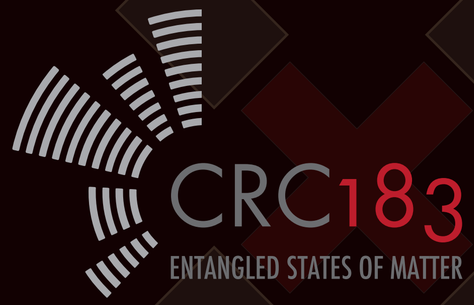
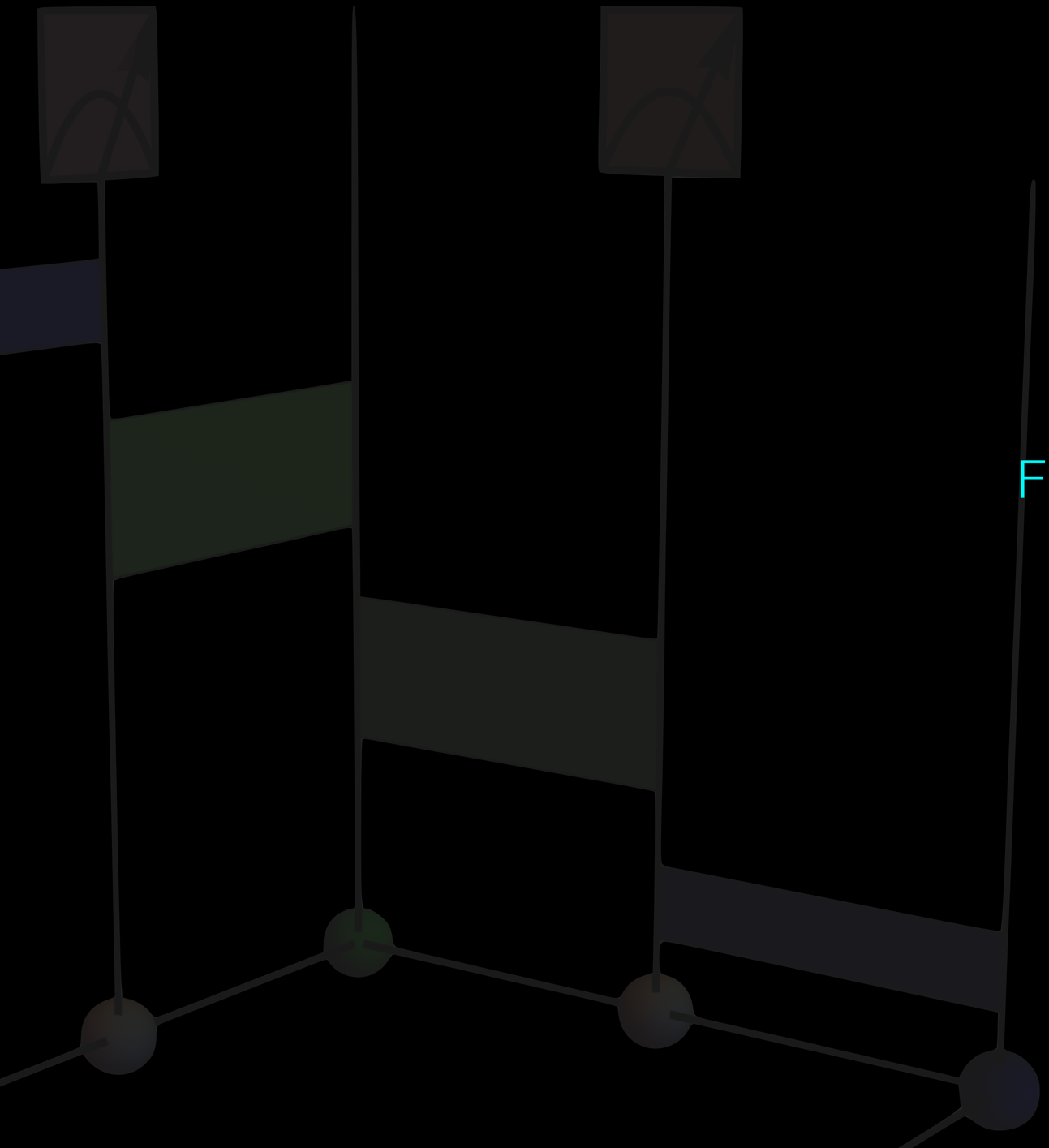
Qubit Fractionalization and Emergent Majorana Liquids in Quantum Circuits



Simon Trebst
University of Cologne

Fractionalization and Emergent Gauge Fields in Quantum Matter

ICTP Trieste, December 2023



Fractionalization & Emergent Gauge Fields

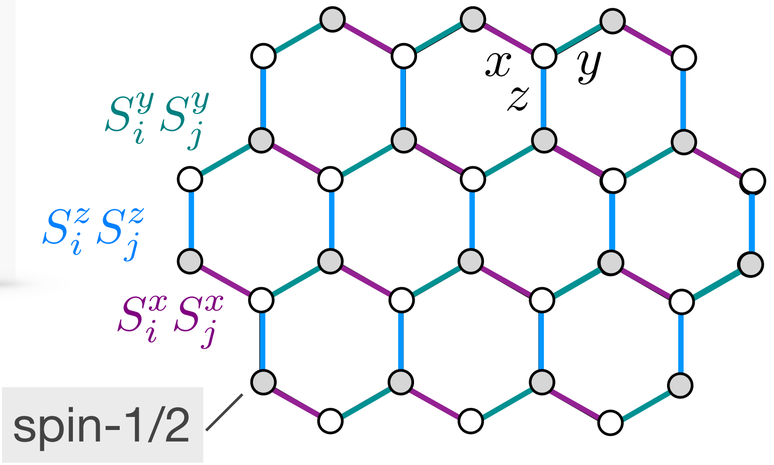
in **Quantum Matter**

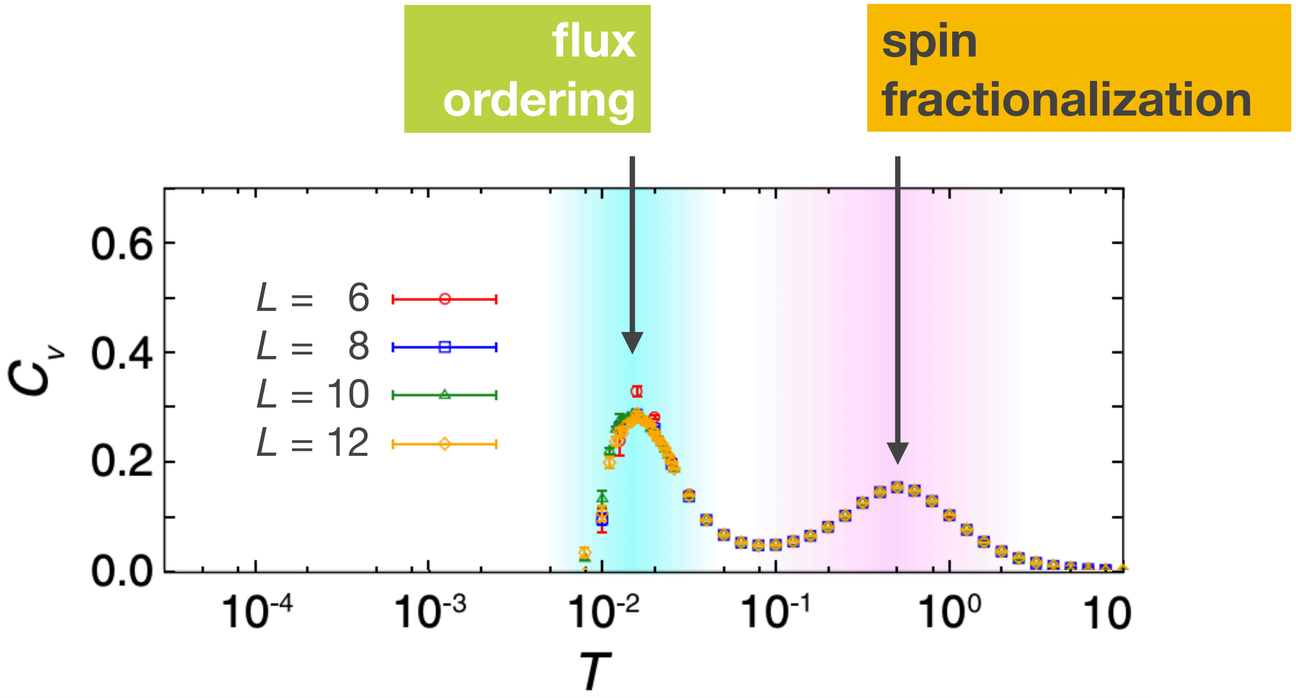
finite-temperature Kitaev spin liquids

PRL **113,** 197205 (2014) PHYSICAL REVIEW LETTERS week ending 7 NOVEMBER 2014

Vaporization of Kitaev Spin Liquids

Joji Nasu,[1] Masafumi Udagawa,[2] and Yukitoshi Motome[2]
[1]*Department of Physics, Tokyo Institute of Technology, Ookayama, 2-12-1, Meguro, Tokyo 152-8551, Japan*
[2]*Department of Applied Physics, University of Tokyo, Hongo, 7-3-1, Bunkyo, Tokyo 113-8656, Japan*
(Received 24 July 2014; revised manuscript received 9 October 2014; published 7 November 2014)





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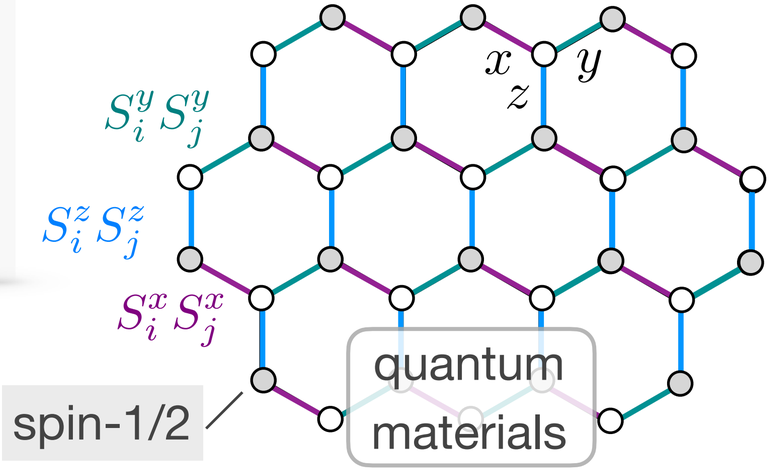

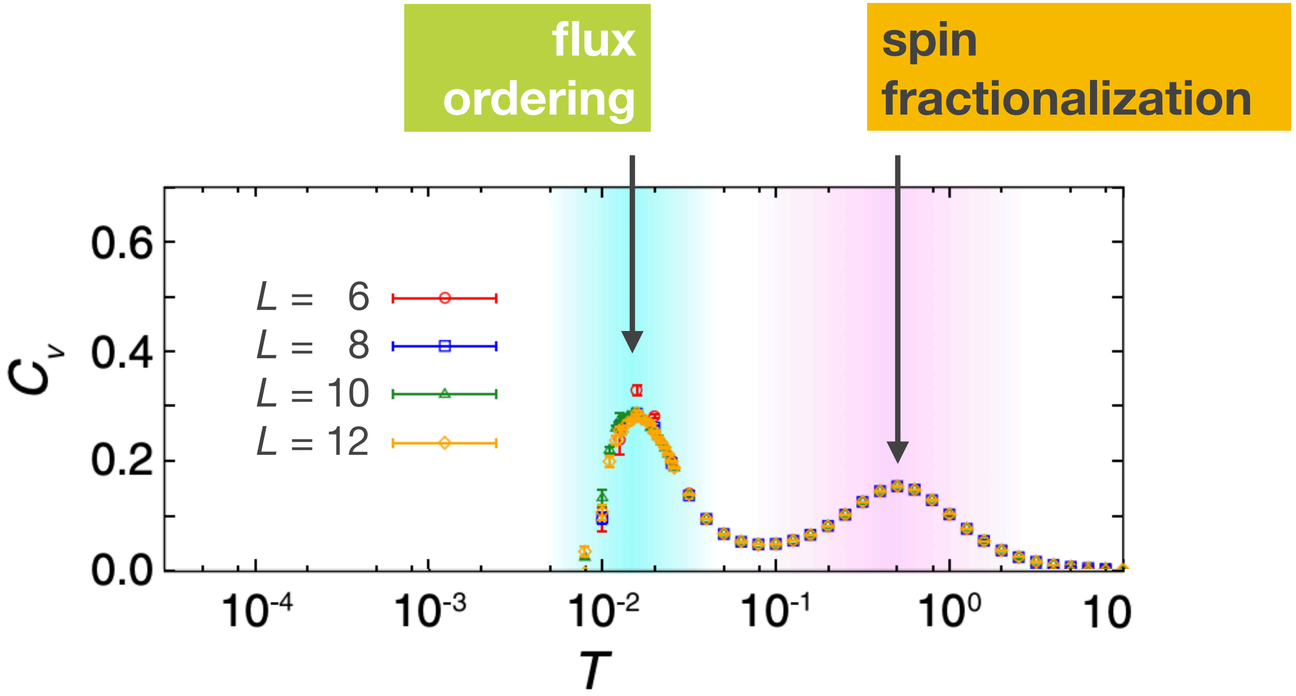

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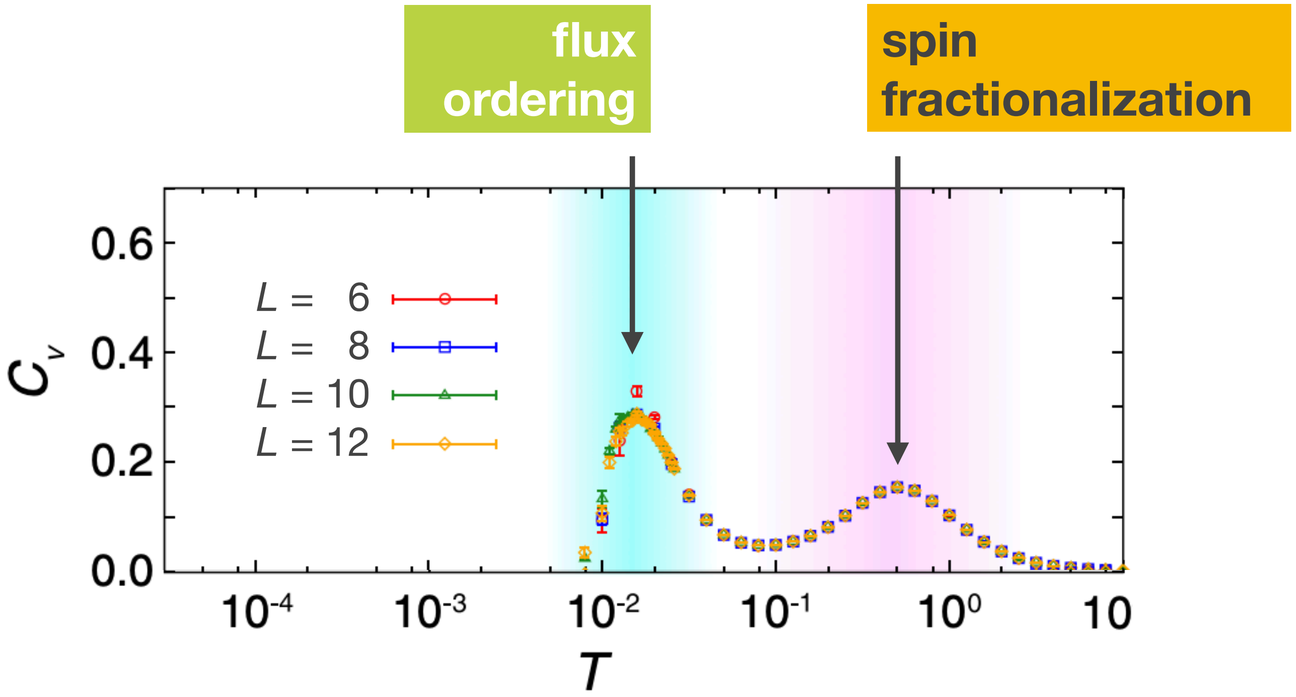
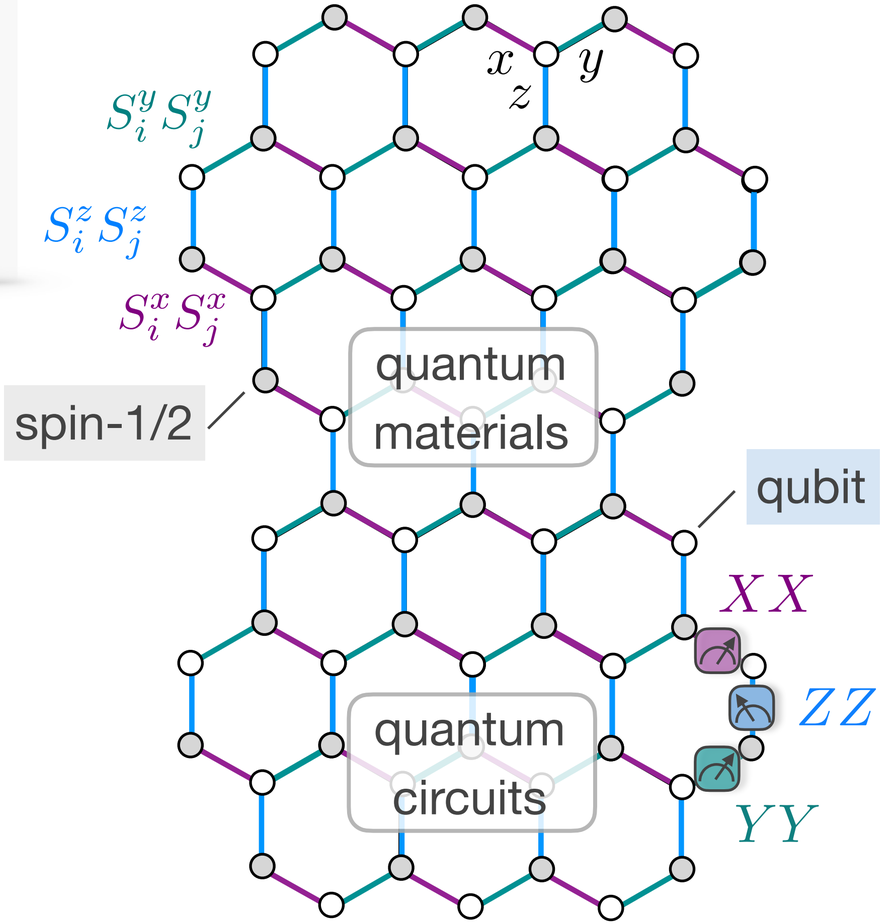
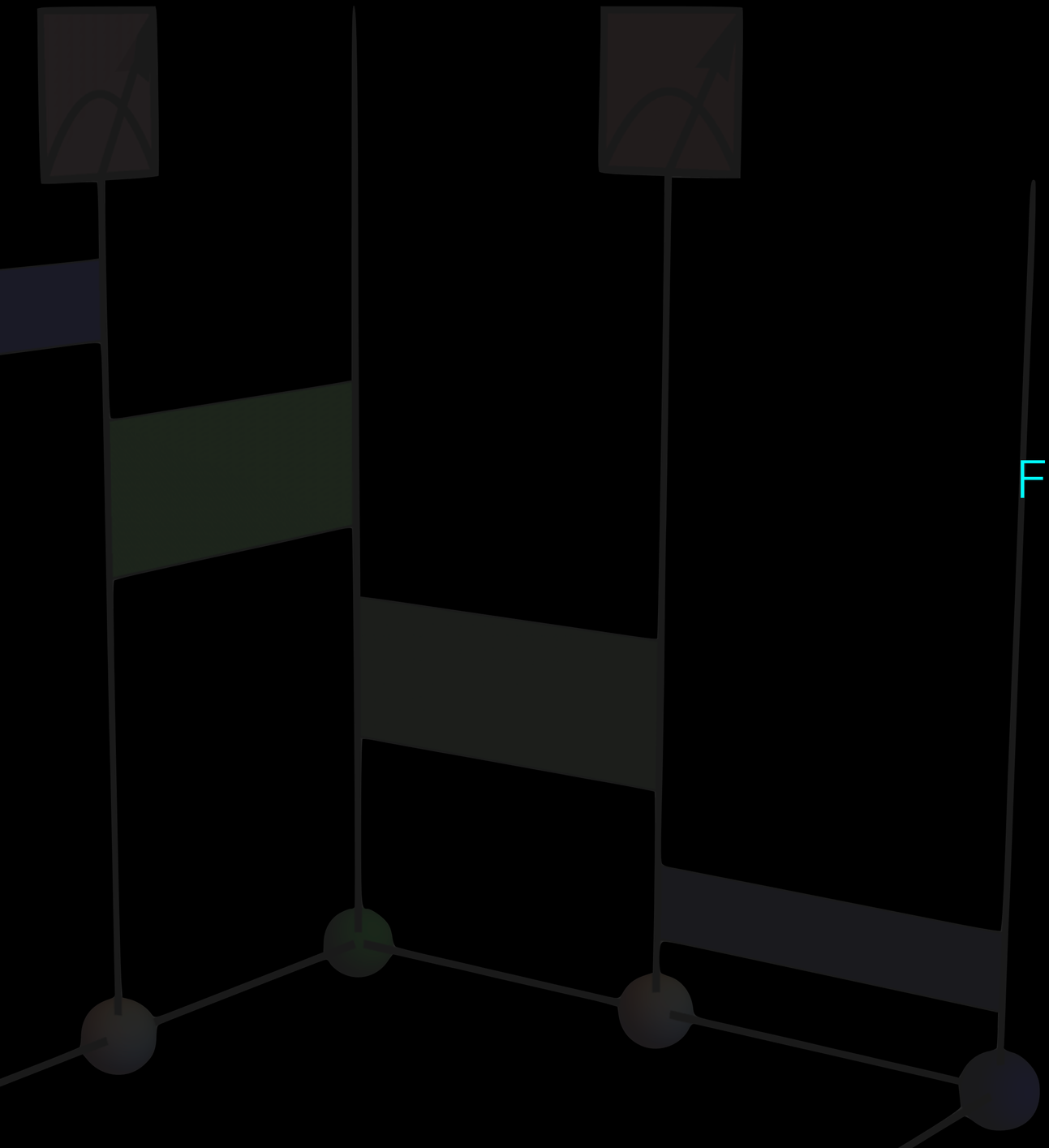


