outline of this course:

Antiferromagnetism and antiferromagnetic spintronics

1) **antiferromagnets - basics** (exchange interaction, frustration, critical temperatures and fields: flip and flop)

2) **conventional application of antiferromagnetism** (exchange bias: keeping the reference layer fixed …)

3) **AF spintronics** (staggered effective spin-orbit-fields, AF domain wall motion, nonlinear responses, …)

Antiferromagnetic order with spin-polarized bands

4) **noncollinear AFM** (Kagome AF …)

5) **altermagnets** (crystal and magnetic symmetries → band structure…)

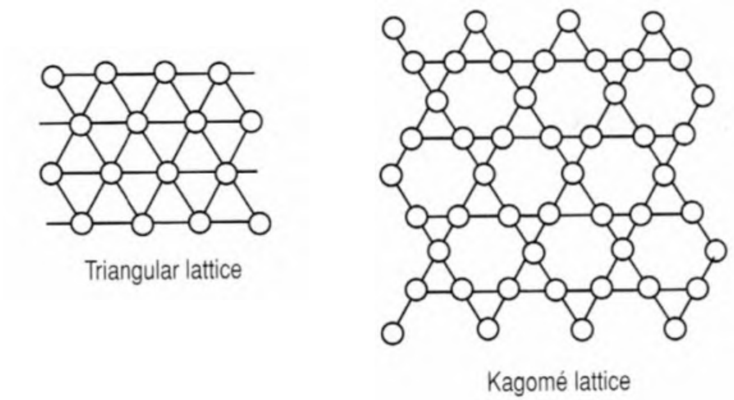
Conclusions

Frustration (part 1)

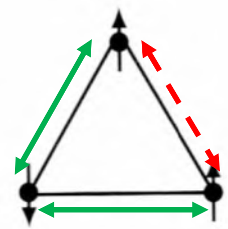
- no frustration in ferromagnetism (parallel moment alignment),

at antiferromagnetic interaction, $-2\mathcal{J}\boldsymbol{S}_i \cdot \boldsymbol{S}_j$ with $\mathcal{J} < 0$, frustration is quite a common feature:

some geometrical frustrated 2dim. lattices:



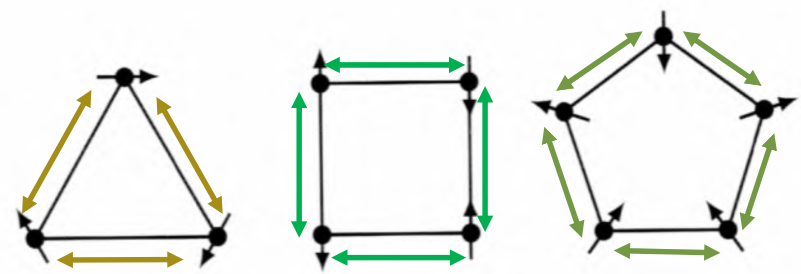
Ising spin



→ total exchange energy divided by the number of bonds is less than $\mathcal{J}$.

→ $T_N \ll |\theta_p|$.

Heisenberg exchange

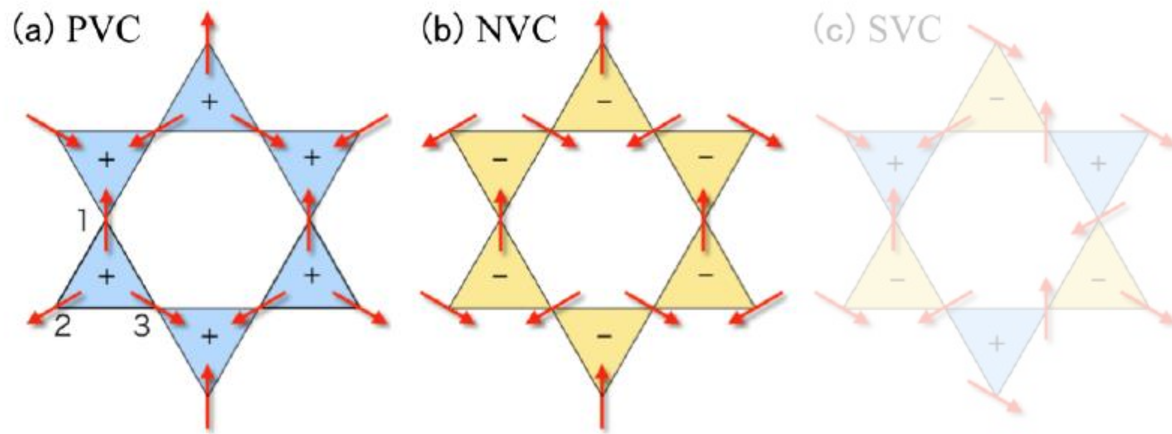


→ significant increase of degenerated ground states

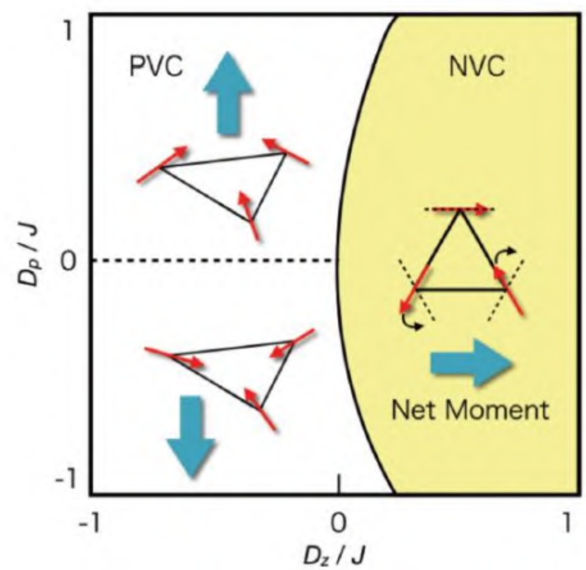
→ **non-collinear moment alignment** to accommodate frustration more energy efficient

Noncollinear moment alignment in Kagome lattices

- possible vector chiralities:



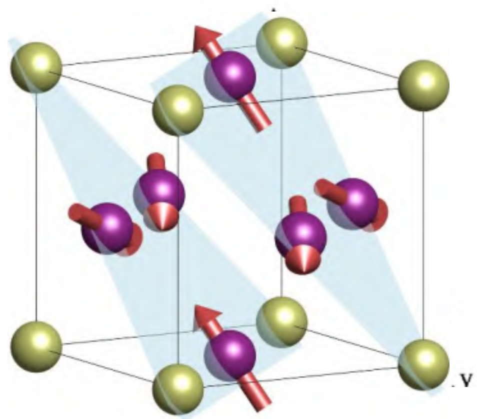
- net-magnetic moment if DMI is present:



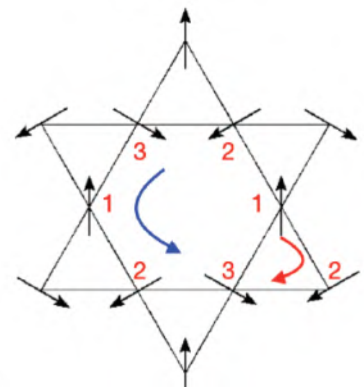
- spin related energy terms: $H_s = J_1 \sum_{\langle ij \rangle_{xy}} \mathbf{S}_i \cdot \mathbf{S}_j + J_2 \sum_{\langle ij \rangle_z} \mathbf{S}_i \cdot \mathbf{S}_j + \sum_{\langle ij \rangle_{xy}} \mathbf{D}_{ij} \cdot \mathbf{S}_i \times \mathbf{S}_j - \sum_i K(\hat{\mathbf{n}}_i \cdot \mathbf{S}_i)^2 .$

Noncollinear moment alignment in a Kagome lattice

$\chi > 0$



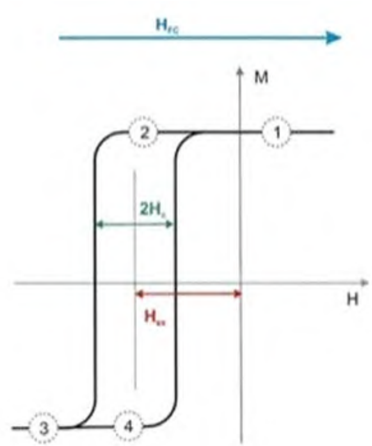
$\chi < 0$



Mn_3Ir, Mn_3Pt, Mn_3Rh

Mn_3Sn, Mn_3Ge , Mn_3Ga

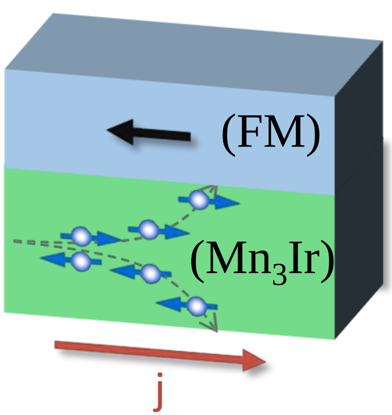
used as efficient exchange bias systems (section 2)



4. Noncollinear AFMs

Giant facet-dependent spin-orbit torque and spin Hall conductivity in the triangular antiferromagnet $IrMn_3$

Weifeng Zhang,[1,2]* Wei Han,[1,3]* See-Hun Yang,[1] Yan Sun,[4] Yang Zhang,[4] Binghai Yan,[4] Stuart S. P. Parkin[1,5†]

