

Title: Simulating Z2 Quantum Spin Liquids Using Quantum Simulators

Speakers: Shiyu Zhou

Series: Machine Learning Initiative

Date: February 07, 2023 - 10:00 AM

URL: <https://pirsa.org/23020036>

Abstract: Recent advances in programmable quantum devices brought to the fore the intriguing possibility of using them to realize and investigate topological quantum spin liquids (QSLs) phase. This new and exciting direction brings about important research questions on how to probe and determine the presence of such exotic, highly entangled phases. In this talk, I will discuss how to construct Z2 QSLs states as the ground state of a static Hamiltonian with only local two-qubit interactions and a transverse field, and demonstrate its realization in the classical limit at the endpoint of quantum annealing protocol, using D-Wave DW-2000Q machine . I will also demonstrate how to probe signatures of Z2 QSLs fractional statistics in quantum simulators via quasiparticle interferometry. At the end, I will show the robustness of this probe against disorders and dephasing -- effects that are generally pervasive in quantum devices nowadays.

Zoom Link: <https://pitp.zoom.us/j/99207971920?pwd=N3R3YUJtWXJWVjFQWIRoZ3hYSDIMZz09>

Simulating \mathbb{Z}_2 Quantum Spin Liquids Using Quantum Simulators

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Claudio Castelnovo, Claudio Chamon



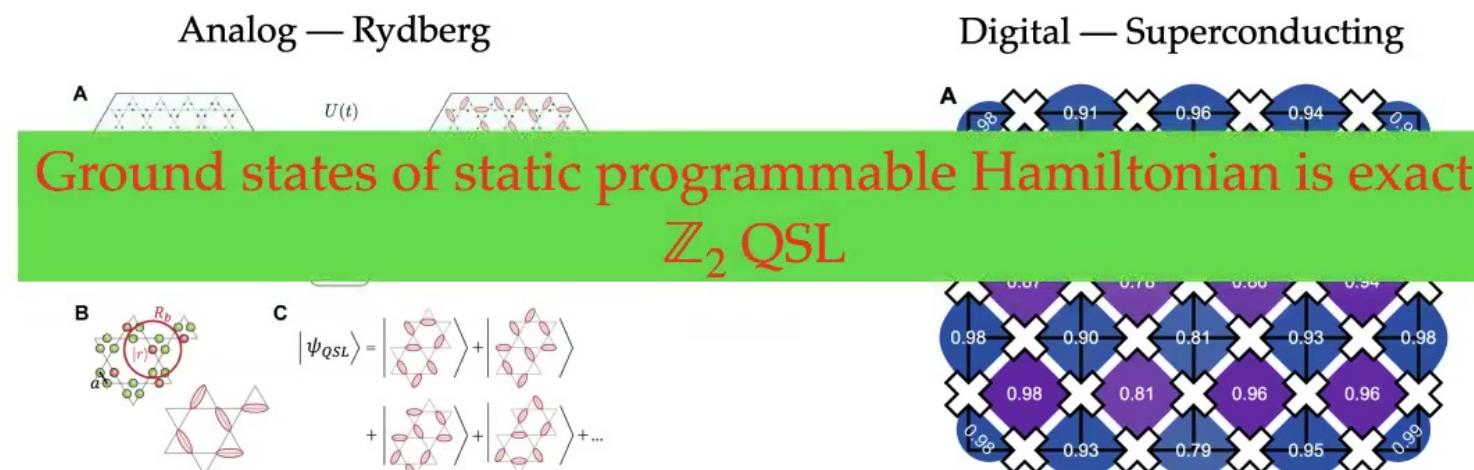
Feb. 07, 2023, Perimeter Institute

Outline

- Quantum simulators and \mathbb{Z}_2 quantum spin liquid (QSL)
- Physically realizable QSL model and its realization in DWave
- Probe fractional statistics of quantum spin liquids in quantum simulators

Quantum Simulators

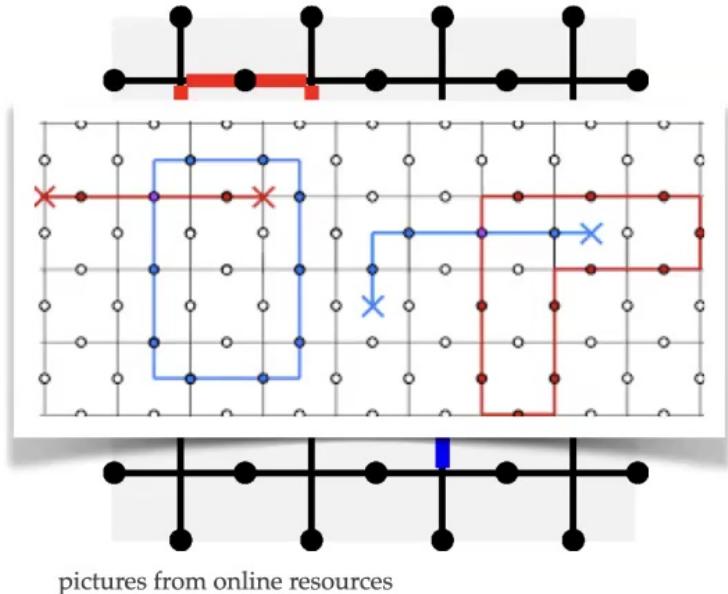
- Two types of quantum computers: a) digital; b) analog
- What are quantum computers known for:
 - Factoring: Shor's algorithm
 - Optimization: traveling salesman problem
 - Simulating physical systems: quantum spin liquids



G. Semeghini, and etc., "Probing topological spin liquids on a programmable quantum simulator", Science, 374(6572):1242–1247, dec 2021.

K. J. Satzinger and etc., "Realizing topologically ordered states on a quantum processor", Science, 374(6572):1237–1241, dec 2021.

Toric Code - Quantum \mathbb{Z}_2 Spin Liquid



Hamiltonian :

$$H = \sum_v A_v - J_m \sum_p B_p$$

$$A_v = \prod_{i \in v} \sigma_i^z \quad ; \quad B_p = \prod_{i \in p} \sigma_i^x$$

Properties :

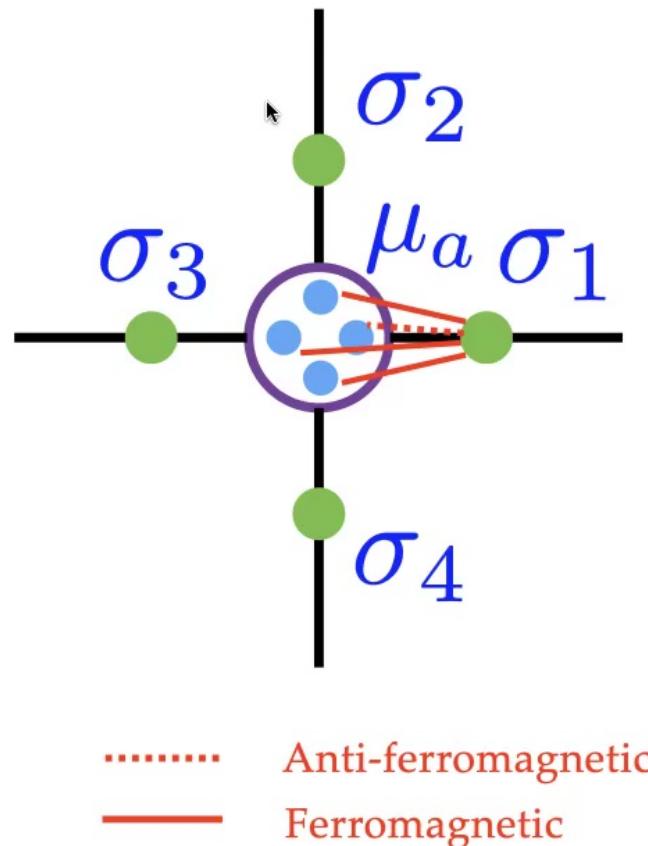
$$[A_v, A_{v'}] = [B_p, B_{p'}] = 0$$

$$[A_v, B_p] = [A_v, H] = [B_p, H] = 0$$

Ground states : $A_v = B_p = 1$

$$|\text{GS}\rangle = \mathcal{N} \prod_v (1 + A_v) |000\dots\rangle = \mathcal{N} \prod_p (1 + B_p) |+++ \dots\rangle$$

Combinatorial gauge symmetry (CGS)



- Single Star :

