Emergent Altermagnetism at Surfaces of Antiferromagnets

C. Lange, R. Jaeschke-Ubiergo, A. Chakraborty, X. H. Verbeek, L. Šmejkal, J. Sinova, **AM**, arXiv:2602.08773 (2026)

Alexander Mook

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February 18th, 2026

SPICE-Spin+X Seminars

Universität Münster

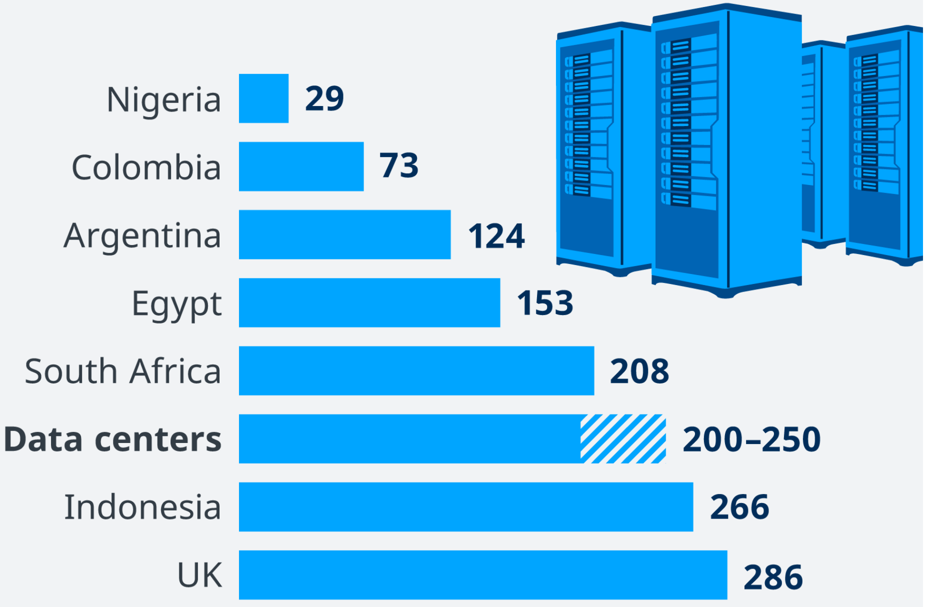
Emmy Noether-Programm

DFG Deutsche Forschungsgemeinschaft

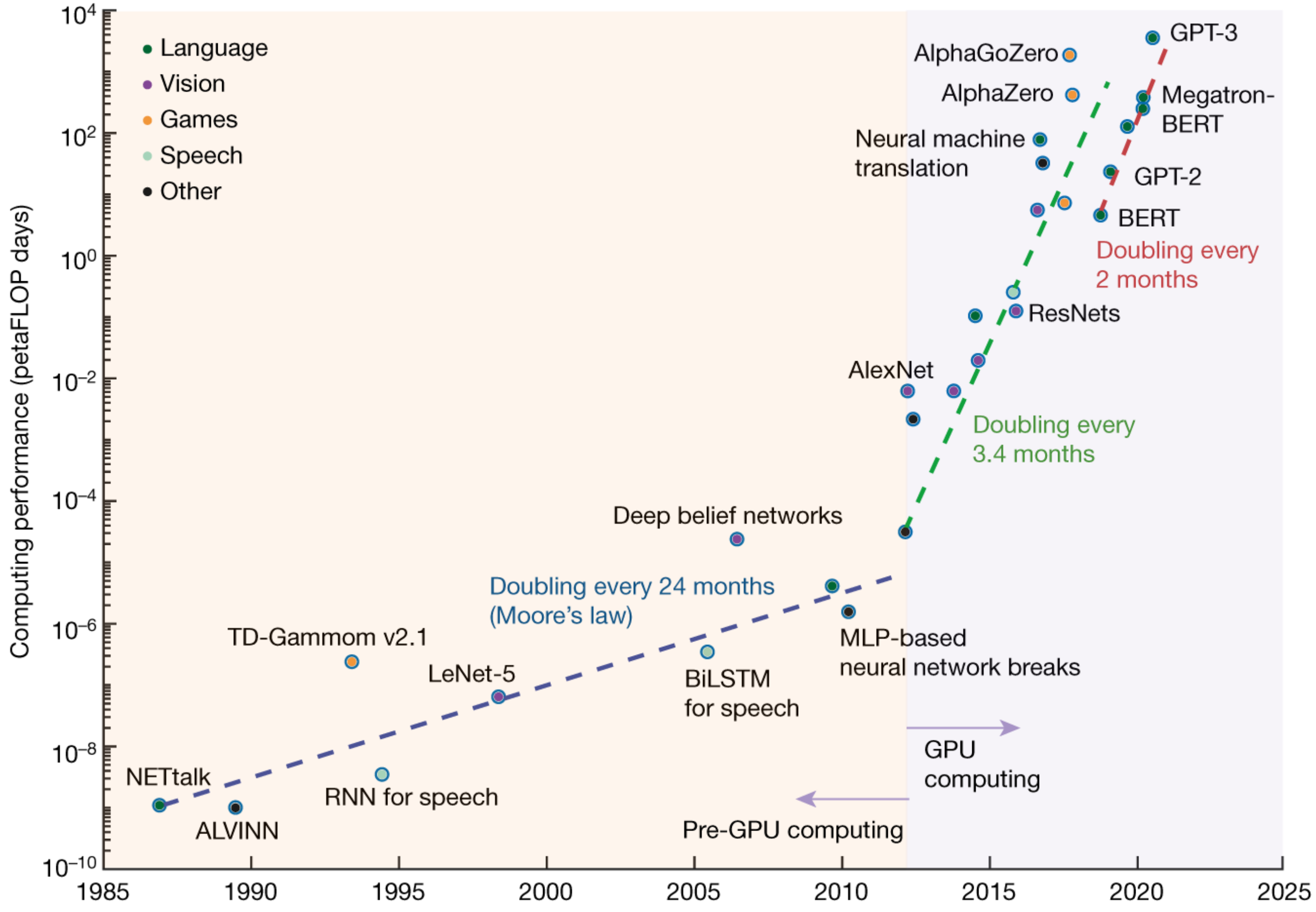
Growing energy consumption

Data centers use more electricity than entire countries

Domestic electricity consumption of selected countries vs. data centers in 2020 in TWh

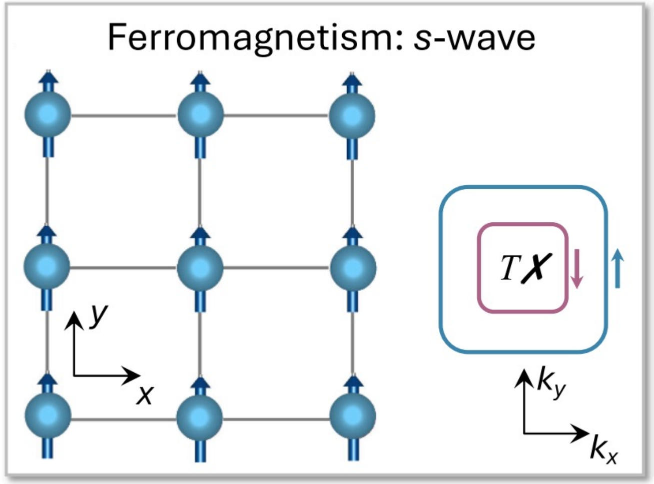


Source: Enerdata, IEA

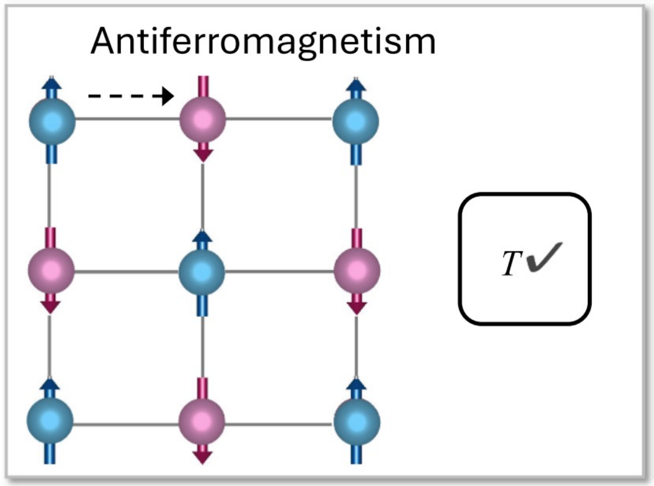


Mehonic, Kenyon, Nature 604, 255-260 (2022)

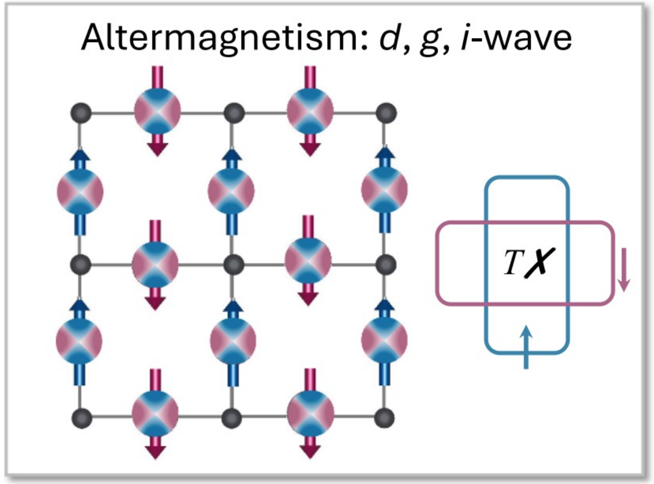
Collinear magnets



spin active
GHz speeds
stray fields



spin inactive
THz speeds
no stray fields



spin active
THz speeds
no stray fields

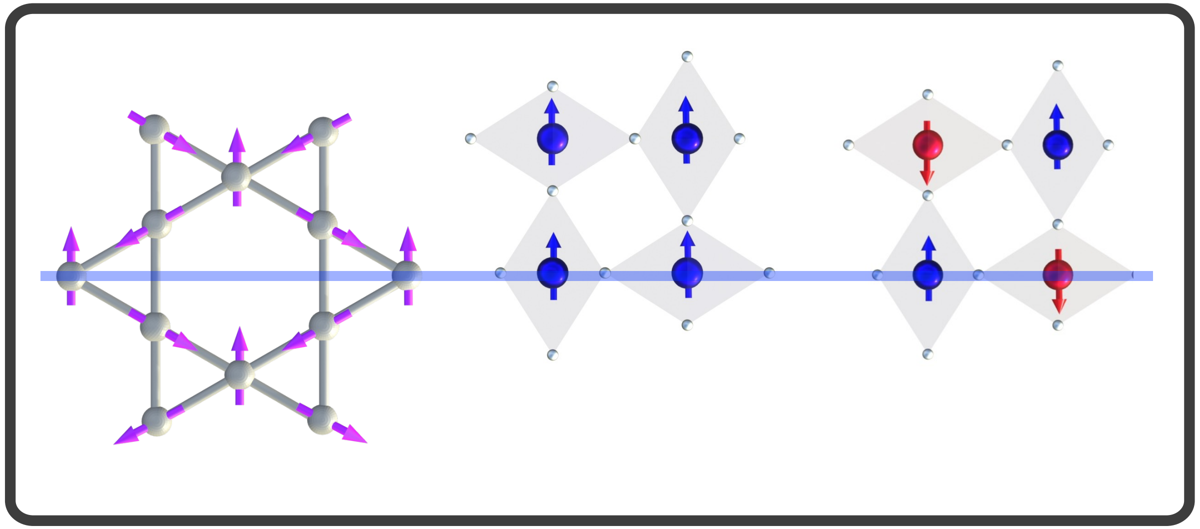
Šmejkal, Sinova, Jungwirth, Phys. Rev. X **12**, 031042 (2022);
Review: Jungwirth, Sinova, Fernandes, Liu, Watanabe, Murakami, Nakatsuji, Šmejkal, Nature **649** (8098), 837 (2026)

Classification

Šmejkal, Sinova, Jungwirth, Phys. Rev. X **12**, 031042 (2022)

Magnetic groups

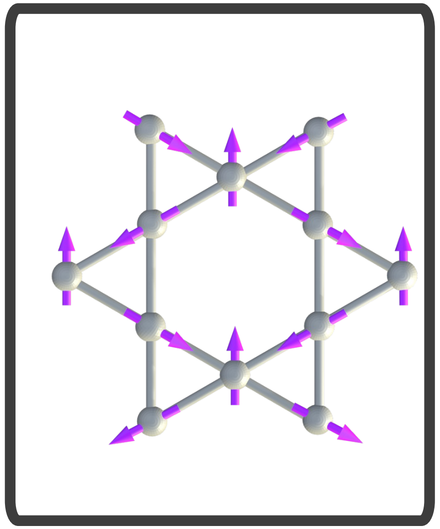
$$\mathcal{H} = \boxed{\mathcal{H}_{\mathrm{mag}} + \mathcal{H}_{\mathrm{rel}}}$$



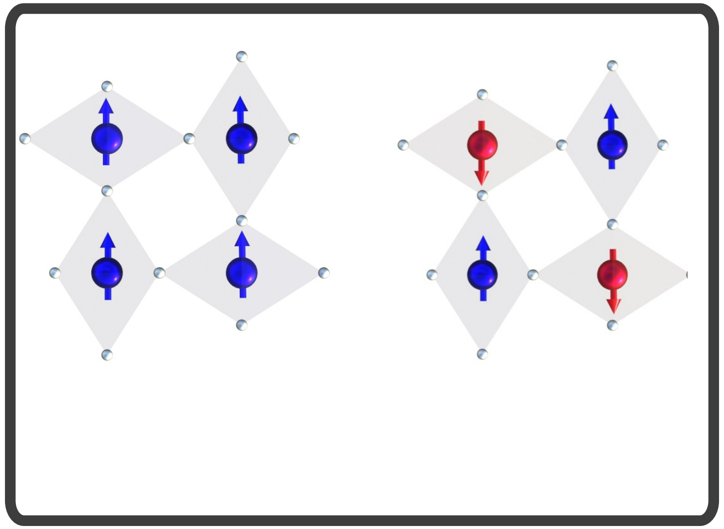
m'm'm

Spin groups

$$\mathcal{H} = \boxed{\mathcal{H}_{\mathrm{mag}}} + \mathcal{H}_{\mathrm{rel}}$$



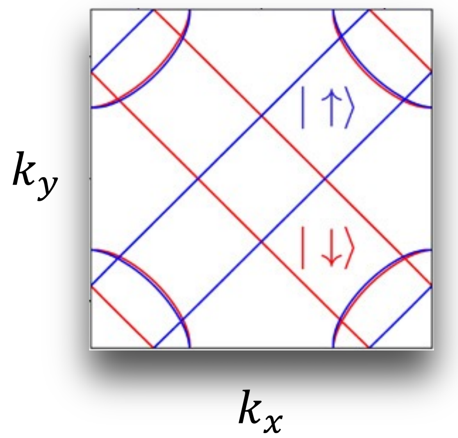
coplanar



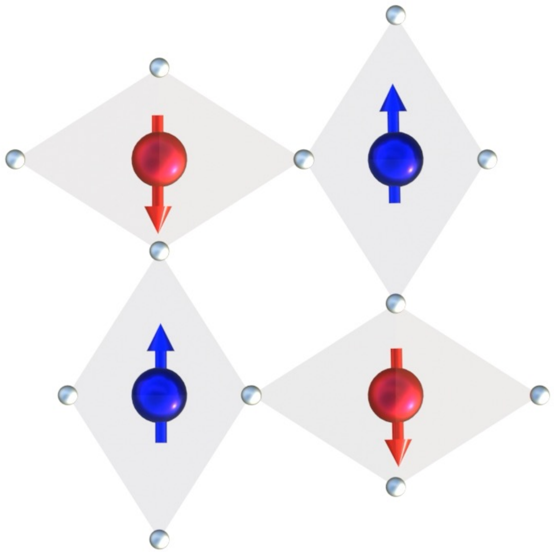
collinear

Spin symmetry in action

Šmejkal, Sinova, Jungwirth, Phys. Rev. X **12**, 031042 (2022)

