TRIMER STATES WITH Z_3 TOPOLOGICAL ORDER IN RYDBERG ATOM ARRAYS

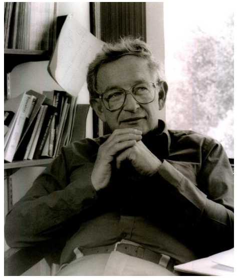
Federica Surace

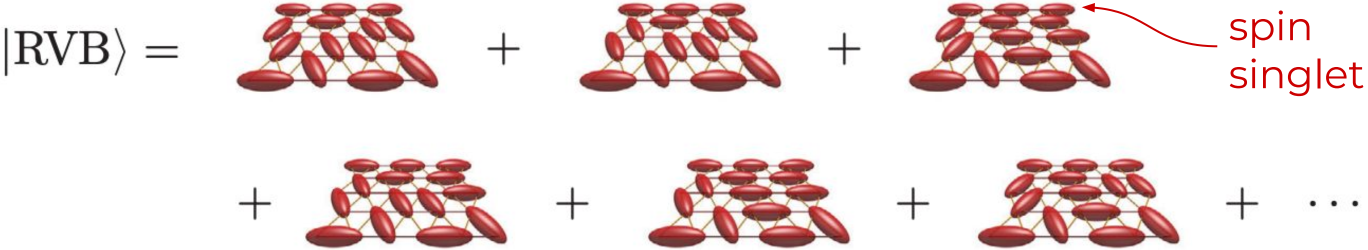
Gauge Workshop Munich - May 11, 2022

Caltech

IQIM

Anderson 1973: **Quantum spin liquids**





Savary, Rep. Prog. Phys 2017

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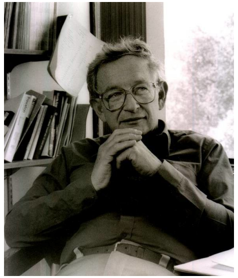

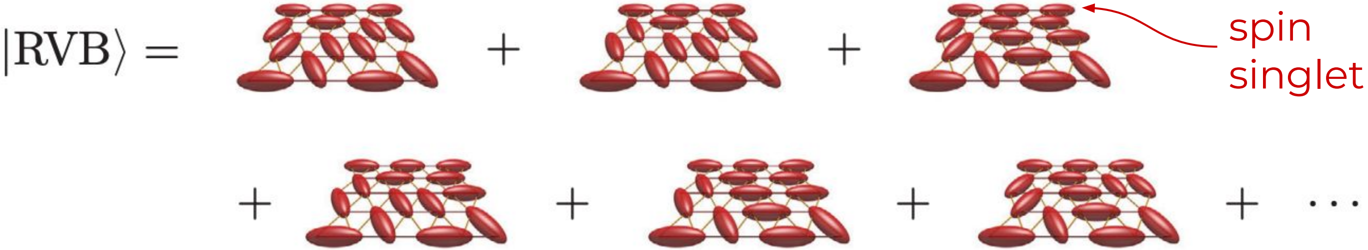

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See also: 1987 Kivelson Rokhsar Sethna, 1988 Affleck Marston, 1991 Read Sachdev, 1991 Wen

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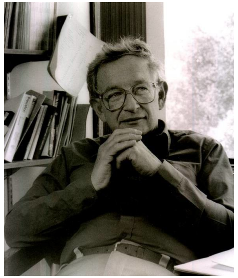

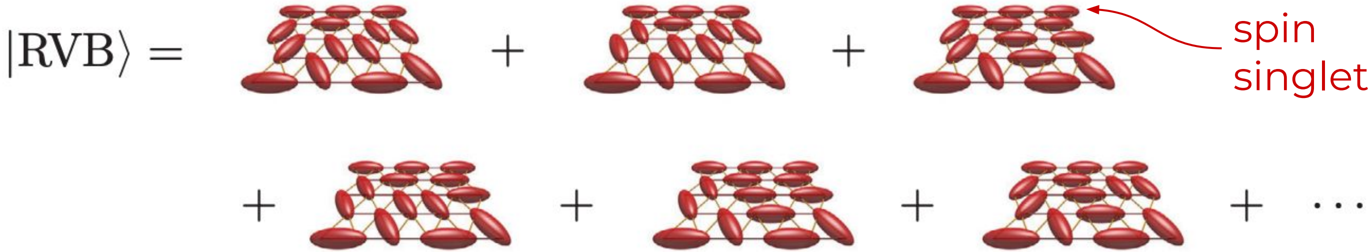

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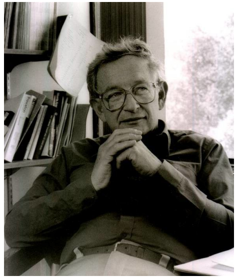

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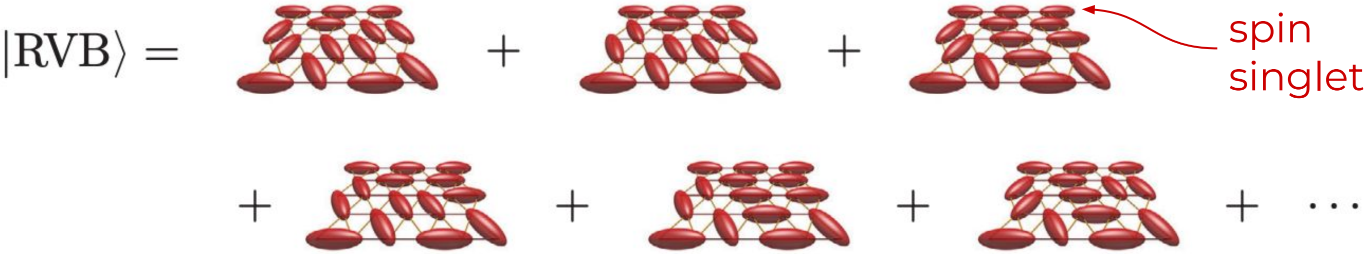

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Moessner Sondhi 2001: **Stable QSL in the dimer model on triangular lattice**

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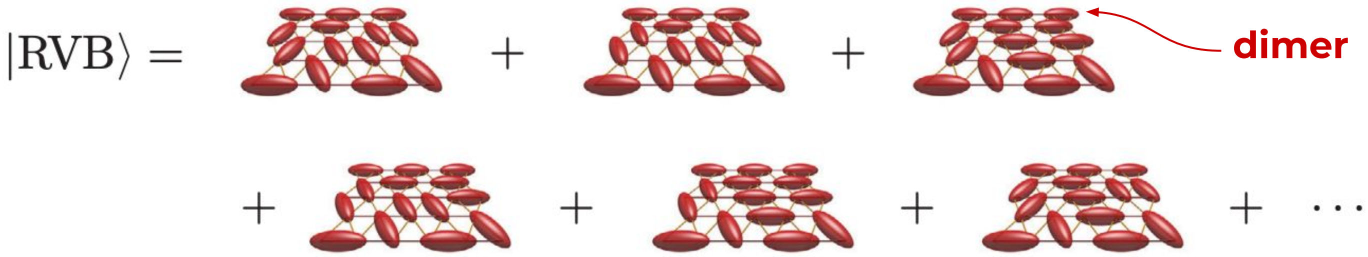
TOPOLOGICAL ORDER IN DIMER MODELS



is it a stable QSL?

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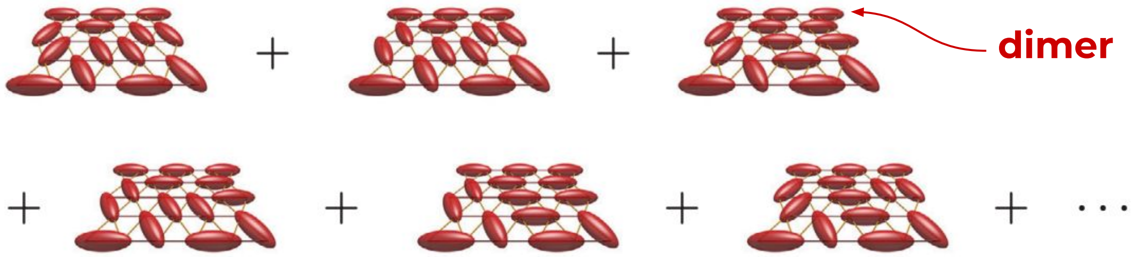

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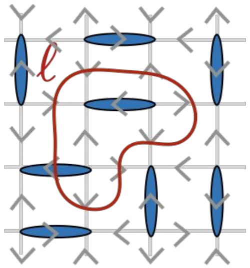
Savary, Rep. Prog. Phys 2017

2D bipartite lattices ✗

U(1) gauge symmetry:

$$\sum_{i\in\ell_{\mathrm{in}}} Z_i - \sum_{i\in\ell_{\mathrm{out}}} Z_i = N_v^A - N_v^B$$



- infinite correlation length
- no deconfined phase (Polyakov)

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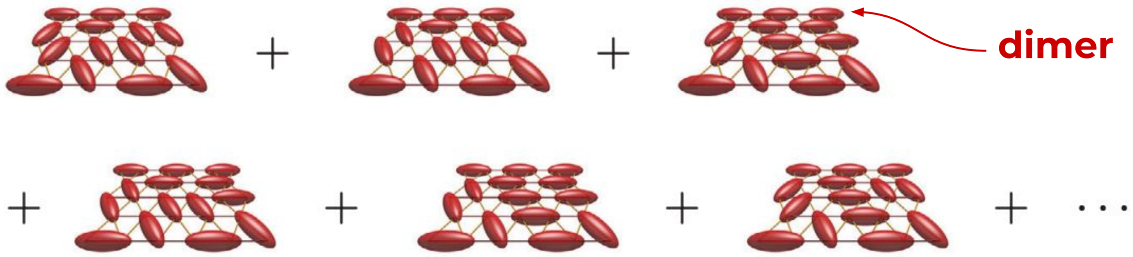

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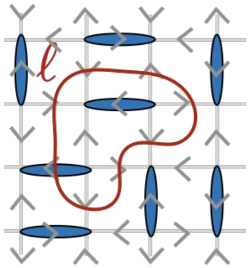

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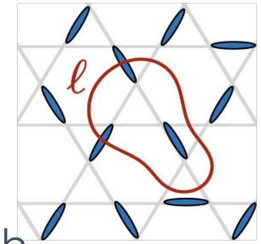
2D non-bipartite lattices ✔

Z_2 gauge symmetry:

$$\prod_{i\in\ell} Z_i = (-1)^{N_v}$$



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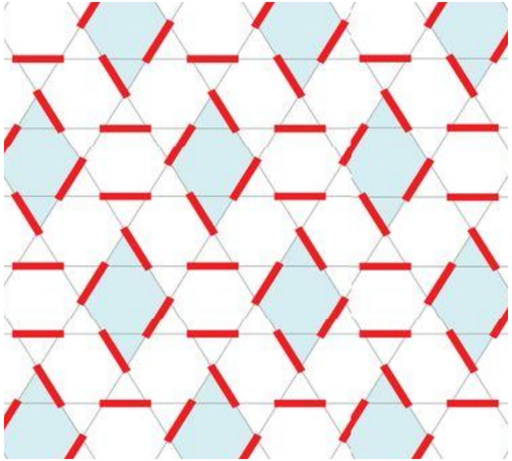
TOPOLOGICAL ORDER IN DIMER MODELS

Dimer RVB state on triangular, kagome lattices have Z_2 topological order



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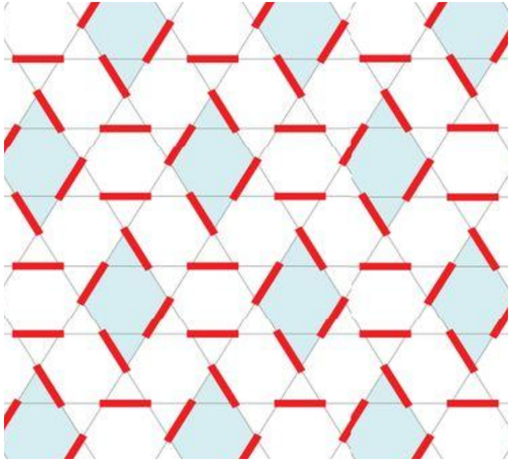
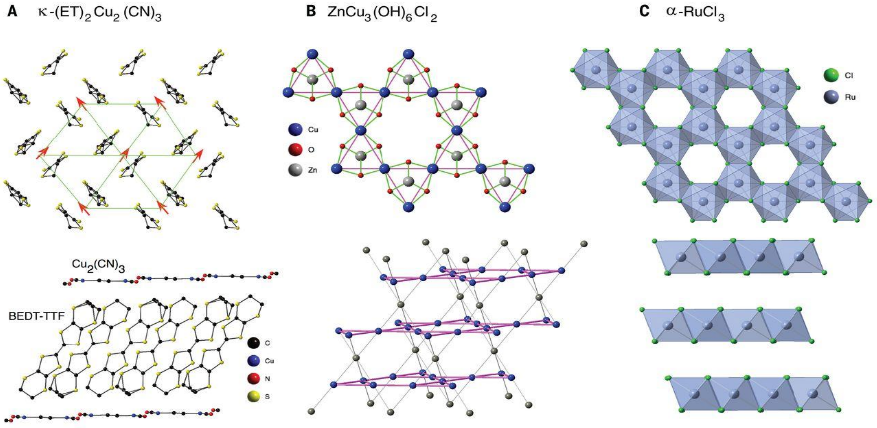


Various candidate materials



Broholm, Science 2020

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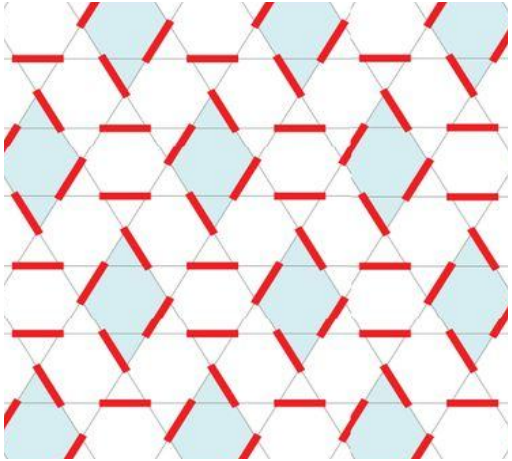

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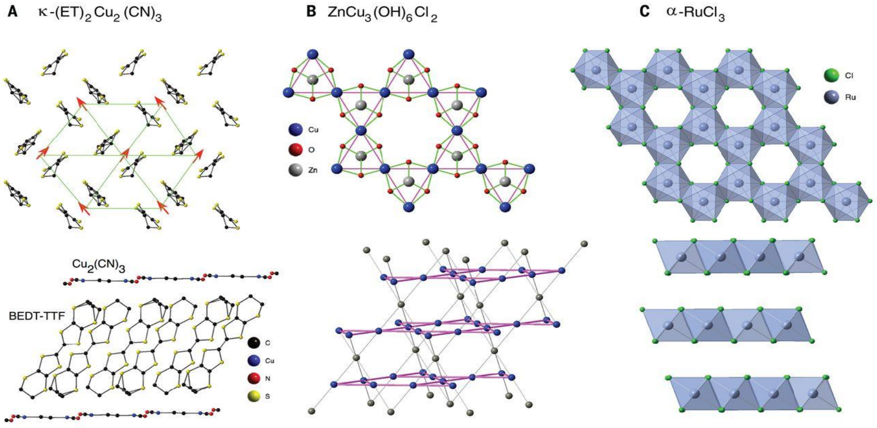
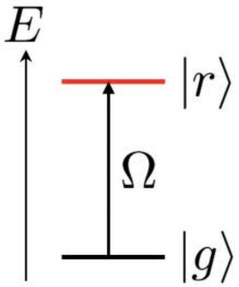


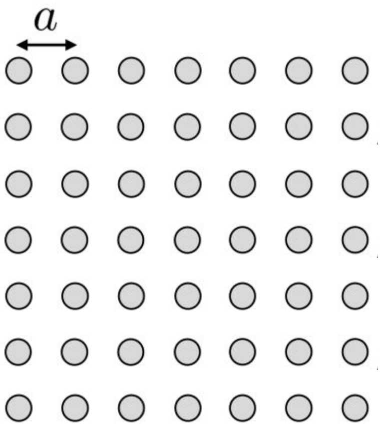
Quantum simulators?