Four gauge spins σ_i^z , and four matter spins μ_j^z

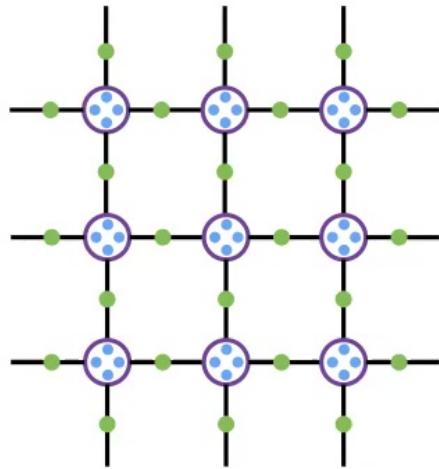
$$H_{\text{star}} = -J \sum_{i=1}^4 \sum_{j=1}^4 W_{ij} \sigma_i^z \mu_j^z$$

- Combinatorial gauge symmetry :

$$W = \begin{pmatrix} -1 & +1 & +1 & +1 \\ +1 & -1 & +1 & +1 \\ +1 & +1 & -1 & +1 \\ +1 & +1 & +1 & -1 \end{pmatrix}$$

Spin permutation + Spin π rotation

Combinatorial gauge symmetry (CGS)

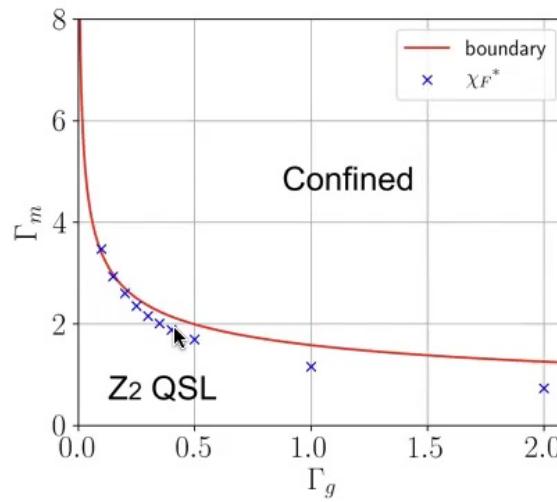


- Hamiltonian :

$$H = -J \sum_s \left[\sum_{i=1}^4 \sum_{j=1}^4 W_{ij} \sigma_j^z \mu_i^z + \widetilde{\Gamma} \sum_i \mu_i^x \right] - \Gamma \sum_j \sigma_j^x$$

- At $\widetilde{\Gamma} \gg J$ limit :

$$H_{\text{eff}} = -\lambda \sum_s \prod_{i \in s} \sigma_i^z - \Gamma \sum_i \sigma_i^x$$



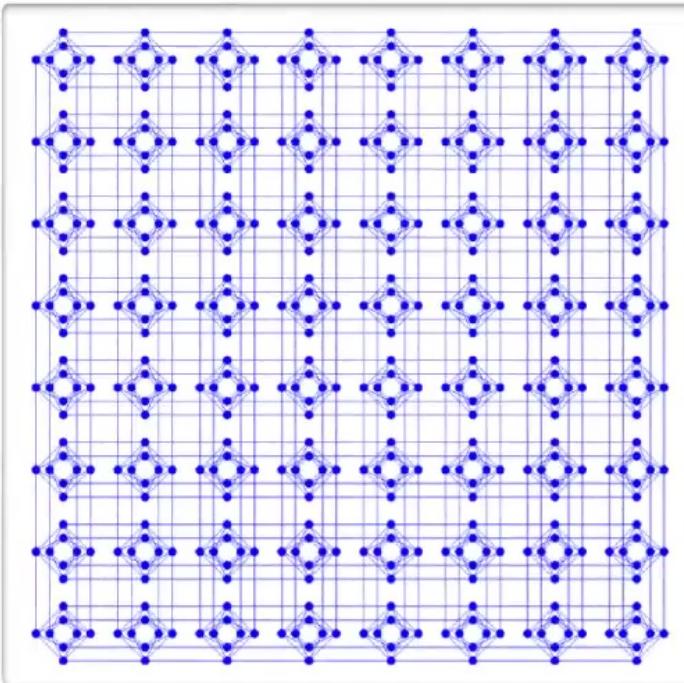
Claudio Chamon, Dmitry Green, and Zhi-Cheng Yang
Phys. Rev. Lett. **125**, 067203

Kai-Hsin Wu, Zhi-Cheng Yang, Dmitry Green, Anders W. Sandvik, and Claudio Chamon. Phys. Rev. B **104**, 085145

D-Wave

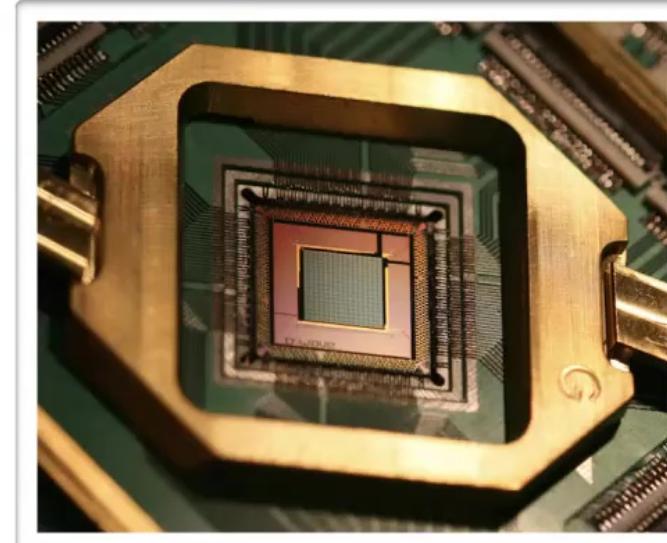
$$H_{\text{dwave}} = \frac{A(s)}{2} \sum_i \sigma_i^x + \frac{B(s)}{2} \left(\sum_i h_i \sigma_i^z + \sum_{i,j} J_{i,j} \sigma_i^z \sigma_j^z \right)$$

Chimera Graph:



Source: D-Wave

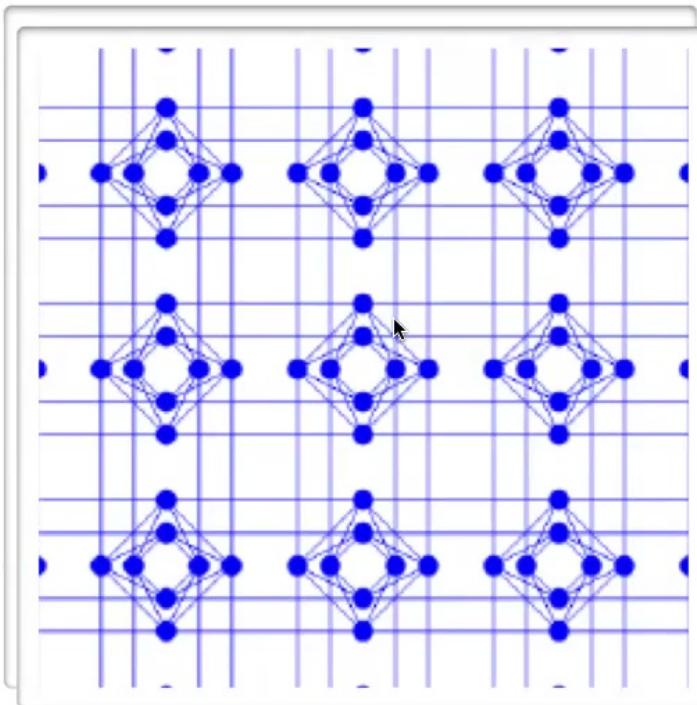
D-Wave 2000Q Chip:



D-Wave

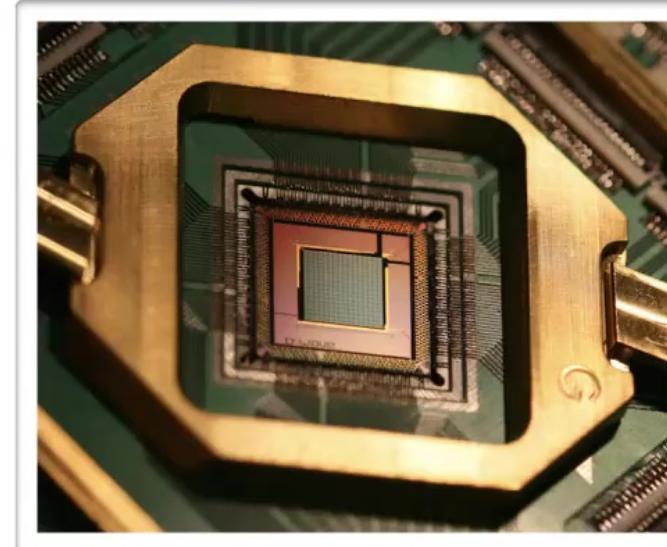
$$H_{\text{dwave}} = \frac{A(s)}{2} \sum_i \sigma_i^x + \frac{B(s)}{2} \left(\sum_i h_i \sigma_i^z + \sum_{i,j} J_{i,j} \sigma_i^z \sigma_j^z \right)$$

Chimera Graph:



Source: D-Wave

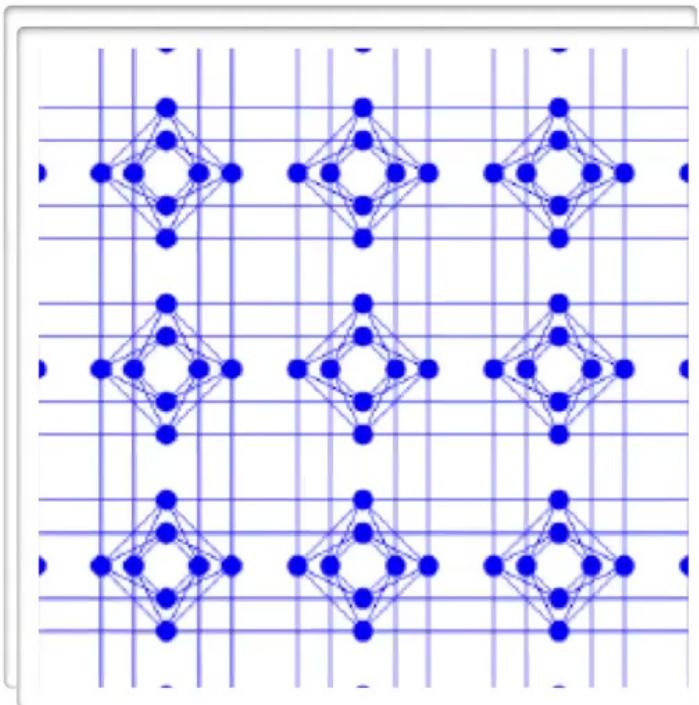
D-Wave 2000Q Chip:



D-Wave

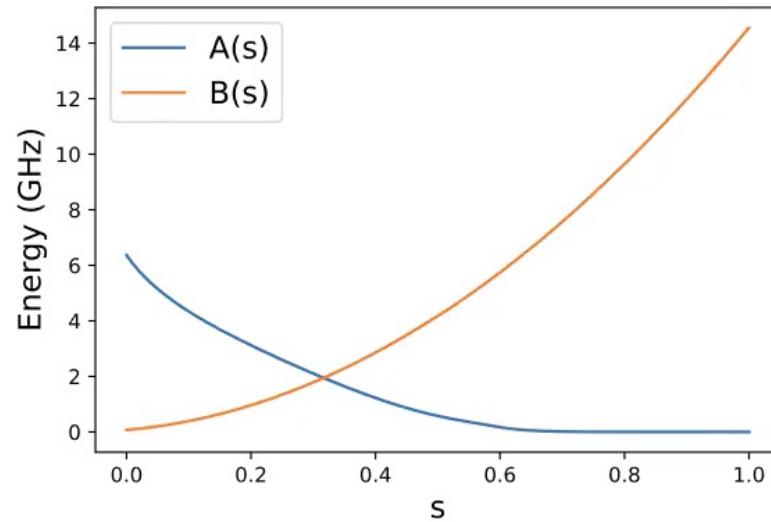
$$H_{\text{dwave}} = \frac{A(s)}{2} \sum_i \sigma_i^x + \frac{B(s)}{2} \left(\sum_i h_i \sigma_i^z + \sum_{i,j} J_{i,j} \sigma_i^z \sigma_j^z \right)$$

Chimera Graph:

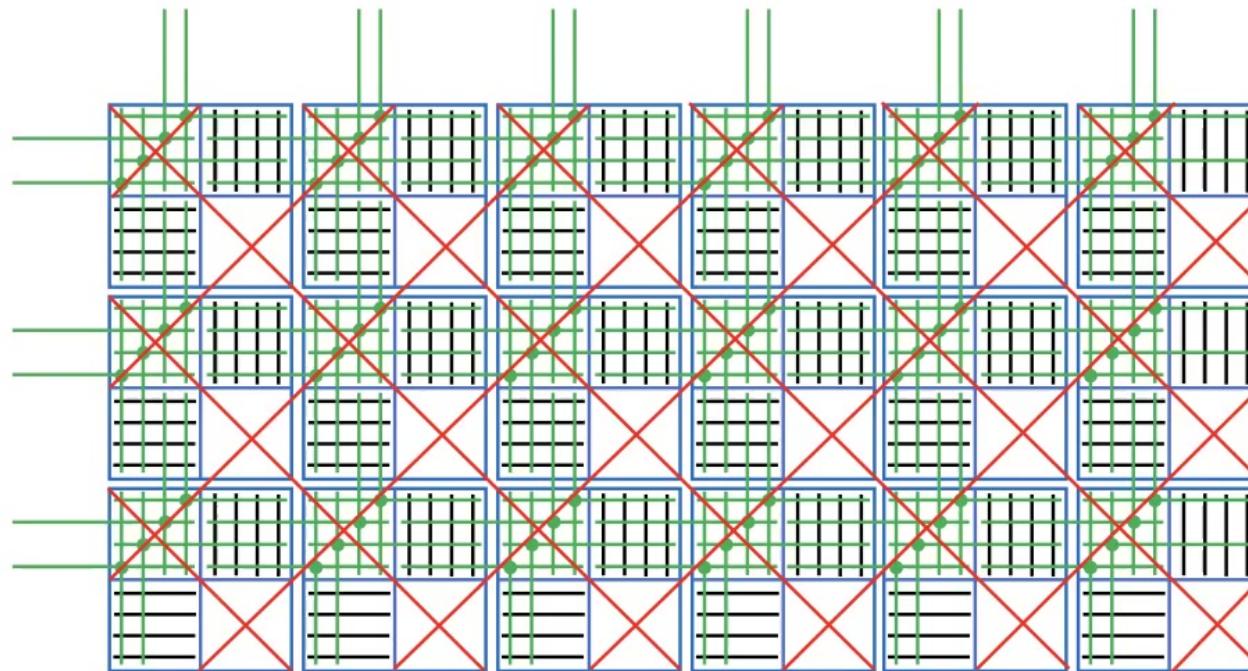


Source: D-Wave

Annealing Schedule:



Embedding in D-Wave

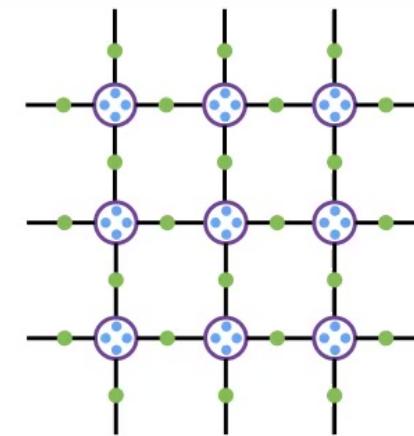
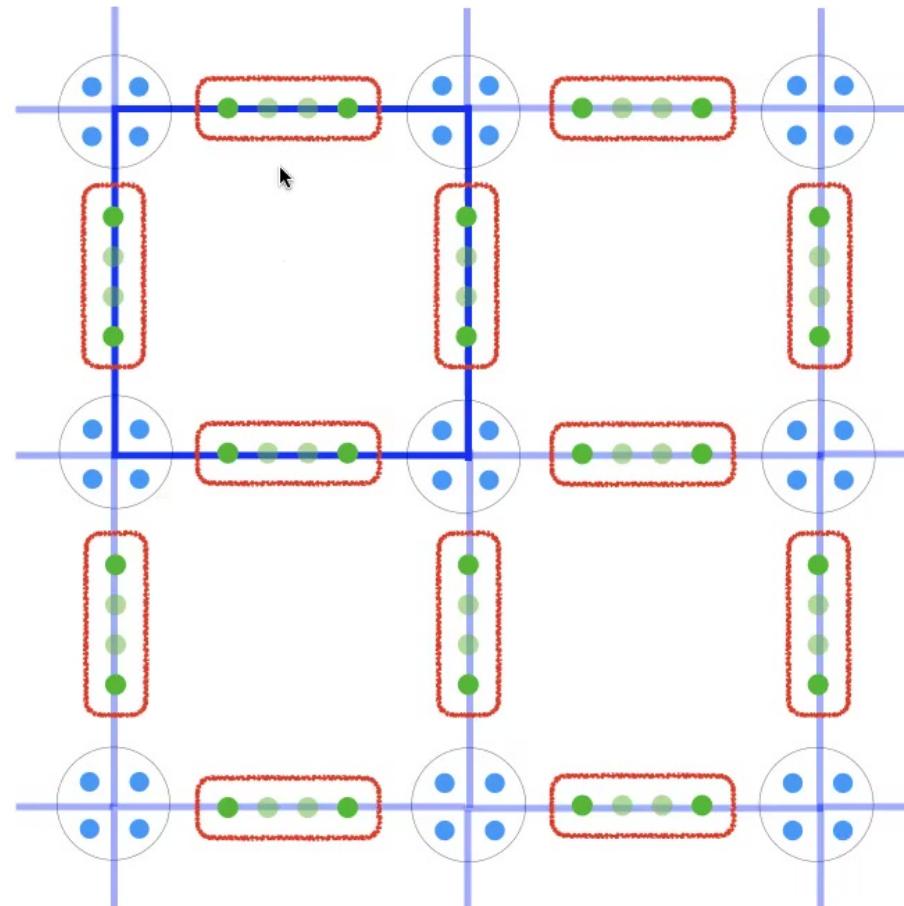


The 2x2 blue boxes represent a 2x2 configuration of unit cells. Qubits are represented not as graph vertices, but as line segments, which is how they are laid out on the chip. The black line segments represent matter spins and the green line segments represent gauge spins. Gauge spins become four-qubit chains. Green nodes represent intersection points between Horizontal and vertical qubits representing a single gauge spin. The red diagonal lattice represents the logical lattice for a Z(2) gauge theory.

