# New magnetic phase in the flatland: two-dimensional altermagnets


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# Special thanks to my collaborators


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ISCRA
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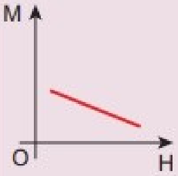
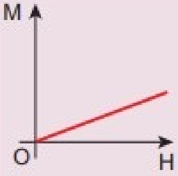
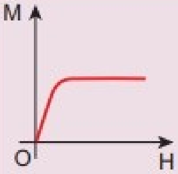
# What kinds of magnetism exist?

# Based on their behavior in magnetic field

| Type of magnetism | Magnetising field is absent (H = 0) | Magnetising field is present ($H \neq 0$) | Magnetisation of the material | Susceptibility | Relative permeability |
|---|---|---|---|---|---|
| Diamagnetism | (Zero magnetic moment) | (Aligned opposite to the field) |  | Negative | Less than unity |
| Paramagnetism | (Net magnetic moment but random alignment) | (Aligned with the field) |  | Positive and small | Greater than unity |
| Ferromagnetism | (Net magnetic moment in a domain but random alignment of domains) | (Aligned with the field) |  | Positive and large | Very large |

**antiferromagnetism**
1930s Néel, Landau

**M = 0**
Néel temperature ($T_c$)

**ferrimagnetism**
1940s Néel
1970 Nobel Prize

**M ≠ 0**

# ALTERMAGNETISM – a brand new magnetic phase

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J. Krempaský, L. Šmejkal, S. W. D'Souza, M. Hajlaoui, G. Springholz, K. Uhlířová, F. Alarab, P. C. Constantinou, V. Strocov, D. Usanov, W. R. Pudelko, R. González-Hernández, A. Birk Hellenes, Z. Jansa, H. Reichlová, Z. Šobáň, R. D. Gonzalez Betancourt, P. Wadley, J. Sinova, D. Kriegner, J. Minár, J. H. Dil & T. Jungwirth

*Nature* **626**, 517–522 (2024) | Cite this article

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## Chiral Magnons in Altermagnetic $RuO_2$

Libor Šmejkal, Alberto Marmodoro, Kyo-Hoon Ahn, Rafael González-Hernández, Ilja Turek, Sergiy Mankovsky, Hubert Ebert, Sunil W. D'Souza, Ondřej Šipr, Jairo Sinova, and Tomáš Jungwirth

Phys. Rev. Lett. **131**, 256703 – Published 20 December 2023

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## Crystal Thermal Transport in Altermagnetic $RuO_2$

Xiaodong Zhou, Wanxiang Feng, Run-Wu Zhang, Libor Šmejkal, Jairo Sinova, Yuriy Mokrousov, and Yu

Phys. Rev. Lett. **132**, 056701 – Published 29 January 2024

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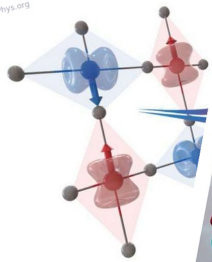
Editors' notes

FEBRUARY 6, 2024 FEATURE

## Altermagnets: A new chapter in magnetism and thermal science

by Tejasri Gururaj , Phys.org



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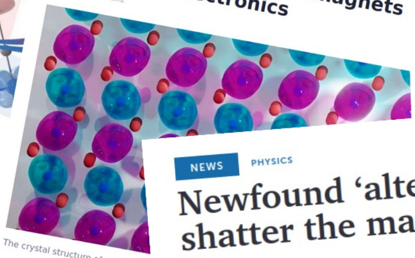
MARCH 13, 2024

## Good prospects for altermagnets spin-based electronics

by Universitaet Mainz

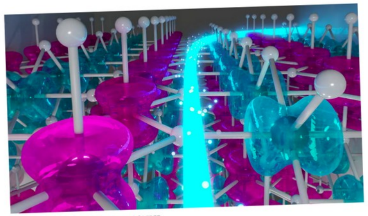


The crystal structure of altermagne

Science and 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



PHOTOGRAPH: LIBOR ŠMEJKAL & MATTHIAS GREBER

NEWS PHYSICS

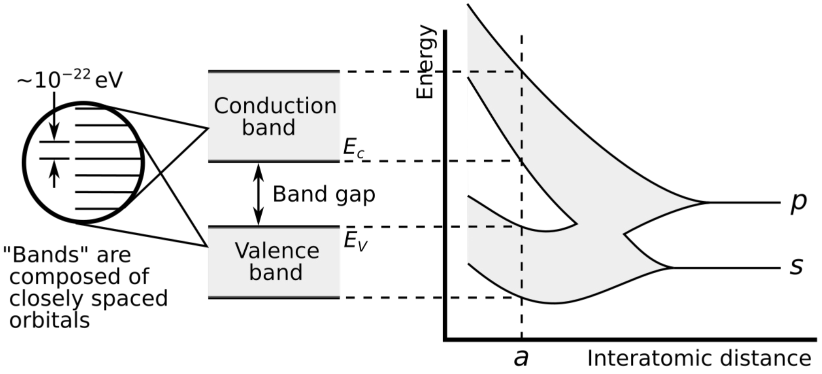
## Newfound 'altermagnets' shatter the magnetic status quo

The materials have attracted attention for their versatile potential

# Why all the fuss about altermagnets?

# Spin degeneracy of electronic bands

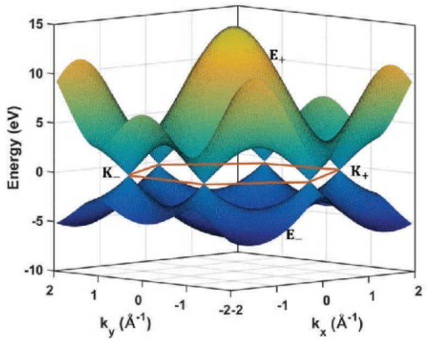
electrons in a periodic crystalline potential
→ **(electronic) energy bands**

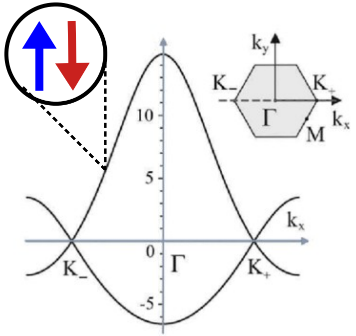



electron crystal momentum | electron spin +1/2 -1/2

**energy band** $E_n(\mathbf{k}, \sigma)$

band index (integer)

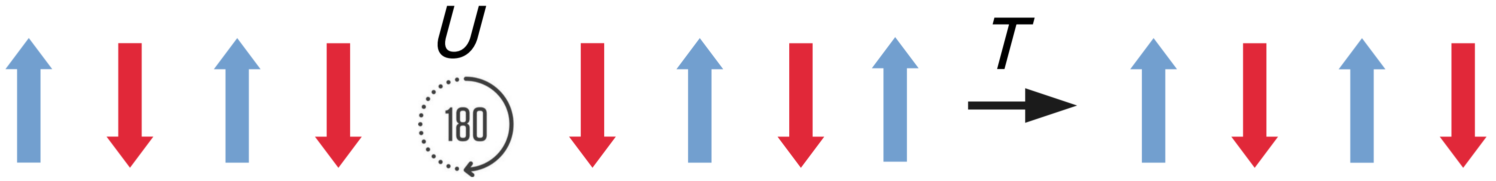



Can magnets have spin-degenerate bands?

