Quenches in a uniform Bose gas

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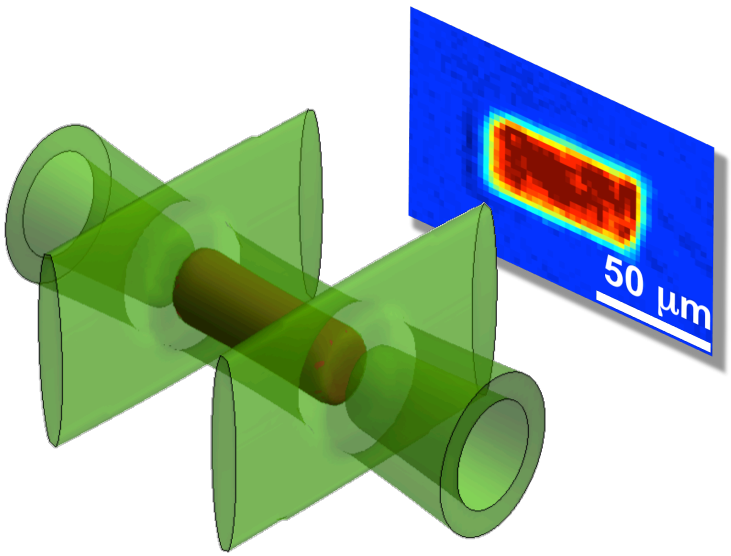
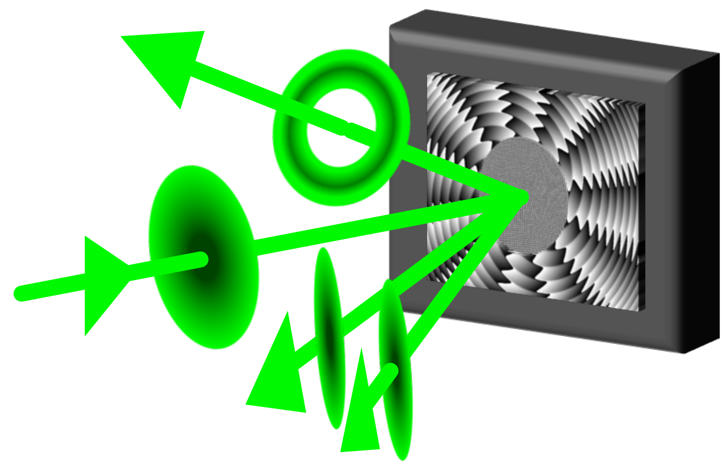
CdF, June 2015

Optical-box trap





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

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

(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)

See also:

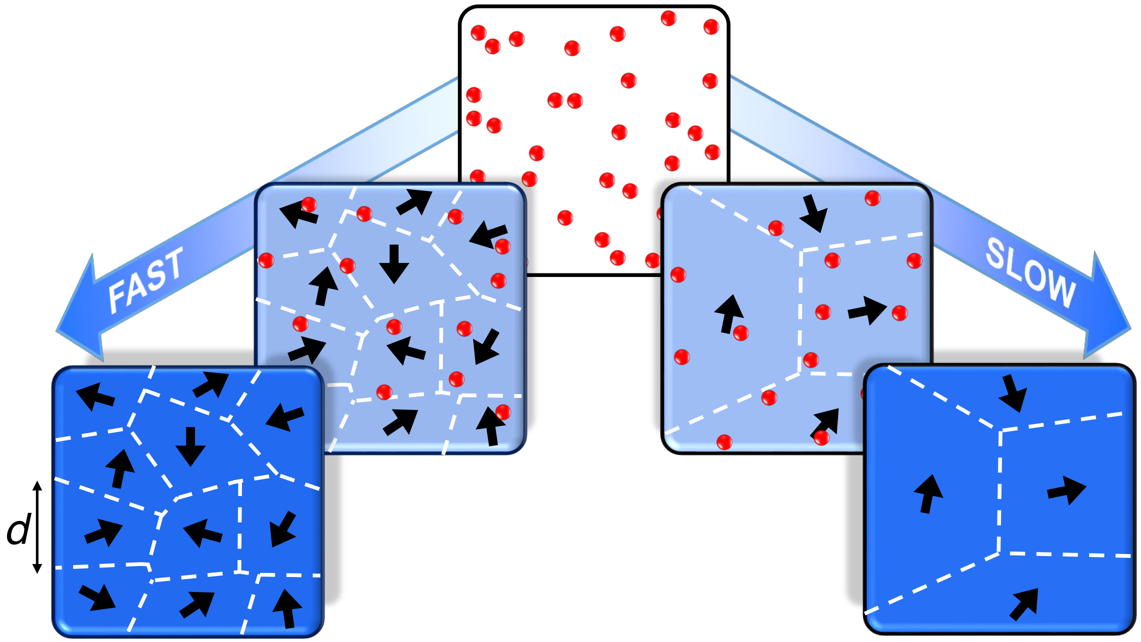
Ring geometry:
L. Corman, L. Chomaz, T. Bienaimé, R. Desbuquois, C. Weitenberg, S. Nascimbène, J. Dalibard, and J. Beugnon, Phys. Rev. Lett. **113**, 135302 (2014)

