ALTERMAGNETISM: AN UNCONVENTIONAL QUANTUM STATE OF MATTER

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SPICE + SPIN-X Seminar

April 08th, 2026

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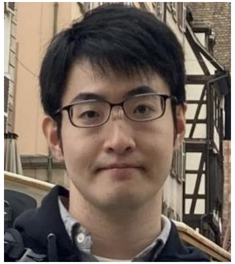

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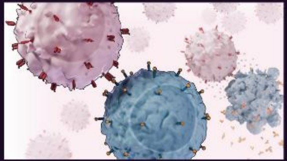
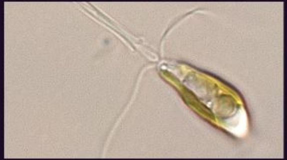
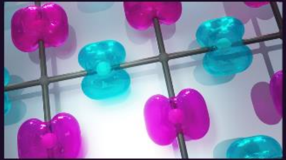
RUNNERS-UP


Unleashing immune cells on autoimmune disease


JWST probes the cosmic dawn


RNA-based pesticides enter the field


Organelle discovery adds an evolutionary twist

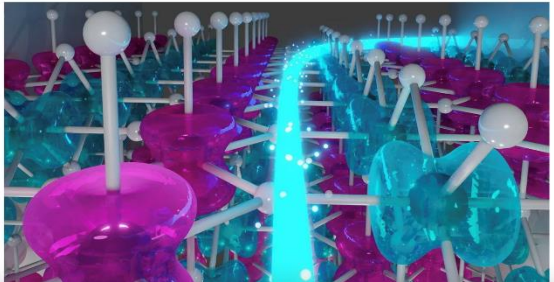

A new type of magnetism emerges


Multicellularity came early for ancient eukaryotes

Science & technology | Magnets. This is how they work

Scientists have found a new kind of magnetic material

"Altermagnets" have been hiding in plain sight for 90 years



FEBRUARY 14, 2024 Editors' notes

Altermagnetism: A new type of magnetism, with broad implications for technology and research

by Miriam Arrell, Paul Scherrer Institute

What are altermagnets?
And why are people excited about them?

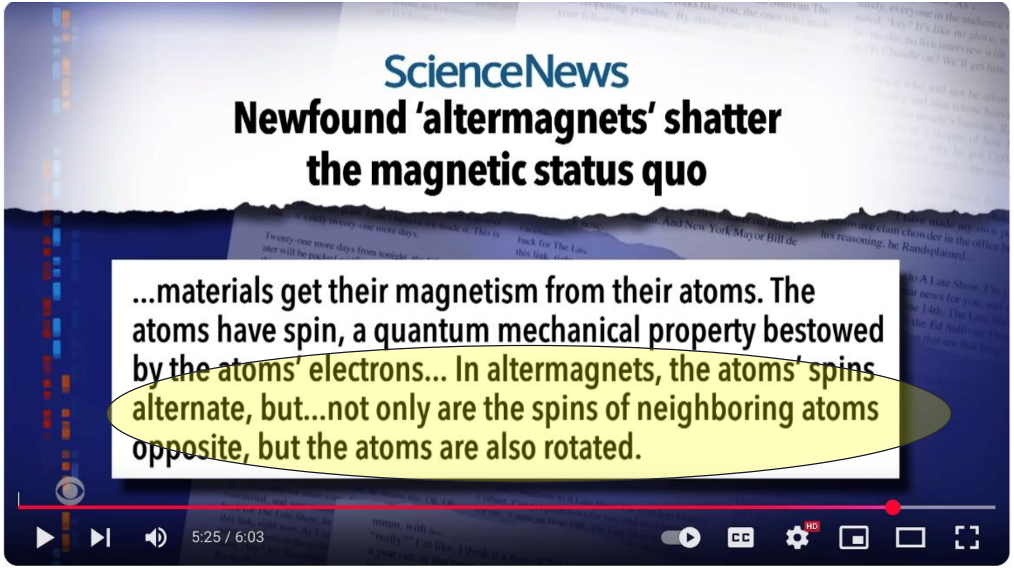
What is an altermagnet?

Dall-E, Feb-2024

- AI was a bit harsh…
- Let's ask Stephen Colbert.

What is an altermagnet?

- AI was a bit harsh…
- Let's ask Stephen Colbert.
- We need to help Colbert! Use symmetries to classify magnetic states.



Outline

1. Ferromagnets, antiferromagnets, and altermagnets: a matter of symmetry.
2. Altermagnetism: where to find them and what to do with them.
3. Correlated electronic phenomena in altermagnets.
4. Topological properties of altermagnets.

Outline

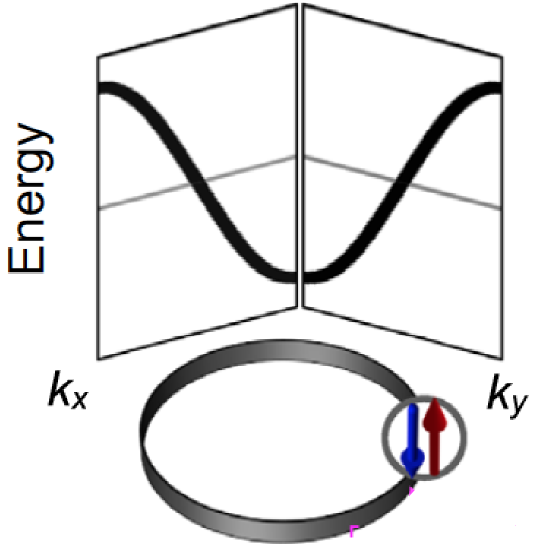
1. Ferromagnets, antiferromagnets, and altermagnets: a matter of symmetry.
2. Altermagnetism: where to find them and what to do with them.
3. Correlated electronic phenomena in altermagnets.
4. Topological properties of altermagnets.

for a recente review:

*Jungwirth, Sinova, RMF, Liu, Watanabe, Murakami, Nakatsuji & Šmejkal, Nature **649**, 837 (2026)*

Prelude: symmetry constraints on the electronic dispersion

- How the symmetries of the system affect the electronic bands degeneracy?
- $E_\sigma(\mathbf{k})$ is the energy at momentum **k** and with spin-component $\sigma = \uparrow, \downarrow$.



$$E_\sigma(\mathbf{k}) \xrightarrow{P} E_\sigma(-\mathbf{k})$$

figure from: Šmejkal et al, PRX (2022)

P : inversion
T : time reversal

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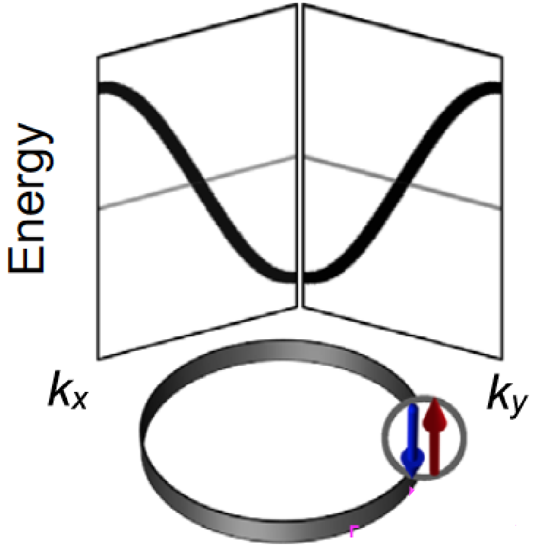

$$E_\sigma(\mathbf{k}) \xrightarrow{P} E_\sigma(-\mathbf{k})$$

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P : inversion
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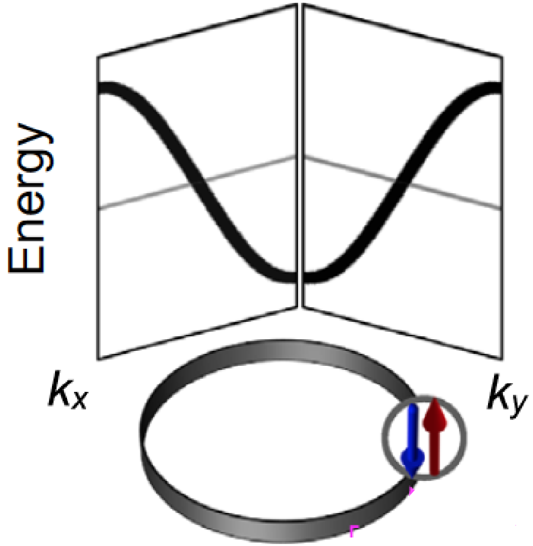

$$\left.\begin{array}{l} E_\sigma(\mathbf{k}) \xrightarrow{P} E_\sigma(-\mathbf{k}) \\ E_\sigma(\mathbf{k}) \xrightarrow{T} E_{-\sigma}(-\mathbf{k}) \end{array}\right\} E_\sigma(\mathbf{k}) \xrightarrow{PT} E_{-\sigma}(\mathbf{k})$$

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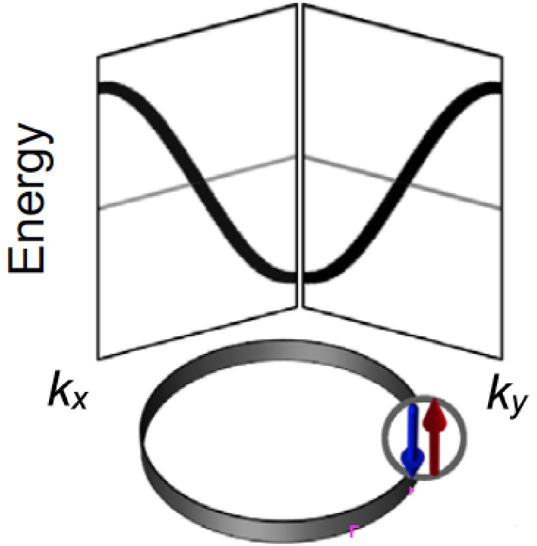


$$\left.\begin{array}{l} E_\sigma(\mathbf{k}) \xrightarrow{P} E_\sigma(-\mathbf{k}) \\ E_\sigma(\mathbf{k}) \xrightarrow{T} E_{-\sigma}(-\mathbf{k}) \end{array}\right\} E_\sigma(\mathbf{k}) \xrightarrow{PT} E_{-\sigma}(\mathbf{k})$$

If a system is invariant under the combination of inversion and time reversal (PT symmetry), its electronic bands are spin-degenerate.

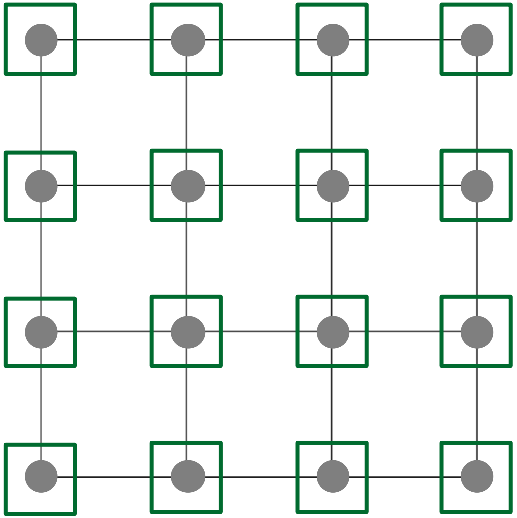
(see Kramers theorem)

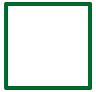
Magnetic states break time-reversal.

What happens to the electronic dispersion?

Classification of magnetic states

- Can a crystal symmetry that acts only on the positions of the atoms "undo" time reversal (flipping the spins)? *No spin-orbit coupling!*

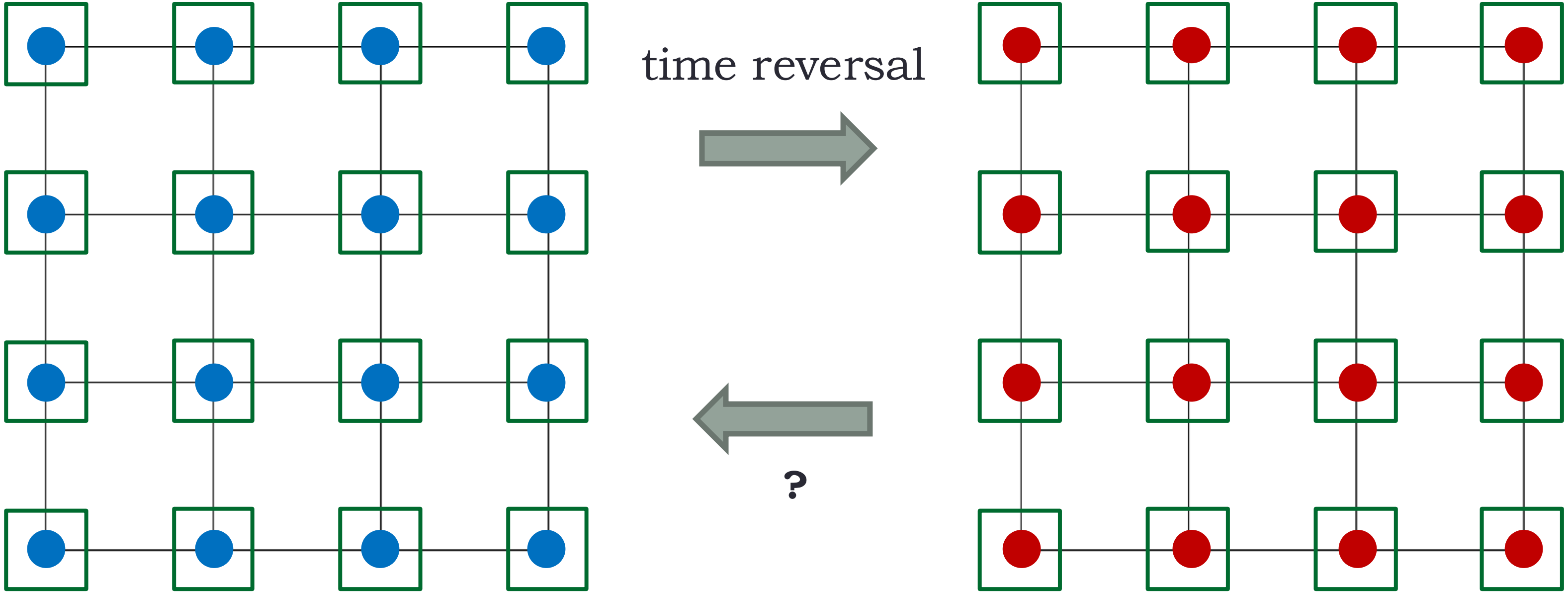




denotes the local atomic environment due to other atoms in the lattice (ligand fields)

Classification of magnetic states

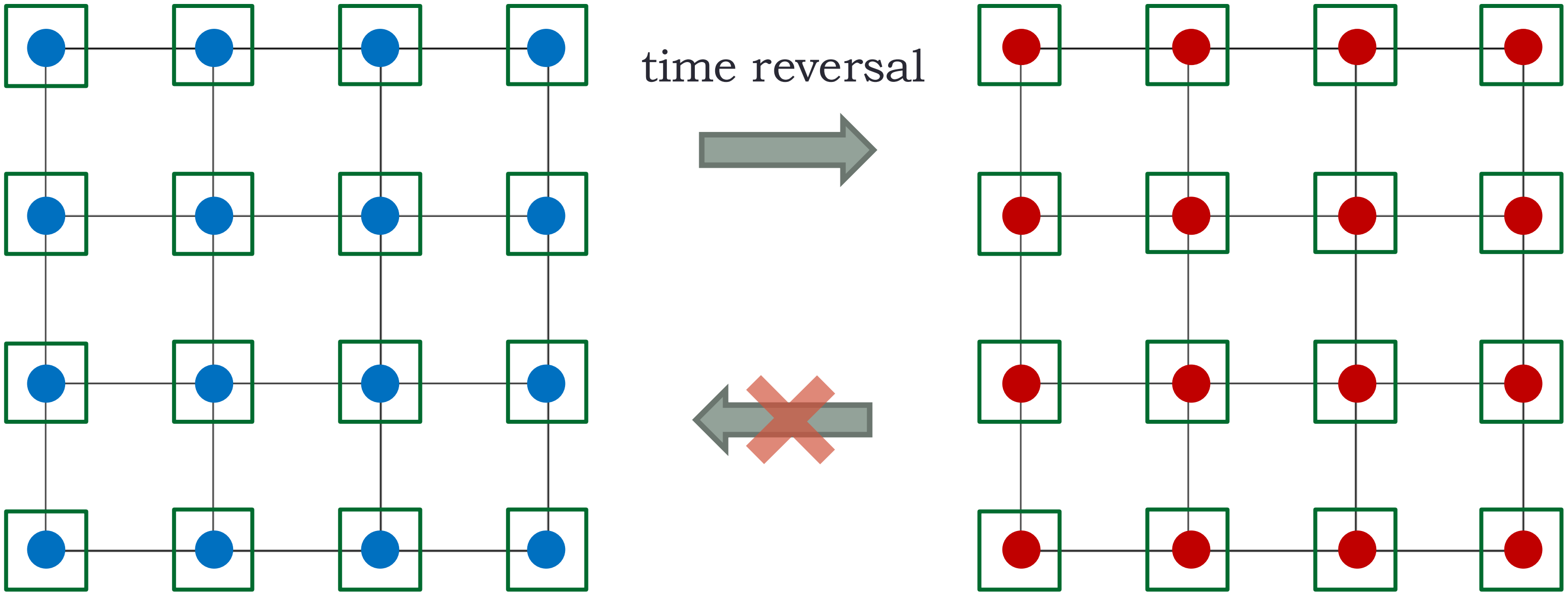
- Can a crystal symmetry that acts only on the positions of the atoms "undo" time reversal (flipping the spins)?
- Ferromagnets (F)



spin up
spin down

Classification of magnetic states

- Can a crystal symmetry that acts only on the positions of the atoms "undo" time reversal (flipping the spins)?
- Ferromagnets (F): **No**



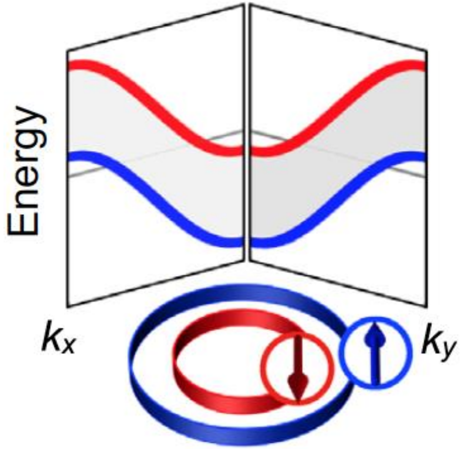
Spin-splitting in ferromagnets (F)

- Can a crystal symmetry that acts only on the positions of the atoms "undo" time reversal (flipping the spins)?
- Ferromagnets (F): **No**
  - Consequence: spin-degeneracy of the bands is lifted, resulting in a uniform Zeeman splitting between spin-up and spin-down bands.

$$E_\sigma(\mathbf{k}) \cancel{\xrightarrow{PT}} E_{-\sigma}(\mathbf{k})$$

P : inversion
T : time reversal

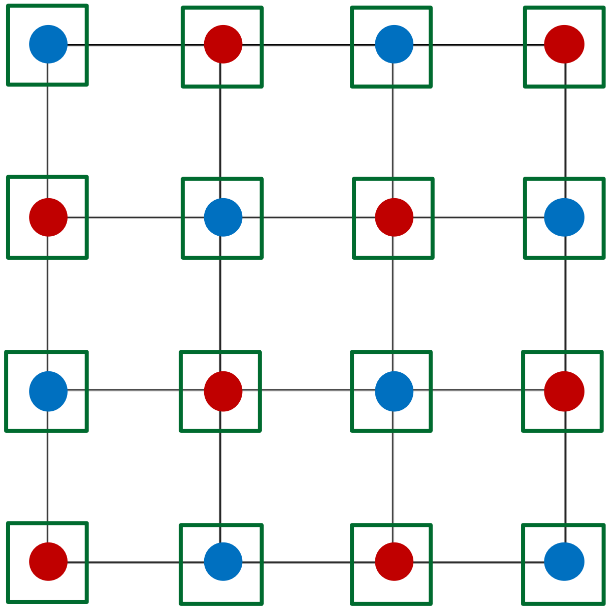
$$\Delta E(\mathbf{k}) \equiv E_\uparrow(\mathbf{k}) - E_\downarrow(\mathbf{k}) = E_0$$



Šmejkal et al, PRX (2022)

Classification of magnetic states

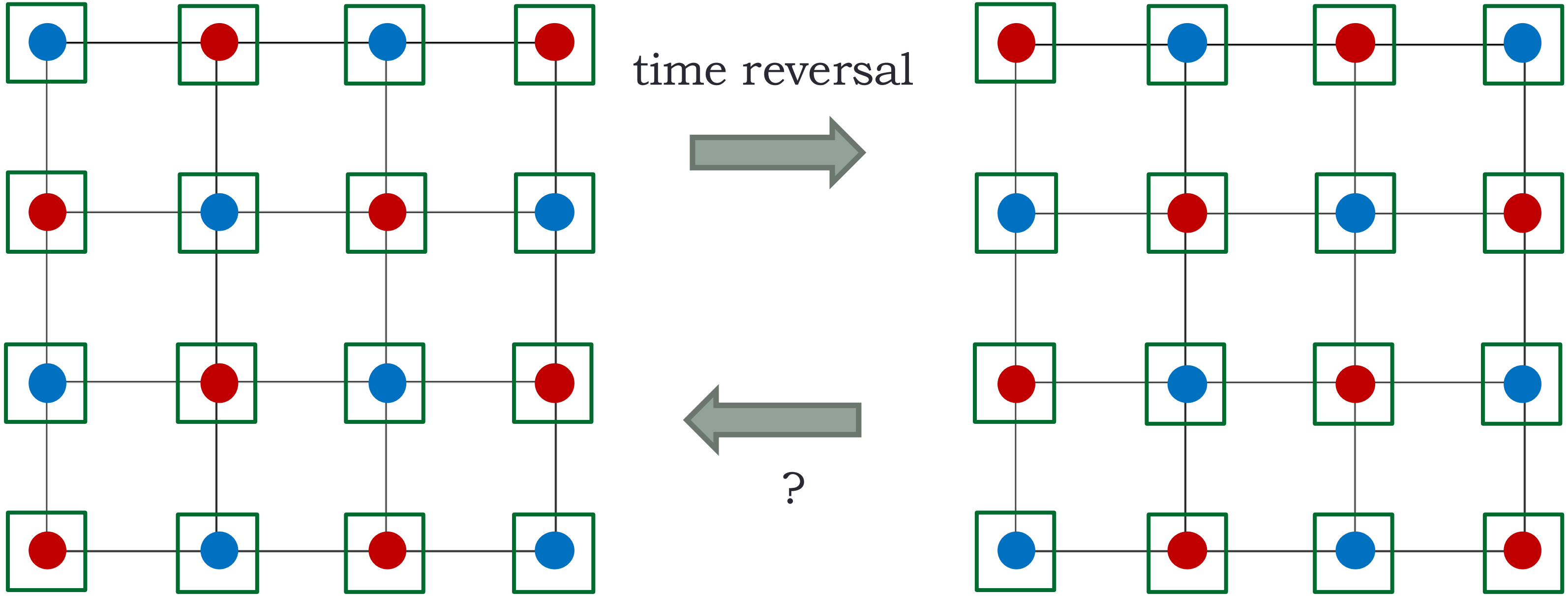
- Can a crystal symmetry that acts only on the positions of the atoms "undo" time reversal (flipping the spins)?
- Antiferromagnets (AF)



