Topological Phases in Polar-Molecule Quantum Magnets (and then overview & discussion)

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Institute for Quantum Information and Matter (IQIM), Caltech

(summer 2013)

Joint Quantum Institute (JQI)
NIST and University of Maryland

Postdoc and graduate student positions available!
(theoretical many-body physics,
quantum information, AMO physics)

KITP workshop on
Fundamental Science and Applications of Ultra-cold Polar Molecules
January 24, 2013

Topological Phases in Polar-Molecule Quantum Magnets

- symmetry protected topological phases [arXiv:1210.5518]:
  S. Manmana, K. Hazzard, A. M. Rey - JILA
  M. Stoudenmire - UCI

- fractional Chern insulators [PRL 109, 266804 (2012) & arXiv:1212.4839]:
  N. Yao, C. Laumann, S. Bennett, E. Demler, M. Lukin - Harvard
  A. Läuchli, P. Zoller - Innsbruck
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Motivation

Interacting dipoles

Electric

Magnetic

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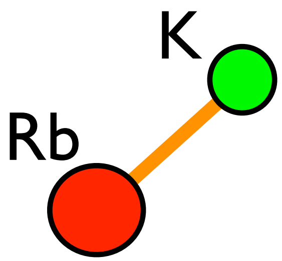

polar molecules

[Ye, Jin, Weidemuller,
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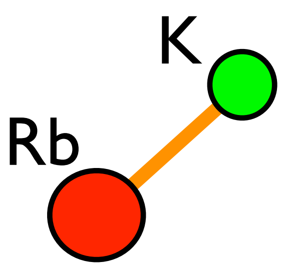

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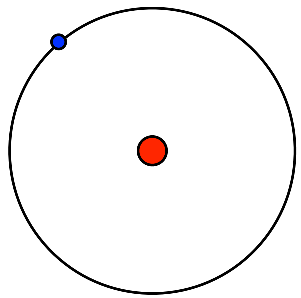

Rydberg atoms

[Grangier, Saffman, Pfau, Bloch, etc...]

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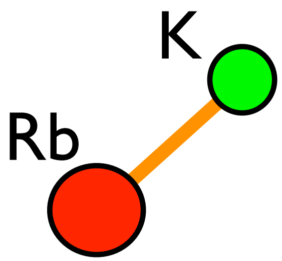

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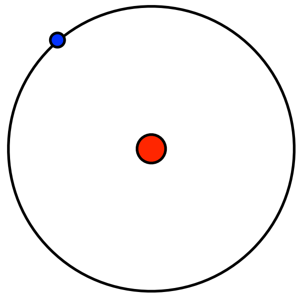

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large electronic angular momentum J

magnetic atoms (e.g. Dy, Er)

[Lev, Ferlaino, etc...]

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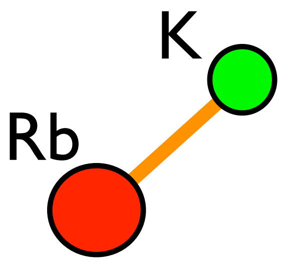

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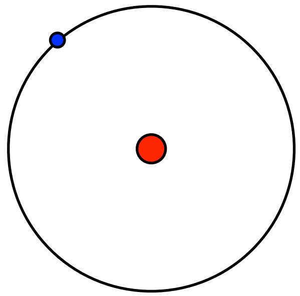

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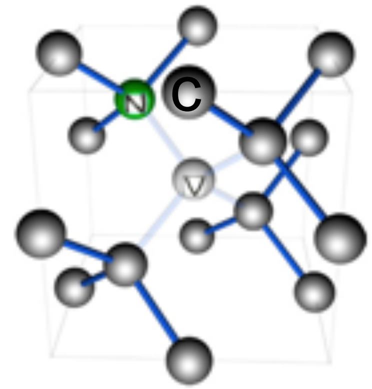

[drawn by Wrachtrup et al.]

NV centers

[Wrachtrup, Jelezko, Lukin, etc...]

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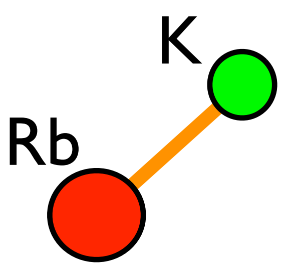

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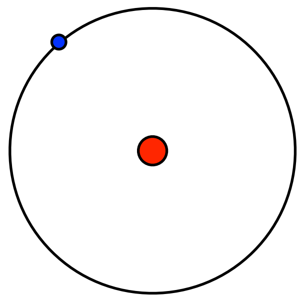

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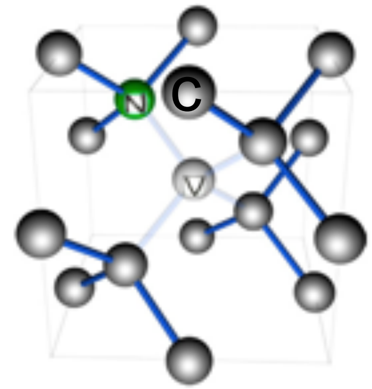

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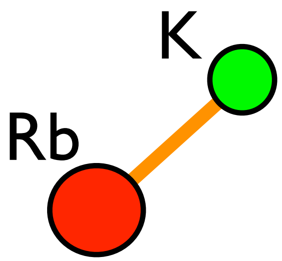

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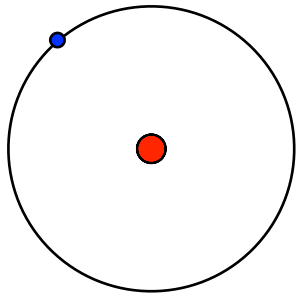

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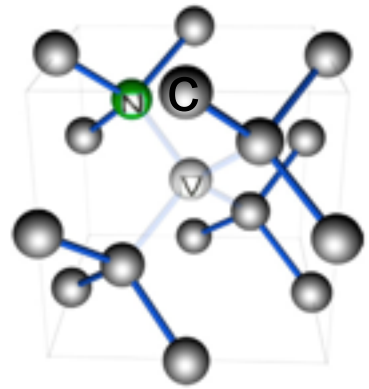

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- KRb already loaded into a 3D optical lattice at JILA!
  [Chotia et al, PRL (2012)]

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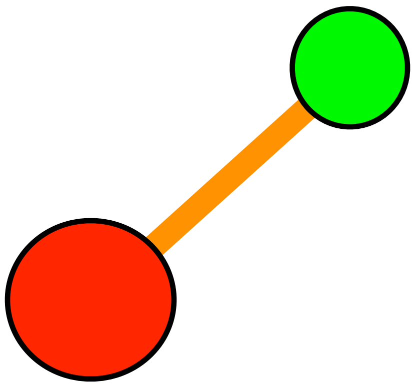

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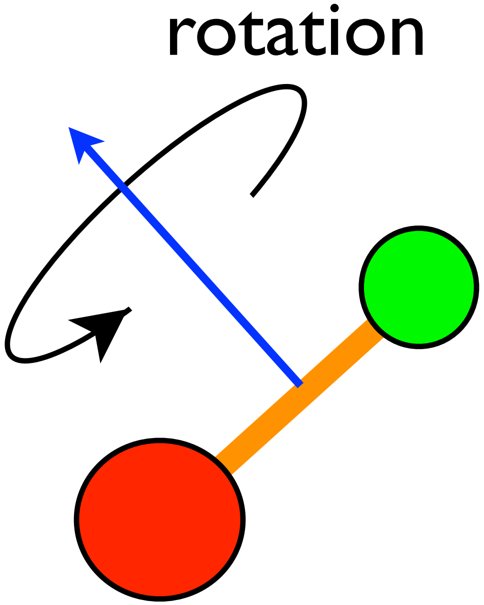

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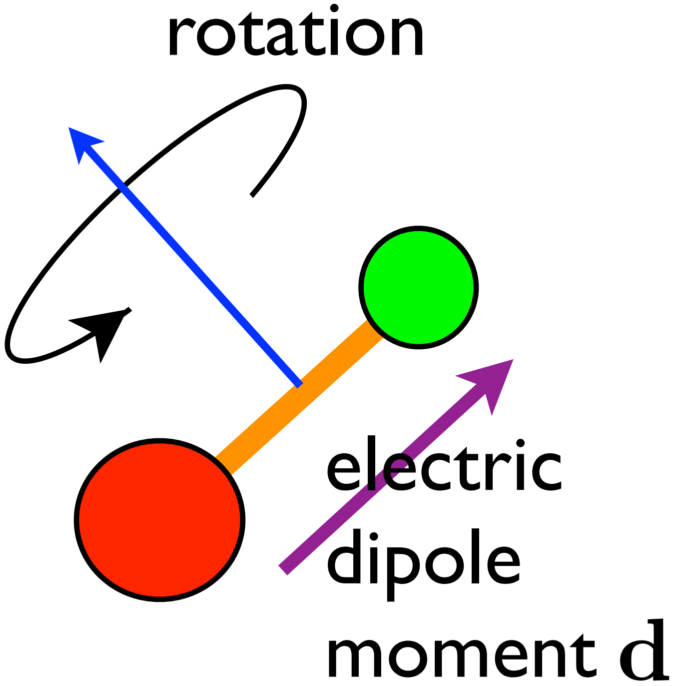

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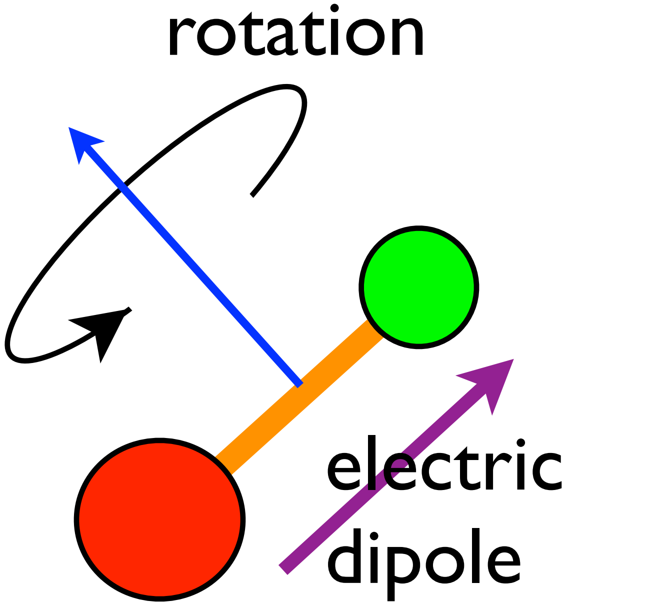

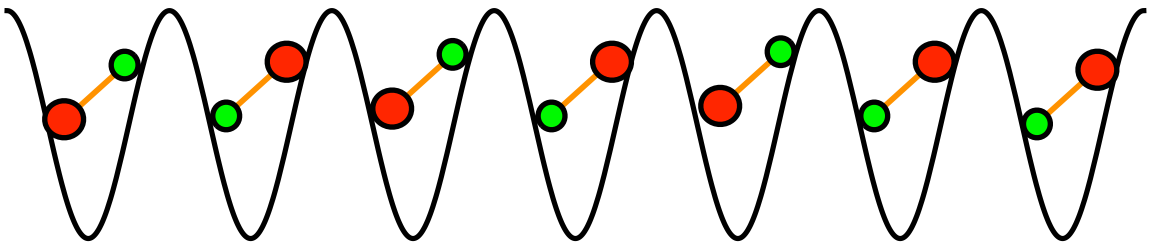

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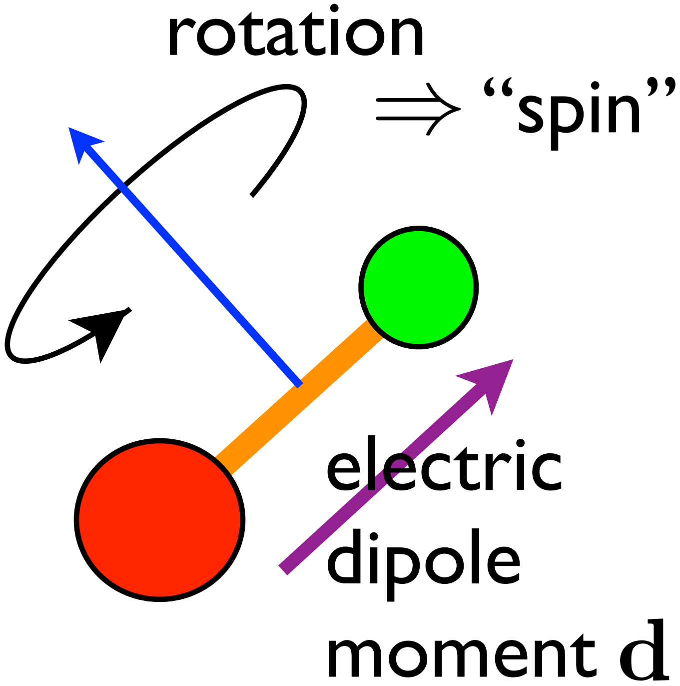

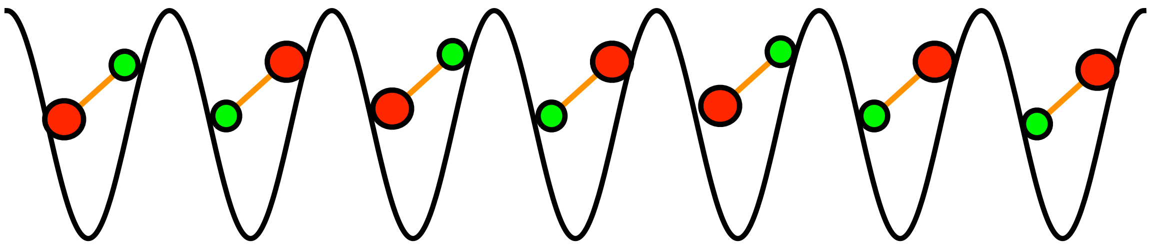

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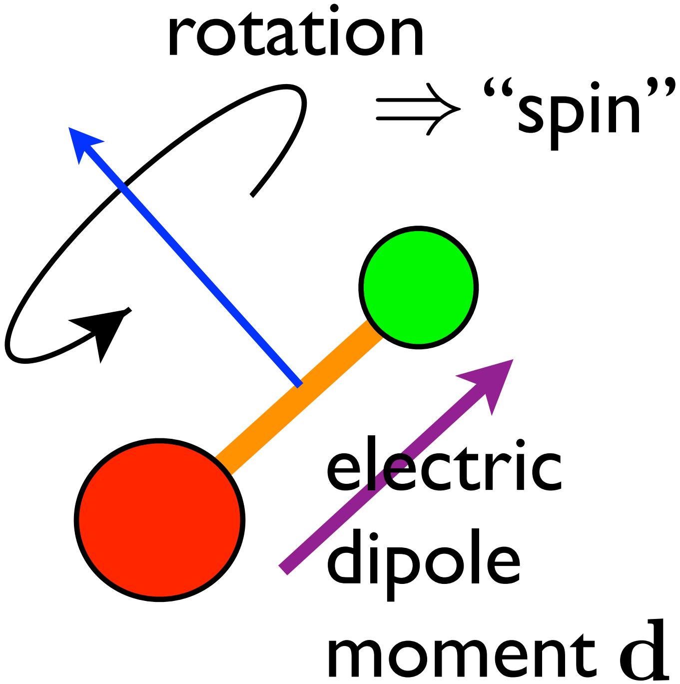

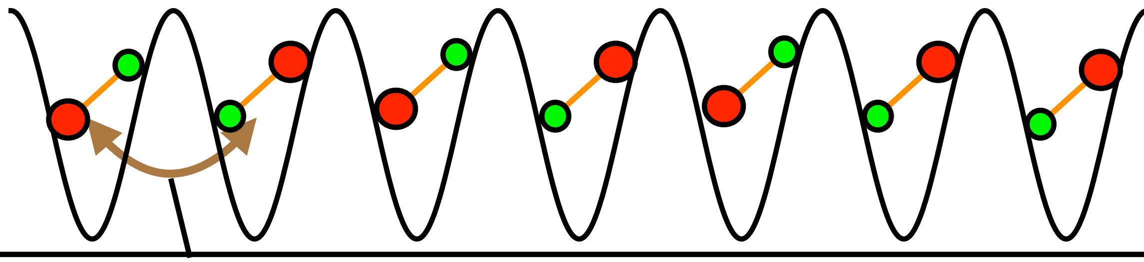

dipole-dipole interactions ⇒ "spin-spin" interactions

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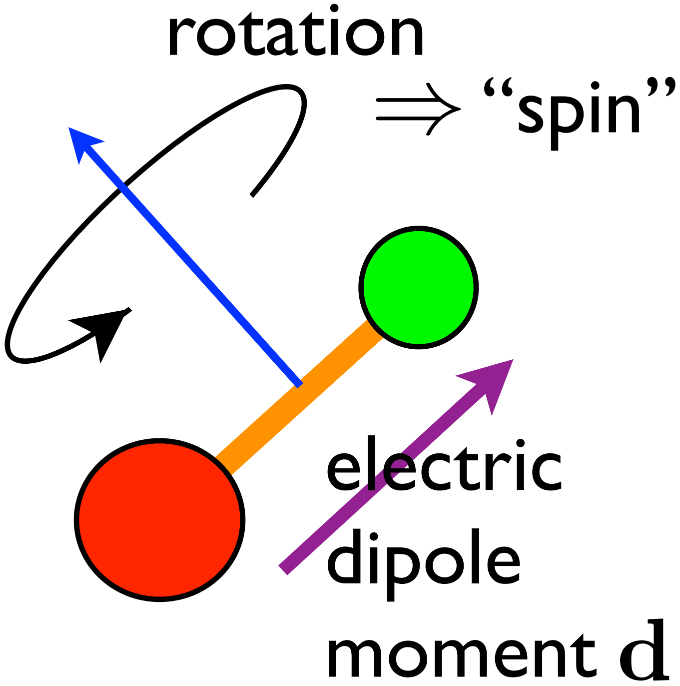
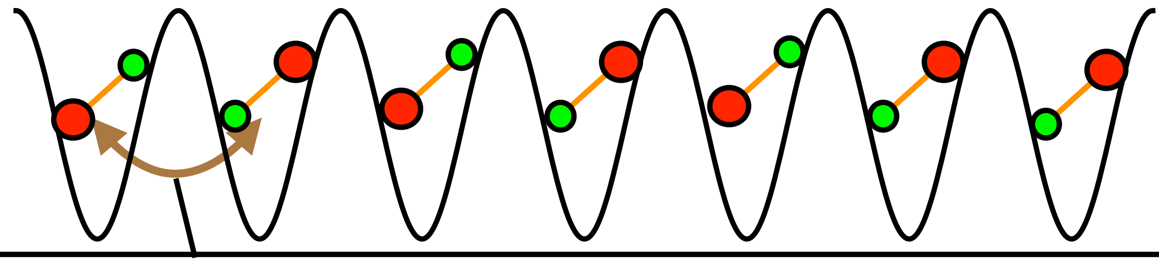


highly tunable exotic spin models



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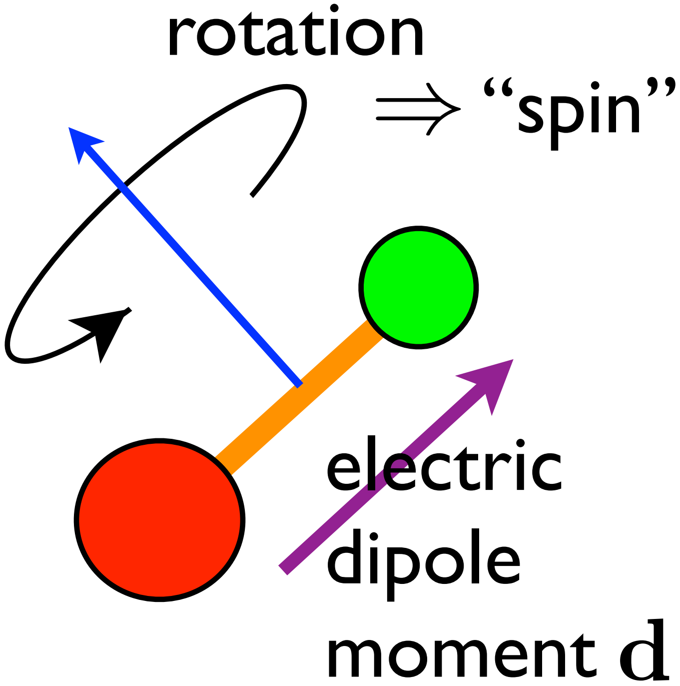

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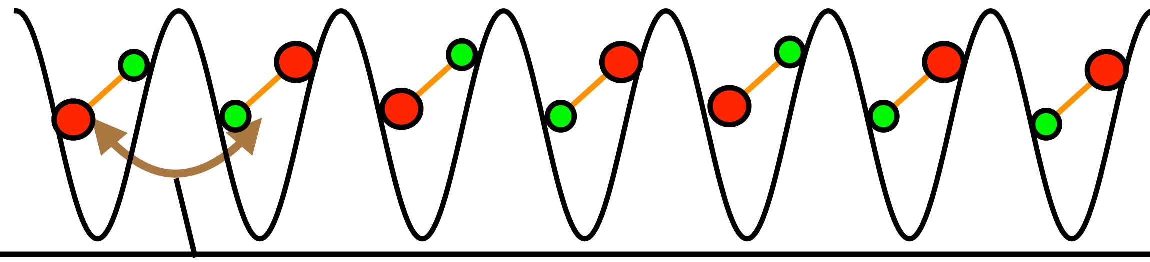

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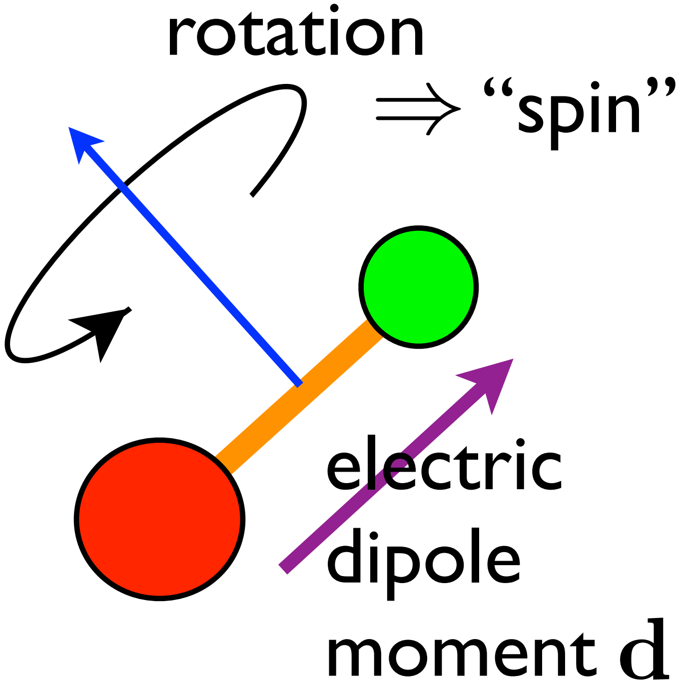
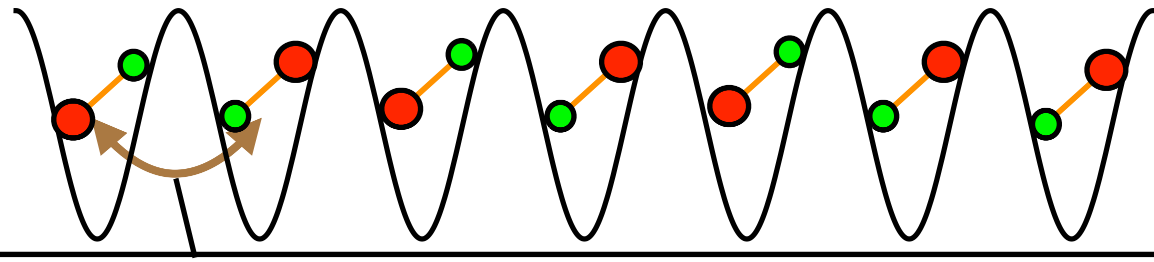


highly tunable exotic spin models

Our achievements:

- stronger interactions
- much higher tunability



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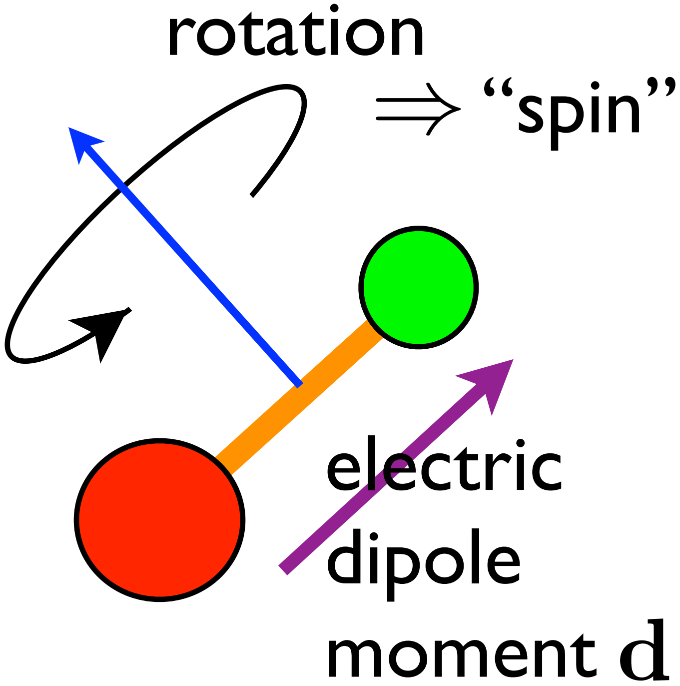
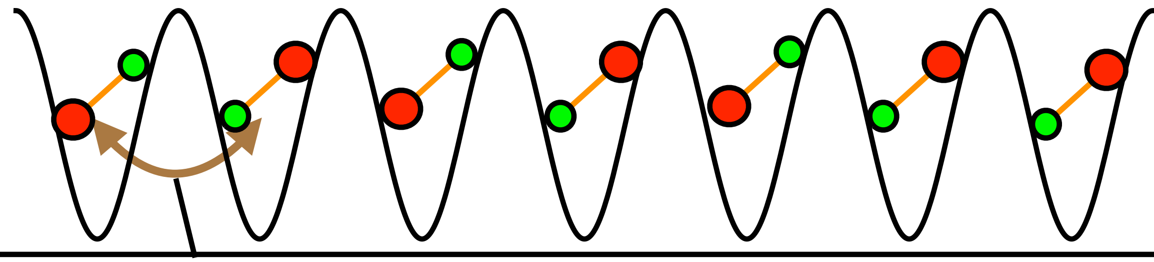


highly tunable exotic spin models

Our achievements:

- stronger interactions
- much higher tunability ⇒ exotic physics



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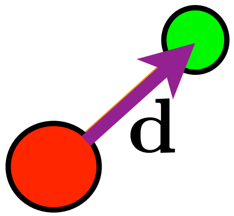
Rigid rotor

$$H_0 = B\mathbf{N}^2$$



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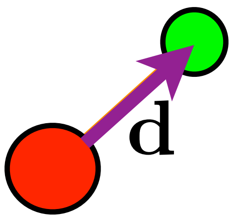
$$\mathbf{N}^2|N, N_z\rangle = N(N+1)|N, N_z\rangle$$



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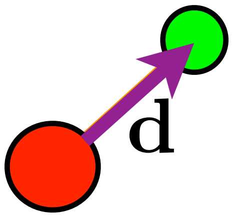

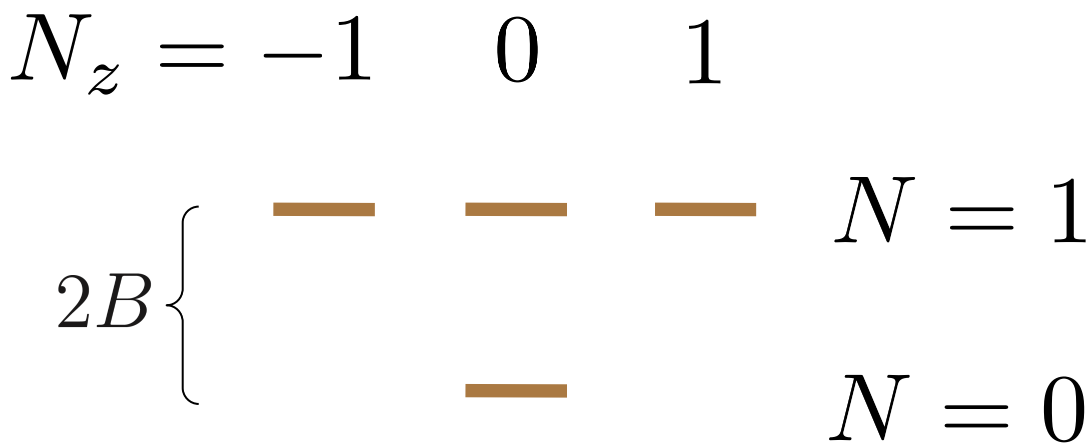

Rigid rotor

$$H_0 = B\mathbf{N}^2$$

$$\mathbf{E} = E\hat{\mathbf{z}}$$

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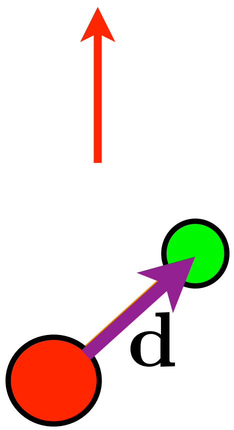
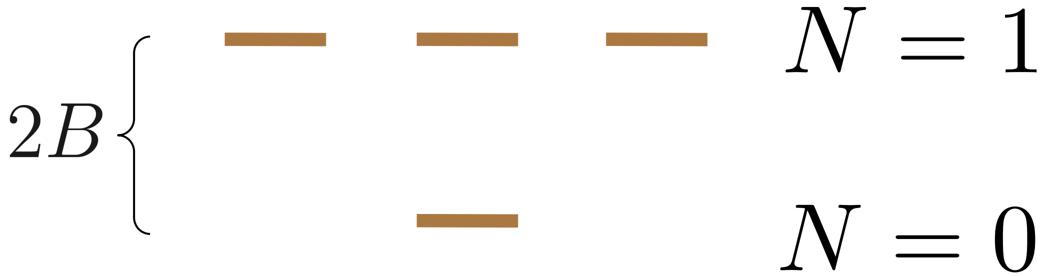


$$N_z = -1 \quad 0 \quad 1$$



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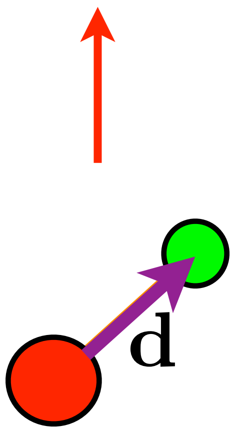

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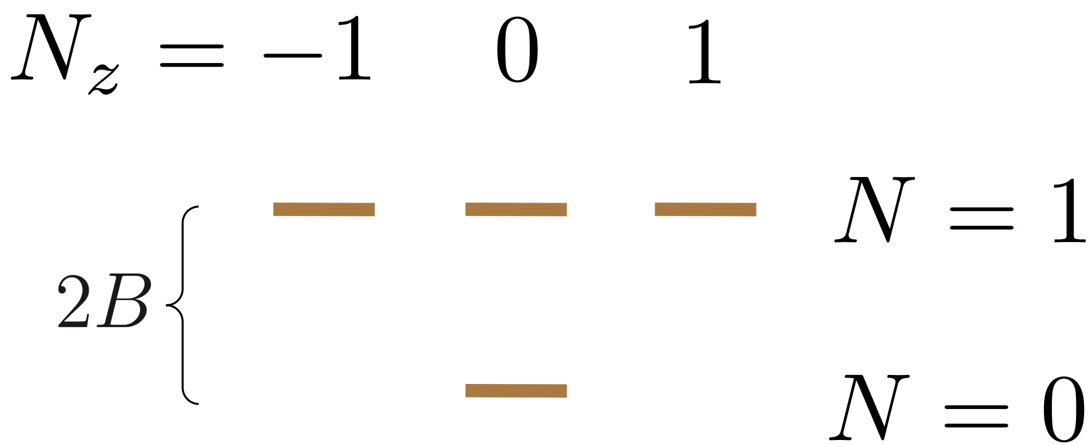

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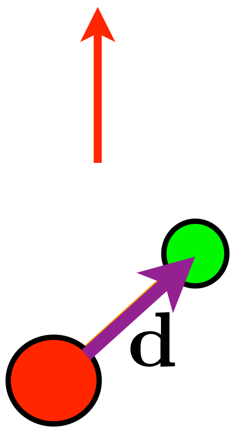

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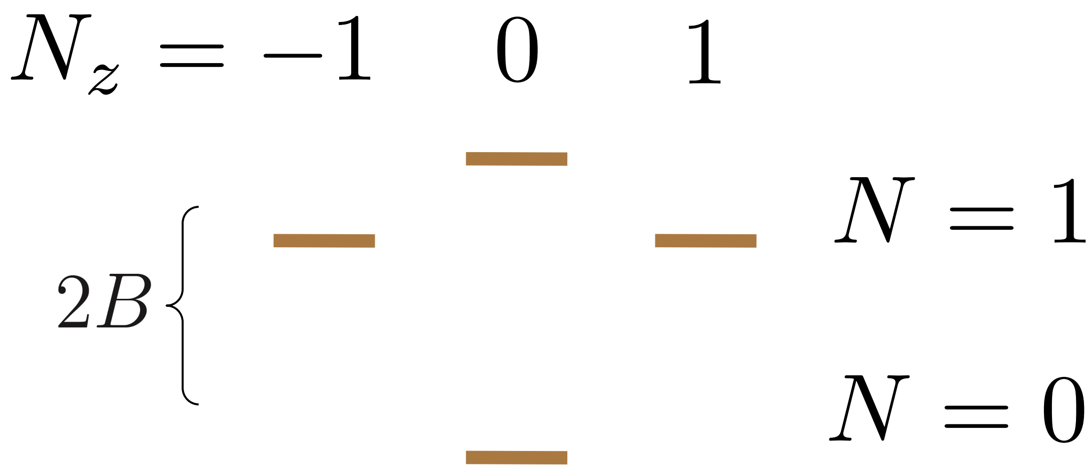

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Simplest spin Hamiltonian

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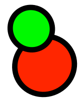
AVG et al, PRL, PRA 2011

Simplest spin Hamiltonian



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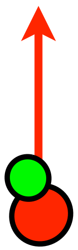

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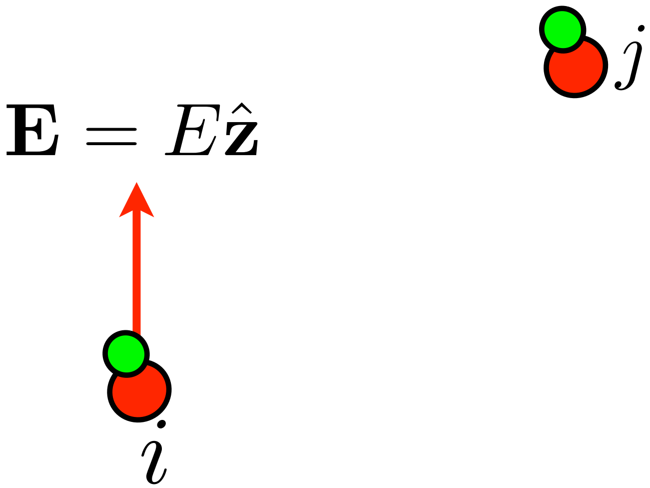

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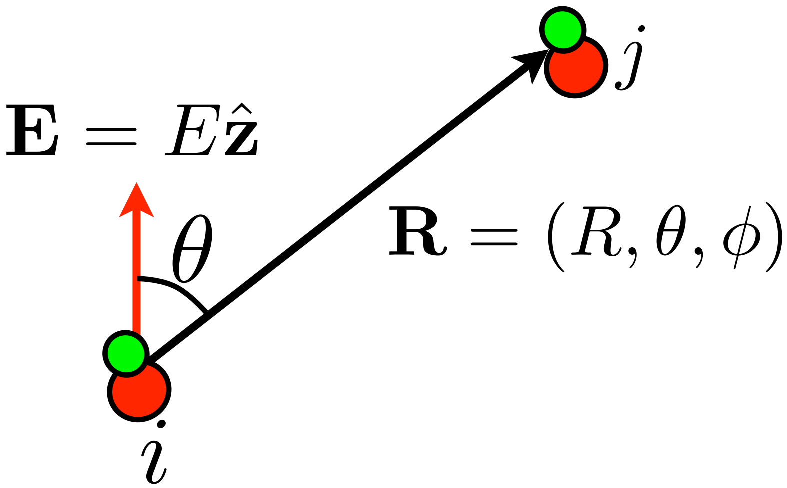

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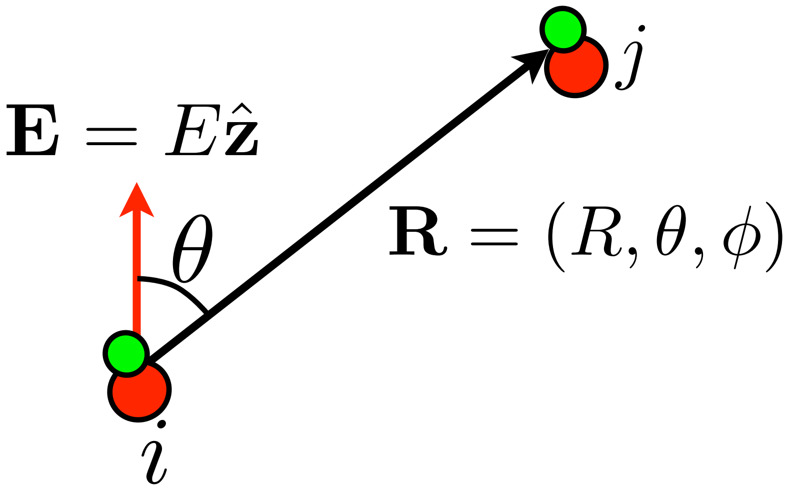
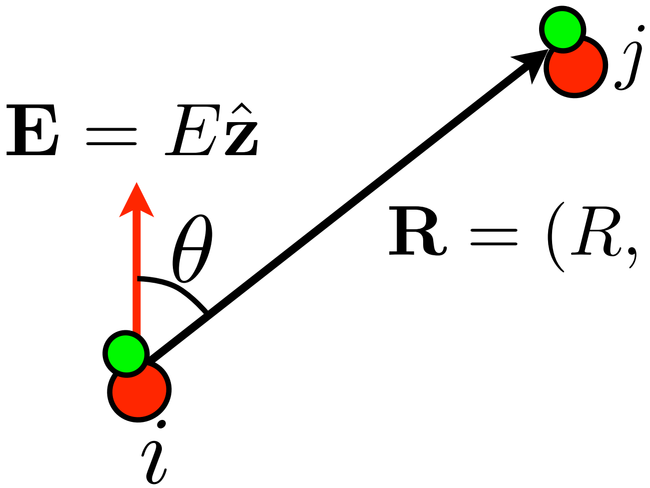
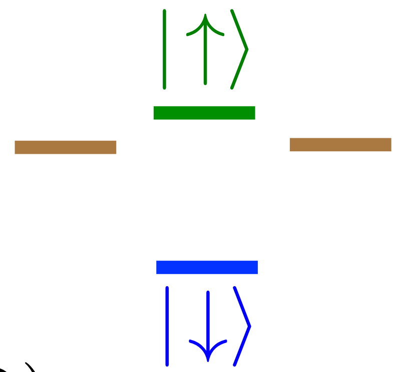


$$R^3 H_{dd} = \mathbf{d}_i \cdot \mathbf{d}_j - 3(\mathbf{d}_i \cdot \hat{\mathbf{R}})(\mathbf{d}_j \cdot \hat{\mathbf{R}})$$

Simplest spin Hamiltonian



$\mathbf{R} = (R, \theta, \phi)$



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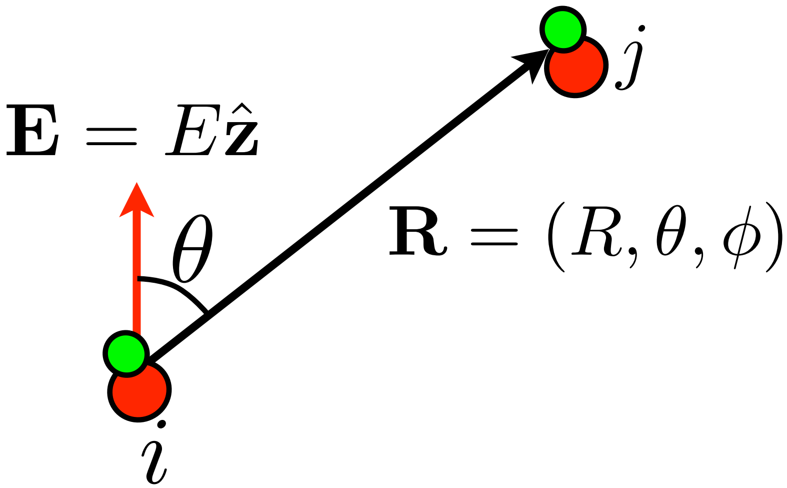

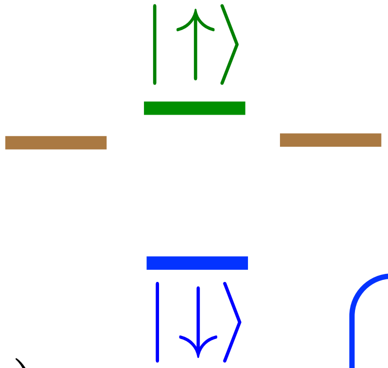

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weak

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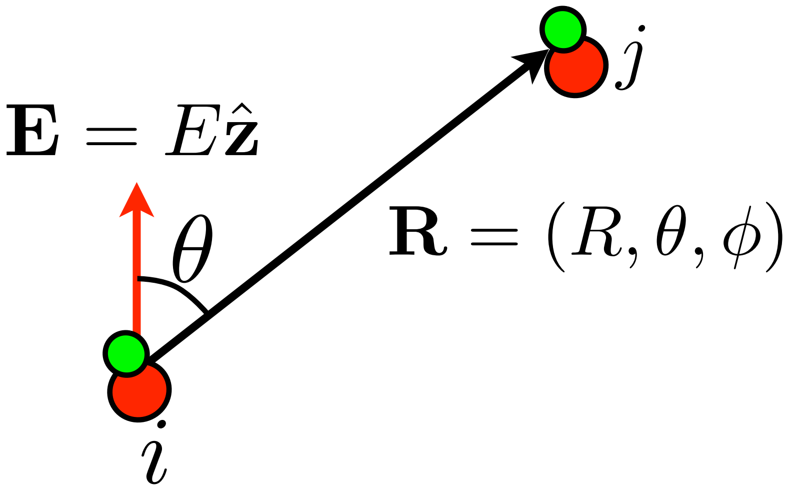

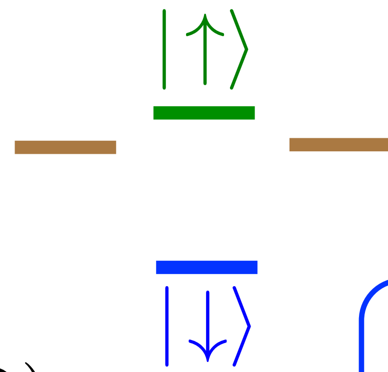

H_{dd}
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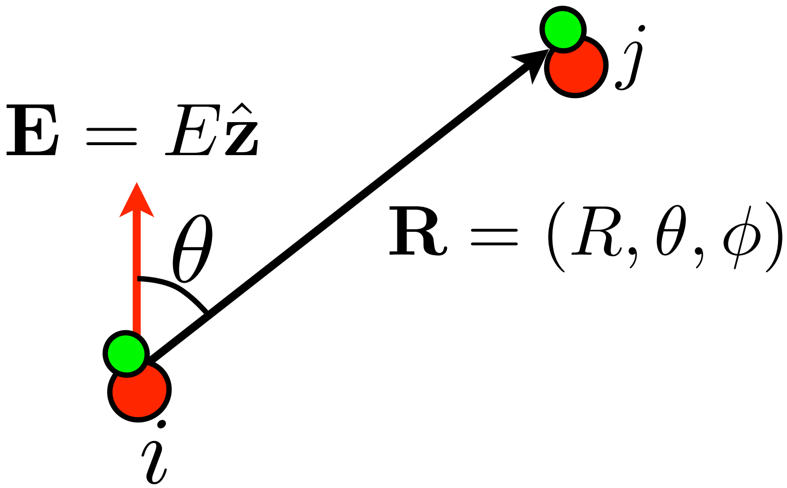
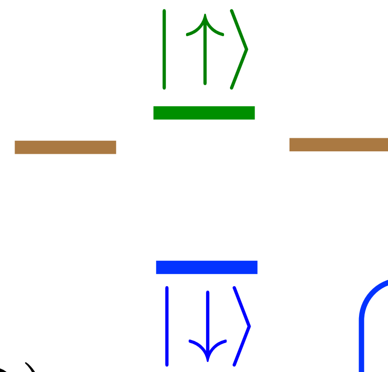
- project on $|\uparrow\rangle$, $|\downarrow\rangle$

AVG et al, PRL, PRA 2011

Simplest spin Hamiltonian





H_{dd} weak

$$R^3 H_{dd} = \mathbf{d}_i \cdot \mathbf{d}_j - 3(\mathbf{d}_i \cdot \hat{\mathbf{R}})(\mathbf{d}_j \cdot \hat{\mathbf{R}})$$

- project on $|\uparrow\rangle, |\downarrow\rangle$

$$R^3 H_{dd} = Y_{2,0}(\theta)[J_z S_i^z S_j^z + J_{xy}(S_i^x S_j^x + S_i^y S_j^y)]$$

$$Y_{2,0} \propto 1 - 3\cos^2\theta$$

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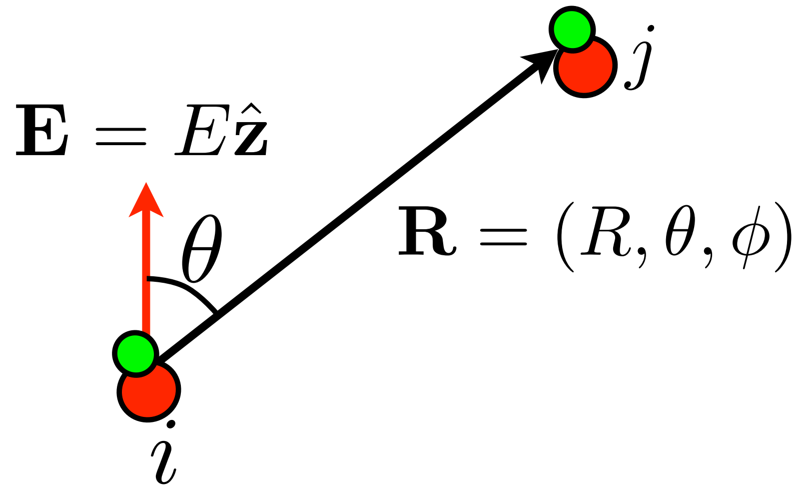

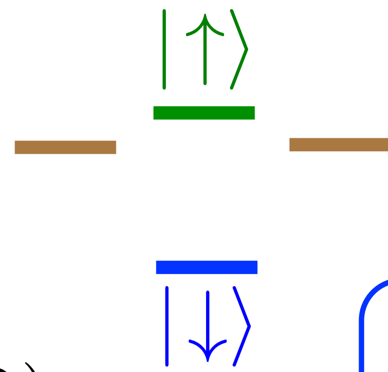

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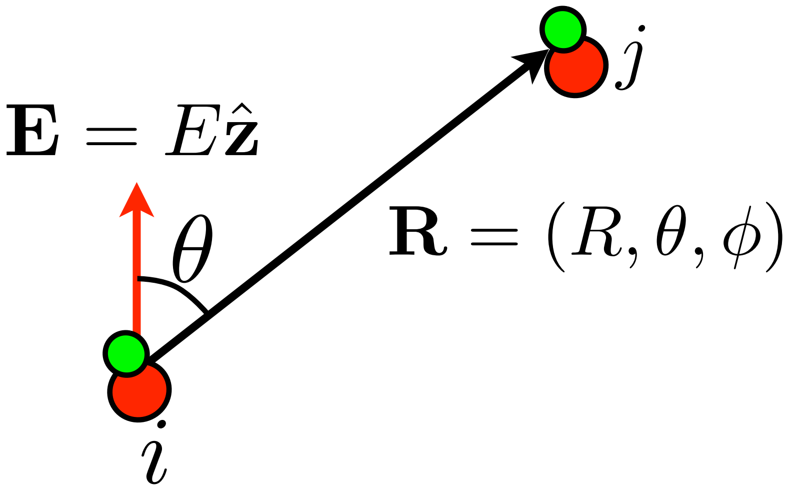

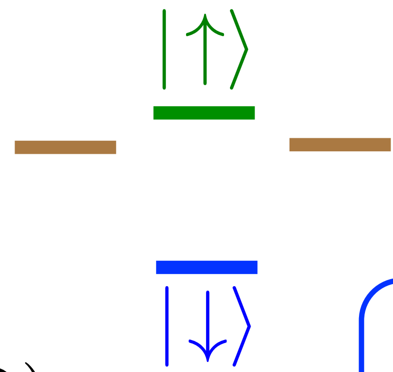

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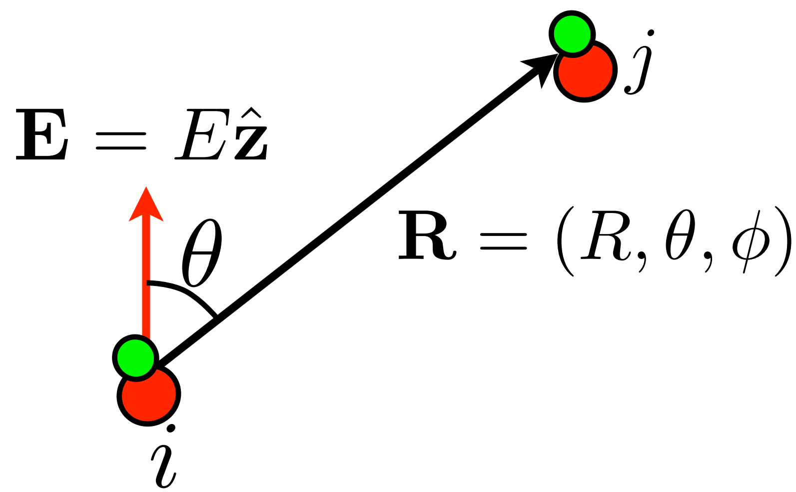

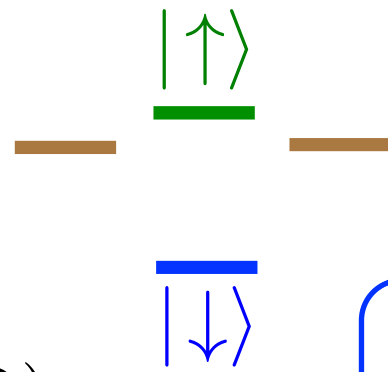

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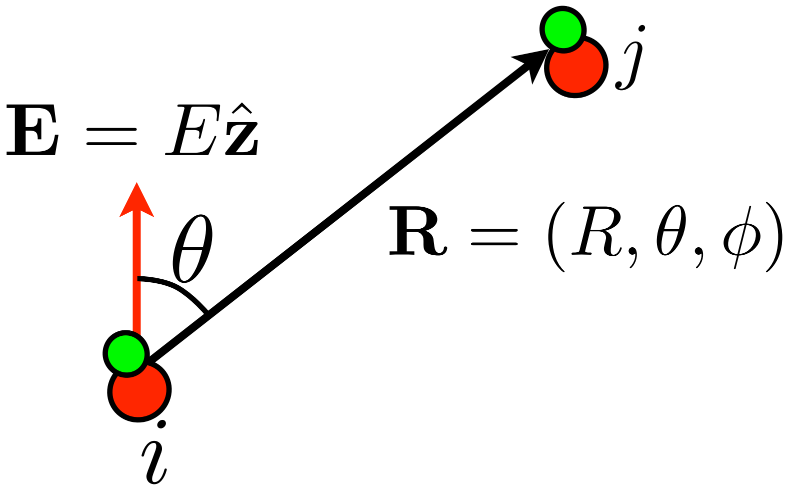