2D geometry:
L. Chomaz, L. Corman, T. Bienaimé, R. Desbuquois, C. Weitenberg, S. Nascimbène, J. Beugnon, and J. Dalibard, Nature Communications **6**, 6162 (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)

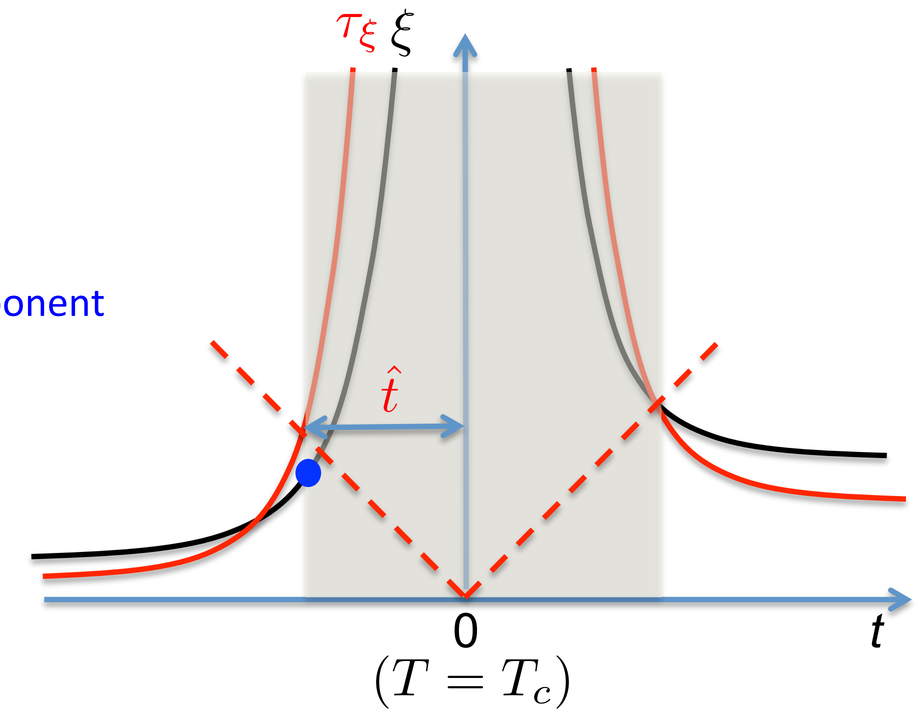
Correlation length at "freeze-out" just above T_C = coherence length at T=0

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:

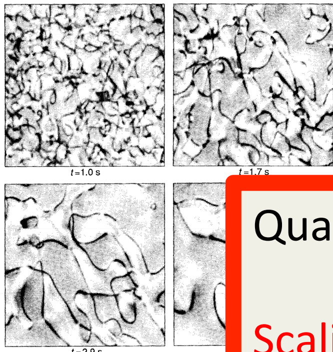
$$d \sim \lambda \left(\frac{\tau_Q}{\tau_0}\right)^b$$

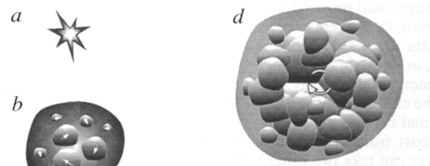
τ_Q - quench time

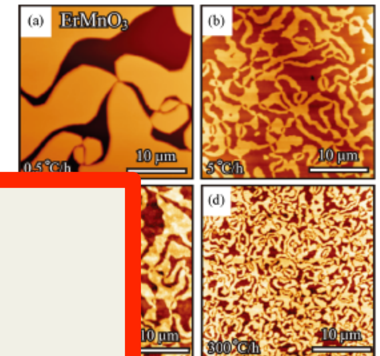
$$b = \frac{\nu}{1 + \nu z}$$

(Some) previous experiments

Condensed matter:







Chuang et al.,

et al., 2012

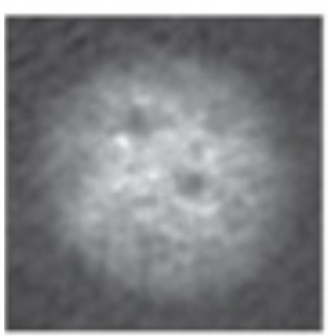
Quantitative issues:

Scaling law

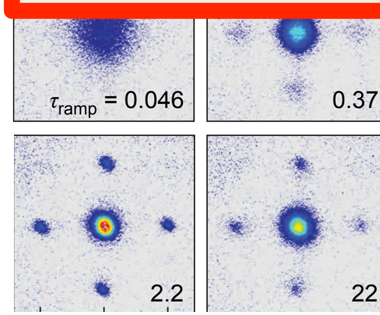
- System inhomogeneity
- Nature of the transition being crossed
- ….