Classification of magnetic states

spin up
spin down

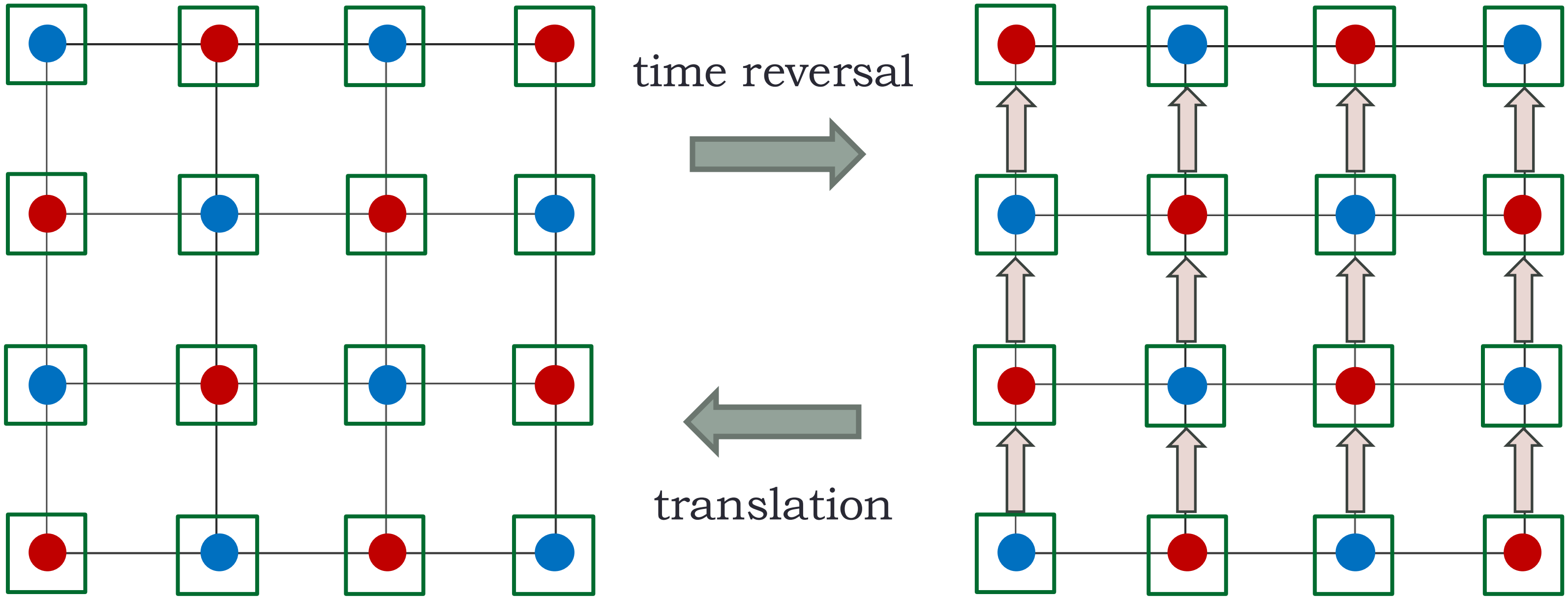
- Can a crystal symmetry that acts only on the positions of the atoms "undo" time reversal (flipping the spins)?
- Antiferromagnets (AF)



Classification of magnetic states

spin up (blue) / *spin down* (red)

- Can a crystal symmetry that acts only on the positions of the atoms "undo" time reversal (flipping the spins)?
- Antiferromagnets (AF): **Yes**



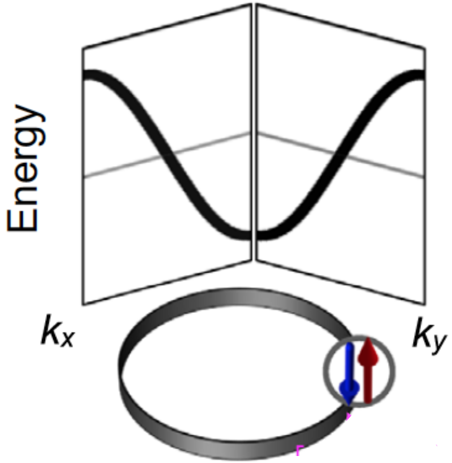
Spin-splitting in antiferromagnets (AF)

- Can a crystal symmetry that acts only on the positions of the atoms "undo" time reversal (flipping the spins)?
- Antiferromagnets (AF): **Yes**
  - ➢ Consequence: spin-degeneracy of the bands is preserved; no Zeeman splitting between spin-up and spin-down bands.

$$E_\sigma(\mathbf{k}) \xrightarrow{PT\tau} E_{-\sigma}(\mathbf{k})$$

$$\tau : \text{translation}$$

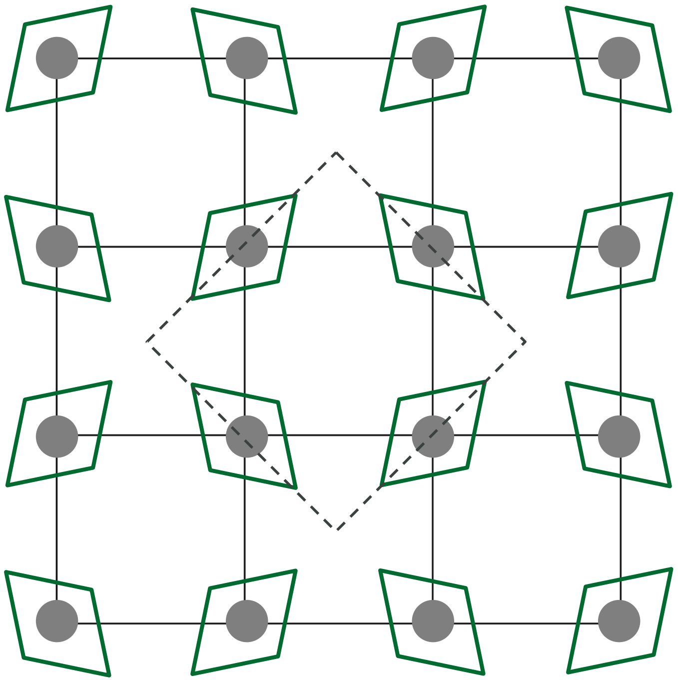
$$\Delta E(\mathbf{k}) \equiv E_\uparrow(\mathbf{k}) - E_\downarrow(\mathbf{k}) = 0$$

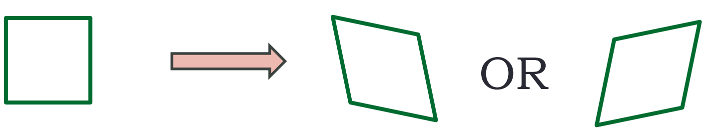


Šmejkal et al, PRX (2022)

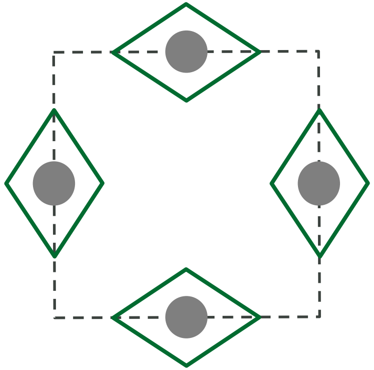
Classification of magnetic states

- Are there any other options besides F and AF?
- Consider the situation with two inequivalent atoms in a unit cell.





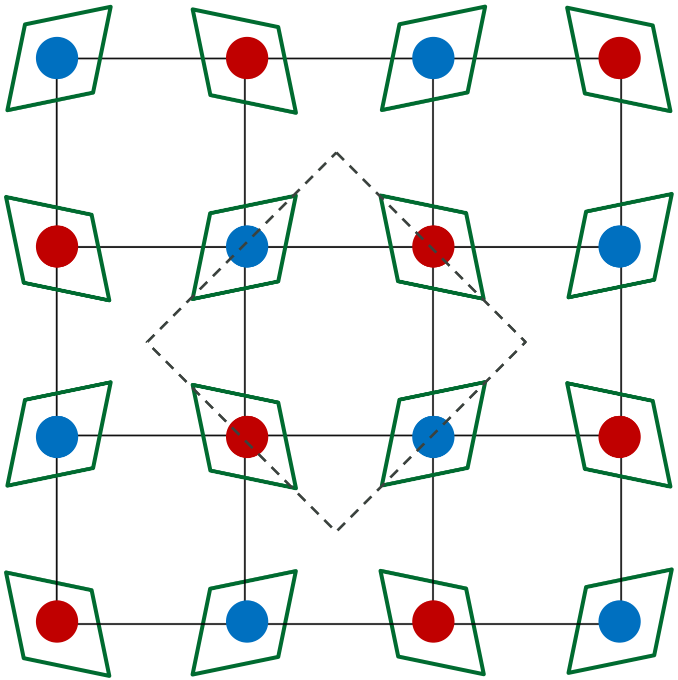
change in the symmetry of the local atomic environment



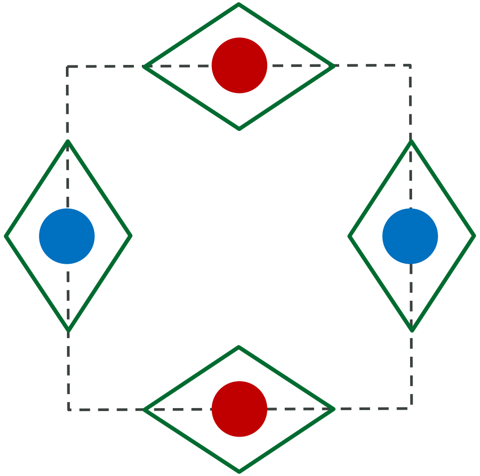
new unit cell

Classification of magnetic states

- Are there any other options besides F and AF?
- Antiparallel-spin configuration: no longer an antiferromagnet.



- *magnetic order no longer breaks translational symmetry (**Q=0**)*



- *translation cannot "undo" time reversal*

Classification of magnetic states

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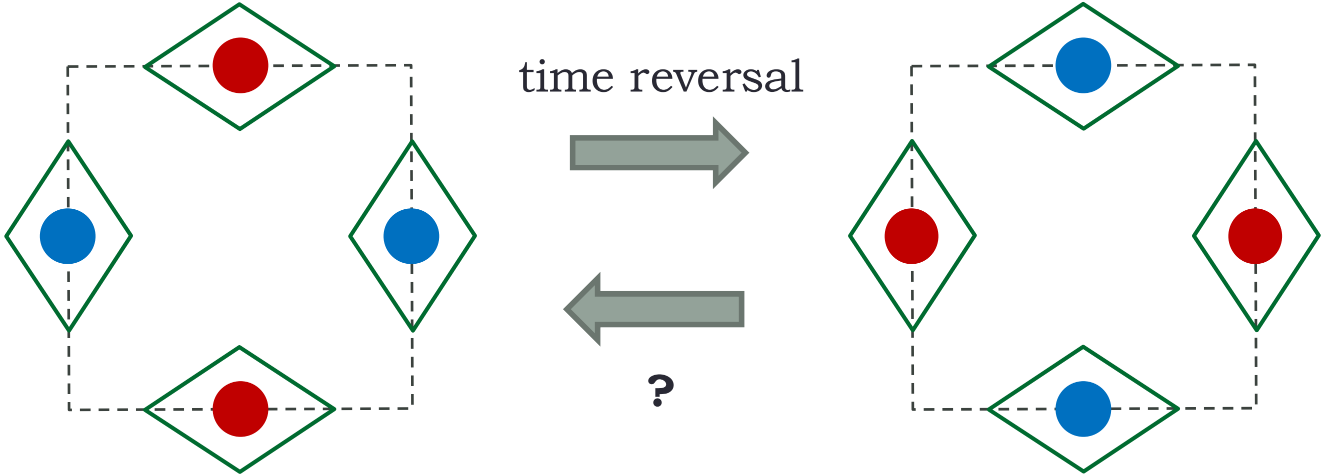

Classification of magnetic states

spin up
spin down

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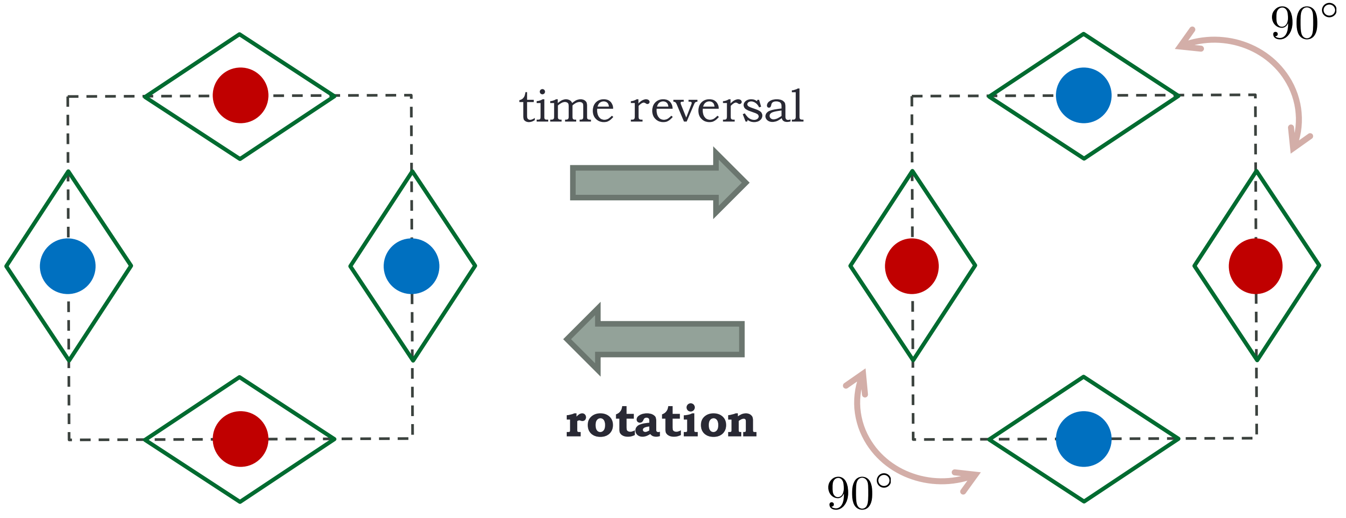

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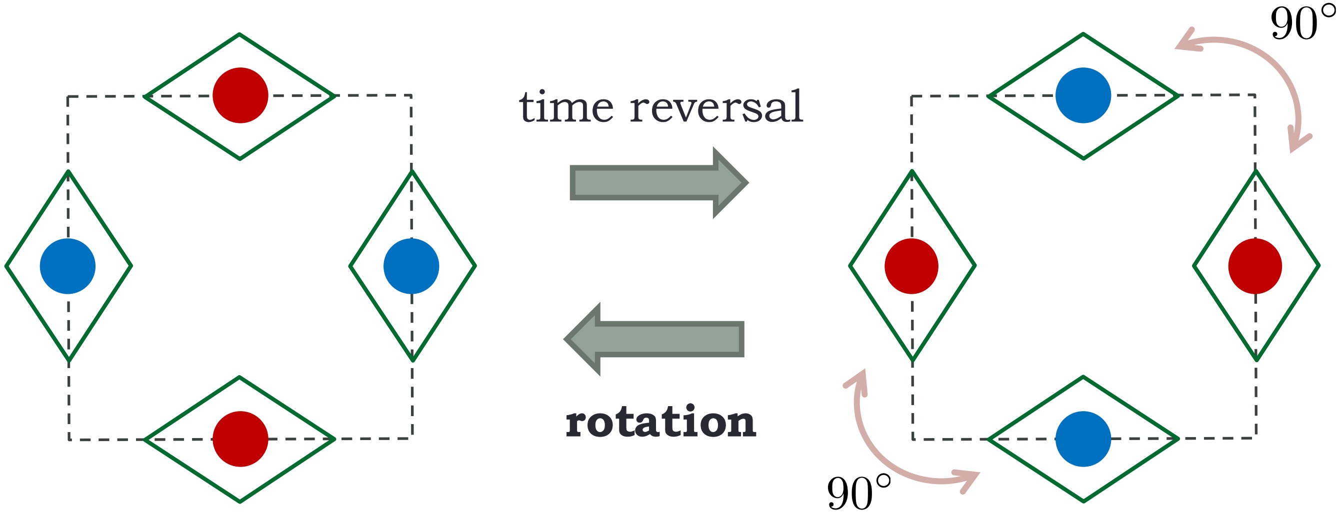

***Altermagnets* (AM): configurations with flipped spins are related by a rotation**

Šmejkal et al, Sci Adv (2020)
Šmejkal et al, PRX (2022)

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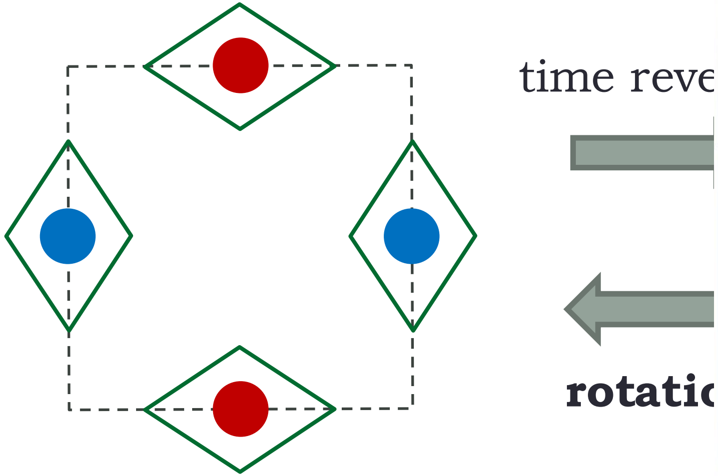
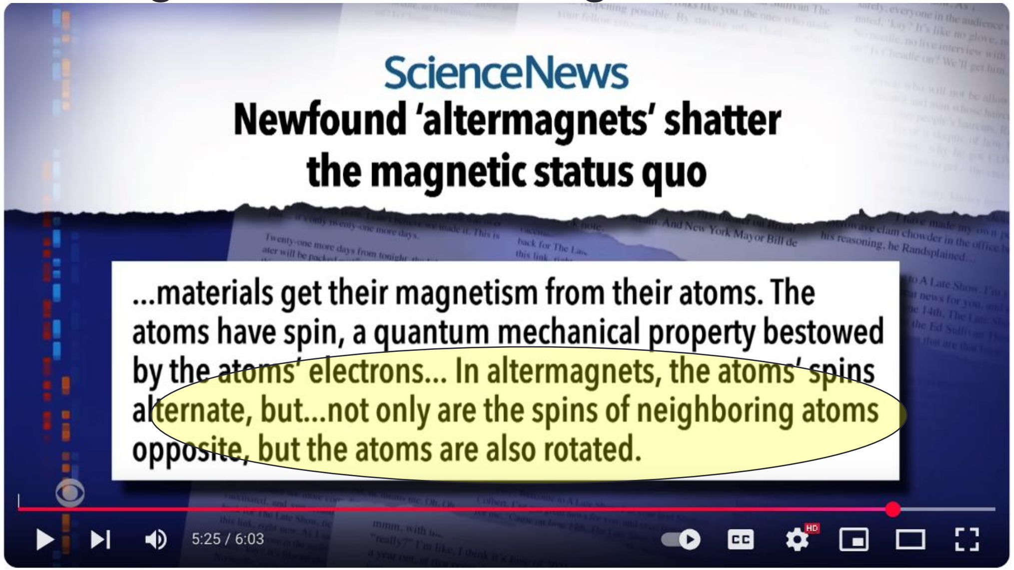




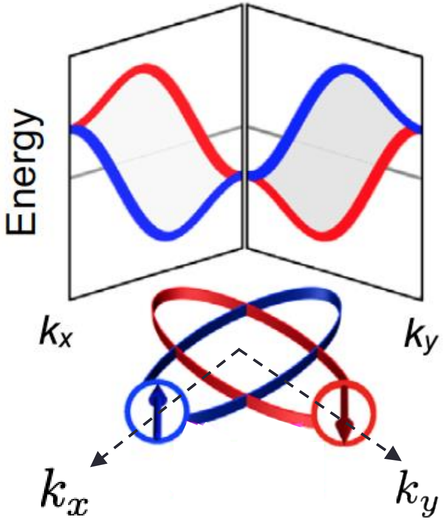
***Altermagnets* (AM): configurations with flipped spins are related by a rotation**

Šmejkal et al, Sci Adv (2020)
Šmejkal et al, PRX (2022)

Spin-splitting in altermagnets (AM)

- Band structure shows spin splitting, despite the vanishing magnetization and the absence of SOC.
- However, the spin-splitting generally has zeroes (nodes) enforced by the type of rotational symmetry $\mathcal{R}$ that characterizes the AM state.

$$E_\sigma(\mathbf{k}) = E_{-\sigma}(\mathcal{R}\mathbf{k})$$



spin-splitting even in the absence of spin-orbit coupling: non-relativistic spin-splitting

Šmejkal, Gonzalez-Hernandez, Jungwirth & Sinova, Science Adv. (2020)

Šmejkal, Sinova & Jungwirth, PRX (2022)

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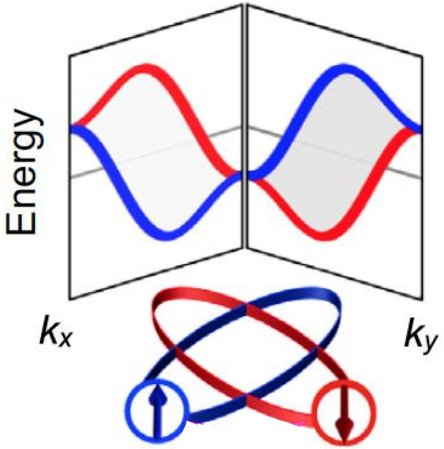
spin-splitting even in the absence of spin-orbit coupling: non-relativistic spin-splitting

Other approaches finding non-relativistic spin splitting: Hayami et al, JPSJ (2019); Naka et al, Nat Comm (2019); Yuan et al, PRB (2020).



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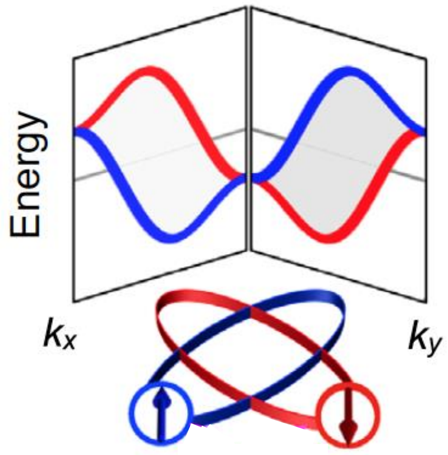
"d-wave magnet"

$$\Delta E(\mathbf{k}) \equiv E_\uparrow(\mathbf{k}) - E_\downarrow(\mathbf{k}) \propto \cos k_x - \cos k_y$$

other symmetries possible:
g-wave, i-wave, etc

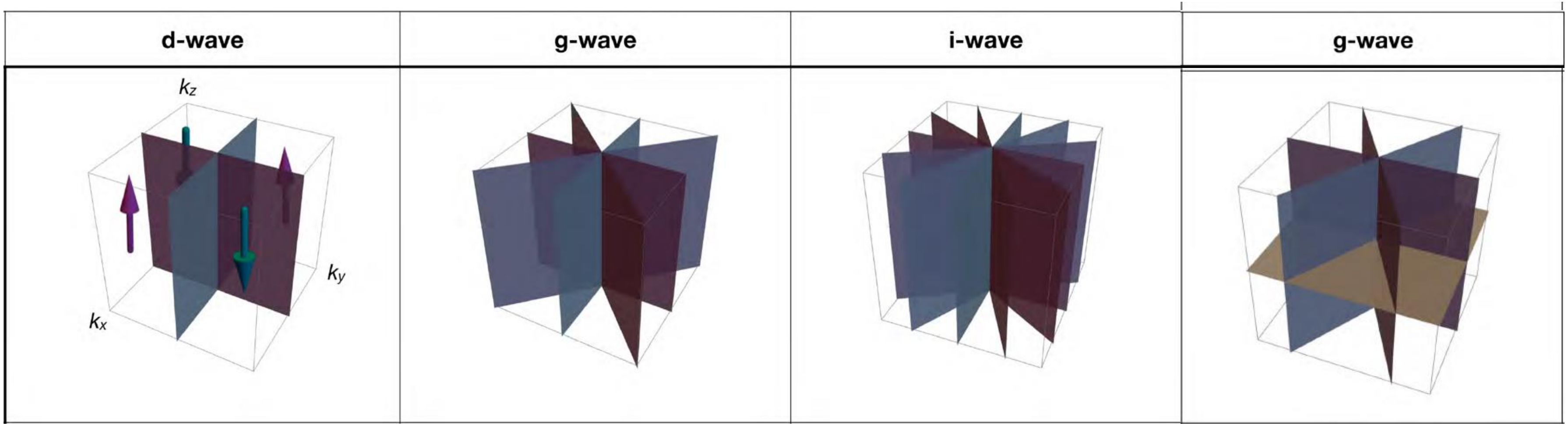


Šmejkal et al, PRX (2022)

Spin-splitting in altermagnets (AM)

- Spin splitting has even symmetry.

$$\Delta E(\mathbf{k}) \equiv E_{\uparrow}(\mathbf{k}) - E_{\downarrow}(\mathbf{k}) = E_0 f(\mathbf{k}) \qquad \begin{cases} f(-\mathbf{k}) = f(\mathbf{k}) \neq \text{const} \\ \langle f(\mathbf{k}) \rangle = 0 \end{cases}$$

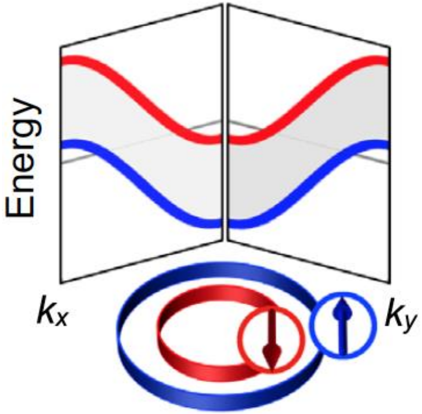


Šmejkal et al, PRX (2022)

Ferromagnets, antiferromagnets, and altermagnets

- Three types of *collinear* magnetic states based on the type of crystalline symmetry that relates configurations with flipped spins. *[Šmejkal et al, PRX (2022)]*[2]

