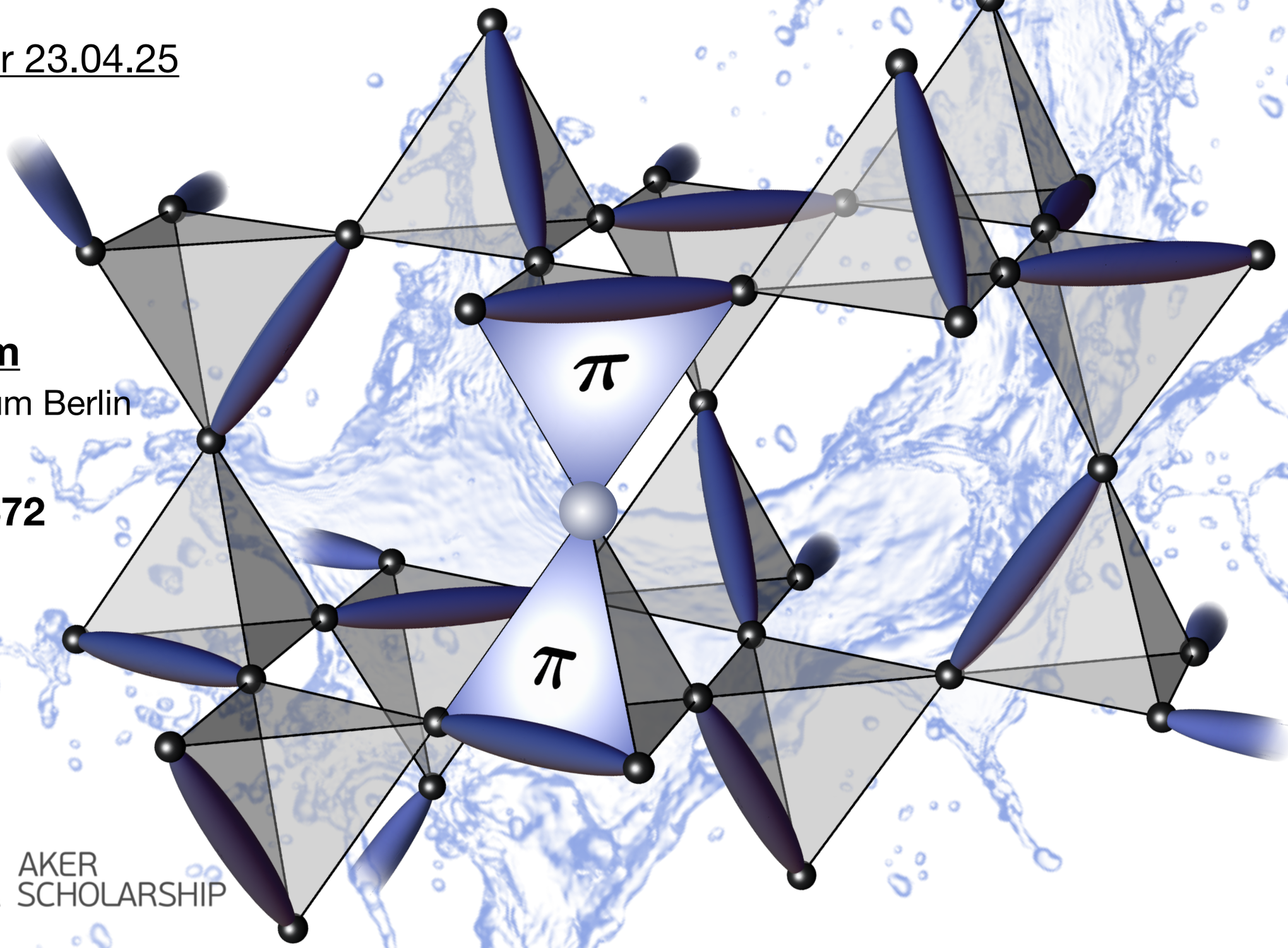
Doping-induced RVB spin liquid
in a frustrated Mott insulator

Theory seminar 23.04.25



Cecilie Glittum
Helmholtz-Zentrum Berlin

arXiv:2408.03372

AKER SCHOLARSHIP

Collaborators



Claudio Castelnovo
University of Cambridge



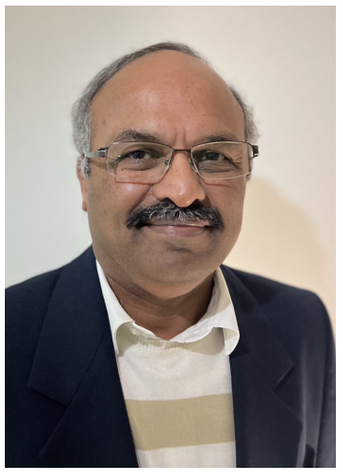
Cristian Batista
University of Tennessee



Antonio Štrkalj
University of Zagreb



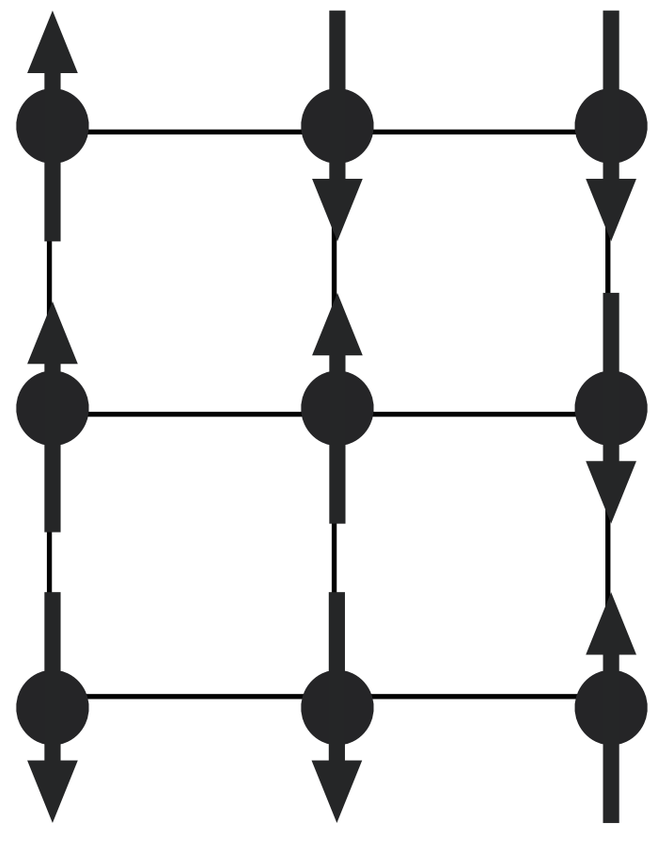
Paul Goddard
University of Warwick



Dharmalingam Prabhakaran
University of Oxford

Doping-induced RVB spin liquid in a frustrated Mott insulator

The Hubbard model captures the most essential features of interacting electrons in a lattice.



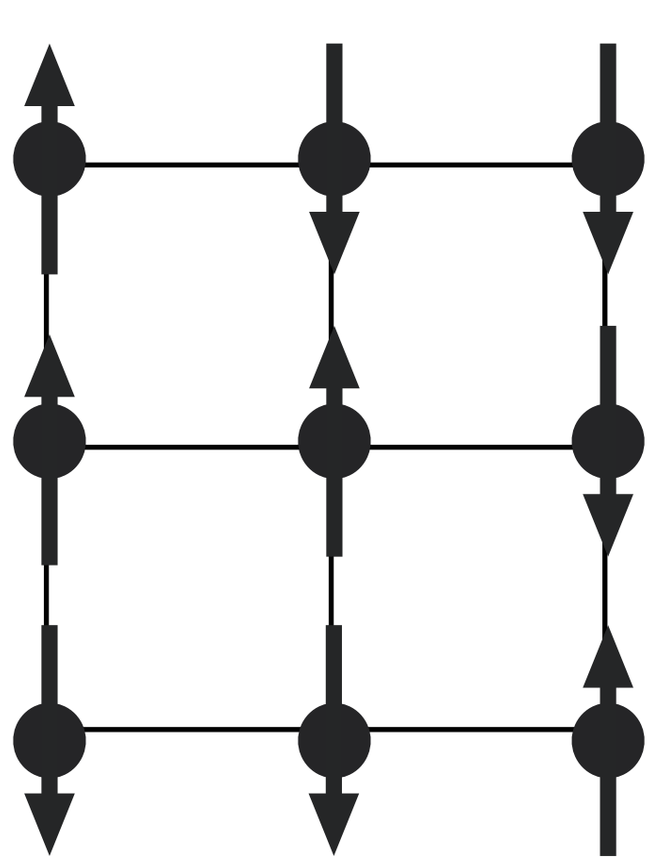
$S = 1/2$

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$$+U \sum_{i} n_{i,\uparrow} n_{i,\downarrow}$$



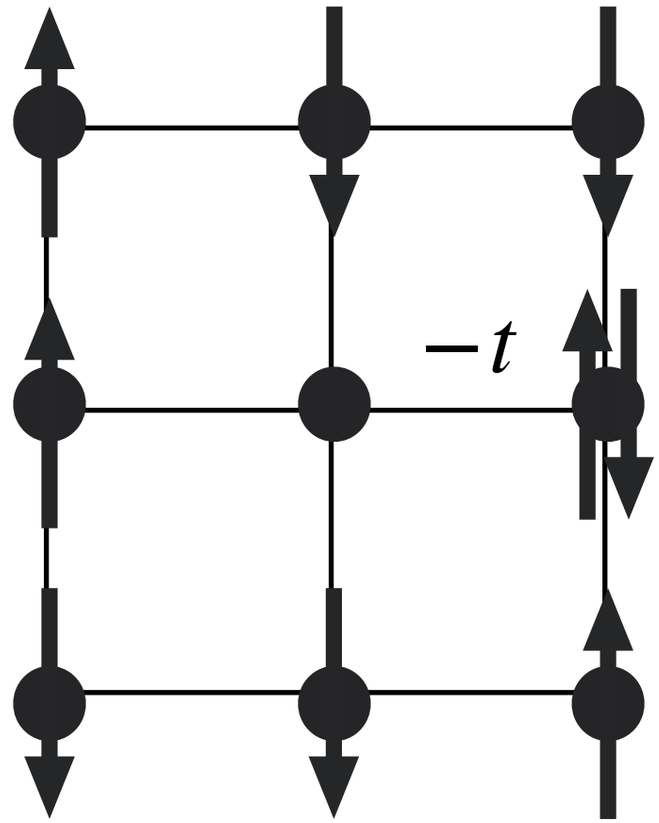
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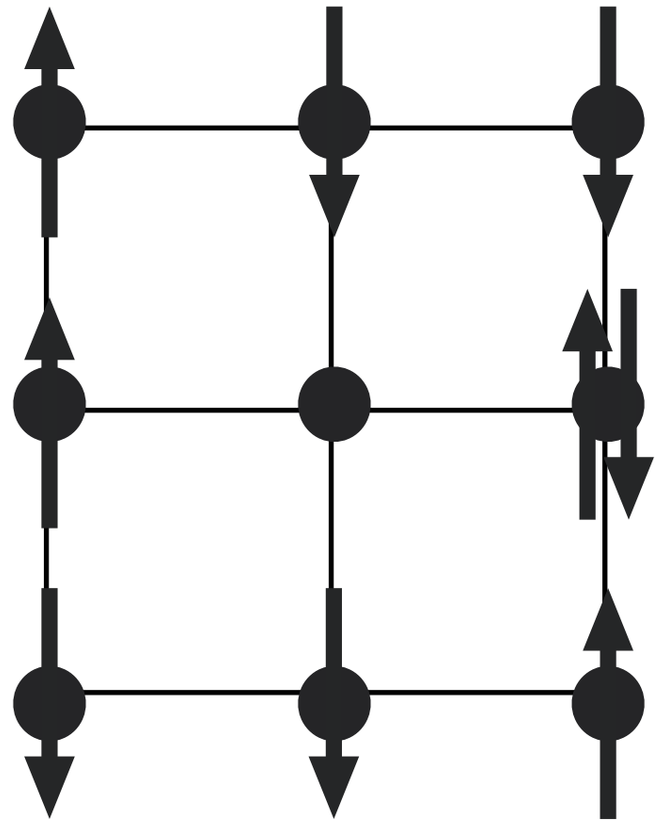
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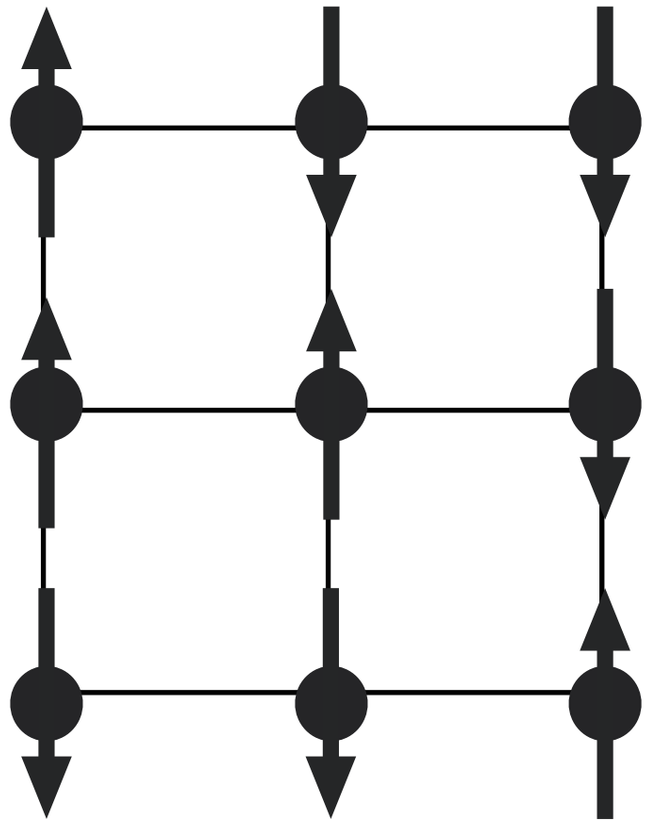
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Large U: Mott insulator



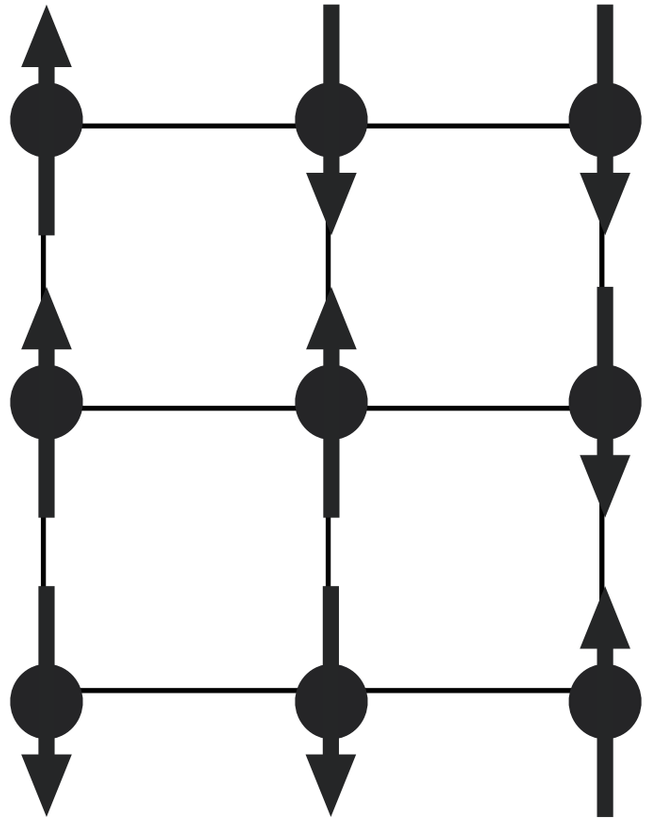
$S = 1/2$

Doping-induced RVB spin liquid in a frustrated Mott insulator

In the large-*U* limit, the Hubbard model at half-filling reduces to the Heisenberg model.

$$H = J \sum_{\langle i,j \rangle} \vec{S}_i \cdot \vec{S}_j$$

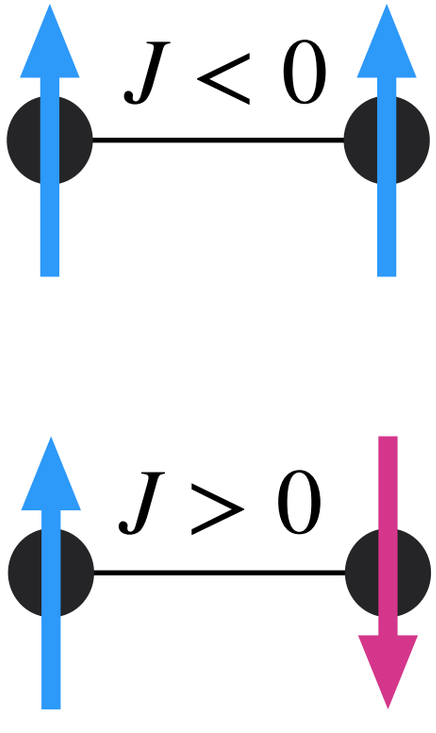
Large *U*: Mott insulator

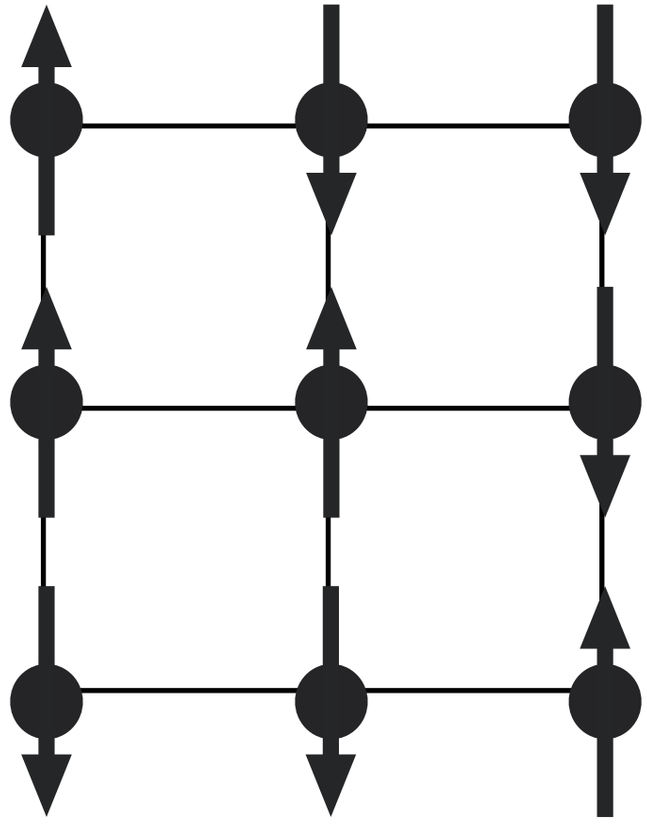


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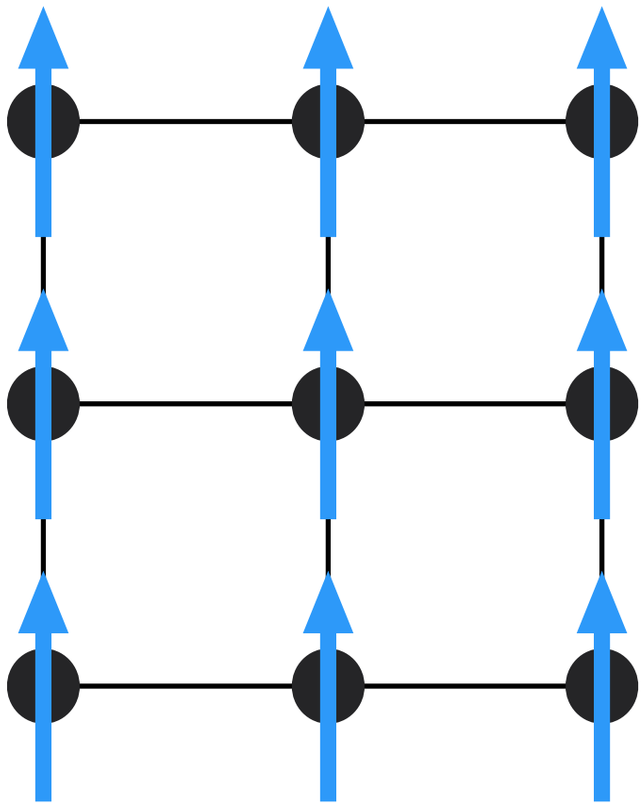




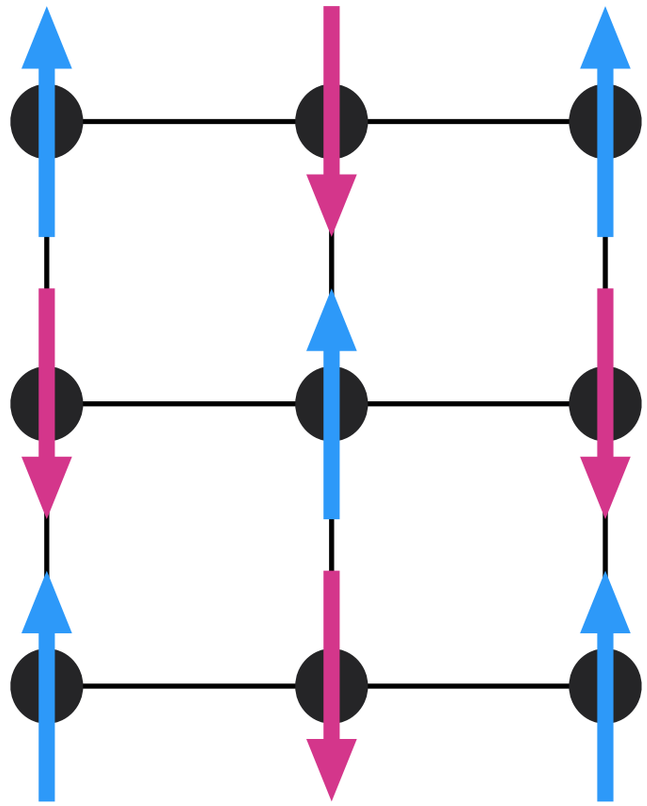
Doping-induced RVB spin liquid in a frustrated Mott insulator

Square lattice with nearest neighbour interactions.

Ferromagnetic

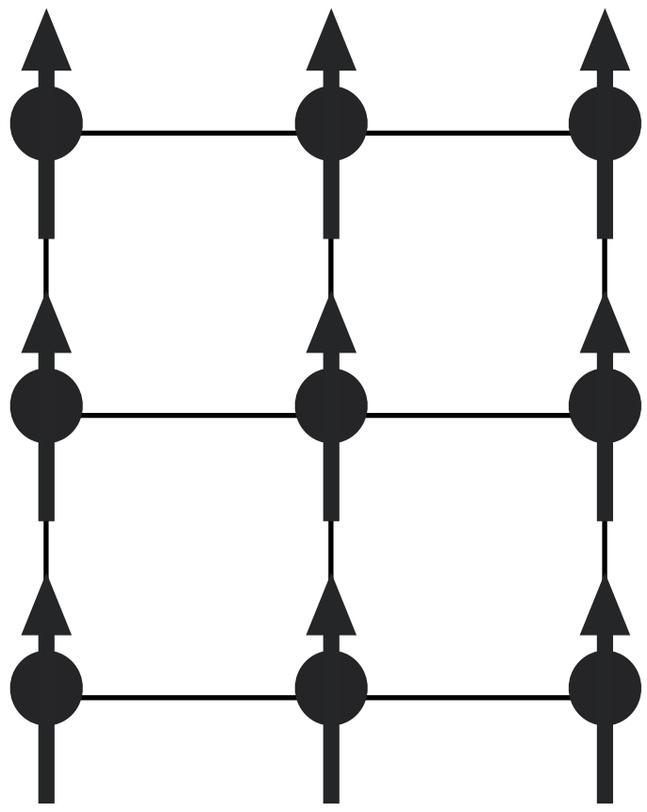


Antiferromagnetic

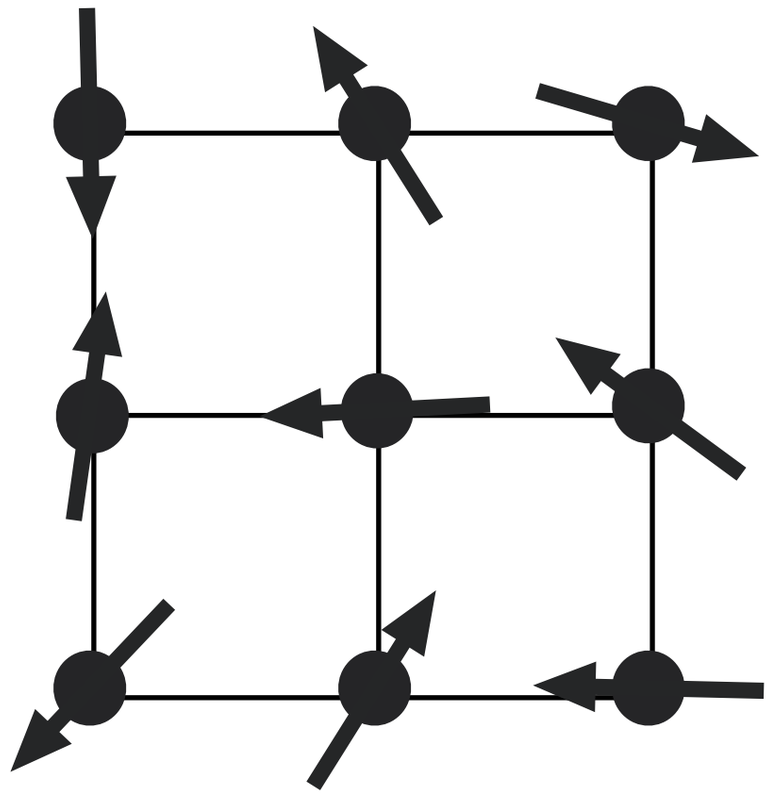


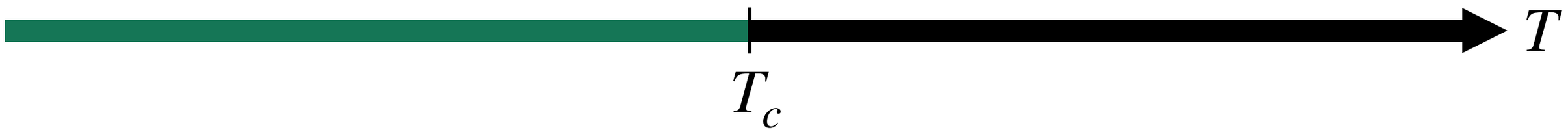
Conventional magnets typically order below a critical temperature.

