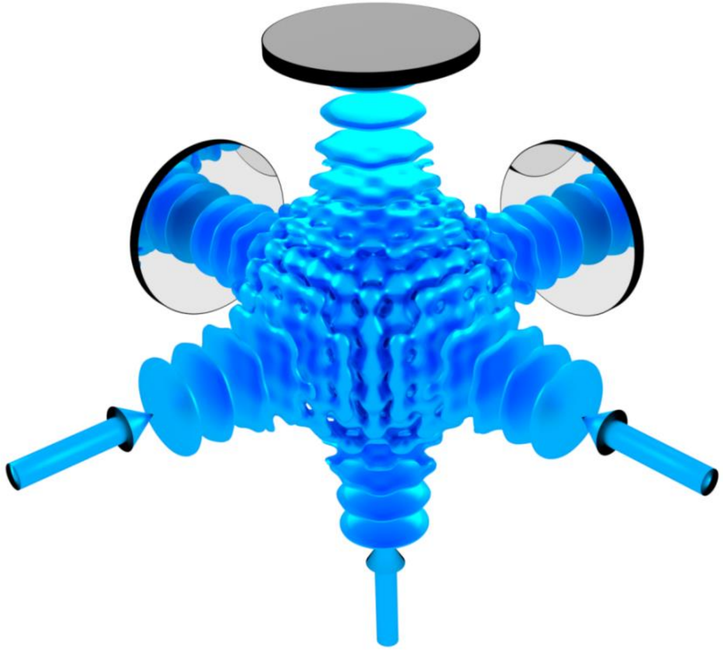
Quantum thermodynamics (and its breakdown) in optical lattices



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Engineering and Physical Sciences Research Council
AQuS
Analog Quantum Simulators for Many-Body Dynamics
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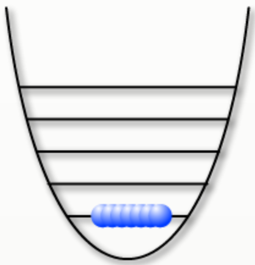
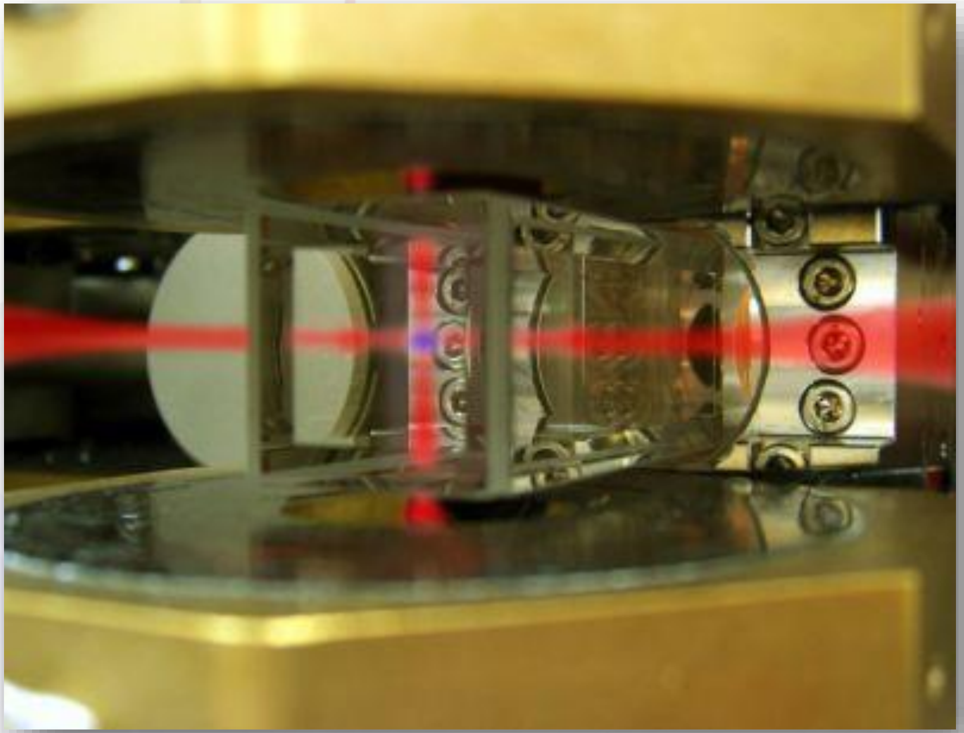
DesOEQ

Ultracold atoms: Isolated many-body systems



Bose-Einstein condensate of Potassium ^{39}K atoms

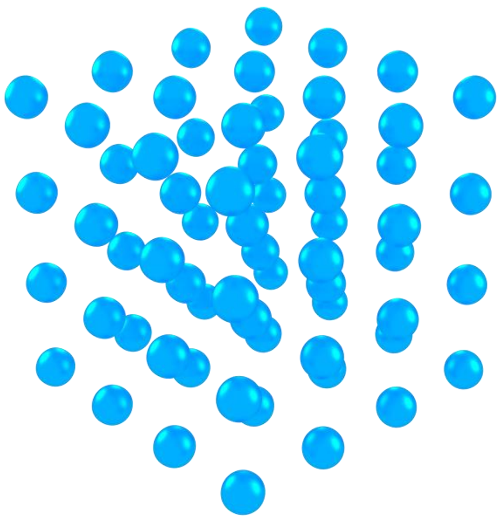
Degenerate Fermi gas ^{40}K



Held by classical magnetic and laser fields

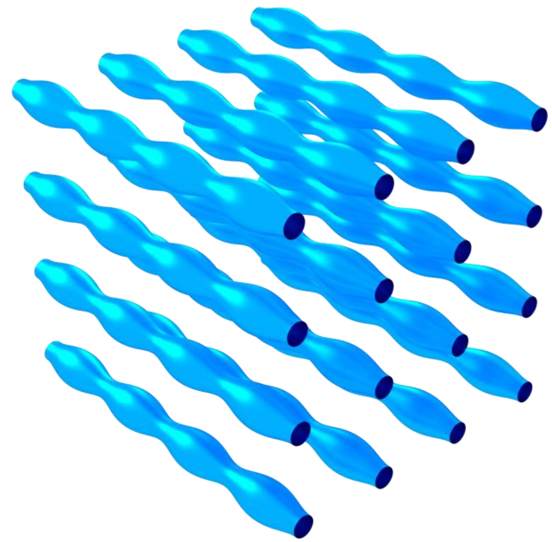
No thermal environment

Controlling dimensionality



0D

- 3D deep lattice
- isolated wells
- no hopping

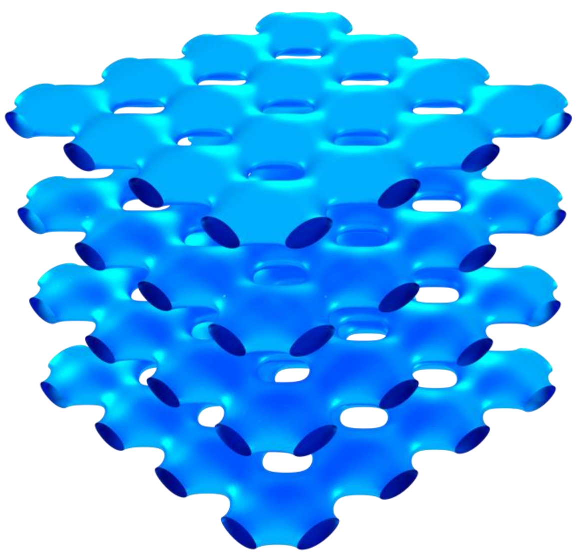


1D

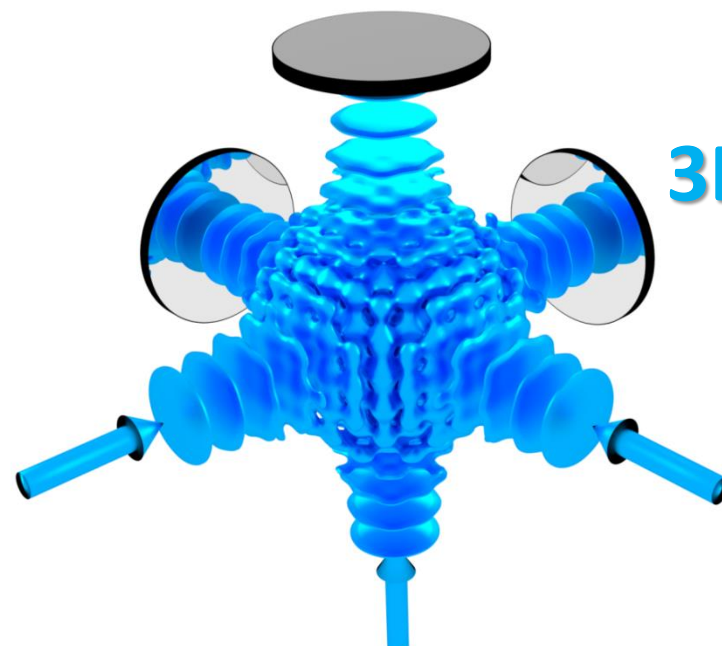
- 2D deep lattice

+1D weaker lattice

- 1D hopping



2D

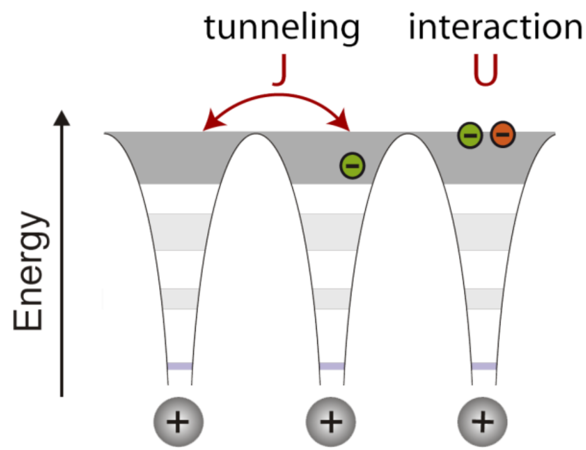


3D

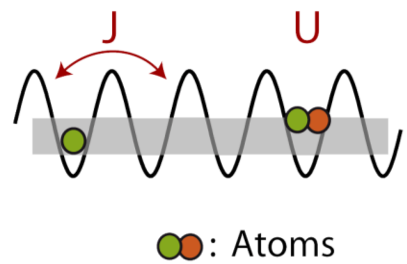
Simulating condensed-matter

- Realizes important model Hamiltonians from solid-state physics:
  ➔ e.g. **Hubbard models**

$$H = -J \sum_{\langle i,j \rangle} a_i^+ a_j + \frac{U}{2} \sum_i n_i (n_i - 1)$$



Potential created by ions

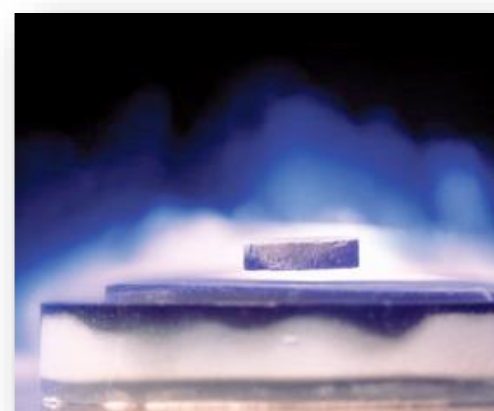


Potential created by standing light wave

Understand and Design Quantum Materials

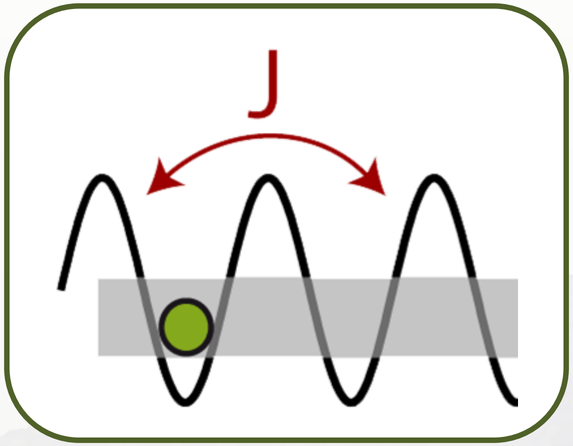
- High temperature superconductivity
- Quantum Magnetism

