Ultrafast spintronics with antiferromagnets and altermagnets

PHYSICAL REVIEW X Perspective

Emerging Research Landscape of Altermagnetism

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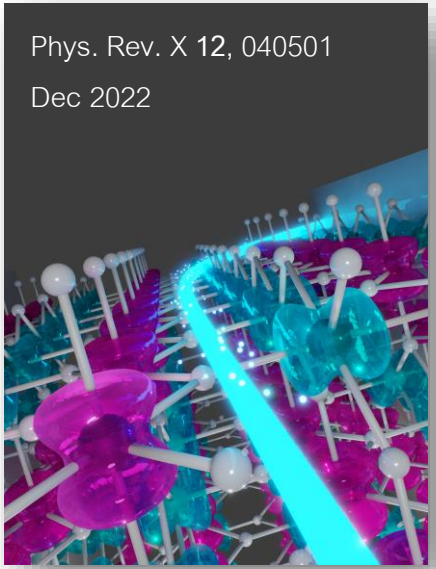
[1]*Johannes Gutenberg University Mainz, Germany*

[2]*Institute of Physics Prague, Czech Academy of Sciences*

[3]*University of Nottingham, United Kingdom*



Spintronics

Antiferromagnetic

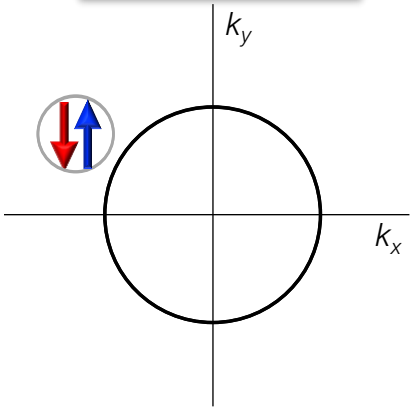
✓ Compensated magnetic order

- no stray field capacity limit
- THz speed

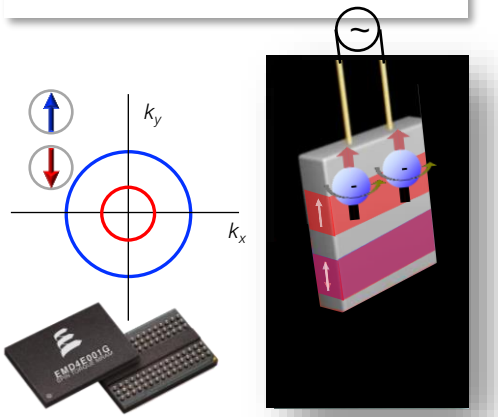
✗ Relativistic spin-orbit coupling

- weaker signals

- no net magnetization
- no spin polarization



cf. ferromagnetic



✓ Non-relativistic spin transport

- strong signals

Review: Šmejkal, Sinova & TJ, PRX ***12****, 040501 (2022)*

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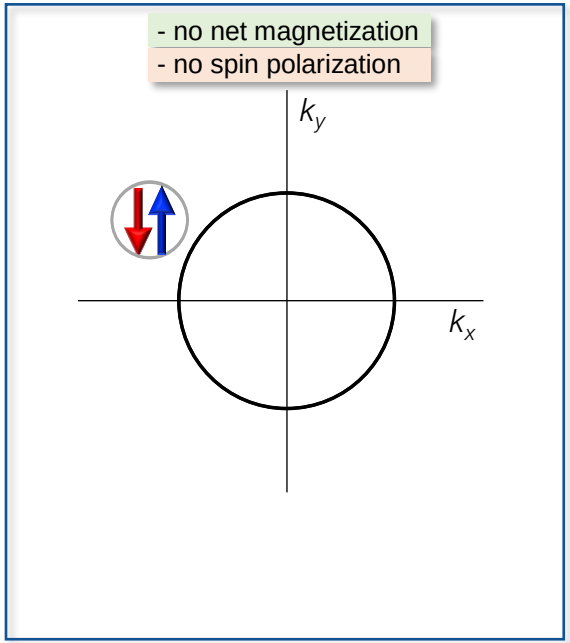

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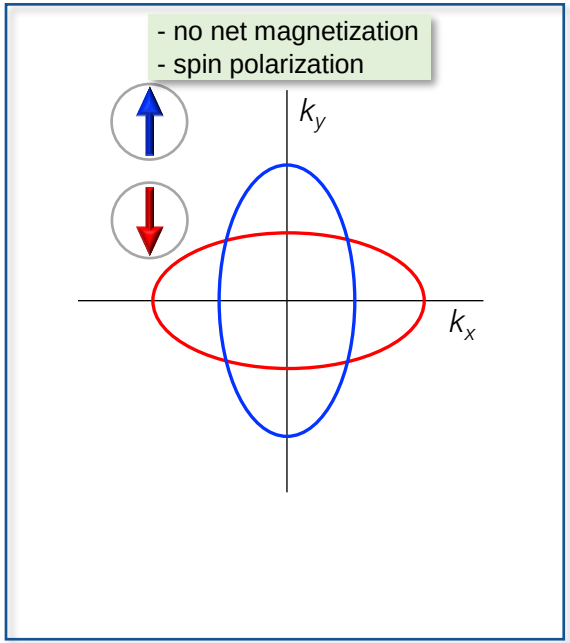

