Resonating valence bond states in the PEPS formalism

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Institute for Quantum Information
RWTH Aachen

joint work with David Pérez-García, Ignacio Cirac, and Didier Poilblanc

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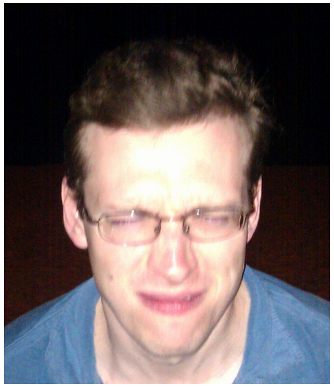

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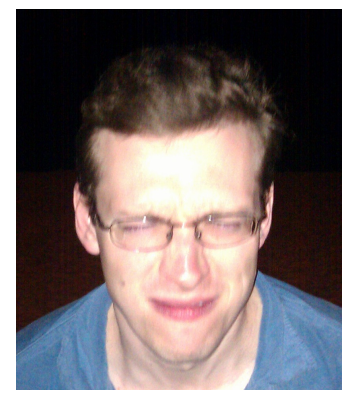

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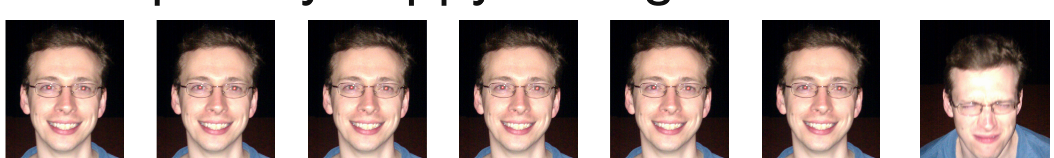
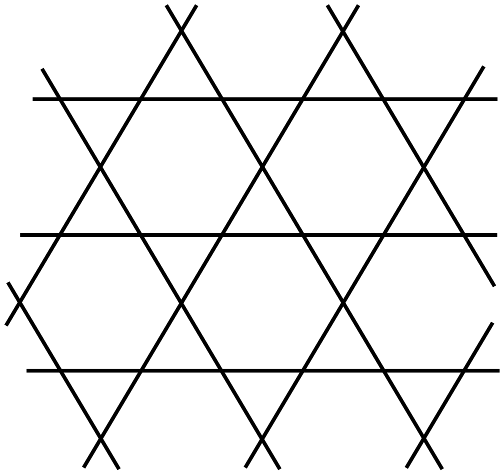


Resonating valence bond states



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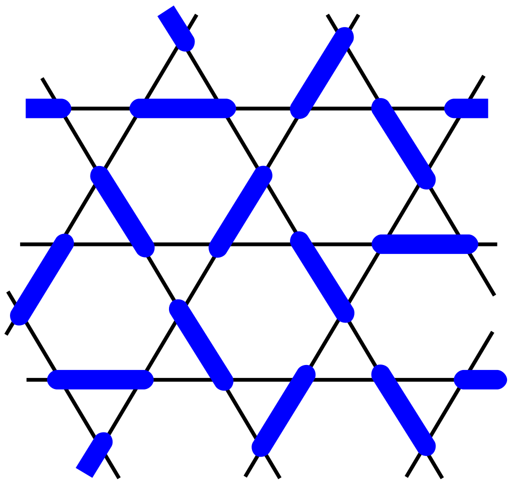
$D =$ 

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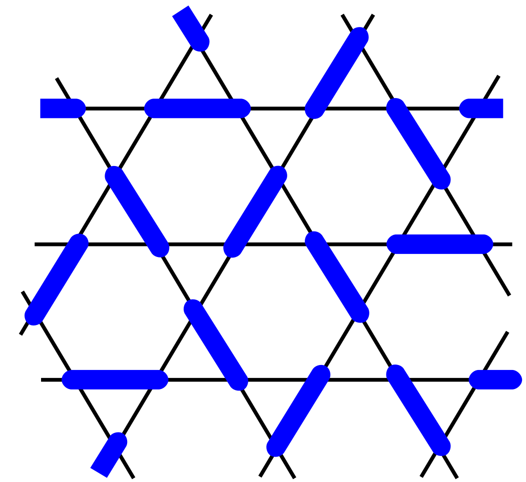
$D =$ 

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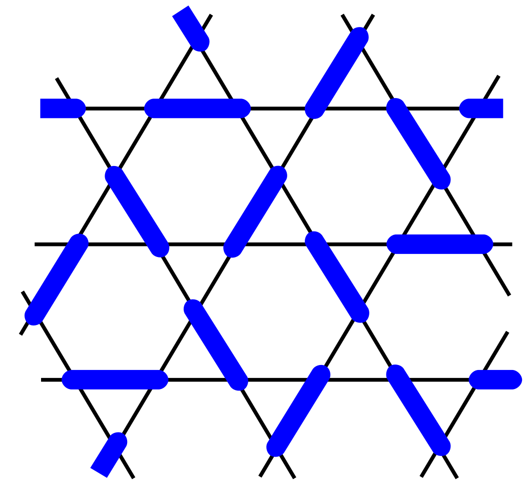

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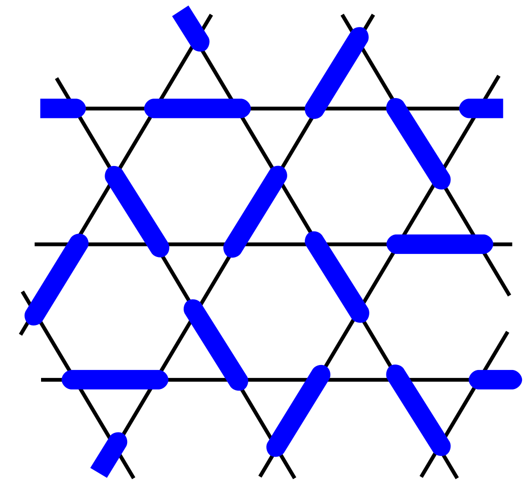

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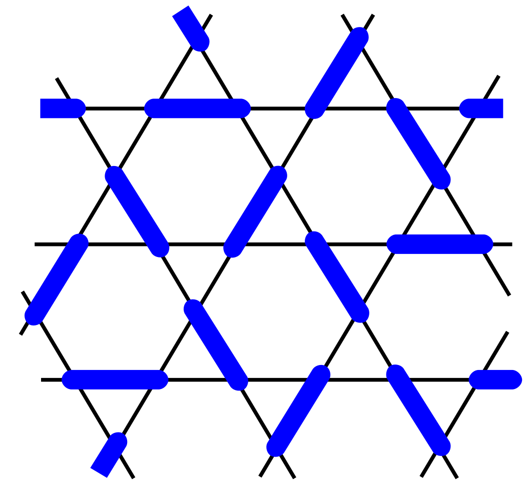

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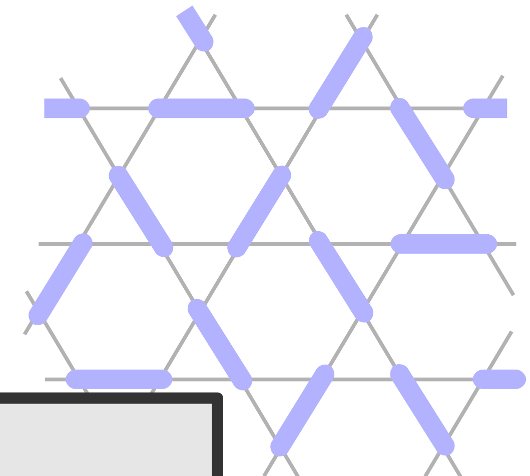

- **Resonatin**

Questions:

- Is the RVB ground state of a local Hamiltonian?
- Does it have a topological ground space structure?
- How does it relate to the Toric Code?
- Does it have long-range order or not?

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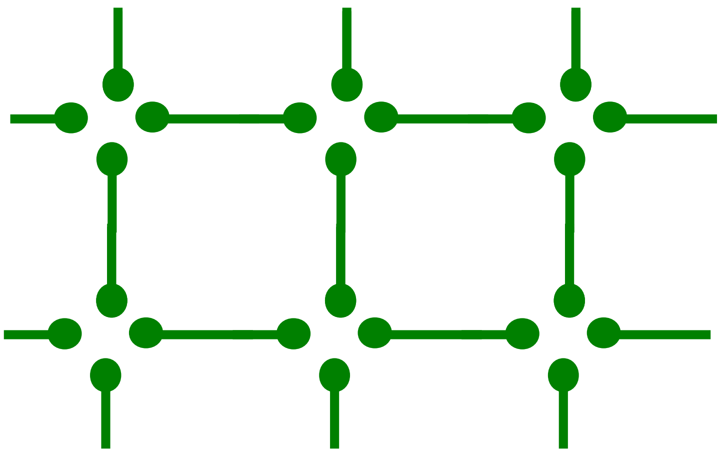

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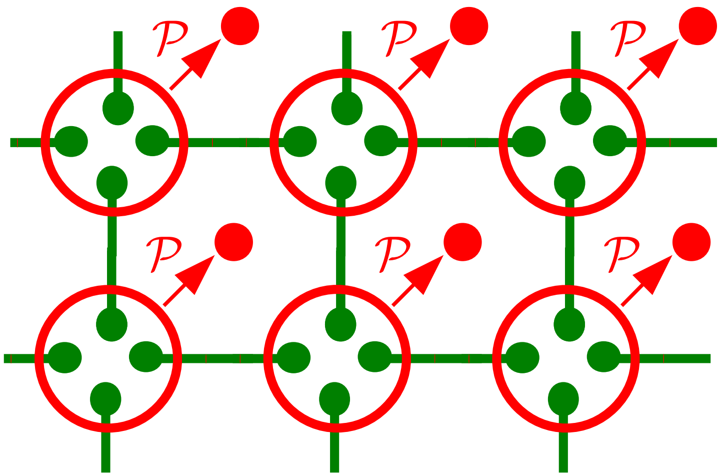

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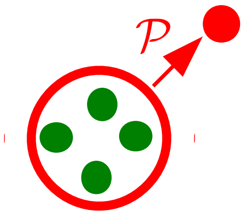

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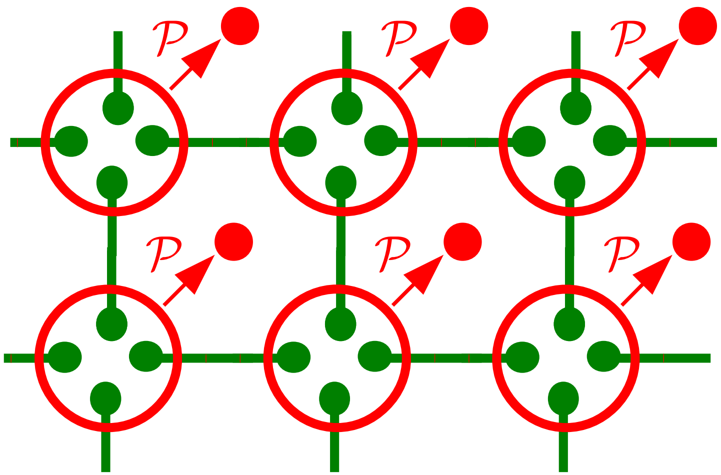

