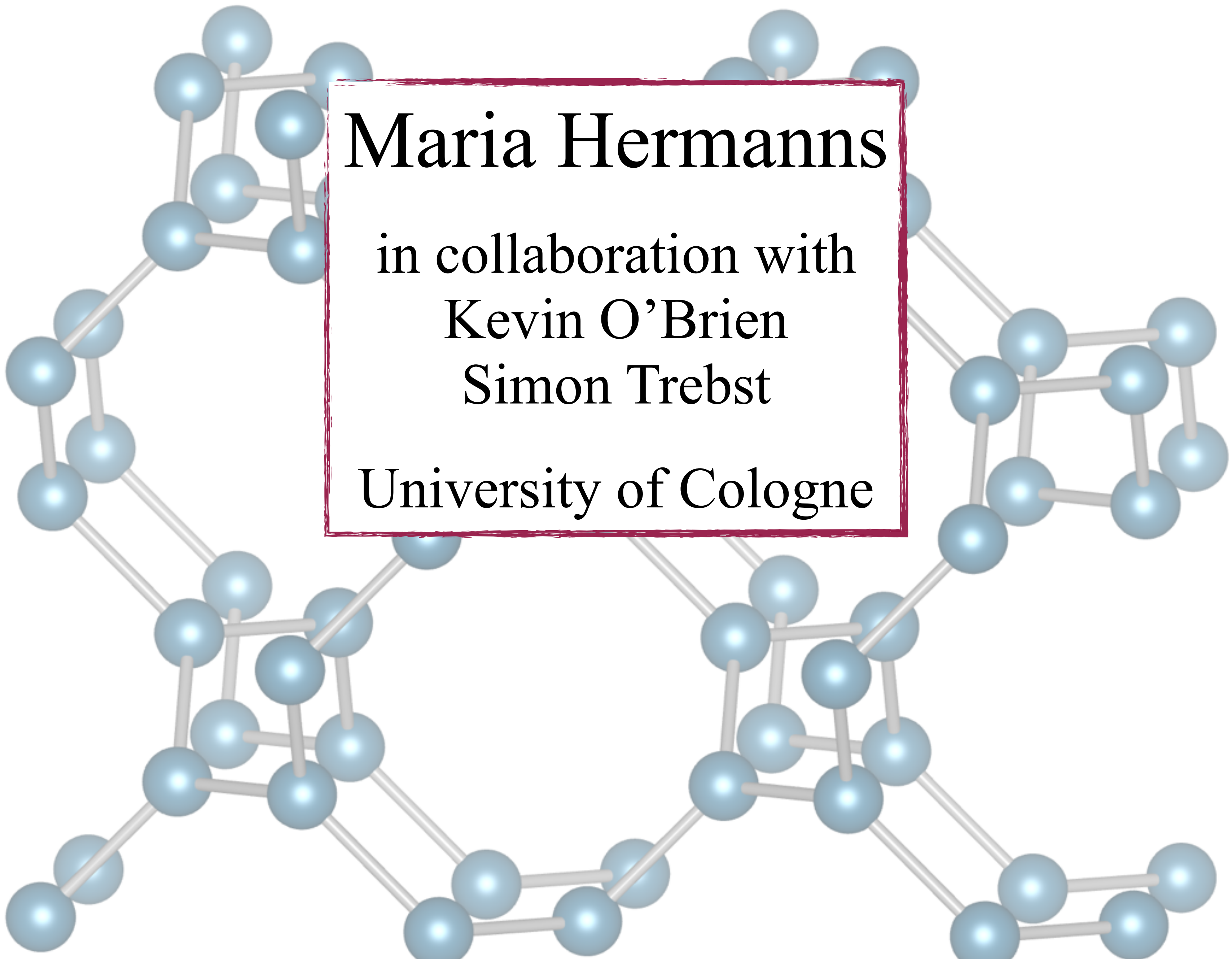
Quantum spin liquid with a Majorana Fermi surface



Maria Hermanns

in collaboration with
Kevin O'Brien
Simon Trebst

University of Cologne

Fractionalization in strongly correlated systems

(Strong) interactions can lead to emergent quasiparticles
with 'fractional' quantum numbers

Fractionalization in strongly correlated systems

(Strong) interactions can lead to emergent quasiparticles
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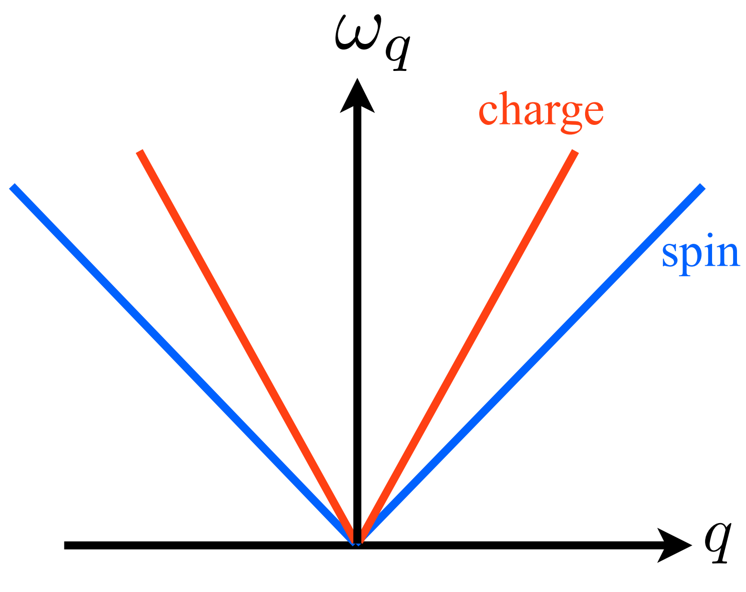
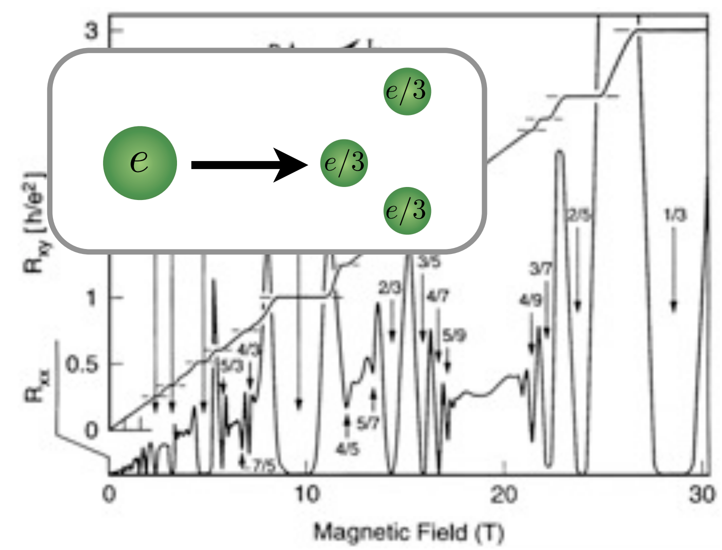
Spin-charge separation

Fermi gas in 1D



Electron fractionalization

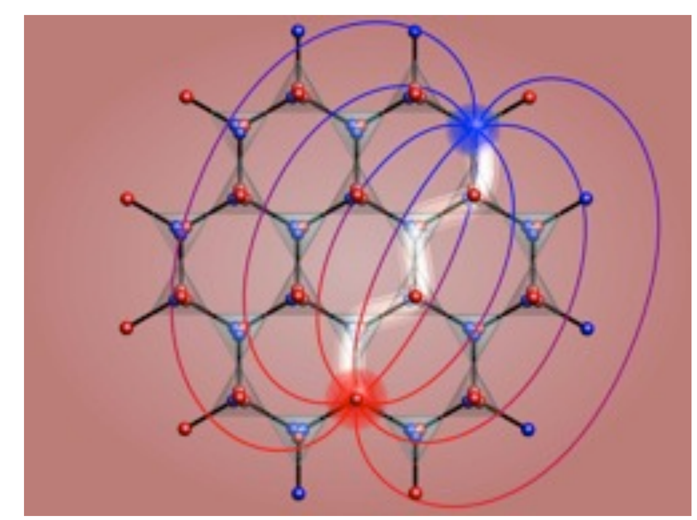
Quantum Hall liquids



Tsui, Störmer, Gossard, PRL **48**, 1559 (1982)

Magnetic monopoles

Spin ice

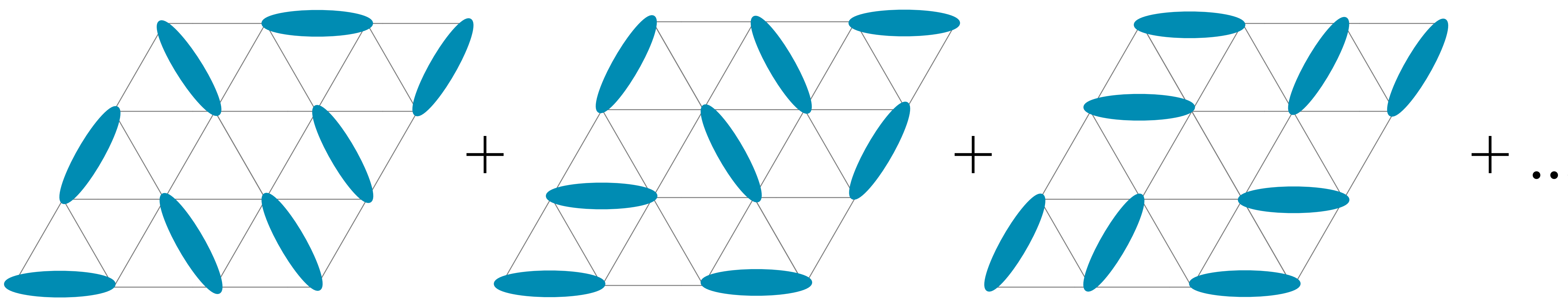


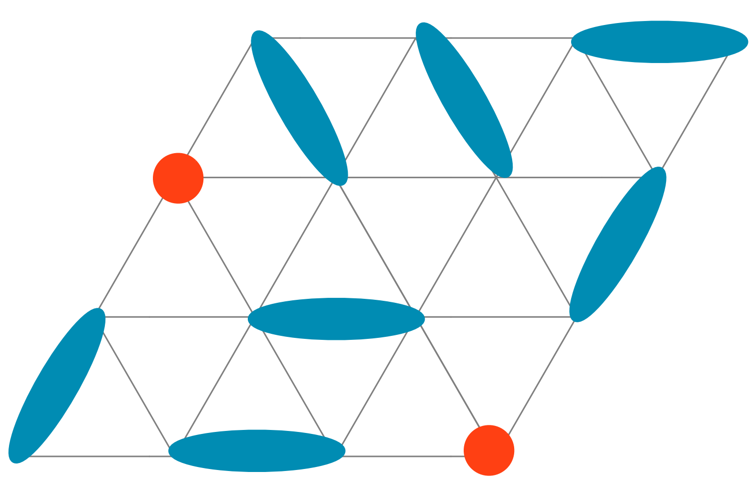
Castelnovo etal, Nature **451**, 22-23 (2007)

Fractionalization in magnetic systems

Moessner, Sondhi PRL 86, 1881 (2000)

Resonating **V**alence **B**ond liquid:

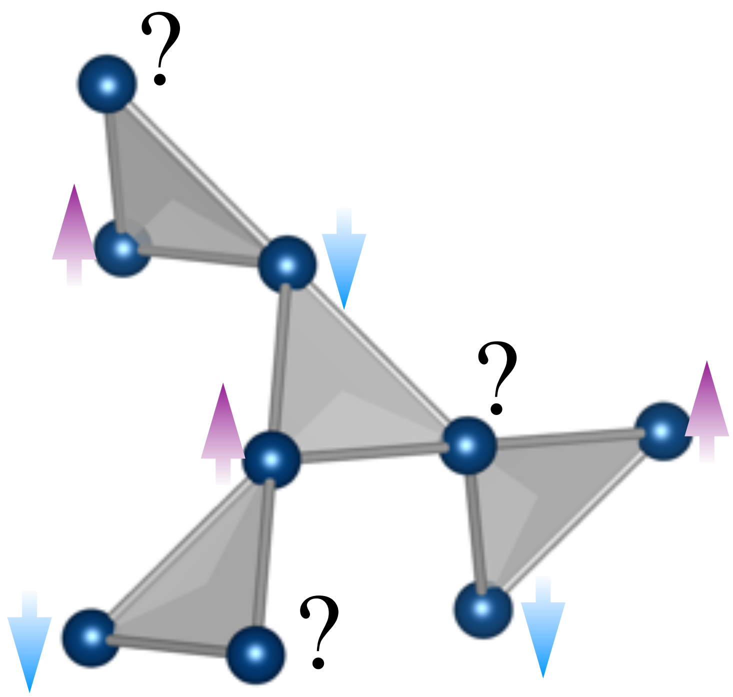




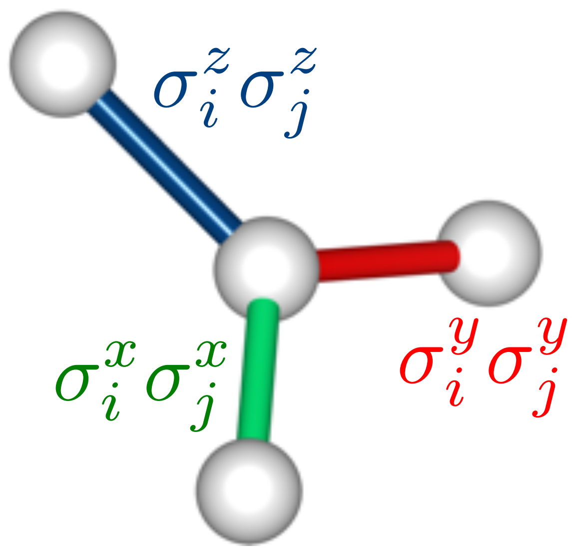
- short-range dimer correlations
- no magnetic order
- gapped, deconfined spinon excitations – spin 1/2

Towards spin liquids – frustration

geometric frustration



exchange frustration



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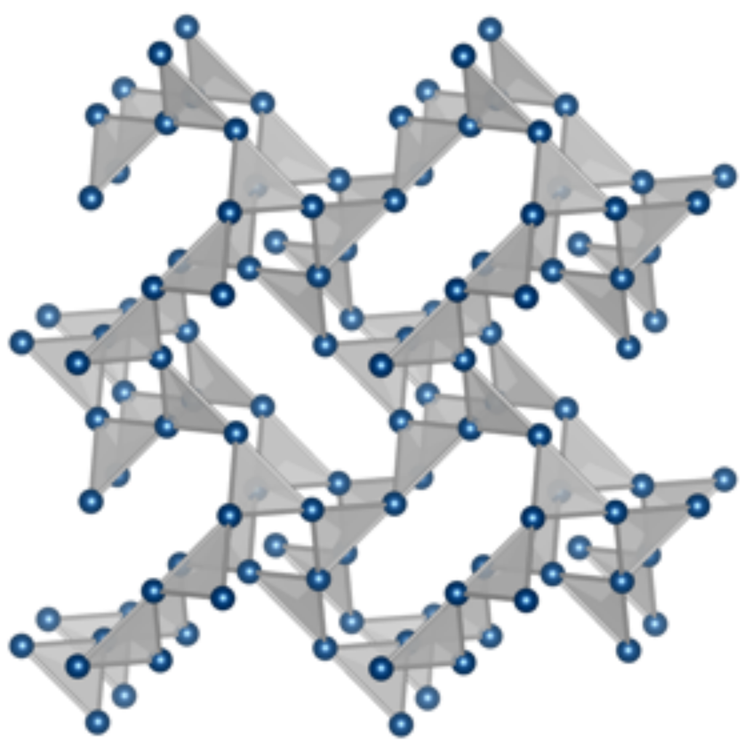
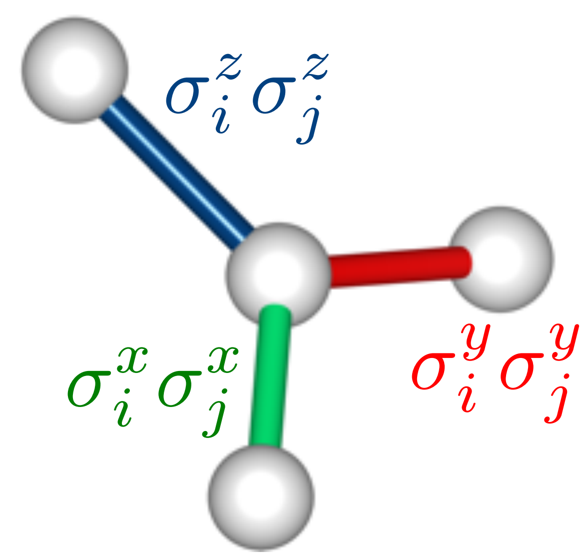


hyperkagome lattice
$Na_4Ir_3O_8$

Y. Okamoto, M. Nohara, H. Aruga-Katori, and H. Takagi, PRL **99**, 137207 (2007)

exchange frustration



Towards spin liquids – frustration

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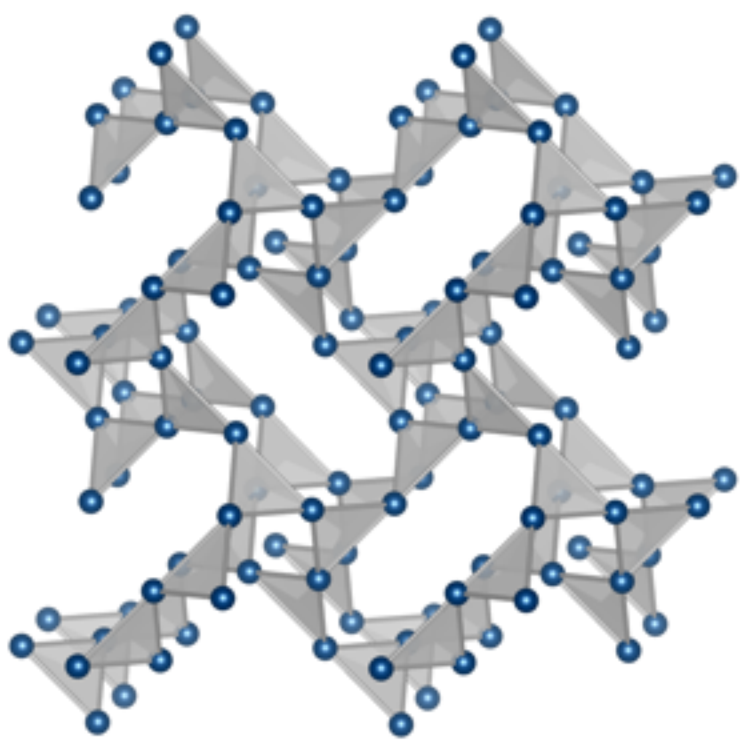

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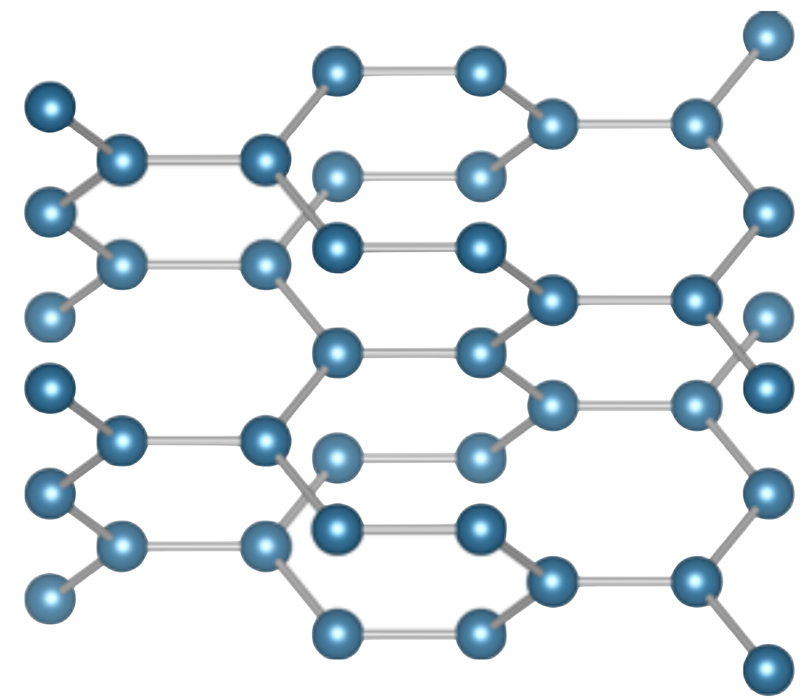
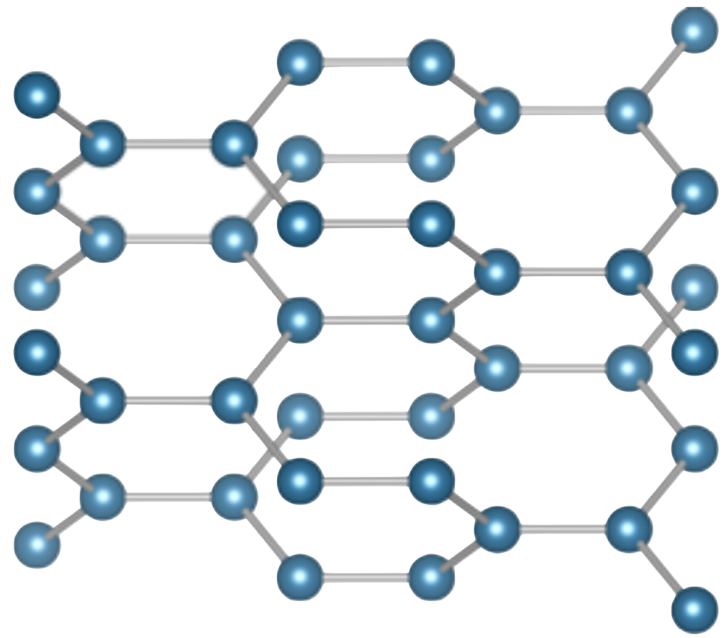


hyperhoneycomb lattice
β-Li_2IrO_3

T. Takayama etal., arXiv:1403.3296 (2014)
K.A. Modic etal. arXiv:1402.3254 (2014)

Zoo of 3D tri-coordinated lattices



Takayama etal., arXiv:1403.3296 (2014)

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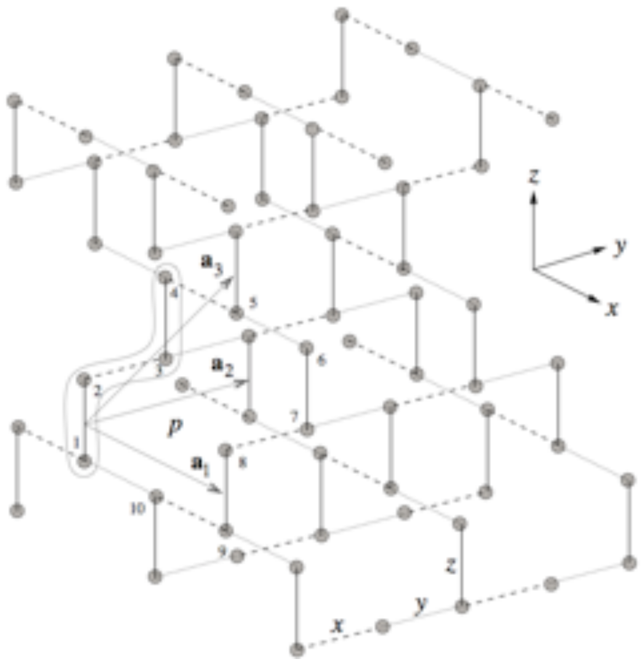
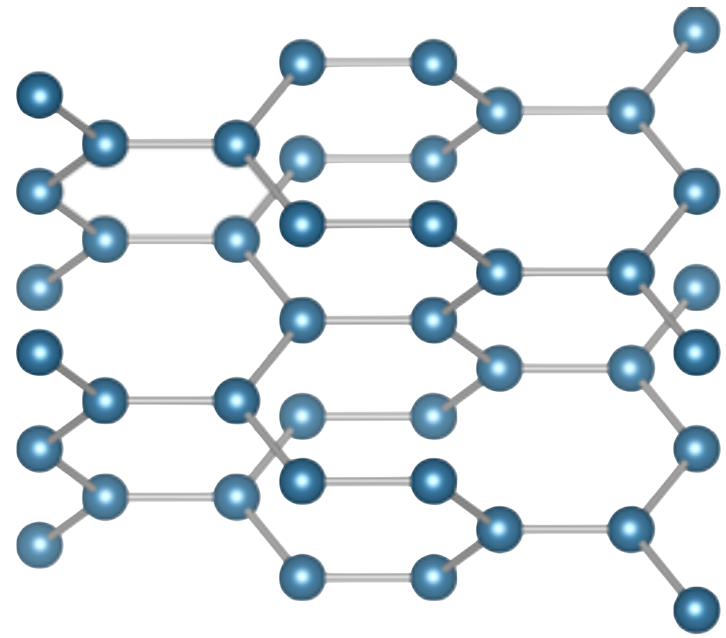


Mandal, Surendran, PRB 79, 024426 (2009)



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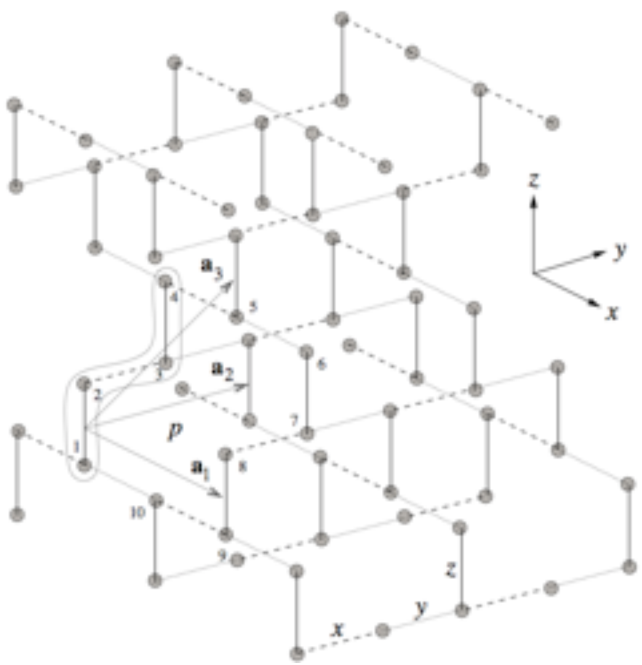

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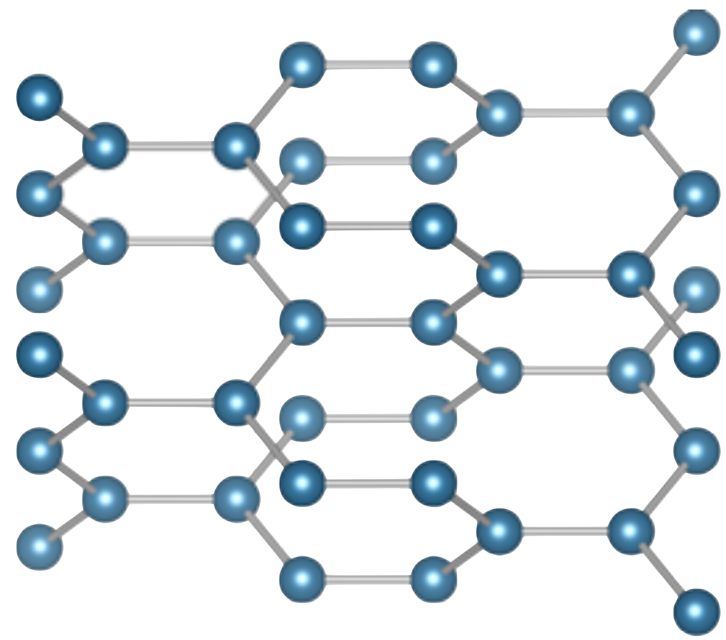

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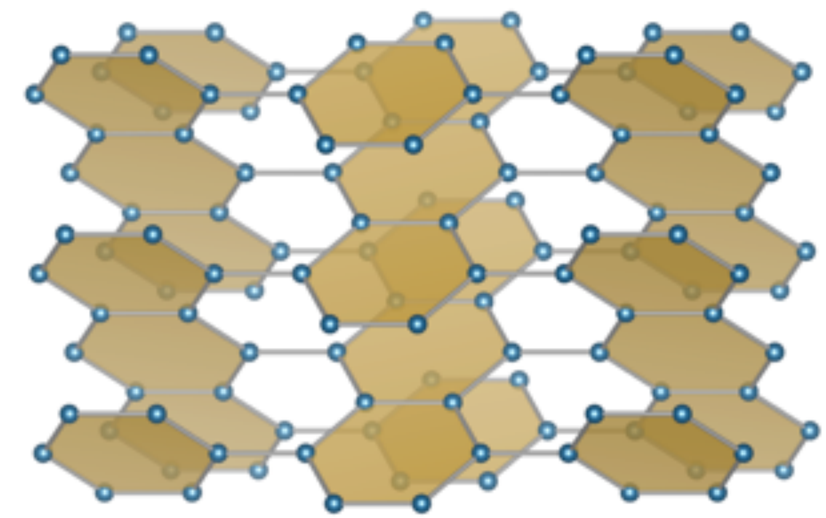

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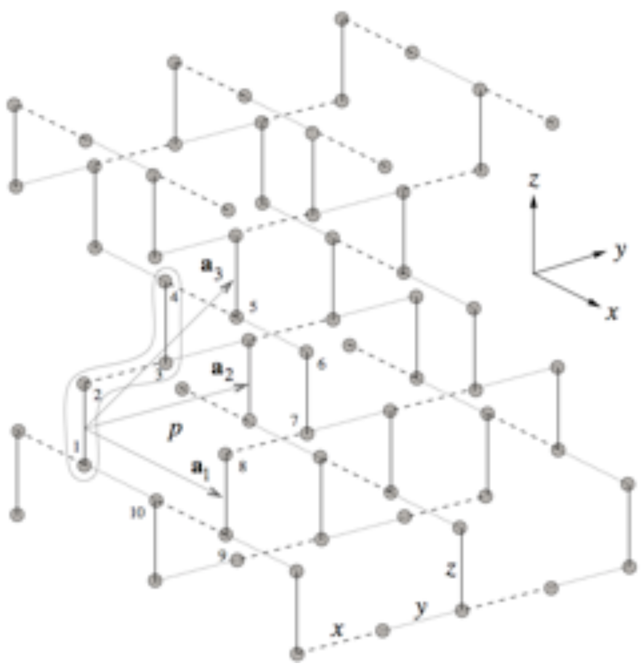

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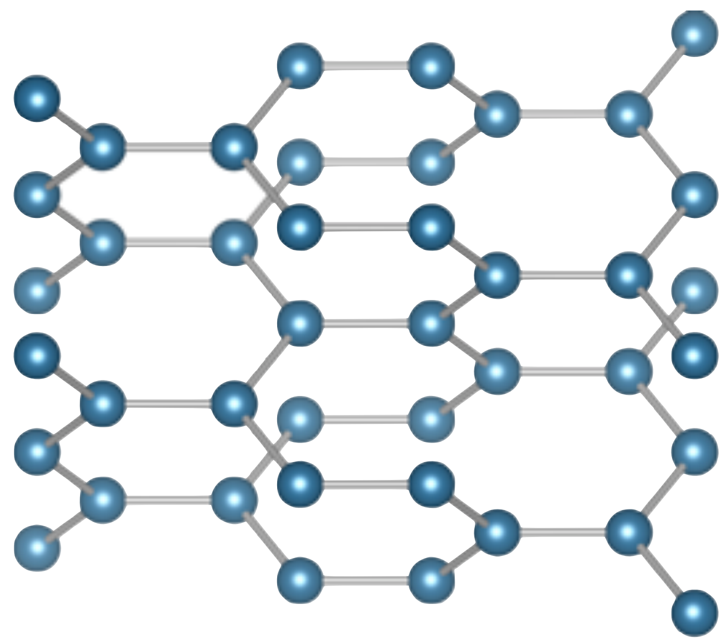

