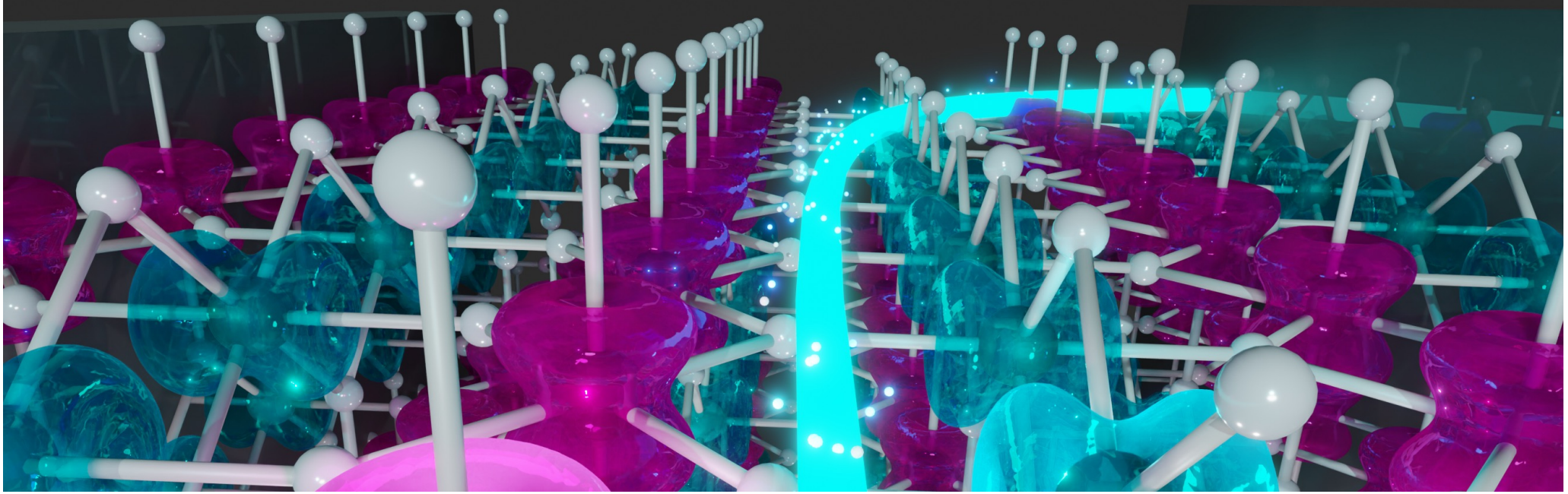
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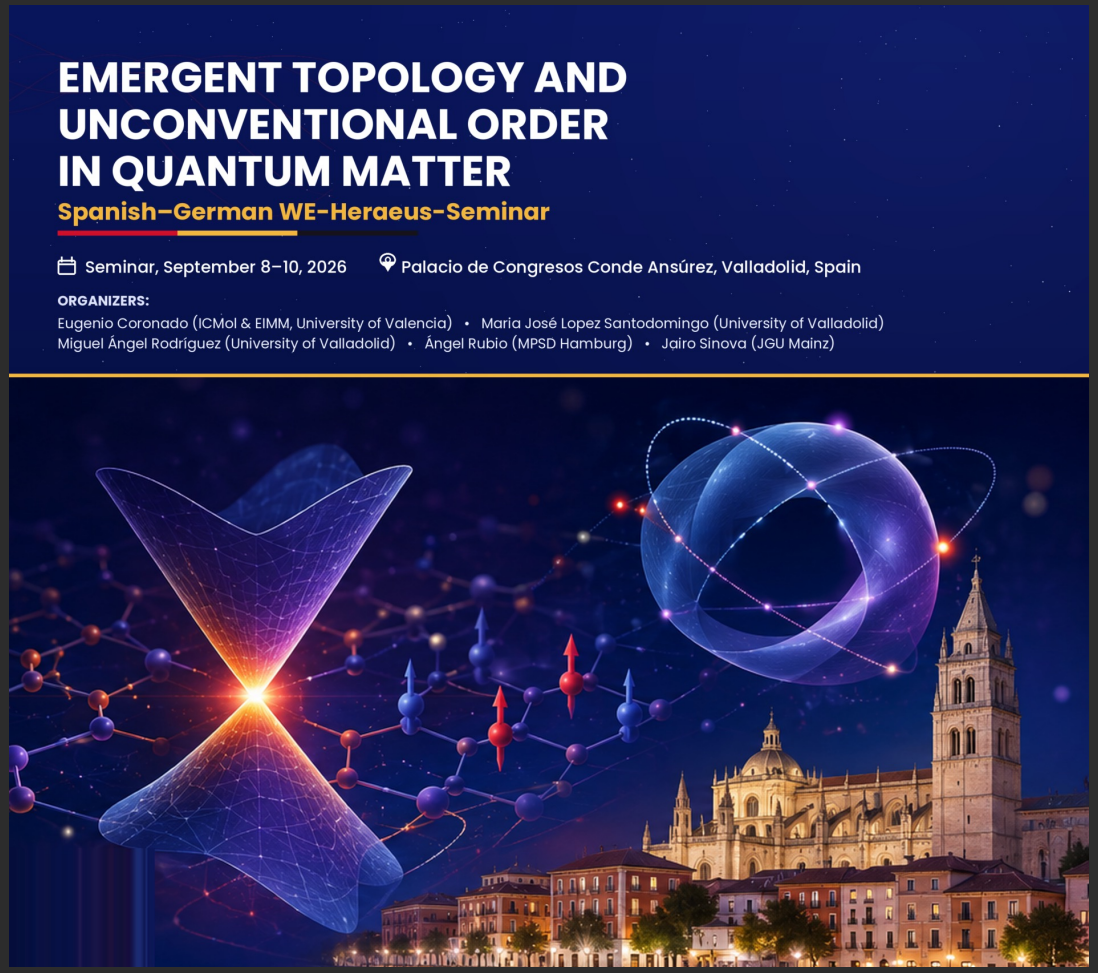
Libor Šmejkal
Max Planck Institute for the Physics of Complex Systems, Dresden, Germany
Max Planck Institute for Chemical Physics of Solids, Dresden, Germany
Institute of Physics, Czech Academy of Sciences, Czech Republic

9.9.2026
Emergent Topology and Unconventional Order in Quantum Matter – Spanish-German WE-Heraeus-Seminar

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Acknowledgement



Acknowledgement

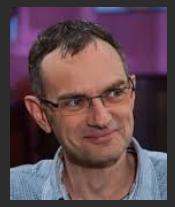


Tomáš
Jungwirth



Jairo
Sinova

Acknowledgement


Tomáš Jungwirth


Jairo Sinova


Igor Mazin


Rafael Gonzalez-Hernandez

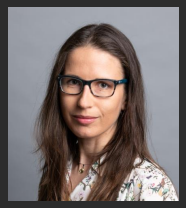

Allan MacDonald


Rafael Fernandes


Eduardo Fradkin


Johannes Knolle


Shuichi Murakami


Helena Reichlova


Dominik Kriegner


Juraj Krempasky

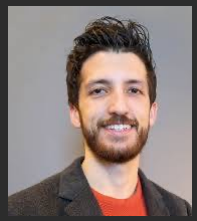

Pete Wadley


Oliver Amin


Alfred Dal Din


Jiaruo Liu

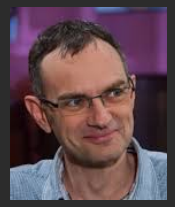

Riccardo Comin


Lucas Caretta


Claudia Ferlser

Yuriy Mokrousov (Jülich), Leonid Golub (Regensburg), Wanxiang Feng, Yugui Yao (Beijing), Hugo Dil (EPFL), Sebastian Goennenwein (Konstanz), Angela Witmann, Olena Gomonay, Ricardo Zarzuela, Hans Joachim Elmers, Martin Jourdan, Mathias Kläui (Mainz), Kyohoon Ahn (Prague),Vincent Baltz (Grenoble), Roser Valenti (Frankfurt), Johannes Knolle (Munich), Laura Classen (MPI Stuttgart), Hikaru Watanabe, Hiroki Yoshida, Satoru Nakatsuji (Tokyo), Andy Thomas, Claire Donelly, Erjian Cheng, Mohsen Yarmohammadi (Georgetown), Maxim Khodas (Racah), Zhongkai Liu (Shanghai)

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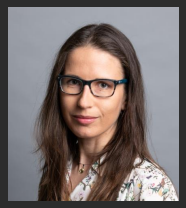

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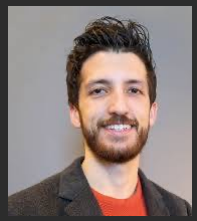

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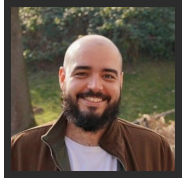

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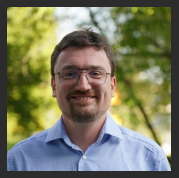

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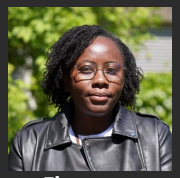
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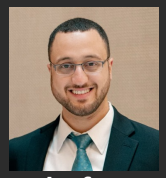
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Functional | Quantum | Matter

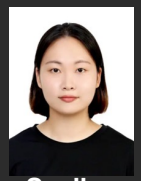

Warlley Campos

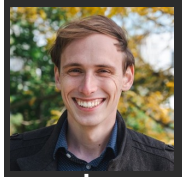

Johannes Mitscherling

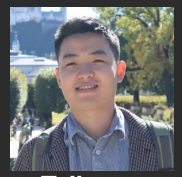

Florette Fobasso


Jaafar Ansari

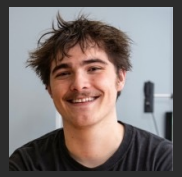

Kartik Samanta

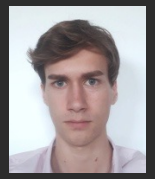

Seojin Kim


Jan Priessnitz


Taikang Chen

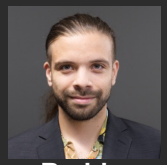

Nicoly Hembeck

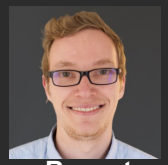

Joseph Poata

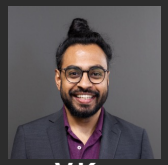

Tobias Polacek


Clara Geschner

DFG TRR TRR 173 Spin+X
(Kairserslautern+Mainz)

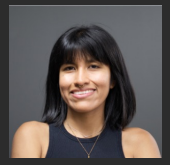

Rodrigo Jaeschke


Bennet Karetta


V.K. Bharadwaj

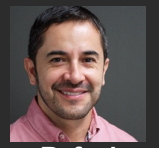
DFG TRR 288 Elasto-Q-Mat
(Frankuft+Karlsruhe+Frankfurt+Dresden)


Atasi Chakraborty


Nayra Alvarez


Xanthe Verbeek

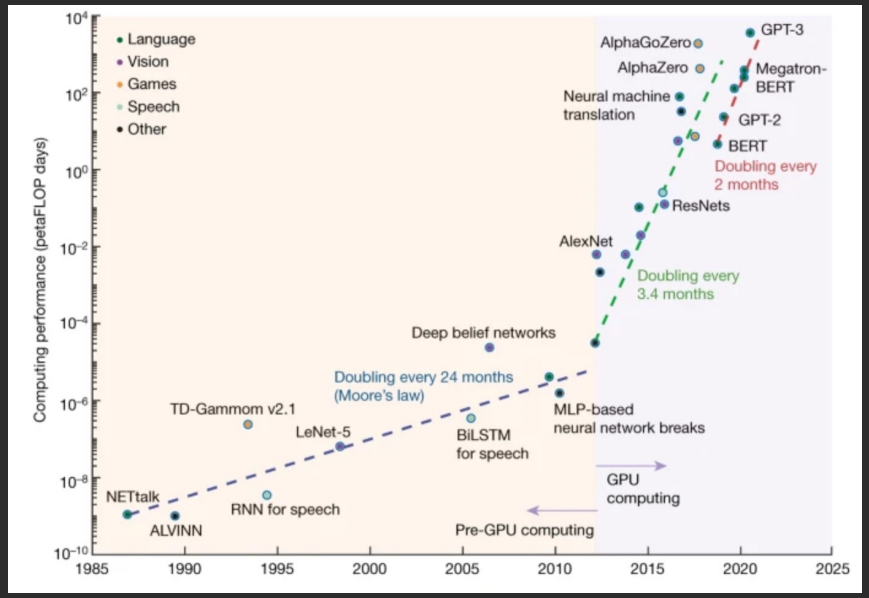
External collaborators


Rafael Gonzalez Hernandez


Anna Birk Hellenes

SPP2558

Motivation: exponentials and scaling problems in AI-era computing

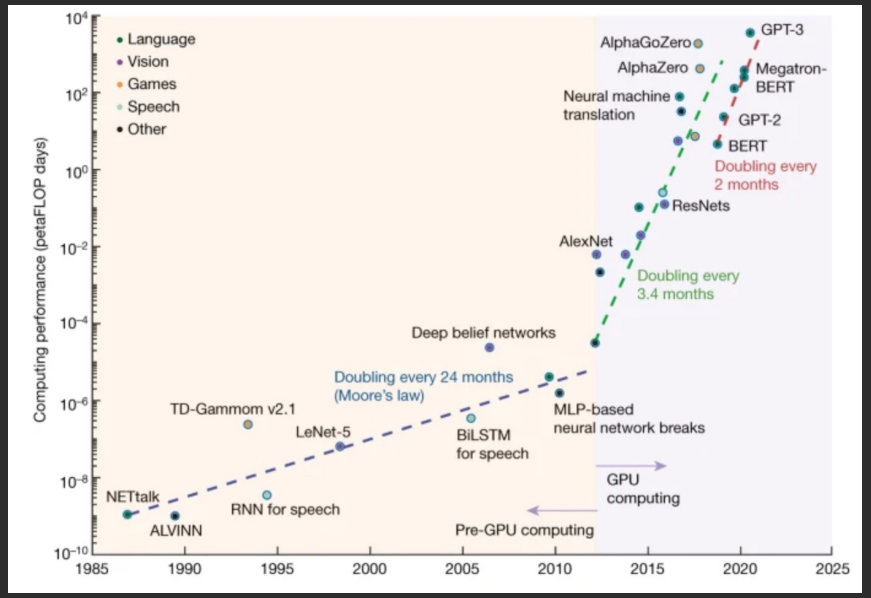


Nature 604, 255–260 (2022)

Computational AI demands are increasing more rapidly than Moore law

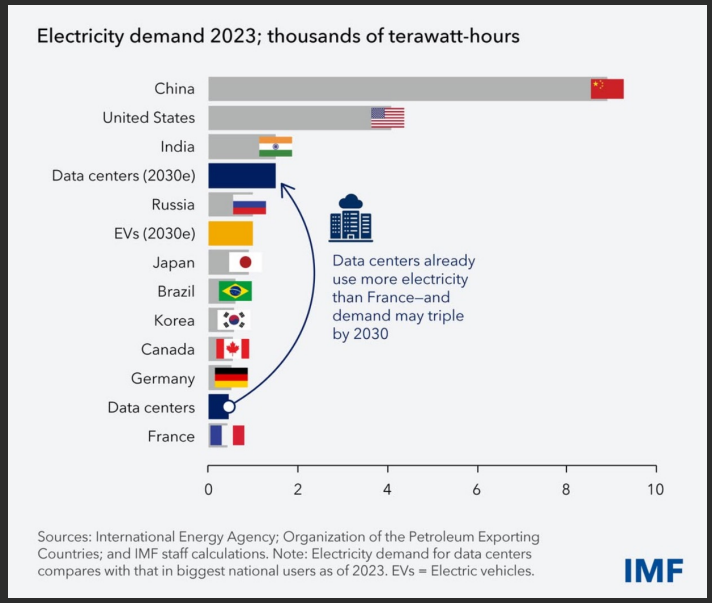
LSMEJKAL@PKS.MPG.DE

Motivation: exponentials and scaling problems in AI-era computing



Nature 604, 255–260 (2022)

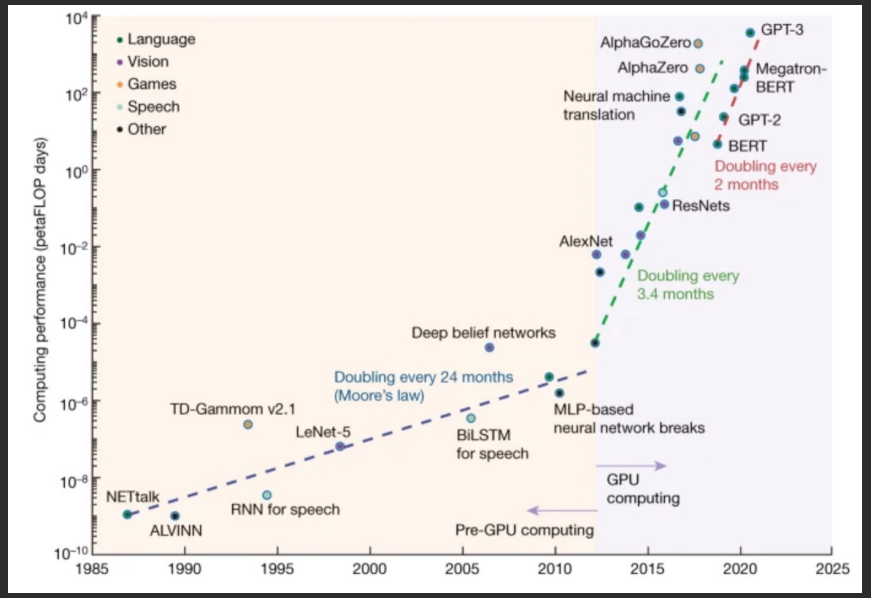
Computational AI demands are increasing more rapidly than Moore law



Data centres use as much power as world largest economies

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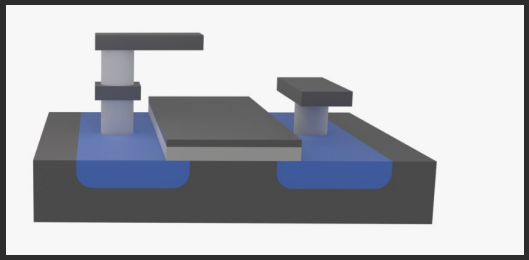
Motivation: exponentials and scaling problems in AI-era computing



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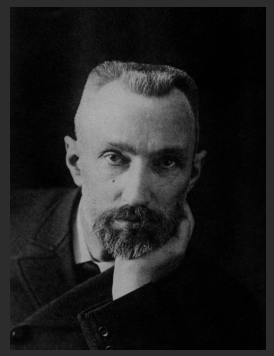
Computational AI demands are increasing more rapidly than Moore law

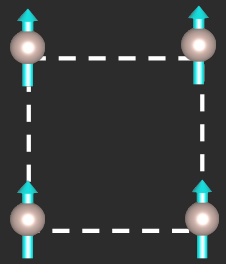
Unconventional quantum materials as platform for ultrafast ultrascalable and energy efficient AI-era IT?



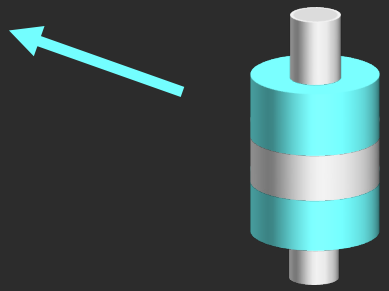
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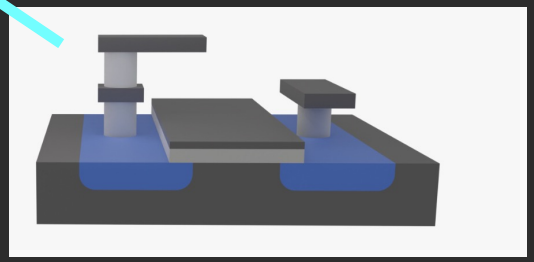
Motivation: magnetism and information technologies





Ferromagnets
***Curie** (1894)*

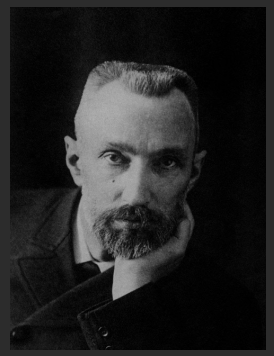


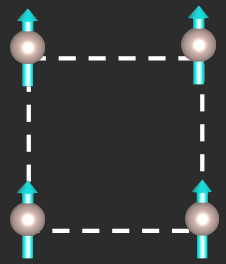


✓ Strong spin polarisation

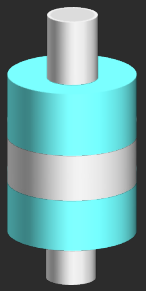
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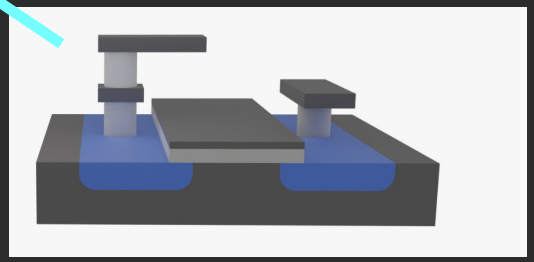
Motivation: magnetism and information technologies





Ferromagnets
***Curie** (1894)*

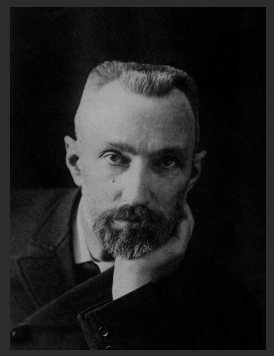


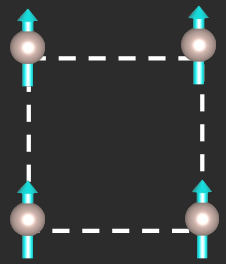


✓ Strong spin polarisation
× Stray fields
× GHz
× Metals

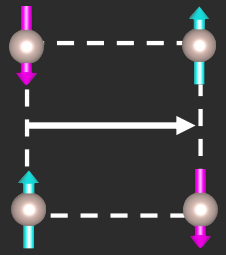
LSMEJKAL@PKS.MPG.DE

Motivation





Ferromagnets
***Curie** (1894)*



Anti-ferromagnets
Néel (1930s)



✓ Strong spin polarisation
× Stray fields
× GHz
× Metals

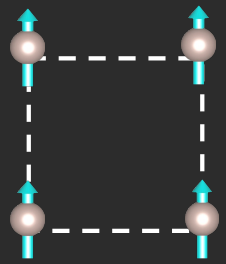
× Supressed spin polarisation
✓ No stray fields
✓ THz
✓ Insulators

1970:
"interesting but useless"

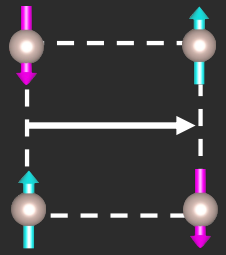
T Jungwirth, J Sinova, A Manchon, X Marti, J Wunderlich, C Felser, Nature Physics 14 (3), 200 (2018)
P Němec, M Fiebig, T Kampfrath, AV Kimel, Nature Physics 14 (3), 229 (2018)
LŠ, Mokrousov, Yan, MacDonald, Nature Physics, Nature physics 14 (3), 242 (2018)

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Motivation



Ferromagnets
***Curie** (1894)*



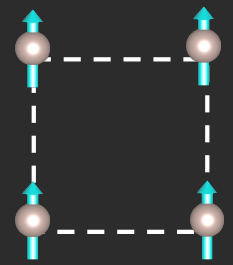
Anti-ferromagnets
Néel (1930s)

✓ Strong spin polarisation	× Supressed spin polarisation
× Stray fields	✓ No stray fields
× GHz	✓ THz
× Metals	✓ Insulators

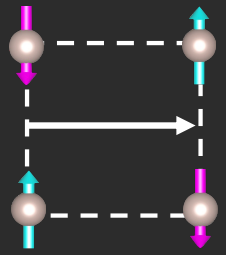
2012: Combine merits?

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Idea



Ferromagnets



Anti-ferromagnets

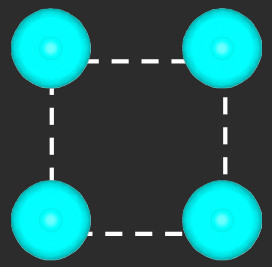


Consider full spin density

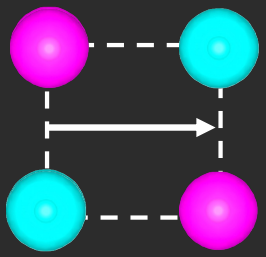
2012: Combine merits?

LSMEJKAL@PKS.MPG.DE

Idea



Ferromagnets



Anti-ferromagnets

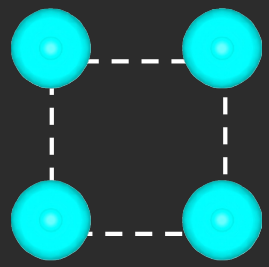


Consider full spin density

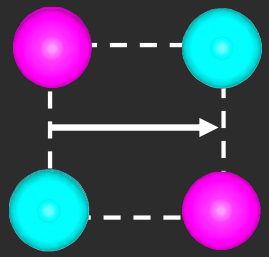
2012: Combine merits?

