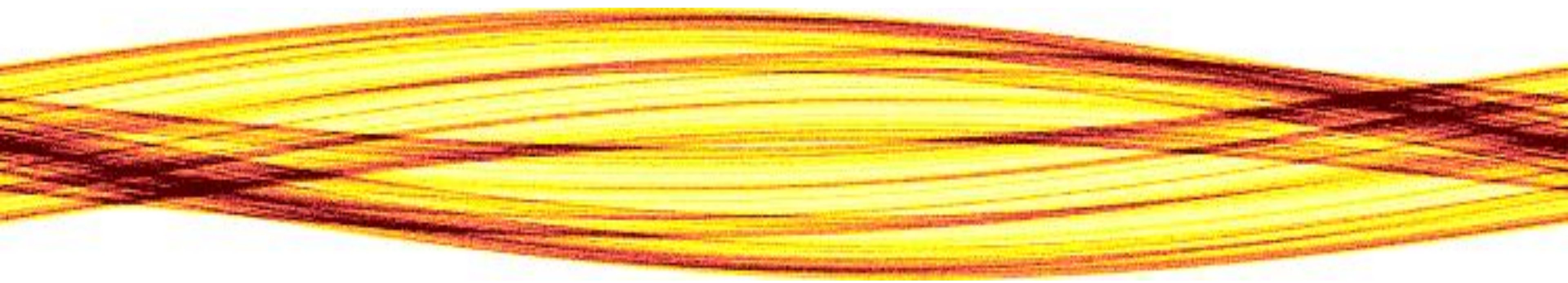
Testing universality of topological defect formation: an update

Adolfo del Campo

Theoretical Division
Los Alamos National Laboratory



Cosmic Strings 2014, Phoenix, AZ
Feb 5th 2014

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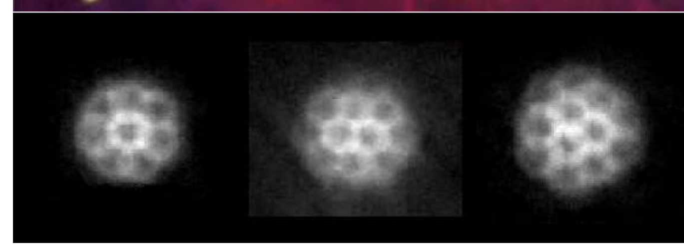
Cosmology in the lab



• Cosmology : symmetry breaking during expansion and cooling of the early universe

• Condensed matter:

  • Vortices in Helium
  • Liquid crystals
  • Superconductors
  • Superfluids

Landau theory: Similar free-energy landscape near a critical point

Kible Zurek mechanism: formation of defects

T. W. B. Kibble, JPA 9, 1387 (1976); Phys. Rep. 67, 183 (1980)
W. H. Zurek, Nature (London) 317, 505 (1985); Acta Phys. Pol. B. 1301 (1993)

References

Tom Kibble and Ajit Srivastava 2013 *J. Phys.: Condens. Matter* **25** 400301
Special section on condensed matter analogues of cosmology

A. del Campo, T. W. B. Kibble. W. H. Zurek, *J. Phys.: Condens. Matter* **25**, 404210 (2013)

References

Tom Kibble and Ajit Srivastava 2013 *J. Phys.: Condens. Matter* **25** 400301
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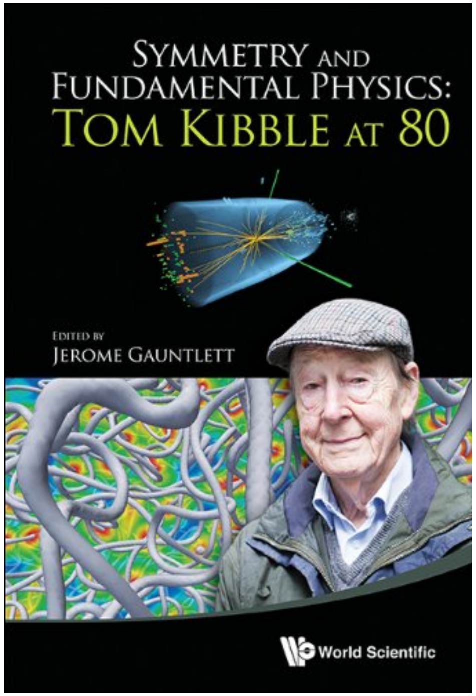

A. del Campo, W. H. Zurek, arXiv:1310.1600 (2013)

Contents

- The Kibble-Zurek mechanism
- Recent Experiments:
  Inhomogeneous phase transitions

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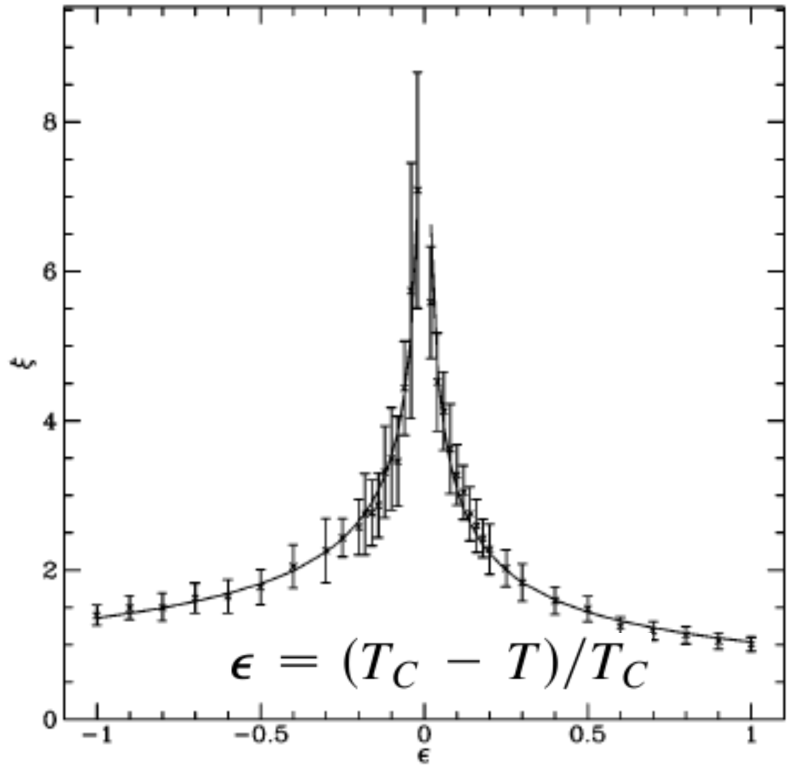
Second order phase transitions

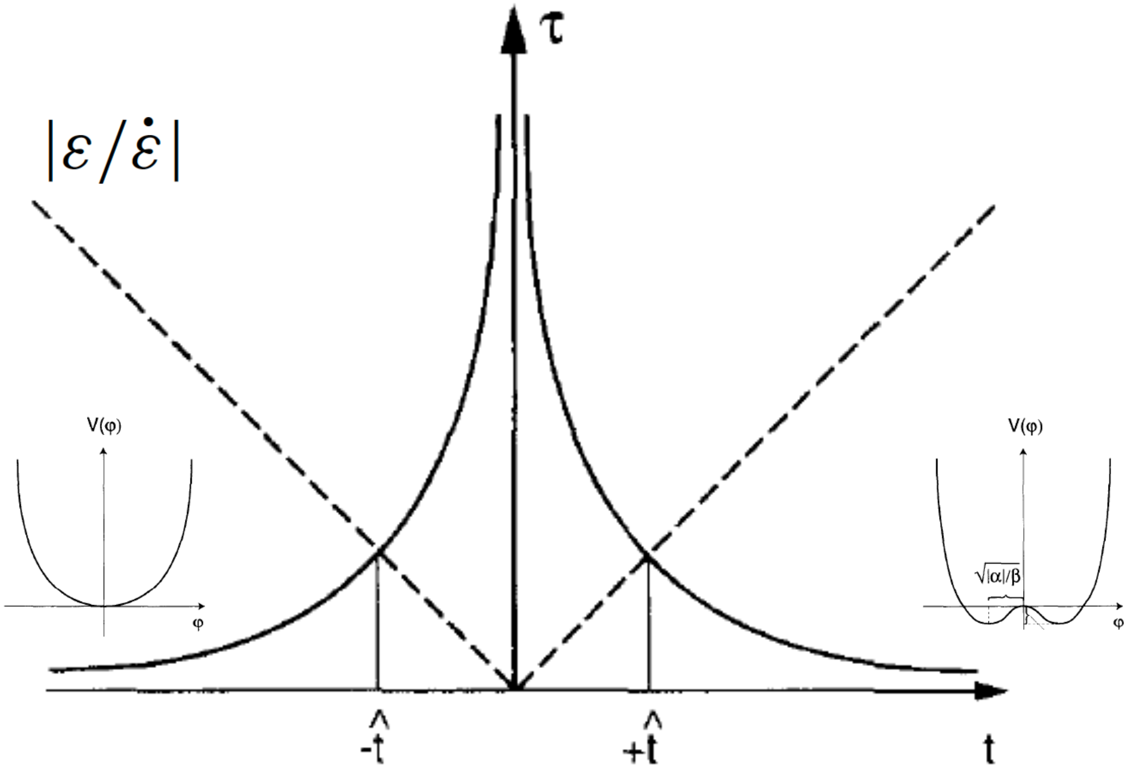
Universal behaviour of the order parameter: divergence of

