RVB STATES IN RYDBERG ATOM ARRAYS

Giuliano Giudici

28/02/2022

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

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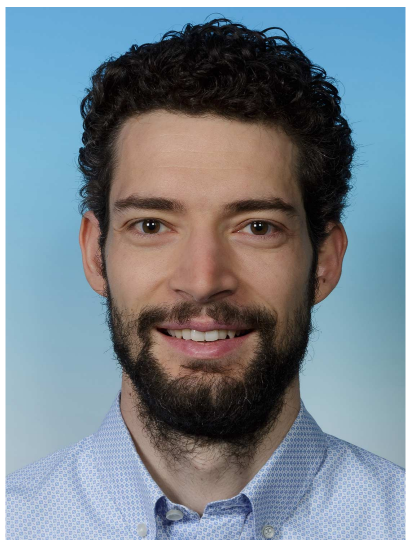
ACKNOWLEDGEMENTS



Hannes
(IQOQI)

Misha
(Harvard)

Giacomo
(MPQ)

Federica
(Caltech)

OUTLINE

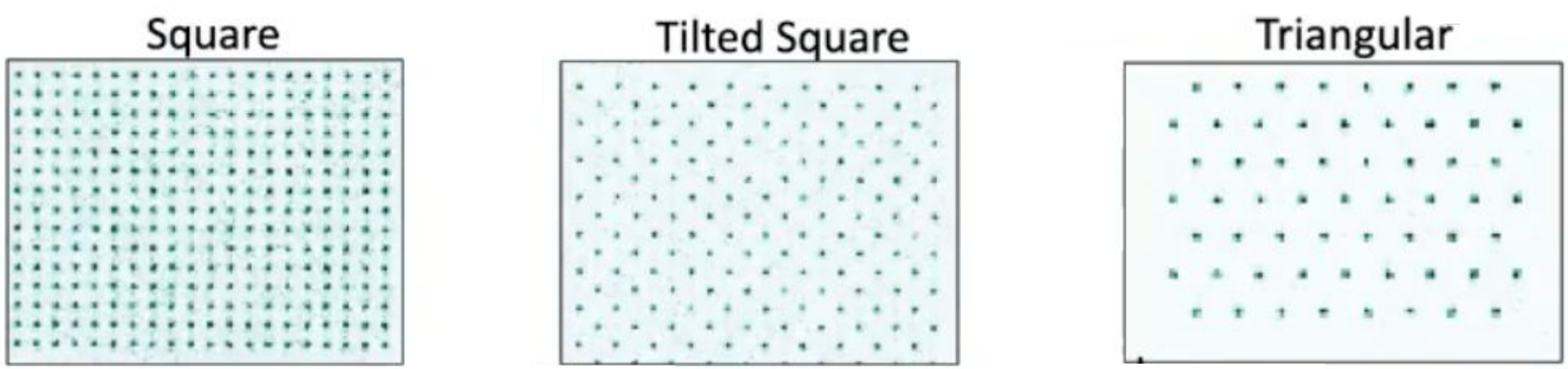
- Rydberg atom arrays as quantum simulators
- Resonating valence bond states (RVB) of dimers in Rydberg atom arrays

arXiv:2201.04034

- Generalization: resonating valence bond states of trimers (tRVB)
- tRVB states with Rydberg atom arrays

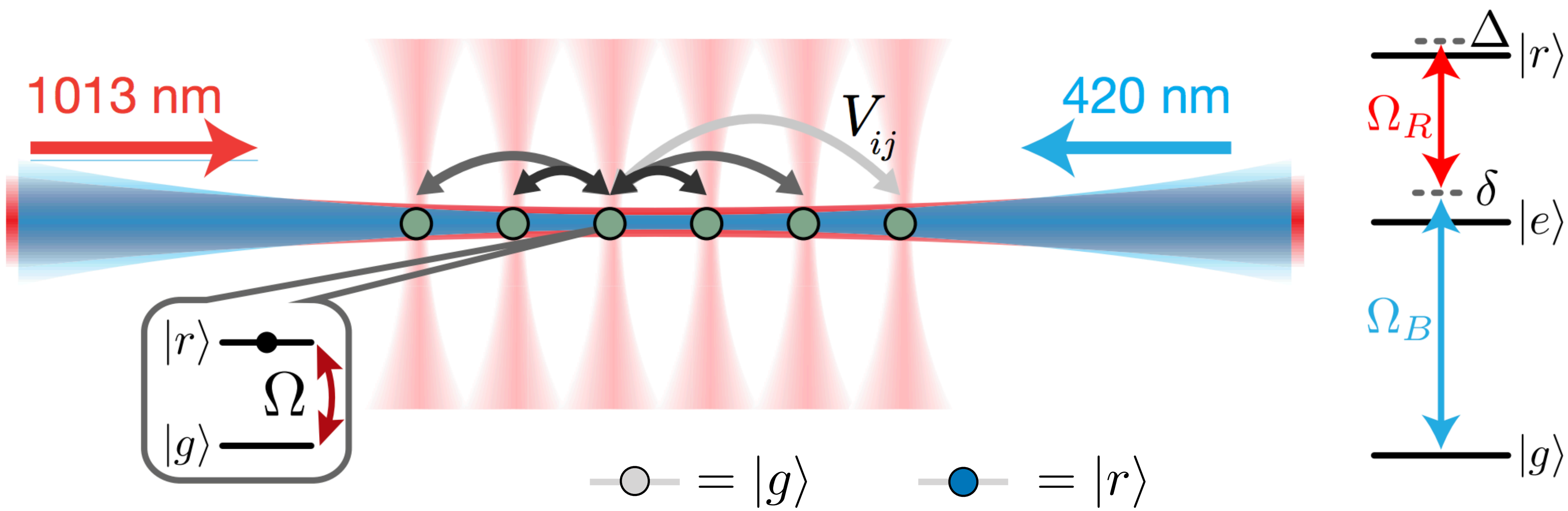
WHAT ARE RYDBERG ATOM ARRAYS?

- Neutral atoms
- Optically trapped into predefined lattice geometries
- Encode a qubit into two electronic states of each atom



T Wang, H Levine, A Keesling, G Semeghini, A Omran, S Ebadi, D Bluvstein, M Greiner, V Vuletic, MD Lukin, 2020

RYDBERG ATOMS HAMILTONIAN



H Bernien, S Schwartz, A Keesling, H Levine, A Omran, H Pichler, S Choi, AS Zibrov, M Endres, M Greiner, V Vuletić, MD Lukin, 2017

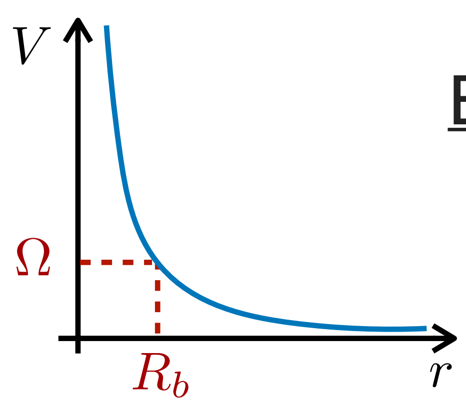
$$H = \frac{\Omega}{2} \sum_{\mathbf{i}} \sigma_{\mathbf{i}}^{x} - \Delta \sum_{\mathbf{i}} n_{\mathbf{i}} + \sum_{\mathbf{i},\mathbf{j}} V(|\mathbf{i}-\mathbf{j}|) n_{\mathbf{i}} n_{\mathbf{j}}$$

$$\sim \frac{1}{|\mathbf{i}-\mathbf{j}|^6}$$

RYDBERG ATOMS HAMILTONIAN

$$H = \frac{\Omega}{2}\sum_{\mathbf{i}} \sigma^x_{\mathbf{i}} - \Delta \sum_{\mathbf{i}} n_{\mathbf{i}} + \sum_{r \leq R_b}^{|\mathbf{i}-\mathbf{j}|=r} V(r) n_{\mathbf{i}} n_{\mathbf{j}} + \sum_{r > R_b}^{|\mathbf{i}-\mathbf{j}|=r} V(r) n_{\mathbf{i}} n_{\mathbf{j}}$$

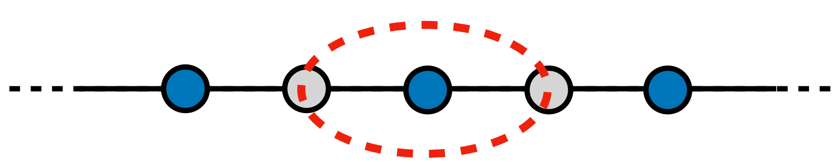
$\simeq \infty$



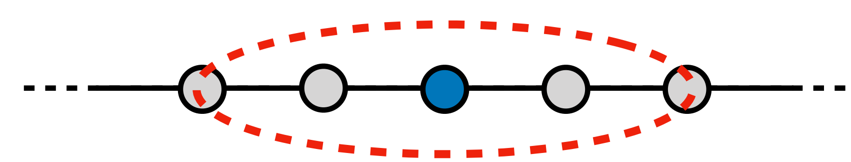
Blockade radius : $V(R_b) := \Omega$

tunable by varying lattice spacing!

- 1D :

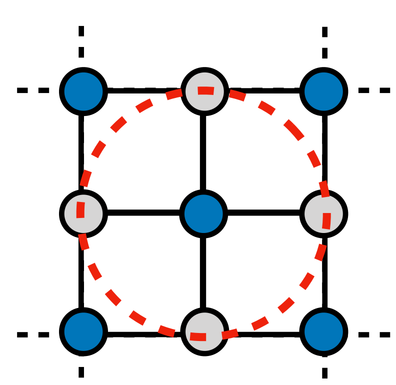


$R_b = 1$

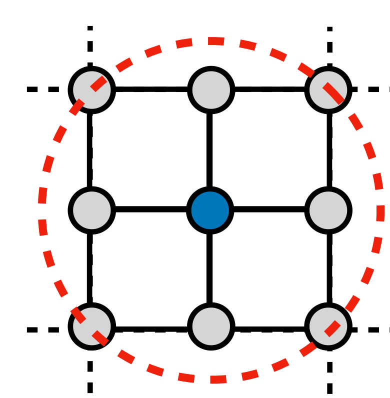


$R_b = 2$

- 2D :



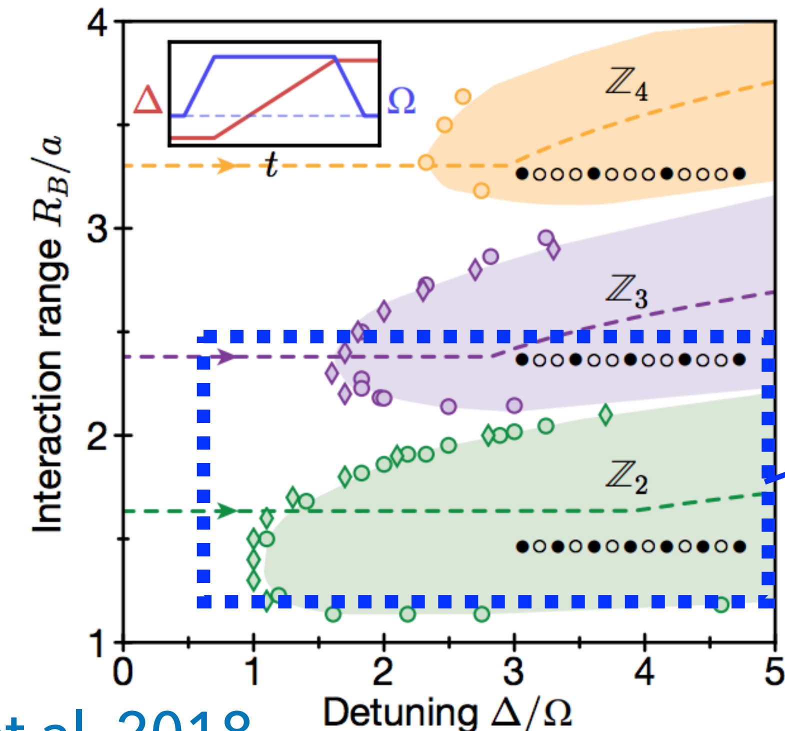
$R_b = 1$



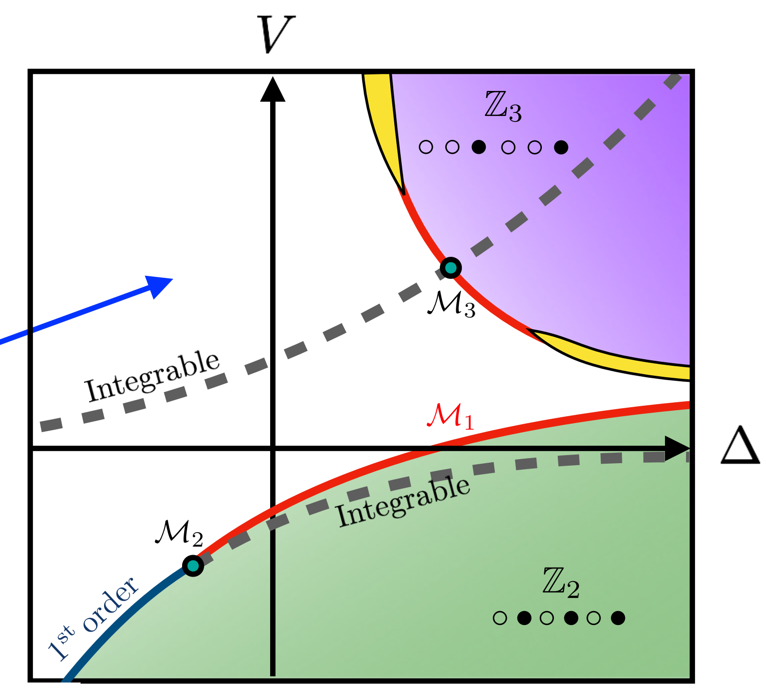
$R_b = \sqrt{2}$

1D : IN & OUT OF EQUILIBRIUM

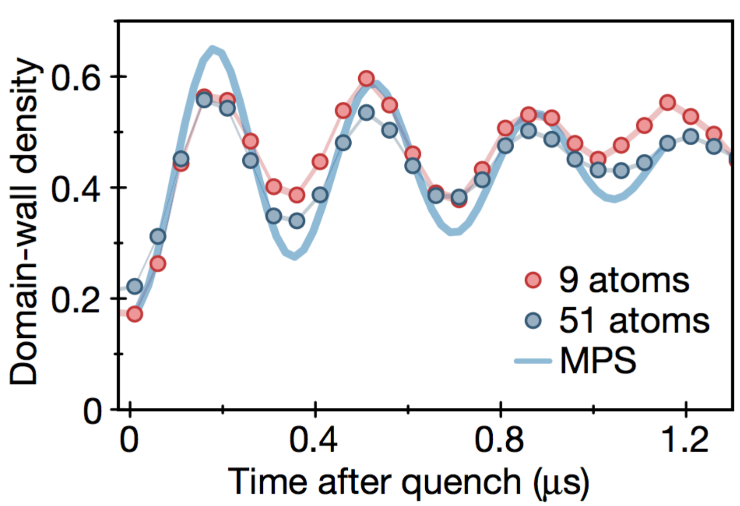
- 1D criticality: CFT universality and beyond