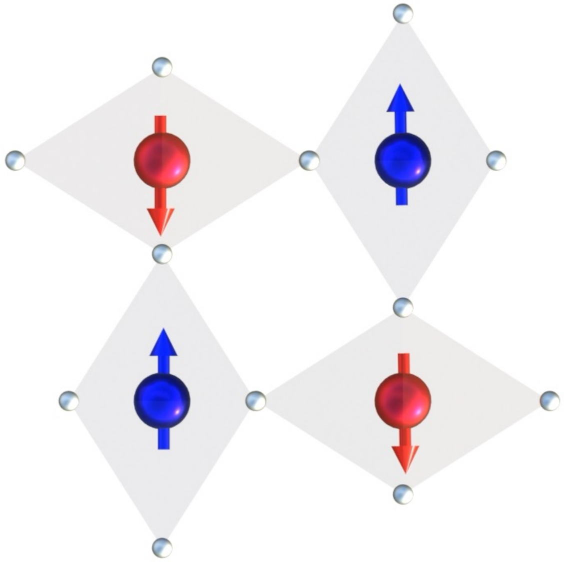


Magnetic symmetry



$[C_4T||C_4T]$

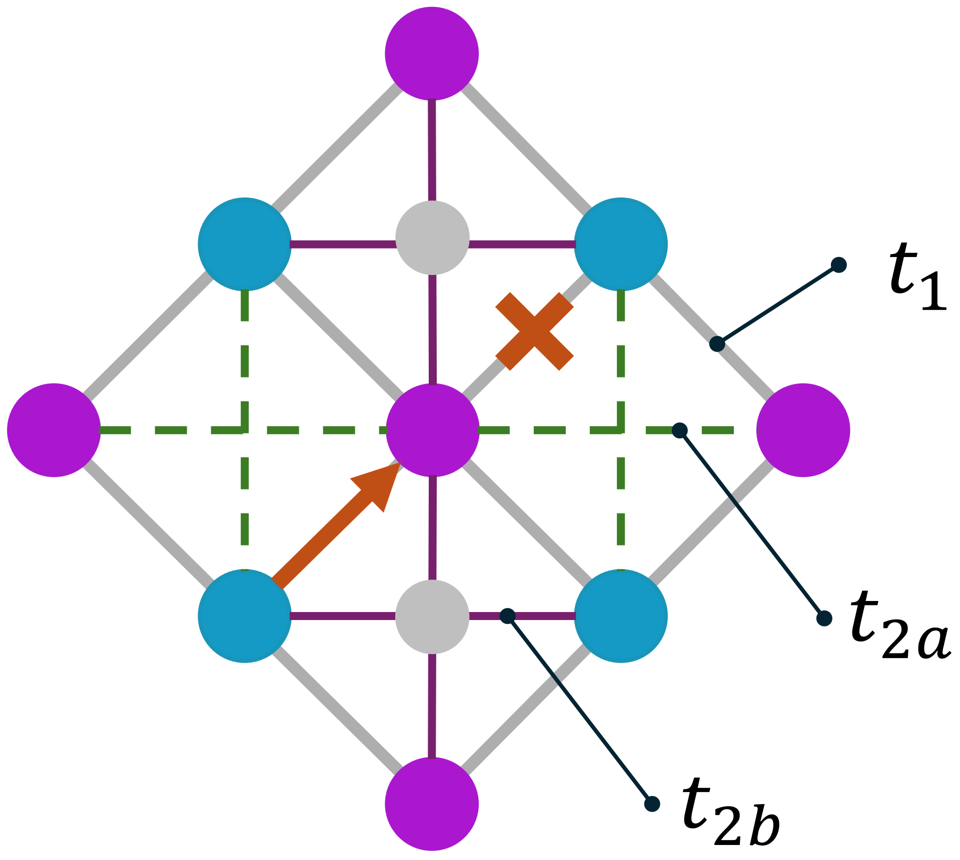
Spin symmetry



$[C_2||C_4]$

Animation credit:
Libor Šmejkal
Jairo Sinova
Tomas Jungwirth

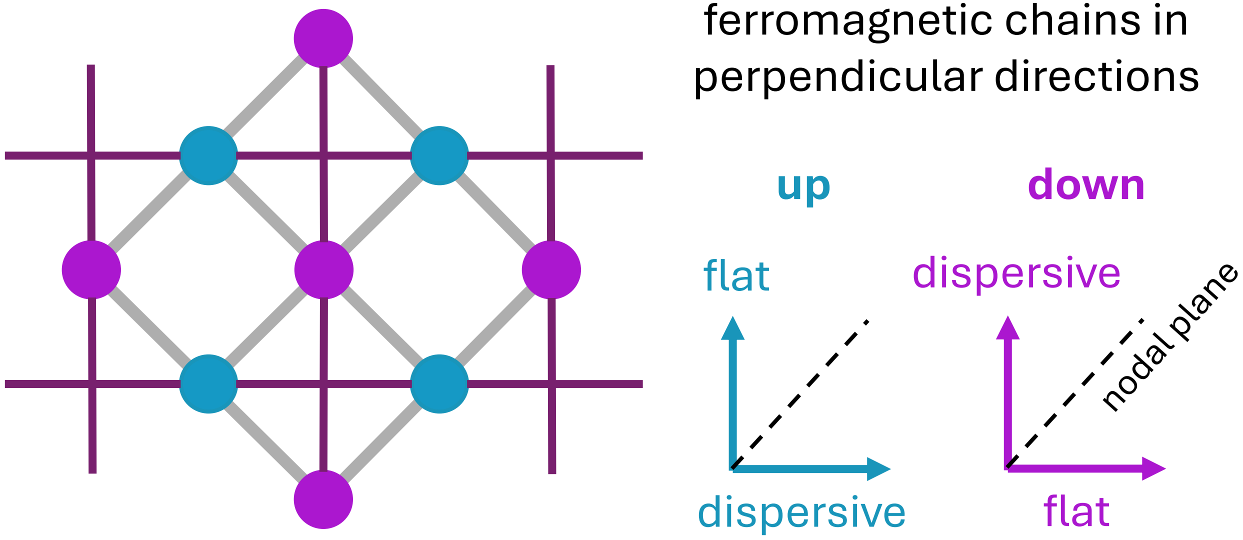
Reminder: Checkerboard altermagnet



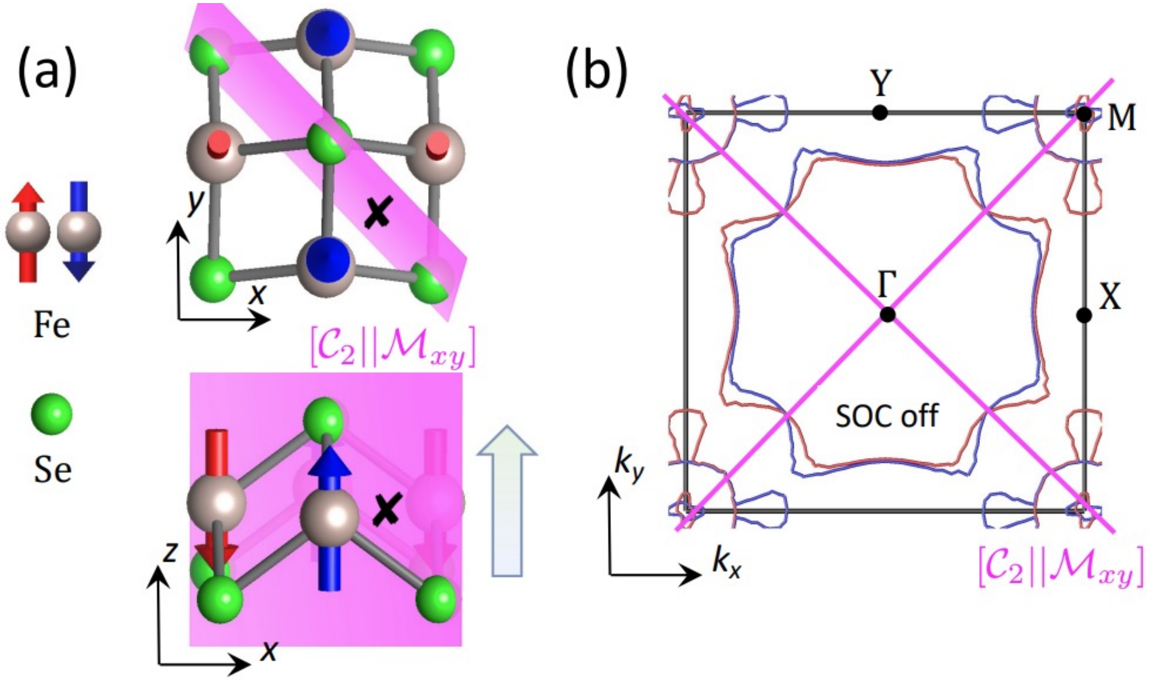
- No PT symmetry
- No $T\boldsymbol{\tau}$ symmetry

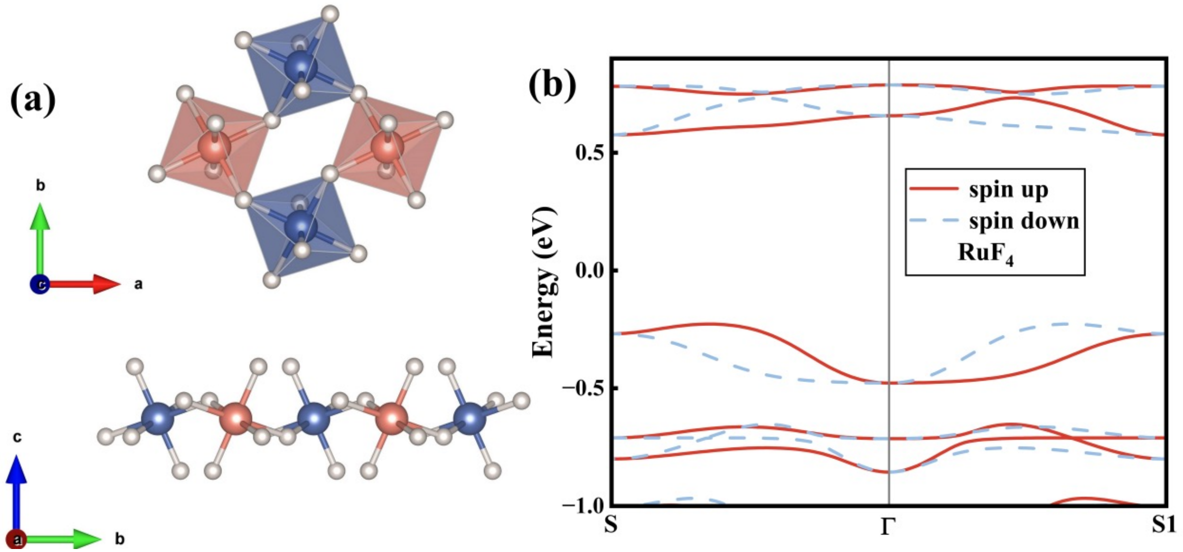
} spin splitting

$[C_{2\perp}||C_{4z}]$



Motivation: 2D altermagnetism

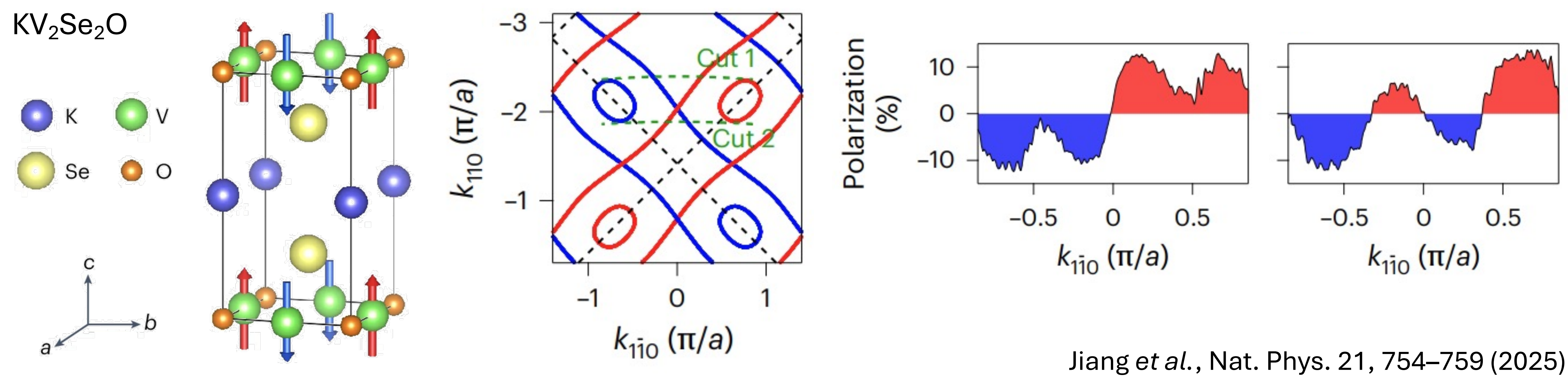




Mazin et al., arXiv:2309.02355 (2023)

Zeng, Zhao, Phys. Rev. B 110, 054406 (2024)

Motivation: Recent experiments



Jiang *et al.*, Nat. Phys. 21, 754–759 (2025)

V_2Se_2O monolayer: Ma *et al.*, Nat. Commun. 12, 2846 (2021)

also $Rb_{1-\delta}V_2Te_2O$: Zhang *et al.*, Nat. Phys. 21, 760–767 (2025)

and $Cs_{1-\delta}V_2Te_2O$: Yang *et al.*, arXiv:2512.00972

Neutron diffraction says the bulk is antiferromagnetic.

Sun *et al.*, Phys. Rev. B 112, 184416 (2025)

What happens at the surface?

See also:

Yuan et al., Nat. Commun. 14, 5301 (2023)

Jana et al., Phys. Rev. B 112, 075127 (2025)

Matsuda et al., Phys. Rev. Lett. 134, 226703 (2025)

Emergent surface altermagnetism

Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)

TopMagIc

How do altermagnetic symmetries emerge at the surfaces of collinear antiferromagnets?

Colin Lange

Rodrigo Jaeschke-Ubiergo

Atasi Chakraborty

Xanthe H. Verbeek

Jairo Sinova

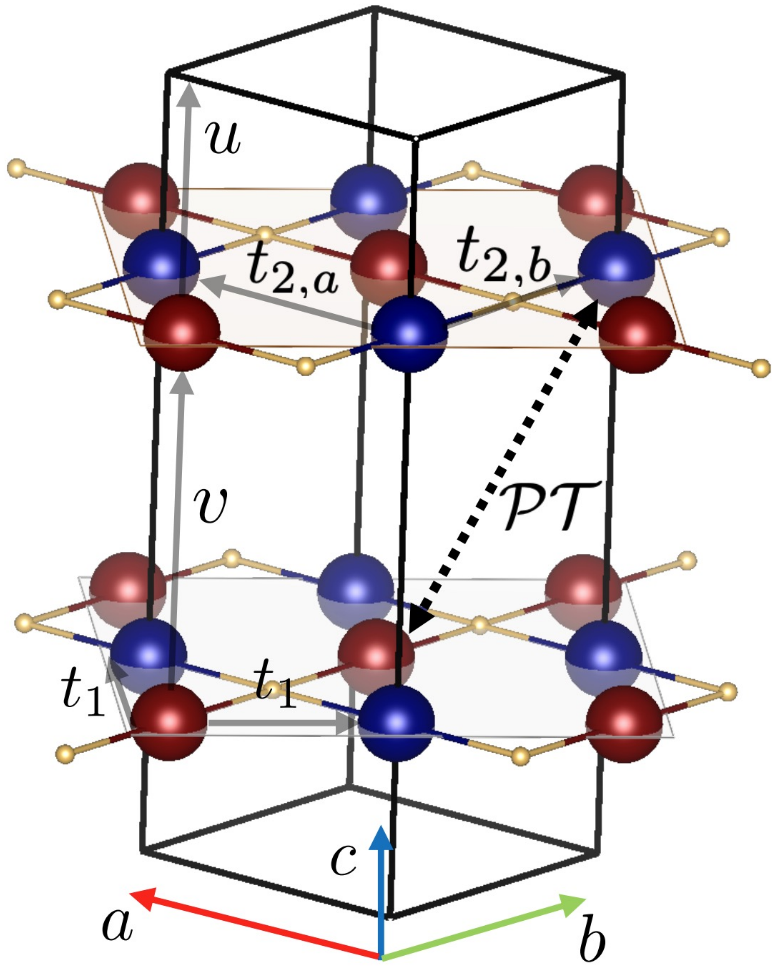
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

mpipks

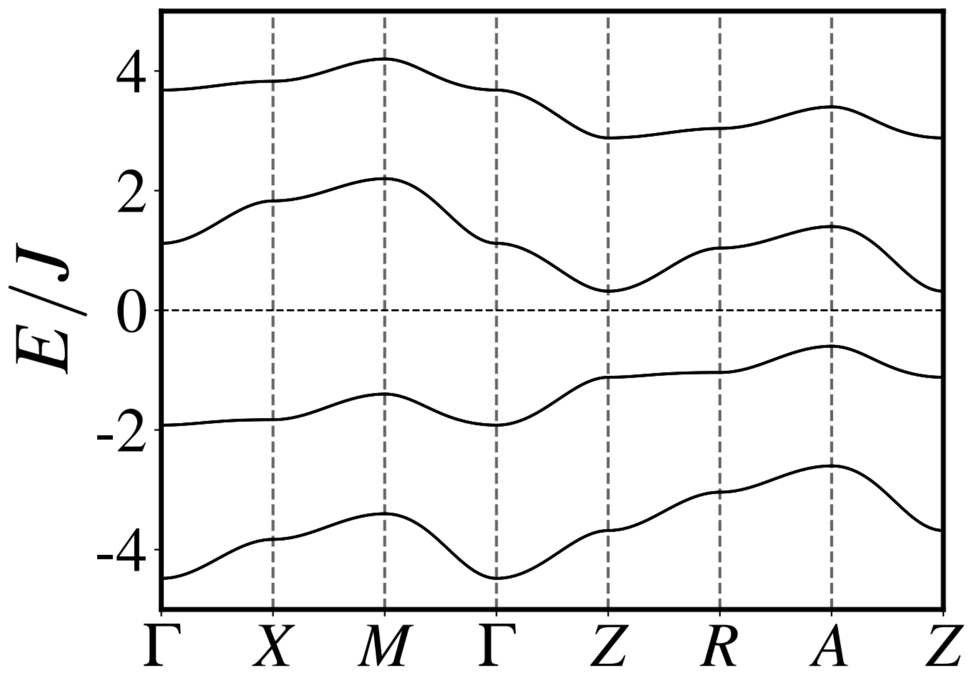
Libor Šmejkal

Minimal model

Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)



