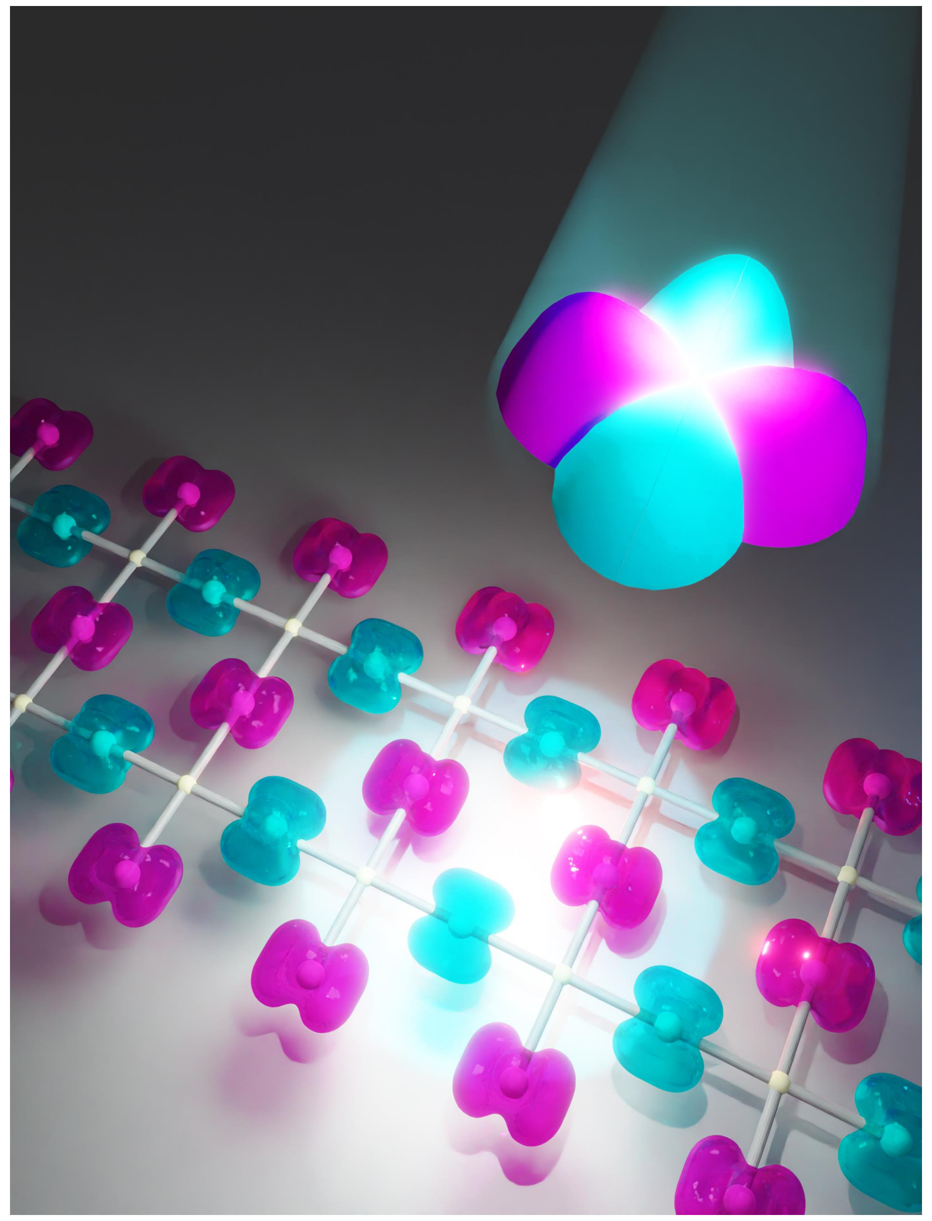
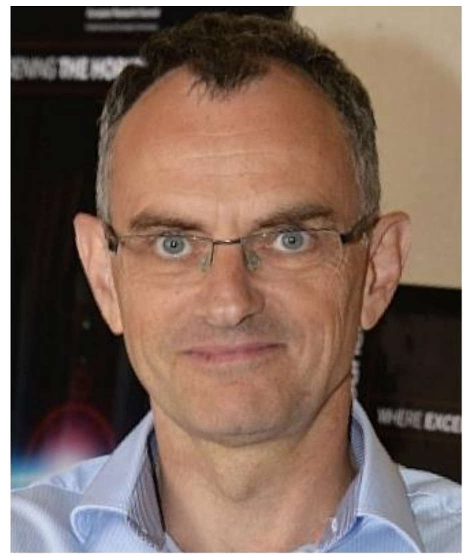
Unconventional magnetism:
the emergence of altermagnetism and its new variants in non-collinear systems

Jairo Sinova
Johannes Gutenberg Universität Mainz





Libor Šmejkal **Tomas Jungwirth**

22nd of April 2024
2024 European School on Superconductivity and Magnetism in Quantum Materials, Gandia, Valencia

	1 Anomalies in spintronics (2018-)	2 Altermagnetism and spin symmetries (2021-)	3 Beyond altermagnets: unconventional p-wave magnetism (2023-)
Prediction	*LŠ et al., Science Adv. (2020) , arxiv:2019* *Mazin, LŠ et al., PNAS 118 (2021)* *LŠ et al. Phys Rev X 12, 011028 (2022) …*	*LŠ, Sinova, Jungwirth, Phys. Rev. X (2022)*	*Birk Hellenes, Jungwirth, Sinova & LŠ* *arXiv:2309.01607v2*
Observation	*Feng*, LŠ* et al., Nature Electron. (2022)* *Fedchenko, LŠ, Science Adv. (2024)*	*Krempasky*, LŠ* et al., Nature (2024)* *Lee, LŠ et al. Phys. Rev. Lett. (2024)* *Reimers, LŠ et al., Nature Com (2024) …*	

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Crystal time-reversal symmetry breaking and spontaneous Hall effect in collinear antiferromagnets

LIBOR ŠMEJKAL, RAFAEL GONZÁLEZ-HERNÁNDEZ, T. JUNGWIRTH, AND J. SINOVA — Authors Info & Affiliations

SCIENCE ADVANCES • 5 Jun 2020 • Vol 6, Issue 23 • DOI: 10.1126/sciadv.aaz8809

PHYSICAL REVIEW X

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Open Access

Beyond Conventional Ferromagnetism and Antiferromagnetism: A Phase with Nonrelativistic Spin and Crystal Rotation Symmetry

Libor Šmejkal, Jairo Sinova, and Tomas Jungwirth
Phys. Rev. X **12**, 031042 – Published 23 September 2022

nature electronics

An anomalous Hall effect in altermagnetic ruthenium dioxide

Received: 10 January 2022
Accepted: 4 October 2022
Published online: 7 November 2022

Zexin Feng[1,8], Xiaorong Zhou[1,8], Libor Šmejkal[2,3,8], Lei Wu[4,5], Zengwei Zhu[4,5], Huixin Guo[1], Rafael González-Hernández[2,6], Xiaoning Wang[1], Han Yan[1], Peixin Qin[1], Xin Zhang[1], Haojiang Wu[1], Hongyu Chen[1], Ziang Meng[1], Li Liu[1], Zhengcai Xia[4,5], Jairo Sinova[2,3], Tomáš Jungwirth[3,7] & Zhiqi Liu[1]

nature

Article | Open access | Published: 14 February 2024

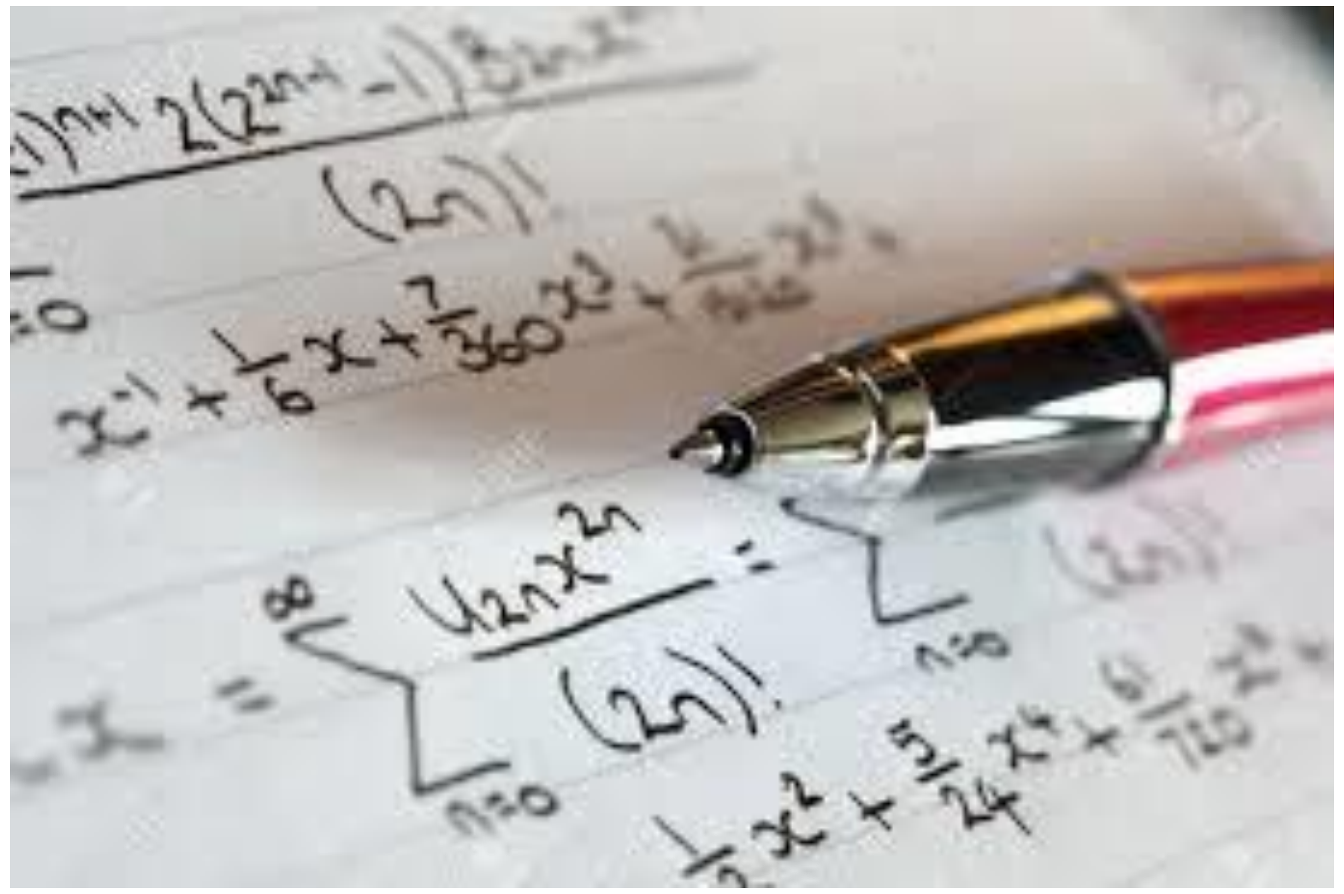
Altermagnetic lifting of Kramers spin degeneracy

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

Our Theory Tools

INSP/RE group
INTERDISCIPLINARY SPINTRONICS RESEARCH



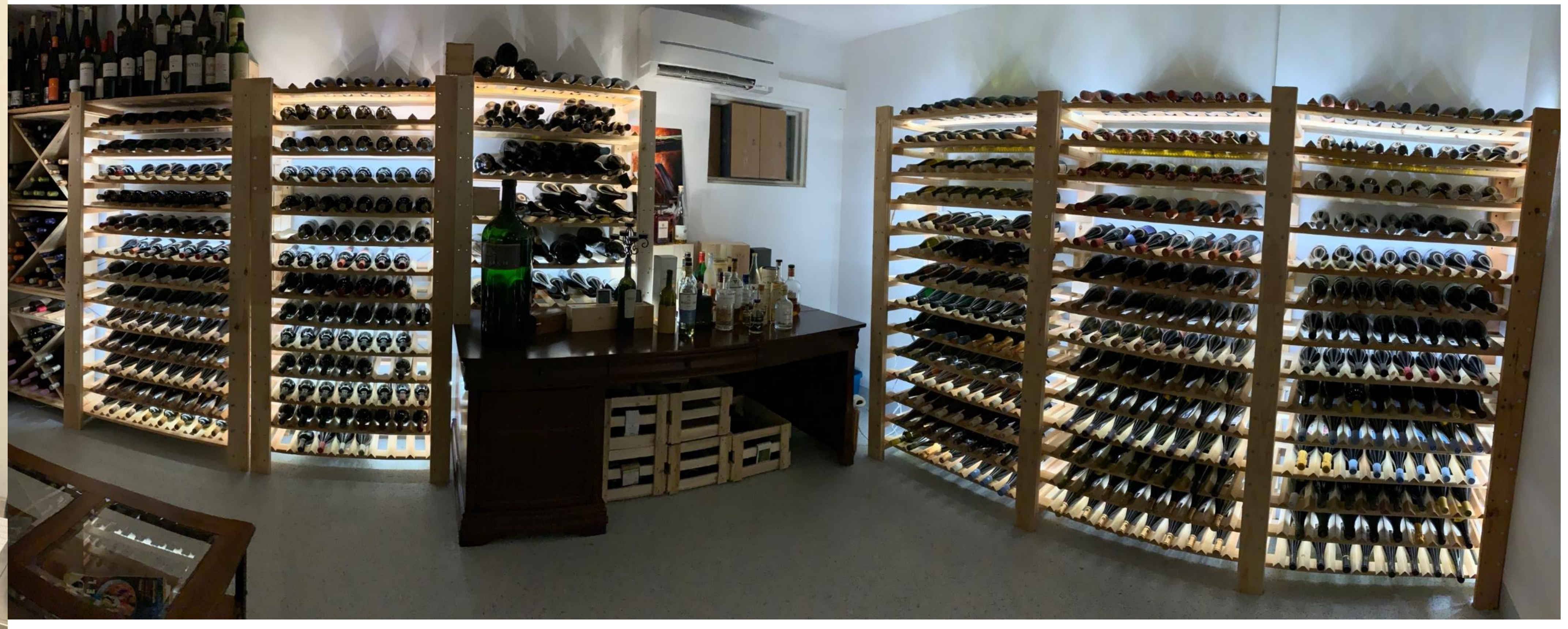
To star thinking

To star computing

To compute seriously

To think seriously

To stay awake



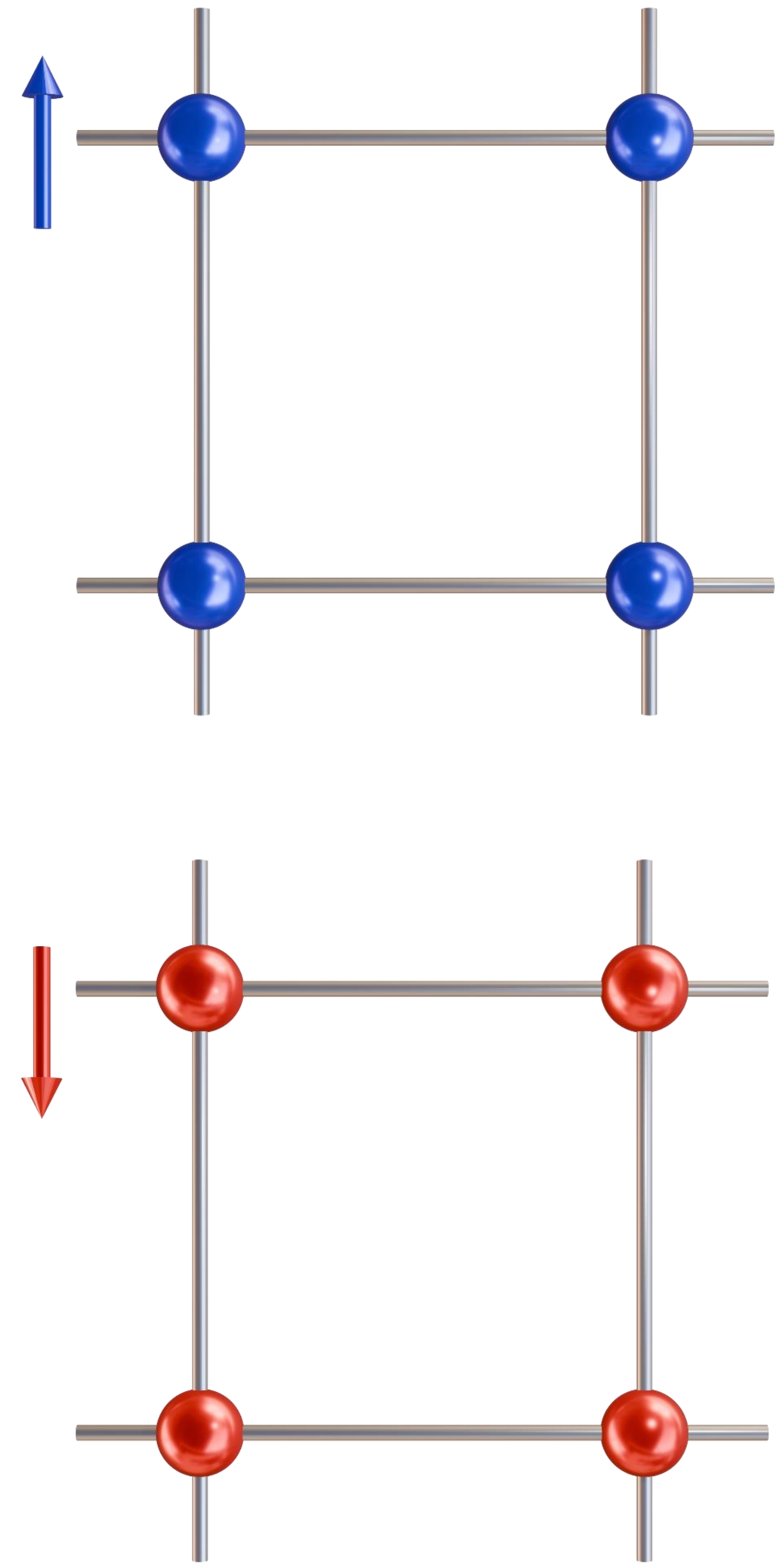
To celebrate successes … or drink your sorrows away …

SP/CE

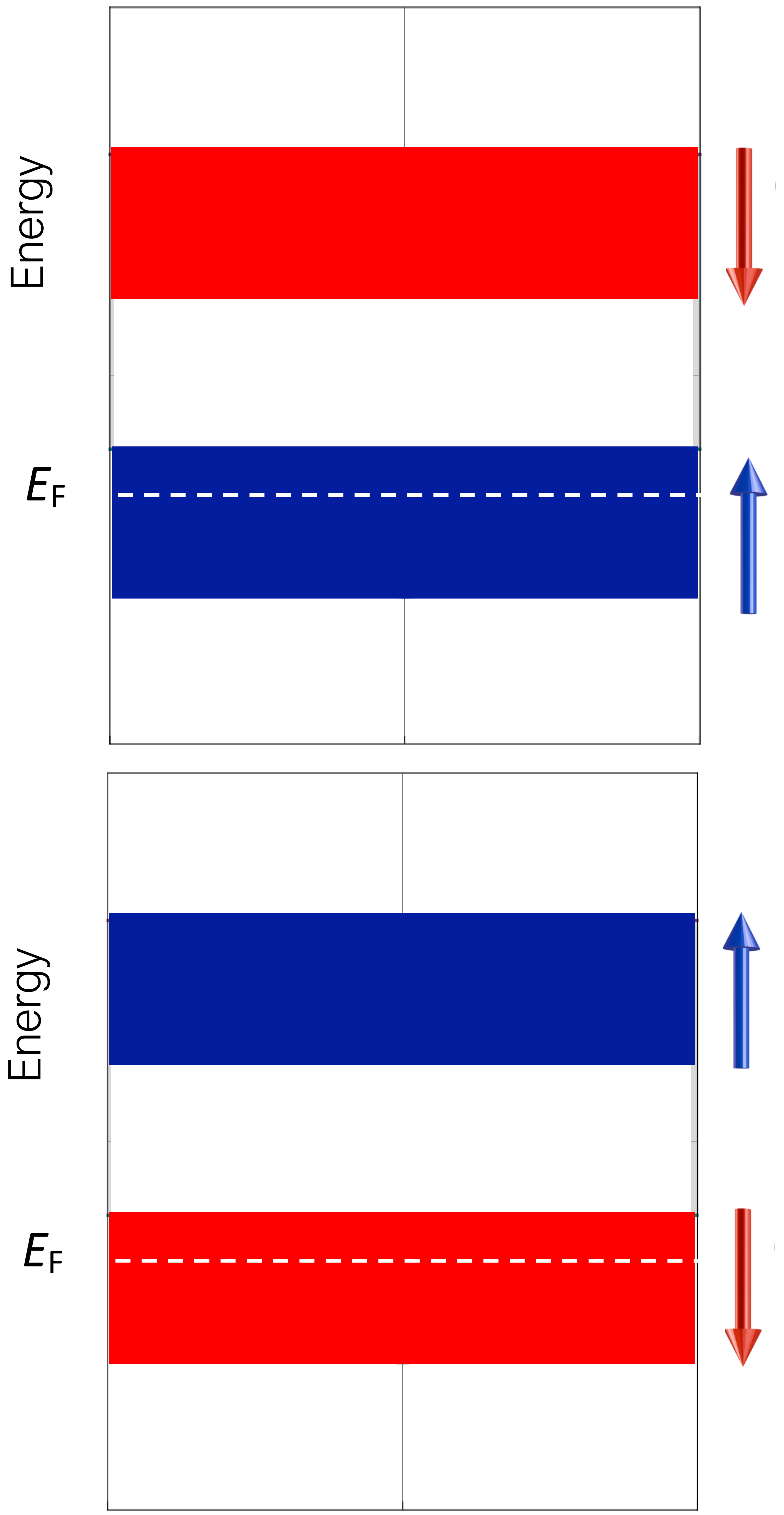
Ferromagnetism and its core spin physics and electronics

INSPIRE group
INTERDISCIPLINARY SPINTRONICS RESEARCH

Iron lattice



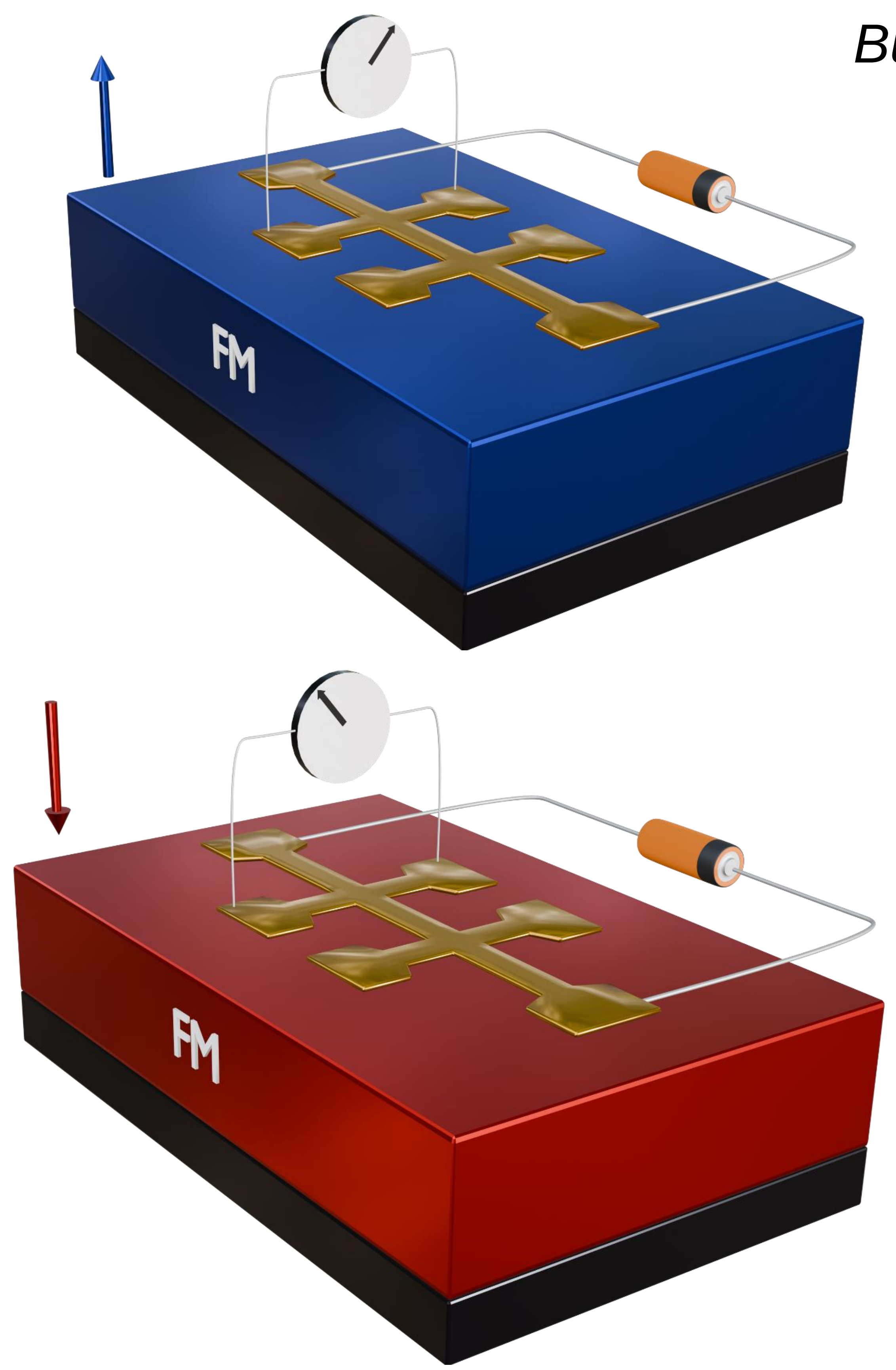
Metallic & spin-split bands



Electronically & magnetically active

Anomalous Hall effect

Hall 1881



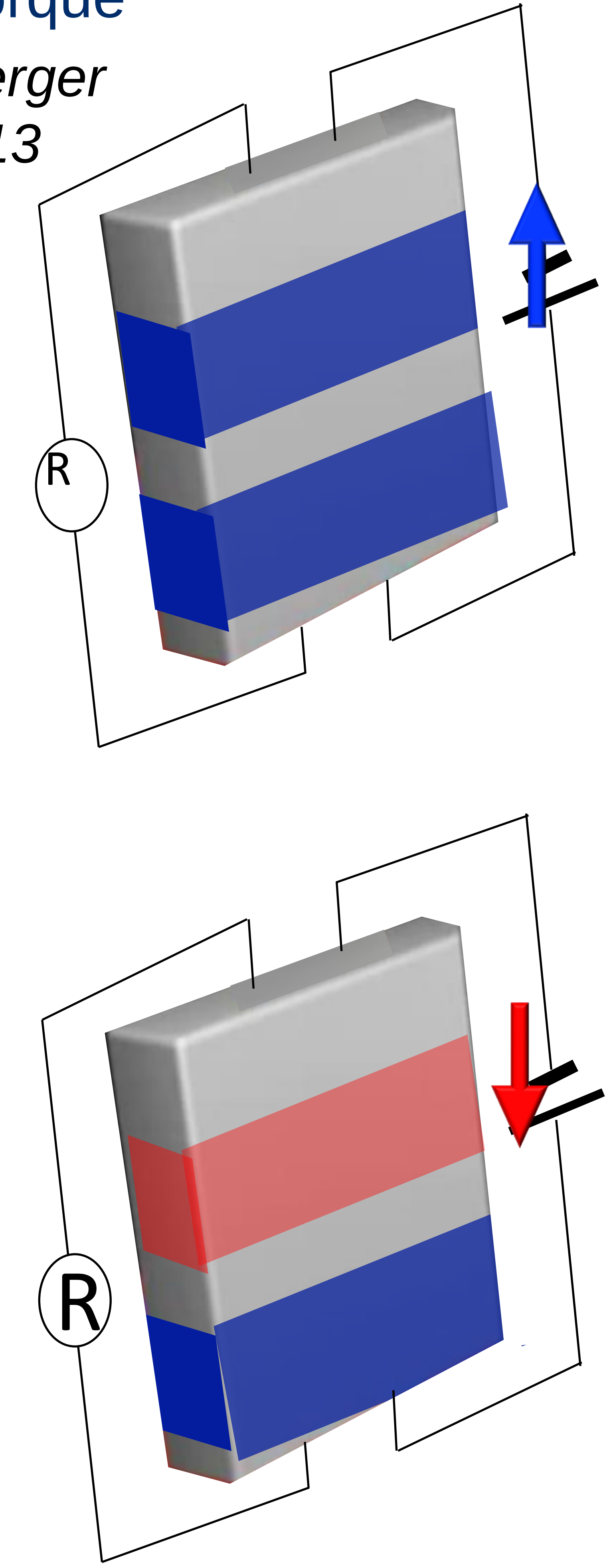
Transverse non-dissipative topological

Spin-transfer torque

Slonczewski & Berger
Buckley Prize 2013

Giant magnetoresistance

Fert & Grünberg
Nobel Prize 2007



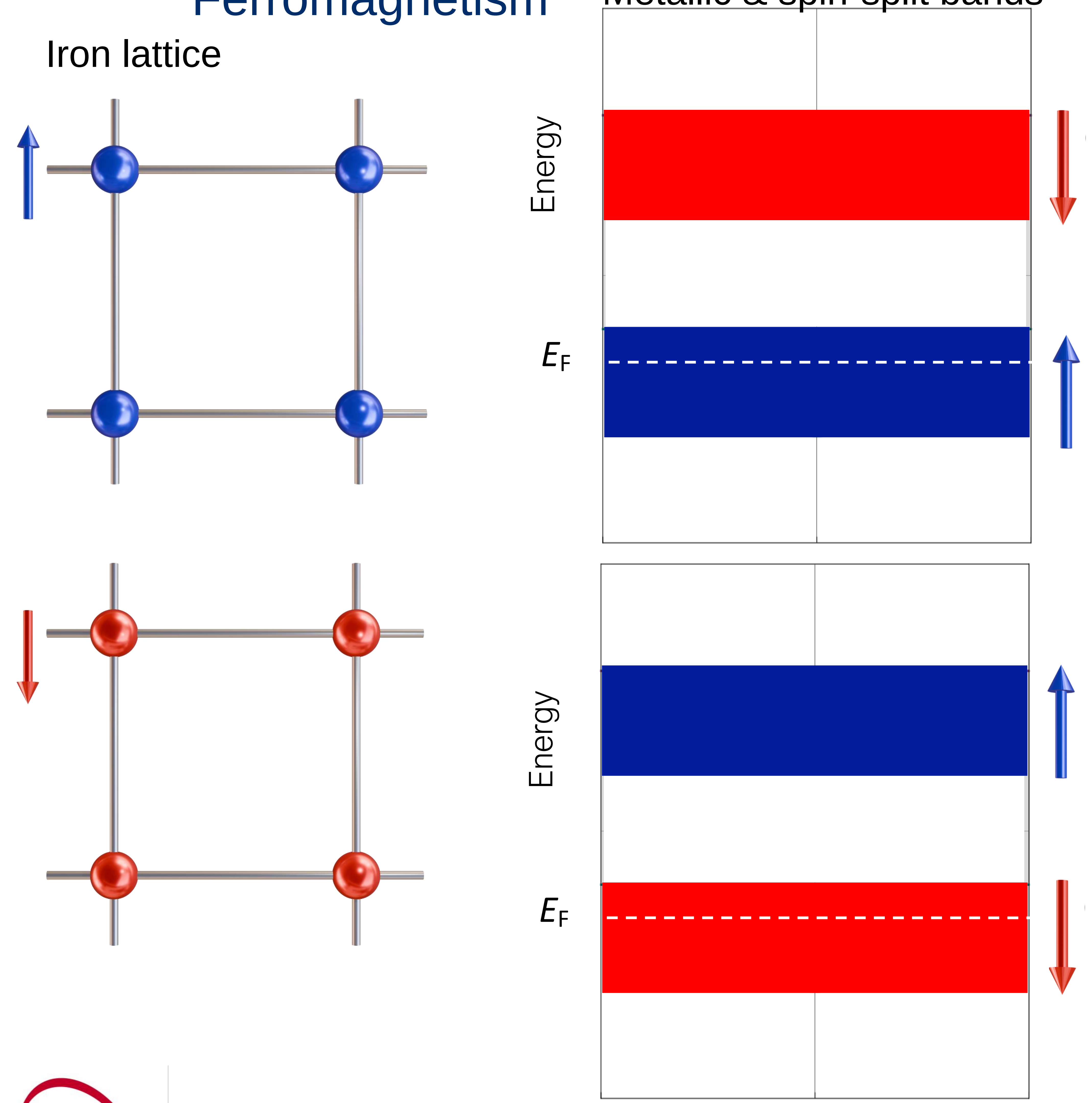
Longitudinal large-signal commercial

Néel's Anti-Ferromagnetism

Ferromagnetism

Metallic & spin-split bands

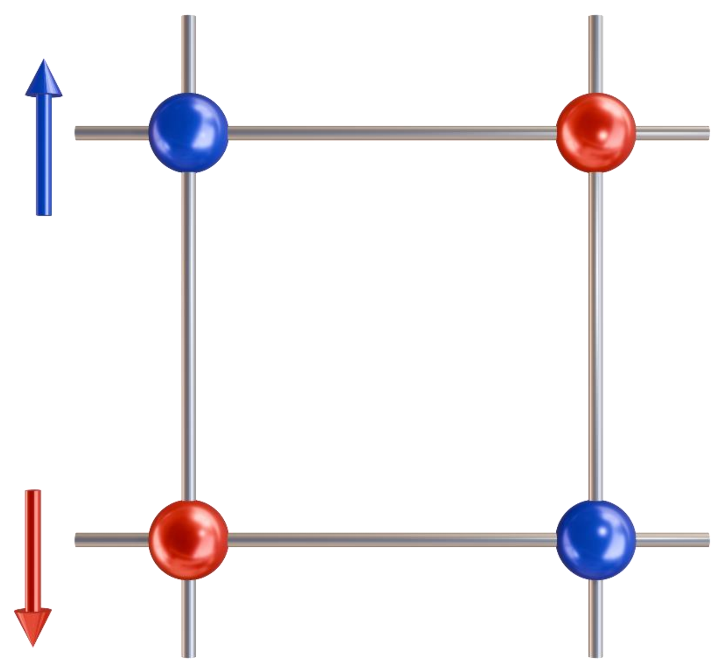
Iron lattice



Electronically & magnetically active

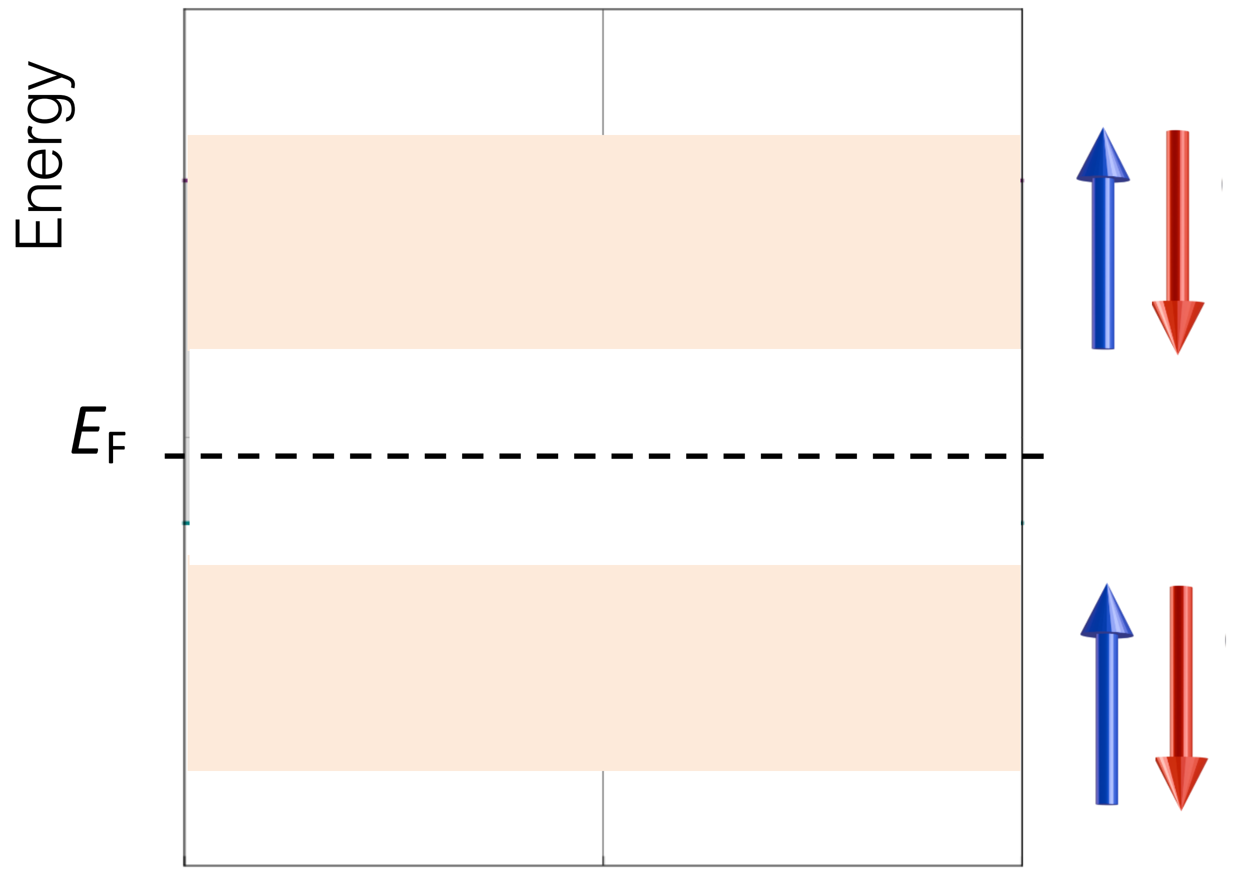
Electronically & magnetically inert

Iron lattice in fluoride rutile



Néel 1930's (Nobel Prize 1970)

Insulating & spin-degenerate bands



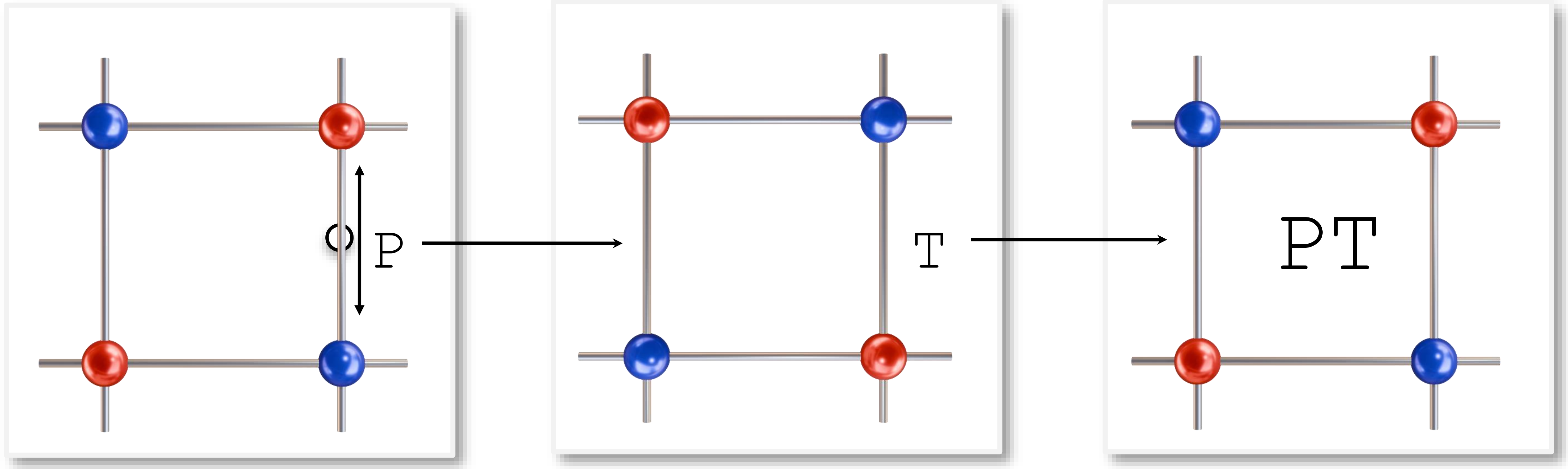
P parity/inversion

T time symmetry

PT transform: PT $\epsilon(\uparrow, \mathbf{k}) = \epsilon(\downarrow, \mathbf{k})$ → $\epsilon(\uparrow, \mathbf{k}) = \epsilon(\downarrow, \mathbf{k})$

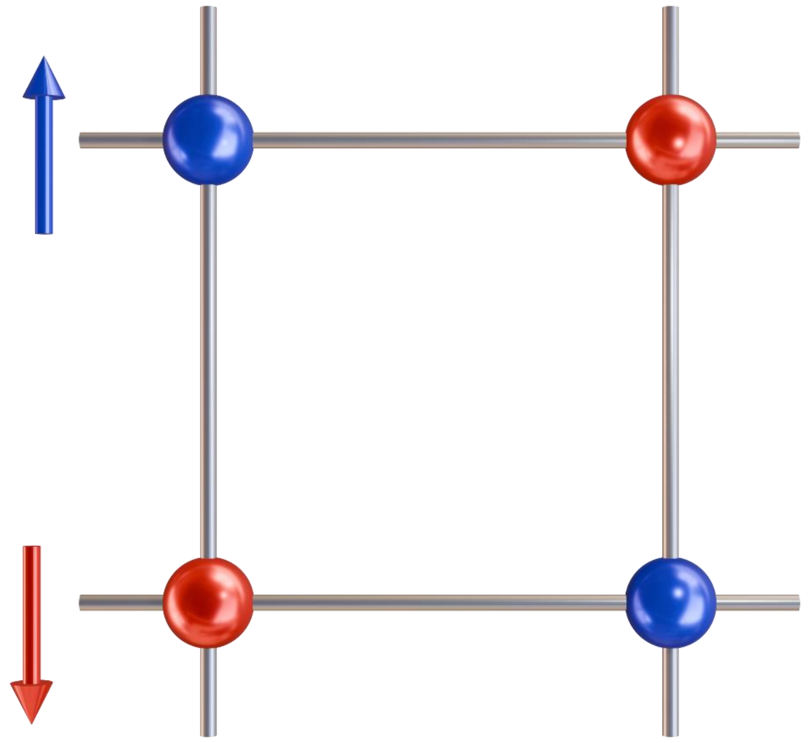
PT symmetry: PT $\epsilon(\uparrow, \mathbf{k}) = \epsilon(\uparrow, \mathbf{k})$

Kramer's Theorem 1930's



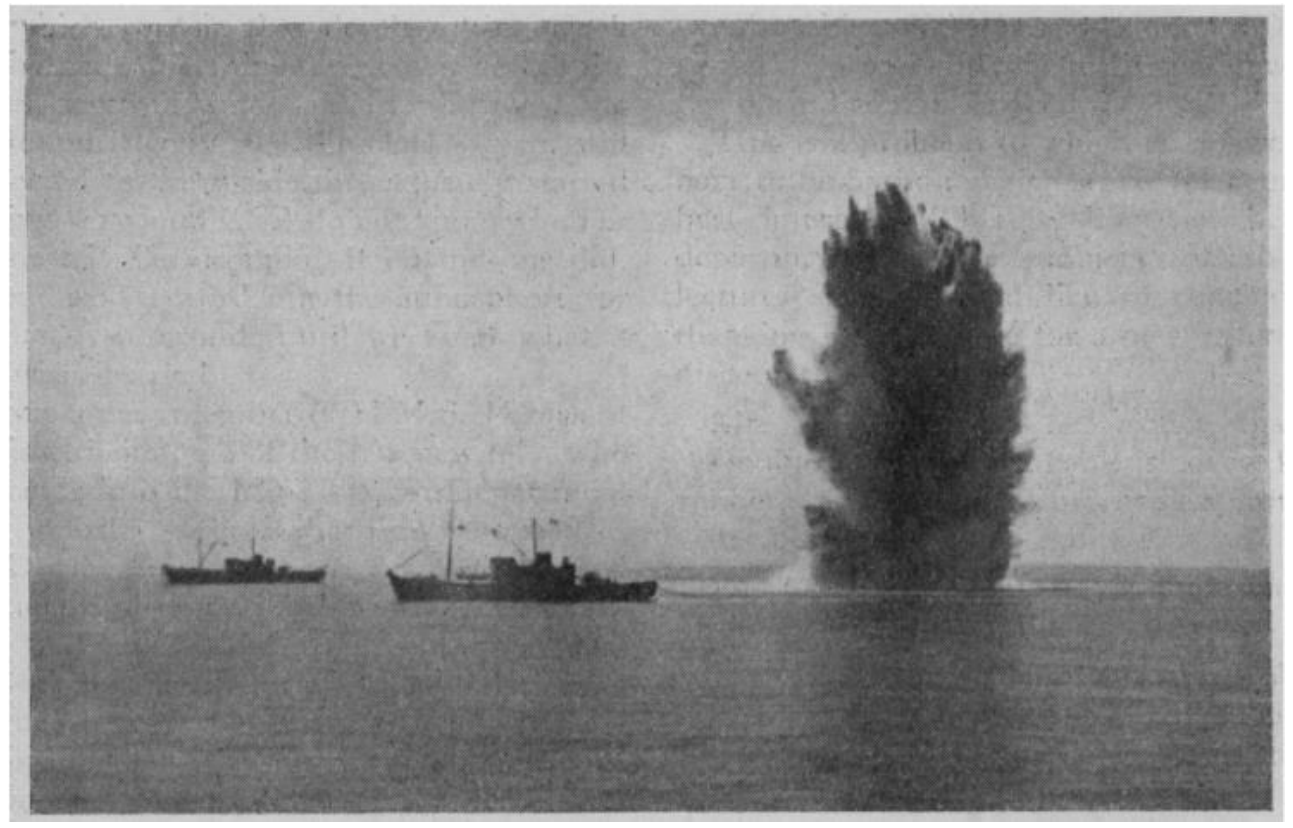
“Néel’s paradox”

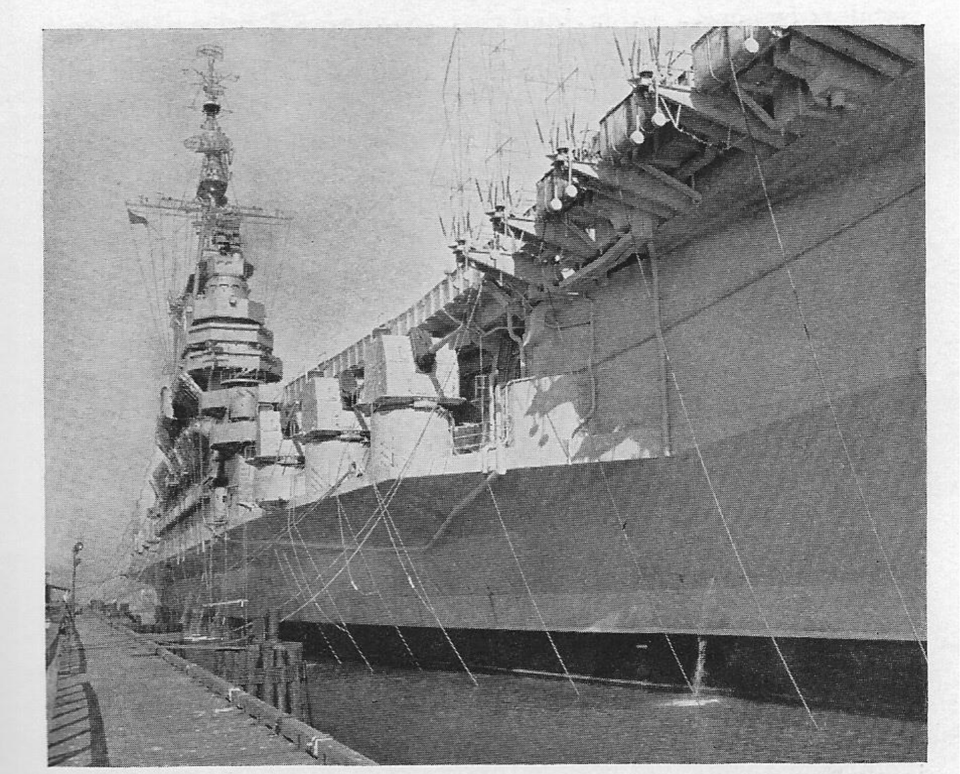
Nobel lecture on the discovery of **antiferromagnetism**



“… interesting but does not appear to have any practical applications…”

Néel come up with the defense against magnetic mines by **demagnetizing** entire ship hulls during 2nd World War





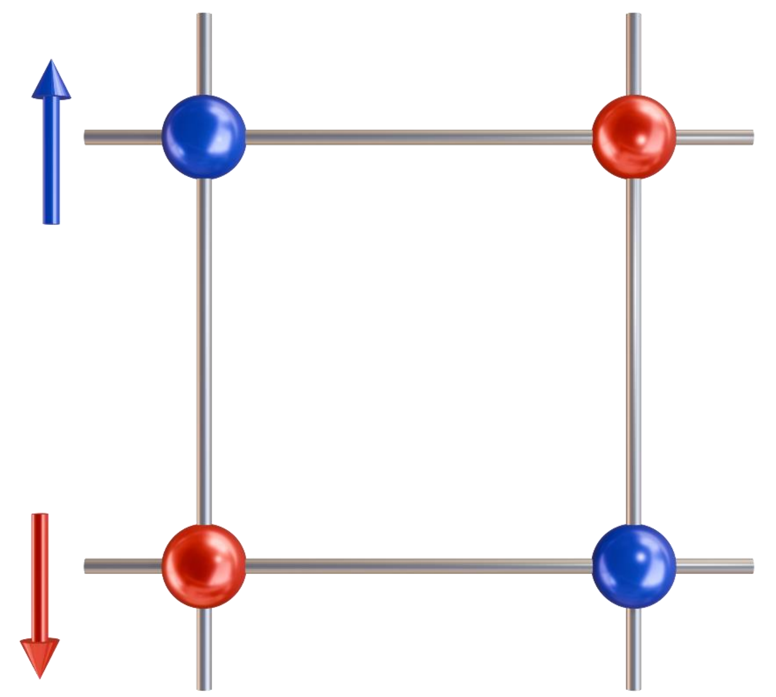
Aircraft carrier wrapped in 5 miles of deperming cable.

