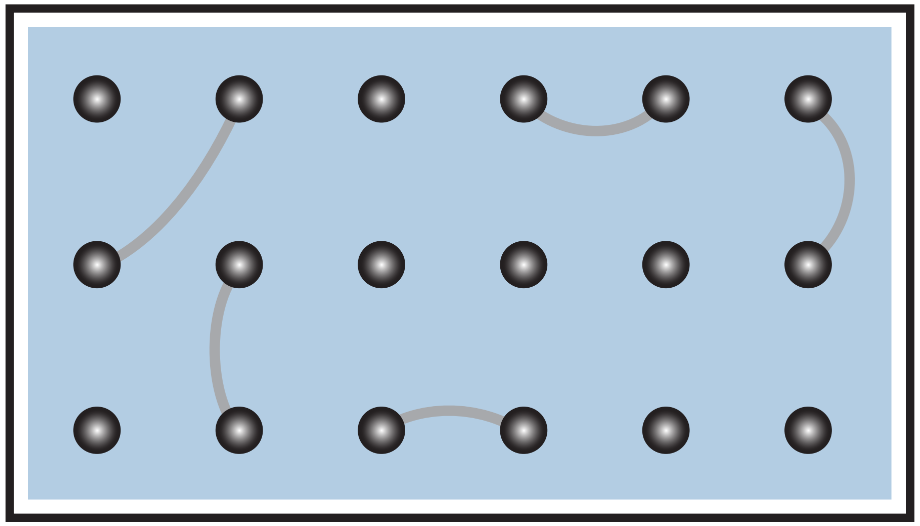
Probing entanglement and correlations dynamics in many-body localized system

Alexander Lukin
Harvard University

Thermalization in quantum system

$|\Psi\rangle$



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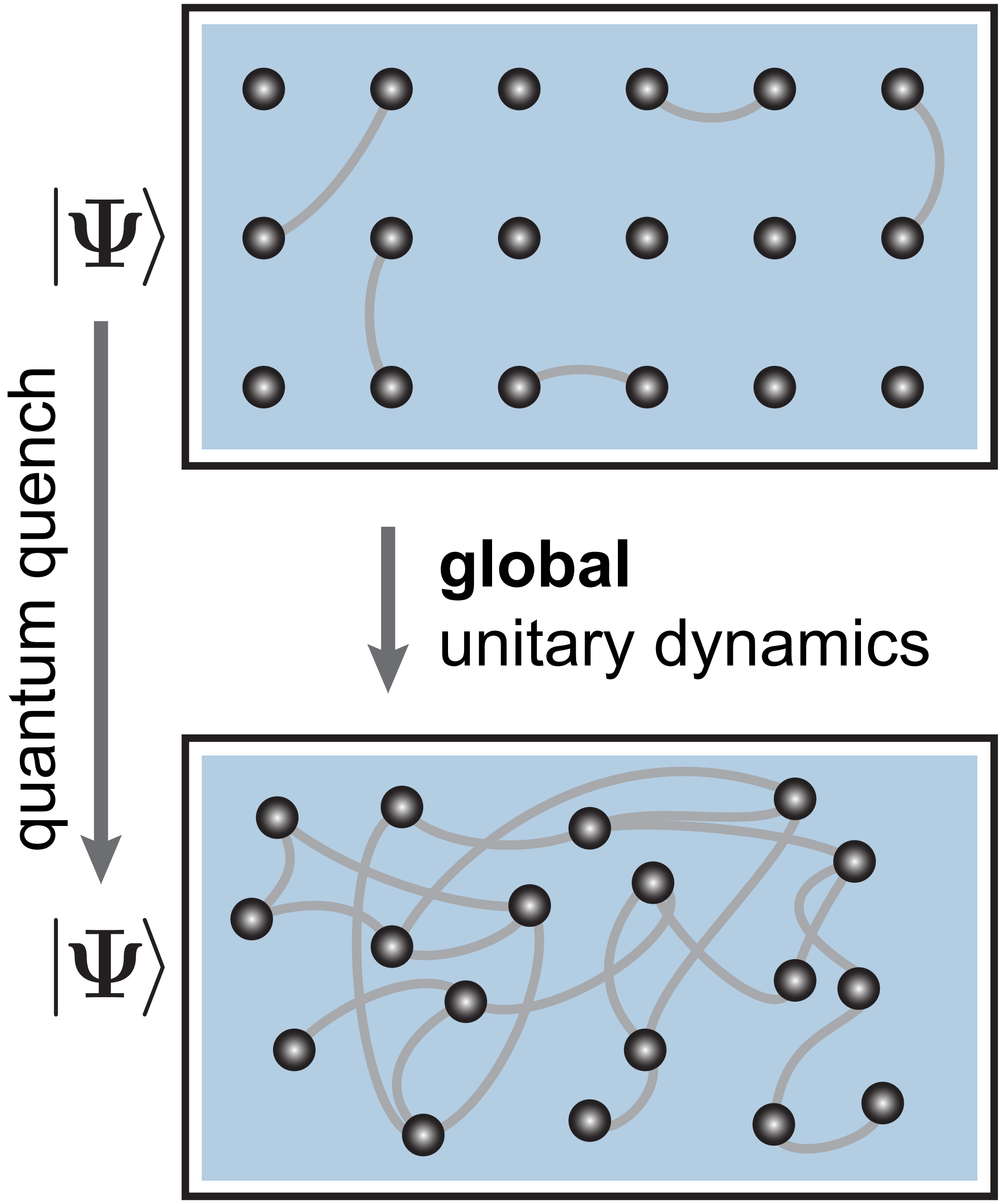

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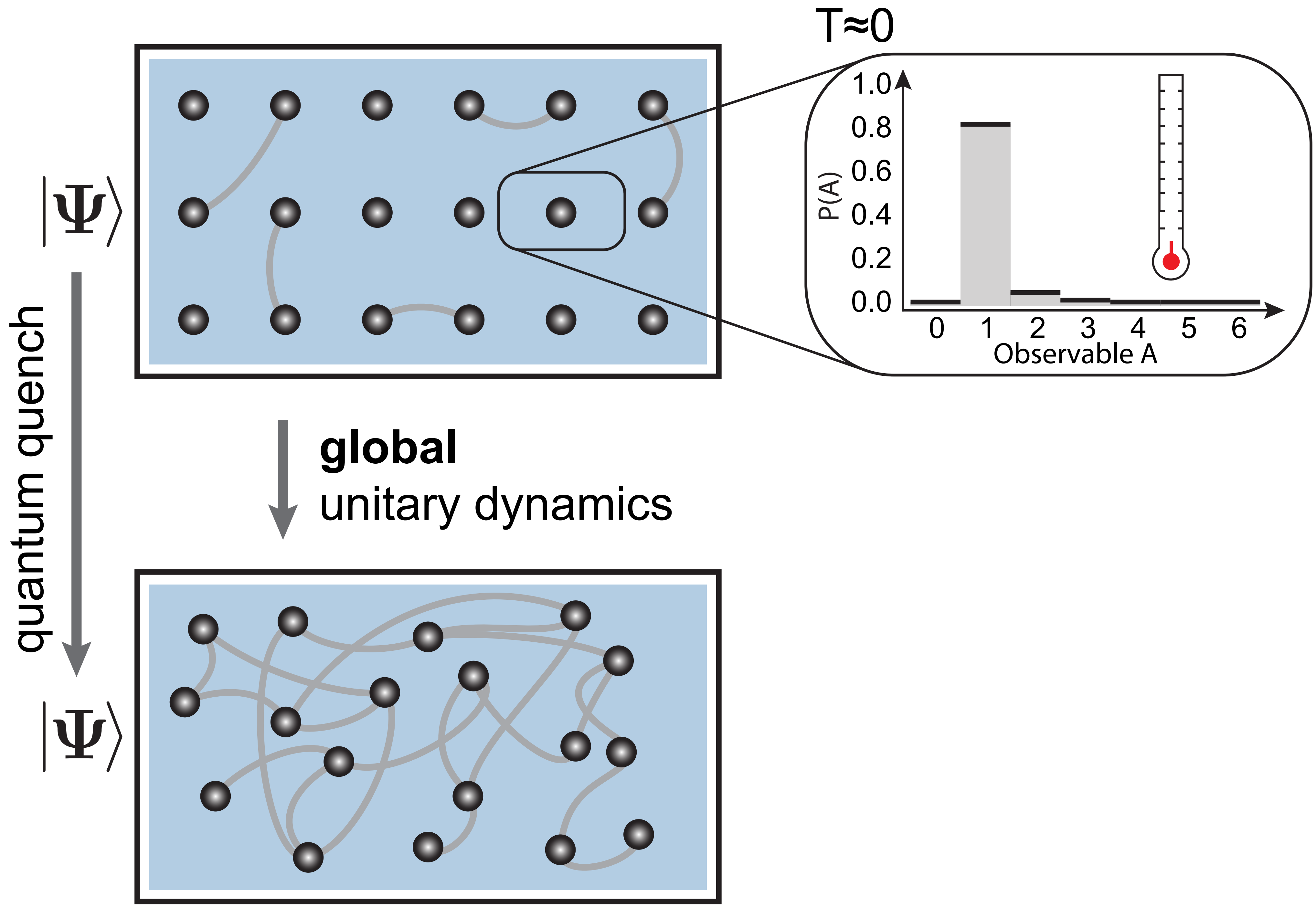

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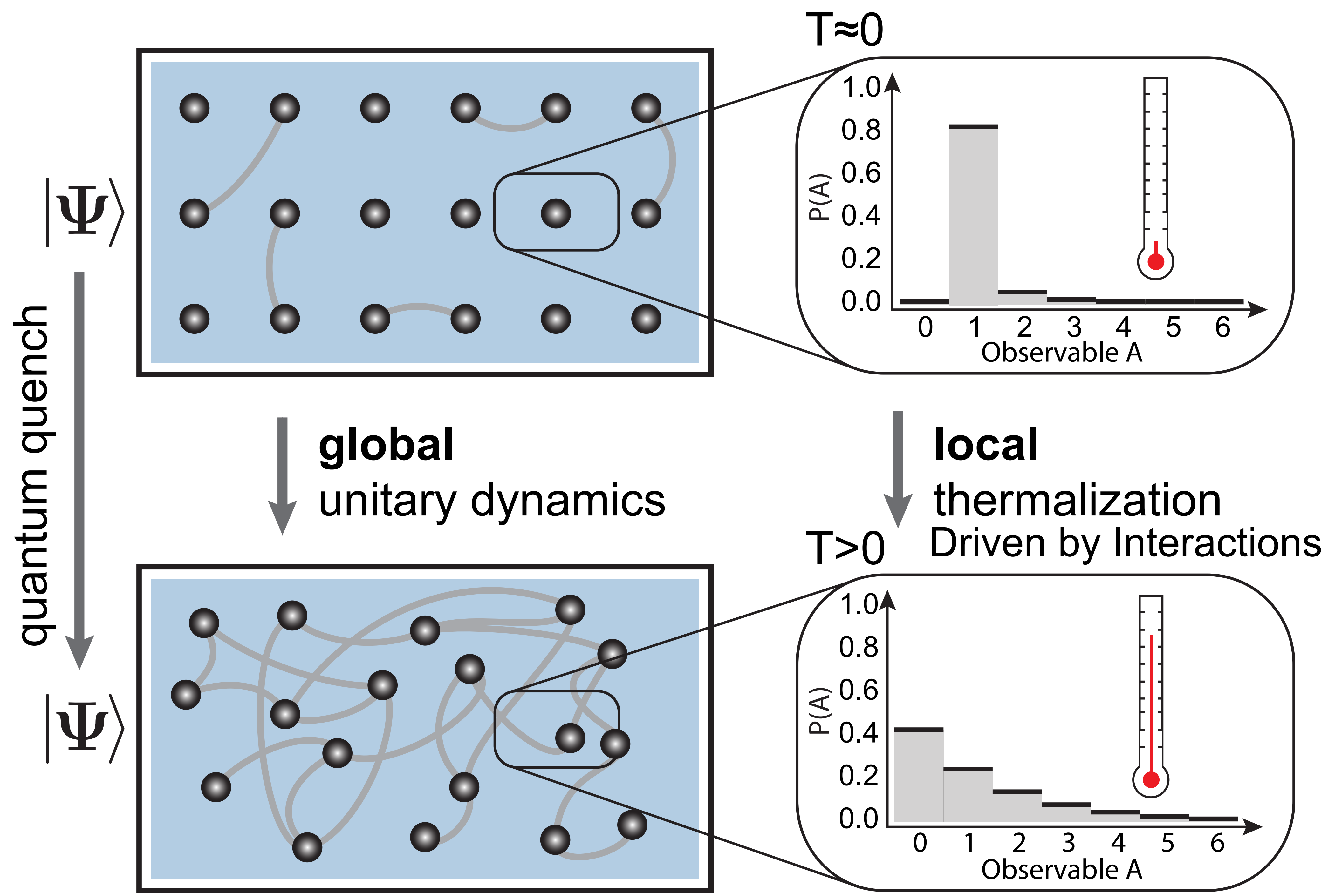

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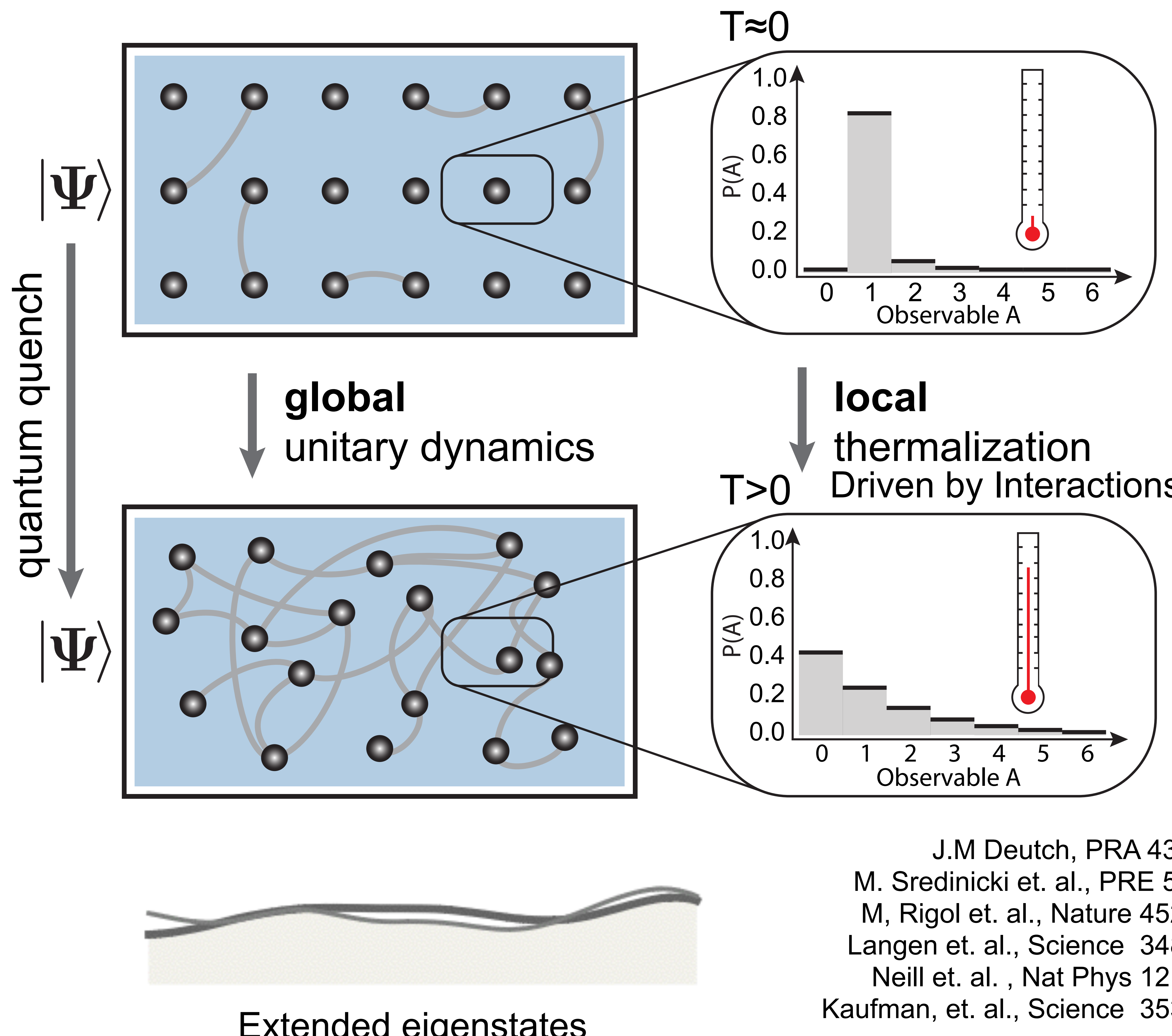

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Single-particle Anderson localization

$$\hat{\mathcal{H}} = -J\sum_i \left(\hat{a}_i^\dagger \hat{a}_{i+1} + h.c.\right) + \sum_i W_i \hat{n}_i$$

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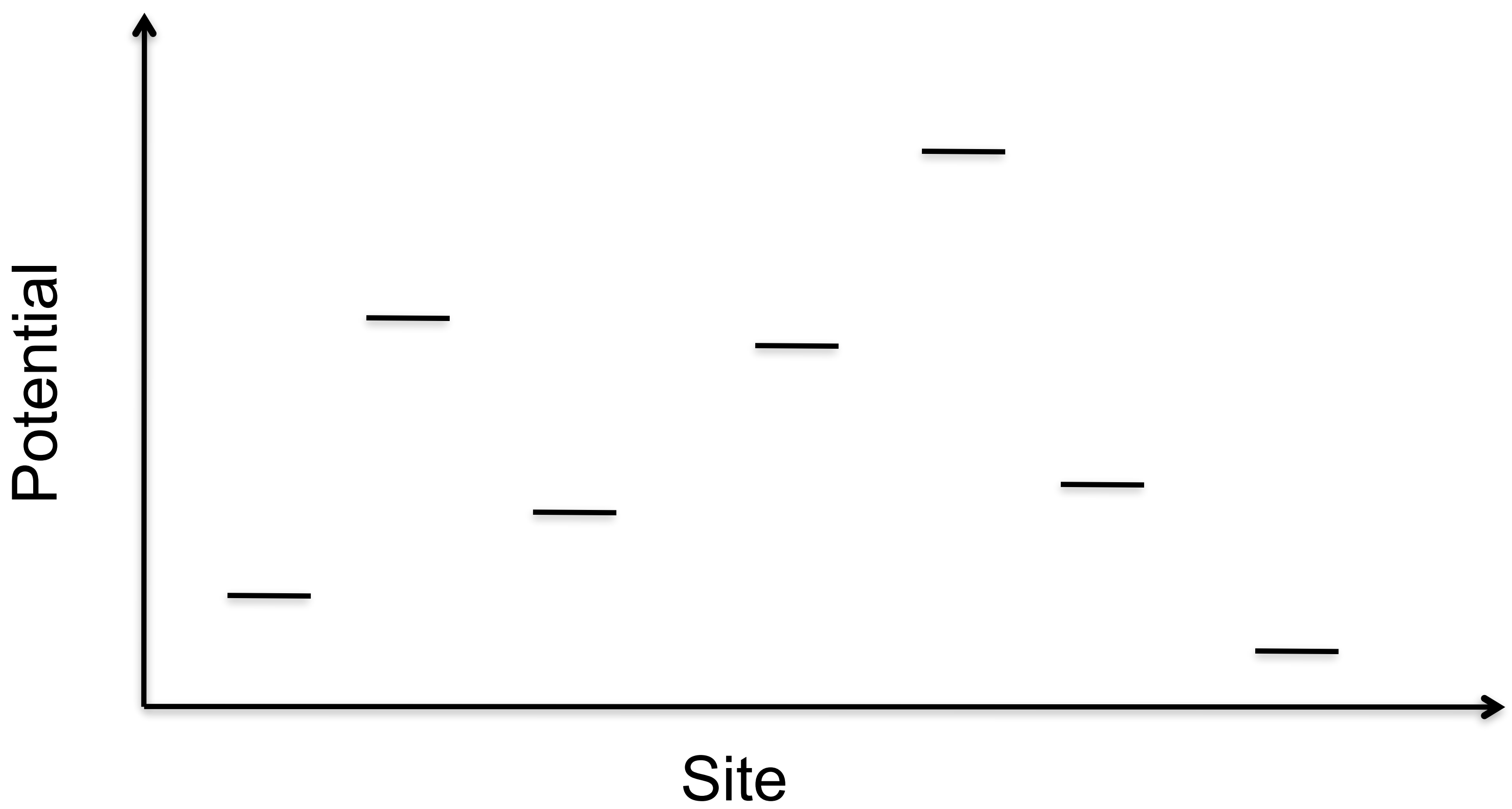

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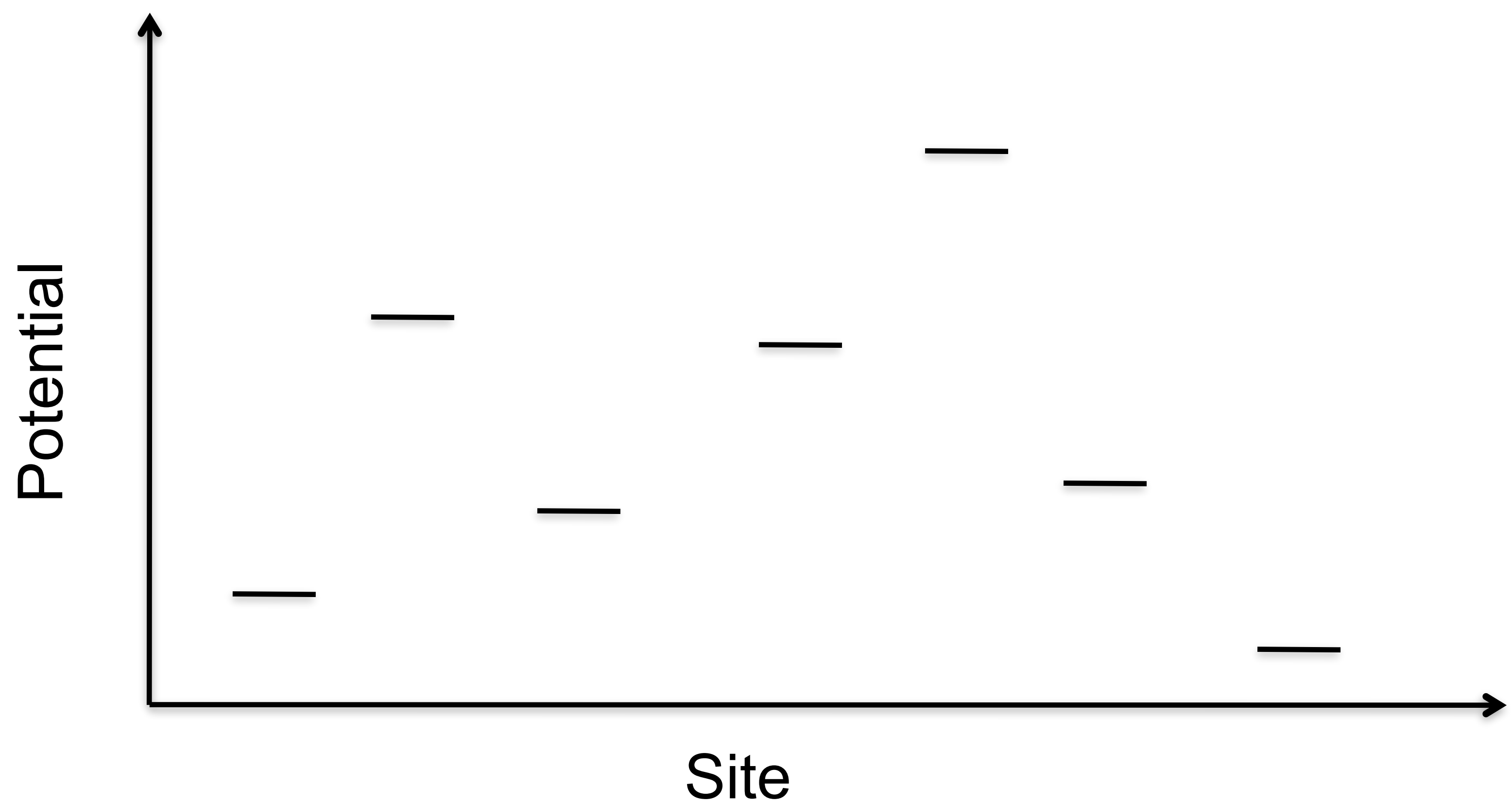

Off-resonant hopping fails to hybridize sites at long-distances

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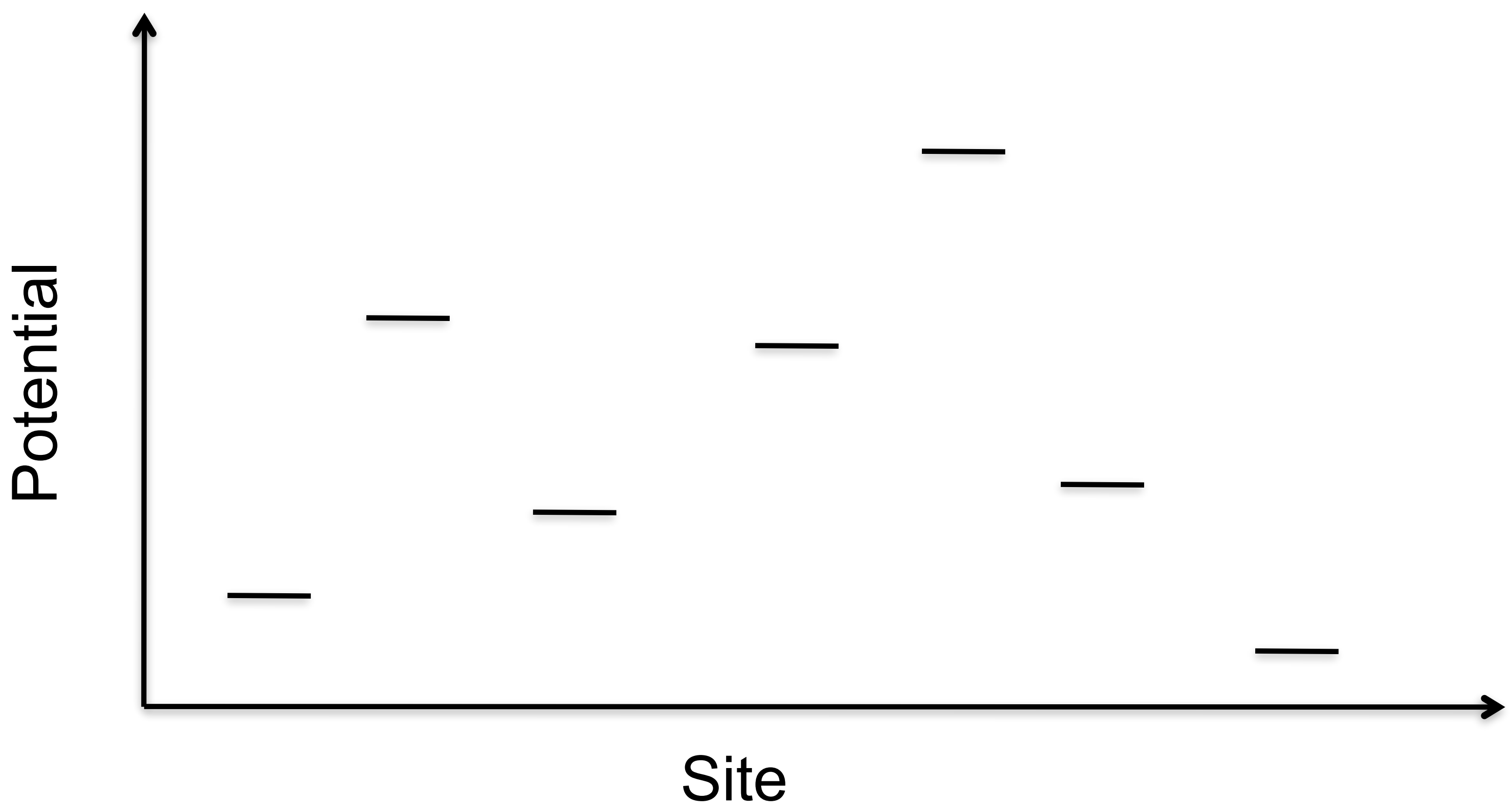

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Localized $|\phi(r)|^2 \sim e^{-r/\xi}$

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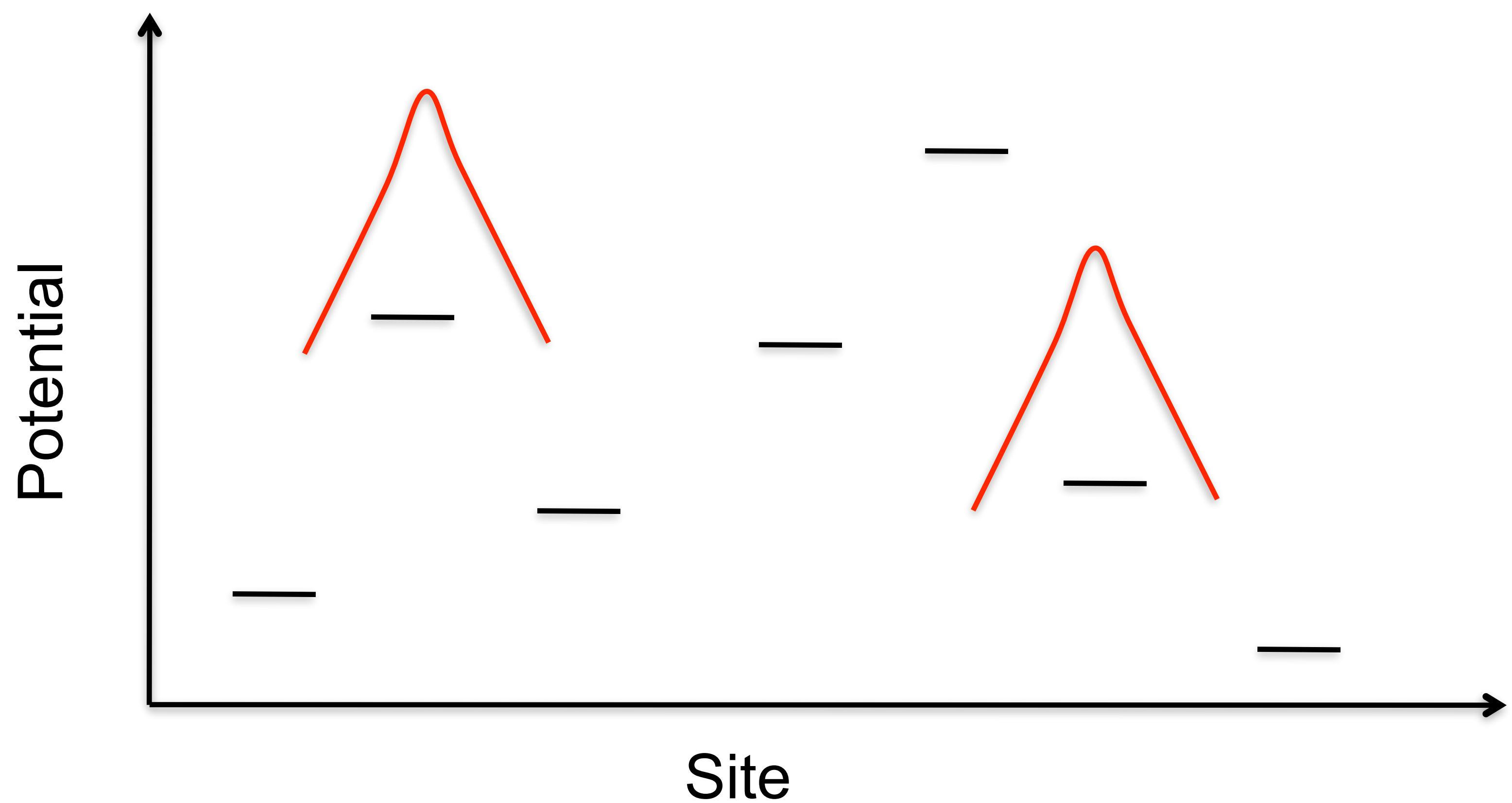

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Many-body localization (MBL)

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Extended eigenstates

Localized eigenstates

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Localized eigenstates

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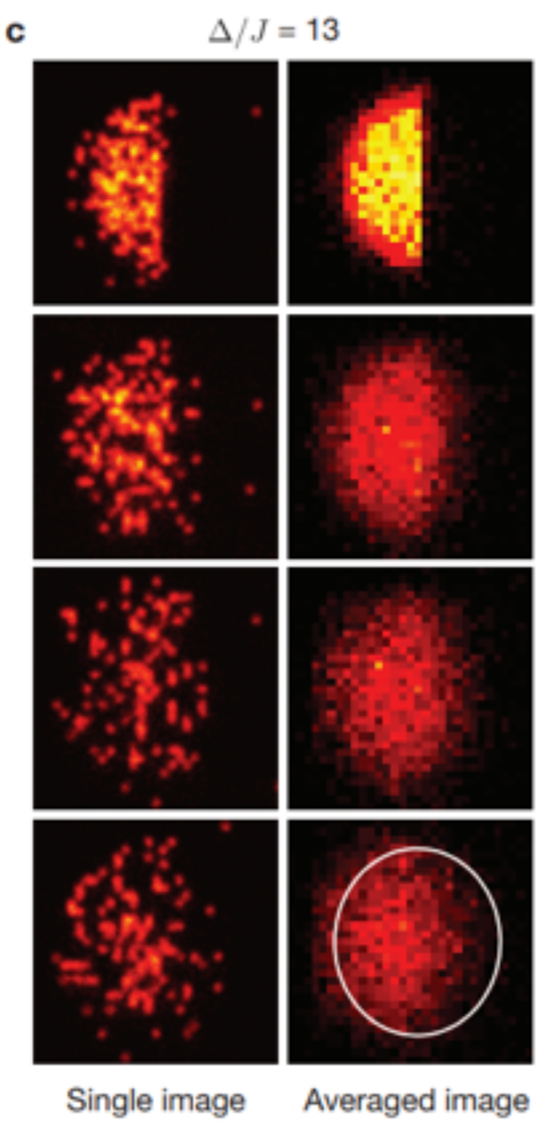

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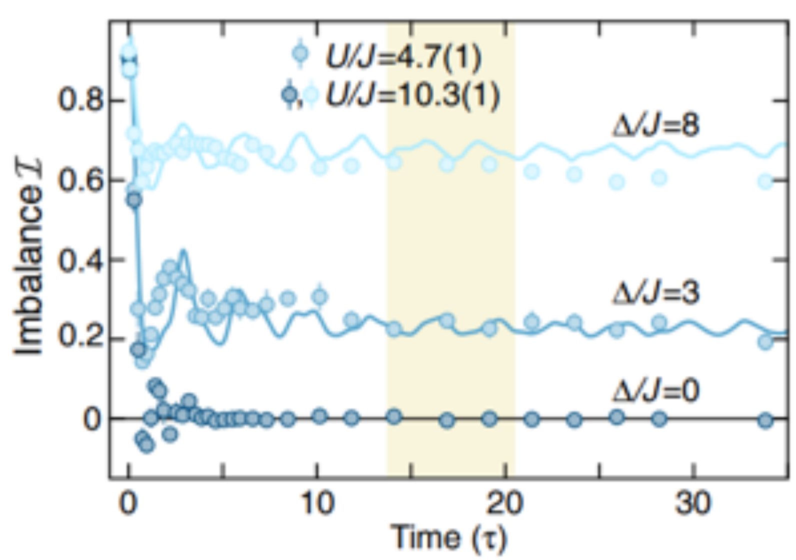

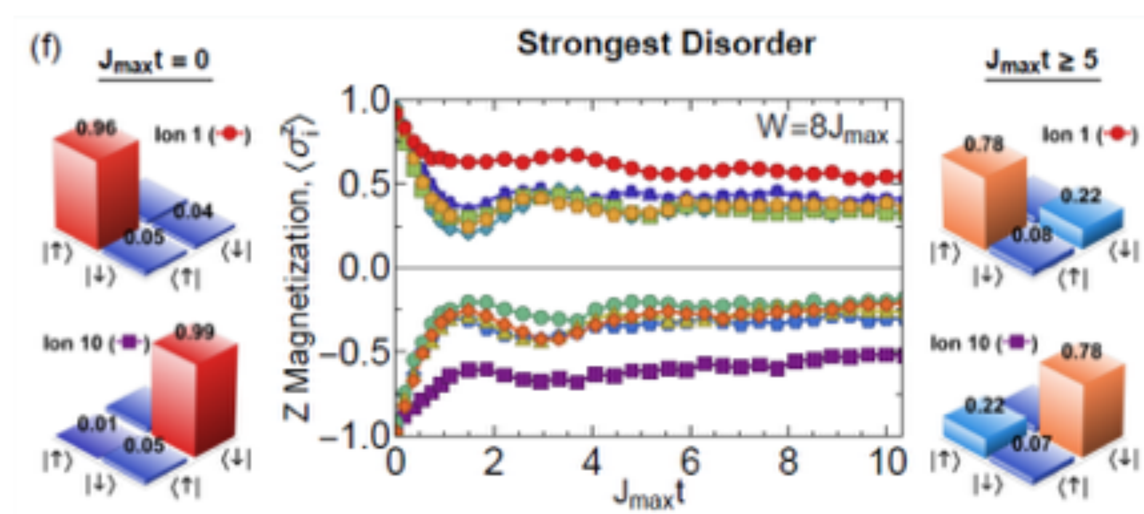

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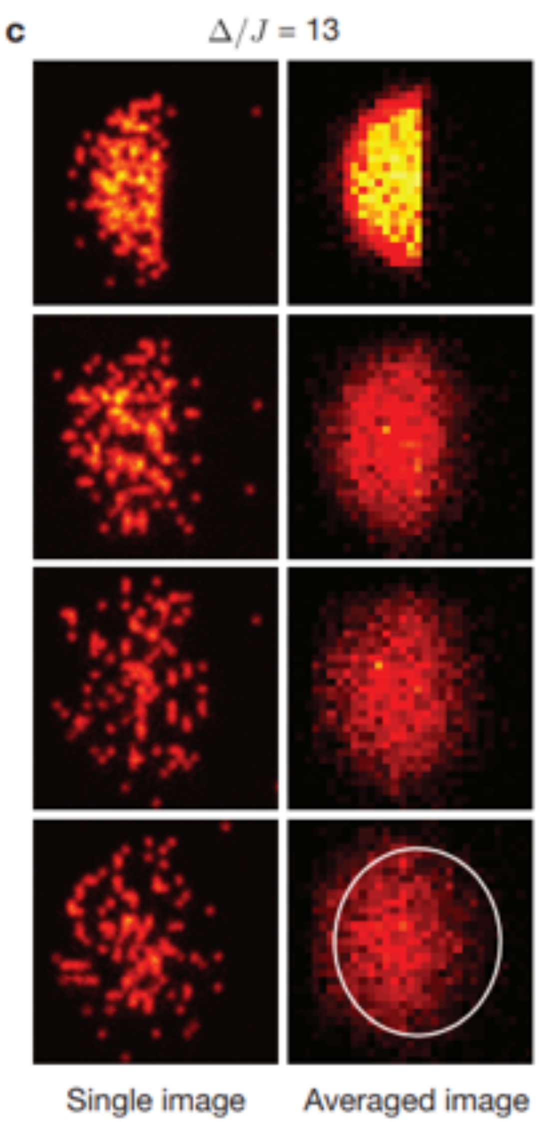