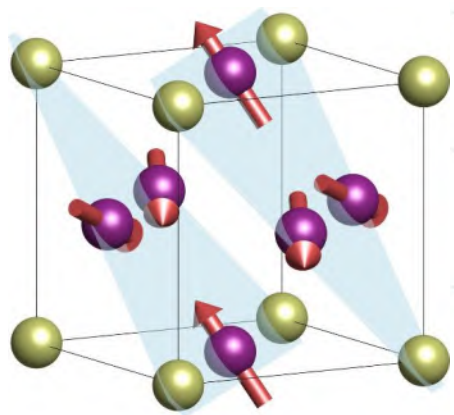


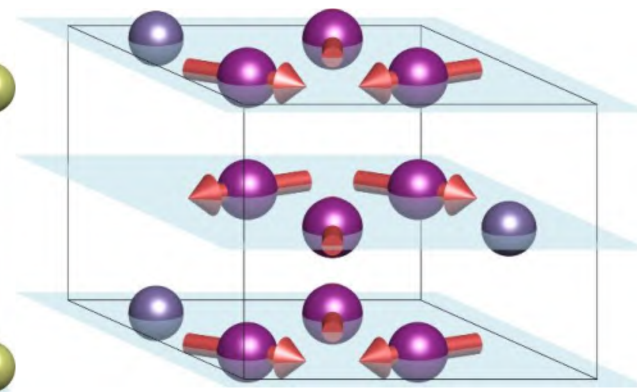
	SHC $\underline{\sigma^y}$	$\underline{\sigma^z}$
symmetry-imposed tensor shape	$\begin{pmatrix} 0 & -\sigma^x_{xx} & -\sigma^x_{yz} \\ -\sigma^x_{xx} & 0 & 0 \\ -\sigma^x_{zy} & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & \sigma^z_{xy} & 0 \\ -\sigma^z_{xy} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$
Mn_3Rh	$\begin{pmatrix} 0 & 276 & -220 \\ 276 & 0 & 0 \\ -70 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 145 & 0 \\ -145 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$
Mn_3Ir	$\begin{pmatrix} 0 & 210 & -299 \\ 210 & 0 & 0 \\ 7 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 163 & 0 \\ -163 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$
Mn_3Pt	$\begin{pmatrix} 0 & 66 & -108 \\ 66 & 0 & 0 \\ -7 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 32 & 0 \\ -32 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$

4. Noncollinear AFMs

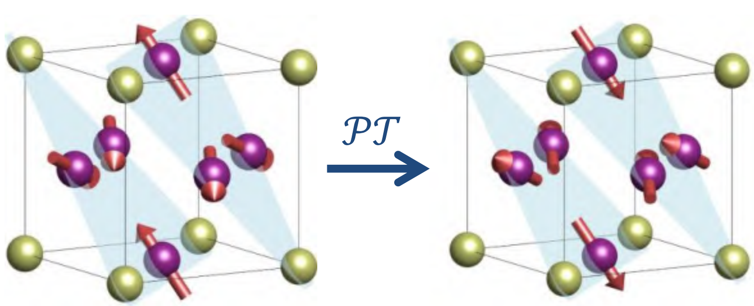
Important spin structures in a Kagome lattice

$\chi > 0$ $\chi < 0$





Mn_3Ir, Mn_3Pt, Mn_3Rh Mn_3Sn, Mn_3Ge , Mn_3Ga



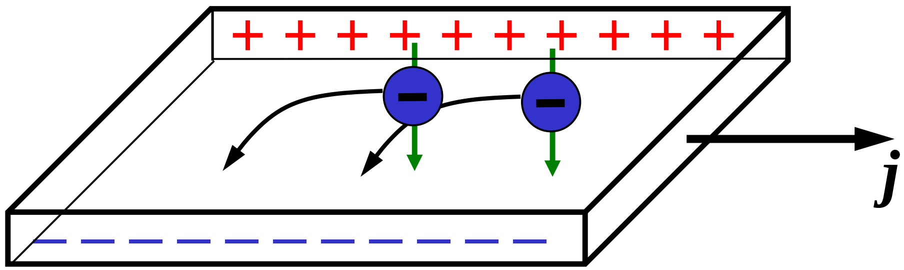
broken $\mathcal{PT}$
broken $\mathcal{T}t$

allows for

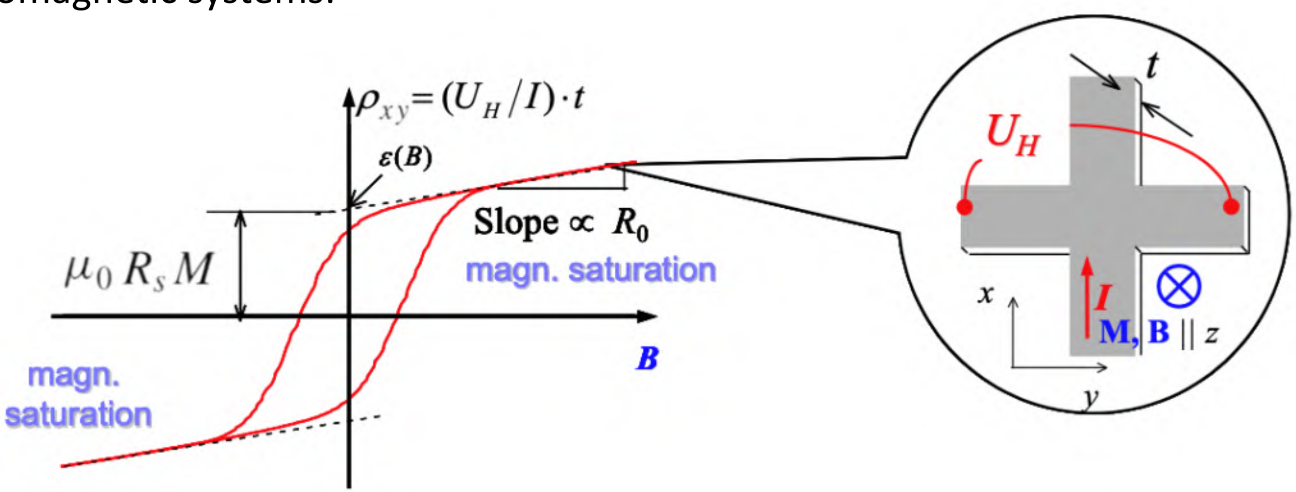
- **anomalous Hall effect** like in FMs

4. Noncollinear AFMs

Anomalous Hall effect (AHE) “odd” under time-reversal



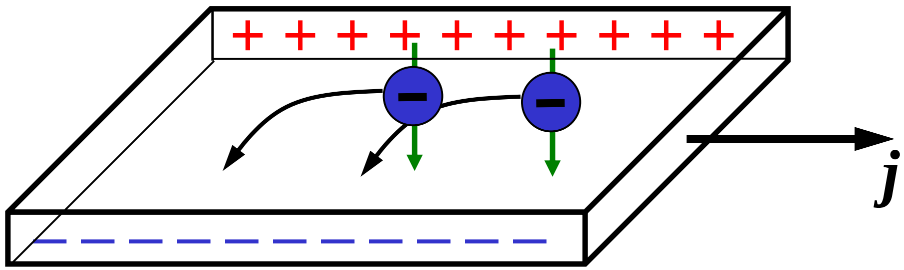
- in many ferromagnetic systems:



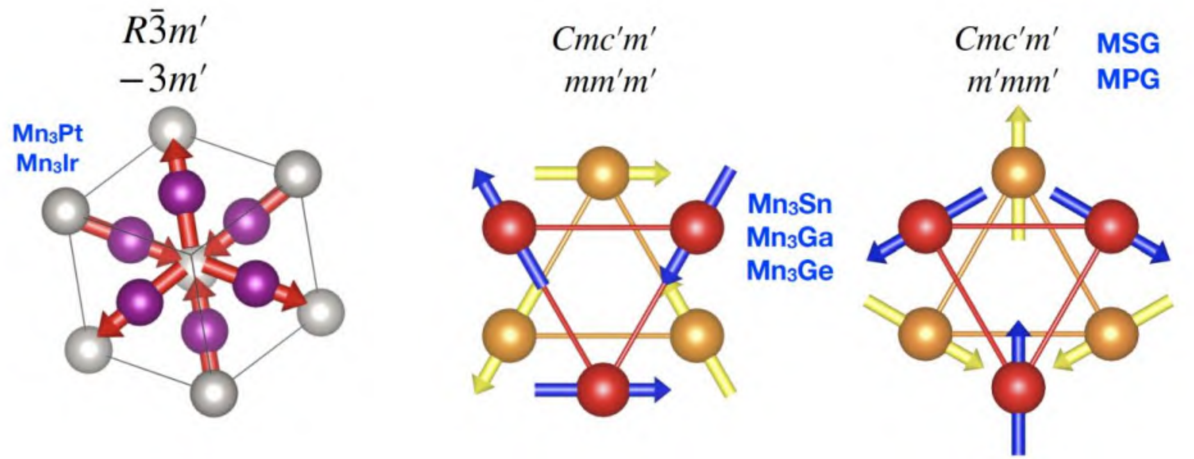
- spatial Isotropic bulk system: $\hat{\varrho} = \begin{bmatrix} \varrho_{xx} & -\varrho_{xy} & 0 \\ \varrho_{xy} & \varrho_{xx} & 0 \\ 0 & 0 & \varrho_{zz} \end{bmatrix}$ $\varrho_{xy} = \mu_0 (R_h H' + R_s M).$

4. Noncollinear AFMs

Anomalous Hall effect (AHE) “odd” under time-reversal



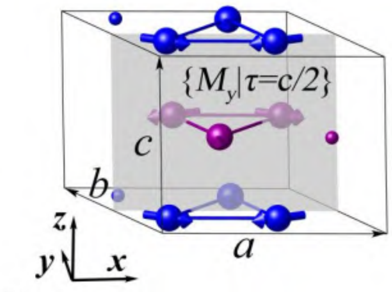
- in noncollinear AFMs:



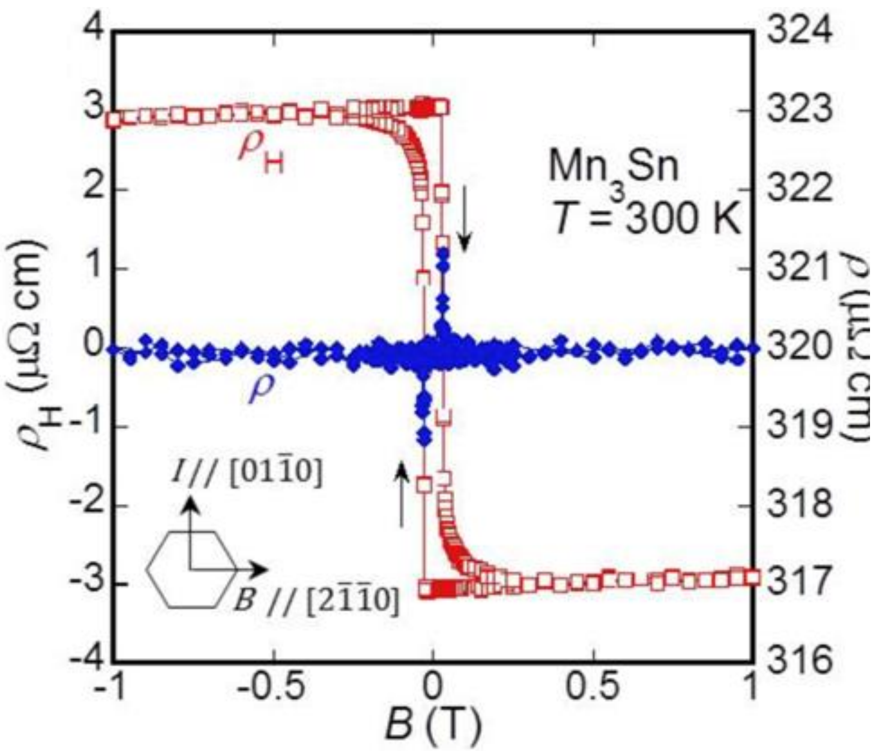
$$\begin{pmatrix} 0 & \sigma_{xy} & 0 \\ -\sigma_{xy} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \sigma_{yz} \\ 0 & -\sigma_{yz} & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & 0 & -\sigma_{zx} \\ 0 & 0 & 0 \\ \sigma_{zx} & 0 & 0 \end{pmatrix}$$