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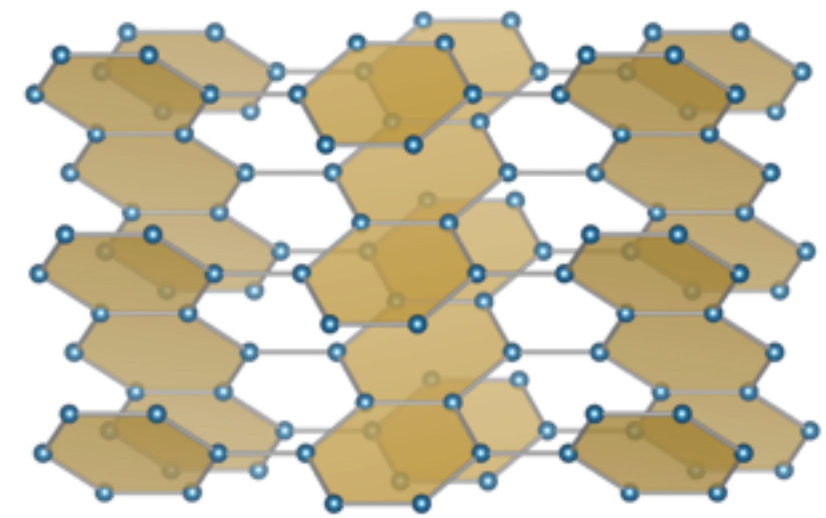

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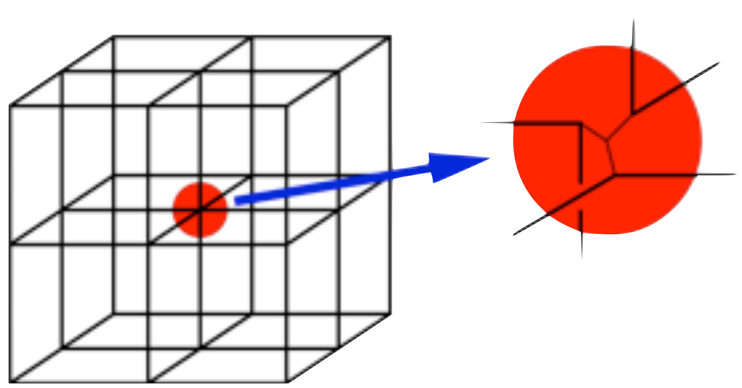

Levin, Wen, PRB 71, 045110 (2005)

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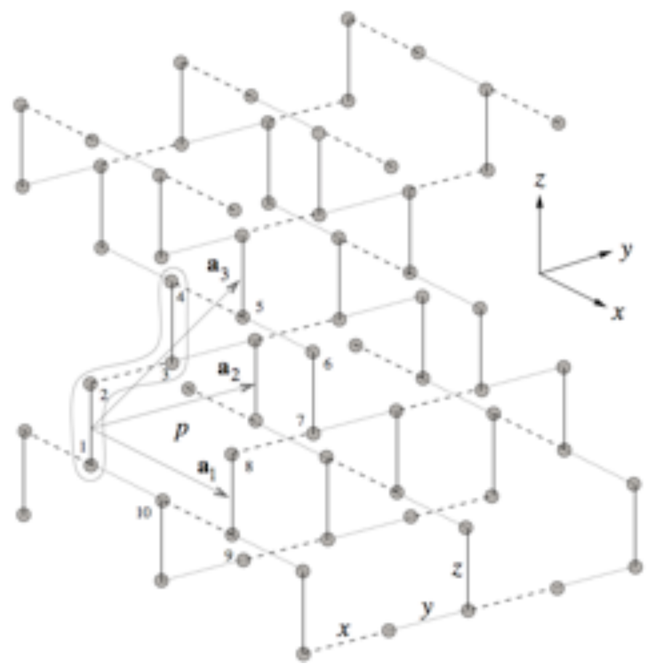

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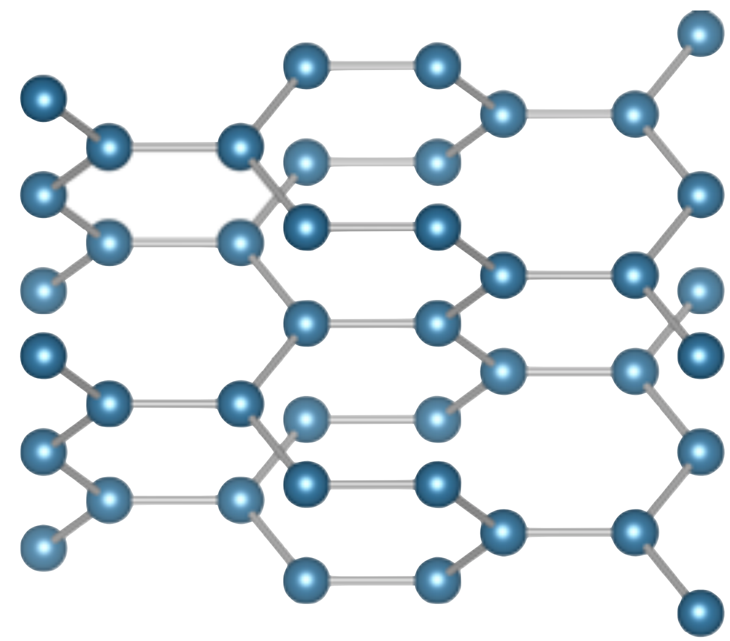

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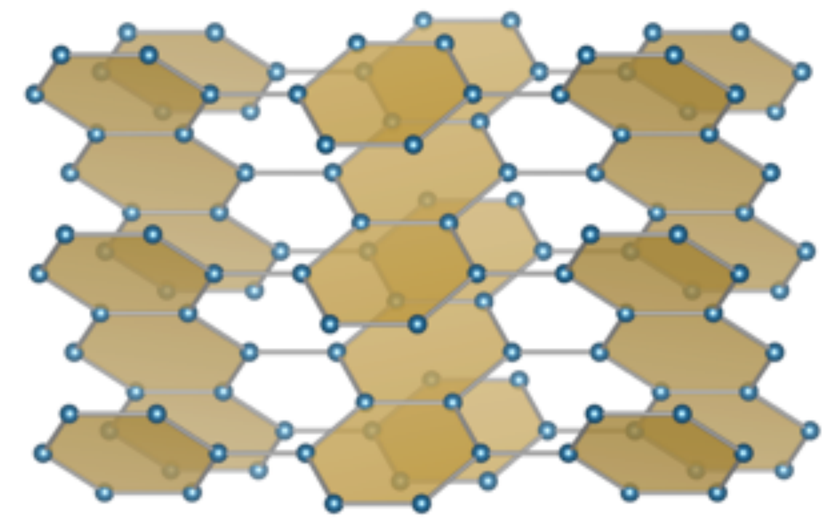
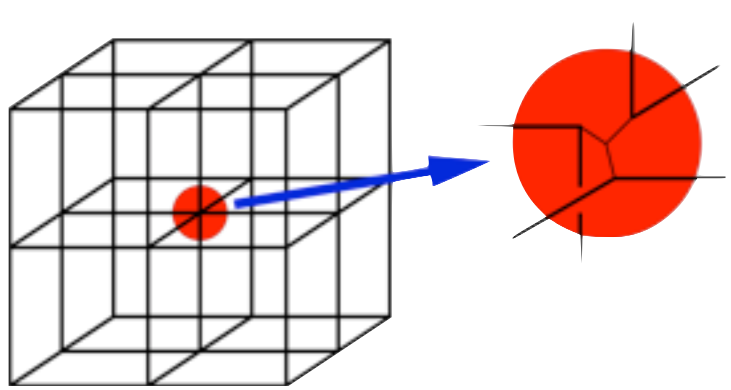
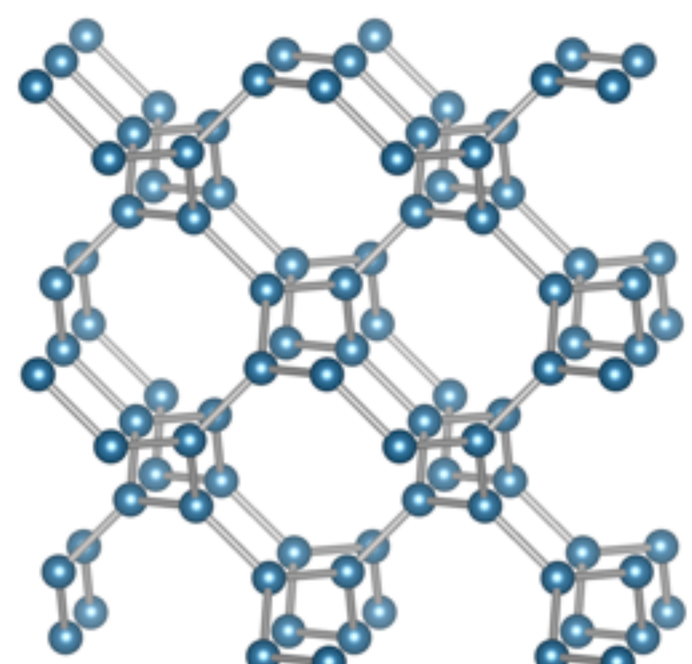


Modic etal. arXiv:1402.3254 (2014)

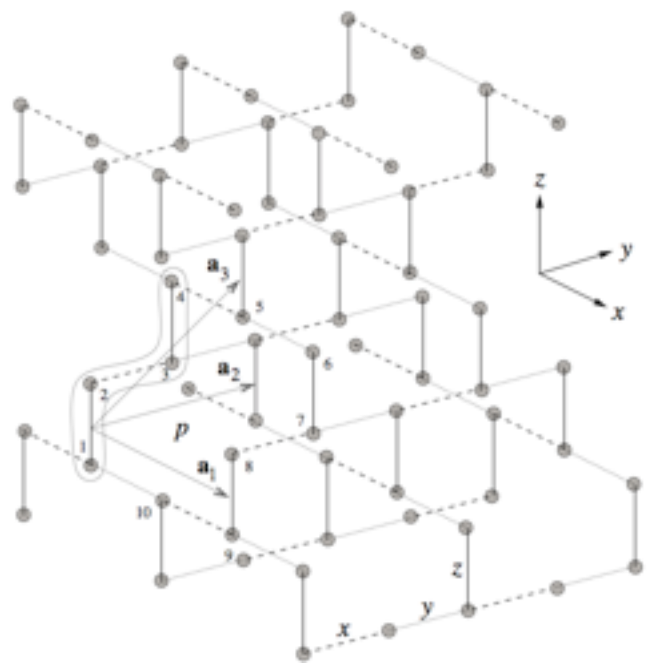


Levin, Wen, PRB 71, 045110 (2005)

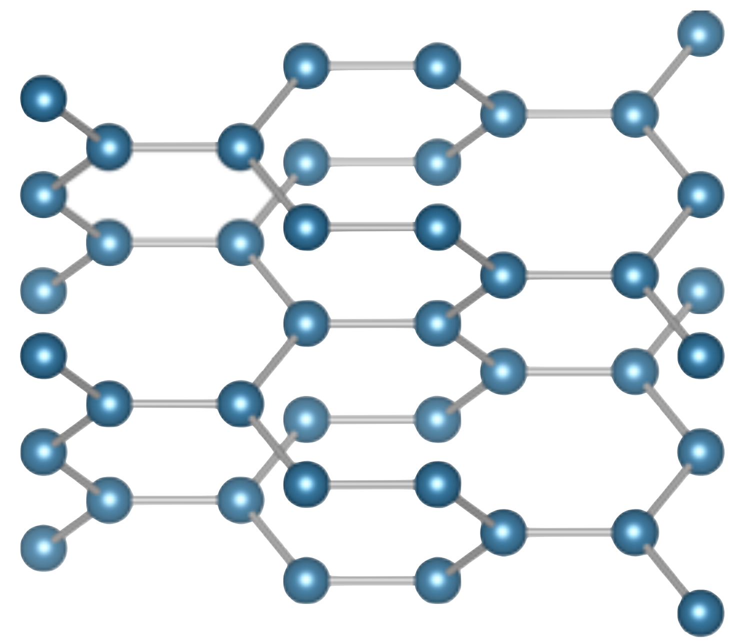


Hermanns, Trebst, PRB 89, 235102 (2014)

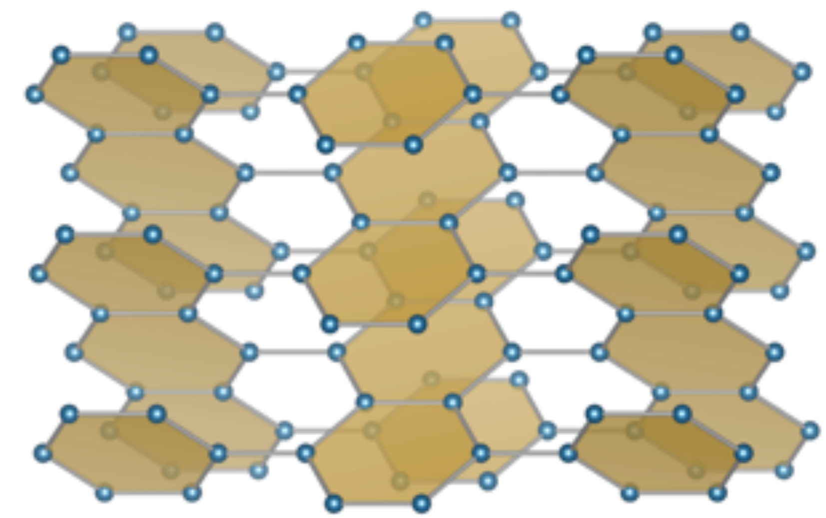
Zoo of 3D tri-coordinated lattices



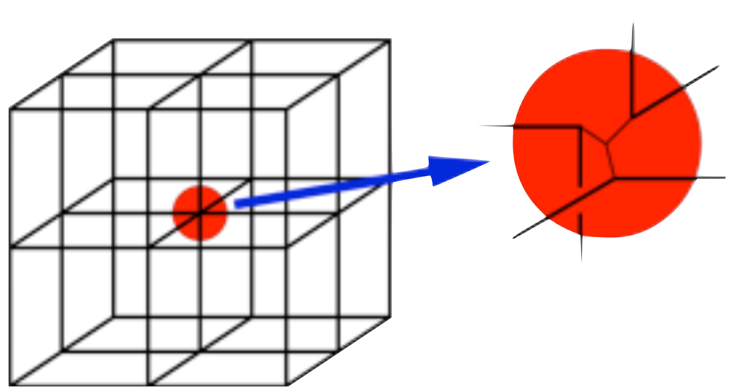
Mandal, Surendran, PRB 79, 024426 (2009)



Takayama etal., arXiv:1403.3296 (2014)



Modic etal. arXiv:1402.3254 (2014)



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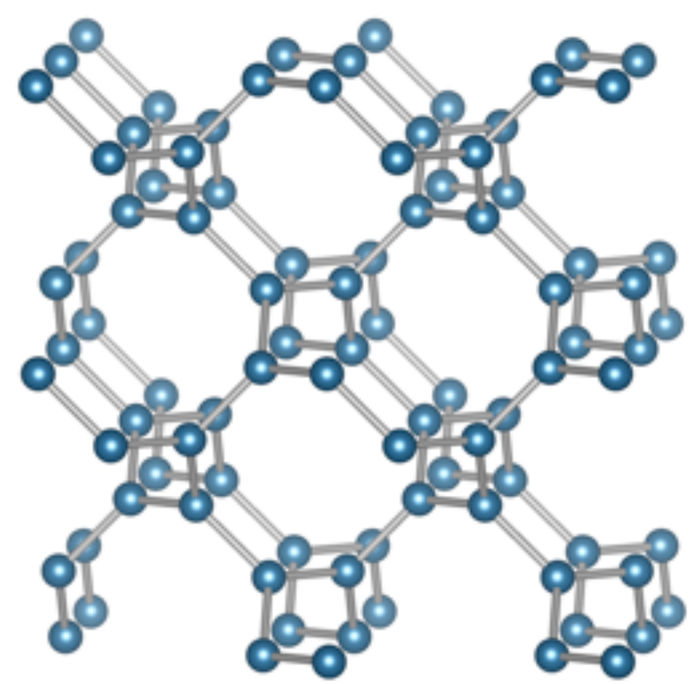

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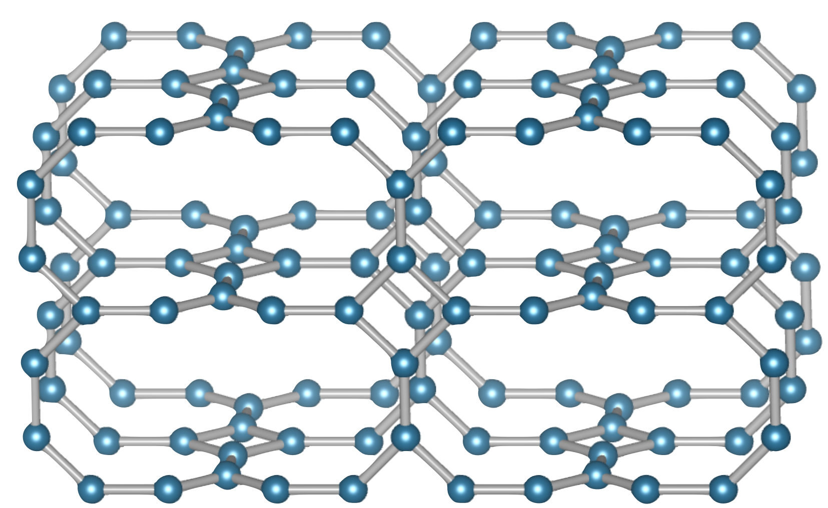
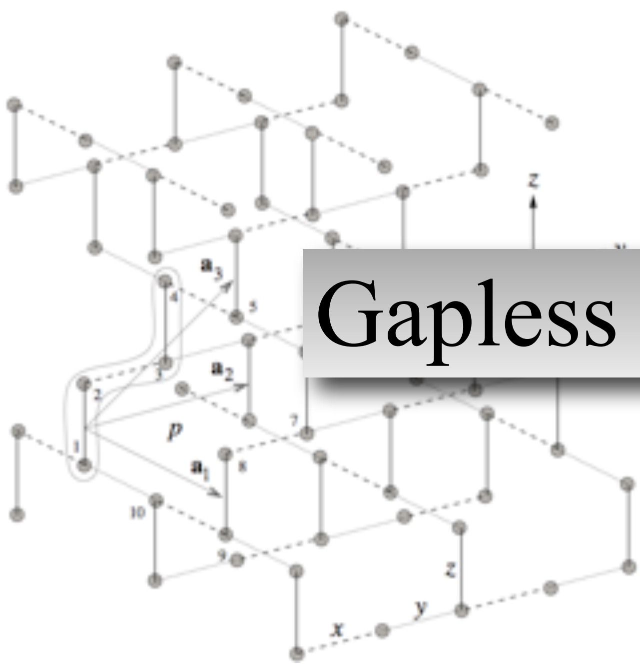
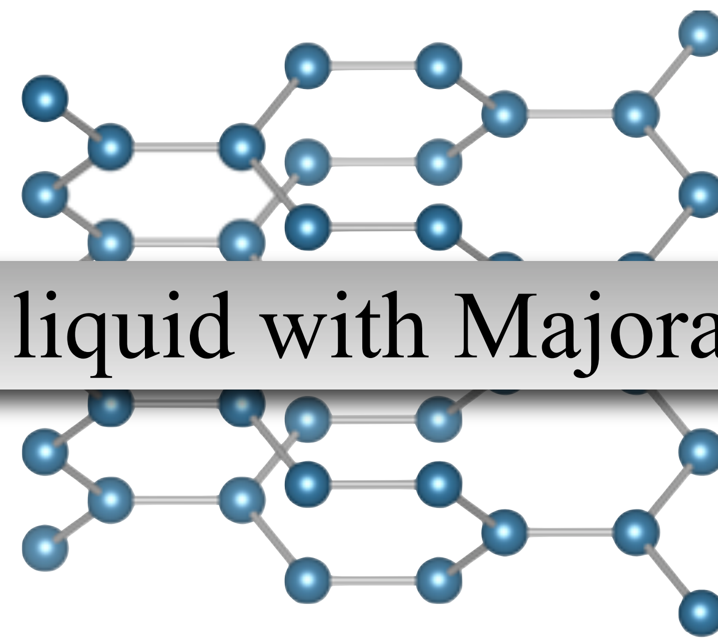
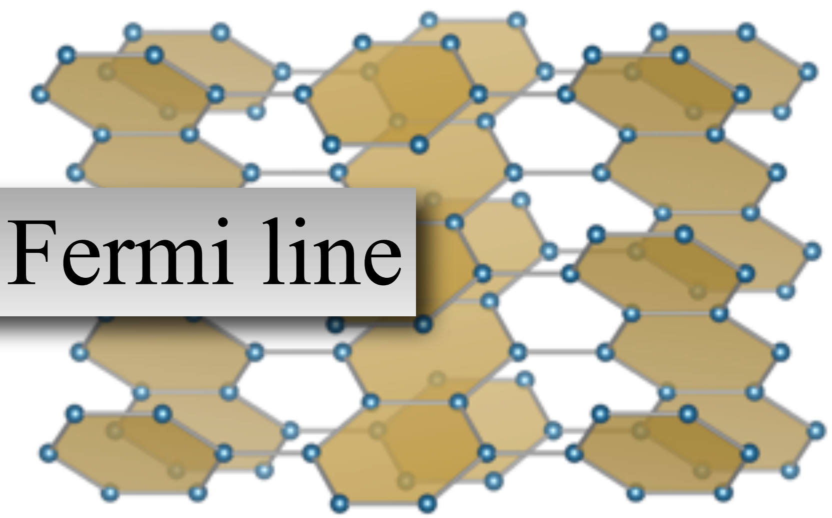


Zoo of 3D tri-coordinated lattices





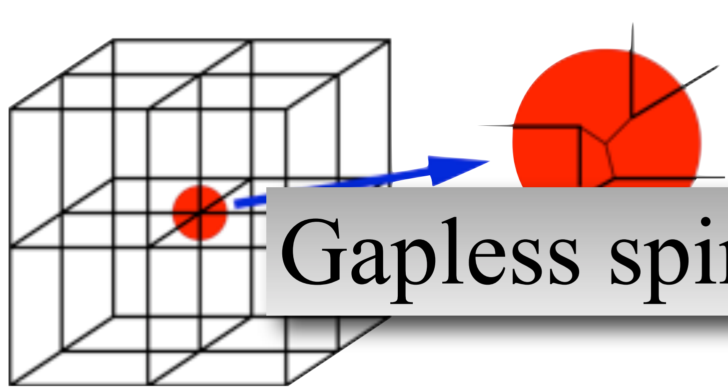


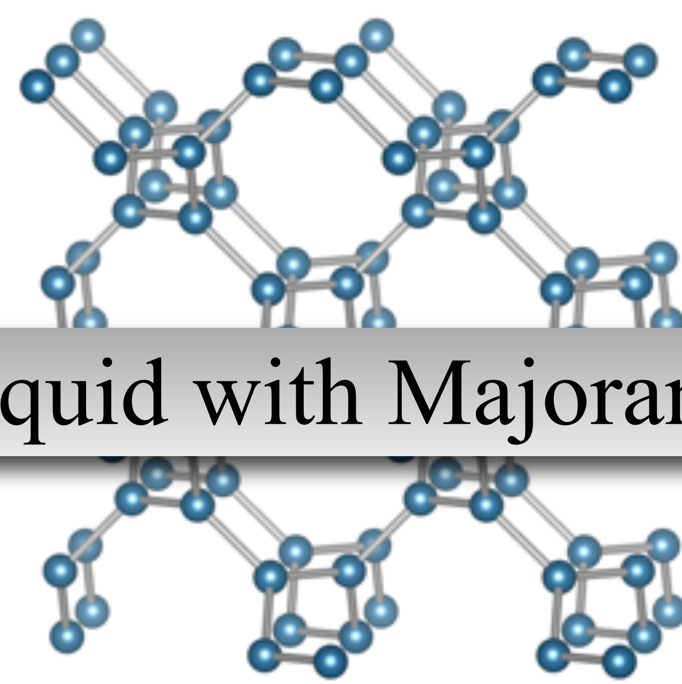
Gapless spin liquid with Majorana Fermi line

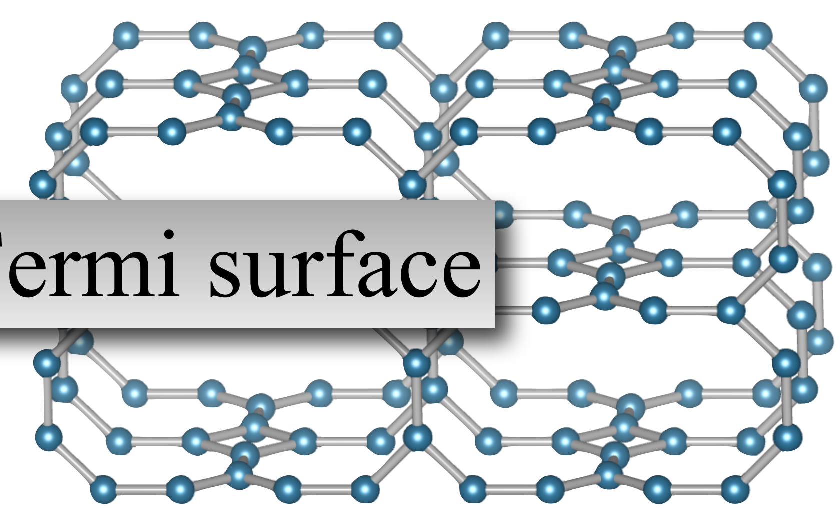
Mandal, Surendran, PRB 79, 024426 (2009)

Takayama etal., arXiv:1403.3296 (2014)

Modic etal. arXiv:1402.3254 (2014)





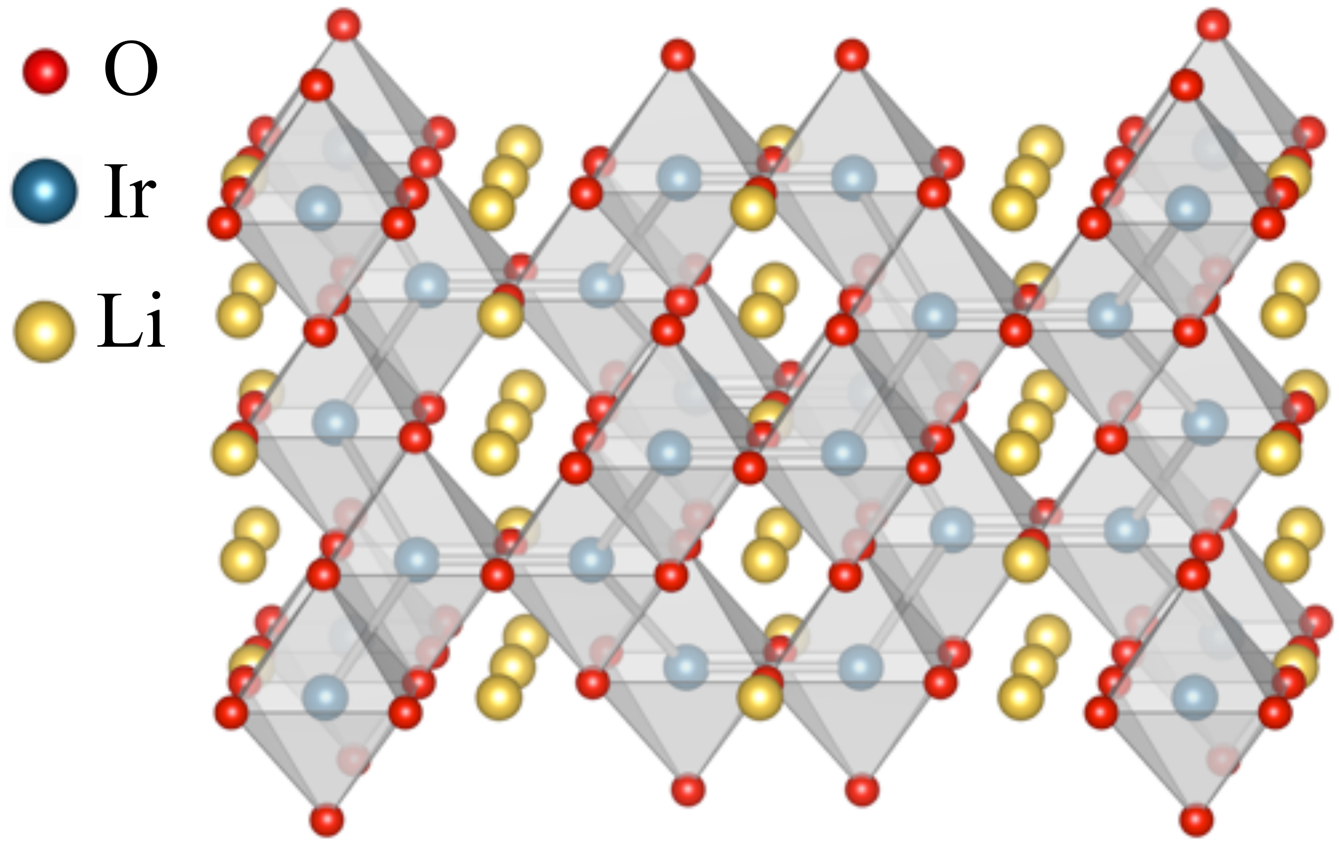


Gapless spin liquid with Majorana Fermi surface

Levin, Wen, PRB 71, 045110 (2005)

Hermanns, Trebst, PRB 89, 235102 (2014)

Hyperhoneycomb material β-Li_2IrO_3



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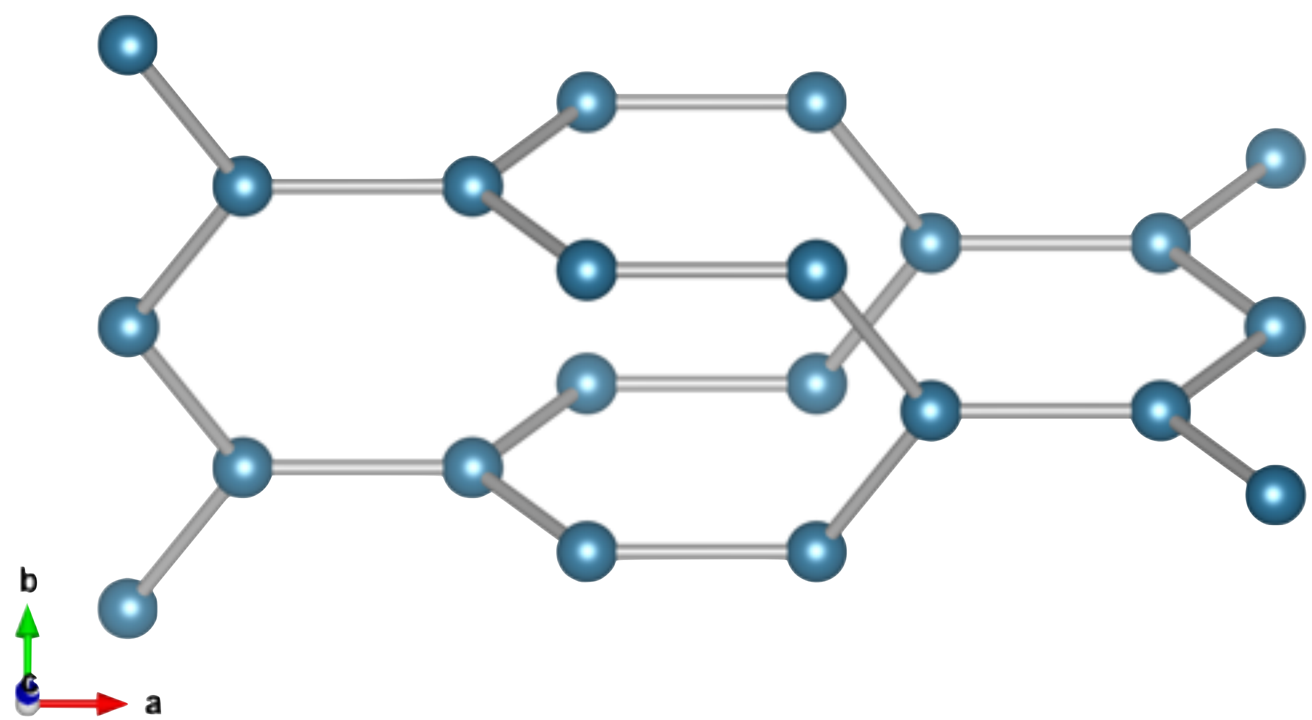