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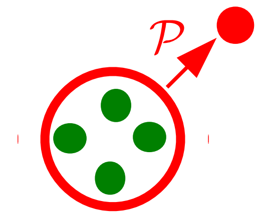

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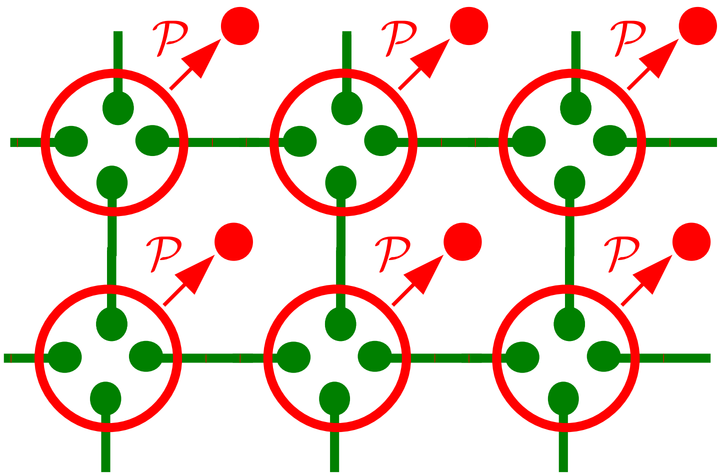

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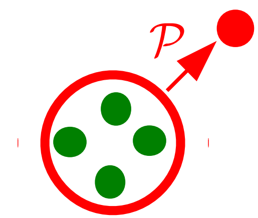

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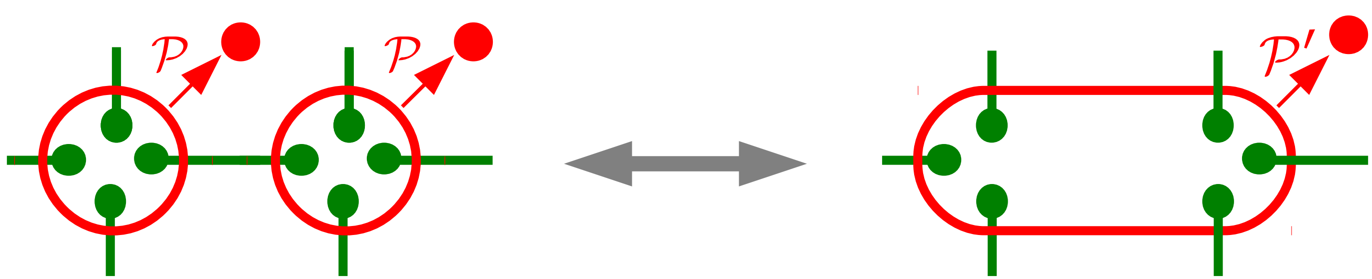
- flexibility in description: **blocking of sites**



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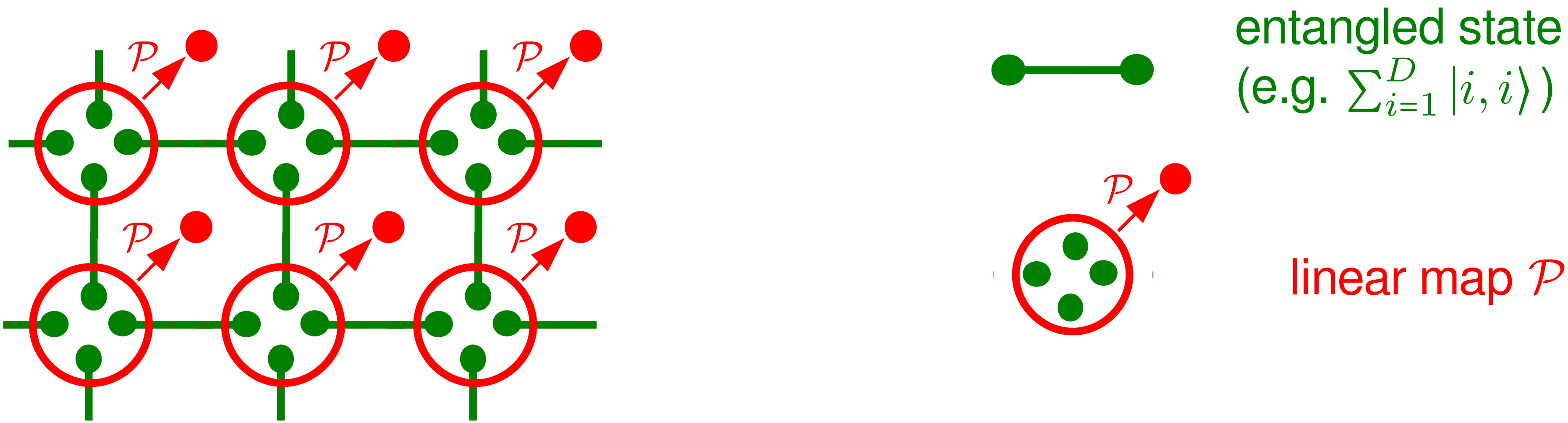

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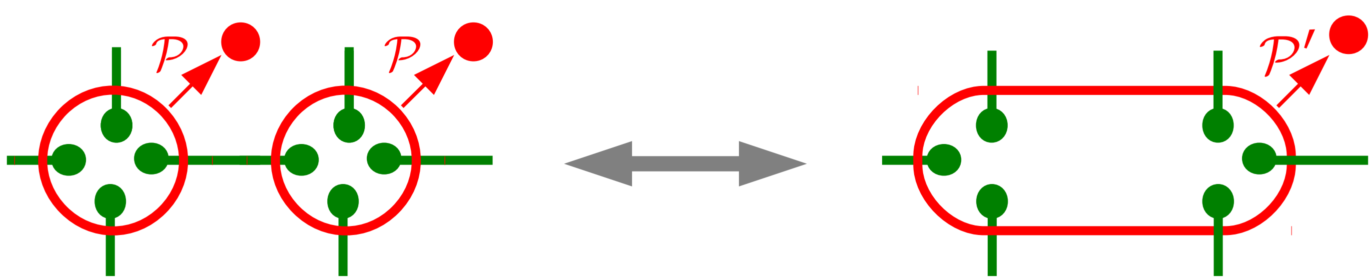

• Relation to **Hamiltonians**? Unique or **topological ground state**?

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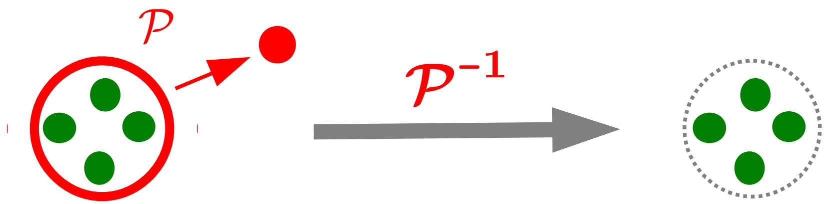

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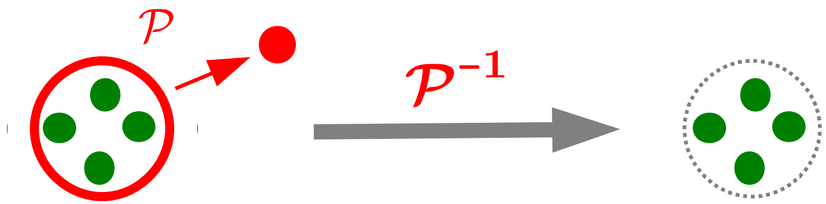

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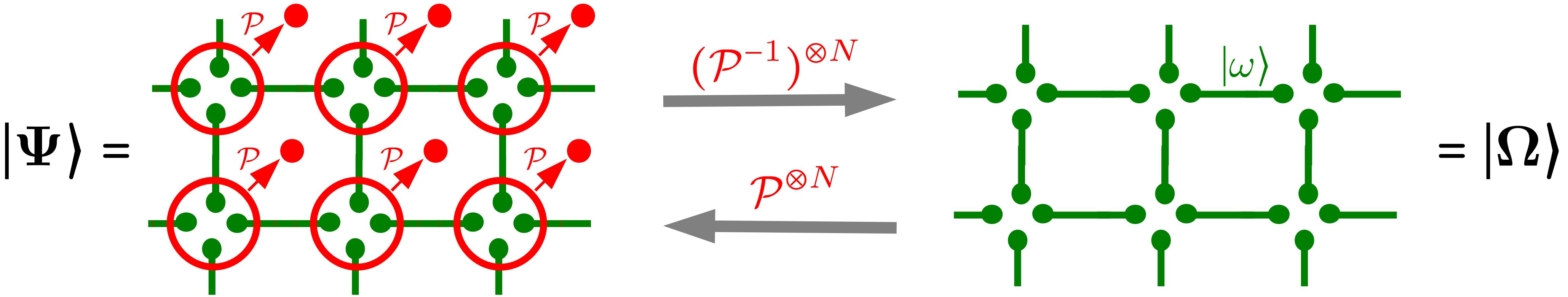

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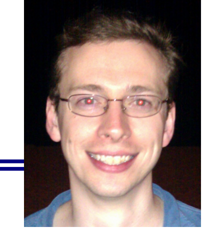

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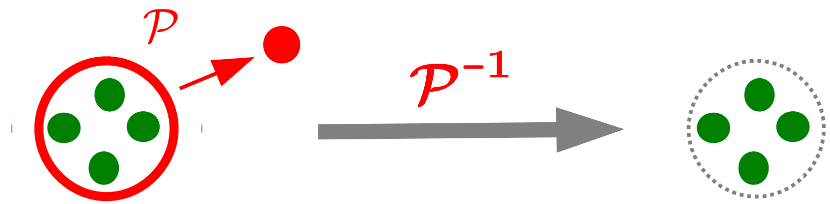

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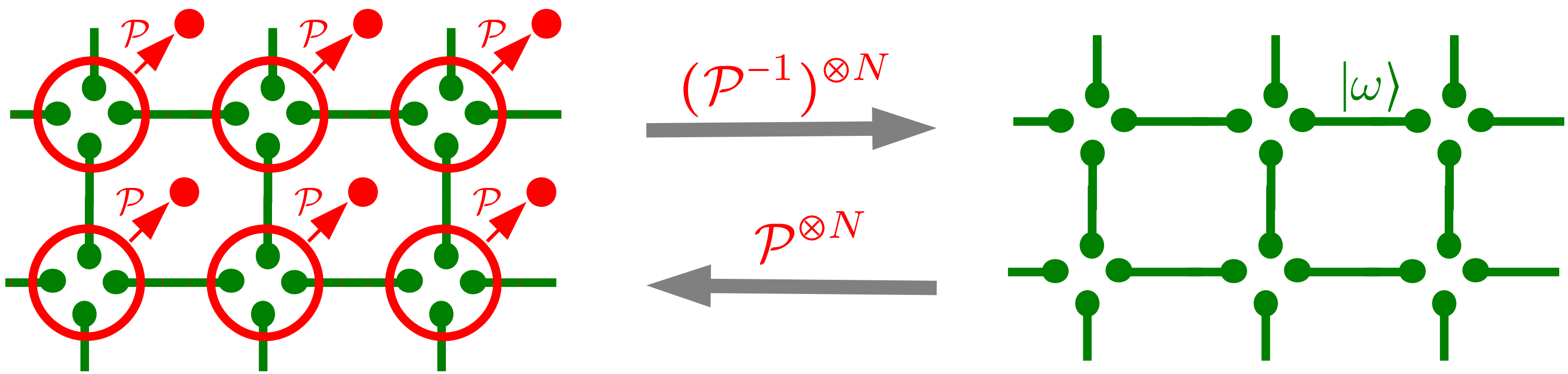
$|\Psi\rangle =$  $= |\Omega\rangle$