Correlation/healing length $$\xi(t) = \frac{\xi_0}{|\varepsilon(t)|^{\nu}}$$

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



The Kibble-Zurek mechanism

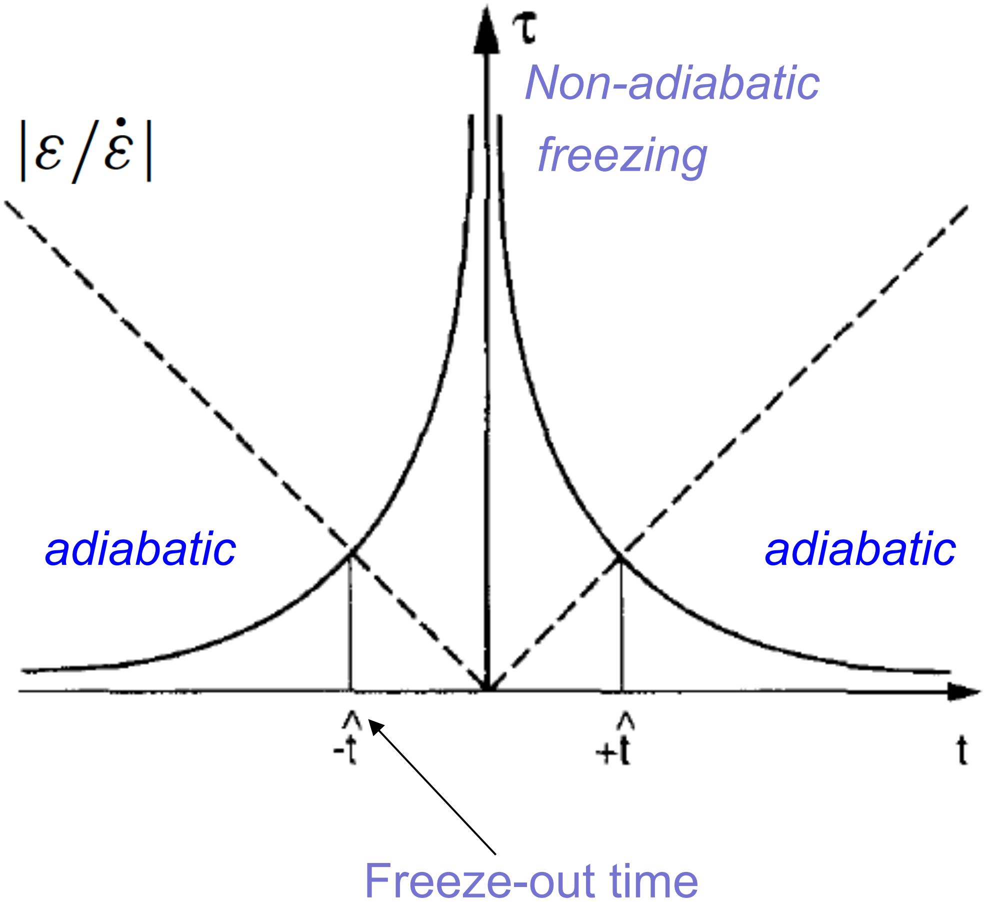


Linear quench

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

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

The Kibble-Zurek mechanism



Linear quench

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

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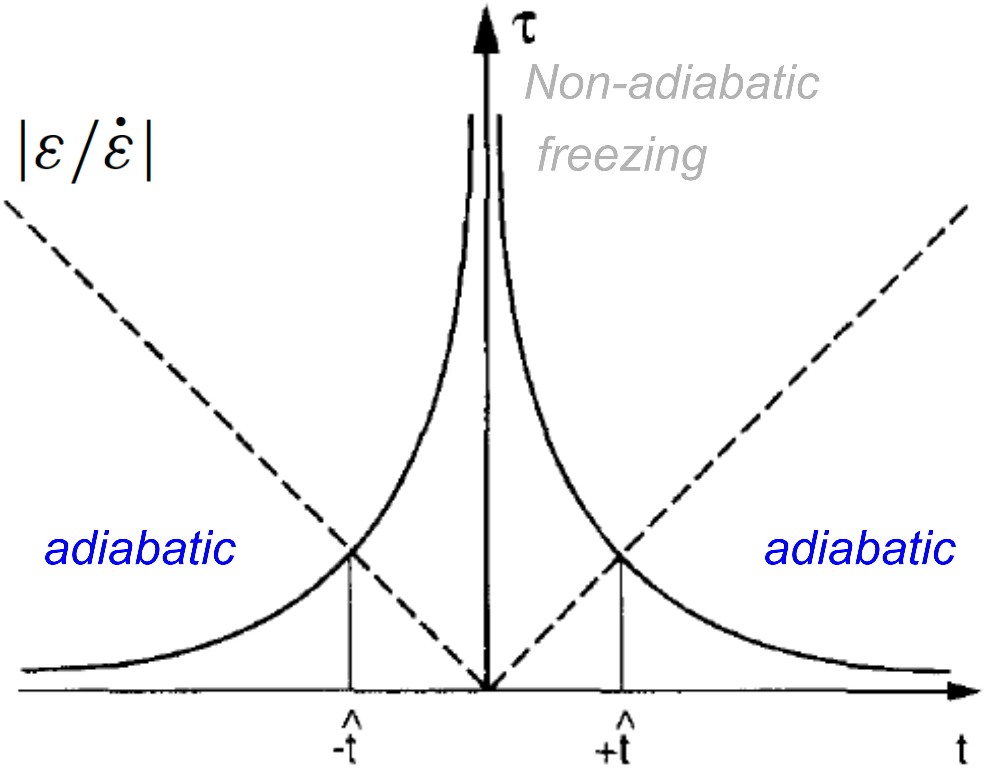
The Kibble-Zurek mechanism



Linear quench

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

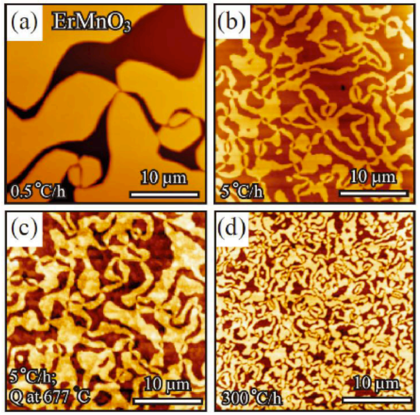
$$\tau(t) = \frac{\tau_0}{|\varepsilon(t)|^{z\nu}}$$

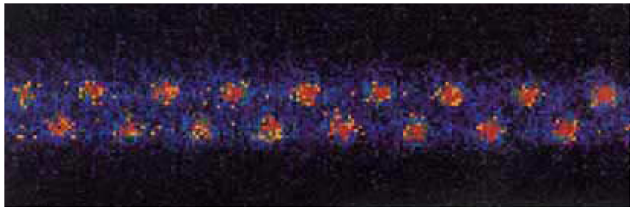
The average domain size is given by the equilibrium correlation length at the freeze-out time

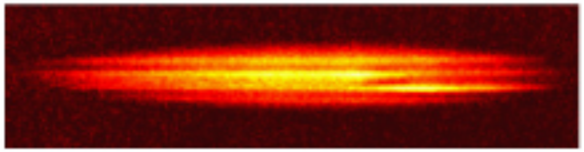
$$\xi(t) = \frac{\xi_0}{|\varepsilon(t)|^{\nu}}$$

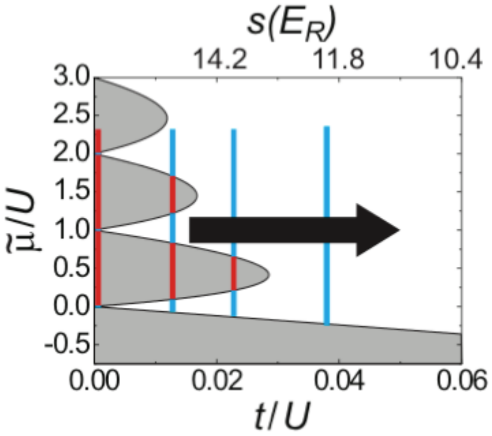
$$\hat{\xi} = \xi(\hat{t}) = \xi_0 \left(\frac{\tau_Q}{\tau_0}\right)^{\frac{\nu}{1+z\nu}}$$

Part 2 Recent experiments









Kink formation in trapped Ion chains

Classical inhomogeneous phase transitions:
T. W. B. Kibble, G.E. Volovik, JETP Lett. 65, 102 (1997).
W. H. Zurek, Phys. Rev. Lett.102,105702 (2009)
A. del Campo et al. Phys. Rev. Lett.105, 075701 (2010)
A. del Campo et al. New J. Phys. 13, 083022 (2011)
A. del Campo, T. W. B. Kibble. W. H. Zurek, *J. Phys.: Condens. Matter* **25**, 404210 (2013)

Structural phases in trapped ions

N ions on a ring trap with harmonic transverse confinement

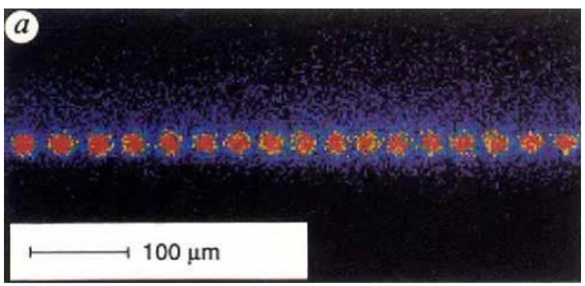
$$H = \frac{1}{2}m\sum_n \dot{\boldsymbol{r}}_n^2 + \frac{1}{2}m\sum_n (\nu_t^2 z_n^2) + \frac{Q^2}{2}\sum_{n\neq n'} \frac{1}{|\boldsymbol{r}_n - \boldsymbol{r}'_n|}$$

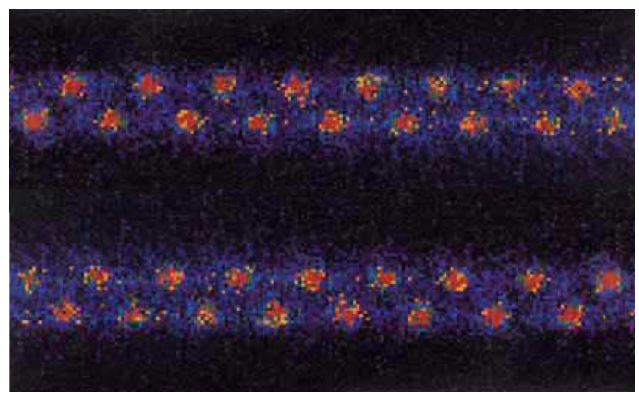
Critical transverse frequency

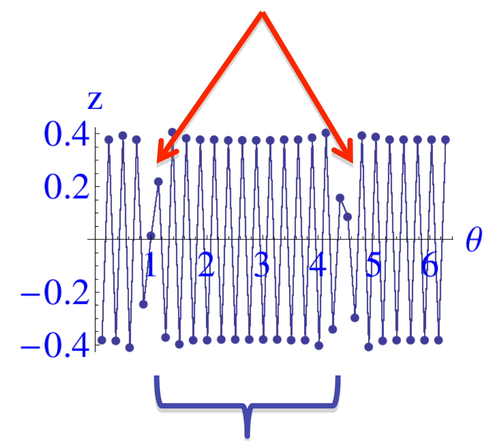
Linear chain

Degenerated zig-zag chains

Excitations (kinks)