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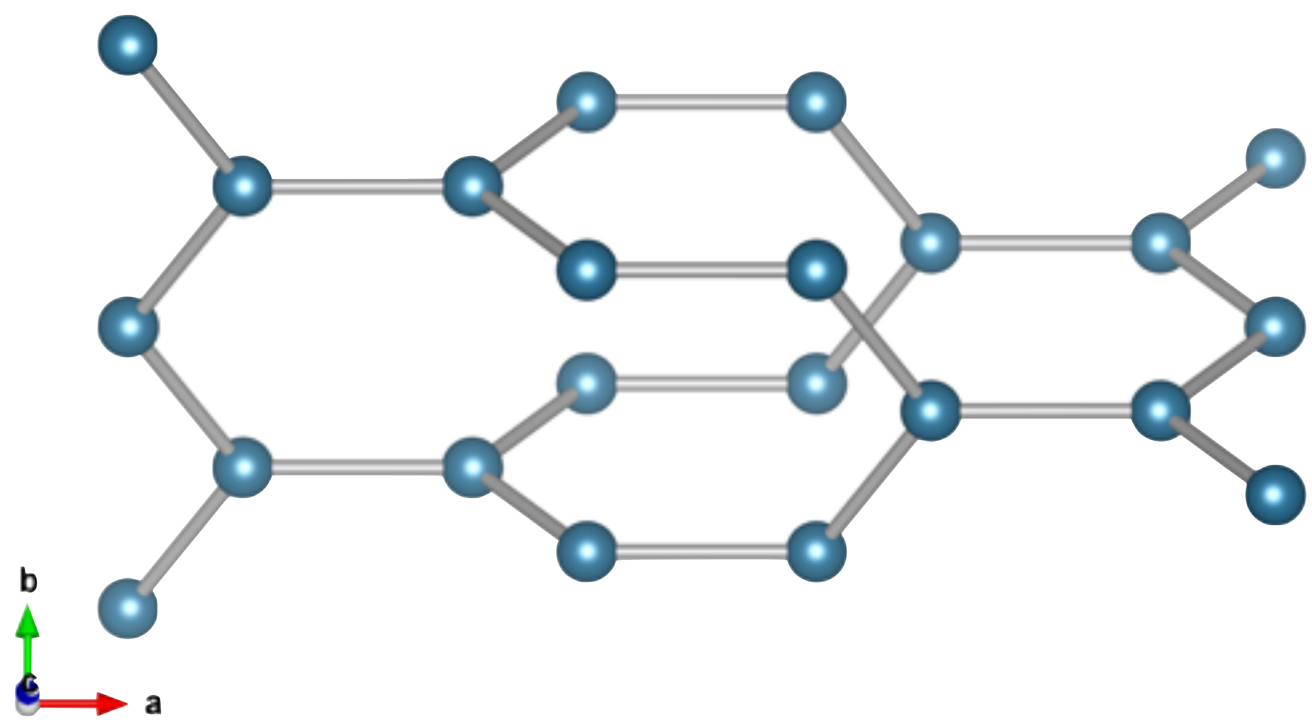
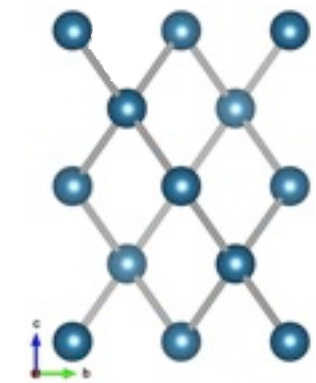
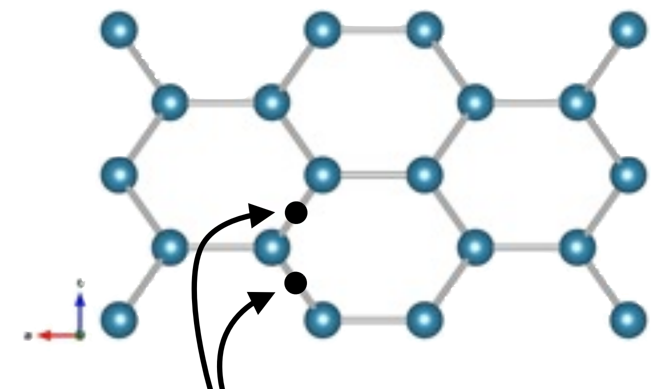




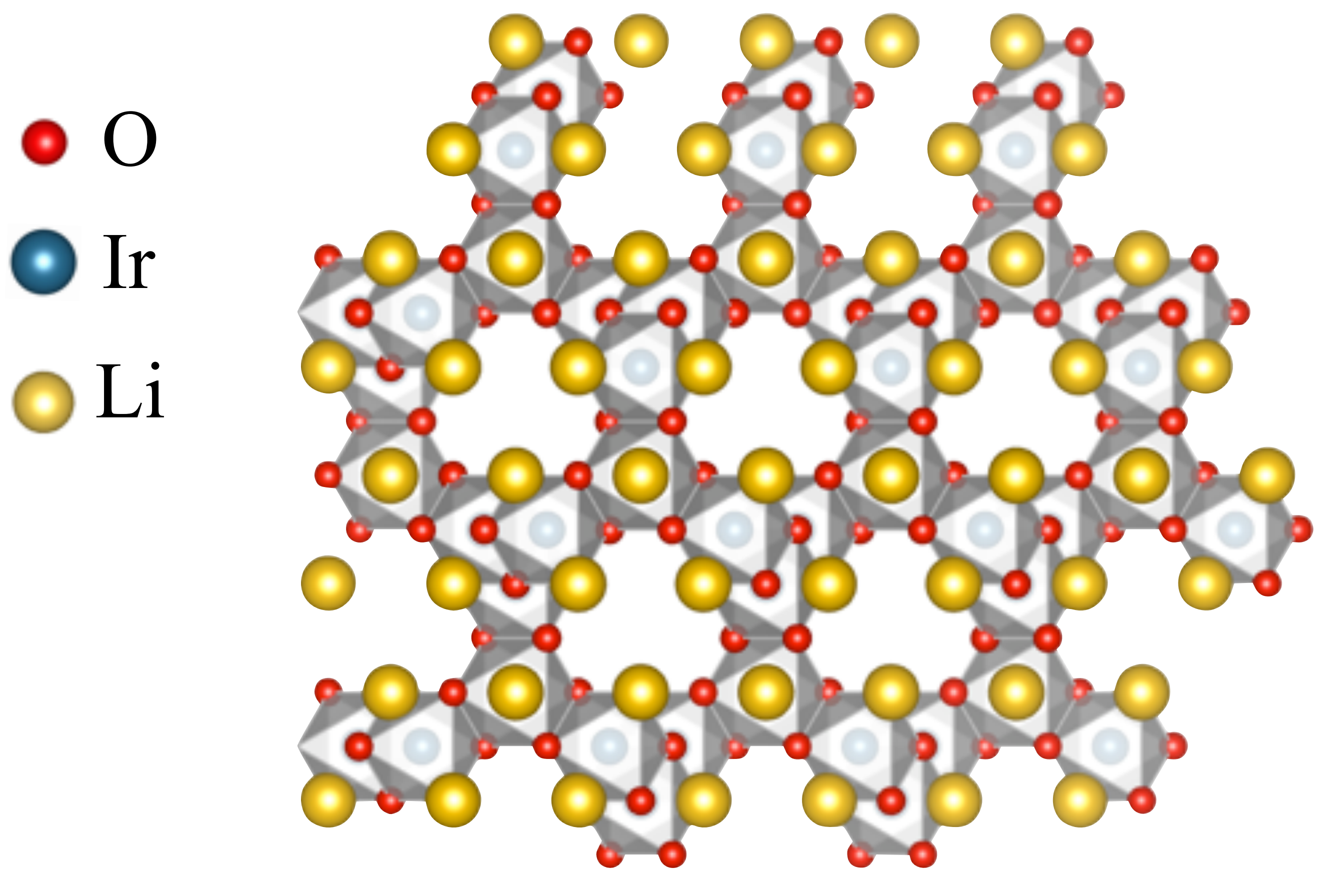
180° rotation



Inversion centers

- tri-coordinated
- inversion symmetric
- preferred direction
- synthesized by - H. Takagi arxiv:1403.3296
  - J. Analytis arxiv:1402.3254

Hyperoctagon material δ-Li_2IrO_3 (?)



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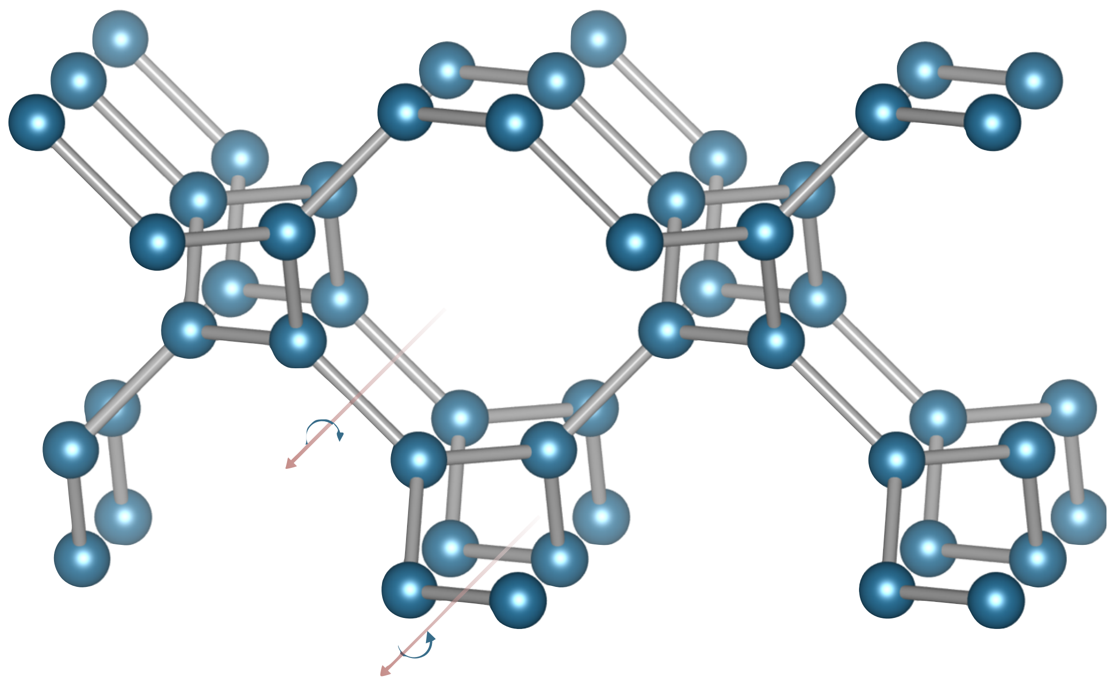

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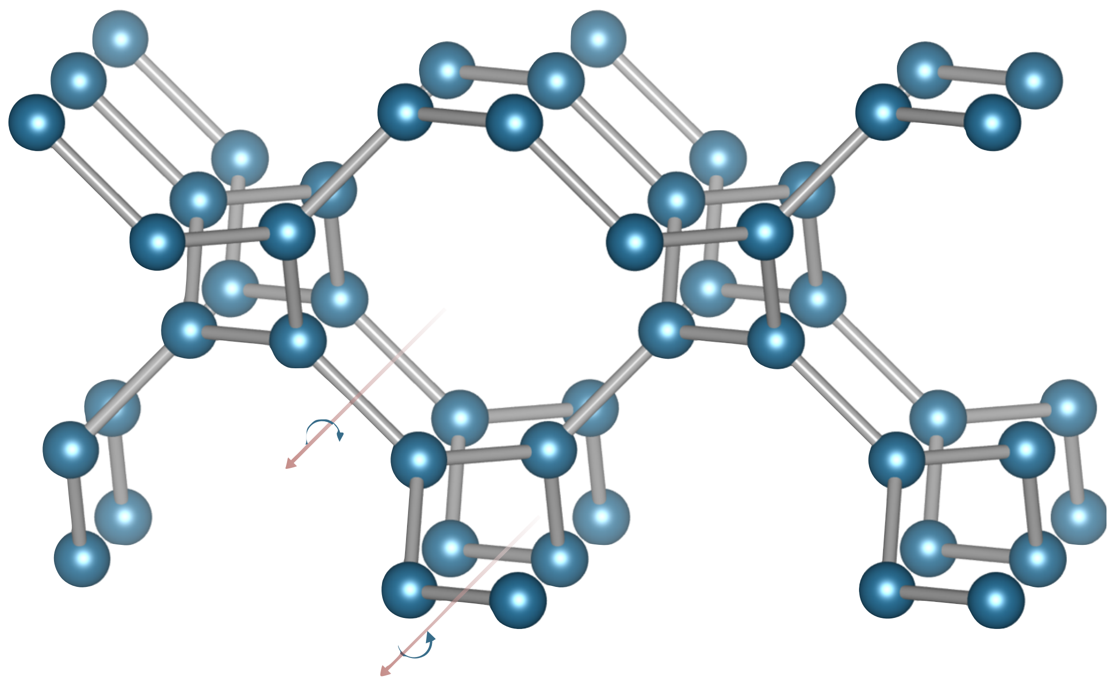
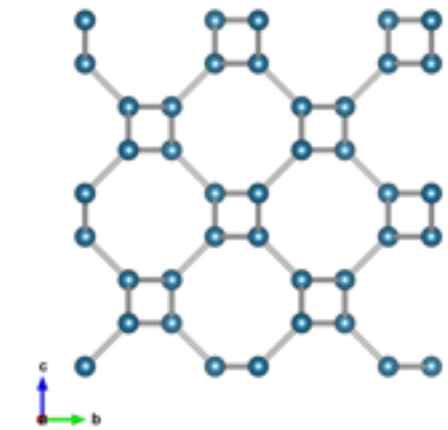
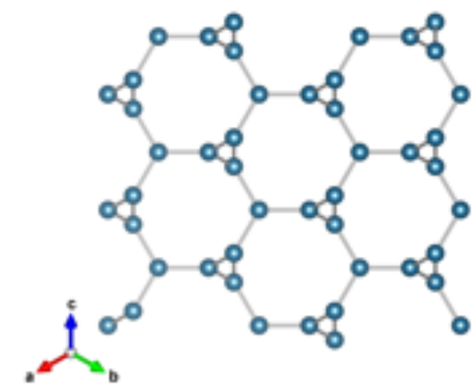


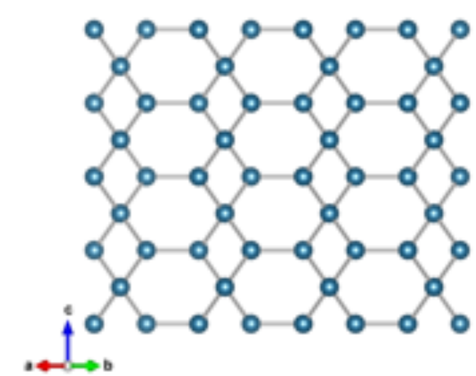
- tri-coordinated
- chiral
- cubic symmetry
- premedial lattice of the hyperkagome
- possible fourth crystalline form of Li_2IrO_3



90° screw-rotation

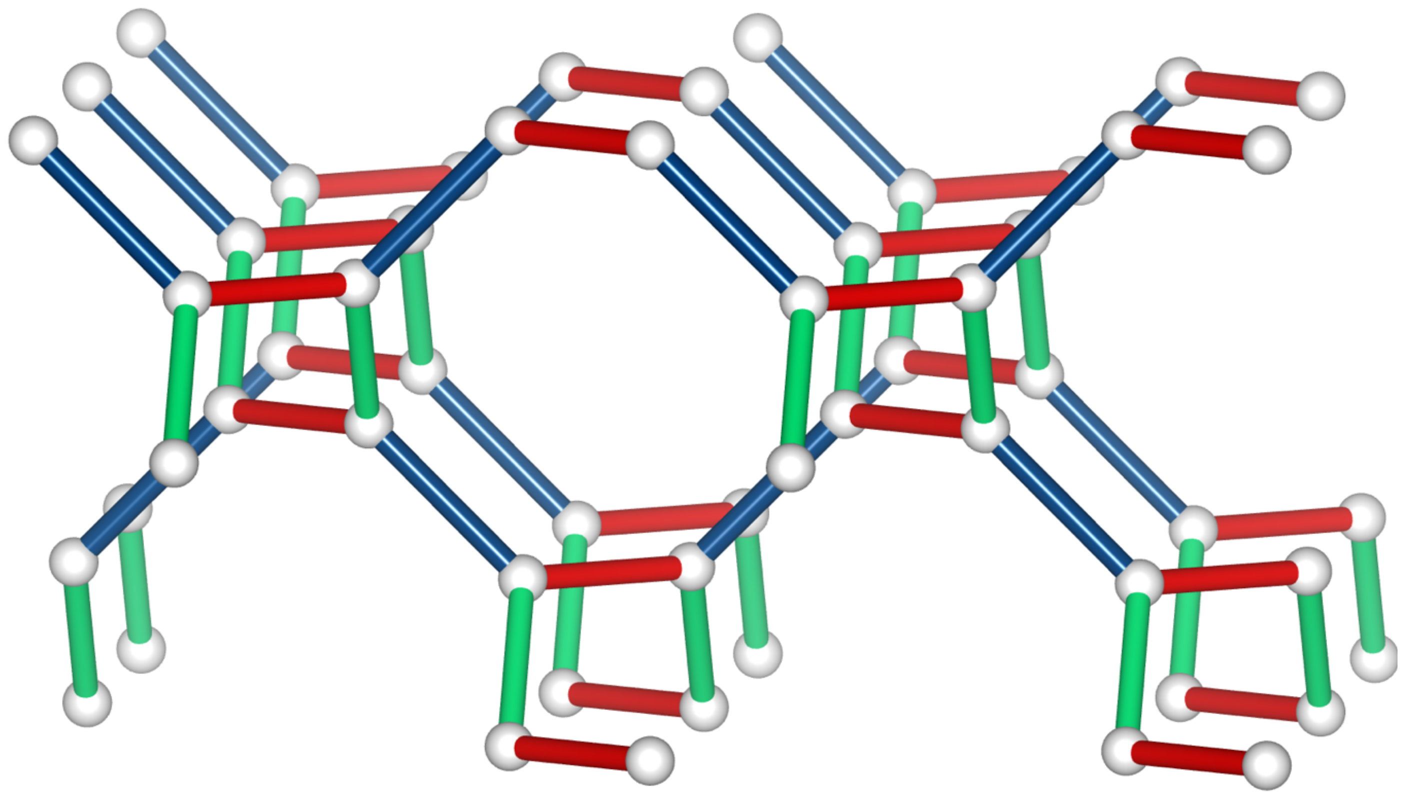


120° rotation



180° rotation

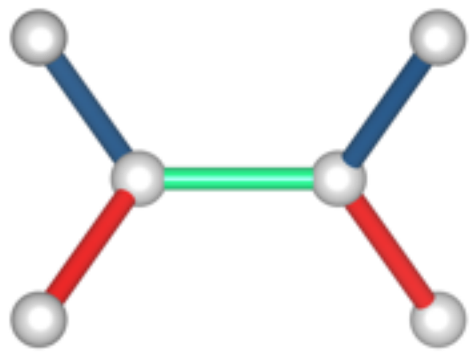
Exchange frustration on the hyperoctagon lattice



$$H = -\sum_{\text{x-bonds}} J_x \sigma_j^x \sigma_k^x - \sum_{\text{y-bonds}} J_y \sigma_j^y \sigma_k^y - \sum_{\text{z-bonds}} J_z \sigma_j^z \sigma_k^z$$

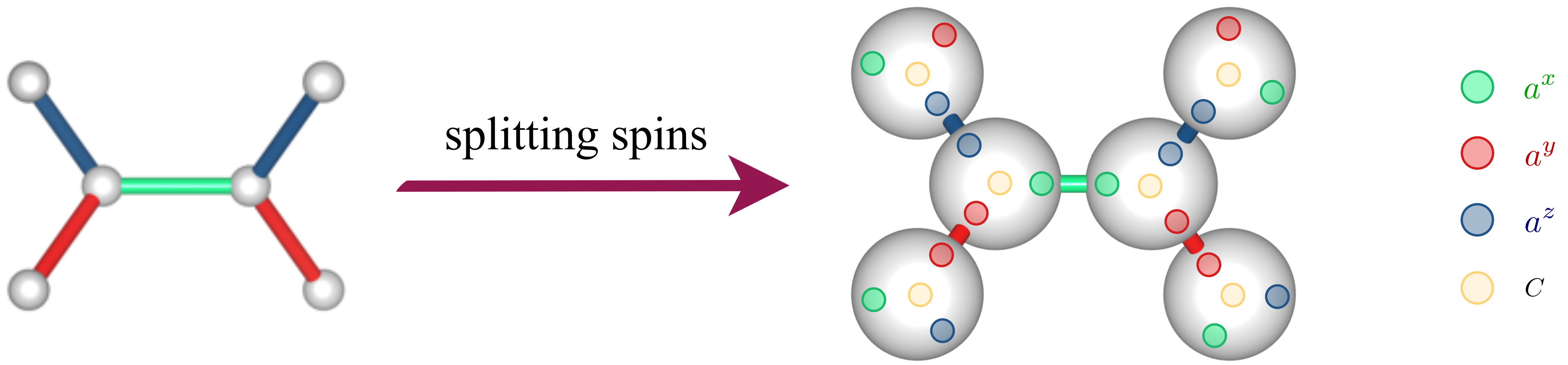
3D generalization of Kitaev's honeycomb model

Spin fractionalization and Majorana fermions



A. Kitaev, Annals of Physics **321**, 2 (2006)

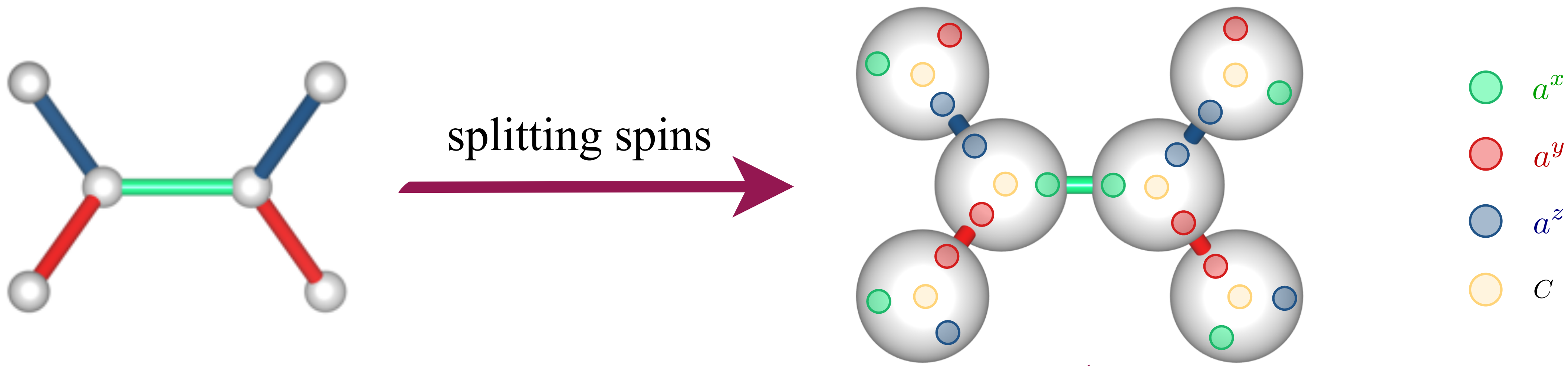
Spin fractionalization and Majorana fermions

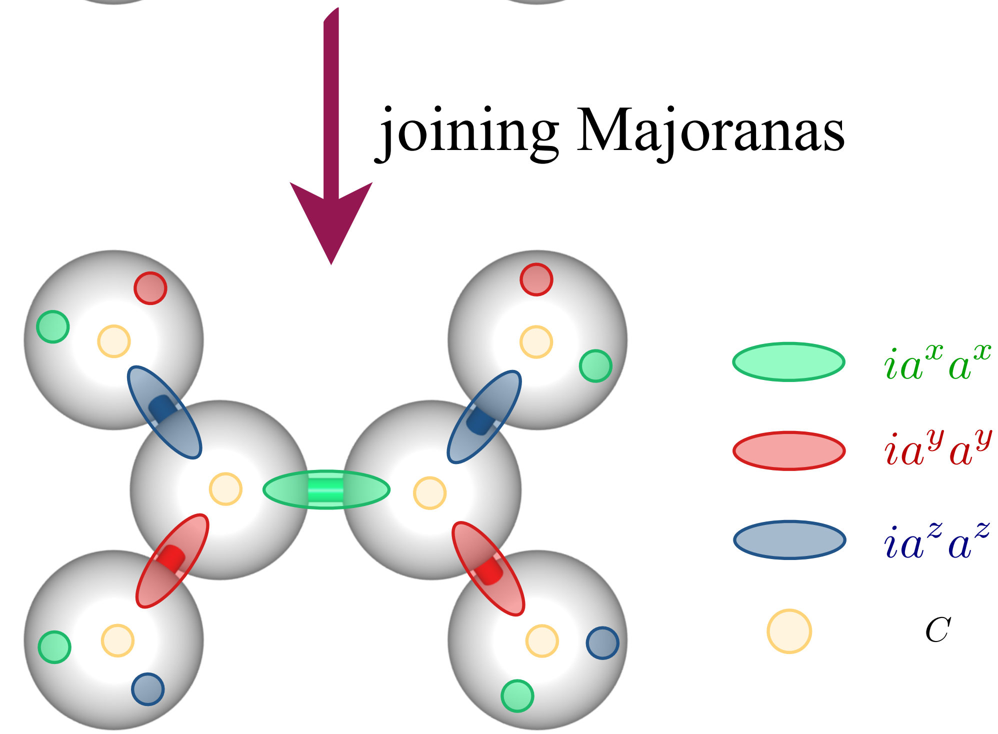


- Represent spins in terms of four **Majorana fermions** $\sigma^\alpha = i a^\alpha c$

A. Kitaev, Annals of Physics **321**, 2 (2006)

Spin fractionalization and Majorana fermions





- Represent spins in terms of four **Majorana fermions** $\sigma^\alpha = ia^\alpha c$

- Bond operators $\hat{u}_{jk} = ia_j^\alpha a_k^\alpha$ realize an emergent **Z_2 gauge field**

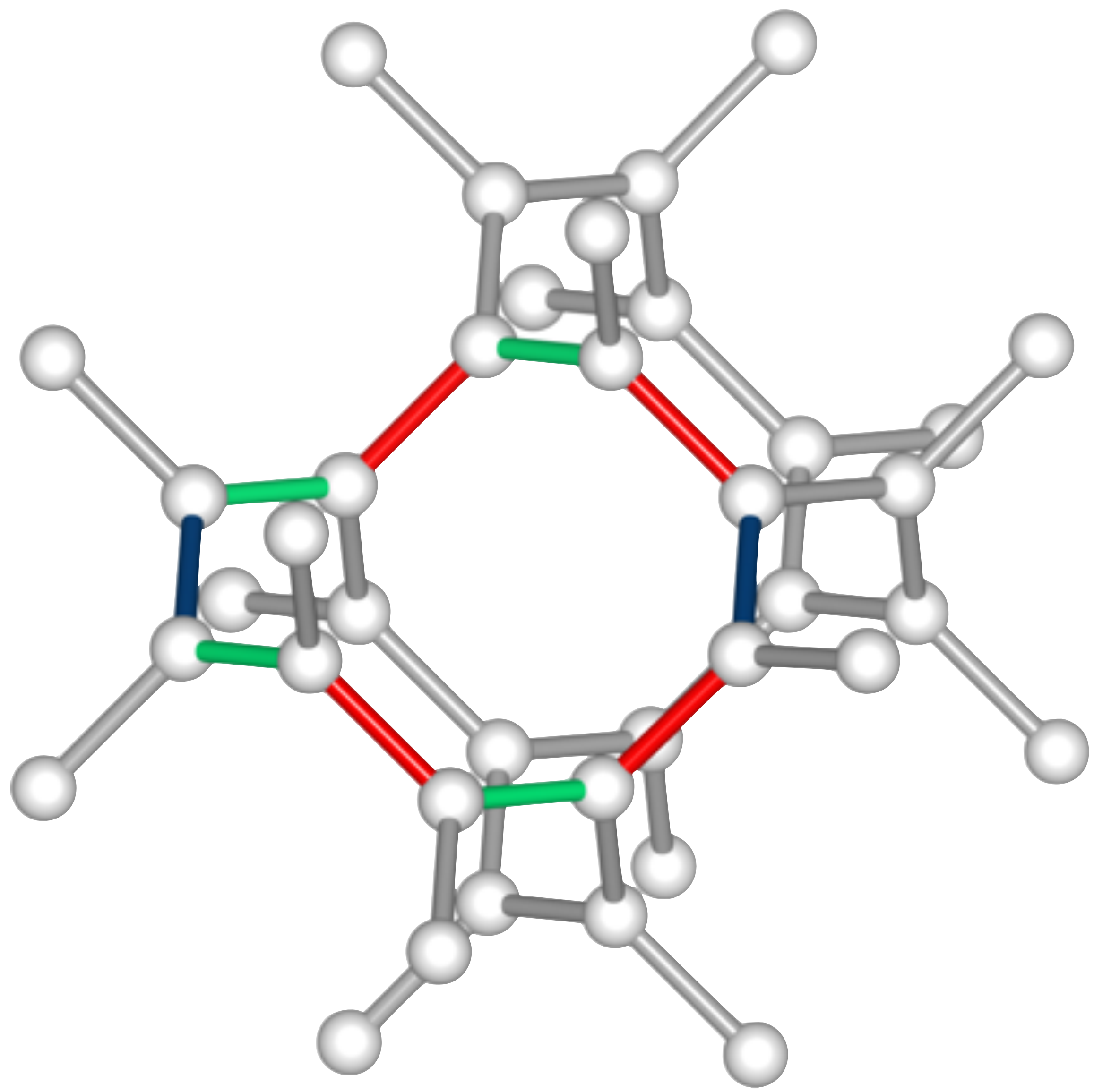
A. Kitaev, Annals of Physics **321**, 2 (2006)

Physics of the Z_2 gauge field

Z_2 gauge field is **static** due to presence of additional conserved quantities

Six fundamental **loop operators** (per unit cell) $W_l = \prod_{\langle\alpha,\beta\rangle\in l} \sigma_\alpha^{\gamma_{\alpha\beta}} \sigma_\beta^{\gamma_{\alpha\beta}}$

conserved quantities



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↓

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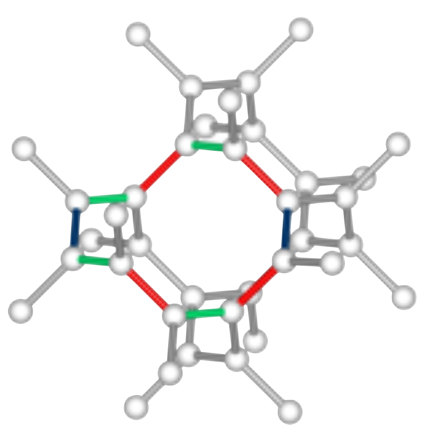