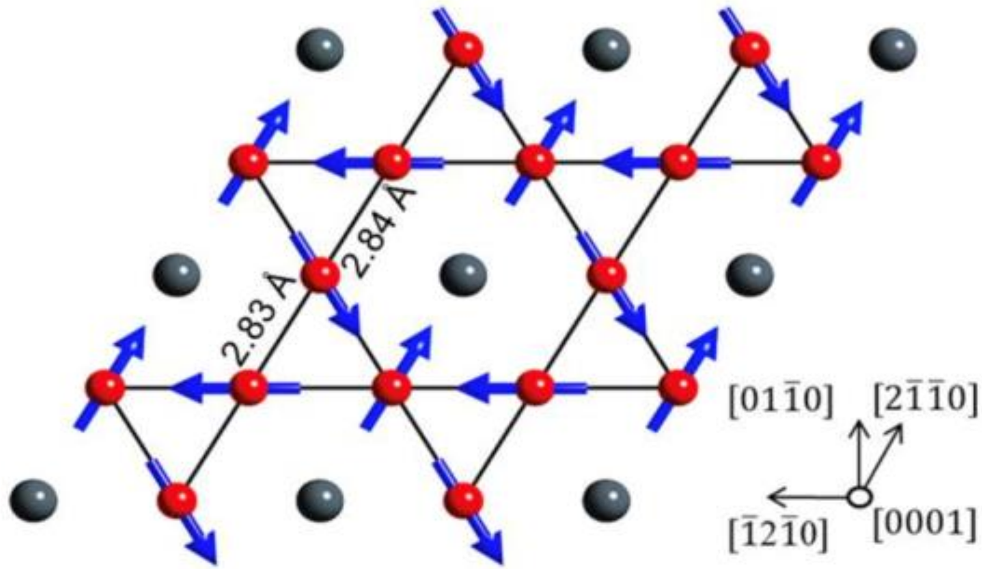
symmetry imposed anomalous Hall conductivity tensor elements

Anomalous Hall effect (AHE) in noncollinear AFMs "odd" under time-reversal



Chen et al., PRL 112, 017205 (2014)
Nakatsuji, et al., Nature 527, 212 (2015)
Nayak, et al., Sci. Adv. 2, e1501870 (2016)
...

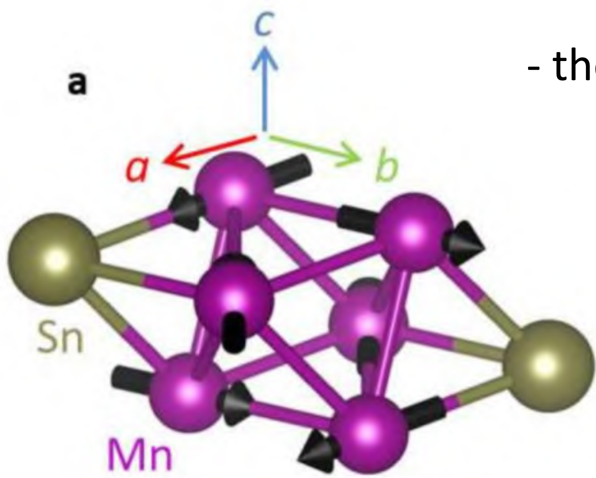




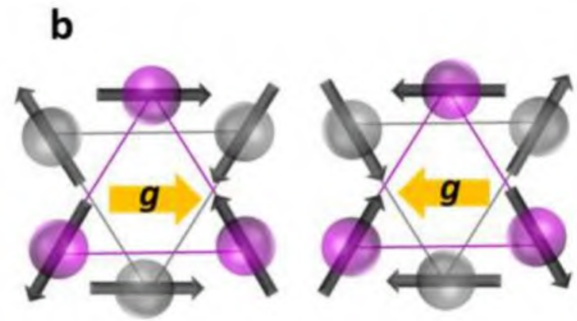
4. Noncollinear AFMs

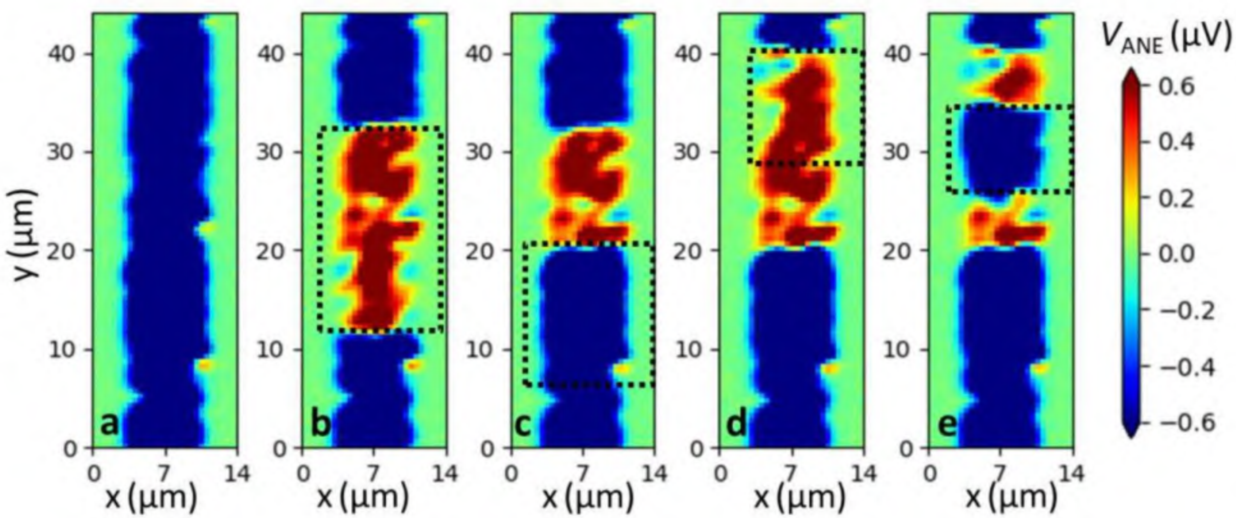
Anomalous Nernst effect (ANE) in noncollinear AFMs: Nakatsuji, et al., Nature 527, 212 (2015)

- used for domain imaging: Reichlova, et al., Nature Commun., 10, 5459 (2919)



- thermally assisted domain writing:





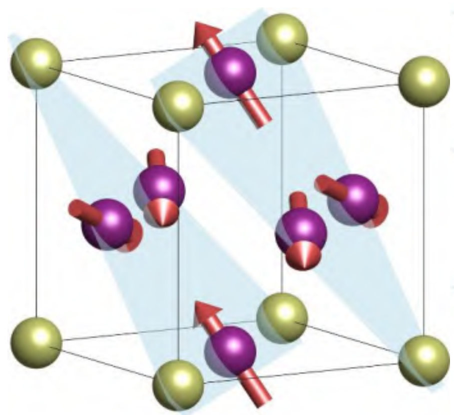
Anomalous Nernst effect

$$\mathbf{E}_{bar} \sim \nabla_z T \times \mathbf{g}$$

4. Noncollinear AFMs

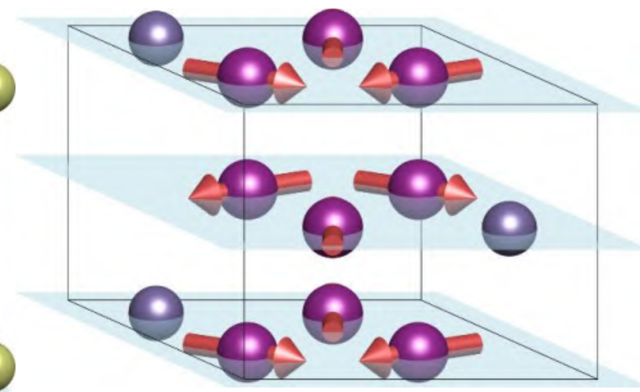
Important spin structures in a Kagome lattice

$\chi > 0$

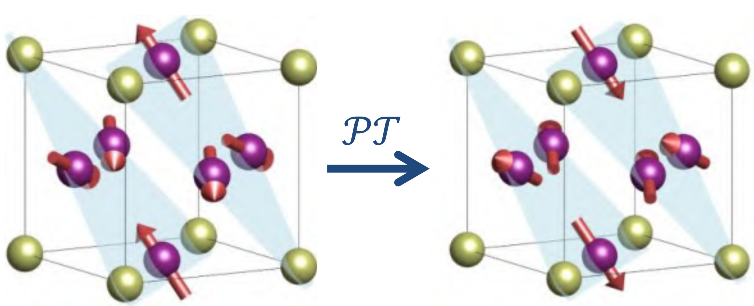


Mn_3Ir, Mn_3Pt, Mn_3Rh

$\chi < 0$



Mn_3Sn, Mn_3Ge , Mn_3Ga



broken $\mathcal{PT}$
broken $\mathcal{T}t$

allows for

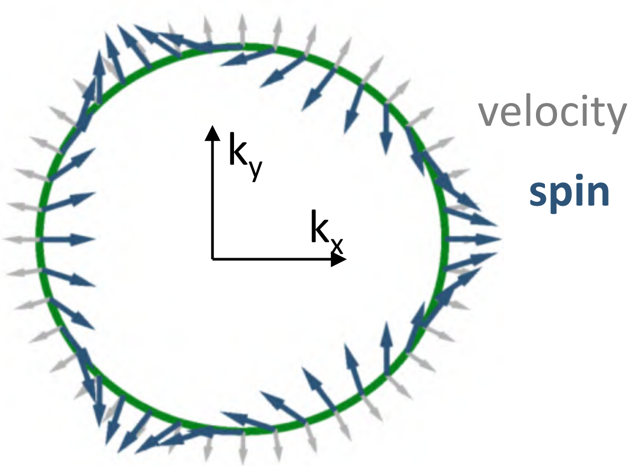
- **anomalous Hall effect** like in FMs
- **odd** (under $\mathcal{T}$ rev) **spin currents**