Broholm, Science 2020

RYDBERG ATOM ARRAYS

$$|r\rangle\langle r| = n \qquad |r\rangle\langle g| = b^\dagger$$





$$H = \frac{\Omega}{2}\sum_{\boldsymbol{i}}\left(b_{\boldsymbol{i}} + b_{\boldsymbol{i}}^\dagger\right)$$

Browaeys, Lahaye, *Nat. Phys.* 16, 132–142 (2020)

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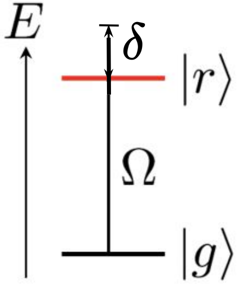

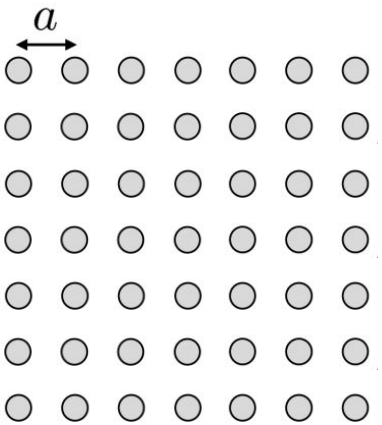

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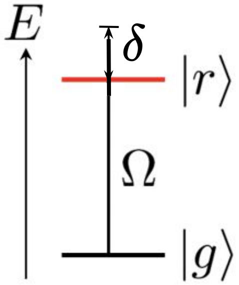

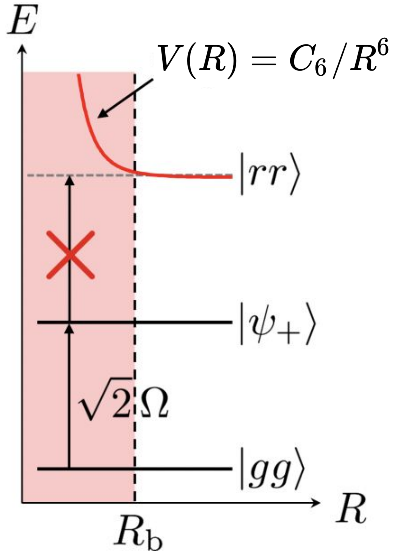

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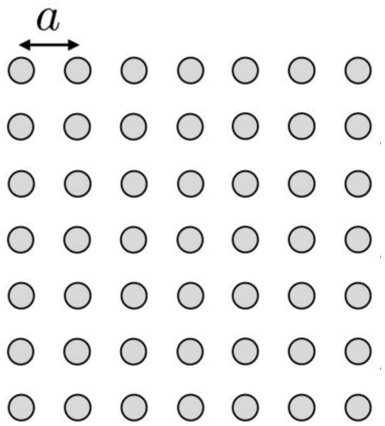

$$H = \frac{\Omega}{2}\sum_{\boldsymbol{i}}\left(b_{\boldsymbol{i}} + b_{\boldsymbol{i}}^\dagger\right) - \delta\sum_{\boldsymbol{i}} n_{\boldsymbol{i}} + \frac{1}{2}\sum_{\boldsymbol{i},\boldsymbol{j}} V(|\boldsymbol{i}-\boldsymbol{j}|)\, n_{\boldsymbol{i}} n_{\boldsymbol{j}}$$

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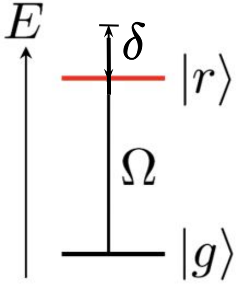

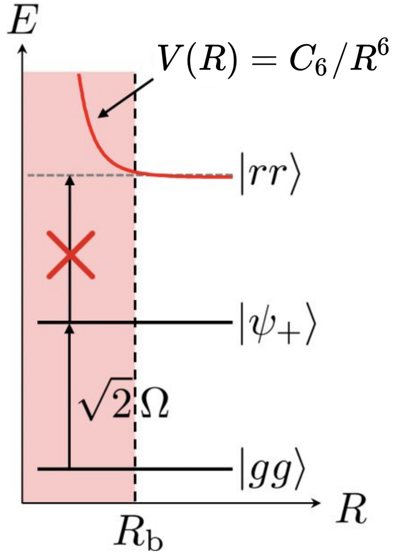

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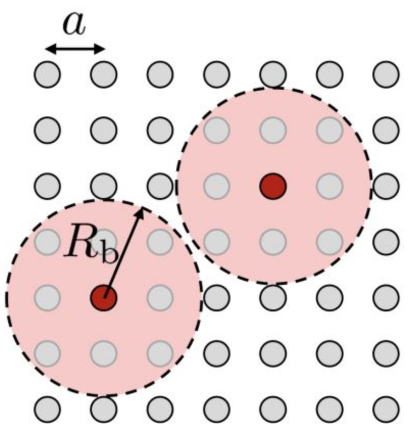

$$V(R_b) := \Omega$$

Blockade radius

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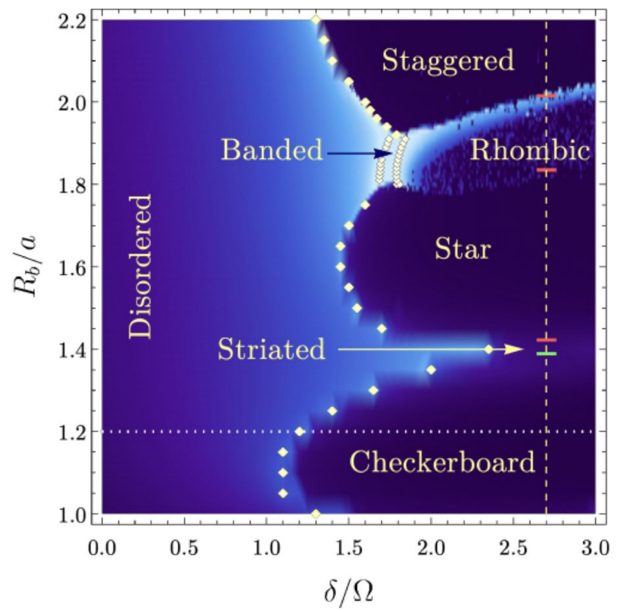
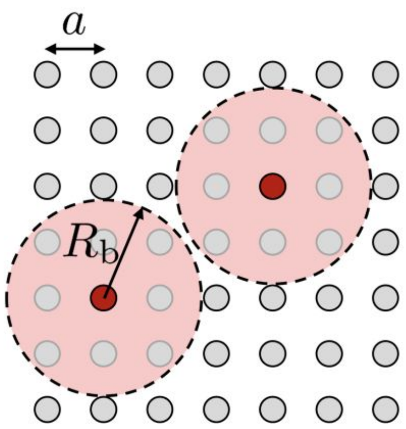


Square lattice

Samajdar, Ho, Pichler, Lukin, Sachdev, PRL **124**, 103601 (2020)

$|r\rangle\langle r| = n$ $\quad |r\rangle\langle g| = b^\dagger$



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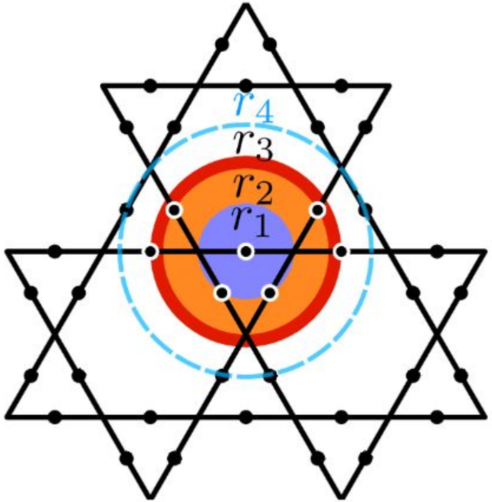
DIMER MODELS FROM RYDBERG BLOCKADE

Ruby lattice



Vishwanath's talk on Monday

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Verresen, Lukin, Vishwanath, Phys. Rev. X 11, 031005 (2021)

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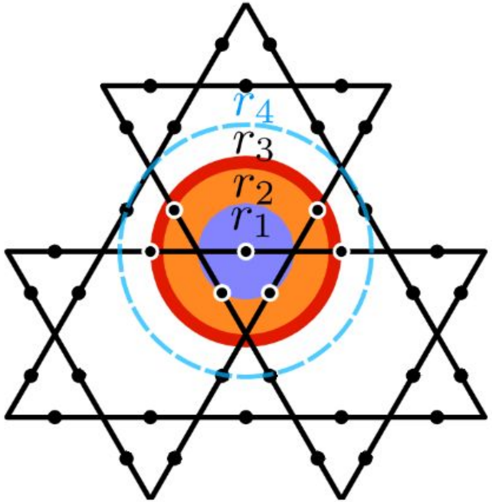

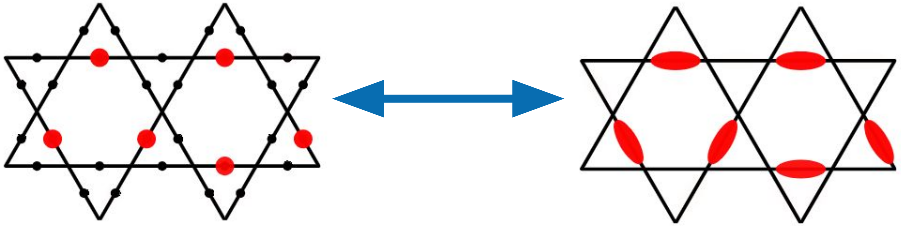

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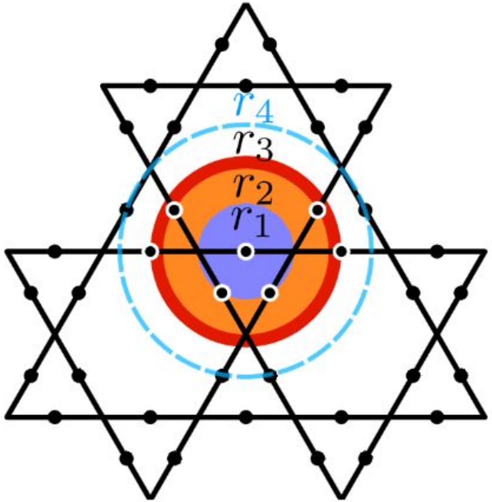

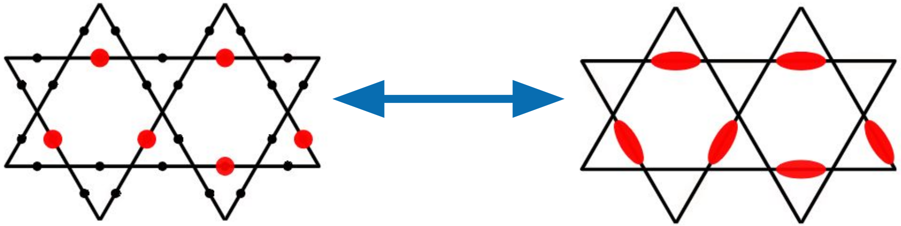

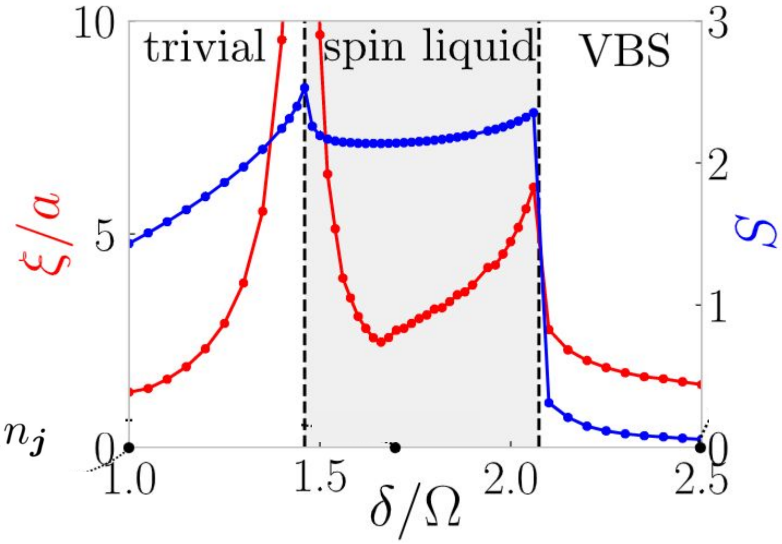

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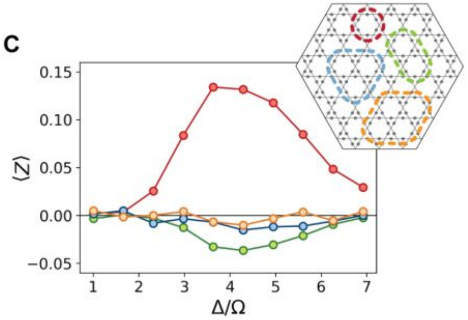
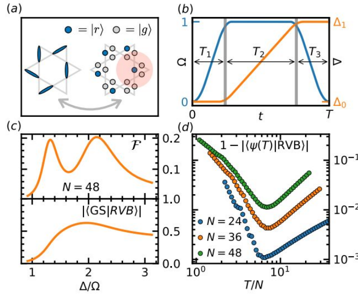


Semeghini et al, Science 2021



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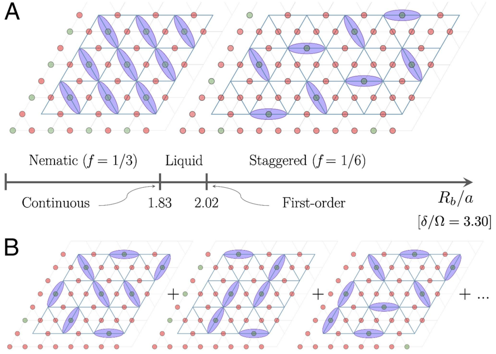

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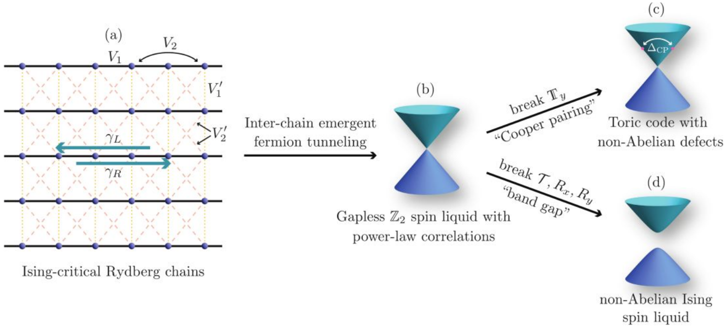

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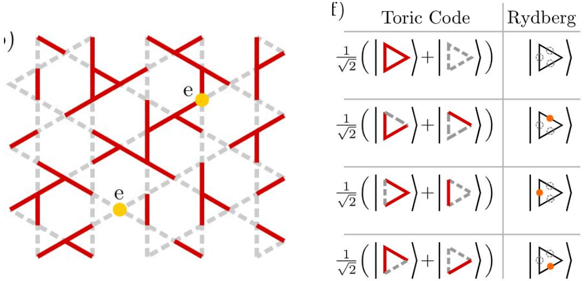

Tarabunga et al, (in preparation)

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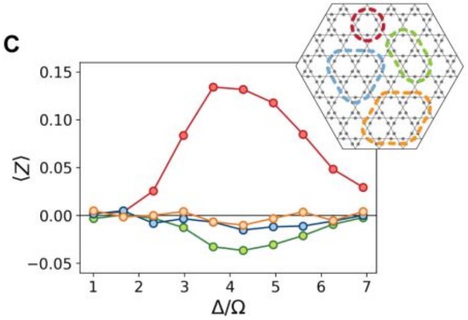

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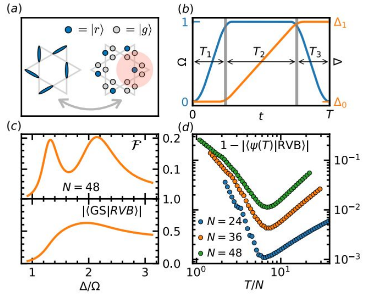

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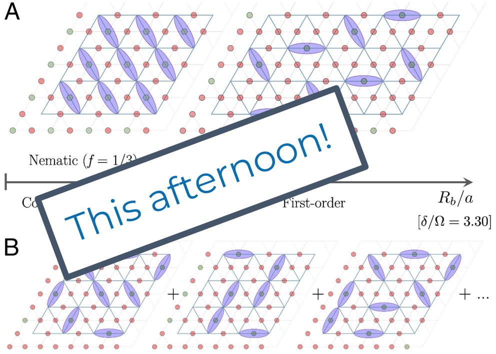

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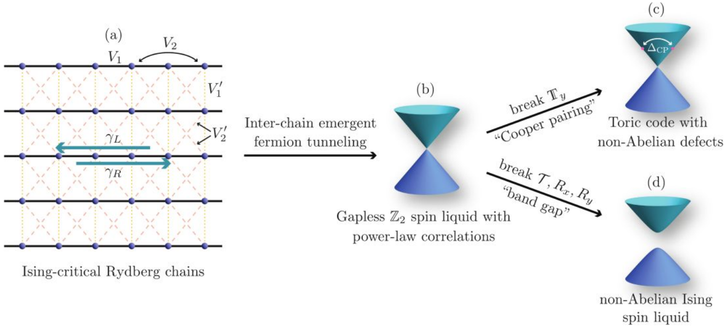

