Quantum Mpemba effect from Stark localization

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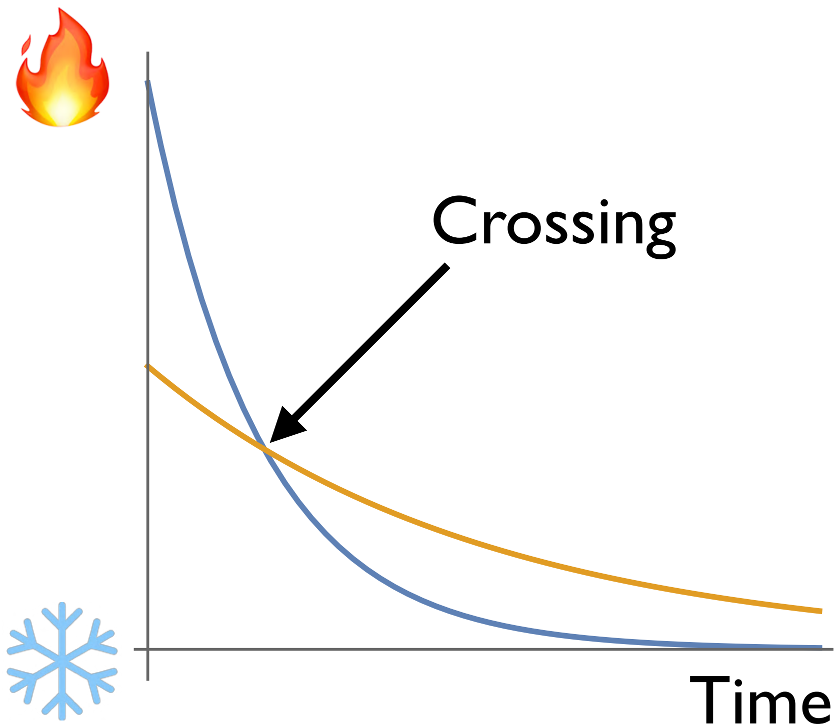
TU Dresden + MPIPKS

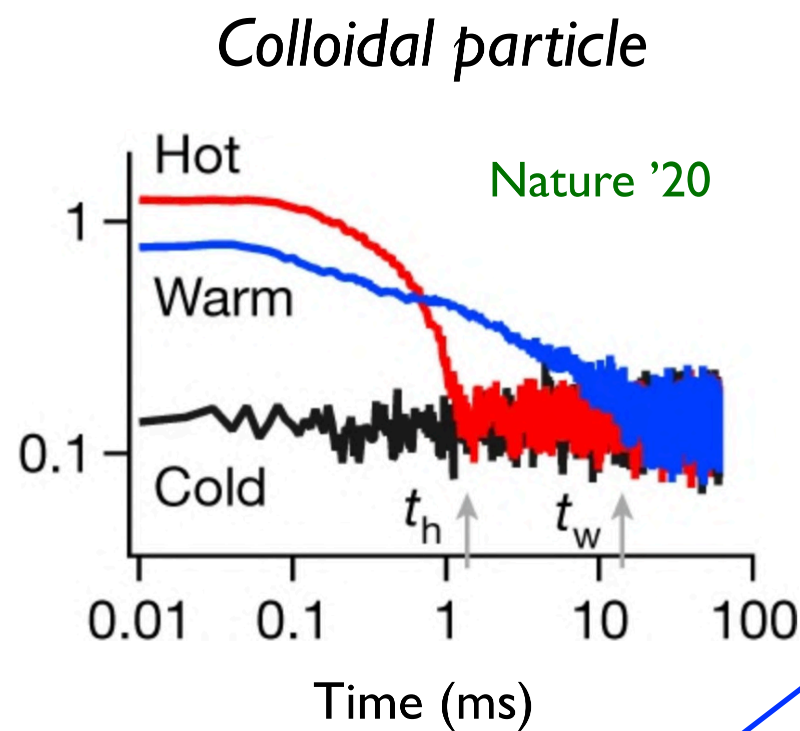
Quantum energy landscapes + rare events $\Longrightarrow$ metastable hierarchy

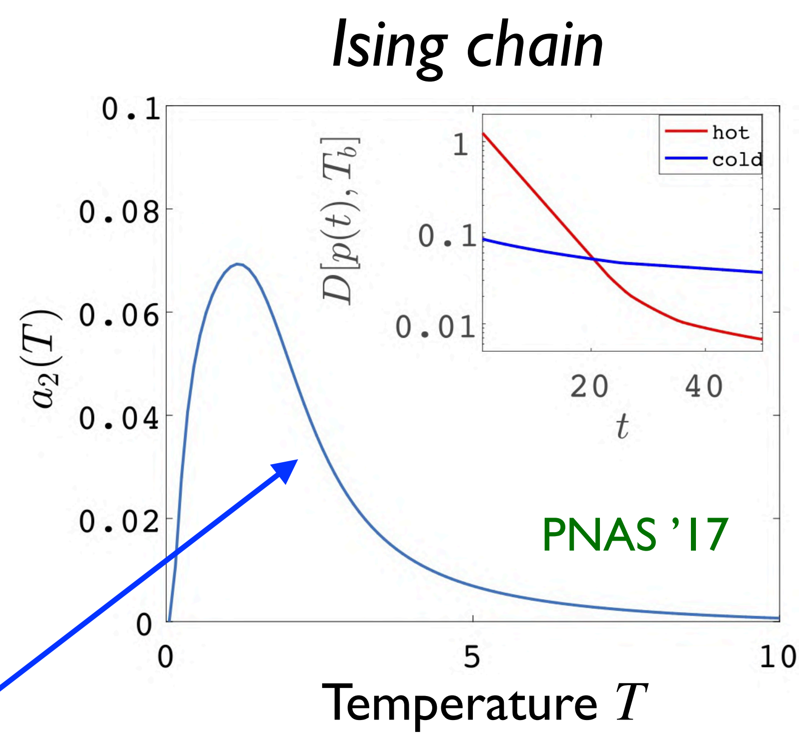
Classical Mpemba effect

Teza *et al*, Phys. Rep. '26
Bechhoefer *et al*, Nat. Rev. Phys. '21

Anomalous relaxation — hotter system cools faster







+ *spin glasses, granular fluids, polymers, …*

Unified description: *nonmonotonic overlap with the slowest relaxing mode*

$$p(t) - p_{eq} = \boxed{a_2(T)}\, v_2\, e^{-\lambda_2 t} + a_3(T)\, v_3\, e^{-\lambda_3 t} + \ldots$$

Generalized to other distance measures from equilibrium / steady state

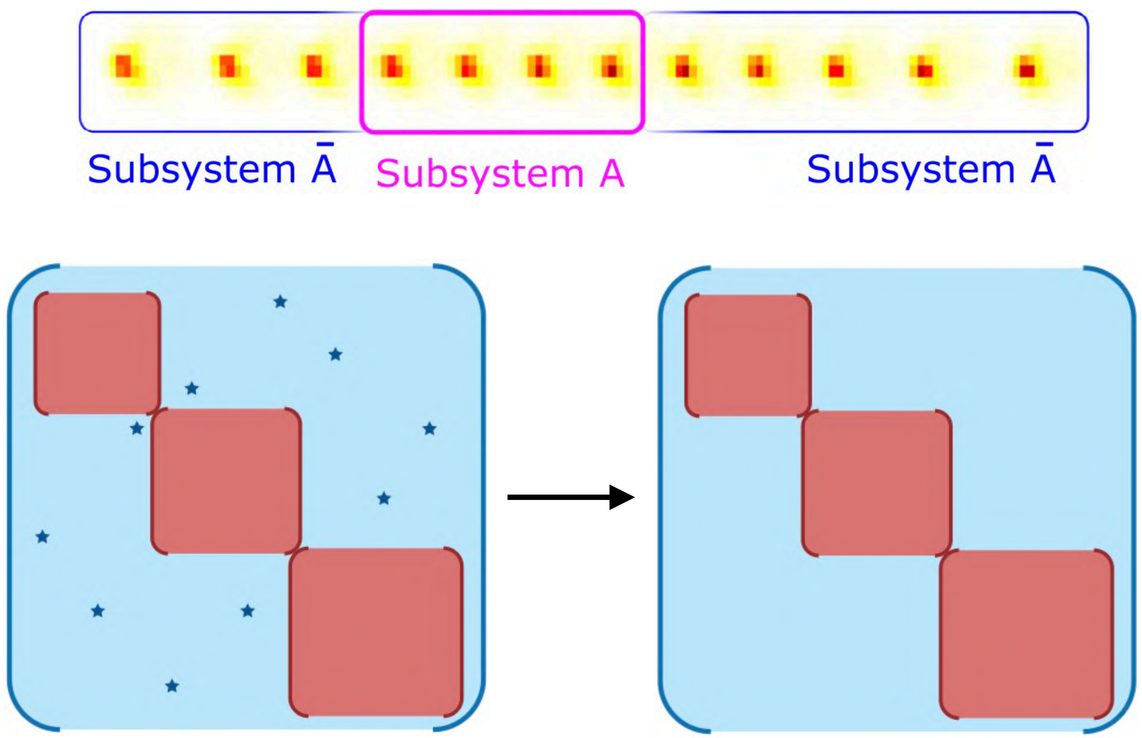
Quantum Mpemba effect — closed systems

Ares, Calabrese, Murciano, Nat. Rev. Phys. '25

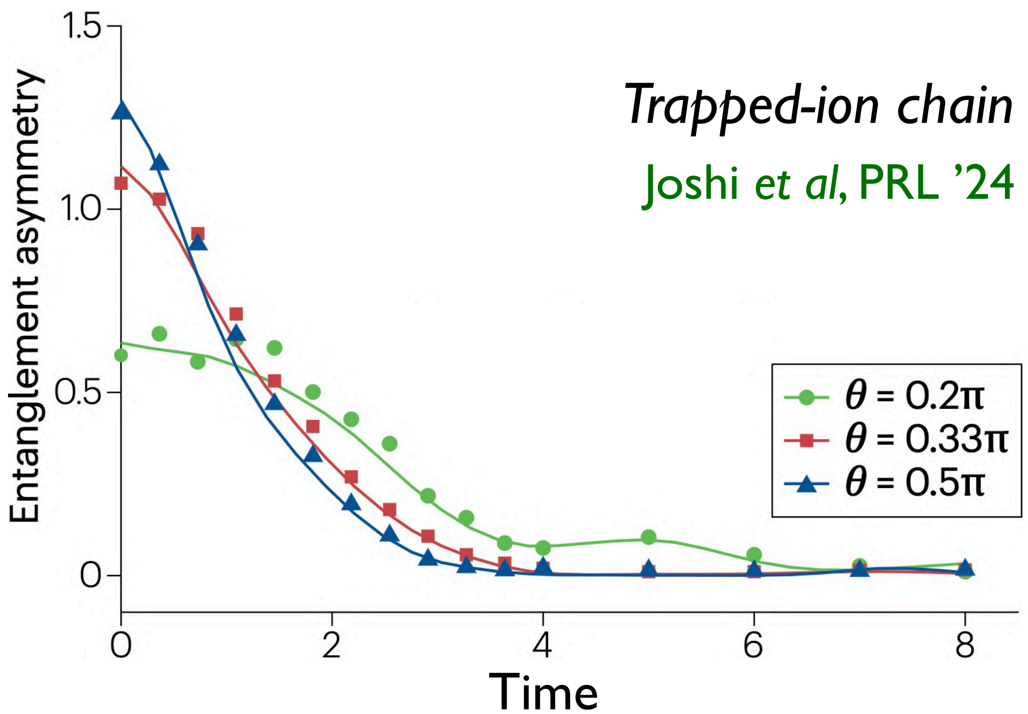
Subsystem thermalization — *symmetry restoration*