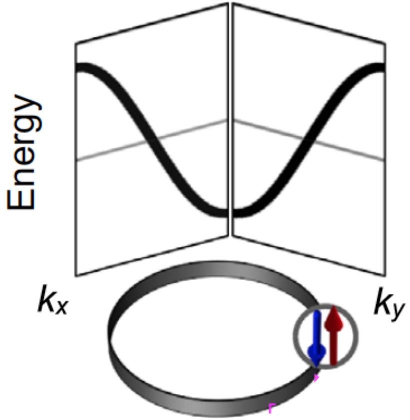
ferromagnetism (F)



no symmetry

$$\Delta E(\mathbf{k}) = E_0$$

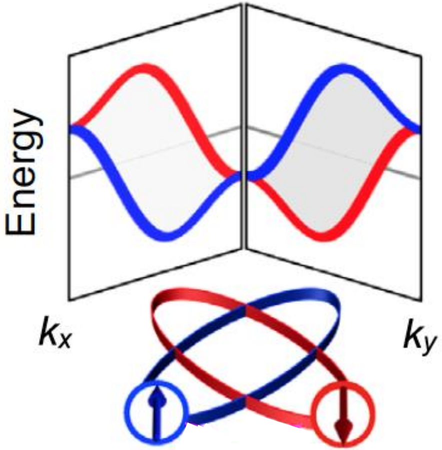
antiferromagnetism (AF)



translation, inversion

$$\Delta E(\mathbf{k}) = 0$$

altermagnetism (AM)



rotation (proper or improper)

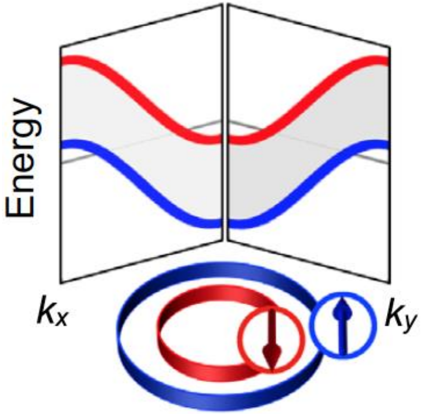
$$\Delta E(\mathbf{k}) = E_0 f(\mathbf{k})$$

$$f(-\mathbf{k}) = f(\mathbf{k}) \neq \text{const}$$

Ferromagnets, antiferromagnets, and altermagnets

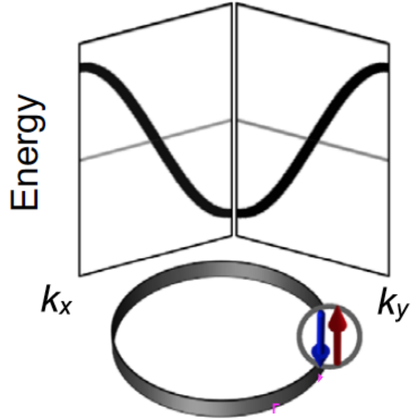
- Three types of *collinear* magnetic states based on the type of crystalline symmetry that relates configurations with flipped spins. [*Šmejkal et al, PRX (2022)*][2]

ferromagnetism (F)



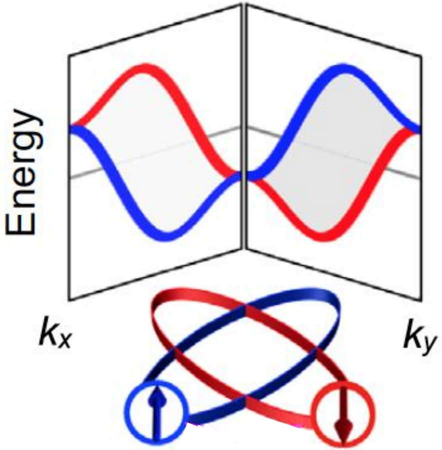
no symmetry

antiferromagnetism (AF)



translation, inversion

altermagnetism (AM)



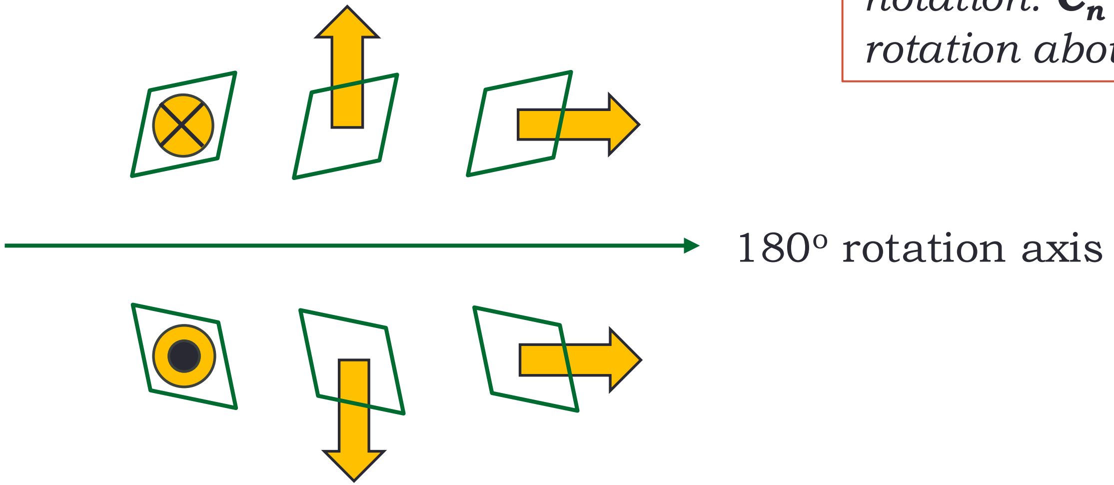
rotation (proper or improper)

can this classification be cast in a formal way using group theory?

Spin groups *vs* magnetic groups

- In the presence of spin-orbit coupling (SOC): a rotation of the crystal also rotates the spins.

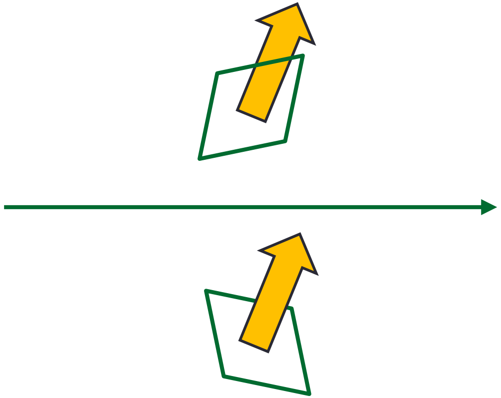
notation: $\boldsymbol{C_n}$ *is an n-fold rotation about an axis*



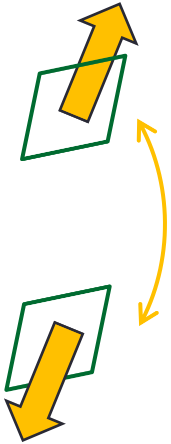
- In group-theory language: spins transform as irreducible representations of the point group (***magnetic groups***). There are four different types of magnetic space groups.

Spin groups *vs* magnetic groups

- Without spin-orbit coupling (SOC): spins can be rotated independently of the crystal lattice.



180° rotation
(C_2 real space)



180° rotation
(C_2 spin space)

- In group-theory language: spins transform as the irreducible representations of the SO(3) group *(**spin groups**)*.

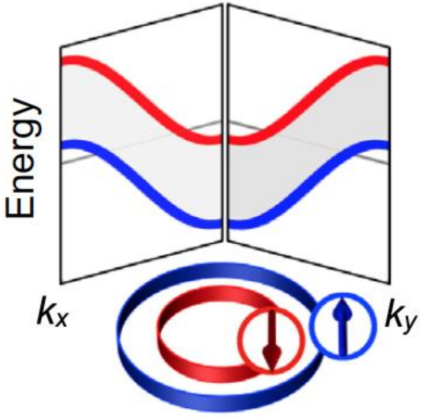
theory of spin groups: Brinkman & Elliott, Proc. R. Soc. A (1966); Litvin & Opechowski, Physica (1974); Litvin, Acta Cryst. (1977)

Ferromagnets, antiferromagnets, and altermagnets

- Robust classification of three different types of *collinear* magnetic states in terms of *spin groups* (no spin-orbit coupling).

Šmejkal et al, PRX (2022)

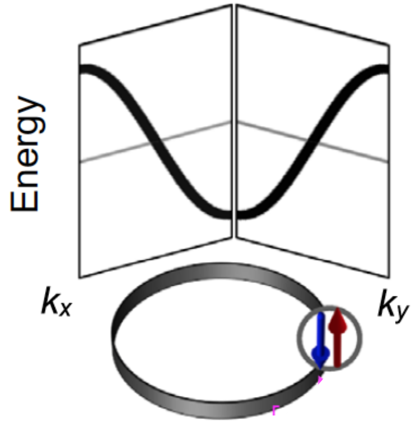
ferromagnetism (F)



$[E||\mathbf{G}]$

type-I SG

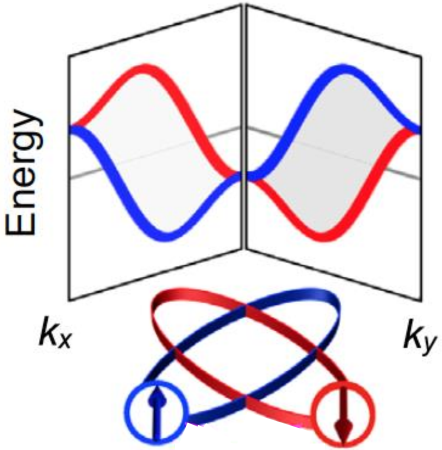
antiferromagnetism (AF)



$[E||\mathbf{G}] + [C_2||\mathbf{G}]$

type-II SG

altermagnetism (AM)



$[E||\mathbf{H}] + [C_2||A\mathbf{H}]$

type-III SG

for non-collinear orders, see: Jiang et al, PRX (2024); Chen et al, PRX (2024); Xiao et al, PRX (2024)


call an altermagnet an
antiferromagnet
I will not call an altermagnet an
antiferromagnet
I will not call an altermagnet an
antiferromagnet
I will not call an altermagne
antiferromagnet
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antiferromagnet

- The distinction between ferromagnets (F), antiferromagnets (AF), and altermagnets (AM) is only sharp without spin-orbit coupling (SOC).

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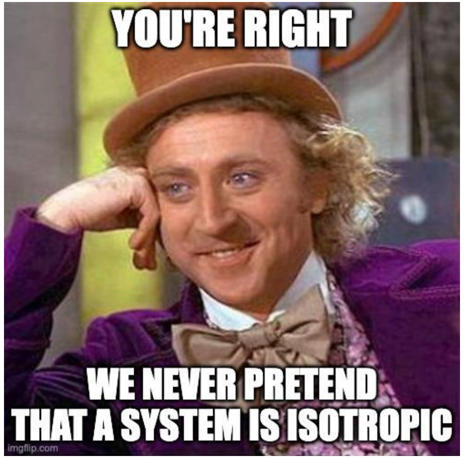
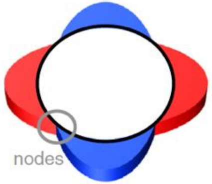
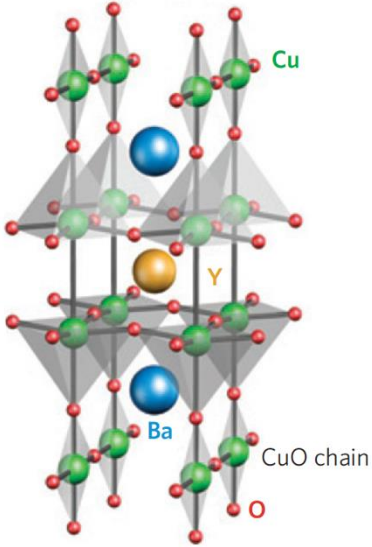


- ***superconductors***

s-wave



d-wave

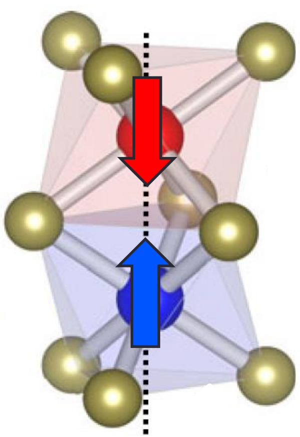


YBCO, the posterchild of high-T_c superconductivity, is an orthorhombic crystal

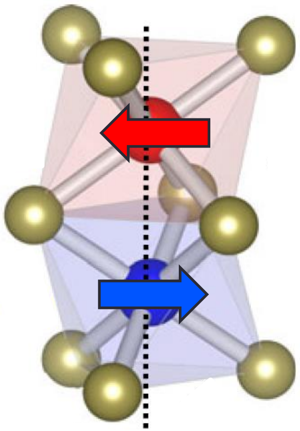
in the orthorhombic point group, s-wave and d-wave have the same symmetry properties…

- The distinction between ferromagnets (F), antiferromagnets (AF), and altermagnets (AM) is only sharp without spin-orbit coupling (SOC).

- This does not mean that SOC is incompatible with AM. Generally, when SOC is included, two outcomes are possible depending on the direction of the magnetic moments: **AM + weak F** or **pure AM**.



out-of-plane:
pure AM
(CrSb)



in-plane:
AM + weak F
(MnTe)

RMF, Carvalho, Birol & Pereira, PRB (2024)

Outline

1. Ferromagnets, antiferromagnets, and altermagnets: a matter of symmetry.
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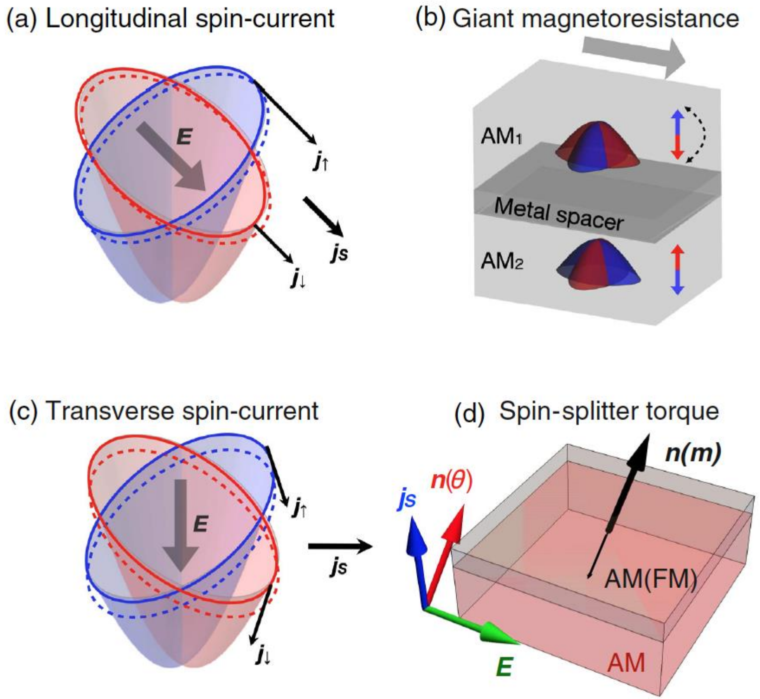
Altermagnetism: potential applications

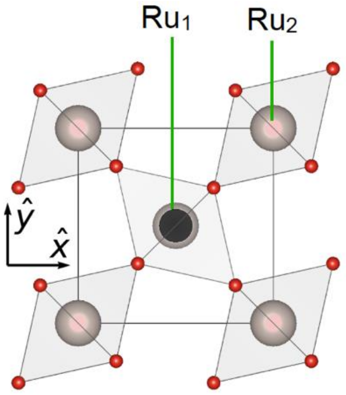
- Promising systems for spintronics: non-zero spin-splitting of the bands (like ferromagnets) and no net magnetization (like antiferromagnets).



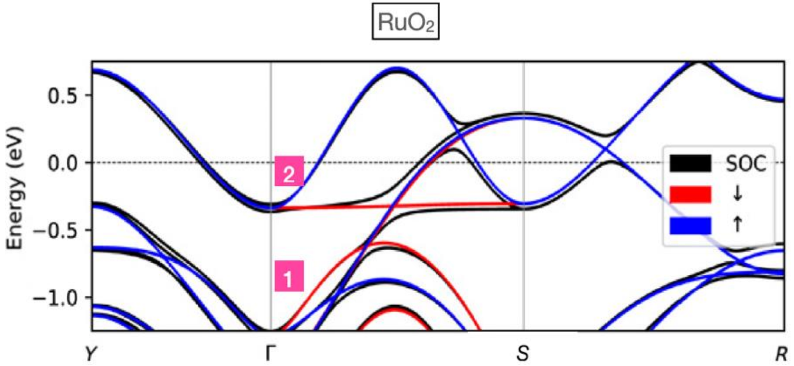
Šmejkal et al, PRX (2022)

Altermagnetic material candidates

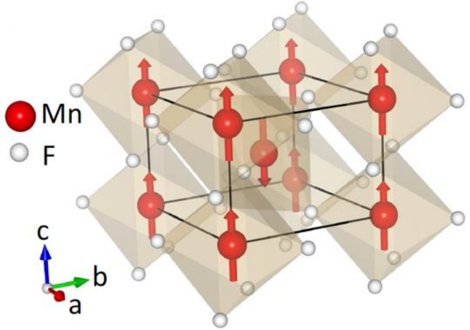
- Materials with rutile structure and collinear magnetic order are prime candidates to realize altermagnetism: RuO_2, MnF_2, CuF_2.



Guo et al,
Mater Today Phys (2023)



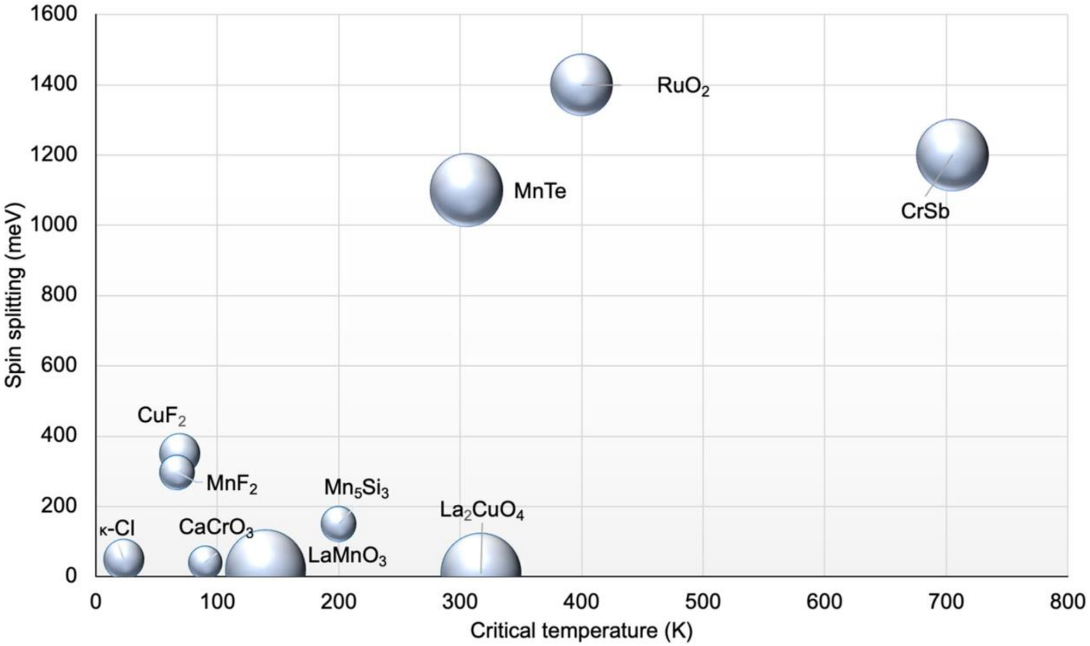
Šmejkal et al, PRX (2022)
Kuneš et al, PRB (2019)
Šmejkal et al, Sci Adv (2020)



Bhowal & Spaldin,
PRX (2023)

Altermagnetic material candidates

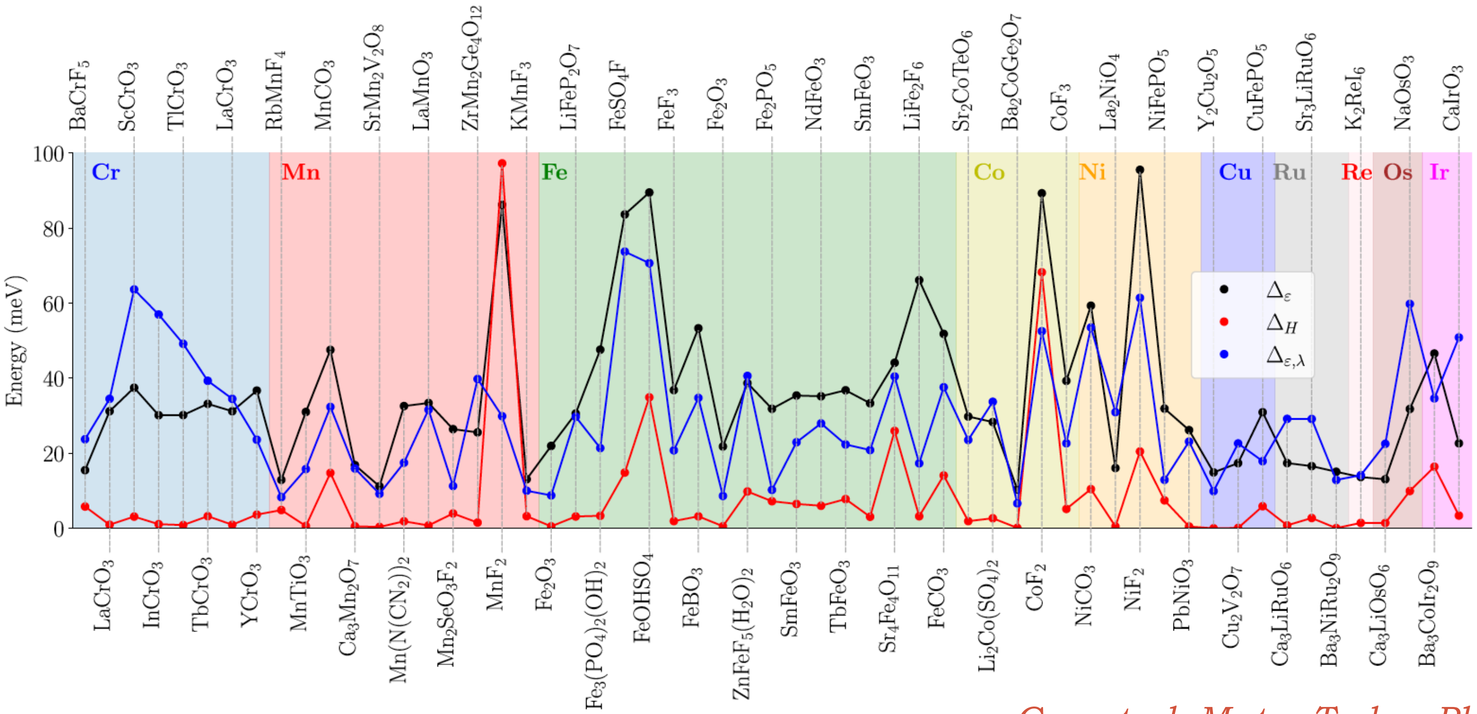
- Spin splitting values can be very large, of the order of electron-Volt, which is much larger than the spin splitting values enabled by SOC.



Šmejkal et al, PRX (2022)

Altermagnetic material candidates

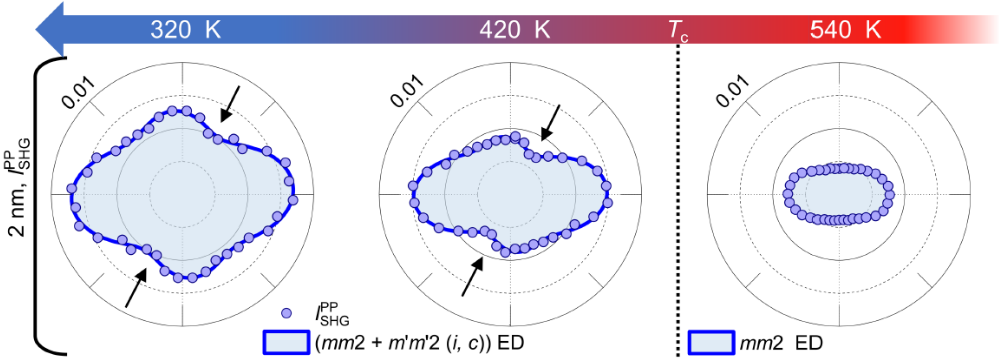
- *Ab initio* calculations reveal a large poll of material candidates displaying a broad range of spin-splitting magnitudes.