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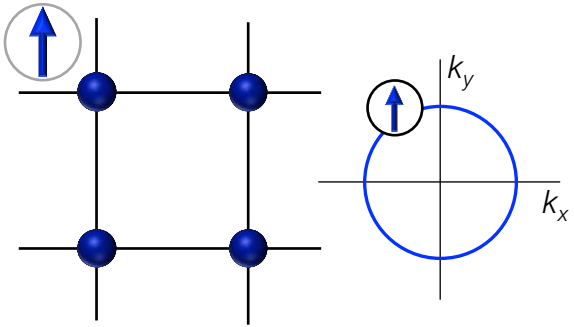
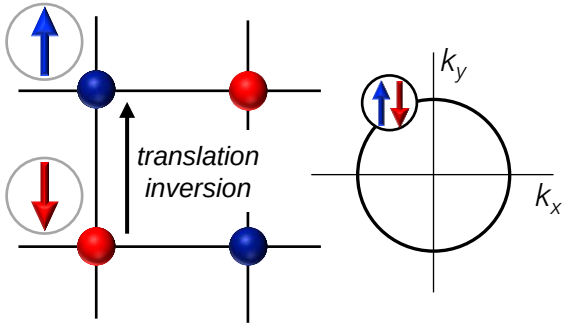
*Review: Šmejkal, Sinova & TJ, PRX **12**, 040501 (2022)*

Emerging third elementary magnetic class: non-relativistic spin-symmetry groups of all collinear magnets

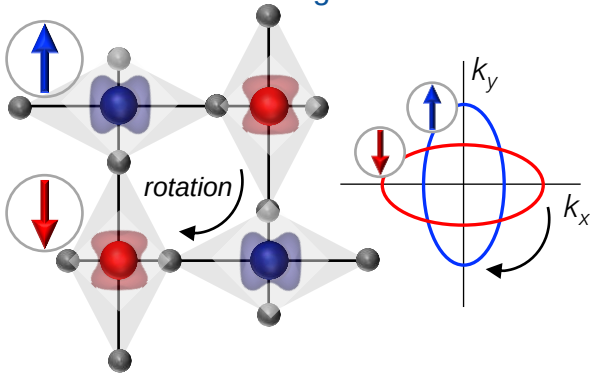
Ferromagnetic



Antiferromagnetic



Altermagnetic



~~spin space / real space~~
~~$[C_2 \parallel \textit{rotation}]$~~
~~$[C_2 \parallel \textit{translation}]$~~
~~$[C_2 \parallel \textit{inversion}]$~~

$[C_2 \parallel \textit{translation}]$
or
$[C_2 \parallel \textit{inversion}]$

~~$[C_2 \parallel \textit{translation}]$~~
~~$[C_2 \parallel \textit{inversion}]$~~

$[C_2 \parallel \textit{rotation}]$

Type-I spin-symmetry groups
$[E \parallel \mathbf{G}]$

Type-II spin-symmetry groups
$[E \parallel \mathbf{G}] + [C_2 \parallel \mathbf{G}]$

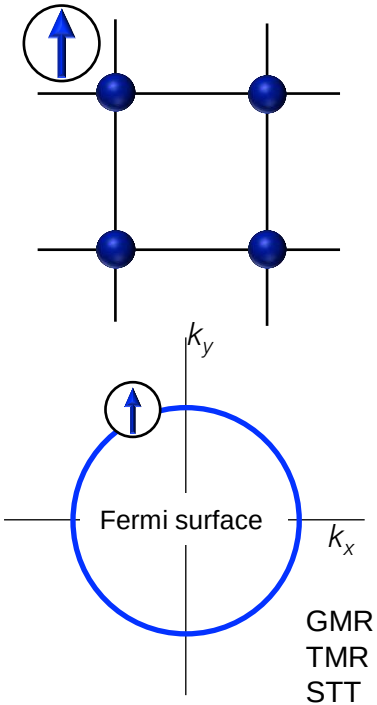
Type-III spin-symmetry groups
$[E \parallel \mathbf{H}] + [C_2 \parallel R\,\mathbf{H}]$

Complete symmetry-group classification of collinear magnets

*Šmejkal, Sinova & TJ, PRX **12**, 031042 (2022)*

Emerging third elementary collinear magnetic class: strong non-relativistic exchange physics