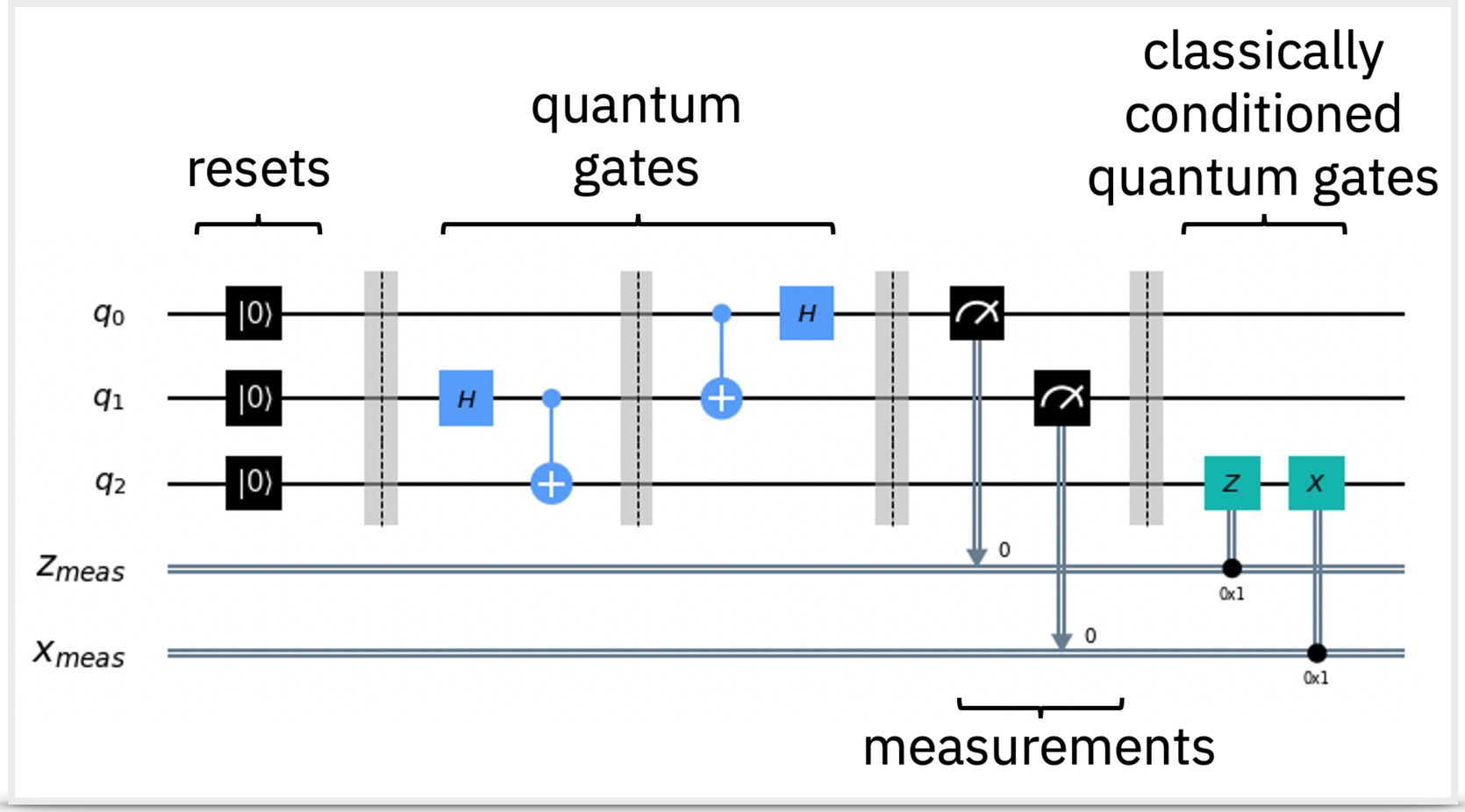




Fractionalization & Emergent Gauge Fields

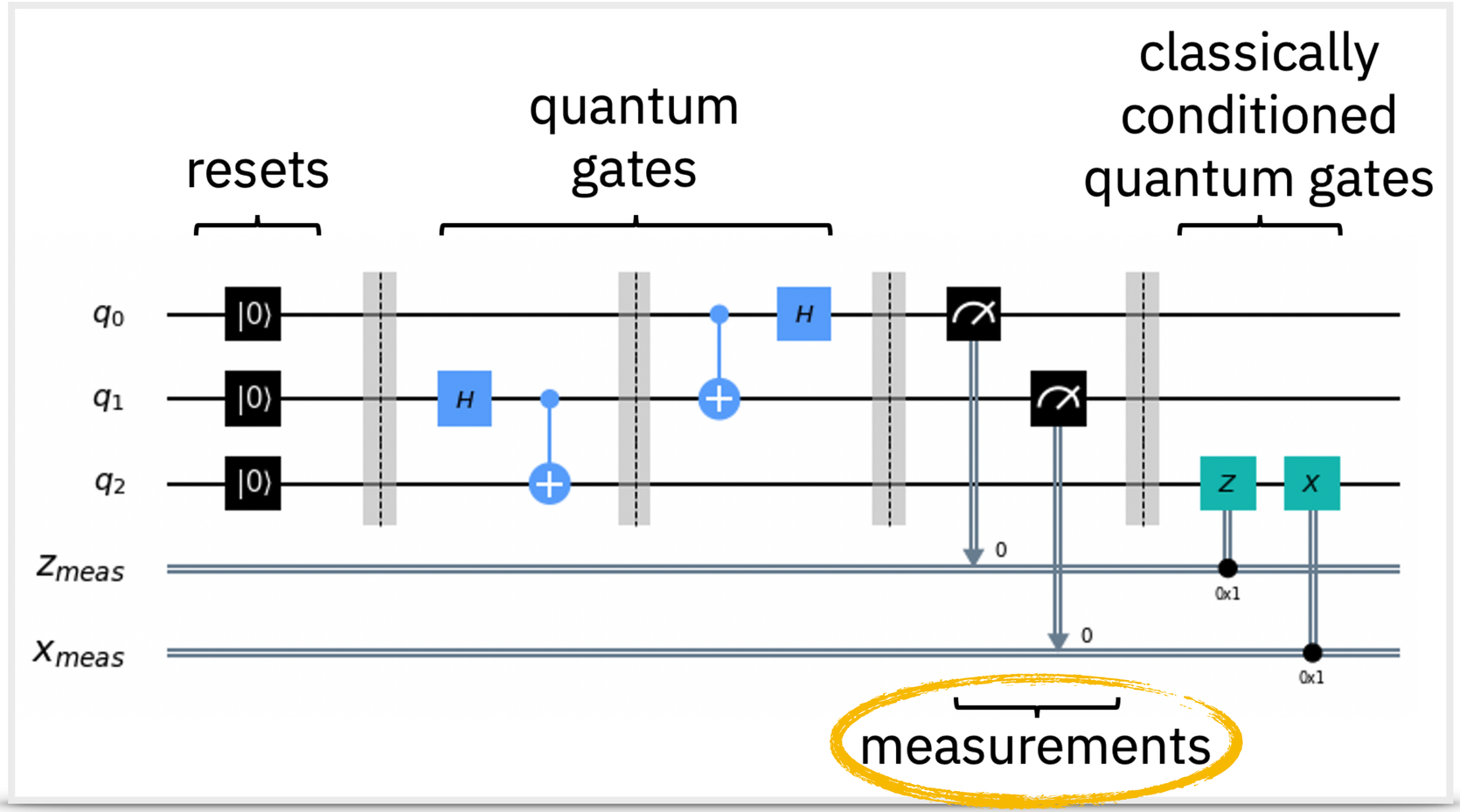
in **Quantum Circuits**

quantum circuits in a nutshell



Quantum computing in a nutshell, Qiskit documentation / IBM Quantum

quantum circuits in a nutshell



Quantum computing in a nutshell, Qiskit documentation / IBM Quantum

quantum measurements

"About your cat, Mr. Schrödinger — I have good news and bad news."

quantum measurements

"About your cat, Mr. Schrödinger — I have good news and bad news."

Quantum measurements can

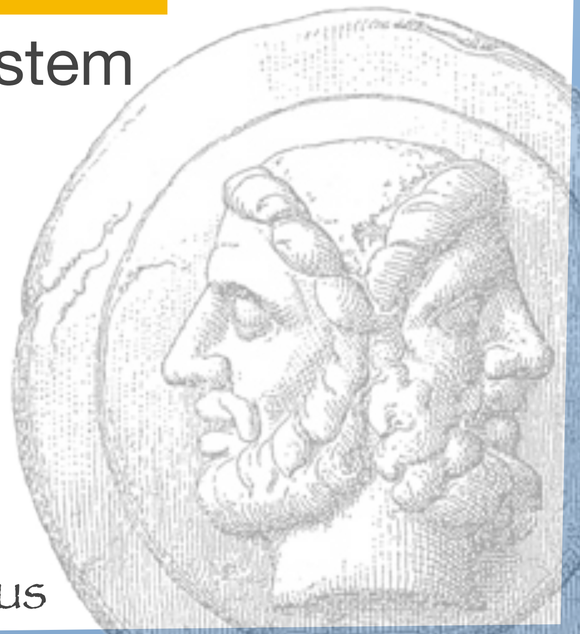
- **extract information** from a system

quantum measurements

"About your cat, Mr. Schrödinger — I have good news and bad news."

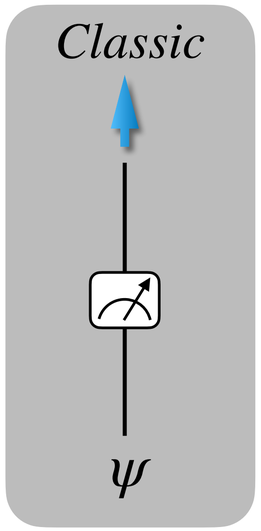
Quantum measurements can

- **extract information** from a system
- **shape entanglement** of a quantum system

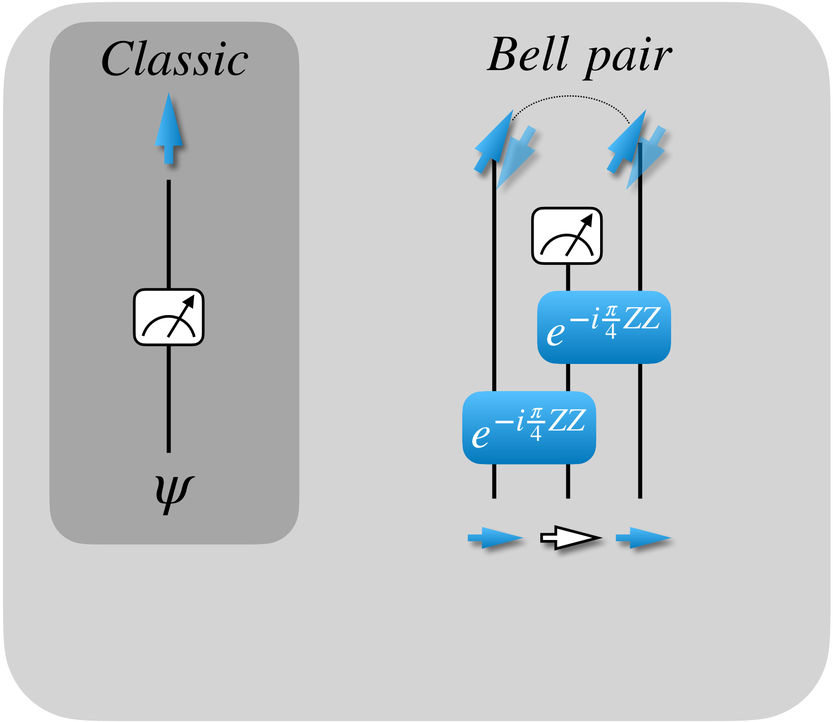


double-faced Janus

quantum states from measurements



quantum states from measurements



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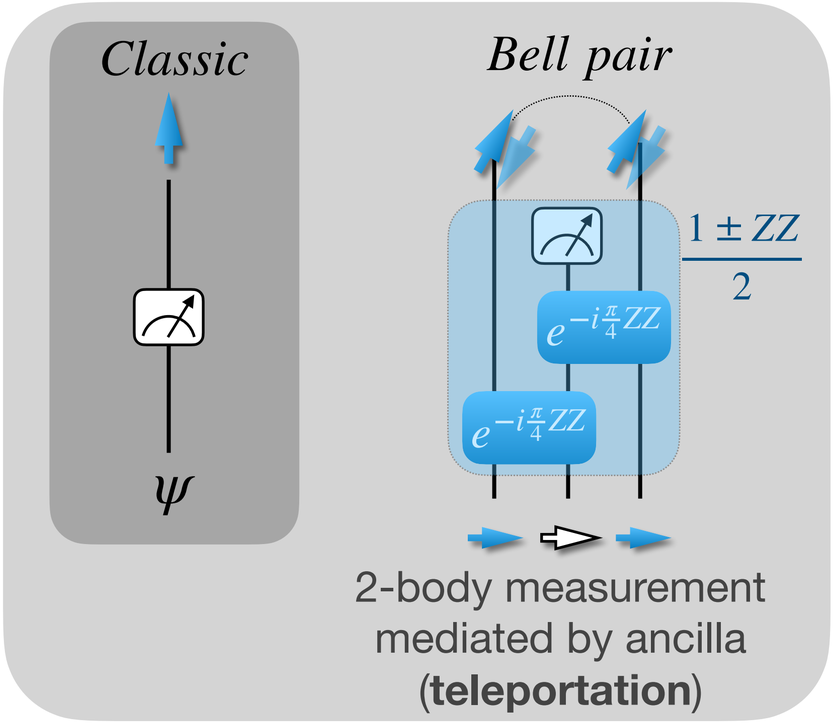
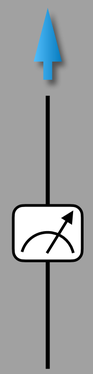


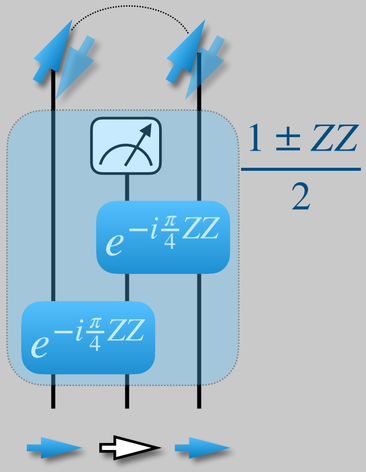
Raussendorf & Briegel, 2001

quantum states from measurements

Classic



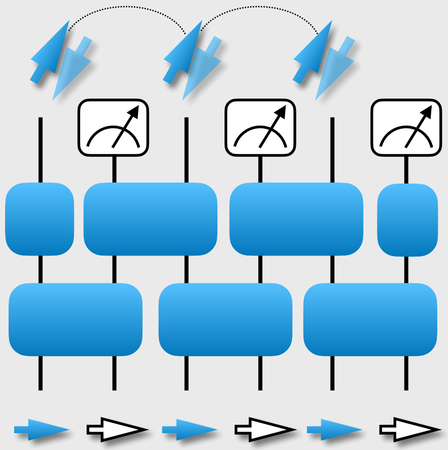
Bell pair



2-body measurement
mediated by ancilla
(**teleportation**)

Raussendorf & Briegel, 2001

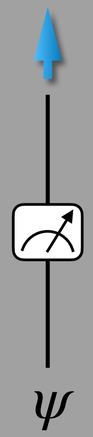
Greenberger – Horne – Zeilinger



Measure local interactions $h_j = Z_j Z_{j+1}$
(**many teleportations**)

quantum states from measurements

Classic



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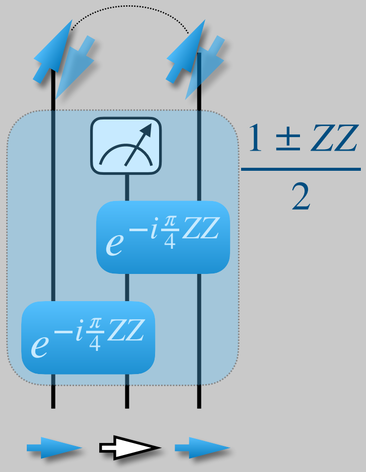

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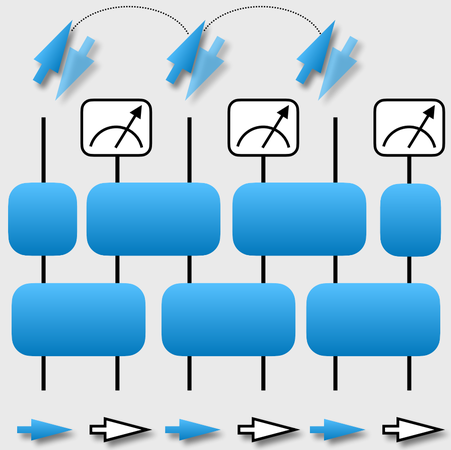

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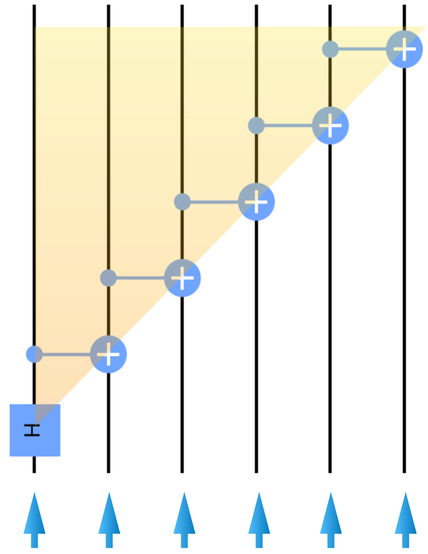
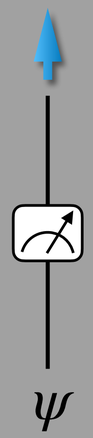
unitary circuit



quantum states from measurements

Classic



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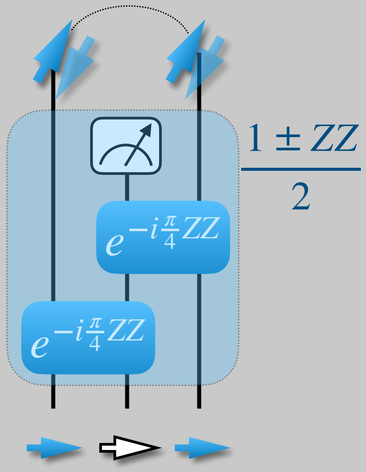

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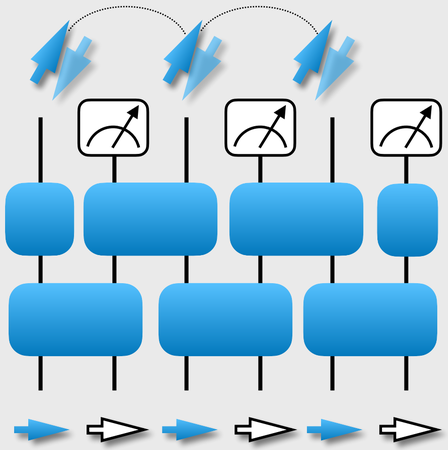

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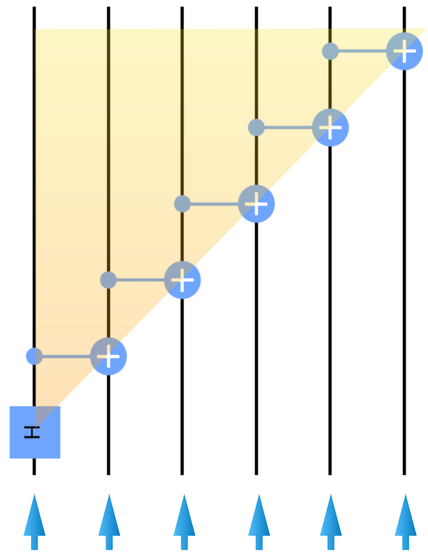
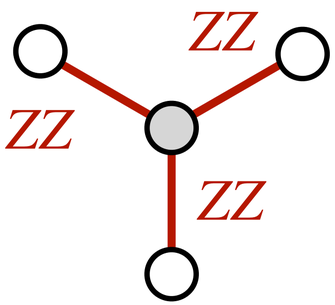
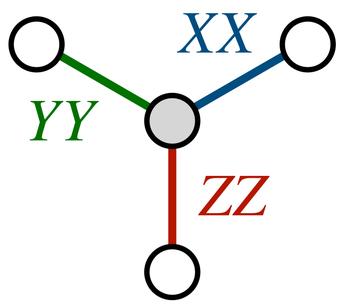


$t \propto O(1)$ ← $t \propto L$

commuting vs non-commuting measurements

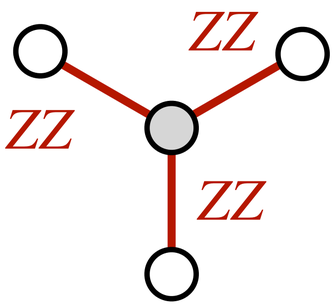


- **commuting**
- parallelized
- no dynamics



- **non-commuting**
- sequential
- dynamics

commuting vs non-commuting measurements



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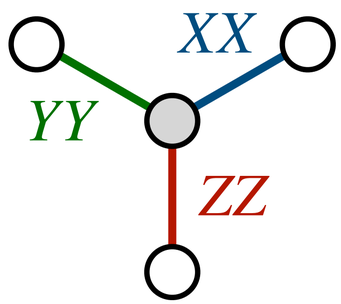
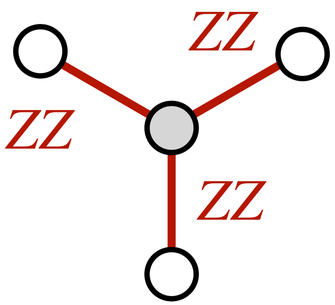


Kitaev spin liquid

- **non-commuting**
- sequential
- dynamics

commuting vs non-commuting measurements



Nishimori's cat

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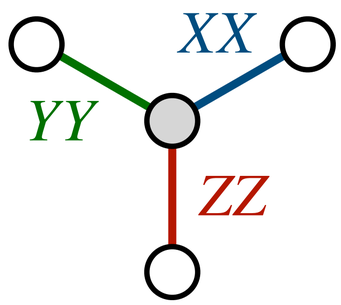

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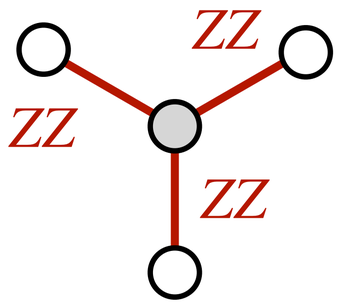

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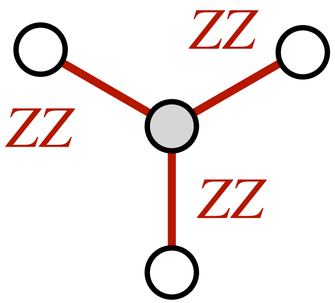
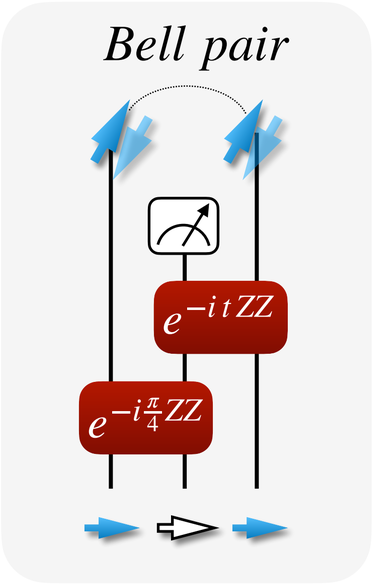


Nishimori's cat



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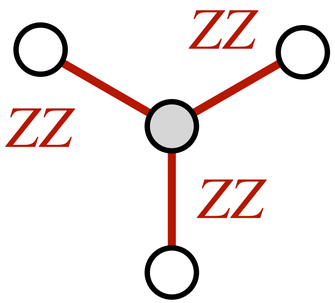

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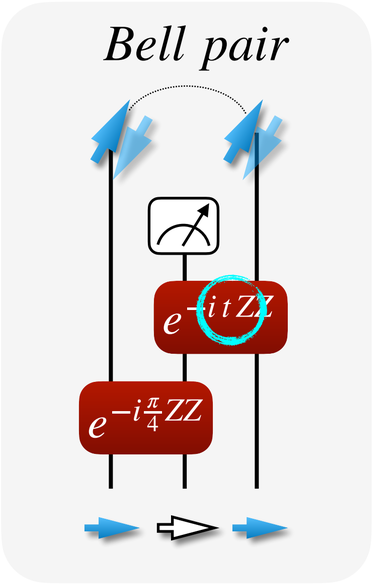

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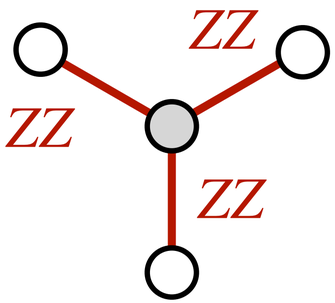

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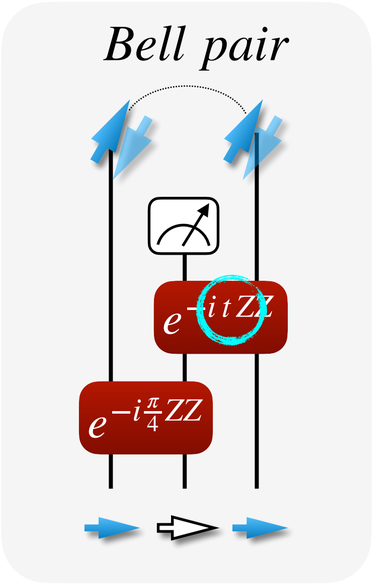
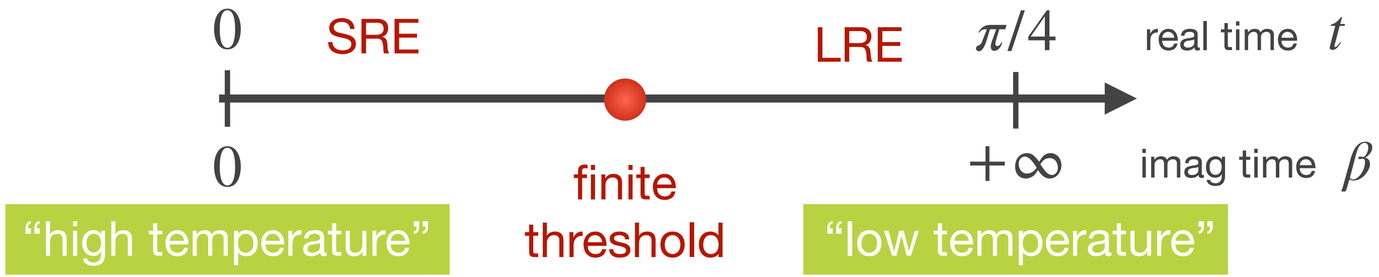


weak measurement

strong measurement



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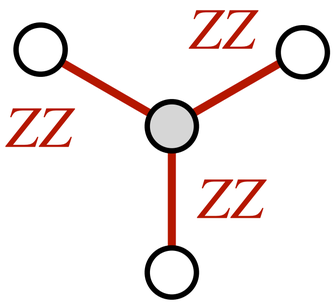