Kramers-degenerate bulk spectrum

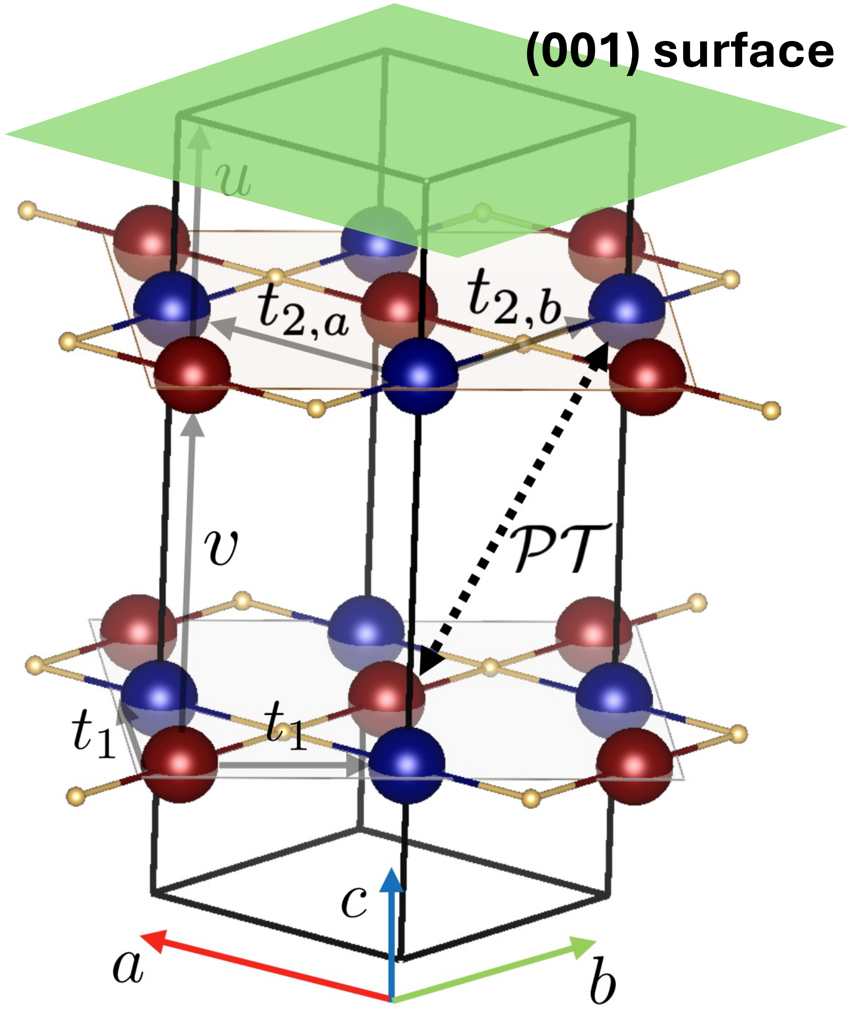


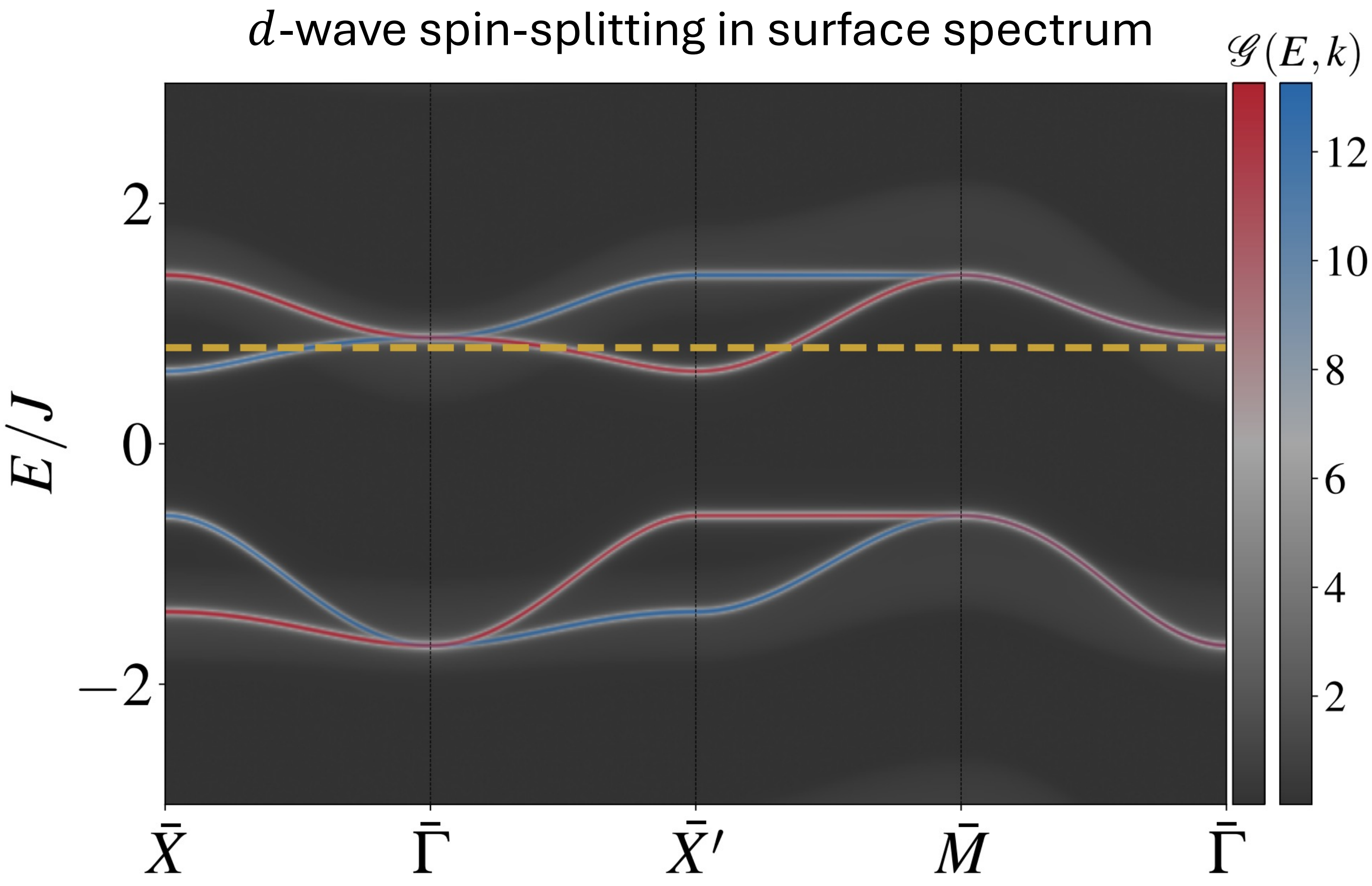
Colin Lange

Rodrigo Jaeschke-Ubiergo

Surface of minimal model

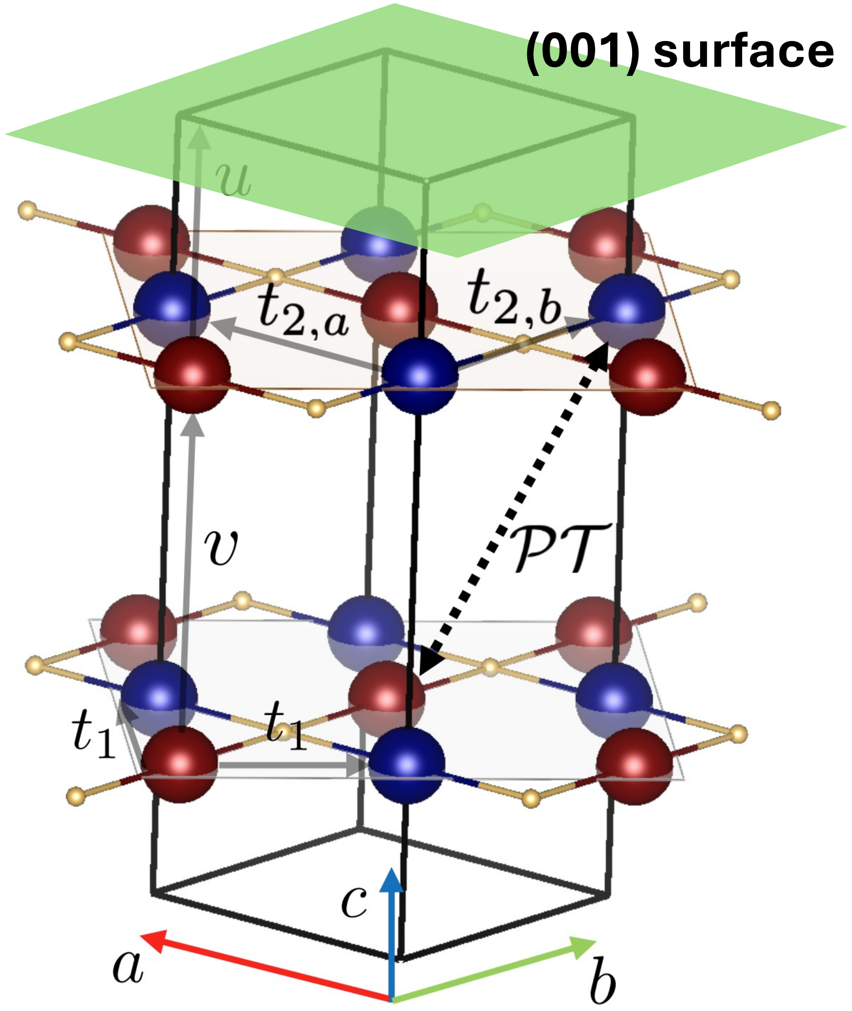
Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)



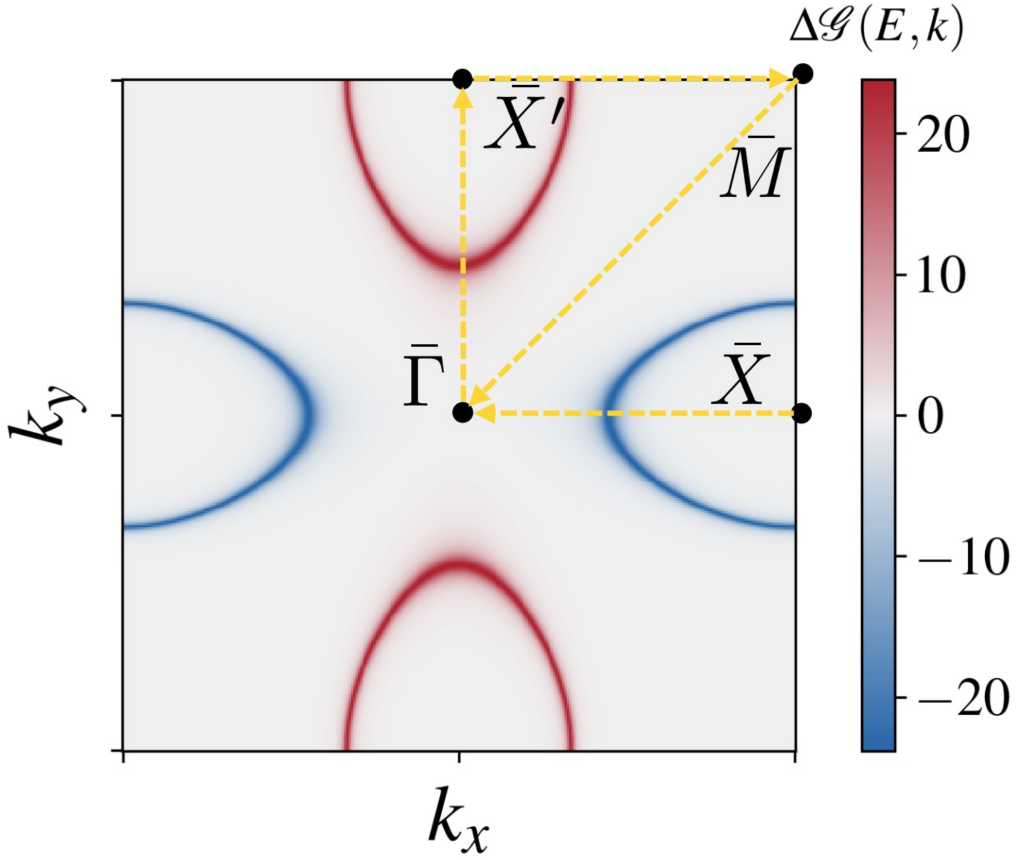


Surface of minimal model

Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)



d-wave spin-splitting in surface spectrum



Need for surface spin groups

Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)

TopMagIc

3D spin point groups

spin degeneracy caused by:

1. $[C_{2\perp}||E]$
2. $[C_{2\perp}||\mathcal{P}]$

Šmejkal, Sinova, Jungwirth, Phys. Rev. X **12**, 031042 (2022)

Surface spin point groups

spin degeneracy caused by:

1. $[C_{2\perp}||E]$

surface breaks inversion

3. $[C_{2\perp}||C_{2n}]$

surface breaks mirror

separate analysis necessary

2D spin point (layer) groups

spin degeneracy caused by:

1. $[C_{2\perp}||E]$
2. $[C_{2\perp}||\mathcal{P}]$
3. $[C_{2\perp}||C_{2n}]$
4. $[C_{2\perp}||m_n]$

Zeng, Zhao, Phys. Rev. B **110**, 054406 (2024)

Surface spin space groups

Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)

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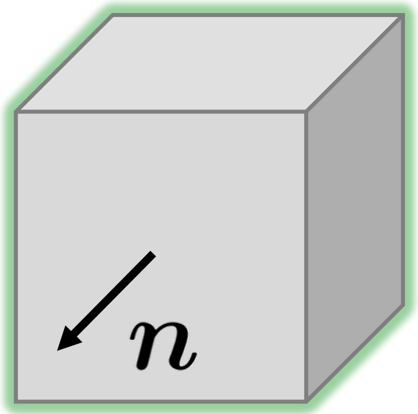
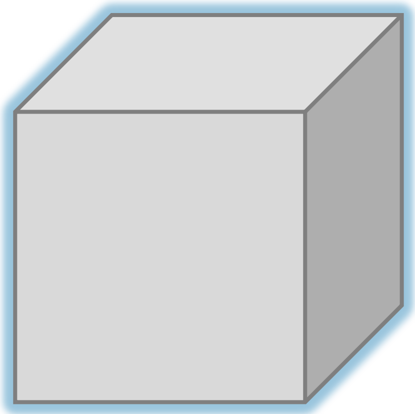
R^s

Element of the *bulk* spin space group that leaves the normal invariant and has no translation in normal direction





