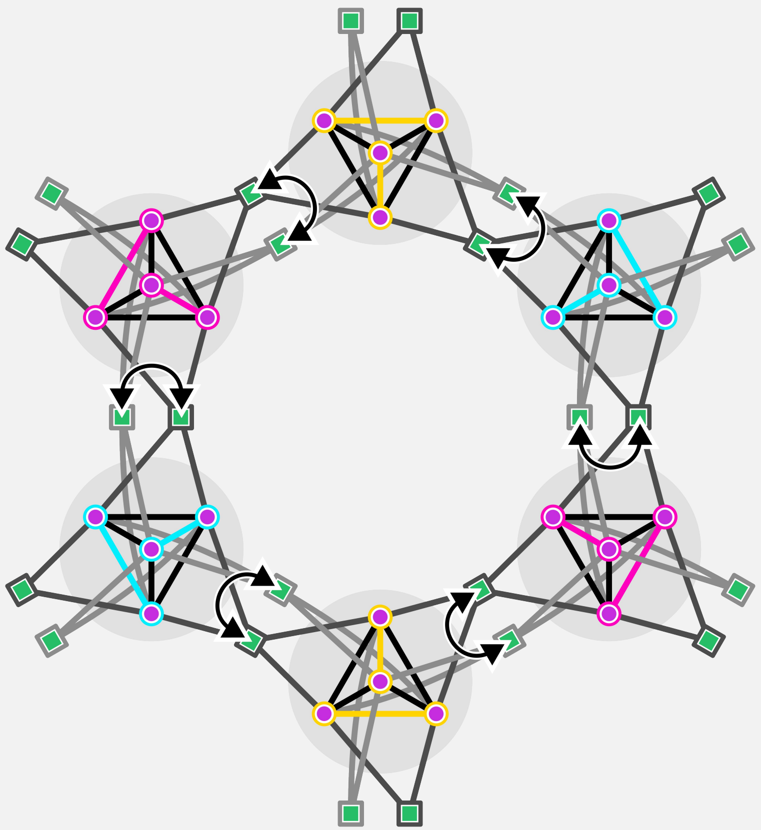
Topological Order with Fully-Symmetric Blockade Structures



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Journal Club @ Neupert Group, University of Zurich

Zurich, December 2025

Institute for Theoretical Physics

University of Stuttgart
Germany

People & Papers

Hans Peter Büchler

Tobias Maier

Simon Fell

Functional completeness of planar Rydberg blockade structures
Simon Stastny, Hans Peter Büchler, and NL
Phys. Rev. B 108, 085138 (2023), doi:10.1103/PhysRevB.108.085138

Topological order in symmetric blockade structures
Tobias F. Maier, Hans Peter Büchler, and NL
PRX Quantum 6, 030340 (2025), doi:10.1103/dtlf-2q82

Featured in Physics

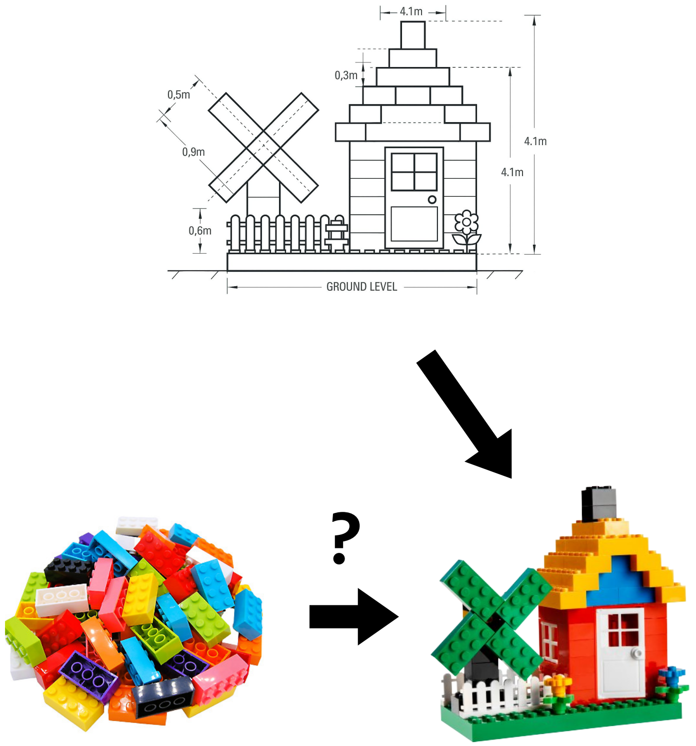
This Talk

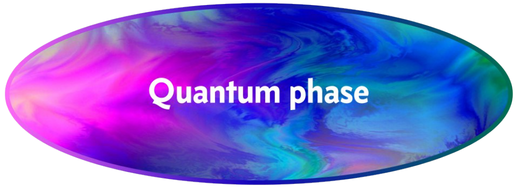
Quantum doubles in symmetric blockade structures
Hans Peter Büchler, Tobias F. Maier, Simon Fell, and NL
arXiv: **2511.04414** (2025)

Spectral gap of a blockade structure with Z_2 topological order
Simon Fell, Tobias F. Maier, Hans Peter Büchler, and NL
In preparation (2025)

Rationale

The **„Inverse Problem“** of quantum many-body physics





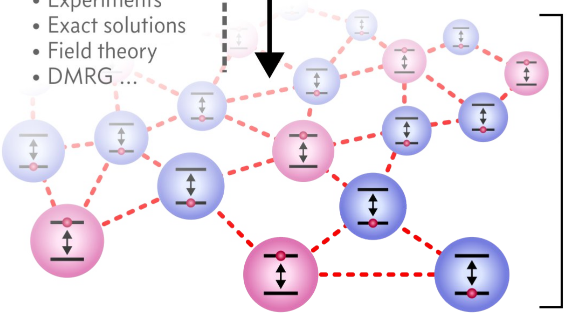
Goal

→ Complex correlations
→ Long-range entanglement
→ Robust

Emergence

- Experiments
- Exact solutions
- Field theory
- DMRG ...

Construction?



Toolbox

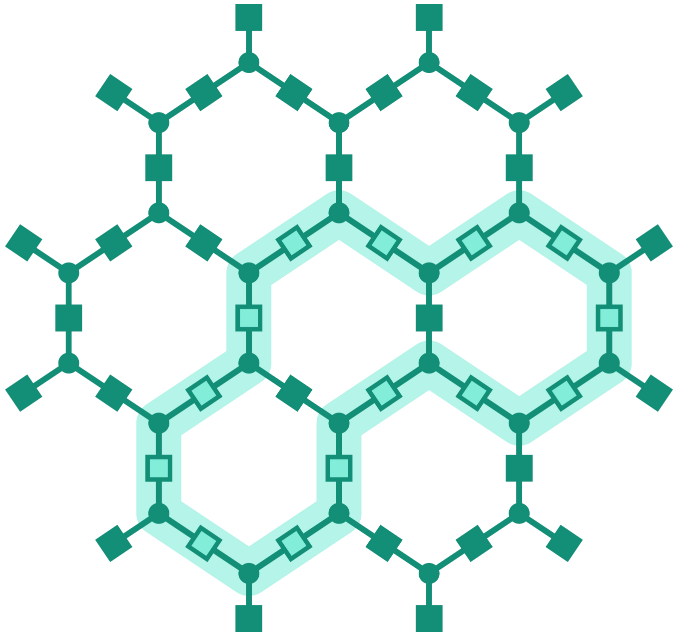
→ Two-level systems
→ Simple interactions
→ Easy to control
→ Potentially noisy

1 **Topological Order** with

3 **Fully-Symmetric**

2 **Blockade Structures**

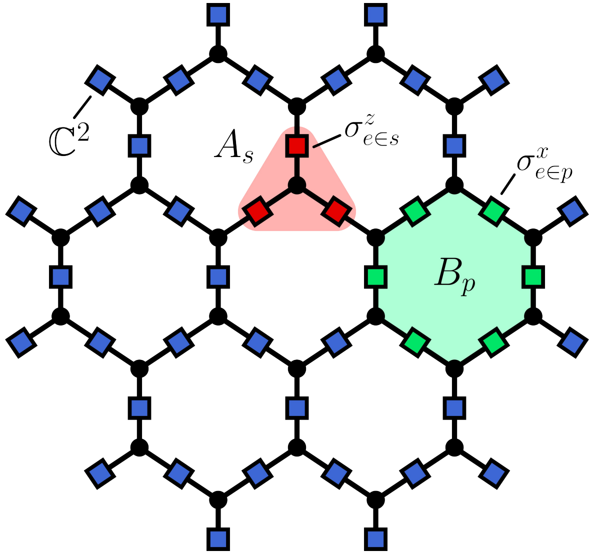
Topological Order with Fully-Symmetric Blockade Structures



Topological Order and the Toric Code

The Toric Code

Honeycomb lattice & **1 × Qubit** per **edge:**



Ground state?

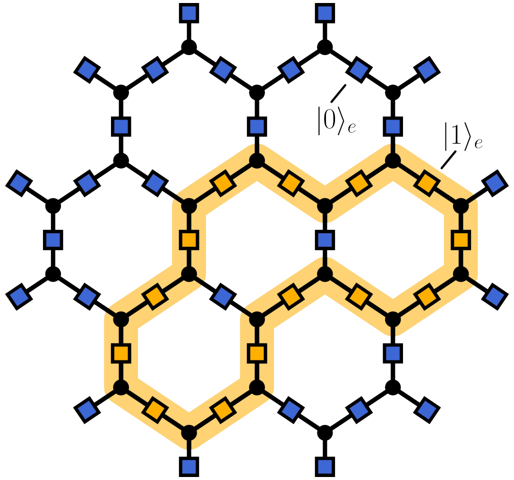
$[A_s, B_p] = 0$

$A_s^2 = \mathbb{1} \quad B_p^2 = \mathbb{1}$

(exactly solvable)

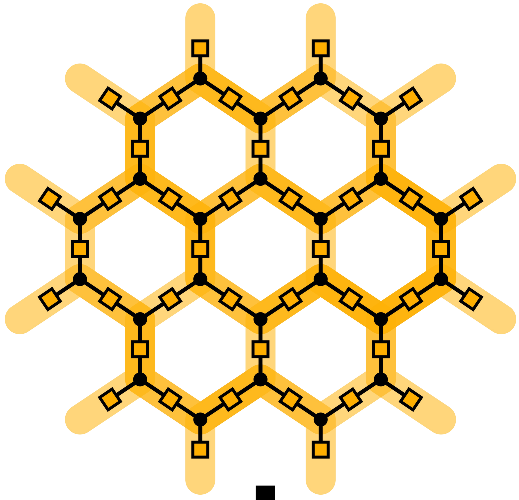
$A_s = +1$ ✓

Loop **constraint:**



$B_p = +1$ ✓

Loop **condensation:**



Star operators

$A_s = \prod_{e\in s} \sigma_e^z$

Plaquette operators

$B_p = \prod_{e\in p} \sigma_e^x$

$$\boxed{H_{\mathrm{TC}} = -J_A \sum_{\text{Vertices } s} A_s - J_B \sum_{\text{Faces } p} B_p}$$

Couplings $J_A, J_B > 0$

Ground state

$$\boxed{|\Omega_{\mathrm{TC}}\rangle \propto \sum_{\boldsymbol{n}\in L_{\mathrm{Loop}}} |\boldsymbol{n}\rangle}$$

All loop patterns

„Loop condensate“

Fault-tolerant quantum computation by anyons
A. Kitaev
Annals of Physics **303**(1), 2 (2003), doi:10.1016/s0003-4916(02)00018-0

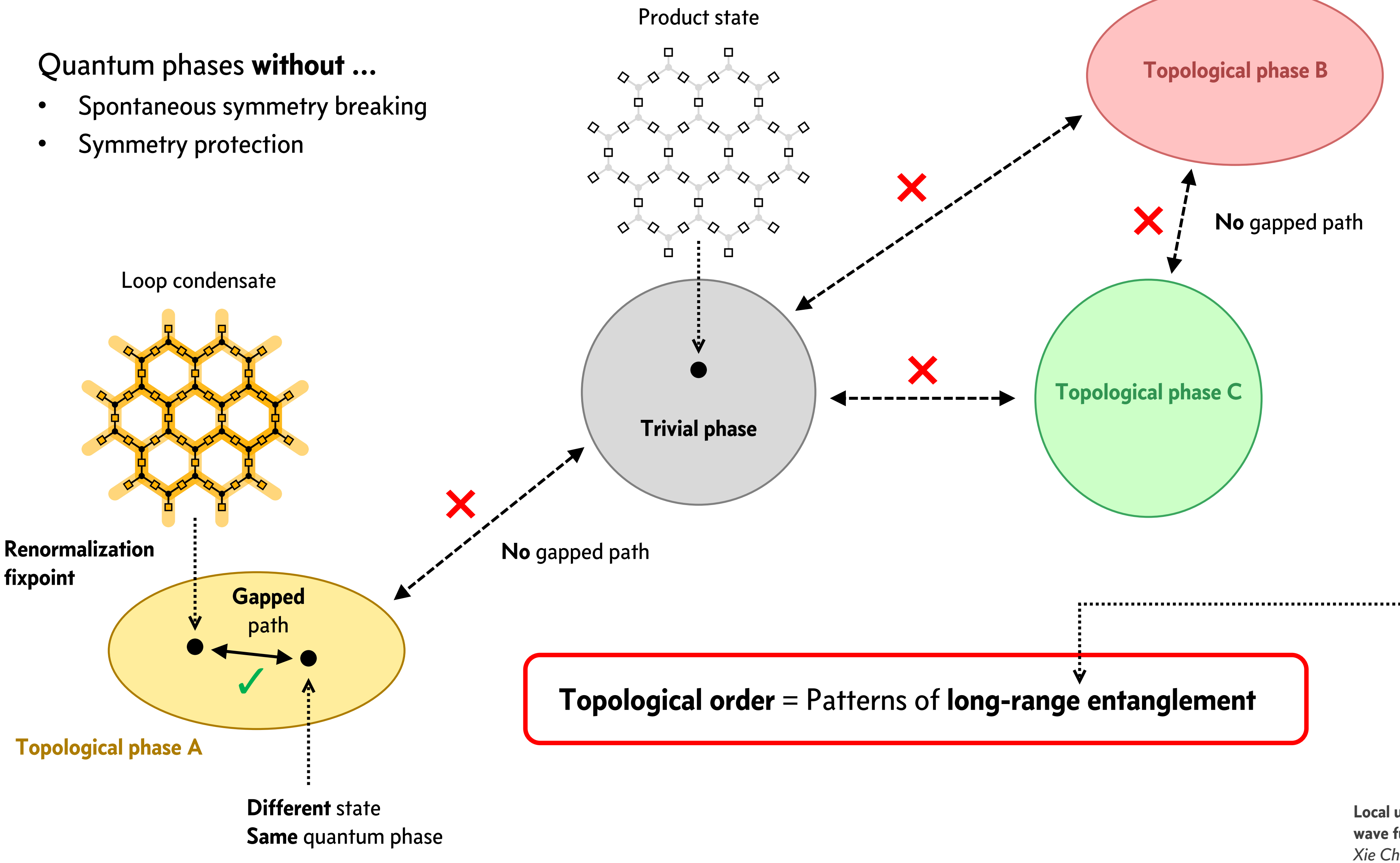
String-net condensation: A physical mechanism for topological phases
M. A. Levin and X.-G. Wen
Physical Review B **71**, 045110 (2005), doi:10.1103/physrevb.71.045110