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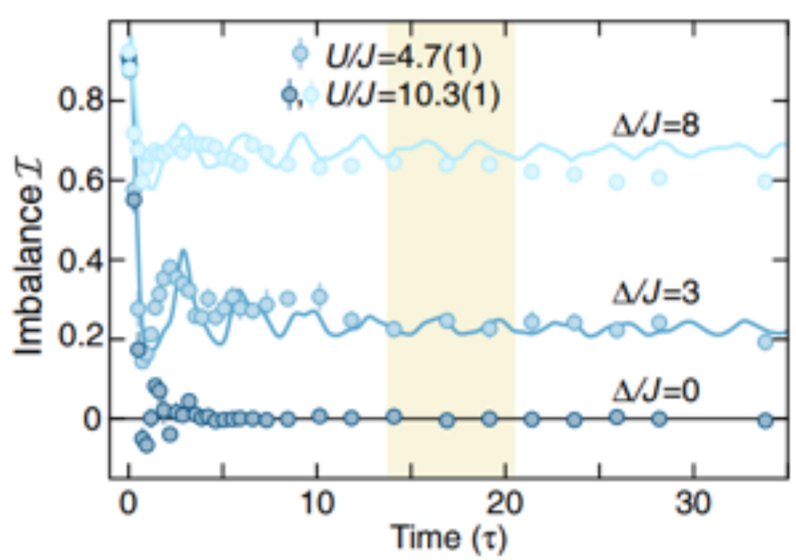
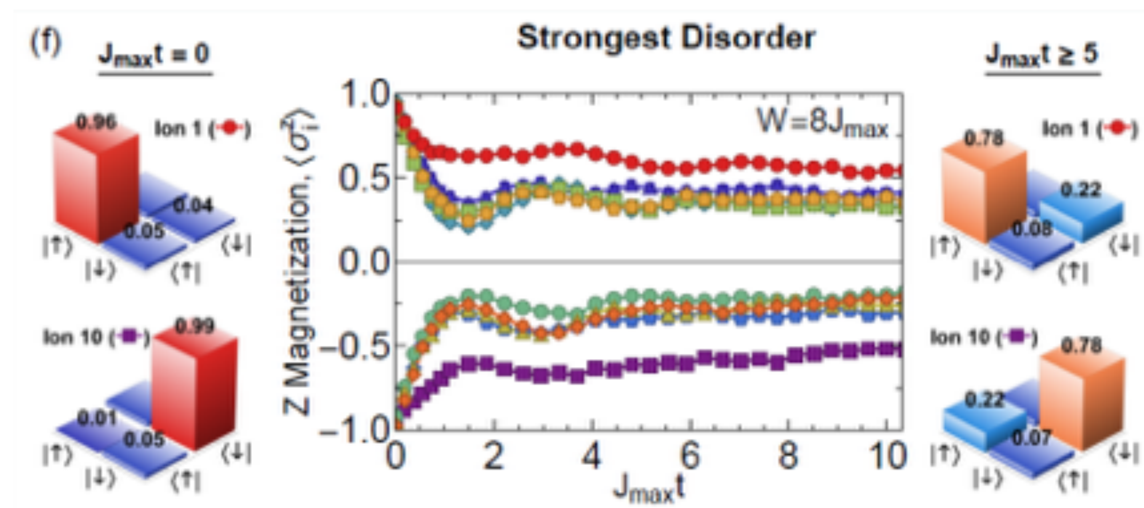
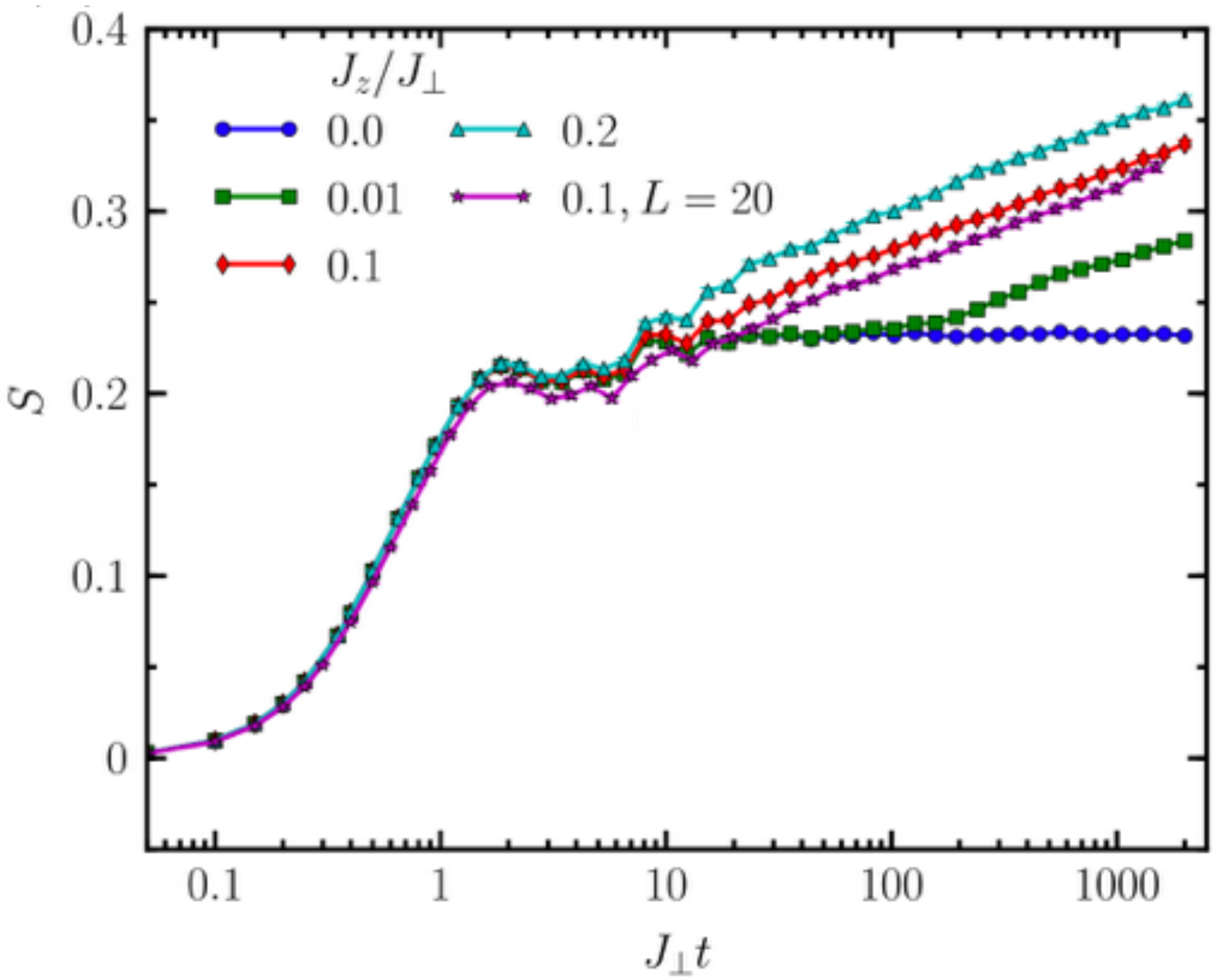




dynamics limited by decoherence

Hidden quantum many-body dynamics



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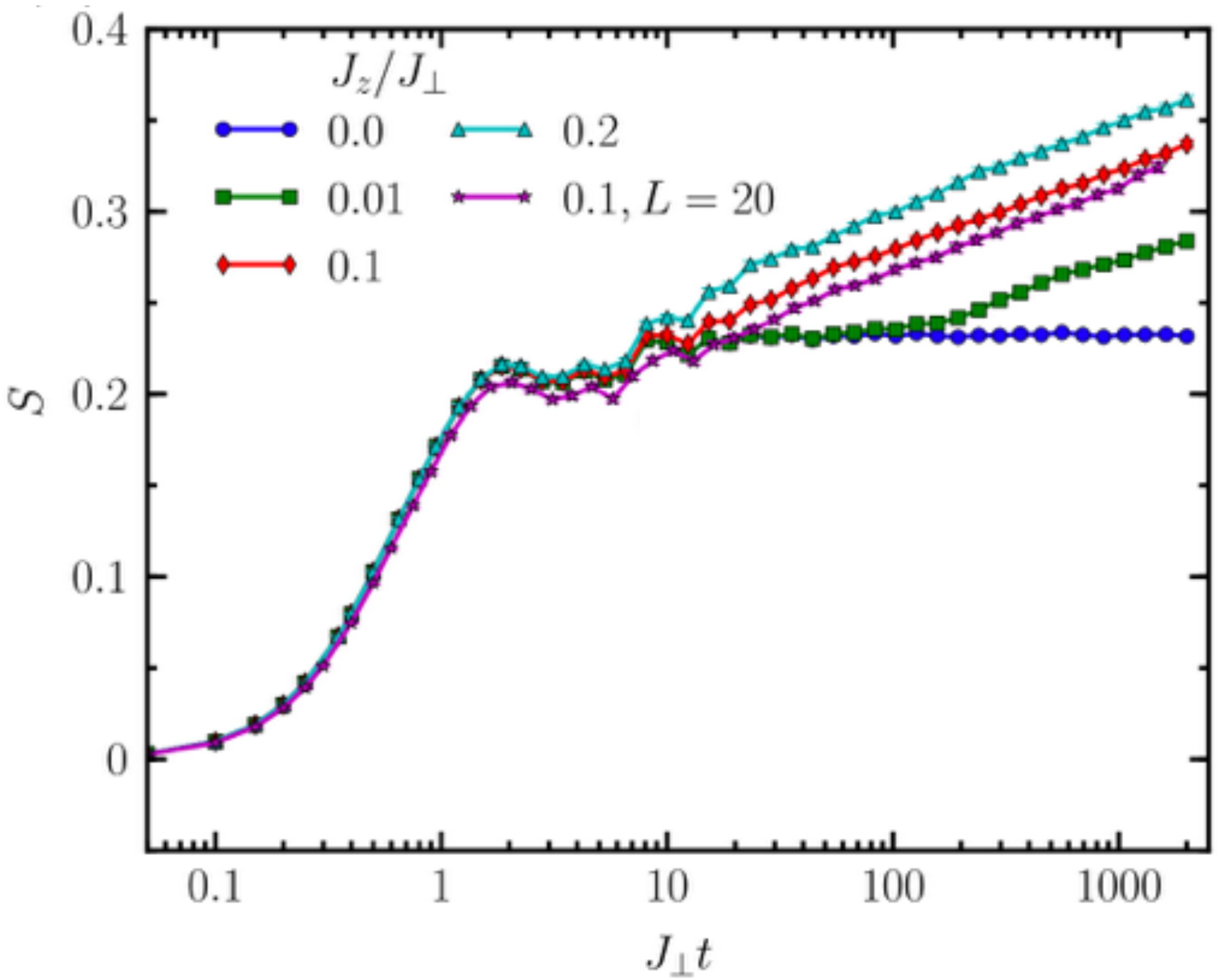

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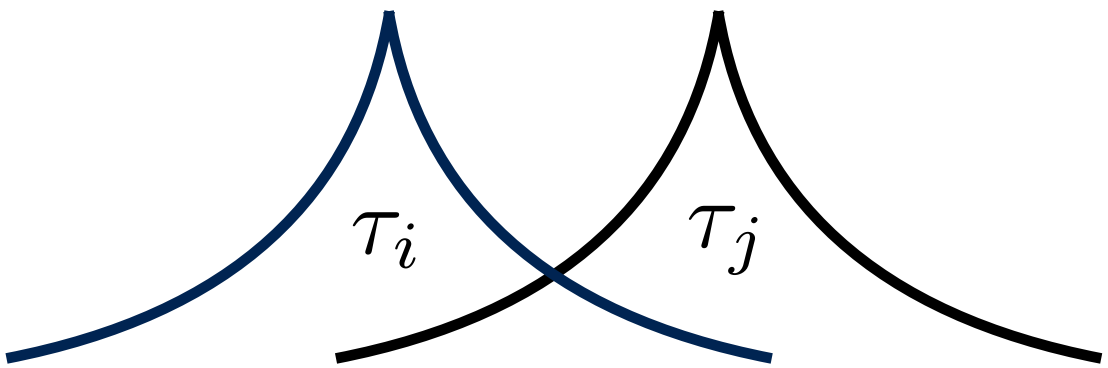
concerned operators
with exponentially localized support



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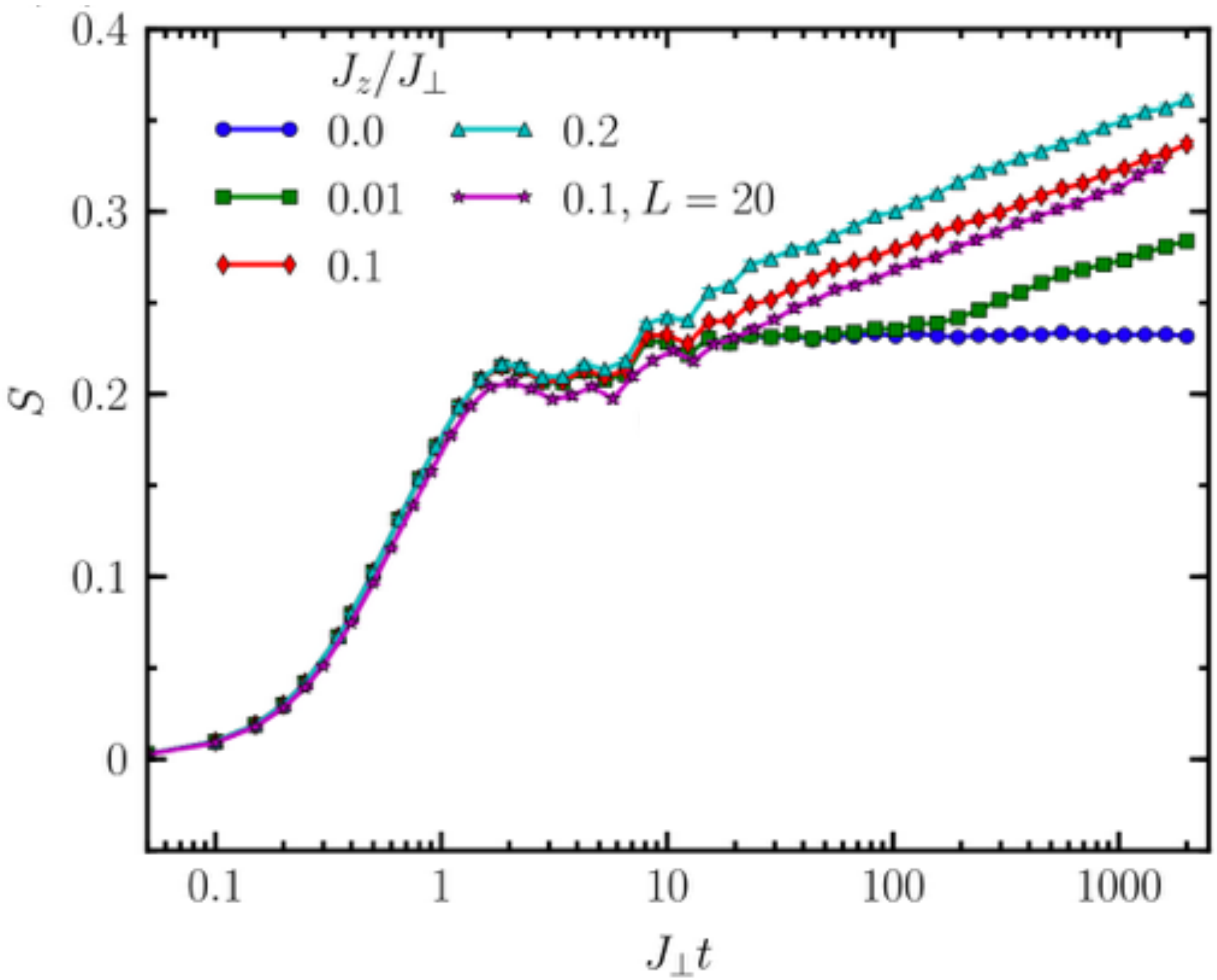

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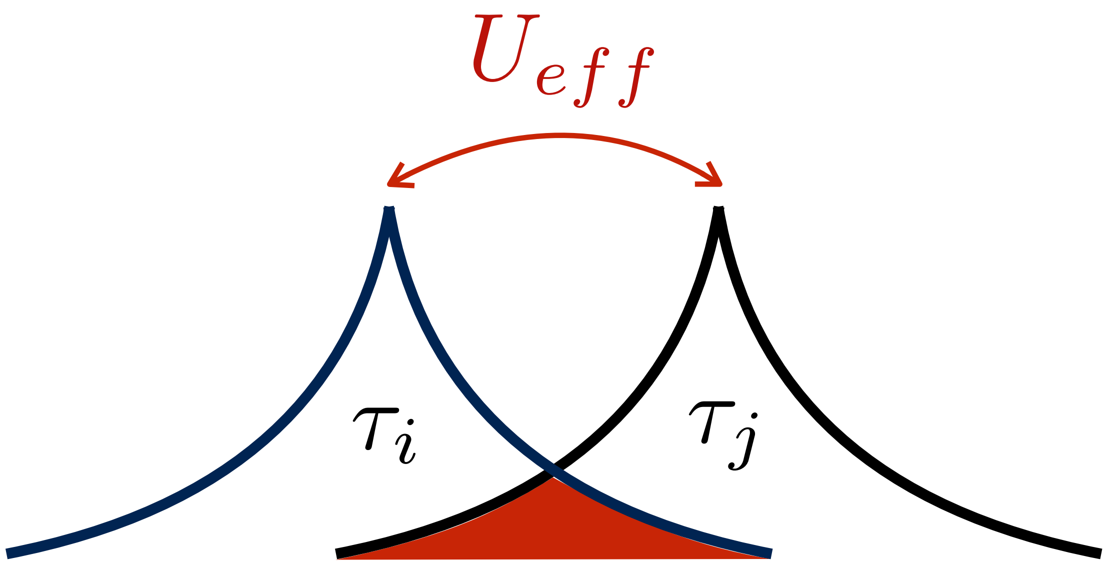

$$\hat{\mathcal{H}} = \sum_{i,j} U_{eff}^{ij} \tau_i \tau_j$$

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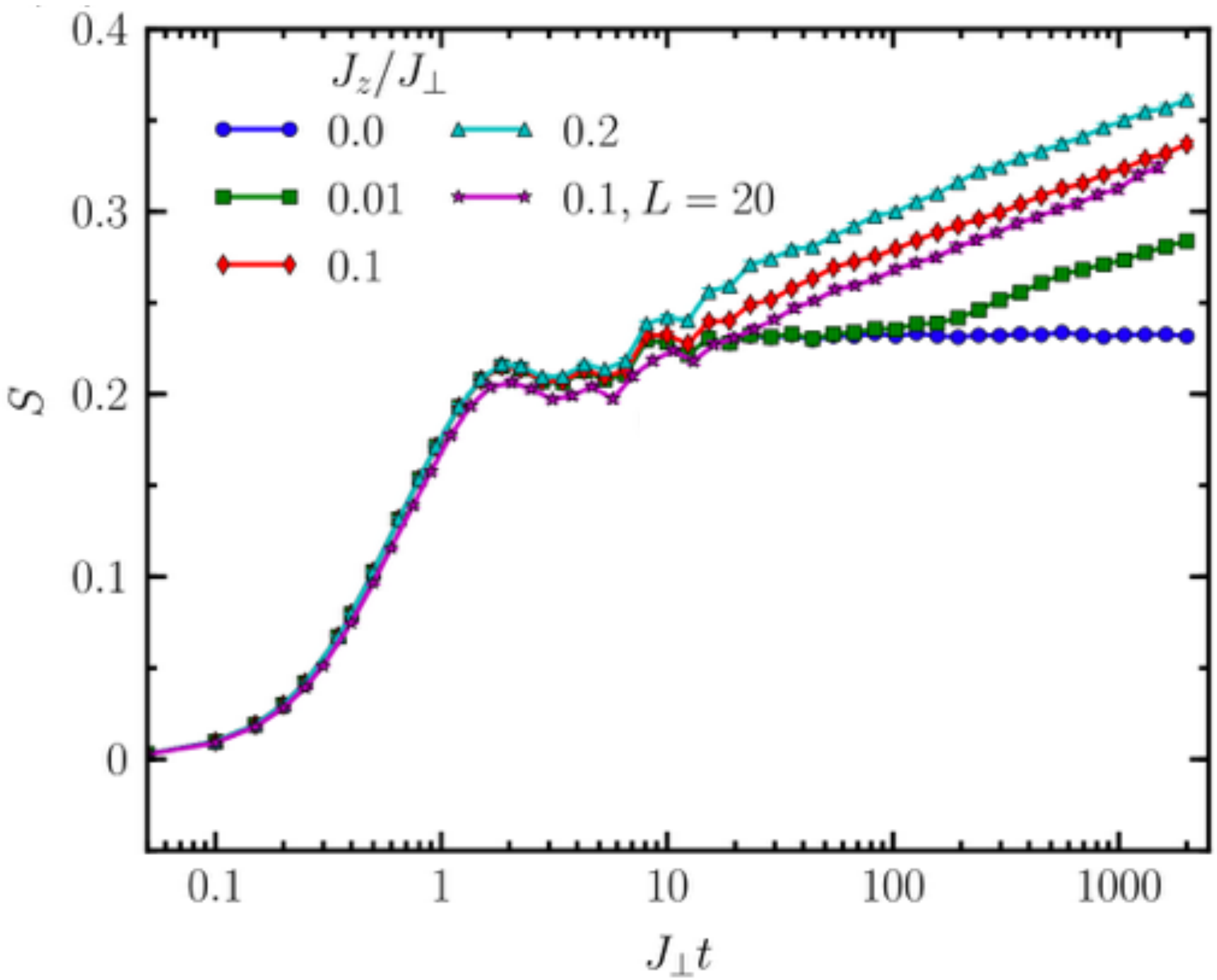

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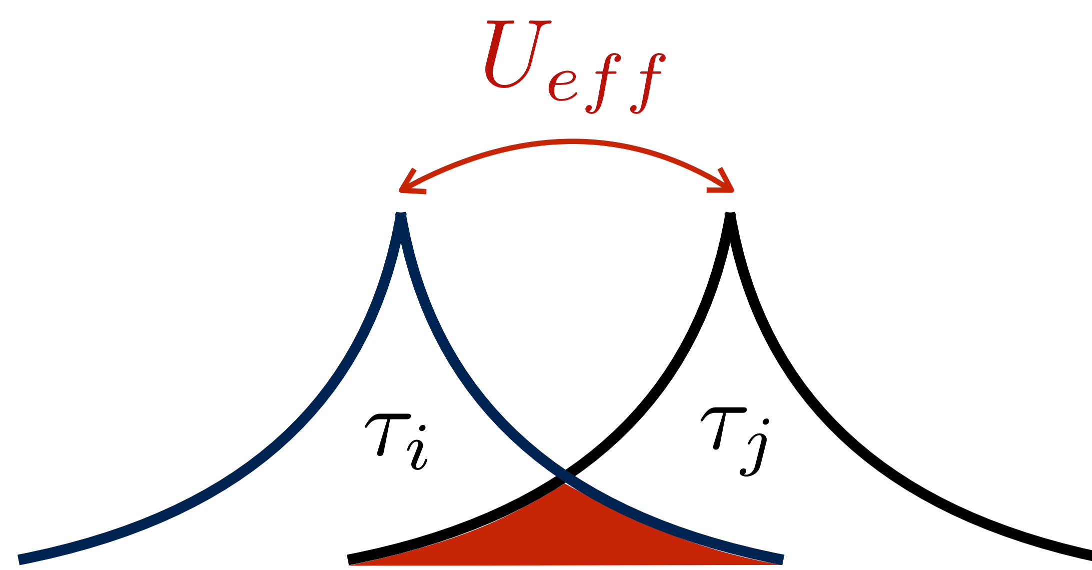

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local interactions + tunneling + disorder

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non-local quantum dynamics hidden from local probes

Quantum quenches

Ergodic to MBL:
transition in exited eigenstates

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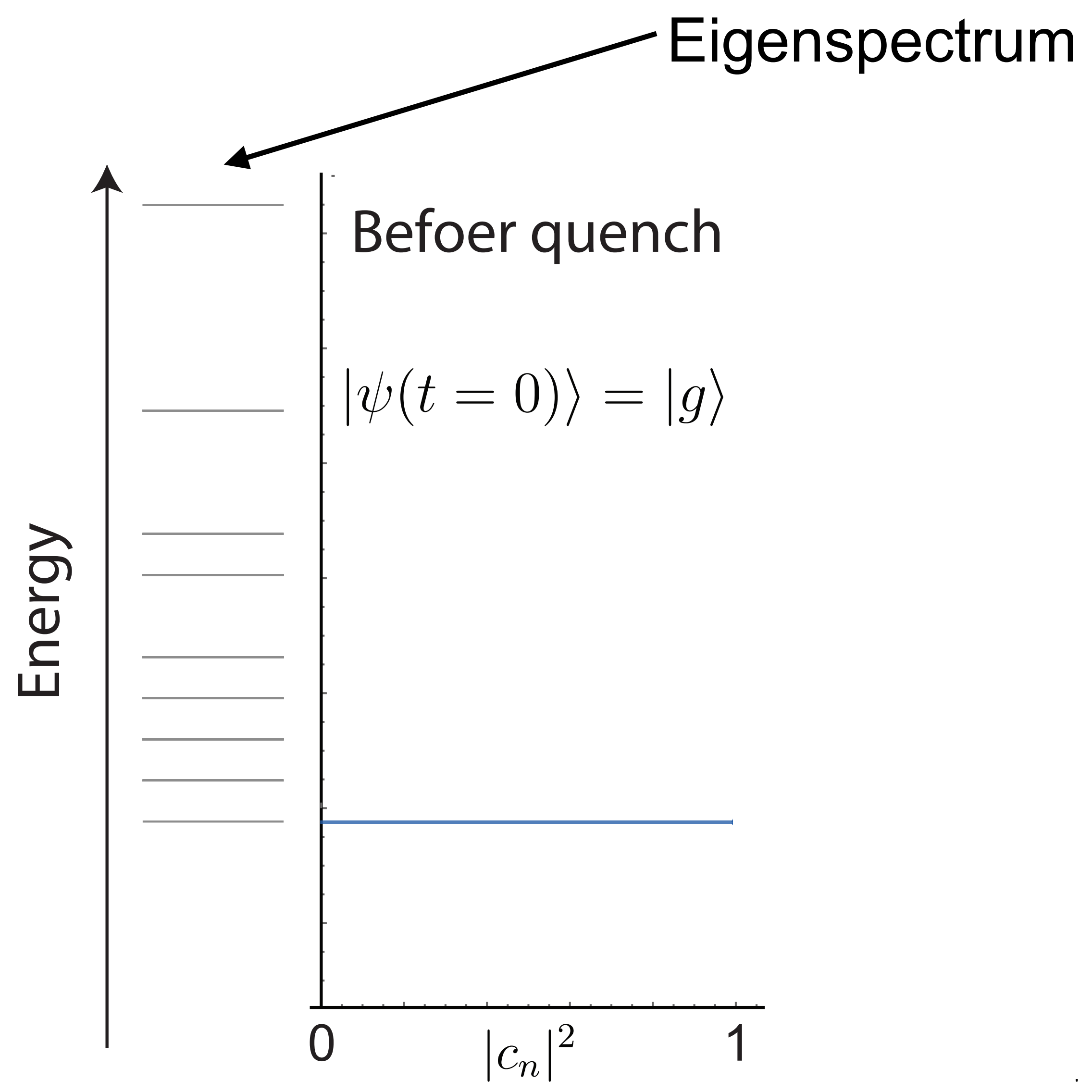
transition in exited eigenstates



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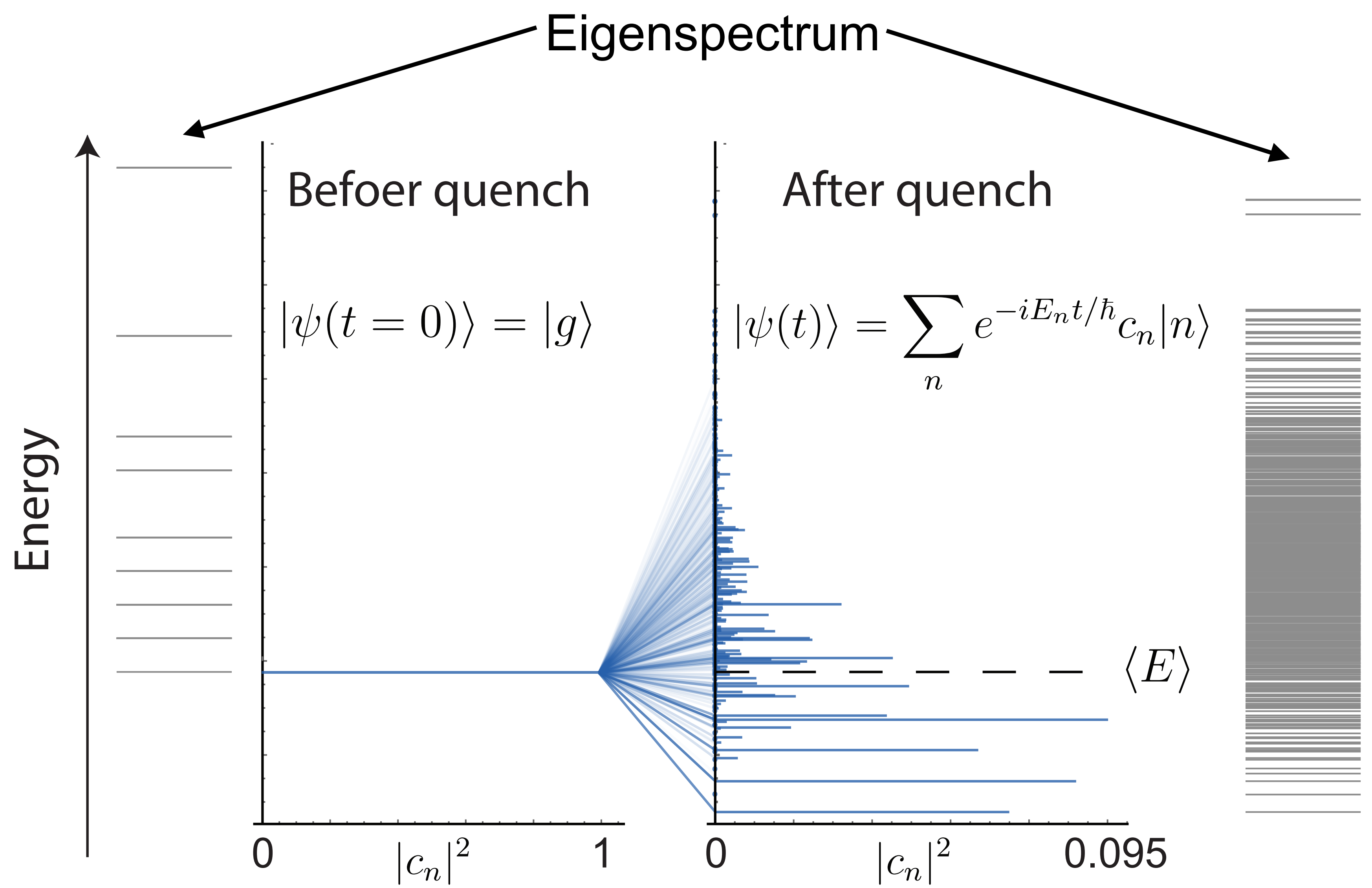

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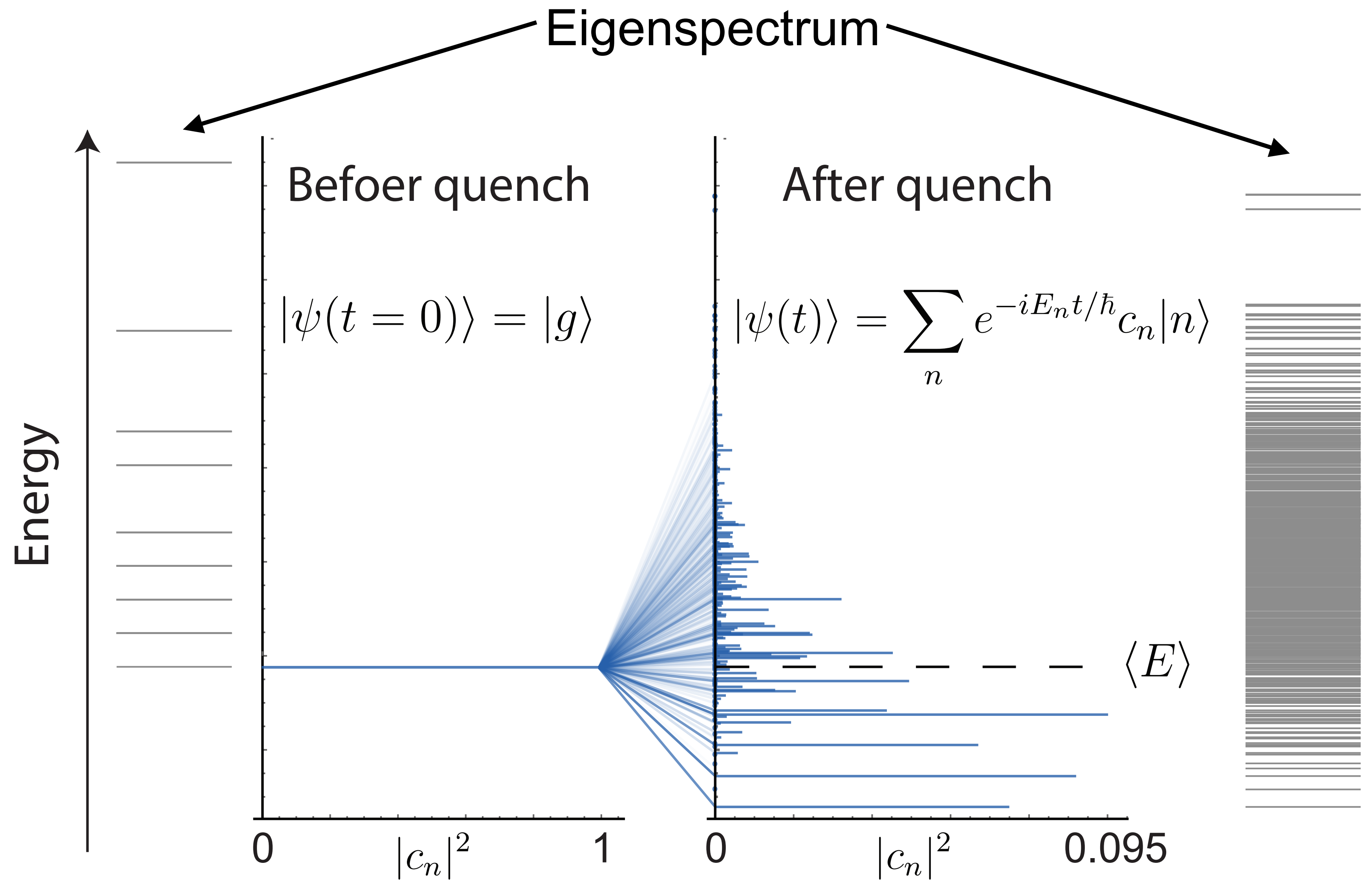

$$\langle O(t) \rangle = \sum_{m,n} c_m^* c_n O_{mn} e^{i(E_m - E_n)t/\hbar}$$

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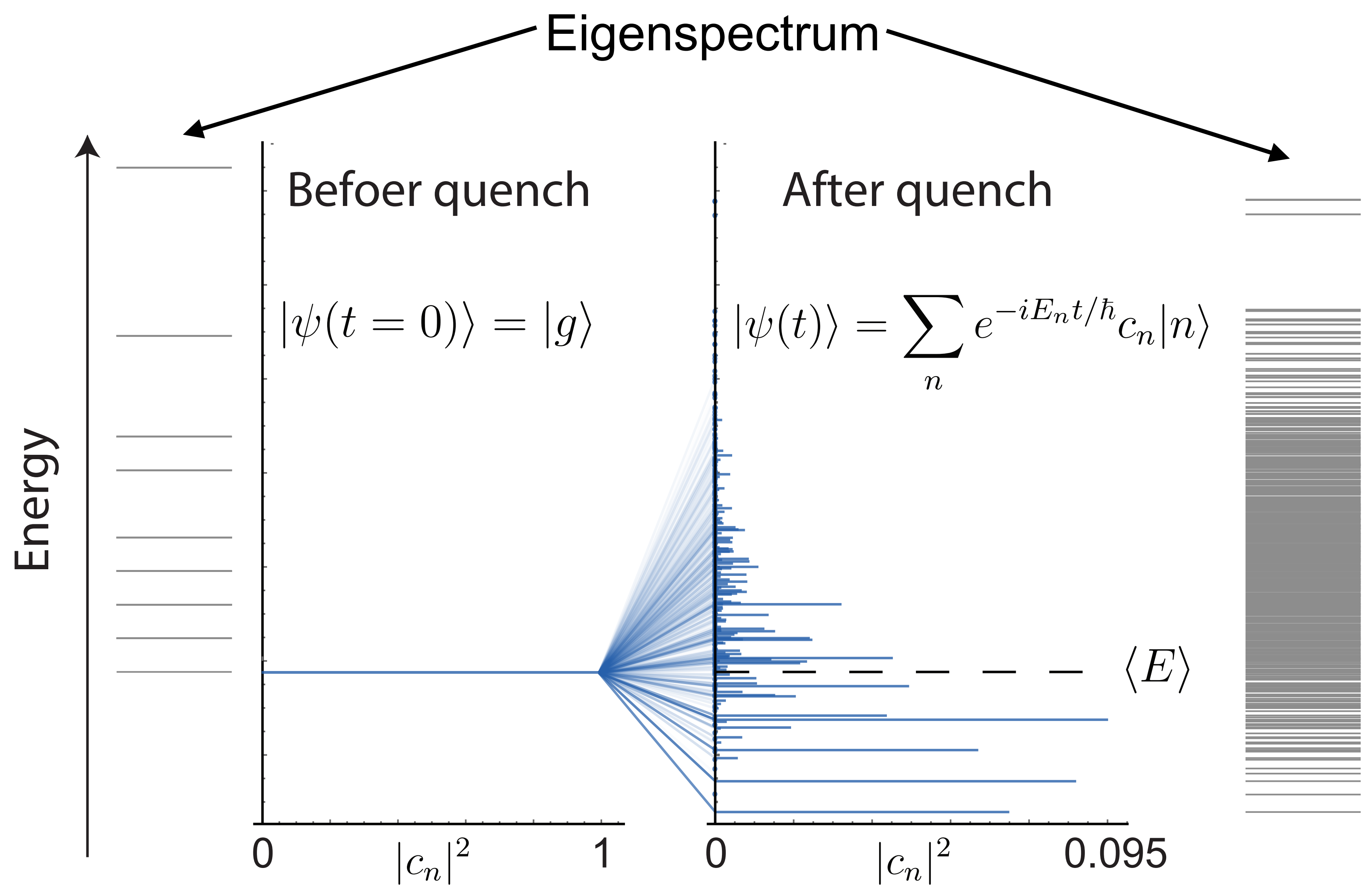

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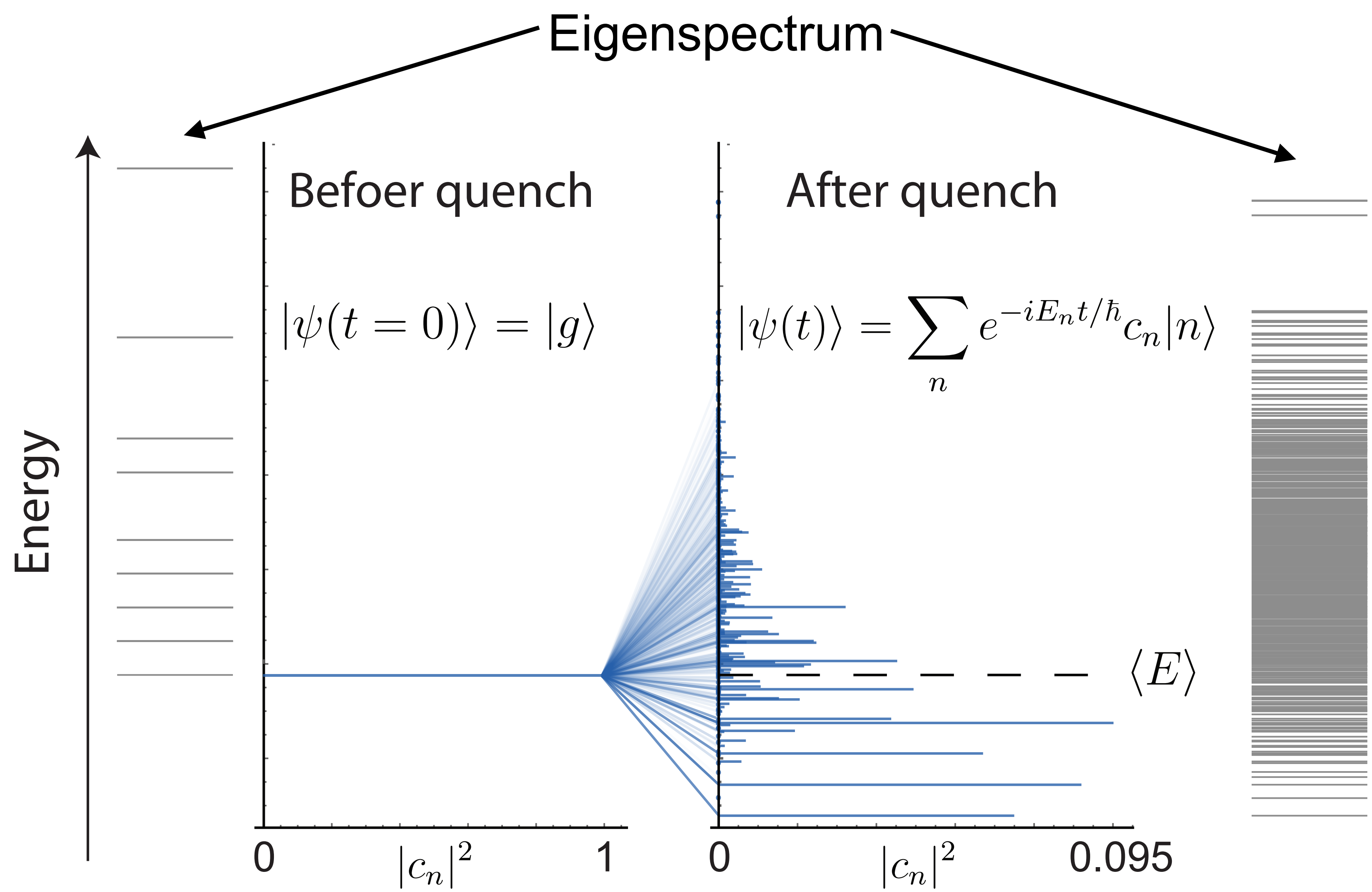

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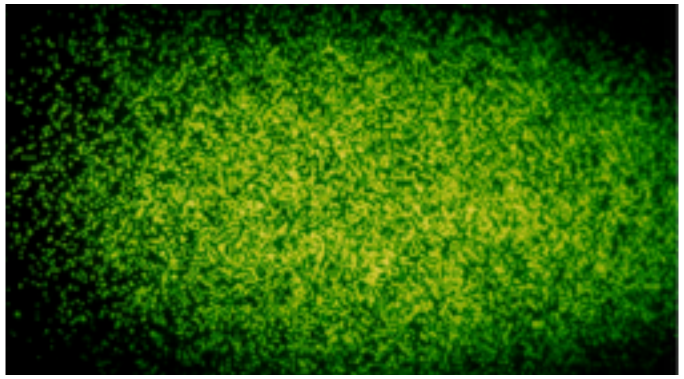
Long coherent evolution required!

