Topology & Entanglement in Driven (Floquet) Many Body Quantum Systems

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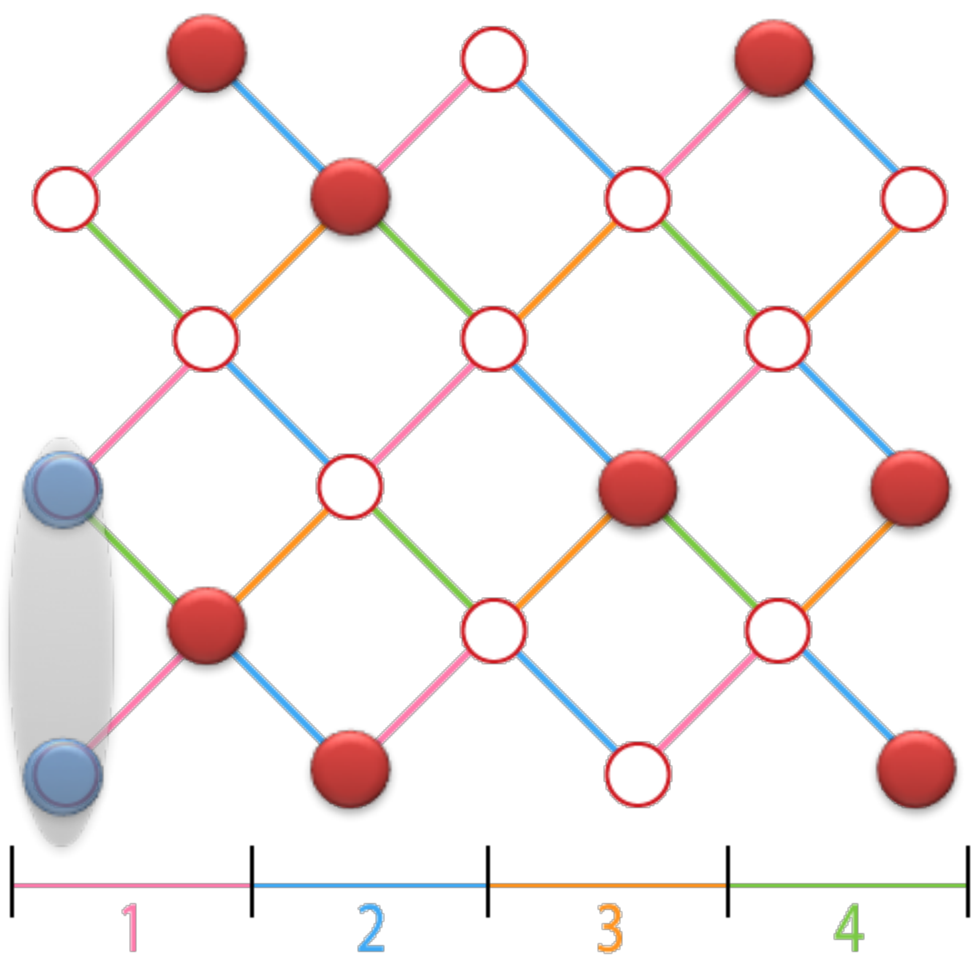
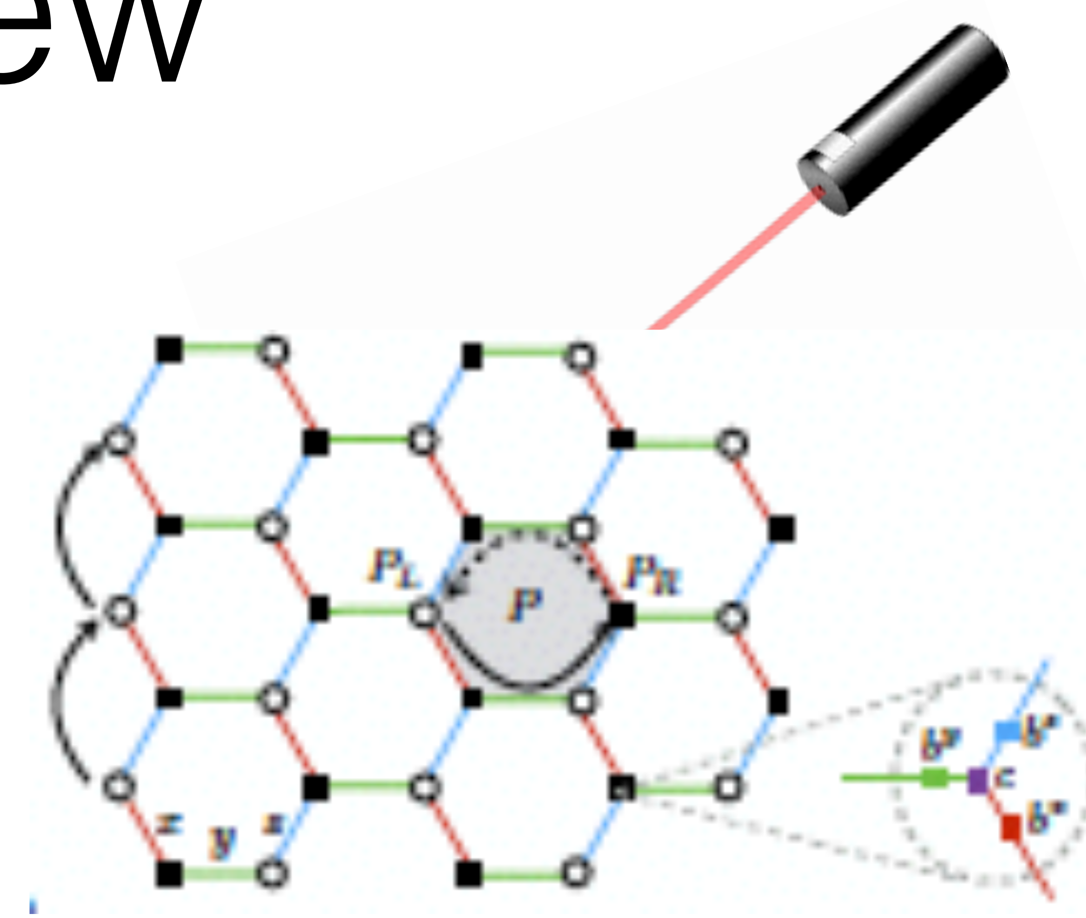
Overview





$$\nu = \log p - \log q$$

Chiral phases in driven systems.

arXiv:1701.01440. Chiral Floquet phases. *Po, Fidkowski, Morimoto, Potter, AV. Phys. Rev. X 6, 041070 (2016)*

$$\nu = \frac{1}{2}\log 2$$

The Driven Toric code.

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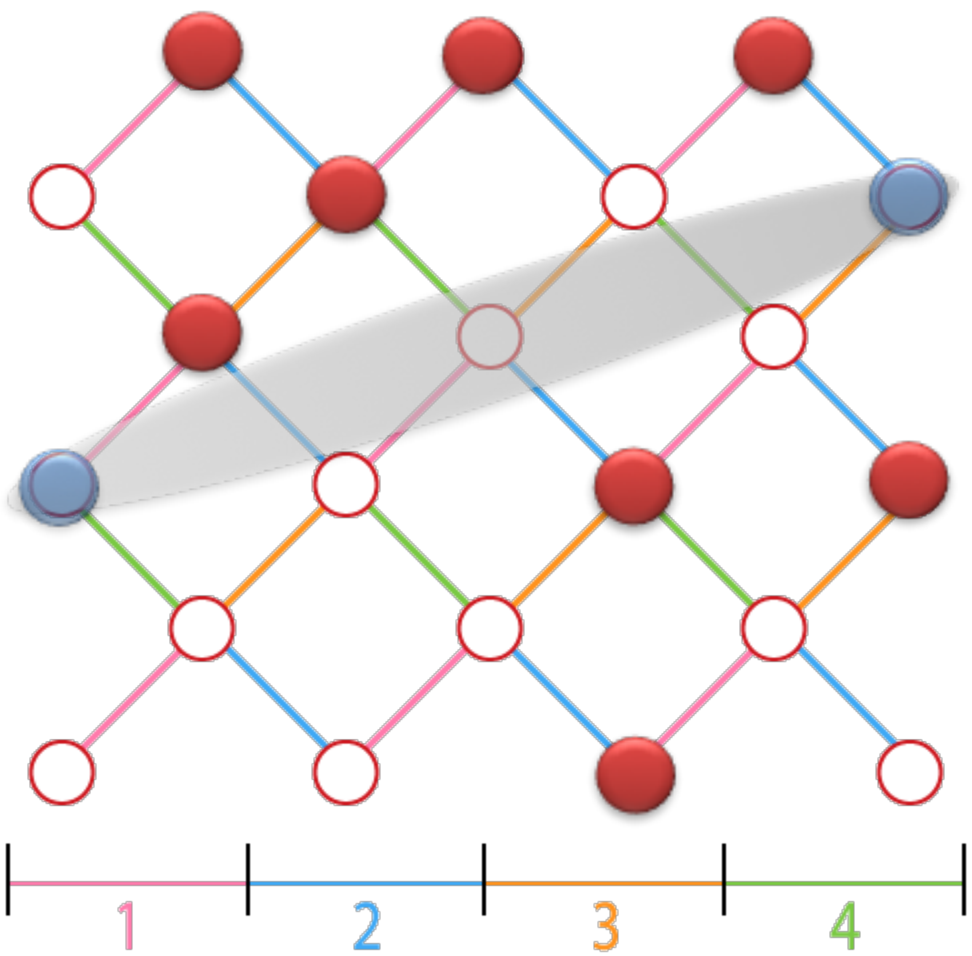

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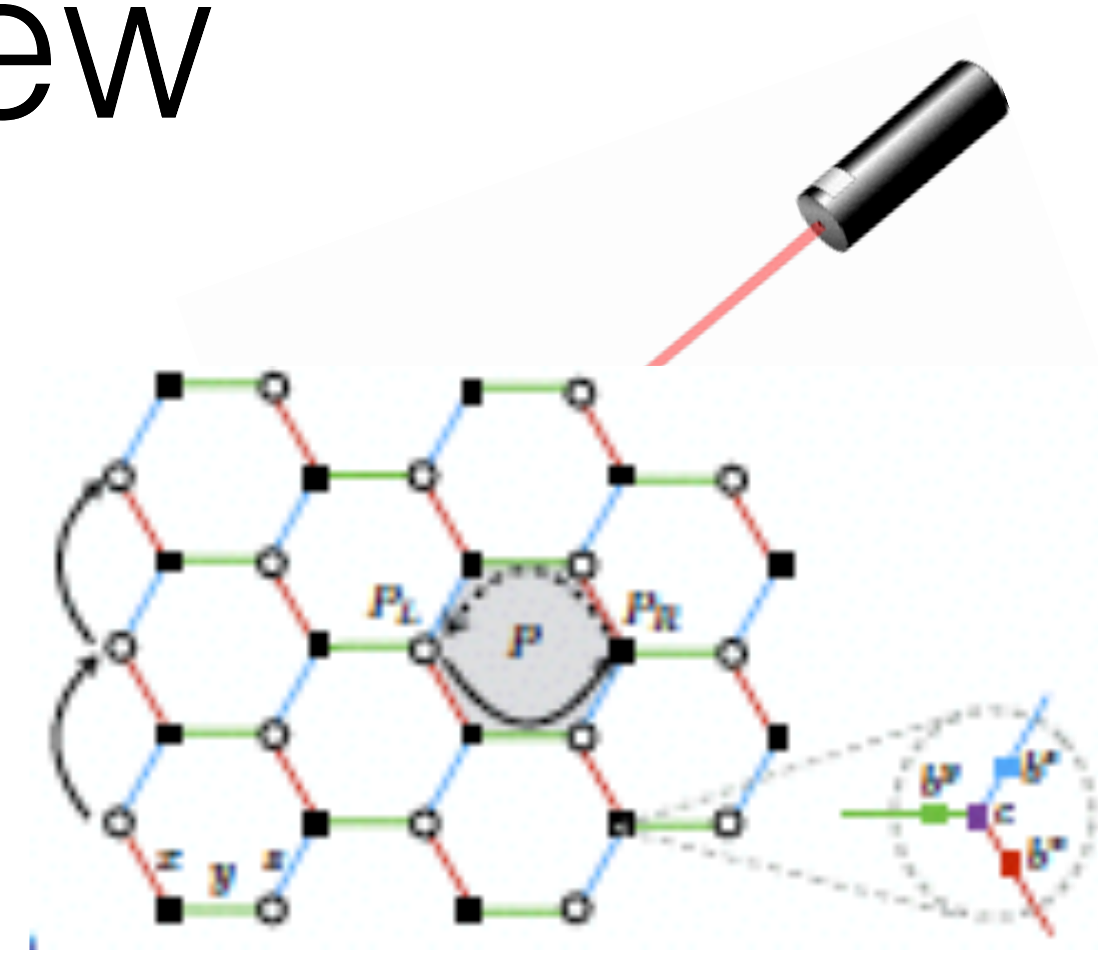

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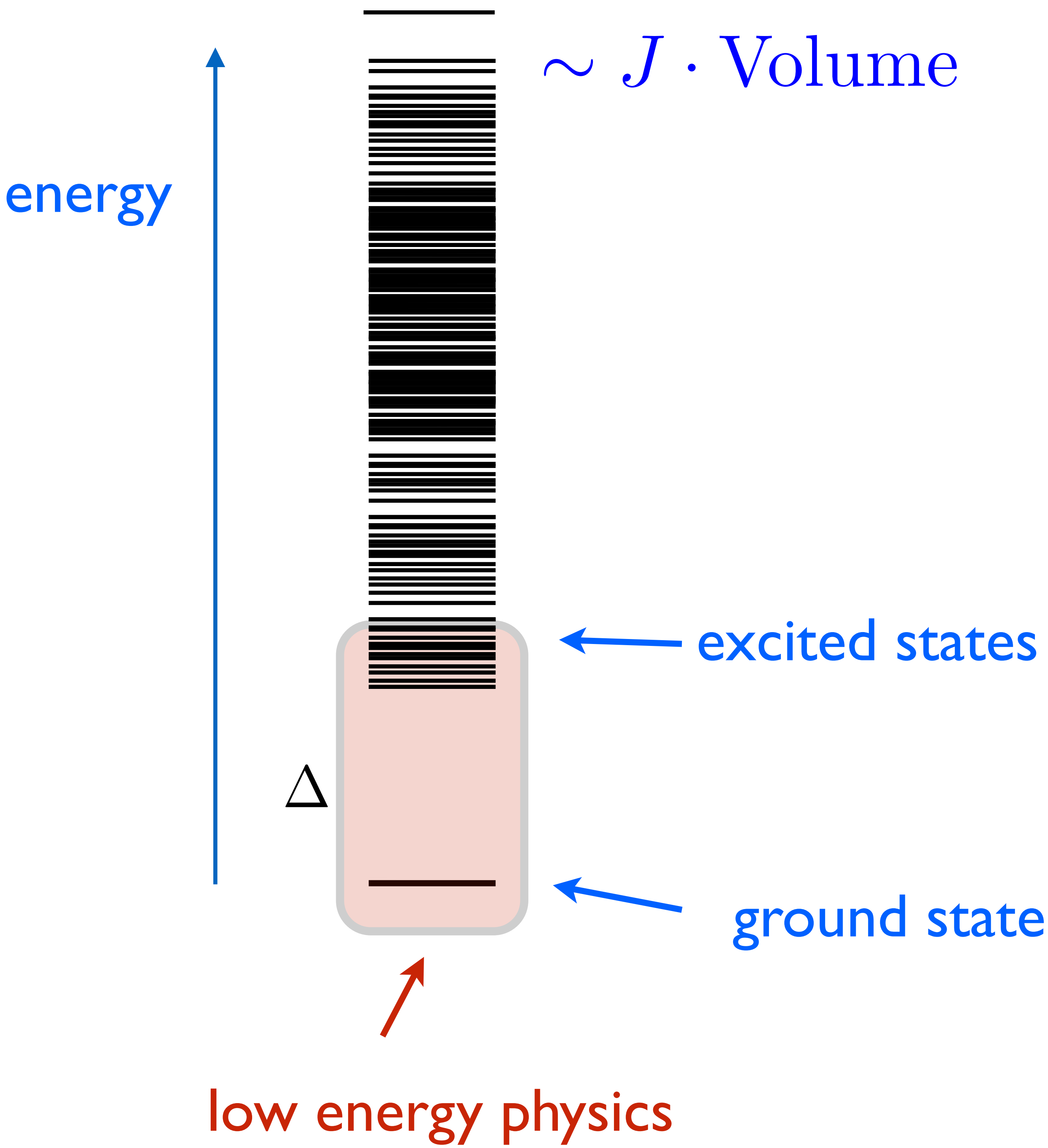
Introduction: A gapped Hamiltonian