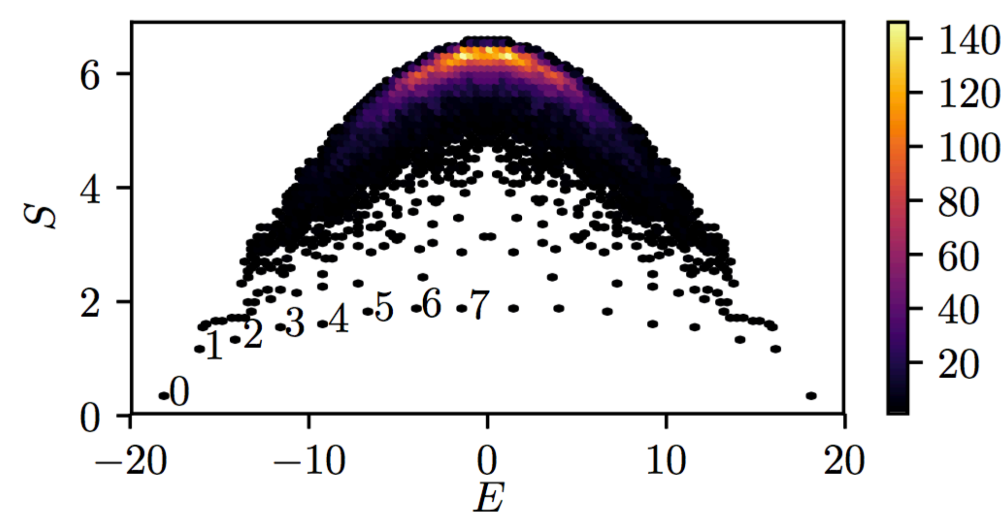
A Keesling et al, 2018



- Slow dynamics: many-body quantum scars



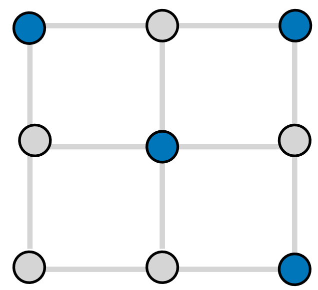
H Bernien et al, 2017



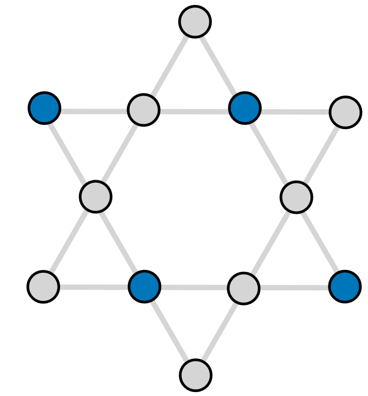
CJ Turner et al, 2017

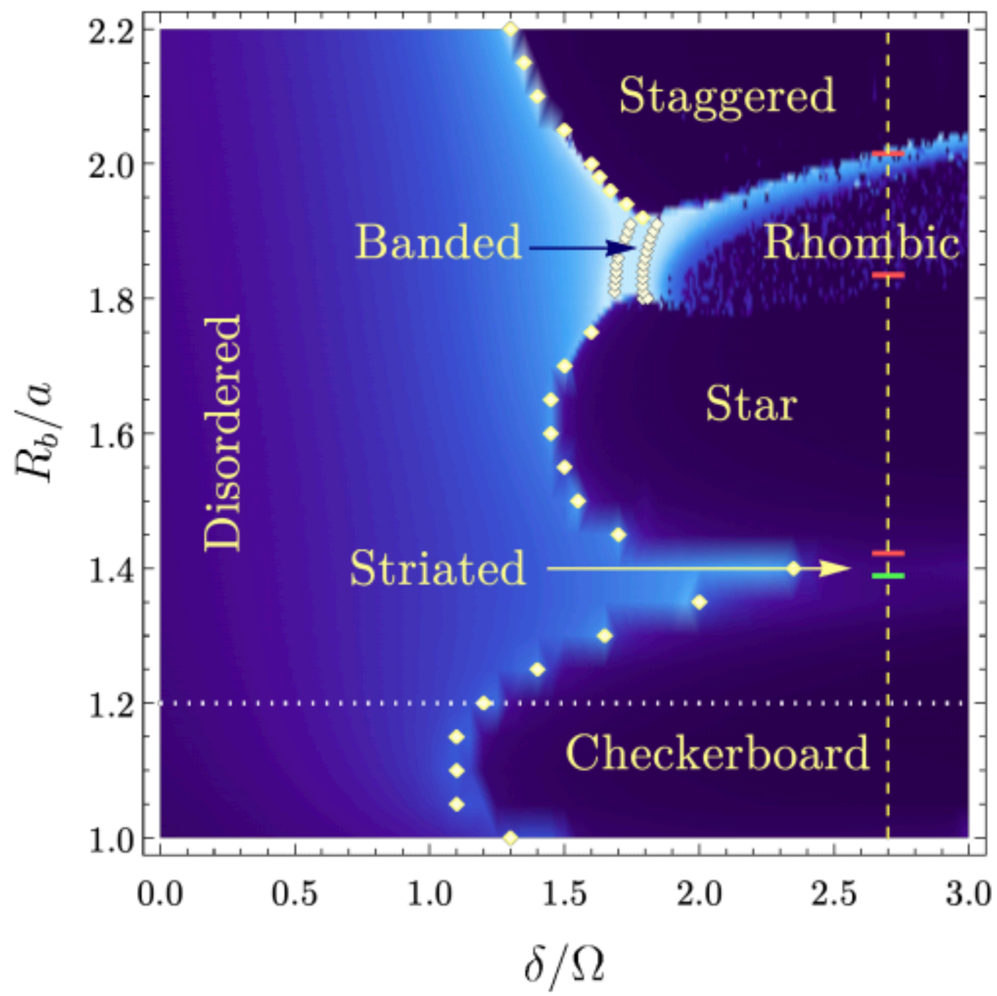
2D : IN EQUILIBRIUM

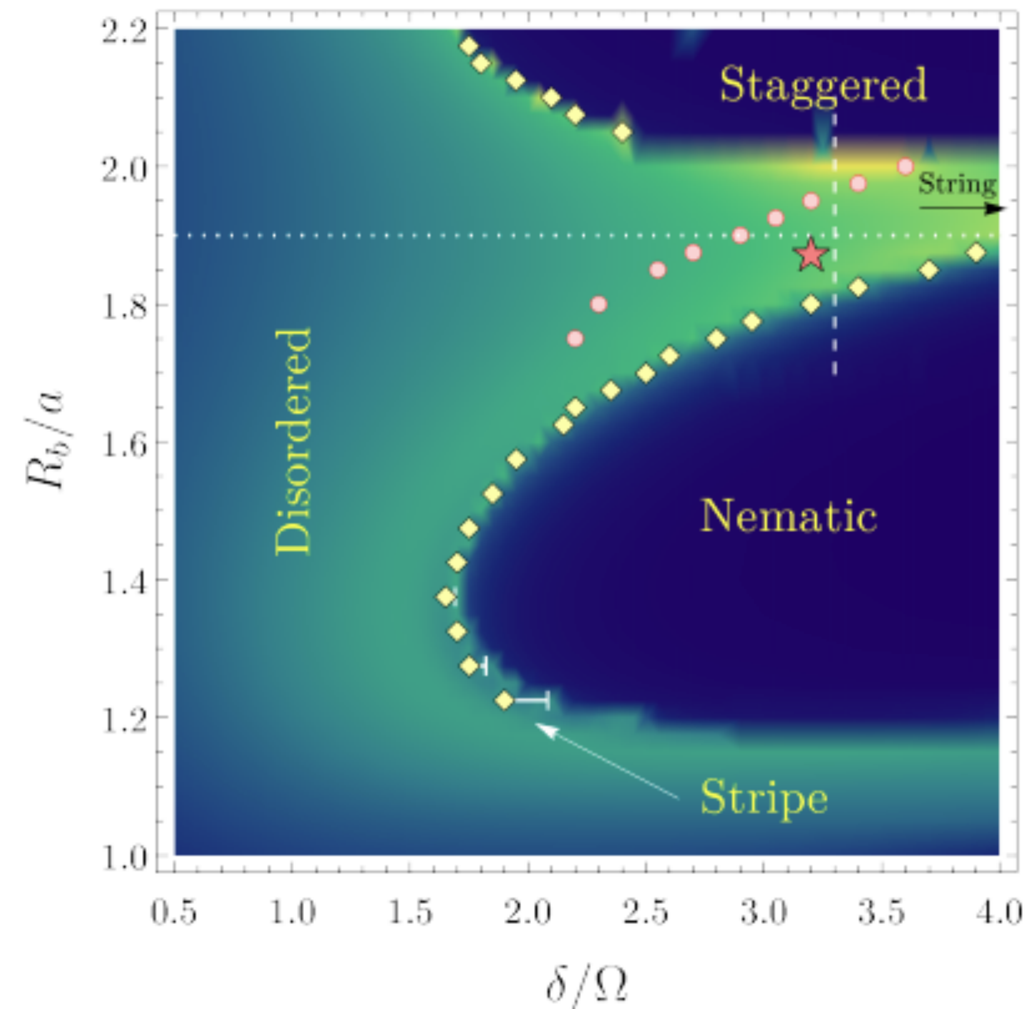
Square



Kagome





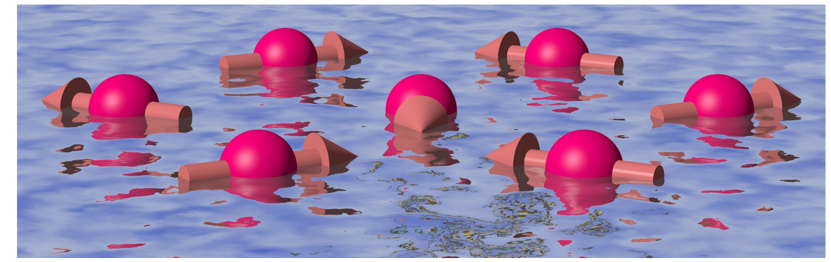


*All **classically** ordered phases.. anything **quantum** ordered?*

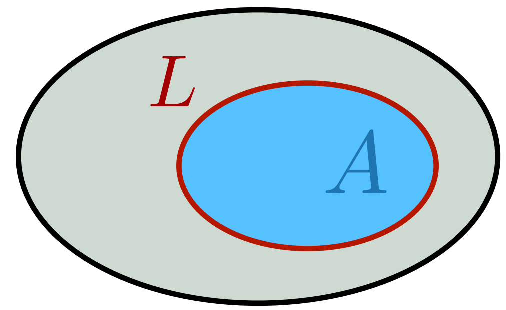
R Samajdar, WW Ho, H Pichler, MD Lukin, S Sachdev, 2019, 2020

QUANTUM SPIN LIQUIDS

- No symmetry breaking

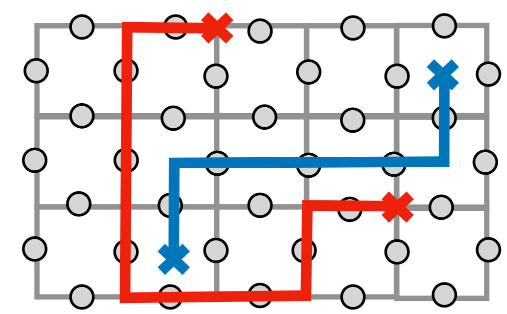


- Long range entanglement

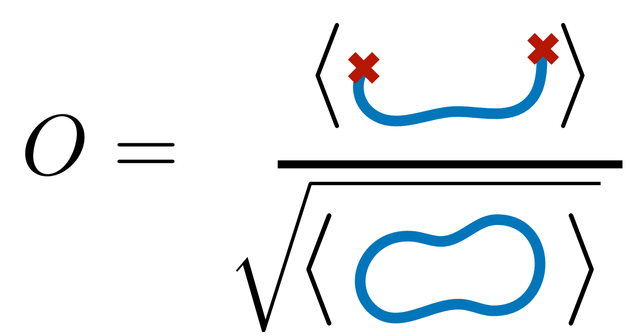


$$S_A = \alpha L - \gamma$$

- Non-local excitations

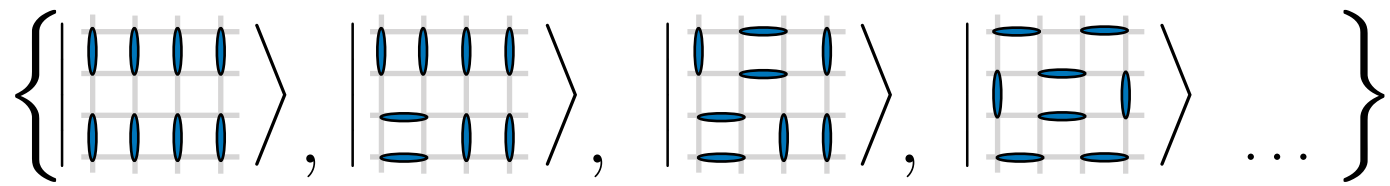


- Emergent deconfined gauge fields



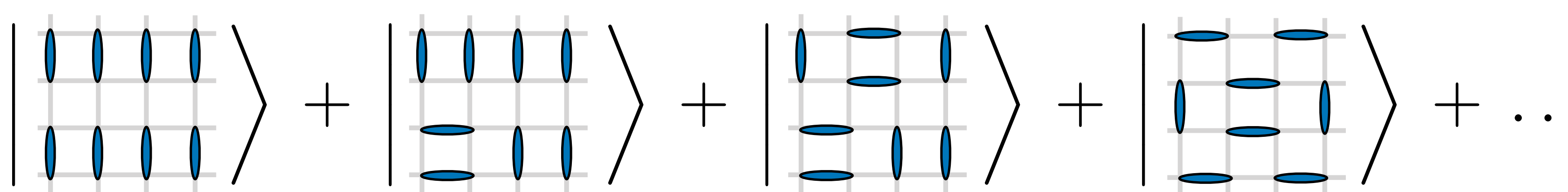
- Non-local order parameters

RVB STATES IN DIMER MODELS

- Dimer model : $\mathcal{H} =$ 

- Resonating valence bond (RVB) state:

  equal weight superposition of all dimer coverings

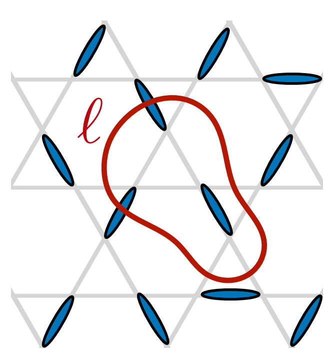
$|\mathrm{RVB}\rangle =$ 

Simplest representative of quantum spin liquid state

Non-bipartite lattice

- Finite correlation length
- $\mathbb{Z}_2$ Gauss' law

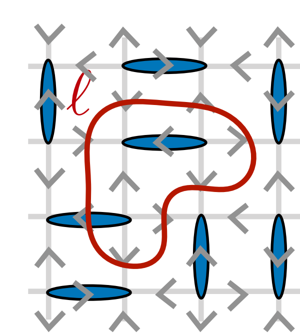
$$\prod_{i\in\ell} Z_i = (-1)^{N_v}$$



Bipartite lattice

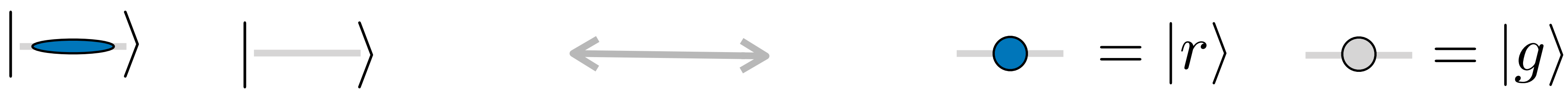
- Infinite correlation length
- $U(1)$ Gauss' law