Hamiltonian has $U(1)$ symmetry (e.g., total S^z conservation), but initial state doesn't

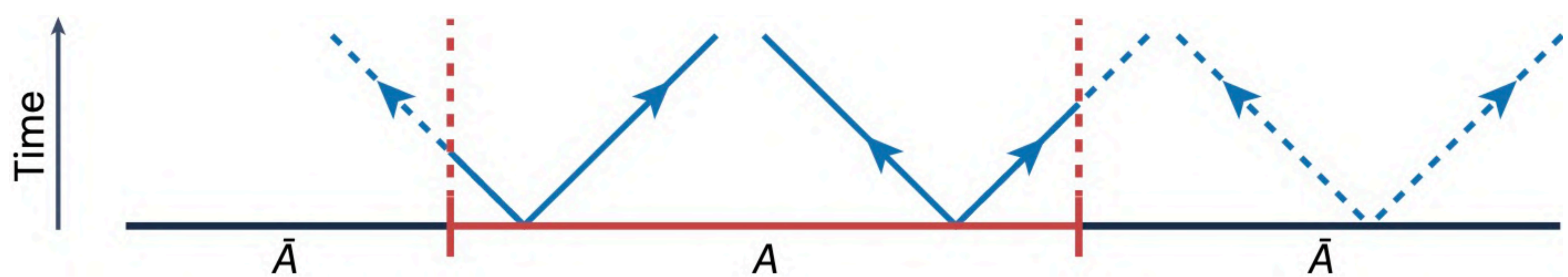
ρ_A :



Long-range $(1/r)$ XY chain



Physical origin for integrable systems: *Hotter quasiparticles escape faster*



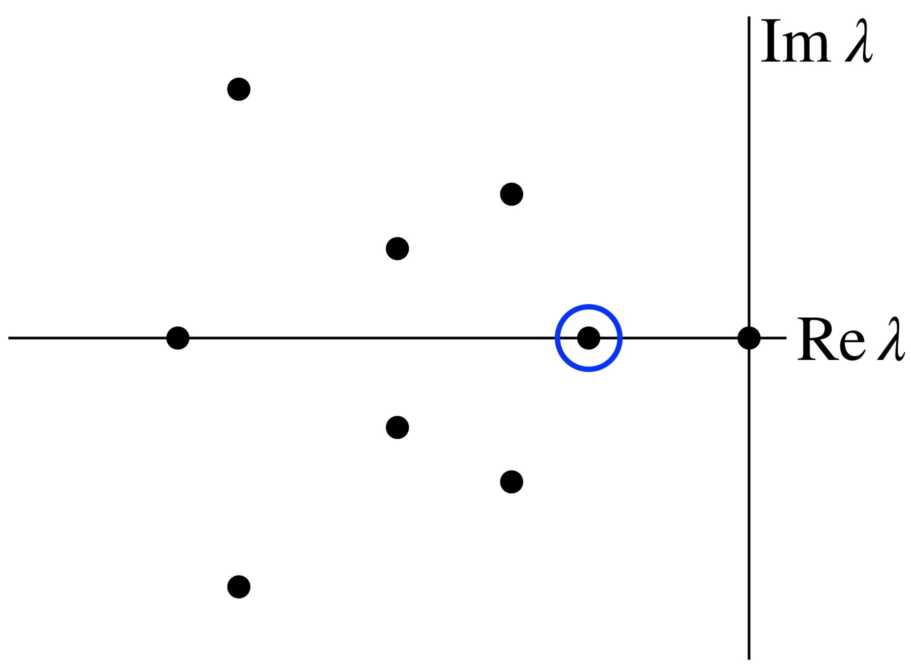
Rylands *et al*, PRL '24

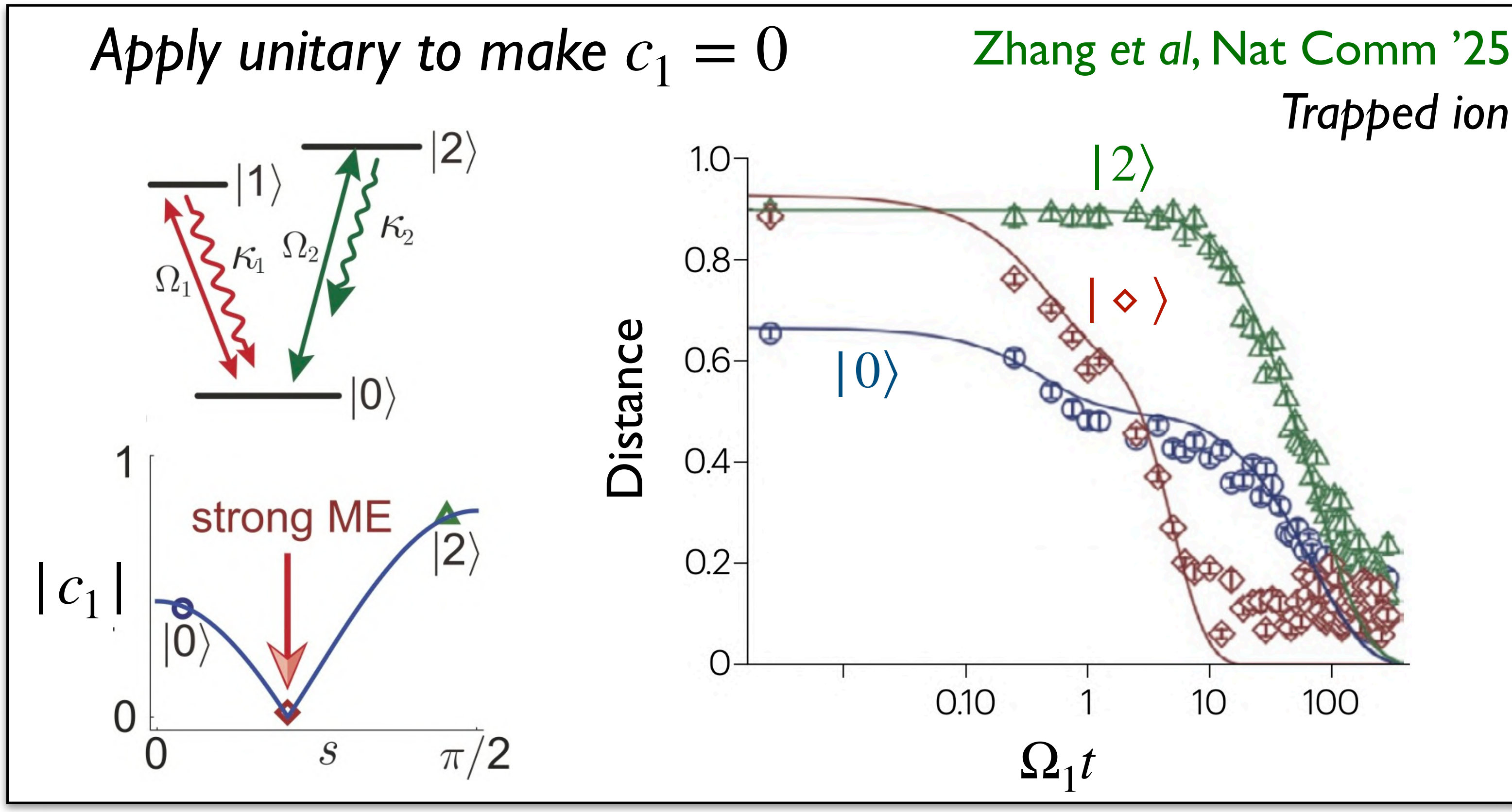
Quantum Mpemba effect — open systems

Ares, Calabrese, Murciano, Nat. Rev. Phys. '25

Slowest Liouvillian mode controls relaxation

$$\rho(t) = \rho_0 + c_1\, \rho_1\, e^{\lambda_1 t} + \ldots$$





Subsystem equilibration in closed systems also recast in terms of slow-mode overlap