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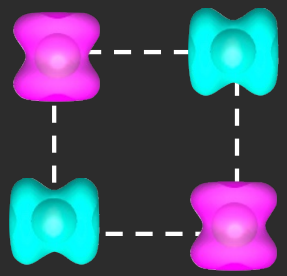
#1: anomalous effects (2018)



Ferromagnets



Anti-ferromagnets

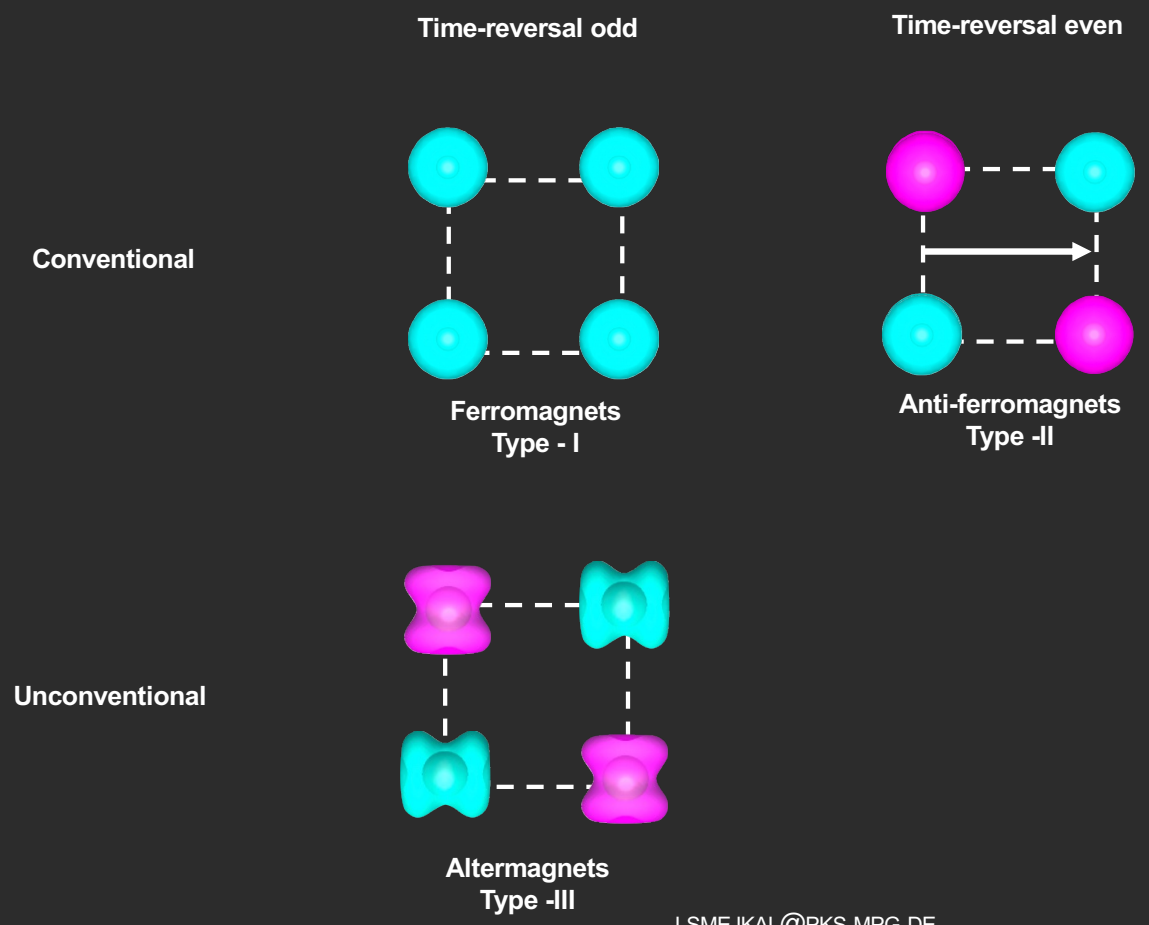


- ✓ Strong and unconventional spin polarisation
- ✓ No stray fields
- ✓ THz
- ✓ Metals, insulators, semiconductors
- ✓ Sustainable (no heavy of f-elements needed)

Science Adv. 6, eaaz8809 (2020)
PNAS 118 (2021)
Nature Comm. 15 (1), 4961(2024)

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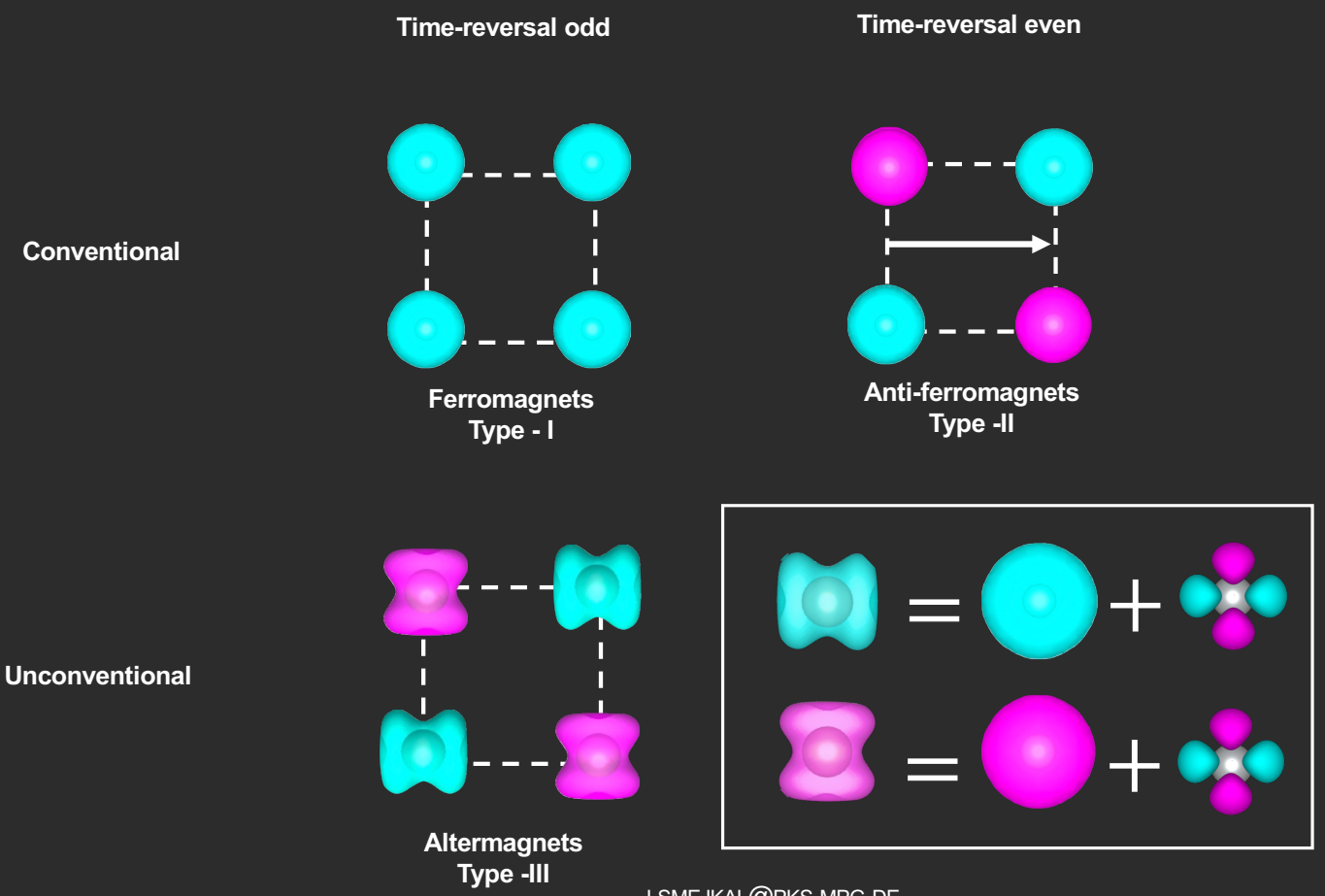
#2: spin symmetries and altermagnetism (2021)



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Science Adv. 6, eaaz8809 (2020)
PNAS 118 (2021)
Phys. Rev. X 12, 031042 (2022)
Nature 626, 517 (2024)
Nature 649, 837 (2026)

#2: spin symmetries and altermagnetism (2021)



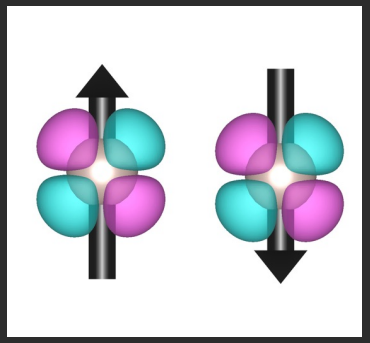
Altermagnets are neither ferromagnets nor antiferromagnets!

Science Adv. 6, eaaz8809 (2020)
PNAS 118 (2021)
Phys. Rev. X 12, 031042 (2022)
Nature 626, 517 (2024)
Nature 649, 837 (2026)

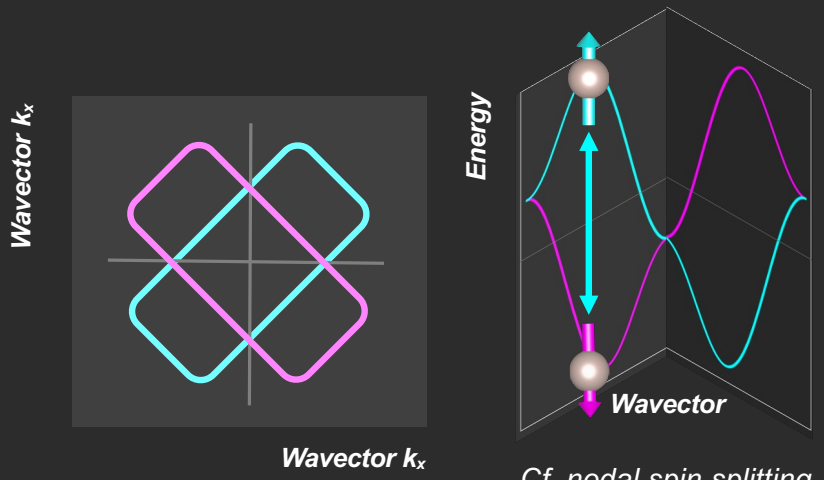
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#2: spin symmetries and altermagnetism (2021)

Altermagnetic spin density
(direct space)



Altermagnetic spin-splitting
(momentum space)

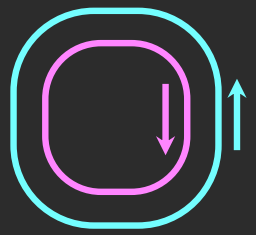
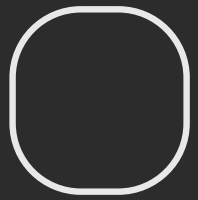
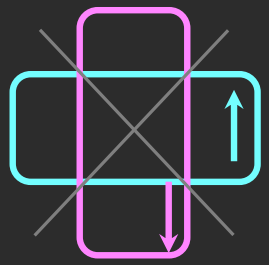


Cf. nodal spin splitting
Cf. band diagrams – maps for electrons
Cf. different from Zeeman and Rashba

Science Adv. 6, eaaz8809 (2020)
PNAS 118 (2021)
Phys. Rev. X 12, 031042 (2022)
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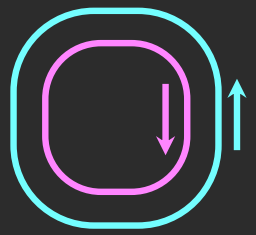
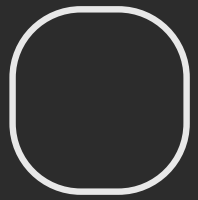
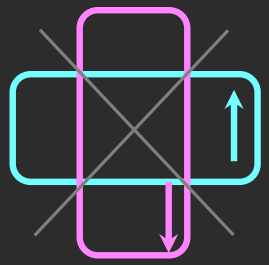
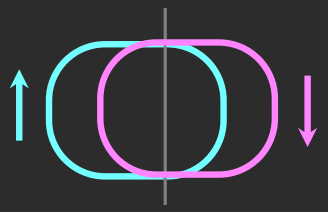
Take home message: altermagnets and antialtermagnets

	Time-reversal odd	Time-reversal even
Conventional	 **Ferromagnets** **s-wave** ***Curie*** *(1894)*	 **Anti-ferromagnets** **no-wave** *Néel (1930s)*
Unconventional *Spontaneous breaking of lattice symmetries*	 **Altermagnets:** **even parity d, g, i-wave** *Phys. Rev. X 12, 031042 (2022)*	

Momentum-space

Latest review: Nature 649, 837 (2026)

Take home message: altermagnets and antialtermagnets

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Unconventional *Spontaneous breaking of lattice symmetries*		
	Altermagnets: **even parity d, g, i-wave** *Phys. Rev. X 12, 031042 (2022)*	**Antialtermagnets:** ***=antiferroic+alternating spin-polarization*** **odd-parity p, f, h-iwave** *arXiv:2309.01607v3, Nature Communication 16, 7270 (2025)*

Momentum-space

Latest review: Nature 649, 837 (2026)



NEWS | PHYSICS

Researchers discover new kind of magnetism

More than 200 materials could be "altermagnets," predicted just a few years ago

6 FEB 2024 · 3:30 PM ET · BY ZACK SAVITSKY

The Economist

Science & technology | Magnets. This is how they work

Scientists have found a new kind of magnetic material

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



ScienceNews

Newfound 'altermagnets' shatter the magnetic status quo

...materials get their magnetism from their atoms. The ntum mechanical property bestowed by the atoms' electrons... In altermagnets, the atoms' spins alternate, but...not only are the spins of neighboring atoms opposite, but the atoms are also rotated.

Science Adv. 6, eaaz8809 (2020)
PNAS 118 (2021)
Phys. Rev. X 12, 031042 (2022)
Nature 626, 517 (2024)
Nature 649, 837 (2026)

Outline

1 From unconventional Hall effect to altermagnets

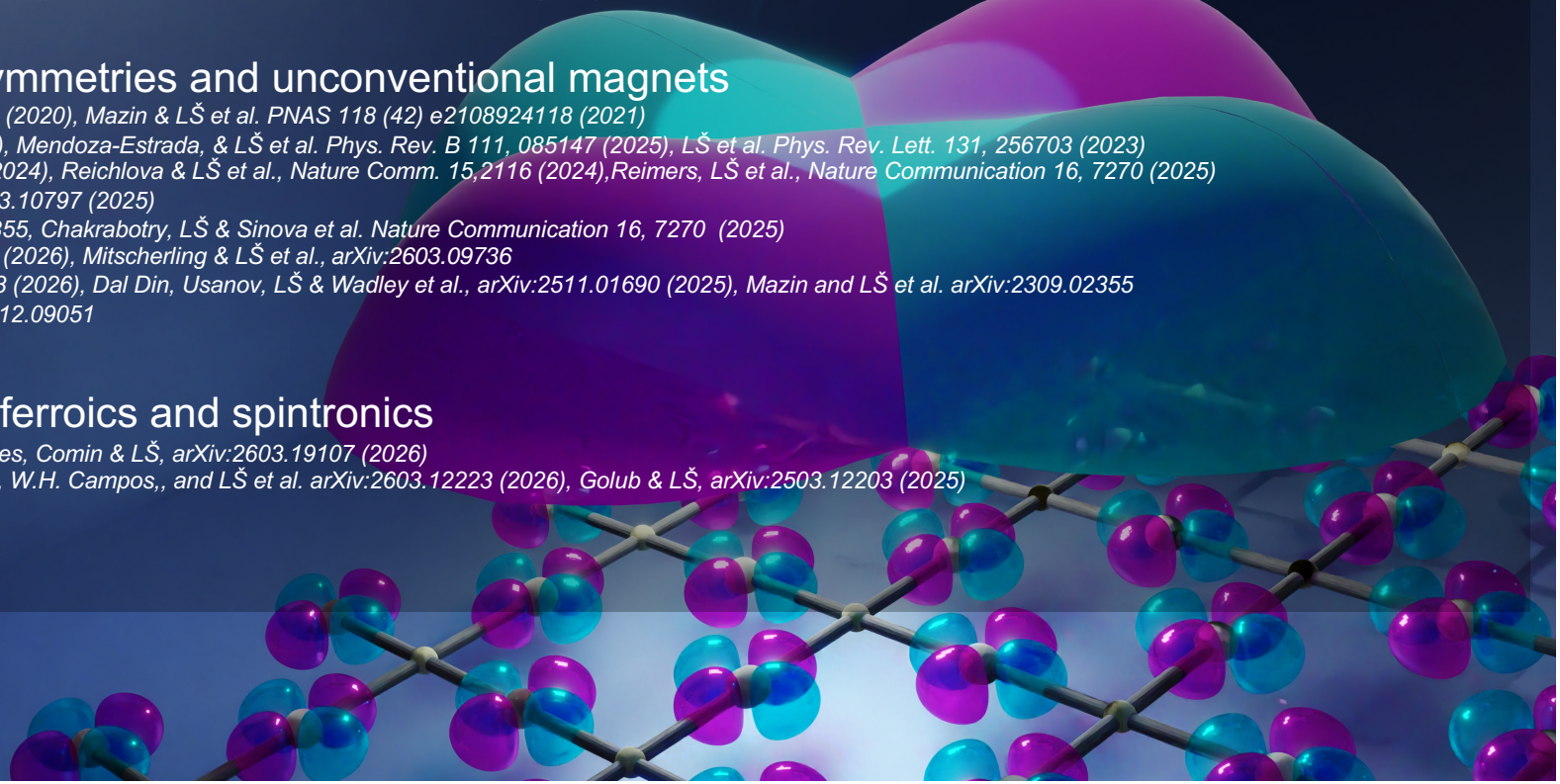
LŠ et al. Science Advances 6, eaaz8809 (2020), Mazin & LŠ et al. PNAS 118 (42) e2108924118 (2021)
Mazin & LŠ et al. PNAS 118 (42) e2108924118 (2021)
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Krempasky, LŠ et al. Nature 626, 517 (2024), Reichlova & LŠ et al., Nature Comm. 15,2116 (2024),Reimers, LŠ et al., Nature Communication 16, 7270 (2025)

2 Foundations: spin symmetries and unconventional magnets

LŠ et al. Science Advances 6, eaaz8809 (2020), Mazin & LŠ et al. PNAS 118 (42) e2108924118 (2021)
LŠ et al. Phys. Rev. X 12, 031042 (2022), Mendoza-Estrada, & LŠ et al. Phys. Rev. B 111, 085147 (2025), LŠ et al. Phys. Rev. Lett. 131, 256703 (2023)
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Birk Hellenes & LŠ et al., arXiv:2309.02355, Chakrabotry, LŠ & Sinova et al. Nature Communication 16, 7270 (2025)
Khodas, LŠ, Mazin, arXiv:2601.19829v1 (2026), Mitscherling & LŠ et al., arXiv:2603.09736
Campos,, and LŠ et al. arXiv:2603.12223 (2026), Dal Din, Usanov, LŠ & Wadley et al., arXiv:2511.01690 (2025), Mazin and LŠ et al. arXiv:2309.02355
Mitscherling, Priessnitz, and LŠ arXiv:2512.09051

3 Functionalities: multiferroics and spintronics

LŠ arXiv:2411.19928 , Priessnitz, Hellenes, Comin & LŠ, arXiv:2603.19107 (2026)
LŠ,et al., Phys Rev X 12, 011028 (2022), W.H. Campos,, and LŠ et al. arXiv:2603.12223 (2026), Golub & LŠ, arXiv:2503.12203 (2025)



Newton – on the cover

Outline

1 From unconventional Hall effect to altermagnets

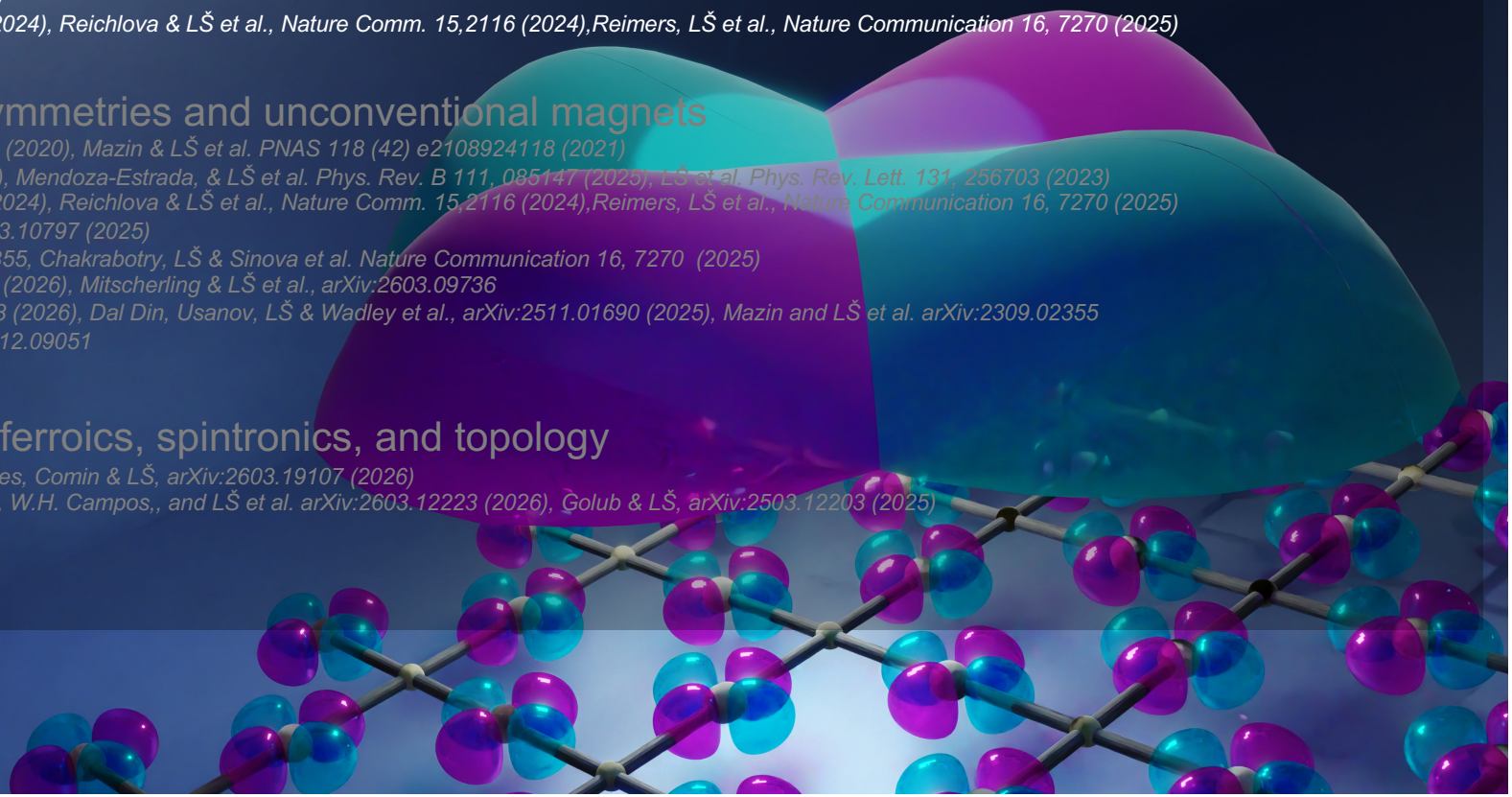
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2 Foundations: spin symmetries and unconventional magnets

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3 Functionalities: multiferroics, spintronics, and topology

LŠ arXiv:2411.19928 , Priessnitz, Hellenes, Comin & LŠ, arXiv:2603.19107 (2026)
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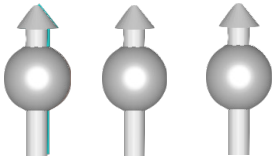


Newton – on the cover

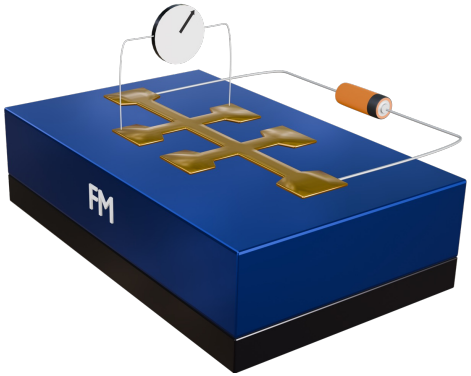
2012: Can we combine merits of ferromagnets and antiferromagnets?

>Decade of search

2014



Ferromagnets



Spontaneous Hall effect

1881
Hall effect discovered
before electron 1897

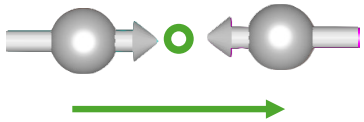
2018
Unconventional crystal anomalous Hall effect
discovered before altermagnets

LŠ, MacDonald, Sinova, Nakatsuji, Jungwirth, Nat. Rev. Mater. (2022)
LŠ, Mazin, under revision (2026)
Jungwirth, Sinova, Fernandes, Liu, Watanabe,
Murakami, Nakatsuji, and LŠ, Nature 649, 837 (2026)

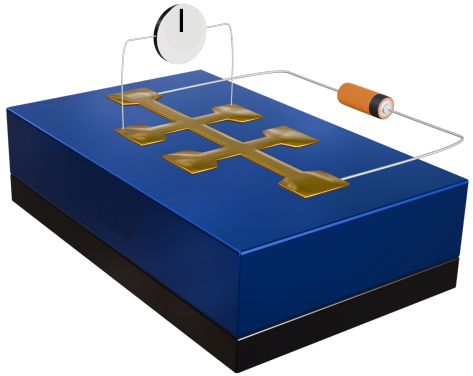
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>Decade of search

2014



Antiferromagnets?



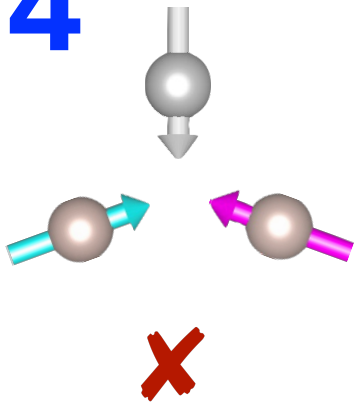
Spontaneous Hall effect?

1960s

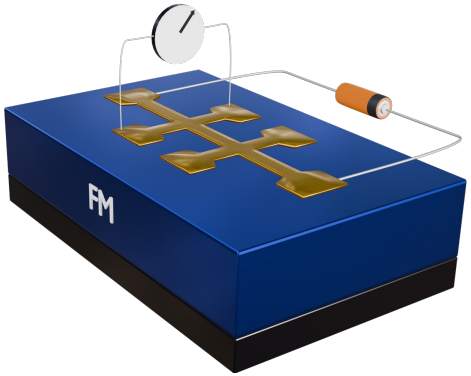
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>Decade of search

2014



Canting or noncollinear



Spontaneous Hall effect!

