Bose gas in a box

Zoran Hadzibabic
University of Cambridge

doctors:
Rob Smith
Nir Navon
Alex Gaunt
Igor Gotlibovych
Tobias Schmidutz

esquire:
Christoph Eigen

EPSRC
Engineering and Physical Sciences
Research Council

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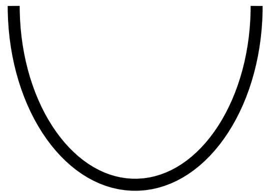
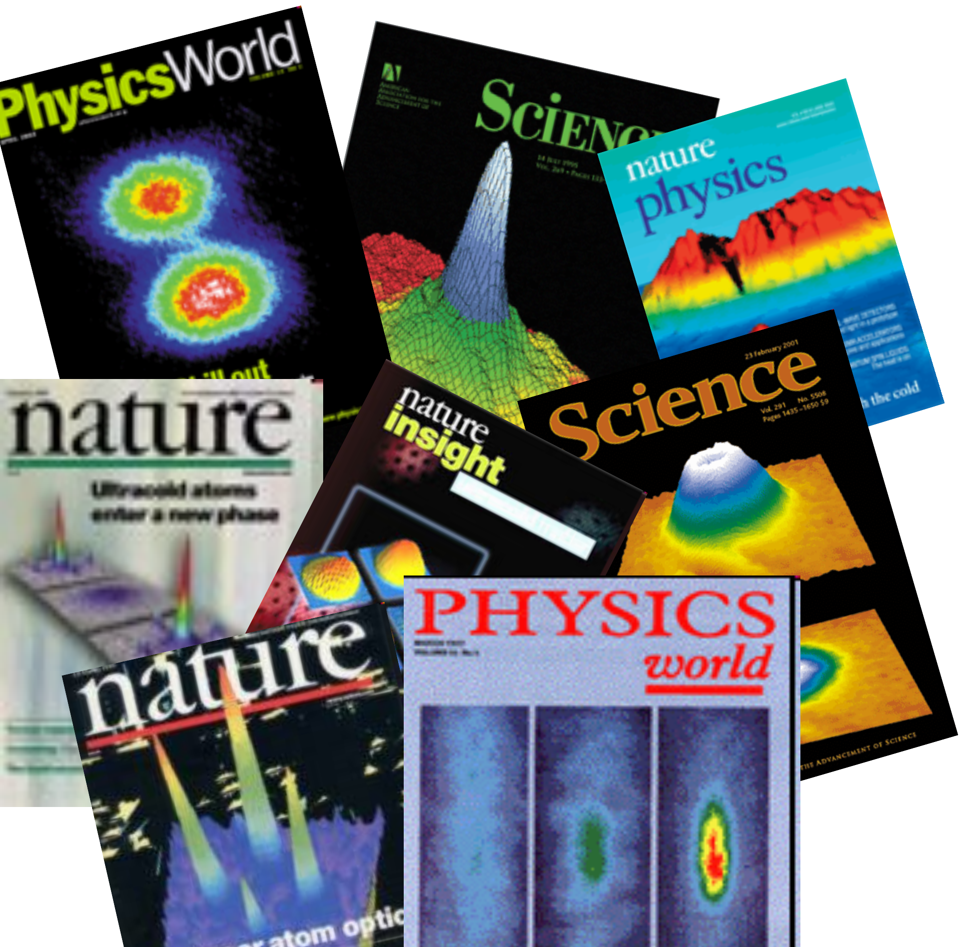
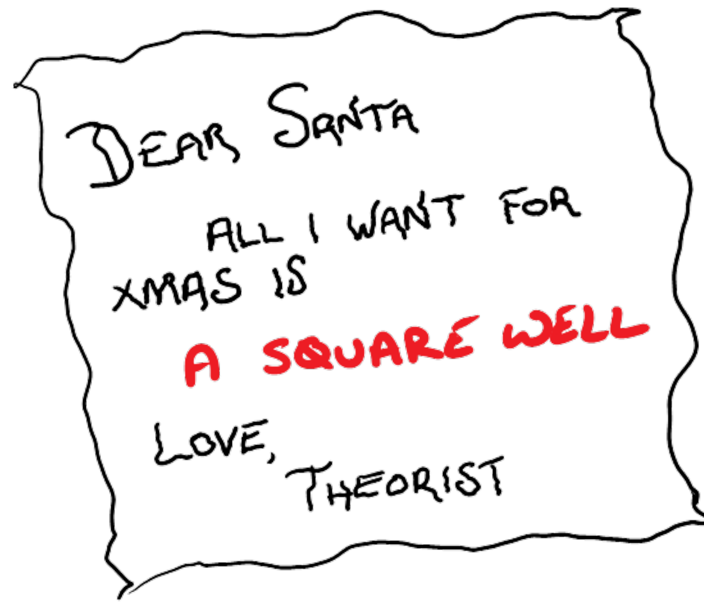
Two kinds of trapping potentials (in physics)







Motivation

- Many-body physics without LDA

  critical phenomena (diverging correlation lengths),

  more generally "power-law physics" (e.g. 2D, turbulence)

- Topological edge states

- "Practical advantages": transport, unitary Bose gas, interferometry,

  zooming in on slivers of the phase diagram…

- Surprises

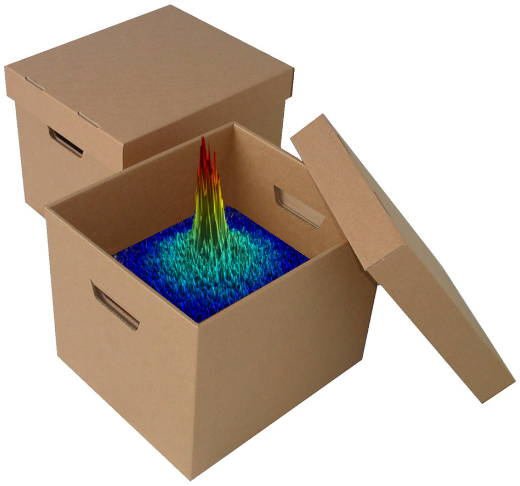
Other (interested) groups:
1. Raizen, Heinzen, Dalibard, Chin, Zwierlein, Cornish…
2. Schneider/Bloch, Salomon, Spielman, Fallani/Inguscio…

Outline of the talk

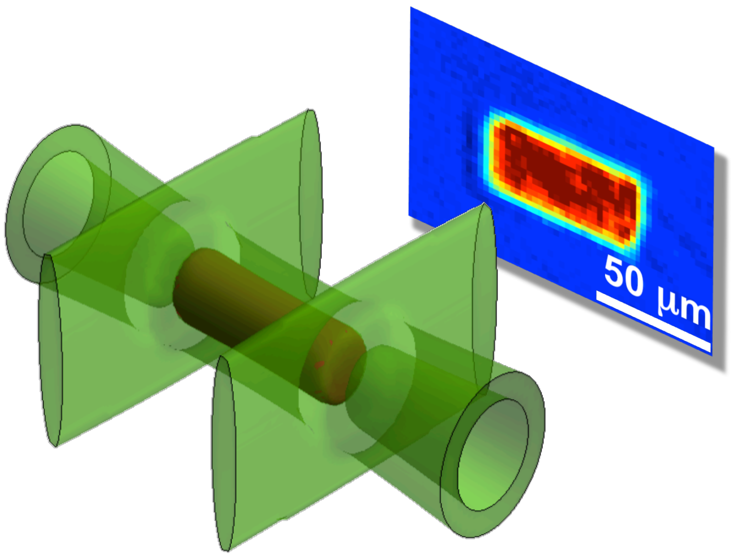
BEC in a box: basics

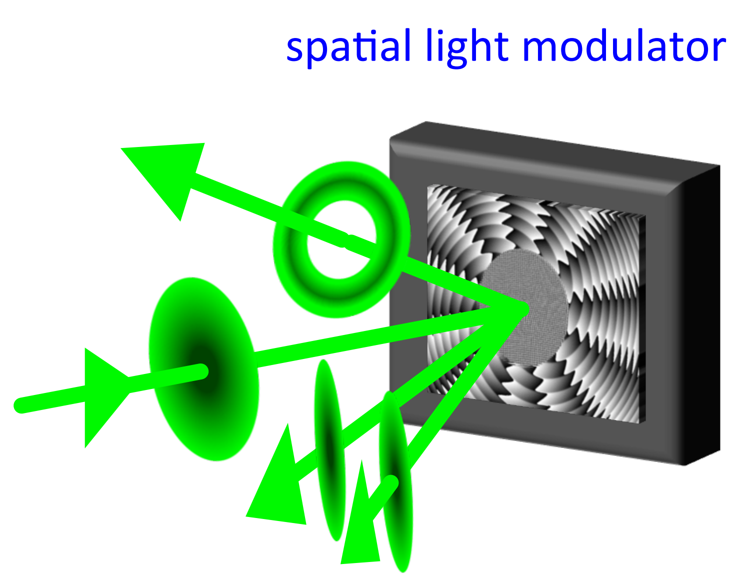
(Kibble-Zurek) Critical dynamics of spontaneous symmetry breaking