Why magnets that microscopically, precisely, and for free “demagnetize” themselves cannot be useful?

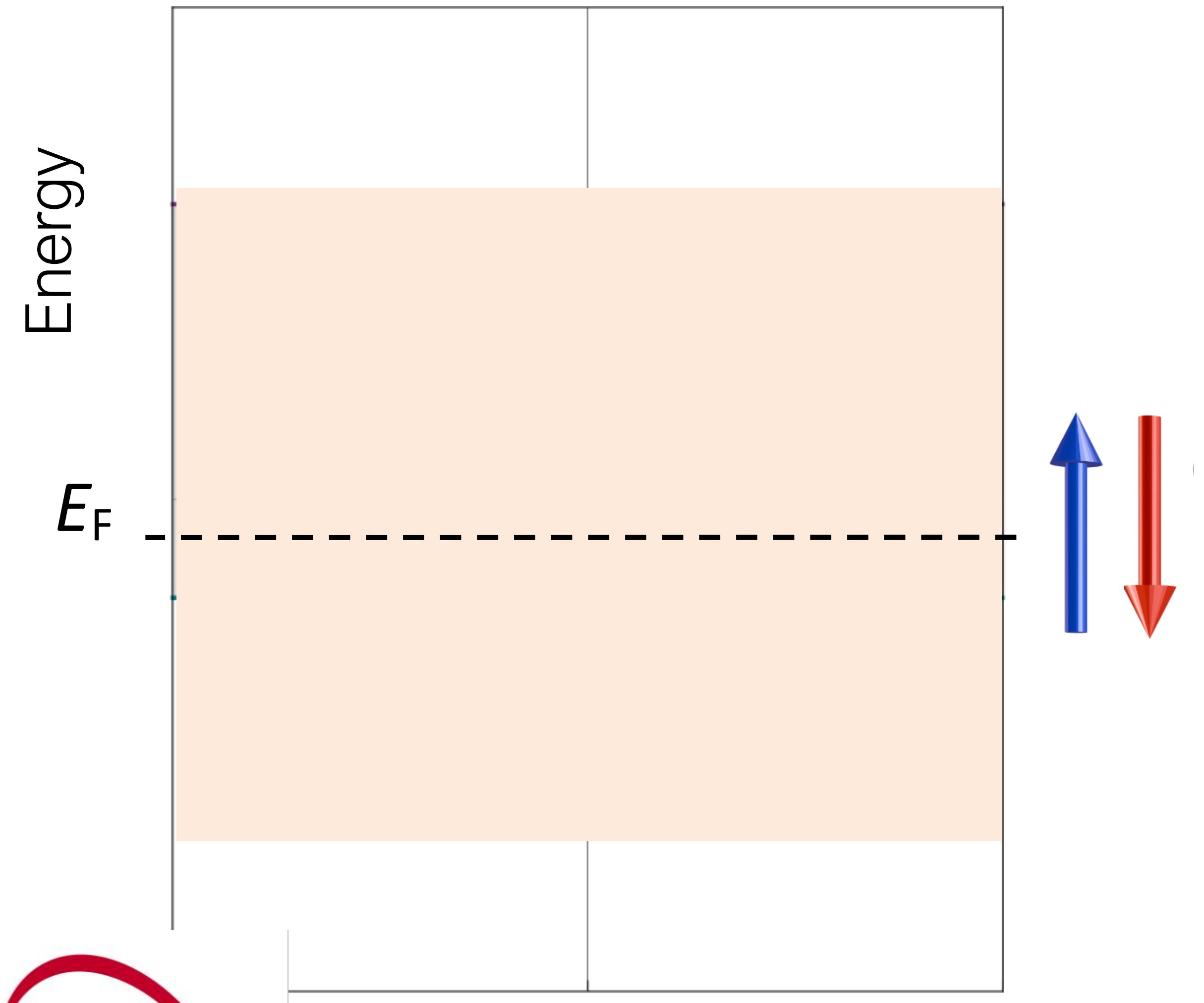
Spintronics without magnetization

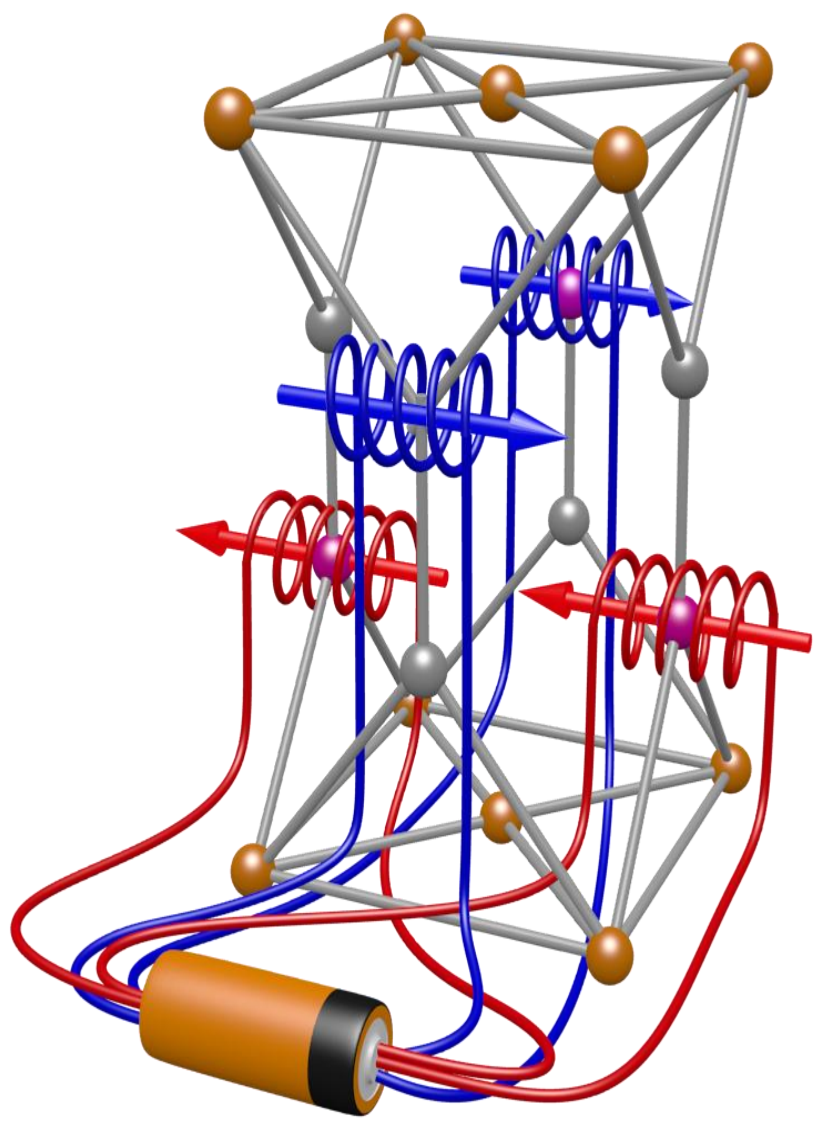
Antiferromagnetism

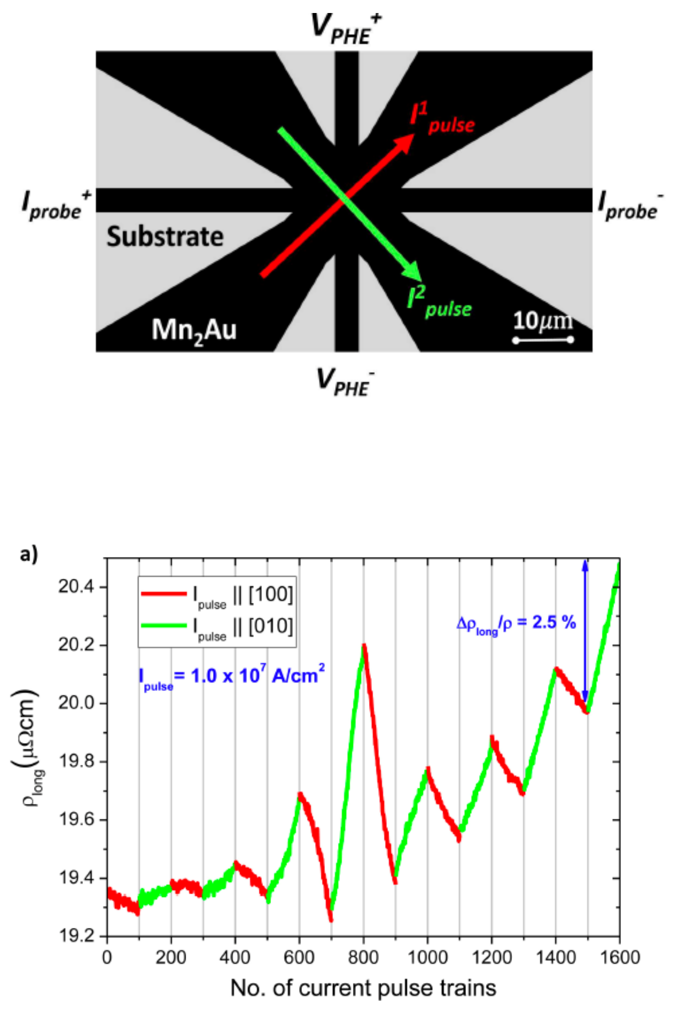
CuMnAs, Mn_2Au

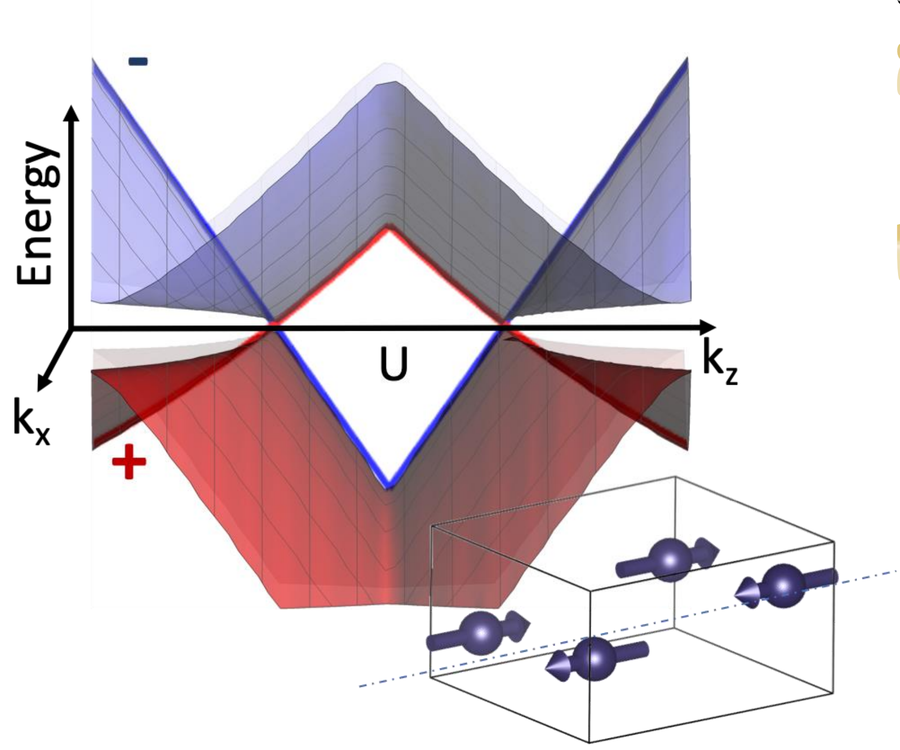


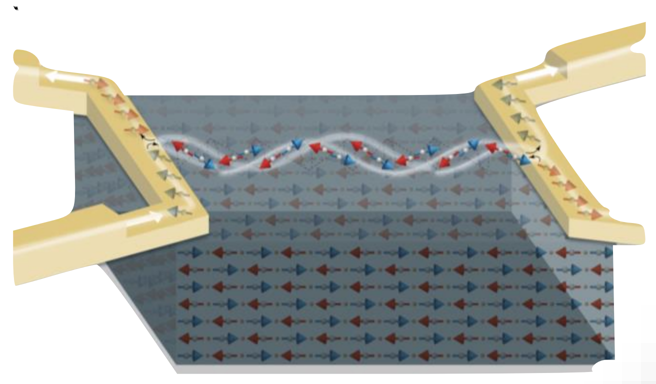
Metallic & spin-degenerate bands











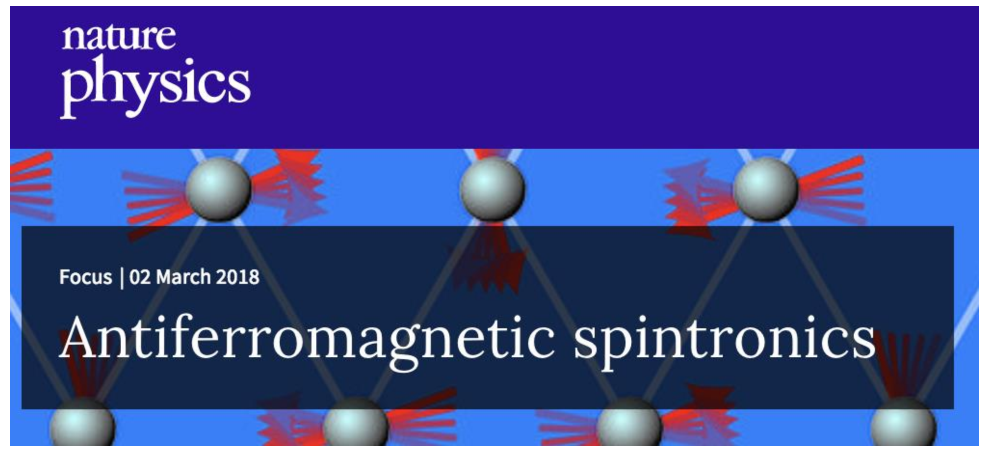
2014 Prediction
2015+ Observations
Néel spin-orbit torque

2016 AFM Dirac fermions

2017 Optical manipulation of AFMs via Néel SOT

2017 Topological antiferromagnetic spintronics

2018 Long distance spin transport in insulating AFM



Reviews: Nature Phys. Focus '18, Baltz et al. RMP '18, Song et al. Nanotech. '18, Siddiqui et al. J. Appl. Phys. '20

Spintronics

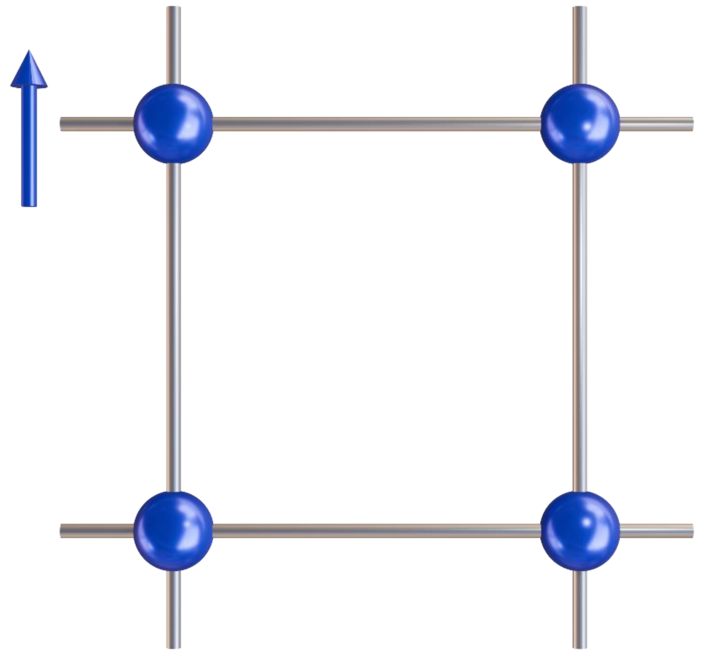
MRAM

✗ stray field capacity limit

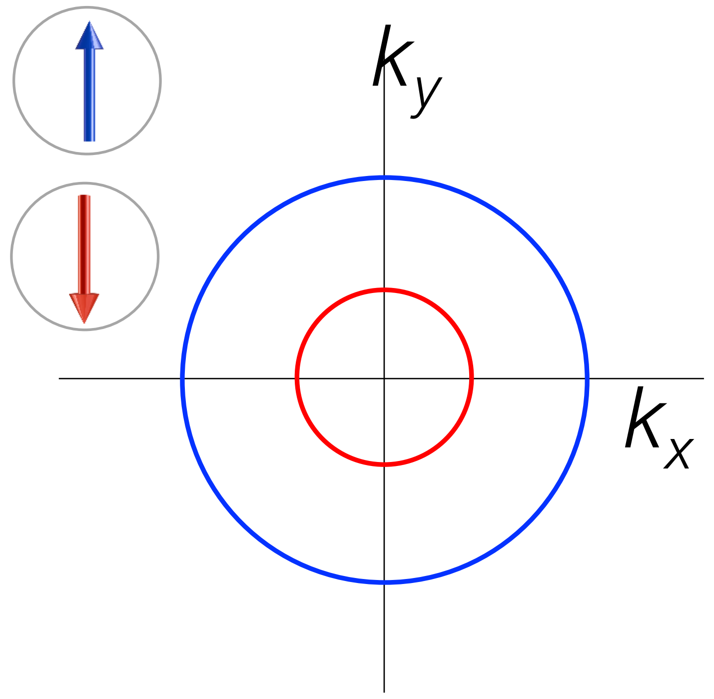
✗ GHz speed

✓ Strong non-relativistic signals

Ferromagnetic

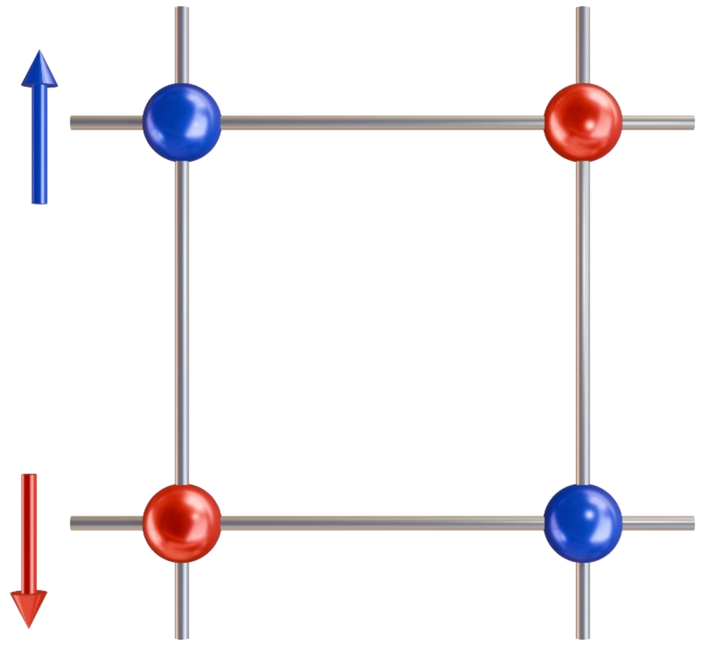


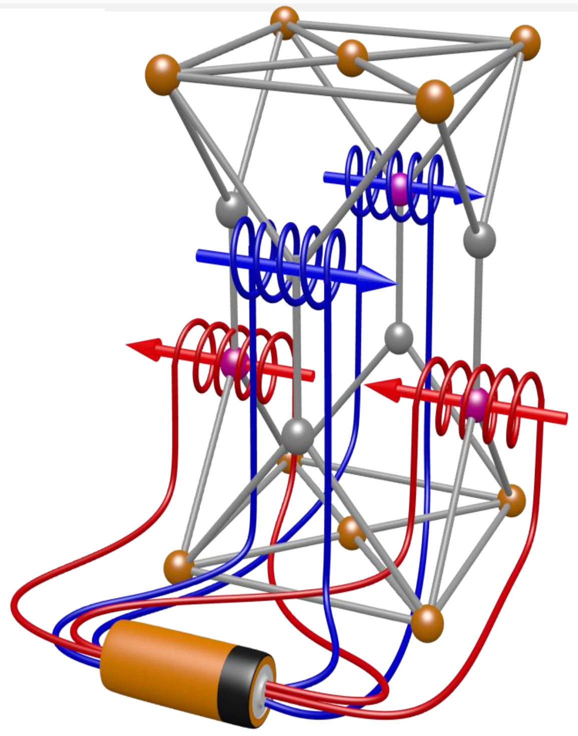
- spin order in direct-space
- net magnetization
- spin order in recip.-space

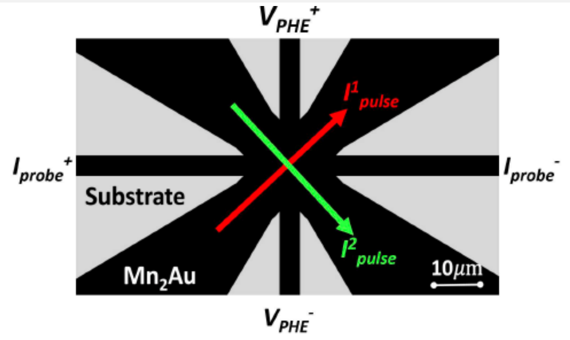


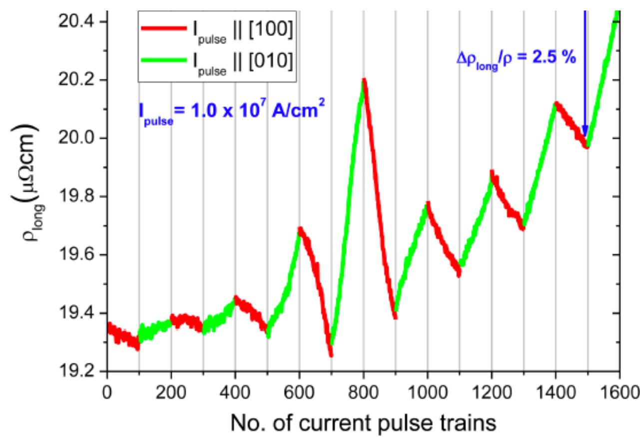
- Reading: Giant (tunneling) magnetoresistance
- Writing: Spin transfer torque

Antiferromagnetic

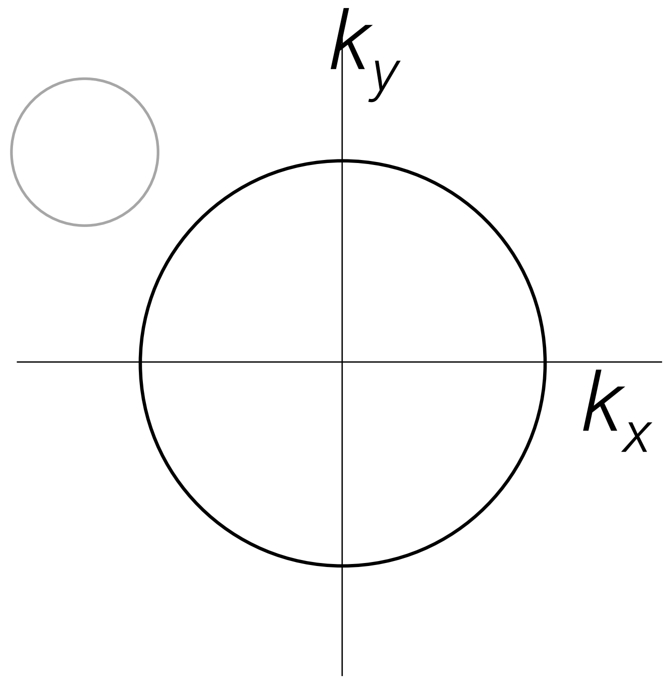








- spin order in direct-space
- no net magnetization
- no spin order in recip.-space



The problem

✓ no stray field capacity limit

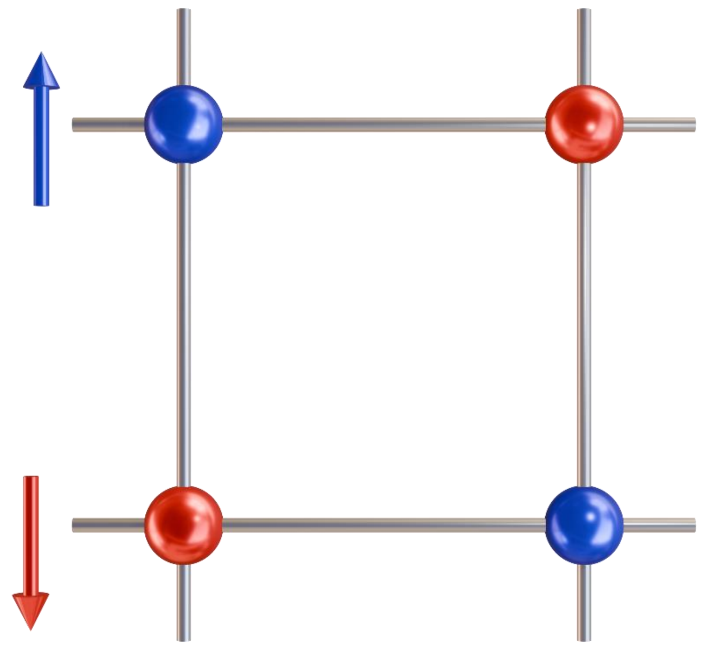
✓ THz speed

✗ Weak relativistic signals

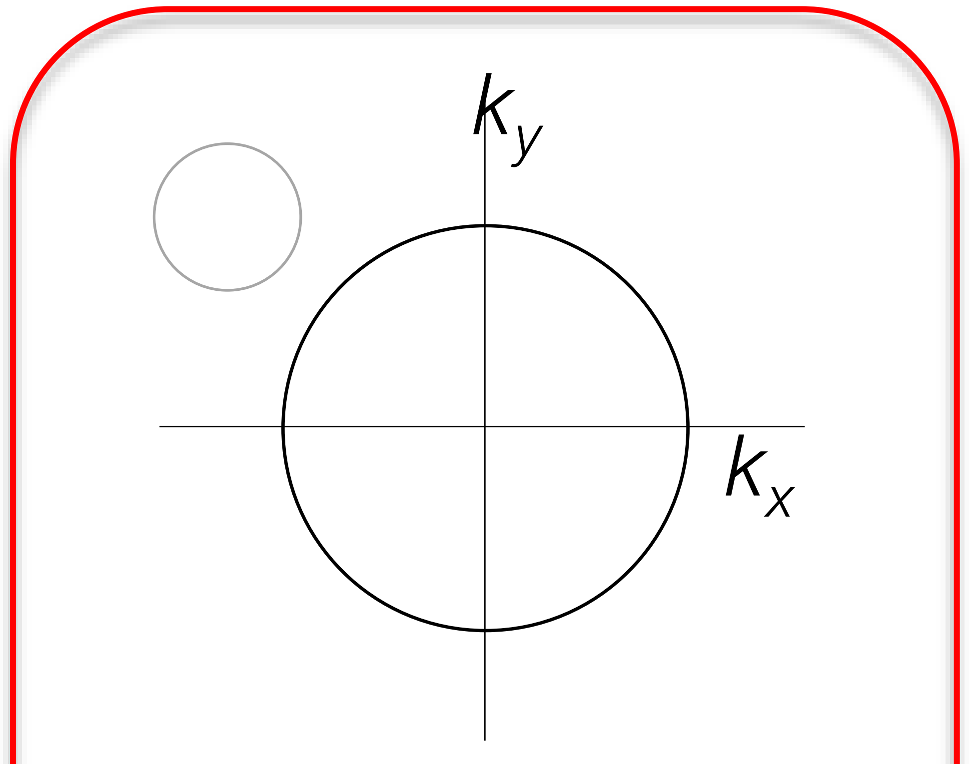
Antiferromagnetic spintronics circumvents the problem exploiting spin-orbit coupling

What is the possible solution?

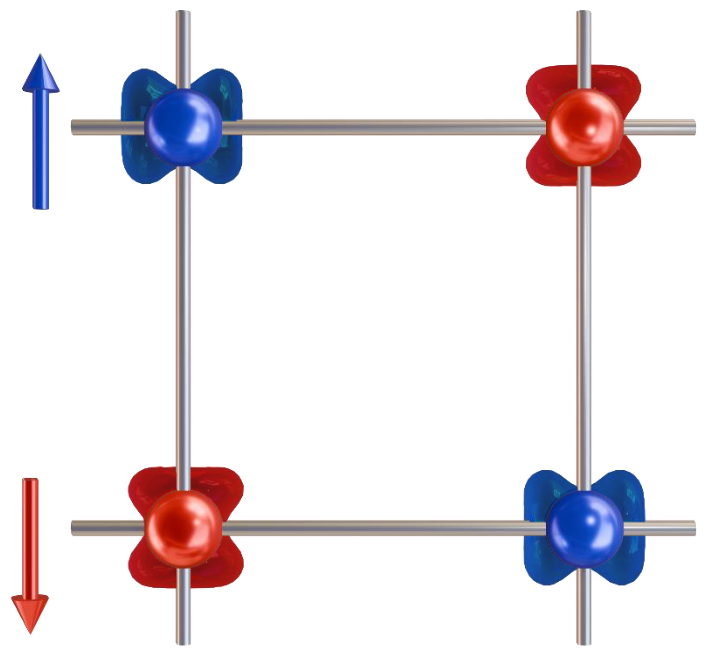
Antiferromagnetic



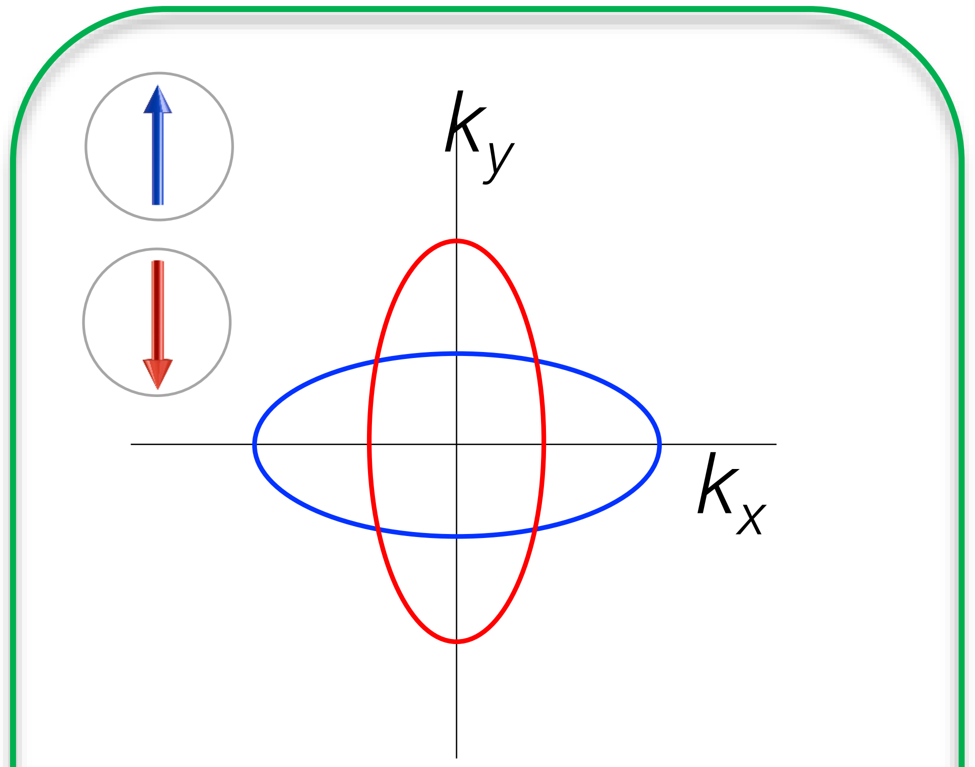
- spin order in direct-space
- no net magnetization
- no spin order in recip.-space



The problem

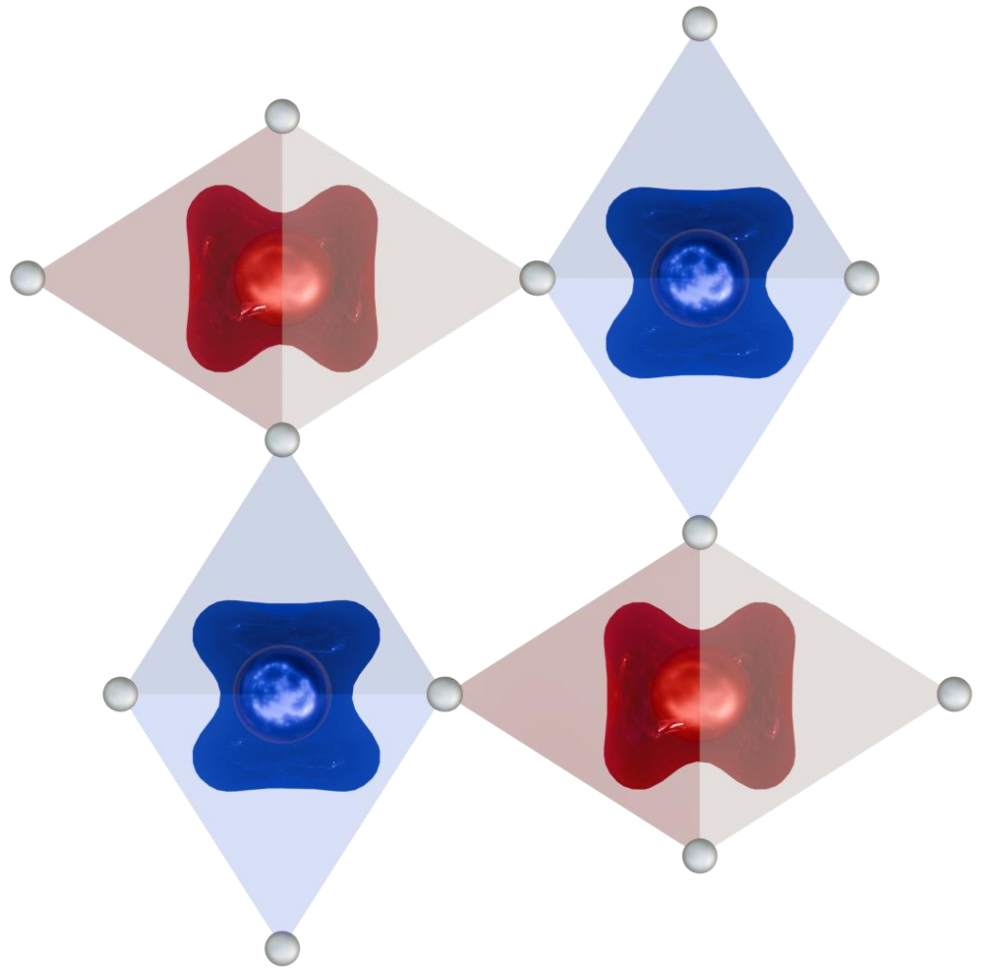


- spin order in direct-space
- no net magnetization
- spin order in recip.-space (fully compensated)

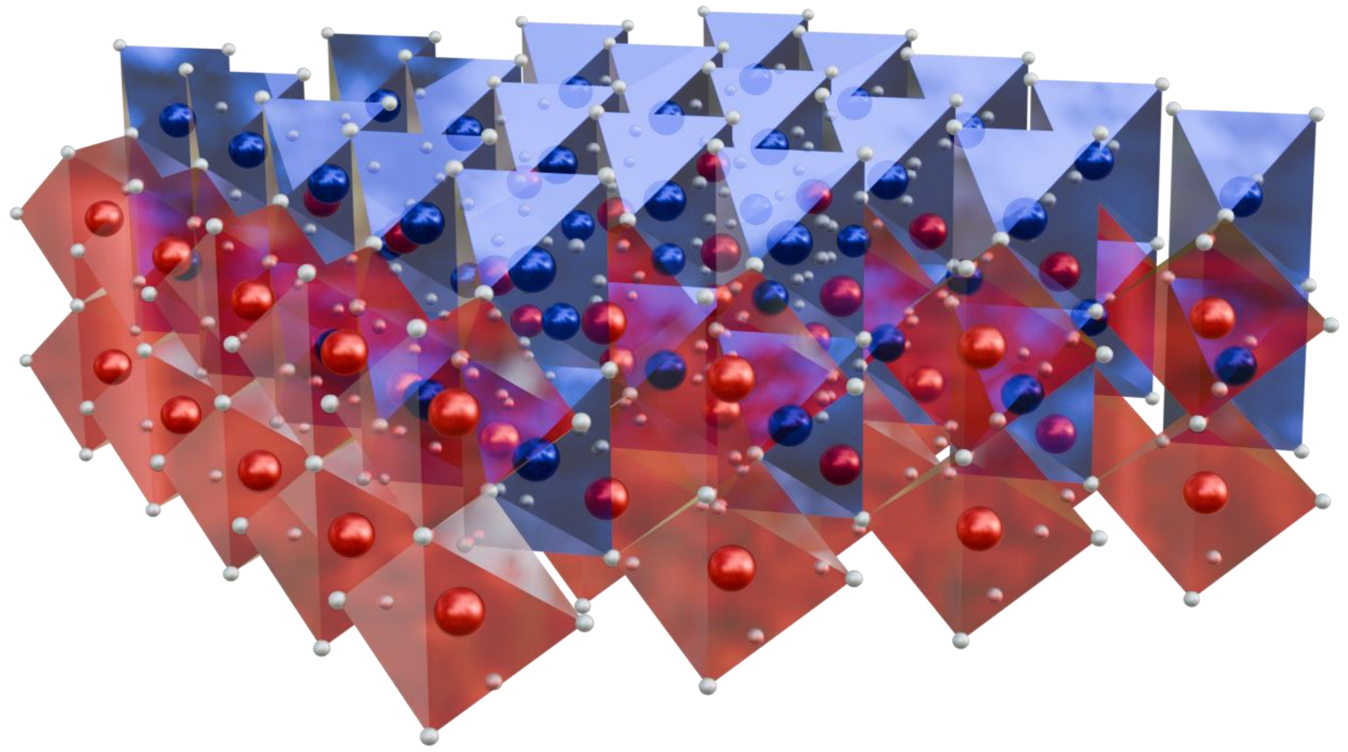


The solution

T-symmetry breaking d-wave spin polarization and anomalous Hall effect in compensated collinear rutile magnet RuO_2