2014

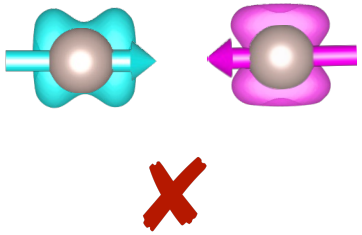
Kübler & Felser, EPL (2014), Chen, Niu & MacDonald, PRL (2014)
Nayak, Felser, Parkin, et al. Science Advacnes (2015), Nakatsuji et al., Nature (2015)
LŠ, MacDonald, Sinova, Nakatsuji, Jungwirth, Nat. Rev. Mater. (2022)
LŠ, Mazin, submitted (2025)

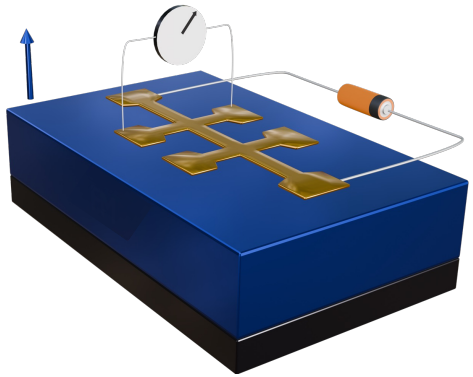
$$\mathcal{T}E_{n\sigma}(\mathbf{k}) = E_{n-\sigma}(-\mathbf{k})$$
$$\mathcal{P}E_{n\sigma}(\mathbf{k}) = E_{n\sigma}(-\mathbf{k})$$
$$\mathcal{PT}\,E_{n,\uparrow}(\mathbf{k}) = E_{n,\downarrow}(\mathbf{k})$$

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>Decade of search

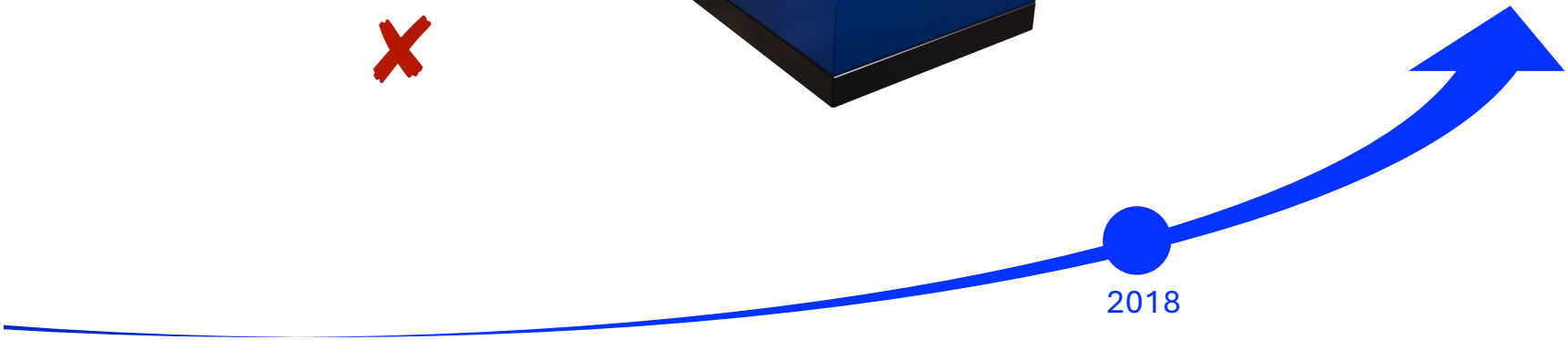
2018





Spontaneous Hall effect!

In perfectly compensated collinear magnet!



LŠ, Gonzalez-Hernandez,Jungwirth & Sinova,
arXiv:1901.00445, Science Advances 6, eaaz8809 (2020)

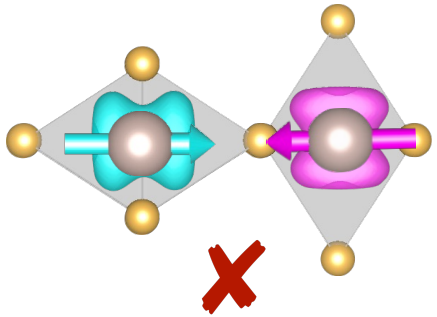
ScienceAdvances

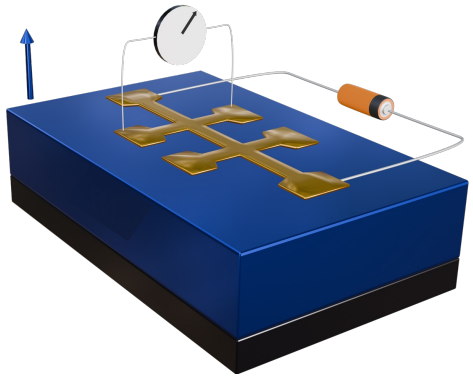
Crystal time-reversal symmetry breaking and spontaneous Hall effect in collinear antiferromagnets

$$\mathcal{T}E_{n\sigma}(\mathbf{k}) = E_{n-\sigma}(-\mathbf{k})$$
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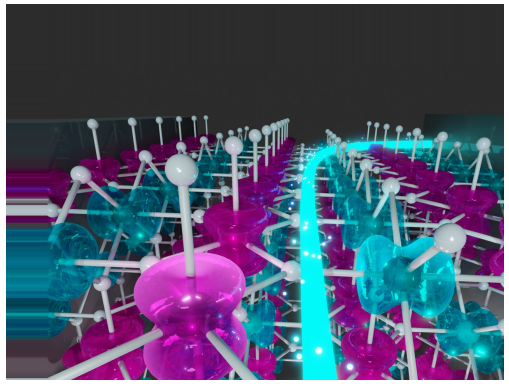
ScienceAdvances

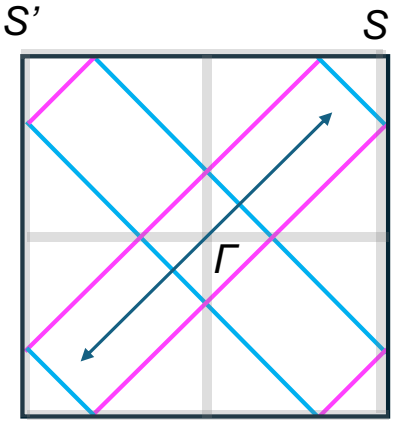
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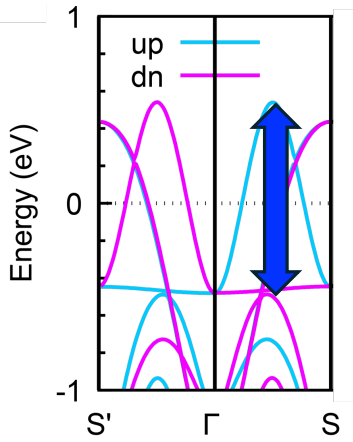
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$$\mathcal{P}E_{n\sigma}(\mathbf{k}) = E_{n\sigma}(-\mathbf{k})$$
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>Decade of search

2018







$\mathcal{T}\, E_{n\sigma}(\mathbf{k}) = E_{n-\sigma}(-\mathbf{k})$ ✗ $\quad \hat{\mathcal{P}}\mathcal{T}\, E_{n\sigma}(\mathbf{k}) = E_{n-\sigma}(-\mathbf{k})$ ✗

eV spin splitting!

LŠ, Gonzalez-Hernandez,Jungwirth & Sinova,
arXiv:1901.00445, Science Advances 6, eaaz8809 (2020)
Nodes: Mazin, LŠ et al., PNAS 118 (2021)

ScienceAdvances

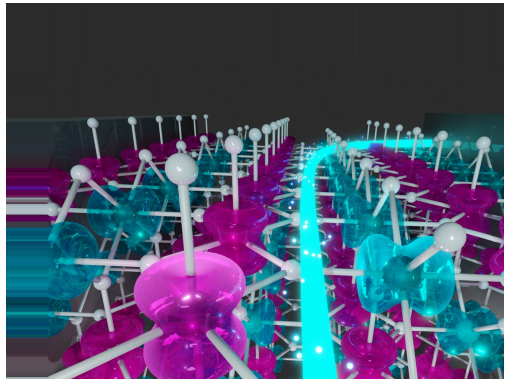
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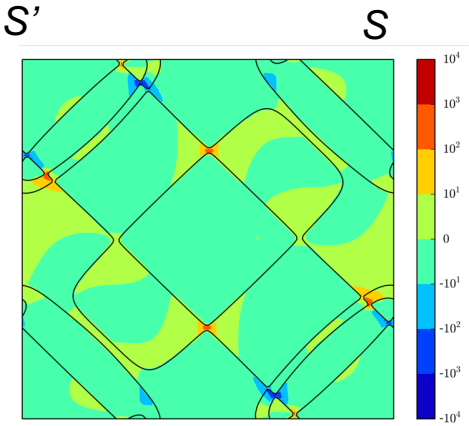
Time-reversal broken electronic structure

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>Decade of search

2018





$$\boldsymbol{v}_n(\boldsymbol{k}) = \frac{\partial \varepsilon_n(\boldsymbol{k})}{\hbar \partial \boldsymbol{k}} - \frac{e}{\hbar}\boldsymbol{E} \times \boldsymbol{\Omega}_n(\boldsymbol{k})$$

LŠ, Gonzalez-Hernandez,Jungwirth & Sinova, arXiv:1901.00445, Science Advances 6, eaaz8809 (2020)
Nodes: Mazin, LŠ et al., PNAS 118 (2021)

ScienceAdvances

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

$\mathcal{T}$ ✗
$\mathcal{PT}$ ✗
$C_2\mathcal{T}$ ✗

Time-reversal broken electronic structure

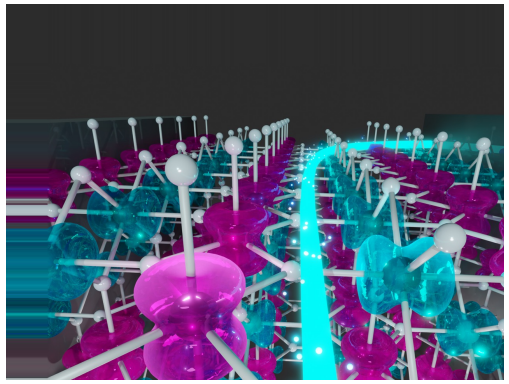
Nonrelativistic spontaneous exchange

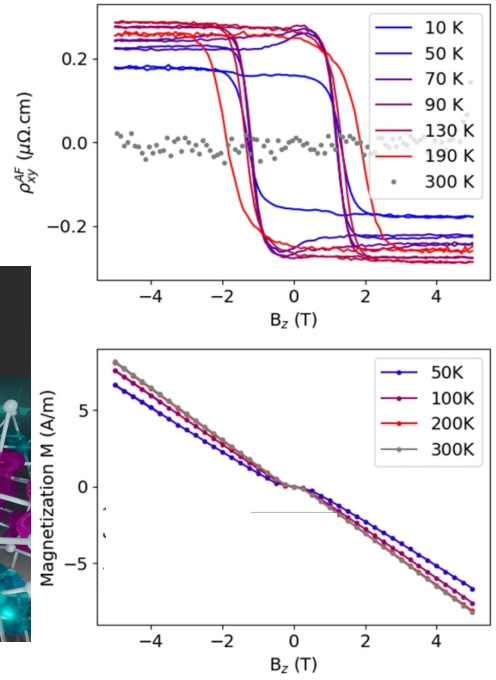
Relativistic spin-orbit coupling

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>Decade of search

2020-25





Spontaneous Hall effect!

Observation in perfectly compensated collinear magnet!

2020 *Reichlova & LŠ et al. Nature Comm. 15 (1), 4961(2024), arXiv:2012.15651*
Bettancourt, LŠ, Kriegner et al. Phys. Rev. Lett. (2023)

LŠ, Gonzalez-Hernandez,Jungwirth & Sinova, arXiv:1901.00445, Science Advances 6, eaaz8809 (2020)

ScienceAdvances

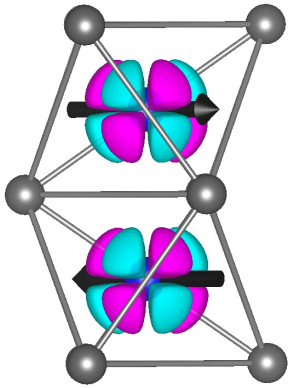
Crystal time-reversal symmetry breaking and spontaneous Hall effect in collinear antiferromagnets

Observation of a spontaneous anomalous Hall response in the Mn_5Si_3 d-wave altermagnet candidate

Helena Reichlova[1,2] ✉, Rafael Lopes Seeger[3], Rafael González-Hernández[4,5], Ismaila Kounta[6], Richard Schlitz[1], Dominik Kriegner[1,2], Philipp Ritzinger[1,2], Michaela Lammel[7,8], Miina Leiviskä[3], Anna Birk Hellenes[5], Kamil Olejník[2], Vaclav Petříček[2], Petr Doležal[9], Lukas Horak[9], Eva Schmoranzerova[10], Antonín Badura[10], Sylvain Bertaina[11], Andy Thomas[1,7], Vincent Baltz[3], Lisa Michez[6], Jairo Sinova[5,12], Sebastian T. B. Goennenwein[1,8], Tomáš Jungwirth[2,13] & Libor Šmejkal[2,5] ✉

LSMEJKAL@PKS.MPG.DE

2021



Three spin symmetry types of collinear magnets!

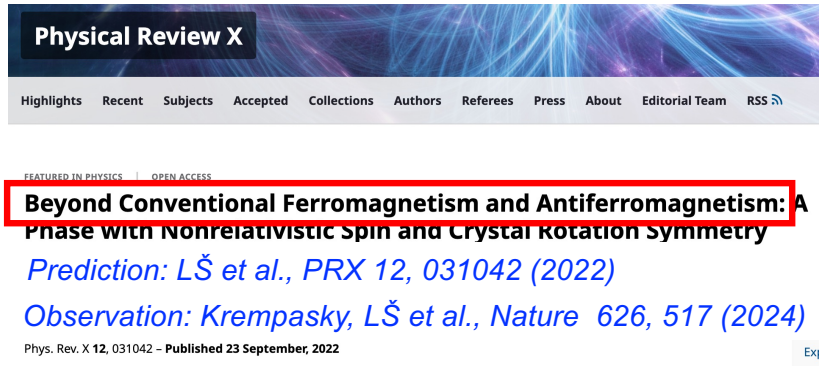
$SO(3)_S \rightarrow SO(2)_S \times \{1, C_2T\}$

Ferromagnet: $\times \{E||R_i\}$

Antiferromagnet: $\times \{E||R_i\} + \{C_2||R_i\}$

Altermagnet: $\times \{E||\mathbf{H}_i\} + \{C_2||\ \mathbf{M}_z\mathbf{H}_i\}$

2021



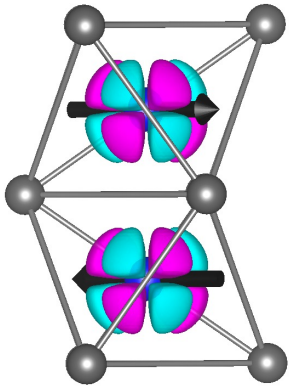
Prediction: LŠ et al., PRX 12, 031042 (2022)

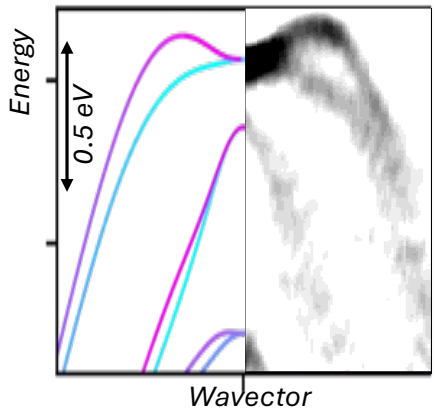
Observation: Krempasky, LŠ et al., Nature 626, 517 (2024)

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>Decade of search

2023





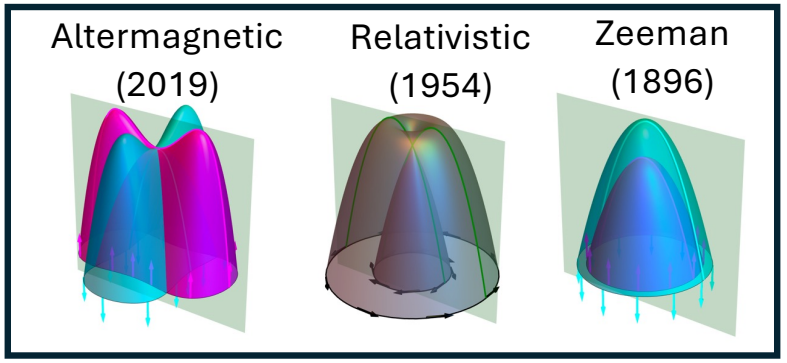
MnTe

Prediction: LŠ et al., PRX 12, 031042 (2022)
Observation: Krempasky, LŠ et al., Nature 626, 517 (2024)
Lee, LŠ, et al. PRL 132, 036702 (2024) …

Altermagnetism

Prediction, classification
Different spin group structure from ferromagnets and antiferromagnets

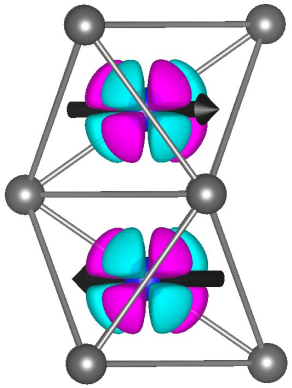
2018 — 2021 — 2023

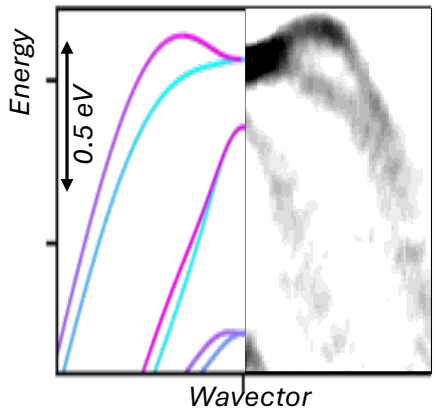


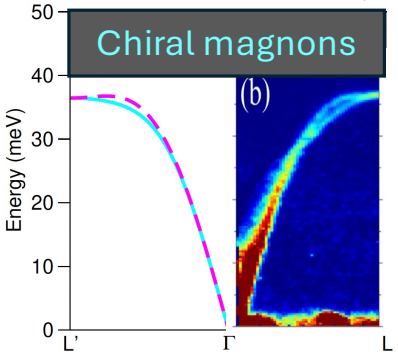
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>Decade of search

2024







Prediction: LŠ et al. Phys. Rev. Lett. 131, 256703 (2023)
Observation: Liu et al., Phys. Rev. Lett. 133, 156702 (2024)

MnTe

Prediction: LŠ et al., PRX 12, 031042 (2022)
Observation: Krempasky, LŠ et al., Nature 626, 517 (2024)
Lee, LŠ, et al. PRL 132, 036702 (2024) …

2021 2023

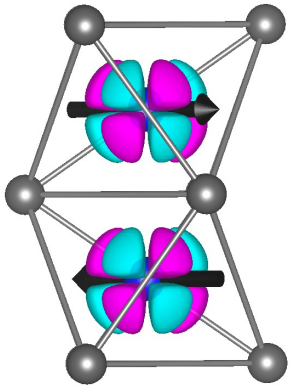
CrSb

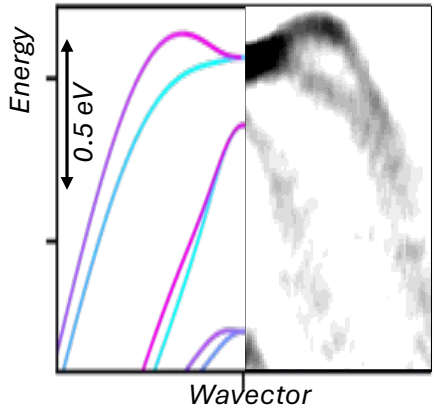
*Reimers, **LŠ**, et al., arXiv:2310.17280, Nature Comm.15, 2116 (2024)*
Yang et al., arXiv:2405.12575, Nature Comm. 16, 1442 (2025)
Ding et al., arXiv:2405.12687, Phys.Rev.Lett.133,206401(2024)
Li et al. arXiv:2405.14777, Comm. Physics 8, 311 (2025)
Zeng et al., arXiv:2405.12679, Advanced Science 2406529, (2024)
Lu et al., arXiv:2407.13497, Nano Lett. 2025, 25, 18, 7343 (2025) …

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Emerging reserch fields

Jungwirth, Sinova, Fernandes, Liu, Watanabe, Murakami, Nakatsuji, and LŠ, Nature 649, 837 (2026)
Jungwirth, Fernandes, Fradkin, MacDonald, Sinova, and LŠ, Newton 1, (6) 100162 (2025)





Altermagnets

Phys. Rev. X 12, 031042 (2022)
Phys. Rev. X 12, 040501 (2022)
Phys. Rev. Lett. 131, 256703 (2023)
Advanced Materials (2024)

Anomalous effects

***Current induced spin polarisation**: arXiv:2503.12203 (2025)*
***Multiferroics**: arXiv:2411.19928 (2024)*
***Chiral magnons**: Phys. Rev. Lett. 131, 256703 (2023)*
***Spin currents, GMR, and TMR**: Phys Rev X 12, 011028 (2022)*
***Spin splitter effect:** Phys. Rev. Lett. 126, 127701 (2021)*
***Spontanous Hall effect: arXiv:1901.00445**, Science Advances 6, eaaz8809 (2020)*
*arXiv:1901.00445, Sci. Adv. **6**, eaaz8809 (2020)*
*arXiv:1902.02506, Nat. Com. **10**, 4305 (2019)*
*arXiv:1902.04436, PRB **99**, 184432 (2019)*
...

2018 2021 2023

Spin symmetries

PRX 12, 031042 (2022)
PNAS 118 (2021)
Phys. Rev. B 111, 085147 (2025)
PRX 14, 031038; 031037; 031039 (2024)
PRX 15, 031006 (2025)

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EMBRACING STRUCTURAL SCIENCE
IUCr 2026
CALGARY, CANADA
AUGUST 11-18

Outline

1 From unconventional Hall effect to altermagnets

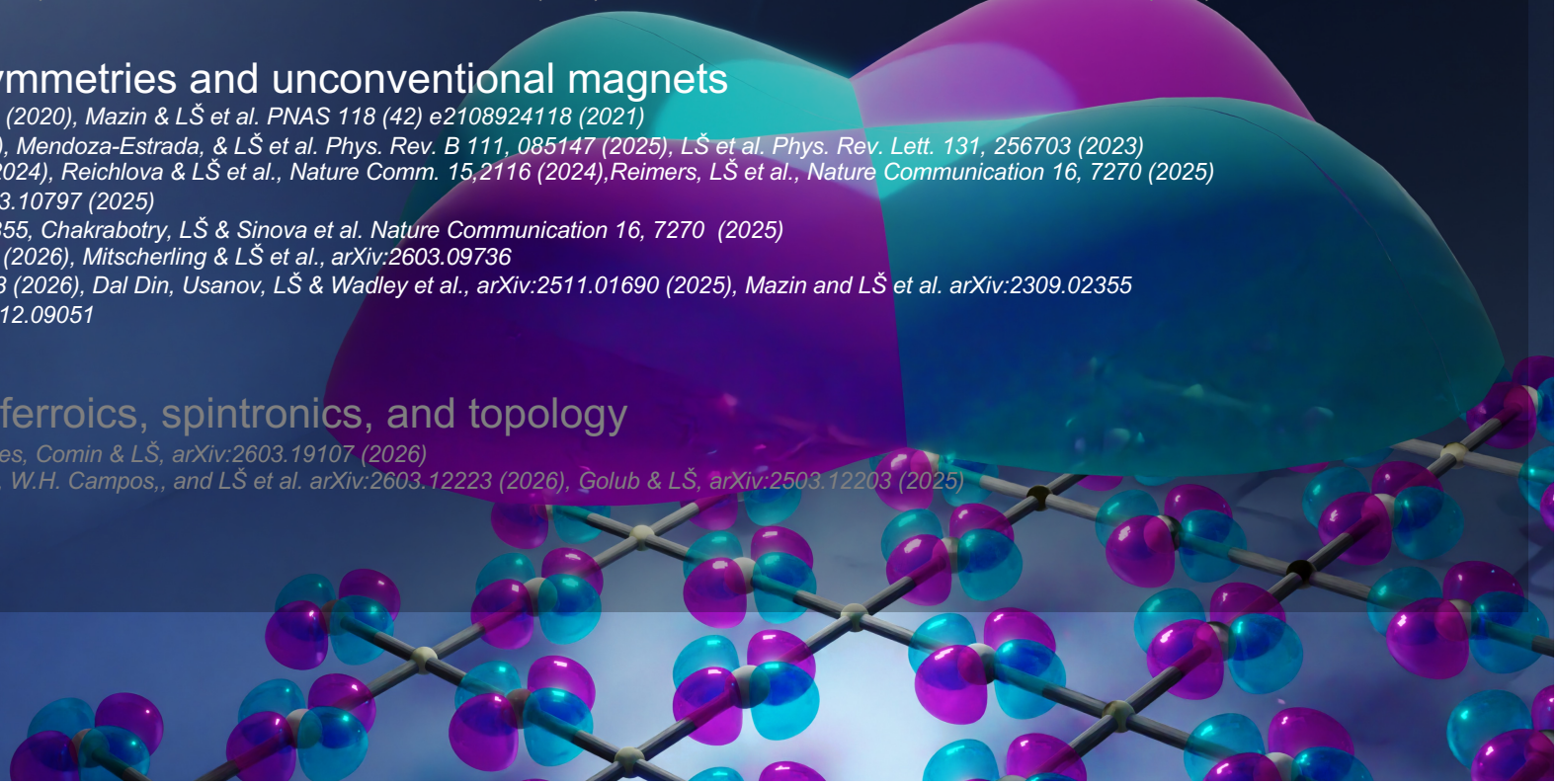
LŠ et al. Science Advances 6, eaaz8809 (2020), Mazin & LŠ et al. PNAS 118 (42) e2108924118 (2021)
Mazin & LŠ et al. PNAS 118 (42) e2108924118 (2021)
LŠ et al. Phys. Rev. X 12, 031042 (2022)
Krempasky, LŠ et al. Nature 626, 517 (2024), Reichlova & LŠ et al., Nature Comm. 15,2116 (2024),Reimers, LŠ et al., Nature Communication 16, 7270 (2025)

2 Foundations: spin symmetries and unconventional magnets

LŠ et al. Science Advances 6, eaaz8809 (2020), Mazin & LŠ et al. PNAS 118 (42) e2108924118 (2021)
LŠ et al. Phys. Rev. X 12, 031042 (2022), Mendoza-Estrada, & LŠ et al. Phys. Rev. B 111, 085147 (2025), LŠ et al. Phys. Rev. Lett. 131, 256703 (2023)
Krempasky, LŠ et al. Nature 626, 517 (2024), Reichlova & LŠ et al., Nature Comm. 15,2116 (2024),Reimers, LŠ et al., Nature Communication 16, 7270 (2025)
Jaeschke, Campos & LŠ et al. arXiv:2503.10797 (2025)
Birk Hellenes & LŠ et al., arXiv:2309.02355, Chakrabotry, LŠ & Sinova et al. Nature Communication 16, 7270 (2025)
Khodas, LŠ, Mazin, arXiv:2601.19829v1 (2026), Mitscherling & LŠ et al., arXiv:2603.09736
Campos,, and LŠ et al. arXiv:2603.12223 (2026), Dal Din, Usanov, LŠ & Wadley et al., arXiv:2511.01690 (2025), Mazin and LŠ et al. arXiv:2309.02355
Mitscherling, Priessnitz, and LŠ arXiv:2512.09051

3 Functionalities: multiferroics, spintronics, and topology

LŠ arXiv:2411.19928 , Priessnitz, Hellenes, Comin & LŠ, arXiv:2603.19107 (2026)
LŠ,et al., Phys Rev X 12, 011028 (2022), W.H. Campos,, and LŠ et al. arXiv:2603.12223 (2026), Golub & LŠ, arXiv:2503.12203 (2025)



Newton – on the cover

How to classify all possible magnetic orderings?

