Title: Dynamical analogue quantum simulators

Date: May 12, 2014 11:25 AM

URL: http://pirsa.org/14050068

Abstract: Complex quantum systems out of equilibrium are at the basis of a number of long-standing questions in physics. This talk will be concerned on the one hand with recent progress on understanding how quantum many-body systems out of equilibrium eventually come to rest, thermalise and cross phase transitions, on the other hand with dynamical analogue quantum simulations using cold atoms [1-4]. In an outlook, we will discuss the question of certification of quantum simulators, and will how this problem also arises in other related settings, such as in Boson samplers [5,6]. [1] S. Braun, M. Friesdorf, S. S. Hodgman, M. Schreiber, J. P. Ronzheimer, A. Riera, M. del Rey, I. Bloch, J. Eisert, U. Schneider, arXiv:1403.7199.
[2] M. Kliesch, M. Kastoryano, C. Gogolin, A. Riera, J. Eisert, arXiv:1309:0816.
[3] S. Trotzky, Y.-A. Chen, A. Flesch, I. P. McCulloch, U. Schollwoeck, J. Eisert, I. Bloch, Nature Physics 8, 325 (2012).
[4] A. Riera, C. Gogolin, M. Kliesch, J. Eisert, in preparation (2014).
[5] C. Gogolin, M. Kliesch, L. Aolita, J. Eisert, in preparation (2014) and arXiv:1306.3995.
[6] S. Aaronson, A. Arkhipov, arXiv:1309.7460.


Dynamical analog(ue) quantum simulators
Probing quantum many-body systems out of equilibrium
Jens Eisert
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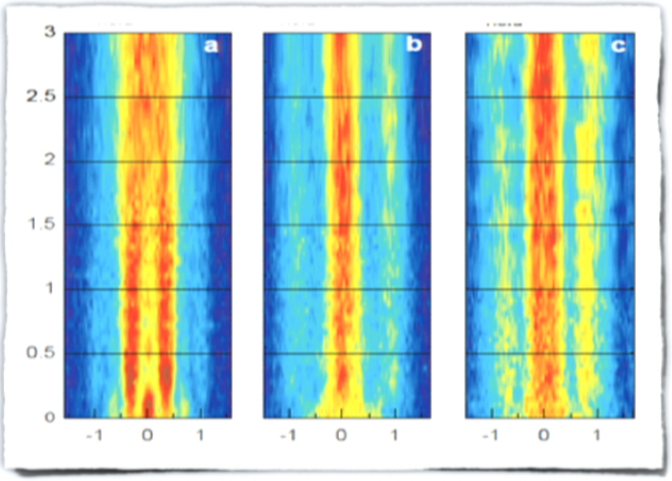
Probing quantum many-body systems out of equilibrium



Jens Eisert

Freie Universität Berlin

Quantum many-body dynamics, Perimeter Institute, May 12, 2014

Mentions joint work with M. Friesdorf, C. Gogolin, M. Kliesch, A. Riera, M. del Rey, S. Braun, S. Trotzky, I. McCulloch, A. Flesch, Y.-U. Chen, U. Schneider, and I. Bloch

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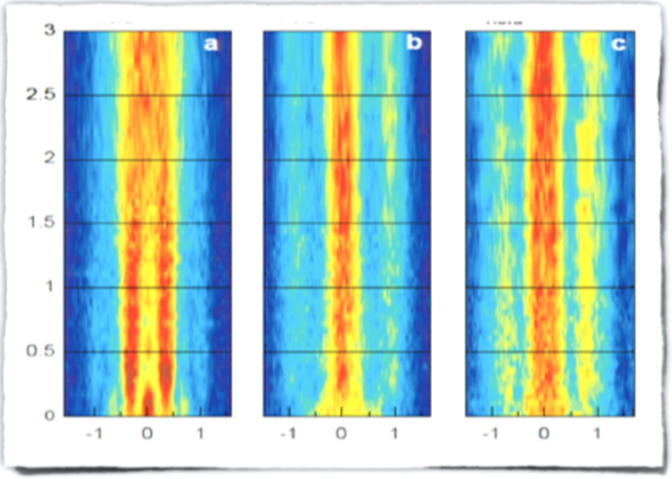

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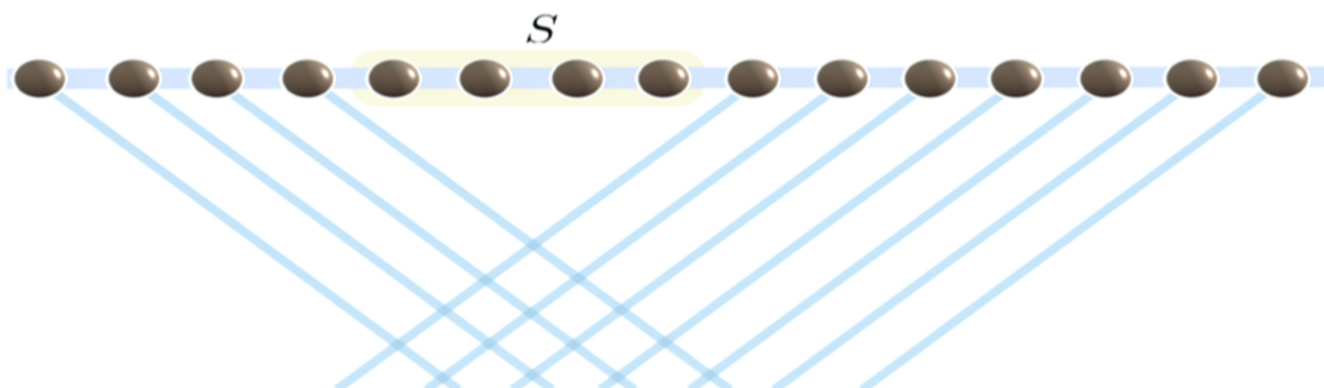
quilibration (to generalised Gibbs ensemble) with time scales