Topological Order

True in 2D and higher …
(for bosonic systems)

Quantum phases **without …**

- Spontaneous symmetry breaking
- Symmetry protection



Fancy features:

- **Anyonic** excitations
- Topological **ground state degeneracy**
- Described by **TQFTs**

Applications in
Quantum Computing …

Topological order = Patterns of **long-range entanglement**

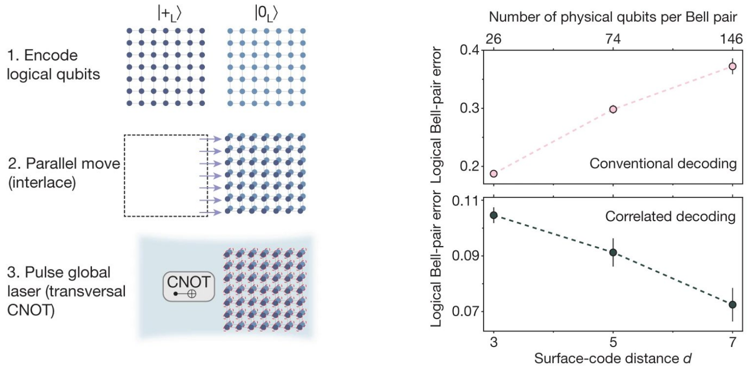
Local unitary transformation, long-range quantum entanglement, wave function renormalization, and topological order
Xie Chen, Zheng-Cheng Gu, and Xiao-Gang Wen
Phys. Rev. B **82**, 155138 (2010), doi:10.1103/PhysRevB.82.155138

Applications

Topological quantum **computing** ✗
Topological quantum **memory** ✓

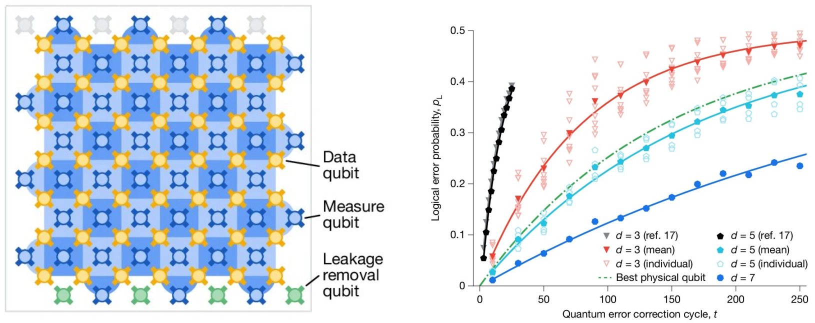
Toric code = **Abelian** topological order

Neutral atoms
(Rydberg atoms)



Logical quantum processor based on reconfigurable atom arrays
Bluvstein et al.
Nature **626**, 58–65 (2024), doi:10.1038/s41586-023-06927-3

Superconducting circuits
(Transmons)

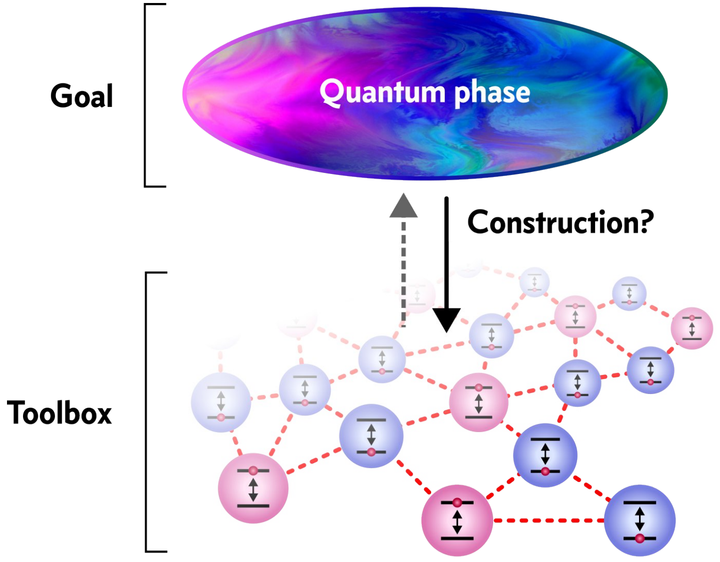


Quantum error correction below the surface code threshold
Google Quantum AI and Collaborators
Nature **638**, 920–926 (2025), doi:10.1038/s41586-024-08449-y

Beware!
Loop condensate ≠ Ground state of Hamiltonian

This Talk:
Design Hamiltonian → Ground state = Loop condensate

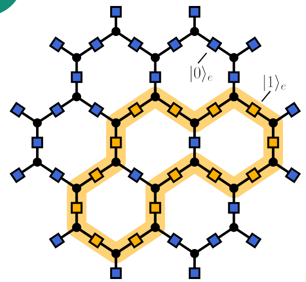
Toolbox?



✓ 1

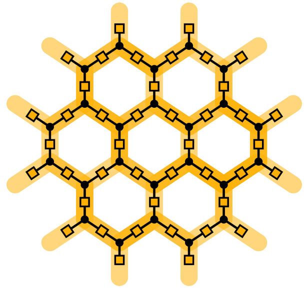
Loop **constraint**

$A_s = +1$



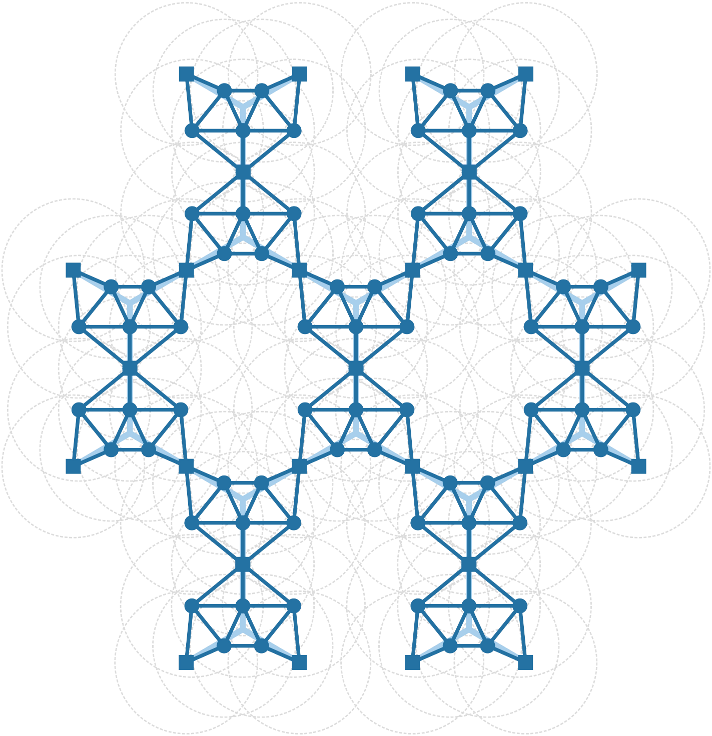
Loop **condensation**

$B_p = +1$



?

Topological Order with Fully-Symmetric Blockade Structures



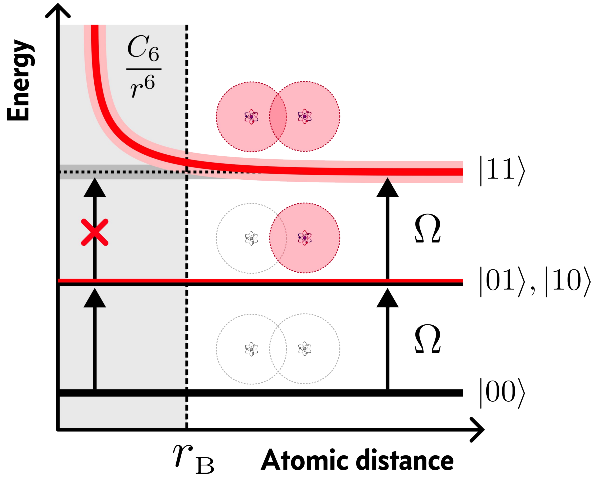
Functional Completeness of Blockade Structures

Context & Motivation

Versatile platform!

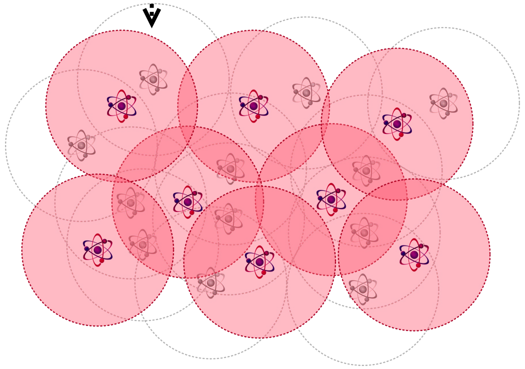
Many experiments ...

Strong **van der Waals interaction**



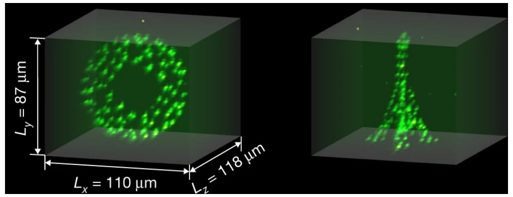
Blockade radius

Rydberg blockade

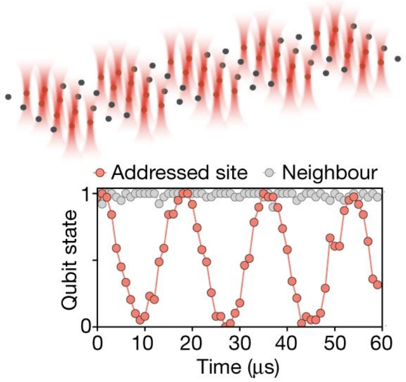


Spatial control

(Optical tweezers)

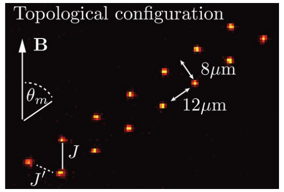


Single-site addressability



Fast Quantum Gates for Neutral Atoms
D. Jaksch, J. I. Cirac, P. Zoller, S. L. Rolston, R. Côté and M. D. Lukin
Physical Review Letters **85**(10), 2208 (2000), doi:10.1103/physrevlett.85.2208

Quantum simulation

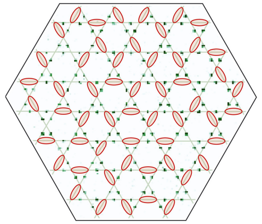


Probing many-body dynamics on a 51-atom quantum simulator
Hannes Bernien et al.
Nature **551**, 579–584 (2017), doi:10.1038/nature24622

Observation of a symmetry-protected topological phase of interacting bosons with Rydberg atoms
Sylvain de Léséleuc et al.
Science **365** (6455), 775-780 (2019), doi:10.1126/science.aav9105

…

Artificial quantum matter

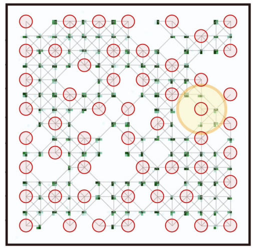


Prediction of Toric Code Topological Order from Rydberg Blockade
Ruben Verresen, Mikhail D. Lukin, and Ashvin Vishwanath
Phys. Rev. X **11**, 031005 (2021), doi:10.1103/PhysRevX.11.031005

Probing topological spin liquids on a programmable quantum simulator
G. Semeghini et al.
Science **374** (6572), 1242-1247 (2021), doi:10.1126/science.abi8794

Optimization

(„Geometric programming")



Rydberg quantum wires for maximum independent set problems
Minhyuk Kim et al.
Nature Physics **18**, 755–759 (2022), doi:10.1038/s41567-022-01629-5

Quantum optimization of maximum independent set using Rydberg atom arrays
S. Ebadi et al.
Science **376** (6598), 1209-1215 (2022), doi:10.1126/science.abo6587