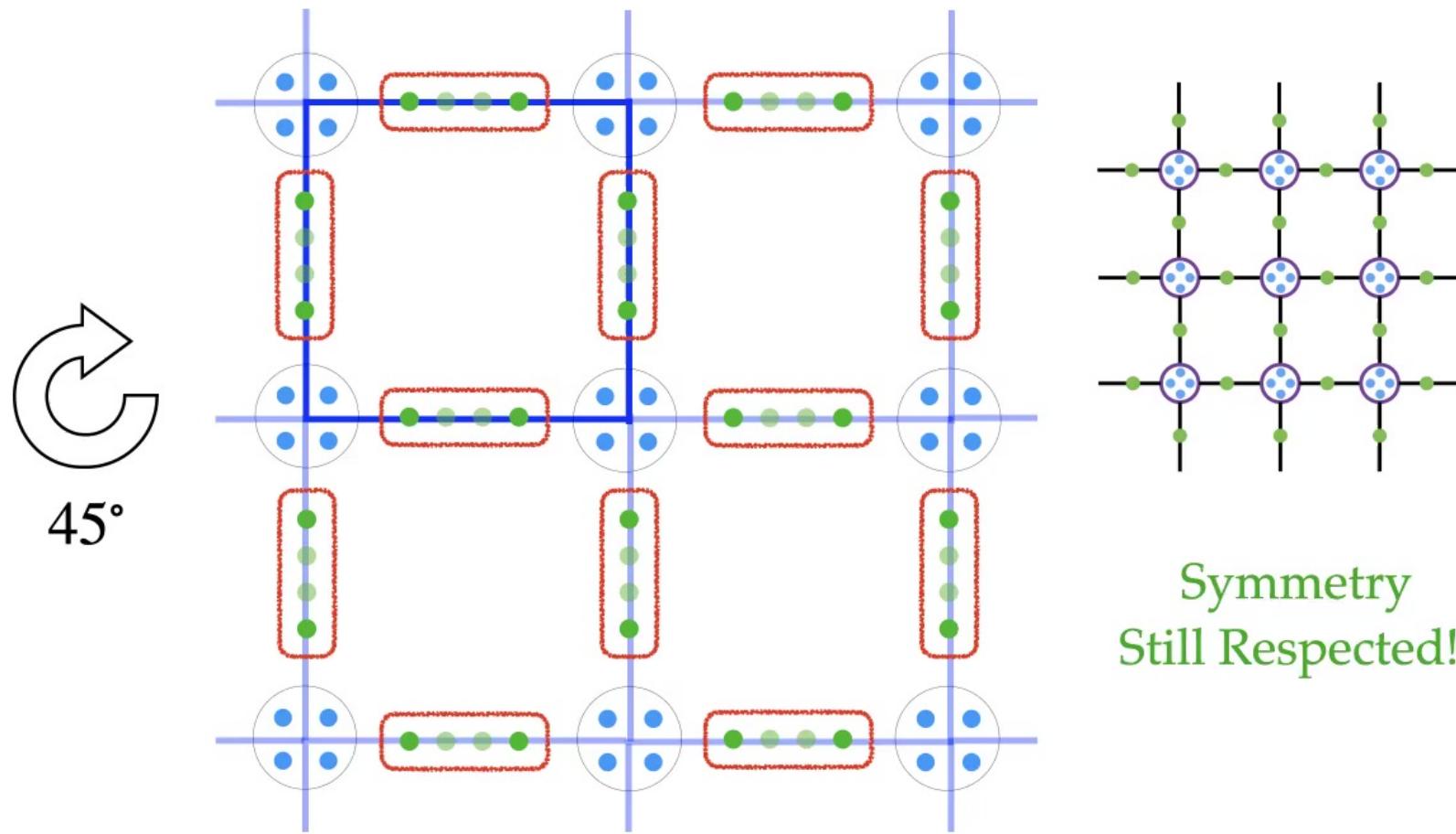
Embedding in D-Wave



45°

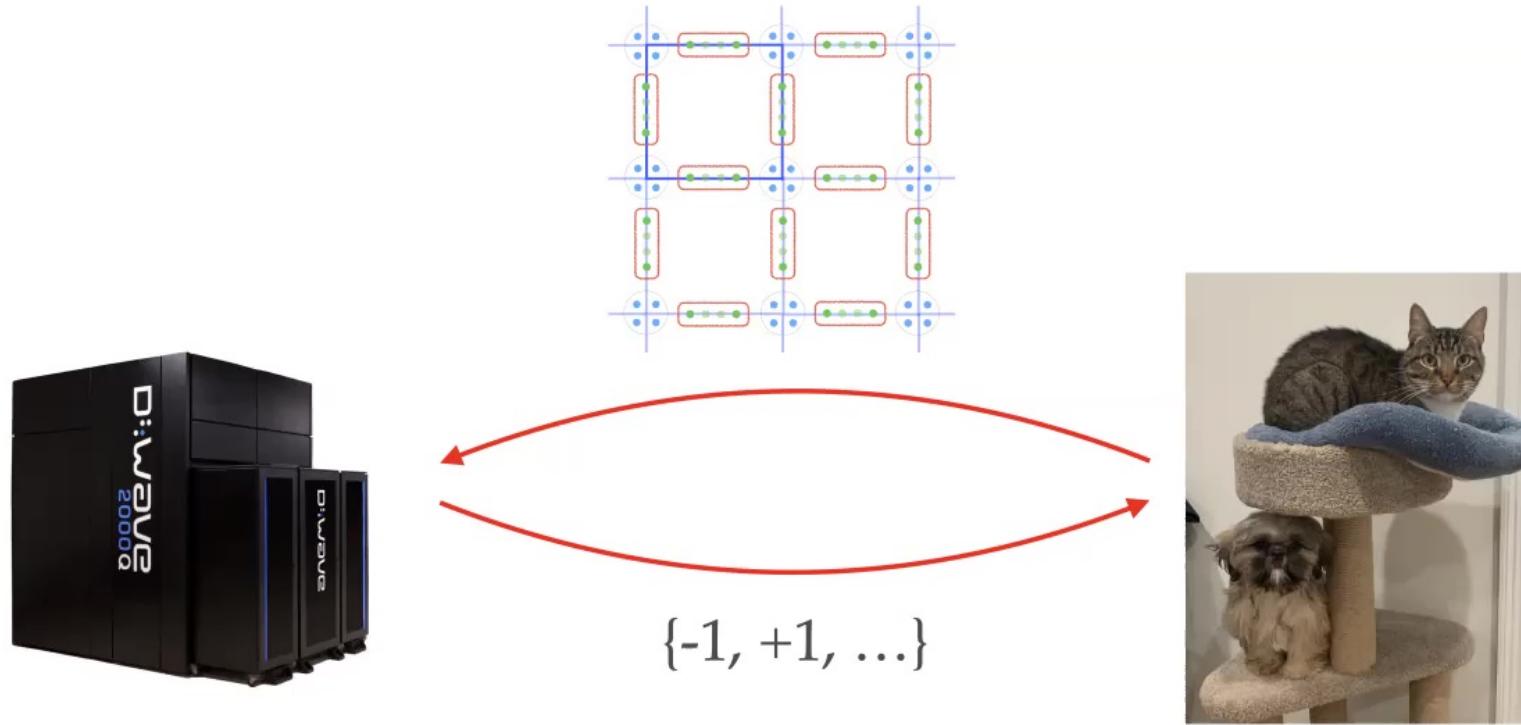


Embedding in D-Wave



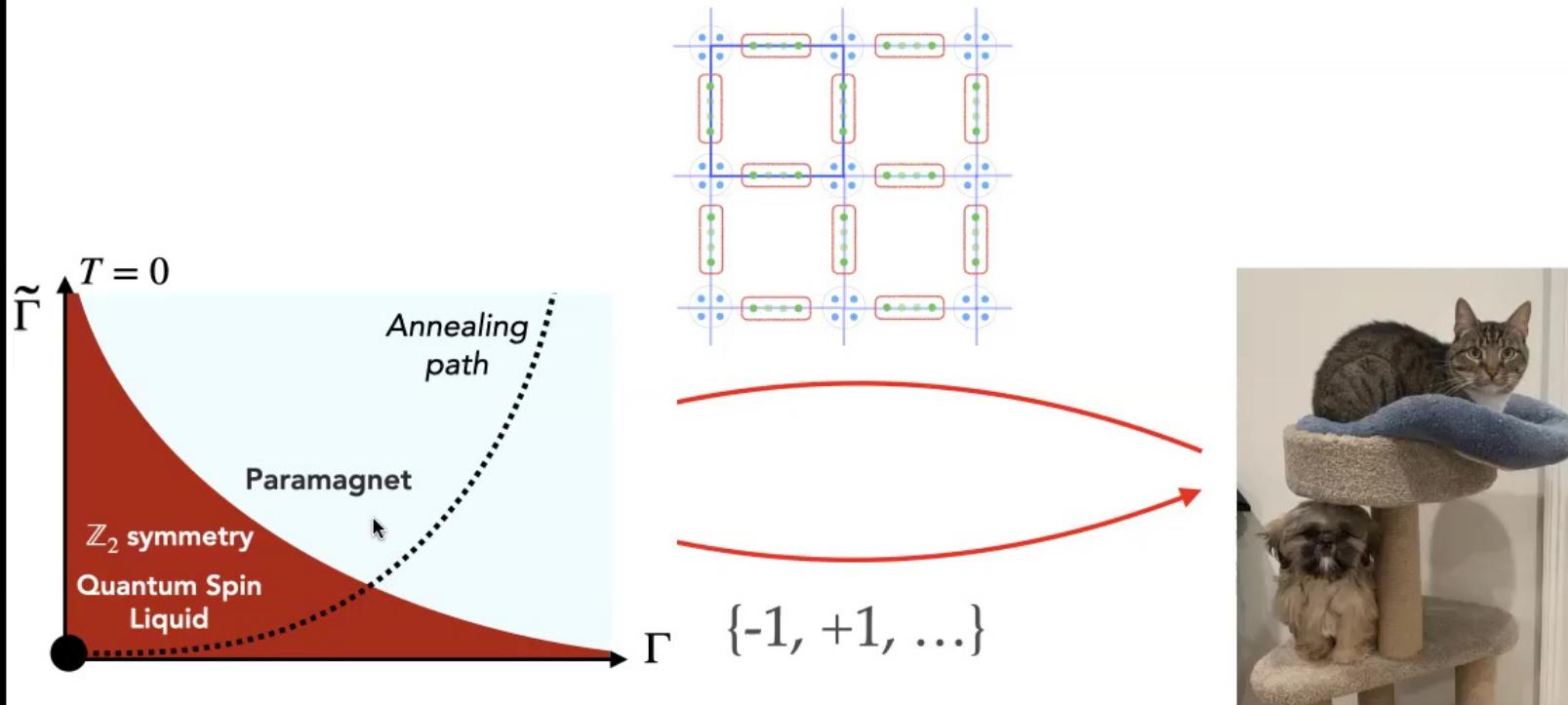
Symmetry
Still Respected!!

On the way to D-Wave in LANL



$$H = -J \sum_s \left[\sum_{i=1}^4 \sum_{j=1}^4 W_{ij} \sigma_j^z \mu_i^z + \Gamma \sum_i \mu_i^x \right] - \widetilde{\Gamma} \sum_j \sigma_j^x \quad \rightarrow \quad \widetilde{\Gamma} \sim \Gamma^4$$

On the way to D-Wave in LANL