→ **"magnetic" SHE**

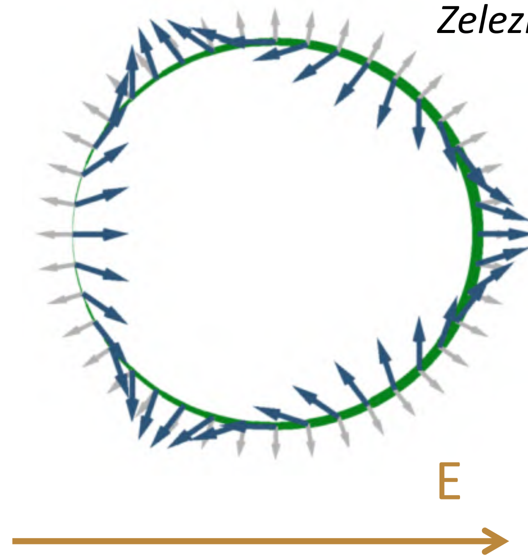
4. Noncollinear AFMs

- geometrically frustrated antiferromagnetic **exchange** in Mn_3X:

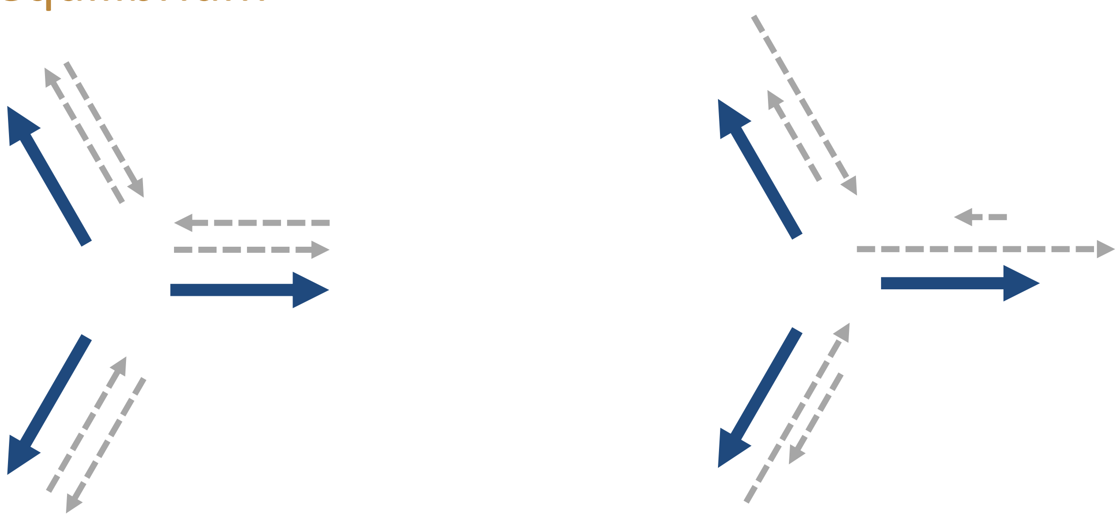
Zelezny et al., PRL 119, 187204 (2017)

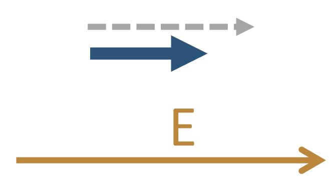


in equilibrium



$$\sum \text{velocity}_{\parallel}\, \text{spin}_{\perp}$$

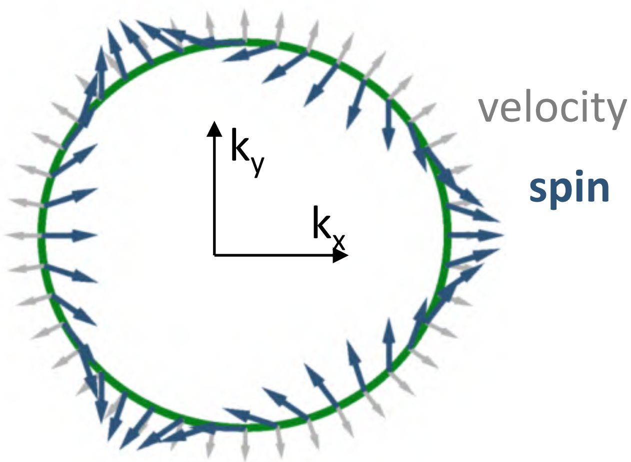




→ longitudinal **spin-polarized current** (of non-relativistic origin) – **odd** under time-reversal

- due to geometrically frustrated antiferromagnetic **exchange** in Mn_3X:
  reciprocal space:

Zelezny et al., PRL 119, 187204 (2017)



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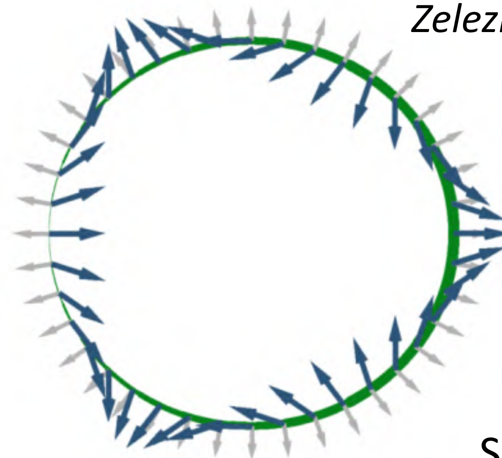
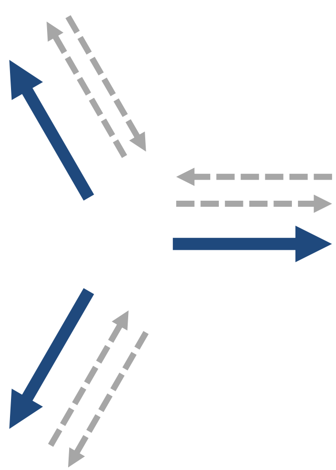
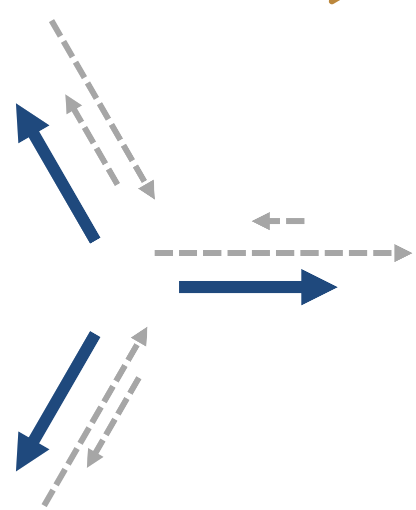


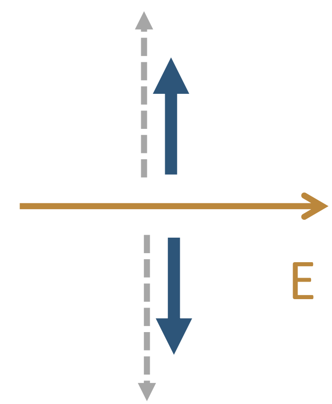
$$\sum_{\text{velocity} \perp \text{spin}}$$