…

Blockade structures

Ground state

Rydberg state

$\sigma_i^x = |0\rangle\langle 1|_i + |1\rangle\langle 0|_i$

$r_{ij} := |\boldsymbol{r}_i - \boldsymbol{r}_j|$

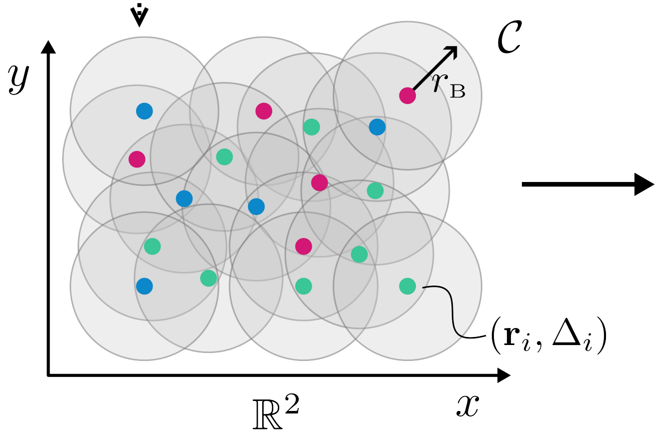
Blockade Hamiltonian

$$\boxed{H_{\mathcal{C}}(\Omega) = \sum_{i<j} U(r_{ij})\, n_i n_j + \sum_i \left(\Omega\, \sigma_i^x - \Delta_i\, n_i\right)}$$

$n_i = |1\rangle\langle 1|_i$

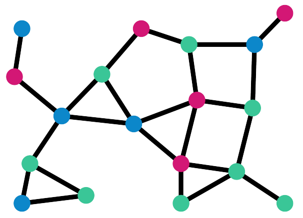
$$U(r) := \begin{cases} 0 & \text{for } r > r_{\mathrm{B}} \\ \infty & \text{for } r \leq r_{\mathrm{B}} \end{cases}$$

$\boldsymbol{\Delta} := \{\Delta_i\}_{i \in V}$



Unit disk embedding

$G_{\mathcal{C}} = (V, E, \boldsymbol{\Delta})$



Weighted blockade graph

Blockade structures

Ground state

Rydberg state

$$\sigma_i^x = |0\rangle\langle 1|_i + |1\rangle\langle 0|_i$$

$$r_{ij} := |\boldsymbol{r}_i - \boldsymbol{r}_j|$$

Blockade Hamiltonian

$$\boxed{H_{\mathcal{C}}(\Omega) = \sum_{i<j} U(r_{ij})\, n_i n_j + \sum_i \left(\Omega\, \sigma_i^x - \Delta_i\, n_i\right)}$$

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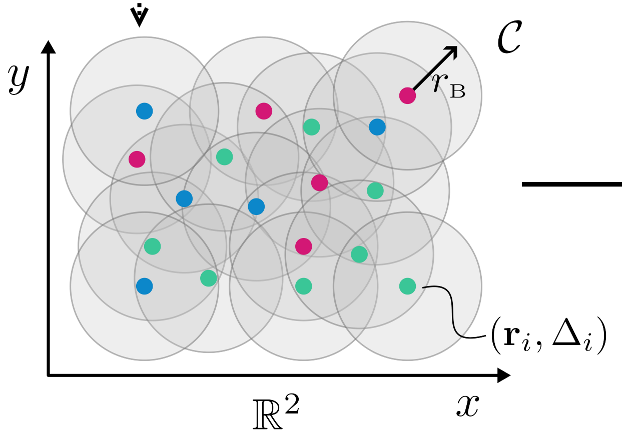
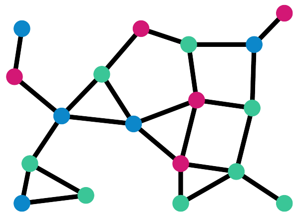


Unit disk embedding

$$G_{\mathcal{C}} = (V, E, \boldsymbol{\Delta})$$



Weighted blockade graph

$$\xrightarrow[\Omega = 0]{H_{\mathcal{C}}(\Omega)}$$

$$\boxed{\Omega = 0} \qquad \Delta_i \in \{1\Delta, 2\Delta, \ldots\} > 0$$

Degenerate ground state manifold

$$\mathcal{H}_{\mathcal{C}} \equiv \mathrm{span}\{|\boldsymbol{n}\rangle \mid \boldsymbol{n} \in L_{\mathcal{C}}\}$$

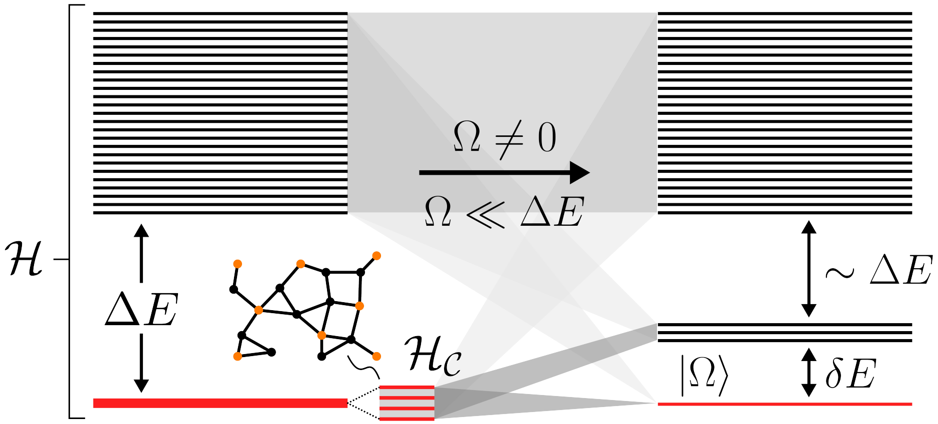
Excitation pattern

Maximum-weight independent sets

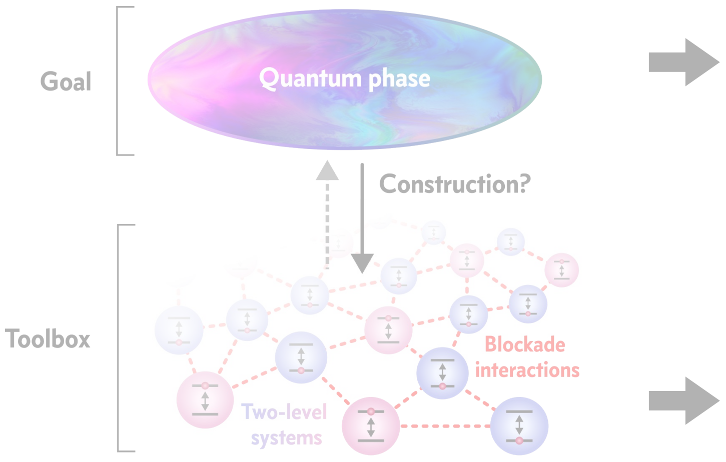
$$\boxed{\Omega \neq 0}$$

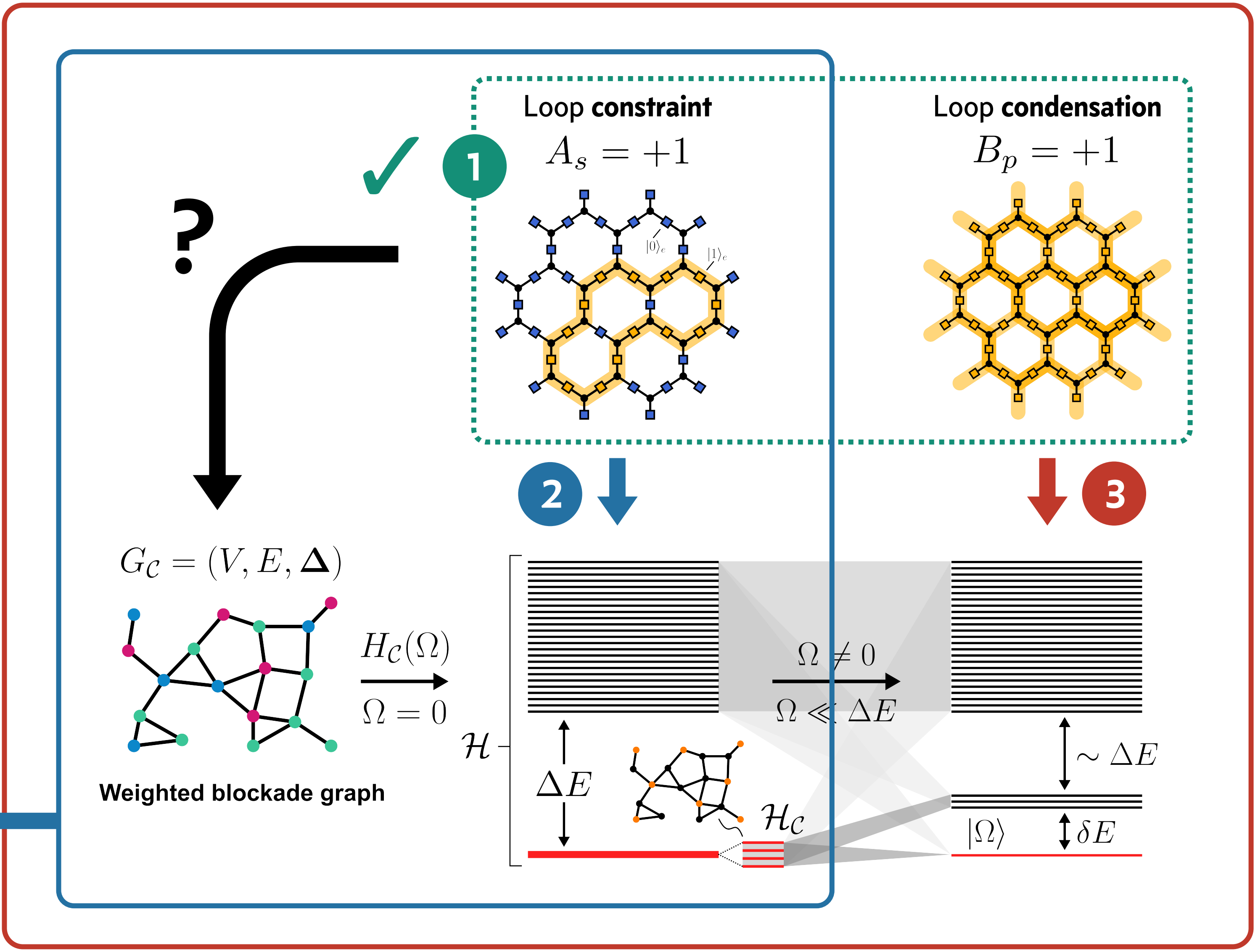
Unique ground state

$$|\Omega\rangle = \sum_{\boldsymbol{n} \in L_{\mathcal{C}}} \lambda_{\boldsymbol{n}}(\Omega)\, |\boldsymbol{n}\rangle + \sum_{d \geq 1} \left(\frac{\Omega}{\Delta E}\right)^d \sum_{\boldsymbol{n} \in L_{\mathcal{C}}^d} \eta_{\boldsymbol{n}}(\Omega)\, |\boldsymbol{n}\rangle$$



Objective for the remainder of this talk ...



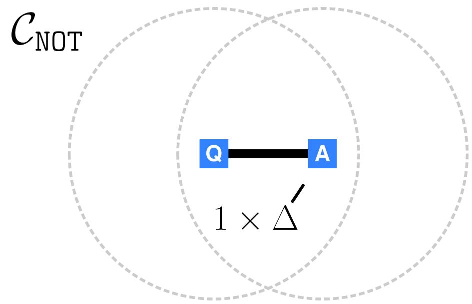


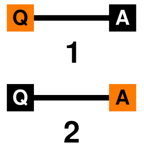
For now:

No quantum fluctuations!

$$\Omega = 0$$

Logic with Atoms



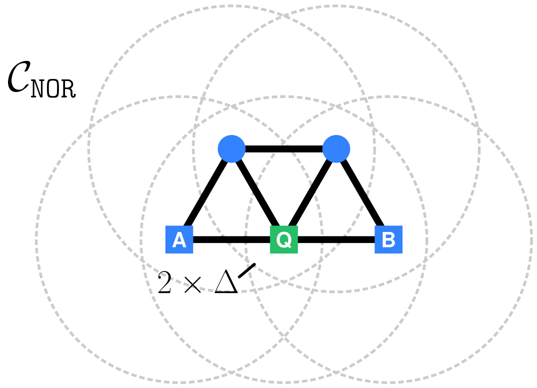


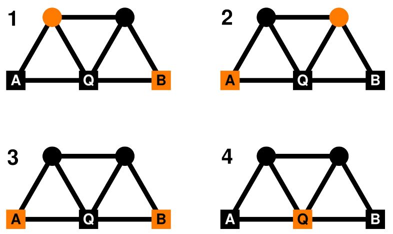
Ground state	Atom	A	Q
	1	0	1
	2	1	0

Unit disk embedding

Ground states

Truth table





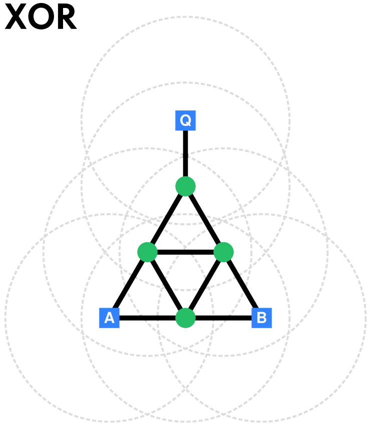
Ground state	Atom	A	B	Q
	1	0	1	0
	2	1	0	0
	3	1	1	0
	4	0	0	1

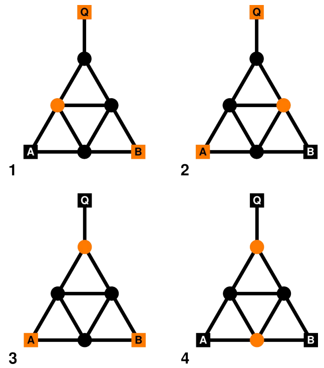
$$\mathtt{NOR}(x, y) \equiv x \downarrow y := \overline{x \vee y}$$

Universal gate

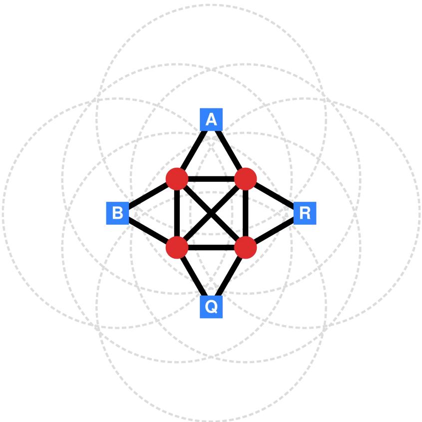
Other gates ... (useful later)