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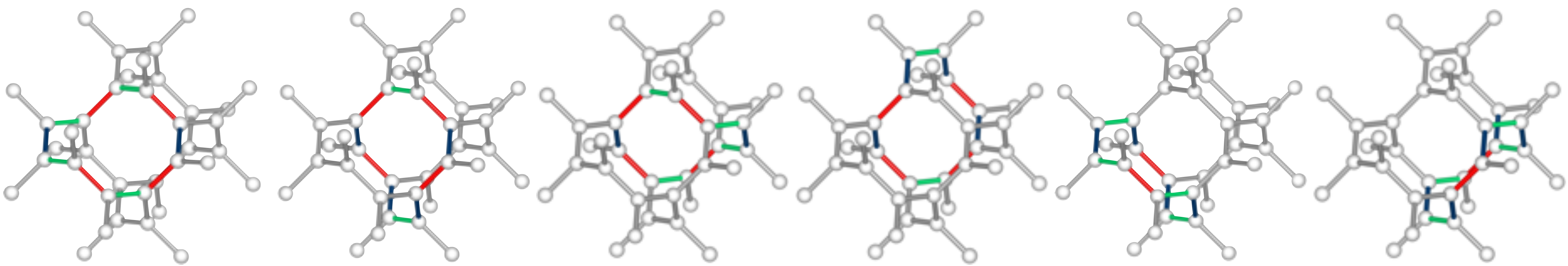

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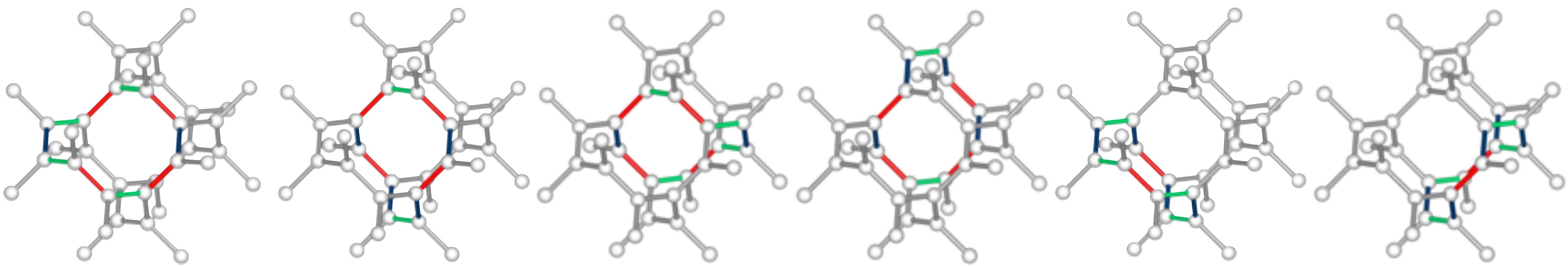
↓

conserved quantities



loop operators define closed Z_2 flux loops – **no monopoles**

Physics of the Z_2 gauge field

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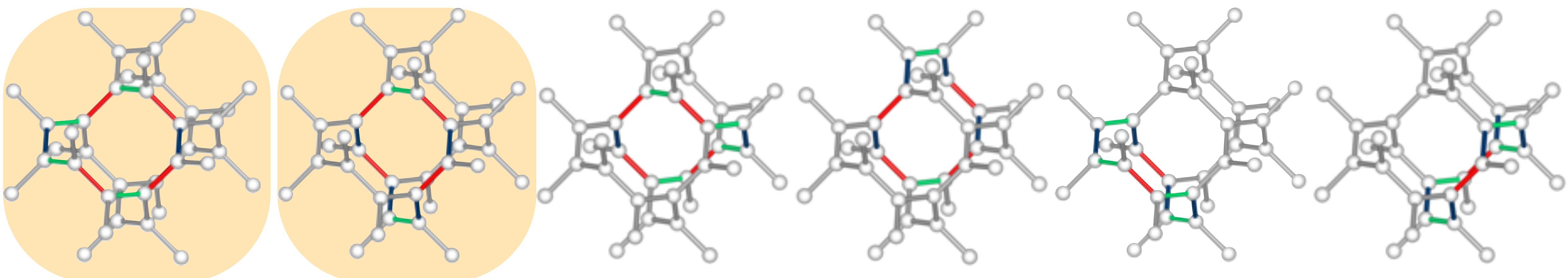
conserved quantities



loop operators define closed Z_2 flux loops – **no monopoles**

Physics of the Z_2 gauge field

Z_2 gauge field is **static** due to presence of additional conserved quantities

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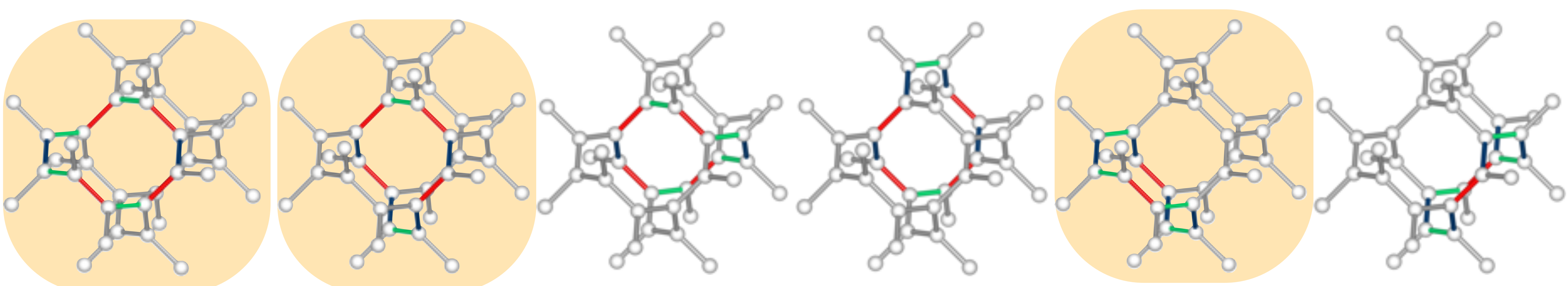
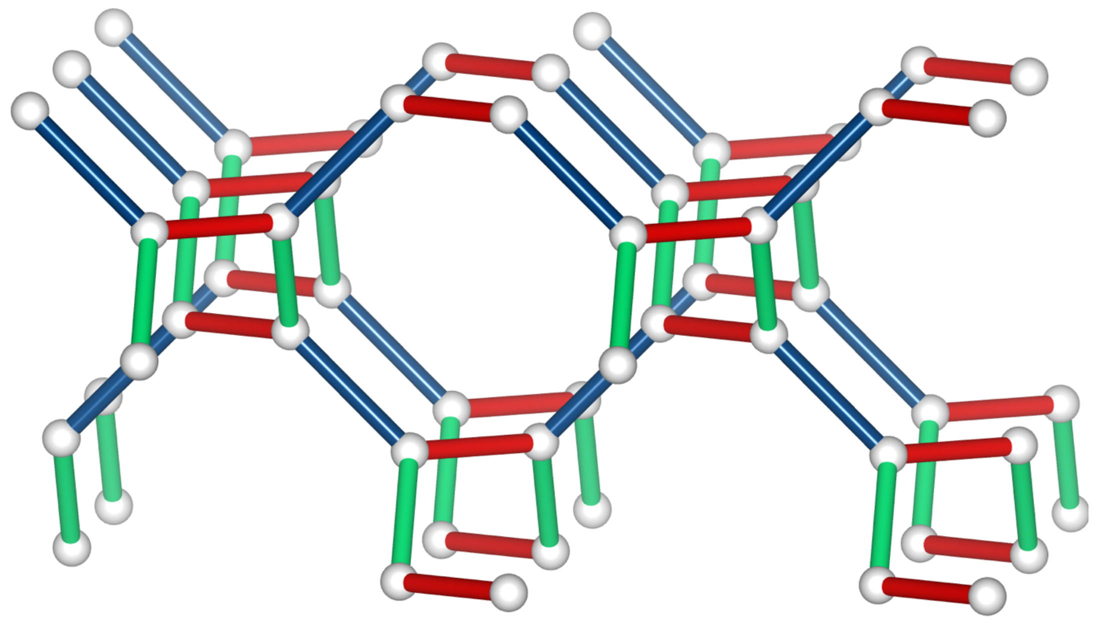


loop operators define closed Z_2 flux loops – **no monopoles**

only two loop operators per unit cell are linearly independent

Exchange frustration on the hyperoctagon model



$$H = -\sum_{\text{x-bonds}} J_x \sigma_j^x \sigma_k^x - \sum_{\text{y-bonds}} J_y \sigma_j^y \sigma_k^y - \sum_{\text{z-bonds}} J_z \sigma_j^z \sigma_k^z$$

Hilbert space split into two separate sectors: $2^N = 2^{N/2} \times 2^{N/2}$

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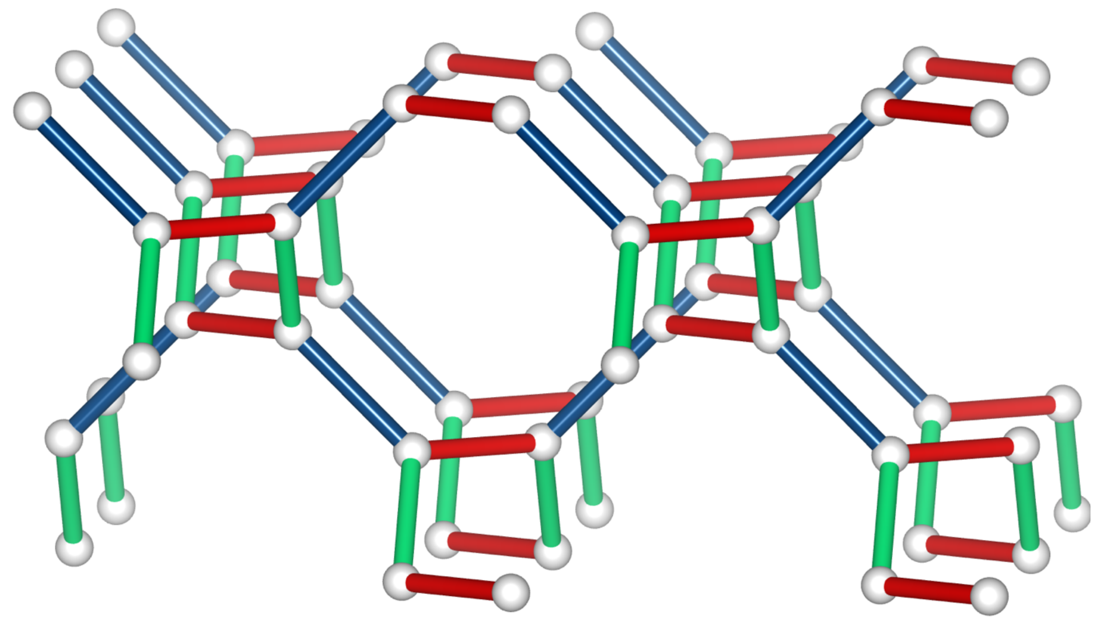

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Majorana fermions c_j
"**spinons**"

flux loops "**visons**"
(static and gapped)

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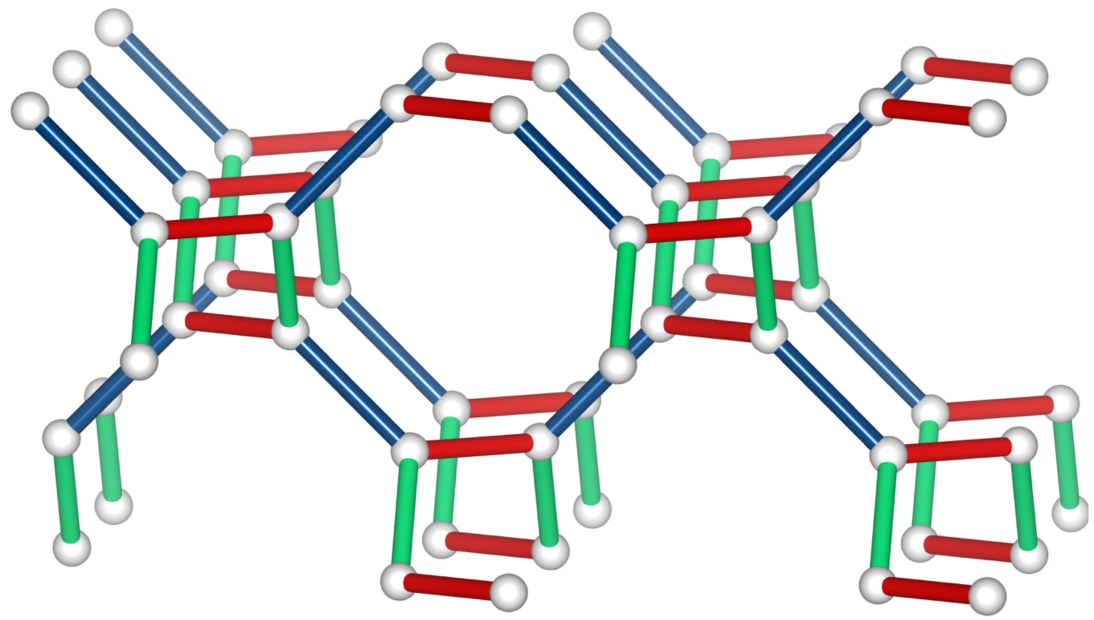

$$H = i \sum_{\gamma-\text{bond}} J_\gamma c_j c_k$$

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"**spinons**"

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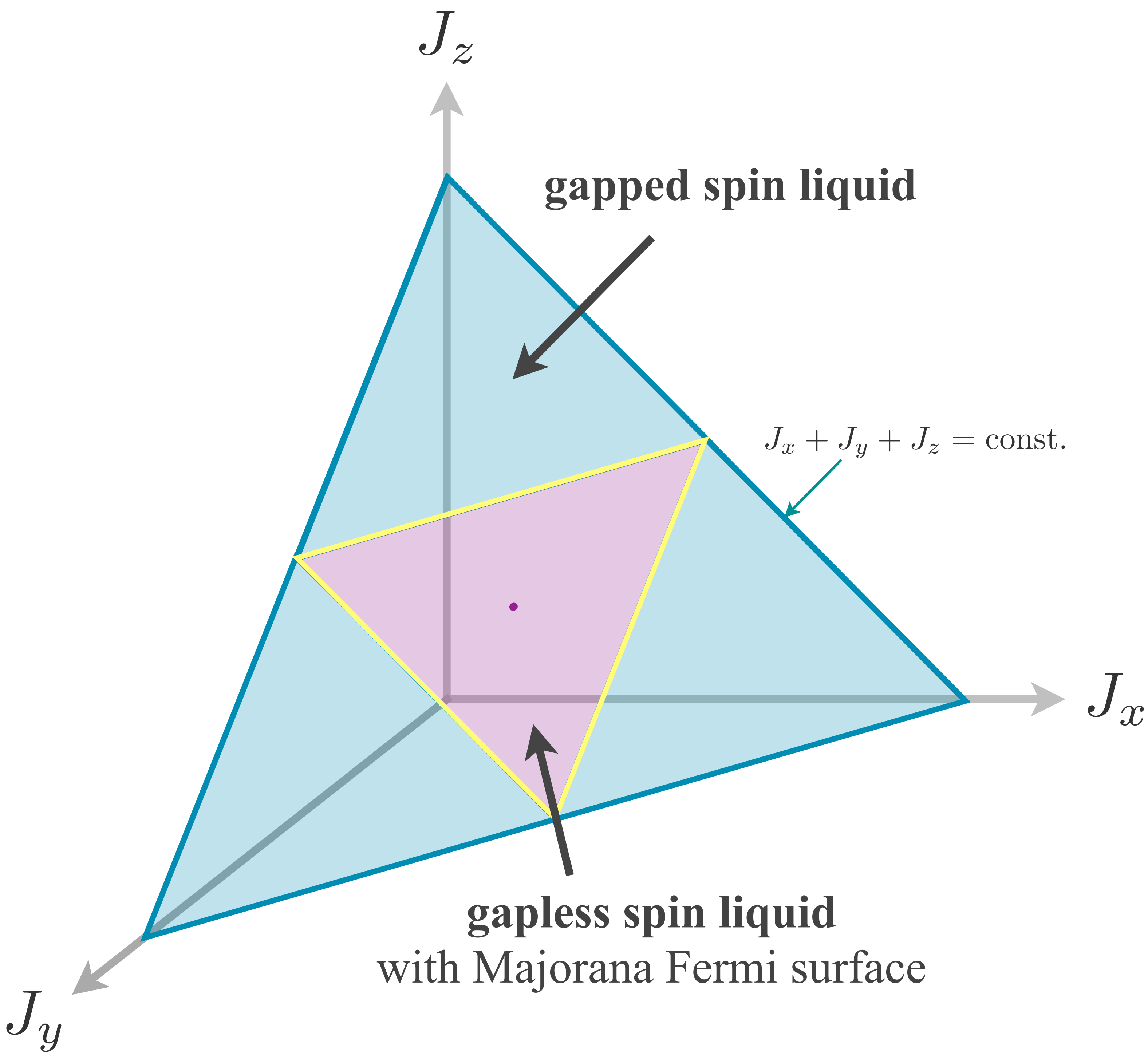
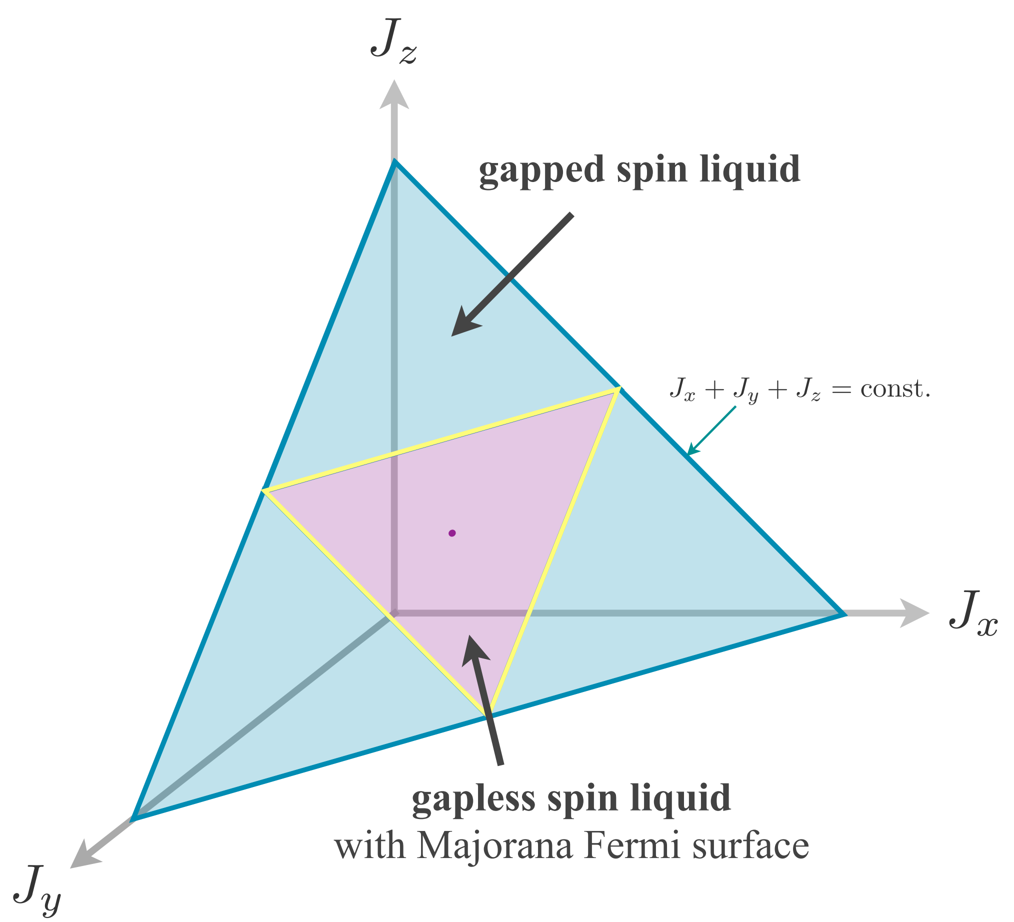
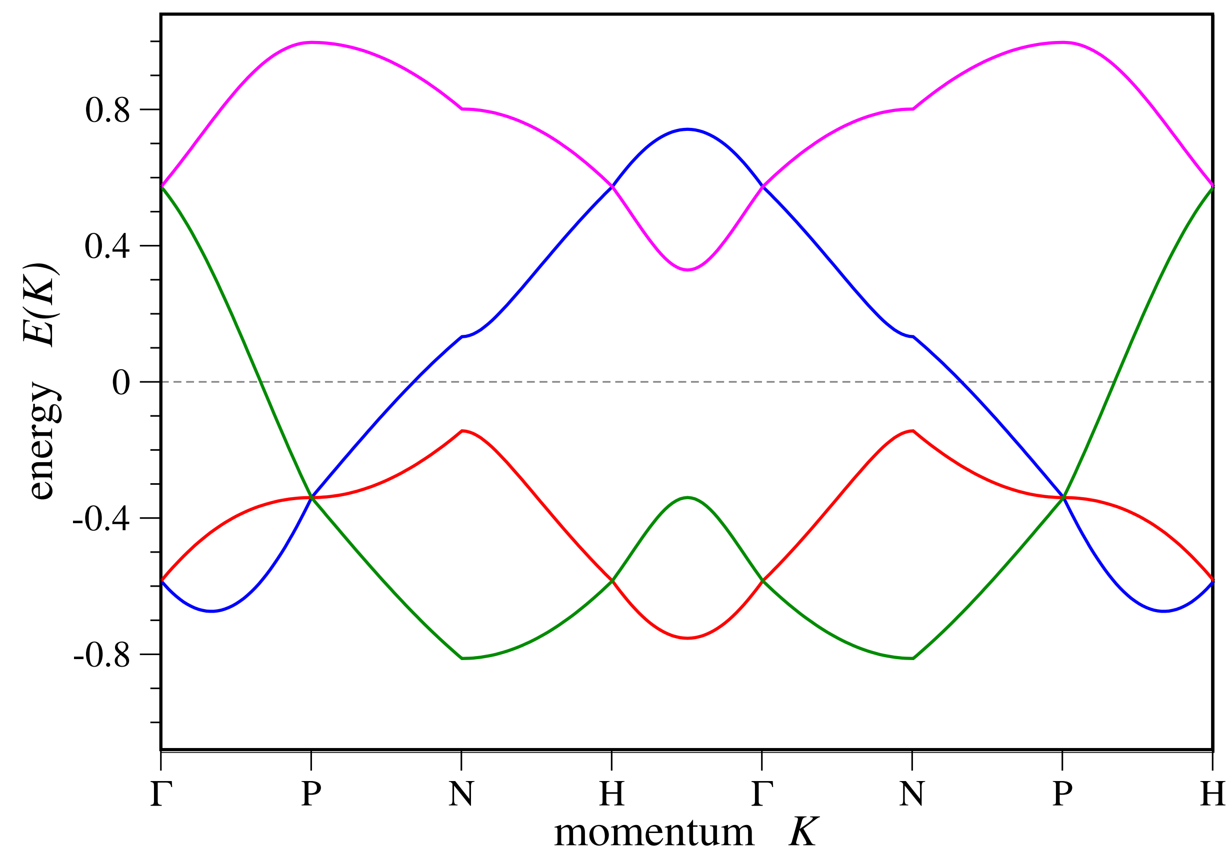
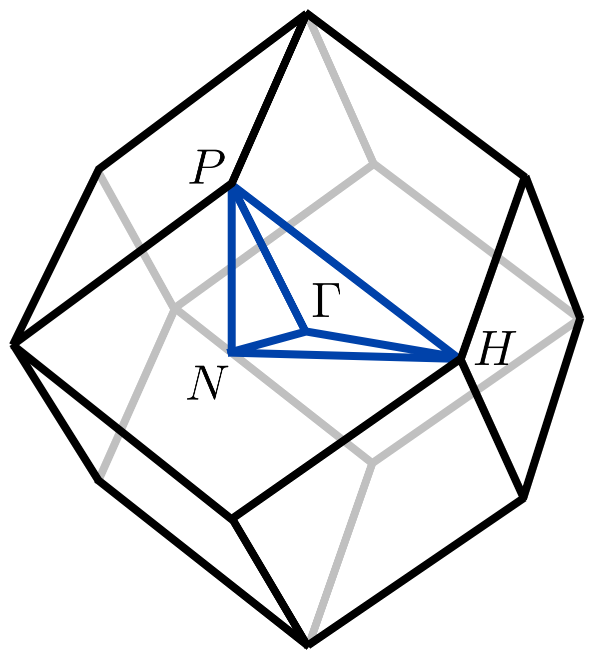
The phase diagram



Majorana Fermi surface







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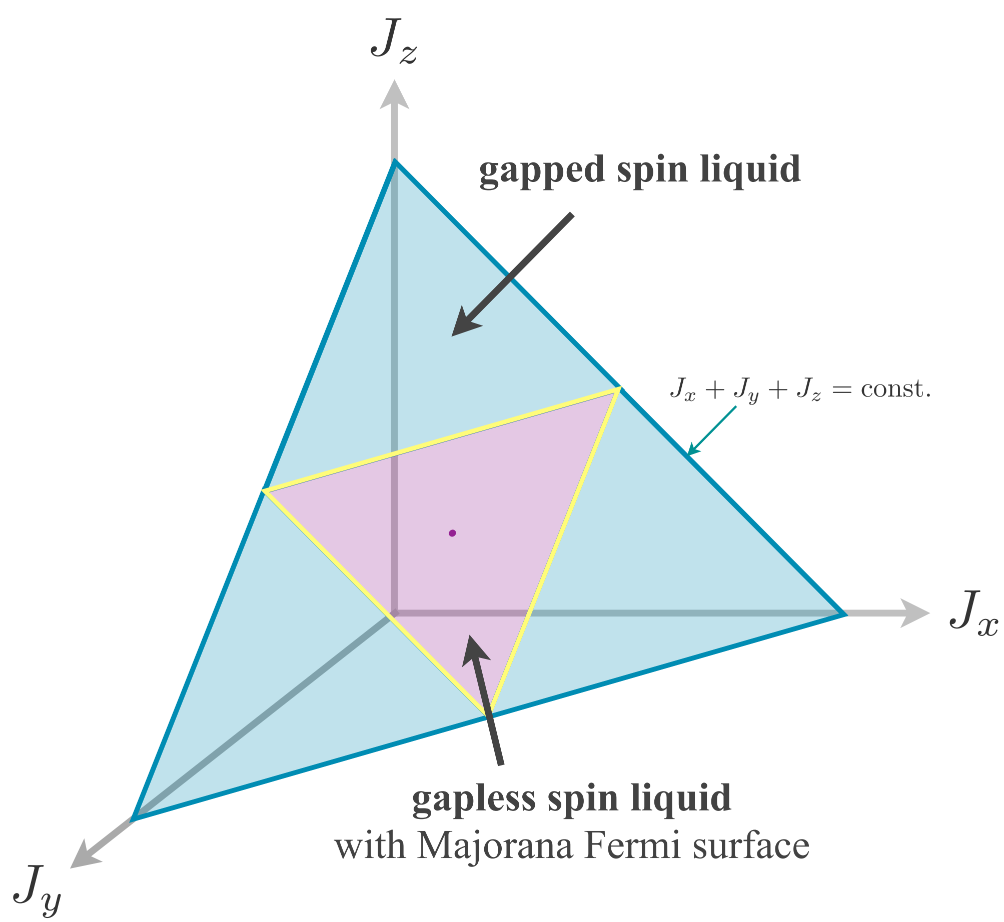
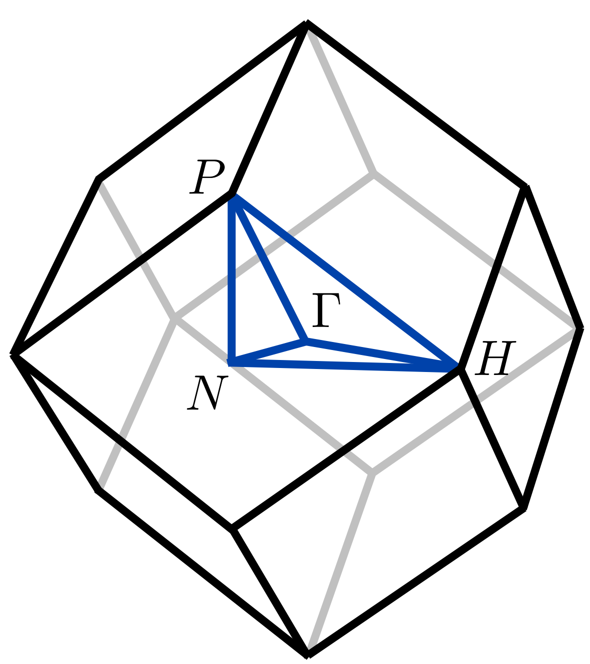
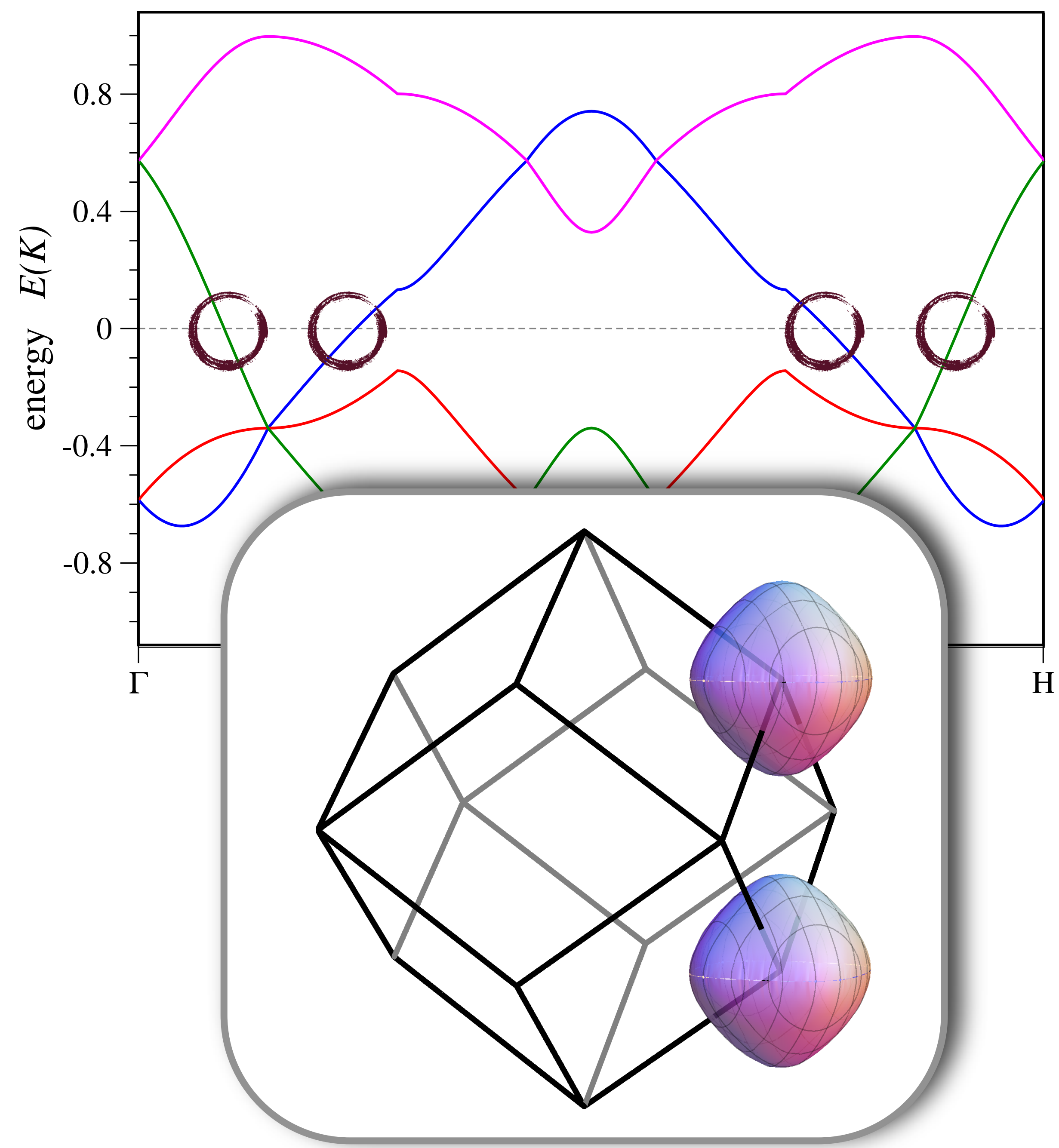
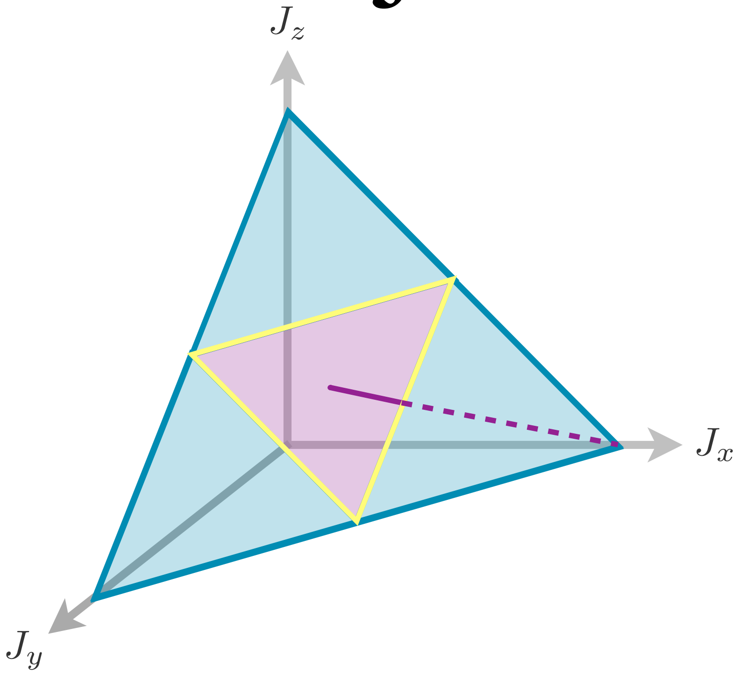
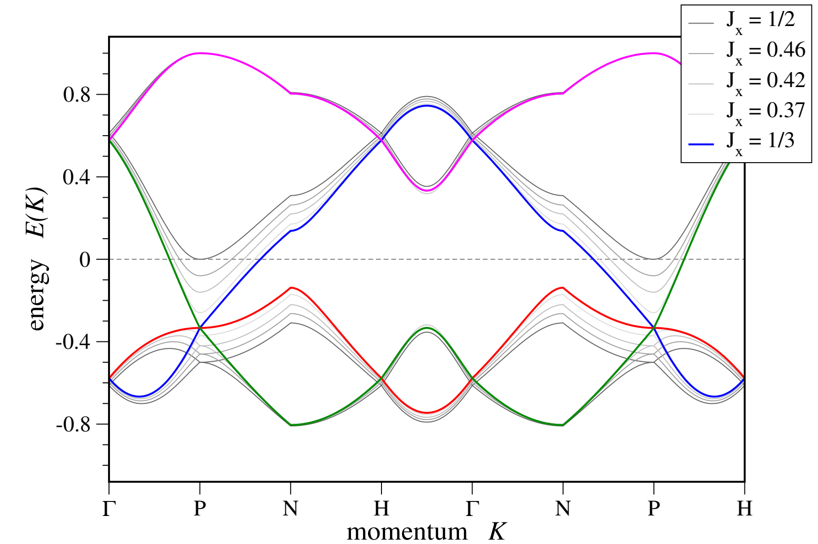