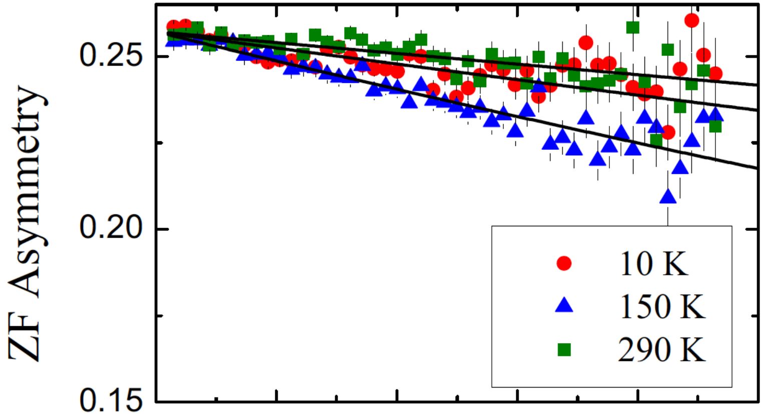


Guo et al, Mater Today Phys (2023)

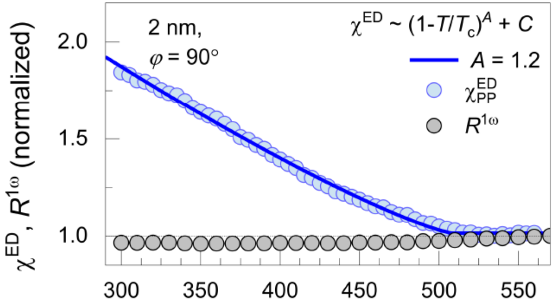
Altermagnetic materials: experimental results

- Altermagnetic status of RuO_2 under debate (bulk *vs* thin films?).





Second-harmonic generation data in thin films show fingerprints of altermagnetic order. Strain effect seems crucial to stabilize magnetism.



Jeong, ..., RMF, ... et al, PNAS (2026)

muon spin rotation: no oscillations

Kessler et al, npj Spintronics (2024)

earlier scattering experiments:

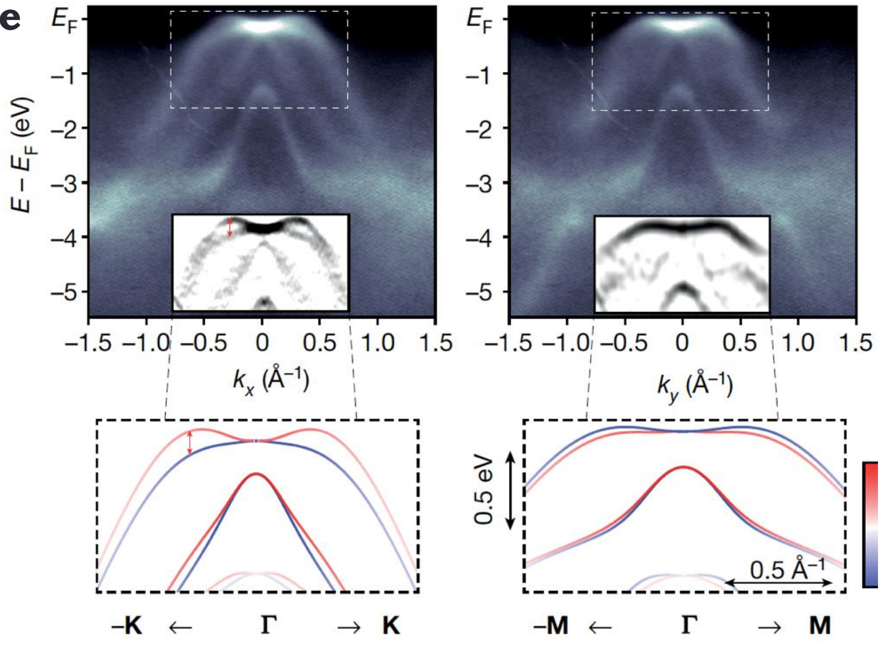
Berlijn et al, PRL (2017)

Zhu et al, PRL (2019)

Altermagnetic materials: experimental results

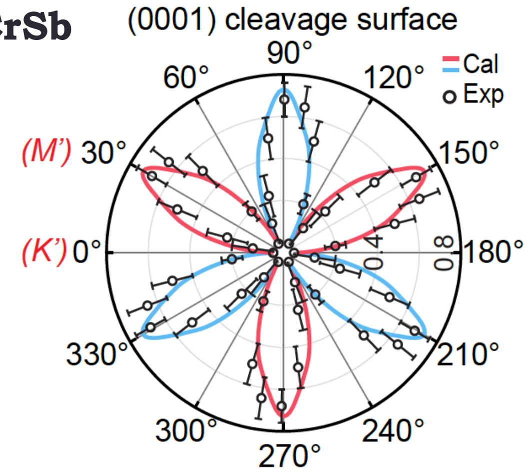
- ARPES measurements on MnTe and CrSb demonstrate altermagnetism.

MnTe



Krempansky et al, Nature (2024)

CrSb



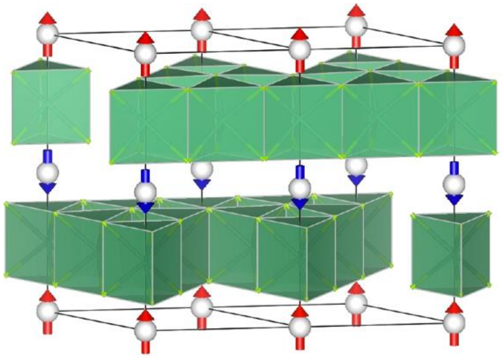
Ding et al, PRL (2024)

Zeng et al, Adv. Science (2024)

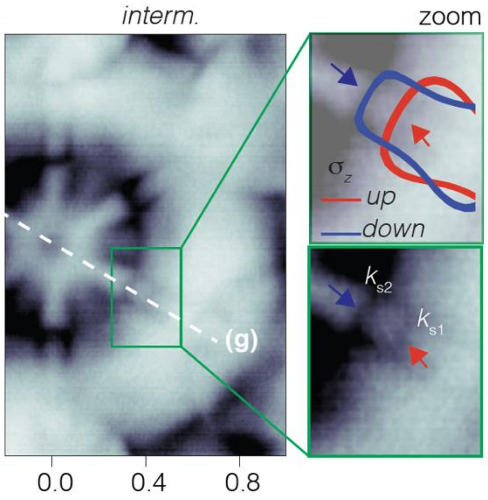
Yang et al, Nature Comm (2025)

Altermagnetic materials: experimental results

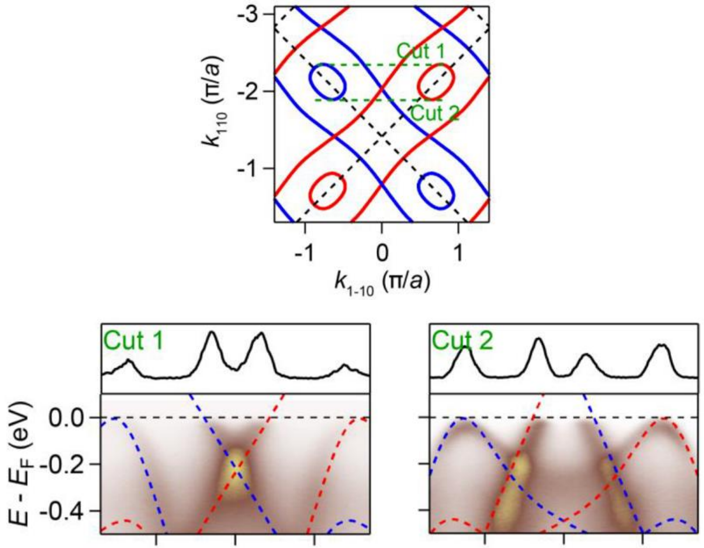
- Spin-resolved ARPES measurements in $Co_{1/4}NbSe_2$ and KV_2Se_2O (surface only) also show spin splitting characteristic of altermagnets.



Babu Regmi et al, Nature Comm (2025)



de Vita et al, arxiv (2025)



Jiang et al, Nature Phys (2025)

Zhang et al, Nature Phys (2025)

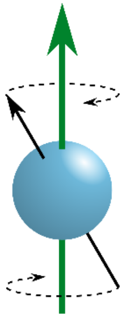
Sun et al, PRB (2025)

Thermodynamic signatures of altermagnetism

- Is there another way to probe altermagnetism besides probing its spin-resolved band structure?
- Altermagnets are invariant under a combination of TR and rotation.

Thermodynamic signatures of altermagnetism

- Is there another way to probe altermagnetism besides probing its spin-resolved band structure?
- Altermagnets are invariant under a combination of TR and rotation.
- Magnetic fields break time-reversal symmetry, whereas strain can break the rotational symmetry around a particular axis.

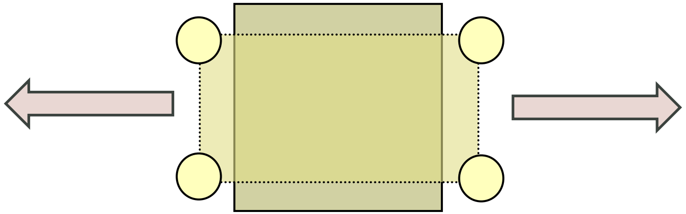


$\vec{H}$

(axial vector)

$$\varepsilon_{\alpha\beta} = \frac{1}{2}\left(\partial_\alpha u_\beta + \partial_\beta u_\alpha\right)$$

(symmetric rank-2 tensor)



- Thus, one expects that, in altermagnets, application of a magnetic field should induce strain and vice versa. This property is called **piezomagnetism**.

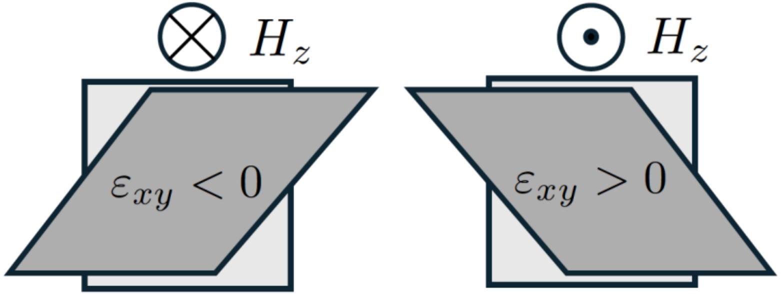
Thermodynamic signatures of altermagnetism

- Altermagnets display **piezomagnetism**.

Dzyaloshinskii, JETP (1958)

$$\varepsilon_{\alpha\beta} = \Lambda_{\alpha\beta\gamma} H_{\gamma}$$

see also: Steward, RMF, Schmalian PRB (2023); McClarty & Rau, PRL (2024)



- Piezomagnetism: strain induces magnetization whereas magnetic fields induce symmetry-breaking lattice distortions.
- Certain piezomagnetic tensor elements are proportional to the AM order parameter: direct experimental detection.
- Different than magnetostriction, which is quadratic in the field.

new effects in the presence of disorder: Chakraborty, Schmalian & RMF, PRB (2025); Meese & RMF, in preparation

Fingerprints of altermagnetism: summary

- **For any direction of the moments:**
- ➢ *band structure with nodal spin splitting* (spin-resolved ARPES and STM).
- ➢ *piezomagnetism* (x-rays in magnetic fields, NMR under strain, elasto-resistivity).
- ➢ *linear magnetic birefringence* (optical counterpart of piezomagnetism).
- ➢ *magnetic-field induced lattice softening* (resonant ultrasound spectroscopy in magnetic fields)
- ➢ *chiral magnons* (neutron scattering).
- ➢ *elasto-Hall conductivity* (transport).

- **For specific directions of the moments *and* in the presence of SOC:**
- *anomalous Hall effect* (transport).
- *spontaneous Kerr effect* (optics).
- *x-ray magnetic circular dichroism* (x-rays).

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for a recente perspective:

Jungwirth, RMF, Fradkin, MacDonald, Sinova & Šmejkal, *Newton* ***1***, *100162 (2025)*

Altermagnetism and multipolar magnetism

- Any magnetization density can be expanded in multipoles:

 $(\mathbf{r}) =$

Altermagnetism and multipolar magnetism

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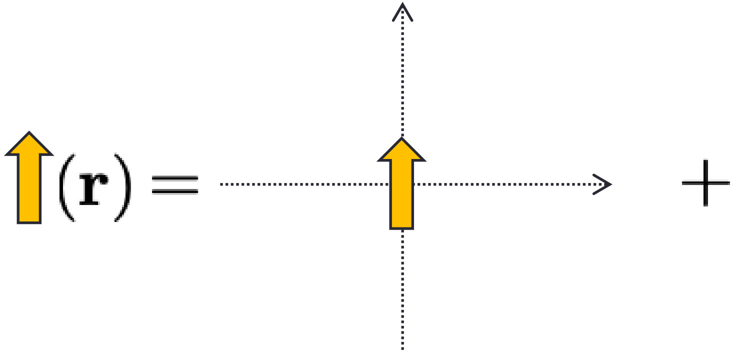

magnetic dipole

Altermagnetism and multipolar magnetism

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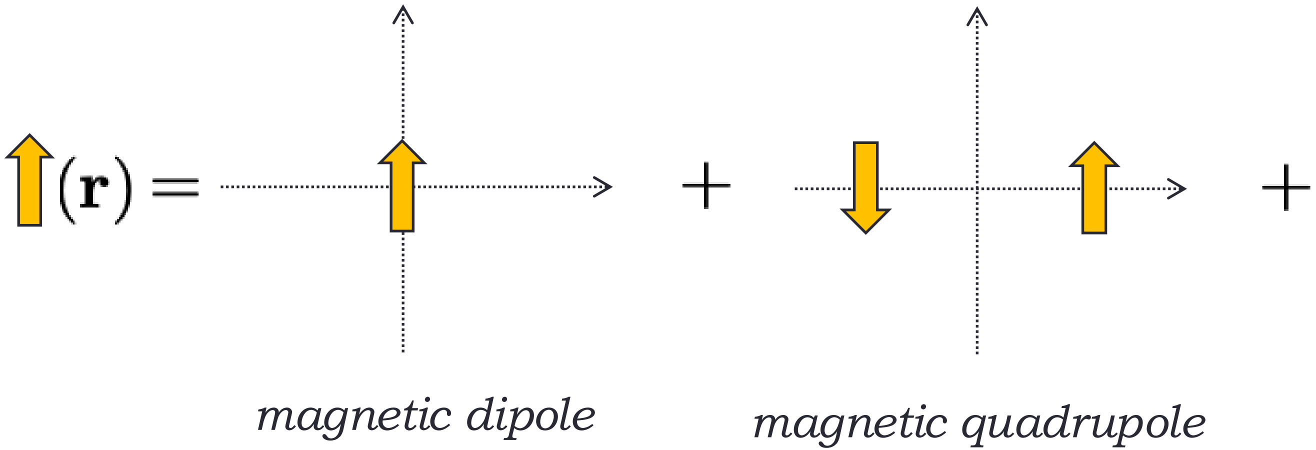

Altermagnetism and multipolar magnetism

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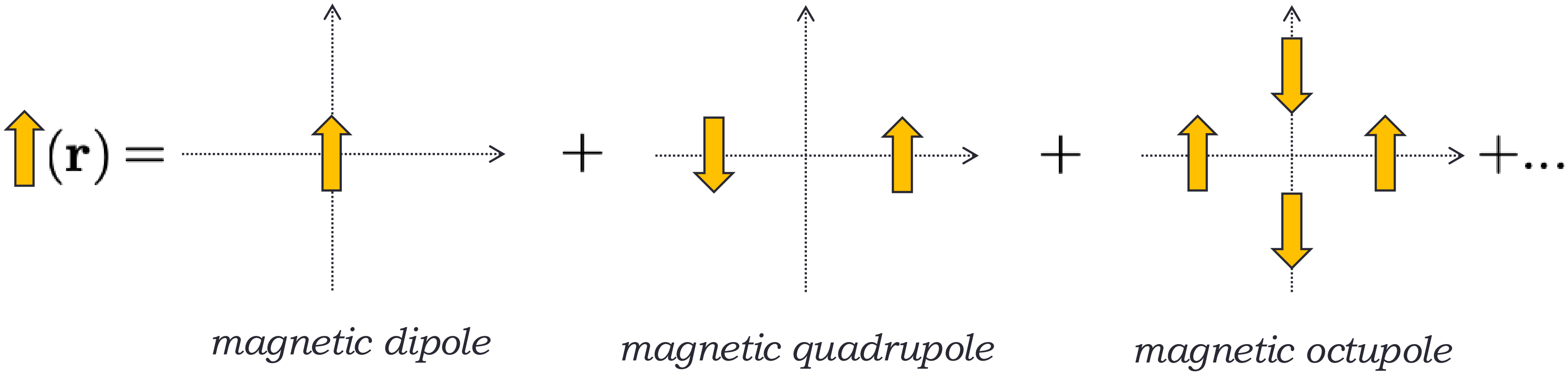

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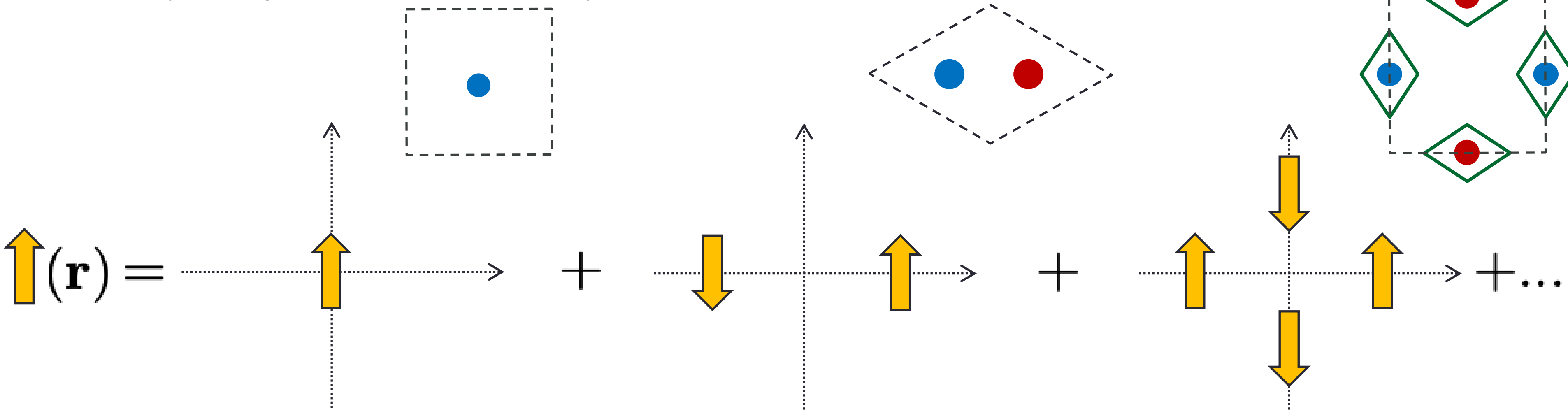


magnetic dipole | *magnetic quadrupole* | *magnetic octupole*

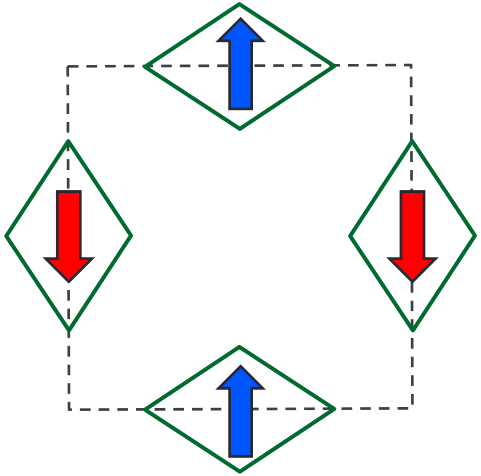
ferromagnet | **antiferromagnet** | **altermagnet**

relationship between magnetic octupoles and altermagnetism

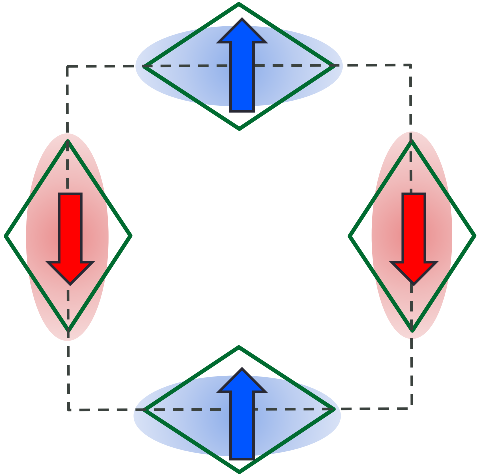
Bhowal & Spaldin, PRX (2023)
RMF et al, PRB (2024)

Altermagnetism and multipolar magnetism

- Spin density plays a key role in describing the multipolar character of altermagnets.



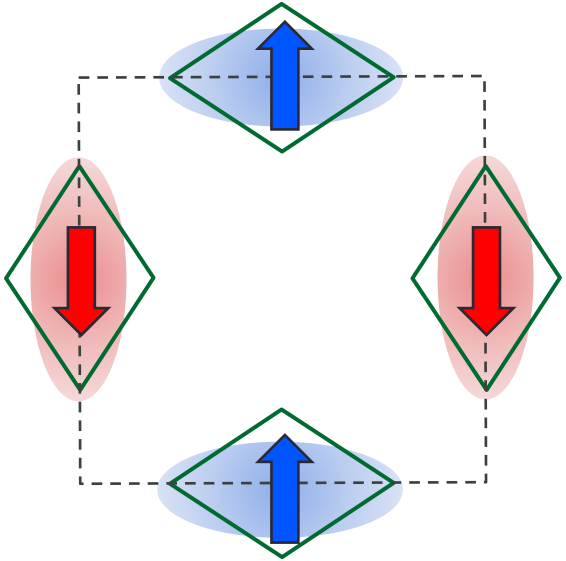
dipole moments at the atomic positions

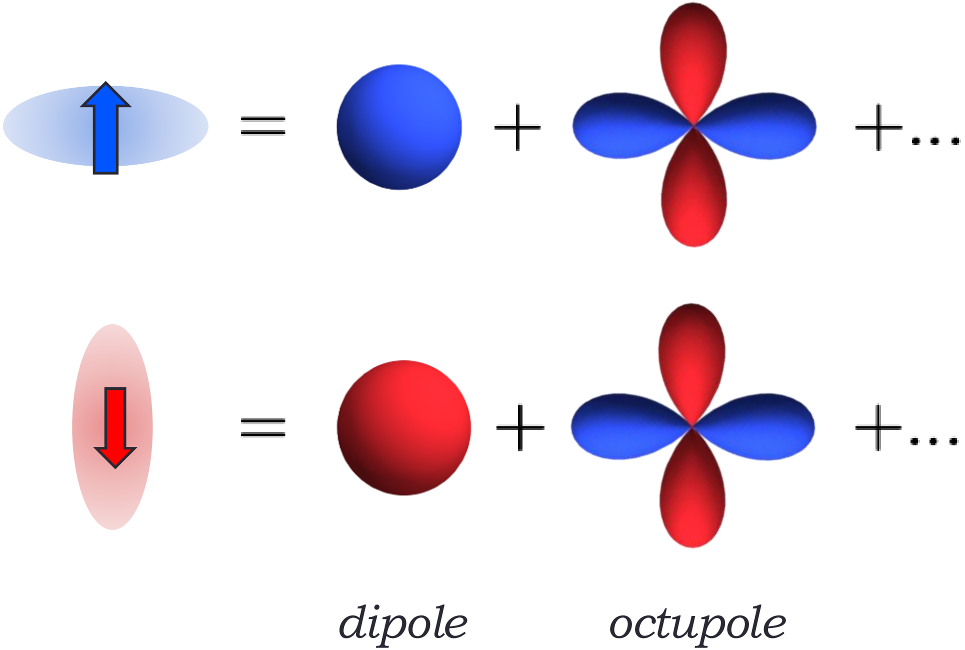


spin-density around the atomic positions

Altermagnetism and multipolar magnetism

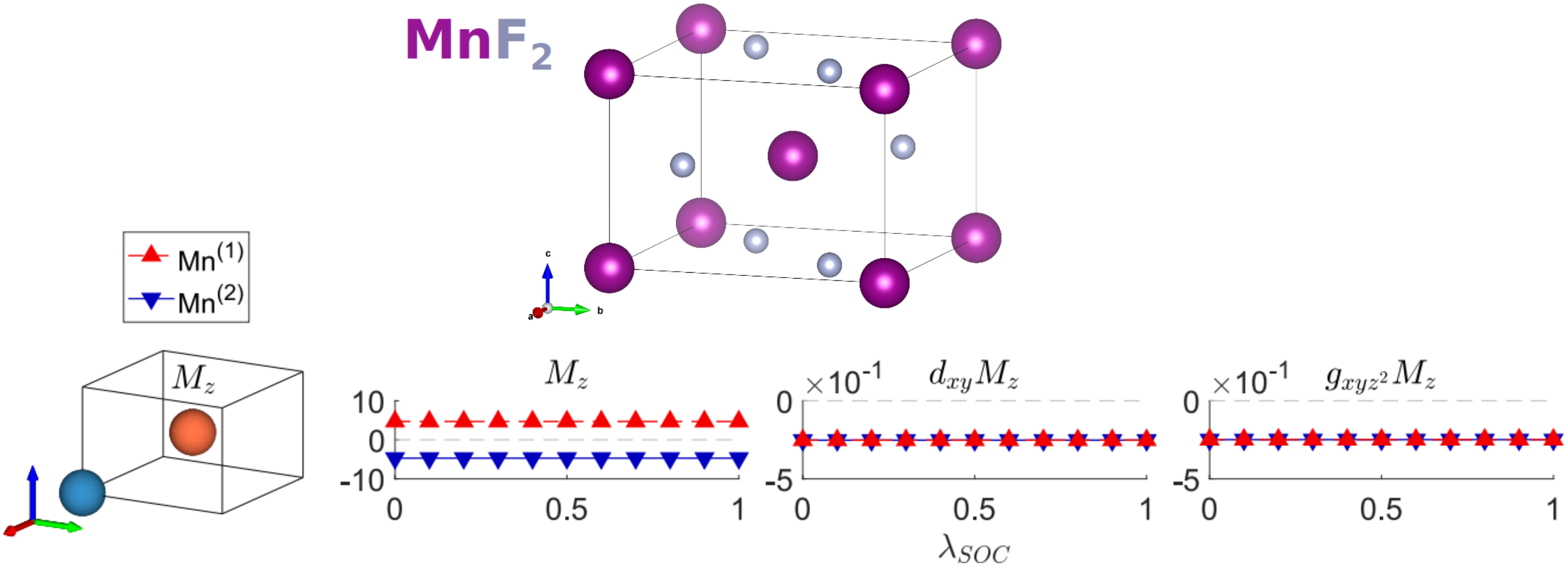
- Decomposition of the local spin density: antiparallel dipoles, parallel octupoles.