Outlook: key features of MBL

- Experimental setup



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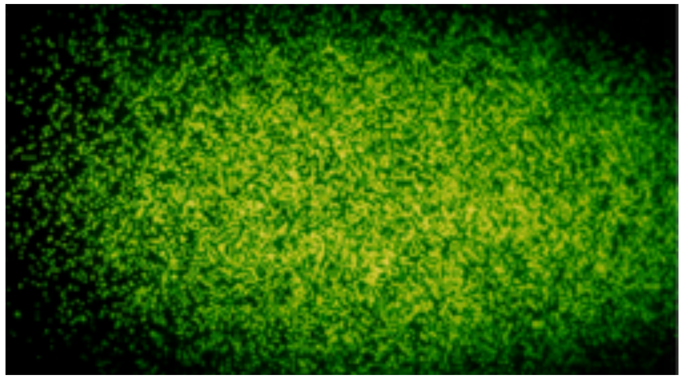

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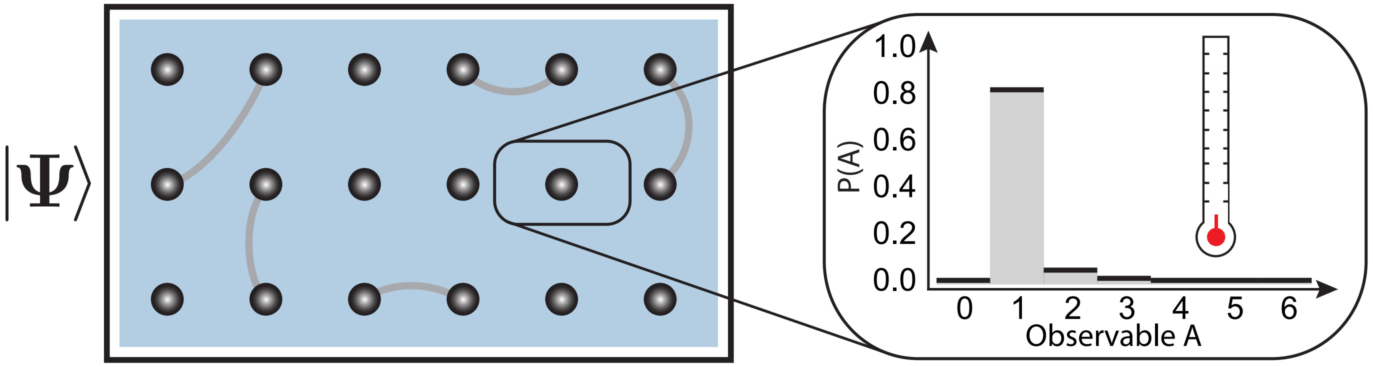

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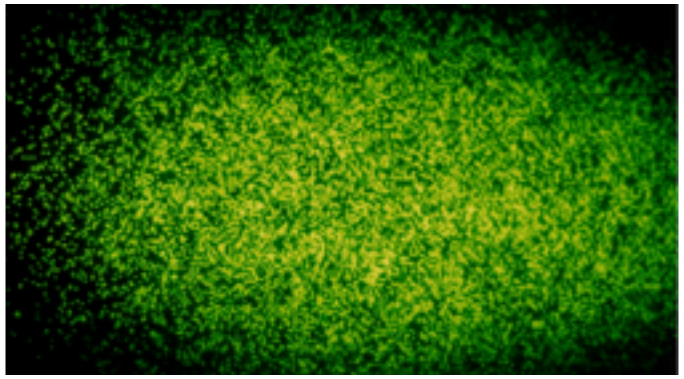

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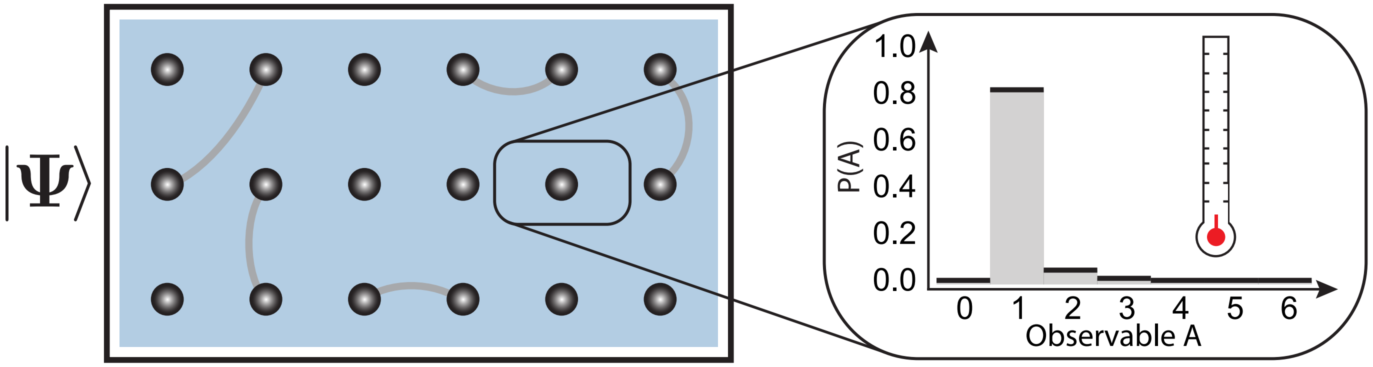

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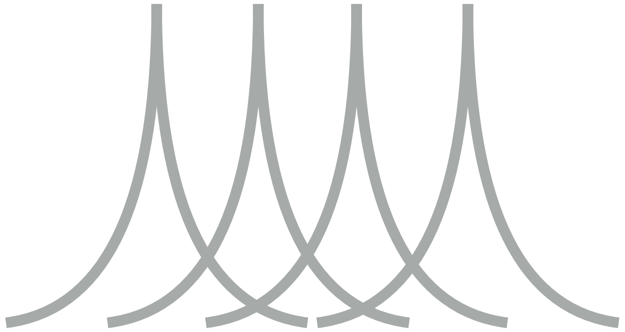

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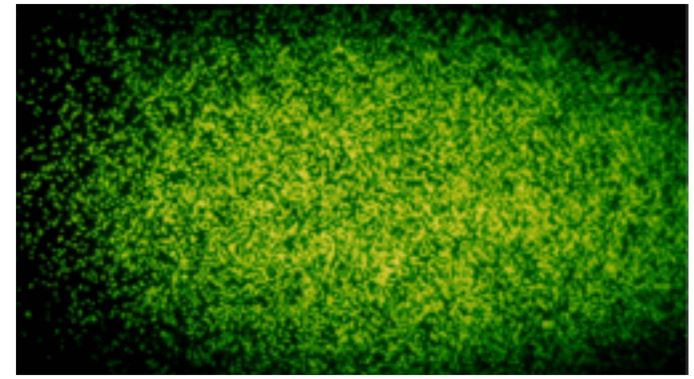

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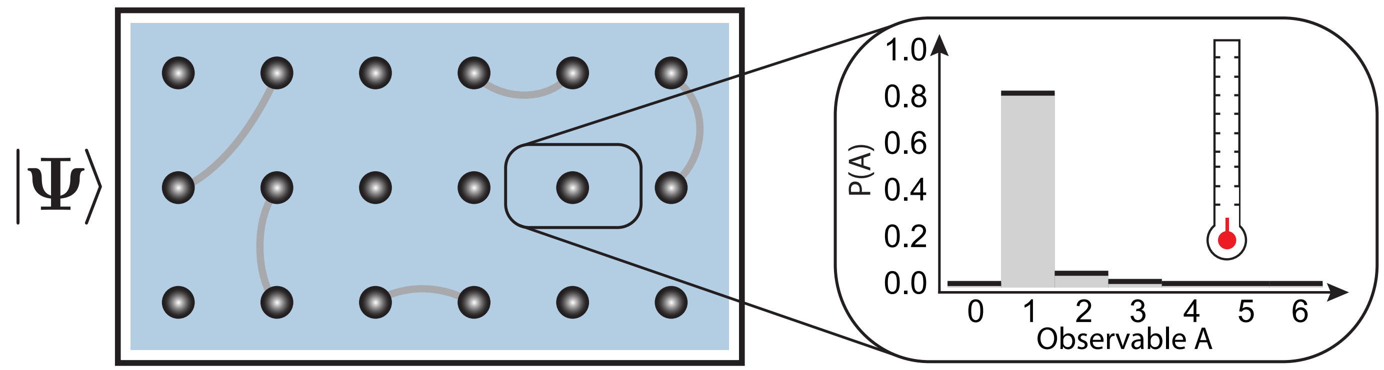

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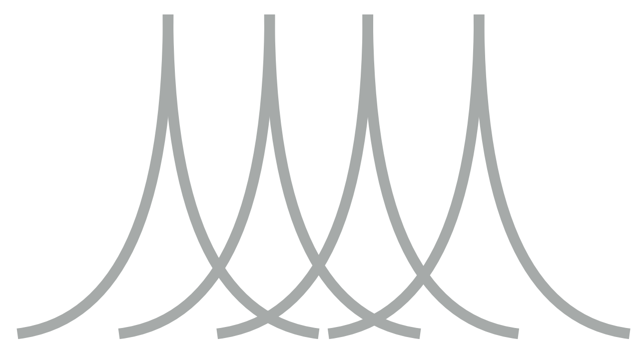

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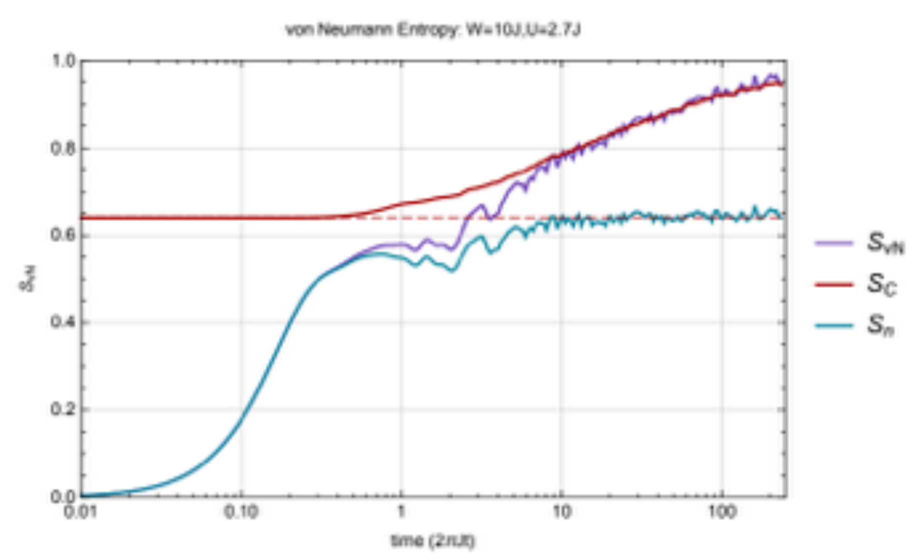

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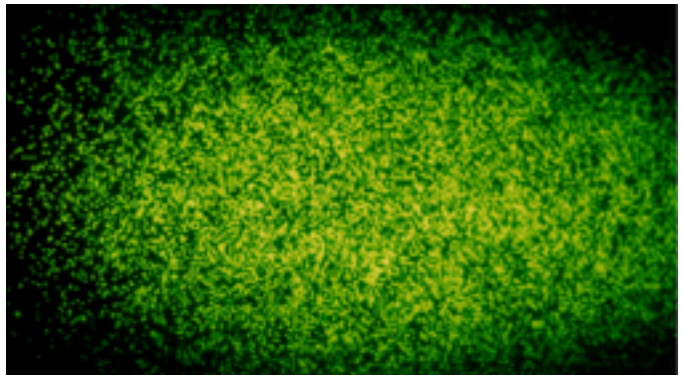

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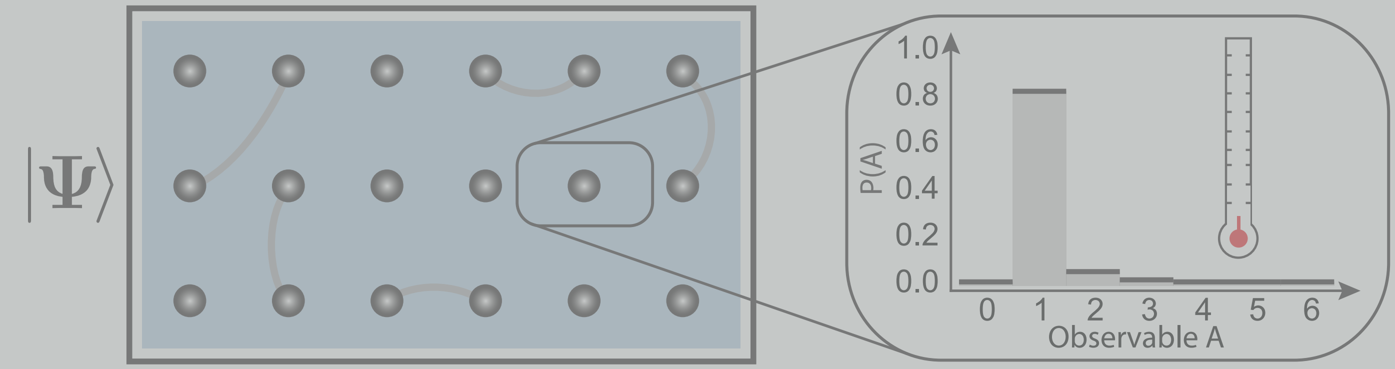

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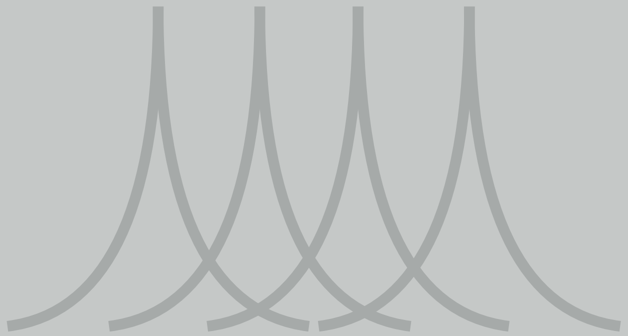

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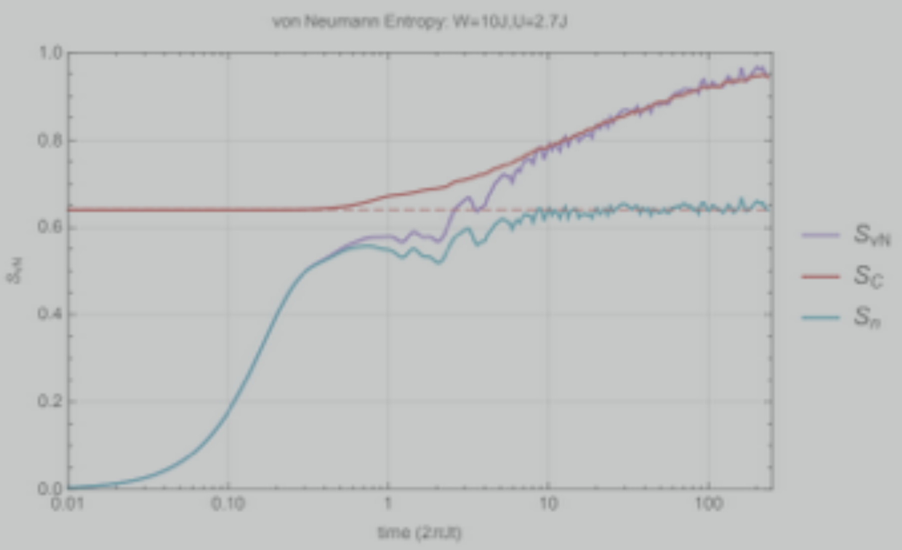
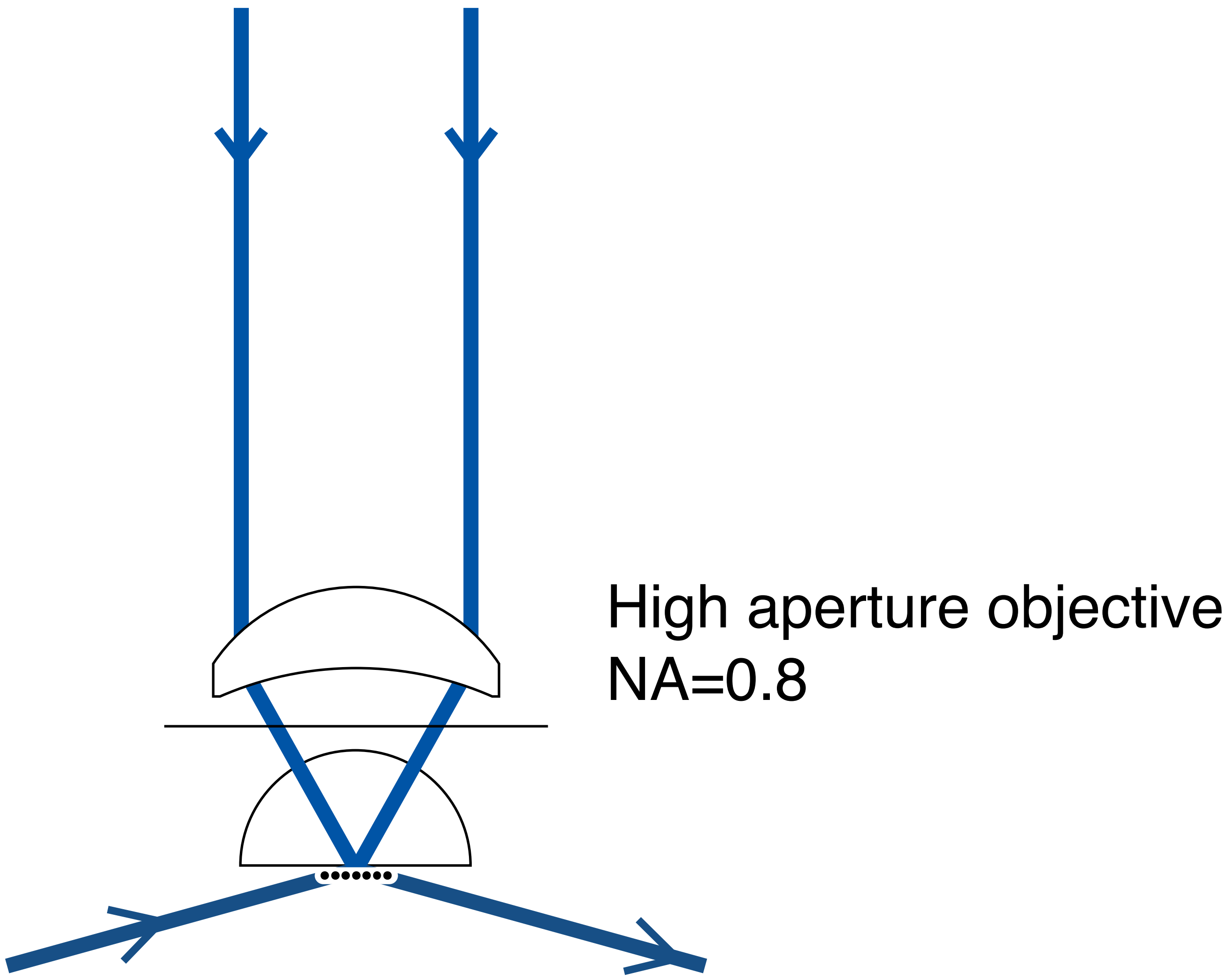


Quantum gas microscope



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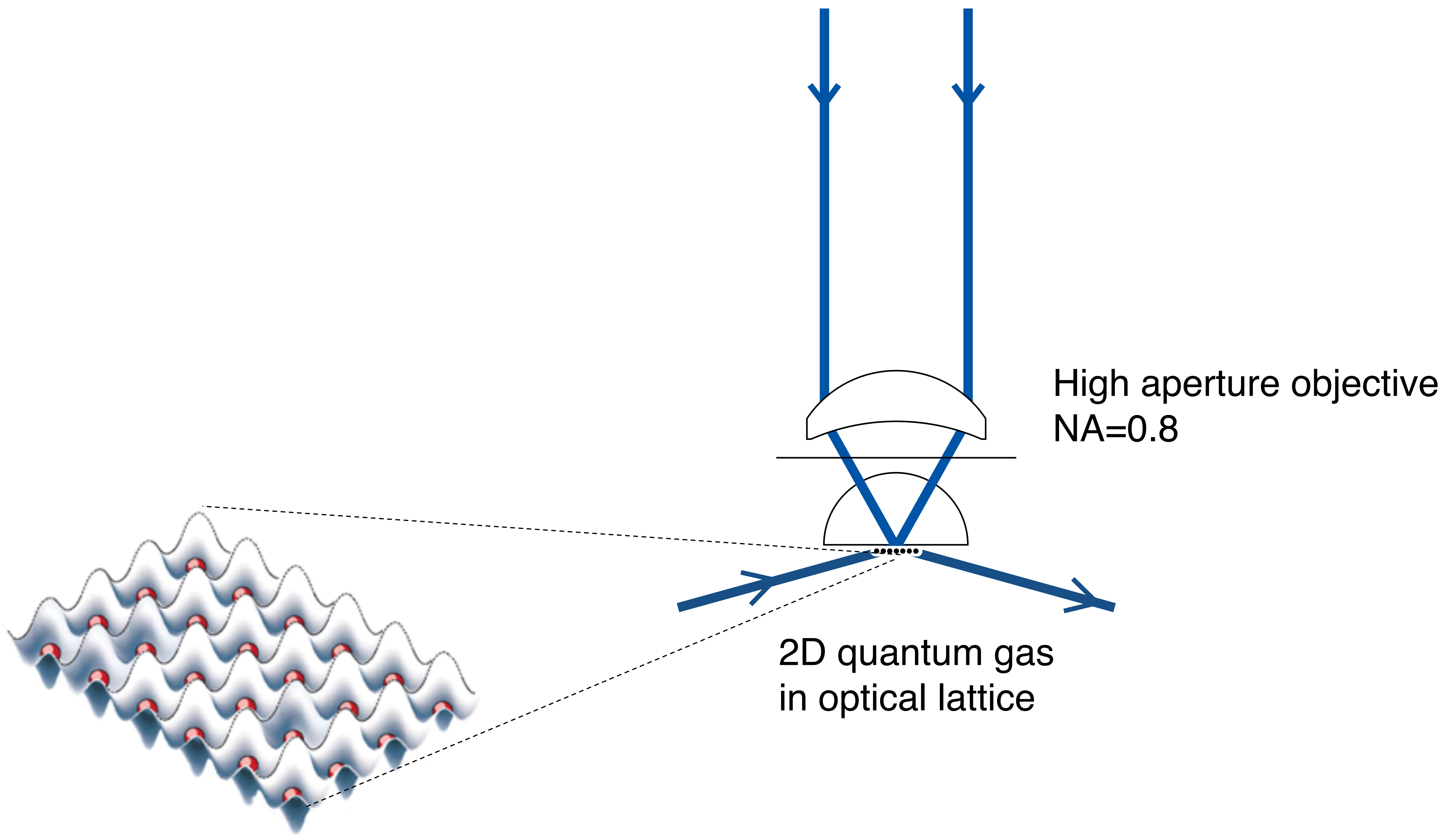

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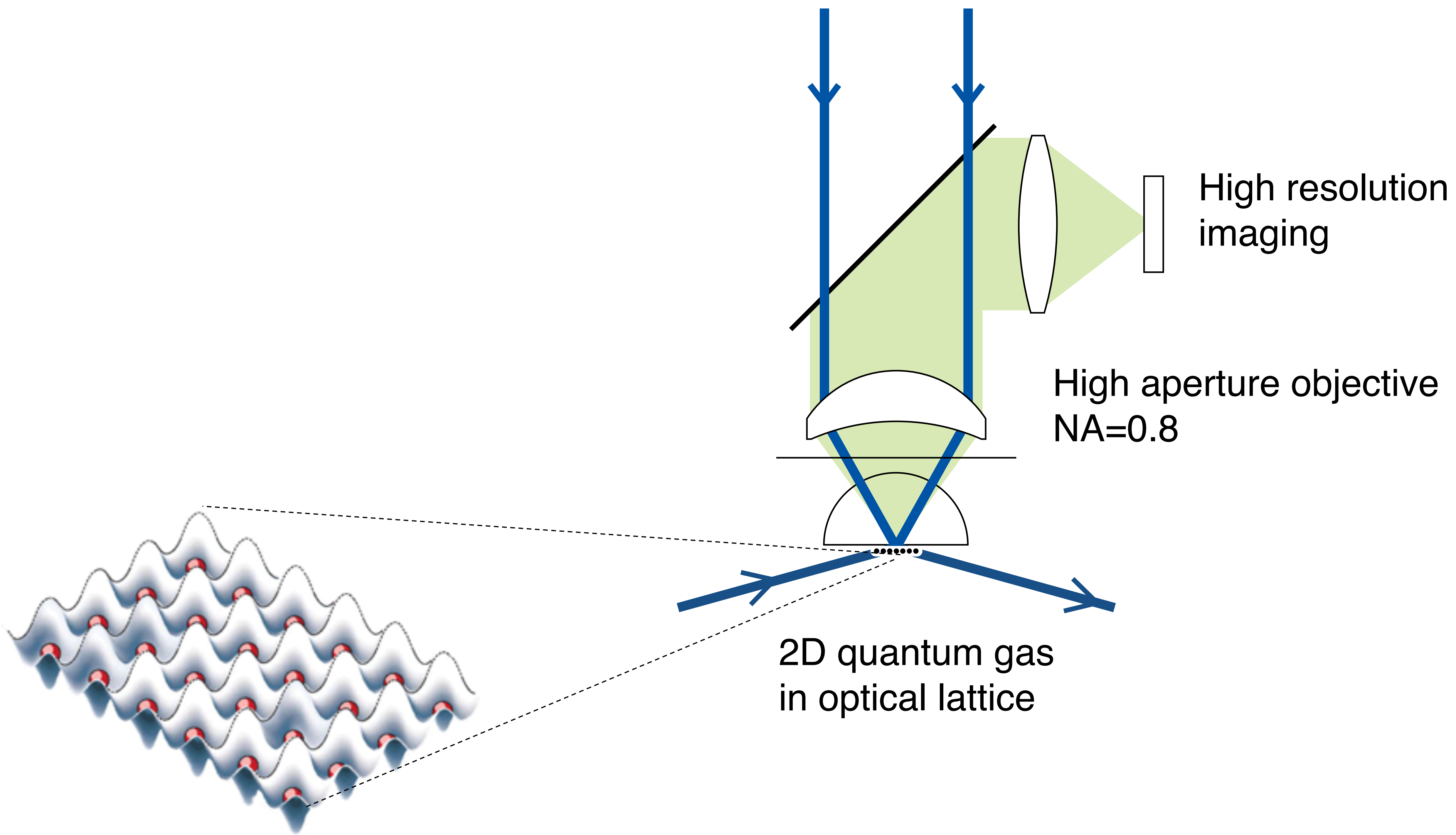
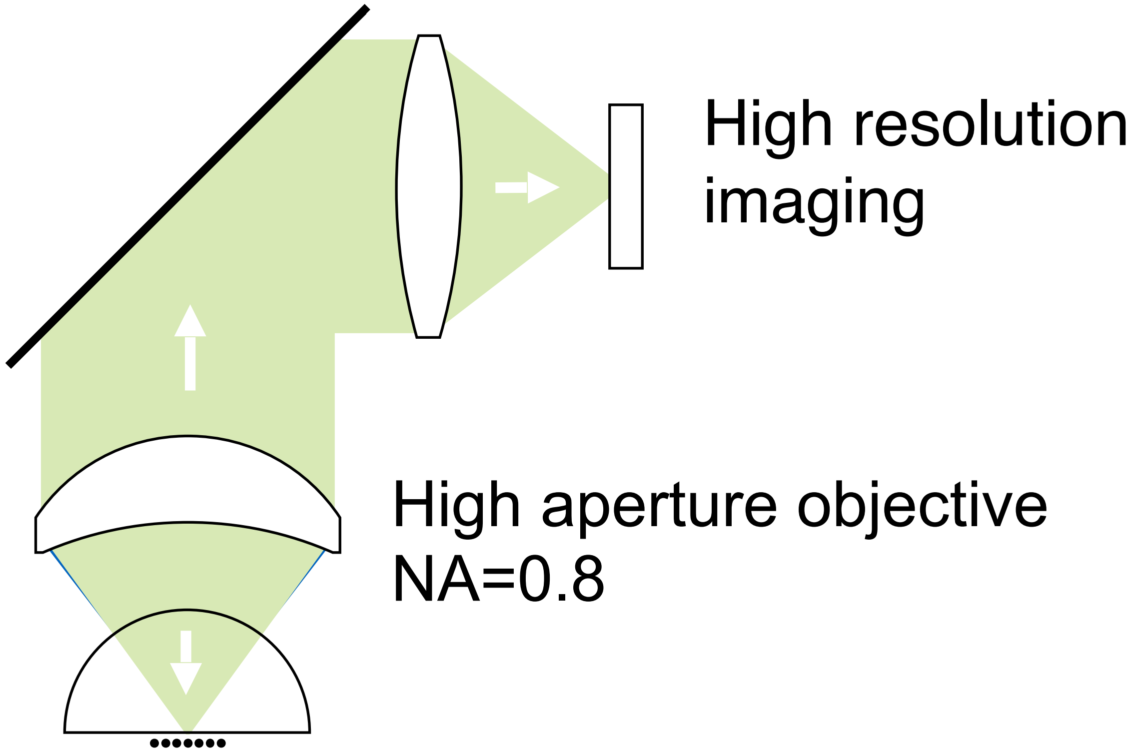


Fourier plane DMD



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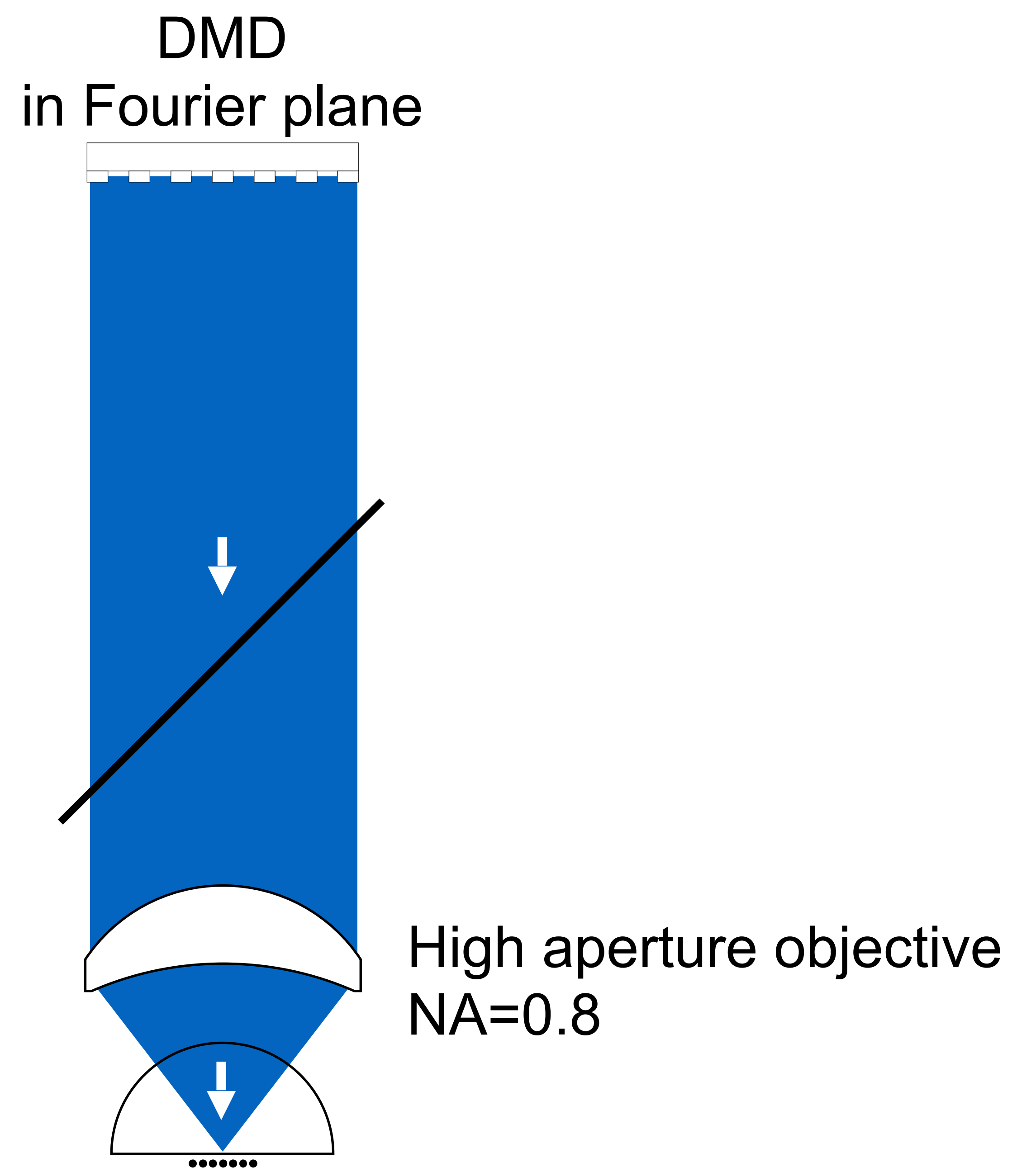

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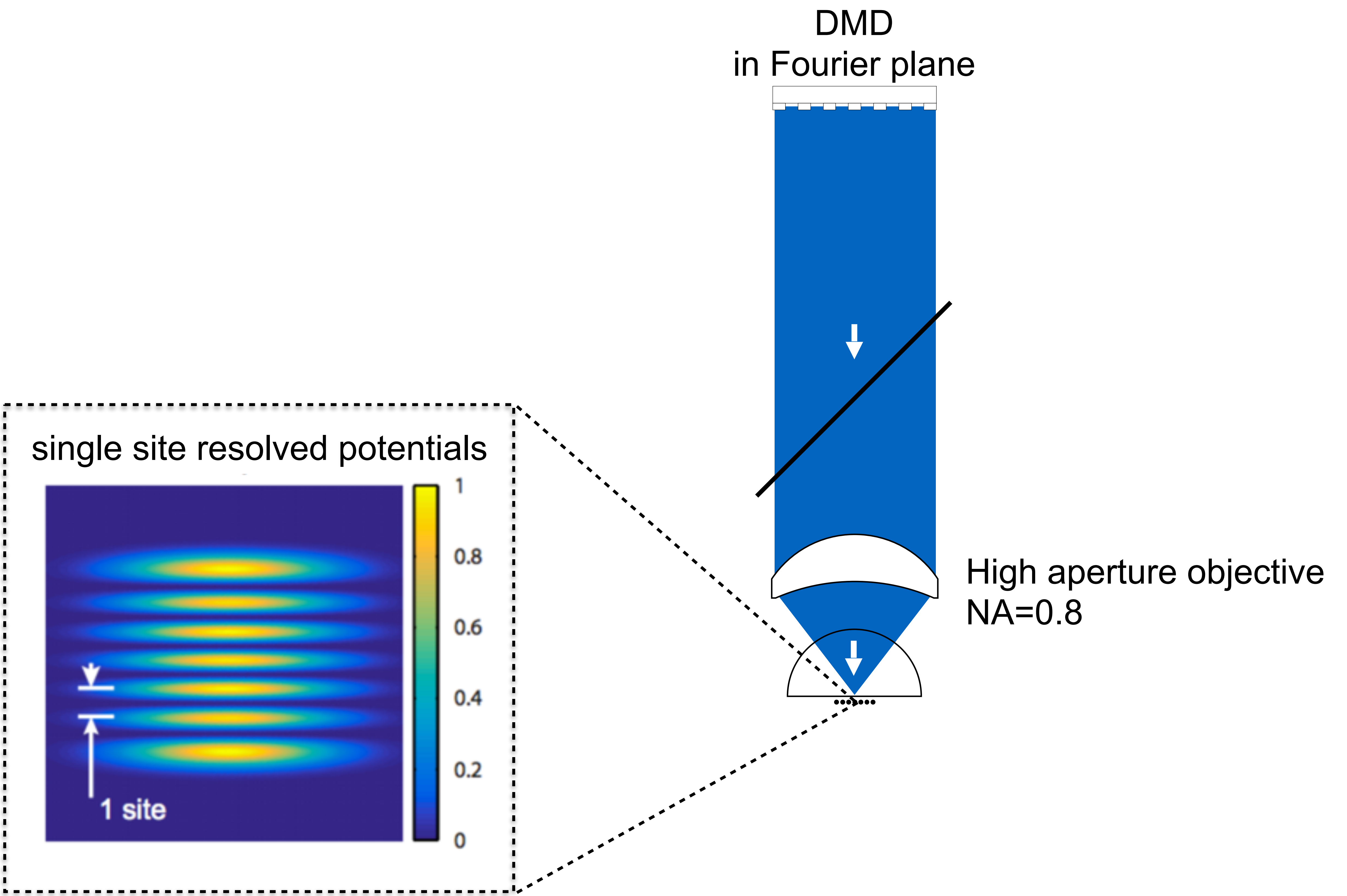