Outlook & some new stuff (very preliminary)



Optical-box trap



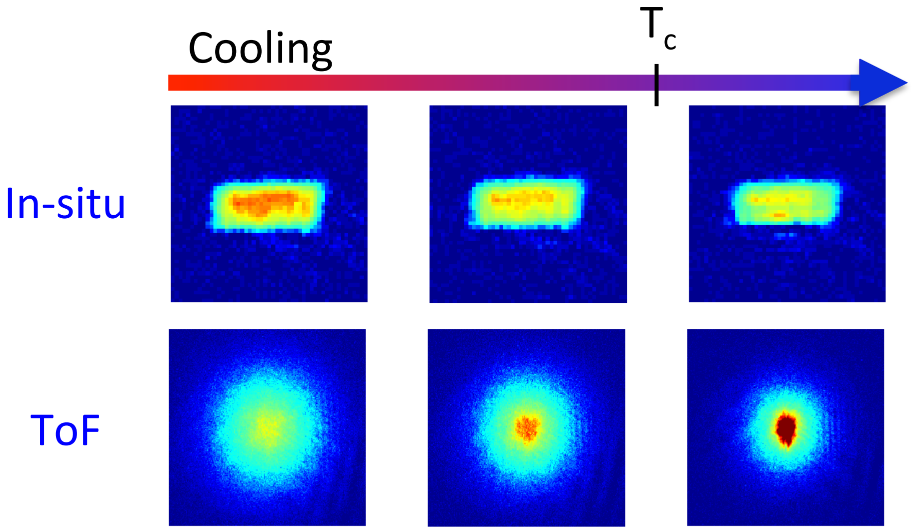


Basic protocol:

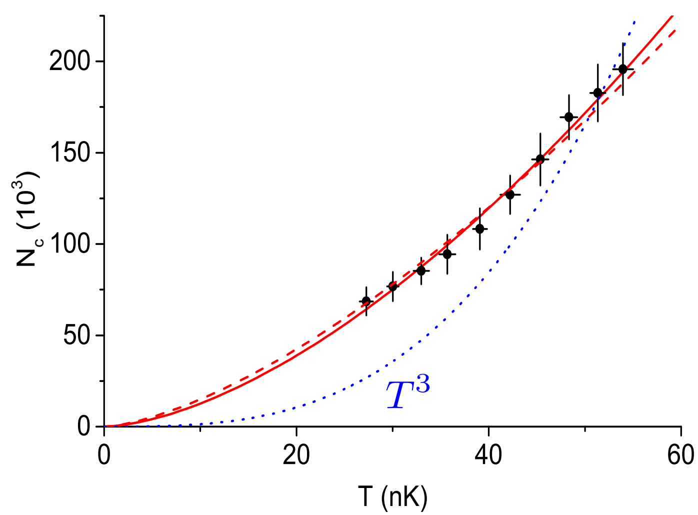
- Pre-cool in harmonic trap
- Transfer into optical box & cancel gravity (at 10^{-4} level)
- Cool more…

Methods also compatible w/ other geometries, Feshbach resonances, optical lattices, fermions…

Condensation in a box



Condensation in momentum space *only*



Critical point: $N_c \propto T^{3/2}$

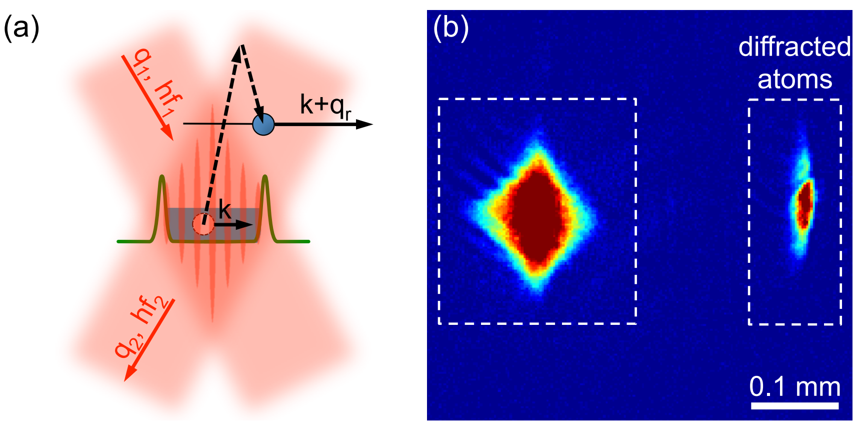
Leading-order deviation from a perfect box potential: $U \sim r^{15-20}$

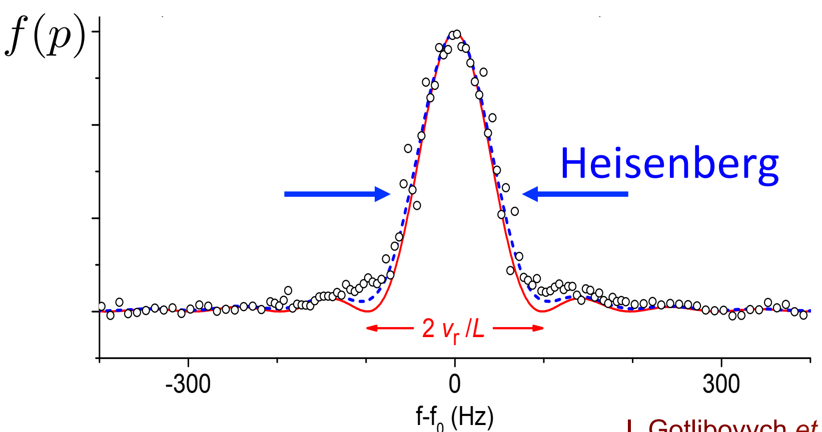
(Quasi-pure) BEC properties

Momentum distribution, interaction energy, ToF expansion dynamics…

Bragg spectroscopy:

M. Kozuma, W. D. Phillips, et al., PRL **82**, 871 (1999)
J. Stenger, W. Ketterle, et al., PRL **82**, 4569 (1999)





I. Gotlibovych *et al.*,
PRA **89**, 061604(R) (2014)

$$hf = h(f_1 - f_2) \qquad hf = hf_r + \frac{\hbar^2}{m}k_z q_r + \Delta E_{\mathrm{int}}$$

…all agree with with Heisenberg and Gross-Pitaevskii

Trap-bottom roughness: $< 1\ \mathrm{nK}$

(Kibble-Zurek)

