Shortcuts in critical systems

Rhapsody on a theme of Kibble and Zurek

Adolfo del Campo

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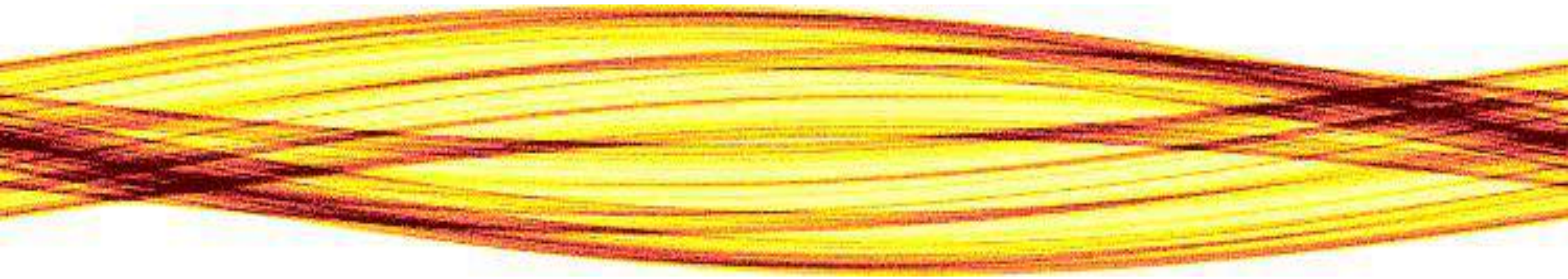
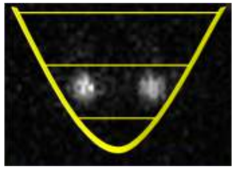
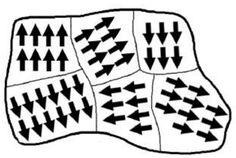


XVIII Giambiagi Winter School: Quantum Chaos & Control

July 25-29 2016, Buenos Aires



Talk 1: STA in noncritical systems



Talk 2: STA in critical systems

Talk 3: Quantum Speed Limits

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Adolfo del Campo: adolfo.delcampo@umb.edu

Talk 2: Contents

The Kibble-Zurek mechanism

- Universal phase-transition dynamics
- Quantum Annealing

Ways out

- Inhomogeneous driving
- Counterdiabatic driving

Adolfo del Campo: adolfo.delcampo@umb.edu

Adiabatic dynamics

Slow driving of a system

Provides good control

No excitations

Ground state

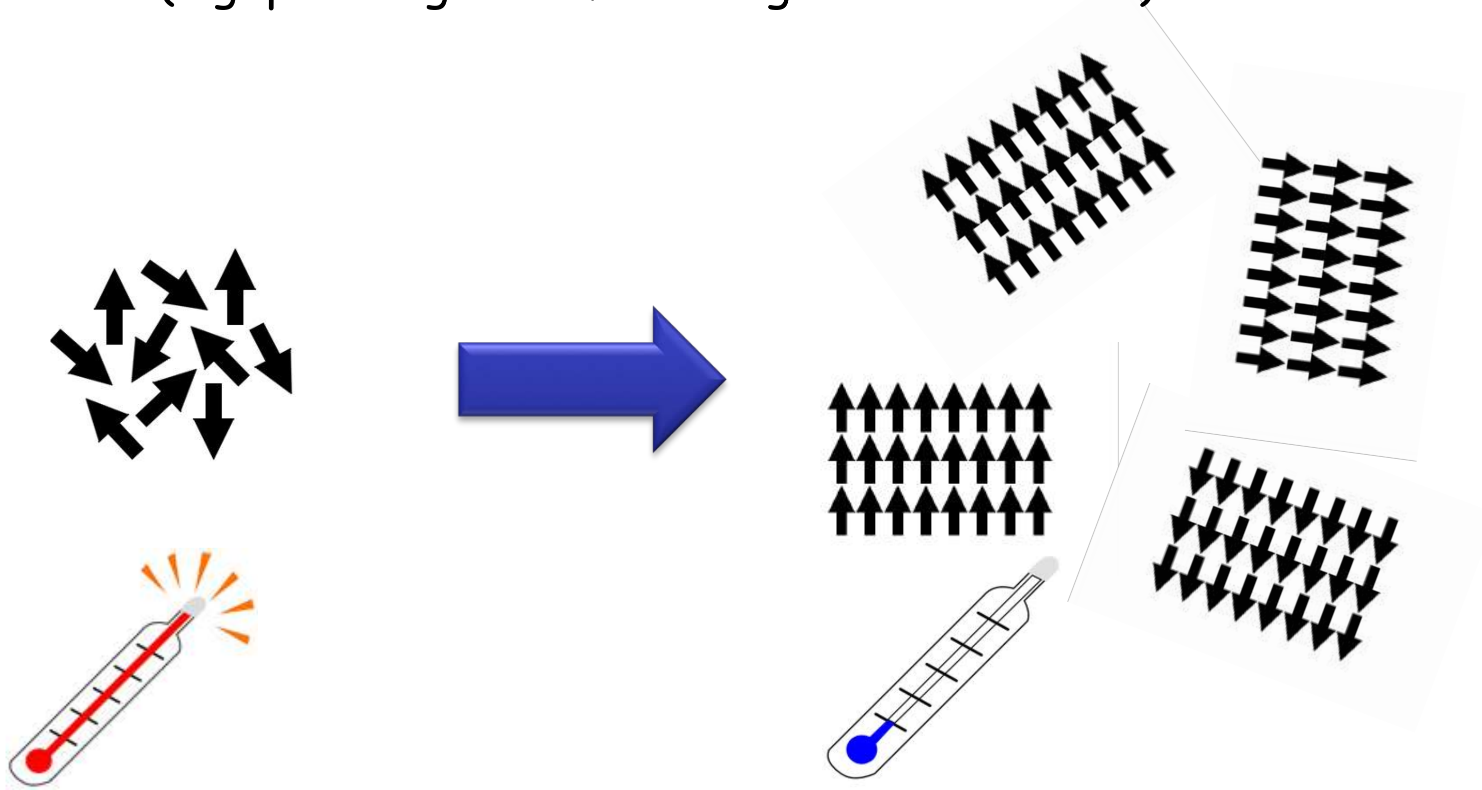
So?

Breaking symmetries

Breaking adiabatic dynamics
in critical systems

Spontaneous symmetry breaking

Driving through a phase transition
(e.g. paramagnetic-ferromagnetic transition)

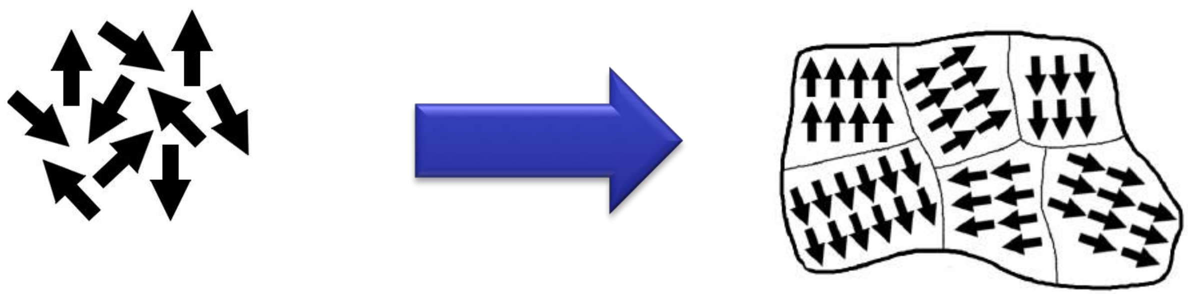


degenerate ground states

Spontaneous symmetry breaking

Driving through a phase transition
(e.g. paramagnetic-ferromagnetic transition)

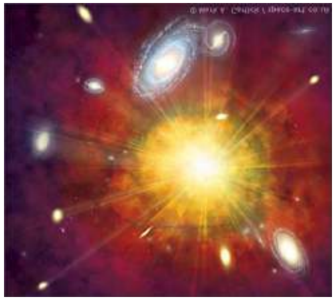
Cooling at finite rate



Broken symmetry
Size of the domains?
How many?
The Kibble-Zurek mechanism

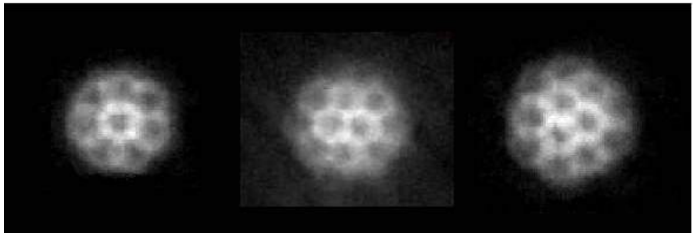
Tom W. B. Kibble

Madras - London
June 3rd 2016



T. W. B. Kibble, JPA 9, 1387 (1976)
T. W. B. Kibble, Phys. Rep. 67, 183 (1980)

Wojciech H. Zurek



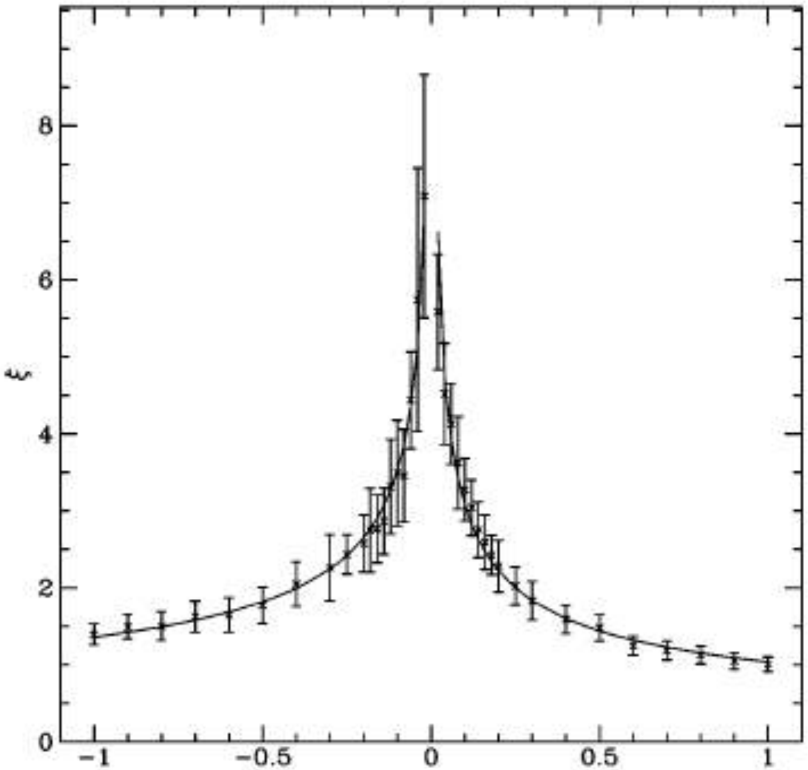
W. H. Zurek, Nature (London) 317, 505 (1985)
W. H. Zurek, Acta Phys. Pol. B. 1301 (1993)

Scaling theory near critical point

Universal divergence of

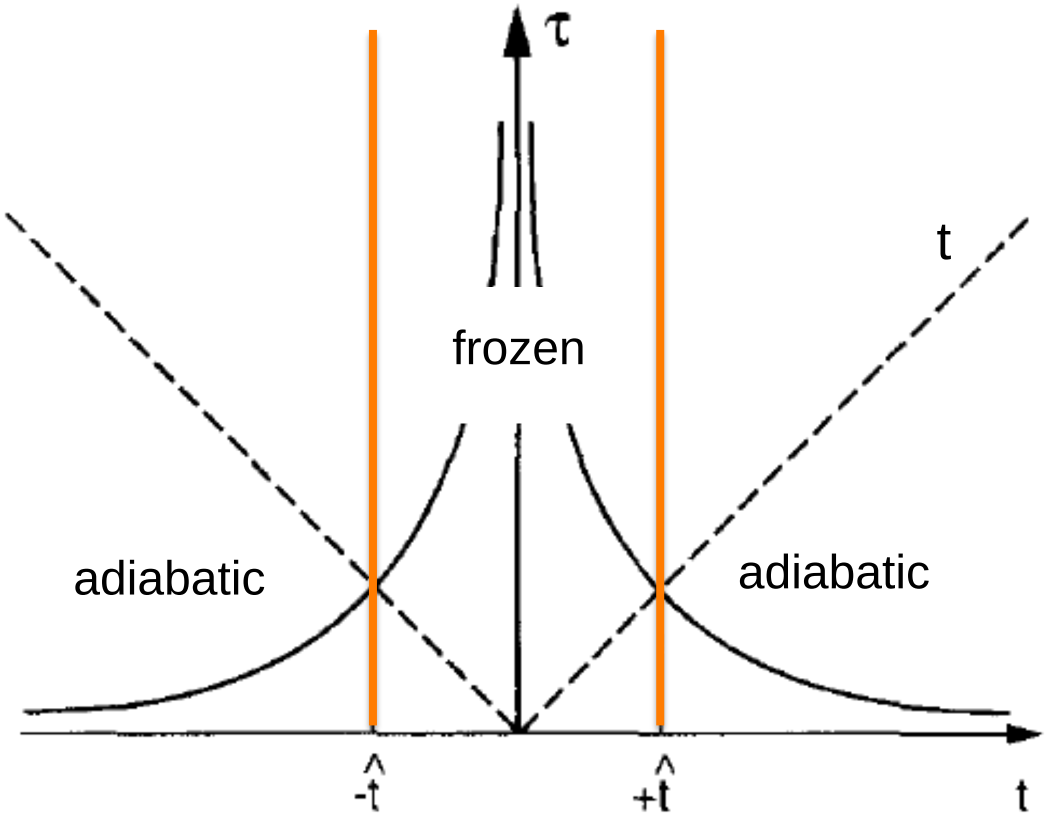
Correlation length $\xi(t) = \frac{\xi_0}{|\varepsilon(t)|^\nu}$