Summer et al, PRX '26

Yamashika, Hamazaki, arXiv '26

Mpemba effect $\leftrightarrow$ nonmonotonic variation of c_1 with distance

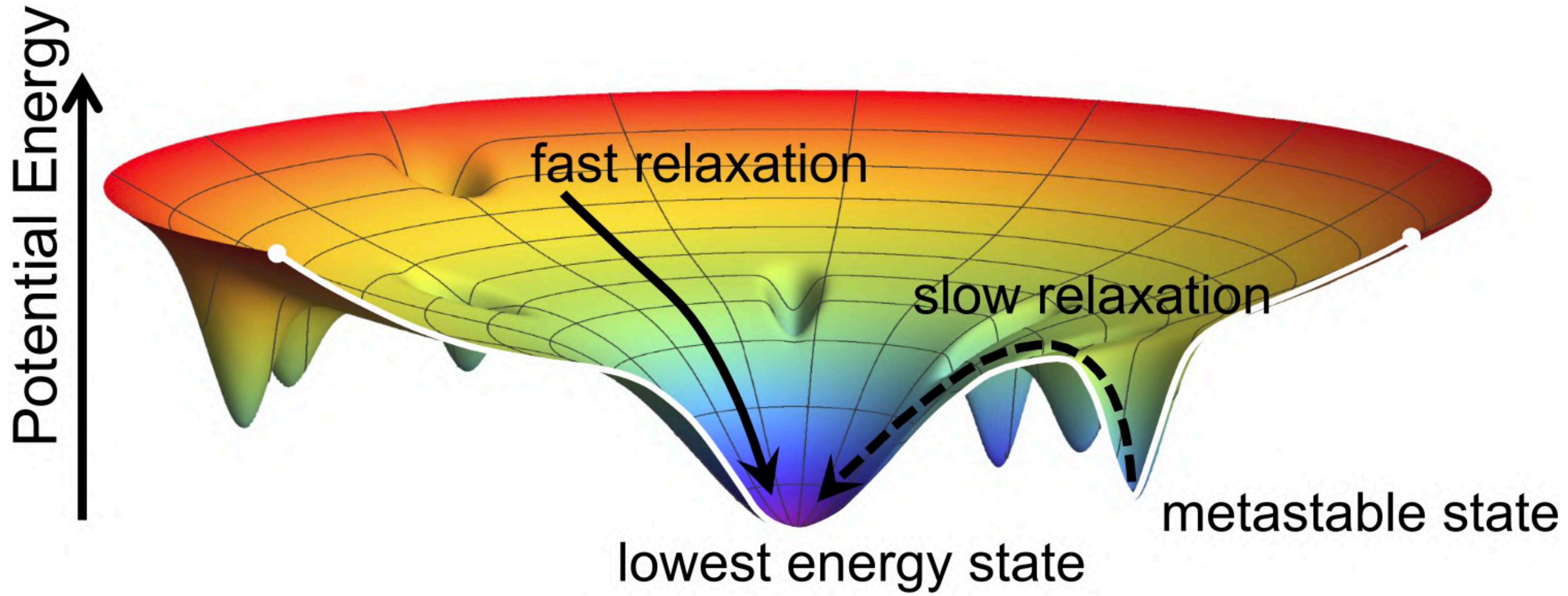
— Numerically found to arise from *symmetry, nonlinearity, criticality, metastability, noise, …*

Yet, physical/intuitive origin remains unclear

Energy landscape picture — classical

Classical Monte-Carlo / Fokker-Planck dynamics

Lu, Raz, PNAS '17



(How) Can this picture work in quantum systems?

Uncertainty principle + evolution local on the energy surface

Quantum: Energy landscape + rare events

How do you design a (total) energy landscape w/ dissipative flow?

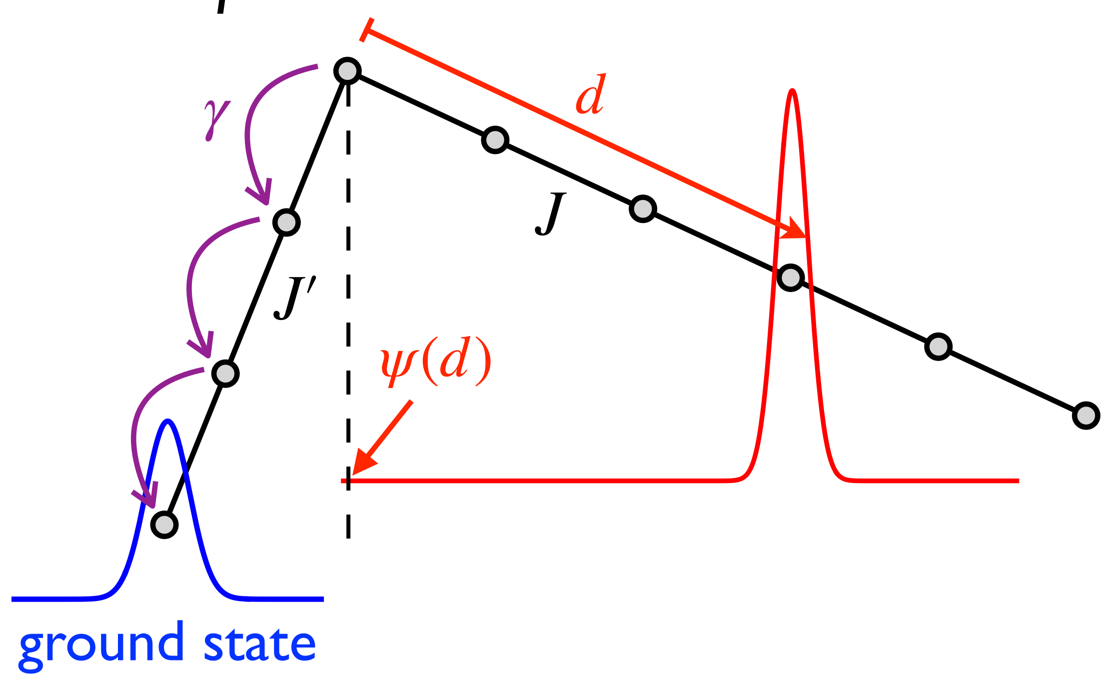
Dynamics local in position space

$\Longrightarrow$ need correspondence between total energy & position — localized eigenstates

$\Longrightarrow$ Hopping model w/ $\underbrace{\text{disorder / quasiperiodic}}_{\text{random}}$ potentials / tilted (Stark) potential

$\downarrow$ structured

Minimal setup:



Cool by incoherent hopping

(light-assisted hop + spontaneous emission / measurement + feedback)

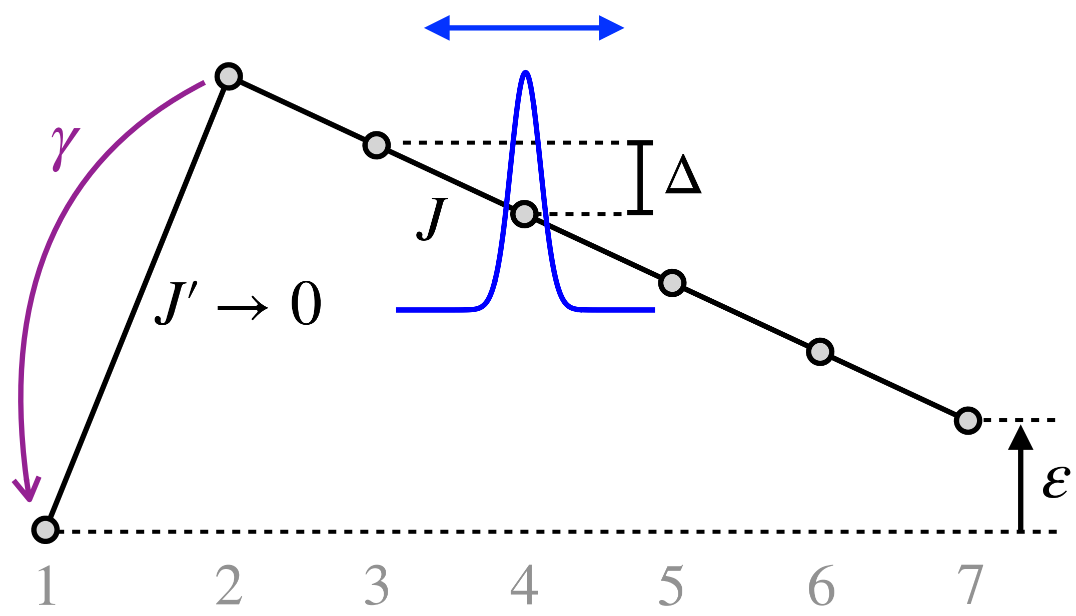
Cooling rate $= \gamma\,|\psi(d)|^2$

Falls off (super)exponentially with d

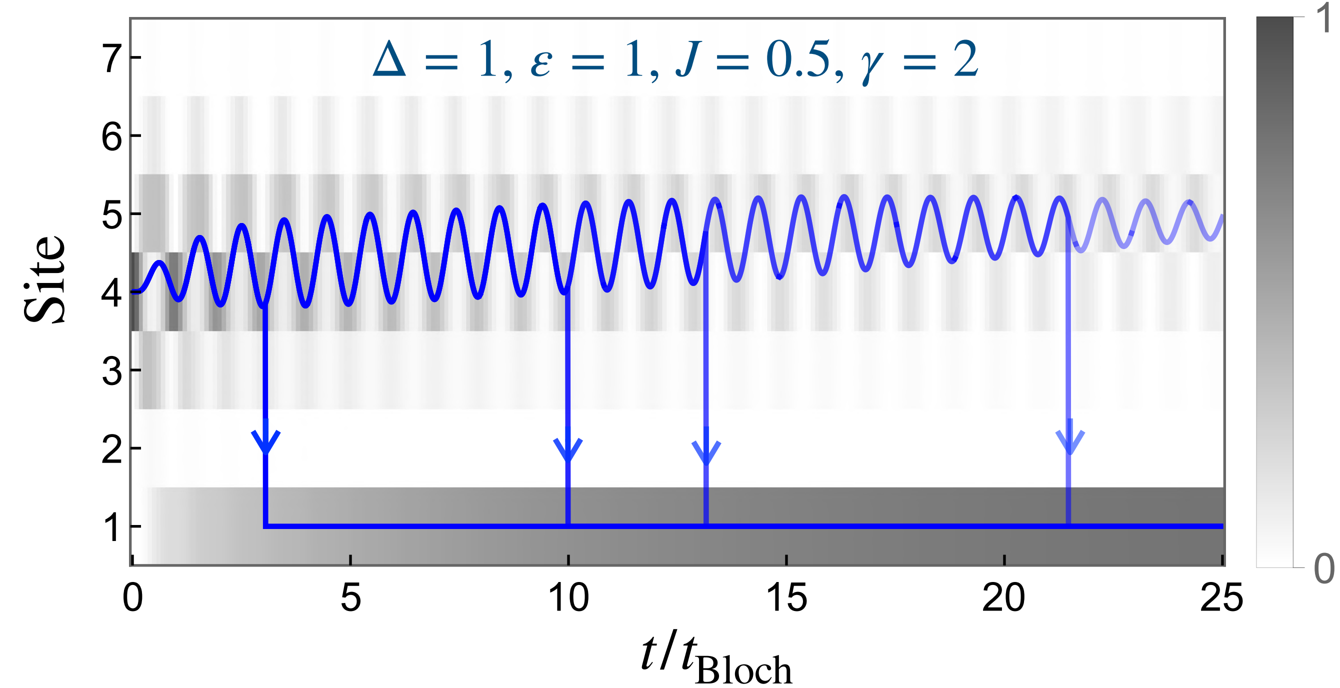
$\Longrightarrow$ higher-energy states cool faster!