- entangled states $|\Omega\rangle$ unique ground state of local Hamiltonian

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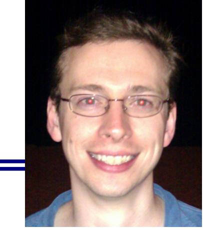

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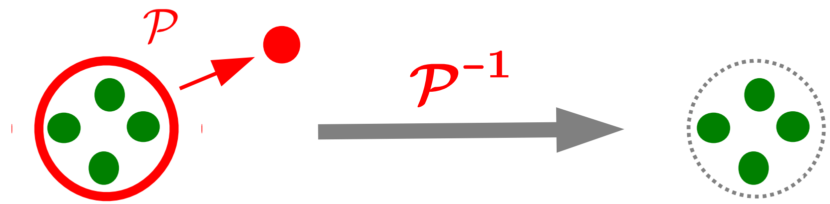

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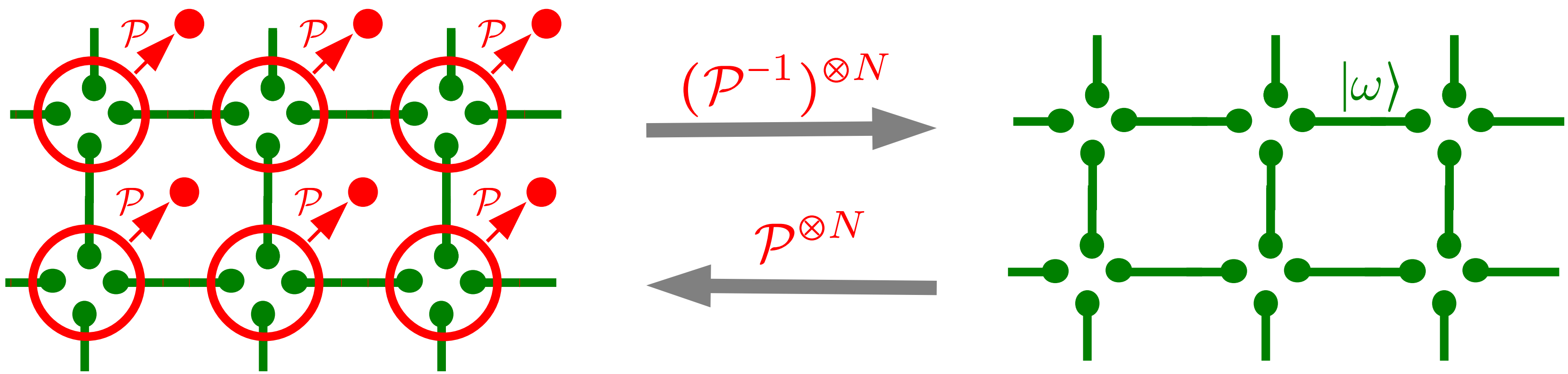

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$\Rightarrow$ PEPS $|\Psi\rangle$ **unique ground state** of local **"parent Hamiltonian"** $H' = \sum h'$,

$$\boldsymbol{h' = (\mathcal{P}^{-1} \otimes \mathcal{P}^{-1})^{\dagger} h (\mathcal{P}^{-1} \otimes \mathcal{P}^{-1})} \ : \quad h' \geq 0, \qquad h'|\Psi\rangle = 0$$

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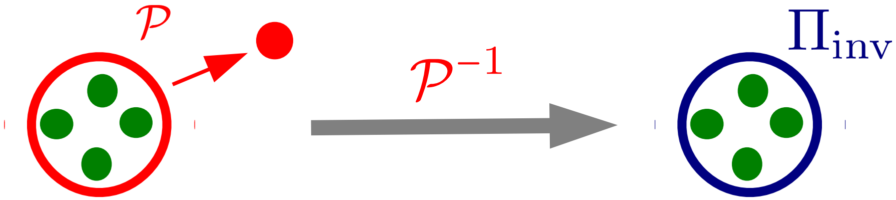

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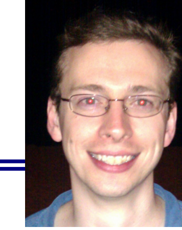

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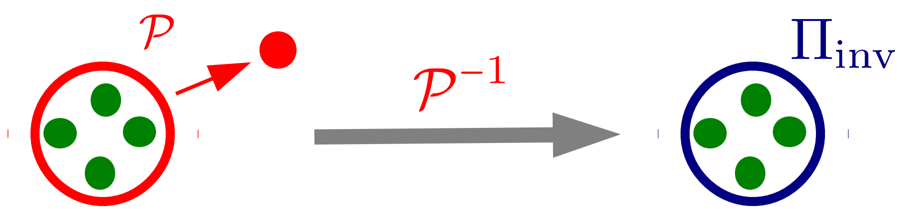

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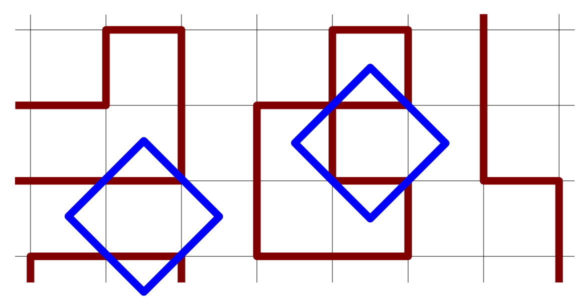

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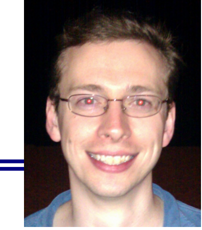

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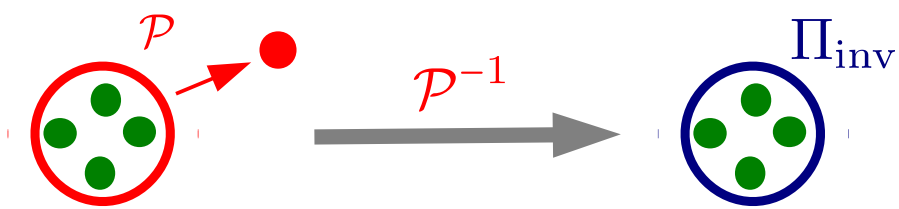

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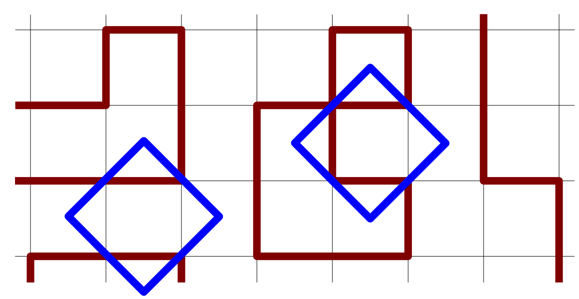

- G-injectivity $\Rightarrow$ PEPS is ground state of **local parent Hamiltonian** with **topological ground space degeneracy**
  (Proof: e.g. for $\mathbb{Z}_2$-injectivity $\to$ reversible mapping to Toric Code state + Hamiltonian)
- structure of ground space etc. is inherited from Toric Code

PEPS representation of the RVB state

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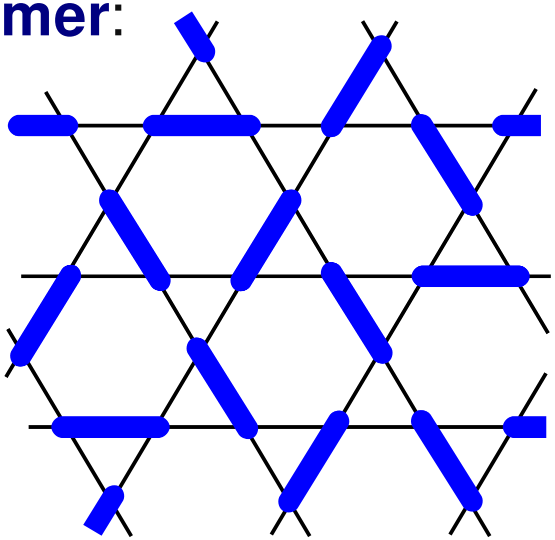

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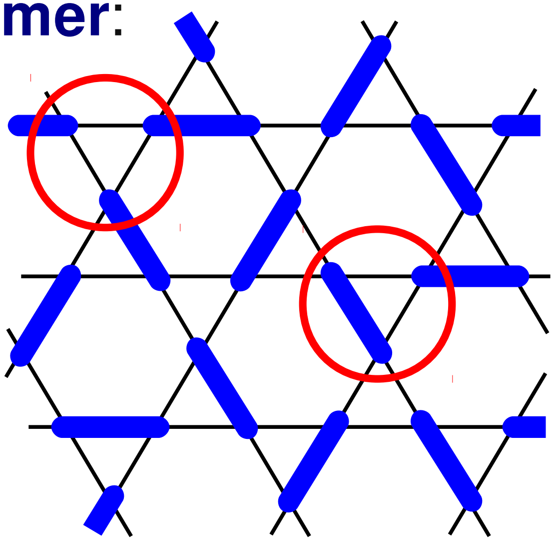

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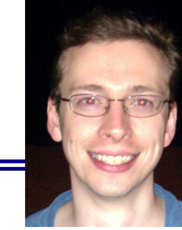

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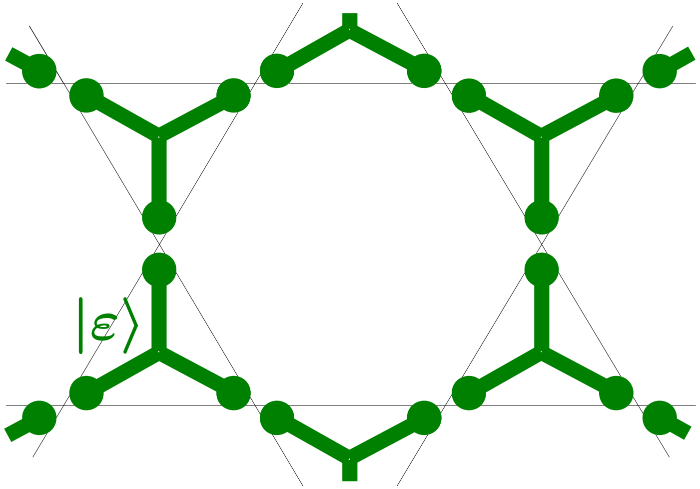