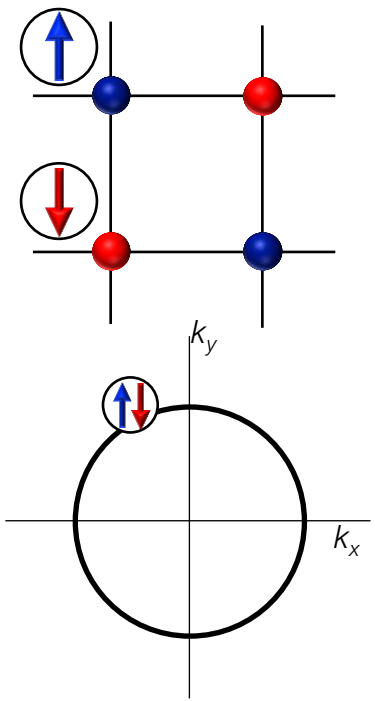
Ferromagnetic



GMR
TMR
STT

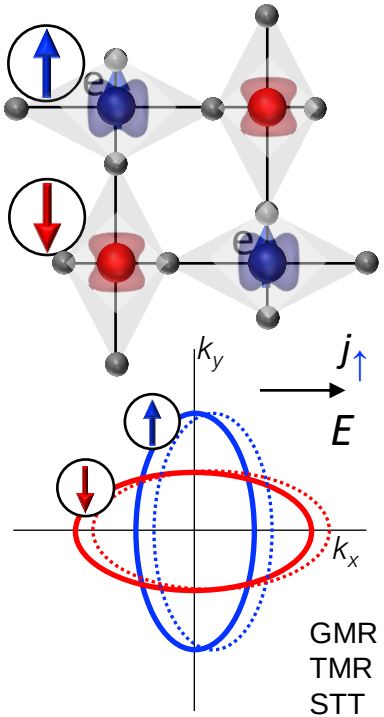
Non-relativistic spin transport

Antiferromagnetic



~~Non-relativistic spin transport~~

Altermagnetic



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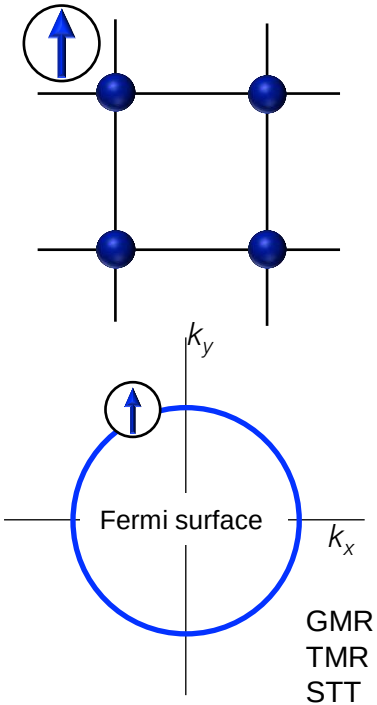

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Non-relativistic spin transport

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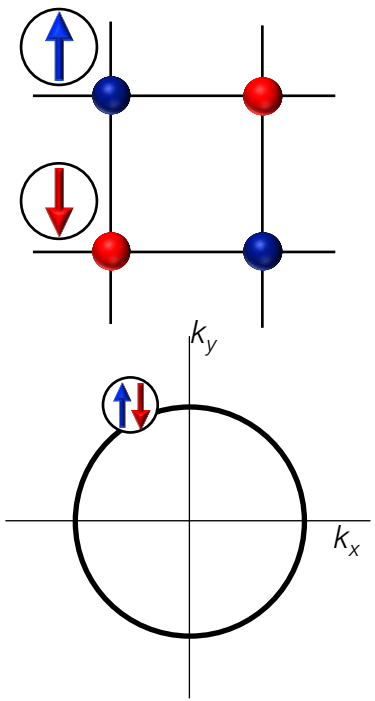
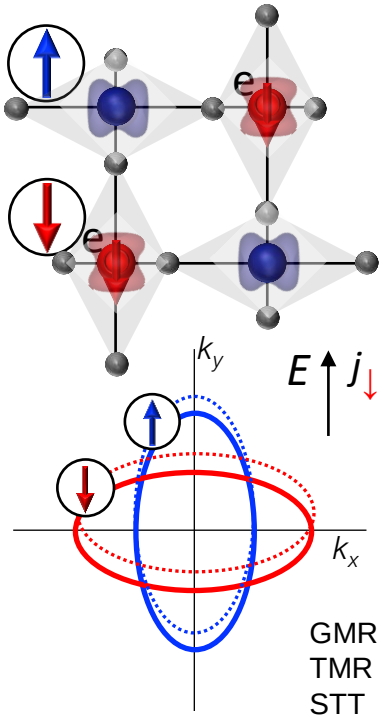


~~Non-relativistic spin transport~~

Altermagnetic



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Non-relativistic spin transport

*Review: Šmejkal, Sinova & TJ, PRX **12**, 040501 (2022)*

Emerging third elementary collinear magnetic class: strong non-relativistic exchange physics

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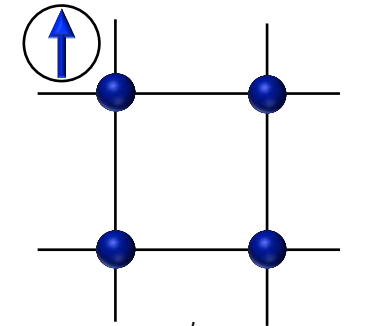