Construction similar to surface *magnetic* groups in Weber *et al.*, Phys. Rev. X **14**, 021033 (2024)

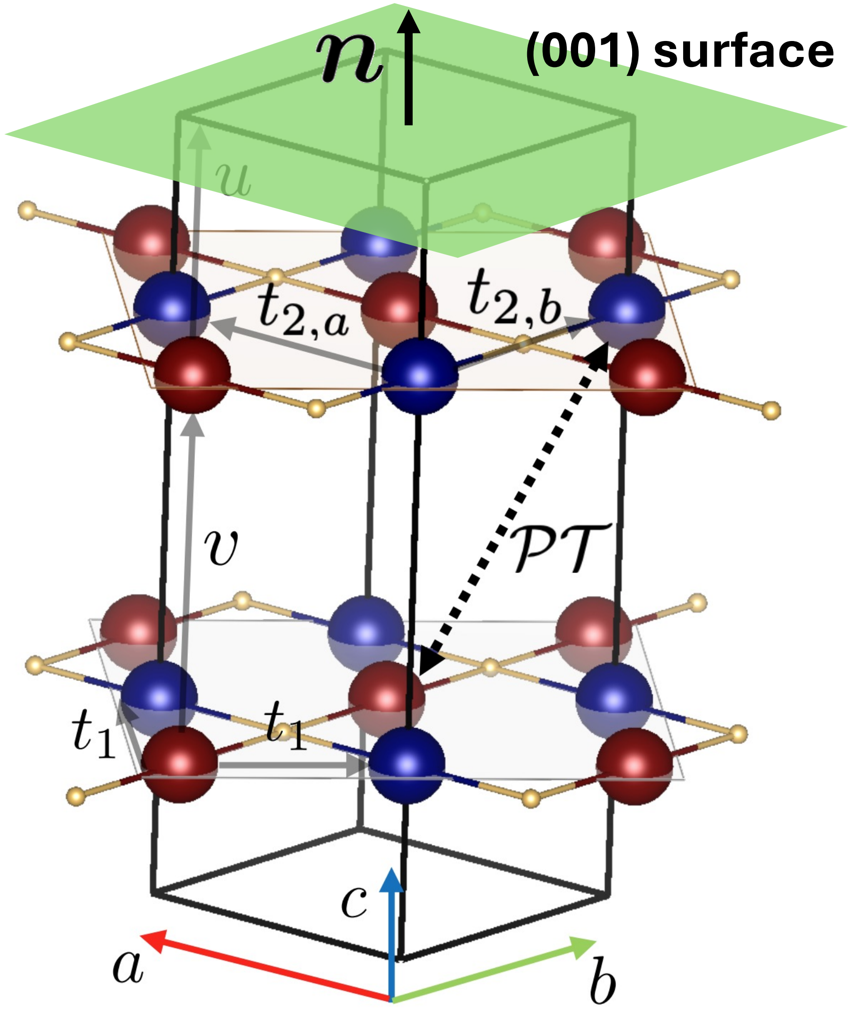
$$R^s_{\boldsymbol{n}} \longrightarrow \mathcal{R}^s_{\boldsymbol{n}} \longrightarrow \mathbb{Z}_2^{[E||\mathcal{P}]} \times \mathcal{R}^s_{\boldsymbol{n}}$$

surface spin point group

surface spin Laue group

Surface spin group of minimal model

Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)



The bulk spin point group

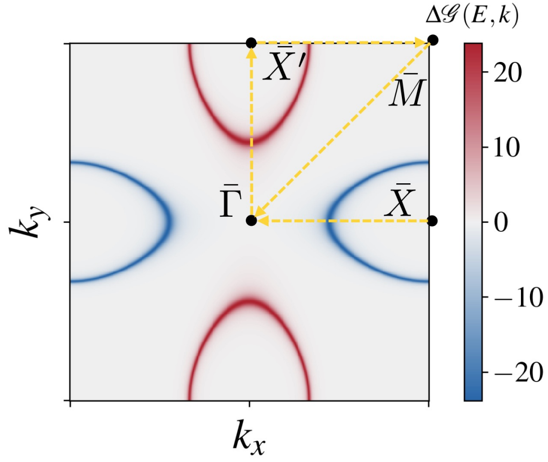
$$\mathbb{Z}_2^{[C_{2\perp}||E]} \times {}^{1}4/{}^{1}m^{1}m^{1}m = [E||4/mmm] + [C_{2\perp}||4/mmm]$$

is broken down to the surface spin point group ${}^{2}4^{1}m^{2}m$, i.e., to the surface spin Laue group

$${}^{2}4/{}^{1}m^{1}m^{2}m = [E||mmm] + [C_{2\perp}||4/mmm - mmm]$$

at the (001) surface.

$$[C_{2\perp}||C_{4z}]$$



Altermagnetic surface spin groups

Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)

Surf. partial-wave character	Surf. spin point group	Surf. spin Laue group	Spin split surf. states?
d-wave			
	${}^{2}4\,{}^{2}m\,{}^{1}m$	${}^{2}4/{}^{1}m\,{}^{2}m\,{}^{1}m$	✓

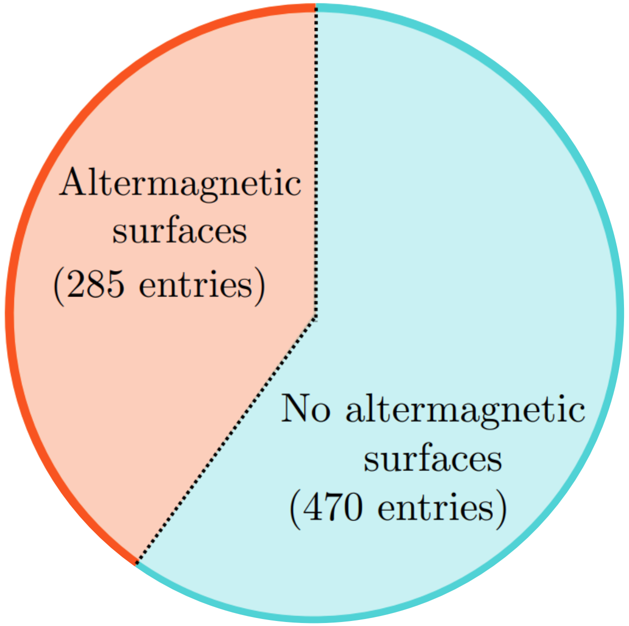
Screening for surface altermagnetism

Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)

MAGNDATA database
~ 2700 magnetic structures

755 are collinear AFM

Number of total material entries: 755



Colin Lange

Rodrigo Jaeschke-Ubiergo

Libor Šmejkal

Gallego *et al.*, J. Appl. Cryst. 49, 1750-1776 (2016)

Result of screening

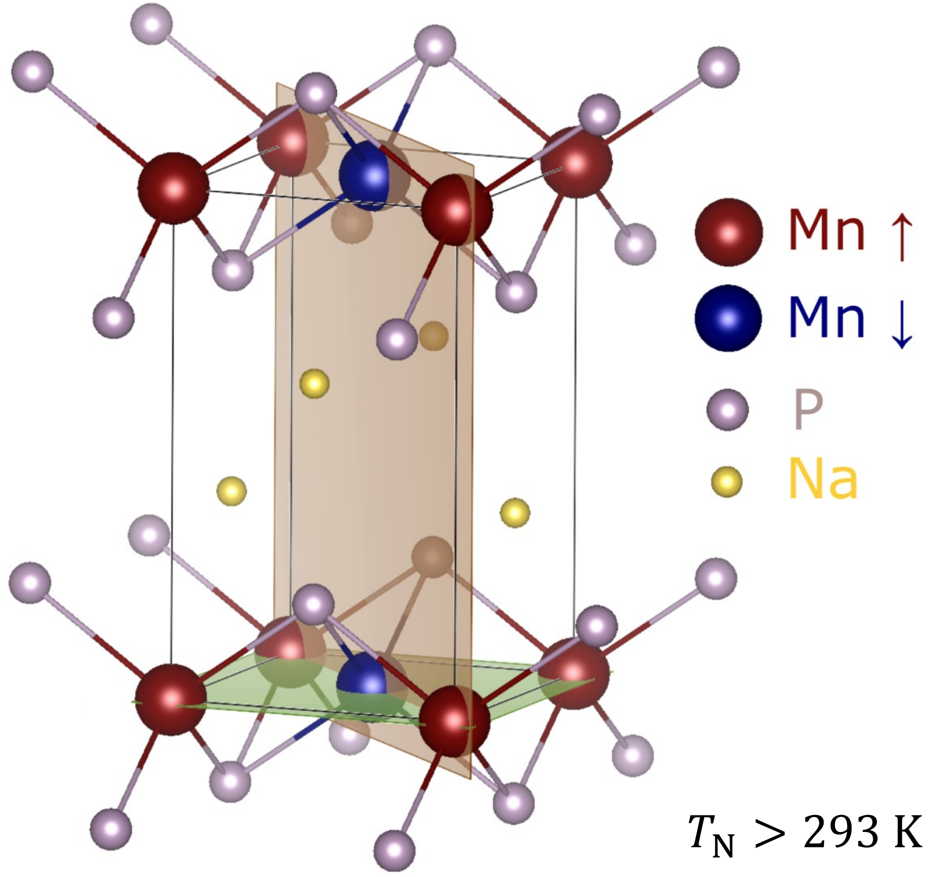
Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)

TopMagIc

No.	Material entry	Index	Normals	Surf. spin Laue group	Surface character
1	$AgNiO_2$	1.50	[001]	$\bar{1}$	AFM
			[010]	$^{2}2_z/^{2}m_z$	SD-SAM
⋮	⋮	⋮	⋮	⋮	⋮
191	NaMnP	0.628	[001]	$^{2}4/^{1}m^{1}m^{2}m$	d-wave
			$[1\bar{1}0]$	$^{2}m^{2}m^{1}m$	d-wave
			[110]	$^{2}m^{2}m^{1}m$	d-wave
⋮	⋮	⋮	⋮	⋮	⋮
285	ZnV_2O_4	1.24	[001]	$^{2}2_z/^{2}m_z$	SD-SAM
			$[1\bar{1}0]$	$2/m$	AFM
			[110]	$2/m$	AFM

Surface altermagnetism in NaMnP

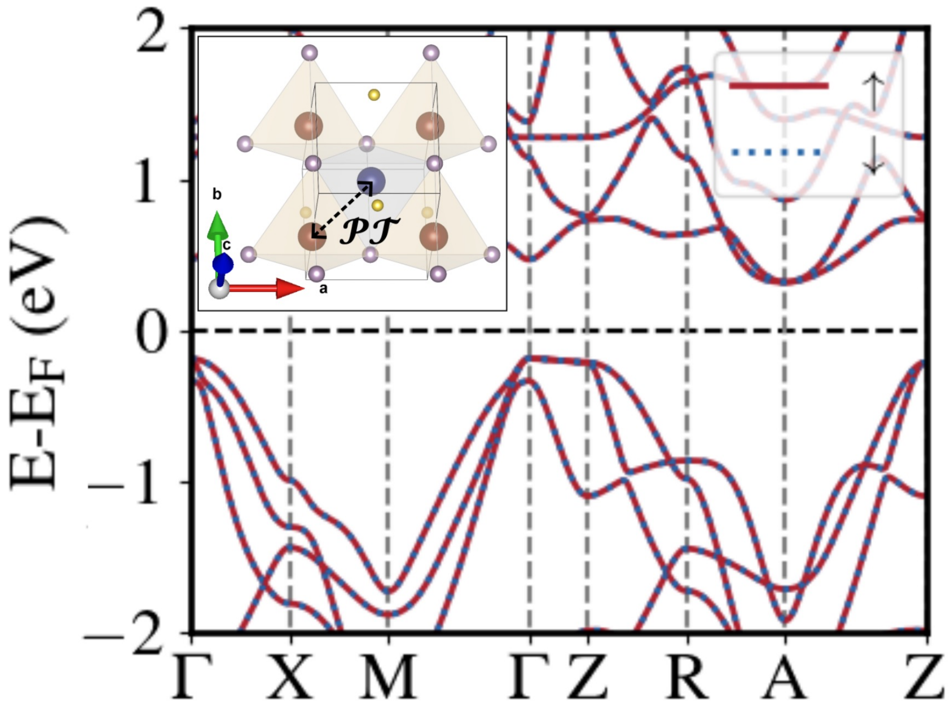
Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)



Bronger *et al.*, Z. anorg. allg. Chem. 539, 175 – 182 (1986)

experiment: $3.64\ \mu_B$ DFT: $3.51\ \mu_B$

Kramers-degenerate bulk spectrum



Atasi Chakraborty

Xanthe H. Verbeek

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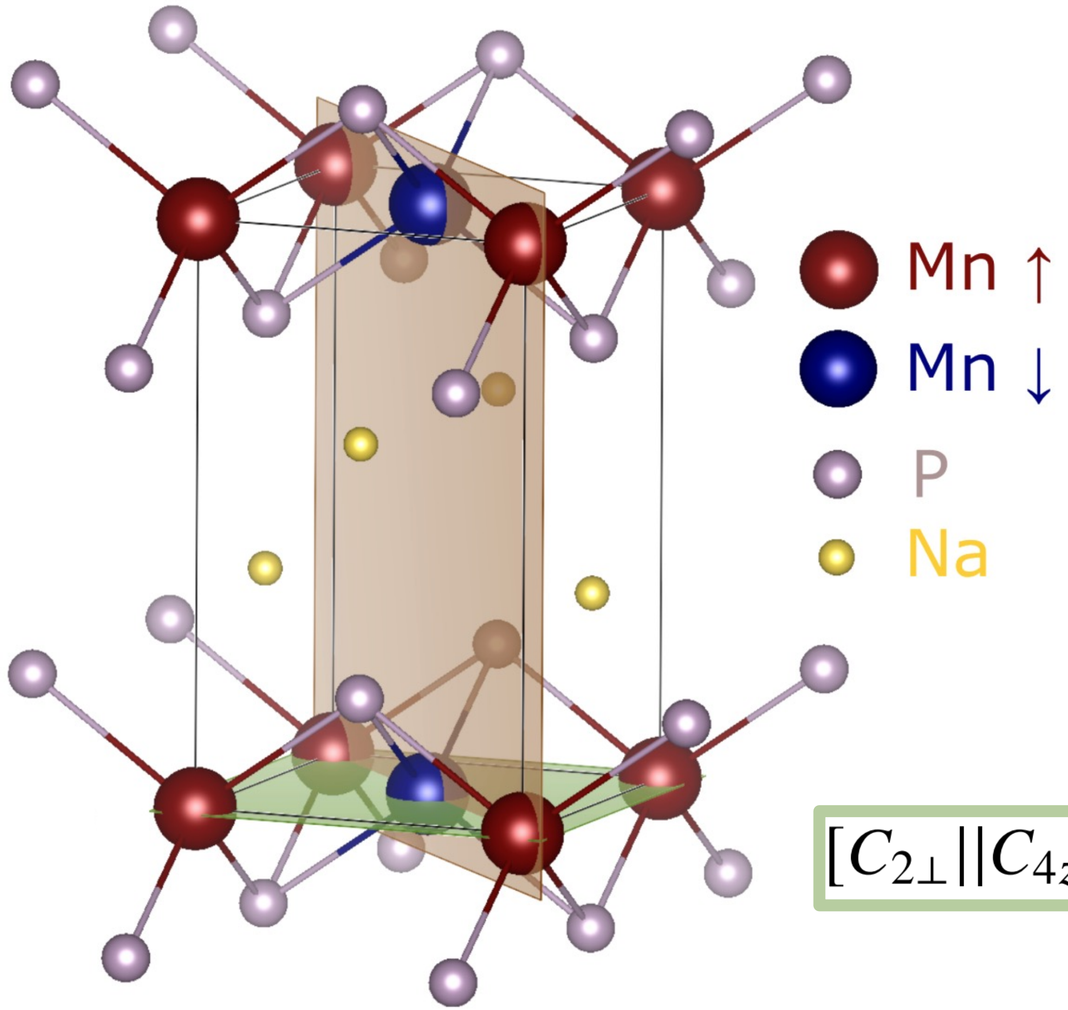
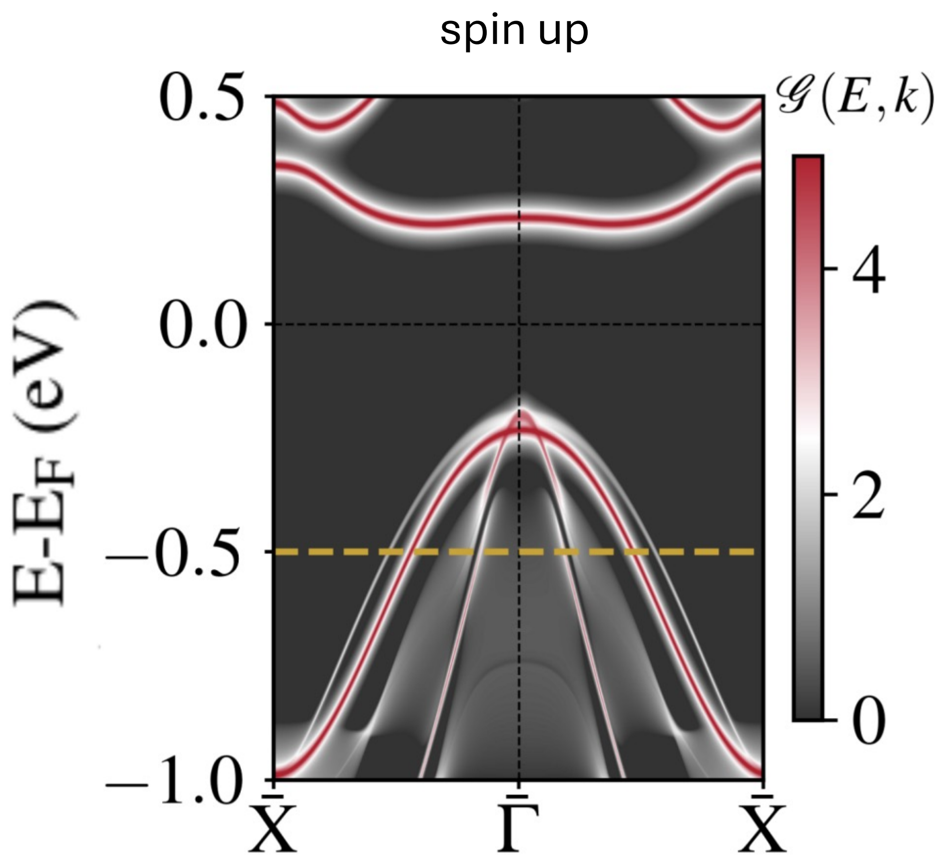