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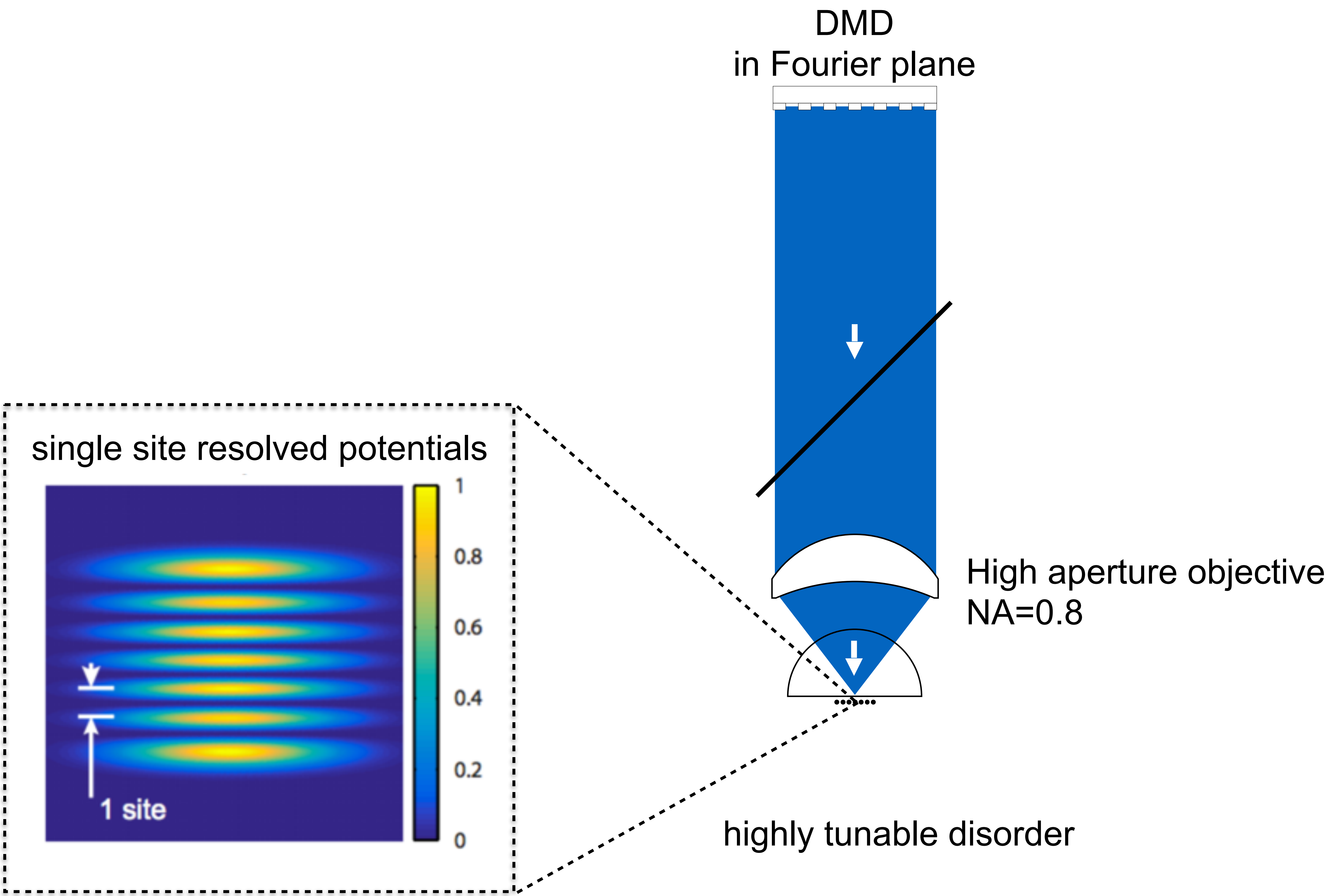

Experimental system

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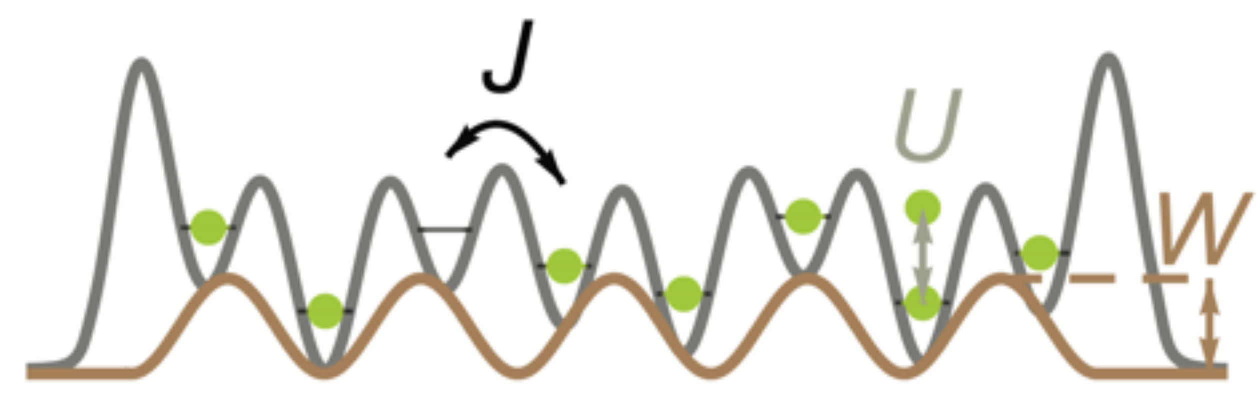

interacting Bosonic Aubry-André model

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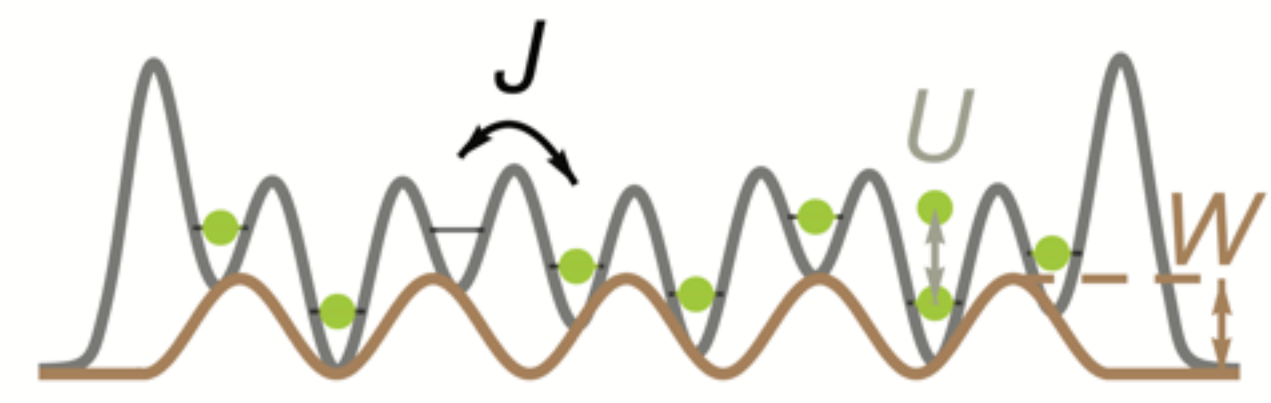

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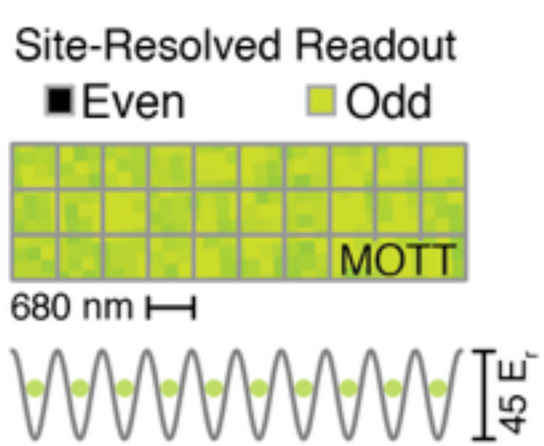

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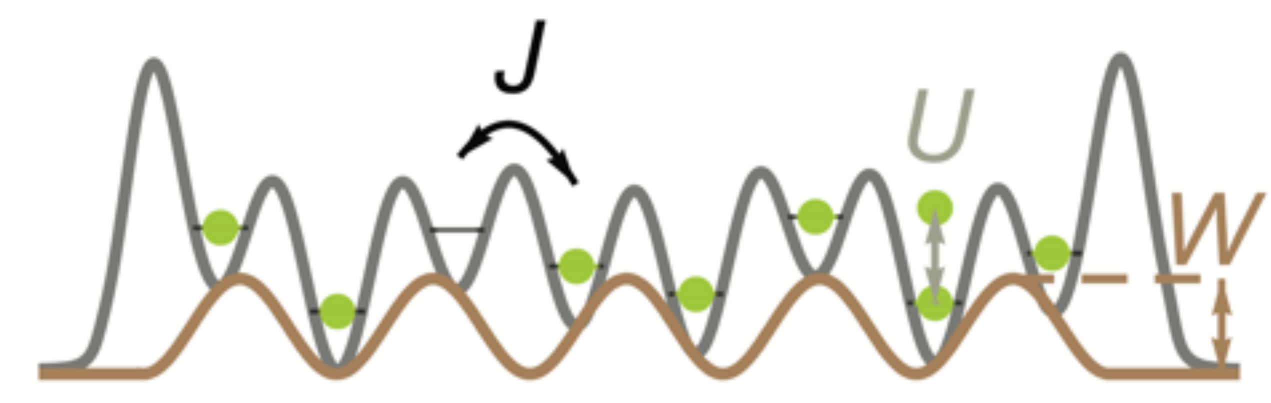
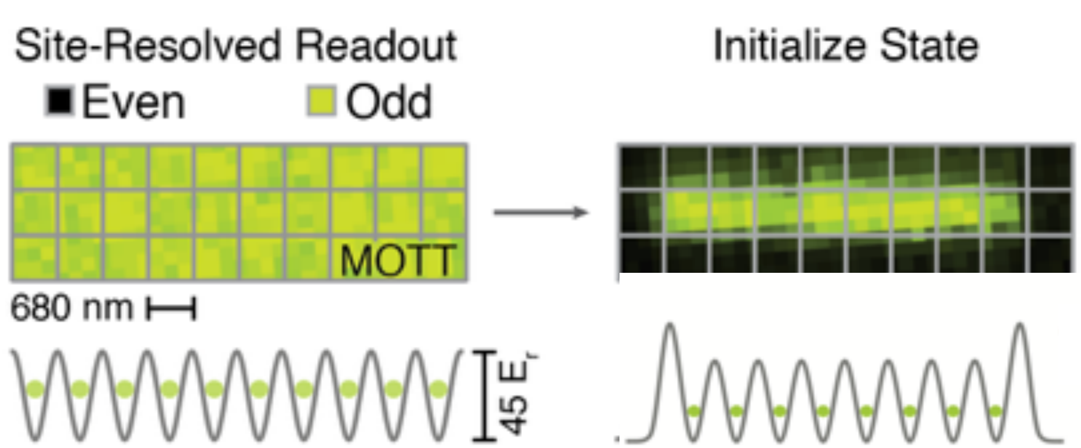


interacting Bosonic Aubry-André model



Experimental system

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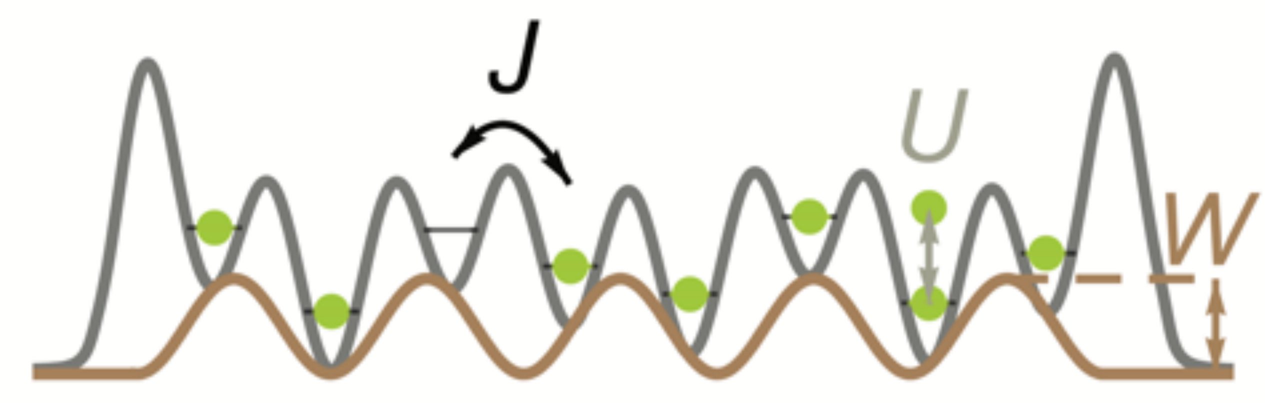

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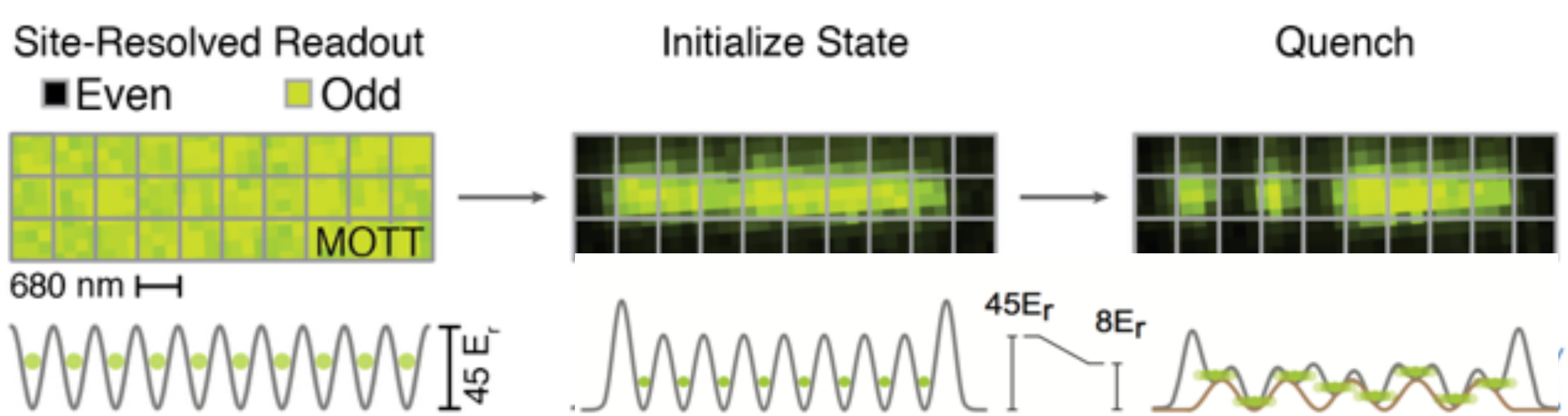

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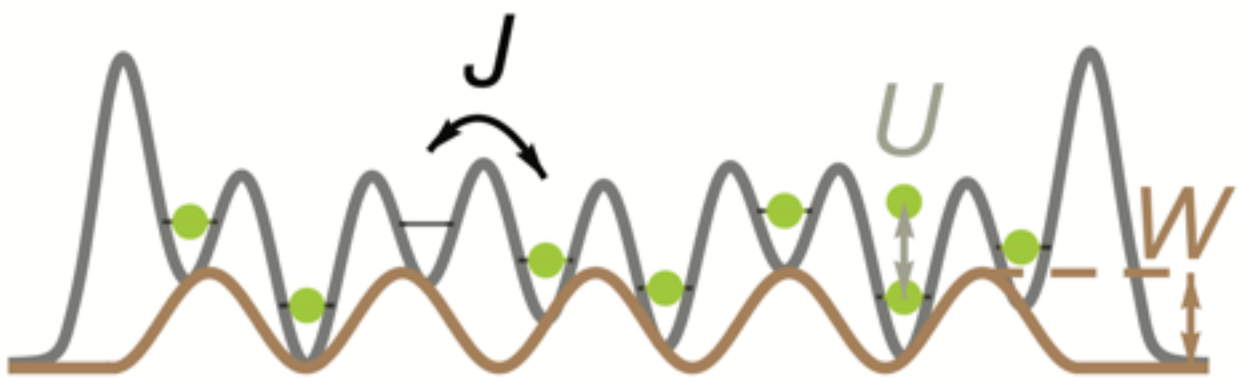

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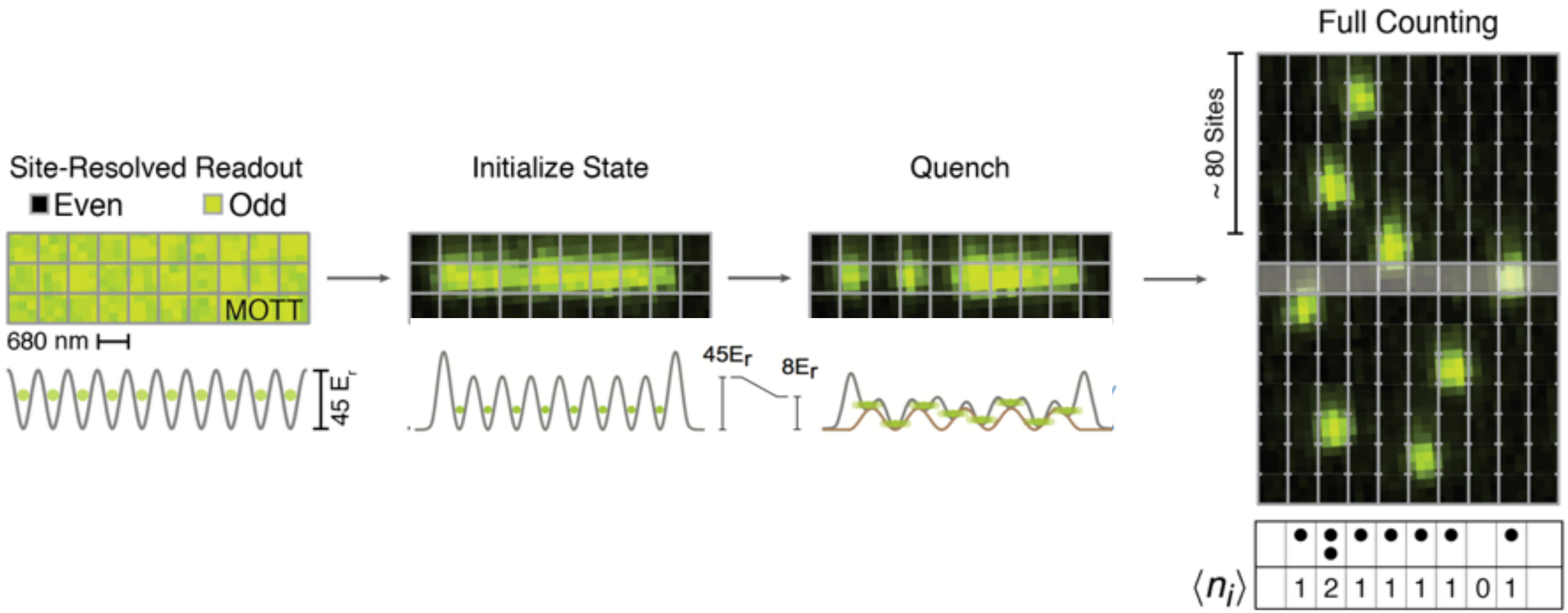

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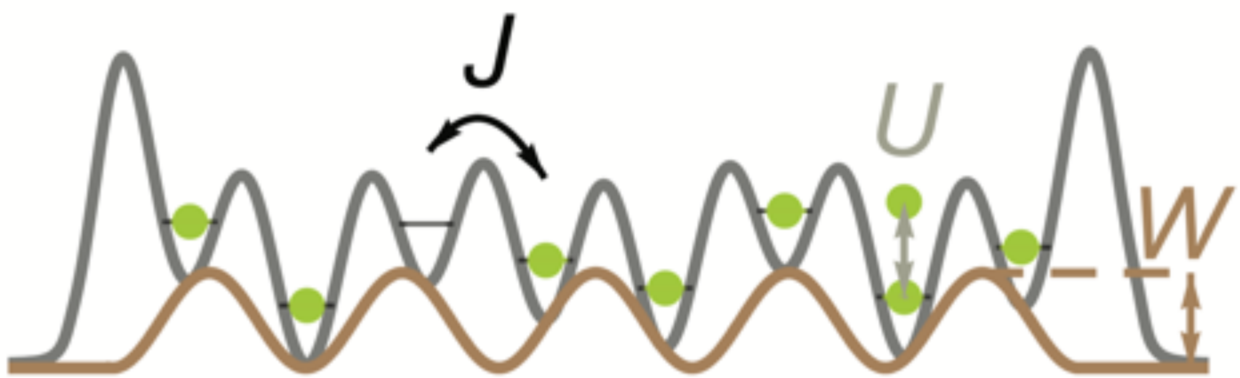

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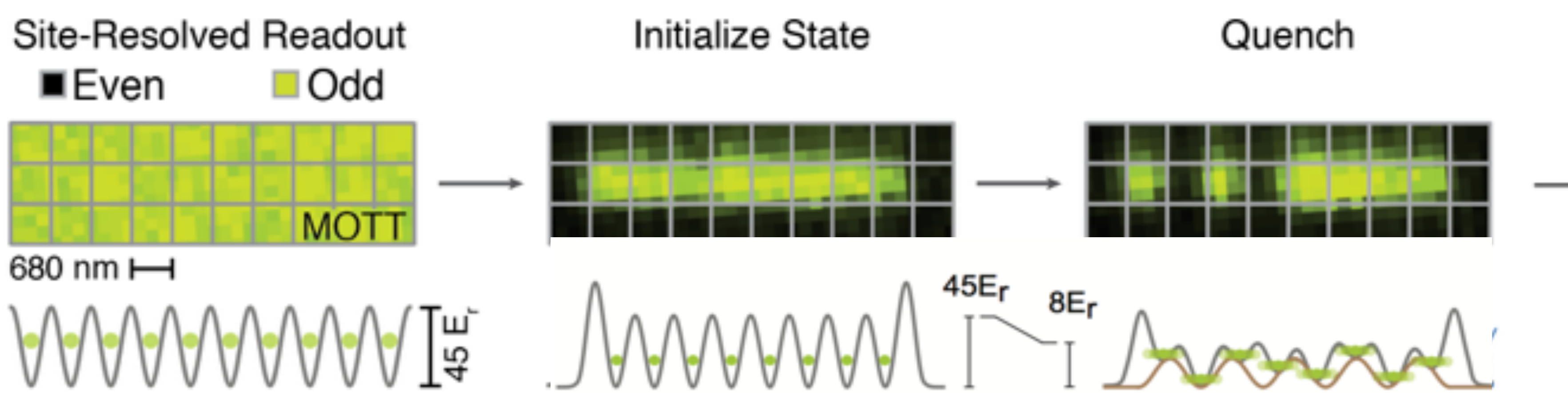
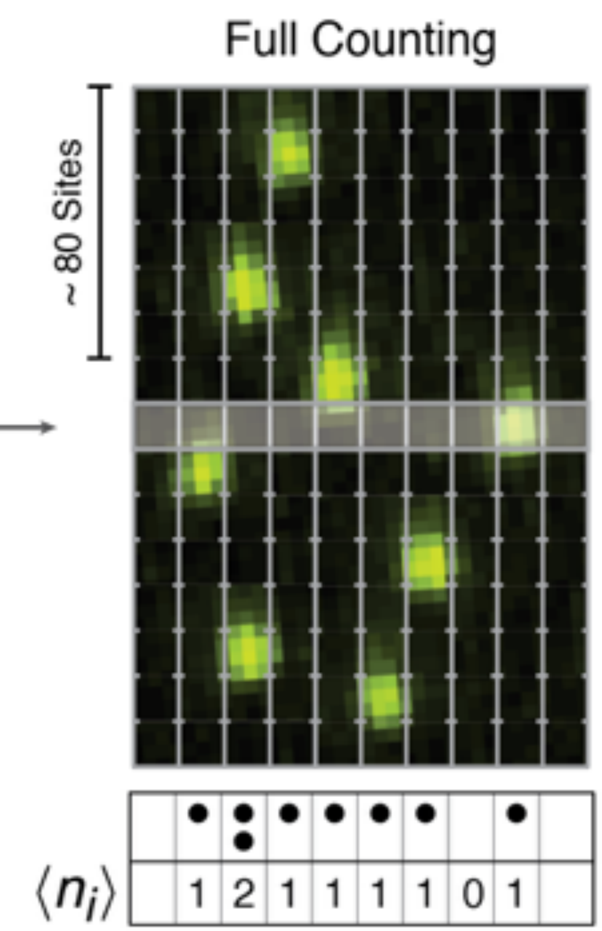
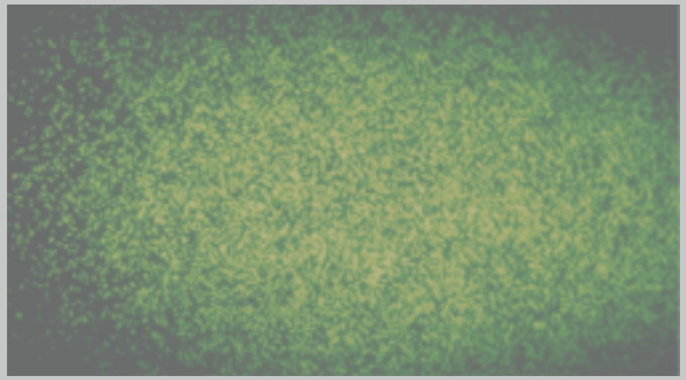




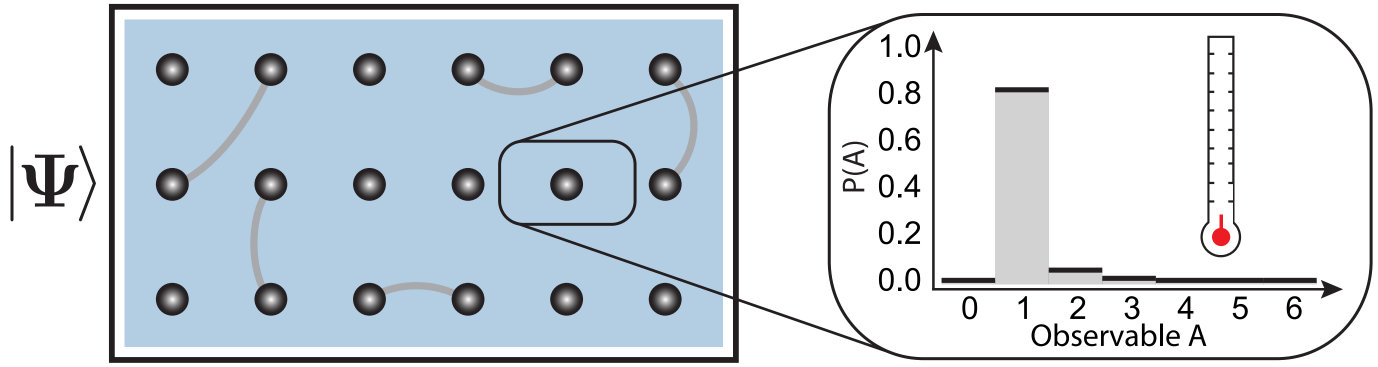
Fully coherent evolution of the system

Key features of MBL

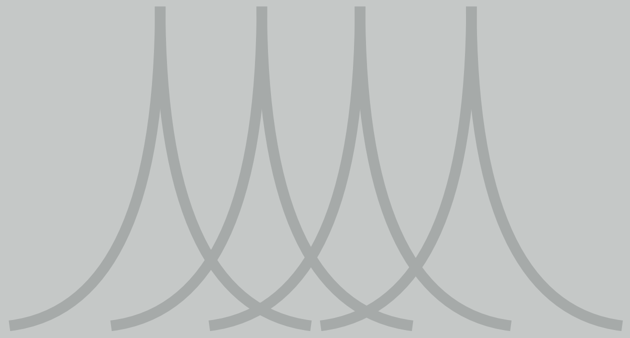
- Experimental setup



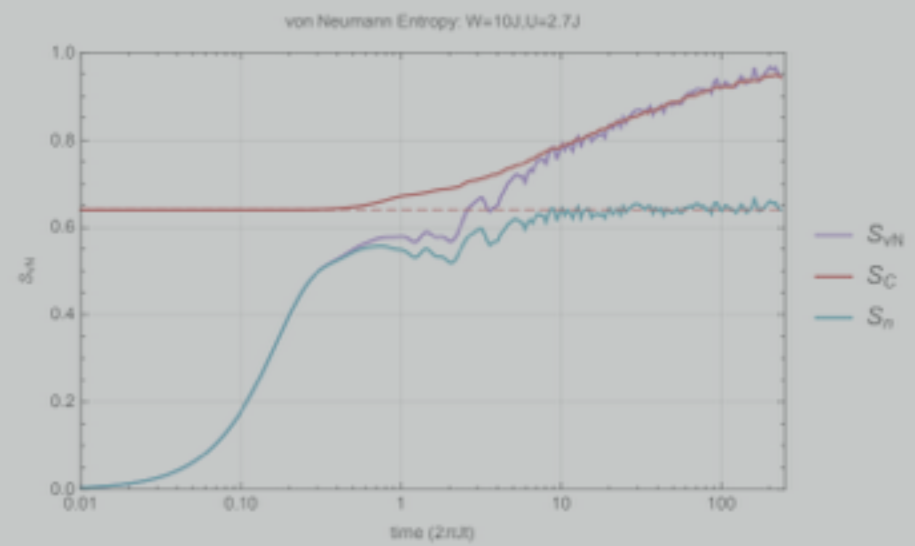
- Breakdown of thermalization



- Spatial localization

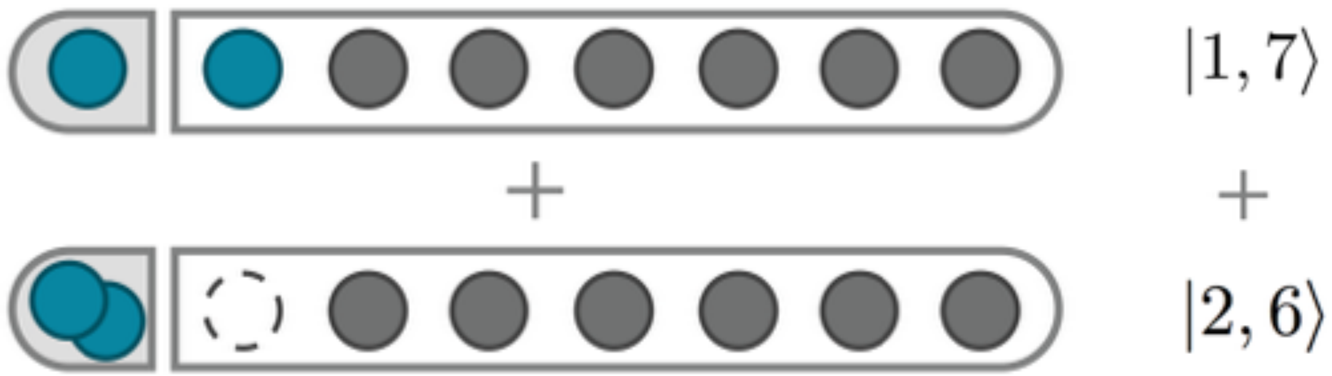


- Entanglement growth



Single site entropy

Single site entropy



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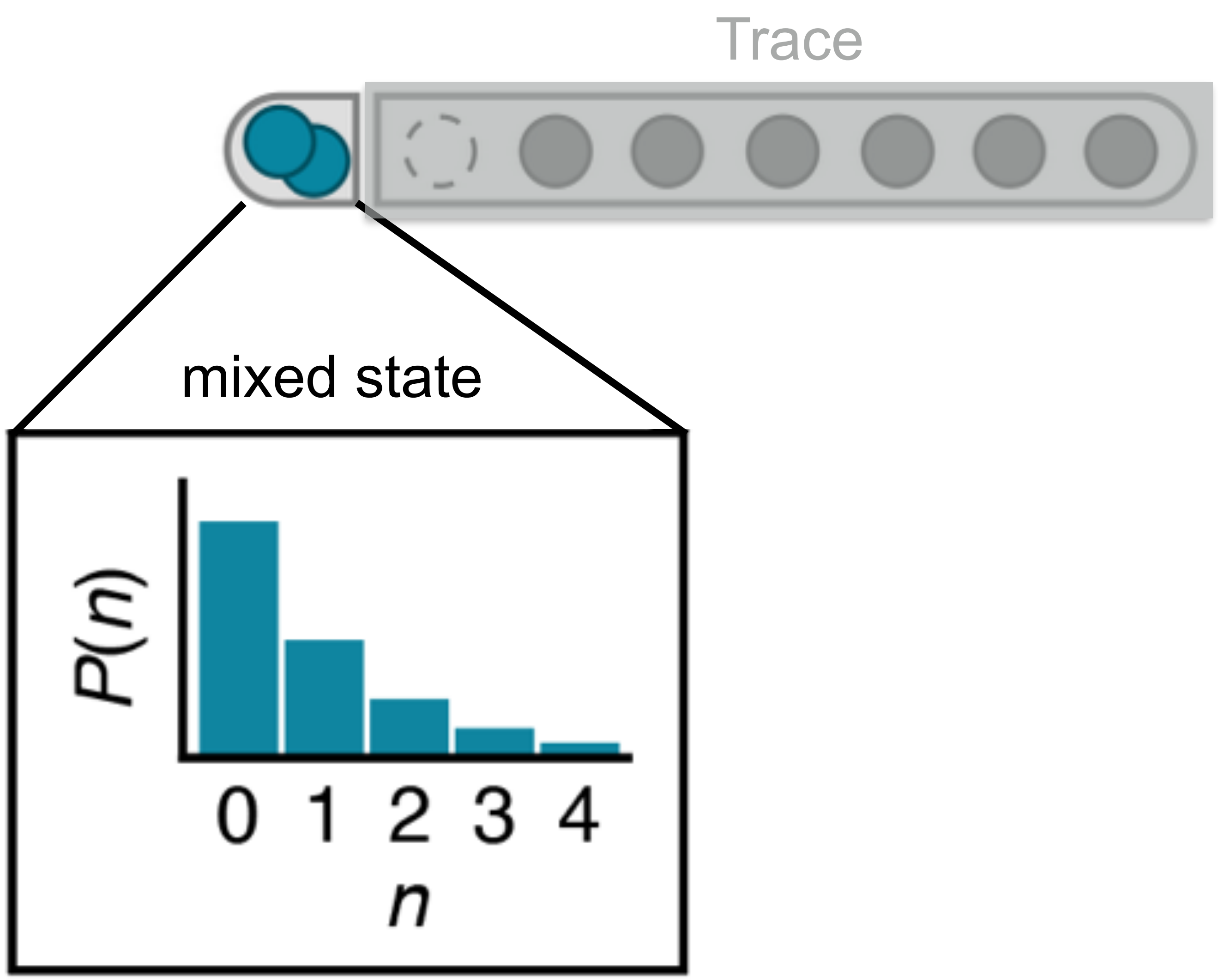

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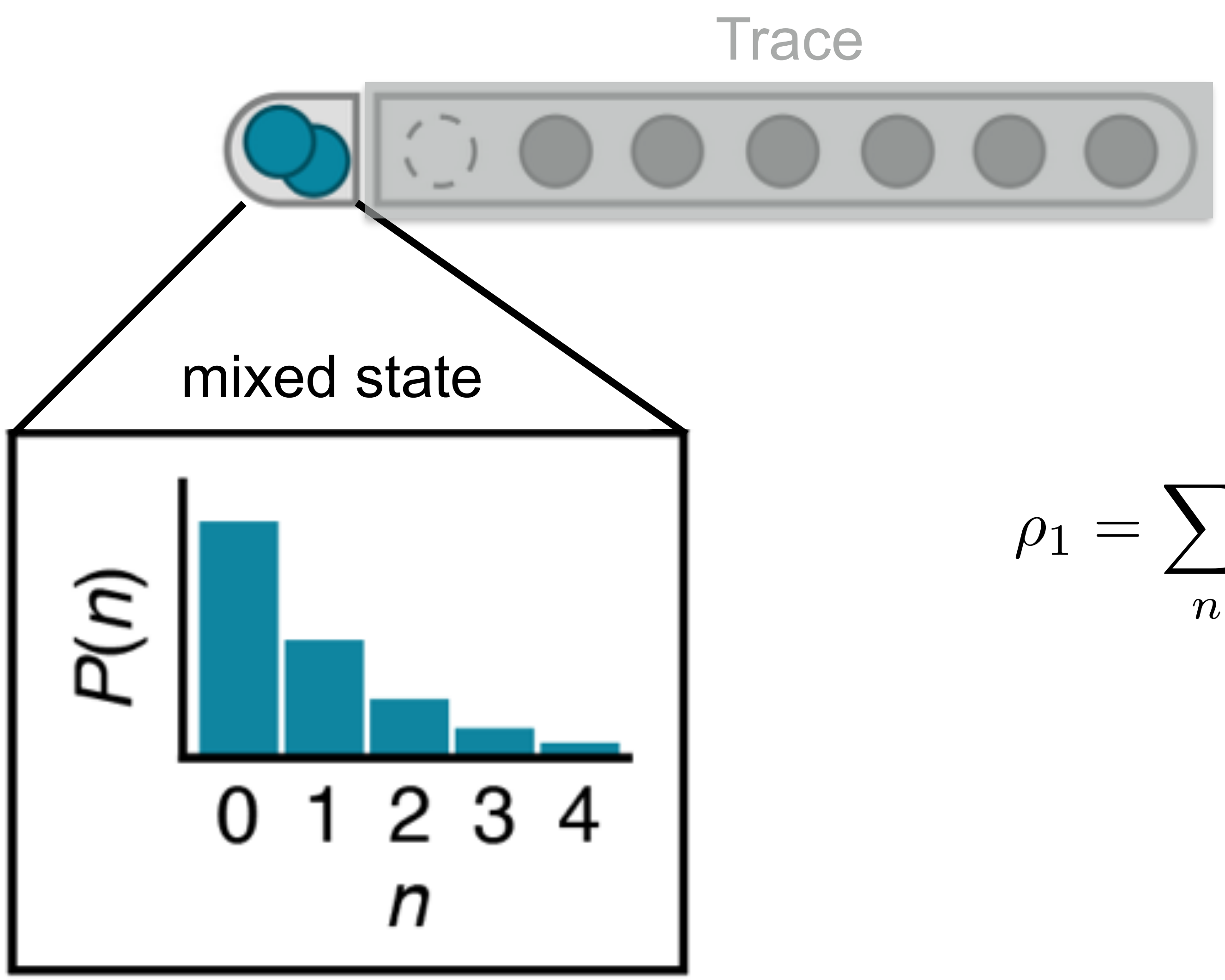

$$\rho_1 = \sum_n P(n) |n\rangle \langle n|$$

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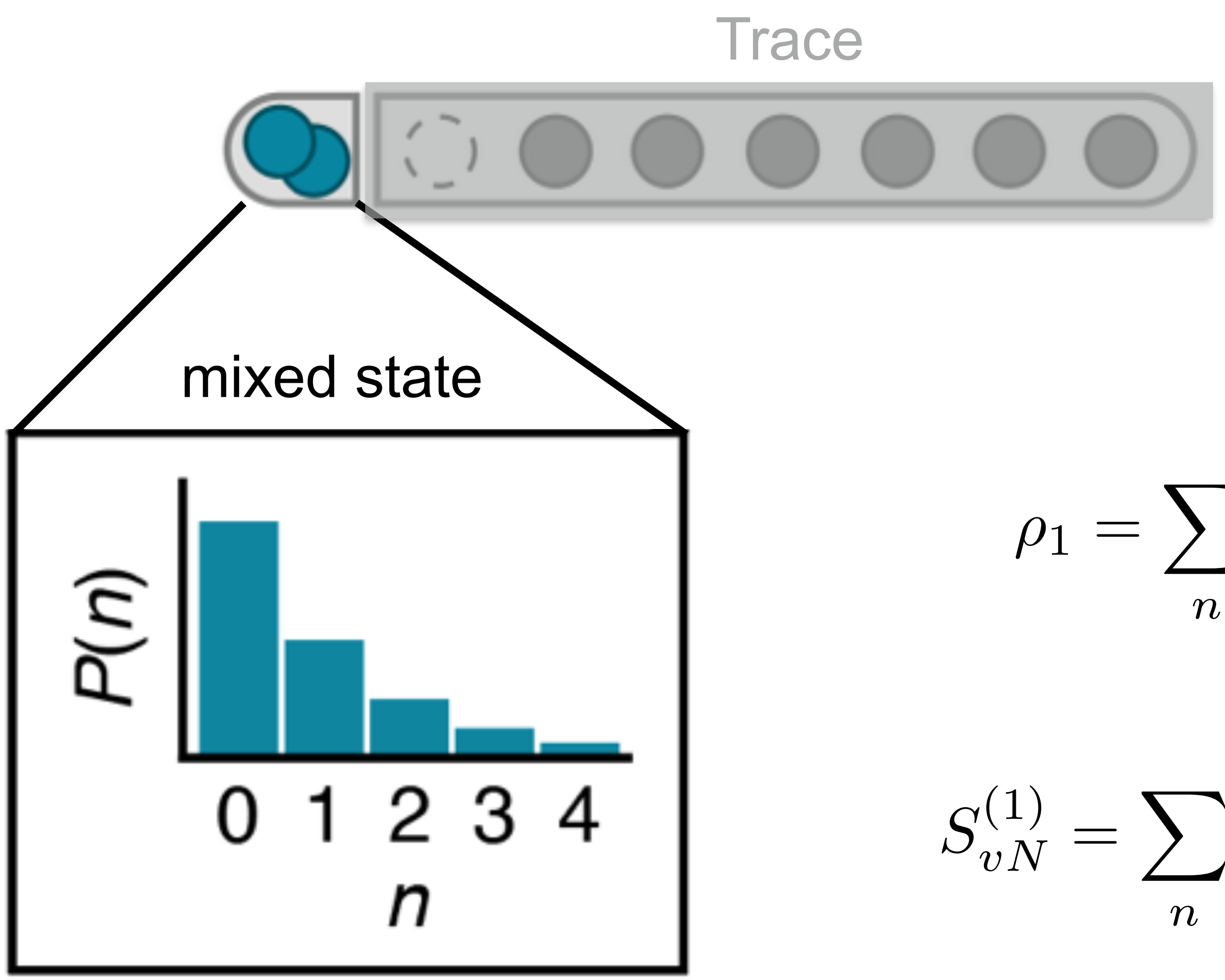