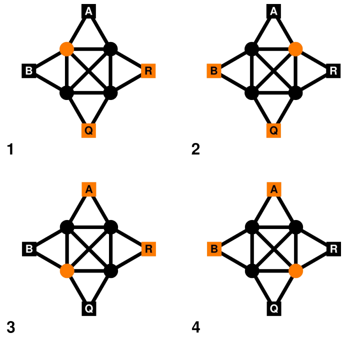
XOR





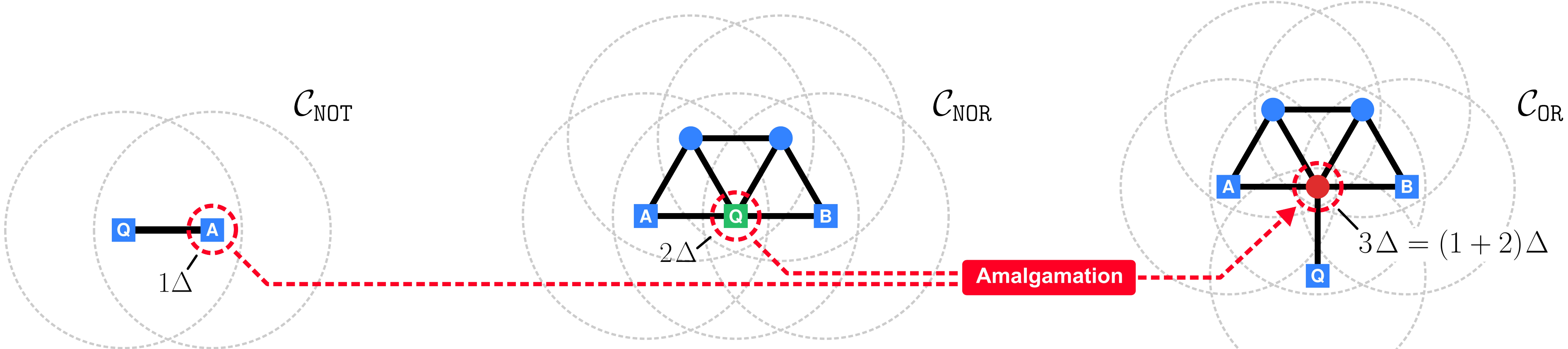
Inverted crossing (ICRS)

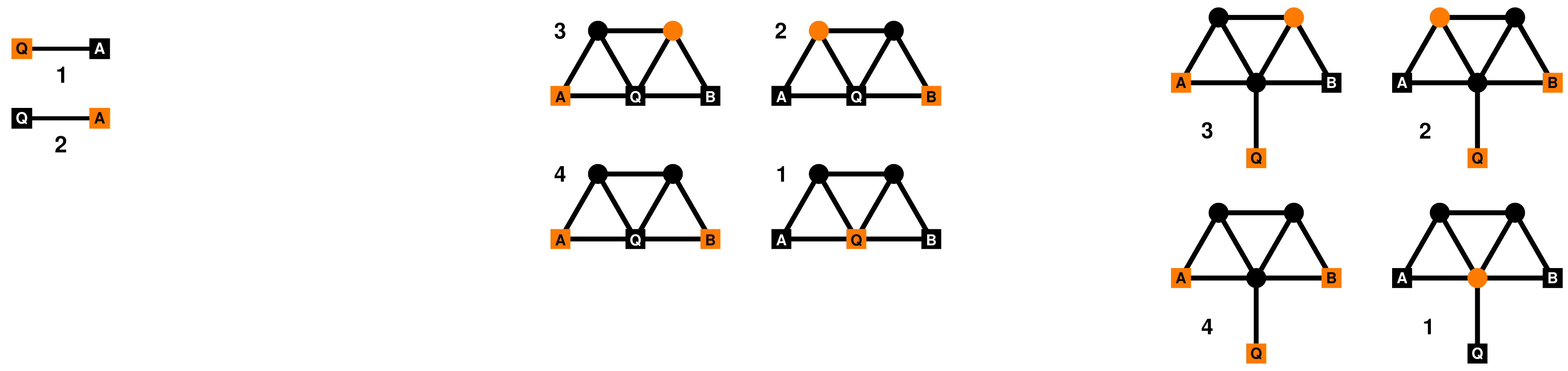


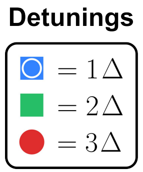


Amalgamation

Can gates be **combined**?

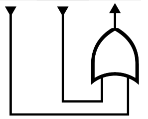






Ground state / Atom	A	B	Q
1	0	0	0
2	0	1	1
3	1	0	1
4	1	1	1

$$Q = \overline{A \downarrow B}$$
$$= A \vee B$$



Gates can be combined to Boolean circuits!

Functional Completeness

- Constructive (but convoluted)
- Unit-disk embeddable
- Ancillas needed

NOR-Gate & **Amalgamation**

For every **Boolean function** f exists a **blockade structure** $\mathcal{C}_f$ with **ground state manifold**

$$\mathcal{H}_{\mathcal{C}_f} = \mathrm{span}\{\, |\mathbf{n}\rangle \mid f(\mathbf{n}) = 1 \,\}$$

→ Blockade structures are **functionally complete**

E.g. **String-net Hilbert spaces**:

- $\mathbb{Z}_2$ Toric Code
- Fibonacci fusion rules
- …

Artificial quantum matter
(Local constraints)

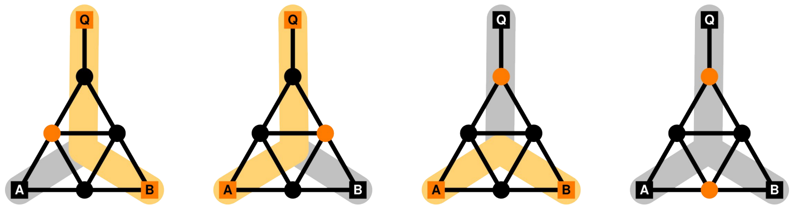
Functional completeness of planar Rydberg blockade structures
Simon Stastny, Hans Peter Büchler, and NL
Phys. Rev. B 108, 085138 (2023), doi:10.1103/PhysRevB.108.085138

Optimization
(„Geometric programming“)

Quantum optimization with arbitrary connectivity using Rydberg atom arrays
M.-T. Nguyen et al.
PRX Quantum 4, 010316 (2023), doi:10.1103/PRXQuantum.4.010316

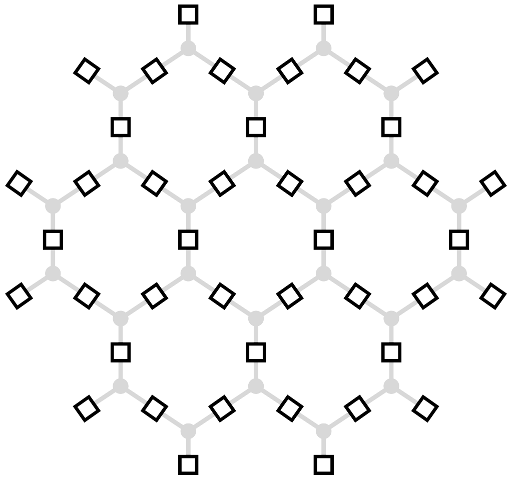
Example: Constucting a Loop Hilbert Space

Observation

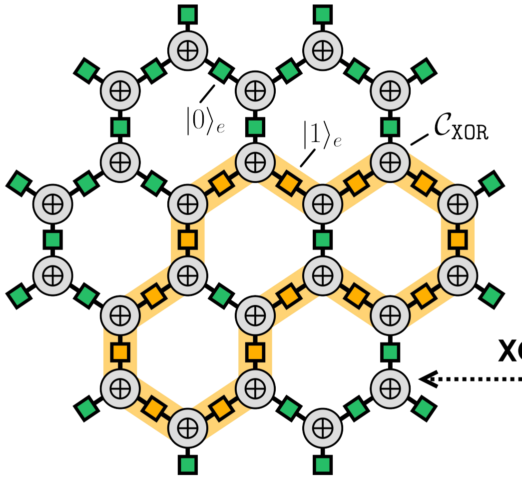


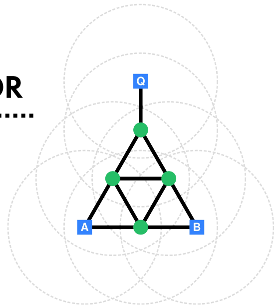
Trivalent **loop** constraint = **XOR** constraint

1 × Atom per edge:

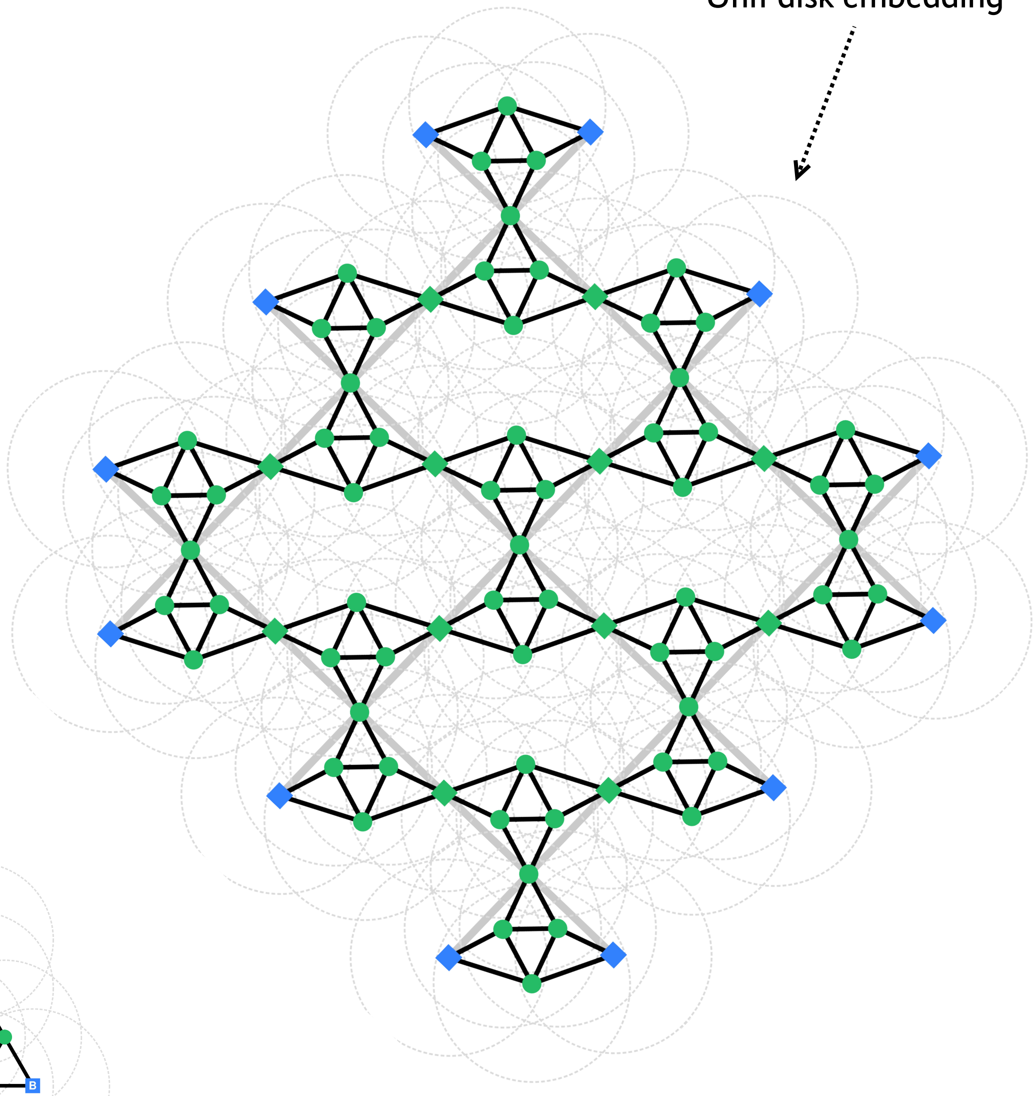


Amalgamate **XOR gates** on sites:



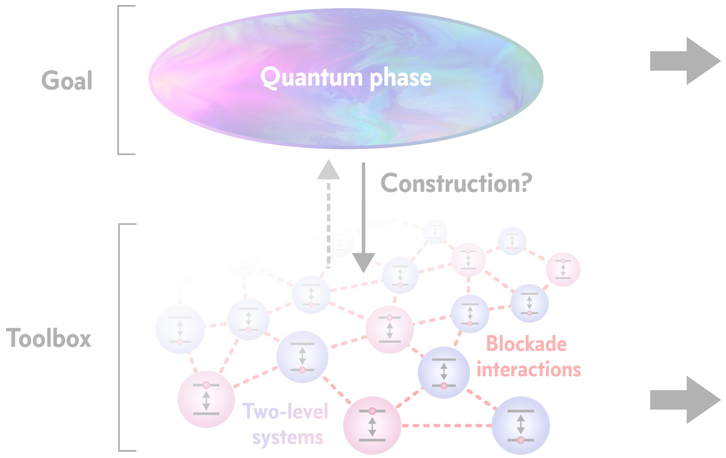


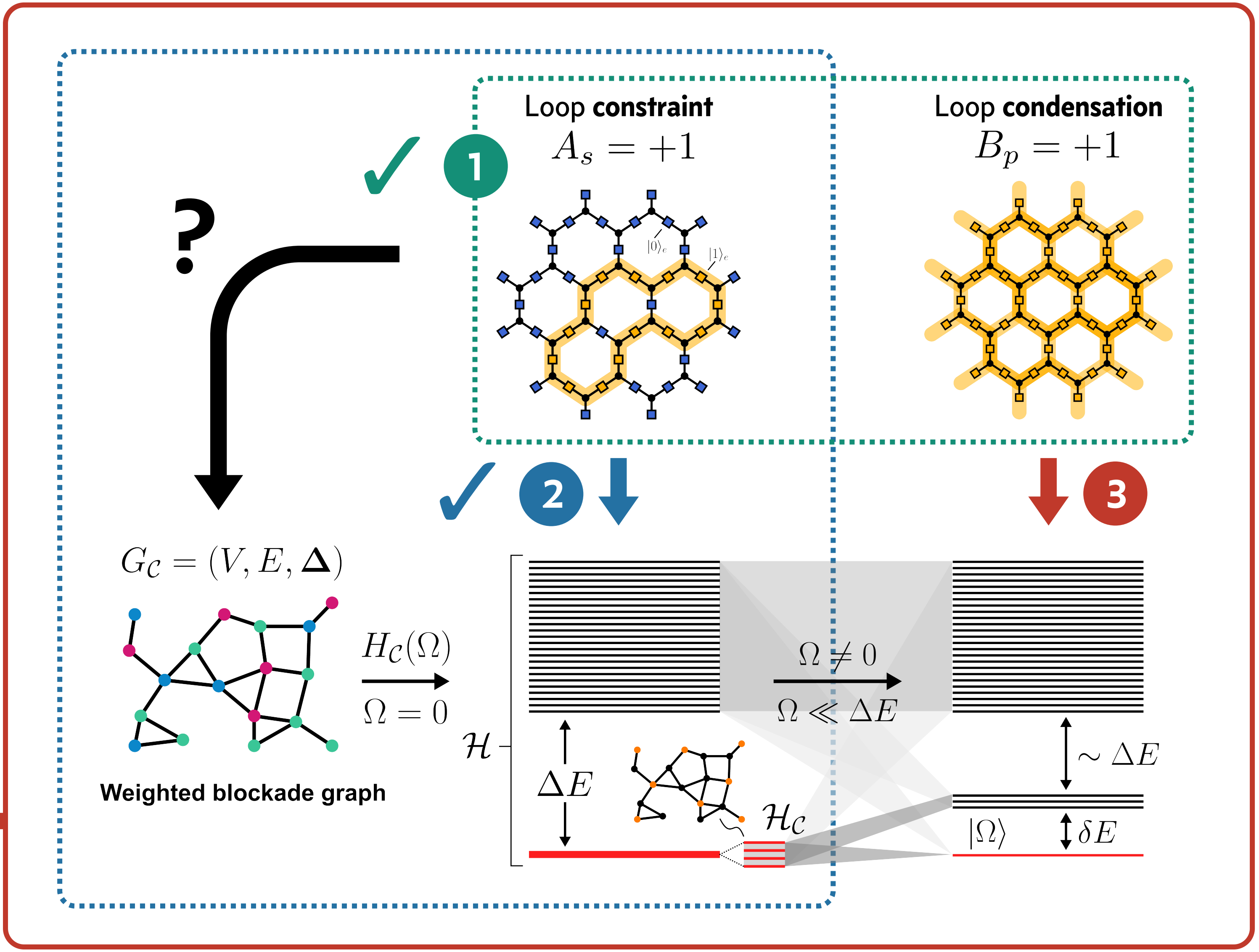
Unit disk embedding



(Honeycomb lattice ~ Square lattice)

Objective for the remainder of this talk ...



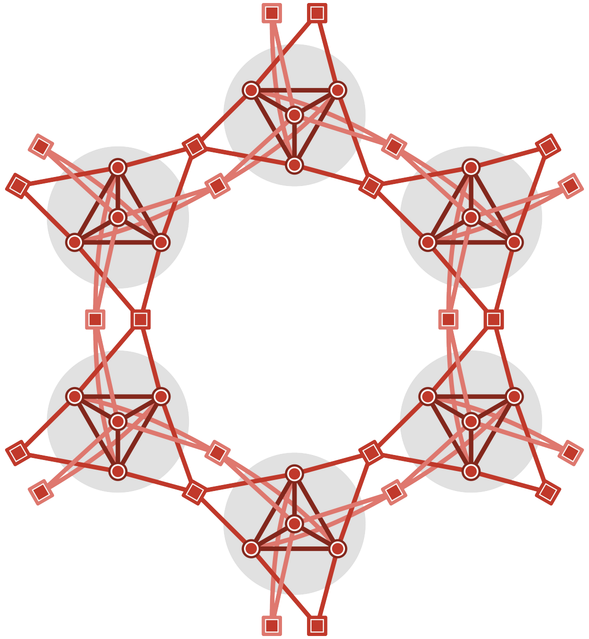


Finally:

Quantum fluctuations!

$$\Omega \neq 0$$

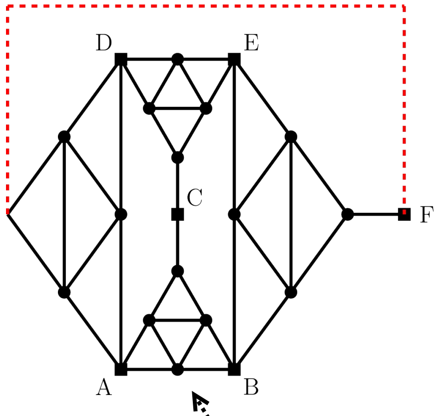
Topological Order with **Fully-Symmetric** Blockade Structures

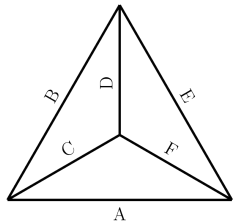


Full Symmetry and Equal-weight Superpositions

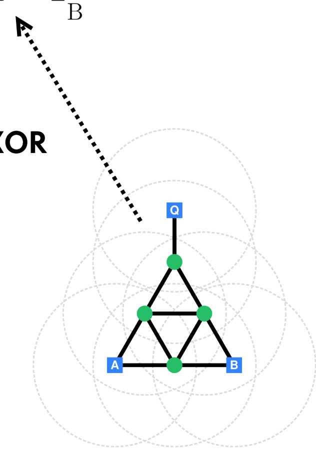
First try: Toric Code + Quantum Fluctuations

Simplification:
Toric code on **minimal sphere** (Tetrahedron)

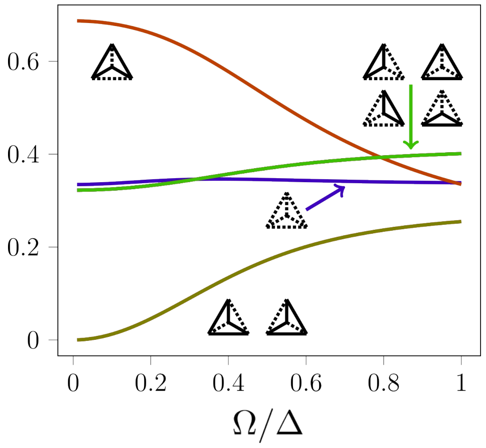




4 × XOR



Exact diagonalization



Not equal-weight!

Explanation:
Hamming distances

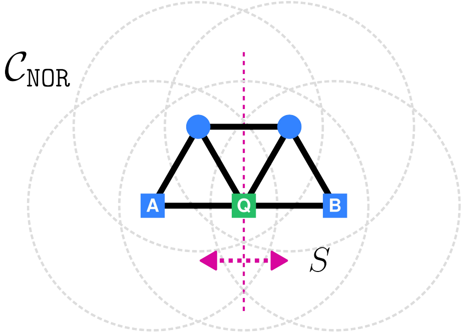
	-	10	14	10	10	8	10	14
		-	10	16	10	8	16	10
			-	10	14	8	10	10
				-	10	12	12	10
					-	8	10	14
						-	12	8
							-	10
								-

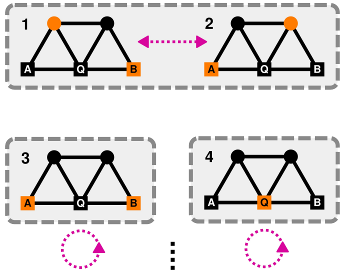
Some transitions dominate others ...

How to enforce **equal-weight superpositions**?

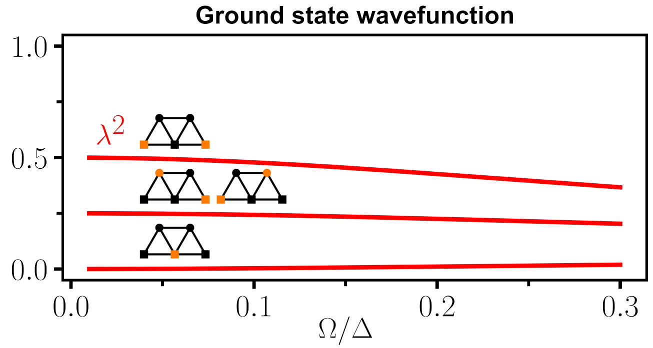
Quantum many-body phases with gauge constraints
Tobias F. Maier
Bachelor Thesis, University of Stuttgart (2023)

Second try: Logic Gates + Quantum Fluctuations



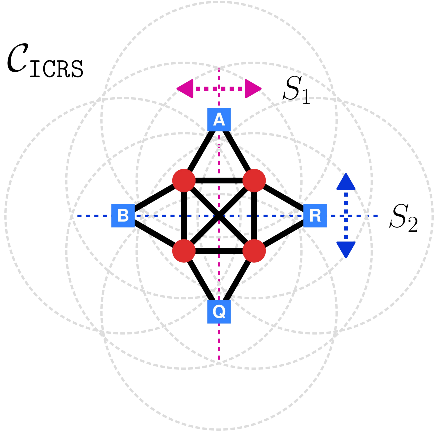


Multiple orbits

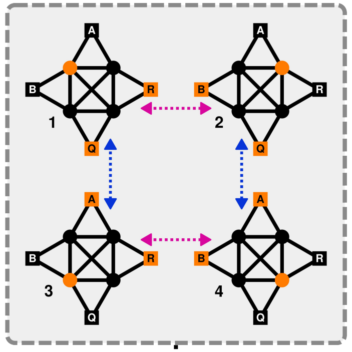


Not equal-weight ...

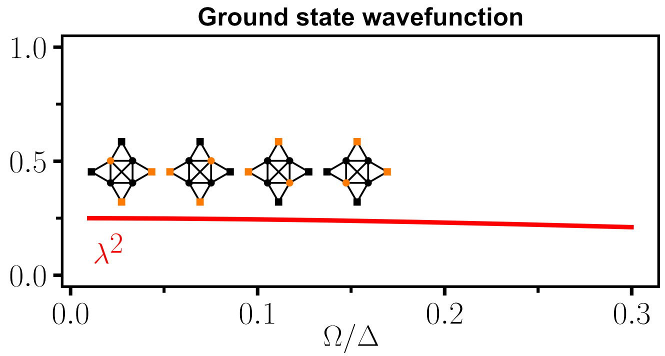
?



ICRS = Inverted Crossing



Single orbit



Equal-weight!

?

Full Symmetry

Definition

$$\phi : V \to V \qquad G_{\mathcal{C}} = (V, E, \boldsymbol{\Delta})$$

Graph automorphism iff:

$$\{\phi(i), \phi(j)\} \in E \;\Leftrightarrow\; \{i, j\} \in E$$

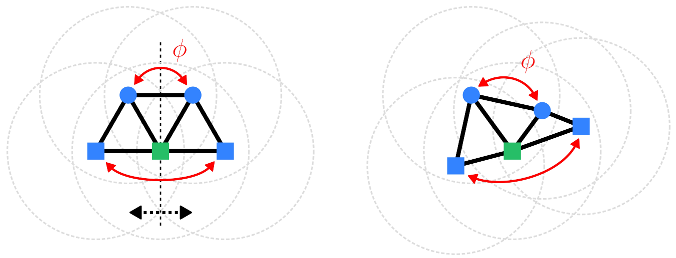
$$\& \quad \Delta_i = \Delta_{\phi(i)}$$

⬇

Automorphism group

$$\mathcal{A}_{\mathcal{C}} := \mathrm{Aut}\,(G_{\mathcal{C}})$$

Beware!
Graph automorphisms ≠ Euclidean symmetries:



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$\Downarrow$

Automorphism group

$$\mathcal{A}_\mathcal{C} := \mathrm{Aut}\,(G_\mathcal{C})$$

Observation

Unitary action: $U_\phi \, |\boldsymbol{n}\rangle := |\phi \cdot \boldsymbol{n}\rangle$

Graph automorphisms → Symmetries:

$$\phi \in \mathcal{A}_\mathcal{C} \;\Rightarrow\; [H_\mathcal{C}, U_\phi] = 0$$

Definition

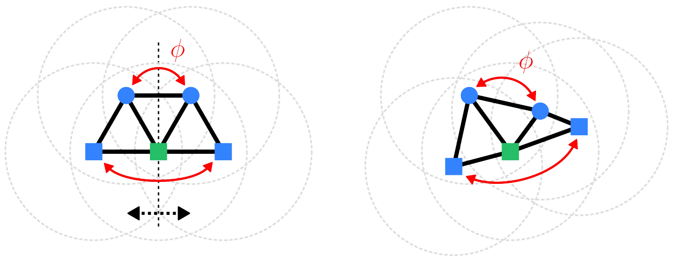
$\mathcal{C}$ **fully symmetric** iff:

All ground state patterns

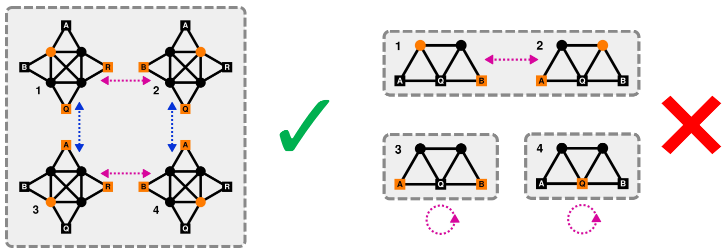
$$\underbrace{\left| L_\mathcal{C} / \mathcal{A}_\mathcal{C} \right|}_{\#\ \text{Orbits}} = 1$$