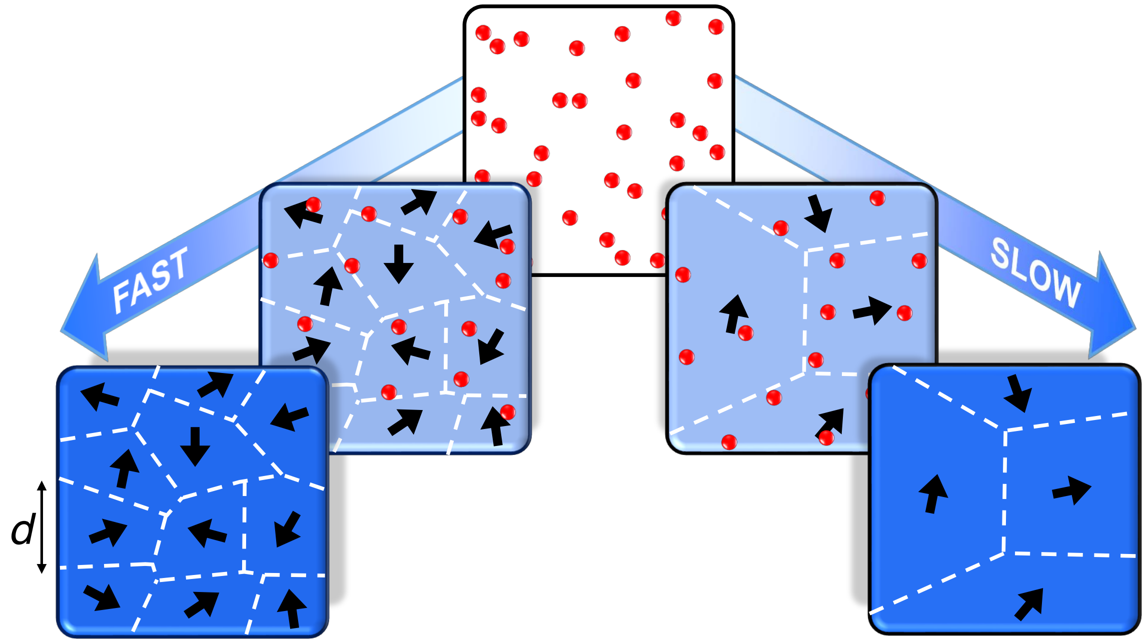
Critical dynamics of spontaneous symmetry breaking in a homogeneous Bose gas

N. Navon, A.L. Gaunt, R.P. Smith, and ZH, Science **347**, 167 (2015)

Kibble-Zurek picture

Key concepts: diverging correlation length *above* T_C ("critical opalescence") $\xi \to \infty$

critical slowing down $\tau_\xi \to \infty$



phase-space density:

$\rho > \rho_c$

$\rho >> \rho_c$

(also topological defects, formed at domain boundaries)

Correlation length at "freeze-out" just above T_C = coherence length at T=0

Same picture for: (homogeneous) BEC, magnetism, early universe, quantum phase transitions…

Domain size (& defect density) follow "universal" power-law scaling

KZ math

$$\varepsilon = (T - T_c)/T_c$$

$$\xi \sim \lambda\, \varepsilon^{-\nu}$$

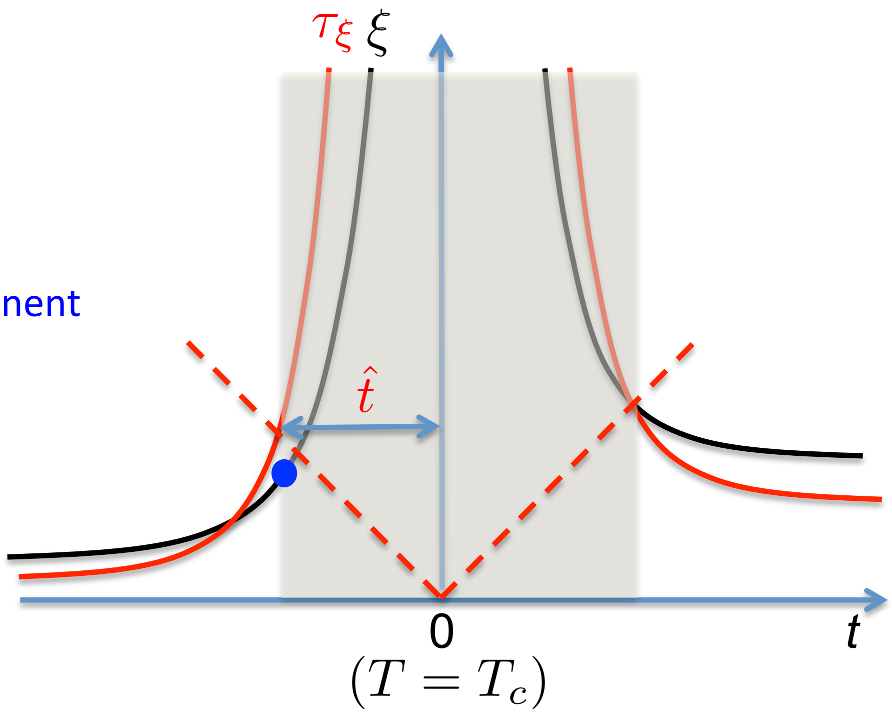
ν - correlation length critical exponent

λ - microscopic distance

$$\tau_\xi \sim \tau_0\, \varepsilon^{-z\nu}$$

z - dynamical critical exponent

τ_0 - microscopic time



KZ hypothesis:

Freeze-out time: $\tau_\xi(-\hat{t}) = \hat{t}$

Domain size *d* (= coherence length below T_c) set by ξ at freeze-out:

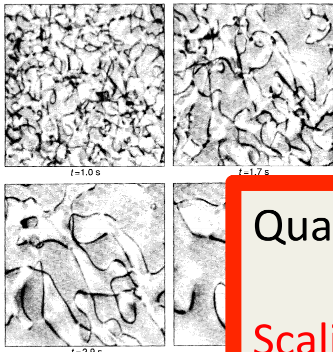
$$d \sim \lambda \left(\frac{\tau_Q}{\tau_0}\right)^b$$

τ_Q - quench time

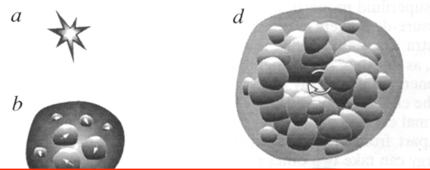
$$b = \frac{\nu}{1 + \nu z}$$

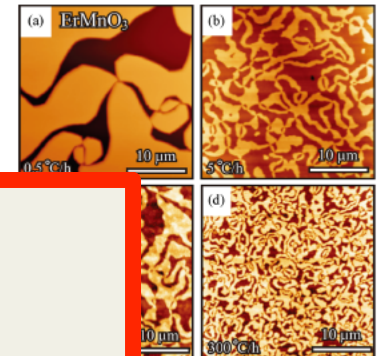
(Some) previous experiments

Condensed matter:



Chuang et al.,





et al., 2012

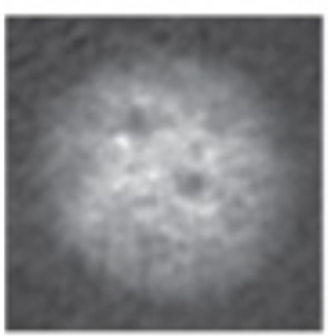
Quantitative issues:

Scaling law

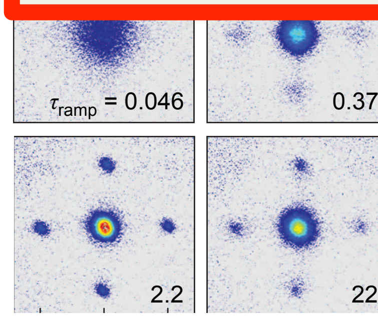
- System inhomogeneity
- Nature of the transition being crossed
- ….