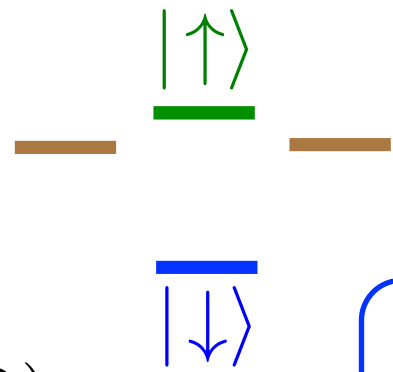

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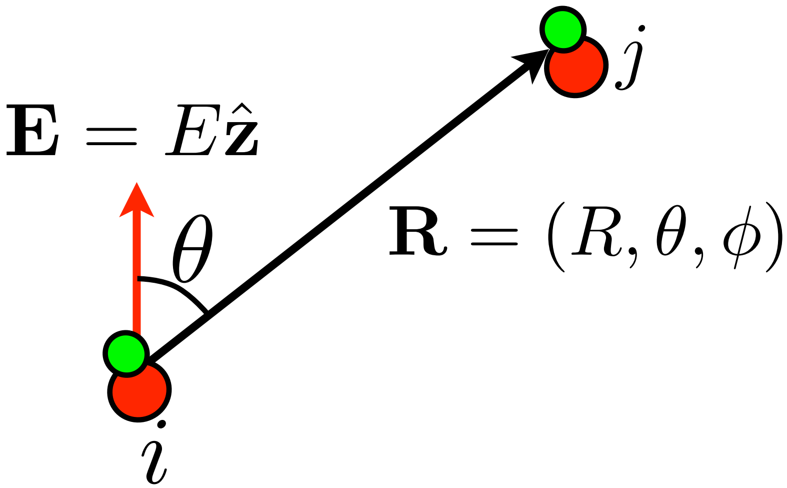

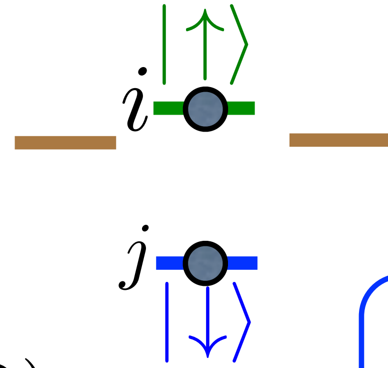

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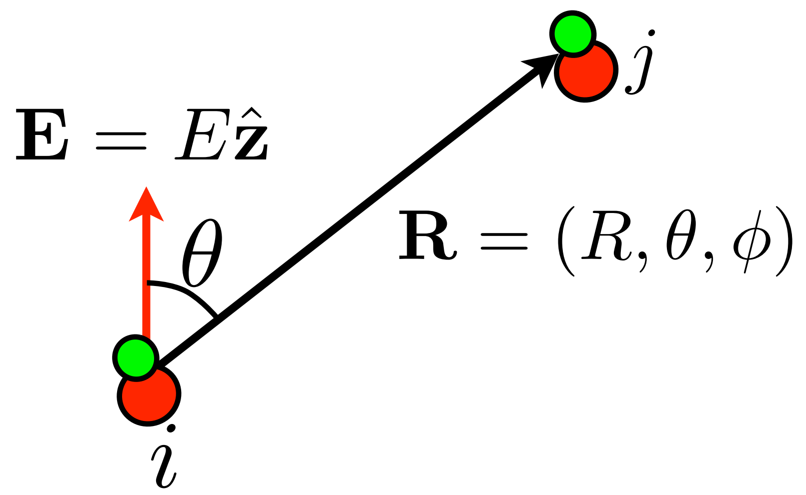

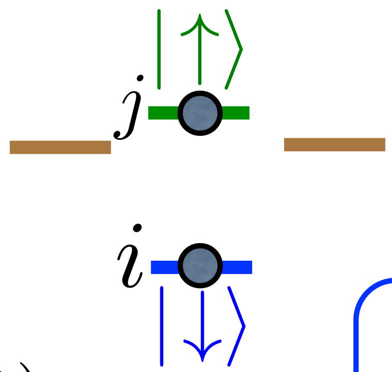

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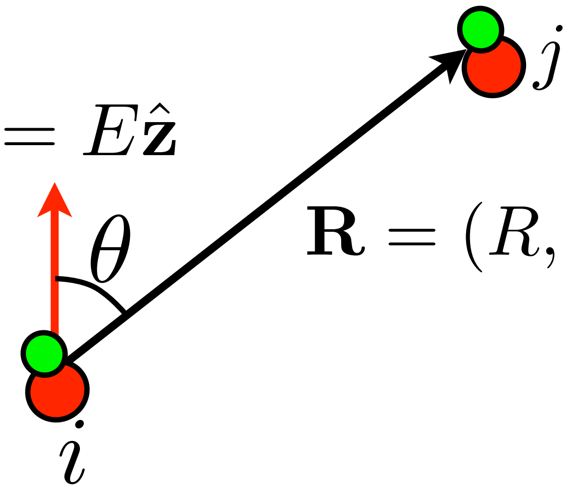
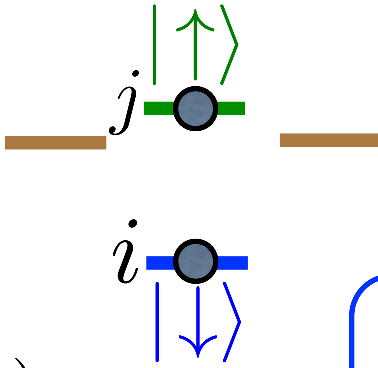
AVG et al, PRL, PRA 2011

Simplest spin Hamiltonian

$\mathbf{E} = E\hat{\mathbf{z}}$



$\mathbf{R} = (R, \theta, \phi)$



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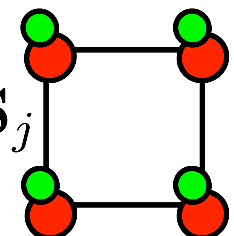
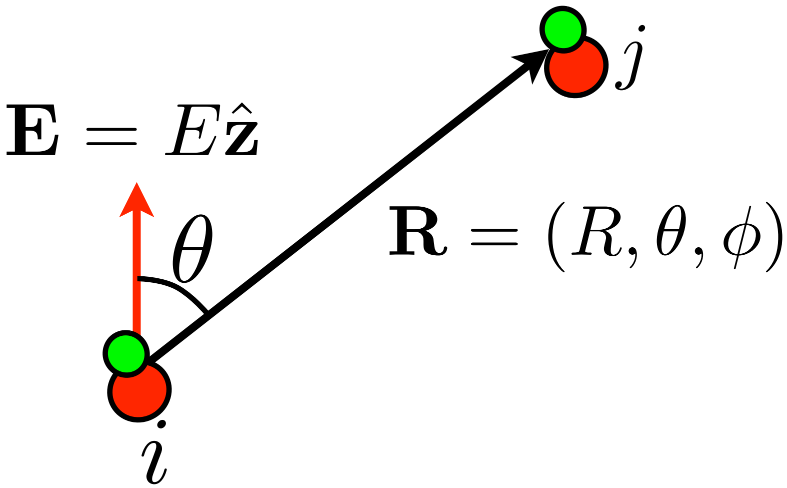
$\mathbf{S}_i \cdot \mathbf{S}_j$

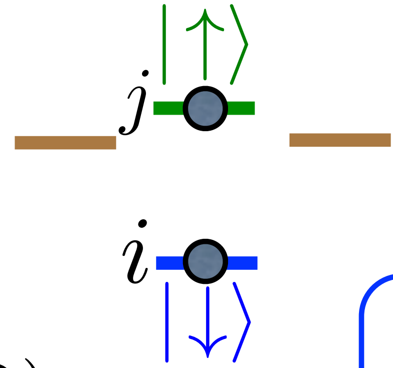


$S_i^z S_j^z$

AVG et al, PRL, PRA 2011

Simplest spin Hamiltonian





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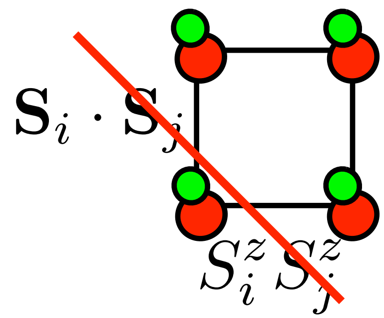

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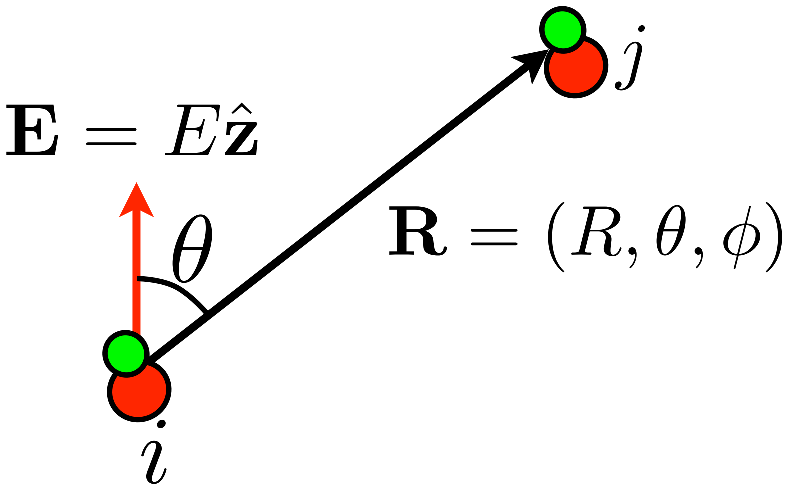

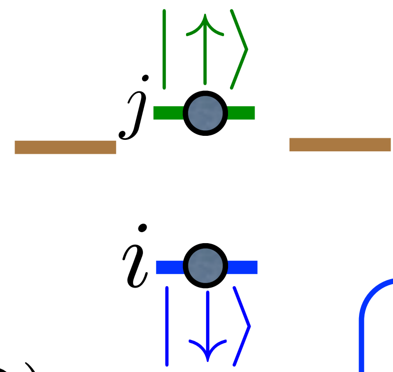

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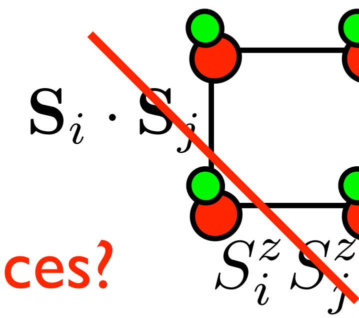

- can J_z and J_{xy} come with different angular dependences?

AVG et al, PRL, PRA 2011

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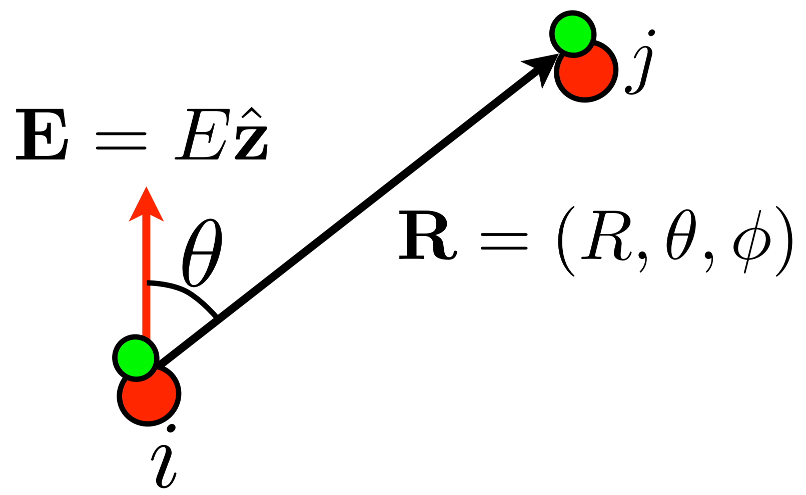

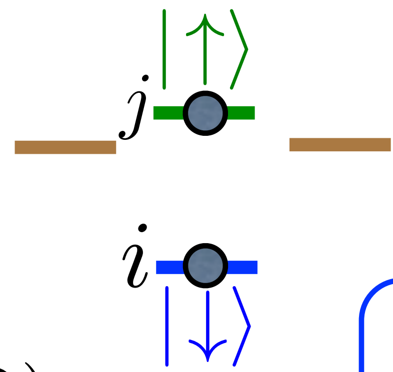

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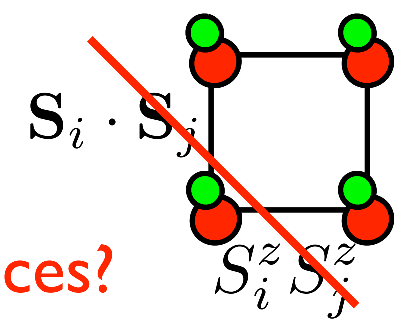

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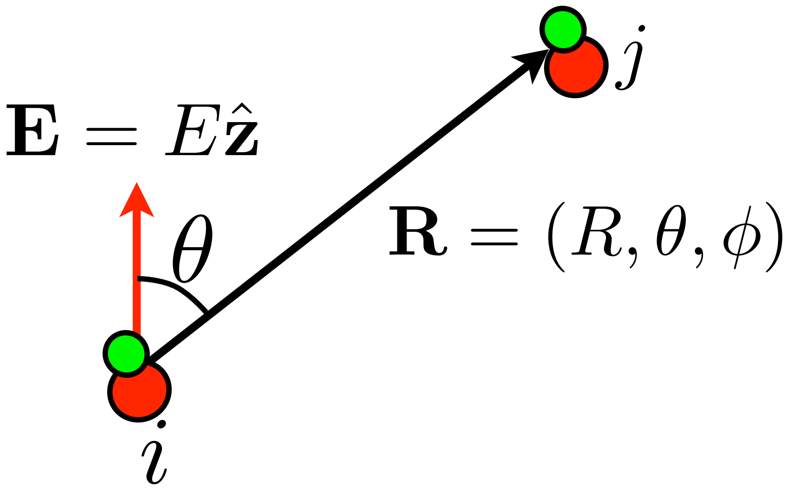
YES!

AVG et al, PRL, PRA 2011

Spin Hamiltonian from dressed states



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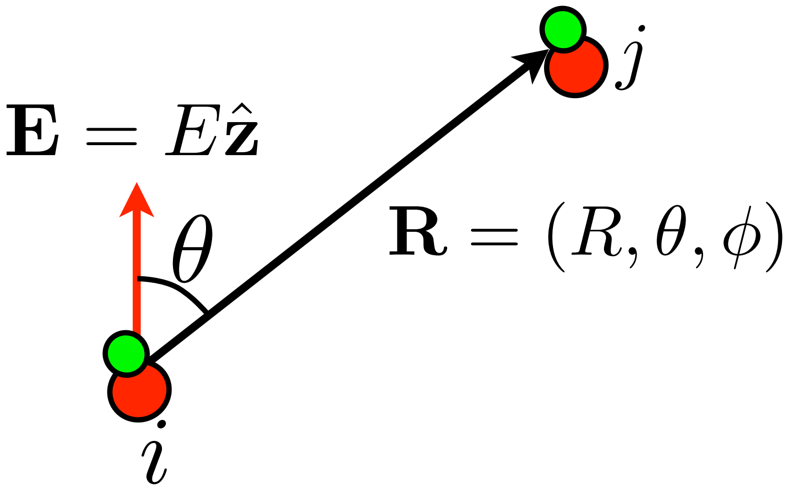

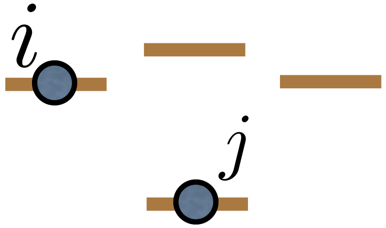

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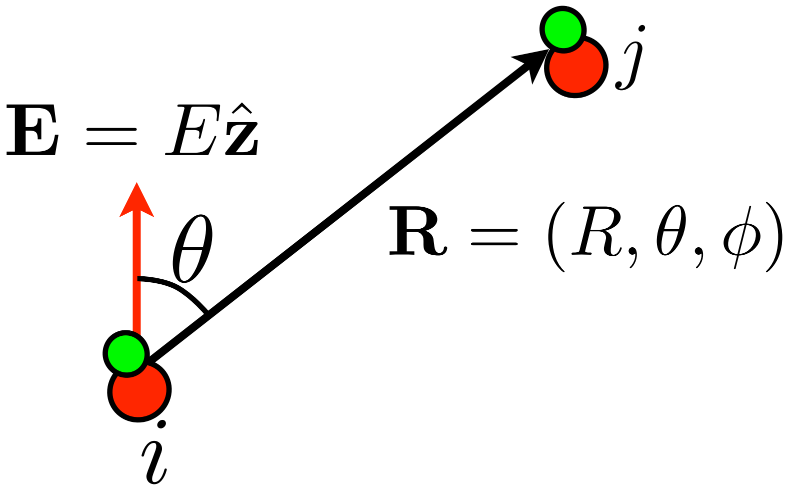

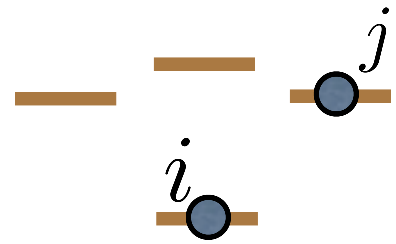

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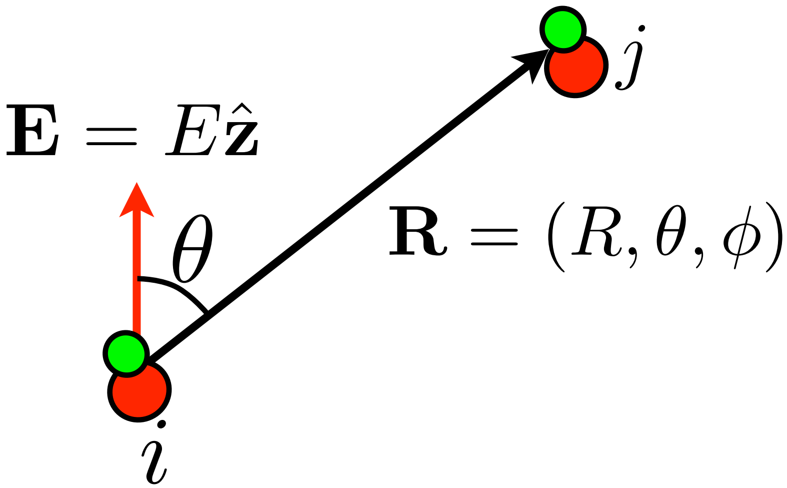

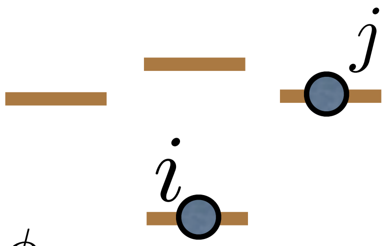

$$Y_{2,-2} \propto \sin^2\theta e^{-2i\phi}$$

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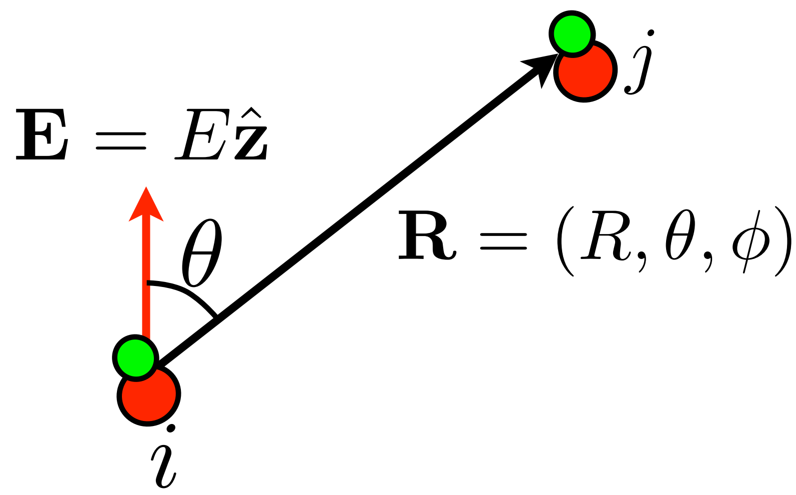

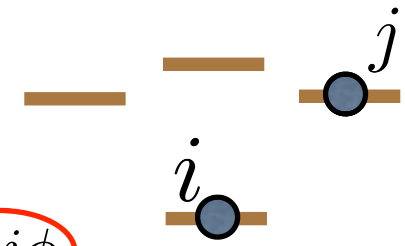

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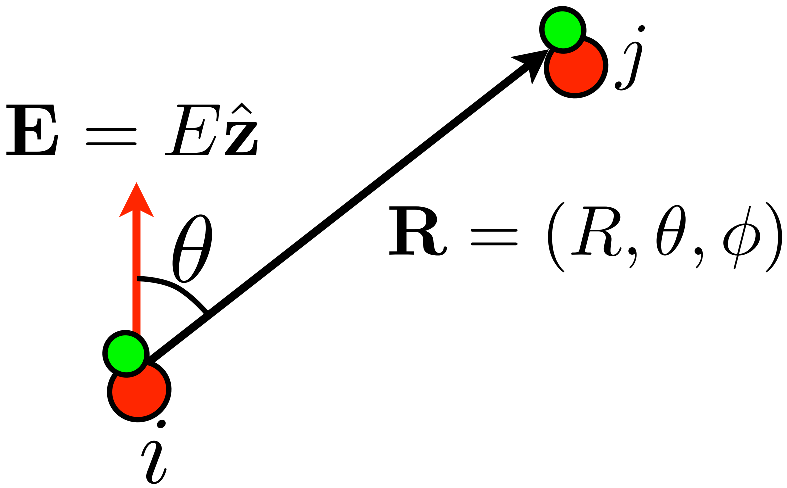

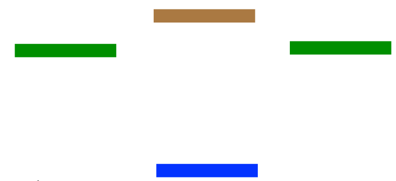

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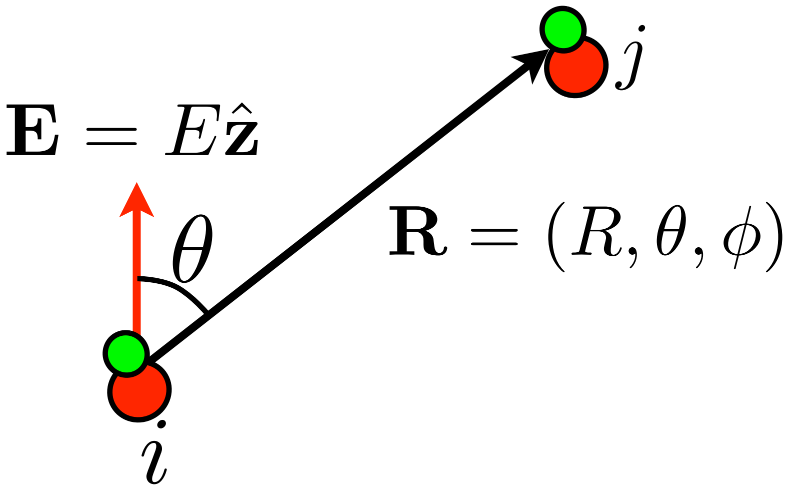

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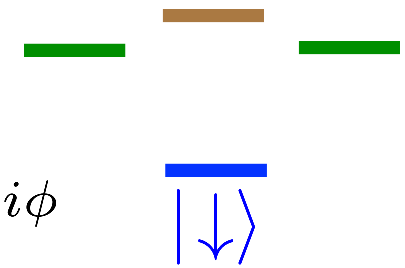

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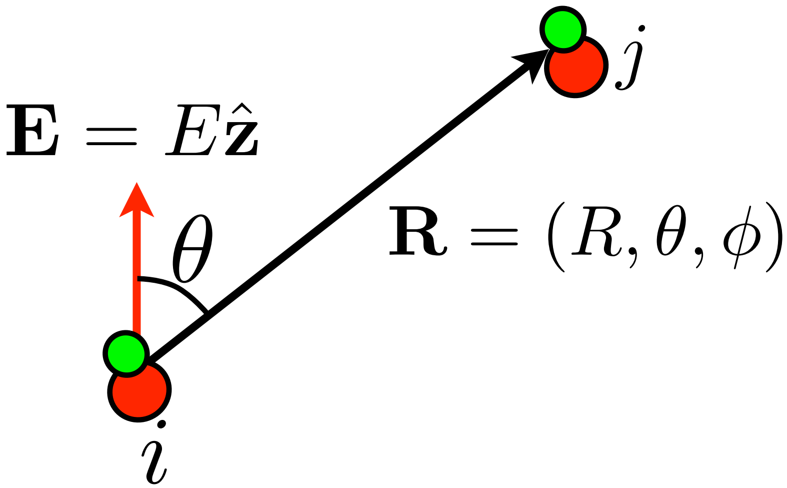

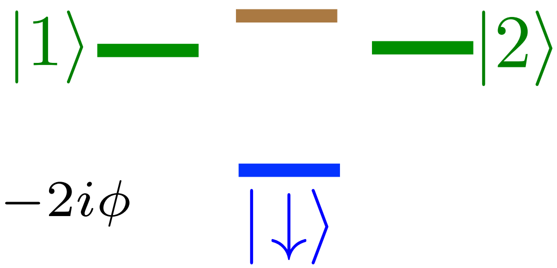

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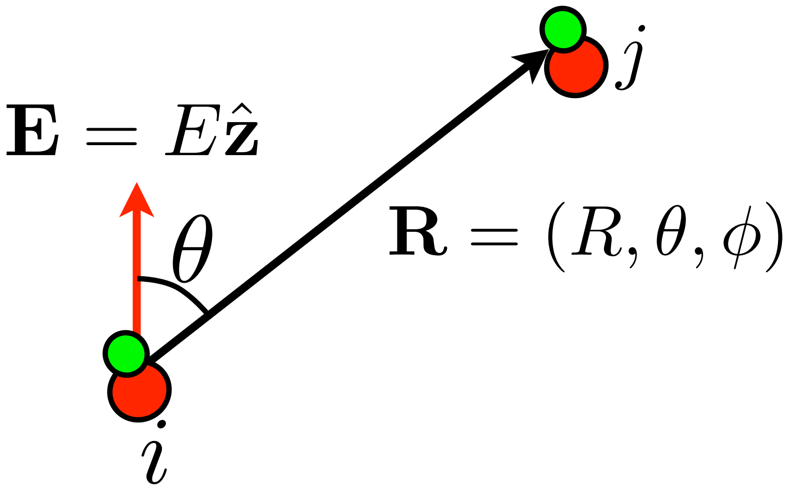