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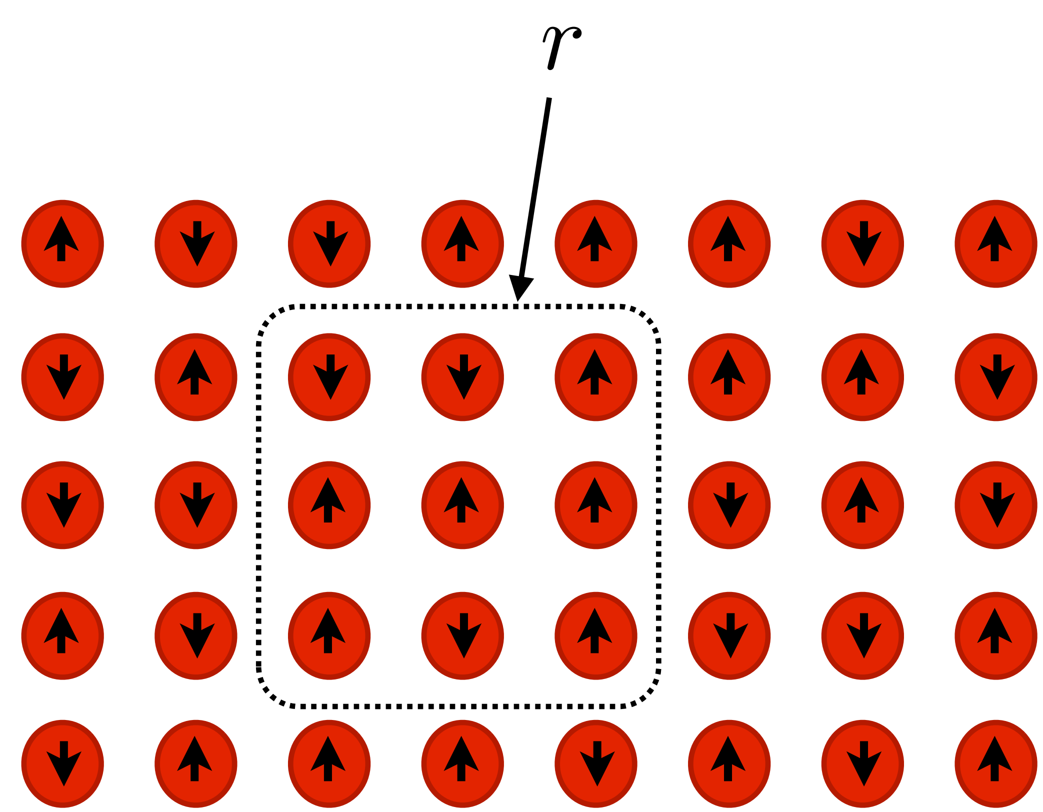
$$H = \sum_r H_r$$

$$J = \max_{\mathrm{r}} |\mathrm{H_r}|$$



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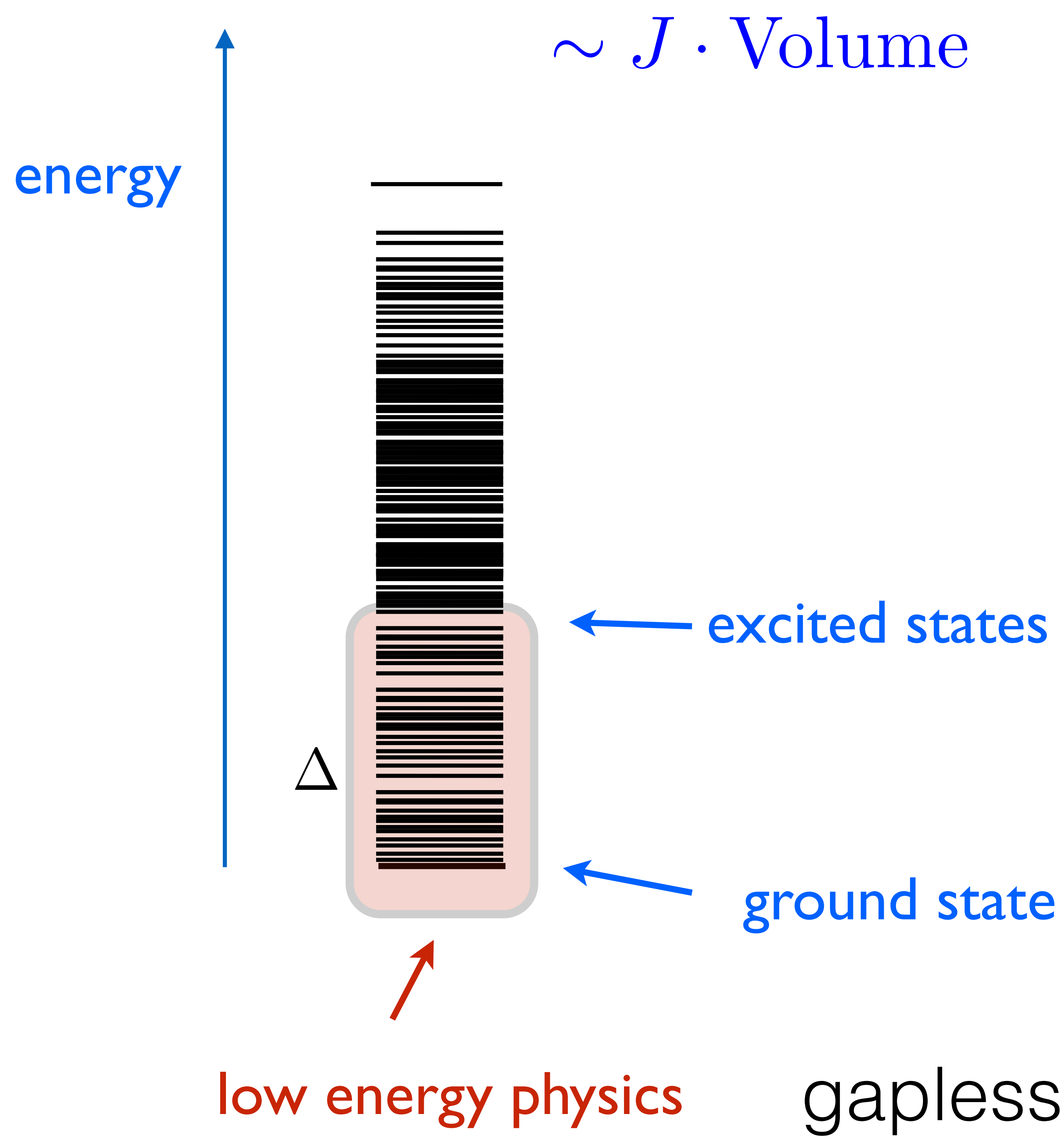

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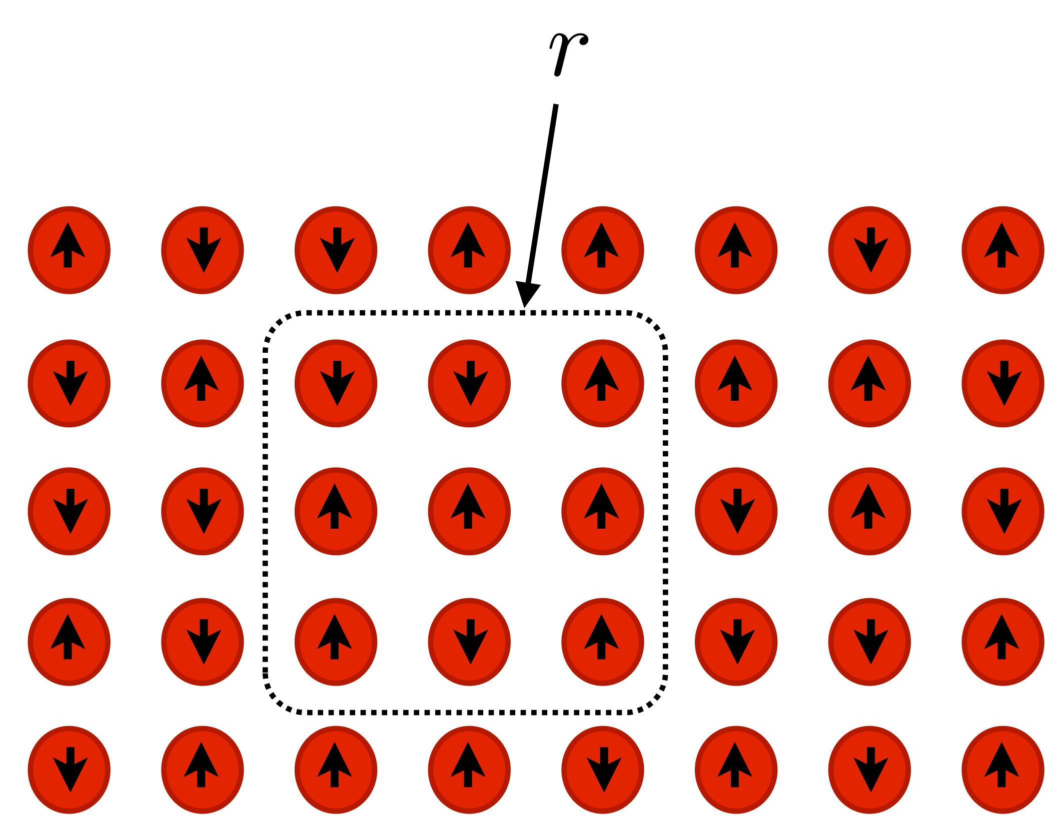

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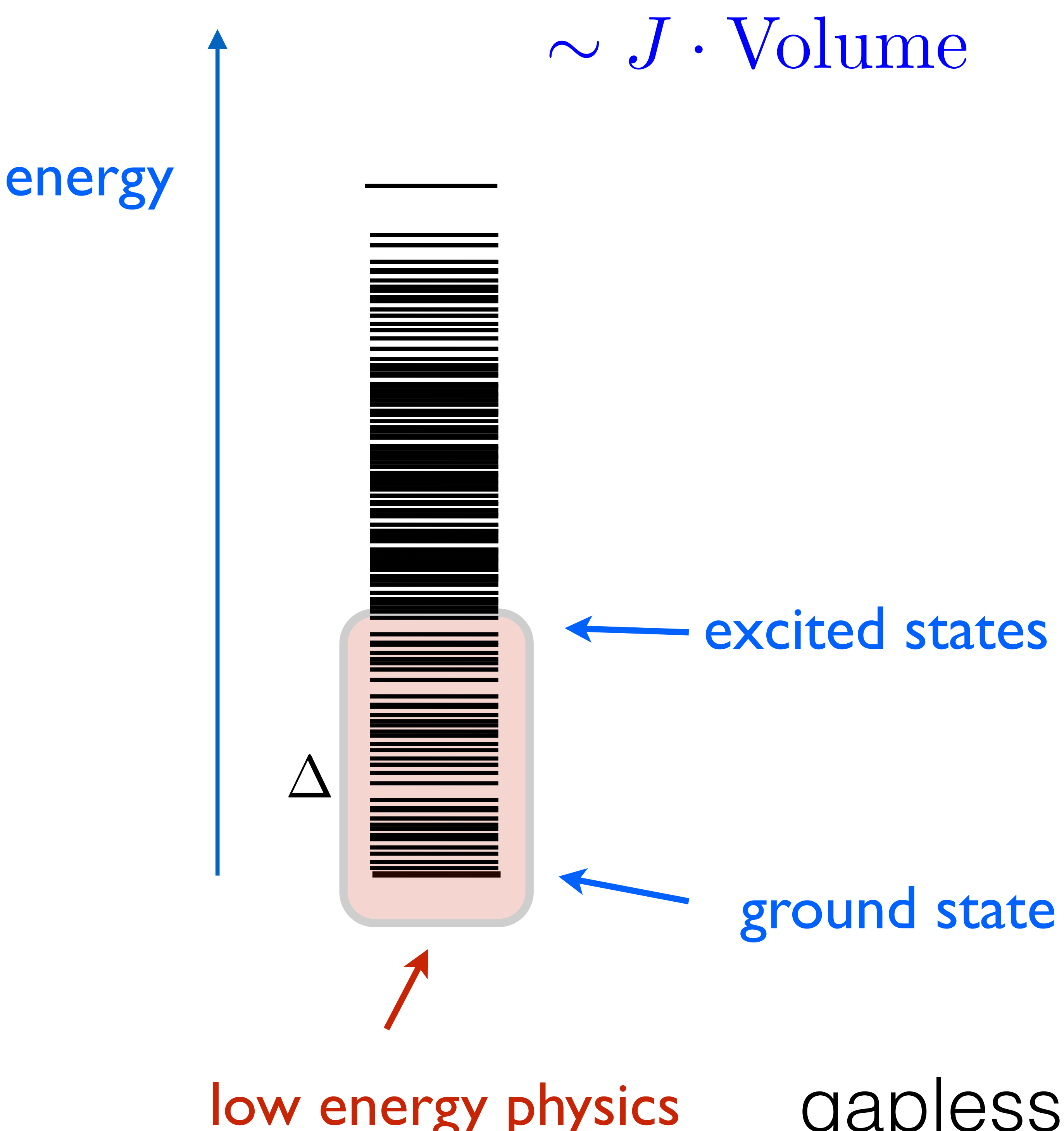

Need **cooling (T=0)**

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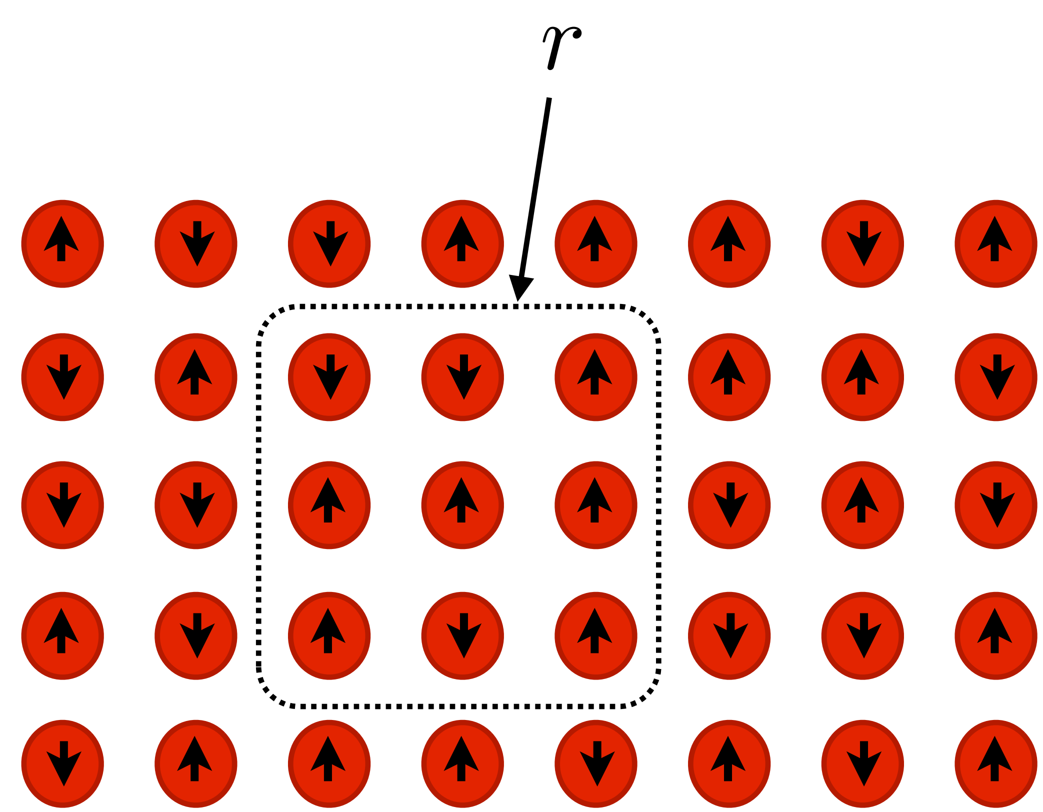


Introduction: Entanglement Signatures

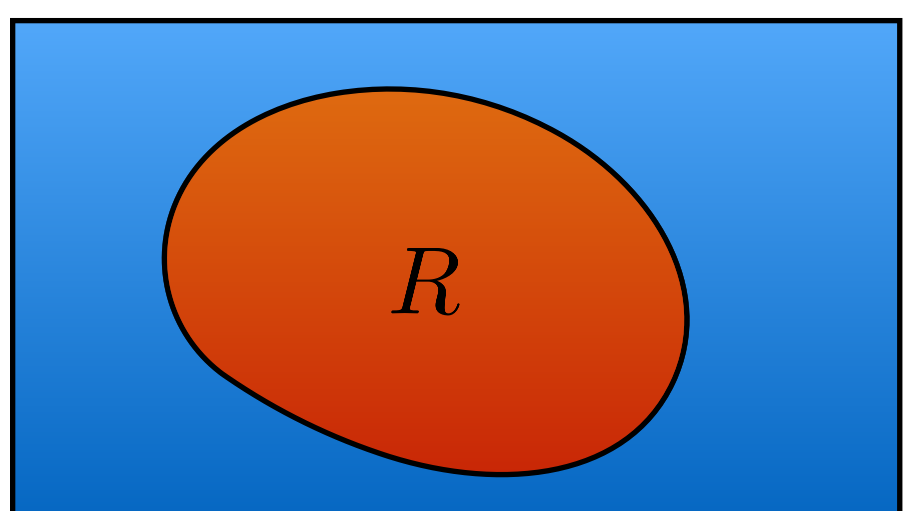
Gapped Phases

Gapless Phases

$S(\rho_R) \sim \alpha|\partial R| - \frac{1}{2}\log D + \cdots$

Area Law* $\log \partial R$

Area Law



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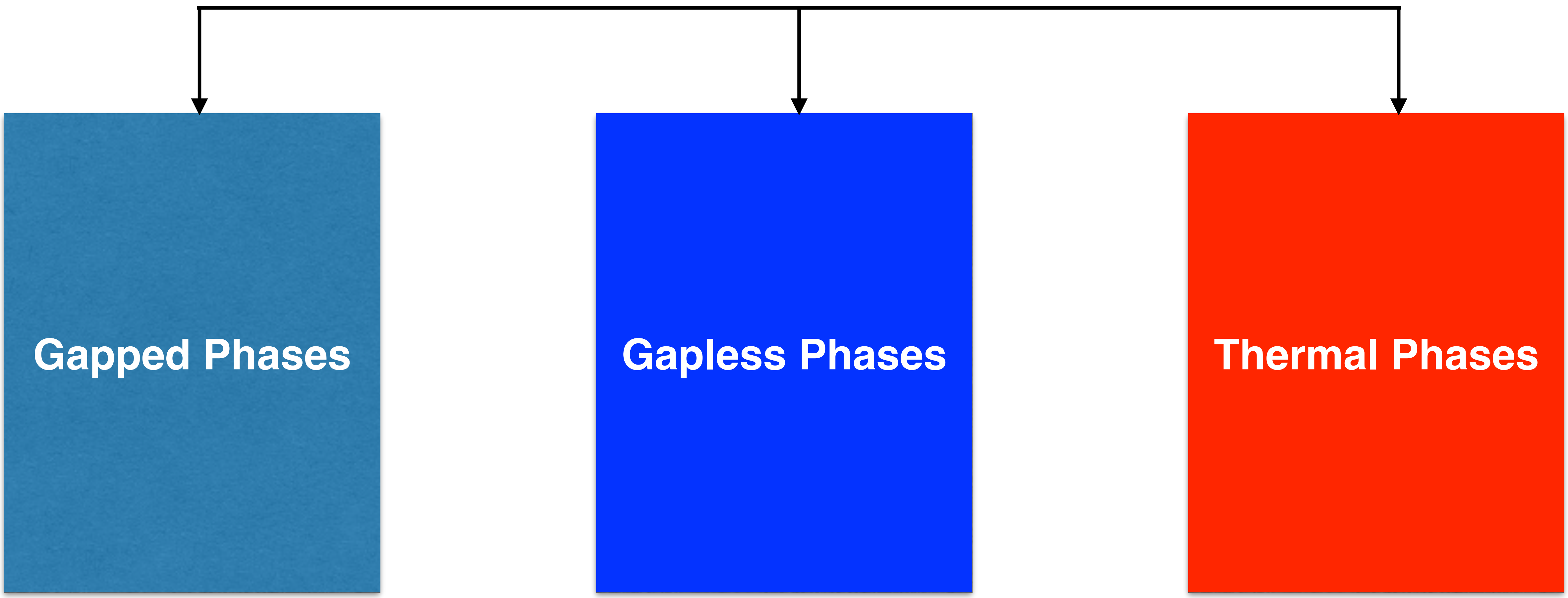
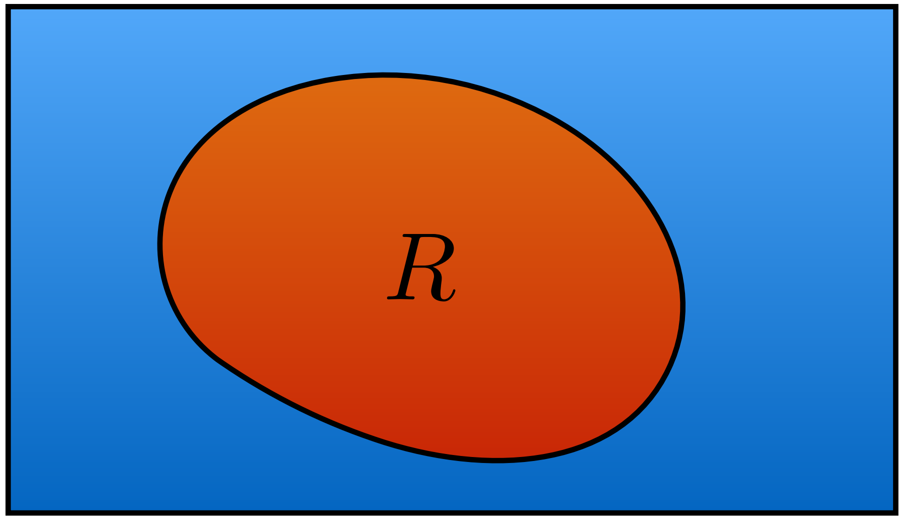


$S(\rho_R) \sim \alpha|\partial R| - \frac{1}{2}\log D + \cdots$

Area Law* $\log \partial R$

$S \sim \mathrm{Volume}(R)$

Area Law



Volume Law

Introduction: Classifying Gapped Quantum Phases

Ground states of gapped local Hamiltonians

How do we classify
gapped
ground states?