Validity of the freeze-out hypothesis

Atomic:

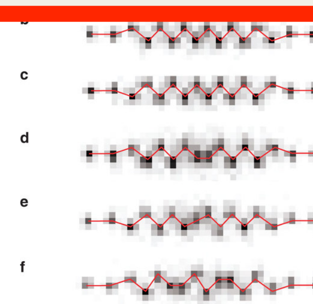


Weiler et al., 2008



Chen et al., 2011

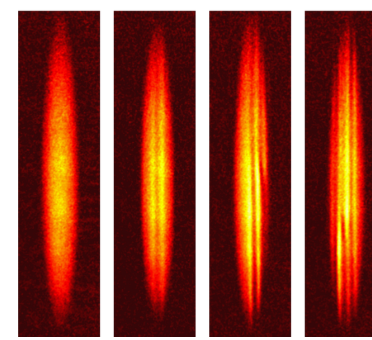
Braun et al., 2014



Ulm et al., 2013

Pyka et al., 2013

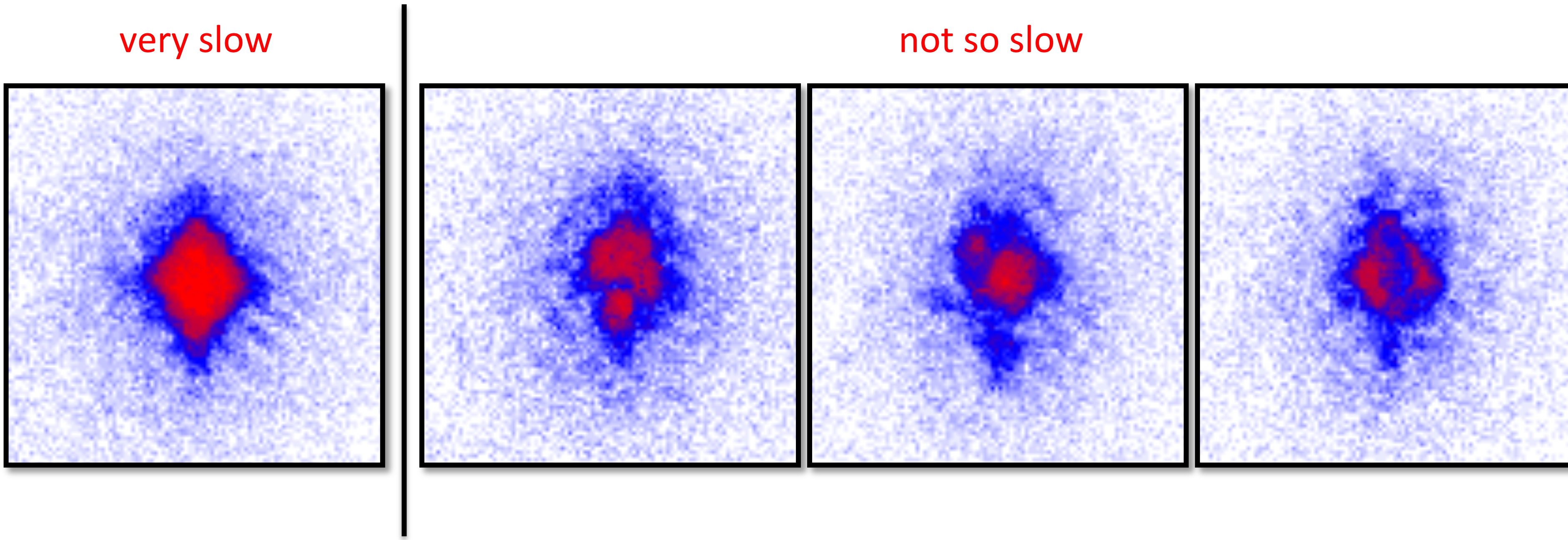
Ejtemaee & Haljan, 2013



Lamporesi et al., 2013

(Very) qualitative: ToF images

Cooling through T_C at different rates



(all pictures have same N = 10^5 and T = 10 nK, phase-space density $\rho > 10$)

Quantitative: two-point correlation functions

$$g_1(x) = \langle \Psi(x) \Psi^*(0) \rangle$$

One approach:

Momentum distribution (Bragg spectroscopy) + Fourier transform

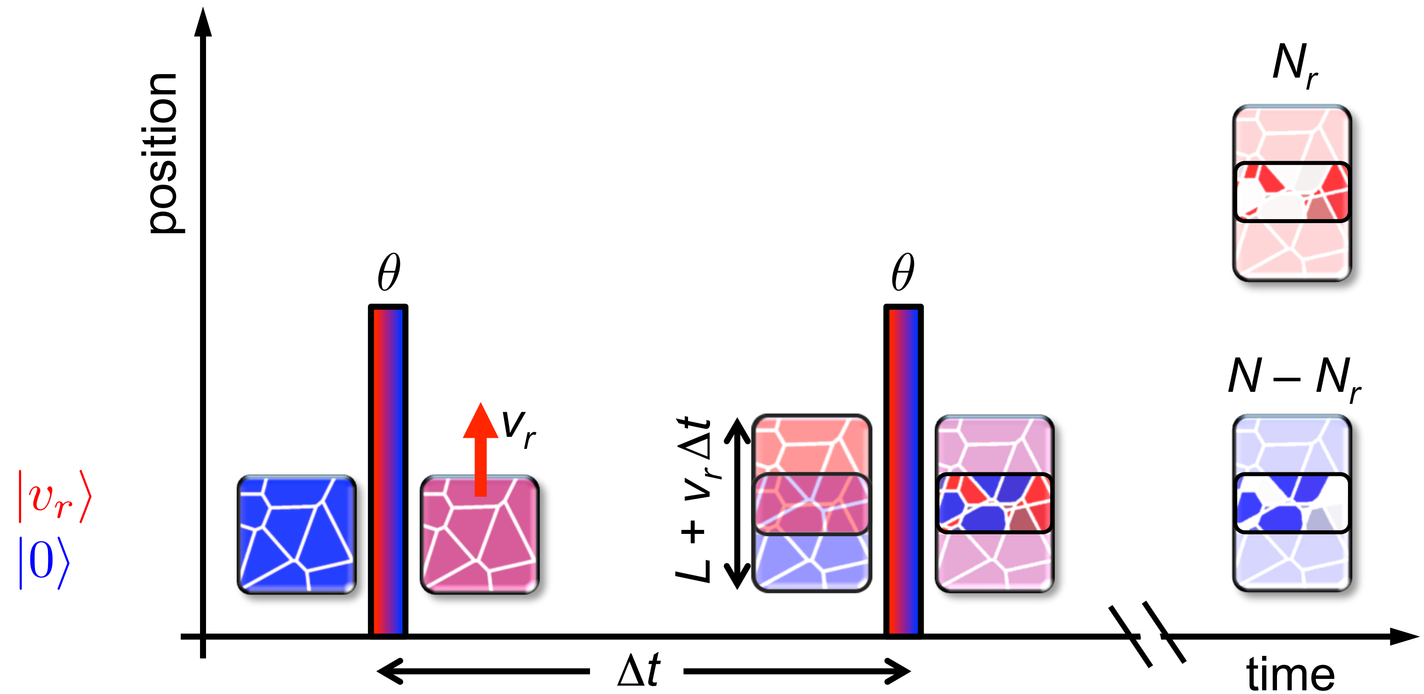
Better approach:

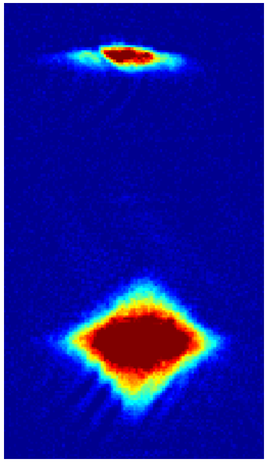
E. W. Hagley, W. D. Phillips, et al., Phys. Rev. Lett. **83**, 3112 (1999).