Ferromagnet



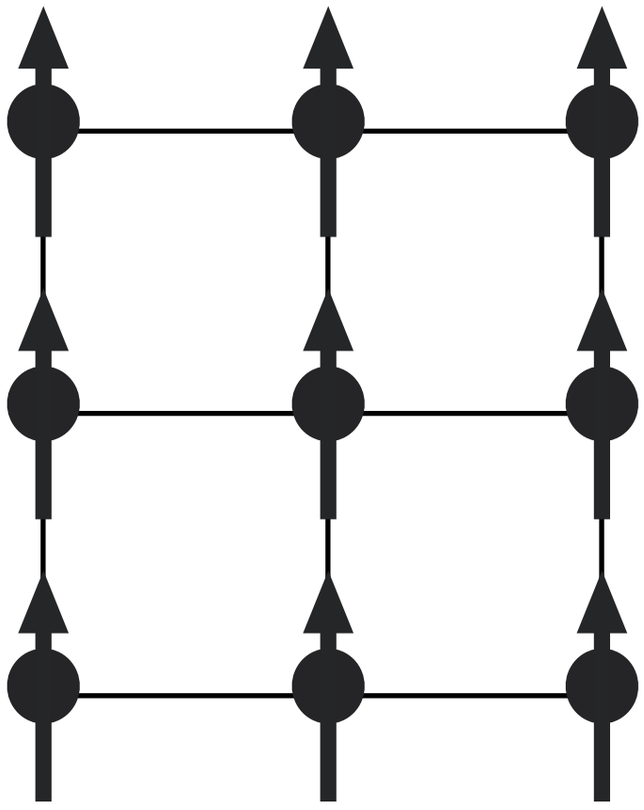
Paramagnet



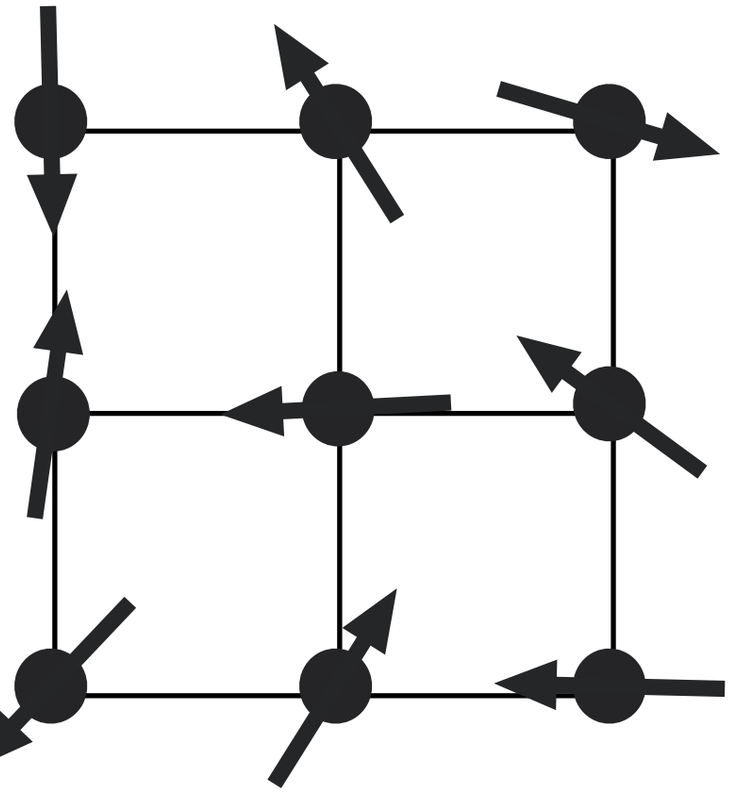


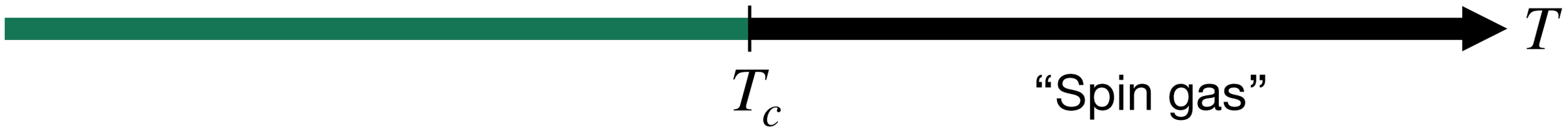
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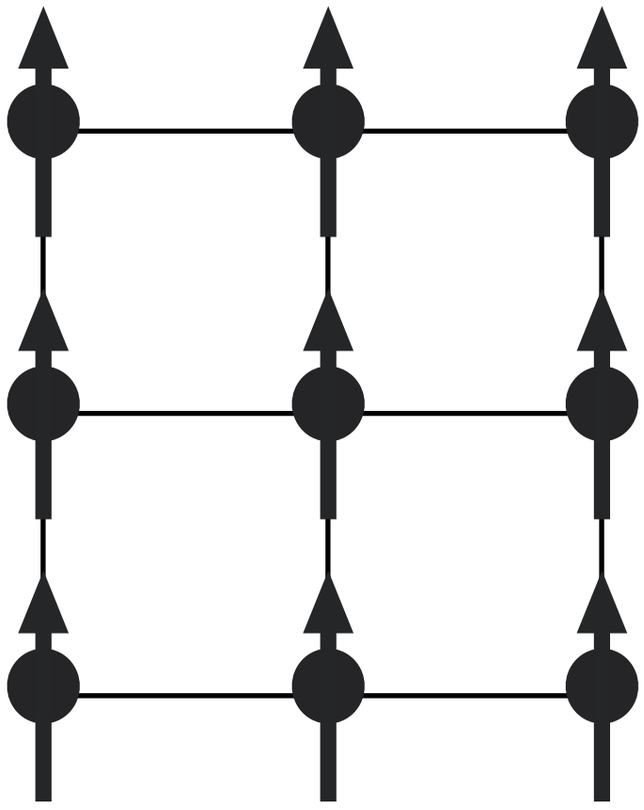
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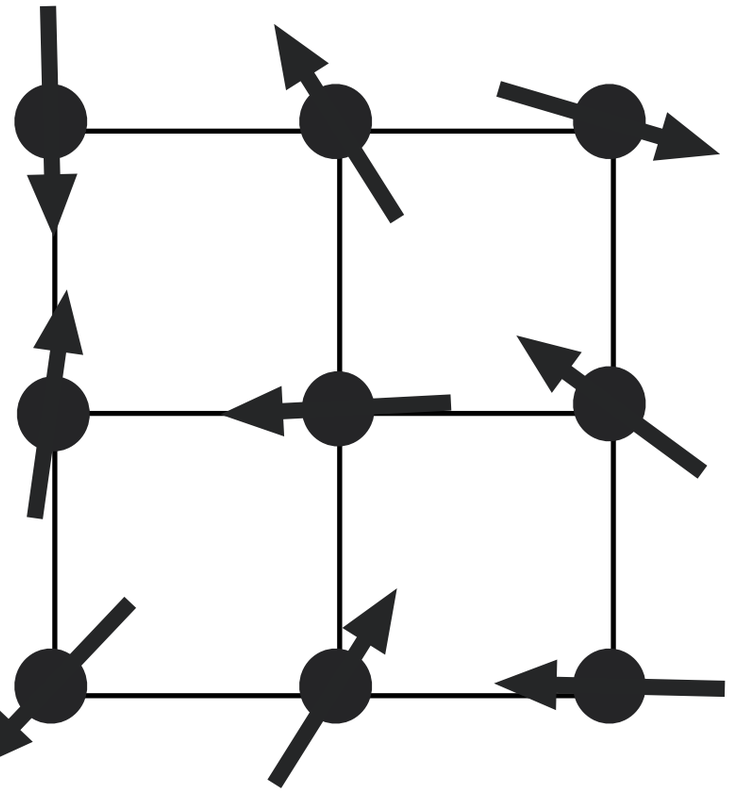


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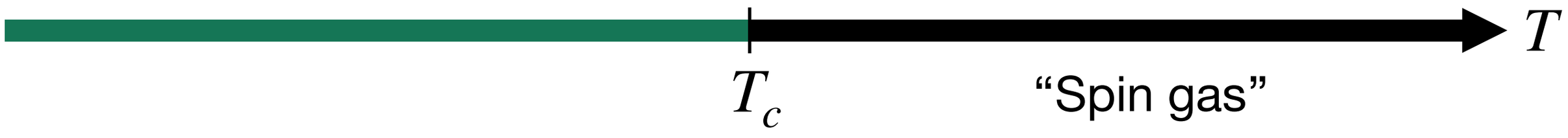
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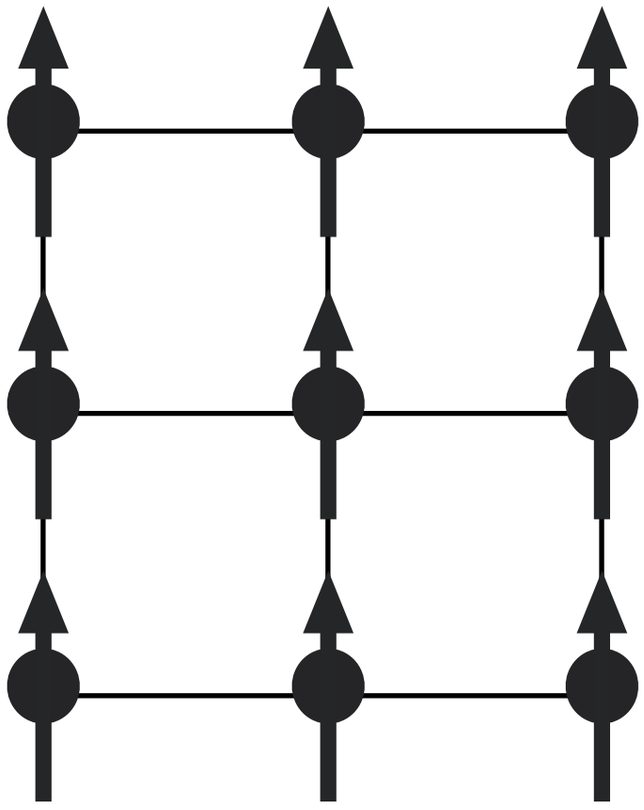


SYMMETRY BREAKING

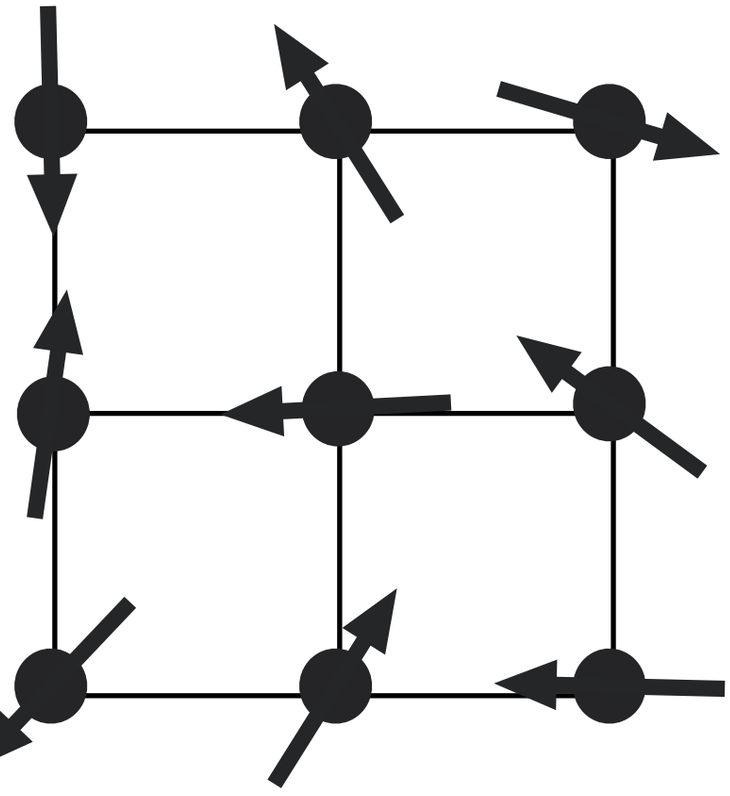


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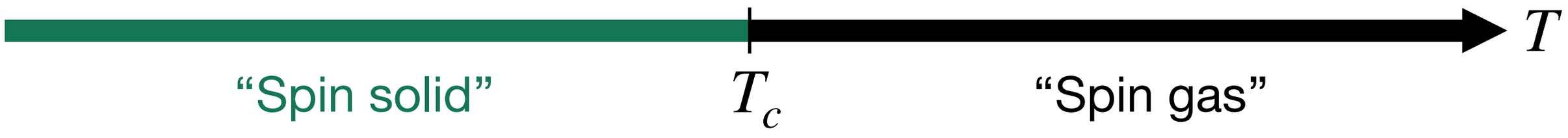
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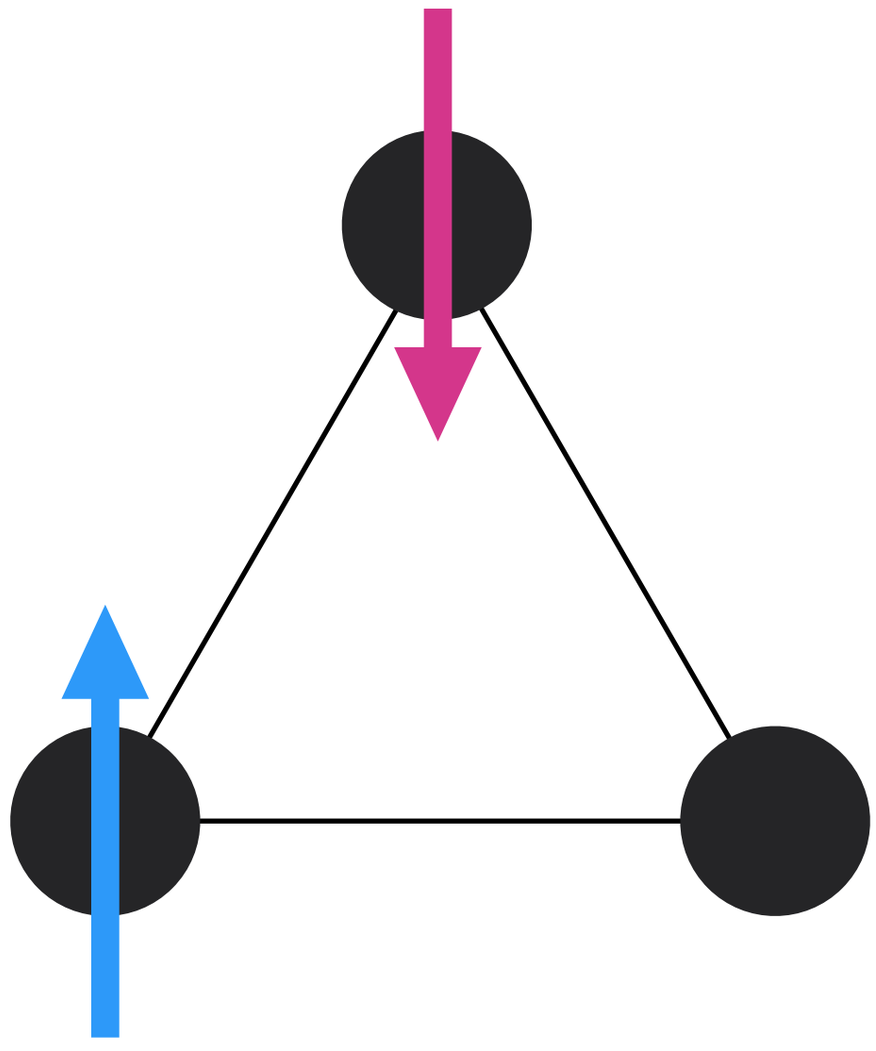


SYMMETRY BREAKING



Frustrated magnets cannot satisfy all interactions simultaneously.

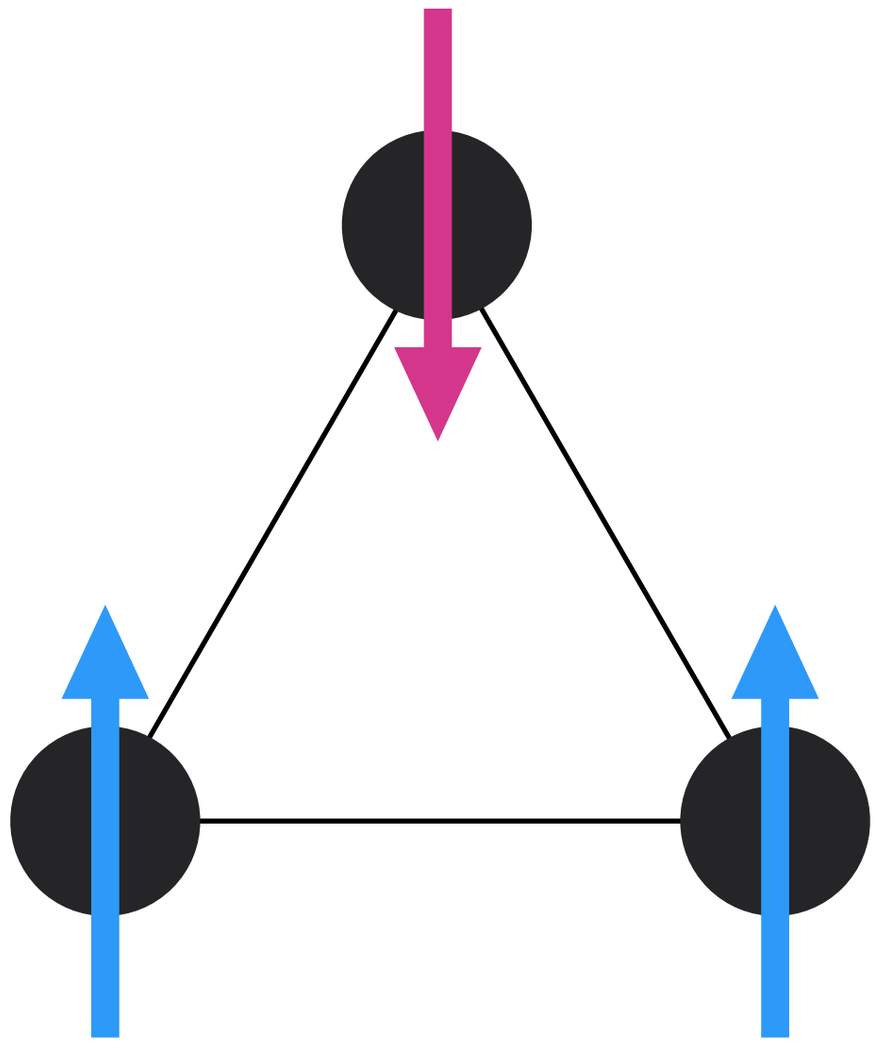
Simplest example: Ising antiferromagnet on a triangle



Doping-induced RVB spin liquid in a frustrated Mott insulator

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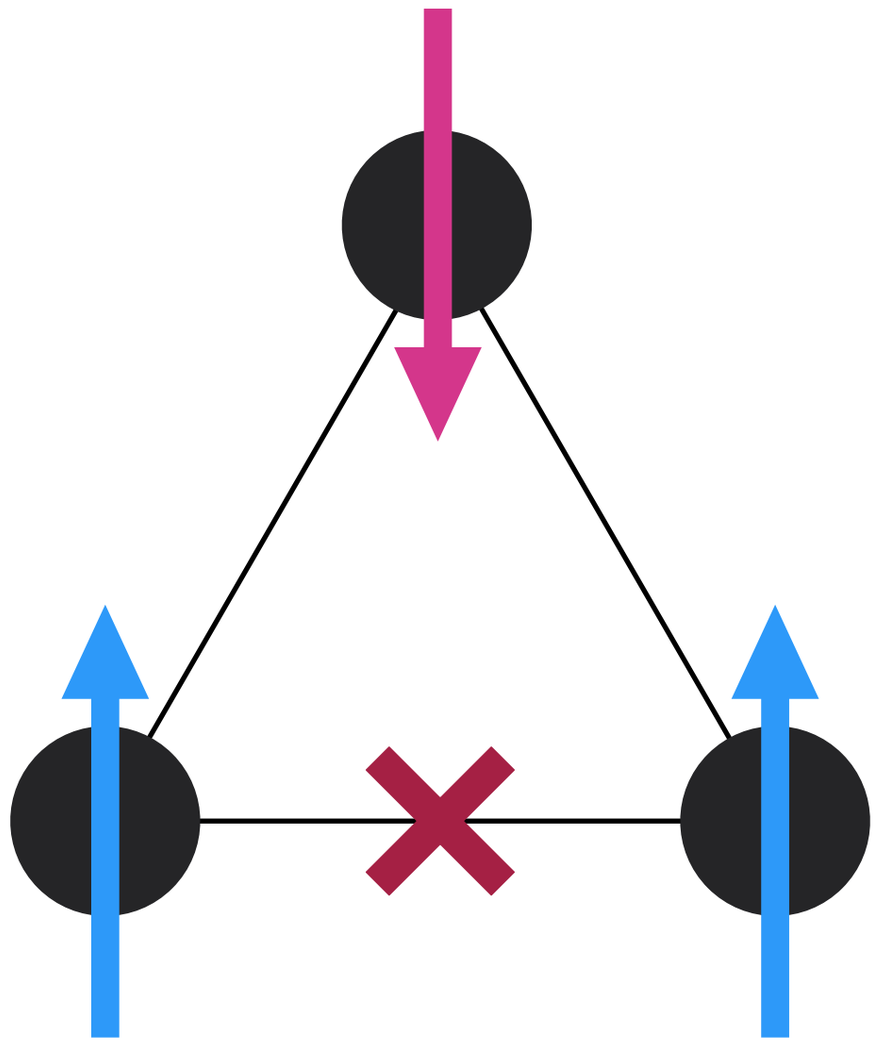
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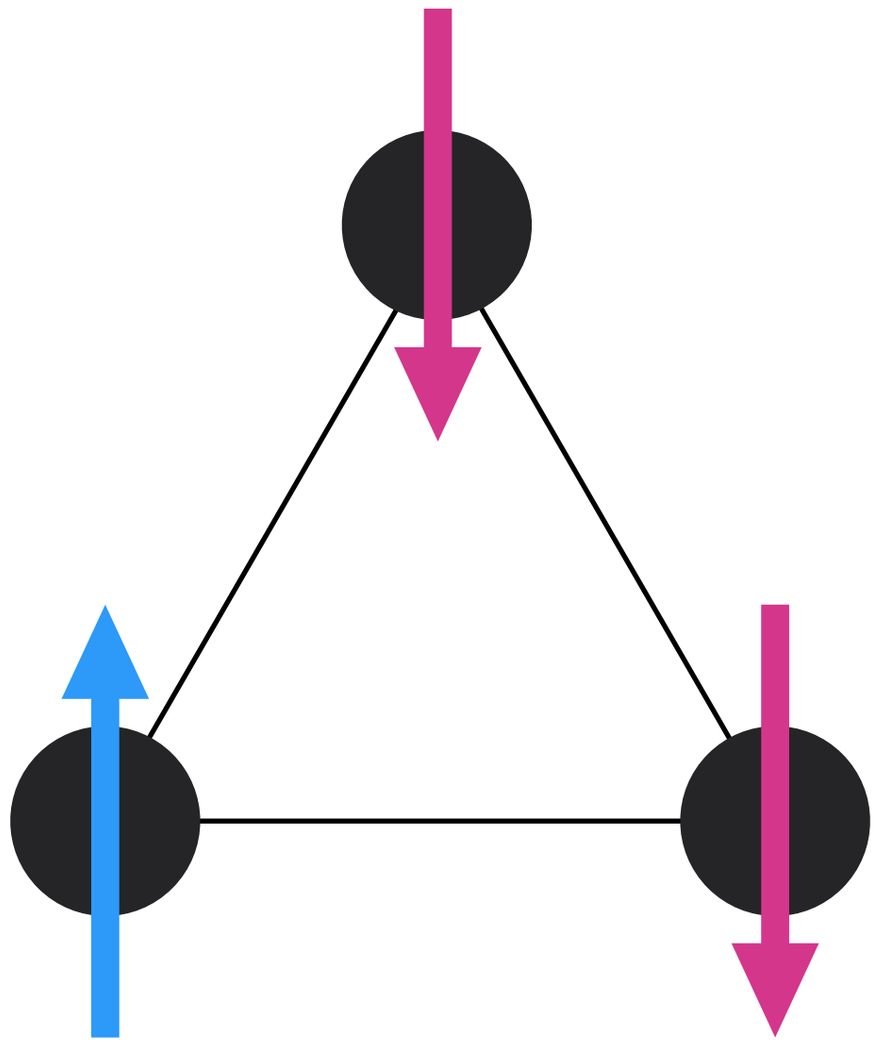
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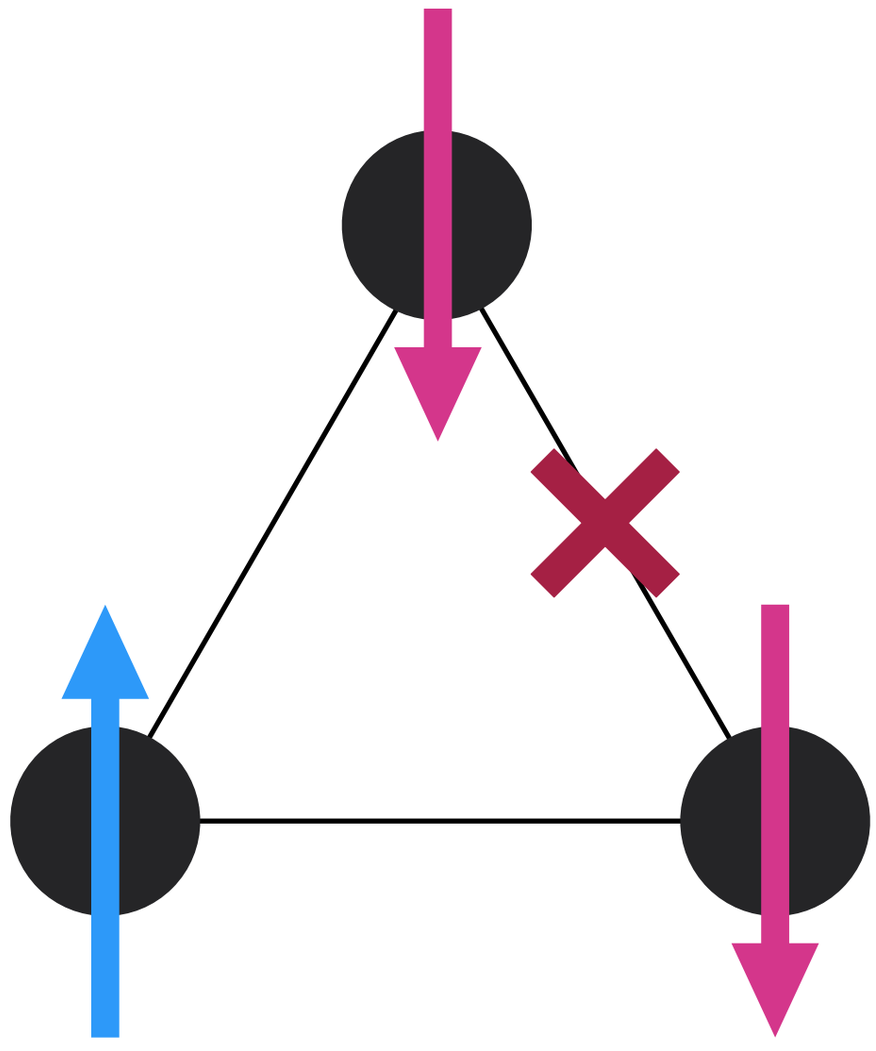
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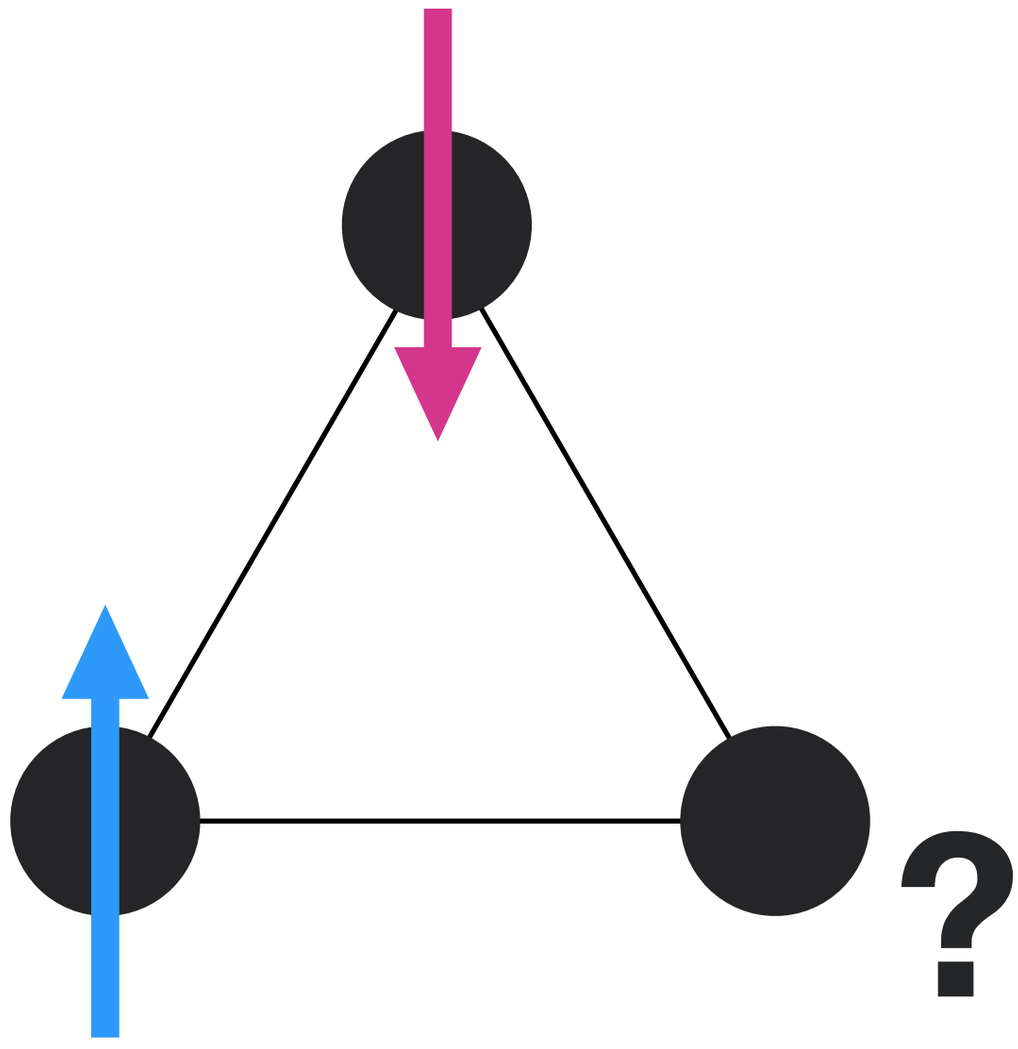
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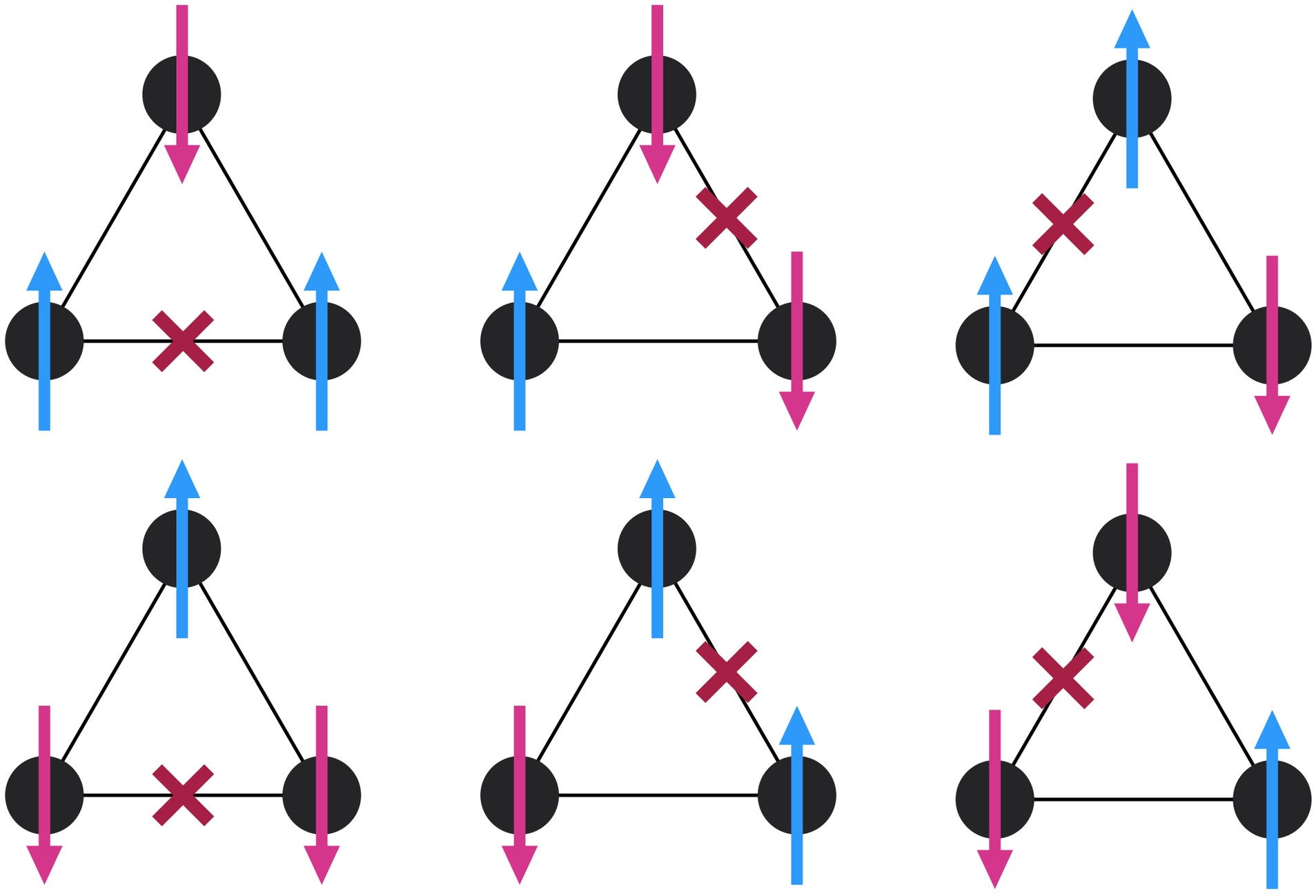
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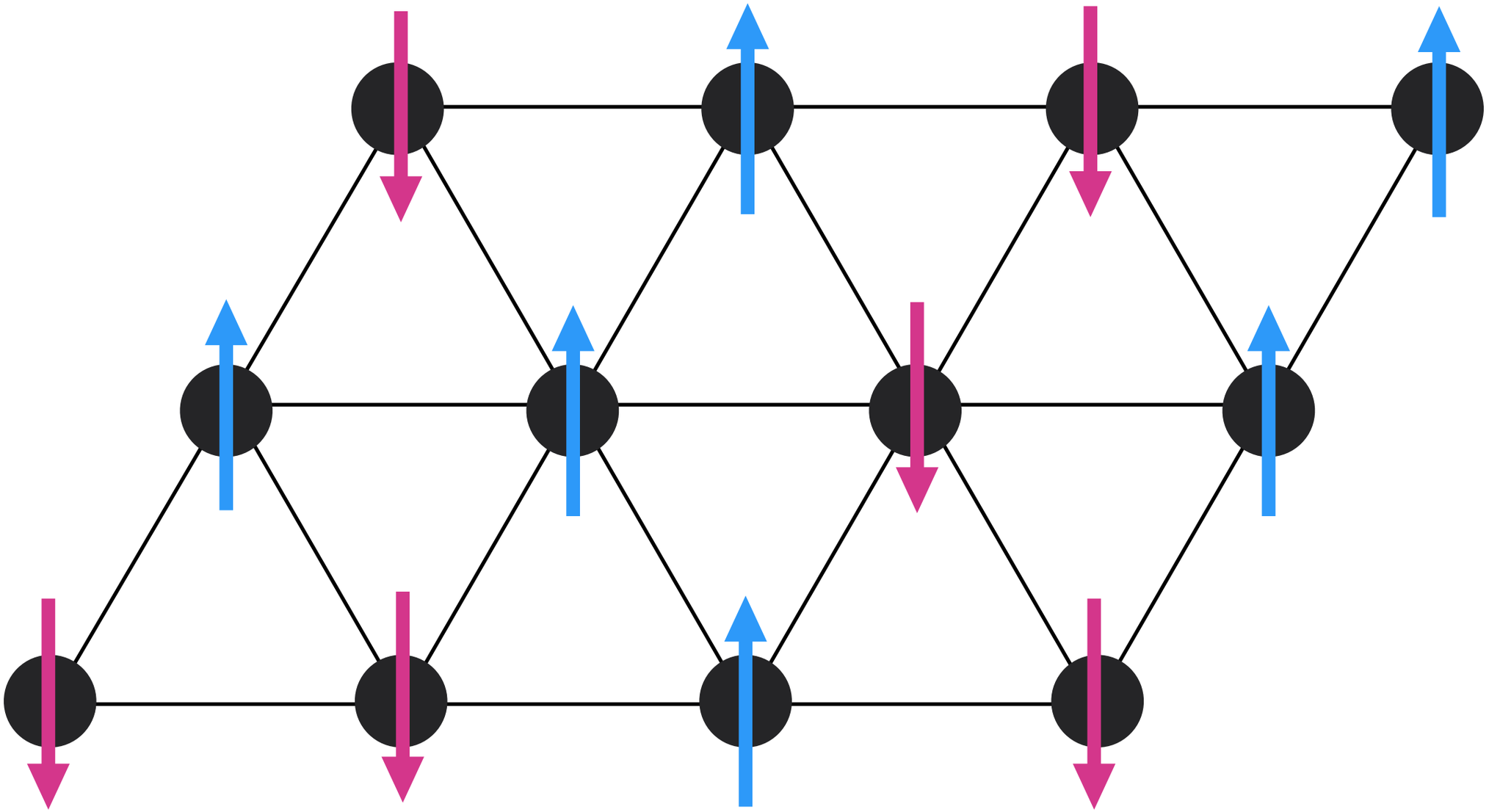
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Frustrated magnets often have an extensive ground state degeneracy.