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



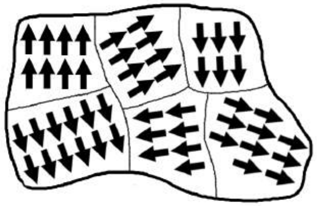
$$\varepsilon = (T_c - T)/T_c$$

The Kibble-Zurek mechanism

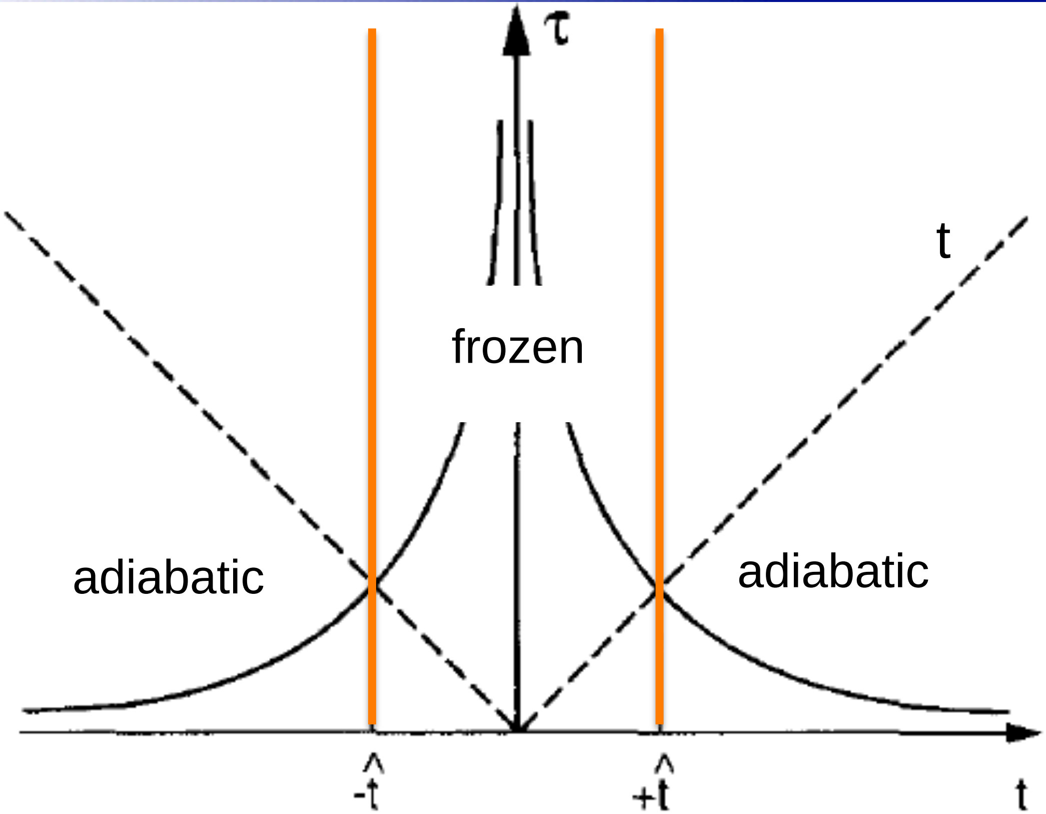


$$\varepsilon(t) = t/\tau_Q$$

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



The Kibble-Zurek mechanism



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

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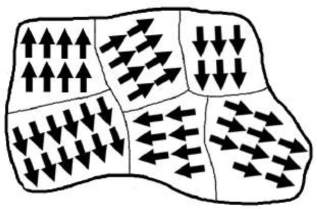

Domain size set by equilibrium correlation length at freeze-out time

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

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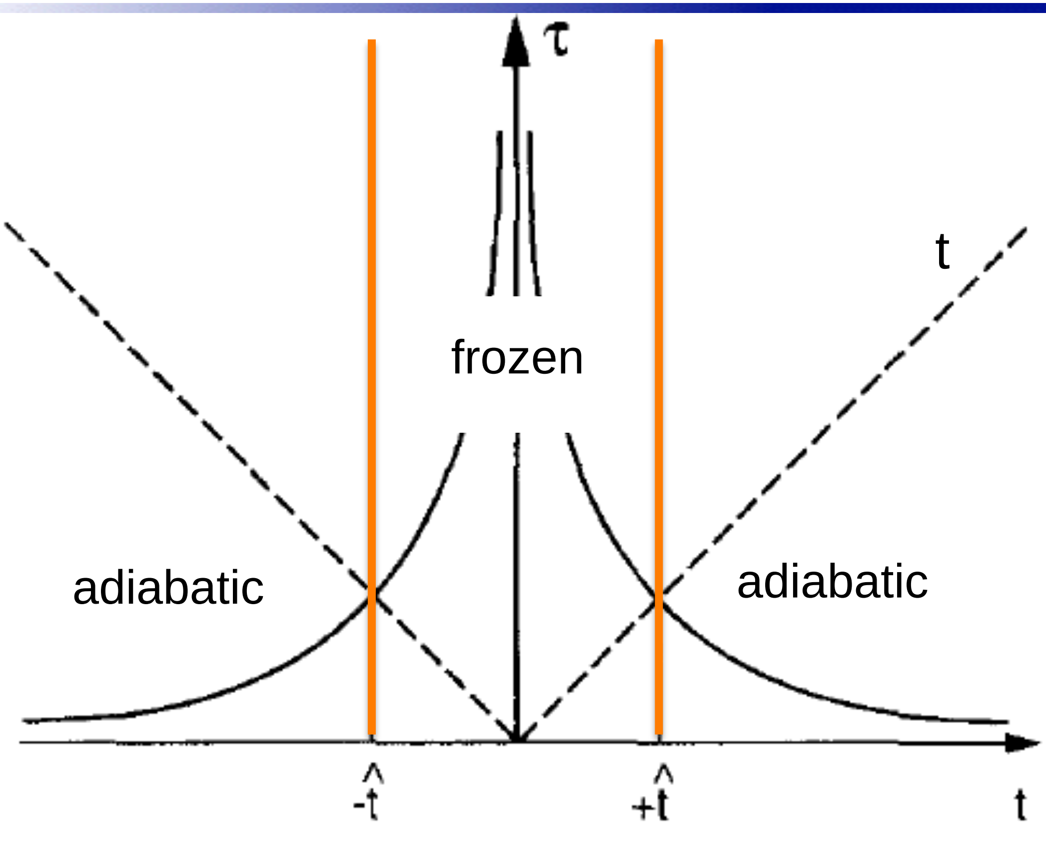
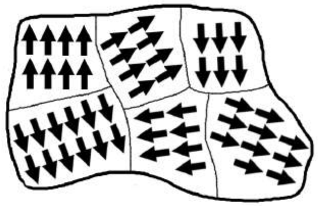
The Kibble-Zurek mechanism



Linear quench

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

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



Density of excitations (quantum & classical)

$$n_0 \sim \xi(\hat{t}) \propto \tau_Q^{-\nu/(1+z\nu)}$$

Universality: The Kibble-Zurek mechanism

The KZM is broadly applicable

Tested numerically in integrable and nonintegrable models

Explored in many experiments, consistent with KZM

AdC and W. H. Zurek, Int. J. Mod. Phys. A 29, 1430018 (2014)

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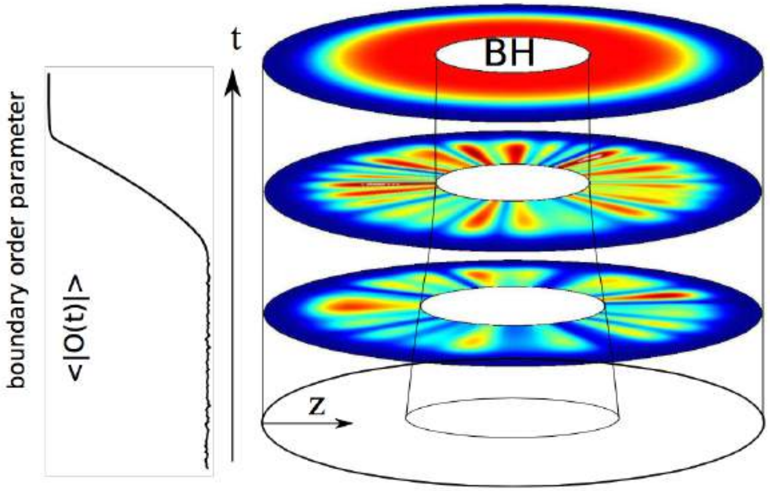
Universality

KZM holds even in strongly coupled systems

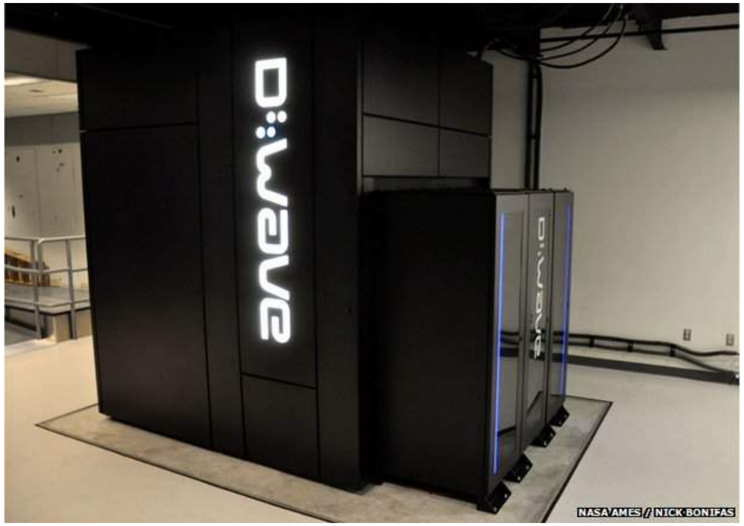
e.g. AdS-CFT/Holographic systems with no quasiparticles