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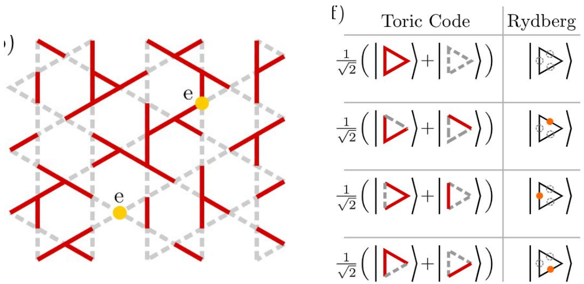

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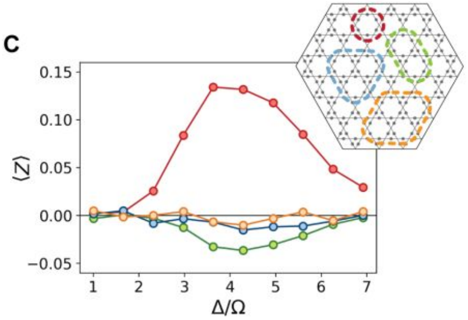

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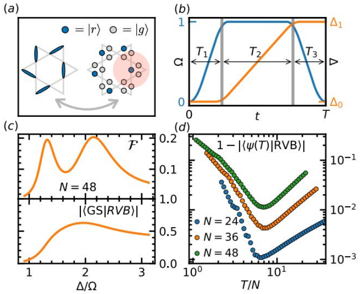

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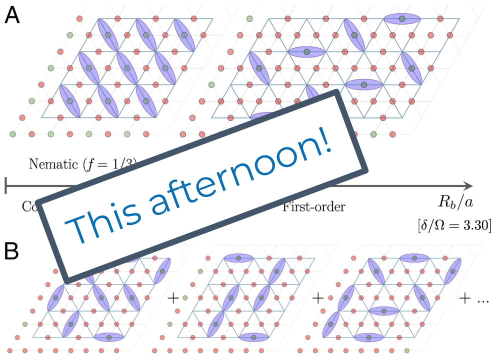

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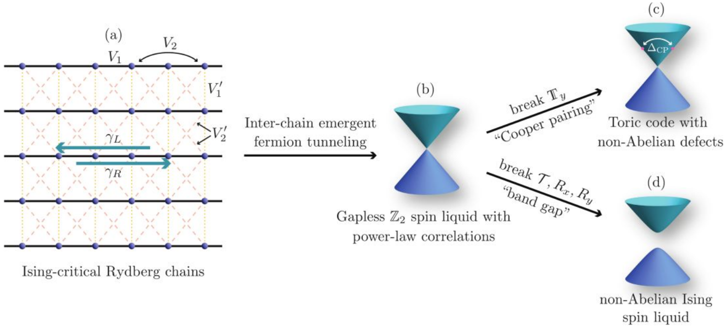

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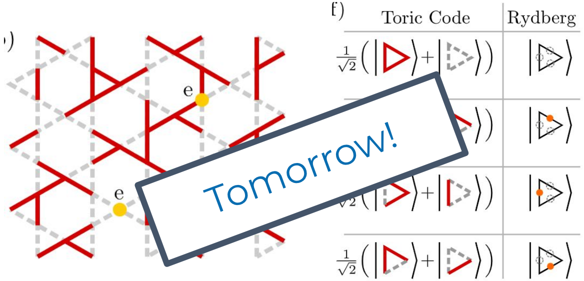

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Beyond dimer models:

Can other types of topological order emerge in constrained models?

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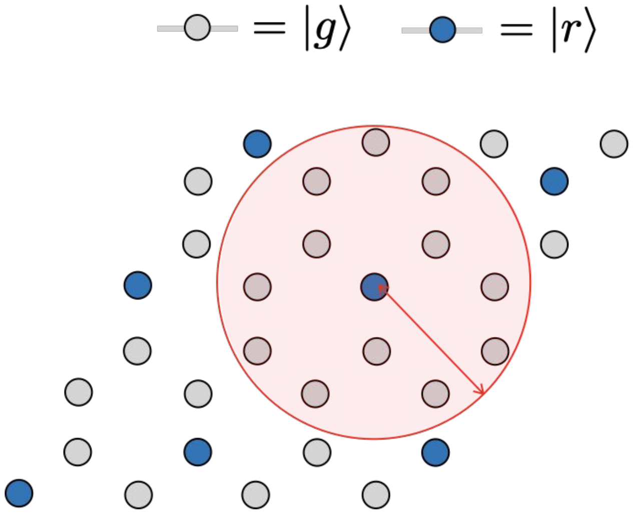
Can they be probed with Rydberg atoms?

BEYOND DIMER MODELS

Example: honeycomb lattice



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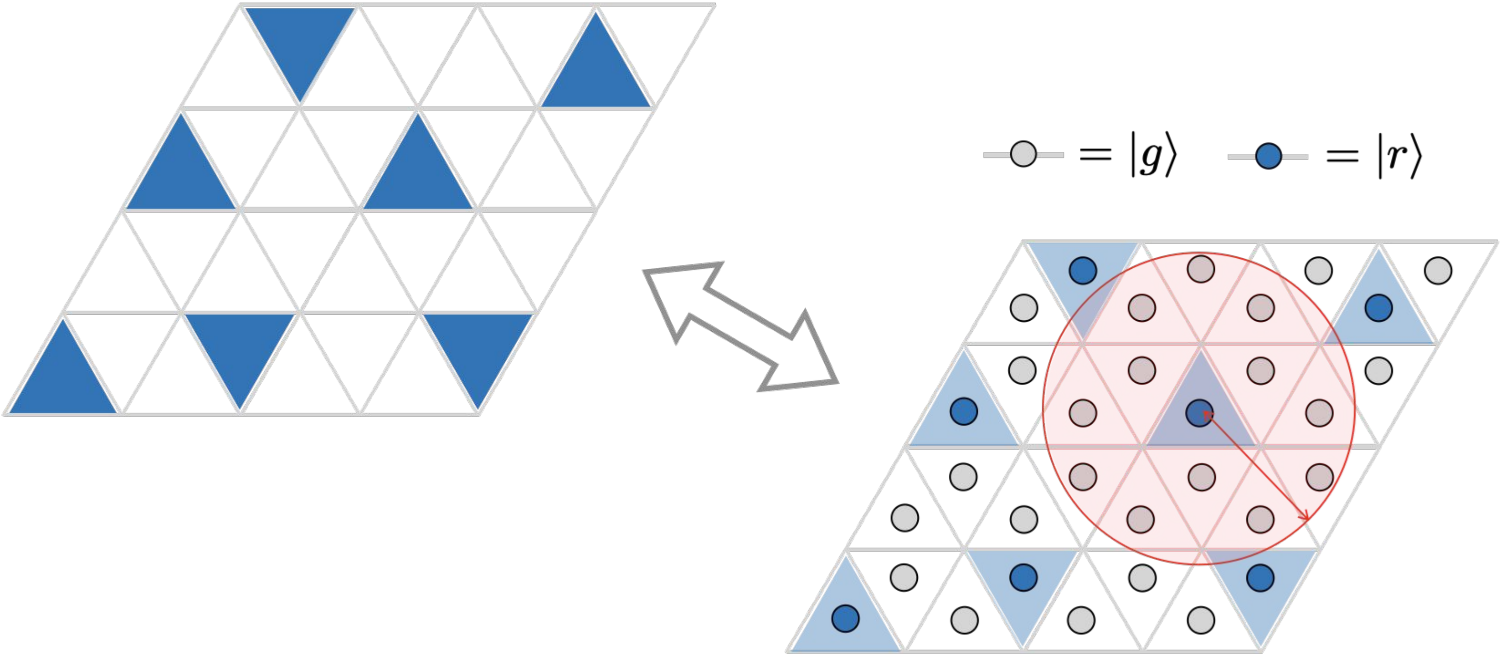
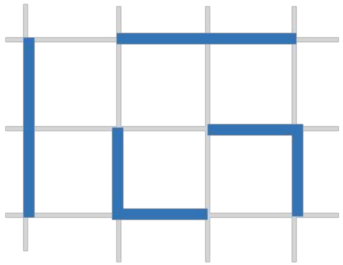
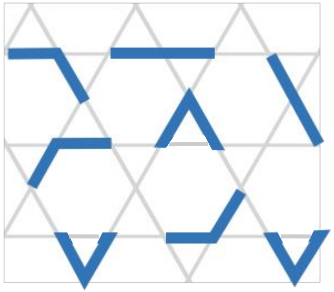
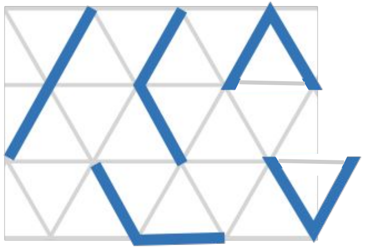


TRIMER MODELS

Trimer = two adjacent links







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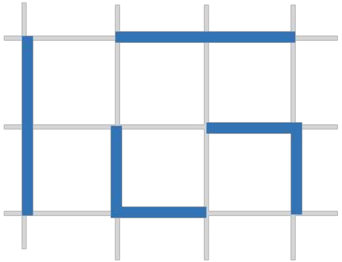
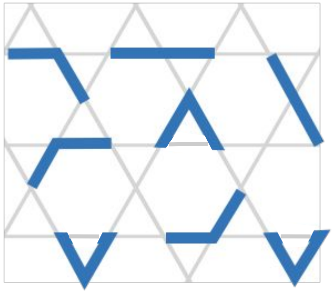
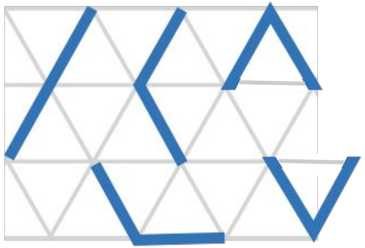
TRIMER MODELS

Trimer = two adjacent links



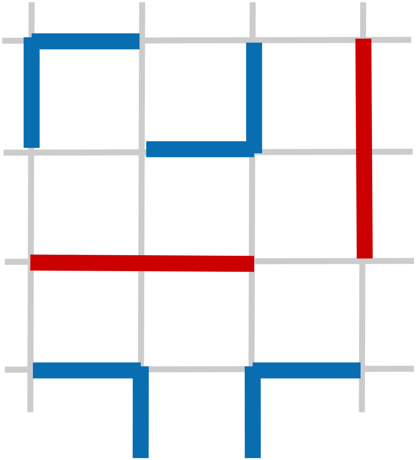




...

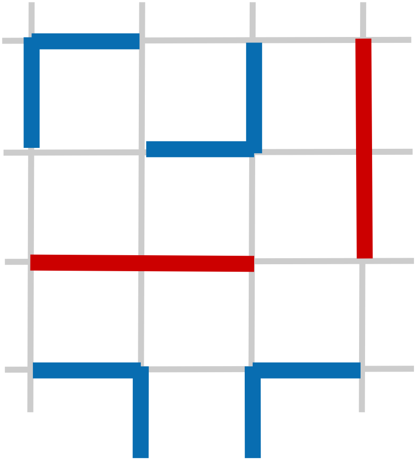
Much more freedom than with dimers...

TRIMER MODELS



Lee, Ho, Han, Katsura, PRB 2017
Dong, Chen, Tu, PRB 2018
Jandura, Iqbal, Schuch, PRR 2020

TRIMER MODELS



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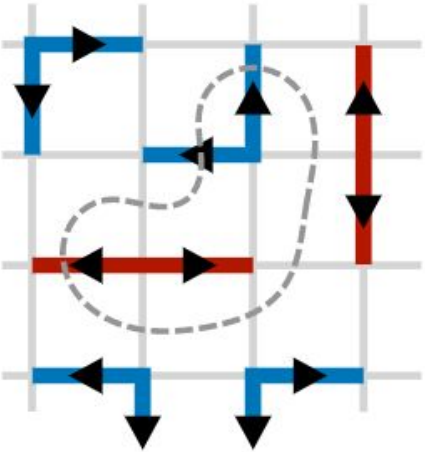
Z_3 topological order can emerge

TRIMER MODELS



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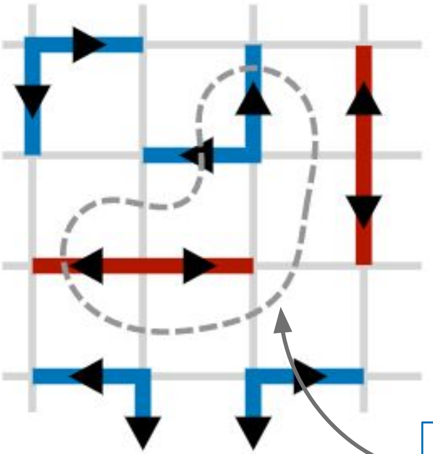

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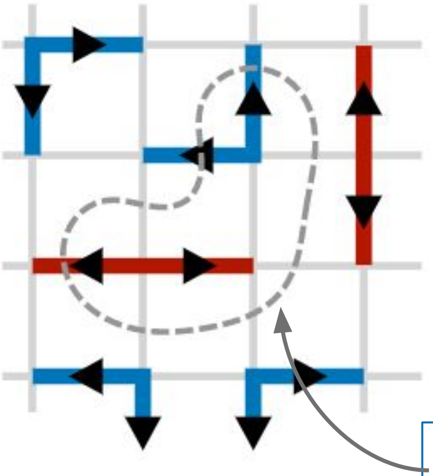
Z_3 **topological order** can emerge

Region with N_s vertices → Flux = $2N_s \bmod 3$

Z_3 Gauss law

TRIMER MODELS



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But some trimer models have a “larger” local symmetry and no gapped QSL

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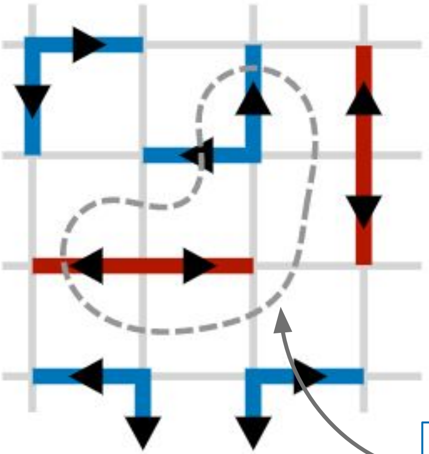

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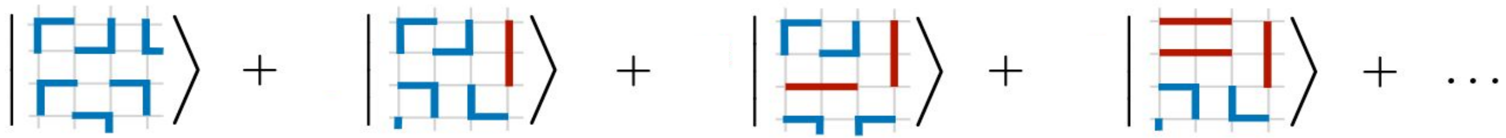
But some trimer models have a “larger” local symmetry and no gapped QSL

Is there a general criterion?

