Ergodicity breaking in kinetically constrained open quantum systems

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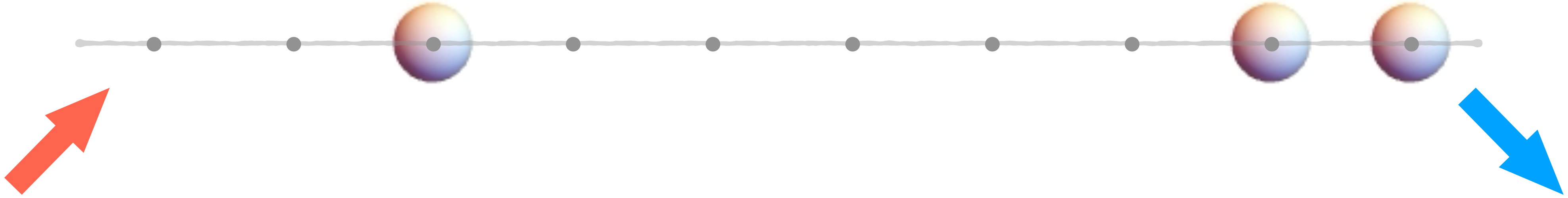

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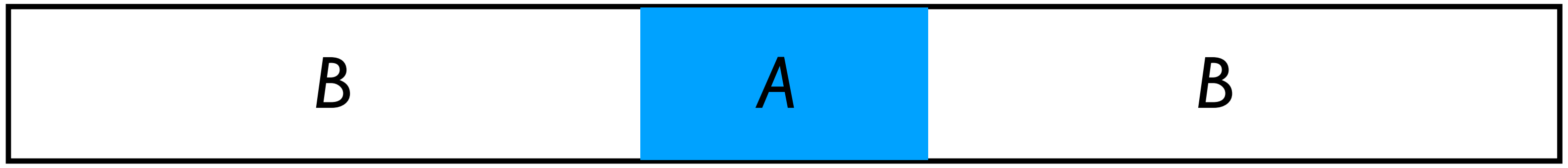
Thermalisation in isolated quantum systems



— Subsystem evolves to thermal state: $\lim_{t\to\infty} \hat{\rho}_A(t) = \mathrm{Tr}_B(\hat{\rho}^{\mathrm{eq}}) \sim e^{-\beta \hat{H}_A}$

— *B* acts as thermal bath for *A*

Ergodicity: Long-time average = microcanonical ensemble avg
(for any initial state in a small energy window)

$\Longrightarrow$ **Eigenstate Thermalisation Hypothesis** (ETH)

- Local operators are smooth functions of energy $\langle E_\alpha | \hat{O} | E_\beta \rangle \sim \delta_{\alpha,\beta} f_O(E_\alpha)$
- Level repulsion (Wigner-Dyson statistics)
- Expected to hold for generic nonintegrable systems

D'Alessio, Kafri, Polkovnikov, Rigol, Adv. Phys. 2016
Gogolin, Eisert, Rep. Prog. Phys. 2016

Ergodicity breaking in isolated quantum systems

Taxonomy:

Moudgalya, Bernevig, Regnault, Rep. Prog. Phys. 2022
Papic, arXiv 2021

	Strong/weak ETH	Entanglement	Level statistics
Ergodic	Yes/yes	Volume	Wigner–Dyson
Integrable	No/no	Volume/sub-volume	Poisson
MBL	No/no	Area	Poisson
Quantum scarred weakly fragmented	No/yes	Volume/sub-volume	Wigner–Dyson
Strongly fragmented	No/no	Volume/sub-volume	Poisson

- *Integrability*

  — extensive number of conserved quantities; No ETH (e.g. transverse Ising)

- *Many-body localisation*

  — eigenstates localised due to disorder; No ETH (e.g. disordered XXZ)

- *Quantum scars*

  — small set of initial states don't thermalise; Weak ETH (e.g. PXP)

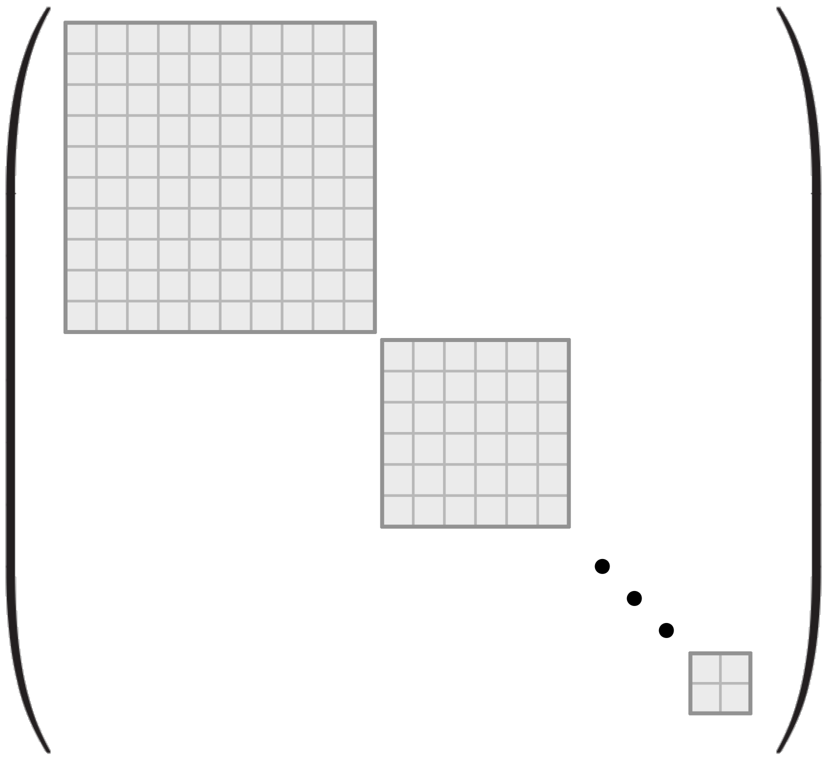
- ***Hilbert-space fragmentation***

  — different levels of ergodicity breaking in the same system

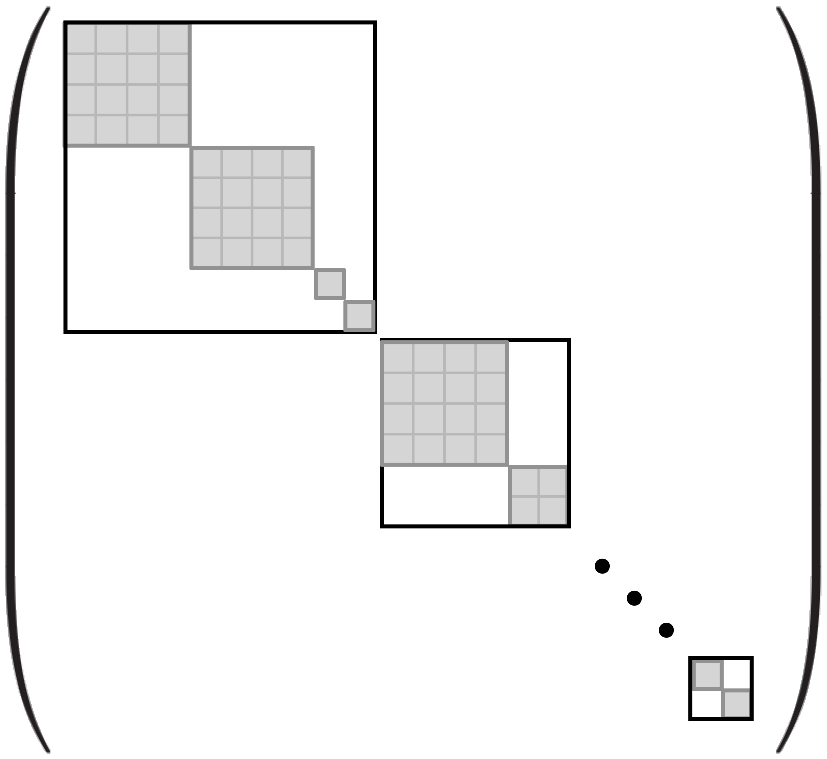
Hilbert-space fragmentation

Kinetic constraints fragment Hilbert space into exponentially many subspaces

Conventional symmetry



Fragmented Krylov subspaces



Moudgalya, Prem, Nankishore, Regnault, Bernevig, arXiv 2019
Hahn, McClarty, Luitz, SciPost 2021