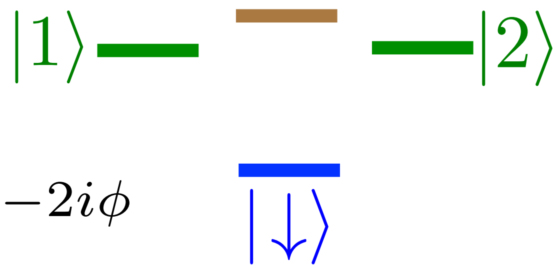

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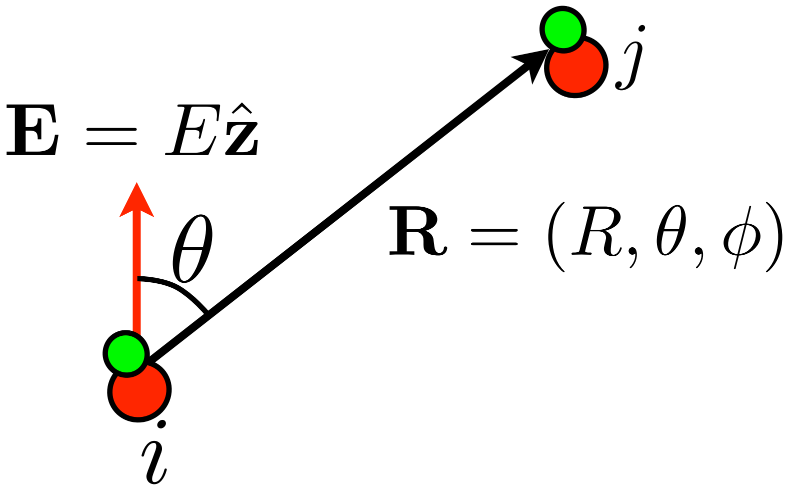
Spin Hamiltonian from dressed states



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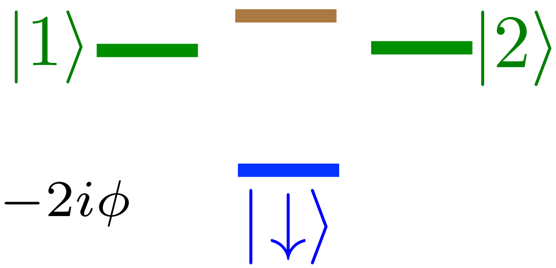

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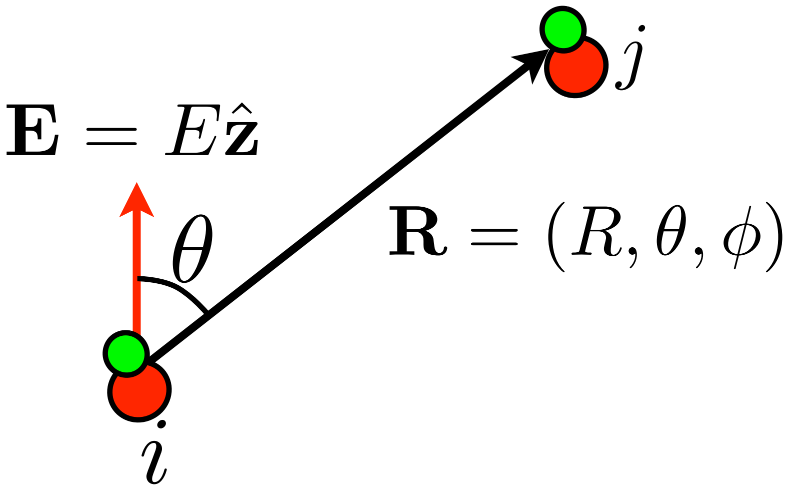

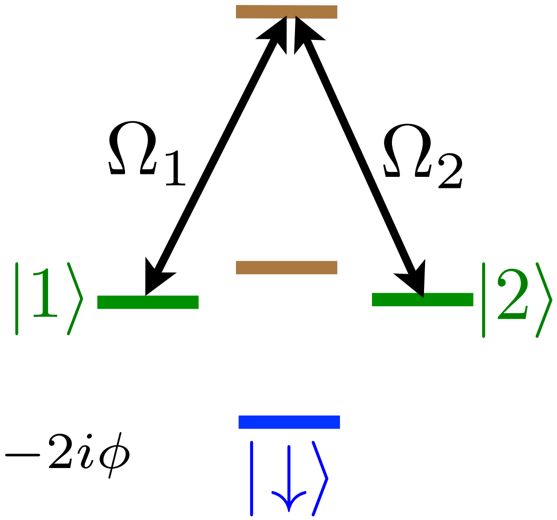

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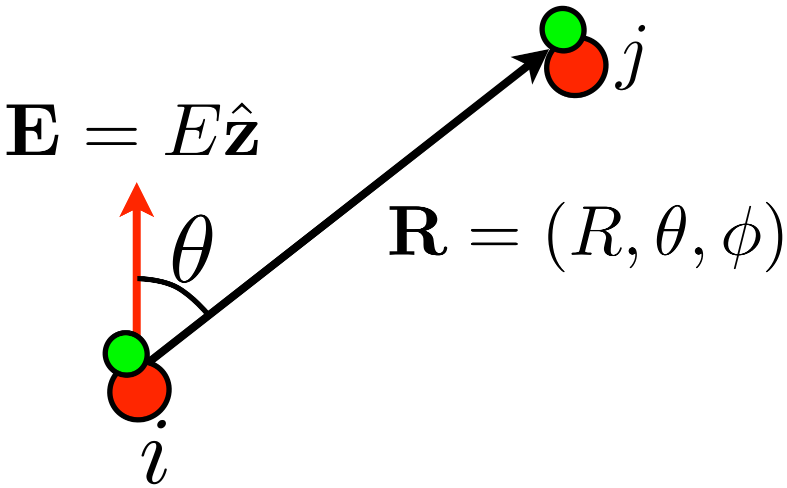

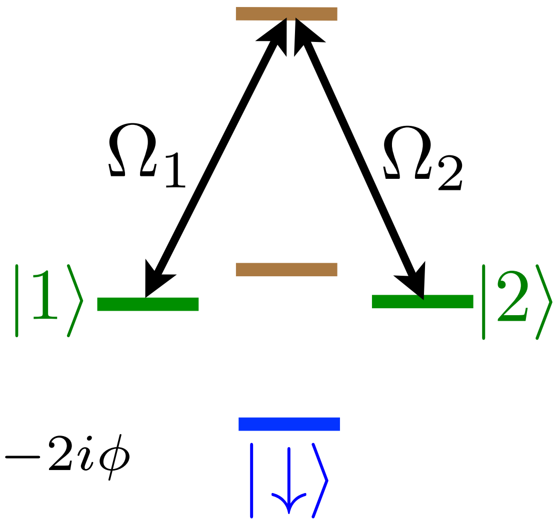

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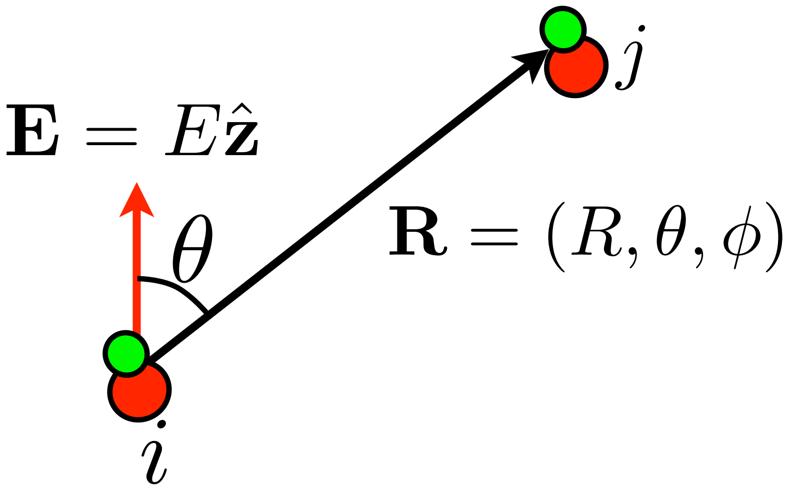
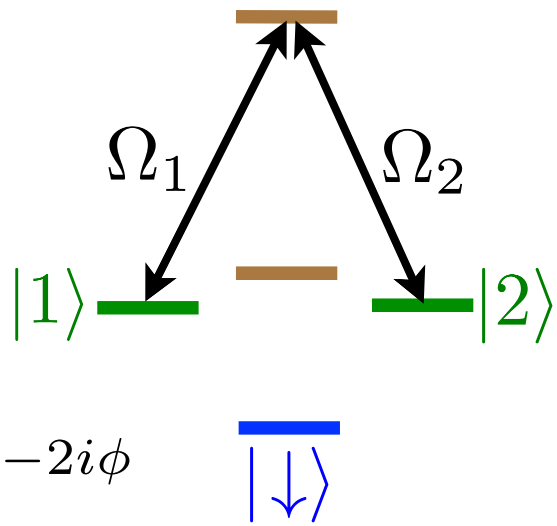
Spin Hamiltonian from dressed states





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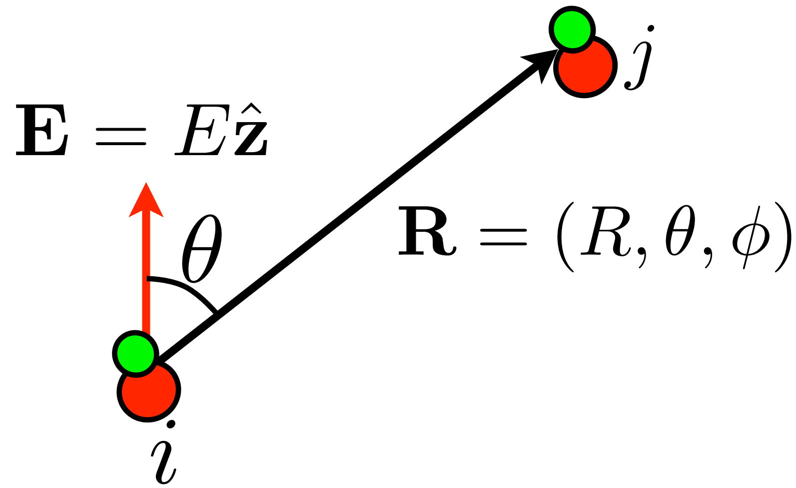
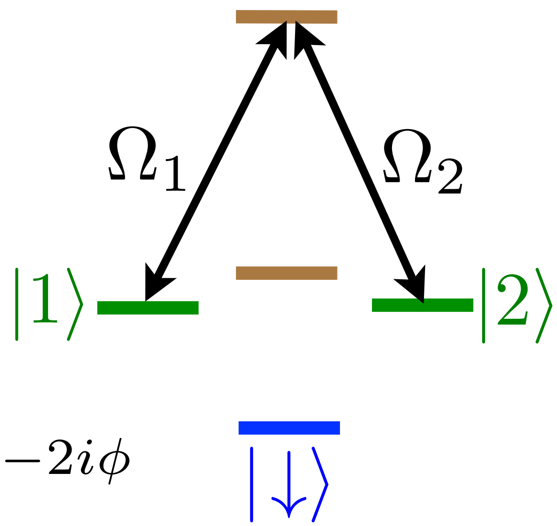
Spin Hamiltonian from dressed states





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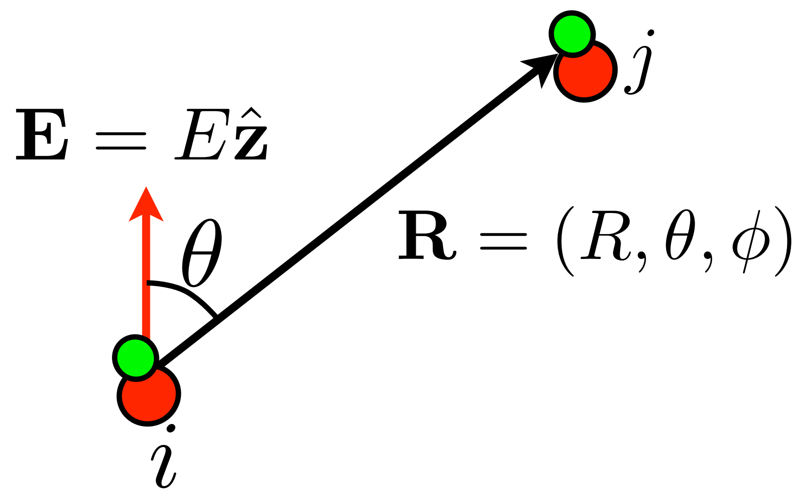

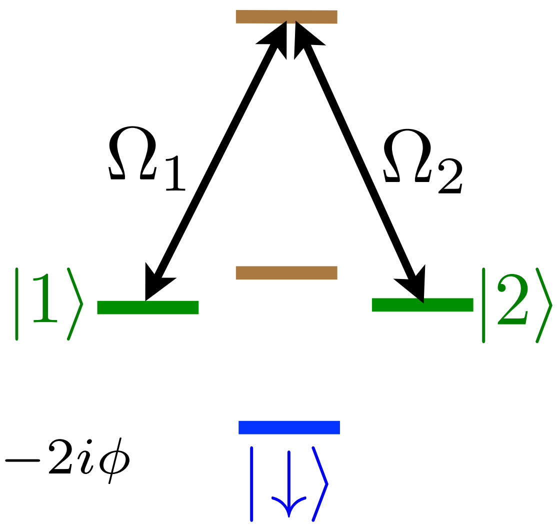

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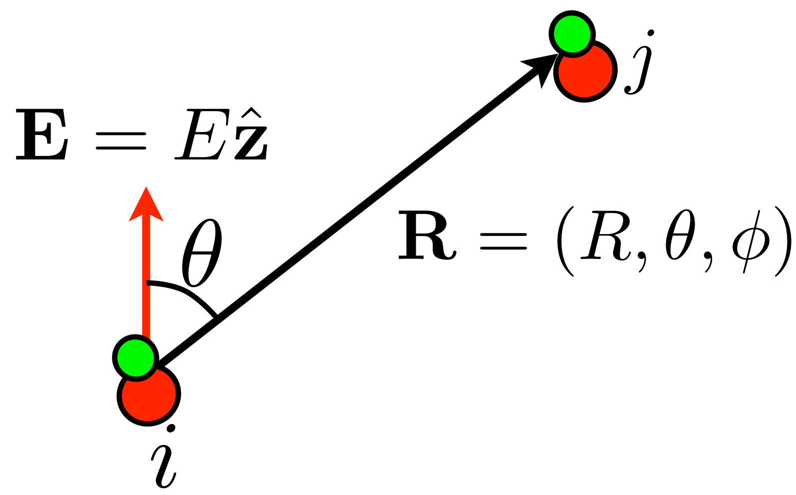

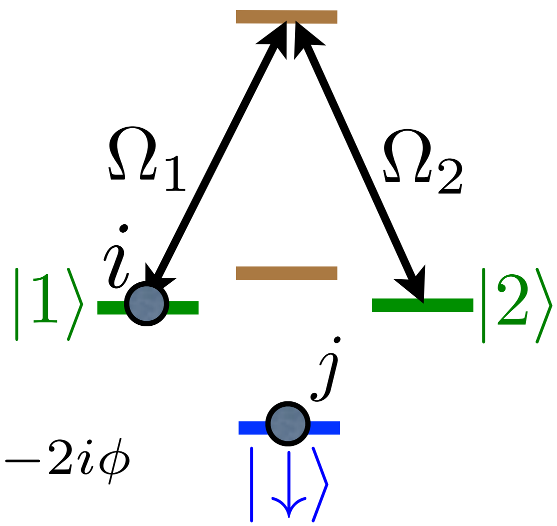

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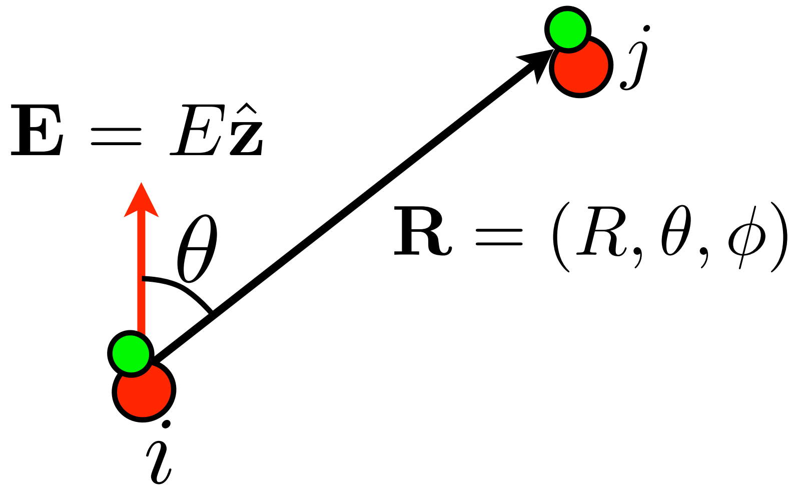

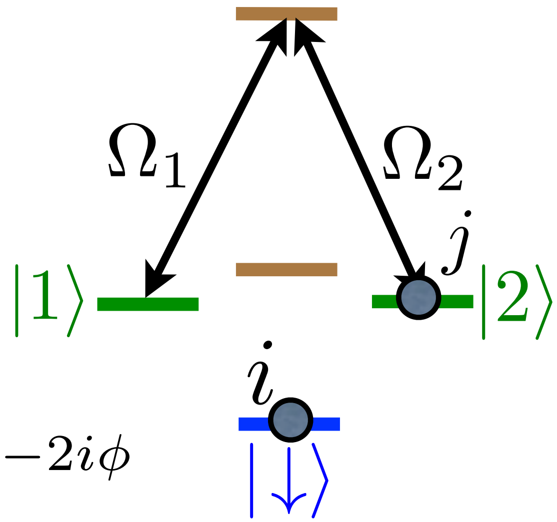

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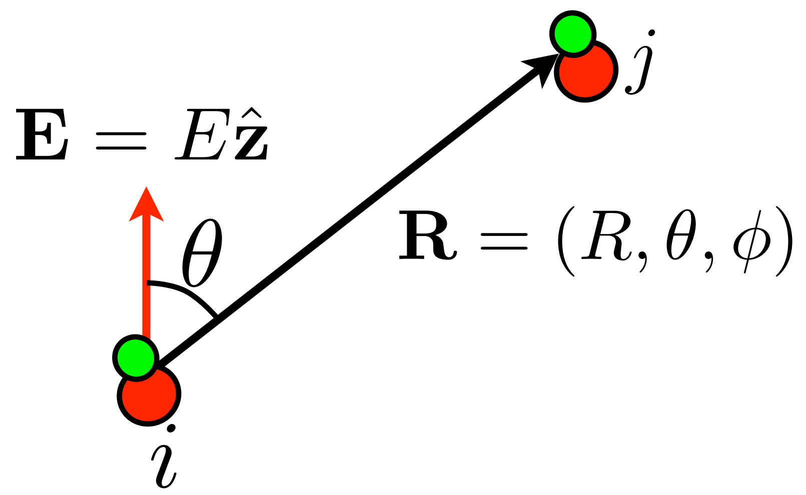

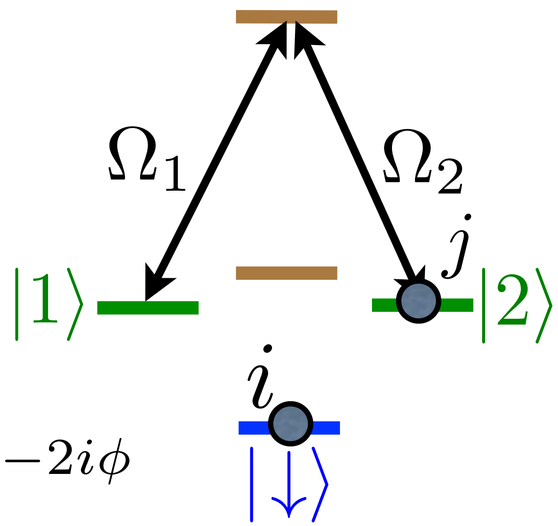

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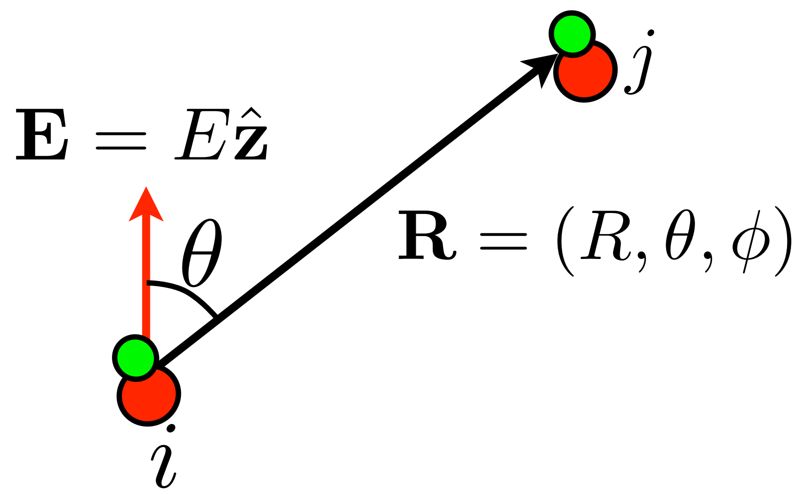

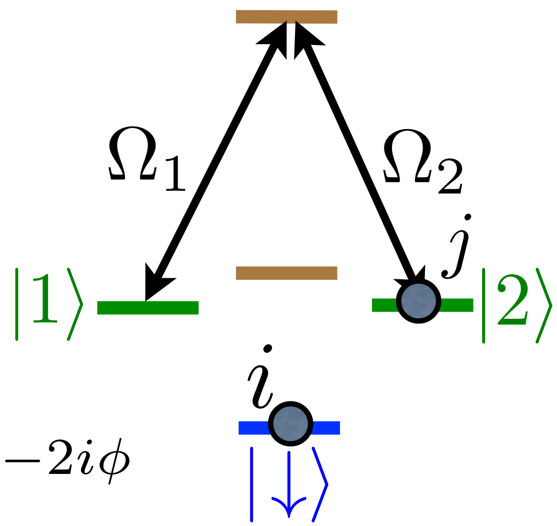

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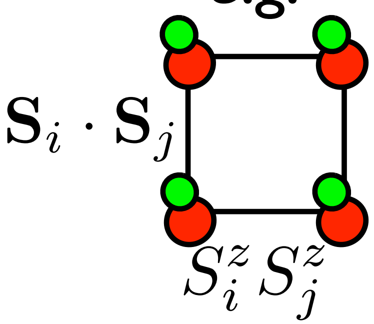

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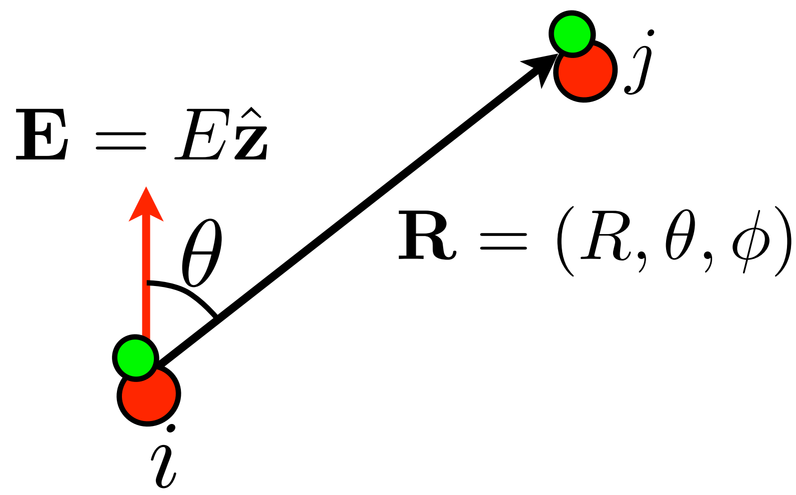

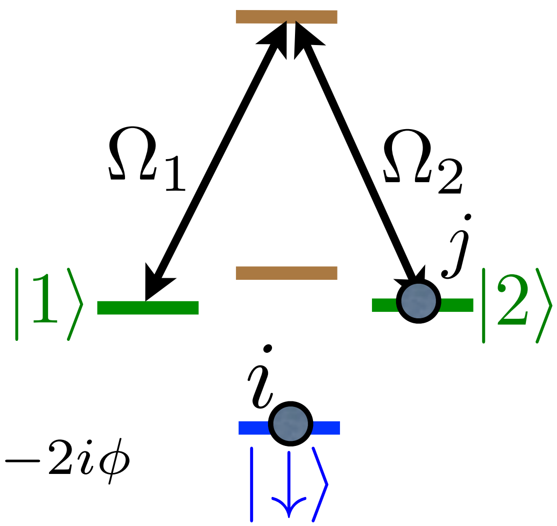

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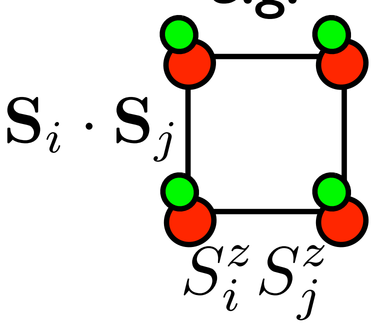

- what can we implement with this?