Domain of size

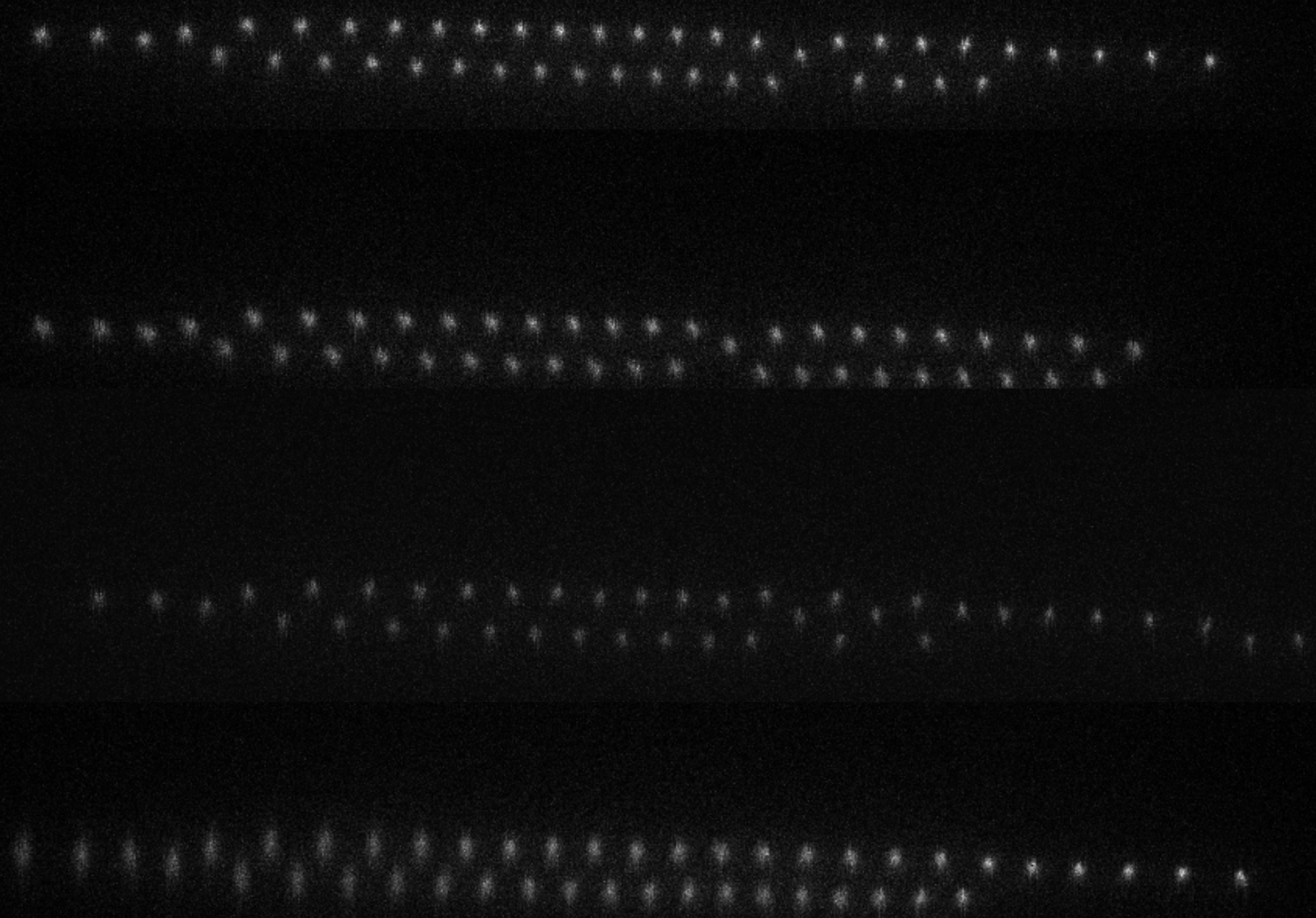
$$\nu_t^{(c)2} = 4\frac{Q^2}{ma(0)^3}$$

Fishman PRB ‘08

$$\hat{\xi}_x = a\omega_0(\tau_Q/\delta_0)^{1/3}$$

Kinks Zoo

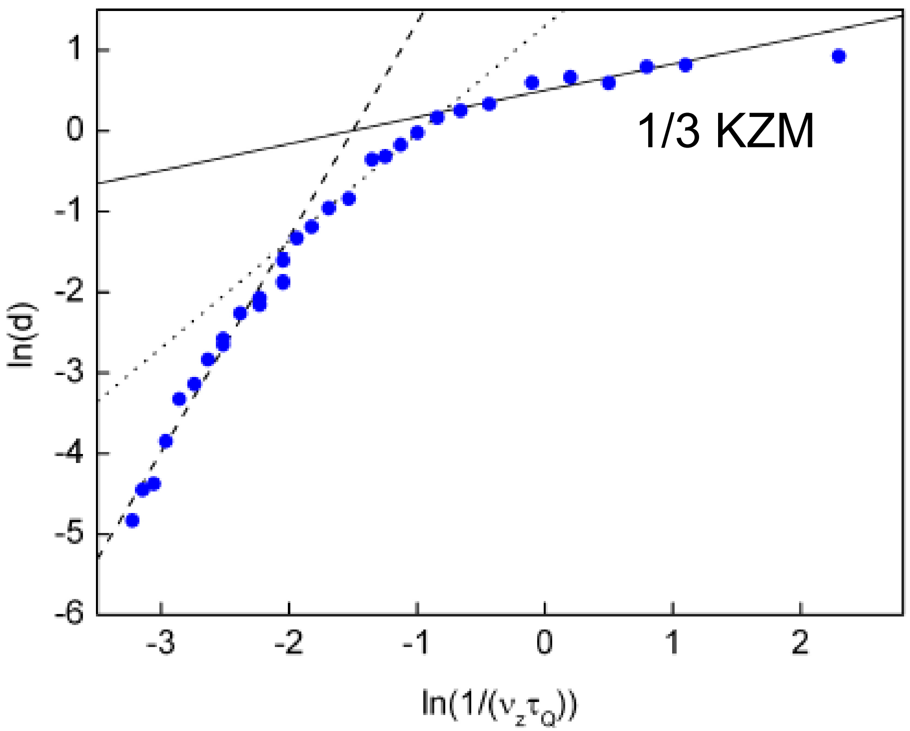
courtesy of Tobias Schaetz (MPQ)



Testing KZM in the lab

Axial and transverse harmonic potential (instead of a ring trap)

$$H = \frac{1}{2} m \sum_n \dot{\boldsymbol{r}}_n^2 + \frac{1}{2} m \sum_n (\nu_t^2 z_n^2 + \nu^2 x_n^2) + \frac{Q^2}{2} \sum_{n \neq n'} \frac{1}{|\boldsymbol{r}_n - \boldsymbol{r}'_n|}$$



MD numerics: Langevin dynamics including laser cooling (damping)
N=50, 2000 realizations, quench of the transverse trapping frequency

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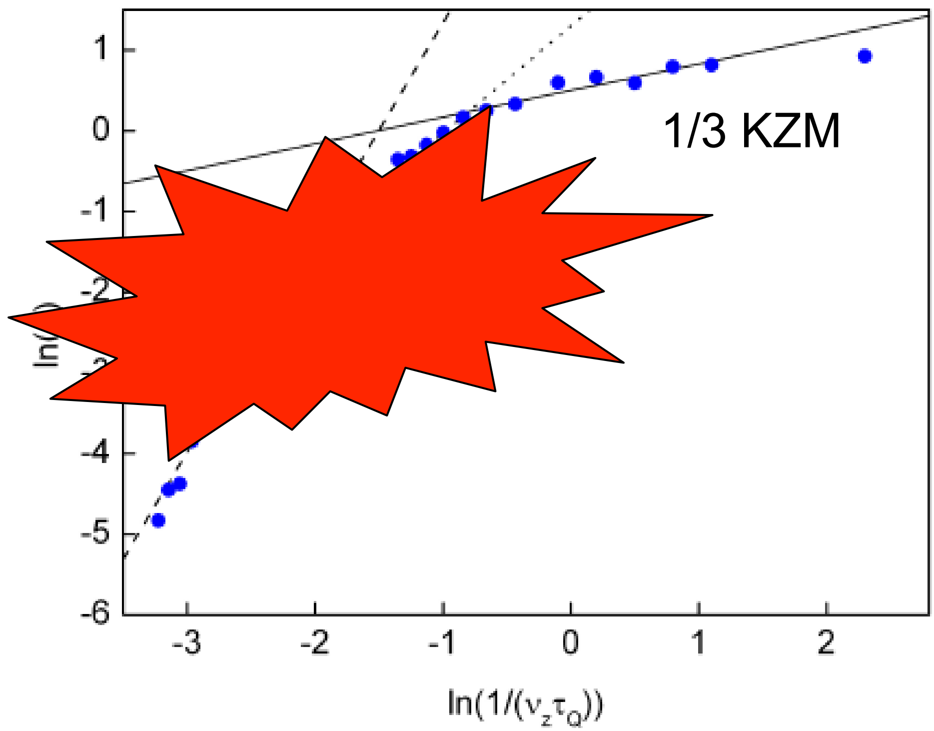