MAIN RESULT

Trimer RVB states

$$|\mathrm{tRVB}\rangle =$$



G. Giudice, FMS, H. Pichler, G. Giudici, in preparation

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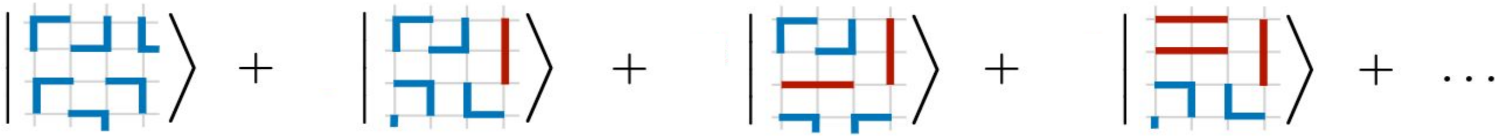

Tripartite

- tRVB has infinite correlation length
- U(1)xU(1) Gauss' law

G. Giudice, FMS, H. Pichler, G. Giudici, in preparation

MAIN RESULT

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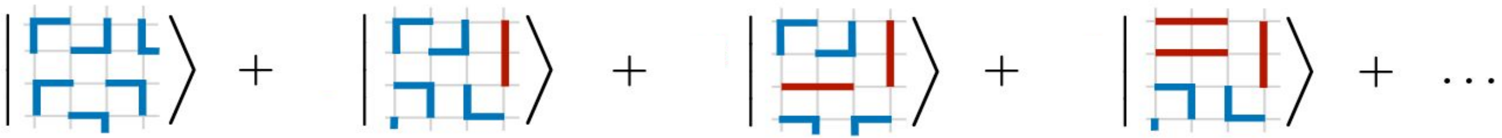


Tripartite

- tRVB has infinite correlation length
- U(1)xU(1) Gauss' law

Non-tripartite

- tRVB can have finite correlation length
- Z_3 Gauss' law

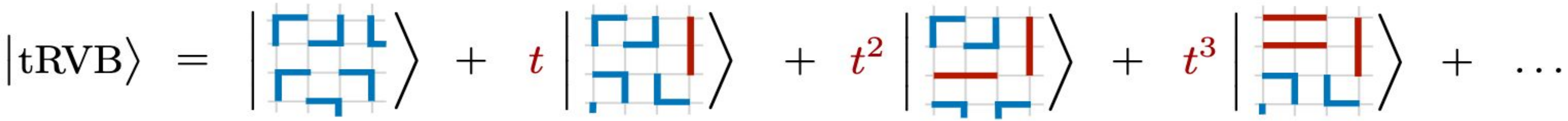
G. Giudice, FMS, H. Pichler, G. Giudici, in preparation

OUTLINE

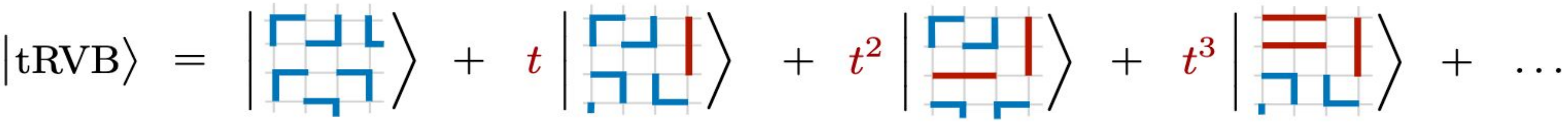
- **Resonating trimer states**
  - Definition (square lattice)
  - Tensor network representation
  - Gauge symmetry: Z_3 vs U(1)xU(1)
  - Other lattices
- **Dilute trimer state**
  - Stability
  - Hamiltonian
- **Implementation with Rydberg atom**
  - Square lattice

1. RESONATING TRIMER STATES

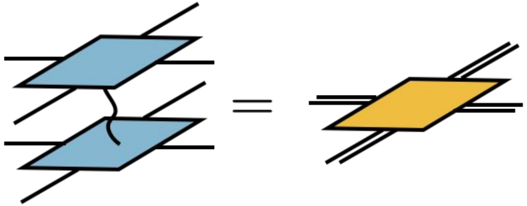
RESONATING TRIMER STATE



RESONATING TRIMER STATE



Tensor network representation



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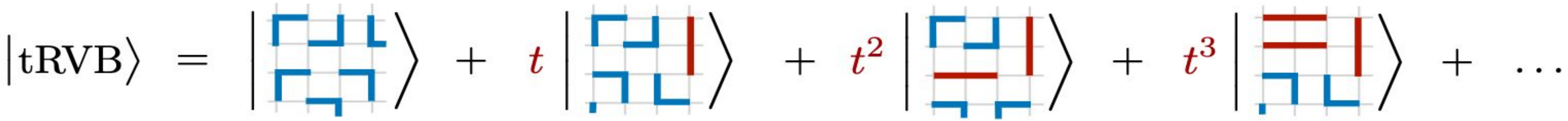

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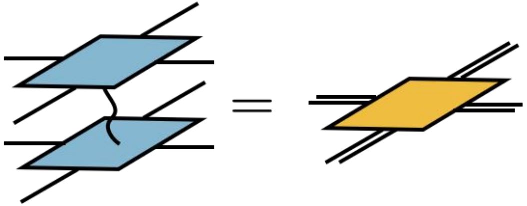
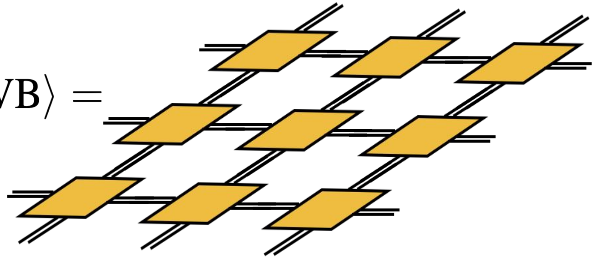
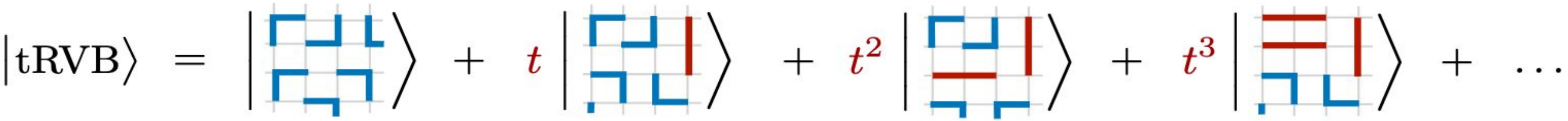


$Z = \langle \mathrm{tRVB} | \mathrm{tRVB} \rangle =$ 

classical statmec
partition function

RESONATING TRIMER STATE



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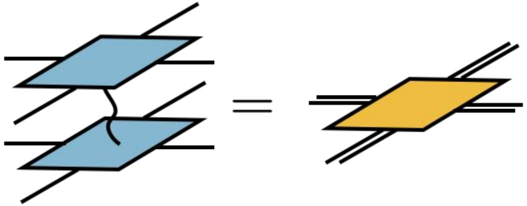
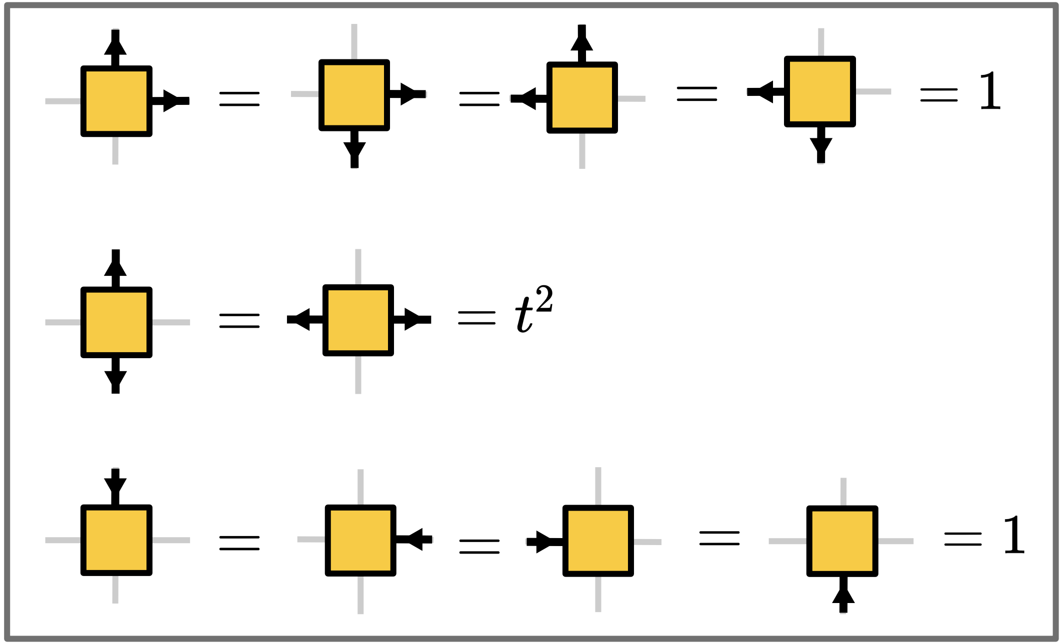
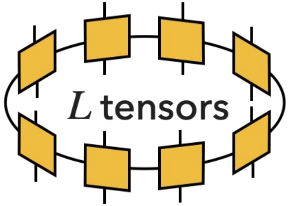


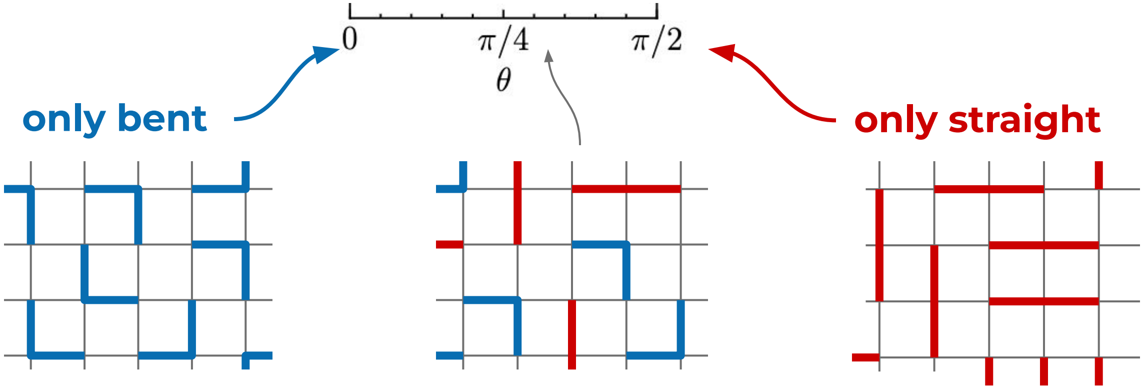
virtual indices ↔ gauge fields



NUMERICAL RESULTS

Cylinder transfer matrix





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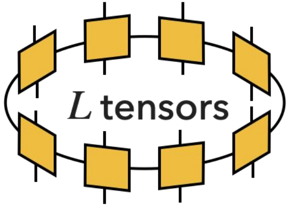

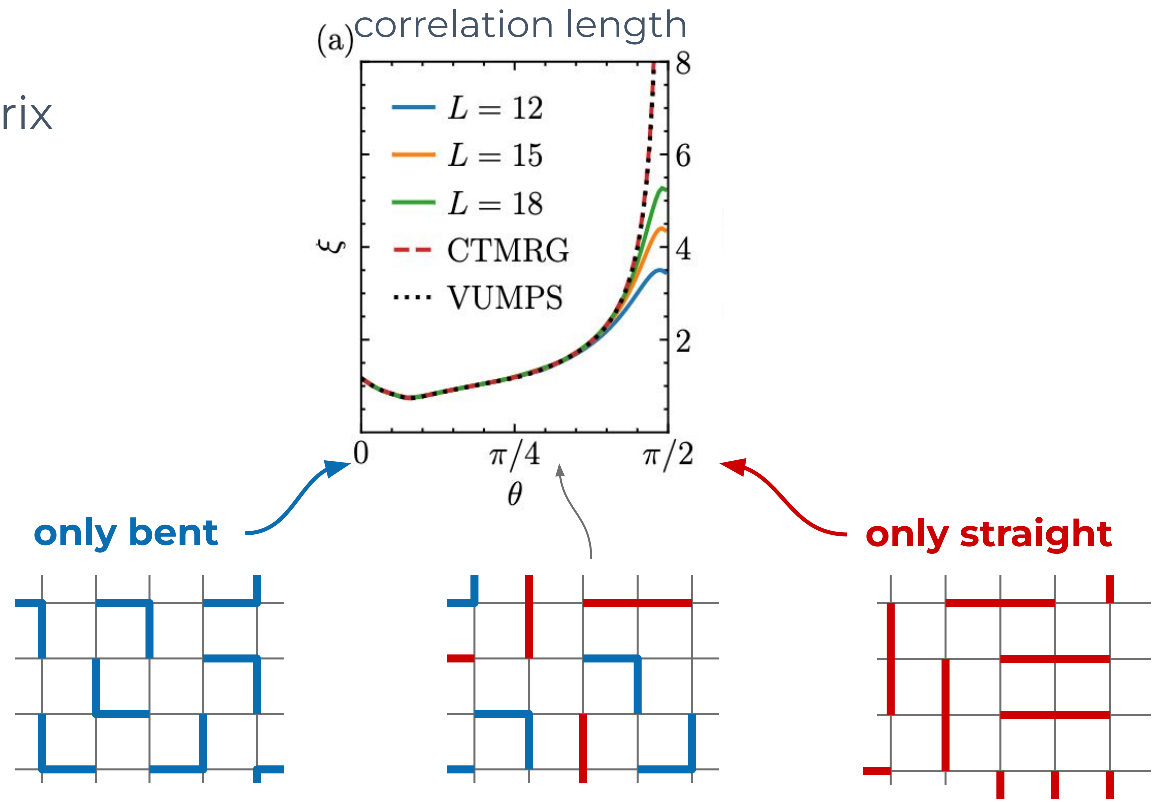

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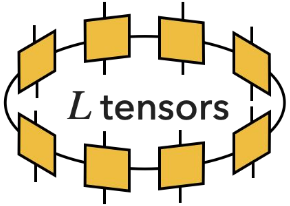

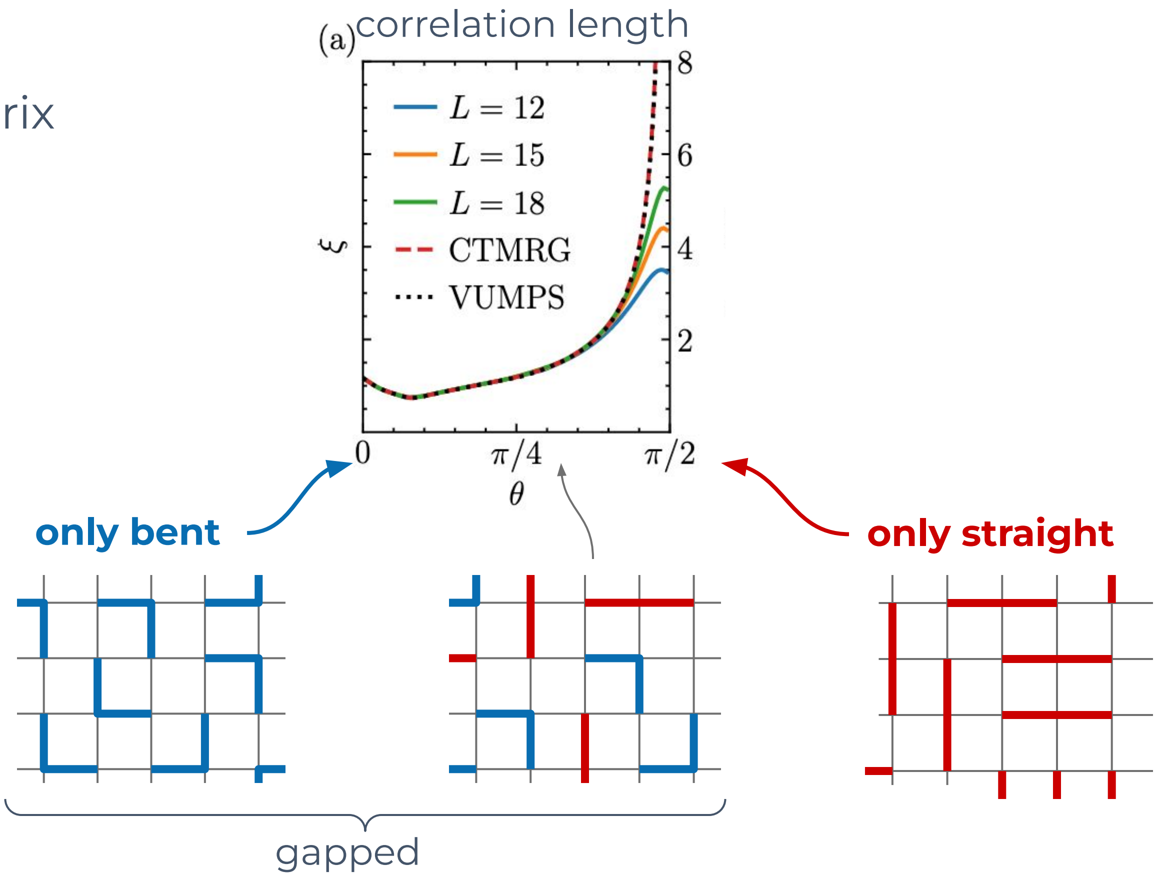

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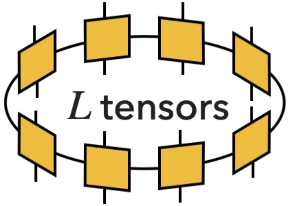