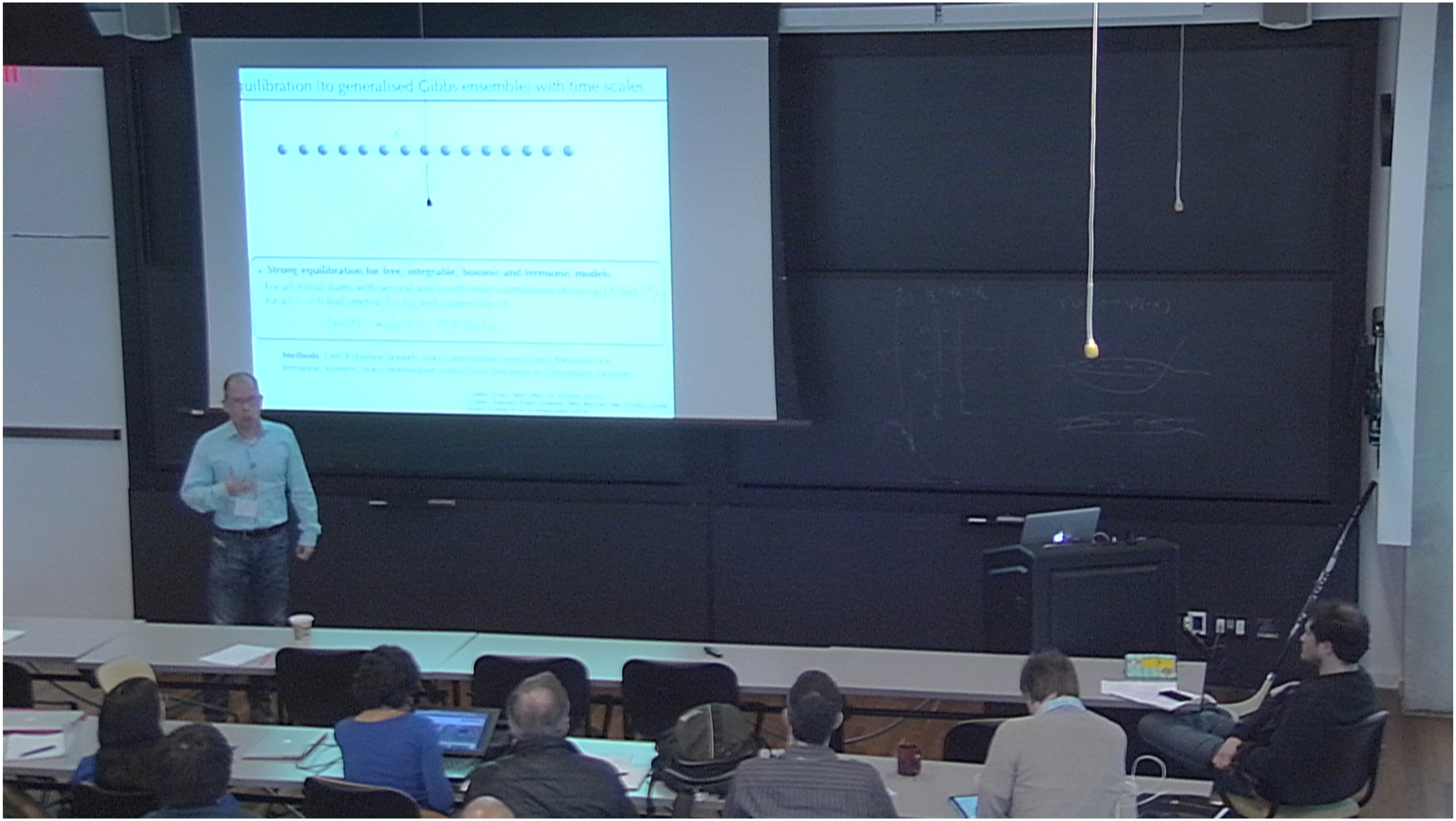
- **Strong equilibration for free, integrable, bosonic and fermionic models**

  For all initial states with second and fourth order correlations decaying $O(\text{dist}^{-2})$, for all $\varepsilon > 0$ find interval $[t_1, t_2]$ and system size s.t.

$$\|\rho_S(t) - \omega_S\|_1 < \varepsilon, \quad \forall t \in [t_1, t_2]$$

Methods: Lieb-Robinson bounds, non-commutative central limit theorems, for fermionic systems, non-commutative central limit theorems in Grassmann variables

Cramer, Eisert, *New J Phys* **12**, 055020 (2010)
Cramer, Dawson, Eisert, Osborne, *Phys Rev Lett* **100**, 030602 (2008)
Eisert, Cramer et al, in preparation (2014)


uilibration (to generalised Gibbs ensemble) with time scales
Strong equilibration for free, integrable, bosonic and fermionic models
Methods

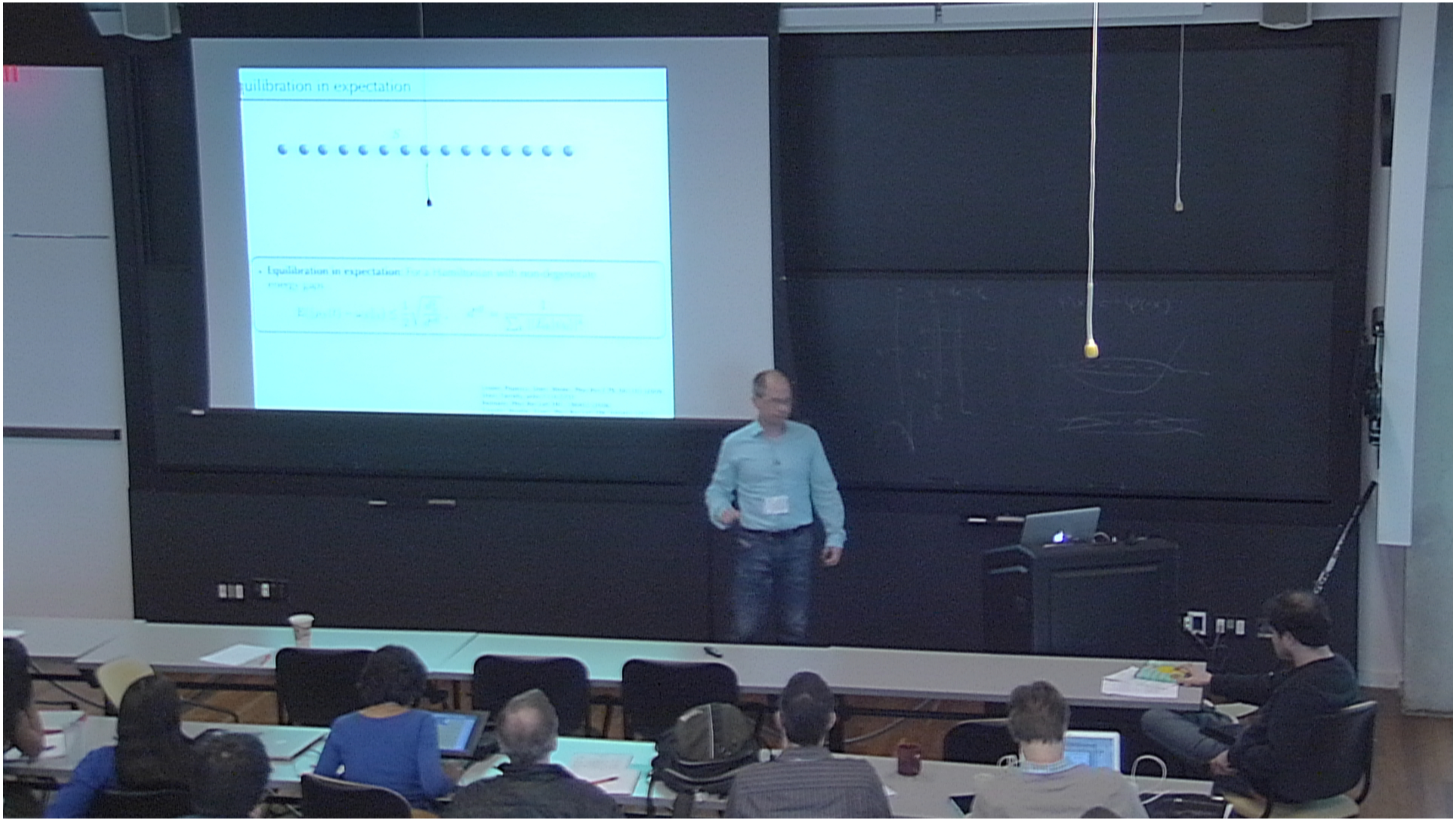
quilibration in expectation

- **Equilibration in expectation:** For a Hamiltonian with non-degenerate energy gaps

$$\mathbb{E}(\|\rho_S(t) - \omega_S\|_1) \leq \frac{1}{2}\sqrt{\frac{d_S^2}{d^{\text{eff}}}}\,, \qquad d^{\text{eff}} = \frac{1}{\sum_k |\langle E_k|\psi_0\rangle|^4}$$