# Symmetry requirements for spin splitting

1. time-reversal $\theta : E_n(\mathbf{k},\sigma) \rightarrow E_n(-\mathbf{k},-\sigma)$
   space inversion $I : E_n(\mathbf{k},\sigma) \rightarrow E_n(-\mathbf{k},\sigma)$
   $\Big\}\ \theta I : E_n(\mathbf{k},\sigma) \rightarrow E_n(\mathbf{k},-\sigma)$

2. 


$$UT : E(\mathbf{k},\sigma) \rightarrow E(\mathbf{k}+\mathbf{K},-\sigma) = E(\mathbf{k},-\sigma)$$

$\theta I$ ✗ $UT$ ✗

bands are spin split if both ***θI*** and ***UT*** symmetries are **broken**

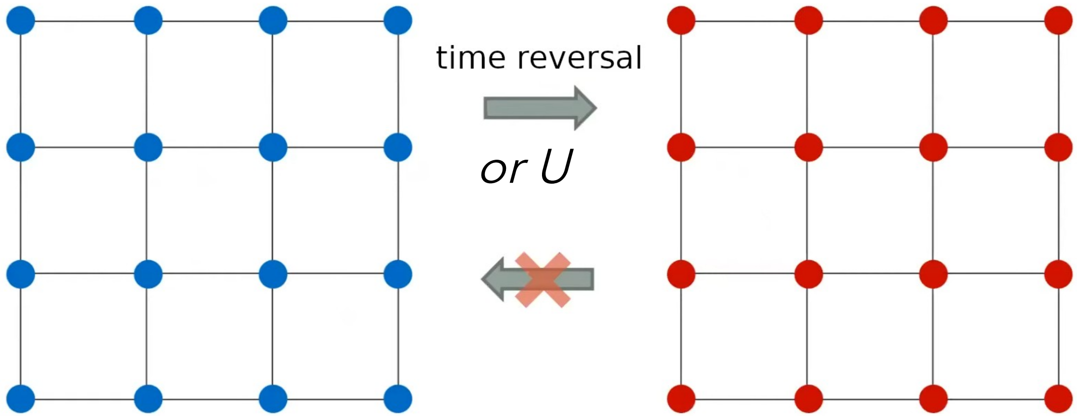
# Ferromagnets (FM)

- apply time reversal and ask: is there a crystal symmetry operation that would restore the initial magnetic state?
- Ferromagnets: NO

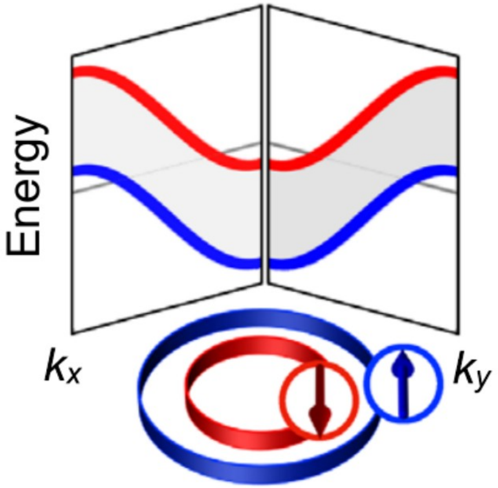
$\theta I$ ✗ $UT$ ✗

● spin-up

● spin-down




adapted from the lecture given by Rafael Fernandes:
*Topological properties of the Zeeman splitting in altermagnets*



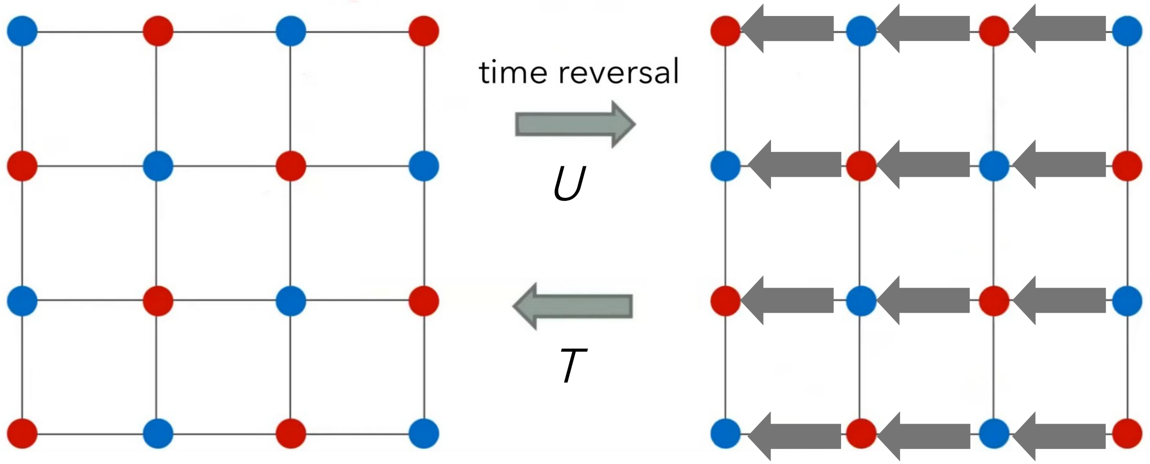

Zeeman splitting

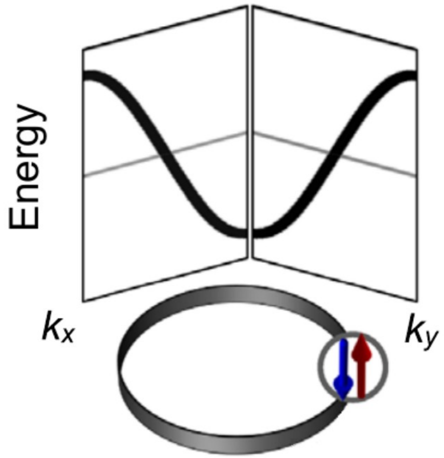
# Antiferromagnets (AF)

- is there a crystal symmetry operation that restores the initial state?
- Antiferromagnets: YES