Validity of the freeze-out hypothesis

Atomic:

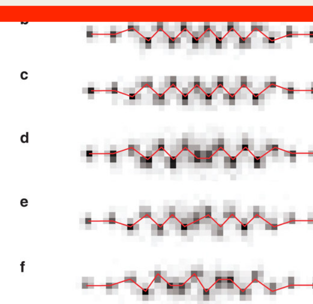


Weiler et al., 2008



Chen et al., 2011

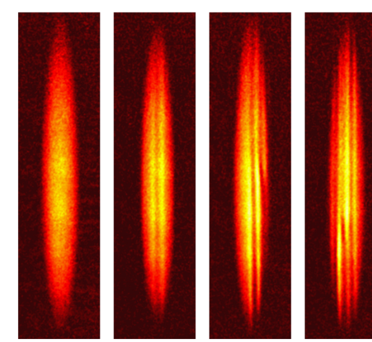
Braun et al., 2014



Ulm et al., 2013

Pyka et al., 2013

Ejtemaee & Haljan, 2013

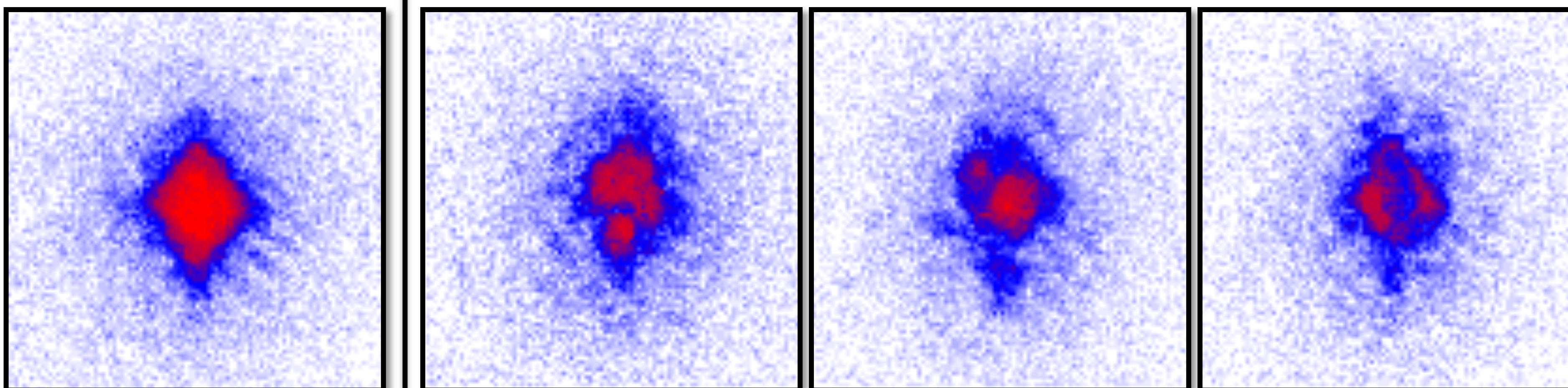


Lamporesi et al., 2013

(Very) qualitative: ToF images

Cooling through T_C at different rates

very slow | not so slow



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

Quantitative: two-point correlation functions

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

One approach:

Momentum distribution (Bragg spectroscopy) + Fourier transform

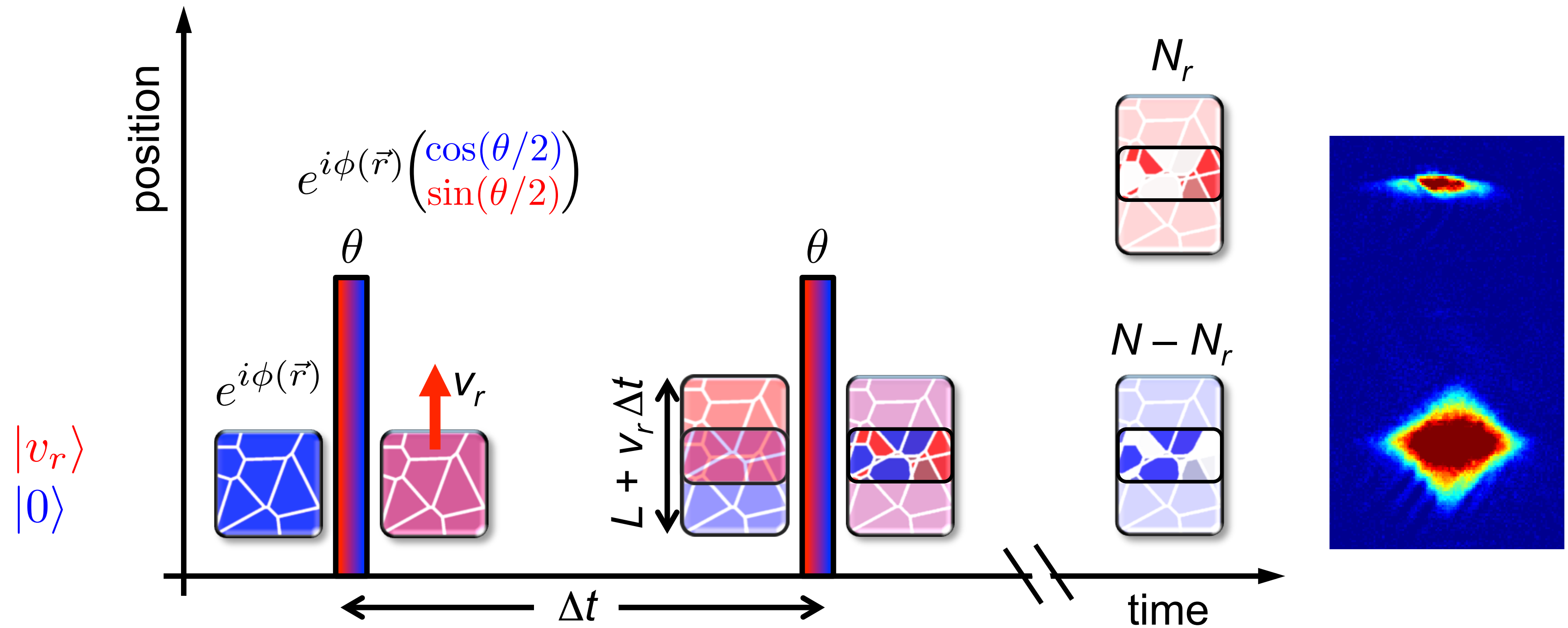
Better approach:

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

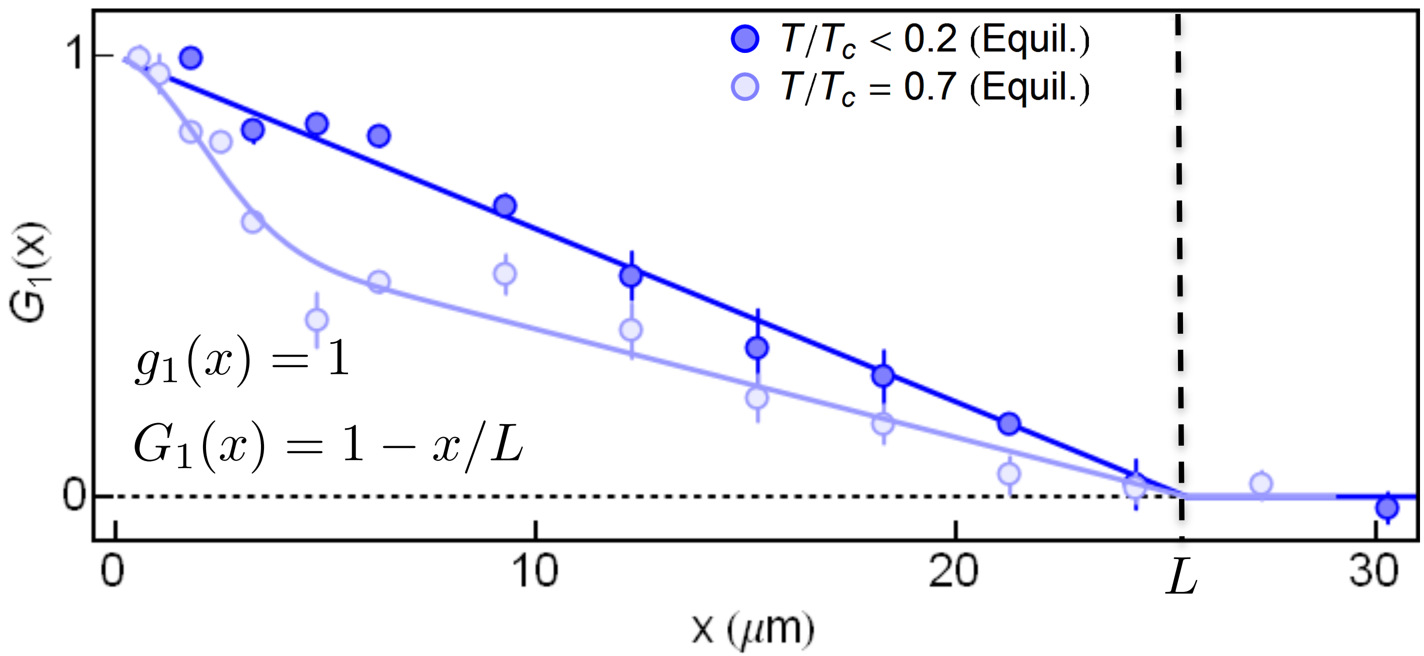


$$\frac{N_r}{N} = \frac{1}{2}\left[1 + \underbrace{\left(1 - \frac{x}{L}\right) g_1(x)}_{G_1(x)}\right]\sin^2(\theta)$$