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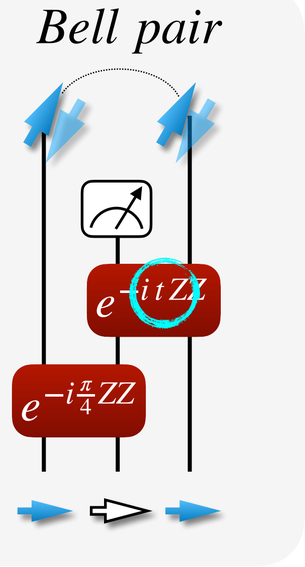

weak measurement

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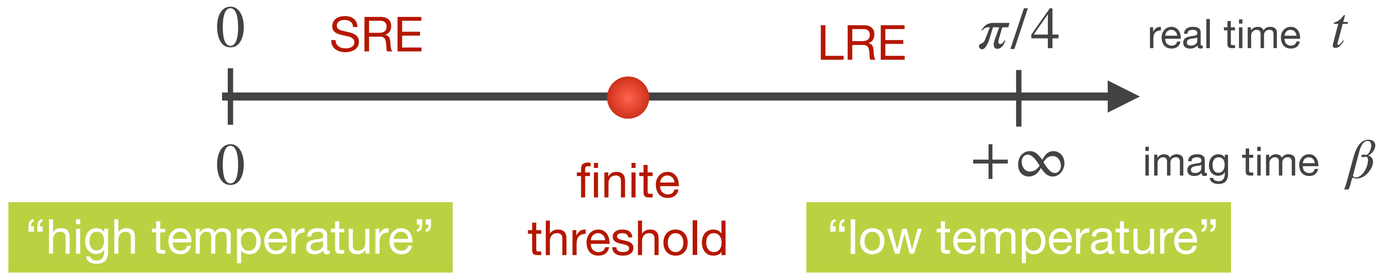
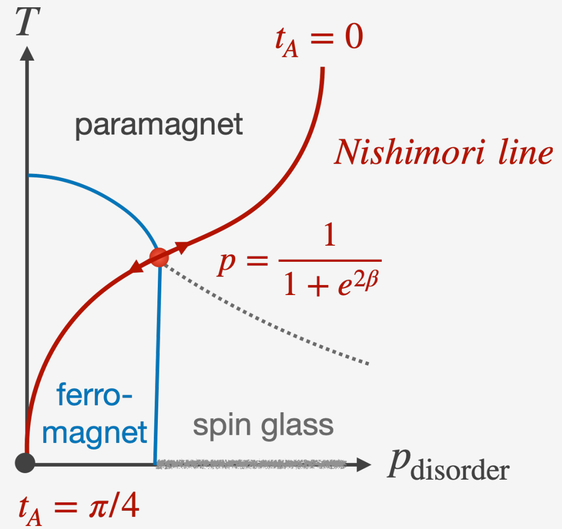


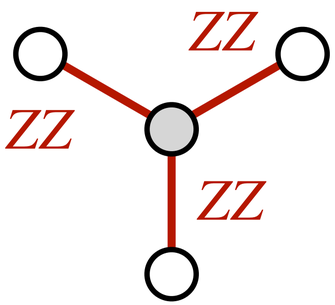
thermal fluctuations and disorder are **locked**

Nishimori (1981)



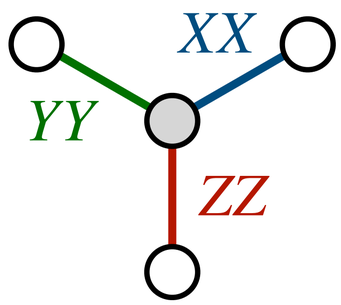
theory – Phys. Rev. Lett. 131, 200201 (2023)
experiment (IBM) – arXiv:2309.02863 (2023)

commuting vs non-commuting measurements



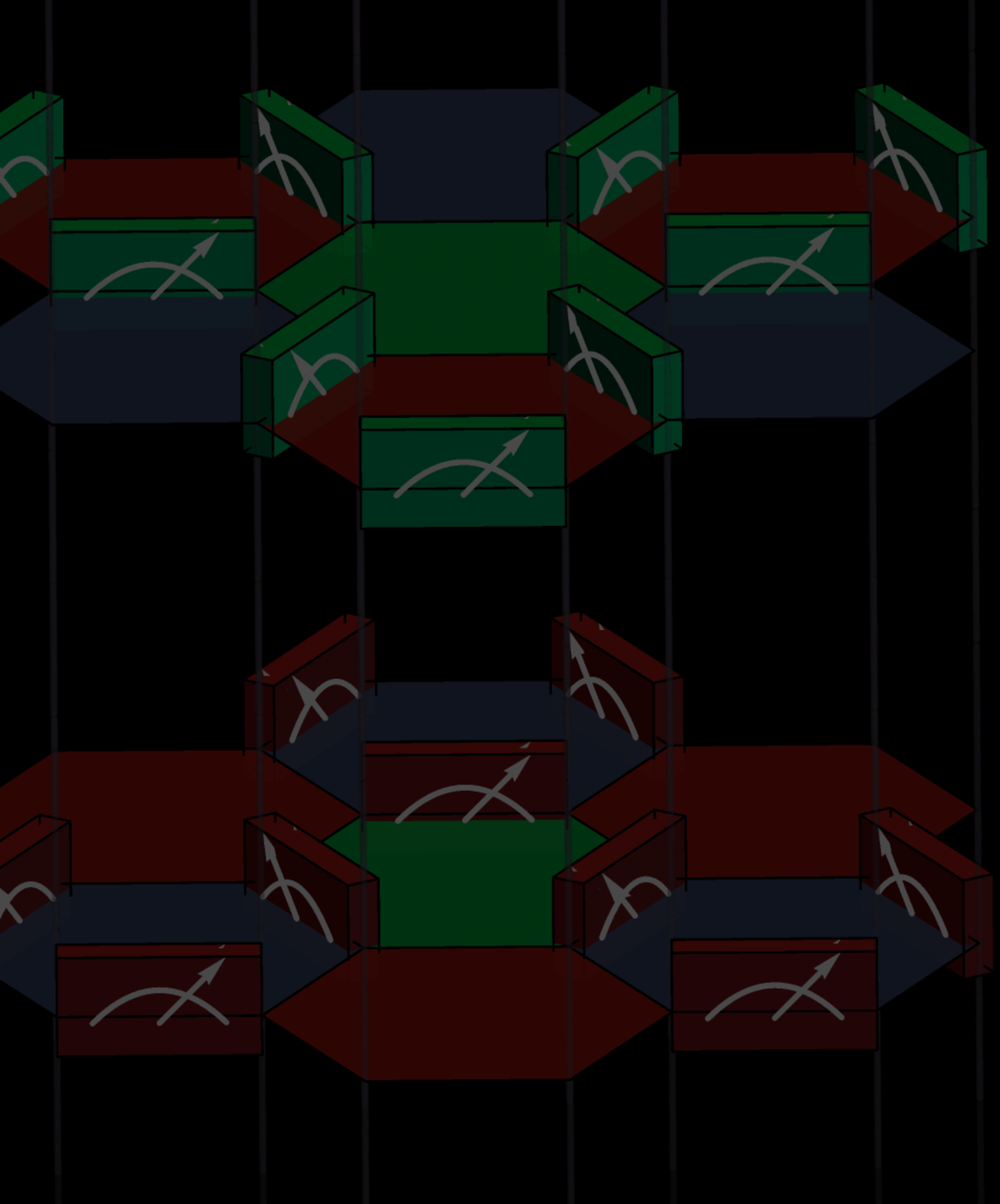
Nishimori's cat

- **commuting**
- parallelized
- no dynamics



Kitaev spin liquid

- **non-commuting**
- sequential
- dynamics



Floquet codes

frustration and entanglement

Kitaev (2006)

$\mathcal{H}$

magnetic exchange

Hamiltonian

measurement

qubit

Clifford gates

$S_i^y S_j^y$

$S_i^z S_j^z$

$S_i^x S_j^x$

x y z

XX

ZZ

YY

spin-1/2

ground state

minimizes global energy

dynamical state

eigenstate of measurements

frustration and entanglement

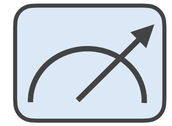
$\mathcal{H}$

magnetic exchange

Kitaev (2006)

Hamiltonian

measurement



Clifford gates

qubit

$S_i^y S_j^y$

$S_i^z S_j^z$

$S_i^x S_j^x$

x y z

XX

ZZ

YY

spin-1/2

ground state

minimizes global energy

dynamical state

eigenstate of measurements

no state can satisfy every local interaction

frustration

non-commuting operators

- cannot be measured simultaneously
- will be over-written

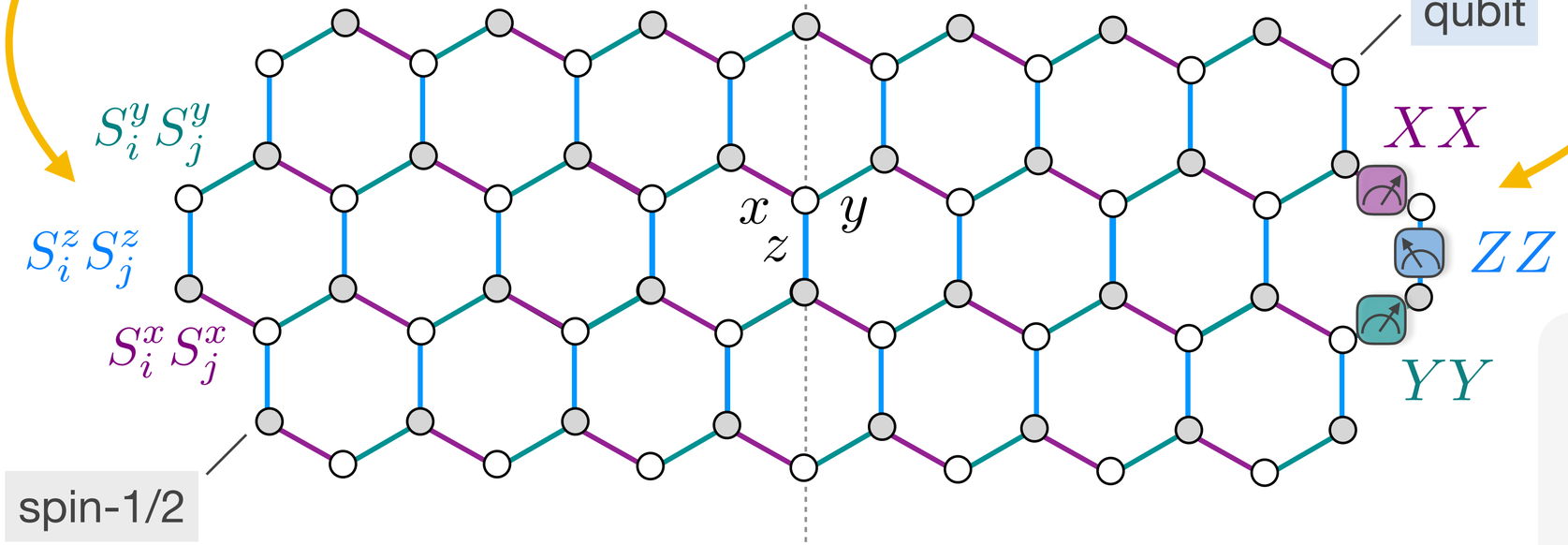
frustration and entanglement

$\mathcal{H}$

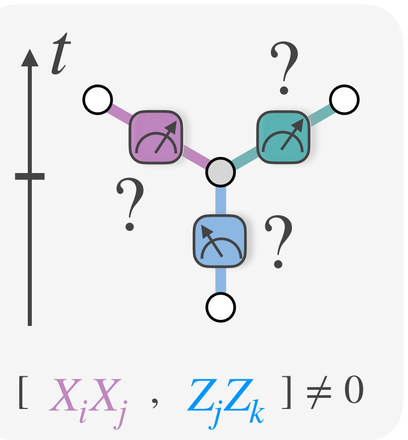
Hamiltonian | **measurement**

magnetic exchange

Kitaev (2006)



Clifford gates



ground state

minimizes global energy

dynamical state

eigenstate of measurements

no state can satisfy every local interaction

frustration

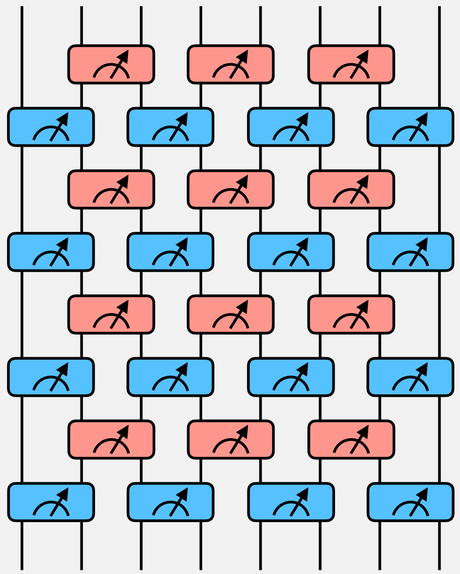
non-commuting operators
- cannot be measured simultaneously
- will be over-written

imaginary time vs. measurement-only

Hamiltonian ground state

$$e^{-\beta H}|\psi_0\rangle$$

$e^{-\tau H_r}$



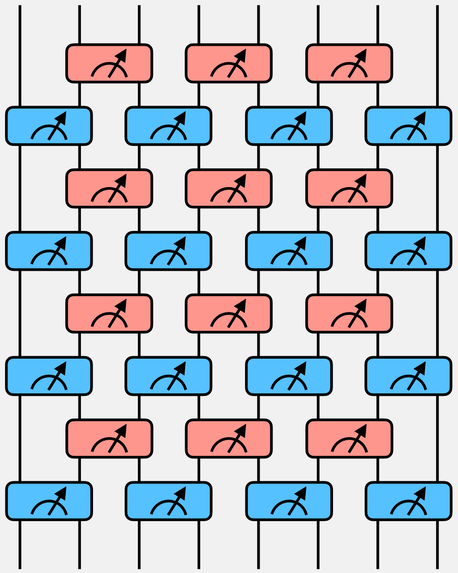
- brickwall circuit
- no disorder
- $\tau \ll 1$

imaginary time vs. measurement-only

Hamiltonian ground state

$$e^{-\beta H}\,|\psi_0\rangle$$

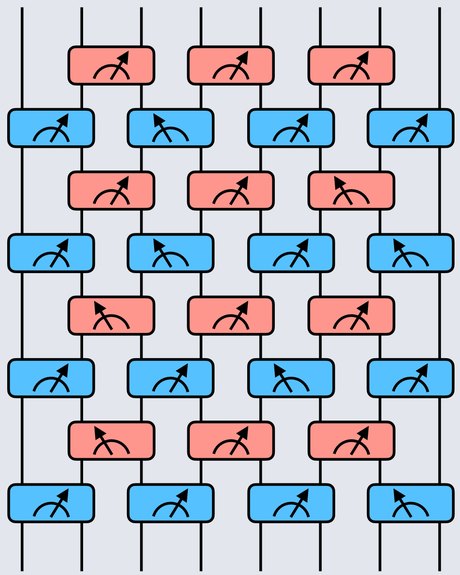
$e^{-\tau H_r}$



- brickwall circuit
- no disorder
- $\tau \ll 1$

Floquet weak measurement

$$\left(e^{\mp\tau H_r}\cdots e^{\mp\tau H_0}\right)|\psi_0\rangle$$



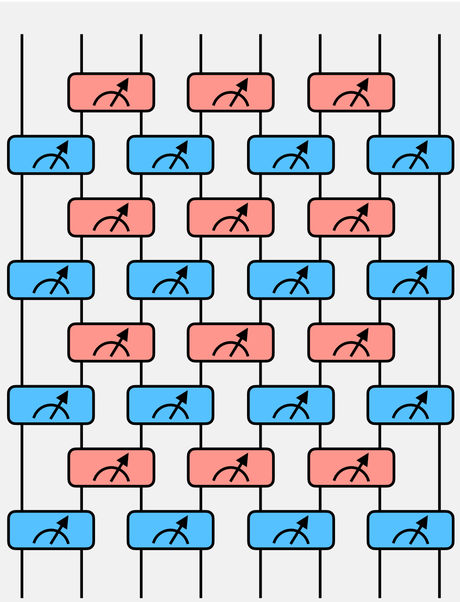
- brickwall circuit
- **Born** disorder
- $\tau \in [0, +\infty)$

imaginary time vs. measurement-only

Hamiltonian ground state

$$e^{-\beta H}\,|\psi_0\rangle$$

$e^{-\tau H_r}$



- brickwall circuit
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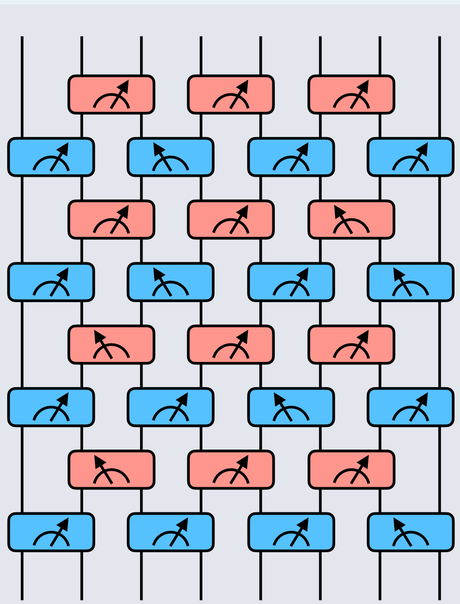
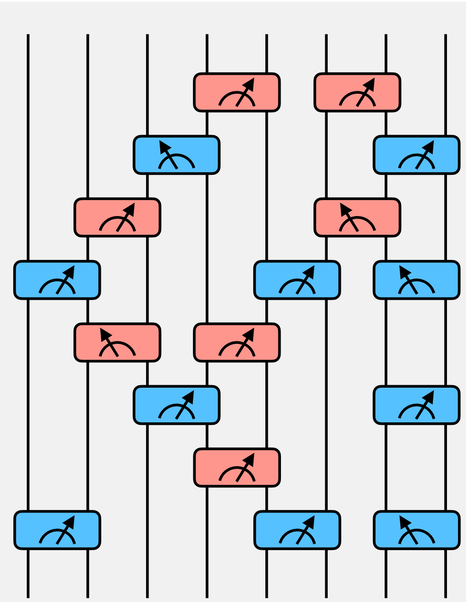


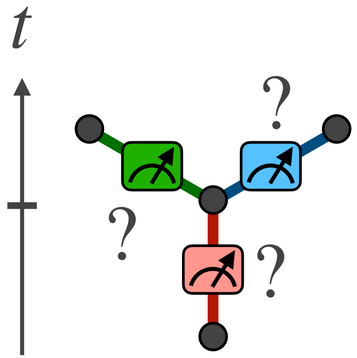
- brickwall circuit
- **Born** disorder
- $\tau \in [0, +\infty)$

random weak/strong measurement

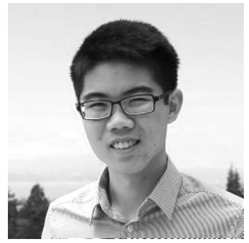


- **stochastic** circuit
- **Born** disorder
- $\tau \in [0, +\infty)$

random projective Kitaev measurements



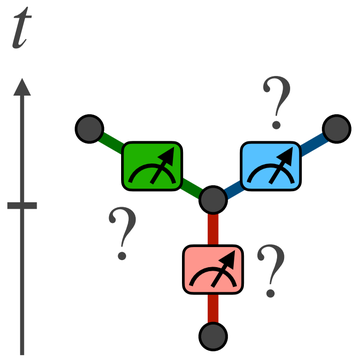
Guo-Yi Zhu

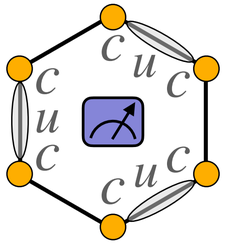


Nathanan Tantivasadakarn

Nahum, Skinner 2020; Lavasani, Luo, Vijay 2022; Sriram, Rakovszky, Khemani, Ippoliti 2022; **Zhu, Tantivasadakarn, ST 2023: + Majorana interaction**

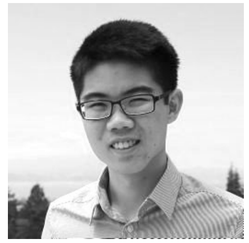
random projective Kitaev measurements





Majorana interaction
→ Majorana surface code

Guo-Yi Zhu



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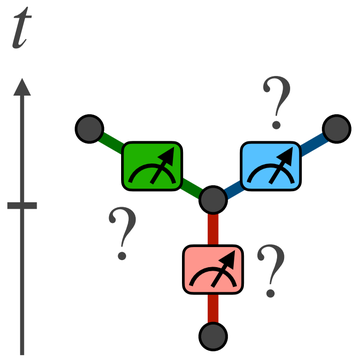
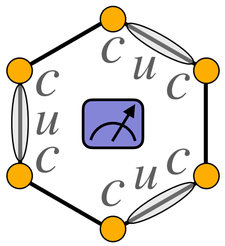
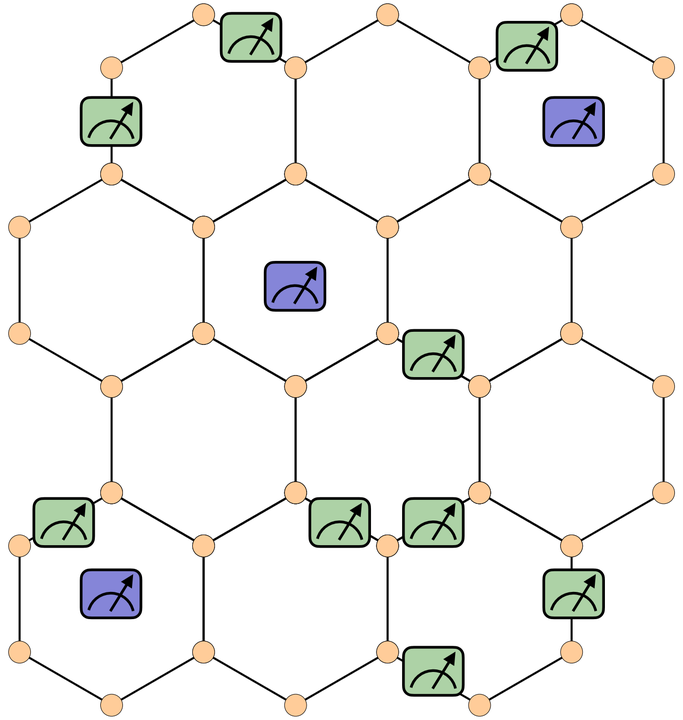


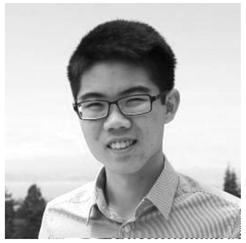


Majorana interaction
→ Majorana surface code

a snapshot: randomly chosen measurements



Guo-Yi Zhu



Nathanan Tantivasadakarn

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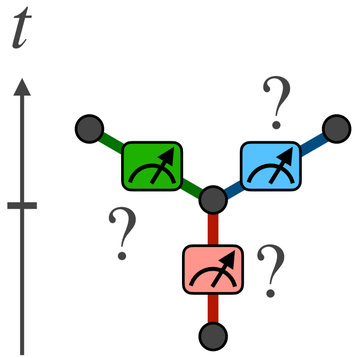
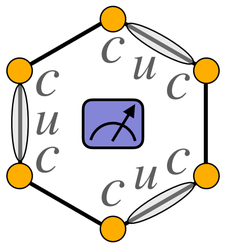
random projective Kitaev measurements