RuO_2

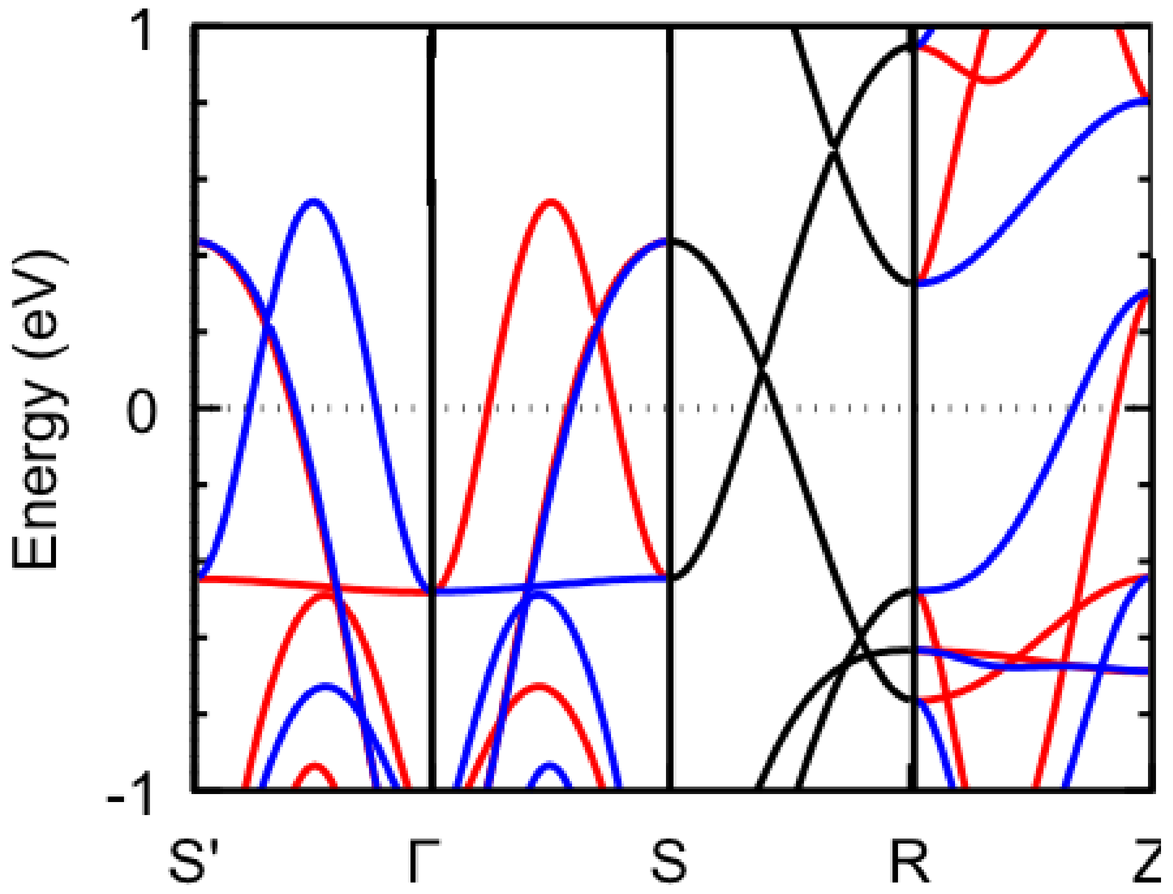


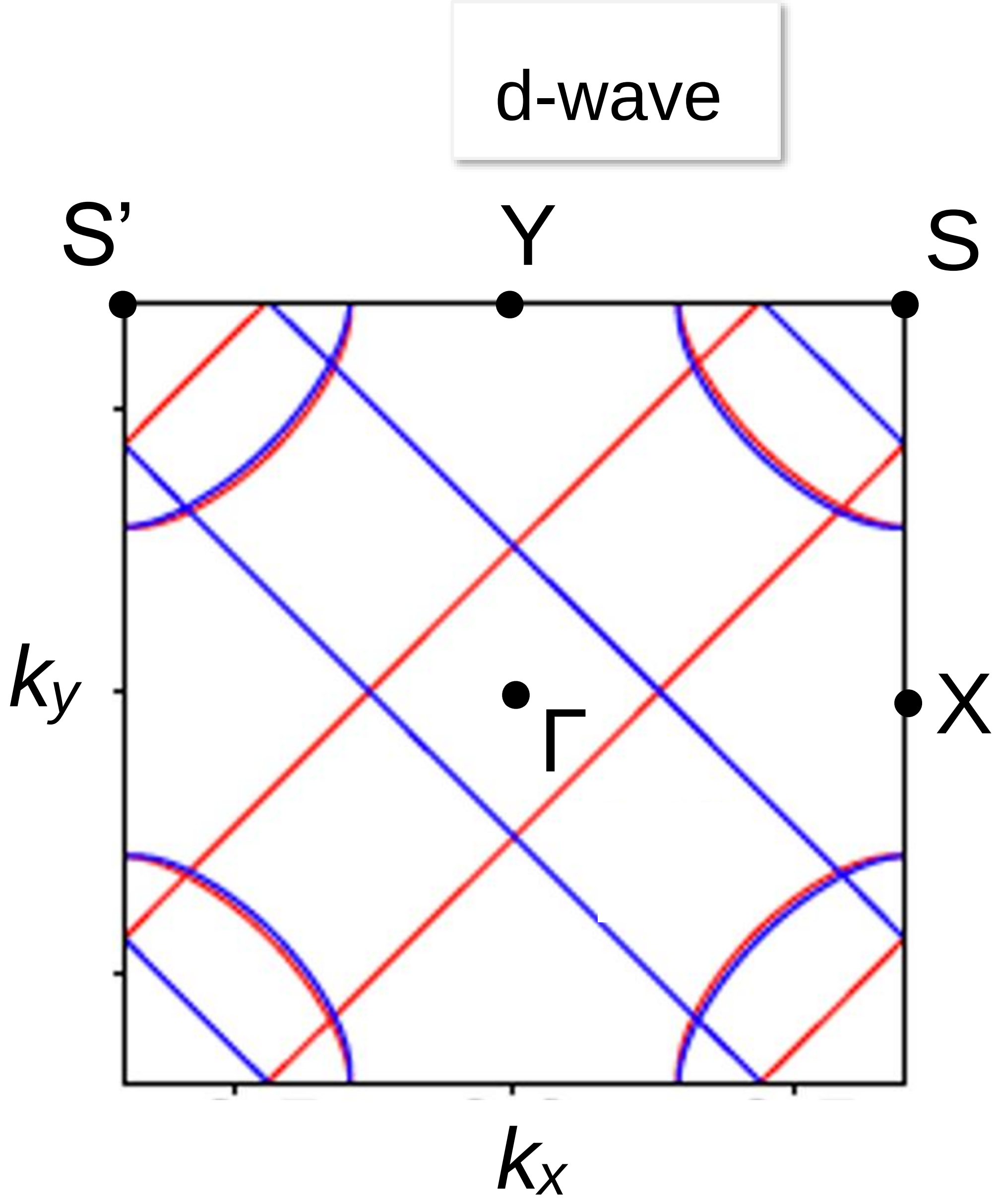
ScienceAdvances 6, eaaz8809 (2020)
Šmejkal, González-Hernández, Jungwirth, Sinova

DFT in metallic room-T RuO_2:

- Non-relativistic spin-splitting on eV-scale comparable to ferromagnets

- Anomalous Hall effect comparable to ferromagnets experimentally confirmed





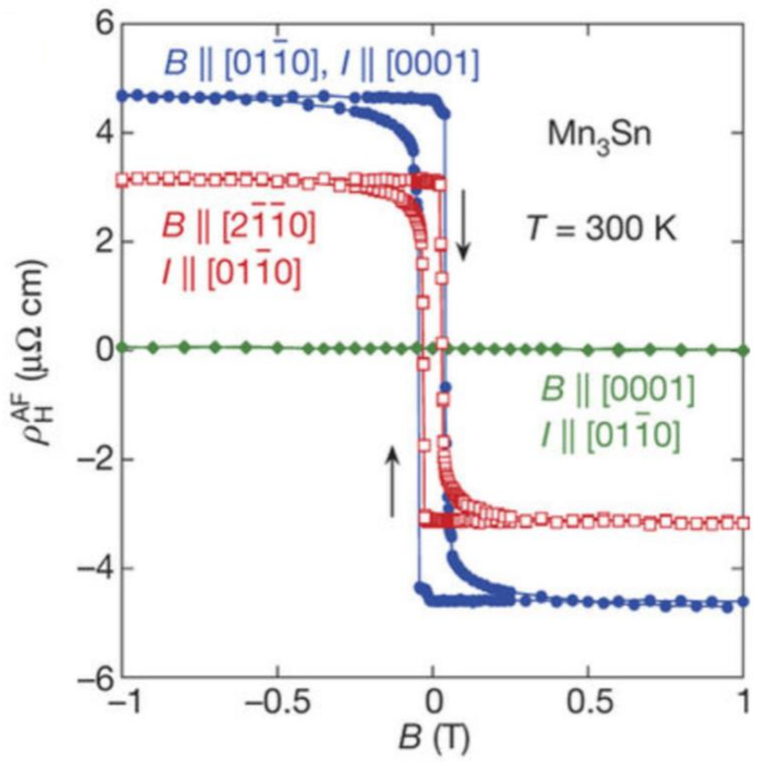
Anomalous Hall effect

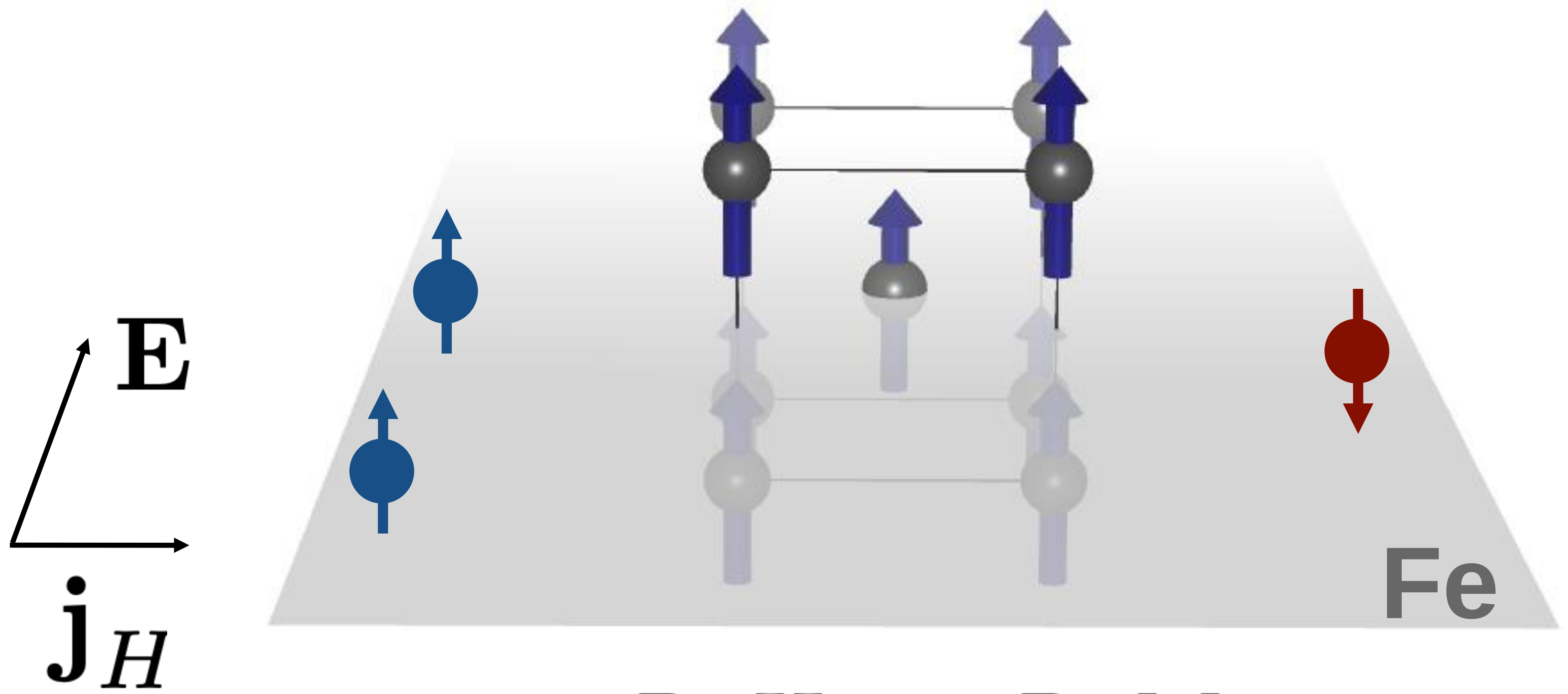
$$\mathbf{j}_{Hall} = \mathbf{h} \times \mathbf{E}$$ **Odd in time axial vector (Onsager relations)**

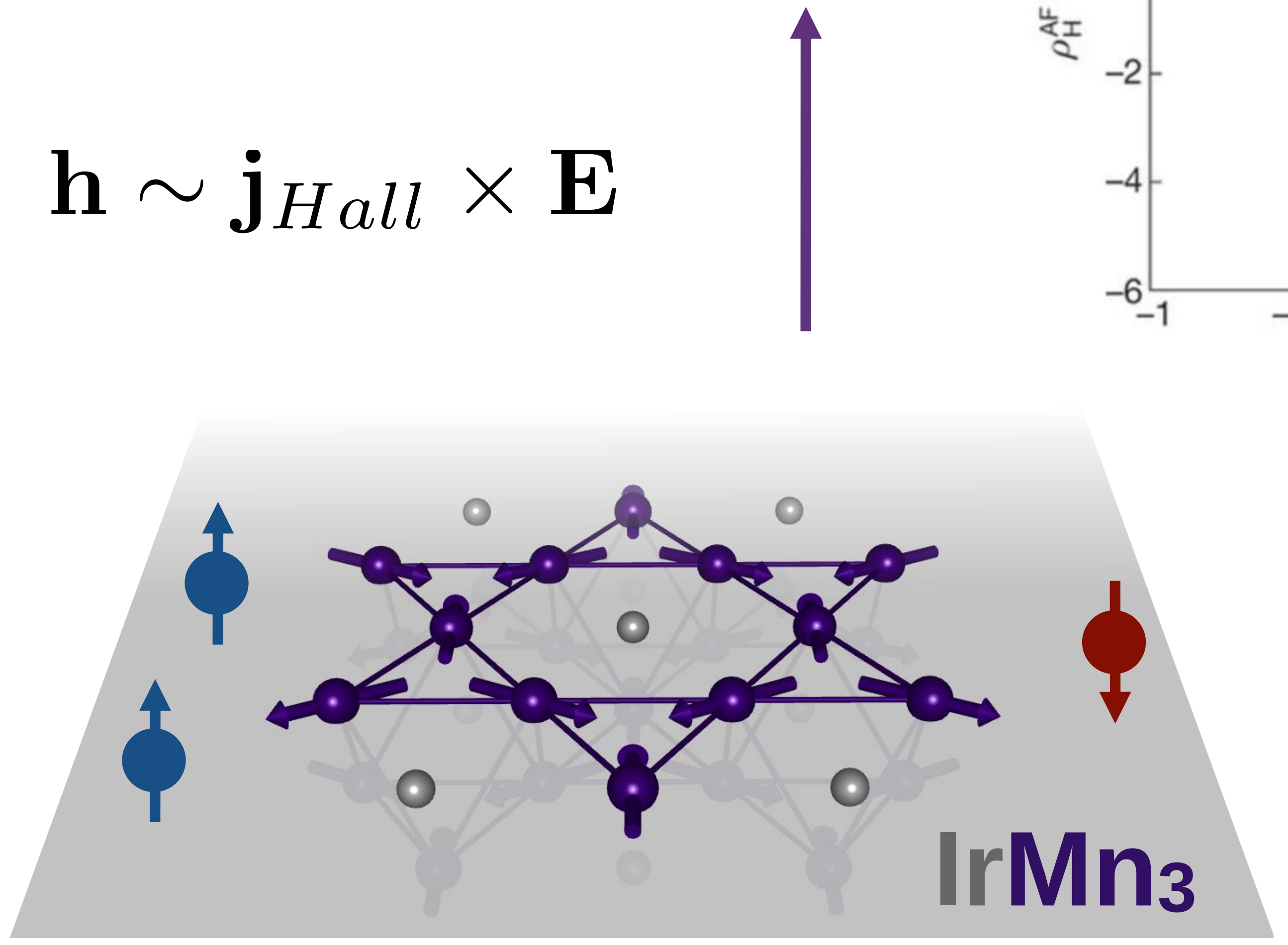
Hall vector $\mathbf{h} = (\sigma_{zy}, \sigma_{xz}, \sigma_{yx})$

For **M** along high symmetry axis
h is parallel to **M**

$\mathbf{h} \sim \mathbf{j}_{Hall} \times \mathbf{E}$







$$\rho_H = R_0 H_\perp + R_s M_\perp$$

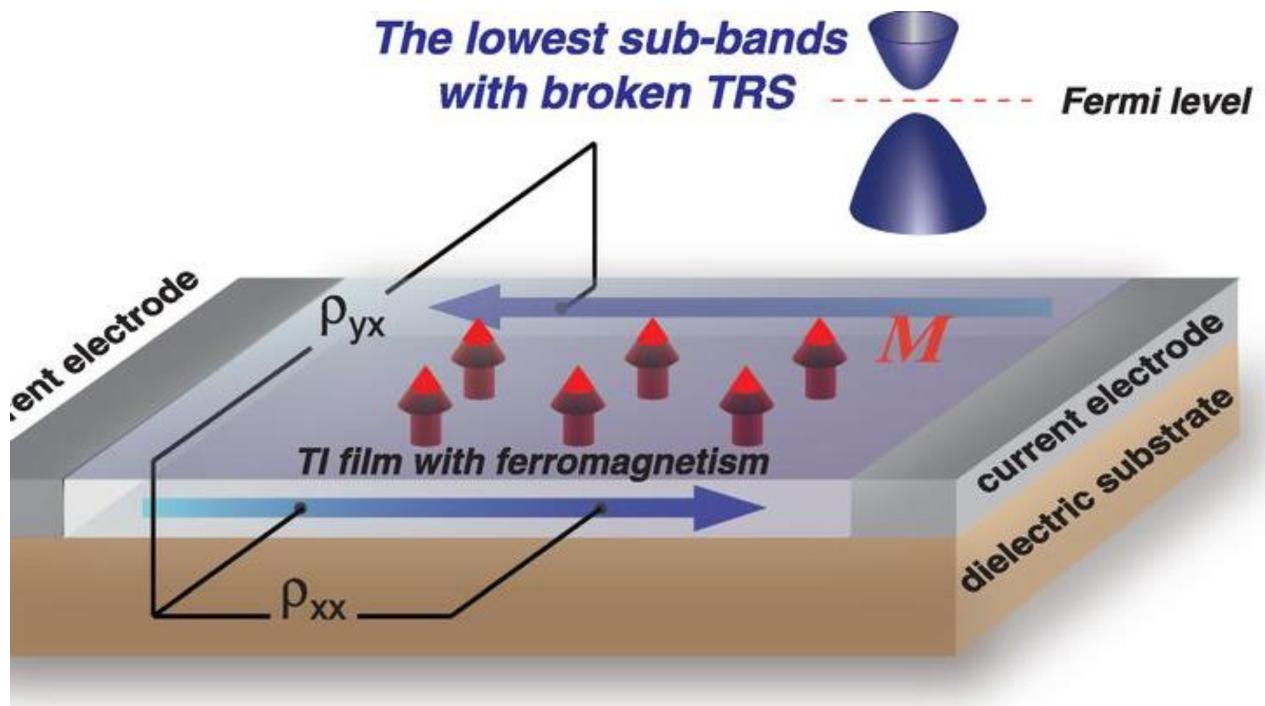
$$\rho_H = R_0 H_\perp + R_s M_\perp + \rho_{AF-H}$$

Hall, Phill.Mag. (1881)
Nagaosa, JS, et al, RMP (2010)

$\rho_{AF-H} \propto h_\perp$

Hua Chen et al., PRL (2014)
Nakatsuji et al., Nature (2015)
Nayak et al., Sci. Adv. (2016)

Genealogy of Hall effects



2013 Quantum anomalous Hall in topological insulators

1988 Haldane: quantum Hall effect **without Landau levels**

Spontaneous Hall effect in collinear antiferromagnetism?

2015 Anomalous Hall effect in non collinear antiferromagnets **without magnetization**

Nakatsuji, Nature (2015)

Felser and Parkin, Sci.Adv.(2016

2010 without dipolar-magnetic order

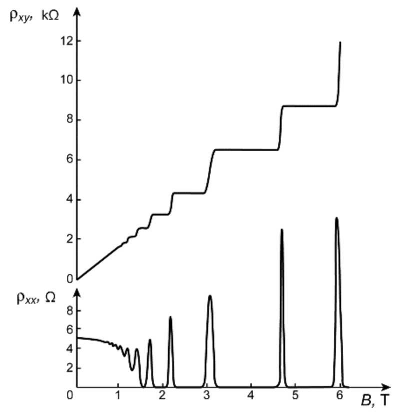
Machida, Nature (2010)

2002 Berry curvature - **topological properties of wave functions**

Jungwith et al. PRL (2002), Nagaosa et al., PRL (2002)

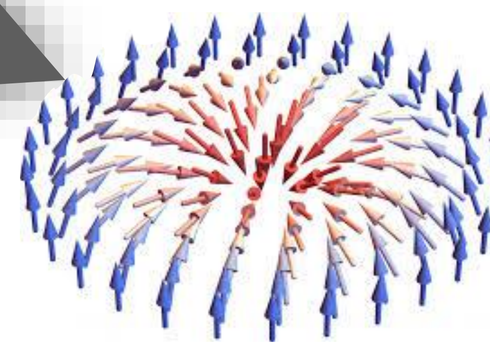
1879 Hall effect from field
1881 Hall effect from magnetisation

1980 Quantum Hall effect



1955+ Role of spin-orbit coupled impurities
1953/58+ Kohn-Luttinger

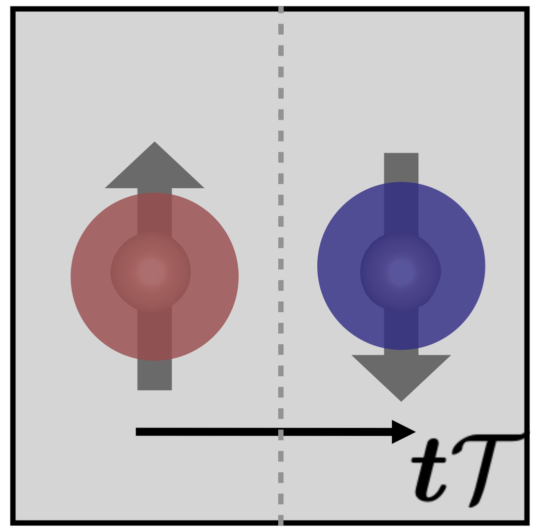
1996 “Topological” Hall effect **without spin-orbit coupling**



Microscopically: spin-polarisation and spin-orbit coupling

Transposing translational + time

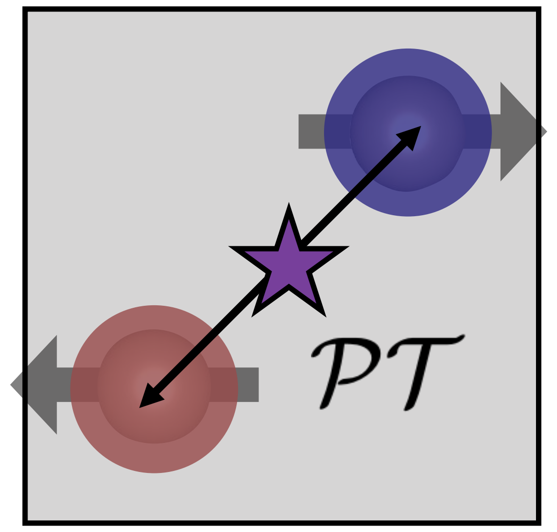
$$\vec{L} = \vec{M}_1 - \vec{M}_2$$



$$\boldsymbol{t}\mathcal{T}\vec{L} = \vec{L}$$

$$\boldsymbol{t}\mathcal{T}\vec{j}_{Hall} = -\vec{j}_{Hall} \;\; \Rightarrow \vec{j}_{Hall} = 0 \;\; \text{no AHE}$$

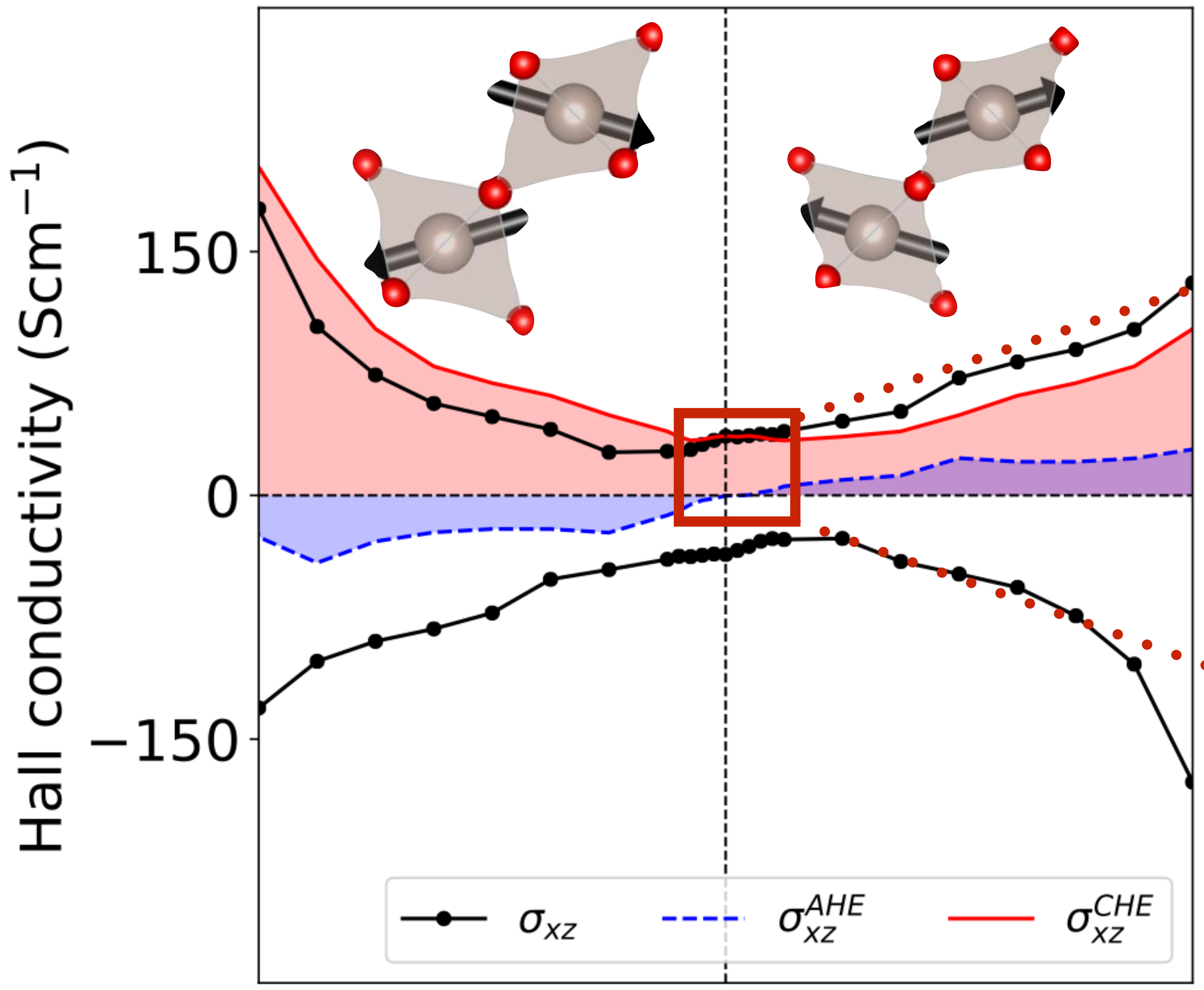
Transposing inversion + time

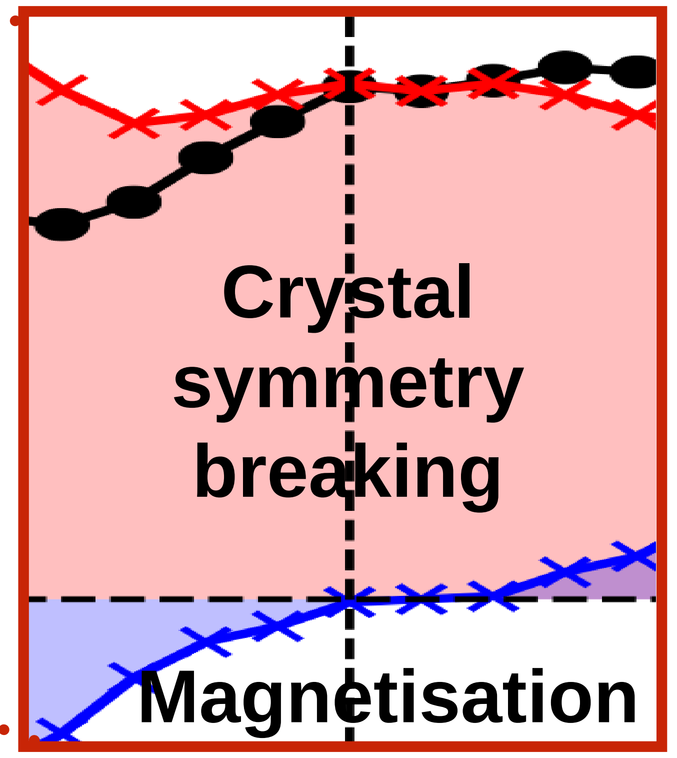


$$\mathcal{PT}\vec{L} = \vec{L}$$

$$\mathcal{PT}\vec{j}_{Hall} = -\vec{j}_{Hall} \;\; \Rightarrow \vec{j}_{Hall} = 0 \;\; \text{no AHE}$$

Anomalous crystal Hall effect in RuO_2





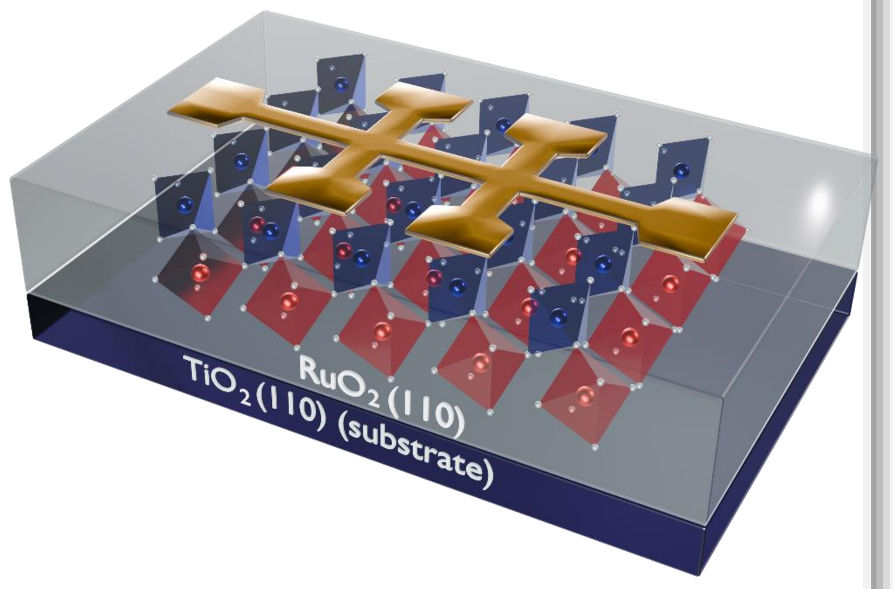
The Hall vector, not the magnetization, is the key

$$\sigma_{xy} = \frac{e^2}{h}\int_{BZ}\frac{d\mathbf{k}}{(2\pi)^3}\sum_n f(\mathbf{k})b_z^n(\mathbf{k})$$

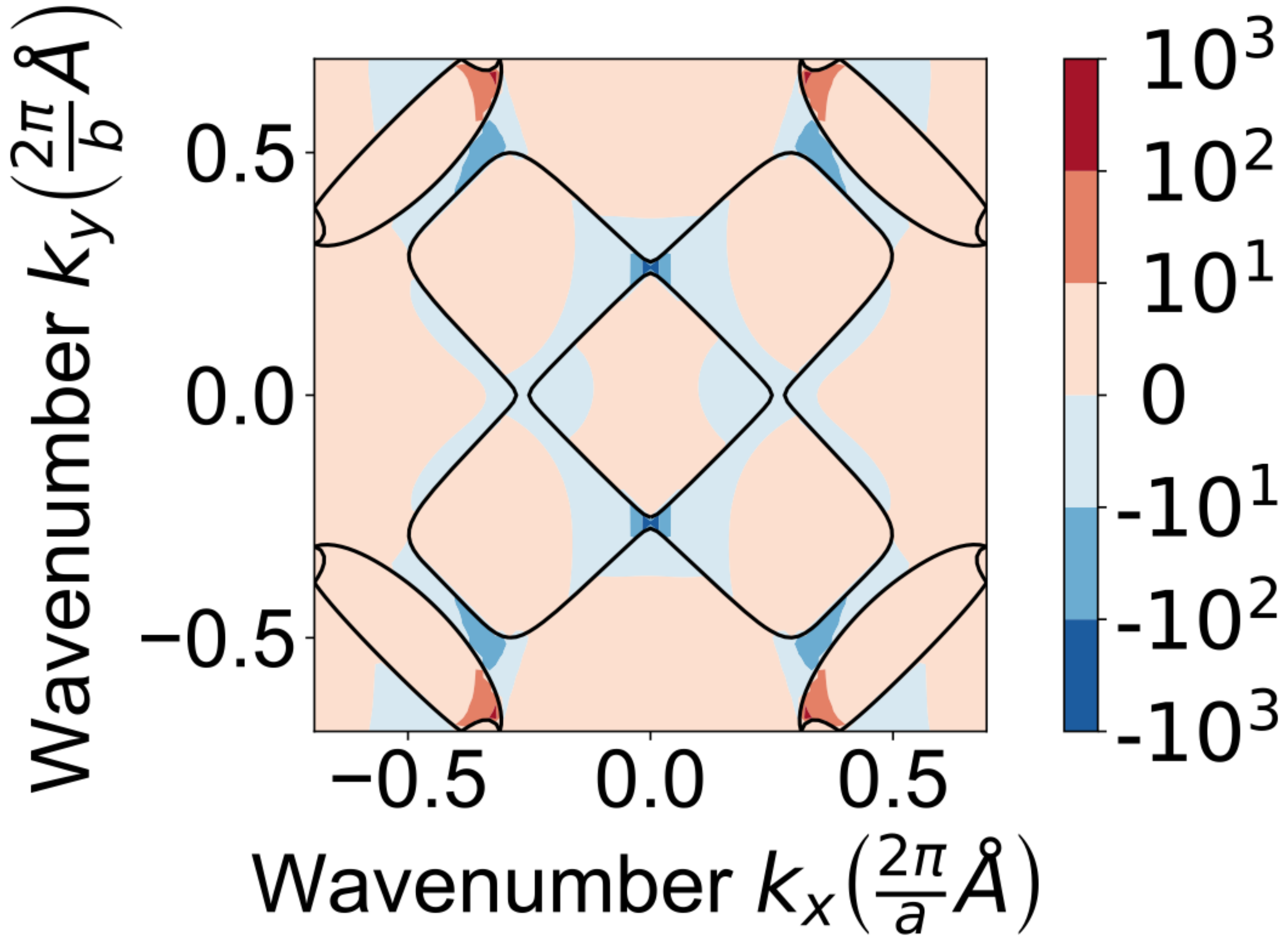
$$\sigma_{xz}^{CH} = \frac{\sigma_{xz}(\mathbf{n},\mathbf{m}) + \sigma_{xz}(\mathbf{n},\mathbf{-m})}{2}$$

$$\sigma_{xz}^{AH} = \frac{\sigma_{xz}(\mathbf{n},\mathbf{m}) - \sigma_{xz}(\mathbf{n},\mathbf{-m})}{2}$$

$$\sigma_{xz}(\mathbf{n},\mathbf{m}) = -\sigma_{xz}(-\mathbf{n},\mathbf{-m})$$



$$\sigma_{xy} = \frac{e^2}{h}\int_{BZ}\frac{d\mathbf{k}}{(2\pi)^3}\sum_n f(\mathbf{k})b_z^n(\mathbf{k})$$



	Weak magnetisation 1960s	Anomalous Hall vector 2018
Microscopic mechanism	Relativistic Dzyaloshinskii–Moriya interaction	Topological Berry curvature + local magnetisation densities
Magnitude	**~0.05 μB** per unit cell	**330 S/cm**

Science Advances 6, eaaz8809 (2020)
Šmejkal, González-Hernández, Jungwirth, Sinova

Experimental observation of anomalous crystal Hall effect in RuO2

INSP/RE group
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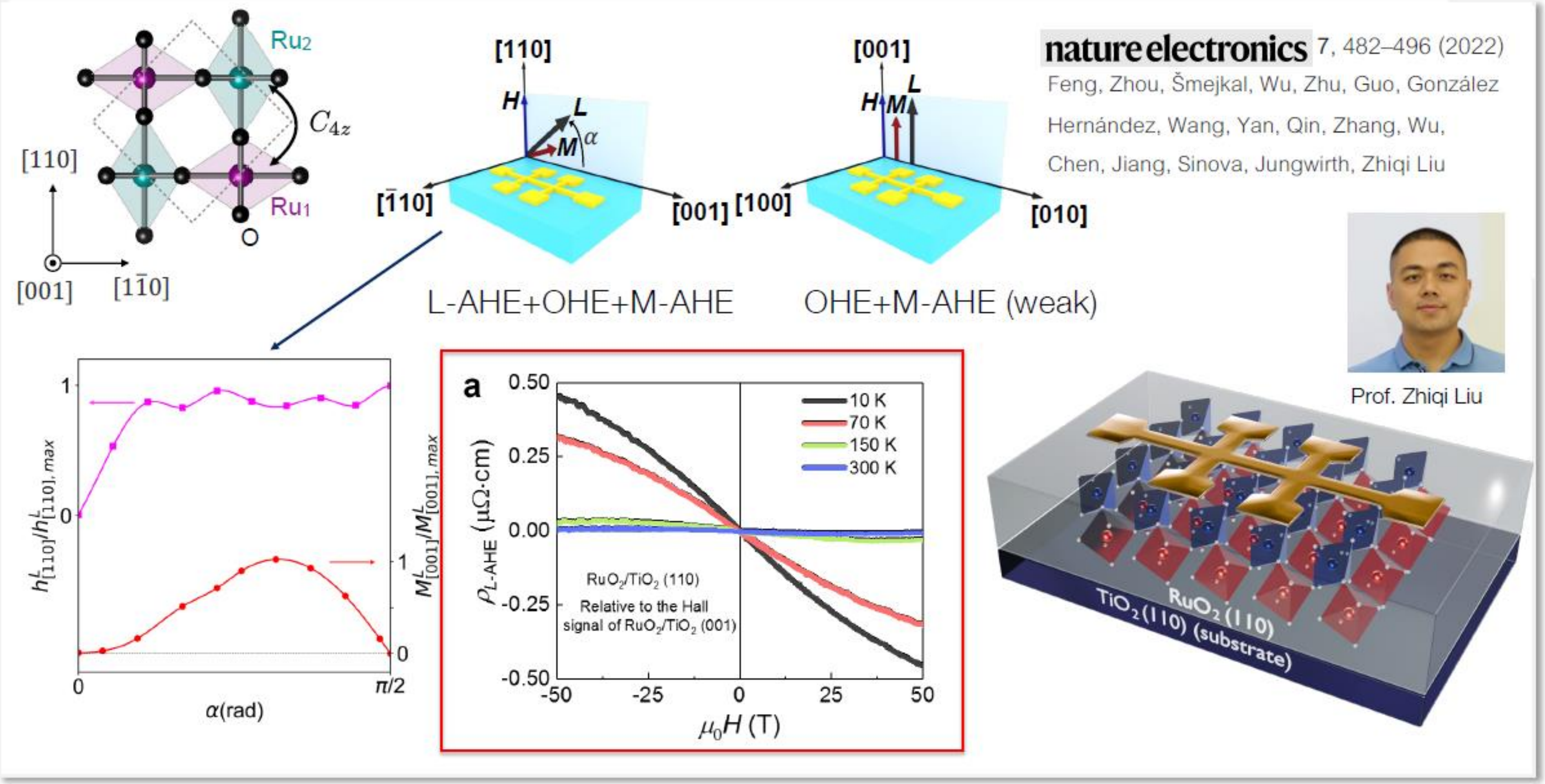
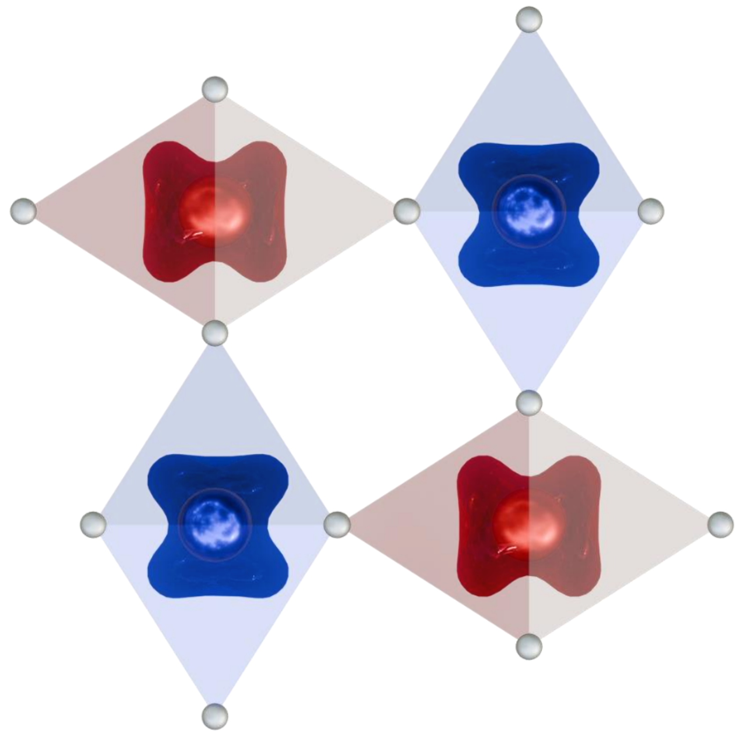


AHE in RuO_2

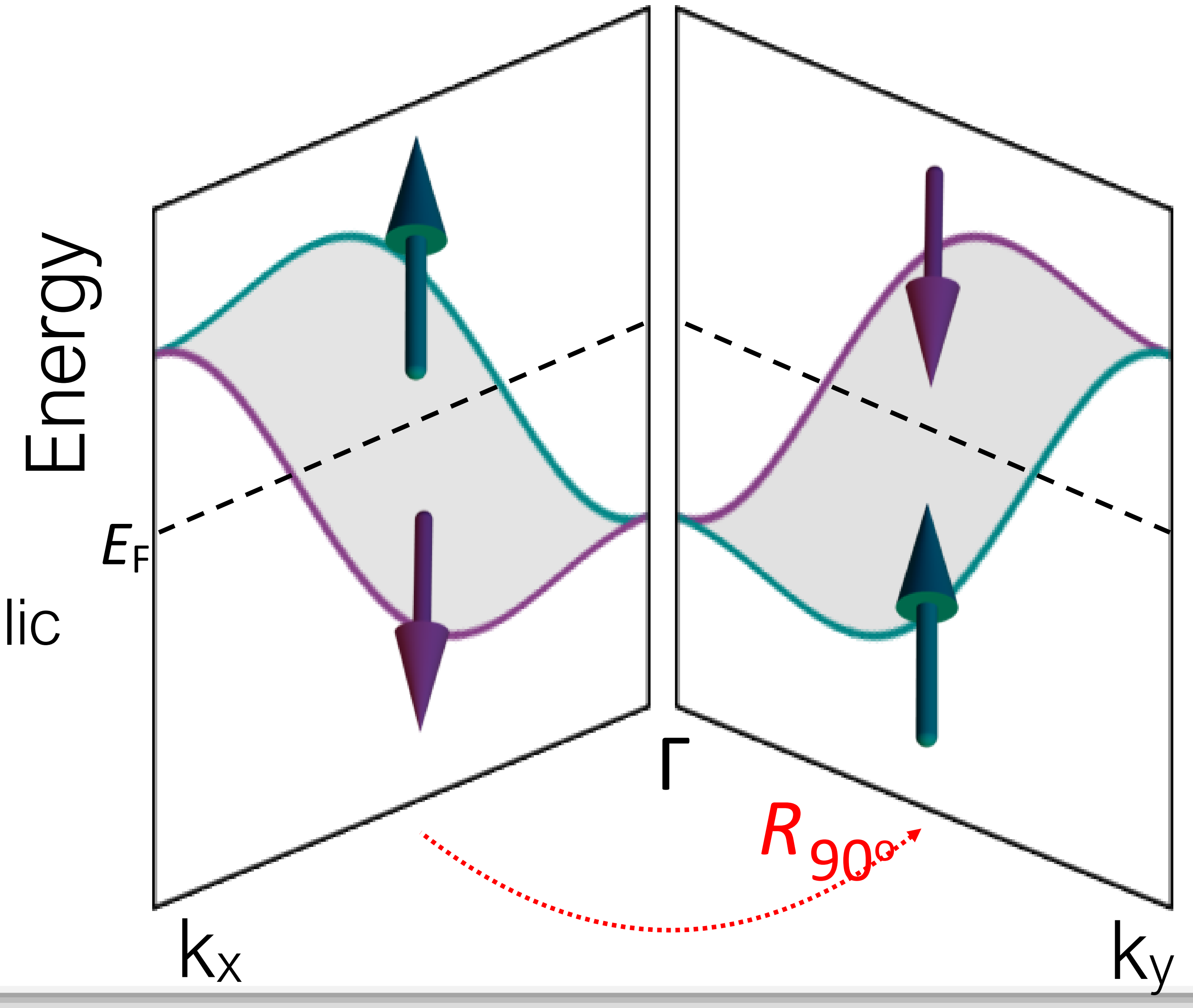
- AHE **can be turned on/off** by symmetry controlled by the reorientation of Neel vector
- Berry's phase structure is controled by the crystal symmetry
- **Band crossings** (large Berry's phase AHE) are **not accidental**, they are **imposed by the symmetry** of alternating spin-splitting
- Large AHE conductivities that require **no magnetization**
- AHE can also be **controlled by the crystal symmetry** – not only the Neel vector
- **AHE vector (current) direction is more complex** than in ferromagnets and depends on the magnetic crystal symmetry