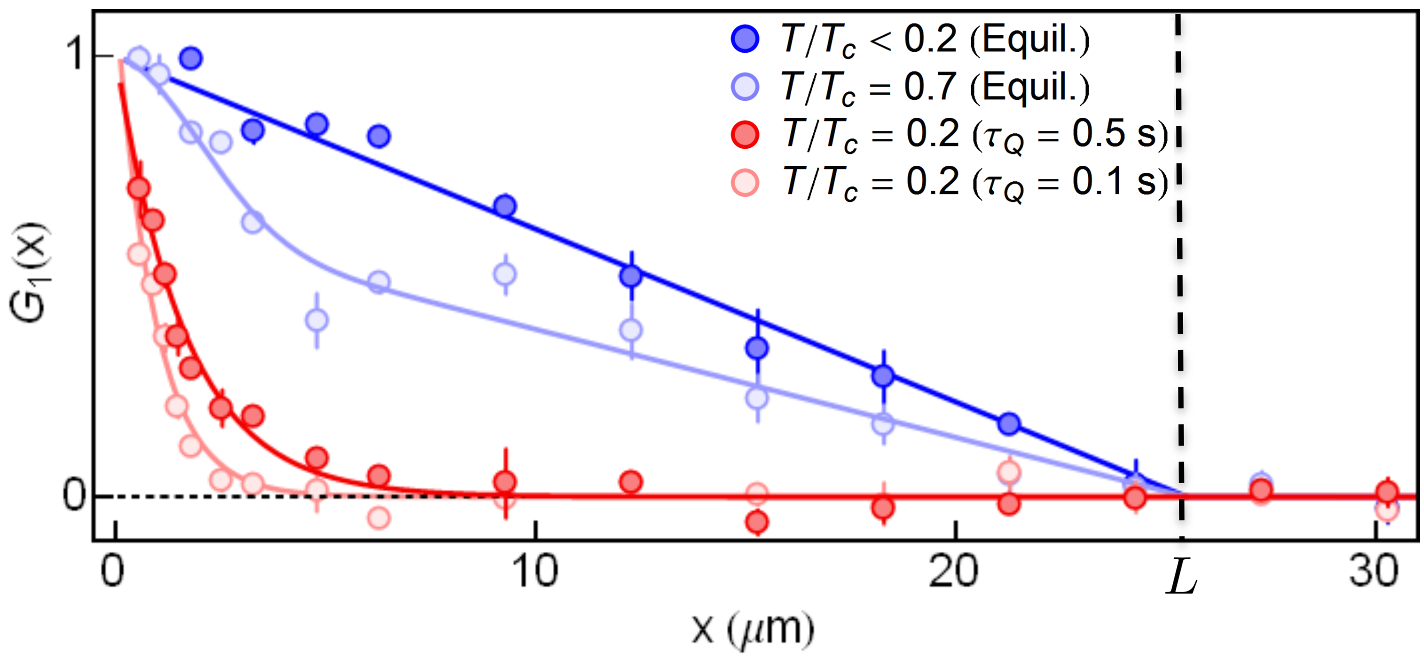
L – box length

G_1 in equilibrium

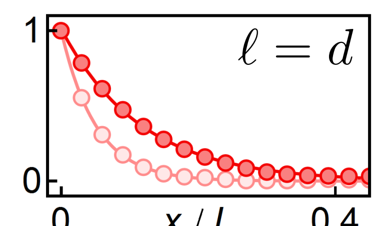
cool (very) slowly and wait for a (very) long time



G_1 in equilibrium and after a quench



supported by simulations:



No equilibrium interpretation

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

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:

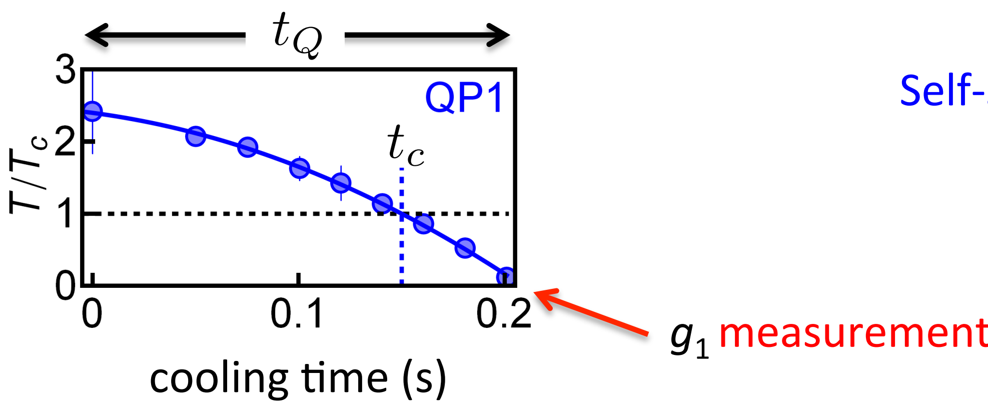
$$\left.\begin{array}{rcl} \nu & = & 2/3 \\ z & = & 3/2 \end{array}\right\} b = 1/3$$

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…

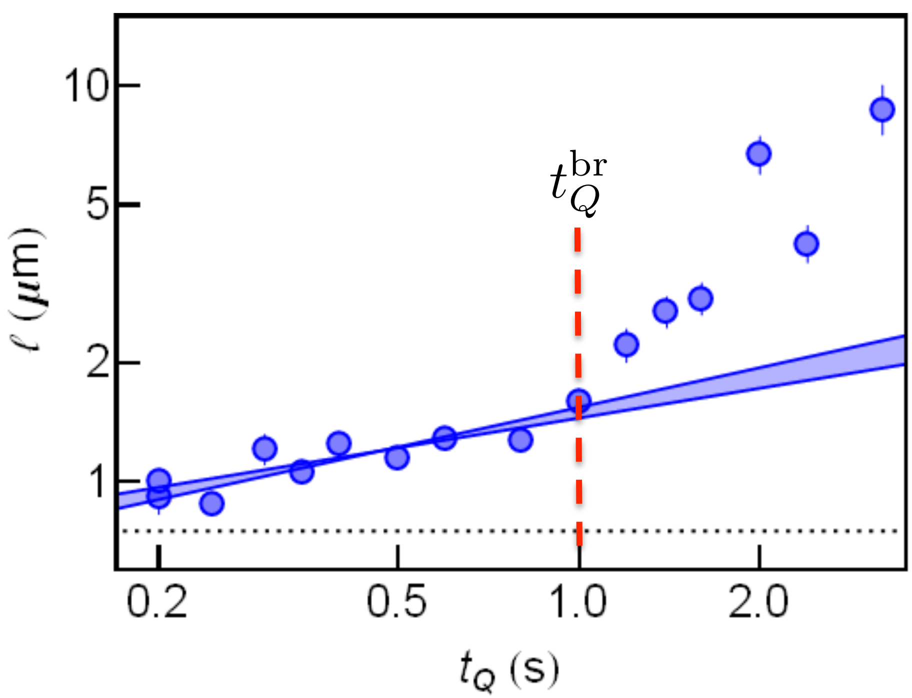
Quench protocol (1) – KZ scaling and its breakdown