No symmetry except
t -> t+a

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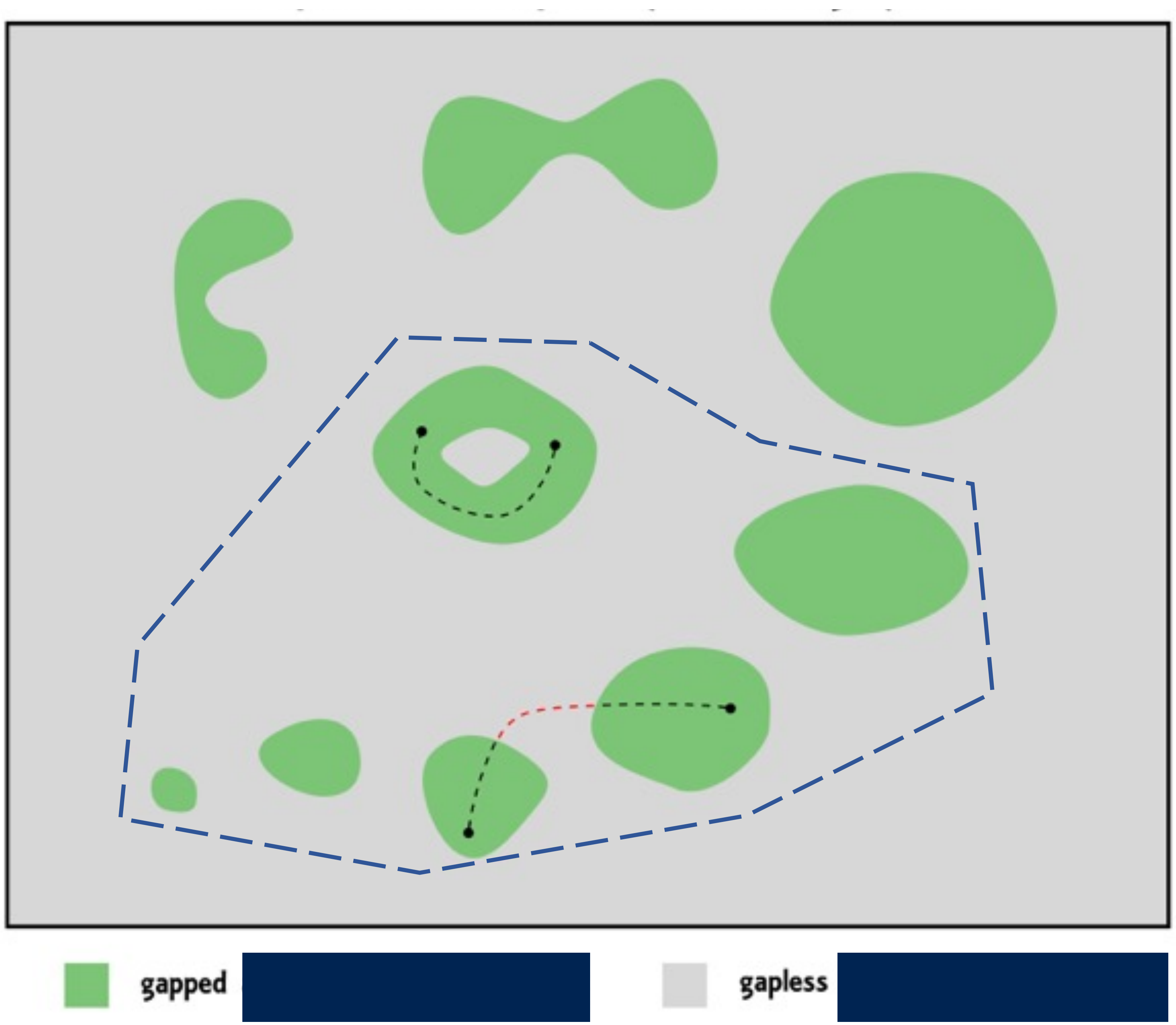
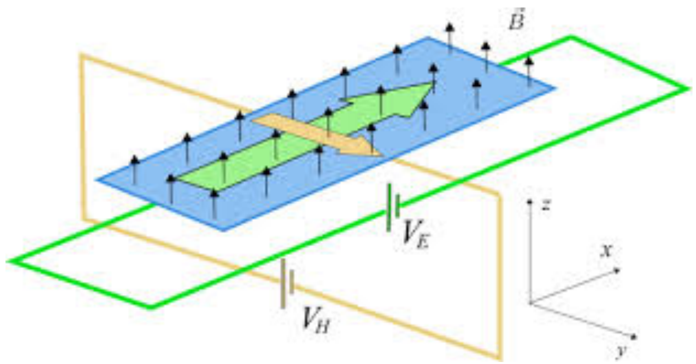
Ground states of gapped local Hamiltonians



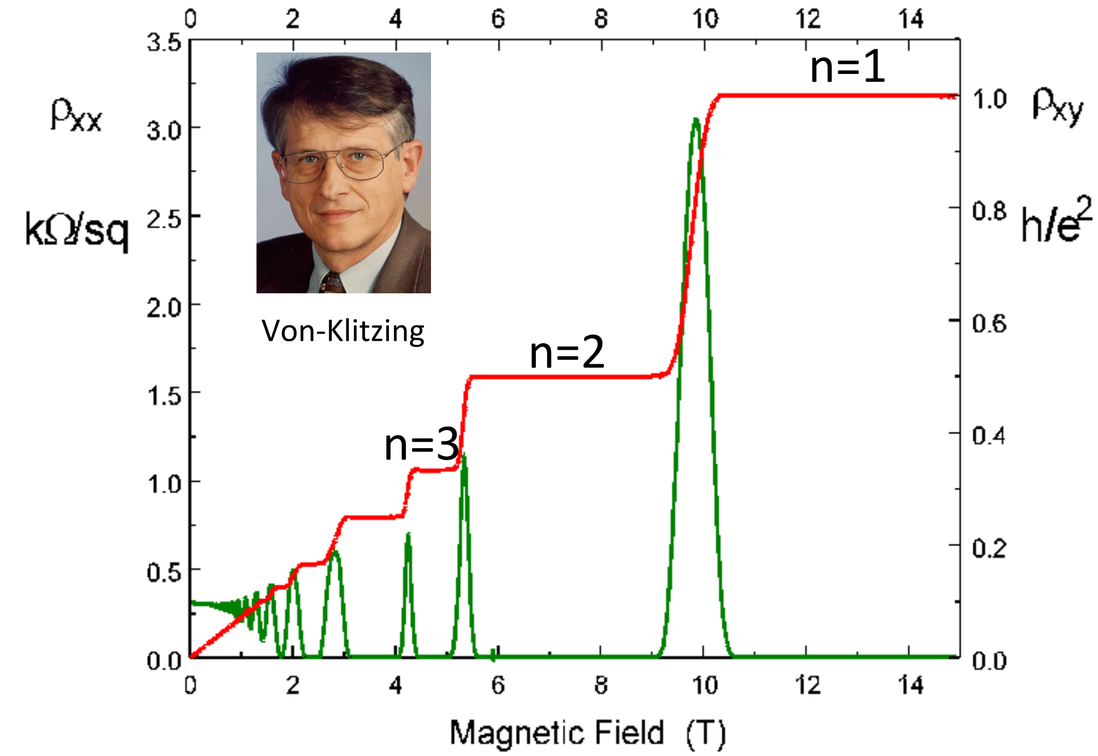
How do we classify gapped ground states?

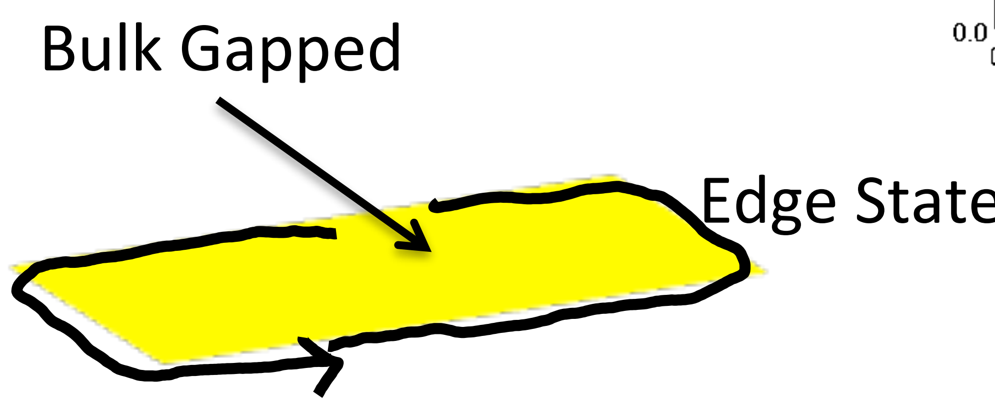
No symmetry except t -> t+a

Example 1:Quantum Hall Phases



$$\rho_{xy} = \frac{h}{e^2}\frac{1}{n}$$





- Different integers - different phases.
- Need to cool to low temperatures - protected by energy gap.
- Also differentiated by *Thermal-Hall*. Integer in the right units.

Example 2:Topological Order

- Topological order (Witten, Wen). eg. Fractional Quantum Hall & Toric Code/Z_2 Gauge theory

$$S(\rho_R) \sim \alpha|\partial R| - \frac{1}{2}\log D + \cdots$$

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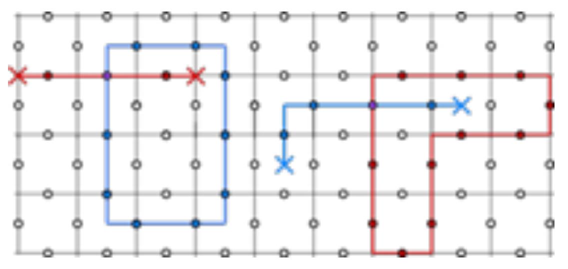

topological ground state degeneracy on a torus

anyonic excitations

topological entanglement entropy

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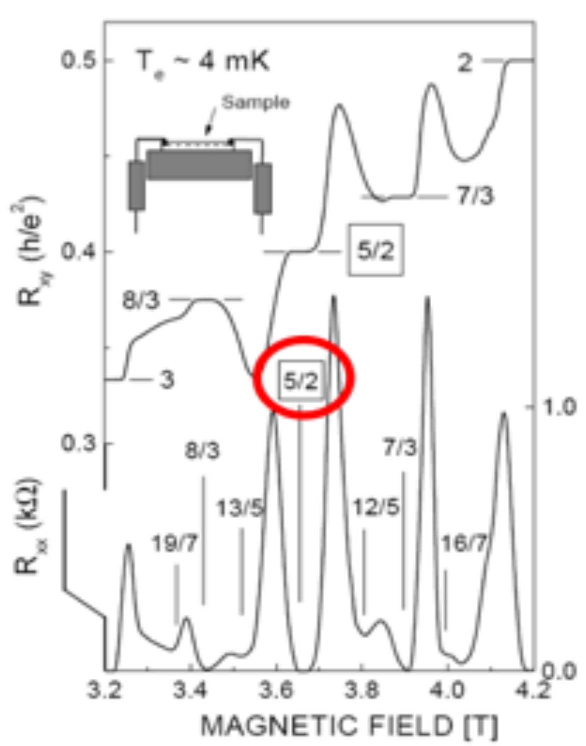

Pan et al. PRL 83, (1999)

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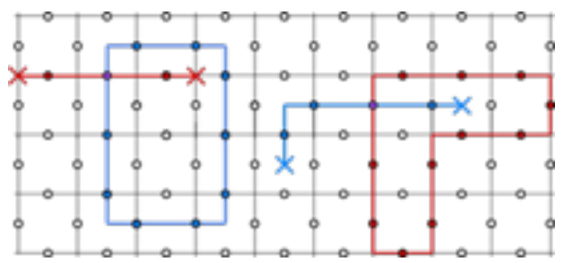

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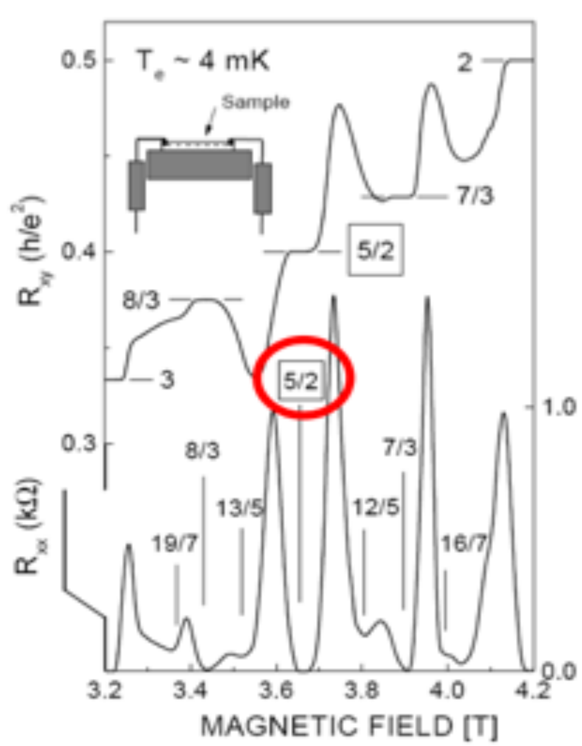

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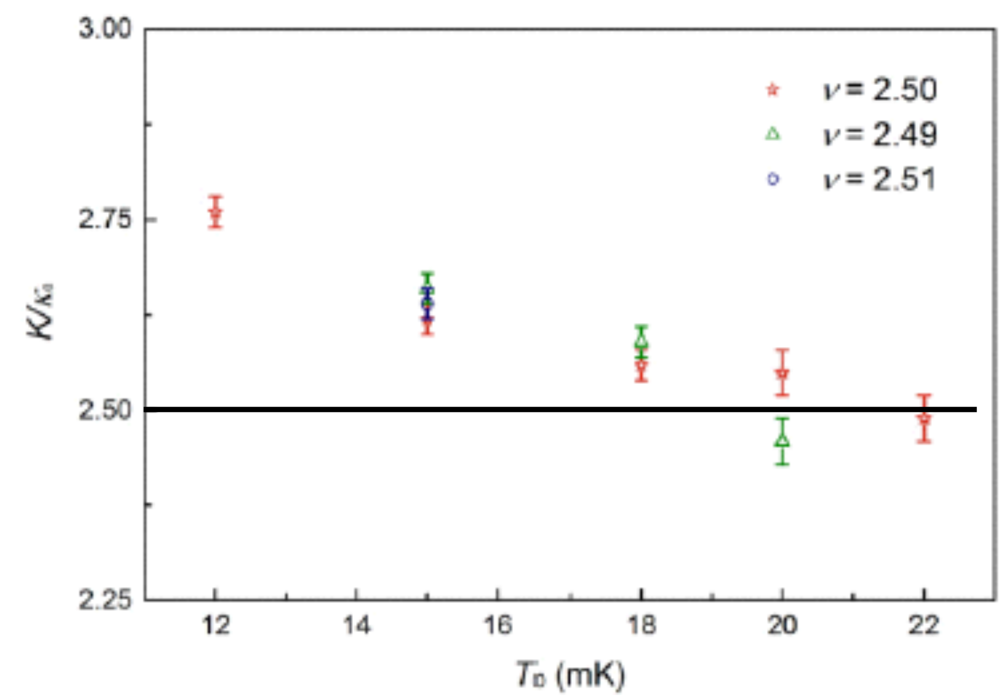
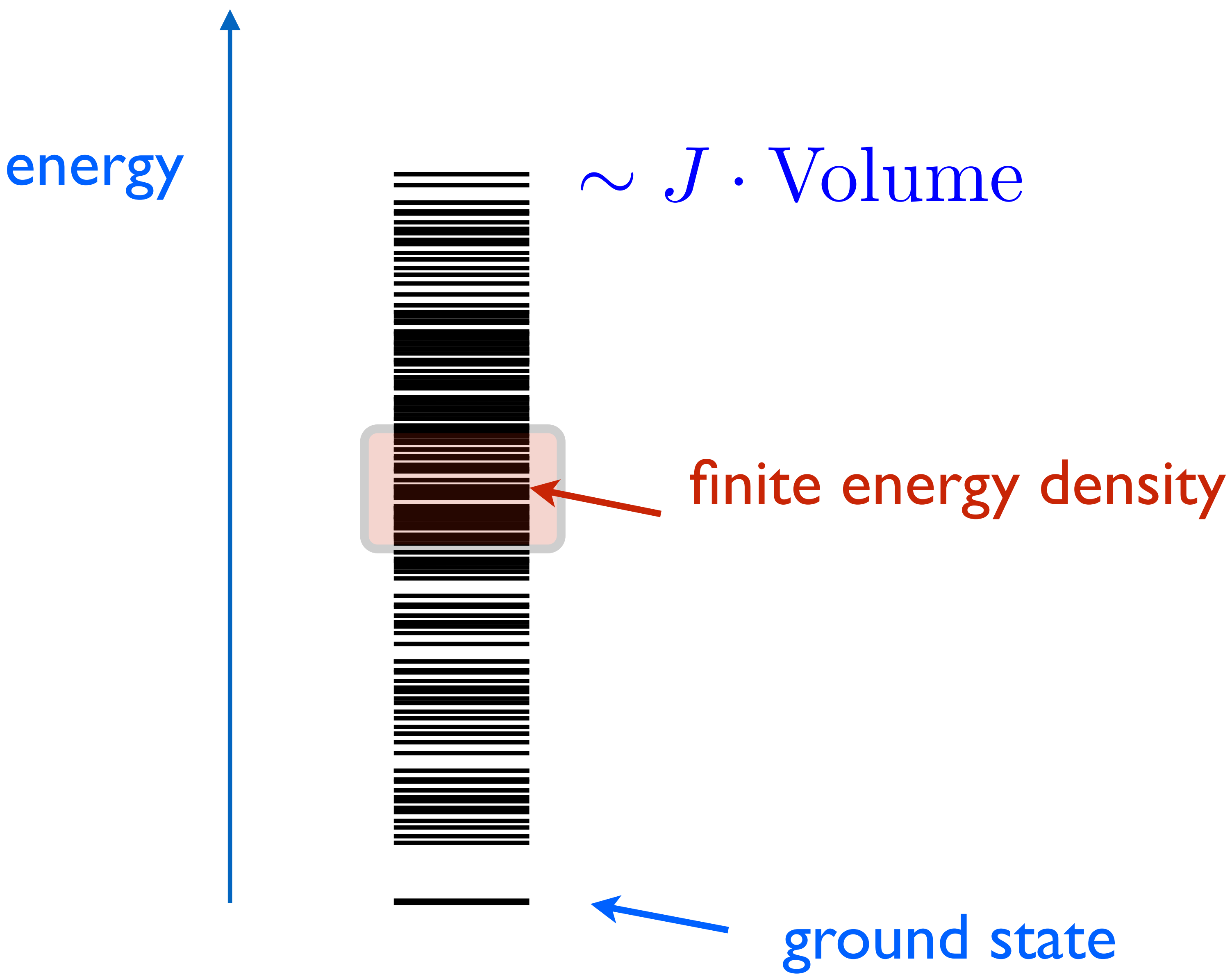
Half quantized thermal Hall c=5/2