● spin-up
● spin-down

$\theta I$ ✗ $UT$ ✓

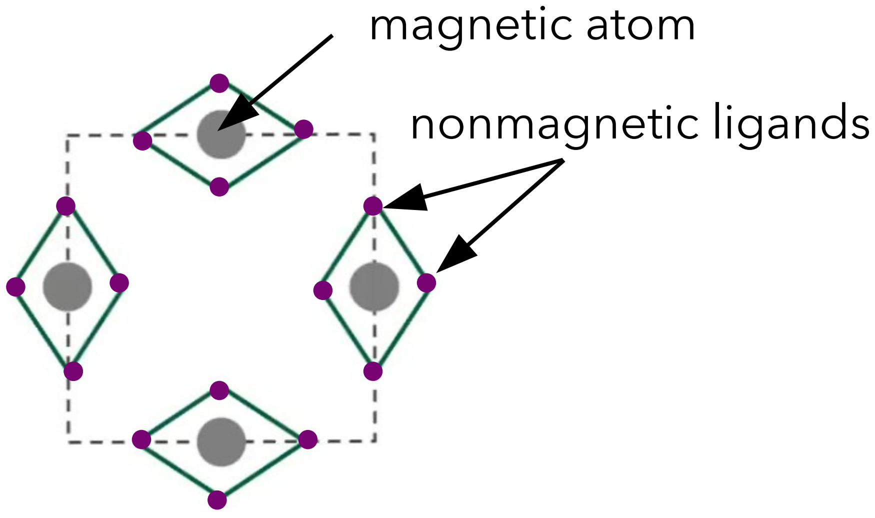


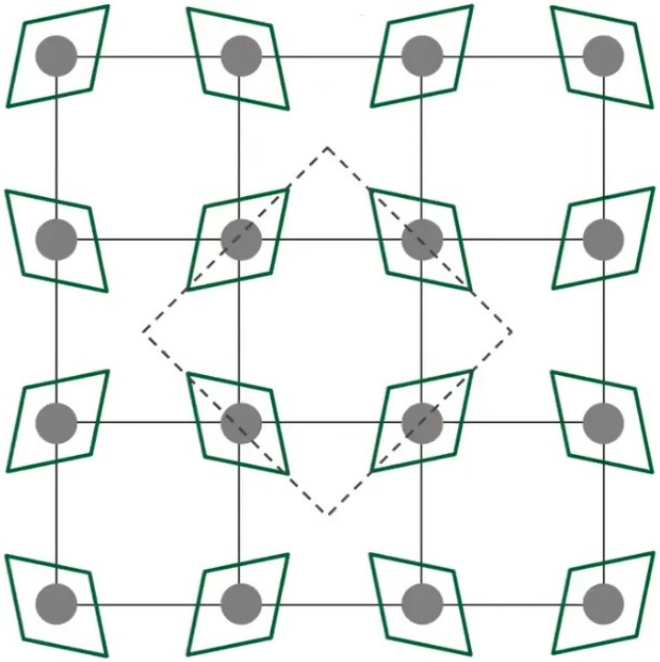
Kramers degeneracy

# Is there a third option besides FM and AF?

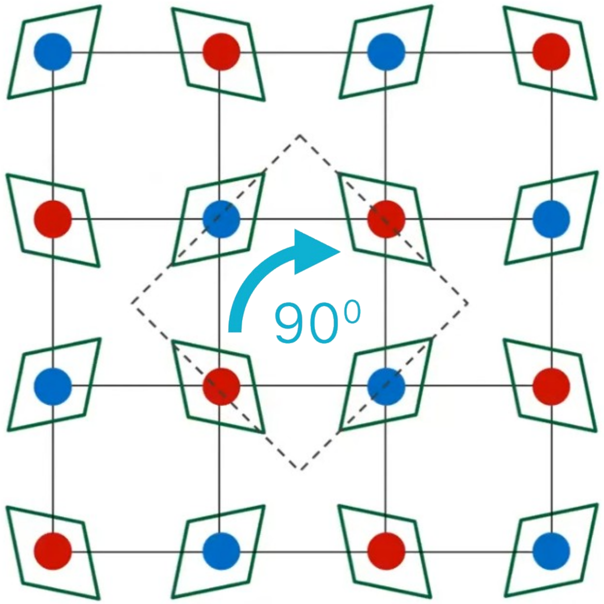
two structural motifs in crystal structure due to different orientation of nonmagnetic ligands




unit cell of the crystal



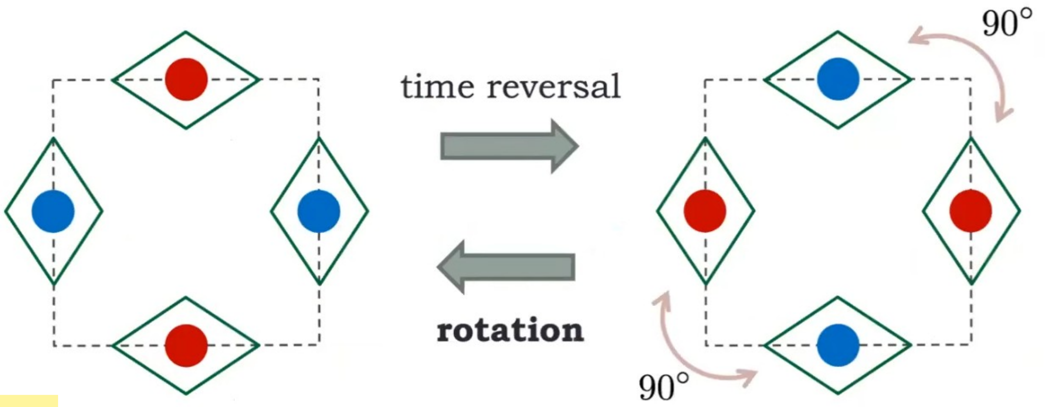
# Altermagnets (AM) is the third option




spin-up
spin-down

translation/inversion cannot restore the initial state

- two opposite-spin sublattices (like in antiferromagnets) but *UT* symmetry is broken
- $C_4$ **rotation operation** needed to restore the initial state

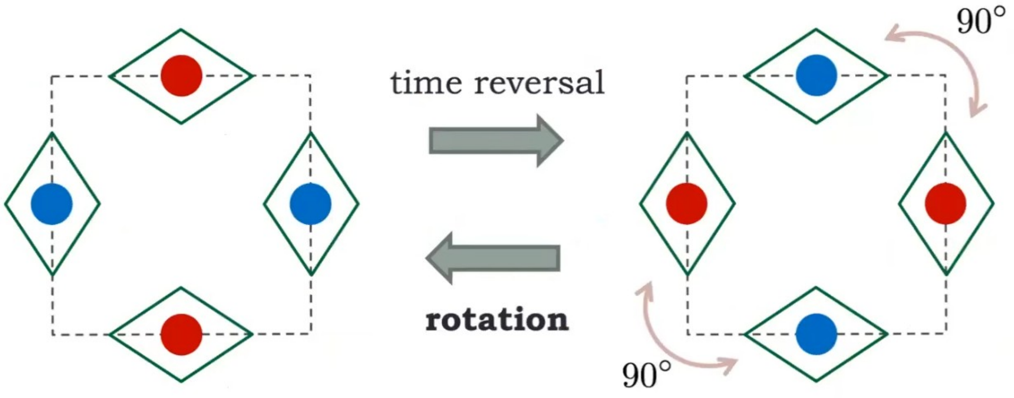


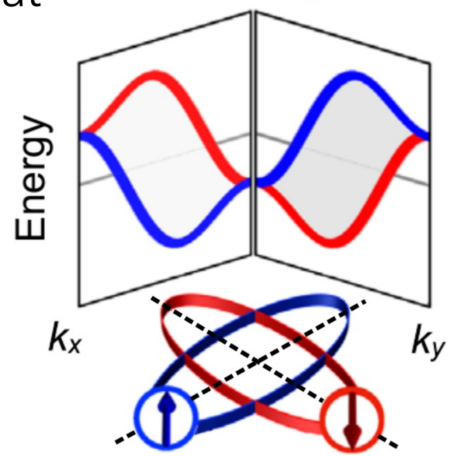

L. Šmejkal et al.: Phys. Rev. X **12**, 031042 (2022)
L. Šmejkal et al.: Phys. Rev. X **12**, 040501 (2022)

# Non-relativistic spin splitting in altermagnets

$\theta I$ ✗ $UT$ ✗

… but there is a **rotation** that does not exist in FM!

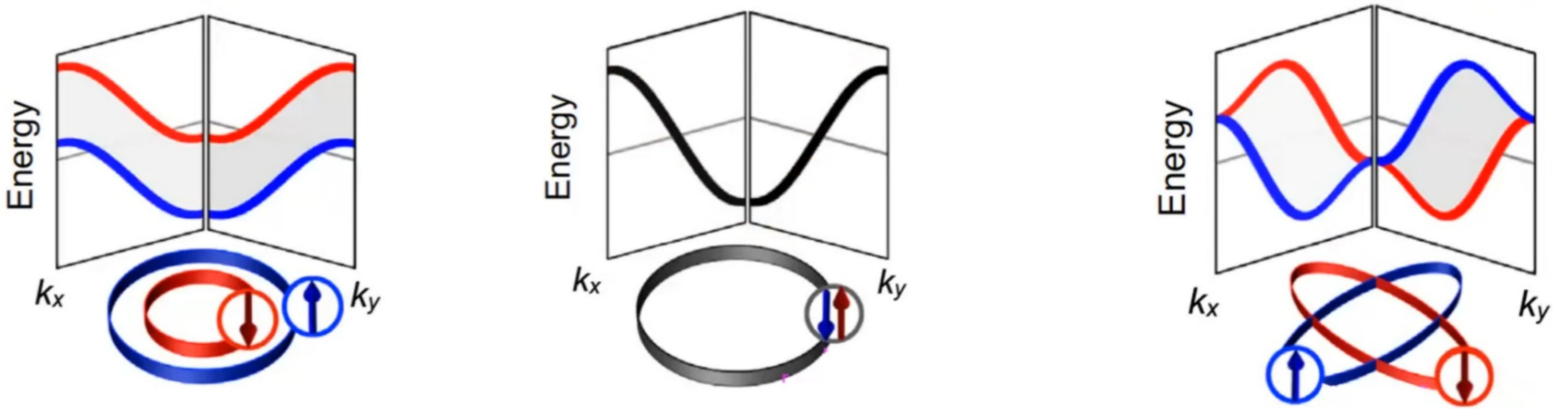



$$\Delta E\left(\mathbf{k}\right) \equiv E_{\uparrow}\left(\mathbf{k}\right) - E_{\downarrow}\left(\mathbf{k}\right) \propto \sin k_x \sin k_y$$