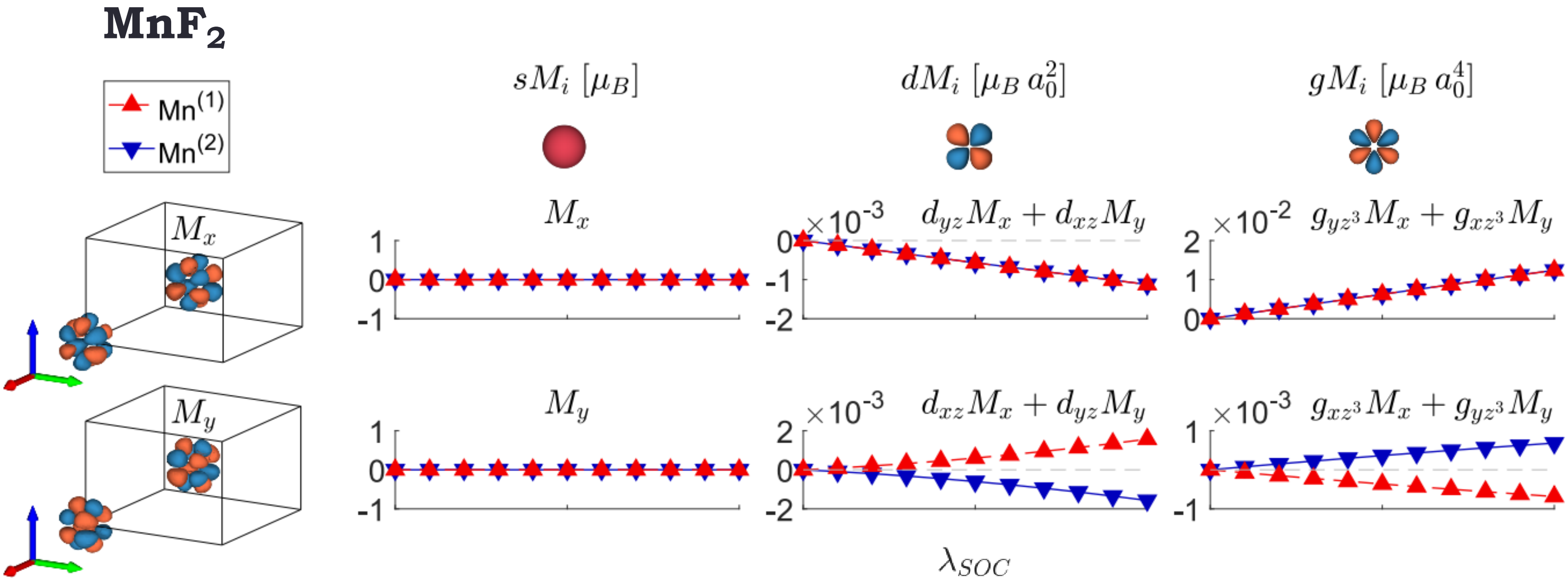
Altermagnetism and multipolar magnetism

- First-principles calculations can be used to quantify the multipolar decomposition locally.



Buiarelli, RMF & Birol, PRB (2026)

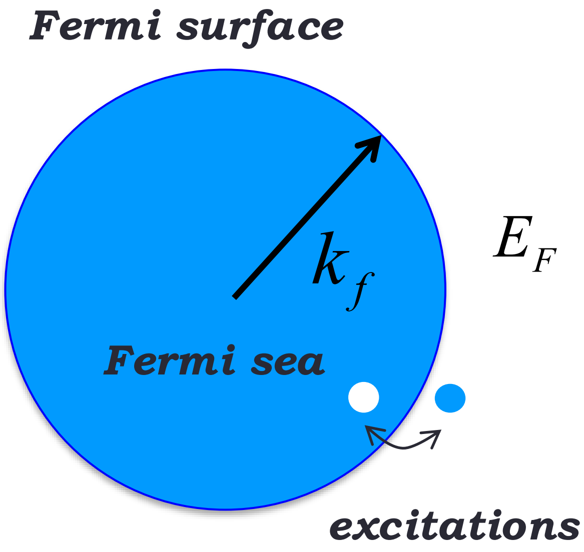
- The presence of SOC triggers spin-density multipoles for the non-collinear components of the spin.

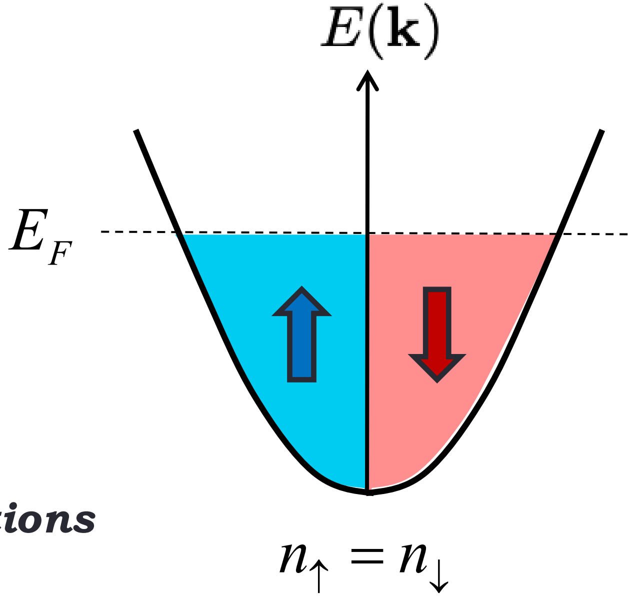


Buiarelli, RMF & Birol, PRB (2026)

Altermagnetism and correlated electronic systems

- It is well established that a metal undergoes a ferromagnetic transition when the Stoner criterion is satisfied.





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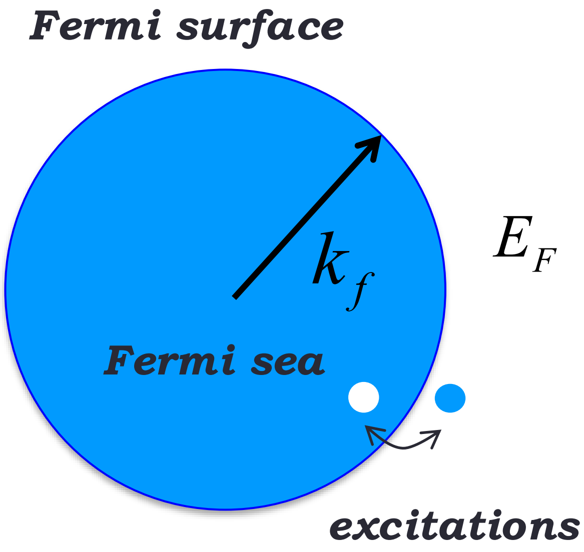

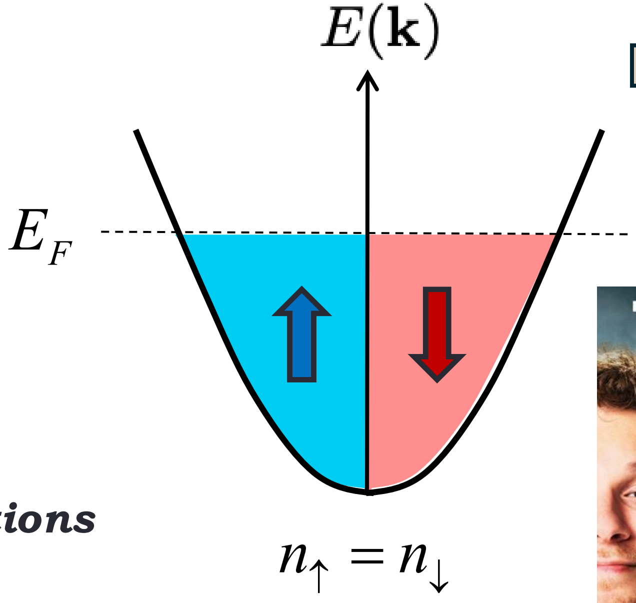

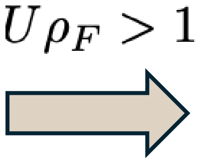

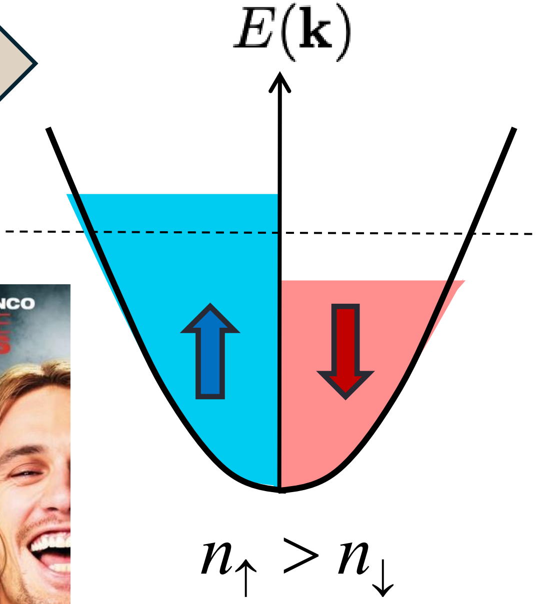

Altermagnetism and correlated electronic systems

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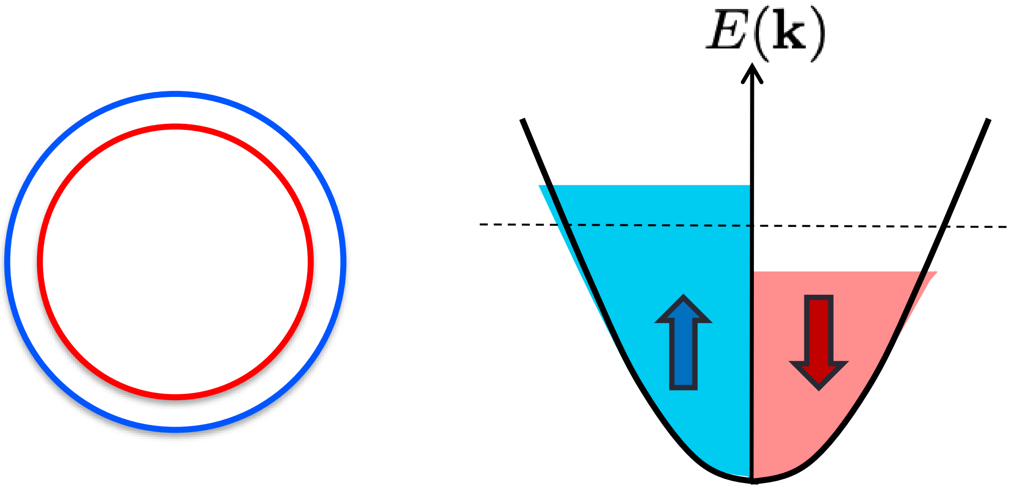
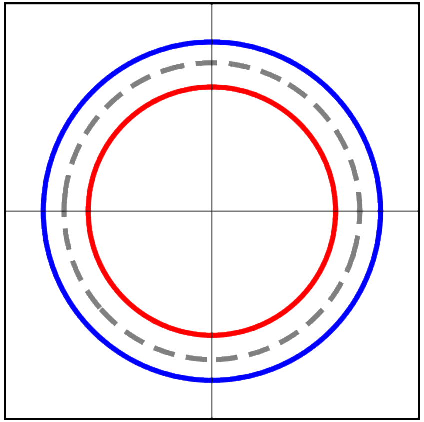


- A more thorough analysis showed that other types of Fermi surface distortions are possible due to interactions: ***Pomeranchuk instabilities***.

Pomeranchuk, JETP (1959)

Altermagnetism and correlated electronic systems

- Magnetic Pomeranchuk instabilities of the interacting electron gas cause Fermi surface distortions characterized by angular momentum l.



$$l = 0$$

ferromagnetism
(s-wave)

Altermagnetism and correlated electronic systems

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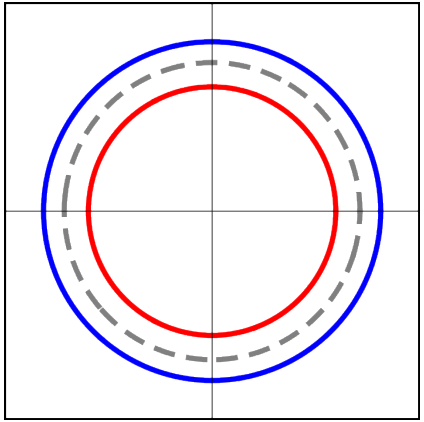
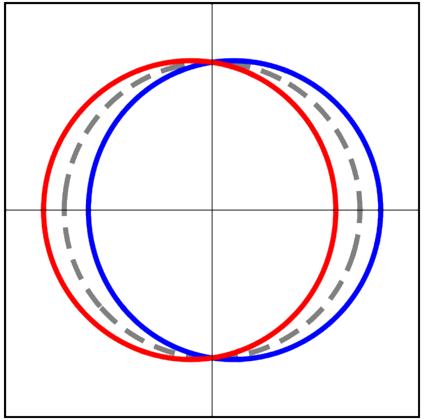


$l = 0$

ferromagnetism (s-wave)



$l = 1$

spin current (p-wave)

Hirsch, PRB (1990)

Wu & Zhang, PRL (2004)

Altermagnetism and correlated electronic systems

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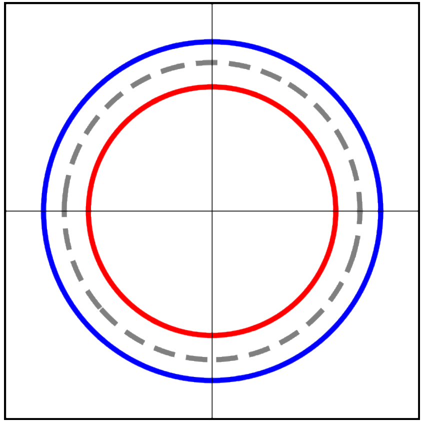
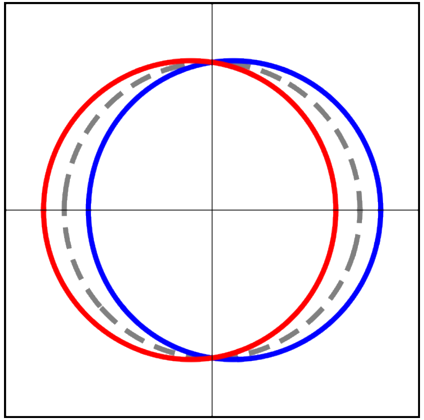


$l = 0$

ferromagnetism
(s-wave)



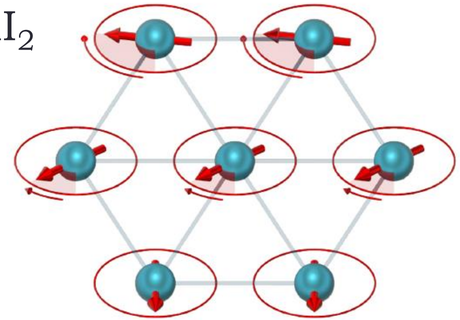
$l = 1$

spin current
(p-wave)

Hellenes et al, arxiv (2024)

p-wave magnetism can be realized in certain non-collinear magnetic configurations (without SOC)

NiI_2



Song, ..., RMF, Picozzi & Comin, Nature (2025)

Altermagnetism and correlated electronic systems

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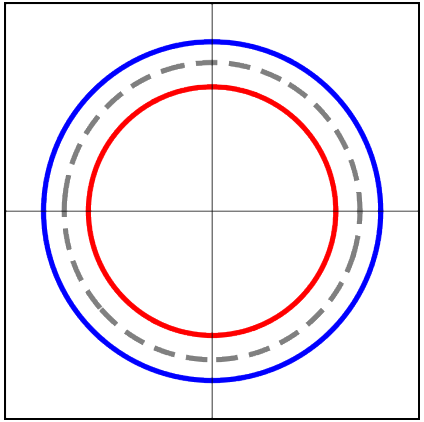
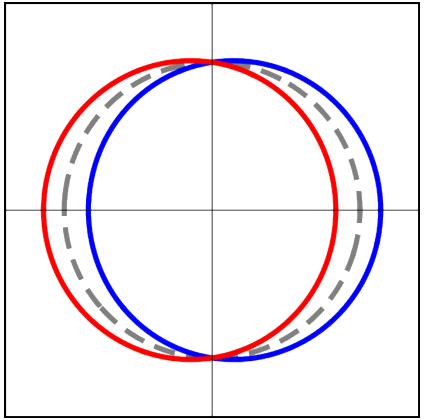


$l = 0$

ferromagnetism

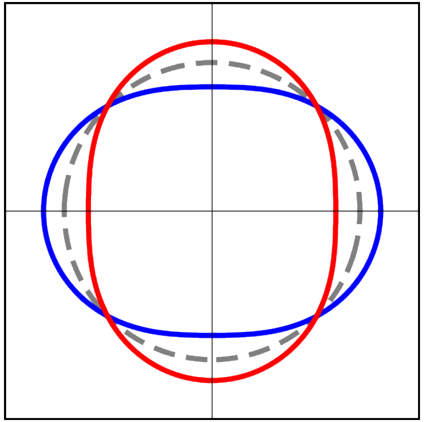
(s-wave)



$l = 1$

spin current

(p-wave)



$l = 2$

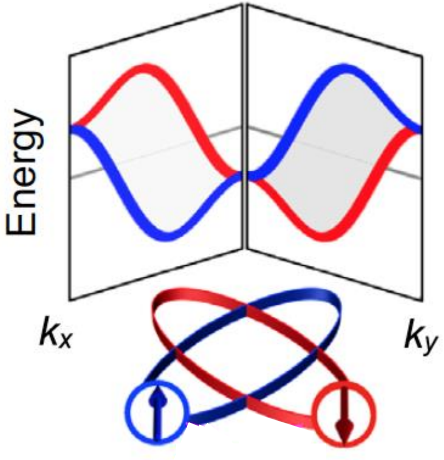
magnetic octupolar order

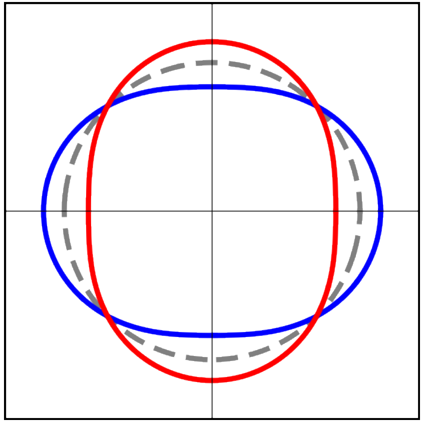
(d-wave)

Wu, Sun, Fradkin & Zhang, PRB (2007)

Altermagnetism and correlated electronic systems

- The ground state of any even-parity ($l > 0$) magnetic Pomeranchuk instability has the same symmetry as an altermagnetic state.

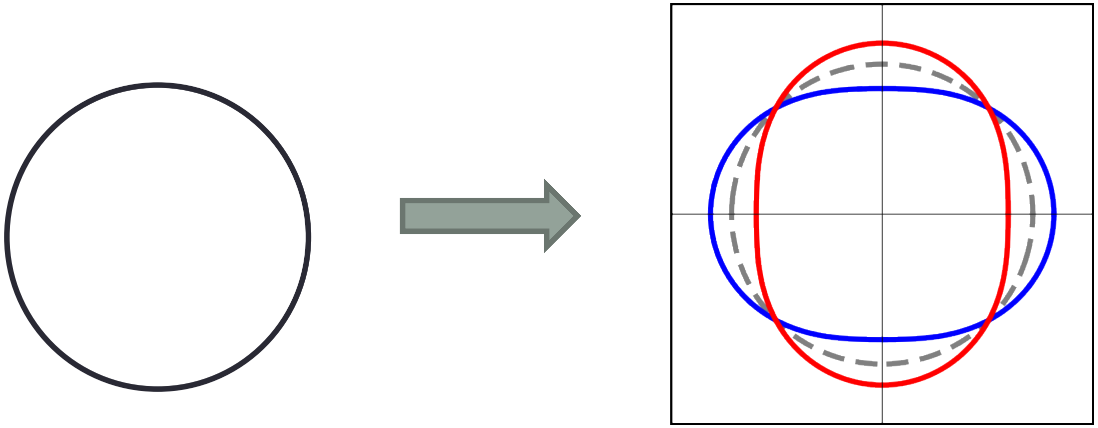




Are the microscopic mechanisms different?

Altermagnetism and correlated electronic systems

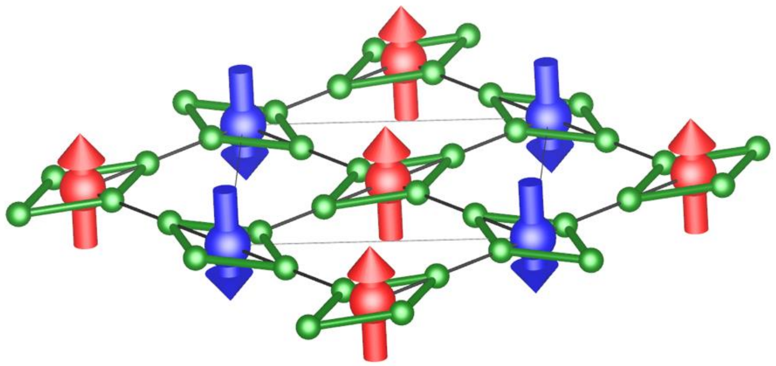
- A Pomeranchuk instability is a **purely electronic** instability of a metal.
  - ➢ not a weak-coupling effect: interaction must overcome a threshold value.
  - ➢ *L* > *0* instabilities are usually sub-leading with respect to the *L* = *0* instability.



Altermagnetism and correlated electronic systems

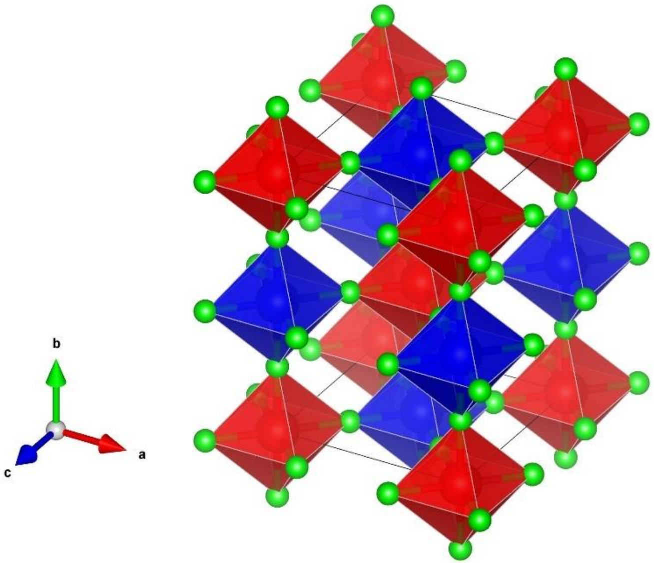
- A Pomeranchuk instability is a **purely electronic** instability of a metal.
  - not a weak-coupling effect: interaction must overcome a threshold value.
  - $L > 0$ instabilities are usually sub-leading with respect to the $L = 0$ instability.