Symmetry protected topological (SPT) phases

Shnyder et al 2008, Kitaev 2009, Gu & Wen 2009

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- topological ≈ no local order parameter, exotic

local order parameter:
e.g. ↑↓↑↓↑↓

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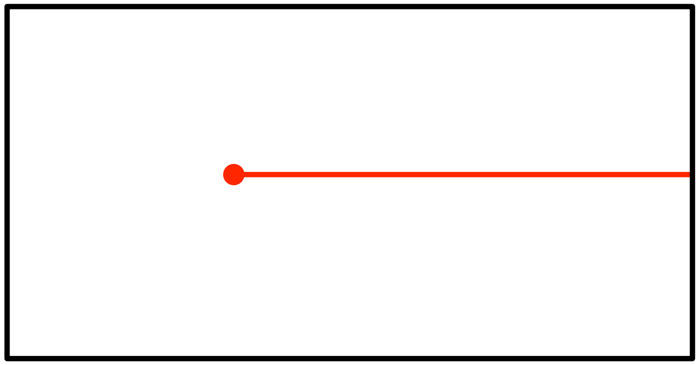

← line of phase transitions

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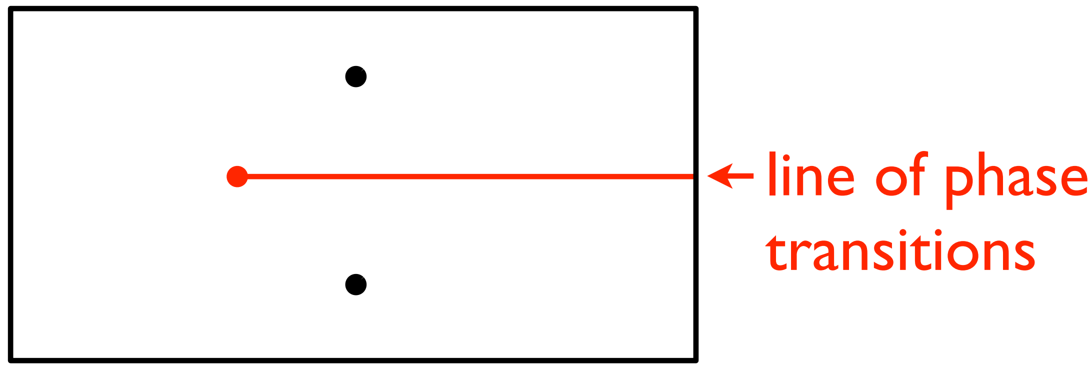

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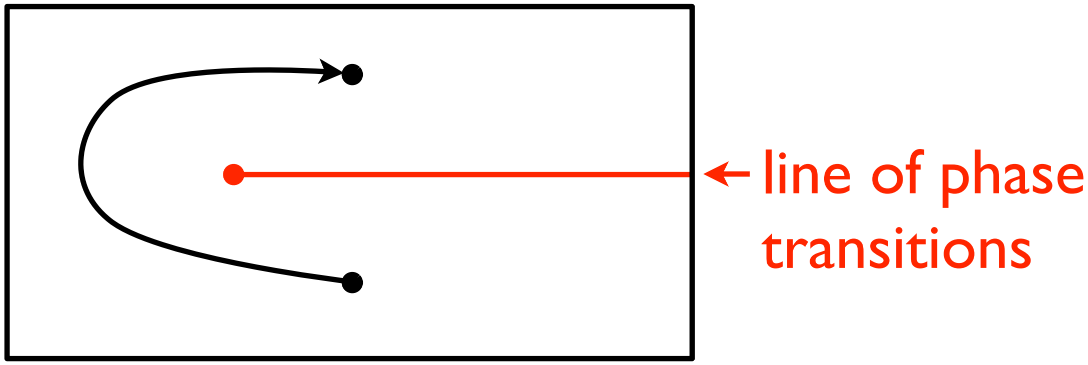

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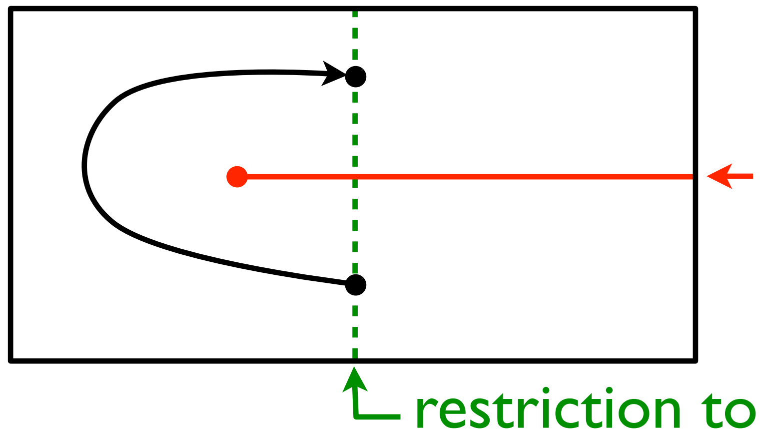

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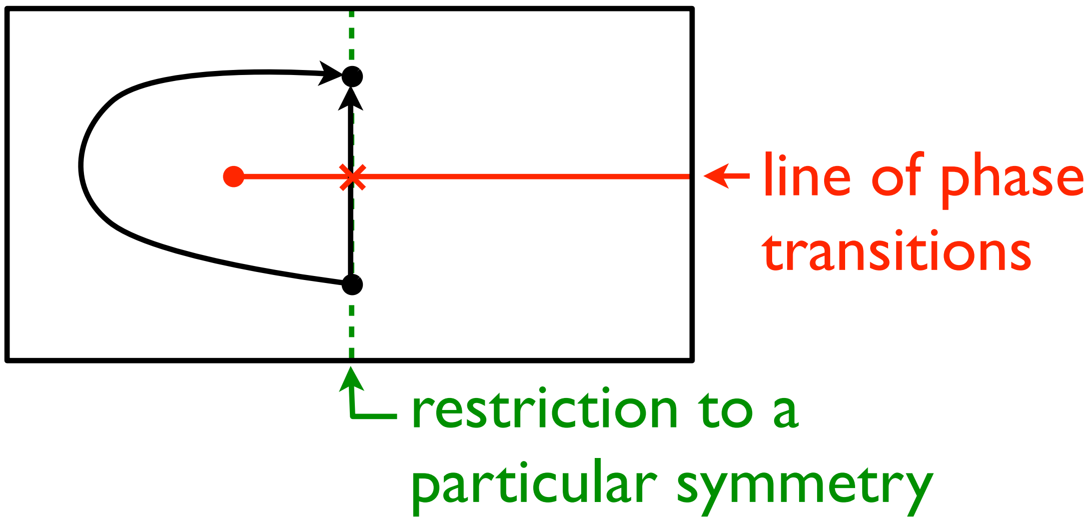

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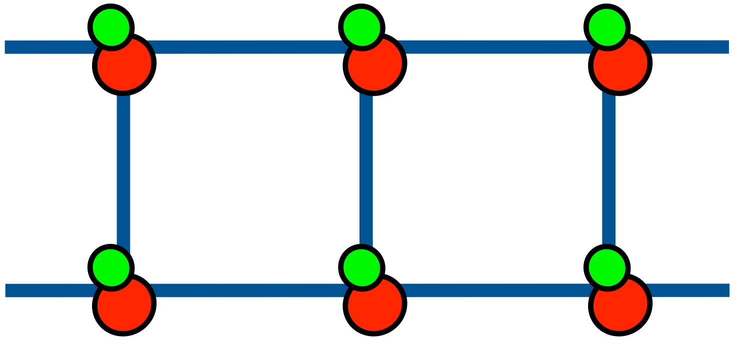
SPT phases in spin-1/2 ladders



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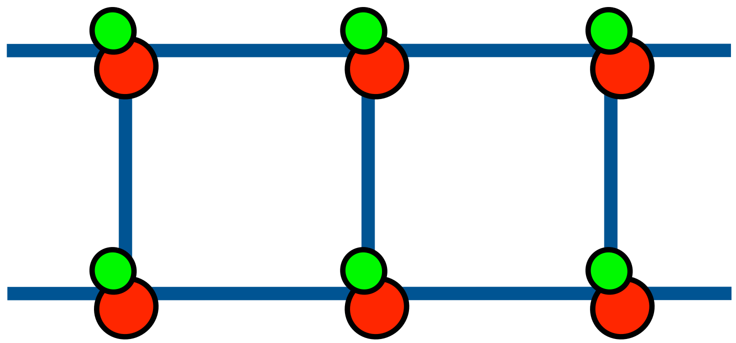

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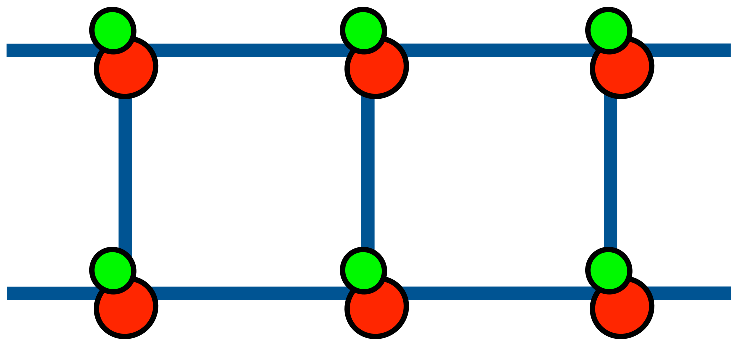

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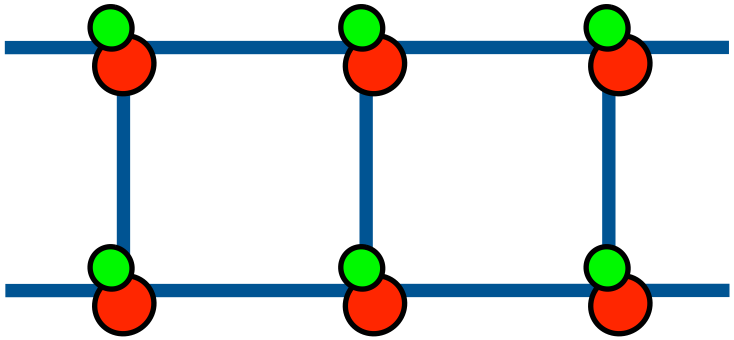

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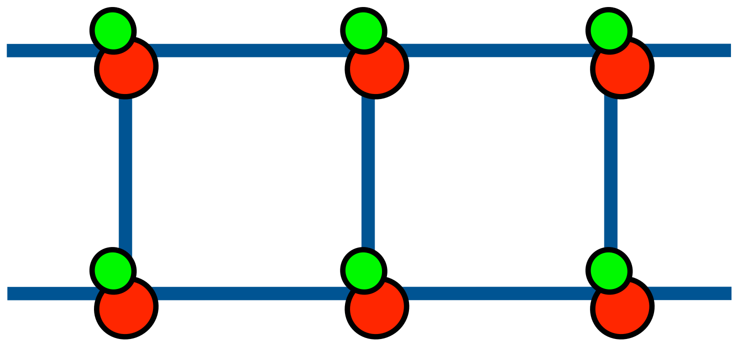

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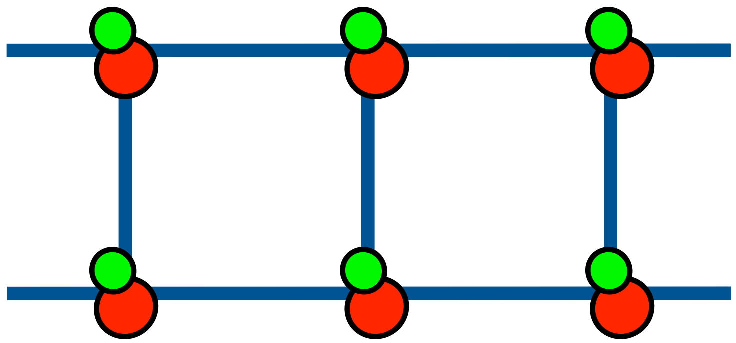

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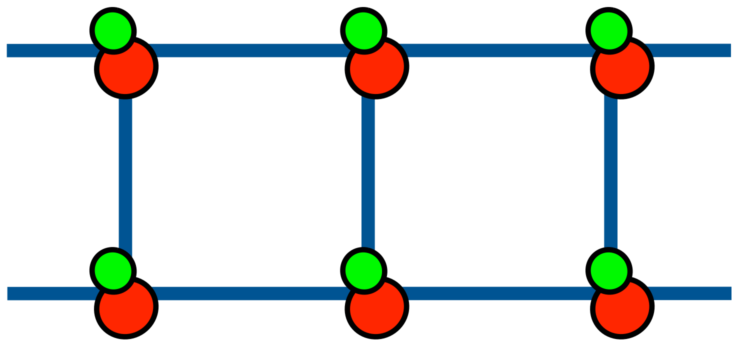

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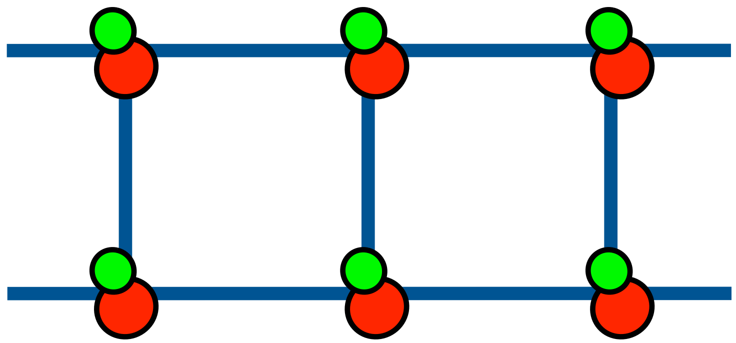

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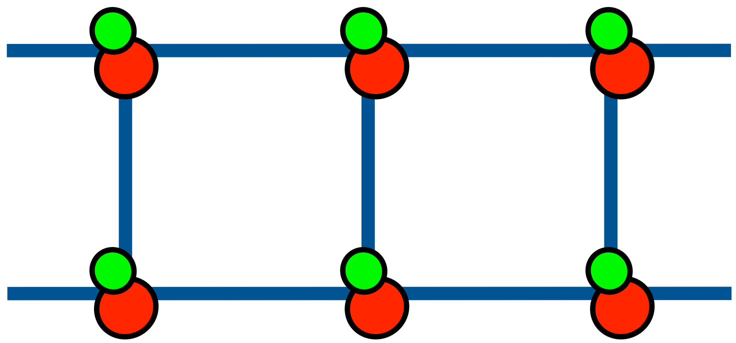

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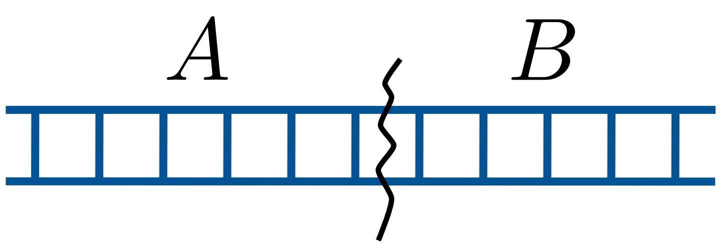

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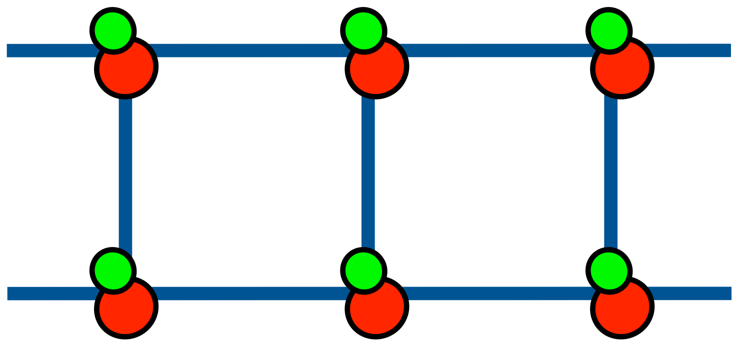

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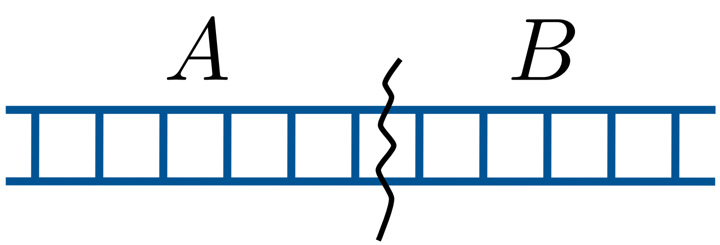

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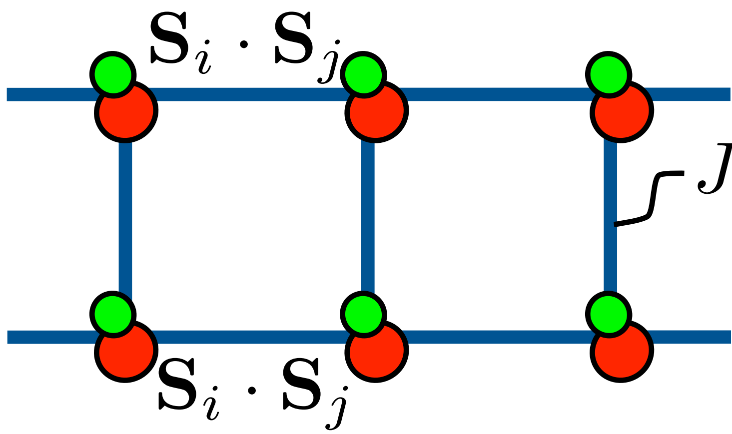

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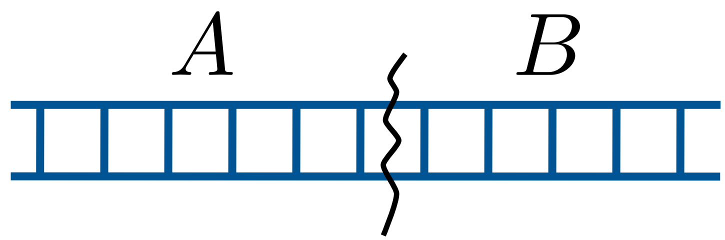

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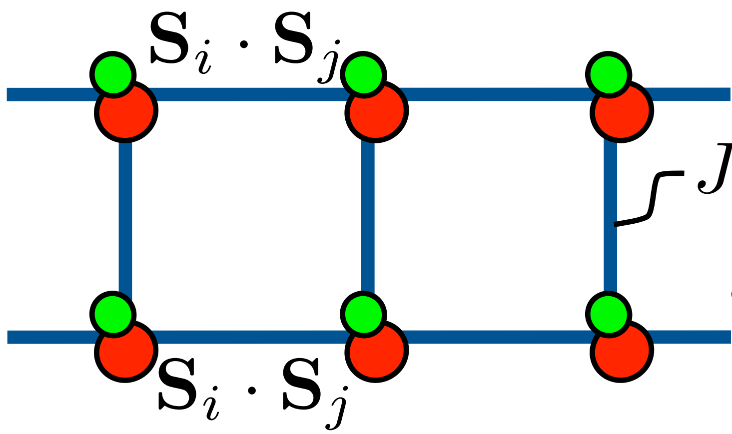

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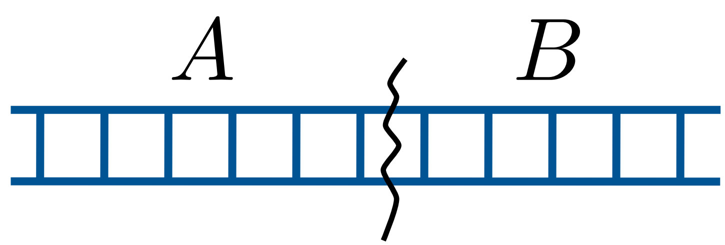

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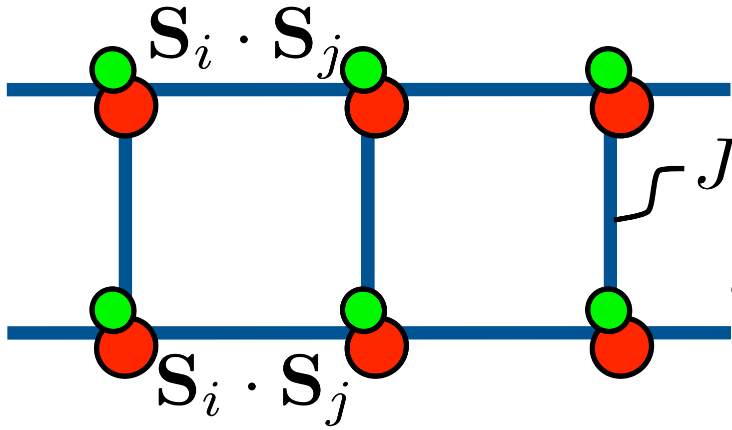

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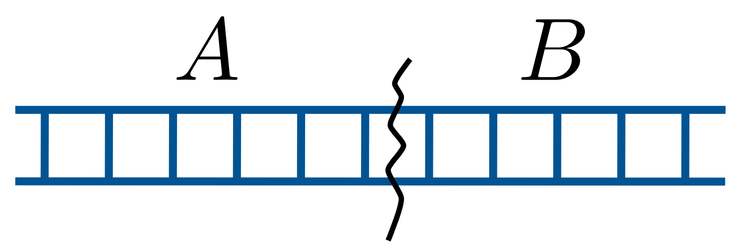

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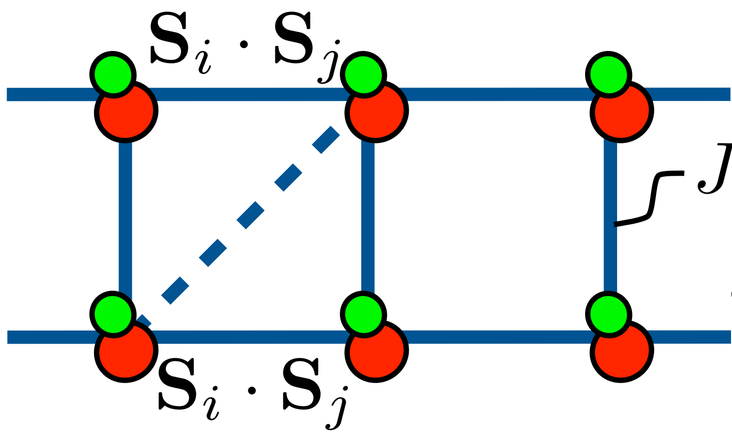

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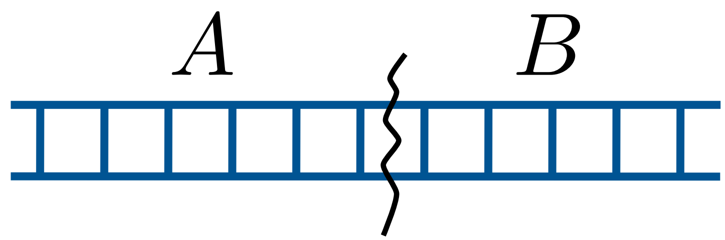

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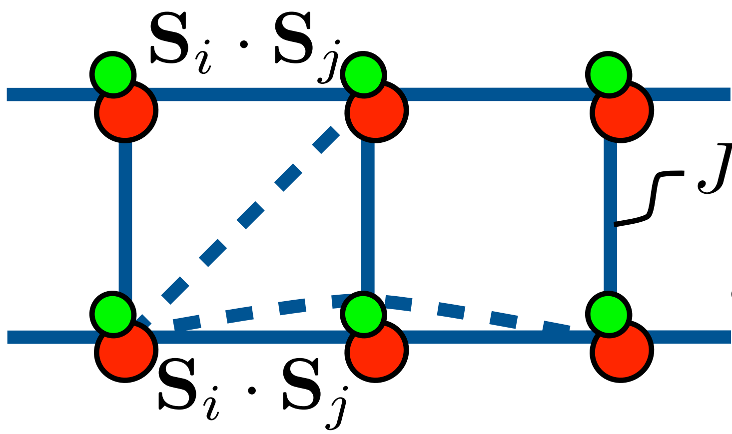

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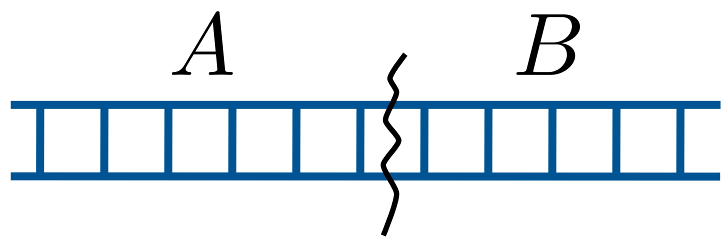

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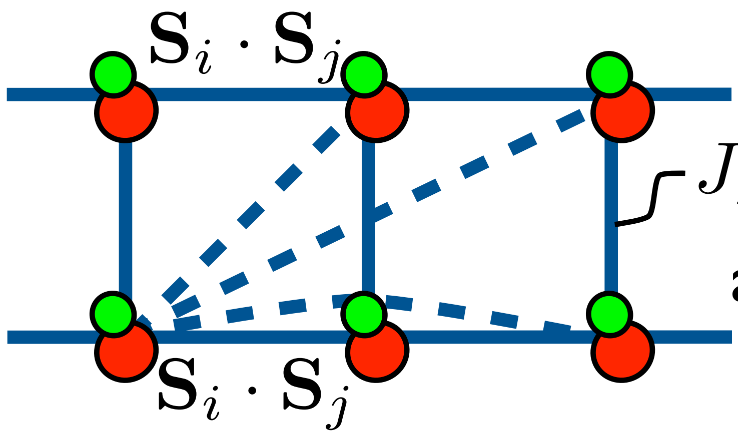

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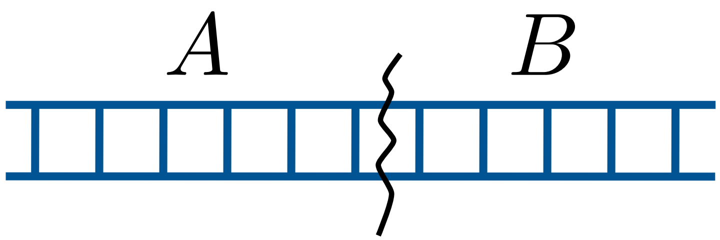

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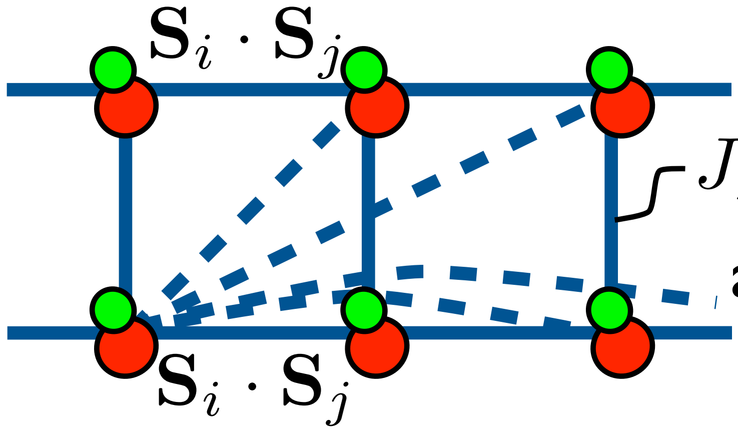