Hilbert-space fragmentation

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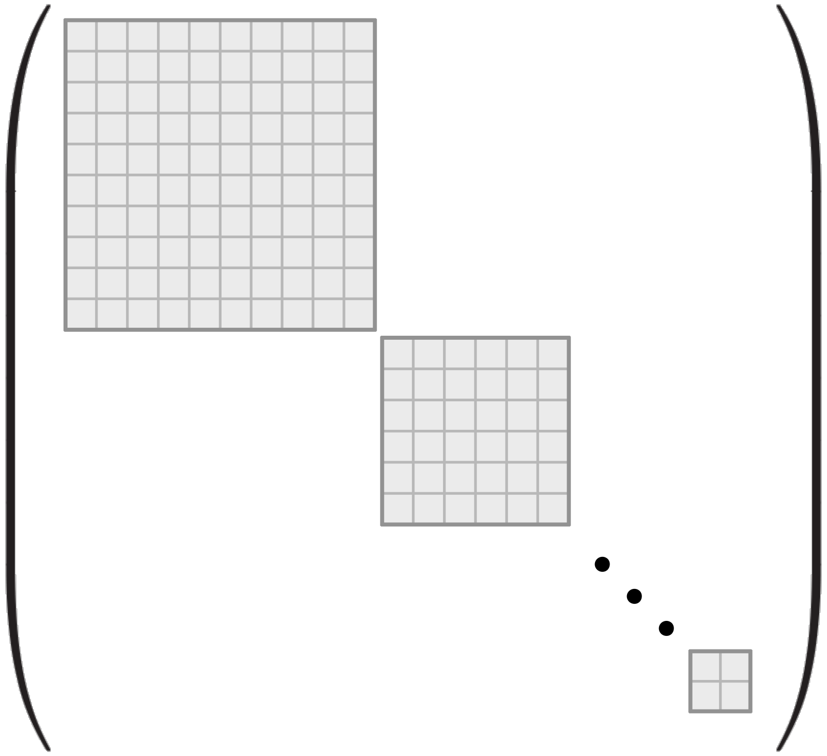
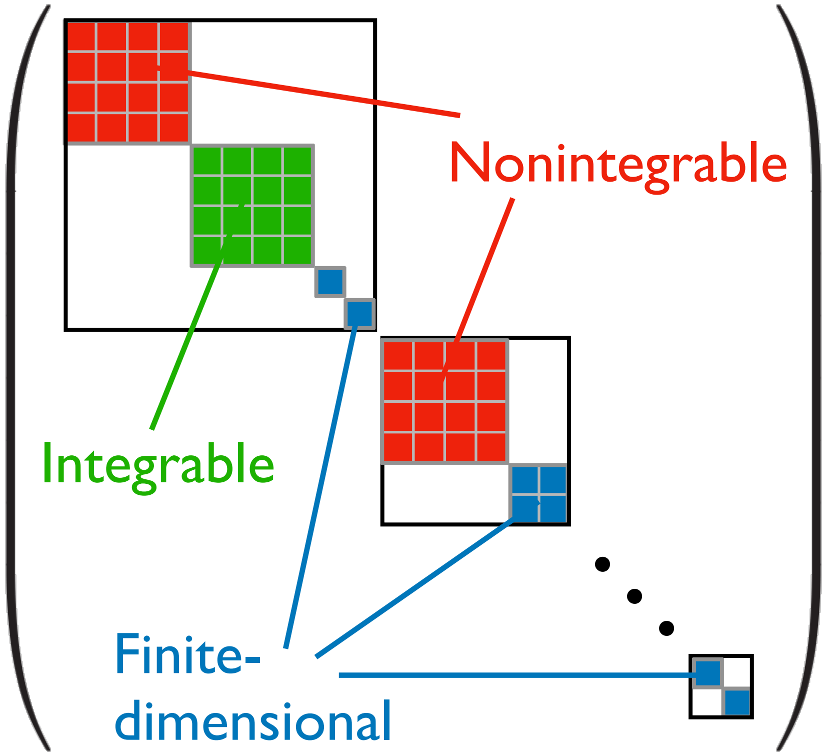


Fragmented Krylov subspaces



Dynamics within different Krylov subspaces can satisfy full / weak / no ETH!

Moudgalya, Prem, Nandkishore, Regnault, Bernevig, arXiv 2019
Hahn, McClarty, Luitz, SciPost 2021

Fragmentation in a dipole-conserving chain

$\hat{H}$ that conserves a $U(1)$ charge and its dipole moment

$$\hat{H} = \sum_{i=2}^{L-2} \left(\hat{c}_{i-1}^{\dagger}\hat{c}_{i}\,\hat{c}_{i+1}\hat{c}_{i+2}^{\dagger} + \textbf{h.c.}\right) + V(\{\hat{n}_i\})$$

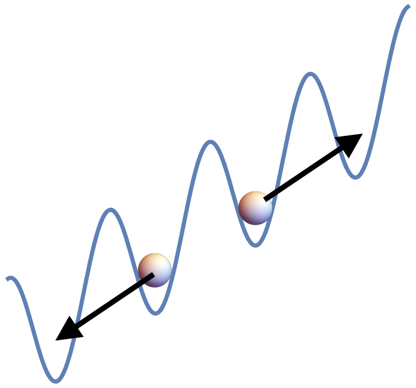
Pair-hopping model

Moudgalya *et al* '19, '22

— conserves particle number N & dipole moment $D = \sum_i i n_i$ (centre of mass)

— models (i) interacting fermions on a strongly tilted lattice

(ii) quantum Hall physics on a thin cylinder



of (N, D) sectors $\sim L^3/6$ — polynomially many

Frozen states: $\underbrace{1\;1\;1}_{\geq 3}\;\underbrace{0\;0\;0}_{\geq 3}\;1\;1\;1 \ldots 0\;0\;0$ — exponentially many

2-dimensional subspaces: $1\;1\;1\;0\;0\;0\boxed{1\;0\;0\;1}0\;0\;0 \ldots 1\;1\;1$ — exponentially many

Exponentially large integrable subspace: $\underbrace{1\;0}_{\Uparrow}\;\underbrace{0\;1}_{\Downarrow}\;\underbrace{0\;1}_{\Downarrow}\;\underbrace{1\;0}_{\Uparrow}\;\underbrace{0\;1}_{\Downarrow}\ldots\underbrace{1\;0}_{\Uparrow}$ — $\hat{H}_{XX}$

Interaction range controls fragmentation

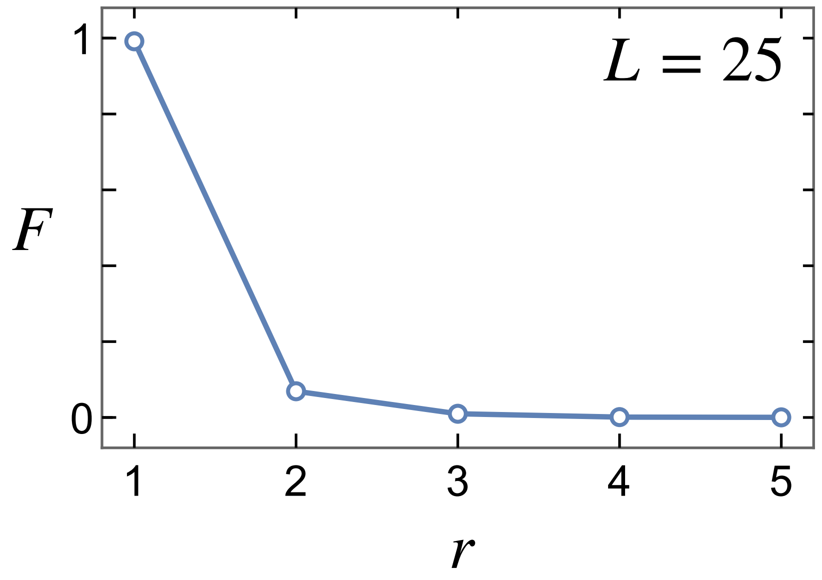
$$\hat{H} = \sum_i \sum_{j=i+1}^{i+r} \left(\hat{c}^\dagger_{i-1}\hat{c}_i\, \hat{c}_j\hat{c}^\dagger_{j+1} + \textbf{h.c.} \right) + V(\{\hat{n}_i\})$$

- Fragmented for any finite r

Exponentially many frozen states $\underbrace{1\ 1 \ldots 1}_{\geq r+2}\ \underbrace{0\ 0 \ldots 0}_{\geq r+2}\ 1\ 1 \ldots 1 \ldots$