> *Rare detection events give a hierarchy of cooling times (due to localization)*

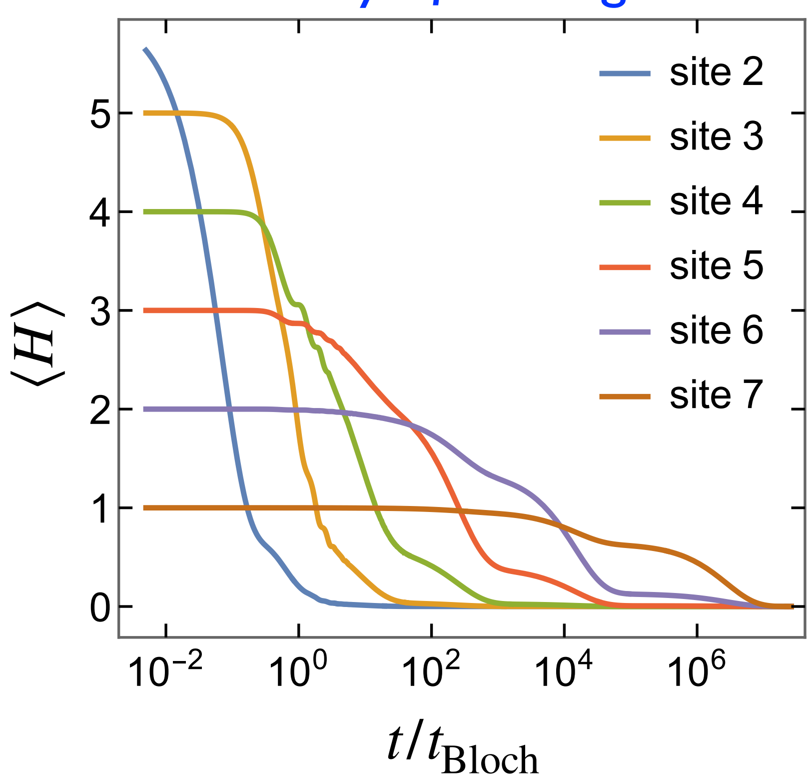
Quantum: Energy landscape + rare events



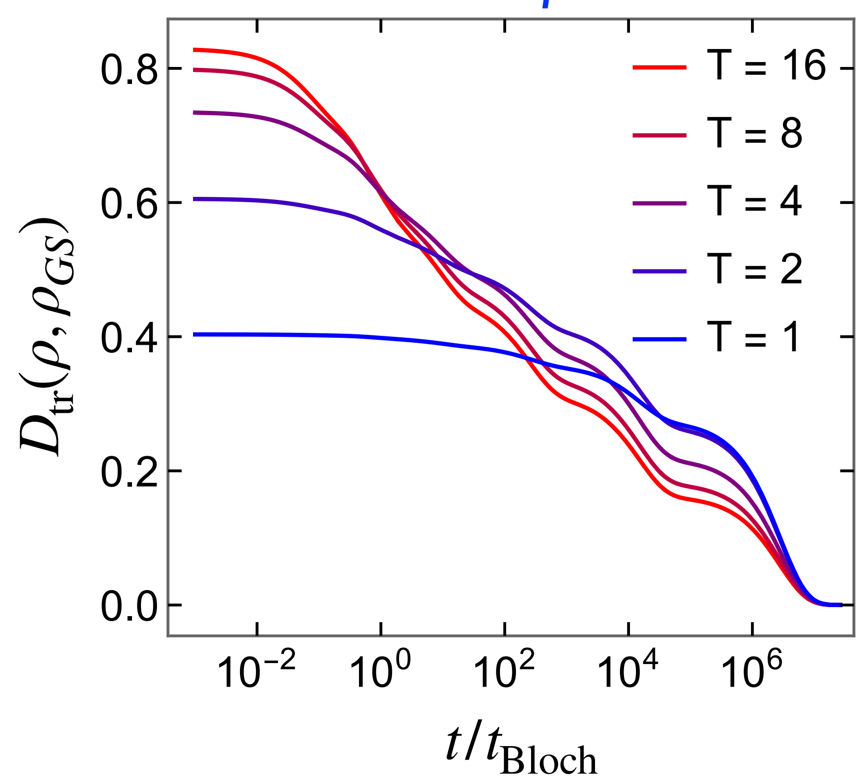
Trajectories + Average



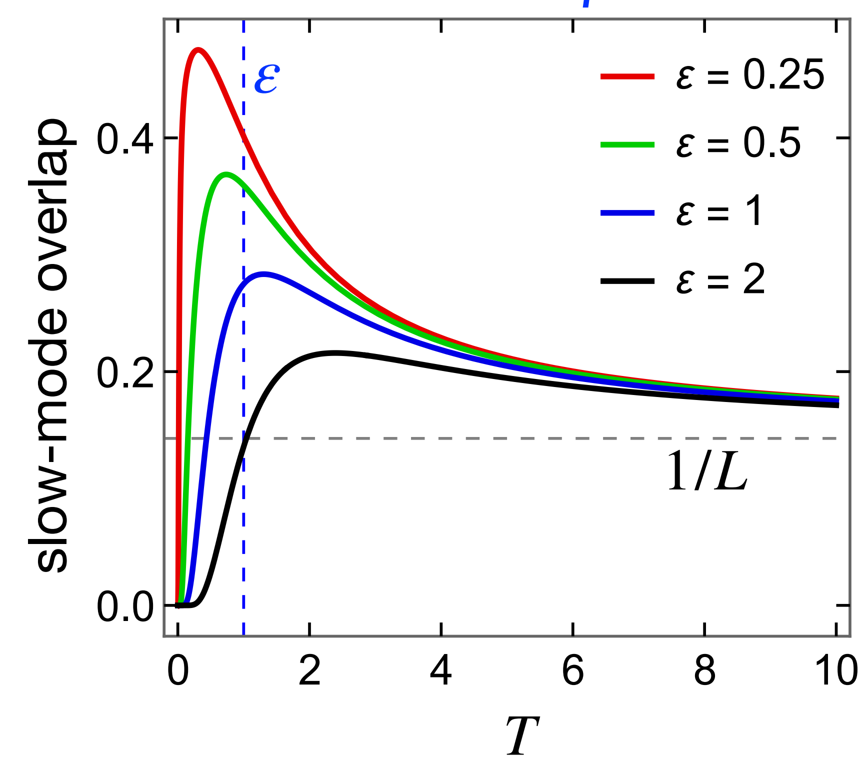
Hierarchy of cooling times



Thermal Mpemba

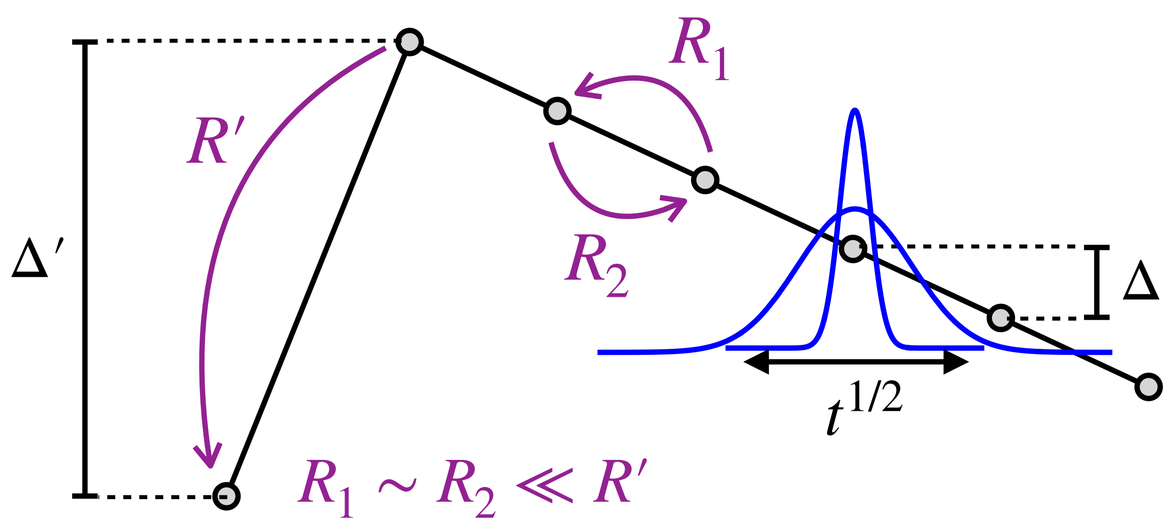


Tunable overlap curve

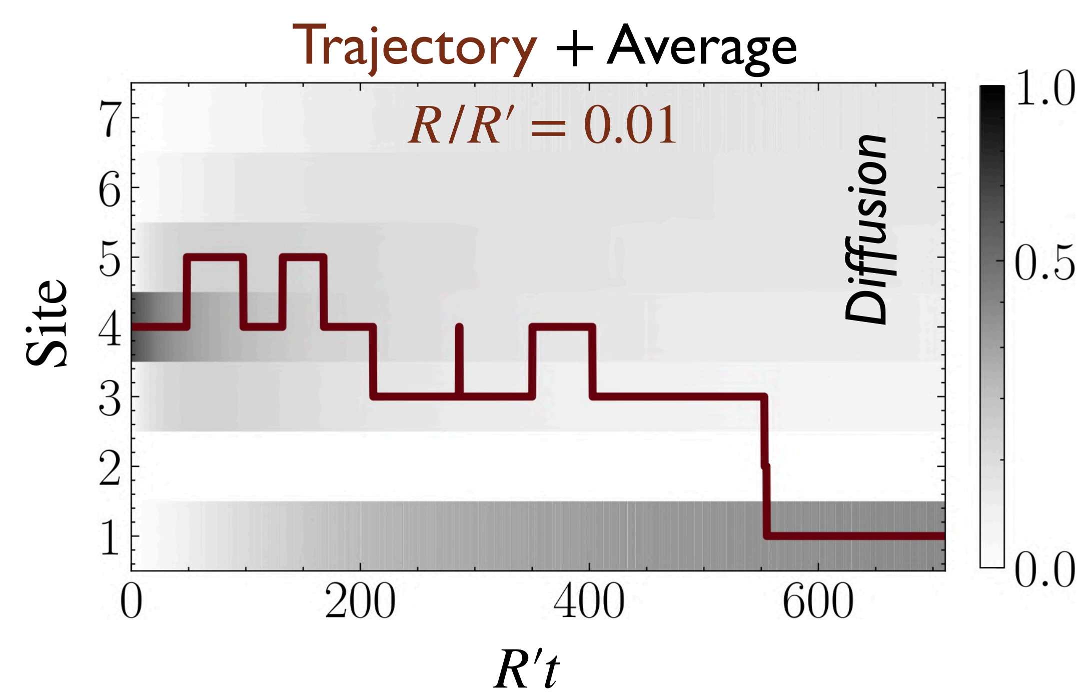


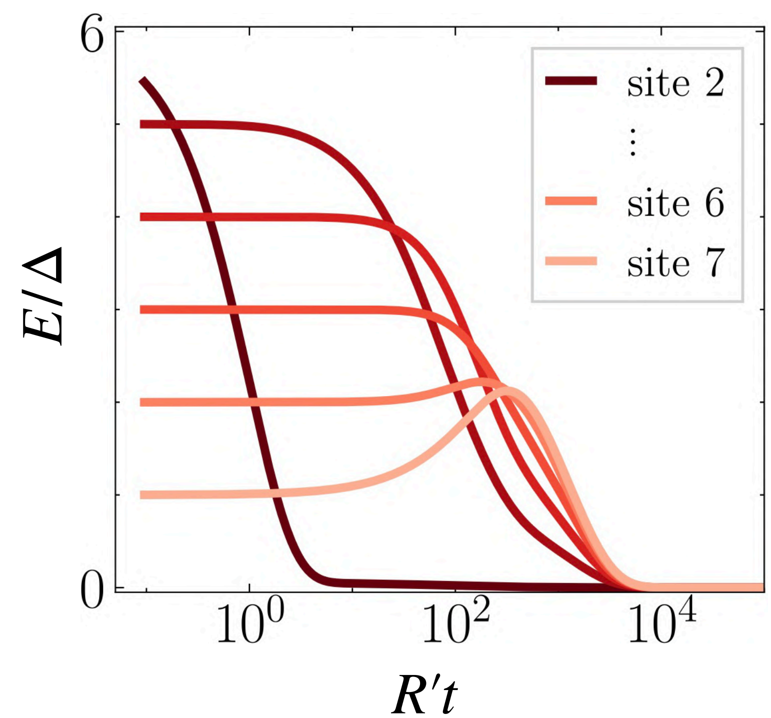
Coherence crucial — contrast w/ classical

Classical cooling: $\dot{p}_i = \sum_j R_{i,j} p_j$ *"If all hops were incoherent"*

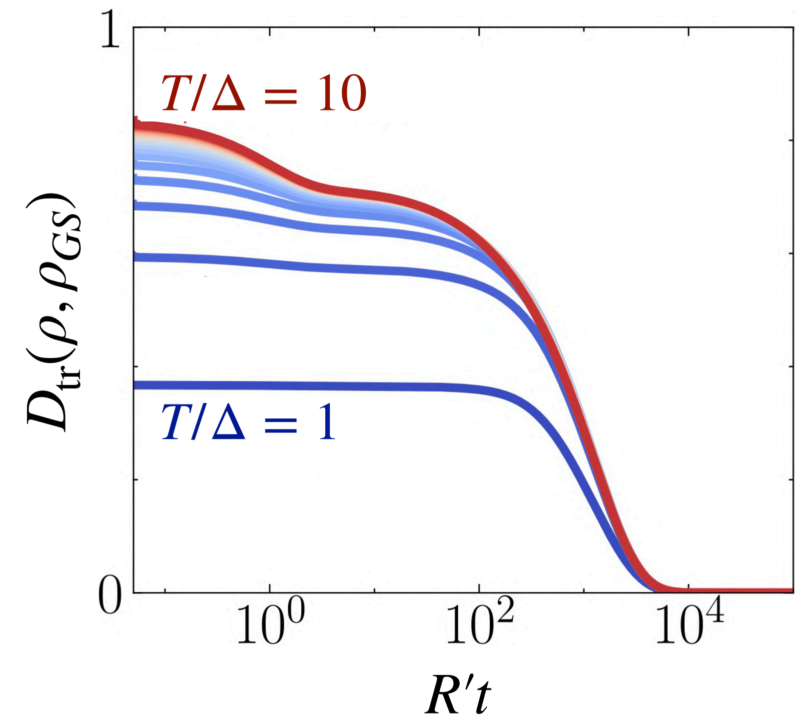


(Metropolis w/ $\Delta \lesssim T \ll \Delta'$)