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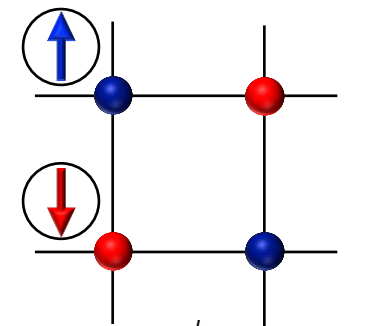
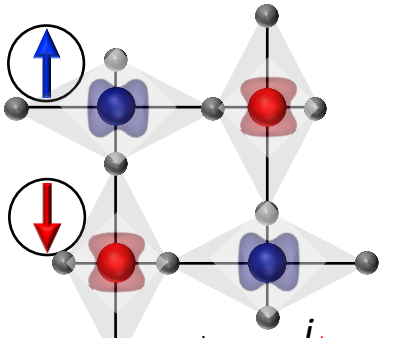
Non-relativistic spin transport

Antiferromagnetic



~~Non-relativistic spin transport~~

Altermagnetic



GMR
TMR
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Non-relativistic spin transport

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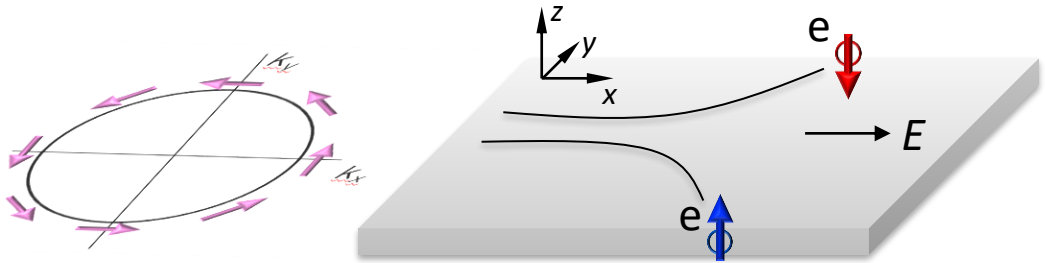
Emerging third elementary collinear magnetic class: strong non-relativistic exchange physics

Non-magnetic relativistic

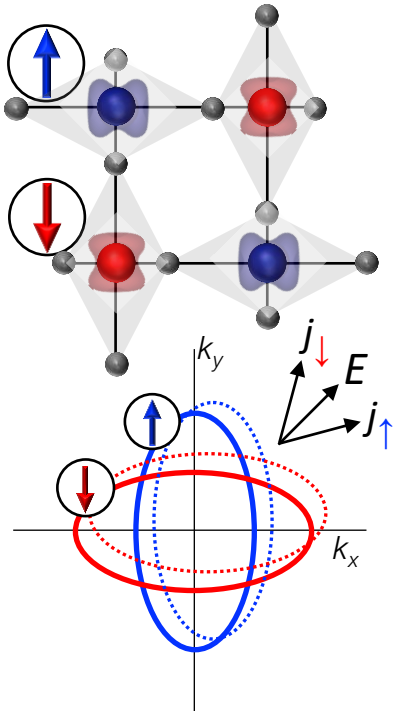
Weak spin separation and coherence



Transverse spin current
via spin Hall effect

Review: Sinova & TJ, Rev. Mod. Phys. 87, 1213 (2015)

Altermagnetic



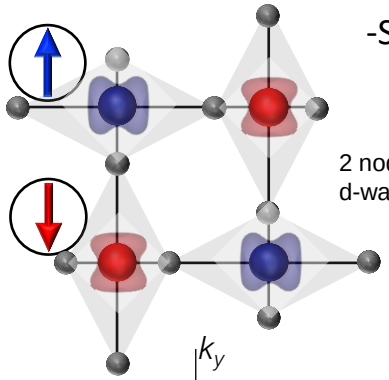
Transverse spin current
via spin splitter effect

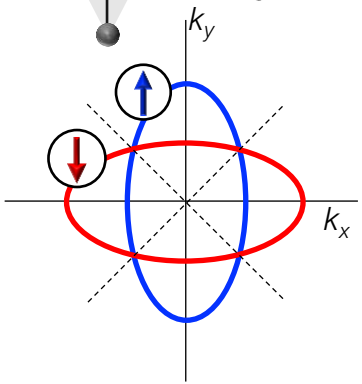
*Review: Šmejkal, Sinova & TJ, PRX **12**, 040501 (2022)*

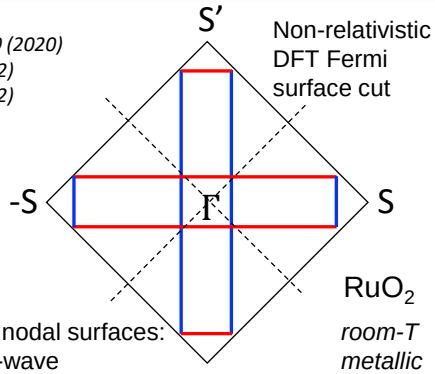
Emerging third elementary collinear magnetic class: altermagnetic rutiles