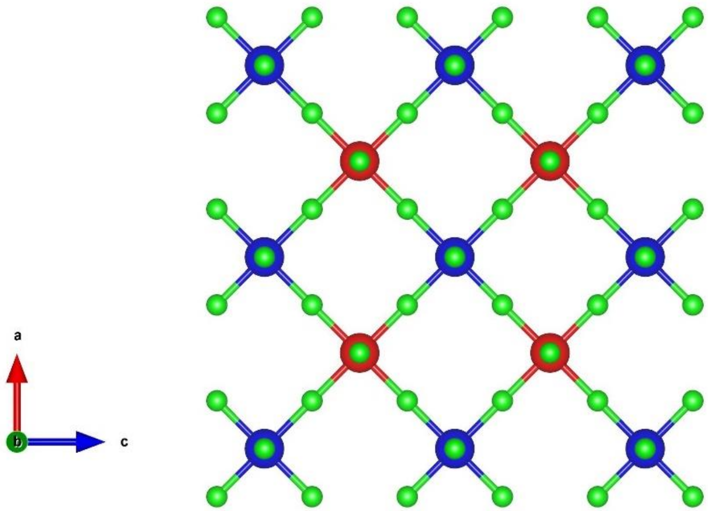
- Altermagnetism: divide and conquer.
  - **electronic interactions** cause anti-alignment of spins.
  - **crystalline interactions** create different (but symmetry-related) crystalline environments for the anti-parallel spins.
  - not restricted to metals: Mott insulators can also be altermagnetic!



Altermagnetism and correlated electronic systems

- Many ABO_3 perovskites are Mott insulators with seemingly AF order.



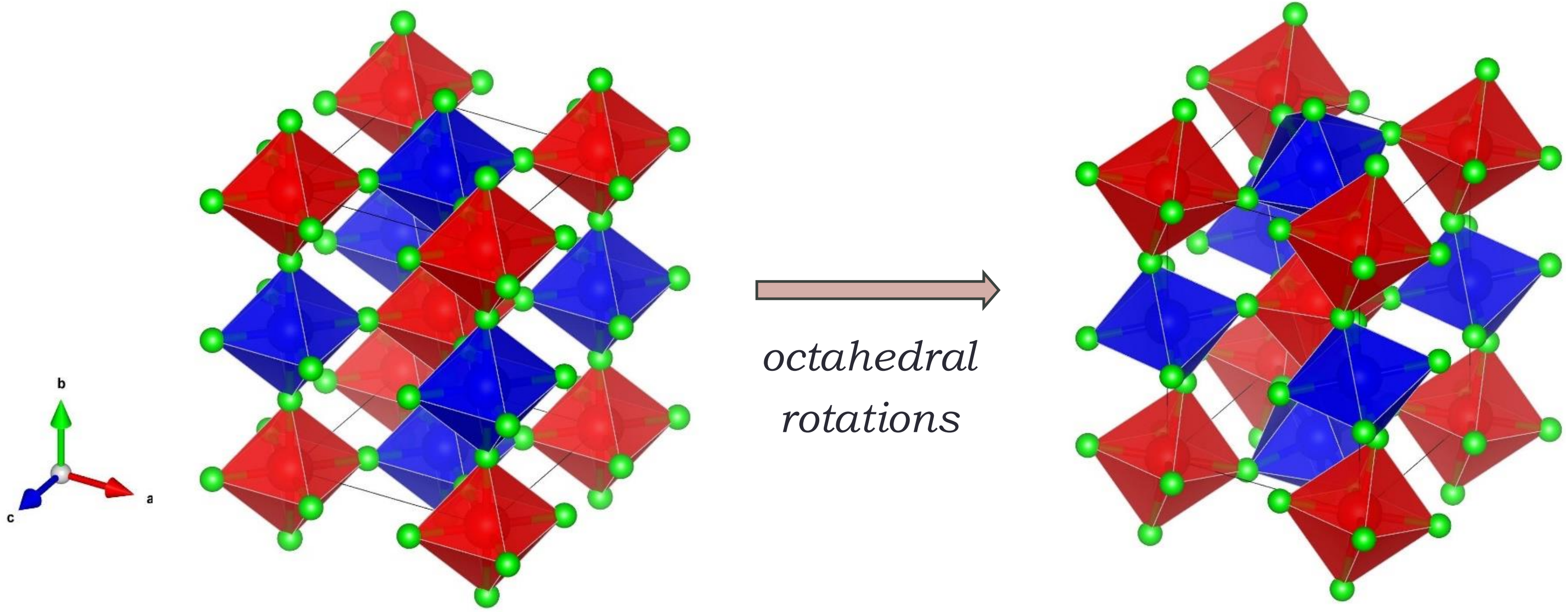


B atom: *cuprates (Cu), manganites (Mn), titanates (Ti), ruthenates (Ru), vanadates (V), …*

"B" spin up
"B" spin down
oxygen

Altermagnetism and correlated electronic systems

- In many of these perovskites, the O octahedra rotate to accommodate the *A* atom, leading to a larger unit cell with orthorhombic symmetry (*Pnma*).

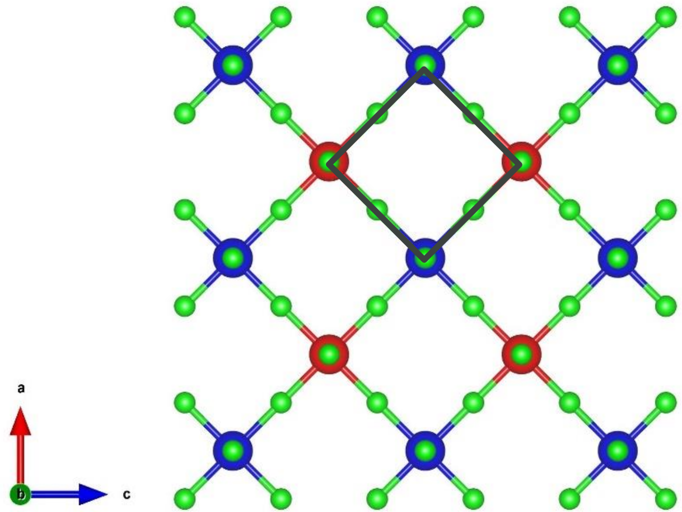


Altermagnetism and correlated electronic systems

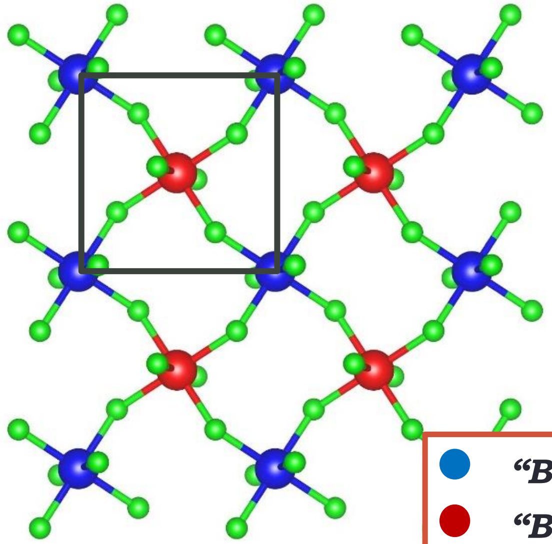
- In the presence of octahedral rotations, AF becomes AM order.

paramagnetic unit cell	$\neq$	*magnetic unit cell*

paramagnetic unit cell	$=$	*magnetic unit cell*



octahedral rotations



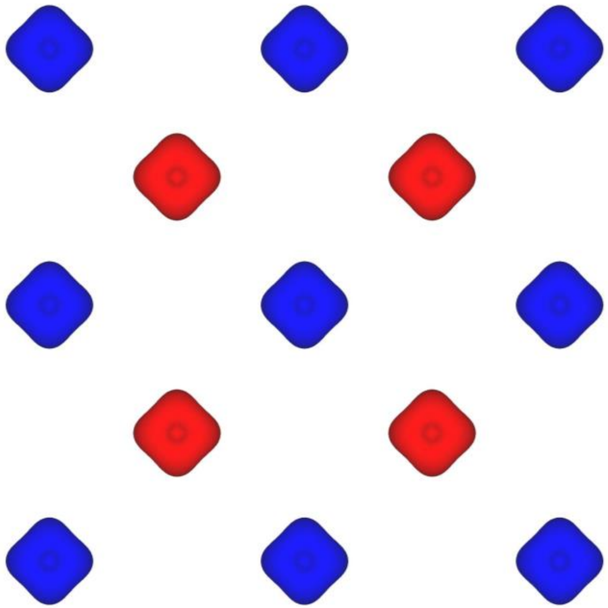
"B" spin up
"B" spin down
oxygen

RMF, Carvalho, Birol & Pereira, PRB (2024)

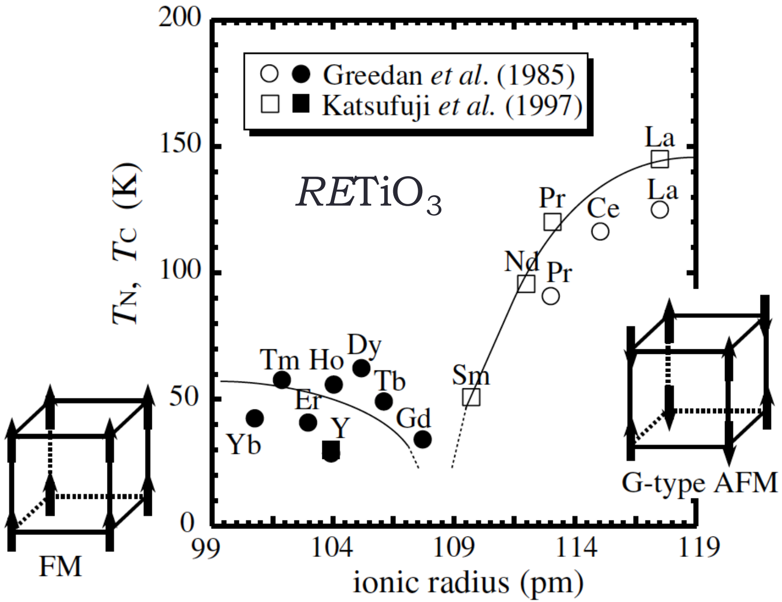
see also: Bernardini et al, arxiv (2024); Rooj et al, PRB (2025); Bandyopadhyay et al, arxiv (2025)

Altermagnetism and correlated electronic systems

- Octahedral rotations control the size of the altermagnetic order parameter.
  - ➢ In rare-earth titanates, rotations can be controlled via the *A* atom or strain.



spin up
spin down



Mochizuki & Imada, NJP (2004)

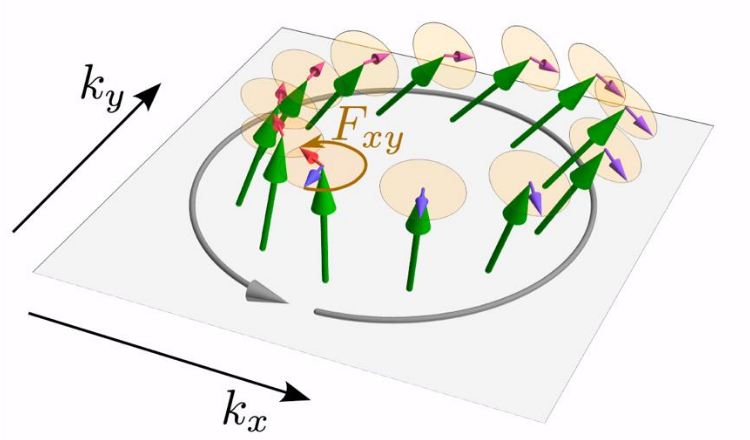
Outline

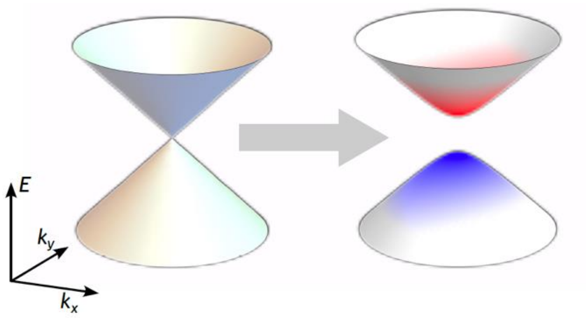
1. Ferromagnets, antiferromagnets, and altermagnets: a matter of symmetry.
2. Altermagnetism: where to find them and what to do with them.
3. Correlated electronic phenomena in altermagnets.
4. Topological properties of altermagnets.

Topological properties of altermagnets

- Topological properties are encoded in the Berry curvature (BC), which behaves as a magnetic field in momentum space.

$$\Omega_{\alpha\beta}^{(n)}(\boldsymbol{k}) = i\left(\left\langle \partial_{k_\alpha} u_{\boldsymbol{k},n} \mid \partial_{k_\beta} u_{\boldsymbol{k},n} \right\rangle - \left\langle \partial_{k_\beta} u_{\boldsymbol{k},n} \mid \partial_{k_\beta} u_{\boldsymbol{k},n} \right\rangle\right)$$





Concentration of Berry curvature from gapping of a Dirac point

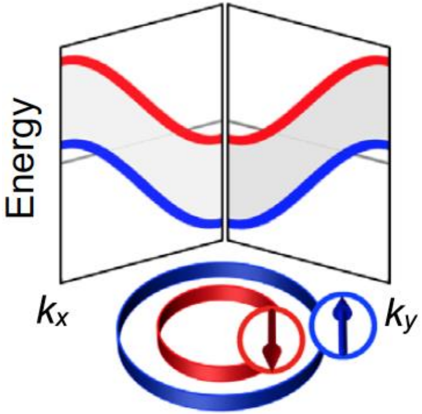
➢ *The same symmetries that enforce the spin-splitting properties of collinear magnets also constrain the Berry curvature.*

figures from: Bzdusek, arxiv (2025)

Topological properties of altermagnets

- Topological properties are encoded in the Berry curvature (BC), which behaves as a magnetic field in momentum space.

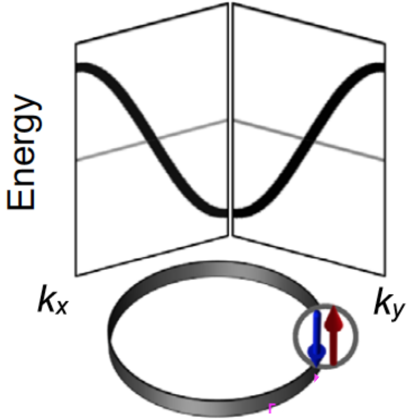
ferromagnetism (F)



$$\boldsymbol{\Omega}(\mathbf{k}) = \Omega_0 \hat{\mathbf{n}}$$

BC monopole

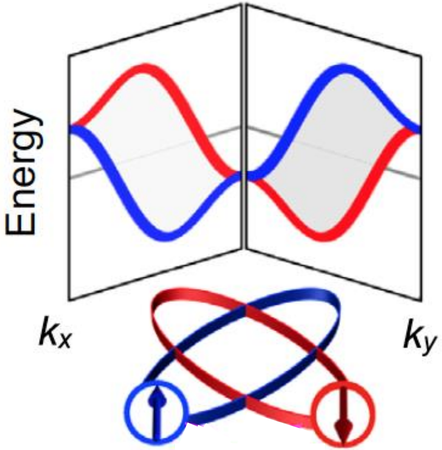
antiferromagnetism (AF)



$$\boldsymbol{\Omega}(\mathbf{k}) = 0$$

BC is identically zero

altermagnetism (AM)



$$\boldsymbol{\Omega}(\mathbf{k}) = \Omega_0 f(\mathbf{k}) \hat{\mathbf{n}}$$

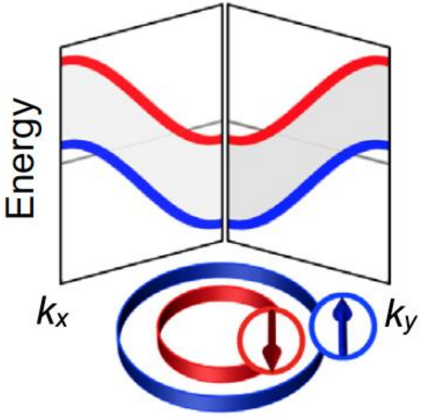
BC multipole

For BC multipoles, see also: Sodemann & Fu, PRL (2015); Zhang et al, PRB (2023); Fang et al, PRL (2024)

Topological properties of altermagnets

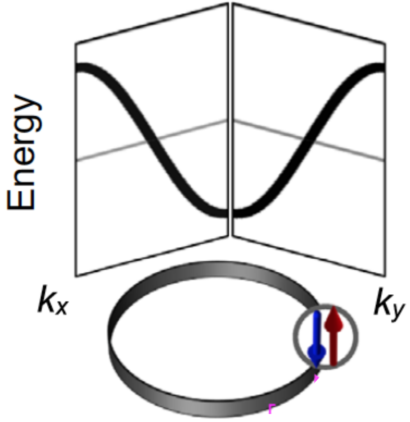
- Topological properties are encoded in the Berry curvature (BC), which behaves as a magnetic field in momentum space.

ferromagnetism (F)



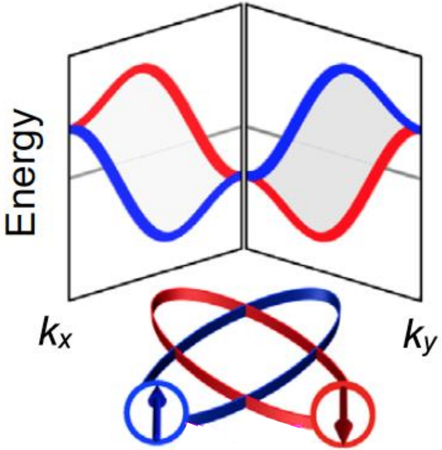
$$\mathbf{\Omega}(\mathbf{k}) = \Omega_0 \hat{\mathbf{n}}$$

antiferromagnetism (AF)



$$\mathbf{\Omega}(\mathbf{k}) = 0$$

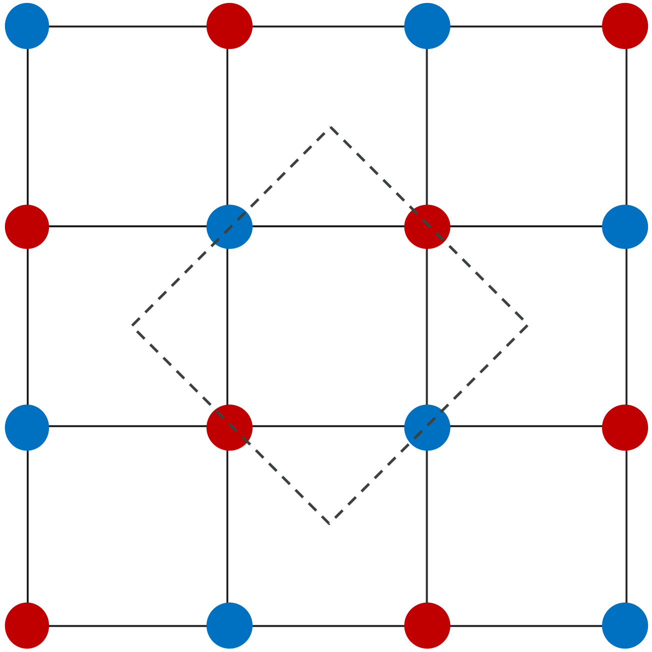
altermagnetism (AM)



$$\mathbf{\Omega}(\mathbf{k}) = \Omega_0 f(\mathbf{k}) \hat{\mathbf{n}}$$

- ➢ ***What are the sources of Berry curvature in altermagnets?***
- ➢ ***How to measure a Berry curvature multipole?***

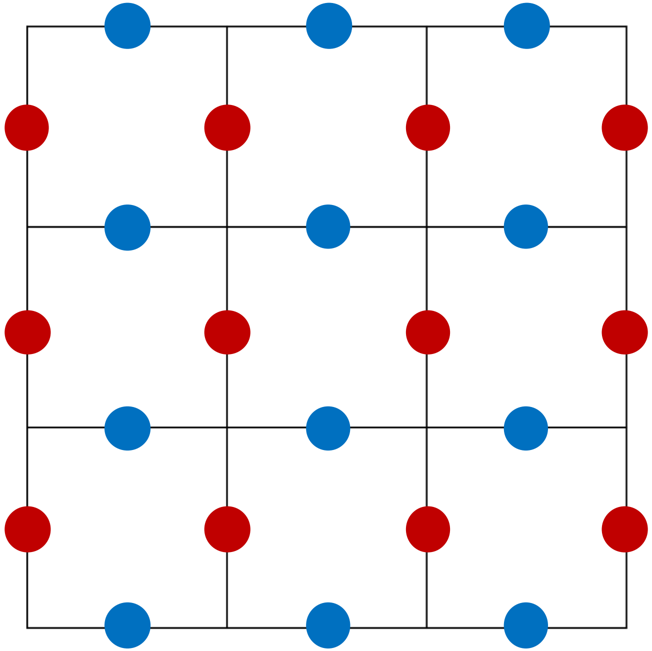
Minimal model for altermagnetism: the Lieb lattice



increase the unit cell to make opposite spins be related by a rotation rather than a translation

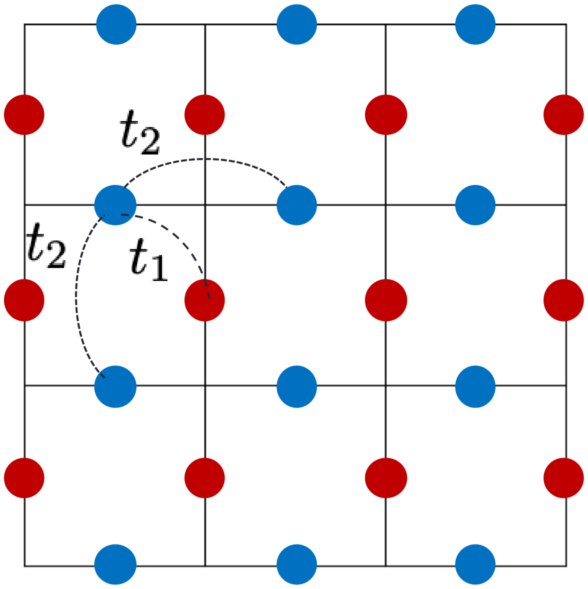
spin up

spin down

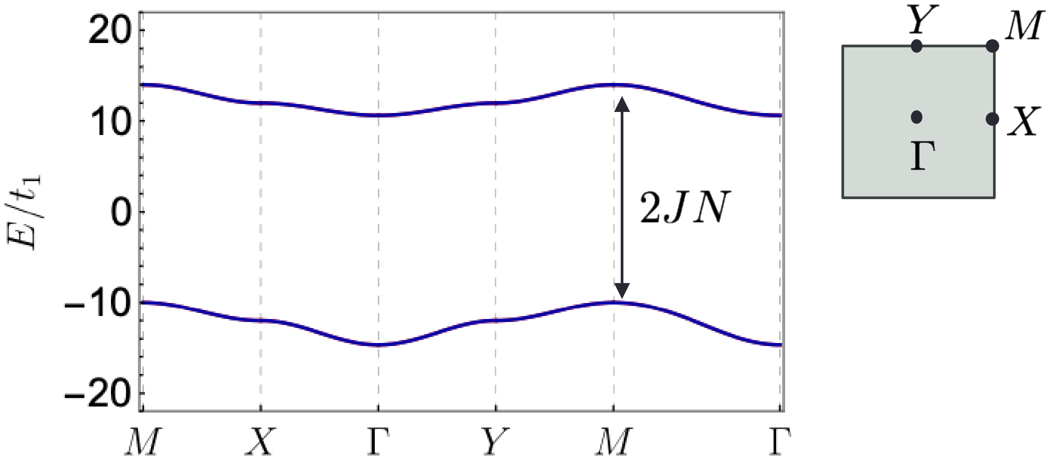


Minimal model for altermagnetism: the Lieb lattice

- Sublattice: $\boldsymbol{\tau}$
- Spin: $\boldsymbol{\sigma}$
- Staggered magnetization: $\boldsymbol{N}$



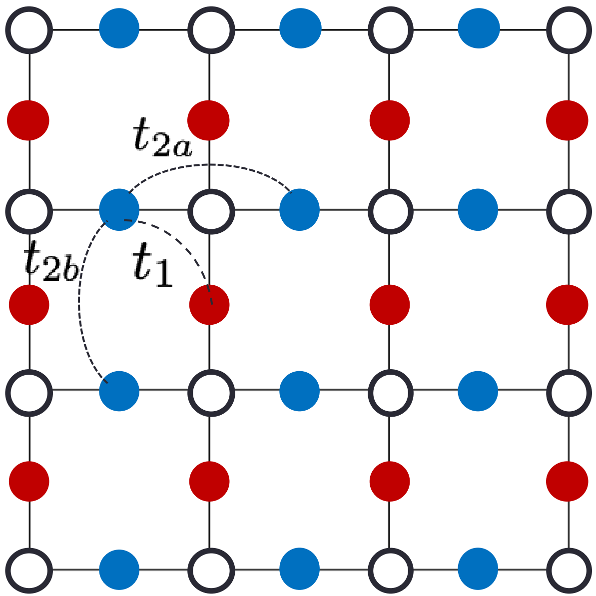
$$\mathcal{H}_0(\boldsymbol{k}) = -4t_1 \cos\frac{k_x}{2}\cos\frac{k_y}{2}\tau_x - 2t_2(\cos k_x + \cos k_y)\tau_0 + J\tau_z \boldsymbol{N}\cdot\boldsymbol{\sigma}$$