Two short Bragg pulses separated by a variable time (Ramsey style)

Directly measure in real space rather than momentum space

Homodyne measurement of g_1



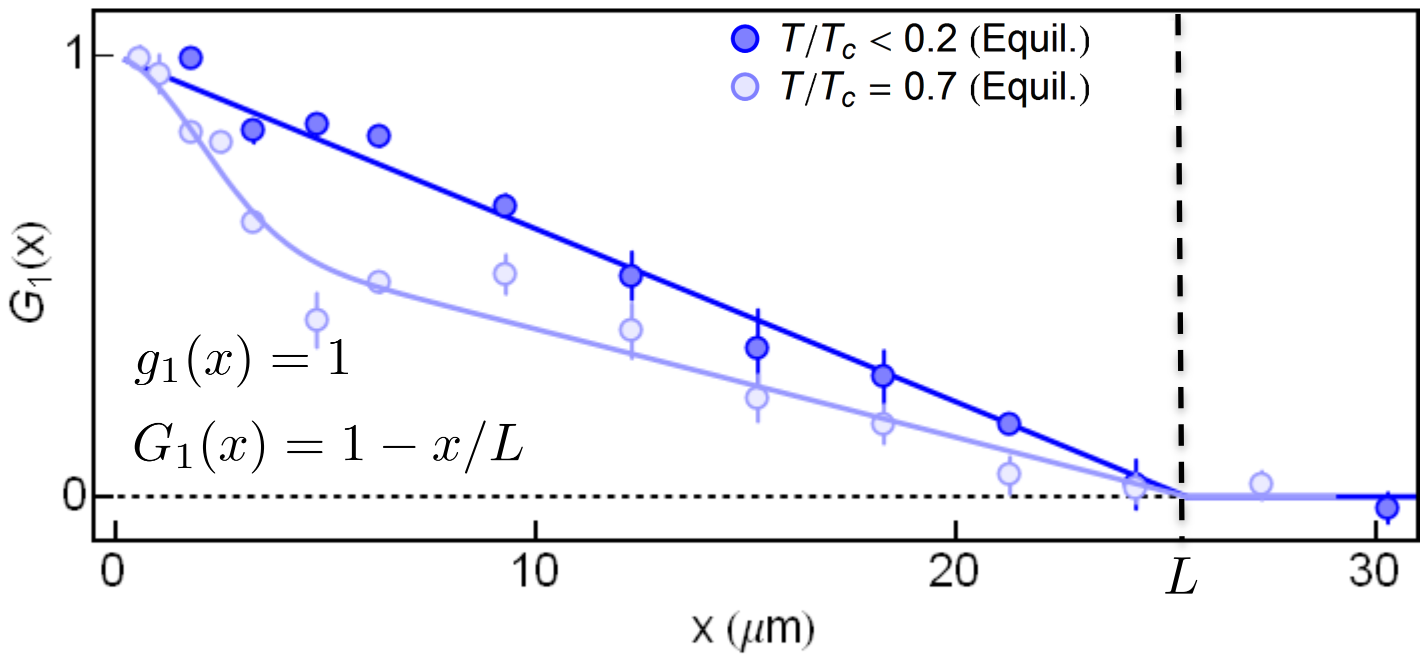


$$\frac{N_r}{N} = \frac{1}{2}\left[1 + \underbrace{\left(1 - \frac{x}{L}\right) g_1(x)}_{G_1(x)}\right] \sin^2(\theta)$$

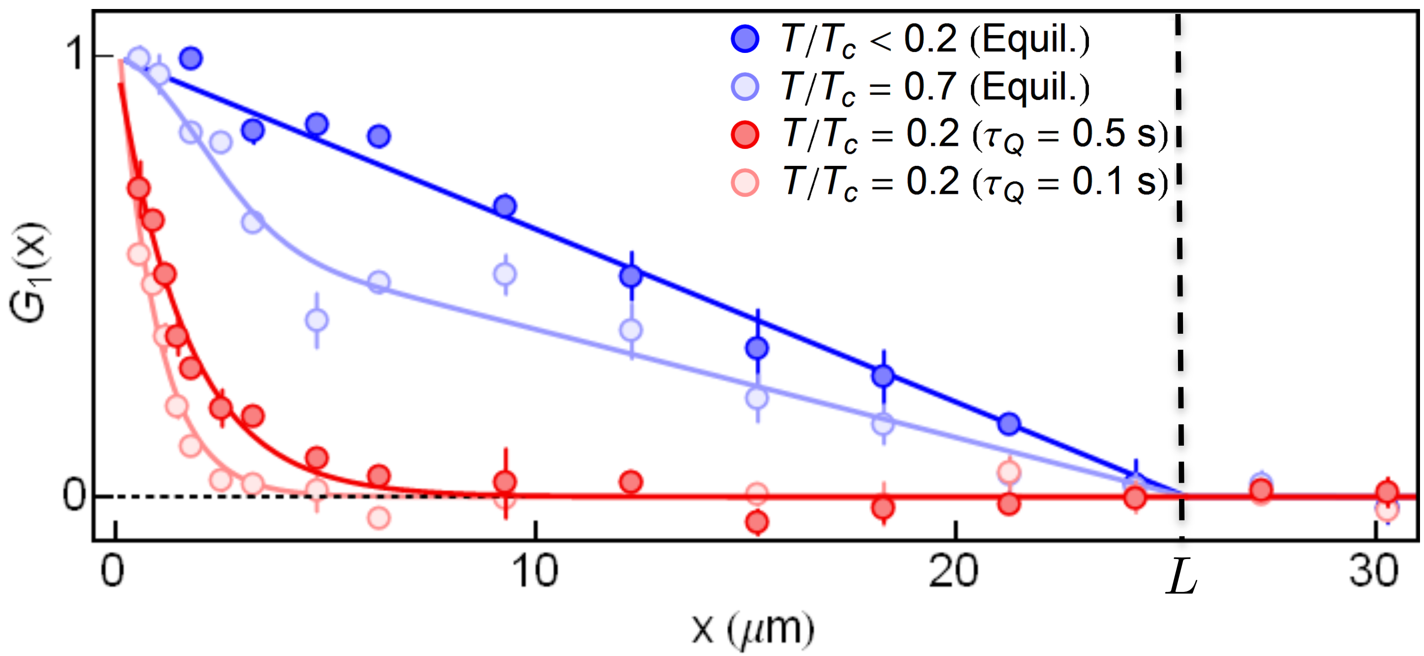
L – box length

G_1 in equilibrium

cool (very) slowly and wait for a (very) long time



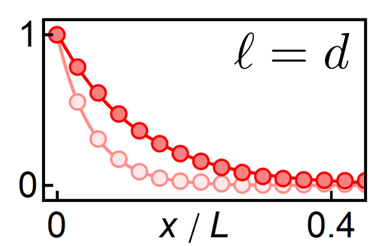
G_1 in equilibrium and after a quench



No equilibrium interpretation

Fitted by $g_1(x) = e^{-x/\ell}$

supported by simulations:



What do we expect from KZ theory?

$$\ell \sim \lambda \left(\frac{\tau_Q}{\tau_0}\right)^b$$

$$b = \frac{\nu}{1+\nu z}$$

λ - short distance (1 μm)
τ_Q - quench time
τ_0 - short time (30 ms)

Mean-field:

$$\left.\begin{array}{rcl} \nu & = & 1/2 \\ z & = & 2 \end{array}\right\} b = 1/4$$

Beyond mean-field:

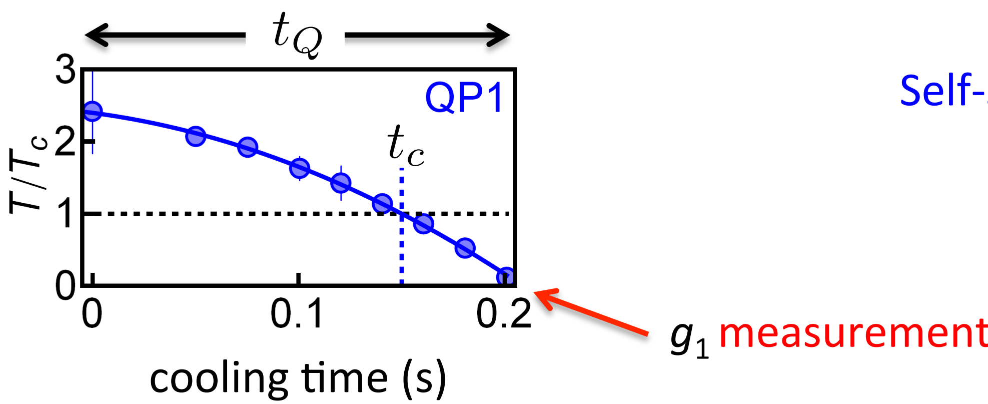
$$\left.\begin{array}{rcl} \nu & = & 2/3 \\ z & = & 3/2 \end{array}\right\} b = 1/3$$