the spin splitting is momentum-dependent
→ **spin-momentum locking**

# Spin groups classification of collinear magnets

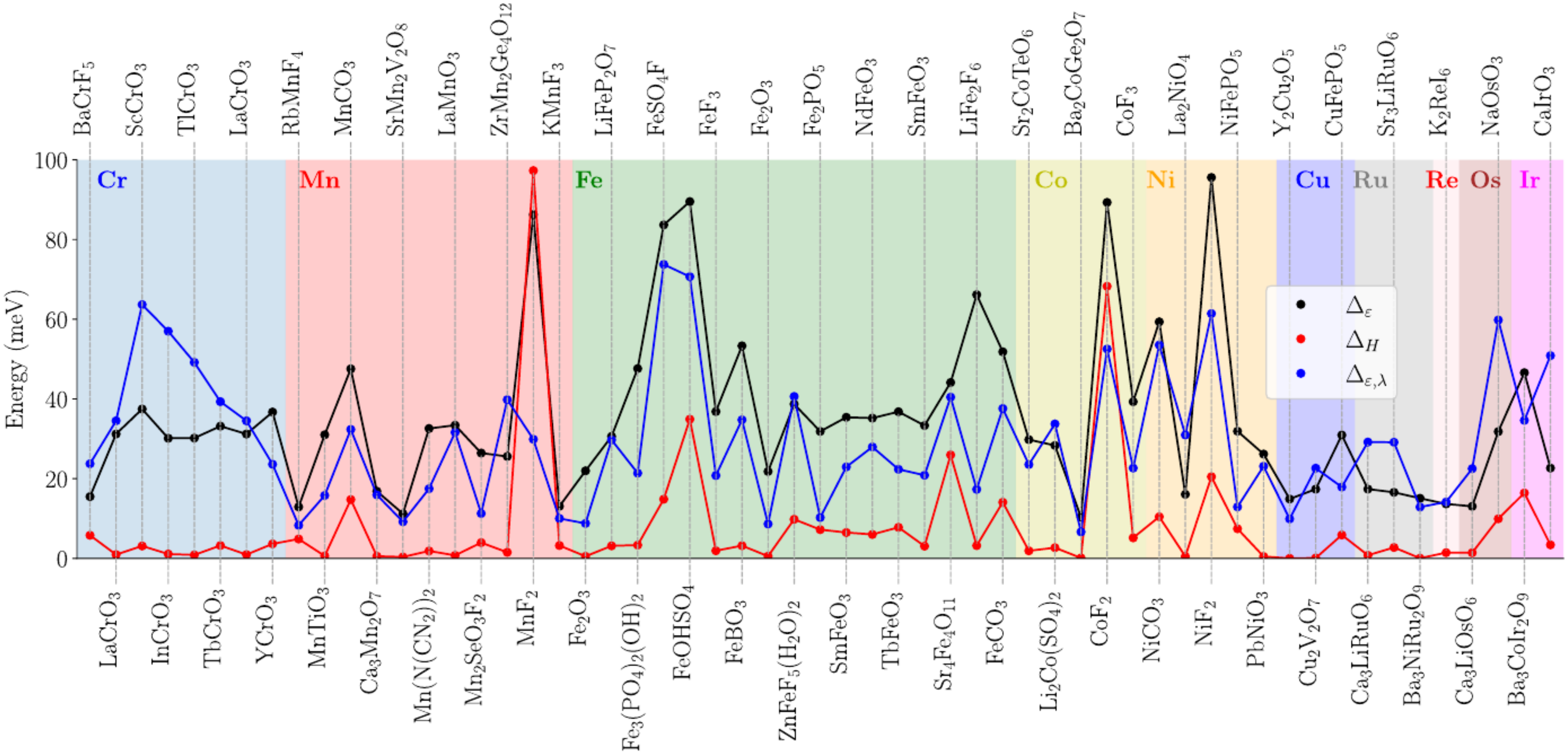



| ferromagnets (FM) | antiferromagnets (AF) | altermagnets (AM) |
| --- | --- | --- |
| $[E\|\|\mathbf{G}]$ | $[E\|\|\mathbf{G}] + [C_2\|\|\mathbf{G}]$ | $[E\|\|\mathbf{H}] + [C_2\|\|A\mathbf{H}]$ |
| type-I spin groups | type-II spin groups | type-III spin groups |

this classification is valid only if the spin-orbit coupling is neglected!


D. B. Litvin et al.: Physica 76, 538 (1974)
D. B. Litvin: Acta Crystallogr. A 33, 279 (1977)
P. Liu et al.: Phys. Rev. X 12, 021016 (2022)
L. Šmejkal et al.: Phys. Rev. X **12**, 031042 (2022)

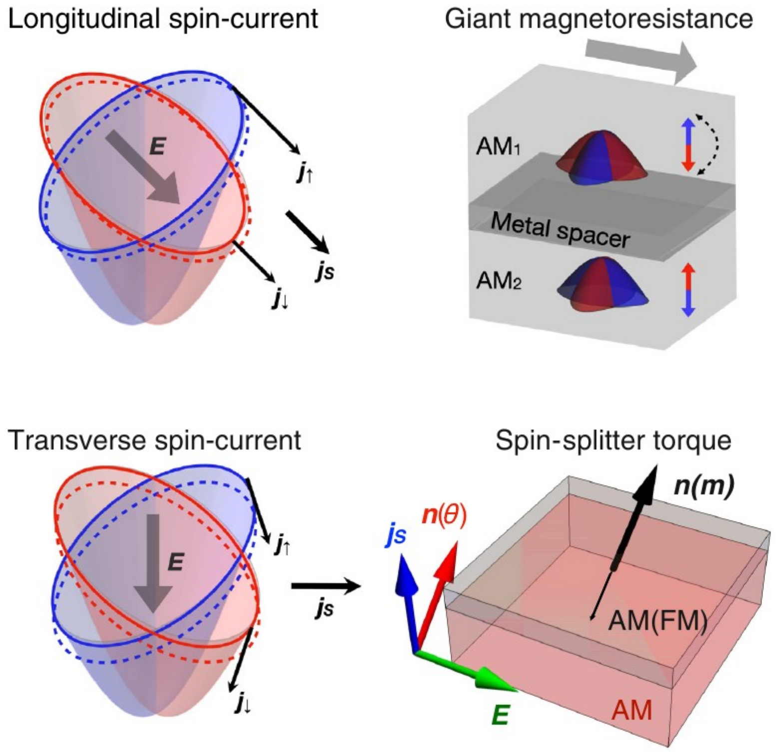
# Spin splitting in 3D altermagnets (in meV)




Y. Guo et al.: Materials Today Physics **32**, 100991 (2023)

# Potential application of altermagnets in technology

- non-relativistic spin-splitting (like in FM) with zero net magnetization (like in AF)




- application in **SPINTRONICS** – spin-polarized currents controlled with external electric field
- ultrafast dynamics in THz regime → FM which have GHz dynamics
- altermagnets are robust against demagnetizing stray fields
- spin-splitting is non-relativistic → no need for heavy elements

L. Šmejkal et al.: Phys. Rev. X **12**, 040501 (2022)
X. Zhou et al.: Phys. Rev. Lett. **132**, 056701 (2024)

# Are there any two-dimensional altermagnets around?

# Van der Waals altermagnet: $RuF_4$

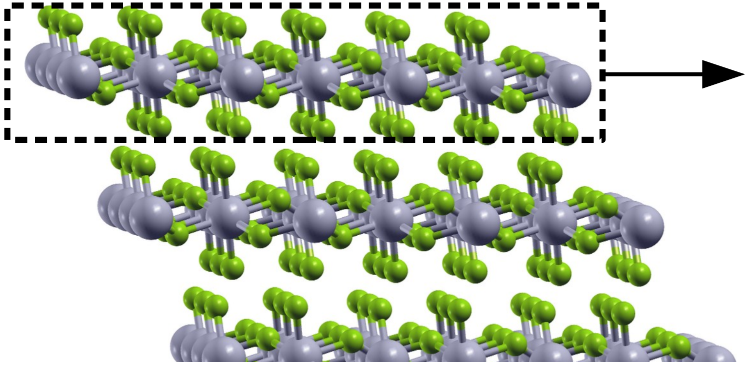
## bulk (3D crystal)