Self-similar cooling curves with

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

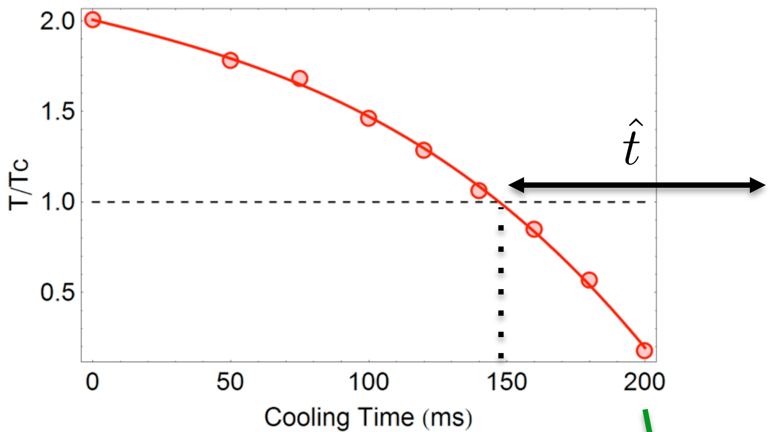
$$t_c \approx 0.72\, t_Q$$

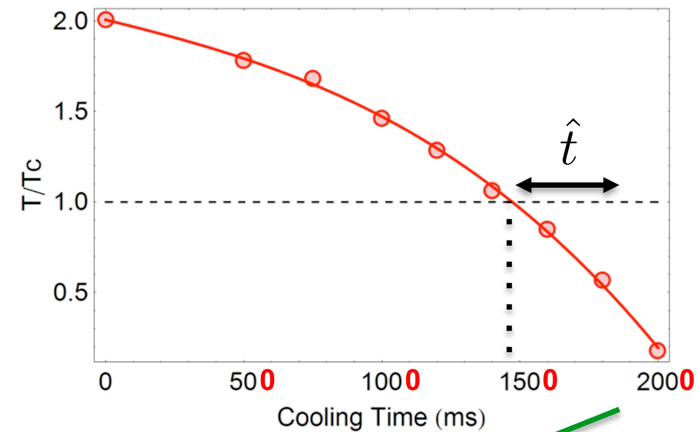


$b = 1/4 - 1/3$

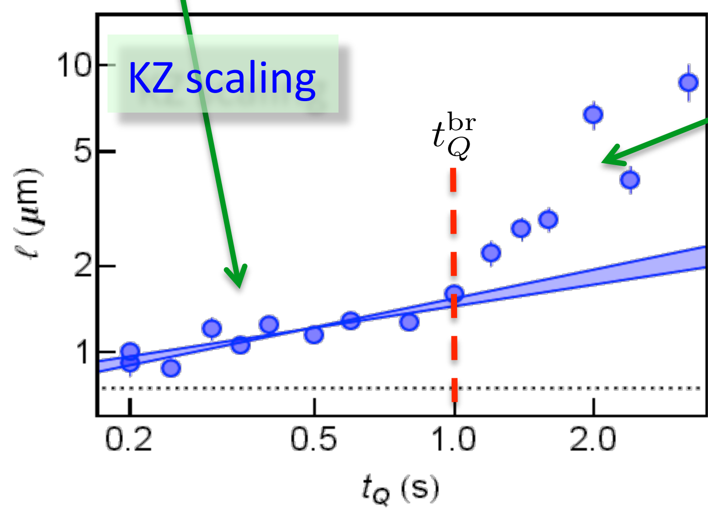
Breakdown of KZ scaling?

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





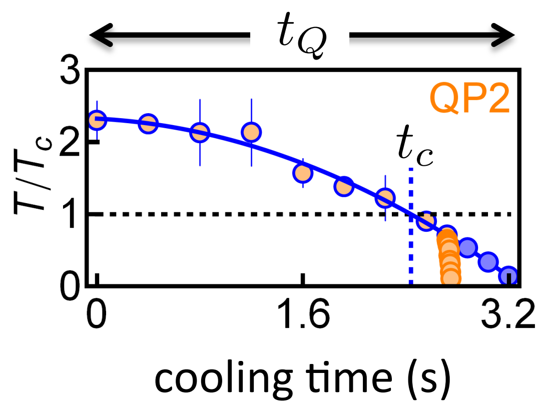
KZ scaling



De-freezing and domain-coarsening during the last cooling stage!