Emergent many-body phenomena



YBCO

Non-Equilibrium physics



$J \sim 1 - 1000$ Hz

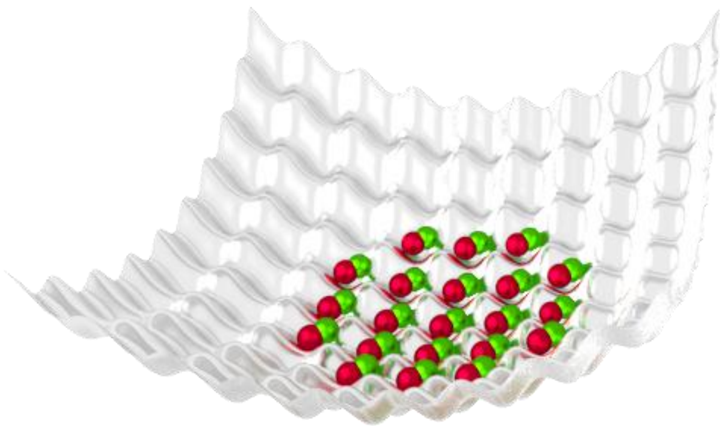
$$\tau = \frac{\hbar}{J} \sim 0.1\text{ms} - 1\text{s}$$

- Can control and observe real-time dynamics

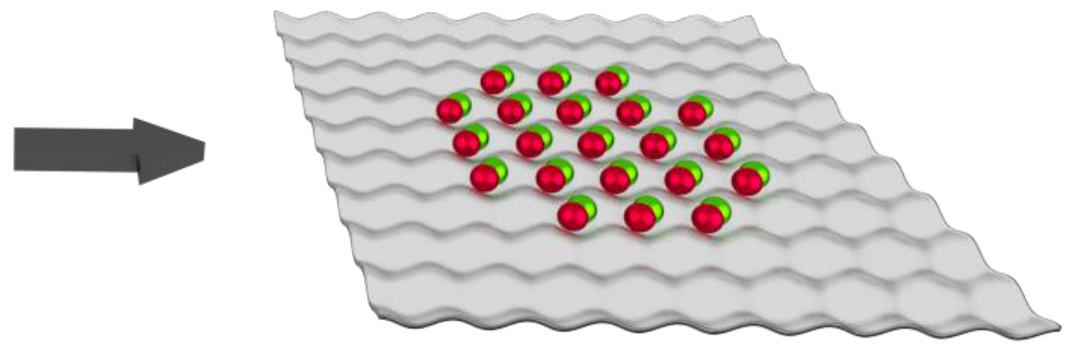
Fermionic Expansion

fermionic ^{40}K

2D

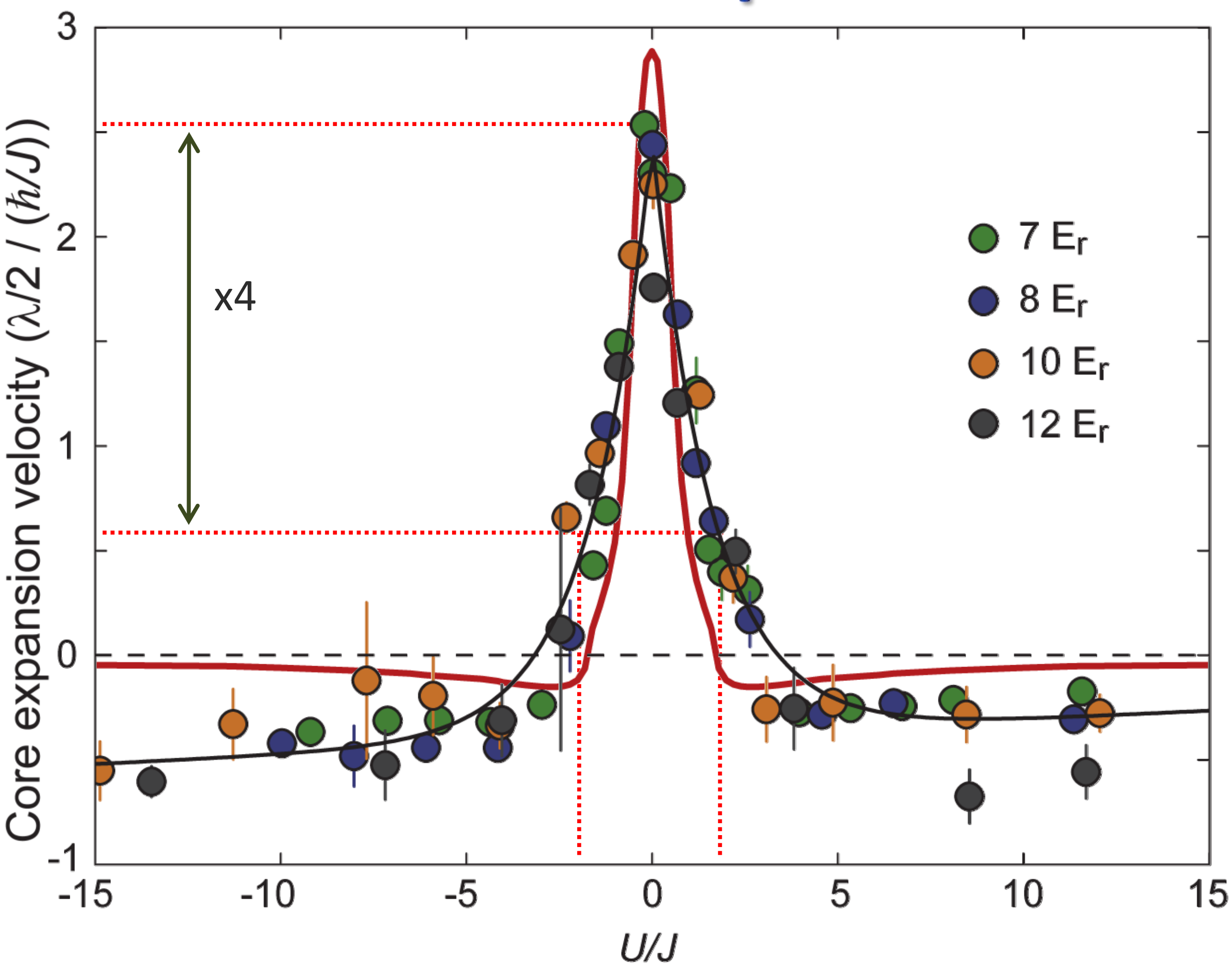


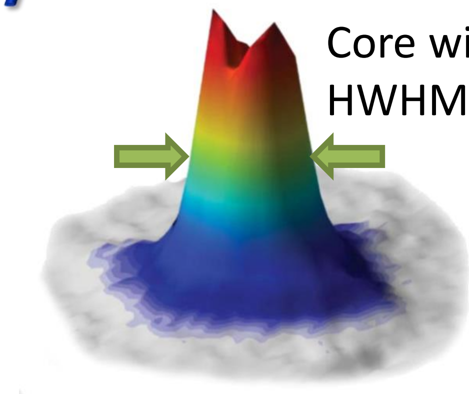
band insulator: two spin states



Dynamics within lattice

Fermionic Expansion velocity in 2D





No qm calculations
possi
Too
lex??

No!

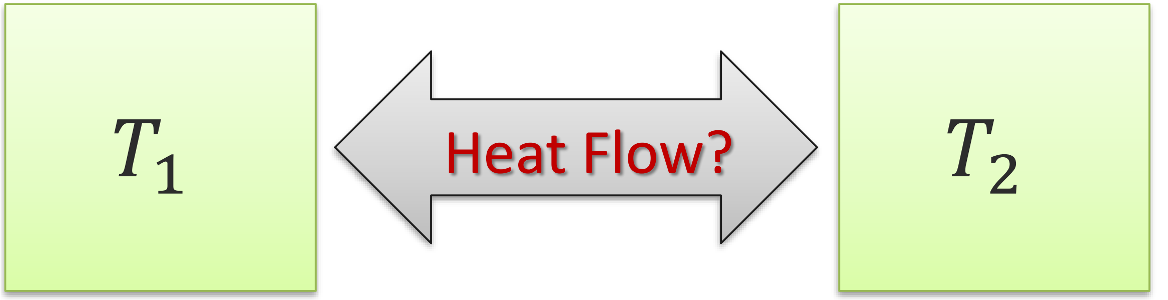
red line:
Boltzmann equation
in relaxation time
approximation
(A. Rosch *et.al.*)

- **fast local thermalization** due to frequent scattering
- slower global dynamics driven by gradients in temperature & chemical potential

U. Schneider *et al.*, Nat. Phys. 8, 213 (2012)

Negative absolute temperatures

Temperature

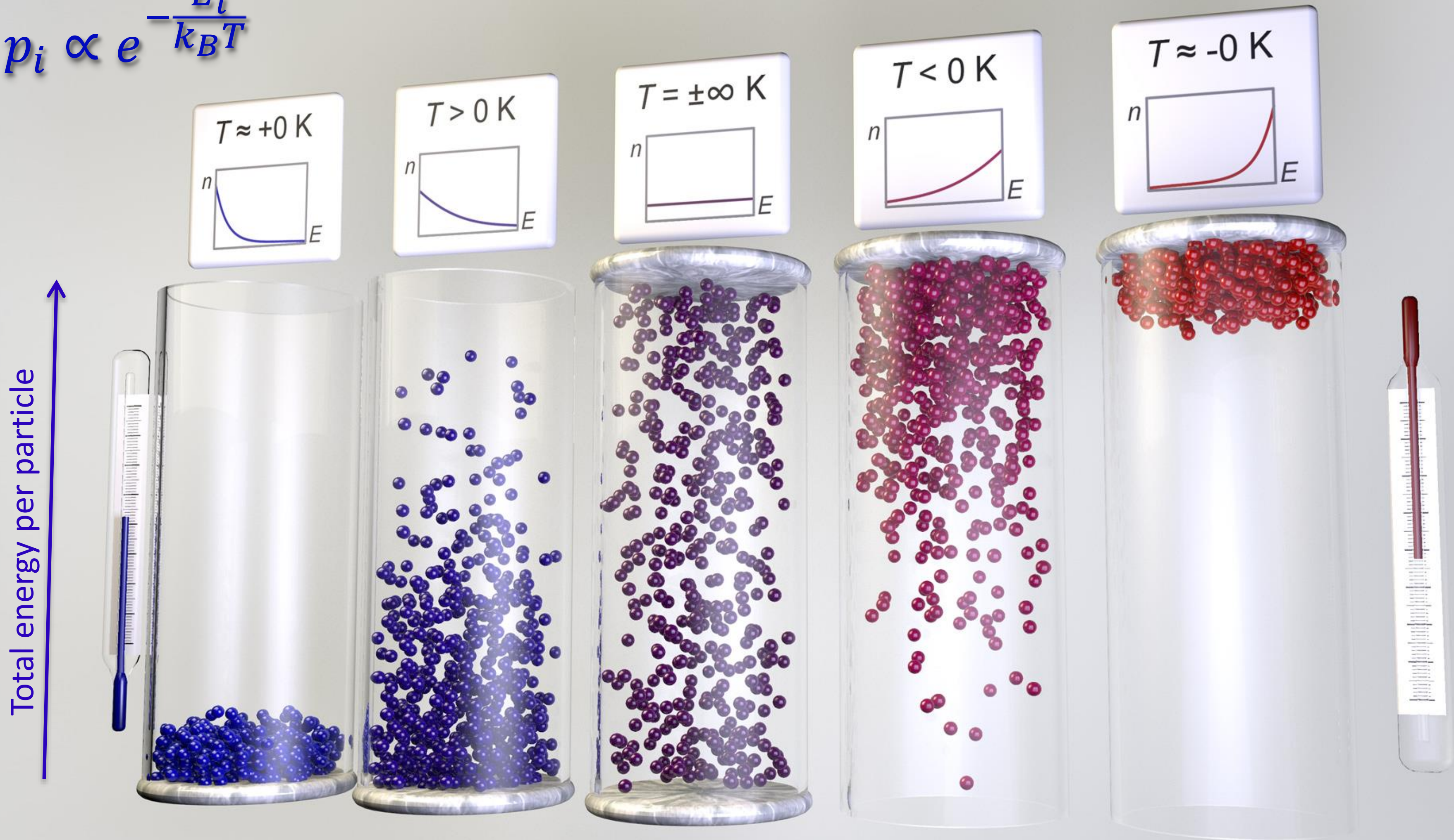


- Heat always flows from the hotter to the colder system, until both systems have the same temperature

Temperature defines an ordering relation between systems!