- crystallographic space group #14 ($P2_1/c$)
- synthesized in 1992
  W. J. Casteel Jr. et al.: Inorg. Chem. 31, 3124 (1992)

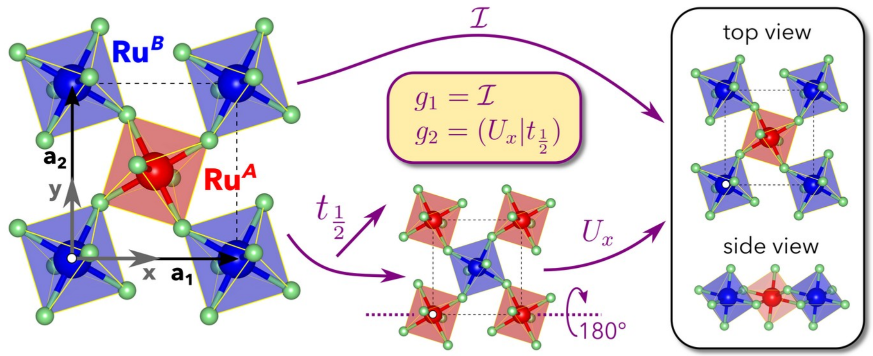
## monolayer (2D crystal)

- layer group $p2_1/b11$ (layer group #17), MSG of type-I (equal to parent SG)

- predicted to be stable and exfoliable
  N. Wang et al.: PRB **106**, 064435 (2022)



$$G = \{e, \mathcal{I}, (U_x|t_{\frac{1}{2}}), \mathcal{I}(U_x|t_{\frac{1}{2}})\}$$

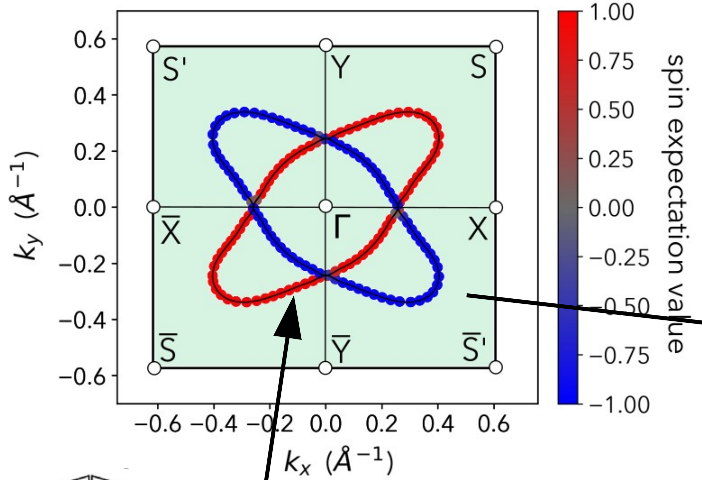


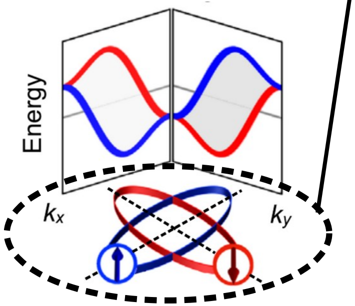

M. Milivojević, M. Orozović, M. Gmitra, S. Picozzi, **SS**: 2D Mater. 11, 035025 (2024)

J. Sødequist, T. Olsen: Appl. Phys. Lett. **124**, 182409 (2024) ← other 2D altermagnets as well

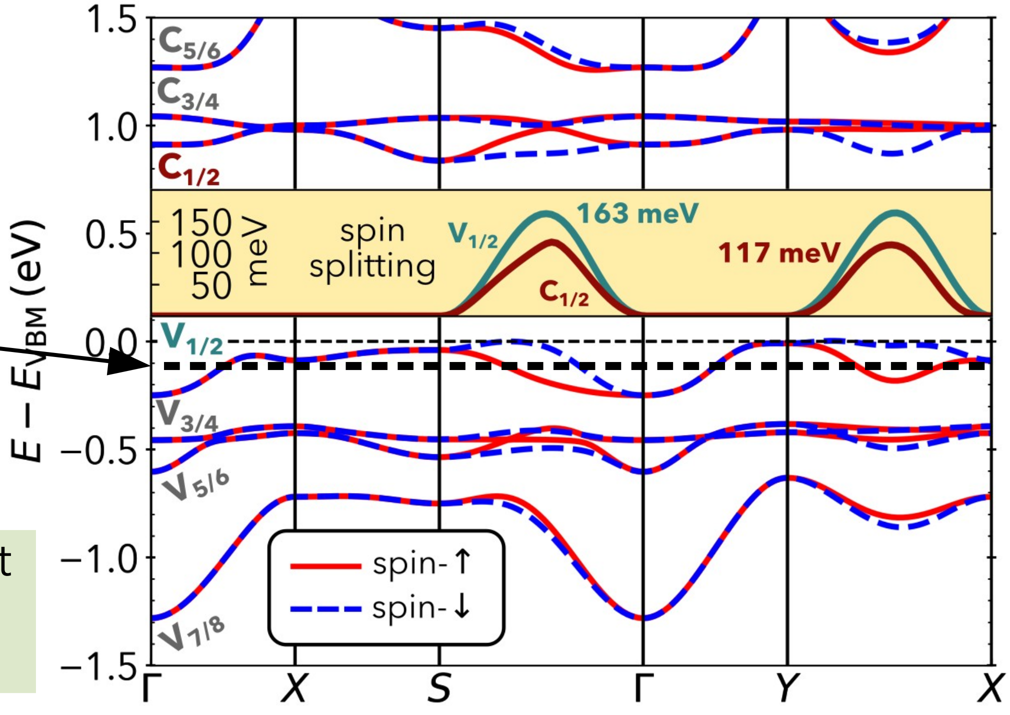
# Non-relativistic spin splitting of bands in $RuF_4$

Brillouin zone




d-wave altermagnet
with spin splitting
~150 meV




conduction bands

valence bands

M. Milivojević, M. Orozović, M. Gmitra, S. Picozzi, **SS**: 2D Mater. 11, 035025 (2024)

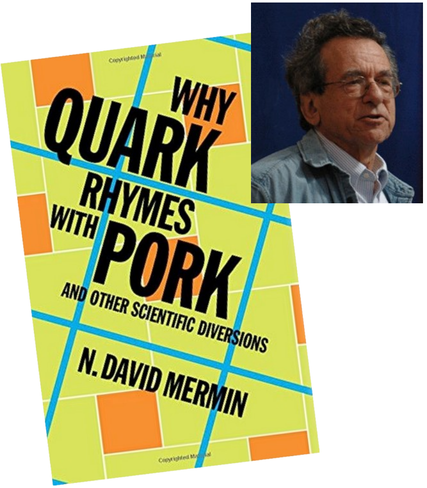
# Why are 2D (alter)magnets different from 3D (alter)magnets?