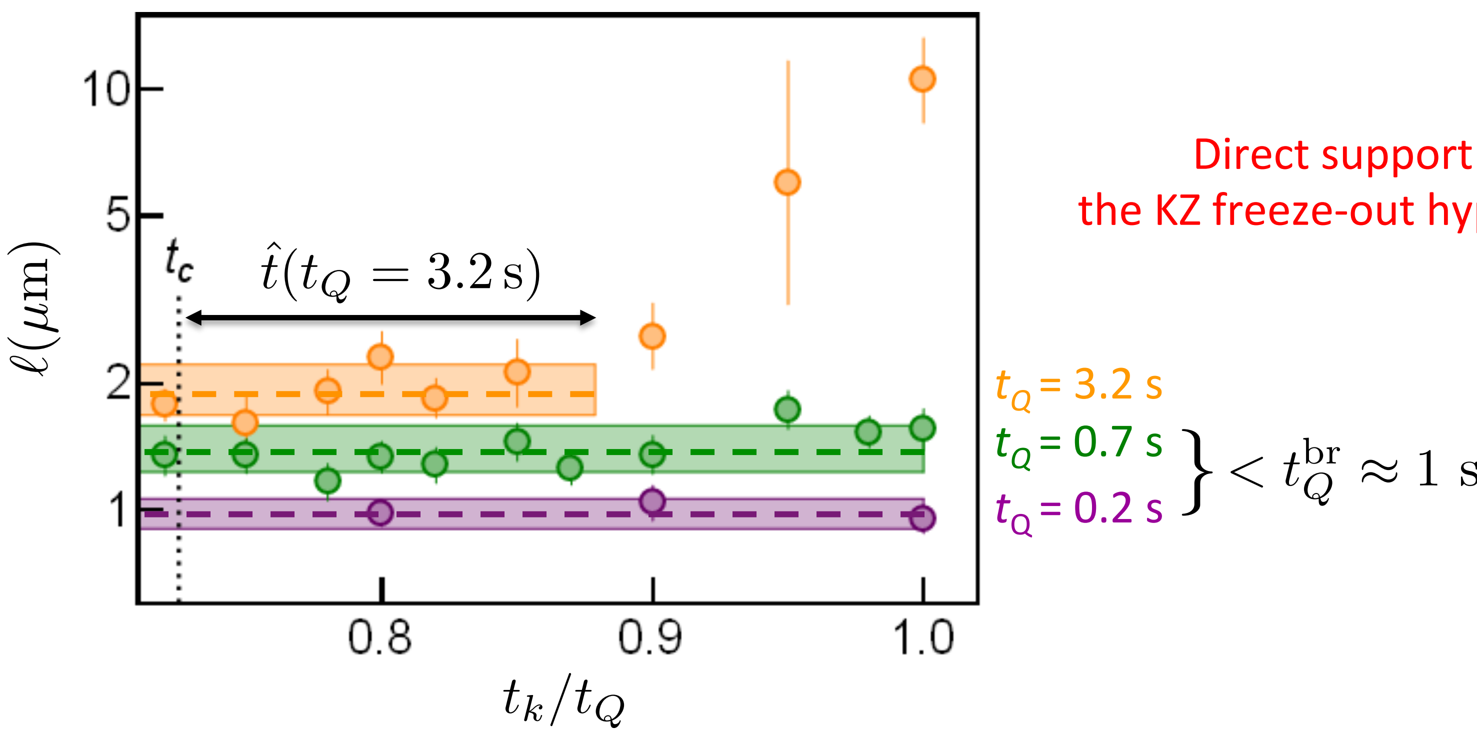
$$t_c \approx 0.72\, t_Q \quad \Rightarrow \quad \hat{t} \approx 0.28 \sqrt{t_Q t_Q^{\rm br}}$$