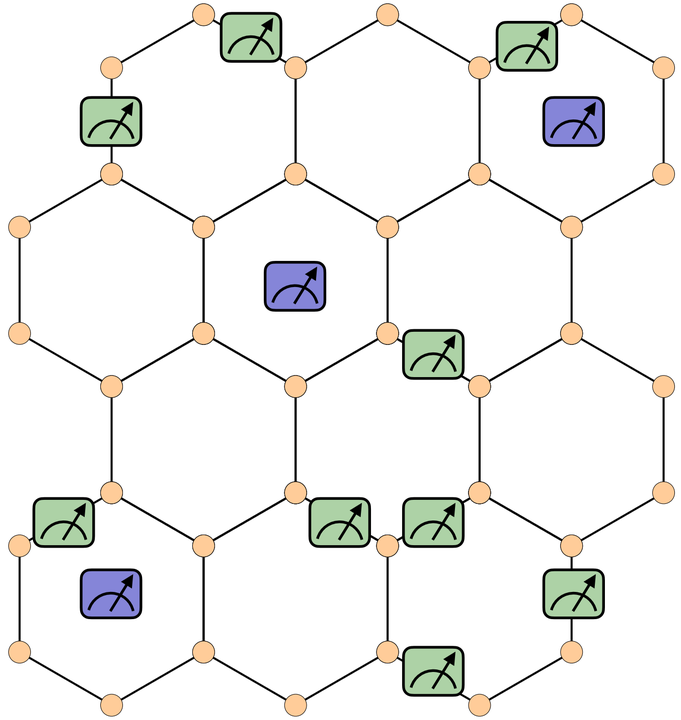


Majorana interaction
→ Majorana surface code

Clifford circuit

even **interacting** problem can be simulated in polynomial time (in Heisenberg picture)

a snapshot: randomly chosen measurements



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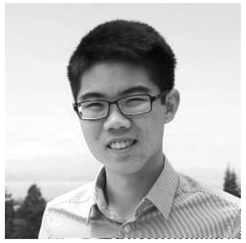

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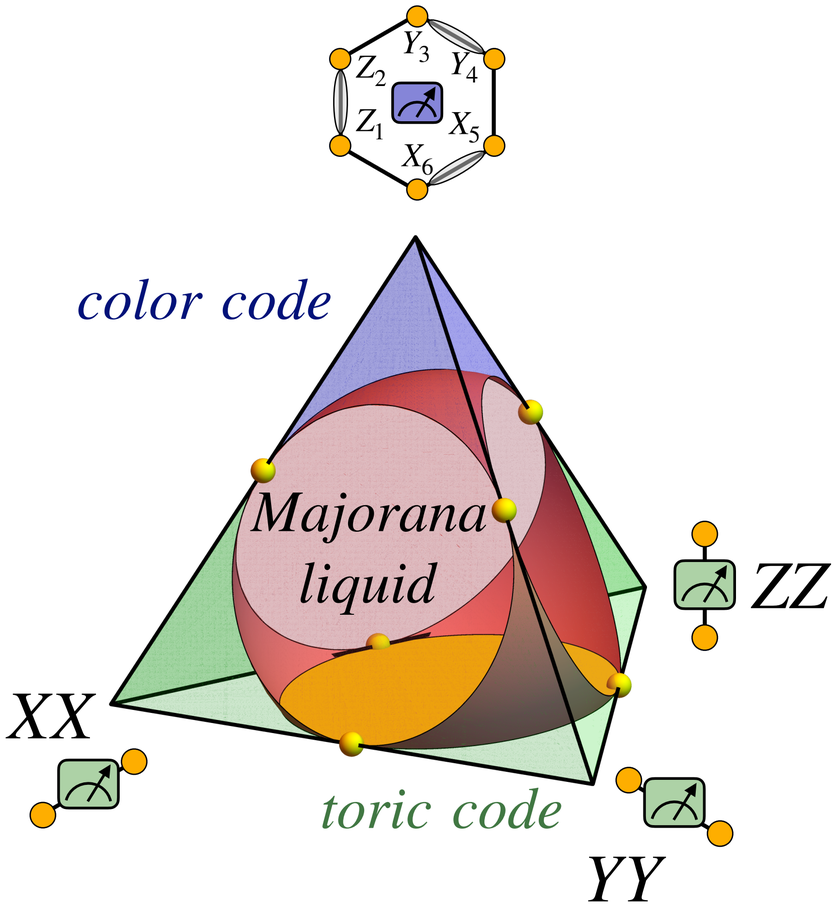
entanglement phase diagram



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Zhu, Tantivasadakarn, ST 2023: + Majorana interaction

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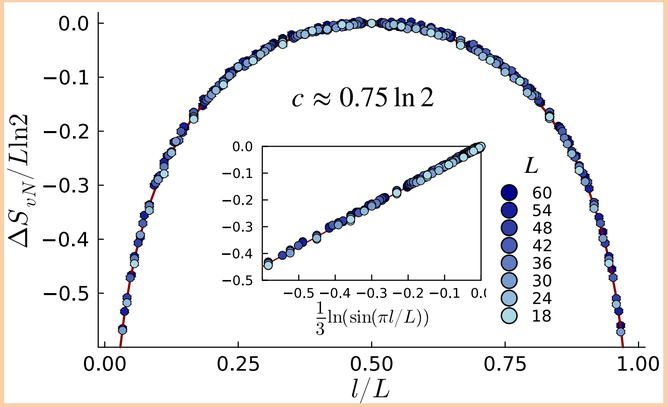
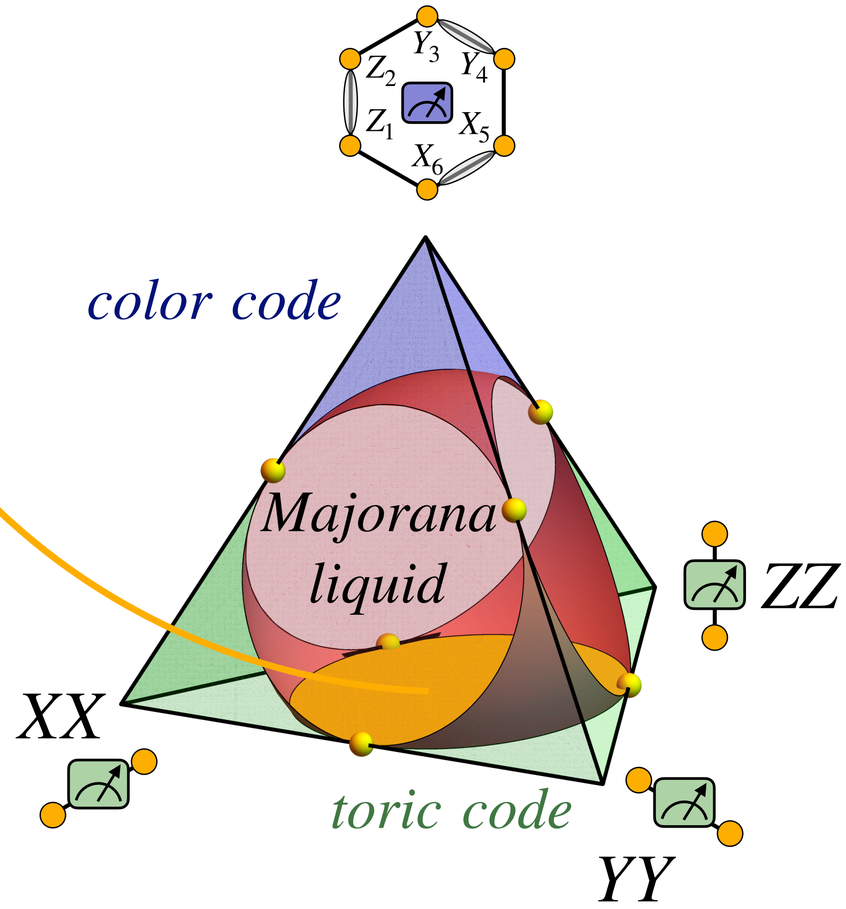


Fermi-surface scaling

$$S_{vN}(l,L) = \frac{cL}{3} \ln\left(\frac{L}{\pi} \sin\frac{\pi l}{L}\right) + \cdots$$



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Zhu, Tantivasadakarn, ST 2023: + Majorana interaction

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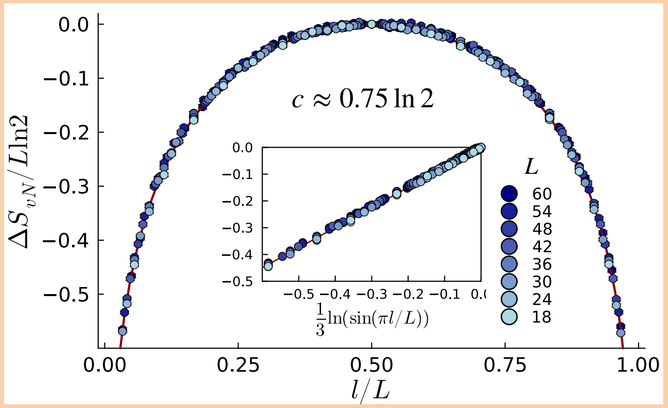

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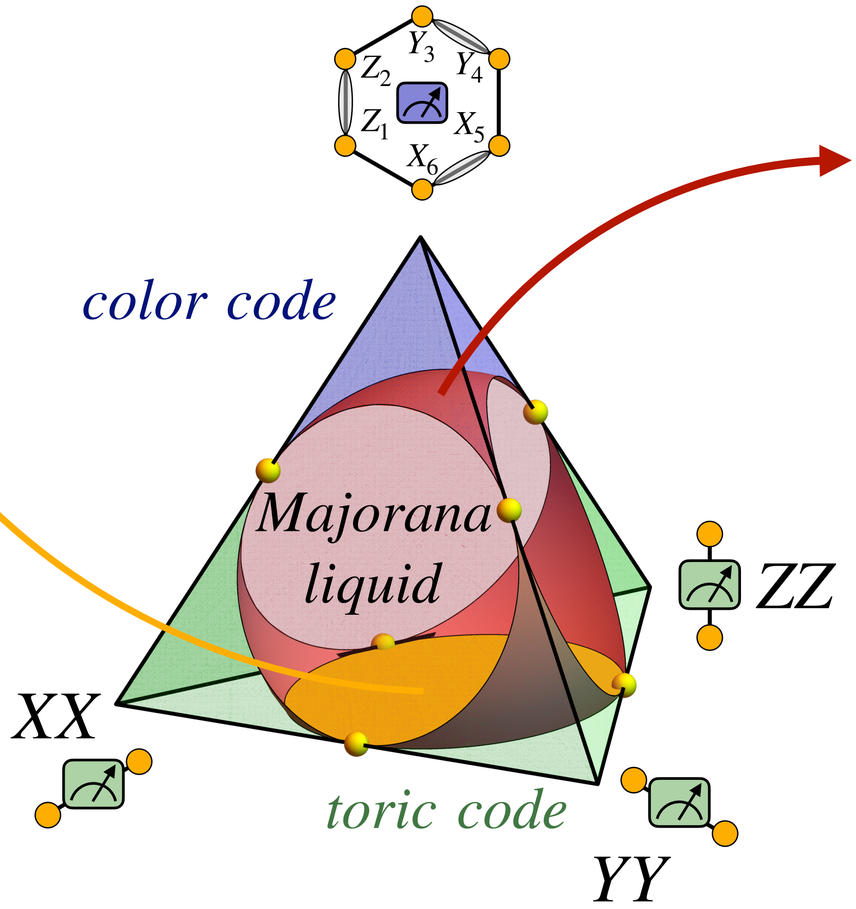
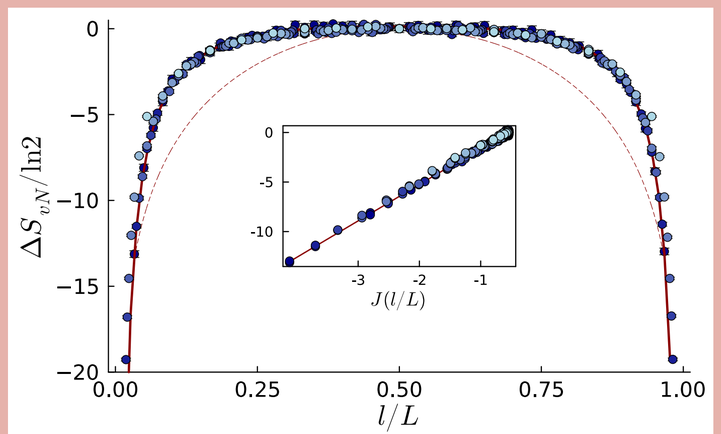


quantum Lifshitz scaling



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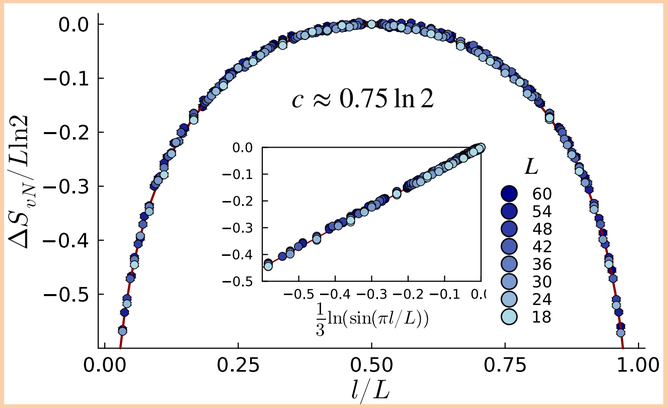
Zhu, Tantivasadakarn, ST 2023: + Majorana interaction

entanglement phase diagram



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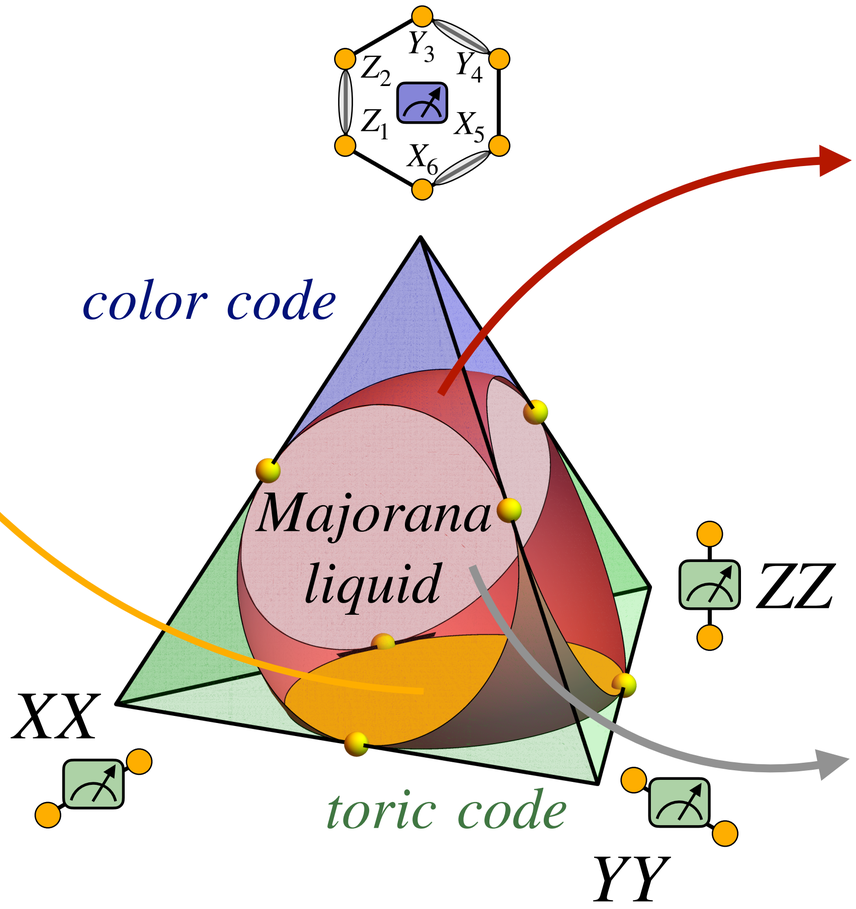

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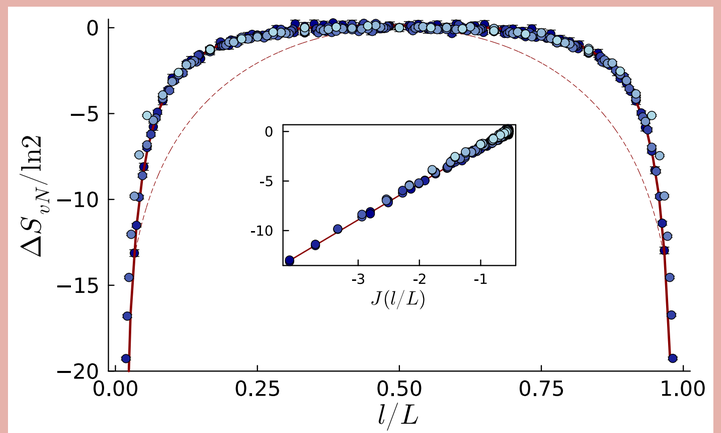
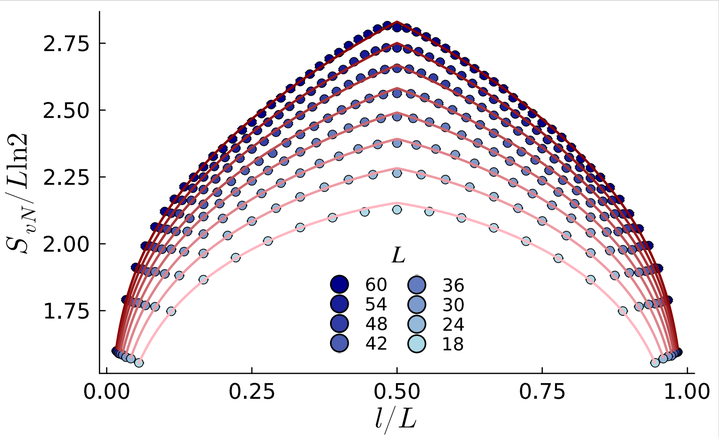


volume − law + L ln L



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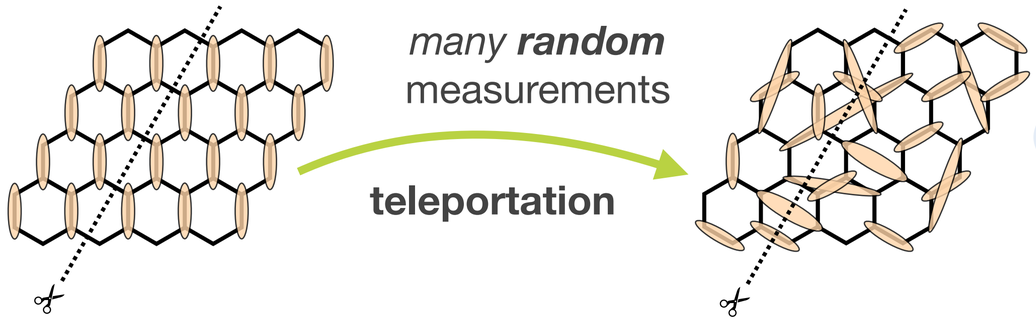
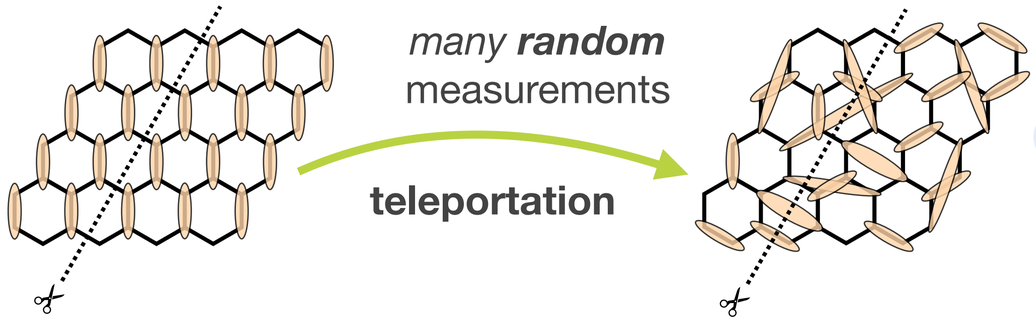
Zhu, Tantivasadakarn, ST 2023: + Majorana interaction

measurement, teleportation, and beyond



long-range entangled
“valence bond crystal”

measurement, teleportation, and beyond



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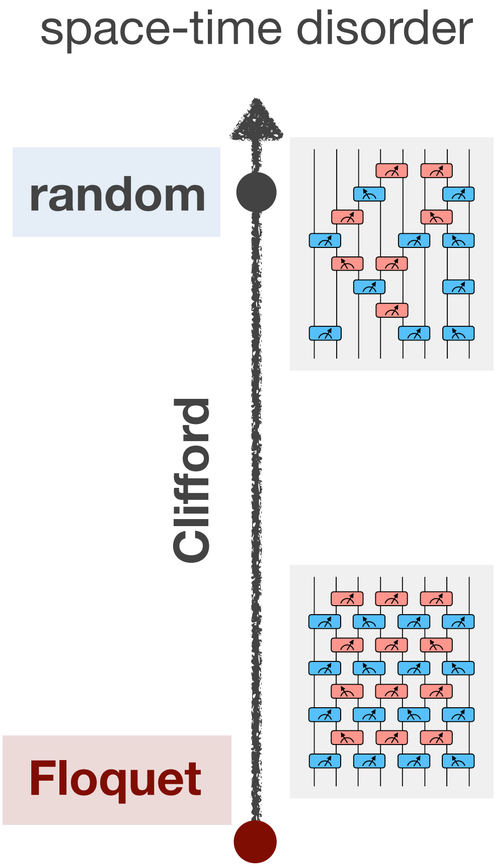
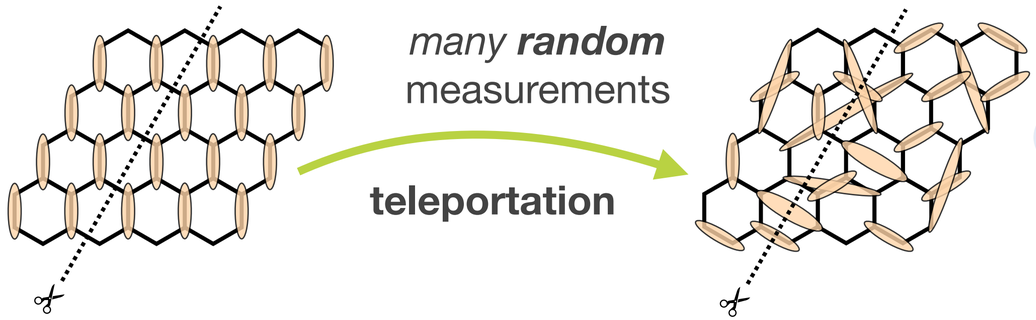
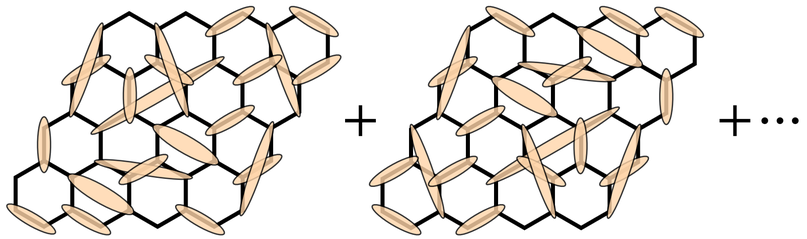


measurement, teleportation, and beyond





long-range entangled
"valence bond crystal"

space-time disorder

random

Clifford

?

long-range entangled
"resonating valence bond"