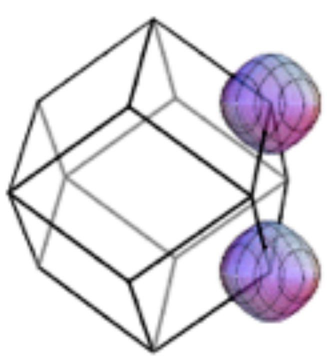


Majorana Fermi surface in gapless region

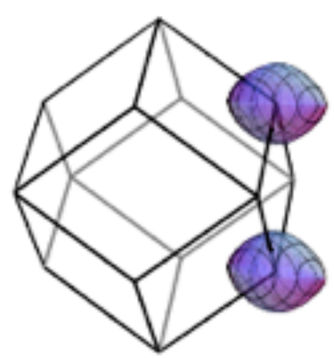




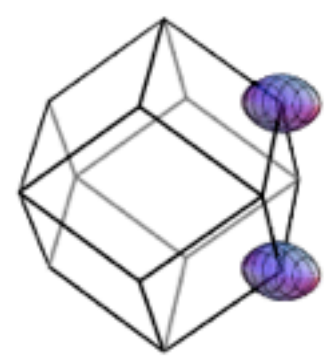
$J_x = 0.37$



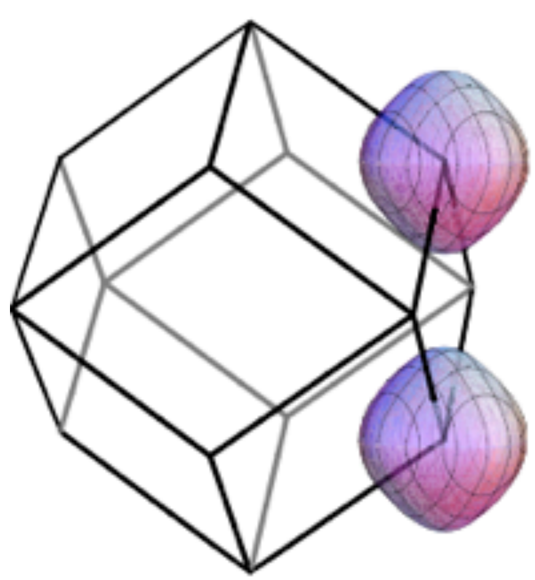
$J_x = 0.42$



$J_x = 0.46$

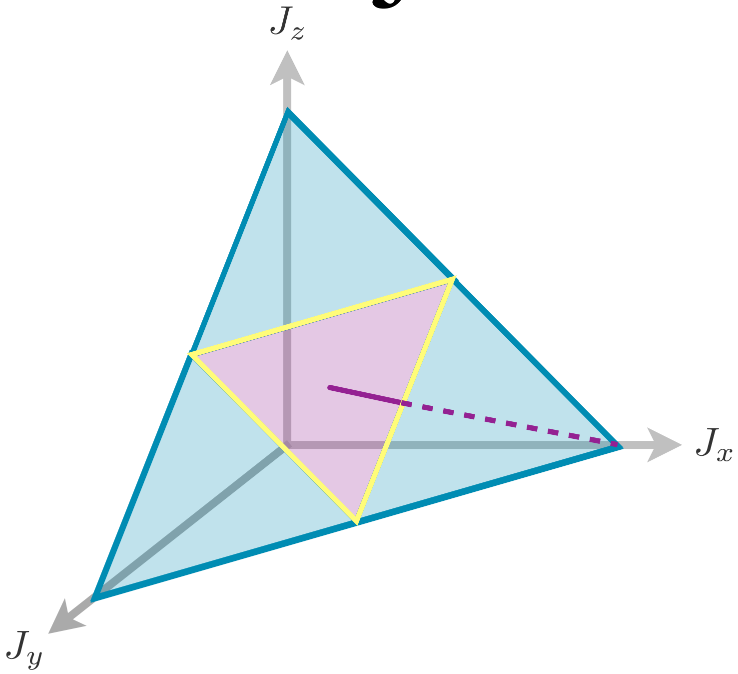


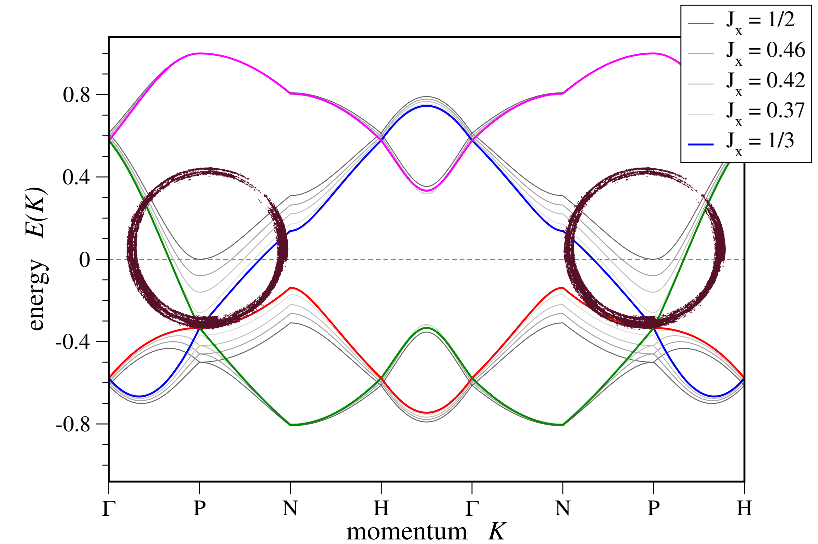
$J_x = 0.499$



$J_x = 1/3$

Majorana Fermi surface in gapless region





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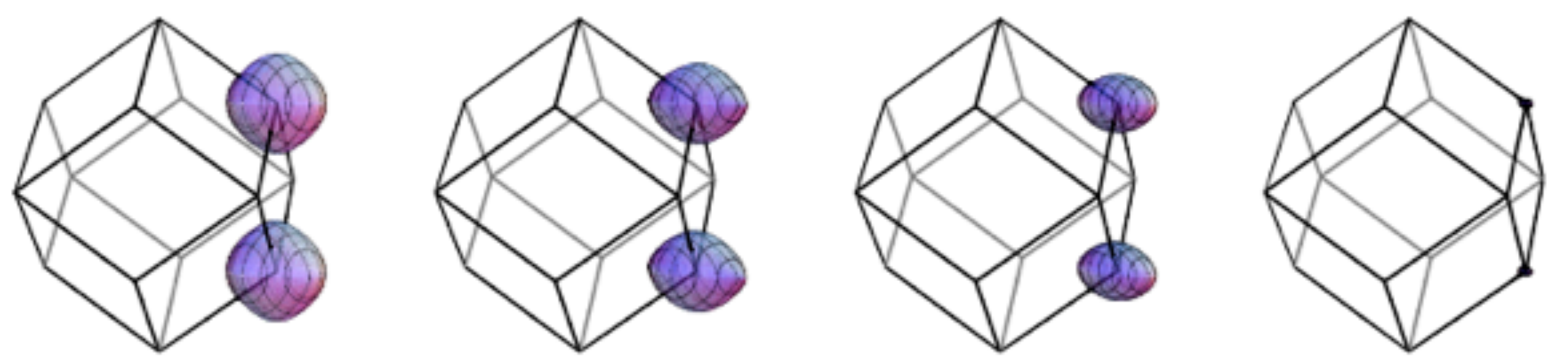

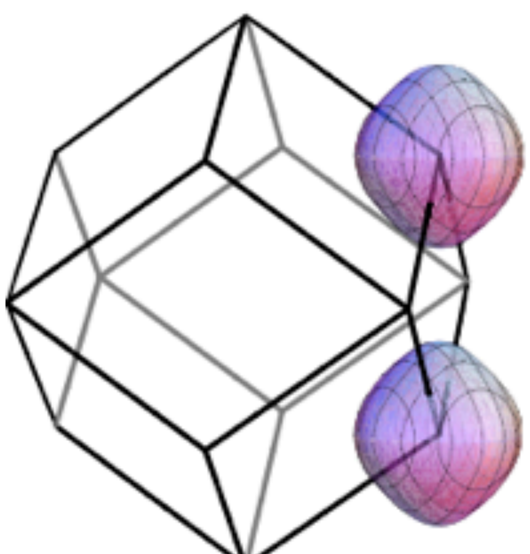

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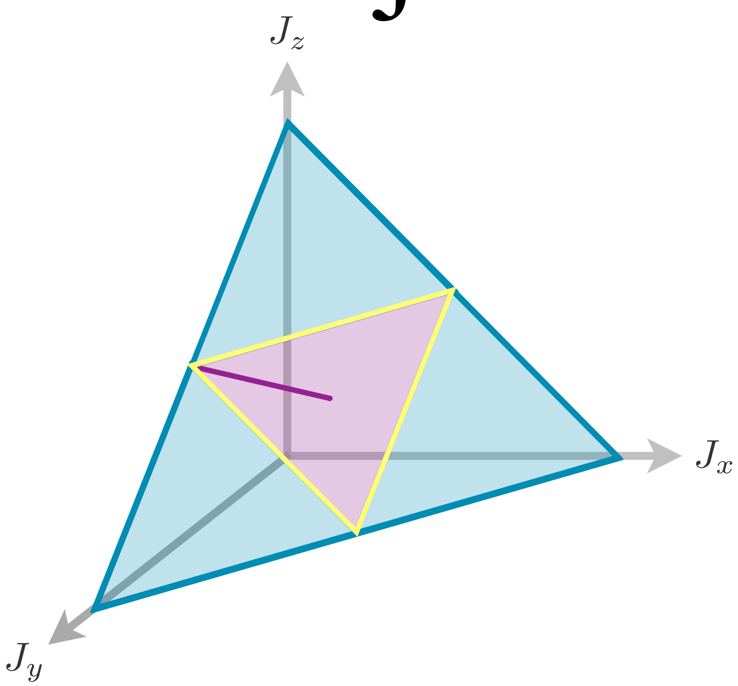

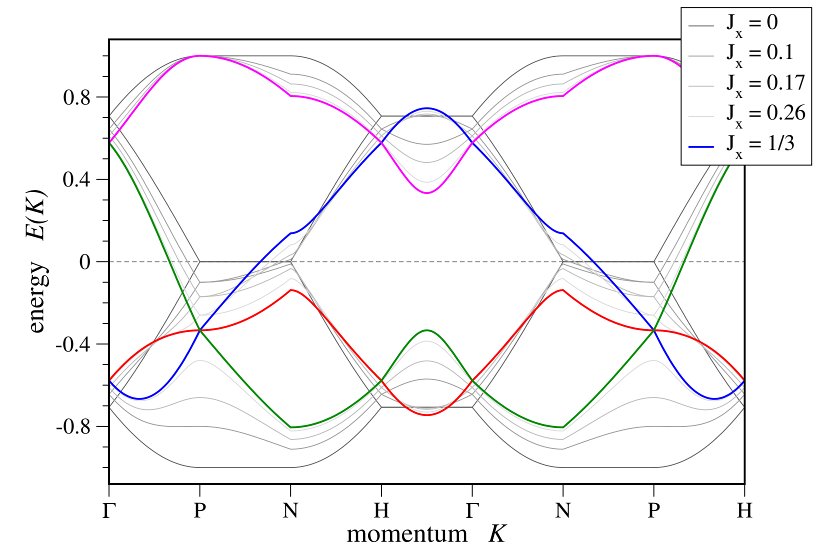

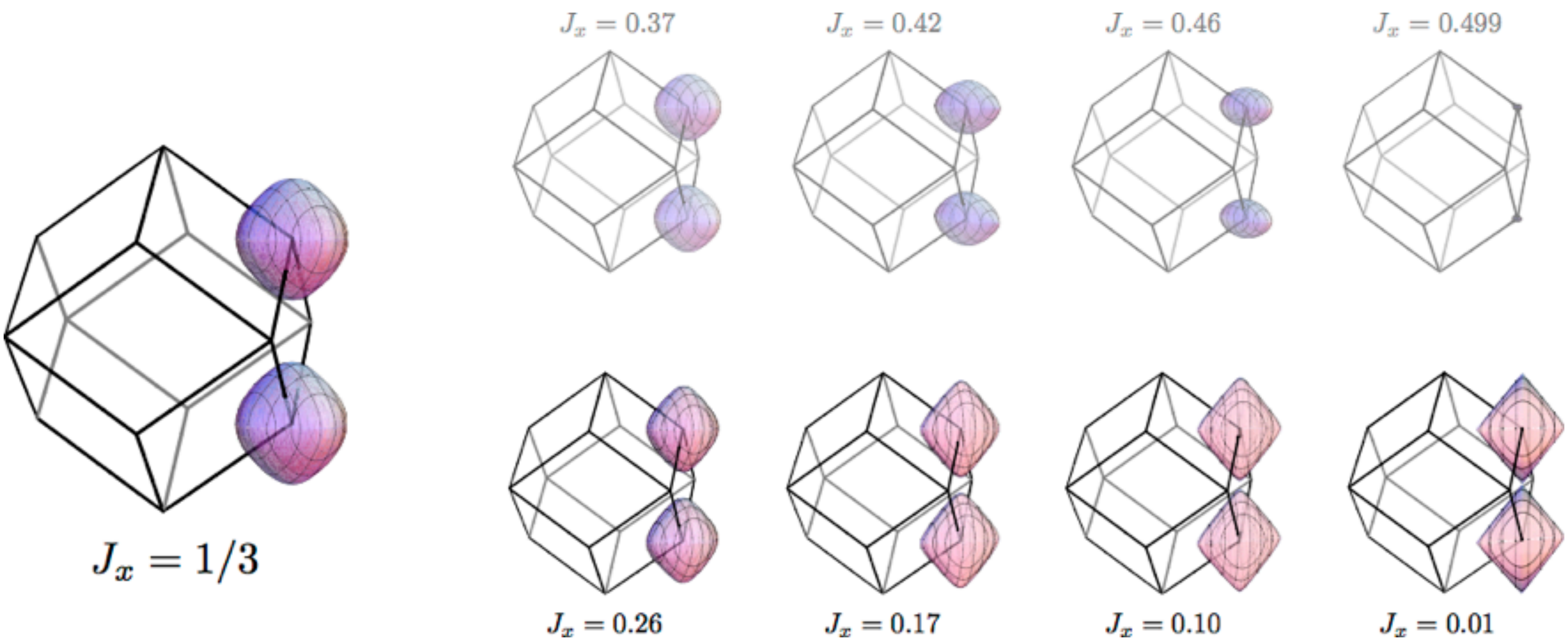

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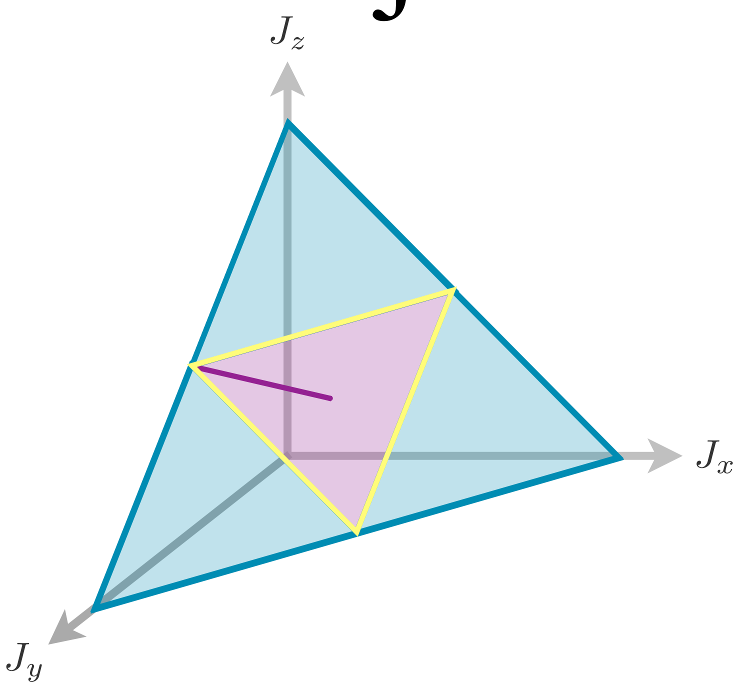

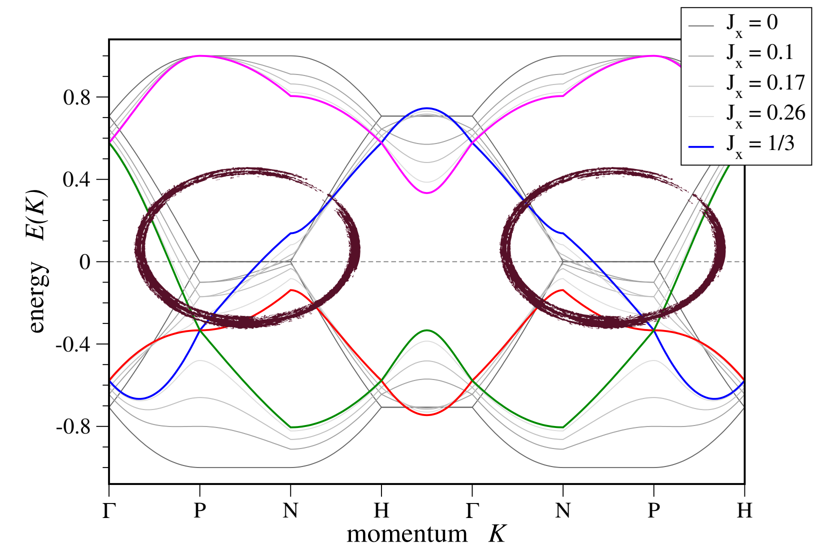

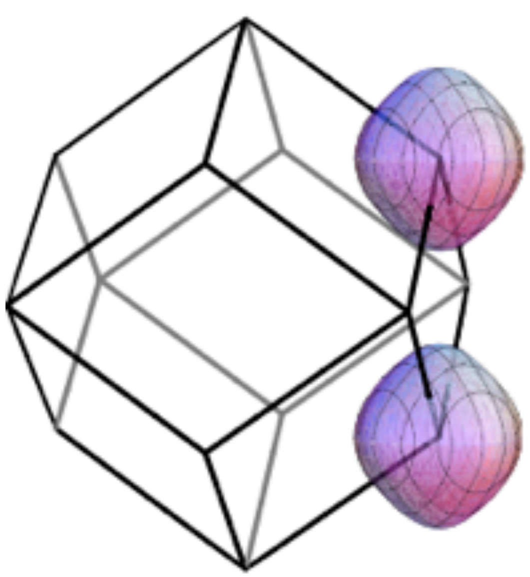

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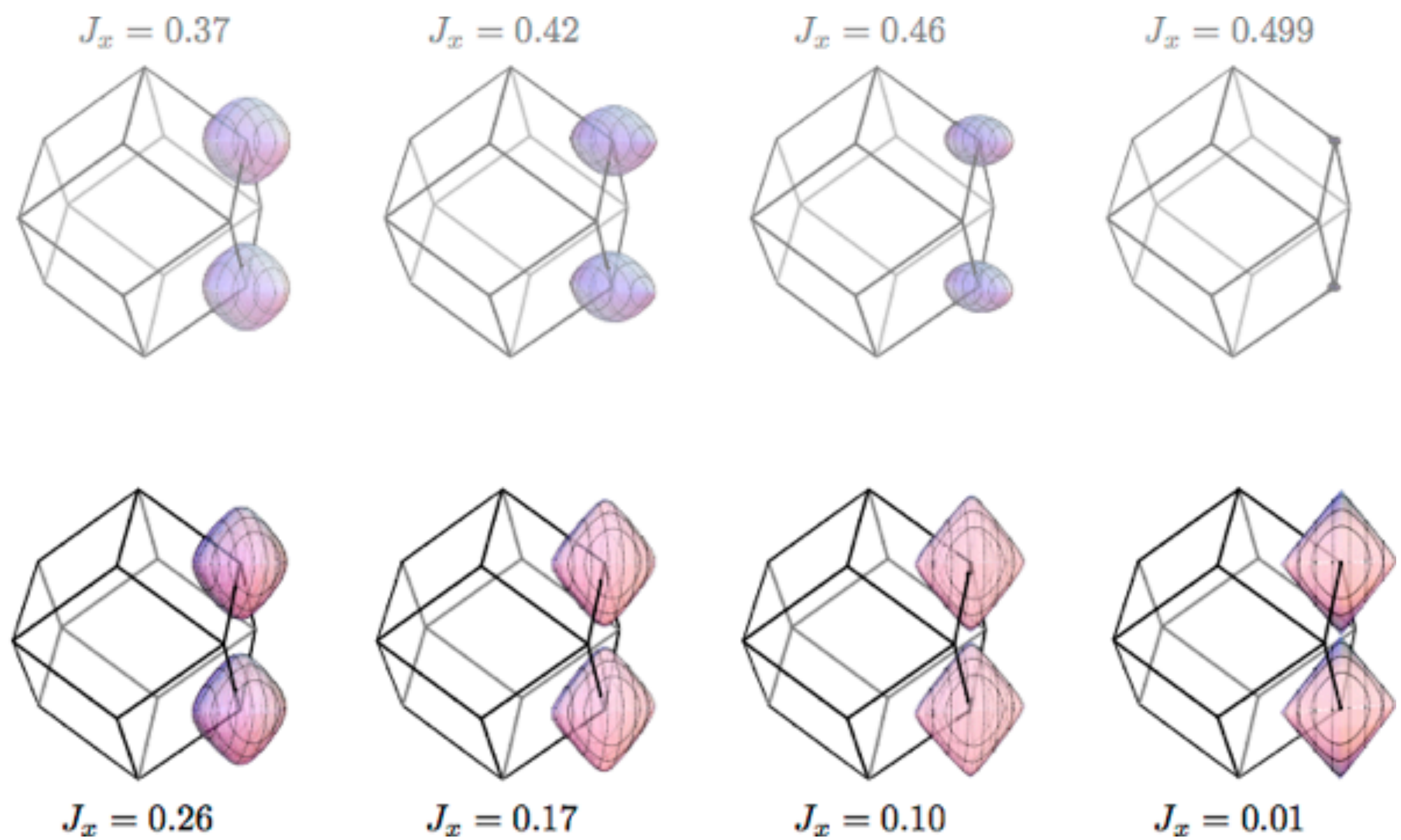
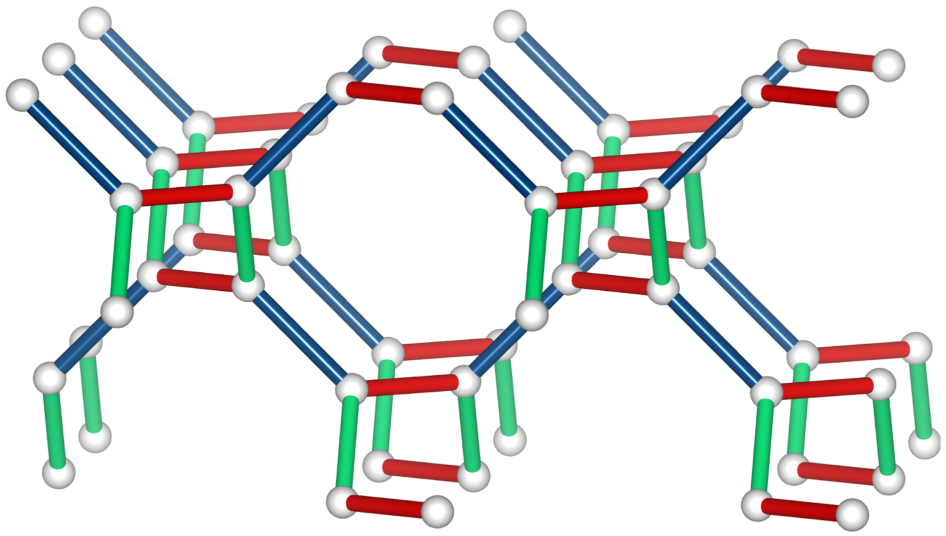


Zoo of gapless spin liquids



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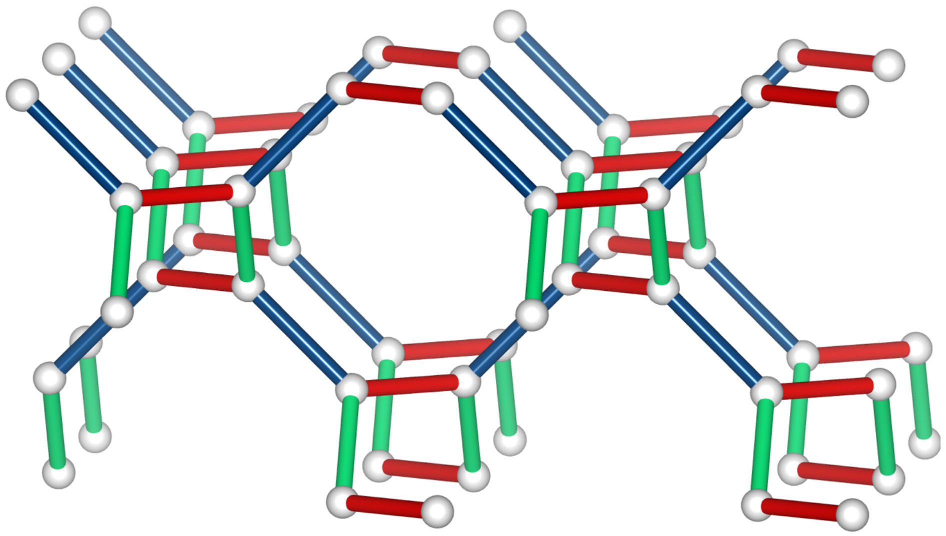

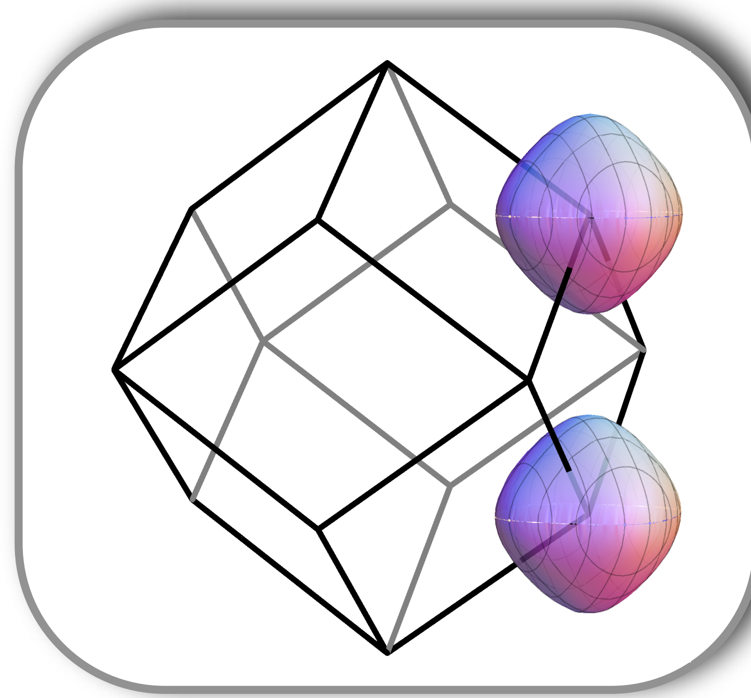

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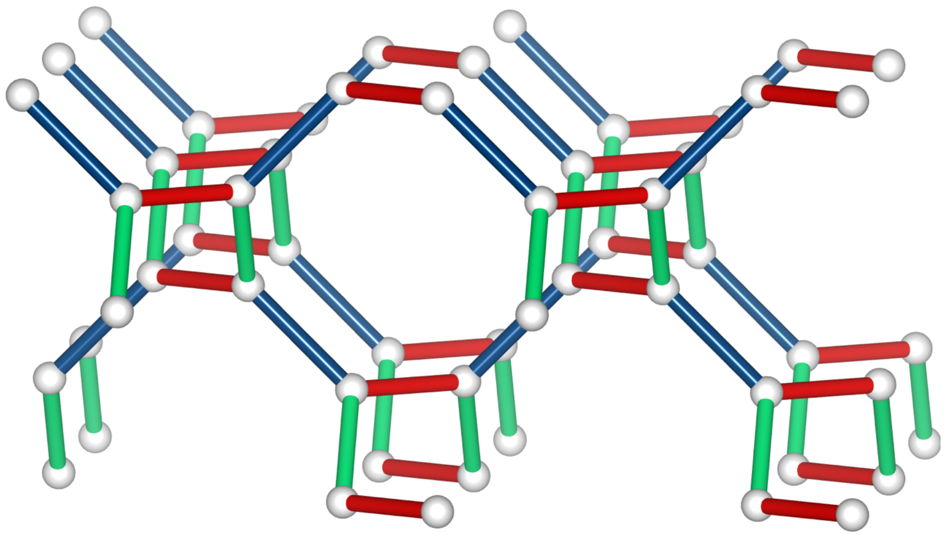