- Degree of fragmentation falls with r

$$F = 1 - \frac{\text{max subspace dimension}}{\text{size of symmetry sector}}$$



Sala, Rakovszky, Verresen, Knap, Pollmann, PRX 2020
Khemani, Hermele, Nandkishore, PRB 2020

Interaction range controls transport

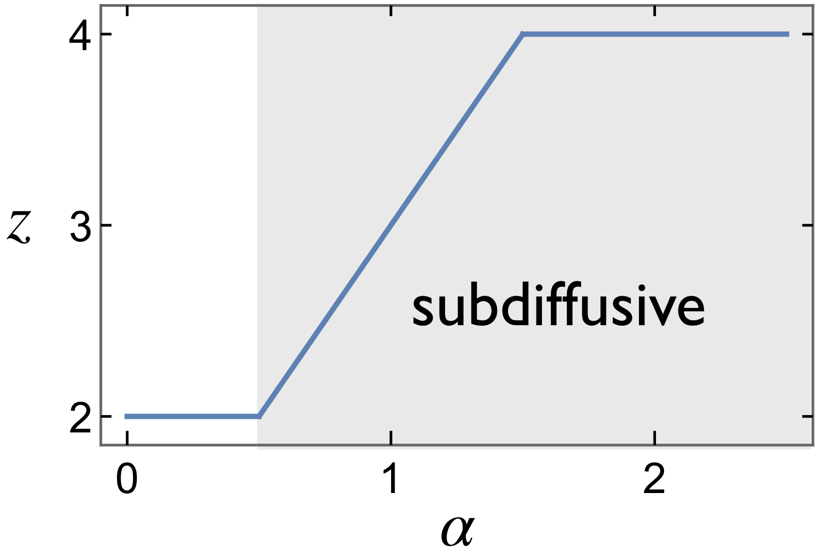
$$\hat{H} = \sum_i \sum_j \frac{J}{|i-j|^{\alpha}} \left(\hat{c}^{\dagger}_{i-1} \hat{c}_i \, \hat{c}_j \hat{c}^{\dagger}_{j+1} + \textbf{h.c.} \right) + V(\{\hat{n}_i\})$$

How long-wavelength excitations relax (to uniform infinite-temperature state)

$e^{-\gamma_k t}$, $\gamma_k \sim k^z$ for small k z : dynamical exponent

$\alpha \to \infty$: charge & dipole locally conserved $\Longrightarrow$ subdiffusion w/ $z = 4$

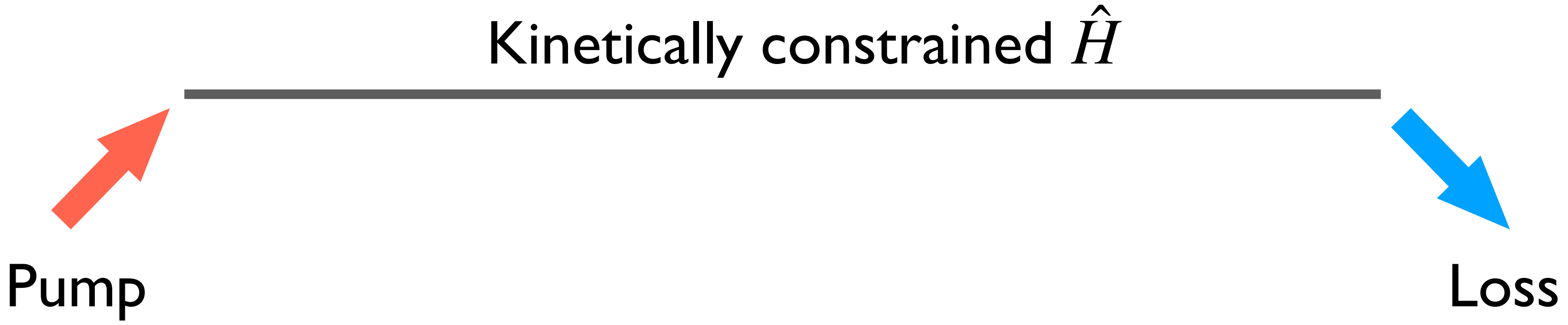
$\alpha \to 0$: only charge locally conserved $\Longrightarrow$ diffusion ($z = 2$)



Morningstar, O'Dea, Richter, PRB 2023

Gliozzi, May-Mann, Hughes, De Tomasi, arXiv 2023

Our setup



Kinetically constrained $\hat{H}$

Pump

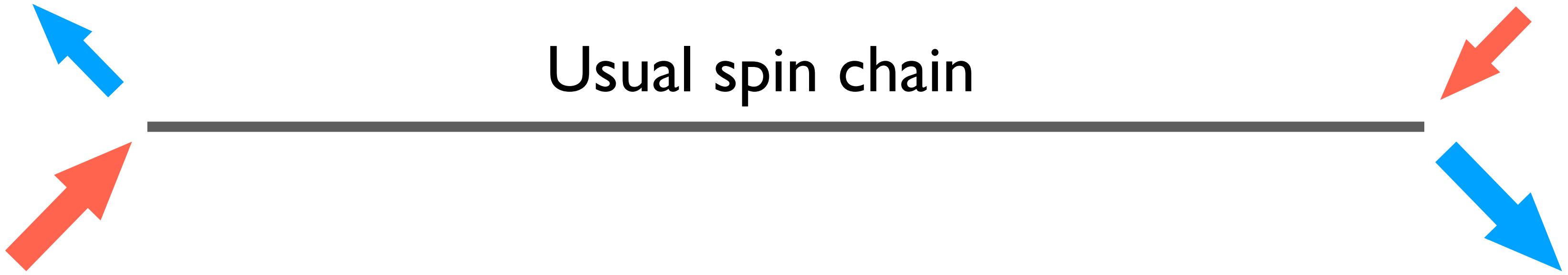
Loss

Can we drive a current?

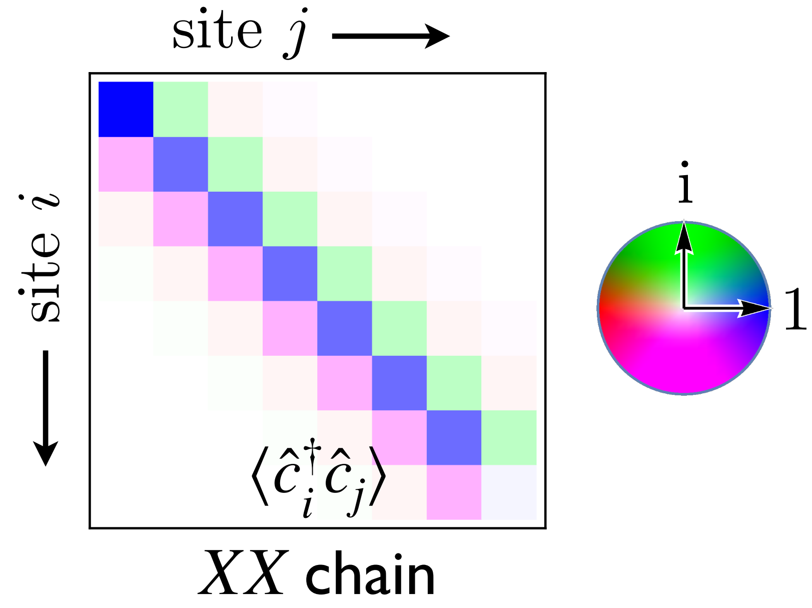
What is the structure of the steady states?

Does fragmentation survive?