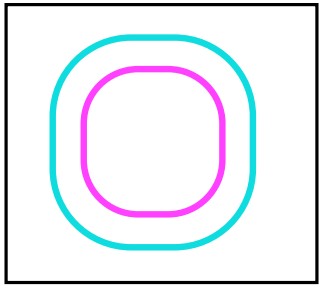
What is a magnet?

Ferromagnet = SO(3) rotation symmetry in spin space spontaneously broken

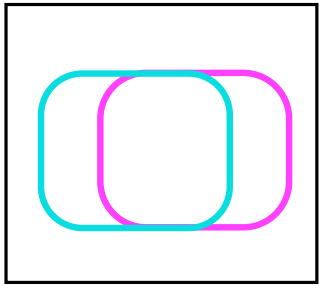
Unconventional quantum phases of matter: organizing principles

Conventional

Unconventional
=higher partial-wave phase which breaks lattice symmetries



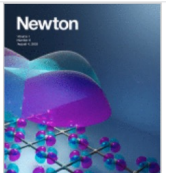
s-wave



p-wave



Superfluids	Hg superconductor (1957)	He-3 A-type superfluidity (1972)	$U(1) \times SO(3)_L \times SO(3)_S$ *Legget, Phys. Rev. (1970s)*
Magnets	Fe Ferromagnet (1928)	**CeNiAsO Antialtermagnet (2021)**	**Spin group theory** *SO(3)$_S$x G* *Phys. Rev. X 12, 031042 (2022)*

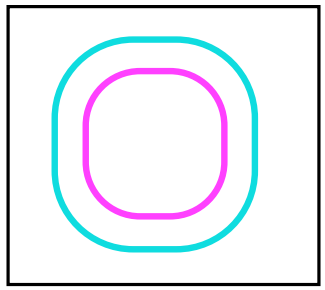


T. Jungwirth, J. Sinova, R. M. Fernandes, Q. Liu, H. Watanabe, S. Murakami, S. Nakatsuji, and L. Šmejkal, Nature 649, 837 (2026)
T. Jungwirth, R. M. Fernandes, E. Fradkin, A. H. MacDonald, J. Sinova, and L. Šmejkal, Newton – Cell press 1, (6) 100162 (2025)

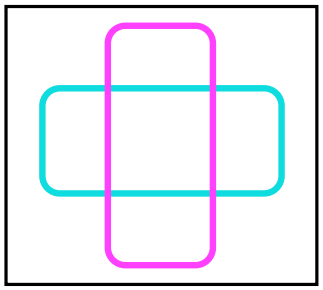
Unconventional quantum phases of matter: organizing principles

Conventional

Unconventional
=higher partial-wave phase which breaks lattice symmetries



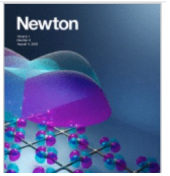
s-wave



d-wave



Superfluids	Hg superconductor (1957)	Cuprate superconductors (1986)	$U(1) \times SO(3)_L \times SO(3)_S$ *Legget, Phys. Rev. (1970s)*
Magnets	Fe Ferromagnet (1928)	**MnTe Altermagnets (2021)**	**Spin group theory** *SO(3)$_S$x G* *Phys. Rev. X 12, 031042 (2022)*



T. Jungwirth, J. Sinova, R. M. Fernandes, Q. Liu, H. Watanabe, S. Murakami, S. Nakatsuji, and L. Šmejkal, Nature 649, 837 (2026)
T. Jungwirth, R. M. Fernandes, E. Fradkin, A. H. MacDonald, J. Sinova, and L. Šmejkal, Newton – Cell press 1, (6) 100162 (2025)

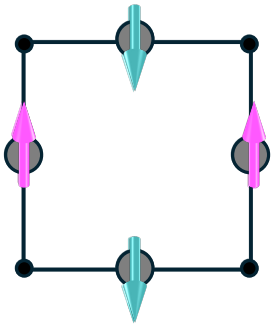
Spin group theory and spin crystallography

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Magnetic symmetries

Relativistic quantum mechanics
(exchange interaction + spin-orbit coupling)

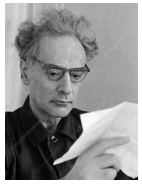
Coupled spin and lattice space → Single operation acts **simultaneously** on spin and lattice space



$\mathcal{C}_4$

broken symmetry

1651 space groups, μeV – meV energy scale

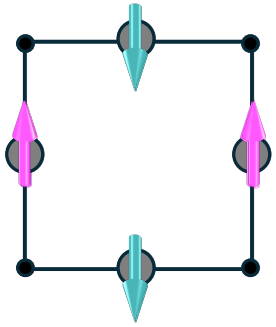


Shubnikov, Landau, 1960s
***LŠ**, A. MacDonald et al., Nat. Phys. **14**, 242 (2018)*
*B.A. Bernevig, C. Felser, H. Beidenkopf, Nature **603**, 41 (2022)*

Spin symmetries

Nonrelativistic quantum mechanics
(exchange interaction)

Partially coupled spin and lattice spaces → Pairs of operations acting on spin and lattice space



$[C_2 \| C_4]$

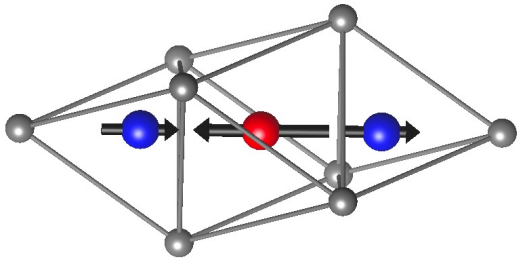
Spin space | Lattice space

>100 000 space groups, 100 meV – 1 eV energy scale

D. B. Litvin, 1970s
*... half a century gap ... **LŠ** et al. PNAS 118 42 (2021)*
***LŠ** et al., Phys. Rev. X **12**, 031042 (2022), arXiv:2012.15651, ...*
PRX 14, 031038; 031037; 031039 (2024), PRX 15, 031006 (2025)

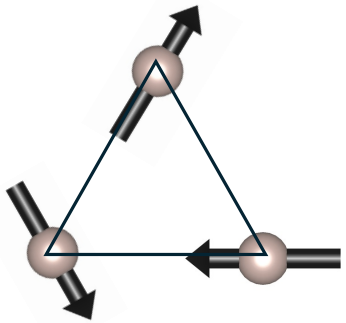
Classification of all possible magnetic orderings and exchange forces → spin crystallography paradigm

Classification of magnets: conventional magnetic symmetries?



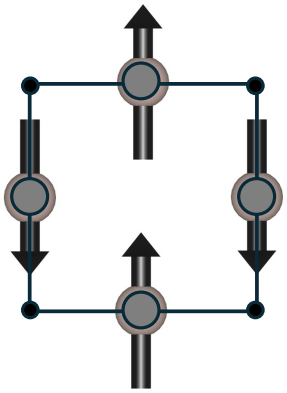
Collinear Heusler

$m'm'm$



Noncolliner kagome

$m'm'm$



$m'm'm$

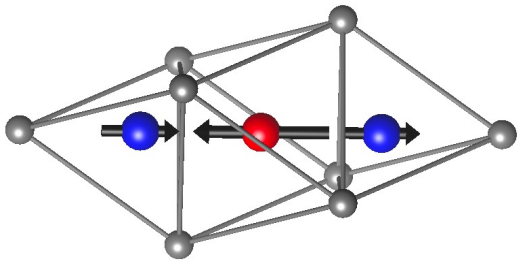
Magnetic symmetries

LŠ *et al. Phys. Rev. X 12, 031042 (2022), Nature 649, 837 (2026), LŠ & I. Mazin, under revision (2026)*

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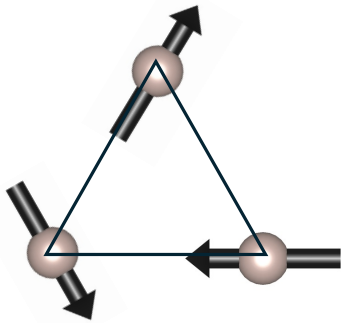
Classification of magnets: collinearity

Spin symmetries



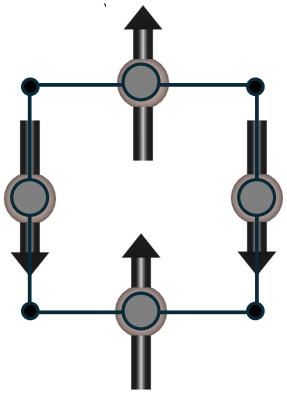
$$\mathrm{SO}(2) \rtimes \mathbb{Z}_2^{\mathcal{T}\mathcal{C}_2}$$

$${}^{1}m\,{}^{1}\bar{3}\,{}^{1}m$$



$$\boxed{\mathbb{Z}_2^{\mathcal{T}\mathcal{C}_2}}$$

$${}^{3_z}6_3/{}^{1}m\,{}^{2_x}m\,{}^{2_{xy}}m$$



$$\mathrm{SO}(2) \rtimes \mathbb{Z}_2^{\mathcal{T}\mathcal{C}_2}$$

$$\boxed{{}^{2}4/}\,{}^{2}m\,{}^{2}m\,{}^{1}m$$

LŠ et al. Phys. Rev. X 12, 031042 (2022), Nature 649, 837 (2026), LŠ & I. Mazin, under revision (2026)

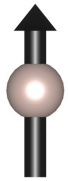
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Spin crystallography and altermagnetism

$SO(3)_S \rightarrow SO(2)_S \times \{1, C_2T\}$

Type I
Ferromagnets
Curie (1894)

x [E||G]

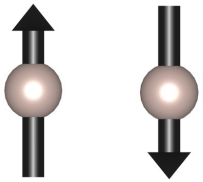


$\boldsymbol{M}_i$

Magnetisation

Type II
Antiferromagnets
Néel (1930)

x [E||G] +[C_2||G]

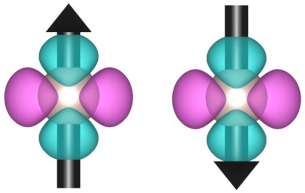


$\boldsymbol{N}_i = \boldsymbol{M}_i^A - \boldsymbol{M}_i^B$

Sublattice magnetisation
"Néel vector"

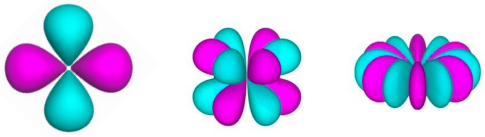
Type III
Altermagnets
Phys. Rev. X 12, 031042 (2022)

x [E||**H**] +[C_2||**AH**]



$\boldsymbol{M}_i^{jk}$

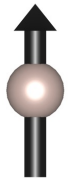
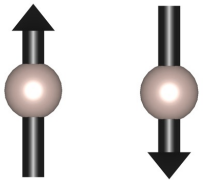
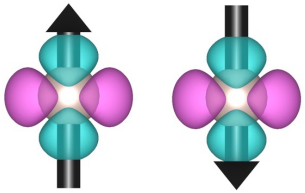
d, g, or i-wave magnetisation



LŠ et al., Phys. Rev. X 12, 031042 (2022)
LŠ et al., Sci. Adv. 6, eaaz8809 (2020)

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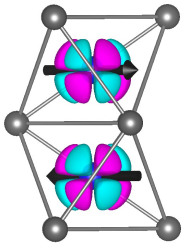
Spin crystallography and altermagnetism

	Type I Ferromagnets *Curie (1894)*	**Type II** Antiferromagnets *Néel (1930)*	**Type III** Altermagnets *Phys. Rev. X 12, 031042 (2022)*
$SO(3)_S \rightarrow SO(2)_S \times \{1, C_2T\}$	x [E||G]	x [E||G] +[C_2||G]	x [E||**H**] +[C_2||**AH**]
			
	$\boldsymbol{M}_i$	$\boldsymbol{N}_i = \boldsymbol{M}_i^A - \boldsymbol{M}_i^B$	$\boldsymbol{M}_i^{jk}$
	Magnetisation	*Sublattice magnetisation* *"Néel vector"*	*d, g, or i-wave magnetisation*
	Magnetic field	*Unphysical staggered field*	*Magnetic field x strain*

LŠ et al., Phys. Rev. X 12, 031042 (2022)
LŠ et al., Sci. Adv. 6, eaaz8809 (2020)

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Spin crystallography and altermagnetism



1 Crystal imprinted including insulators MnTe, CrSb

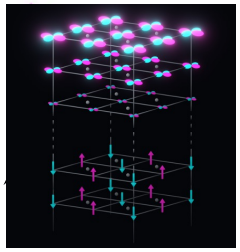
*LŠ et al., Sci. Adv. **6**, eaaz8809 (2020)*

*Reichlova & LŠ et al. Nature Comm. **15** (1), 4961(2024), arXiv:2012.15651*

Type III

Altermagnets

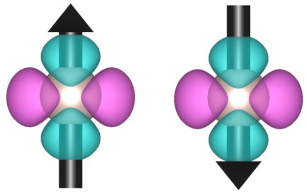
Phys. Rev. X 12, 031042 (2022)



2 Two dimensions and surfaces e.g. of KV_2Se_2O

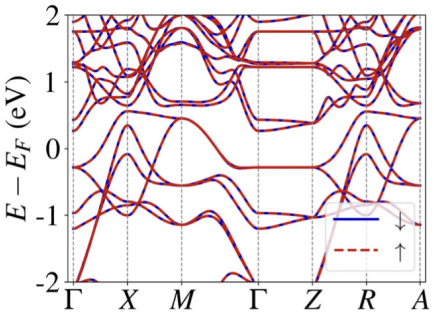
Mazin & LŠ et al., arXiv:2309.02355

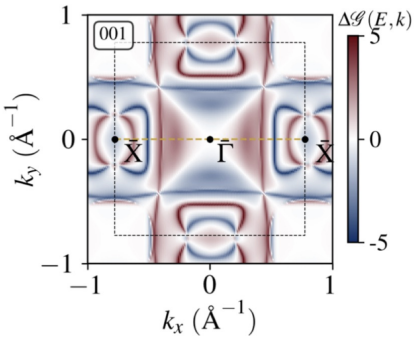
Lange, LŠ, et al., arXiv:2602.08773, Phys. Rev. X, in press (2026)





Colin Lange



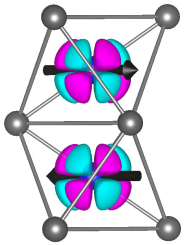


LŠ et al., Phys. Rev. X 12, 031042 (2022)

LŠ et al., Sci. Adv. 6, eaaz8809 (2020)

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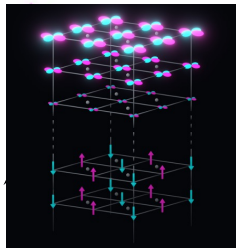
Spin crystallography and altermagnetism



1 Crystal imprinted including insulators MnTe, CrSb

LŠ et al., Sci. Adv. ***6,*** *eaaz8809 (2020)*

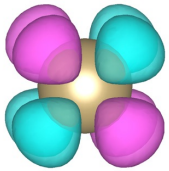
Reichlova & LŠ et al. Nature Comm. ***15*** *(1), 4961(2024), arXiv:2012.15651*



2 Two dimensions and surfaces e.g. of KV_2Se_2O

Mazin & LŠ et al., arXiv:2309.02355

Lange, LŠ, et al., arXiv:2602.08773, Phys. Rev. X, in press (2026)



3 Correlated orbital order ?

Leeb, LŠ et al. Phys. Rev. Lett. ***132****, 236701 (2024)*

Jaeshke & LŠ et al., arXiv:2503.10797, resubmitted (2026)

GitHub
https://github.com › amchecker

amcheck

amcheck is the program (and a library) to check, based on the symmetry arguments, whether a given material is an altermagnet. Altermagnet is a collinear ...

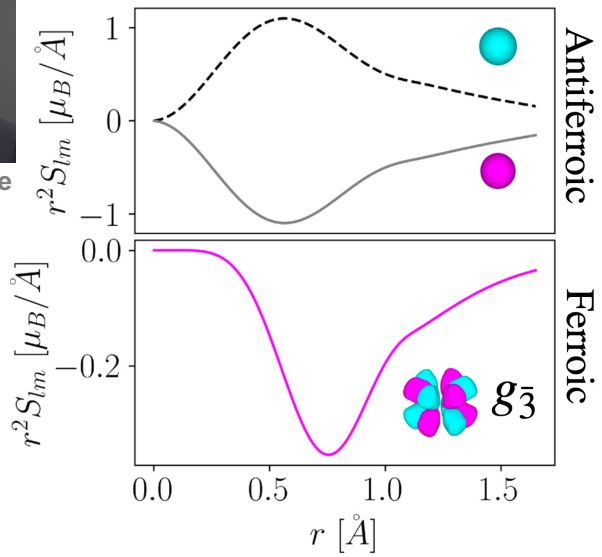


Rodrigo Jaeschke

Type III

Altermagnets

Phys. Rev. X 12, 031042 (2022)

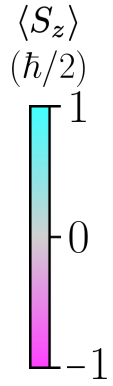


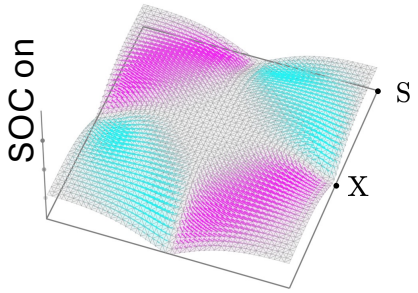
LŠ et al., Phys. Rev. X 12, 031042 (2022)

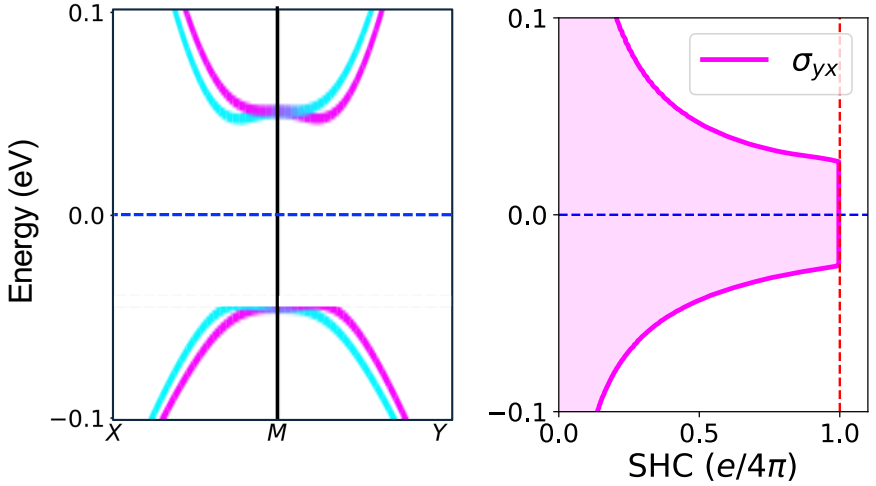
LŠ et al., Sci. Adv. 6, eaaz8809 (2020)

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Spin-orbit coupled altermagnetic spin polarisation in 2D







Mazin & LŠ et al., arXiv:2309.02355
Yoshida, LŠ et al, PRL136, 096701 (2026)
Antonenko et al, PRL134, 096703 (2025)

Campos, Mbognou, Hellenes, Poata, Chen, Priessnitz, and LŠ, arXiv:2603.12223 (2026)

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Spin-orbit coupled altermagnetic spin polarisation

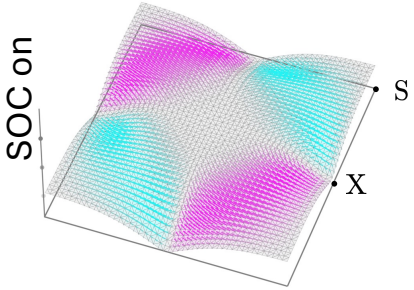
Non-persistent

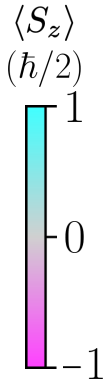


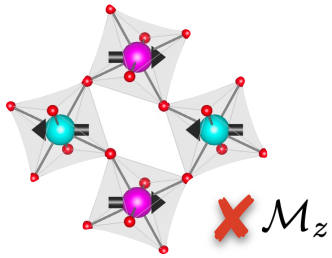
Warlley Campos

Poster session

Mazin & LŠ et al., arXiv:2309.02355







Can we realize collinear altermagnetic spin polarization in the presence of large spin-orbit coupling?