Thermal states: Canonical distribution

$$p_i \propto e^{-\frac{E_i}{k_B T}}$$

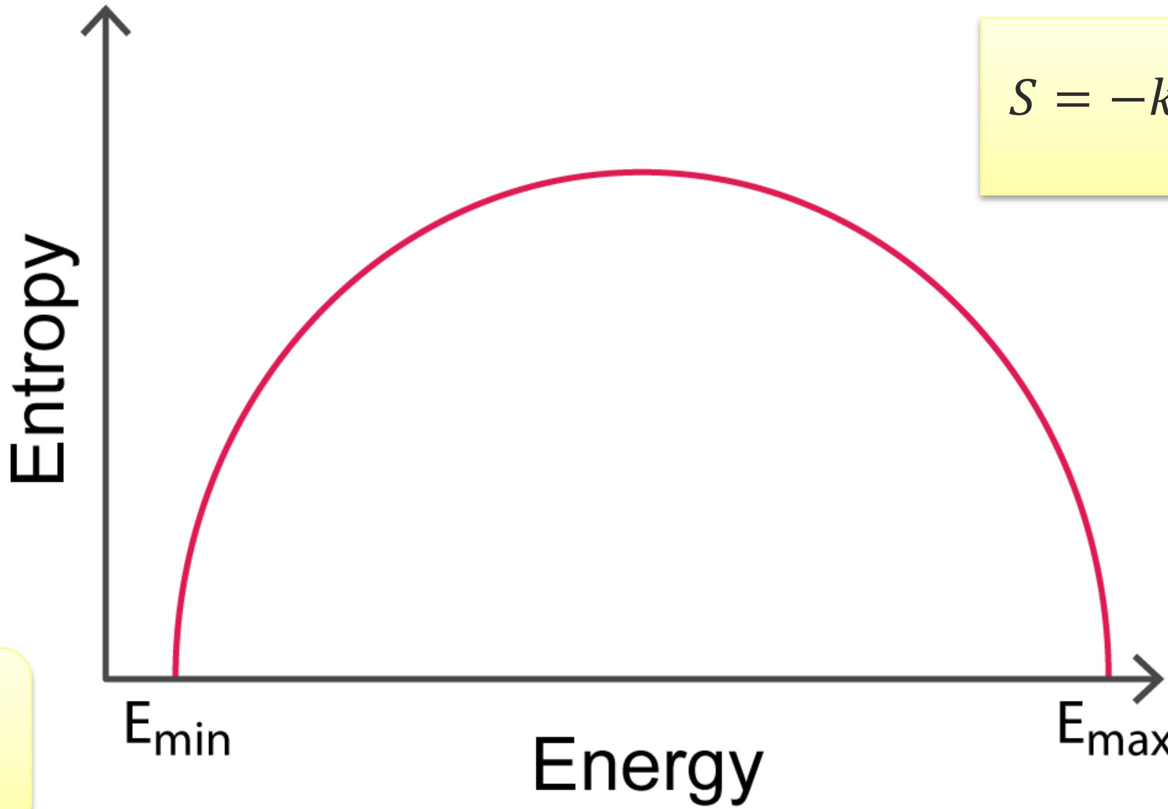


Negative Temperatures are *hotter* than all positive temperatures

Energy-Entropy relation

$$S = -k_B \sum_i p_i \log p_i$$

(canonical)

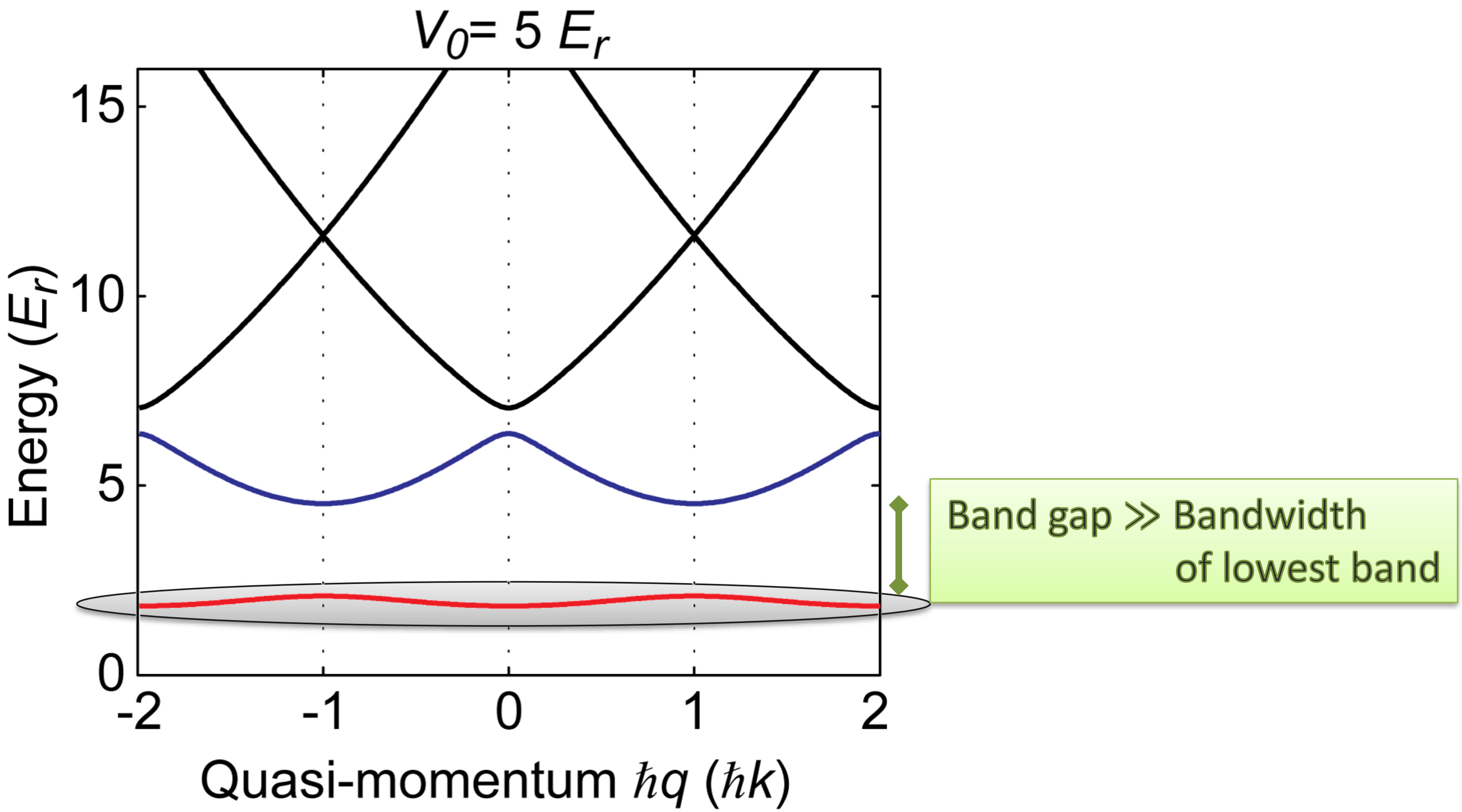


$$\frac{1}{T} = \frac{\partial S}{\partial E}$$

$T \to 0^+$ $\quad$ $T \to \pm\infty$ $\quad$ $T \to 0^-$

Requirement: Hamiltonian locally bounded from above: $\frac{E}{N} \leq \epsilon_{max}$

Optical lattice band structure (1D)



➔ kinetic energy is bounded from above and below

How to get to negative Temperatures?

- Heat, Heat, Heat, ?

  Impossible: Above $T = \infty$ entropy decrease again

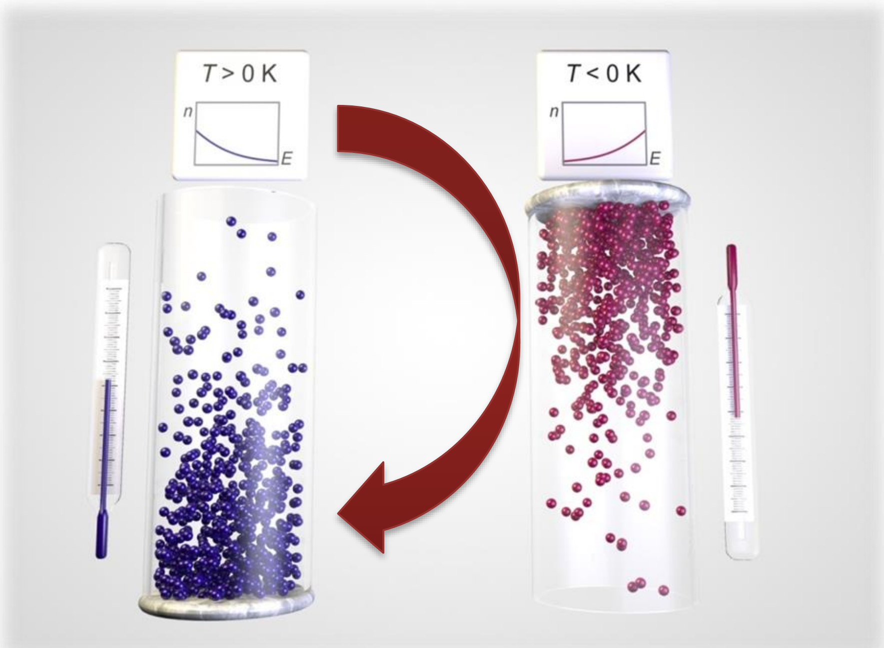
  → Cannot dissipate work in heat anymore

- Quasi-static state change ?

  Impossible: No (classical) adiabatic path can change sign of T (Landsberg 1959)

- **„Flip" the energy axis:**

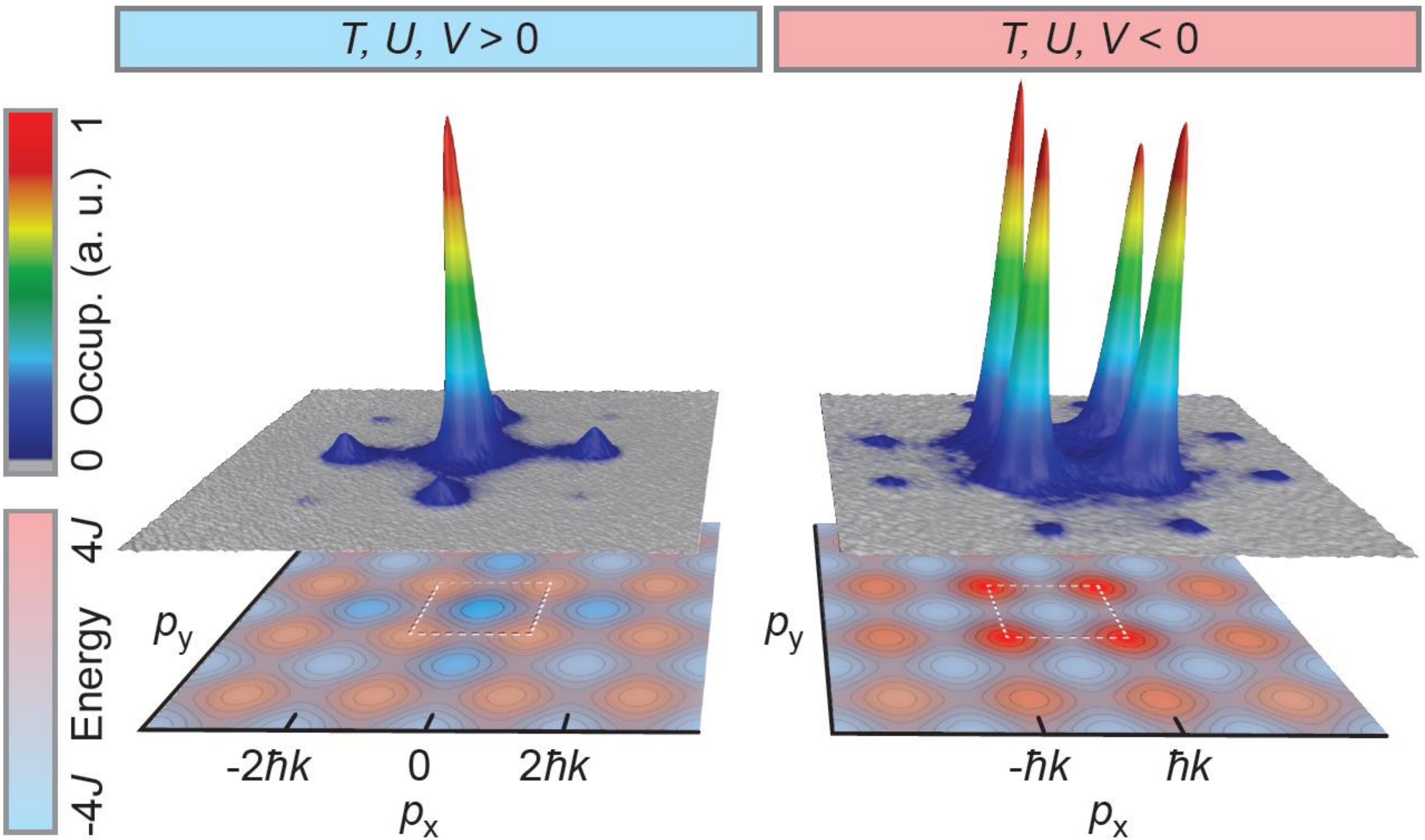
$$\text{"}\hat{H} \Rightarrow -\hat{H}\text{"}$$



Mott insulator:
$U \Rightarrow -U$

→Feshbach resonance

Bose gas at pos. and negative Temperature



Science **339**, 52 (2013)

Are negative temperatures stable?

In isolated systems: Yes!

Due to energy conservation they cannot relax to positive temperatures.