No separation of timescales



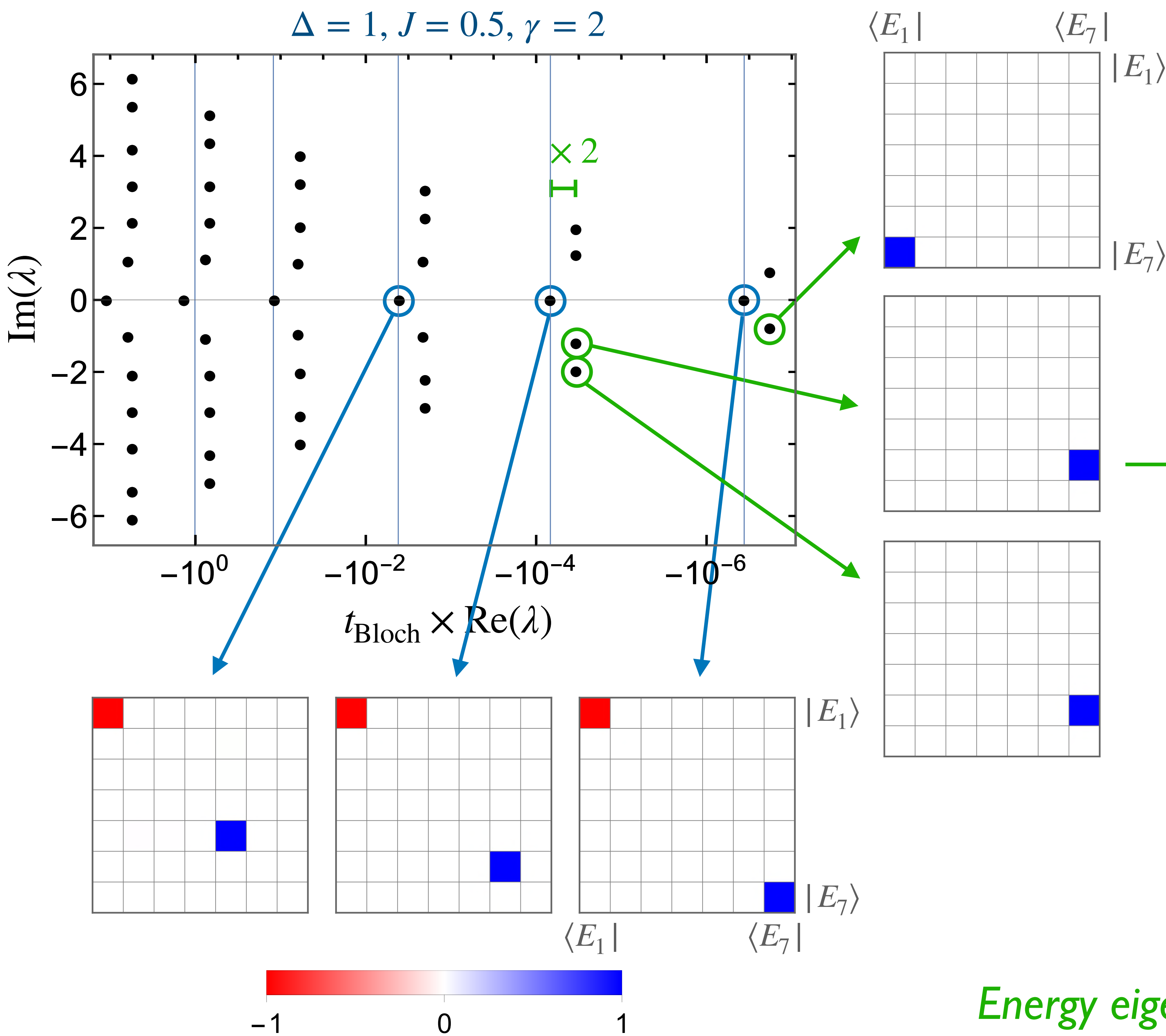
Negligible thermal Mpemba

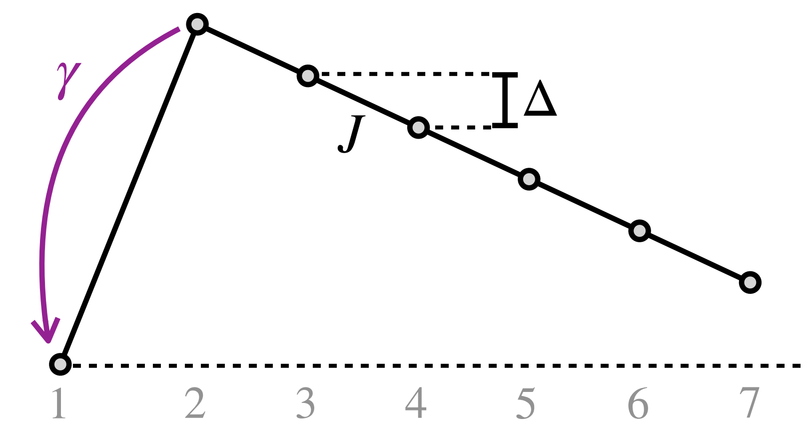
Quantum — metastable hierarchy

Normally one group of metastable states

Macieszczak *et al*, PRR '21
Jäger *et al*, PRL '22

Liouvillian spectrum





$$|\psi(0)\rangle = \alpha_6|E_6\rangle + \alpha_7|E_7\rangle$$

$$\alpha_j(t) \sim e^{-iE_jt - \frac{1}{2}\Gamma_j t}$$

$$\Gamma_j \sim \gamma|\langle 2|E_j\rangle|^2$$

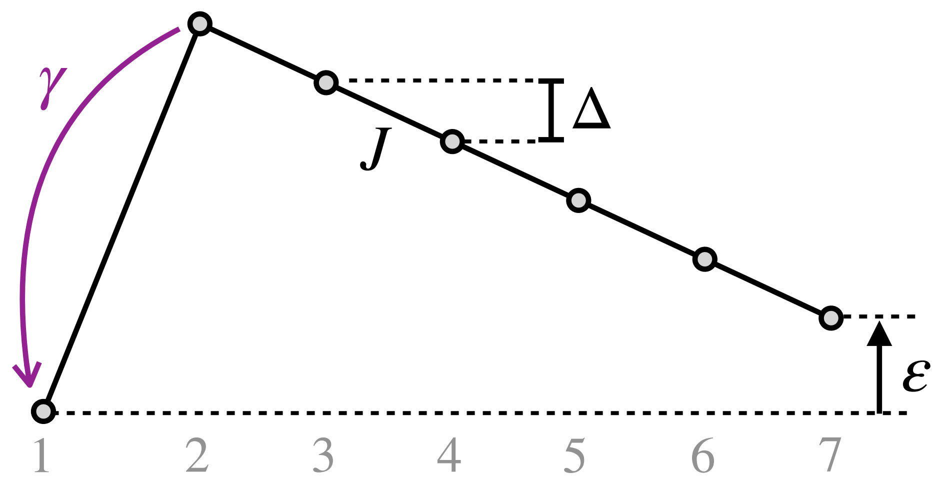
$$\implies \alpha_6^*\alpha_7 \sim e^{i(E_6-E_7)t - \frac{1}{2}(\Gamma_6+\Gamma_7)t}$$

$$\sim e^{-i\Delta t - \frac{1}{2}\Gamma_6 t}$$

$$|\alpha_6|^2 \sim e^{-\Gamma_6 t}$$

Energy eigenstates evolve independently

Enhancement by attraction — collective decay



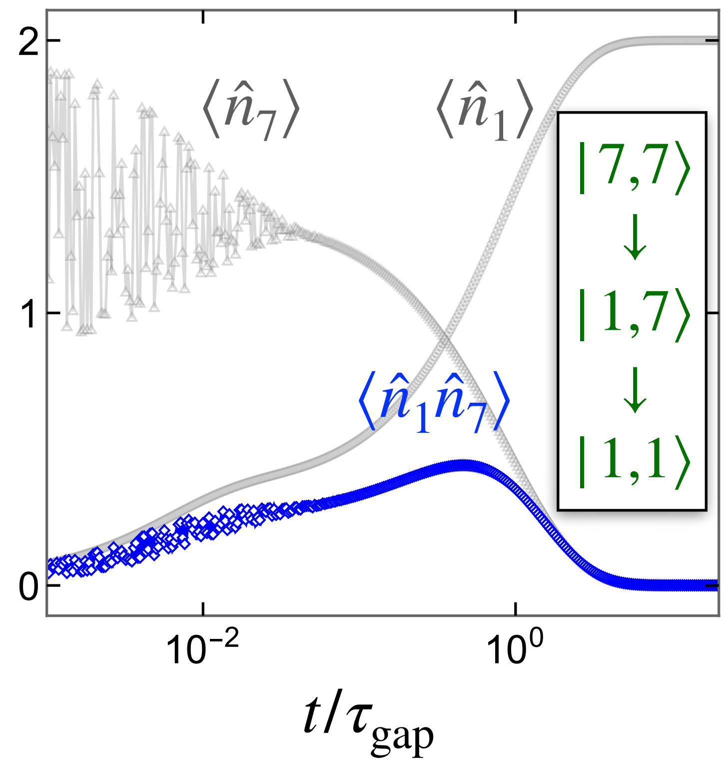
Two bosons with on-site interaction $U \leq 0$

Same protocol cools to ground state $|1\rangle \otimes |1\rangle$

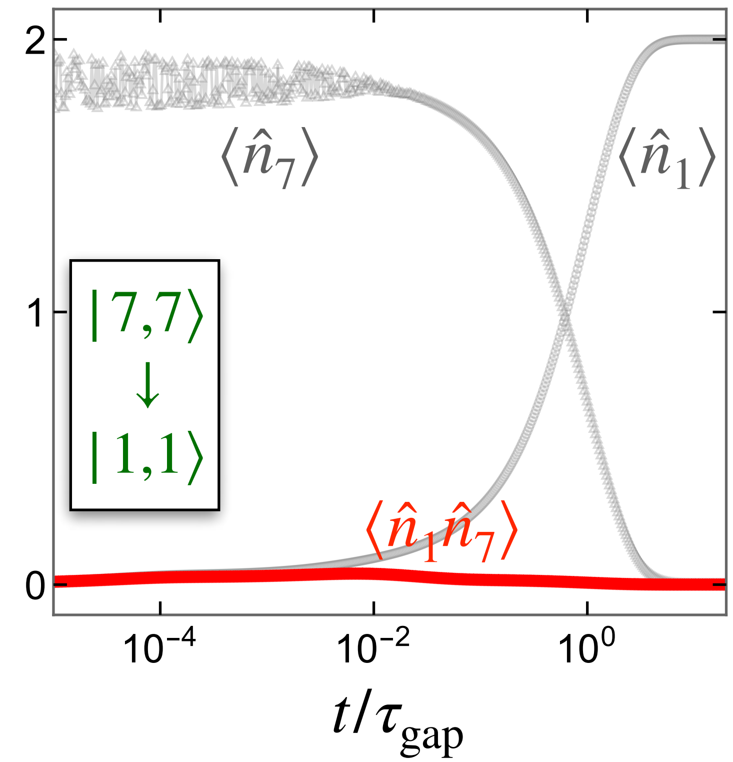
Two coordinates — but on average higher energy states cool faster

Slow mode depends on U *— distinct evolution starting from* $|7\rangle \otimes |7\rangle$ $\Delta = 1,\ \varepsilon = 1/4,\ J = 1/2,\ \gamma = 10$