J. Sonner, A. del Campo, W. H. Zurek, Nat. Commun. **6**, 7406 (2015)

P. M. Chesler, A. M. Garcia-Garcia, H. Liu, PRX **5**, 021015 (2015)

KZM in AQC



A. Dutta, A. Rahmani, A. del Campo, arXiv:1605.01062 (to appear in PRL)

M. M. Rams, M. Mohseni, A. del Campo, arXiv:1606.07740

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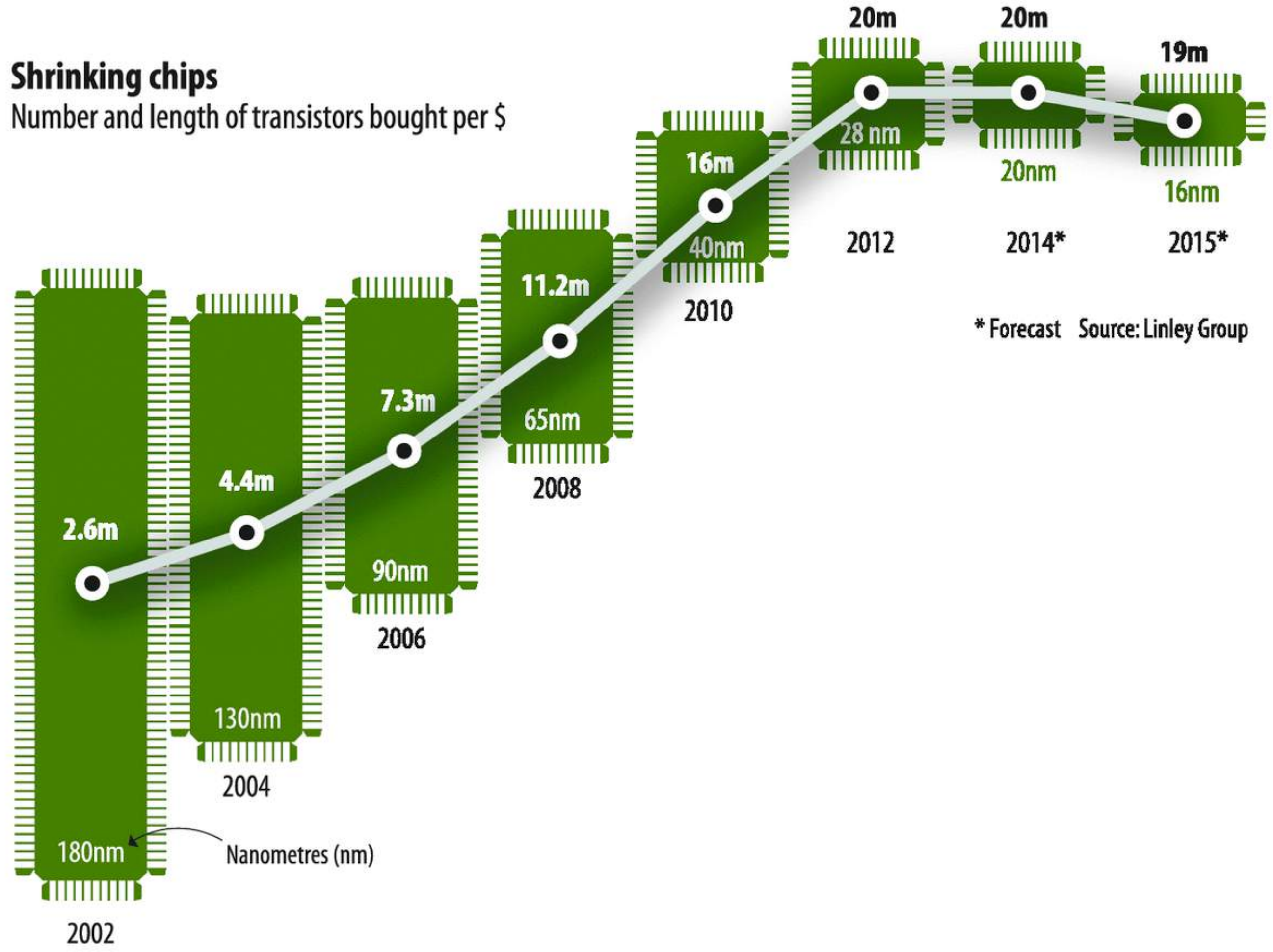
IT companies & security agencies exploring Quantum

Why?



Shrinking chips
Number and length of transistors bought per $
2.6m
180nm
2002
4.4m
130nm
2004
7.3m
90nm
2006
11.2m
65nm
2008
16m
40nm
2010
20m
28 nm
2012
20m
20nm
2014*
19m
16nm
2015*
Nanometres (nm)
* Forecast Source: Linley Group

Why?

MIT Technology Review

Chip Makers Admit Transistors Are About to Stop Shrinking

In the next five years, it will be too expensive to further miniaturize—but chip makers will innovate in different ways.

by Jamie Condliffe July 25, 2016

International Technology Roadmap for Semiconductors Examines Next 15 Years of Chip Innovation

FINAL INSTALLMENT OF BIANNUAL REPORT OUTLINES SHORT-TERM AND LONG-TERM CHALLENGES AND OPPORTUNITIES FACING SEMICONDUCTOR TECHNOLOGY

Published Friday, July 8, 2016 2:00 pm
by Dan Rosso
WASHINGTON—July 8, 2016—The Semiconductor Industry Association (SIA), representing U.S. leadership in semiconductor manufacturing, design, and research, today announced the release of the 2015 International Technology Roadmap for Semiconductors (ITRS), a collaborative report that surveys the technological challenges

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Adiabatic Quantum Computation?

Recast optimization problem as an annealing problem

Evolve adiabatically from a trivial Hamiltonian to a different one whose ground state encodes the solution to the optimization problem

Go Quantum (Nishimori, Farhi, …)

PHYSICAL REVIEW E VOLUME 58, NUMBER 5 NOVEMBER 1998

Quantum annealing in the transverse Ising model

Tadashi Kadowaki and Hidetoshi Nishimori
Department of Physics, Tokyo Institute of Technology, Oh-okayama, Meguro-ku, Tokyo 152-8551, Japan

A Quantum Adiabatic Evolution Algorithm Applied to Random Instances of an NP-Complete Problem

Edward Farhi,[1*] Jeffrey Goldstone,[1] Sam Gutmann,[2] Joshua Lapan,[3] Andrew Lundgren,[3] Daniel Preda[3]

Kibble-Zurek scaling in AQC

Density of excitations

Crossing of a quantum critical point $n_0 \propto \tau^{-\frac{d\nu}{1+z\nu}}$

- Quantum Ising chain $n_0 \propto 1/\sqrt{\tau}$
- Quantum Ising chain with quenched disorder

$$n_0 \propto 1/(\log \tau)^2$$

Idea I
Defect suppression: Inhomogeneous driving

Idea

Phase transition induced by crossing the critical point locally

Choice of the broken symmetry biased by the neighboring regions

that have already entered the new phase

IOP PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER
J. Phys.: Condens. Matter **25** (2013) 404210 (10pp) doi:10.1088/0953-8984/25/40/404210

Causality and non-equilibrium second-order phase transitions in inhomogeneous systems

A del Campo[1,2], T W B Kibble[3] and W H Zurek[1]

[1] Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[2] Center for Nonlinear Studies, Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[3] Blackett Laboratory, Imperial College, London SW7 2AZ, UK

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Vol. 29, No. 8 (2014) 1430018 (49 pages)

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World Scientific
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Universality of phase transition dynamics: Topological defects from symmetry breaking*

Adolfo del Campo[†,‡] and Wojciech H. Zurek[†]

[†] Theoretical Division, Los Alamos National Laboratory, USA
[‡] Center for Nonlinear Studies, Los Alamos National Laboratory, USA

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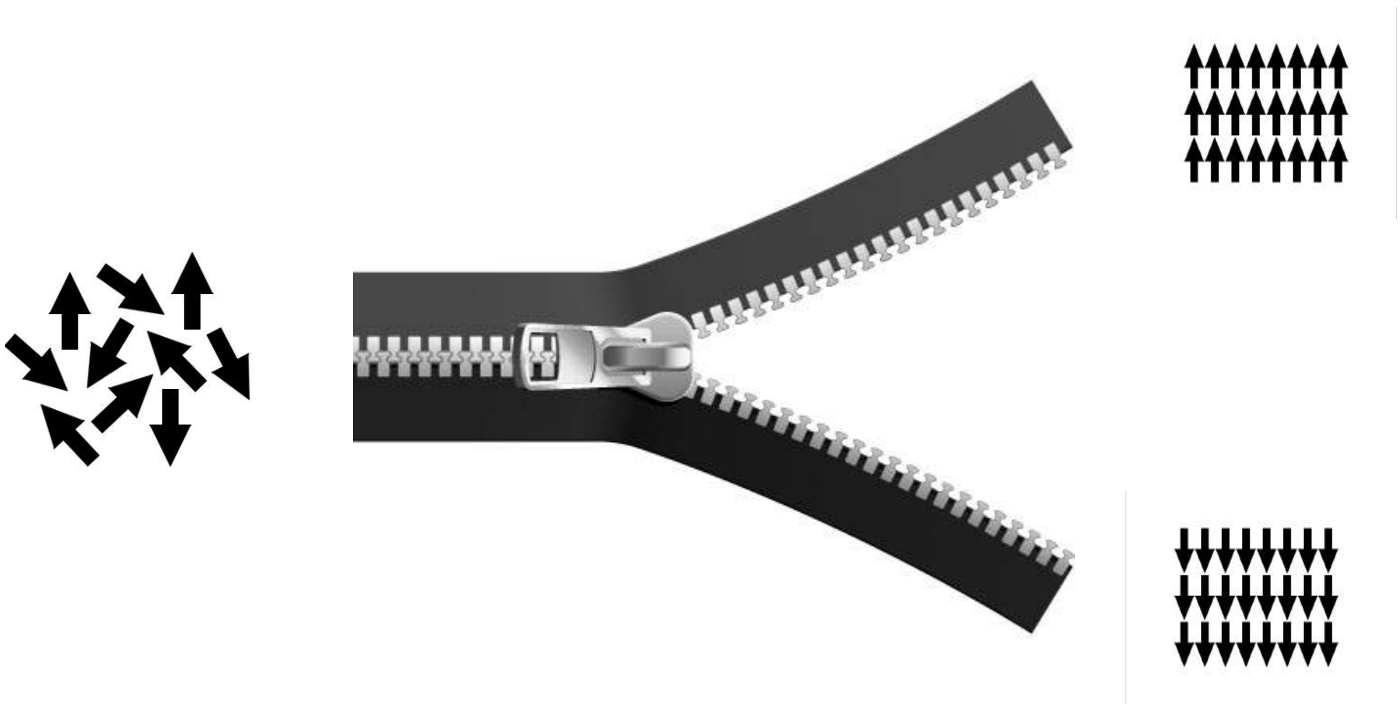
Idea

Phase transition induced by crossing the critical point locally



Example: Structural phases in trapped ions

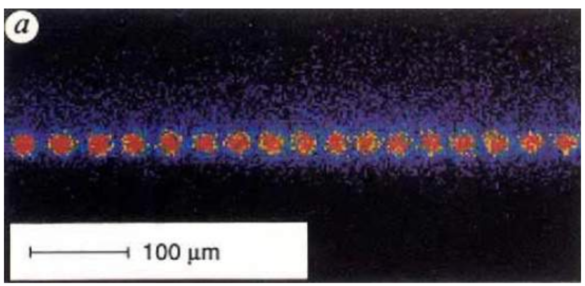
N ions on a ring trap with harmonic transverse confinement

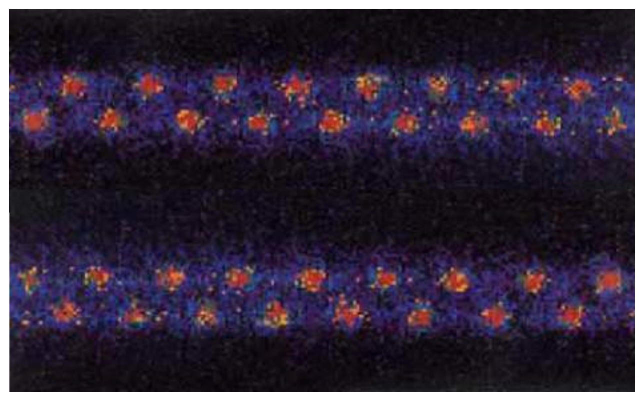
$$H = \frac{1}{2}m\sum_n \dot{\boldsymbol{r}}_n^2 + \frac{1}{2}m\sum_n(\nu_t^2 z_n^2) + \frac{Q^2}{2}\sum_{n\neq n'}\frac{1}{|\boldsymbol{r}_n - \boldsymbol{r}'_n|}$$

Critical transverse frequency

Linear chain

Degenerated zig-zag chains





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

Structural phases in trapped ions

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Critical transverse frequency

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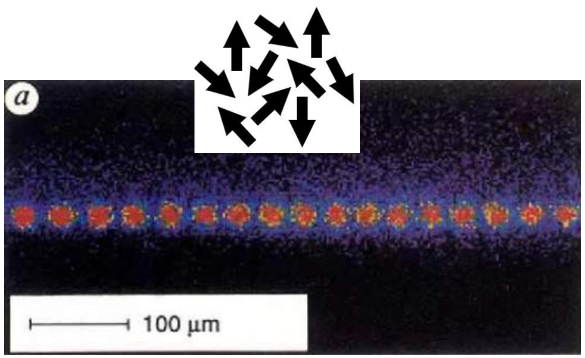
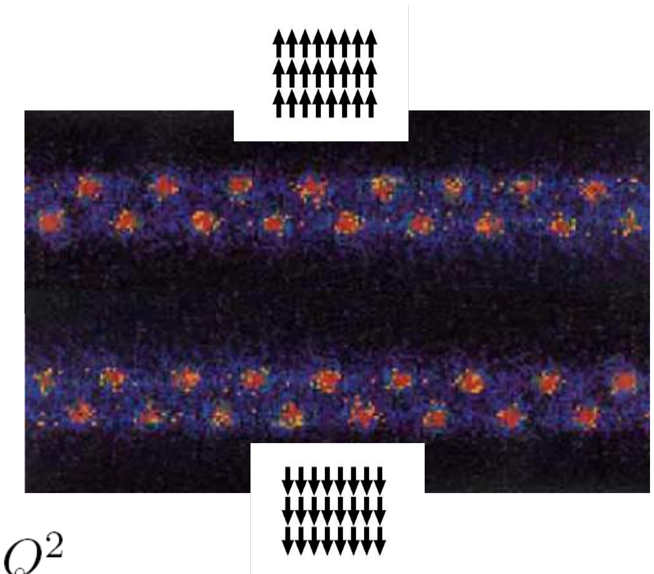