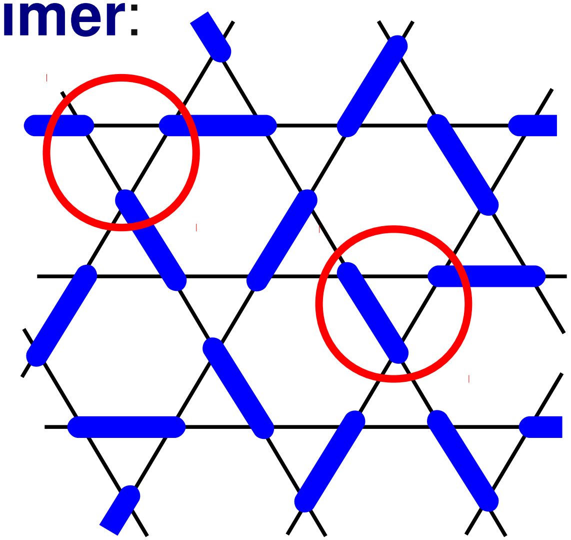

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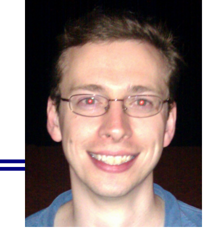

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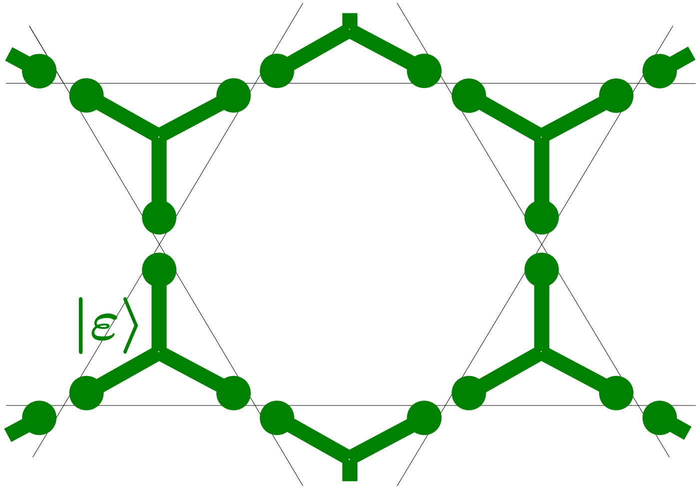
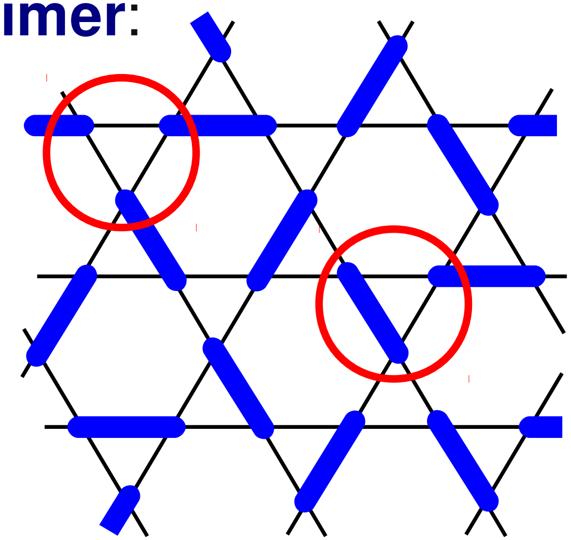


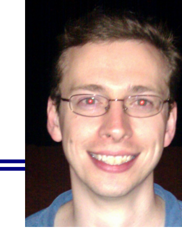


$|0\rangle, |1\rangle$: spin-$\frac{1}{2}$ subspace

- Triangles have **no or one singlet:**

$|2\rangle$: “no singlet” tag

$$|\epsilon\rangle = \frac{1}{\sqrt{2}} \sum \epsilon_{ijk} |ijk\rangle + |222\rangle = \frac{1}{\sqrt{2}} (|01\rangle - |10\rangle)|2\rangle + \mathrm{perm.} + |222\rangle$$



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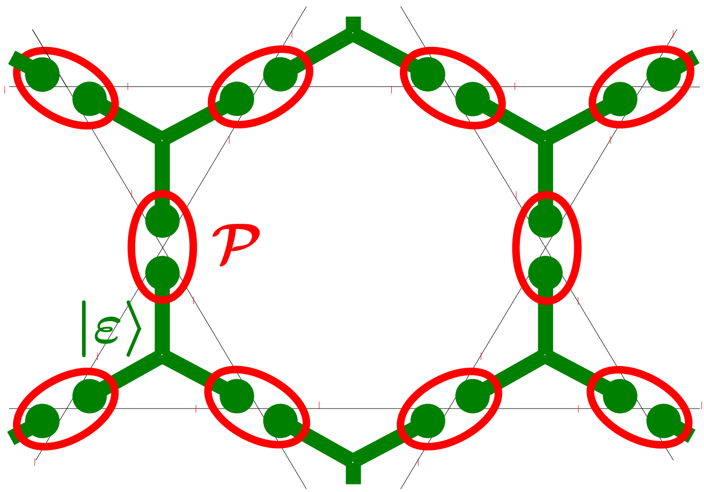

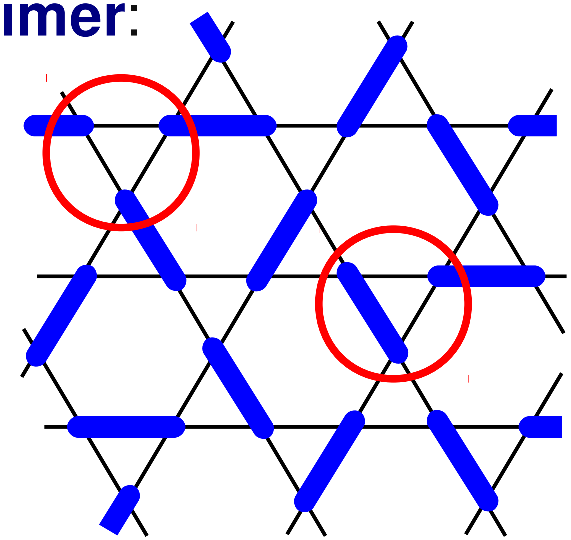

$|0\rangle, |1\rangle$: spin-$\frac{1}{2}$ subspace

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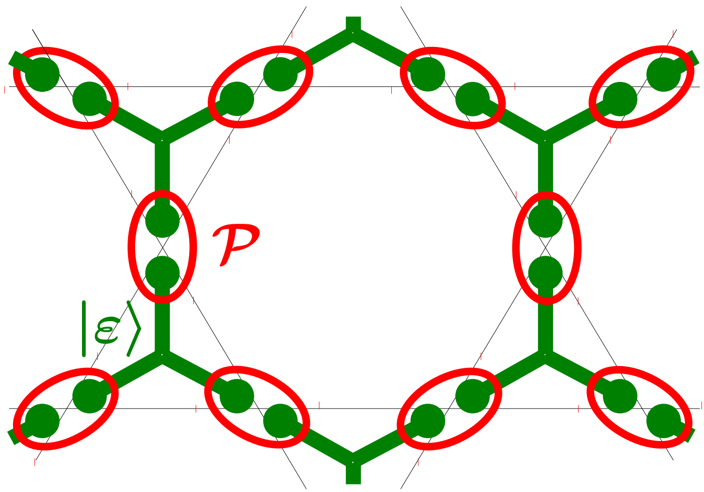

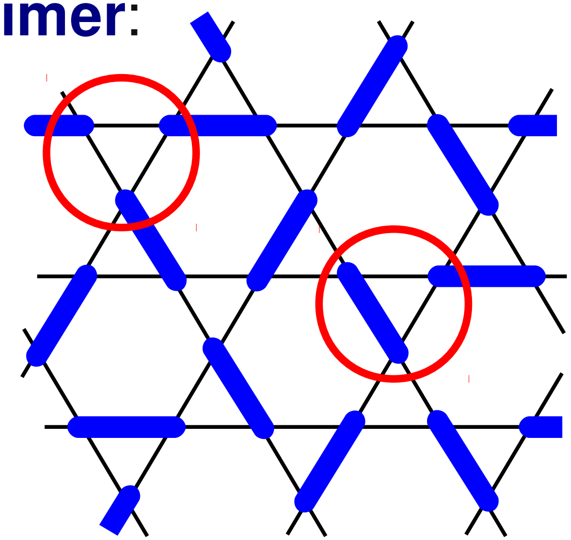

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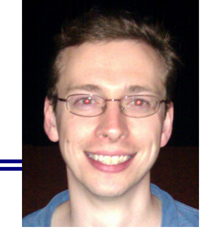

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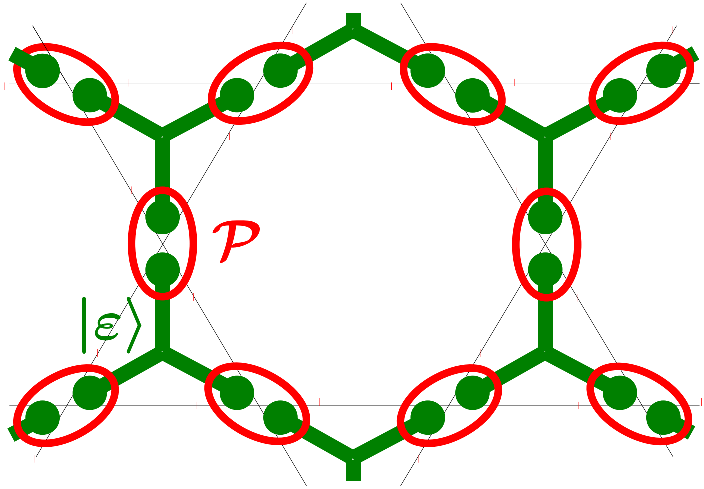