Linden, Popescu, Short, Winter, *Phys Rev E* **79**, 061103 (2009)
Short, Farrelly, arXiv:1110.5759
Reimann, *Phys Rev Lett* **101**, 190403 (2008)
Gogolin, Mueller, Eisert, *Phys Rev Lett* **106**, 040401 (2011)


uilibration in expectation


uilibration in expectation
Equilibration in expectation:

essons

- **Lesson**: Systems generically locally "appear relaxed", although dynamics is entirely unitary

- Proven in *strong sense* for general states in *integrable limit* of Bose-Hubbard model
- True in slightly weaker sense generically

- **Time scales for non-integrable models?**

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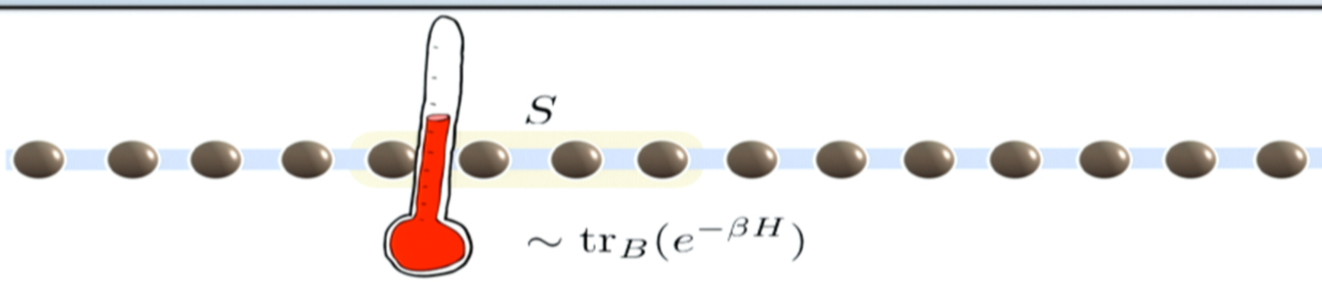
rategies towards thermalisation



sumptions about $|E_k\rangle$

Assumptions about $\langle E_k|\psi_0|E_k\rangle$

"Eigenstate thermalization hypothesis"

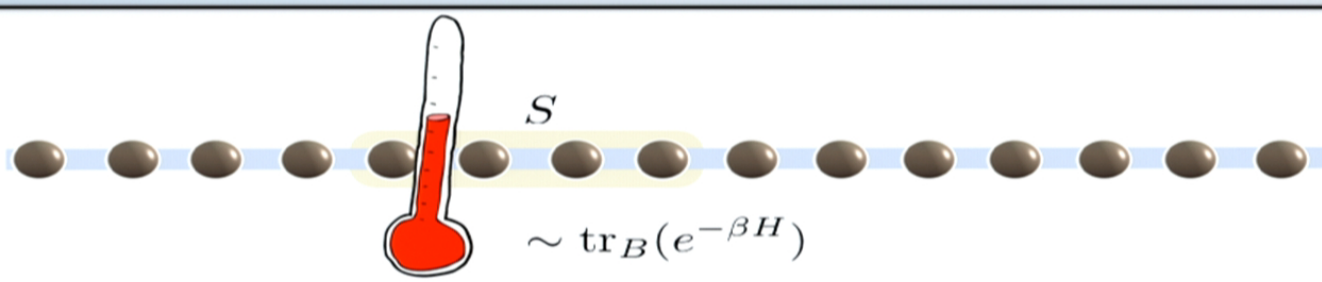
This approach

Thermalisation

tsch, *Phys Rev A* **43**, 2046 (1991)
lnicki, *Phys Rev E* **50**, 888 (1994)
l, Dunjko, Olshanii, Nature **452**, 854 (2008)

Riera, Gogolin, Eisert, *Phys Rev Lett* **108**, 080402 (2012)
Riera, Kliesch, Gogolin, Eisert, in preparation (2014)

ermalization



- **Progress on thermalisation question**

- Consider **1D local Hamiltonians** H of n sites, translationally invariant,
- Initial states with a flat energy distribution in $[nE, n(E+\Delta)]$ locally equilibrate towards a Gibbs state, even if they are **initially far from equilibrium:** can bound

$$\|\mathrm{tr}_B(e^{-\beta H})/Z - \omega_S\|_1 \leq \delta$$

with δ that depends on Δ , E, and basic spectral properties of $H = \sum_j h_j$

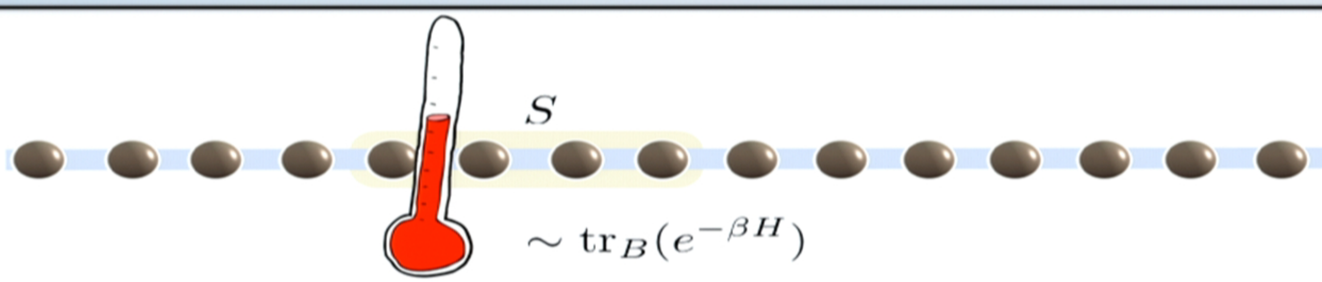
Methods: Spectral perturbation theory, concentration of measure and typicality tools

Riera, Gogolin, Eisert, *Phys Rev Lett* **108**, 080402 (2012)
Riera, Gogolin, Eisert, in preparation (2014)

Mueller, Adlam, Masanes, Wiebe, arXiv:1312.7420
Tasaki, *Phys Rev Lett* **80**, 1373 (1998)
Popescu, Short, Winter, *Nature Phys* **2**, 754 (2006)
Goldstein, Lebowitz, Tumulka, Zanghi, *Phys Rev Lett* **96**, 050403 (2006)


ermalization
Lesson

hermalization



- **Lesson**: Very weakly coupled systems with narrow initial energies thermalise

- Criteria for models *not* thermalising: If *effective entanglement in eigenbasis*

$$R(\psi_0) = \sum_k |\langle E_k|\psi_0\rangle|^2 \, \|\mathrm{tr}_B(|E_k\rangle\langle E_k| - \psi_0^S\|_1$$

is small, infinite memory of initial condition remains

Gogolin, Mueller, Eisert, Phys Rev Lett **106**, 040401 (2011)

- Present in many-body localised models

Pal, Huse, Phys Rev B 82, 174411 (2010)
Bauer, Nayak, J Stat Mech, P09005 (2013)