Campos, Mbognou, Hellenes, Poata, Chen, Priessnitz, and LŠ, arXiv:2603.12223 (2026)

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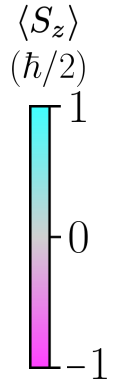
Spin-orbit coupling: classification of persistent altermagnetism

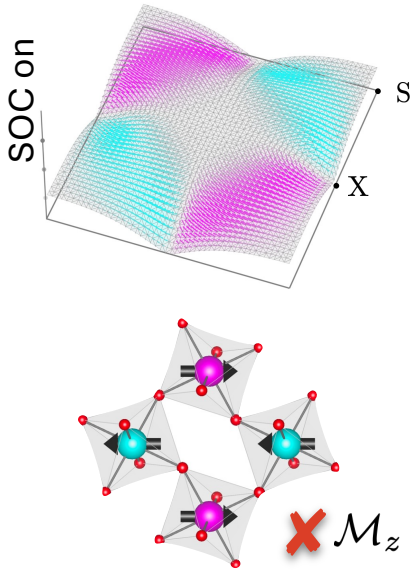


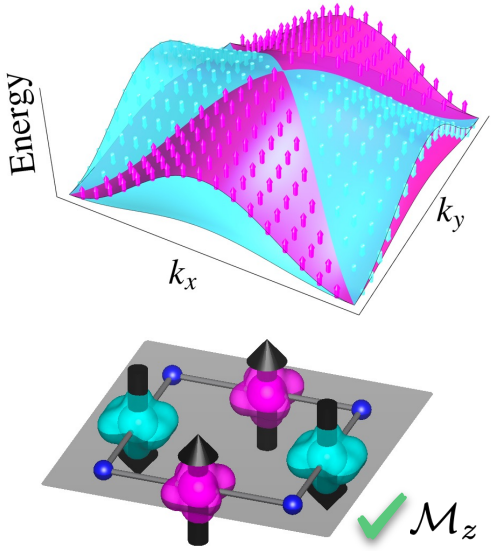
Warlley Campos

Non-persistent | persistent

Mazin & LŠ et al., arXiv:2309.02355



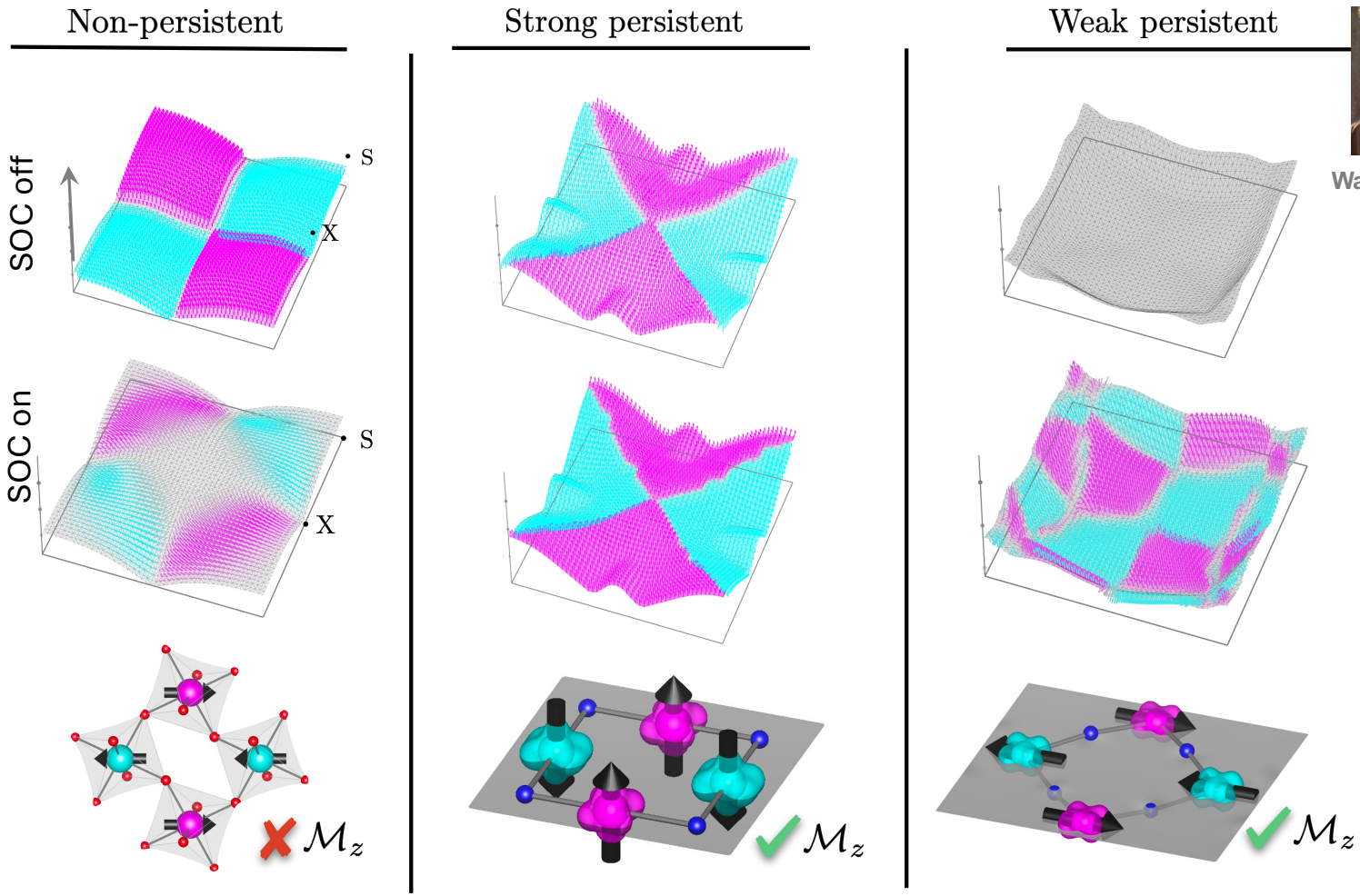




Campos, Mbognou, Hellenes, Poata, Chen, Priessnitz, and LŠ, arXiv:2603.12223 (2026)

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Spin-orbit coupling: classification of persistent altermagnetism





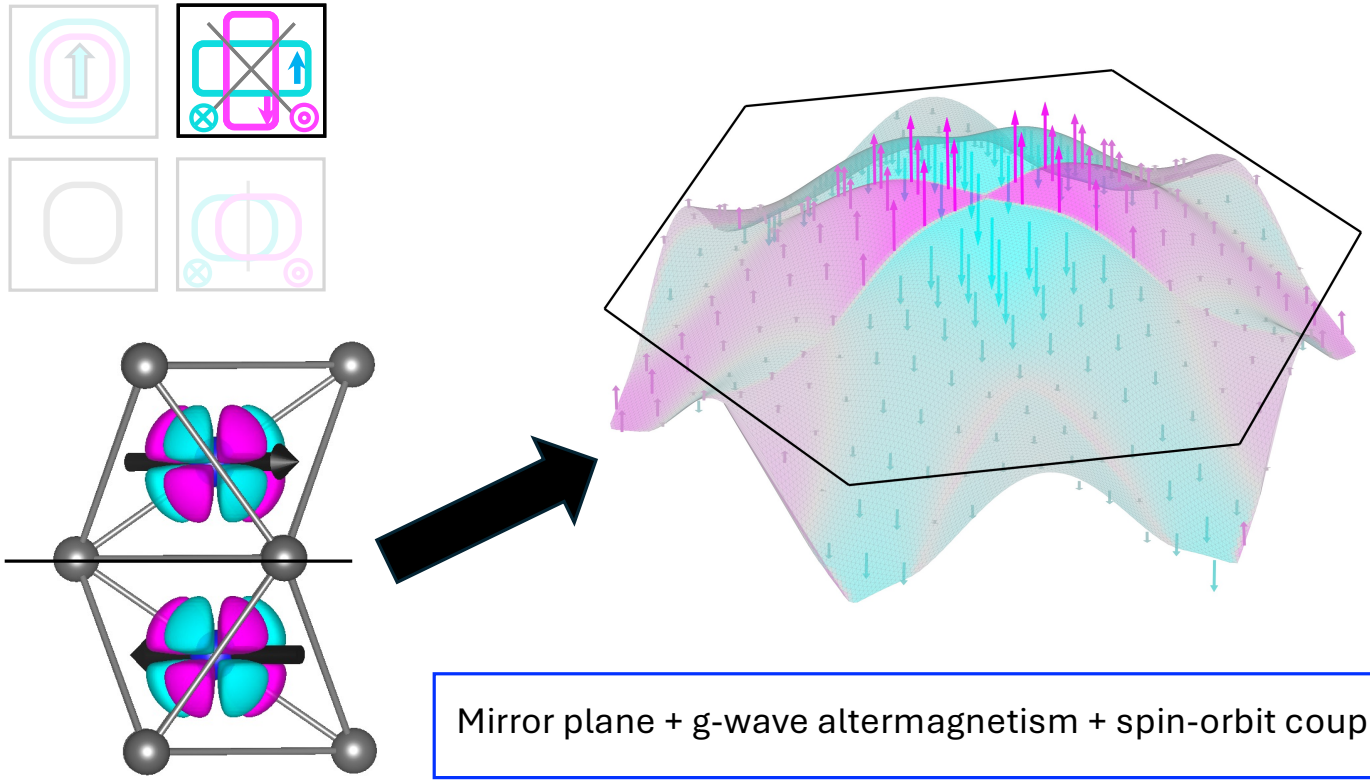
Warlley Campos

Mazin & LŠ et al., arXiv:2309.02355

Campos, Mbognou, Hellenes, Poata, Chen, Priessnitz, and LŠ, arXiv:2603.12223 (2026)

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Spin-orbit coupling: collinear persistent spin polarisation in 3D MnTe

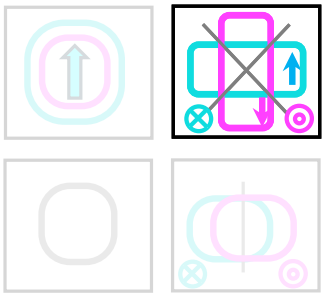


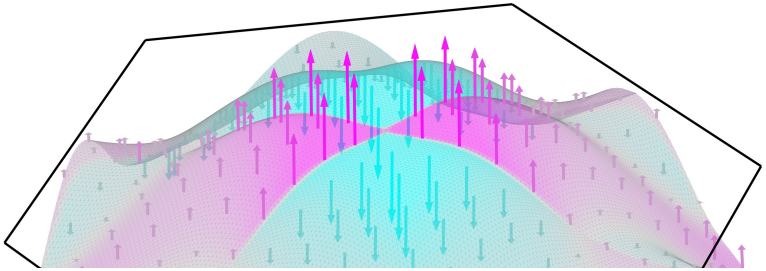
Mirror plane + g-wave altermagnetism + spin-orbit coupling = d-wave (+ s-wave)

Krempasky, LŠ et al., Nature 626, 517 (2024)
Dal Din, Usanov, Šmejkal, WHC & Wadley et al., arXiv:2511.01690
Campos, Mbognou, Hellenes, Poata, Chen, Priessnitz, and LŠ, arXiv:2603.12223 (2026)

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Spin-orbit coupling: *how to observe the spin polarisation?*



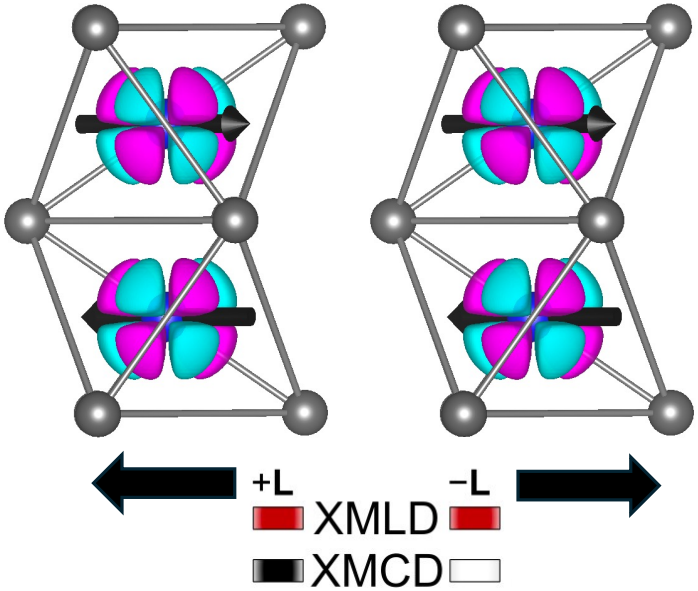


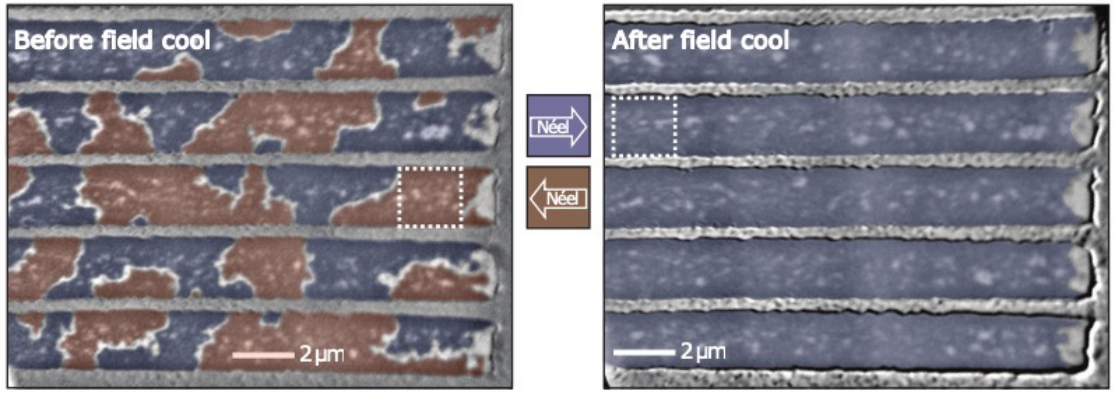


Oliver Amin



Alfred Dal Din

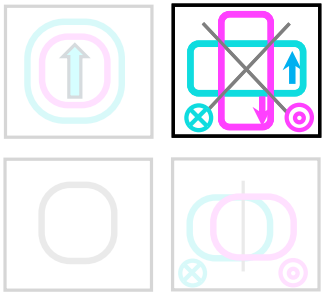


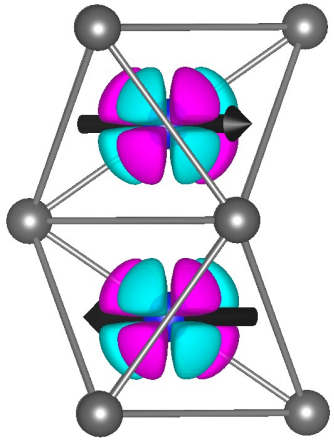


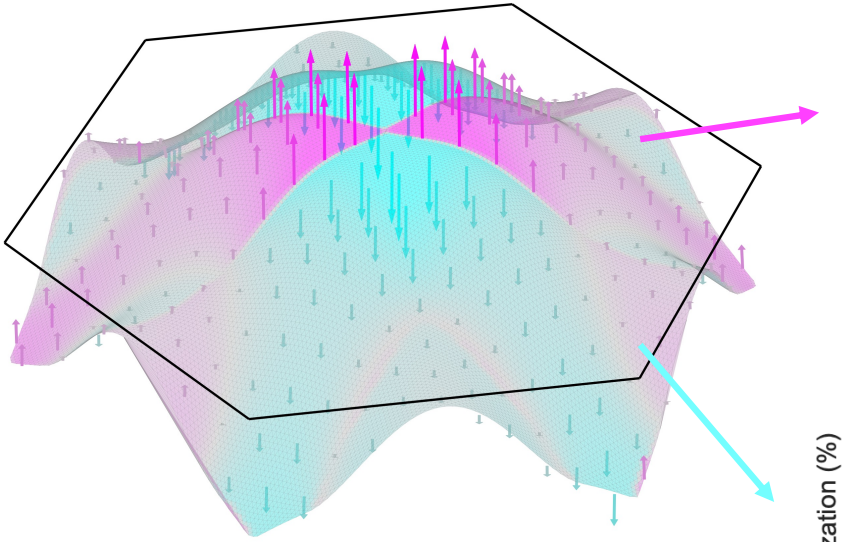
Amin, LŠ & Wadley et al, Nature 636, 348 (2024)
Hariki, LŠ et al, Phys. Rev. Lett. 132, 176701 (2024)
LŠ et al., Science Advances 6, eaaz8809 (2020)
Krempasky, LŠ et al., Nature 626, 517 (2024)
Dal Din, Usanov, Šmejkal, WHC & Wadley et al., arXiv:2511.01690
Campos, Mbognou, Hellenes, Poata, Chen, Priessnitz, and LŠ, arXiv:2603.12223 (2026)

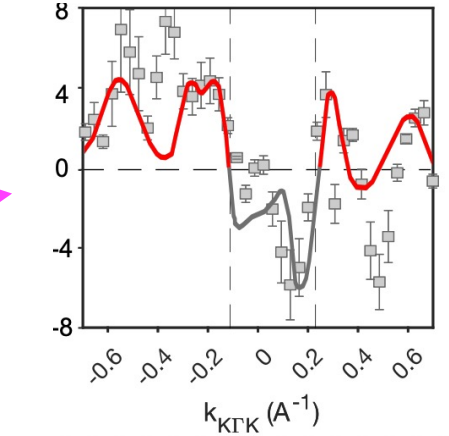
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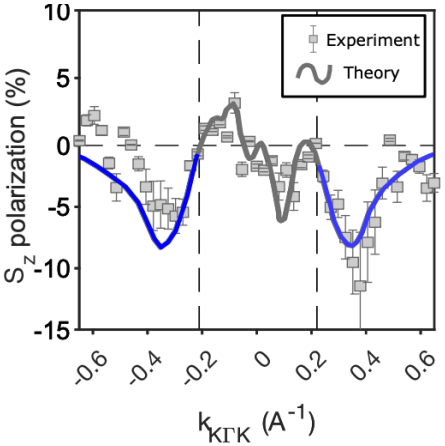
Spin-orbit coupling: *observation of the spin polarisation*











Krempasky, LŠ et al., Nature 626, 517 (2024)
Dal Din, Usanov, Šmejkal, WHC & Wadley et al., arXiv:2511.01690
Campos, Mbognou, Hellenes, Poata, Chen, Priessnitz, and LŠ, arXiv:2603.12223 (2026)

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Outline

1 From unconventional Hall effect to altermagnets

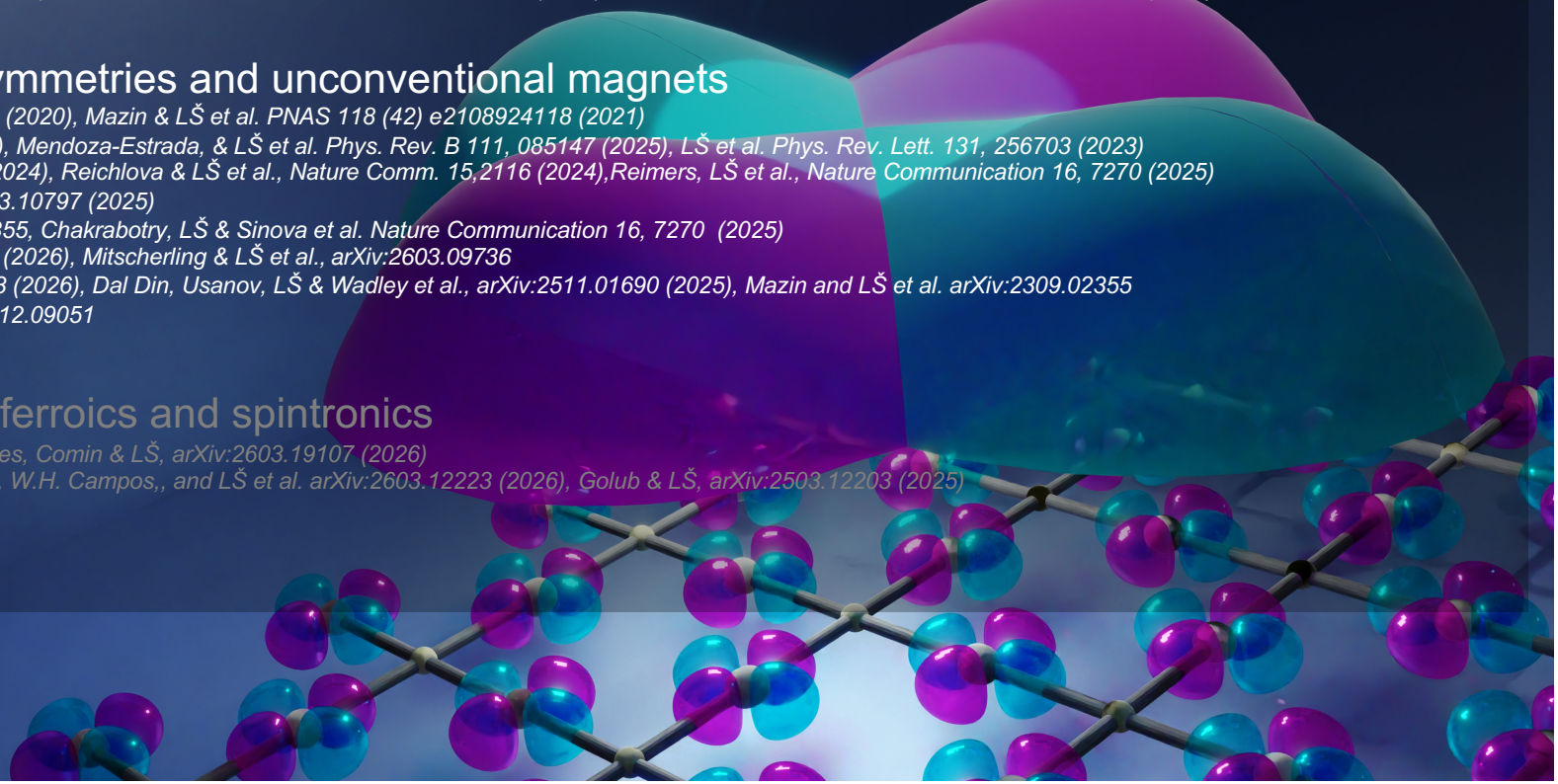
LŠ et al. Science Advances 6, eaaz8809 (2020), Mazin & LŠ et al. PNAS 118 (42) e2108924118 (2021)
Mazin & LŠ et al. PNAS 118 (42) e2108924118 (2021)
LŠ et al. Phys. Rev. X 12, 031042 (2022)
Krempasky, LŠ et al. Nature 626, 517 (2024), Reichlova & LŠ et al., Nature Comm. 15,2116 (2024),Reimers, LŠ et al., Nature Communication 16, 7270 (2025)

2 Foundations: spin symmetries and unconventional magnets

LŠ et al. Science Advances 6, eaaz8809 (2020), Mazin & LŠ et al. PNAS 118 (42) e2108924118 (2021)
LŠ et al. Phys. Rev. X 12, 031042 (2022), Mendoza-Estrada, & LŠ et al. Phys. Rev. B 111, 085147 (2025), LŠ et al. Phys. Rev. Lett. 131, 256703 (2023)
Krempasky, LŠ et al. Nature 626, 517 (2024), Reichlova & LŠ et al., Nature Comm. 15,2116 (2024),Reimers, LŠ et al., Nature Communication 16, 7270 (2025)
Jaeschke, Campos & LŠ et al. arXiv:2503.10797 (2025)
Birk Hellenes & LŠ et al., arXiv:2309.02355, Chakrabotry, LŠ & Sinova et al. Nature Communication 16, 7270 (2025)
Khodas, LŠ, Mazin, arXiv:2601.19829v1 (2026), Mitscherling & LŠ et al., arXiv:2603.09736
Campos,, and LŠ et al. arXiv:2603.12223 (2026), Dal Din, Usanov, LŠ & Wadley et al., arXiv:2511.01690 (2025), Mazin and LŠ et al. arXiv:2309.02355
Mitscherling, Priessnitz, and LŠ arXiv:2512.09051

3 Functionalities: multiferroics and spintronics

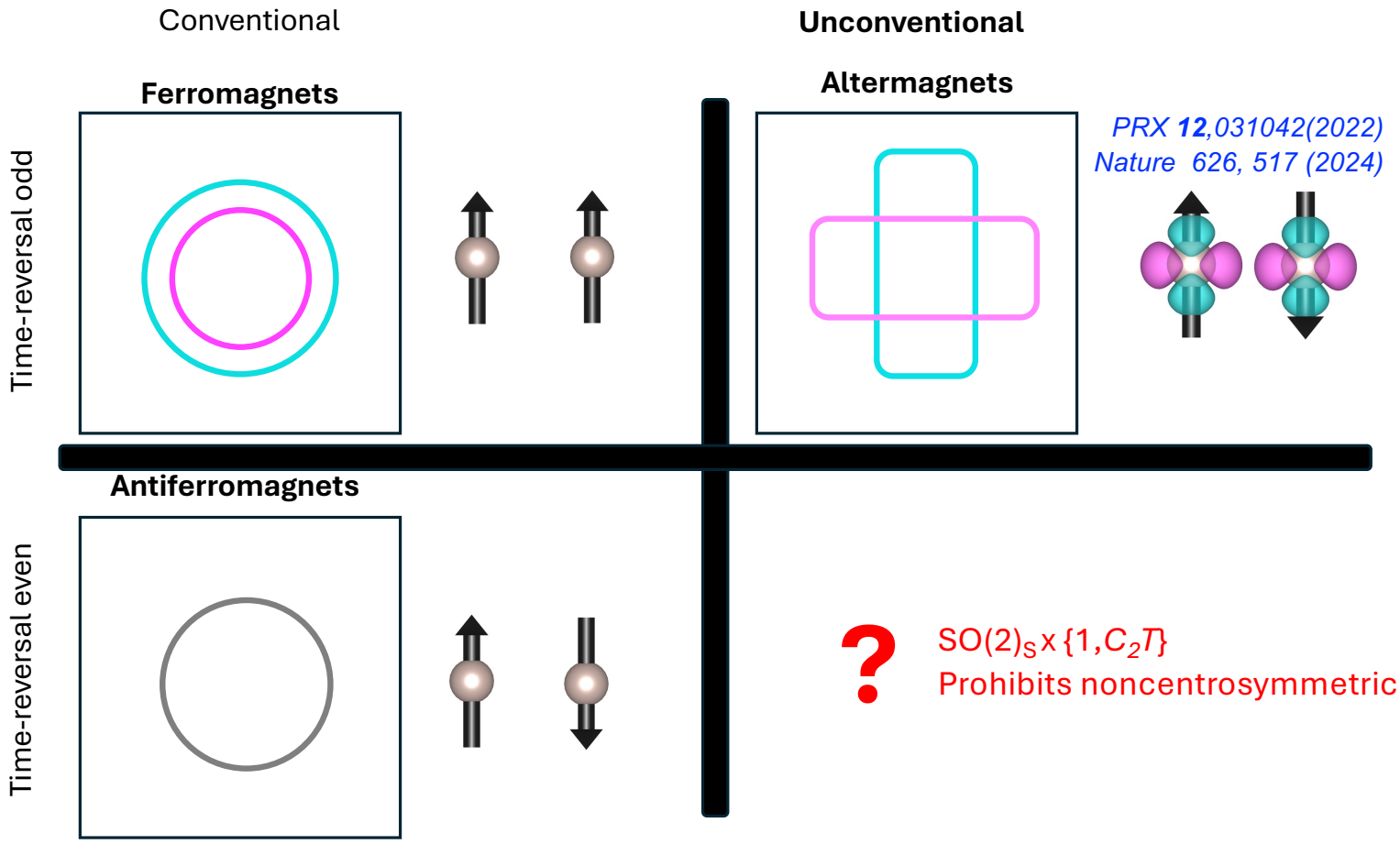
LŠ arXiv:2411.19928 , Priessnitz, Hellenes, Comin & LŠ, arXiv:2603.19107 (2026)
LŠ,et al., Phys Rev X 12, 011028 (2022), W.H. Campos,, and LŠ et al. arXiv:2603.12223 (2026), Golub & LŠ, arXiv:2503.12203 (2025)



Newton – on the cover

P-wave magnets?

Spin group theory classification



*PRX **12**,031042(2022)*
Nature 626, 517 (2024)

?