(Same argument as stability of isolated large positive tempratures.)

In contact with an environment:

Yes, if environment also at negative T.

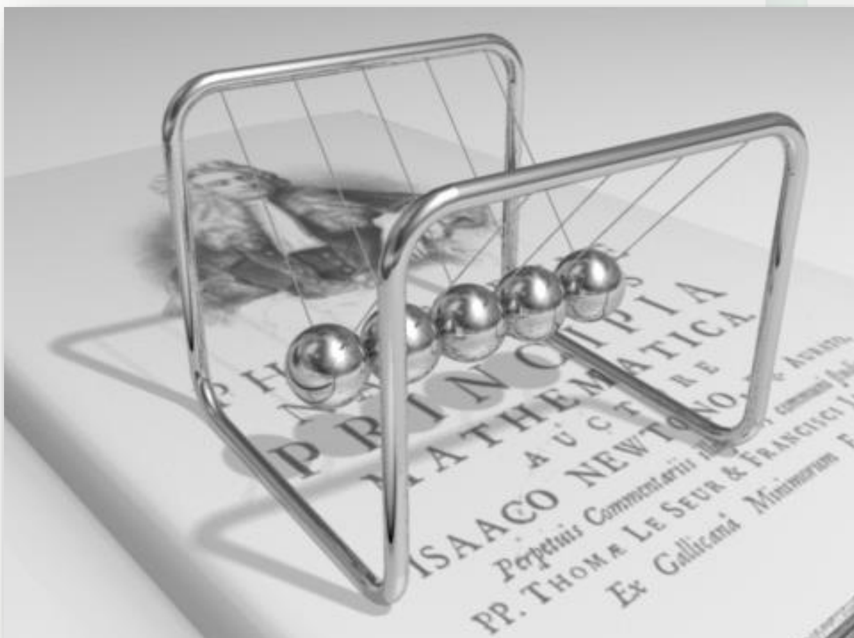
$T > 0 \quad \leftrightarrow \quad T < 0$

"equivalent" to

matter ↔ antimatter

both stable on their own,
but do not mix!

Dynamics in different dimensions



1D: **NO** Thermalization

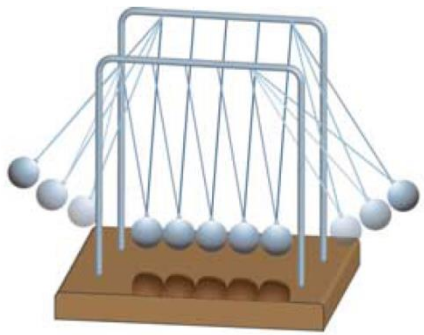
(Proximity to) Integrability

2D: Thermalization

$$p_i \propto \exp\left(-\frac{E_i}{k_B T}\right)$$

Independent of all other initial conditions

What can be different in 1D?



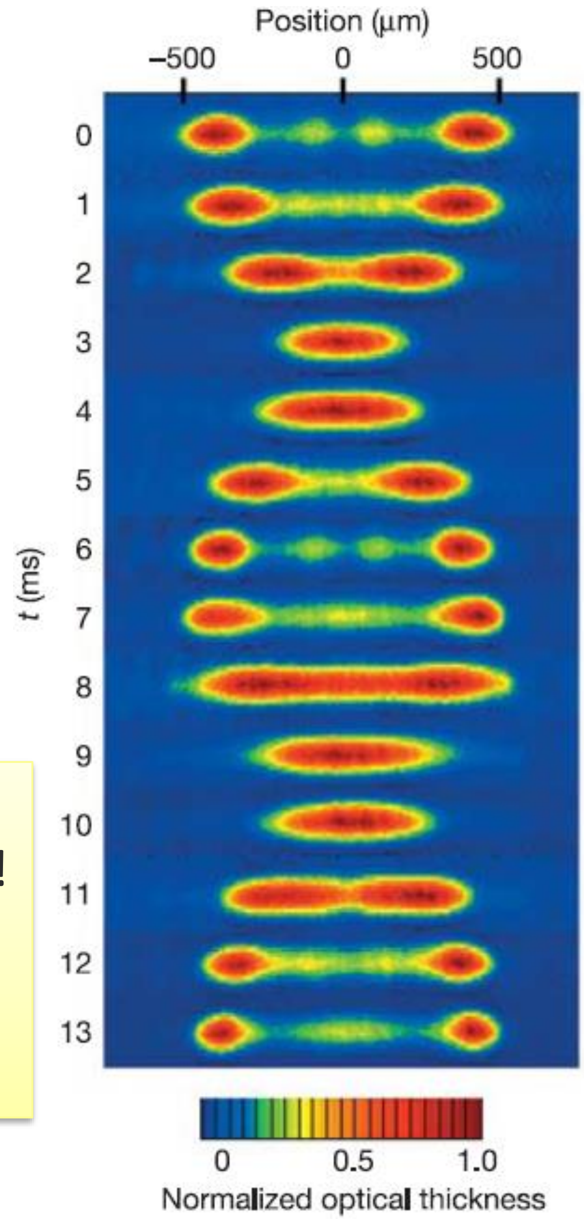
Classically: Two-body collisions can only exchange momentum, but *not redistribute* it!

$$n(k,t) = const. \text{ w.r.t. } t$$

Repulsive 1D Bosons with point-like interaction without a lattice are integrable in homogeneous case!

→Lieb-Liniger model

Thermalization constrained by conserved quantities.



T. Kinoshita *et al.*, Nature (2006)

Fineprint: Trap, 3-body collisions, quasi 1D

1D Bosons on a lattice

- 1D Bose–Hubbard model is (in general) *not integrable!*

  classically chaotic for intermediate U and intermediate energy

  M. Hiller et al. PRA **79**, 023621 (2009)

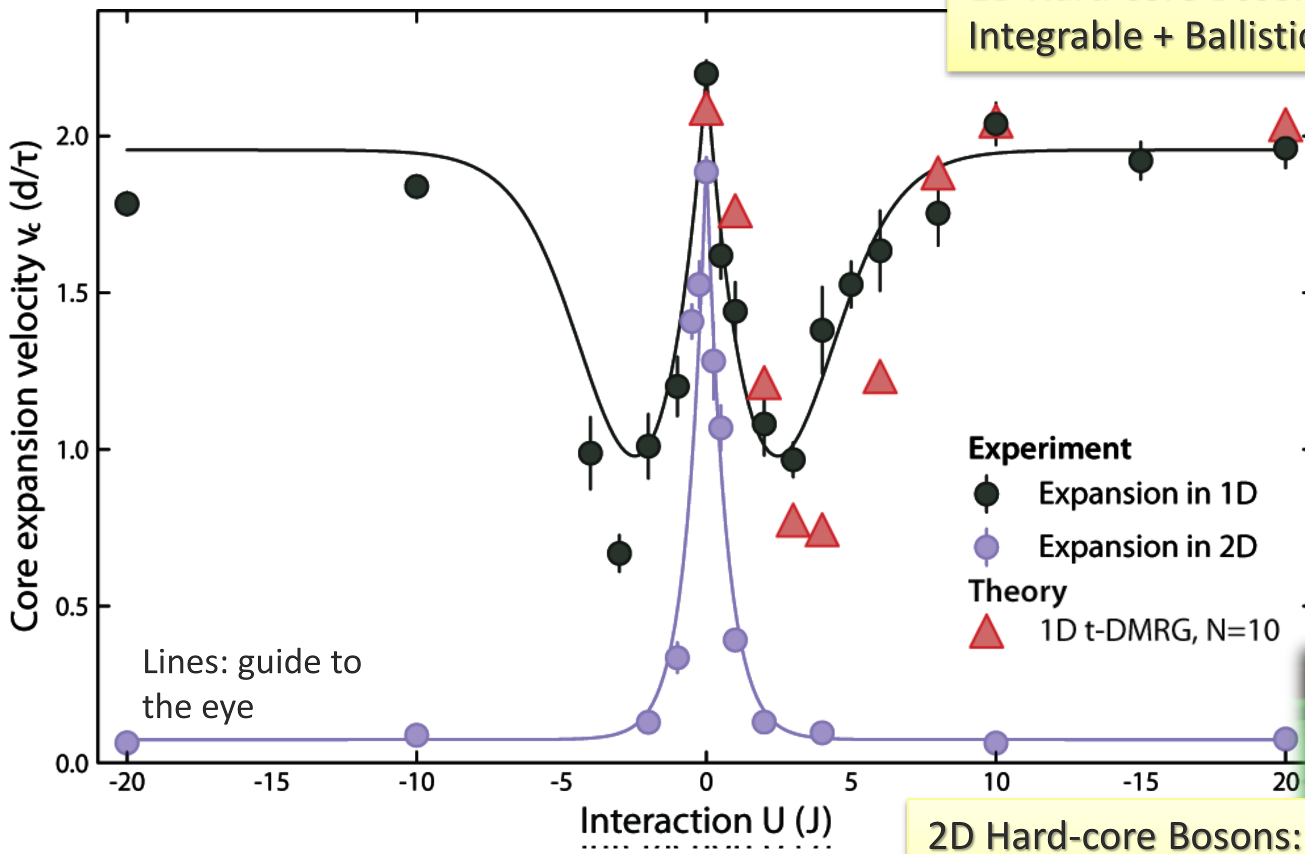
- Integrable limits:
  - Non-interacting
  - Hard-core Bosons: $U \gg J$, $n \in \{0, 1\}$

    i.e. no higher occupancies

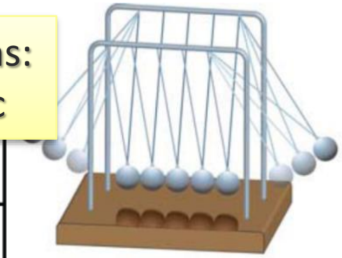
    equivalent to non–interacting spinless Fermions

    (Jordan–Wigner transformation)

Bosonic Expansion velocities



1D Hard-core Bosons:
Integrable + Ballistic



2D Hard-core Bosons:
Thermalizing + Diffusive

In general, no exact calculations available for D>1
→ Quantum Simulations

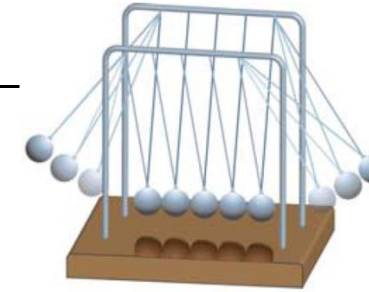
PRL **110**, 205301 (2013) & PRL **115**, 175301 (2015)