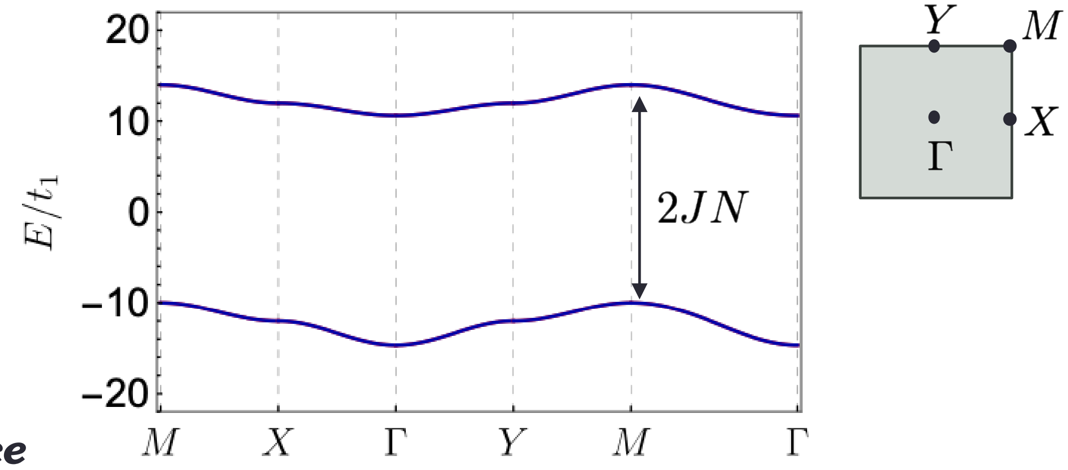
two spin-degenerate bands:
no spin-splitting (antiferromagnet)

Minimal model for altermagnetism: the Lieb lattice

- Sublattice: $\boldsymbol{\tau}$
- Spin: $\boldsymbol{\sigma}$
- Staggered magnetization: $\boldsymbol{N}$



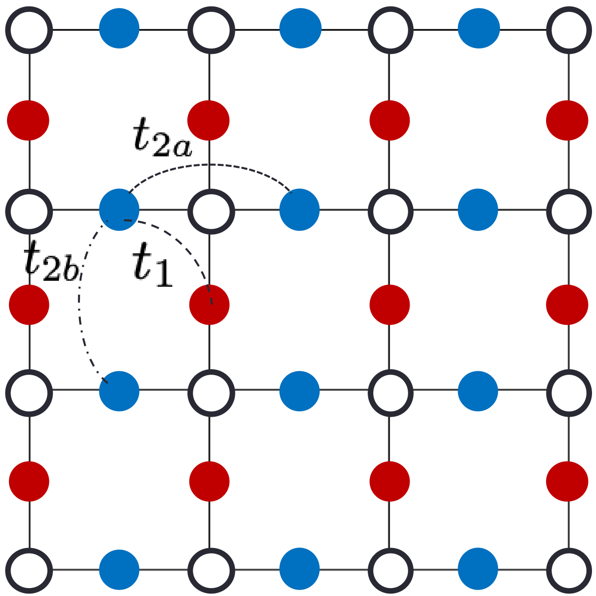
$$\mathcal{H}_0(\boldsymbol{k}) = -4t_1 \cos\frac{k_x}{2}\cos\frac{k_y}{2}\tau_x - 2t_2(\cos k_x + \cos k_y)\tau_0 + J\tau_z \boldsymbol{N}\cdot\boldsymbol{\sigma}$$



Include a non-magnetic atom to enforce the symmetries: Lieb lattice

Minimal model for altermagnetism: the Lieb lattice

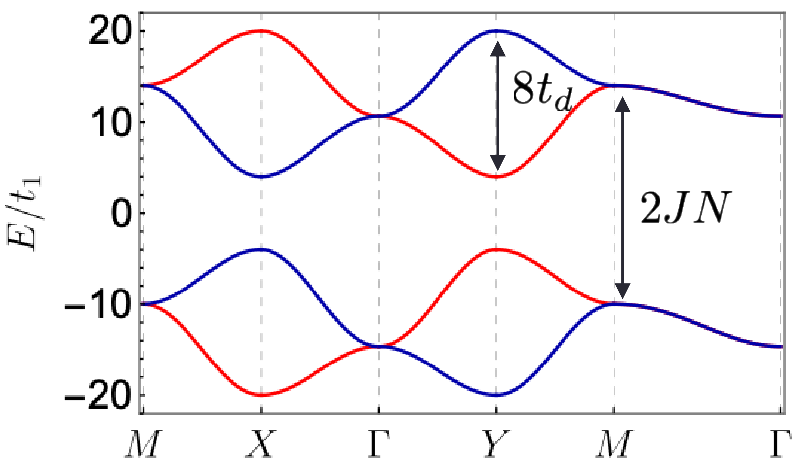
Antonenko, RMF, Venderbos, PRL (2025)
for a related model: Brekke et al, PRB (2023)

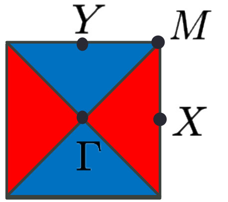


- Sublattice: $\boldsymbol{\tau}$
- Spin: $\boldsymbol{\sigma}$
- Staggered magnetization: $\boldsymbol{N}$

$$t_d \equiv t_{2a} - t_{2b}$$

$$\mathcal{H}_0(\boldsymbol{k}) = -4t_1 \cos\frac{k_x}{2}\cos\frac{k_y}{2}\tau_x - 2t_2(\cos k_x + \cos k_y)\tau_0 - 2t_d(\cos k_x - \cos k_y)\tau_z + J\tau_z \boldsymbol{N}\cdot\boldsymbol{\sigma}$$



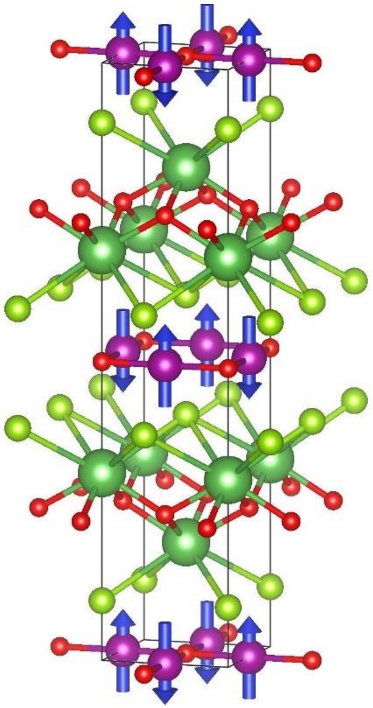


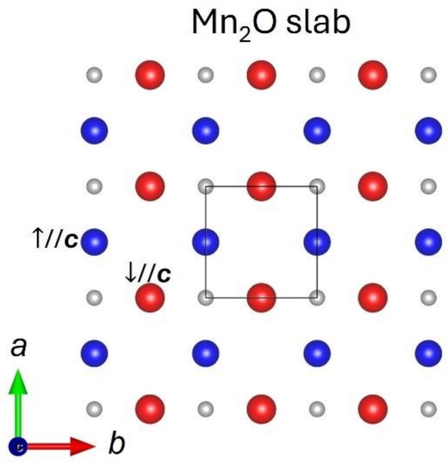
$d_{x^2-y^2}$ **-wave altermagnet**

see Roig et al, PRB (2024) for a comprehensive classification of minimal models for AM

Experimental realizations of the Lieb lattice AM

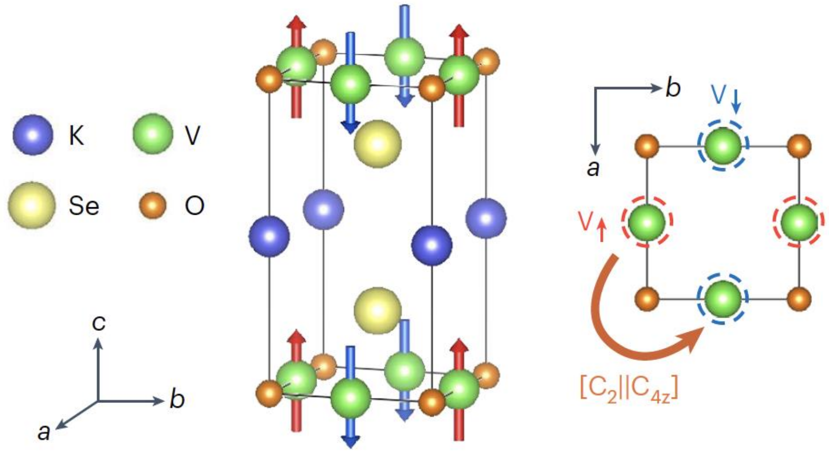
- Mott insulating $La_2O_3Mn_2Se_2$





Wei, …, RMF, …, Ji, PRM (2025)

- Metallic AV_2Se_2O (surface only; bulk is AFM)



Jiang et al, Nature Phys (2025)

Zhang et al, Nature Phys (2025)

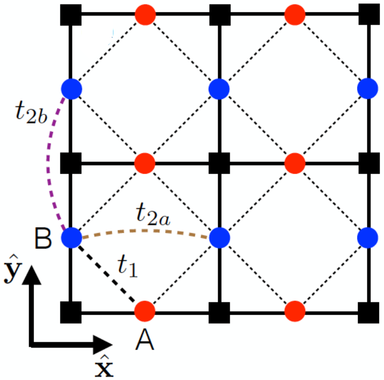
Sun et al, PRB (2025)

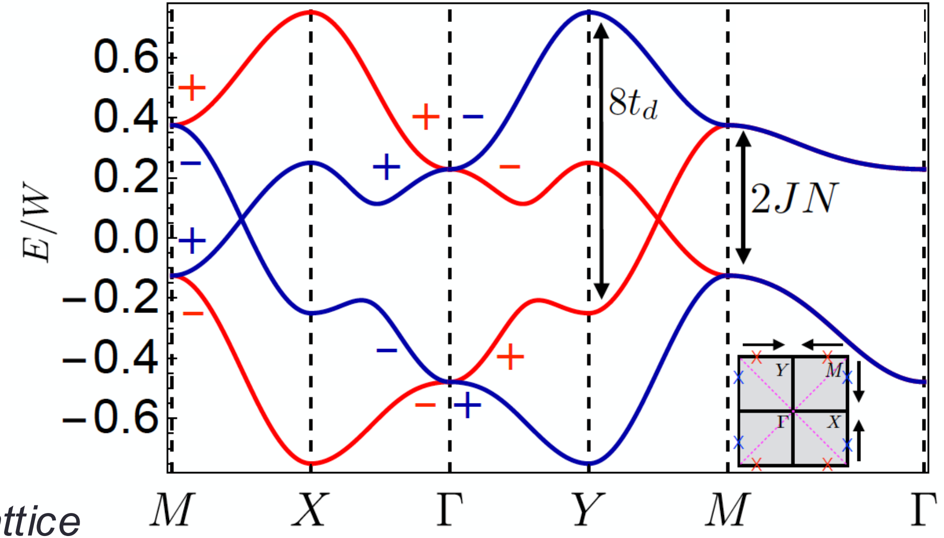
Nodal lines and Dirac points in altermagnets

- When the exchange J and the hopping anisotropy t_d are comparable, additional bands crossings emerge.

spin up

spin down





- *color denotes spin*
- *sign denotes sublattice*

Nodal lines and Dirac points in altermagnets

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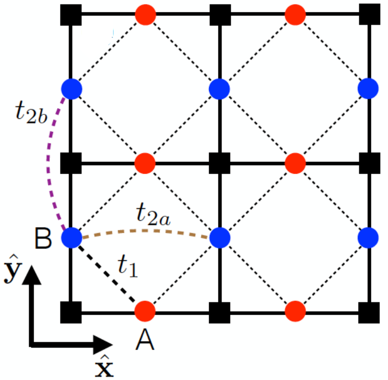
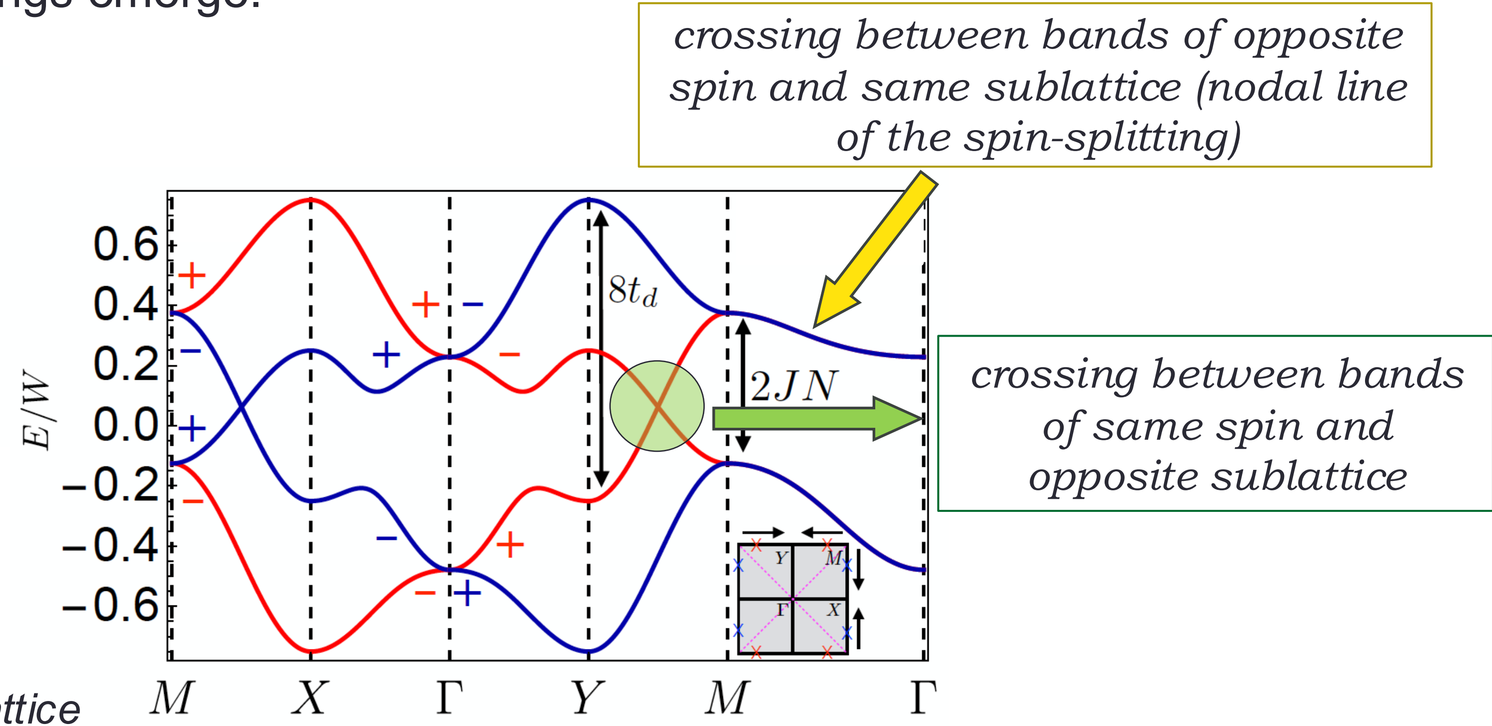




- *color denotes spin*
- *sign denotes sublattice*

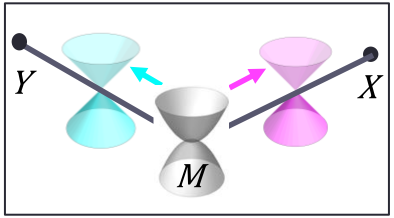
Antonenko, RMF, Venderbos, PRL (2025)

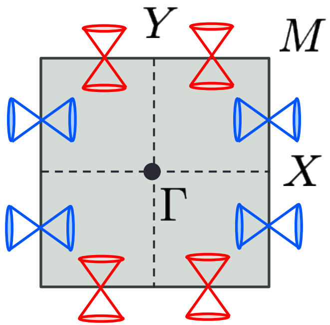
Nodal lines and Dirac points in altermagnets

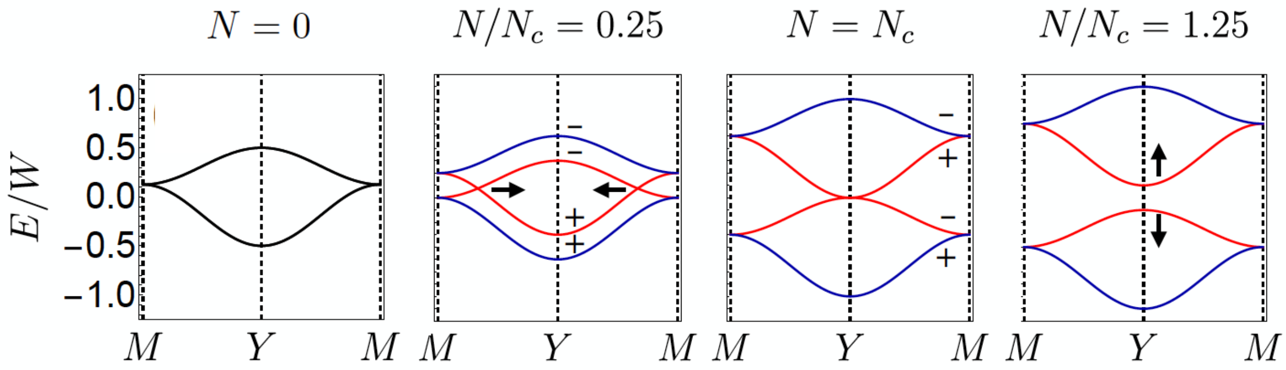
- Dirac points protected by *vertical* mirror symmetry that originate from a quadratic band crossing at the Brillouin zone corner (*M* point).

see also:
Sun et al, PRL (2009)

$$\mathcal{H}_0^{\uparrow,\downarrow}(\boldsymbol{q}+\boldsymbol{Q}_M) = \epsilon_q \tau_0 - \left[t_2(q_x^2 - q_y^2) \mp JN\right]\tau_z - t_1 q_x q_y \tau_x$$







➢Above a magnetization threshold value, Dirac points are removed at *X*/*Y* points.

Mirror Chern bands in altermagnets

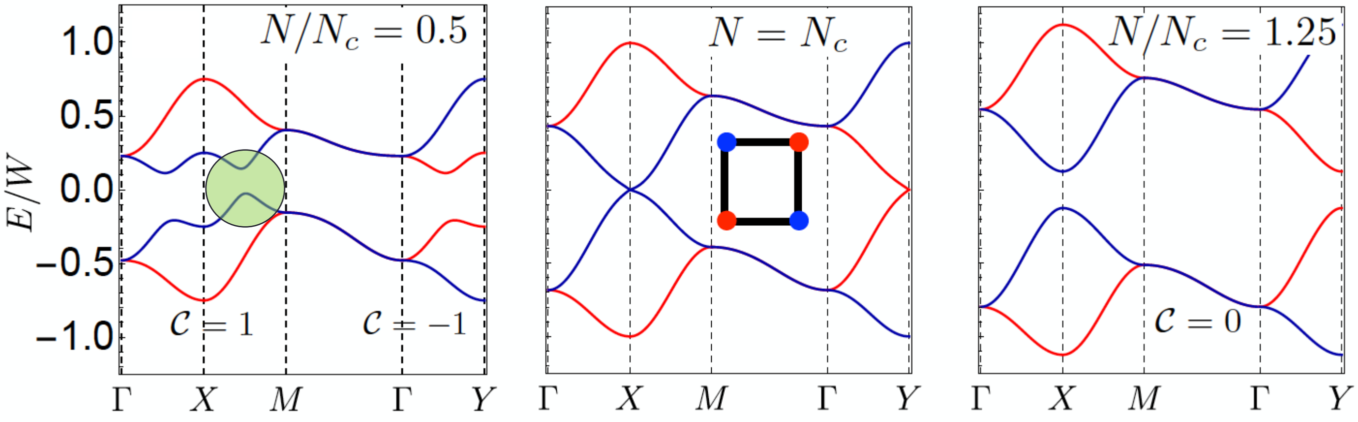
- Once SOC is turned on and the **moments point out of the plane**, the Dirac cones are gapped resulting in large local Berry curvature.

$$\mathcal{H}_{\mathrm{SO}}(\boldsymbol{k}) = \lambda \sin \frac{k_x}{2} \sin \frac{k_y}{2} \tau_y \sigma_z$$

Kane & Mele, PRL (2005)
Weeks & Franz, PRB (2010)

- Depending on the chemical potential, we find Chern bands protected by *horizontal* mirror plane.

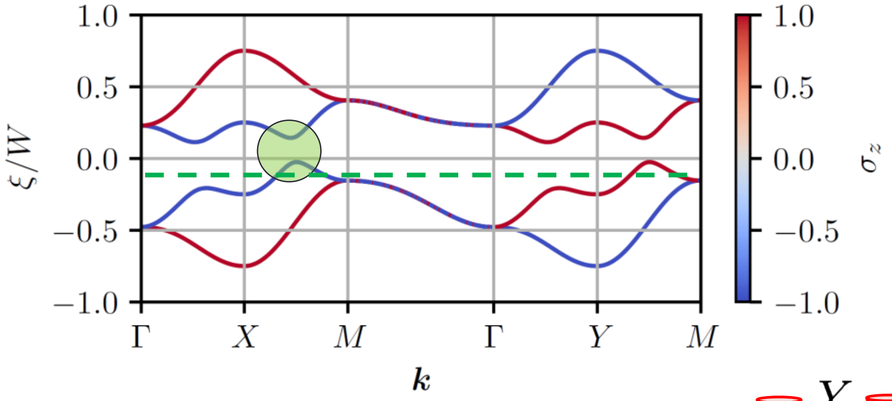
mirror Chern insulator

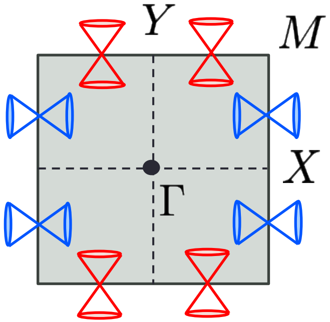


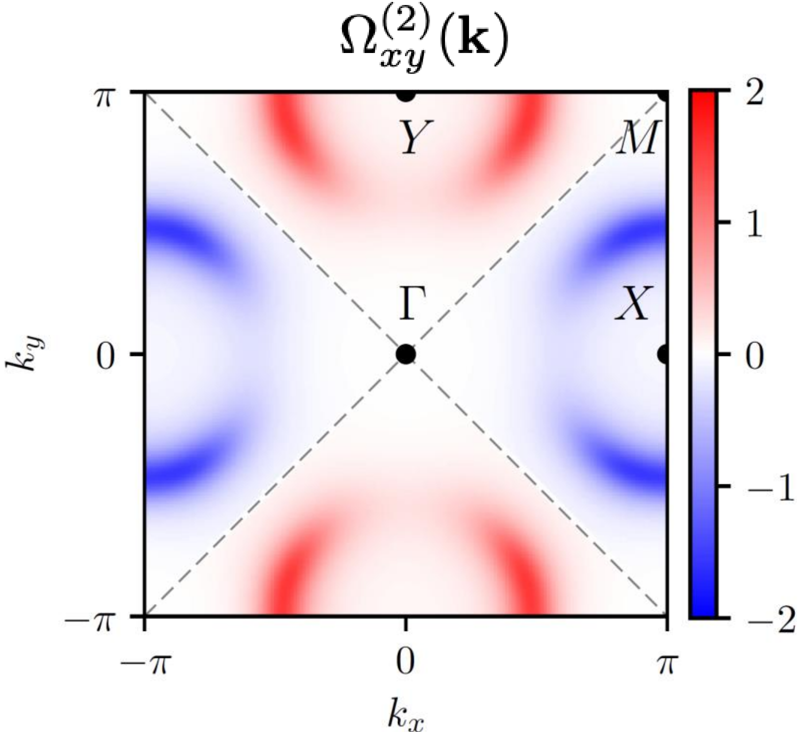
trivial insulator

Berry curvature quadrupole in altermagnets

- The gapped Dirac points are sources of large Berry curvature, resulting in a **Berry curvature (BC) quadrupole.** $\Omega^{(2)}_{xy}(k_x, k_y) = -\Omega^{(2)}_{xy}(-k_y, k_x)$







Takahashi, …, RMF, & Schmalian, PRB (2025)

see also: Mazin et al, arxiv (2023); Hu et al, PRX (2025)

Berry curvature quadrupole in altermagnets

- How to experimentally probe the Berry curvature quadrupole?