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Inhomogeneous KZM

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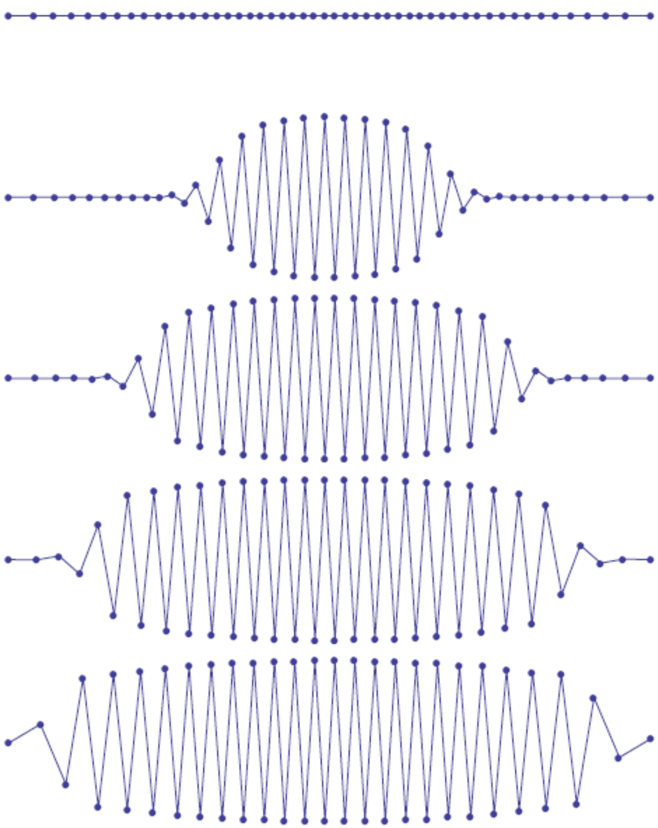


$$\nu_t^{(c)2} = 4\frac{Q^2}{ma(0)^3}$$

$$\nu_t^{(c)}(x)^2 = 4\frac{Q^2}{ma(x)^3}$$

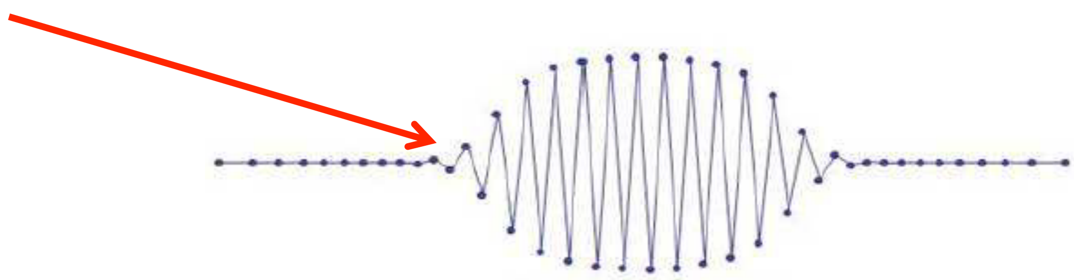
Spatially dependent critical frequency (within LDA)

Inhomogeneous KZM

Causality restricts the effective size of the chain

Front velocity v_F

Sound velocity $\hat{v}_x$



Adiabatic dynamics $v_F < \hat{v}_x$

Kink formation $v_F > \hat{v}_x$ Chain effective system fraction $2|\hat{X}_*|$

New power law

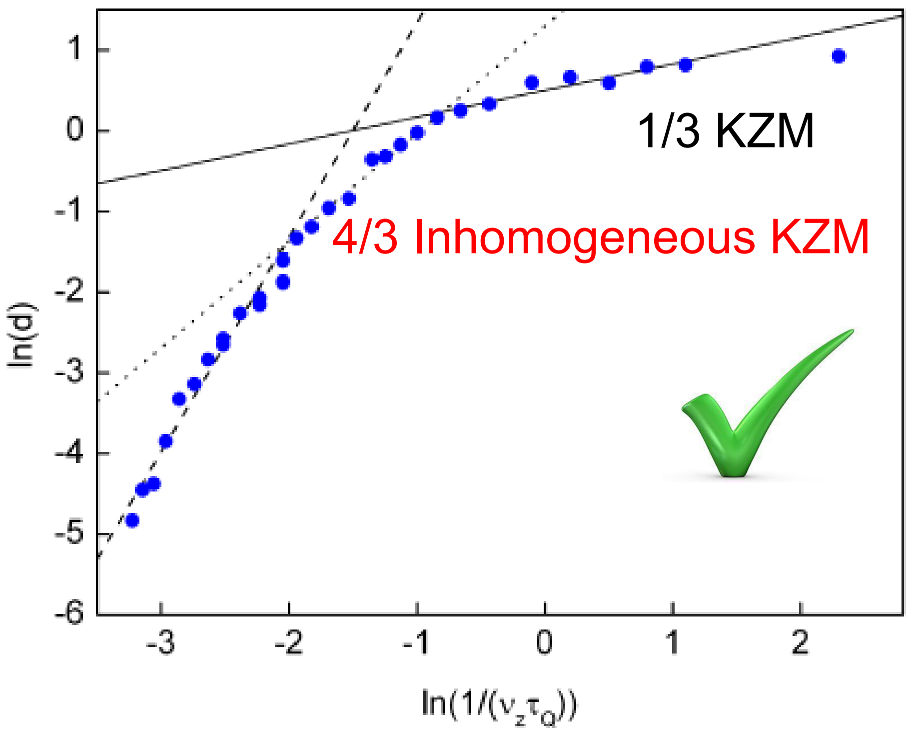
$$d_{\rm u} \sim \frac{2|\hat{X}_*|}{\hat{\xi}} = \frac{L}{3\nu_t^{(c)}(0)^2 a^2 \omega_0^2} \left(\frac{\delta_0}{\tau_Q}\right)^{4/3}$$

AdC et al. *PRL*105, 075701 (2010)

Testing KZM in the lab

Axial and transverse harmonic potential (instead of a ring trap)

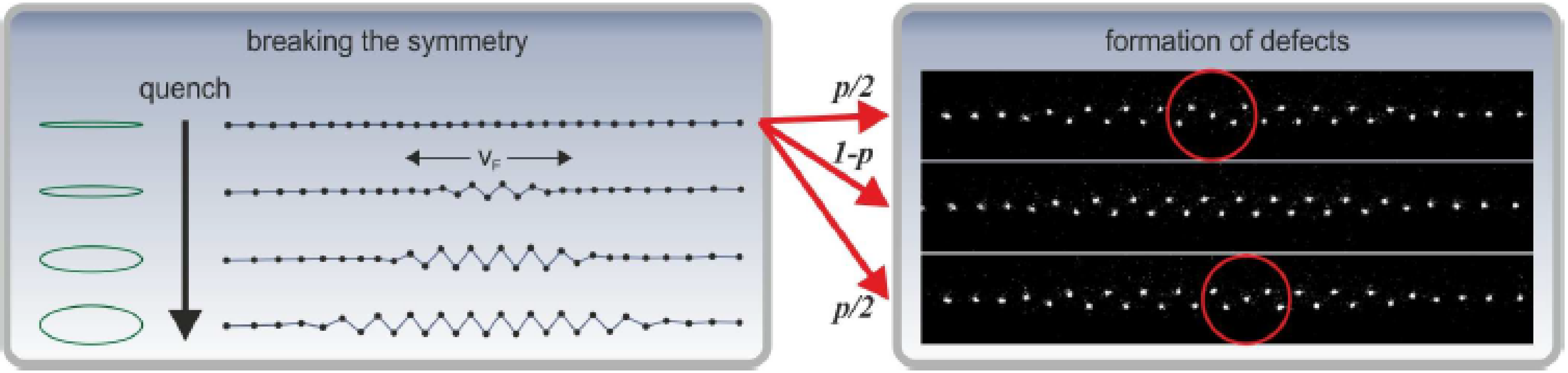
$$H = \frac{1}{2}m\sum_n \dot{\boldsymbol{r}}_n^2 + \frac{1}{2}m\sum_n(\nu_t^2 z_n^2 + \nu^2 x_n^2) + \frac{Q^2}{2}\sum_{n\neq n'}\frac{1}{|\boldsymbol{r}_n - \boldsymbol{r}'_n|}$$

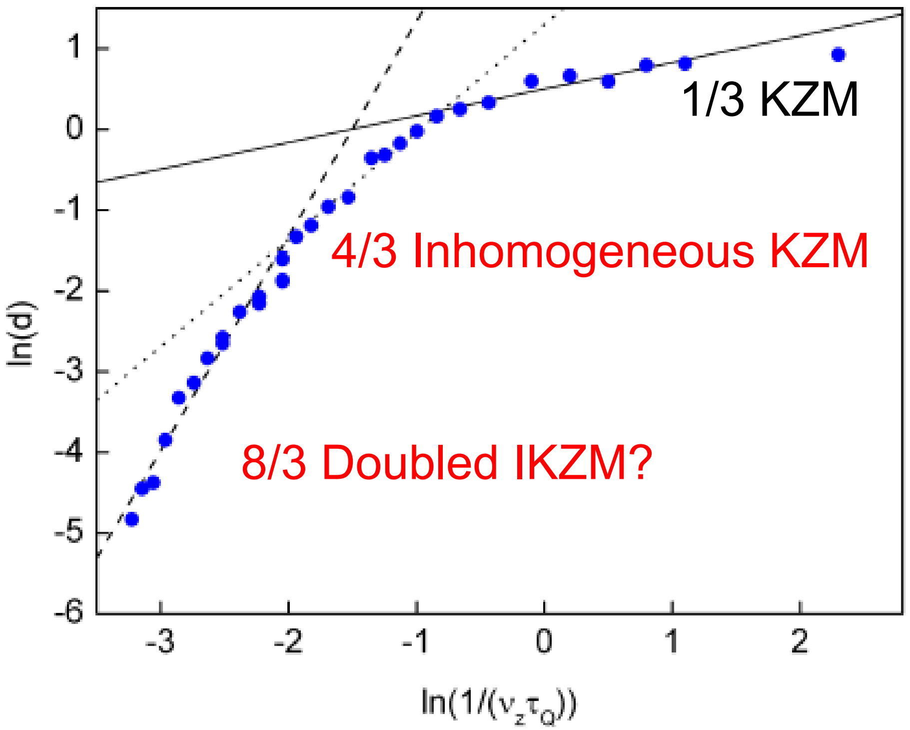


MD numerics: Langevin dynamics including laser cooling (damping)
N=50, 2000 realizations, quench of the transverse trapping frequency

First Experiment -

Collaboration with T. E. Mehlstaubler's group at PTB





With only {0,1} defects
third scaling:
Rivers et al. Doubling of IKZM?

$$p_1 \simeq \left[\frac{2\hat{x}}{\hat{\xi}(0)}\right]^2 \propto \left(\frac{\tau_0}{\tau_Q}\right)^{\frac{2(1+2\nu)}{1+\nu z}} = \left(\frac{\tau_0}{\tau_Q}\right)^{\frac{8}{3}}$$