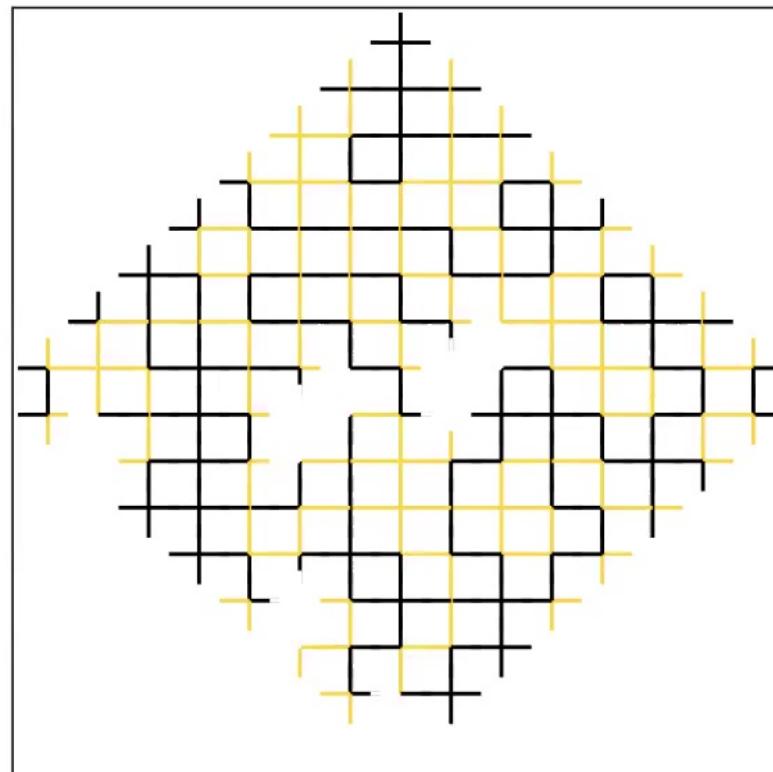


$$H = -J \sum_s \left[\sum_{i=1}^4 \sum_{j=1}^4 W_{ij} \sigma_j^z \mu_i^z + \Gamma \sum_i \mu_i^x \right] - \widetilde{\Gamma} \sum_j \sigma_j^x \quad \rightarrow \quad \widetilde{\Gamma} \sim \Gamma^4$$

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\mathbb{Z}_2 Spin Liquids

— : Spin up — : Spin down

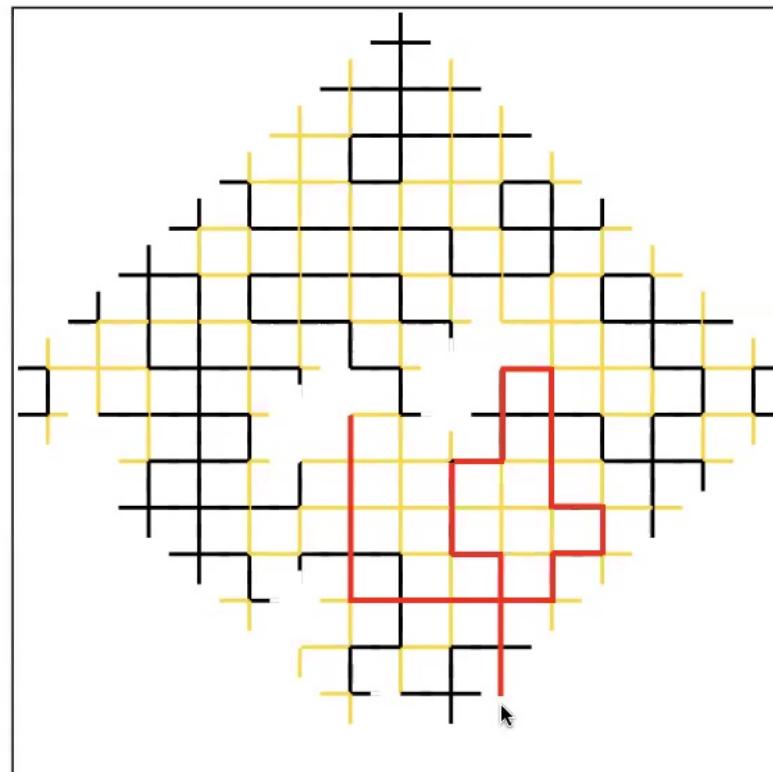


Shiyu Zhou, Dmitry Green, Edward D. Dahl, and Claudio Chamon
Phys. Rev. B **104**, L081107