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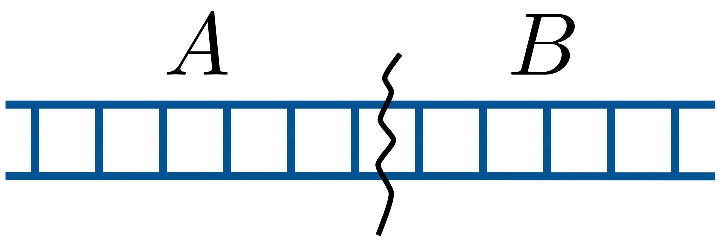

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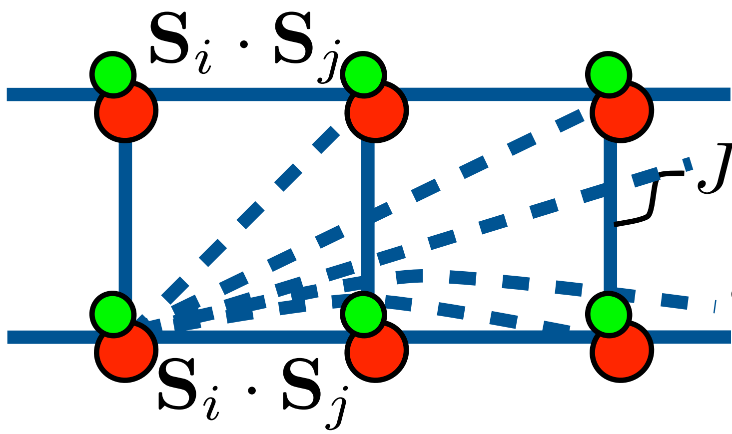

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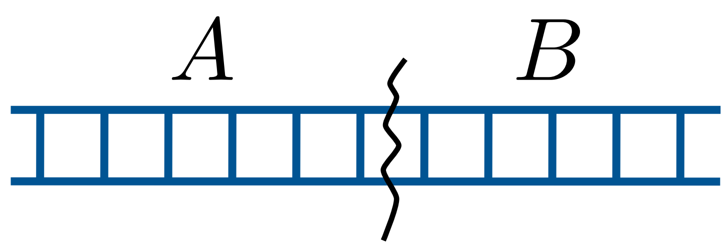

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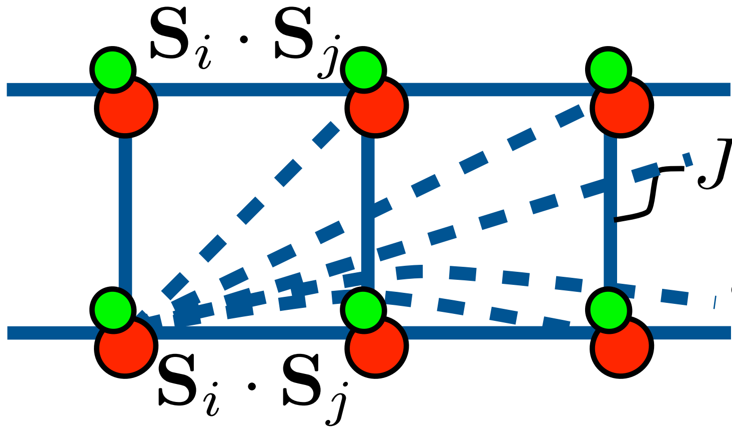

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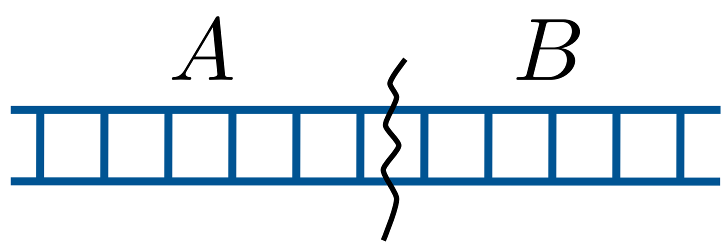

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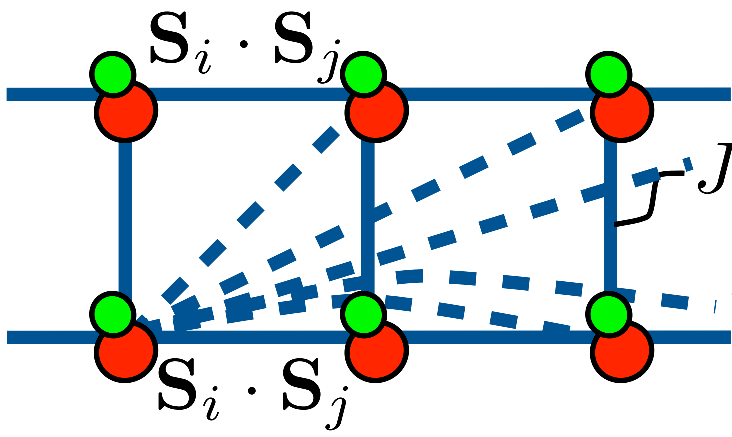

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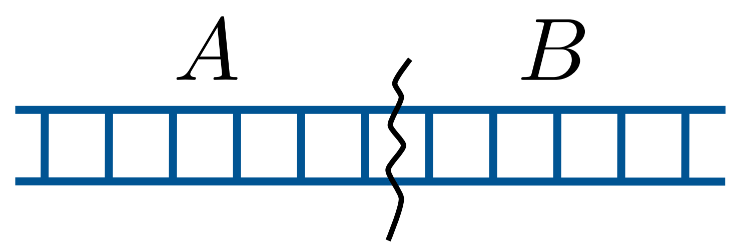

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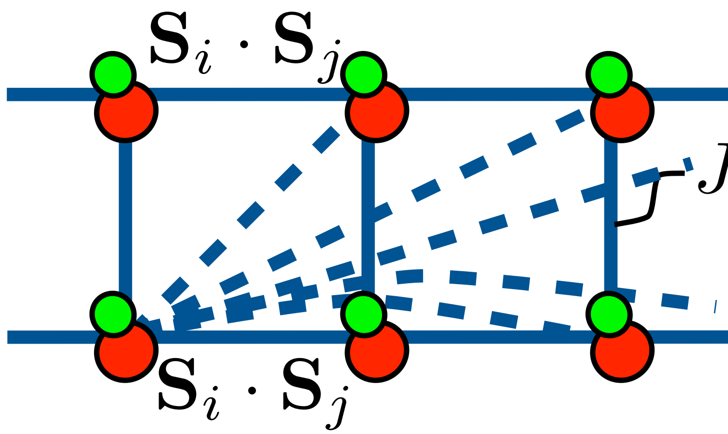

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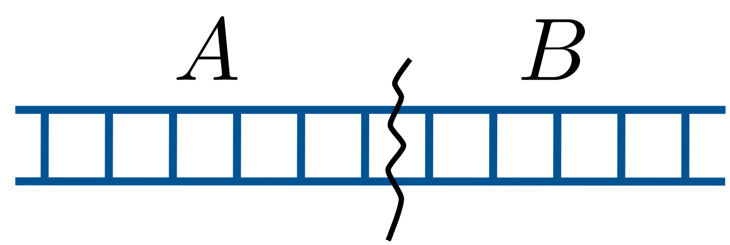

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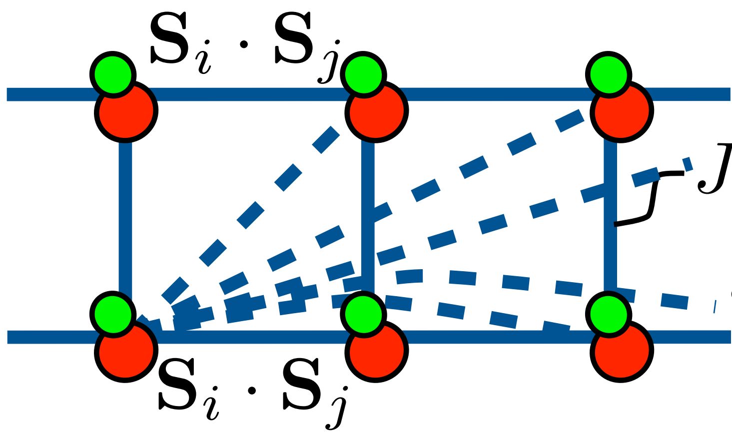

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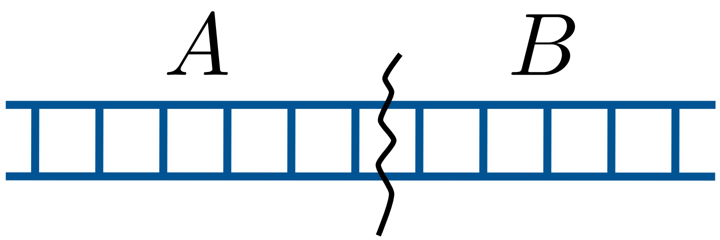

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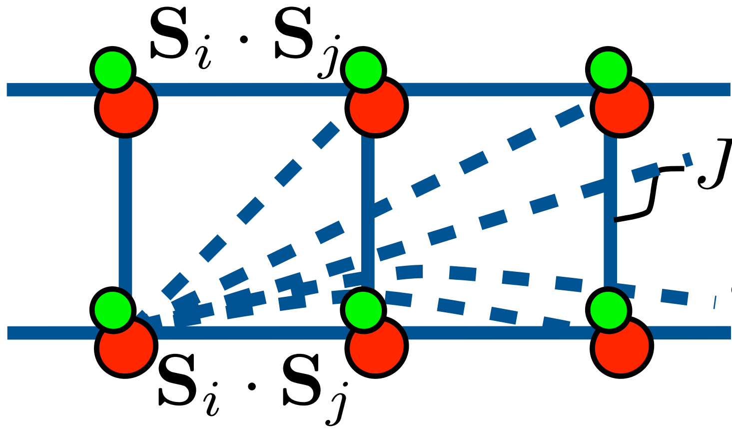

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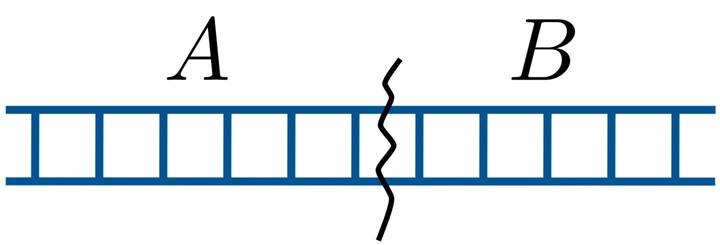

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Topological flat bands
and
fractional Chern insulators

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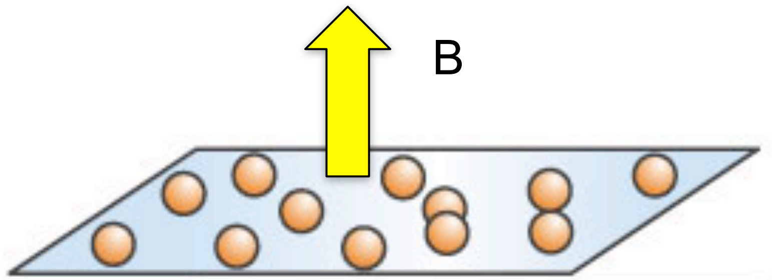

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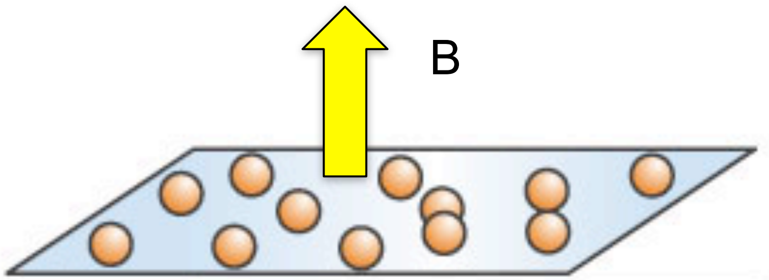

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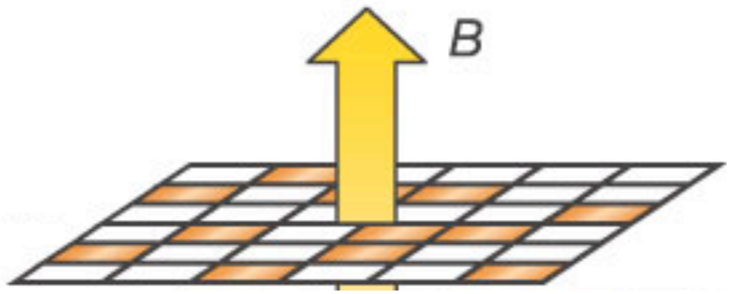

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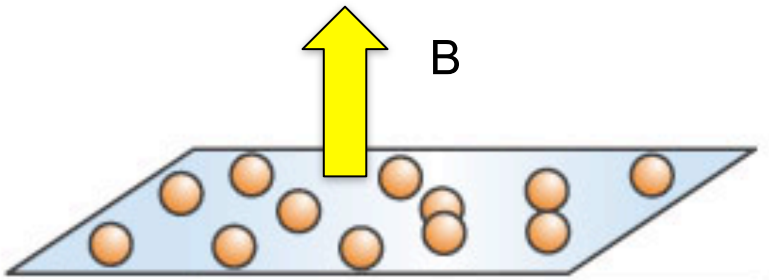

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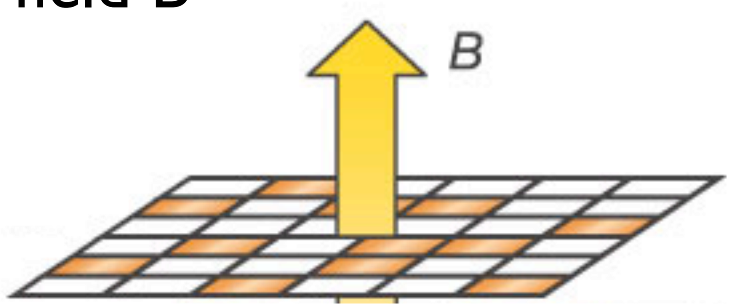

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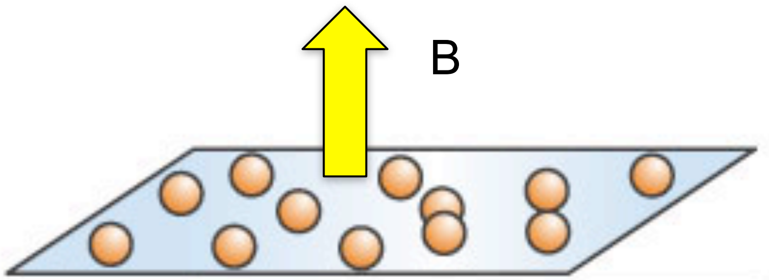

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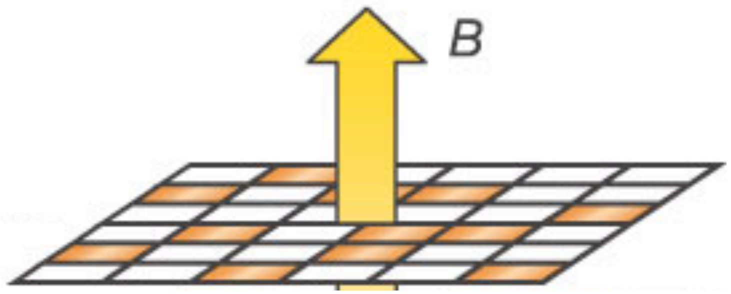

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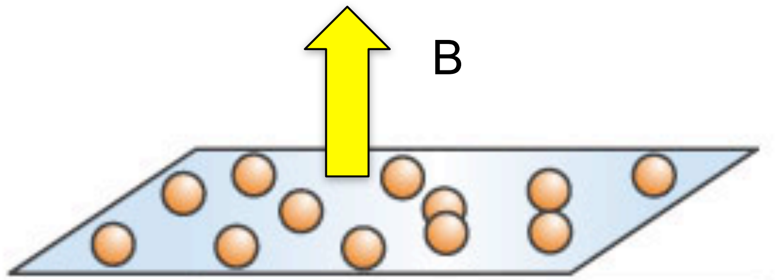

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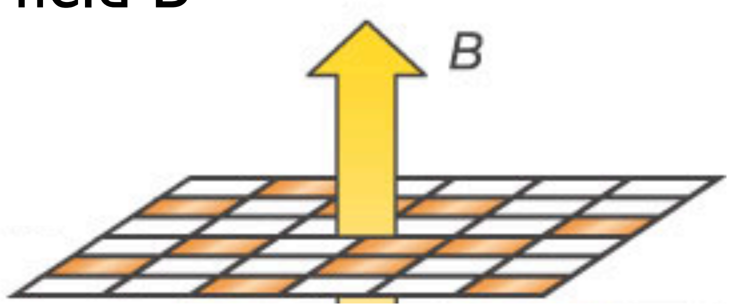

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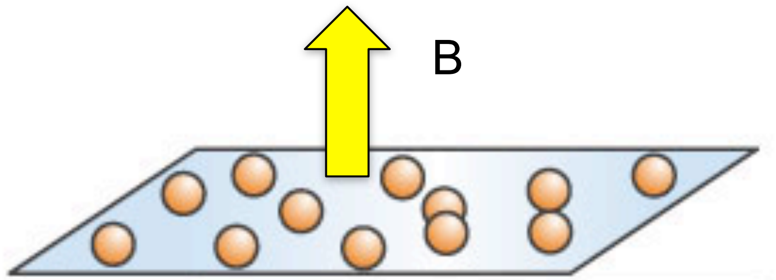

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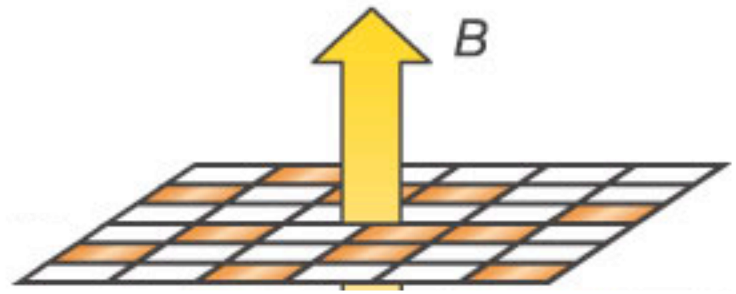

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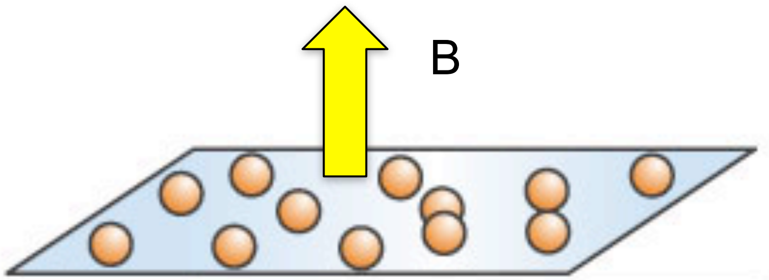

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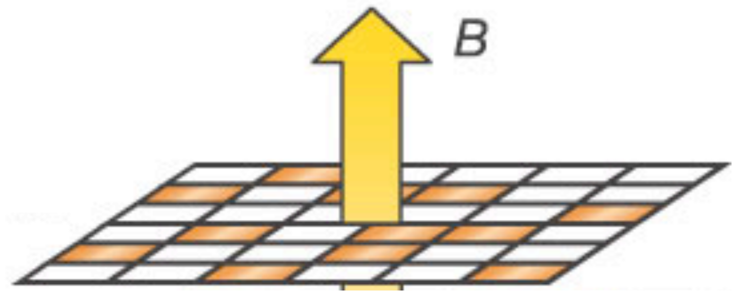

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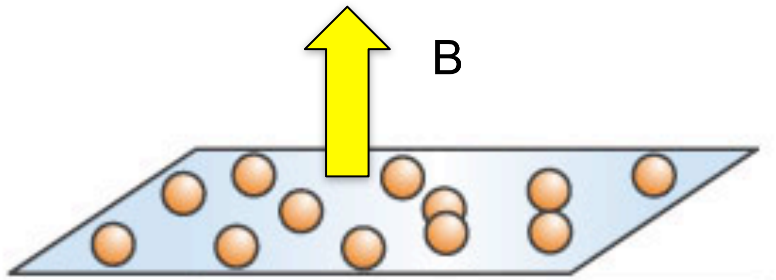

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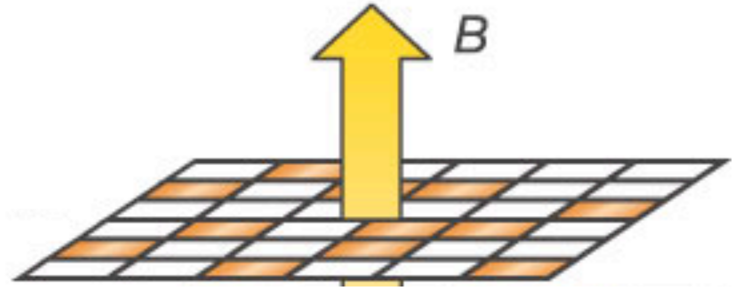

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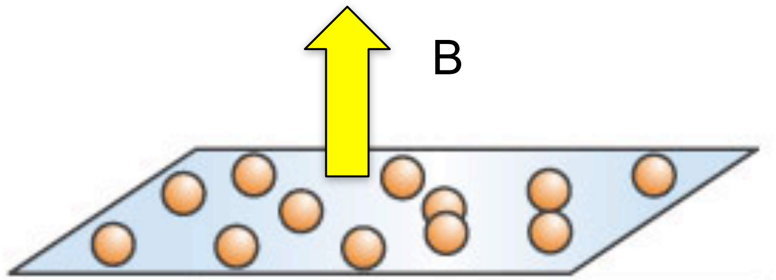

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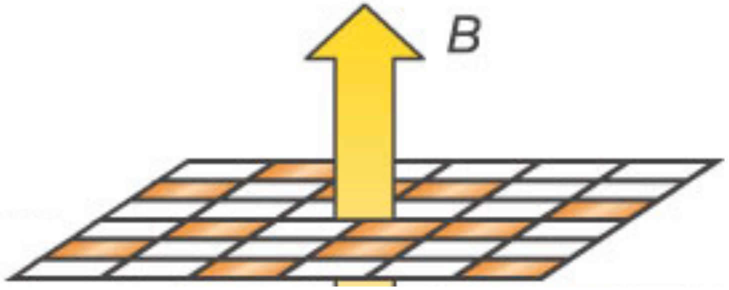

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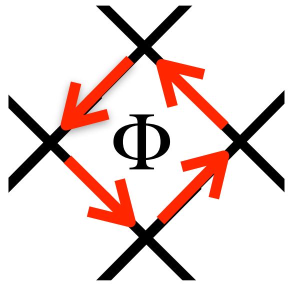

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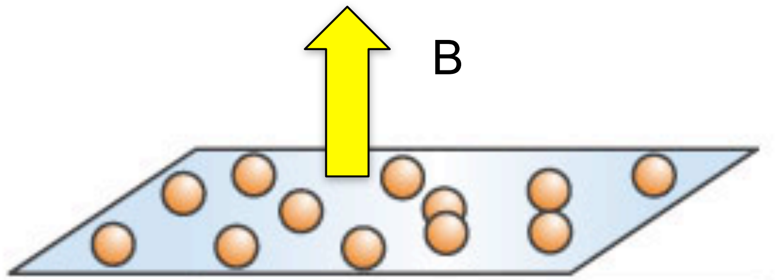

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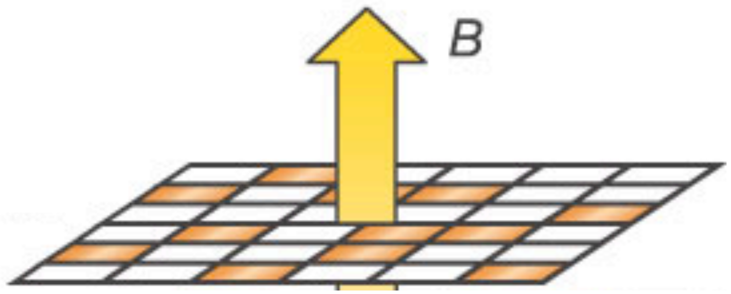

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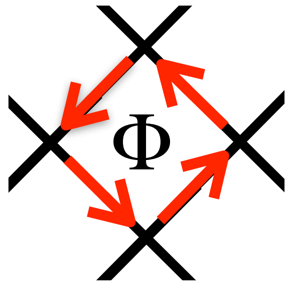

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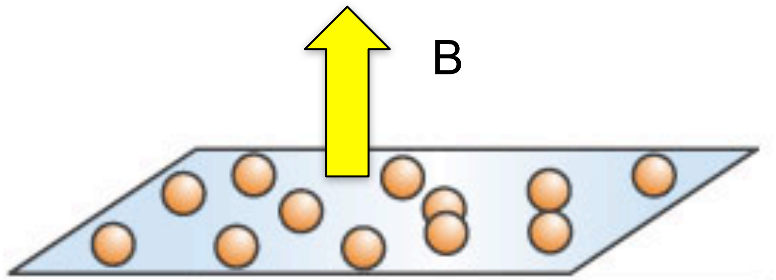

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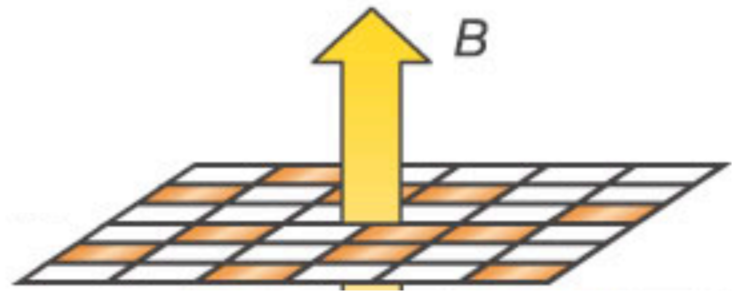

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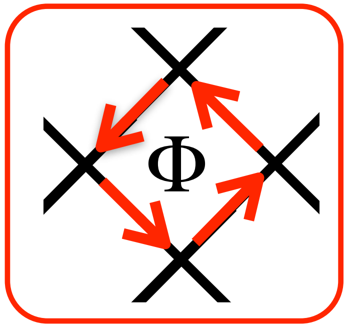

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Flat topological bands

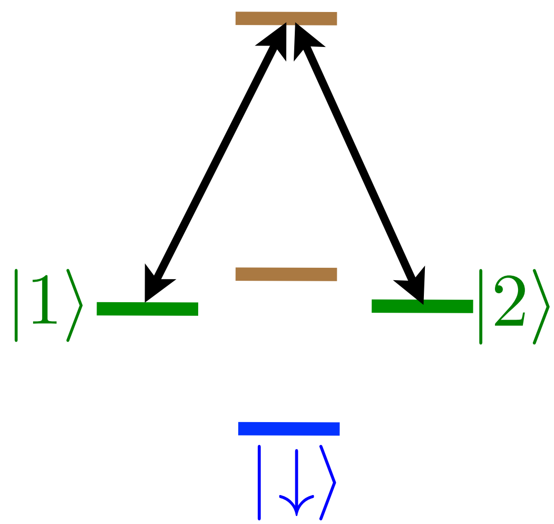
F. D. M. Haldane, PRL 61, 2015 (1988) [IQHE]
E. Tang, J-W. Mei, and X-G. Wen, PRL 106, 236802 (2011)
T. Neupert, L. Santos, C. Chamon, and C. Mudry, PRL 106, 236804 (2011)
K. Sun, Z. -C Gu, H. Katsura, and S. Das Sarma, PRL 106, 236803 (2011)
T. Grass, M.A. Baranov, M. Lewenstein, PRA 84, 043605 (2011)
Y.-F. Wang, Z. -C Gu, C.-D. Gong, D. Sheng, PRL 107 146803 (2011)
Z. Liu, E. J. Bergholtz, H. Fan, R. Moessner, A. M. Laeuchli PRL 109, 186805 (2012), arXiv:1207.6094 (2012)
S. Yang, Z.-C. Gu, K. Sun, S. Das Sarma, arXiv:1205.5792 (2012)
… many more …

- realistic physical system missing
- dipolar spin systems (e.g. polar molecules) naturally admit topological flat bands and fractional Chern insulator (~FQHE) ground states!