$[C_{2\perp}||C_{4z}]$



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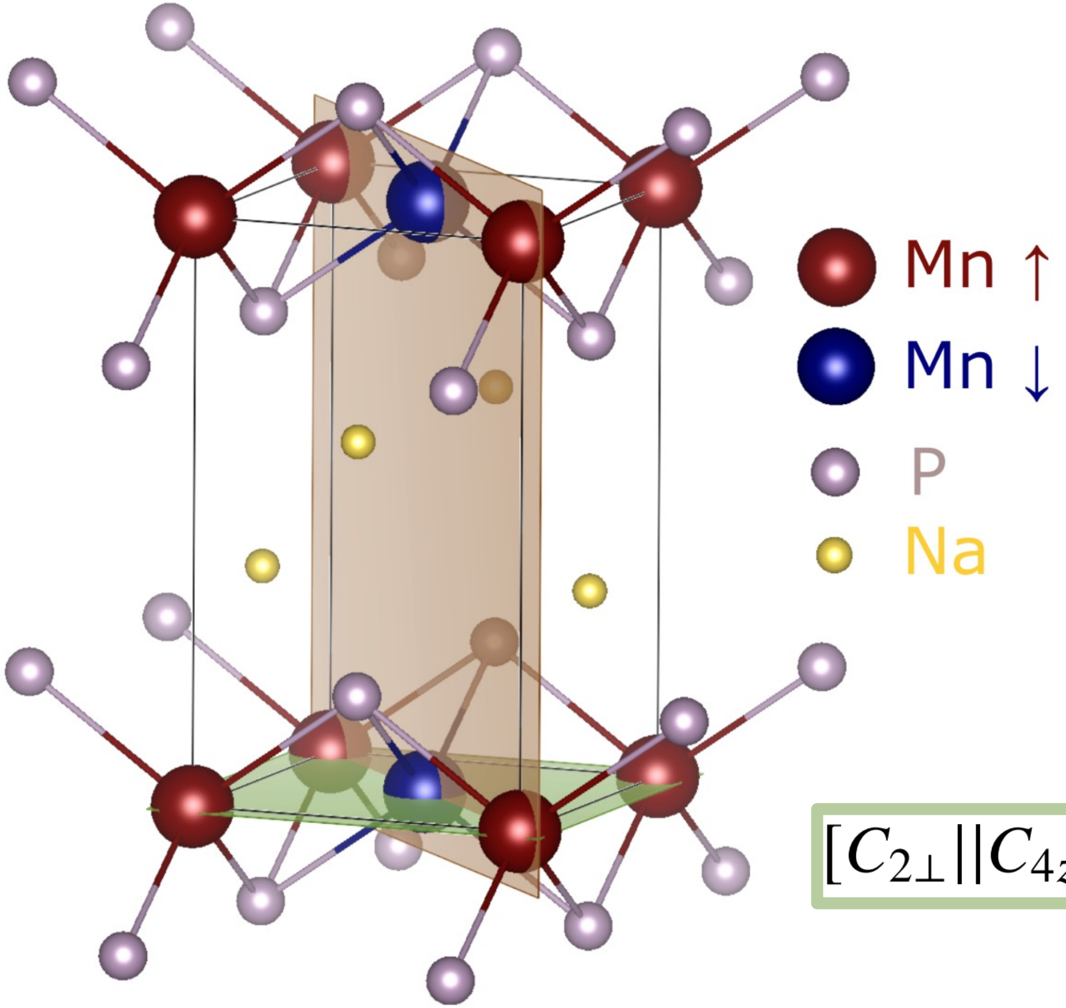

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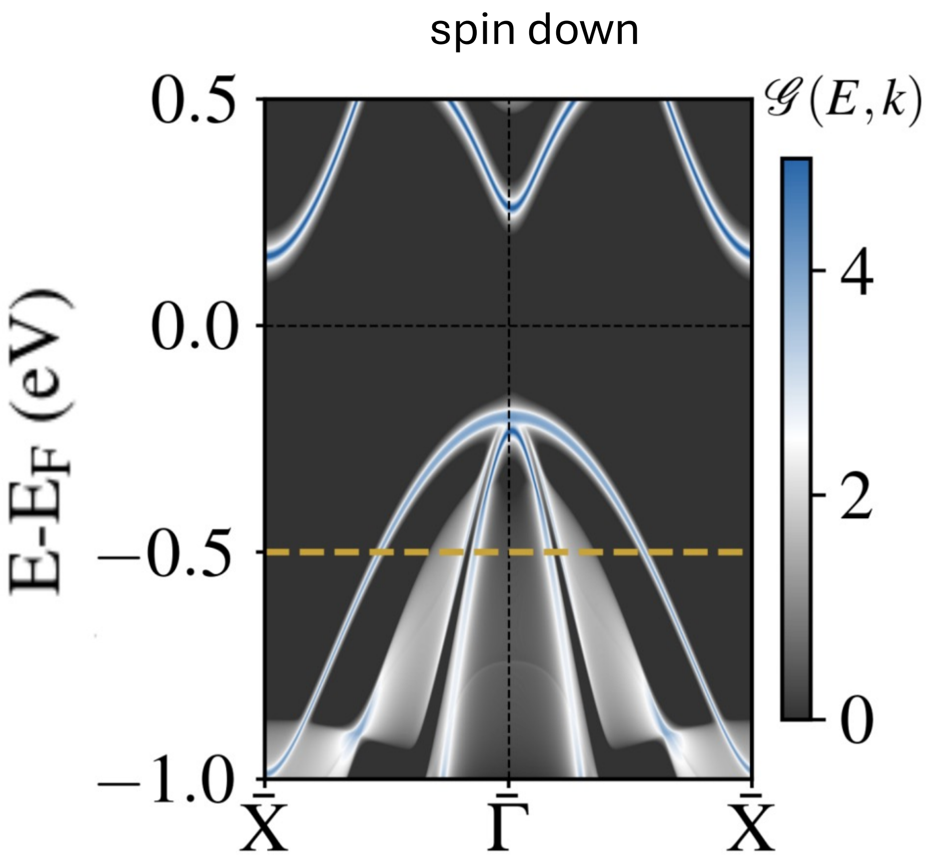

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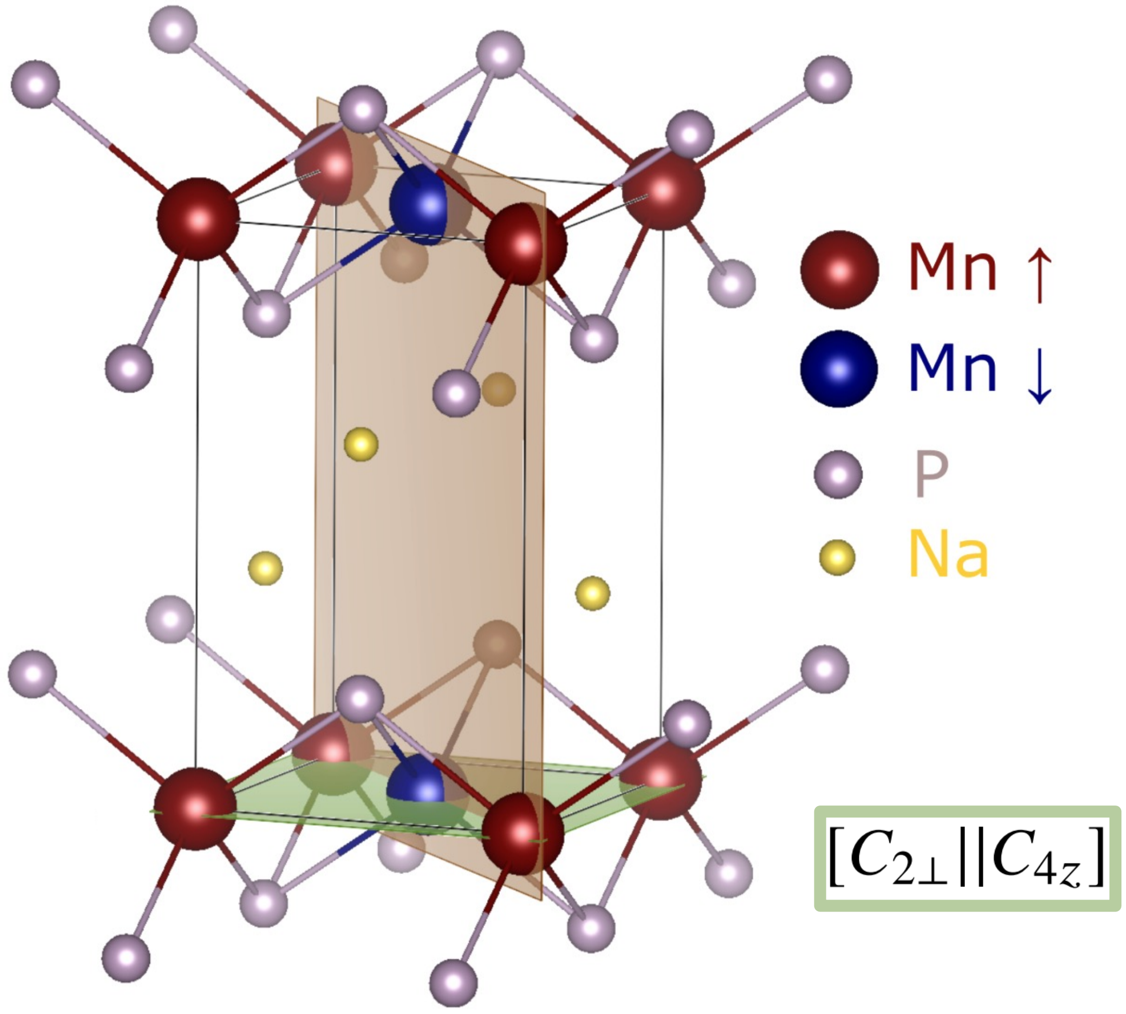