RuO_2



Alternating spin-splitting & zero magnetization

metallic

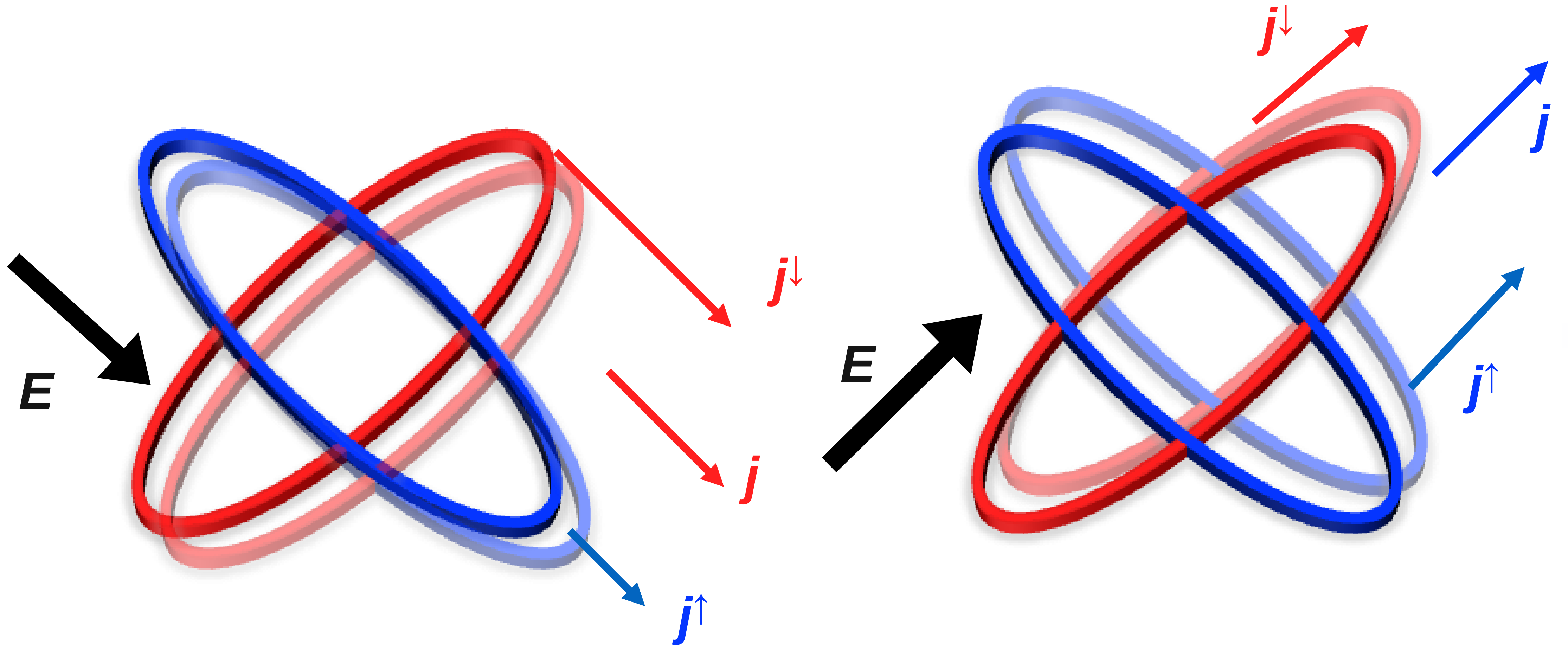


INSP/RE group
INTERDISCIPLINARY SPINTRONICS RESEARCH

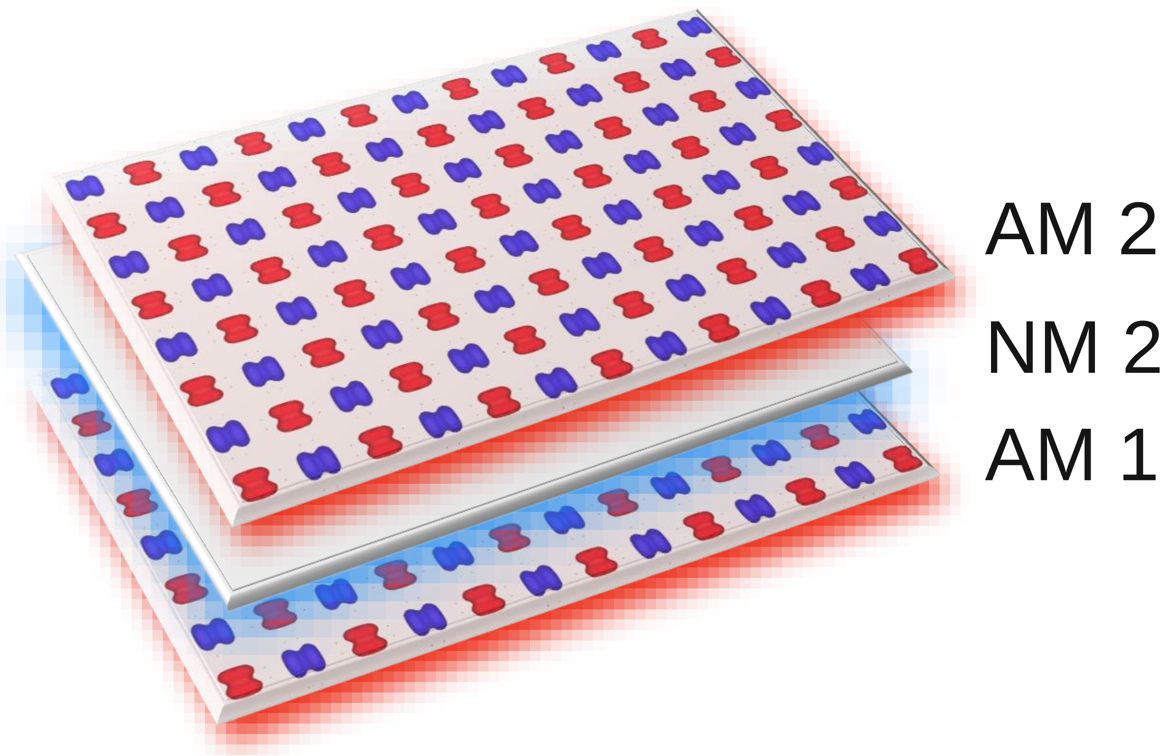
Strongly polarized current without SOC in a compensated collinear magnet

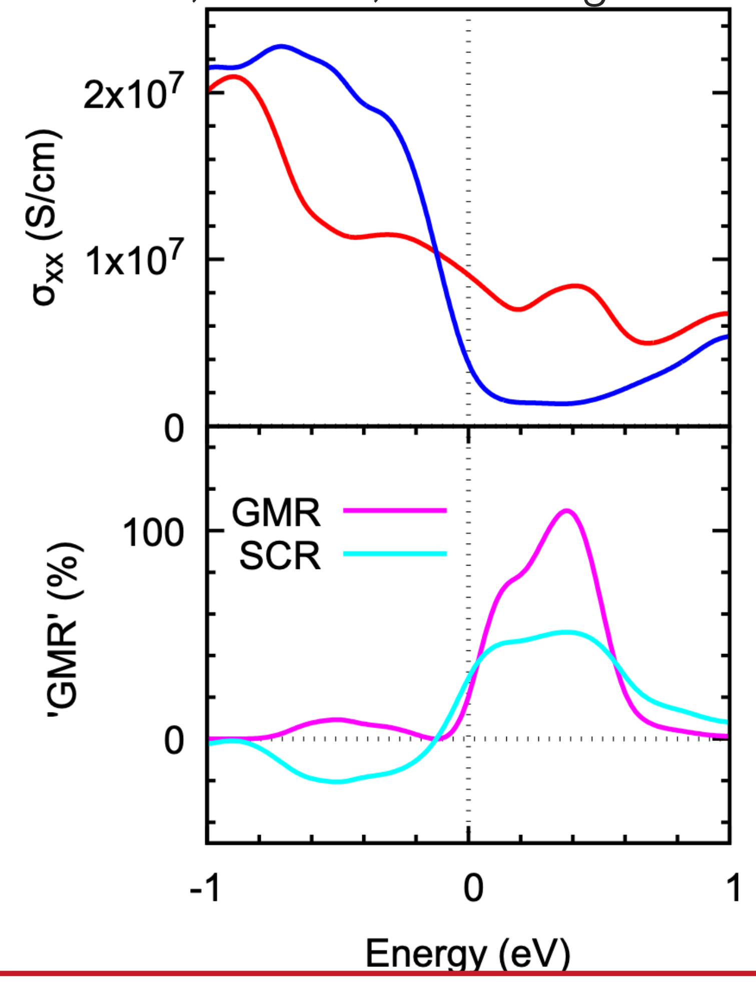
PHYSICAL REVIEW X **12**, 011028 (2022)

Šmejkal, Birk Hellenes, González-Hernández, Sinova, and Jungwirth



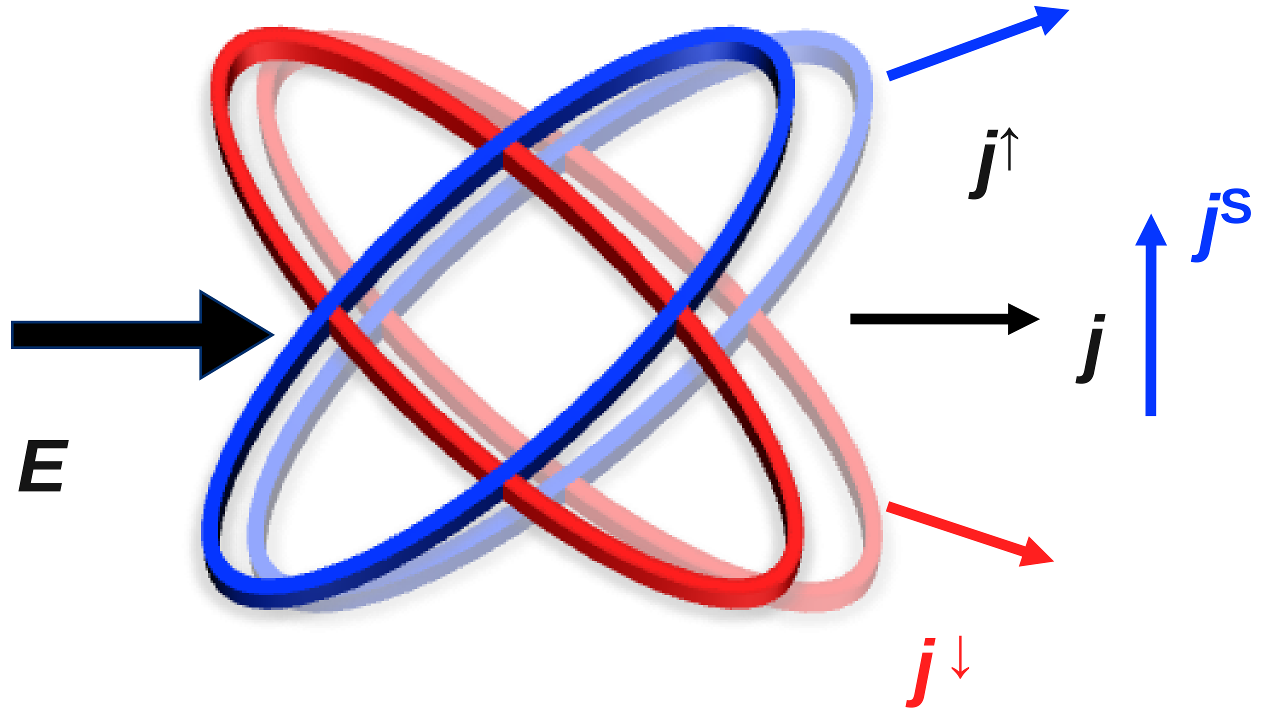
Giant magnetoresistance



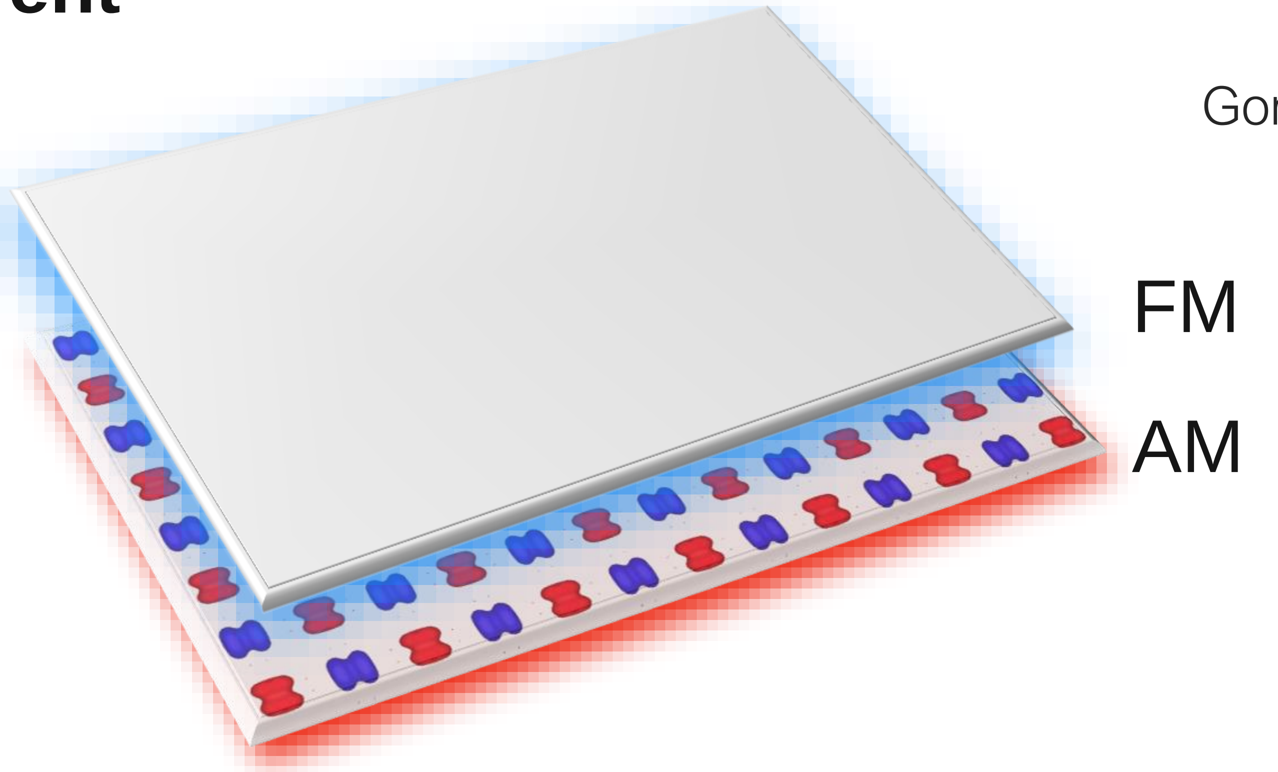


Nonrelativistic electrical spin splitter

Unconventional transverse spin-current



Spin-splitter torque



PHYSICAL REVIEW LETTERS **126**, 127701 (2021)

González-Hernández, Šmejkal, Výborný, Yahagi, Sinova, Jungwirth, Železný

SCR 34 deg >> 20 000 SHE materials

Experimental indications: RuO_2/NiFe

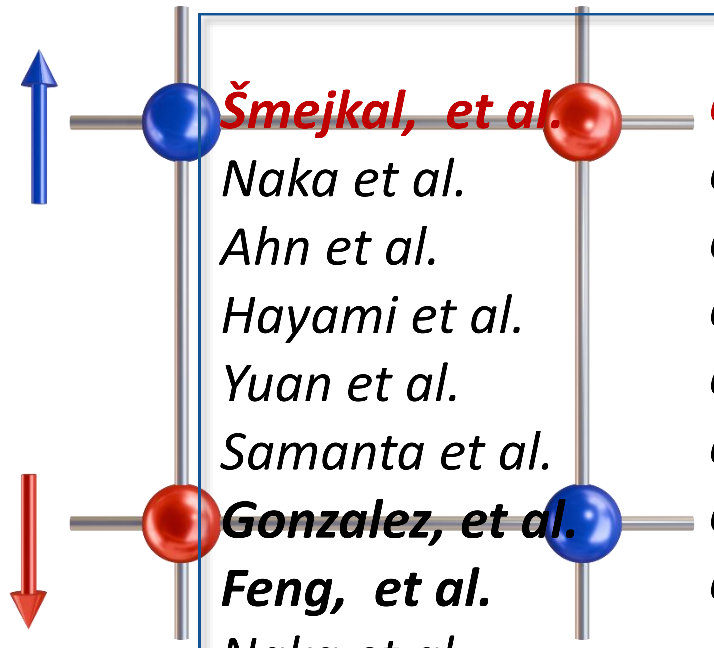
Bose, Ralph et al. arXiv: 2012.15651, Nat Elec (2022)

Bai et al. arXiv:2109.05933, PRL (2022)

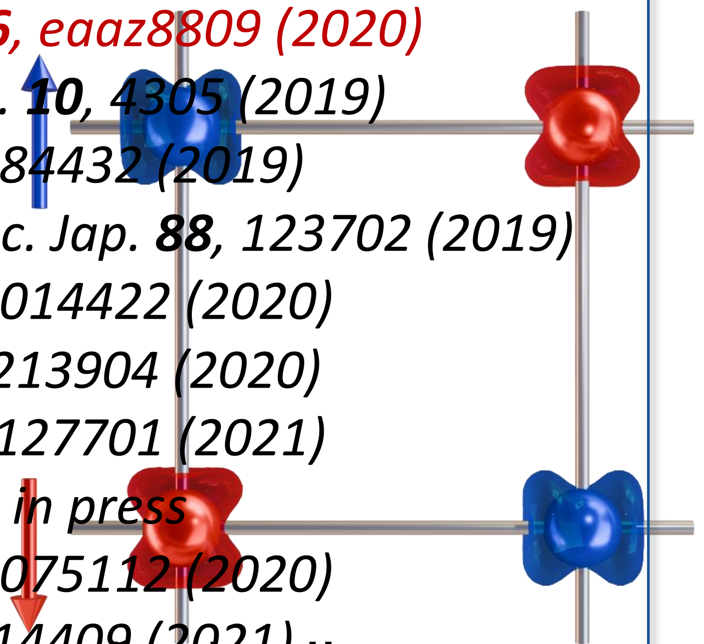
Karube et al., arXiv:2111.07487, PRL (2022)

INSP/RE group
INTERDISCIPLINARY SPINTRONICS RESEARCH

Antiferromagnetic

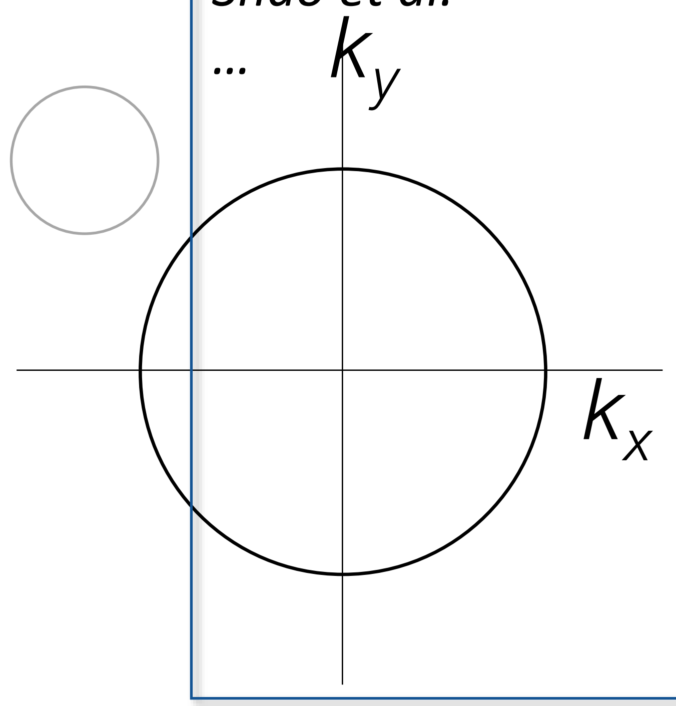


Šmejkal, et al.	*arXiv:1901.00445, Sci. Adv. **6**, eaaz8809 (2020)*
Naka et al.	*arXiv:1902.02506, Nat. Com. **10**, 4305 (2019)*
Ahn et al.	*arXiv:1902.04436, PRB **99**, 184432 (2019)*
Hayami et al.	*arXiv:1908.08680, J. Phys.Soc. Jap. **88**, 123702 (2019)*
Yuan et al.	*arXiv:1912.12689, PRB **102**, 014422 (2020)*
Samanta et al.	*arXiv:2002.05393, JAP **127**, 213904 (2020)*
Gonzalez, et al.	*arXiv:2002.07073, PRL **126**, 127701 (2021)*
Feng, et al.	*arXiv:2002.08712, Nat. Elec. in press*
Naka et al.	*arXiv:2004.04578, PRB **102**, 075112 (2020)*
Yuan et al.	*arXiv:2008.08532, PRM **5**, 014409 (2021)*
Hayami et al.	*arXiv:2008.10815, PRB **102**, 144441 (2020)*
Naka et al.	*arXiv:2011.12459, PRB **103**, 125114 (2021)*
Reichlova et al.	*arXiv:2012.15651*
Shao et al.	*arXiv:2103.09219, Nat. Com. **12**, 7061 (2021)*
…	*…*

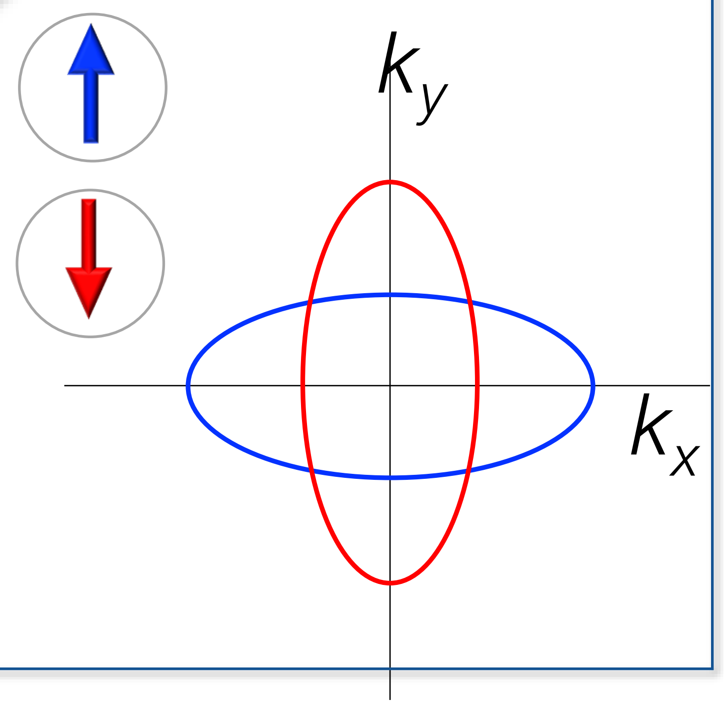


- spin order in direct-space
- no net magnetization
- no spin order in recip.-space

- spin order in direct-space
- no net magnetization
- spin order in recip.-space

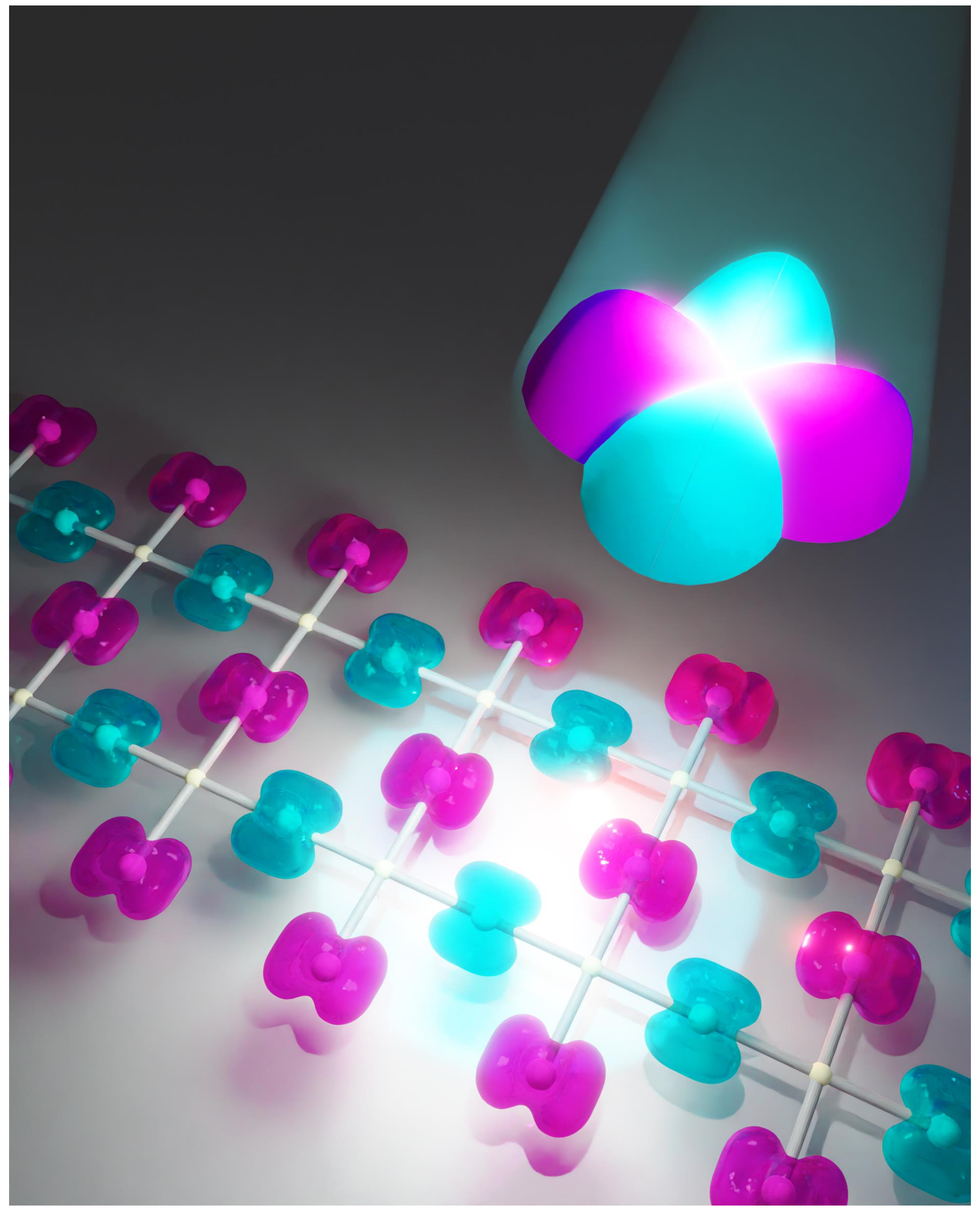


The problem



The solution

Altermagnets: 3rd distinct spin-symmetry class of collinear magnets



PHYSICAL REVIEW X **12**, 031042 (2022)

Šmejkal, Sinova, and Jungwirth

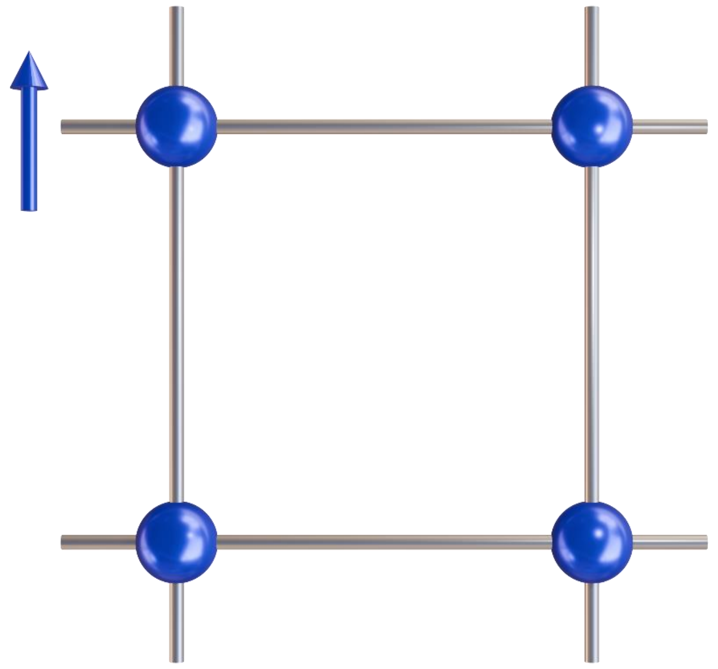
PHYSICAL REVIEW X (Perspective) **12**, 040501 (2022)

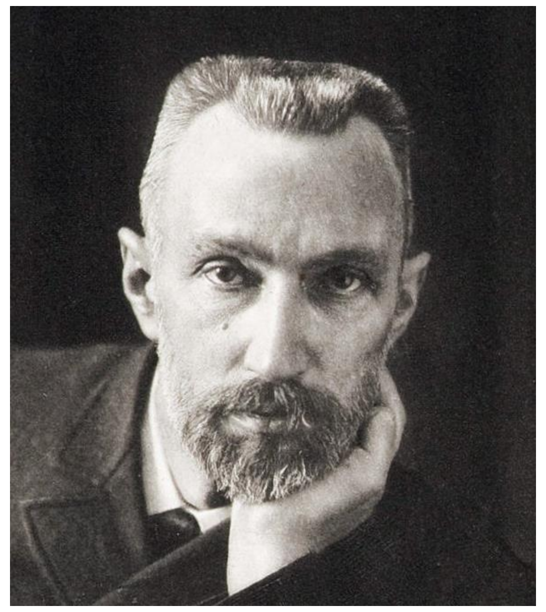
Šmejkal, Sinova, and Jungwirth

What symmetries delimits the magnetic phases?

Ferromagnetism

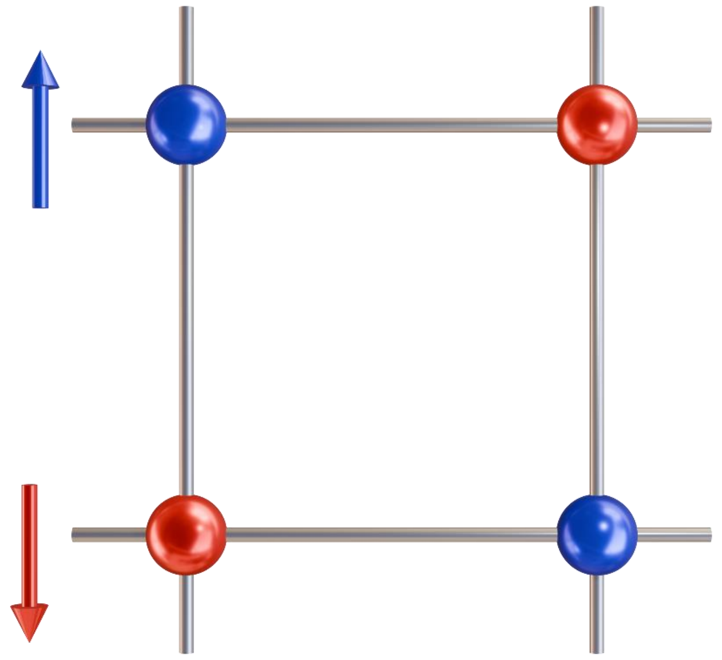
Direct space

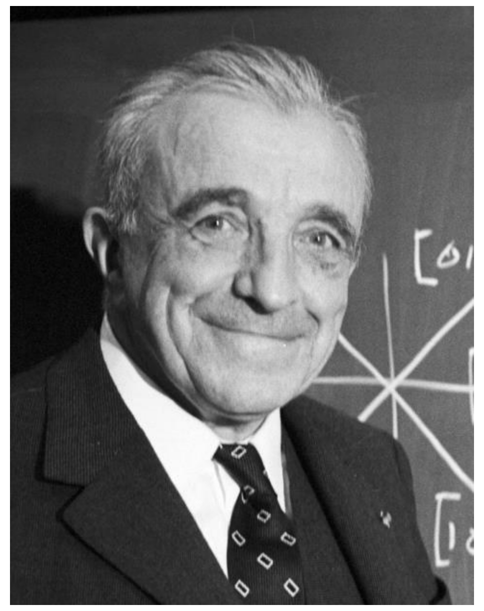




Curie, 1896

Antiferromagnetism

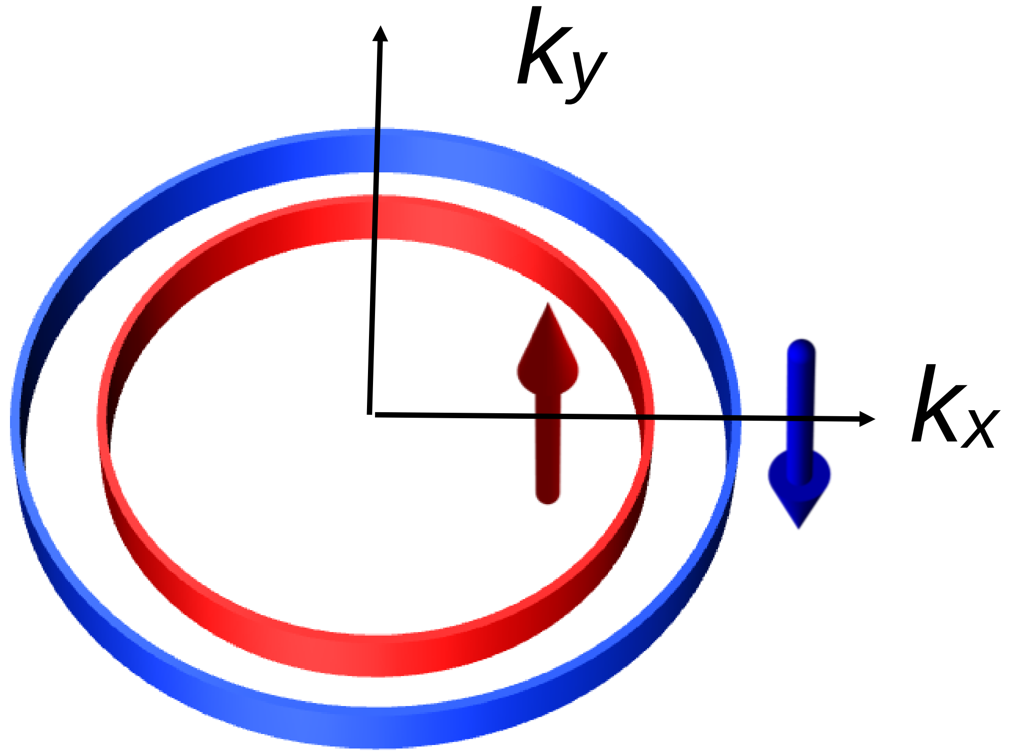


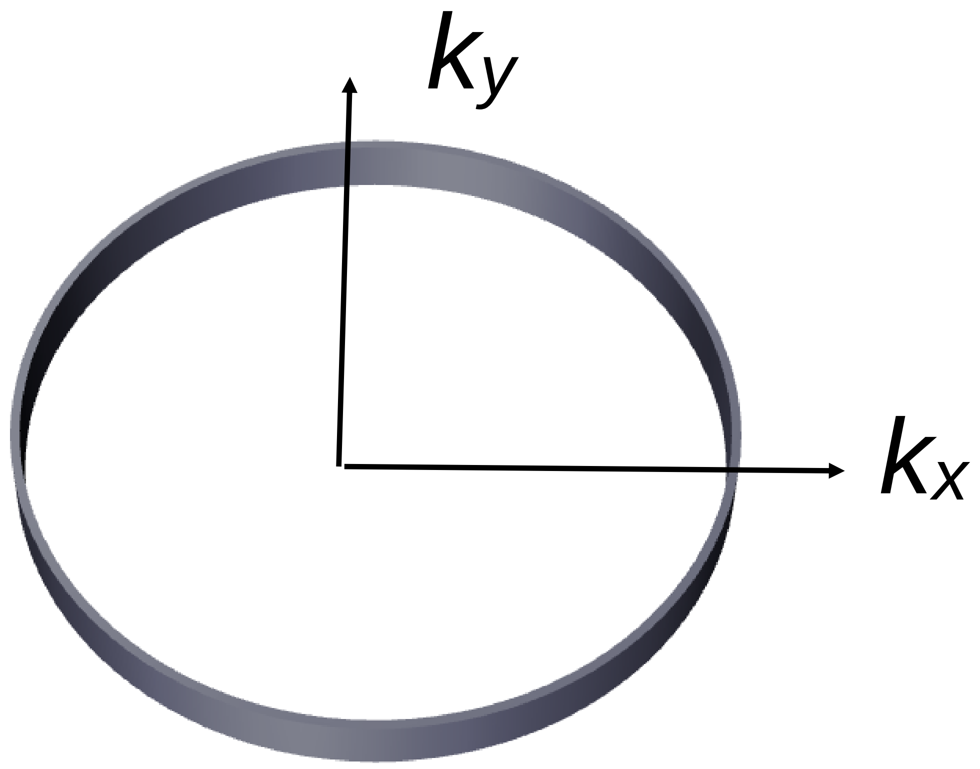


Neel, 1930

Spin order

Reciprocal space

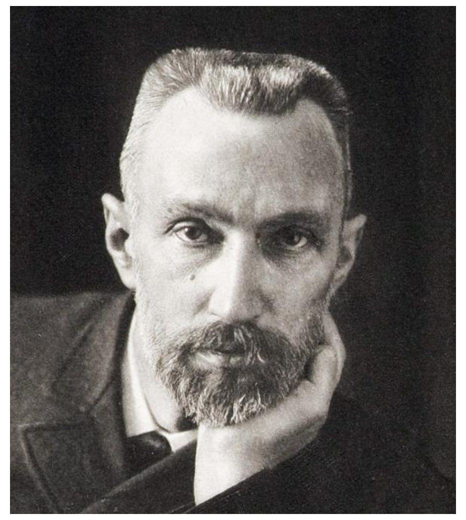


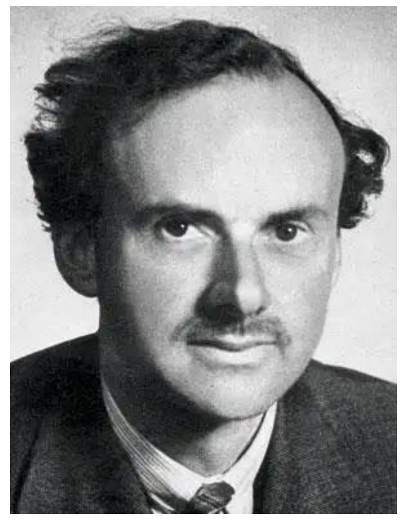


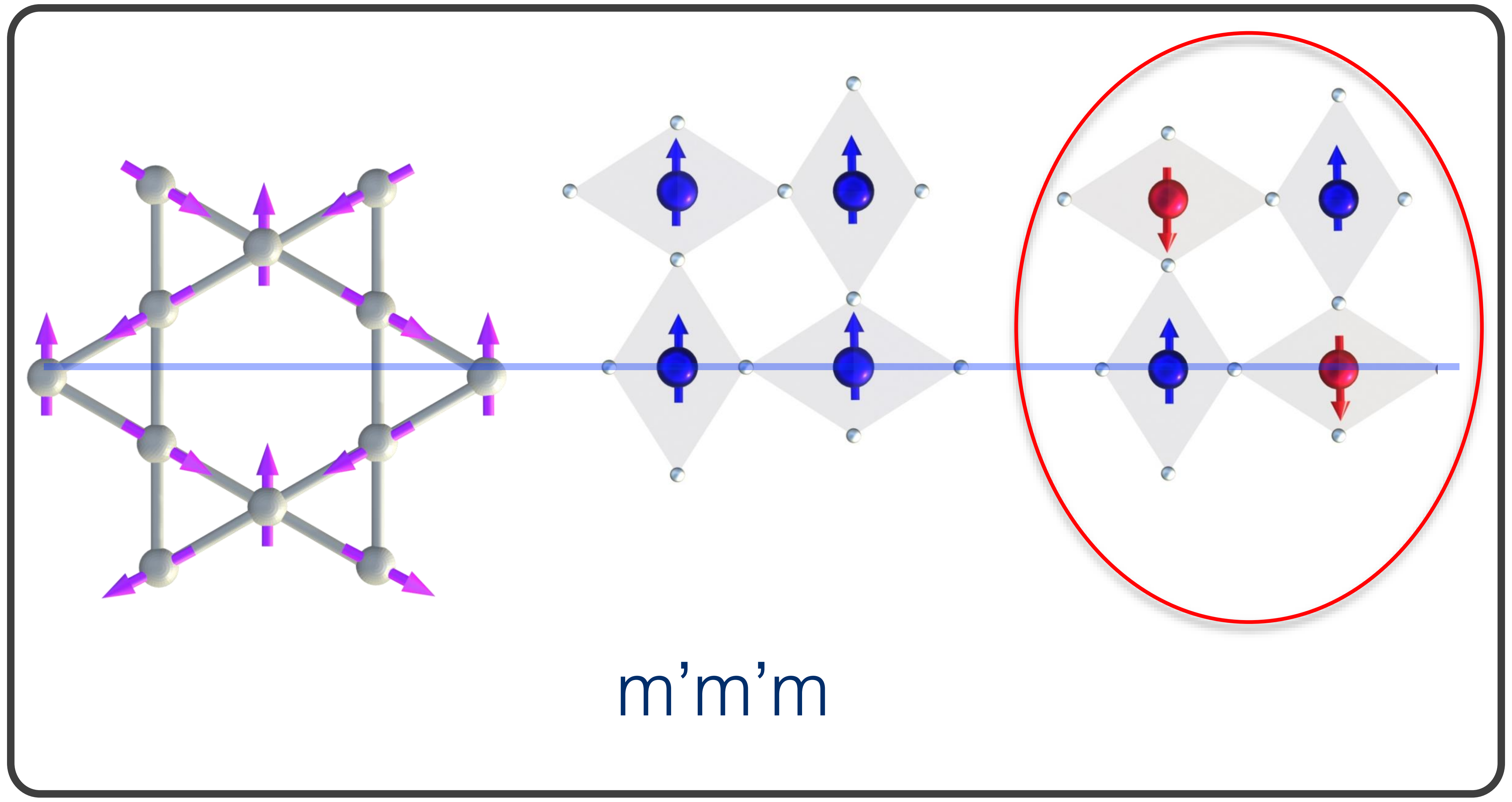
Magnetic symmetries? (122 possibilities)

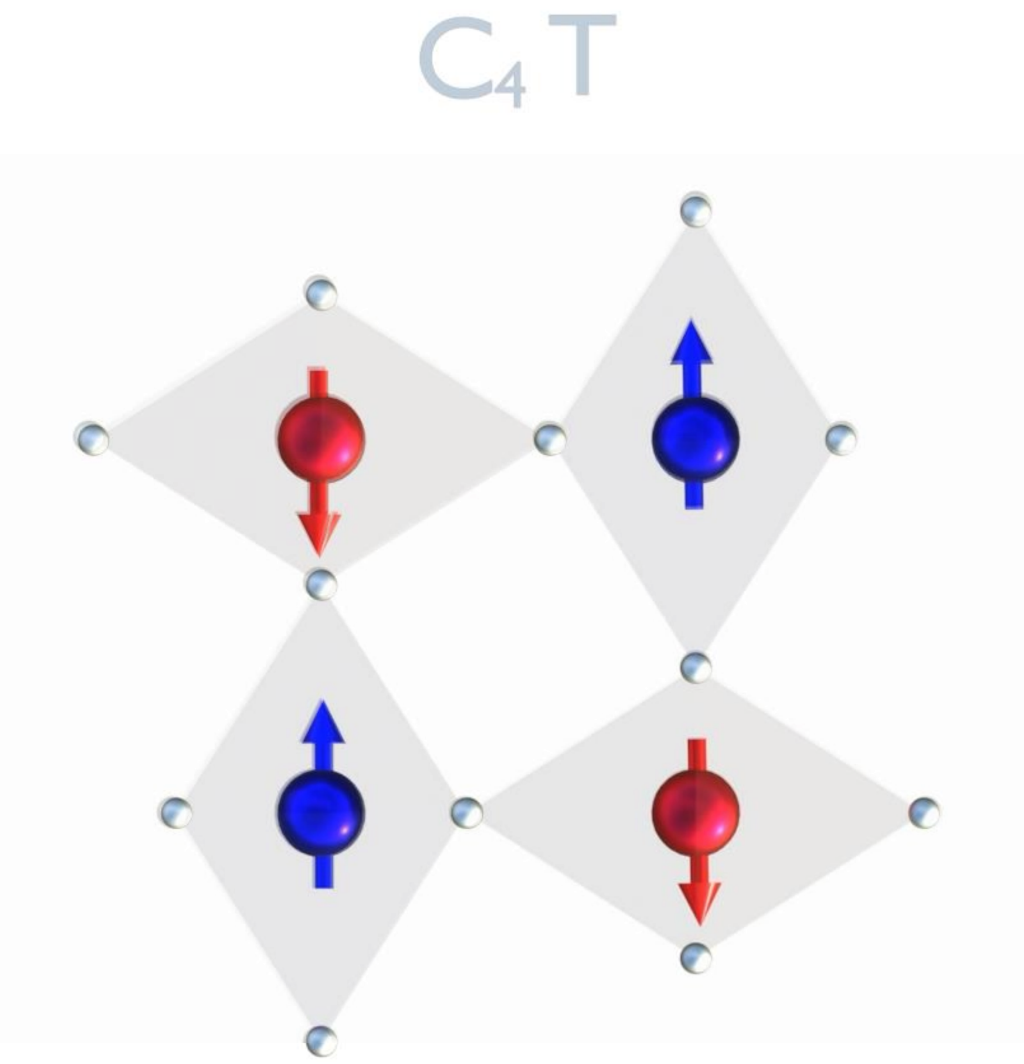
act simultaneously on spins and crystal

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

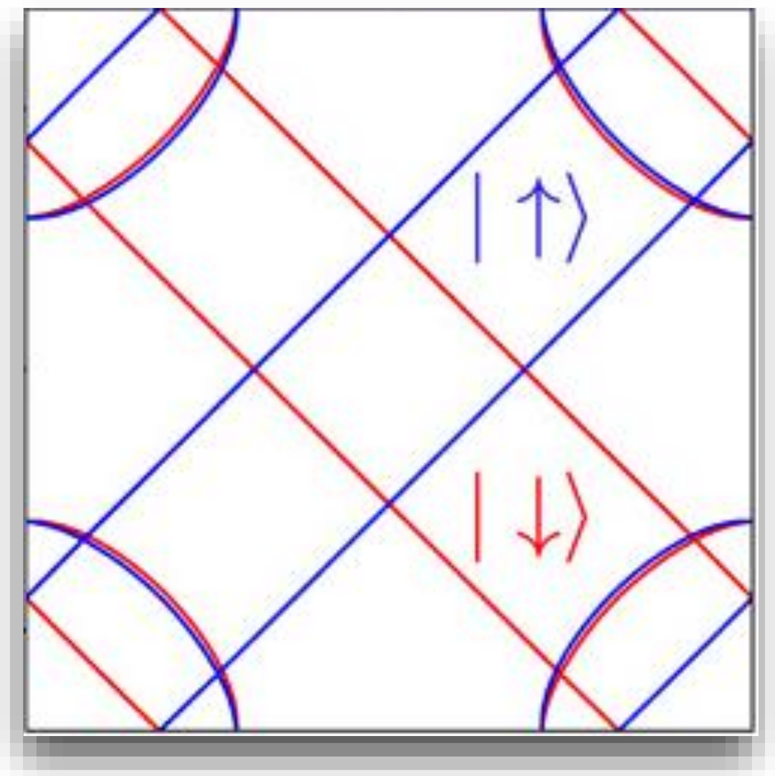








Fermi surface in k_x-k_y plane



~~C_4~~’=C_4T

[C_4T||C_4T]

Spin space   Crystal space

m’m’m or ~~C_4~~’=C_4T ?