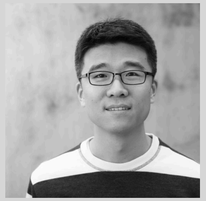
Floquet

weak

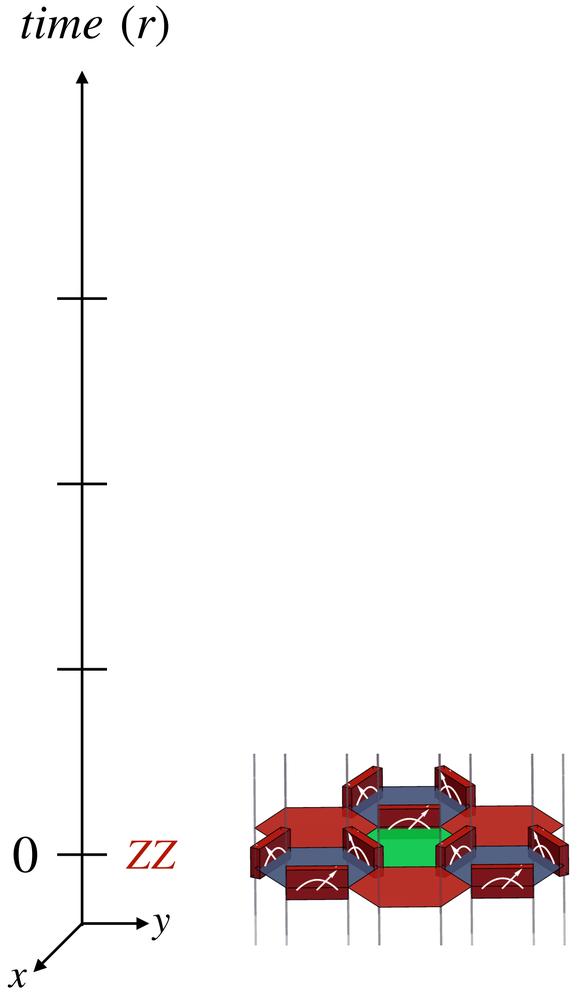
strong

measurement strength

dynamical protocol

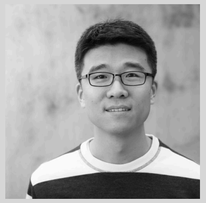



Hastings, Haah (2021)



$\rho_0 \propto \mathbb{I}$

dynamical protocol

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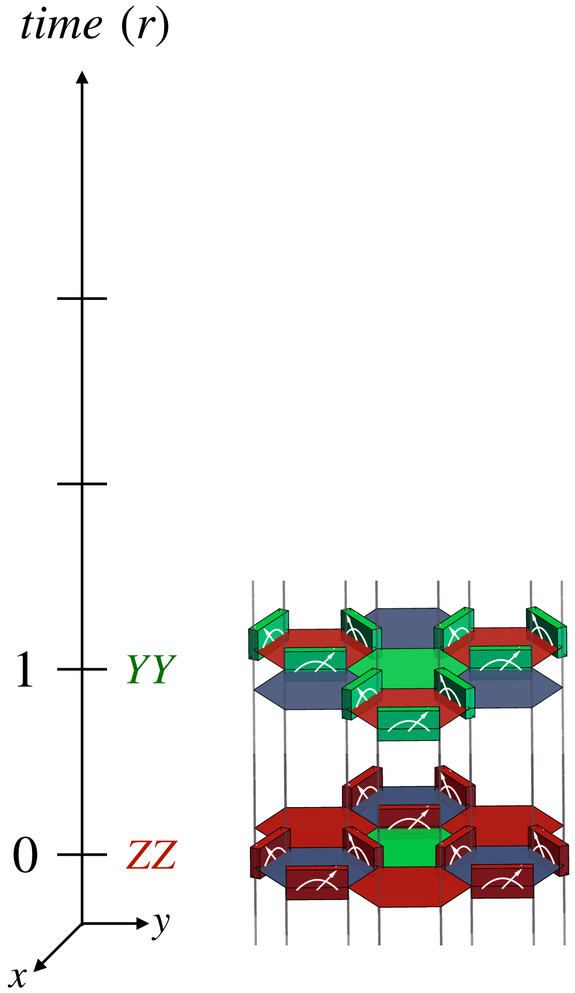

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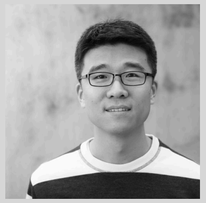

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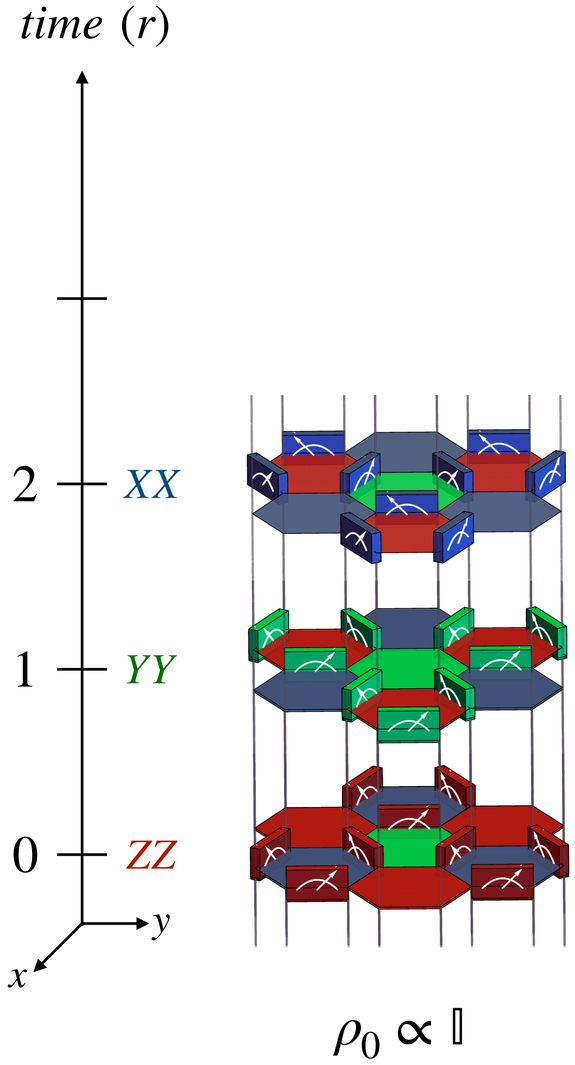
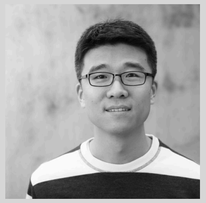


$\rho_0 \propto \mathbb{I}$

dynamical protocol

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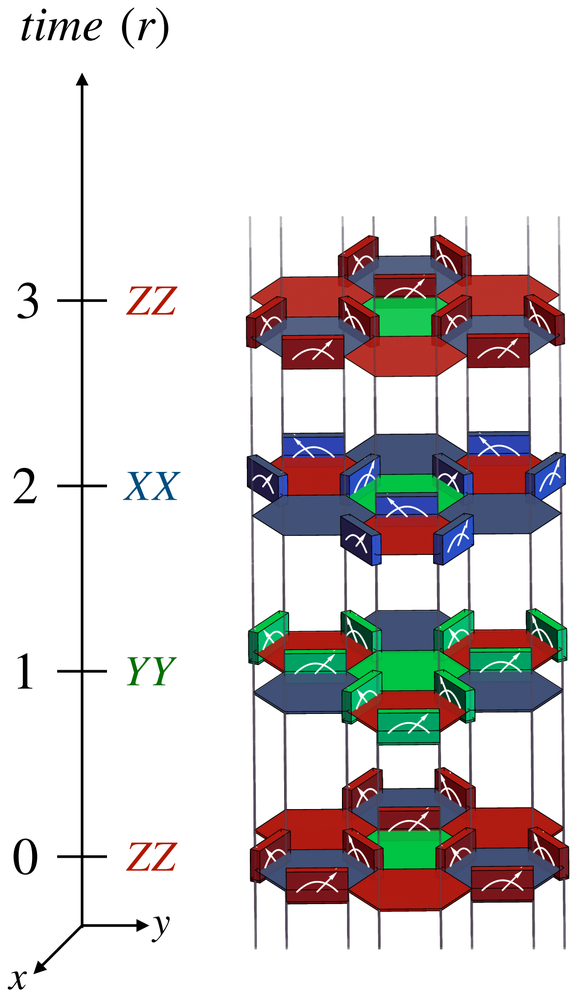
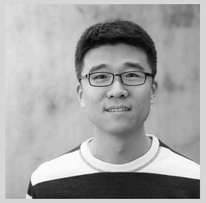


$\rho_0 \propto \mathbb{I}$

dynamical protocol

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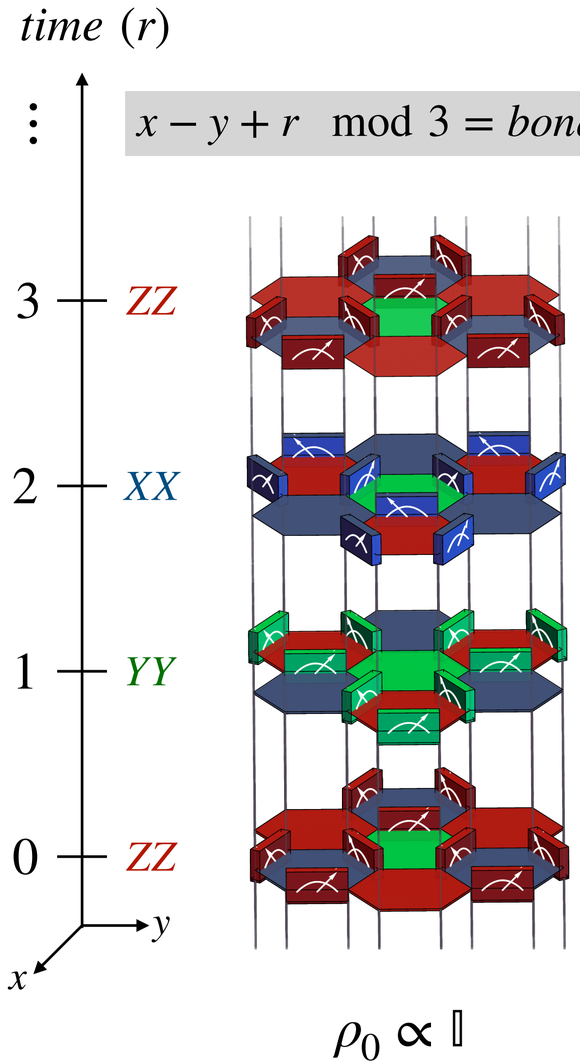
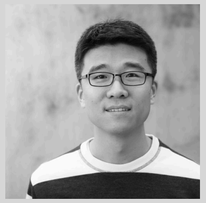


$\rho_0 \propto \mathbb{I}$

dynamical protocol

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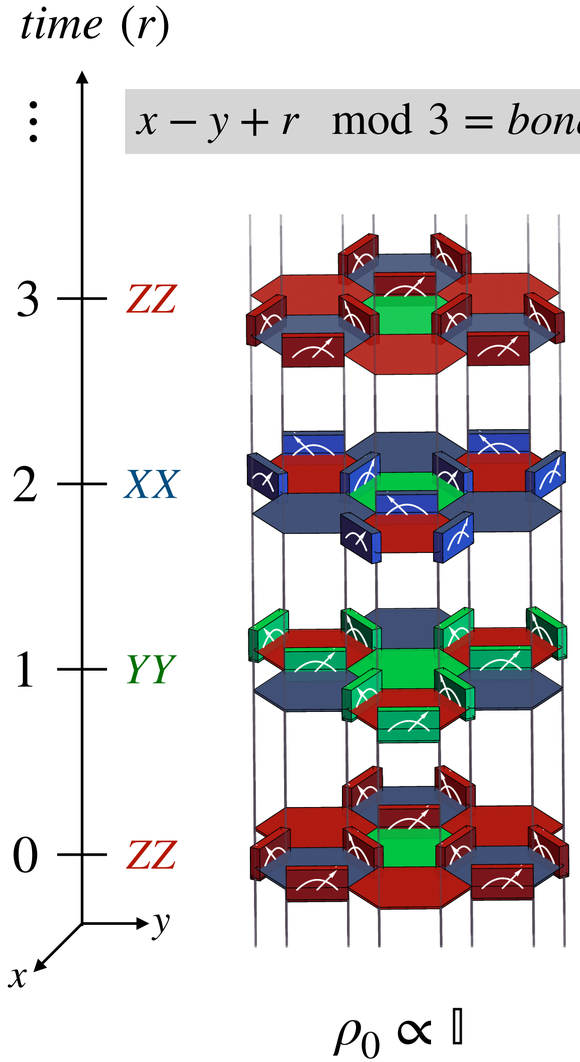
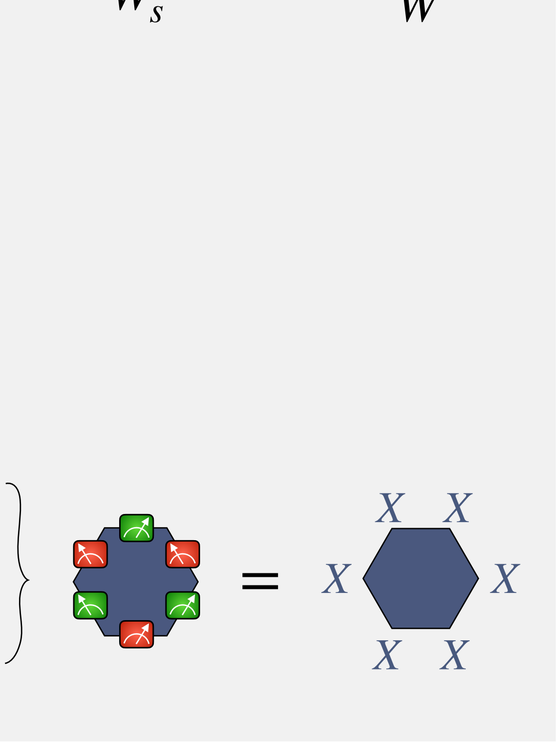
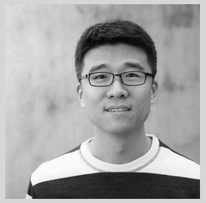




$\rho_0 \propto \mathbb{I}$

dynamical protocol

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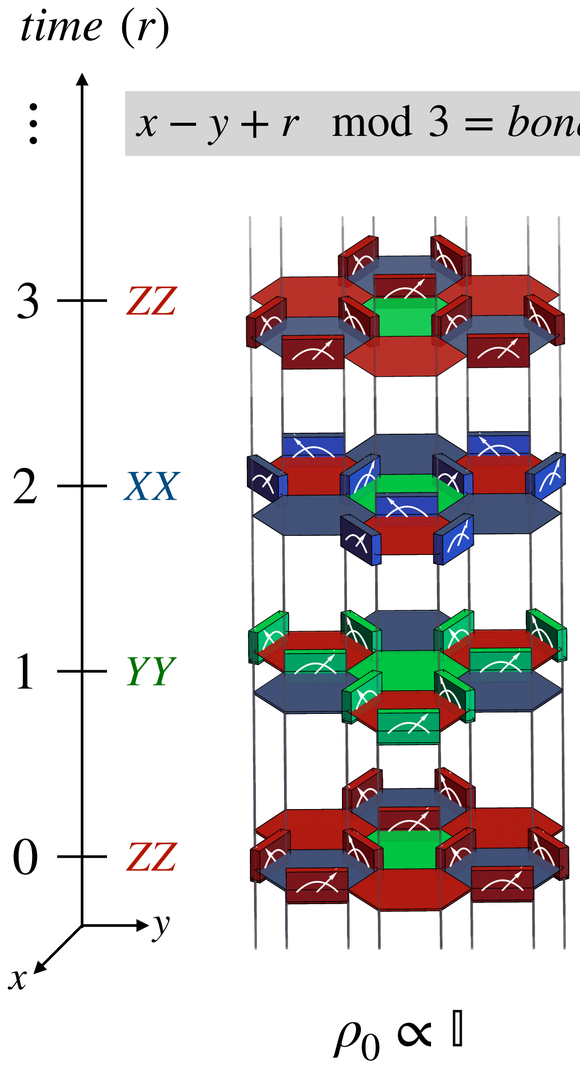
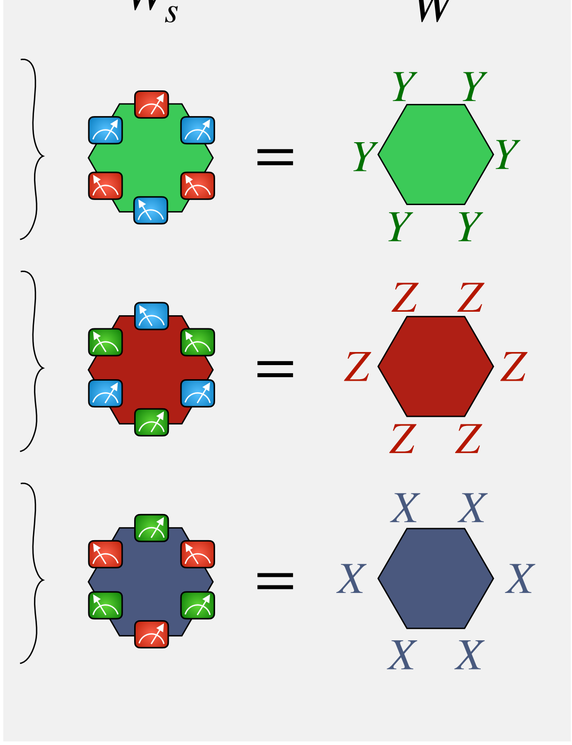
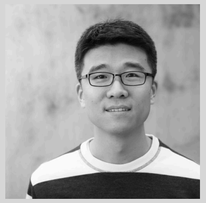




$\rho_0 \propto \mathbb{I}$

dynamical protocol

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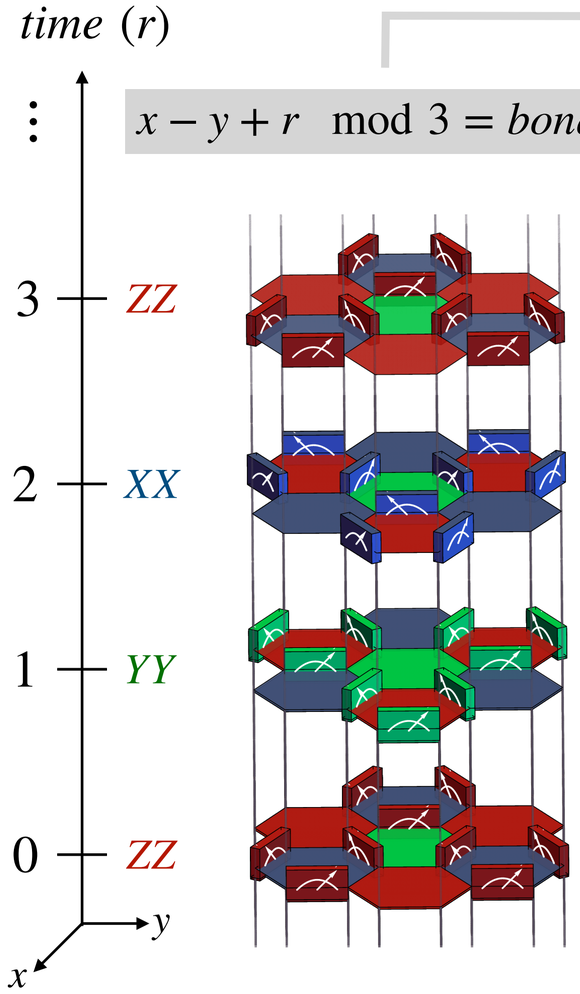

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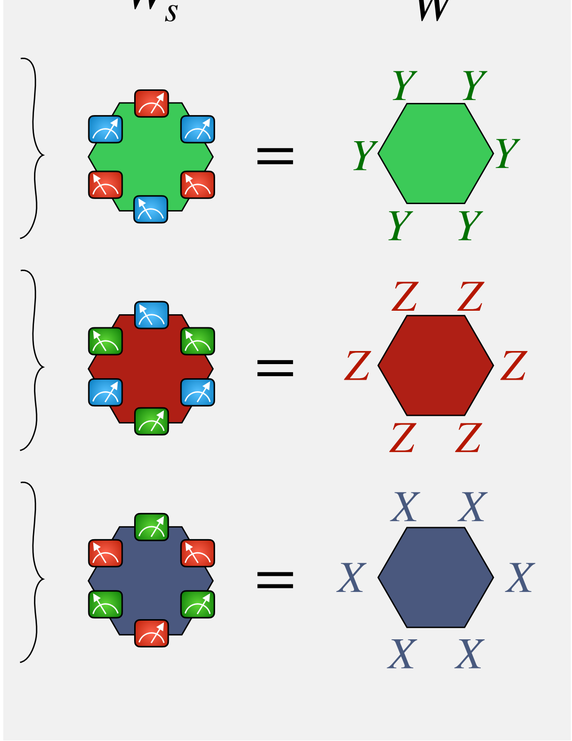

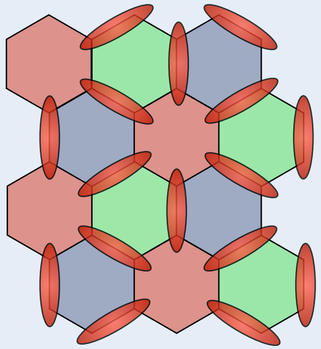

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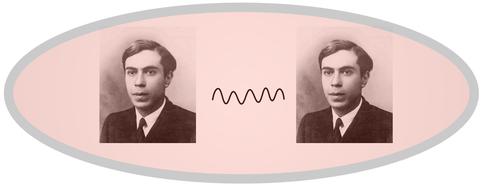
Gauge flux → a glassy toric code

Majoranas are confined in *hard-core* dimers



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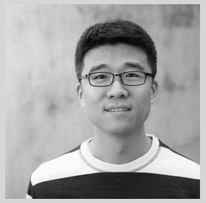

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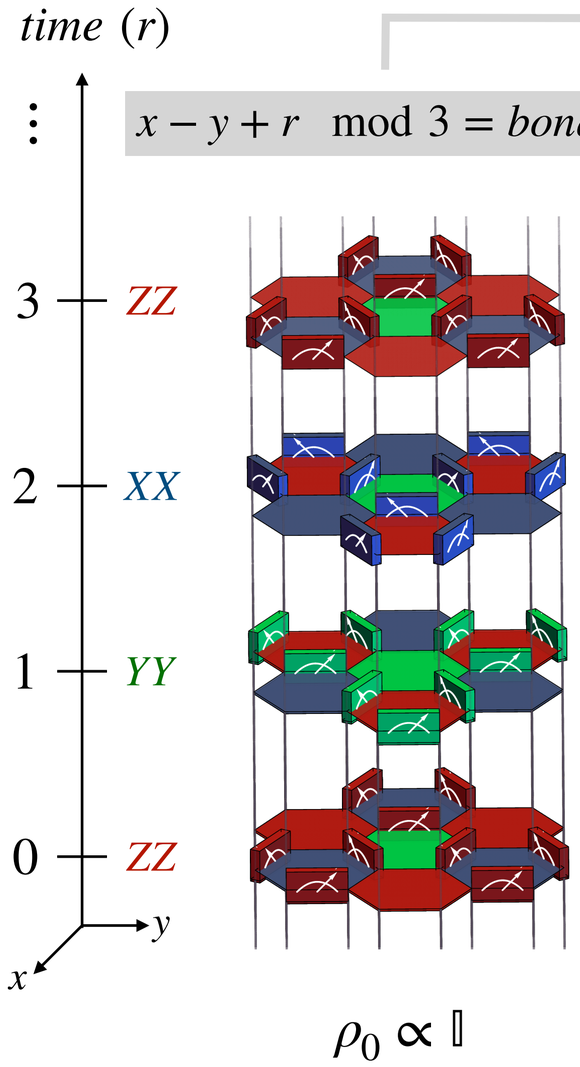

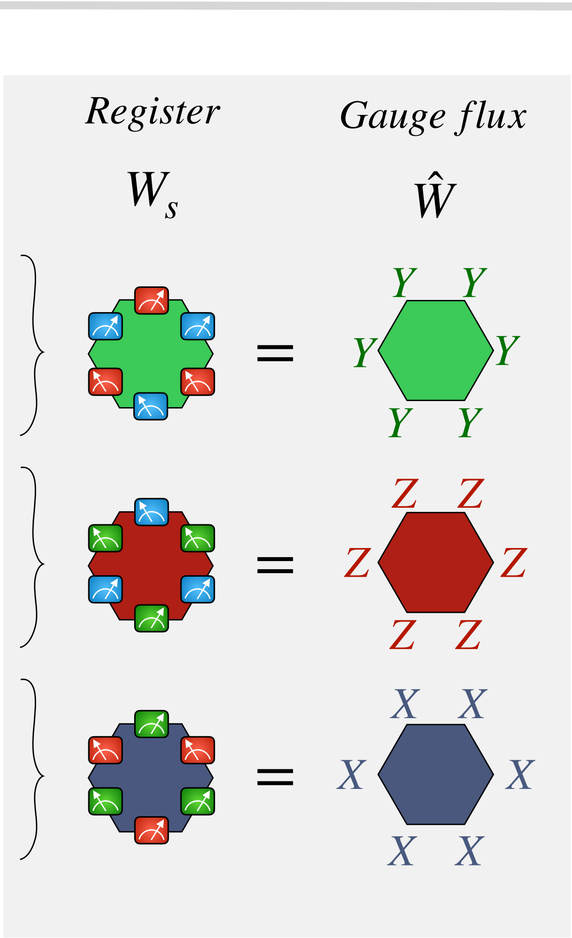

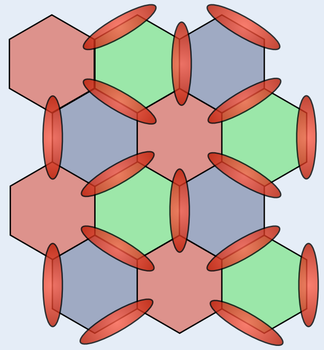

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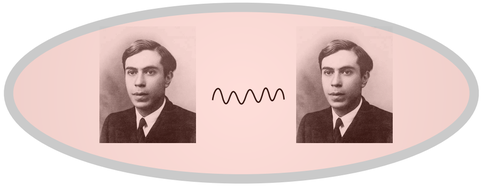