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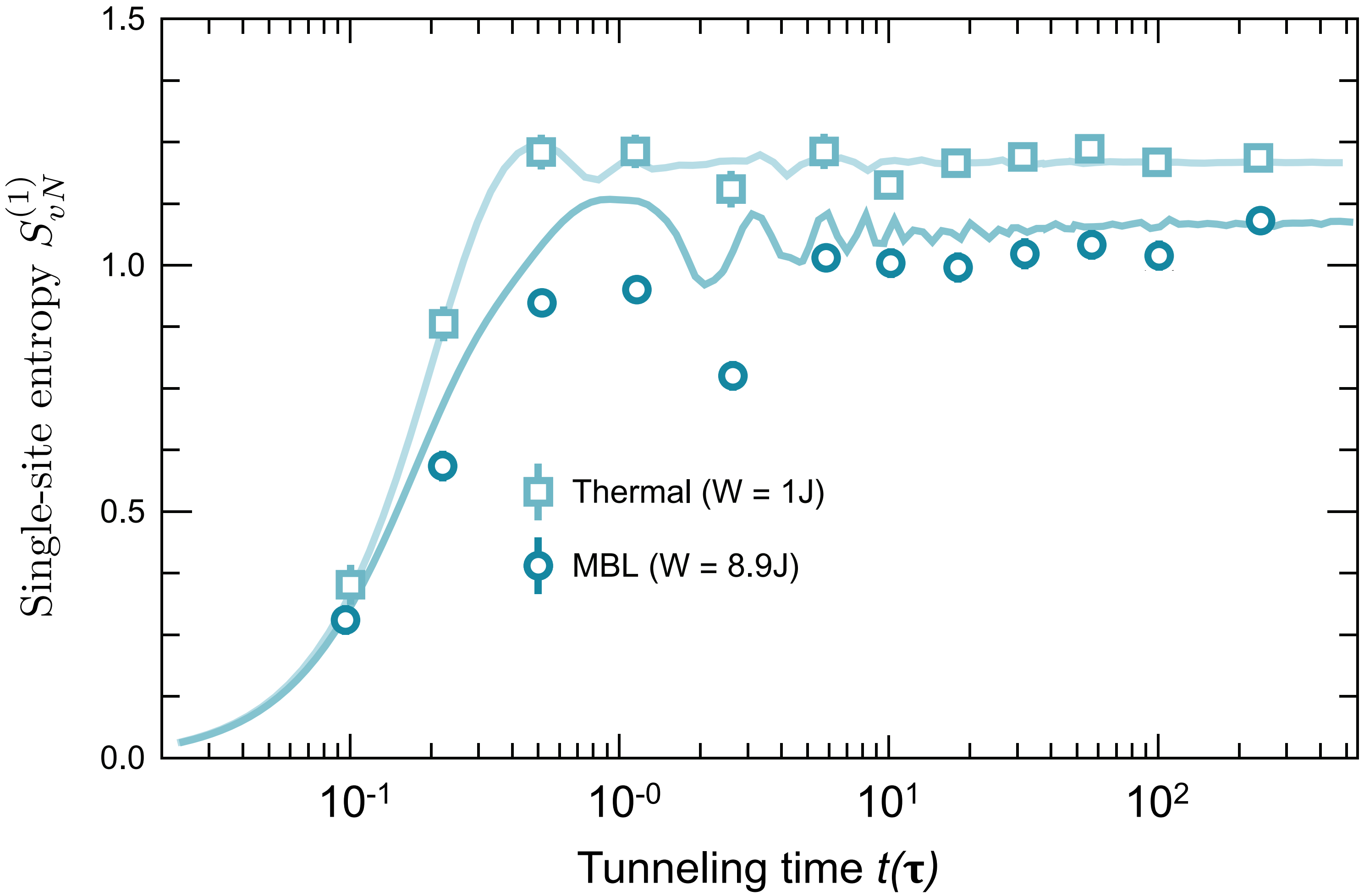

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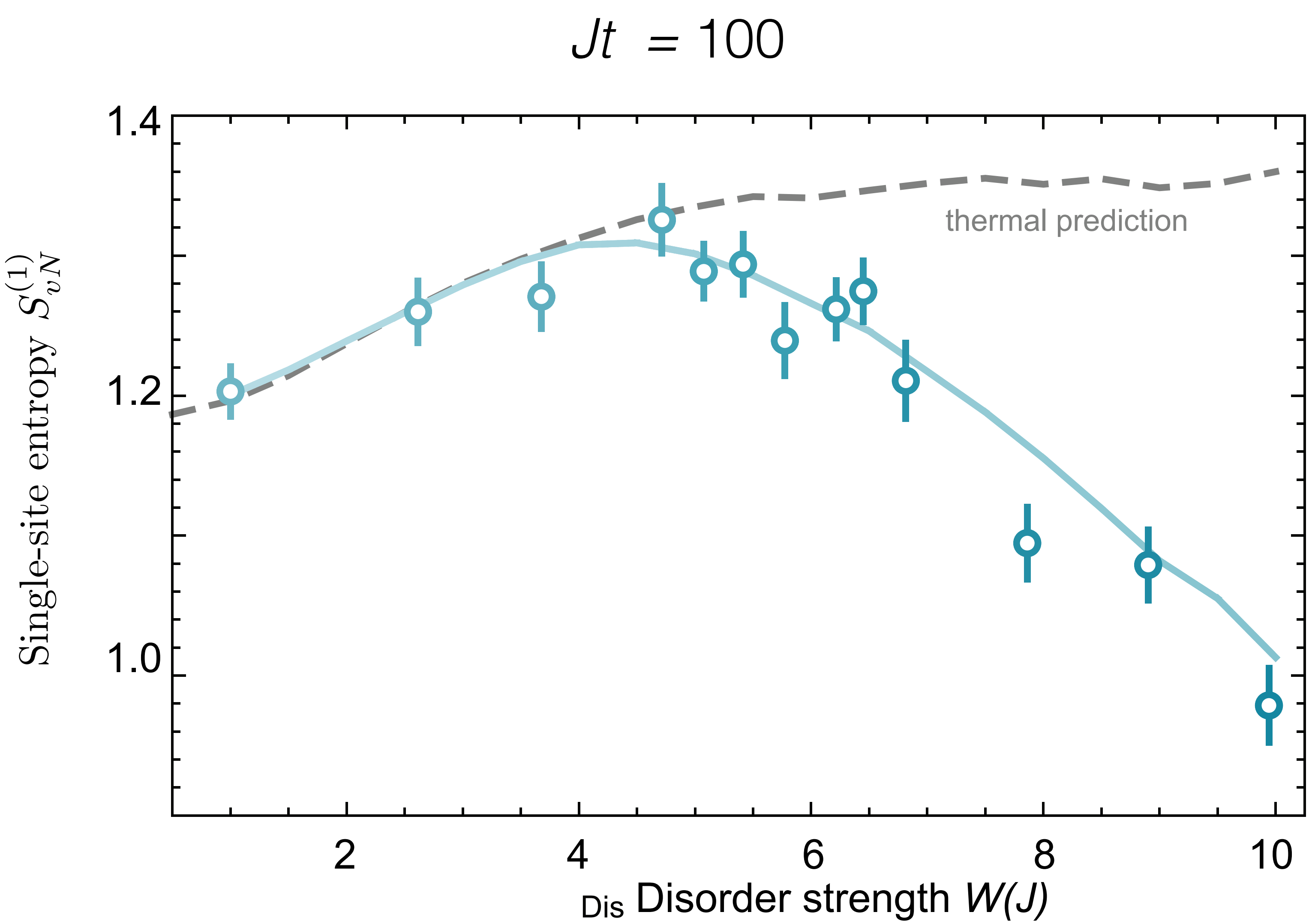

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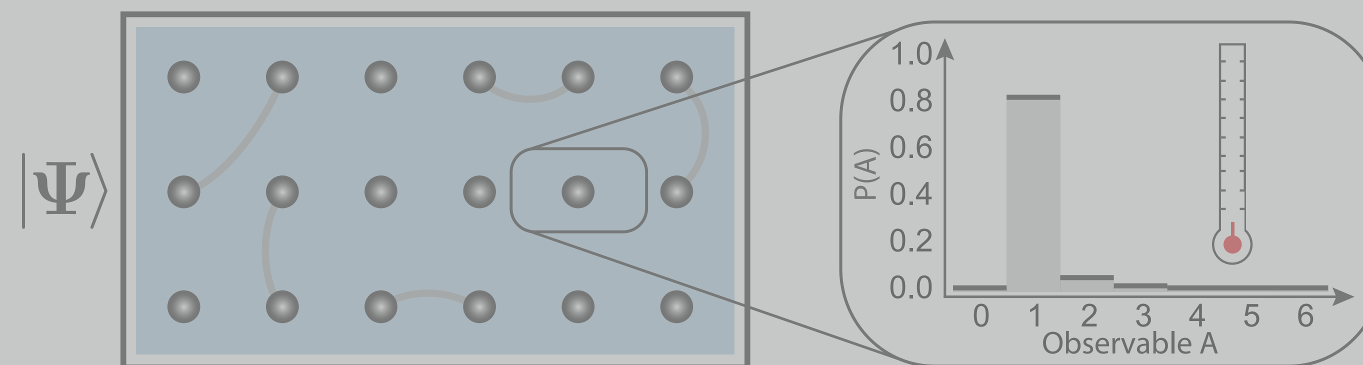

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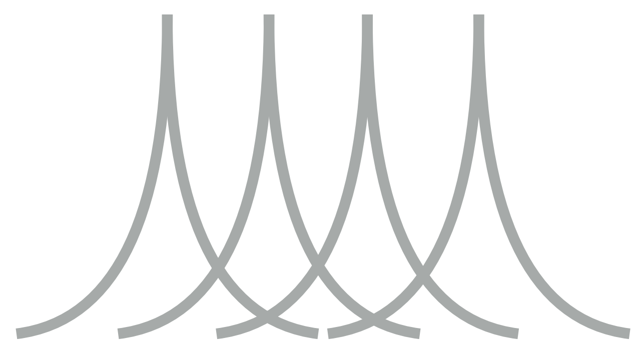

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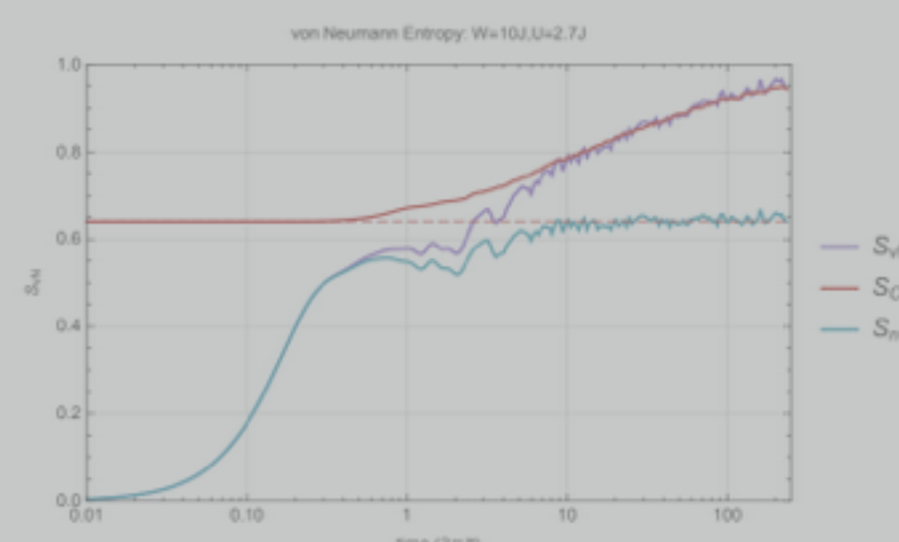

Spatial localization

$$G^{(2)}(d) = \langle n_i n_{i+d} \rangle - \langle n_i \rangle \langle n_{i+d} \rangle$$

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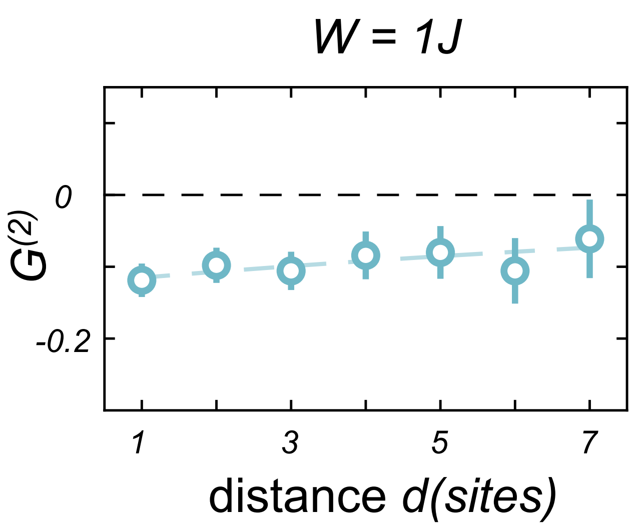

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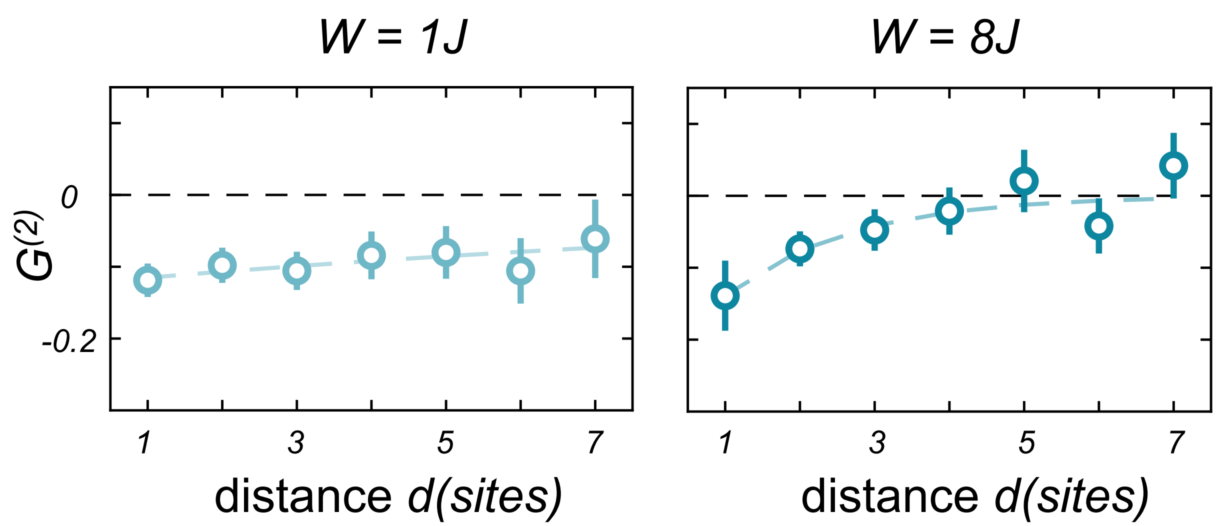

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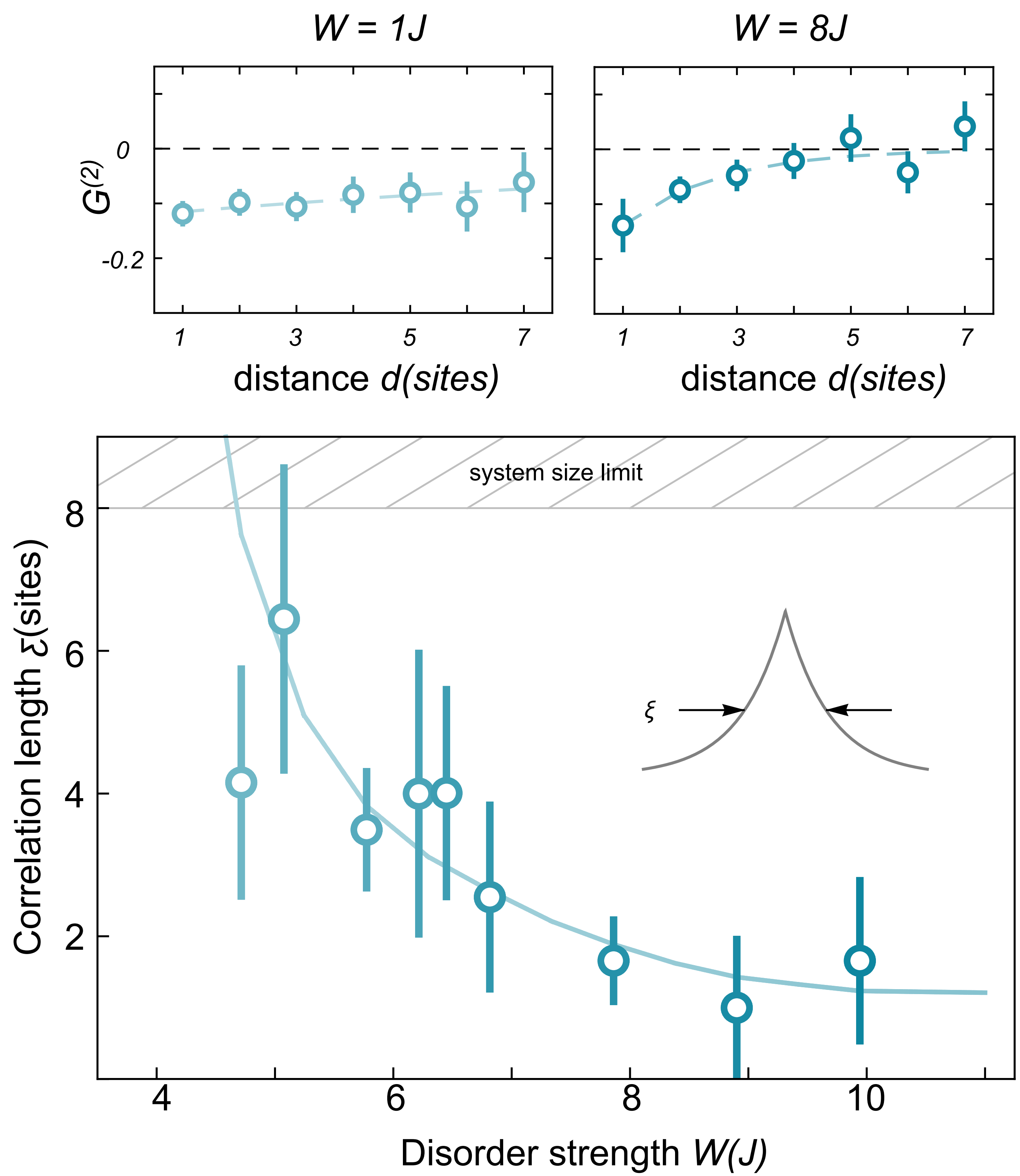

Key features of MBL

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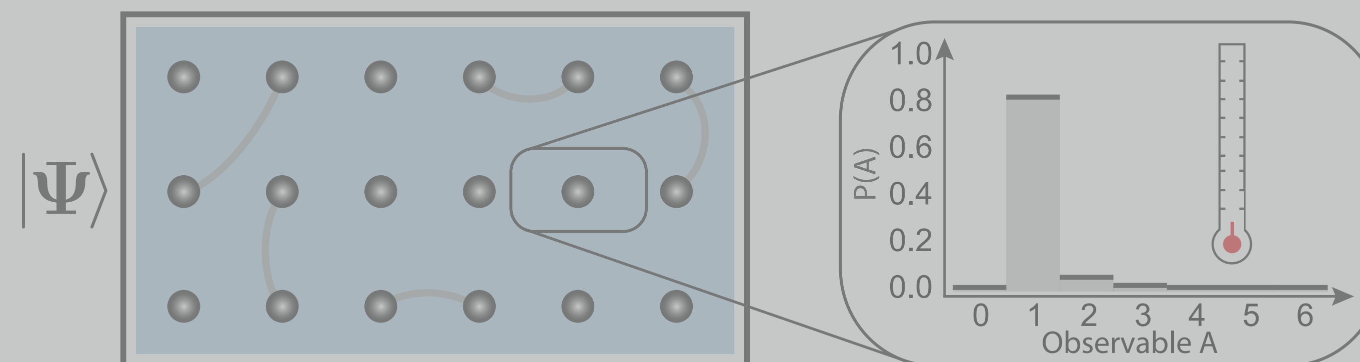

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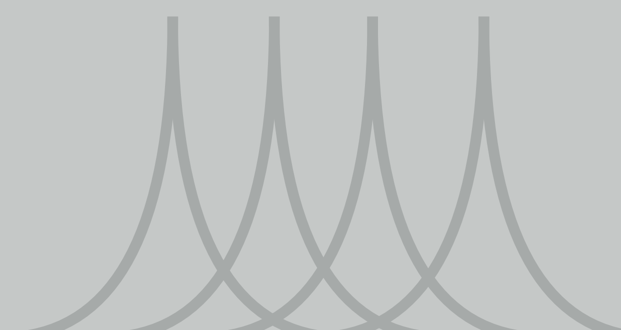

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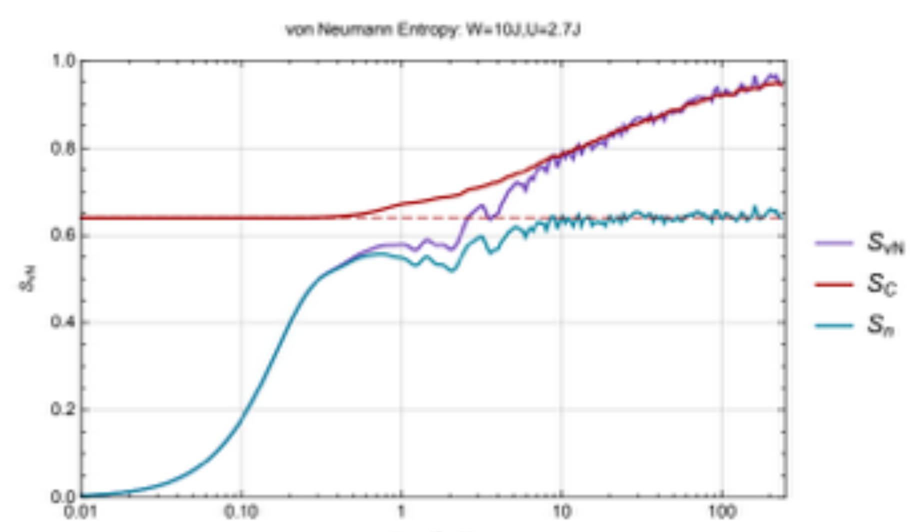
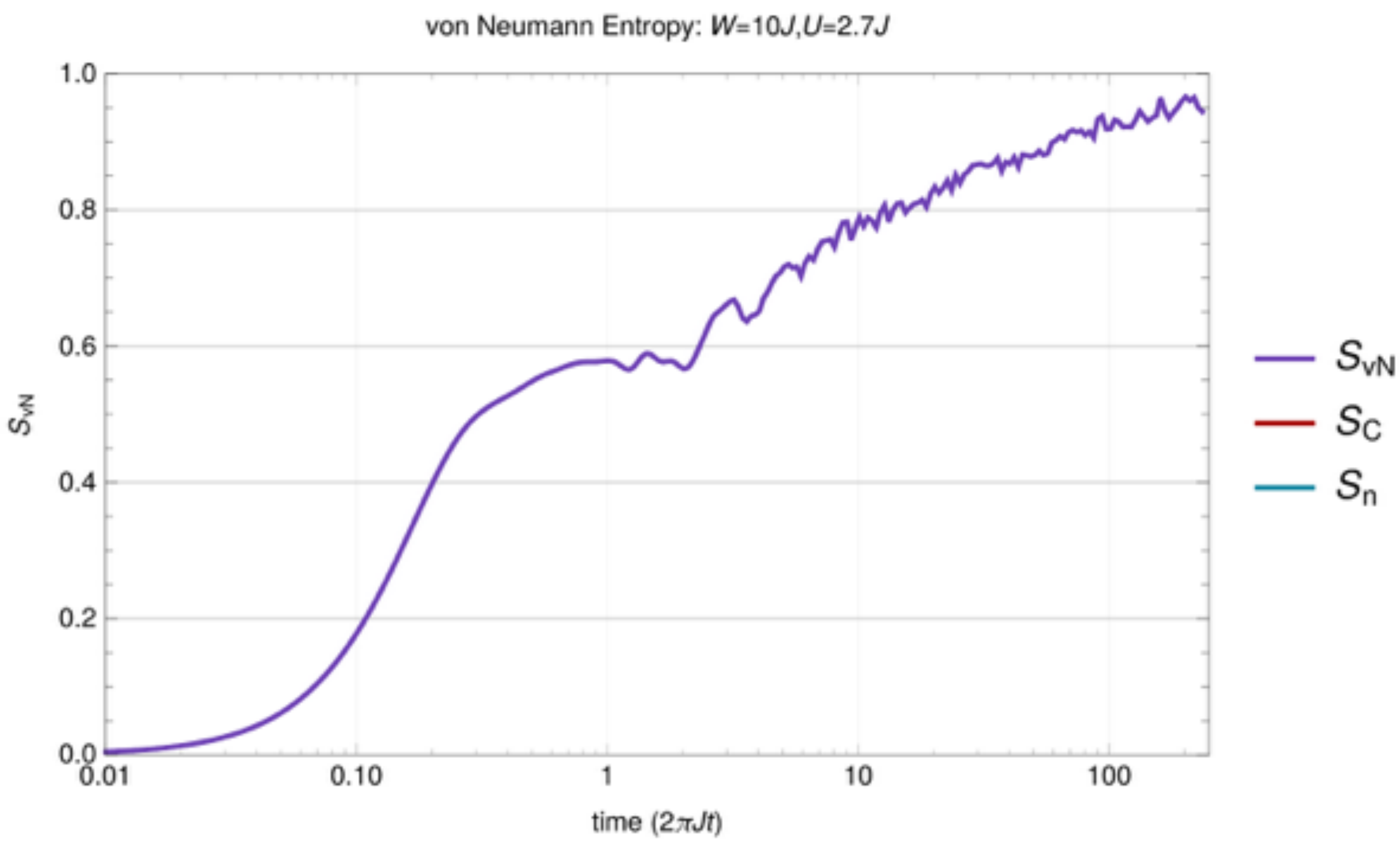
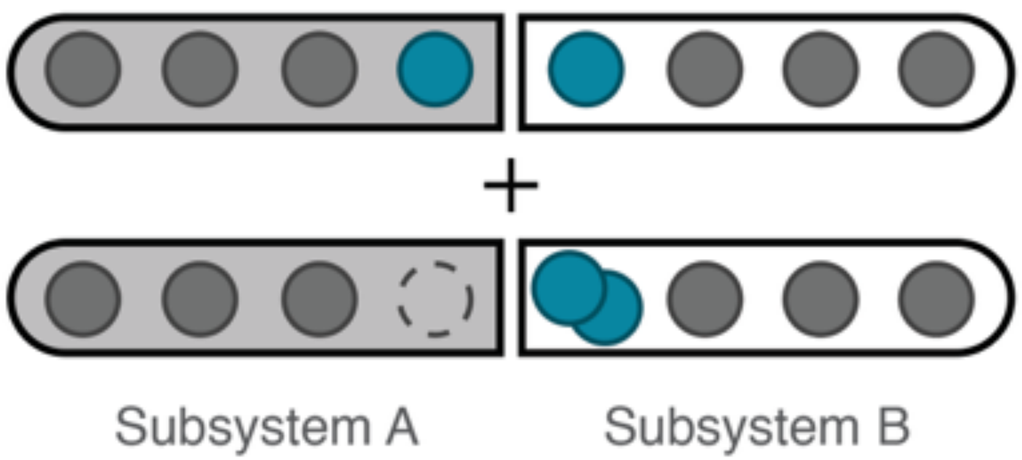


Logarithmic grows of entanglement



Two types of entanglement

Number entanglement



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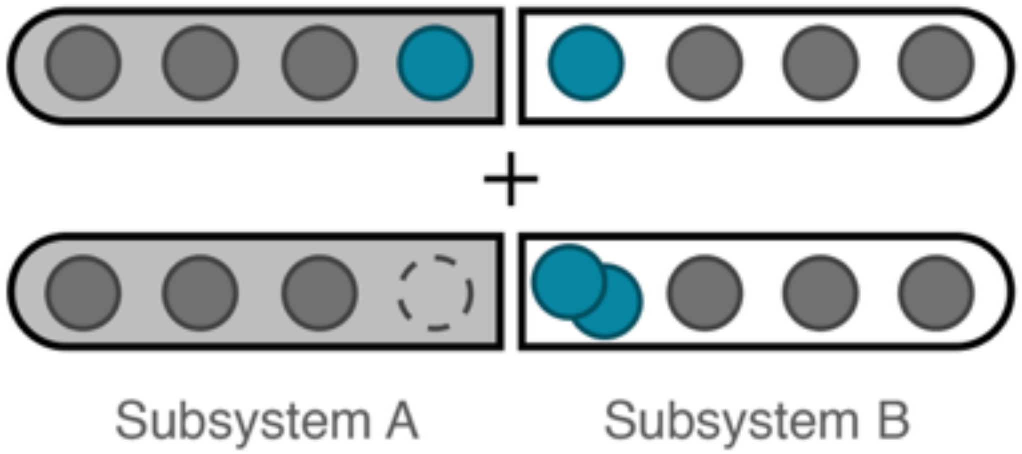

particle tunneling

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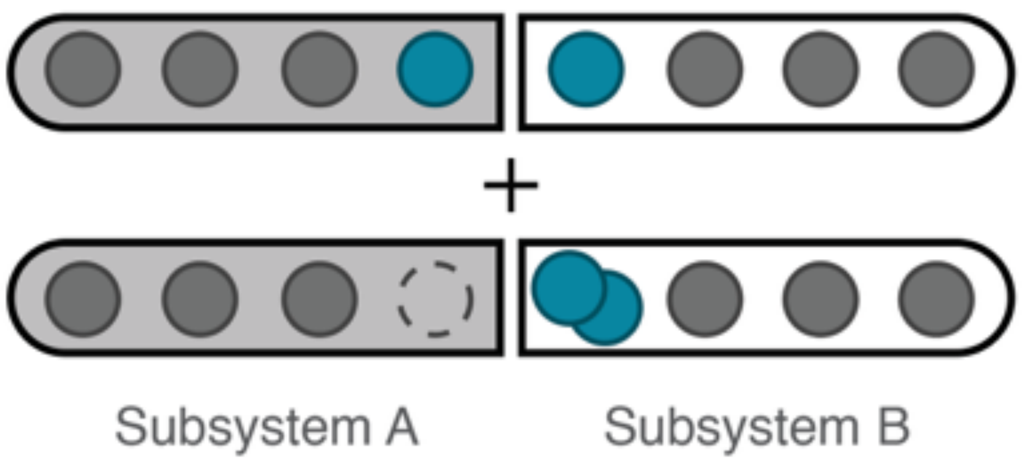
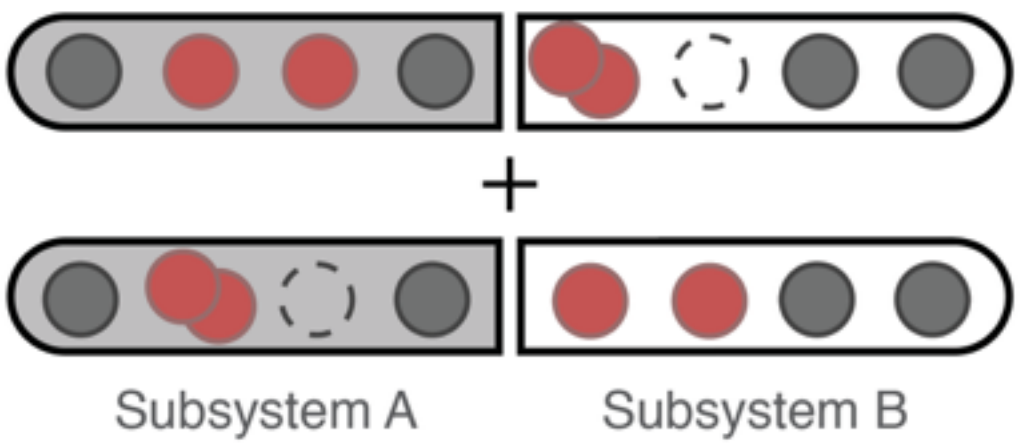


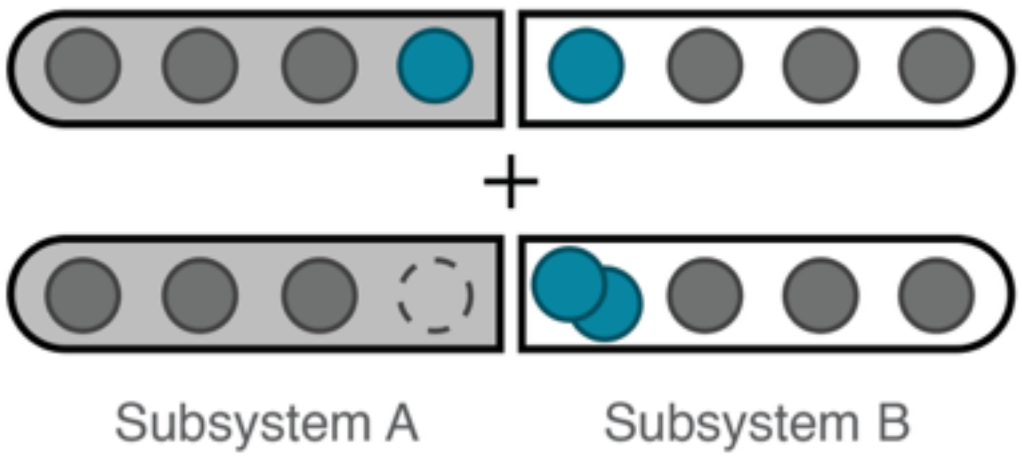
particle tunneling

Configurational entanglement



Two types of entanglement

Number entanglement



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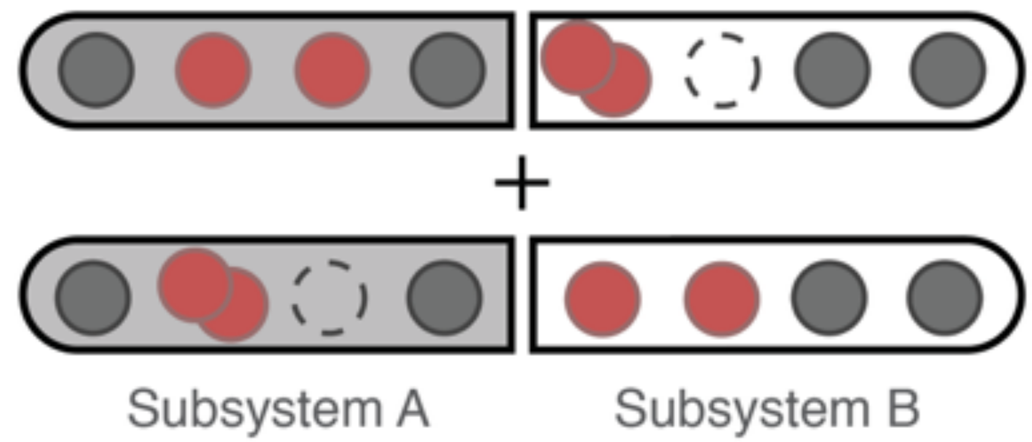
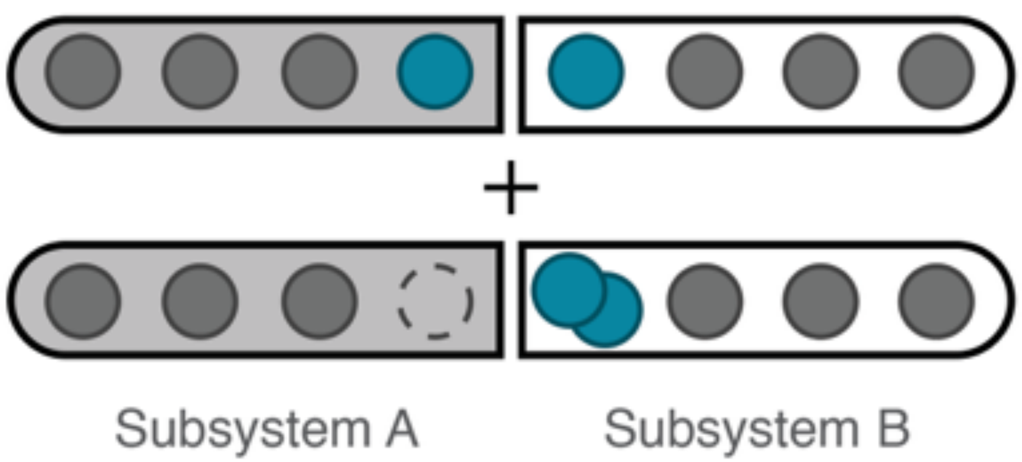


non-local quantum correlations

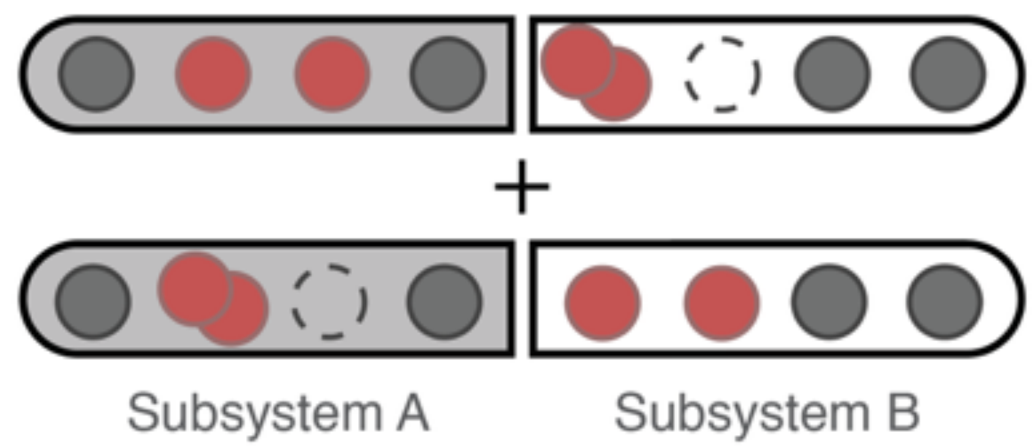
Two types of entanglement

Number entanglement



particle tunneling

Configurational entanglement



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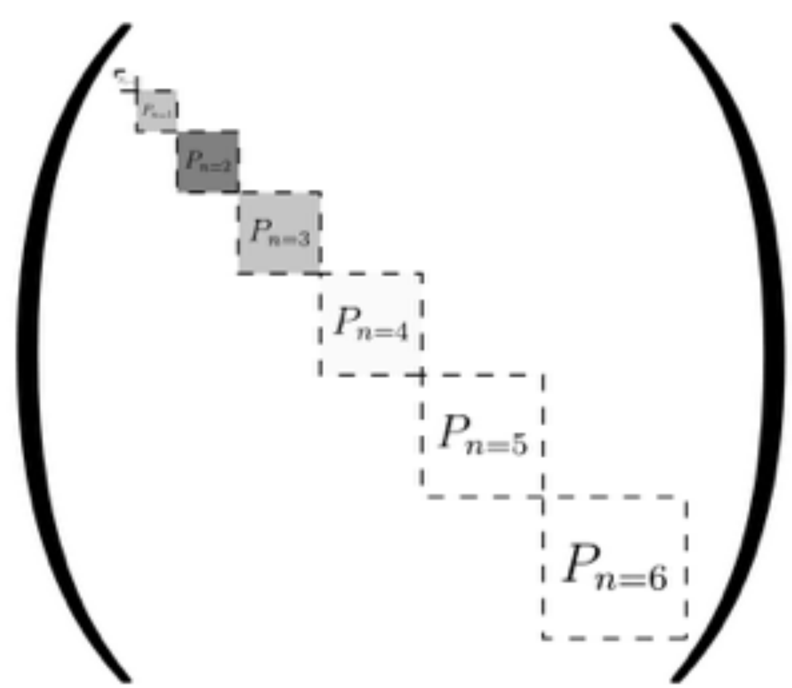