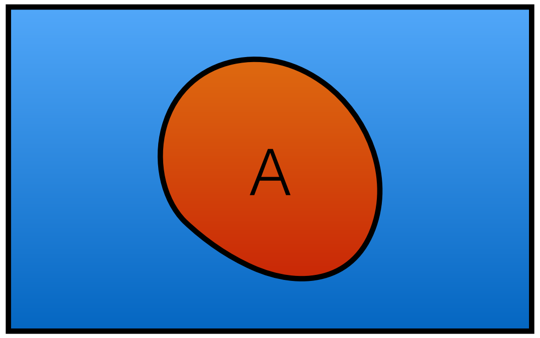


Banerjee et al.1710.00492

Can we observe topological properties at finite energy density?

Conventional answer: No





Deutsch 91, Srednicki 94

Eigenstate Thermalization Hypothesis (ETH)

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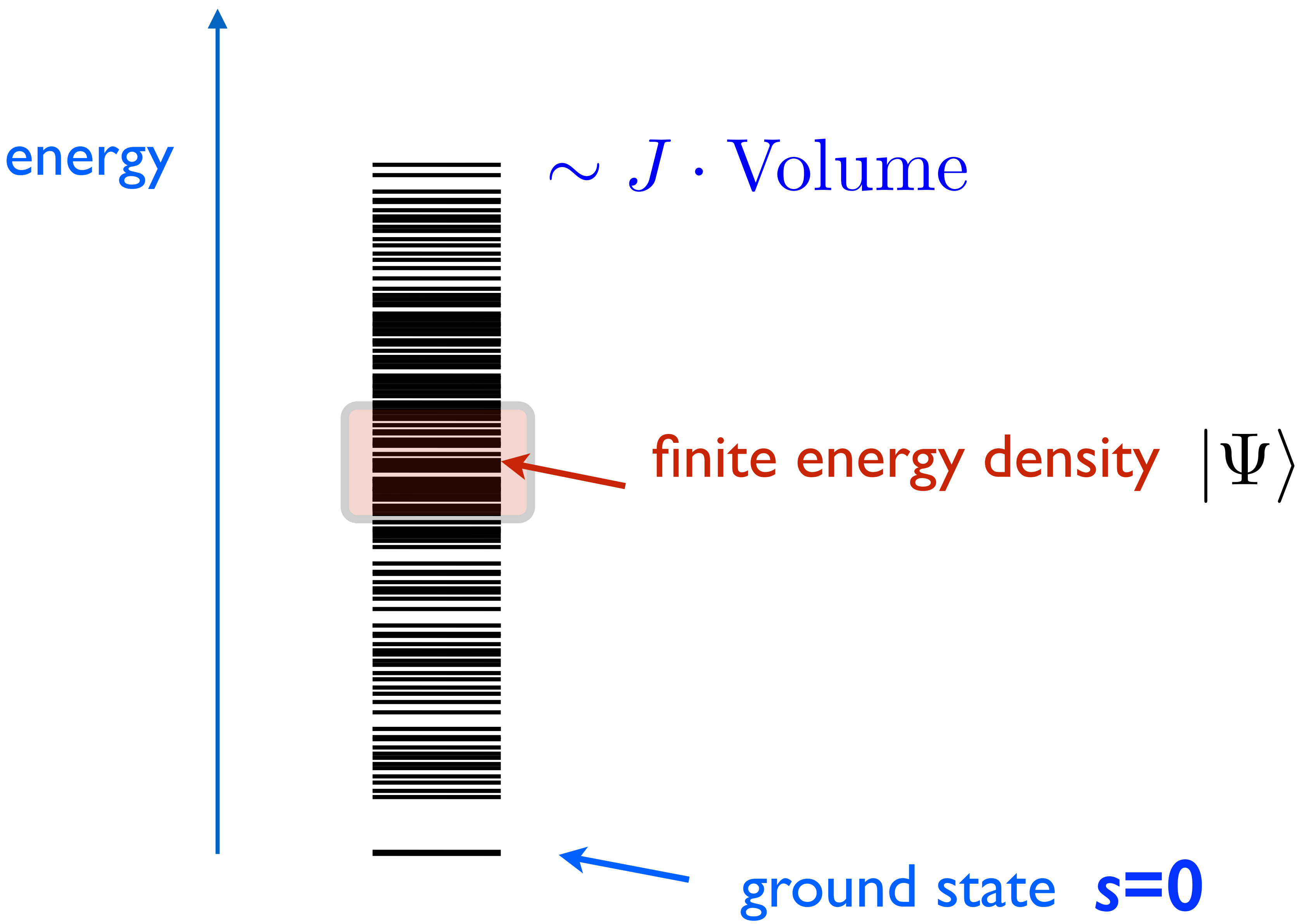

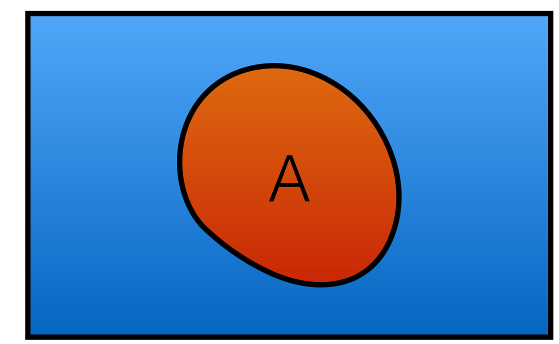

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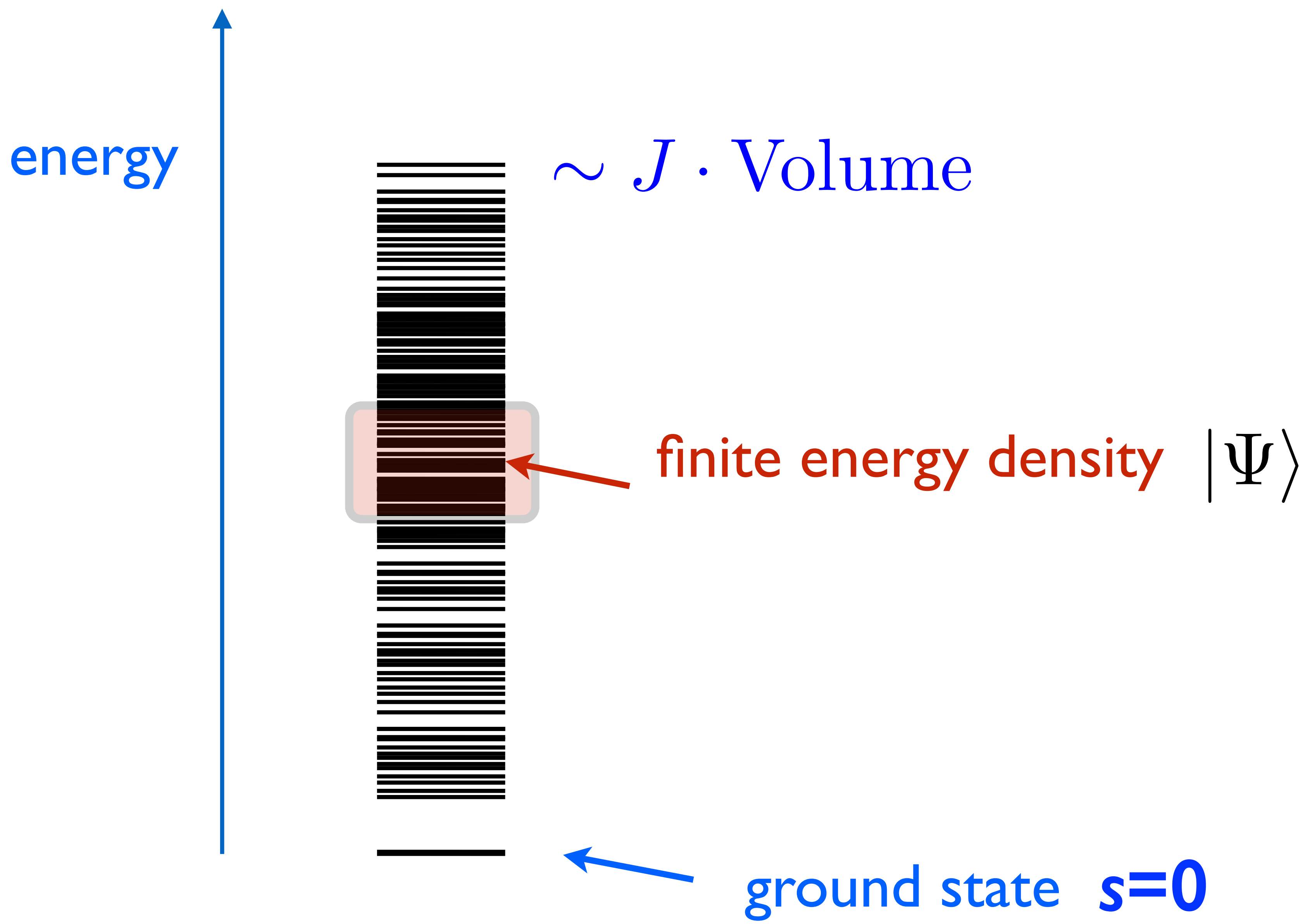

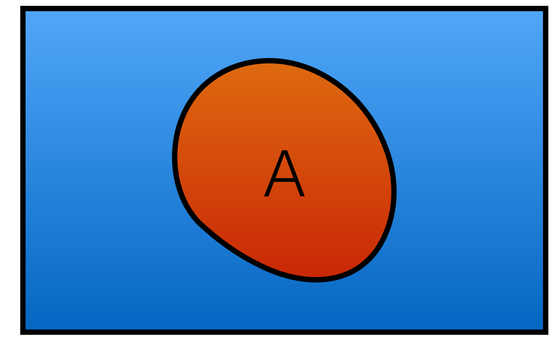

$$\rho_a = e^{-H/k_B T}$$

$$s = S_A / N_A$$

Deutsch 91, Srednicki 94

Eigenstate Thermalization Hypothesis (ETH)

Avoiding thermalization

- Hamiltonian made of commuting terms:

$$H_0 = h \sum_j \sigma_j^z$$

← Pauli z matrix on site j

all eigenstates of H are area law entangled

(could also do e.g. toric code)

- BUT unstable to small perturbations due to translation symmetry:

$$H = h \sum_j \sigma_j^z + J \sum_j \sigma_j^x \sigma_{j+1}^x + \cdots$$

finite energy density eigenstates are volume law entangled

Avoiding thermalization

- Hamiltonian made of commuting terms with *disordered* coefficients:

disordered couplings

$$H_0 = \sum_i h_i \sigma_i^z + \sum_{i,j} J_{i,j} \sigma_i^z \sigma_j^z + \ldots$$

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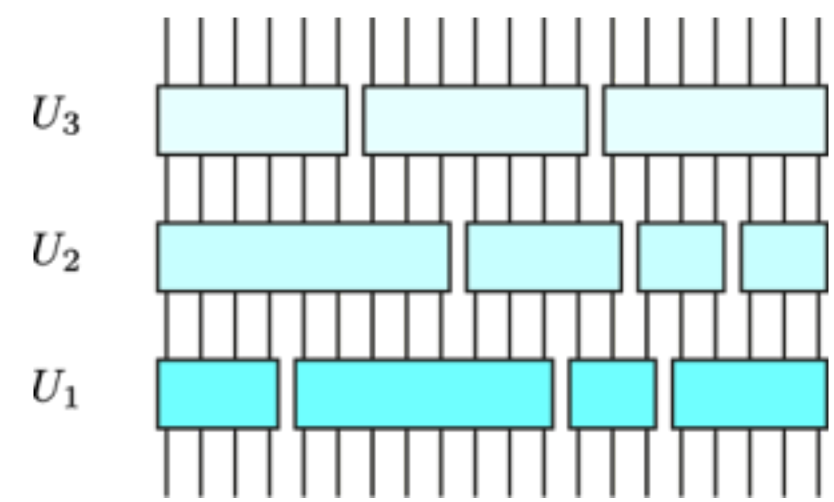

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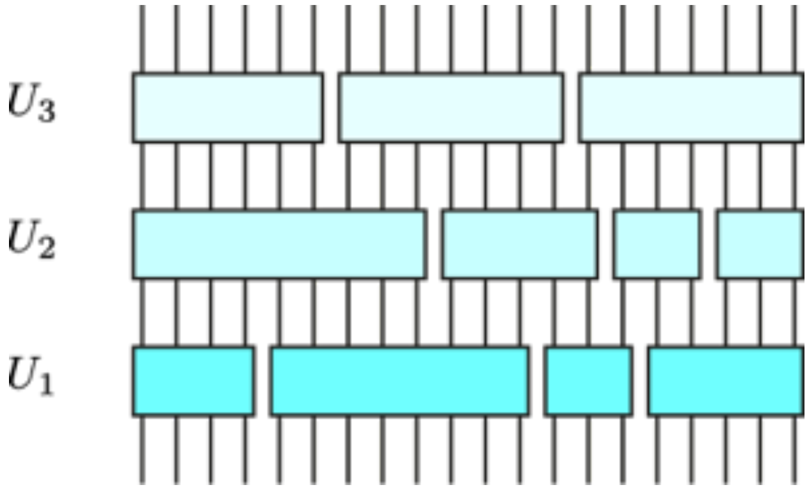

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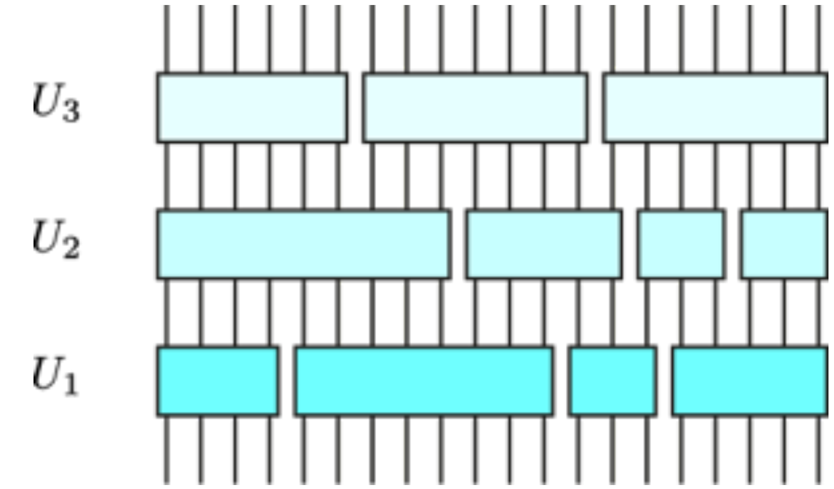

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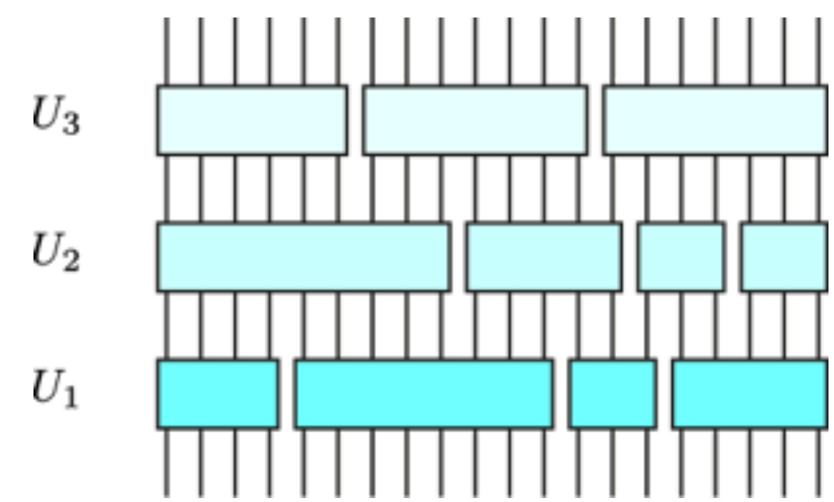