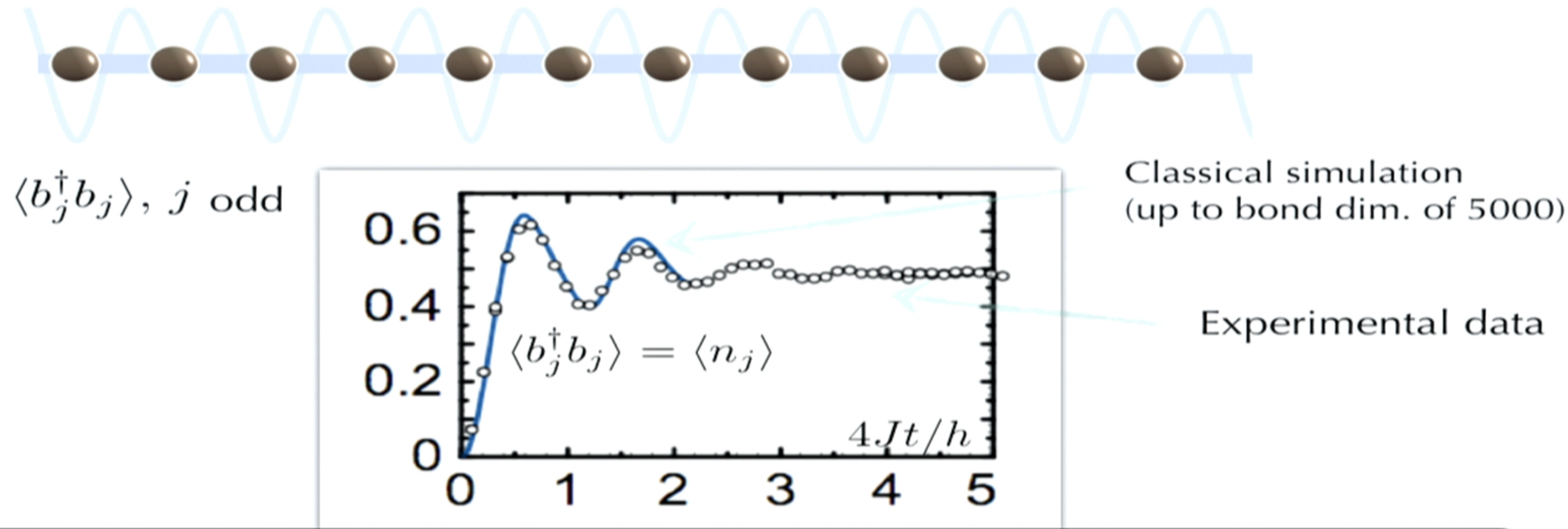
- Robust many-body translationally invariant models?

Compare Matthew's, Arijeet's talks

- **Many questions wide open**


n experiment probing dynamics of a strongly correlated model

lassical matrix product state simulation

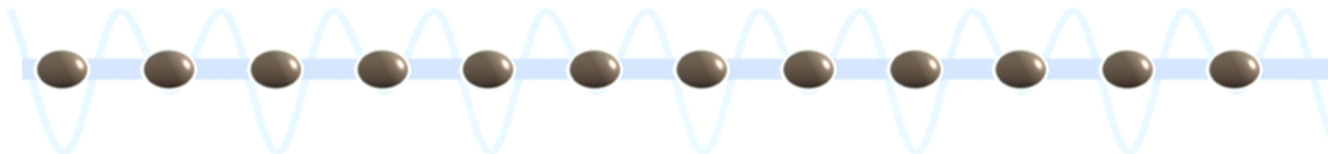


- **Observation 4: Short times matrix-product state (MPS) simulation**

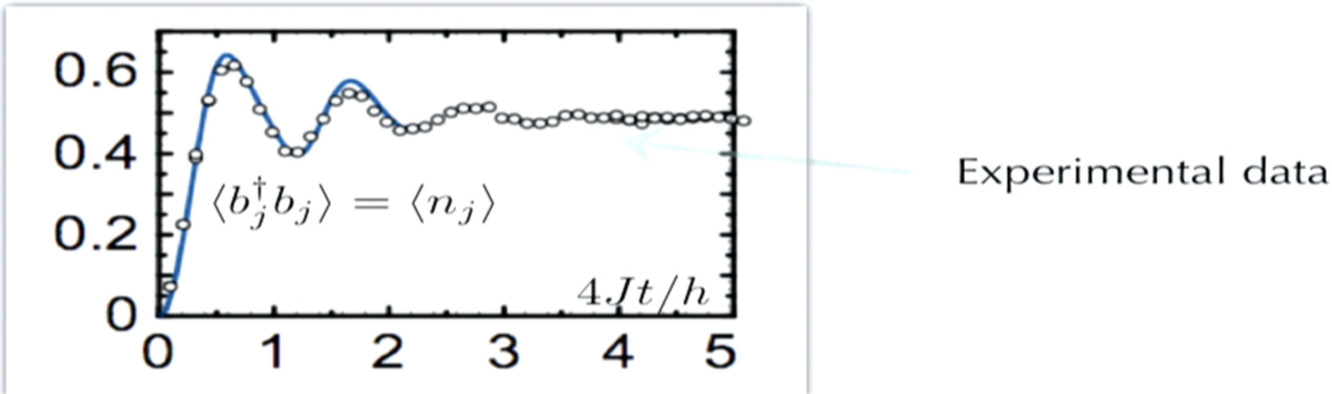
- **Short times:** Practically to machine precision with t-DMRG (5000 MPS-dim)
- Variational method based on MPS
- **Long times:** Exponential blow-up of bond dimension in time

Schollwoeck, *Rev Mod Phys* **77**, 259 (2005)
Verstraete, Cirac, Murg, *Adv Phys* **57**, 143 (2008)
Eisert, Cramer, Plenio, *Rev Mod Phys* **82**, 277 (2010)

uantum simulation



$\langle b_j^\dagger b_j \rangle$, j odd

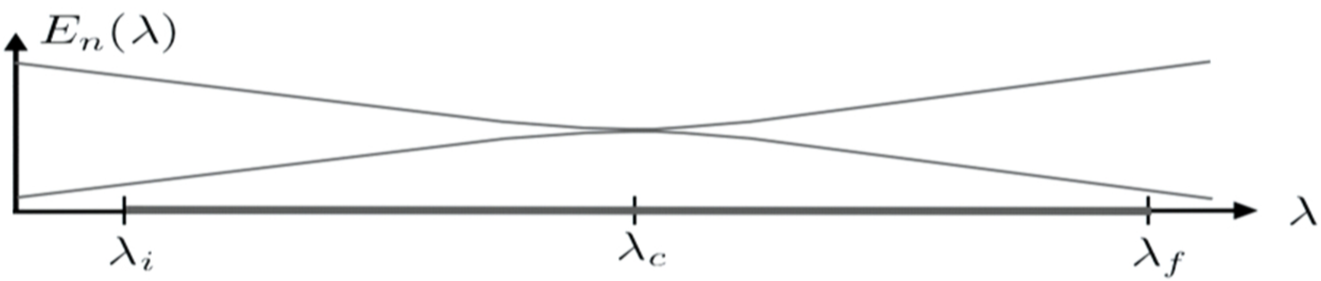


- **Observation 5: Long time dynamics of many-body dynamics in experiment**
- Can accurately probe dynamics for long times (exp vs poly decay, ...)
- "Outperforms" **best available classical simulation** on supercomputers