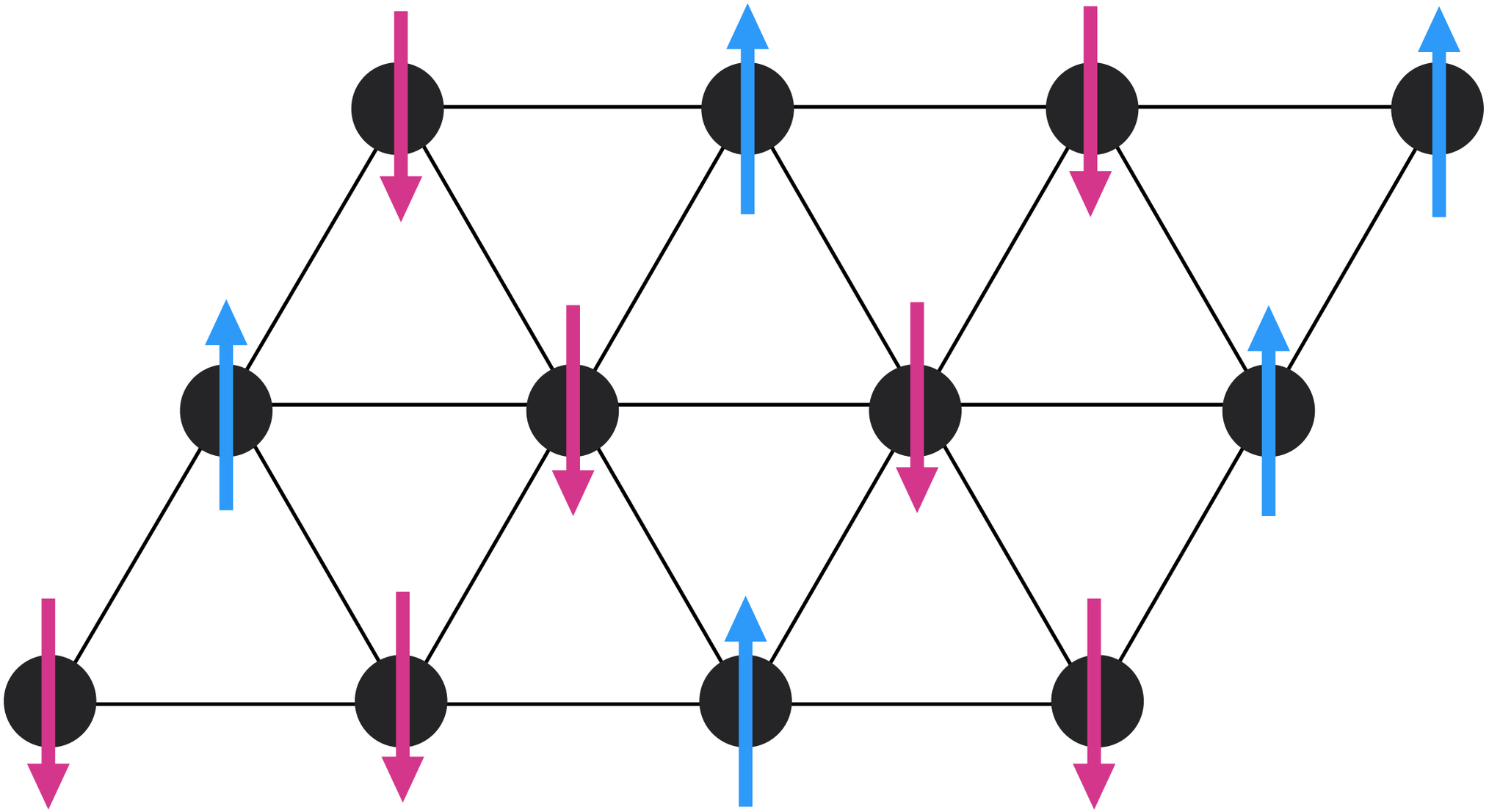
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Antiferromagnetic Ising model on triangular lattice…



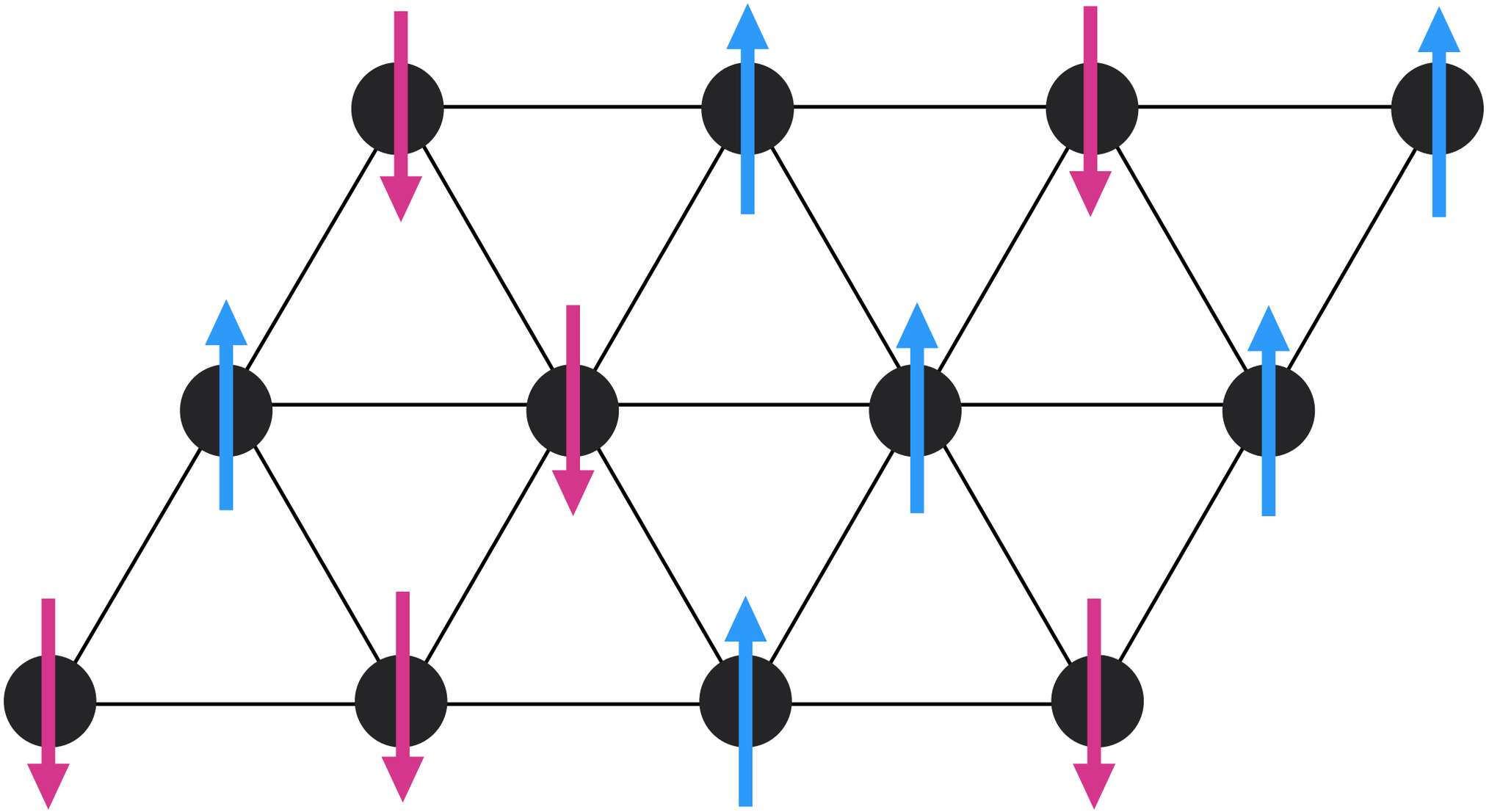
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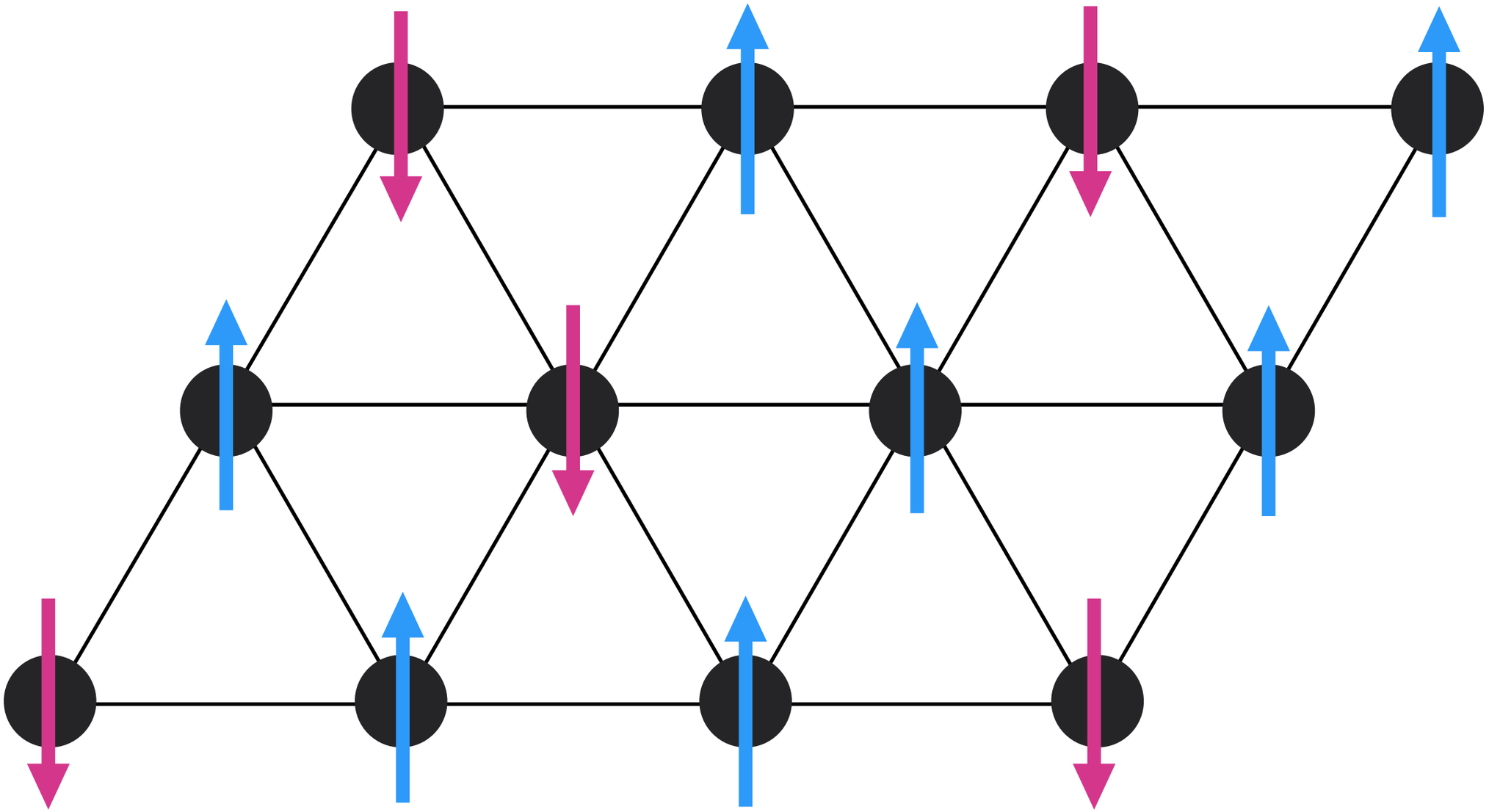
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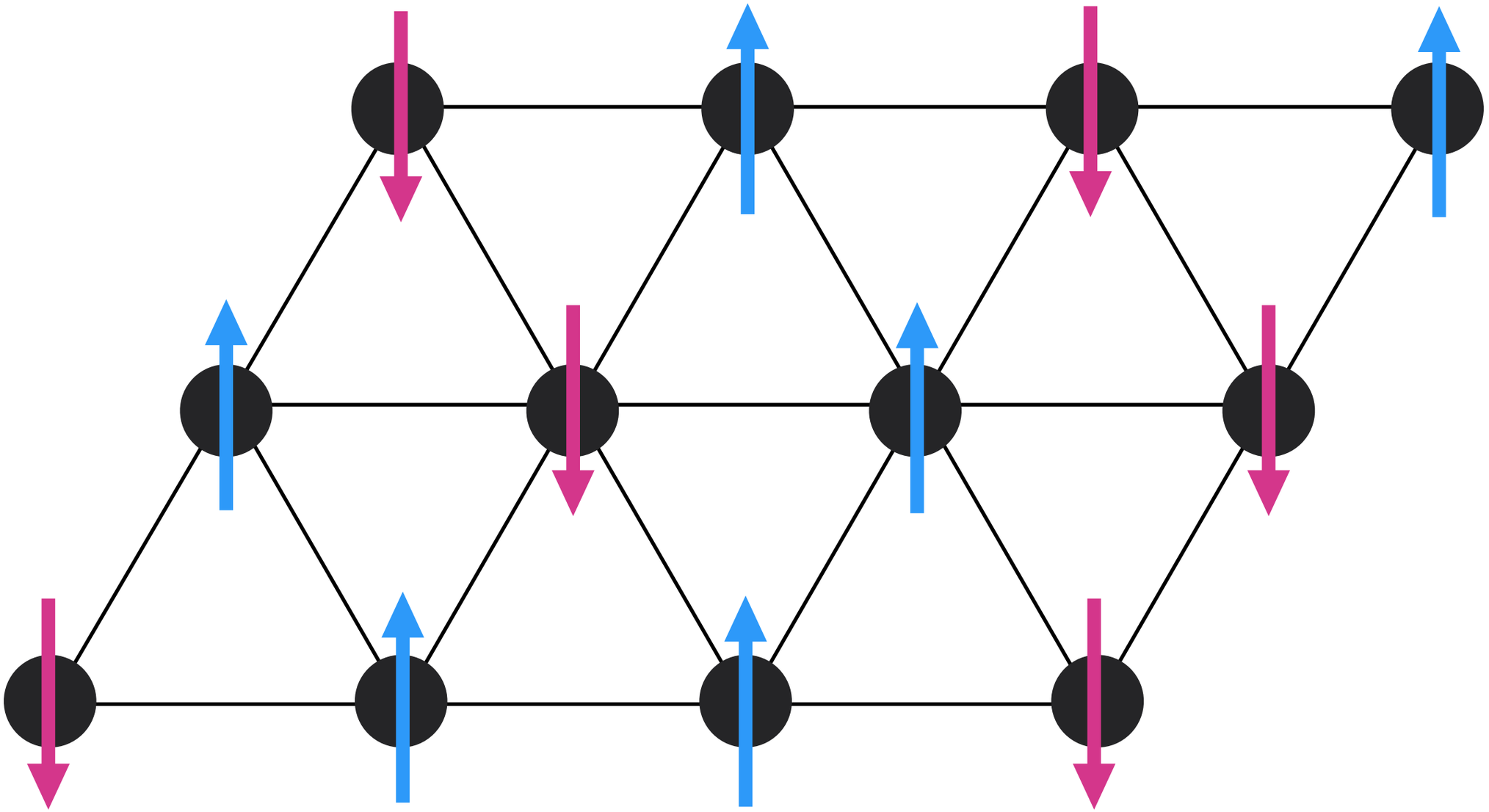
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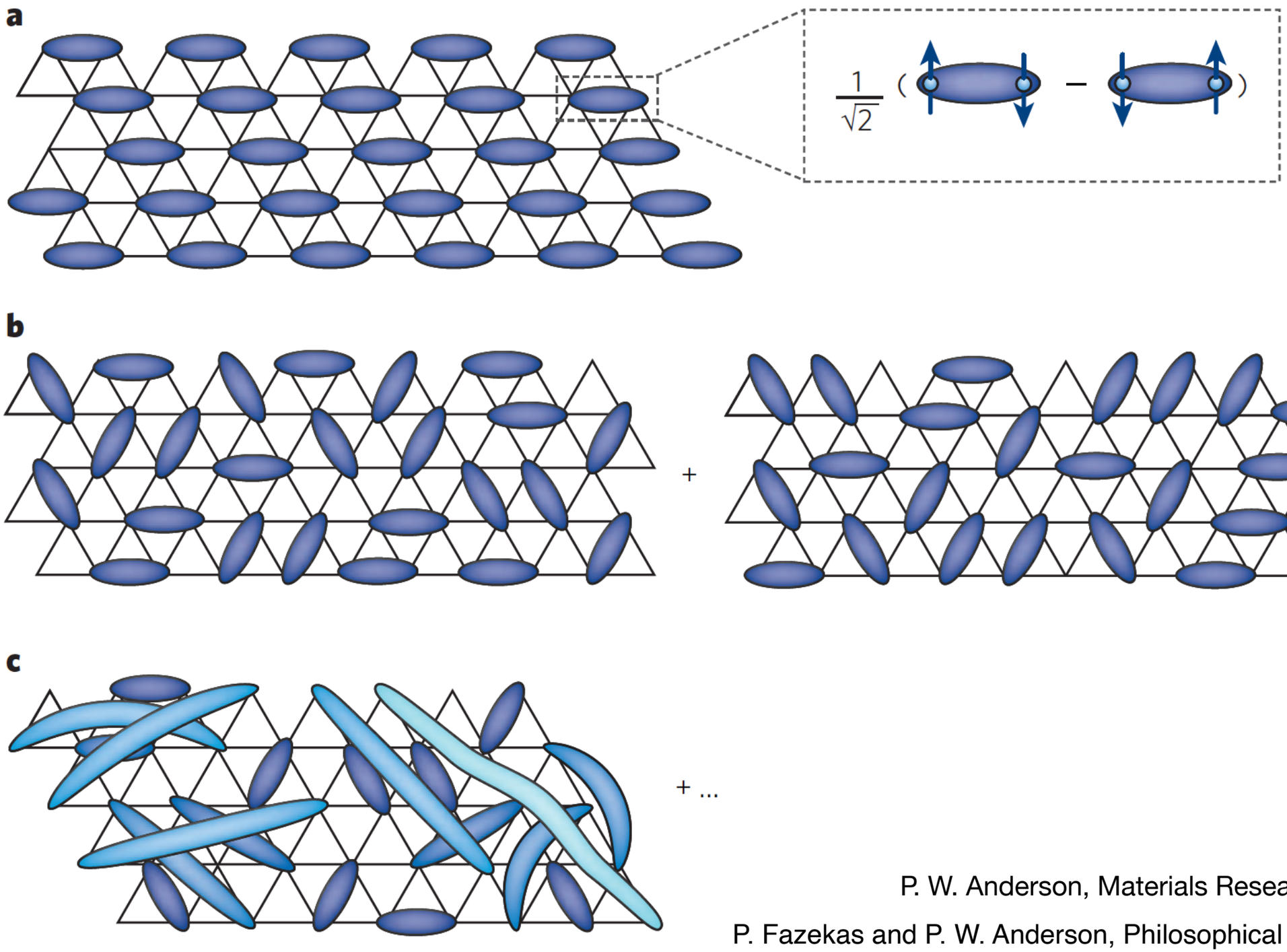
Doping-induced RVB spin liquid in a frustrated Mott insulator

Lack of ordering leads to a strongly correlated spin liquid.



Doping-induced RVB spin liquid in a frustrated Mott insulator

The resonating valence bond (RVB) liquid: proposed ground state for antiferromagnetically interacting spins.



P. W. Anderson, Materials Research Bulletin **8**, 153 (1973)

P. Fazekas and P. W. Anderson, Philosophical Magazine **30**, 423 (1974)

Fig: L. Balents, Nature **464**, 199 (2010)

Doping-induced RVB spin liquid in a frustrated Mott insulator

There has been an intensive search for RVB liquids for several reasons.