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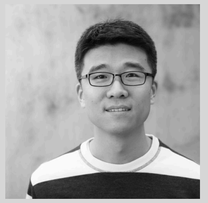

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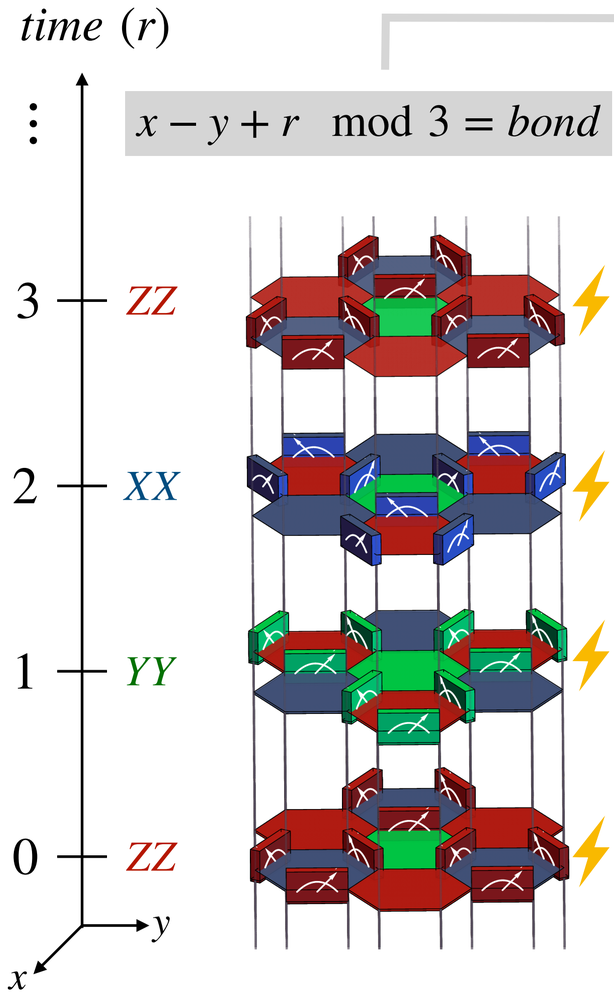

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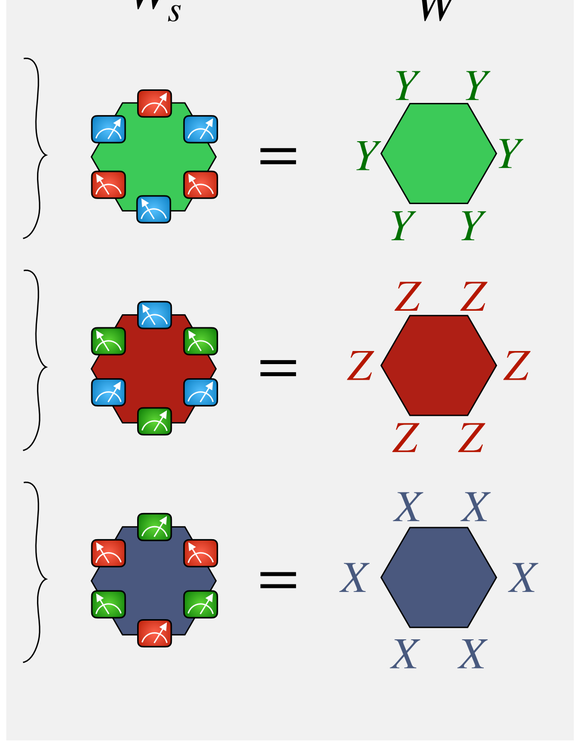

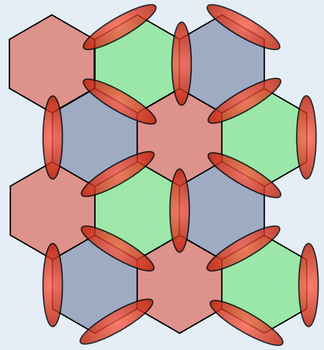

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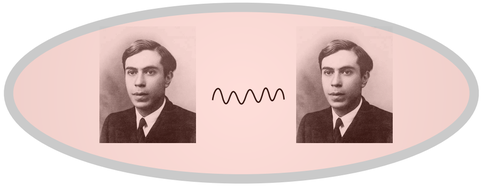
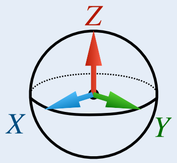


coherent error / weak measurement →

soften dimers – a channel for Majorana to escape !

Majorana, flux pillars, loops

Guo-Yi Zhu



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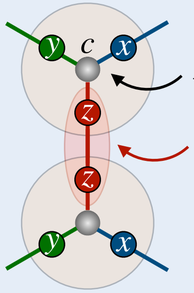

Majorana

gauge field

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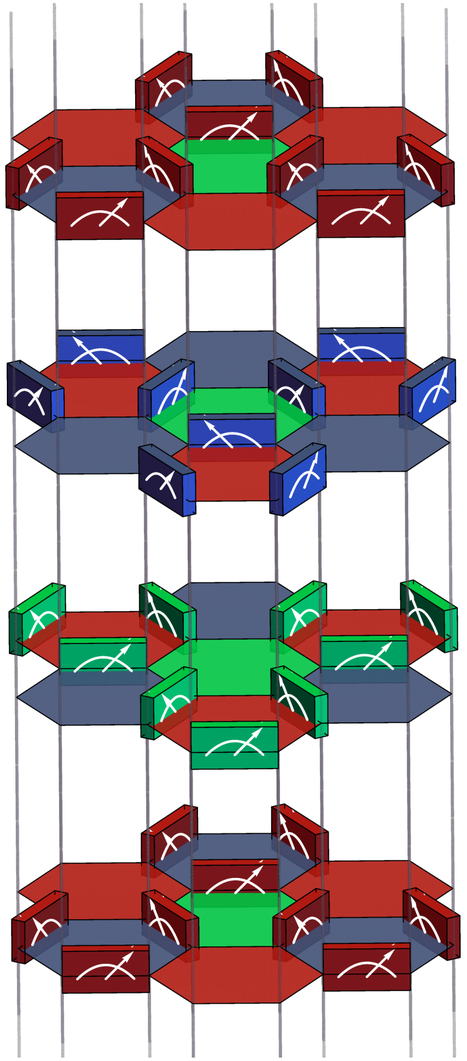

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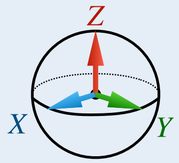

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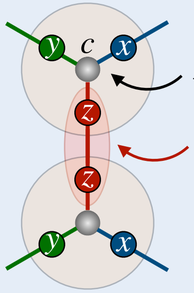

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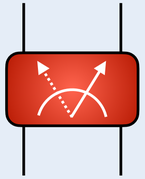

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measurement strength

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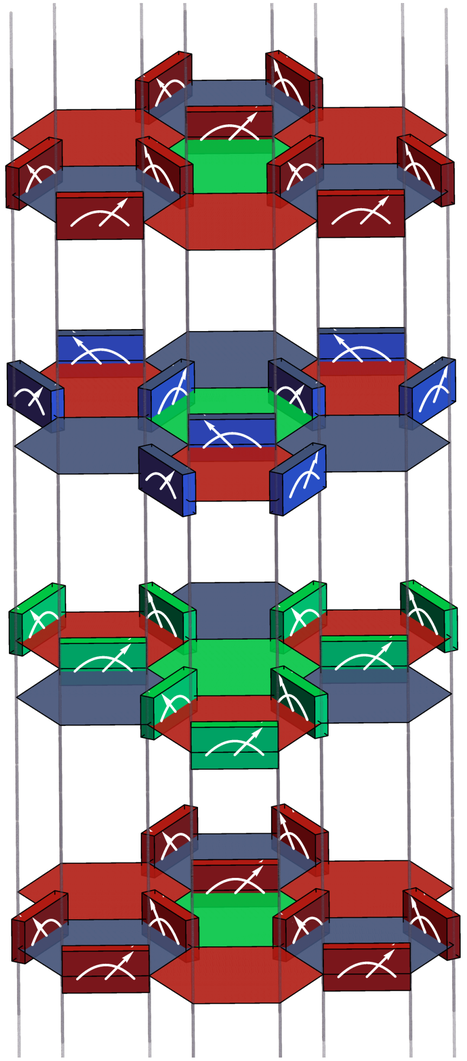
net gauge field

Majorana bilinear



Majorana, flux pillars, loops

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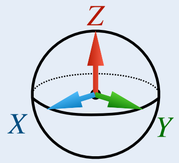

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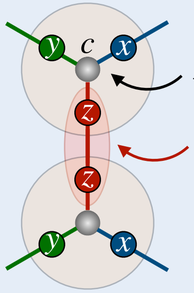

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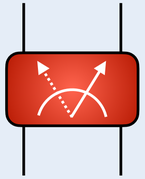

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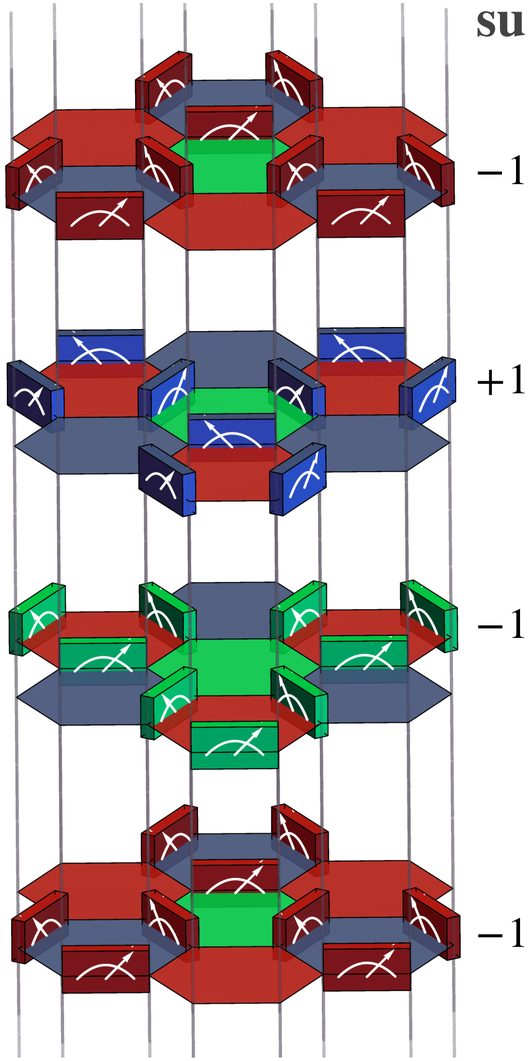

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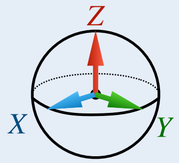

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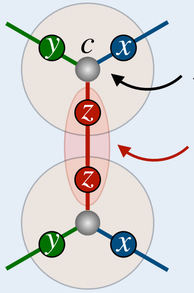

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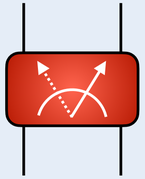

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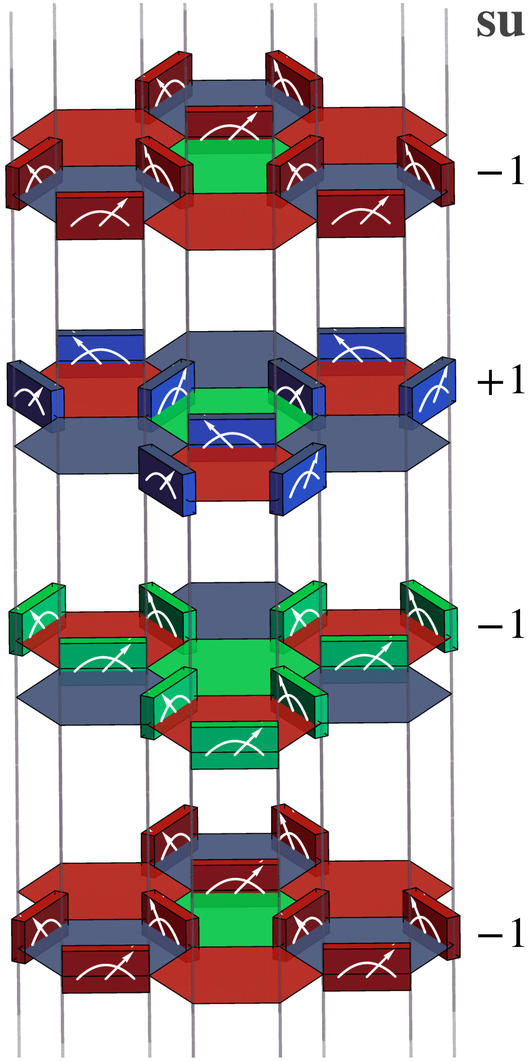

random Gaussian fermion circuit
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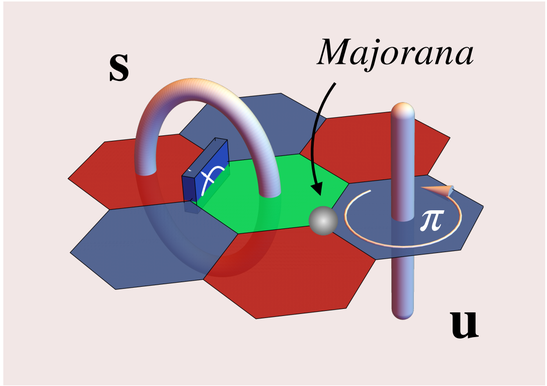
gauge trajectory su



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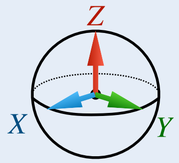

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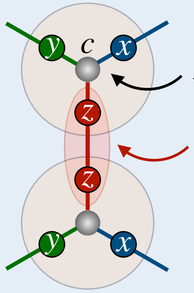

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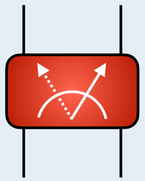

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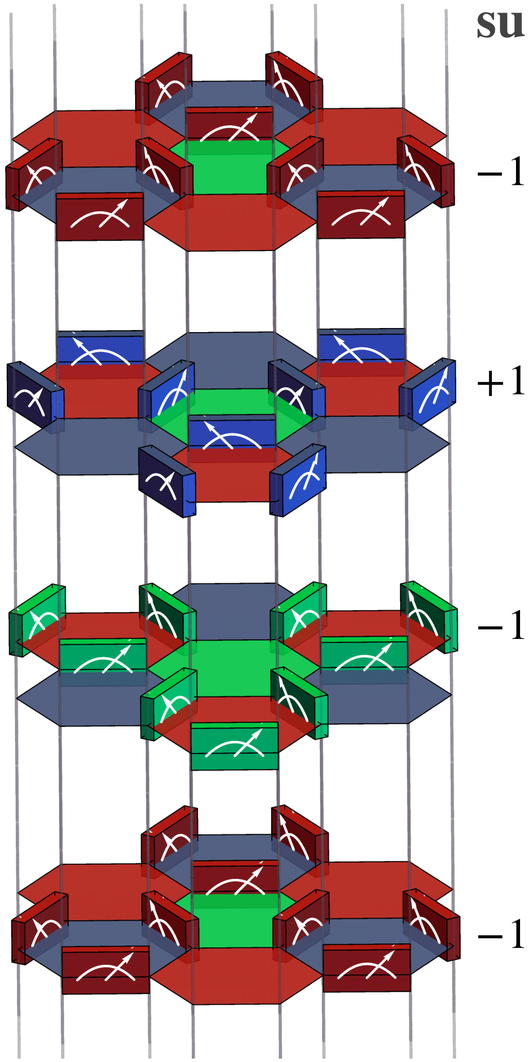

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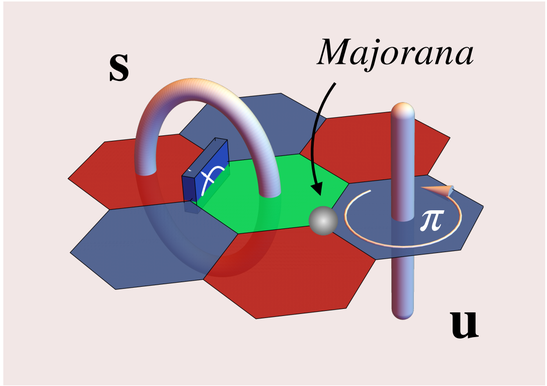
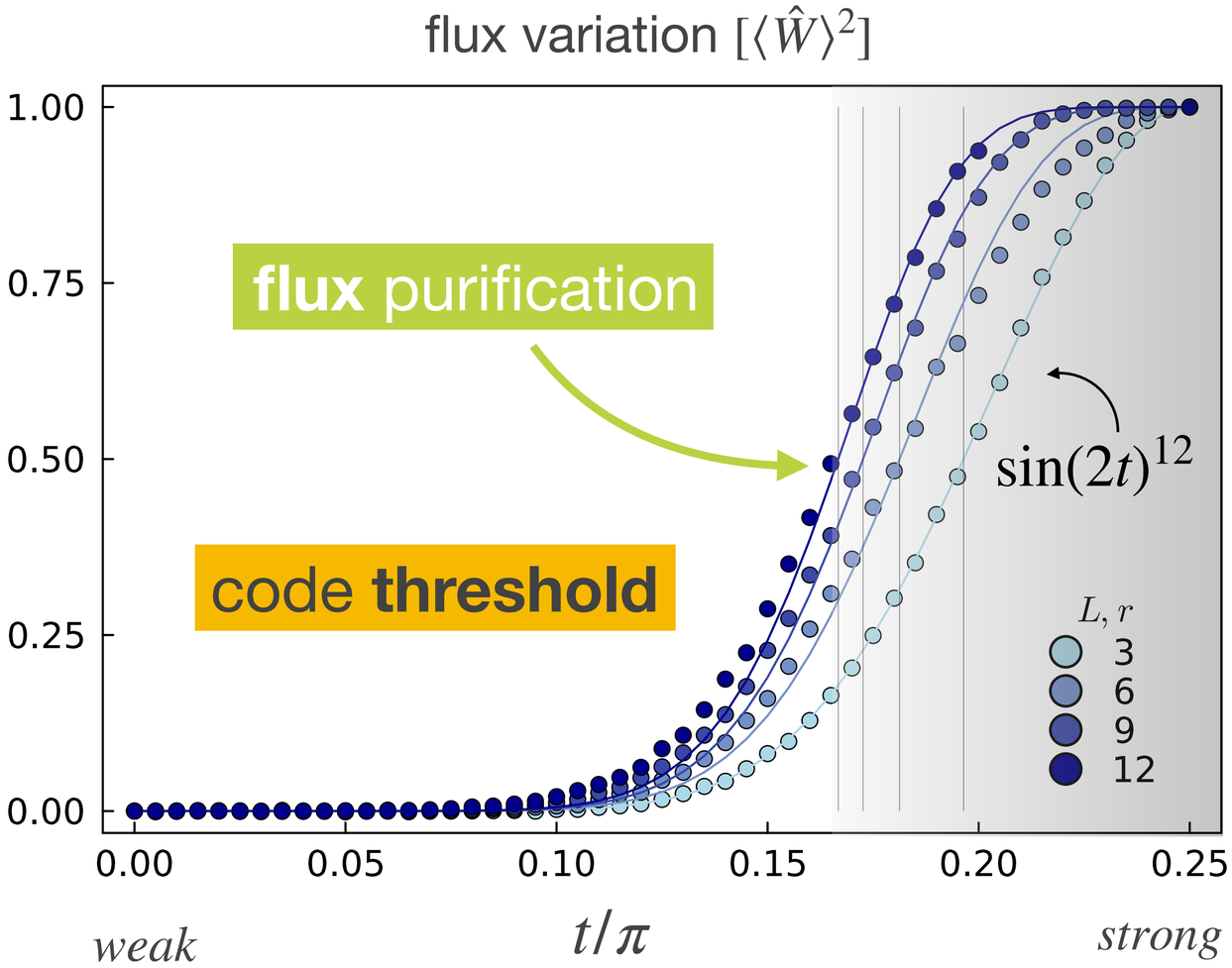


Born probability

=

Majorana partition function

purification of fluxes



- **flux** expectation value

quantum average

$$[\langle \hat{W} \rangle] = 0$$

measurement average

- **Edwards-Anderson** order parameter

$$[\langle \hat{W} \rangle^2] = \sum_{\mathbf{s}} P(\mathbf{s}) \langle \hat{W} \rangle_{\mathbf{s}}^2 = \sum_{q} \sum_{\mathbf{s},\mathbf{u}} \frac{p_{\mathbf{s}} \cdot p_{\mathbf{su}}}{P(\mathbf{s})} \left(\prod_{l \in q} u_l \right)$$

- **exponential** purification

$$S_u := -\log_2 \frac{1 + [\langle \hat{W} \rangle^2]}{2} \approx \left(-\log_2 \frac{1 + \sin(2t)^{12}}{2} \right)^{\frac{r+1}{4}}$$