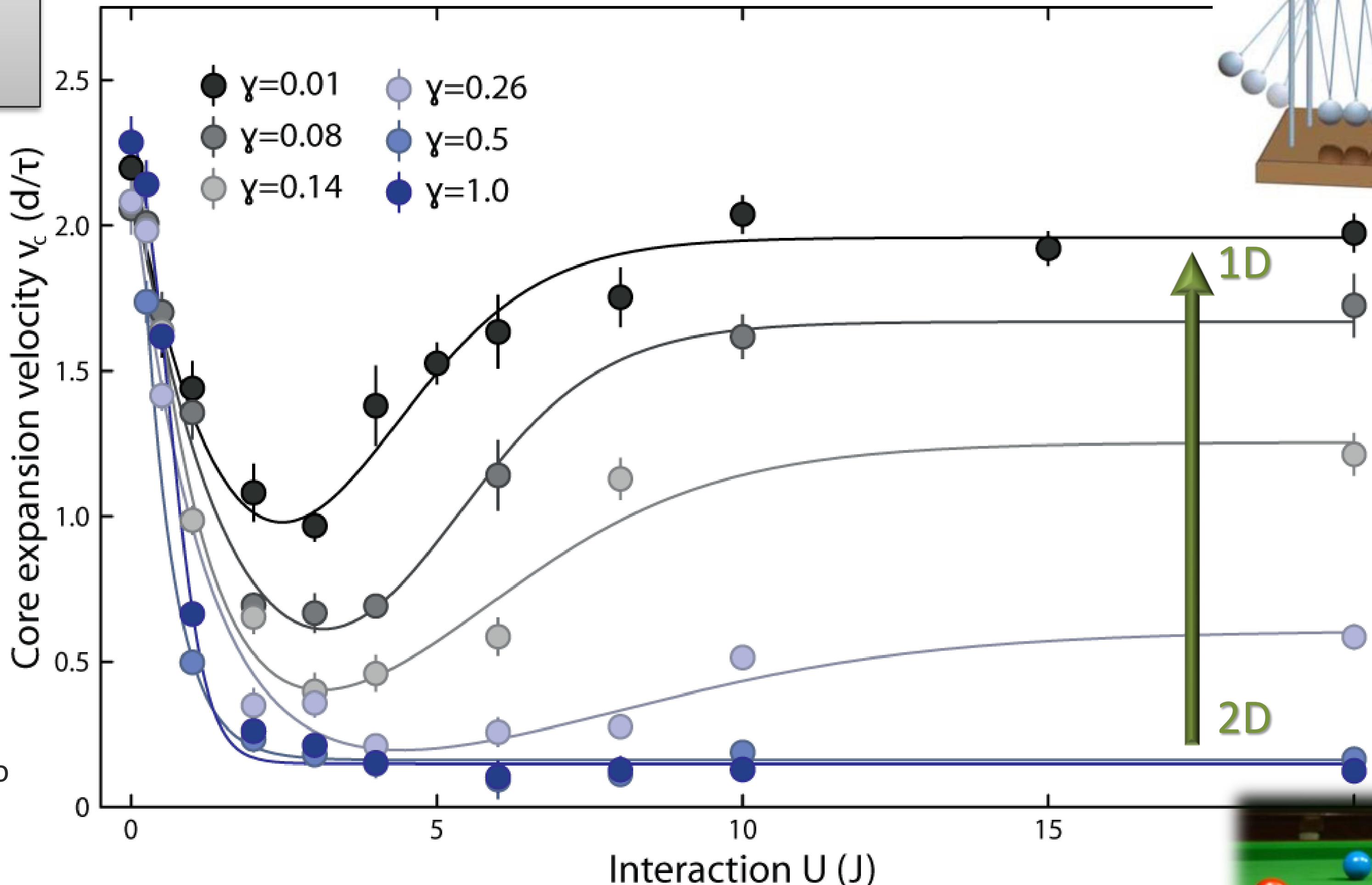
1D-2D Crossover

$$\gamma = \frac{J_y}{J_x}$$

1D: $\gamma = 0$

2D: $\gamma = 1$

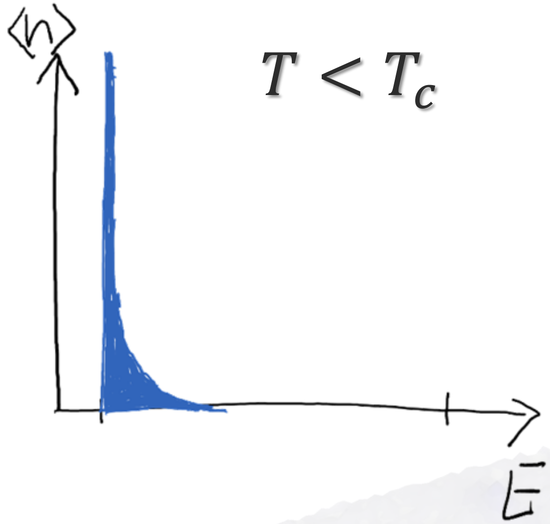


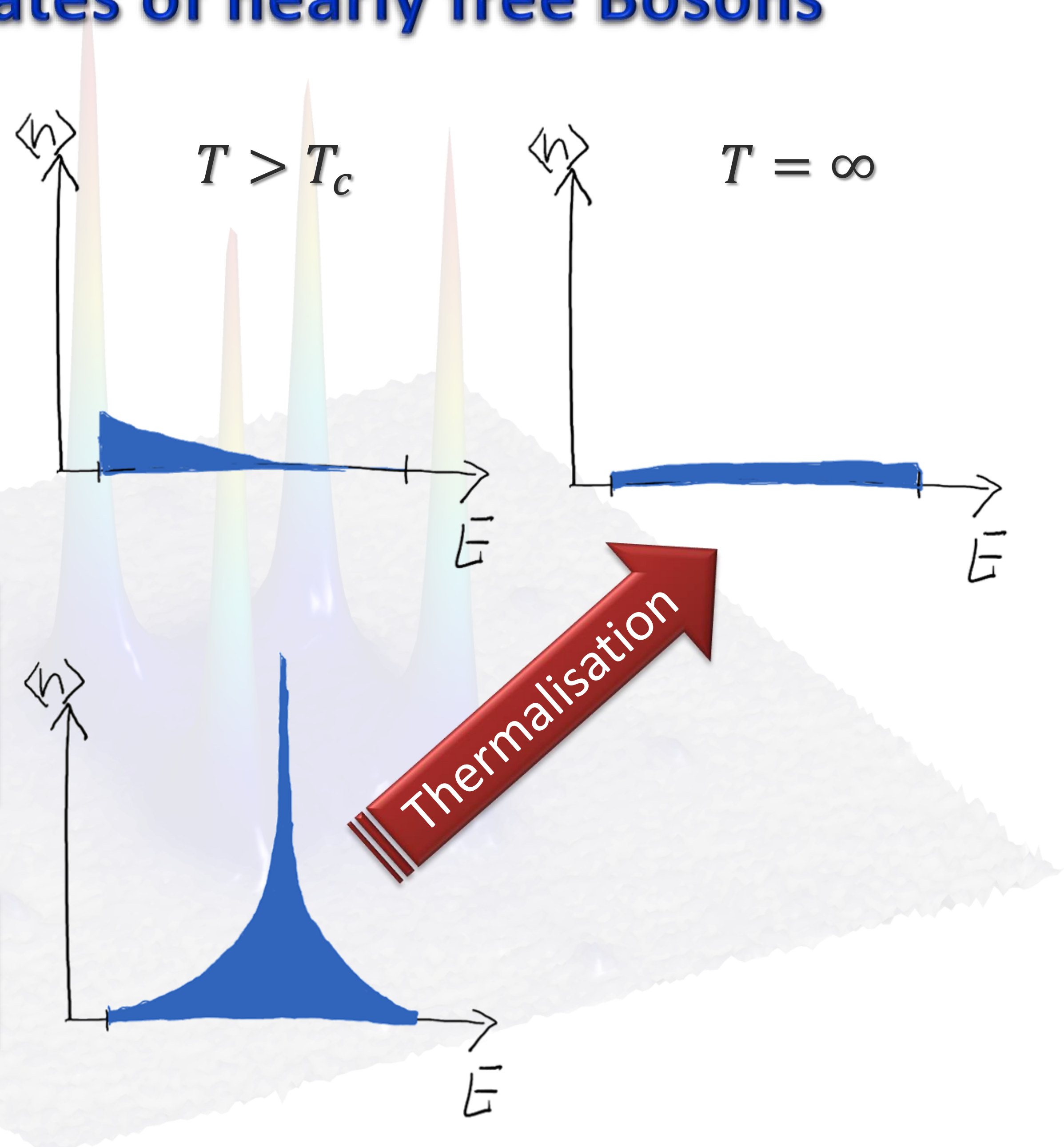


Lines: guide to the eye

PRL 110, 205301 (2013)

Thermal states of nearly free Bosons

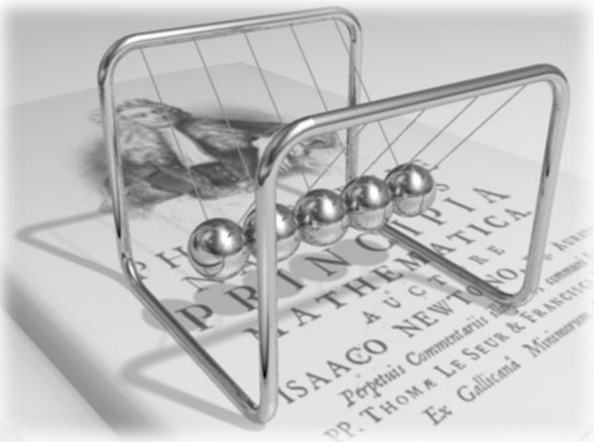




Can Bosons also bunch in the middle of the spectrum?

Not in thermal equilibrium!

1D Hard-Core Bosons on a lattice



- Hard-core Bosons:

  Jordan-Wigner Transformation

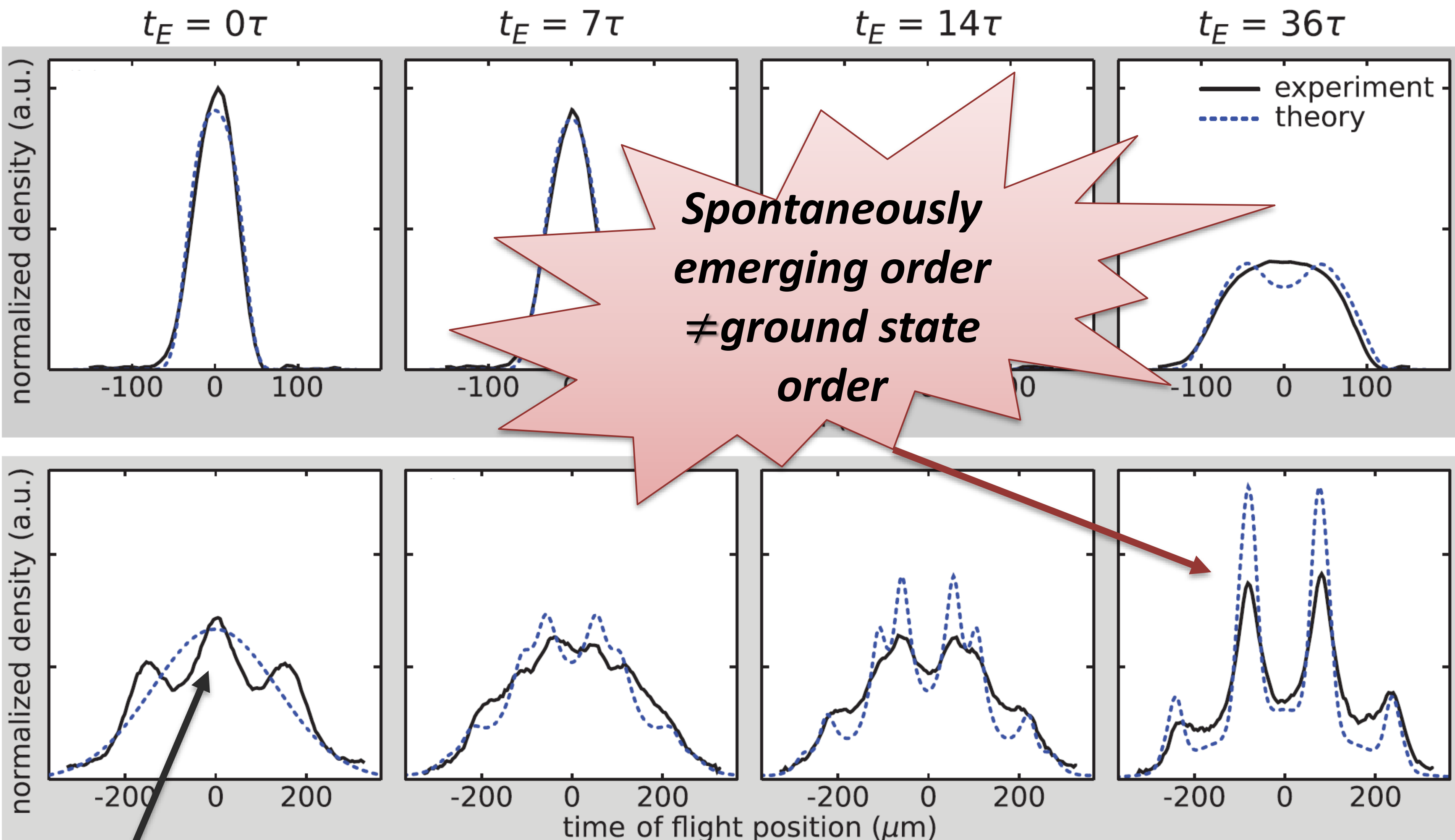
$$n_r^B(t) = n_r^F(t)$$

$$n_k^B(t) \neq n_k^F(t)$$

Experiments:

Paredes, Bloch, Weiss, Nägerle,…

Emergence of correlations



Spontaneously emerging order ≠ground state order

Residual $q = 0$ coherence in initial state

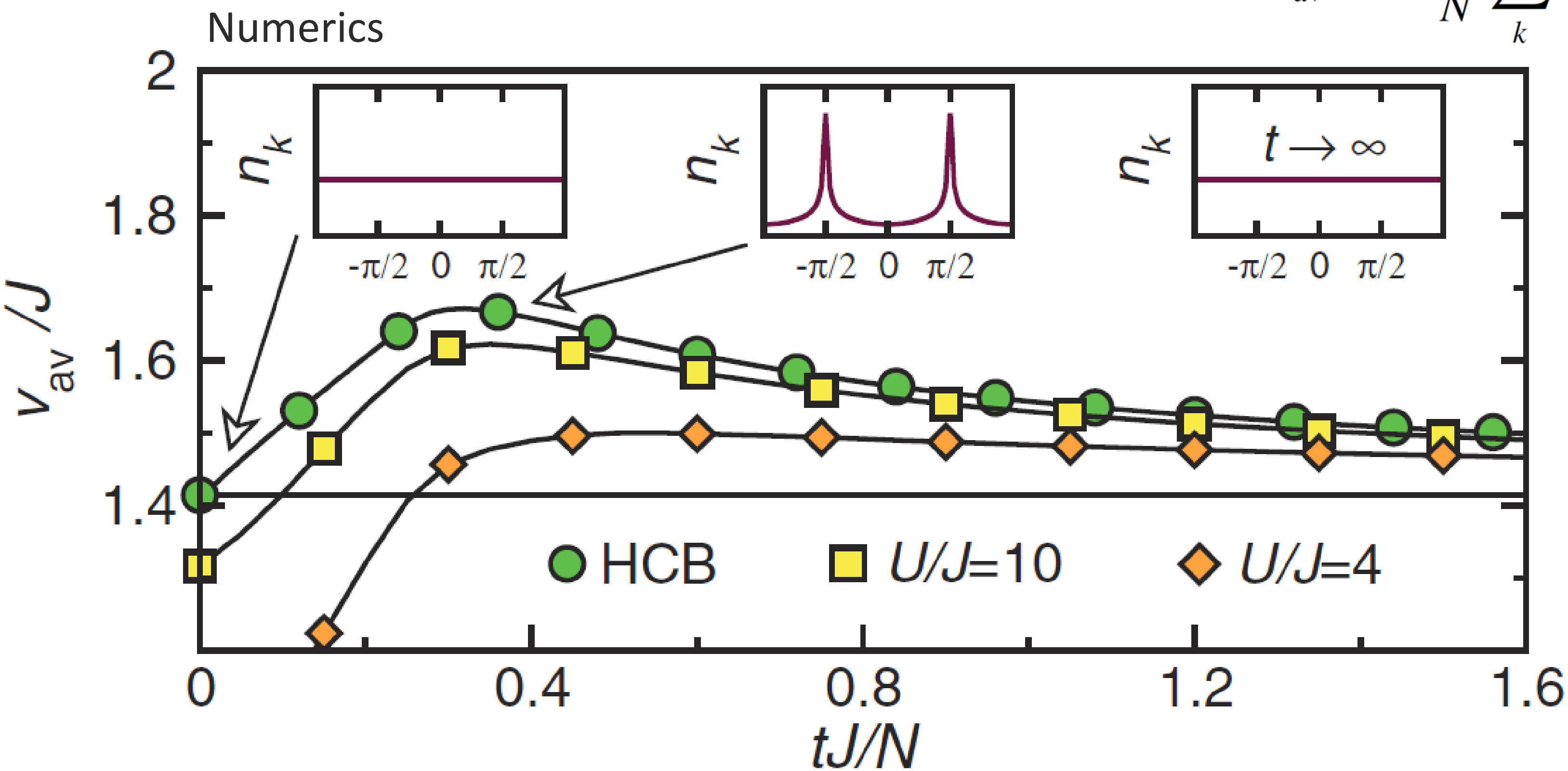
- Lattice pulsed to broaden Wannier envelope
- Finite time-of-flight

First proposal: M. Rigol *et al.*

L. Vidmar *et al.* PRL **115**, 175301 (2015)

Long time behaviour of expanding 1D HCB

$$v_{\rm av}^2(t) = \frac{1}{N}\sum_k n_k(t) v_k^2$$



- Quasicondensation is transient effect
- Long times: Fermionization
- Timescales depends on chain length
- Experiment done in parallel on different chains

L. Vidmar et. al, PRB **88**, 235117 (2013)

Robust alternatives to thermalization ?

Localization

- Anderson (1958):

  A single particle in a disordered potential can become localized by disorder

  → ***Anderson localization***

1D: arbitrarily small disorder localizes Eigenstates *at all energies*

→ *quantum-mechanical interference effect*

- ***Interactions: Many-body localization***

  Theory: *Yes!* D. M. Basko, I. L. Aleiner, B. L. Altschuler

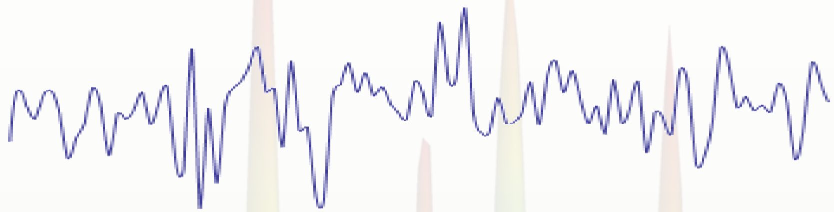
  \+ *essentially everyone* (since 2005)

  Experiments:

  Cold Atoms (Aspect, Modugno, DeMarco, Schneble, …)

  Ions (Monroe), NV Centers (Lukin), Disordered supraconductors (Sharhar)

Many-body localization



Stability of (disorder induced) Anderson localization

in the presence of interactions (and finite energy density)

So what?

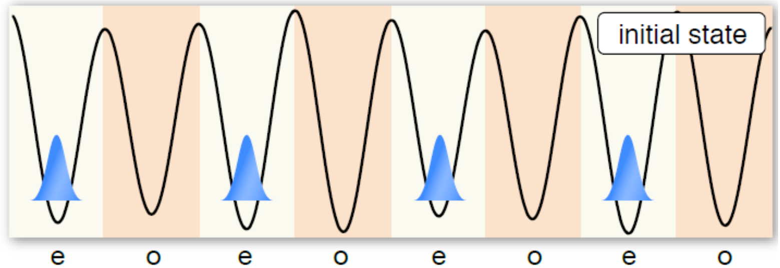
Non-ergodic behaviour!

No thermalization, no standard statistical mechanics

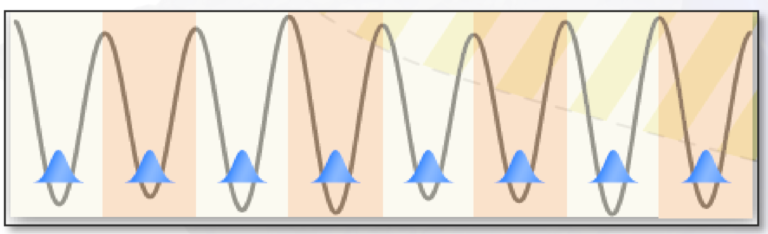
➔ *Potential for novel long-time dynamics*

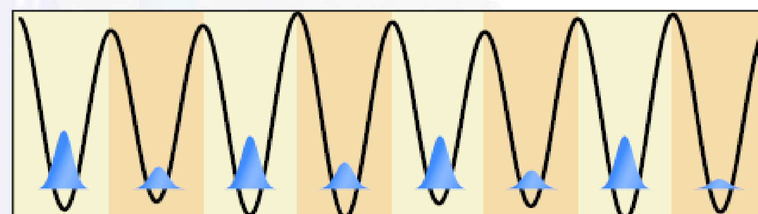
Ergodicity breaking in Many-body localization

Initial state



- fermionic ^{40}K
- free evolution





Ergodic time evolution destroys initial CDW

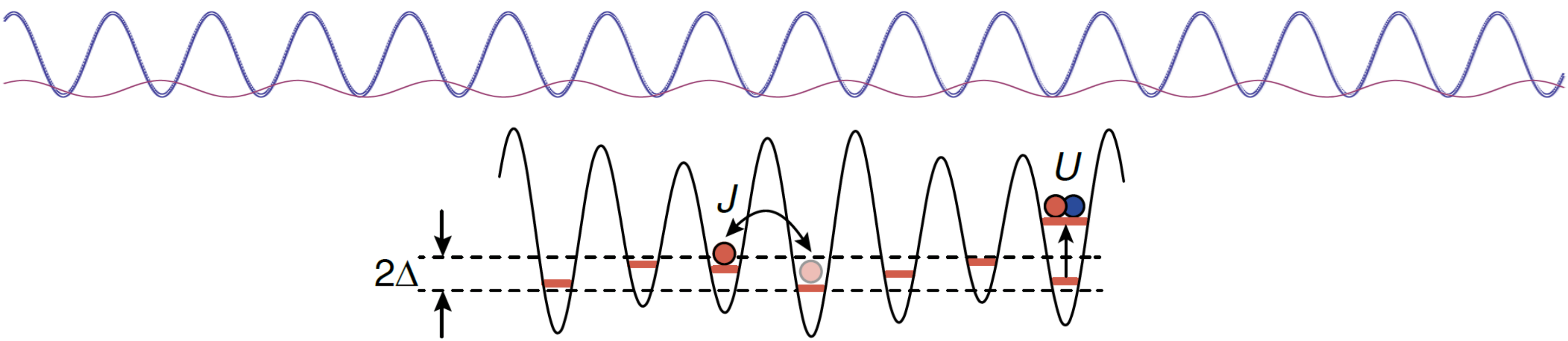
Imbalance

$$I = \frac{N_e - N_o}{N_e + N_o}$$

Persistent CDW signals non-ergodic behavior → localization

Aubry-André model

- Superimpose two ***in-commensurable*** lattices ($\lambda_s \approx 532\,nm, \quad \lambda_d \approx 738\,nm$)
  →projected version of 2D Harper hamiltonian



$$H = -J \sum_{i,\sigma} \left(\hat{c}^{+}_{i,\sigma} \hat{c}_{i+1,\sigma} + h.c \right) + \Delta \sum_{i,\sigma} \sin(2\pi\beta i + \phi) \hat{c}^{+}_{i,\sigma} \hat{c}_{i,\sigma}$$

irrational

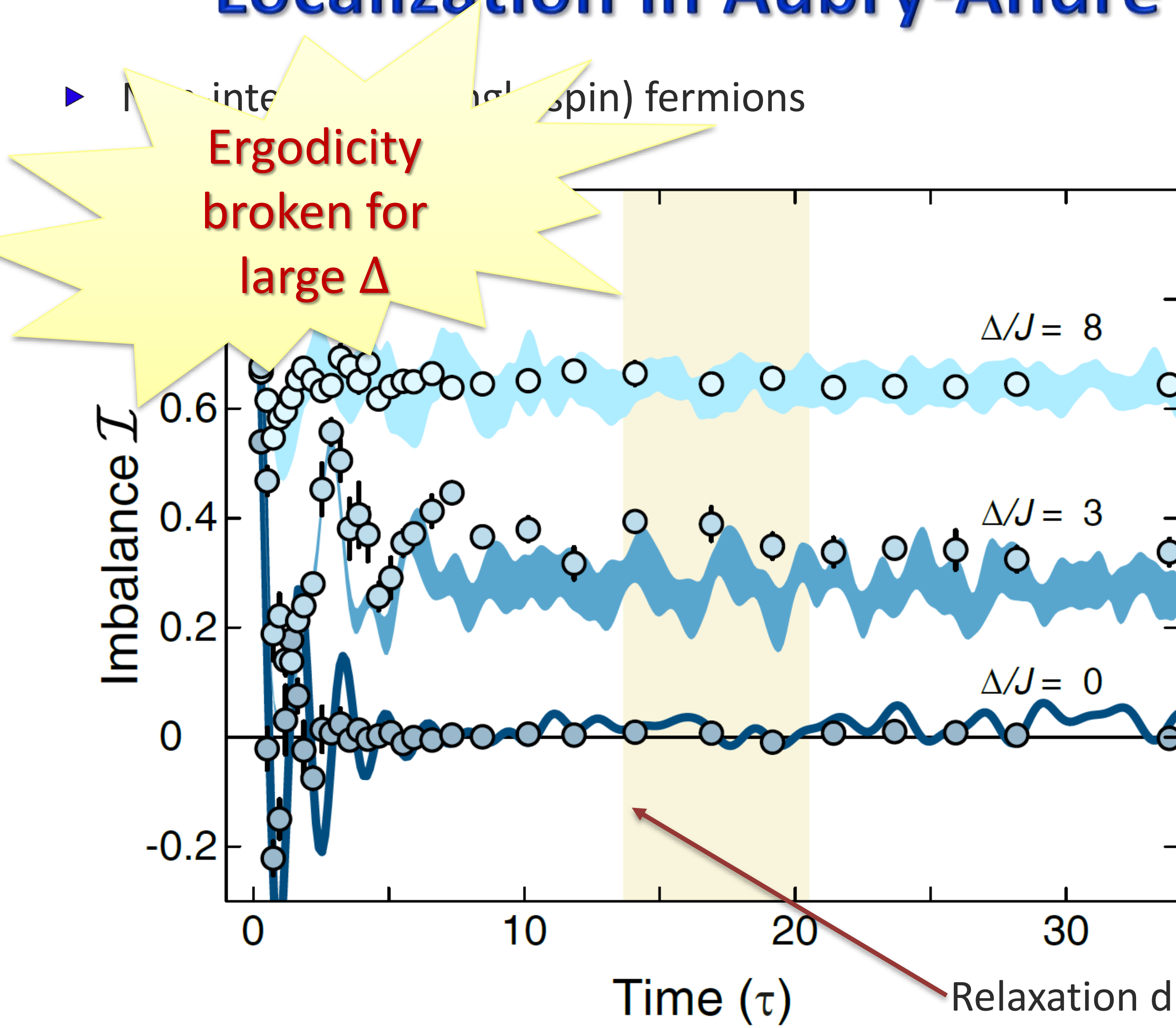
- Real random: Localization for $\Delta > 0$
- Quasi-periodic: Localization for $\Delta > 2J$

- Critical behaviour controlled by β!