Degenerated zig-zag chains

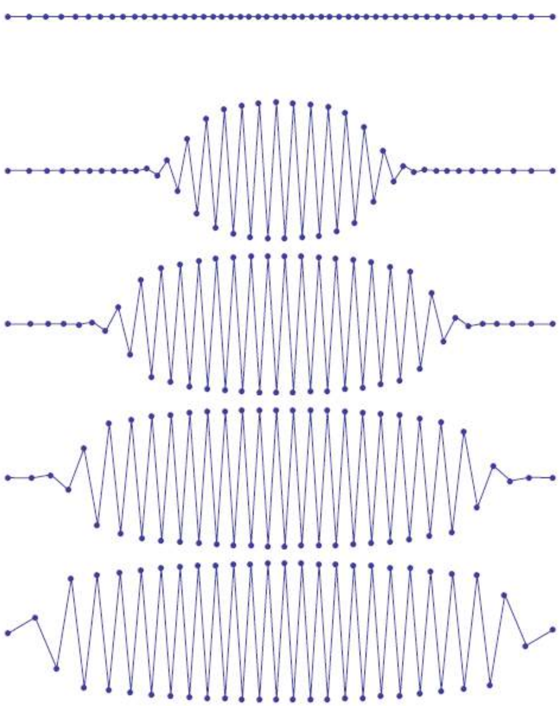


$$\nu_t^{(c)2} = 4\frac{Q^2}{ma(0)^3}$$

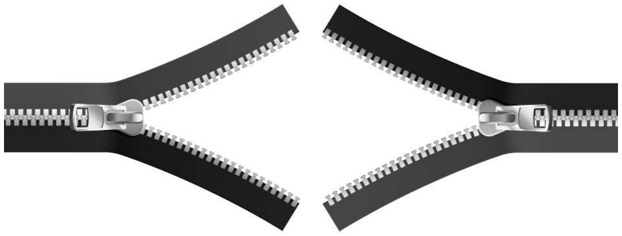
Inhomogeneous driving

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

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



Spatially dependent critical frequency (within LDA)



Inhomogeneous driving

Causality reduces the effective system for defect formation

Front velocity v_F

Sound velocity c

Adiabatic dynamics $v_F < c$

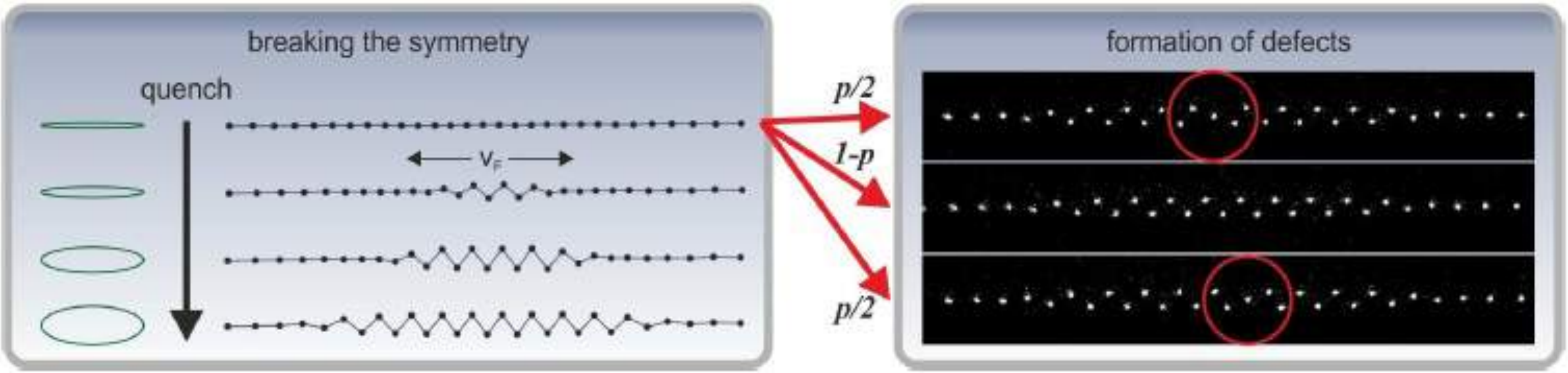
Kink formation $v_F > c$ in an effective system size $L_{\rm eff}(\tau_Q)$

Density of defects: New power law $d = \frac{L_{\rm eff}(\tau_Q)}{\hat{\xi}}\frac{1}{L} \sim \left(\frac{1}{\tau_Q}\right)^{4/3}$

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

In the lab

Collaboration with
Mehlstaubler's group at PTB



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

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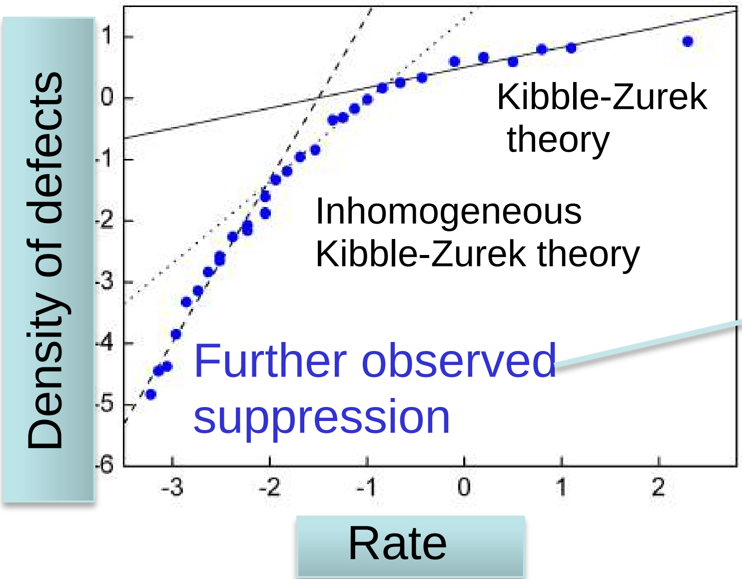
Numerics & Experiment

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

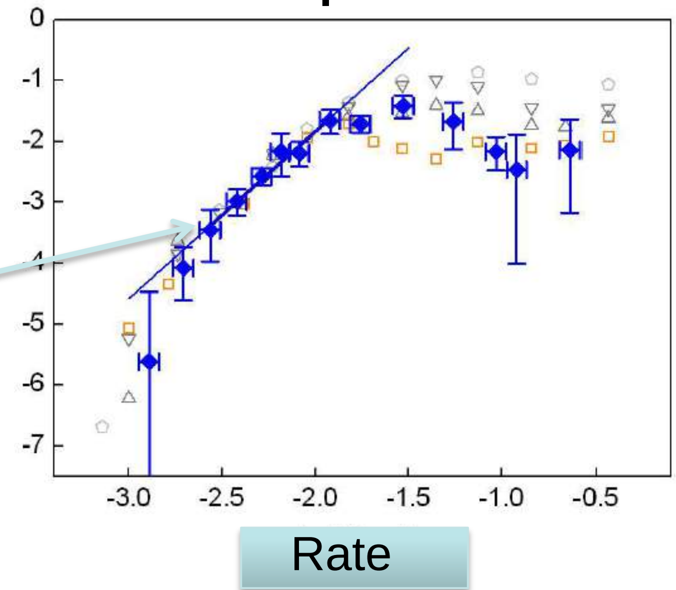
Kibble-Zurek theory fails at the onset of adiabatic dynamics

Regime of interest to quantum simulation

Numerics



Experiment



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

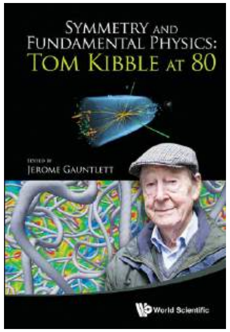
Pyka et al. Nat. Commun. 4, 2291 (2013)

Several experiments

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

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

A. del Campo, W. H. Zurek
Int. J. Mod. Phys. A 29, 1430018 (2014)



Inhomogeneous driving

Inhomogeneous driving helps to suppress defect formation

Applicability to adiabatic quantum computation?

It does NOT require diagonalization of the Hamiltonian

Experimental tests restricted to small systems

Onset of adiabatic dynamics needs theory

IOP PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER
J. Phys.: Condens. Matter 25 (2013) 404210 (10pp) doi:10.1088/0953-8984/25/40/404210

Causality and non-equilibrium second-order phase transitions in inhomogeneous systems

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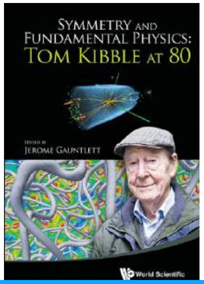

AdC, W. H. Zurek
Int. J. Mod. Phys. A 29, 1430018 (2014)

The Kibble-Zurek scalings in AQC

Density of excitations

Crossing of a quantum critical point $n_0 \propto \tau^{-\frac{d\nu}{1+z\nu}}$

- Quantum Ising chain $n_0 \propto 1/\sqrt{\tau}$

- Quantum Ising chain with quenched disorder

$$n_0 \propto 1/(\log \tau)^2$$

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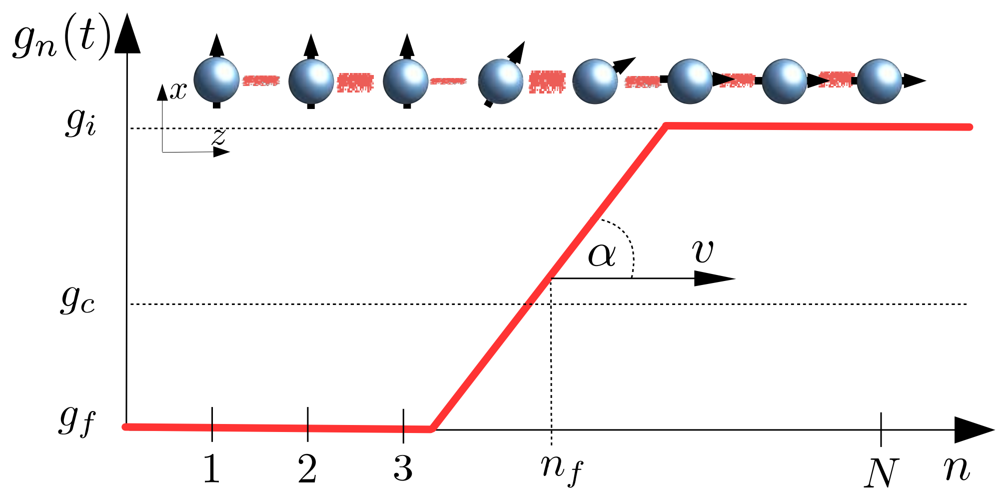
Inhomogeneous AQC

Transverse-field quantum Ising chain **with (weak) disorder**

$$\hat{H}/\mathcal{J} = -\sum_{n=1}^{N-1} J_n \sigma_n^x \sigma_{n+1}^x - \sum_{n=1}^{N} g_n \sigma_n^z$$

$$P(J_n) = \begin{cases} 1 & \text{for } J_n \in (1/2, 3/2), \\ 0 & \text{otherwise.} \end{cases}$$

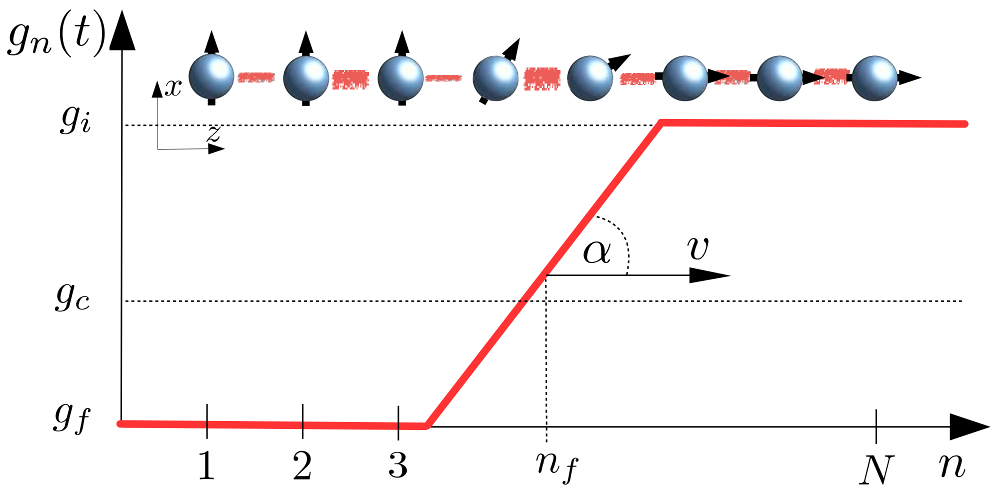


M. M. Rams, M. Mohseni, A. del Campo, arXiv:1606.07740

Inhomogeneous KZM

Transverse-field quantum Ising chain with weak disorder

$$\hat{\xi} \sim \alpha^{-\frac{\nu}{\nu+1}} \qquad v_t \sim \alpha^{\frac{(z-1)\nu}{\nu+1}}$$