- can make H diagonal in z-basis using finite depth local unitary U

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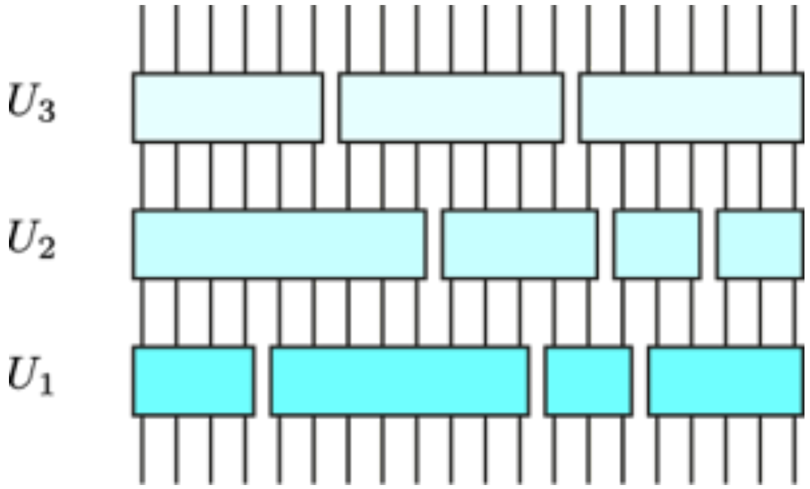

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(Imbrie)

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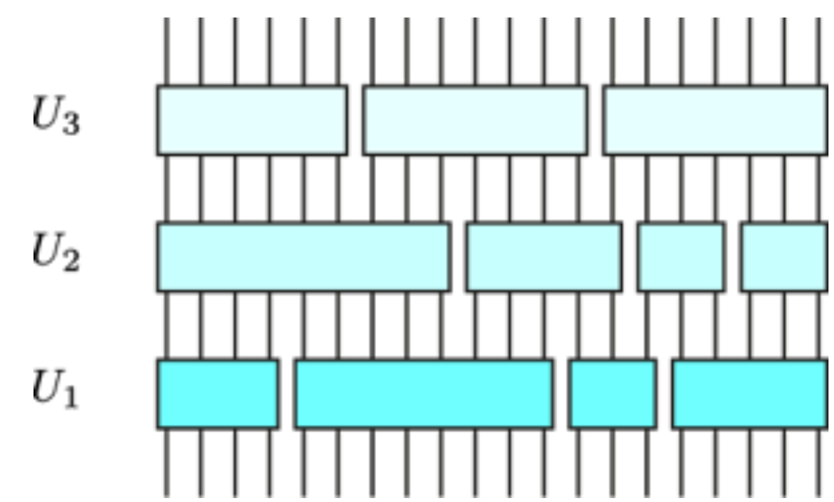

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$$U^\dagger X U$$

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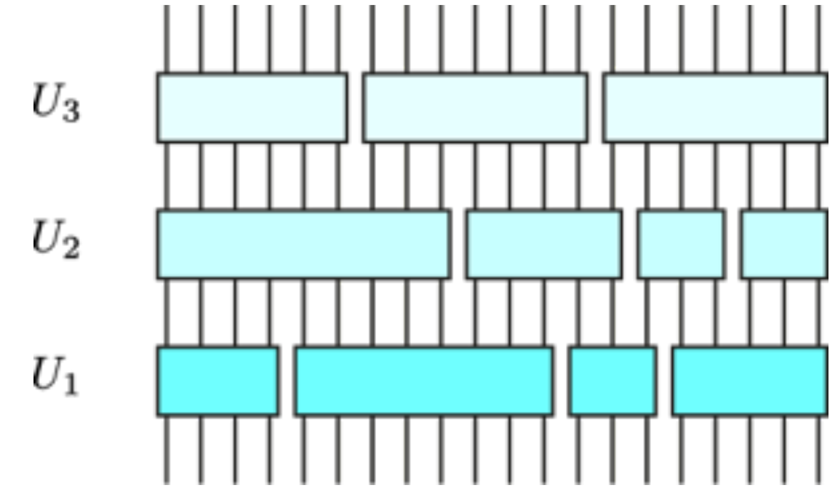


- can make H diagonal in z-basis using finite depth local unitary U

(Imbrie)

if ***X*** is a local operator, then $U^\dagger X U$ ‘dressed’ quasi-local operator.

Many-body localization

(Anderson, Mirlin et al., Basko, Aleiner, Altschuler; Oganesyan, Huse, Pal)

- can make H diagonal in z-basis using finite depth unitary U:

$$U^\dagger H U = \sum_i h'_i \tau_i^z + \sum_{ij} J'_{ij} \tau_i^z \tau_j^z + \ldots$$

- eigenstates of H are all of the form $U|\psi\rangle$; ← product state in z-basis

in particular, area law entangled - excited states `like' ground states!

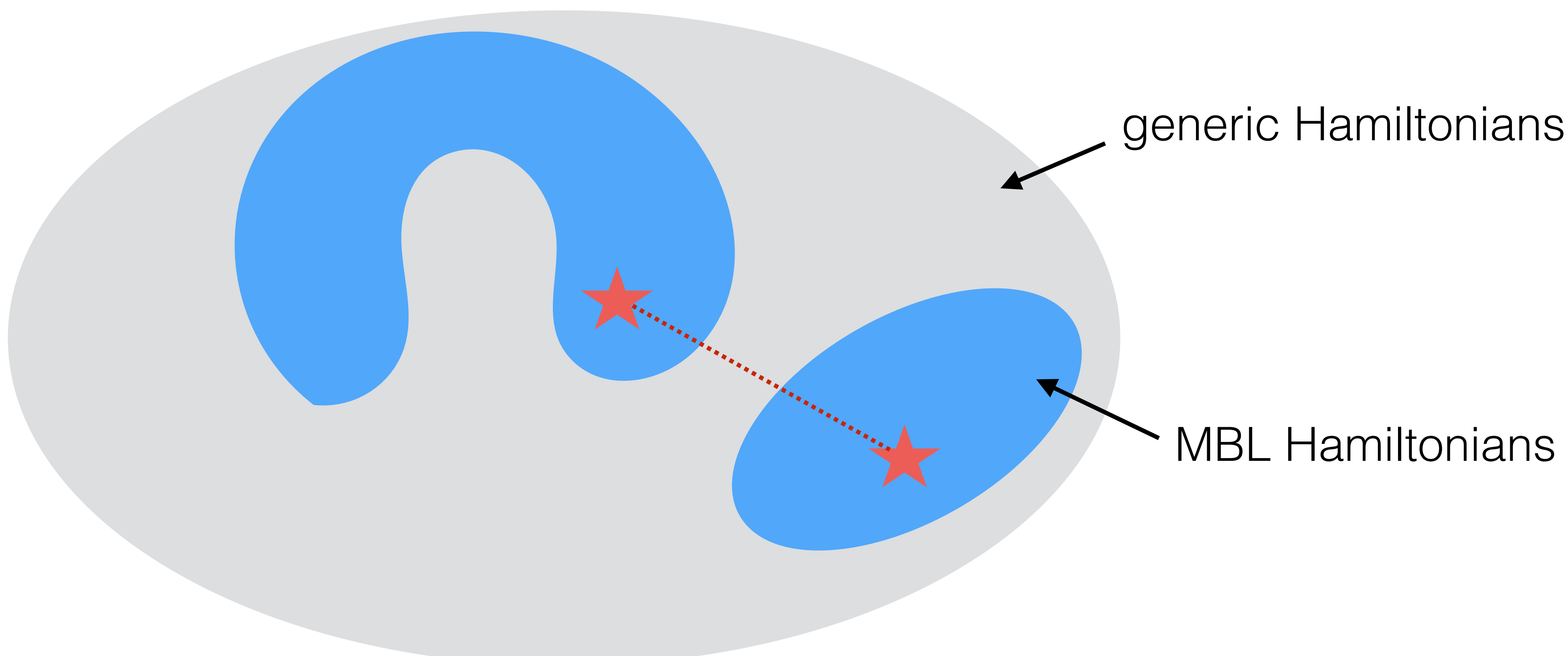
- $U \tau_i^z U^\dagger$ forms complete set of quasi-local conserved quantities

↑ `l-bits'

(Huse, Nandkishore, Oganesyan
Serbyn, Papic, Abanin,
Vosk&Altman)

Many-body localization and topological phases

- replace ‘gapped’ with ‘many-body localized’ (MBL)



- topological order / symmetry protected topological phases at finite energy density

  (Bahri, Vosk, Altman, AV; Chandran, Khemani, Laumann, Sondhi, Huse, Nandkishore, Oganesyan, Pal)

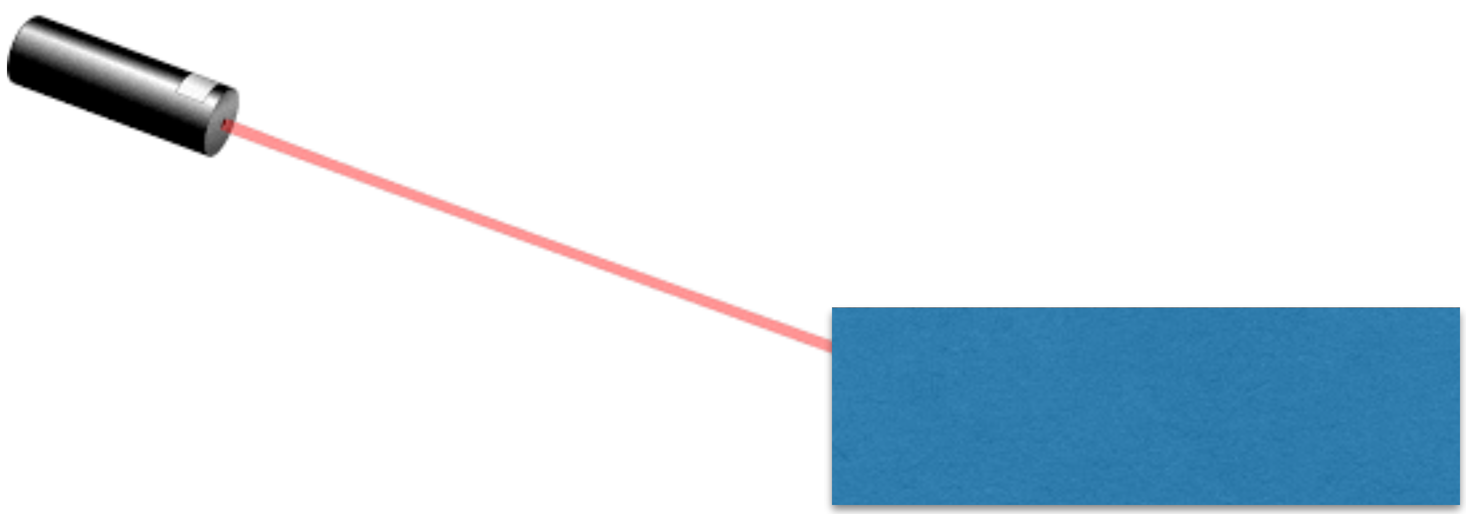
- BUT no chiral (quantum hall) phases allowed in MBL excited states. Commuting projectors incompatible with thermal Hall

- (Kitaev, Levin, Potter-AV)

Floquet driving

- periodic time dependent Hamiltonian:

$$H(t+T) = H(t) \qquad U_F = T\exp\left(i\int_0^T H(t)dt\right)$$



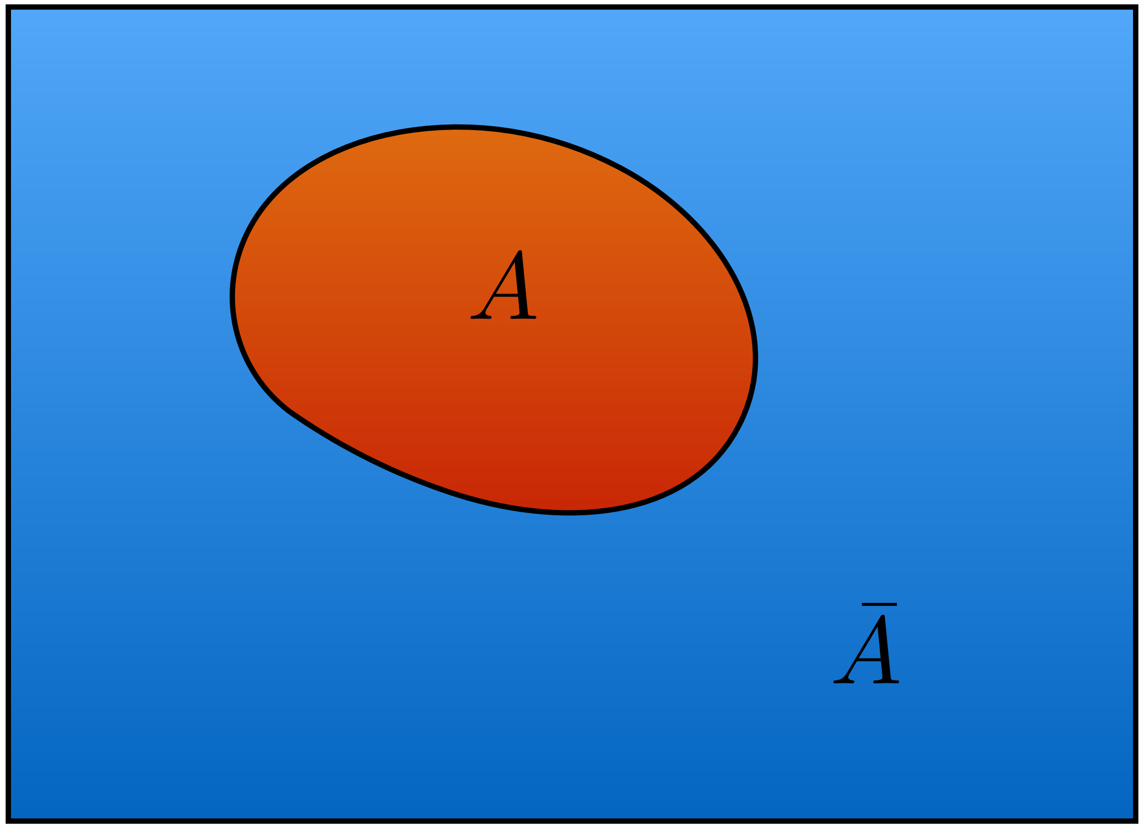
- diagonalize the ‘Floquet unitary’ U_F

  Energy not conserved.

  Only `quasi-energy’ mod $\hbar\omega = \frac{h}{T}$

Floquet systems: heating problem

- generically, system will absorb energy until it is at infinite temperature:



$$\rho_A(t) = \mathrm{Tr}_{\bar{\mathrm{A}}} \left|\Psi(\mathrm{t})\right\rangle\left\langle\Psi(\mathrm{t})\right|$$

$$\rho_A(t) \to \mathbf{1} \quad \left(= \frac{1}{Z} e^{-\beta H}\right)$$

$$\text{as } \beta \to 0$$

- entropy has been maximized,
- no energy constraint.
- Temperature ->∞

MBL in Floquet systems:

- MBL can be stable upon turning on a time dependent periodic perturbation:

Ponte, Papic, Huveneers, Abanin;
Lazarides, Das, Moessner

$$U_F = e^{-iTH_{\mathrm{eff}}}$$

with

$$U^\dagger H_{\mathrm{eff}} U = \sum_i h'_i \sigma^z_i + \sum_{i,j} J'_{i,j} \sigma^z_i \sigma^z_j$$

- schematically,

$$U_F = \prod_\alpha U_\alpha$$

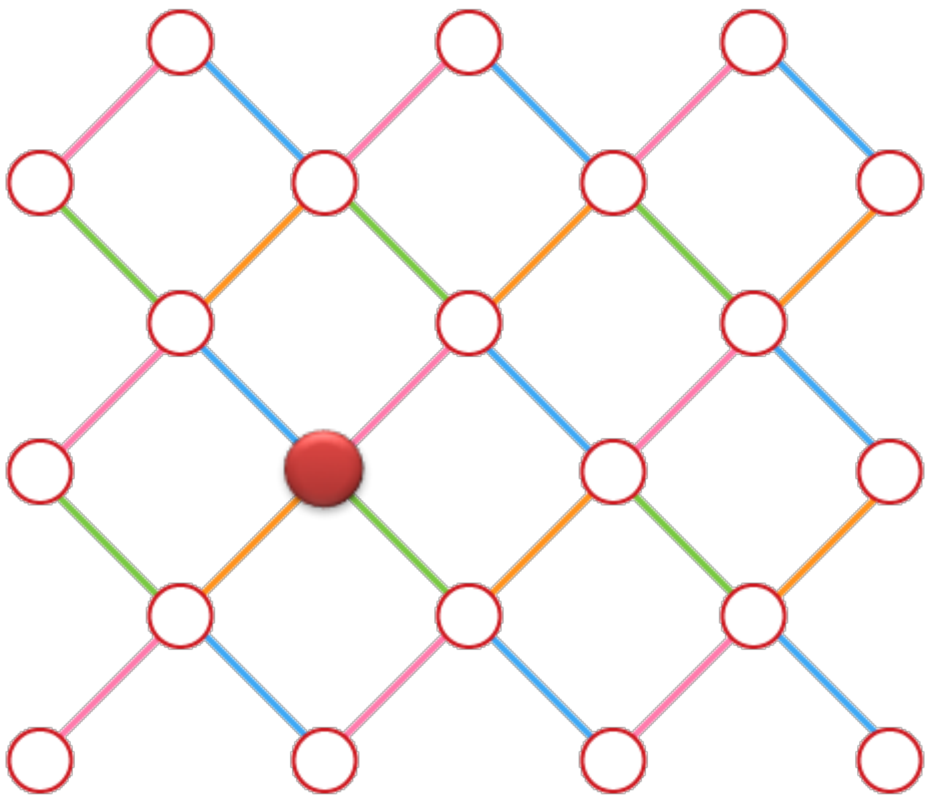
quasi-local commuting unitaries

- Can we find MBL Floquet phases that have no equilibrium analogue? What distinguishes them? No symmetries.

Floquet SPTs in 1D & 3D: Else, Bauer, Nayak. Kayserlingk, Sondhi, Potter, Morimoto, AV. Potter, AV, Fidkowski.
Free fermions (here bosons/Spins): Kitagawa, Demler, Rudner,Lindner, Berg, Levin. Rafael. Harper, Roy.

MODEL of a CHIRAL Floquet phase:

$U = U_1\ U_2\ U_3 U_4$ SWAP operation along different links



EDGE: Advances one unit in each period

Rudner,Lindner, Berg, Levin.