Spin current = spin × velocity

$$\hat{j}^s_{ij} = \frac{1}{2}\{\hat{s}_i, \hat{v}_j\}$$





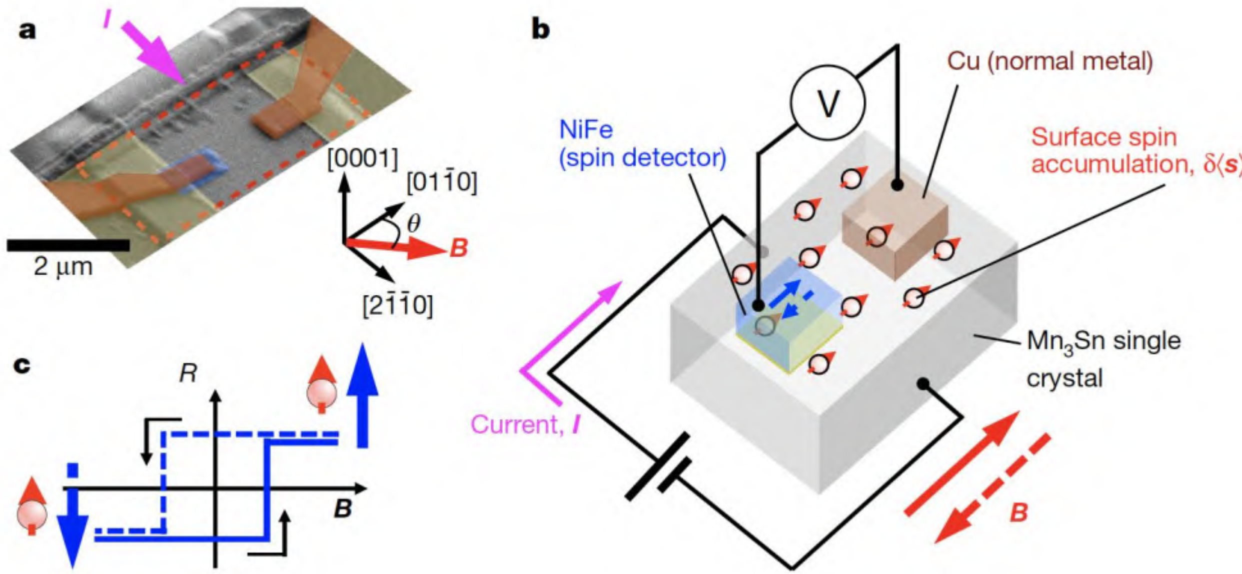


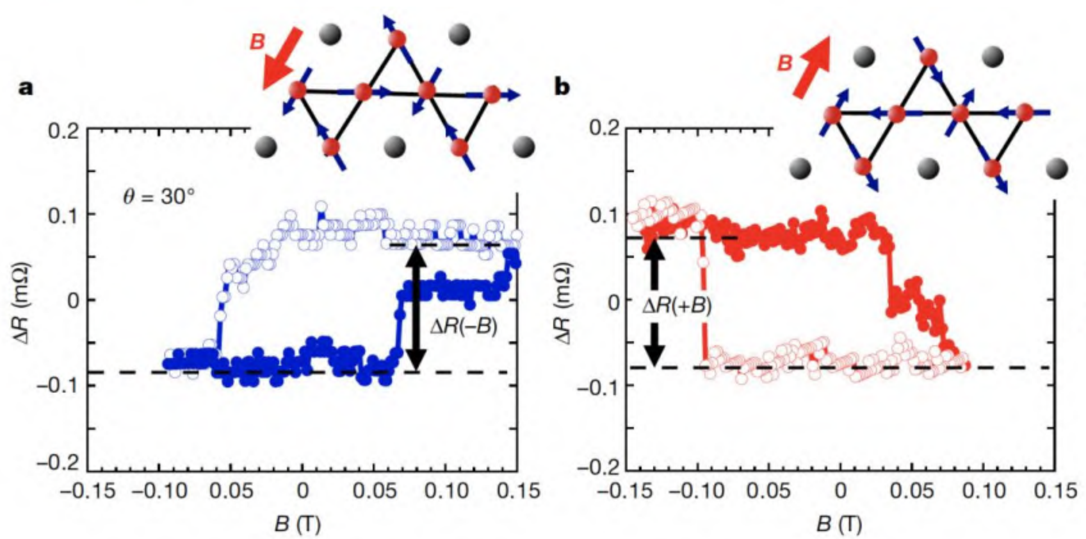
→ transverse **spin-current** (of non-relativistic origin) – **odd** under time-reversal - “magnetic **SHE**”

4. Noncollinear AFMs

- Magnetic and magnetic inverse spin Hall effects in a non-collinear antiferromagnet

Kimata et al., Nature 565, 627–630 (2019)





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Antiferromagnetic order with spin-polarized bands

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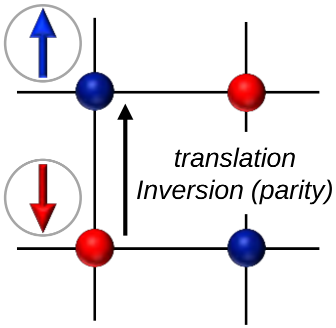
Conclusions

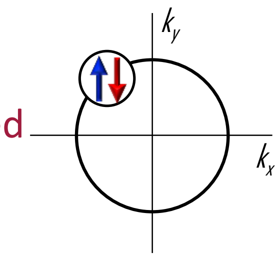
- **"conventional" antiferromagnets** with combined **translation and time reversal symmetry** ($t\mathcal{T}$)
or **inversion and time reversal symmetry** ($\mathcal{P}\mathcal{T}$)



$$t\mathcal{T}\,\epsilon(\uparrow, \mathbf{k}) = \epsilon(\downarrow, \mathbf{k})$$

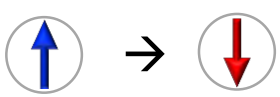
$$\mathcal{P}\mathcal{T}\,\epsilon(\uparrow, \mathbf{k}) = \epsilon(\downarrow, \mathbf{k})$$

→ Bands are spin-degenerated



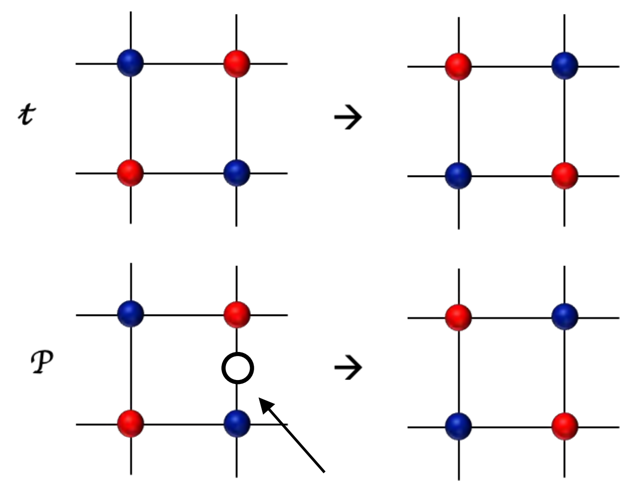
- ignoring spin-orbit coupling → seperating symmetry operations in „spin space" and „real space"

spin space:

C_2 

[rotation by 180 deg]

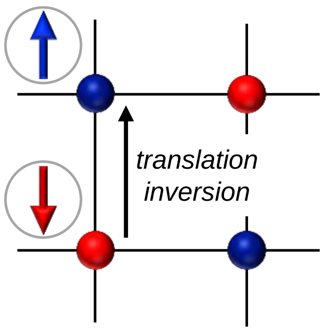
real space:



inversion center

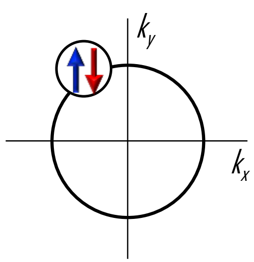
5. Altermagnets

conventional Antiferromagnets



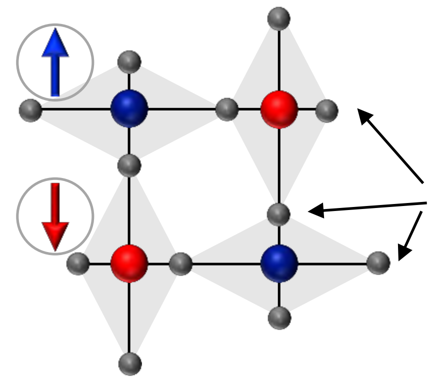
spin space real space

[C_2 || *translation*]
or
[C_2 || *inversion*]

→ 

Bands are spin-degenerated

Altermagnets

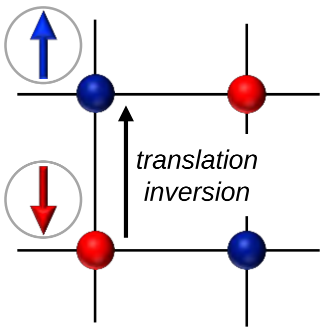


Non-magnetic atoms break both t or $\mathcal{P}$ symmetry of the crystal

spin space real space

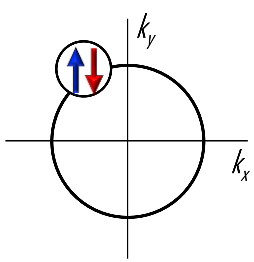
~~[C_2 || *translation*]~~
~~[C_2 || *inversion*]~~

conventional Antiferromagnets



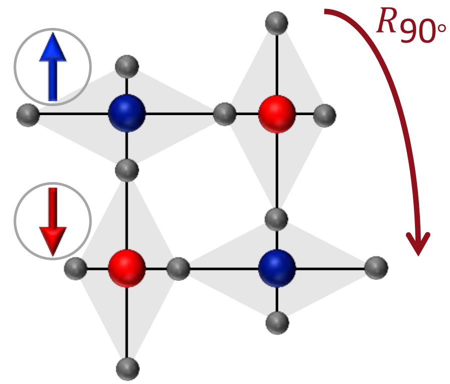
spin space real space

[C_2 || *translation*]
or
[C_2 || *inversion*]

→ 

spin-degenerated bands

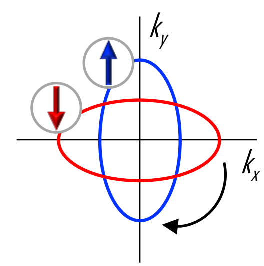
Altermagnets



spin space real space

~~[C_2 || *translation*]~~
~~[C_2 || *inversion*]~~

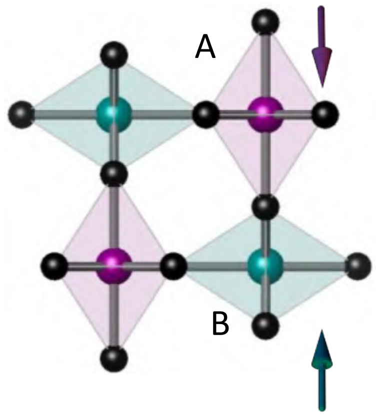
[C_2 || *rotation*]

→ 

spin-polarized bands

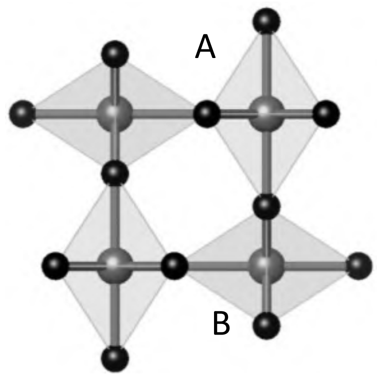
Crystal Symmetry and related spin-splitting of the bands

antiferromagnetically ordered RuO_2

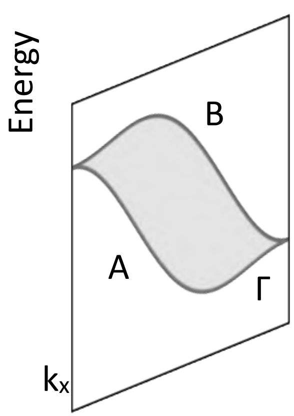


Crystal Symmetry and related Spin-splitting of the bands

(imagine) non-magnetic RuO_2

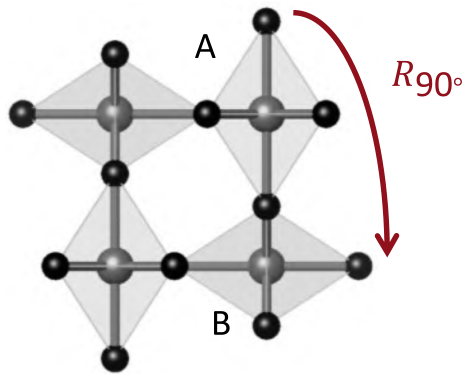


1) k-dependent spin-splitting due to crystal field



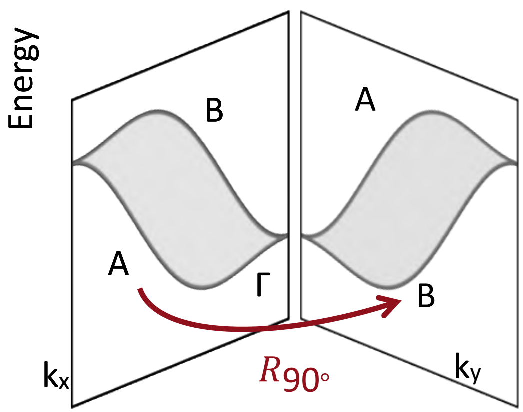
Crystal Symmetry and related anisotropic Spin-splitting of the bands