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



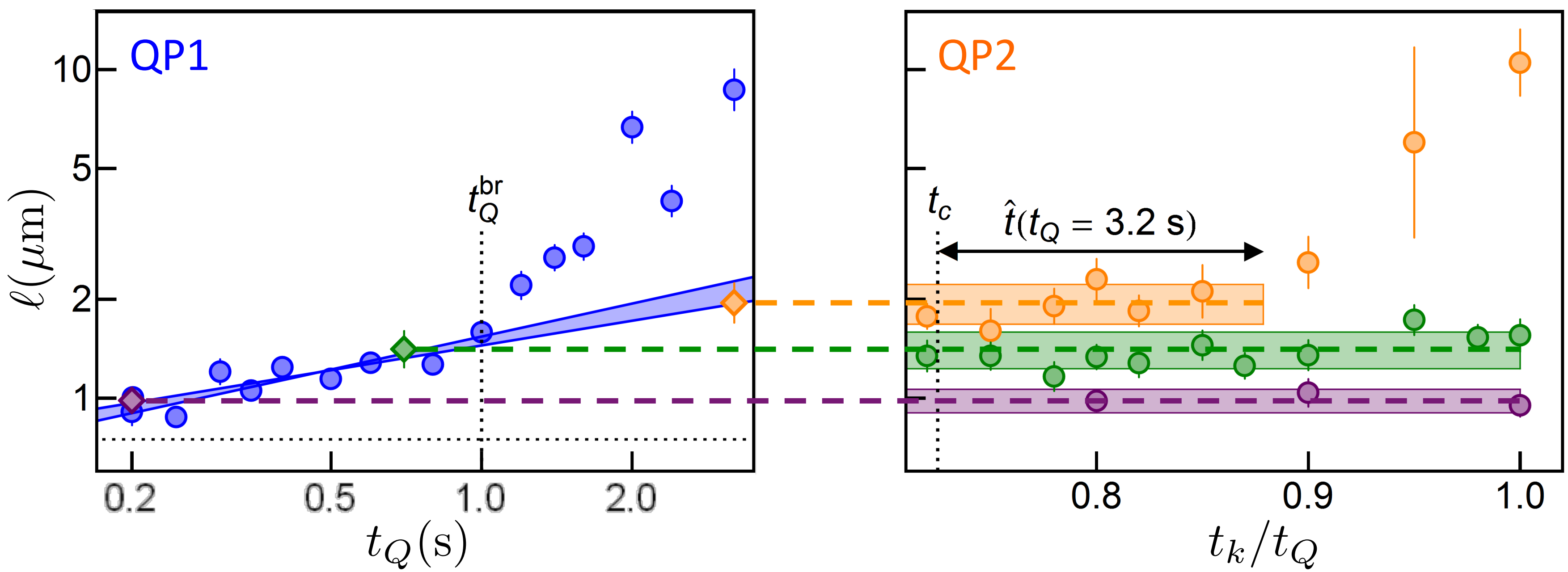
Accelerated quench after T_c

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

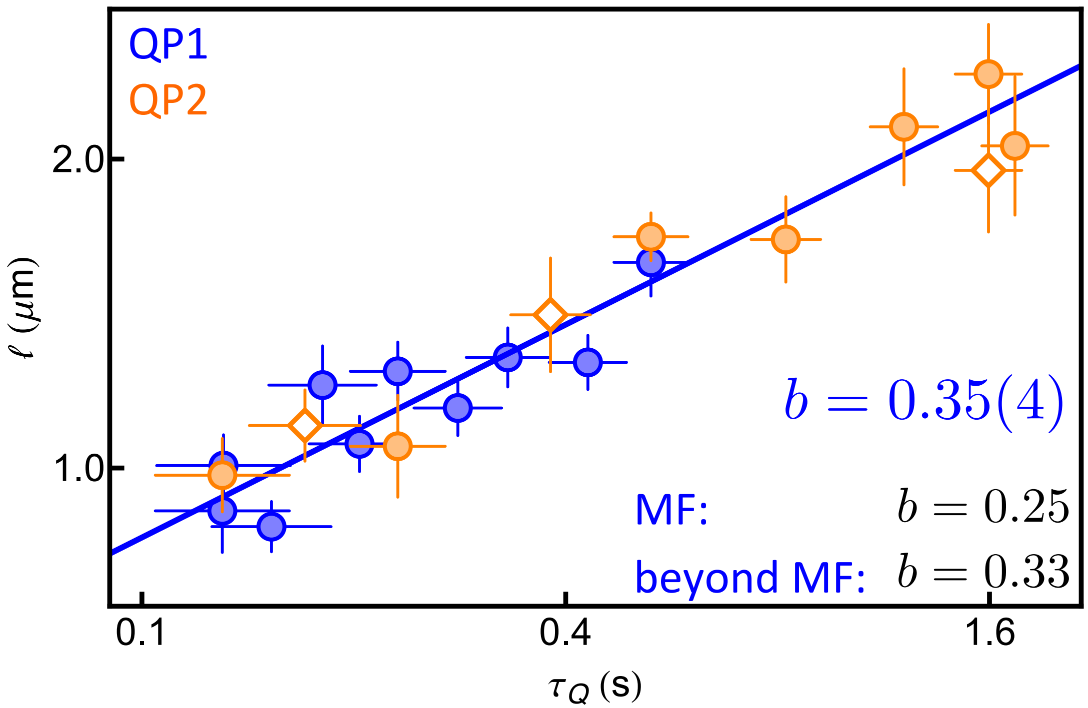


Direct support for
the KZ freeze-out hypothesis!

Extending the KZ range



Homogeneous-system KZ scaling law



N. Navon, et al., Science **347**, 167 (2015)

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?

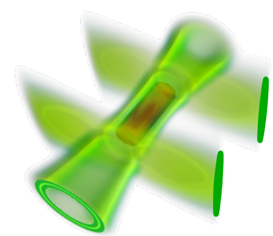
Continuous tuning of the universality class?

Post-quench phase-ordering kinetics

Closed vs. open systems

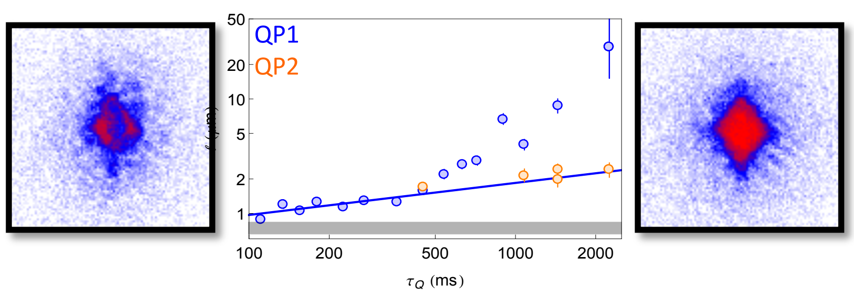
Summary

BEC in a box



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

Quenches & critical dynamics



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

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

THE END