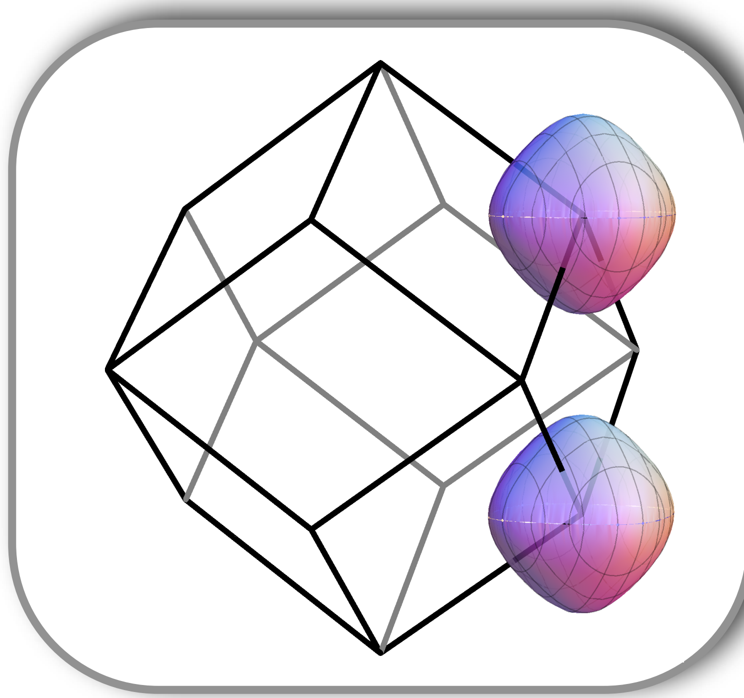

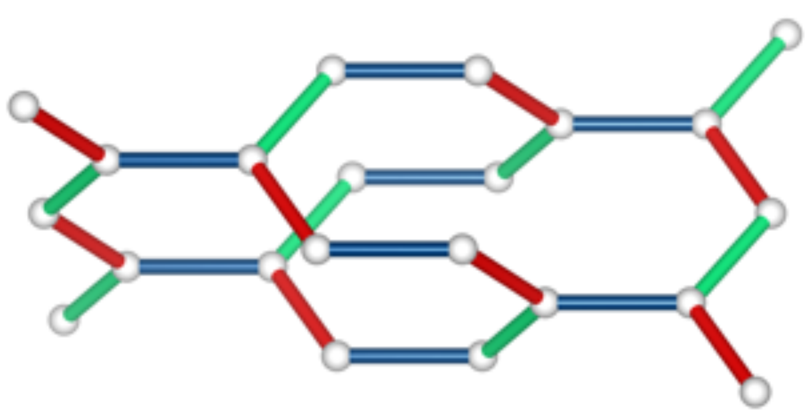

S. Mandal, N. Surendran, PRB 79, 024426 (2009)
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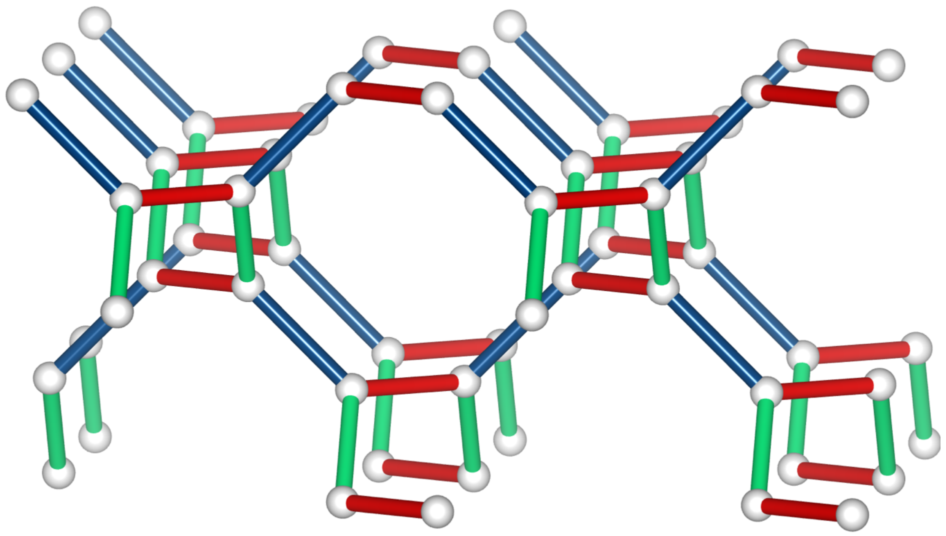

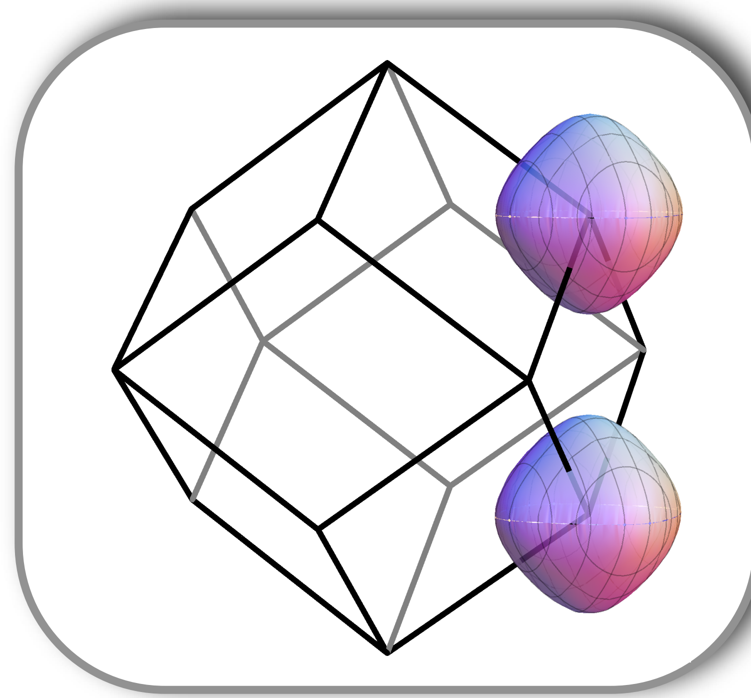

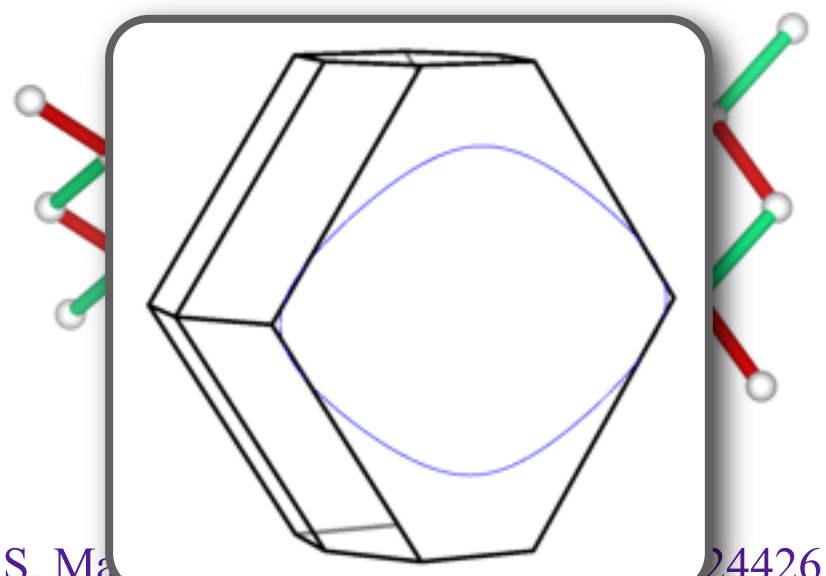

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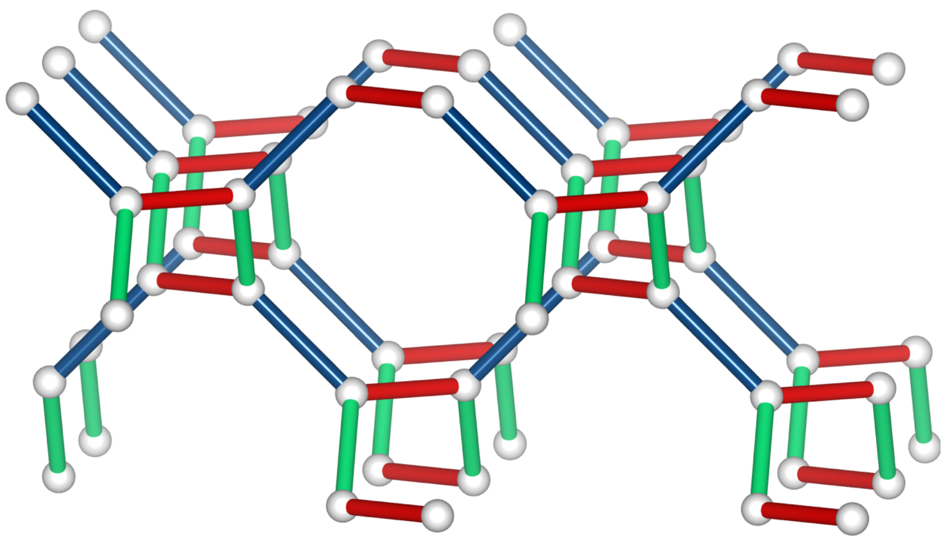

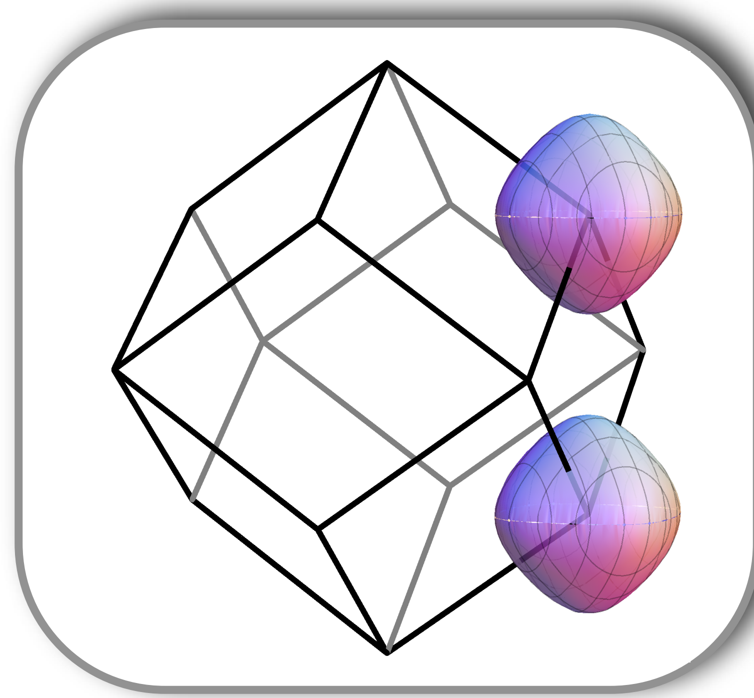

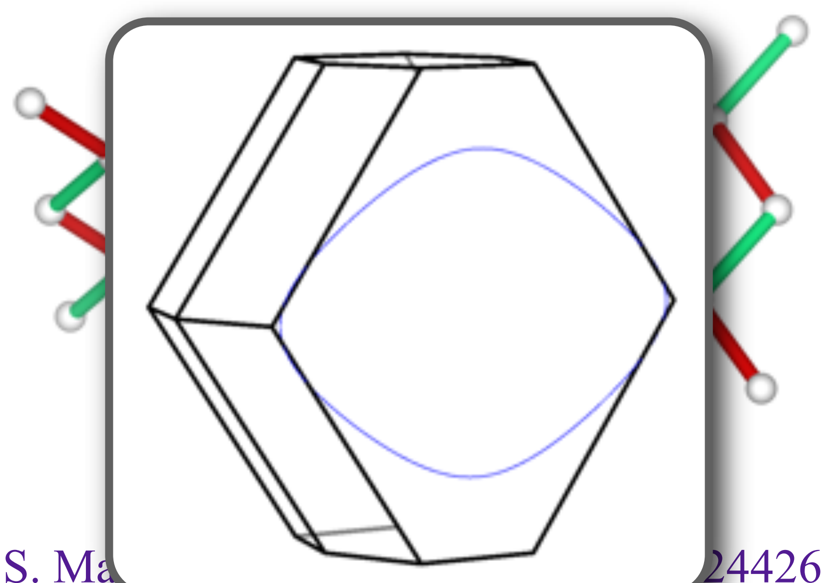

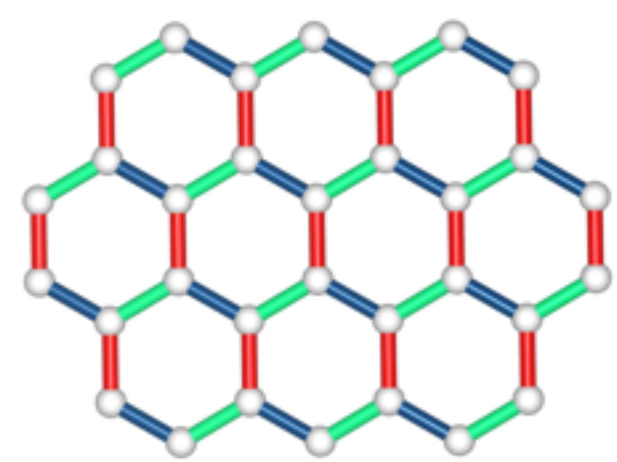

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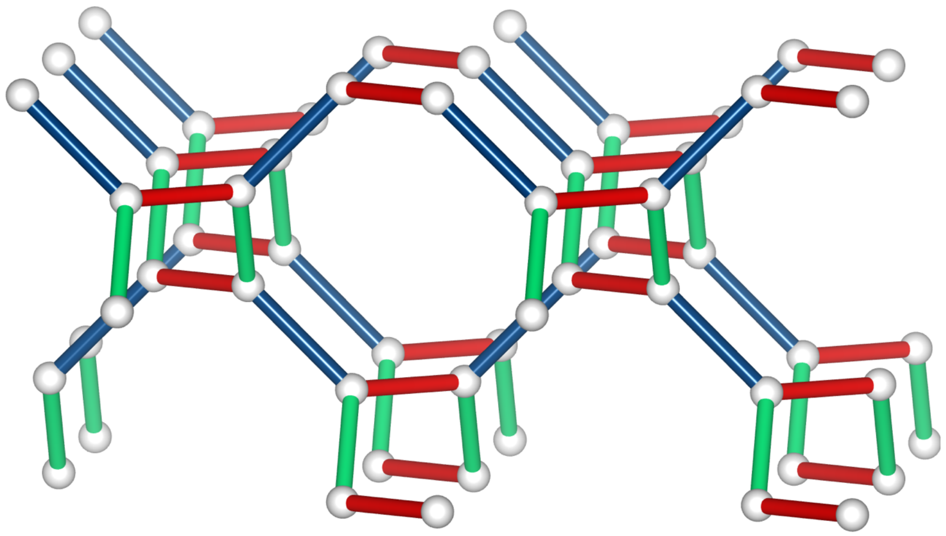

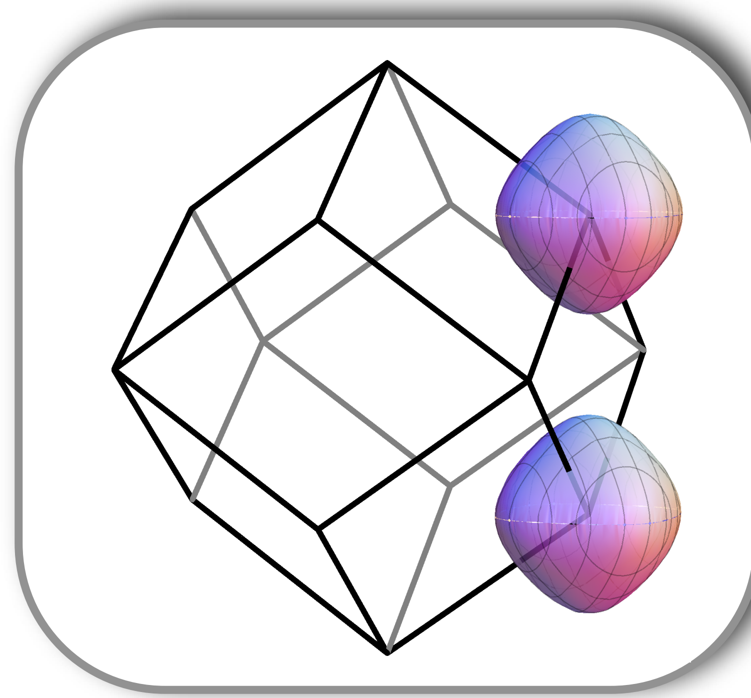

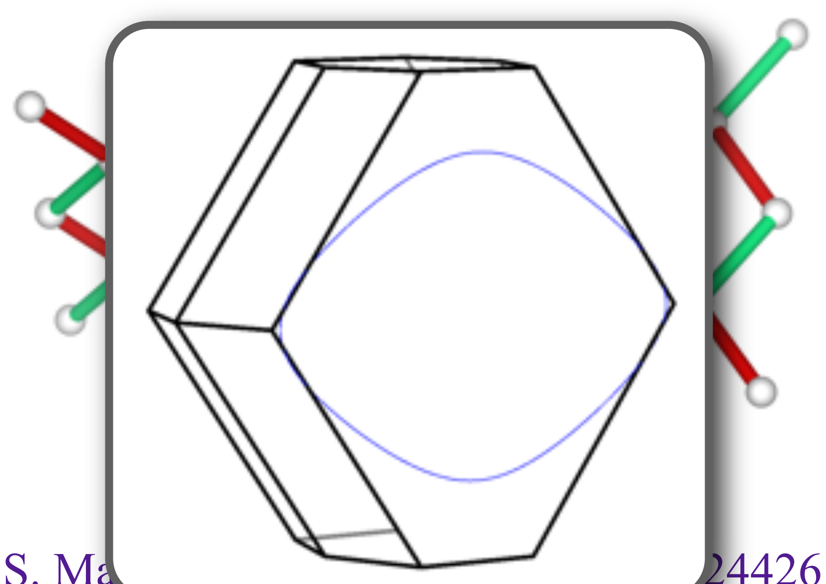

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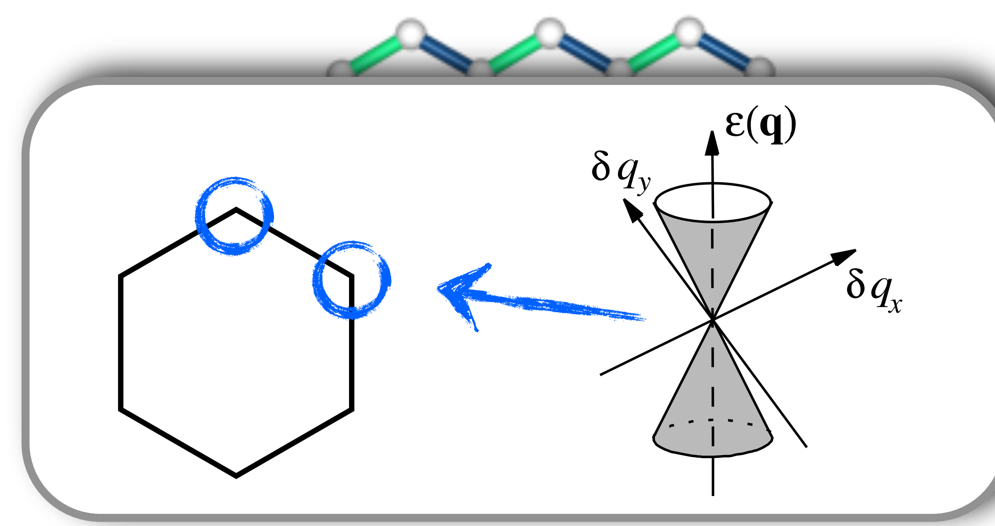

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Thermodynamics

static spin correlation functions $\langle\sigma_i^\alpha(\vec{r})\sigma_j^\beta(0)\rangle$ decay exponentially

Bond-energy correlation functions $\langle\mathcal{B}_\gamma(0)\mathcal{B}_\gamma(\vec{r})\rangle - \langle\mathcal{B}_\gamma(0)\rangle\langle\mathcal{B}_\gamma(\vec{r})\rangle$

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Different 3D gapless spin liquids can be **experimentally distinguished** by measuring the **specific heat coefficient** C(T)/T

Z_2 spin liquid with spinon Fermi line (hyperhoneycomb)	$C(T) \sim T^2$	$C(T)/T \to 0$
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U(1) spin liquid with spinon Fermi surface (slave-fermion + MF)	$C(T) \sim T \ln T$	$C(T)/T \to \infty$

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Majorana metal!

Symmetries in Majorana Systems

Particle-hole symmetry	$\epsilon(\mathbf{k}) = -\epsilon(-\mathbf{k})$

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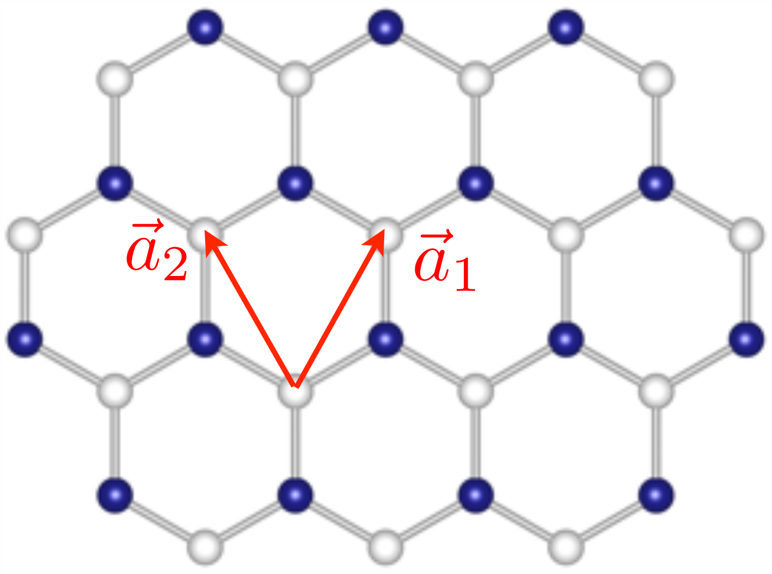

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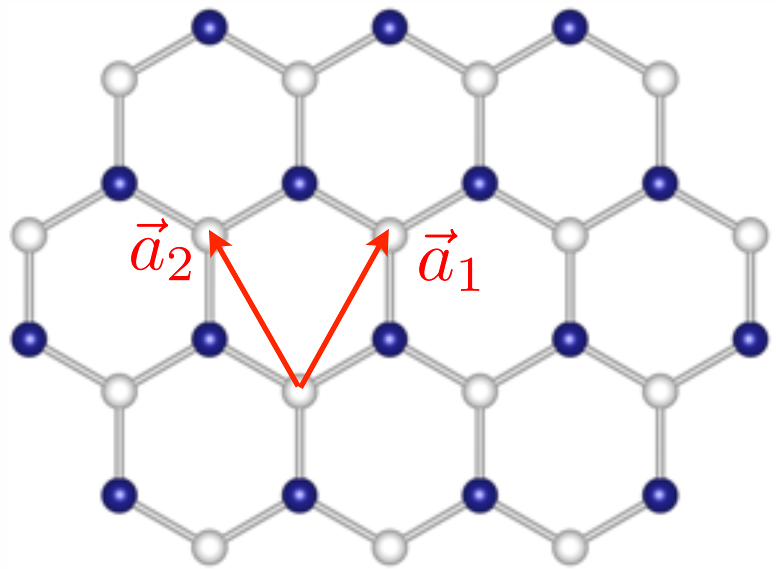
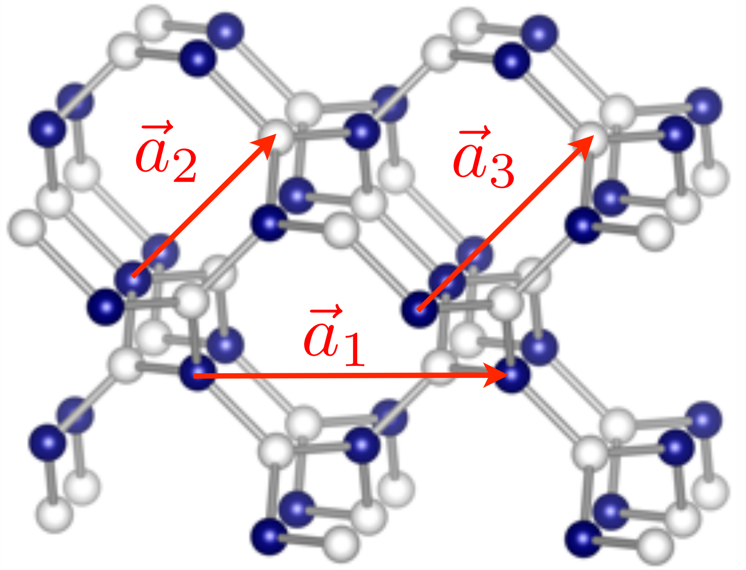


hyperoctagon lattice



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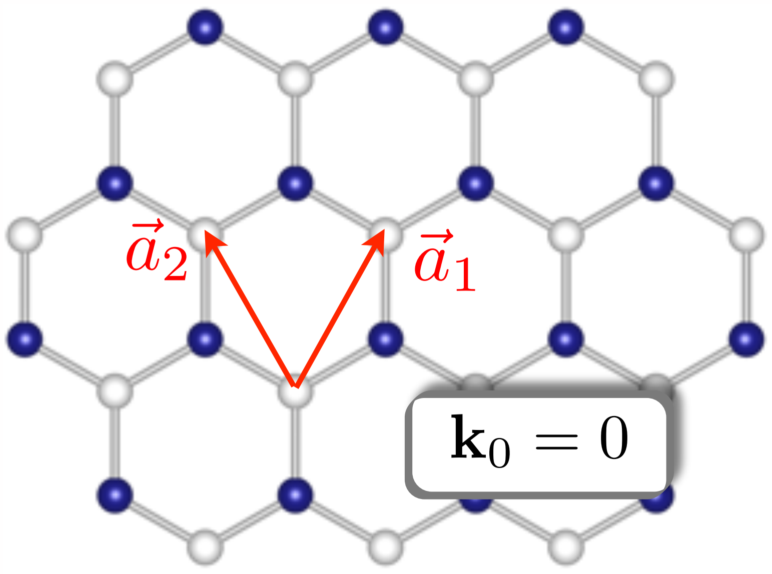
$\mathbf{k}_0$ is the reciprocal lattice vector of the translation vector of the sublattice

honeycomb lattice



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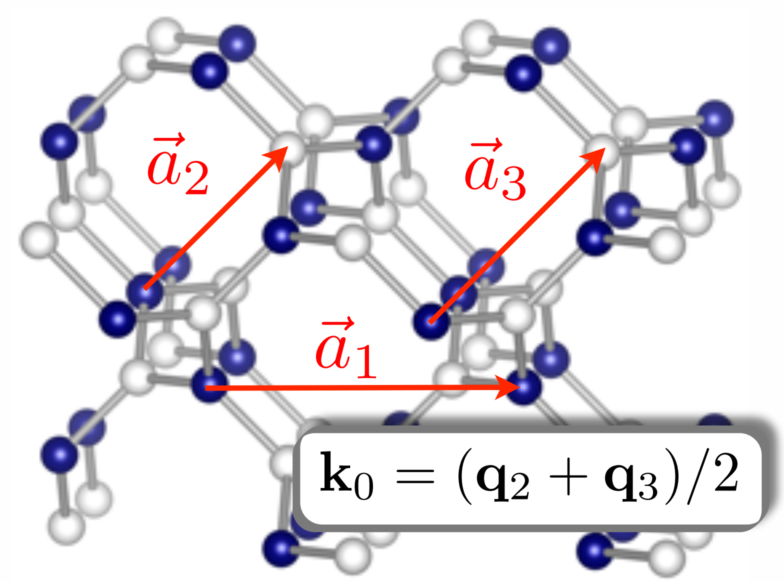

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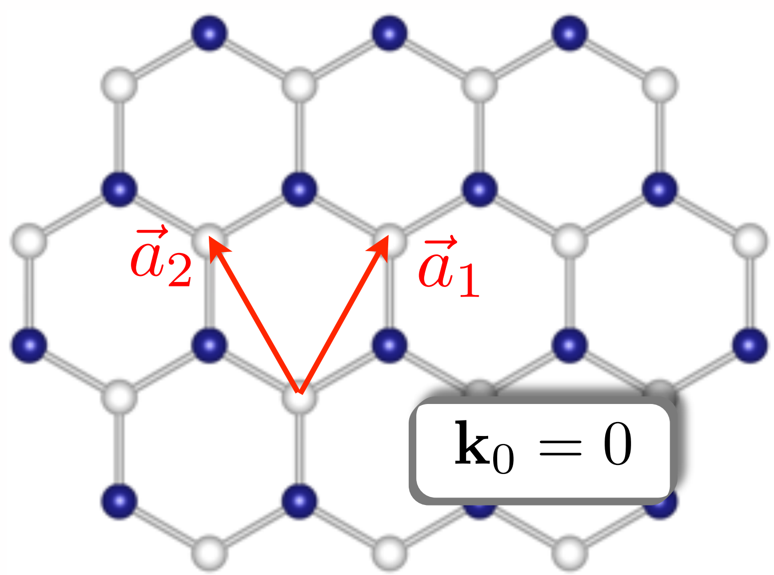

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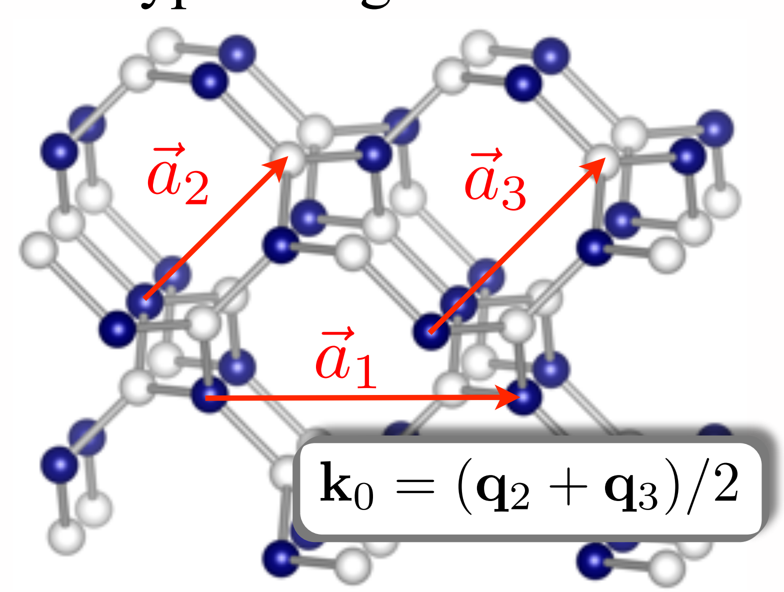