Some concerns…

1. Does this even make sense?
   implies that making a pure BEC takes an hour (not true)

2. Conditions for applicability of the KZ scaling law?
   actually reconciles things…

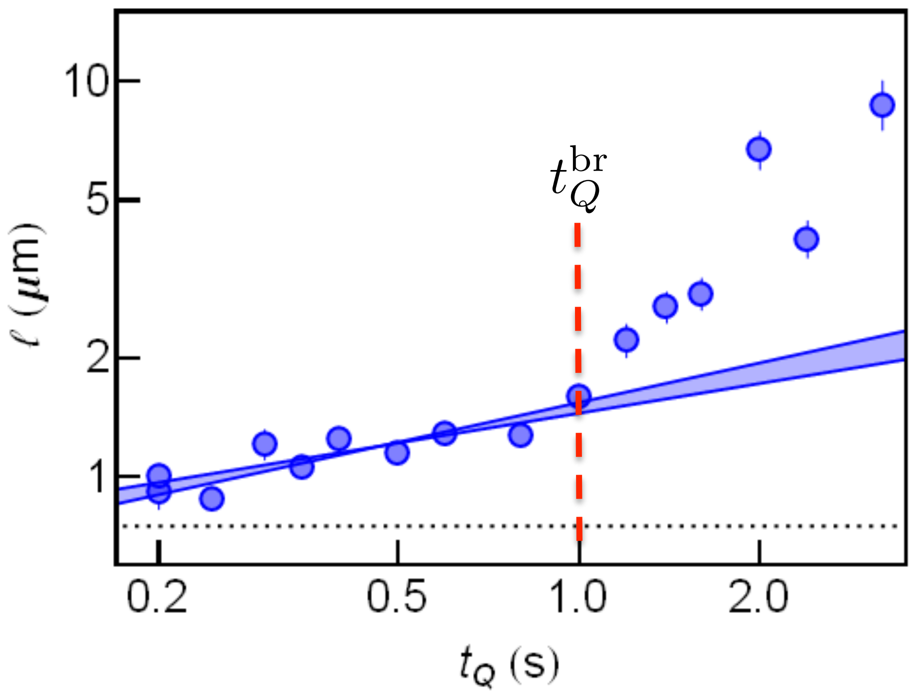
Quench protocol (1) – KZ scaling and its breakdown



Self-similar cooling curves with

$$t_Q = 0.2 \rightarrow 3.5 \text{ s}$$

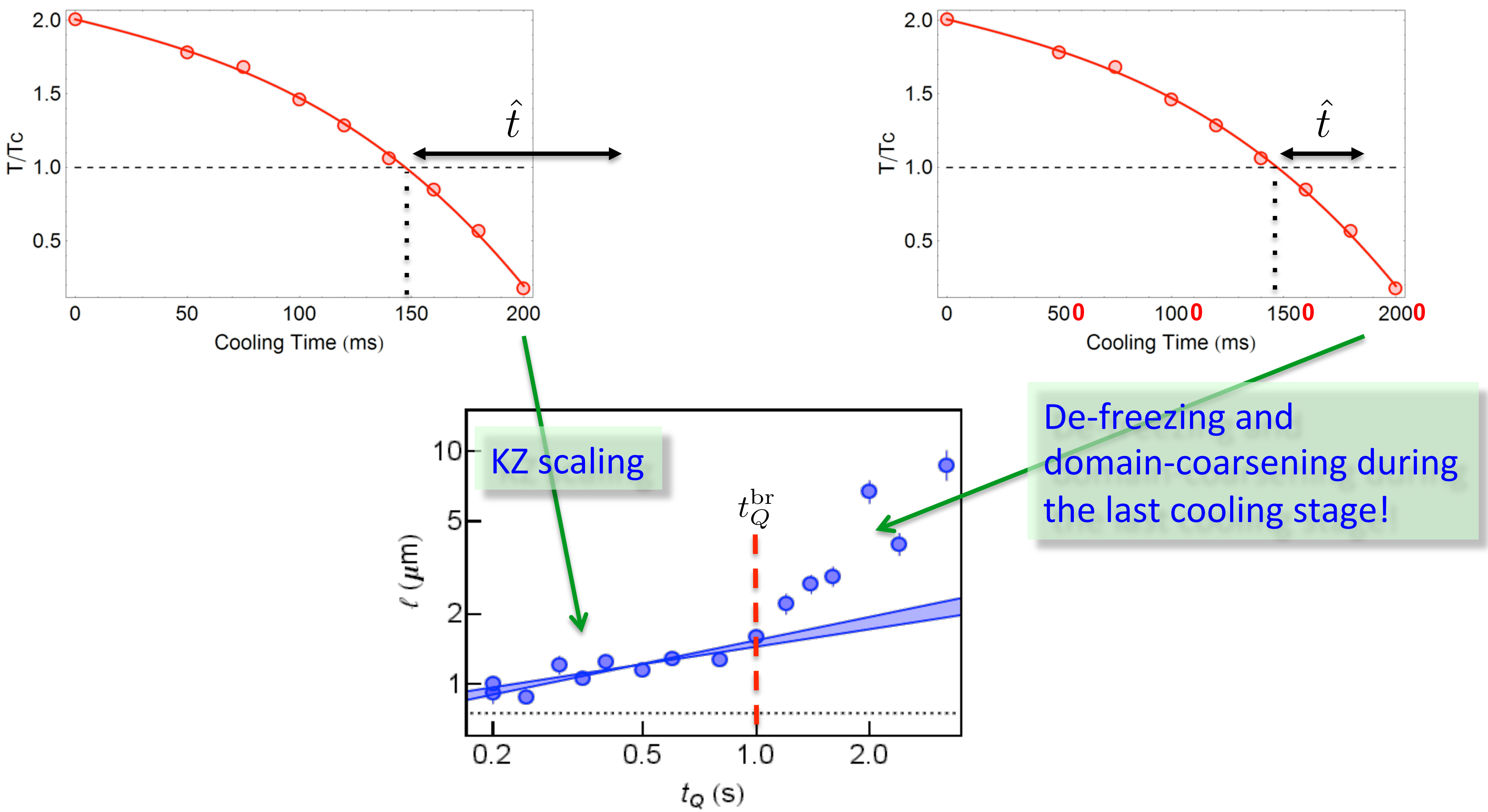
$$t_c \approx 0.72\, t_Q$$



$b = 1/4 - 1/3$

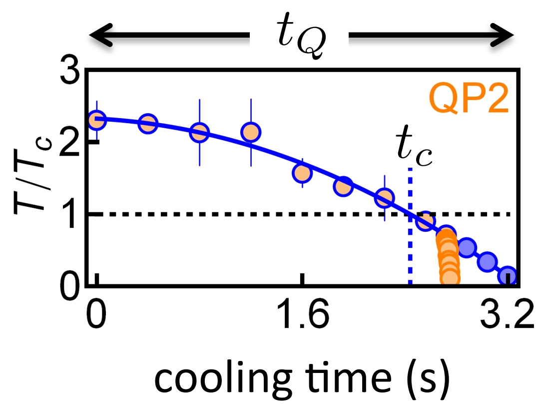
Breakdown of KZ scaling?