Šmejkal, TJ, et al. Science Adv. ***6****, eaaz8809 (2020)*
Šmejkal, Sinova & TJ, PRX ***12****, 031042 (2022)*
Šmejkal, Sinova & TJ, PRX ***12****, 040501 (2022)*

Altermagnets





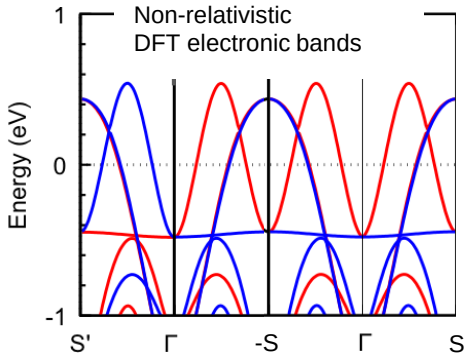


Non-relativistic DFT Fermi surface cut

RuO_2

2 nodal surfaces: d-wave

room-T metallic



Non-relativistic spin-splitter effect, GMR, TMR

DFT theory: *Gonzalez,TJ et al., PRL* ***126****, 127701 (2021)*
Šmejkal, TJ et al., PRX ***12****, 011028 (2022)*

Experiment: *Bose et al., Nat. Elec.* ***5****, 263 (2022)*
Bai et al., PRL ***128****, 197202 (2022)*
Karube et al., PRL ***129****, 137201 (2022)*

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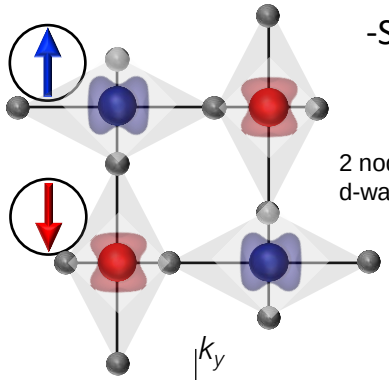

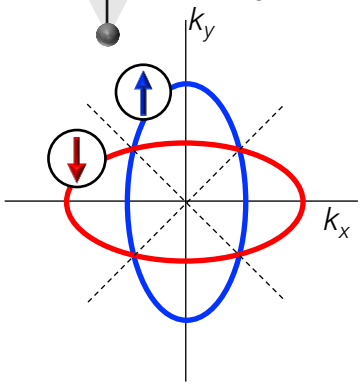

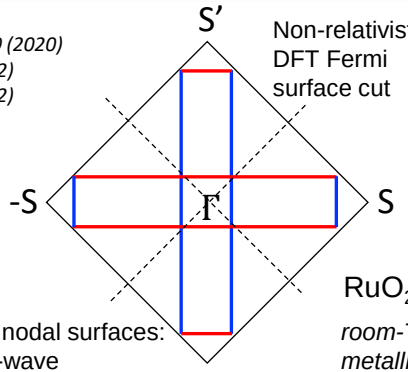

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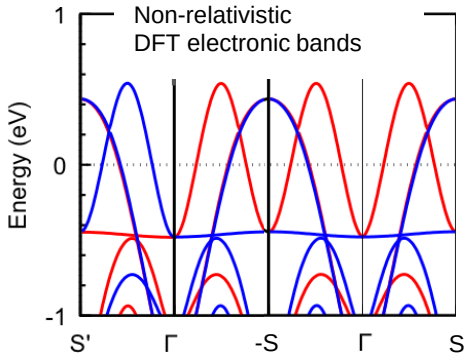

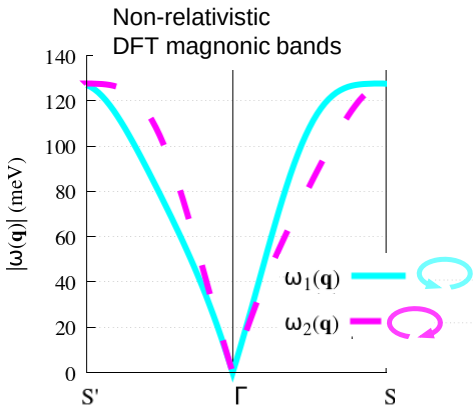

DFT theory:
Šmejkal,TJ et al., PRL in press, arXiv:2211.13806

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DFT theory: *Gonzalez,TJ et al., PRL* ***126****, 127701 (2021)*
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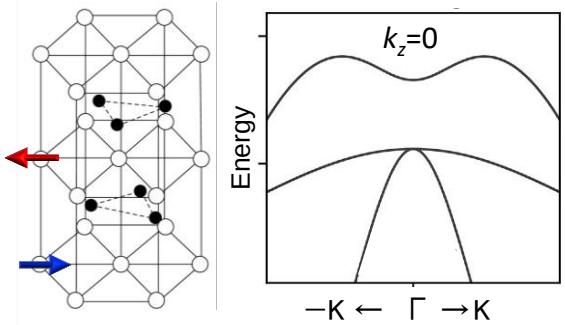
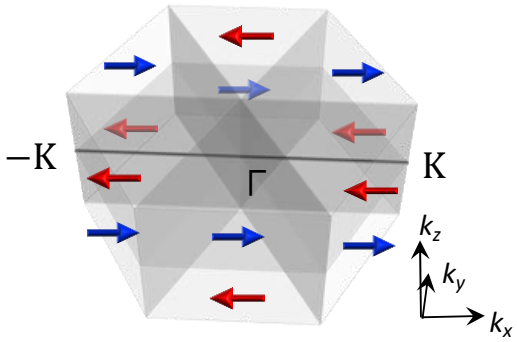
Karube et al., PRL ***129****, 137201 (2022)*