All automorphisms

Beware!
Graph automorphisms ≠ Euclidean symmetries:



Examples:



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Graph automorphisms → Symmetries:

$$\phi \in \mathcal{A}_{\mathcal{C}} \;\Rightarrow\; [H_{\mathcal{C}}, U_\phi] = 0$$

Definition

$\mathcal{C}$ **fully symmetric** iff:

$$\underbrace{\left| L_{\mathcal{C}} / \mathcal{A}_{\mathcal{C}} \right|}_{\#\ \text{Orbits}} = 1$$

All ground state patterns

All automorphisms

Theorem

$\mathcal{C}$ finite & **fully symmetric**

$$H_{\mathcal{C}}(\Omega \neq 0)$$

has **unique ground state**

$$|\Omega\rangle = \lambda(\Omega) \sum_{\boldsymbol{n} \in L_{\mathcal{C}}} |\boldsymbol{n}\rangle + \sum_{d \geq 1} \left(\frac{\Omega}{\Delta E}\right)^d \sum_{\boldsymbol{n} \in L_{\mathcal{C}}^d} \eta_{\boldsymbol{n}}(\Omega) \, |\boldsymbol{n}\rangle$$

In particular:

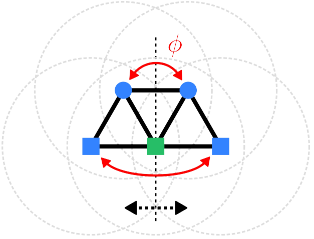
$$U_\phi \, |\Omega\rangle = |\Omega\rangle$$

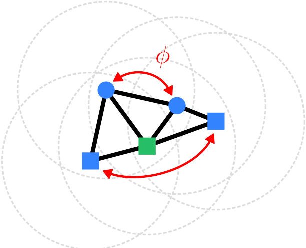
We want:

Loop constraint & Full symmetry

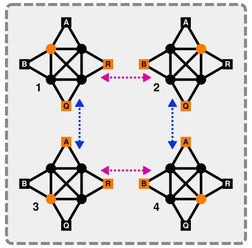
Beware!

Graph automorphisms ≠ Euclidean symmetries:

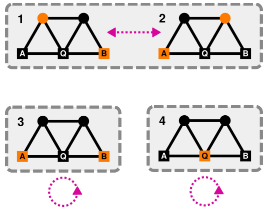




Examples:

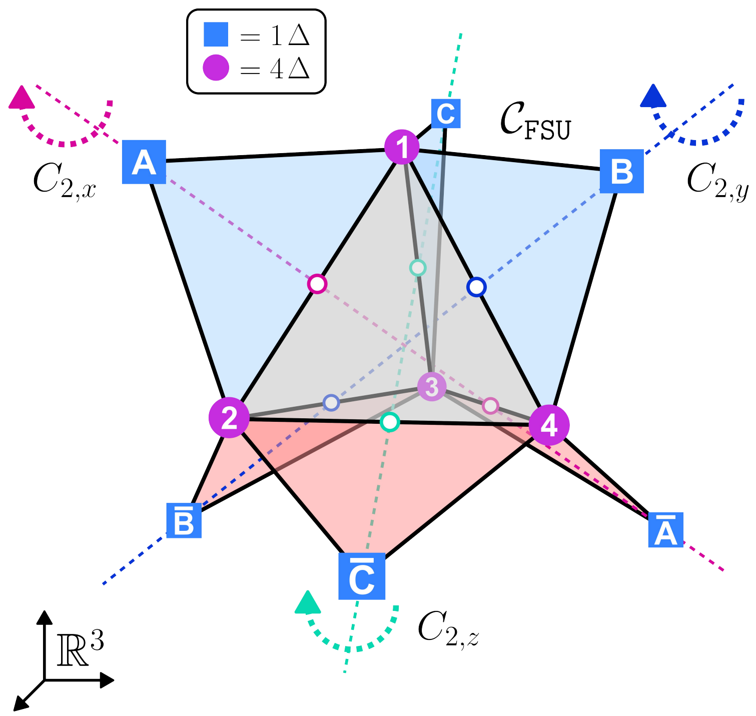


✓



✗

Preparation: The Fully-symmetric Universal Gate

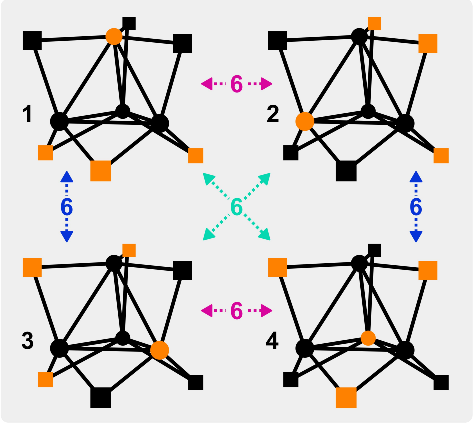


Automorphism group:

$$\mathcal{A}_{\mathrm{FSU}} \simeq S_4 > V = \{\mathbb{1}, C_{2,x}, C_{2,y}, C_{2,z}\}$$

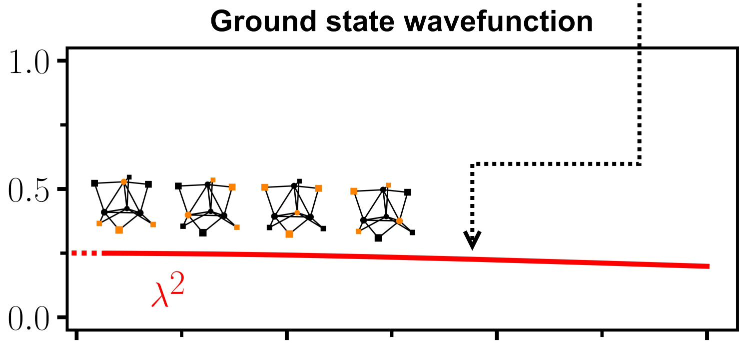
Tetrahedral symmetry

Klein four-group



Gate	A (Input)		B (Input)		XOR	XNOR	NOR	$\mathrm{INH}_{\mathrm{AB}}$	AND	$\mathrm{INH}_{\mathrm{BA}}$
Atom	**A**	**$\bar{\mathrm{A}}$**	**B**	**$\bar{\mathrm{B}}$**	**C**	**$\bar{\mathrm{C}}$**	**1**	**2**	**3**	**4**
Ground state 1	0	1	0	1	0	1	1	0	0	0
2	0	1	1	0	1	0	0	1	0	0
3	1	0	0	1	1	0	0	0	0	1
4	1	0	1	0	0	1	0	0	1	0

Single orbit → **Fully symmetric**



XOR

XNOR

$$\underbrace{A \oplus B = C}_{\text{Upper "wings"}} \Leftrightarrow \overline{A \oplus B} = \overline{C} \Leftrightarrow \underbrace{\overline{A} \odot \overline{B} = \overline{C}}_{\text{Lower "wings"}}$$

Constructing a Fully-symmetric Loop Hilbert Space

Observation 1

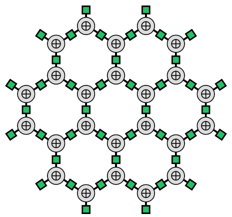
Extensive!

$$\underbrace{\left| L_{\mathcal{C}} \,/\, \mathcal{A}_{\mathcal{C}} \right|}_{\#\text{Orbits}} \overset{\text{FS}}{=} 1 \quad \overset{\text{Burnside}}{\Rightarrow} \quad |\mathcal{A}_{\mathcal{C}}| \geq |L_{\mathcal{C}}|$$

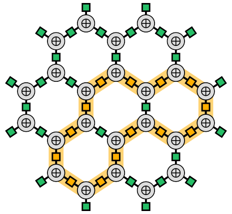
Local automorphisms needed!

&

Observation 2



Permutation?



Encode **qubits on edges** in **two atoms** that are in blockade!

Constructing a Fully-symmetric Loop Hilbert Space

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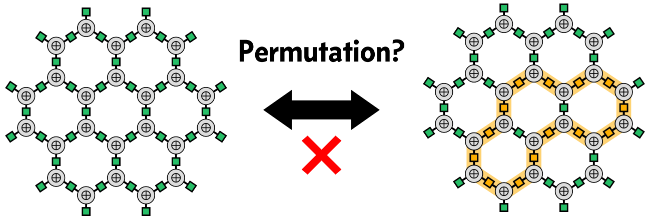
Observation 2



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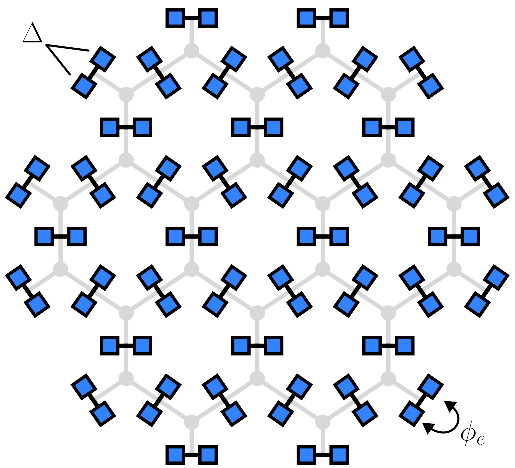
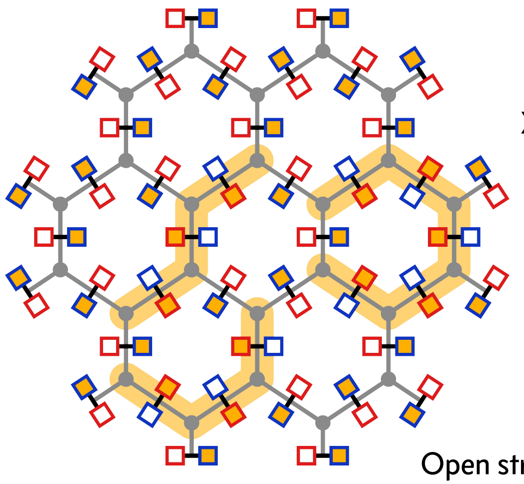


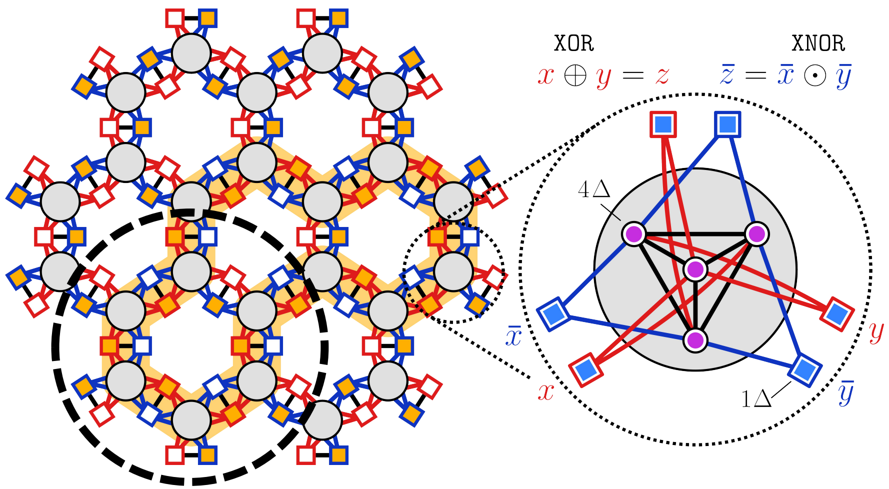
Fully symmetric

One qubit per edge



Enforce **XOR/XNOR** on sites

Open strings still allowed ...



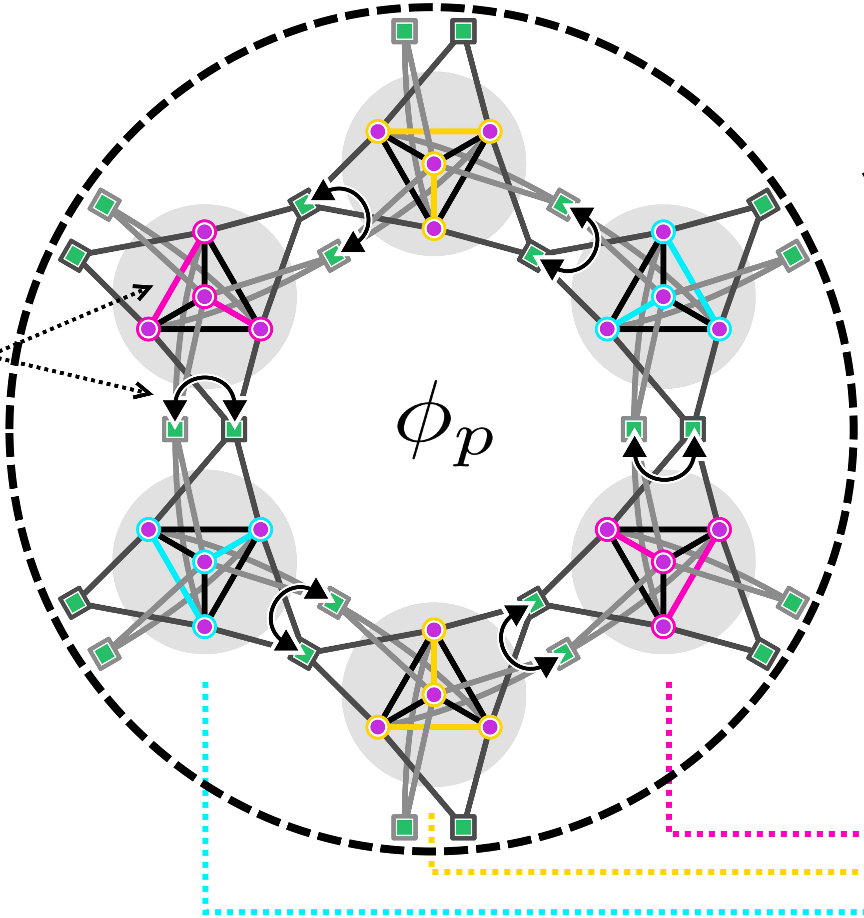
FSU gate has all required properties!

$$\text{String} \;:\leftrightarrow\; |10\rangle_e \quad \text{and} \quad \text{Empty} \;:\leftrightarrow\; |01\rangle_e$$

Local Graph Automorphisms

Graph automorphisms of tessellation?