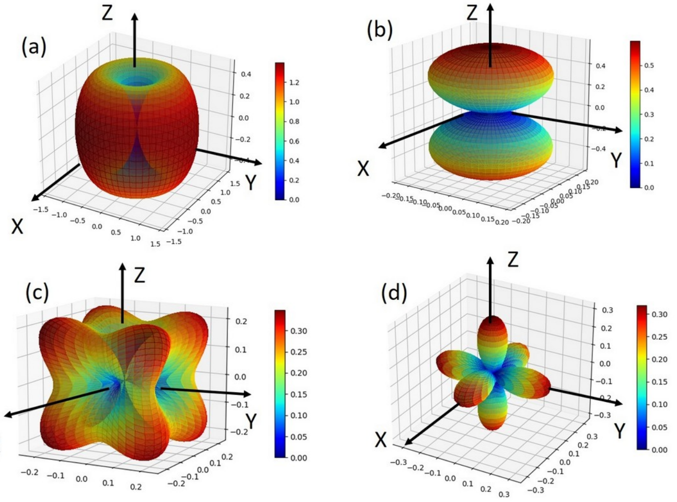
# Mermin-Wagner theorem (1960s)

ABSENCE OF FERROMAGNETISM OR ANTIFERROMAGNETISM
IN ONE- OR TWO-DIMENSIONAL ISOTROPIC HEISENBERG MODELS*

N. D. Mermin† and H. Wagner‡
Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York
(Received 17 October 1966)

It is rigorously proved that at any nonzero temperature, a one- or two-dimensional isotropic spin-$S$ Heisenberg model with finite-range exchange interaction can be neither ferromagnetic nor antiferromagnetic. The method of proof is capable of excluding a variety of types of ordering in one and two dimensions.

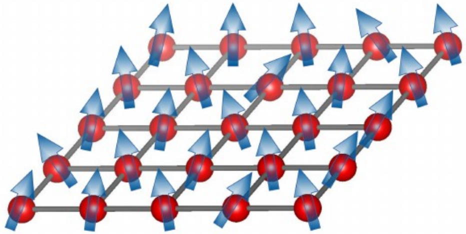



Isotropic Heisenberg model

$$\mathcal{H} = \frac{1}{2}\sum_{i\neq j} J_{ij}\, \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

$J_{ij} < 0 \rightarrow$ FM
$J_{ij} > 0 \rightarrow$ AF, AM



**Magnetic anisotropy** is required for the long-range order of spins in two dimensions at finite temperatures

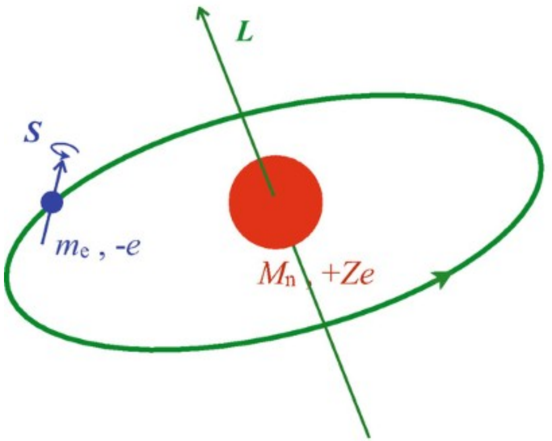
# Magnetic anisotropy comes from spin-orbit coupling

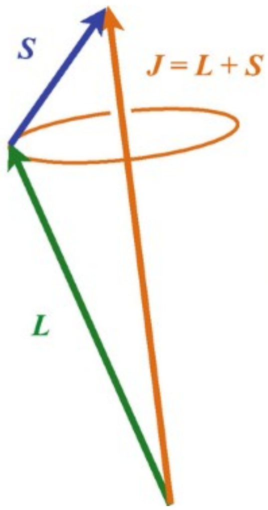
**Spin-orbit coupling (SOC)** is the dipole interaction between the spin of an electron and the magnetic field created by the electron's own orbital motion.

relativistic origin

$$\mathcal{H}_{so} = \lambda\, \boldsymbol{L} \cdot \boldsymbol{S}$$

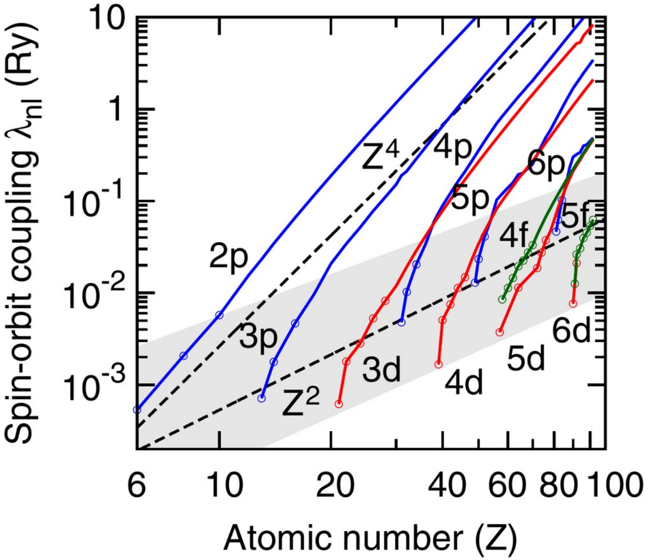
*spin-orbit coupling*

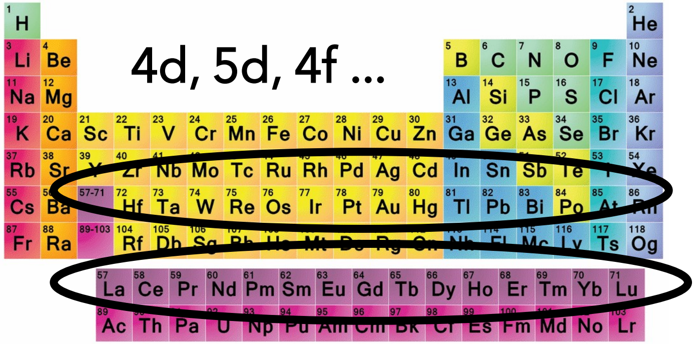



heavy atoms = strong SOC

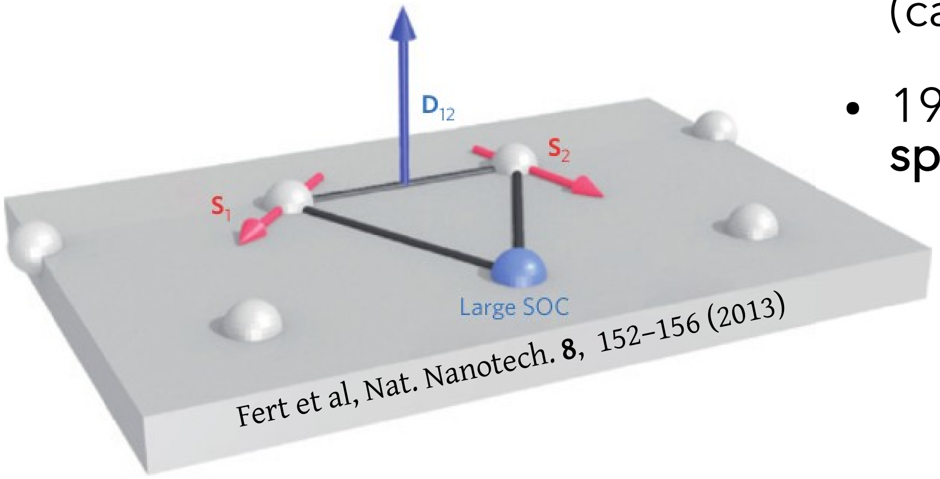
Popović et al, Phys. Rev. B **92**, 035135 (2015)



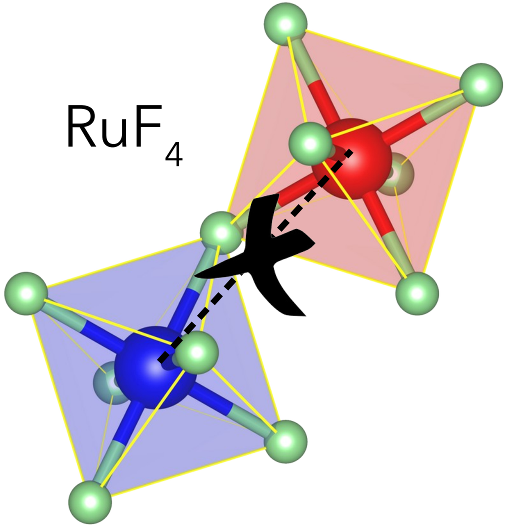
# … as well as the Dzyaloshinskii-Moriya interaction (DMI)

$$H_{DM} = \mathbf{D}_{12} \cdot (\mathbf{S}_1 \times \mathbf{S}_2)$$




- 1958 - I. Dzyaloshinskii explained weak ferromagnetism in hematite $\alpha$-$Fe_2O_3$ (canting angle ~0.06°)
- 1960 - T. Moriya: DMI appears due to **spin-orbit coupling** (no SOC → no DMI).