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

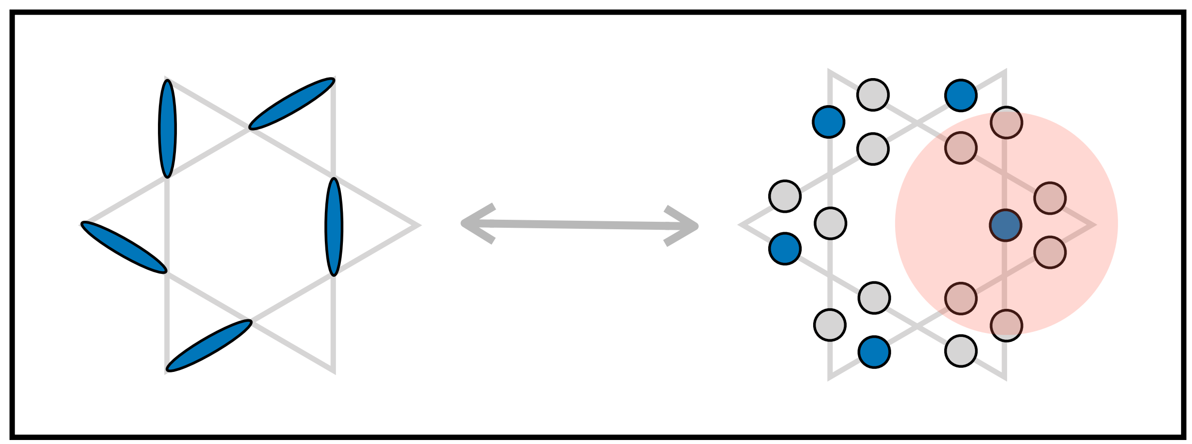


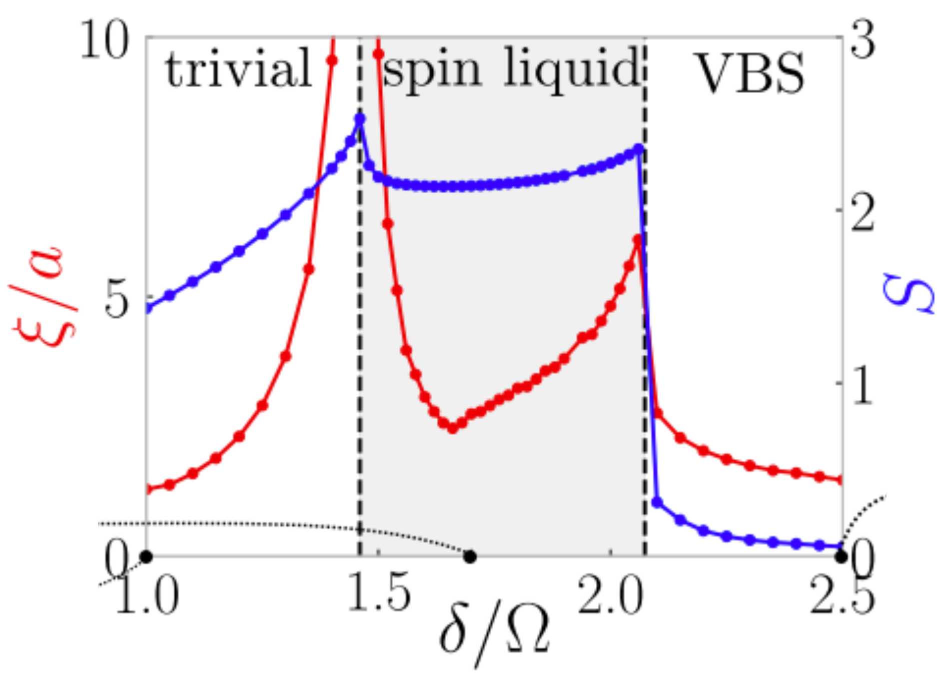
DIMER MODELS & RYDBERG ATOMS

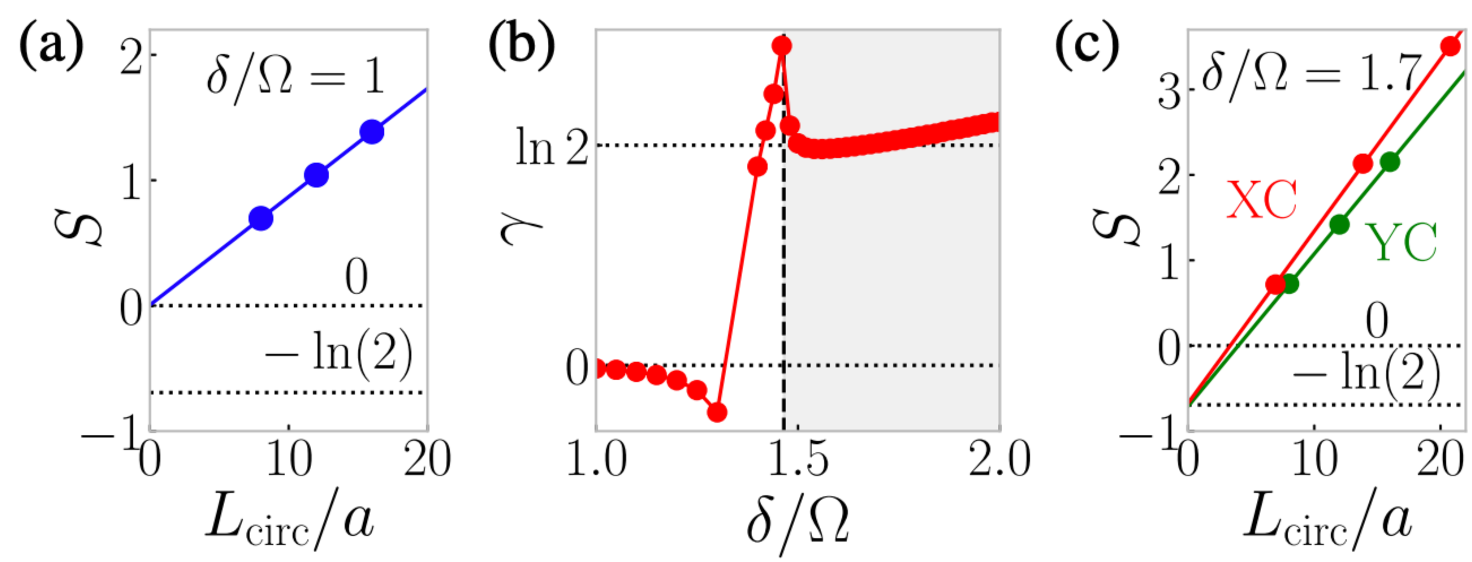
- Rydberg atoms on the links



- Rydberg blockade as dimer constraint

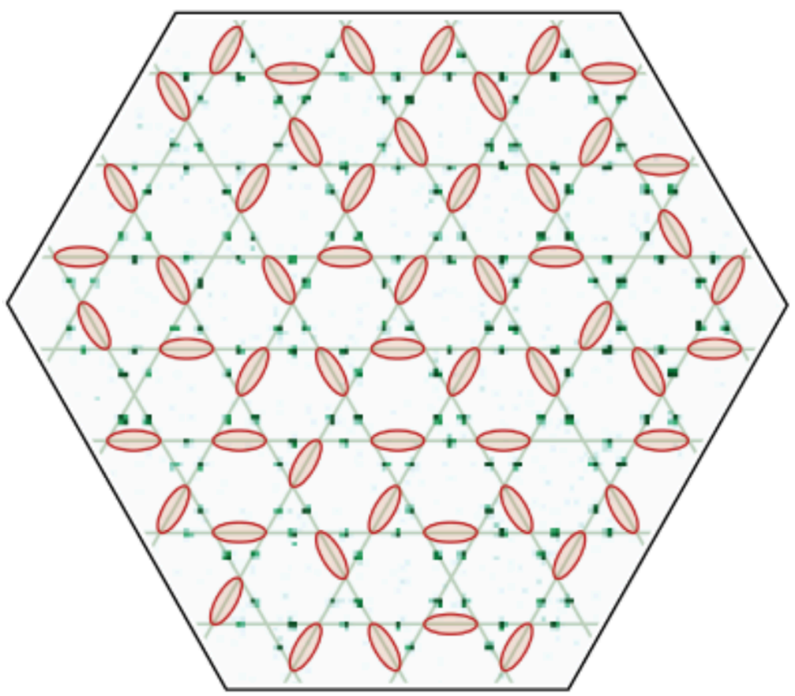






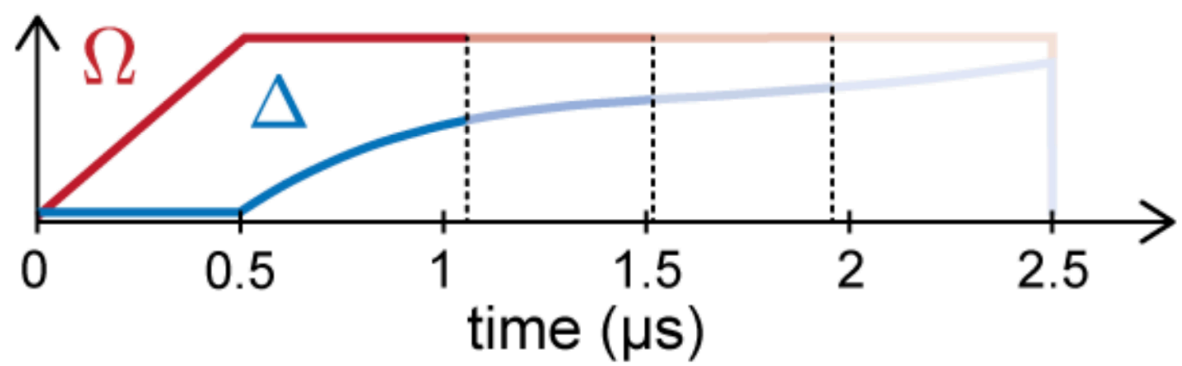
R Verresen, MD Lukin, A Vishwanath, 2020

DIMER MODELS & RYDBERG ATOMS



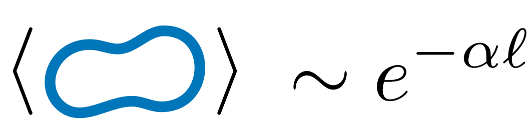
State preparation : $|\psi_0\rangle = |0\rangle$

$$H(t) = \frac{\Omega(t)}{2}\sum_i \sigma_i^x - \Delta(t)\sum_i n_i + \sum_{r=|i-j|} V(r) n_i n_j$$

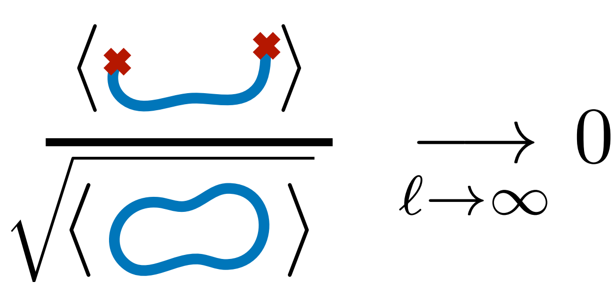


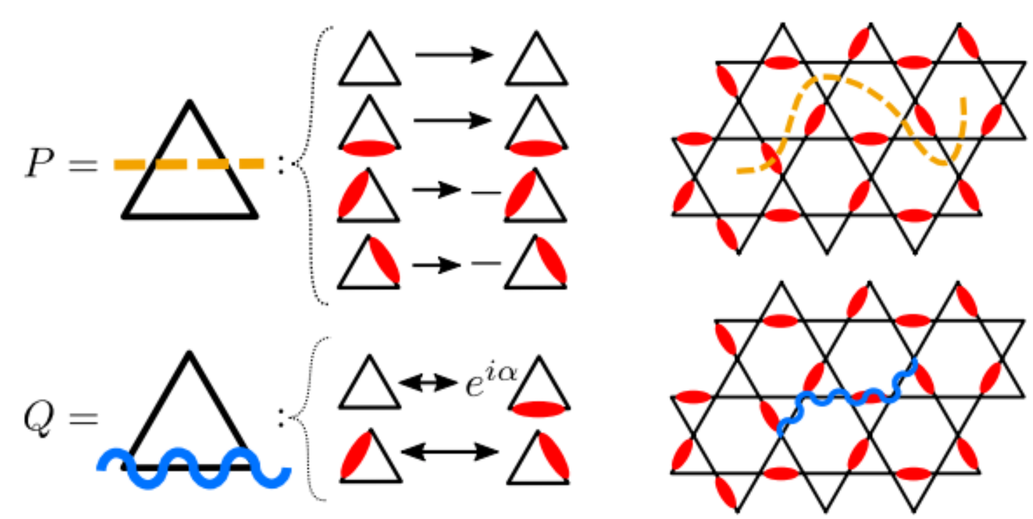
Experimental detection : non-local order parameters

- Closed loops : perimeter law



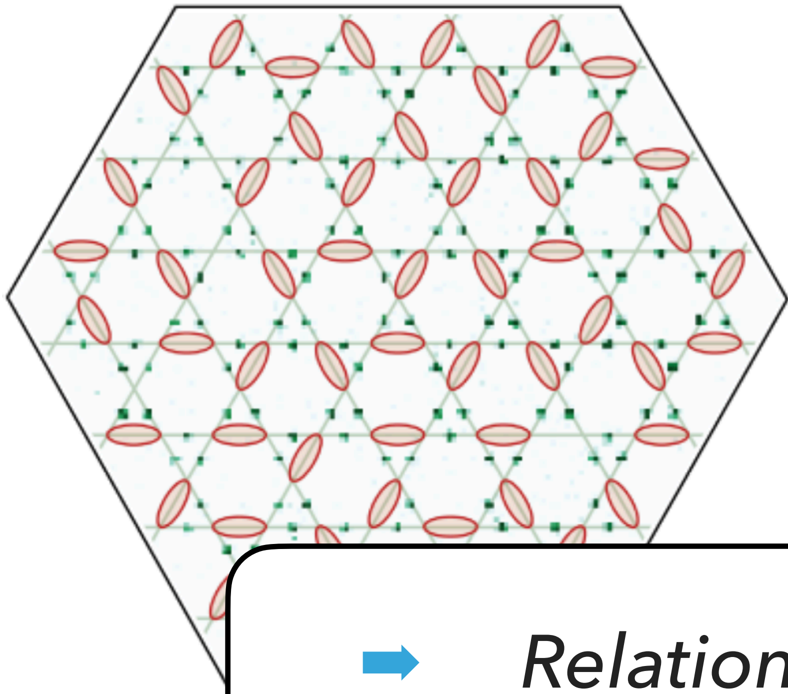
- BFFM order parameters :