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\mathbb{Z}_2 Spin Liquids

— : Spin up — : Spin down



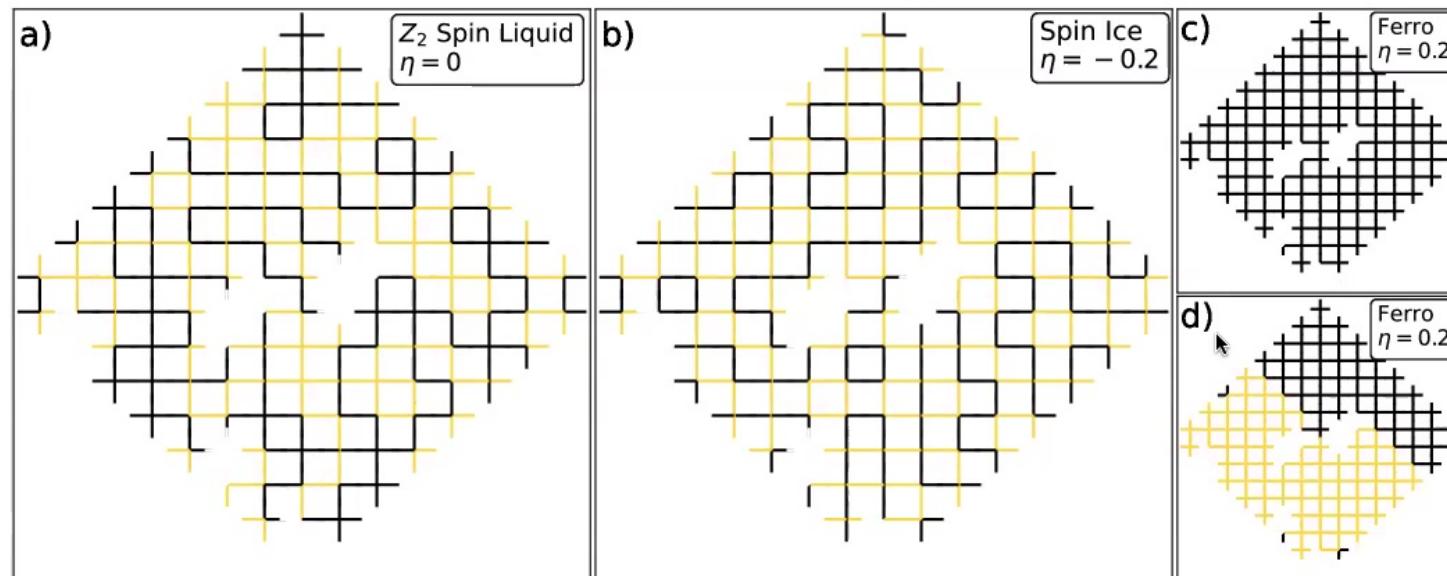
Shiyu Zhou, Dmitry Green, Edward D. Dahl, and Claudio Chamon
Phys. Rev. B **104**, L081107

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Spin liquid, Spin Ice & Ferromagnetic

$$W = \begin{pmatrix} -1 + \eta & +1 & +1 & +1 \\ +1 & -1 + \eta & +1 & +1 \\ +1 & +1 & -1 + \eta & +1 \\ +1 & +1 & +1 & -1 + \eta \end{pmatrix} \quad \left\{ \begin{array}{ll} \text{Spin Ice} & \eta < 0 \\ \mathbb{Z}_2 \text{ Spin Liquid} & \eta = 0 \\ \text{Ferromagnetic} & \eta > 0 \end{array} \right.$$

— : Spin up — : Spin down



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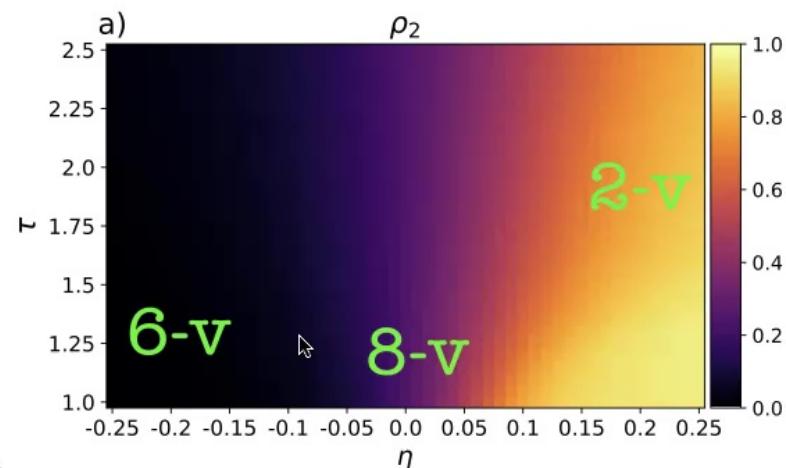
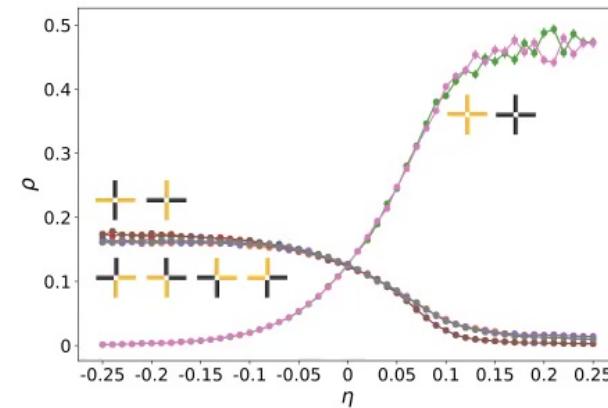
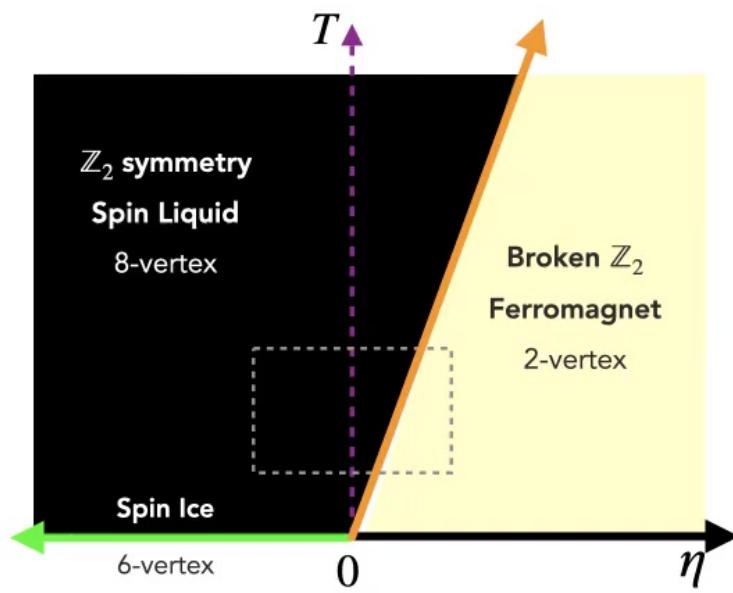
8-Vertex Model



6 - vertex



2 - vertex



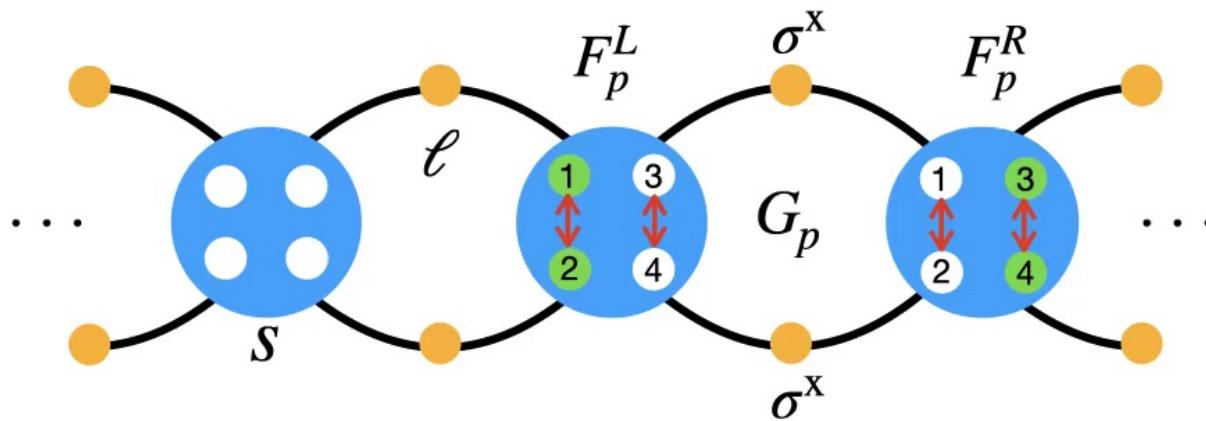
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Quantum ??

Can we observe signatures of quantum spin liquids?