Boundary-driven spin chains



Typically: Unique current-carrying steady state



Large body of literature:

- Dissipative phase transitions
- Ballistic, diffusive, anomalous transport
- Exact matrix-product state solutions

⋮

Landi, Poletti, Schaller, RMP 2022
Prosen, Pižorn, PRL 2008
Žnidarič, PRL 2011
Prosen, PRL 2011
Purkayastha, Dhar, Kulkarni, PRB 2017

Steady state(s) of (Markovian) dissipative systems

- Generically, steady state is unique
  $\{\hat{H}, \hat{L}_1, \hat{L}_2, \dots\}$ generate the entire algebra of operators ("ergodic") Evans, 1977

- *Strong symmetry* $\Longrightarrow$ Multiple mixed steady states
  $[\hat{S}, \hat{H}] = [\hat{S}, \hat{L}_j] = 0$ — each symmetry sector has at least 1 steady state
  Buča, Prosen, NJP 2012
  Albert, Jiang, PRA 2014

- *Decoherence-free subspace (DFS)*
  Eigenstates of $\hat{H}$ that are unaffected by dissipation: $\hat{L}_j |E_k\rangle = 0 \;\; \forall j$
  DFS: $\{\,|E_k\rangle, k = 1,2,\dots\Lambda\}$ — evolves unitarily Λ : DFS dimension
  Lidar, Chuang, Whaley, PRL 1998

- *Noiseless subsystem*
  Eigenstates of the form $|\alpha_i\rangle_A \otimes |\beta_j\rangle_B$ where dissipation acts only on A
  $\Longrightarrow$ steady states: $\hat{\rho}_A \otimes |\beta_j\rangle\langle\beta_k|$ Knill, Laflamme, Viola, PRL 2000

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- Memory of initial state, quantum memory, passive error correction Lidar, Brun, 2013

Back to our setup

$$\hat{H} = \sum_{i<j} J_{i,j}\big(\hat{c}^\dagger_{i-1}\hat{c}_i\,\hat{c}_j\hat{c}^\dagger_{j+1} + \textbf{h.c.}\big) + V(\{\hat{n}_i\})$$

Two limits:

- All $J_{i,j}$ are nonzero $\Longrightarrow$ No fragmentation

  All Fock states with a given (N, D) are connected by $\hat{H}$

- $J_{i,j} \neq 0$ only if $j = i + 1$ (pair-hopping model) $\Longrightarrow$ Strongly fragmented

Two types of boundary drive:

- Pump & loss at opposite ends
- Pump & loss at both ends

Note: pump/loss does NOT preserve N or D

Case I A.

Unfragmented (but dipole-conserving) $\hat{H}$

$+$

Pump-loss at *opposite* ends

Case I A. *Unfragmented* + pump-loss at *opposite* ends

Minimal model

$$\begin{tikzcd}
\hat{H} = \sum_{i,j} \hat{c}^{\dagger}_{i-1}\hat{c}_i \, \hat{c}_j \hat{c}^{\dagger}_{j+1} \arrow[d, leftrightarrow] & \hat{L}_1 = \hat{c}^{\dagger}_1 \arrow[d, leftrightarrow] & \hat{L}_2 = \hat{c}_L \arrow[d, leftrightarrow] \\
\hat{H} = \sum_{i,j} \hat{S}^{+}_{i-1}\hat{S}^{-}_i \, \hat{S}^{-}_j \hat{S}^{+}_{j+1} & \hat{L}_1 = \hat{S}^{+}_1 & \hat{L}_2 = \hat{S}^{-}_L
\end{tikzcd}$$

$0\ 0\ 0\ 0\ 0\ 0\ldots0 \longrightarrow 1\ 0\ 0\ 0\ 0\ 0\ldots0$

$1\ 1\ 1\ 1\ 1\ 1\ldots1 \longrightarrow 1\ 1\ 1\ 1\ 1\ldots1\ 0$

$1\ 1\ 0\ 0\ 0\ 0\ldots0$ Frozen

$1\ 1\ 1\ 0\ 0\ 0\ldots0$ Frozen

$\Longrightarrow \underbrace{1\ 1\ldots1}_{\geq 1}\ \underbrace{0\ 0\ldots0}_{\geq 1}$ $(L-1)$ frozen states with 1 domain wall

Any superposition also frozen! e.g. $|1\ 1\ 0\ 0\ 0\ 0\rangle + |1\ 1\ 1\ 1\ 0\ 0\rangle$ (entangled)

Case I A. *Unfragmented* + pump-loss at *opposite* ends

Other frozen states? $1\ 0\ 1\ 0\ 0\ 0 \ldots 0$ ✓

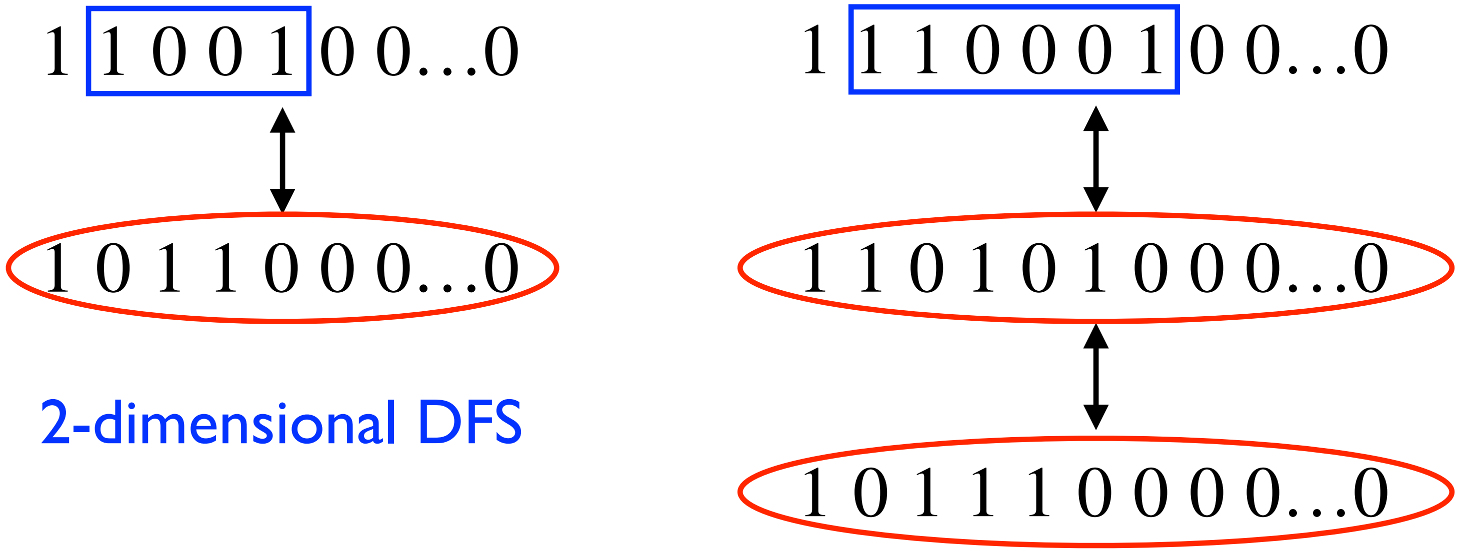
$1\ 1\ 0\ 1\ 0\ 0 \ldots 0$ ✓

$$\Longrightarrow \underbrace{1\ 1 \ldots 1}_{\geq 1} \boxed{0\ 1} \underbrace{0\ 0 \ldots 0}_{\geq 1} \qquad (L-3) \text{ frozen states}$$

How about $1\ 0\ 1\ 0\ 1\ 0\ 0 \ldots 0 \longleftrightarrow 0\ 1\ 1\ 1\ 0\ 0\ 0 \ldots 0 \longrightarrow 1\ 1\ 1\ 1\ 0\ 0\ 0 \ldots 0$

×

× $1\ 0\ 0\ 1\ 0\ 0 \ldots 0 \longleftrightarrow 0\ 1\ 1\ 0\ 0\ 0 \ldots 0 \longrightarrow 1\ 1\ 1\ 0\ 0\ 0 \ldots 0$



$$\begin{tikzcd} 1\ \boxed{1\ 0\ 0\ 1}\ 0\ 0 \ldots 0 \arrow[d, leftrightarrow] \\ 1\ 0\ 1\ 1\ 0\ 0\ 0 \ldots 0 \end{tikzcd} \qquad \begin{tikzcd} 1\ \boxed{1\ 1\ 0\ 0\ 0\ 1}\ 0\ 0 \ldots 0 \arrow[d, leftrightarrow] \\ 1\ 1\ 0\ 1\ 0\ 1\ 0\ 0\ 0 \ldots 0 \arrow[d, leftrightarrow] \\ 1\ 0\ 1\ 1\ 1\ 0\ 0\ 0\ 0 \ldots 0 \end{tikzcd}$$

2-dimensional DFS

3-dimensional DFS

Other states w/ same (N, D)

Case I A. *Unfragmented* + pump-loss at *opposite* ends

Root configurations

Active block

$$\underbrace{1\;1\ldots1}_{\geq 1}\;\underbrace{1\;1\ldots1}_{n-1}\;\underbrace{0\;0\ldots0}_{n}\;1\;\underbrace{0\;0\ldots0}_{\geq 1} \qquad\qquad n \geq 0$$

Frozen wings

Couples to other configurations with the same (N, D)

How large is the DFS?

$$\underbrace{x_1 + x_2 + \ldots + x_n}_{\text{positions of } 1\text{'s}} = \frac{n(n-1)}{2} + 2n \qquad 1 \leq x_1 < x_2 < \ldots < x_n \leq 2n$$

$$y_i := x_i - i \implies \quad y_1 + y_2 + \ldots + y_n = n \qquad 0 \leq y_1 \leq y_2 \leq \ldots \leq y_n \leq n$$

$\implies$ DFS size $=$ Number of integer partitions of $n \;\equiv p(n)$!