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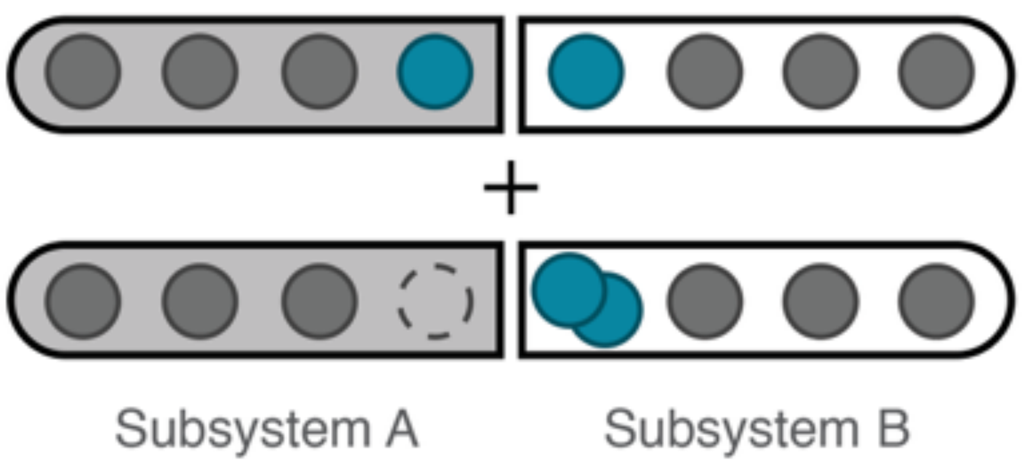
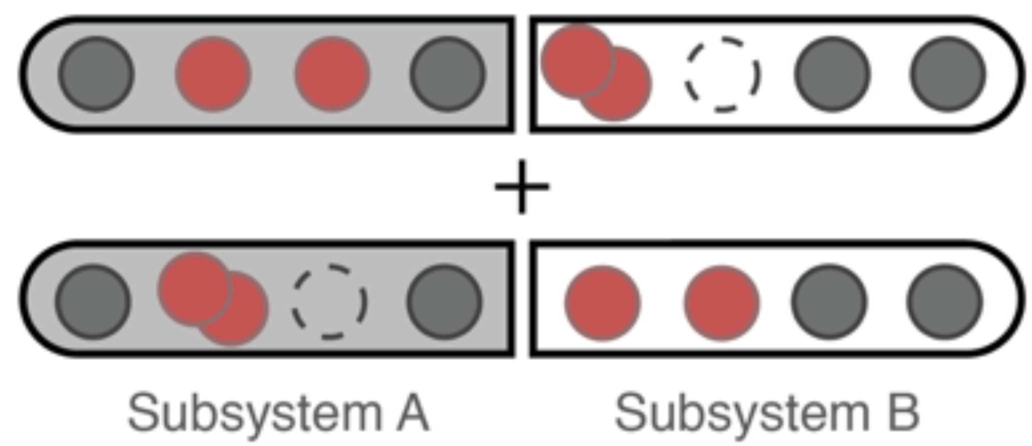


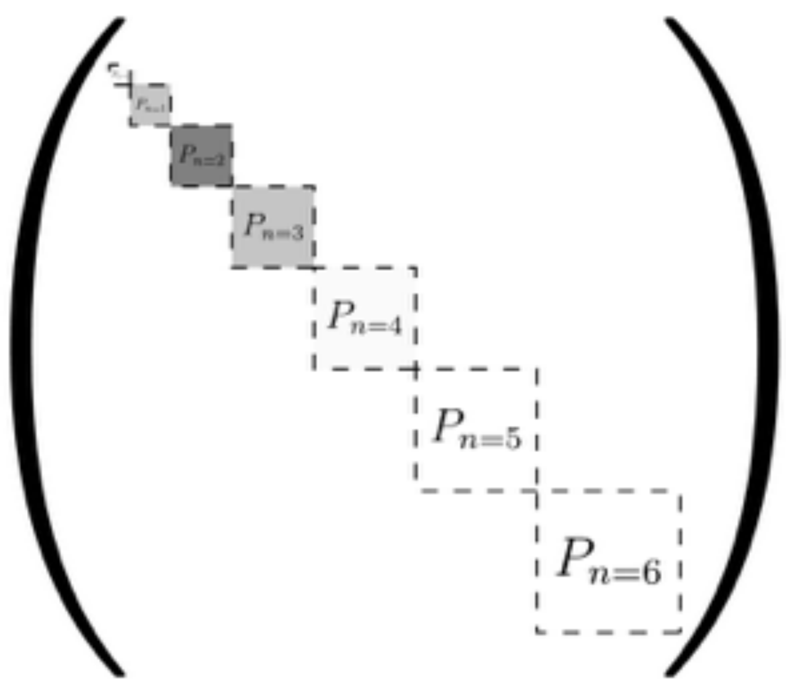
particle tunneling

Configurational entanglement



non-local quantum correlations

distribution
between the blocks



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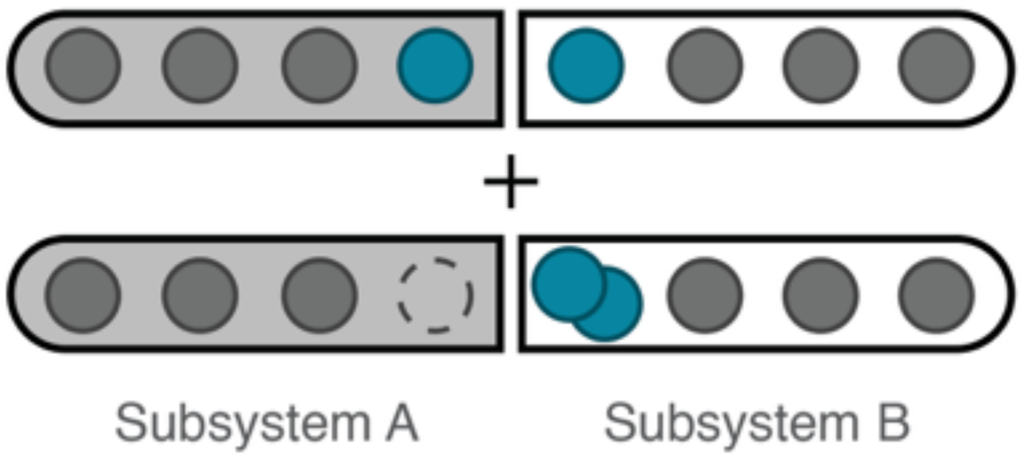

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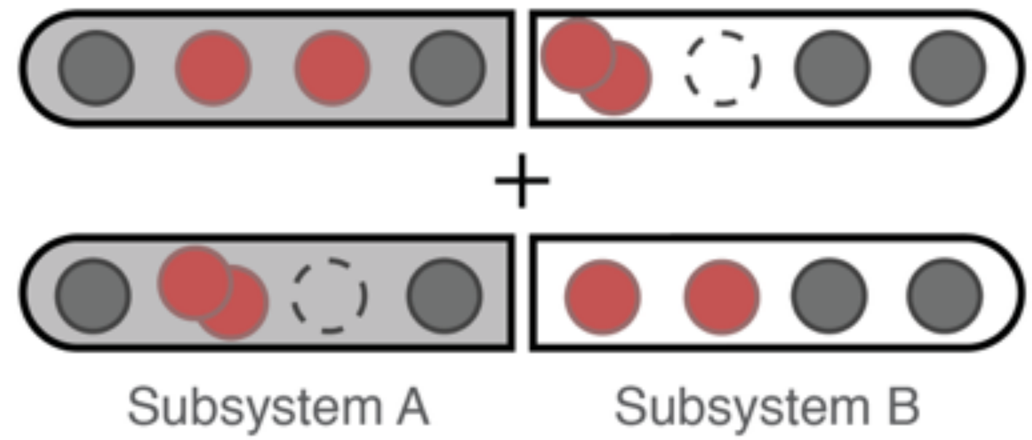

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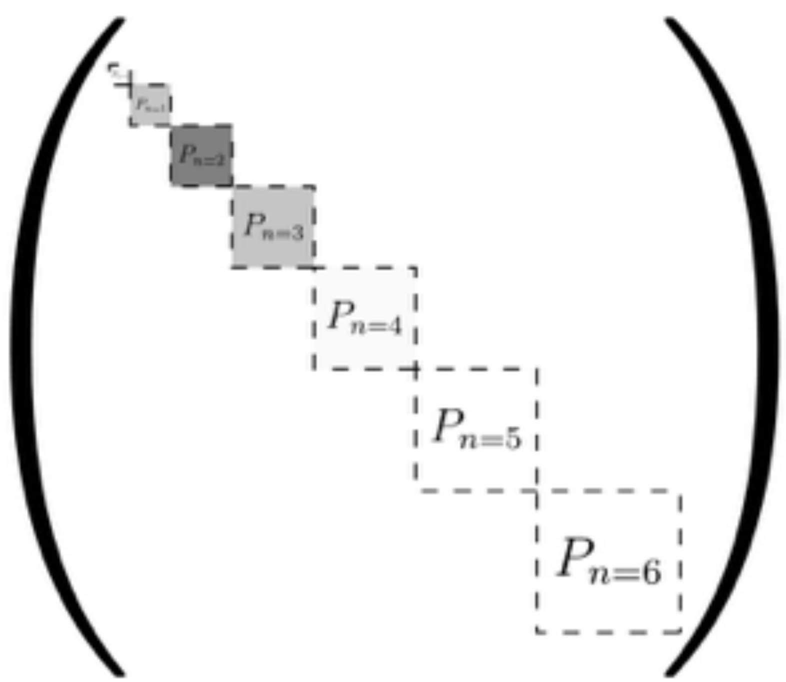
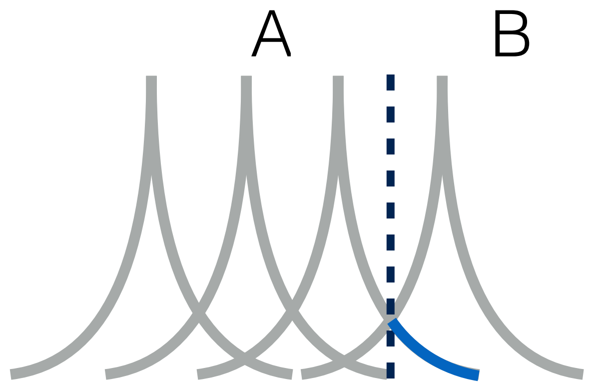


number of populated states
within the blocks

Number entanglement in MBL



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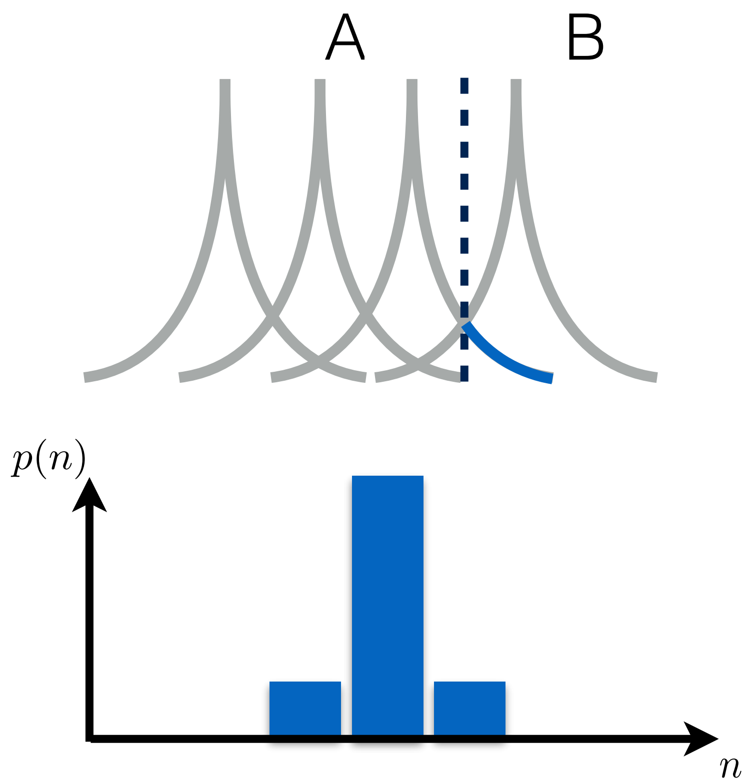

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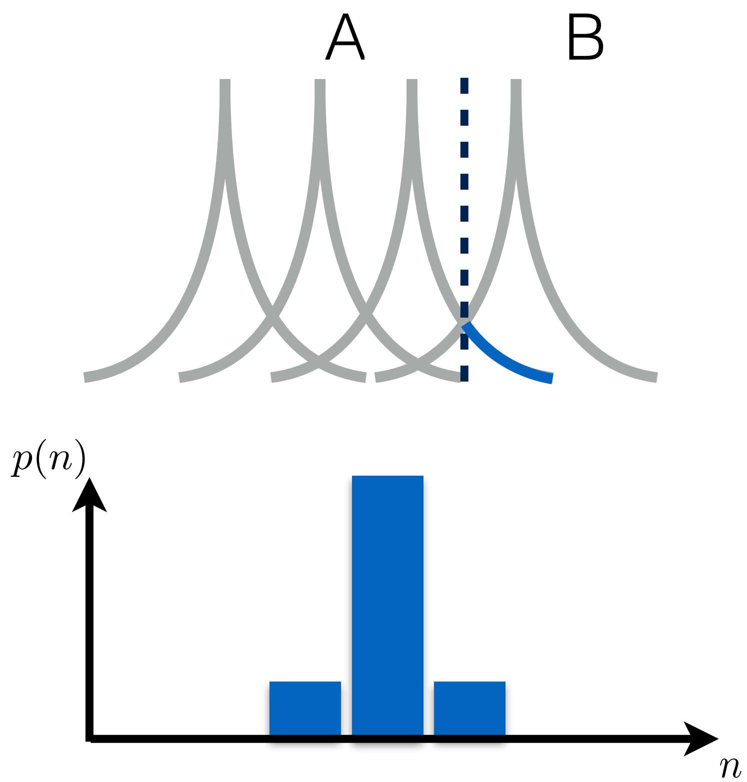

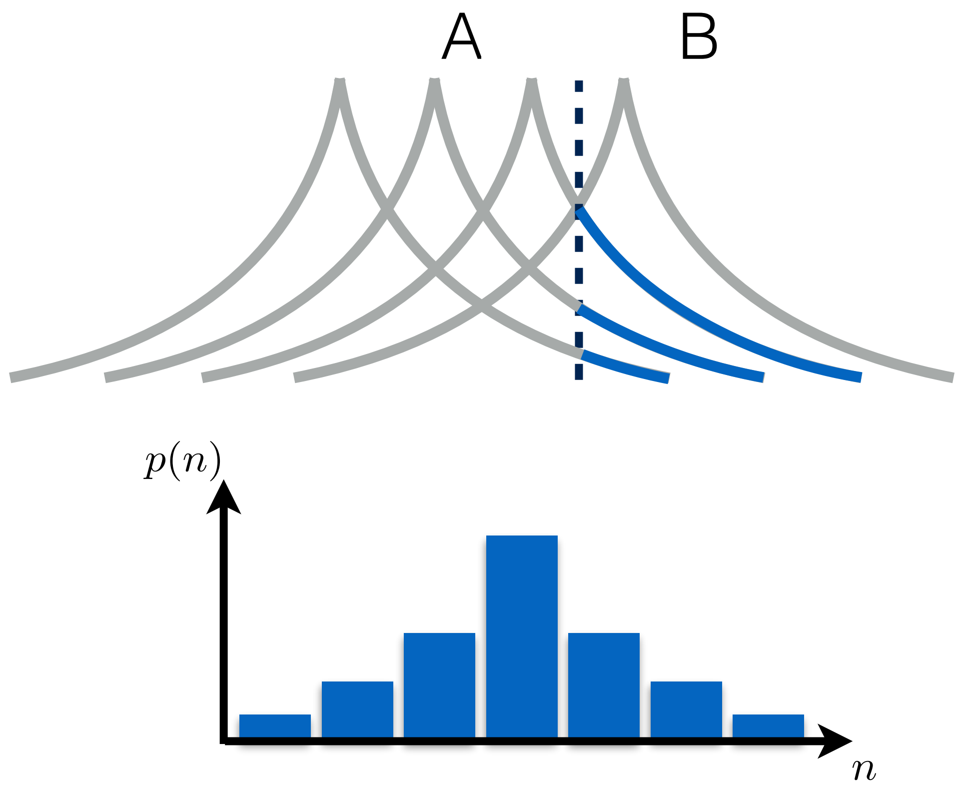

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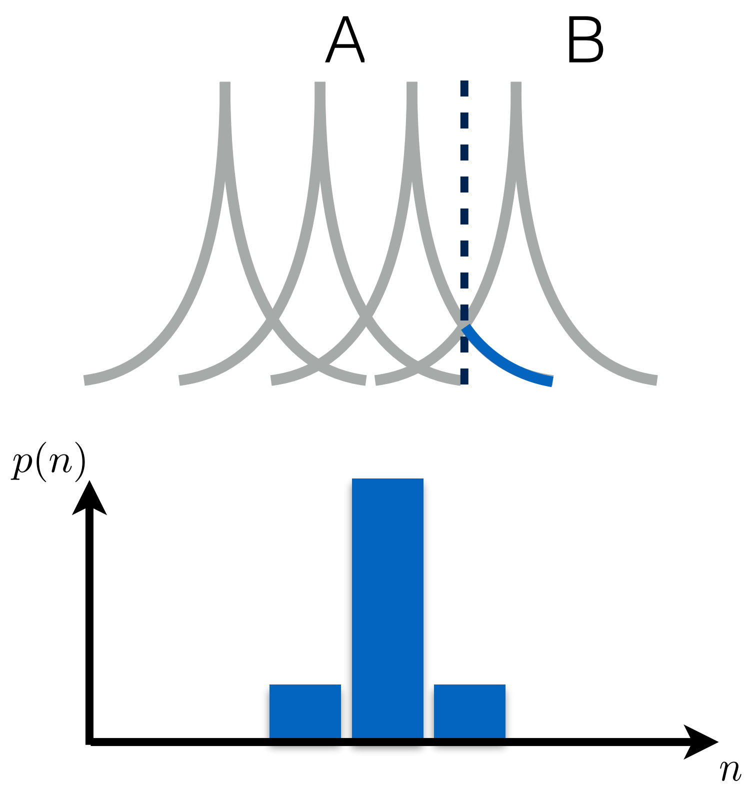
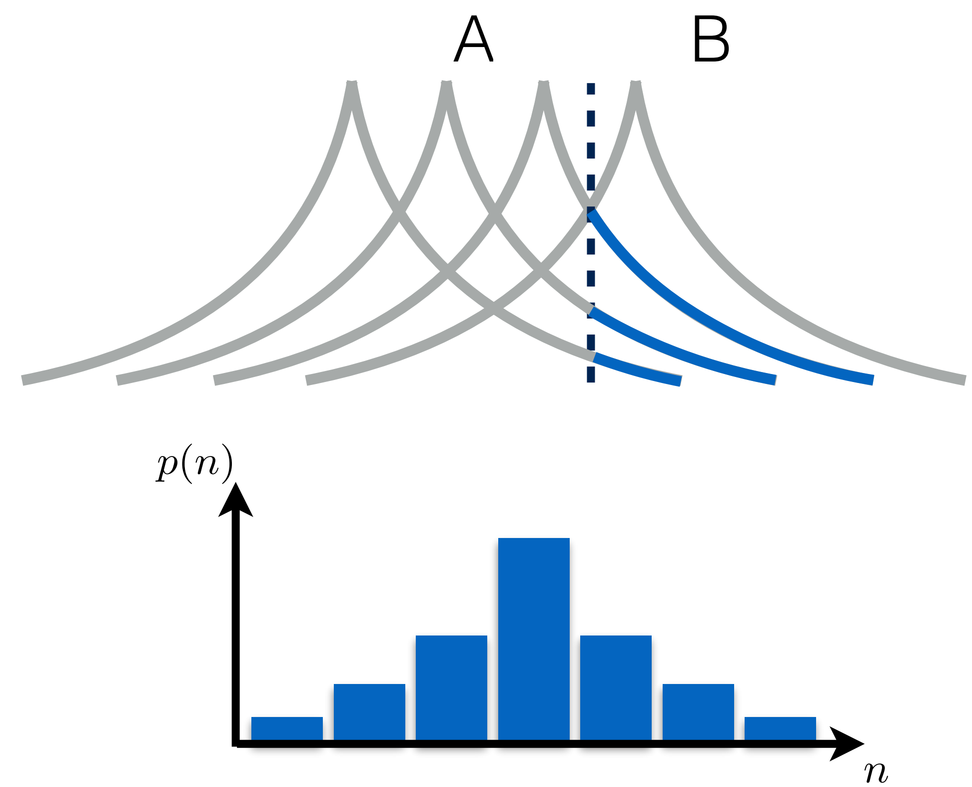
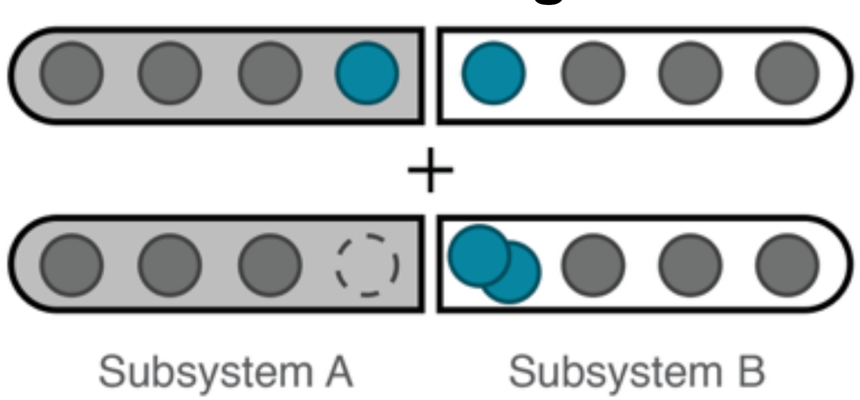




$$S_{\mathrm{n}} = -\sum_n p_n \log\left(p_n\right)$$

Number entanglement



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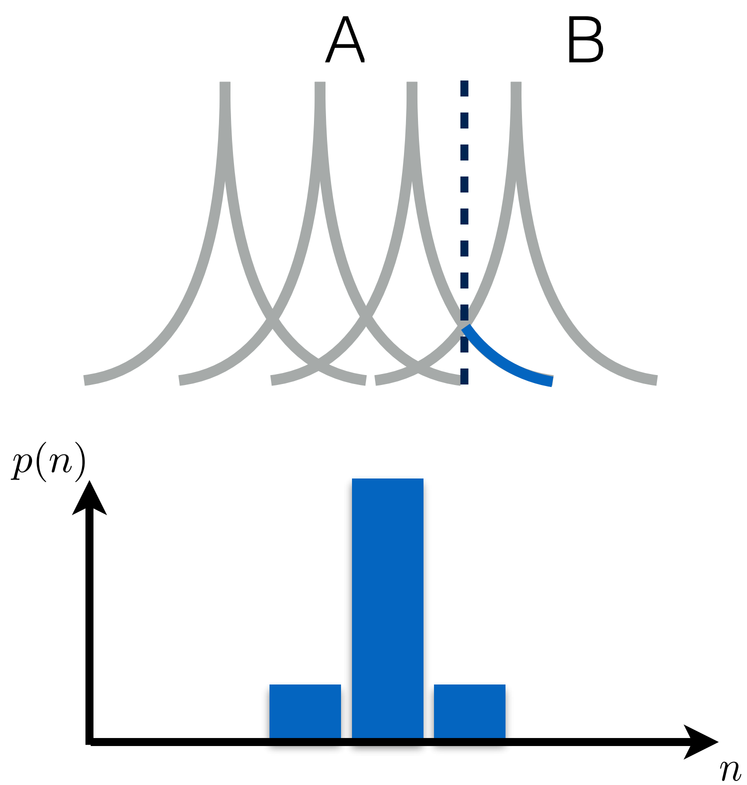

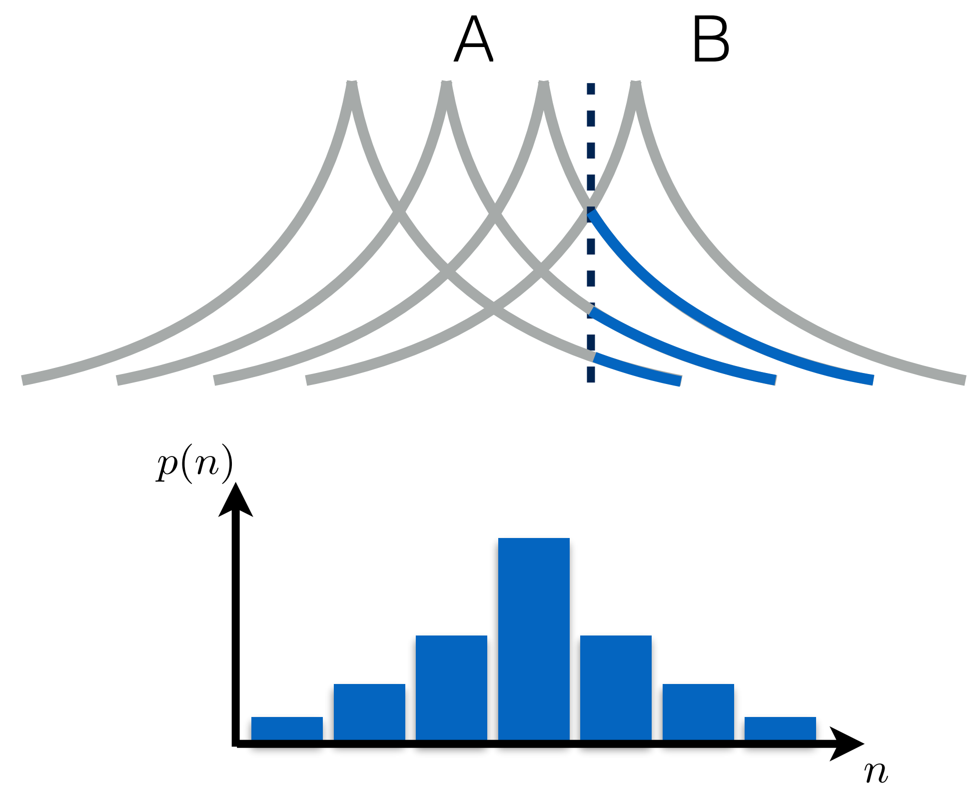

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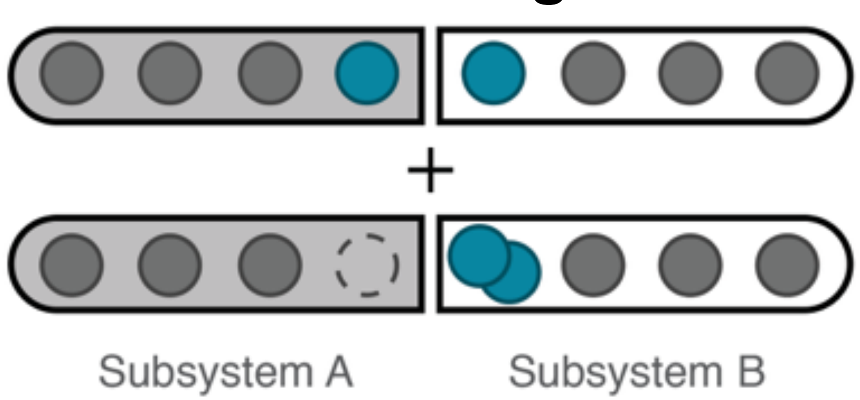
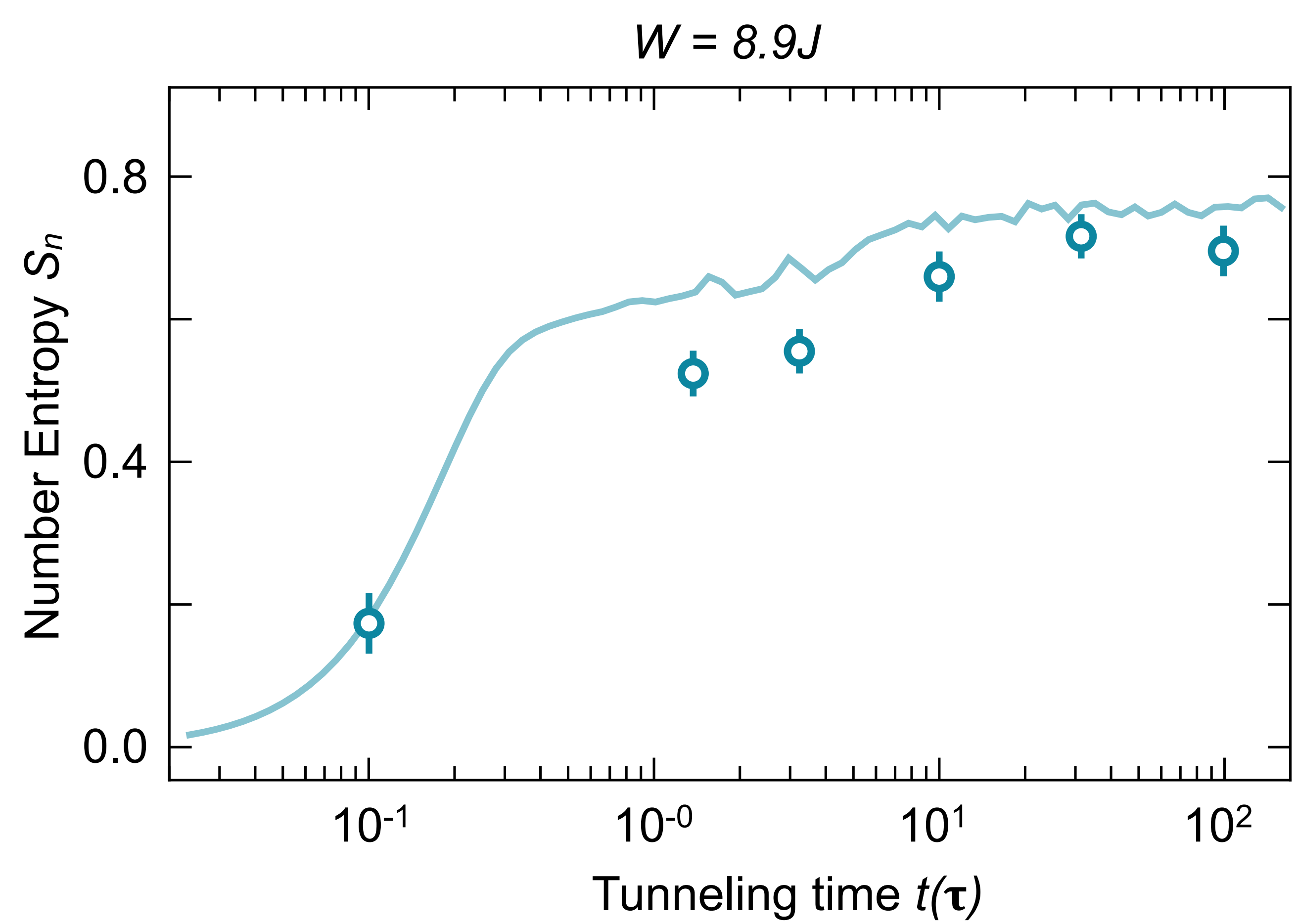
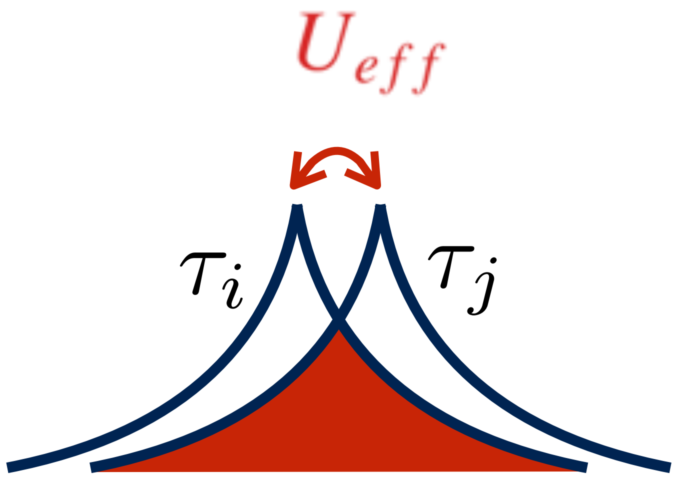


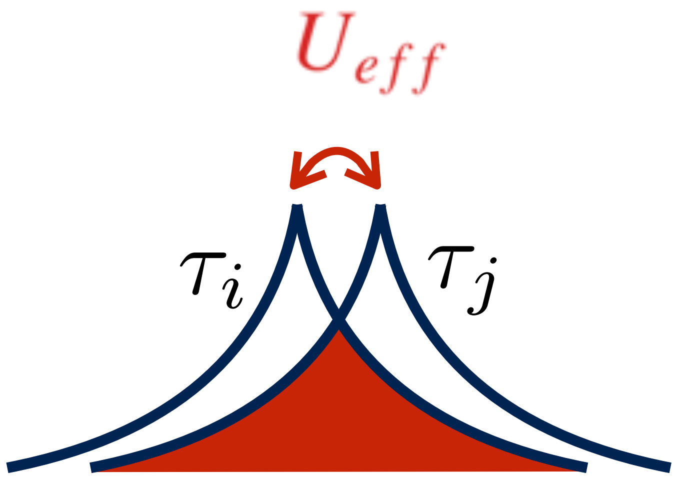


Configurational entanglement in MBL



$$\hat{\mathcal{H}} = \sum_{i,j} U_{eff}^{ij} \tau_i \tau_j$$

Configurational entanglement in MBL



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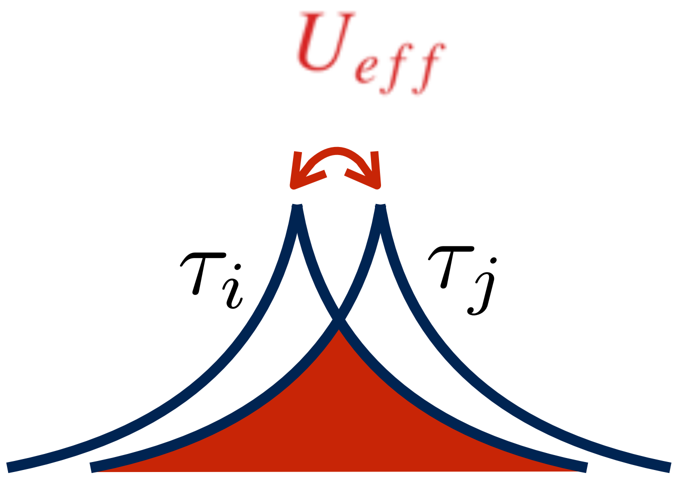
unentangled product state

$$\tau_i \otimes \tau_j = (|0\rangle + |1\rangle)_i \otimes (|0\rangle + |1\rangle)_j$$

Configurational entanglement in MBL



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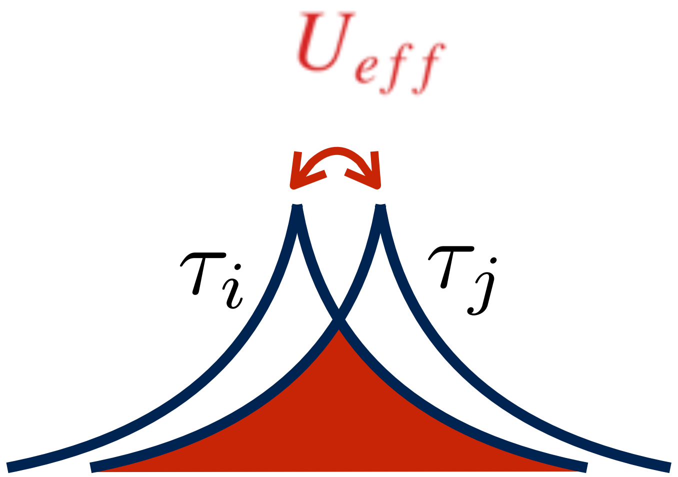

