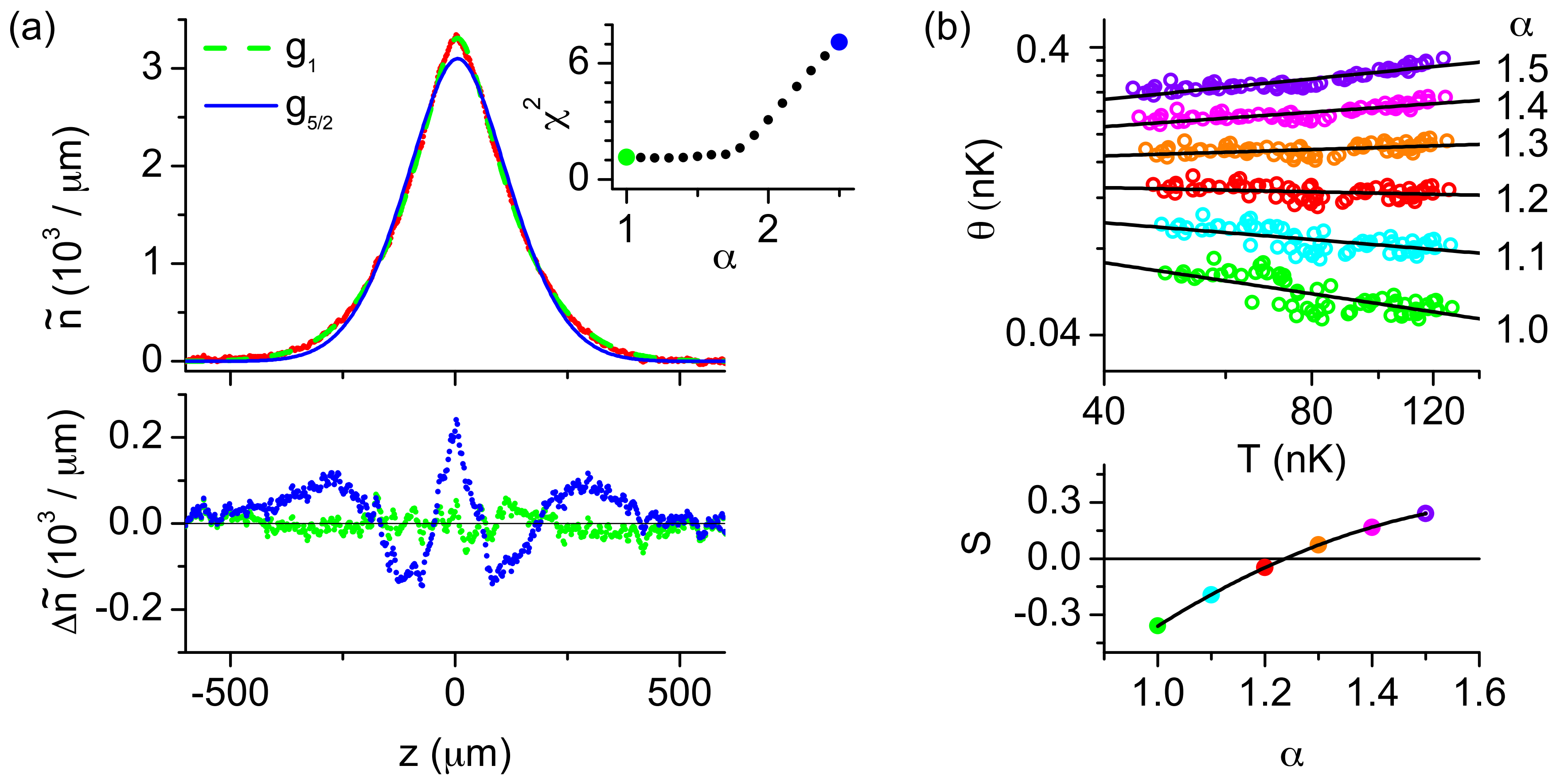
Evaporation in a box

in (50 ms) time-of-flight



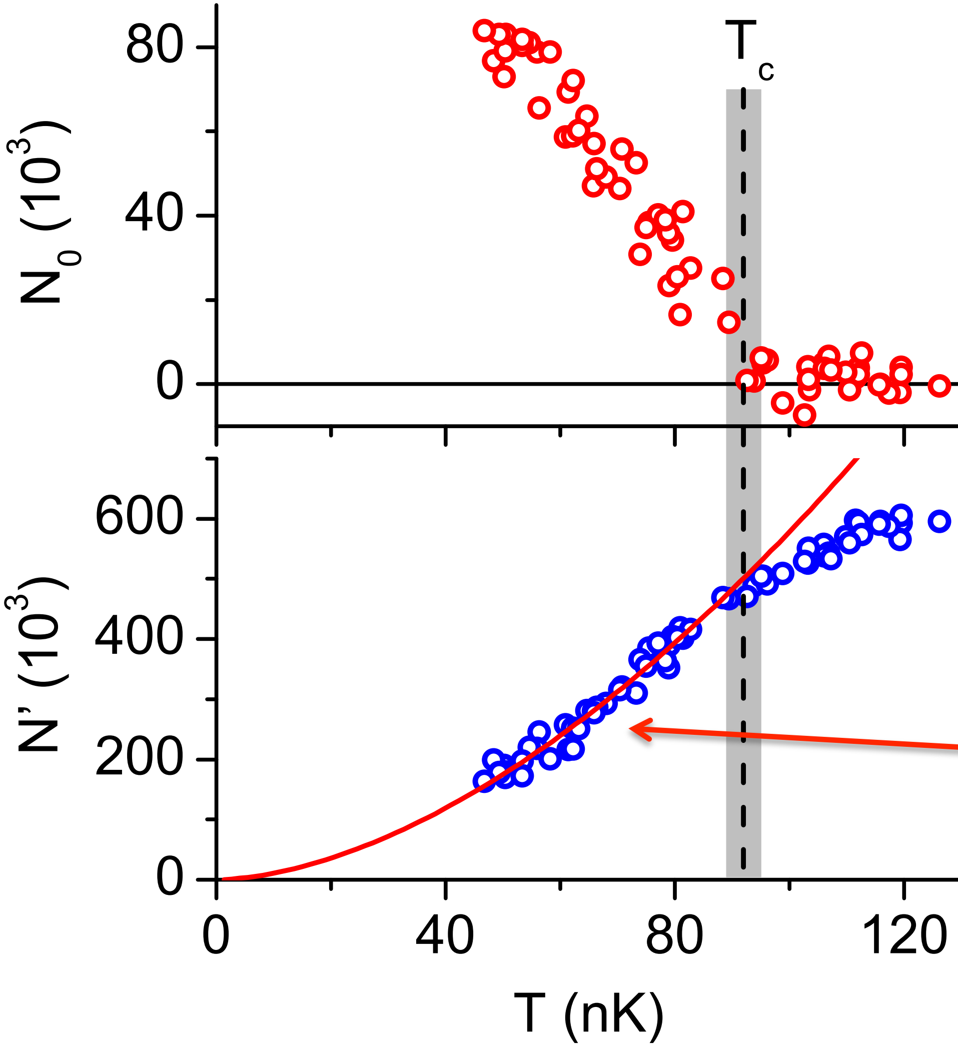
How uniform?

$$V(r) \propto r^n \qquad n(z) \propto \left(\frac{T}{\theta}\right)^{\alpha+1/2} g_\alpha\left(e^{\beta(\mu-\varepsilon(z))}\right) \qquad \alpha = 1 + 3/n$$



leading correction $\propto r^{13\pm2}$

Thermodynamics of condensation



$T_c = 92 \pm 3 \text{ nK}$

predicted for
a uniform system:

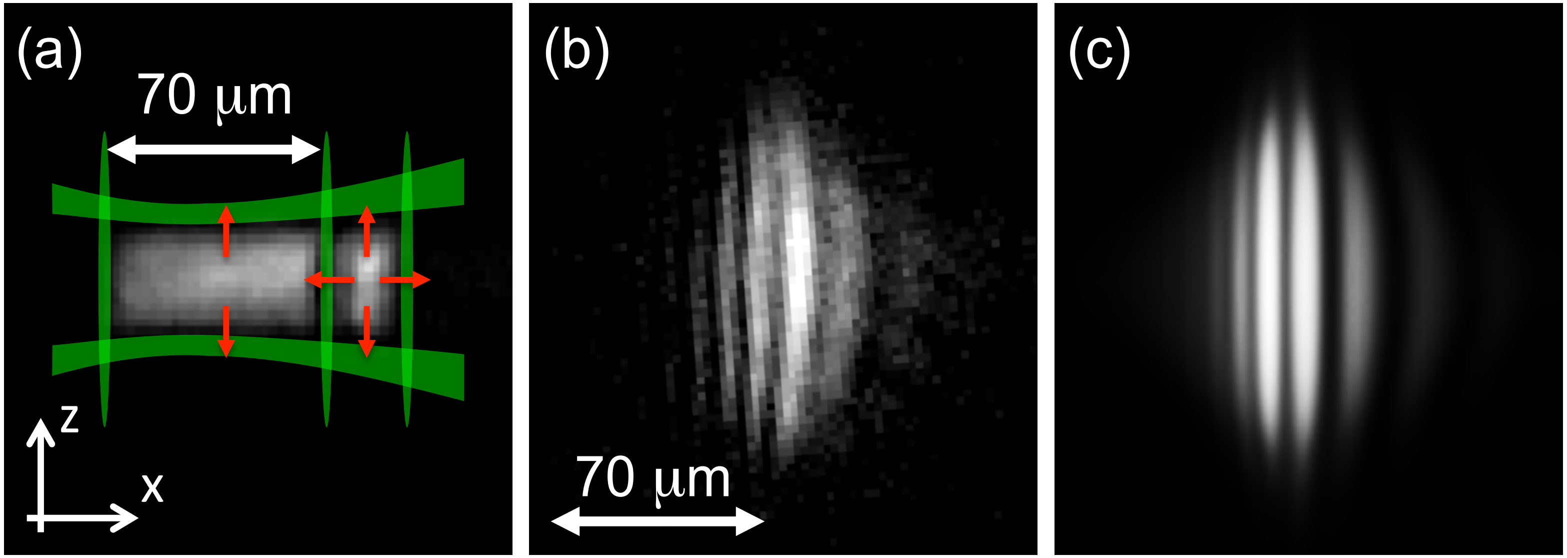
$T_c^0 = 98 \pm 10 \text{ nK}$

$N' \propto T^{1.73 \pm 0.06}$

cf uniform: $T^{3/2}$

harmonic: T^3

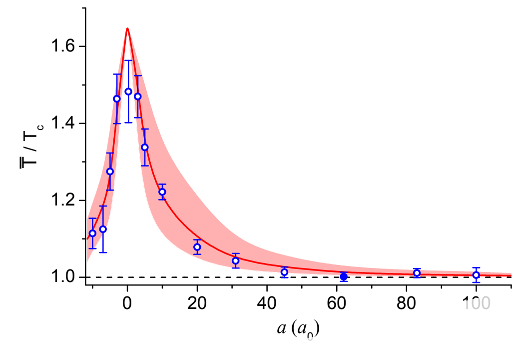
Coherence

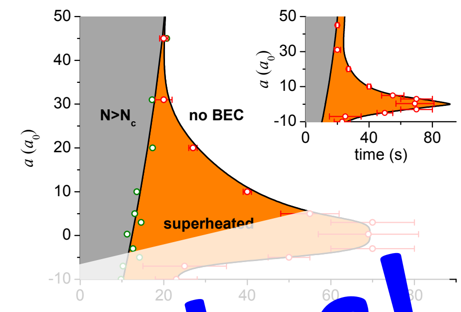


Summary

Superheated (harmonic) Bose gas

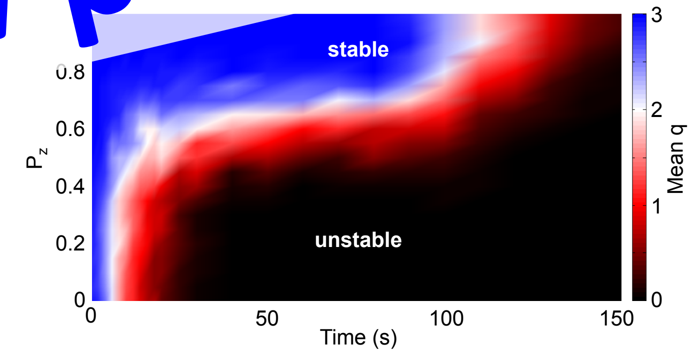
A.L. Gaunt *et al.*, Nature Physics ??? (2013) (arXiv:1212.5833)





Persistent currents in (toroidal) spinor condensates

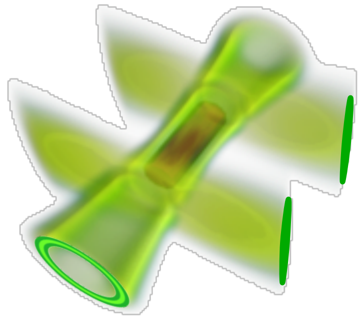
S. Beattie *et al.*, PRL **110**, 025301 (2013)

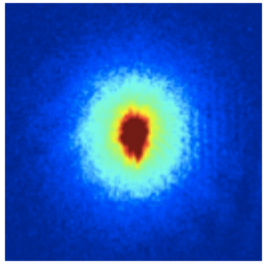


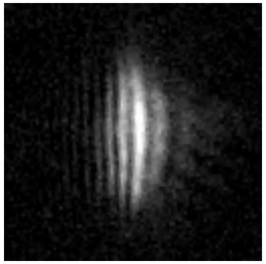
Looking for a new postdoc!

(Quasi-)uniform BEC

A.L. Gaunt *et al.*, arXiv:1212.4453







THE END