(imagine) non-magnetic RuO_2



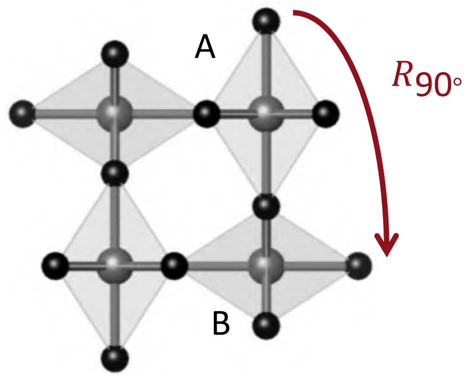
1) k-dependent spin-splitting due to crystal field

2) 90° rotated swaps contributions from sublattice A and B

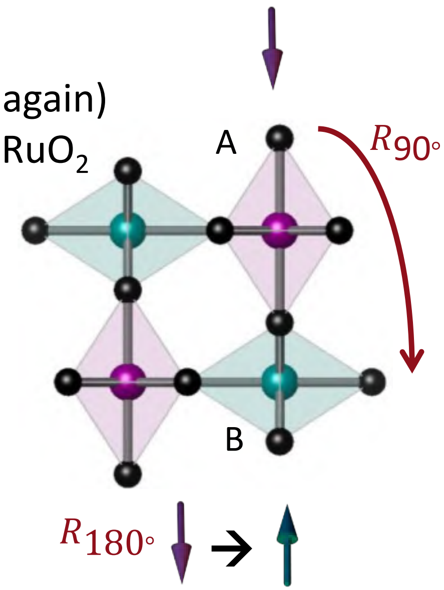


Crystal Symmetry and related anisotropic Spin-splitting of the bands

(imagine) non-magnetic RuO_2

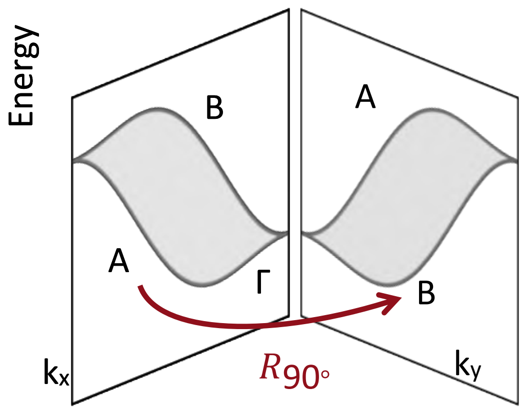


(consider again) magnetic RuO_2



1) k-dependent spin-splitting due to crystal field

2) 90° rotated swaps contributions from sublattice A and B

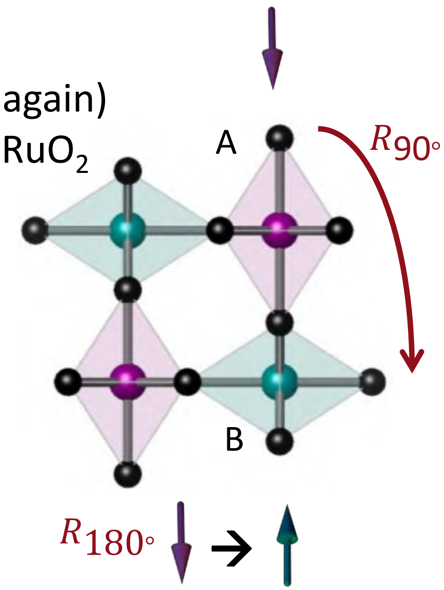


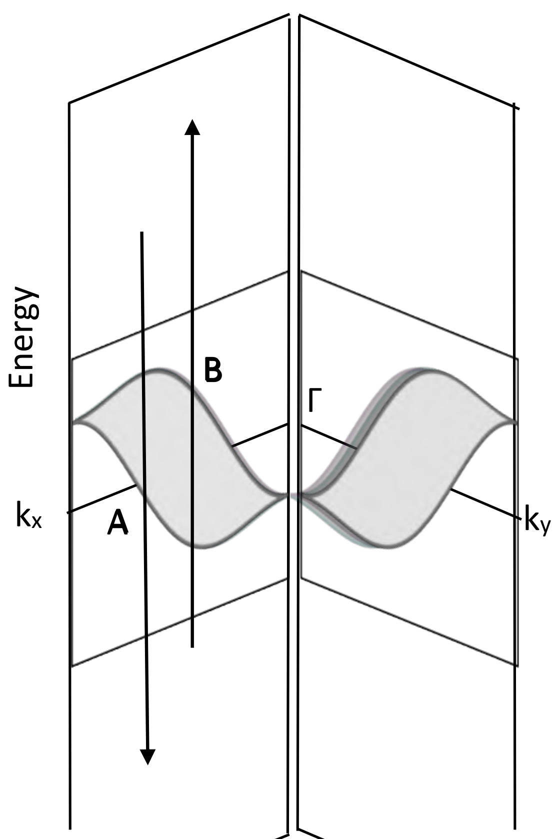
5. Altermagnets

Crystal Symmetry and related anisotropic Spin-splitting of the bands

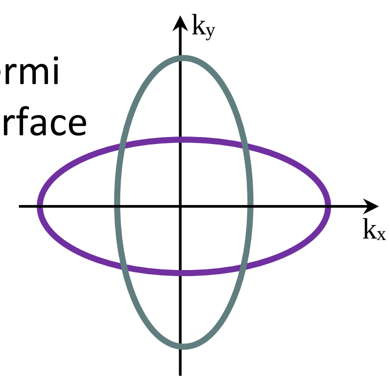
- **k**-dependent spin-splitting
- **k**-independent exchange-splitting

(consider again)
magnetic RuO_2





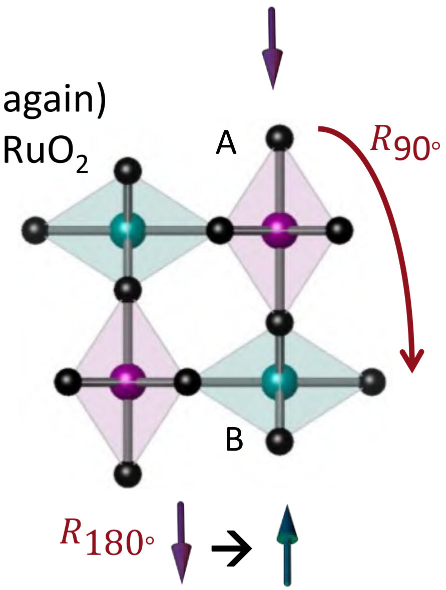
Fermi
surface



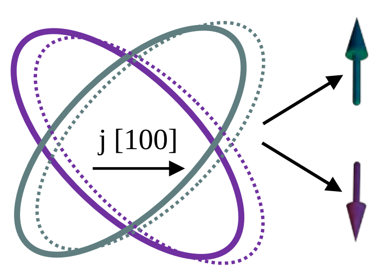
Crystal Symmetry and related anisotropic Spin-splitting of the bands

- **k**-dependent spin-splitting
- **k**-independent exchange-splitting

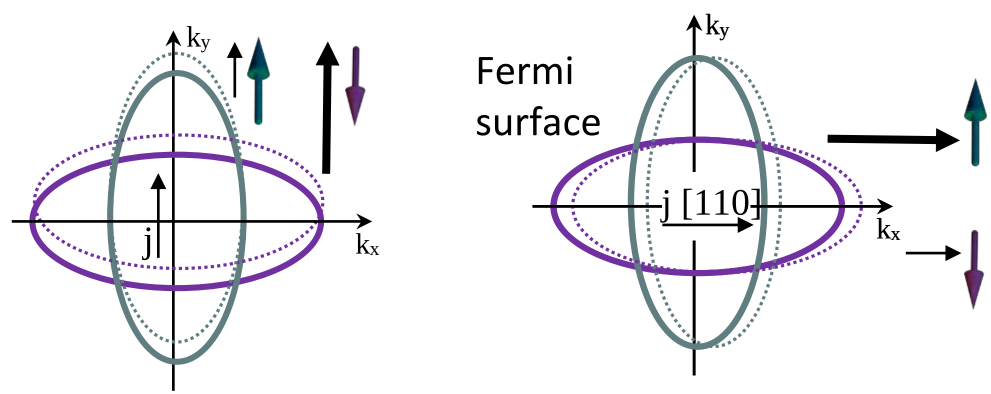
(consider again)
magnetic RuO_2



transverse pure spin currents
(magnetic spin Hall effect)

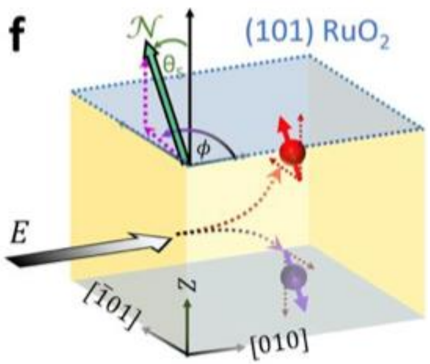


Spin-polarized longitudinal charge currents

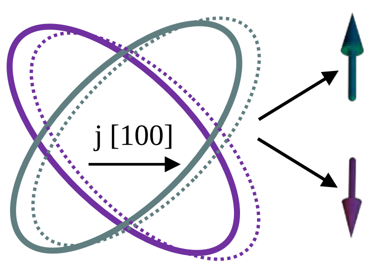


experimental observations: **spin current**

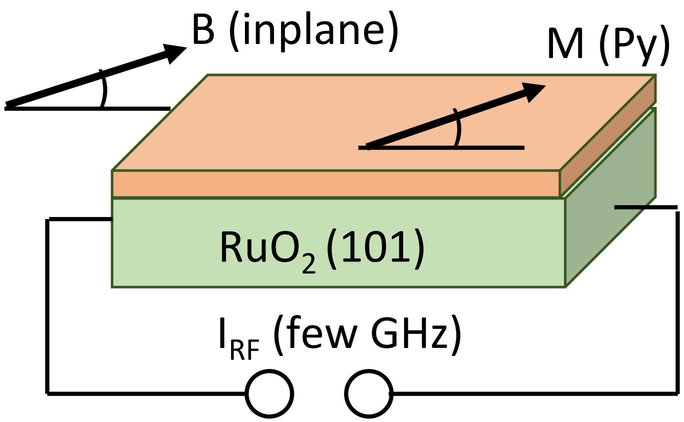
Bose et al., Nat. Elec. ***5****, 263 (2022)* (Cornell)
Bai et al., PRL ***128****, 197202 (2022)* (Beijing)
Karube et al., PRL ***129****, 137201 (2022)* (Tohoku)