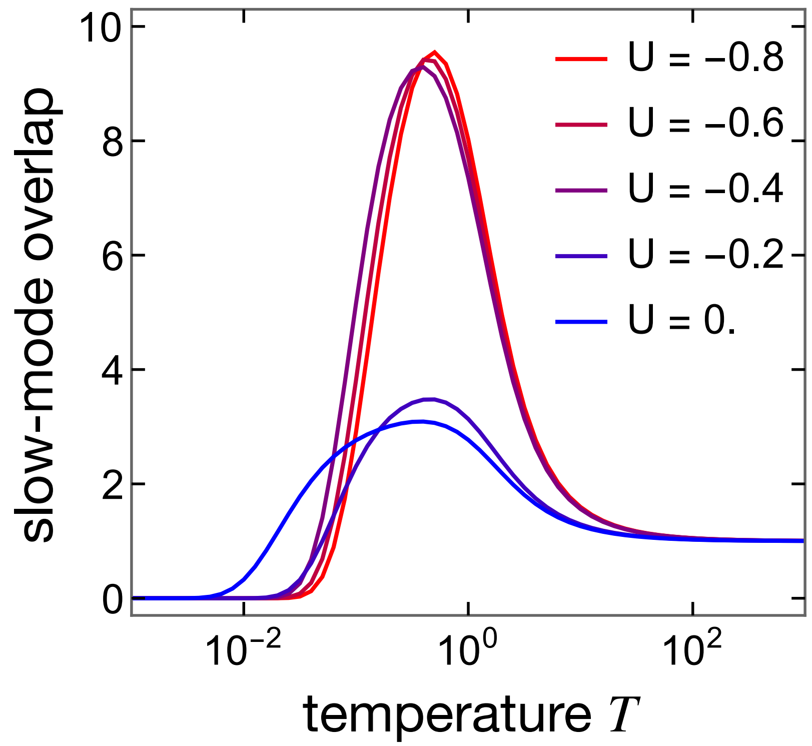
$U = 0$: *Independent decay*



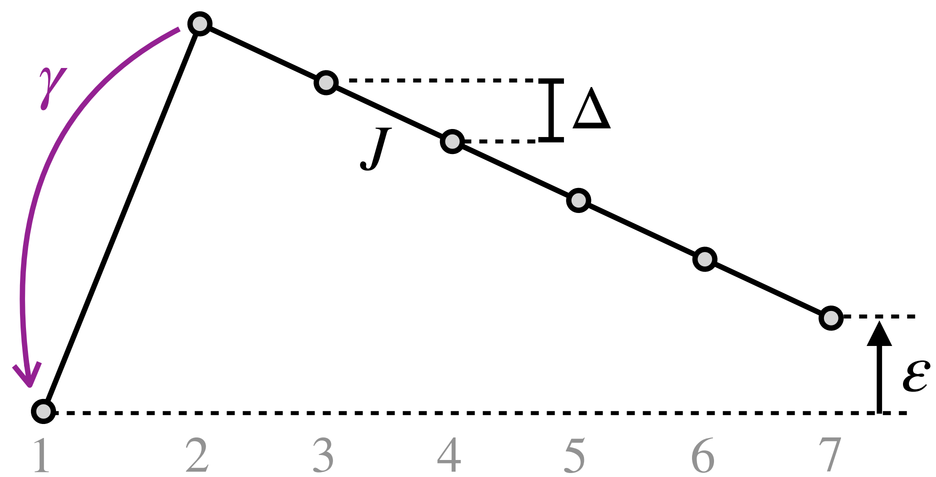
$U = -2$: *Collective decay*



Transition



Suppression by repulsion — collective decay

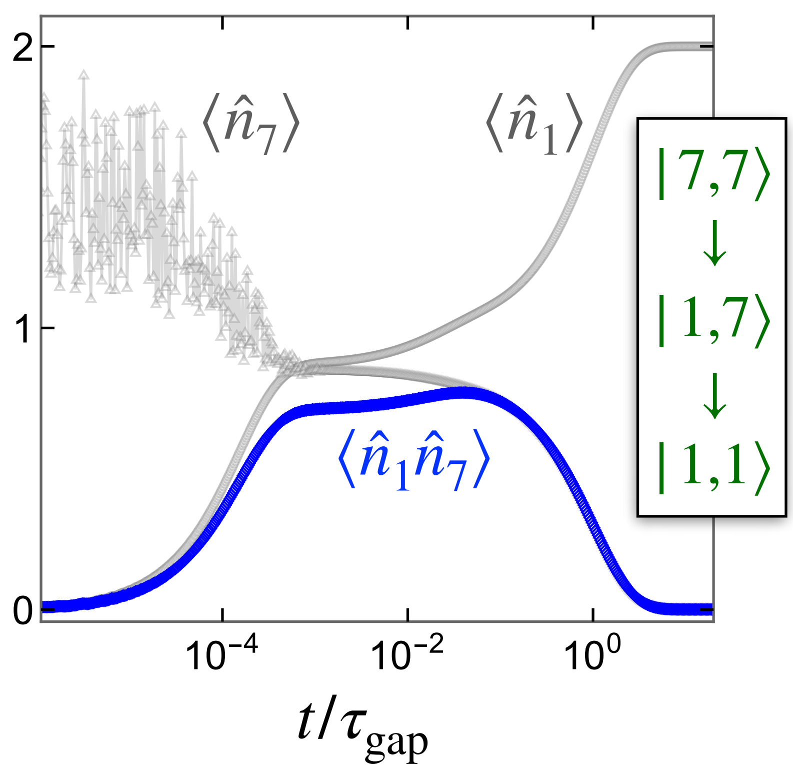


For $U > 0$, $|1\rangle \otimes |1\rangle$ is not (generally) ground state

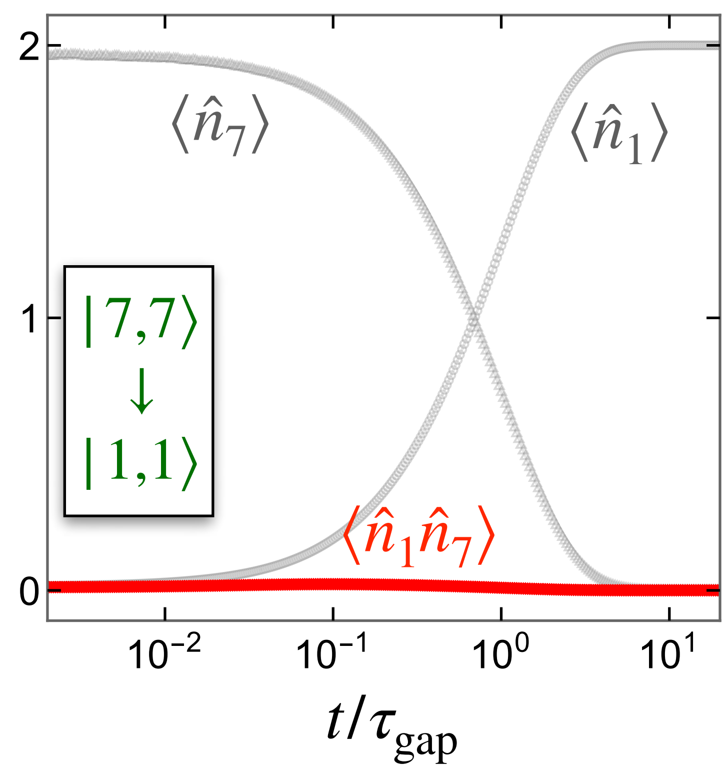
Simple "solution": Set $U = 0$ at site 1

Same transition, Opposite effect: "collective" slow mode $|7\rangle \otimes |7\rangle$ *has high energy* $\Longrightarrow$ *No Mpemba*