KZ freeze-out time: $\hat{t} \propto \sqrt{t_Q}$



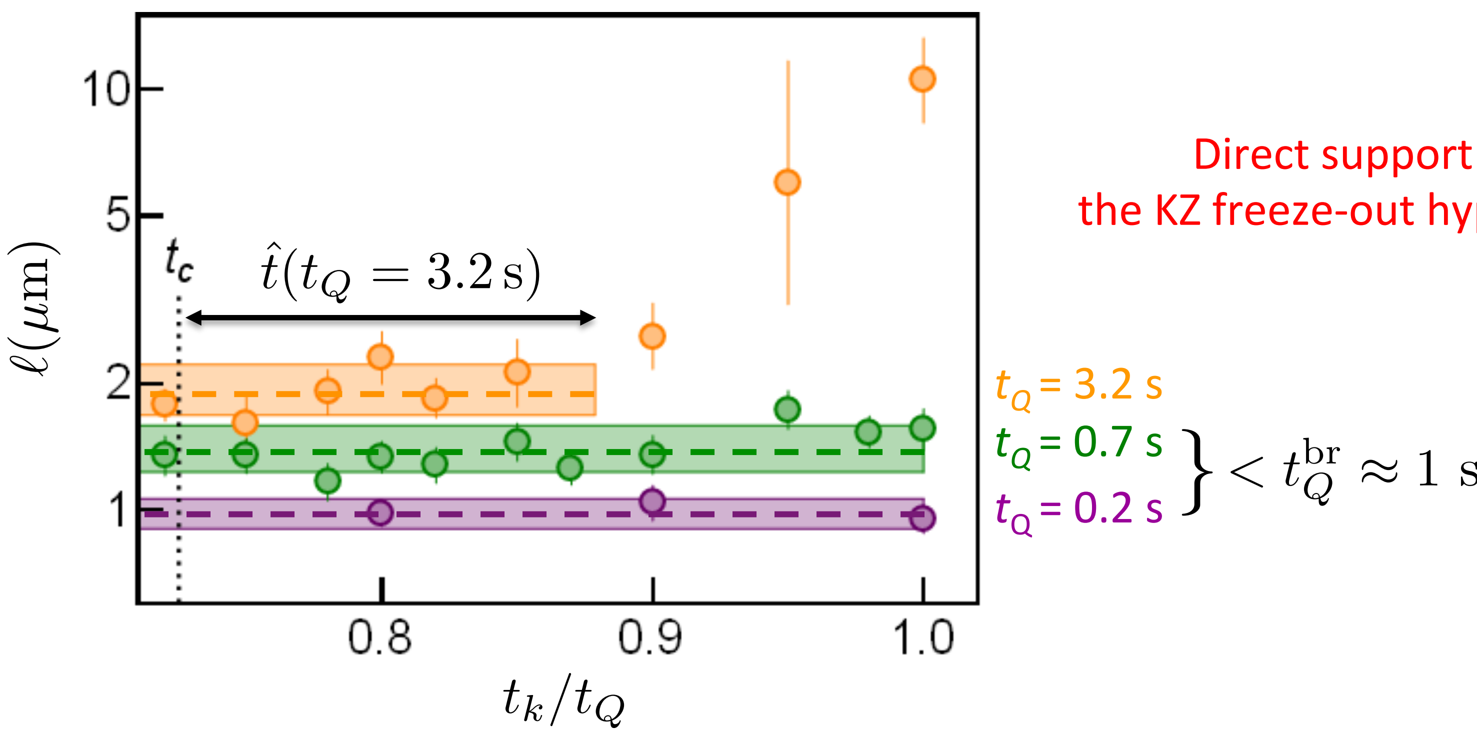
$$t_c \approx 0.72\, t_Q \quad \Rightarrow \quad \hat{t} \approx 0.28 \sqrt{t_Q t_Q^{\rm br}}$$

Quench protocol (2) – testing the freeze-out hypothesis



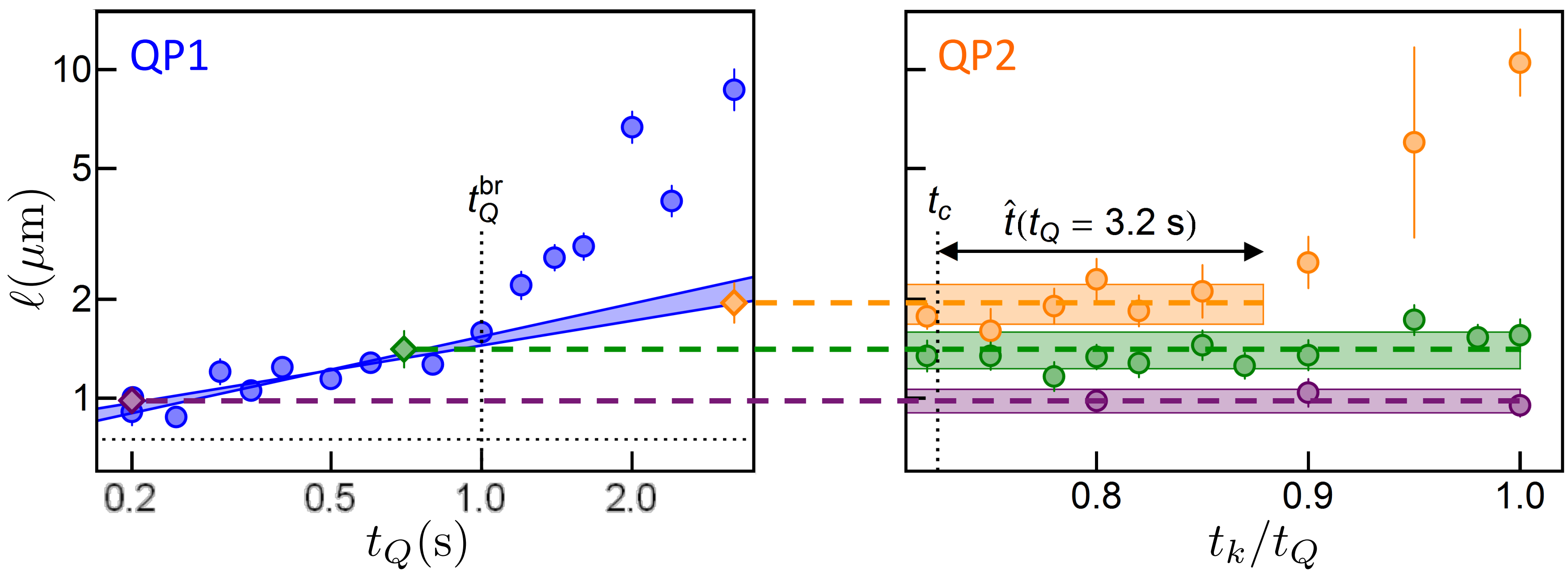
Accelerated quench after T_c

"kink" at $t_c \lesssim t_k \leq t_Q$

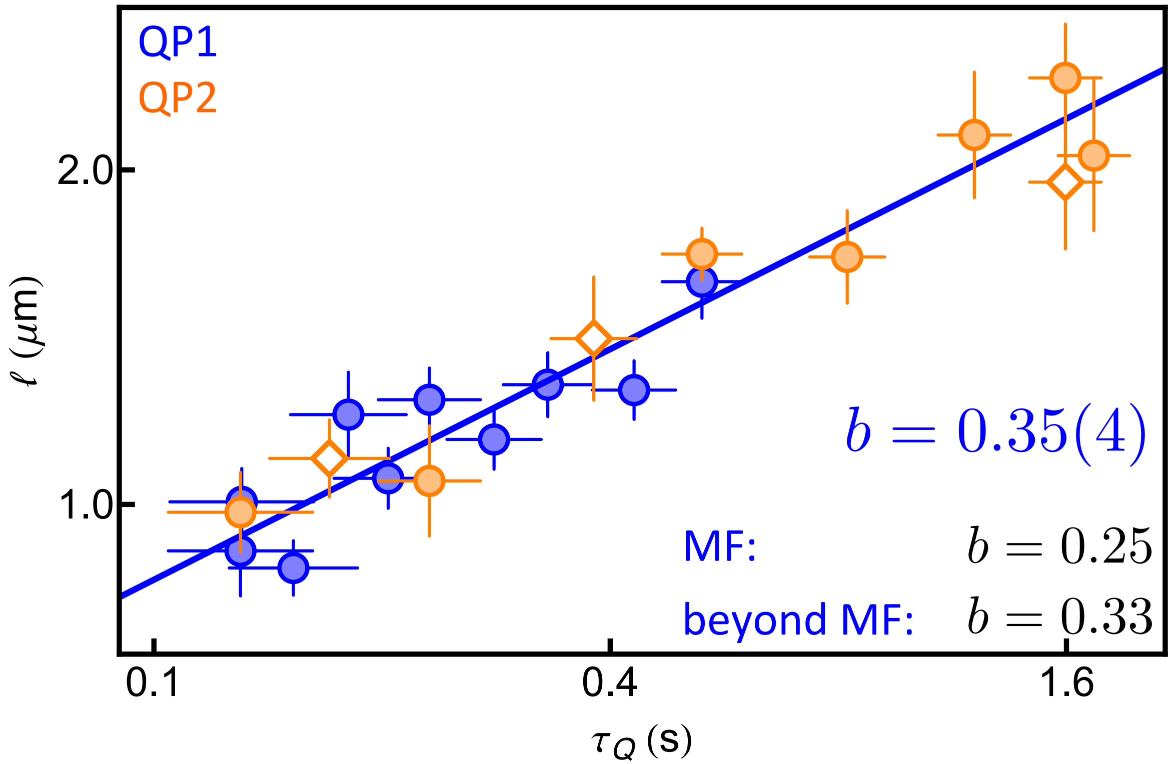


Direct support for
the KZ freeze-out hypothesis!