- First example of a quantum spin liquid
- **Quantum technology:** Long-range entanglement, topological order and fractionalisation
- **High-Tc superconductivity**
- **Traditionally, the search for RVB liquids has been through frustrated magnetic exchange interactions**

Doping-induced RVB spin liquid in a frustrated Mott insulator

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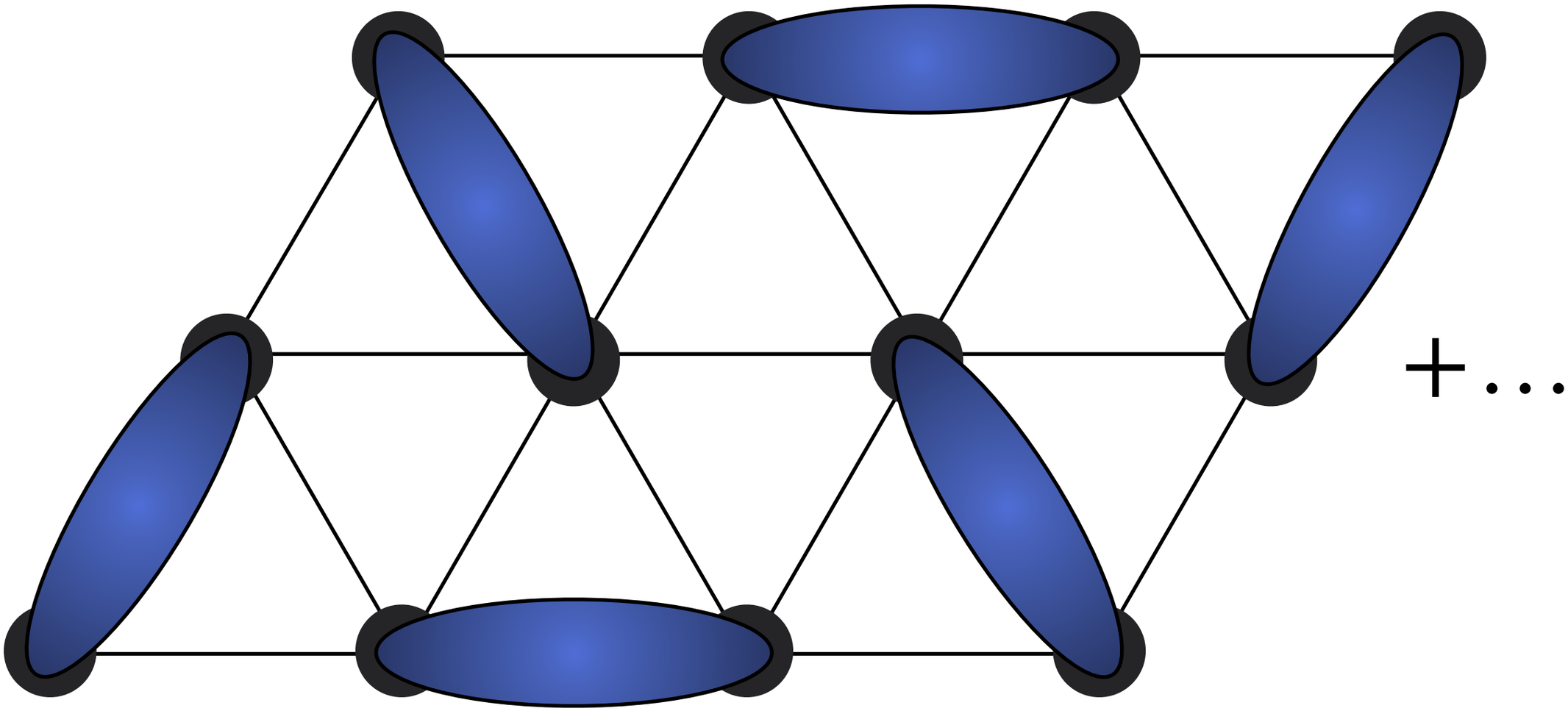
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Anderson's original proposal has until now evaded discovery.

Doping-induced RVB spin liquid in a frustrated Mott insulator

Instead of forming an RVB spin liquid…

$$H = J \sum_{\langle i,j \rangle} \vec{S}_i \cdot \vec{S}_j$$

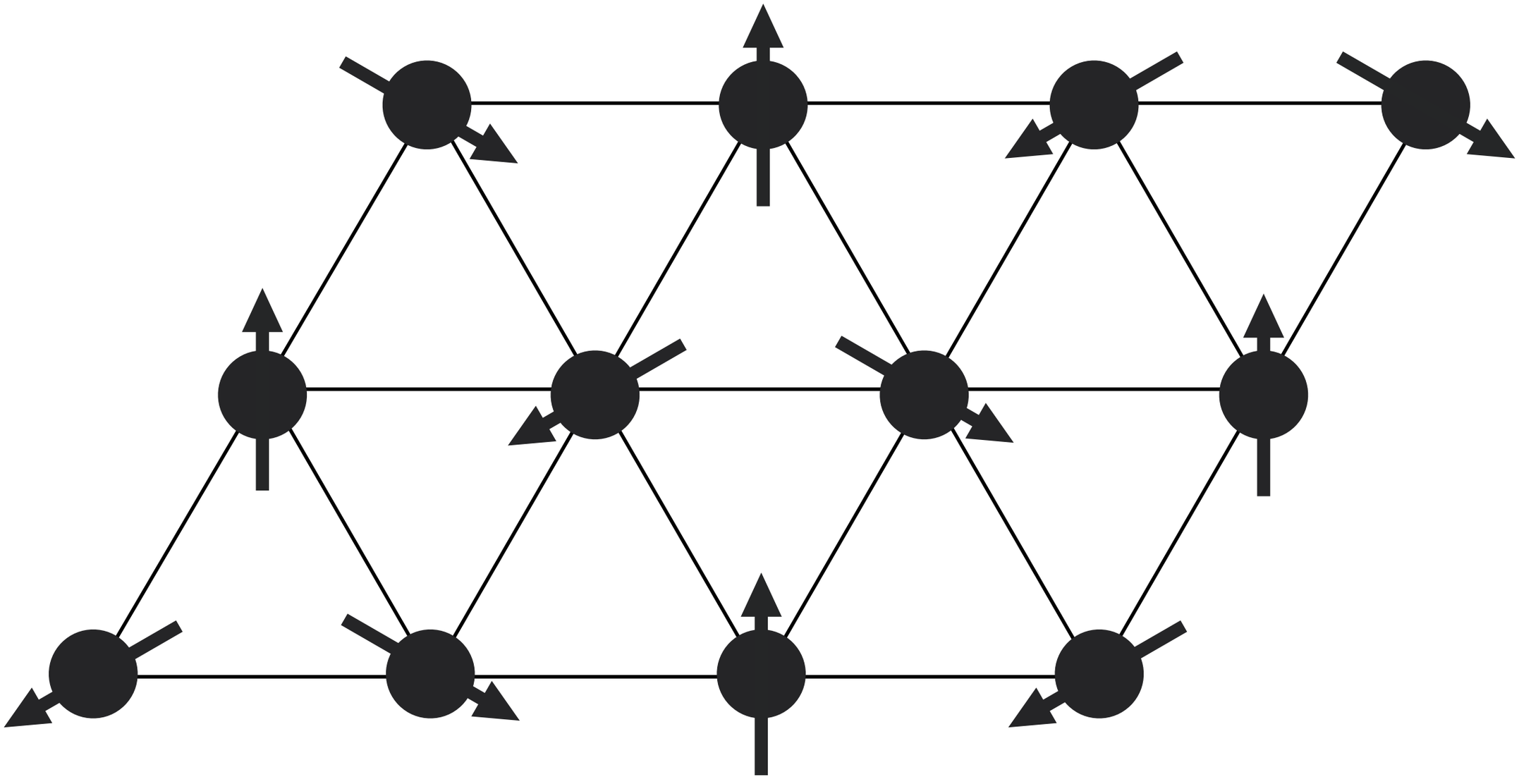


+…

Doping-induced RVB spin liquid in a frustrated Mott insulator

… the Heisenberg model on the triangular lattice orders in a 120 degree phase.

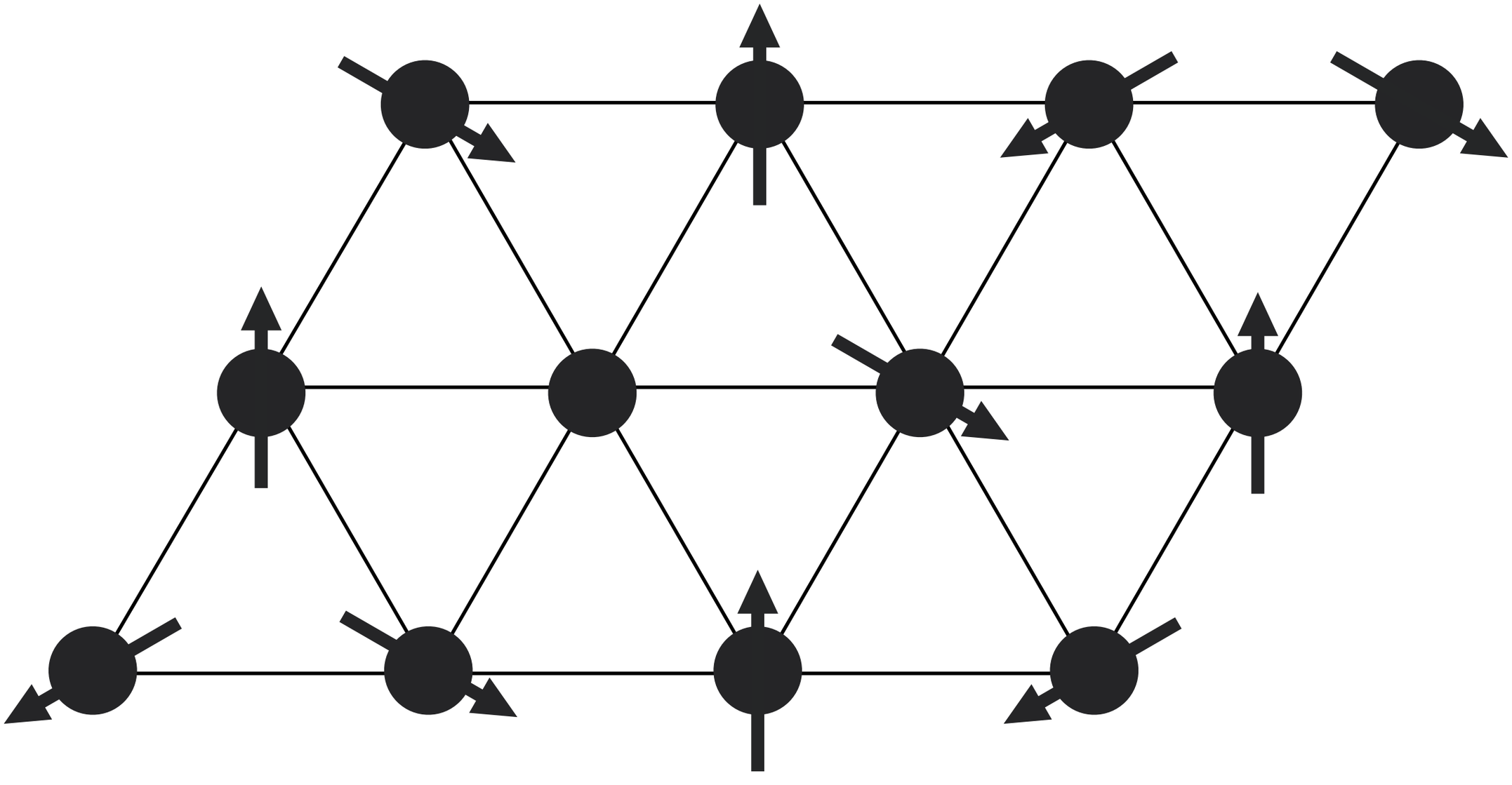
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Doping-induced RVB spin liquid in a frustrated Mott insulator

Different approach: kinetic frustration from doping

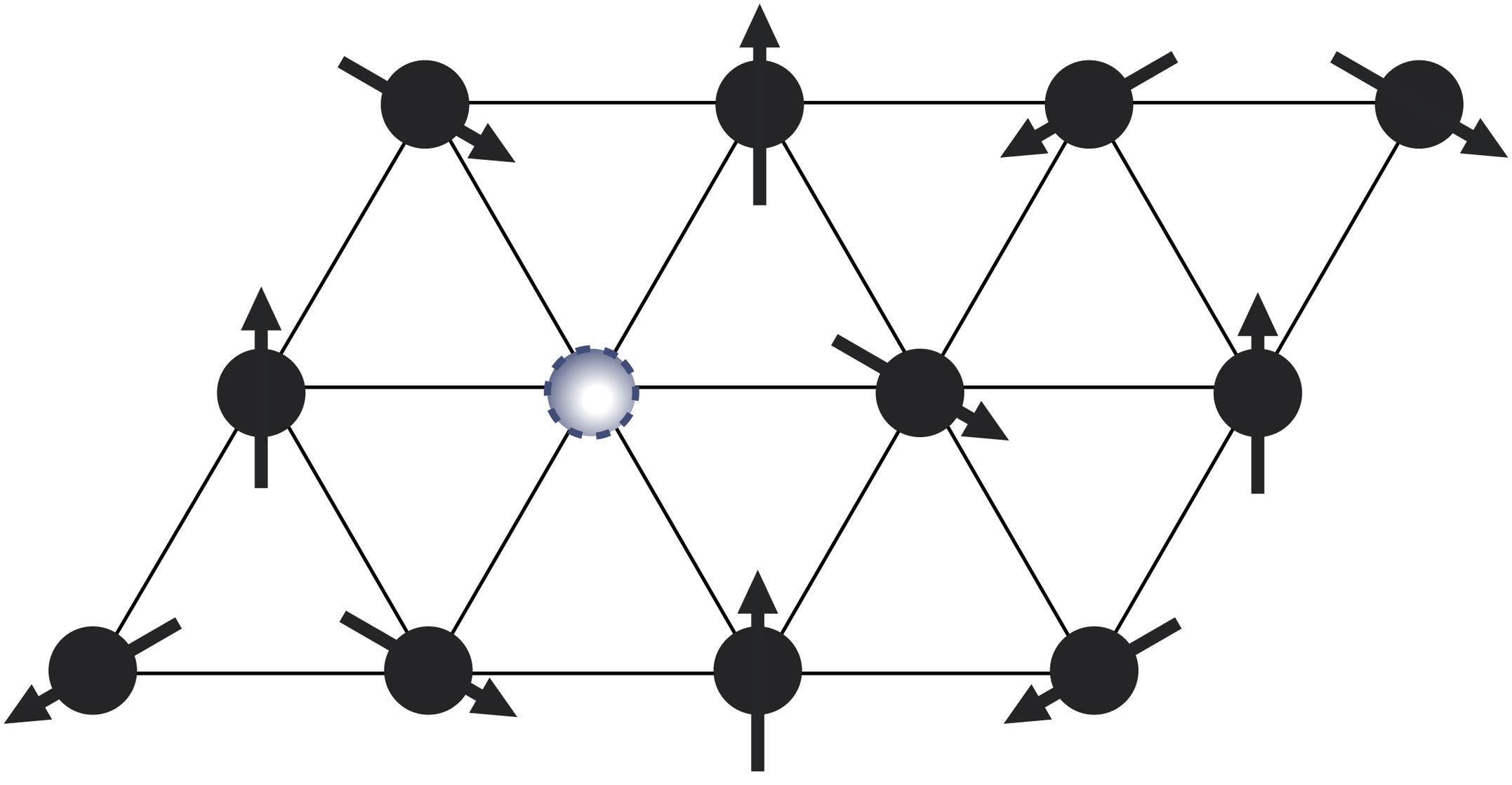
$$H = -t \sum_{\langle i,j \rangle\, \sigma} \left[P_{i\sigma} c^{\dagger}_{i\sigma} c_{j\sigma} P_{j\sigma} + h.c. \right] + J \sum_{\langle i,j \rangle} \vec{S}_i \cdot \vec{S}_j$$



Doping-induced RVB spin liquid in a frustrated Mott insulator

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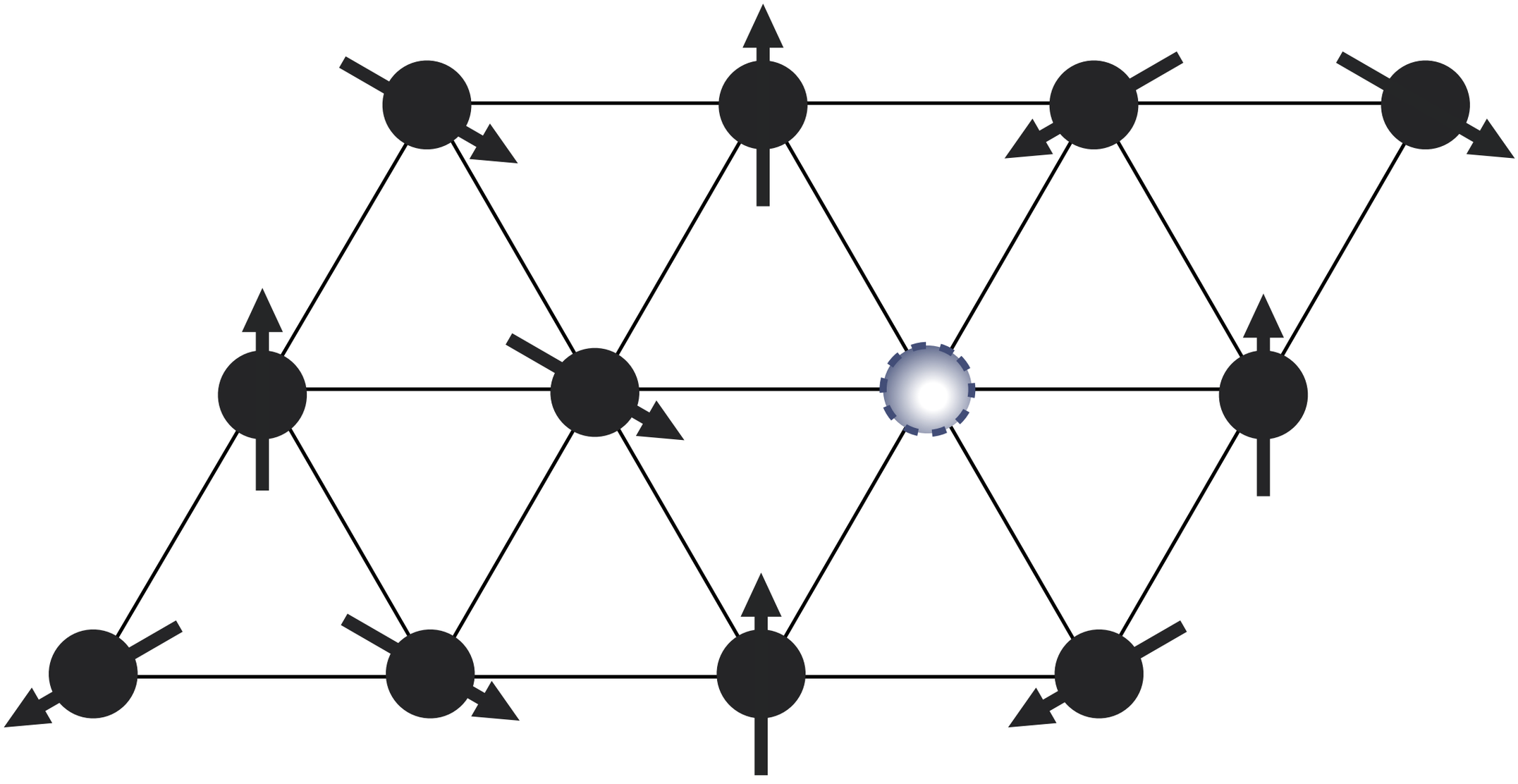
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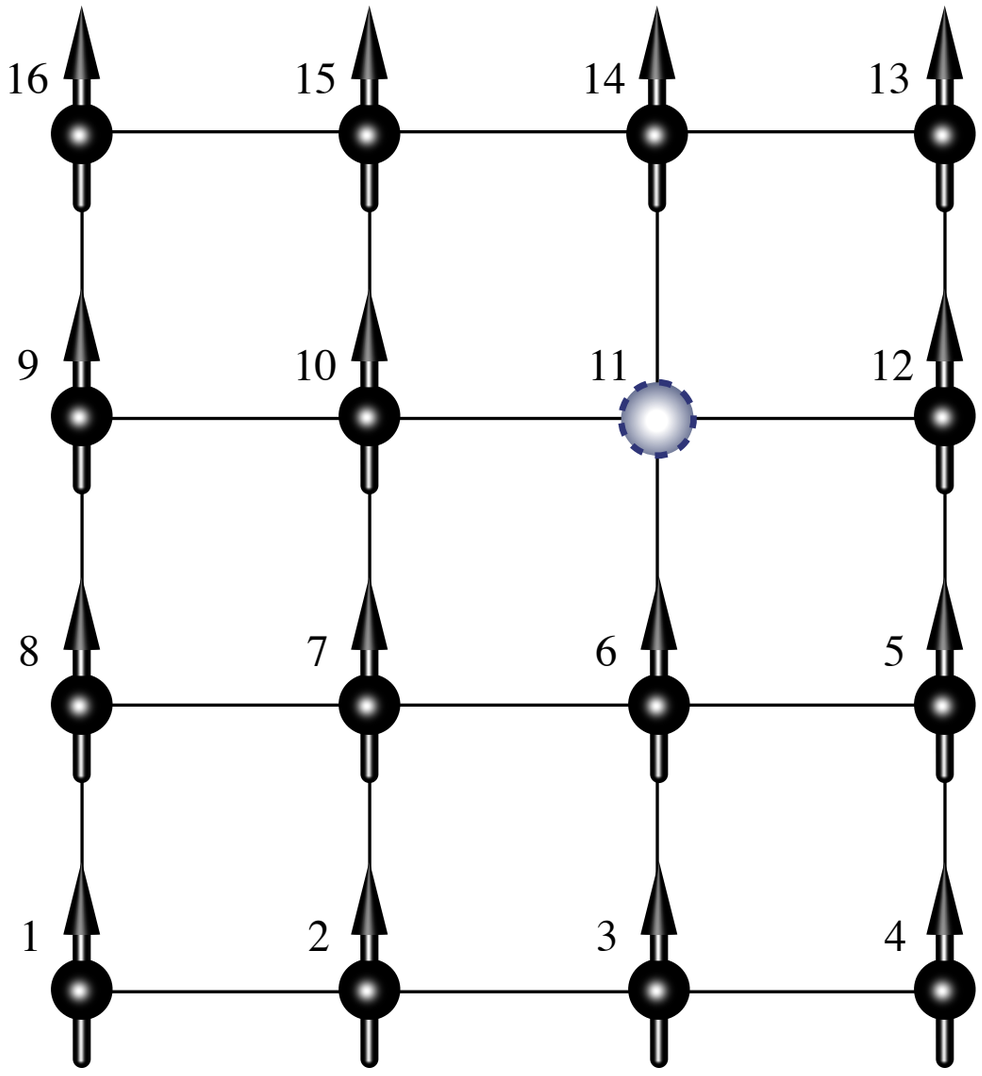
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Doping-induced RVB spin liquid in a frustrated Mott insulator

The Nagaoka effect: Doping leads to effective FM spin exchange.

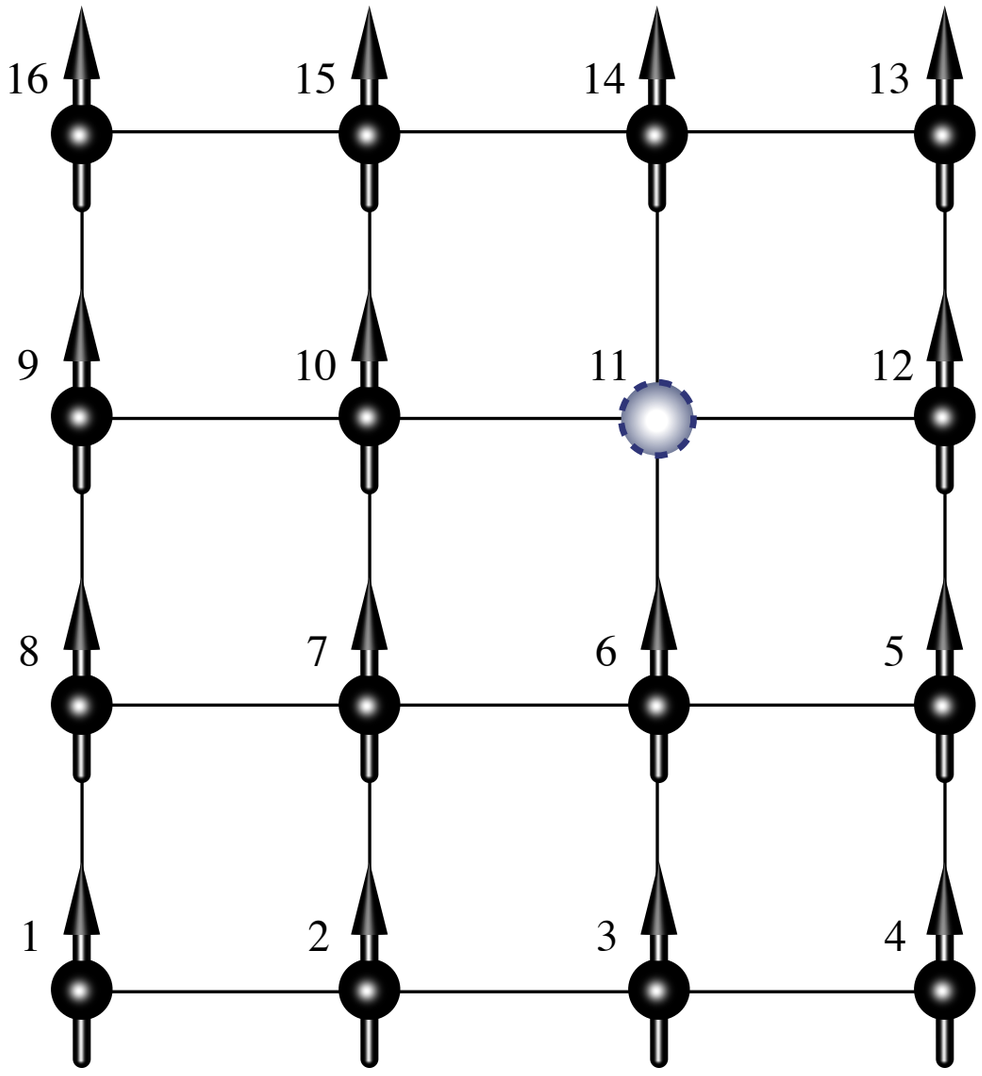


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Nagaoka, Phys. Rev. **147**, 392 (1966)

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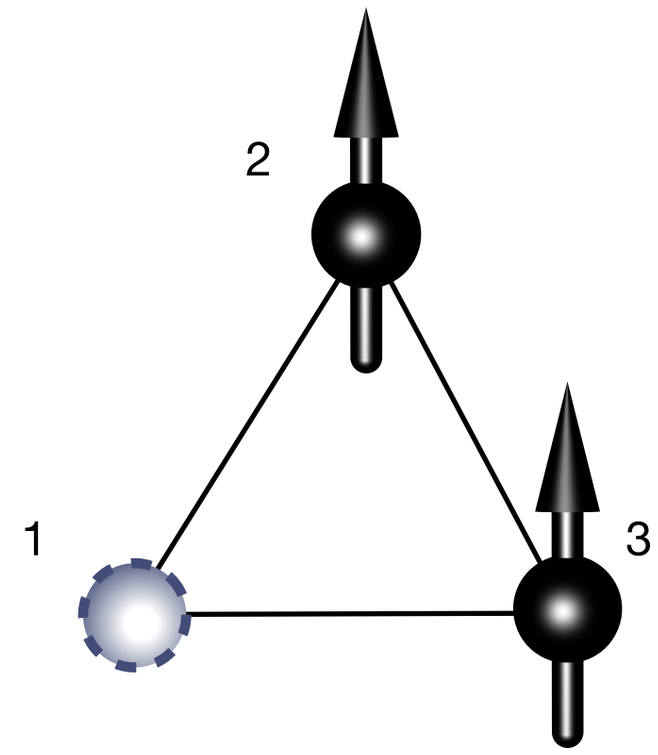
$$|\mathrm{GS}\rangle = \frac{1}{\sqrt{N_{\mathrm{sector}}}} \sum_{n,\sigma_n} |\vec{r}_n, \sigma_n\rangle,$$

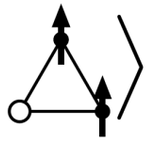
$$E = -z|t|$$

Doping-induced RVB spin liquid in a frustrated Mott insulator

Non-bipartite lattices are *kinetically frustrated*. Simple example: single hole on a triangle.