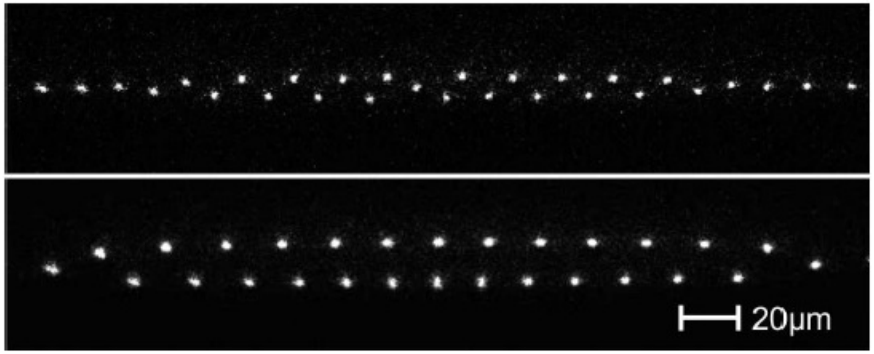
First Experiment -

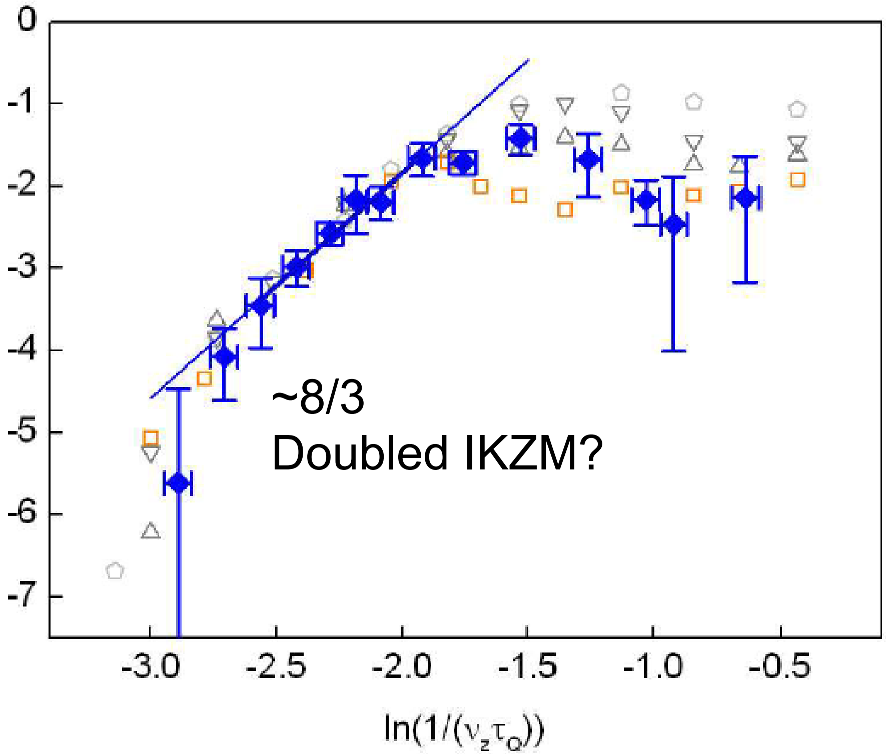
Collaboration with T. E. Mehlstaubler's group at PTB

32 ions, only {0,1} defects per realization

Stabilization: mapping to extended kinks

Counting where losses are minimized



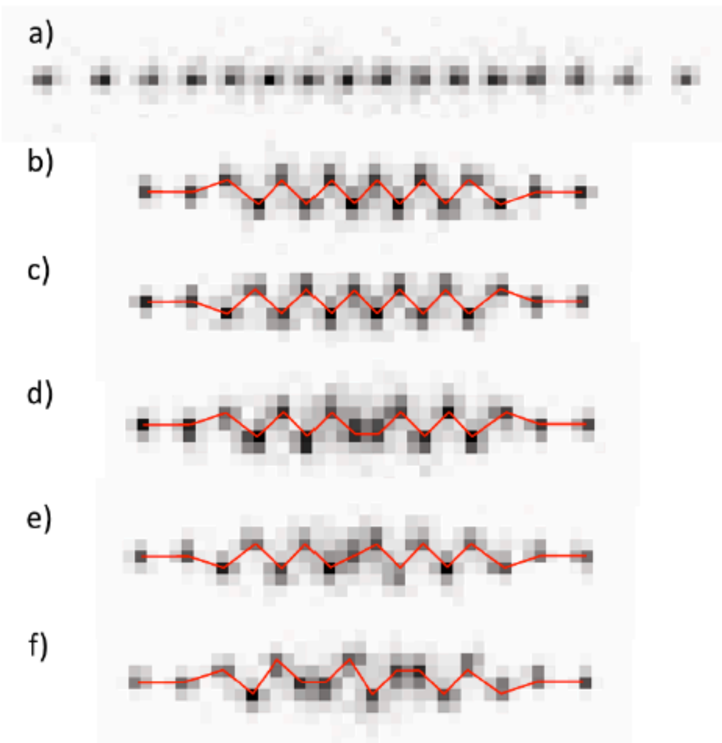


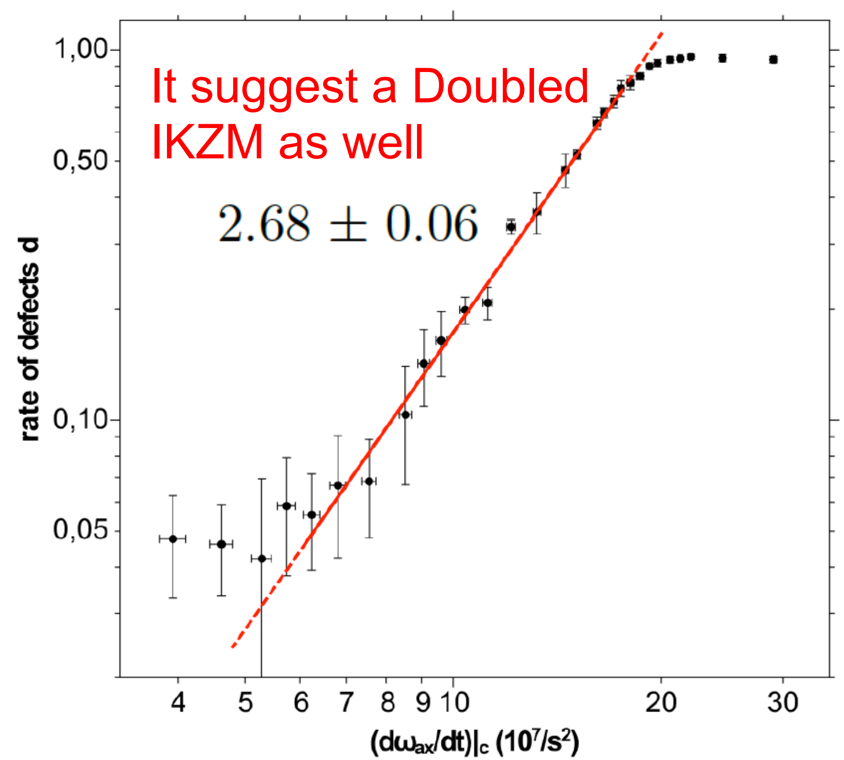
Nature Communications 4, 2291 (2013)

Second Experiment

Schmidt-Kahler's group at Mainz
Nature Communications 4, 2290 (2013)

16 ions, only {0,1} defects per realization

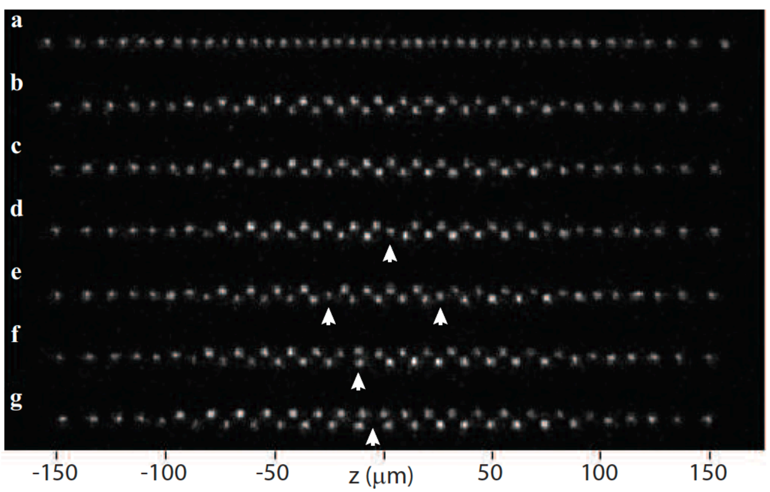


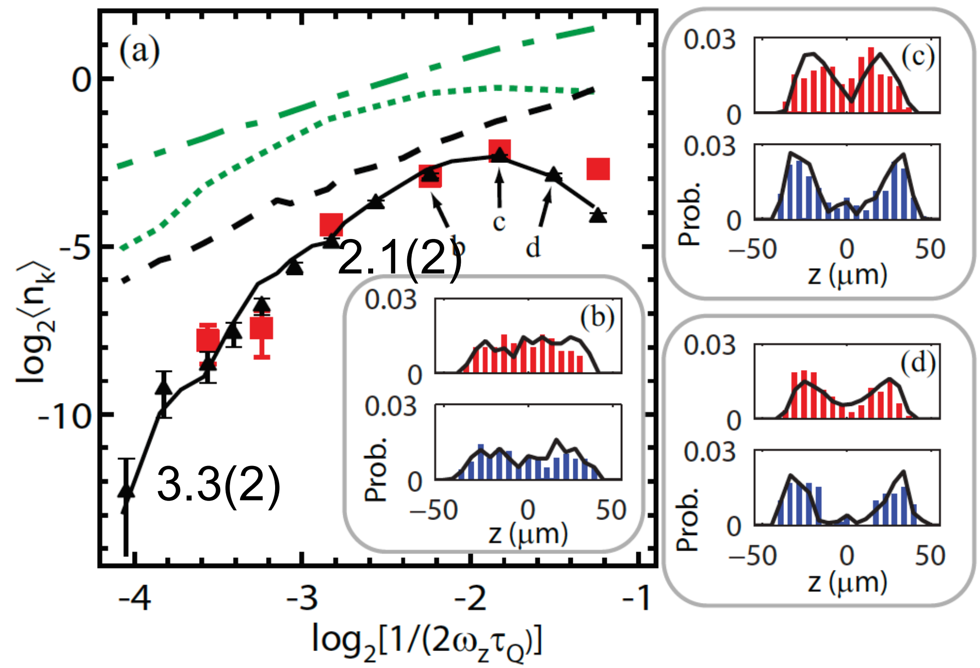


Third Experiment

Haljan's group at Simon-Fraser University
Phys. Rev. A 87, 051401(R) (2013)

42 ions, only {0,2} defects per realization
Numerical agreement between KZM and simulations
Disagreement with experiment