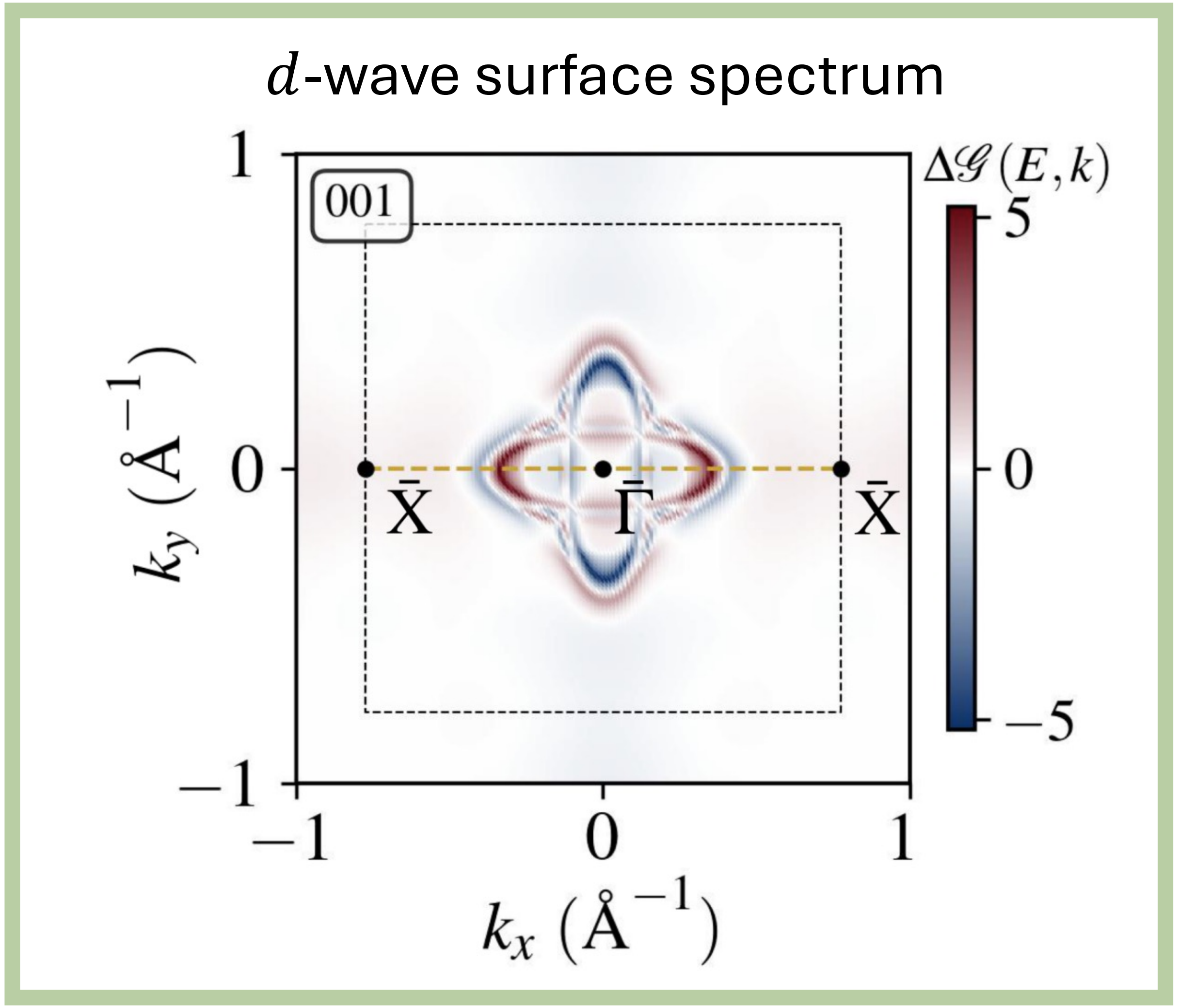

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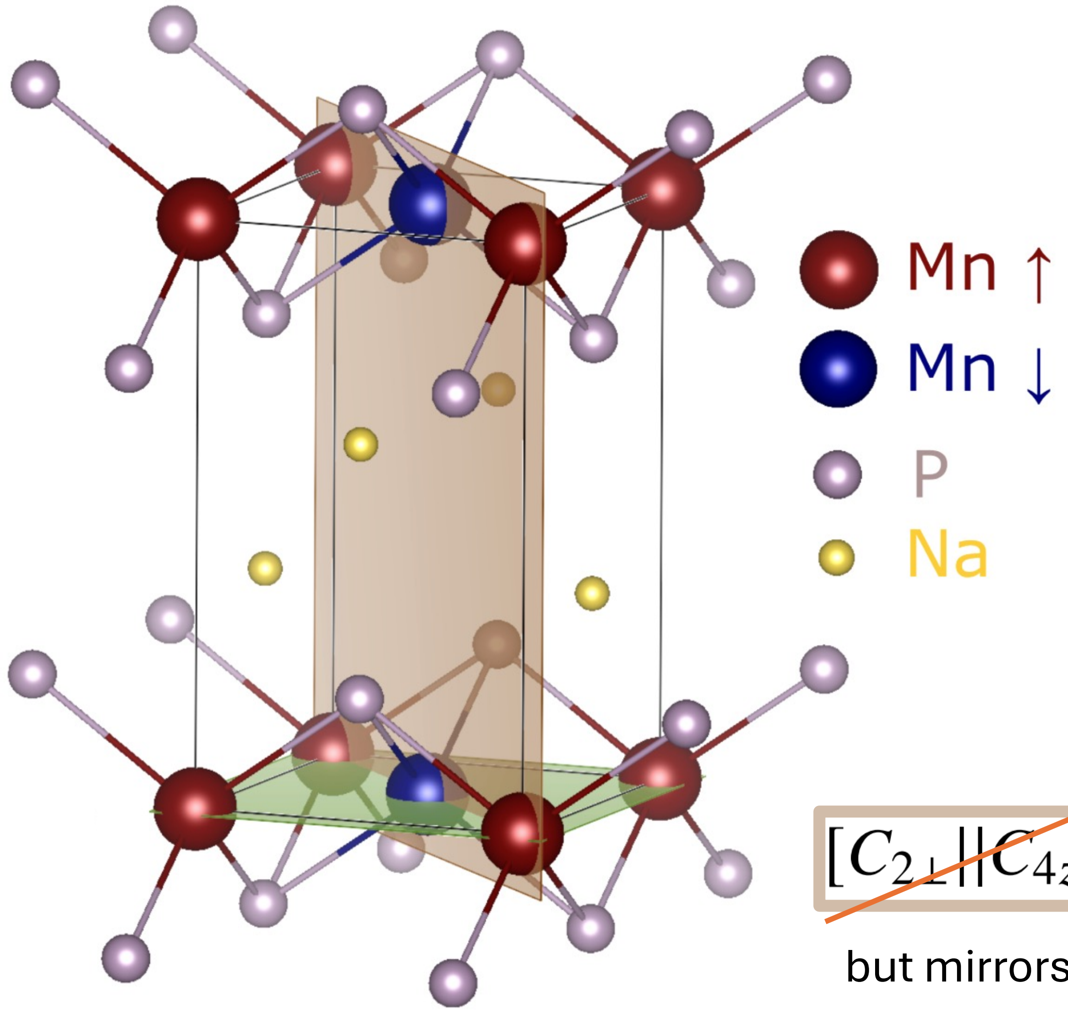
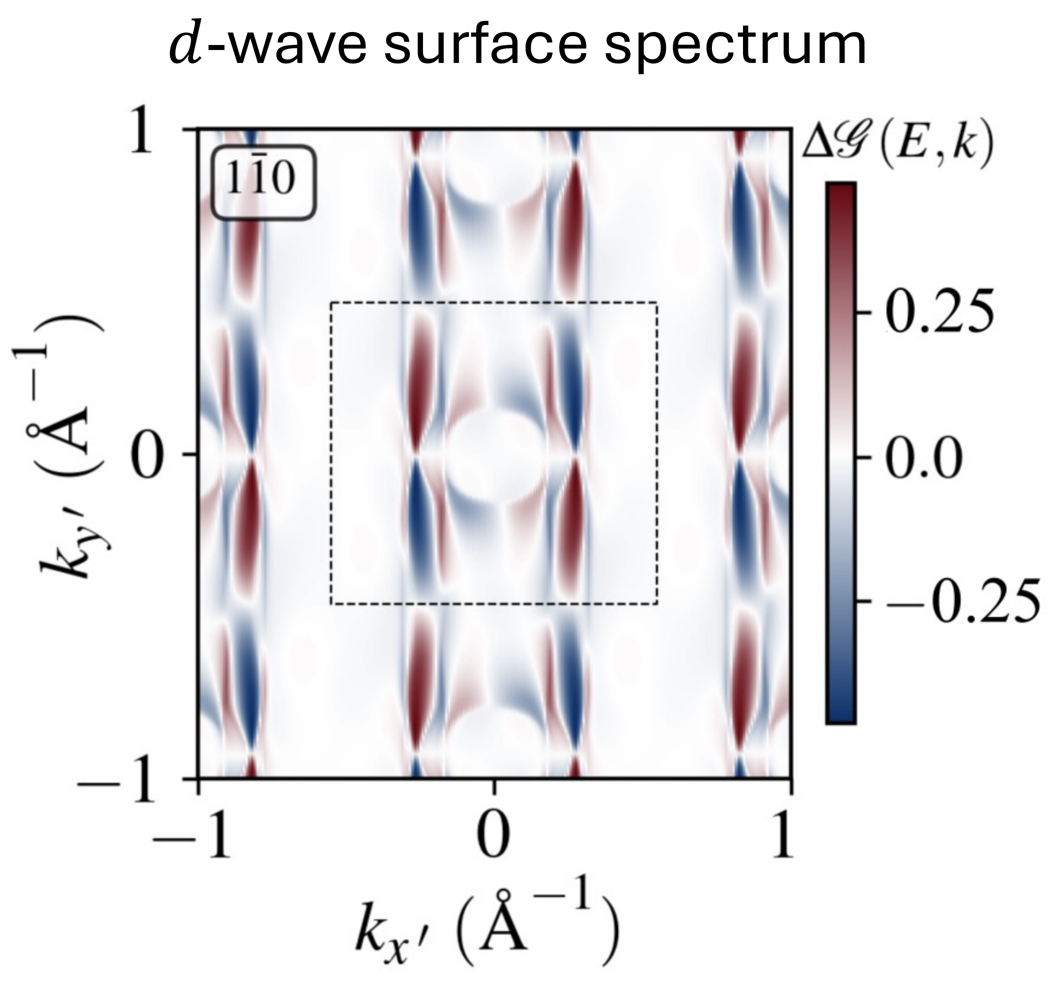


$[C_{2\perp}||C_{4z}]$

but mirrors



Result of screening

Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)

TopMagIc

No.	Material entry	Index	Normals	Surf. spin Laue group	Surface character
1	$AgNiO_2$	1.50	[001] [010]	$\bar{1}$ $^{2}2_z/^{2}m_z$	AFM SD-SAM
⋮	⋮	⋮	⋮	⋮	⋮
191	NaMnP	0.628	[001] [1$\bar{1}$0] [110]	$^{2}4/^{1}m^{1}m^{2}m$ $^{2}m^{2}m^{1}m$ $^{2}m^{2}m^{1}m$	d-wave d-wave d-wave
⋮	⋮	⋮	⋮	⋮	⋮
285	ZnV_2O_4	1.24	[001] [1$\bar{1}$0] [110]	$^{2}2_z/^{2}m_z$ $2/m$ $2/m$	SD-SAM AFM AFM

Result of screening

Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)

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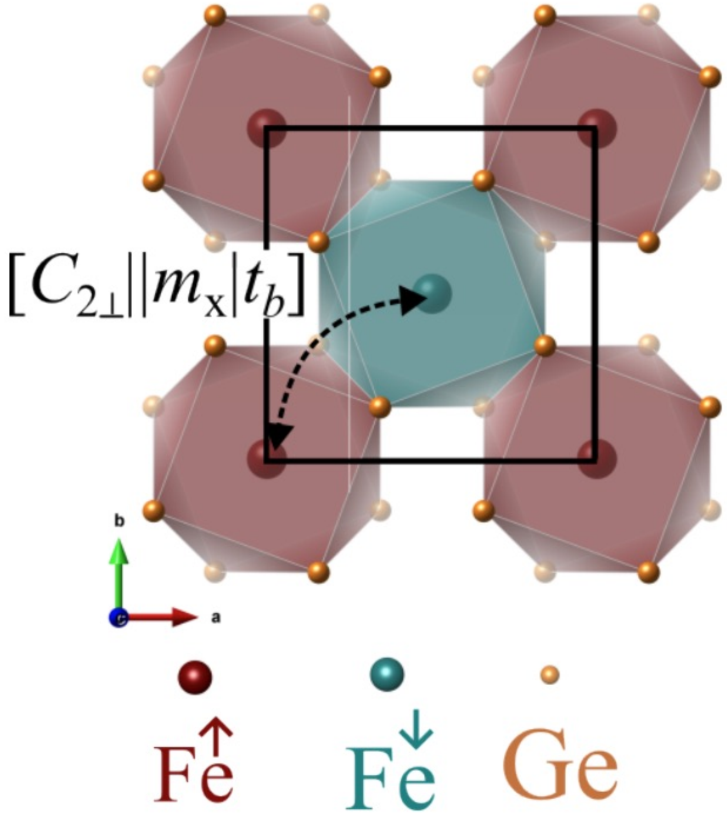
No.	Material entry	Index	Normals	Surf. spin Laue group	Surface character
1	$AgNiO_2$	1.50	[001] [010]	$\bar{1}$ ${}^{2}2_z/{}^{2}m_z$	AFM SD-SAM
⋮	⋮	⋮	⋮	⋮	⋮
113	$FeGe_2$	1.557	[001] $[1\bar{1}0]$ [110]	${}^{1}4/{}^{1}m{}^{2}m{}^{2}m$ mmm mmm	g-wave AFM AFM
⋮	⋮	⋮	⋮	⋮	⋮
285	ZnV_2O_4	1.24	[001] $[1\bar{1}0]$ [110]	${}^{2}2_z/{}^{2}m_z$ $2/m$ $2/m$	SD-SAM AFM AFM

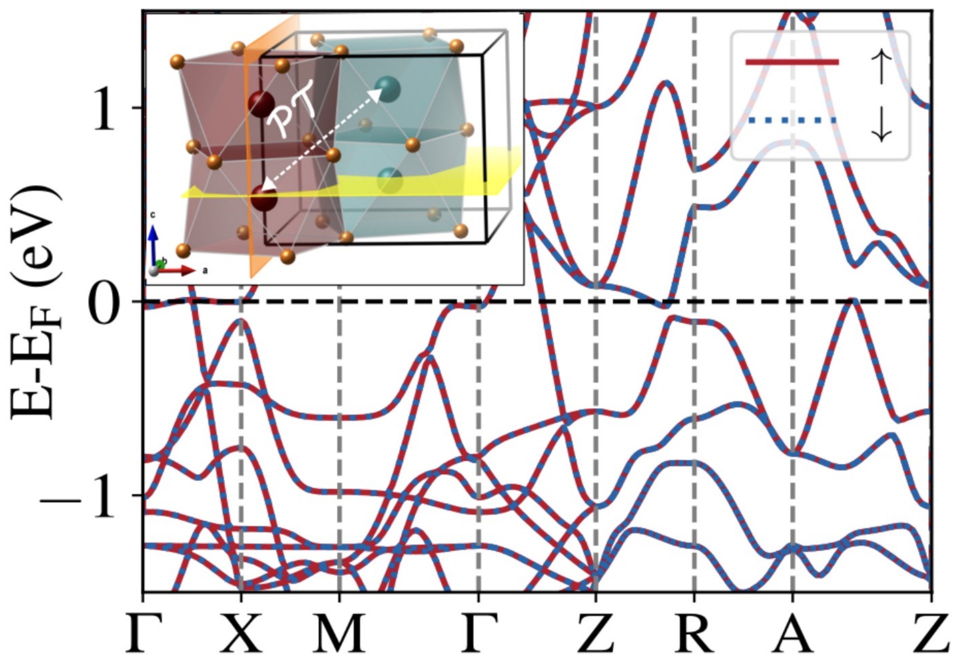
Surface altermagnetism in $FeGe_2$

Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)

TopMagIc



Kramers-degenerate bulk spectrum




Atasi Chakraborty


Xanthe H. Verbeek

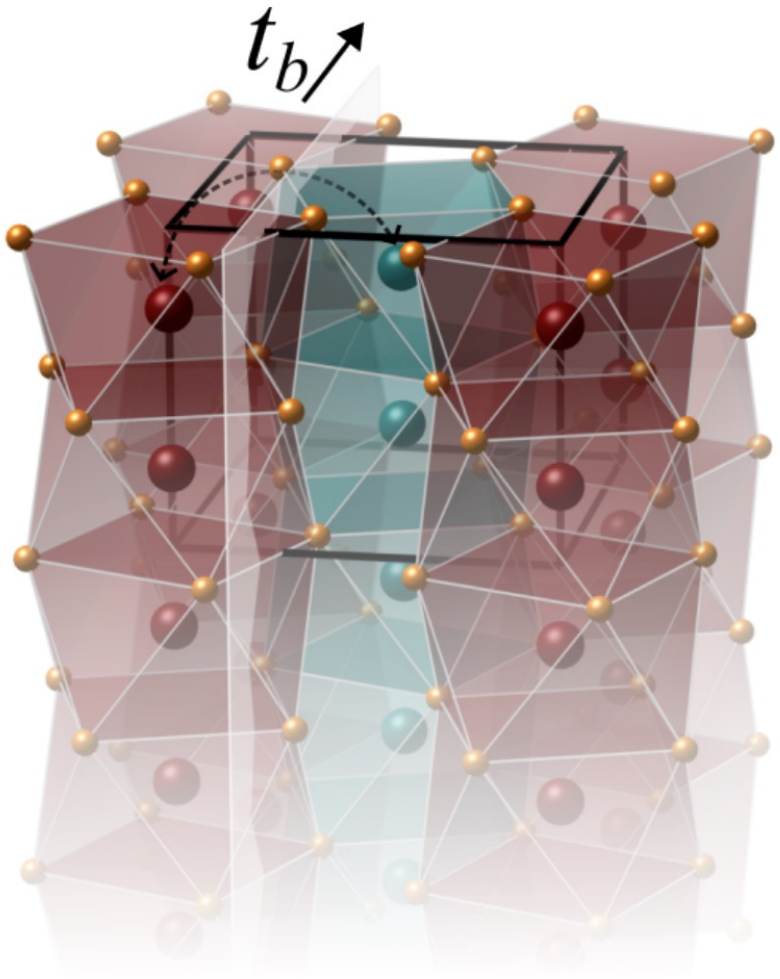
$T_N = 315$ K

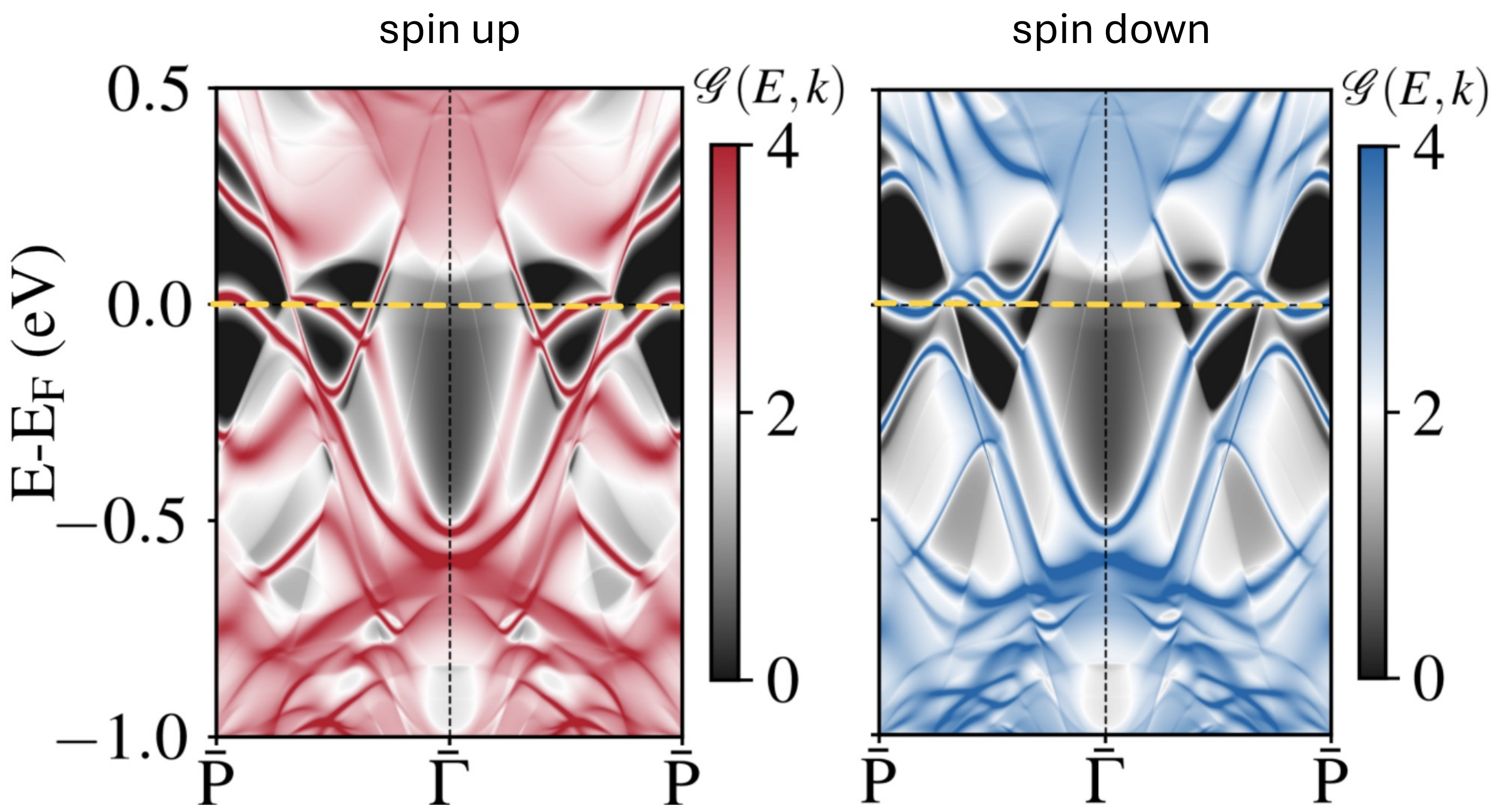
Murthy *et al.*, *Solid State Commun.*, 3, 113 - 116 (1965)