Intertwines: relativistic effects and exchange effects; collinear and noncollinear; ferromagnets and antiferromagnets

Unsuitable to delimit the different phases or identify exchange-driven physics (e.g. unconventional d-wave or higher even parity magnetism)

Heesch, Shubnikov, Landau, …

Spin symmetries (598 possibilities)

INSP/RE group
INTERDISCIPLINARY SPINTRONICS RESEARCH

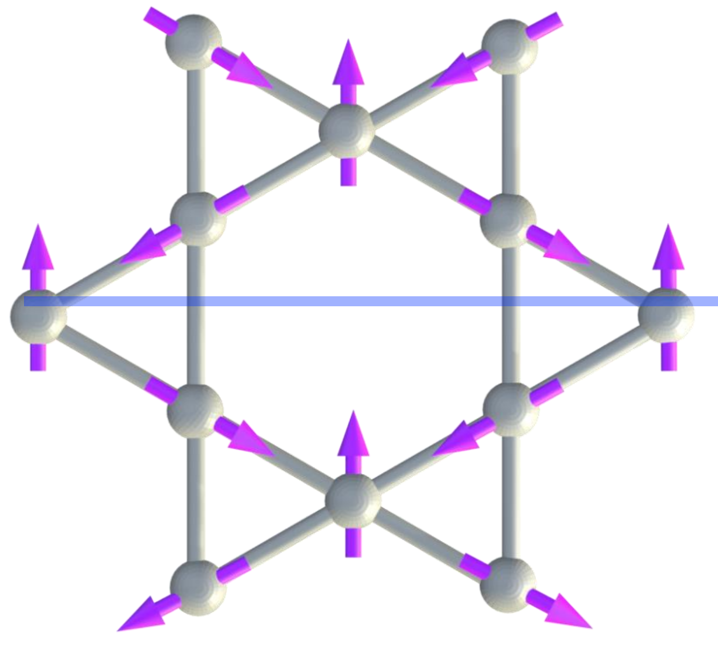
act separately in spin and crystal space

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

Spin group: spin-only x non-trivial spin group

$[R_1||R_2]$ $\quad$ $[R_1||E]$ x $[R_1||R_2]$

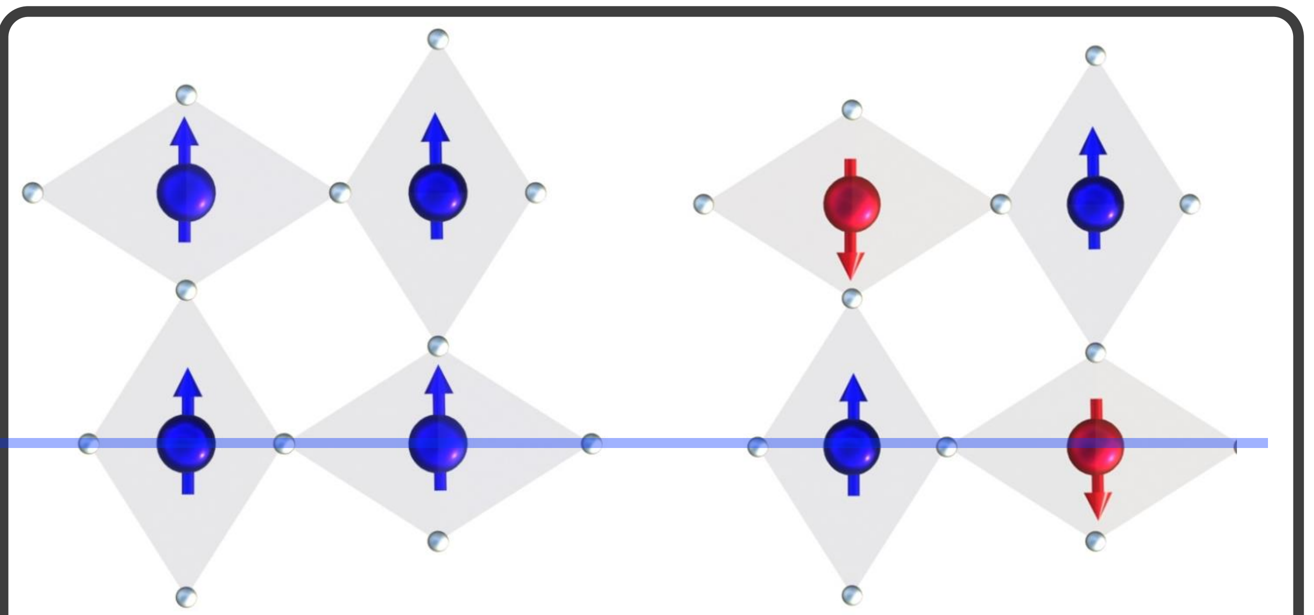
Spin space $\quad$ Crystal space



$[C_3 \,||\, C_6]$

$[C_{2\perp}T \,|\, T]$

coplanar



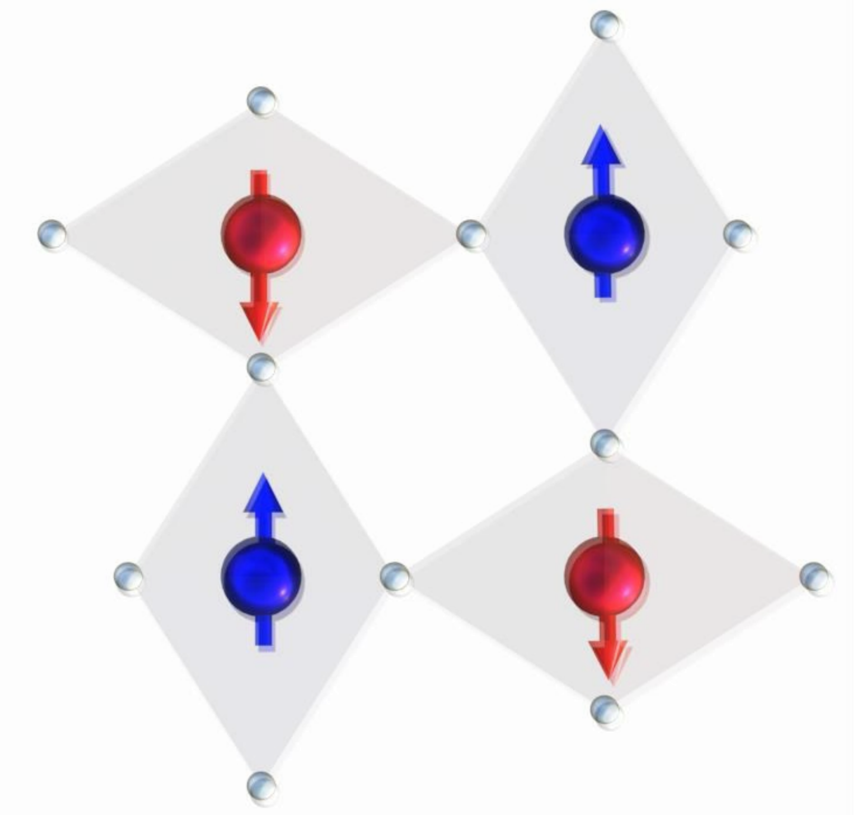
$[E \,||\, C_4]$ $\quad$ $[C_2 \,||\, C_4]$

m'm'm

$[C_\infty \,||\, E]$x{E,$[C_2T||T]$}

collinear

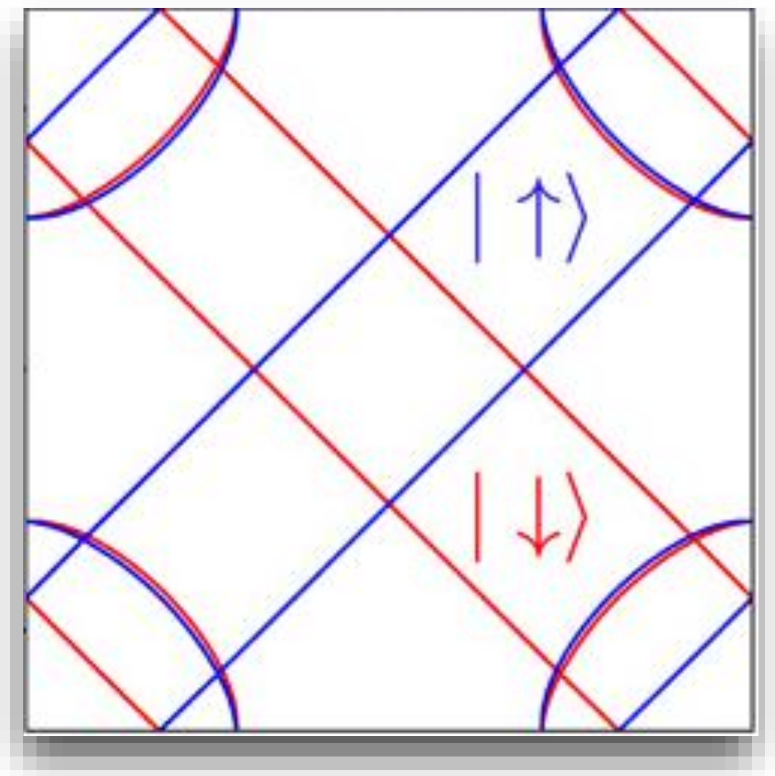
***Nonmagnetic** all rotations*



$[C_2||C_4]$ ✓

Spin space $\quad$ Crystal space

Fermi surface in k_x-k_y plane



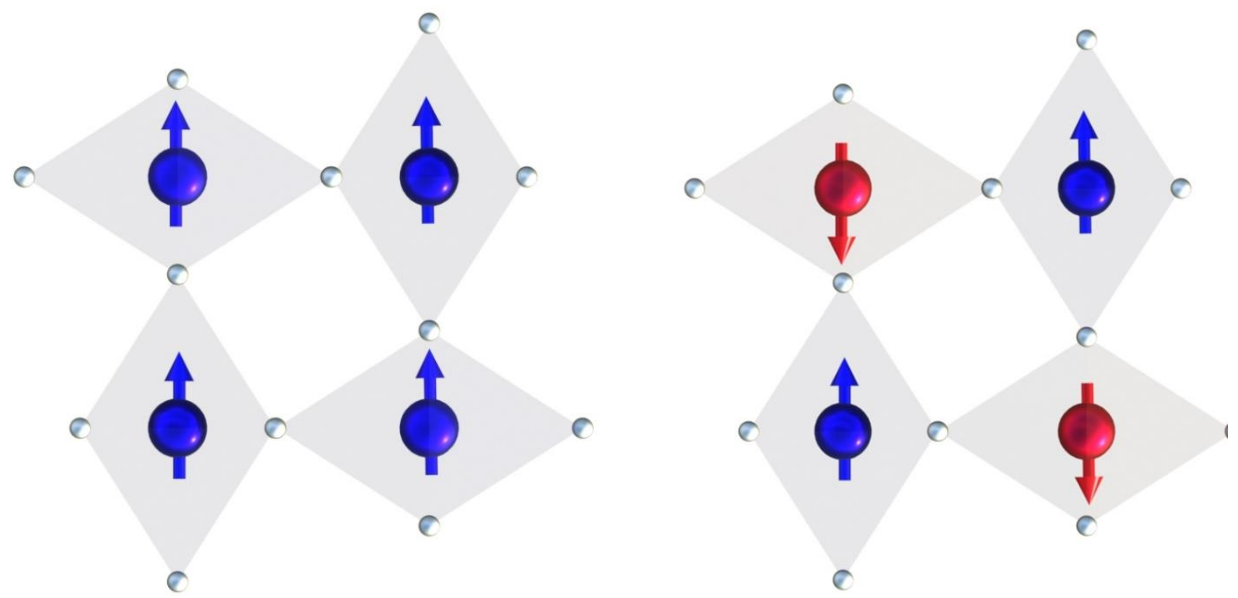
PHYSICAL REVIEW X **12**, 031042 (2022)

Šmejkal, Sinova, and Jungwirth

INSP/RE group
INTERDISCIPLINARY SPINTRONICS RESEARCH

act separately in spin and crystal space

$$\mathcal{H} = \mathcal{H}_{\text{mag}}$$



$[E \,||\, C_4]$ $[C_2 \,||\, C_4]$

$[C_\infty \,||\, E]\times\{E,[C_2T||T]\}$

collinear

Spin group: spin-only x non-trivial spin group

$[R_1||R_2]$ $[R_1||E]$ x $[R_1||R_2]$

Spin space Crystal space

ALL non-relativistic band structures of collinear systems are symmetric, even for systems that break P

For systems with P:

Apply operation: P $E(\uparrow, \mathbf{k}) = E(\uparrow, -\mathbf{k})$

It is a symmetry: P $E(\uparrow, \mathbf{k}) = E(\uparrow, \mathbf{k})$

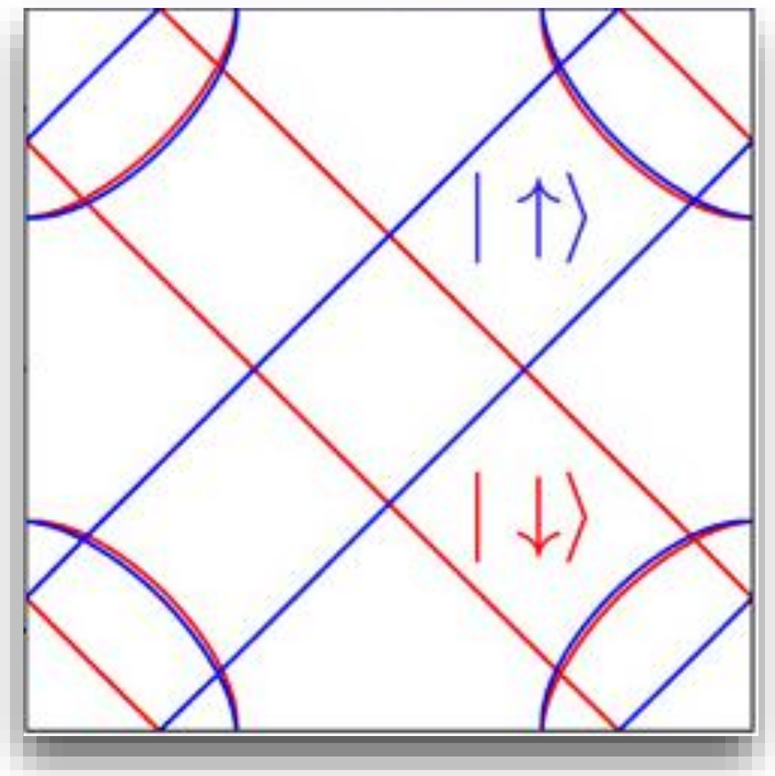
$[C_2T||T]$

Apply operation: $[C_2T||T]$ $E(\uparrow, \mathbf{k}) = E(\uparrow, -\mathbf{k})$

It is a symmetry: $[C_2T||T]$ $E(\uparrow, \mathbf{k}) = E(\uparrow, \mathbf{k})$

Therefore $E(\uparrow, \mathbf{k}) = E(\uparrow, -\mathbf{k})$

Fermi surface in k_x-k_y plane



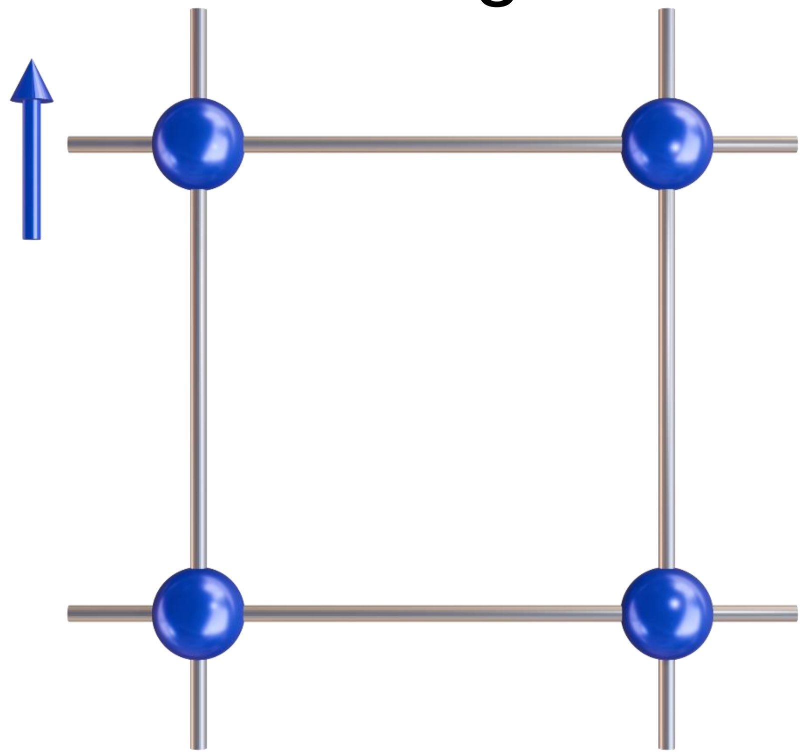
PHYSICAL REVIEW X **12**, 031042 (2022)

Šmejkal, Sinova, and Jungwirth

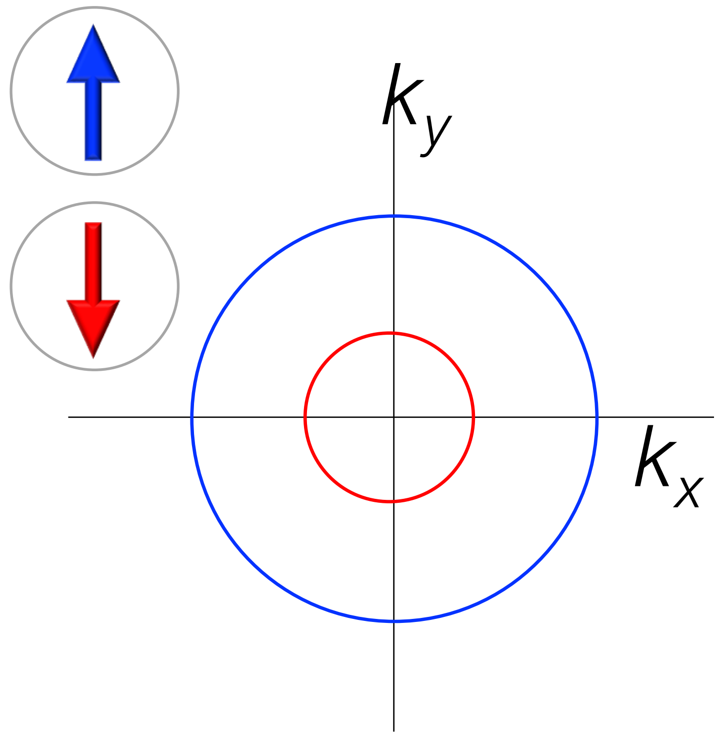
SP/CE

Spin symmetries delimit the three collinear magnetic orders

Ferromagnetic



1. spin order in direct-space
2. net magnetization
3. spin order in recip.-space

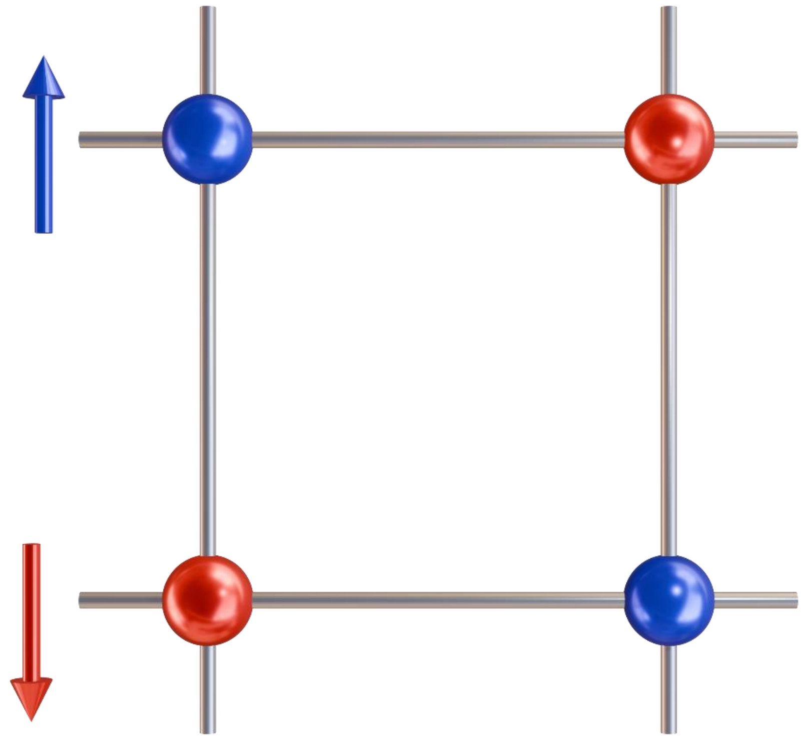


1. broken symmetry: spin-rotation

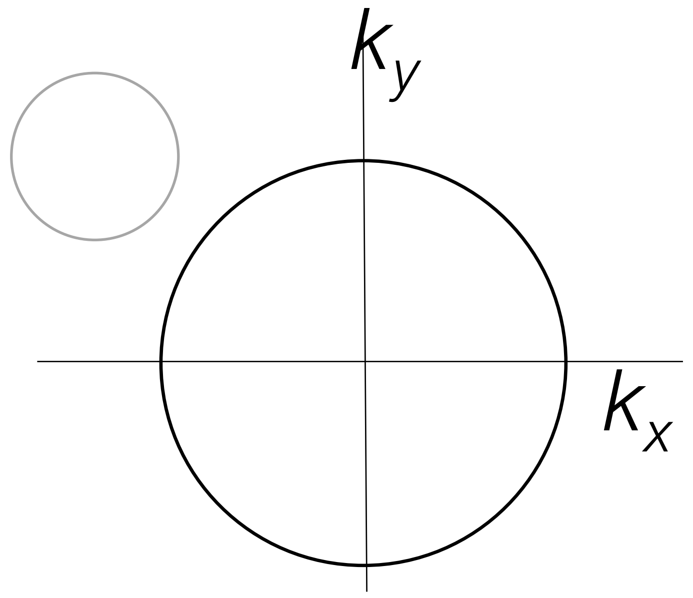
2,3. broken symmetry: spin-rotation with crystal transformation

Pierre Weiss

Antiferromagnetic



1. spin order in direct-space
2. no net magnetization
3. no spin order in recip.-space



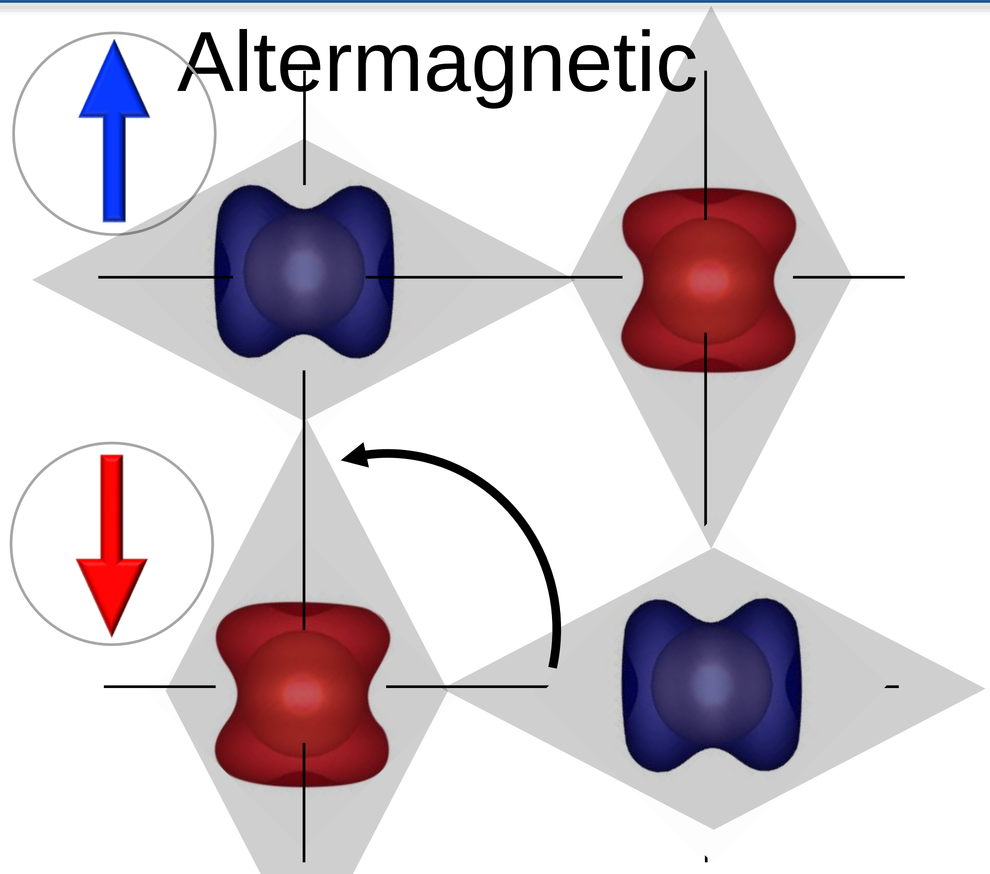
1. broken symmetry: spin-rotation

2,3. symmetry: 180^o spin-rotation with translation or inversion

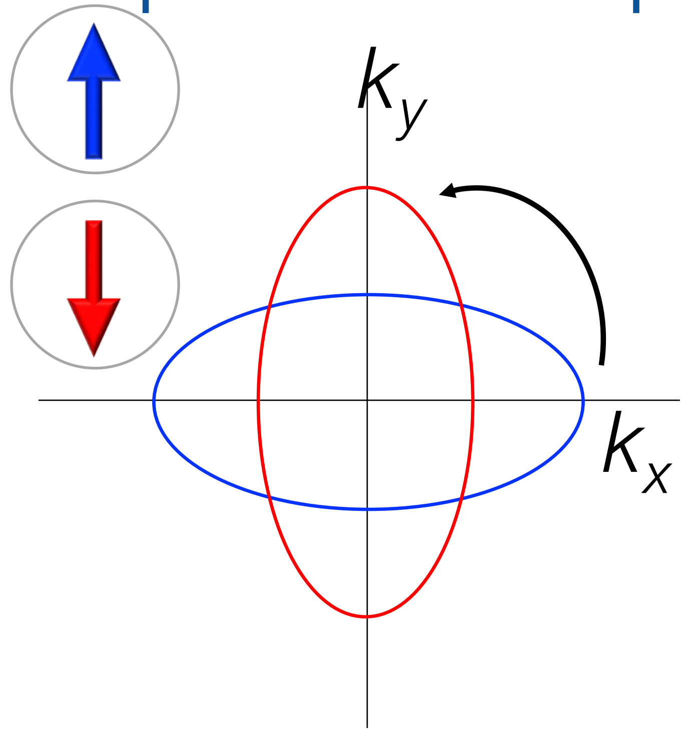
$[C_2||P$ or $\mathbf{t}]$

Louis Néel

Altermagnetic



1. spin order in direct-space
2. no net magnetization
3. spin order in recip.-space



1. broken symmetry: spin-rotation

2. symmetry: 180^o spin-rotation with a **crystal-rotation**

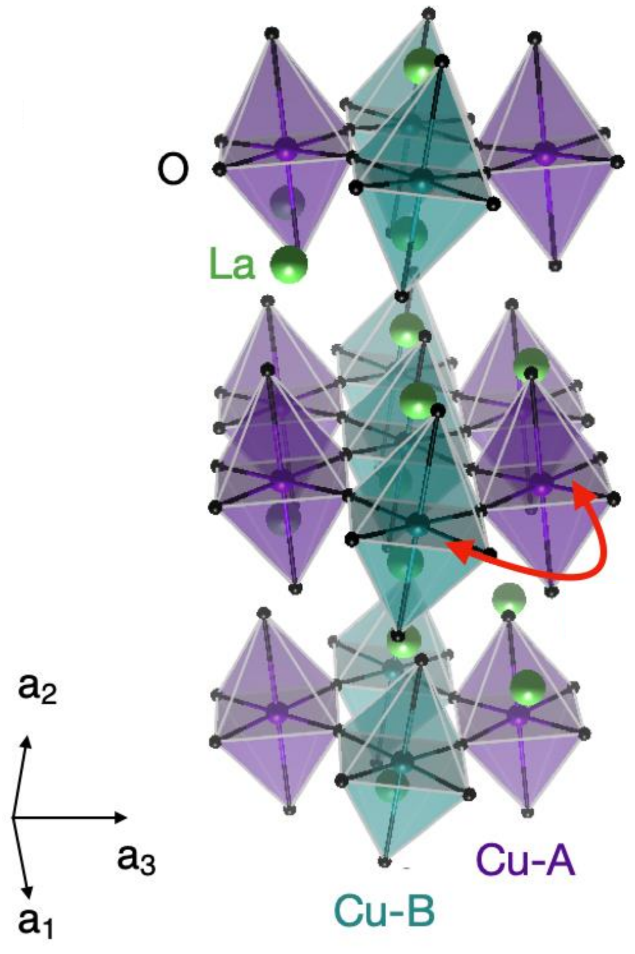
3. broken symmetries: both 180^o spin-rotation with translation or inversion

PHYSICAL REVIEW X 12, 031042 (2022)

Šmejkal, Sinova, and Jungwirth

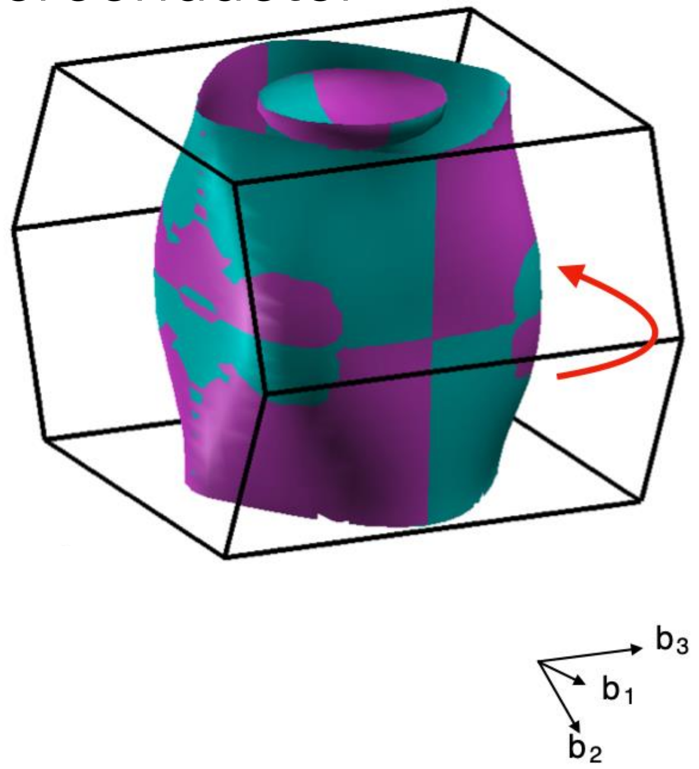
Altermagnetism

Spin symmetries give a complete classification of collinear magnetic order: identification of altermagnetic materials

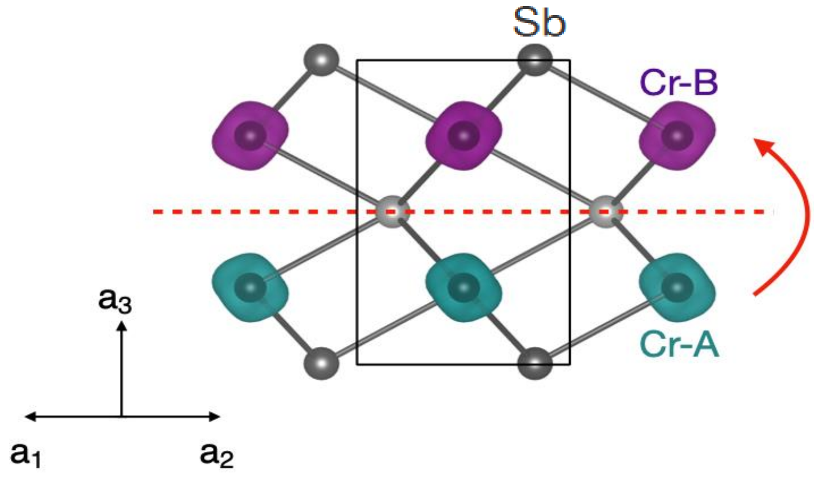


La_2CuO_4: Parent cuprate of high T_c d-wave superconductor

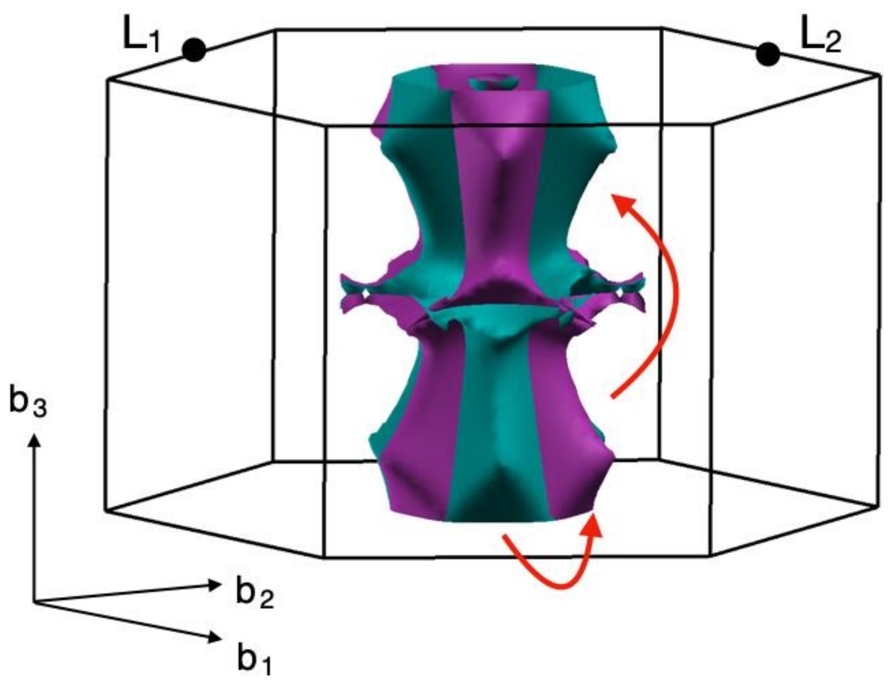
Fermi surface

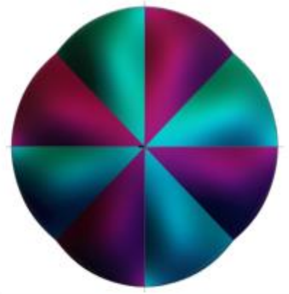
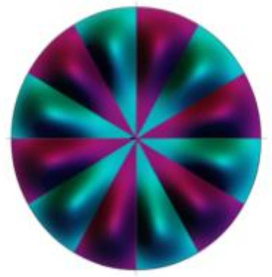
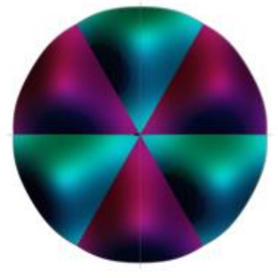
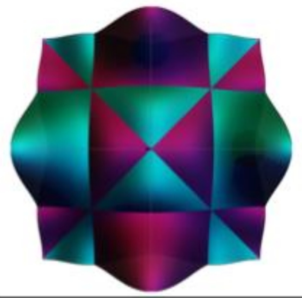


CrSb: Metallic & T_N > 700 K



Fermi surface



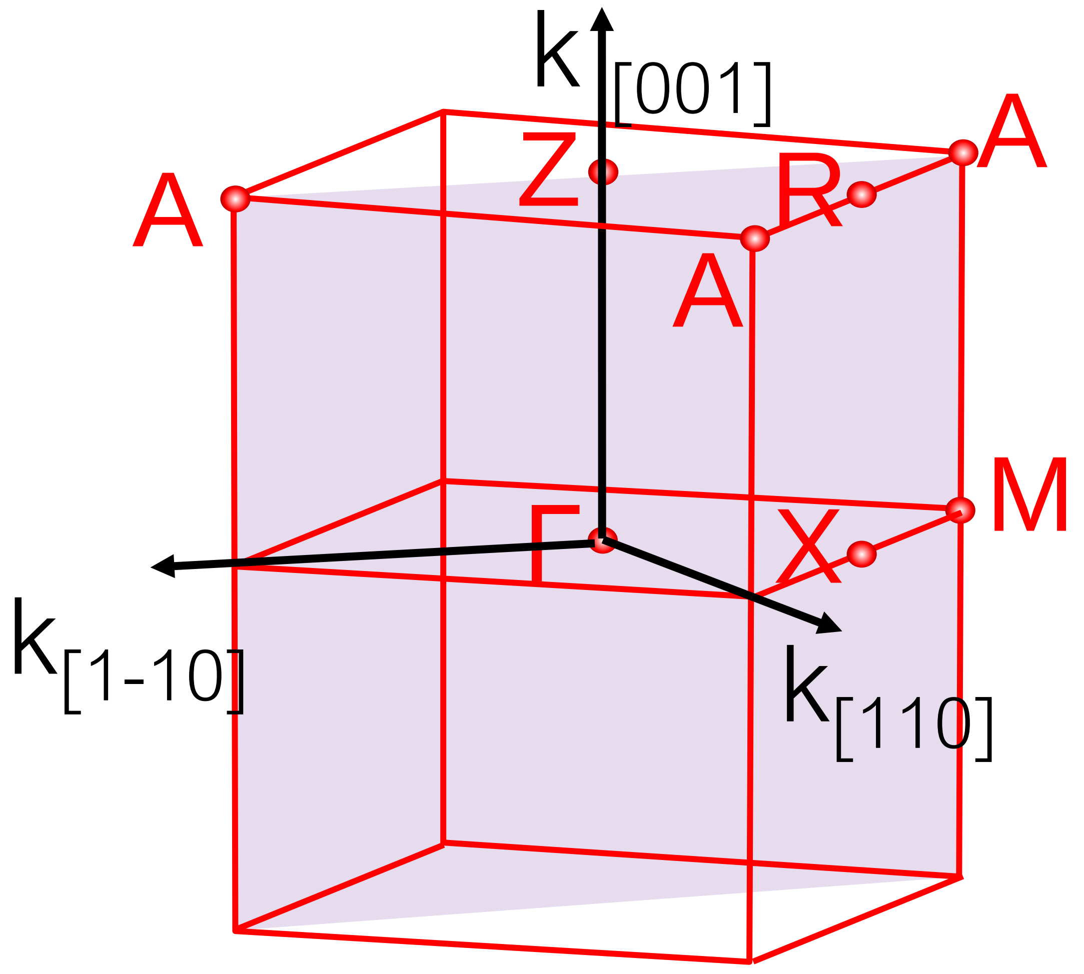
AM material	AM spin group	AM crystallographic group	AM spin winding number			AM orbital harmonic
La_2CuO_4, $FeSb_2$	$2_m2_m1_m$ (8)	$2/m$	Planar  $(k_{x/y},k_z)$	P-2	 (k_x,k_y)	d-wave
KRu_4O_8	$2_{4/}1_m$ (8)					
RuO_2, MnO_2, MnF_2	$2_{4/}1_m1_m1_m$ (16)	mmm				
$KMnF_3$	$1_{4/}1_m2_m2_m$ (16)	$4/m$		P-4		g-wave
	$1_{6/}1_m2_m2_m$ (24)	$6/m$		P-6		i-wave
CuF_2	$2_{2/}2_m$ (4)	$\bar{1}$	Bulk 	B-2		d-wave
CoF_3, FeF_3, Fe_2O_3	$1_{\bar{3}}2_m$ (12)	$\bar{3}$		B-4		g-wave
	$2_{6/}2_m$ (12)					
CrSb, MnTe, VNb_3S_6	$2_{6/}2_m2_m1_m$ (24)	$\bar{3}m$				
	$1_m1_{\bar{3}}2_m$ (48)	$m\bar{3}$		B-6		i-wave

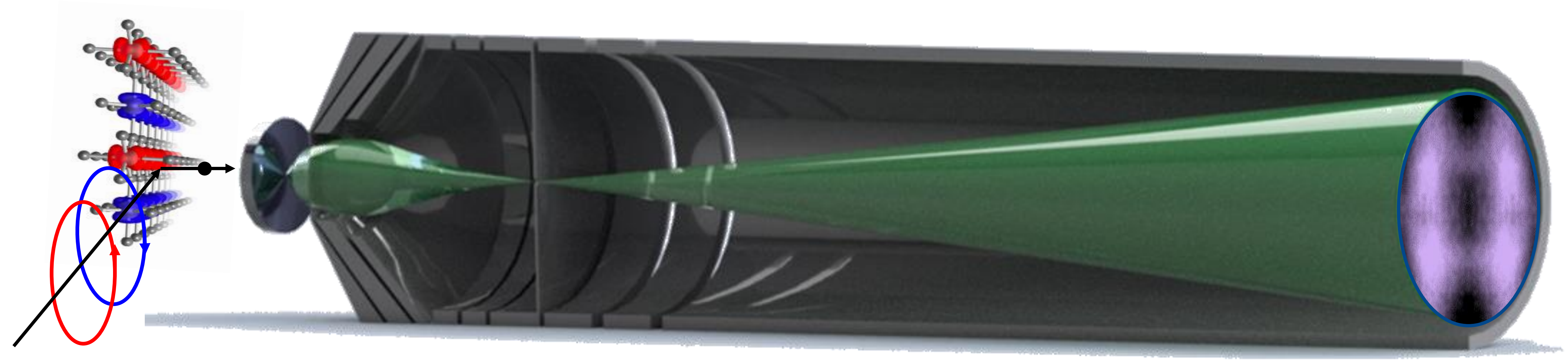
AM crystallographic group

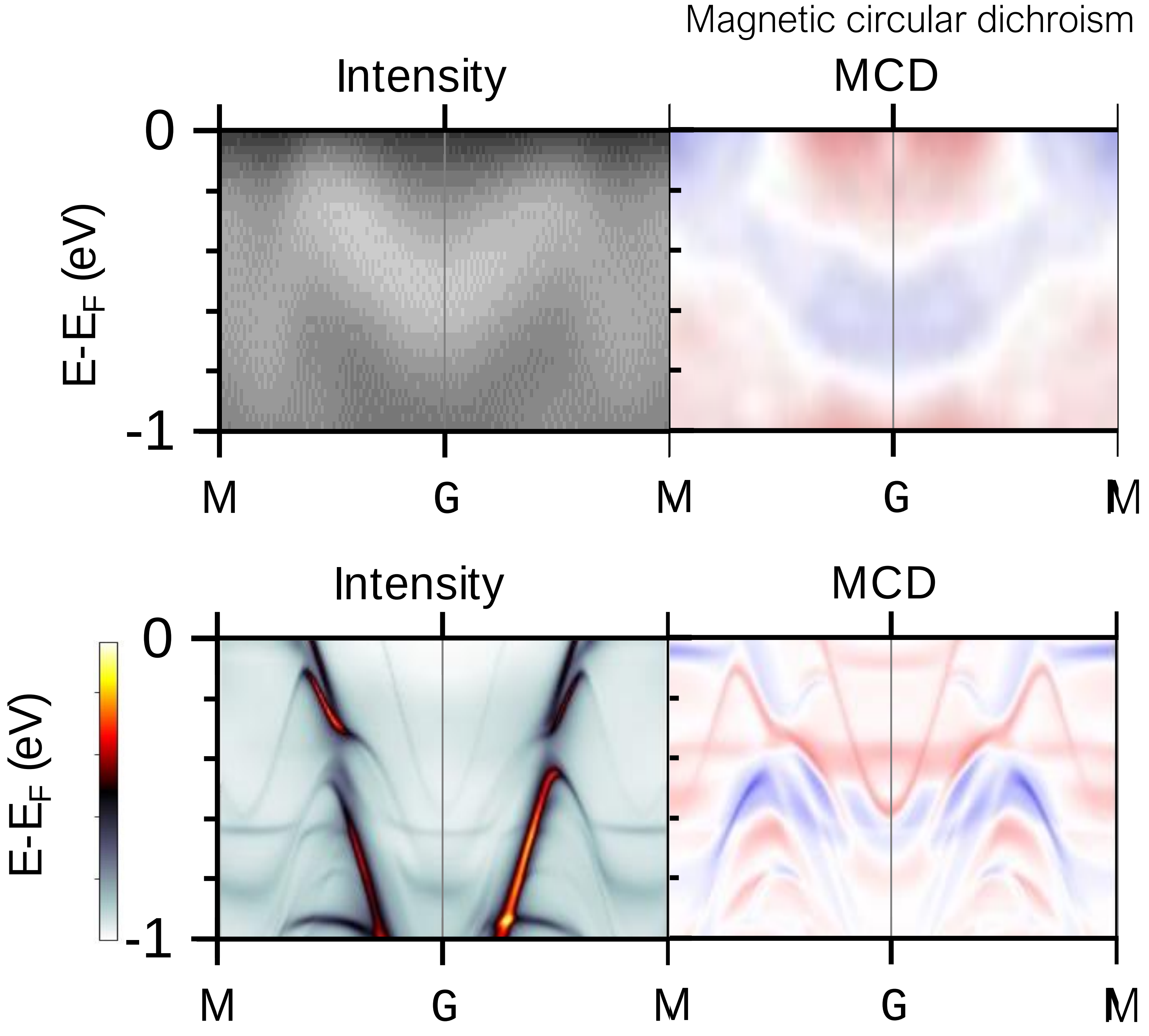
PHYSICAL REVIEW X **12**, 031042 (2022)