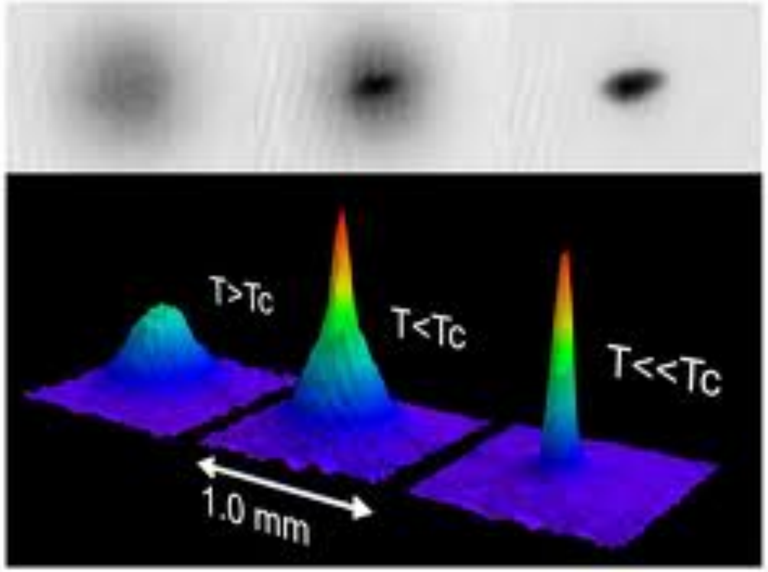


Comparison

$n \propto \tau_Q^{-\alpha}.$

Group	Number of ions	Kink number	Fitted exponent α
Mainz University[14]	16	$\{0, 1\}$	2.68 ± 0.06
PTB[15]	29 ± 2	$\{0, 1\}$	2.7 ± 0.3
Simon Fraser University[13]	42 ± 1	$\{0, 2\}$	3.3 ± 0.2

Soliton formation in Bose-Einstein condensation

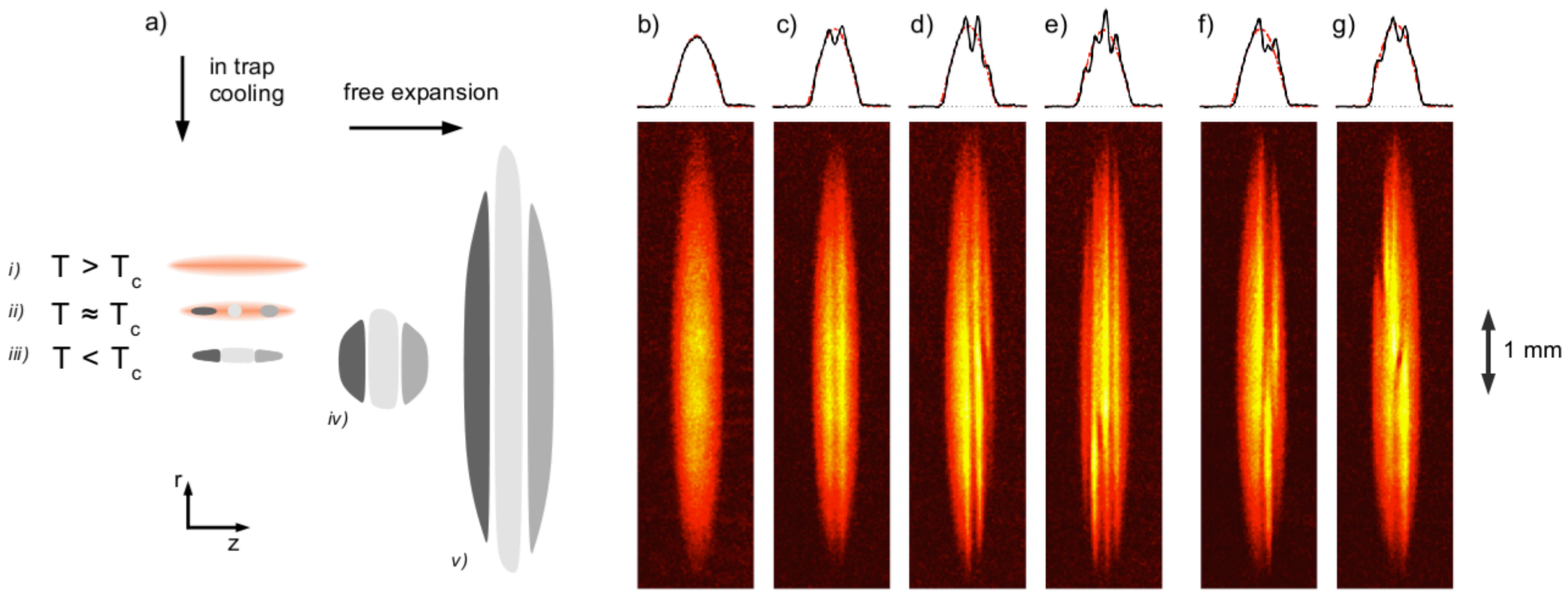


Soliton formation

BEC in cigar-shaped traps, U(1) symmetry breaking, inhomogeneous transition

$$\mathcal{E}^{\mathrm{GP}}[\Phi] = \int \left(\frac{\hbar^2}{2m} |\nabla \Phi|^2 + [V(\mathbf{r}) - \mu] |\Phi|^2 + \frac{g}{2} |\Phi|^4 \right) \mathrm{d}^3\mathbf{r}$$

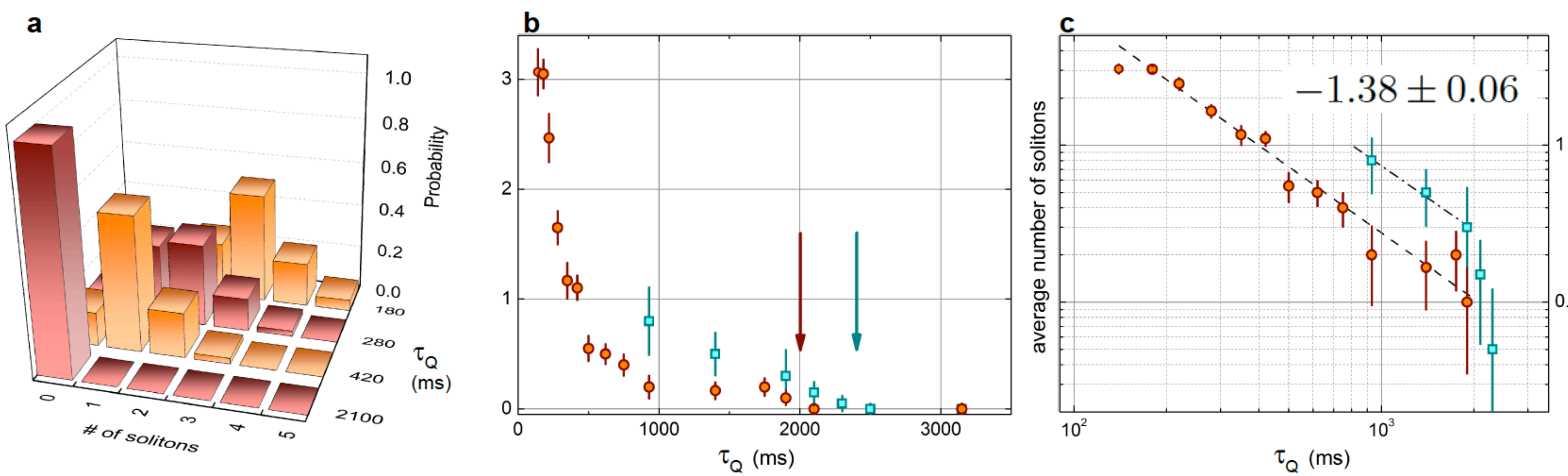
Proposal: W. H. Zurek Phys. Rev. Lett.**102**, 105702 (2009)
Detailed analysis: AdC, A. Retzker, M. B. Plenio, NJP 13, 083022 (2011)
Experiment @ Trento: Nature Physics **9**, 656 (2013)



Soliton formation

BEC in cigar-shaped traps
Experiment @ Trento: Nature Physics **9**, 656 (2013)

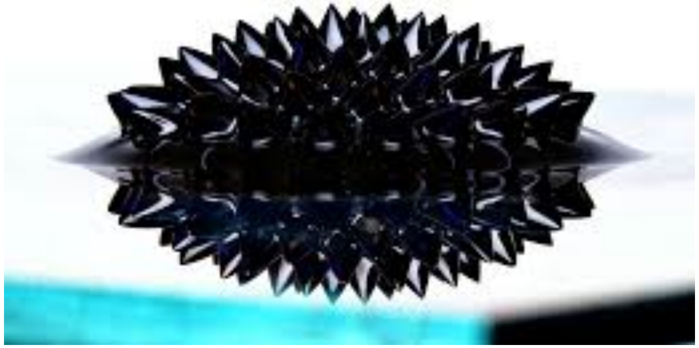
4/3 Inhomogeneous KZM



Unknown exact value of the dynamic critical exponent "z"
Power-law scaling consistent with the IKZM

Nature Physics **9**, 656 (2013)

Vortex antivortex formation in ferrofluids

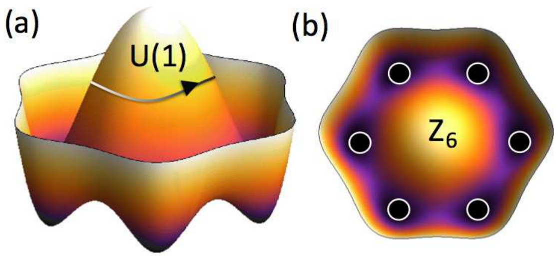


Multiferroics

Multiple ferroic orders in hexagonal manganites

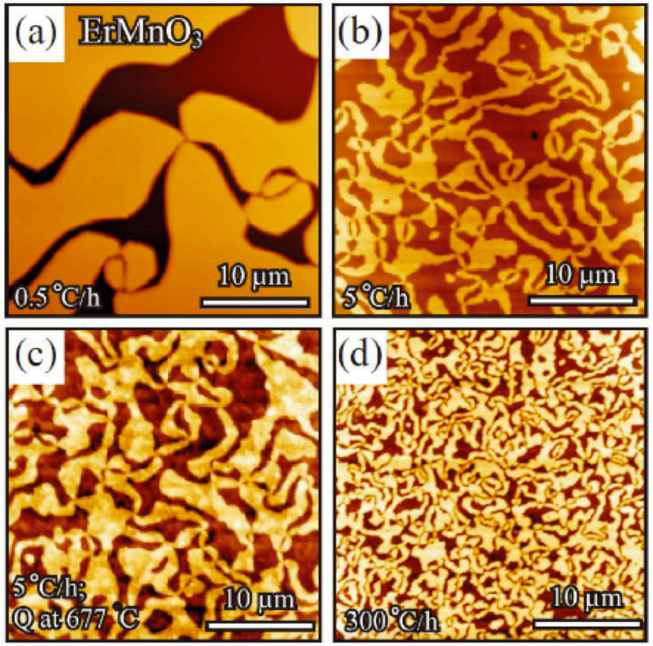
$REMnO_3$

Thermal ferroelectric transition ~1700 K



vortex-antivortex domain patterns

simulation:
2D six-state clock model



$$\mathcal{H} = J\sum_{\langle i,j\rangle}\cos(\theta_i-\theta_j)+J'\sum_{\langle\langle i,j\rangle\rangle}\cos(\theta_i-\theta_j)$$