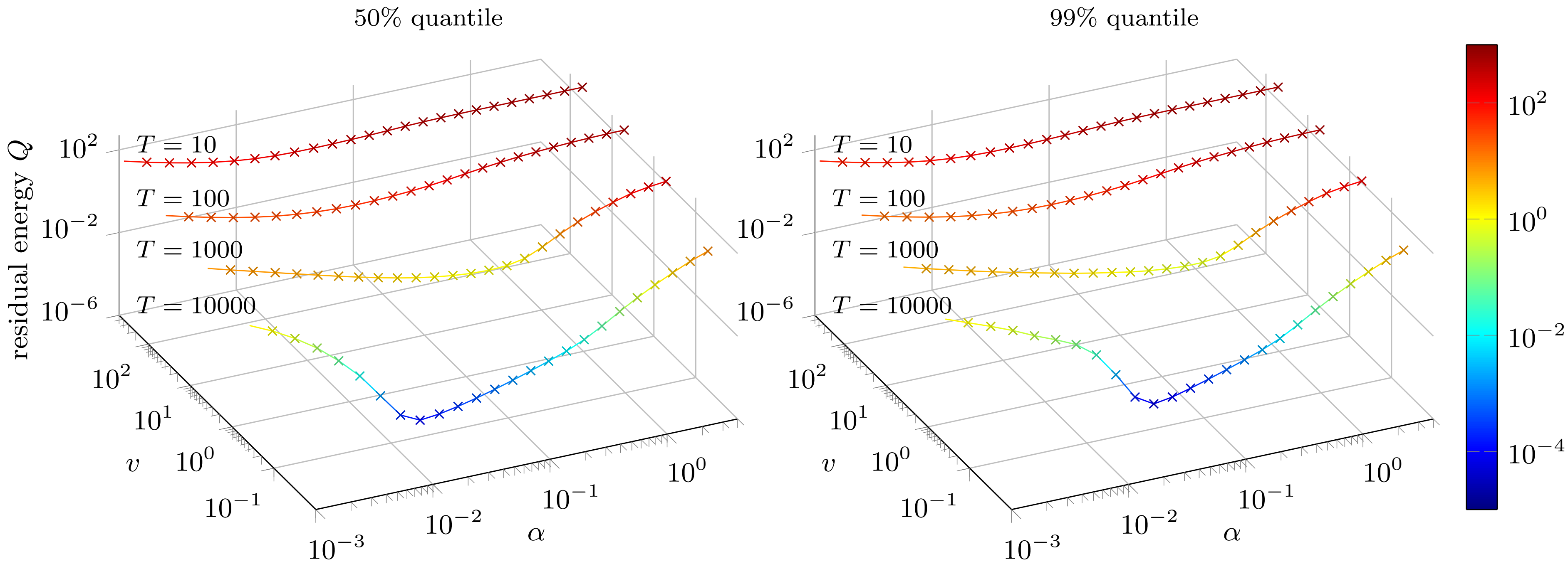


Naively setting z→∞ suggests Inhomogeneous driving does not help

M. M. Rams, M. Mohseni, A. del Campo, arXiv:1606.07740

Inhomogeneous AQC

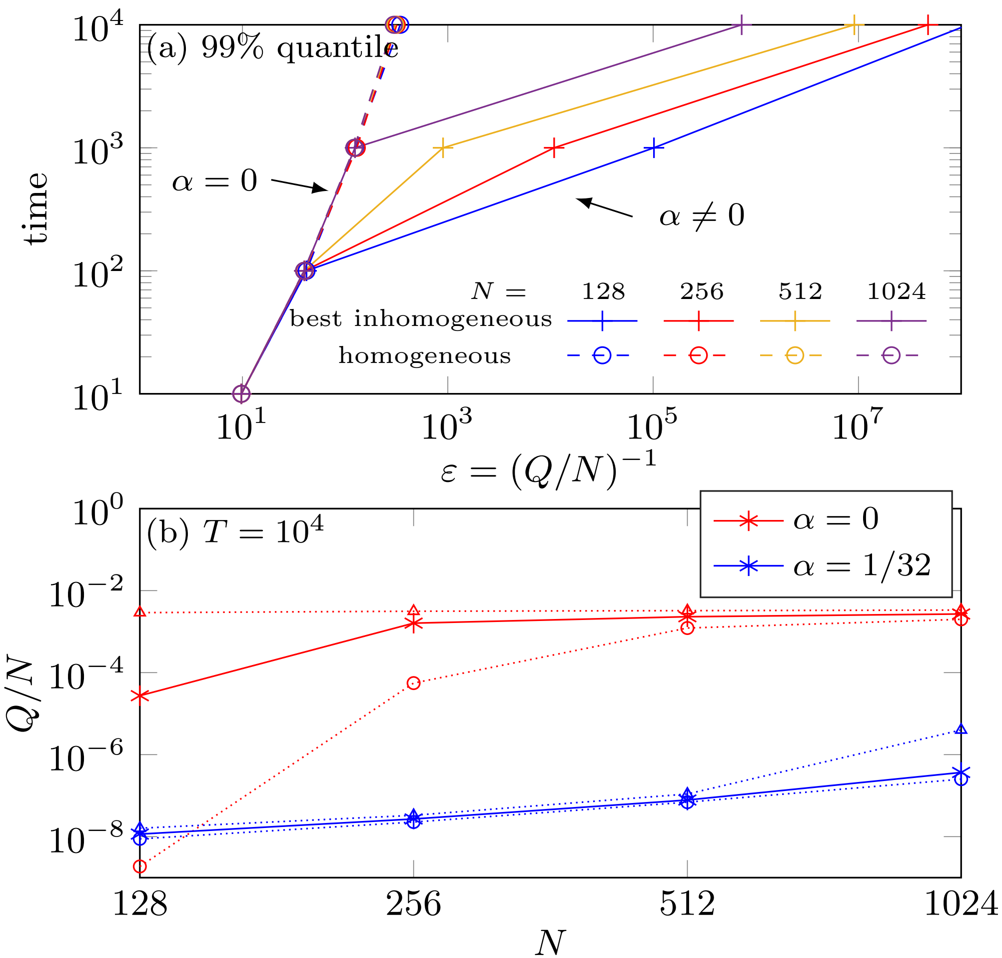
Performance



M. M. Rams, M. Mohseni, A. del Campo, arXiv:1606.07740

Inhomogeneous AQC

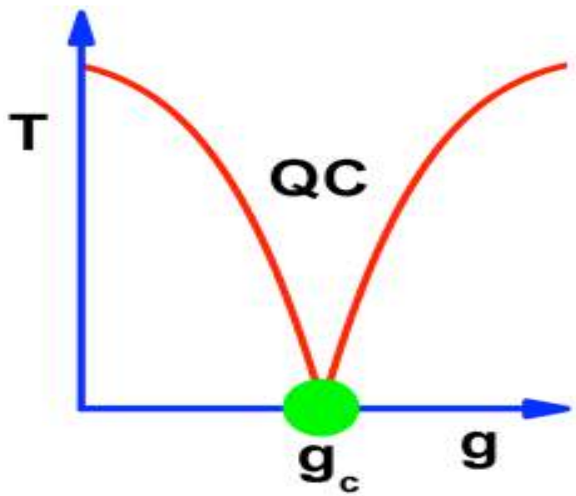
Supremacy over conventional homogeneous protocols



M. M. Rams, M. Mohseni, A. del Campo, arXiv:1606.07740

Idea II

Counterdiabatic driving in a Quantum Phase Transition



Example: 1d Quantum Ising Chain

Ising chain Hamiltonian $$\hat{H}_0(t) = -\sum_{n=1}^{N}\left[\sigma_n^x\sigma_{n+1}^x + g(t)\sigma_n^z\right]$$

Critical point $g_c = 1$

$g \gg 1$ $|\rightarrow\rightarrow\rightarrow\cdots\rightarrow\rangle$

z-axis

$g \ll 1$ $|\uparrow\uparrow\uparrow\ldots\uparrow\rangle$

$|\downarrow\downarrow\downarrow\ldots\downarrow\rangle$

x-axis

Excitations: $|\ldots\uparrow\downarrow\downarrow\downarrow\downarrow\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\downarrow\downarrow\downarrow\uparrow\uparrow\uparrow\uparrow\downarrow\downarrow\downarrow\downarrow\ldots\rangle$

Ways out of the Kibble-Zurek mechanism?

Counterdiabatic driving: Ising Chain

Counterdiabatic driving?

Auxiliary control

$$\hat{H}_1(t) = i\hbar \sum_n \left(|\partial_t n\rangle\langle n| - \langle n|\partial_t n\rangle |n\rangle\langle n| \right)$$

Diagonalization: Jordan Wigner transformation + Fourier transform

$$\hat{H}_0(t) = 2\sum_{k>0} \Psi_k^\dagger \left[\sigma_k^z (g(t) - \cos k) + \sigma_k^x \sin k\right] \Psi_k$$

$$\hat{H}_1(t) = -\dot{g}(t) \sum_{k>0} \frac{1}{2} \frac{\sin k}{g^2 + 1 - 2g\cos k} \Psi_k^\dagger \sigma_k^y \Psi_k$$

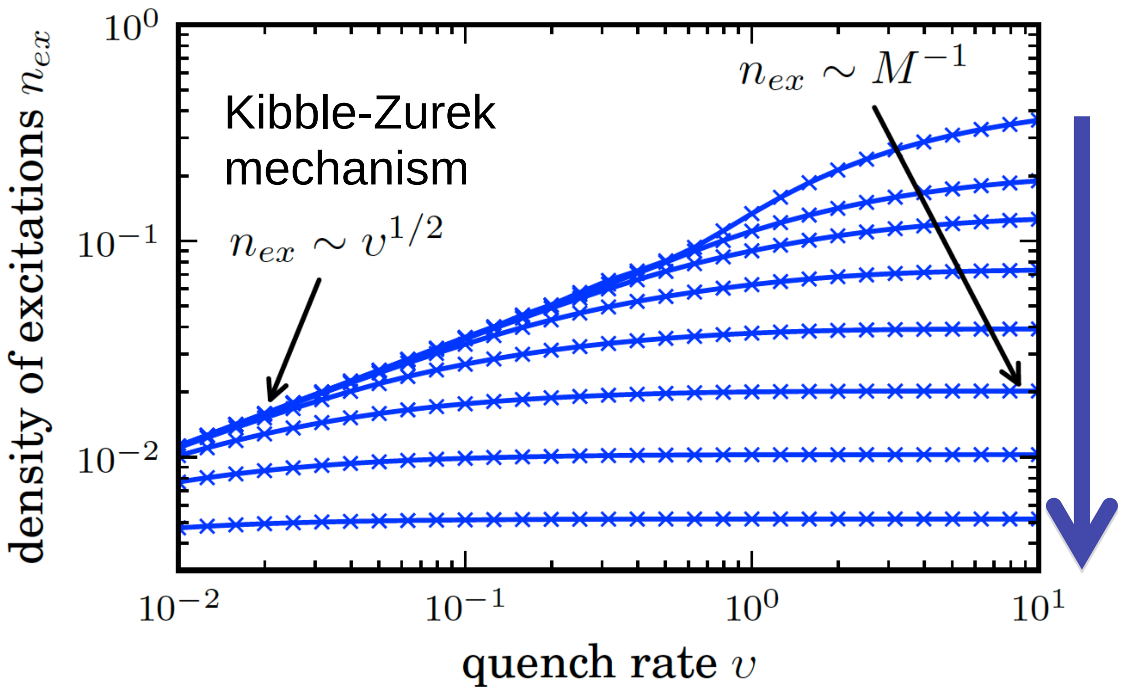
Long-range many-body interaction!

A. del Campo, M. M. Rams, W. H. Zurek, PRL 109, 115703 (2012)

Truncated Auxiliary Hamiltonian

Quench through the critical point $g(t) = g_c - vt$

Truncated Auxiliary Hamiltonian



Range of auxiliary Hamiltonian

Suppressing Kibble-Zurek mechanism

A. del Campo, M. M. Rams, W. H. Zurek, PRL 109, 115703 (2012)

Truncated Auxiliary Hamiltonian

Quench through the critical point $g(t) = g_c - vt$

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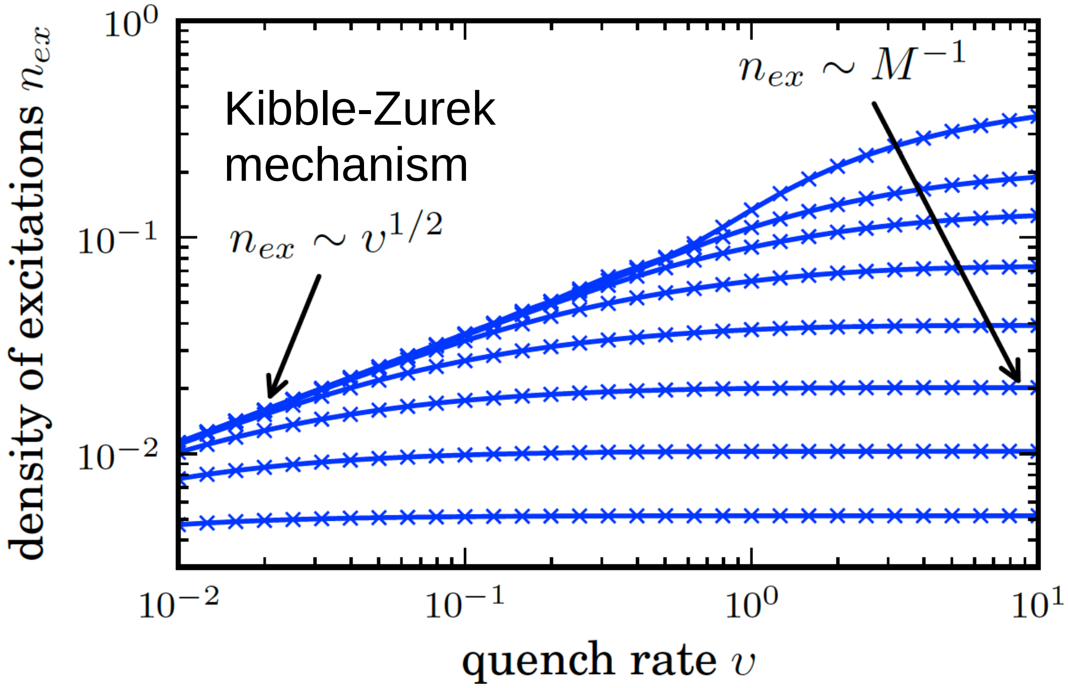