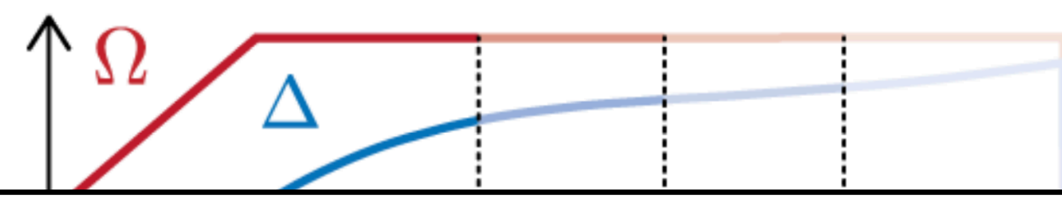
G Semeghini et al, 2020

DIMER MODELS & RYDBERG ATOMS

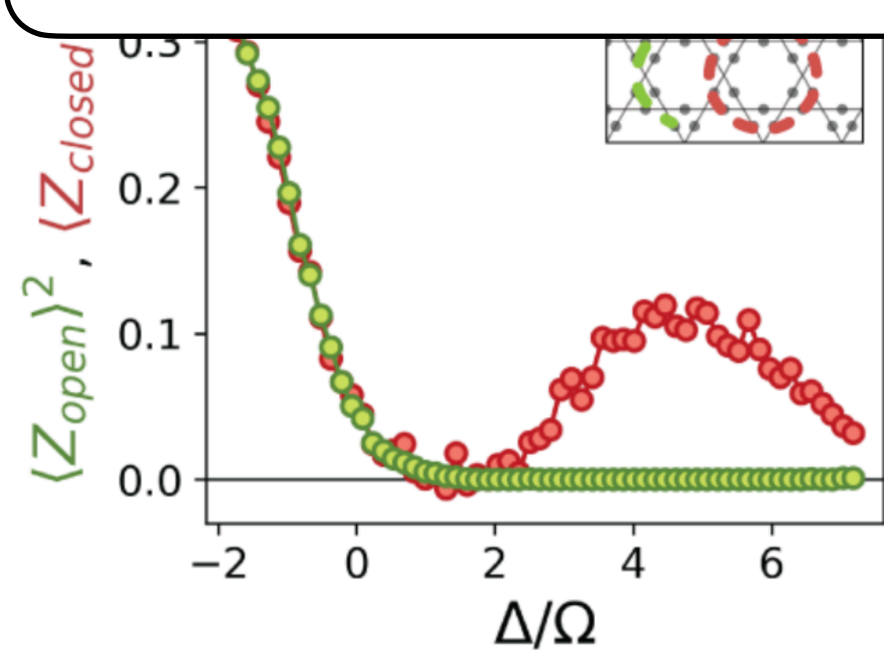


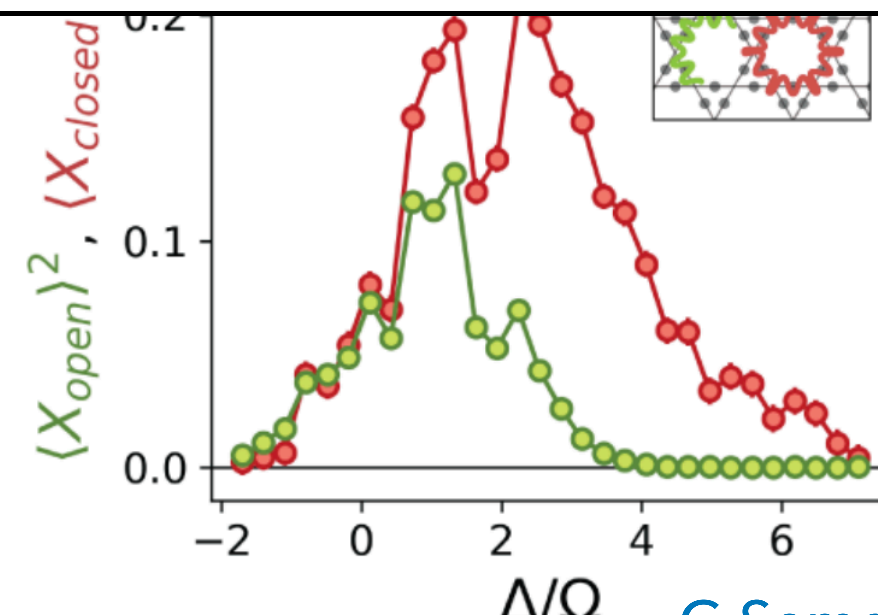
State preparation : $|\psi_0\rangle = |0\rangle$

$$H(t) = \frac{\Omega(t)}{2}\sum_i \sigma_i^x - \Delta(t)\sum_i n_i + \sum_{r=|i-j|} V(r) n_i n_j$$



- ➡ *Relation between this many-body state and RVB?*
- ➡ *Simple representation for large-scale calculations?*

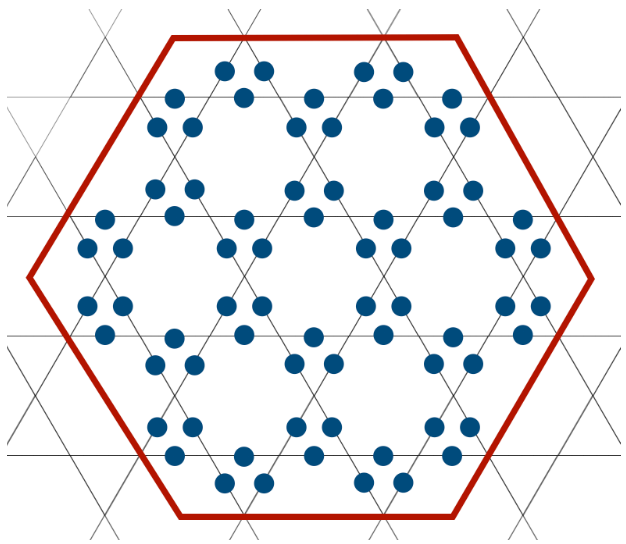


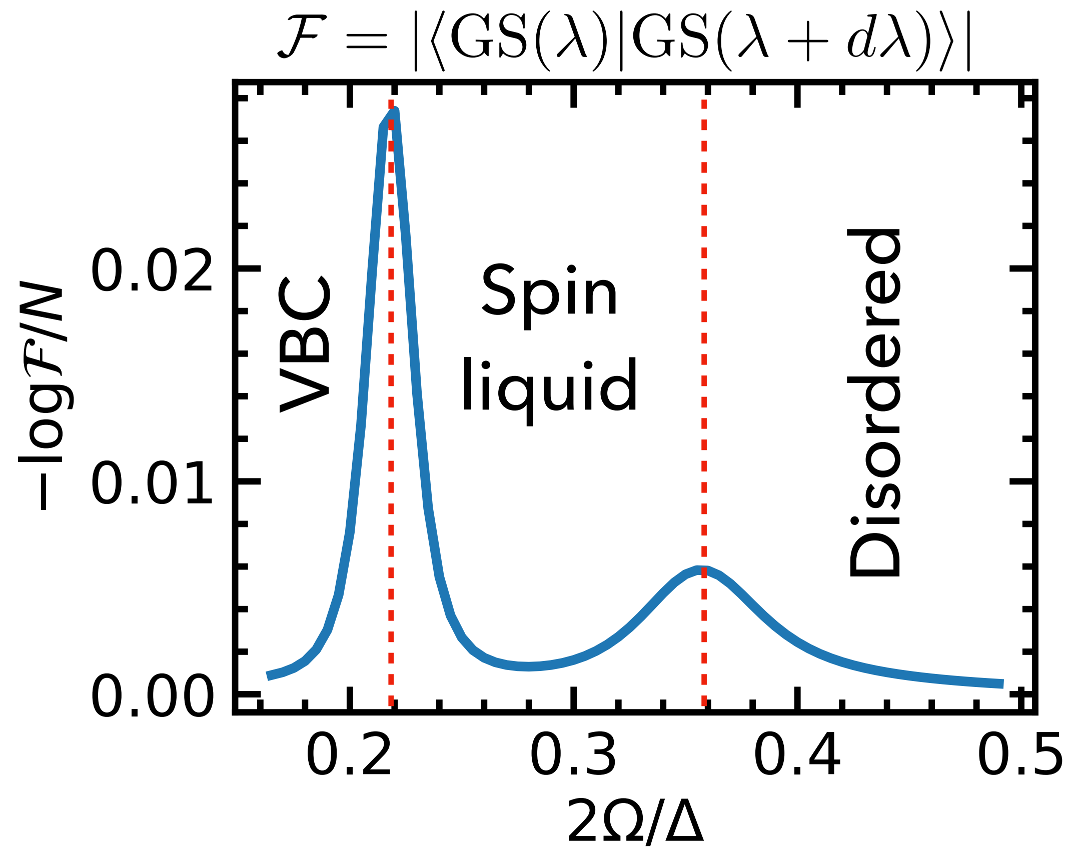


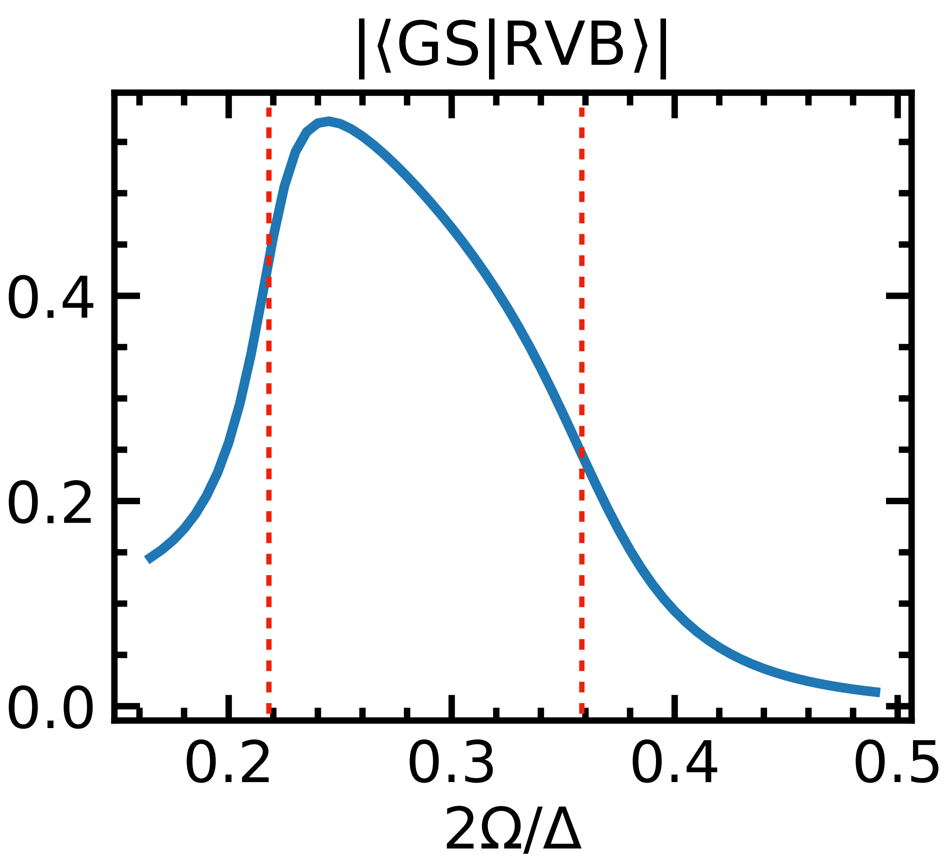
G Semeghini et al, 2020

GROUND STATE

ED on periodic clusters ($N = 72$)







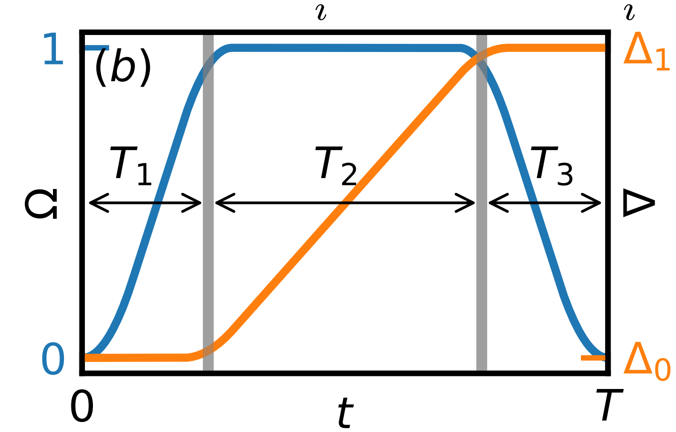
*Defects on full dimer coverings are allowed (**diluted** RVB)*