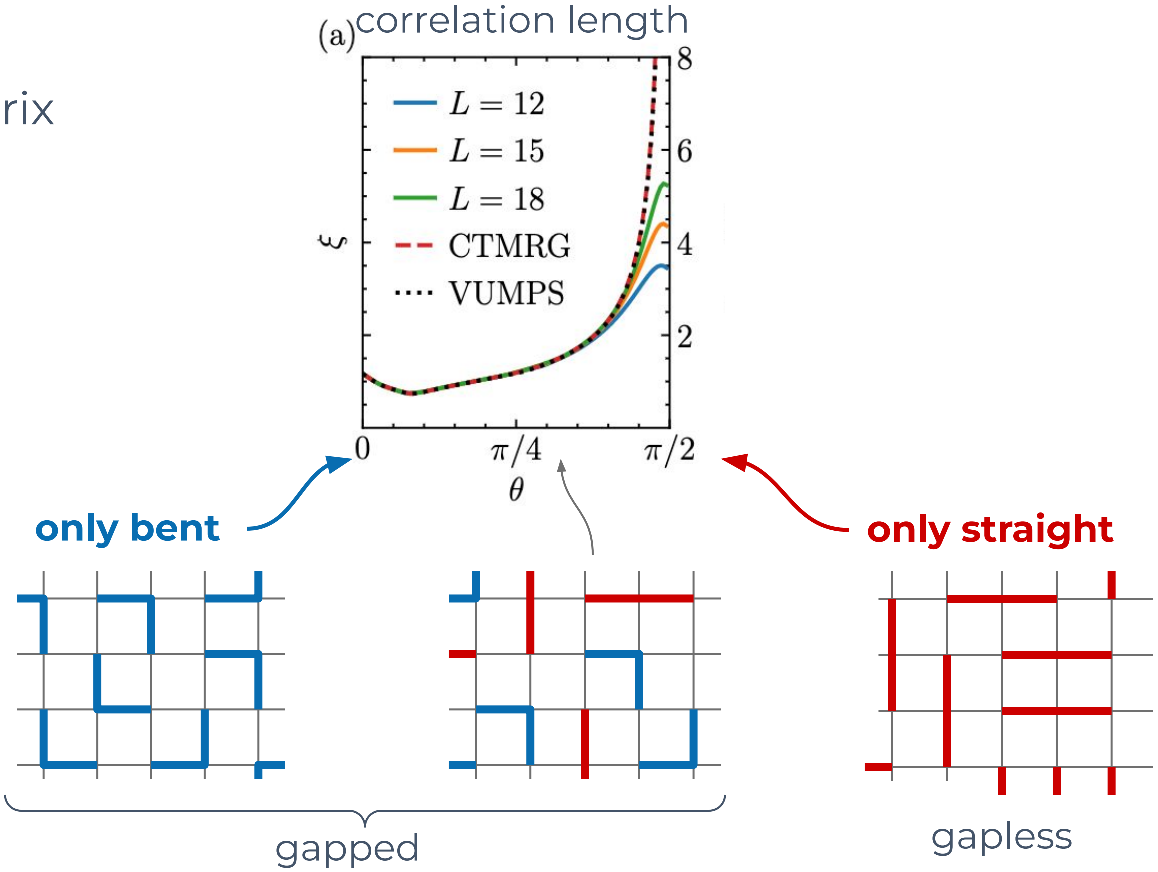

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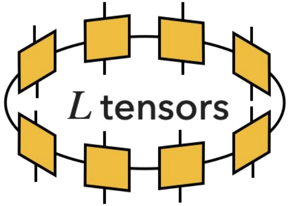
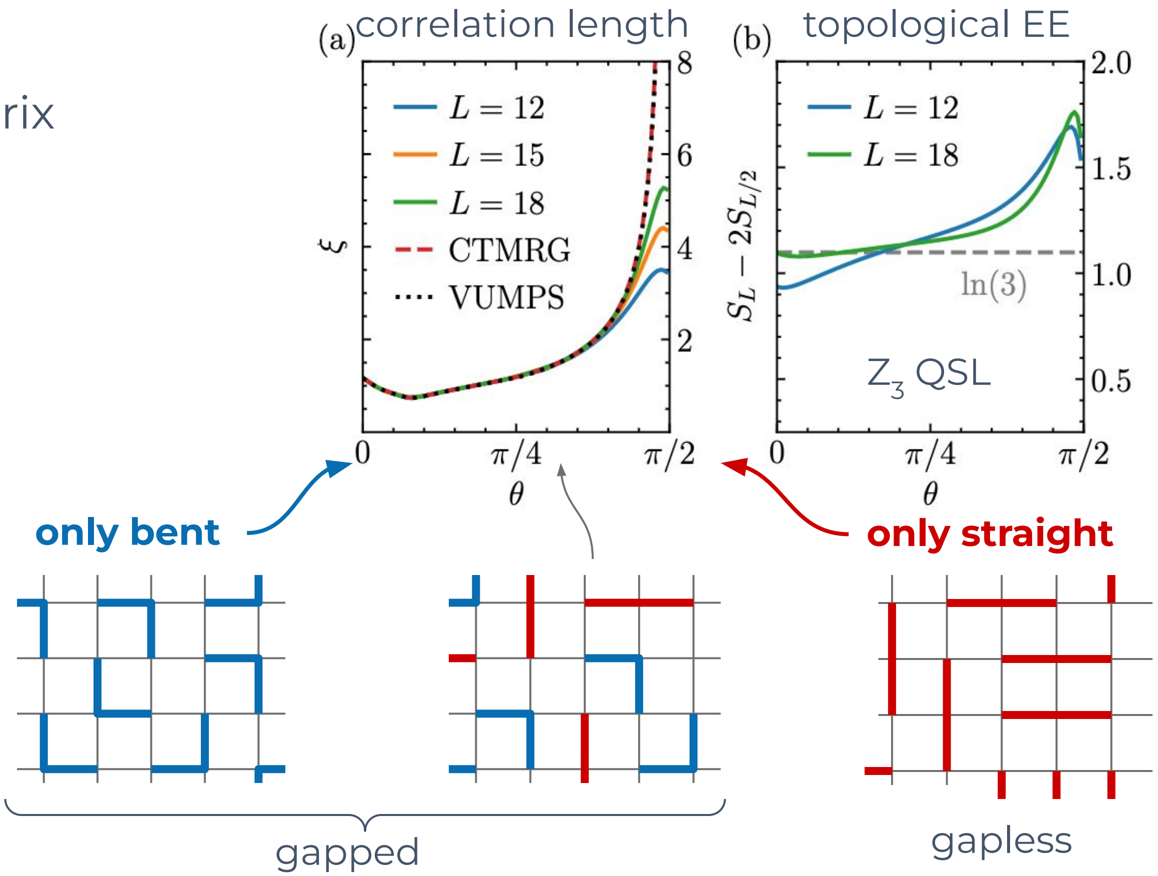
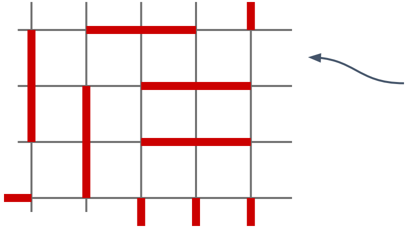




GAPLESS CASE



Why is it gapless?

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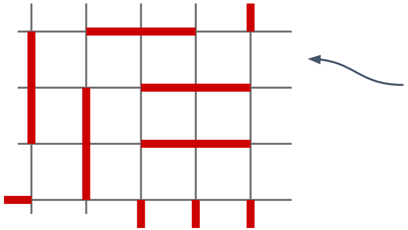
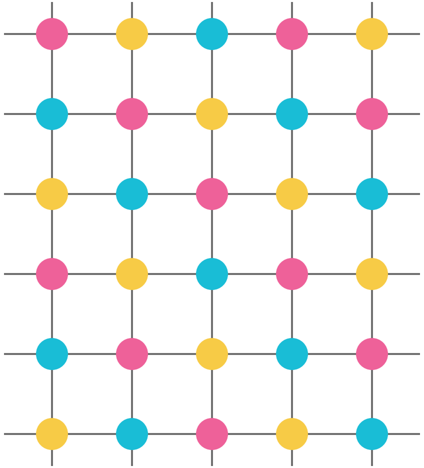


Why is it gapless?

3 sublattices: A, B, C



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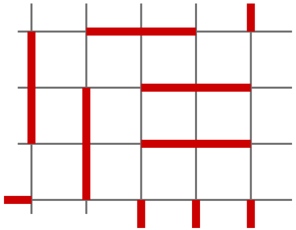

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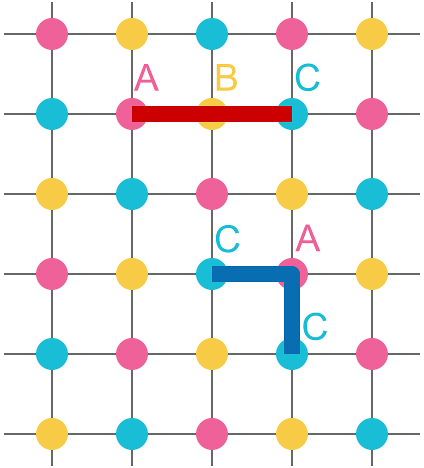

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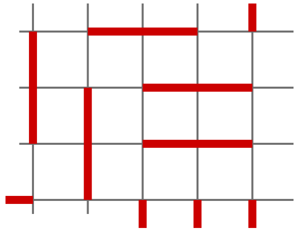

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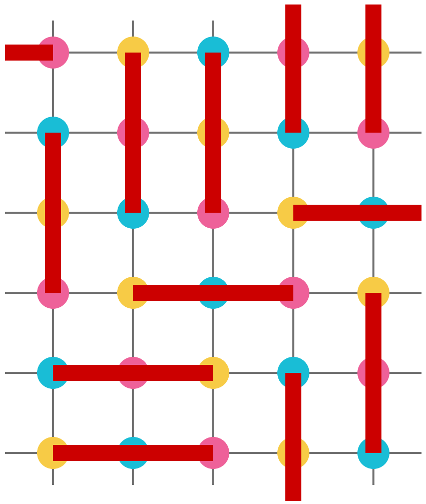

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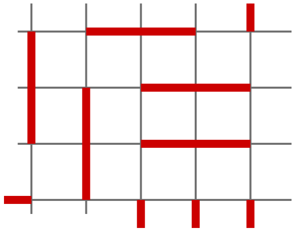

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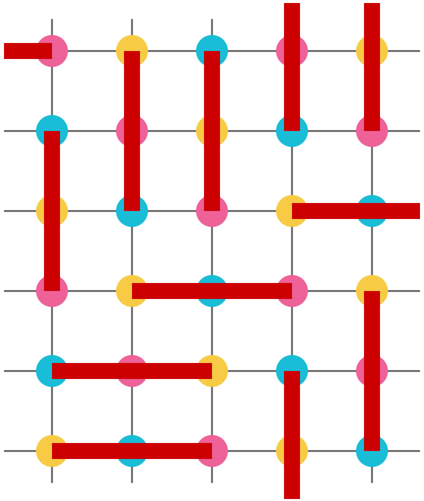
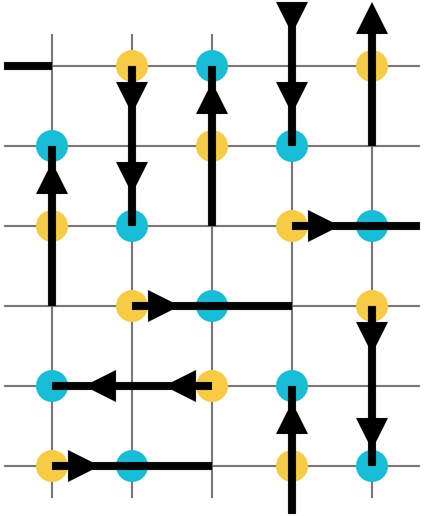
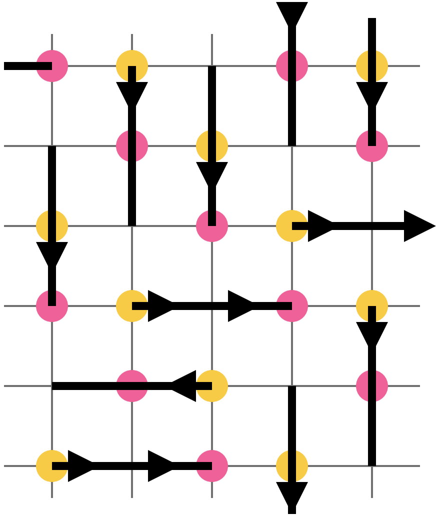


Electric field 1: B→C



Electric field 2: B→A



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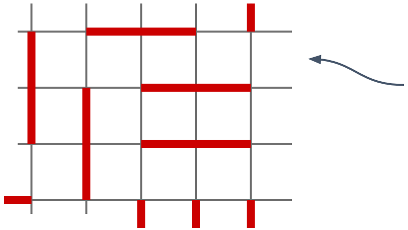

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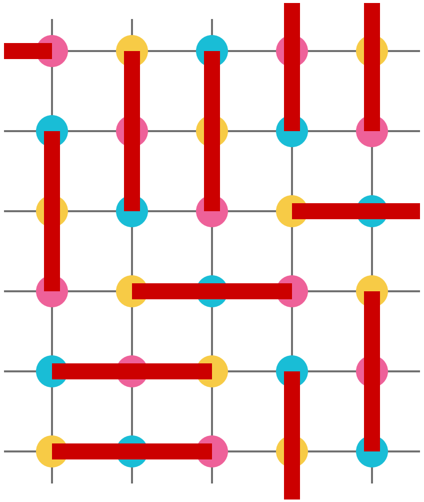
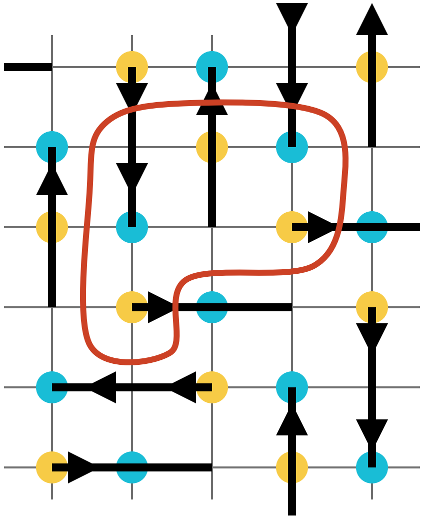


Flux = N_B-N_C

Electric field 1: B→C



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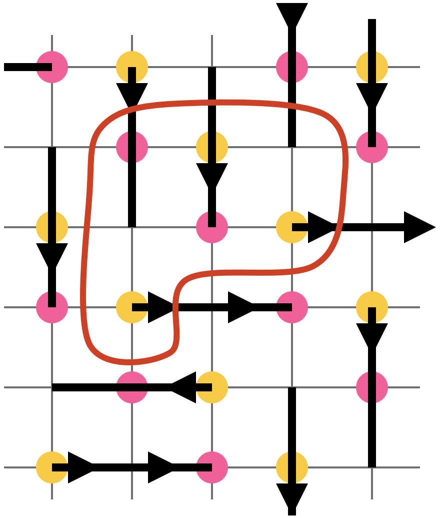

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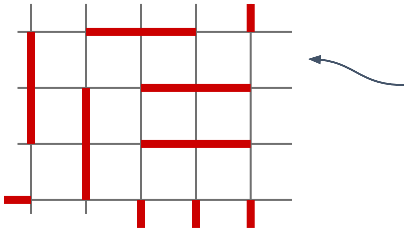
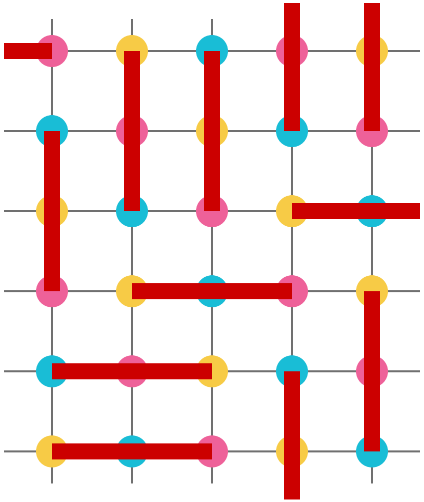


Why is it gapless?

U(1)xU(1) gauge symmetry:
no gapped QSL phase

3 sublattices: A, B, C



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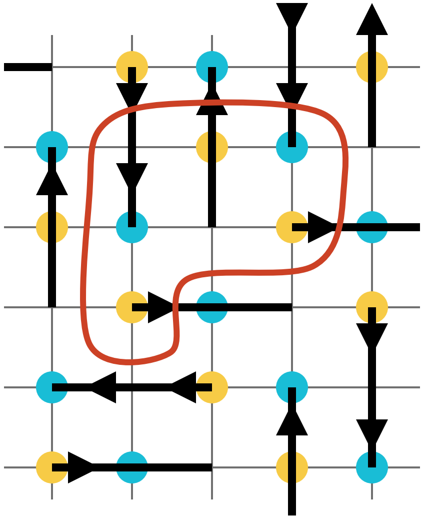

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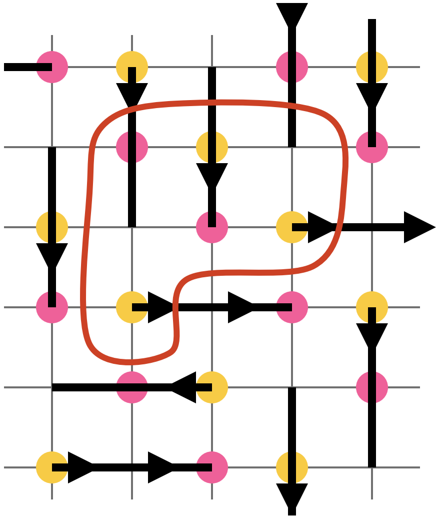

GENERAL CRITERION

Definition:

A trimer model is tripartite if there exist 3 sublattices (A, B, C) such that each trimer touches all 3 sublattices

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Depends both on the lattice and on the shapes of the trimers!