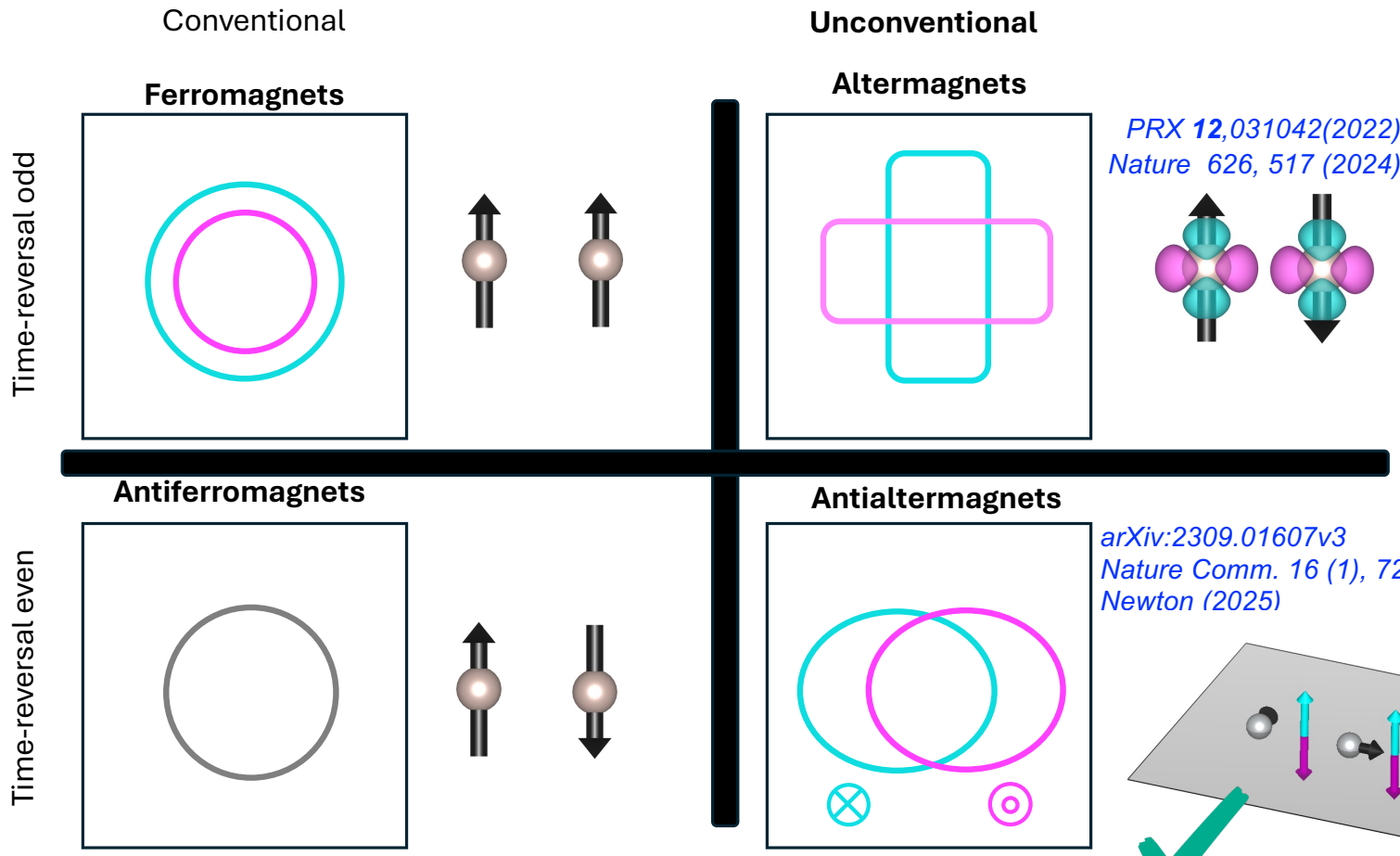
$SO(2)_S \times \{1, C_2T\}$
Prohibits noncentrosymmetric bandstructures

arXiv:2309.01607v1

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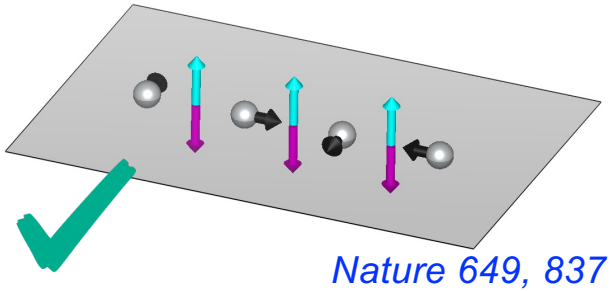
Nature 649, 837 (2026)

Spin group theory classification



*PRX **12**,031042(2022)*
Nature 626, 517 (2024)

arXiv:2309.01607v3
Nature Comm. 16 (1), 7270
Newton (2025)

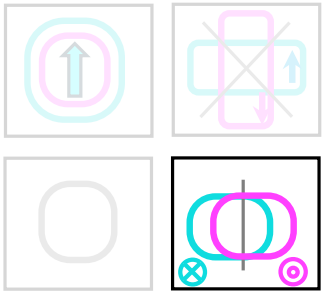


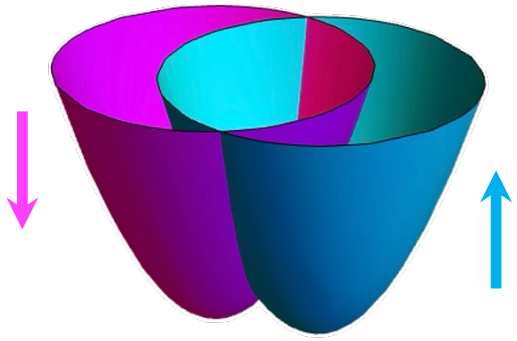
Nature 649, 837 (2026)

arXiv:2309.01607v1

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Noncollinearity: p, f, ...-wave antialtermagnets



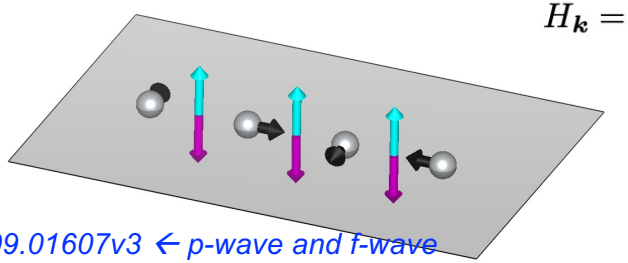




Anna Birk Hellenes

Against notion of magnetism (time-reversal symmetric and perpendicular to direct space order)

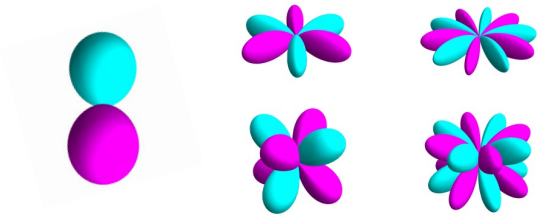
$$\langle S_\perp \rangle_n(\mathbf{k}) \propto -\mathrm{sign}[k_x] \frac{\mathbf{J}_x \times \mathbf{J}_y}{|\mathbf{J}_x \times \mathbf{J}_y|}$$



$$H_{\boldsymbol{k}} = 2t(\cos\frac{k_x}{2}\tau_1 + \cos k_y) + 2t_J(\sin\frac{k_x}{2}\sigma_x\tau_2 + \cos k_y\sigma_y\tau_3).$$

Minimal simplified Hamiltonian

$$H^{\mathrm{eff}}_{\boldsymbol{k}} = \frac{k_x^2}{2m} - \frac{k_0 k_x}{m}\sigma_z + \frac{2}{m}k_y^2$$



p-wave *f-wave* *h-wave* ...

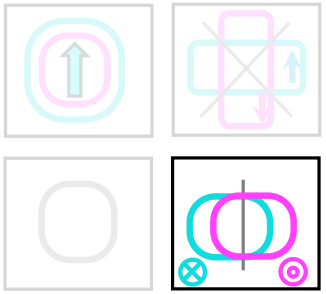
Prediction

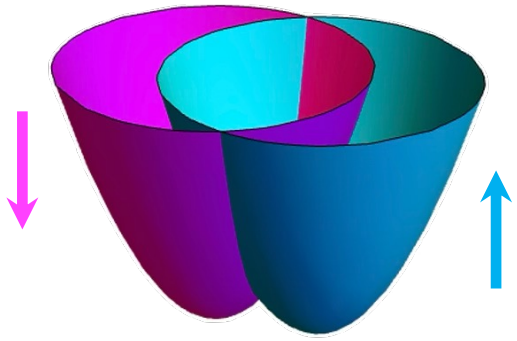
Birk Hellenes & LŠ et al. arXiv:2309.01607v3 ← p-wave and f-wave
Chakraborty, LŠ et al. Nature Comm. 16, 7270 (2025)
Jungwirth & LŠ, Nature 649, 837 (2026)
Jungwirth & LŠ et al. Newton 1, (6) 100162 (2025)

Mitscherling, Priessnitz, Geschner & LŠ, arXiv:2603.09736
Khodas, LŠ, and Mazin, Phys. Rev. B 114, L080505 (2026)
Yu, Agterberg et al., Phys. Rev. Lett. 135, 046701 (2025) ← h-wave
Elcoro et al., arXiv:2606.19254 (2026) ← j-wave, l-wave
Lange, Sinova et al. arXiv:2608.19056 (2026)

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Noncollinearity: p, f, ...-wave antialtermagnets



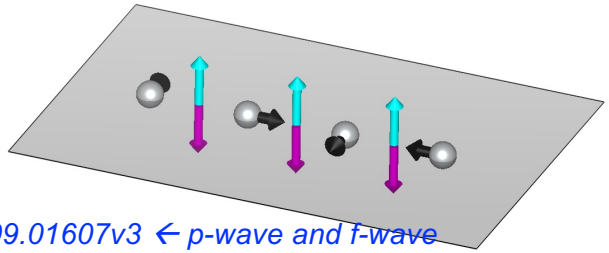




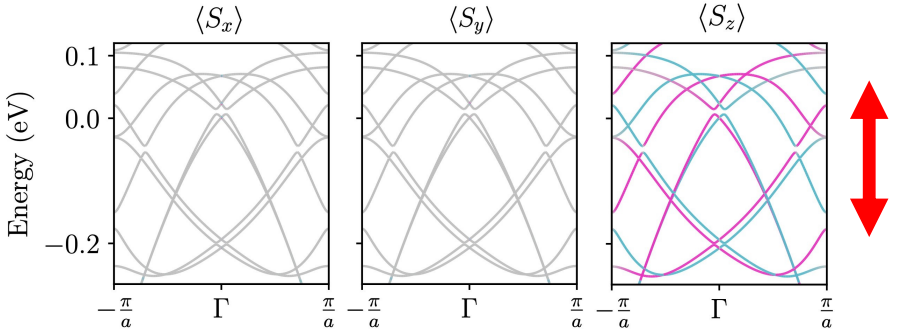
Anna Birk Hellenes

Against notion of magnetism (time-reversal symmetric and perpendicular to direct space order)

$$\langle S_\perp \rangle_n(\mathbf{k}) \propto -\,\mathrm{sign}\left[k_x\right] \frac{\mathbf{J}_x \times \mathbf{J}_y}{|\mathbf{J}_x \times \mathbf{J}_y|}$$



CeNiAsO



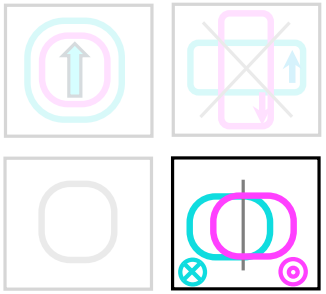
Prediction

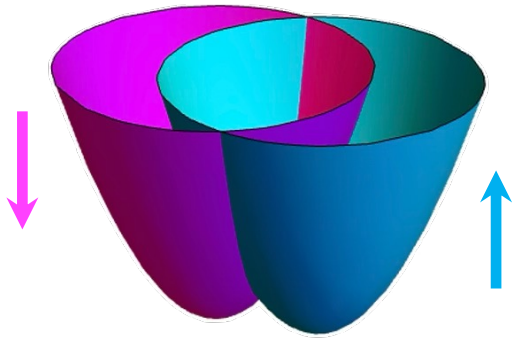
Birk Hellenes & LŠ et al. arXiv:2309.01607v3 ← p-wave and f-wave
Chakraborty, LŠ et al. Nature Comm. 16, 7270 (2025)
Jungwirth & LŠ, Nature 649, 837 (2026)
Jungwirth & LŠ et al. Newton 1, (6) 100162 (2025)

Mitscherling, Priessnitz, Geschner & LŠ, arXiv:2603.09736
Khodas, LŠ, and Mazin, Phys. Rev. B 114, L080505 (2026)
Yu, Agterberg et al., Phys. Rev. Lett. 135, 046701 (2025) ← h-wave
Elcoro et al., arXiv:2606.19254 (2026) ← j-wave, l-wave
Lange, Sinova et al. arXiv:2608.19056 (2026)

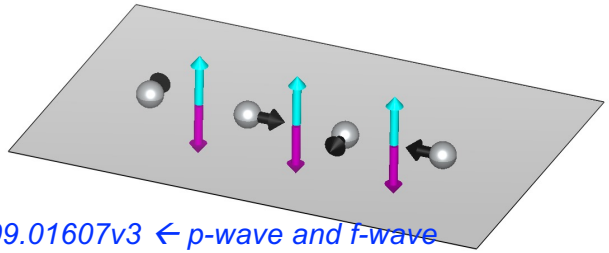
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Noncollinearity: p, f, ...-wave antialtermagnets





$$\langle S_\perp \rangle_n(\mathbf{k}) \propto -\mathrm{sign}[k_x] \frac{\mathbf{J}_x \times \mathbf{J}_y}{|\mathbf{J}_x \times \mathbf{J}_y|}$$



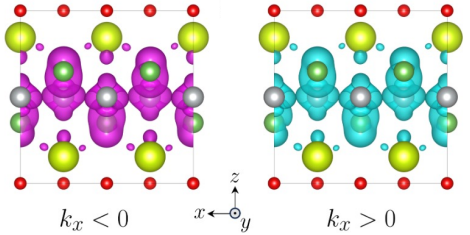






Johannes Mitscherling Clara Geschner Anna Birk Hellenes

3 Direct space hidden order



4 Complete classification of four-band Hamiltonians

$\langle \hat{\mathbf{S}} \rangle_n(\mathbf{k})$	Ferromagnet	Altermagnet	p-wave magnet
$\mathbf{m} \cdot \mathbf{h}(\mathbf{k})$	$\mathbf{d}_0(\mathbf{k})$	0	0
$\mathbf{m} \cdot \mathbf{h}_\star(\mathbf{k})$	0	$d_3(\mathbf{k})\,\mathbf{d}_3(\mathbf{k})$	0
$\mathbf{m} \cdot \mathbf{h}_{\star\star}(\mathbf{k})$	$d_1(\mathbf{k})^2\,\mathbf{d}_0(\mathbf{k})$	0	$d_1(\mathbf{k})\,\mathbf{d}_2(\mathbf{k}) \times \mathbf{d}_3(\mathbf{k})$

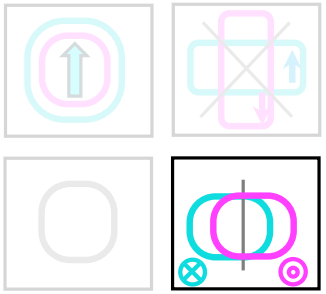
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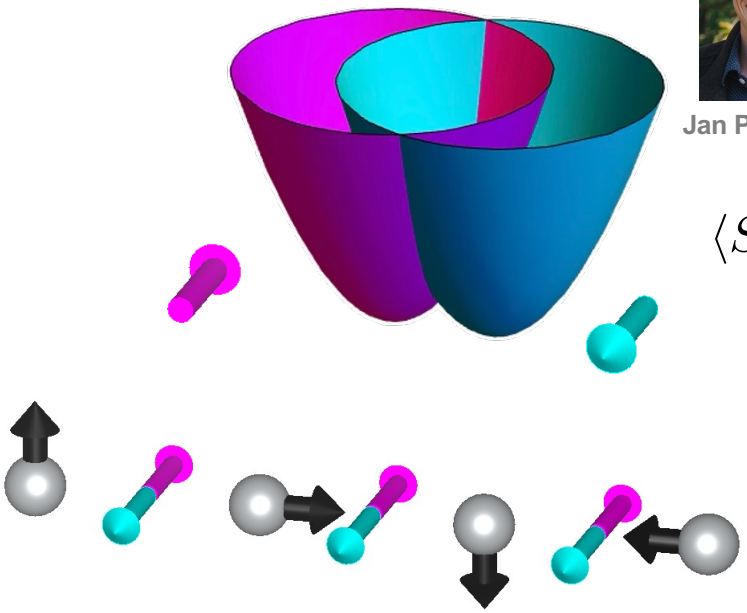
Birk Hellenes & LŠ et al. arXiv:2309.01607v3 ← p-wave and f-wave
Chakraborty, LŠ et al. Nature Comm. 16, 7270 (2025)
Jungwirth & LŠ, Nature 649, 837 (2026)
Jungwirth & LŠ et al. Newton 1, (6) 100162 (2025)

Mitscherling, Priessnitz, Geschner & LŠ, arXiv:2603.09736
Khodas, LŠ, and Mazin, Phys. Rev. B 114, L080505 (2026)
Yu, Agterberg et al., Phys. Rev. Lett. 135, 046701 (2025) ← h-wave
Elcoro et al., arXiv:2606.19254 (2026) ← j-wave, l-wave
Lange, Sinova et al. arXiv:2608.19056 (2026)

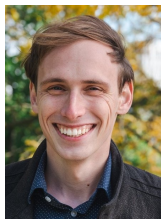
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Observation of archetypal *p*-wave splitting

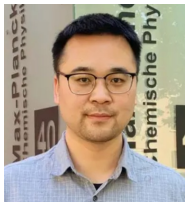




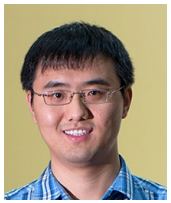
$\langle S_\perp \rangle$



Jan Priessnitz



Erjian Cheng



Junwei Liu

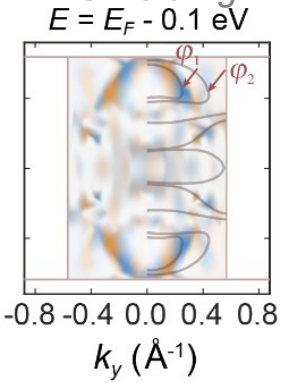


Zhongkai Liu



Claudia Felser

Theory
Unfolding

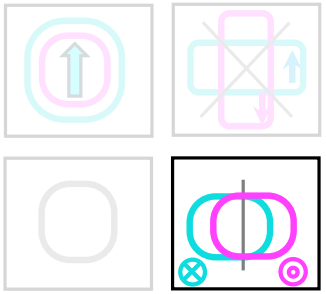


Prediction:
Birk Hellenes & LŠ et al. arXiv:2309.01607v3
Chakraborty, LŠ et al. Nature Comm. 16, 7270 (2025)
Mitscherling, Priessnitz, Geschner & LŠ, arXiv:2603.09736

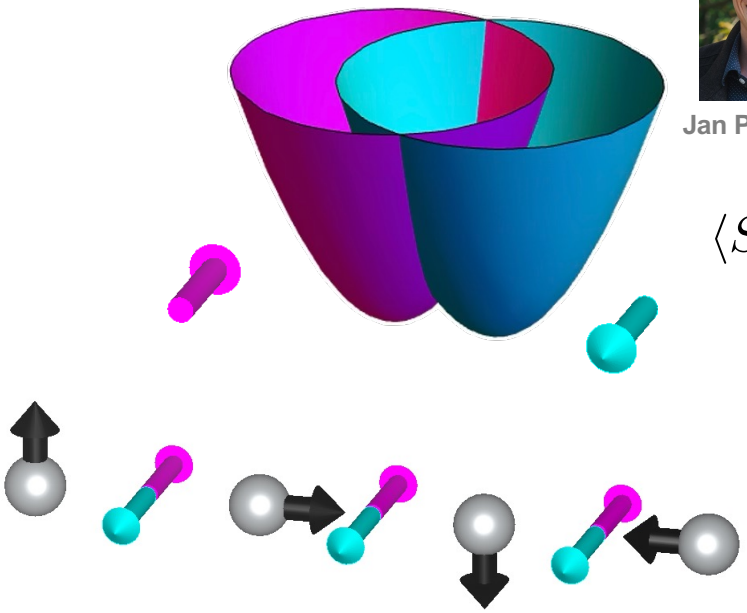
Observation: Cheng, LŠ, Liu & Felser et al. resubmitted

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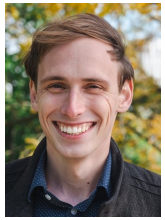
Observation of archetypal *p*-wave splitting



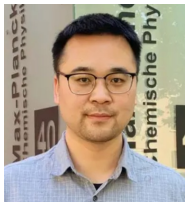
Experiment



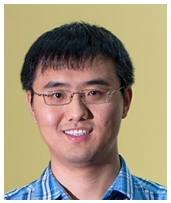
$\langle S_\perp \rangle$



Jan Priessnitz



Erjian Cheng



Junwei Liu

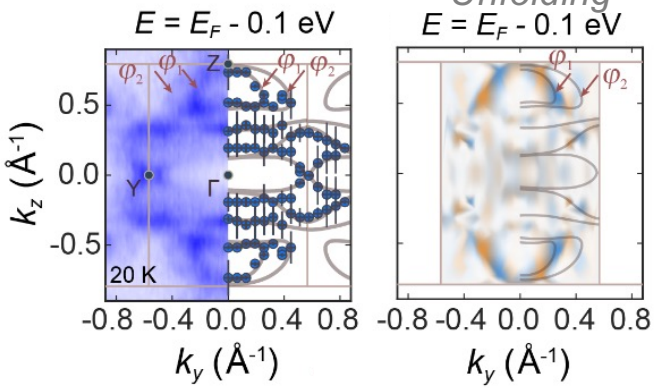


Zhongkai Liu



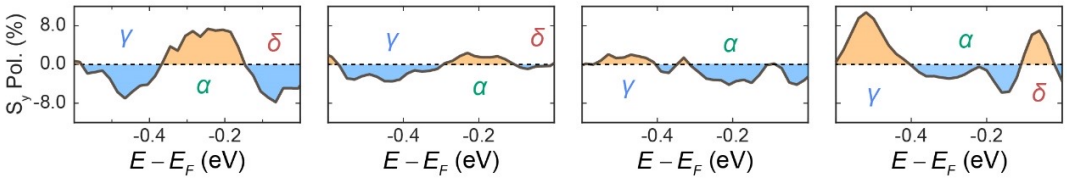
Claudia Felser

Experiment *Theory Unfolding*



Prediction:
Birk Hellenes & LŠ et al. arXiv:2309.01607v3
Chakraborty, LŠ et al. Nature Comm. 16, 7270 (2025)
Mitscherling, Priessnitz, Geschner & LŠ, arXiv:2603.09736

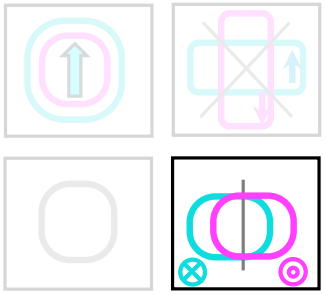
Observation: Cheng, LŠ, Liu & Felser et al. resubmitted

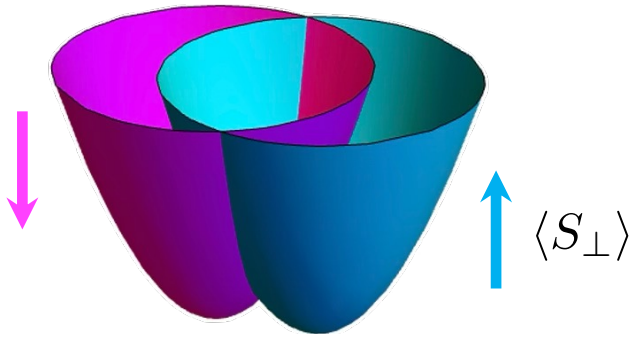


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Multiple works on CeNiAsO

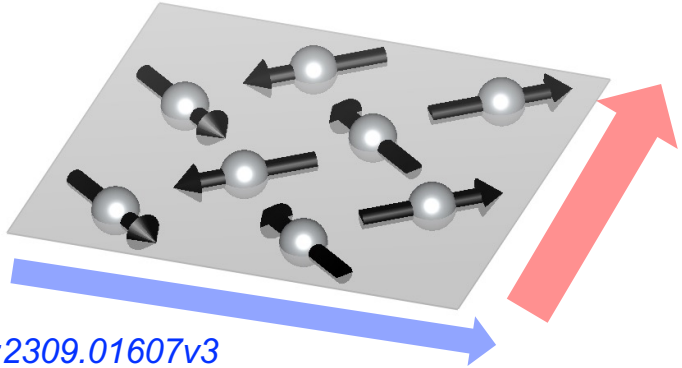
Noncollinearity: p, f, h-wave antialtermagnets

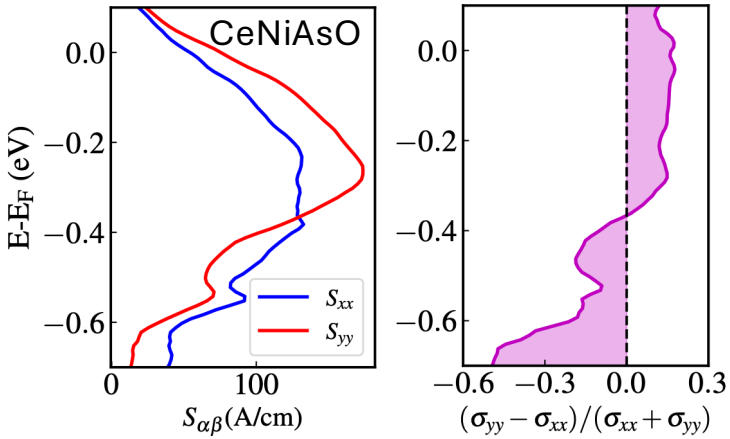





Atasi Chakraborty


Anna Birk Hellenes





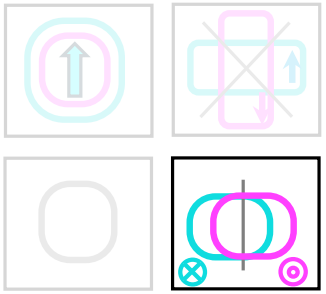
Prediction
Birk Hellenes & LŠ et al. arXiv:2309.01607v3
Chakraborty, LŠ et al. Nature Comm. 16, 7270 (2025)

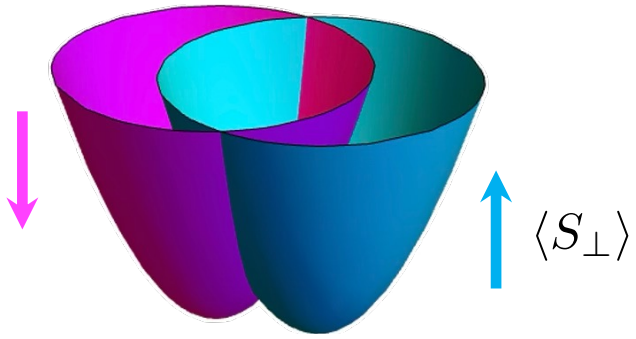
Experiments
Song et al., Nature 642, 64 (2025)
Yamada et al., Nature 646, 847 (2025)

Experimental verification
Zhou et al., arXiv:2509.07351v1 (2025)
Multiple recent arXives?