RuF$_4$



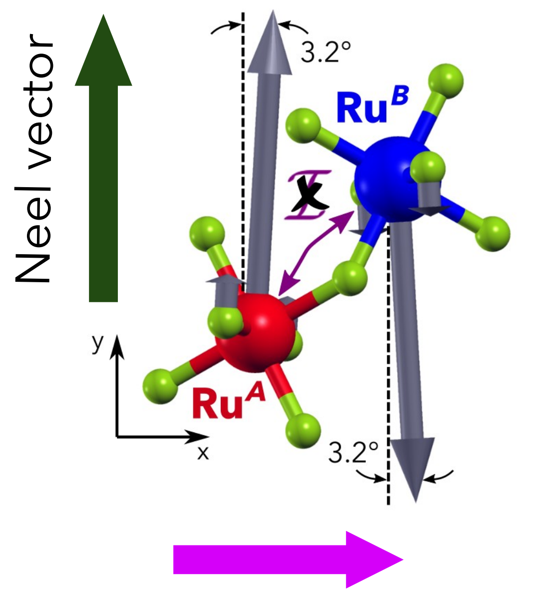
Ru-Ru bond has no point of inversion

→ **DMI allowed**

- DMI is the **antisymmetric anisotropic exchange:** $S_1$ $S_2$ bond must lack the point of inversion

# DMI induces spin canting in $RuF_4$

Ru magnetic moments ~ 1.5 $\mu_B$




weak magnetization $M_x$ ~ 0.22 $\mu_B$

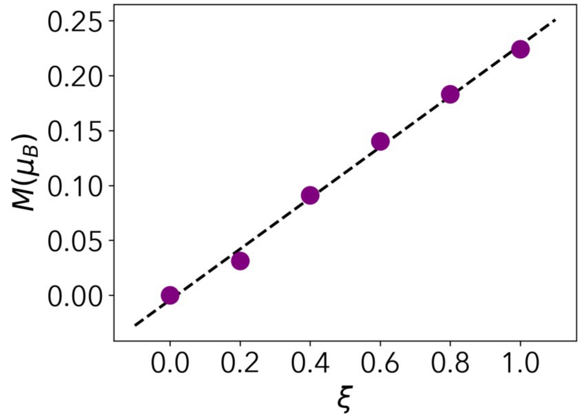
- DMI induces **weak magnetization** in the in-plane direction **perpendicular** to the Neel vector

$$(U_x|t_{\frac{1}{2}})(M_x, M_y, M_z) \rightarrow (M_x, -M_y, -M_z)$$

- canting angle 3.2° - much larger than 0.06° in hematite

- weak magnetization is linear in SOC strength

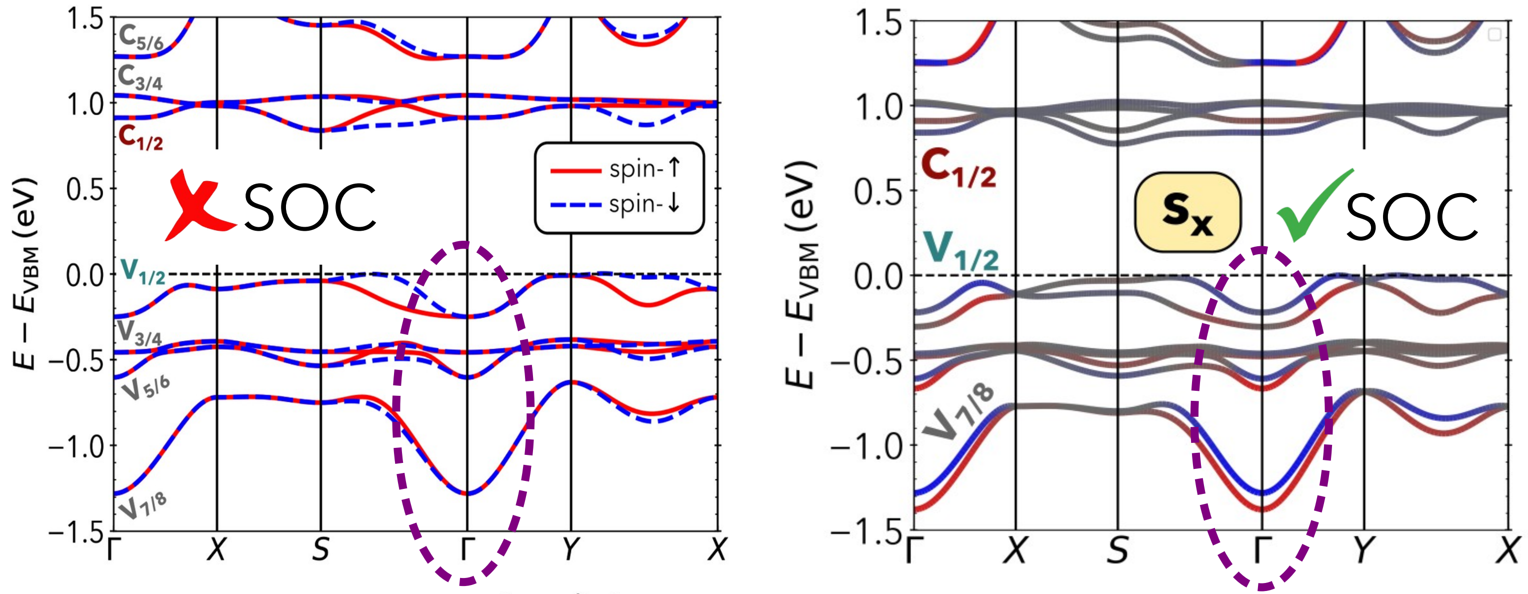
$$E_{\rm SOC} = \xi \lambda \mathbf{L} \cdot \mathbf{S}$$
$$\xi \in [0, 1]$$

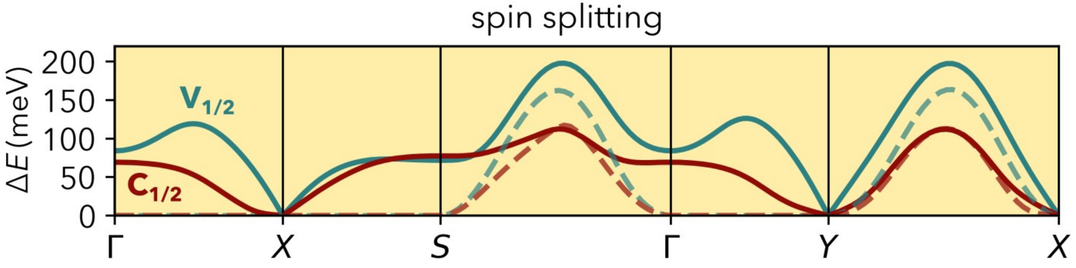



M. Milivojević, M. Orozović, M. Gmitra, S. Picozzi, **SS**: 2D Mater. 11, 035025 (2024)

# How spin-orbit coupling changes the spin splitting of bands?

# Relativistic spin splitting of bands in $RuF_4$




- SOC induces band splitting the same order of magnitude as altermagnetic splitting (~100 meV)