Altermagnetic MnTe

Global 3D non-relativistic g-wave

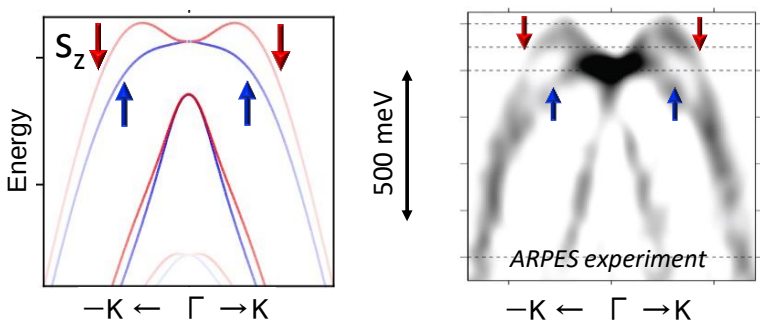


Centrosymmetric
Symmetric spin splitting

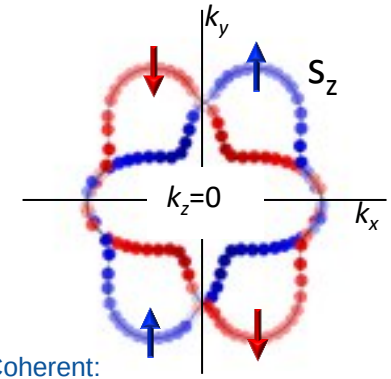


Semi-coherent:
k-independent spin axis
without spin-orbit coupling

Local 2D (k_z=0) relativistic d-wave



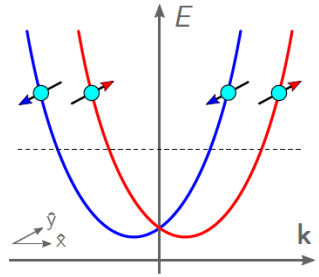
Centrosymmetric
Symmetric spin splitting



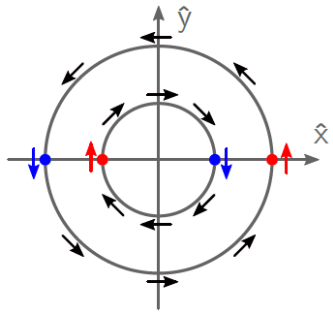
Coherent:
k-independent spin axis
with spin-orbit coupling

Krempasky, TJ, et al., Nature in press (2023), arXiv:2308.10681

cf. 2D relativistic Rashba



cf. Non-centrosymmetric
Anti-symmetric spin splitting

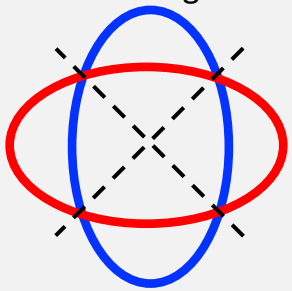


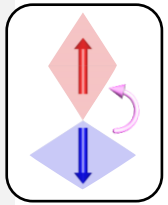
cf. Textured:
k-dependent spin axis

Unconventional p-wave magnetism: Non-relativistic anti-symmetric spin splitting

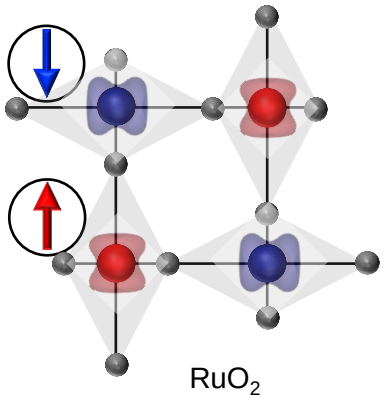
Symmetric (d-wave)