experiment: $1.21\ \mu_B$ DFT: $1.53\ \mu_B$

Surface altermagnetism in $FeGe_2$

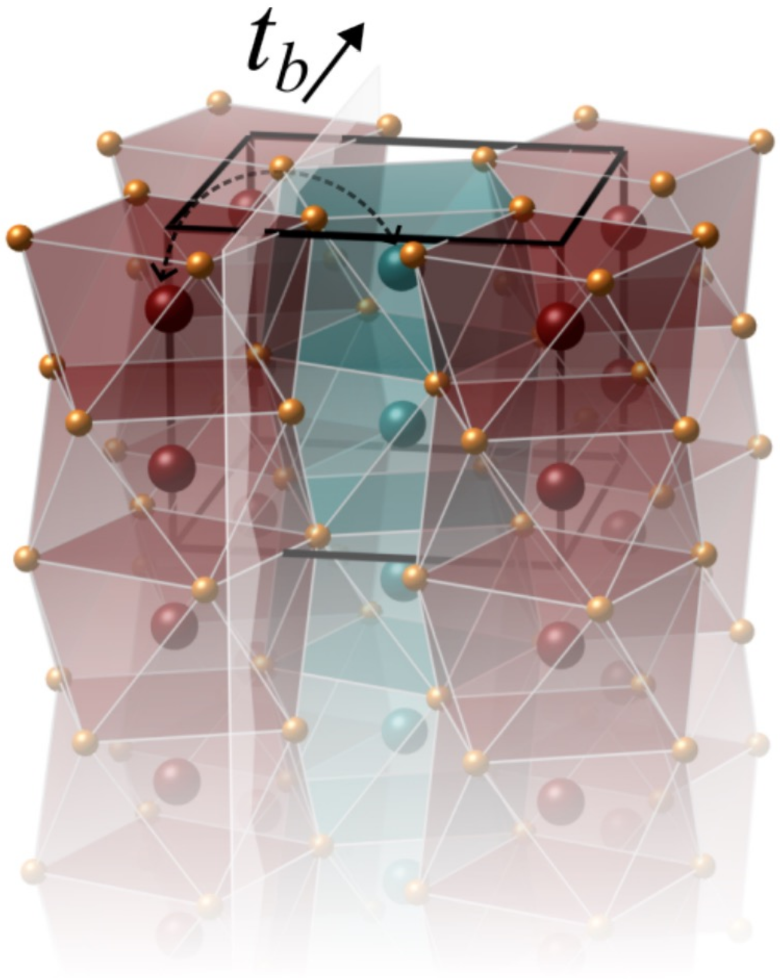
Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)



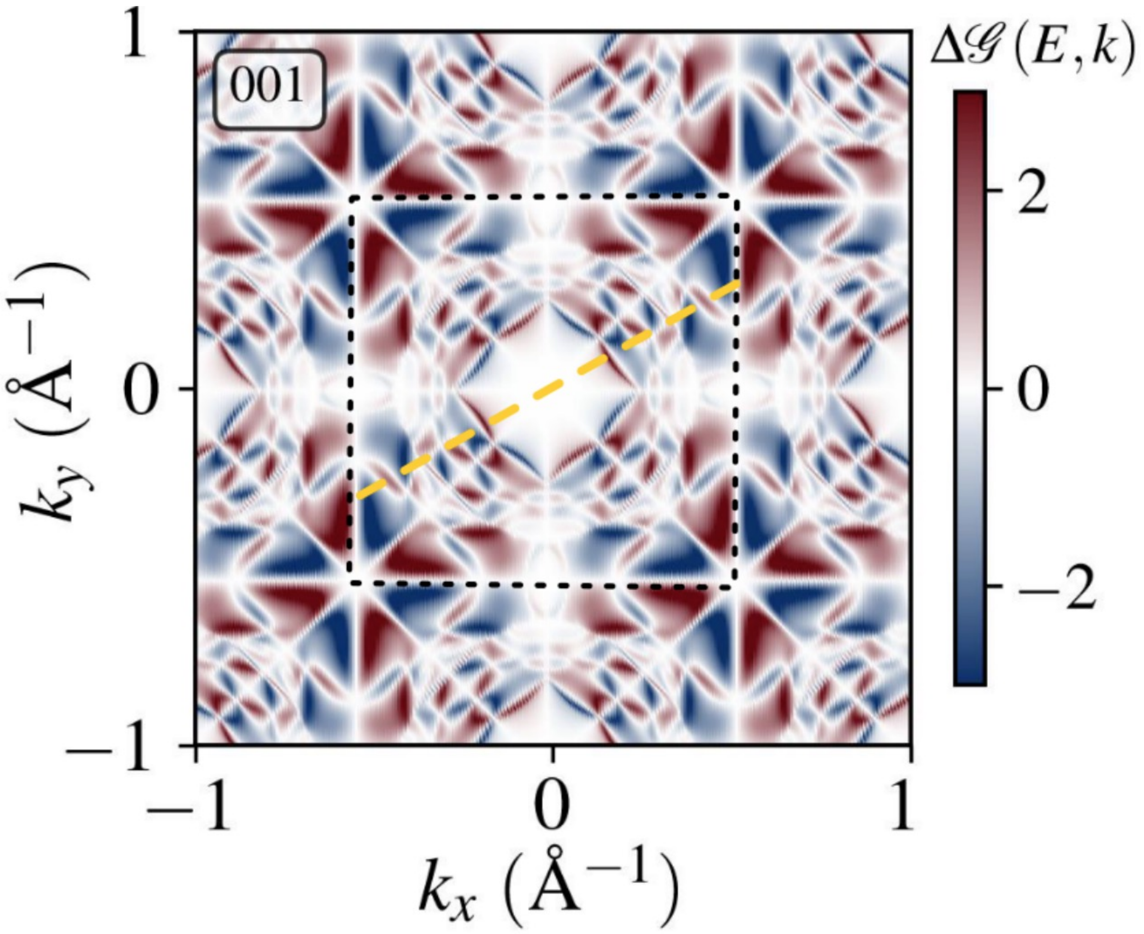


Surface altermagnetism in $FeGe_2$

Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)



g-wave surface spectrum



Result of screening

Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)

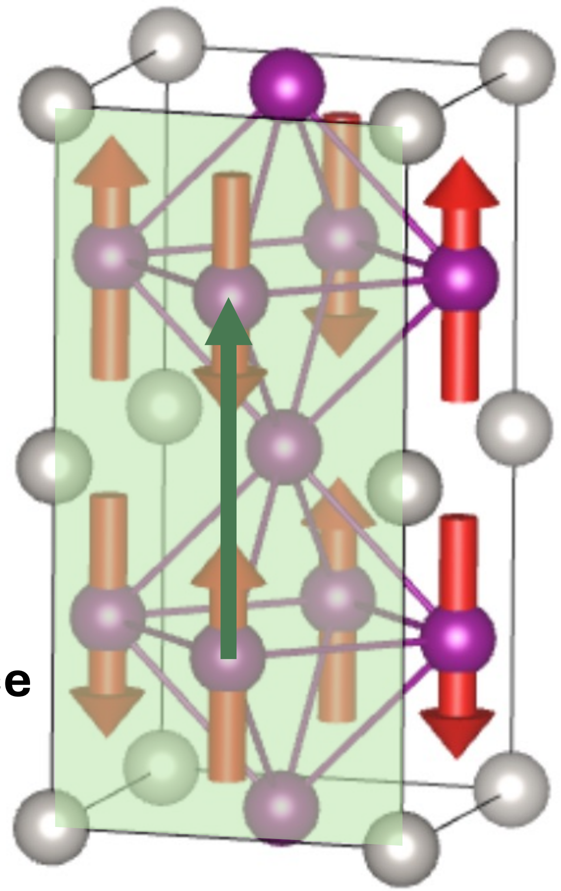
TopMagIc

No.	Material entry	Index	Normals	Surf. spin Laue group	Surface character
1	$AgNiO_2$	1.50	[001] [010]	$\bar{1}$ ${}^{2}2_z/{}^{2}m_z$	AFM SD-SAM
⋮	⋮	⋮	⋮	⋮	⋮
285	ZnV_2O_4	1.24	[001] [1$\bar{1}$0] [110]	${}^{2}2_z/{}^{2}m_z$ $2/m$ $2/m$	SD-SAM AFM AFM

Other material candidates

Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)

tetragonal
Mn_3Pt



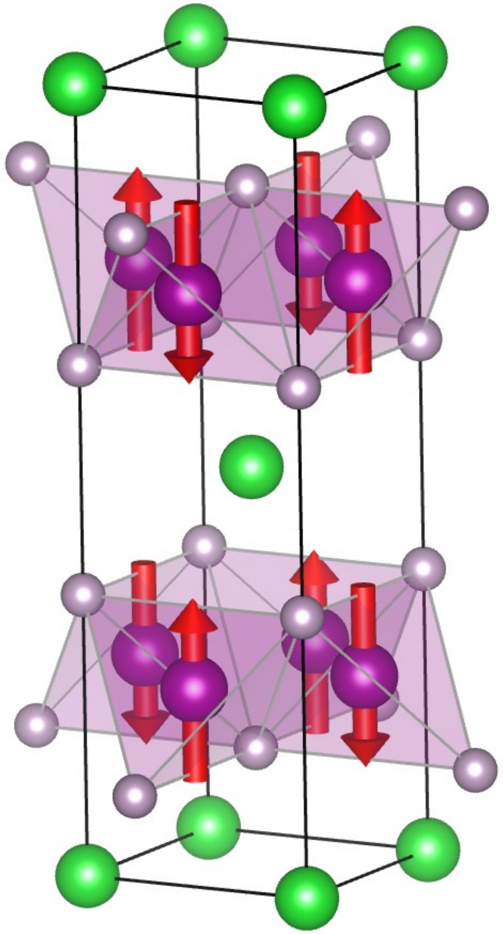
(100) surface

[001]	$^{2}4/^{1}m^{1}m^{2}m$	d-wave
[100]	mmm	AFM
[$1\bar{1}0$]	mmm	AFM
[010]	mmm	AFM
[110]	mmm	AFM

Other material candidates

Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)

$\mathrm{BaMn_2}X_2$
$(X = \mathrm{P, Ge, As, Sb, Bi})$

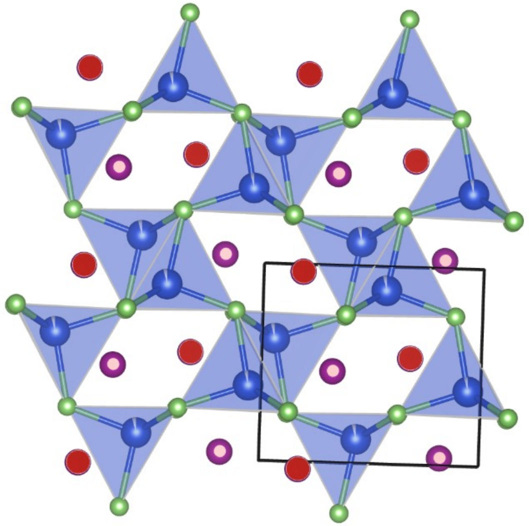


[001]	${}^{2}4/{}^{1}m{}^{1}m{}^{2}m$	d-wave
[100]	${}^{2}m{}^{1}m{}^{2}m$	SD-SAM
$[1\bar{1}0]$	${}^{2}m{}^{2}m{}^{1}m$	d-wave
[010]	${}^{2}m{}^{1}m{}^{2}m$	SD-SAM
[110]	${}^{2}m{}^{2}m{}^{1}m$	d-wave

see also: Sasioglu, Mertig, Lounis, arXiv:2602.08790

Other material candidates

Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)

orthorhombic CuMnAs  [010] ${}^{2}2/{}^{2}m$ d-wave

Topological semimetal: Tang et al., Nat. Phys. 12, 1100–1104 (2016)
Šmejkal, Phys. Rev. Lett. 118, 106402 (2017)

see also: Leeb, d'Ornellas, Juan, Grushin, arXiv:2602.10108

Other material candidates

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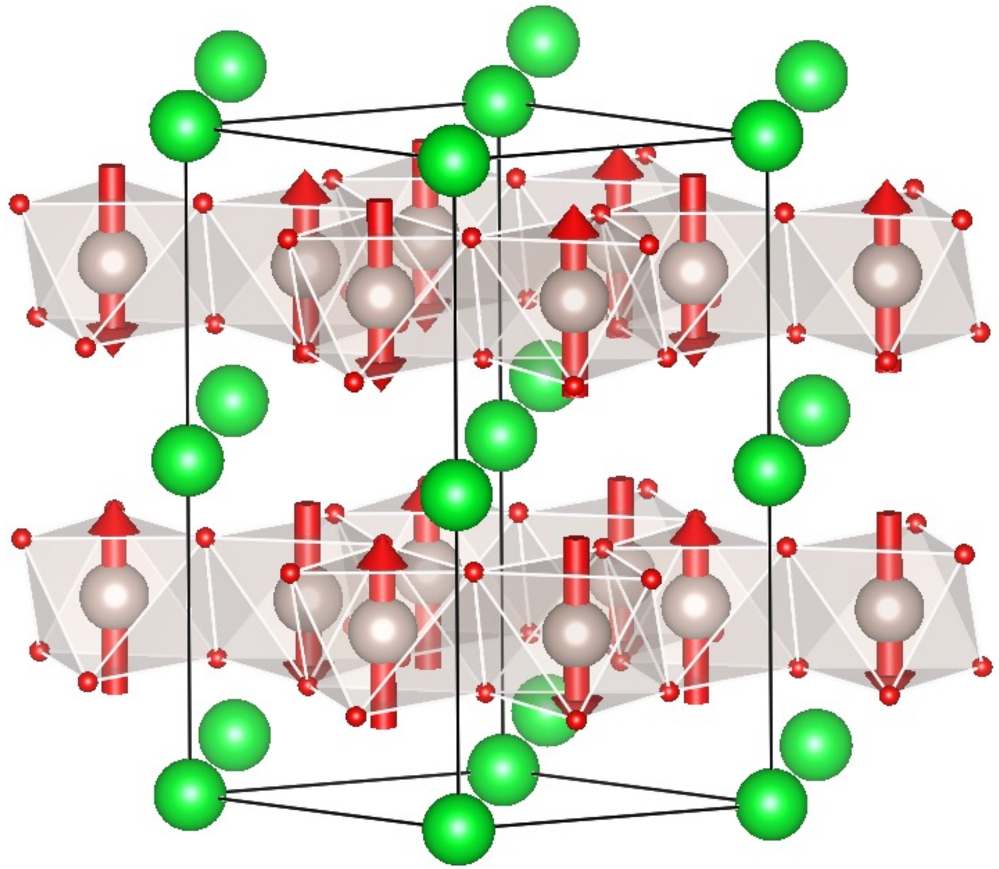
Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)