Transpositions

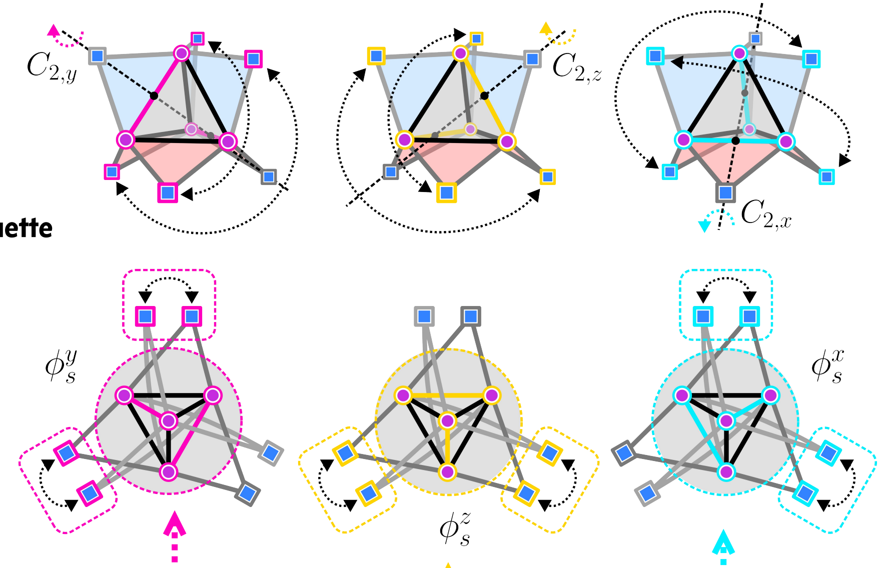


→ **Plaquette *symmetries*** $U_p\,|\mathbf{n}\rangle := |\phi_p \cdot \mathbf{n}\rangle$

$$[U_p, U_q] = 0 \quad \text{and} \quad [H_{\text{Loop}}, U_p] = 0$$

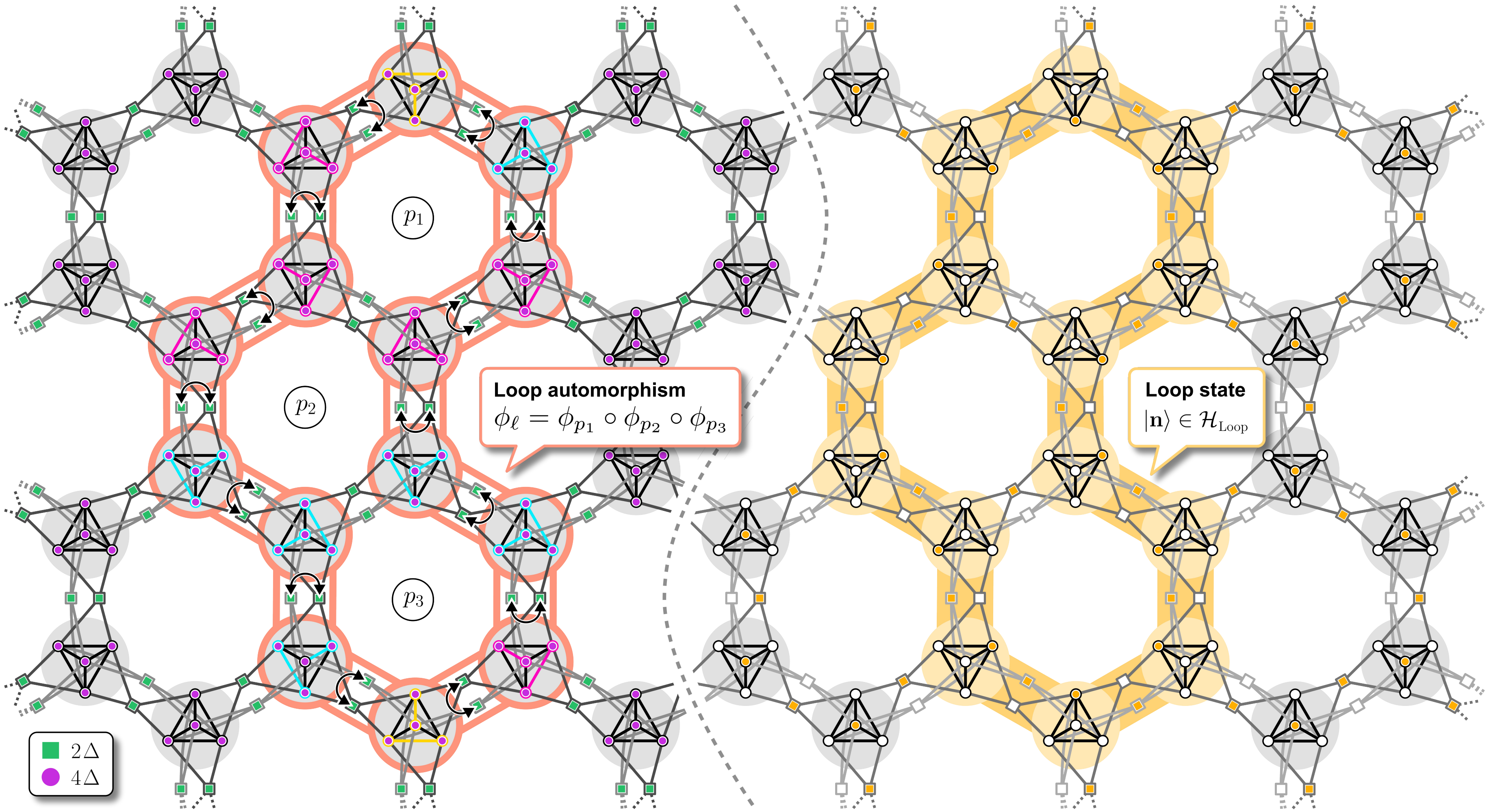
$$U_p^2 = \mathbb{1} \qquad U_p^\dagger = U_p$$

Only **combination** of **all transpositions around plaquette** is automorphism!



→ **Plaquette *automorphisms***

Putting it all together



→ **Loop automorphisms**

→ **Loop states/patterns**

Not a unit disk embedding!

But:
Extended version **can** be embedded in **quasi-2D**. 😁

Ground states
=
Loop patterns

No-loop state &
All loop automorphisms
→ **All** loop patterns

Fully symmetric! 😁

Topological Order?

Fully symmetric

Unique ground state
(finite system)

$$|\Omega\rangle = \underbrace{\lambda(\Omega) \sum_{\boldsymbol{n}\in L_{\text{Loop}}} |\boldsymbol{n}\rangle}_{=:\Lambda|\Omega_0\rangle} + \underbrace{\sum_{d\geq 1} \left(\frac{\Omega}{\Delta E}\right)^d \sum_{\boldsymbol{n}\in L^d_{\text{Loop}}} \eta_{\boldsymbol{n}}(\Omega)\,|\boldsymbol{n}\rangle}_{=:\sqrt{1-\Lambda^2}|\Omega_\eta\rangle}$$

Valid for arbitrary boundary conditions

No fixpoint Hamiltonian possible

Topologically ordered 😁

Valid for arbitrary Ω

Can **destroy** topological order! 🥺 ?

Topological Order!

Auxiliary Hamiltonian

Unphysical!

$$\tilde{H}(\Omega,\omega) := H_{\text{Loop}}(\Omega) + \frac{\omega}{2}\sum_p (\mathbb{1} - U_p)$$

Topologically ordered!

$$\Omega = 0 < \omega$$

$$0 < |\Omega| \ll \omega$$

$$\sum_{\boldsymbol{n}\in L_{\text{Loop}}} |\boldsymbol{n}\rangle \;\propto\; |\Omega_0\rangle \xrightarrow[\omega>0]{\Omega=0\,\to\,\Omega\neq 0} |\Omega^*\rangle \;\longrightarrow\; |\Omega^*\rangle \xrightarrow[\Omega\neq 0]{\omega>0\,\to\,\omega=0} |\Omega\rangle = |\Omega^*\rangle$$

Gap stability
(LTQO & Frustration-free)

Local symmetry
$$[\tilde{H}(\Omega,\omega), U_p] = 0$$

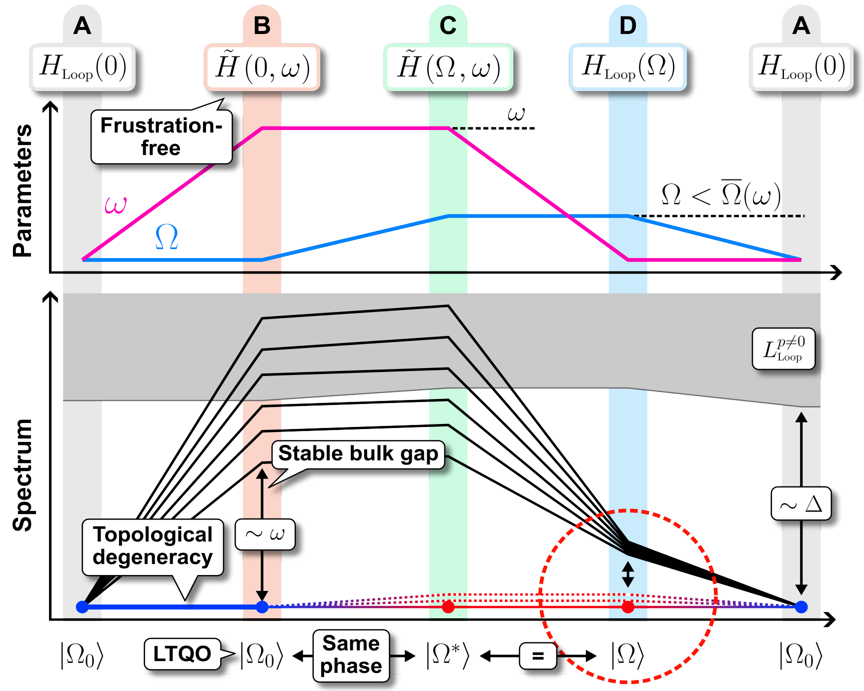
Summary

Topologically ordered!

$$\overbrace{|\Omega_0\rangle \sim |\Omega^*\rangle}^{\text{Same phase}} \underbrace{\;= |\Omega\rangle}_{\text{Same state}} = \Lambda\,|\Omega_0\rangle + \sqrt{1-\Lambda^2}\,|\Omega_\eta\rangle$$

Does not destroy topological order! 😁

$$H_{\text{Loop}}(\Omega) = \tilde{H}(\Omega, 0)$$

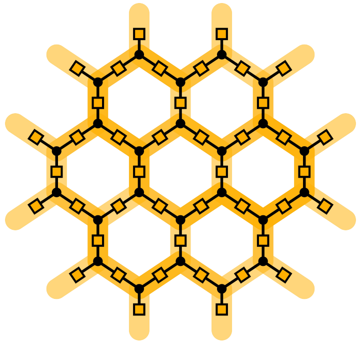


Open question: **Gap in charge sector?**

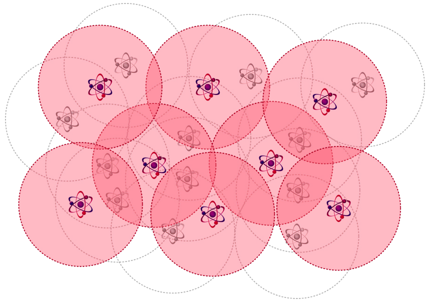
Stability of frustration-free Hamiltonians
S. Michalakis and J. P. Zwolak
Communications in Mathematical Physics **322**(2), 277 (2013), doi:10.1007/s00220-013-1762-6

Summary & Outlook

Toric code topological order



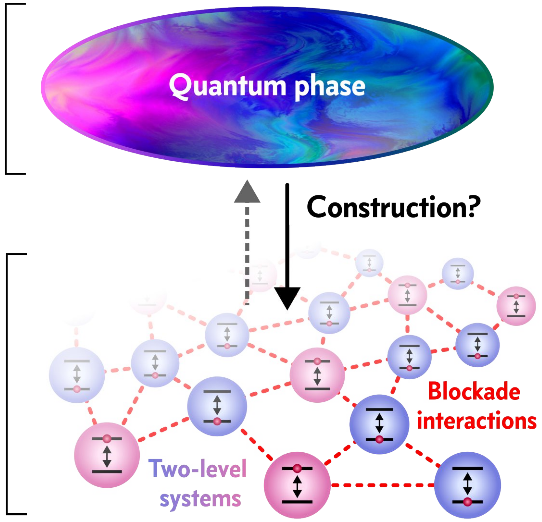
Rydberg platform



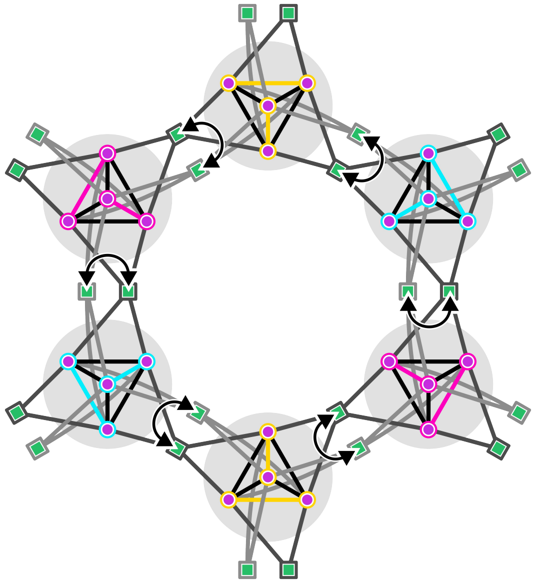
The Inverse Problem
of quantum many-body physics

Goal

Toolbox



Topological Order with
Fully-Symmetric
Blockade Structures



Existence of charge gap?