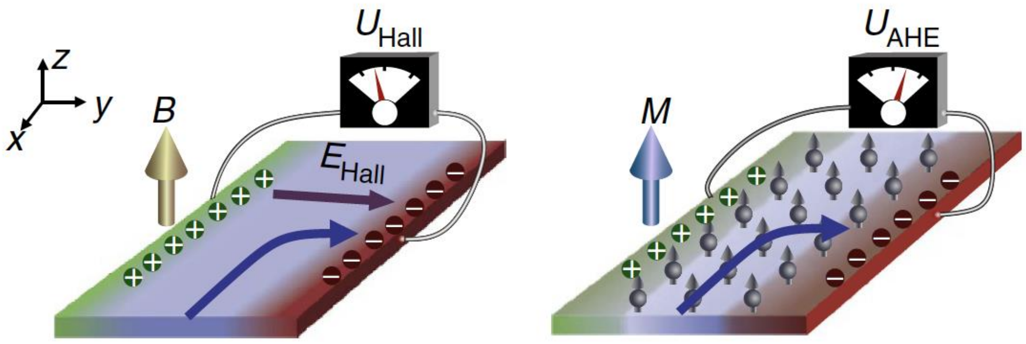


figure from: Maryenko et al, Nature Comm. (2017)

$$\sigma_{\alpha\beta} = -\frac{e^2}{\hbar}\sum_{n,\boldsymbol{k}} n_F\left(E_{n,\boldsymbol{k}}\right)\Omega^{(n)}_{\alpha\beta}\left(\boldsymbol{k}\right)$$

anomalous Hall conductivity — Berry curvature

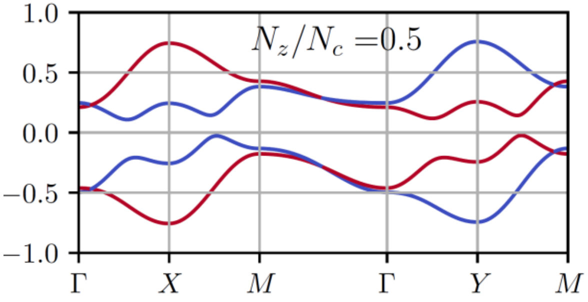
- The anomalous Hall effect (AHE) is sensitive only to the Berry curvature monopole, which is zero in pure altermagnets. $\langle \Omega^{(n)}_{\alpha\beta}(\mathbf{k})\rangle_{\mathrm{BZ}} = 0$
- Alternative: nonlinear Hall effect (but it is cubic in field, and thus usually small).

Fang, Cano, Ghorashi, PRL (2024) *Farajollahpour et al, npj QM (2025)*

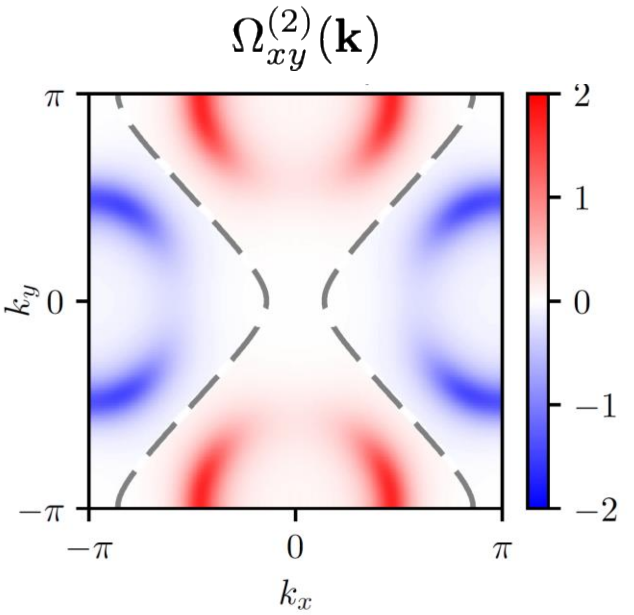
Berry curvature quadrupole in altermagnets

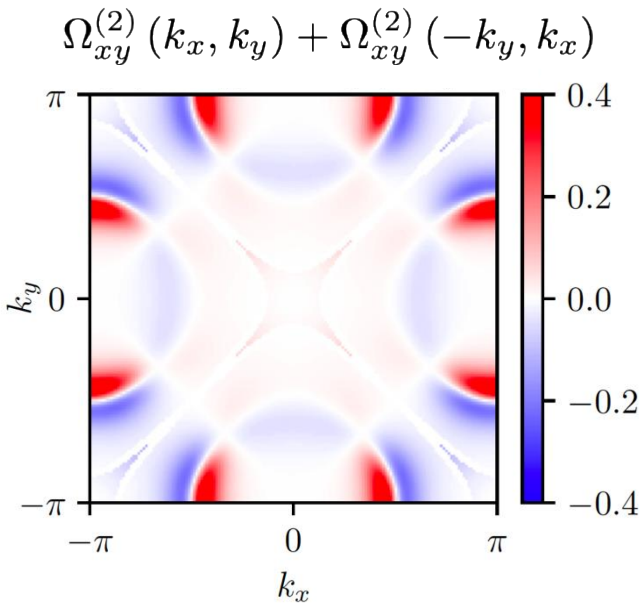
- How to experimentally probe the Berry curvature quadrupole?
  - Application of small symmetry-breaking strain induces a Berry curvature monopole.

$$\varepsilon_{xx} - \varepsilon_{yy} \neq 0$$



Takahashi, …, RMF & Schmalian, PRB (2025)

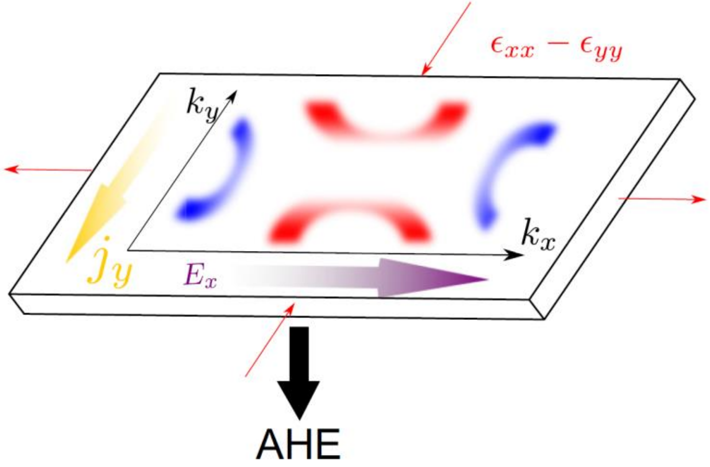




the distorted Berry curvature quadrupole no longer averages to zero, resulting in an anomalous Hall effect (AHE)

Elasto-Hall conductivity as a probe of altermagnetism

- Anomalous Hall effect is thus induced by a small symmetry-breaking strain.
- Corresponding response function: **elasto-Hall conductivity.**



$$j_\alpha = \nu^{(a)}_{\alpha\beta\gamma\delta} E_\beta \varepsilon_{\gamma\delta}$$

anti-symmetric conductivity components

- Closely related to the elasto-conductivity widely employed in studies of electronic nematicity of unconventional superconductors.

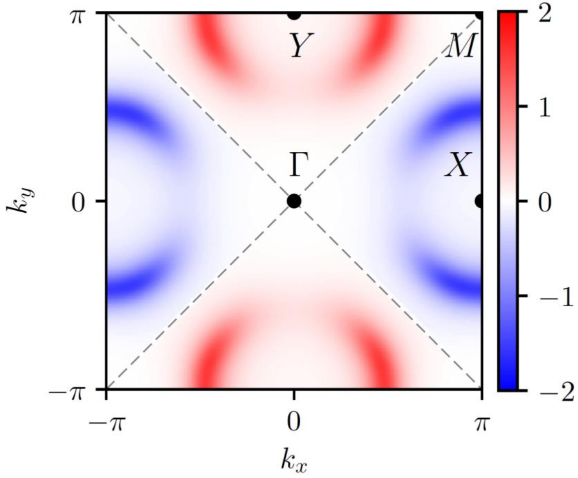
$$j_\alpha = \nu^{(s)}_{\alpha\beta\gamma\delta} E_\beta \varepsilon_{\gamma\delta}$$

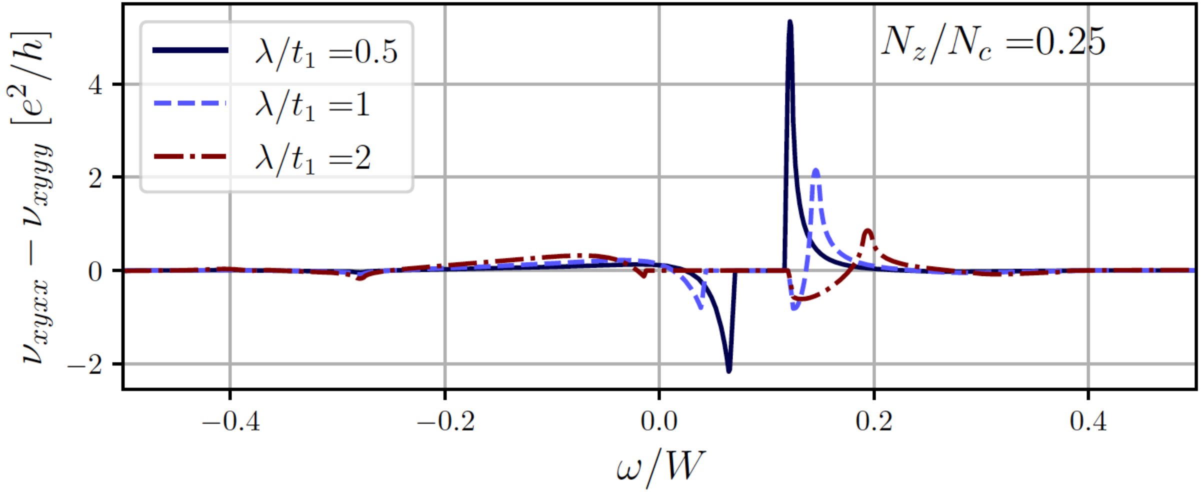
symmetric conductivity components

Chu et al, Science (2012)

Elasto-Hall conductivity as a probe of altermagnetism

- Elasto-Hall conductivity in the Lieb lattice model.





Elasto-Hall conductivity as a probe of altermagnetism

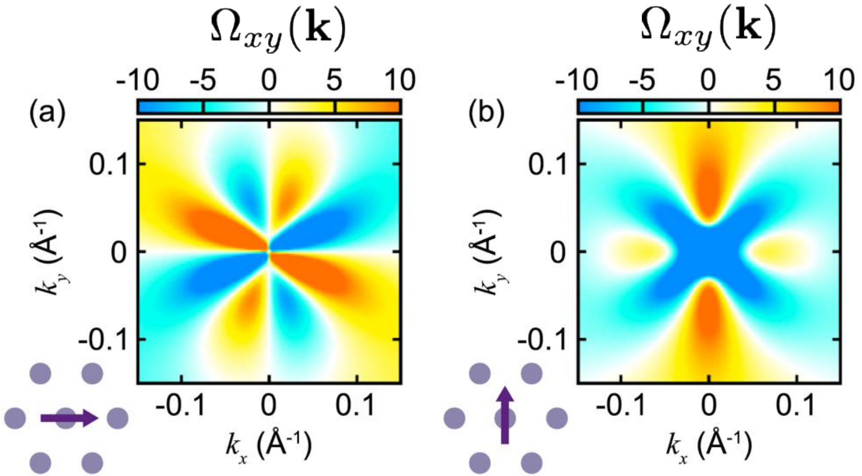
Elasto-Hall conductivity is a general property of altermagnets, proportional to an odd-power of the the altermagnetic order parameter.

	AM irrep.	MPG	Elasto-Hall conductivity
orthorh., D_{2h} (mmm)	A_{1g}^-	mmm (8.1.24)	$\nu_{yzyz},\ \nu_{zxxz}, \nu_{xyxy}$
trigon. D_{3d} $(\bar{3}m)$	A_{1g}^-	$\bar{3}m$ (20.1.71)	$\nu_{xzxx} = \nu_{zxyy} = \nu_{zyxy}, \nu_{xzxz} = \nu_{yzyz}$
tetrag., D_{4h} $(4/mmm)$	A_{1g}^-	$4/mmm$ (15.1.53)	$\nu_{yzyz} = -\nu_{zxxz}$
	B_{1g}^-	$4'/mm'm$ (15.4.56)	$\nu_{yzyz} = \nu_{zxxz}, \nu_{xyxy}$
	B_{2g}^-	$4'/mm'm$ (15.4.56)	$\nu_{yzxz} = -\nu_{zxyz}, \nu_{xyxx} = -\nu_{xyyy}$
hexag., D_{6h} $(6/mmm)$	A_{1g}^-	$6/mmm$ (27.1.100)	$\nu_{yzyz} = -\nu_{zxxz}$
	B_{1g}^-	$6'/m'mm'$ (27.5.104)	$\nu_{yzxy} = \nu_{zxxx} = -\nu_{zxyy}$
	B_{2g}^-	$6'/m'mm'$ (27.5.104)	$\nu_{zxxy} = \nu_{yzyy} = -\nu_{yzxx}$
	E_{2g}^-	$(1, 0)$ mmm (8.1.24)	$\nu_{yzyz}, \nu_{zxxz}, \nu_{xyxy}$
		$(1, \frac{1}{\sqrt{3}})$ $m'm'm$ (8.4.27)	$\nu_{xyxx}, \nu_{xyyy}, \nu_{xyzz}, \nu_{xzyz}, \nu_{yzxz}$
		$(1, b)$ $2/m$ (5.1.12)	$\nu_{xzxx}, \nu_{xzyy}, \nu_{xzzz}, \nu_{xyyz}, \nu_{yzyz}, \nu_{xzxz}, \nu_{xyxy}, \nu_{yzxy}$
cubic, O_h $(m\bar{3}m)$	A_{1g}^-	$m\bar{3}m$ (29.1.109)	–
	A_{2g}^-	$m\bar{3}m'$ (32.4.121)	$\nu_{yzyz} = \nu_{zxxz} = \nu_{xyxy}$
	E_g^-	$(1, 0)$ $4/mmm$ (15.1.53)	$\nu_{yzyz} = -\nu_{zxxz}$
		$(1, \frac{1}{\sqrt{3}})$ $4'/mm'm$ (15.4.56)	$\nu_{yzyz} = \nu_{zxxz}, \nu_{xyxy}$
		$(1, b)$ mmm (8.1.24)	$\nu_{yzyz}, \nu_{zxxz}, \nu_{xyxy}$
	T_{2g}^-	$(1, 0, 0)$ $4'/mm'm$ (15.4.56)	$\nu_{yzxz} = -\nu_{zxyz}, \nu_{xyxx} = -\nu_{xyyy}$
		$(1, 1, 0)$ $m'm'm$ (8.4.27)	$\nu_{yzxx}, \nu_{yzyy}, \nu_{yzzz}, \nu_{xyxz}, \nu_{xzxy}$
		$(1, 1, 1)\bar{3}m$ (20.1.71)	$\nu_{xzxy} = \nu_{zyyy} = \nu_{yzxx}, \nu_{xzxz} = \nu_{yzyz}$
		$(1, b, 0)$ $2'/m'$ (5.5.16)	$\nu_{xyxx}, \nu_{yzxx}, \nu_{xyyy}, \nu_{yzyy}$ $\nu_{xyzz}, \nu_{yzzz}, \nu_{xzyz}, \nu_{xyxz}, \nu_{yzxz}, \nu_{xzxy}$
		$(1, 1, c)$ $2/m$ (5.1.12)	$\nu_{xzxx}, \nu_{xzyy}, \nu_{xzzz}, \nu_{xyyz}, \nu_{yzyz}, \nu_{xzxz}, \nu_{xyxy}, \nu_{yzxy}$
		$(1, b, c)$ -1 (2.1.3)	all elements $\nu_{\alpha\beta\gamma\delta}$ are nonzero where $\alpha \neq \beta$

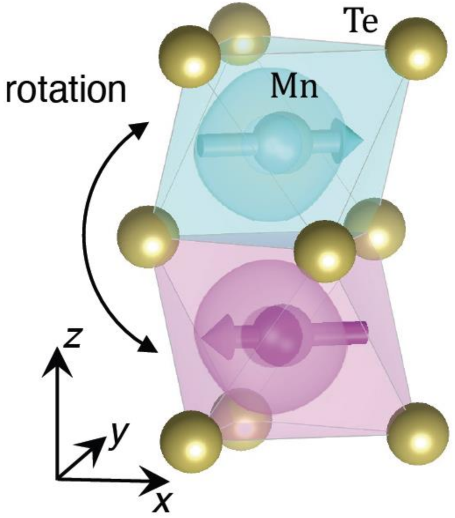
Anomalous Hall effect in altermagnets

- When SOC is included, weak ferromagnetism can be induced in an AM state for certain directions of the magnetic moments. Berry curvature multipole is distorted even without strain, resulting in an AHE.

MnTe: in-plane moments along the *y*-axis distort a BC hexadecapole



Kluczyk et al, PRB (2024)



see also Attias et al, PRB (2024)

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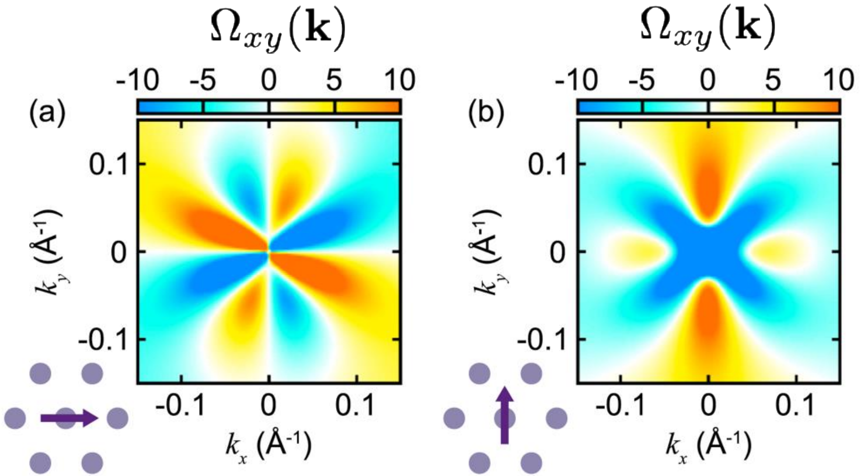
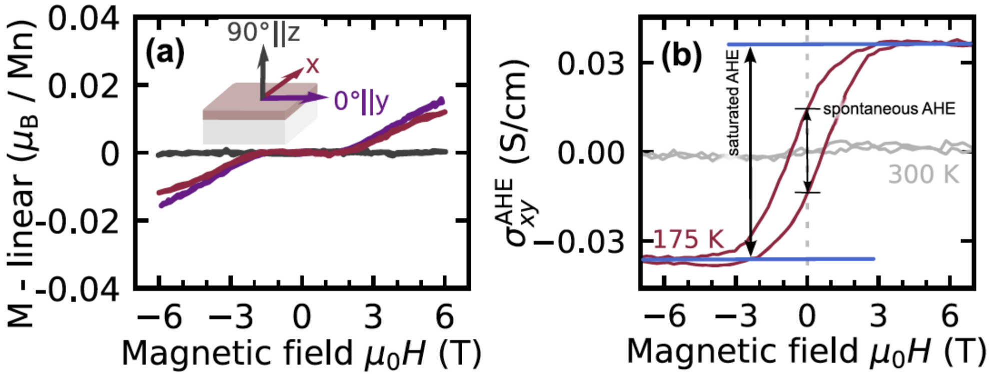


Kluczyk et al, PRB (2024)

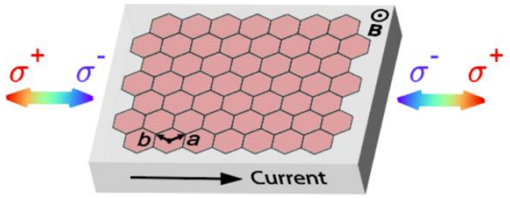


Gonzalez Betancourt et al, PRL (2023)

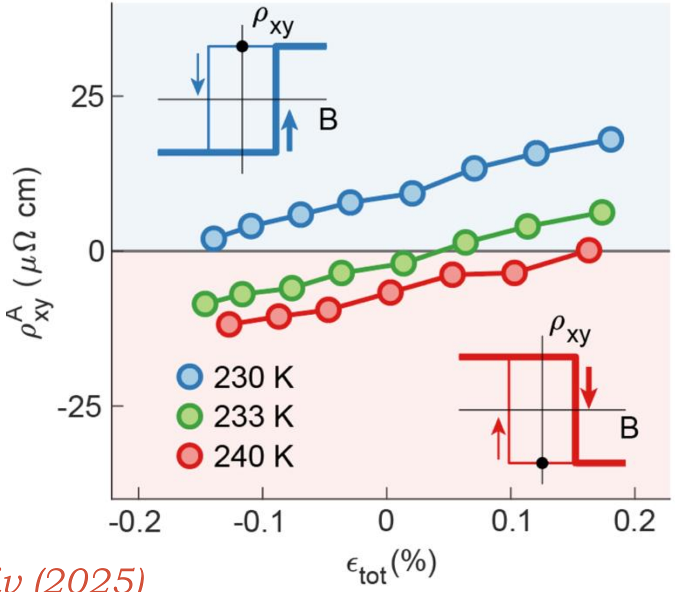
large AHE but very small magnetization

Anomalous Hall effect in altermagnets

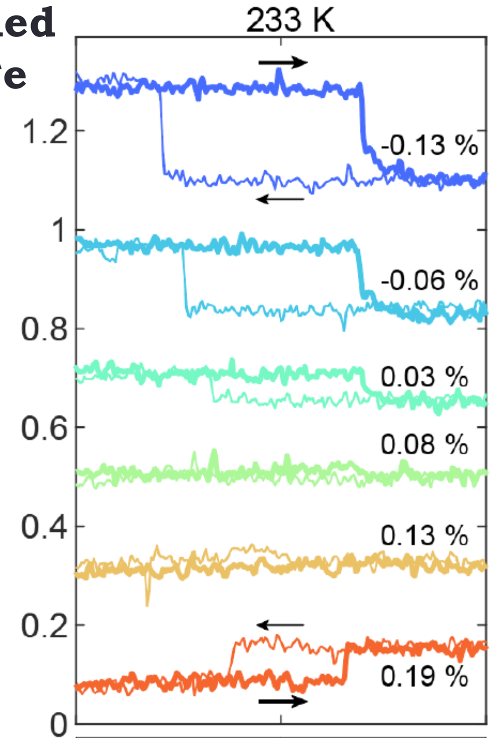
- Even in the case where the zero-strain BC multipole is distorted by the SOC, strain can be used to manipulate the AHE.



$$\sigma_{xy}^{\mathrm{AHE}} = AN^3 + BN\varepsilon$$



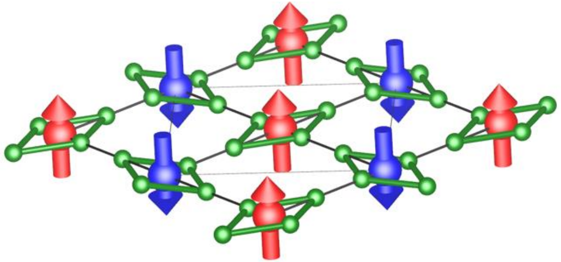
strained MnTe

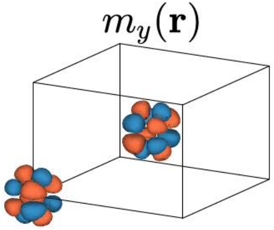


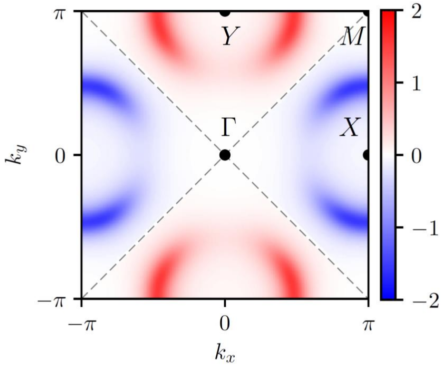
Liu, (...), RMF, Chu & Dai, arxiv (2025)

see also: Smolenski et al, arxiv (2025)

Summary







- Altermagnets encompass a broad range of insulating, metallic, and semiconducting materials of interest to spintronics, correlated electron systems, and topological matter.
- Altermagnets host a broad landscape of non-trivial topological phenomena, such as Dirac points, Weyl nodal lines, and Berry curvature quadrupoles.
- Elasto-Hall conductivity is a general property of altermagnets, complementary to piezomagnetism, that provides access to their non-trivial Berry curvature.

RMF, Carvalho, Birol & Pereira, *Phys. Rev. B* ***109***, *024404 (2024)*

Antonenko, RMF & Venderbos, *Phys. Rev. Lett.* ***134***, *096703 (2025)*

Takahashi, Steward, Ogata, RMF & Schmalian, *Phys. Rev. B* ***111***, *184408 (2025)*

Jungwirth, Sinova, RMF, Liu, (…), & Šmejkal, *Nature* **649**, 837 (2026)