Ramanujan: $p(n) \sim \dfrac{1}{4n\sqrt{3}} \exp\left(\pi\sqrt{2n/3}\right) \qquad n \leq L/2 - 1$

Case I A. *Unfragmented* + pump-loss at *opposite* ends

Root configurations

Active block

$$\underbrace{1\;1\ldots1}_{\geq 1}\;\underbrace{1\;1\ldots1}_{n-1}\;\underbrace{0\;0\ldots0}_{n}\;1\;\underbrace{0\;0\ldots0}_{\geq 1} \qquad n \geq 0$$

Frozen wings

DFS labeled by (N, n) or equivalently (N, D)

$$N = 1, 2, \ldots, L-1$$

$$n = 0, 1, \ldots, \min(N-1,\, L-N-1)$$

Number of disjoint DFSs $\sim L^2/4$

Total number of (N, D) sectors $\sim L^3/6$

$\Longrightarrow$ Only $O(1/L)$ of the sectors become DFSs

DFS size $\Lambda_{N,n} = p(n)$

$\Longrightarrow$ Total number of decoherence-free states $= \sum_{N,n} \Lambda_{N,n} \sim \exp\left(\pi\sqrt{L/3}\right)$

No net flow in steady state!

Case I B.

Unfragmented (but dipole-conserving) $\hat{H}$

$+$

Pump-loss at *both* ends

Case I B. *Unfragmented* + pump-loss at *both* ends

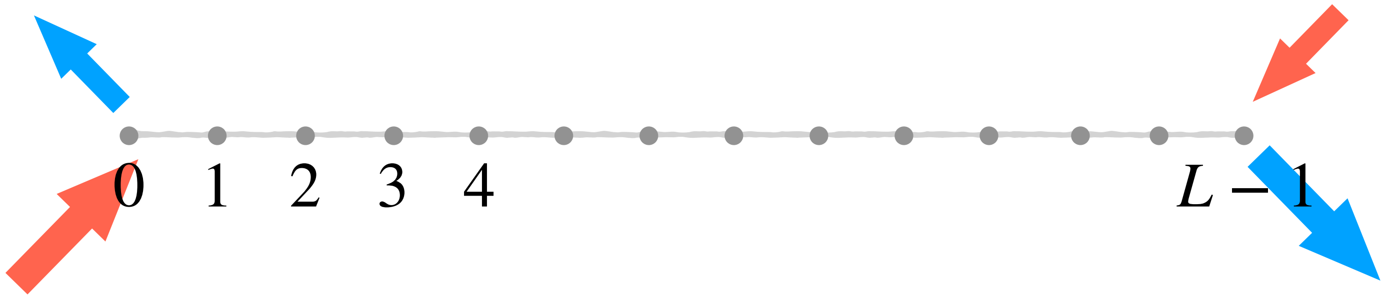
Minimal model $\hat{H} = \sum_{i,j} \hat{c}^\dagger_{i-1}\hat{c}_i \, \hat{c}_j \hat{c}^\dagger_{j+1}$ $\quad \hat{L}_1 = \hat{c}^\dagger_1 \quad \hat{L}_2 = \hat{c}_L \quad \hat{L}_3 = \sqrt{\gamma}\, \hat{c}_1 \quad \hat{L}_4 = \sqrt{\gamma}\, \hat{c}^\dagger_L$

No frozen states

$$1\;1\;0\;1\;0\;0 \ldots 0 \longrightarrow 0\;1\;0\;1\;0\;0 \ldots 0 \longleftrightarrow 1\;0\;0\;0\;1\;0 \ldots 0 \longrightarrow 1\;0\;0\;0\;1\;0 \ldots 1 \longleftrightarrow \cdots$$

In fact, No DFS.

Unique steady state? No, because there is a strong symmetry! Buča, Prosen, NJP 2012



$D \to D \pm (L-1)$

$\Longrightarrow$ $D \bmod (L-1) \equiv D_{\text{mod}}$ is preserved!

$\Longrightarrow$ $L-1$ mixed steady states w/ $D_{\text{mod}} = 0, 1, 2, \ldots, L-2$

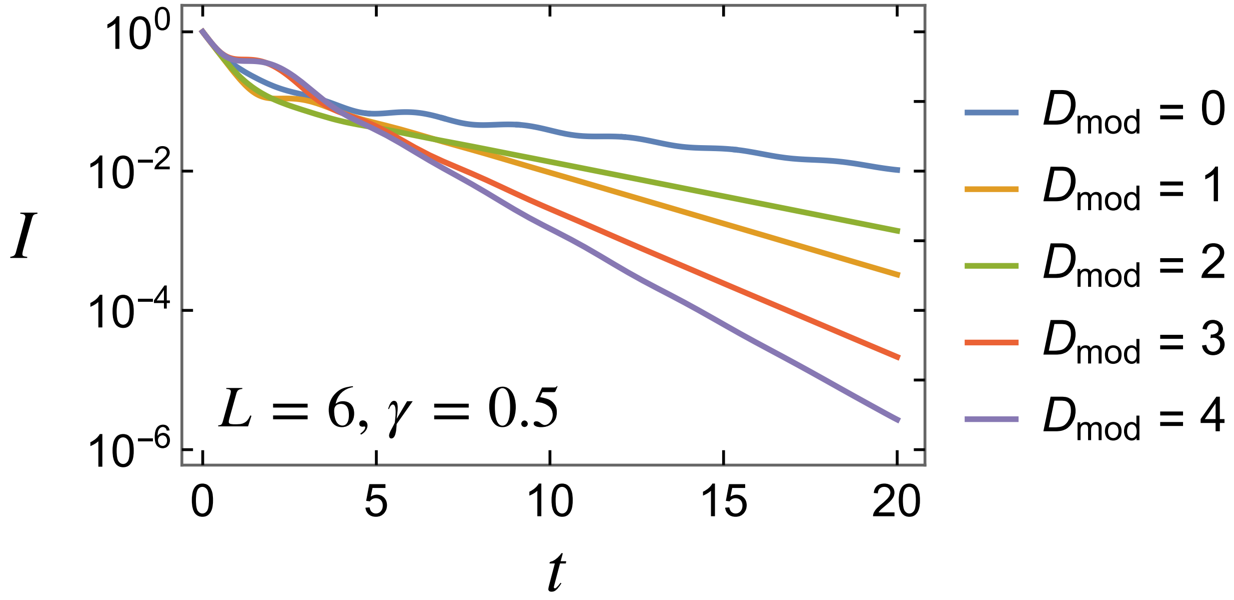
Case I B. *Unfragmented* + pump-loss at *both* ends

Current in steady states? NO

$\hat{L}_1 = \hat{c}_1^\dagger \quad \hat{L}_2 = \hat{c}_L \quad \hat{L}_3 = \sqrt{\gamma}\, \hat{c}_1 \quad \hat{L}_4 = \sqrt{\gamma}\, \hat{c}_L^\dagger$

(heating within each sector)