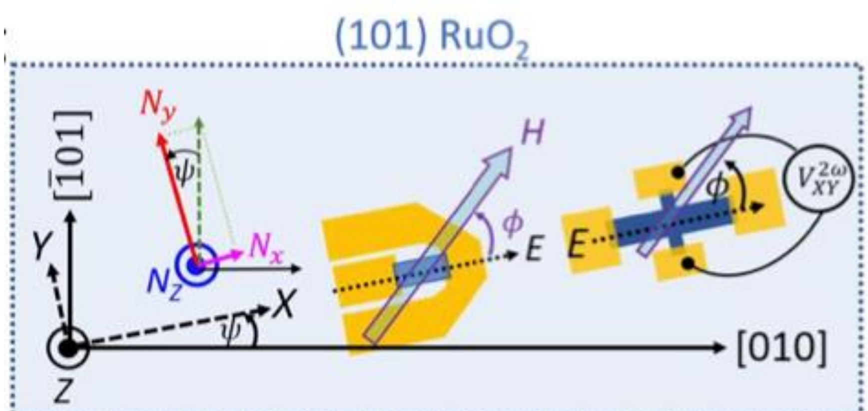
transverse pure spin currents
(magnetic spin Hall effect)



Spin-Torque FMR excitation by
Spin current injection from RuO_2

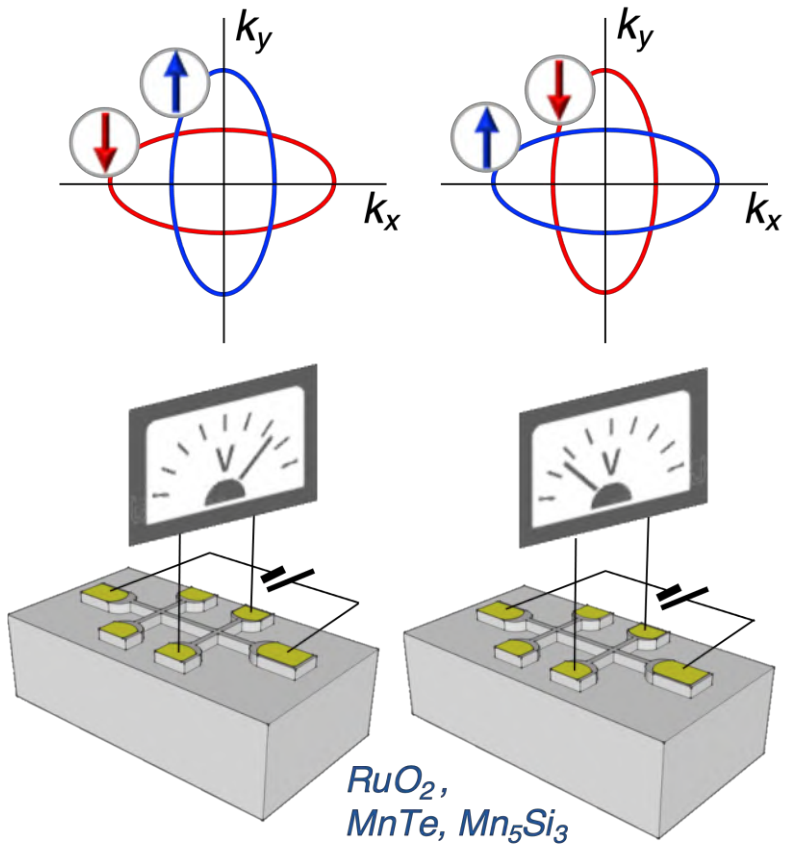


Second harmonic measurements



experimental observations**: anomalous Hall effect**

Broken time-reversal symmetry by compensated magnetic order



Šmejkal, et al., Sci. Adv. ***6****, eaaz8809 (2020); Nat. Rev. Mater.* ***7****, 482 (2022)*

Feng, et al., Nat. Elec. ***11****, 735 (2022)*

Betancourt, et al., PRL 130, 036702 (2023)

Reichlová, TJ et al., arXiv:2012.15651

5. Altermagnets

~ 200 altermagnetic materials identified to date

RuO_2 , CrSb ,
metals

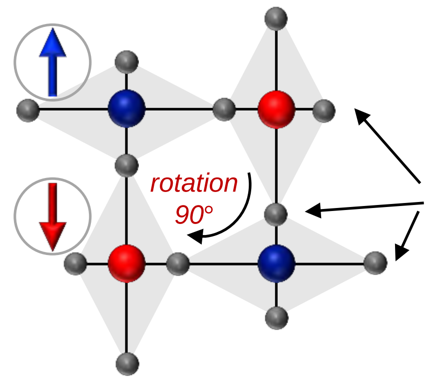
FeF_2 , Fe_2O_2 ,
insulators

MnTe ,
semiconductors

La_2CuO_4
superconductors

Šmejkal, et al. arXiv:1901.00445, Sci. Adv. **6**, eaaz8809 (2020)
Naka et al. arXiv:1902.02506, Nat. Com. **10**, 4305 (2019)
Ahn et al. arXiv:1902.04436, PRB **99**, 184432 (2019)
Hayami et al. arXiv:1908.08680, J. Phys.Soc. Jap. **88**, 123702 (2019)
Yuan et al. arXiv:1912.12689, PRB **102**, 014422 (2020)
Samanta et al. arXiv:2002.05393, JAP **127**, 213904 (2020)
Gonzalez,et al. arXiv:2002.07073, PRL **126**, 127701 (2021)
Feng, et al. arXiv:2002.08712, Nat. Elec. **11**, 735 (2022)
Naka et al. arXiv:2004.04578, PRB **102**, 075112 (2020)
Yuan et al. arXiv:2008.08532, PRM **5**, 014409 (2021)
Hayami et al. arXiv:2008.10815, PRB **102**, 144441 (2020)
Naka et al. arXiv:2011.12459, PRB **103**, 125114 (2021)
Shao et al. arXiv:2103.09219, Nat. Com. **12**, 7061 (2021)
Šmejkal, et al. arXiv:2103.12664, PRX **12**, 011028 (2022)
Ma et al. arXiv:2104.00561, Nat. Com. **12**, 2846 (2021)
Šmejkal, et al. arXiv: 2105.05820, PRX **12**, 031042 (2022)
Šmejkal, et al. arXiv:2107.03321, Nat. Rev. Mater. **7**, 482 (2022)
Bose et al. arXiv:2108.09150, Nat. Elec. **5**, 263 (2022)
Bai et al. arXiv:2109.05933, PRL **128**, 197202 (2022)
Karube et al. arXiv:2111.07487, PRL **129**, 137201 (2022)
Betancourt, et al. arXiv:2112.06805, PRL **130**, 036702 (2023)
Šmejkal, et al. arXiv:2204.10844, PRX **12**, 040501 (2022)
...

Altermagnets

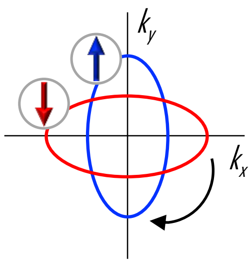


Non-magnetic atoms break both $\mathcal{T}$ or $\mathcal{P}$ symmetry of the crystal

spin space real space

~~[C_2 || *translation*]~~
~~[C_2 || *inversion*]~~

[C_2 || *rotation*]

→ 

spin-polarized bands

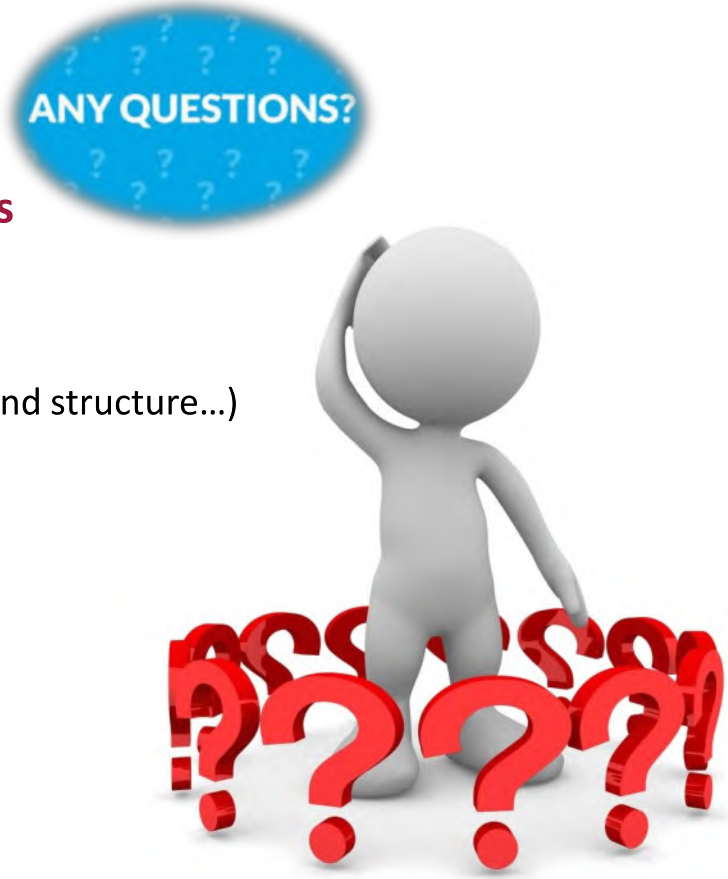
5. Altermagnets

Antiferromagnetism and antiferromagnetic spintronics

1) **antiferromagnets - basics** (exchange interaction, frustration, critical temperatures and fields: flip and flop)

2) **conventional application of antiferromagnetism** (exchange bias: keeping the reference layer fixed …)

3) **AF spintronics** (staggered effective spin-orbit-fields, AF domain wall motion, nonlinear responses, …)



Antiferromagnetic order with spin-polarized bands

4) **noncollinear AFM** (Kagome AF …)

5) **altermagnets** (crystal and magnetic symmetries → band structure…)

Conclusions

Could antiferromagnetism become similarly important as ferromagnetism is?