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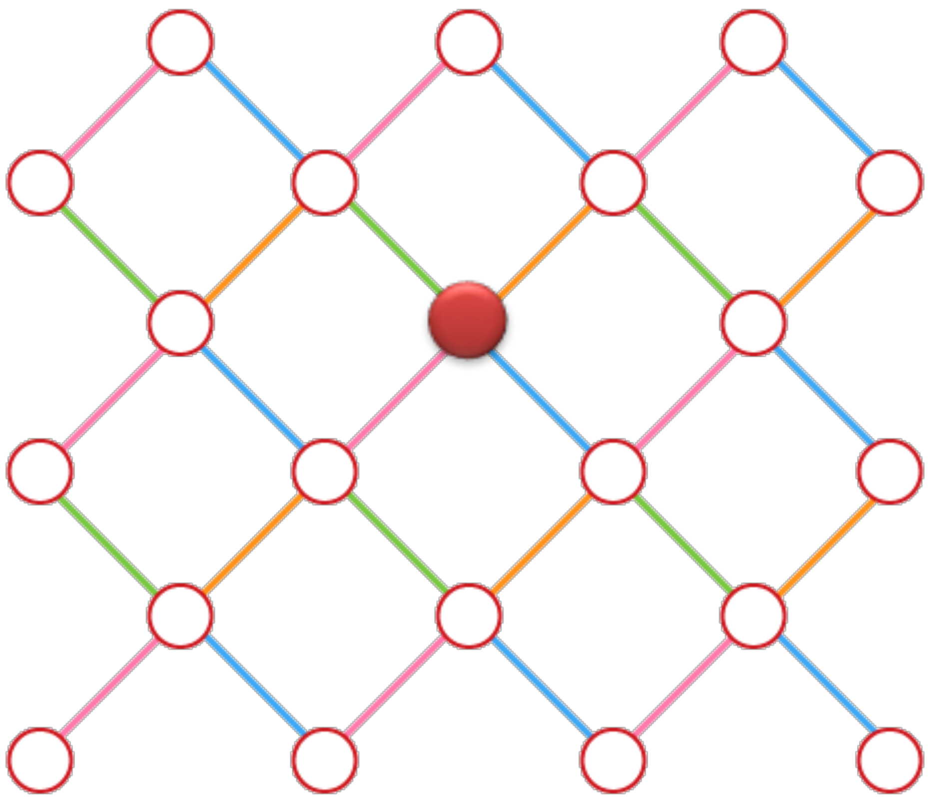

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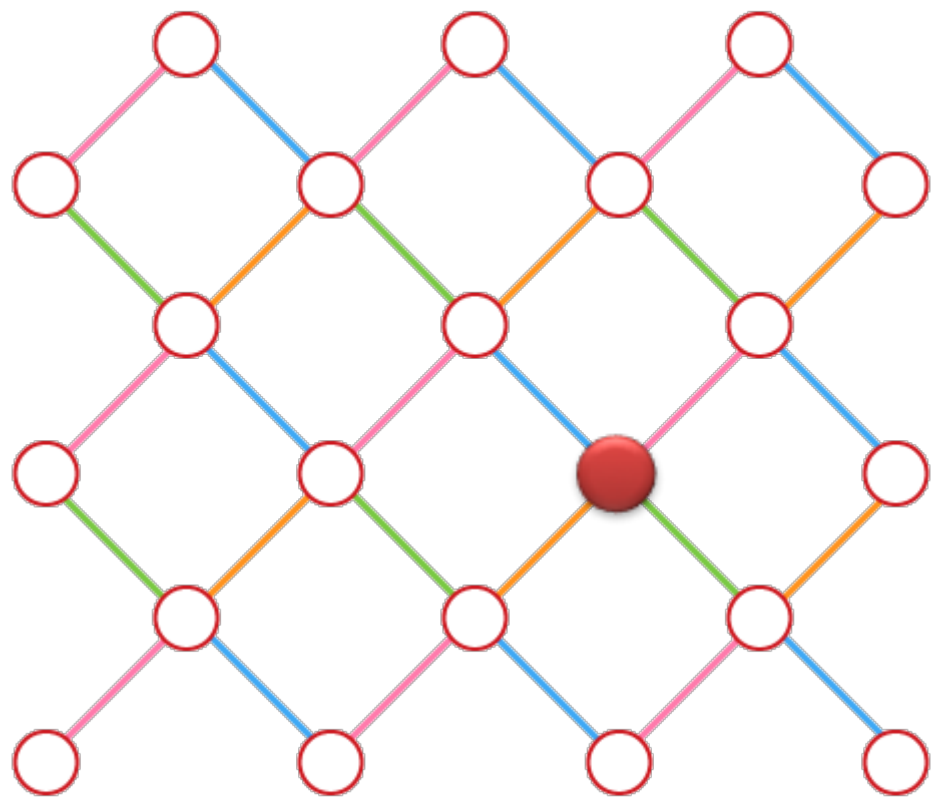

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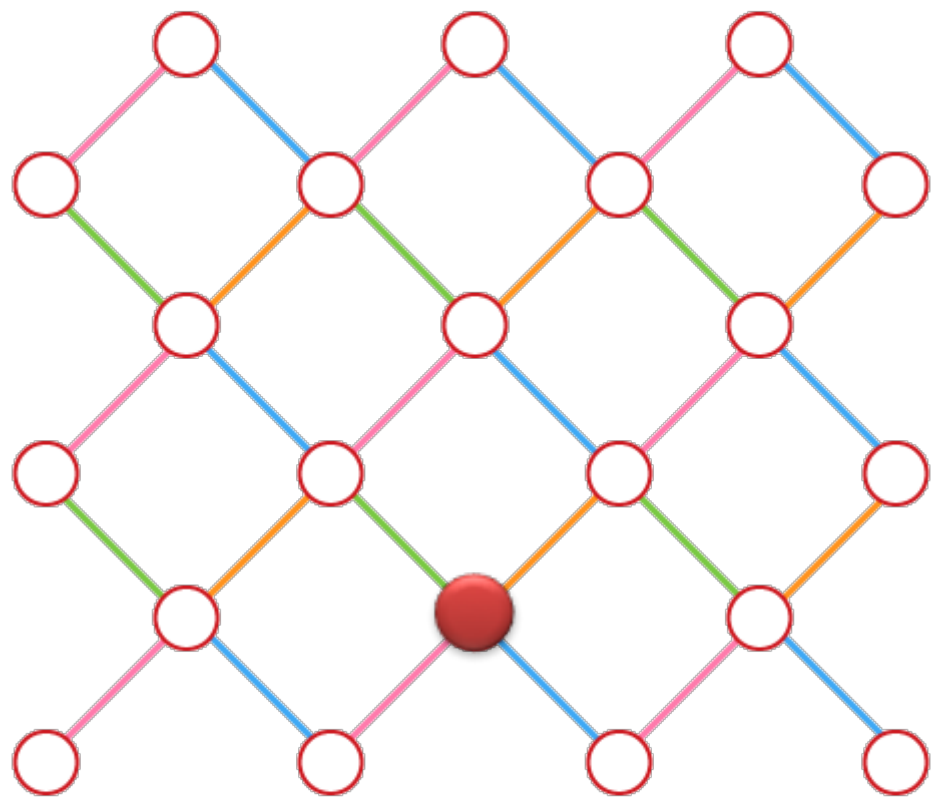

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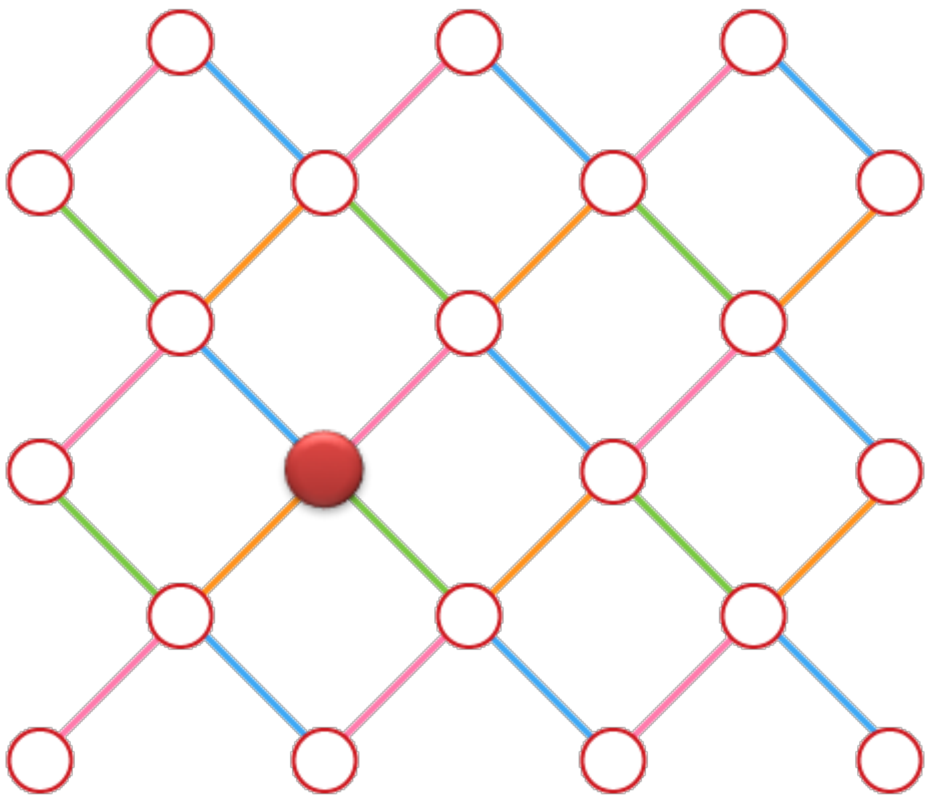

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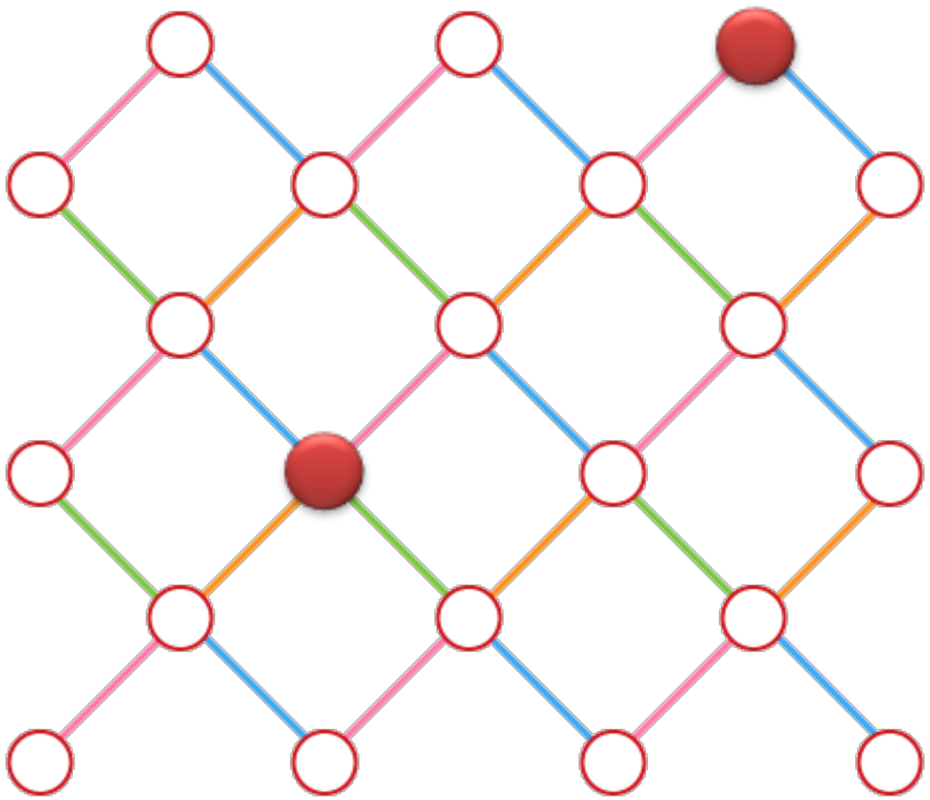

EDGE: Advances one unit in each period

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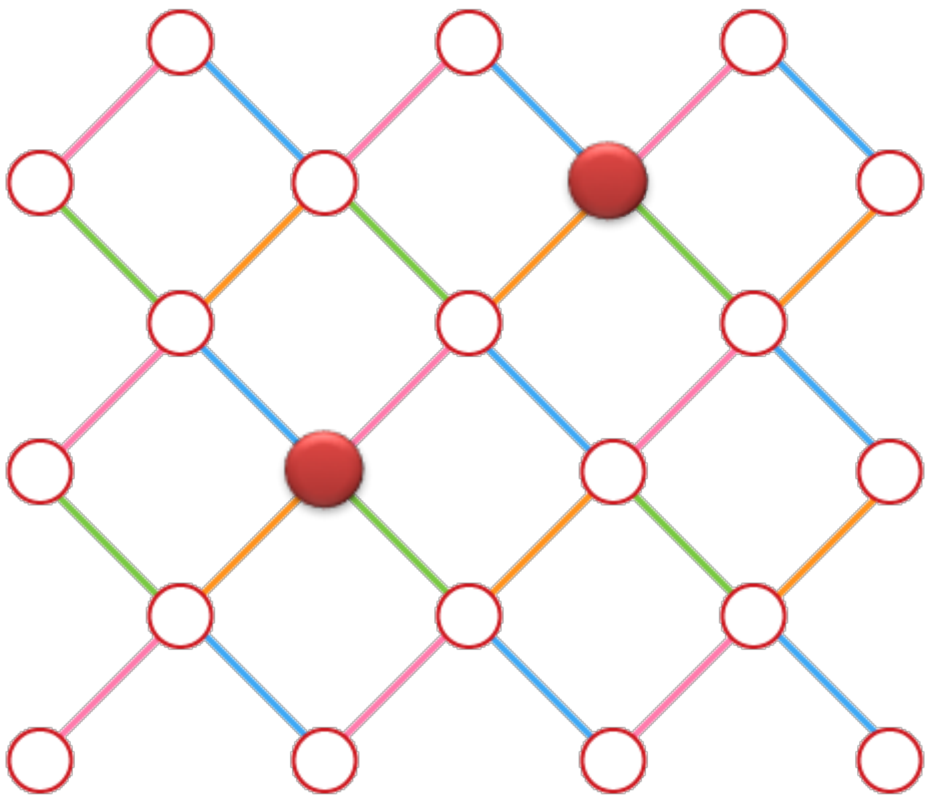

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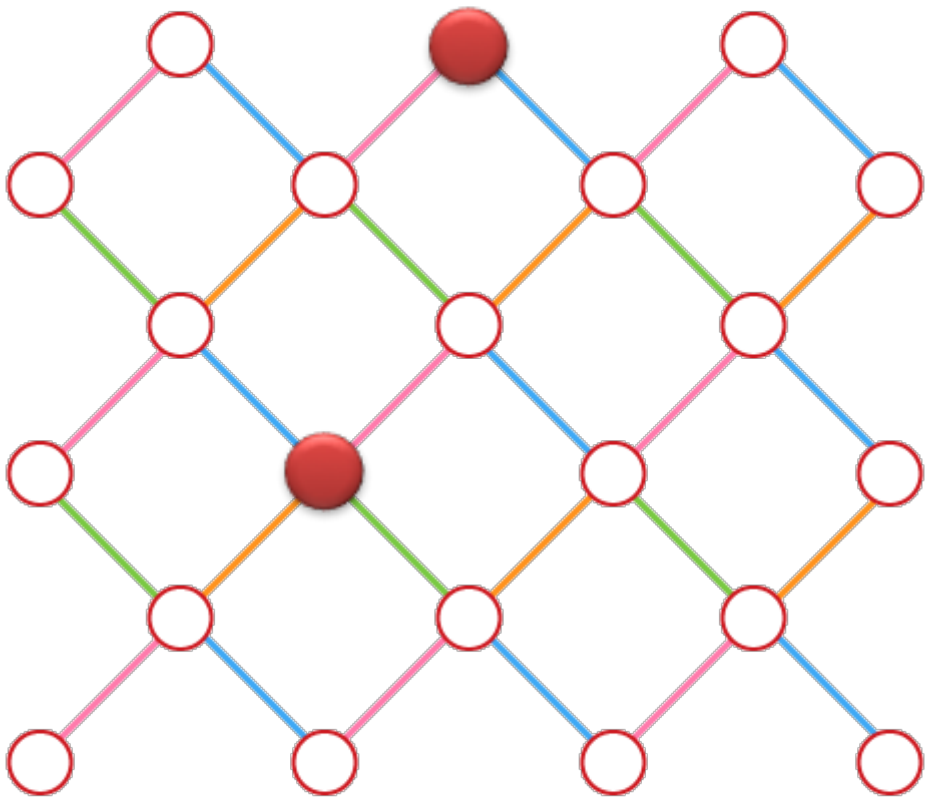

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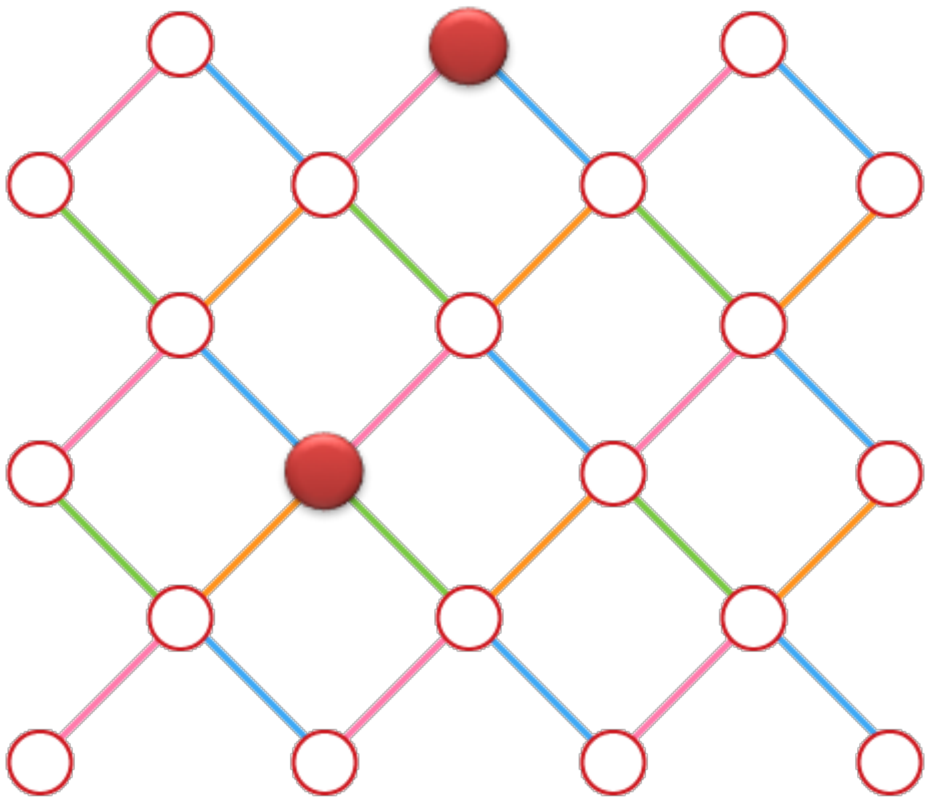