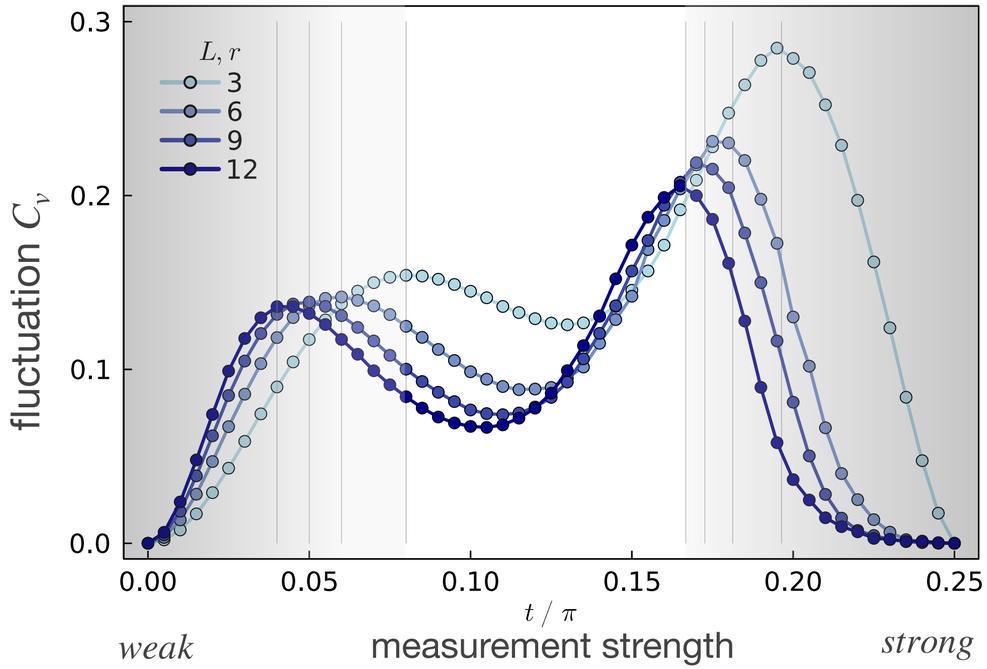
but there is more – double-peaks

weak measurement-only circuit

circuit depth

$$\rho_{\mathbf{su}} \propto \exp\left(-\frac{\beta}{4}\mathbf{c}H_{\mathbf{su}}\mathbf{c}\right)$$

effective Hamiltonian



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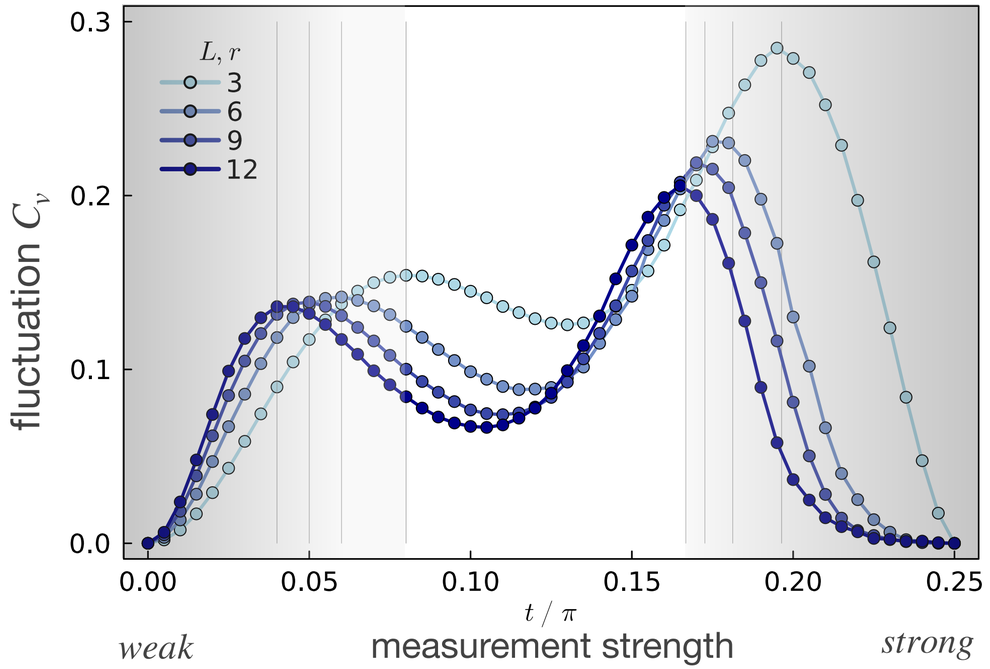
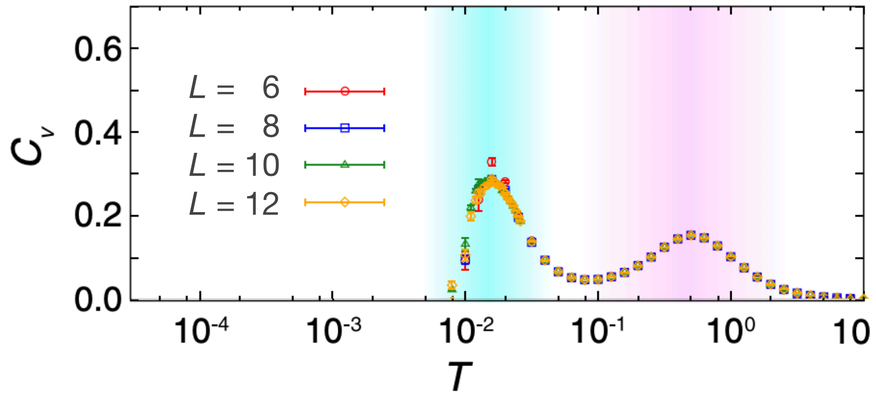


Hamiltonian at finite temperature



Nasu, Udagawa, Motome, 2014

PRL **113,** 197205 (2014) PHYSICAL REVIEW LETTERS week ending 7 NOVEMBER 2014

Vaporization of Kitaev Spin Liquids

Joji Nasu,[1] Masafumi Udagawa,[2] and Yukitoshi Motome[2]

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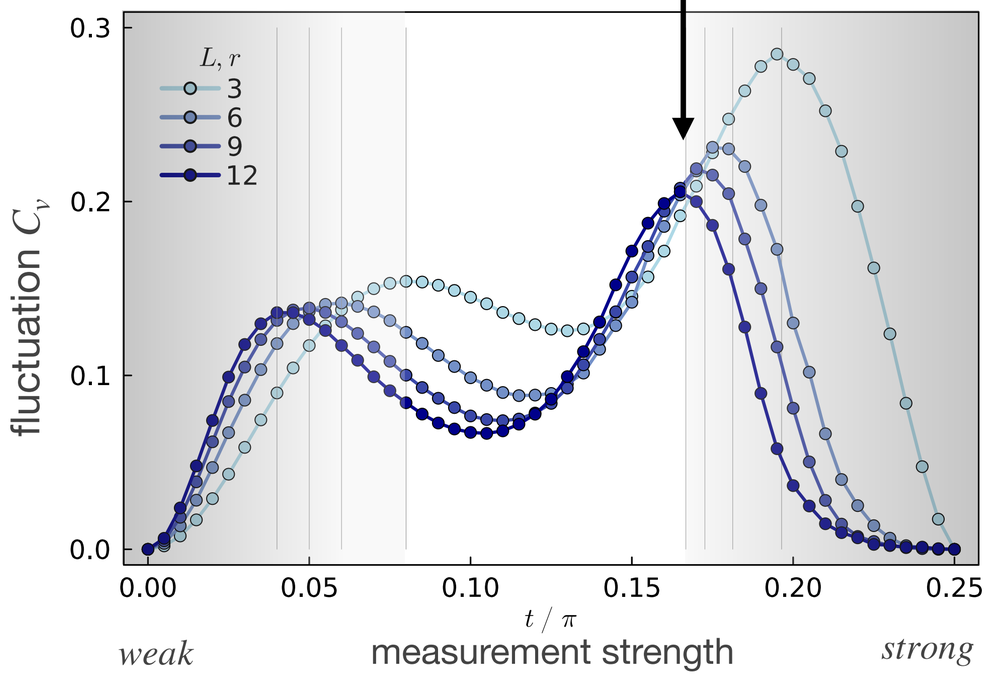

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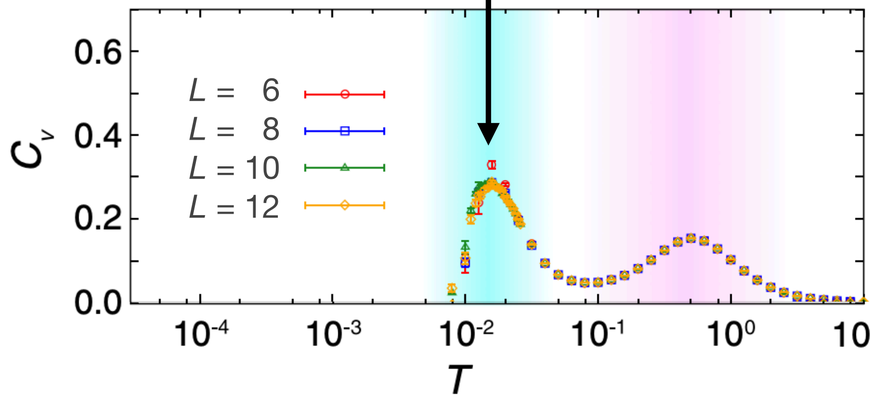

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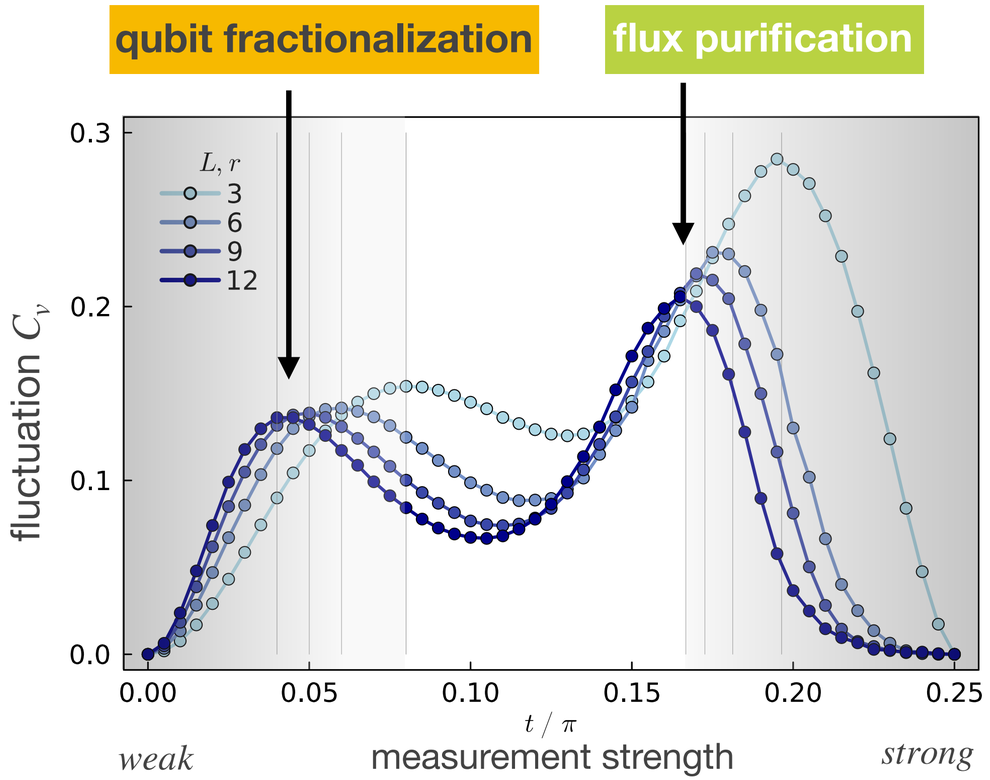

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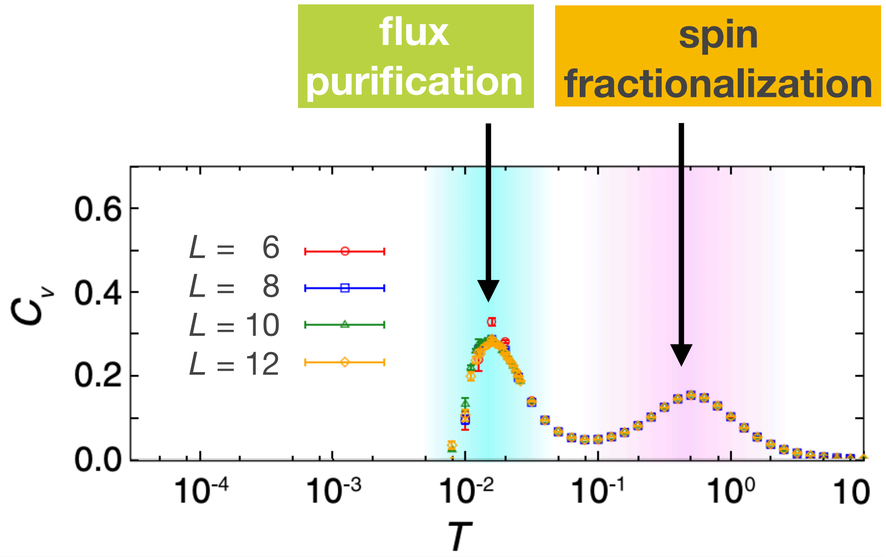

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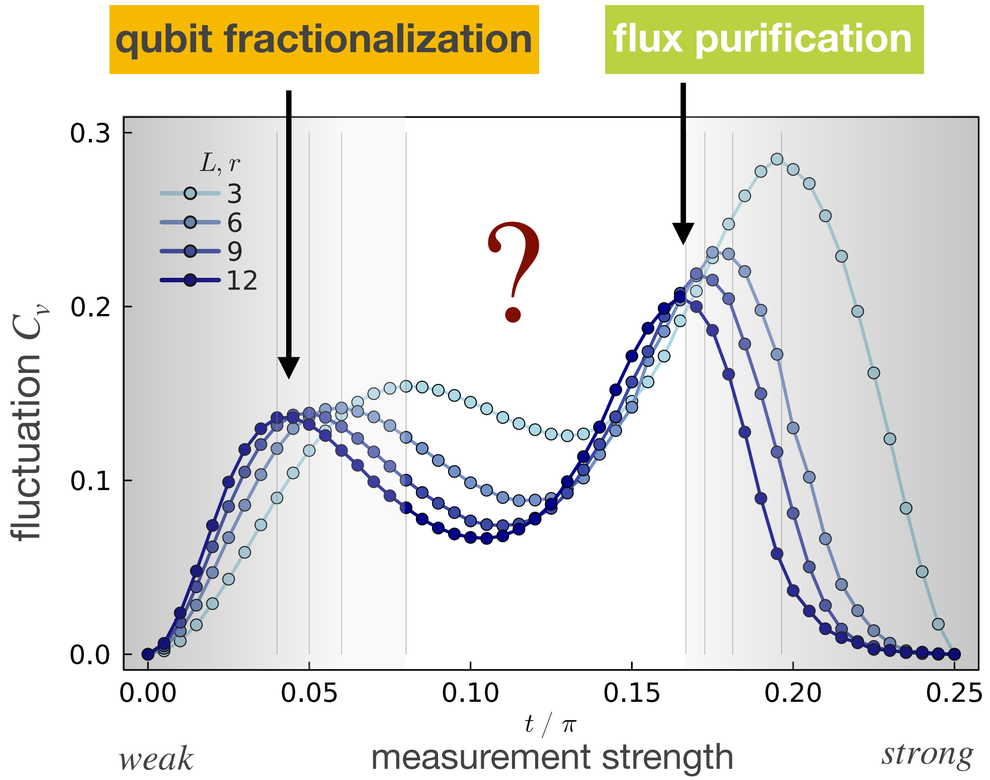
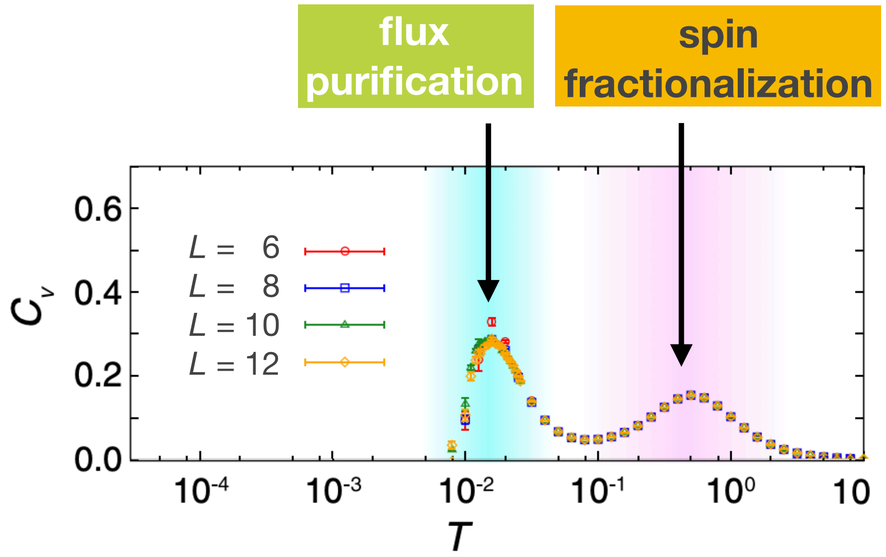


Hamiltonian at finite temperature



Nasu, Udagawa, Motome, 2014

PRL **113,** 197205 (2014) PHYSICAL REVIEW LETTERS week ending 7 NOVEMBER 2014

Vaporization of Kitaev Spin Liquids

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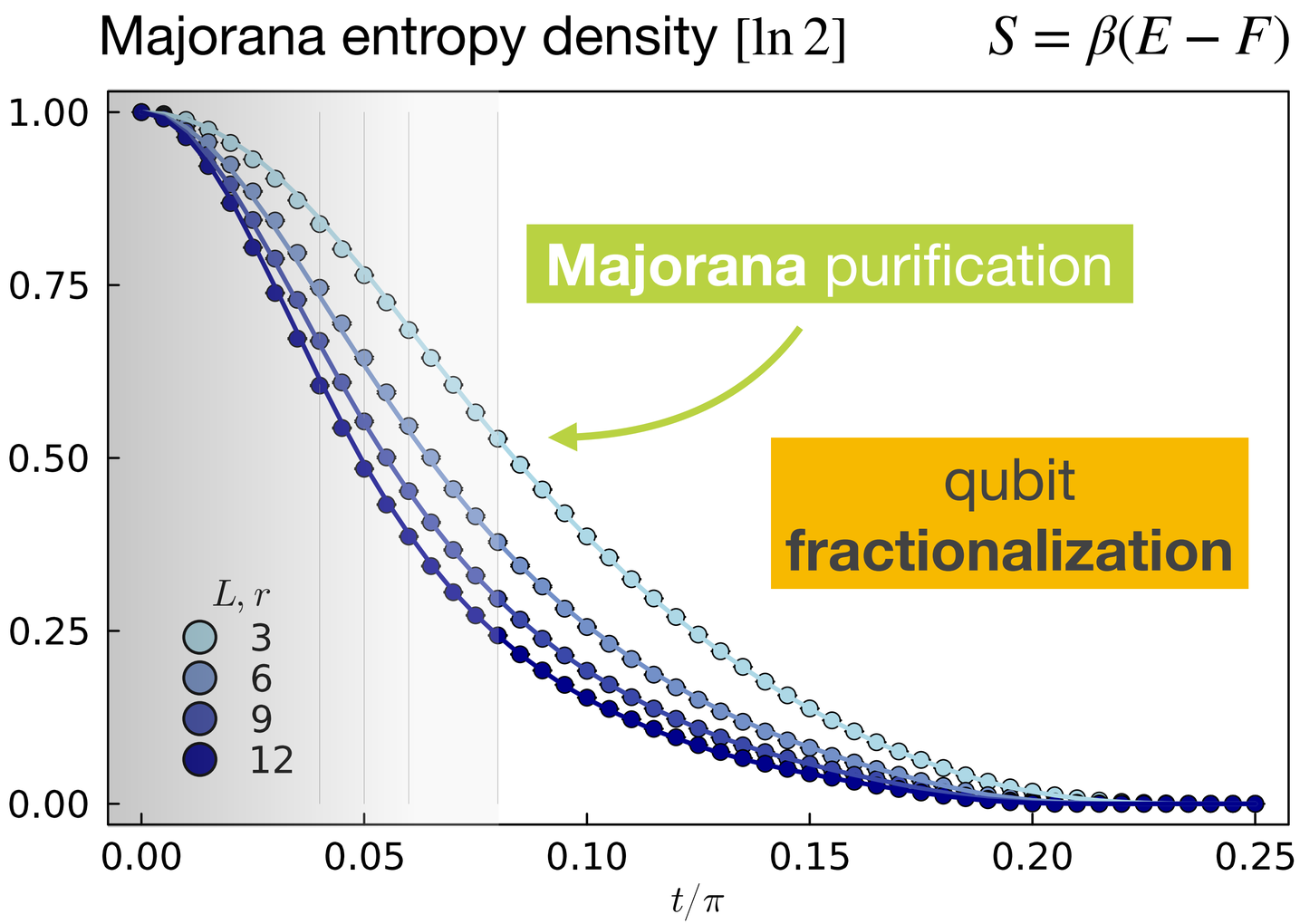
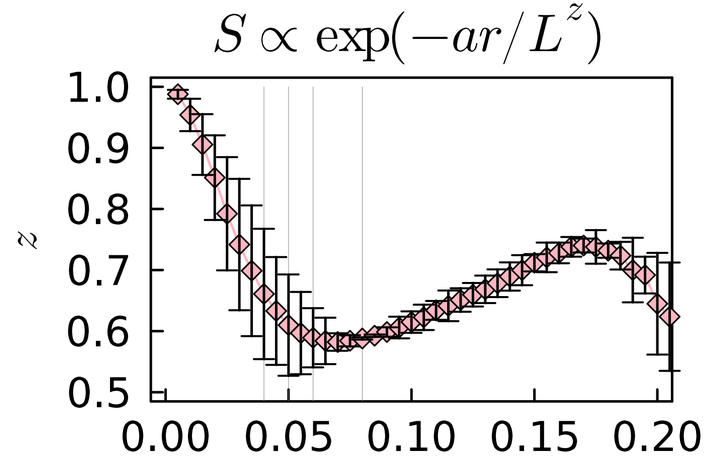
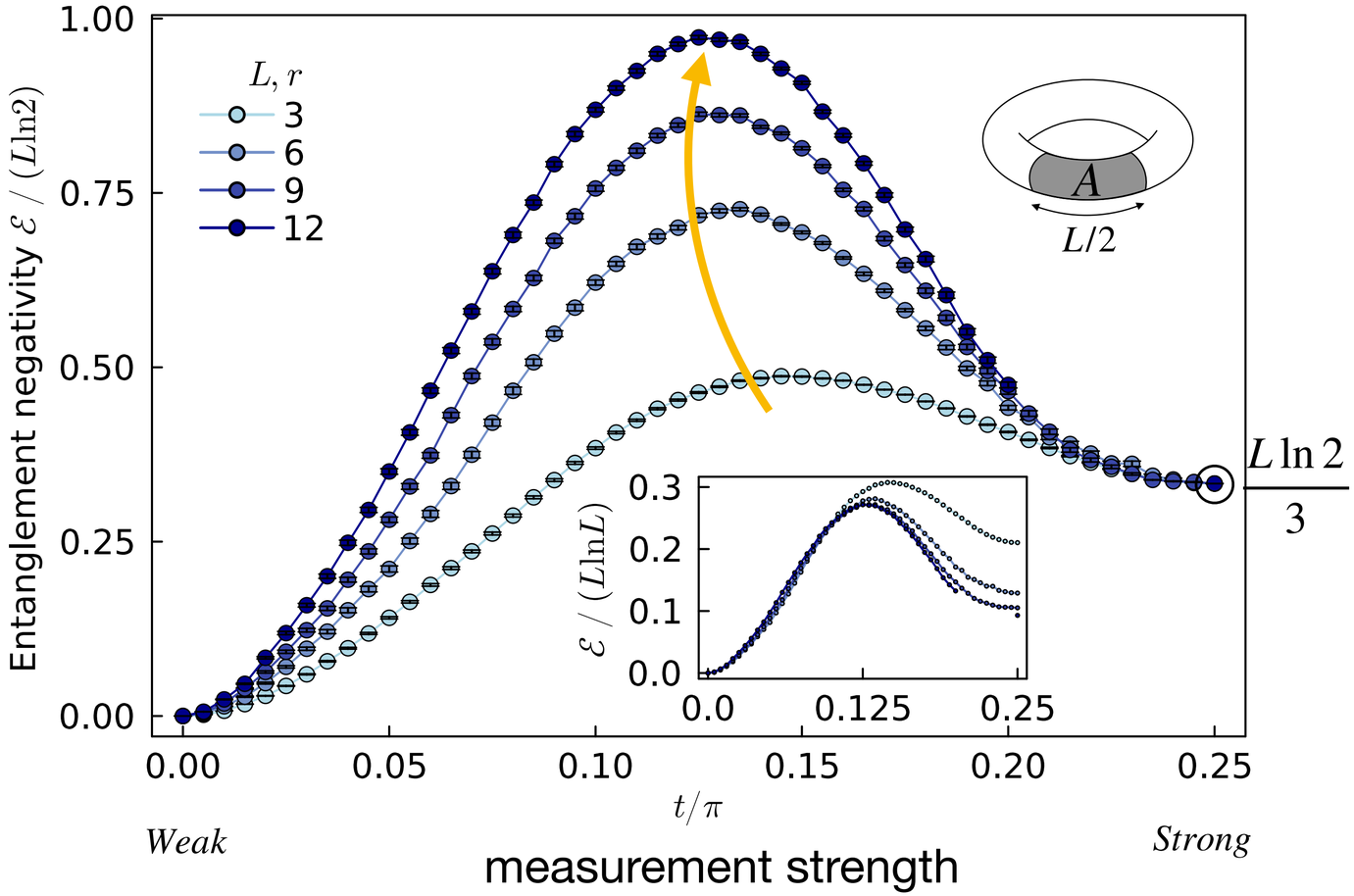
purification of Majoranas





dynamical
critical exponent

Majorana liquid



- fermionic **entanglement negativity**
  - definition: response under ***partial*** **time reversal**
  - property: **distill out thermal entropy**
  - diagnose: **mixed state entanglement**