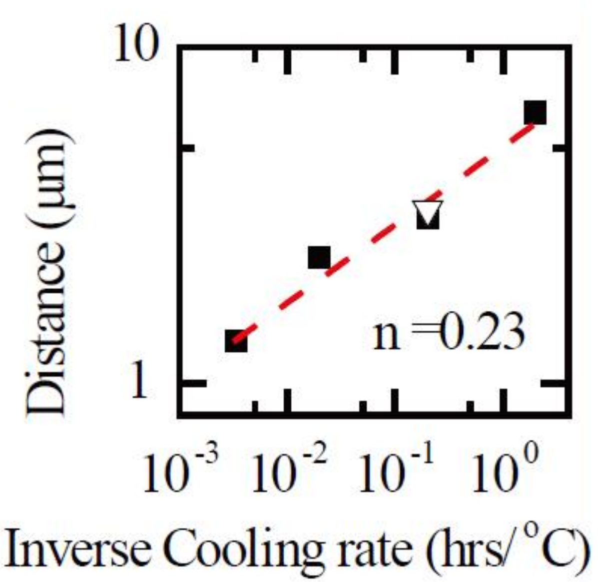
$$\theta_j = n2\pi/6\ (0\le n\le 5);\qquad J,J'<0$$

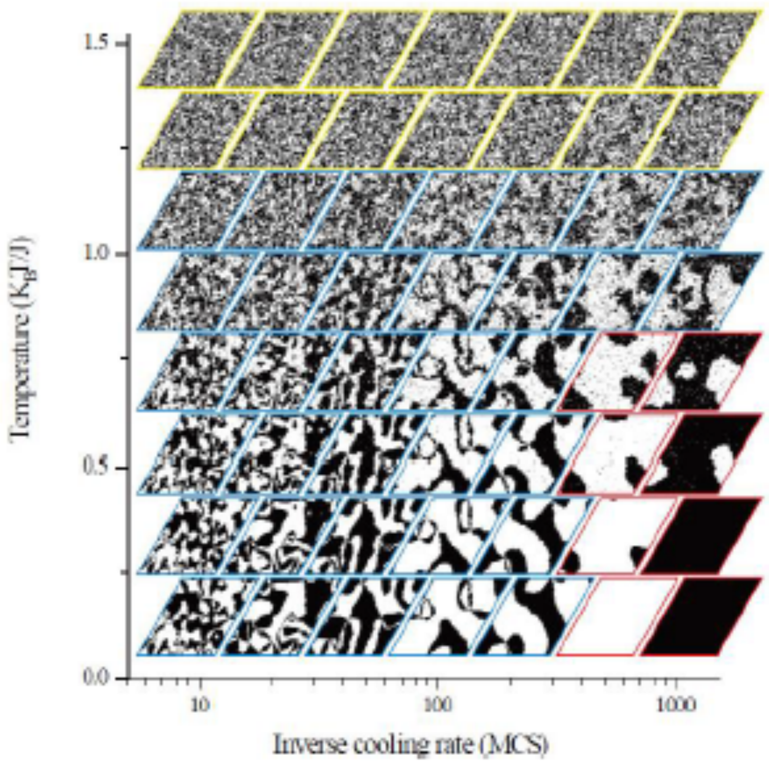
S. C. Chae, N. Lee, Y. Horibe, M. Tanimura, S. Mori, B. Gao, S. Carr, and S-W. Cheong, Phys. Rev. Lett. 108, 167603 (2012).

S. M. Griffin, M. Lilienblum, K. Delaney, Y. Kumagai, M. Fiebig, N. A. Spaldin, Phys. Rev. X 2, 041022 (2012)

Multiferroics

power law exponent
KZM prediction: 0.3
Measured: 0.23

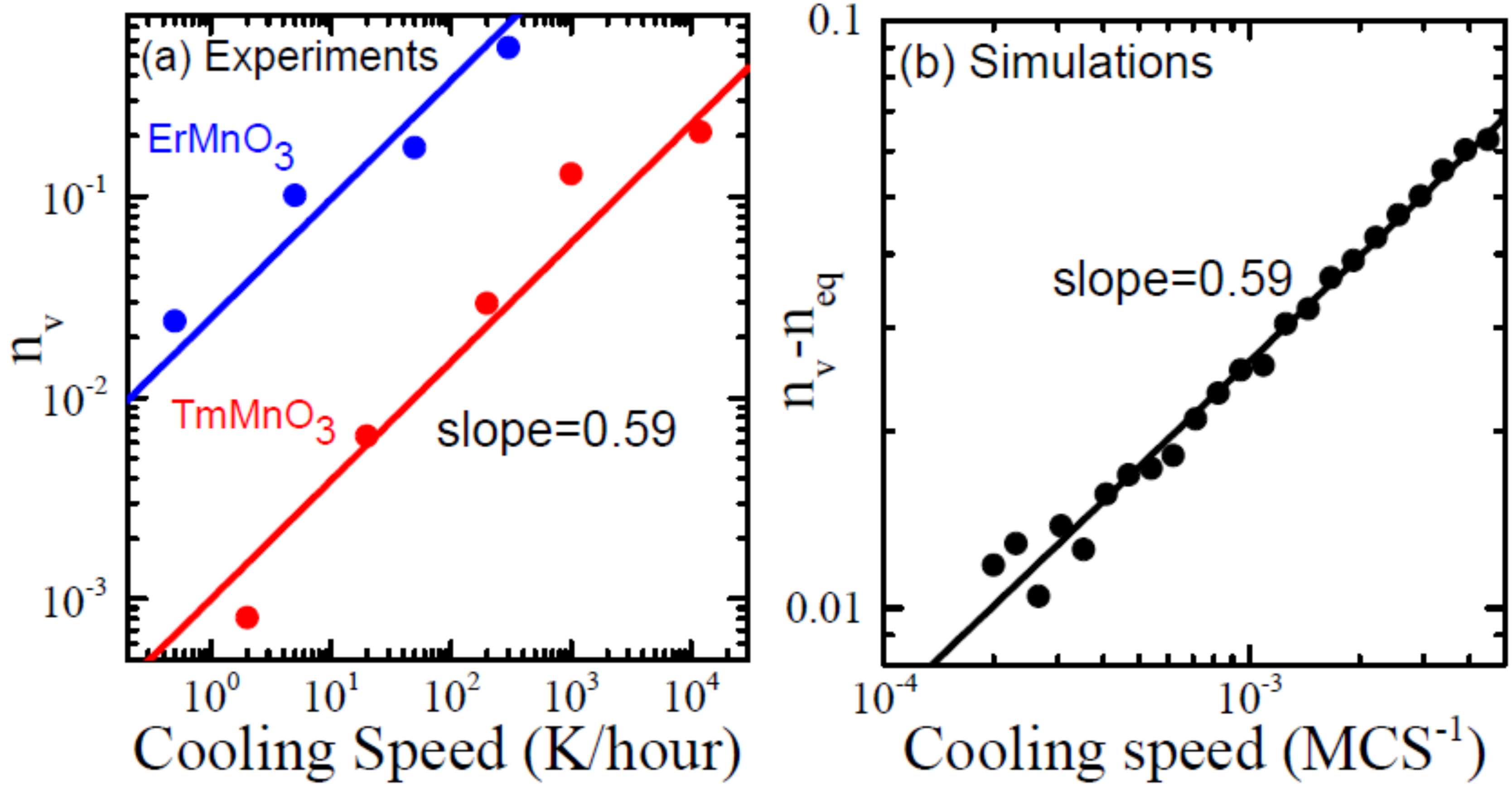




Issues:
Unknown order of the transition
Long thermal quenches (~hours) hard to control (inhomogeneous cooling)

S. C. Chae, N. Lee, Y. Horibe, M. Tanimura, S. Mori, B. Gao, S. Carr, and S-W. Cheong, Phys. Rev. Lett. 108, 167603 (2012).

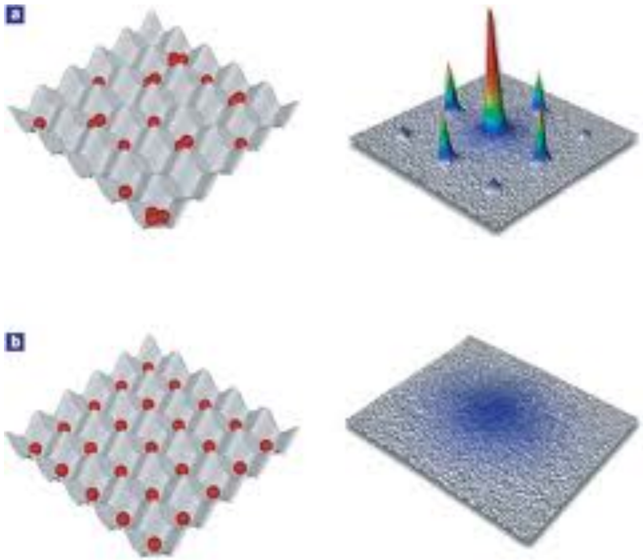
Ongoing work - Multiferroics



3D XY universality, exponent for vortex density: $2\nu/(1+z\nu) \approx 0.6$

z depends on the dynamics. Microscopic dynamics of RMnO3 is expected to be local. We use the local Glauber dynamics in the simulations, $z \approx 2$.