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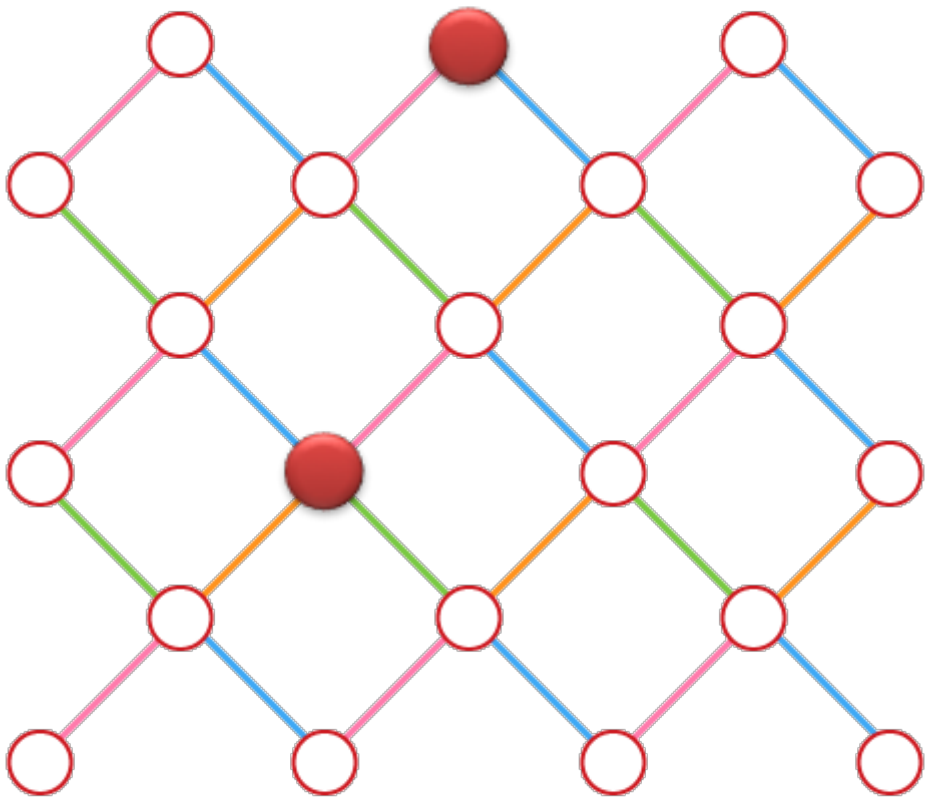

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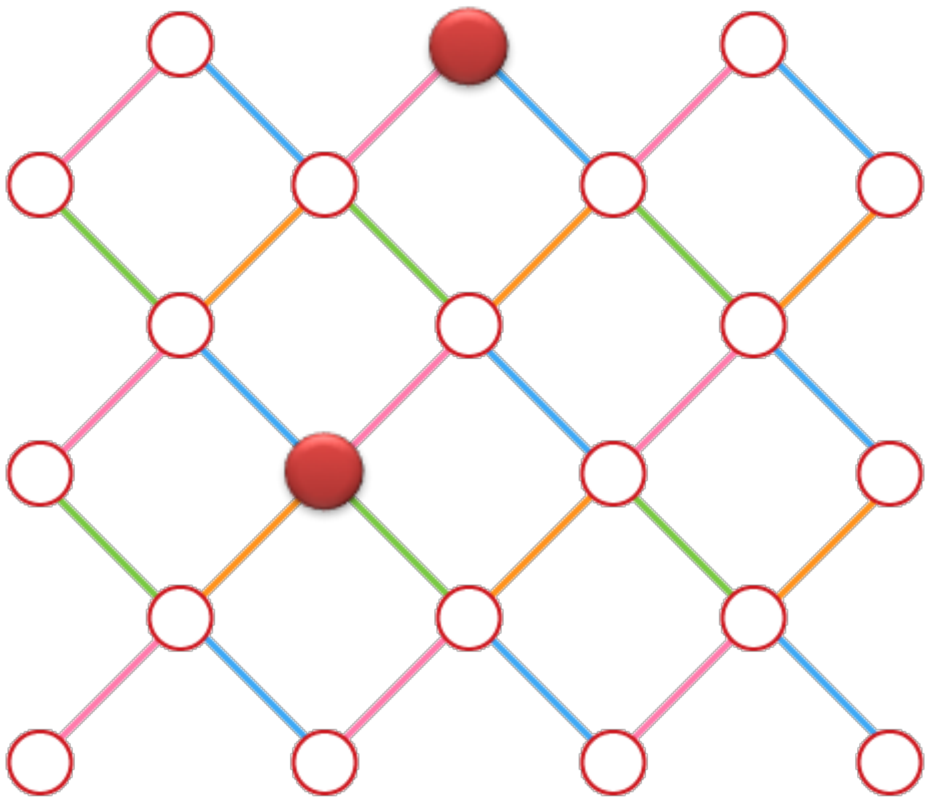

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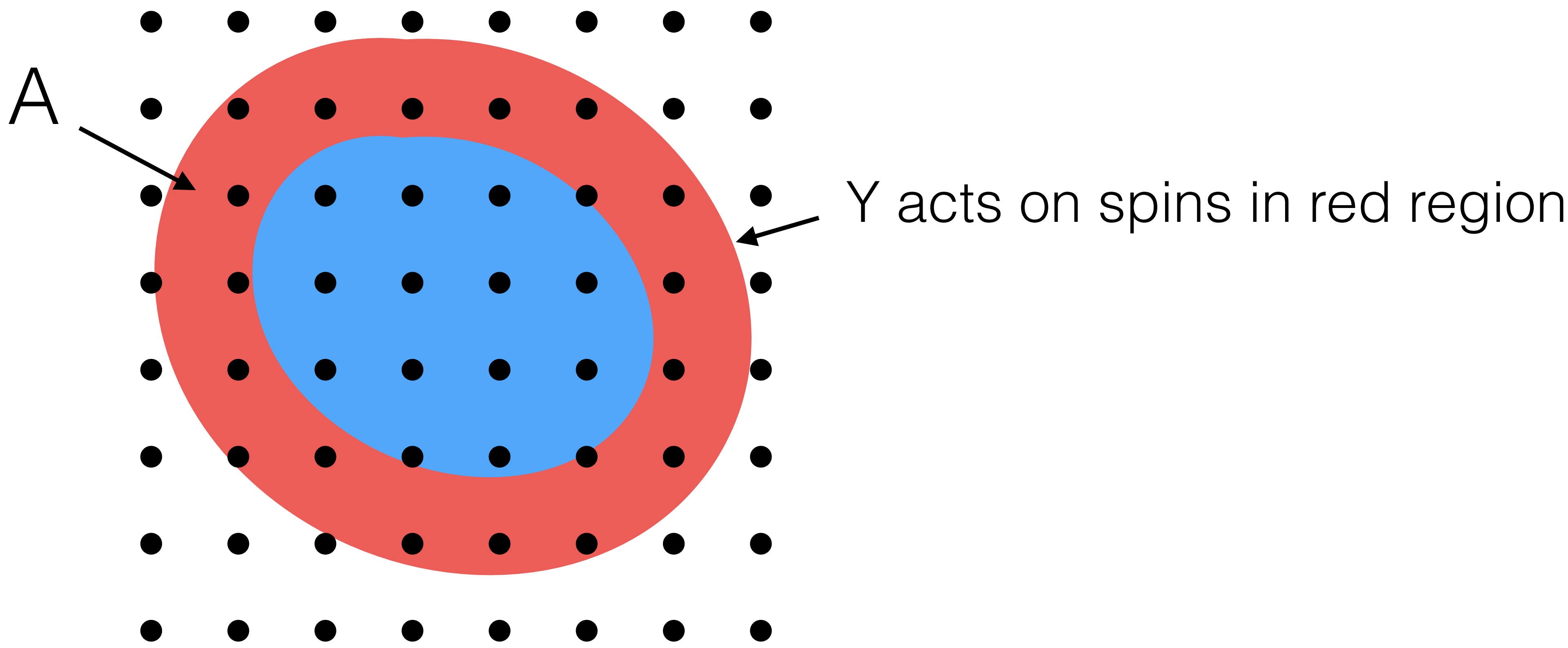
EDGE: Advances one unit in each period

Independent of particle distribution!

Note: if SWAPs are not perfect - heating. MBL gives a stable phase.

Rudner,Lindner, Berg, Levin.

Classification of Chiral Unitaries



- Y is locality preserving: for any local operator $\mathcal{O}$,
  $Y^\dagger \mathcal{O} Y$ is a (quasi)-local operator supported nearby.

- is Y the Floquet operator of some (quasi)-local 1d Hamiltonian?
- OR is it anomalous - NO local 1D Hamiltonian such that:

$$Y_{1D} = e^{-i \int_0^T H_{1D}(t')dt'}$$

Classification of Locality Preserving 1D Unitaries

Commun. Math. Phys. 310, 419–454 (2012)
Digital Object Identifier (DOI) 10.1007/s00220-012-1423-1

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D. Gross[1,2], V. Nesme[1,3], H. Vogts[1], R.F. Werner[1]

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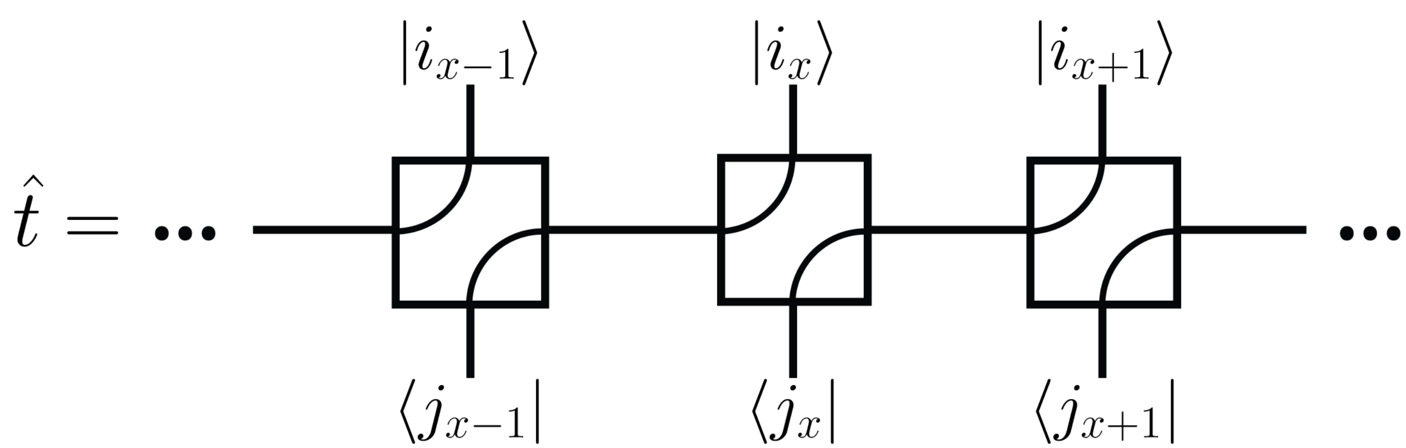

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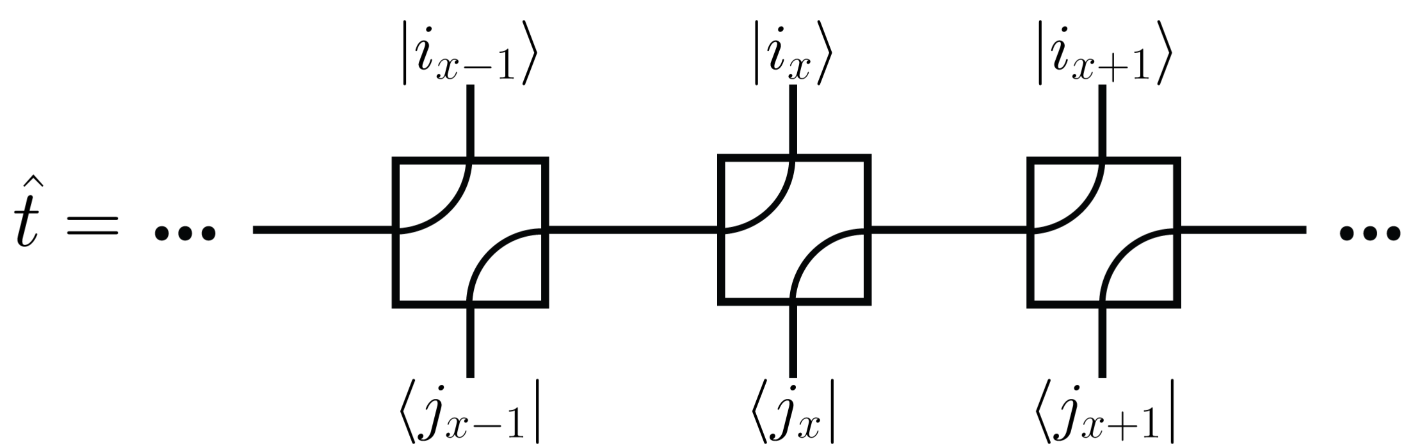

Dimension of microscopic Hilbert space enters

e.g. p=2, q=3: a qu***b***it cannot cancel a qu***tr***it!

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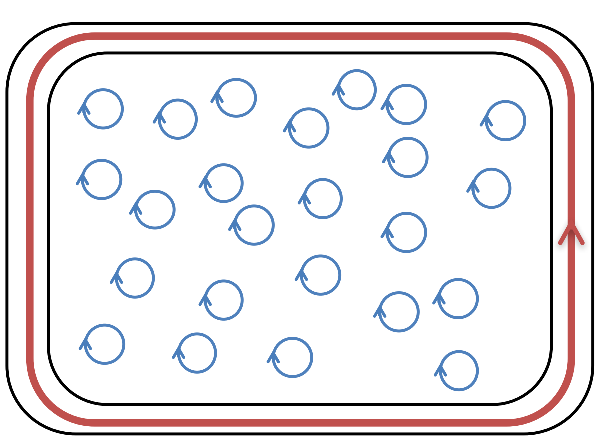
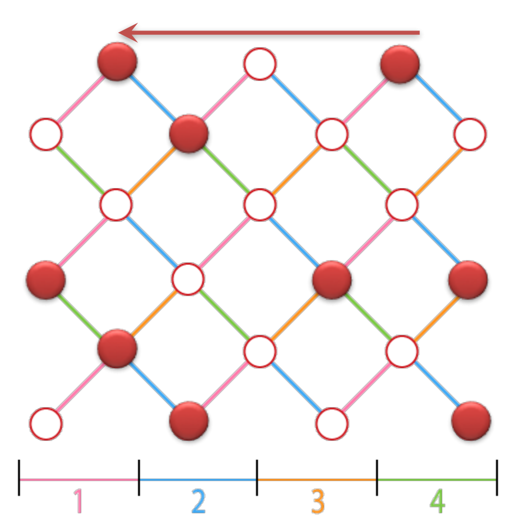
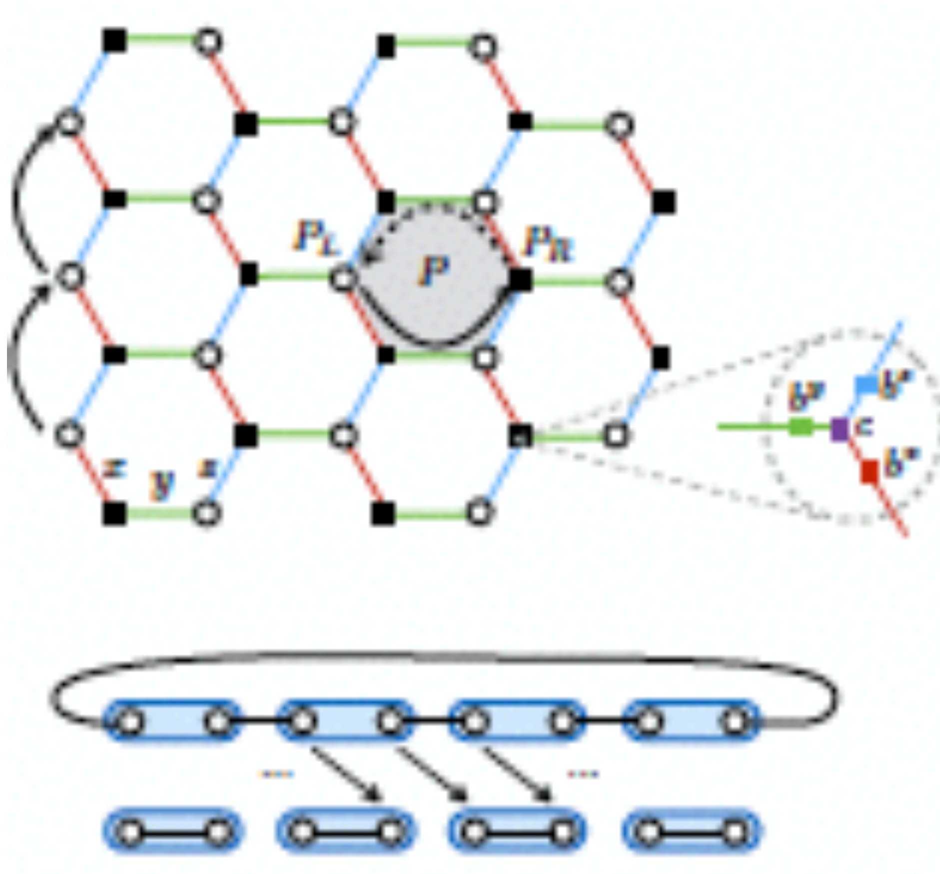
Analogy with Quantum Hall Effect

zero temperature 2d topological phase		MBL Floquet system
Bulk gap	⟷	Bulk MBL
Low energy field theory for the 1d edge	⟷	Locality preserving unitary Y on the 1d edge
lack of 1d UV completion for low energy edge theory (e.g. chiral anomaly)	⟷	Impossibility of writing Y as the Floquet evolution of a 1d driving Hamiltonian





Floquet Enriched Toric Code



Radical chiral Floquet phases in a periodically driven Kitaev model and beyond

Hoi Chun Po,[1,2] Lukasz Fidkowski,[3,4] Ashvin Vishwanath,[1,2] and Andrew C. Potter[5]

$$U(T) = e^{-ih^{[z]}} e^{-ih^{[y]}} e^{-ih^{[x]}}, \quad h^{[j]} = \frac{\pi J}{4} \sum_{\langle \mathbf{r}\mathbf{r}' \rangle \in j} S_{\mathbf{r}}^j S_{\mathbf{r}'}^j$$

Bulk Eigenstates have Z_2 topological order.