Experimentalist's view

A. del Campo, M. M. Rams, W. H. Zurek, PRL 109, 115703 (2012)

Tailoring control fields

H. Saberi, T. Opatrný, K. Mølmer, AdC, Phys. Rev. A 90, 060301(R) (2014)

Tailoring auxiliary interactions

Set of available controls $\{L_k\}$

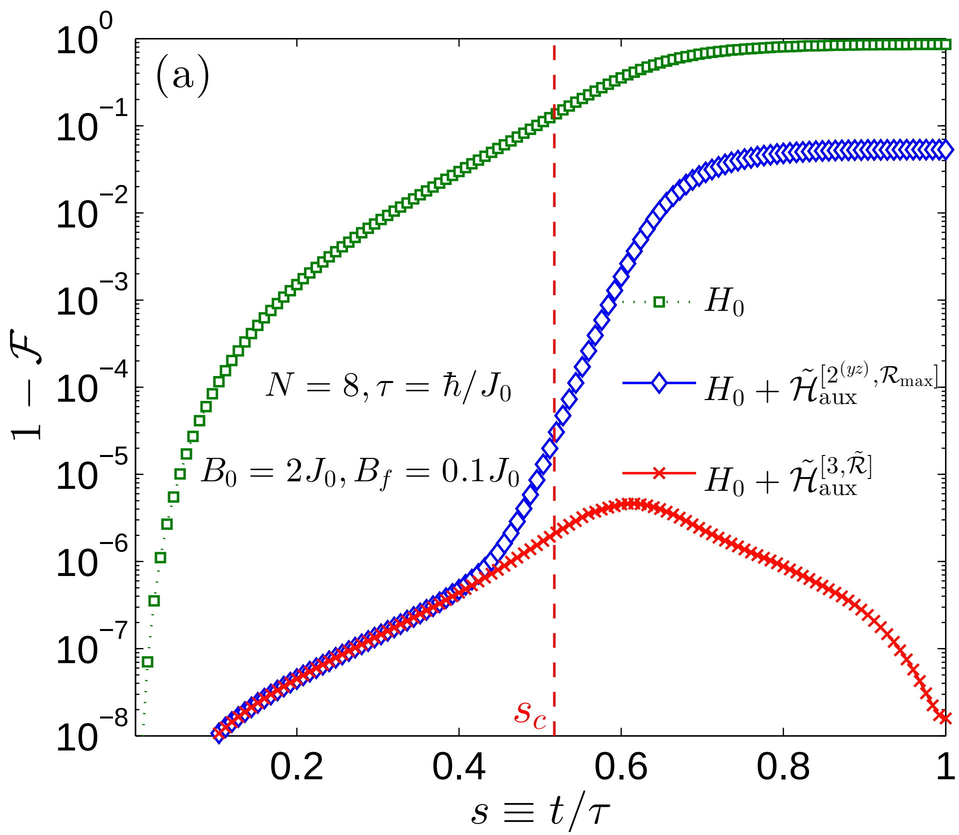
Approximated Auxiliary Hamiltonian $\tilde{H}_1 = \sum_{k=1}^{K} \alpha_k L_k$

Minimize the norm $\min_{\{\alpha_k\}} ||(H_1 - \tilde{H}_1)|GS(t)\rangle||^2$

T. Opatrný, K. Mølmer, NJP 16, 015025 (2014)
H. Saberi, T. Opatrný, K. Mølmer, AdC, Phys. Rev. A 90, 060301(R) (2014)

Suppressing KZM/excitations

Approximated Auxiliary Hamiltonian $$\tilde{H}_1(t) = \sum_{i_1,i_2}{}^{\prime} h^{y,z}_{i_1,i_2}(t)\, \sigma^y_{i_1} \otimes \sigma^z_{i_2}$$



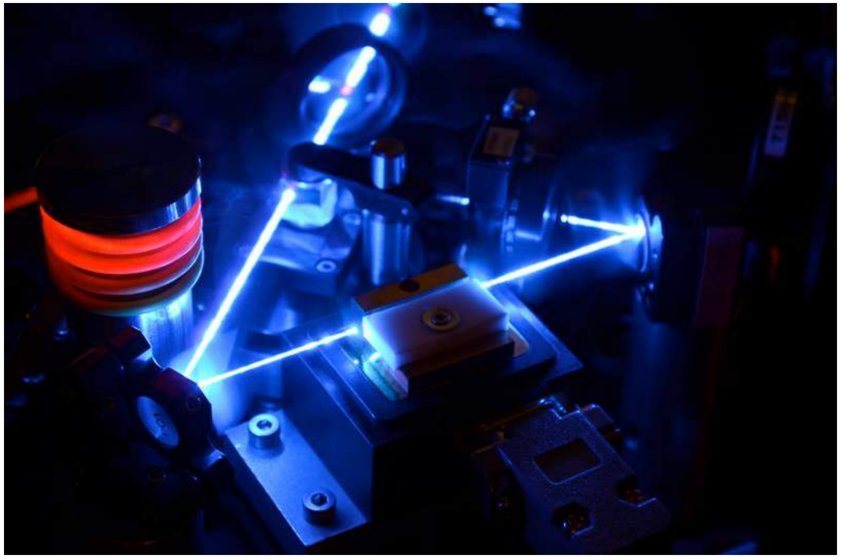
Ising

Ising + 2 body

Ising + 2 & 3 body

H. Saberi, T. Opatrný, K. Mølmer, AdC, Phys. Rev. A 90, 060301(R) (2014)

Testing KZM in a Quantum Simulator



Jin-Ming Cui, Yun-Feng Huang, Zhao Wang, Dong-Yang Cao, Jian Wang, Wei-Min Lv,

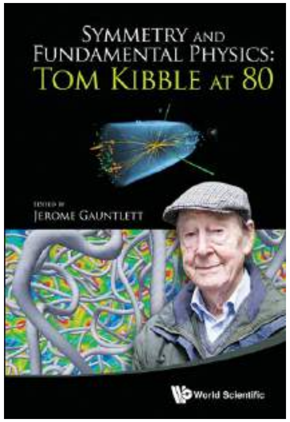
Yong Lu, Le Luo, Adolfo del Campo, Yong-Jian Han, Chuan-Feng Li, Guang-Can Guo,

arXiv:1505.05734

Case for Quantum Simulation

- Experimental tests of KZM focused on **thermal** phase transitions
- Challenges: varying quench rate, counting of defects, determining universality class

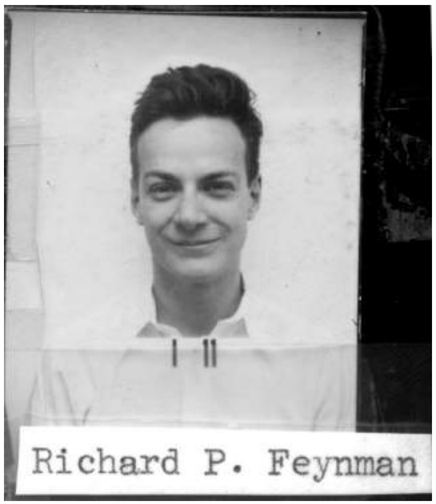
A. del Campo, W. H. Zurek
Int. J. Mod. Phys. A **29**, 1430018 (2014)



- Experiments in the **Quantum** regime are even mode difficult
- Additional challenges: ground-state cooling, decoherence

Quantum Simulation

- Use a simple quantum system to simulate a more complex one



Simulating Physics with Computers

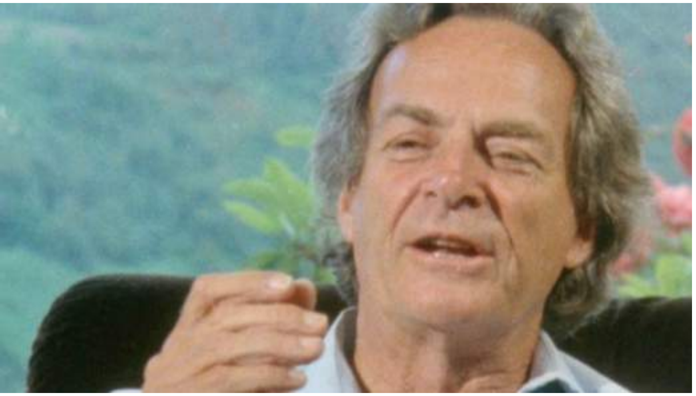
Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

Quantum Simulation

- Use a simple quantum system to simulate a more complex one



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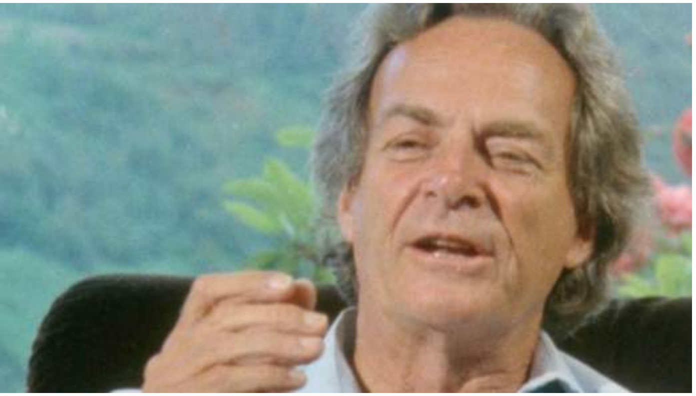

Simulating Physics with Computers

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- Testing KZM in the Quantum Regime
  - Simulated system: Quantum Phase Transition in 1D Ising spin chain
  - Quantum Simulator: a single qubit, trapped ion

Simulated system: 1d Quantum Ising Chain

Ising chain Hamiltonian $$\hat{H}_0(t) = -\sum_{n=1}^{N}\left[\sigma_n^x\sigma_{n+1}^x + g(t)\sigma_n^z\right]$$

Critical point $g_c = 1$

$g \gg 1 \quad |\rightarrow\rightarrow\rightarrow\cdots\rightarrow\rangle$

z-axis

$g \ll 1 \quad |\uparrow\uparrow\uparrow\dots\uparrow\rangle$

$|\downarrow\downarrow\downarrow\dots\downarrow\rangle$

x-axis

Excitations: $|\dots\uparrow\downarrow\downarrow\downarrow\downarrow\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\downarrow\downarrow\downarrow\uparrow\uparrow\uparrow\uparrow\downarrow\downarrow\downarrow\downarrow\dots\rangle$

→ With PBC Equivalent to LZ crossings

Simulated system: 1d Quantum Ising Chain

Ising chain Hamiltonian

$$\hat{H}_0(t) = -\sum_{n=1}^{N}\left[\sigma_n^x\sigma_{n+1}^x + g(t)\sigma_n^z\right]$$

Critical point $g_c = 1$

$$g \gg 1 \qquad |\rightarrow\rightarrow\rightarrow\cdots\rightarrow\rangle$$

z-axis

$$g \ll 1 \qquad |\uparrow\uparrow\uparrow\ldots\uparrow\rangle \qquad |\downarrow\downarrow\downarrow\ldots\downarrow\rangle$$

x-axis

Excitations

$$|\ldots\uparrow\downarrow\downarrow\downarrow\downarrow\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\downarrow\downarrow\downarrow\uparrow\uparrow\uparrow\uparrow\downarrow\downarrow\downarrow\downarrow\ldots\rangle$$

Mapping via Jordan-Wigner & Fourier Transforms [Dziarmaga PRL '05]

$$i\hbar\frac{d}{d\tau}\begin{bmatrix}\mu_k\\ \nu_k\end{bmatrix} = \frac{1}{2}\begin{bmatrix}-\Delta_k\tau & 1\\ 1 & \Delta_k\tau\end{bmatrix}\begin{bmatrix}\mu_k\\ \nu_k\end{bmatrix}$$

$$k = \pm\frac{1}{2}\frac{2\pi}{Na},\ldots,\pm\left(\frac{N}{2}-\frac{1}{2}\right)\frac{2\pi}{Na}$$

Simulated system: 1d Quantum Ising Chain

Ising chain Hamiltonian $$\hat{H}_0(t) = -\sum_{n=1}^{N}\left[\sigma_n^x\sigma_{n+1}^x + g(t)\sigma_n^z\right]$$