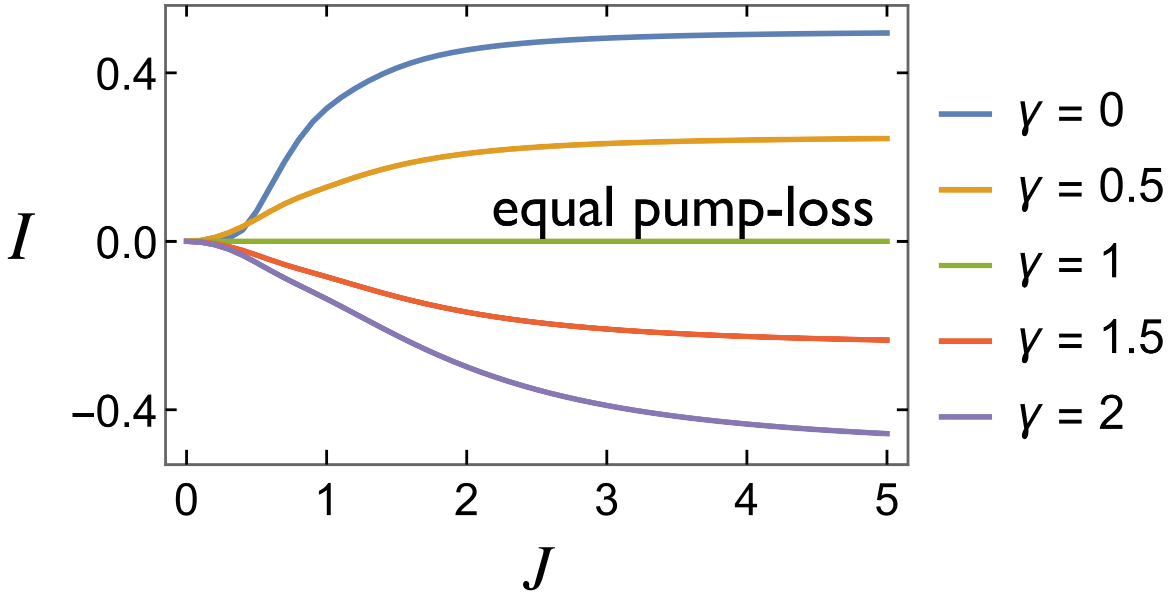
$I \equiv$ net injection rate at site 1



Current restored by breaking symmetry in $\hat{H}$

$$\hat{H} = \sum_{i,j} \hat{c}_{i-1}^\dagger \hat{c}_i \, \hat{c}_j \hat{c}_{j+1}^\dagger$$

$$-J \sum_i \hat{c}_i^\dagger \hat{c}_{i+1} + \textbf{h.c.}$$



Case II A.

Strongly *fragmented* $\hat{H}$

$+$

Pump-loss at *opposite* ends

Case II A. *Fragmented* + pump-loss at *opposite* ends

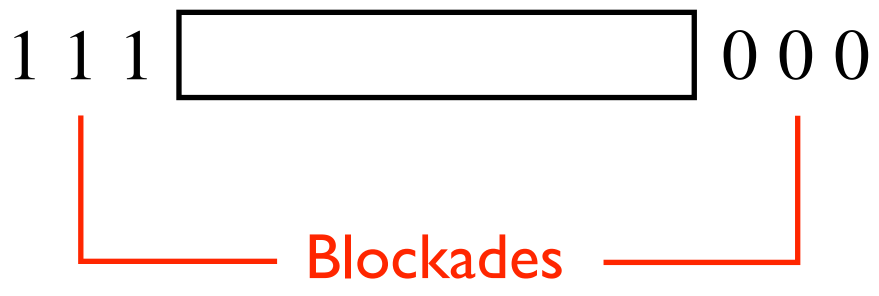
Minimal model $\hat{H} = \sum_i \hat{c}^\dagger_{i-1}\hat{c}_i\,\hat{c}_{i+1}\hat{c}^\dagger_{i+2} + \textbf{h.c.}$ $\quad \hat{L}_1 = \hat{c}^\dagger_1 \quad \hat{L}_2 = \hat{c}_L$

More constrained $\Longrightarrow$ larger number of decoherence-free states (Λ)

Previously $2L-4$ frozen configurations — Now exponentially many:

$$\underbrace{1\;1\;1}_{\geq 3}\;\underbrace{0\;0\;0}_{\geq 3}\;1\;1\;1 \ldots 0\;0\;0$$

Decoherence-free (not necessarily frozen) states:



$$1\;1\;1\;\boxed{}\;0\;0\;0$$

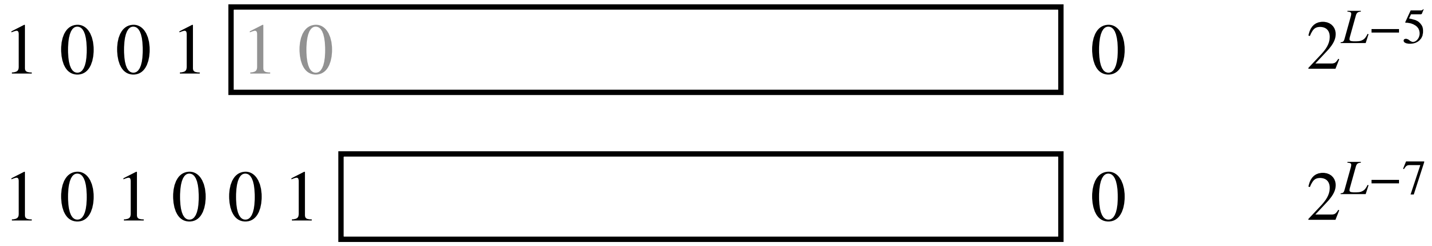
$\Longrightarrow \Lambda \geq 2^{L-6}$

(many disjoint subspaces)

Can we find Λ exactly? Yes!

Case II A. *Fragmented* + pump-loss at *opposite* ends

Which states start with 1, ends with 0 but NOT decoherence free?



$1\ 0\ 0\ 1\ \boxed{1\ 0\ \quad\quad\quad\quad\quad\quad}\ 0 \qquad 2^{L-5}$

$1\ 0\ 1\ 0\ 0\ 1\ \boxed{\quad\quad\quad\quad\quad\quad}\ 0 \qquad 2^{L-7}$

Case II A. *Fragmented* + pump-loss at *opposite* ends

Which states start with 1, ends with 0 but NOT decoherence free?

$$1\,0\,\underline{0\,1}\,\boxed{\color{gray}{0\,0\,1}\qquad\qquad\qquad\qquad\qquad}\;0 \qquad 2^{L-5}$$

$$1\,0\,1\,0\,\underline{0\,1}\,\boxed{\qquad\qquad\qquad\qquad\qquad}\;0 \qquad 2^{L-7}$$

$$1\,0\,0\,0\,1\,\underline{1\,0}\,\boxed{\qquad\qquad\qquad\qquad}\;0 \qquad 2^{L-8}$$

Expansion rule:

$$\underline{0\,1} \to 1\,0\,\underline{0\,1}, \quad 0\,0\,1\,\underline{1\,0}$$

$$\underline{1\,0}\,\color{gray}{0\,1\,0} \to 0\,1\,\underline{1\,0}, \quad 1\,1\,0\,\underline{0\,1}$$

$\Longrightarrow$ 1001 family

$$\Uparrow \dots \Uparrow \color{red}{0} \Downarrow \dots \Downarrow \color{red}{1} \Uparrow \dots \Uparrow \color{red}{0} \Downarrow \dots \quad \dots \boxed{\Downarrow \Uparrow}\,\boxed{\qquad\qquad\qquad}\;0$$

Active edge

$$\Uparrow \equiv 1\,0 \qquad \Downarrow \equiv 0\,1$$

Case II A. *Fragmented* + pump-loss at *opposite* ends

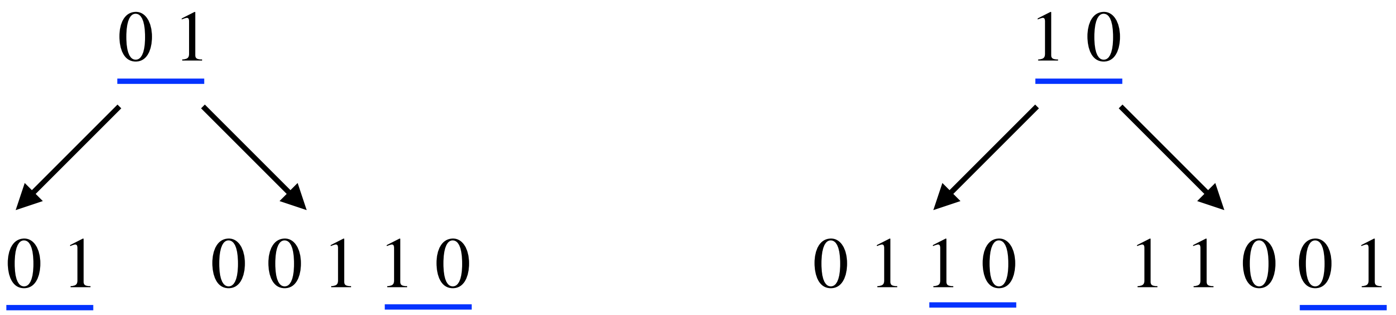
Which states start with 1, ends with 0 but NOT decoherence free?

$$1\;0\;\underline{0\;1}\;\boxed{0\;0\;1\qquad\qquad\qquad\qquad\qquad}\;0 \qquad 2^{L-5}$$

$$1\;0\;1\;0\;\underline{0\;1}\;\boxed{\qquad\qquad\qquad\qquad\qquad}\;0 \qquad 2^{L-7}$$

$$1\;0\;0\;0\;1\;\underline{1\;0}\;\boxed{\qquad\qquad\qquad\qquad}\;0 \qquad 2^{L-8}$$