Fractional Chern insulator with polar molecules

Fractional Chern insulator with polar molecules

Recall SPT discussion:



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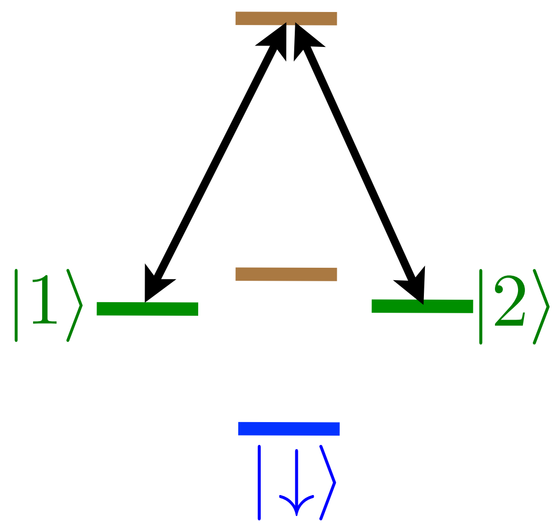

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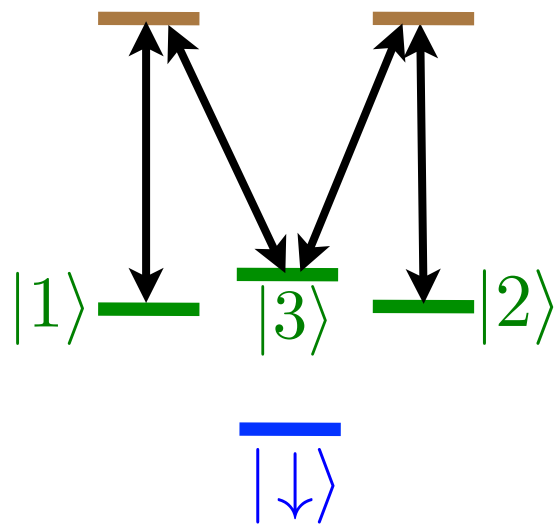

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[PRL 109, 266804 (2012)
& arXiv:1212.4839]

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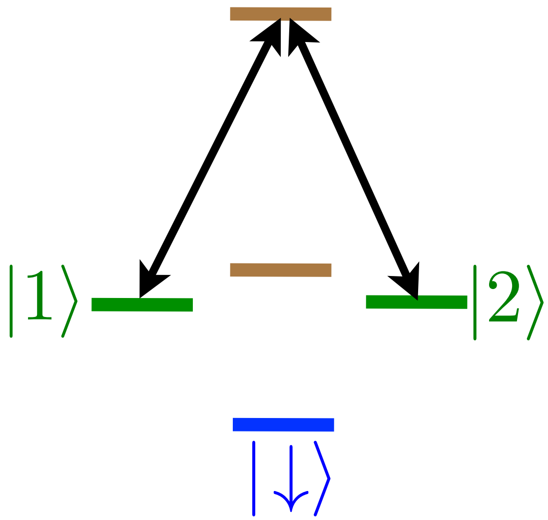

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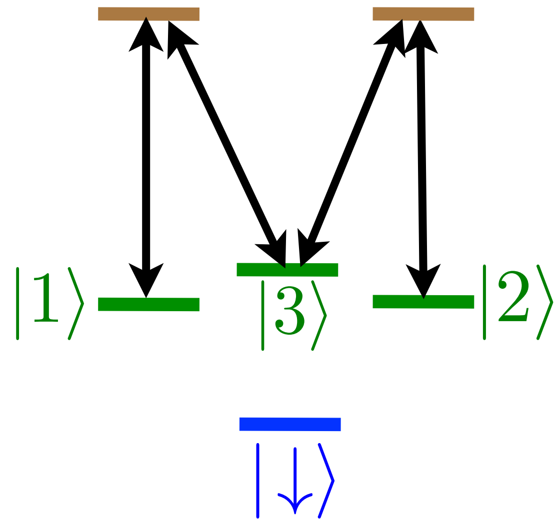

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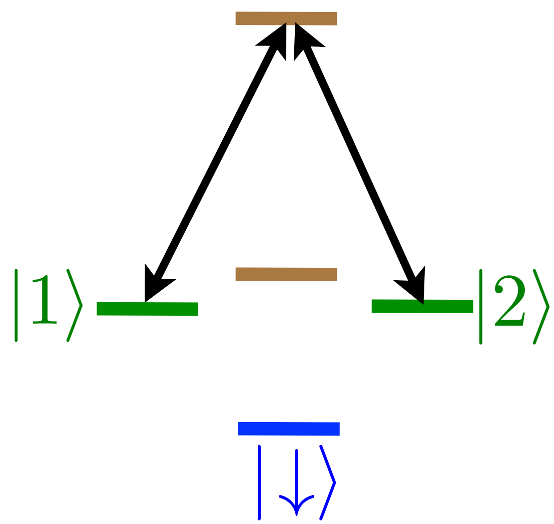

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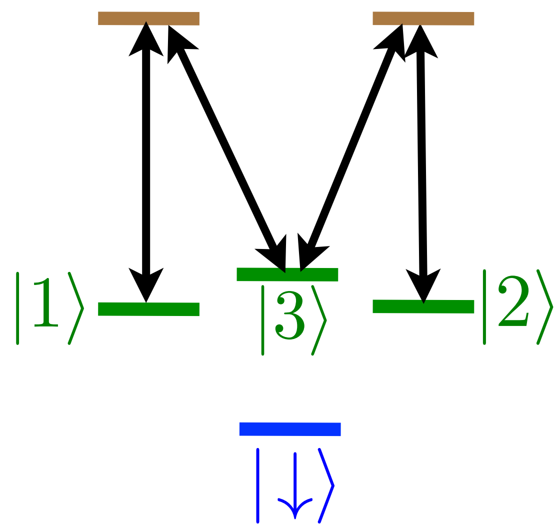

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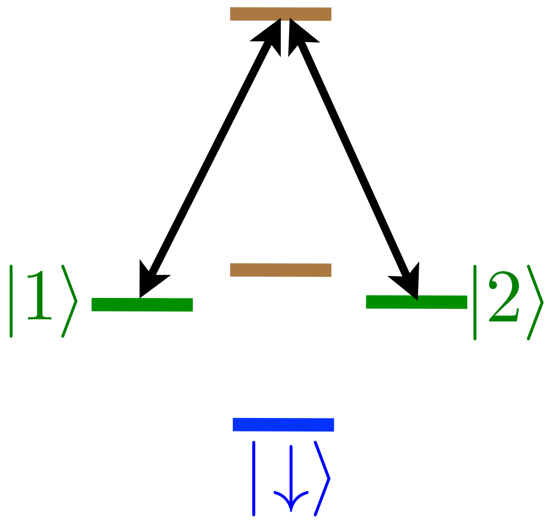

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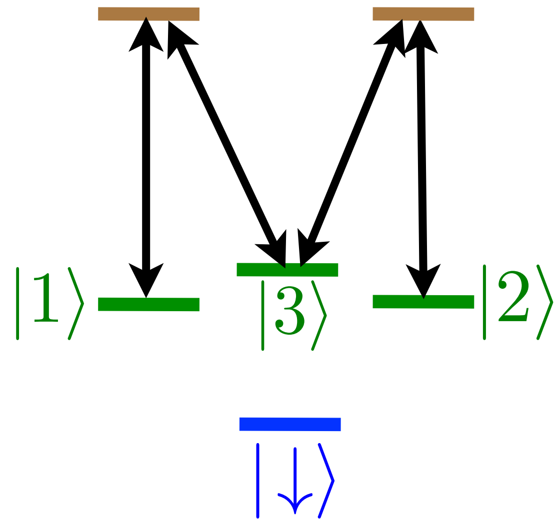

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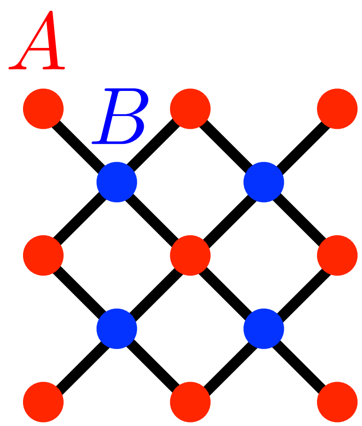

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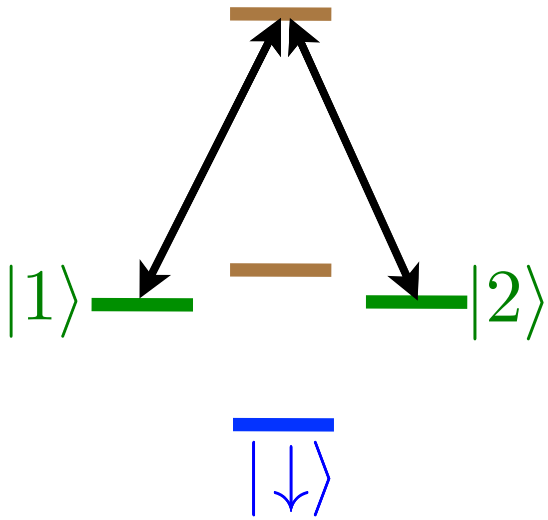

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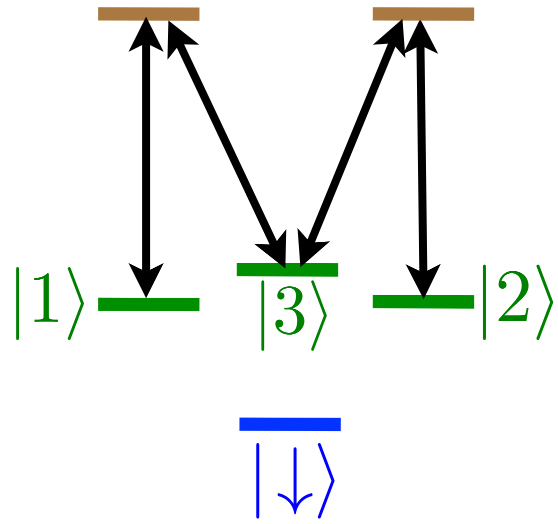

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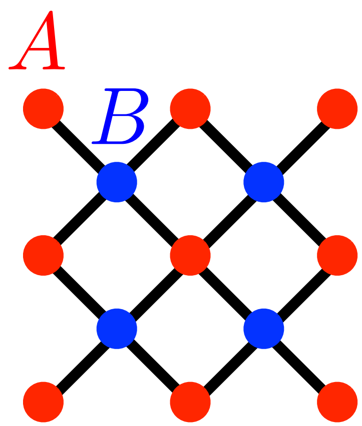

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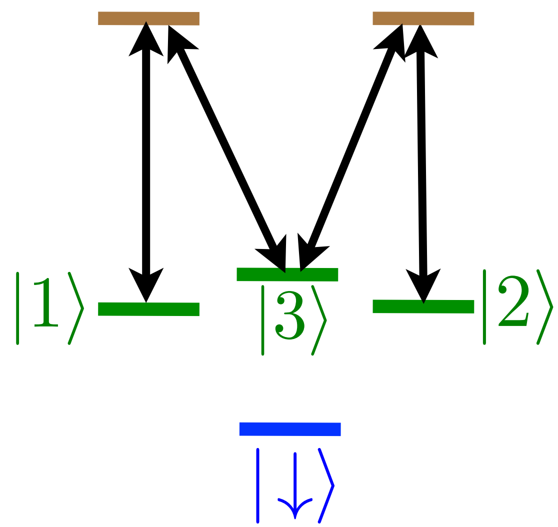

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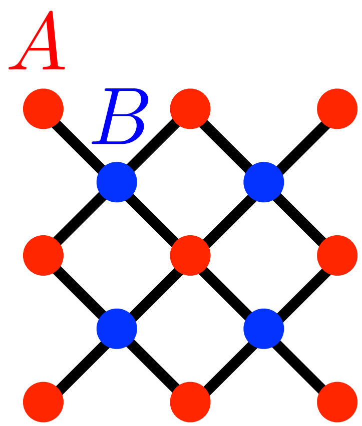

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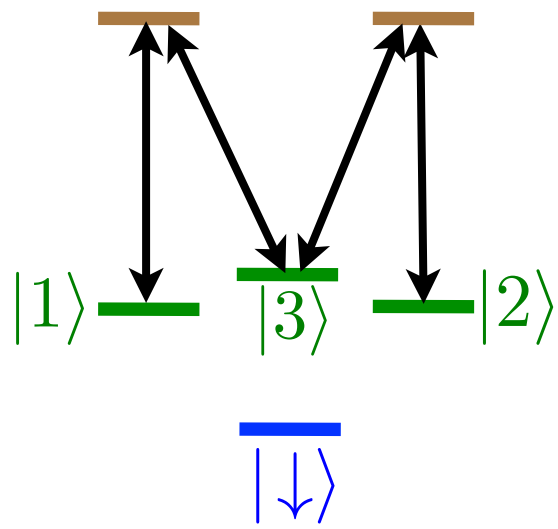

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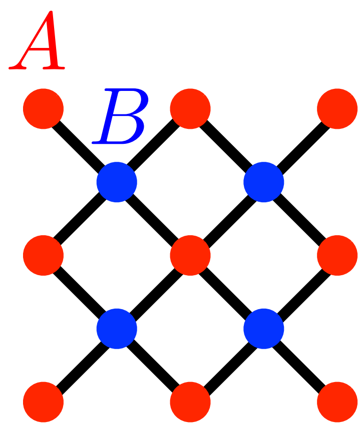

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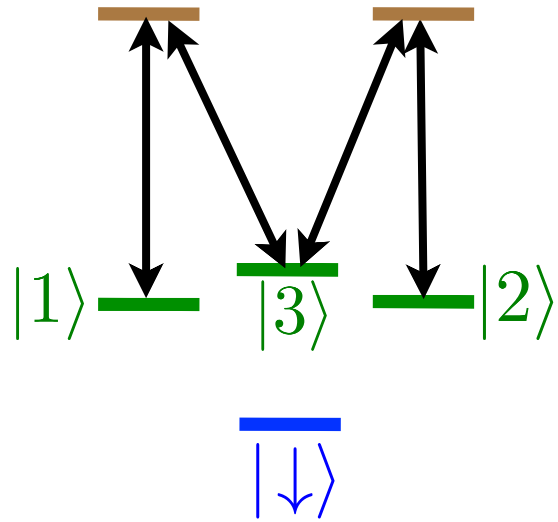

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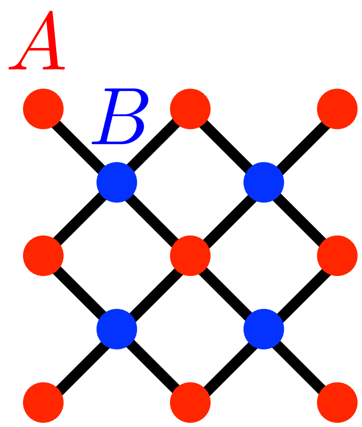

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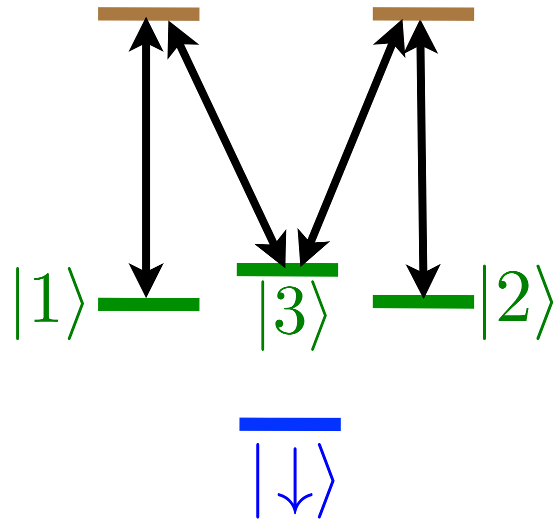

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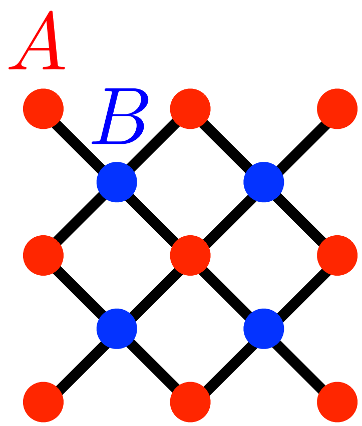

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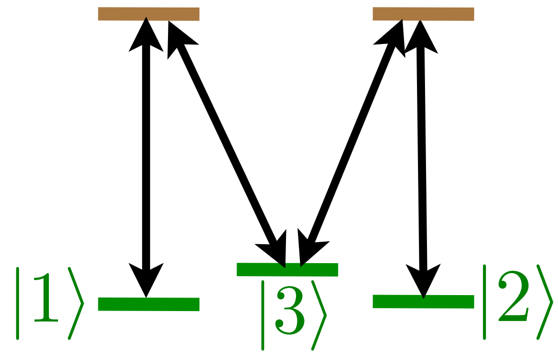

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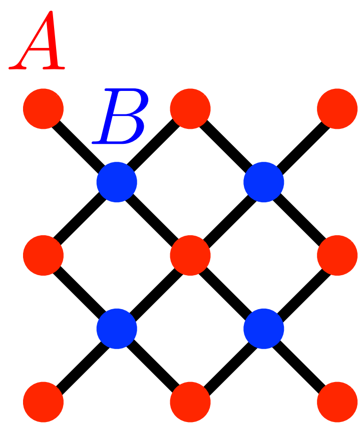

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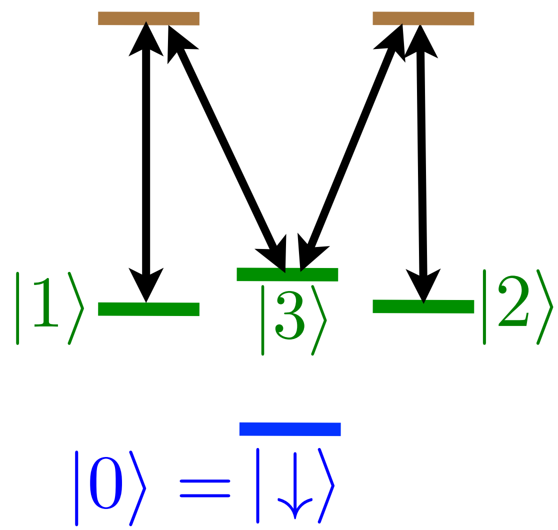

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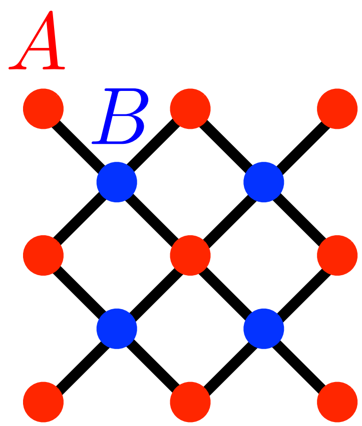

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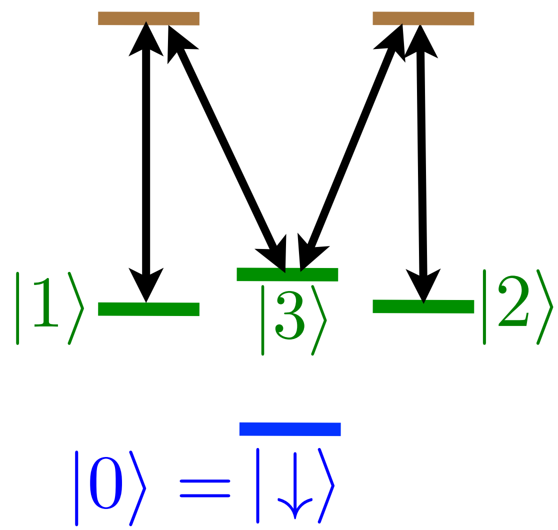

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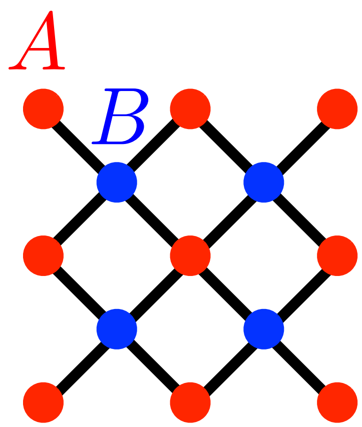

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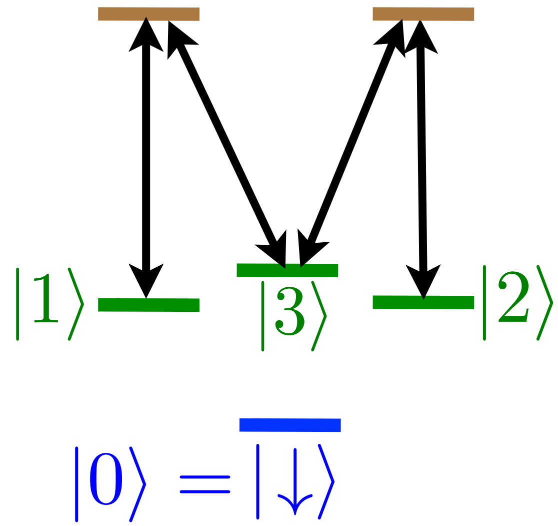

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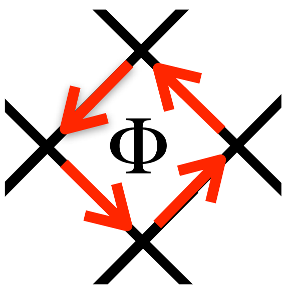

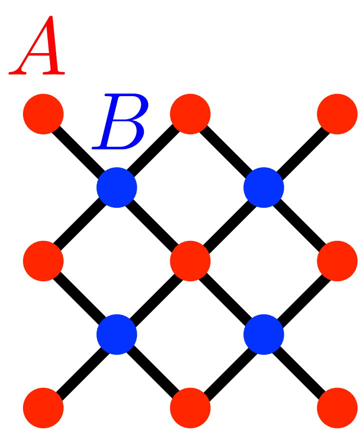

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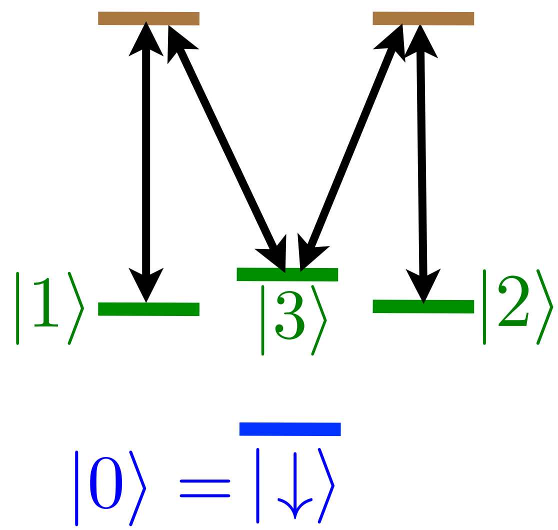

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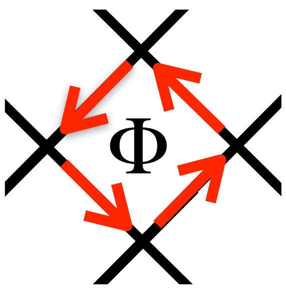