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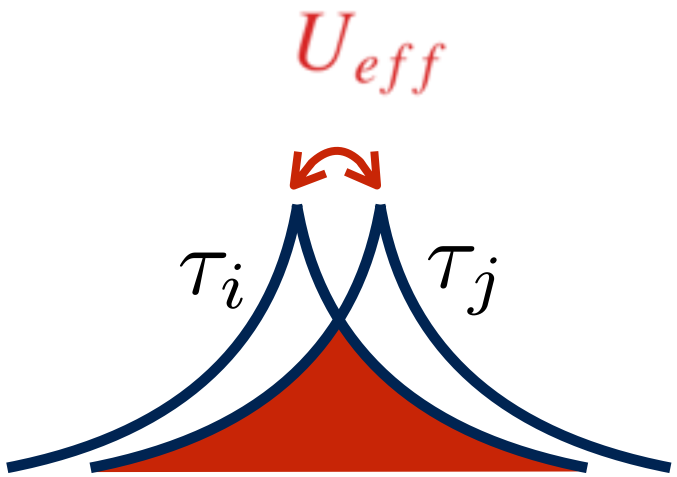
Configurational entanglement in MBL



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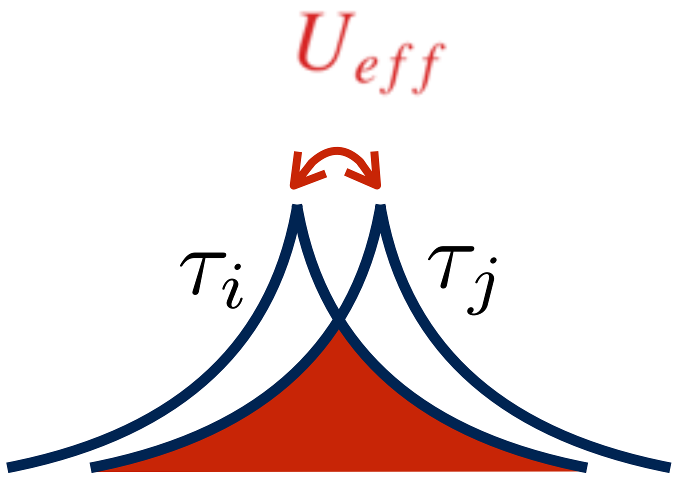
$$|00\rangle + |01\rangle + |10\rangle + e^{iU_{eff}t}|11\rangle \rightarrow |00\rangle + |01\rangle + |10\rangle - |11\rangle =$$

Configurational entanglement in MBL



$$\hat{\mathcal{H}} = \sum_{i,j} U_{eff}^{ij} \tau_i \tau_j$$

unentangled product state

$$\tau_i \otimes \tau_j = (|0\rangle + |1\rangle)_i \otimes (|0\rangle + |1\rangle)_j = |00\rangle + |01\rangle + |10\rangle + |11\rangle$$

$$|00\rangle + |01\rangle + |10\rangle + e^{iU_{eff}t} |11\rangle \rightarrow |00\rangle + |01\rangle + |10\rangle - |11\rangle =$$
$$= |0\rangle (|0\rangle + |1\rangle) + |1\rangle (|0\rangle - |1\rangle)$$

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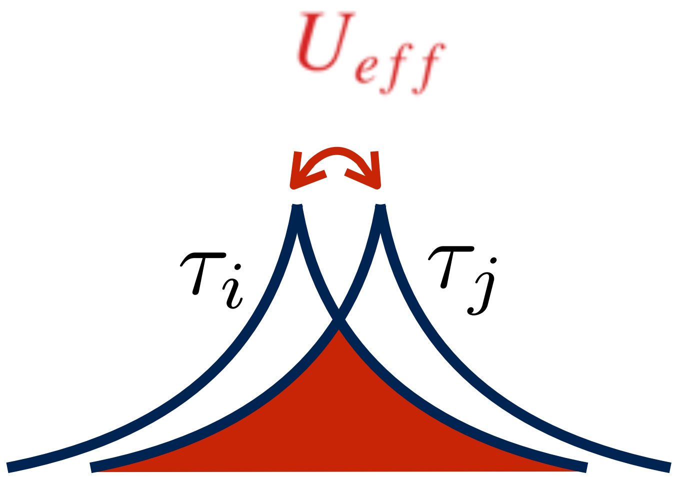

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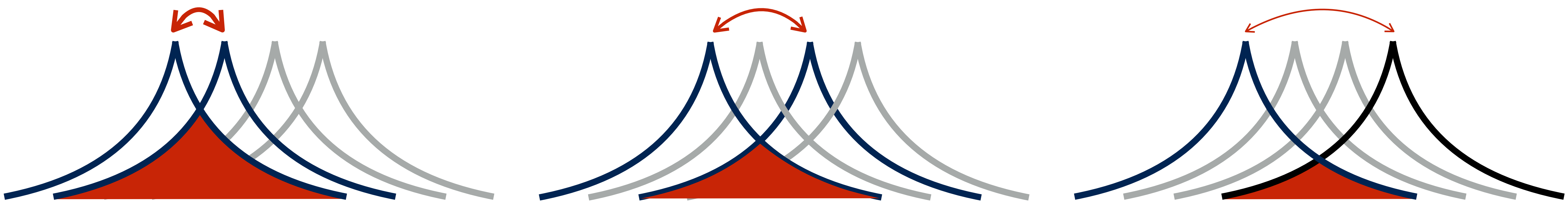
entangled state

Configurational entanglement in MBL

$$U_{eff} \sim U_o e^{-|x_i - x_j|/\xi}$$



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Configurational entanglement in MBL

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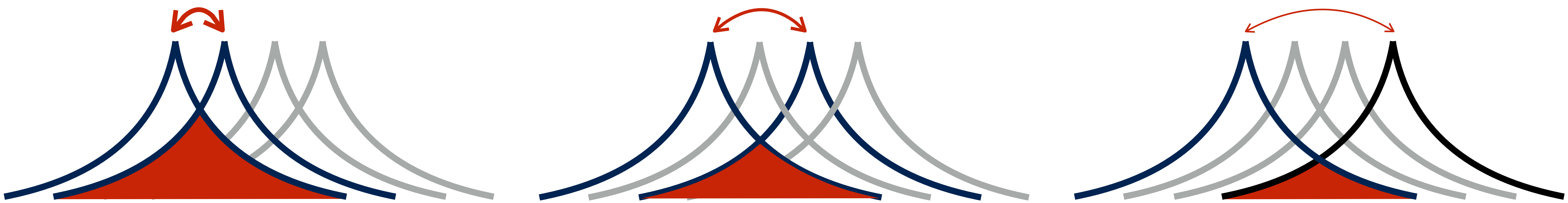
phase effects are cumulative



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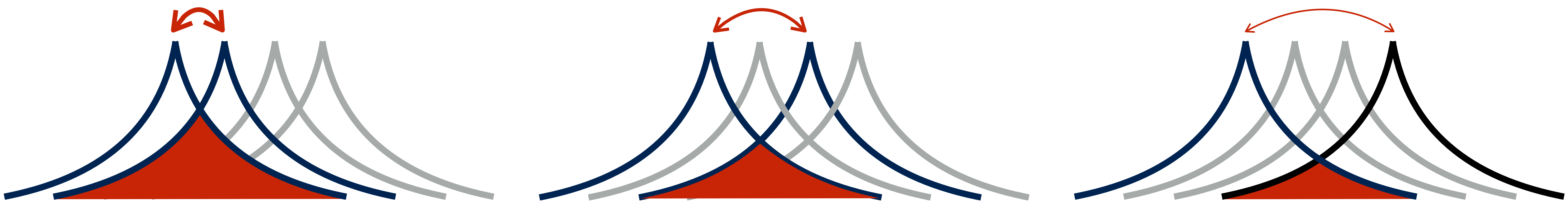

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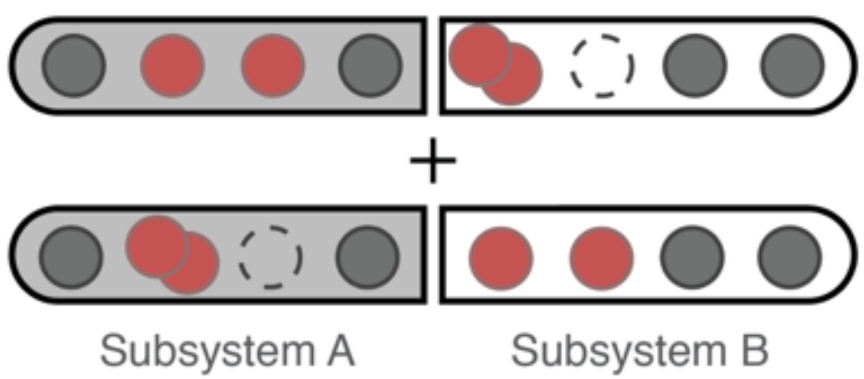
$$C = \sum_{\{A_n\},\{B_n\}} |p(A_n \otimes B_n) - p(A_n)p(B_n)|$$

Configurational entanglement



Configurational entanglement in MBL

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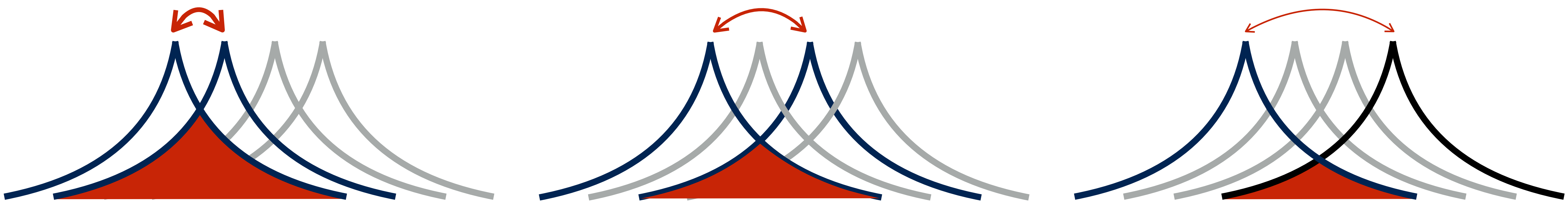

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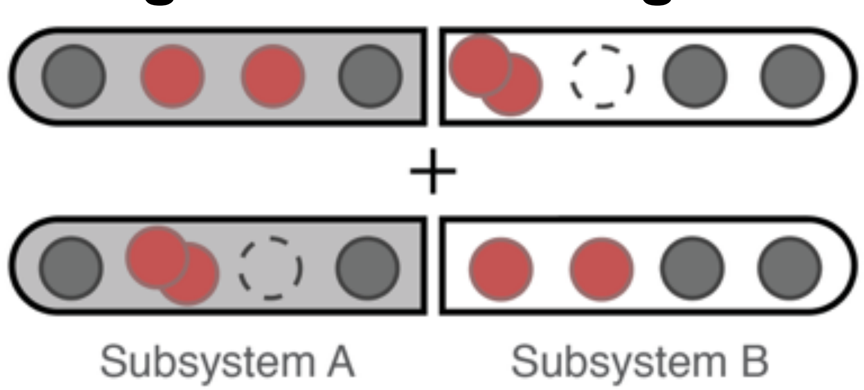
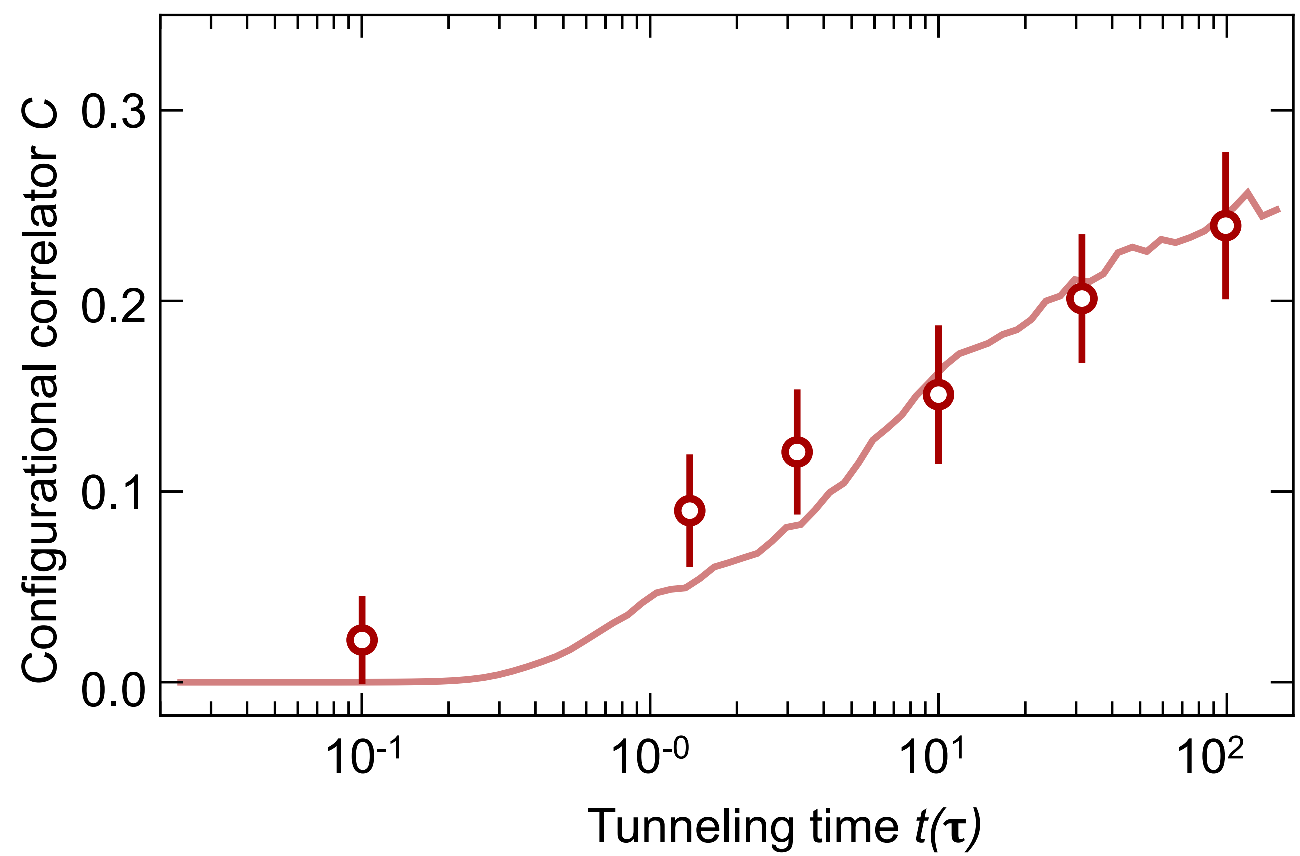
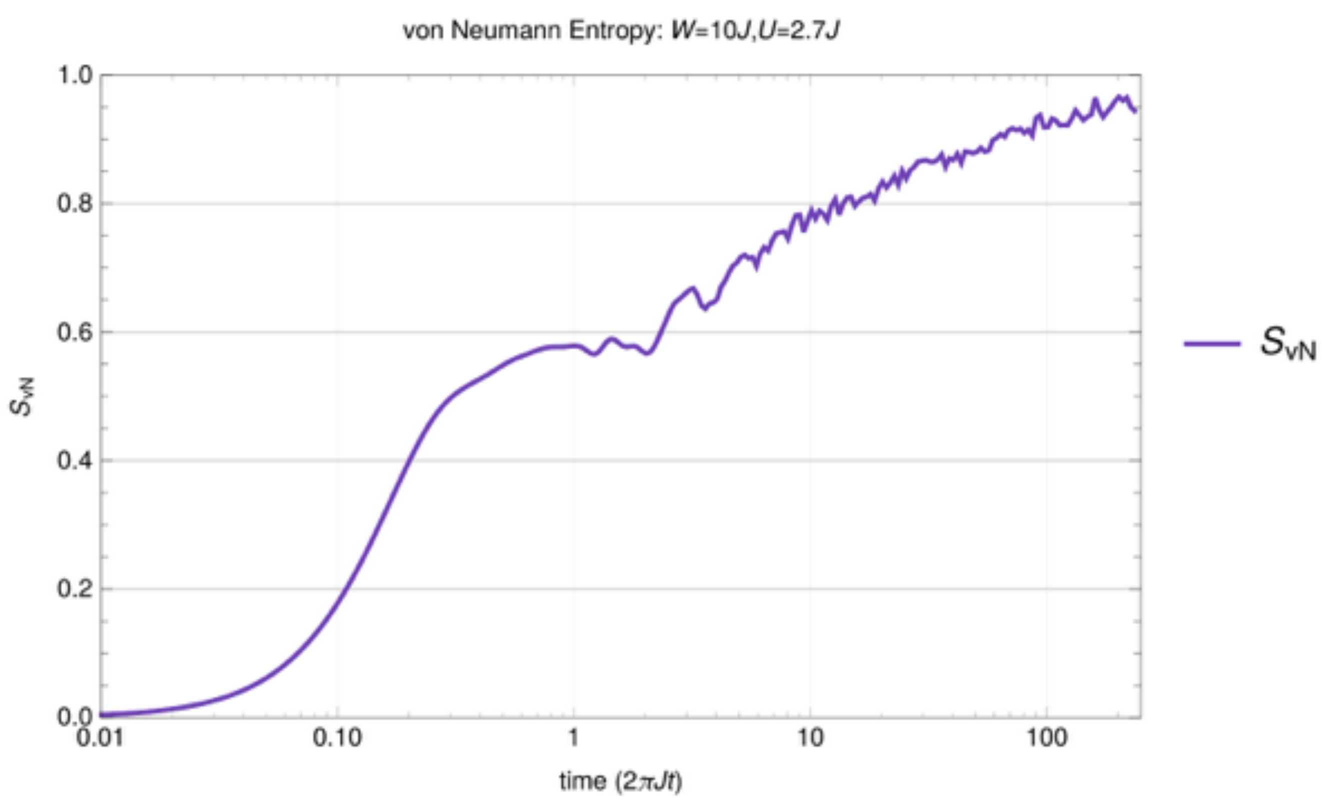




Logarithmic grows of entanglement



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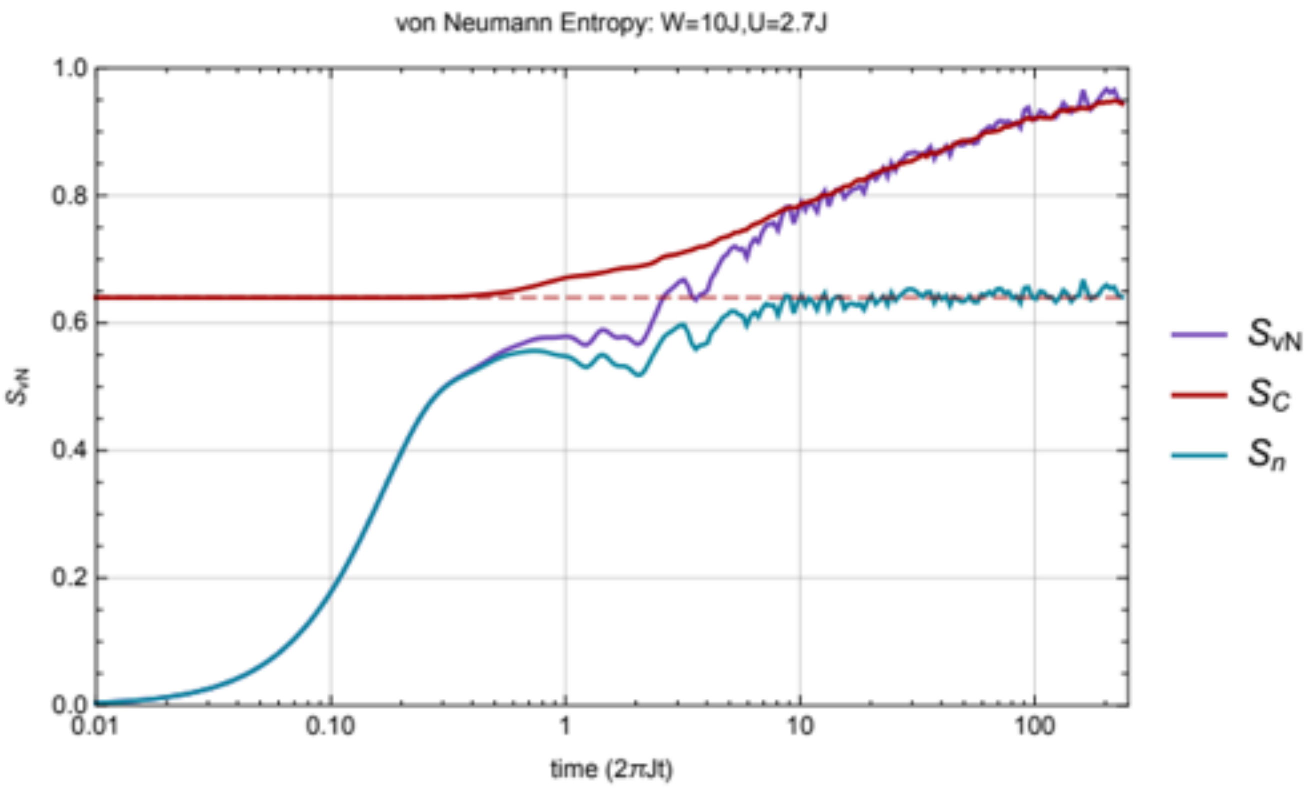
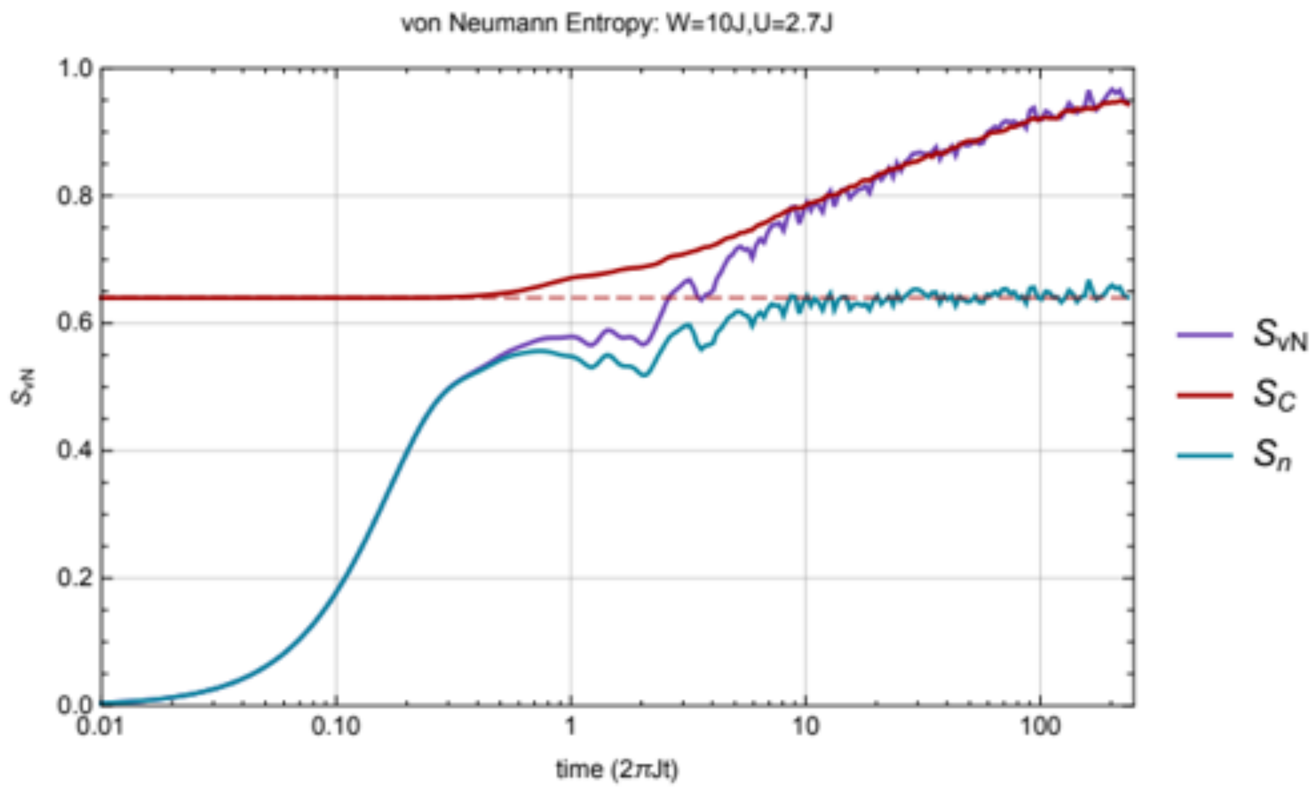
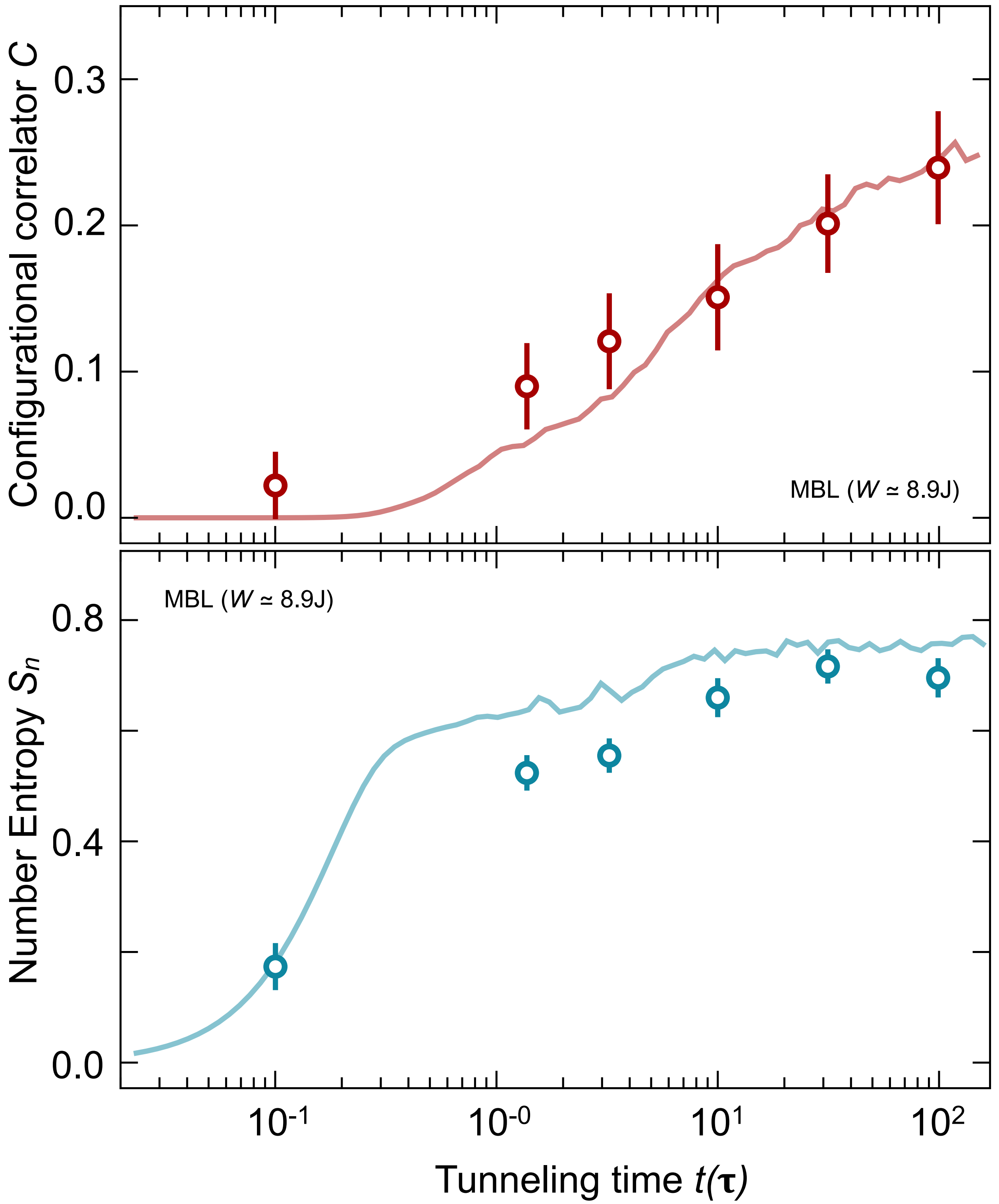


Logarithmic grows of entanglement

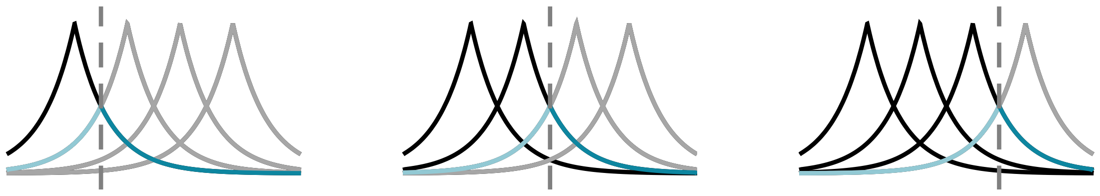




system is limited by finite evolution time, rather then size

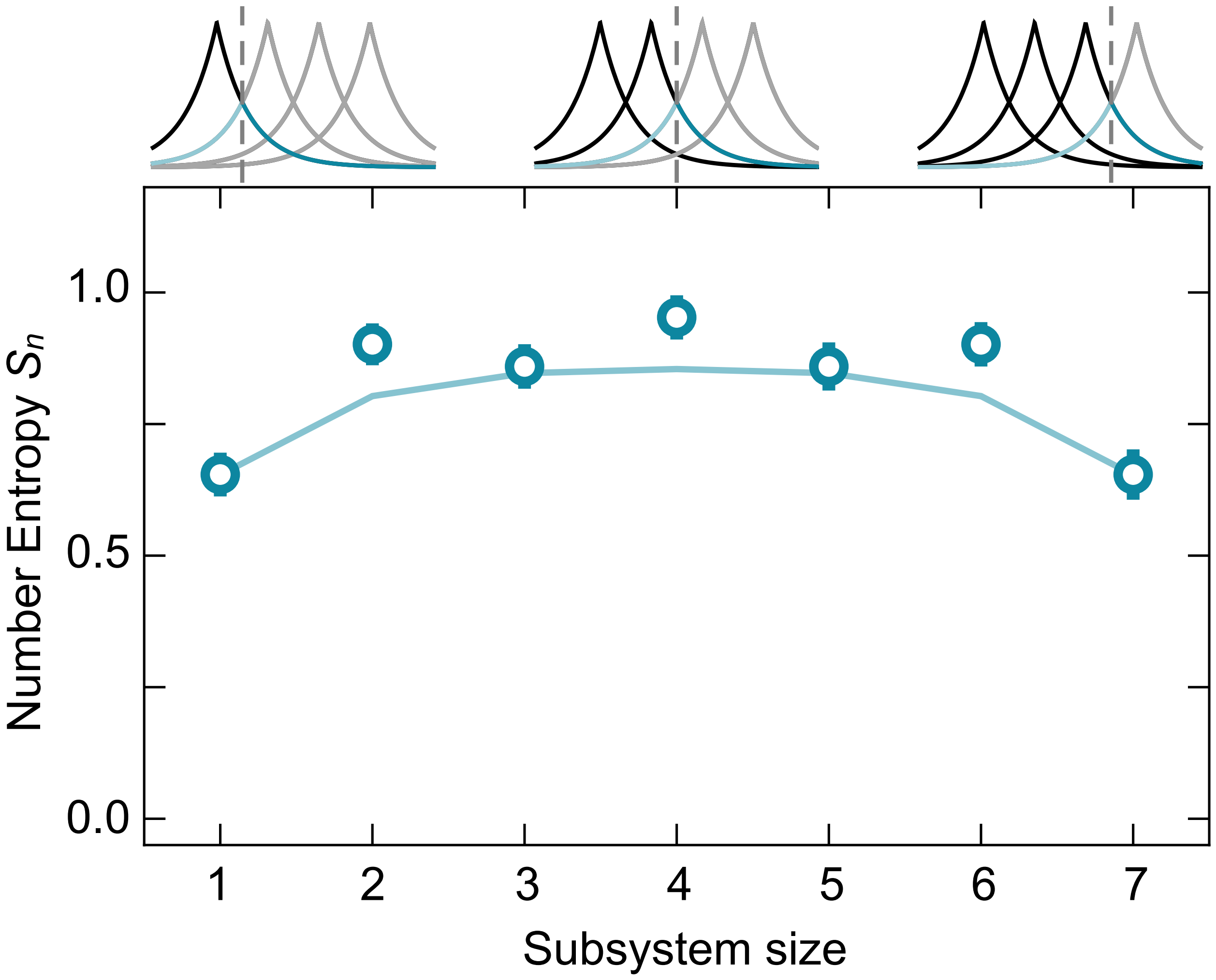
Entanglement scaling

Area law



Entanglement scaling

Area law



Entanglement scaling

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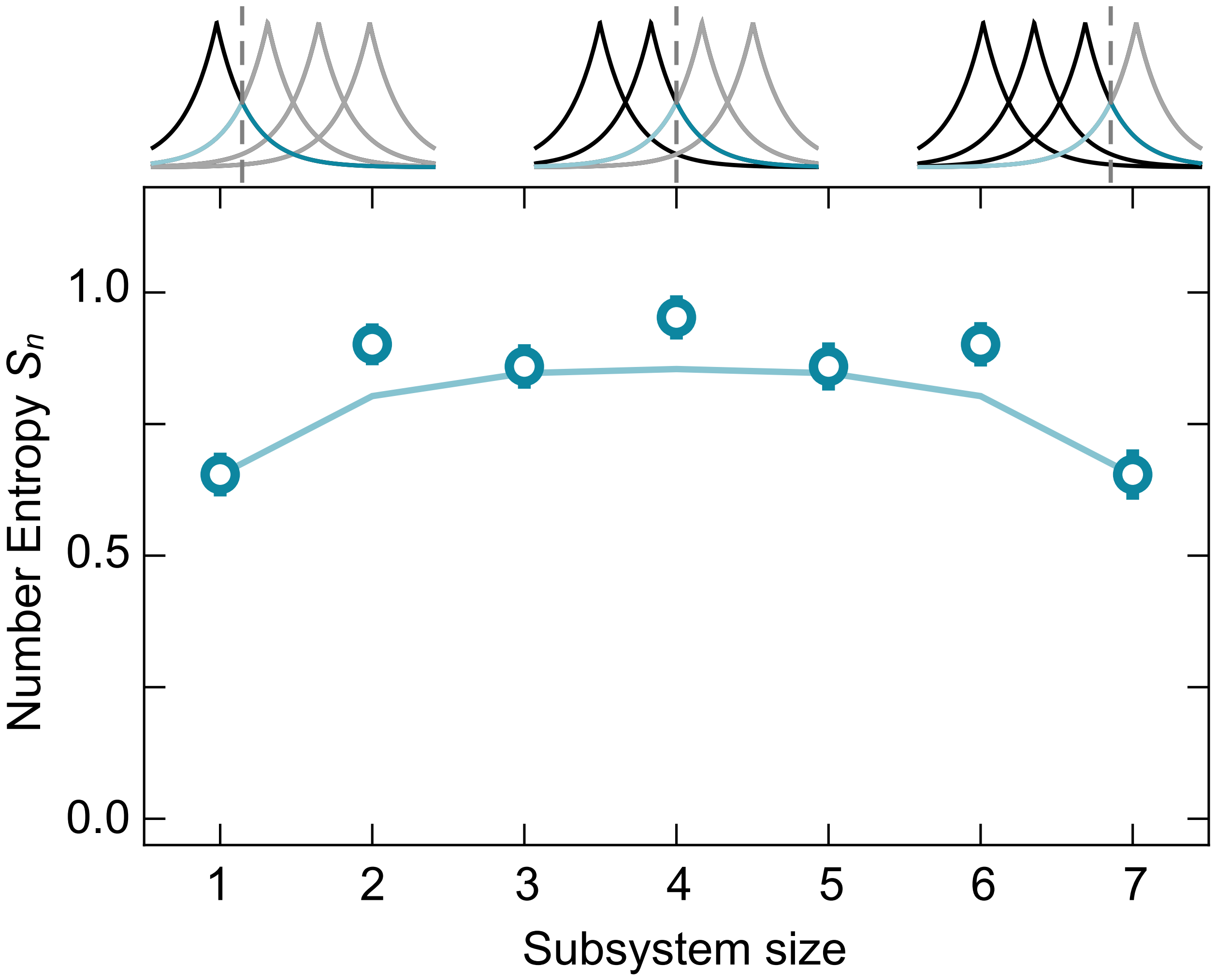
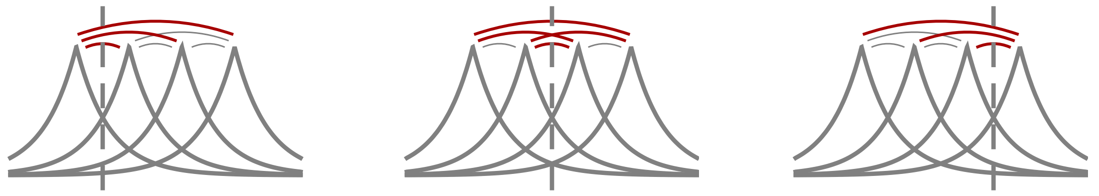
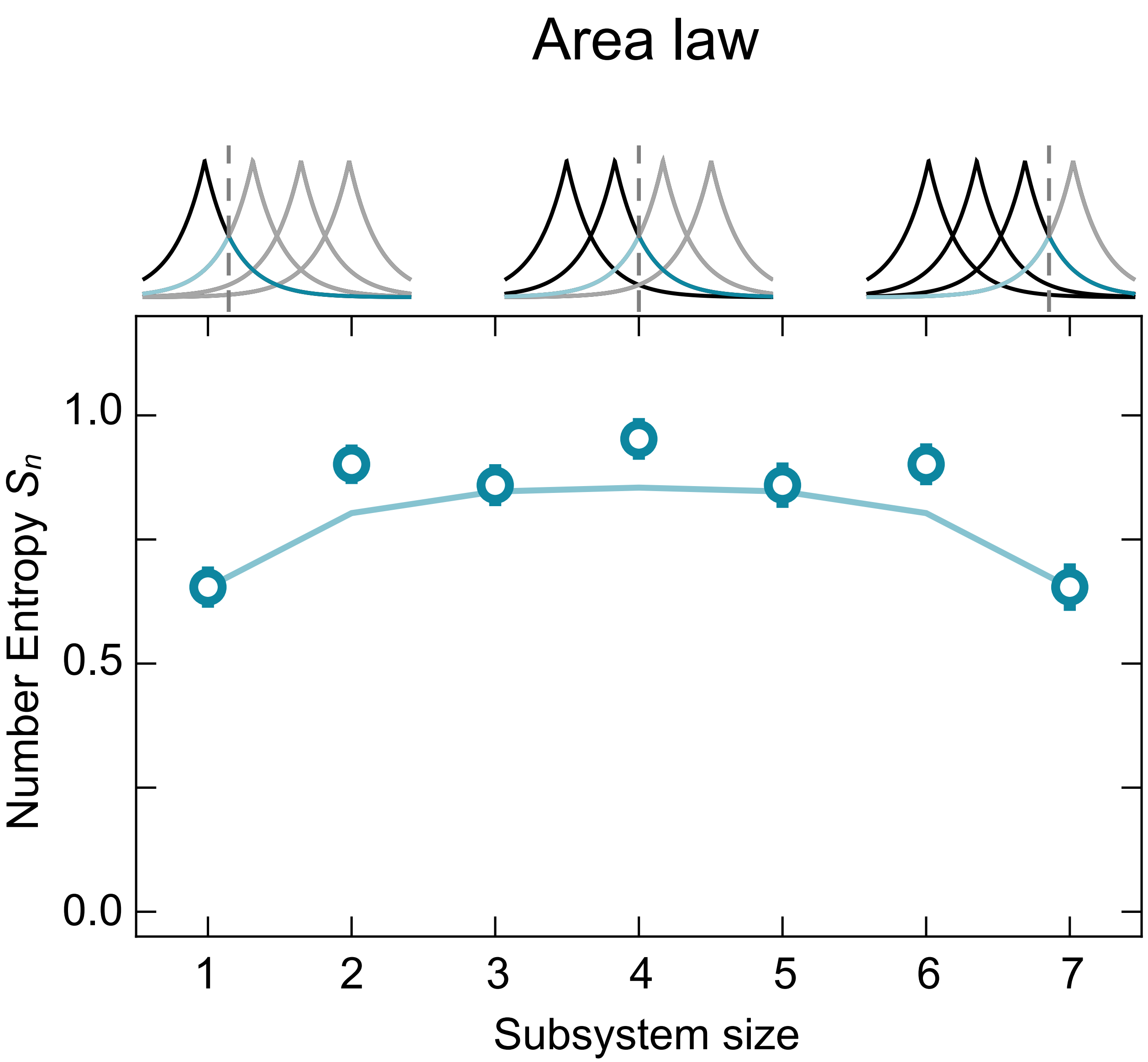
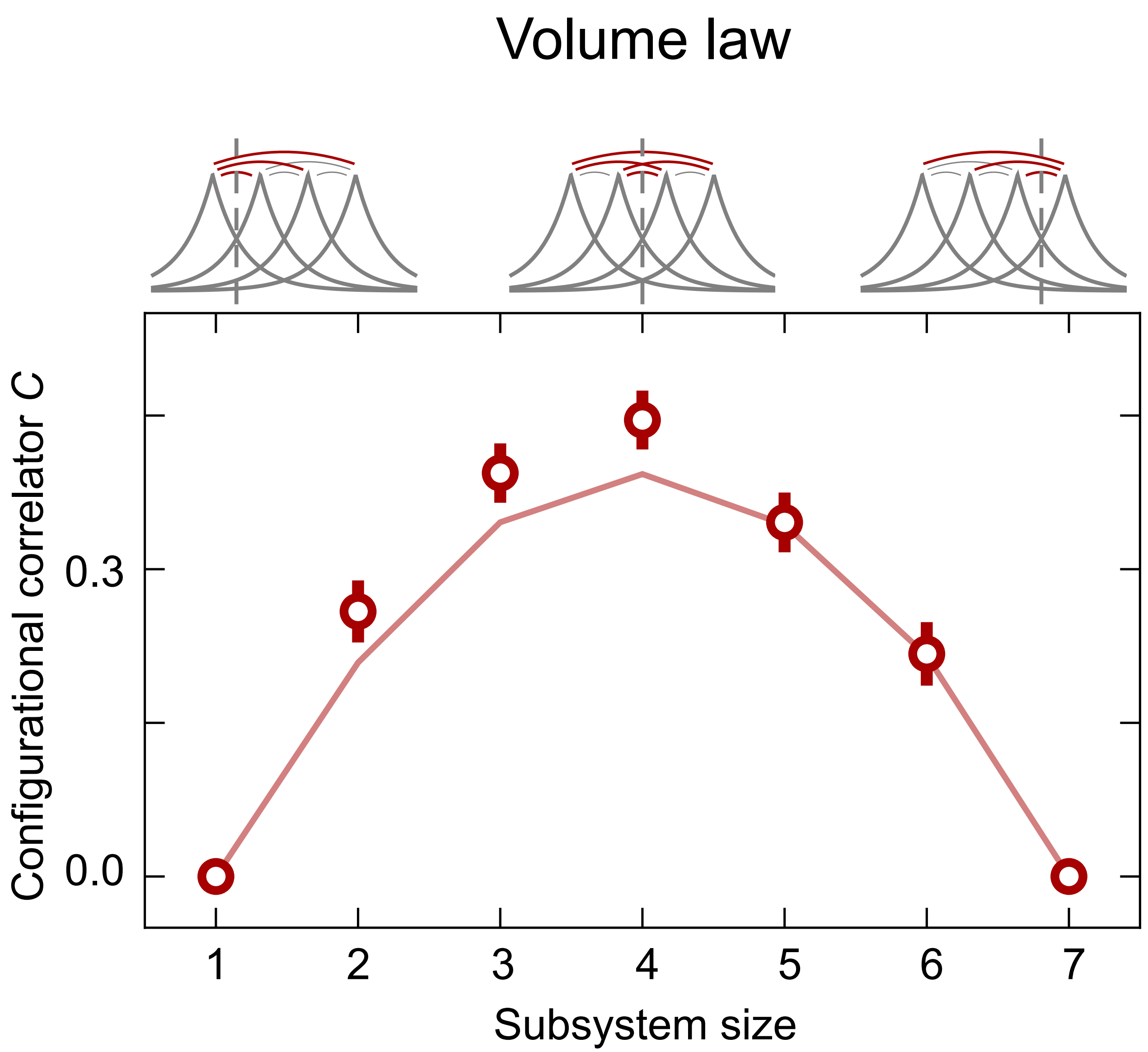