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Noncollinearity: p, f, h-wave antialtermagnets







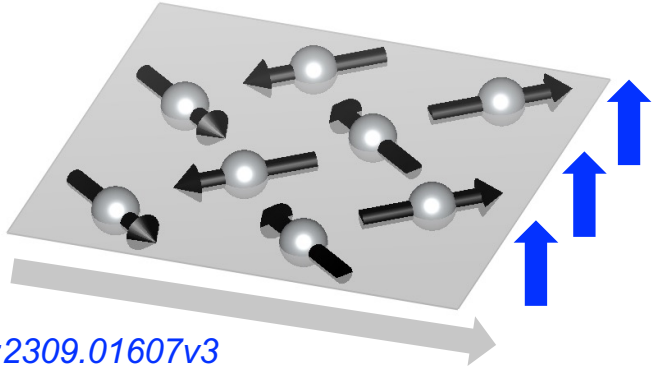
Atasi Chakraborty

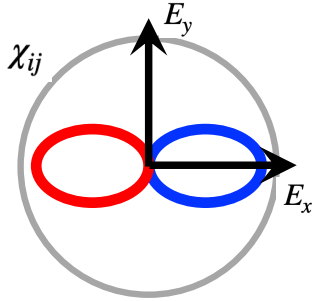


Anna Birk Hellenes

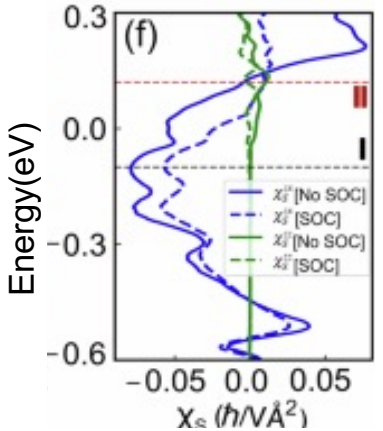


Nayra Alvarez





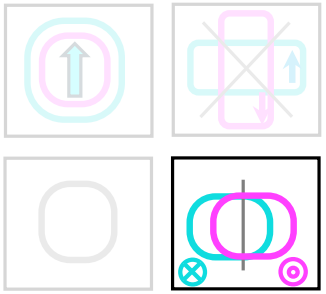
$\chi_{ij} \propto \alpha m \tau$

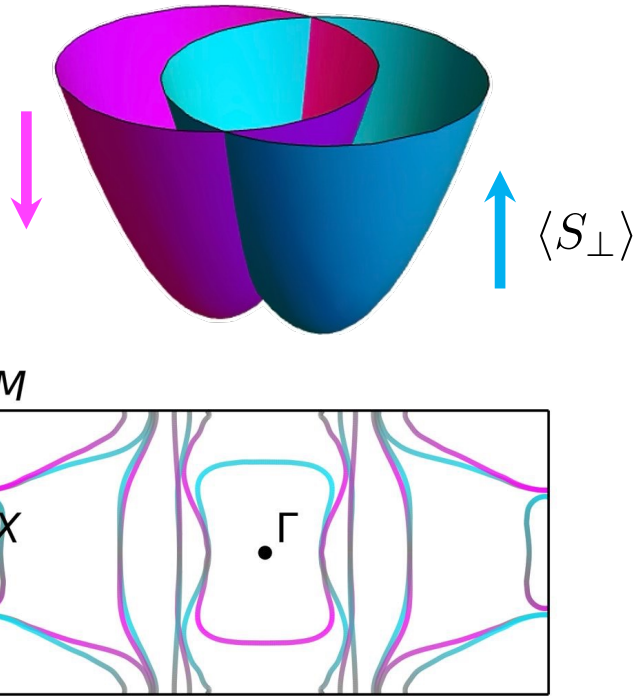


Birk Hellenes & LŠ et al. arXiv:2309.01607v3
Chakraborty, LŠ et al. Nature Comm. 16, 7270 (2025)
Hu et al. Nature Communications 16 (1), 8529 (2025)
Pari, LS et al. Phys. Rev. B 112, 024404 (2025)

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Nonrelativistic Ising superconductivity



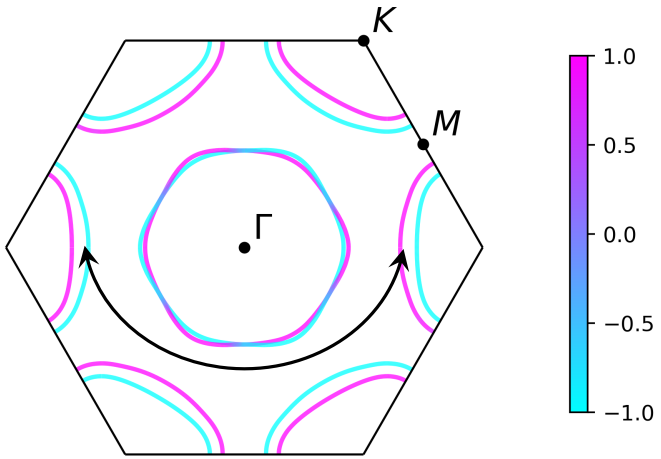




Maxim Khodas



Igor Mazin



CeNiAsO	**$NbSe_2$**
Wavefunction + exchange ~ bandwidth: triplet:singlet	*Wavefunction + SOC << bandwidth: singlet*
Anisotropic	*Isotropic*
P-wave	*F-wave*

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Khodas, LŠ, Mazin, Phys. Rev. B 114, L080505 (2026)

Outline

1 From unconventional Hall effect to altermagnets

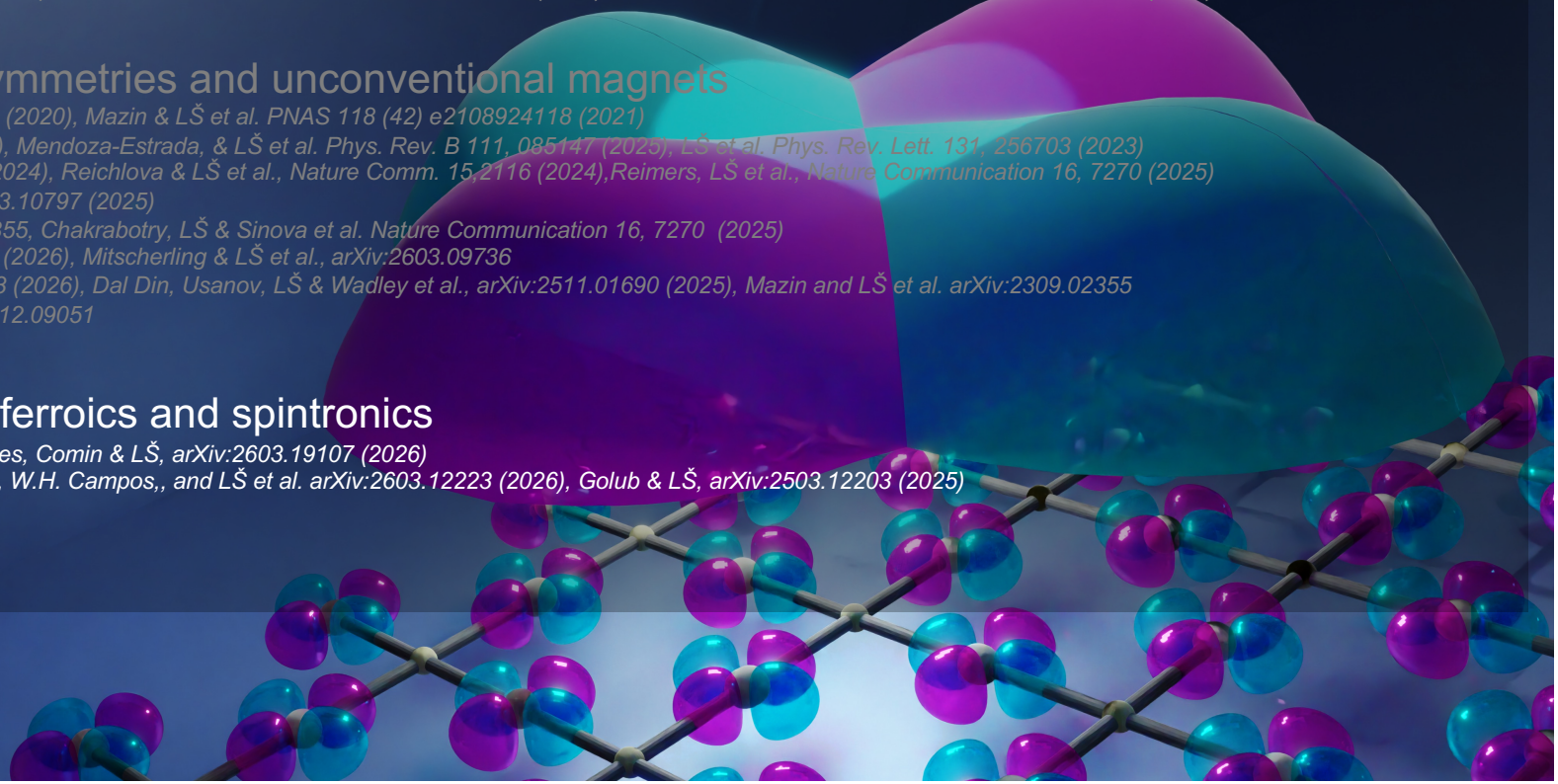
LŠ et al. Science Advances 6, eaaz8809 (2020), Mazin & LŠ et al. PNAS 118 (42) e2108924118 (2021)
Mazin & LŠ et al. PNAS 118 (42) e2108924118 (2021)
LŠ et al. Phys. Rev. X 12, 031042 (2022)
Krempasky, LŠ et al. Nature 626, 517 (2024), Reichlova & LŠ et al., Nature Comm. 15,2116 (2024),Reimers, LŠ et al., Nature Communication 16, 7270 (2025)

2 Foundations: spin symmetries and unconventional magnets

LŠ et al. Science Advances 6, eaaz8809 (2020), Mazin & LŠ et al. PNAS 118 (42) e2108924118 (2021)
LŠ et al. Phys. Rev. X 12, 031042 (2022), Mendoza-Estrada, & LŠ et al. Phys. Rev. B 111, 085147 (2025), LŠ et al. Phys. Rev. Lett. 131, 256703 (2023)
Krempasky, LŠ et al. Nature 626, 517 (2024), Reichlova & LŠ et al., Nature Comm. 15,2116 (2024),Reimers, LŠ et al., Nature Communication 16, 7270 (2025)
Jaeschke, Campos & LŠ et al. arXiv:2503.10797 (2025)
Birk Hellenes & LŠ et al., arXiv:2309.02355, Chakrabotry, LŠ & Sinova et al. Nature Communication 16, 7270 (2025)
Khodas, LŠ, Mazin, arXiv:2601.19829v1 (2026), Mitscherling & LŠ et al., arXiv:2603.09736
Campos,, and LŠ et al. arXiv:2603.12223 (2026), Dal Din, Usanov, LŠ & Wadley et al., arXiv:2511.01690 (2025), Mazin and LŠ et al. arXiv:2309.02355
Mitscherling, Priessnitz, and LŠ arXiv:2512.09051

3 Functionalities: multiferroics and spintronics

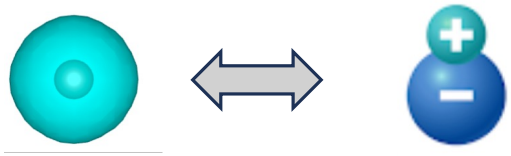
LŠ arXiv:2411.19928 , Priessnitz, Hellenes, Comin & LŠ, arXiv:2603.19107 (2026)
LŠ,et al., Phys Rev X 12, 011028 (2022), W.H. Campos,, and LŠ et al. arXiv:2603.12223 (2026), Golub & LŠ, arXiv:2503.12203 (2025)



Newton – on the cover

Nonrelativistic altermagneto-electric couplings?

Conventional magnetoelectric effect

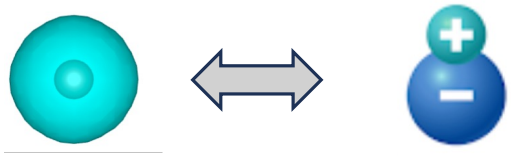


$$M_i = \alpha_{ij} E_j$$

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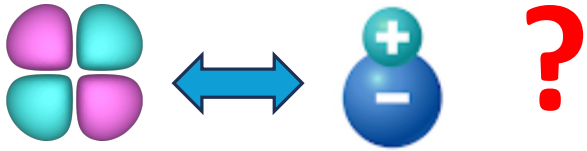
Nonrelativistic altermagneto-electric couplings?

Conventional magnetoelectric effect



$$M_i = \alpha_{ij} E_j$$

Can we couple altermagnetism with ferroelectricity?



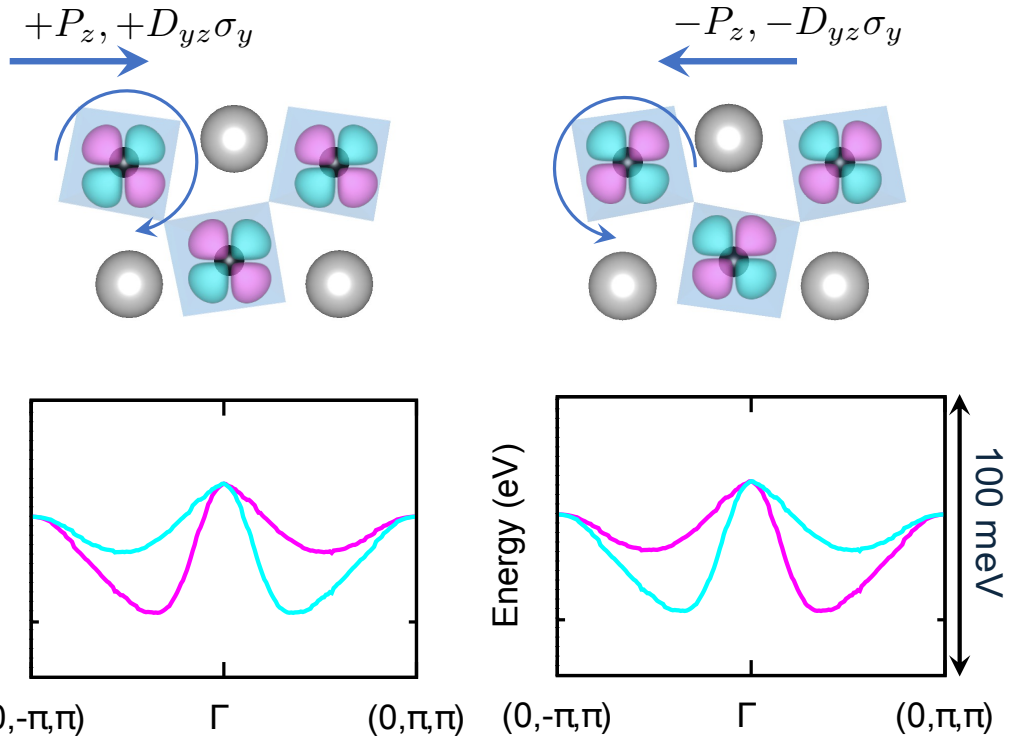
$$M^i_{jk} = \alpha^i_{jkl} E_l$$

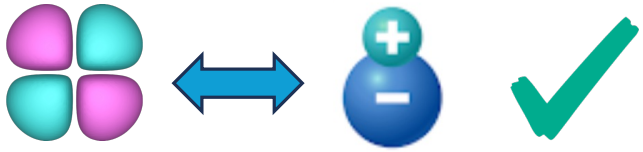
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LŠ, arXiv:2411.19928 (2024)

Altermagnetoelectric effect – nonrelativistic coupling of AM order and E-field

Can we couple altermagnetism with ferroelectricity?





$$M^{i}_{jk} = \alpha^{i}_{jkl} E_l$$

spin

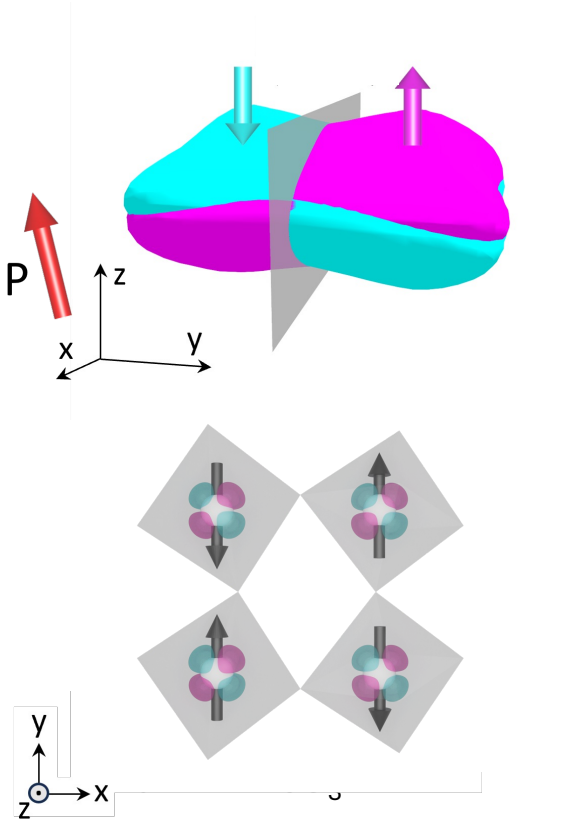
lattice



LŠ, arXiv:2411.19928 (2024), under revision
Gu et al. arXiv:2411.14216, PRL134, 106802 (2025)
Duan, Zutic et al., PRL134, 106801 (2025)

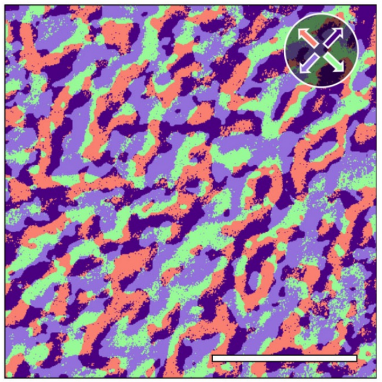
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Altermagnetic multiferroics

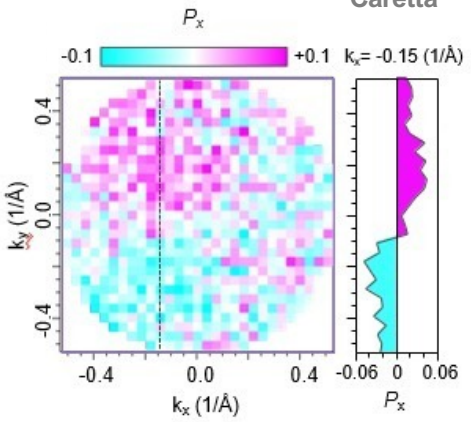




Lucas Caretta



XMCD



Spin ARPES

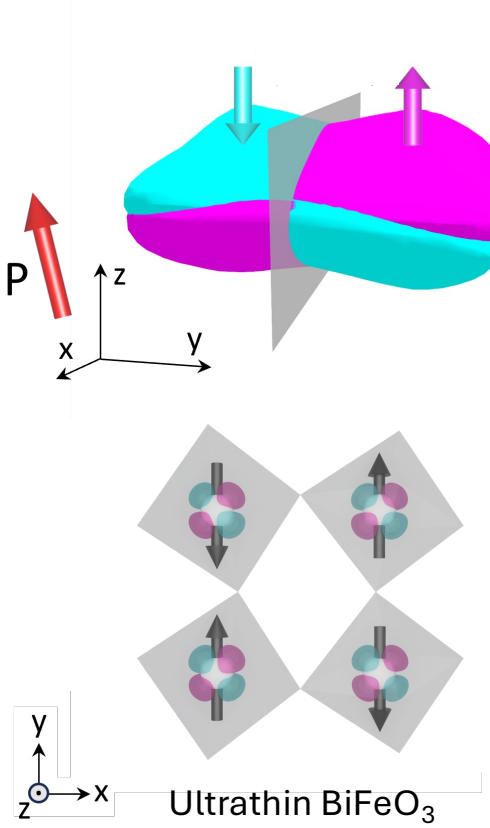
Fratian, Ramesh, LŠ, Caretta et al. arXiv:2601.09970, Nature Mater., in press
Priessnitz & LŠ et al., arXiv:2603.19107 (2026)
LŠ, arXiv:2411.19928 (2024)
LŠ et al. Sci. Adv. 6, eaaz8809 (2020)
Amin, LŠ et al. Nature 636, 348–353 (2024)

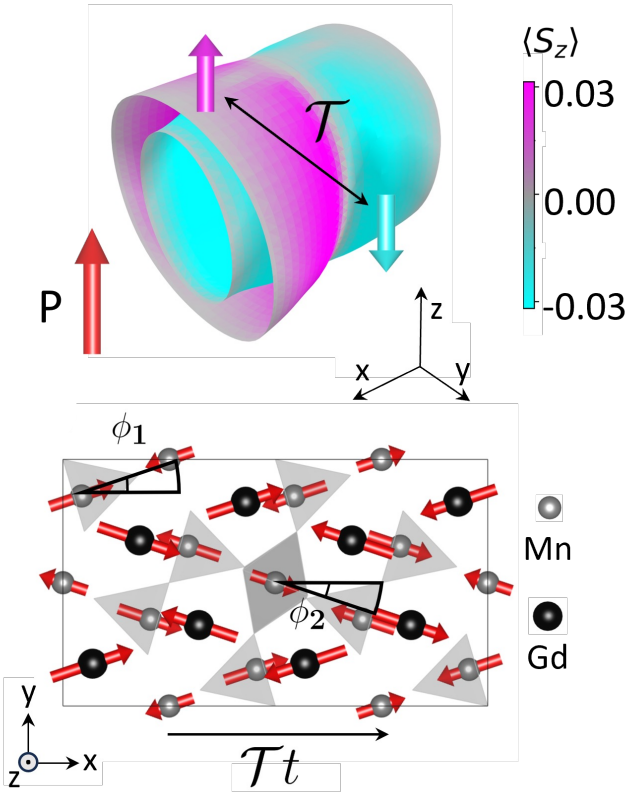
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Antialtermagnetic multiferroics - classification



Jan Priessnitz

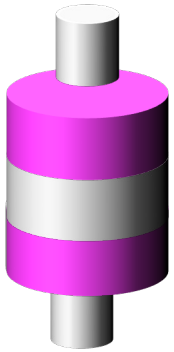




Priessnitz, Hellenes, Comin & LŠ et al., arXiv:2603.19107 (2026)

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All-electrical altermagnetic tunnelling junction



Can we build all-altermagnetic tunnel junction/memory?