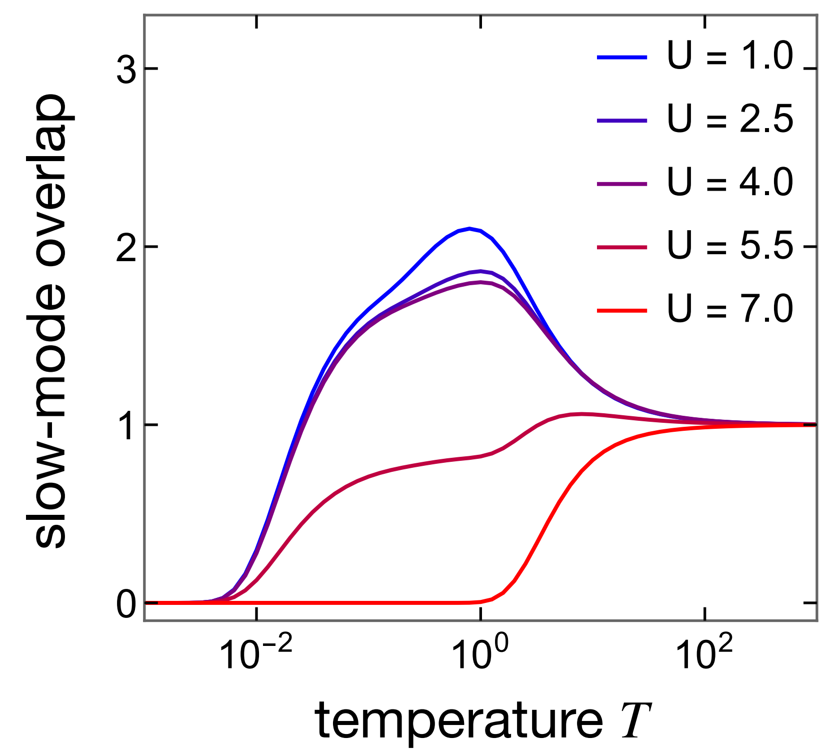
$U = 2$: *Independent decay*



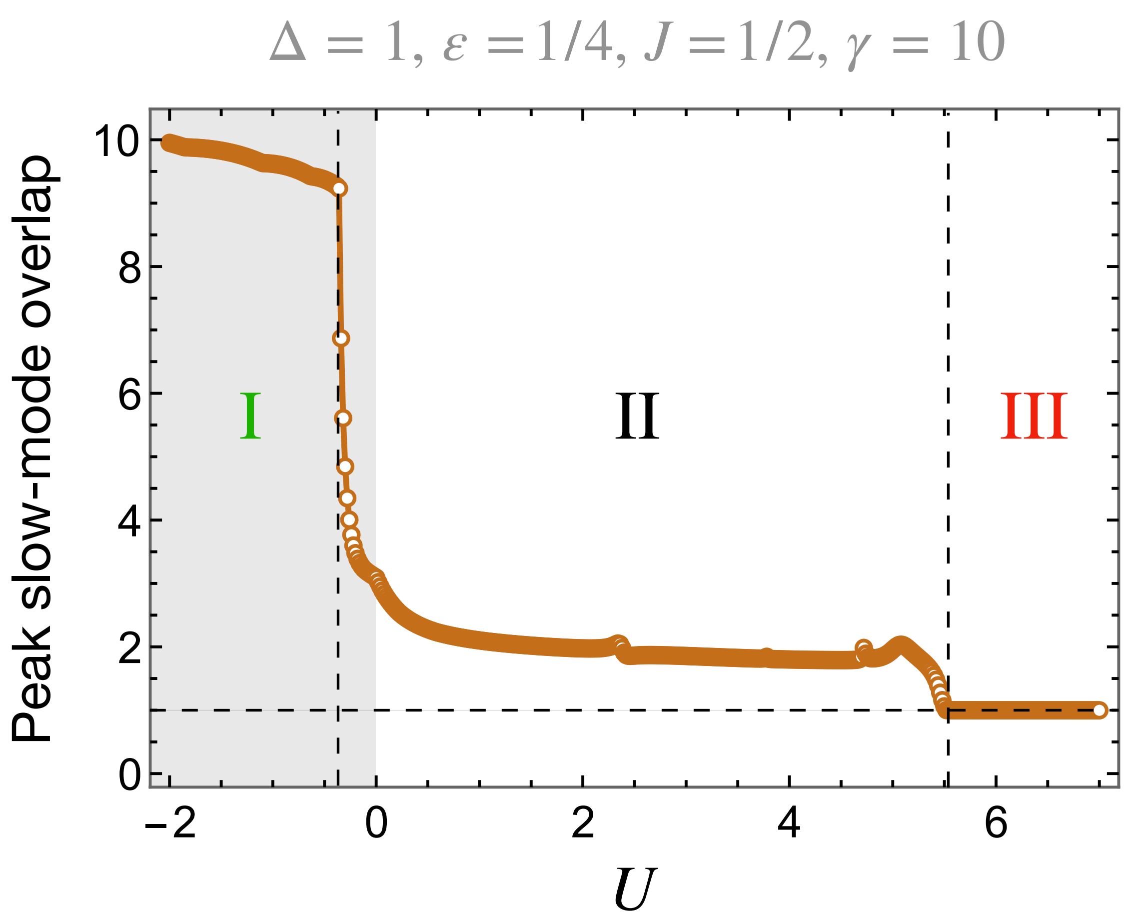
$U = 7$: *Collective decay*



Transition



Three regimes of interaction



I : *Collective (Enhanced Mpemba)*

II : *Independent (Mpemba)*

III : *Collective (No Mpemba)*

Summary

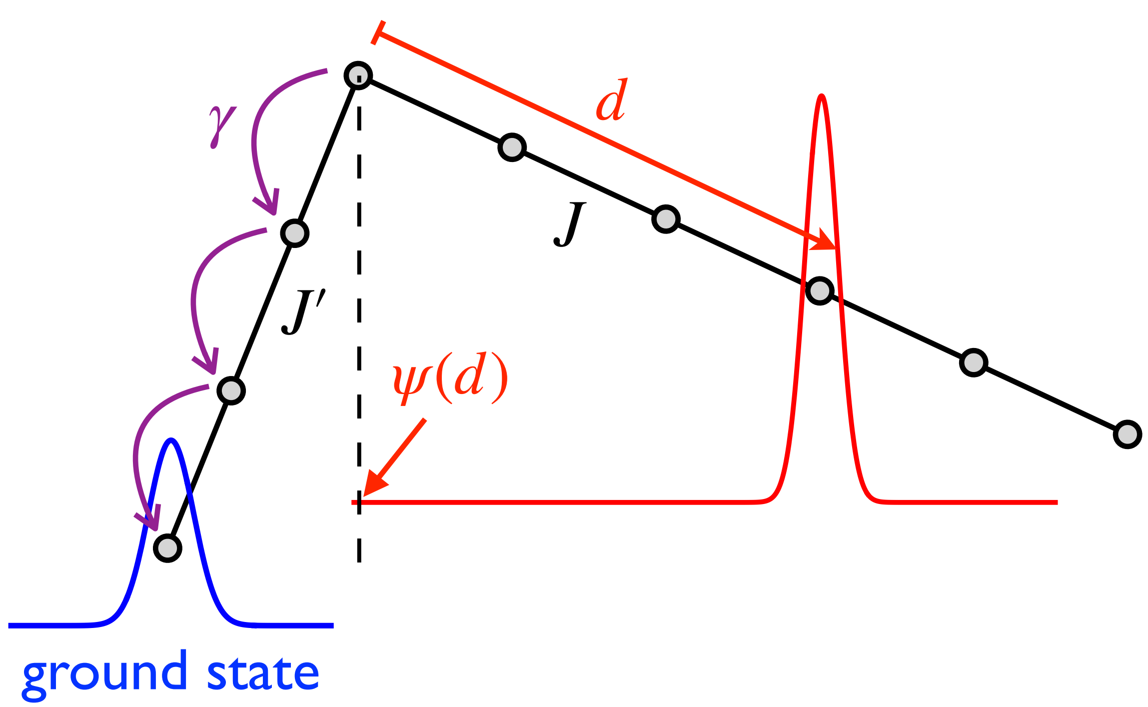
- Use localization to design energy landscape leading to Mpemba
- Rare-events based cooling gives hierarchy of metastable states
- Interactions can enhance / suppress by collective relaxation
- Possible realizations of "incoherent hopping":

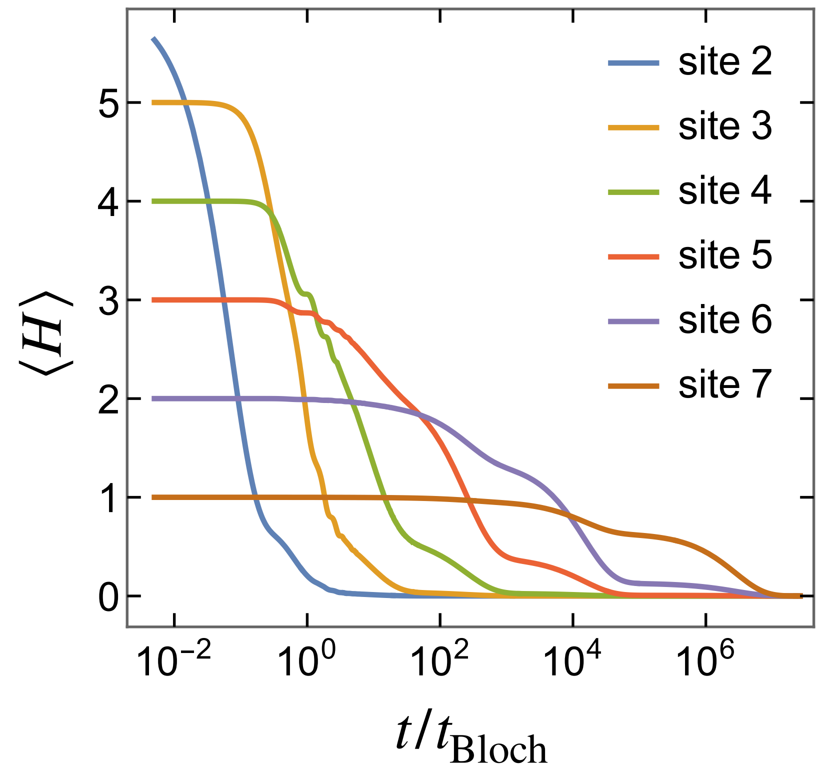
— *laser-assisted hop to an excited state + spontaneous emission*

— *measurement + feedback*

— *single particle ≡ one spin excitation*

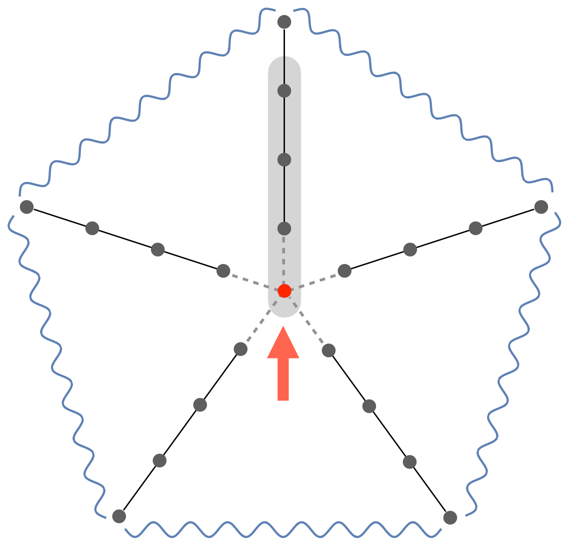
Haga *et al*, PRL '21
Griessner *et al*, NJP '07
Sharma, Mueller, PRA '21