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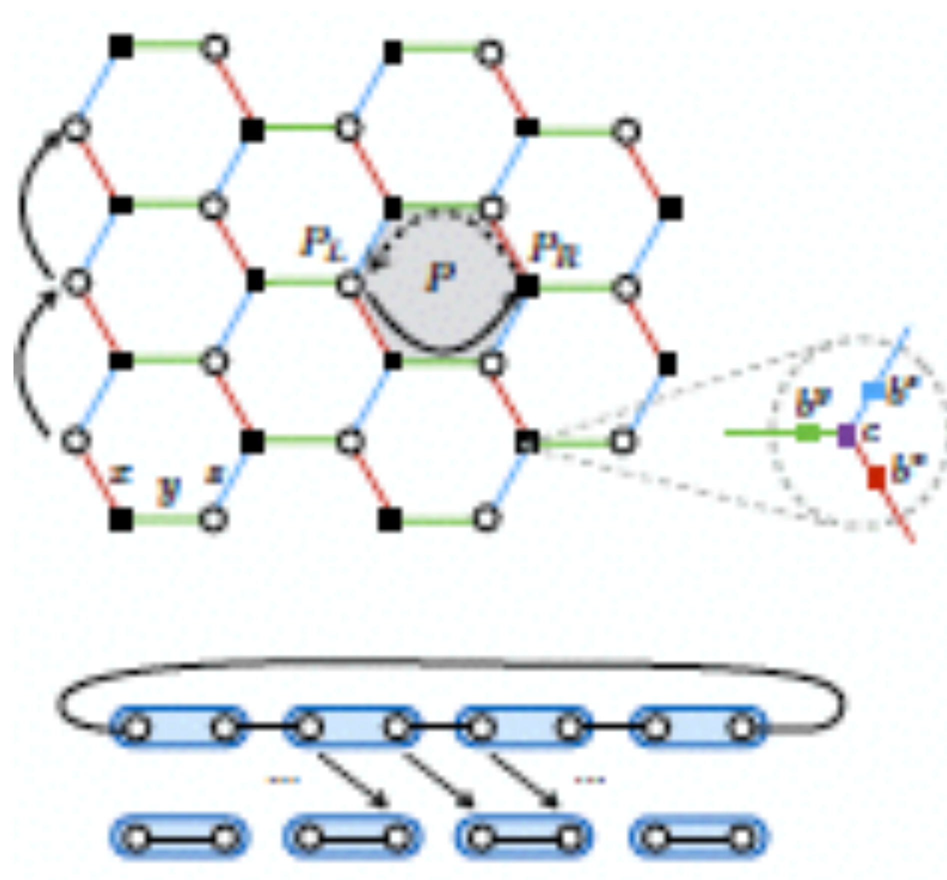

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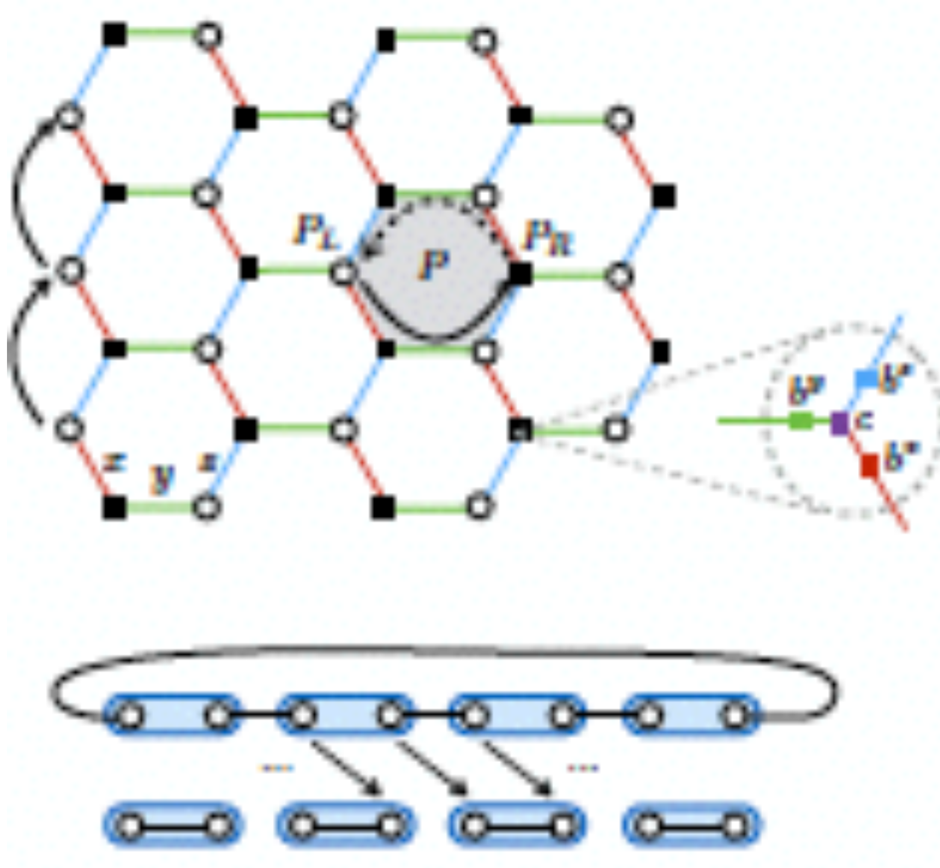

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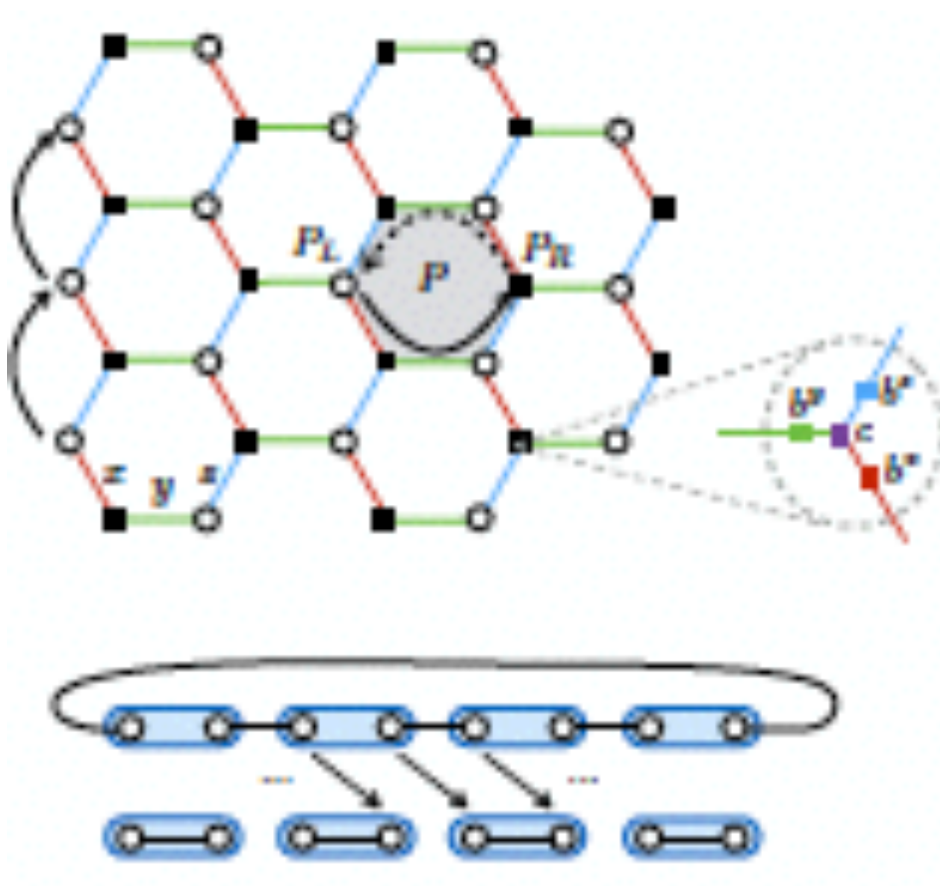

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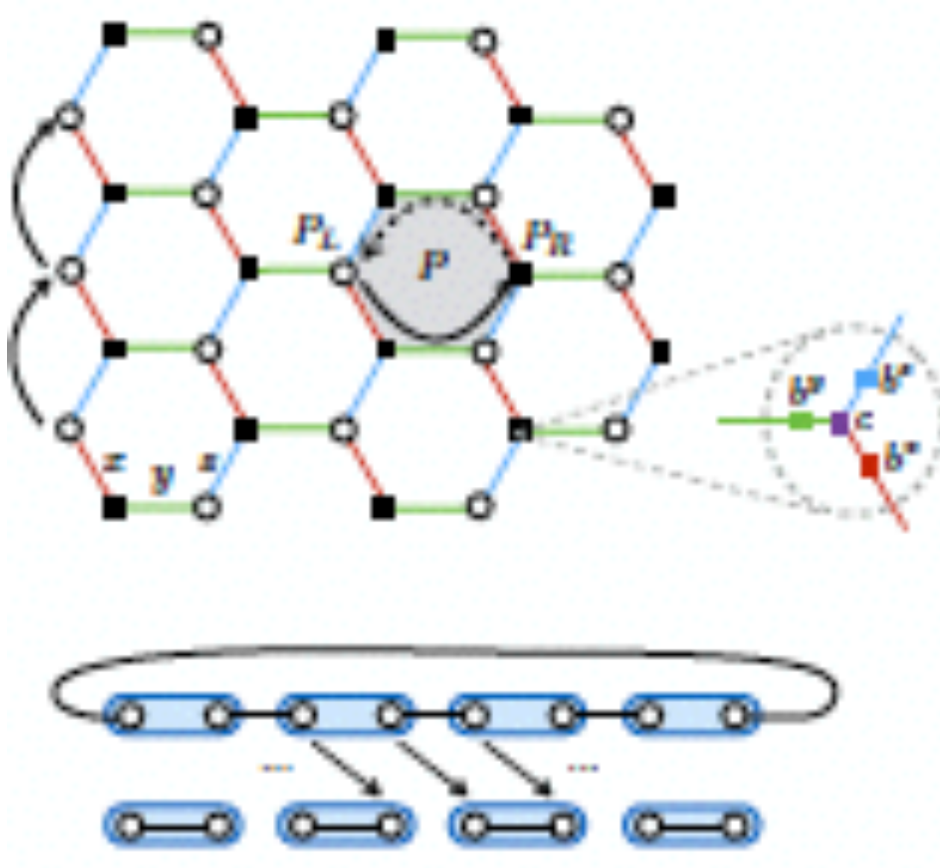

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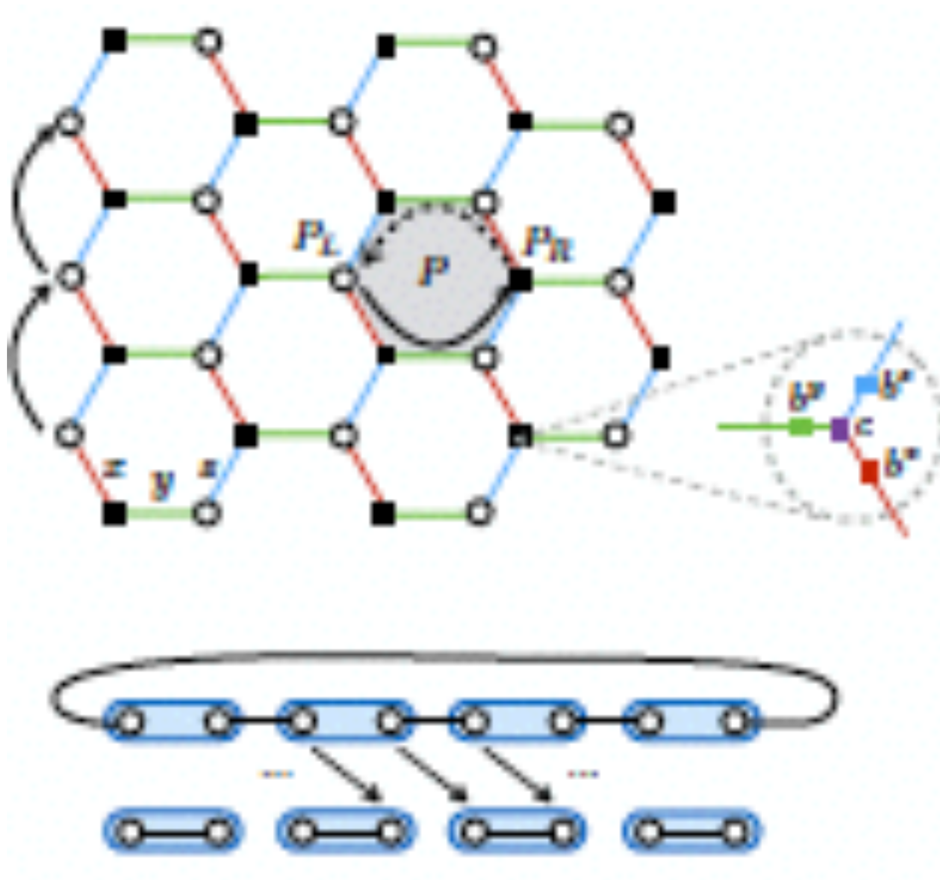

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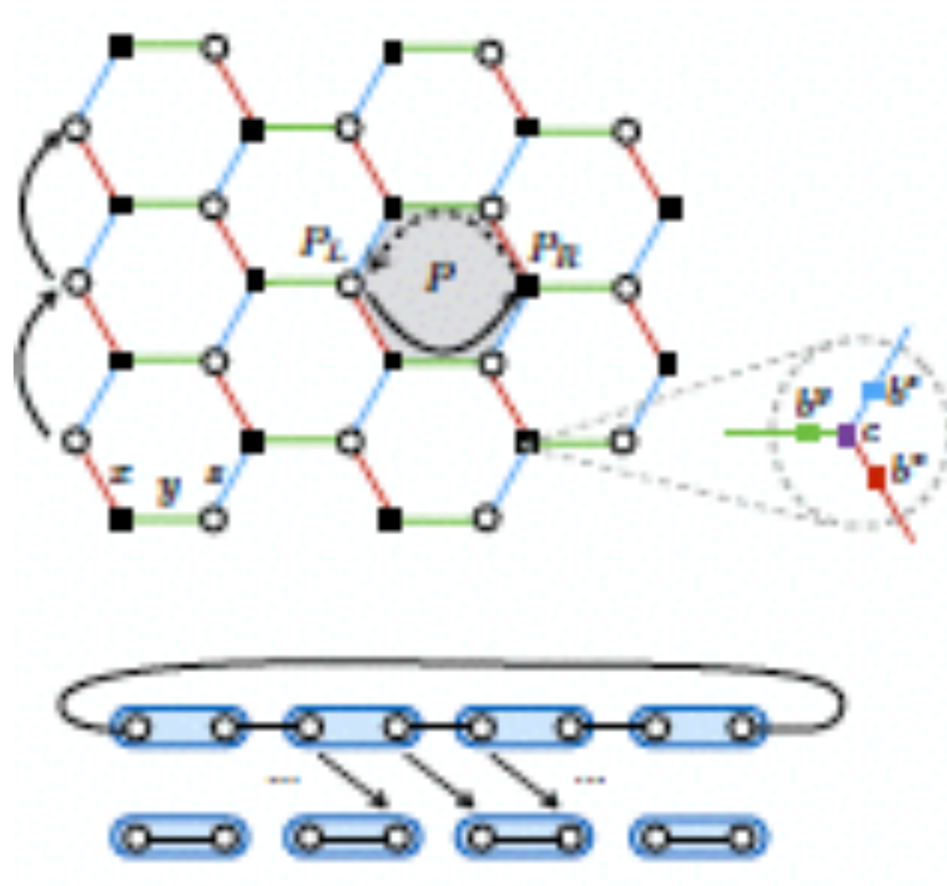

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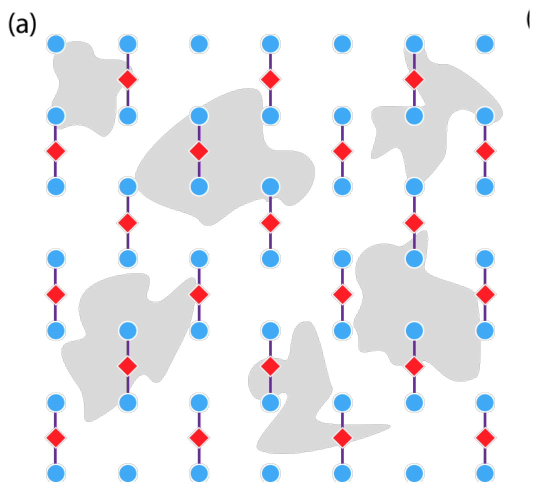
experiment: Monroe group (trapped ions), Lukin group (NV centers)

Future Directions

Towards Experimental realization - in shaken optical lattices (with quasi periodic disorder). What to measure? Could this be an entanglement `bus'?



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- incorporate fermions and symmetries

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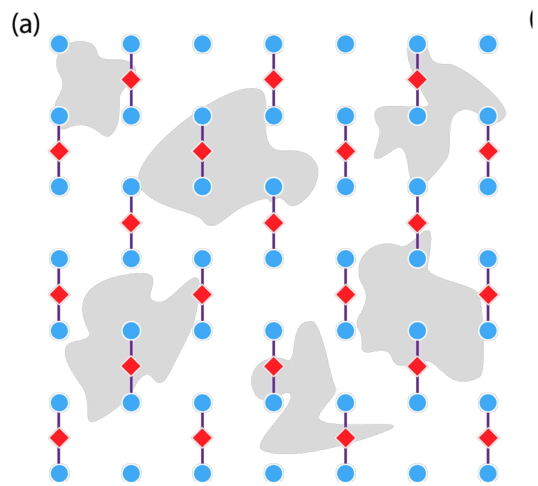

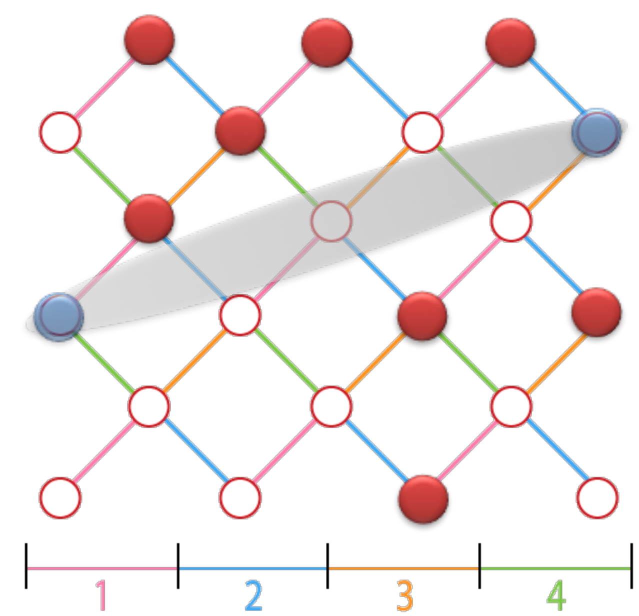

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