A. Szabó, U. Schneider arXiv:1803.09756

Localization in Aubry-André model

- N… inte… …gl… spin) fermions



- *Tunneling time*

$$\tau = \frac{\hbar}{J}$$

- *Imbalance*

$$I = \frac{N_e - N_o}{N_e + N_o}$$

Measured using superlattice

Lines:
exact diag.
including trap

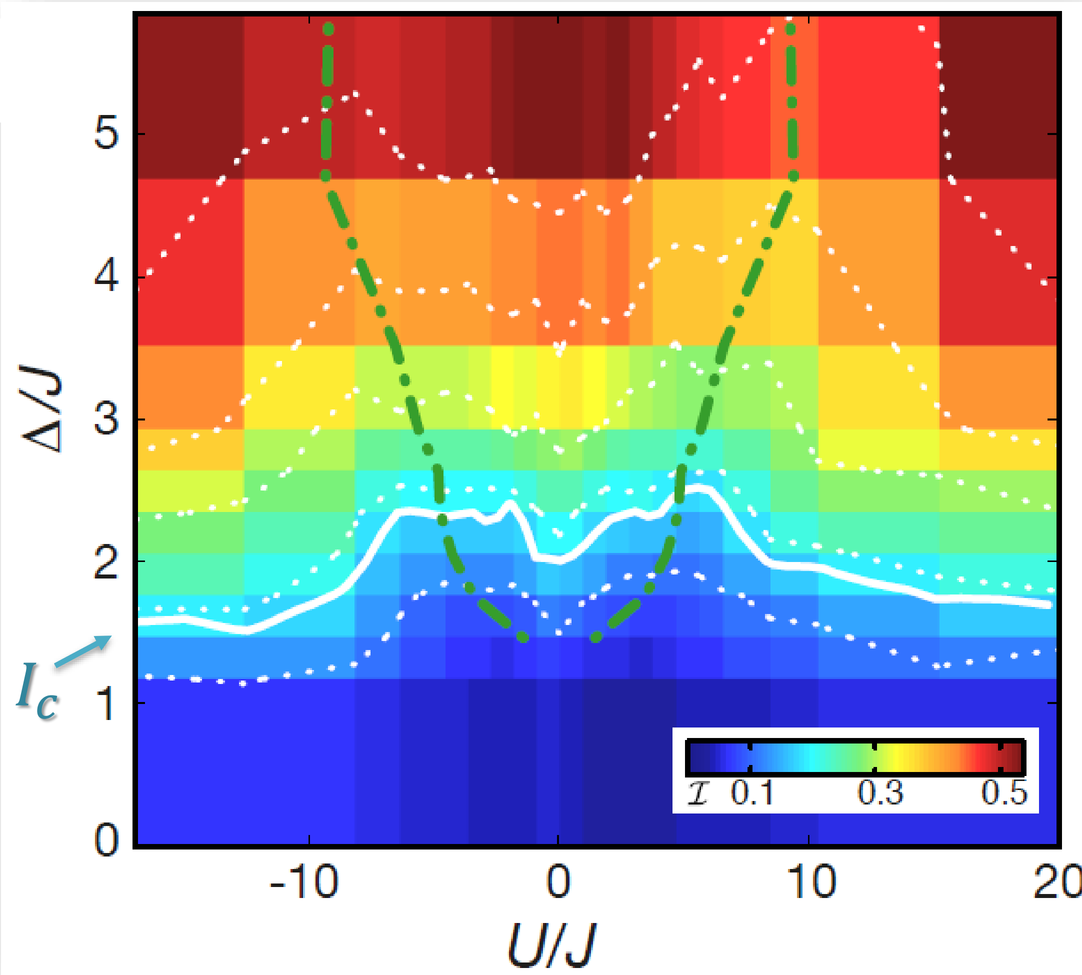
Relaxation during $\lesssim 10\,\tau$

Science **349**,842 (2015)

Many-body localization

- Remaining CDW after $t \approx 15 - 20\ \tau$

Two-component
Fermi gas



Ergodicity broken also for interacting atoms

→ direct observation of **Many-body localization**

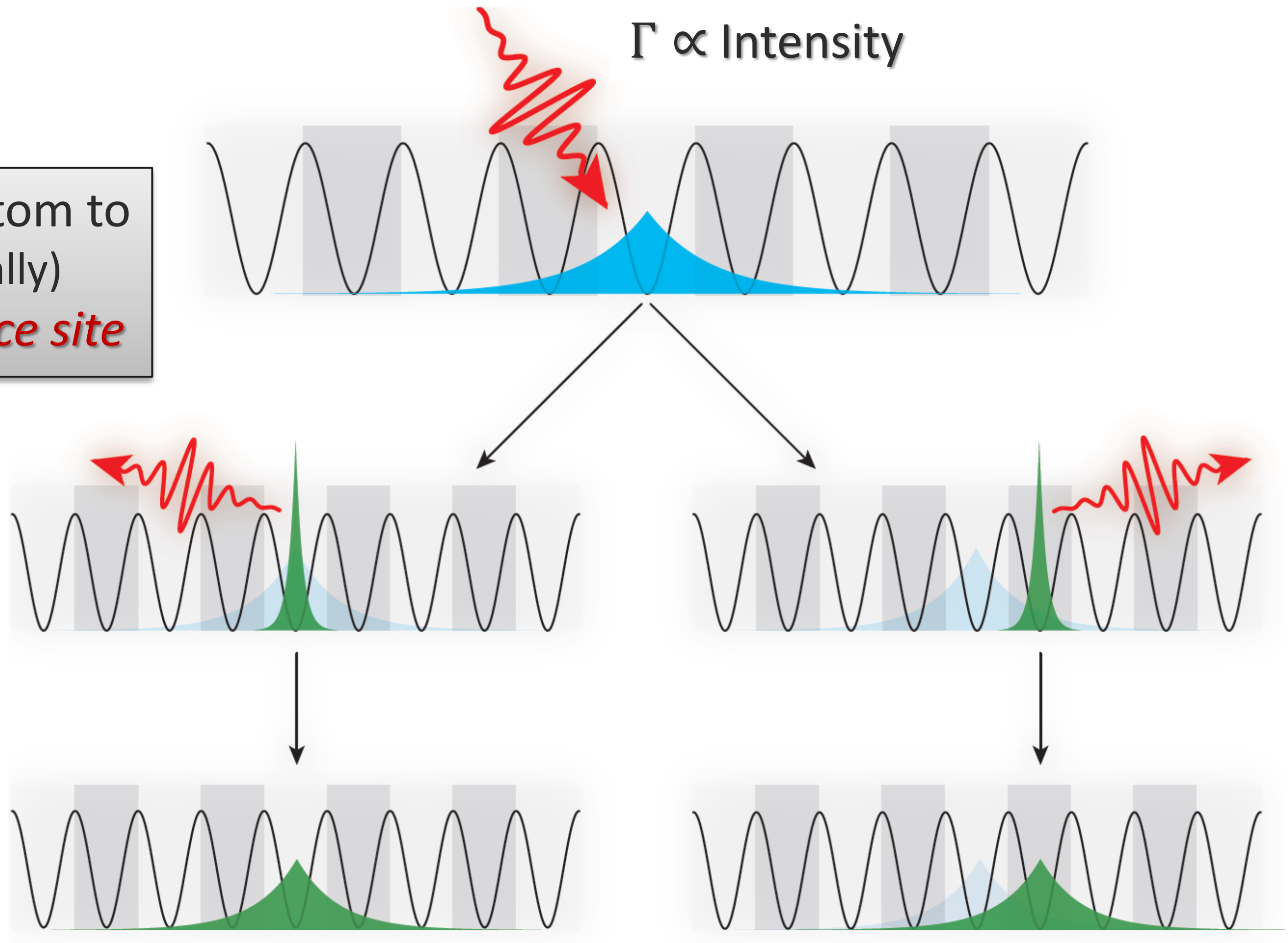
Deep in localized phase
→ Particles only probe their direct surrounding,
→ no differences between quasi-periodic and disordered

Science **349**,842 (2015)

Photon Scattering

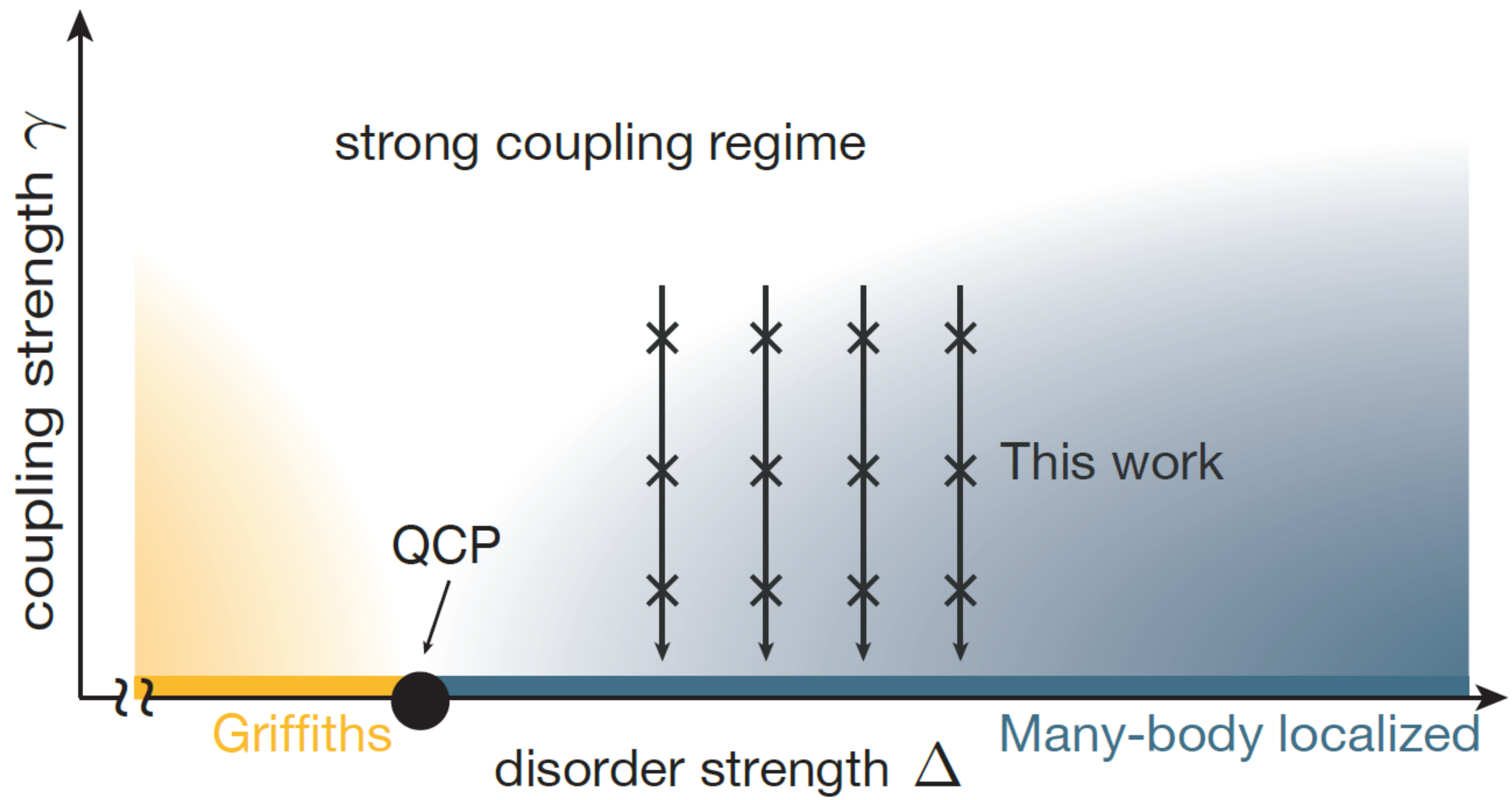
Coupling an MBL system to a $T = \infty$ bath.