Critical point $$g_c = 1$$

$$g \gg 1 \qquad |\rightarrow\rightarrow\rightarrow\cdots\rightarrow\rangle$$

z-axis

$$g \ll 1 \qquad |\uparrow\uparrow\uparrow\ldots\uparrow\rangle$$

$$|\downarrow\downarrow\downarrow\ldots\downarrow\rangle$$

x-axis

Excitations $$|\ldots\uparrow\downarrow\downarrow\downarrow\downarrow\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\downarrow\downarrow\downarrow\uparrow\uparrow\uparrow\uparrow\downarrow\downarrow\downarrow\downarrow\ldots\rangle$$

Mapping via Jordan-Wigner & Fourier Transforms [Dziarmaga PRL '05]

$$n_{ex} = \frac{1}{N}\sum_n^N \frac{1}{2}\langle 1 - \sigma_n^z\sigma_{n+1}^z\rangle = \frac{1}{N}\sum_k^N \gamma_k^\dagger\gamma_k$$

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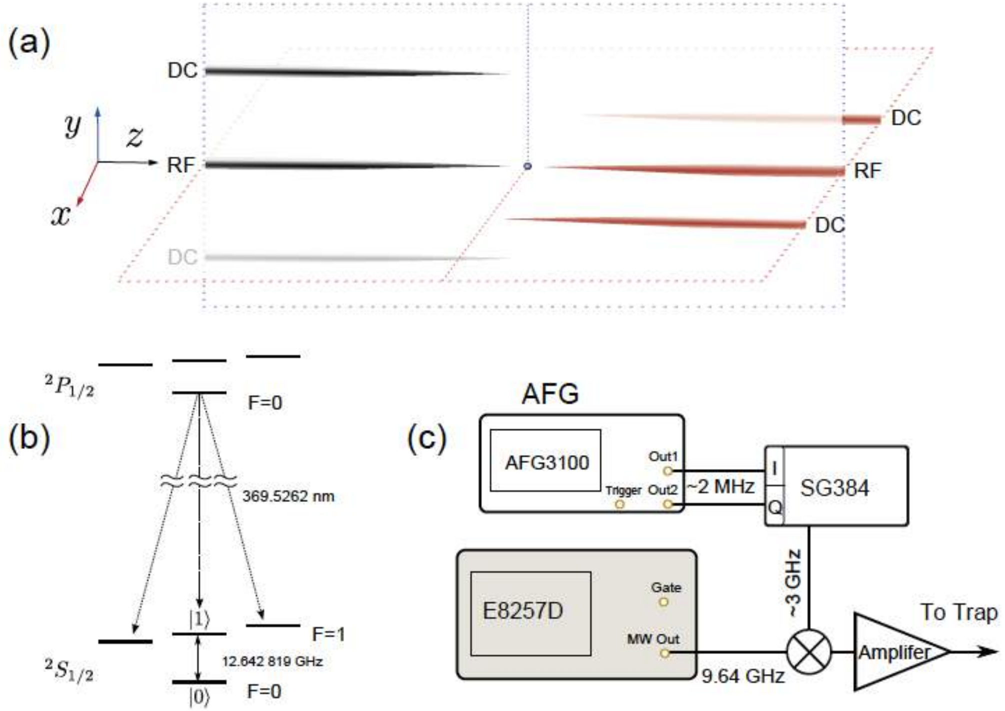
Quantum Simulator: trapped ion

$^{171}Yb^{+}$ confined in a Paul trap

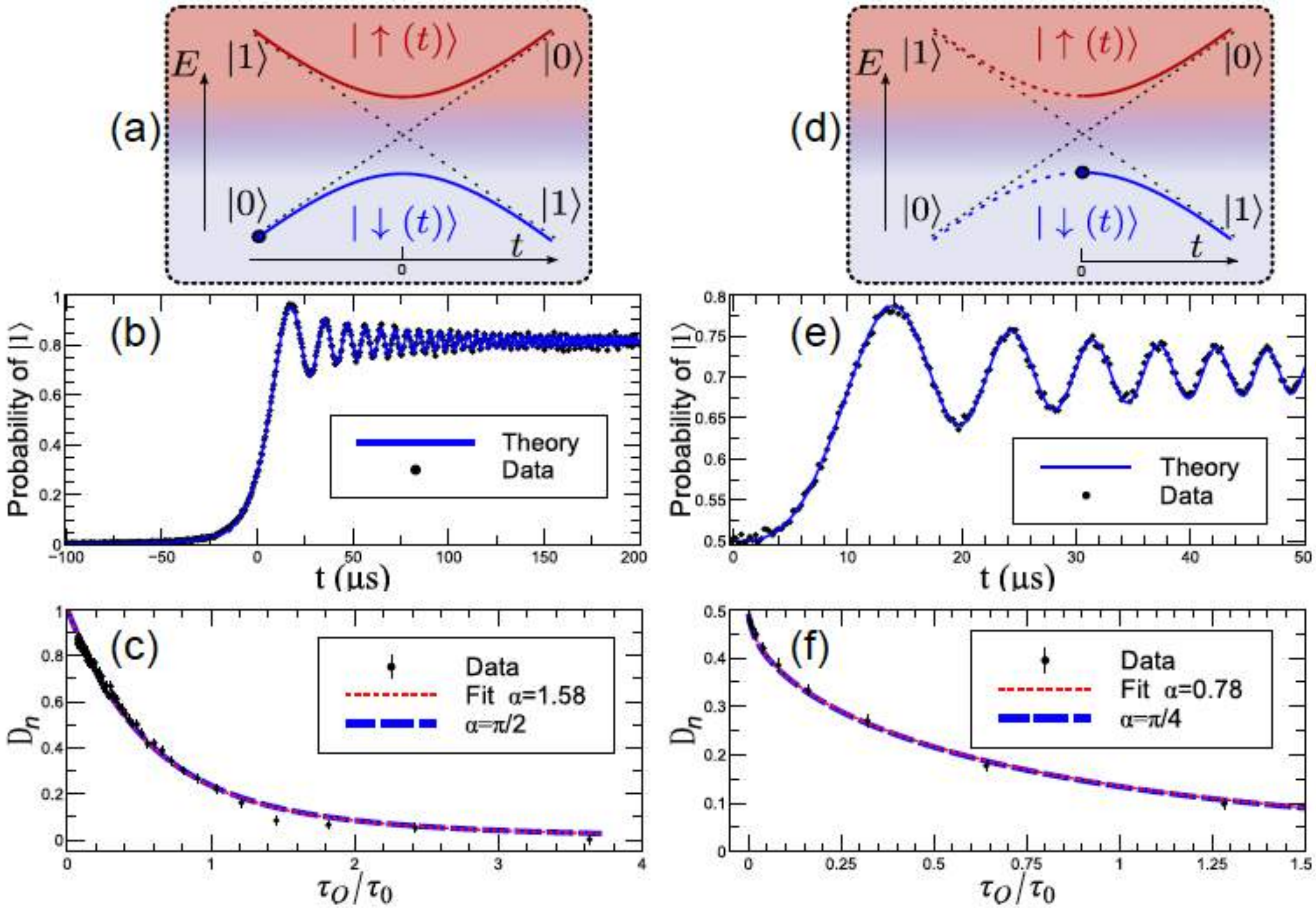
two hyperfine states |0> & |1>

Microwave control



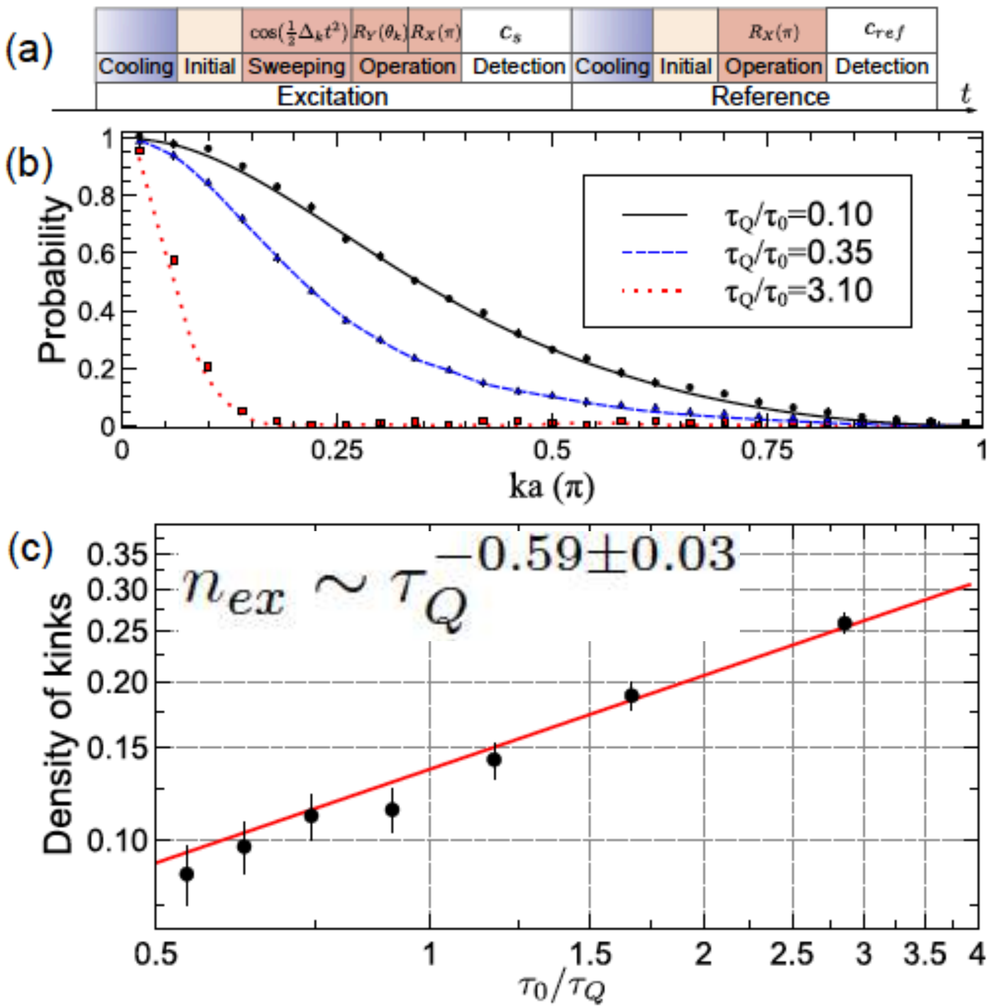
Cui et al. arXiv:1505.05734

Testing Landau-Zener dynamics



Cui et al. arXiv:1505.05734

Observing Quantum Kibble-Zurek scaling



Cui et al. arXiv:1505.05734

Quantum Simulation of QPT dynamics

First Experimental Demonstration of Kibble-Zurek scaling in the Quantum Regime

Ion-trap quantum simulation can be applied to

Nonlinear quenches,

Quantum control,

Shortcuts to Adiabaticity with auxiliary interactions,

Dephasing, Decoherence,

...

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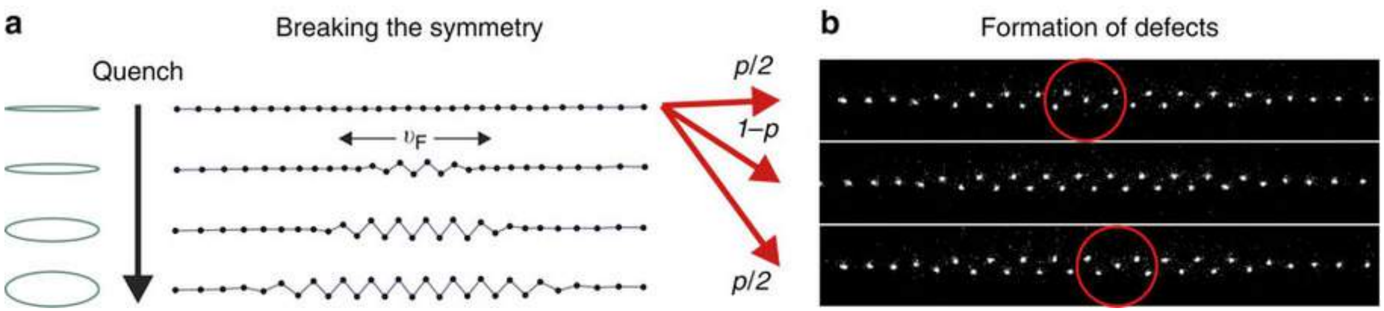
Cui et al. arXiv:1505.05734