Trotzky, Chen, Flesch, McCulloch, Schollwoeck, Eisert, Bloch, *Nature Phys* **8**, 325 (2012)

rossing critical lines

- **Gapped phases:** "Adiabatic theorem ensures equilibrium"
- **Crossing a critical point:** Never sufficiently slow



bble Zurek narrative

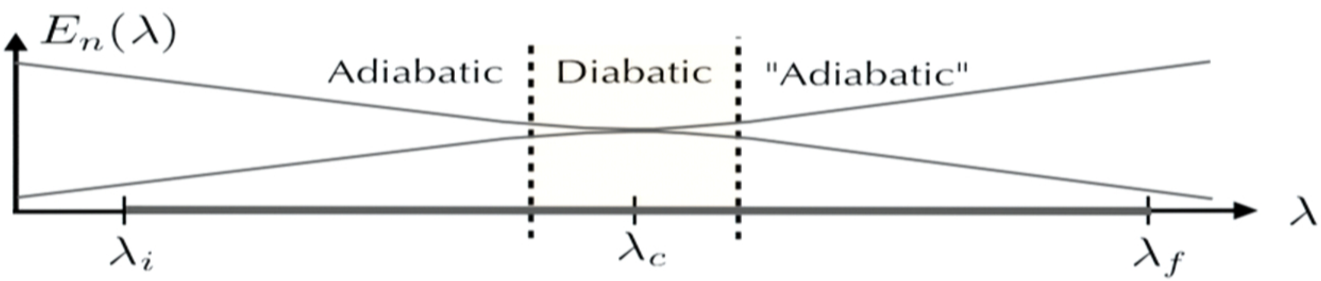
Crude intuitive picture: Dynamics are simplified to

- **Adiabatic regime** $\frac{d\Delta}{dt} \ll \Delta$
- **Diabatic regime**

Universality close to critical point $\xi \sim |\lambda - \lambda_c|^{-\nu}$

$$\Delta \sim |\lambda - \lambda_c|^{z\nu}$$

Predicts **power laws** for correlation lengths in quench time



Zurek, Dorner, Zoller, *Phys Rev Lett* **95**, 105701 (2005)
Dziarmaga, Rams, *New J Phys* **12**, 055007 (2010)
Del Campo, De Chiara, Morigi, Plenio, Retzker, *Phys Rev Lett* **105**, 075701 (2010)

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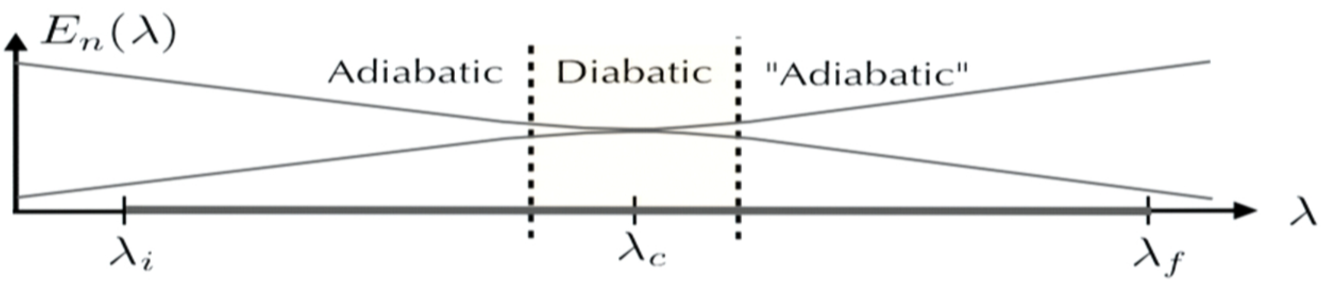

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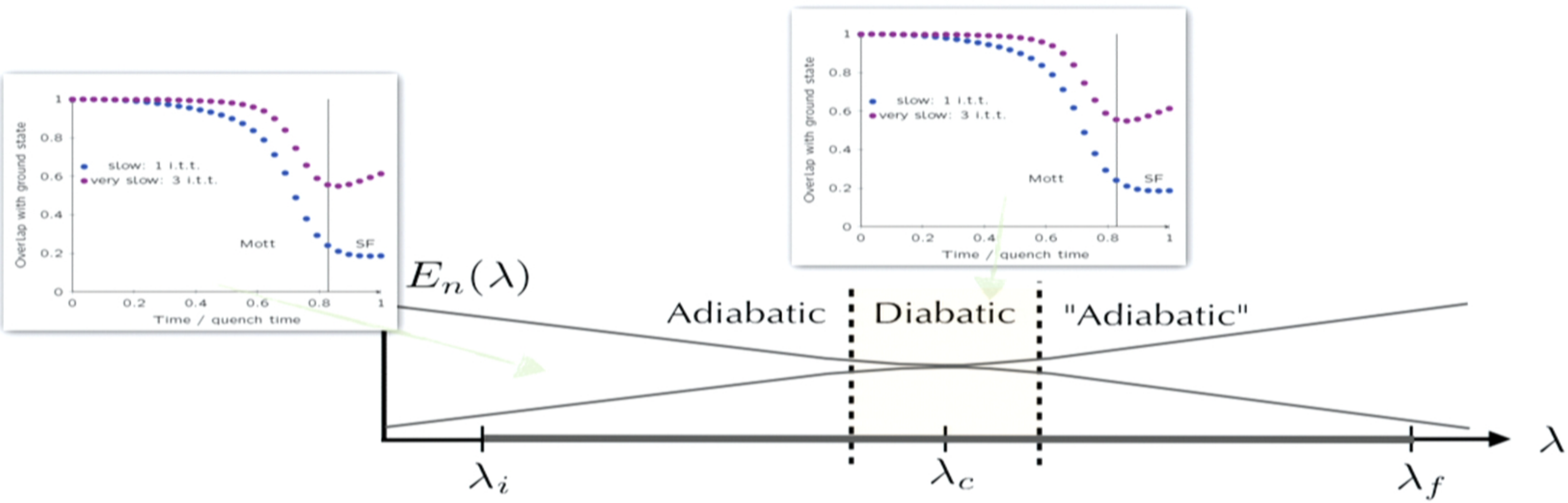
Crude picture is often too crude

Huge literature, no complete understanding

Inequivalent approaches: Free models, adiabatic perturbation theory, scaling collapse



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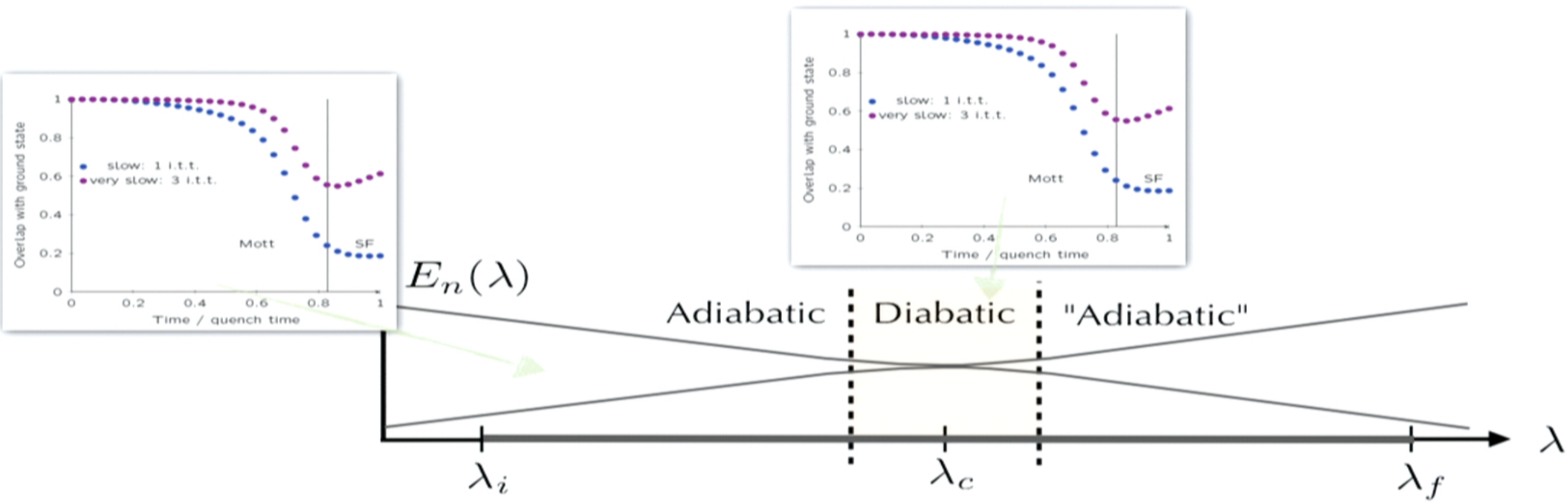