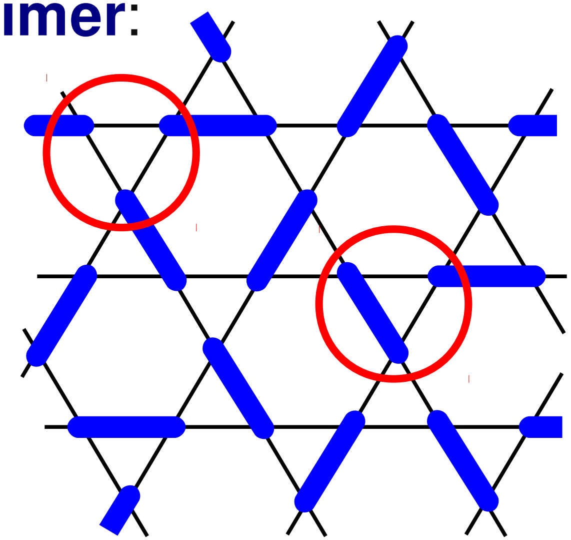

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Relating RVB and Toric Code

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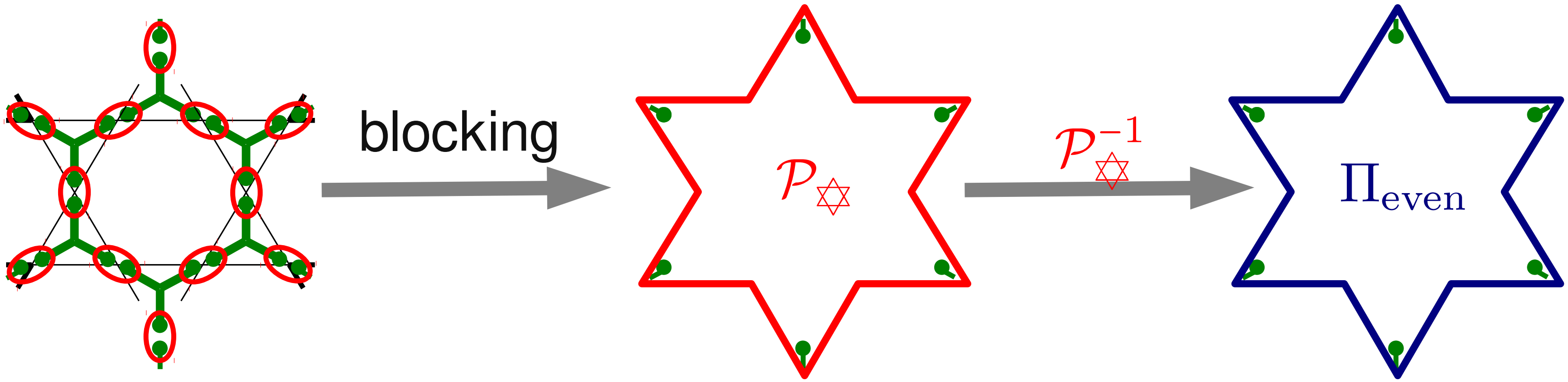

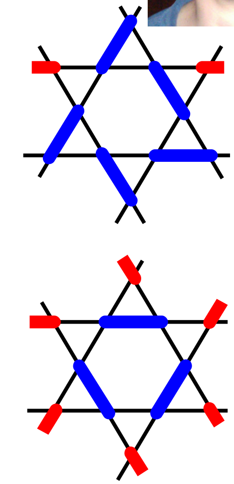

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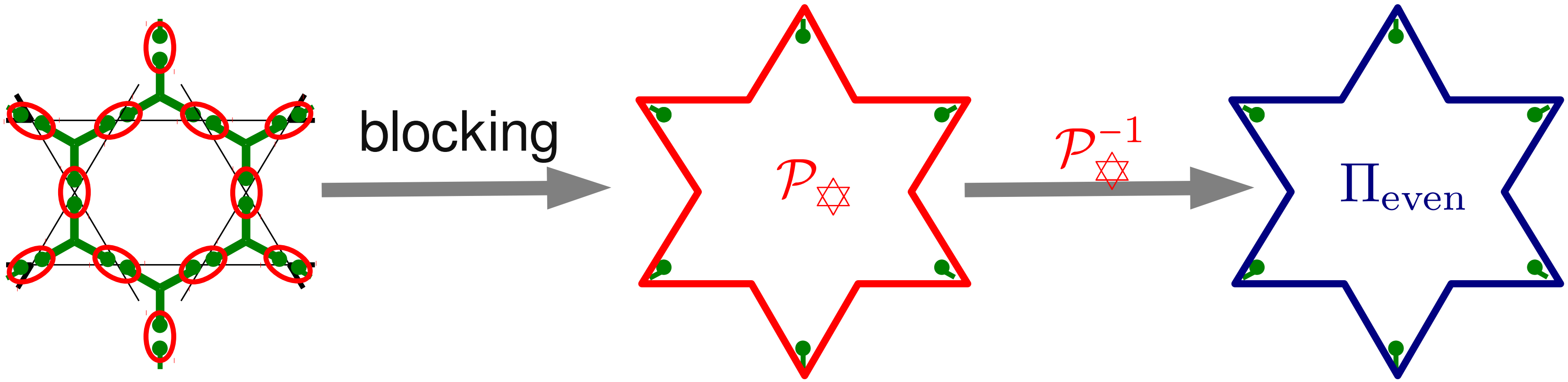

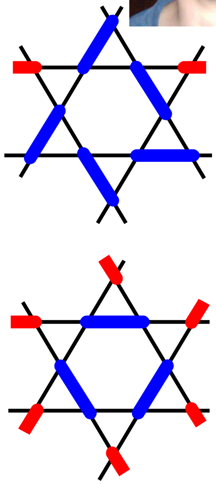

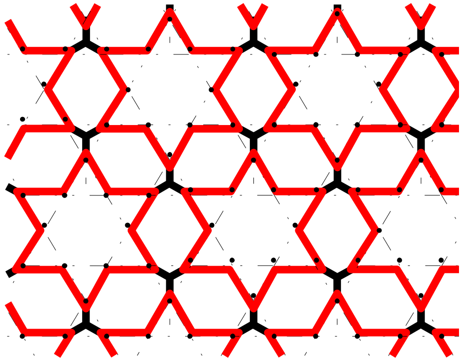

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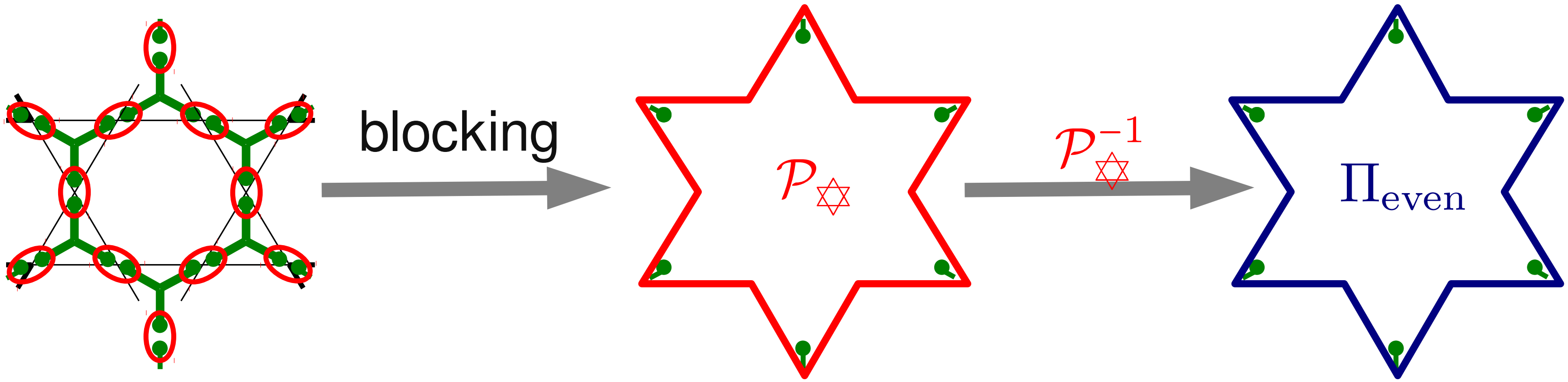

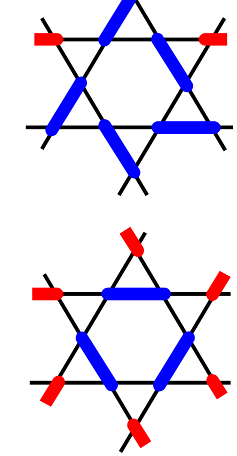

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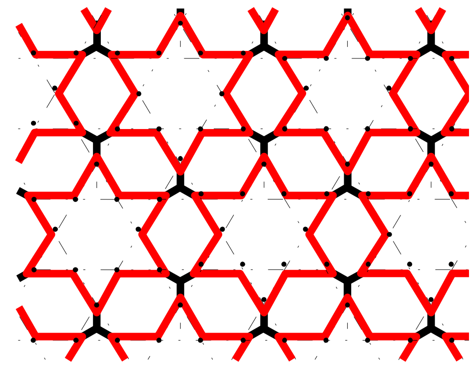

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- Hamiltonian for Toric Code $\Rightarrow$ Ham. for dimer state $\Rightarrow$ **Hamiltonian for RVB**
- **Parent Hamiltonian** with **topological** ground space structure!

Analytical results

- **Resonating Valence Bond** state (RVB):
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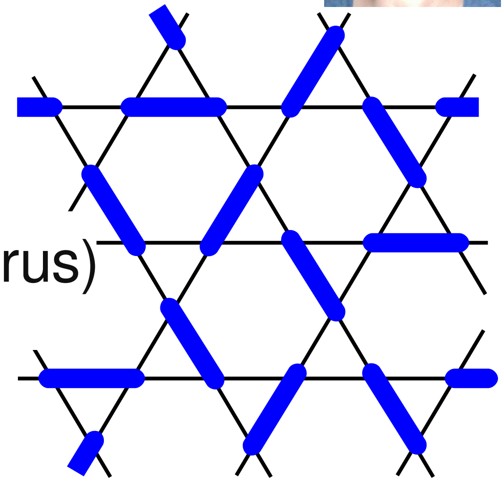

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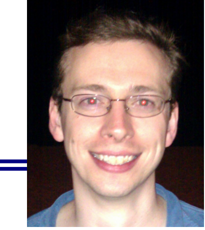

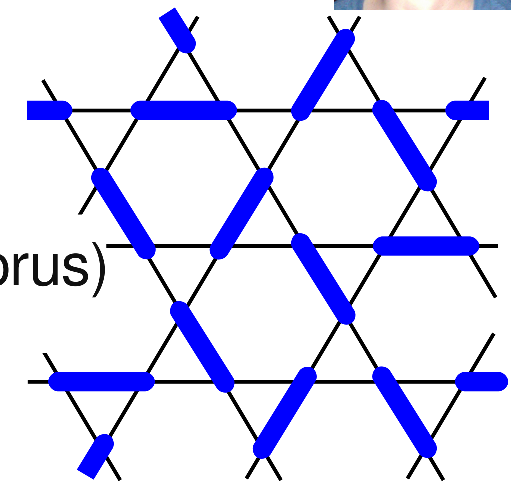

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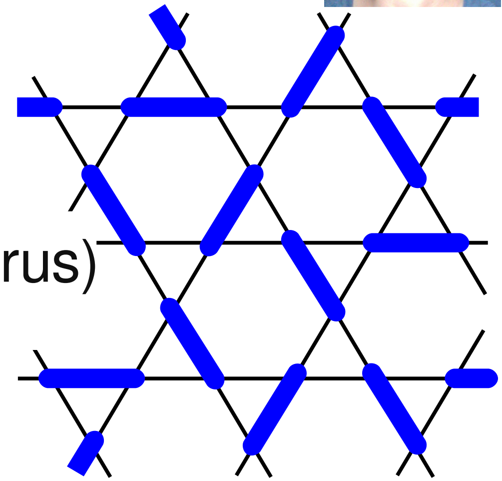