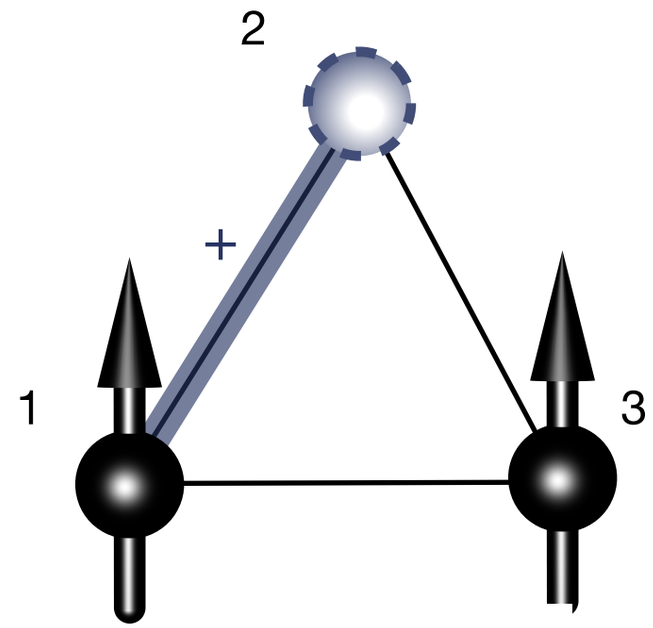
FM sector:



$$|\mathrm{FM}\rangle = +$$ 

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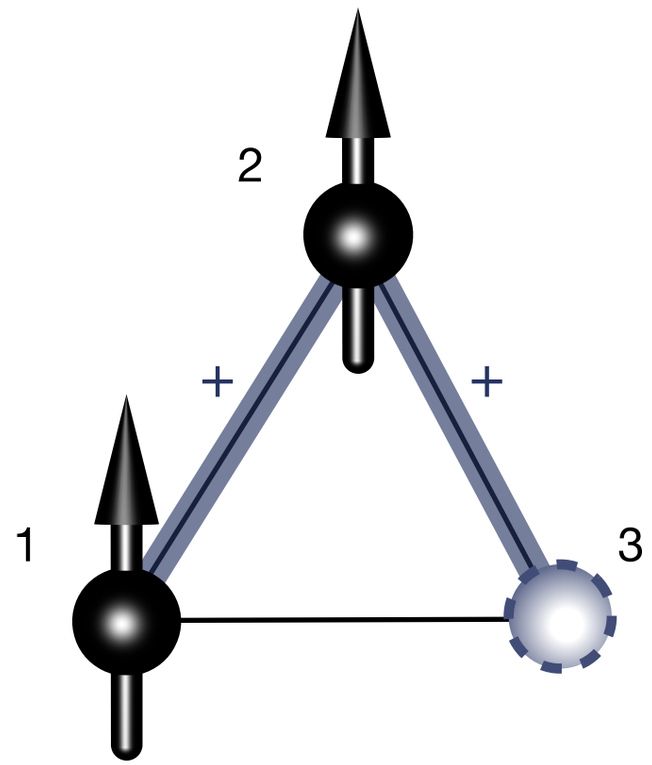
FM sector:



$$|\mathrm{FM}\rangle = + \left|\ \right\rangle + \left|\ \right\rangle$$

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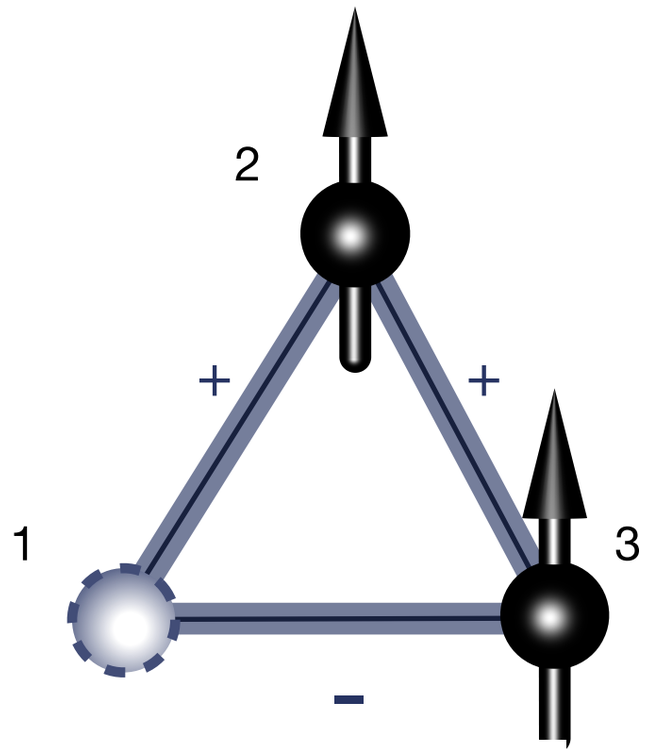
FM sector:



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FM sector:

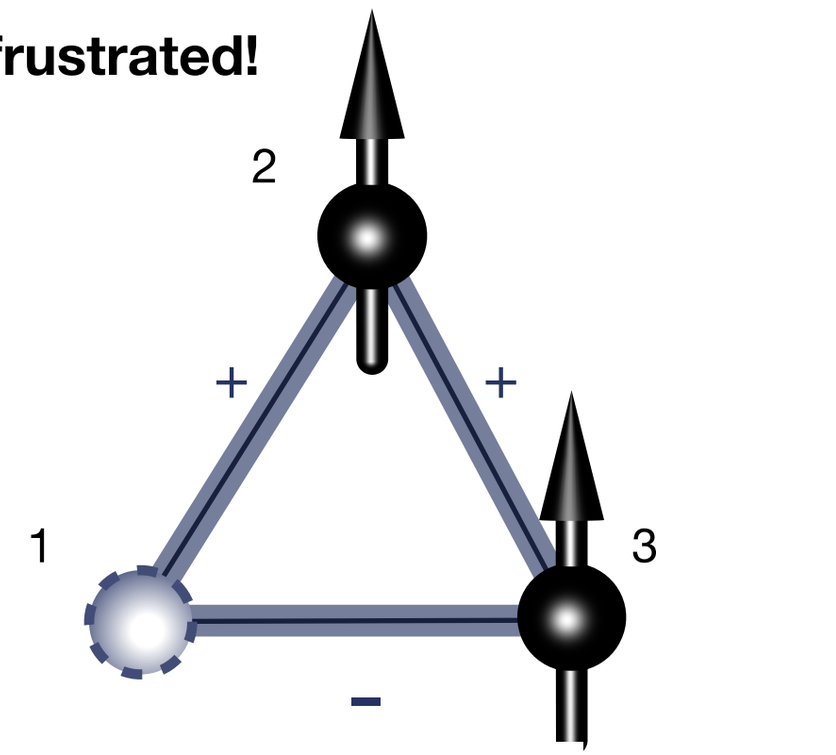


$$|\mathrm{FM}\rangle = + \left|\,\triangle\,\right\rangle + \left|\,\triangle\,\right\rangle + \left|\,\triangle\,\right\rangle$$

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FM sector:

Kinetically frustrated!

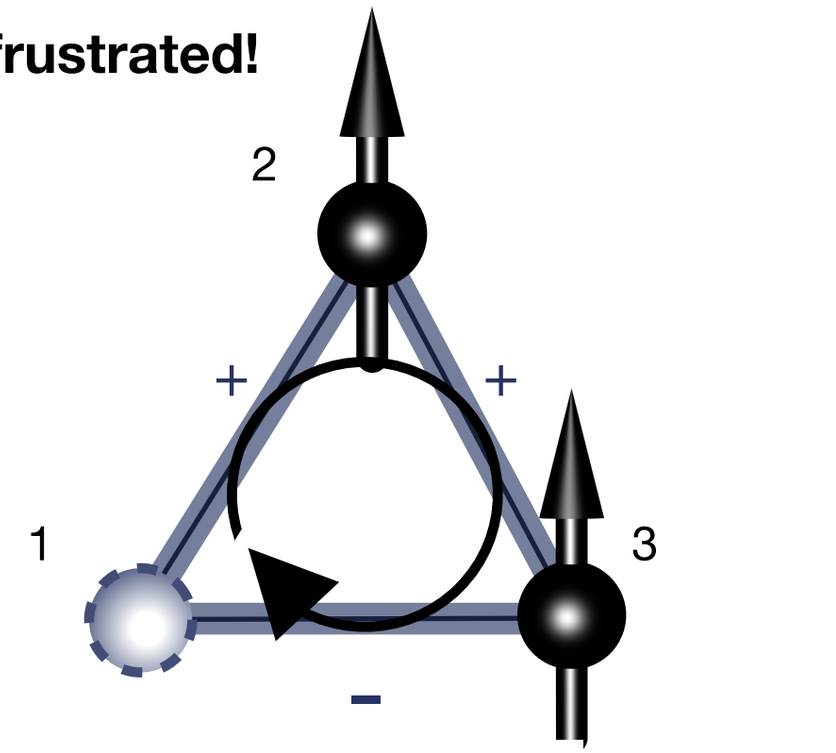


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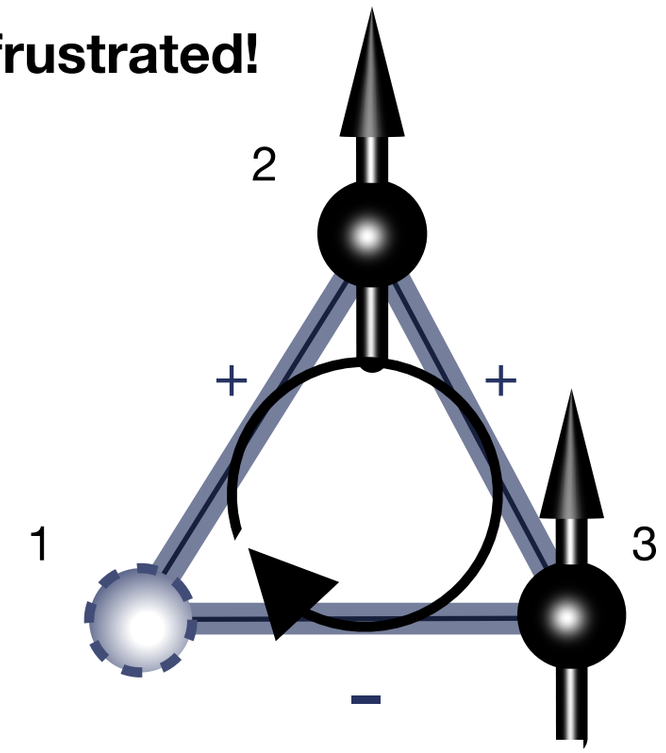


$$|\mathrm{FM}\rangle = + \left|\;\right\rangle + \left|\;\right\rangle + \left|\;\right\rangle$$

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$$|\mathrm{FM}\rangle = +\left|\;\right\rangle + \left|\;\right\rangle + \left|\;\right\rangle$$

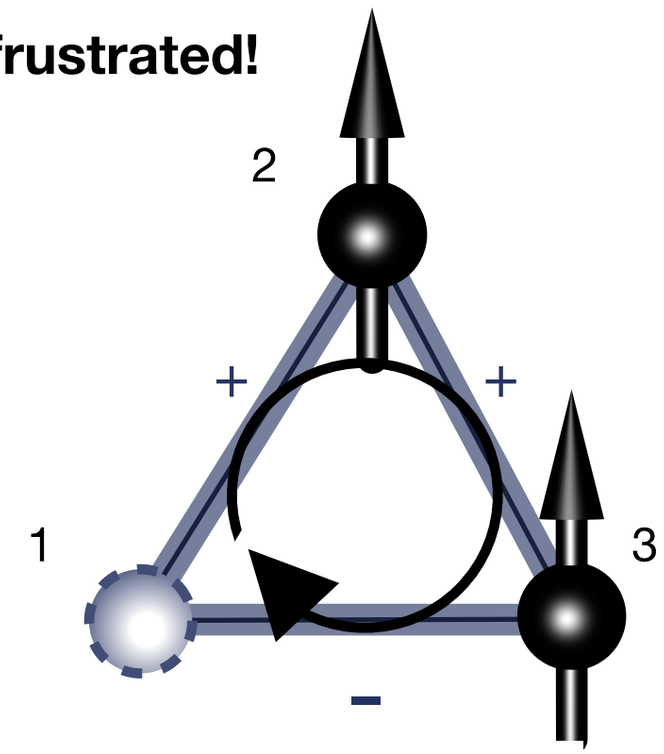
$$|\mathrm{FM}_1\rangle = \frac{1}{\sqrt{2}}\left(\left|\;\right\rangle + \left|\;\right\rangle\right) \qquad |\mathrm{FM}_2\rangle = \frac{1}{\sqrt{2}}\left(\left|\;\right\rangle + \left|\;\right\rangle\right)$$

$$E = -t$$

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FM sector:

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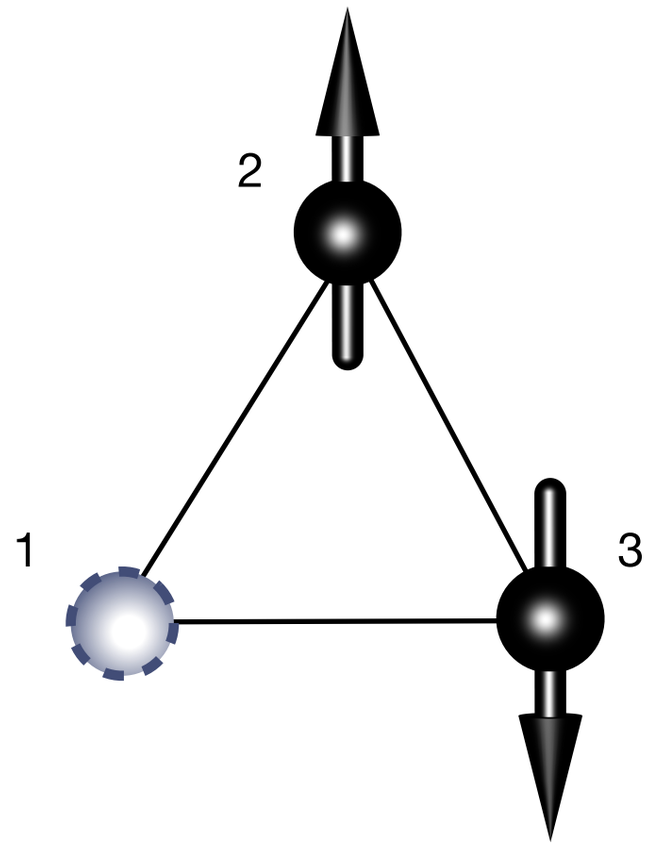


$$|\mathrm{FM}\rangle = + \left| \triangle \right\rangle + \left| \triangle \right\rangle + \left| \triangle \right\rangle$$

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$$E = -t$$

AFM sector:

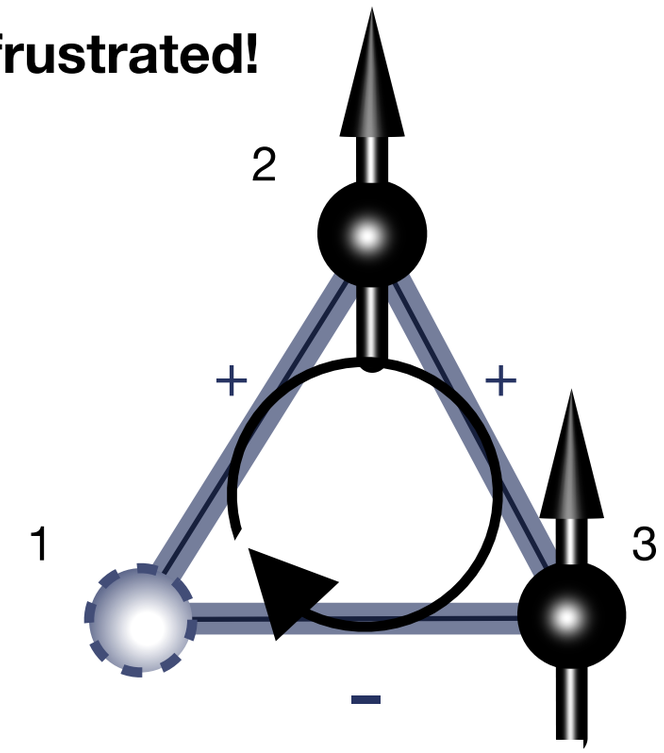


$$|\mathrm{AFM}\rangle = + \left| \triangle \right\rangle$$

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FM sector:

Kinetically frustrated!

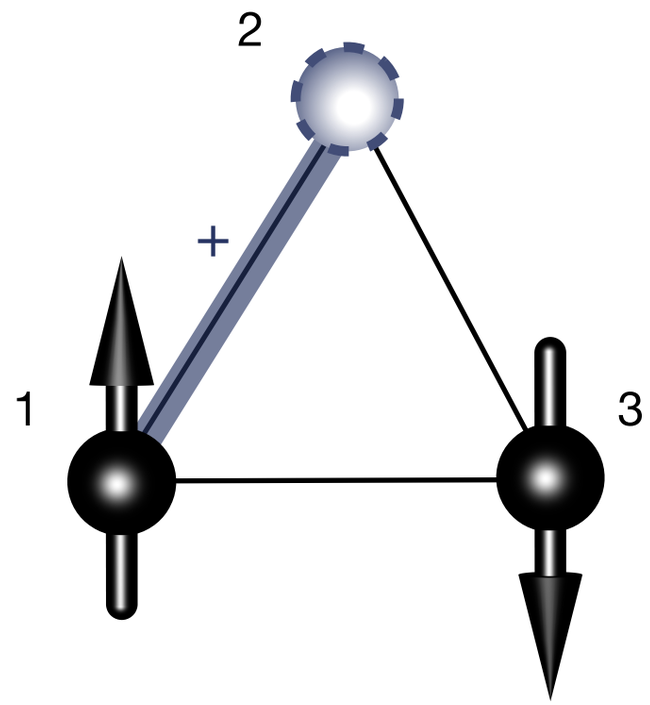


$$|\mathrm{FM}\rangle = + \left|\,\right\rangle + \left|\,\right\rangle + \left|\,\right\rangle$$

$$|\mathrm{FM}_1\rangle = \frac{1}{\sqrt{2}}\left(\left|\,\right\rangle + \left|\,\right\rangle\right) \qquad |\mathrm{FM}_2\rangle = \frac{1}{\sqrt{2}}\left(\left|\,\right\rangle + \left|\,\right\rangle\right)$$

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AFM sector:

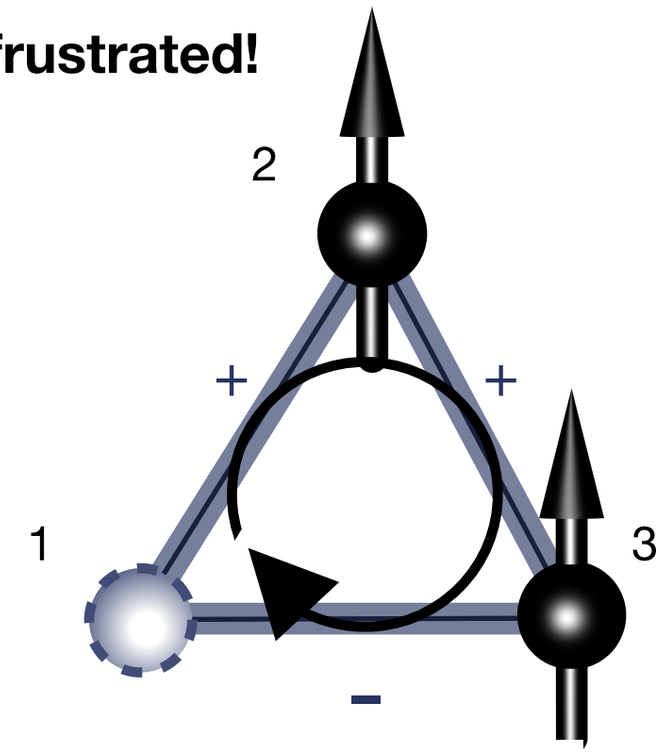


$$|\mathrm{AFM}\rangle = + \left|\,\right\rangle + \left|\,\right\rangle$$

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FM sector:

Kinetically frustrated!

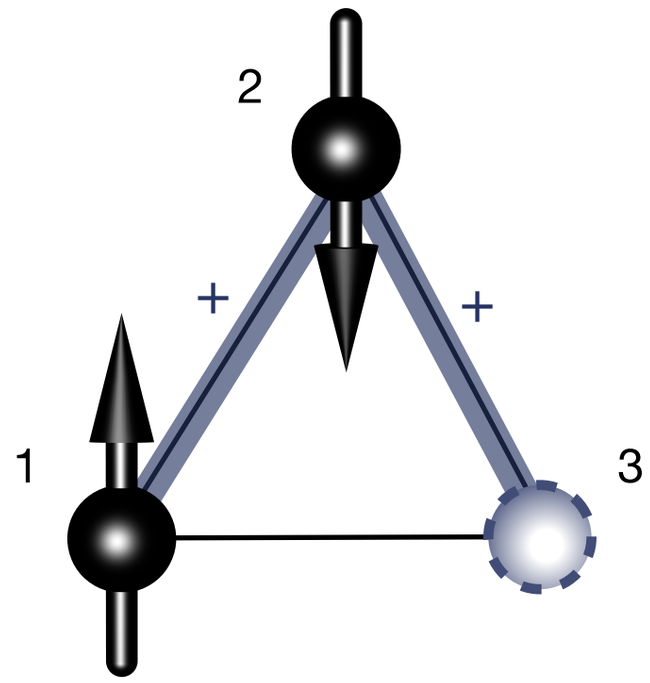


$$|\mathrm{FM}\rangle = + \left|\;\right\rangle + \left|\;\right\rangle + \left|\;\right\rangle$$

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AFM sector:

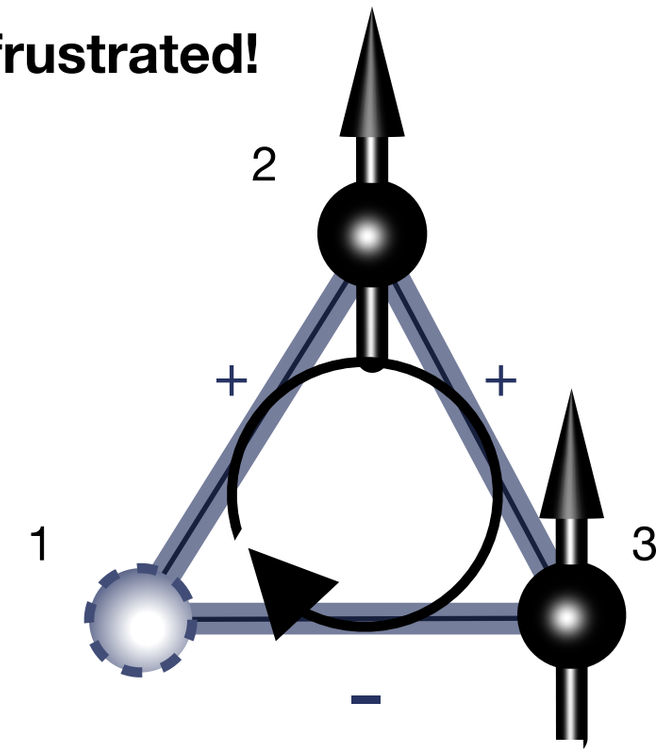


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FM sector:

Kinetically frustrated!

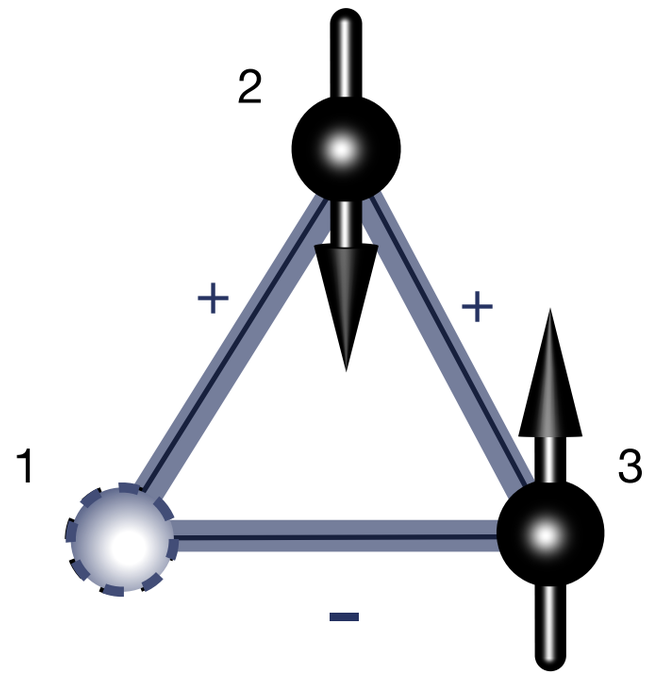


$$|\mathrm{FM}\rangle = + \left|\triangle\right\rangle + \left|\triangle\right\rangle + \left|\triangle\right\rangle$$

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$$E = -t$$

AFM sector:

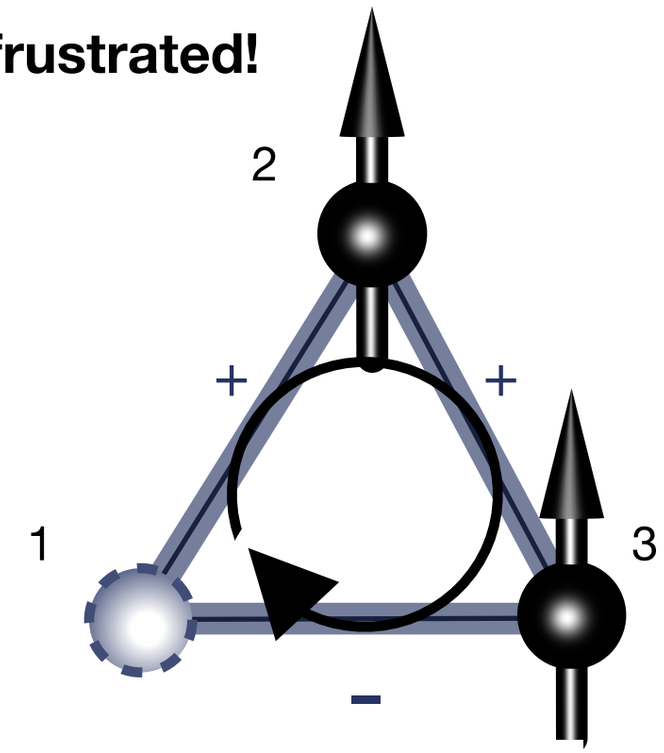


$$|\mathrm{AFM}\rangle = + \left|\triangle\right\rangle + \left|\triangle\right\rangle + \left|\triangle\right\rangle - \left|\triangle\right\rangle$$

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FM sector:

Kinetically frustrated!

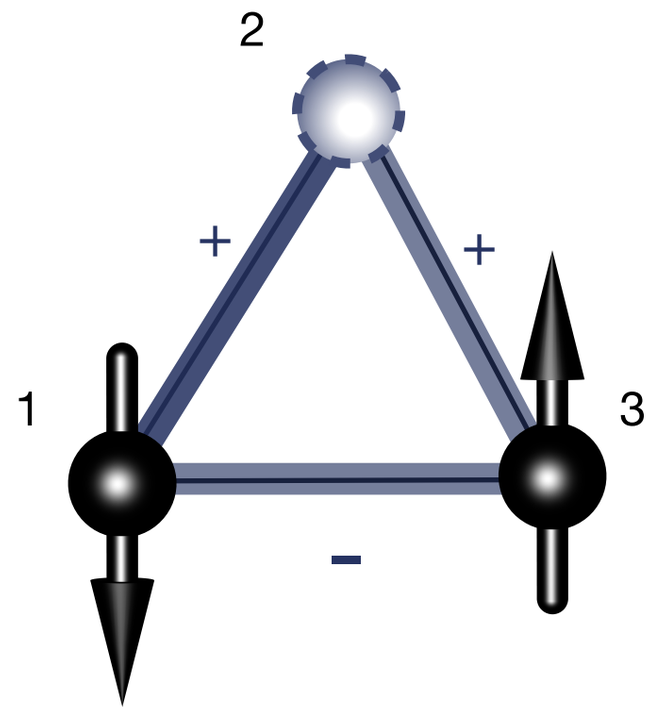


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AFM sector:

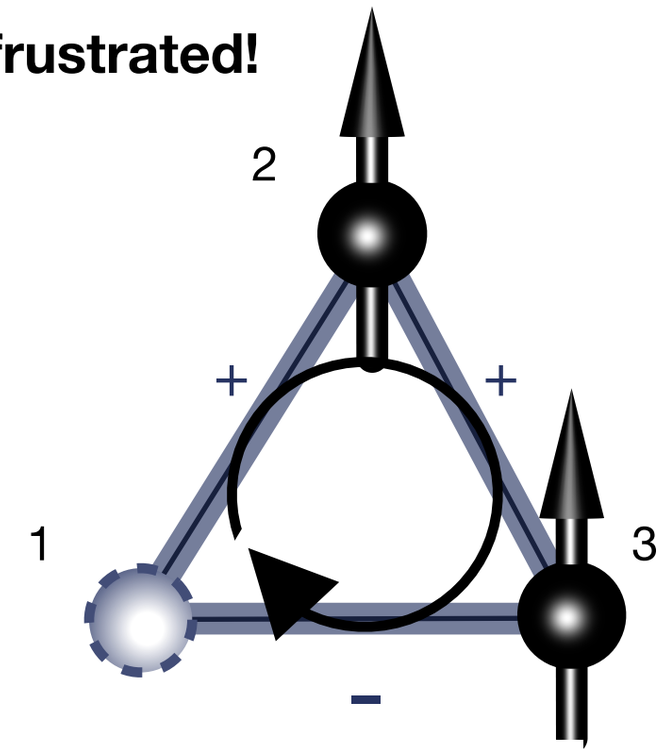


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FM sector:

Kinetically frustrated!