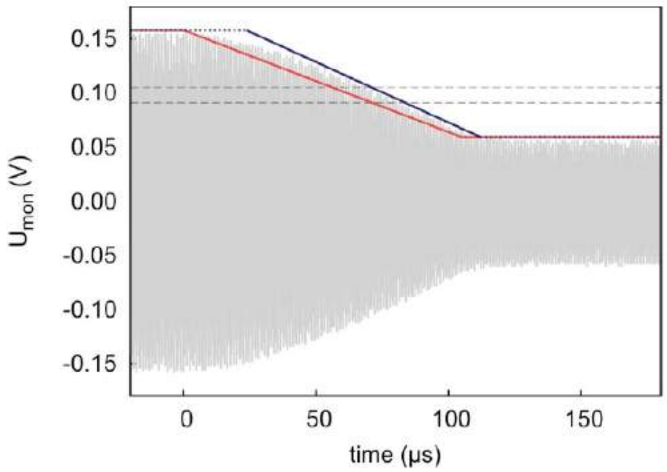
Noise in the controls

A. Dutta, A. Rahmani, A. del Campo, arXiv:1605.01062 (PRL)

Noisy control fields

Present in all experiments, e.g., KZM test squeezing an ion chain





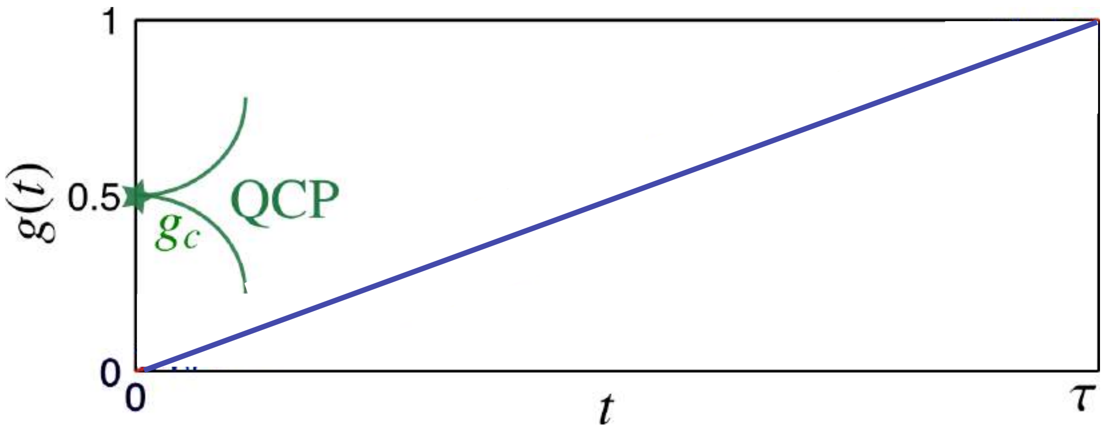
Noisy rf signal during quench

Pyka et al. Nature Communications 4, 2291 (2013)

Quantum Annealing Protocol

Example

$$H = -\Lambda \sum_{n=1}^{N} \left\{ [1 - g(t)]\, \hat{\sigma}_n^x + g(t) \hat{\sigma}_n^z \hat{\sigma}_{n+1}^z \right\}$$



$$H = -\Lambda \sum_{n=1}^{N} \hat{\sigma}_n^x$$

$$H = -\Lambda \sum_{n=1}^{N} \hat{\sigma}_n^z \hat{\sigma}_{n+1}^z$$

A. Dutta, A. Rahmani, A. del Campo, arXiv:1605.01062

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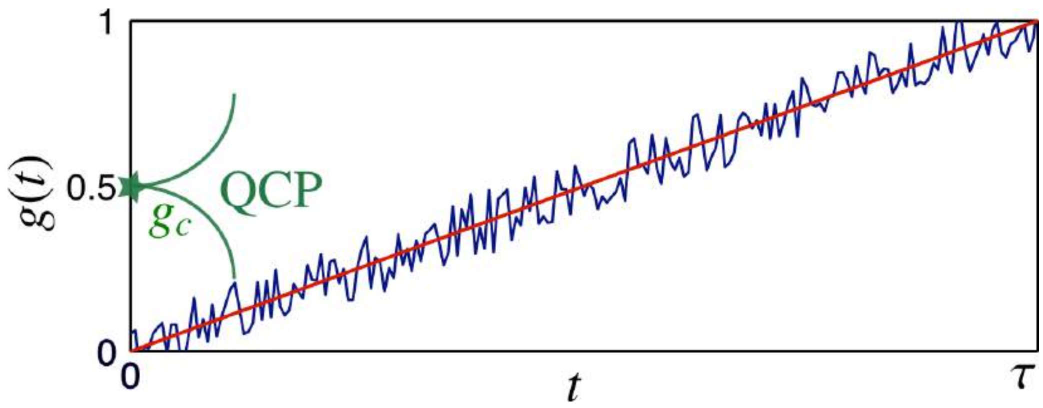
Noise in the control fields



Noisy control field

$$g(t) = t/\tau + \gamma(t), \quad 0 < t < \tau$$

$$\langle \gamma(t)\gamma(t') \rangle = W^2 \delta(t - t')$$

A. Dutta, A. Rahmani, A. del Campo, arXiv:1605.01062

Stochastic many-body Hamiltonians

Full system

$$H(t) = H_0(t) + \gamma(t)V$$

Deterministic and stochastic parts

$$H_0(t) = -\sum_{n=1}^{N} \left\{ [1 - g_0(t)]\, \hat{\sigma}_n^x + g_0(t)\hat{\sigma}_n^z \hat{\sigma}_{n+1}^z \right\}$$

$$V = -\sum_{n=1}^{N} \left(-\hat{\sigma}_n^x + \hat{\sigma}_n^z \hat{\sigma}_{n+1}^z \right)$$

Stochastic Schrodinger equation

$$i\frac{d}{dt}|\psi(t)\rangle = [H_0(t) + \gamma(t)V]\, |\psi(t)\rangle$$

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A. Dutta, A. Rahmani, A. del Campo, arXiv:1605.01062

Noise-Averaged dynamics

Density matrix averaged over realizations

$$\rho(t) = \langle \rho_{\rm st}(t) \rangle = \Big\langle |\psi(t)\rangle\langle\psi(t)| \Big\rangle$$

Master equation requires stochastic unravelling

$$\frac{d}{dt}\rho(t) = -i[H_0(t),\rho] - \int_0^t ds \langle \gamma(t)\gamma(s)\rangle \Big[V, \langle [\hat{U}_{\rm st}(t,s) V \hat{U}^\dagger_{\rm st}(t,s), \rho_{\rm st}(t)]\rangle\Big]$$

Simplified via Novikov's theorem for white noise

$$\boxed{\frac{d}{dt}\rho(t) = -i[H_0(t),\rho(t)] - \frac{W^2}{2}[V,[V,\rho(t)]]}$$

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A. Dutta, A. Rahmani, A. del Campo, arXiv:1605.01062

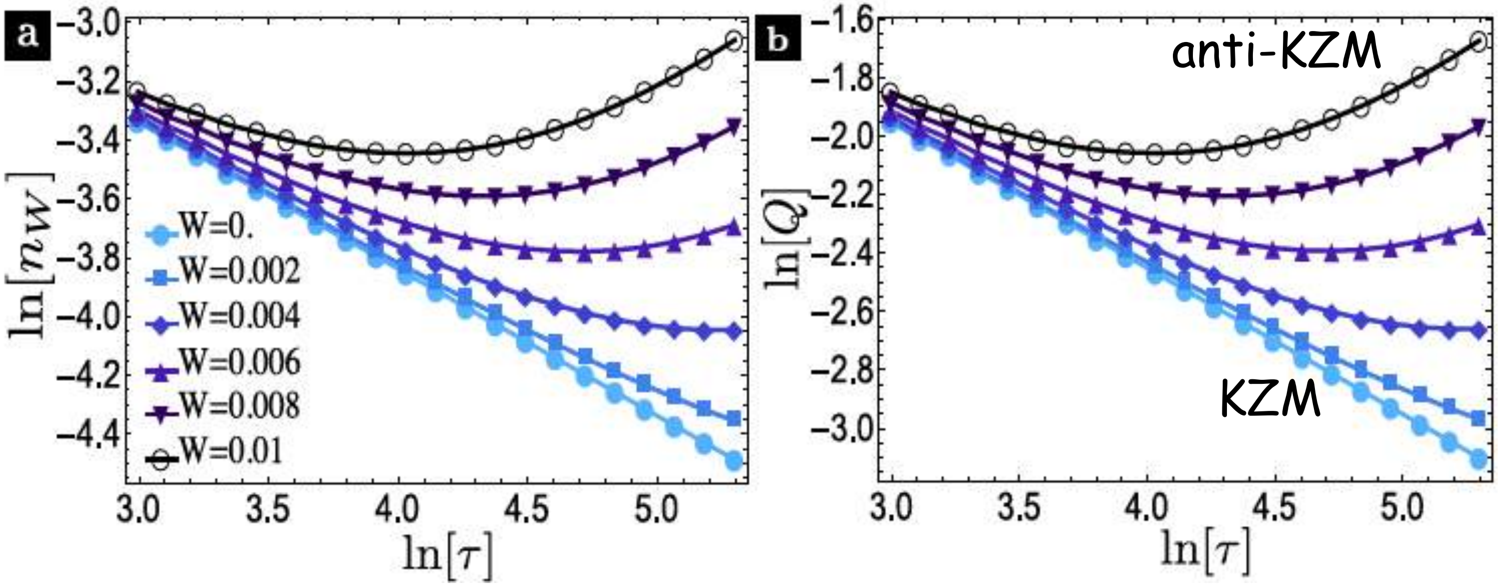
Annealing dynamics

Density of excitations

$$n_W = 1 - \frac{1}{N}\sum_{k>0}\langle G_k(\tau)|\varrho_k(t)|G_k(\tau)\rangle$$

Residual energy

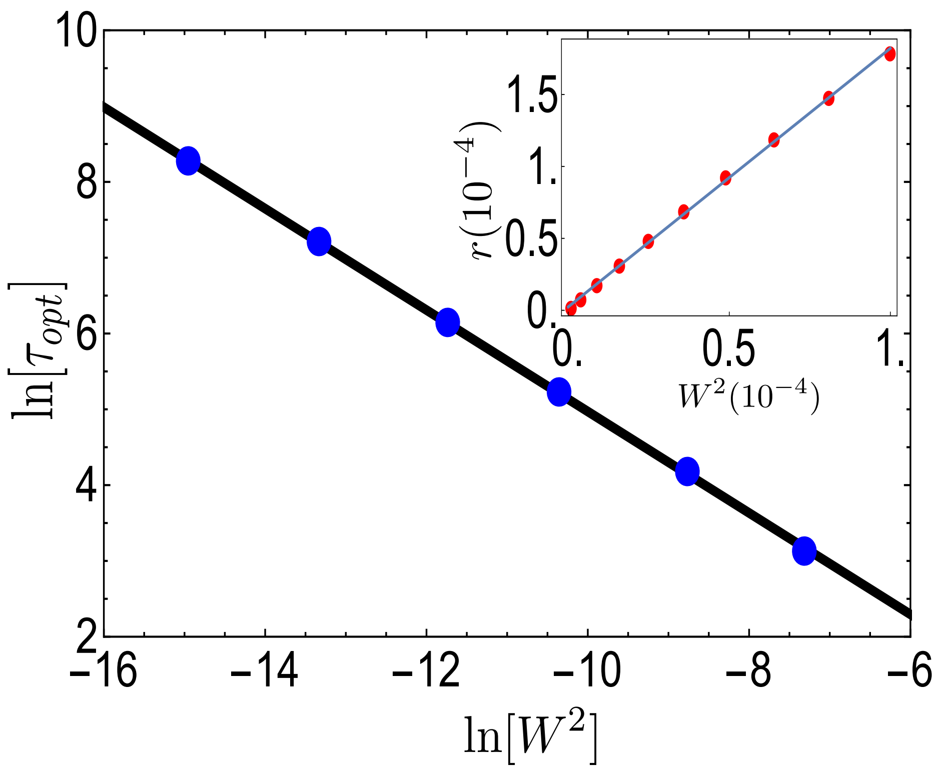
$$Q = [E(\tau) - E_{GS}(\tau)]/N$$



Noise-induced breakdown of adiabatic protocols
Anti-Kibble-Zurek behavior

A. Dutta, A. Rahmani, A. del Campo, arXiv:1605.01062

Universality of optimal annealing time



Density of excitations

$$n_W \approx r\tau + c\tau^{-\beta}$$

Kibble-Zurek exponent

$$\beta = \frac{d\nu}{1 + z\nu}$$

Optimal annealing time

$$\tau_{\rm opt} \propto (W^2)^{-1/(\beta+1)}$$

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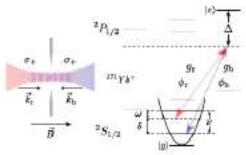
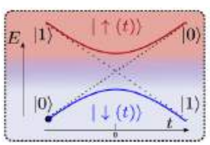
A. Dutta, A. Rahmani, A. del Campo, arXiv:1605.01062

Summary

◆ Kibble-Zurek scaling: long annealing times

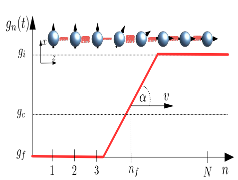


◆ Shortcuts to Adiabaticity provide a way out



◆ First exp test of KZM in the Quantum Regime

◆ Noise: Anti-Kibble Zurek behavior & optimal annealing time



◆ Inhomogeneous Quantum Annealing for AQC

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Thanks for your attention!!

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JTF