Symmetries $\leftrightarrow$ Fermi surface

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$\mathbf{k}_0 = 0$: honeycomb / hyperhoneycomb

$\mathbf{k}_0 \neq 0$: hyperoctagon

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particle-hole symmetry at every **k** point
doubly degenerate zero-modes at same **k**

$$h(\mathbf{k}) = \begin{pmatrix} \mathbf{0} & \mathbf{A} \\ \mathbf{A}^\dagger & \mathbf{0} \end{pmatrix}$$

protected by time-reversal

stable zero-mode manifolds are **separated points** (2D) and **lines** (3D)

$\mathbf{k}_0 \neq 0$: hyperoctagon

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Time-reversal symmetry	$\epsilon(\mathbf{k}) = \epsilon(-\mathbf{k} - \mathbf{k}_0)$
Inversion symmetry	$\epsilon(\mathbf{k}) = \epsilon(-\mathbf{k} - \mathbf{k}_0)$

$\mathbf{k}_0 = 0$: honeycomb / hyperhoneycomb

particle-hole symmetry at every **k** point
doubly degenerate zero-modes at same **k**

$$h(\mathbf{k}) = \begin{pmatrix} \mathbf{0} & \mathbf{A} \\ \mathbf{A}^\dagger & \mathbf{0} \end{pmatrix}$$

protected by time-reversal

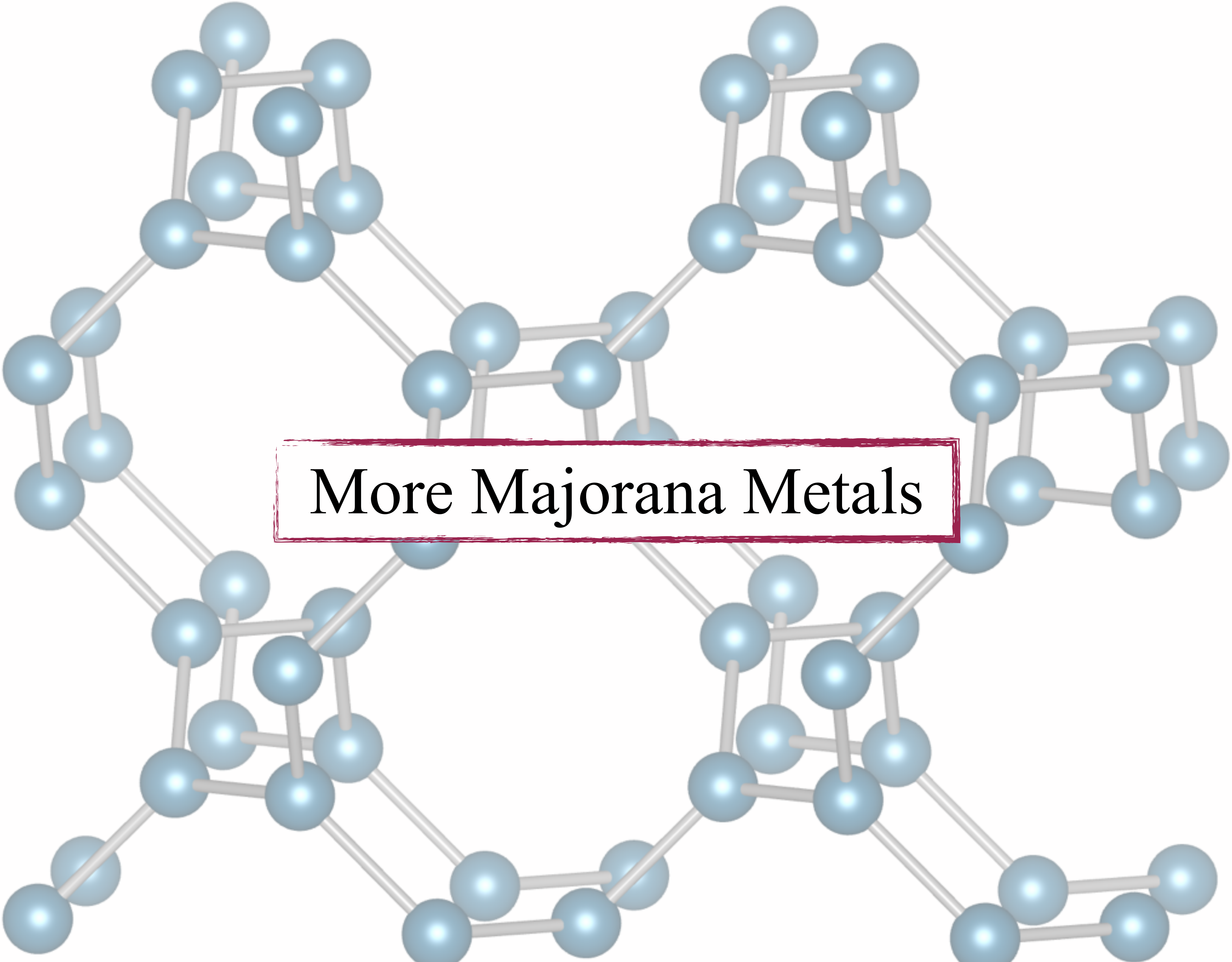
stable zero-mode manifolds are **separated points** (2D) and **lines** (3D)

$\mathbf{k}_0 \neq 0$: hyperoctagon

generic band hamiltonian at given **k**
zero-modes are at different **k**

$$h(\mathbf{k}) = \begin{pmatrix} 0 & & \mathbf{A} \\ & \ddots & \\ \mathbf{A}^\dagger & & 0 \end{pmatrix}$$

stable zero-mode manifolds are **lines** (2D) and **surfaces** (3D)



More Majorana Metals

P-wave pairing instability on the hyperoctagon lattice

Center of Majorana Fermi surfaces are **high-symmetry** points defined by $\mathbf{k}_0/2$

$$\mathbf{K}_{1/2} = (\pi, \pi, \pm\pi)$$

P-wave pairing instability on the hyperoctagon lattice

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$$\mathbf{K}_{1/2} = (\pi, \pi, \pm\pi)$$

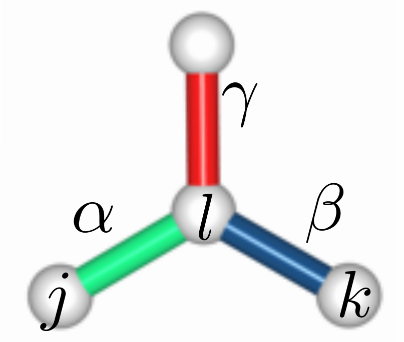
Time-reversal symmetry: $\epsilon(\mathbf{q} + \mathbf{K}_j) = \epsilon(-\mathbf{q} + \mathbf{K}_j)$

p-wave pairing instability in effective spinless Fermion model
(broken translation symmetry)
relevant for additional nearest-neighbor Heisenberg coupling

Breaking time-reversal symmetry

external **magnetic field** in (1,1,1)-direction

$$H_{eff} = -J \sum_{\gamma-bond} \sigma_j^\gamma \sigma_k^\gamma - \kappa \sum_{\langle j,l,k \rangle} \sigma_j^\alpha \sigma_k^\beta \sigma_l^\gamma$$



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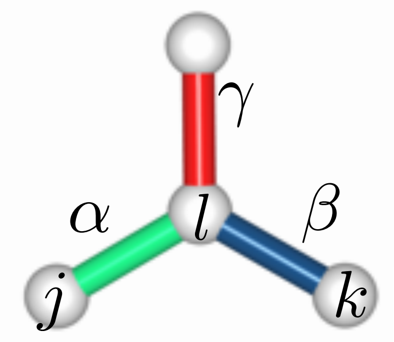

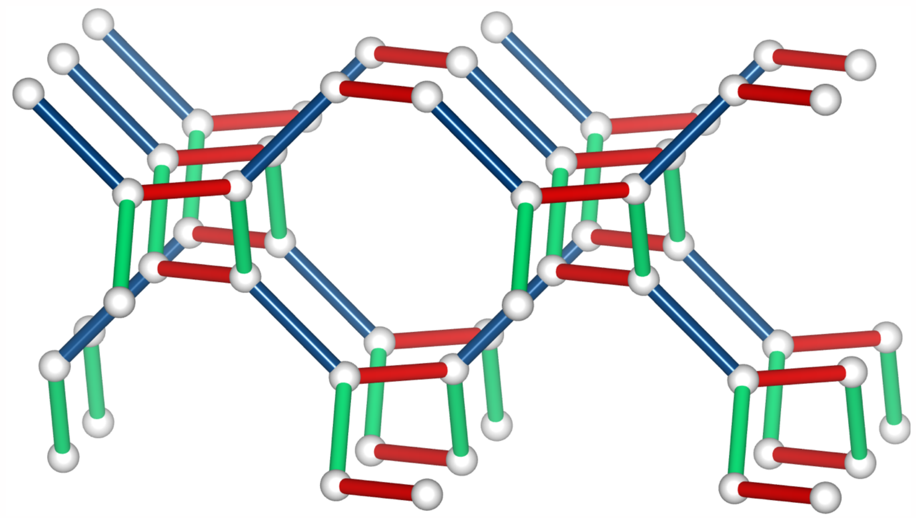

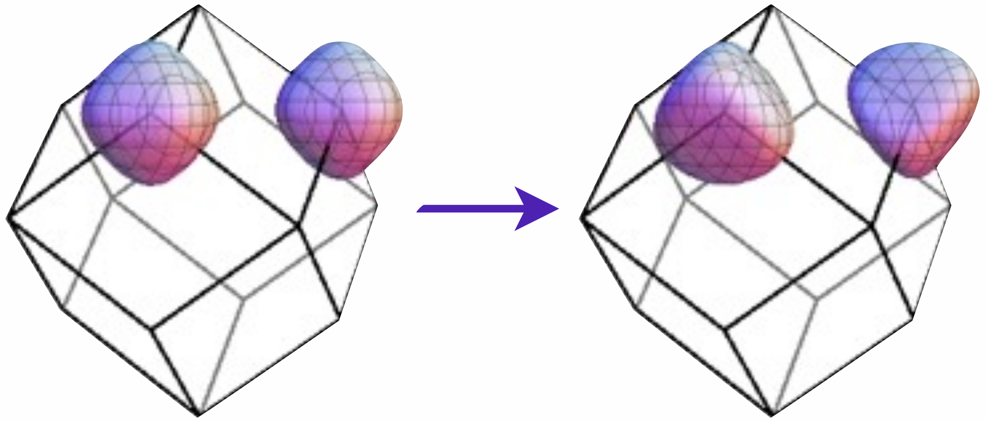

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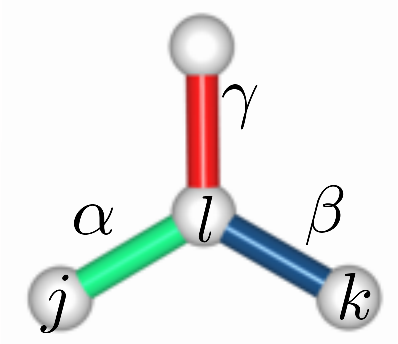

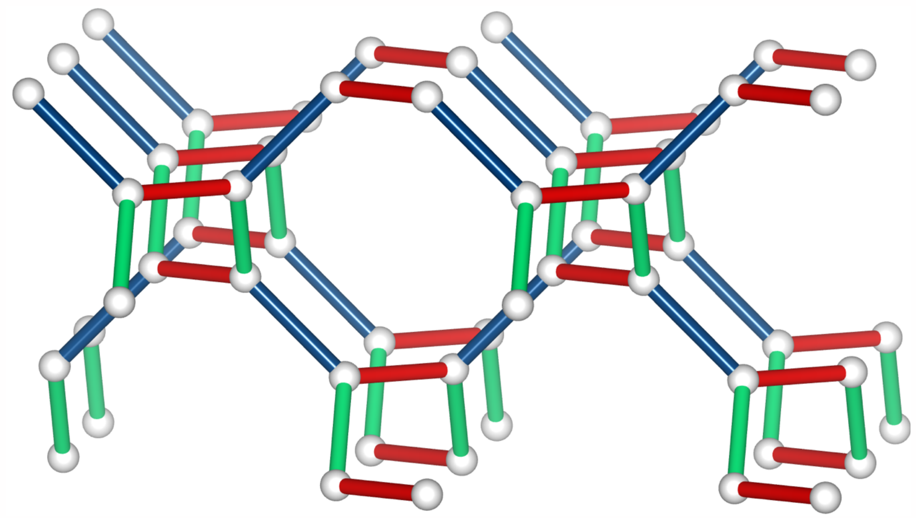

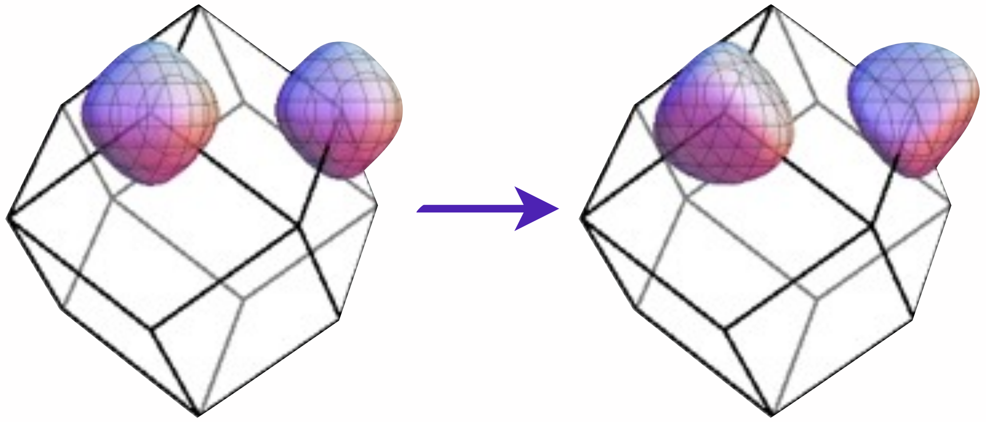

Breaking TR **stabilizes Fermi surface**

Breaking time-reversal symmetry

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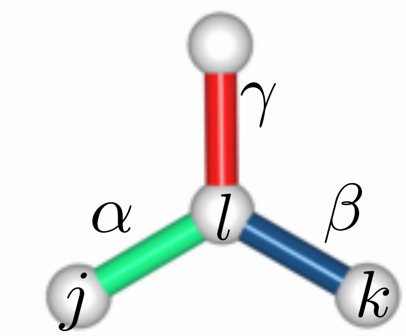

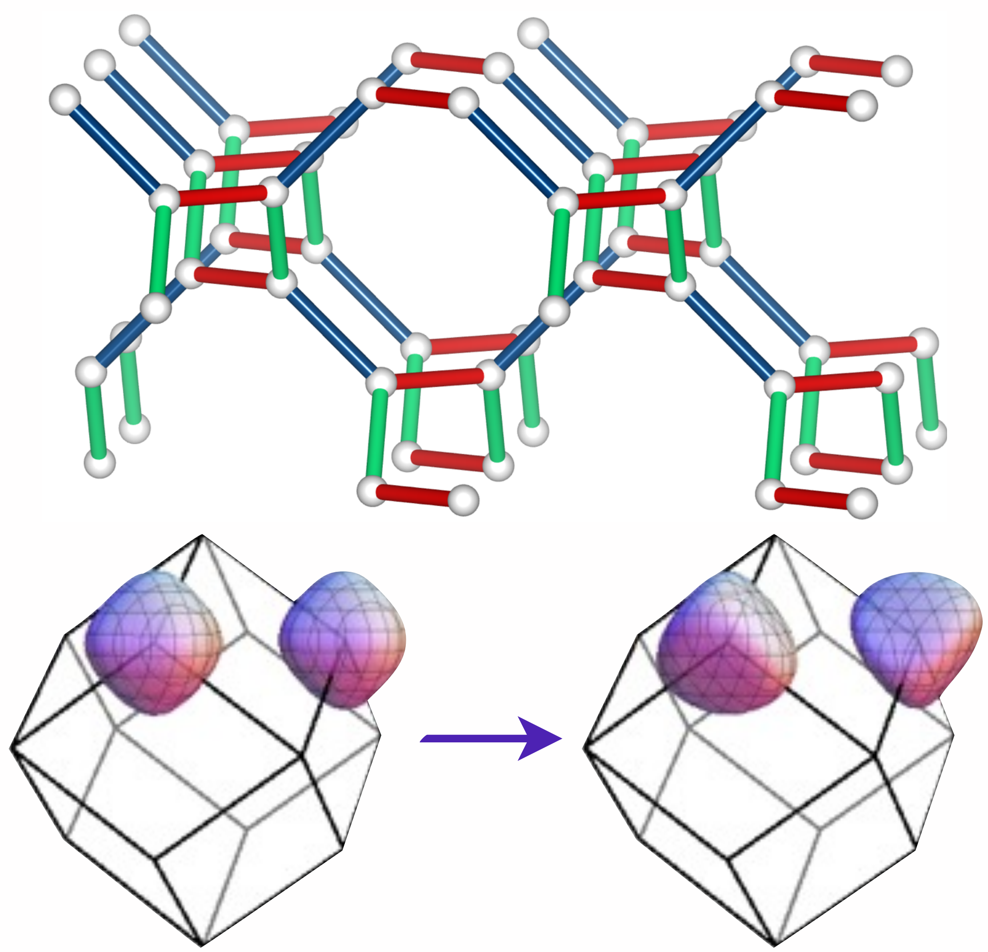

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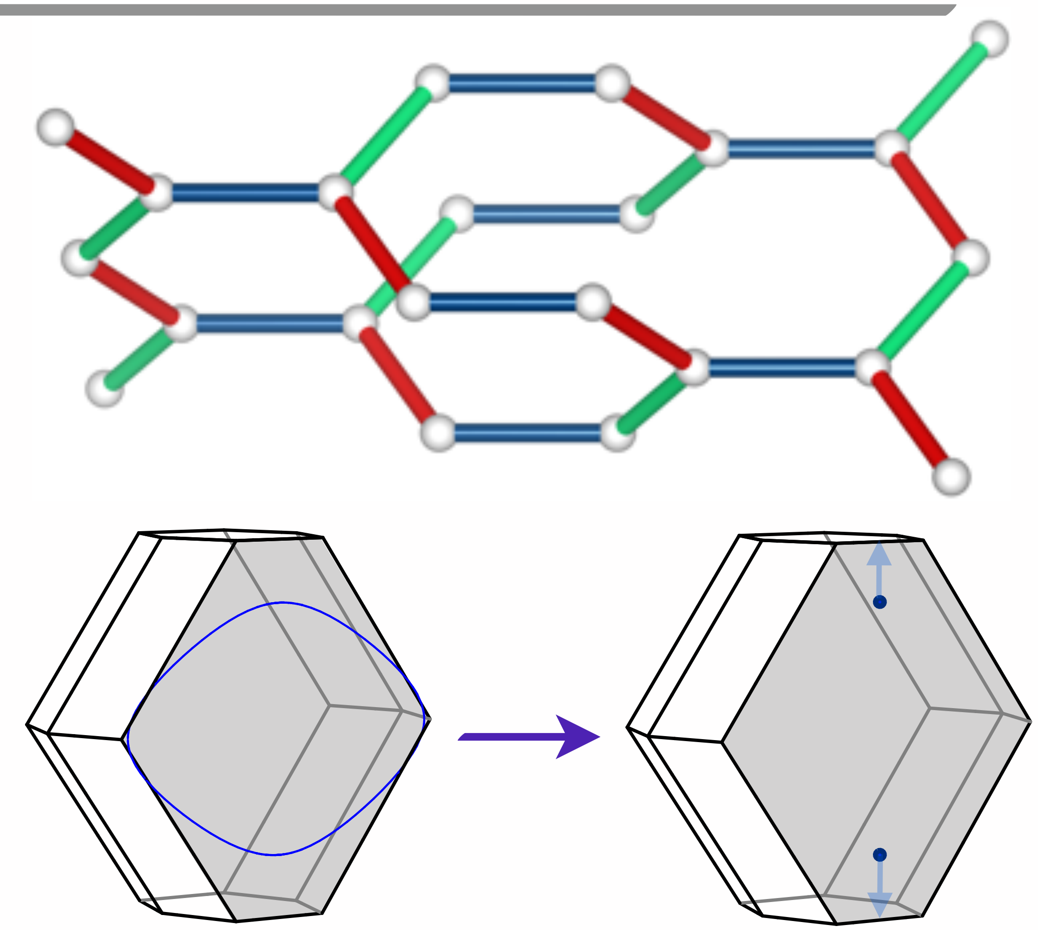

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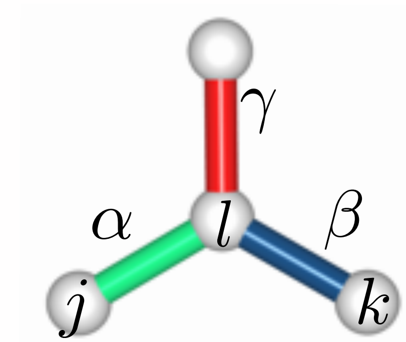

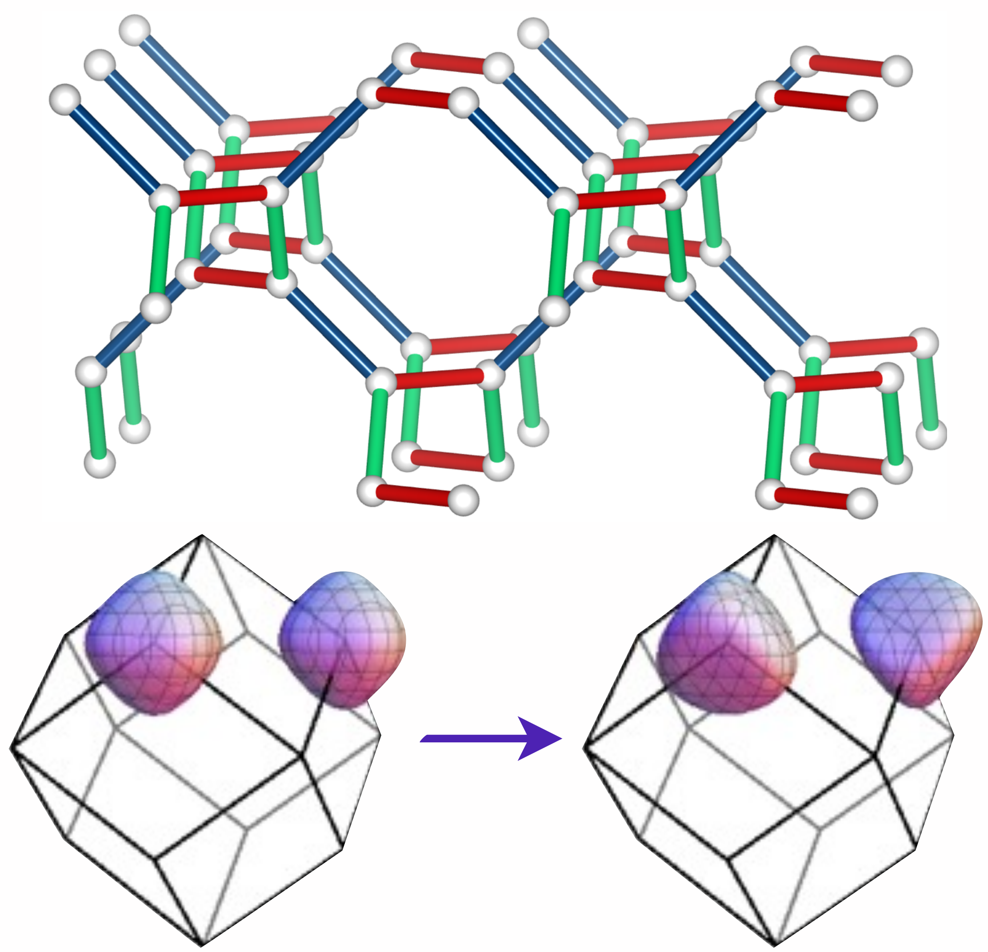

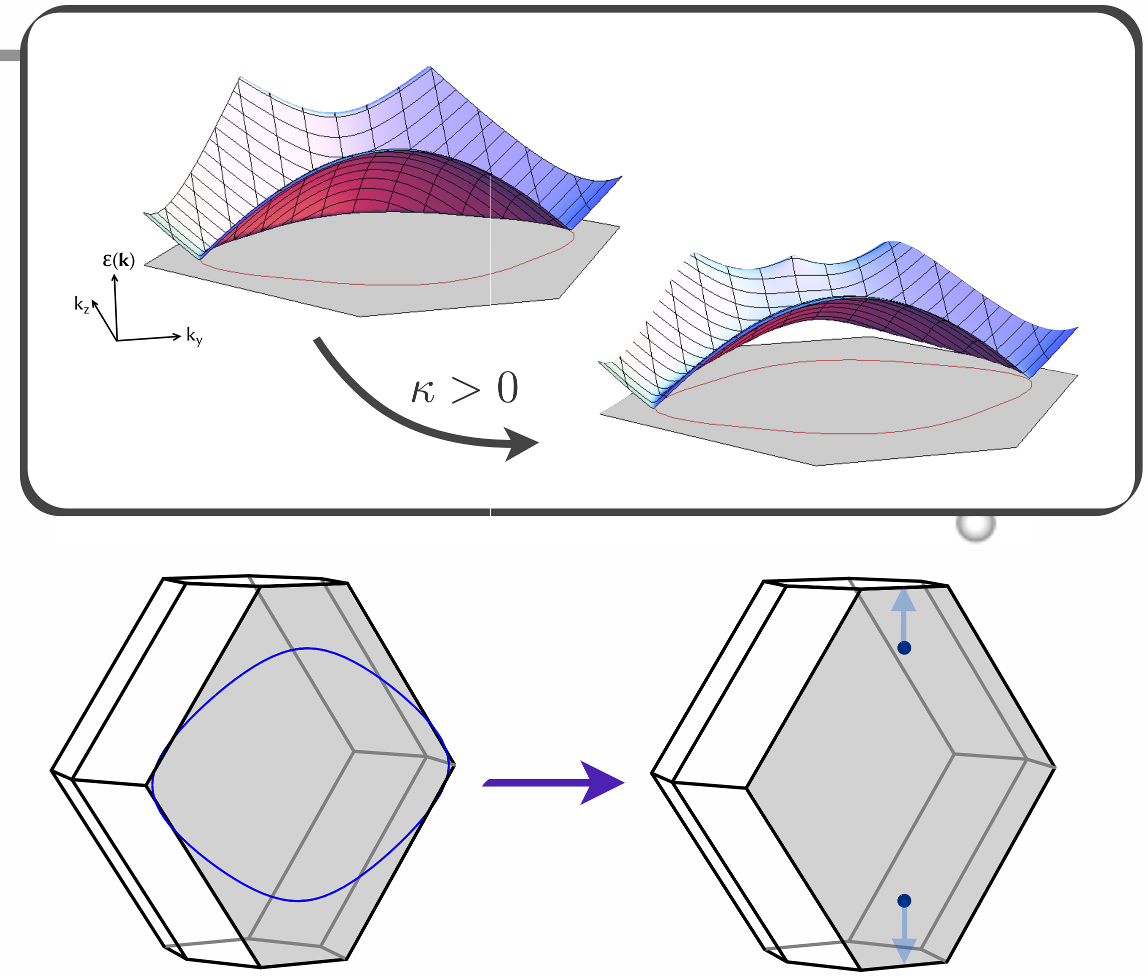

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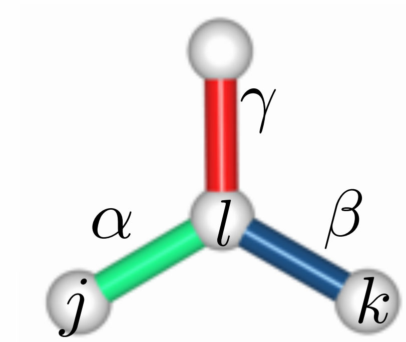

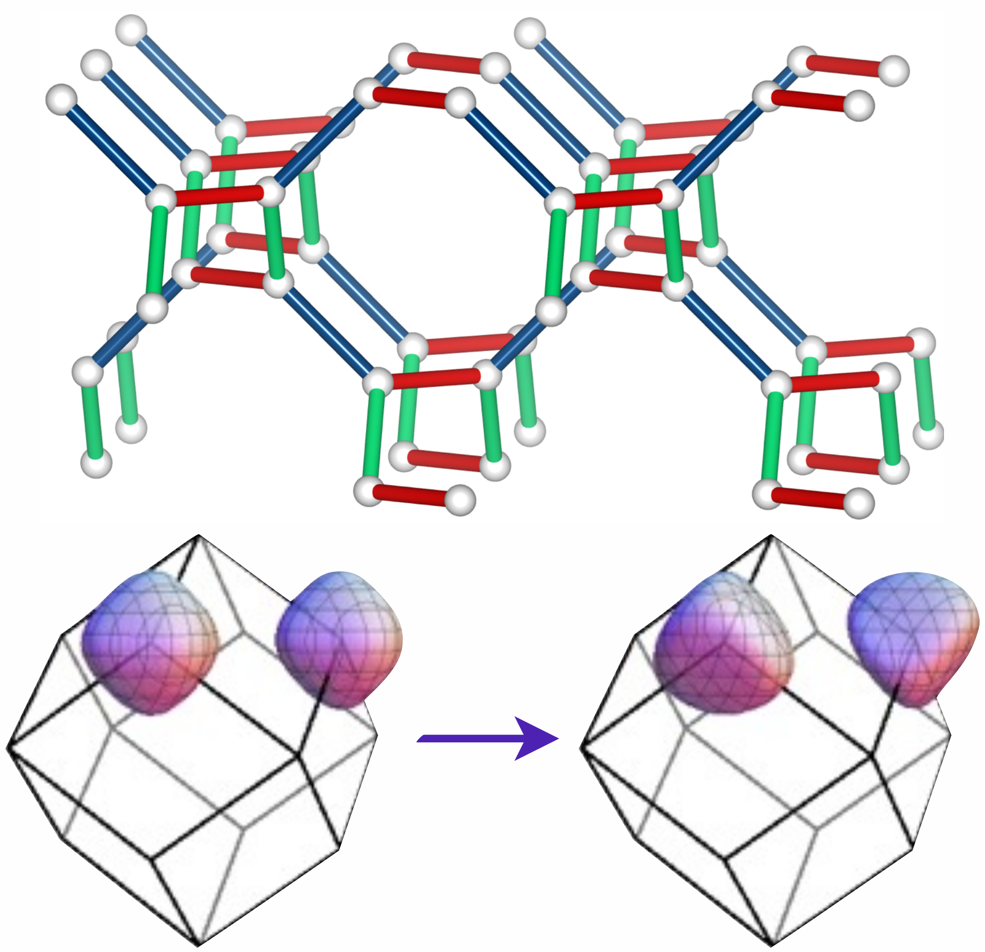

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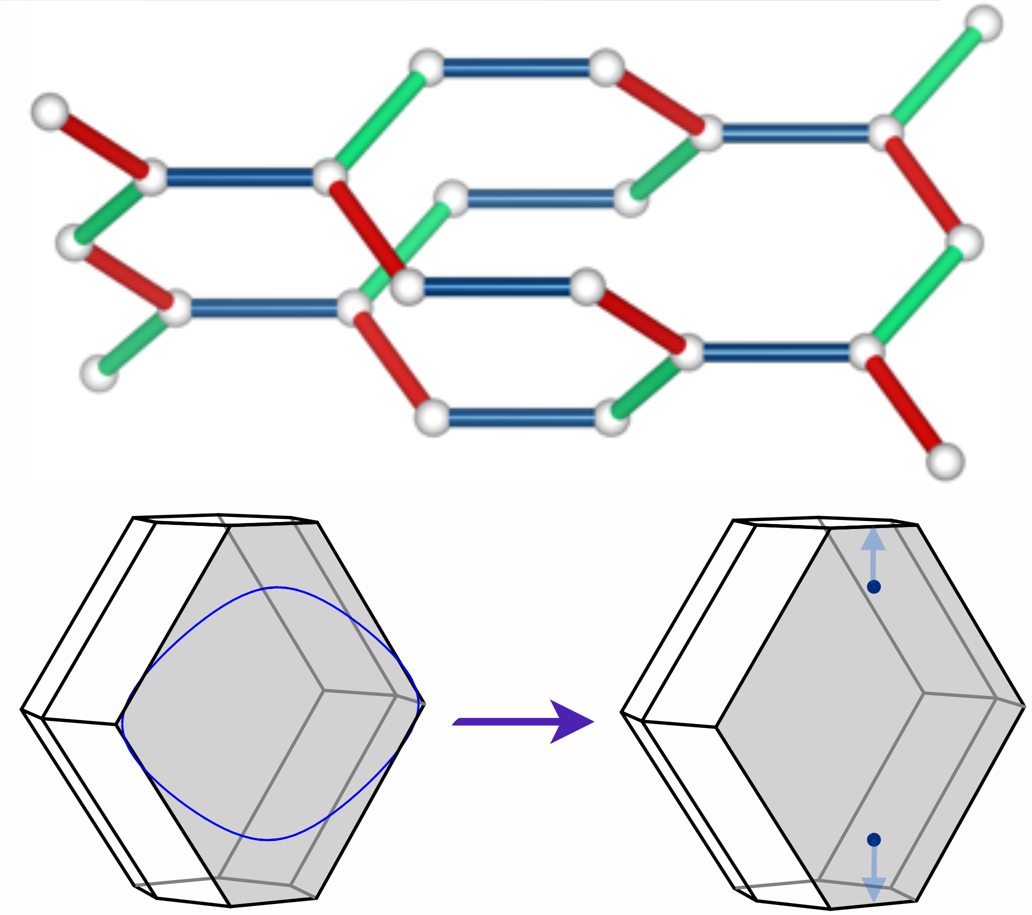