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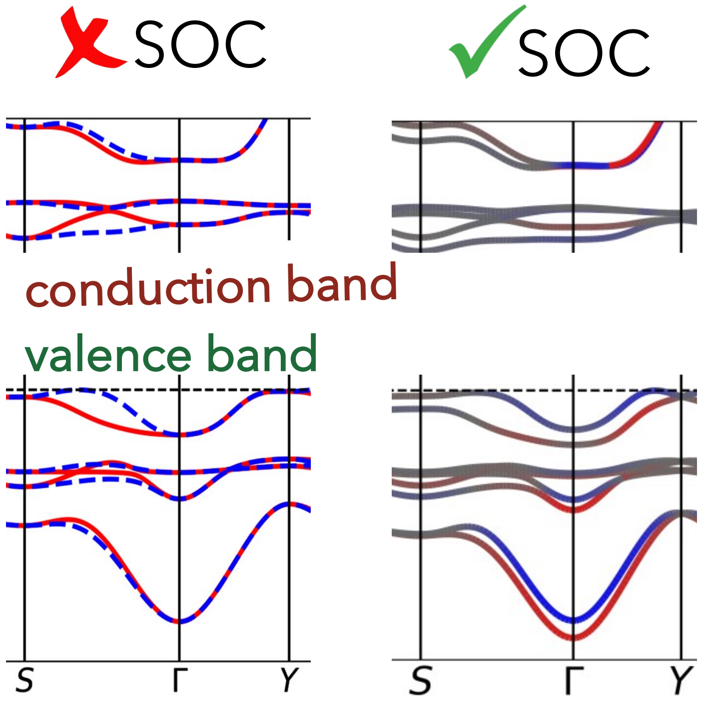
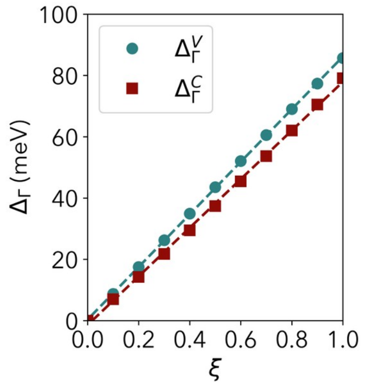
# SOC lifts Γ degeneracy of each band




- spin splitting at Γ is a **cooperative effect** of broken time-reversal symmetry and SOC
- splitting at Γ is linear in SOC constant




$$E_{\mathrm{SOC}} = \xi \lambda \mathbf{L} \cdot \mathbf{S}$$

$$\xi \in [0, 1]$$

- $RuF_4$ has inv. symmetry, splitting near Γ scales as ~$k^2$

$$H_{SOC}(\mathbf{k}) = \Delta_\Gamma \sigma_x + \alpha k_x^2 \sigma_x + \beta k_y^2 \sigma_y$$

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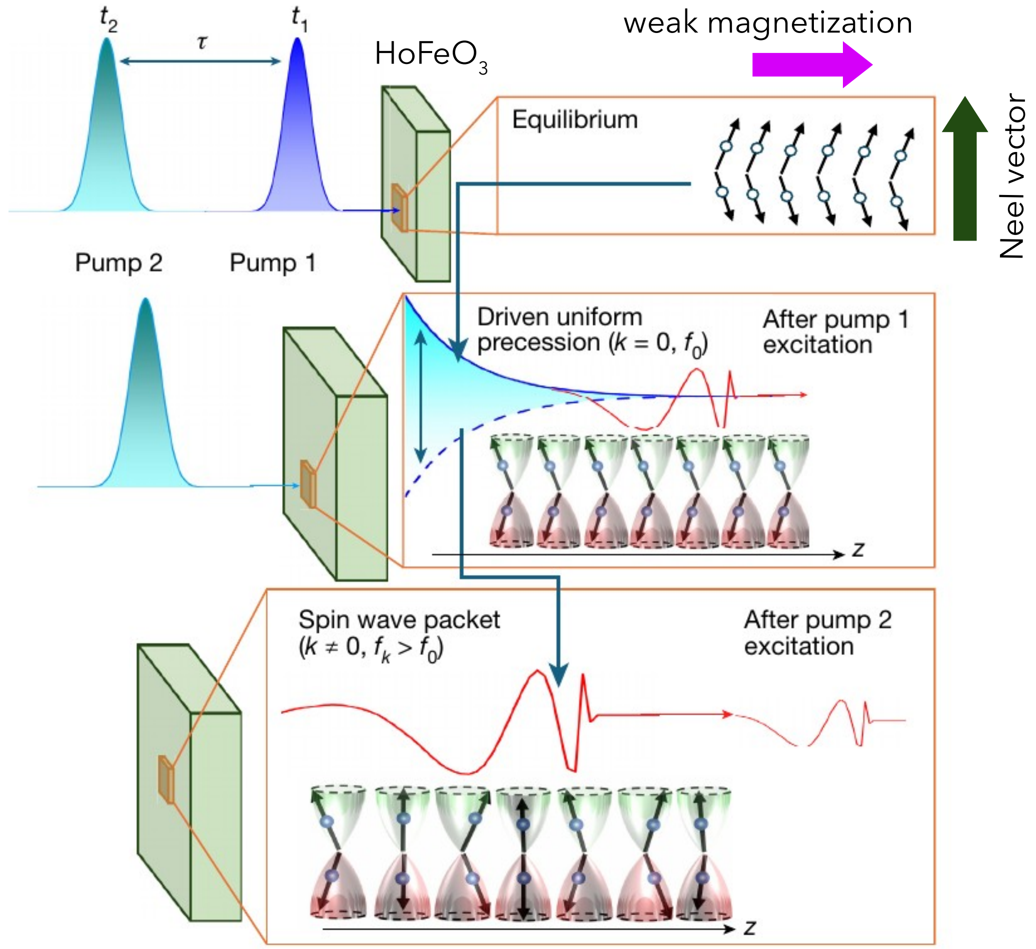
# What is spin canting good for?




Article

## Canted spin order as a platform for ultrafast conversion of magnons

https://doi.org/10.1038/s41586-024-07448-3

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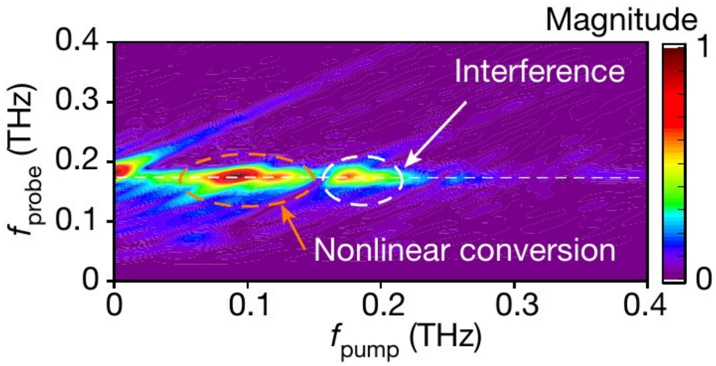


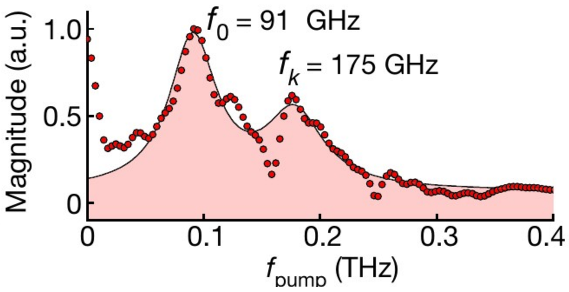

# Keypoints & Take Home Message

- **altermagnets** – a third class of collinear magnets characterized by (1) zero net magnetization and (2) non-relativistic spin splitting.
- altermagnetism is a **non-relativistic approximation**
- **monolayer $RuF_4$** is a **2D altermagnet** but…

  … **spin-orbit coupling** turns it into a **weak ferromagnet** by canting the Ru magnetic moments
- altermagnetic **spin splitting** in $RuF_4$ is drastically changed due to SOC
- spin canting in altermagnets can be used for **magnon conversion**

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link to the paper


"That's all Folks!"
Thanks for you attention!