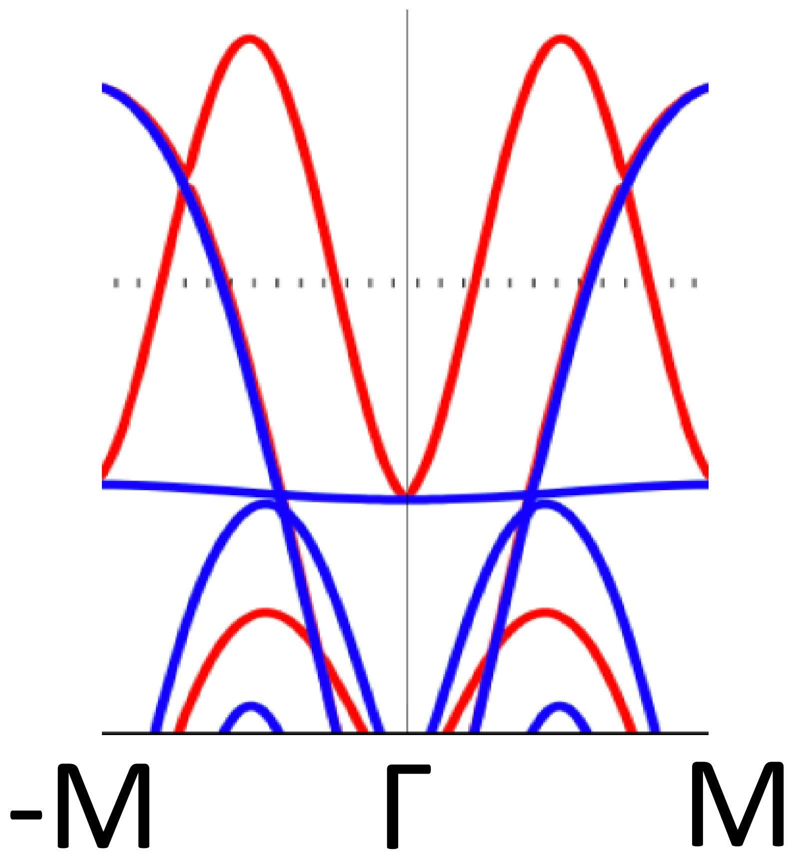
Šmejkal, Sinova, and Jungwirth

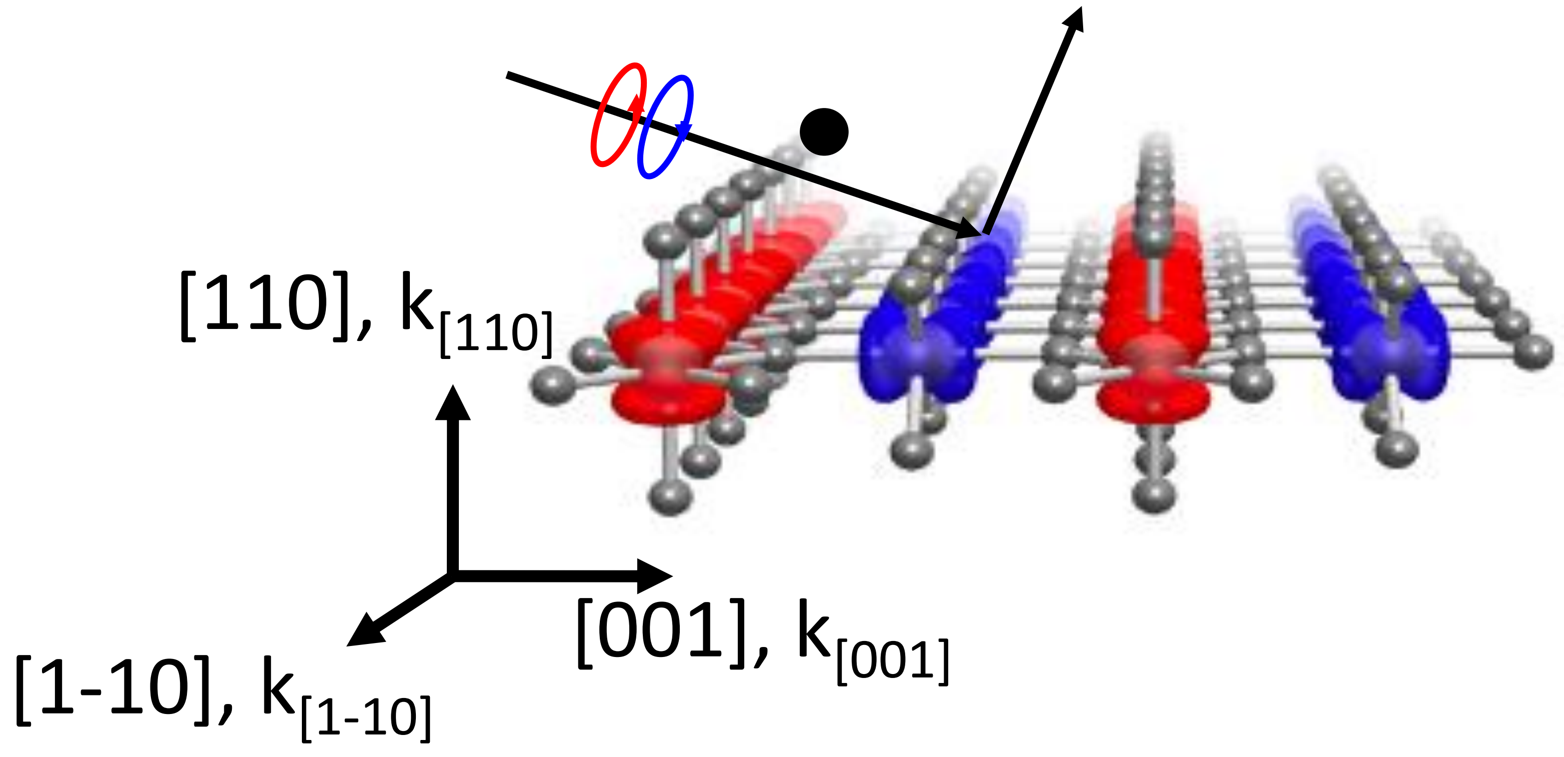
ARPES in Altermagnetic RuO_2











Science Advances 10, eadj4883 (2024)

Fedchenko,…,Jungwirth, Šmejkal, Sinova, Elmers

Observation of broken time reversal ARPES in altermagnetic MnTe

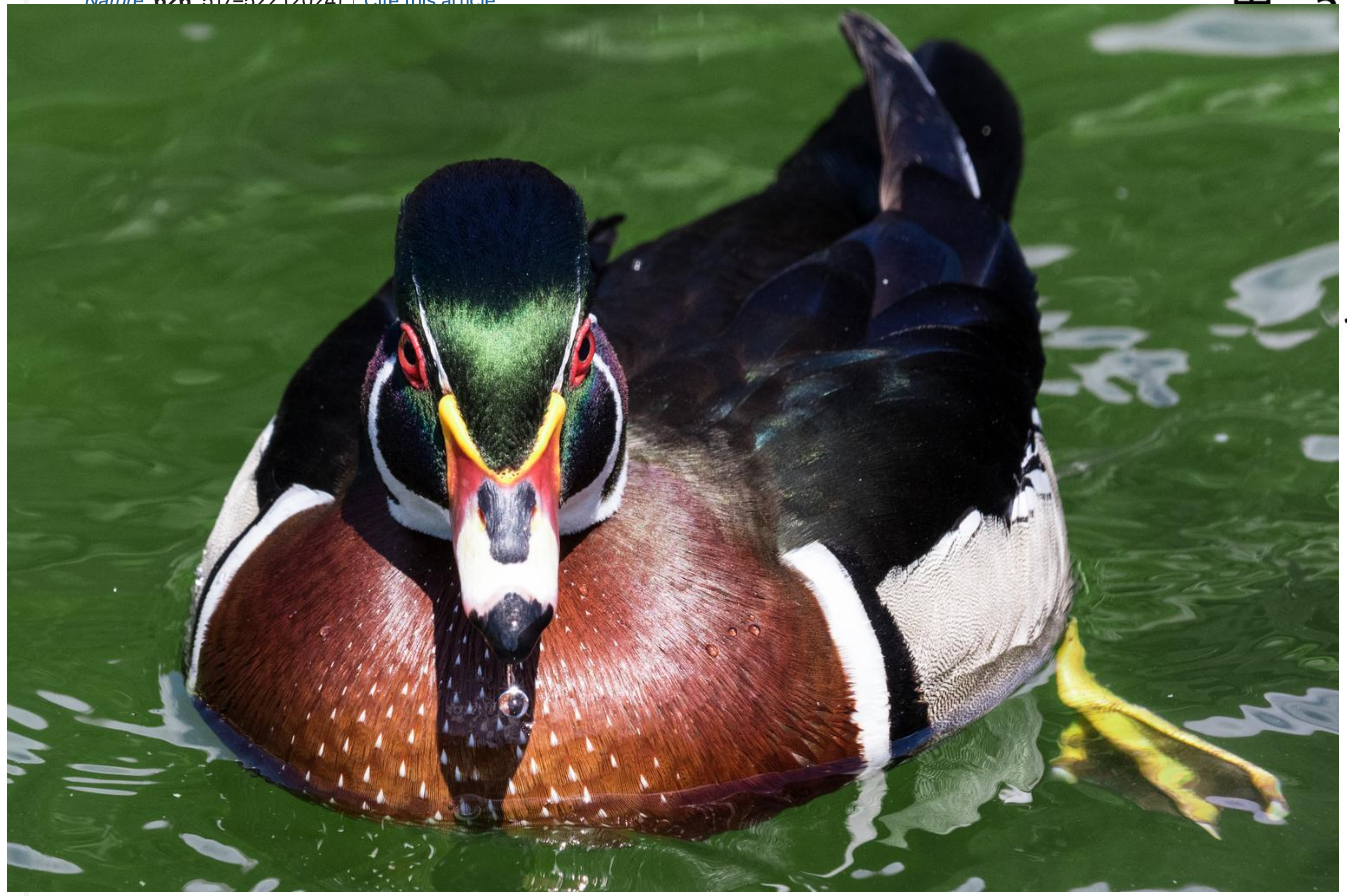
nature

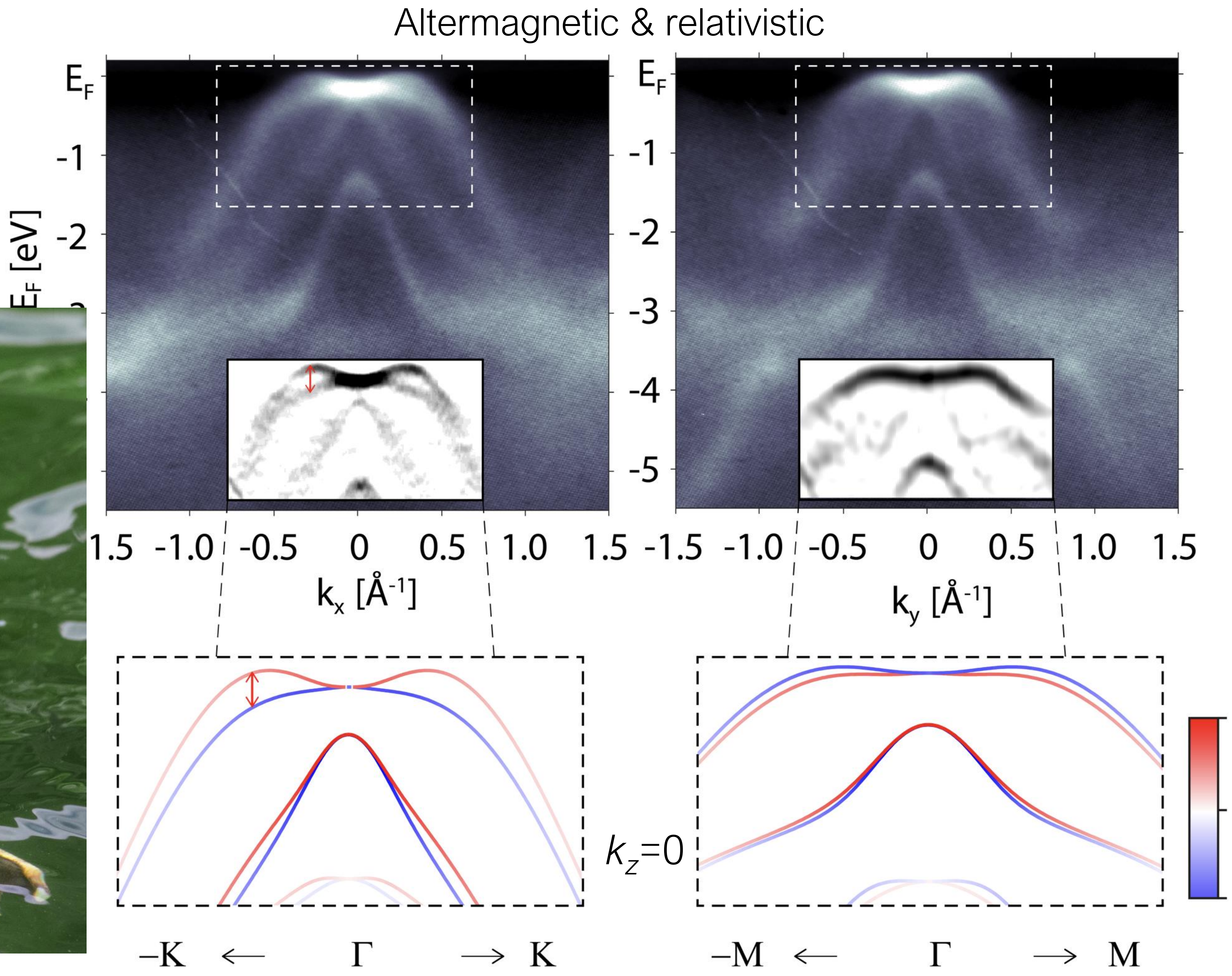
Altermagnetic lifting of Kramers spin degeneracy

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

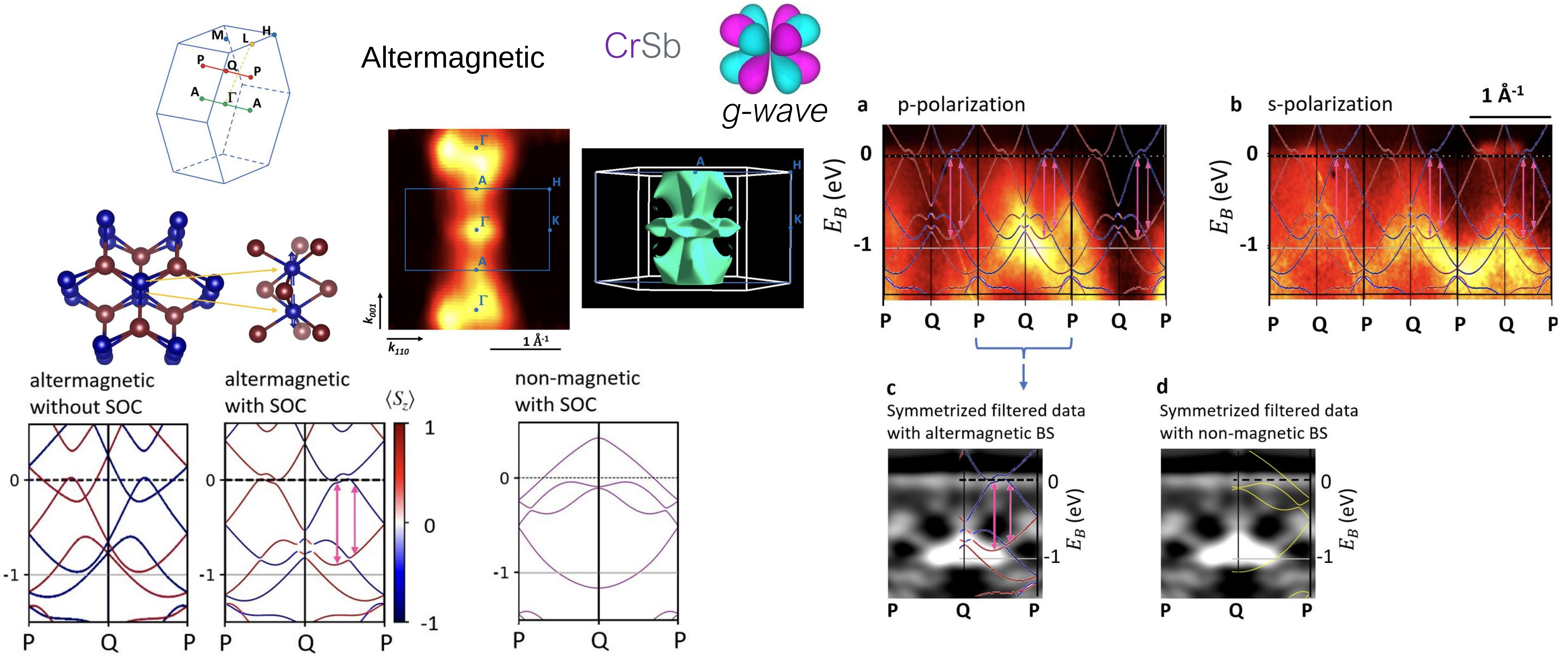
Juraj Krempasky





Observation of altermagnetic band splitting in CrSb

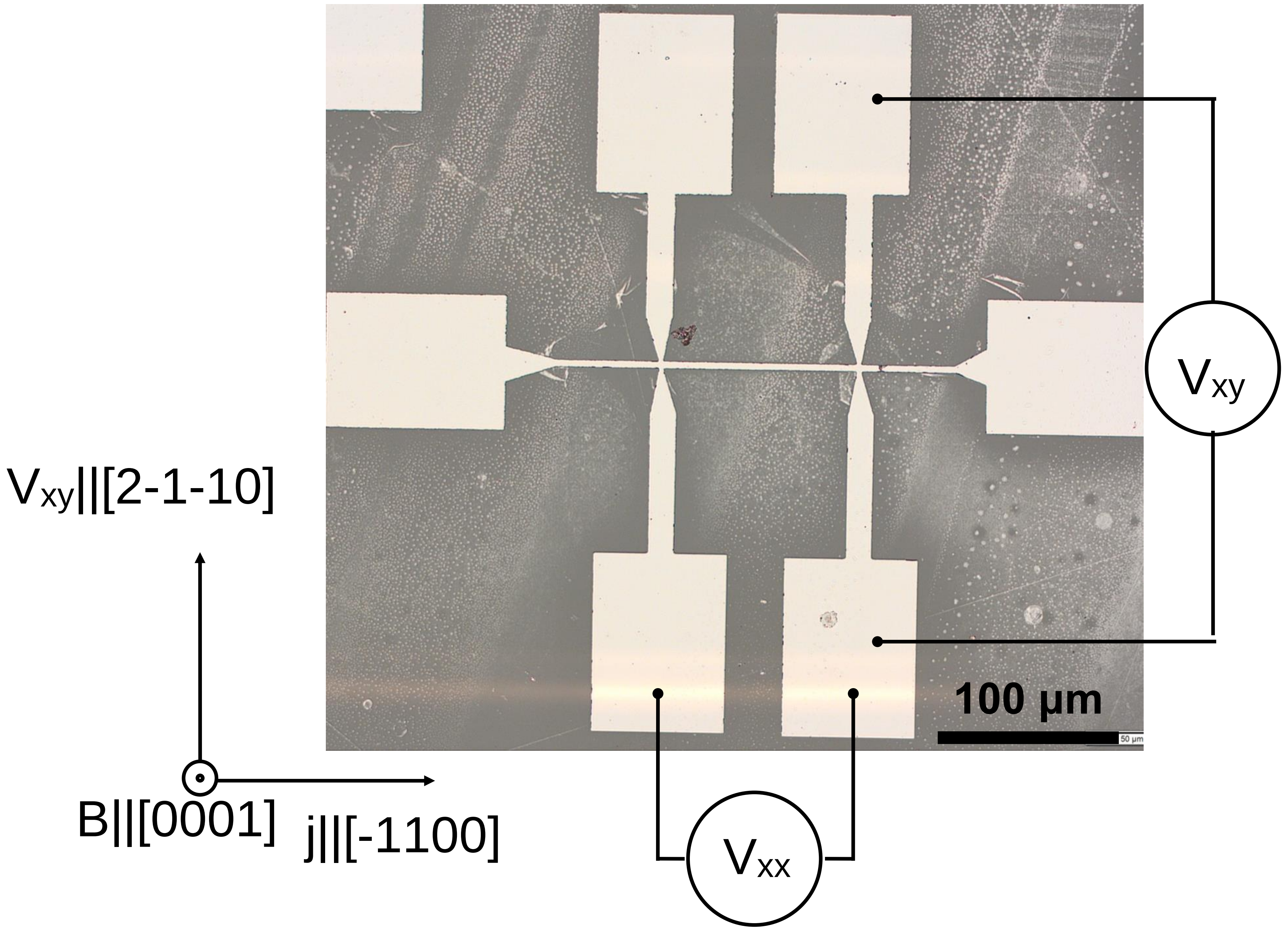
INSP/RE group
INTERDISCIPLINARY SPINTRONICS RESEARCH

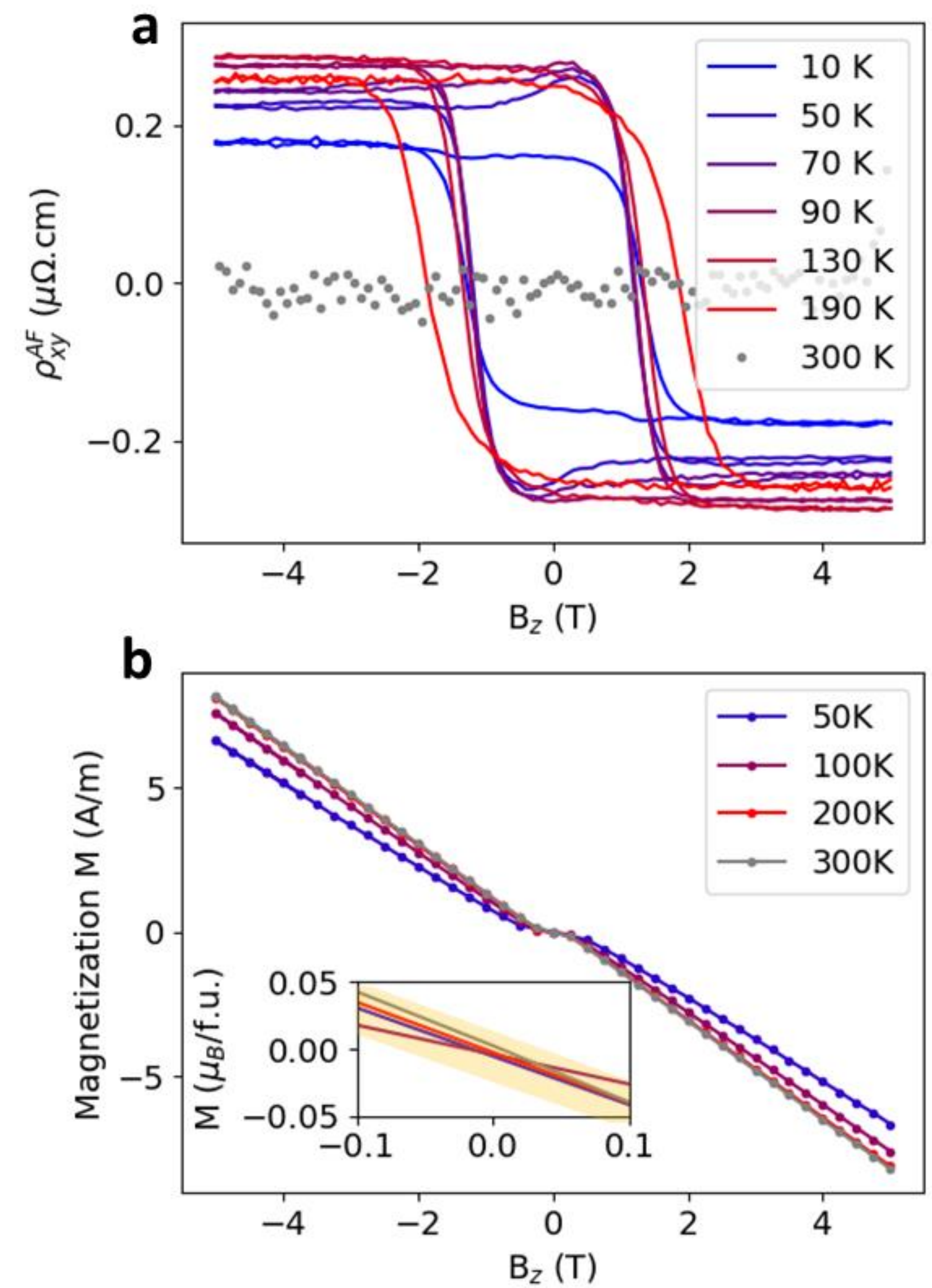


Sonka, …,Šmejkal, Kläui, Sinova, Jourdan, Nat. Comm. **15**, 2116 (2024)

Experimental observation of anomalous Hall effect in Mn_5Si_3





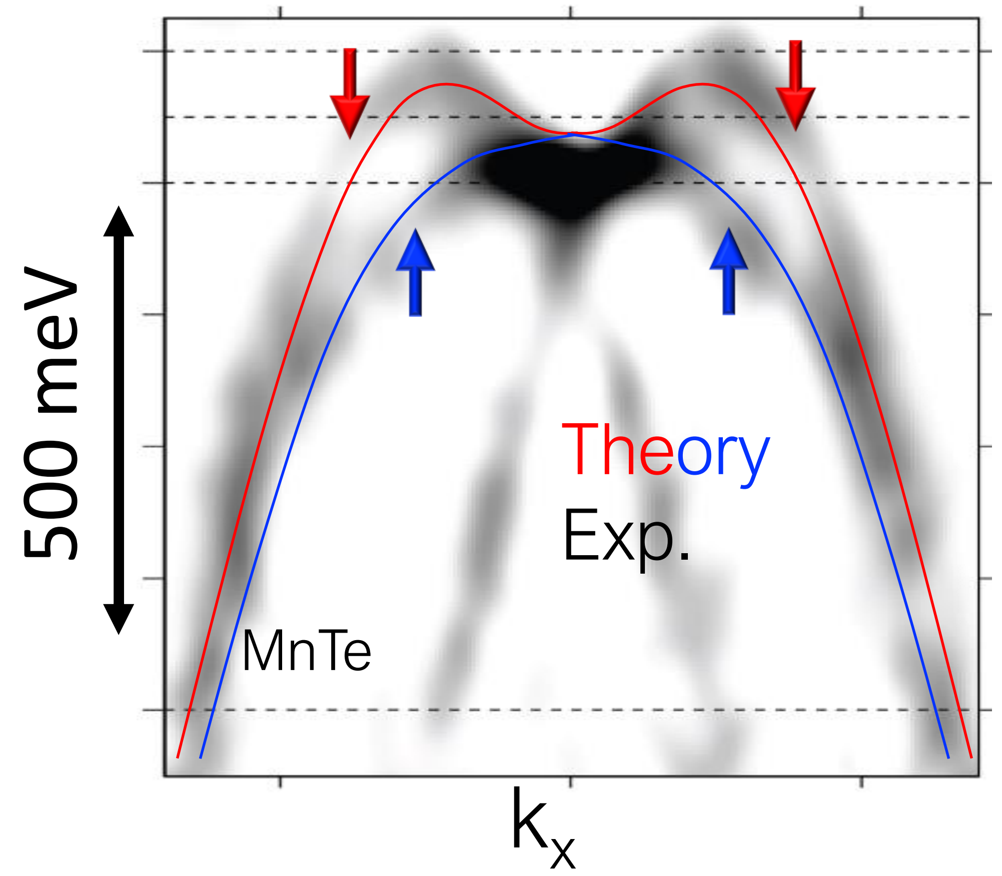


H. Reichlova, et al. arXiv: 2012.15651 (2020), Nat. Comm. 2024

Overview of experiments in altermagnets

INSP/RE group
INTERDISCIPLINARY SPINTRONICS RESEARCH

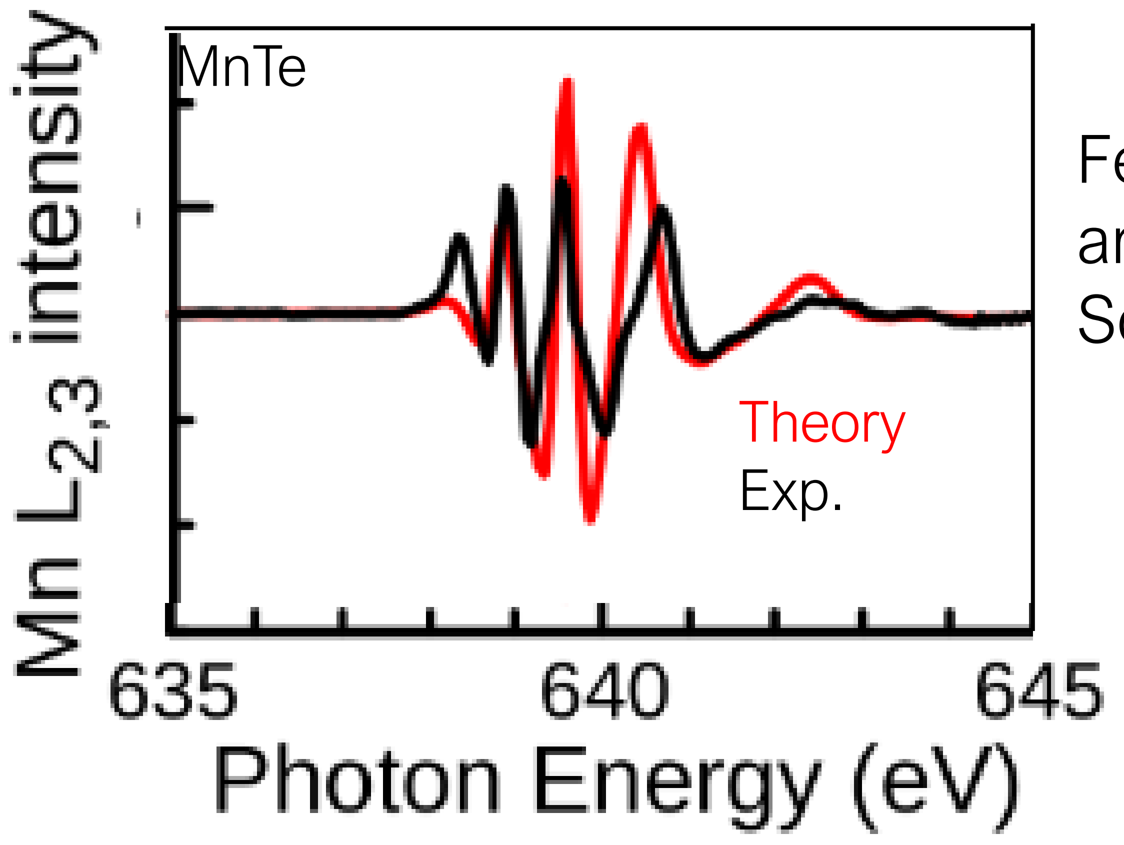
Angle resolved photo-emission



Krempasky, TJ et al., arXiv:2308.10681, Nature 2004

Fedchenko, et al., arXiv: 2306.02170,
Sci. Adv. 10, eadj4883 (2024)
Lee et al., arXiv:2308.11180,
PRL 132, 036702 (2024)
Osumi et al. arXiv: 2308.10117
Hajlaoui, et al., arXiv:2401.09187
Lin et al., arXiv:2402.04995
Sonka et. al. Nat. Comm. 15, 2116
(2024)

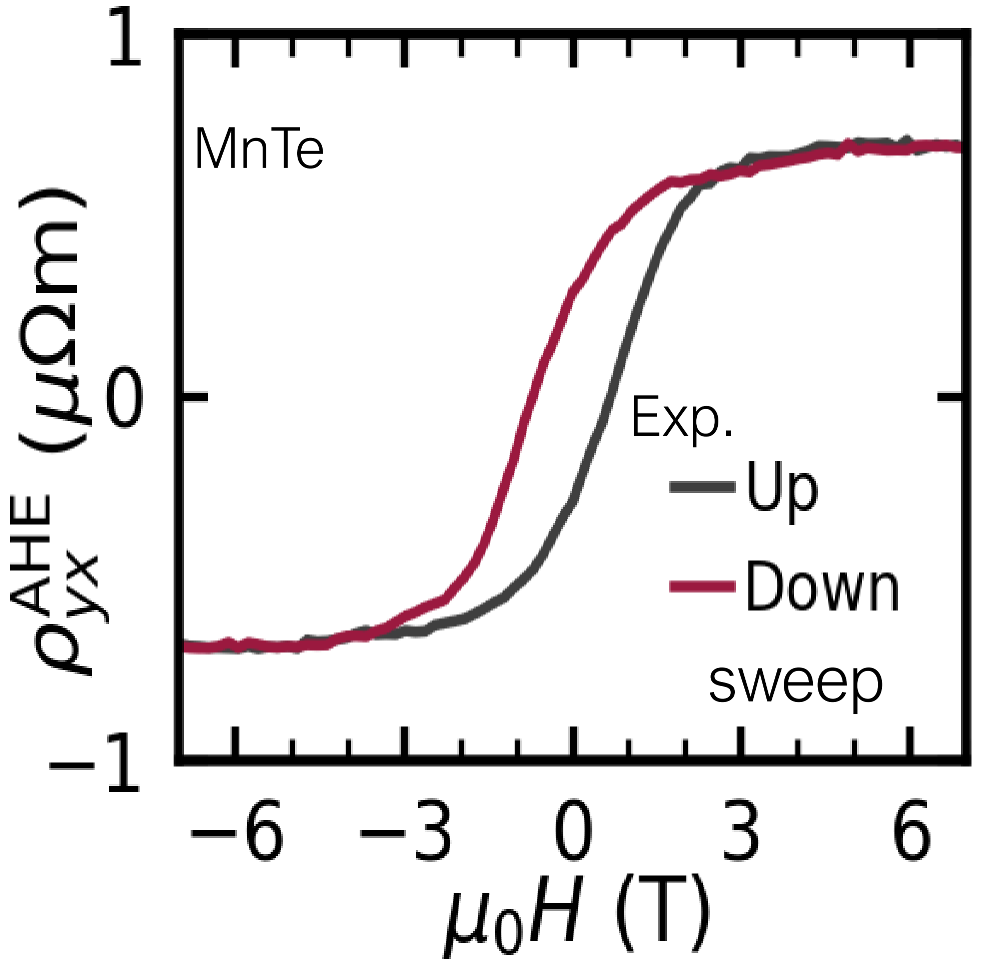
X-ray magnetic circular dichroism



Hariki, TJ et al., arXiv:2305.03588

Fedchenko, et al.,
arXiv: 2306.02170,
Sci. Adv. 10, eadj4883 (2024)

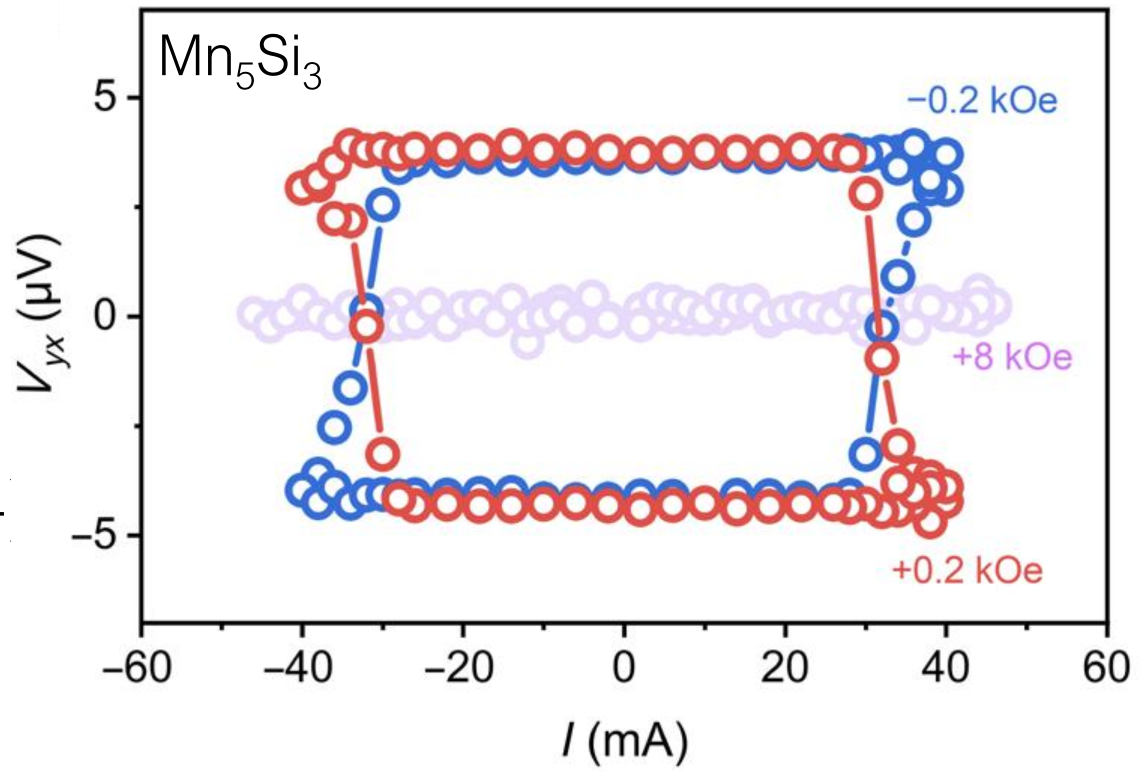
Anomalous Hall effect



Betancourt, et al., arXiv:2112.06805, PRL 130, 036702 (2023)

Feng, et al., arXiv:2002.08712,
Nat. Elec. 11, 735 (2022)
Reichlova, et al., arXiv: 2012.15651
Wang et al., Nat. Com. 14, 8240 (2023)
Kluczyk et al., 2310.09134
Han et al., Sci. Adv. 10, eadn0479 (2024

Spin currents and switching



Han et al., Sci. Adv. 10, eadn0479 (2024)

Bose et al. arXiv:2108.09150,
Nat. Elec. 5, 263 (2022)
Bai et al. arXiv:2109.05933,
PRL 128, 197202 (2022)
Karube et al. arXiv:2111.07487,
PRL 129, 137201 (2022)

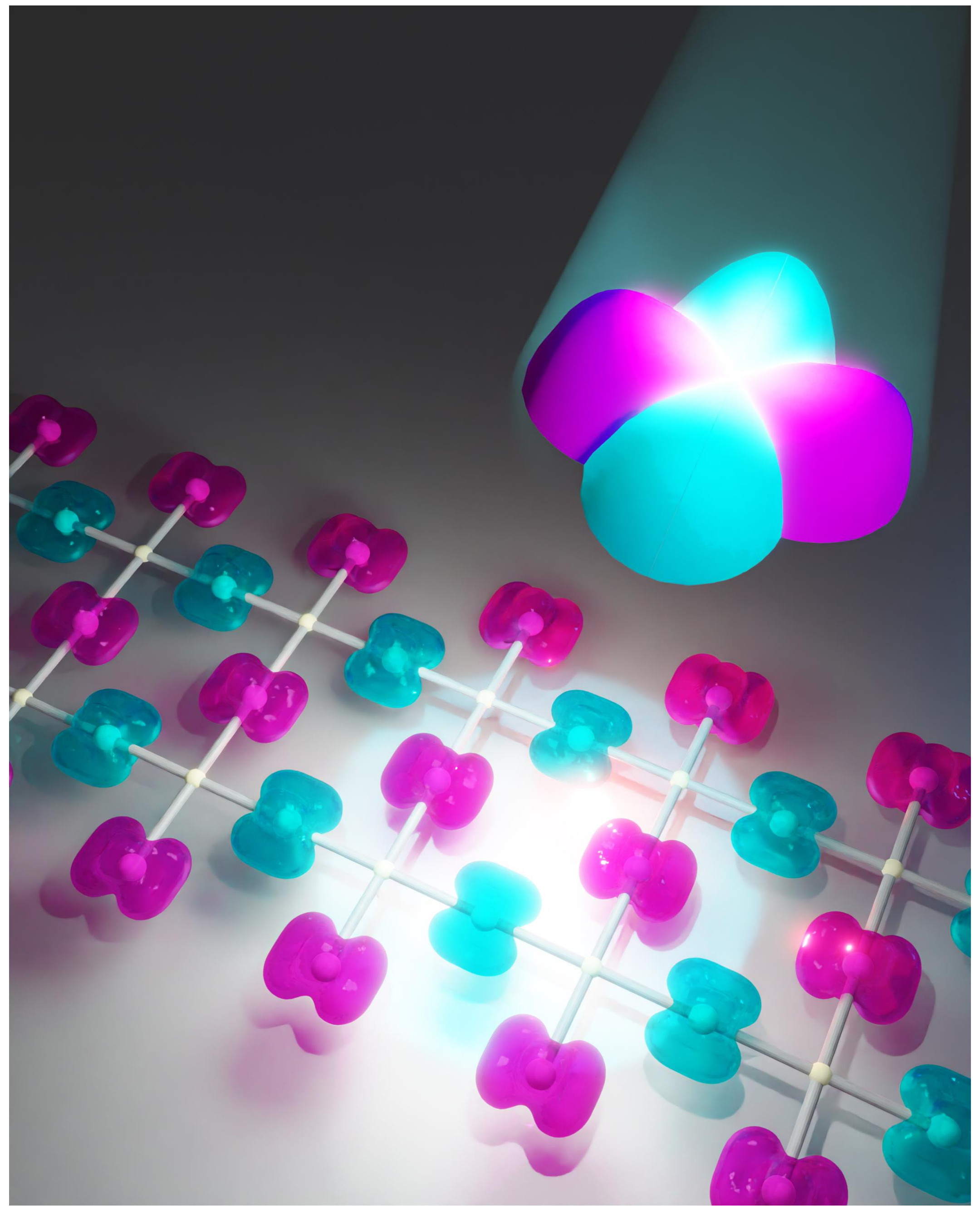
Summary of properties of ferromagnets, antiferromagnets, and *altermagnets*

INSP/RE group
INTERDISCIPLINARY SPINTRONICS RESEARCH

	Ferromagnet	Antiferromagnet	Altermagnet
Spin-order symmetry	S-wave	None	D, G, I - wave
Zero magnetisation	No	Yes	Yes
Anisotropy/nematicitiy (breaking of lattice symmetry)	No	No	Yes
Nodal manifold	1d	3d	2d
Spin splitting	Yes	Possible	Yes
Nonrelativistic valley	No	No	Yes
Chiral, linear THz magnons	No	No	Yes
Time-reversal symmetry broken electronic structure	Yes	None	Yes
Anomalous Hall/magnetooptical Kerr effect/Thermal	Yes	No	Yes
Switchable “crystal” anomalous Hall effect	No	No	Yes
Spin polarised currents	Yes	Possible	Yes
Tunneling/giant magnetoresistance	Yes	No	Yes
Spin splitter current	No	No	Yes

SP/CE

Altermagnets: phenomenological description of d-wave magnetism



PHYSICAL REVIEW LETTERS 131, 256703 (2023)