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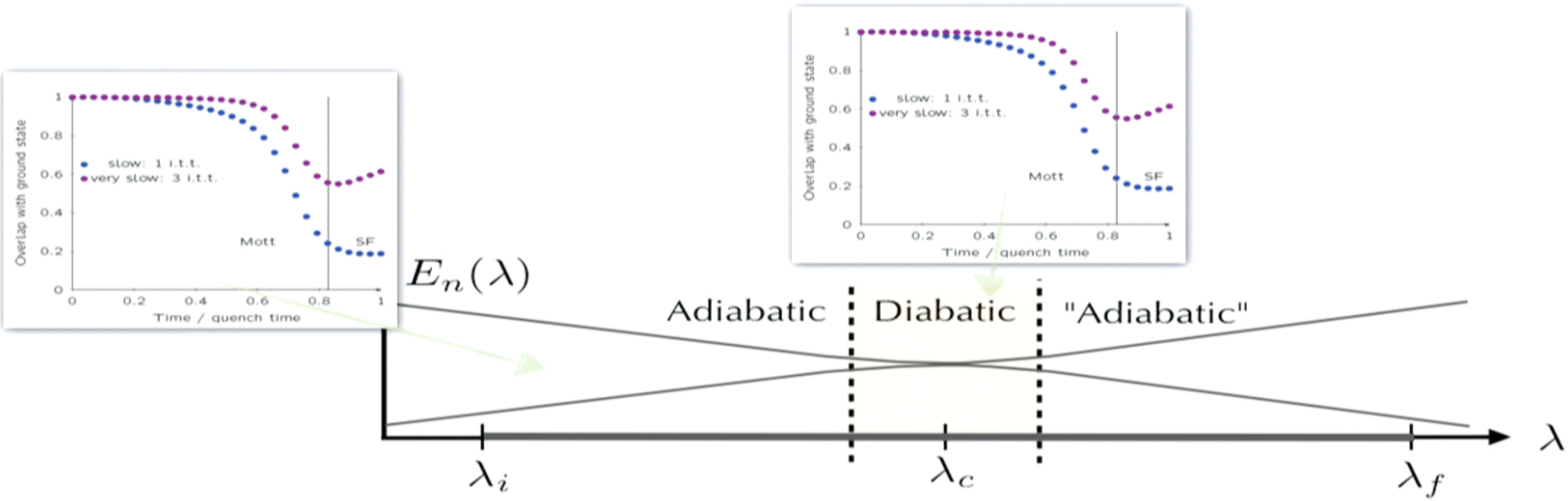

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experiment
Experiment in Immanuel Bloch/Uli Schneider's lab: Mott to superfluid quench
Heavy numerics: DMRG and exact diagonalisation in 1D
Careful study of effects of trap ... excellent agreement with data


experiment
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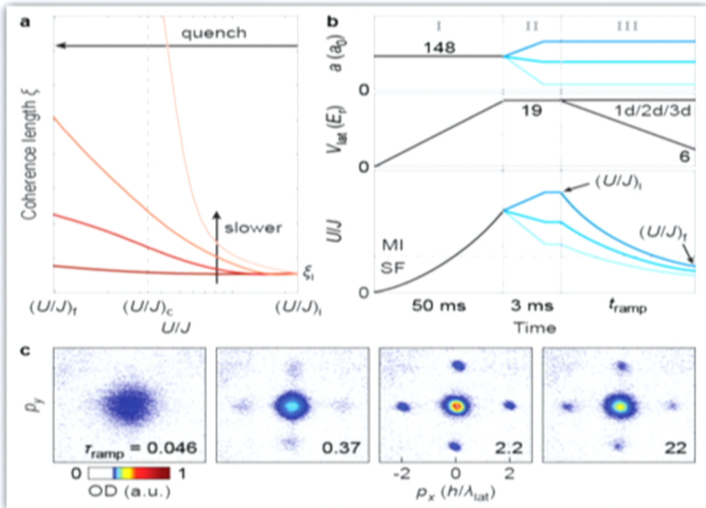
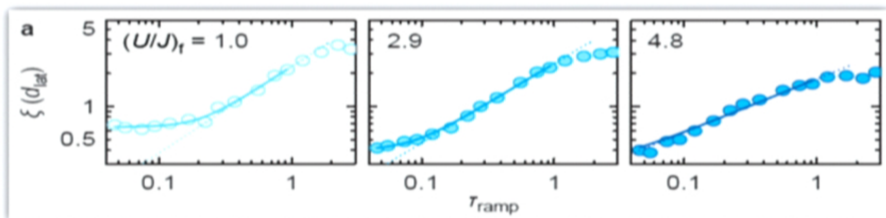