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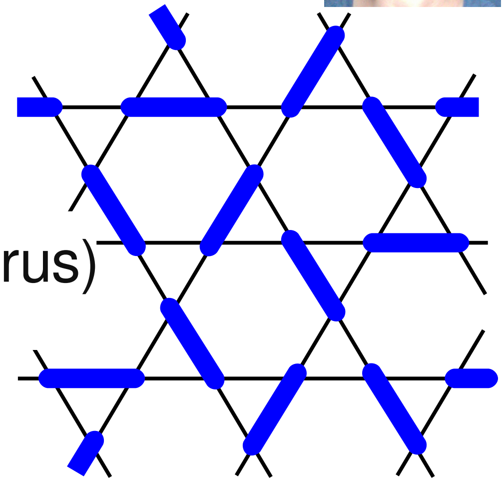

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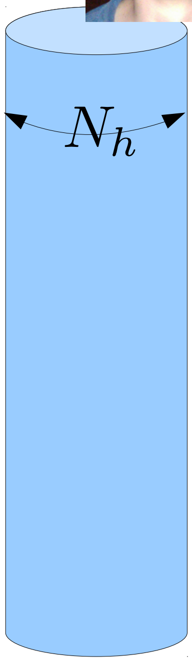

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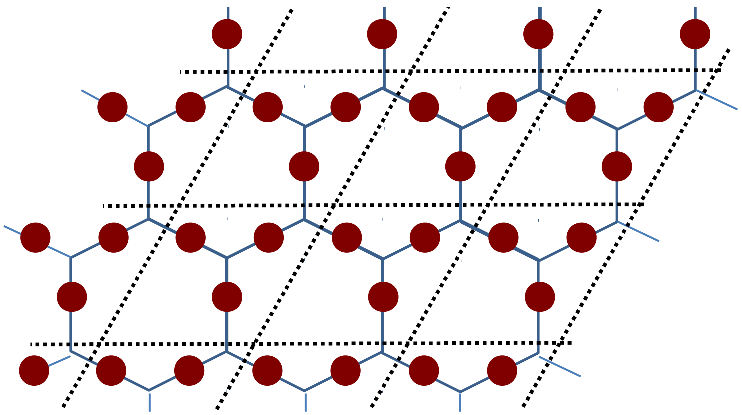

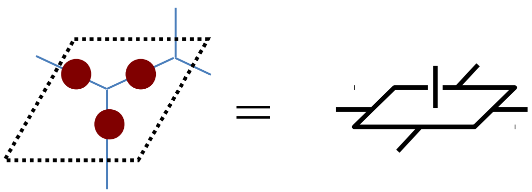

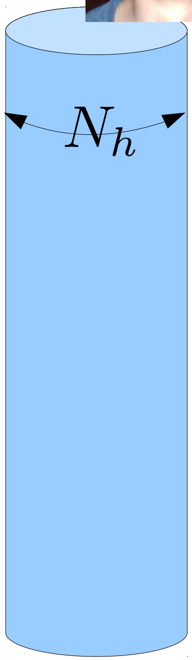

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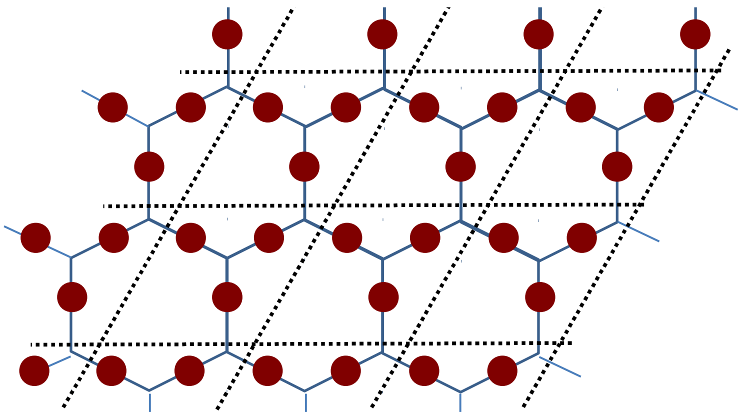

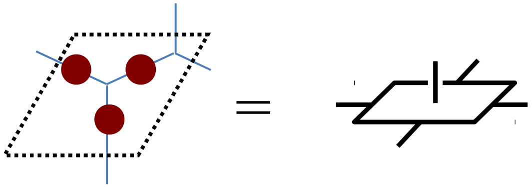

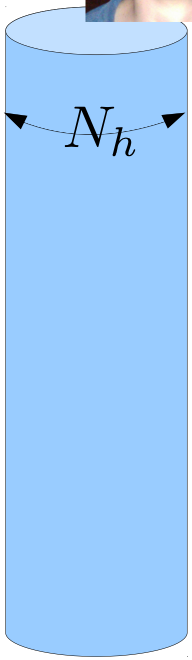

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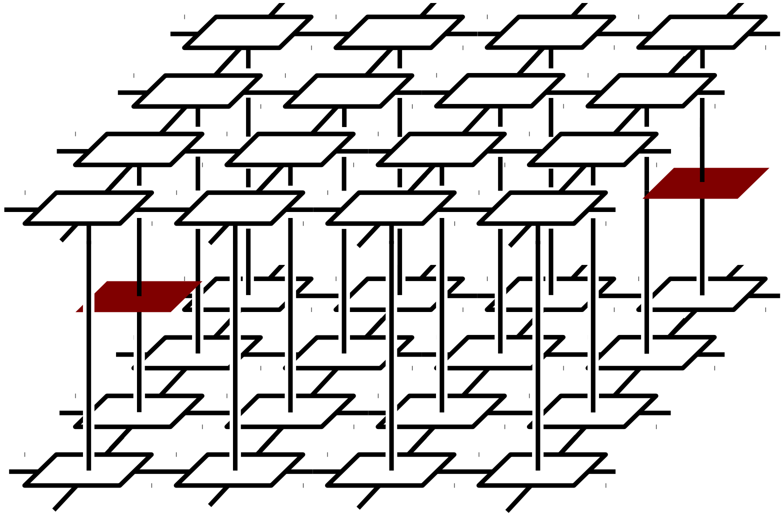

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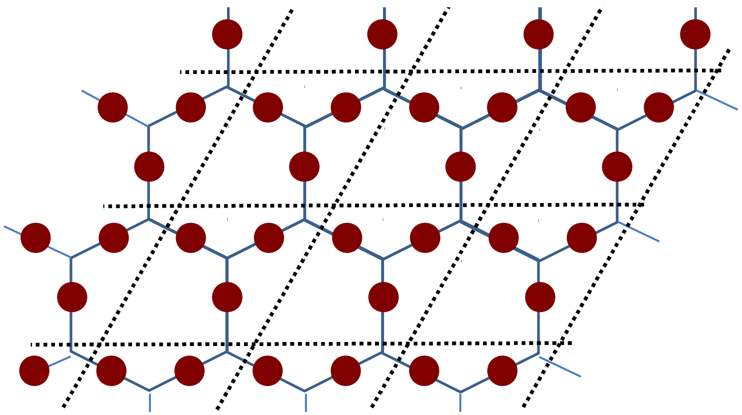

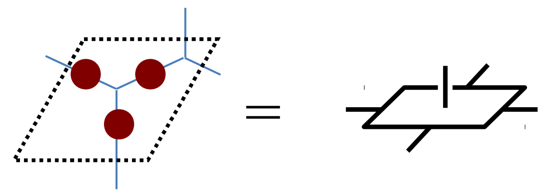

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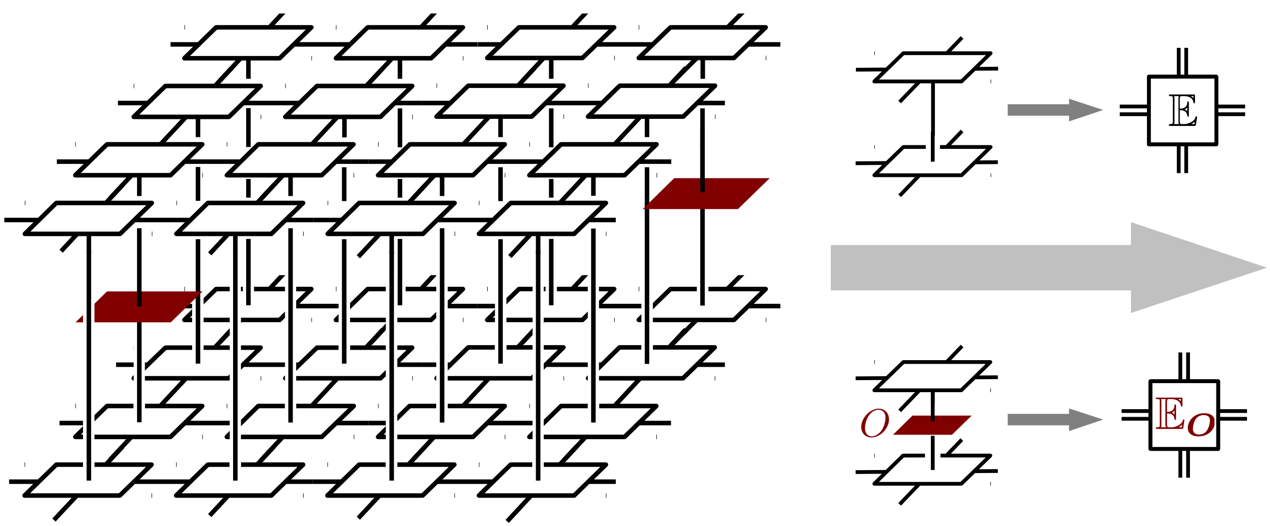

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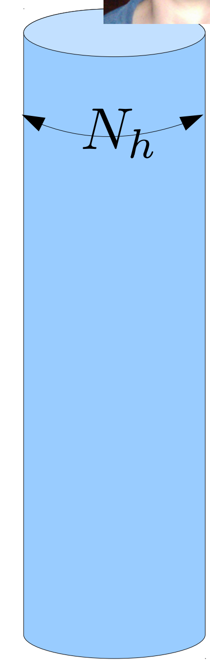

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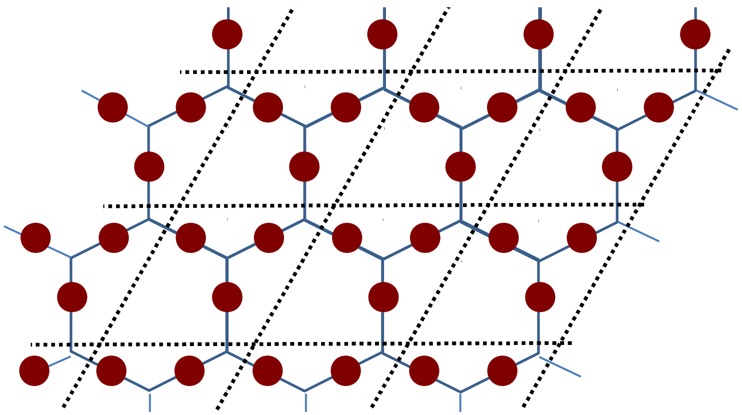