Extending the KZ range



Homogeneous-system KZ scaling law



Ways to uncover beyond-MF physics:
- crank up interactions (Feshbach, lattices)
- reduce dimensionality
- go close to the critical point
- ...

See also: Corman et al., PRL 2014 (ring), Chomaz et al., Nat. Comm. 2015 (2D)

Dynamical critical exponent?

$$b = \frac{\nu}{1+\nu z}$$

$\nu = 0.67$ (MF: $\nu = 1/2$) known from helium (and atoms)

$z = 3/2$ (MF: $z = 2$) never measured

$\nu = 0.67 \quad \& \quad b = 0.35(4) \quad \Rightarrow \quad z = 1.4(4)$

MF inconsistent: $\nu = 1/2 \quad \& \quad b = 0.35(4) \quad \Rightarrow \quad z = 0.9(4)$

Outlook (on KZ)

Directly measure *z*

$\hat{t}(d) \propto d^z$ does not depend on ν

Effects of interactions on critical dynamics

"Ginzburg vs. Kibble-Zurek" – dynamical emergence of critical correlations?

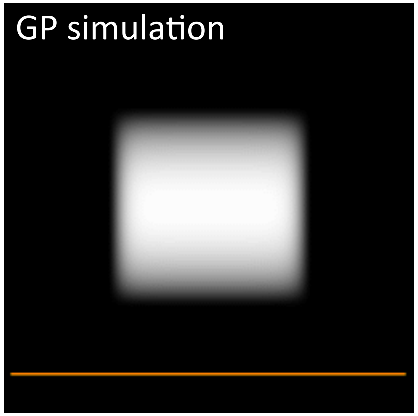
Continuous tuning of the universality class?

Post-quench phase-ordering kinetics

Closed vs. open systems

Shaken, not stirred…

(pre-production trailer…)



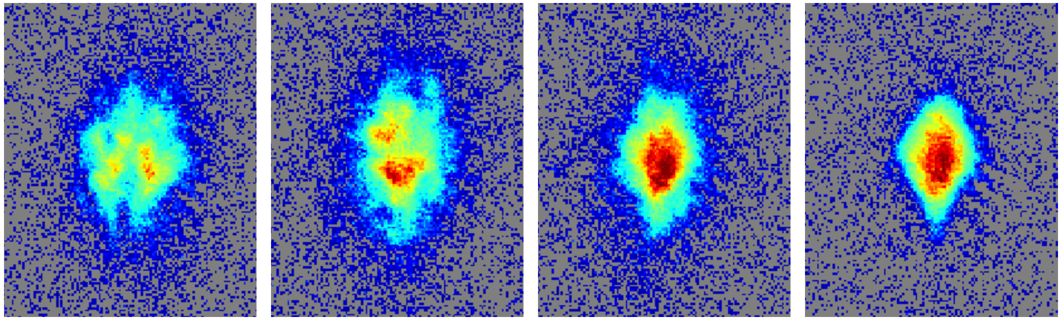
momentum cascade, isotropy

Interesting problems (naïve):

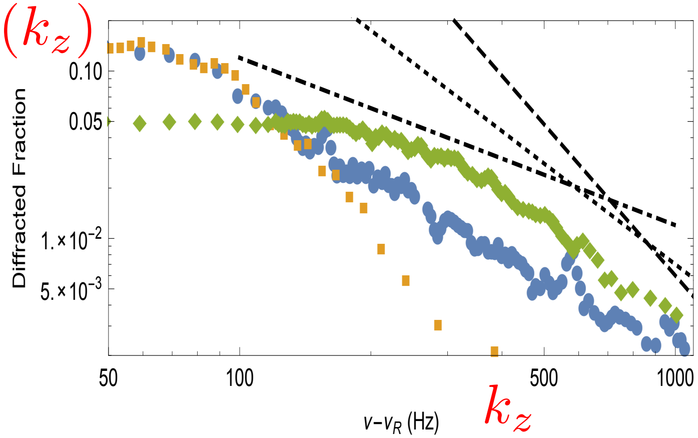
- Basic superfluidity, collective excitations
  (critical velocity, resonances…)

- Driven steady state & Relaxation
  (turbulence, Kolmogorov,
  non-thermal fixed points, AdS/CFT…)

post-shake phase ordering ($\sim$ 1s, $\sim$ no atom loss)

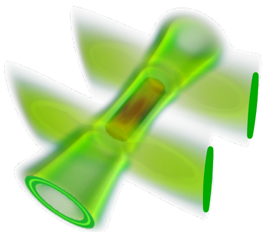


can measure $g_1(r)$ and/or $n(k)$ at any point



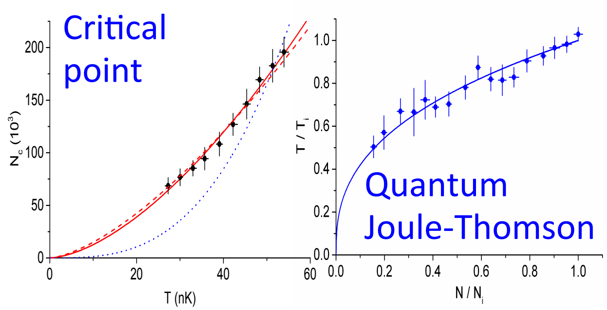
Summary

BEC in a box



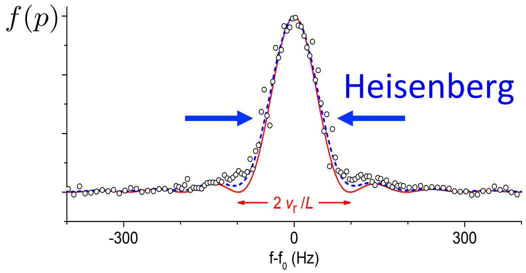
A.L. Gaunt *et al.*,
PRL **110**, 200406 (2013)

Thermodynamics



T.F. Schmidutz *et al.*,
PRL **112**, 040403 (2014)

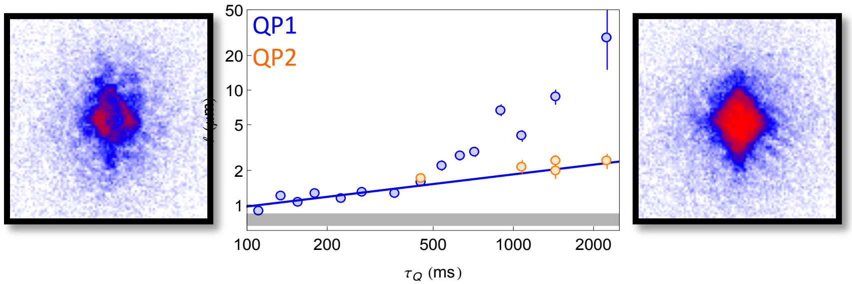
Ground-state properties,
interaction energy, ToF dynamics

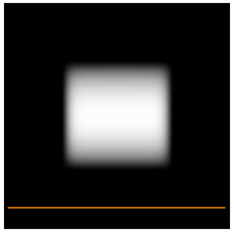


I. Gotlibovych *et al.*,
PRA **89**, 061604(R) (2014)

Non-equilibrium: quenches & critical dynamics, driving & relaxation…

- KZ freeze-out hypothesis
- Beyond-MF KZ scaling law
- Critical exponent(s)
- Phase-ordering kinetics
- Turbulence





N. Navon, A.L. Gaunt, R.P. Smith, ZH, Science **347**, 167 (2015)