Quasi-1D CGS ladder

$$H = - \sum_s \left[J \sum_{a \in s, \ell \in s} W_{a\ell} \mu_a^z \sigma_\ell^z + \Gamma_0 \sum_{a \in s} \mu_a^x \right] - \Gamma_0 \sum_\ell \sigma_\ell^x$$



\mathbb{Z}_2 symmetry generator: $G_p = F_p^L B_p F_p^R$

$$G_p^2 = 1$$

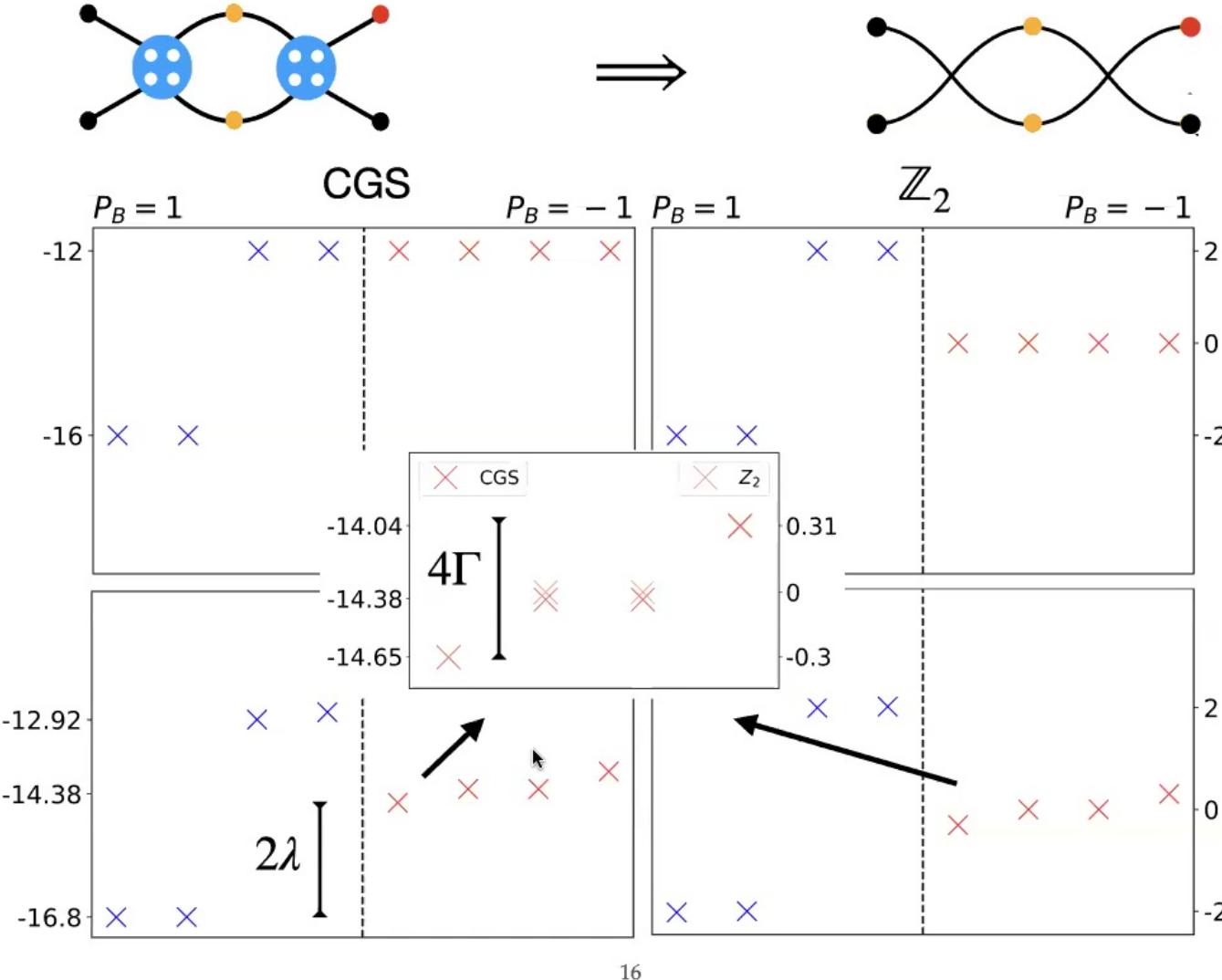
$$F_p^L = \frac{1}{2}(\mathbb{I} + \boldsymbol{\mu}_1 \cdot \boldsymbol{\mu}_2) \quad \mu_1^x \mu_2^x \quad \frac{1}{2}(\mathbb{I} + \boldsymbol{\mu}_3 \cdot \boldsymbol{\mu}_4)$$

$$[G_p, G_{p'}] = 0$$

$$F_p^R = \frac{1}{2}(\mathbb{I} + \boldsymbol{\mu}_1 \cdot \boldsymbol{\mu}_2) \quad \mu_3^x \mu_4^x \quad \frac{1}{2}(\mathbb{I} + \boldsymbol{\mu}_3 \cdot \boldsymbol{\mu}_4)$$

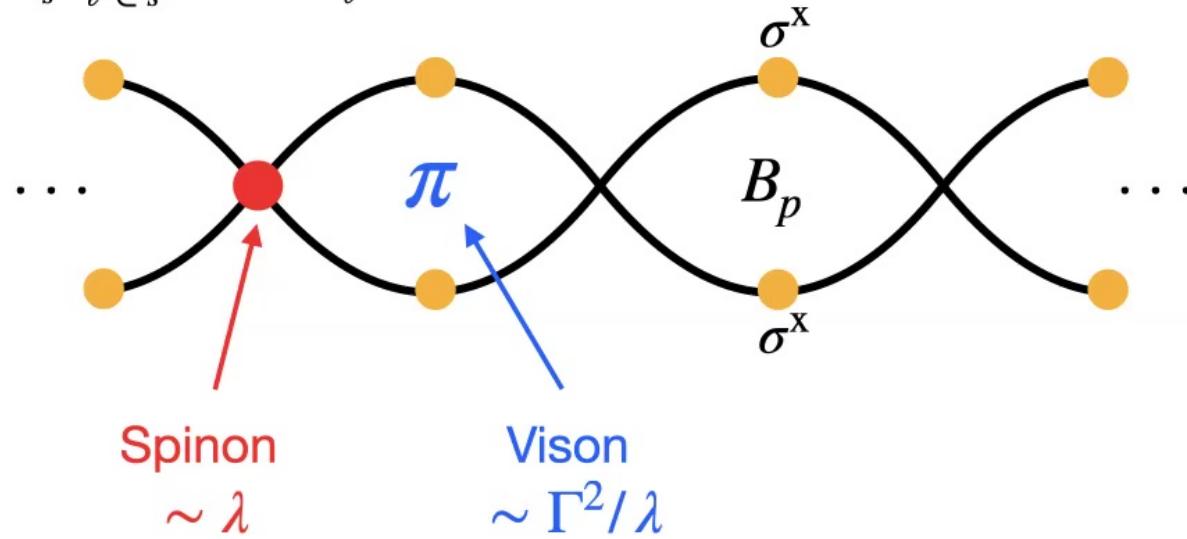
"Probing fractional statistics in quantum simulators of spin liquid Hamiltonians" S. Zhou, M. Zelenayova, O. Hart, C. Chamon, and C. Castelnovo, arXiv:2211.09784

CSG and \mathbb{Z}_2 ladder connection



Quasi-1D \mathbb{Z}_2 ladder

$$H = -\lambda \sum_s \prod_{\ell \in s} \sigma_\ell^z - \Gamma \sum_\ell \sigma_\ell^x \quad (\lambda > \Gamma)$$



Consider finite temperature: $\Gamma^2/\lambda < T < \lambda$

Visons stochastically locate at random plaquettes and are quasi-static.

Spinon dynamics

Spinon propagates
without visons presence

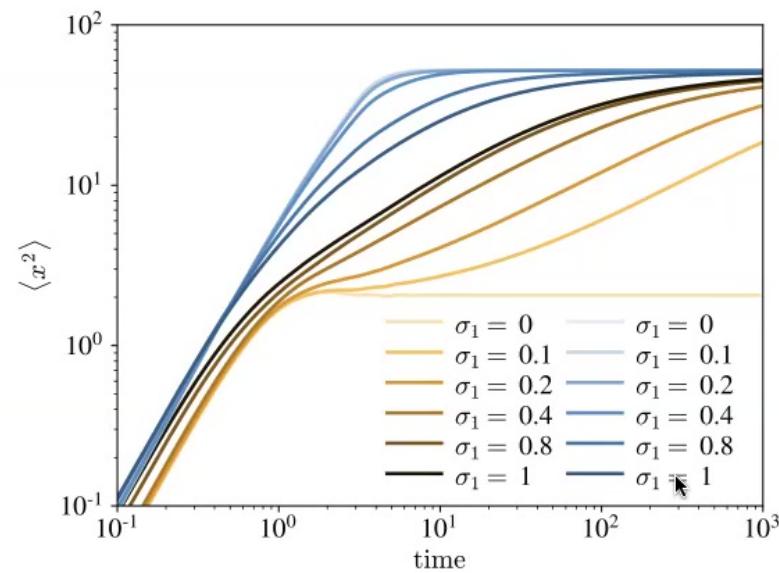
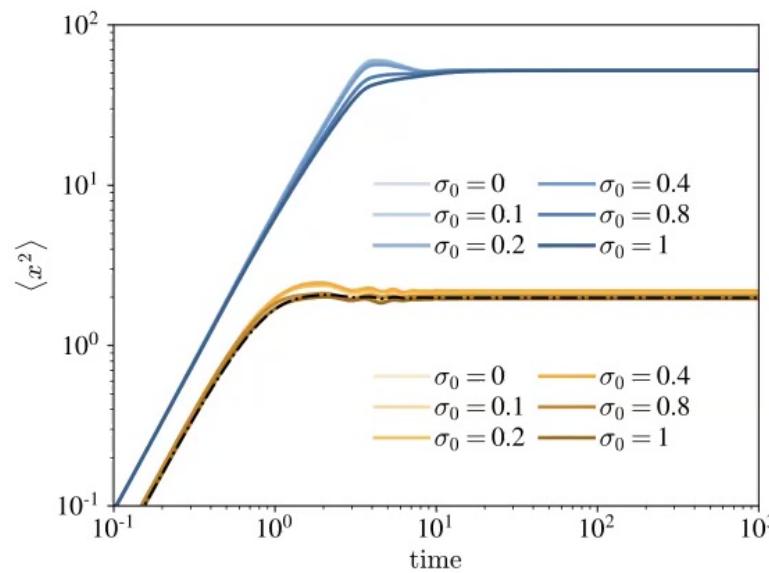
Spinon localize
with visons presence