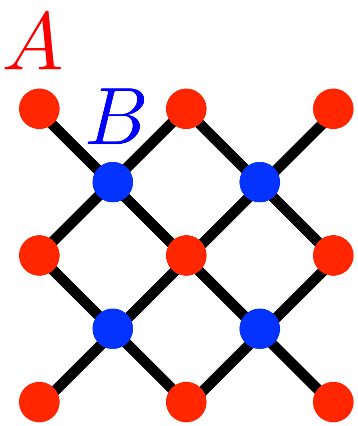

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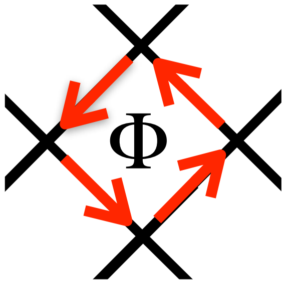
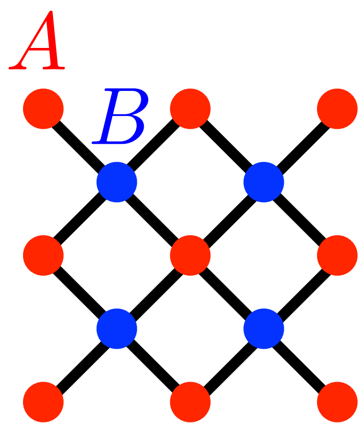
& $Y_{2,2} \propto e^{i2\phi} \Rightarrow$ 



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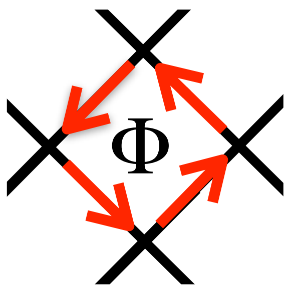

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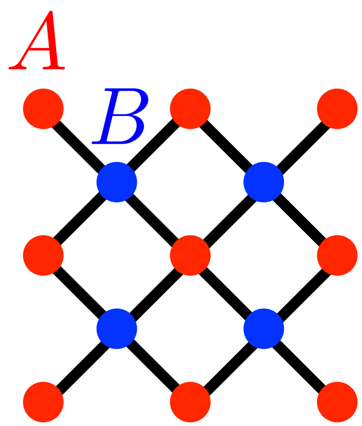

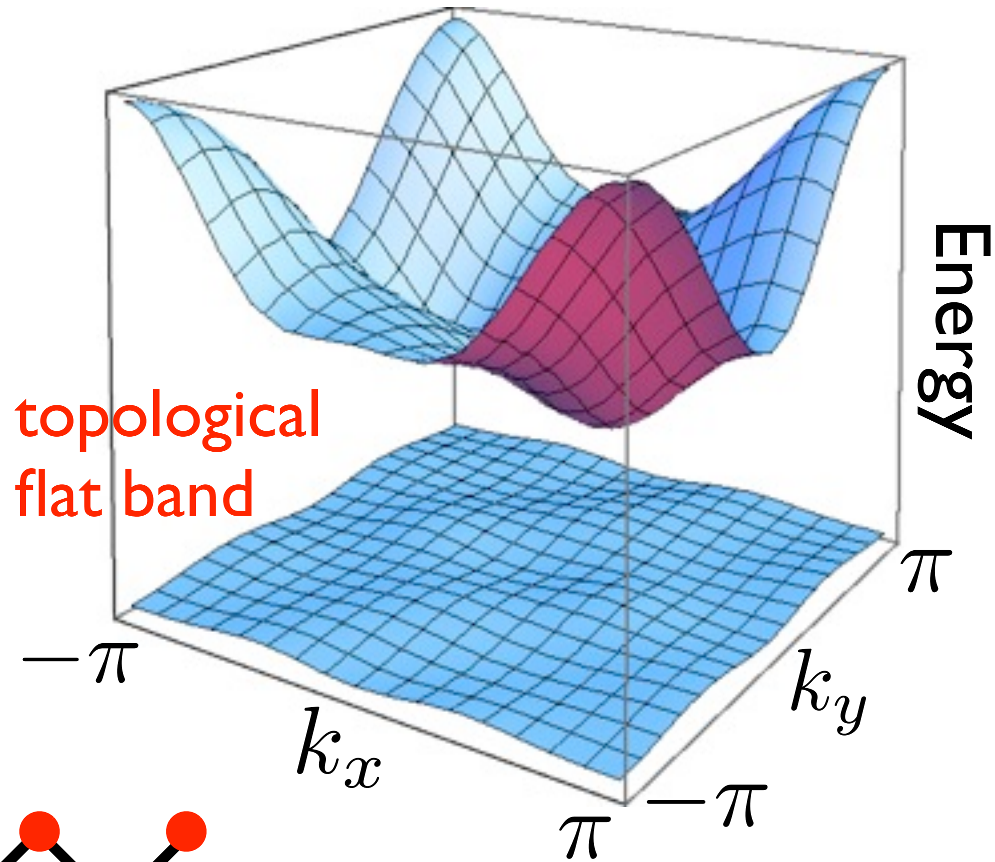

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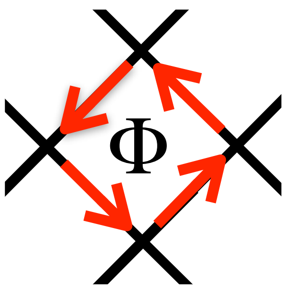
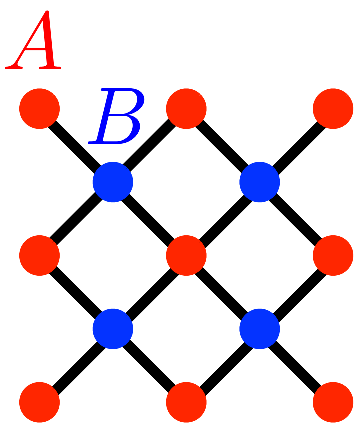
& $Y_{2,2} \propto e^{i2\phi} \Rightarrow$ 



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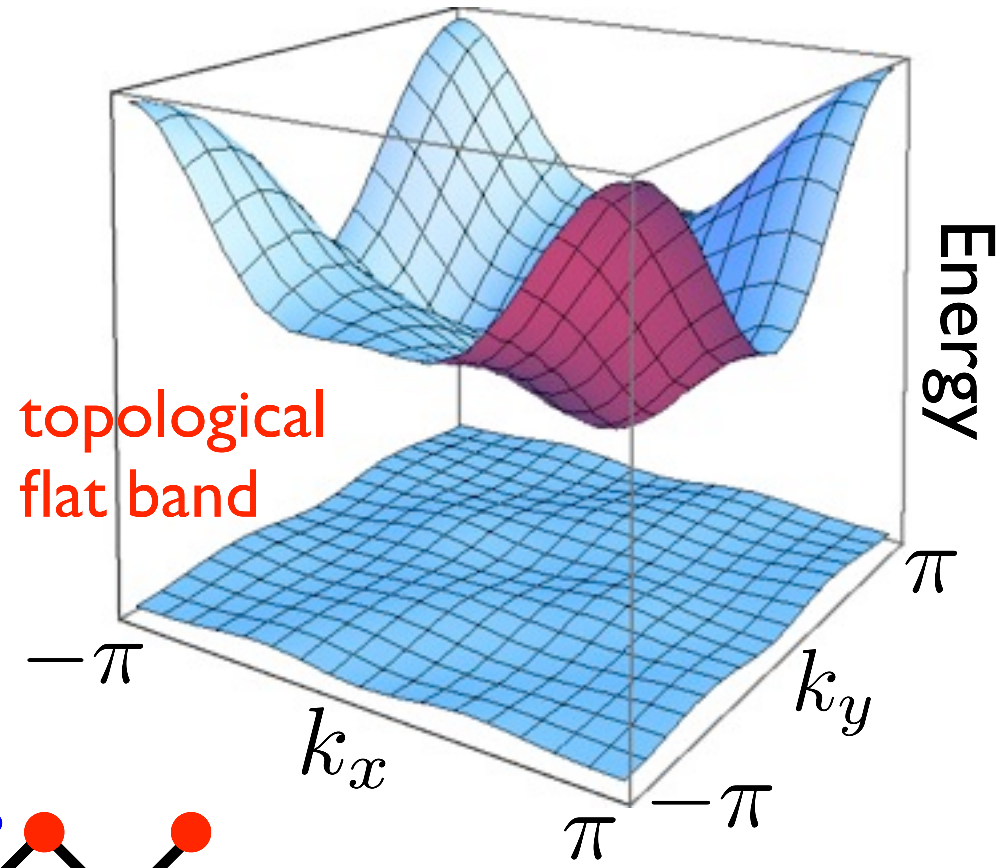

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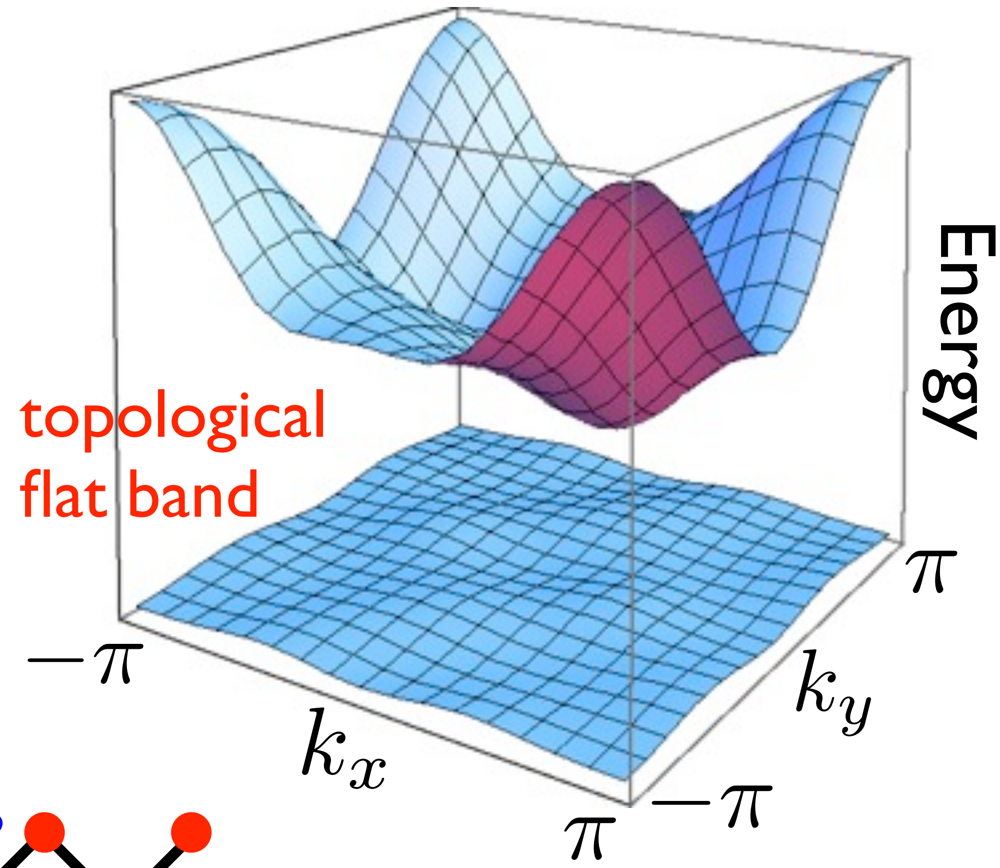

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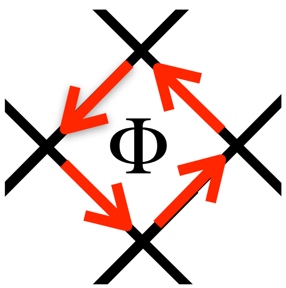
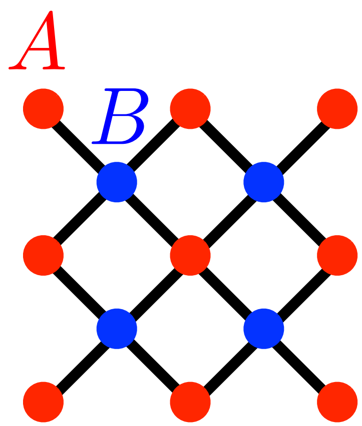
& $Y_{2,2} \propto e^{i2\phi} \Rightarrow$ 



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- Rydberg atoms, magnetic atoms, spins in solid state

(informal)
Overview and discussion
of
many-body physics with polar molecules

M. A. Baranov, M. Dalmonte, G. Pupillo, and P. Zoller,
Condensed Matter Theory of Dipolar Quantum Gases,
Chem. Rev. 112, 5012 (2012); arXiv:1207.1914 [cond-mat.quant-gas].

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But:

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- study all of these separately and in combinations, with DC magnetic and electric field control, microwave and RF control, optical control

Geometry

- 3D
- 2D (pancakes)
- 1D (tubes)
- Lattices:
  - 1D (lattice in a tube),
  - 2D (lattice in a pancake),
  - 3D

3D

Baranov, Dalmonte, Pupillo, Zoller, Chem. Rev. 112, 5012 (2012)

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- weak interactions: $\text{interaction} \ll \text{kinetic energy}$

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To get strong interactions: confine to lower-D and/or use lattice

Baranov, Dalmonte, Pupillo, Zoller, Chem. Rev. 112, 5012 (2012)

2D (pancakes)

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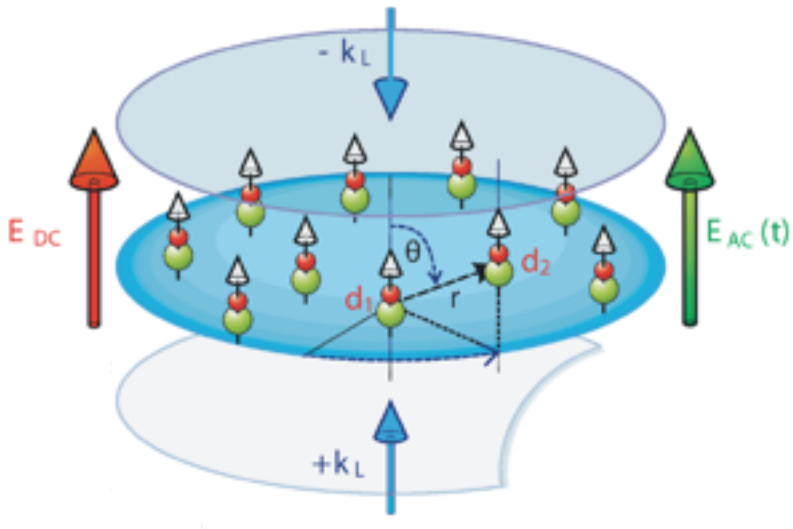

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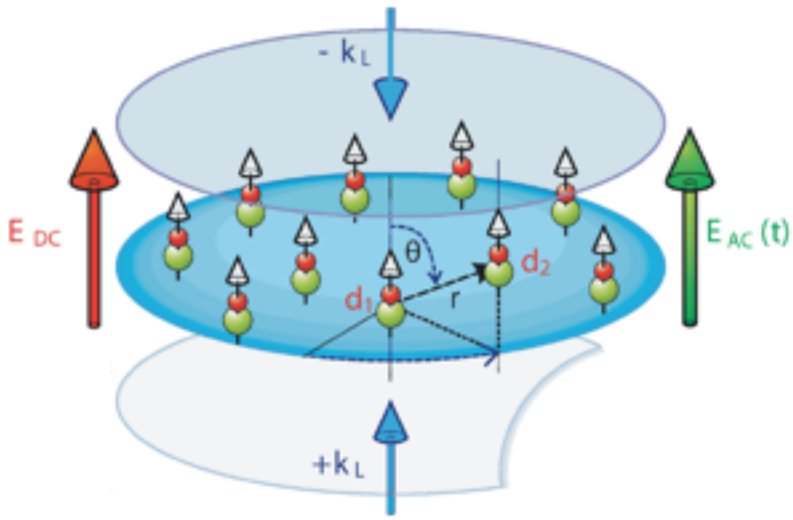
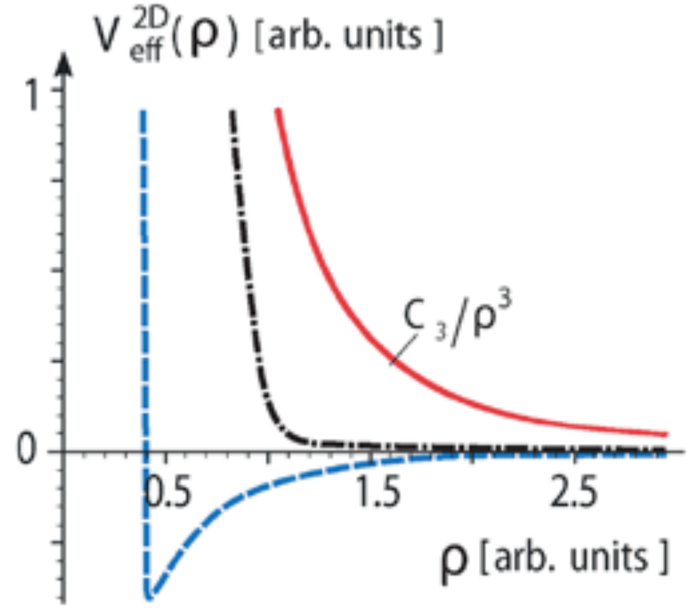


DC & AC fields used to shape the interaction:



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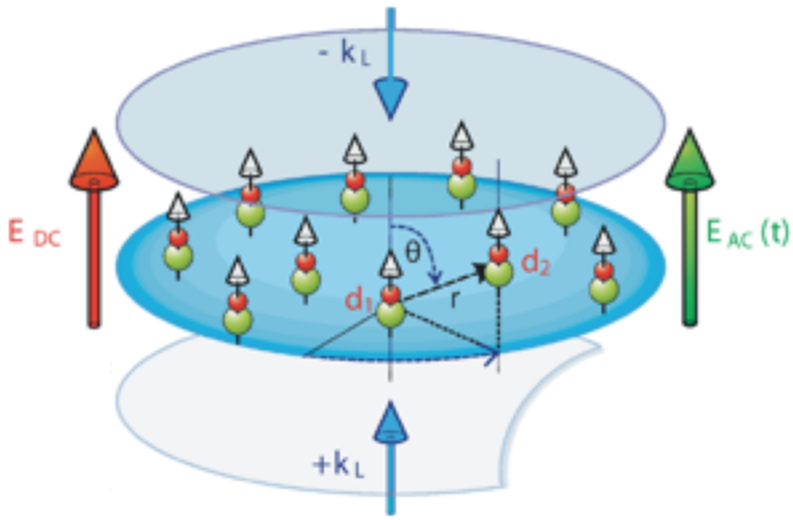

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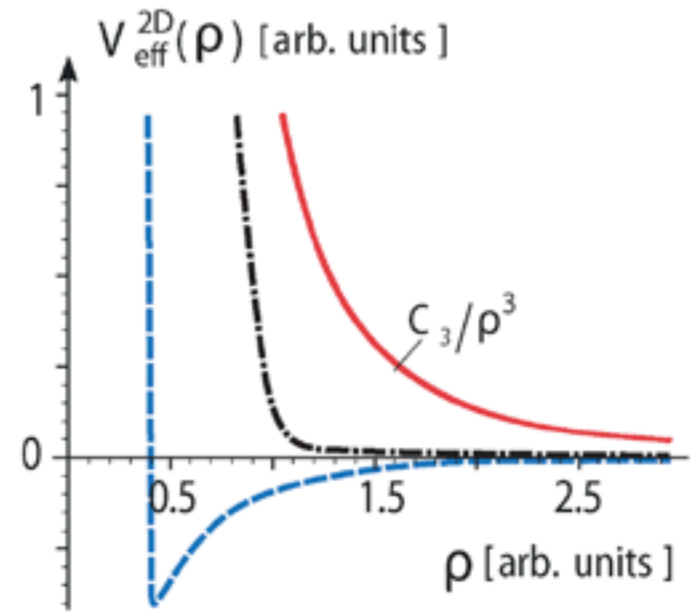

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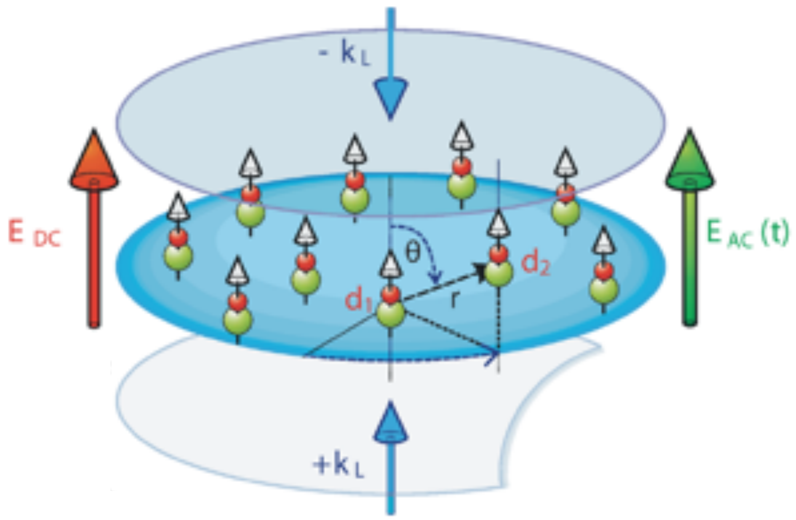

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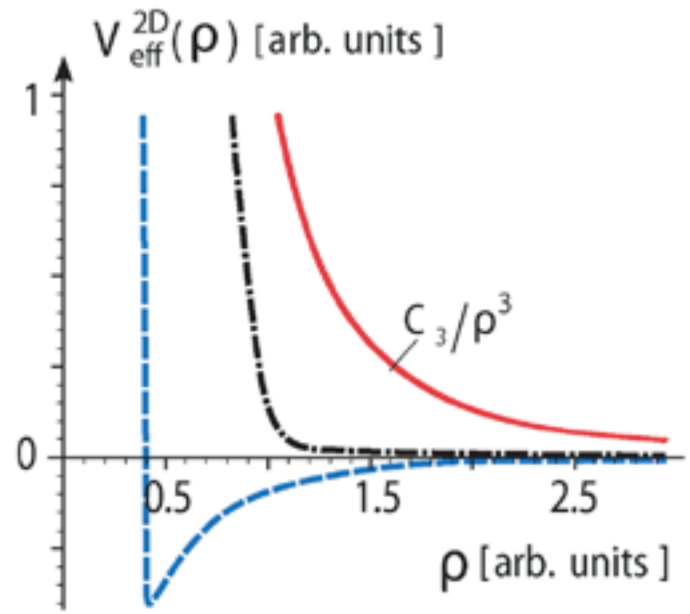

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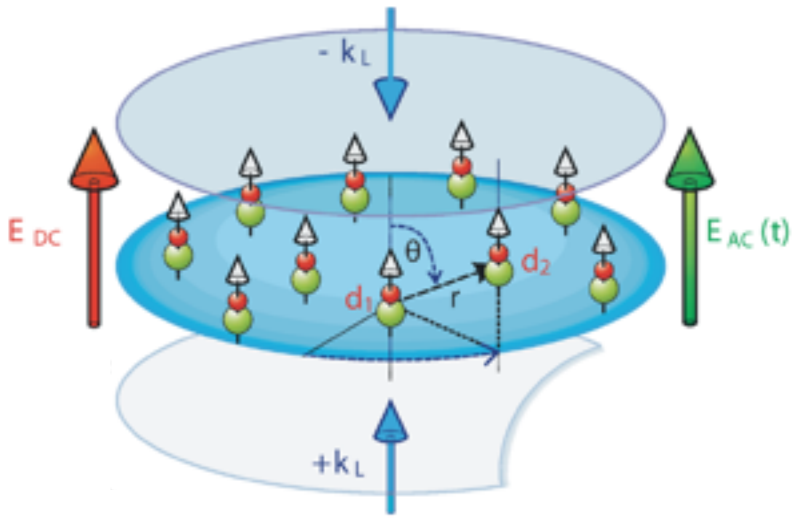

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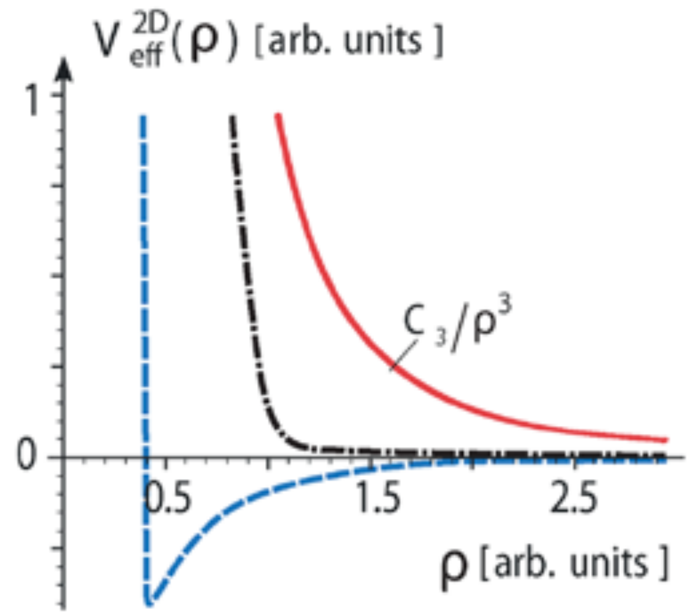

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- ...

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Baranov, Dalmonte, Pupillo, Zoller, Chem. Rev. 112, 5012 (2012)

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with hopping

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  - one- and two-component (e.g. tJ-type models)

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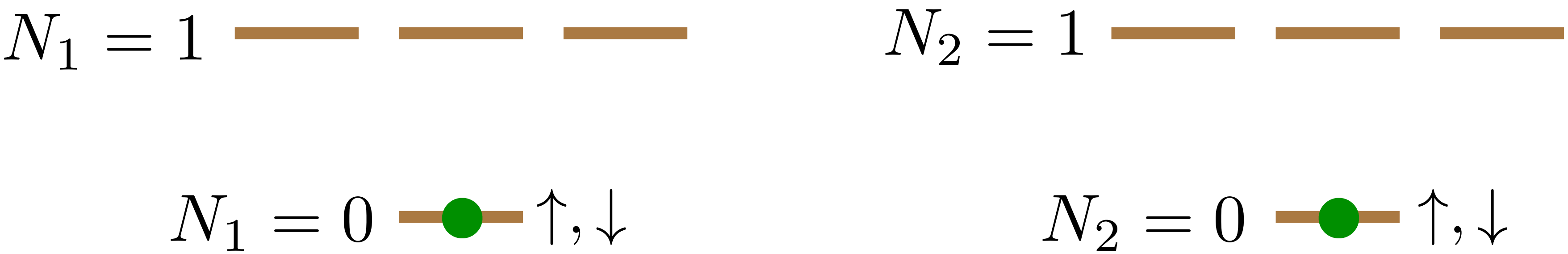

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