altermagnet

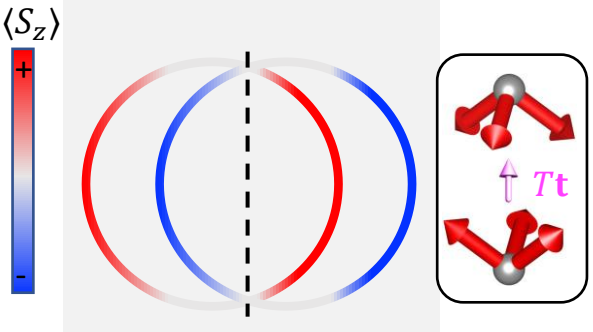




$[C_2 \parallel \mathbf{R}]$

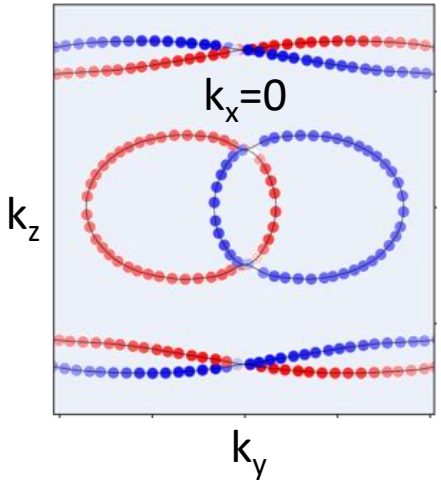


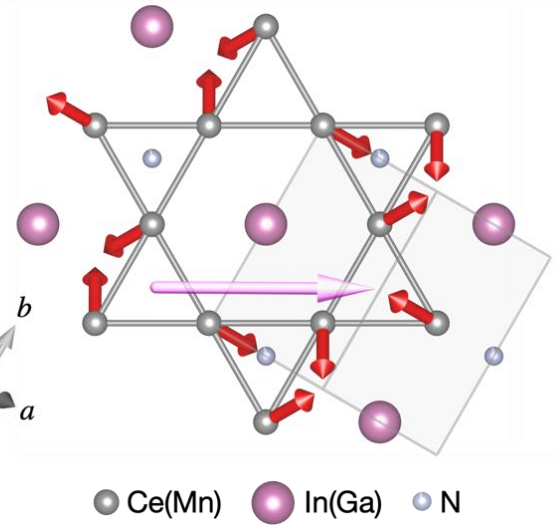
Antisymmetric (p-wave)



Non-relativistic exchange spin-orbit
Spin-splitting ~ 100 meV - eV

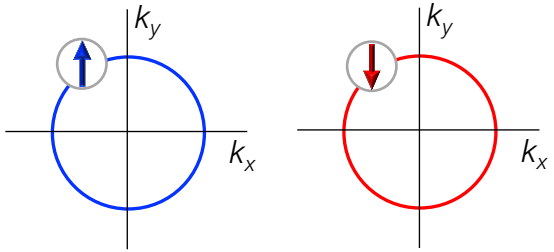
DFT theory:
Hellens, TJ, Sinova, Smejkal, arXiv:2309.01607