Expansion rule:



$\Longrightarrow$ 1001 family

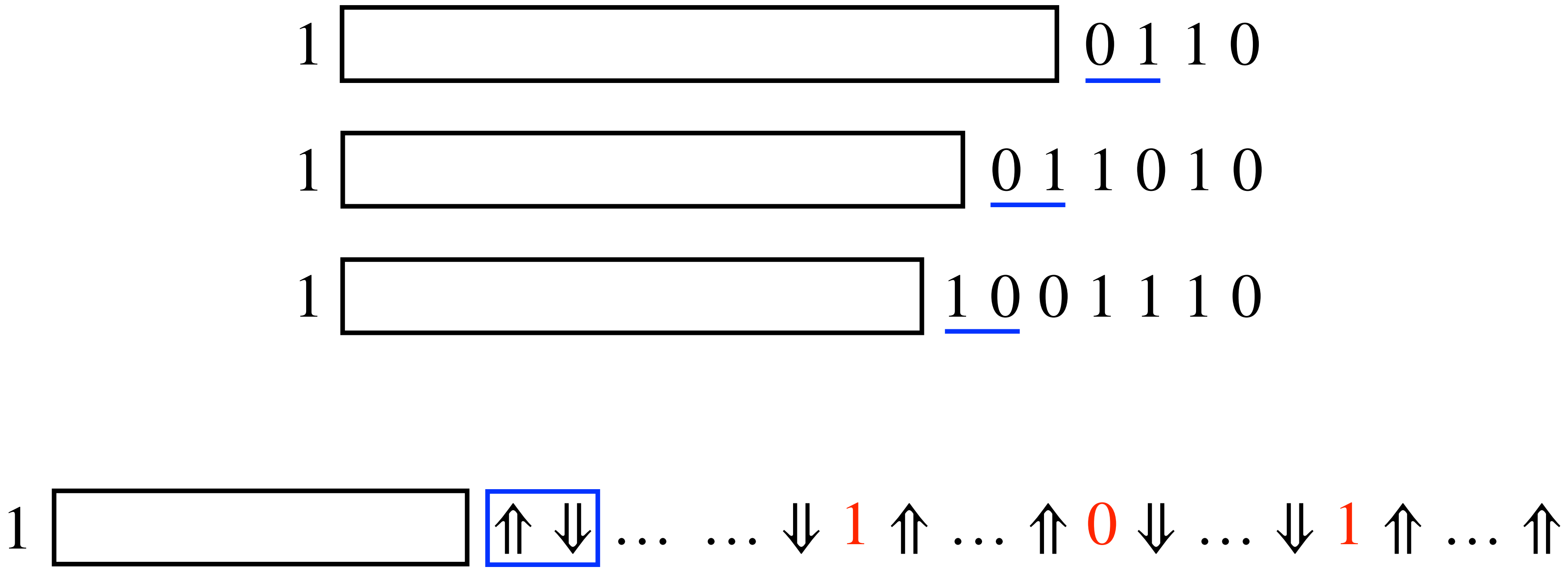
$$\Uparrow \dots \Uparrow \; 0 \; \Downarrow \dots \Downarrow \; 1 \; \Uparrow \dots \Uparrow \; 0 \; \Downarrow \dots \quad \dots \boxed{\Uparrow\,\Downarrow}\;\boxed{\qquad\qquad\qquad\qquad}\;0$$

$\Uparrow \equiv 1\;0 \qquad \Downarrow \equiv 0\;1$

Active edge

Case II A. *Fragmented* + pump-loss at *opposite* ends

Similarly, there is a 0110 family expanding from the right:



$1\ \boxed{\qquad\qquad\qquad}\ \underline{0\ 1}\ 1\ 0$

$1\ \boxed{\qquad\qquad}\ \underline{0\ 1}\ 1\ 0\ 1\ 0$

$1\ \boxed{\qquad}\ \underline{1\ 0}\ 0\ 1\ 1\ 1\ 0$

$1\ \boxed{\qquad}\ \boxed{\Uparrow\Downarrow}\dots\ \dots\Downarrow 1 \Uparrow \dots \Uparrow 0 \Downarrow \dots \Downarrow 1 \Uparrow \dots \Uparrow$

Excluding states in these two families gives all decoherence-free states

$$\Longrightarrow \boxed{\Lambda \approx (2/5)^2 \times 2^L}$$

Case II B.

Strongly *fragmented* $\hat{H}$

$+$

Pump-loss at *both* ends

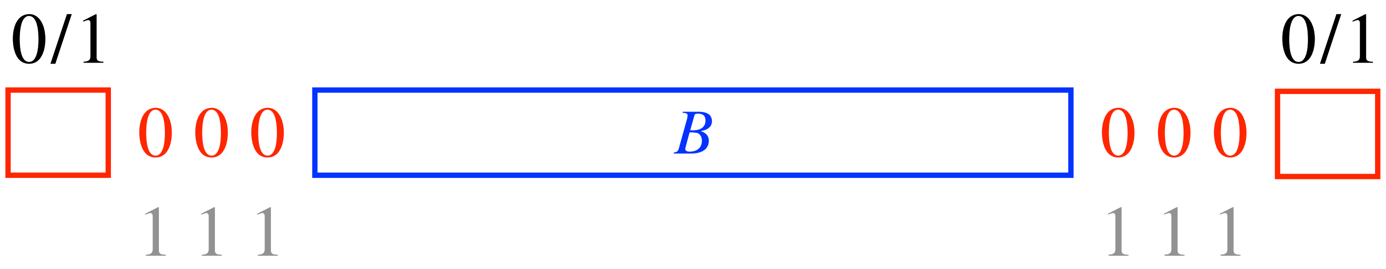
Case II B. *Fragmented* + pump-loss at *both* ends

Minimal model $\hat{H} = \sum_i \hat{c}_{i-1}^\dagger \hat{c}_i \, \hat{c}_{i+1} \hat{c}_{i+2}^\dagger + \textbf{h.c.}$ $\hat{L}_1 = \hat{c}_1^\dagger$ $\hat{L}_2 = \hat{c}_L$ $\hat{L}_3 = \sqrt{\gamma}\hat{c}_1$ $\hat{L}_4 = \sqrt{\gamma}\hat{c}_L^\dagger$

Recall: Case I B had $(L-1)$ mixed steady states — expect more here

But no eigenstate of $\hat{H}$ is a null state of $\hat{L}_j \; \forall j$ $\implies$ No DFS

Shield bulk from boundary by inserting blockades:



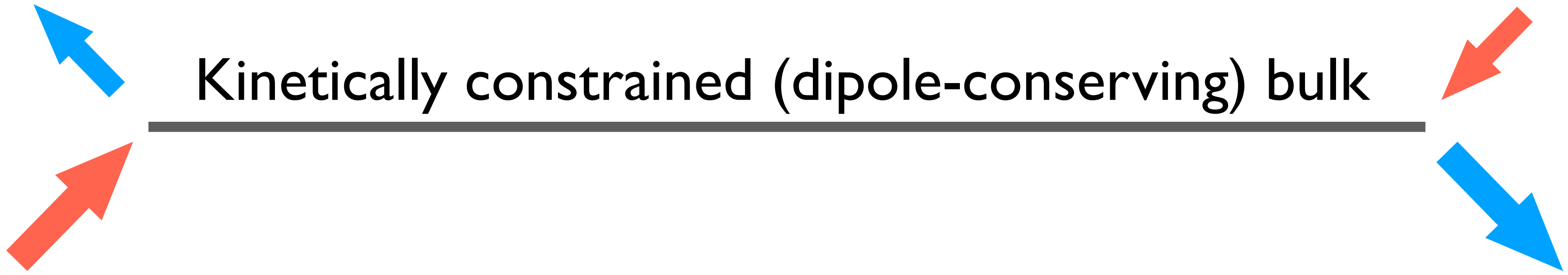
2^{L-6} configs

Steady states: $\hat{\rho}_A \otimes |\varphi_B^j\rangle\langle\varphi_B^k|$ $|\varphi_B^k\rangle$: eigenstates of $\hat{H}_B$

$\implies$ Exponentially large (fragmented) noiseless subsystem — info in B preserved