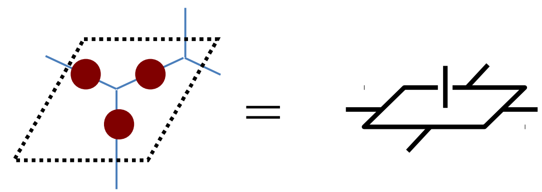

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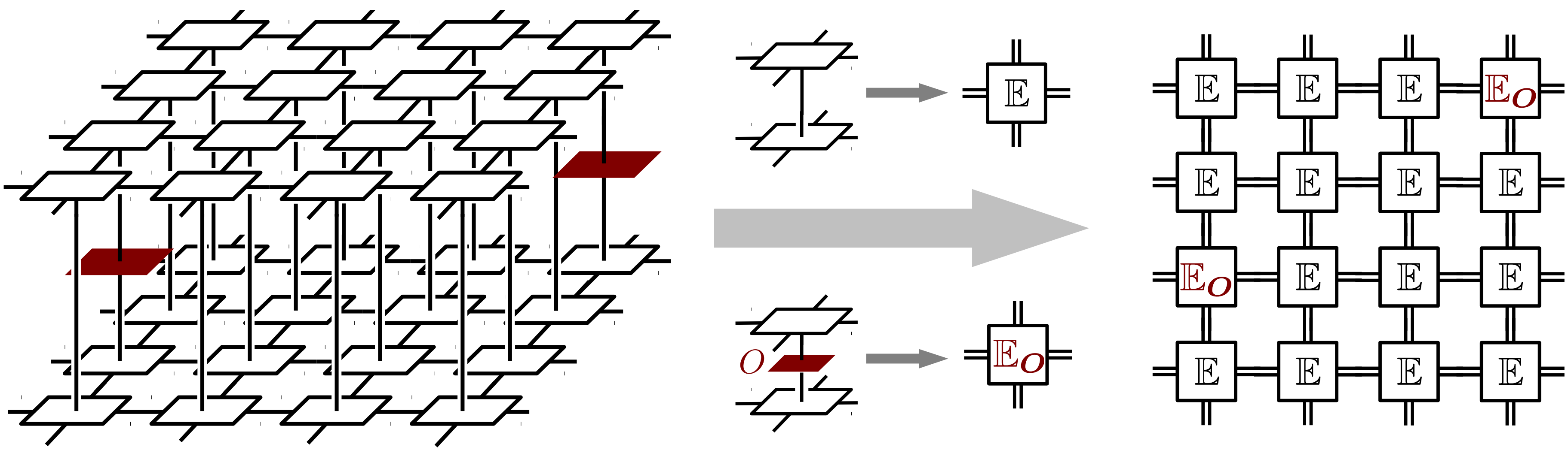

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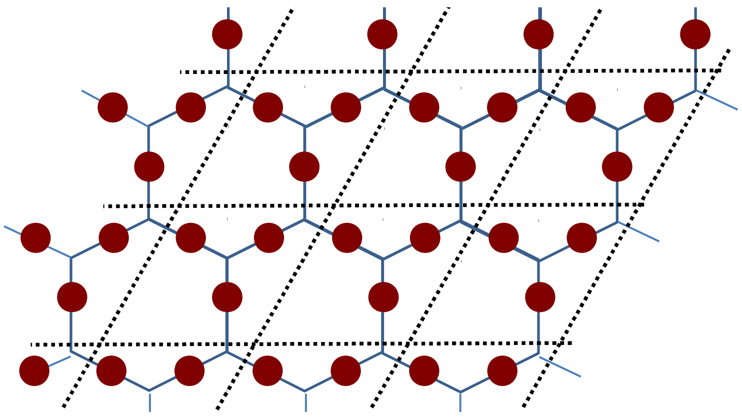

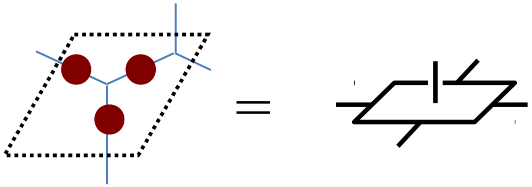

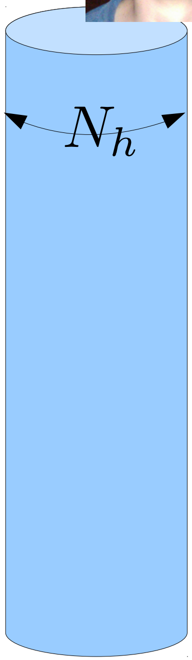

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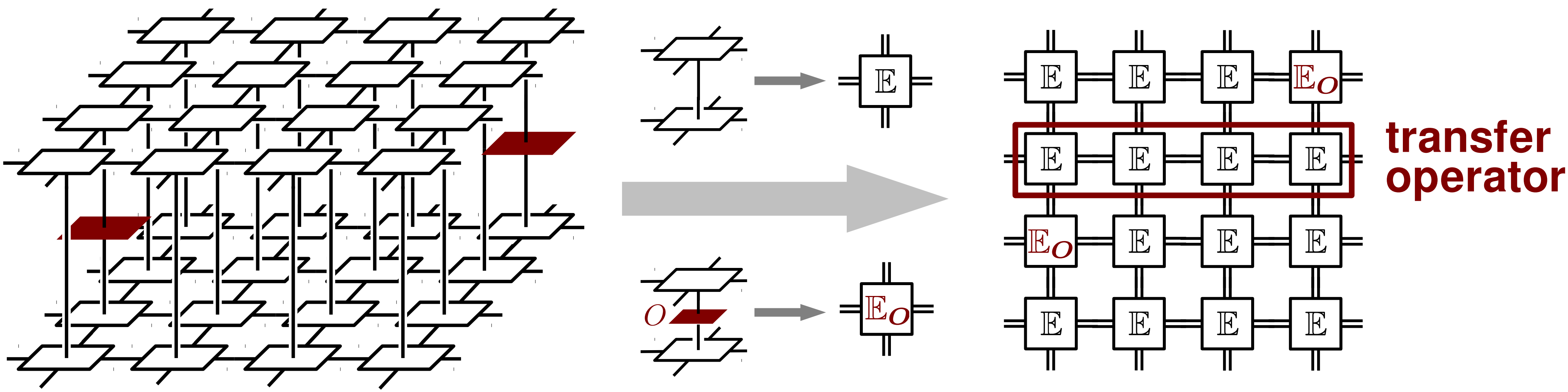

Numerical result: RVB is topological spin liquid

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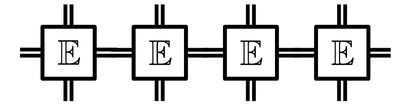

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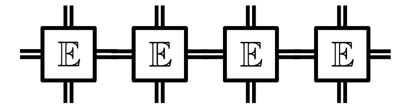

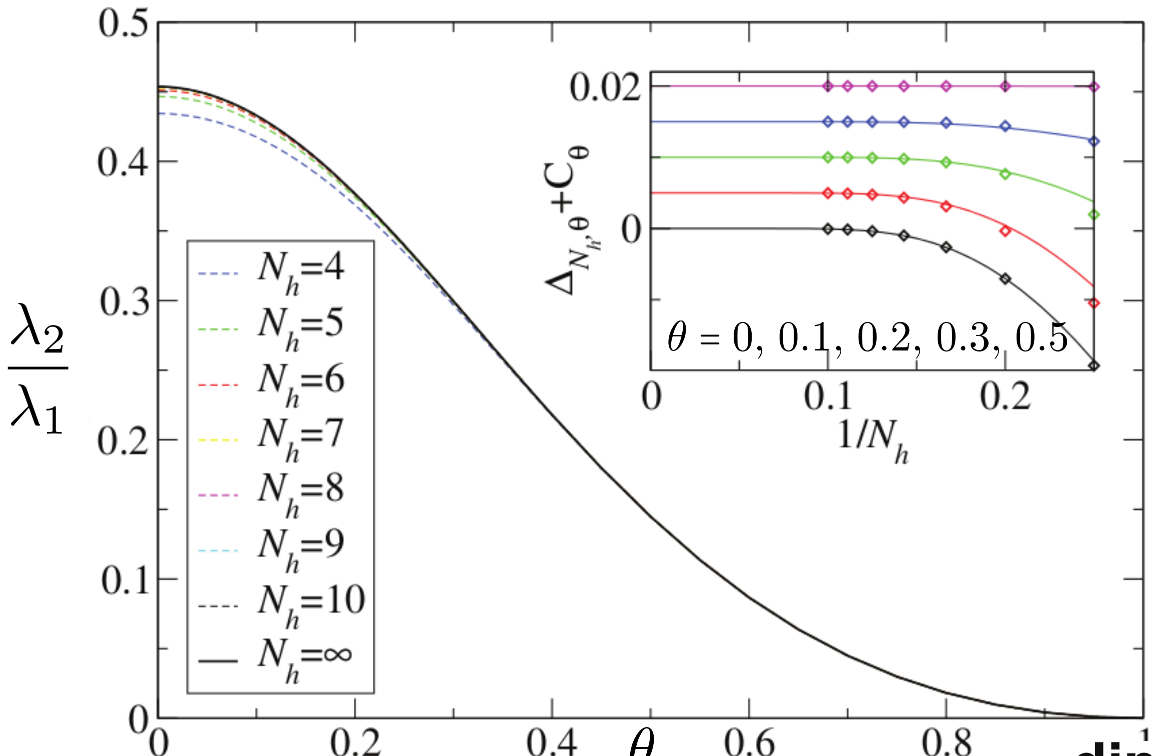

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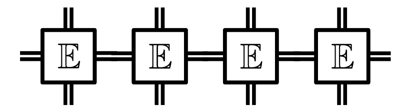