LŠ,et al., Phys Rev X 12, 011028 (2022)
Jaeschke, Campos & LŠ et al. arXiv:2503.10797 (2025)
Campos & LŠ et al. arXiv:2603.12223 (2026)

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

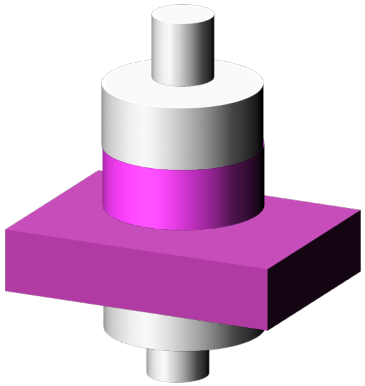
PHYSICAL REVIEW X

Giant and Tunneling Magnetoresistance in Unconventional Collinear Antiferromagnets with Nonrelativistic Spin-Momentum Coupling

Libor Šmejkal,[1,2] Anna Birk Hellenes,[1] Rafael González-Hernández,[3] Jairo Sinova,[1,2] and Tomas Jungwirth[2,4]

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All-electrical *p*-wave tunnelling junction




Jiaruo Li


Qiang Song


Anna Birk Hellenes


Riccardo Comin

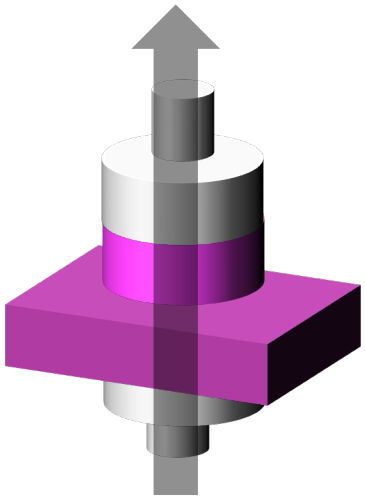
Spin group theory: linear coupling + unconventional p-wave protection

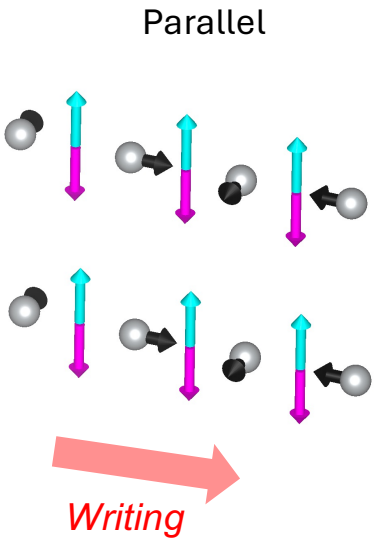
E-field ⟷ Vector chirality ⟷ P-wave spin order

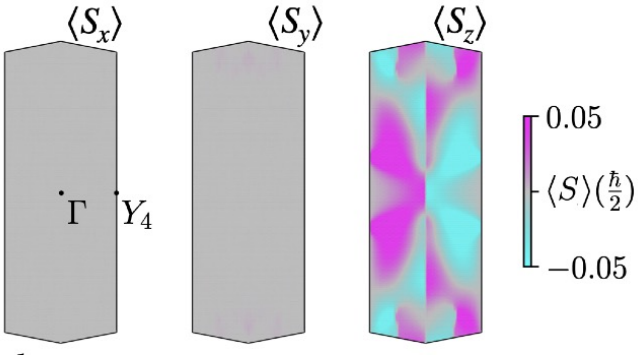
Li, Song, Hellenes, LŠ & Comin et al., submitted
Priessnitz, Hellenes, Comin & LŠ et al., arXiv:2603.19107 (2026)
Song & Comin et al. Nature 642, 64 (2025)

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All-electrical *p*-wave tunnelling junction








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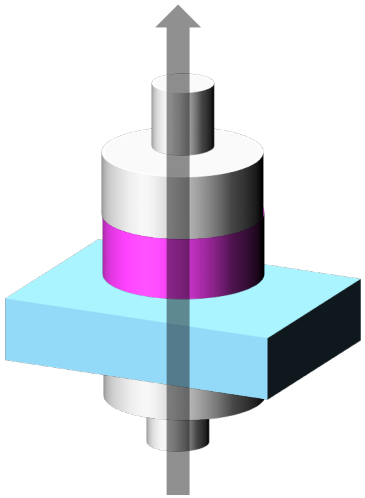
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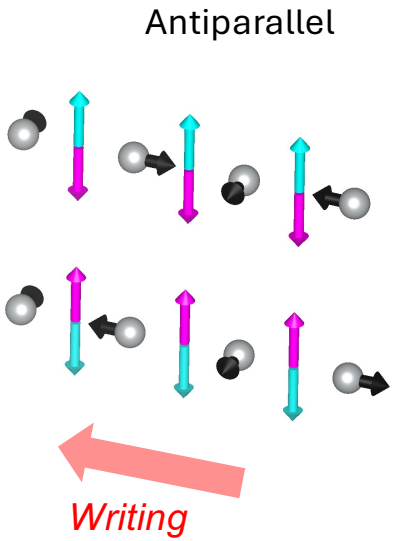
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All-electrical *p*-wave tunnelling junction



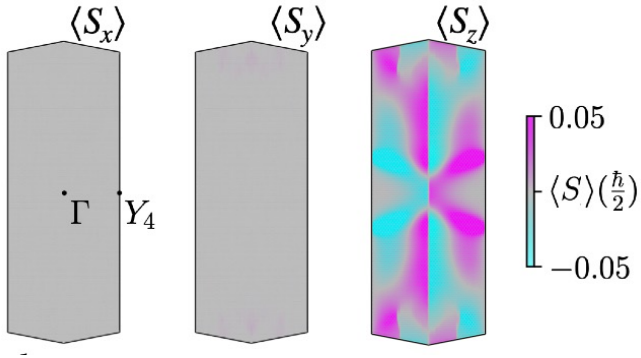



Jiaruo Li


Qiang Song


Anna Birk Hellenes


Riccardo Comin



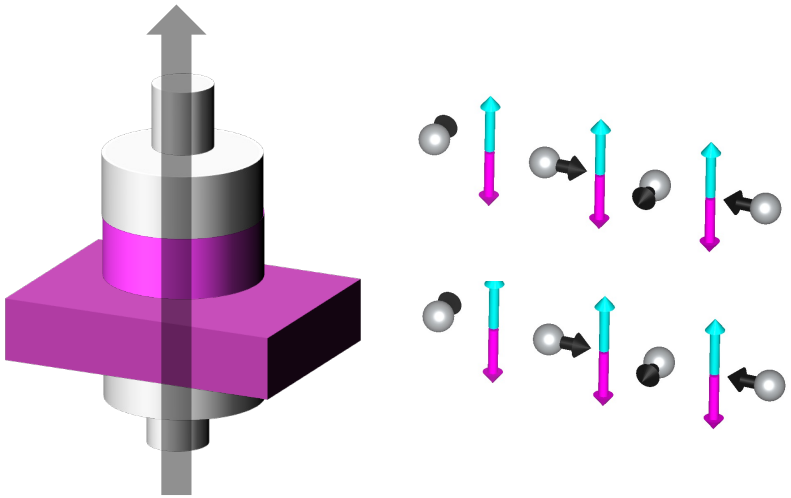
Spin group theory: linear coupling + unconventional p-wave protection

E-field ⟷ Vector chirality ⟷ P-wave spin order

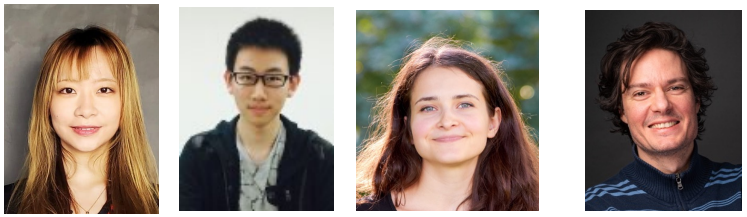
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Priessnitz, Hellenes, Comin & LŠ et al., arXiv:2603.19107 (2026)
Song & Comin et al. Nature 642, 64 (2025)

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All-electrical *p*-wave tunnelling junction

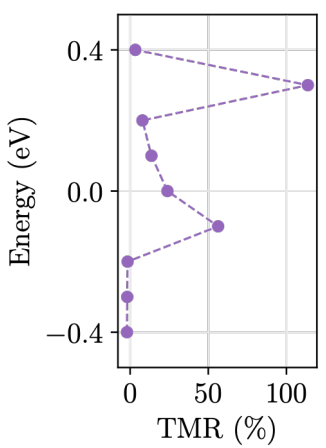


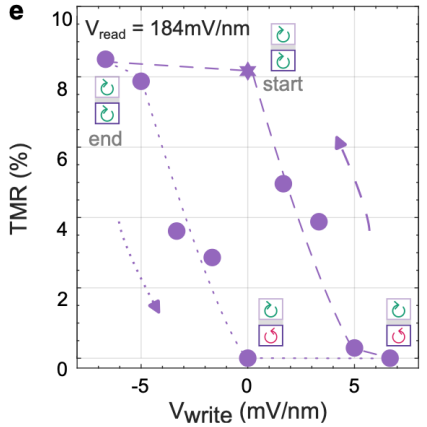
Reading



Jiaruo Li Qiang Song Anna Birk Hellenes Riccardo Comin

Theory ⟷ *Experiment*





Spin group theory: linear coupling

E-field ⟷ Vector chirality ⟷ P-wave spin order

Experimental TMR 8-42%

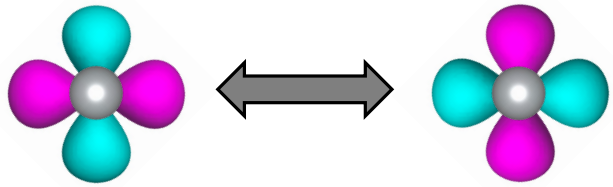
Li, Song, Hellenes, LŠ & Comin et al., submitted
Priessnitz, Hellenes, Comin & LŠ et al., arXiv:2603.19107 (2026)
Song & Comin et al. Nature 642, 64 (2025)

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Altermagnetic spintronics

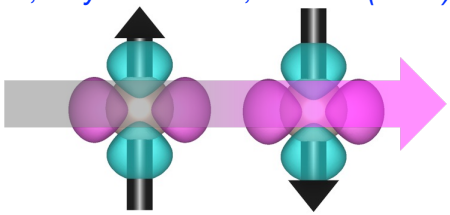
Writing: Persistent altermagnetoelectric effect

Campos & LŠ et al. arXiv:2603.12223 (2026)



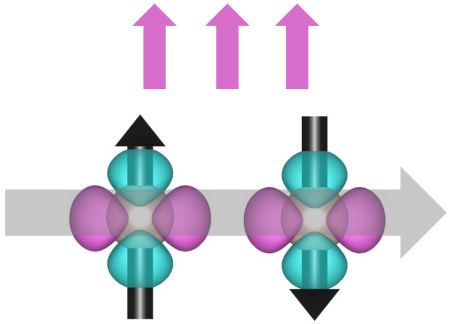
Reading tunneling magnetoresistance

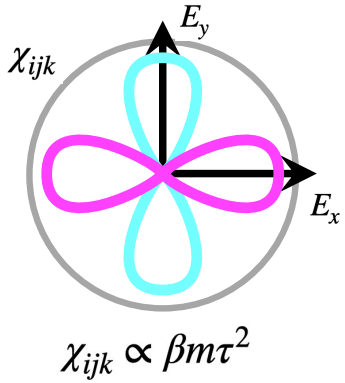
LŠ,et al., Phys Rev X 12, 011028 (2022)



Nonlinear Current induced spin generation

Golub, Campos & LŠ,

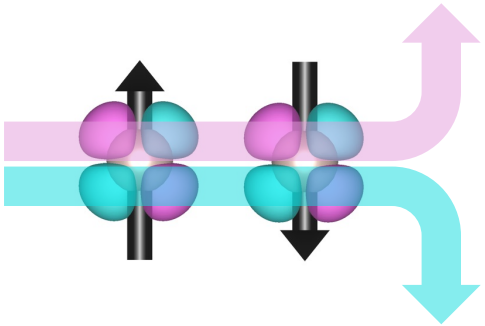


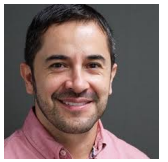


$\chi_{ijk} \propto \beta m \tau^2$

Spin splitter effect

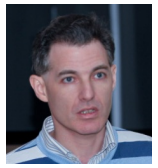
R. G.Hernandez, LŠ et al. Phys. Rev. Lett. (2021)







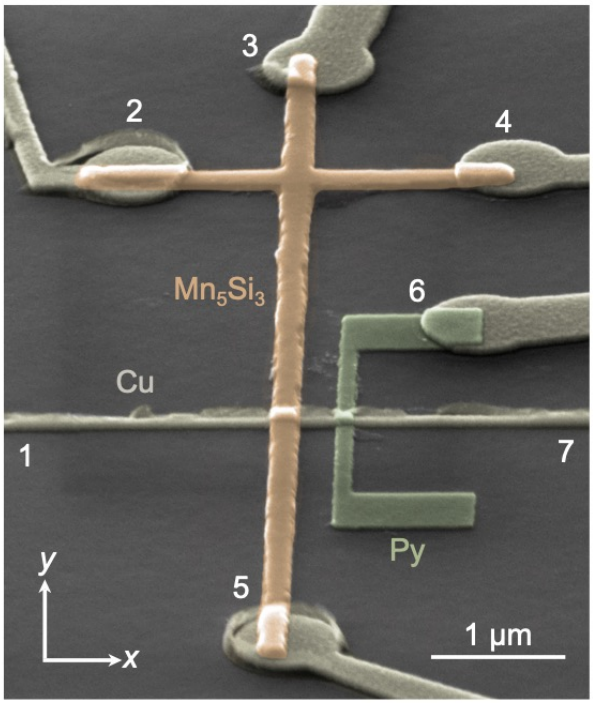


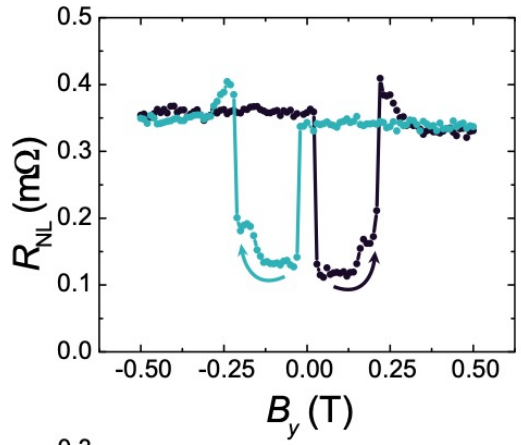


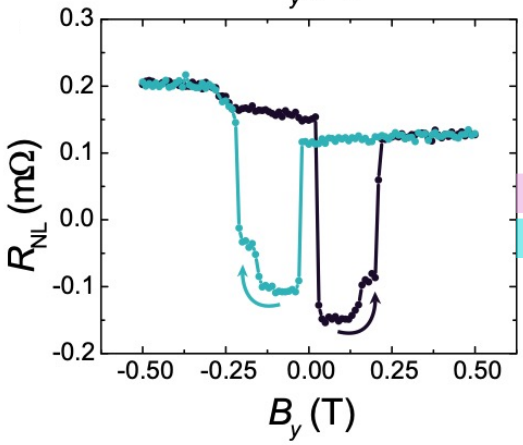
Jungwirth, Sinova, Wadley, Ohno, & LŠ et al. arXiv:2508.09748. Nature Physics

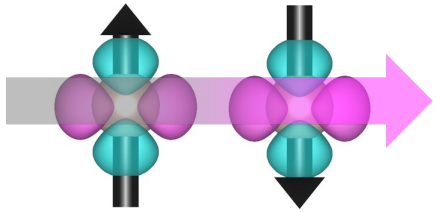
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Time-reversal-symmetry-breaking spin injection from a compensated magnet

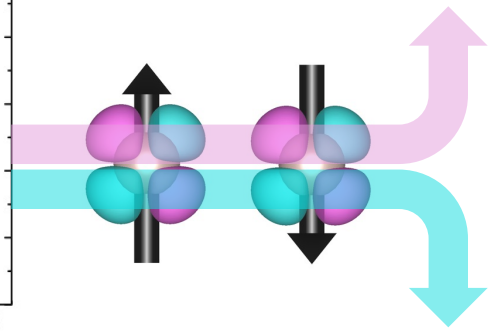








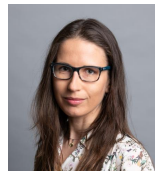
Theory: 10 %
Experiment: 10%



Spin splitter effect



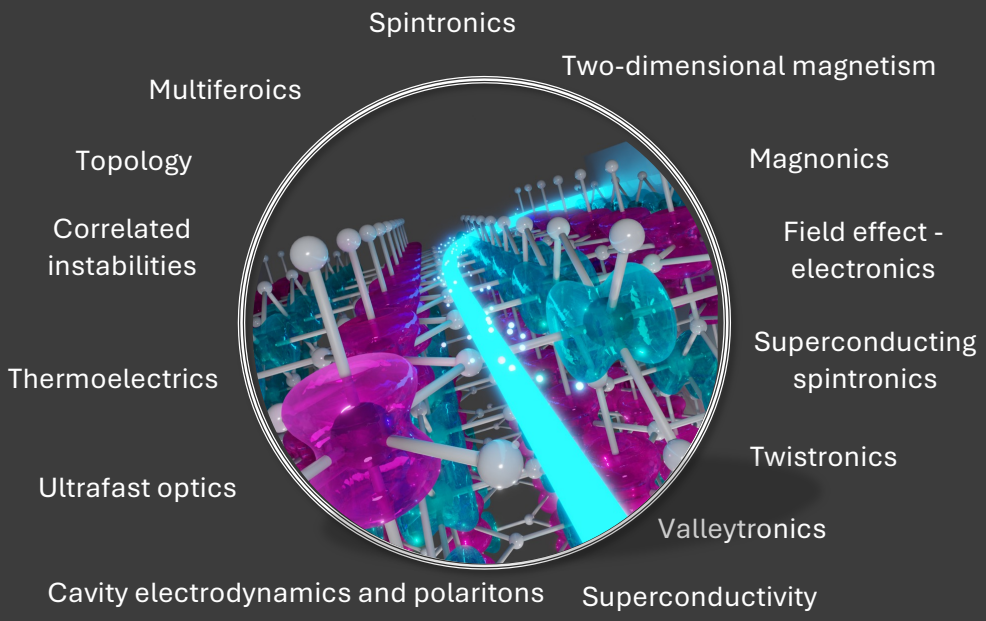





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Mencos, Sinova, LS, Reichlova, Casanova et al. arXiv:2512.17427 (2025), Nature, in press

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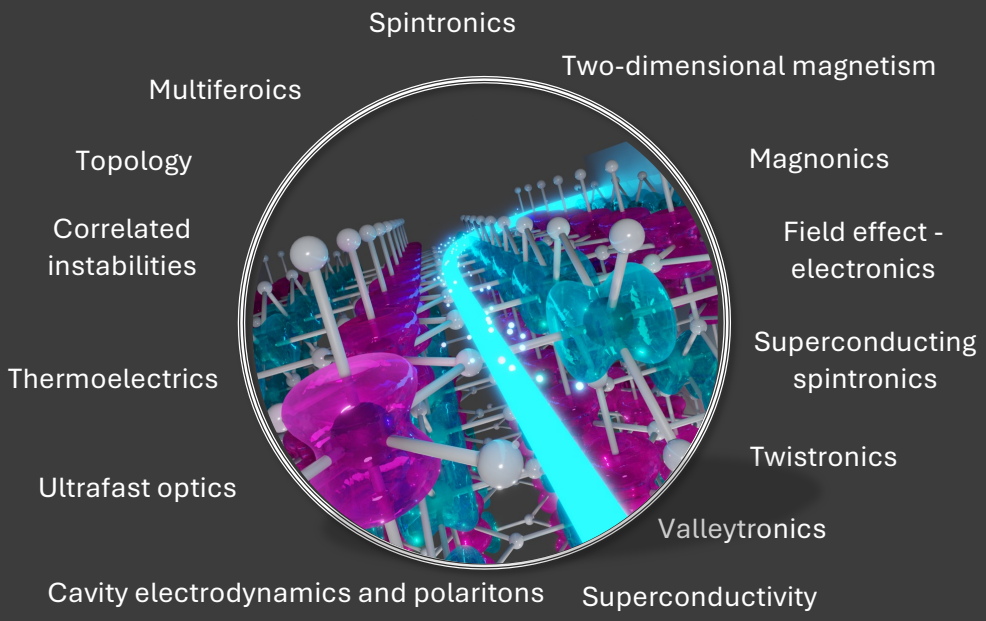
Altermagnetism and beyond: useful in many research areas!



***LŠ** et al. Phys. Rev. X 12, 031042 (2022)*
Birk Hellenes & LŠ, arXiv:2309.01607v3
LŠ, arXiv:2411.19928 (2024)
Jungwirth & LŠ et al. Nature 649, 837 (2026)

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Altermagnetism and beyond: useful in many research areas!



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LŠ, arXiv:2411.19928 (2024)
Jungwirth & LŠ et al. Nature 649, 837 (2026)

Quantum impurity sensing
Bittencourt, LŠ, Marino et al., arXiv:2508.04788, PRL, in press (2026)

Quantization of spin circular photogalvanic effect
Yoshida, Priessnitz, LŠ, and S. Murakami, PRL136, 096701 (2026)

Cavity-induced coherent magnetization and polaritons
Yarmohammadi, LŠ, Freericks, arXiv:2510.16248, PRL, in press (2026)

Altermagnetic valleys
Reichlova & LŠ et al. Nature Comm. 15 (1), 4961(2024), arXiv:2012.15651

Altermagnons
LŠ et al. Phys. Rev. Lett. 131, 256703 (2023)

P-wave magnons
Neuman, LŠ, Mook et al., arXiv:2603.05415 (2026)

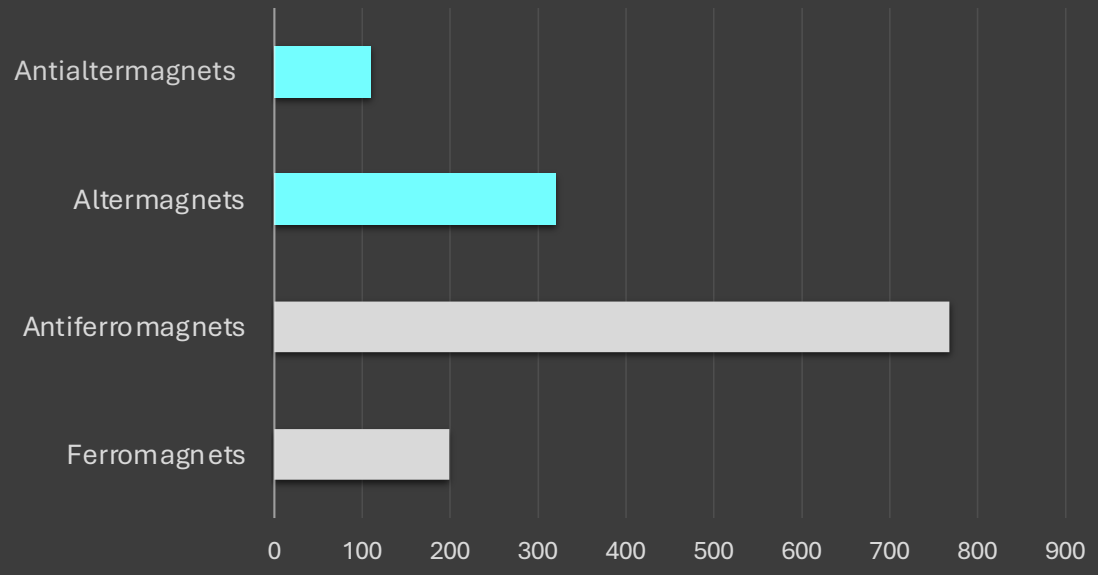
Secondary instabilities
Parheios, LŠ, Classen et al. Phys. Rev. B 112, 214410 (2025)

Correlated altermagnets
Leeb, Mook, LŠ, and Knolle, PRL 132, 236701 (2024)

Nonrelativistic Ising superconductors
Khodas, M., Šmejkal, L., and Mazin, I. I., arXiv:2601.19829

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Altermagnetism and beyond: huge material palate!



***Silicedes**, CeNiAsO, $Gd_3Ru_4Al_{12}$*
NiI_2

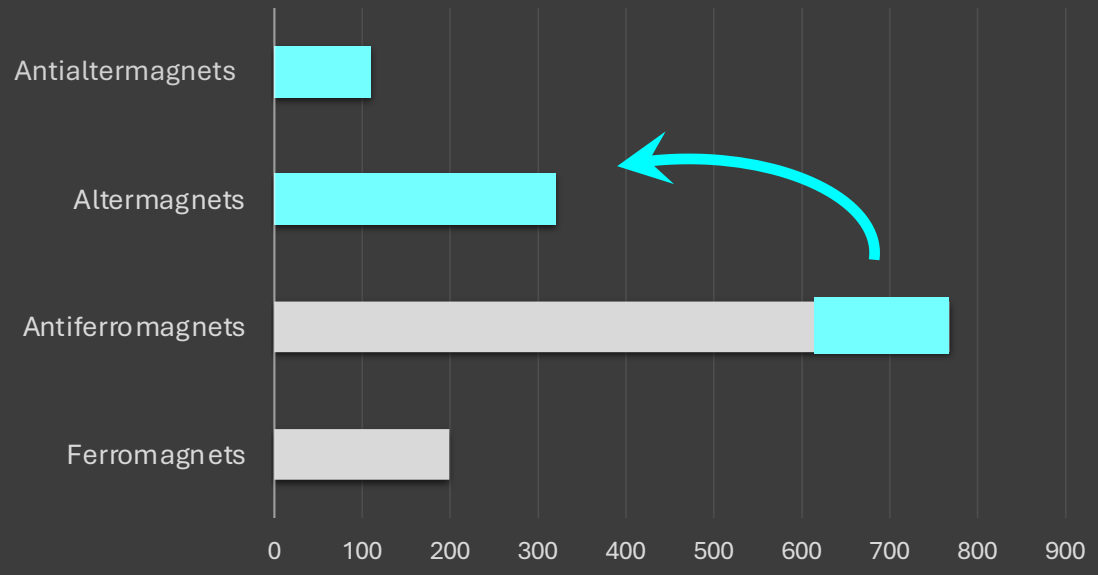
***MnTe, CrSb**, Fe_2O_3, $BiFeO_3$*
FeS, $CrNb_4S_8$ $FeSb_2$,

>500 altermagnetic candidates
>100 antiatlermagnetic candidates
+ beyond!

***10% magndata AHE:** Science Advances 6, eaaz8809 (2020)*
***CrSb, MnTe,** Phys. Rev. X 12, 031042 (2022)*
Adv. Funct. Mater. 2024, 2409327
arXiv:2309.01607v3

LSMEJKAL@PKS.MPG.DE

Altermagnetism and beyond: huge material palate!



***Silicedes**, CeNiAsO, $Gd_3Ru_4Al_{12}$ NiI_2*

***MnTe, CrSb**, Fe_2O_3, $BiFeO_3$ FeS, $CrNb_4S_8$ $FeSb_2$, K-V_2Te_2O surface*

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***10% magndata AHE:** Science Advances 6, eaaz8809 (2020)*
***CrSb, MnTe,** Phys. Rev. X 12, 031042 (2022)*
Adv. Funct. Mater. 2024, 2409327
arXiv:2309.01607v3

> 150 antiferromagnets Lange, LŠ, et al., arXiv:2602.08773 (2026)

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Acknowledgement and thank you!











CONFERENCE ON ALTERMAGNETIM, INGELHEIM, 2023, MAINZ, 2025
70 PARTICIPANTS

ROADMAP FOR ALTERMAGNETISM
NJIT, 2025 AND 2026

SHANGHAI CONFERENCE ON SPIN SYMMETRIES AND ALTERMAGNETIM, SHANGHAI, 2025
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