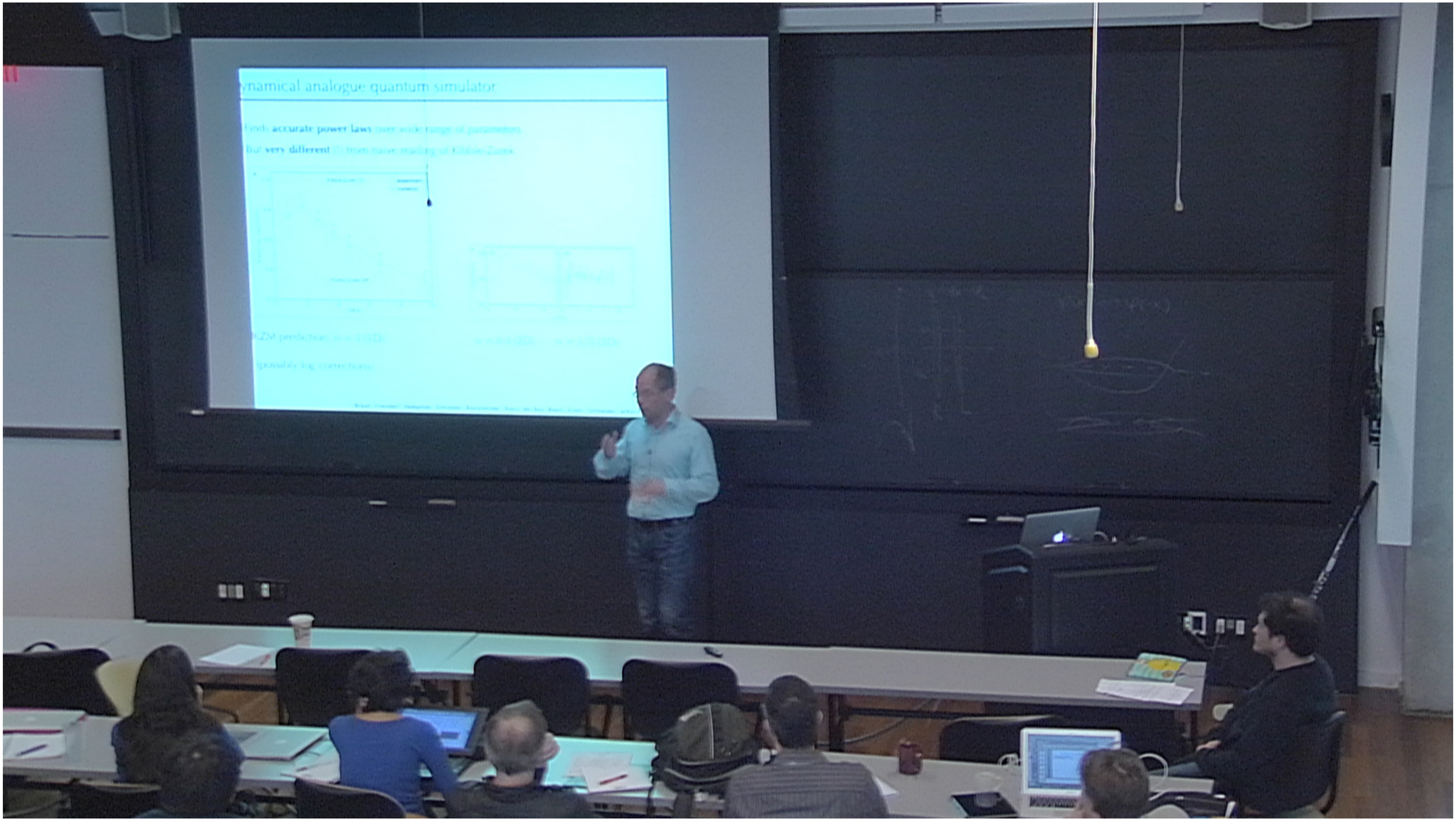


Heavy numerics: DMRG and **exact diagonalisation** in 1D

15 sites, truncation at 9 bosons, 2.581.186 basis states, 5.5 GB size of involved matrices)

Careful study of effects of trap ..., excellent **agreement** with data

Braun, Friesdorf, Hodgman, Schreiber, Ronzheimer, Riera, del Rey, Bloch, Eisert, Schneider, arXiv:1403.7199

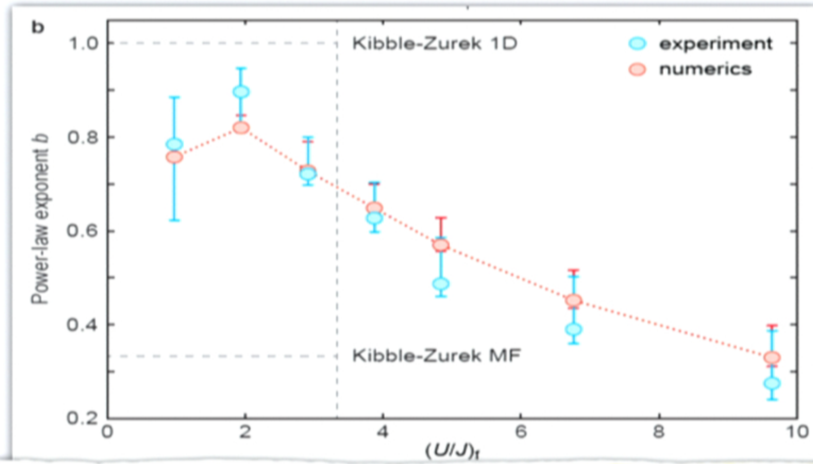

ynamical analogue quantum simulator
accurate power laws
very different

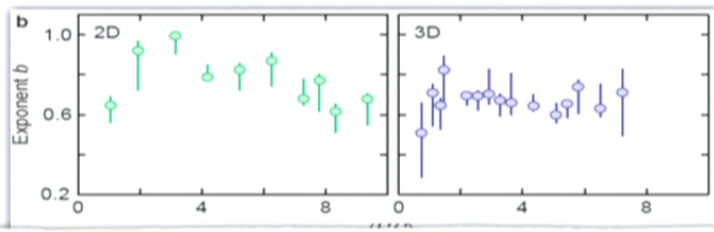

ynamical analogue quantum simulator
Finds accurate power laws over wide range of parameters
But very different from naive reading of Kibble-Zurek

ynamical analogue quantum simulator

Finds **accurate power laws** over wide range of parameters

But **very different** (!) from naive reading of Kibble-Zurek





- **Lesson**: Finds power laws, but different from naive reading of Kibble-Zurek picture
- **"Quantum simulation":** Build trust in correctness of simulation in 1D, experiment allows for assessment of 2D, 3D, alternative schedules etc

Braun, Friesdorf, Hodgman, Schreiber, Ronzheimer, Riera, del Rey, Bloch, Eisert, Schneider, arXiv:1403.7199

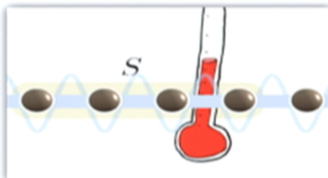
5. Summary and some musings

Gogolin, Kliesch, Aolita, Eisert, arXiv:1306.3995
Gogolin, Kliesch, Aolita, Eisert, in preparation (2014)

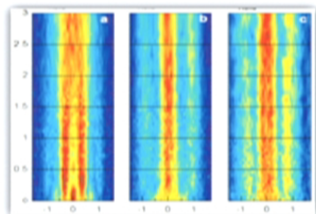
ummary

This talk: Quantum simulations of equilibration and thermalisation processes

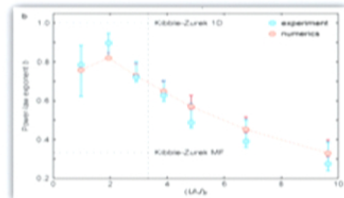
- Equilibration



- Thermalization



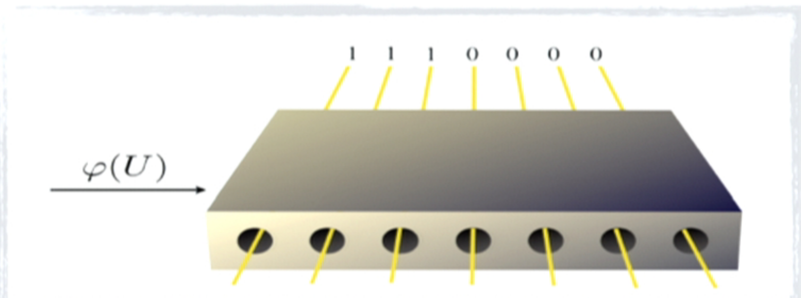
- Experimental fast quenches



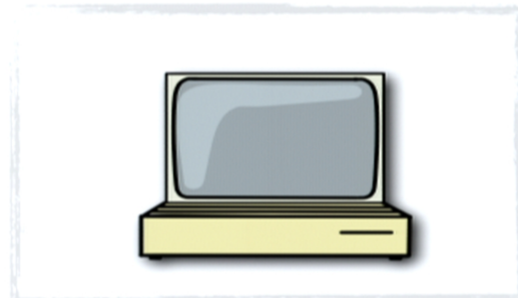
- "Crime story" of slow quenches

ualifiers in terms of complexity classes?