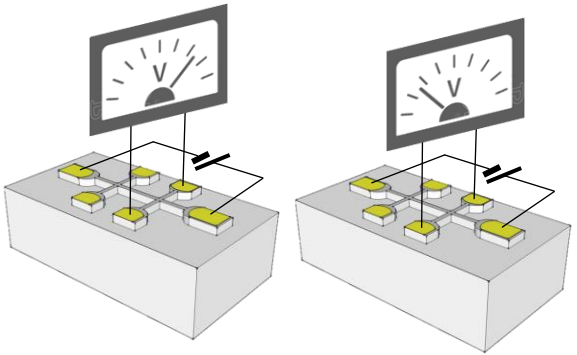


Altermagnetism and strong time-reversal symmetry breaking: AHE/MCD/XMCD

Ferromagnetic

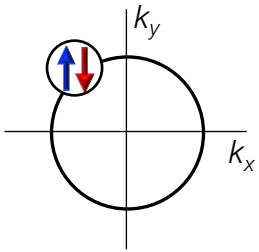


Non-relativistic T-symmetry breaking
by magnetization

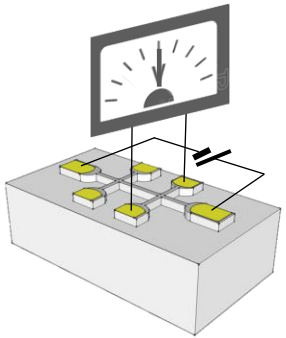


Anomalous Hall effect
with relativistic spin-orbit coupling

Antiferromagnetic

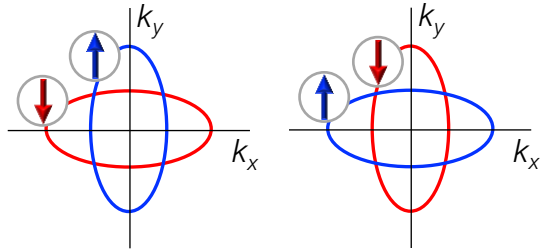


Non-relativistic T-symmetry

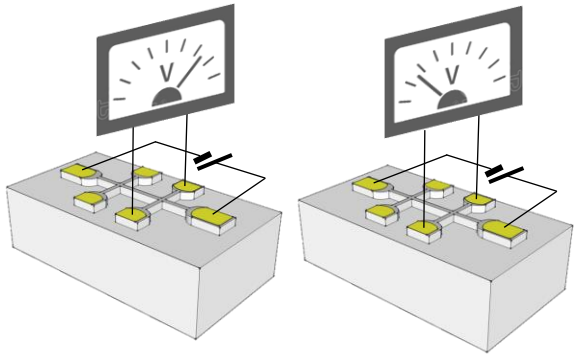


~~Anomalous Hall effect~~

Altermagnetic



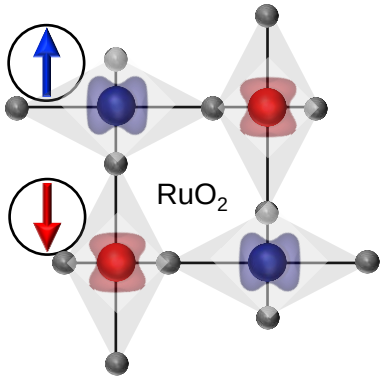
Non-relativistic T-symmetry breaking
by compensated magnetic order

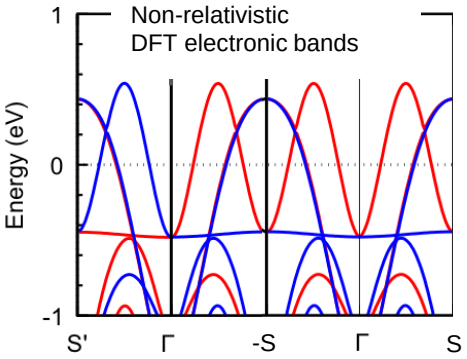


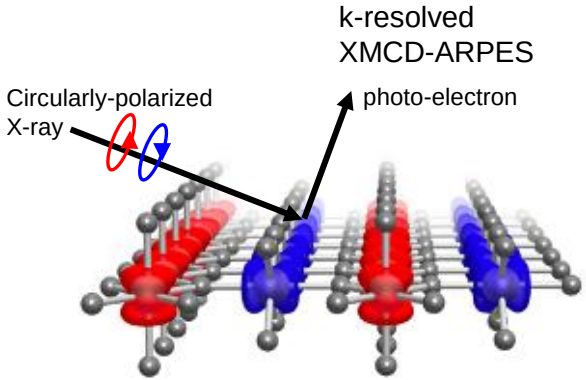
Anomalous Hall effect
with relativistic spin-orbit coupling

Šmejkal, TJ et al., Sci. Adv. ***6****, eaaz8809 (2020), Feng, TJ et al., Nat. Elec.* ***11****, 735 (2022), Betancourt, TJ et al., PRL 130, 036702 (2023), Fedchenko, TJ, et al. arXiv:2306.02170, Hariki, TJ et al., arXiv:2305.03588*

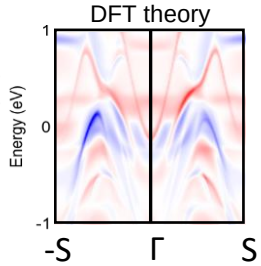
Altermagnetism and strong time-reversal symmetry breaking: AHE/MCD/XMCD

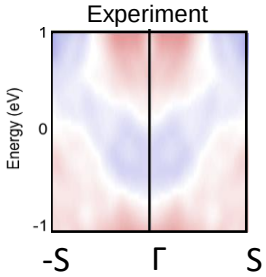




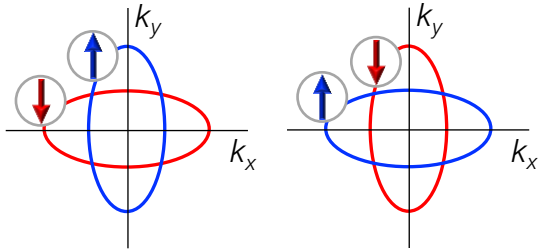


Fedchenko, TJ, et al. arXiv:2306.02170

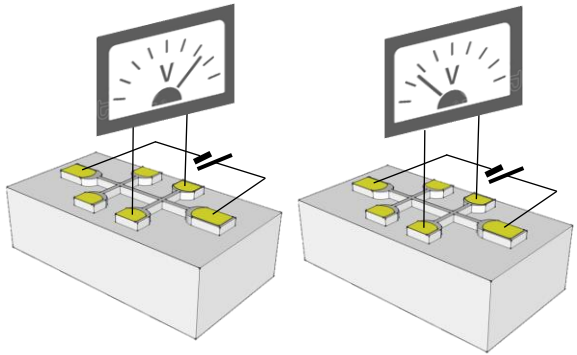




Altermagnetic



Non-relativistic T-symmetry breaking
by compensated magnetic order



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PHYSICAL REVIEW X Perspective

Emerging Research Landscape of Altermagnetism

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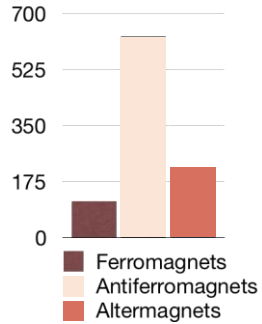

- Spintronics
- Ultra-fast magnetism
- Magnonics
- Spin-caloritronics
- Magneto-electrics & multiferroics
- Topological magnetism
- Unconventional magnetism & superconductivity
- …