Size of charge gap?

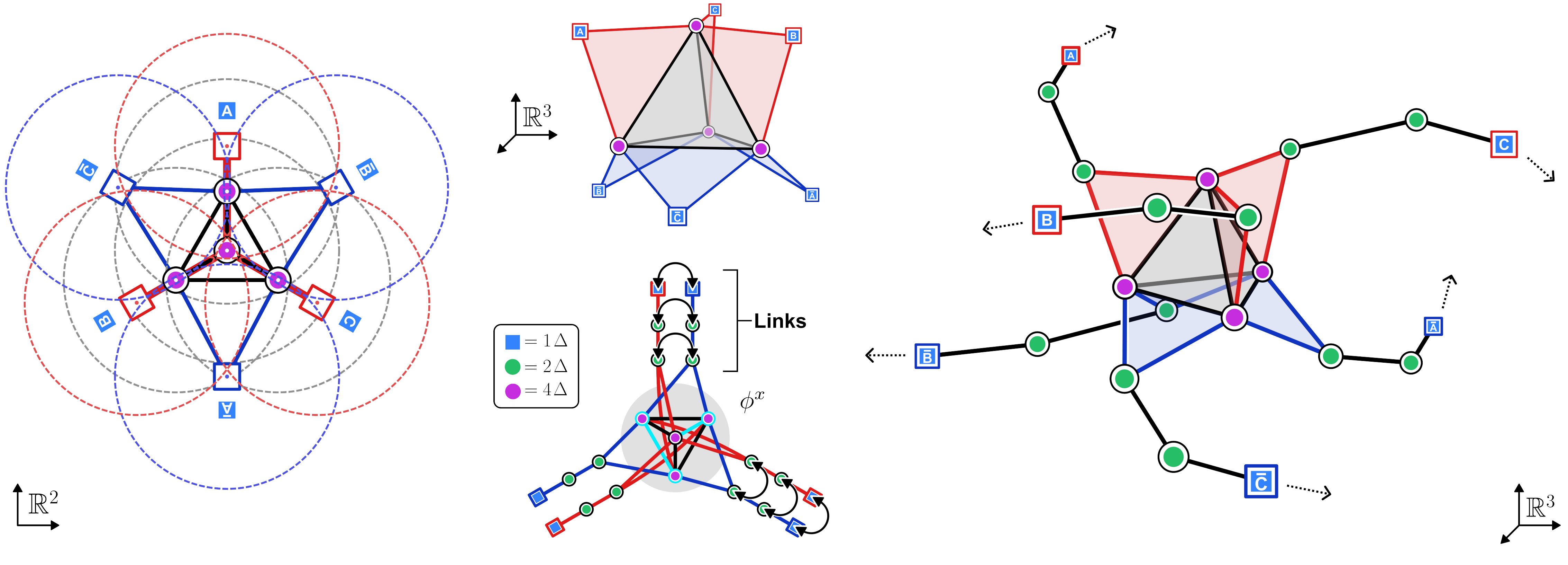
Non-Abelian topological orders?

Effects of van der Waals tails?

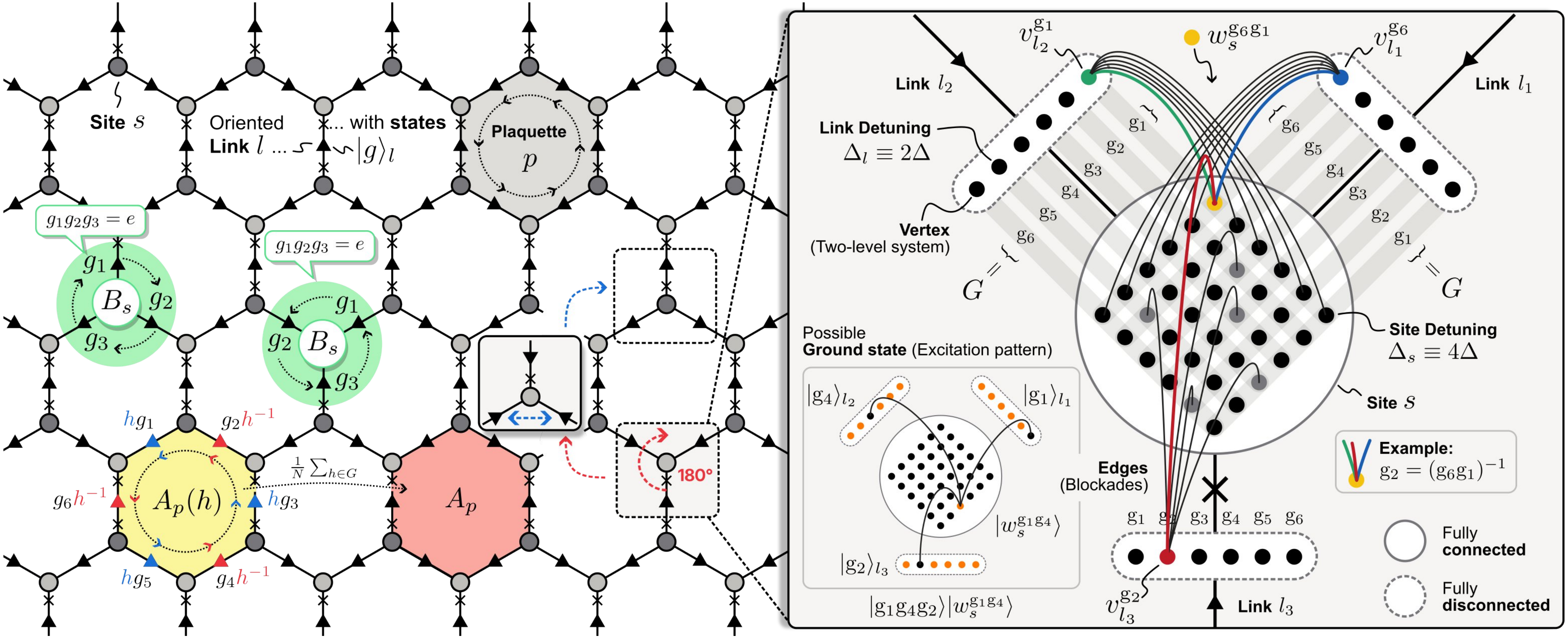
Embeddings?

Non-equal-weight condensates?

Embedding of (extended) FSU vertices

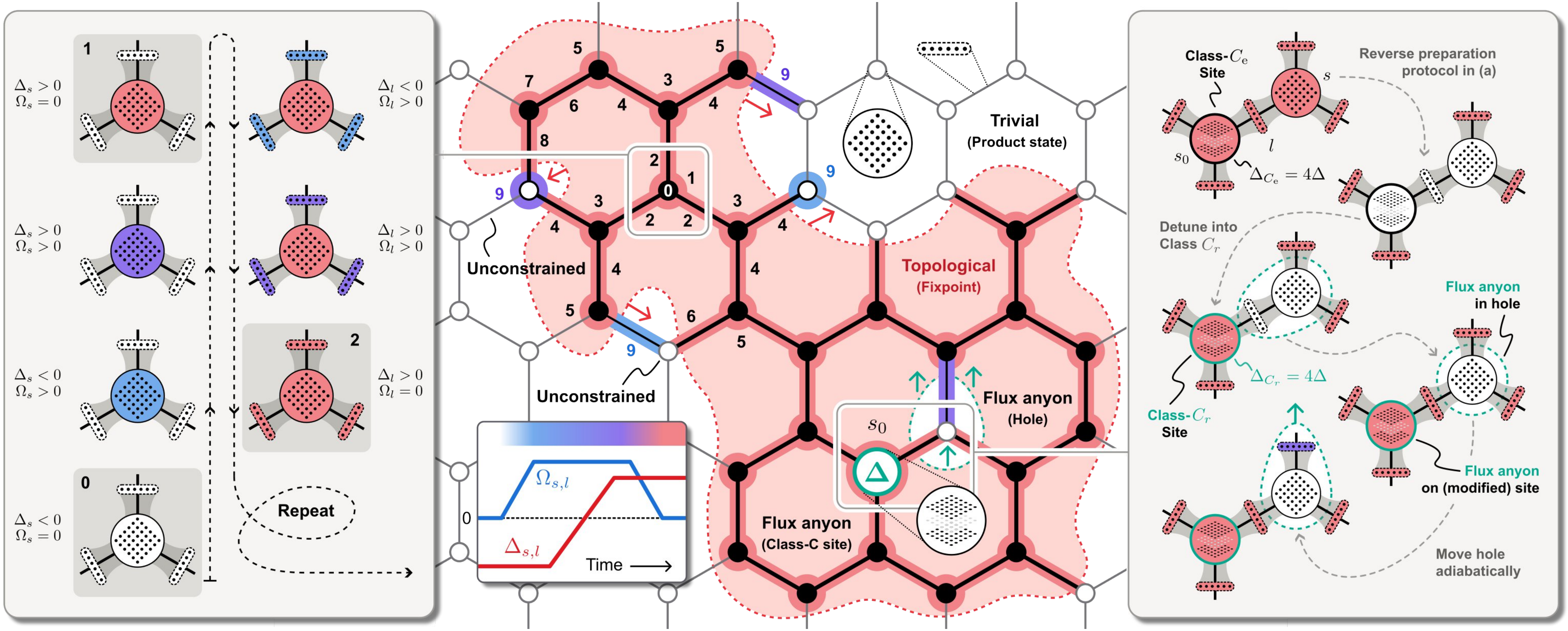


Generalization to Quantum Doubles



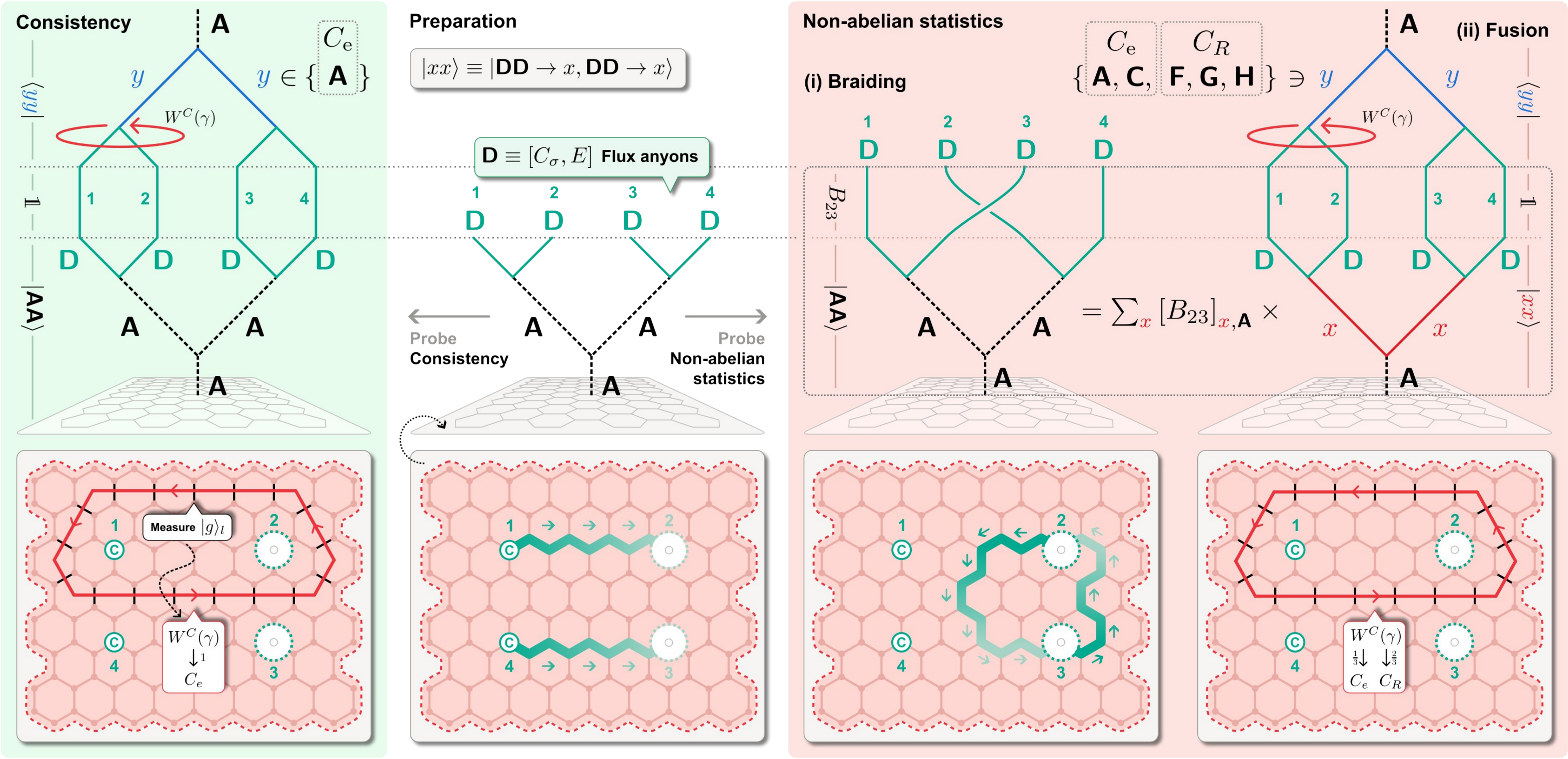
Quantum doubles in symmetric blockade structures
Hans Peter Büchler, Tobias F. Maier, Simon Fell, and NL
arXiv: **2511.04414** (2025)

Preparation



Quantum doubles in symmetric blockade structures
Hans Peter Büchler, Tobias F. Maier, Simon Fell, and NL
arXiv: **2511.04414** (2025)

Braiding



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