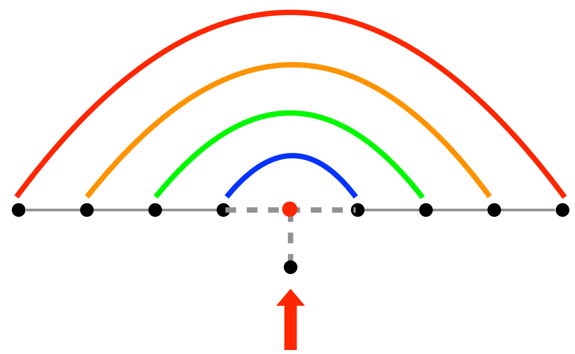




P. S. Quantum many-body networks

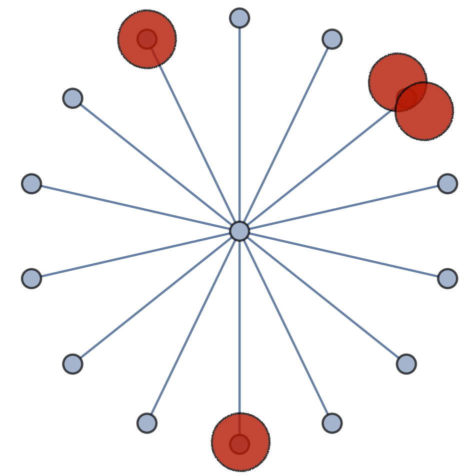
Long-range entanglement from local pump





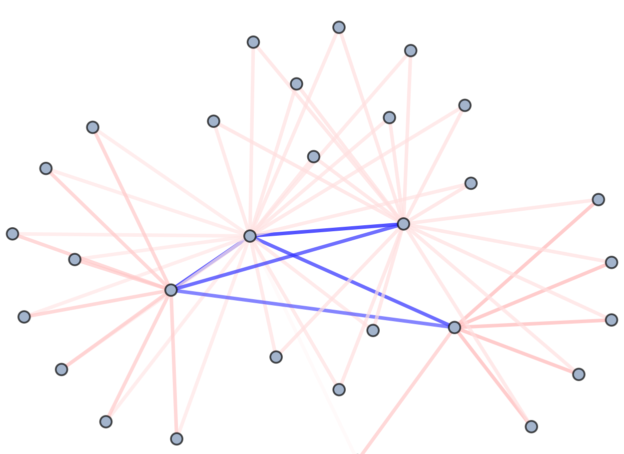
SD, Nigel Cooper, PRL '20
Revathy B S, Nigel Cooper, SD
(Ongoing)

Connectivity-induced non-ergodicity



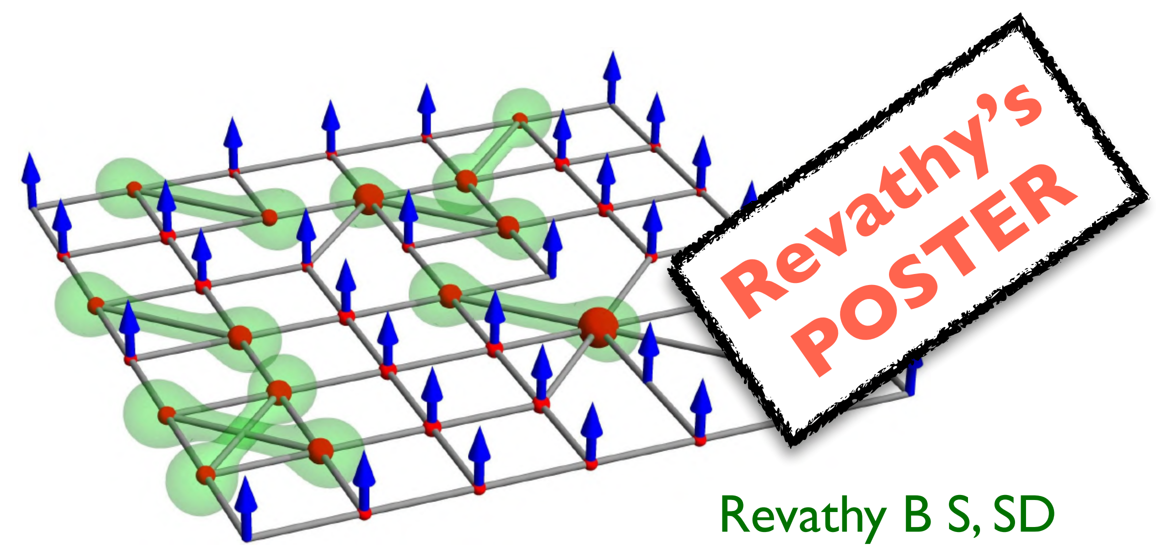
Dona Kundu, SD
(Ongoing)

Local heterogeneity governs total spin



Preethi G, SD
arXiv:2403.09116

Shaping kinetic magnetism by frustration



Revathy B S, SD
arXiv:2507.07886
[PRB(L)]

Summary

Thank you :)

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- Rare-events based cooling gives hierarchy of metastable states
- Interactions can enhance / suppress by collective relaxation
- Possible realizations of "incoherent hopping":

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  — *measurement + feedback*