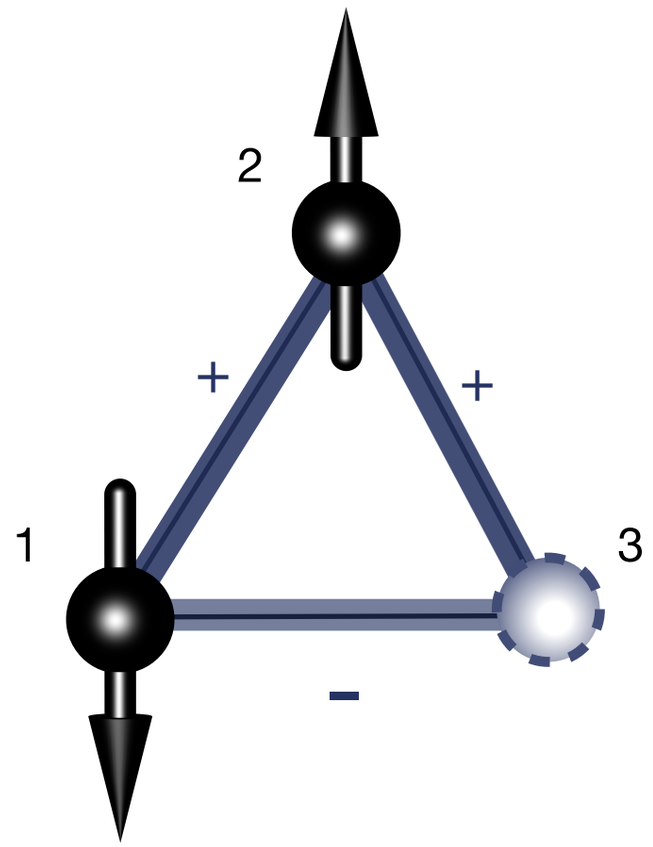


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AFM sector:

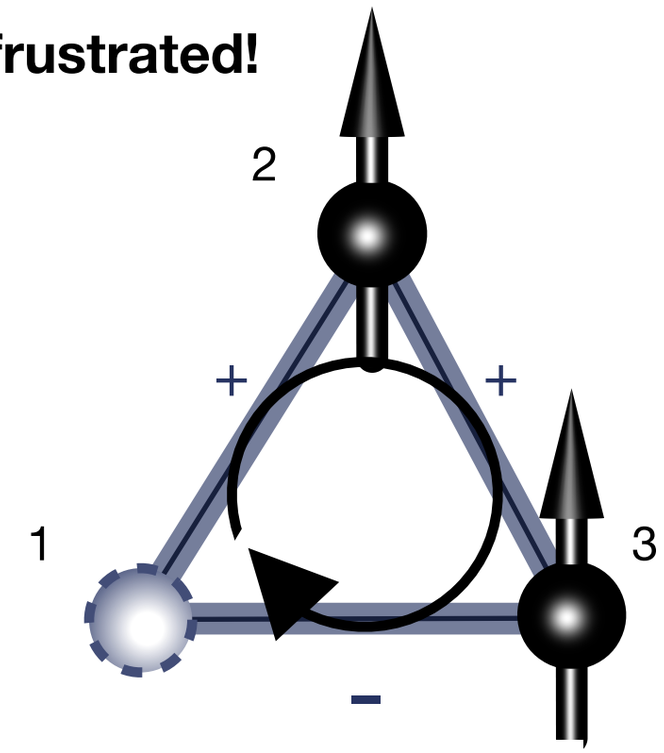


$$|\mathrm{AFM}\rangle = + \left|\triangle\right\rangle + \left|\triangle\right\rangle + \left|\triangle\right\rangle - \left|\triangle\right\rangle - \left|\triangle\right\rangle - \left|\triangle\right\rangle$$

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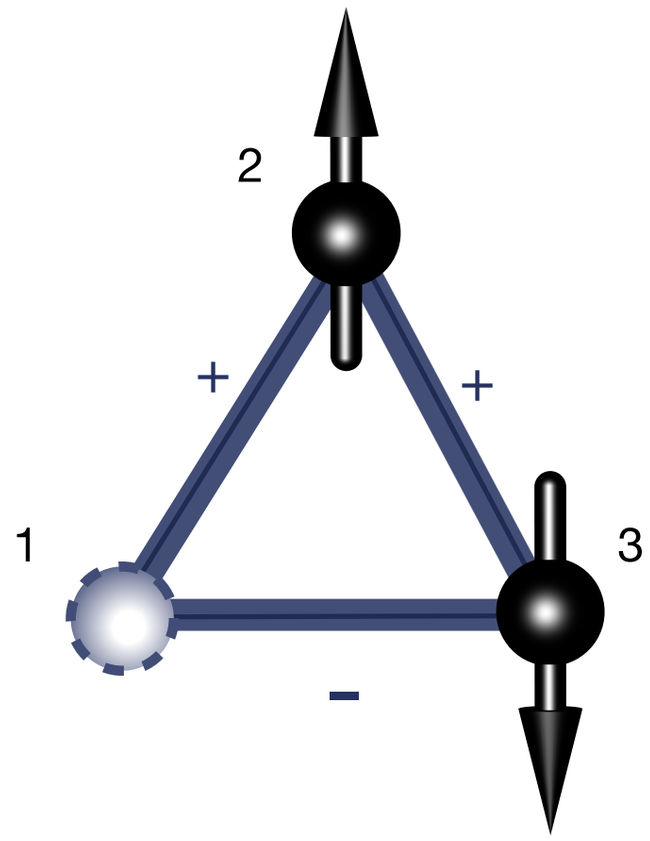


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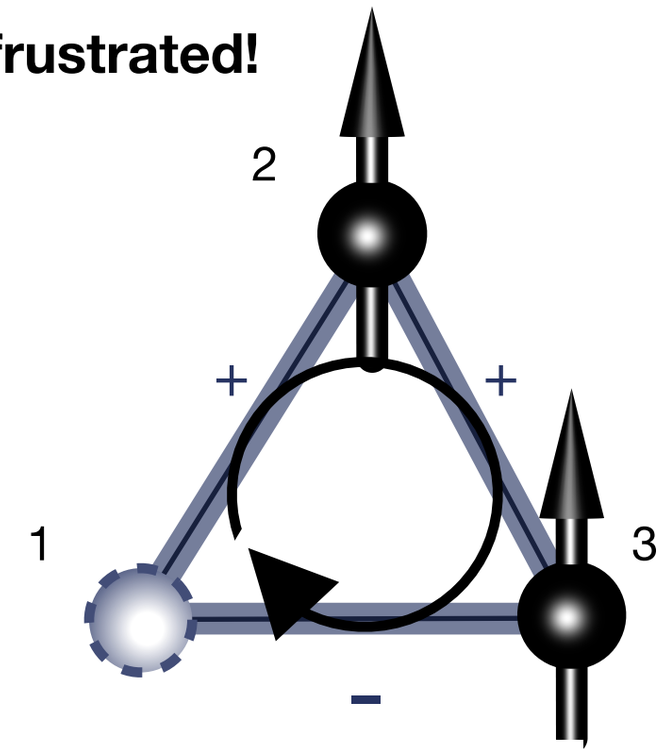


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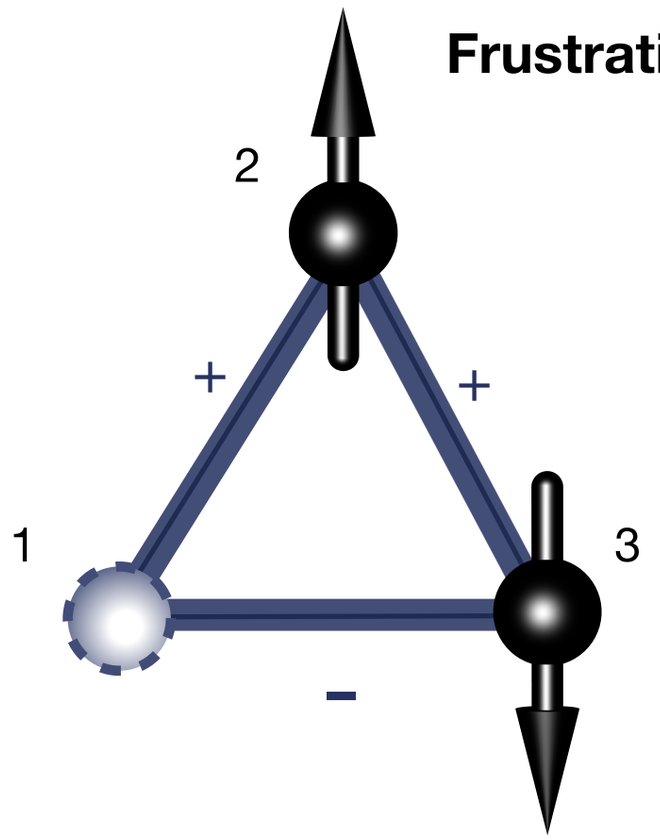
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$$E = -t$$

AFM sector:

Frustration relieved!

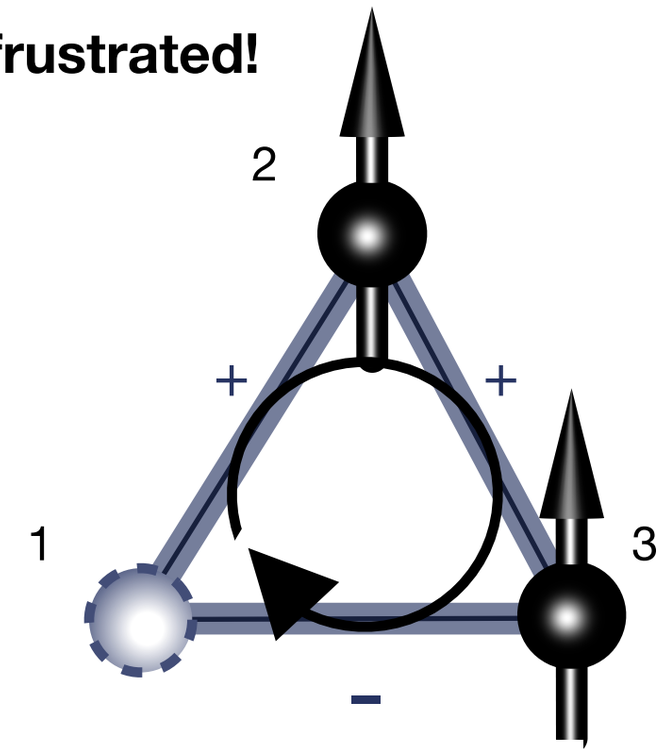


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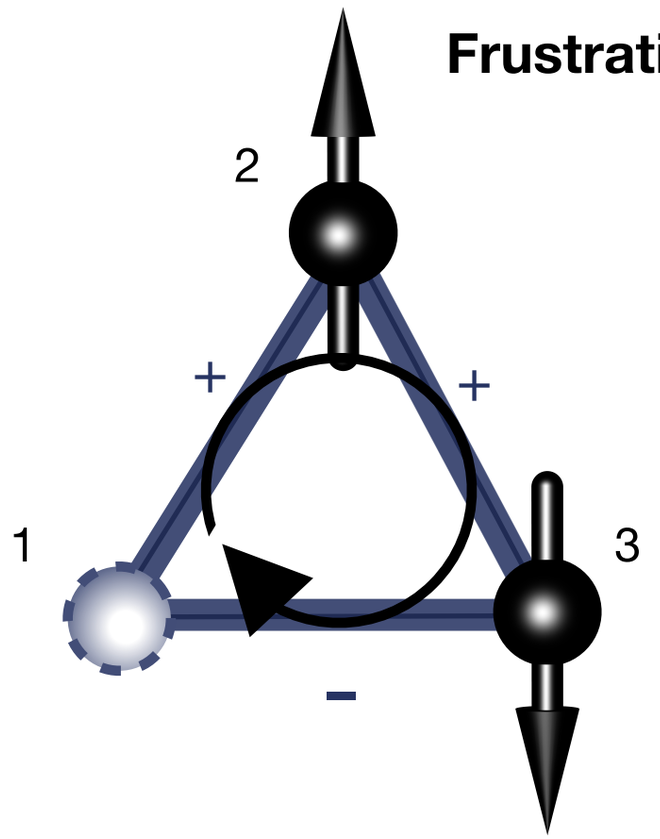
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$$E = -t$$

AFM sector:

Frustration relieved!

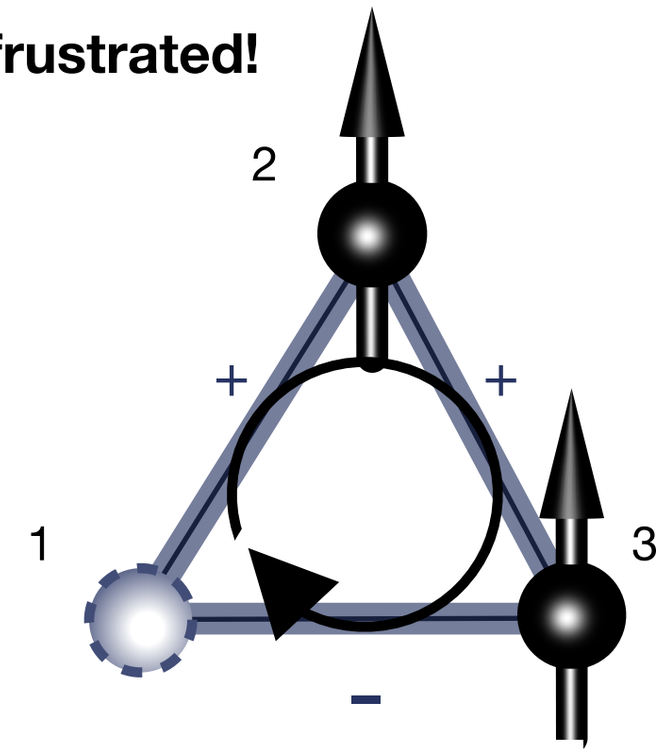


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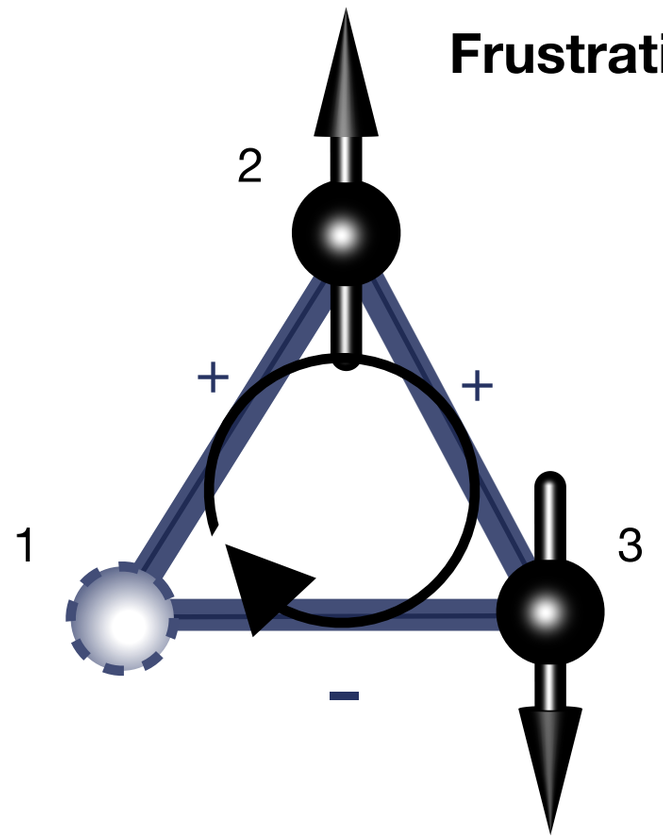
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$$E = -t$$

AFM sector:

Frustration relieved!



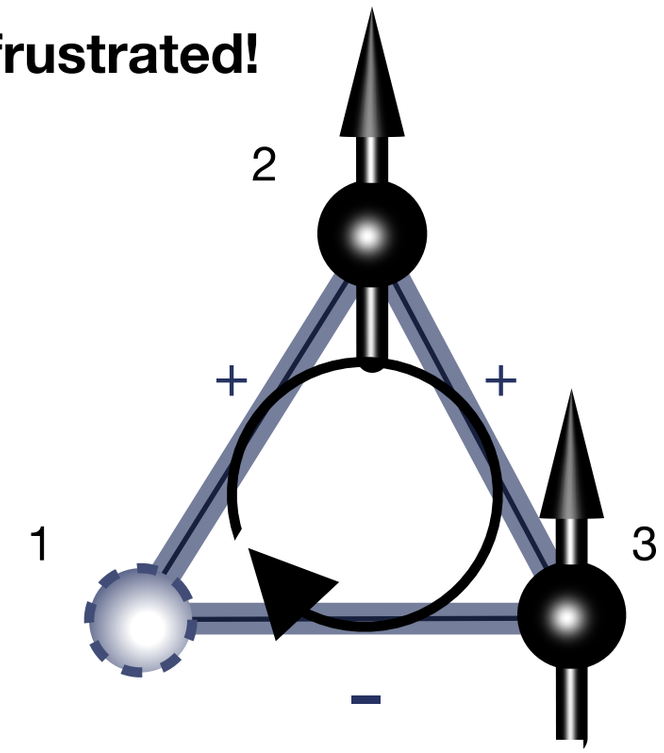
$$|\mathrm{AFM}\rangle = + \left|\,\triangle\,\right\rangle + \left|\,\triangle\,\right\rangle + \left|\,\triangle\,\right\rangle - \left|\,\triangle\,\right\rangle - \left|\,\triangle\,\right\rangle - \left|\,\triangle\,\right\rangle$$

$$E = -2t$$

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Simple example: single hole on a triangle.

FM sector:

Kinetically frustrated!



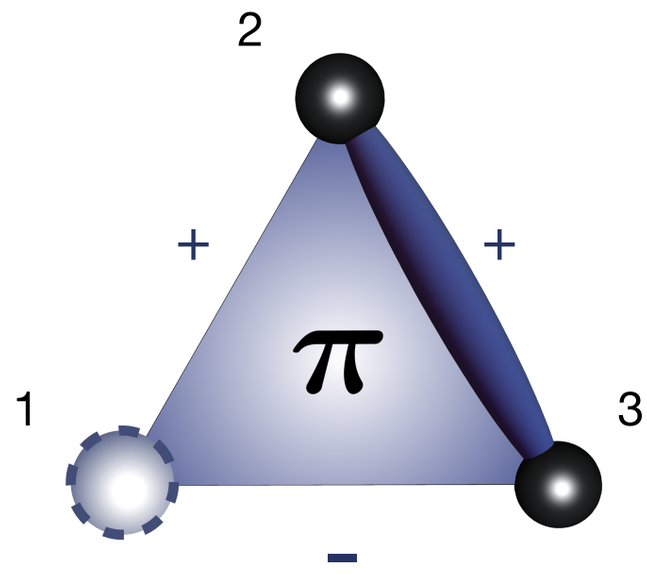
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$$E = -t$$

AFM sector:

Frustration relieved!



$$|\mathrm{AFM}\rangle = + \left|\;\right\rangle + \left|\;\right\rangle + \left|\;\right\rangle - \left|\;\right\rangle - \left|\;\right\rangle - \left|\;\right\rangle = + \left|\;\right\rangle + \left|\;\right\rangle + \left|\;\right\rangle$$

$$E = -2t$$

The counter-Nagaoka effect has been studied on the triangular lattice.

PRL **95,** 087202 (2005) PHYSICAL REVIEW LETTERS week ending 19 AUGUST 2005

Kinetic Antiferromagnetism in the Triangular Lattice

Jan O. Haerter and B. Sriram Shastry
Physics Department, University of California, Santa Cruz, California 95064, USA
(Received 25 May 2005; published 19 August 2005)

PRL **112,** 187204 (2014) PHYSICAL REVIEW LETTERS week ending 9 MAY 2014

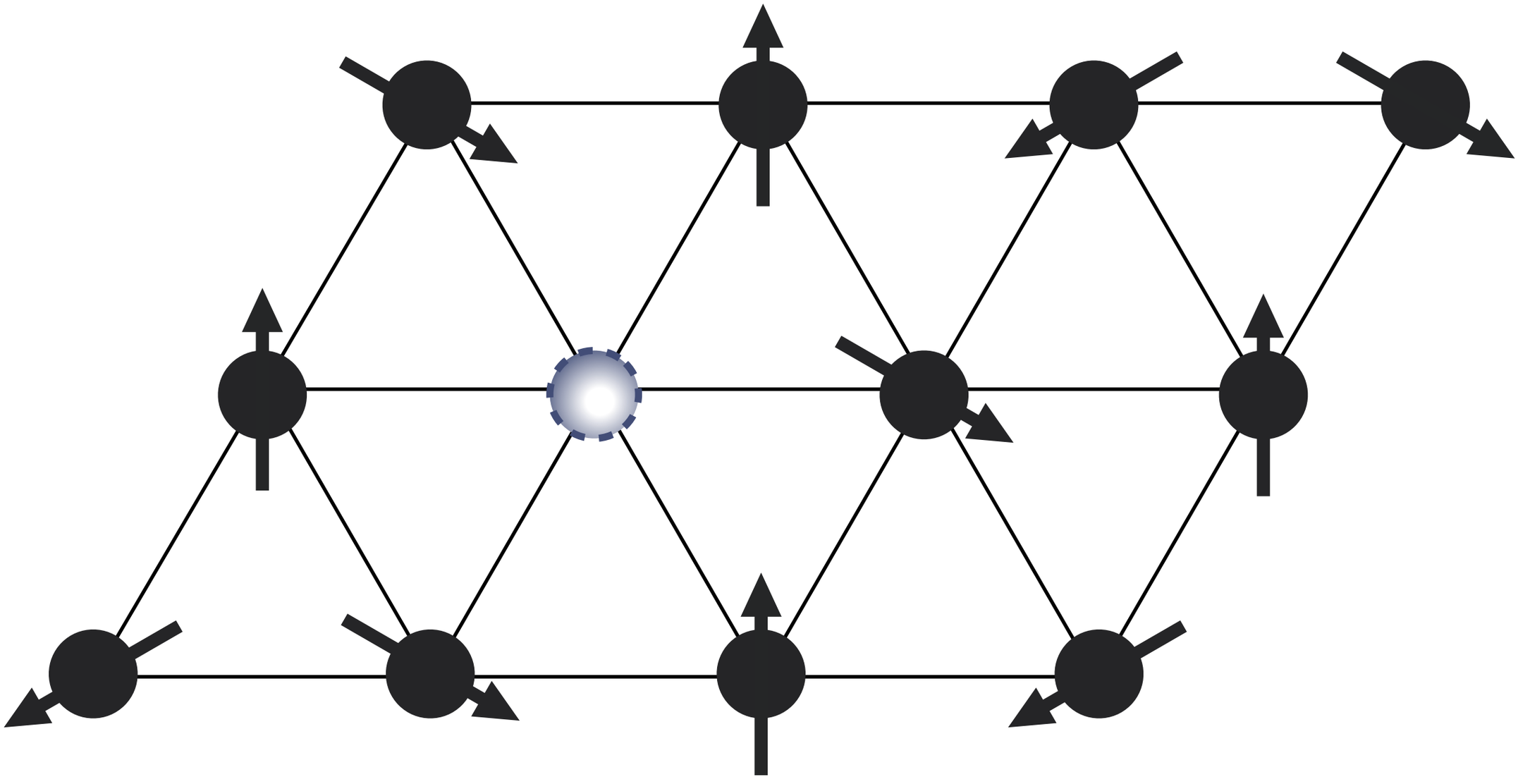
Classical Antiferromagnetism in Kinetically Frustrated Electronic Models

C. N. Sposetti, B. Bravo, A. E. Trumper, C. J. Gazza, and L. O. Manuel
Instituto de Física Rosario (CONICET) and Universidad Nacional de Rosario, Boulevard 27 de Febrero 210 bis, (2000) Rosario, Argentina
(Received 23 December 2013; revised manuscript received 28 February 2014; published 9 May 2014)

Also the pure hopping Hamiltonian on the triangular lattice orders in the 120 degree phase.

$$H = -t \sum_{\langle i,j \rangle\, \sigma} P_{i\sigma} c^{\dagger}_{i\sigma} c_{j\sigma} P_{j\sigma} + h.c.$$

$$H = J \sum_{\langle i,j \rangle} \vec{S}_i \cdot \vec{S}_j$$

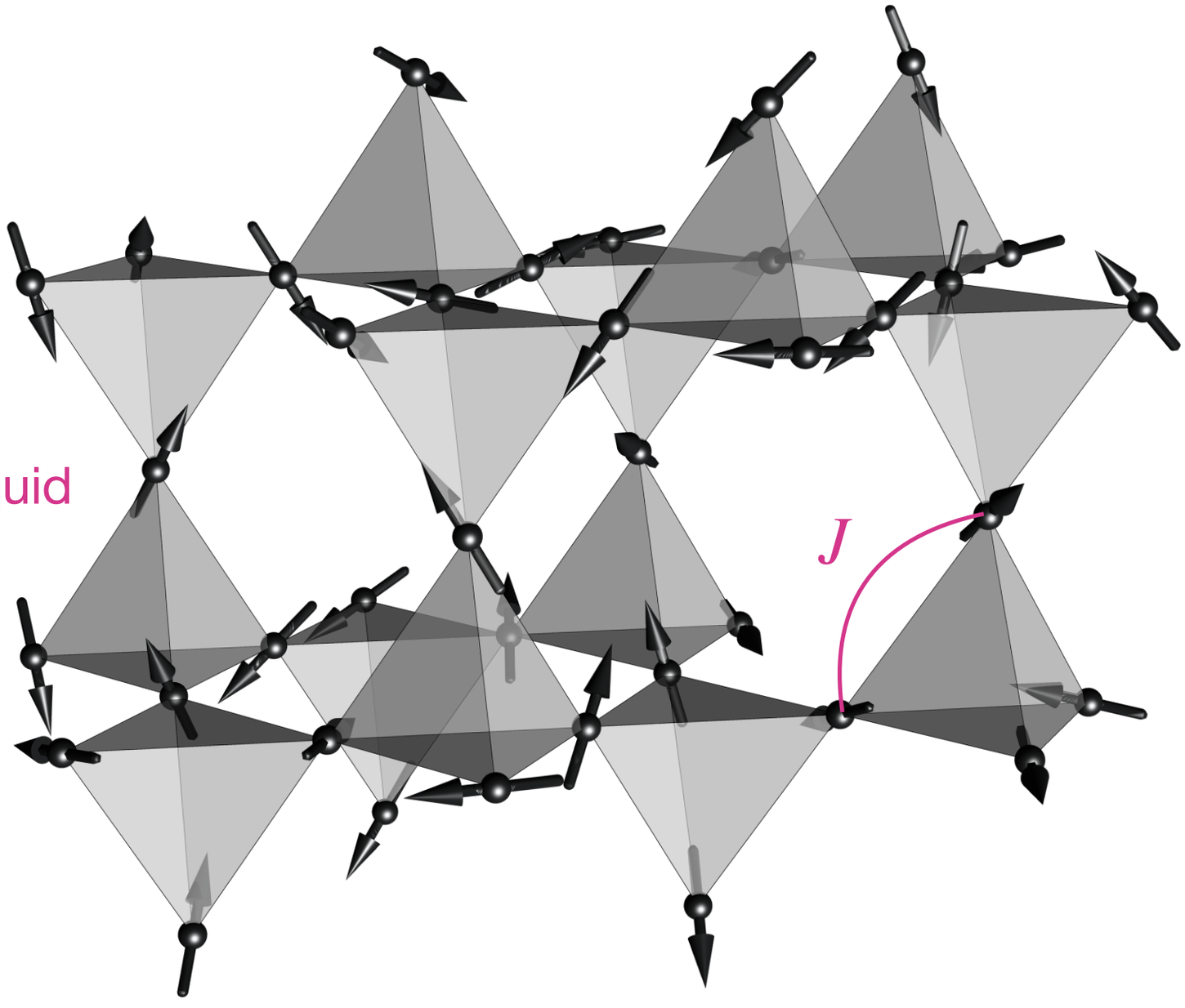


Doping-induced RVB spin liquid in a frustrated Mott insulator

The pyrochlore lattice has received much attention in the search for spin liquids due to its high degree of frustration.