Breaking TR reduces line to **pair of Weyl nodes**

Weyl nodes and Weyl semi-metals

Touching of two bands in 3D is generically **linear**

$$\hat{H} = \vec{v}_0 \cdot \vec{q}\,\mathbb{1} + \sum_{i=1}^{3} \vec{v}_j \cdot \vec{q}\,\sigma_j$$ **Weyl nodes**

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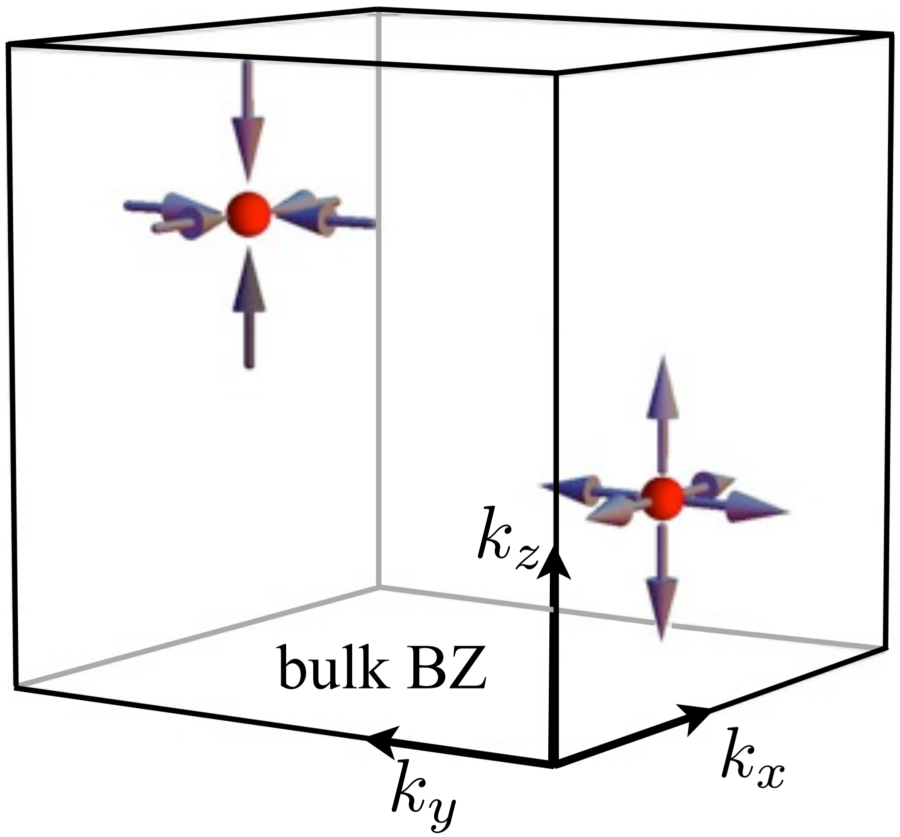
Weyl nodes are **sources/sinks of Berry flux**

$$\vec{B}_n(\vec{k}) = \nabla_{\vec{k}} \times \Big(i \langle n(\vec{k}) | \nabla_{\vec{k}} | n(\vec{k}) \rangle \Big)$$

with chirality $\mathrm{sign}[\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3)]$



Wan etal., PRB 83, 205101 (2011)

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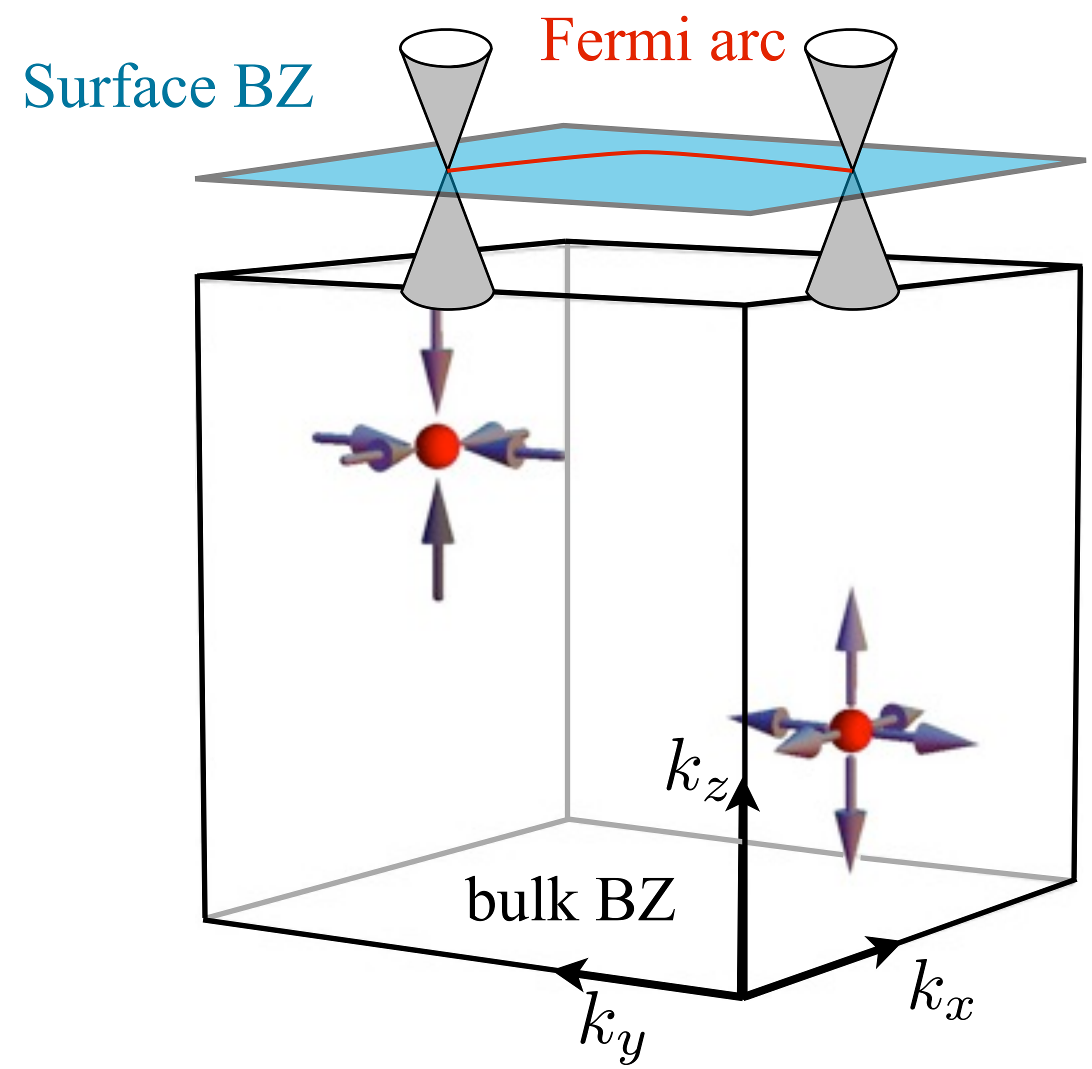
here: Weyl nodes pinned at zero energy!

unusal surface states: **Fermi arcs**

topological semi-metal with **protected** surface states
(metallic cousin of the topological insulator)



Wan etal., PRB 83, 205101 (2011)

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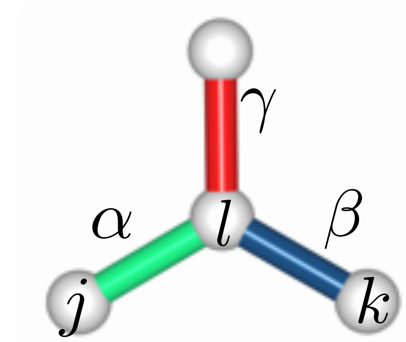

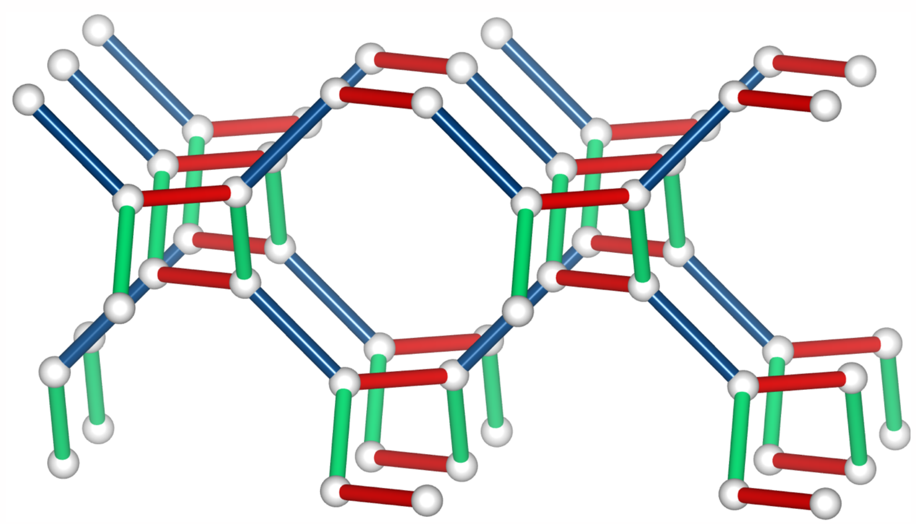

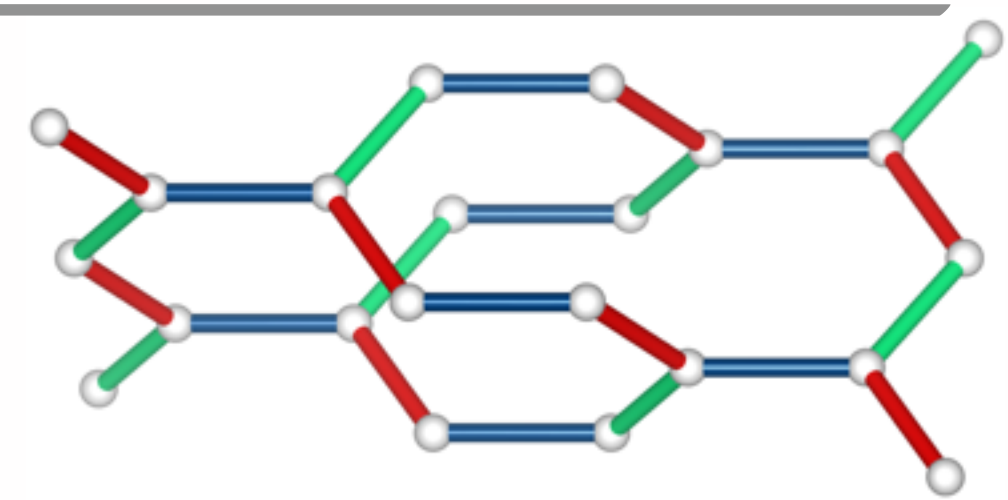

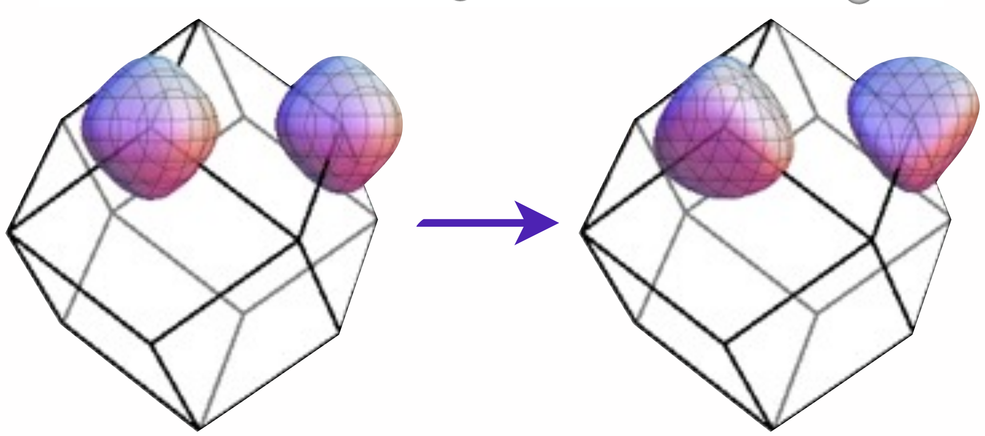

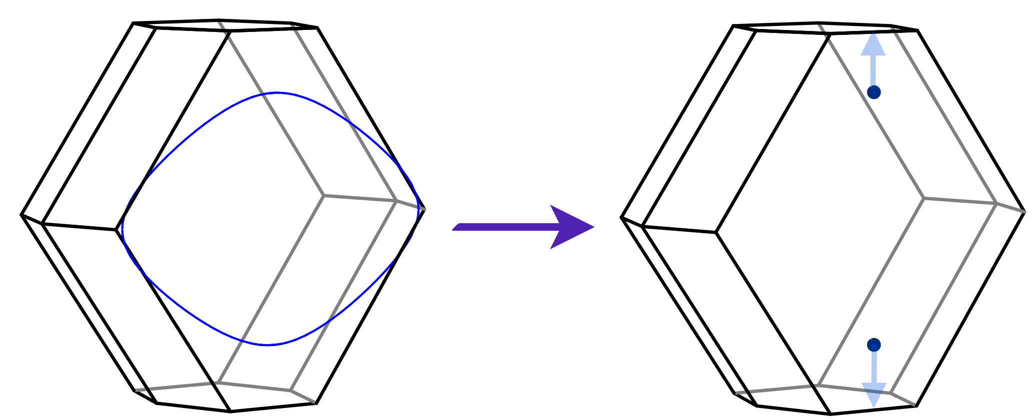

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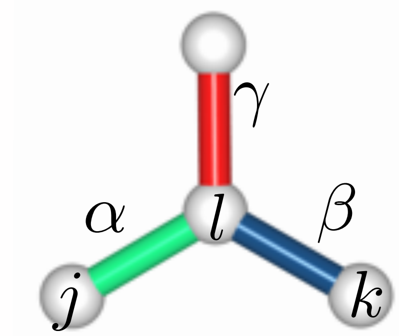
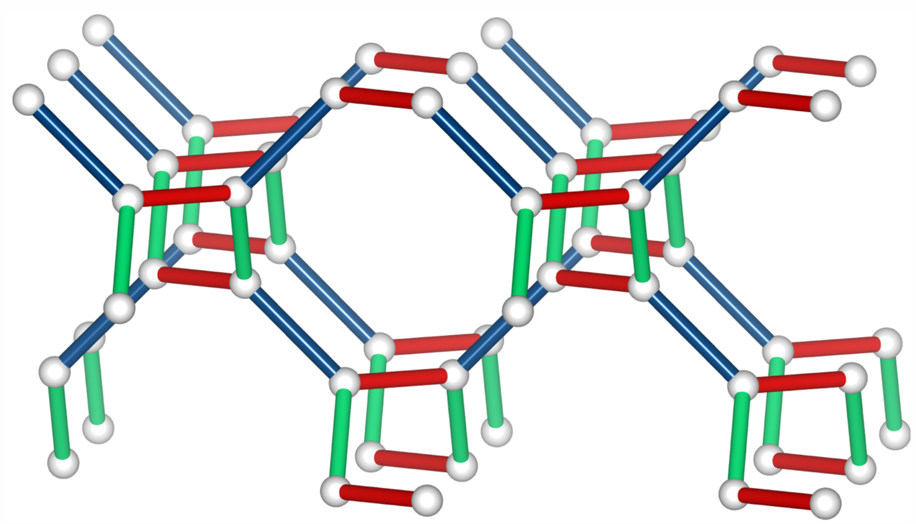
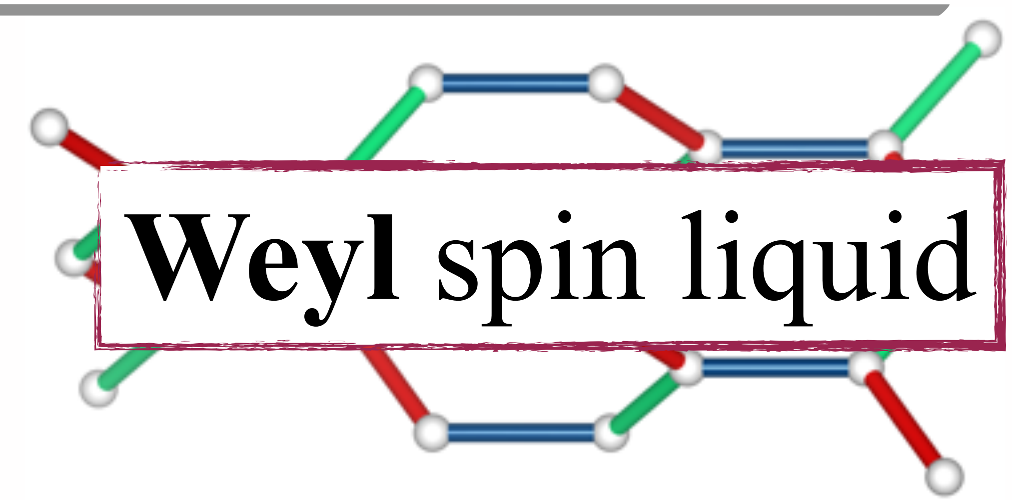
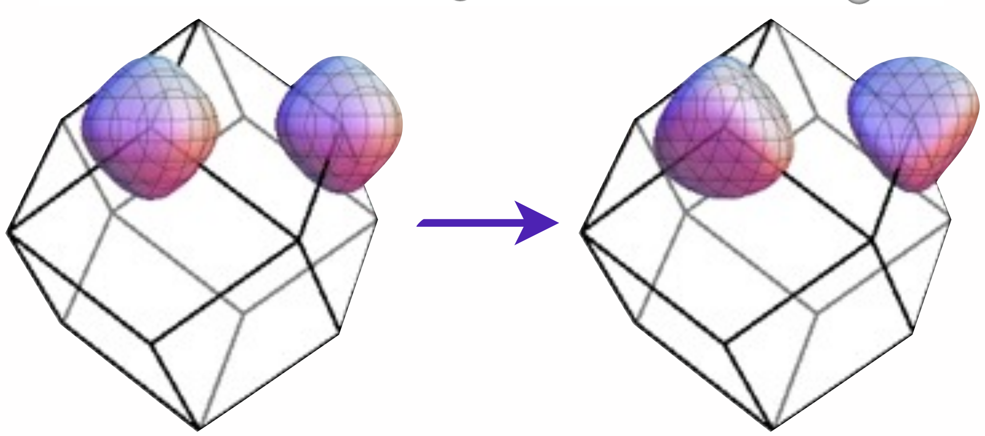






Weyl spin liquid



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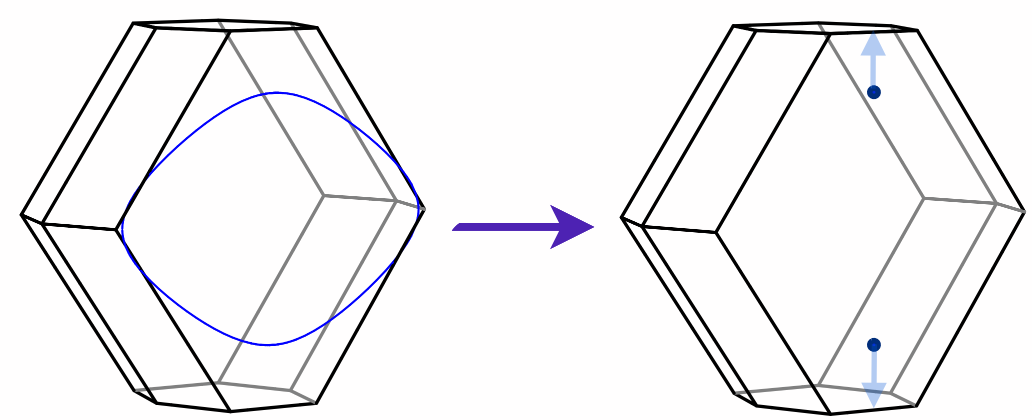

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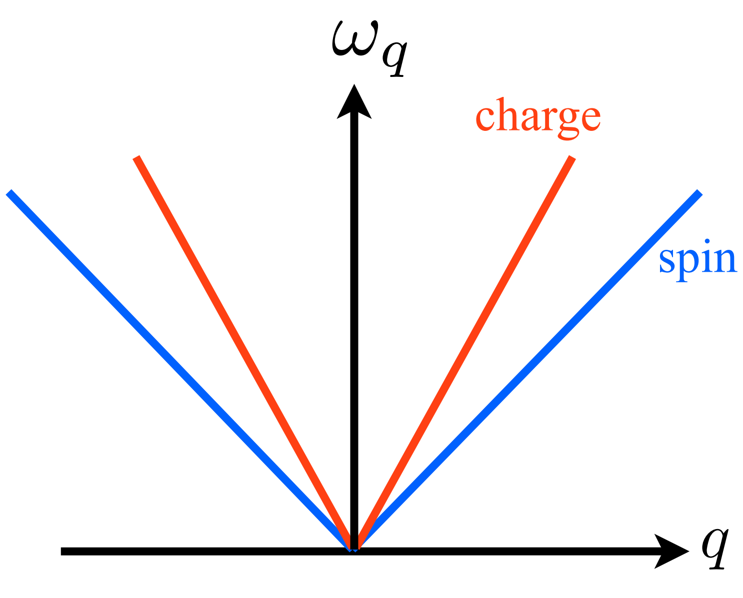
Summary

(Strong) interactions can lead to emergent quasiparticles
with 'fractional' quantum numbers

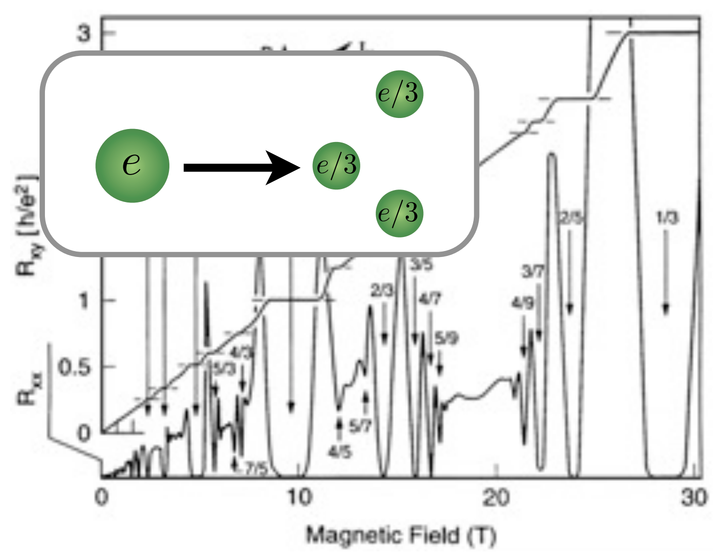
Spin-charge separation

Fermi gas in 1D



Electron fractionalization

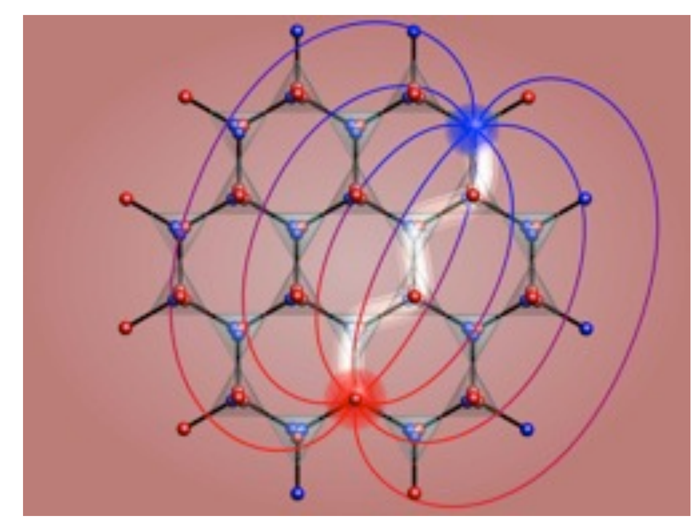
Quantum Hall liquids



Tsui, Störmer, Gossard, PRL **48**, 1559 (1982)

Magnetic monopoles

Spin ice



Castelnovo etal, Nature **451**, 22-23 (2007)

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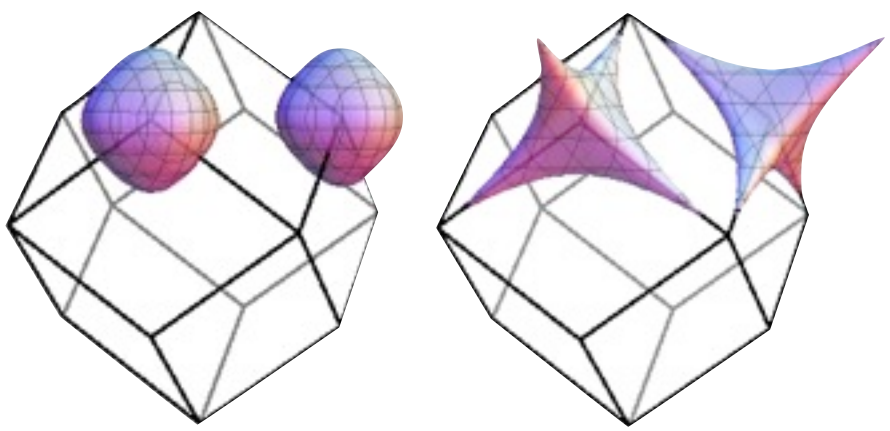
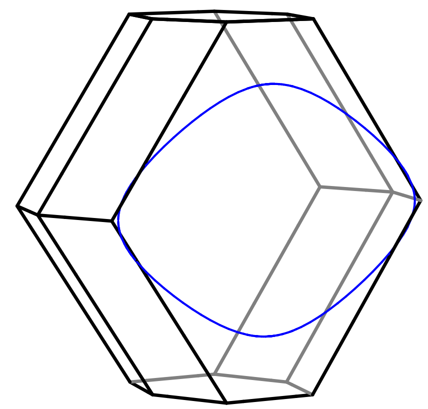
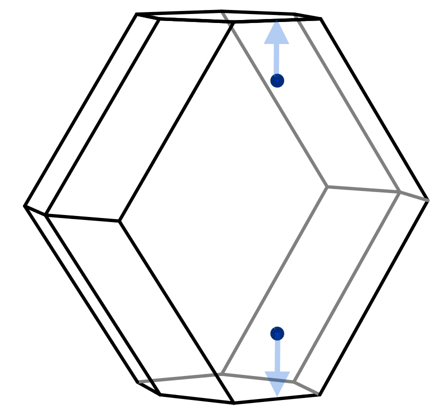
Spin liquid with emergent spinon Fermi surface



Spin liquid with emergent spinon Fermi line



Weyl spin liquid



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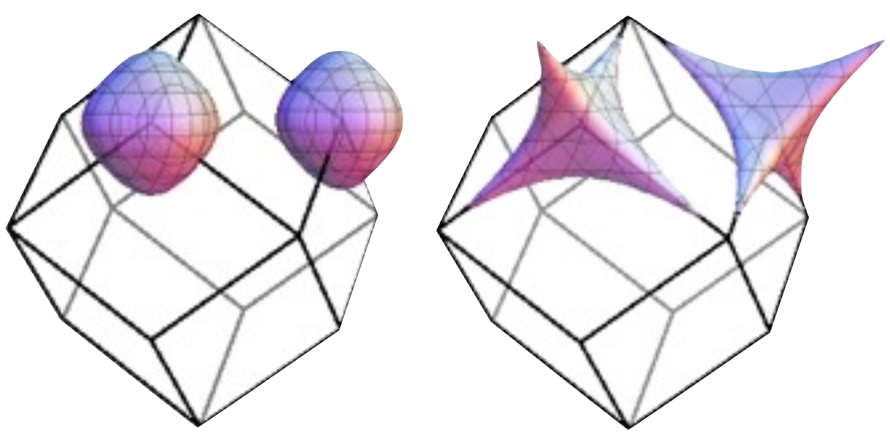

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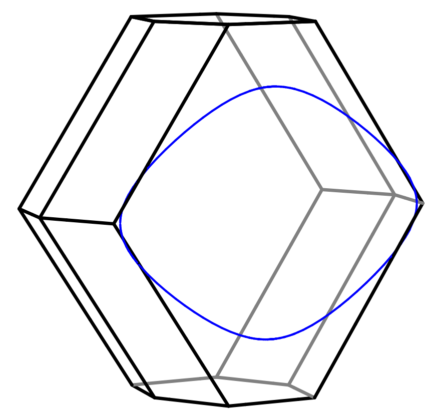

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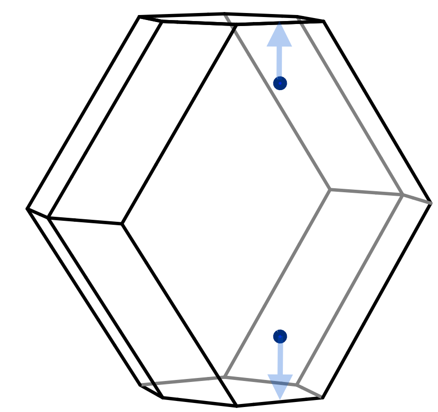

Majorana Metal ⟷ **Majorana semi-metal**

How big is the zoo of Majorana metals?

M. Hermanns and S. Trebst, PRB 89, 235102 (2014)
M. Hermanns, K. O’Brien, and S. Trebst, in preparation