$$|\mathrm{GS}\rangle = |\mathrm{RVB}\rangle + \ldots$$

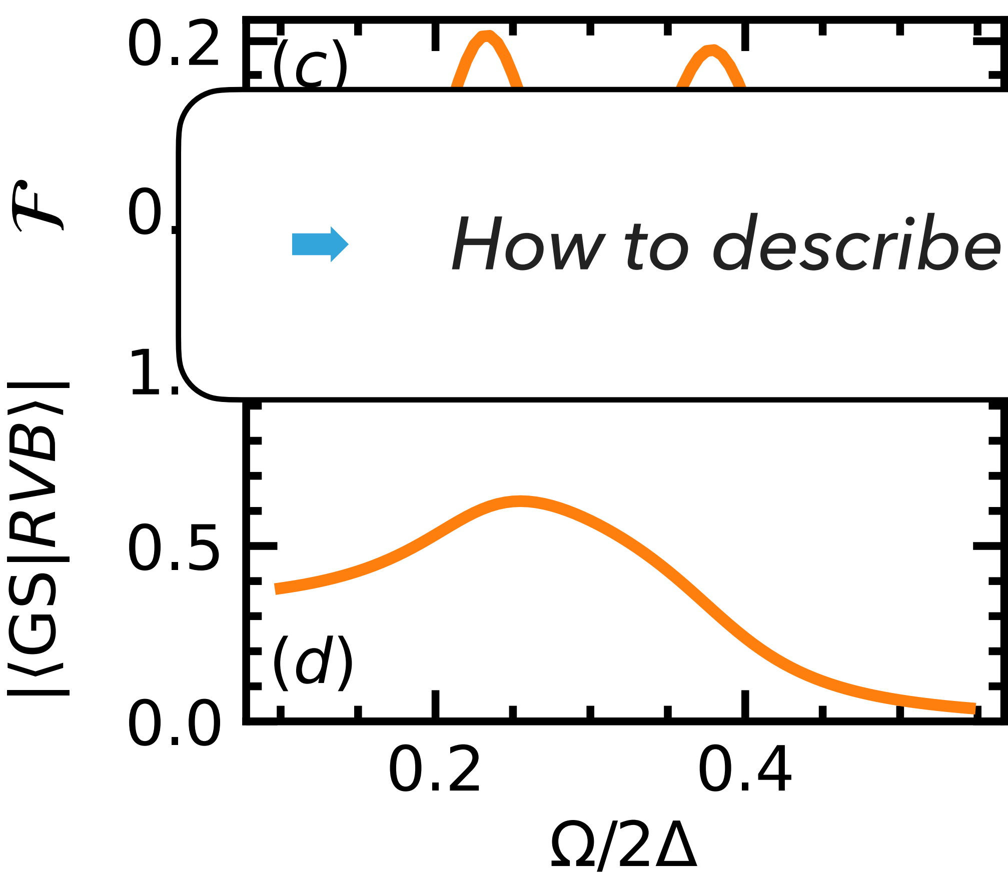
DYNAMICAL PREPARATION

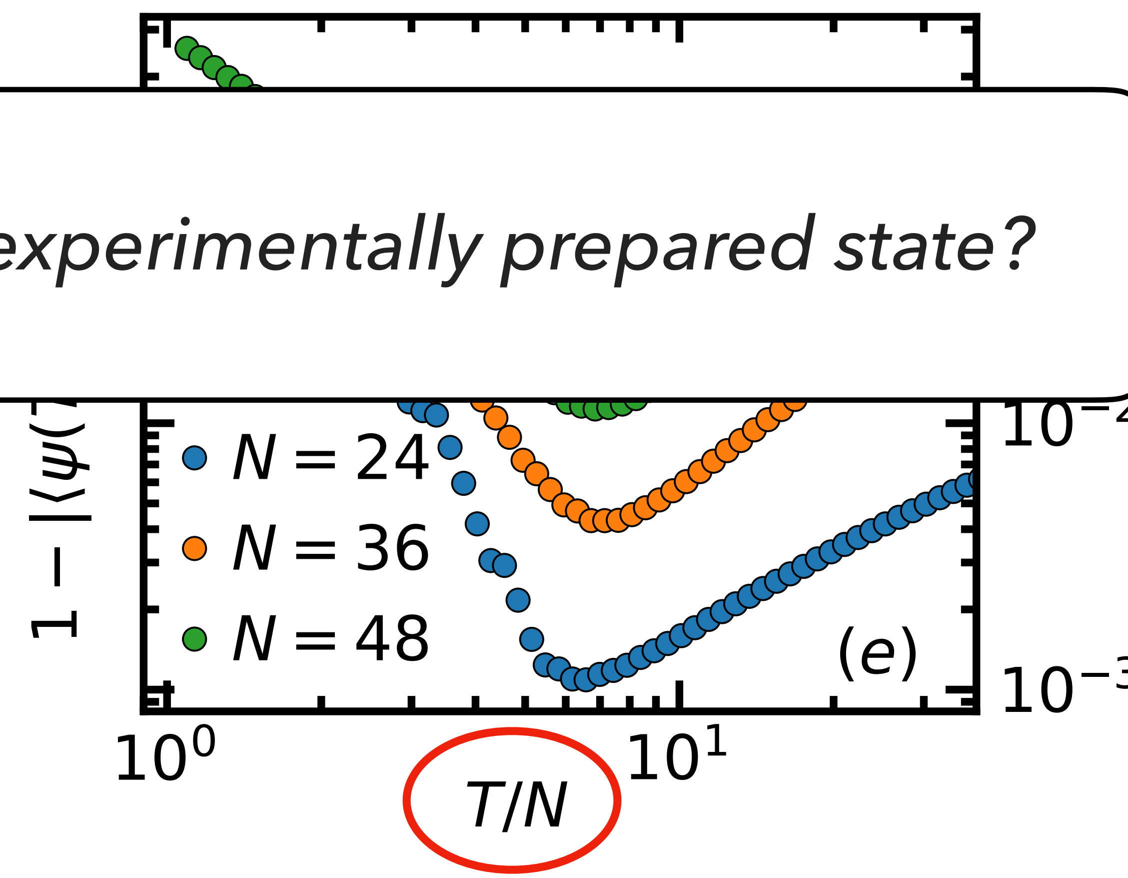
- Optimized dynamical preparation protocol for **pure** RVB state

$$H(t) = \frac{\Omega(t)}{2}\sum_i \sigma_i^x - \Delta(t)\sum_i n_i$$



$$\mathcal{F} = 1 - |\langle \mathrm{GS}(\lambda)|\mathrm{GS}(\lambda + d\lambda)\rangle|$$





➡ *How to describe the experimentally prepared state?*

- Optimal T scales linearly with the number of atoms

GG, MD Lukin, H Pichler, arXiv:2201.04034

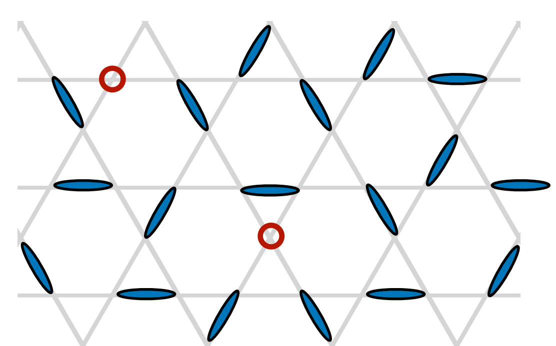
DILUTED RVB ANSATZ

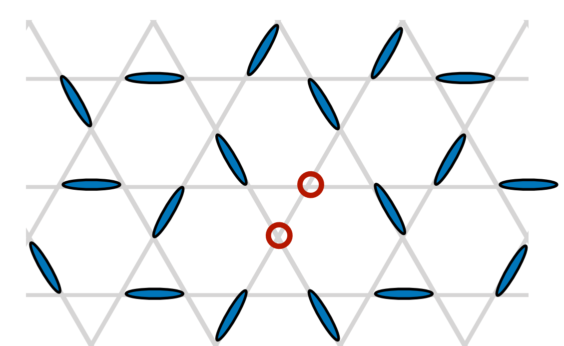
$$|\phi(z_1, z_2)\rangle = \mathcal{P}\left[\bigotimes_{i=1}^{N}(1 + z_2\sigma_i^+)(1+z_1\sigma_i^-)\right]|\mathrm{RVB}\rangle$$

Project onto constrained Hilbert space

Allow monomer pairs to separate by creating dimers

Create monomer pairs by destroying dimers





GG, MD Lukin, H Pichler, arXiv:2201.04034

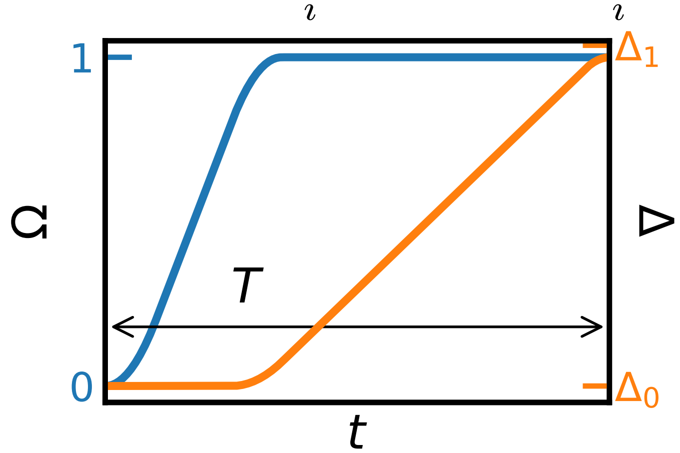
DILUTED RVB ANSATZ

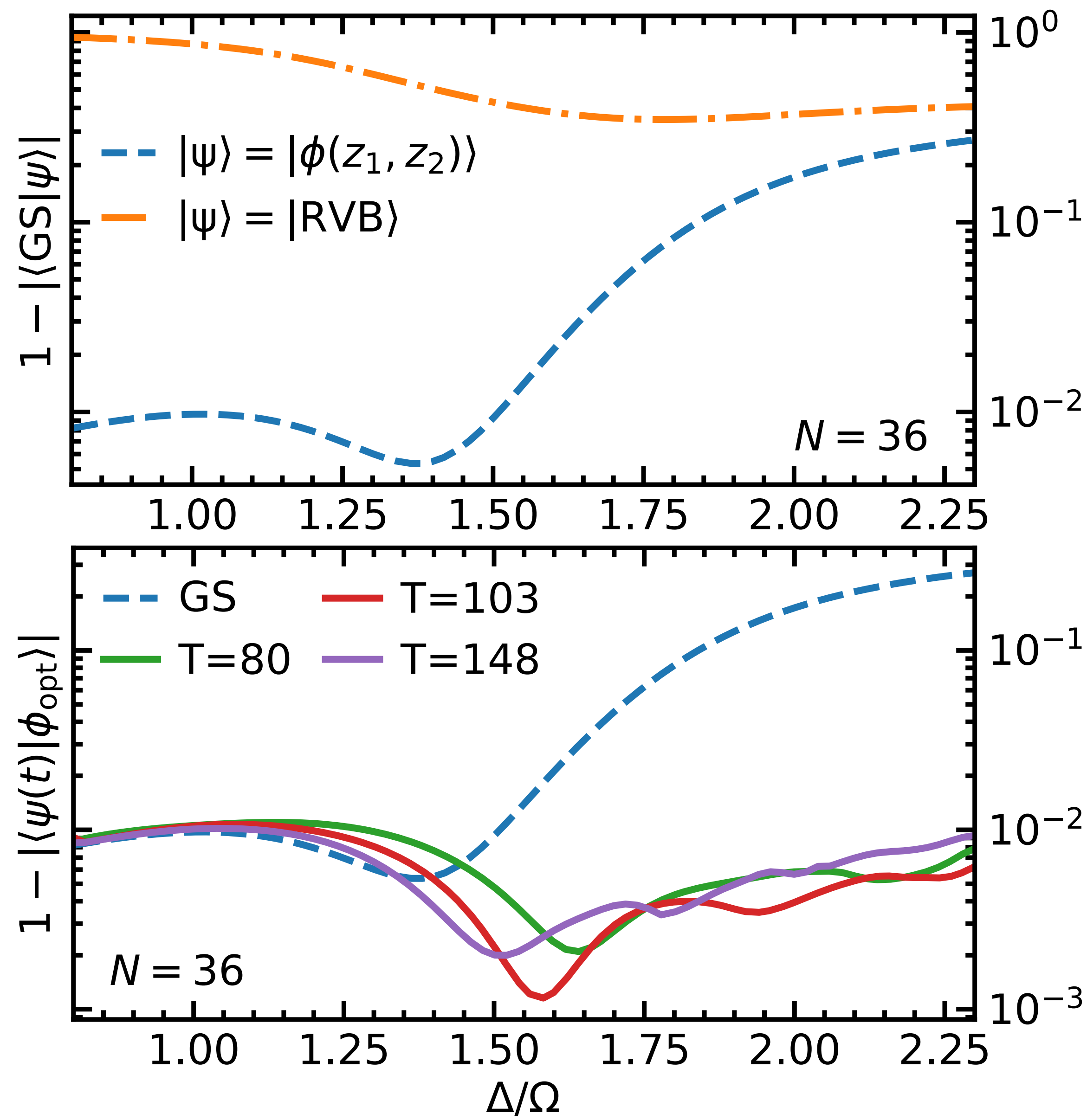
$$|\phi(z_1, z_2)\rangle = \mathcal{P}\left[\bigotimes_{i=1}^{N}\left(1+z_2\sigma_i^+\right)\left(1+z_1\sigma_i^-\right)\right]|\mathrm{RVB}\rangle$$

- Good variational ansatz for the **ground state**

- Even better ansatz for the **preparation dynamics**

$$H(t) = \frac{\Omega(t)}{2}\sum_i \sigma_i^x - \Delta(t)\sum_i n_i$$



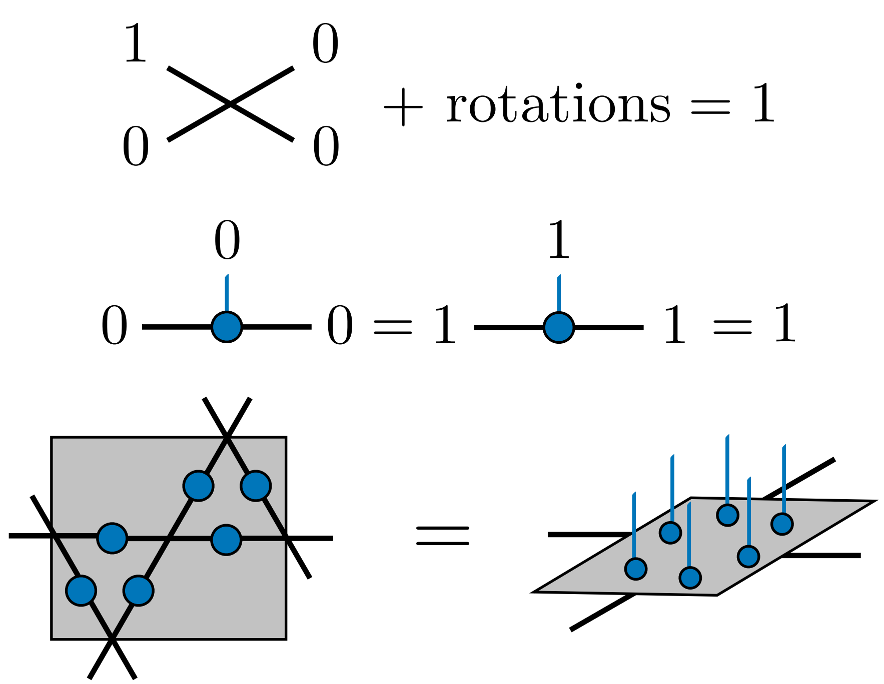


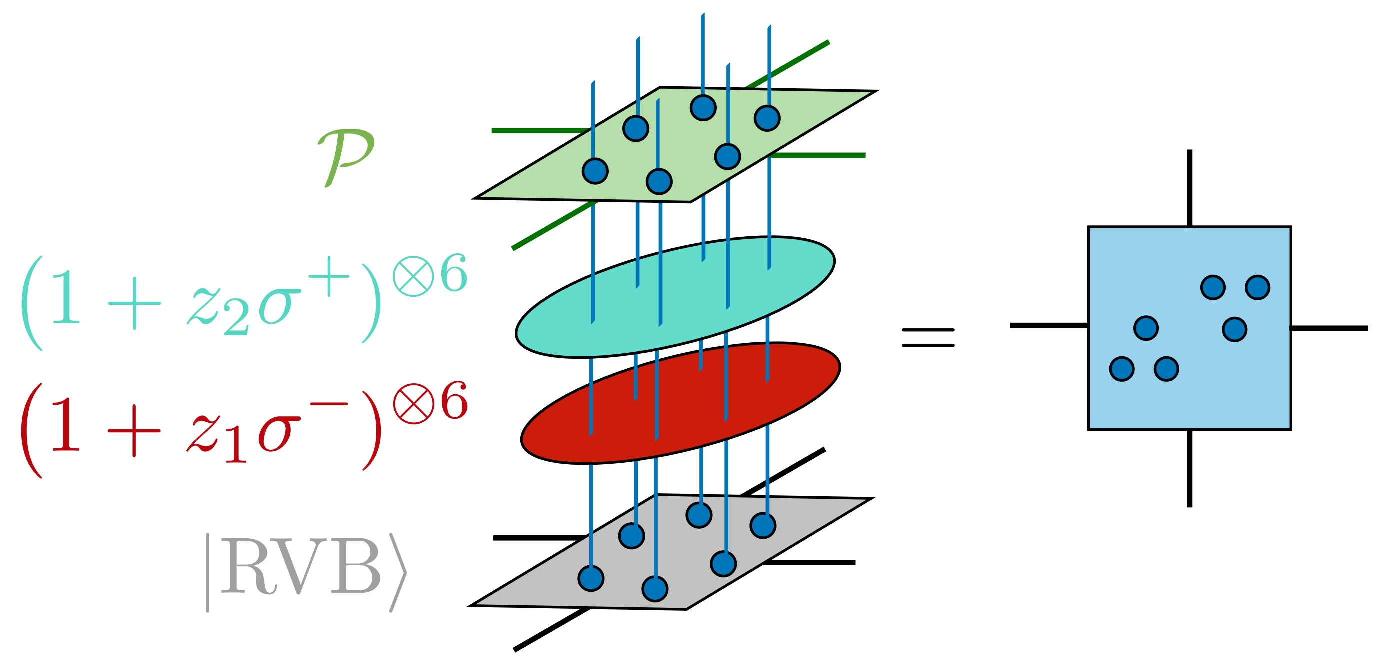
GG, MD Lukin, H Pichler, arXiv:2201.04034