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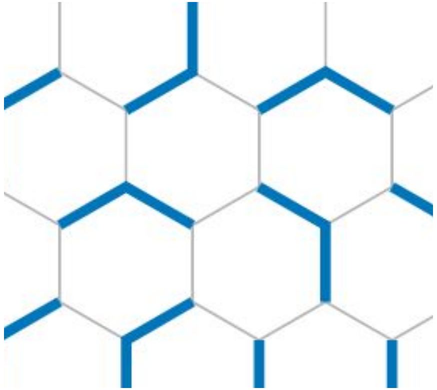
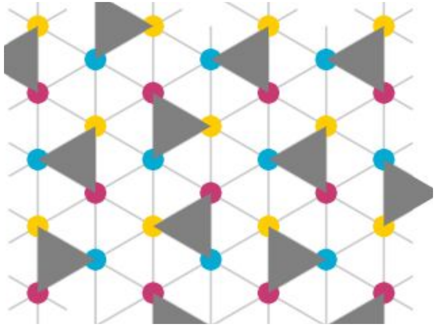
Tripartite trimer models: gapless tRVB

OTHER LATTICES

honeycomb
Z_3 gauge



triangular
U(1)xU(1) gauge



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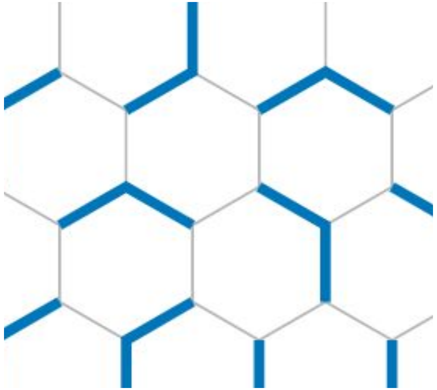

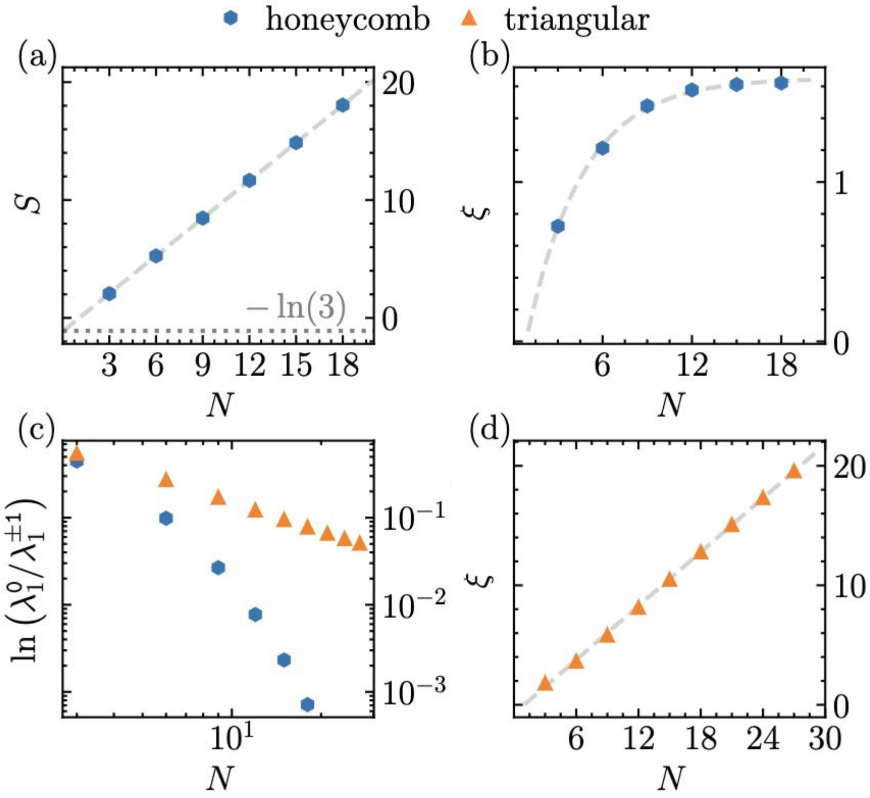

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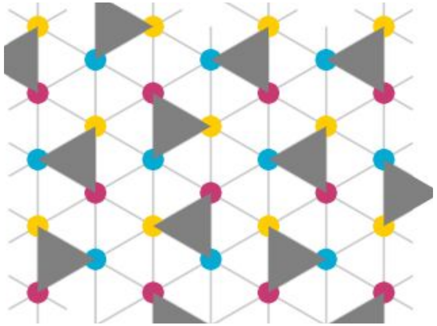

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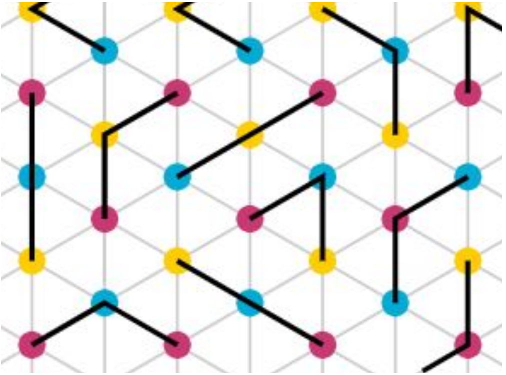
Depends both on the lattice and on the shapes of the trimers!

triangular



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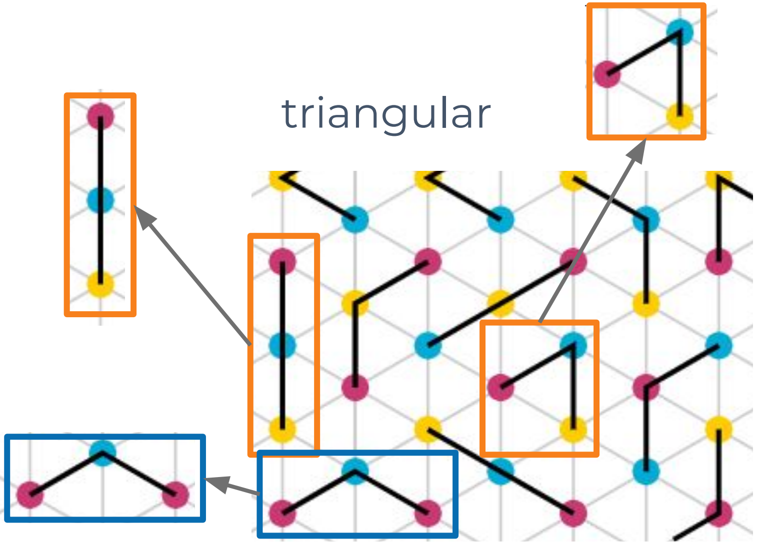

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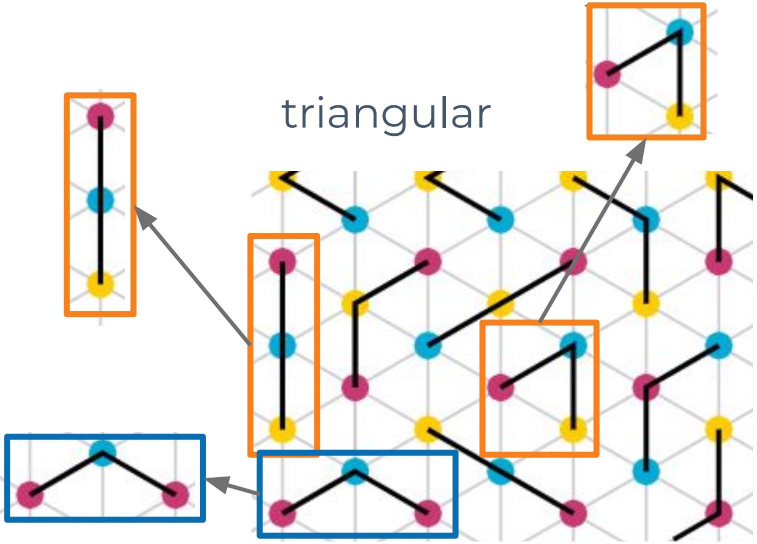
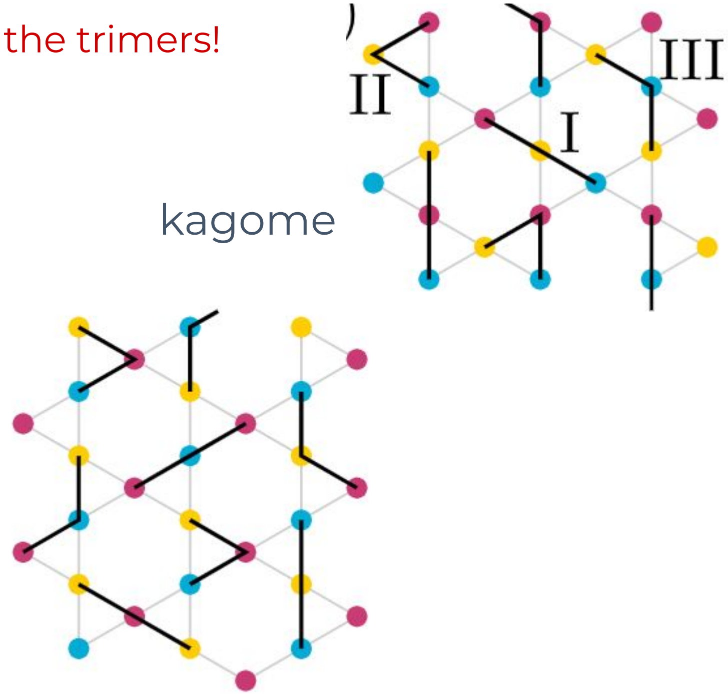


kagome

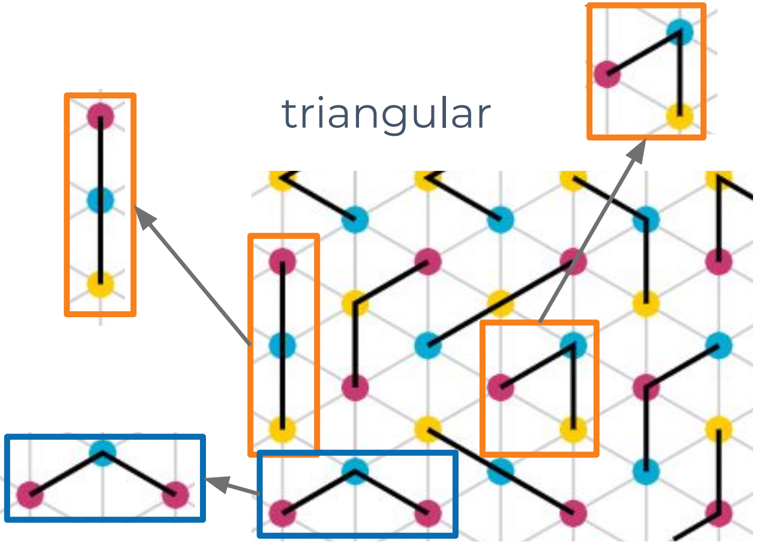


OTHER LATTICES

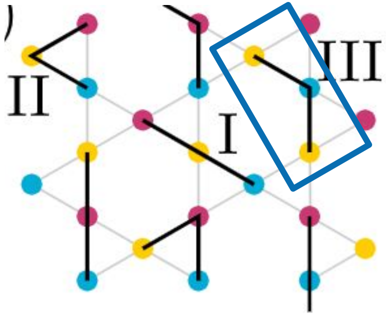
Tripartite trimer models: gapless tRVB

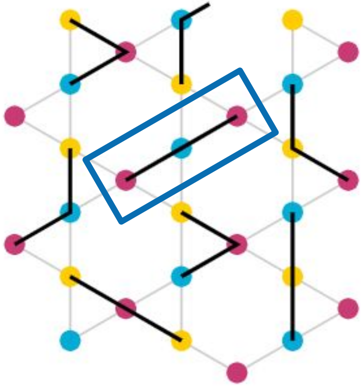
Depends both on the lattice and on the shapes of the trimers!

triangular



kagome

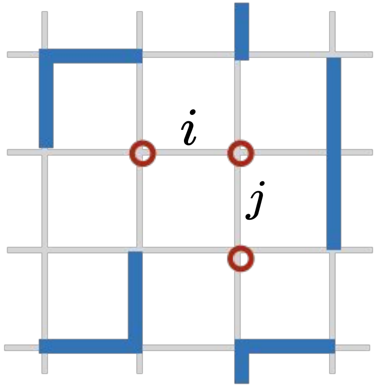




2. DILUTE TRIMER STATE

DILUTE TRIMER STATES

$$|\Phi(t,z)\rangle = \bigotimes_{i,j}(1 + z^2 b_i b_j)|\mathrm{tRVB}(t)\rangle$$



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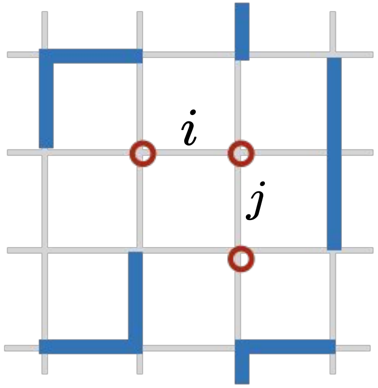
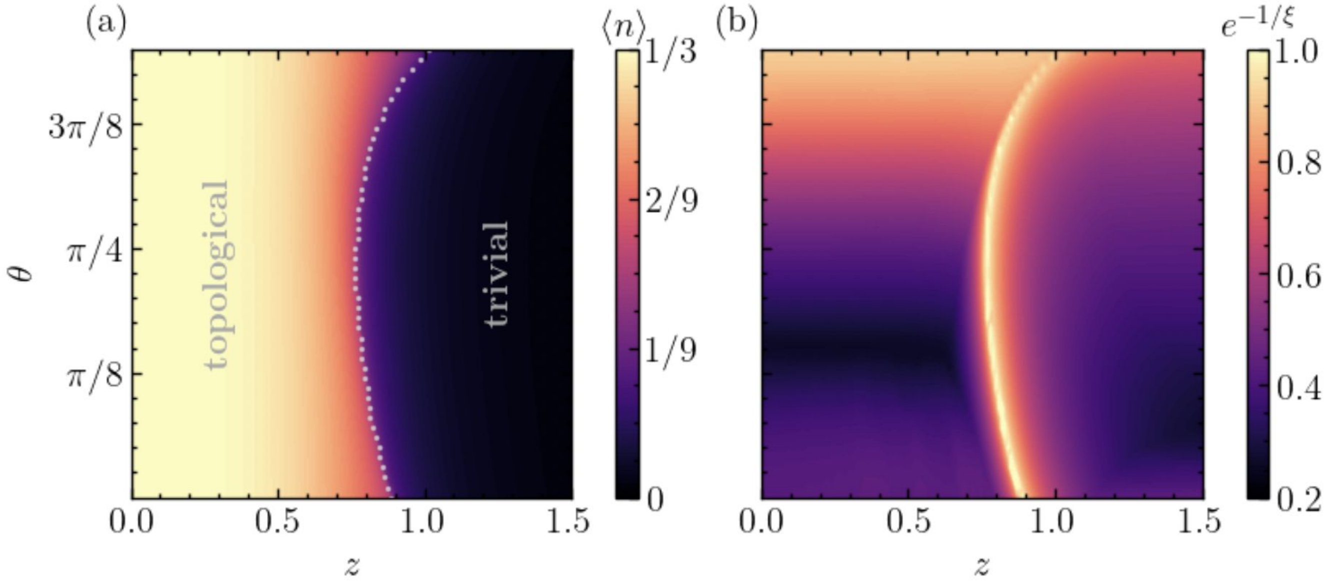


CTMRG results:



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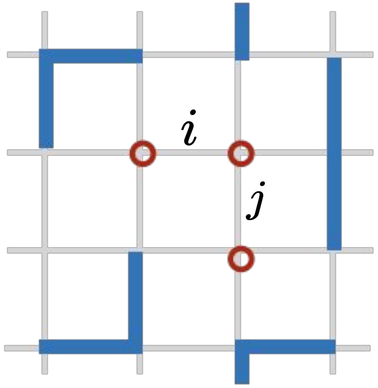

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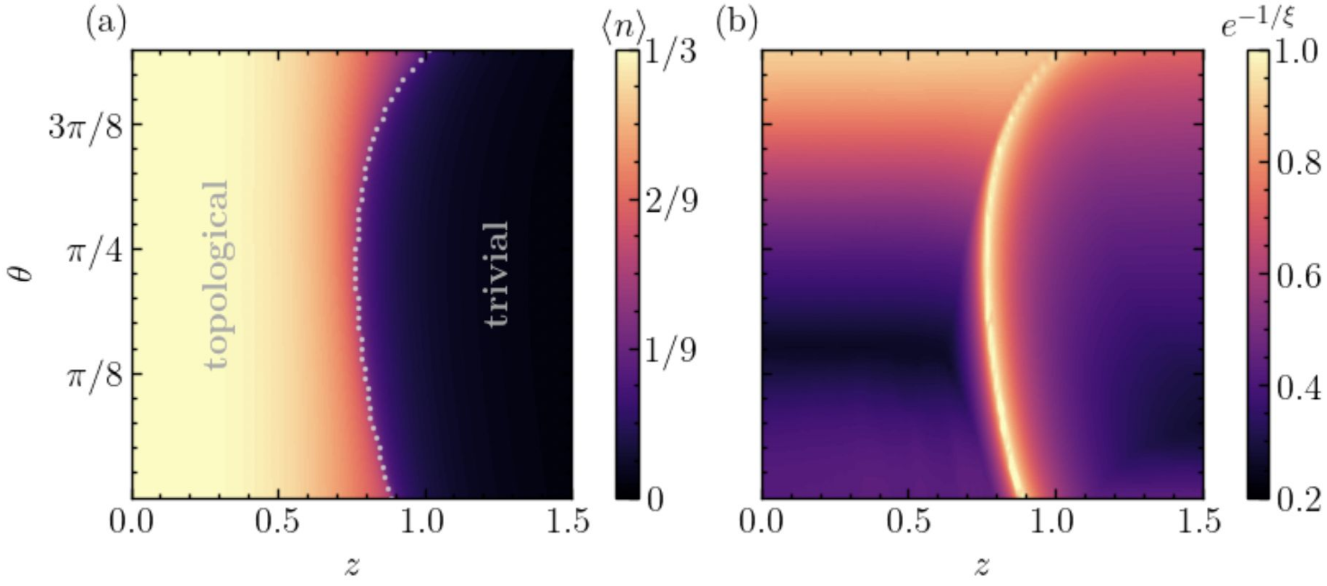

Z_3 topological order is stable against dilution

DILUTE TRIMER STATES

Is there a simple Hamiltonian that has this tRVB as (approximate) ground state?