Spinon propagates
with visons presence
when lower legs are frozen

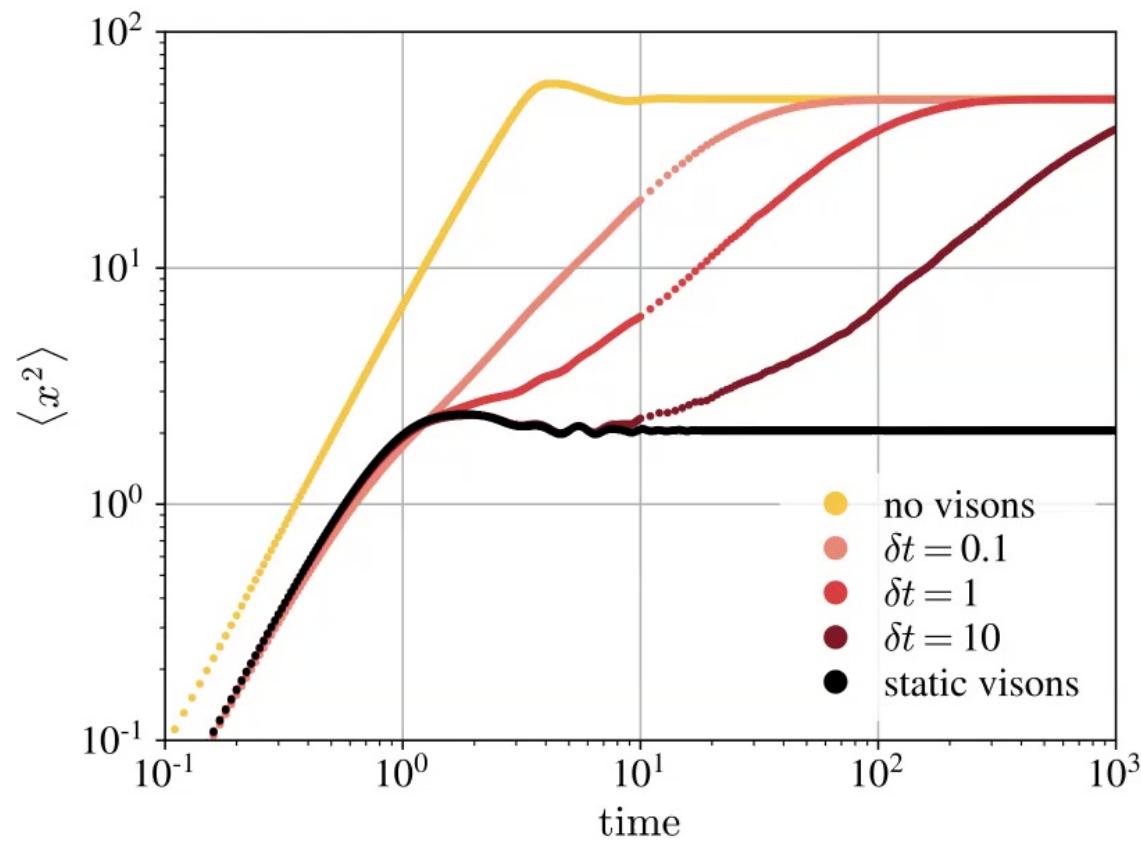
Disorder

$$H_{\text{dis}} = \sum_{s=1}^{L-1} w_{s,s'}^{(o)} (\hat{b}_s^\dagger \hat{b}_{s+1} + \text{h.c.}) + \sum_{s=1}^L w_s^{(d)} \hat{b}_s^\dagger \hat{b}_s$$

$w_{s,s'}^{(o)}$ and $w_s^{(d)}$ are Gaussian distributed with 0 mean
and σ_1 and σ_0 standard deviation.

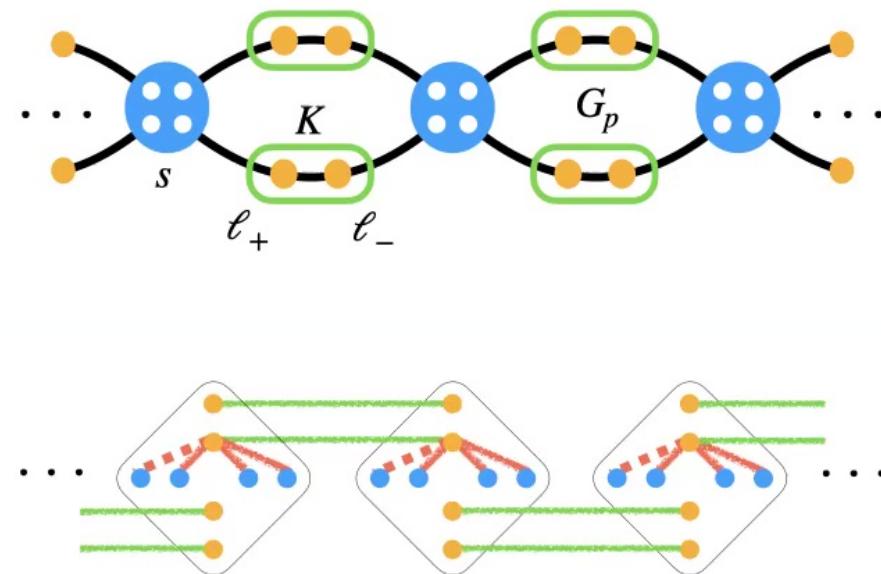
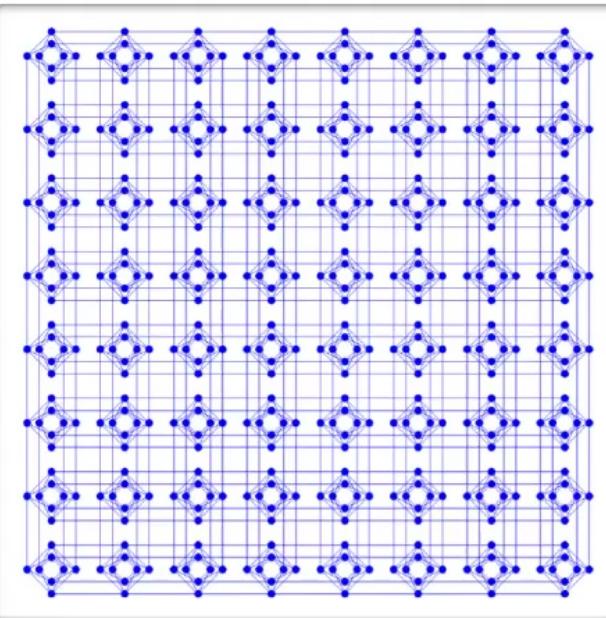


Stroboscopic vison dynamics



Possible implementation in D-Wave

Chimera Graph:



Challenge:

- D-Wave operating temperature (13mK) too high
- Characteristic time scale (\sim ns) much smaller than μ s time scale in D-Wave

Summary & Outlook

- We designed Hamiltonians with the combinatorial gauge symmetry using only local pair-wise interactions where the exact QSLs states are the *ground states of static* Hamiltonians.
- Realized the classical endpoint of \mathbb{Z}_2 Quantum spin liquids states in D-Wave.
- Proposed a “smoking gun” experiment to detect the mutual statistics of quasiparticle excitations in \mathbb{Z}_2 QSLs in quantum simulators.

- Simulating fractal symmetry in quantum simulators.
- What information we can extract from z-basis measurement of quantum simulations
- Machine learning transition from Clifford circuits to universal circuit by adding T gates.