Again, no net flow in steady state

Summary



Kinetically constrained (dipole-conserving) bulk

Symmetry-breaking
drive @ boundary

- Current suppressed in steady state — restored by breaking symmetry in bulk
- Hierarchy of steady states from interplay of fragmentation & dissipation

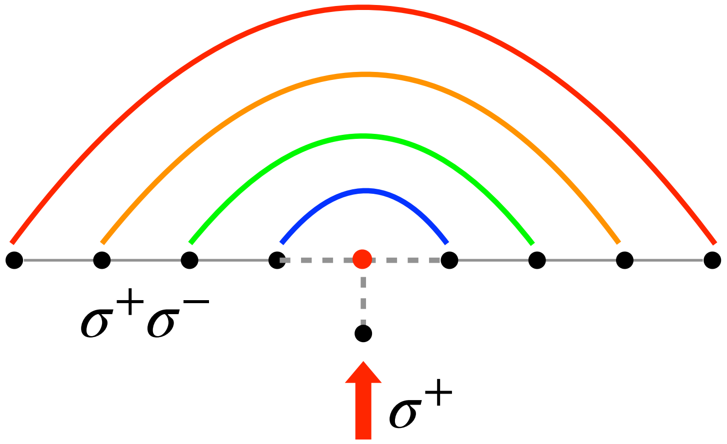
	Un-fragmented $\hat{H}$	Fragmented $\hat{H}$
Pump-loss @opposite ends	$O(L^2)$ DFSs, $\Lambda \sim e^{\pi\sqrt{L/3}}$	Fragmented DFS, $\Lambda \sim 2^L$
Pump-loss @both ends	$L-1$ mixed steady states	Fragmented NS, $\Lambda \sim 2^L$

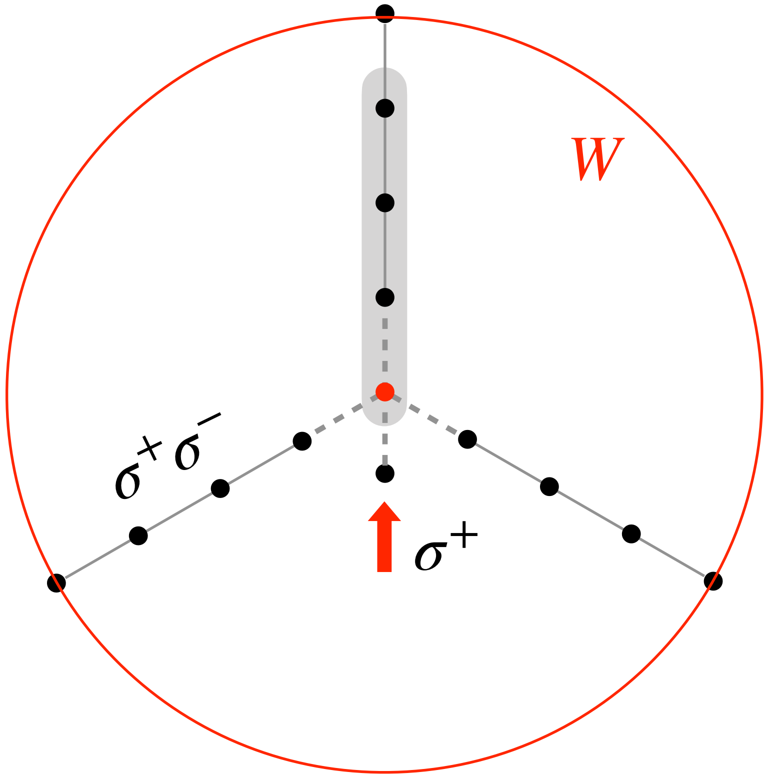
- Non-ergodicity in open quantum systems from fragmentation

A Srivastava and SD, in prep

Other recent developments

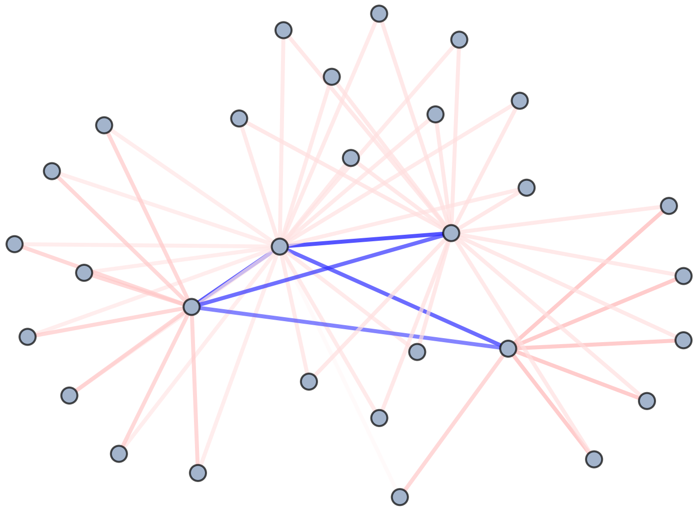
Long-range multipartite entanglement from local drive & static coupling





Quantum many-body physics on complex networks

qubits + $\hat{S}_i \cdot \hat{S}_j$ *bonds — frustrated*

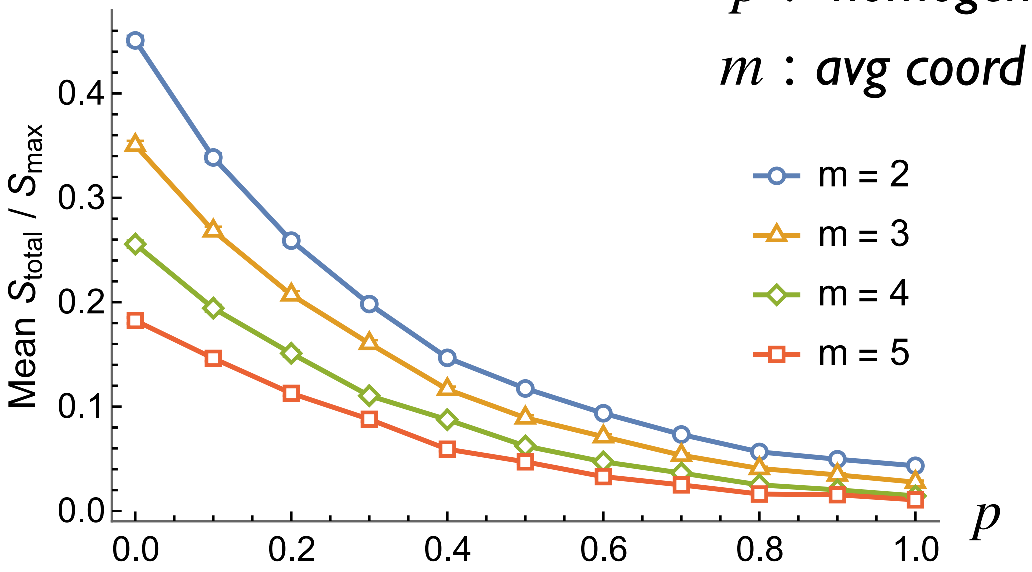


$S_{\text{ground}} = 11$

$(N = 30)$

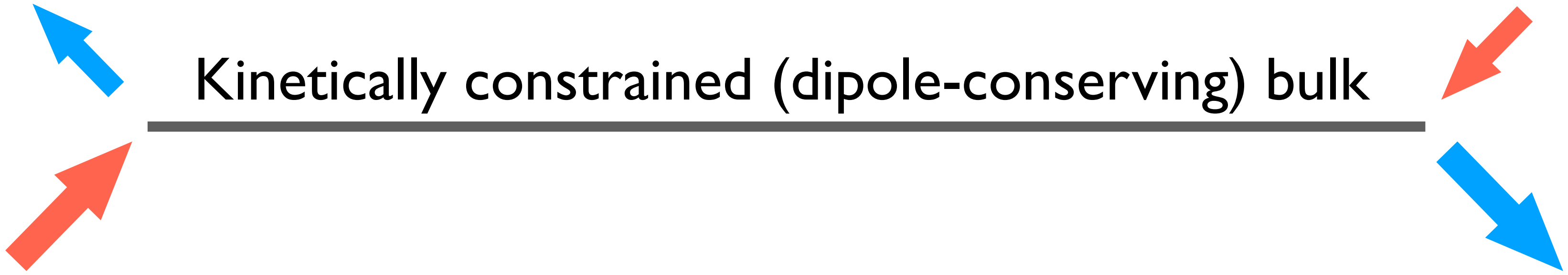
p : *"homogeneity"*

m : *avg coord no.*



Summary

Thank you :)



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A Srivastava and SD, in prep