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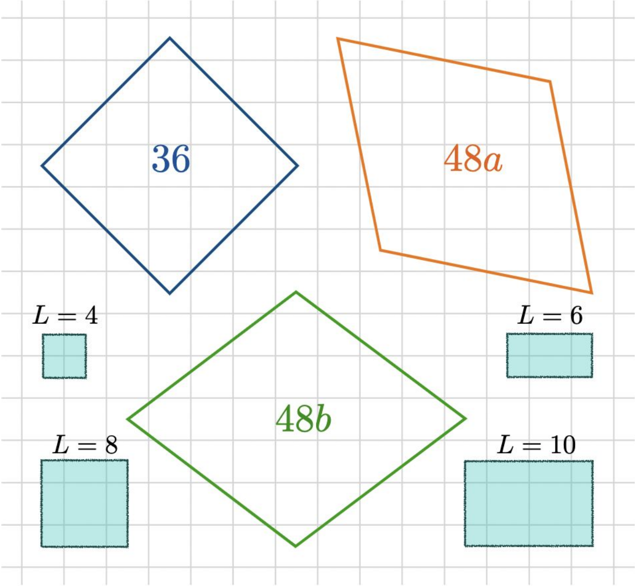
$$H = \frac{\Omega}{2} \sum_{\square} |\square\rangle\langle\square| + \mathrm{h.c.} - \Delta \sum_{\square} |\square\rangle\langle\square| + R_{\frac{\pi}{2}}$$

DILUTE TRIMER STATES

Exact diagonalization on finite systems



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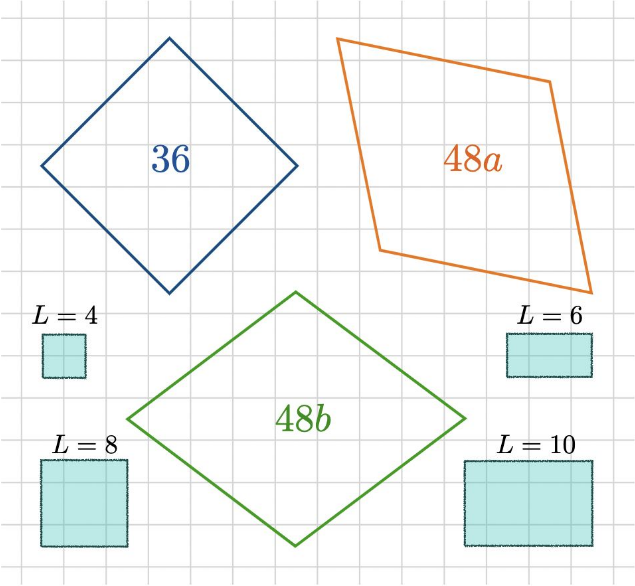

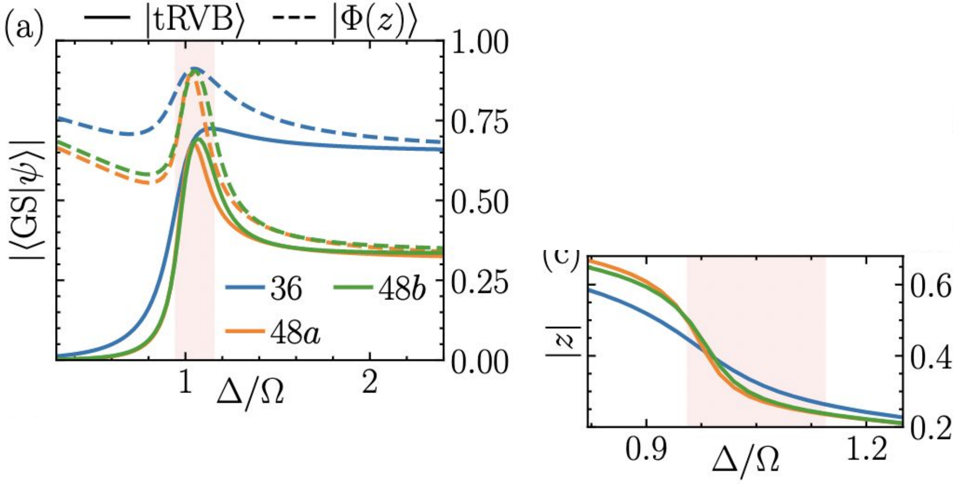

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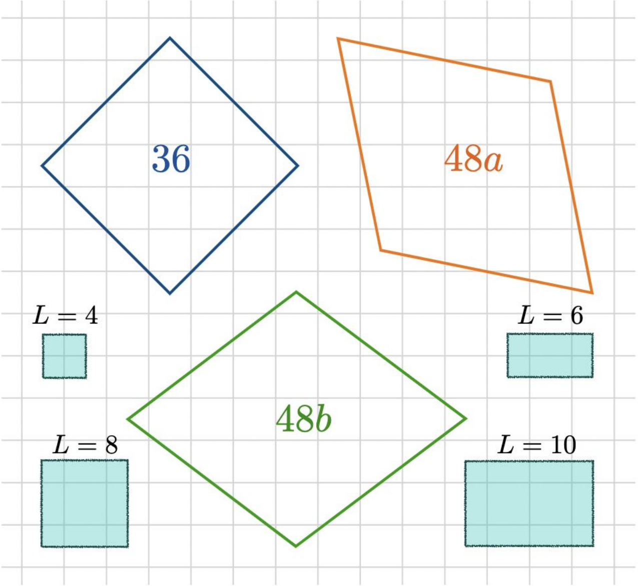

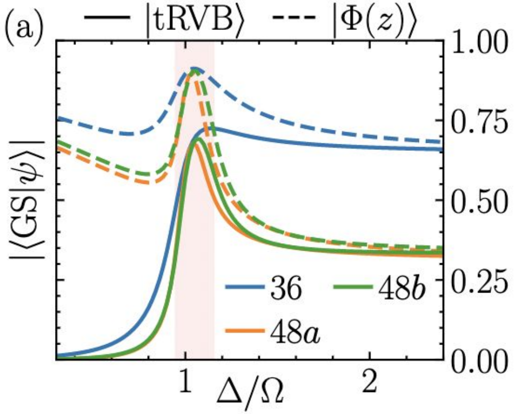

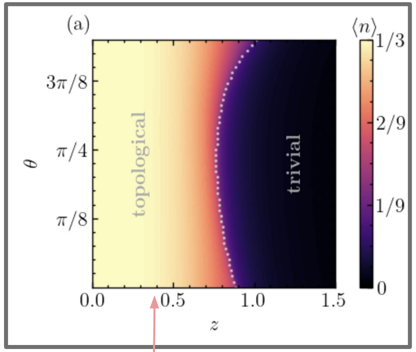

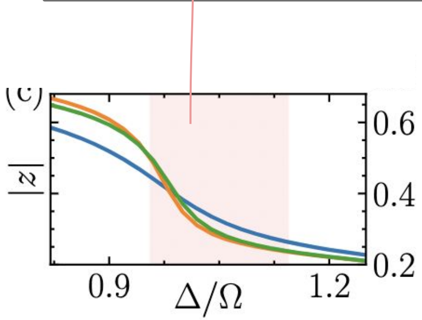

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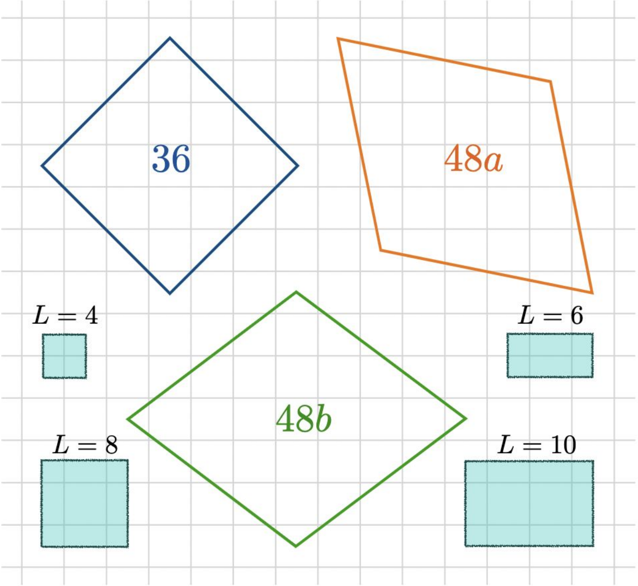

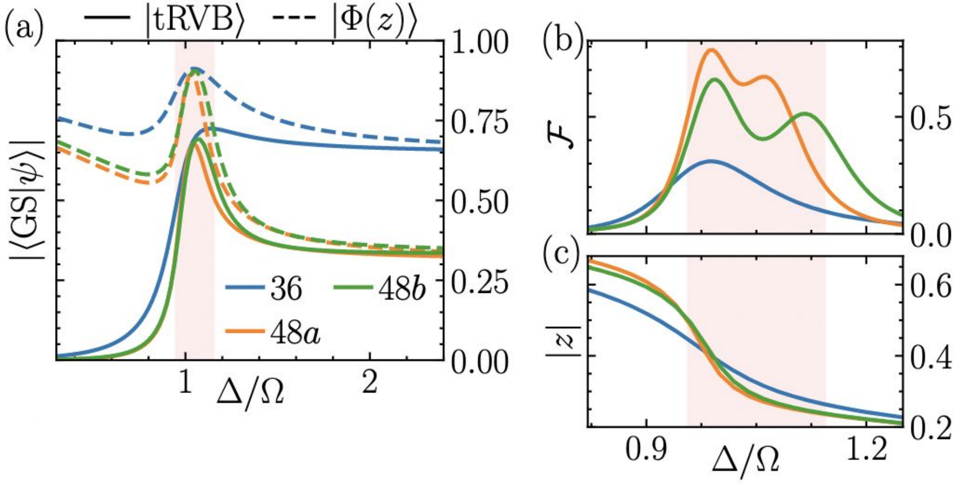

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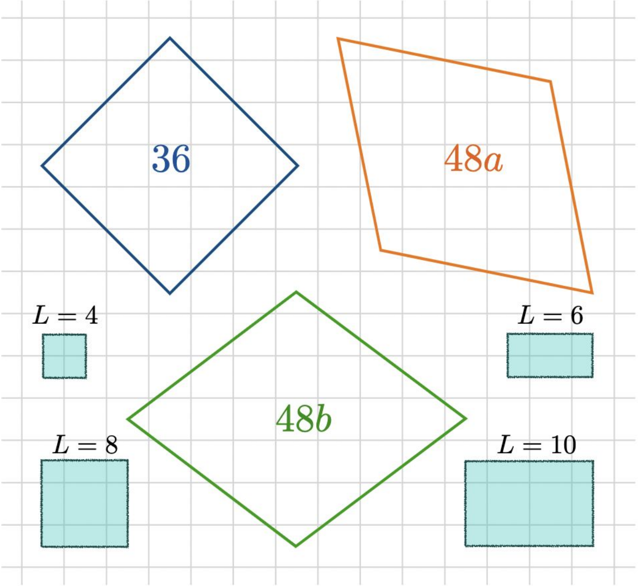

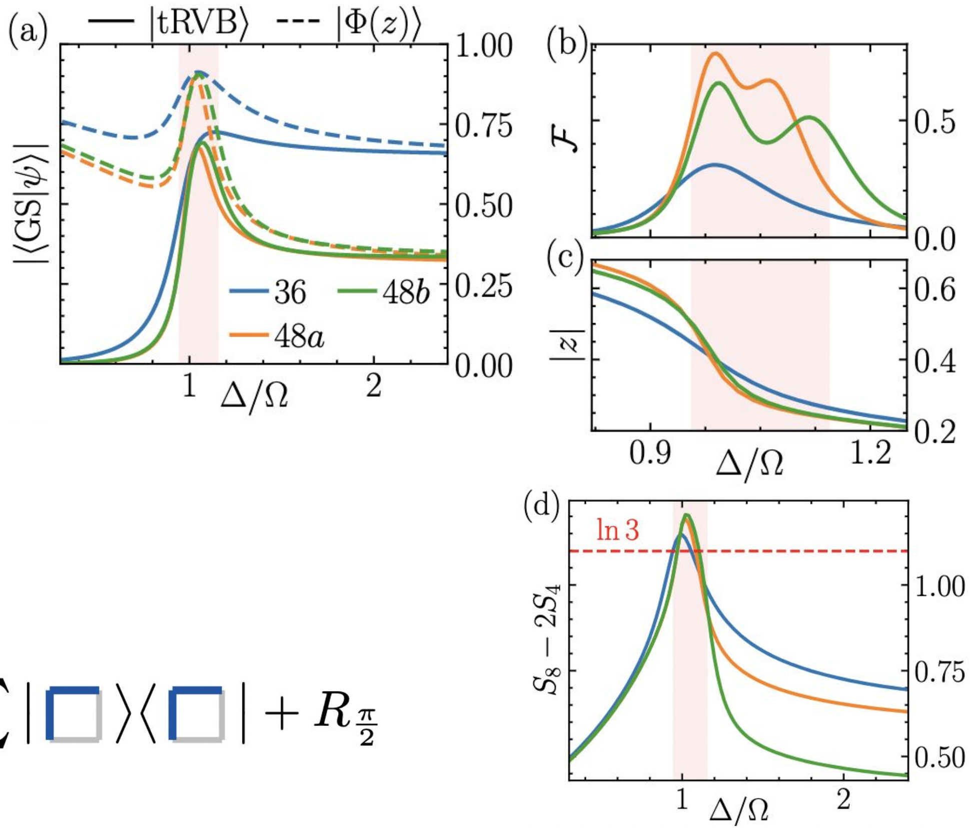

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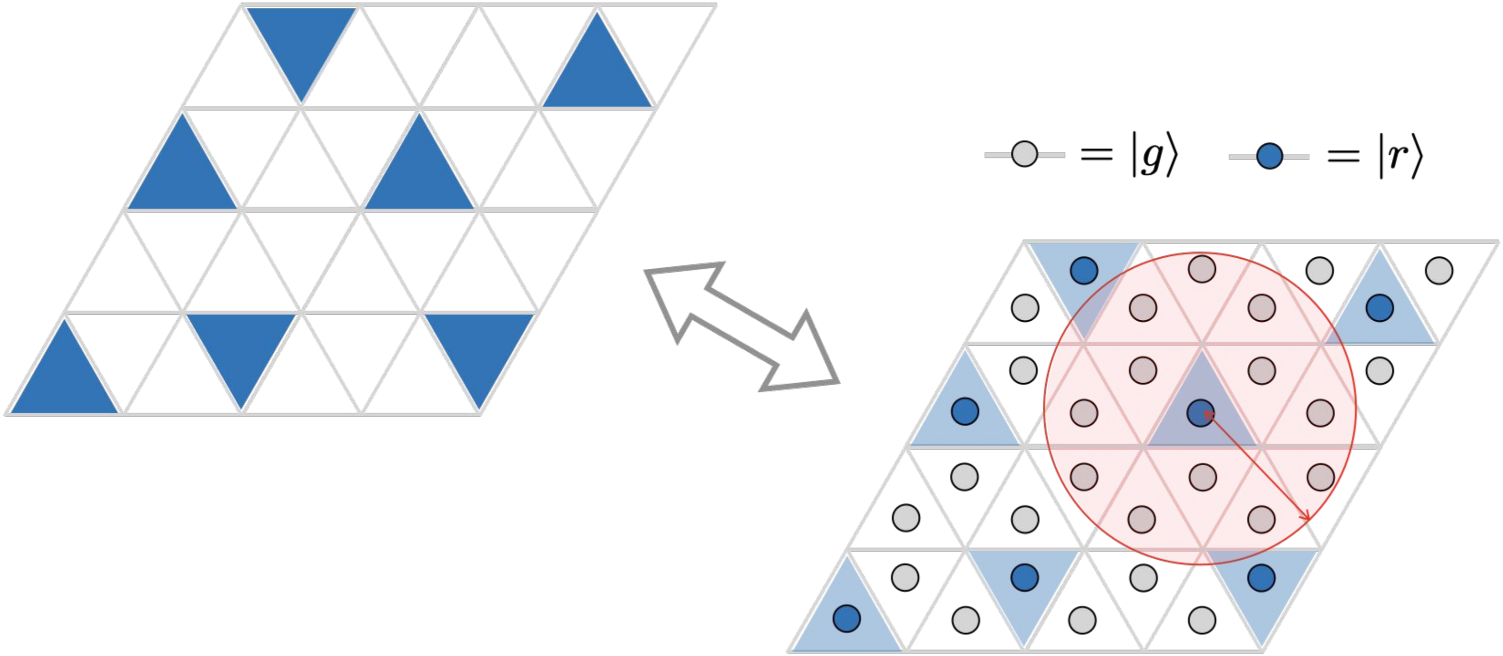
3. RYDBERG IMPLEMENTATION