$SrRu_2O_6$



[001]	$^{1}\bar{3}^{2}m$	i-wave
$[1\bar{1}0]$	$2/m$	AFM
[120]	$2/m$	AFM
[210]	$2/m$	AFM

Altermagnetic surface spin groups

Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)

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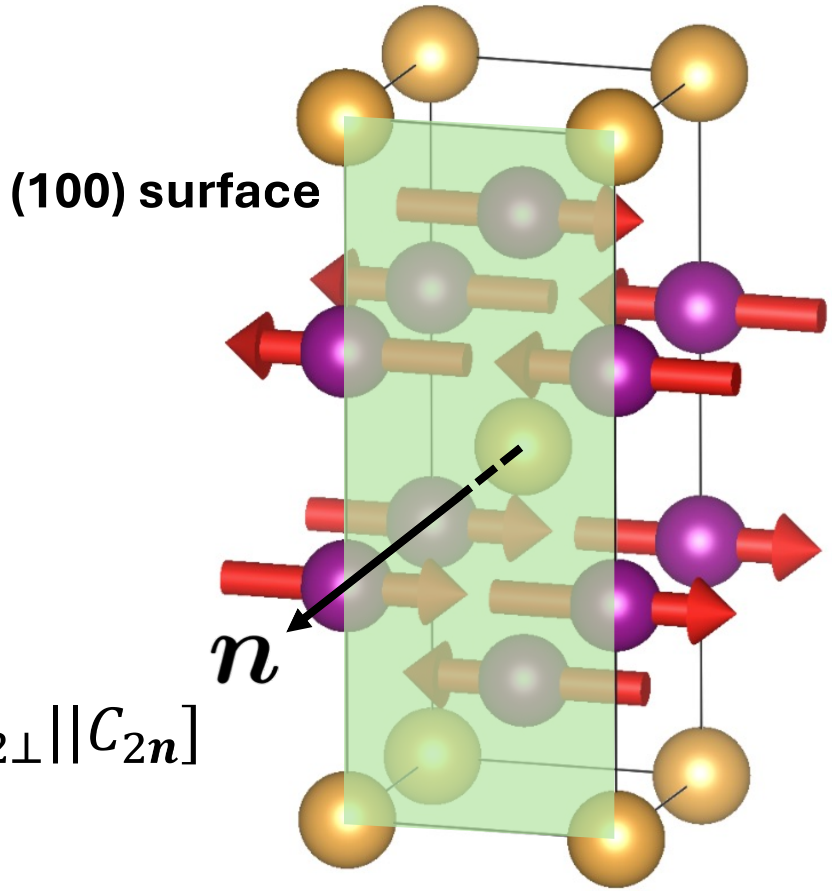
Surf. partial-wave character	Surf. spin point group	Surf. spin Laue group	Spin split surf. states?
d-wave	${}^2m_x\,{}^2m_y\,{}^12_z$	${}^2m_x\,{}^2m_y\,{}^1m_z$	✓
	${}^24\,{}^2m\,{}^1m$	${}^24/{}^1m\,{}^2m\,{}^1m$	✓
	^{24}	${}^24/{}^1m$	✓
	${}^2m_{x/y}$	${}^22_{x/y}/{}^2m_{x/y}$	✓
g-wave	${}^14\,{}^2m\,{}^2m$	${}^14/{}^1m\,{}^2m\,{}^2m$	✓
i-wave	${}^16\,{}^2m\,{}^2m$	${}^16/{}^1m\,{}^2m\,{}^2m$	✓
	${}^13\,{}^2m$	${}^1\bar{3}\,{}^2m$	✓
SD-SAM	${}^2m_{x/y}\,{}^1m_{y/x}\,{}^22_z$	${}^2m_{x/y}\,{}^1m_{y/x}\,{}^2m_z$	✗
	${}^22_z$	${}^22_z/{}^2m_z$	✗
	${}^26\,{}^2m\,{}^1m$	${}^26/{}^2m\,{}^2m\,{}^1m$	✗
	^{26}	${}^26/{}^2m$	✗

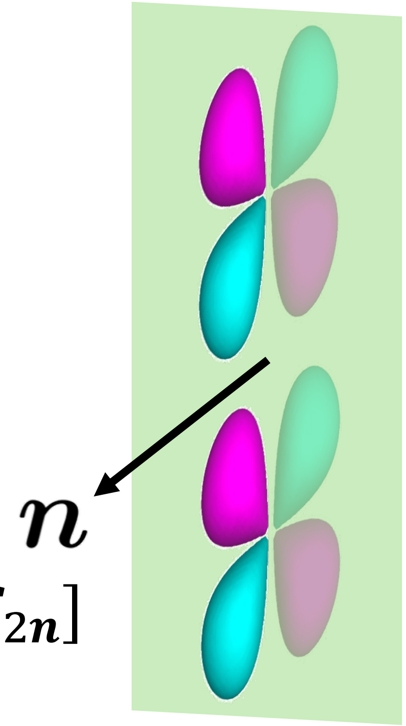
Spin-degenerate surface altermagnets

Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)

Mn_2Au



$[C_{2\perp}||C_{2\boldsymbol{n}}]$



$[C_{2\perp}||C_{2\boldsymbol{n}}]$

Encountered previously in 2D:
Tian *et al.*, arXiv:2508.17864

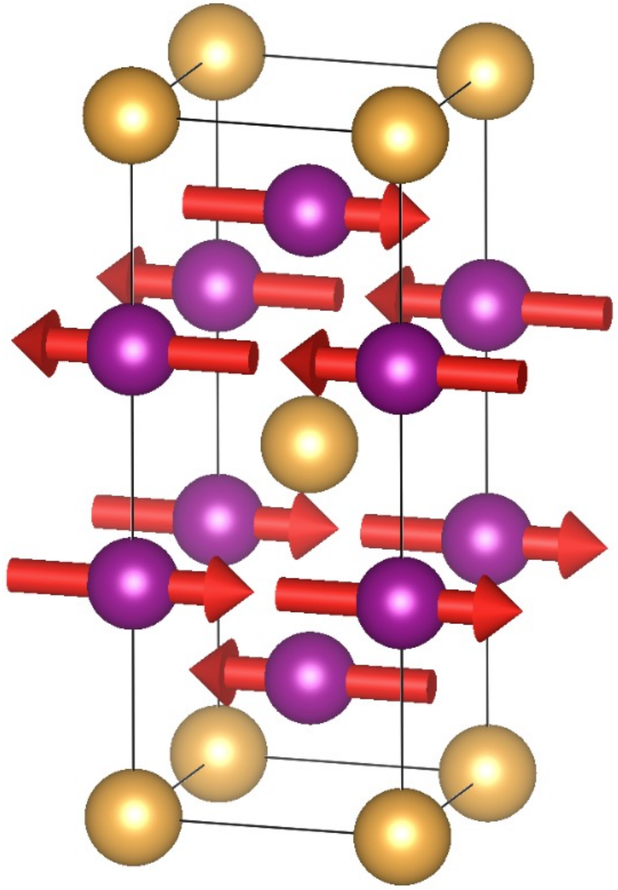
- TRS breaking explicit with SOC

- ferroic order of multipoles
- no nonrelativistic spin splitting (nodal plane)
- different from AFM: point group does not contain TRS

Spin-degenerate surface altermagnets

Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)

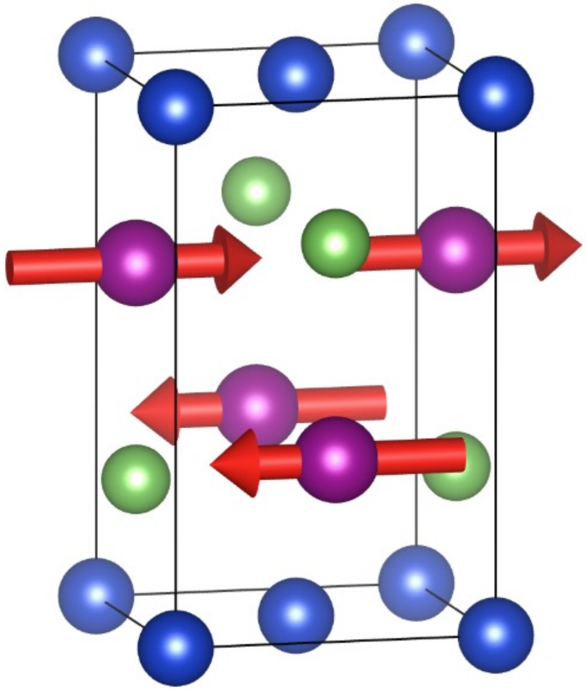
Mn_2Au



[100]	${}^2m{}^1m{}^2m$	SD-SAM
[$1\bar{1}0$]	${}^2m{}^1m{}^2m$	SD-SAM
[010]	${}^2m{}^1m{}^2m$	SD-SAM
[110]	${}^2m{}^1m{}^2m$	SD-SAM

Spin-degenerate surface altermagnets

Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)

tetragonal CuMnAs		$[1\bar{1}0]$	${}^{2}m{}^{1}m{}^{2}m$	SD-SAM
		$[110]$	${}^{2}m{}^{1}m{}^{2}m$	SD-SAM

Spin-degenerate surface altermagnets

Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)

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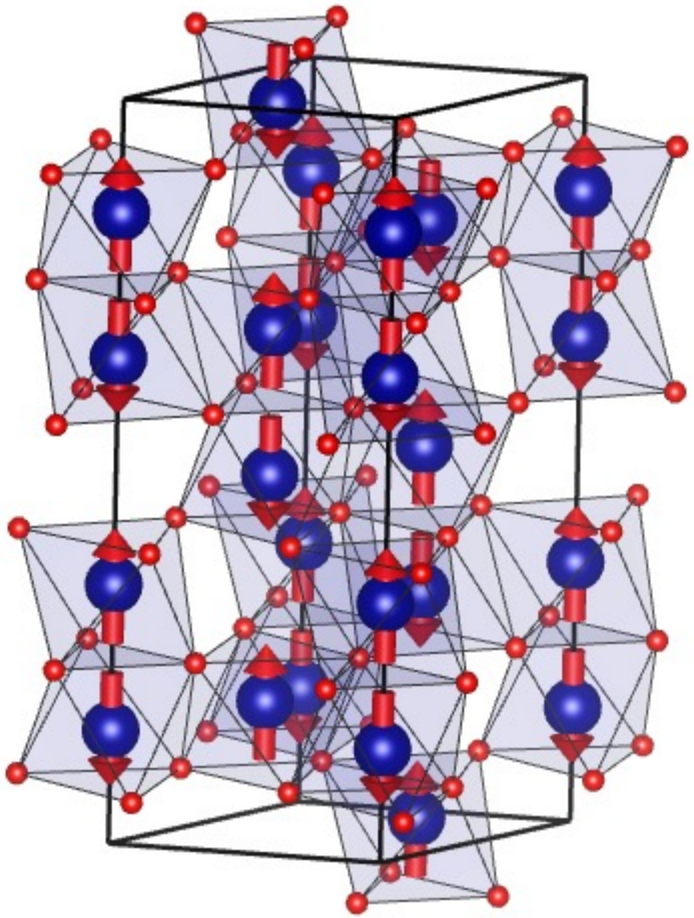
Cr_2O_3



[110]	${}^{2}2_z/{}^{2}m_z$	SD-SAM
[100]	${}^{2}2_z/{}^{2}m_z$	SD-SAM
[010]	${}^{2}2_z/{}^{2}m_z$	SD-SAM

Result of screening

Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)

TopMagIc

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Routes to emergent surface altermagn.

Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)

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Symmetry-induced SAM:

3D AFM → (bulk symmetry + surf. symmetry) → Surf AM

To be analyzed:

- surface relaxation
- surface reconstruction
- magnetic surface effects

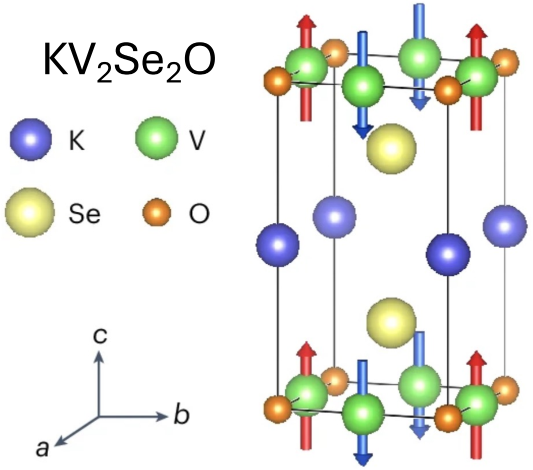
Reconstruction-induced SAM:

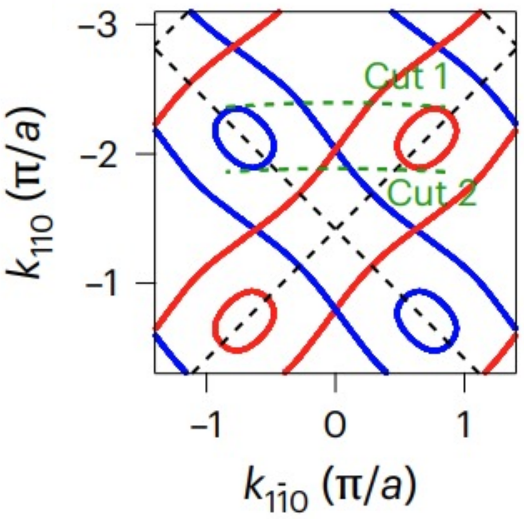
3D AFM → (AFM surface + reconstruction) → Surf AM

- depends on chemistry

Coming back to experiments

Lange, Jaeschke-Ubiergo, Chakraborty, Verbeek, Šmejkal, Sinova, **AM**, arXiv:2602.08773 (2026)





Jiang *et al.*, Nat. Phys. 21, 754–759 (2025)

Other surface-sensitive techniques:

- Spin-polarized STM
- Surface transport
- Magneto-optical Kerr effect
- …

Neutron diffraction says the bulk is antiferromagnetic.

Sun *et al.*, Phys. Rev. B 112, 184416 (2025)

Both experiments are right:
altermagnetism only at the surface

V_2Se_2O monolayer: Ma *et al.*, Nat. Commun. 12, 2846 (2021)

Also $Rb_{1-\delta}V_2Te_2O$: Zhang *et al.*, Nat. Phys. 21, 760–767 (2025)

Also $Cs_{1-\delta}V_2Te_2O$: Yang *et al.*, arXiv:2512.00972

Surface altermagnetism is coming

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Emergent altermagnetism at surfaces of antiferromagnets: full symmetry classification and material identification

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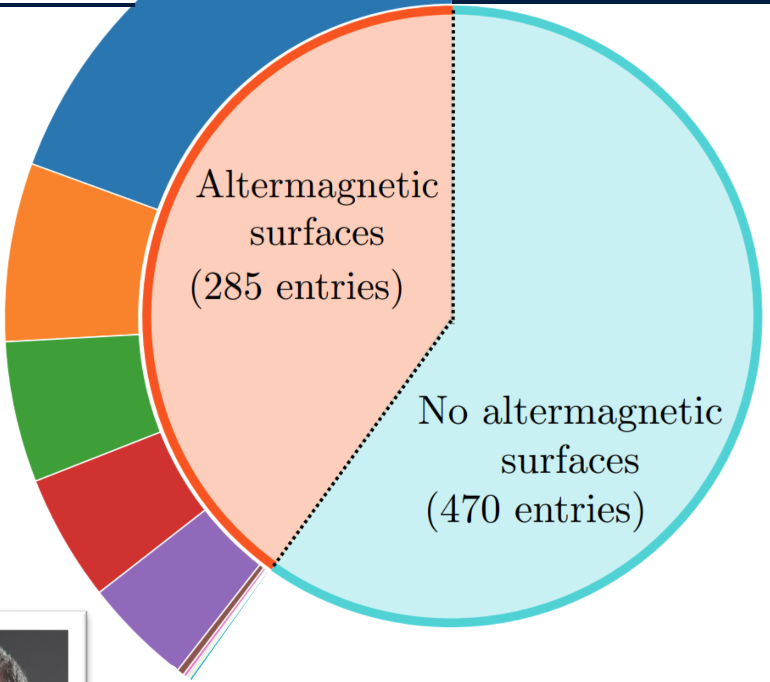
[5] *University of Münster, Institute of Solid State Theory, 48149 Münster, Germany*

arXiv:2602.08773 (2026)

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Jairo Sinova

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