Nonequilibrium dynamics across the Mott insulator-superfluid transition

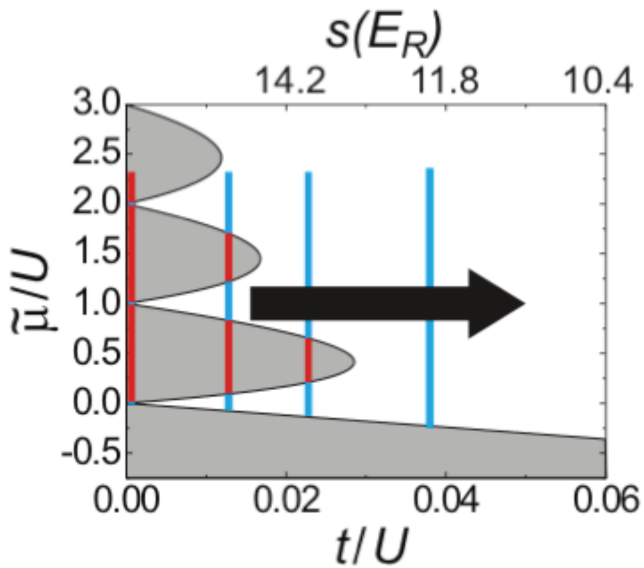


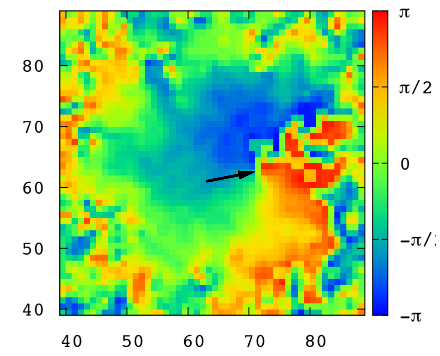
Vortex formation in Mott Insulator-SF transition

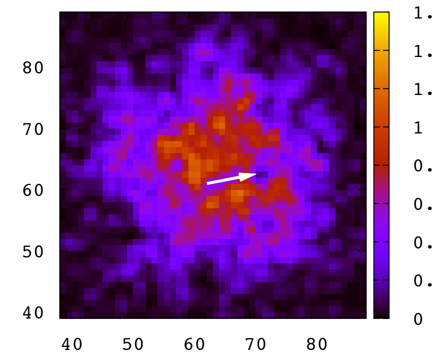
Bose-Hubbard model

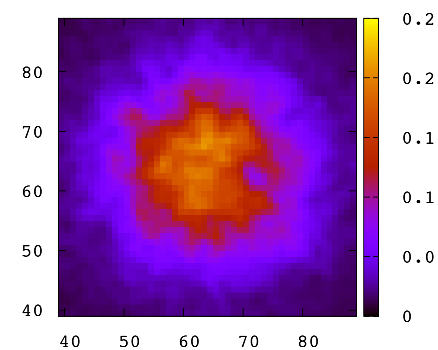
$$\hat{\mathcal{H}}_{BH} = -\sum_{\langle i,j \rangle} J_{ij}(\hat{b}_i^\dagger \hat{b}_j + h.c.) + \frac{U}{2}\sum_i \hat{n}_i(\hat{n}_i - 1) - \mu \sum_i \hat{n}_i$$

Quenching the optical lattice depth





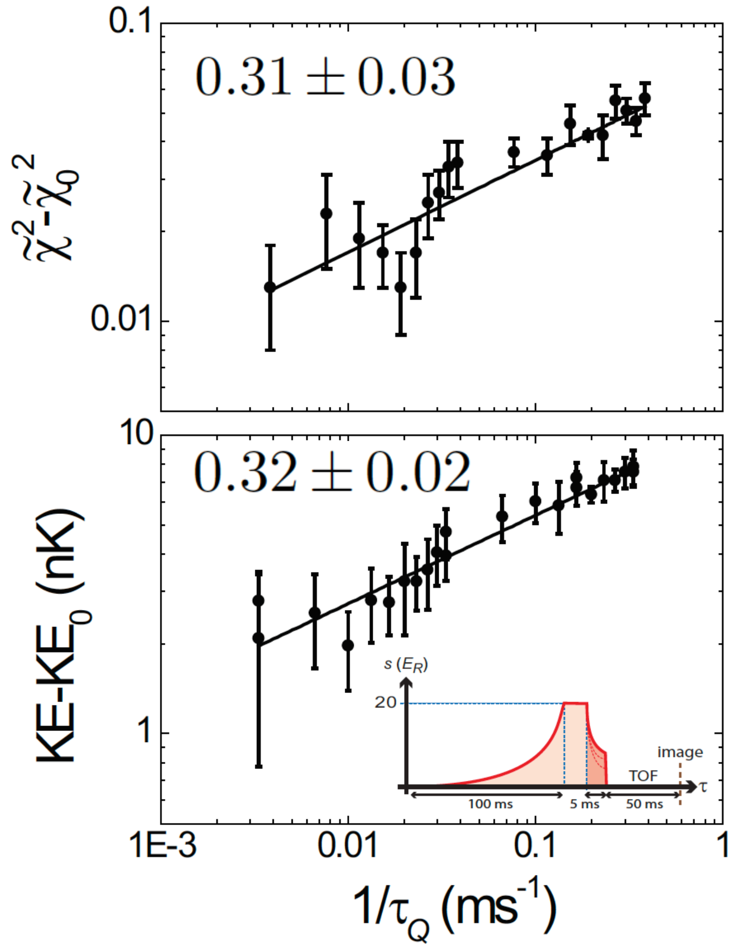




D. Chen, M. White, C. Borries, B. DeMarco, Phys. Rev. Lett. 106, 235304

Experiment: Mott Insulator-SF transition

Bose-Hubbard model



$$1/\tau_Q^{3\nu/(\nu z+1)}$$

$$1/\tau_Q^{3/4}$$

Inhomogeneous, multiple crossing points in space, finite-size,
Indirect measurement of defects/excitations, unknown critical exponents

D. Chen, M. White, C. Borries, B. DeMarco, Phys. Rev. Lett. 106, 235304

Summary

We have witnessed a flurry of experiments in 2012-2013

New ingredients: finite-size, inhomogeneous systems, etc.

Crystal clear conclusive experiments are still to be done

- Technical experimental problems

- Tests of equilibrium properties before studying nonequilibrium

High power law exponents to be explained

Onset of adiabatic dynamics

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W. H. Zurek (T-4)

S. Kirmizialtin (T-6)

T. W. B. Kibble (Imperial College)

Ion traps

Experiments: T. E. Mehlstaubler‘s group

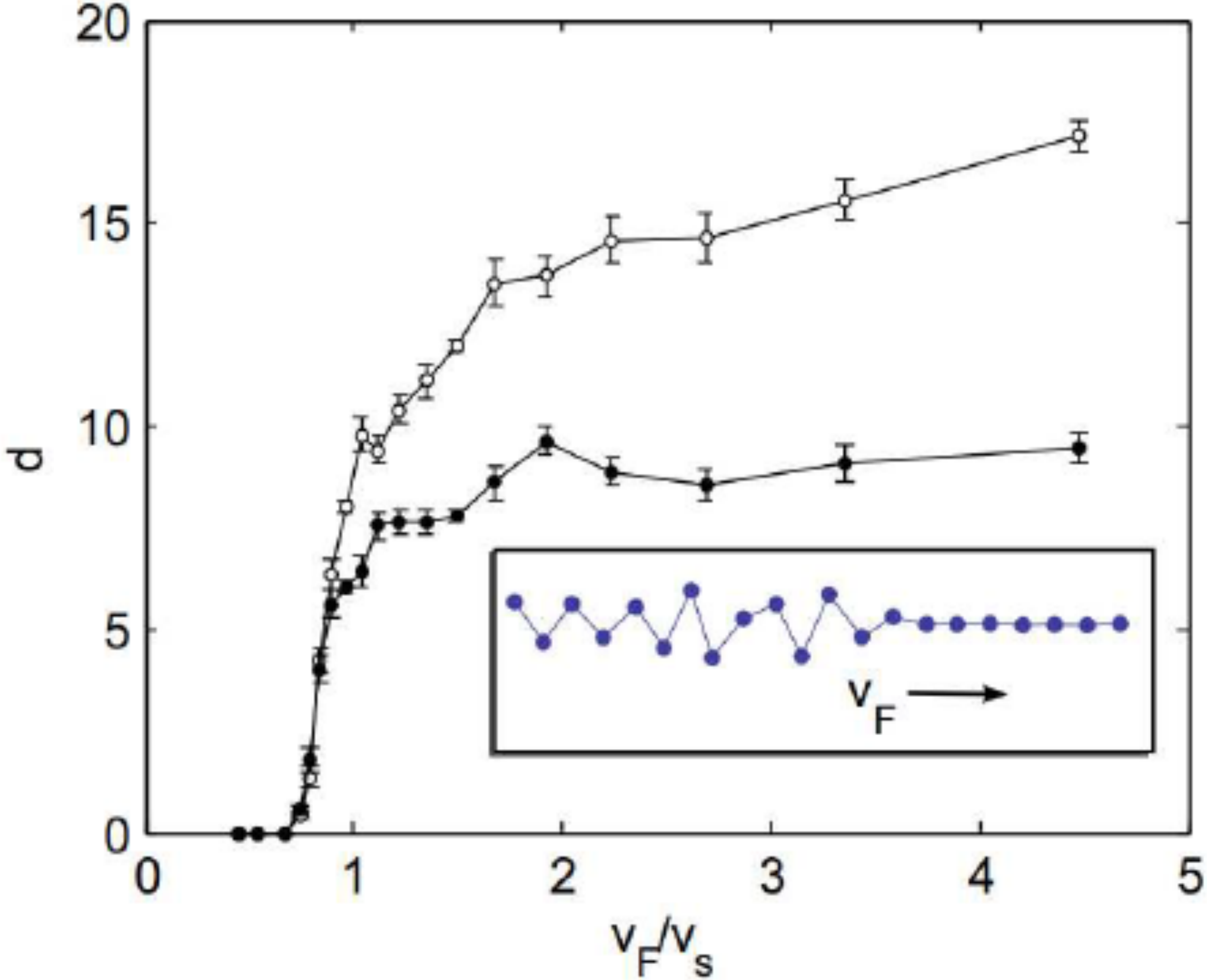
M. B. Plenio (Ulm)

A.Retzker (Jerusalem)

G. De Chiara (Belfast)

G. Morigi (Saarland)


Interested in visiting LANL?
CNLS colloquium
Quantum Seminar
Thanks for your attention!!



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