$$H = J \sum_{\langle i,j \rangle} \vec{S}_i \cdot \vec{S}_j$$

Pyrochlore lattice: corner sharing tetrahedra



Classical spins: classical spin liquid
Quantum spins: unclear

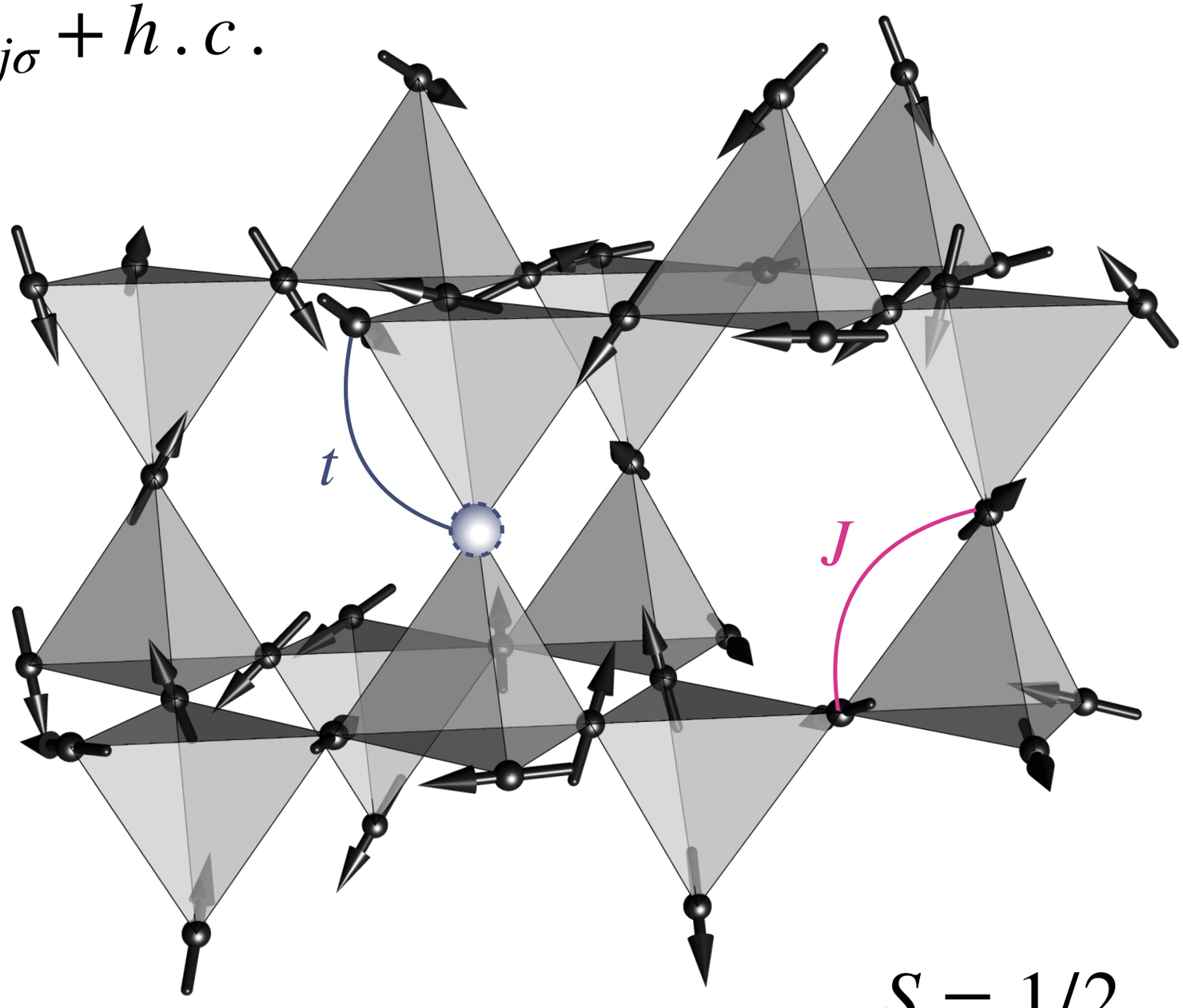
$Y_2Ir_2O_7$ Cu_4O_3

$J > 0$: Antiferromagnetic

Doping-induced RVB spin liquid in a frustrated Mott insulator

$$H = -t \sum_{\langle i,j \rangle\, \sigma} P_{i\sigma} c^{\dagger}_{i\sigma} c_{j\sigma} P_{j\sigma} + h.c.$$

$$+J \sum_{\langle i,j \rangle} \vec{S}_i \cdot \vec{S}_j$$



$t > 0$: Hopping parameter

$J < 0$: Ferromagnetic

$J > 0$: Antiferromagnetic

$S = 1/2$

Doping-induced RVB spin liquid in a frustrated Mott insulator

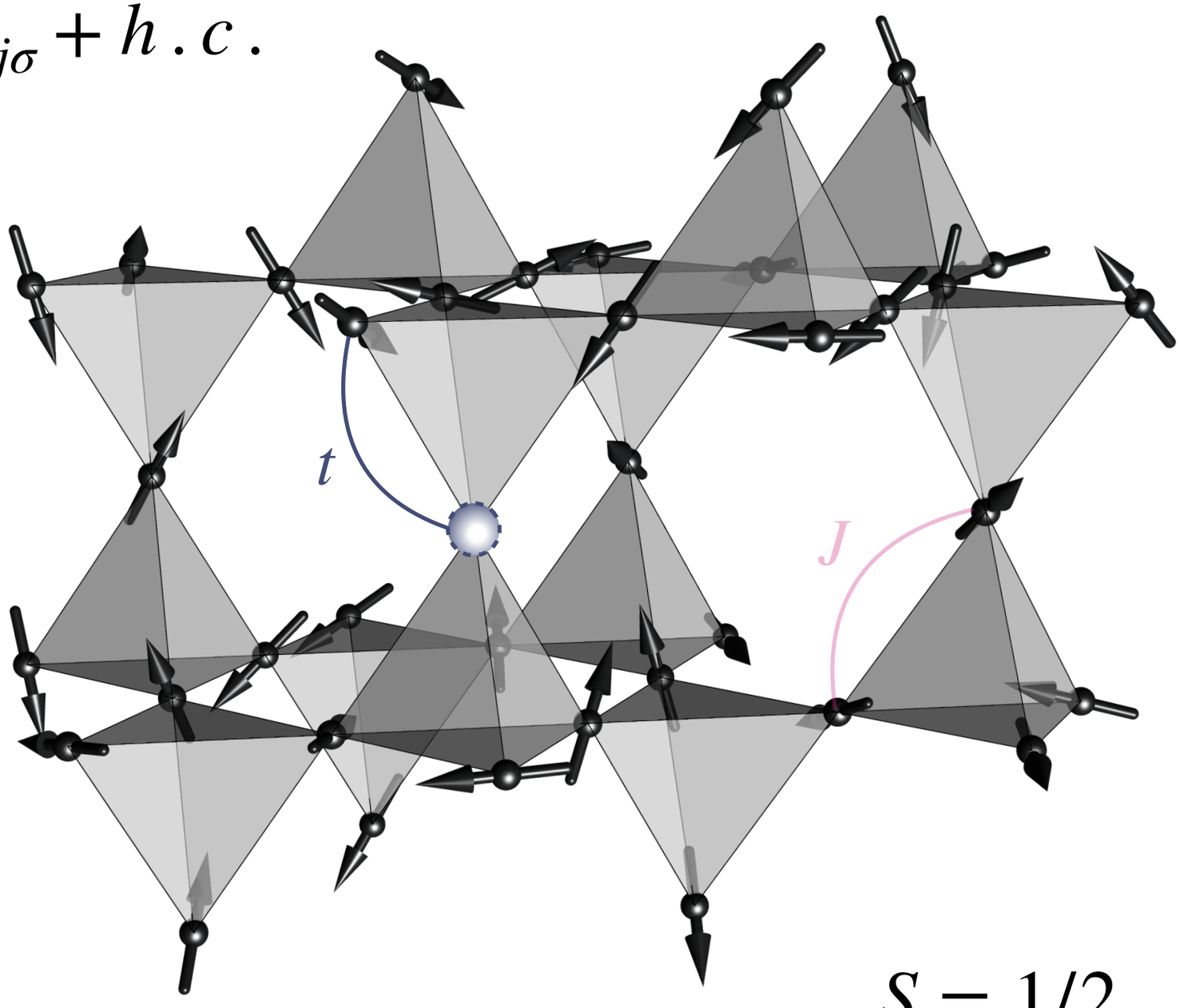
$$H = -t \sum_{\langle i,j \rangle\, \sigma} P_{i\sigma} c^{\dagger}_{i\sigma} c_{j\sigma} P_{j\sigma} + h.c.$$

$$+J \sum_{\langle i,j \rangle} \vec{S}_i \cdot \vec{S}_j$$

$t > 0$: Hopping parameter

$J < 0$: Ferromagnetic

$J > 0$: Antiferromagnetic

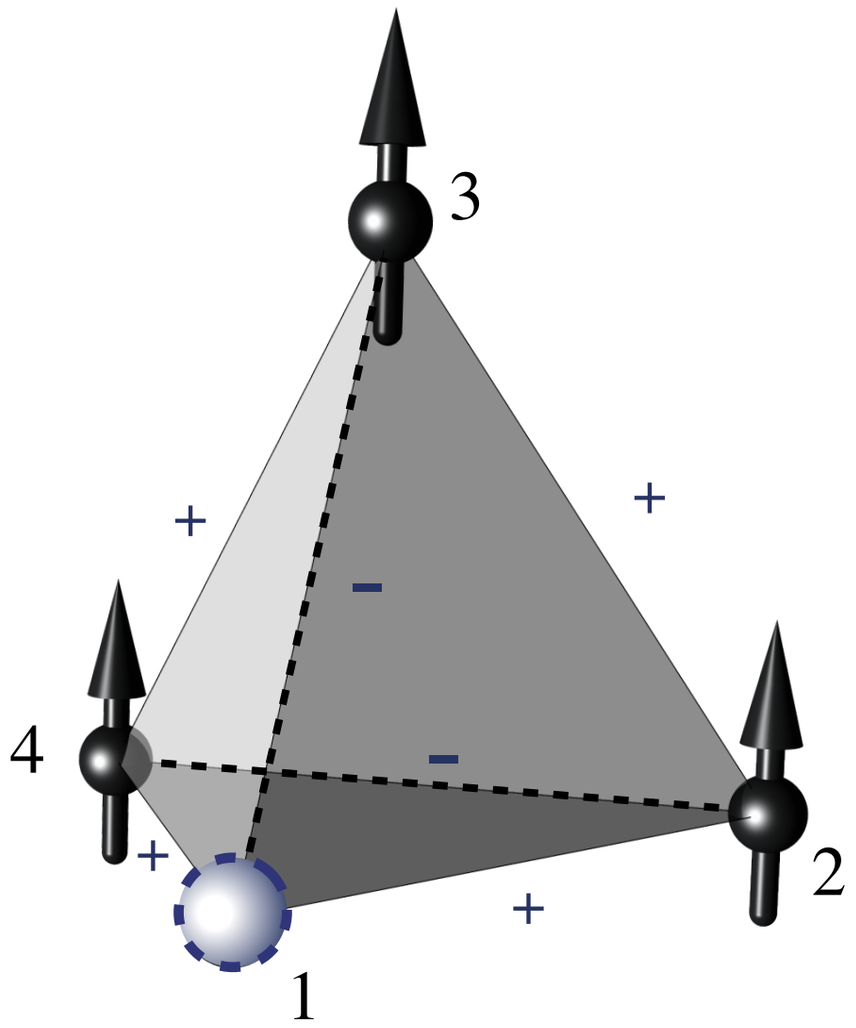


$S = 1/2$

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Smallest possible pyrochlore lattice: the tetrahedron.

4 sites, 1 hole -> 3 spins



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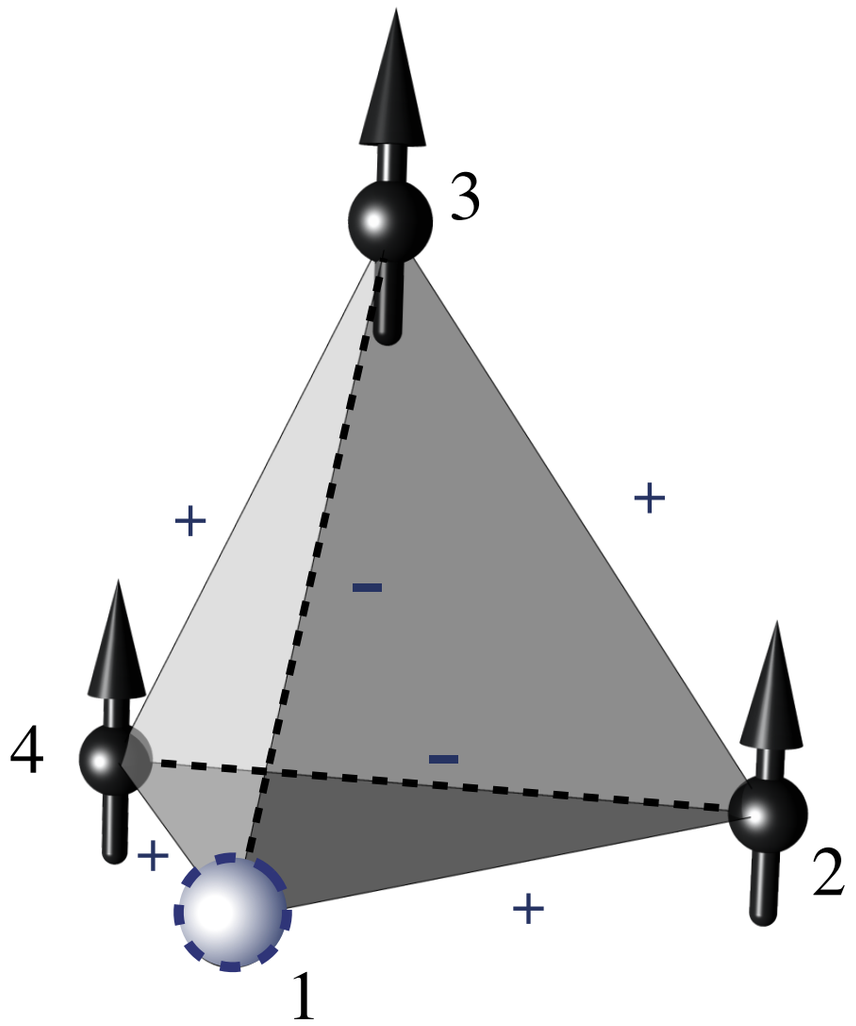
3 up spin sector:

$$|\mathrm{FM}_1\rangle = \frac{1}{\sqrt{2}}\left(|\quad\rangle + |\quad\rangle \right)$$

$$|\mathrm{FM}_2\rangle = \frac{1}{\sqrt{2}}\left(|\quad\rangle + |\quad\rangle \right)$$

$$|\mathrm{FM}_3\rangle = \frac{1}{\sqrt{2}}\left(|\quad\rangle + |\quad\rangle \right)$$

$$E = -t$$



Doping-induced RVB spin liquid in a frustrated Mott insulator arXiv:2408.03372

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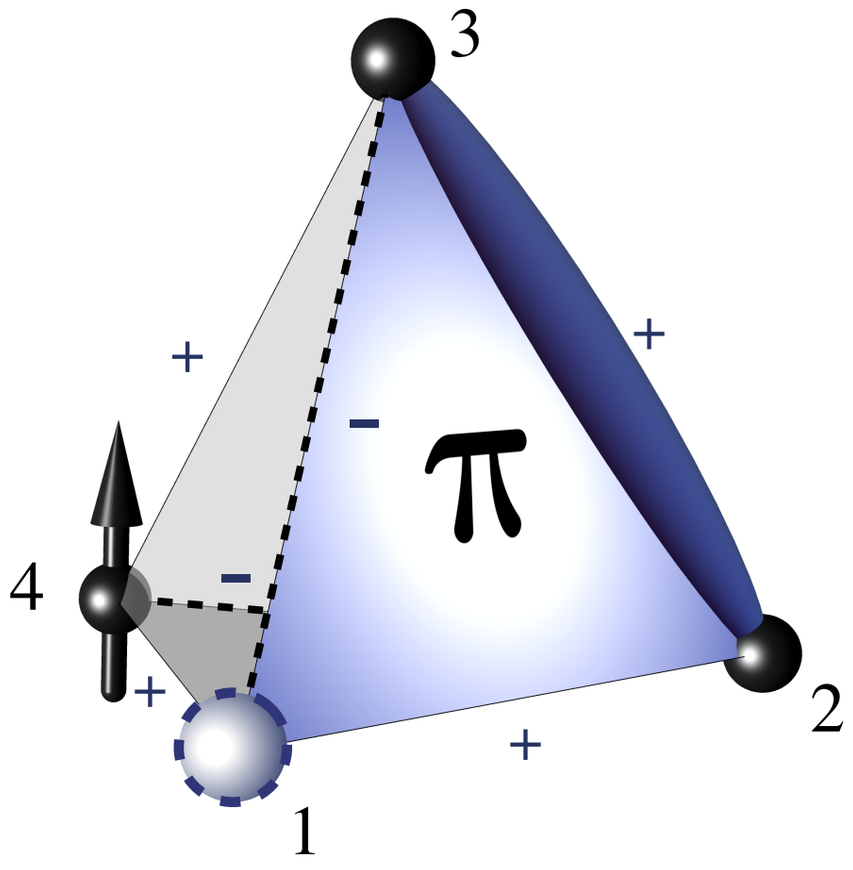
2 up, 1 down spin sector:

$$|\mathrm{AFM}_1\rangle = \frac{1}{\sqrt{3}}\left(|\quad\rangle + |\quad\rangle + |\quad\rangle \right)$$

$$|\mathrm{AFM}_2\rangle = \frac{1}{\sqrt{3}}\left(|\quad\rangle + |\quad\rangle + |\quad\rangle \right)$$

$$|\mathrm{AFM}_3\rangle = \frac{1}{\sqrt{3}}\left(|\quad\rangle + |\quad\rangle + |\quad\rangle \right)$$

$$E = -2t$$

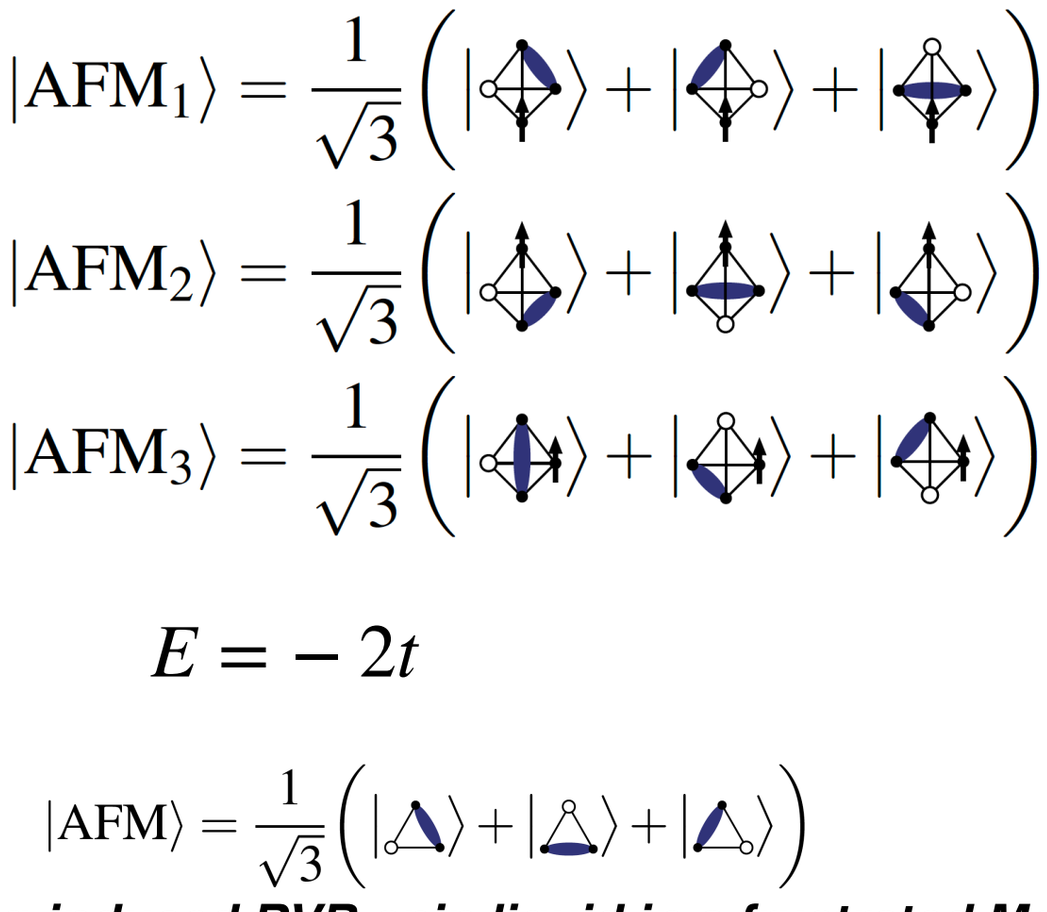


Doping-induced RVB spin liquid in a frustrated Mott insulator arXiv:2408.03372

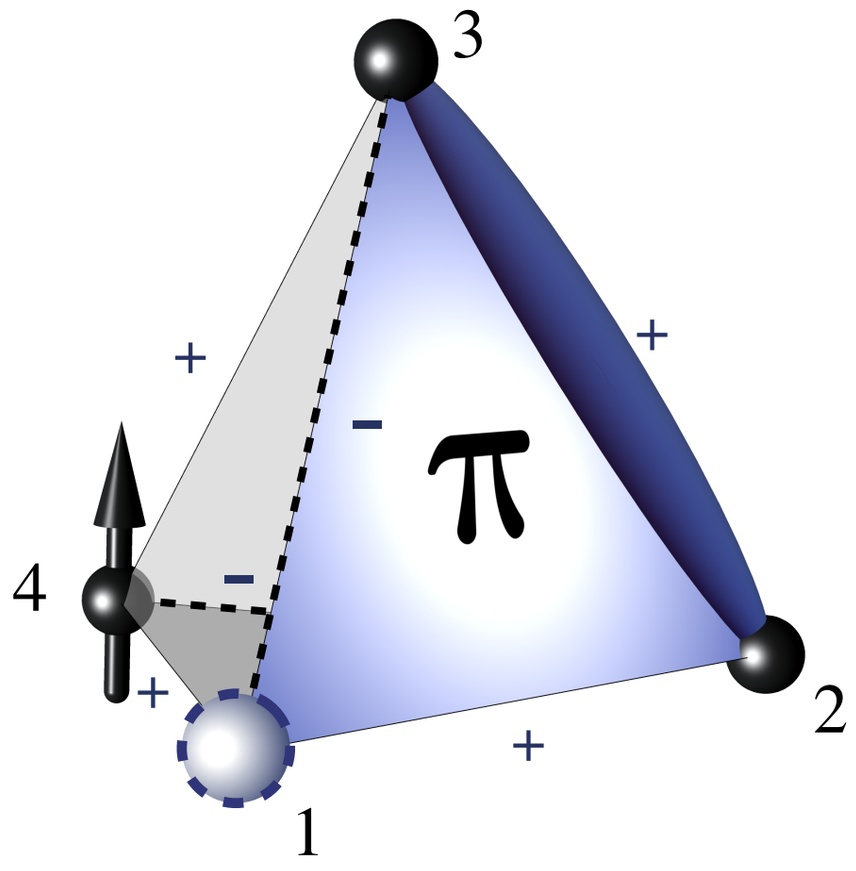
Smallest possible pyrochlore lattice: the tetrahedron.