Néel’s 1971 Nobel lecture:

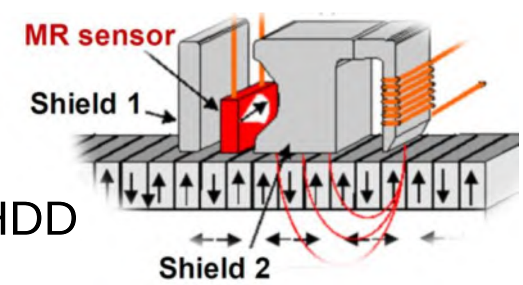
Antiferromagnets are interesting and useless

Conclusions

Could antiferromagnetism become similarly important as ferromagnetism is?

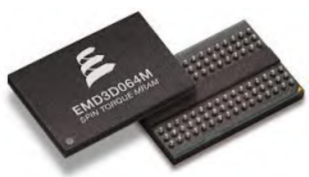
Radiation-hard
Spin not charge based
(as ferromagnets)

Non-volatile
Magnetic order
(as ferromagnets)



HDD

MRAM



Conclusions

Could antiferromagnetism b ... tant as ferromagnetism is?

Fast (THz) dynamics:
switching, domain wall motion
GHz in ferromagnets

Radiation-hard
Spin not charge based
(as ferromagnets)

additional

MERITS

Non-volatile
Magnetic order
(as ferromagnets)

Spin (polarized) currents
(non-col. AFs, Altermagnets)

No macroscopic net moment
→ No stray field generation
→ rel. insensitive
to magnetic fields

insulators (topol.),
semiconductors,
semimetals, metals, …
Ferromagnets mostly metals

Conclusions

Could antiferromagnetism become similarly important as ferromagnetism is?

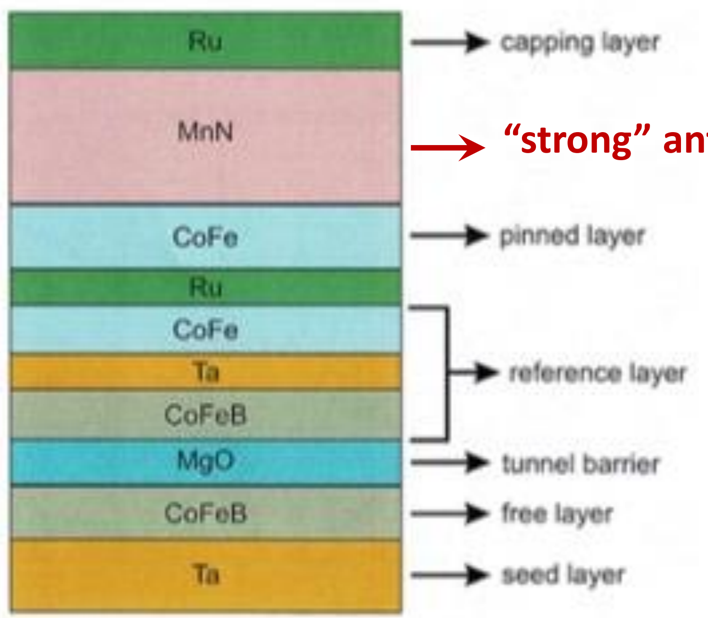
Néel's 1971 Nobel lecture:

Antiferromagnets are interesting and useless

Some important niche application:

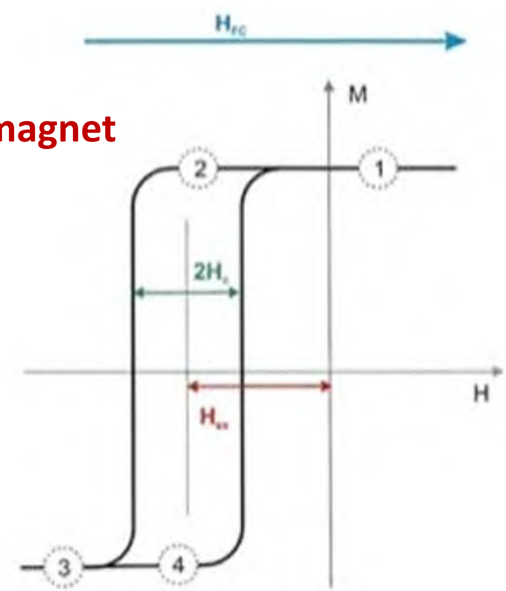
Antiferromagnets stabilizing Ferromagnets

exchanged biased TMR structure



"strong" antiferromagnet

synthetic **antiferromagnet**



Conclusions

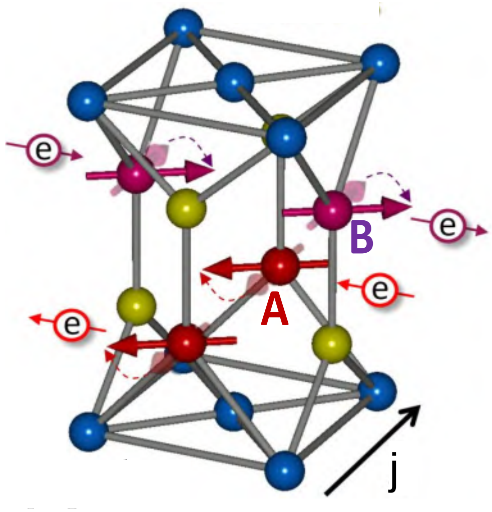
Could antiferromagnetism become similarly important as ferromagnetism is?

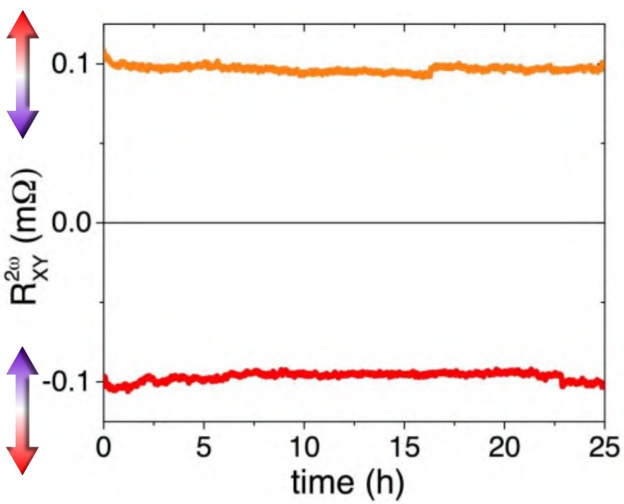
Néel’s 1971 Nobel lecture:

Antiferromagnets are interesting and useless

Antiferromagnetic states can be switched (ultrafast: electrically, optically) and the AF state can be “read” (electrically, optically, thermally)

Staggered SO field → stable 180° switching of uniaxial AF: (ultrafast DW motion)





Conclusions

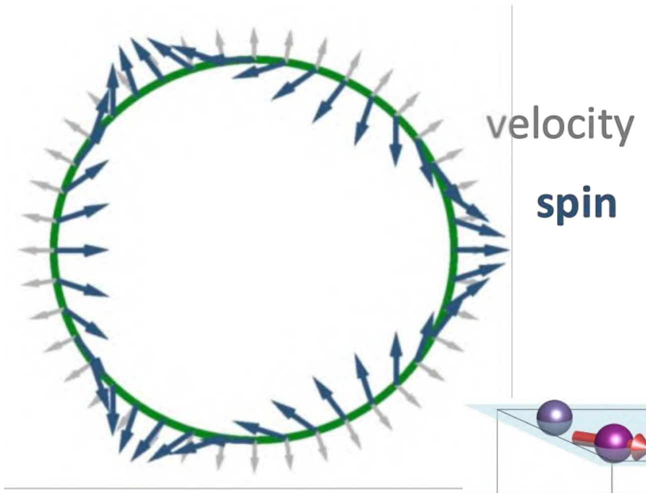
Could antiferromagnetism become similarly important as ferromagnetism is?

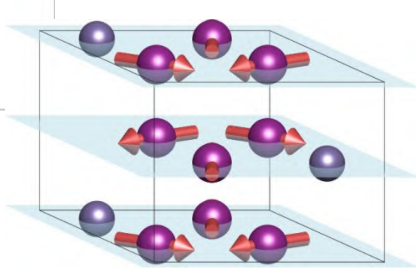
Néel's 1971 Nobel lecture:

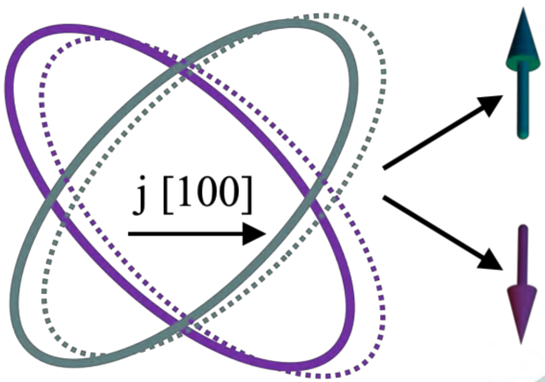
Antiferromagnets are interesting and useless

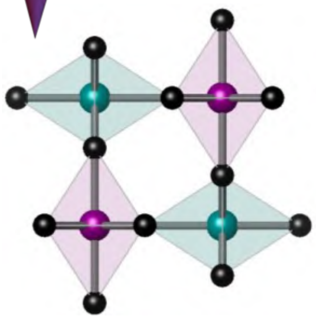
Antiferromagnets become like Ferromagnets (keeping their important properties)

Non-collinear AF, Altermagnets (Néel vector dependent spin (polarized) currents, anomalous Hall effect)









Conclusions

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

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EDITORIAL Altermagnetism – A New Punch Line of Fundamental Magnetism

Igor Mazin and PRX Editors, Dec 2022