DILUTED RVB ANSATZ

$$|\phi(z_1, z_2)\rangle = \mathcal{P}\left[\bigotimes_{i=1}^{N}\left(1+z_2\sigma_i^+\right)\left(1+z_1\sigma_i^-\right)\right]|\mathrm{RVB}\rangle$$

- It is a **tensor network state**

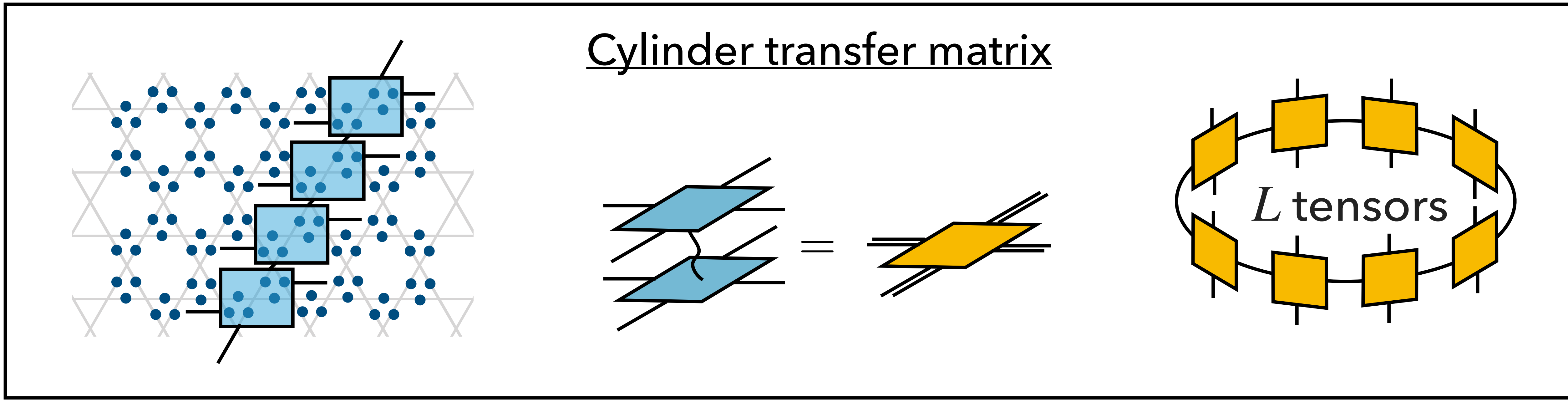


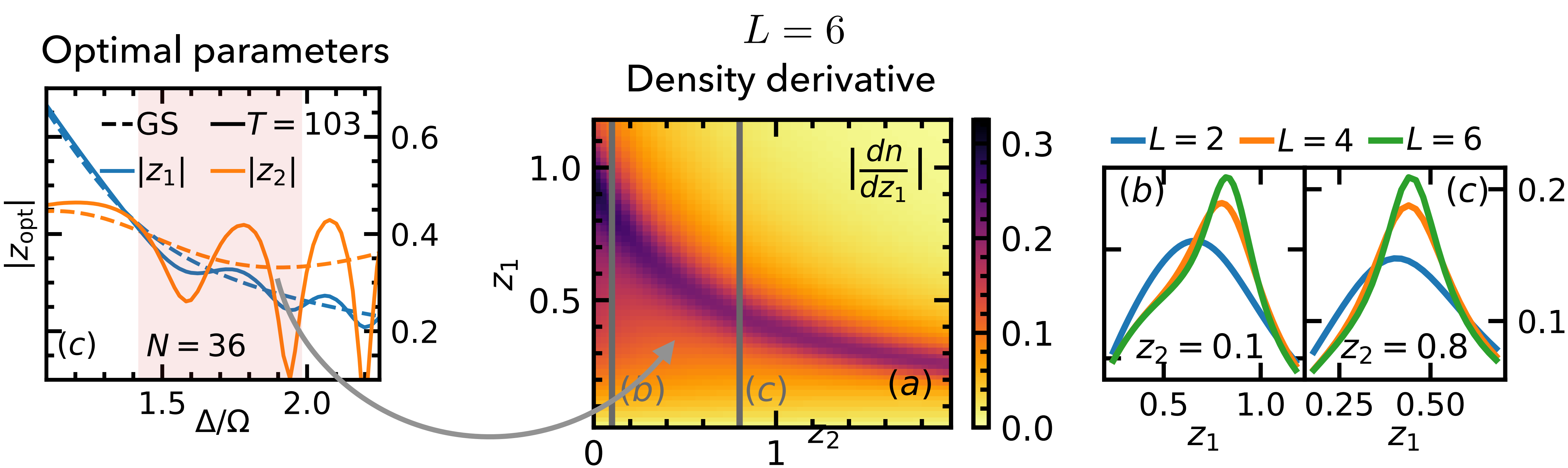


⇨ Suitable for large scale calculations!

GG, MD Lukin, H Pichler, arXiv:2201.04034

STATE PHASE DIAGRAM

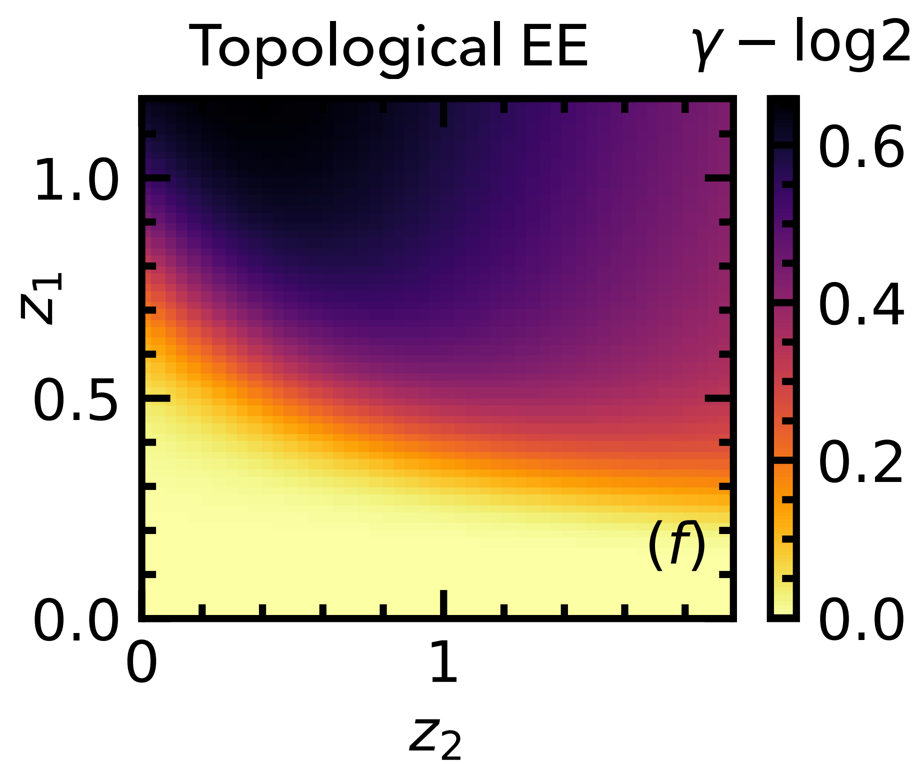




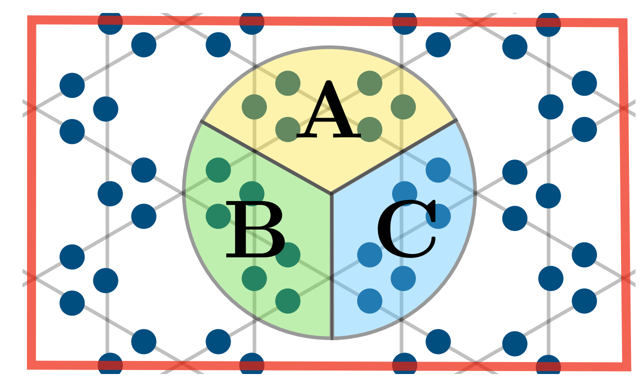
- Topologically ordered phase in the state phase diagram

GG, MD Lukin, H Pichler, arXiv:2201.04034

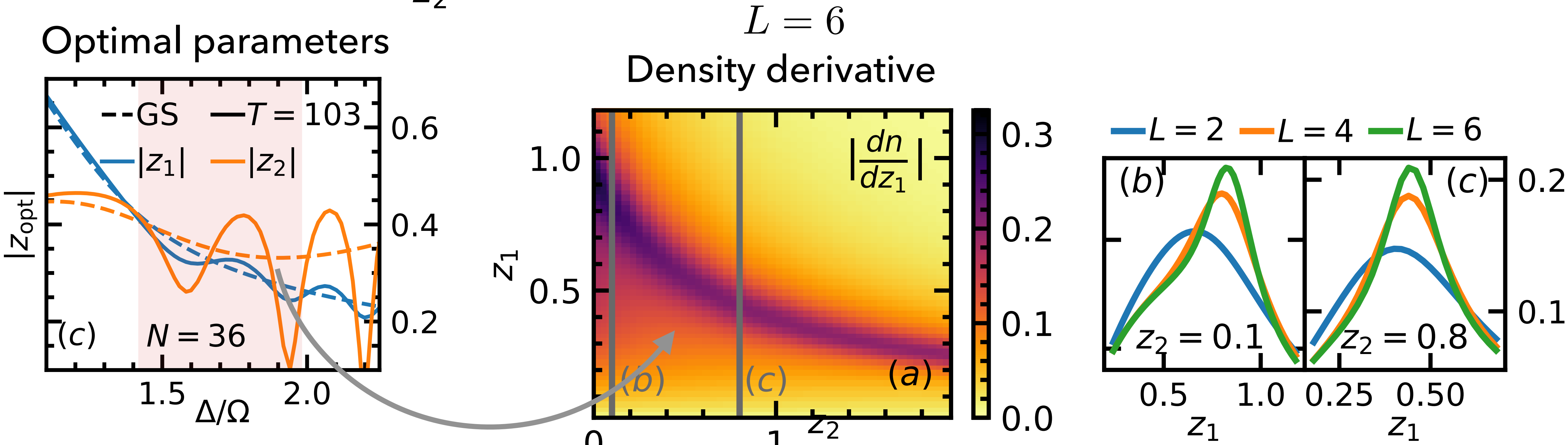
STATE PHASE DIAGRAM



$$\gamma = S_{AB} + S_{BC} + S_{AC} - S_A - S_B - S_C - S_{ABC}$$



$N = 48$



- Topologically ordered phase in the state phase diagram

GG, MD Lukin, H Pichler, arXiv:2201.04034

CONCLUSIONS (1)

- **Pure** RVB states can be prepared dynamically (quasi-adiabatically) in Rydberg atom Hamiltonians with high fidelity

- **Diluted** RVB states arising in Rydberg atom arrays can be accurately described with local perturbations of tensor network states that host topological order

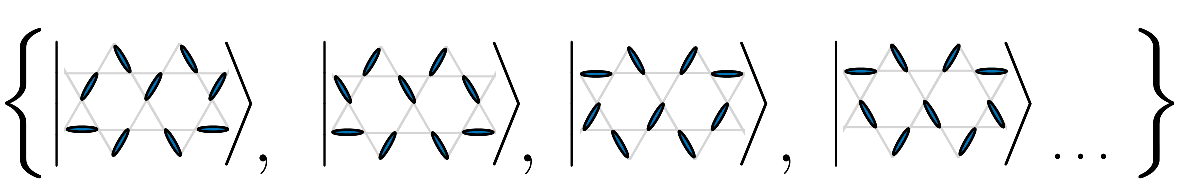
General recipe for topological order :

$$H = \frac{\Omega}{2}\sum_i \sigma_i^x - \Delta \sum_i n_i$$

Effective "PXP" Rydberg Hamiltonian with exact constraint

Maximally occupied degenerate configurations (e.g. dimer coverings)

(Quantum fluctuations)

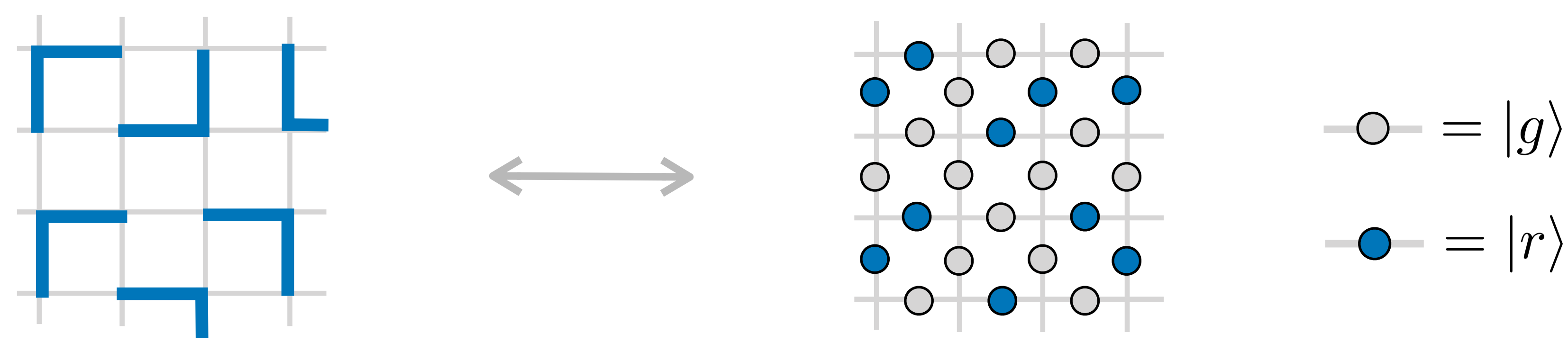


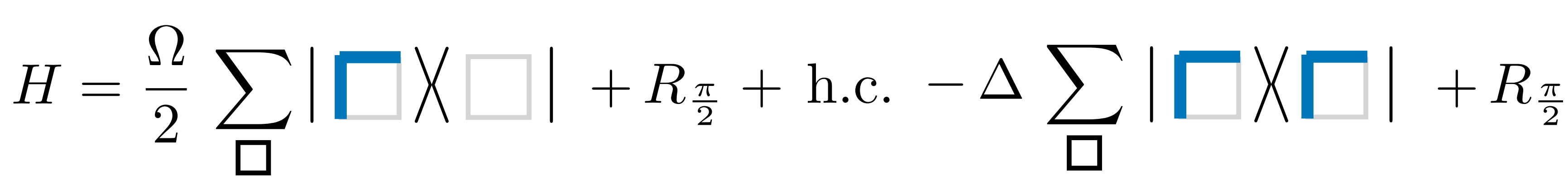
Can this be generalized?