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2 up, 1 down spin sector:

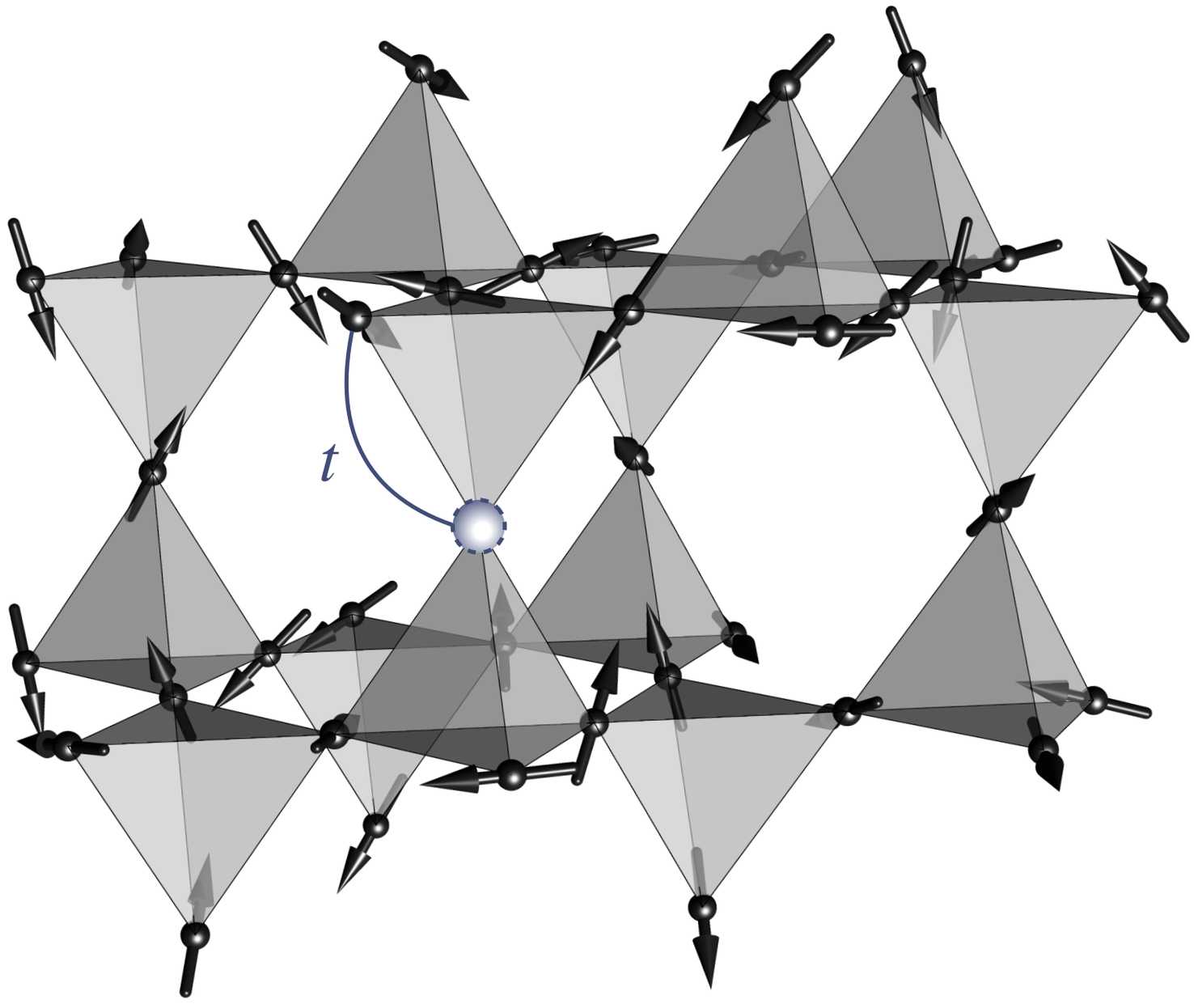


$$E = -2t$$



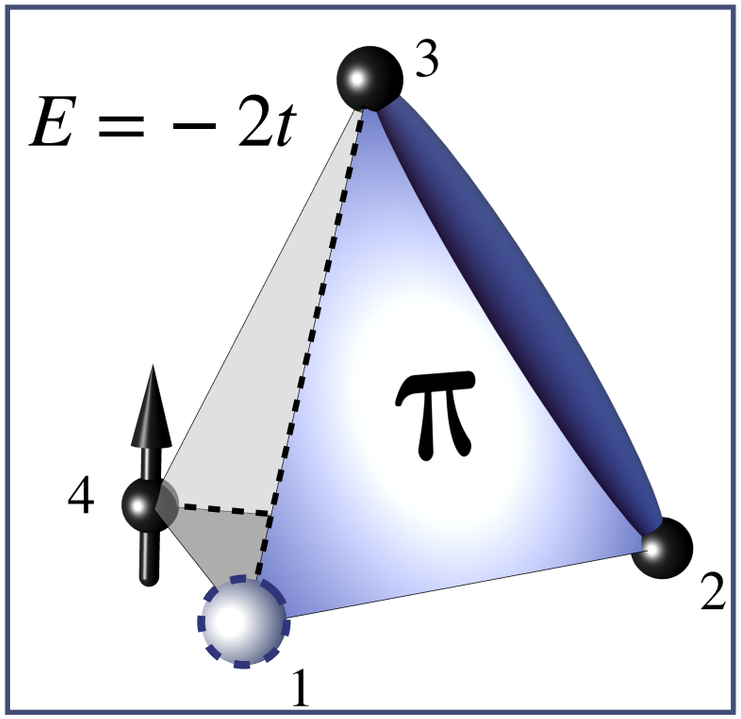
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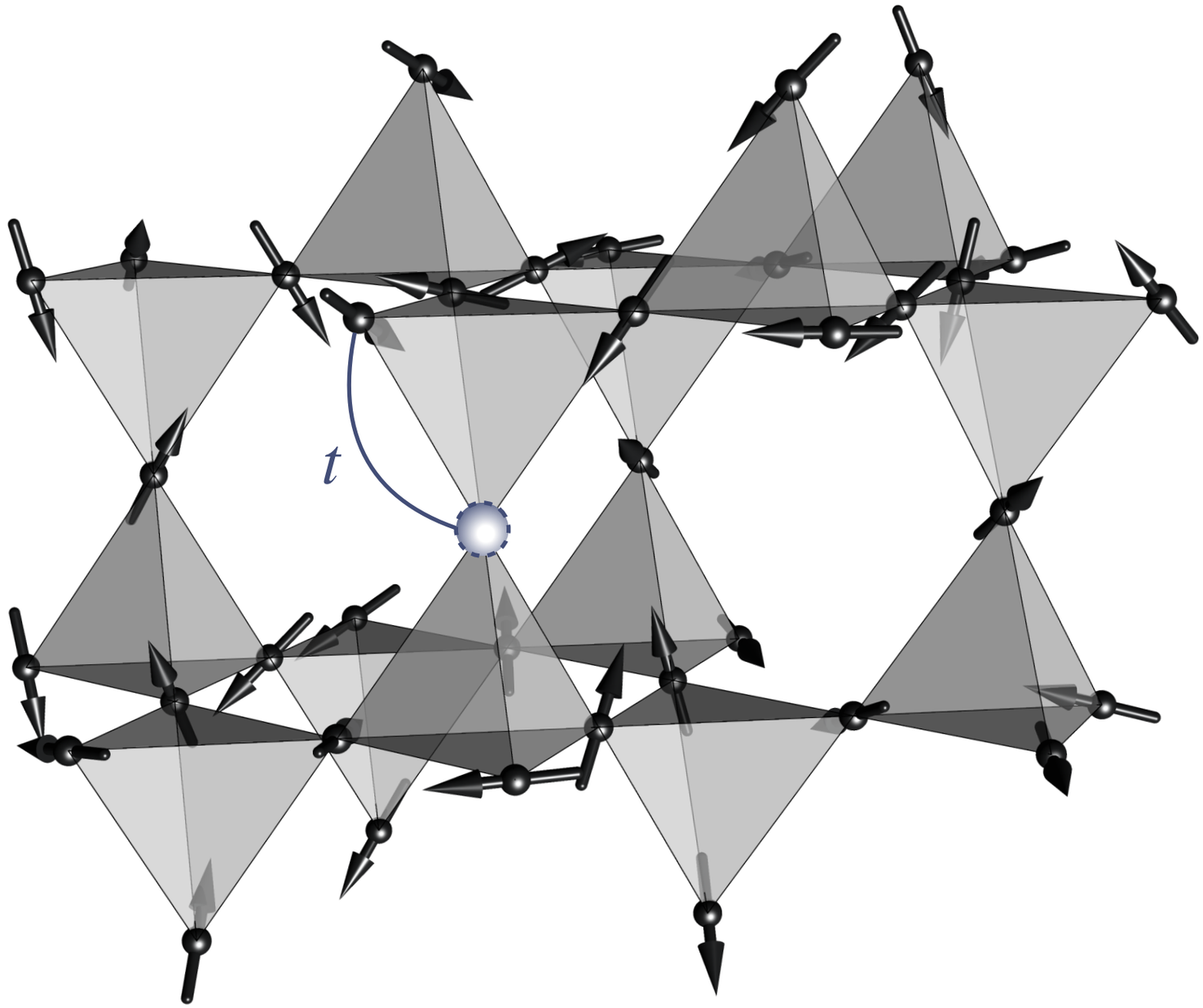
For the full pyrochlore lattice, the ground state energy is lower bound by -4*t*.



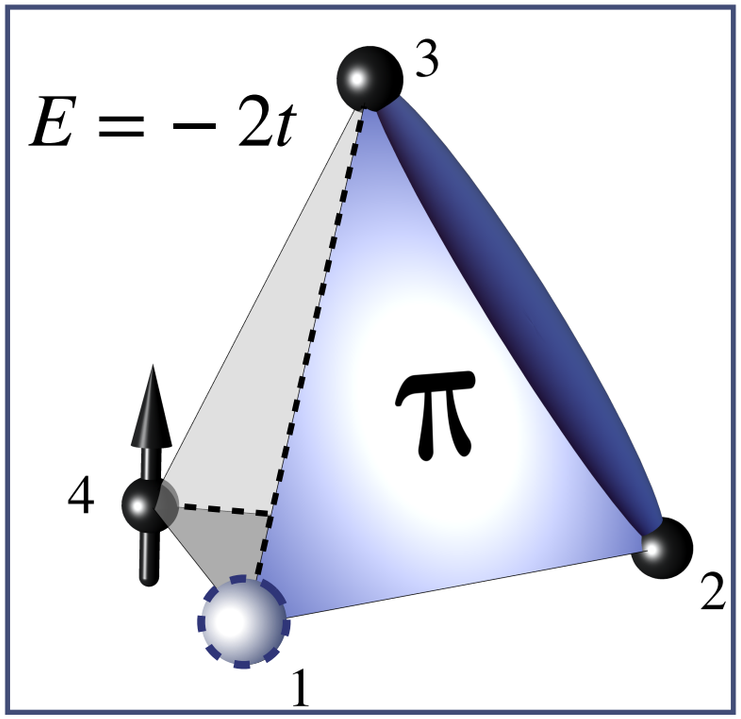
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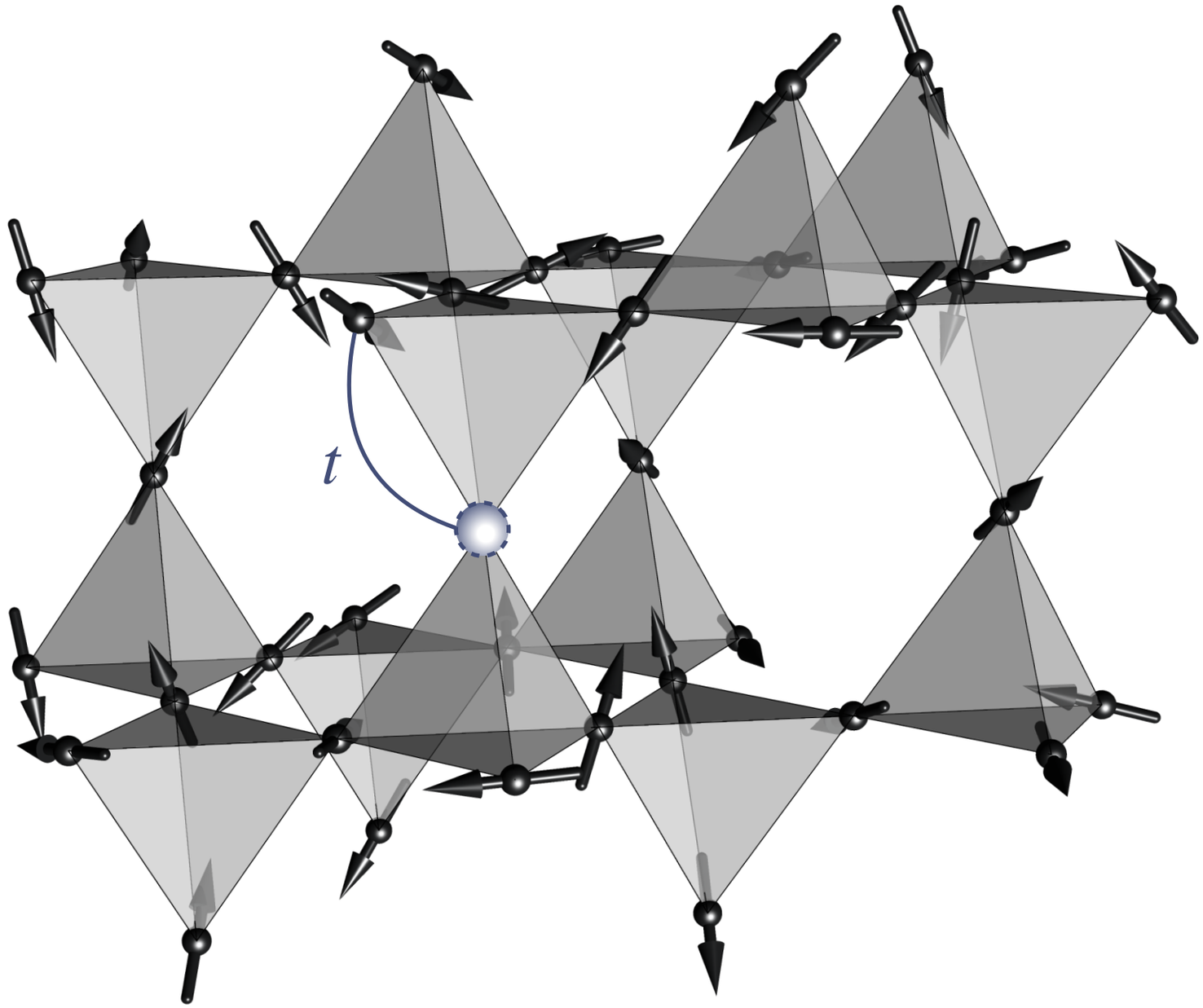
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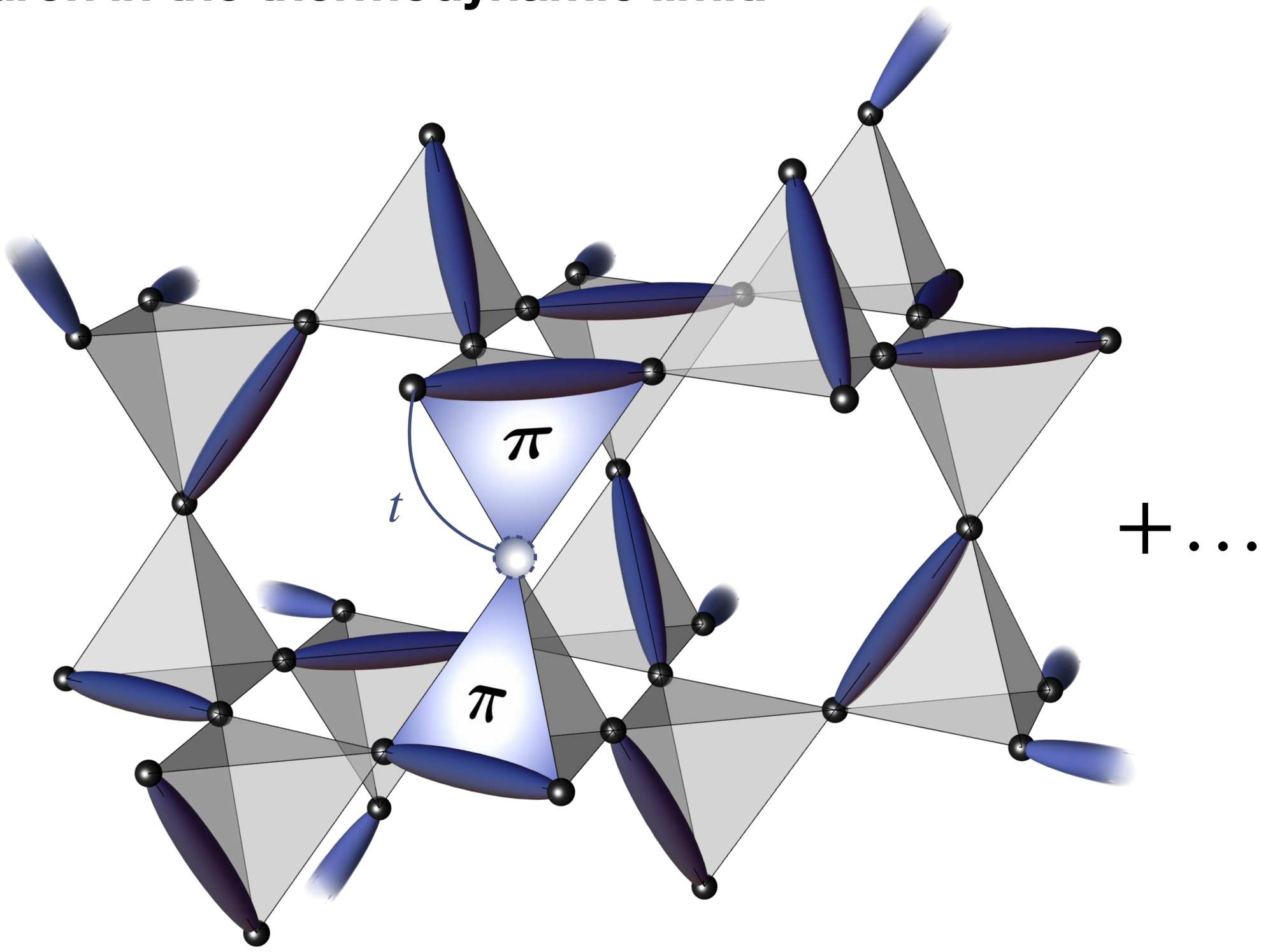




$$E_{\mathrm{GS}} \geq -4t$$

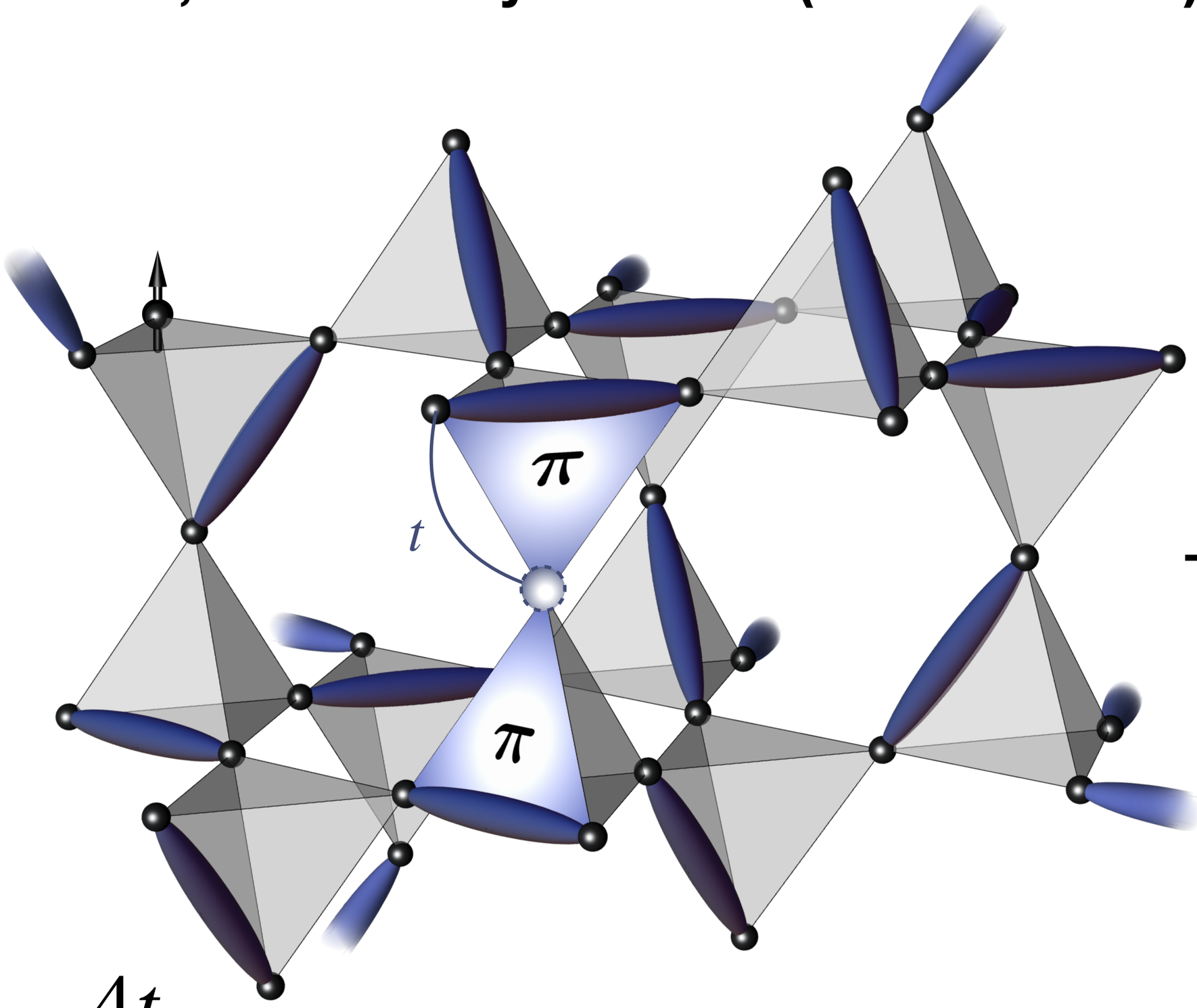
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$E = -4t$ is met by the RVB wave function with one singlet per tetrahedron in the thermodynamic limit.



Doping-induced RVB spin liquid in a frustrated Mott insulator arXiv:2408.03372

Conjectured wave function is the ground state for 16, 24, 32, 36 and 48 sites, as shown by numerics (ED and DMRG).



+…

$$E_{\mathrm{GS}} = -4t$$

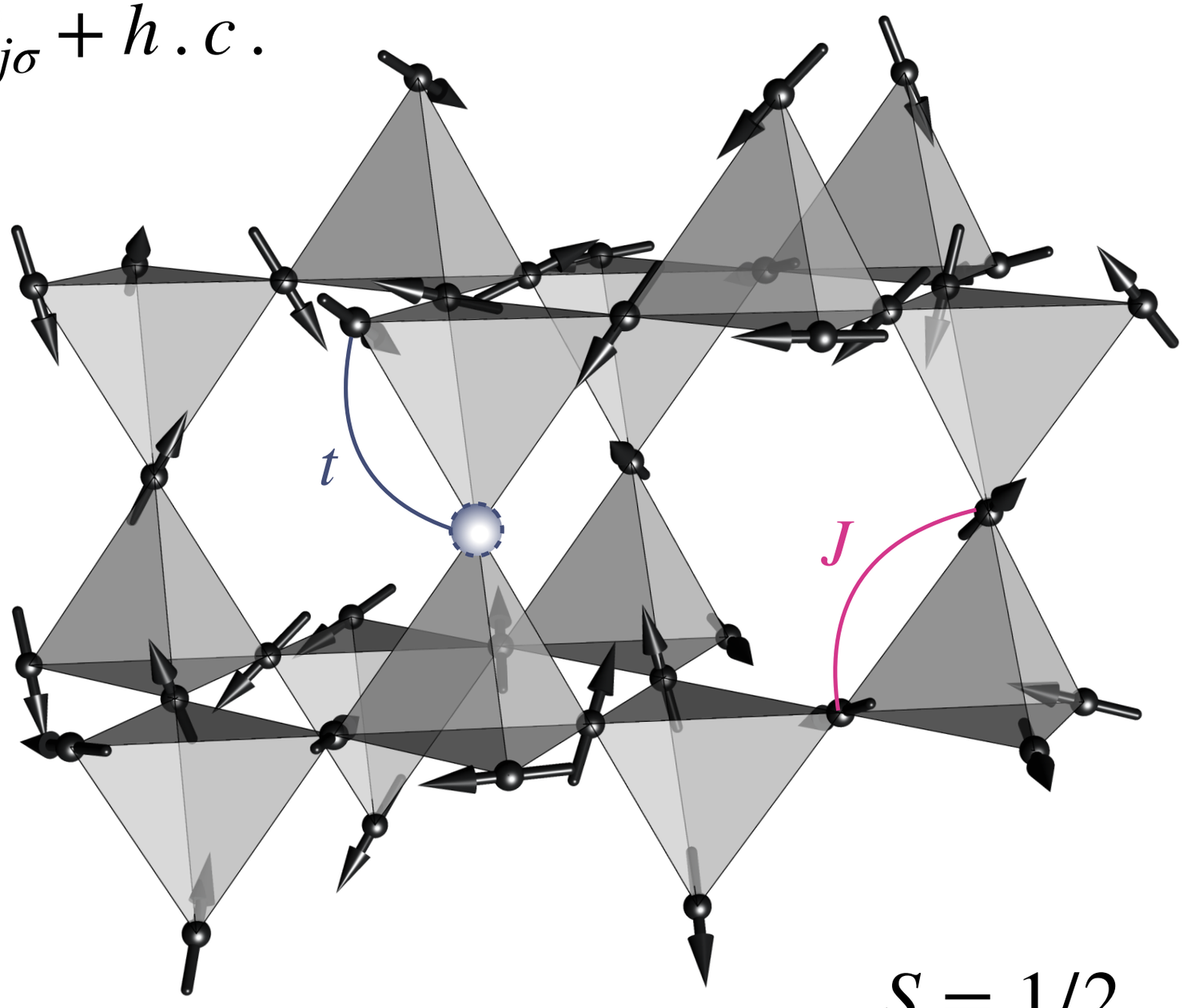
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Relaxing the infinite-*U* constraint: the *t-J* model

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$$+J \sum_{\langle i,j \rangle} \vec{S}_i \cdot \vec{S}_j$$



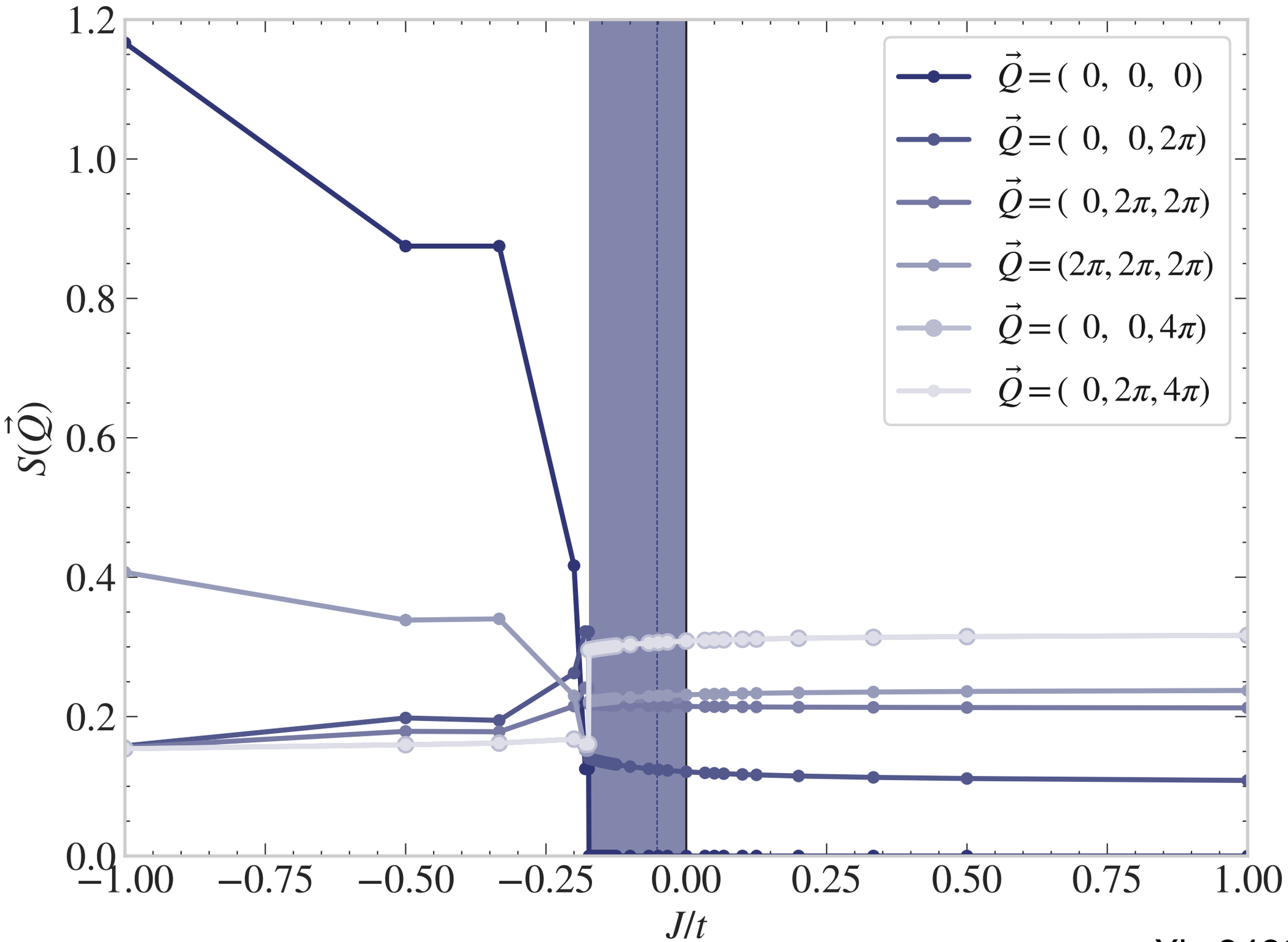
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$J < 0$: Ferromagnetic

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Doping-induced RVB spin liquid in a frustrated Mott insulator

We find the doping-induced RVB state to be stable also upon adding small exchange interactions.



AKER SCHOLARSHIP

The n.n. RVB state is realised in a realistic system through doping

We propose kinetic frustration as a novel route in the search for QSLs

t

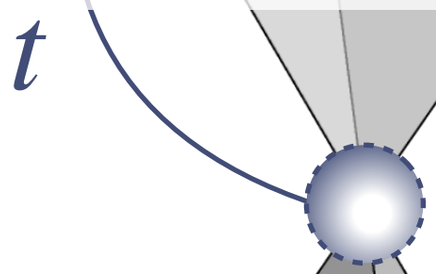
J

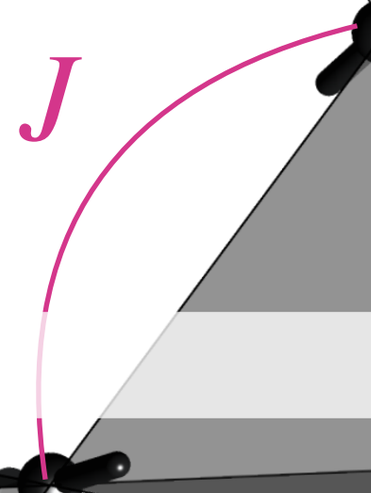
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THANK YOU FOR YOUR ATTENTION!

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