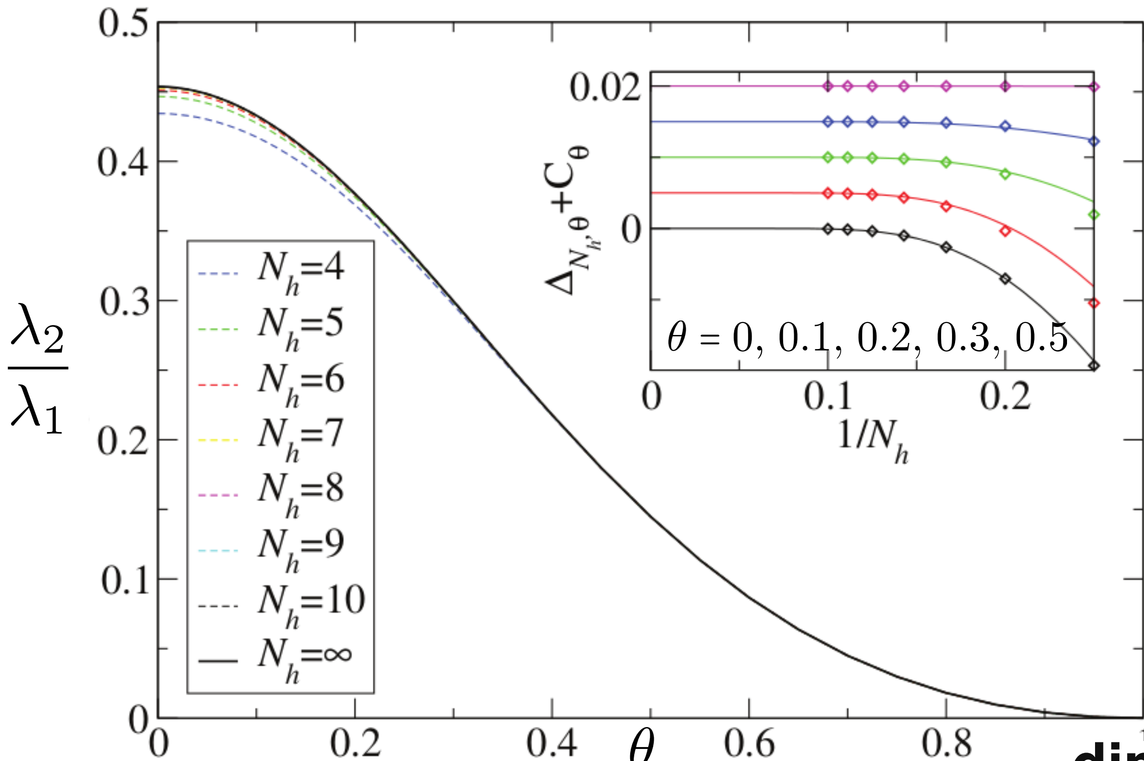

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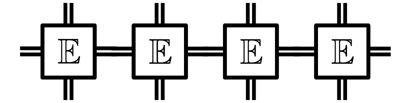

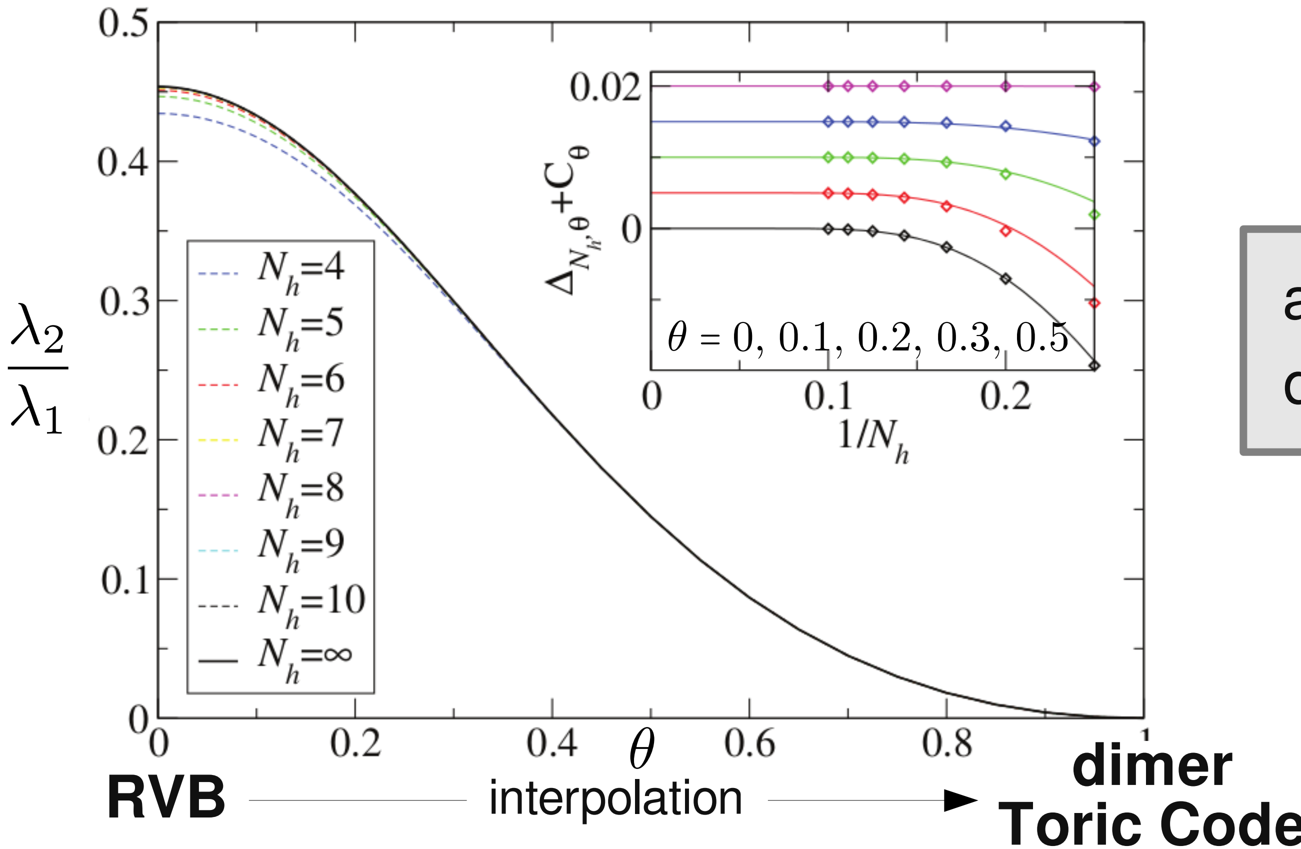

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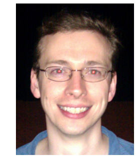
  $\Rightarrow$ RVB is **spin liquid** (=no kind of long-range order)!
- **no divergence** along interpolation $\Rightarrow$ **RVB** is in **same phase as Toric Code**!

Summary



- kagome RVB: ground state of **parent Hamiltonian** with **topologically degenerate ground space**
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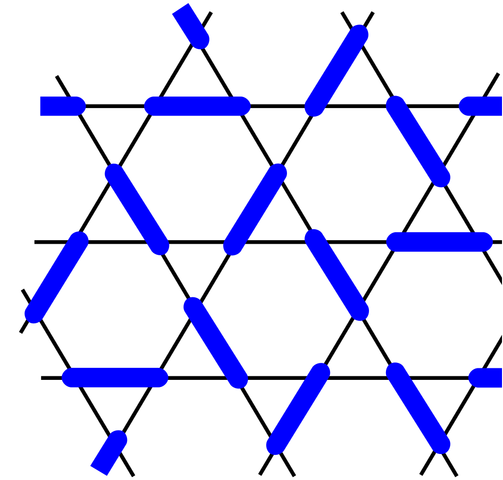

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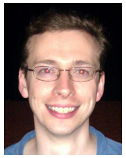
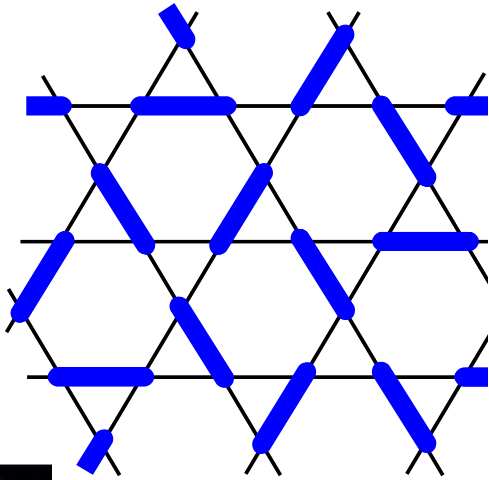
- kagome RVB: ground state of **parent Hamiltonian** with **topologically degenerate ground space** 



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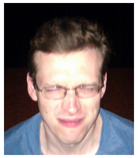
- **Numerical study**: Compelling evidence that **RVB is spin liquid** (= has no long-range order), and is in the same phase as the Toric Code 

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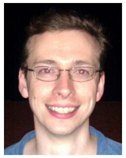

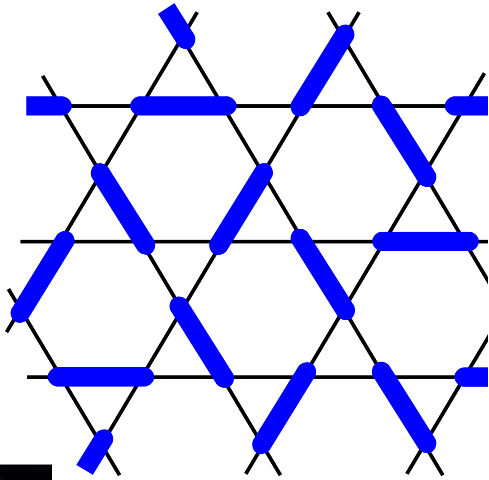

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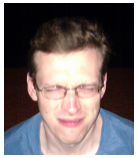

- Tools from quantum information can help us resolve open questions in condensed matter physics ...

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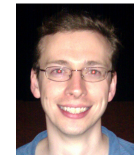
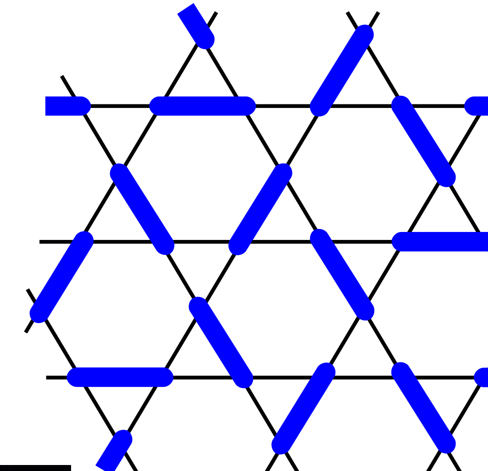
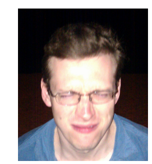
- kagome RVB: ground state of **parent Hamiltonian** with **topologically degenerate ground space**





- tool: $\mathbb{Z}_2$**-injectivity** $\Leftrightarrow$ invertible **mapping to Toric Code**

- **Numerical study**: Compelling evidence that **RVB is spin liquid** (= has no long-range order), and is in the same phase as the Toric Code



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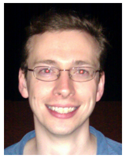

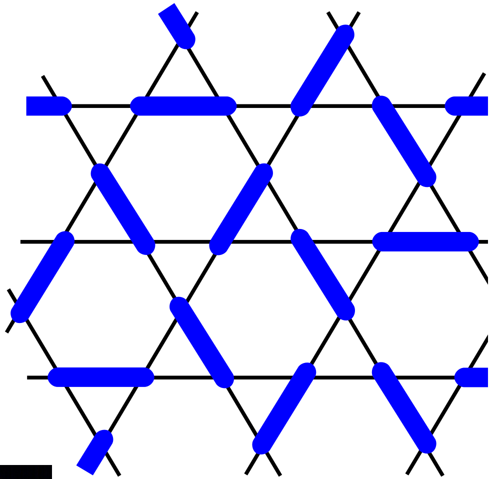

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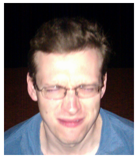

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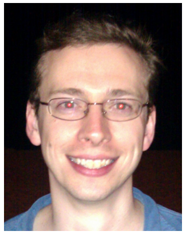

Thank you!