TRIMERS & RYDBERG ATOMS

- **Trimer** : set of 3 nearest neighbour vertices
- **Constraint** : one trimer on each vertex

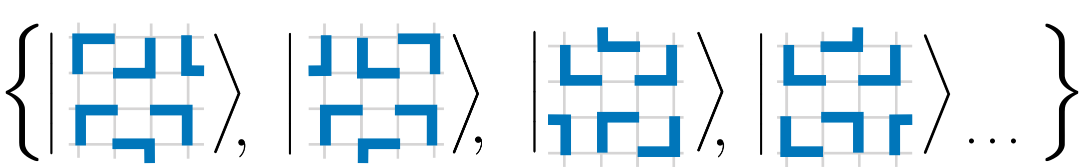
<u>Implementation with Rydberg atoms</u>

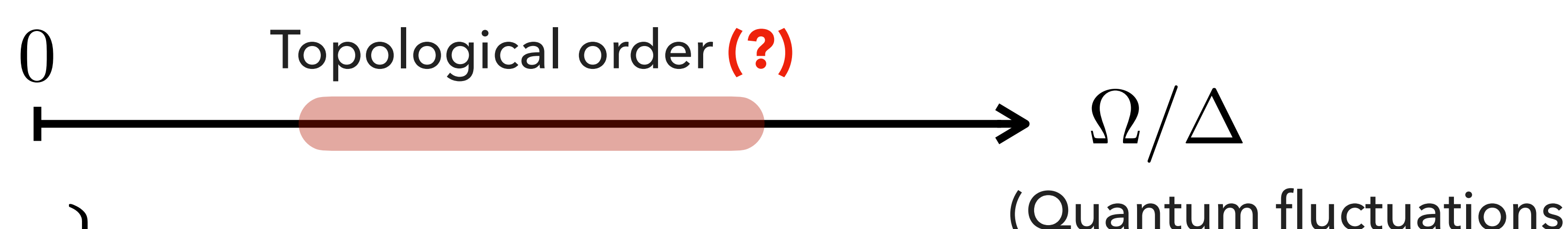




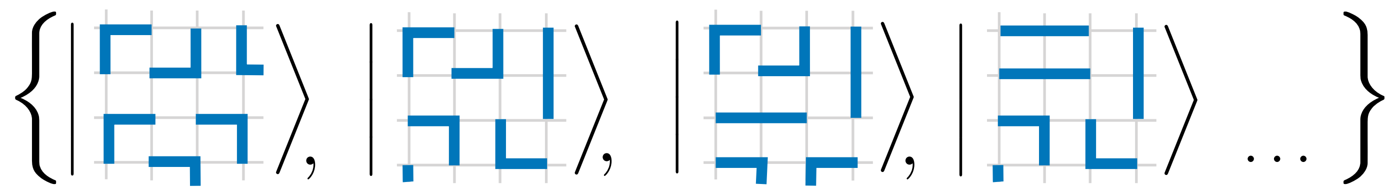
Check the arXiv in a couple of weeks

Maximally occupied degenerate configurations (e.g. **trimer** coverings)



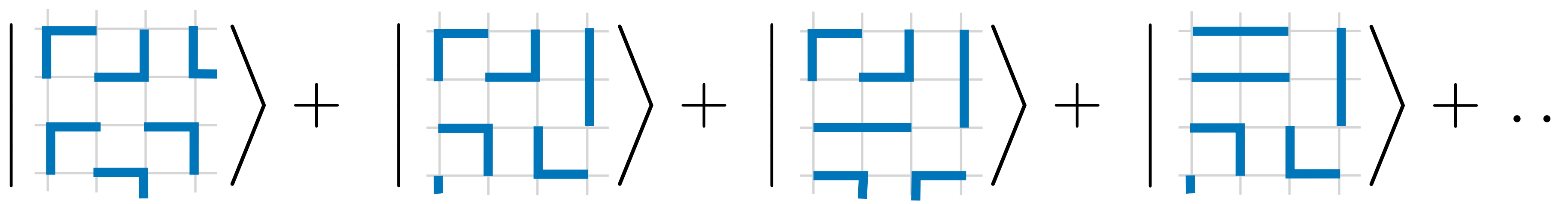


TRVB STATES IN TRIMERS MODELS

- Trimer model : $\mathcal{H} =$ 

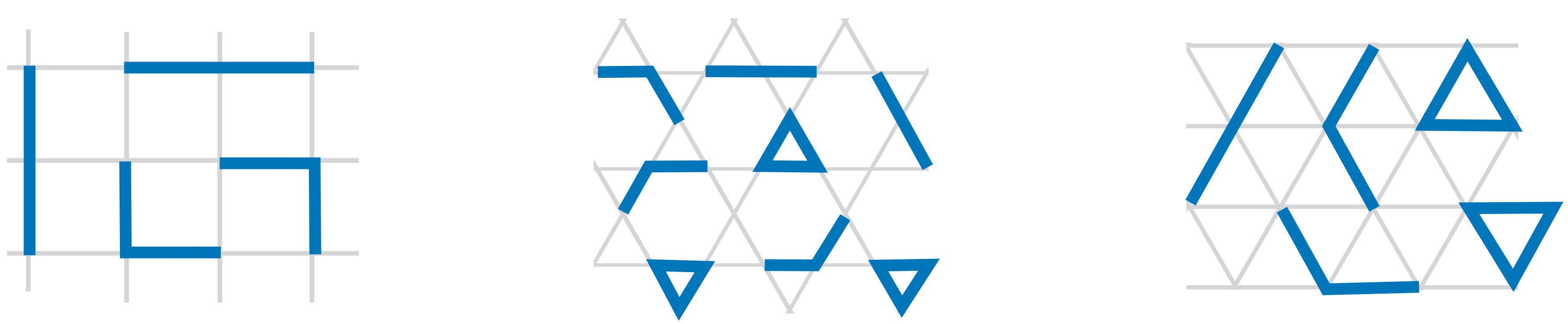
- (Trimer) resonating valence bond (tRVB) state:

  <u>equal weight superposition of all trimer coverings</u>

$|\mathrm{tRVB}\rangle =$ 

Do they provide topological order?

Much more freedom than with dimers ...



...

TRVB: WHAT DO WE KNOW?

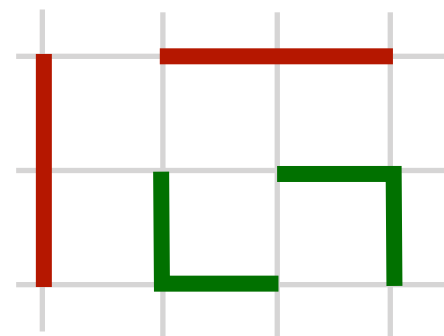
- Admit simple tensor network representations for large system calculations