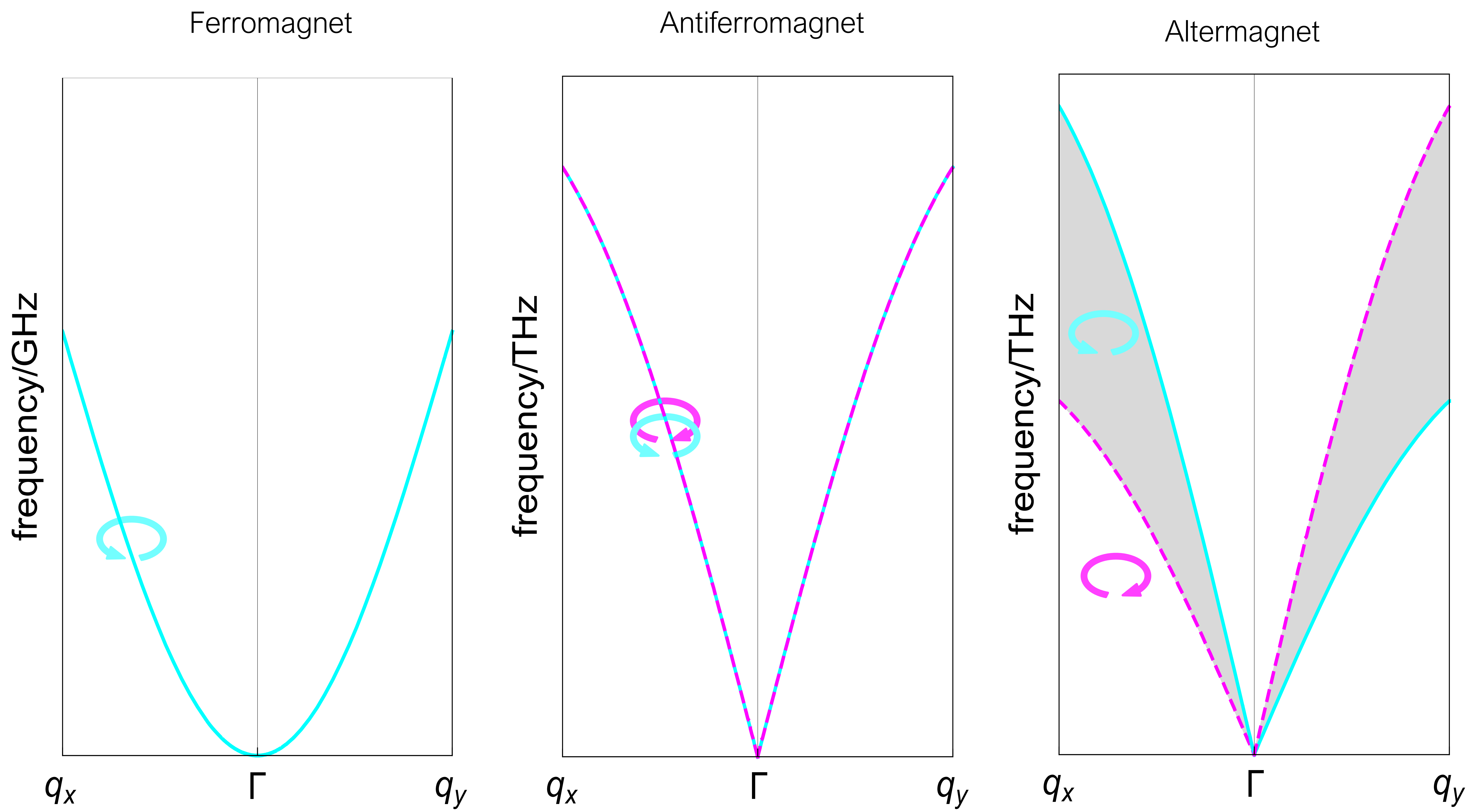
Šmejkal, Marmodoro, Ahn, Gonzalez-Hernandez, Turek, Mankovsky, Ebert, D'Souza, Šipr, Sinova, Jungwirth

arXiv 2403.10218

arXiv:2403.10218

O. Gomonay, V. P. Kravchuk, R. Jaeschke-Ubiergo, K. V. Yershov, T. Jungwirth, L. Šmejkal, J. van den Brink, J. Sinova

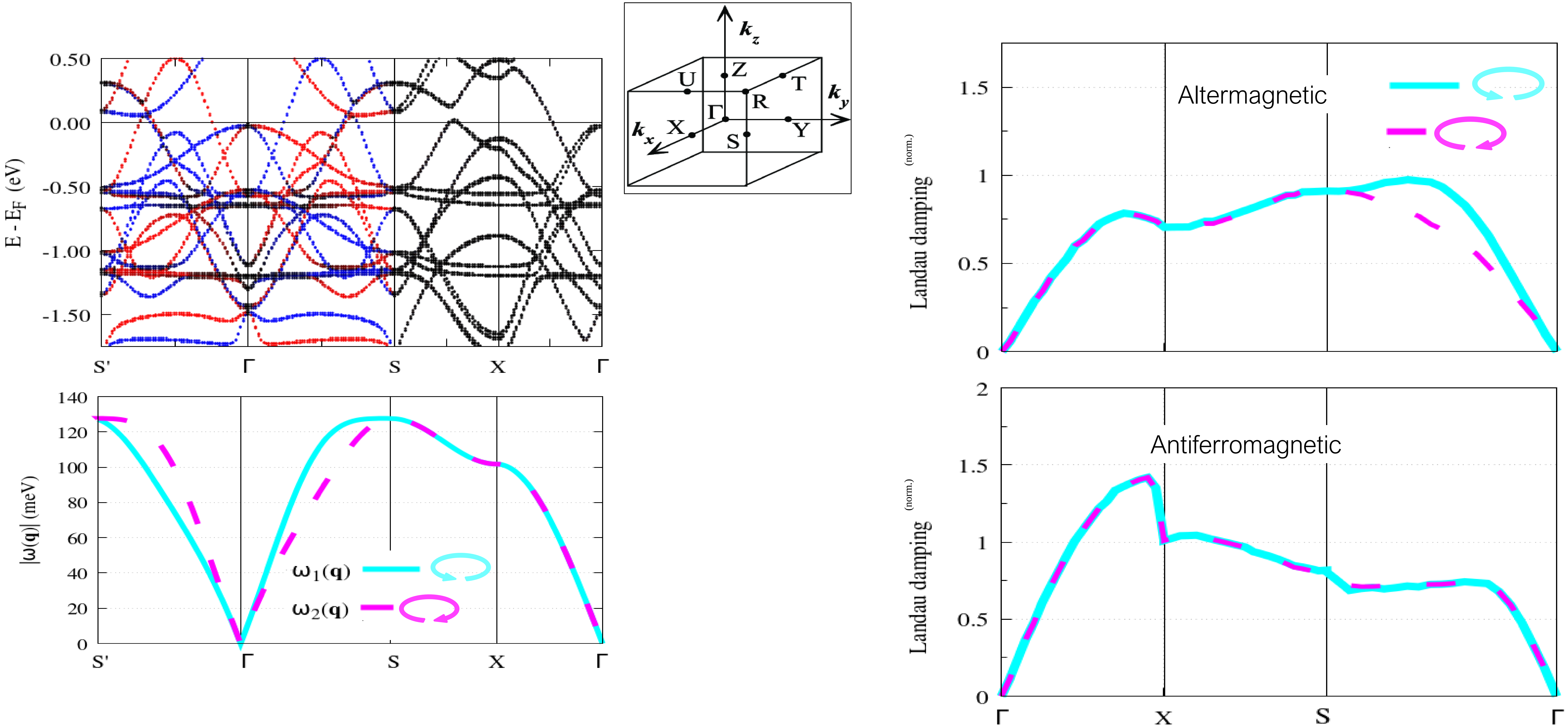
Magnons in Altermagnets



PHYSICAL REVIEW LETTERS 131, 256703 (2023)

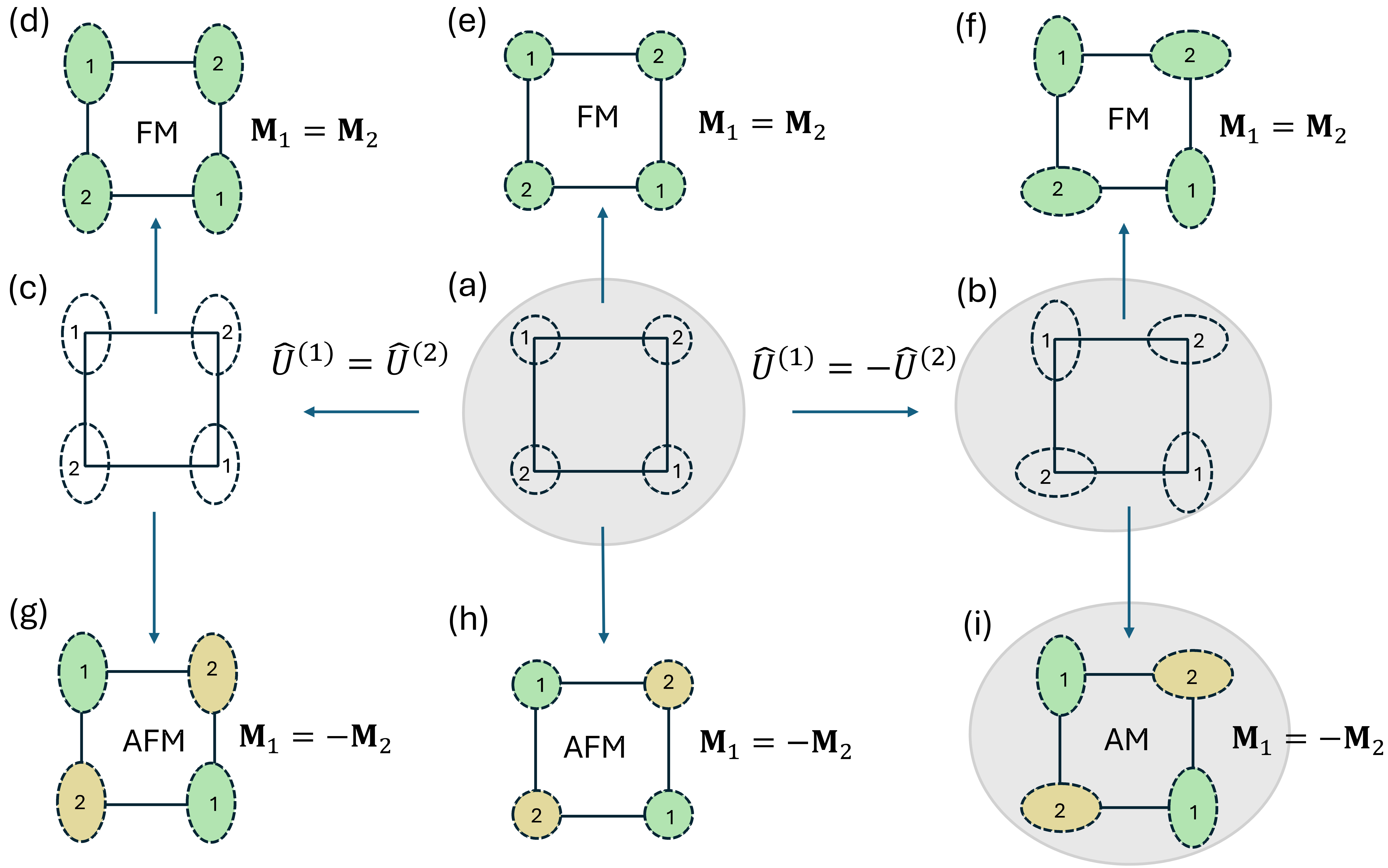
Šmejkal, Marmodoro, Ahn, Gonzalez-Hernandez, Turek, Mankovsky, Ebert, D'Souza, Šipr, Sinova, Jungwirth

Chiral Magnons in Altermagnetic RuO2



Smejkal, Marmodoro, et al, arXiv:2211.13806

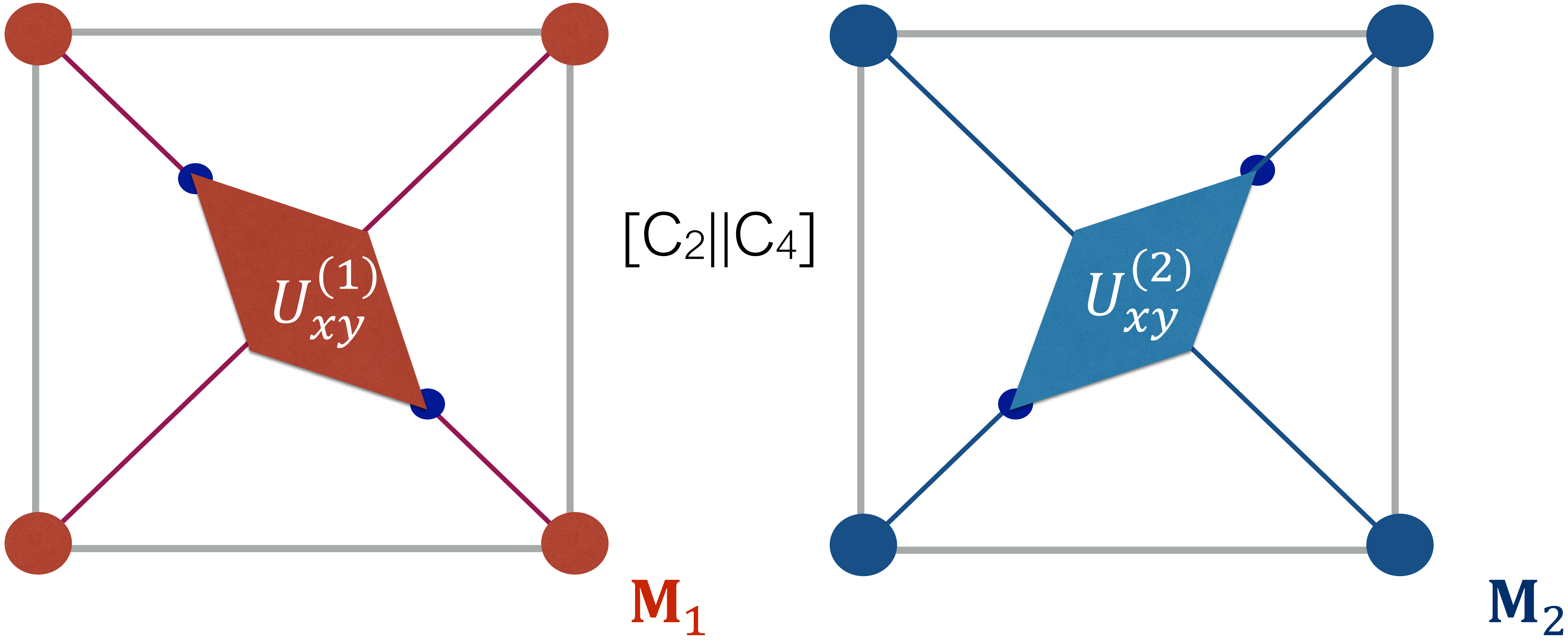
Phenomenological Landau Theory of d-wave altermagents



arXiv:2403.10218

O. Gomonay, V. P. Kravchuk, R. Jaeschke-Ubiergo, K. V. Yershov, T. Jungwirth, L. Šmejkal, J. van den Brink, J. Sinova

Order parameters & symmetry arguments



Symmetry:

$$\mathbf{M}_1 \leftrightarrow \mathbf{M}_2 \qquad U_{xy}^{(1)} \leftrightarrow -U_{xy}^{(2)}$$

$$\mathbf{m} \rightarrow \mathbf{m} \qquad \mathbf{n} \rightarrow -\mathbf{n}$$

$$U_{xy}^{(1)} - U_{xy}^{(2)} \rightarrow -U_{xy}^{(2)} - (-U_{xy}^{(1)}) \rightarrow const$$

INSP/RE group
INTERDISCIPLINARY SPINTRONICS RESEARCH

Altermagnetic features:

- Hidden magnetization => m
- Exchange coupling only => $\mathbf{m}\cdot\mathbf{n}=0$
- Inhomogeneity => $\partial\mathbf{m}\cdot\partial\mathbf{n}$
- Local symmetry $U_{xy}^{(1)} - U_{xy}^{(2)} \Rightarrow \partial_x\partial_y\mathbf{n}$
- Time reversal symmetry

$$\mathcal{F} = A_{\mathrm{AM}}[\partial_x\mathbf{m}\cdot\partial_y\mathbf{n} + \partial_y\mathbf{m}\cdot\partial_x\mathbf{n}]$$

arXiv arXiv:2403.10218

O. Gomonay, V. P. Kravchuk, R. Jaeschke-Ubiergo, K. V. Yershov, T. Jungwirth, L. Šmejkal, J. van den Brink, J. Sinova

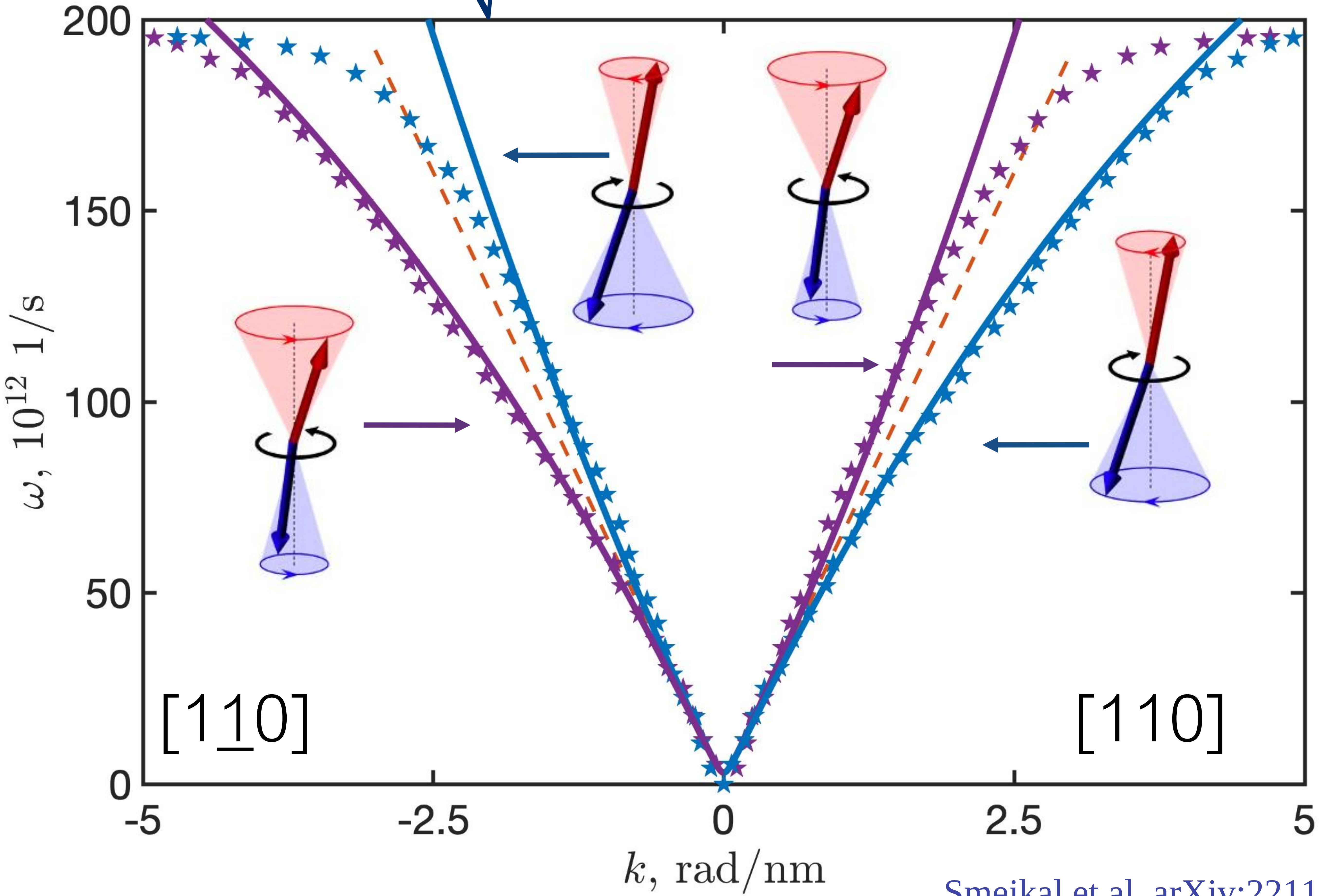
SP/CE

Magnon Dispersion from Phenomenology

INSP/RE group
INTERDISCIPLINARY SPINTRONICS RESEARCH

$$\mathcal{F} = A_{\mathrm{AM}}[\partial_x \mathbf{m} \cdot \partial_y \mathbf{n} + \partial_y \mathbf{m} \cdot \partial_x \mathbf{n}]$$

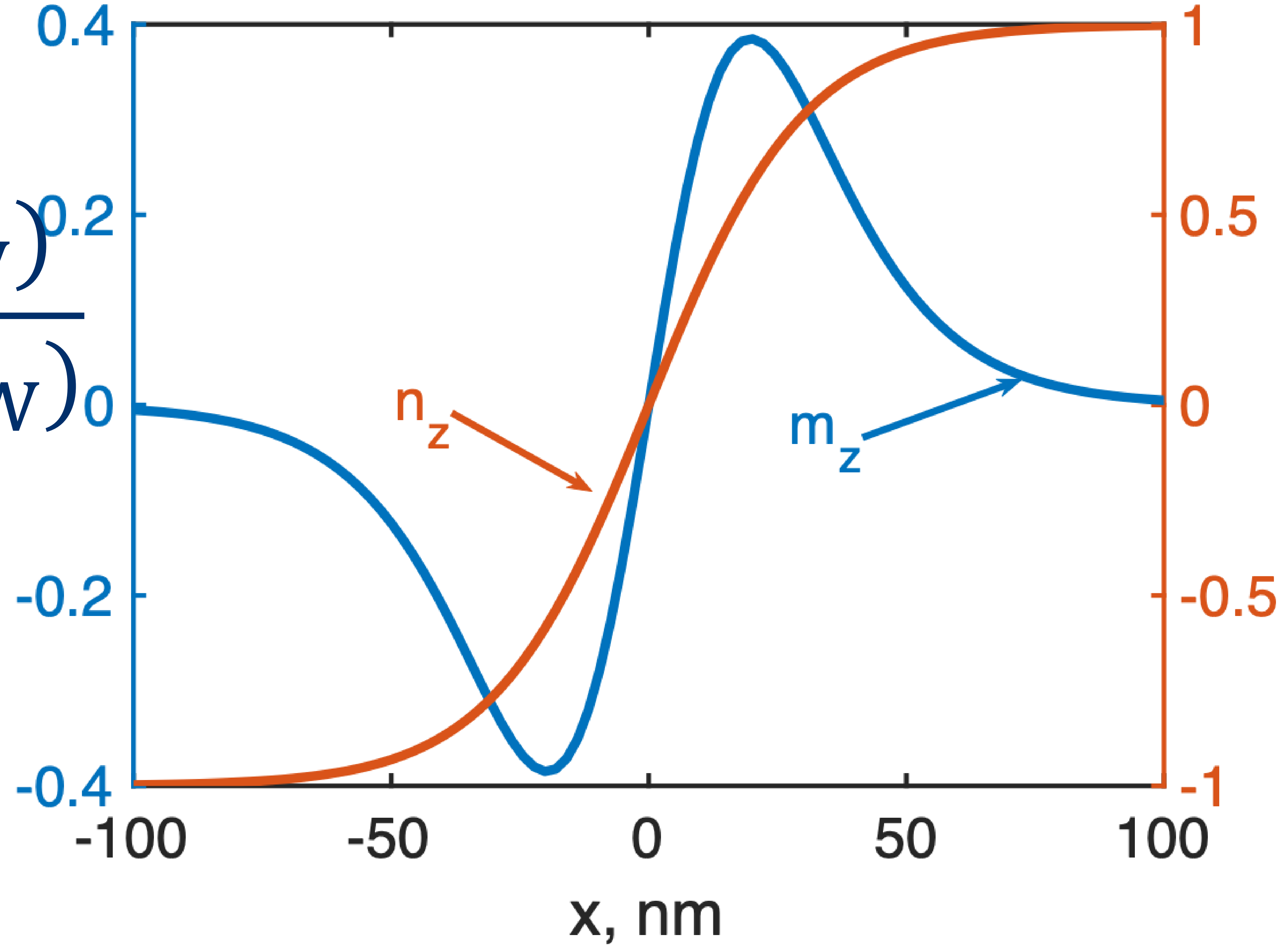
$$\omega_\pm = \sqrt{\omega_0^2 + c^2k^2 \pm 2\gamma A_{\mathrm{AM}} k_x k_y}$$

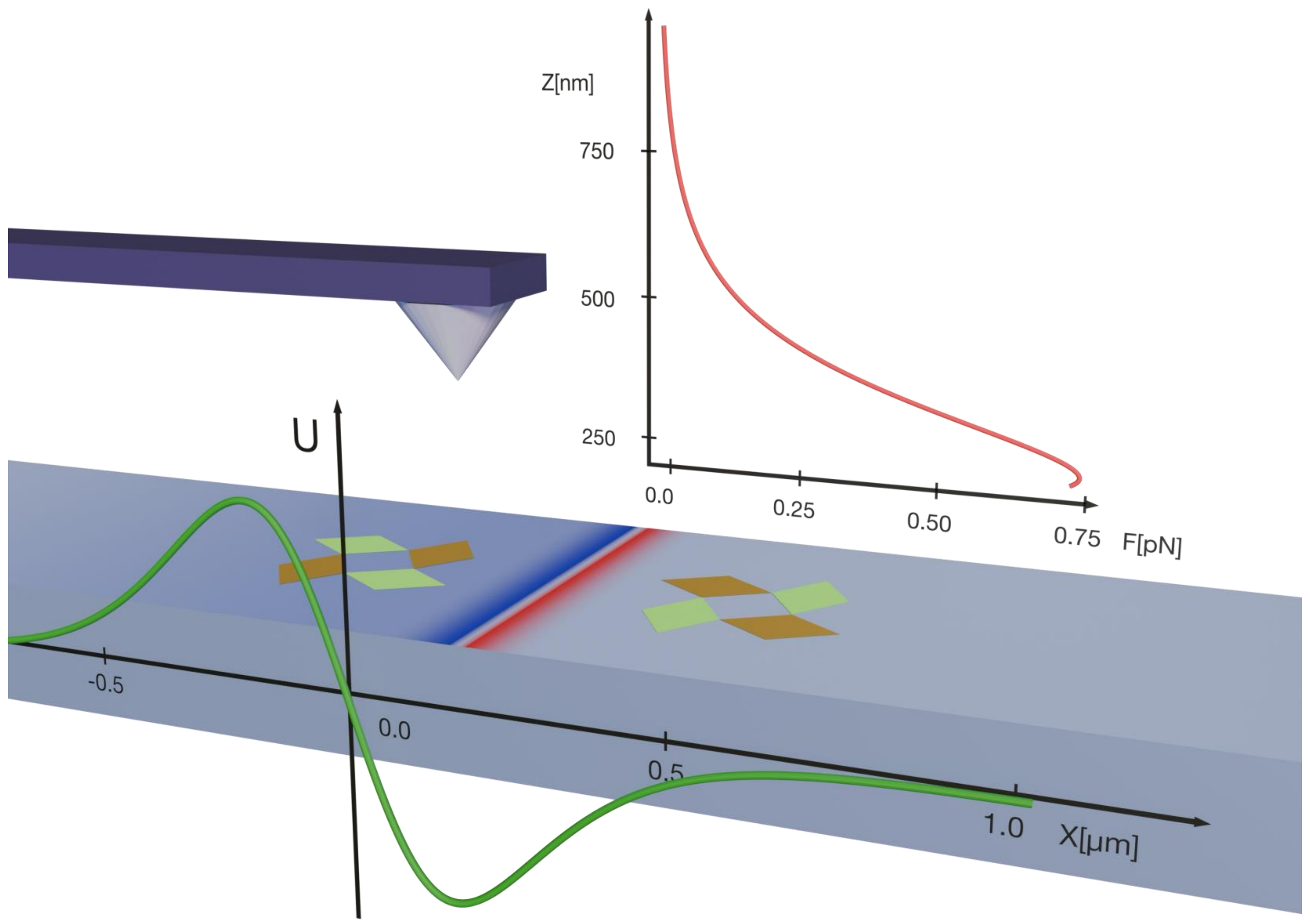


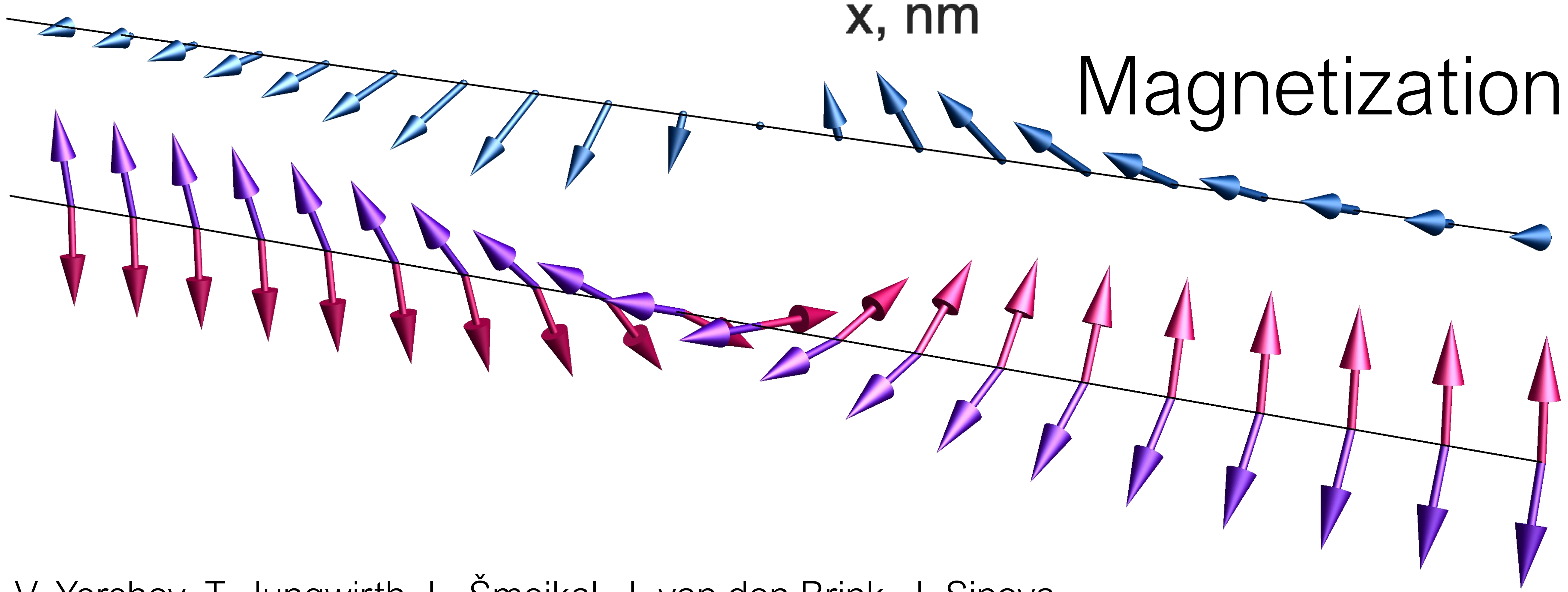
Smejkal et al, arXiv:2211.13806 (PRL 2023)

Structure of the domain wall, magnetization

$$m_z = \frac{2A_{\mathrm{AM}}}{H_{\mathrm{ex}} x_{\mathrm{DW}}^2} \frac{\sinh(x/x_{\mathrm{DW}})}{\cosh^3(x/x_{\mathrm{DW}})}$$







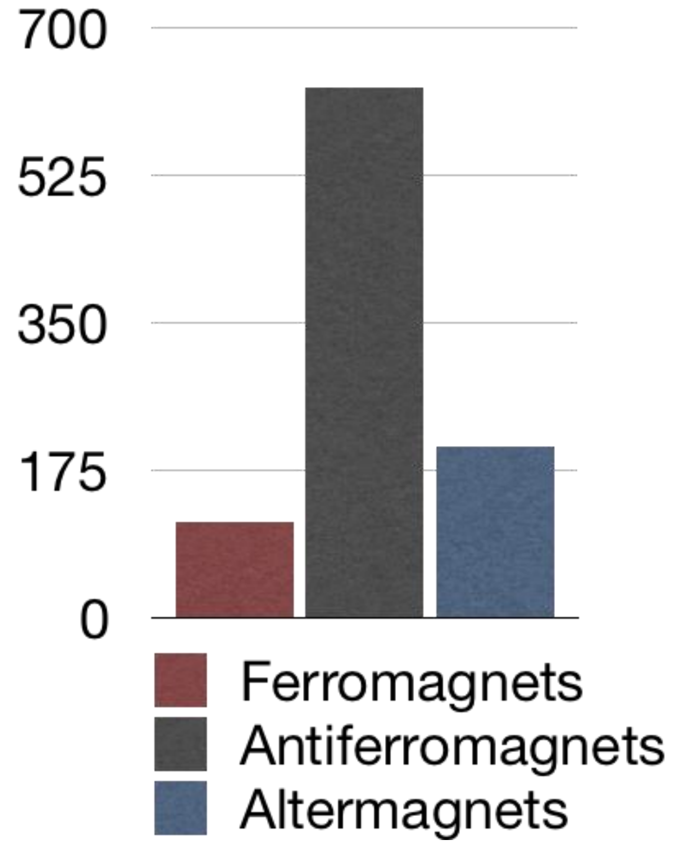
Magnetization

arXiv:2403.10218

O. Gomonay, V. P. Kravchuk, R. Jaeschke-Ubiergo, K. V. Yershov, T. Jungwirth, L. Šmejkal, J. van den Brink, J. Sinova

Emerging research landscape of altermagnetism and p-wave magnetism

Broad range of condensed-matter physics fields:



> 220 material candidates
- insulating
  semiconducting
  semimetallic
  metallic
  superconducting

- rutile, perovskites, corundum,….

- cuprate, ferrite, silicide, pnictide, chalcogenide,…

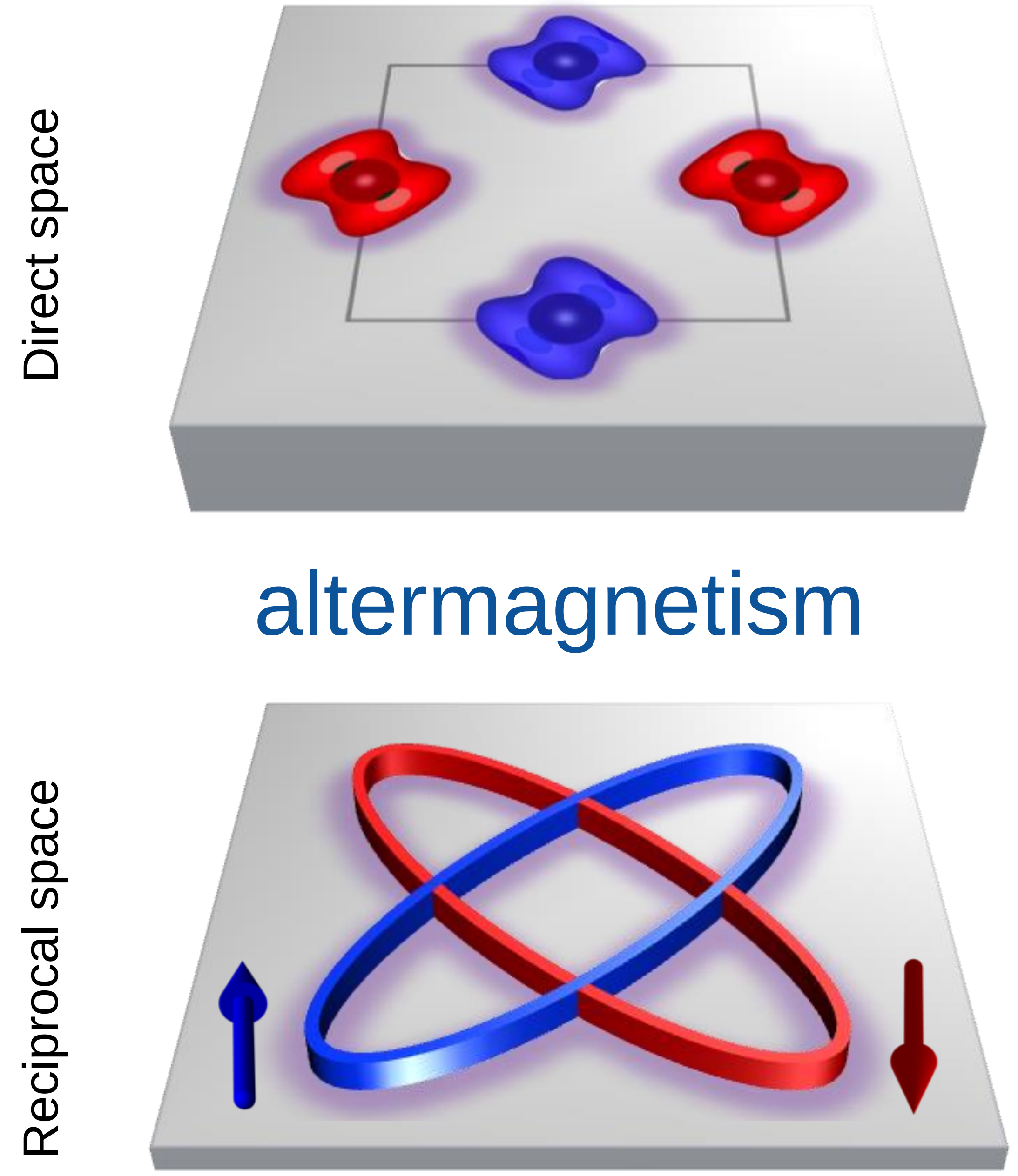
- 3D and 2D

ScienceAdvances 6, eaaz8809 (2020)
(arXiv:1901.00445)Šmejkal, González-Hernández, Jungwirth, Sinova

PHYSICAL REVIEW X **12**, 031042 (2022)
PHYSICAL REVIEW X (Perspective) **12**, 040501 (2022)

Šmejkal, Sinova, and Jungwirth

Spintronics
2D magnetism
Ultrafast optics
Magnetic topological matter
Neuromorphics
Superconductivity
Magnonics
Superconducting spintronics
Valleytronics
Field-effect electronics
Multiferroics
Thermoelectrics

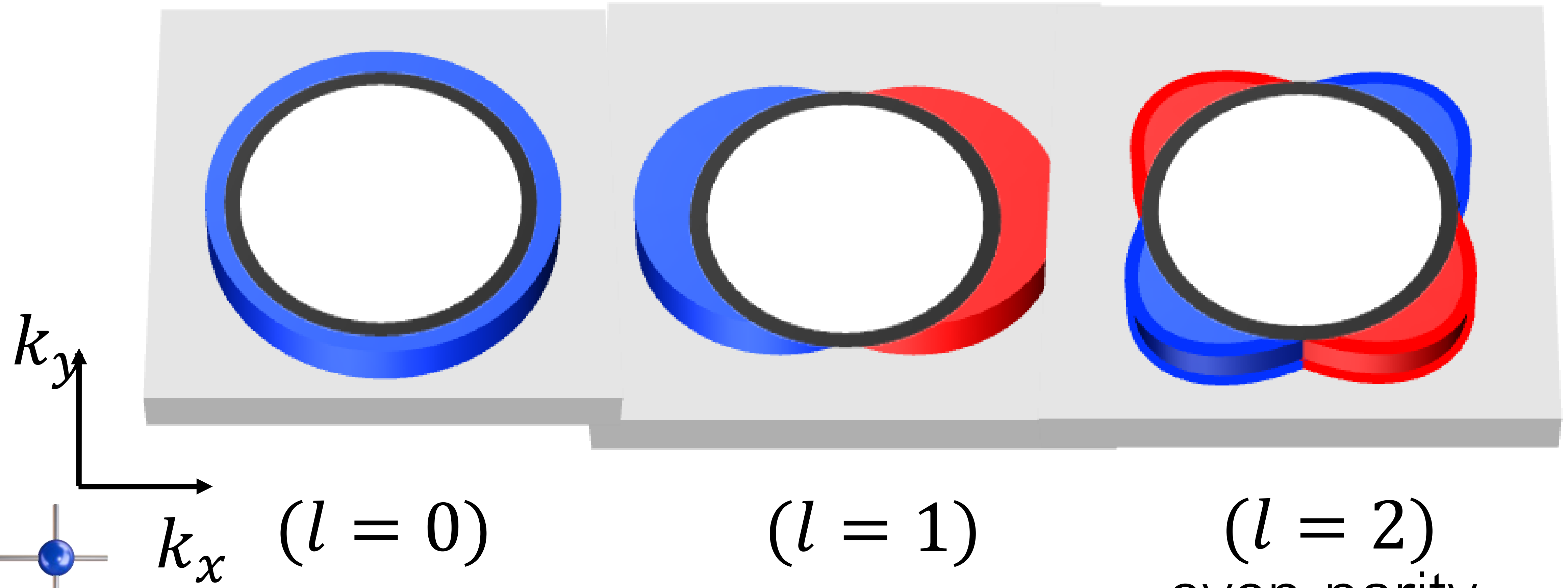


Unconventional p-wave magnetism: *T* – symmetric spin polarization

s-wave superconductivity (Mercury 1911)

p-wave supe (Helium-3 1

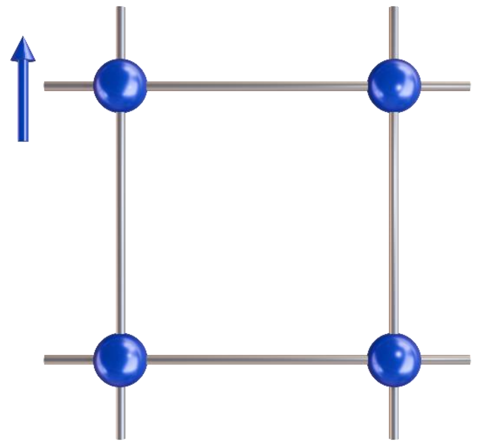
d-wave superconductivity (Cuprates 1986)

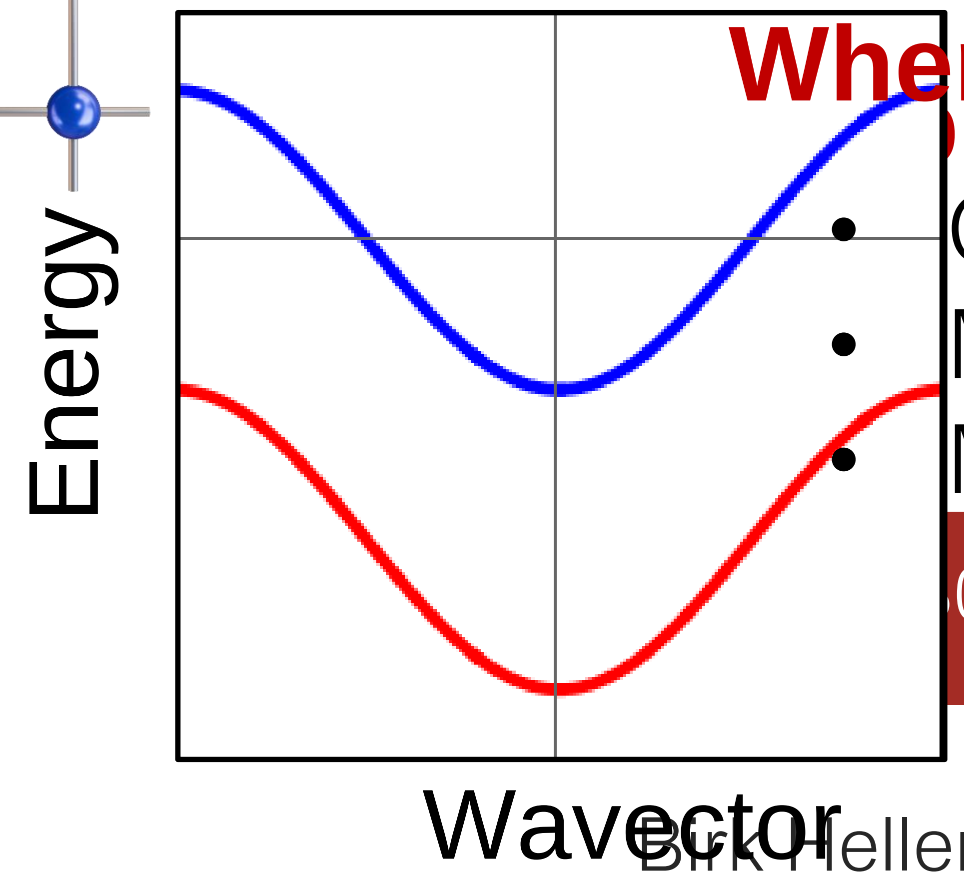


$(l = 0)$ even-parity

$(l = 1)$ odd-parity

$(l = 2)$ even-parity





Where to start looking?