RYDBERG IMPLEMENTATION

Honeycomb lattice



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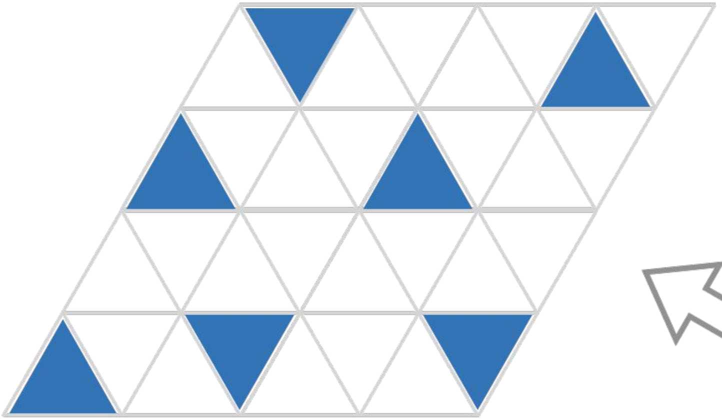
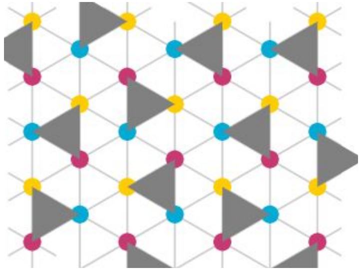
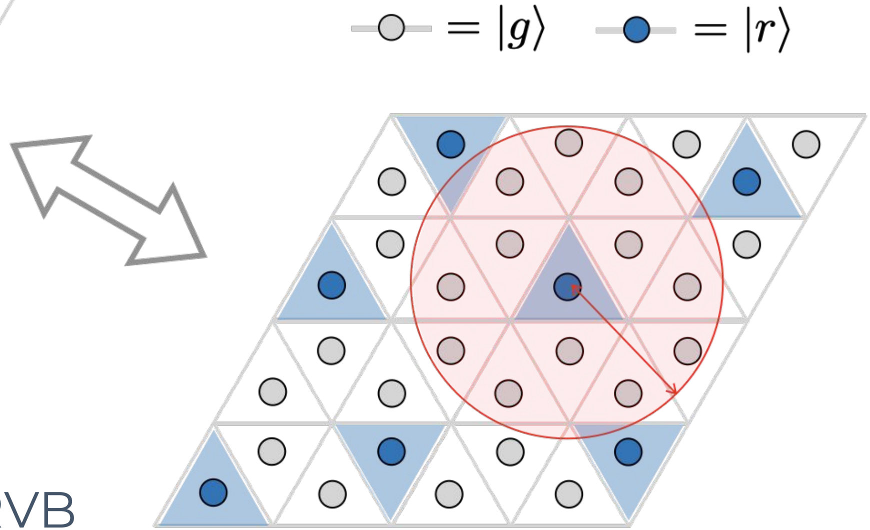




✗ Gapless tRVB



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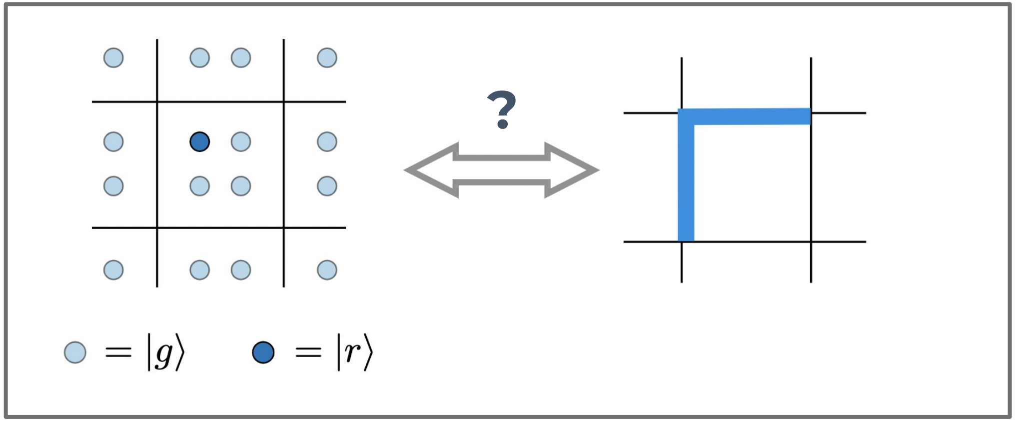

How to obtain trimer constraint from Rydberg blockade?

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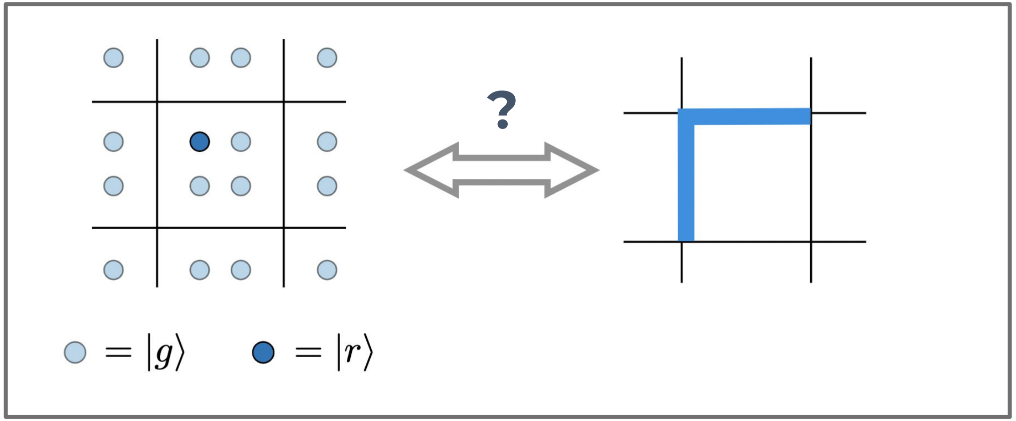

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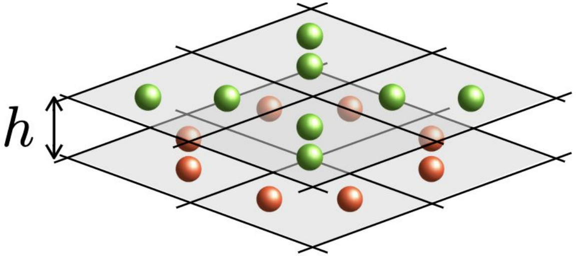
Idea:
two planes



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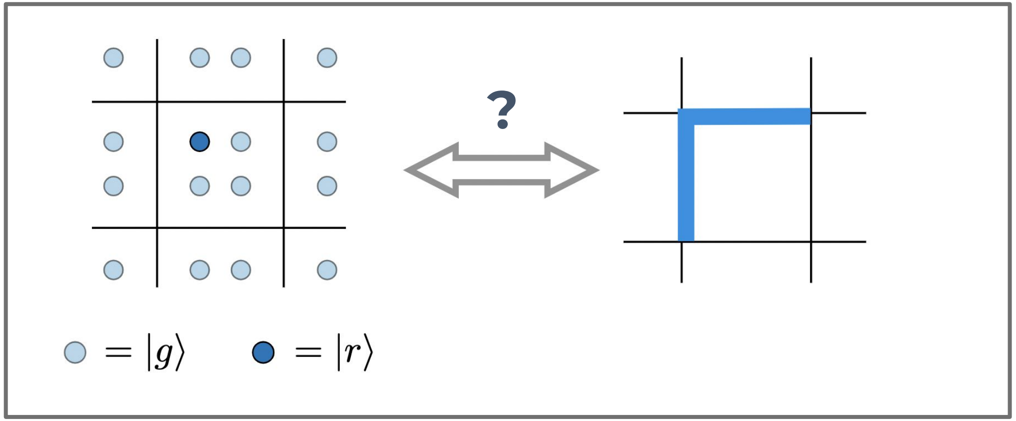

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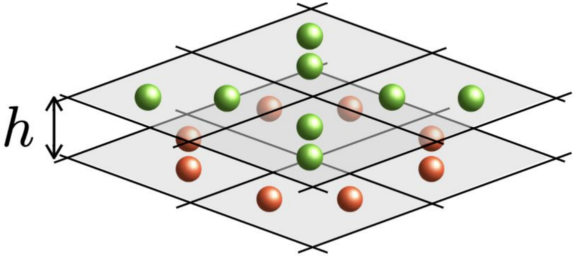
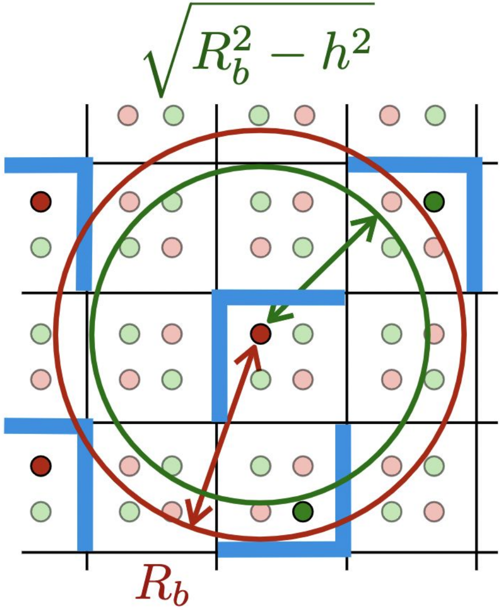
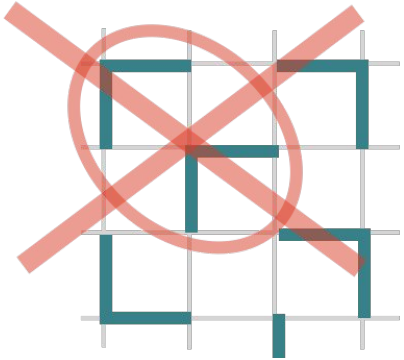




RYDBERG IMPLEMENTATION

Not exactly the same as trimer constraint!



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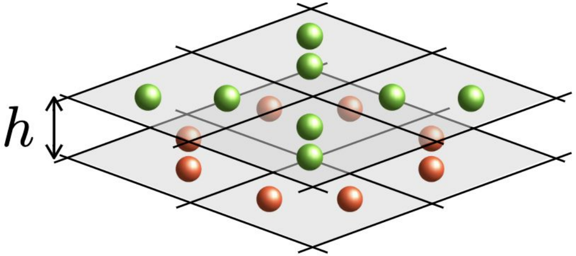

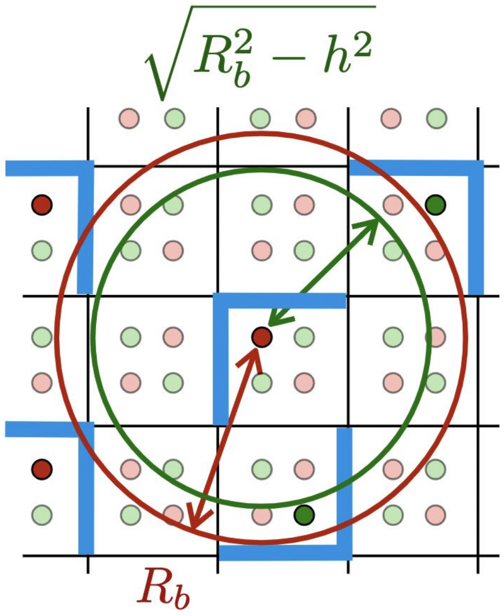

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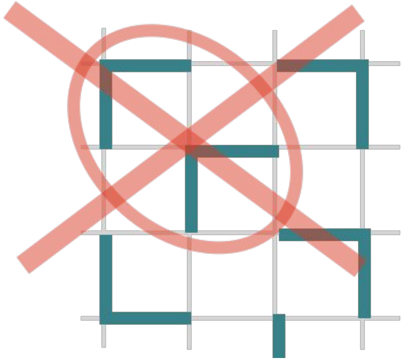

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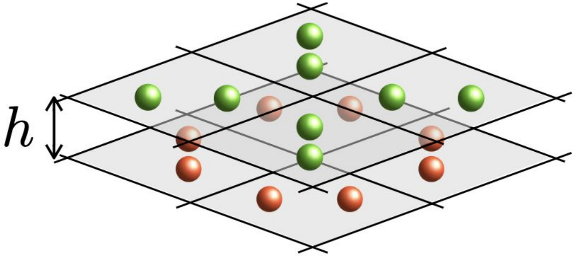

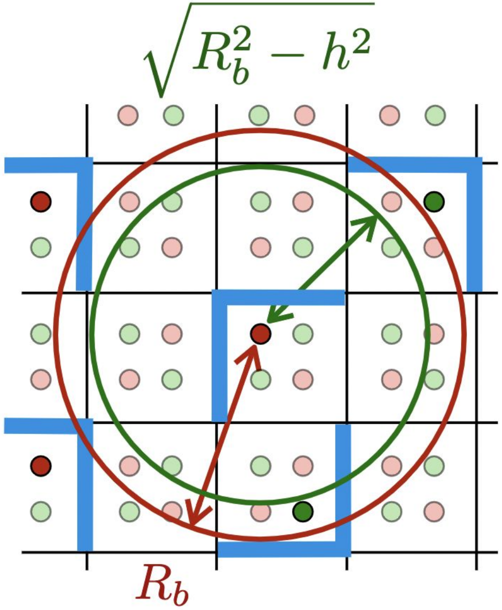

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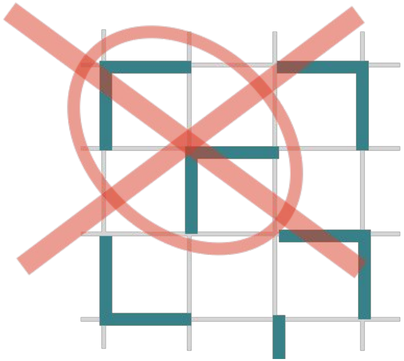

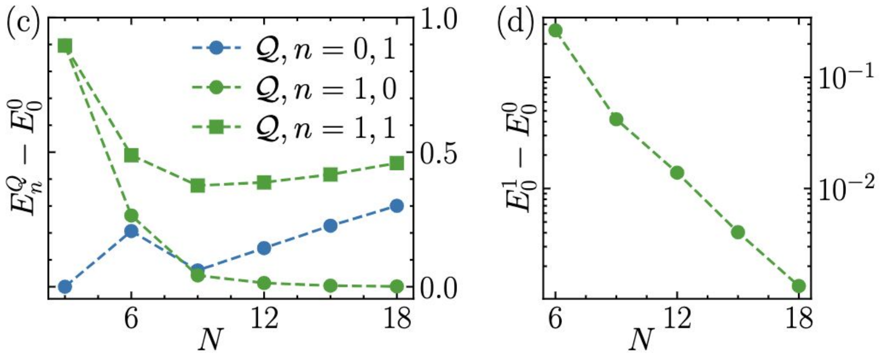

Yes! But with larger correlation length

$$\xi \simeq 1.7$$

CONCLUSIONS AND OUTLOOK

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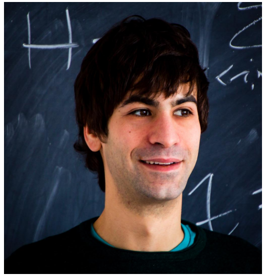
G. Giudice

H. Pichler



G. Giudici

Trimer states with Z_3 topological order, *in preparation*

THANK YOU FOR YOUR ATTENTION!

DYNAMICAL PREPARATION