Localizes atom to (essentially) *single lattice site*



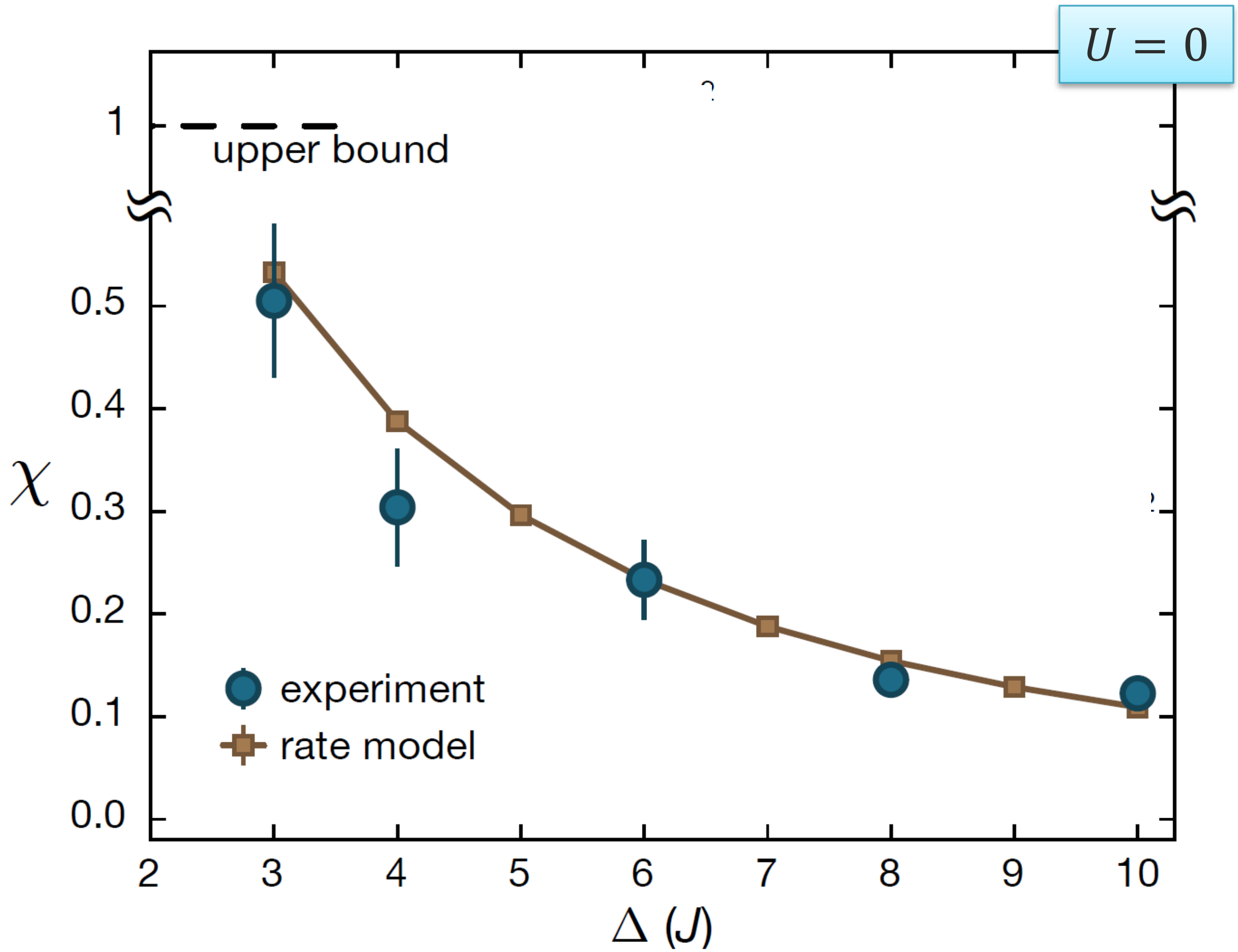
→ *Photon induced hopping: Randomizing positions for* $\Gamma t \to \infty$

Closed System Phase transition?



→ Susceptibility χ expected to diverge at phase transition

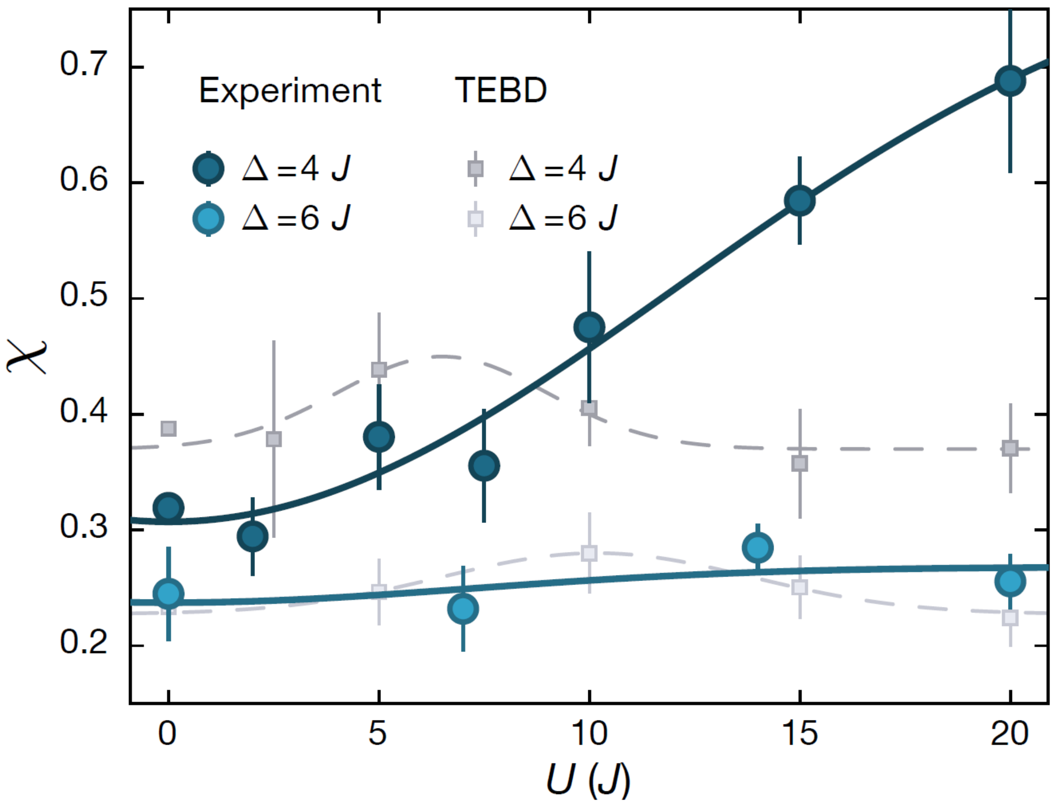
Imbalance dynamics



- Strong dependence on localization length

H.P. Lüschen *et al.*, PRX **7**, 011034 (2017)

Disorder & Interactions



No re-entrant behaviour in Experiment!

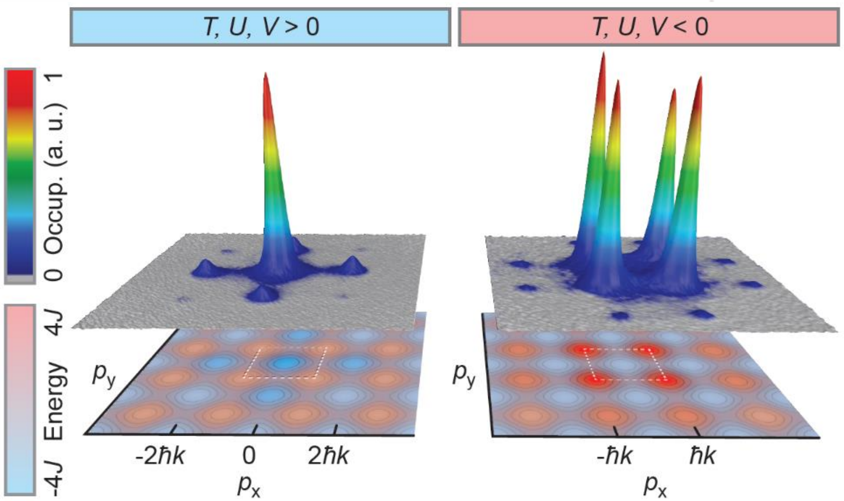
Increasing susceptibility with interaction at small disorder!

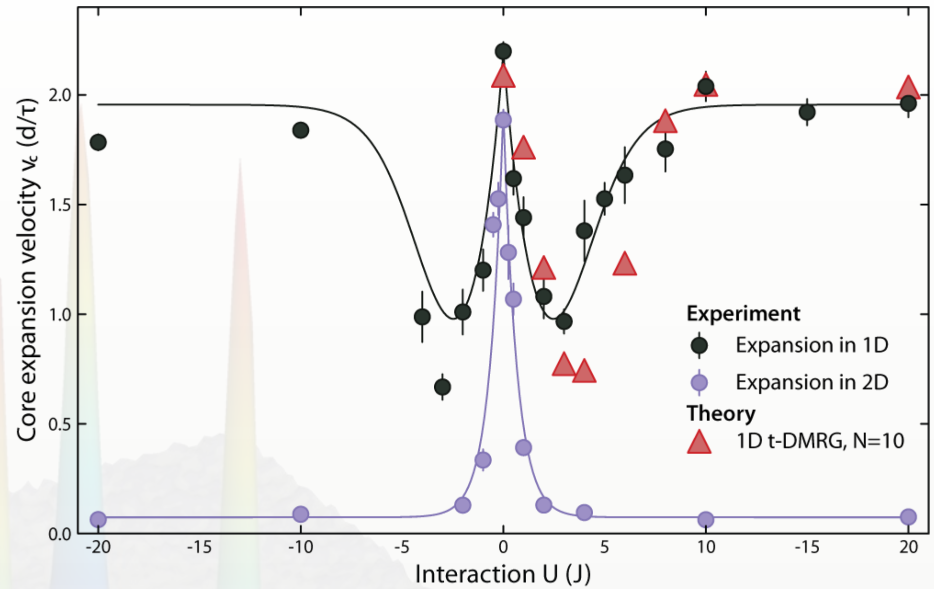
→ *consistent with MBL*

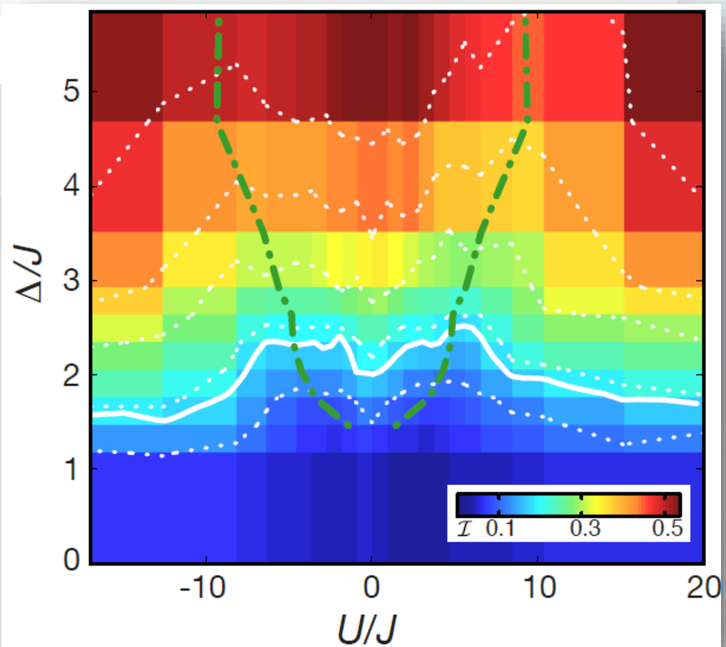
Challenge:

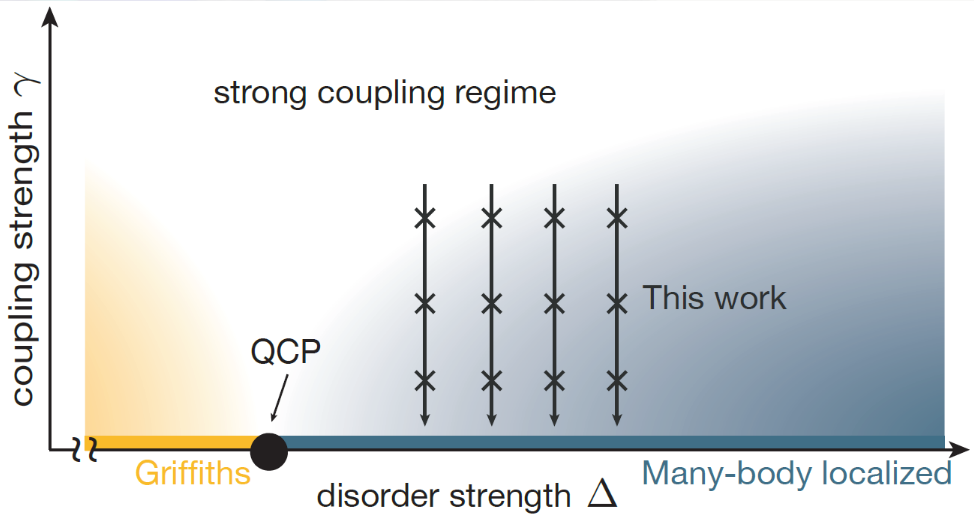
Losses and population of non-localized band become relevant

H.P. Lüschen *et al.*, PRX **7**, 011034 (2017)









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