Volume law

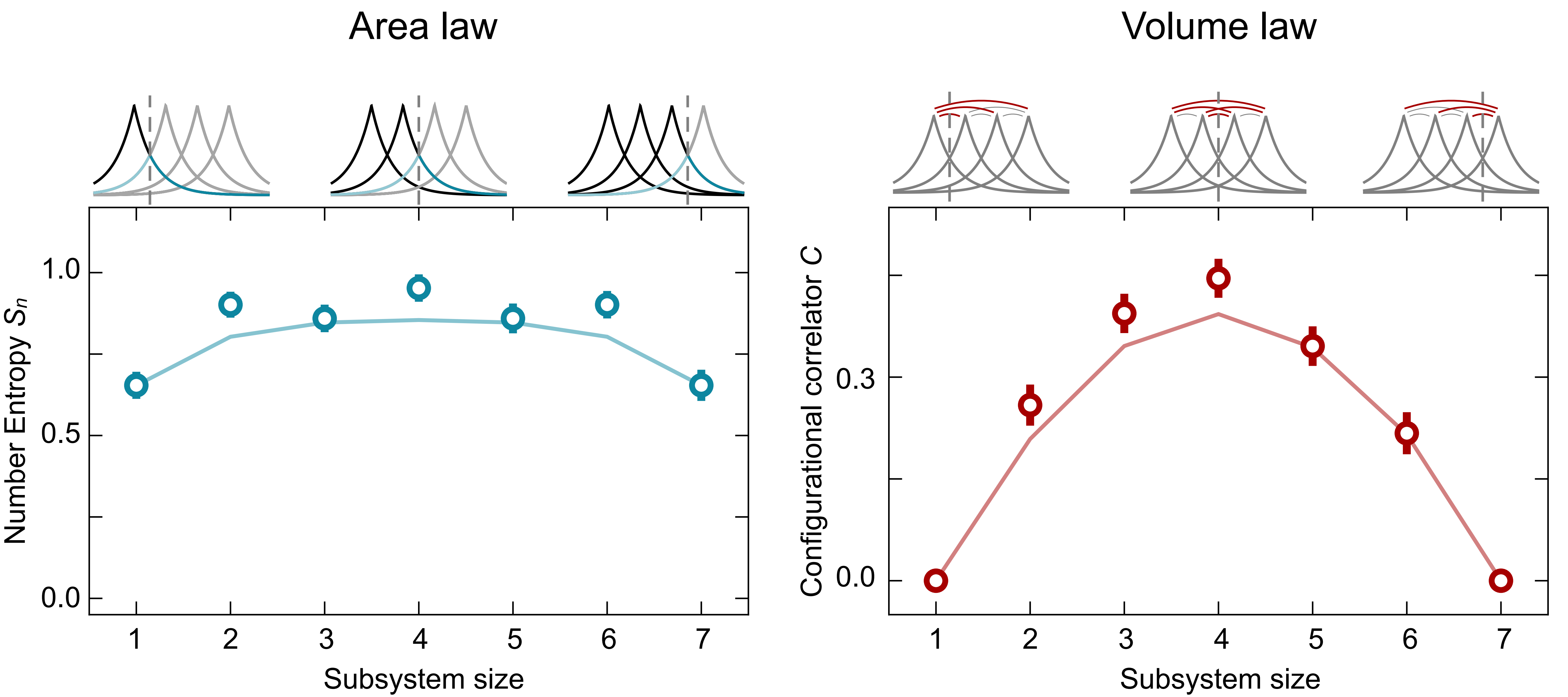


Entanglement scaling





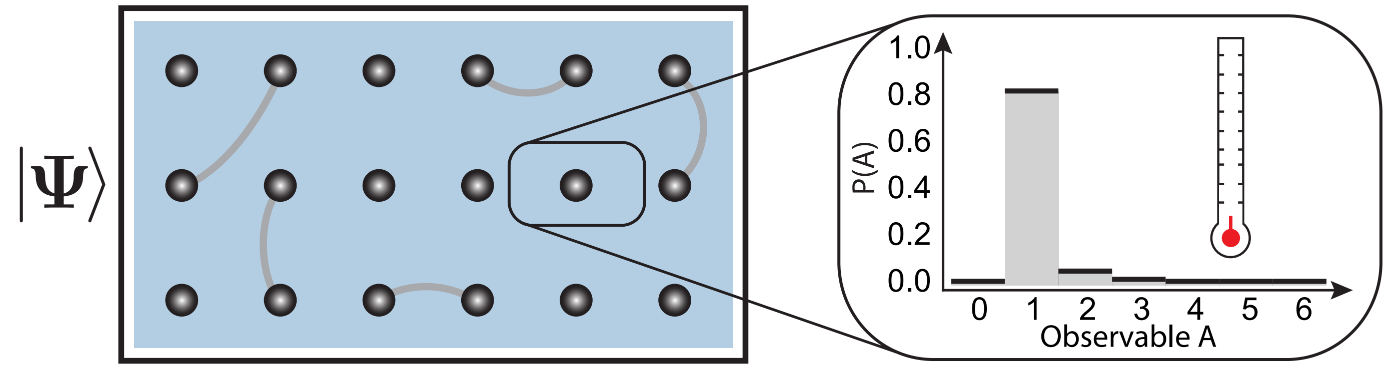
Entanglement scaling



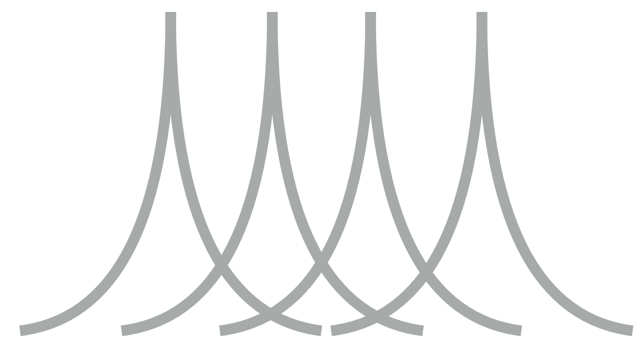
long range correlated state

Conclusions

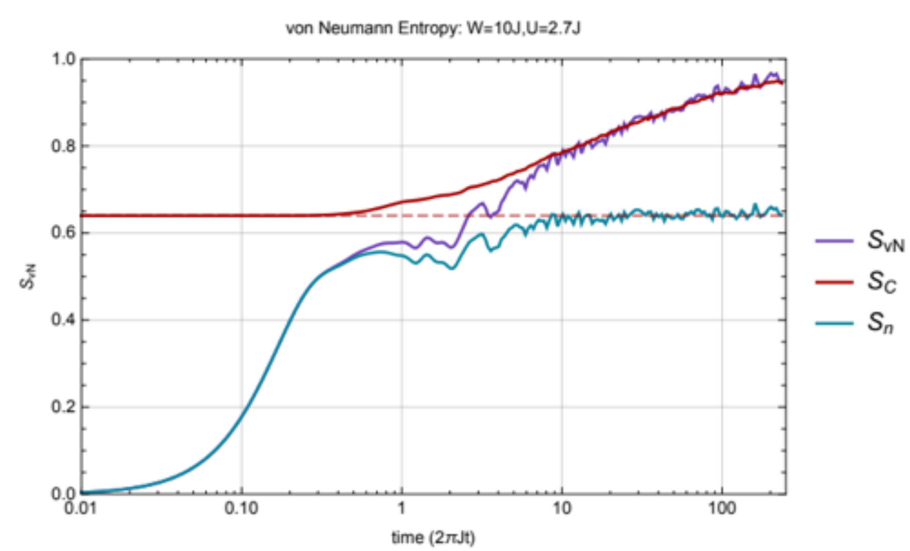
- ✓ Breakdown of thermalization



- ✓ Spatial localization



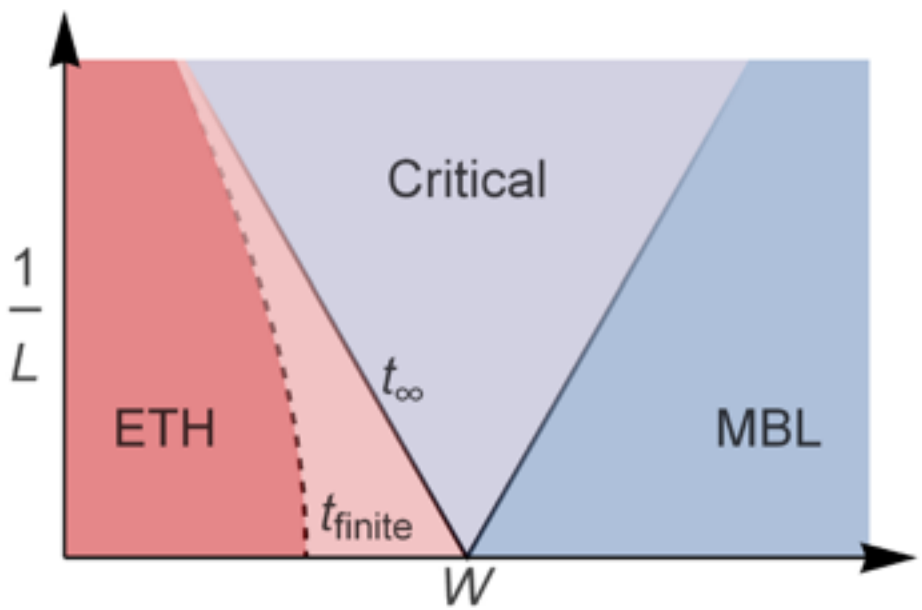
- ✓ Entanglement growth

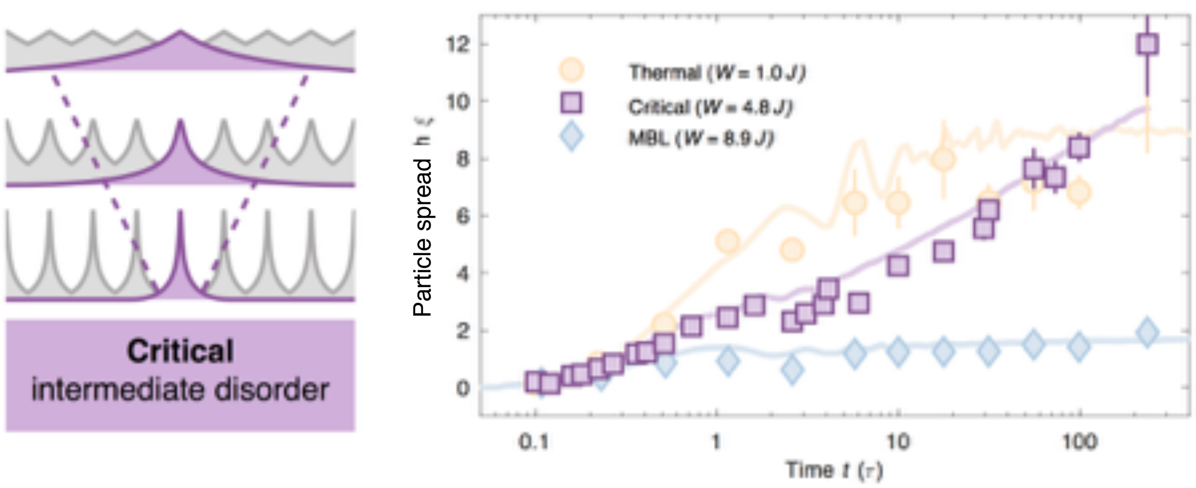


A.L., Matthew Rispoli, Robert Schittko, M. Eric Tai, Adam M. Kaufman, Soonwon Choi, Vedika Khemani, Julian Leonard, and Markus Greiner
arXiv:1805.09819

Outlook

- Study critical dynamics at the phase transition





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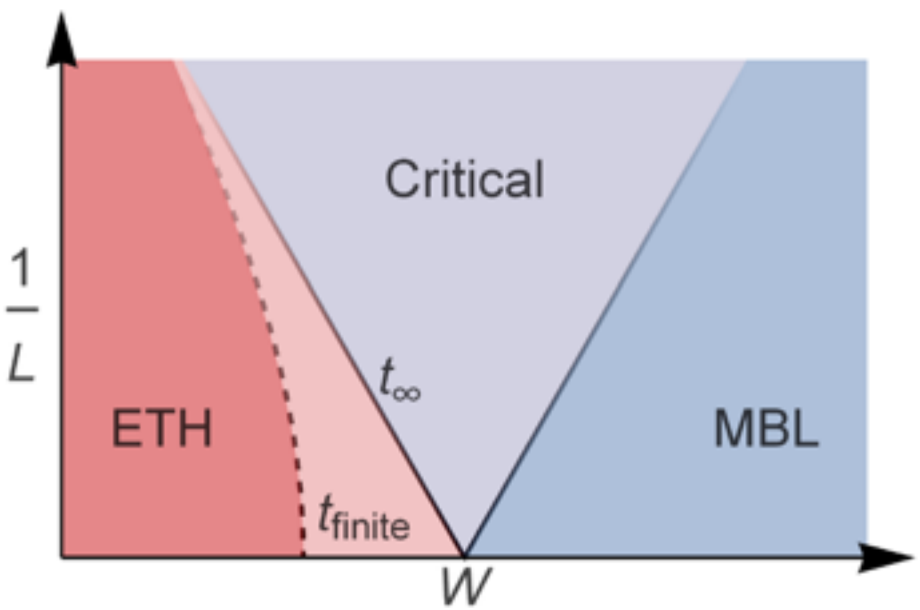
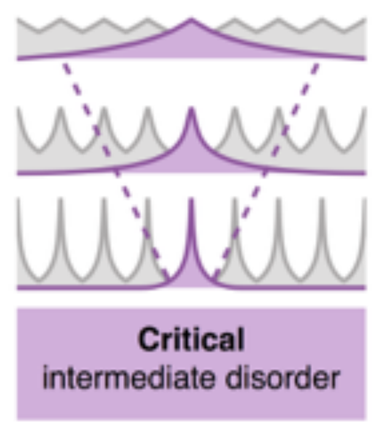
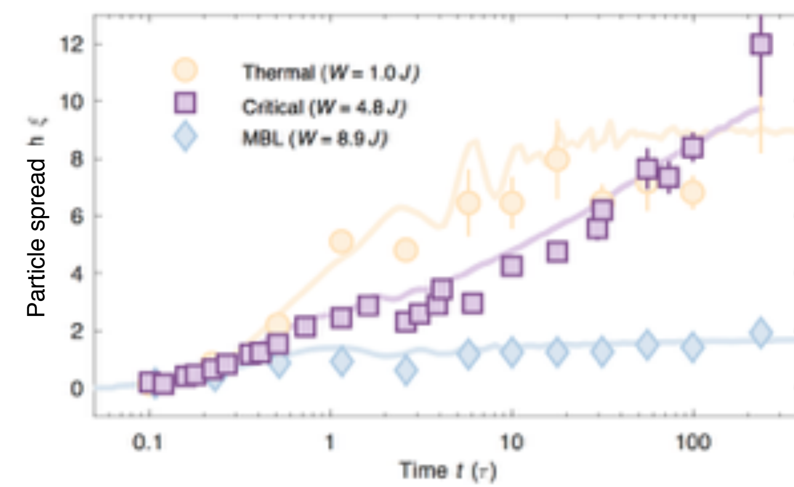
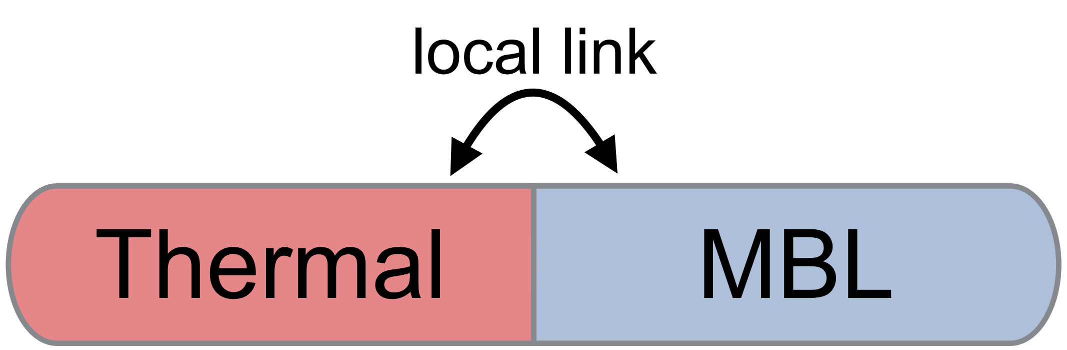
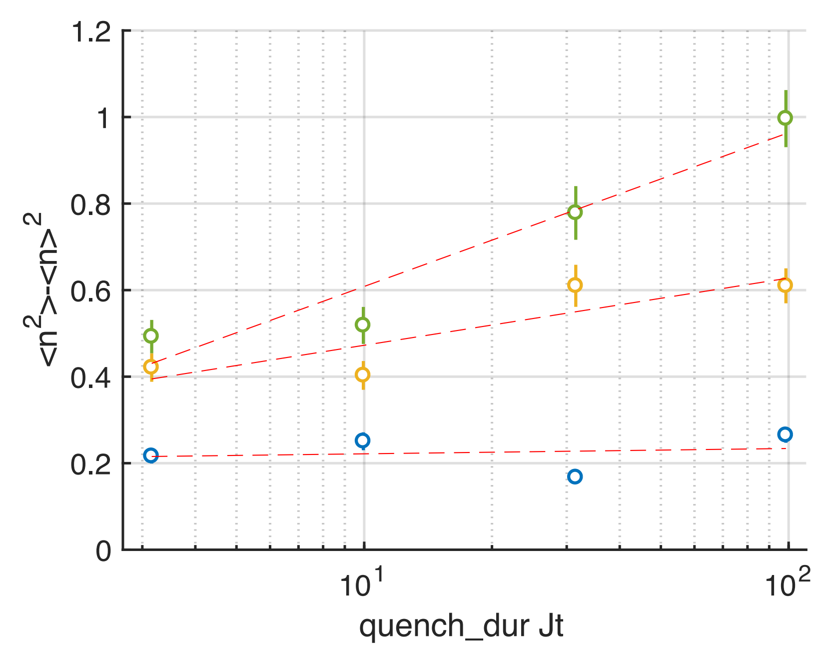




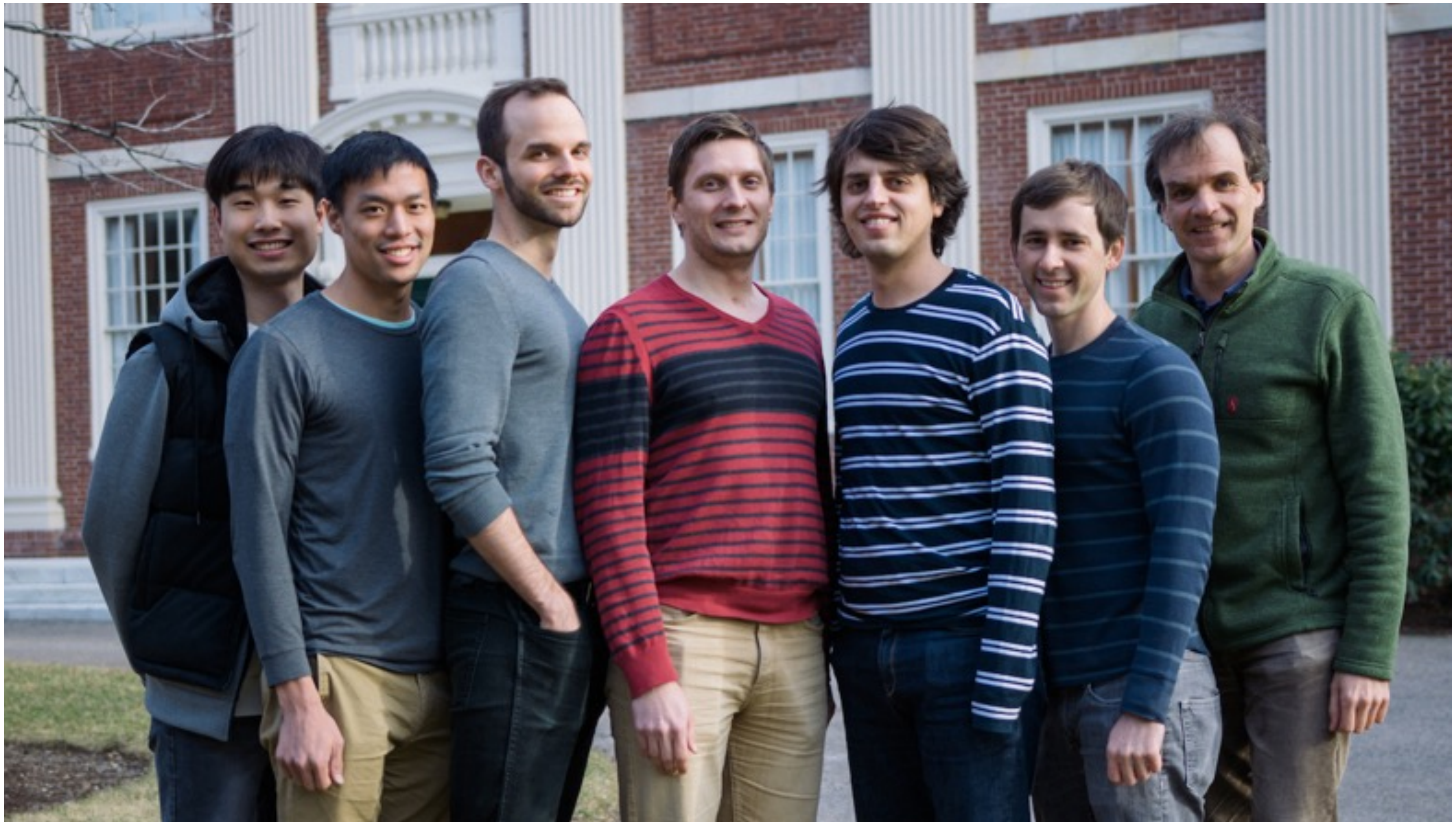


- Explore quantum thermodynamics by locally coupling MBL to a thermal region.





Thank you!



Soochin Kim | Eric Tai | Robert Schittko | A.L. | Julian Leonard | Matthew Rispoli | Markus Greiner

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GORDON AND BETTY MOORE FOUNDATION

MURI Program in Optical Lattices

DARPA

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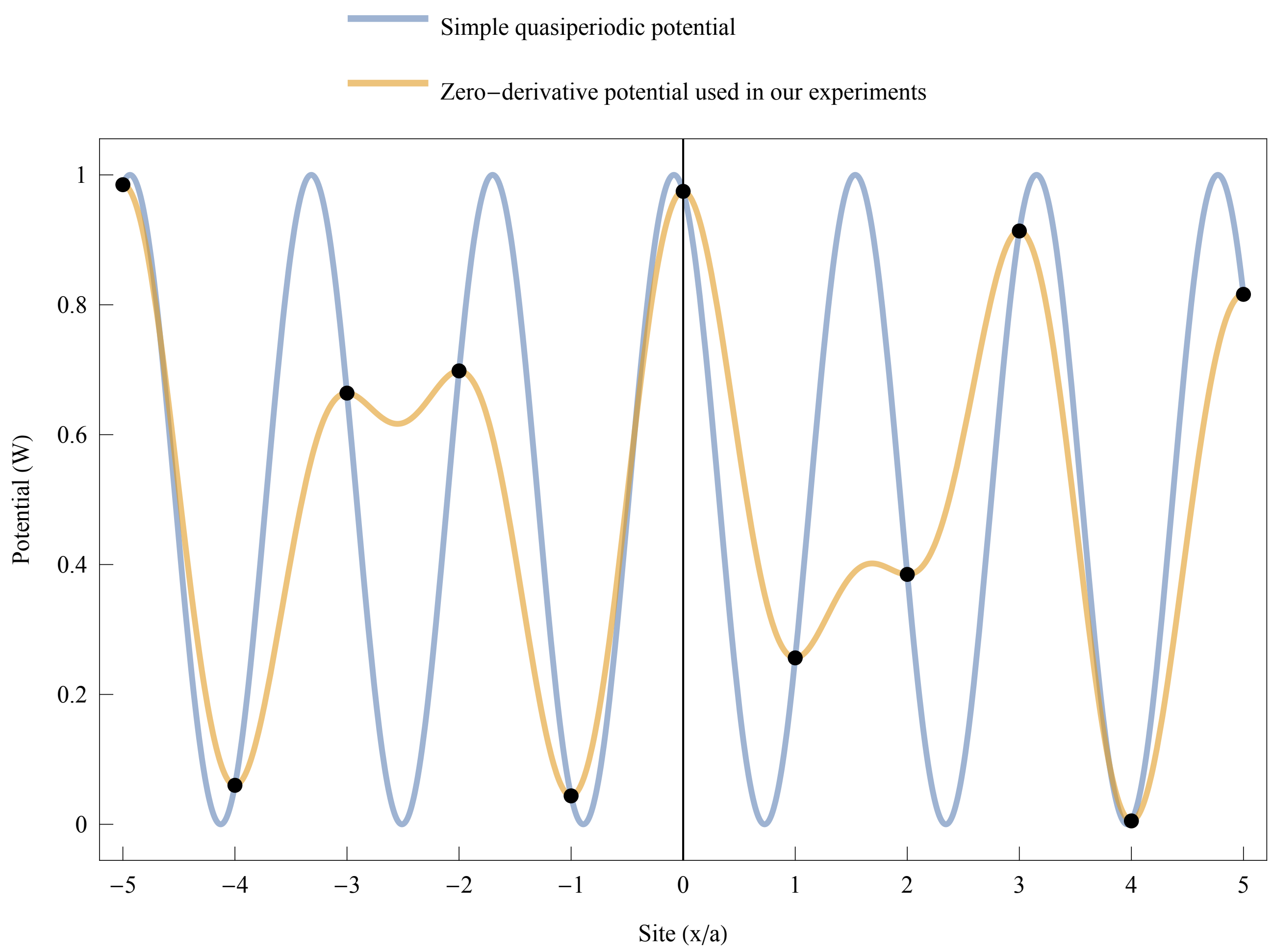
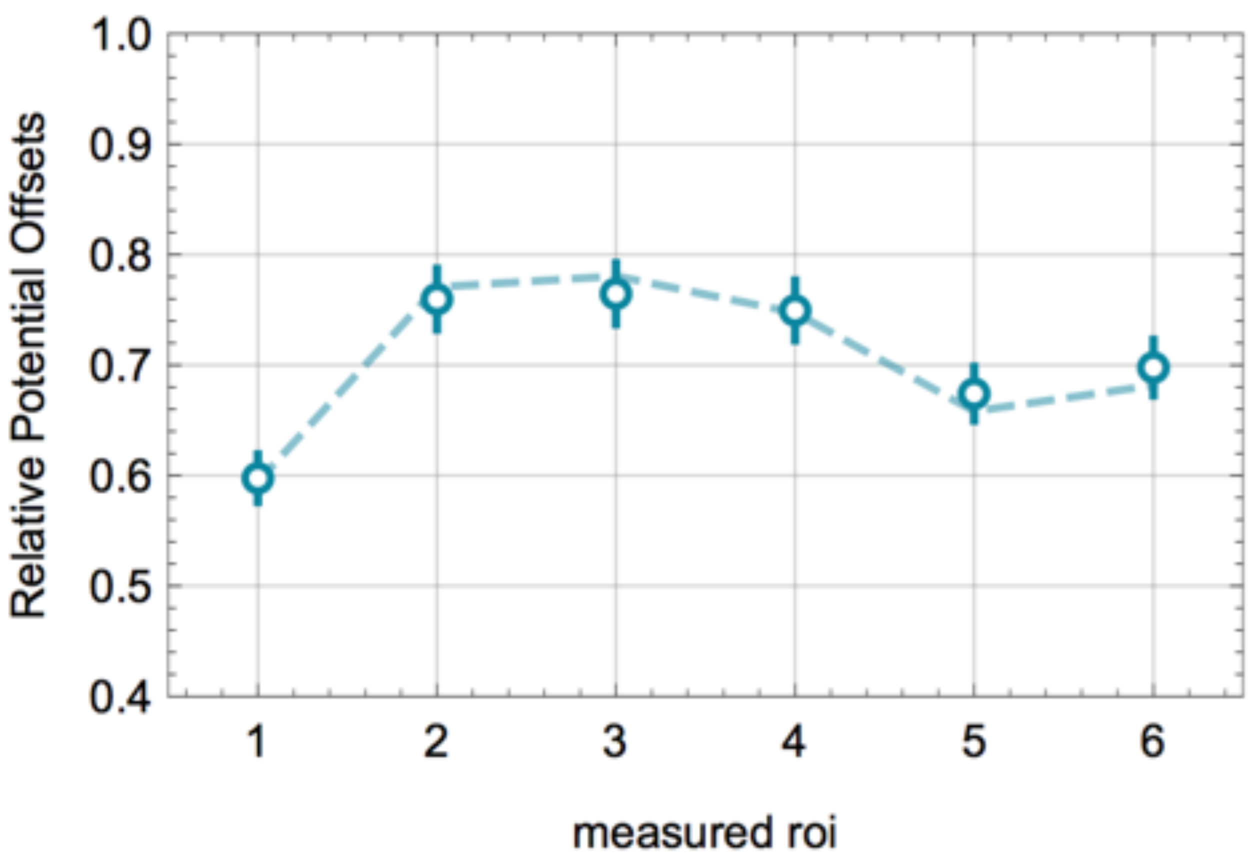
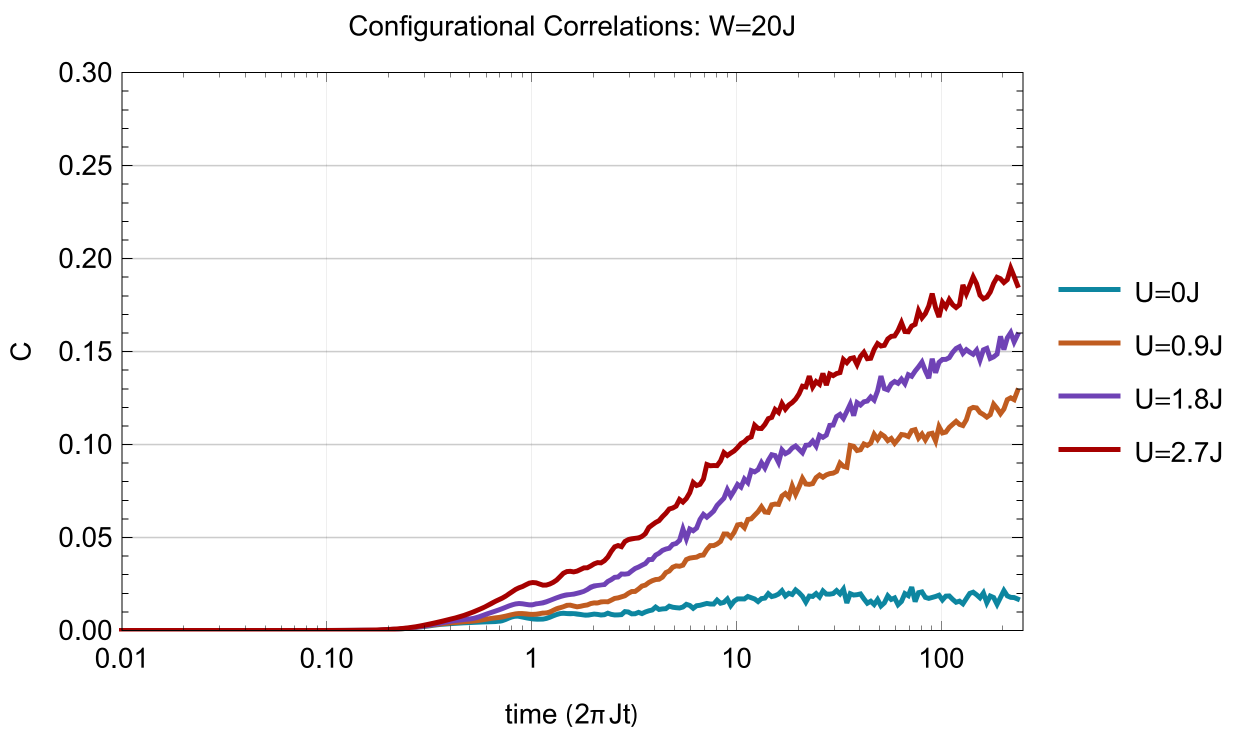
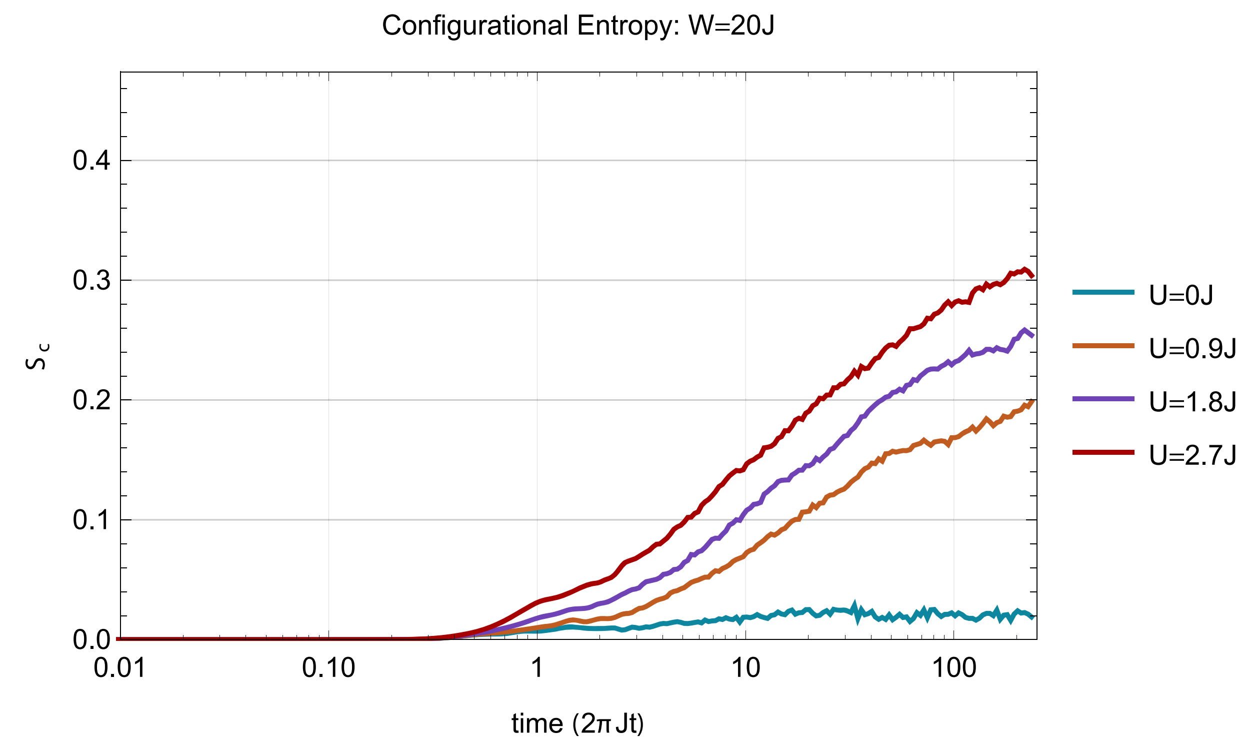
Disorder potential





Configurational entropy and correlator





Disorder potential calibration