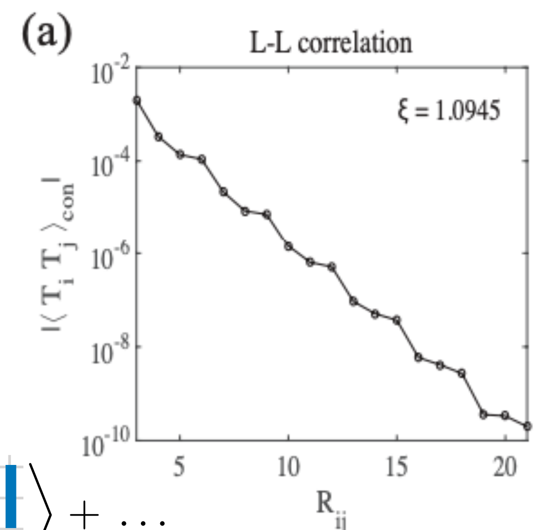
- Square lattice

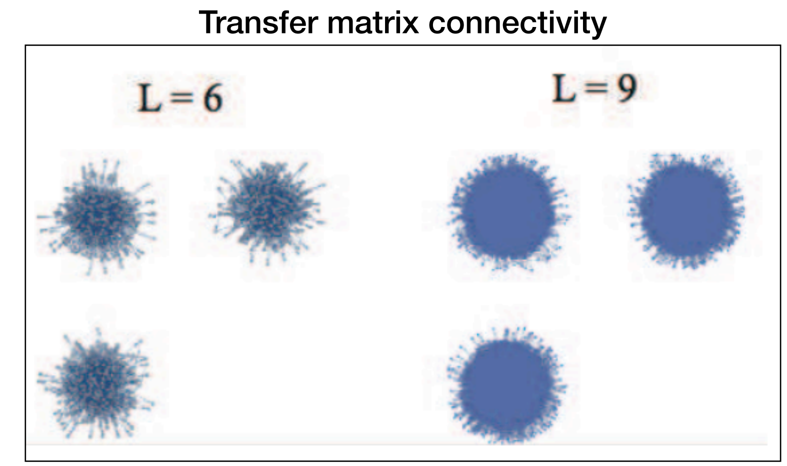
| tRVB > = type 1 + type 2

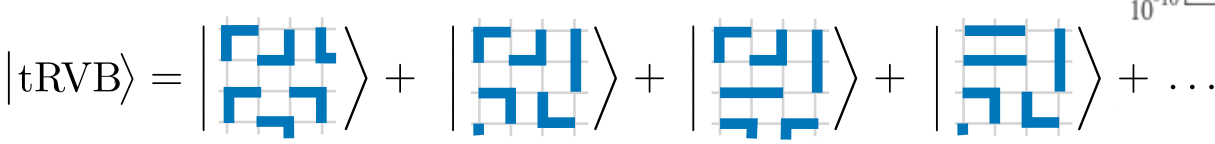
type 1 trimers

type 2 trimers









H Lee, Y Oh, JH Han, H Katsura, 2017

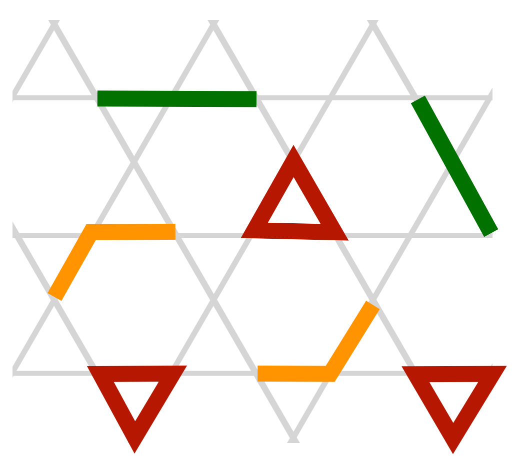
- Kagome lattice

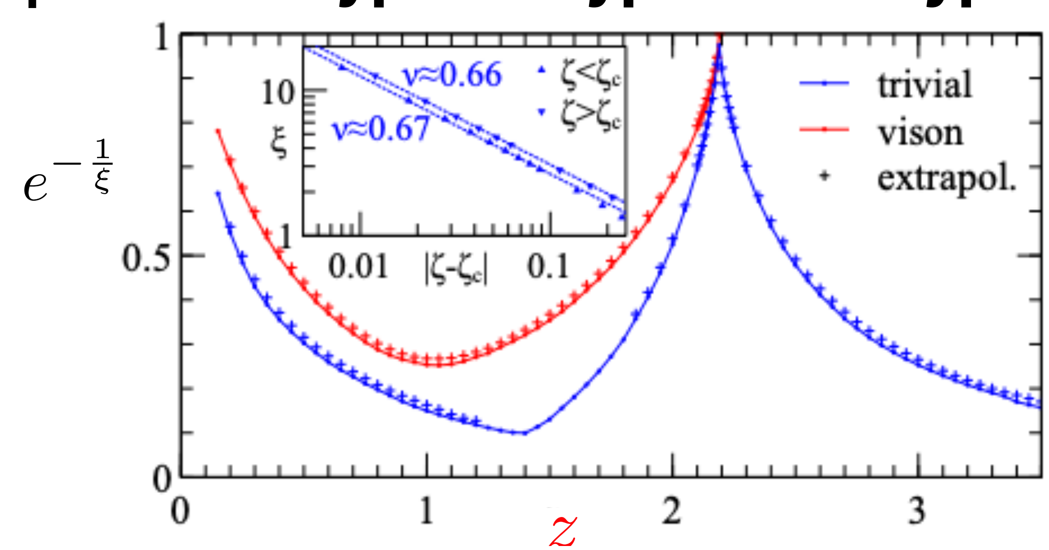
| tRVB > = type 1 + type 2 + z * type 3

type 1 trimers

type 2 trimers

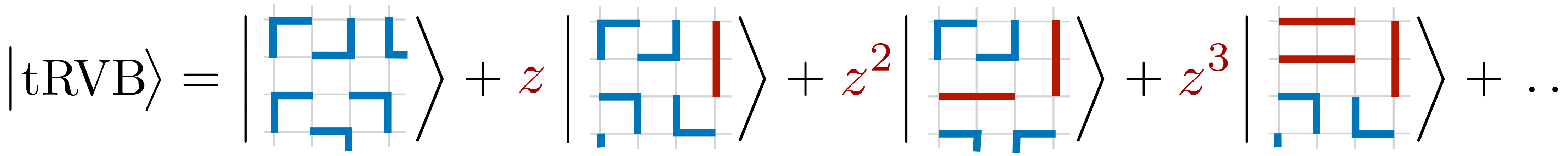
type 3 trimers





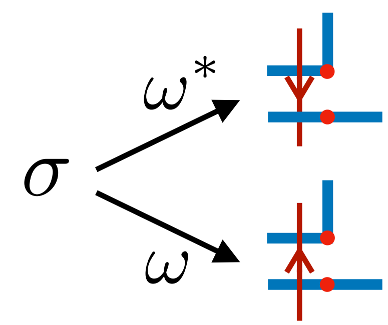
S Jandura, M Iqbal, N Schuch, 2020

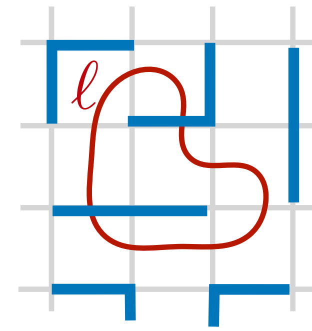
TRVB: SOME NEW RESULTS



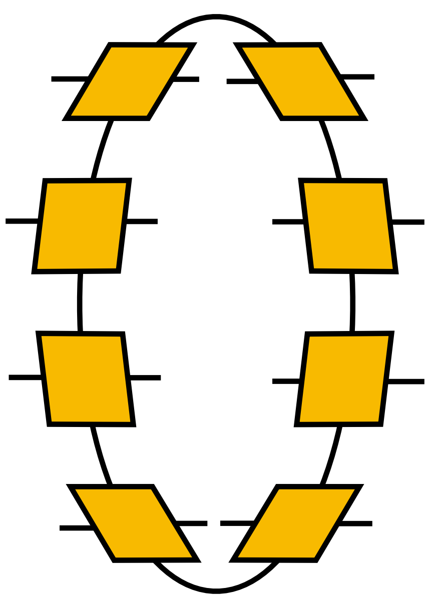
- $\mathbb{Z}_3$ Gauss' law

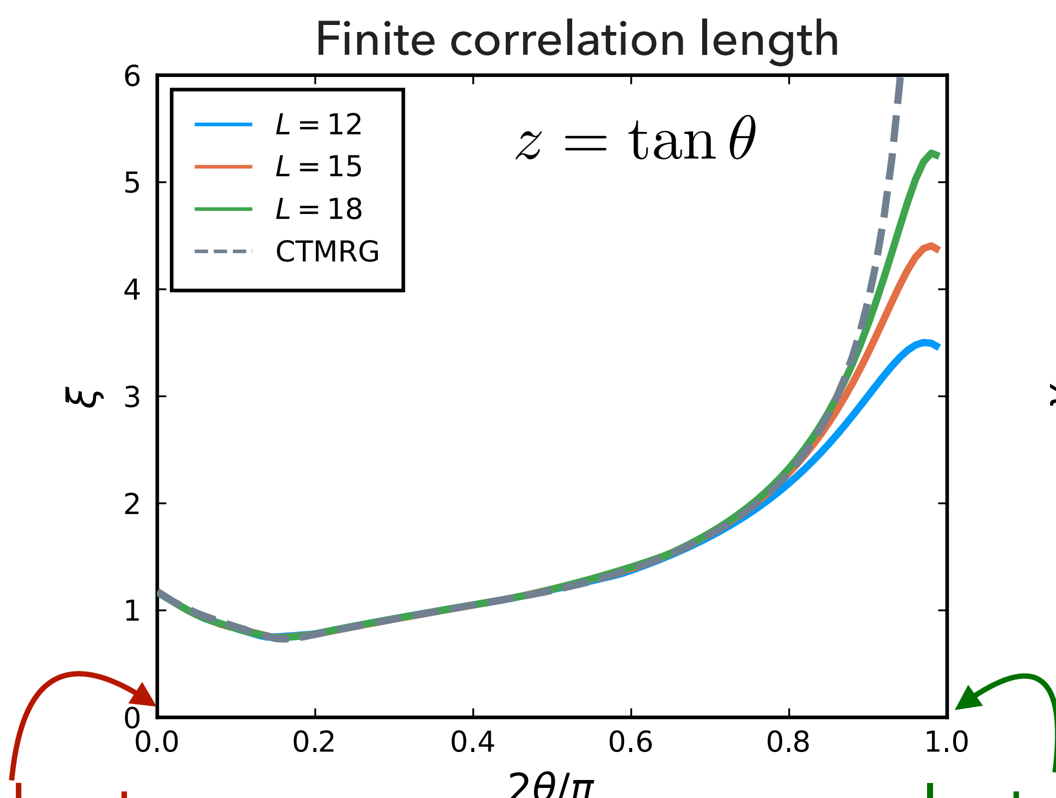
$\omega = e^{i2\pi/3}$

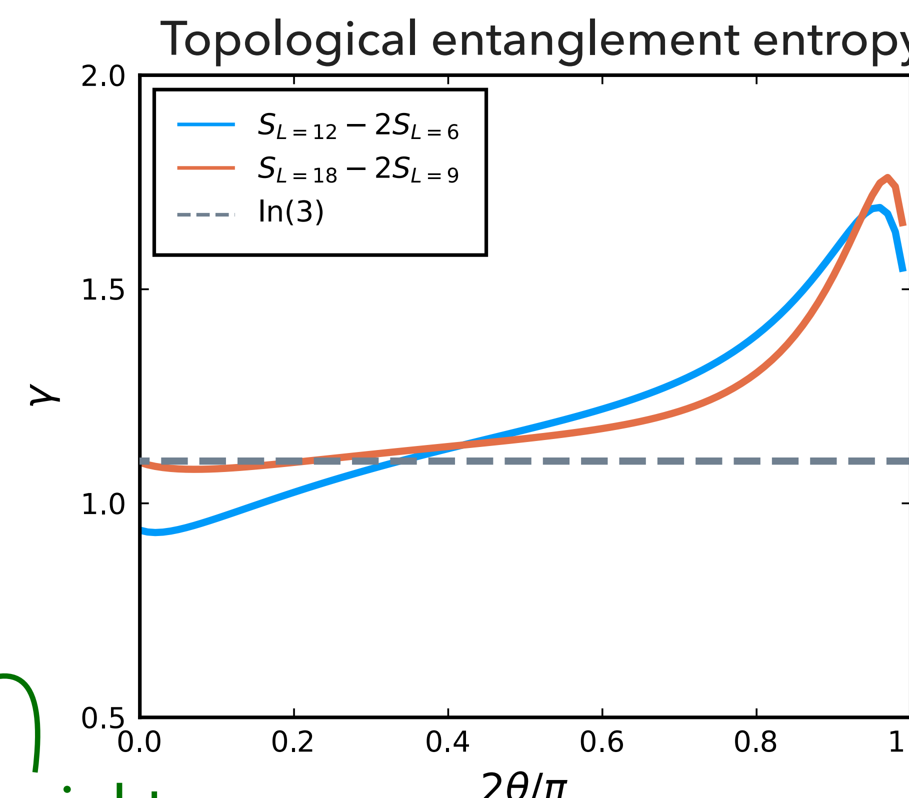




$$\prod_{i\in\ell} \sigma_i = \omega^{N_v}$$







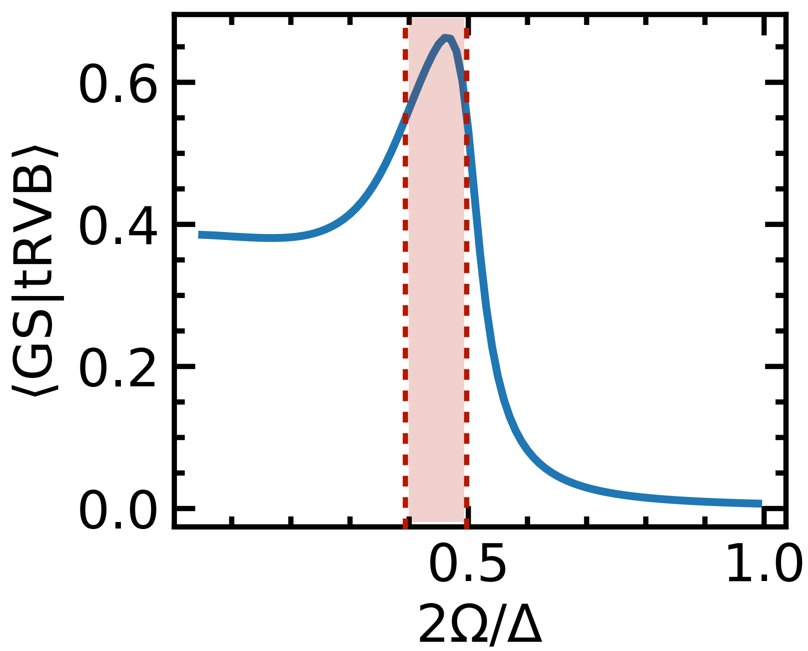
only bent

only straight

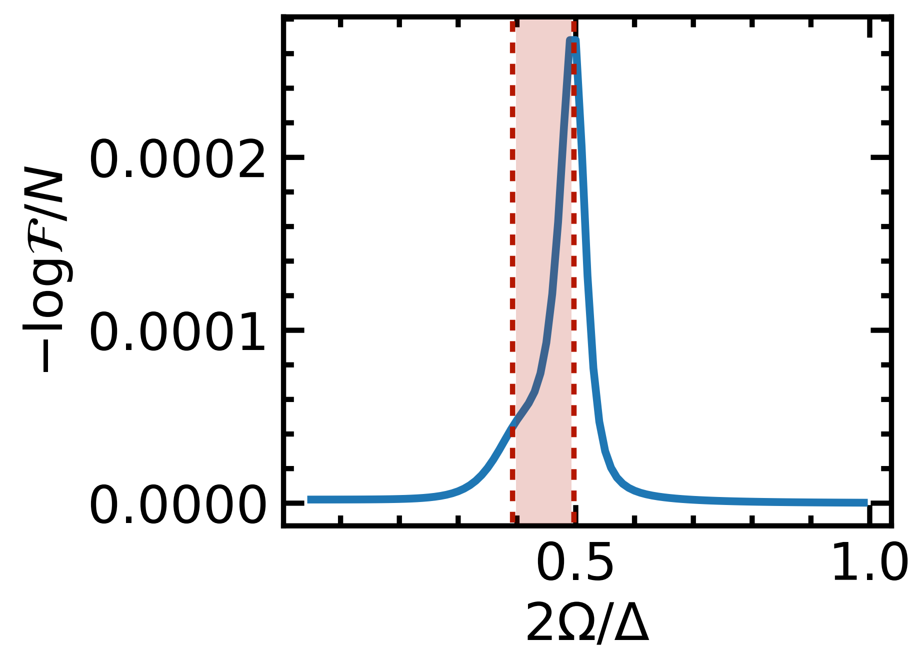
⇨ $\mathbb{Z}_3$ ***topologically ordered for all*** $\theta \neq \frac{\pi}{2}$

BENT TRIMERS ON THE SQUARE LATTICE

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

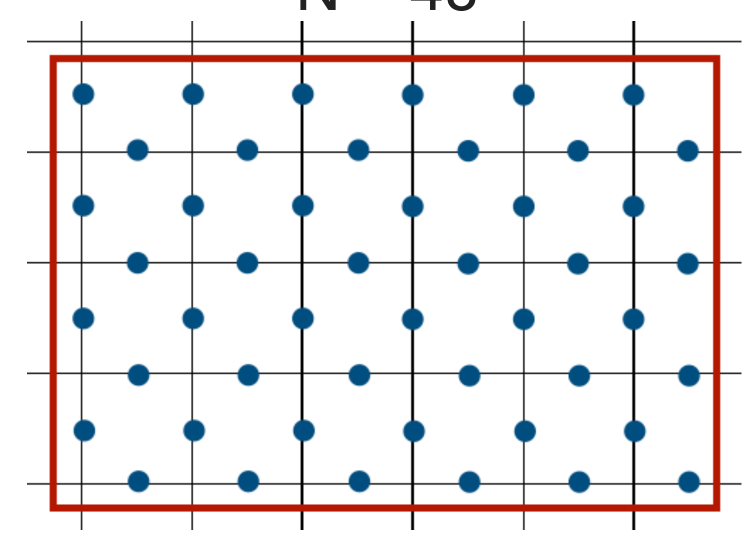


$\mathcal{F} = |\langle \mathrm{GS}(\lambda) | \mathrm{GS}(\lambda + d\lambda) \rangle|$



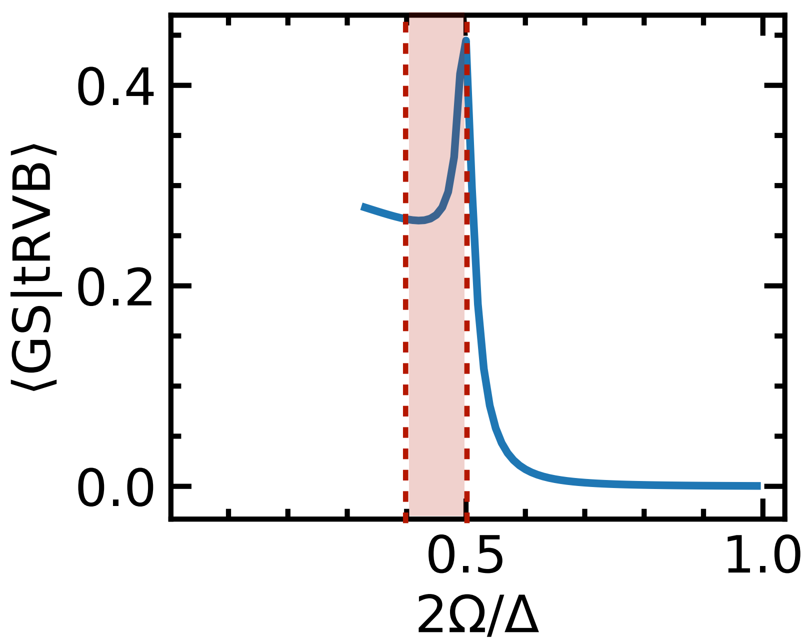
- Intermediate phase with $\mathbb{Z}_3$ topological order?

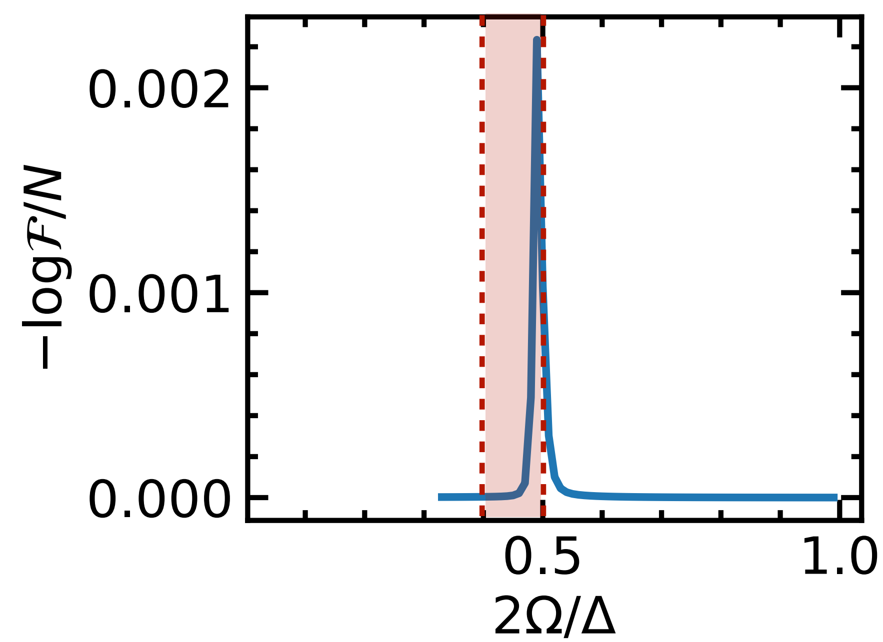
N = 48

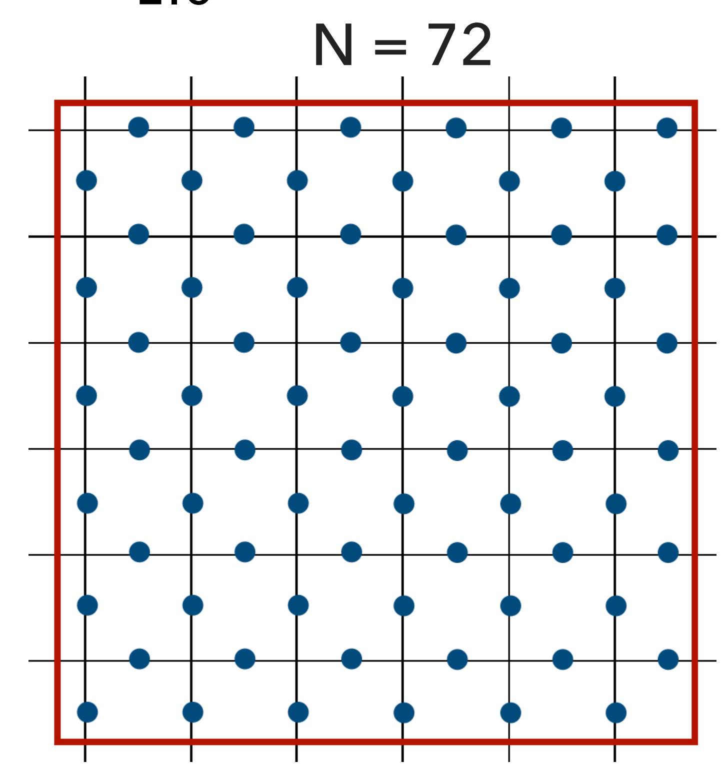


BENT TRIMERS ON THE SQUARE LATTICE

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







- Intermediate phase with $\mathbb{Z}_3$ topological order?
- Unstable with the system size?
- Can we prepare this tRVB states quasi-adiabatically?

… check the arXiv in a couple of weeks

CONCLUSIONS (2)

- tRVB states provide quantum spin liquids with Z3 topological order
- tRVB-like phases might arise from Rydberg atom Hamiltonians
- Are there other topological states that can be engineered?

Thank you!