Shapourian, Shiozaki, Ryu, 2017

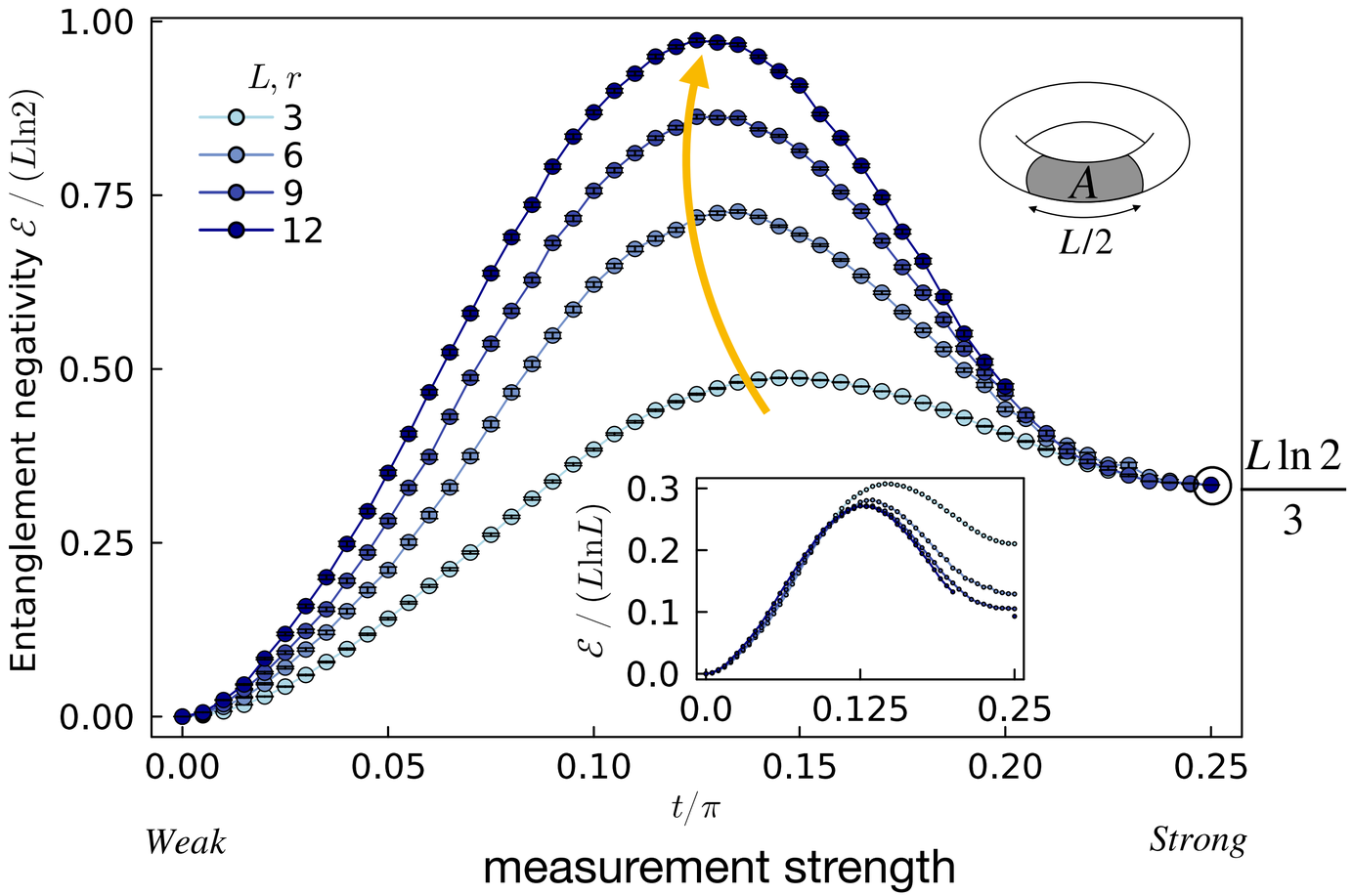
$$\mathscr{E} = \sum_{\mathbf{su}} p_{\mathbf{su}} \cdot \ln || \rho_{\mathbf{su}}^{R_A} ||_1$$

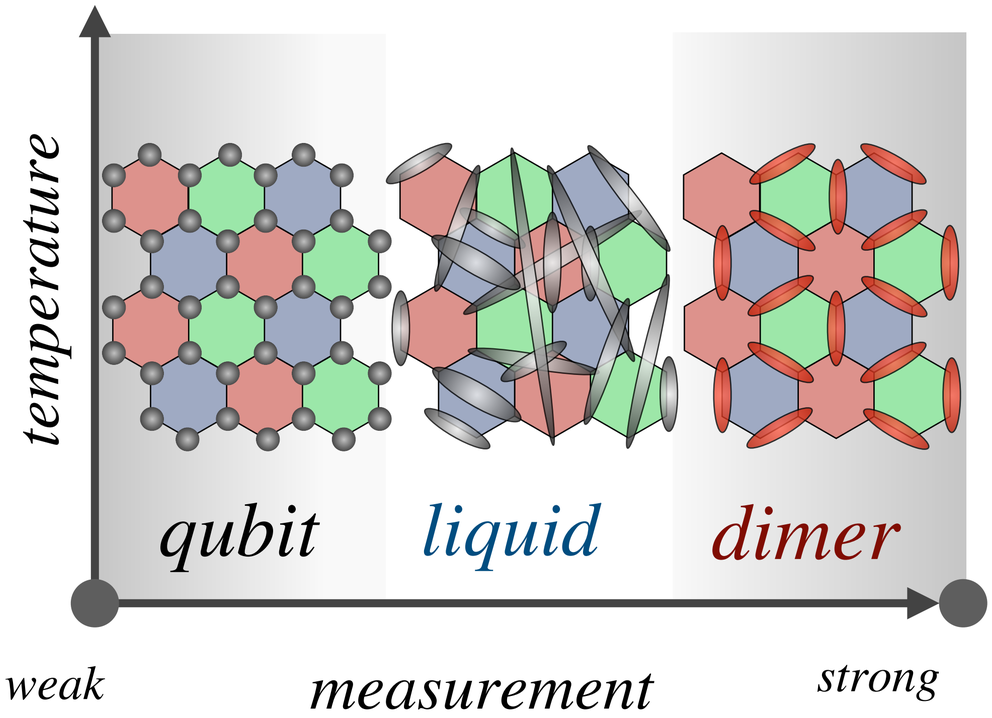
- **entanglement phase transition**

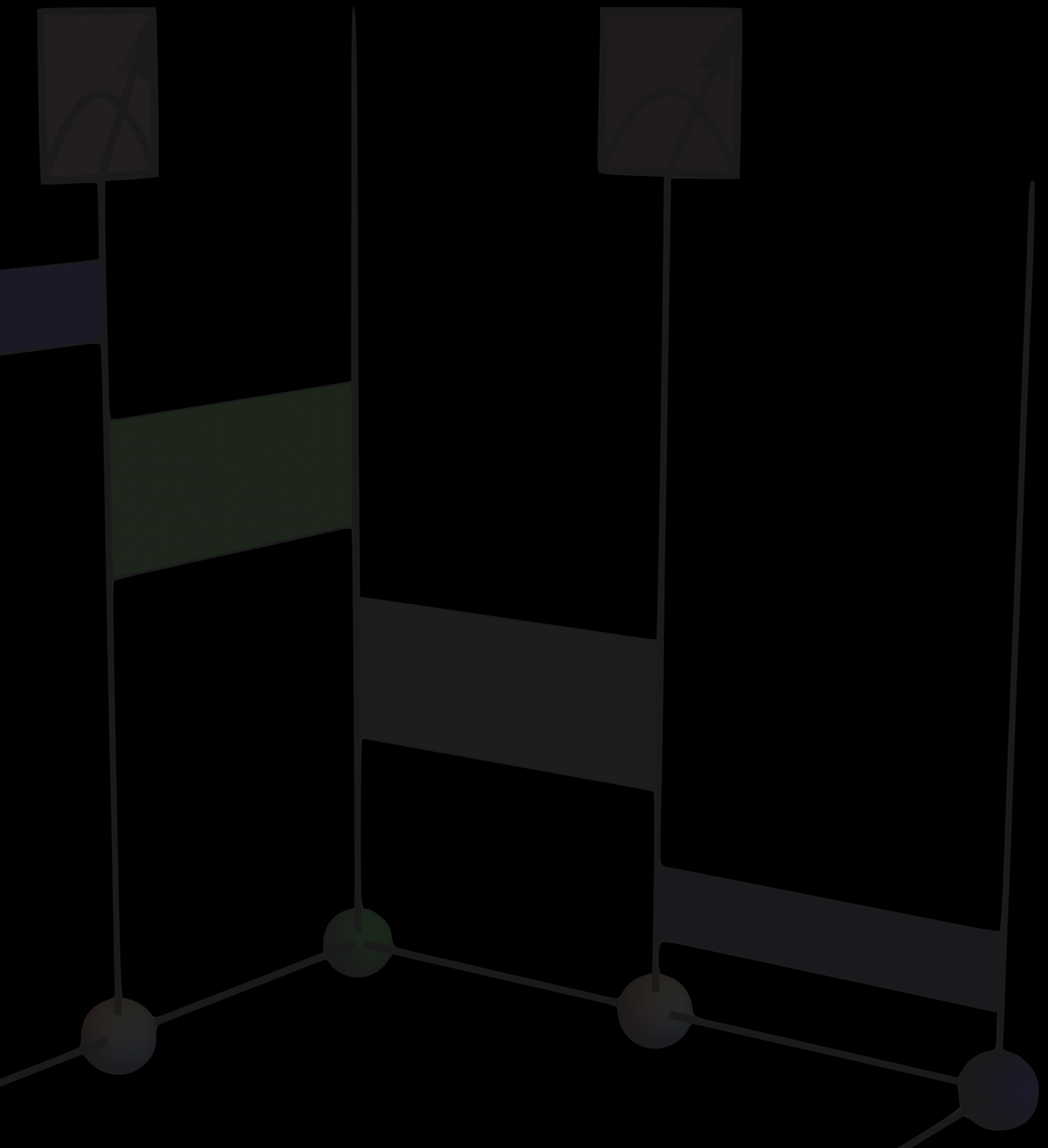
  stable fermion phase with $\mathbf{L}\ln\mathbf{L}$ **entanglement**

Fava, Piroli, Swann, Bernard, Nahum, NLσM, 2023

Majorana liquid





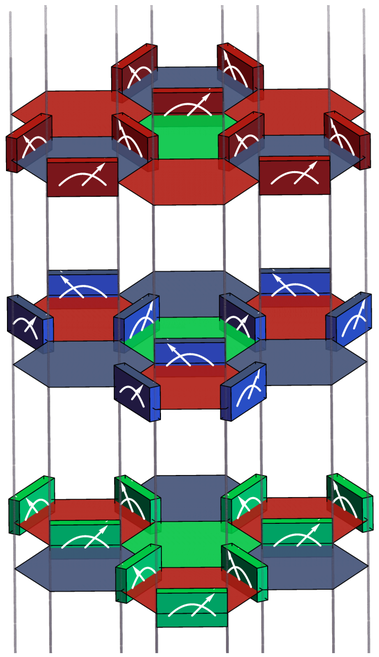


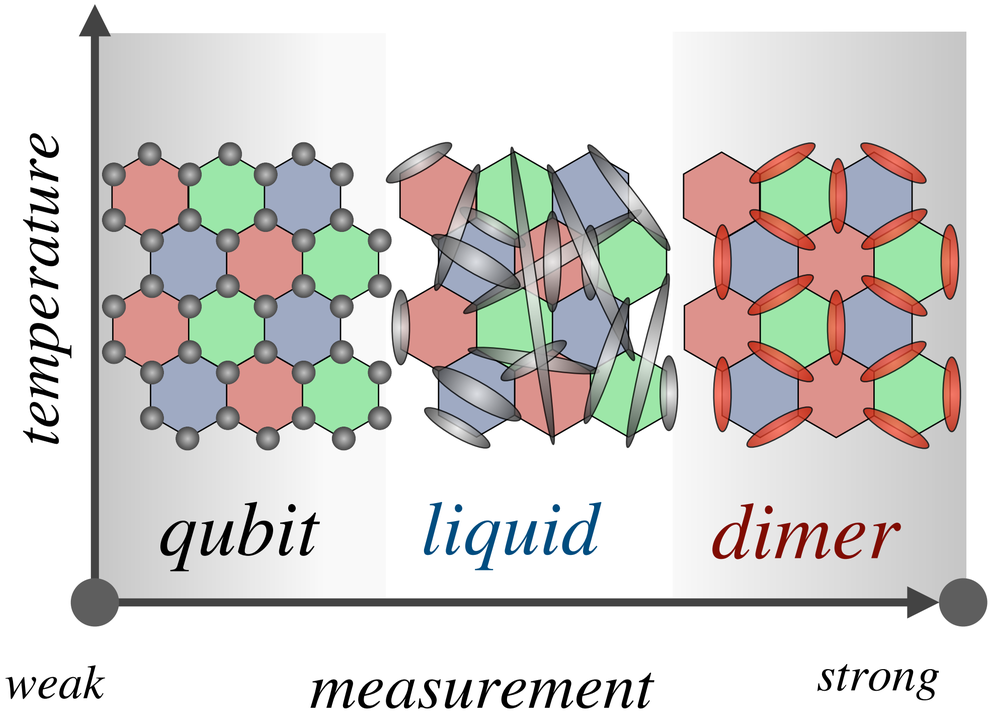
summary

Floquet code — conclusions

Guo-Yi Zhu

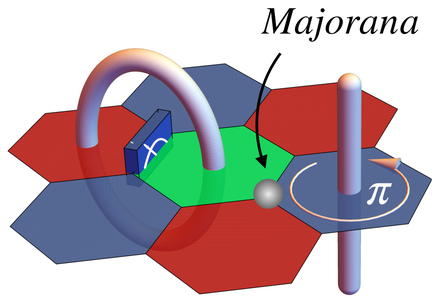
- **frustration** & **qubit fractionalization** by tunable weak measurement
- Floquet code **breakdown** to non-trivial state under coherent error
- **Majoranas** escape confinement and form long-range entangled **liquid**





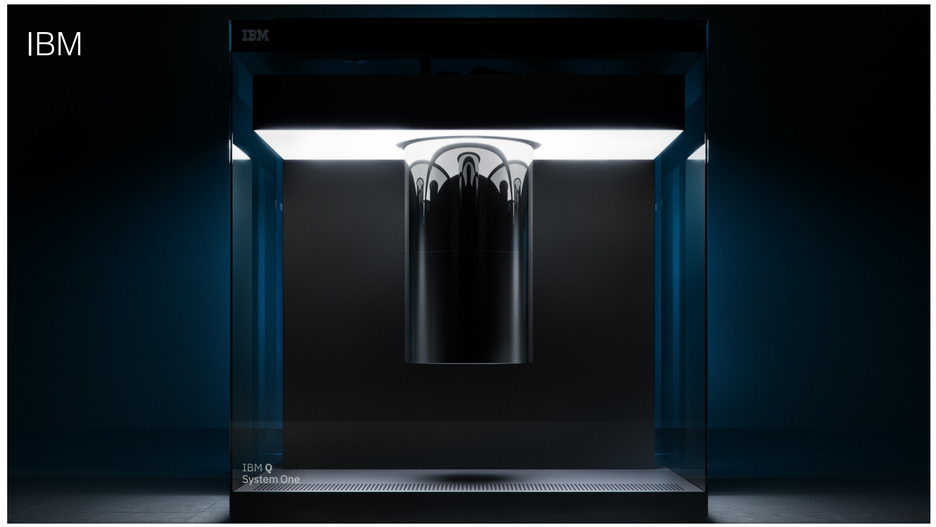
Outlook

- **Feed-forward** deterministic preparation?
- topological phase transition from a parent **color code** (+ Majorana interaction)?



Guo-Yi Zhu & ST, arXiv: 2311.08450

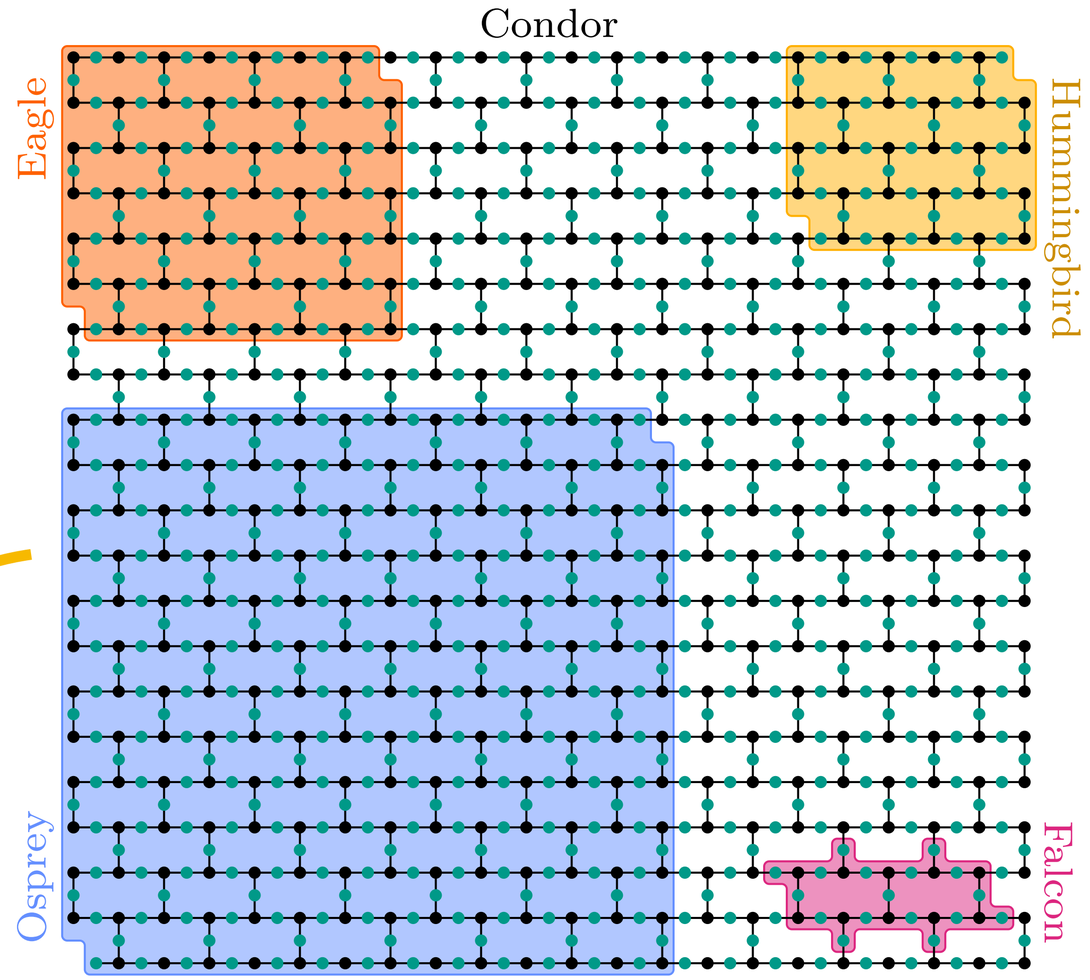
IBM quantum cloud devices



NISQ devices built on transmon qubits

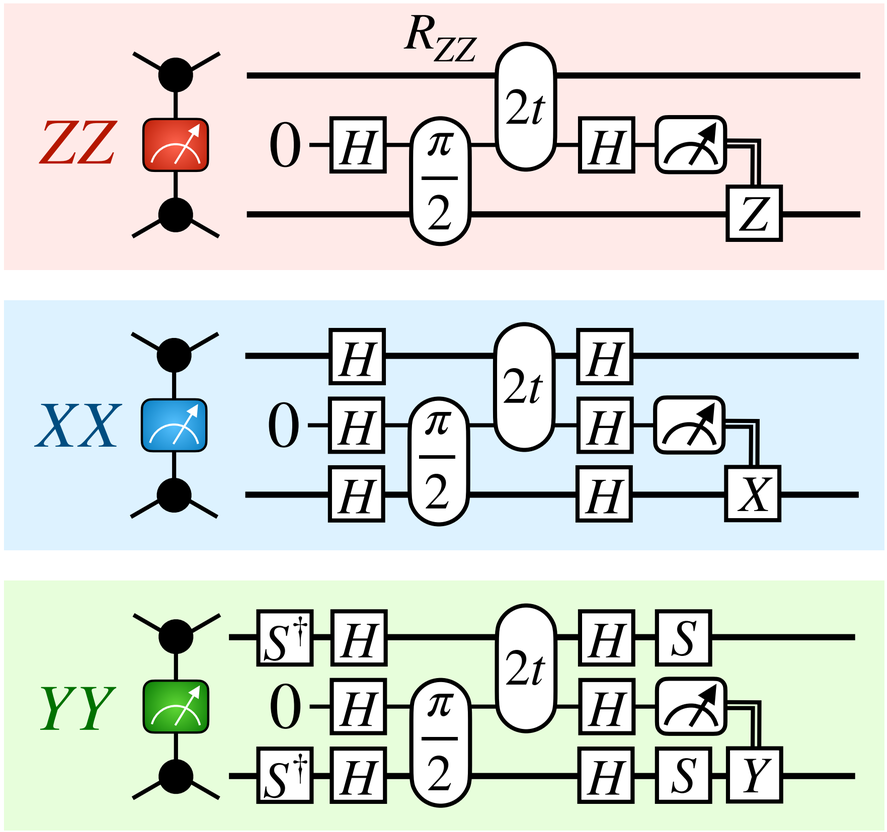
noisy intermediate scale quantum devices

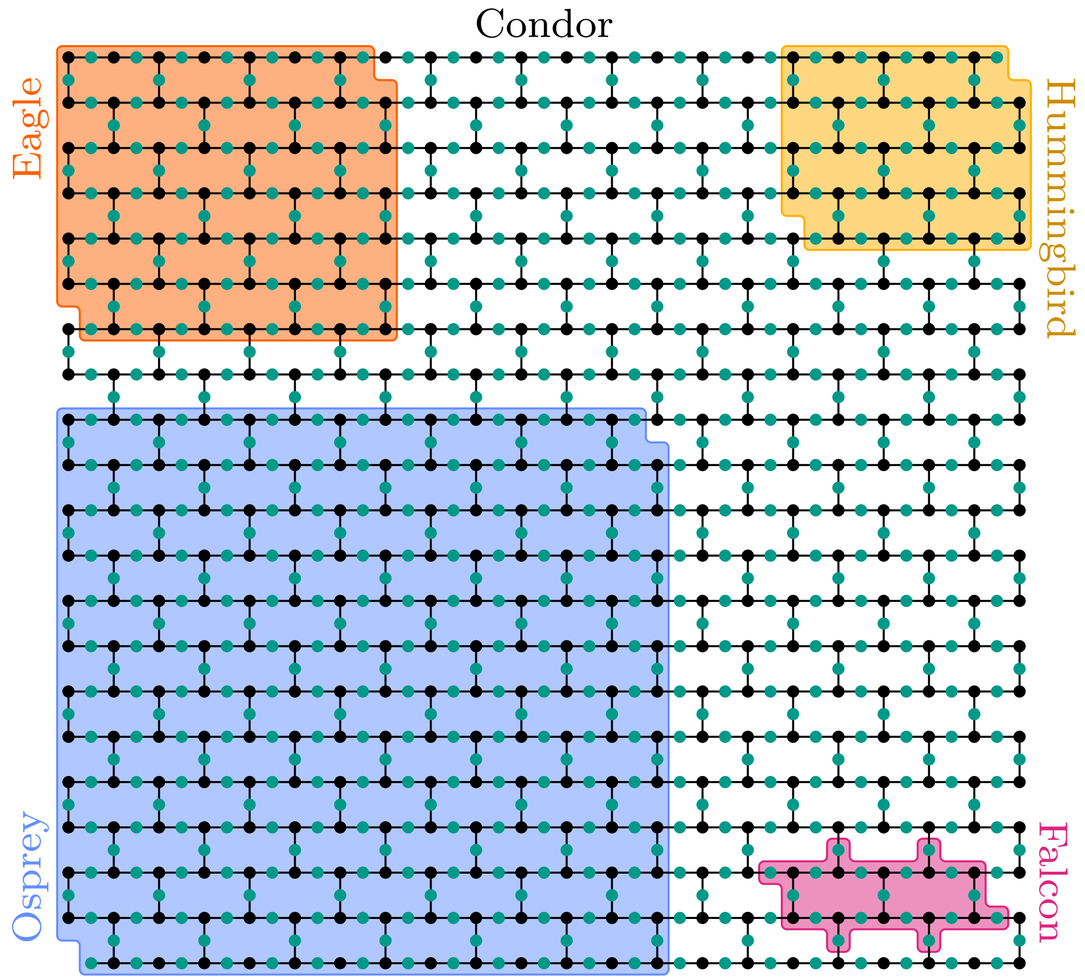
heavy-hexagon
geometry
+
Ising evolution gates



IBM quantum cloud devices

parity checks





two-qubit parity checks