Great **experiments on boson sampling:** Cannot be efficiently classically sampled
(to constant error in 1-norm), unless collapse of polynomial hierarchy



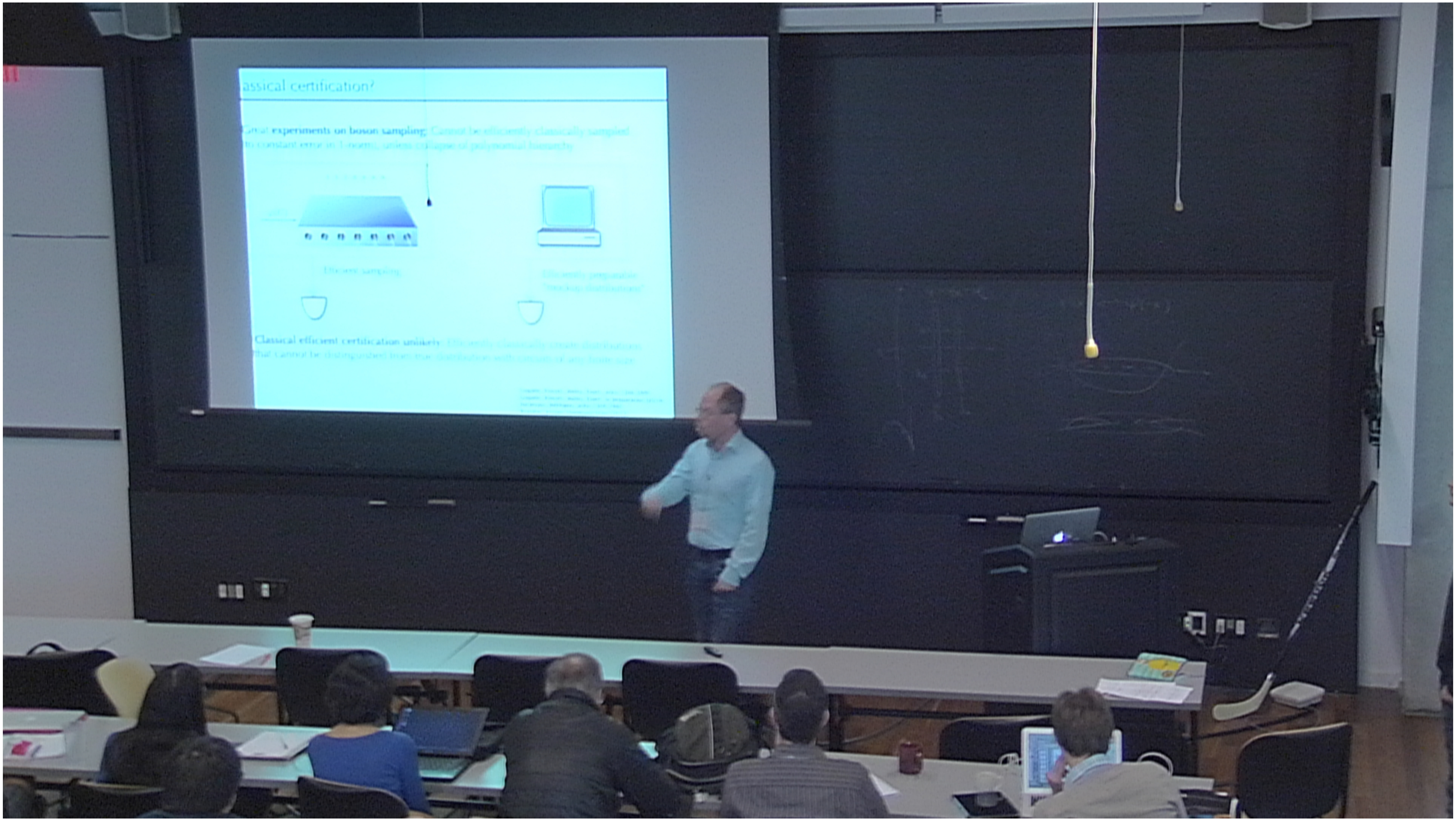
Efficient sampling

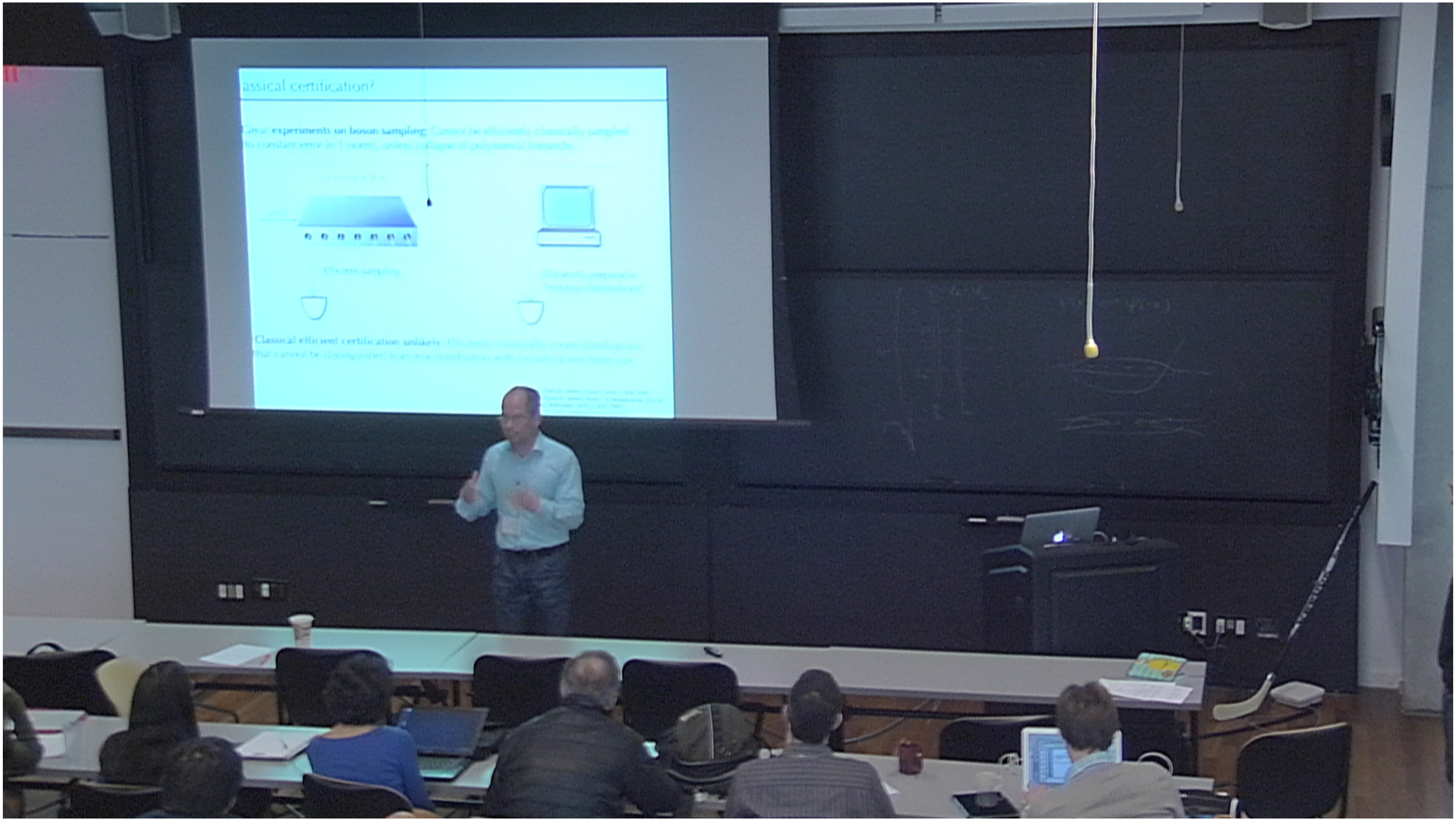


Presumably inefficient sampling

Aaronson, Arkhipov, Proc of ACM Symp Th Comp, STOC (2011)


ualifiers in terms of complexity classes?
experiments on boson sampling


assical certification?
experiments on boson sampling:
Classical efficient certification unlikely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