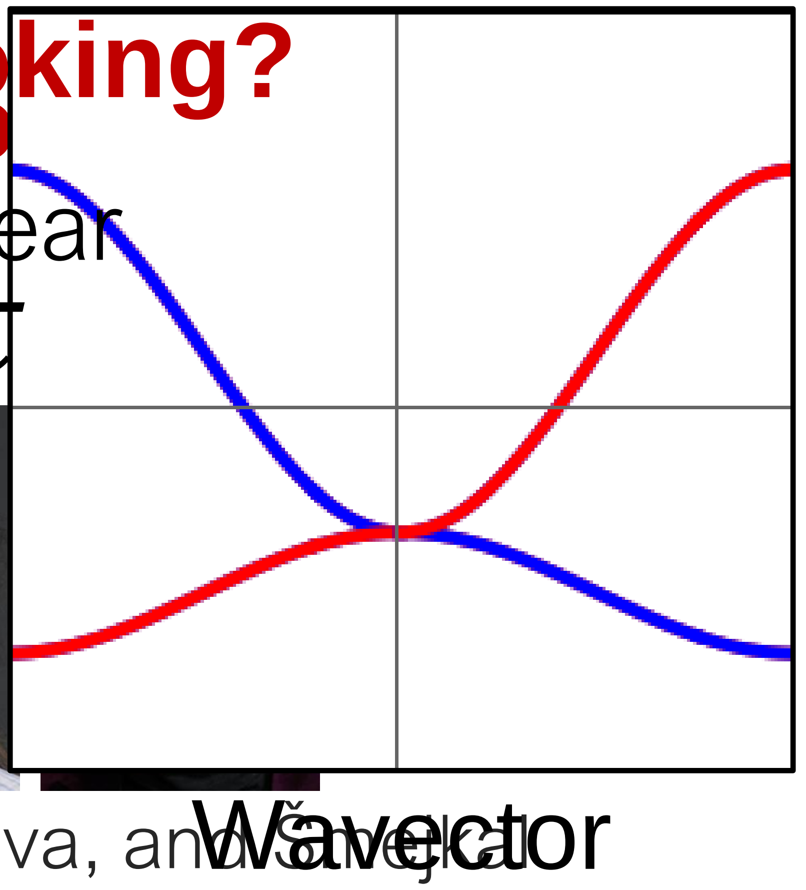
in group theo

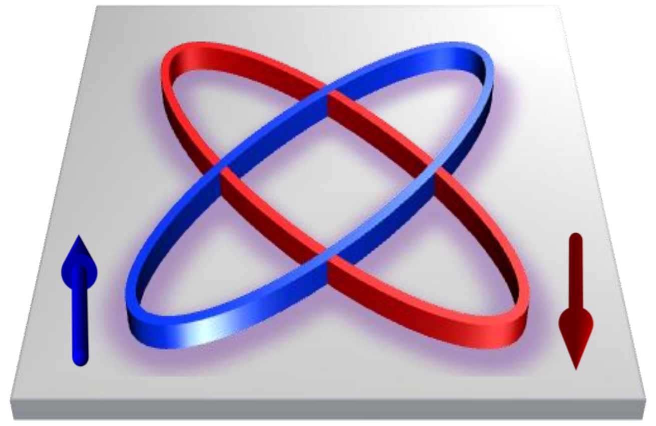
- Cannot be collinear
- Must break $\mathcal{P}\mathcal{T}$
- Must break $\mathcal{P}$

impossible?

09.01607

$\mathcal{T}t$





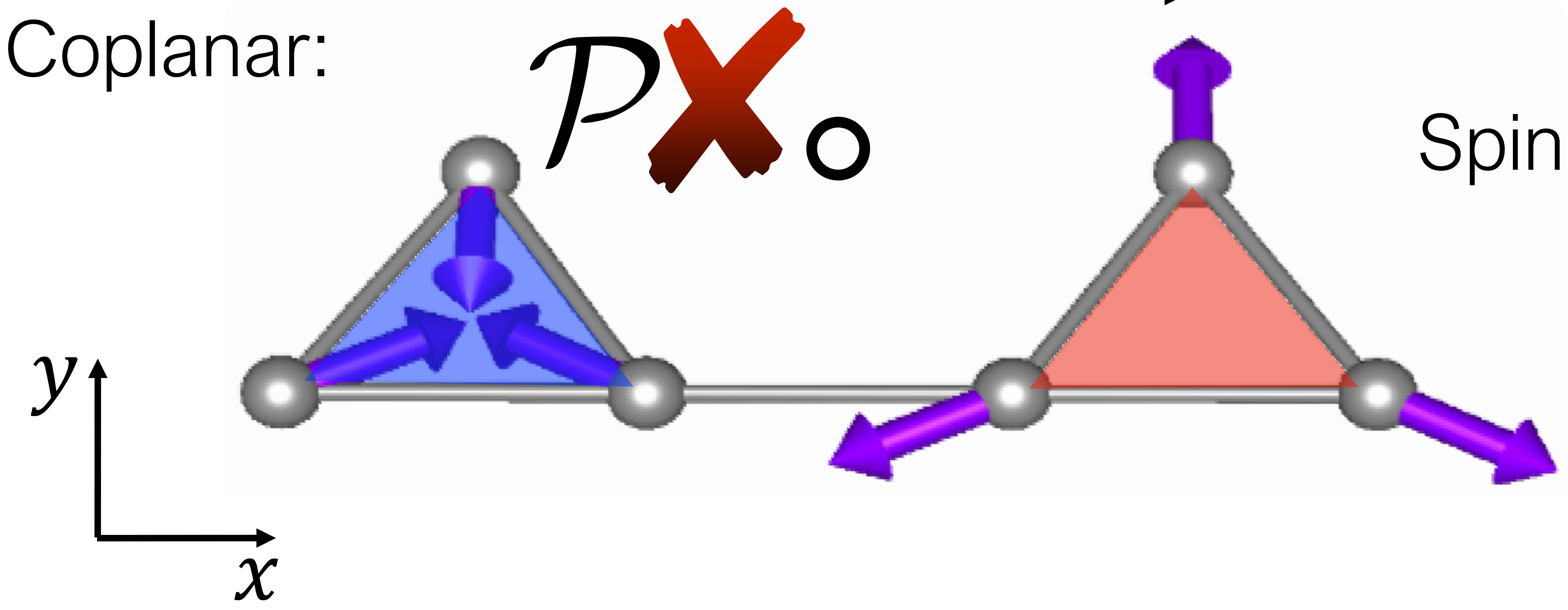
Birk Hellenes, Jungwirth, Sinova, and Šmejkal

Model p-wave magnetism

(magnetic exchange + single-particle physics) + symmetry-protected

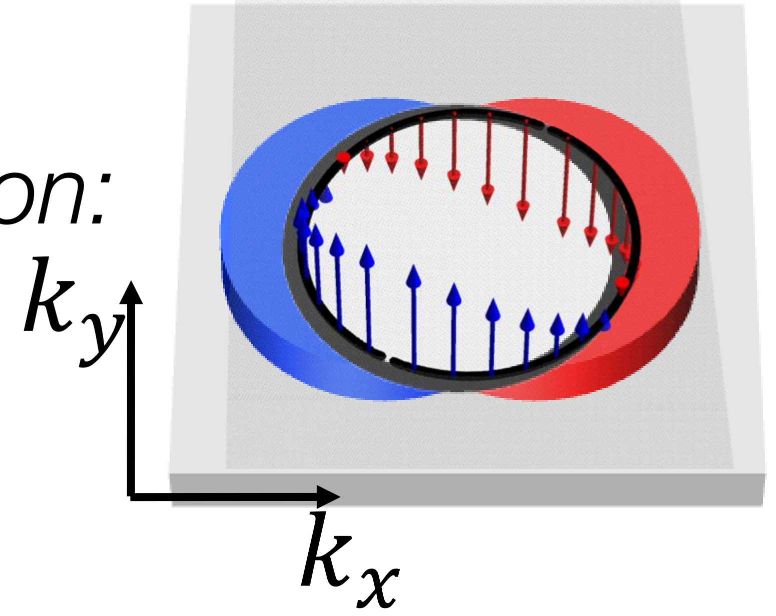
$\mathcal{T}t$ ✔

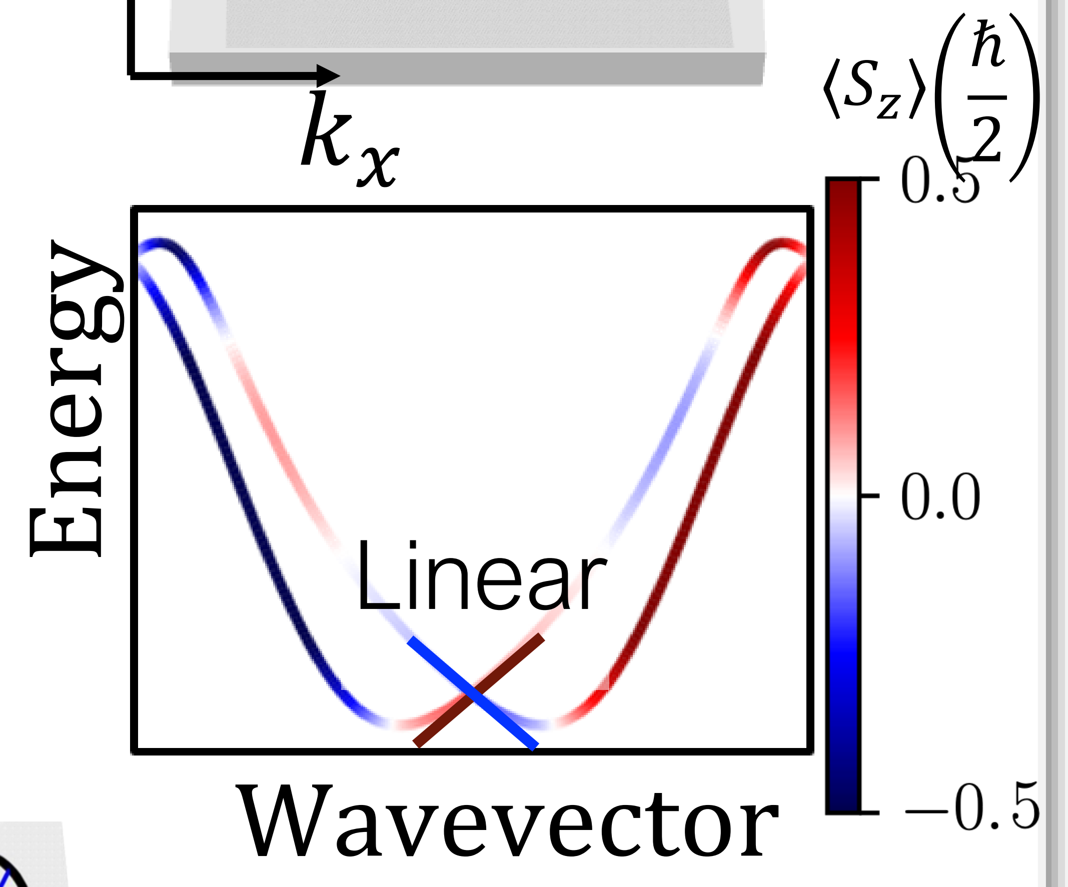
Coplanar: $\mathcal{P}$ ✘ $\circ$



Spin only: $C_{2\perp}\mathcal{T}$ ✔ Collinear

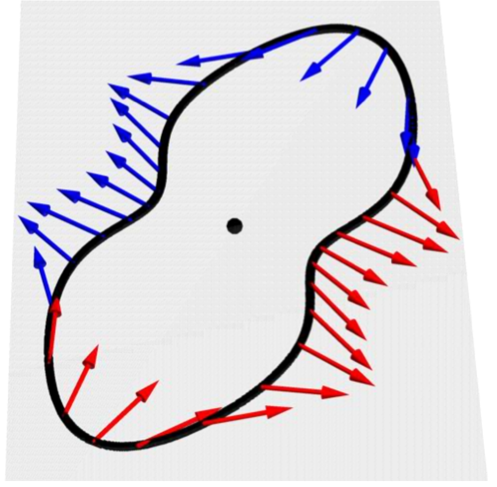
Spin-polarization:

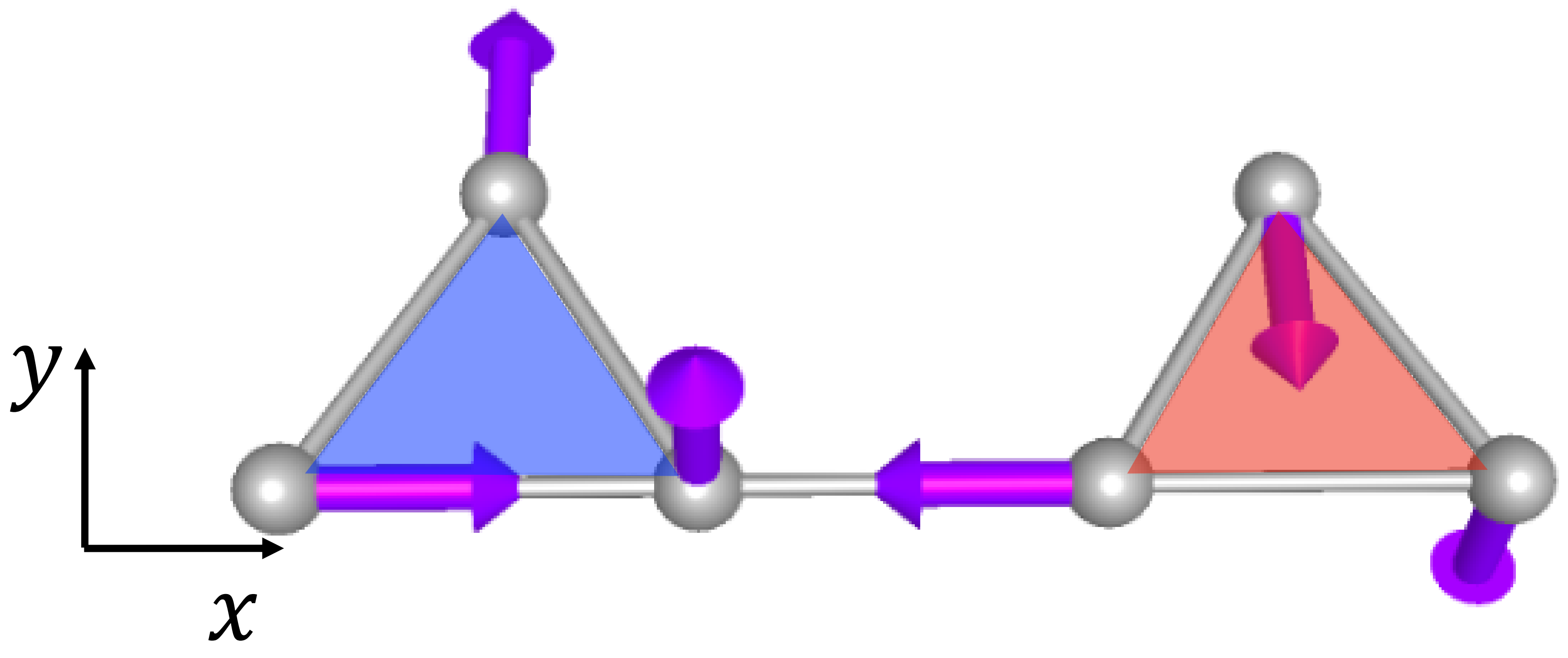




Noncoplanar:

Spin only: $C_{2\perp}\mathcal{T}$ ✘ Coplanar





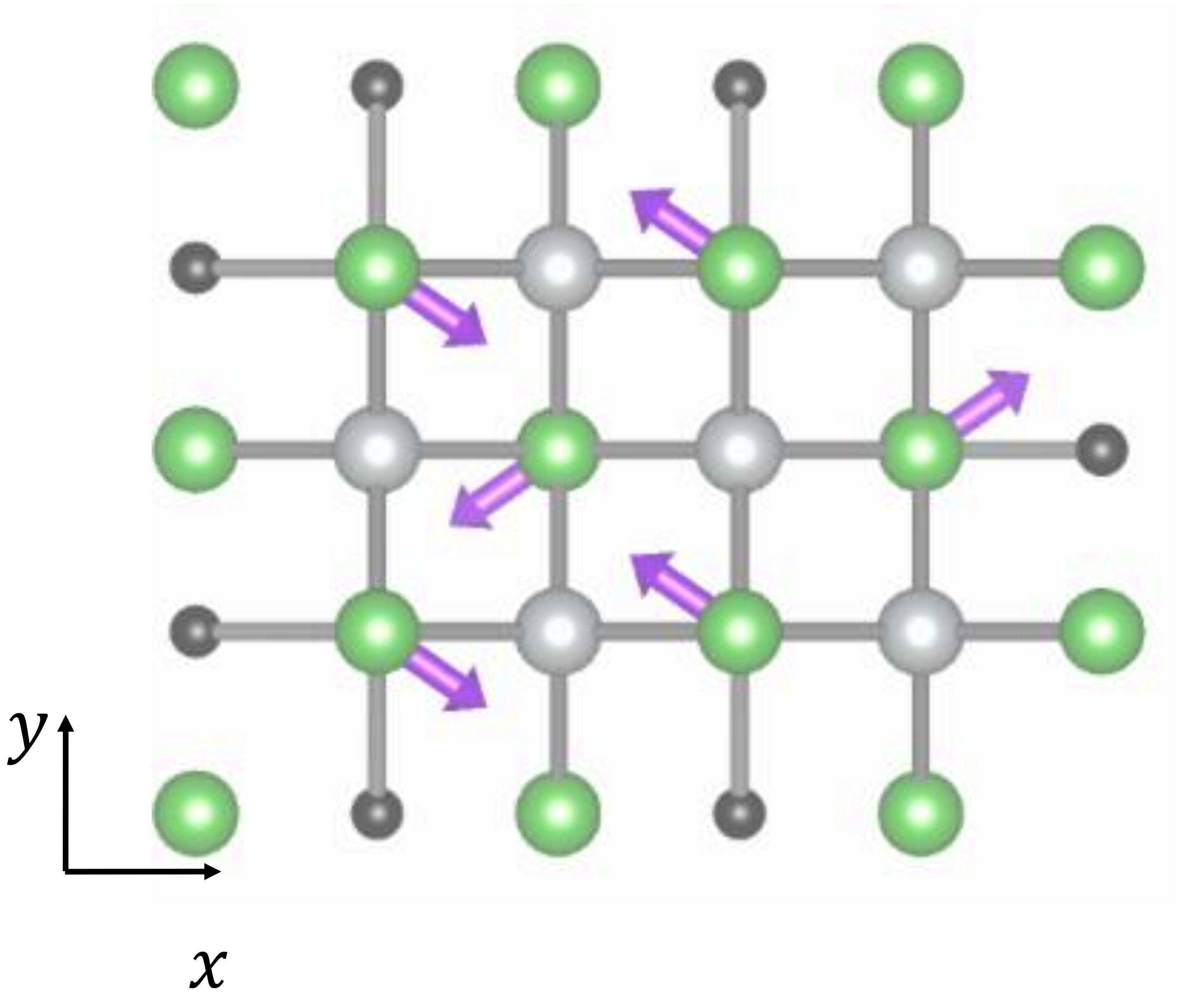
arXiv 2309.01607

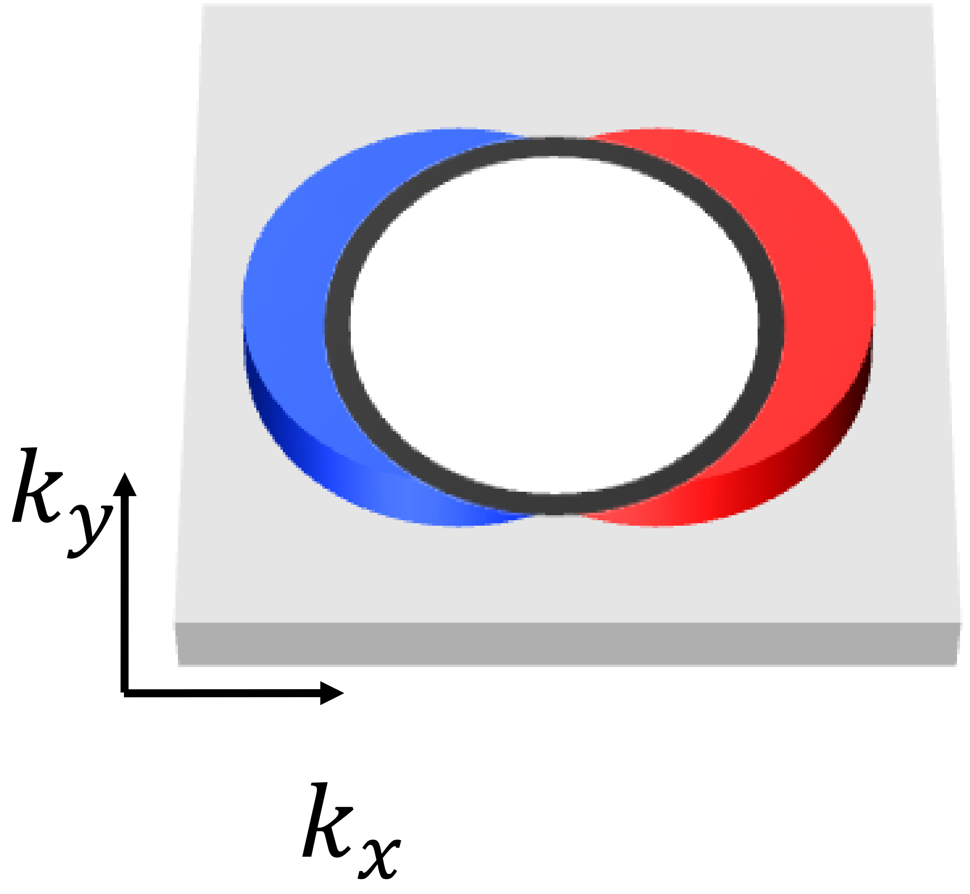
arXiv:2309.01607v2

Birk Hellenes, Jungwirth, Sinova, and Šmejkal

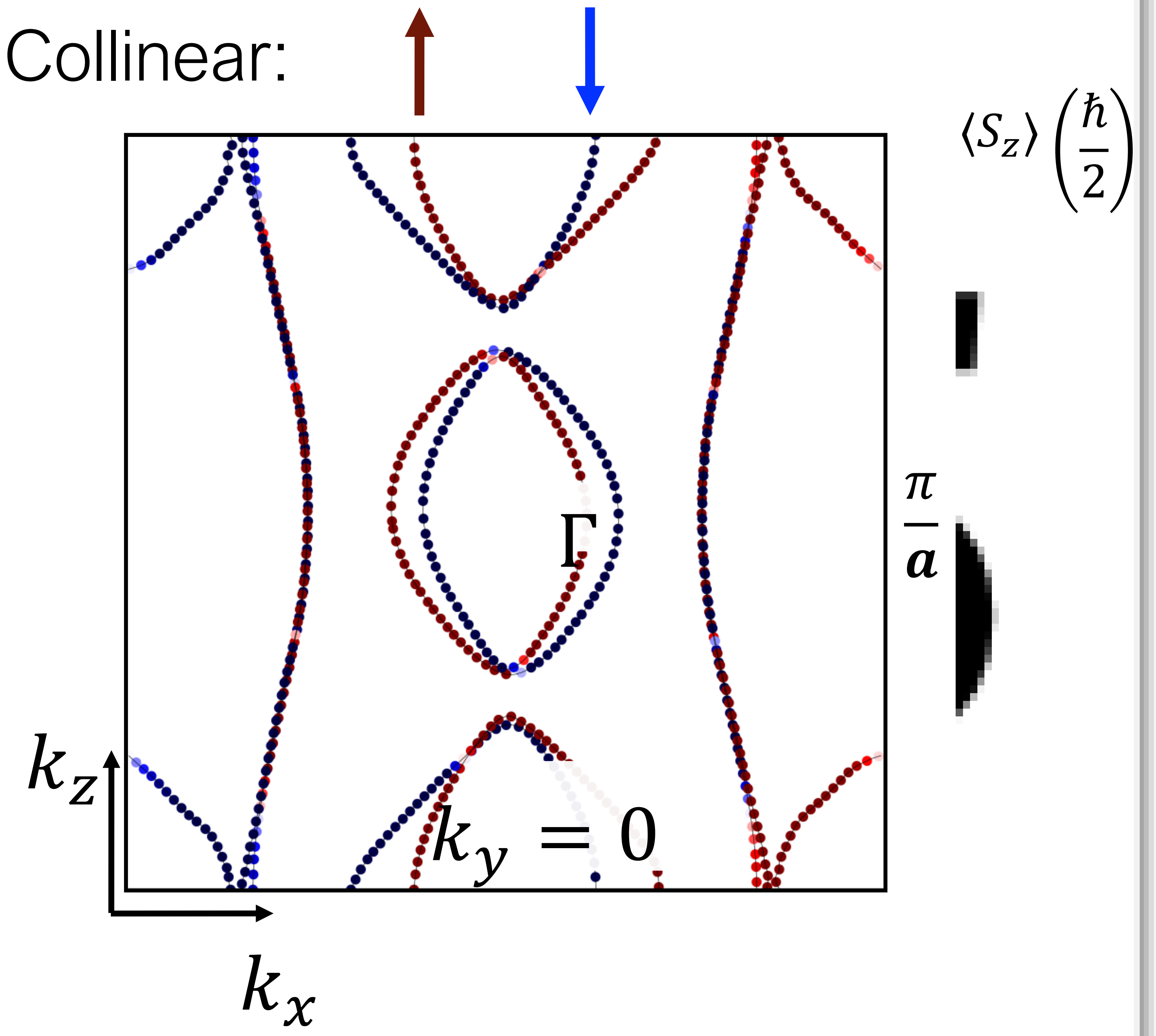
P-wave materials behave as expected

(magnetic exchange + single-particle physics) + symmetry-protected
CeNiAsO





Collinear: ↑ ↓



$\mathcal{T}t \longrightarrow$ ✓

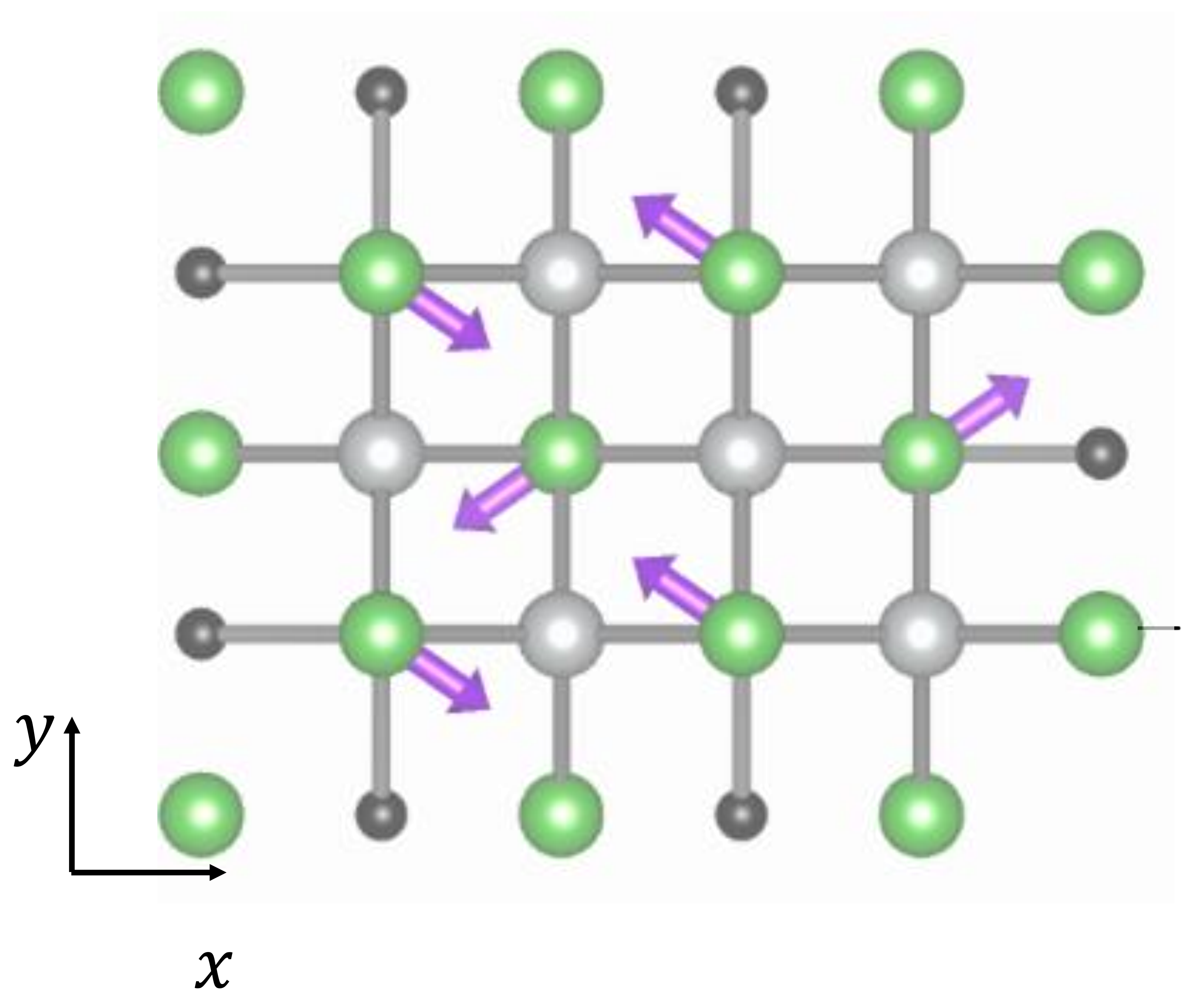
arXiv 2309.01607 arXiv:2309.01607v2

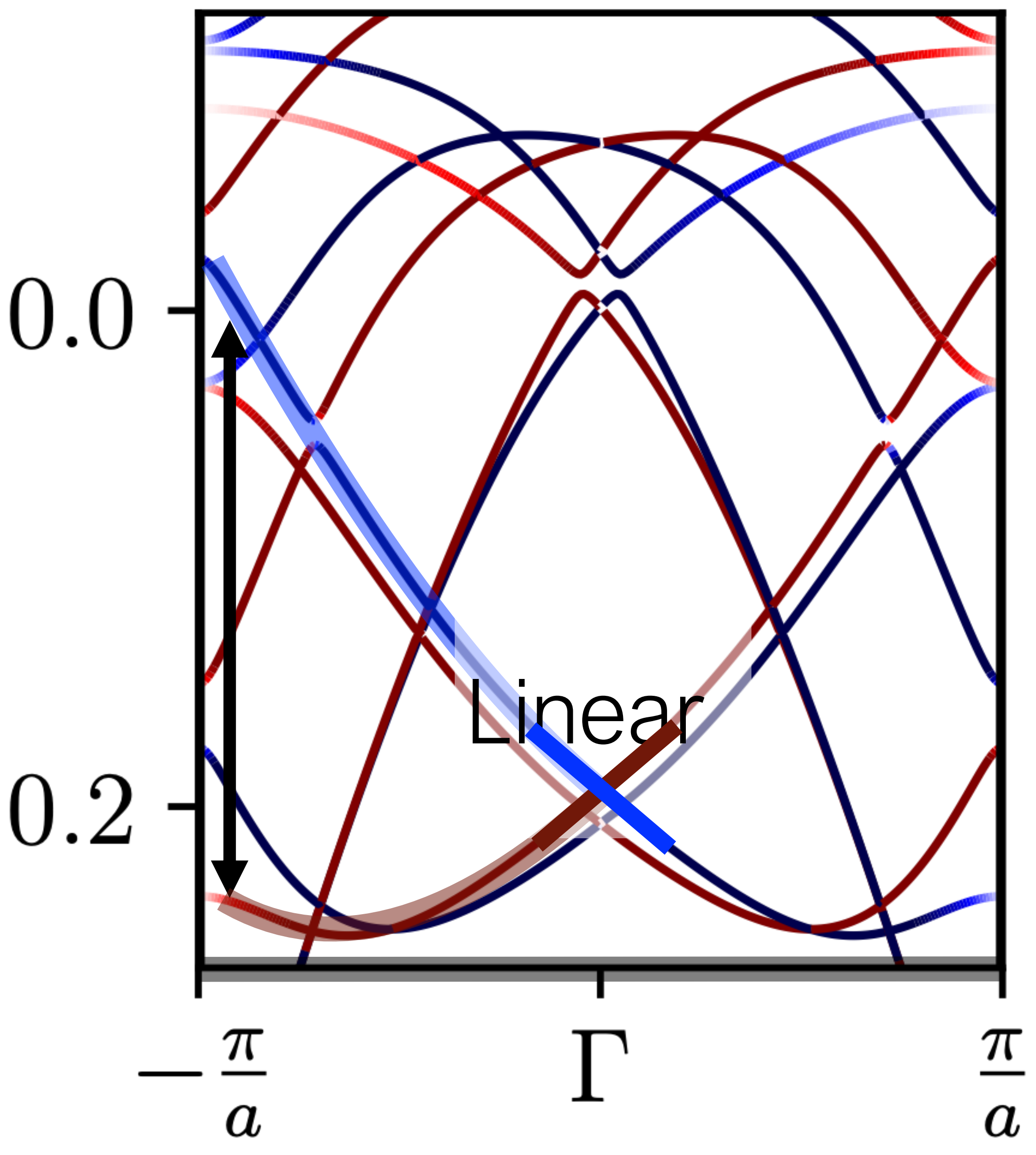
Birk Hellenes, Jungwirth, Sinova, and Šmejkal

P-wave materials behave as expected

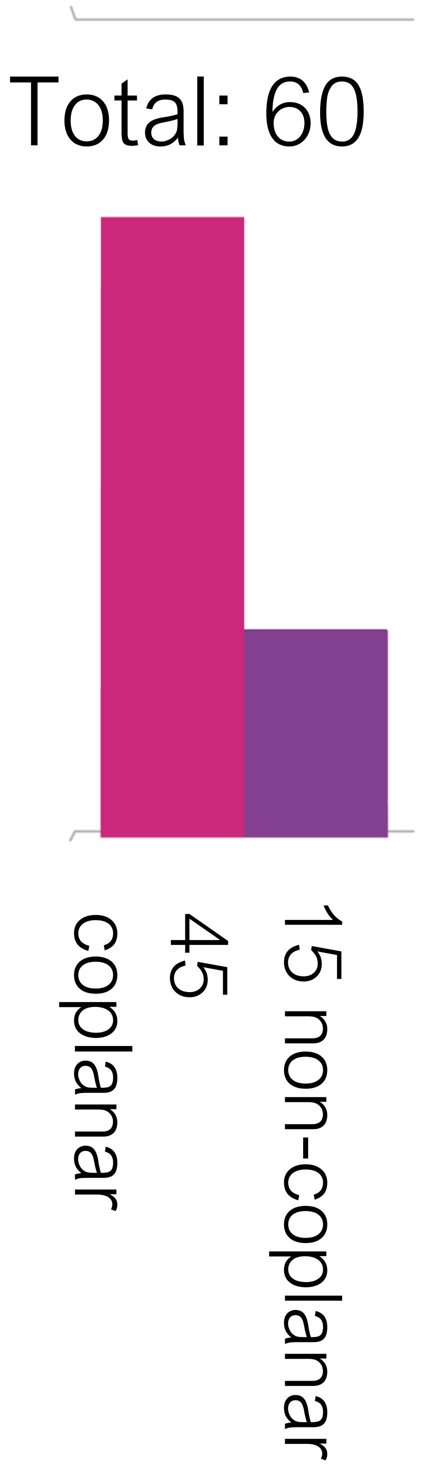
(magnetic exchange + single-particle physics) + symmetry-protected

CeNiAsO





~ 200 meV

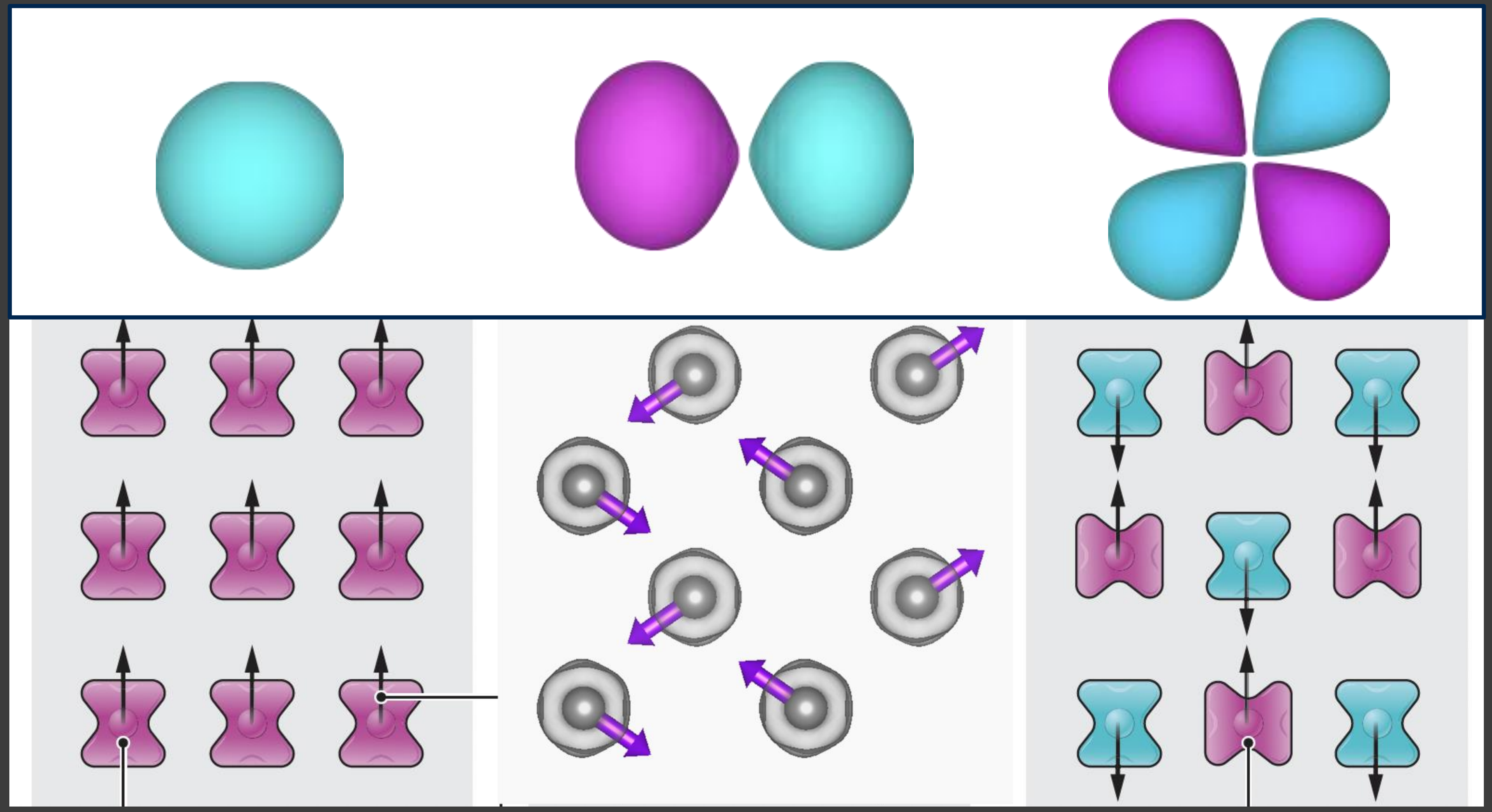


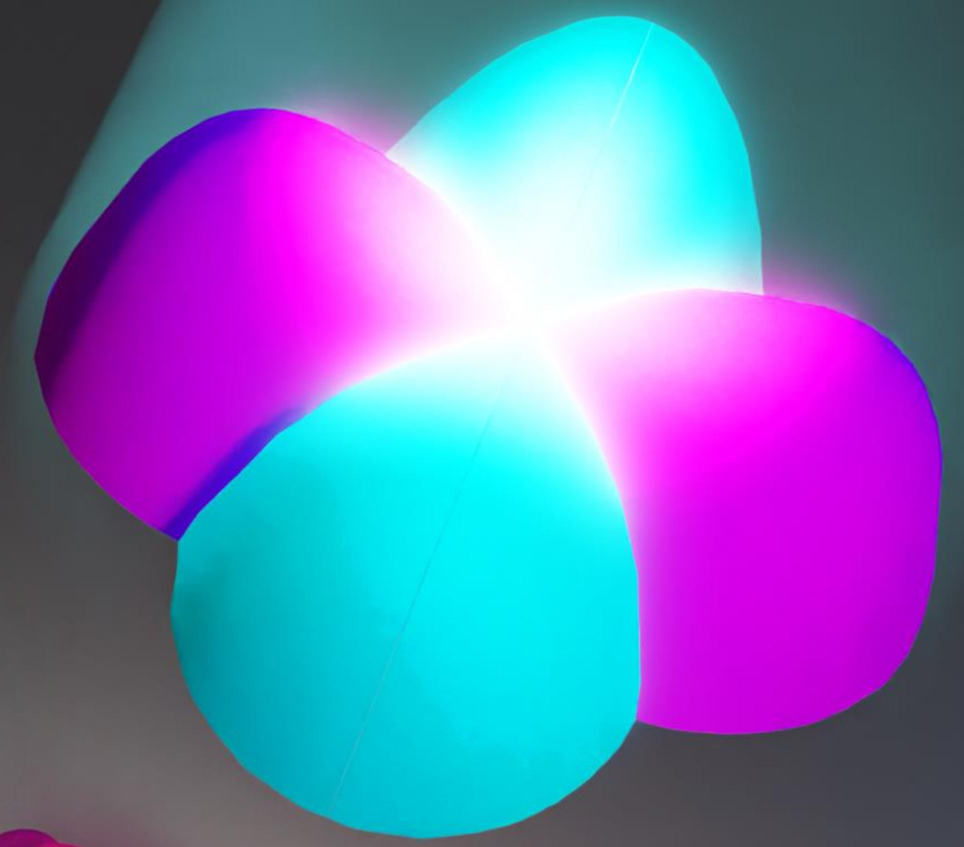
k_x ⟶ ✓

arXiv 2309.01607 arXiv:2309.01607v2

Birk Hellenes, Jungwirth, Sinova, and Šmejkal

Summary: key concepts in discovering magnetic phases





	Anomalies in spintronics (2018-)	Altermagnetism (d-wave magnetism) and spin groups (2021-)	Unconventional p-wave magnets (2023-)
Prediction	LŠ et al., Science Adv. (2020) Mazin, LŠ et al., PNAS 118 (2021) LŠ et al. Phys Rev X 12, 011028 (2022)	LŠ, Sinova, Jungwirth, Phys. Rev. X (2022)	Birk Hellenes, Jungwirth, Sinova & LŠ arXiv:2309.01607v2
Observation	Feng*, LŠ* et al., Nature Electron. (2022) Fedchenko, LŠ, Science Adv. (2024)	Krempasky*, LŠ* et al., Nature (2024) Lee, LŠ et al. Phys. Rev. Lett. (2024) Reimers, LŠ et al., Nature Com (2024)	
	(2022)		

The Magnetic Susceptibility of MnO as a Function of the Temperature

Rayen Welch Tyler
Phys. Rev. **44**, 776 – Published 1 November 1933

Neutron Diffraction by Paramagnetic and Antiferromagnetic Substances

C. G. Shull, W. A. Strauser, and E. O. Wollan
Phys. Rev. **83**, 333 – Published 15 July 1951

INFLUENCE DES FLUCTUATIONS DU CHAMP MOLÉCULAIRE SUR LES PROPRIÉTÉS MAGNÉTIQUES DES CORPS

Par L. NÉEL

Šmejkal

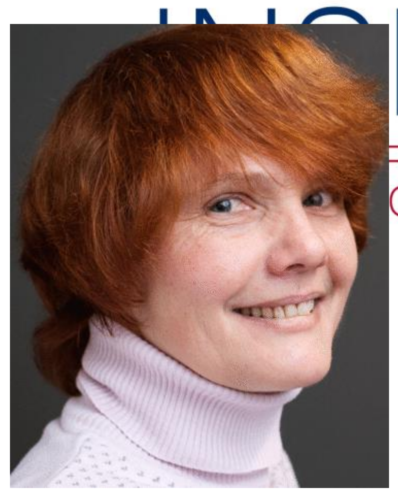
Jungwirth

R. Jaschke

A. Chakraborty

W. Campos

B. Karetta



O. Gomonay

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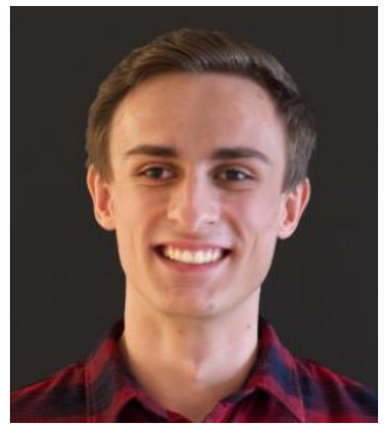
A. B. Hellenes

VK Bharadwaj

N. Alvarez



M. Greber

Rafael Gonzalez-Hernandez (Colombia), Zhiqi Liu (Peking), Vincent Baltz (Grenoble), Lisa Michez (Marseille), Helena Reichlova, Dominik Kriegner, Sebastian Goennenwein, Mathias Kläui, Hans Joachim Elmers, Yuriy Mokrousov (Julich), Juraj Krempasky (PSI) , Roser Valenti (GU Frankfurt), Jan Minar

Open positions: sinova@uni-mainz.de