Topological antiferromagnetic spintronics and the crystal Hall effect

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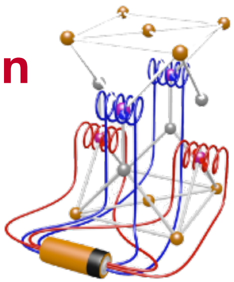
Johannes Gutenberg Universität Mainz

23trd of October 2019
KITP, Santa Barbara

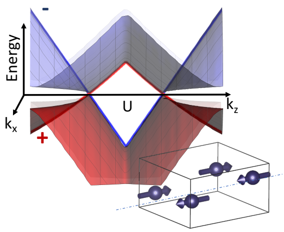
Topological antiferromagnetic spintronics and the crystal Hall effect

I. From Spin-Orbit Torque in FM to Néel Spin-Orbit Torques in Antiferromagnets:



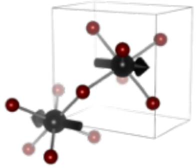
Zelezny, Gao, JS, Jungwirth PRL (2014)
Zelazny, Gao, et al. PRB (2016)
Bodnar, Smejkal, Jourdan, Kläui, Jungwirth, JS, et al, Nat. Com. (2018)

II. Topological Dirac Fermion + Antiferromagnets + Neel SOTs



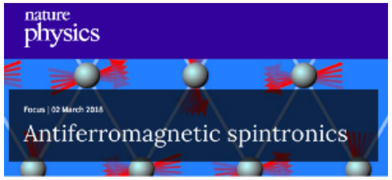
Smejkal, Zelezny, Sinova, Jungwirth PRL (2017)
Smejkal, Jungwirth, Sinova PSS (2017)

III. AHE in collinear AFMs: Crystal Hall Effect



Jungwirth, JS, et al, Nature Physics (AFM spintronics Reviews) (2018)
Surprises of the Spin Hall Effect, Physics Today 70, 7, 38 (2017)
Smejkal, Gonzales, Jungwirth, JS, arXiv 1901.00445 (2019)

Jungwirth, JS, et al, Nature Physics (AFM spintronics Reviews) (2018)



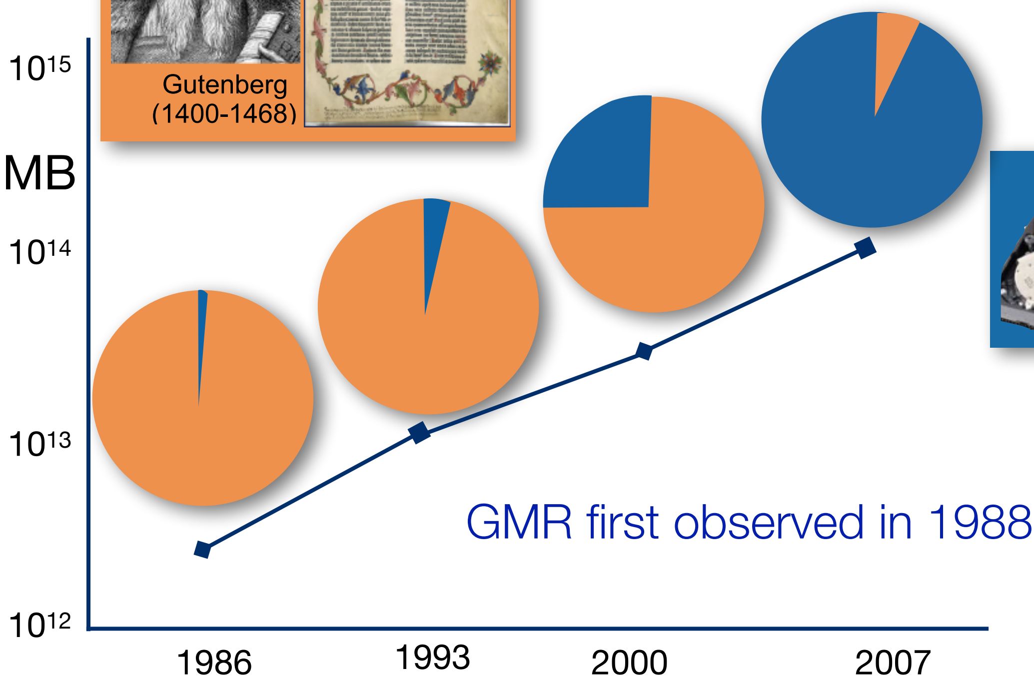
Analog to digital = Ink to Spin

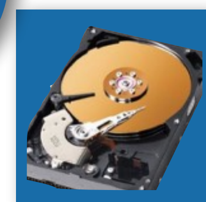
Analog: books, video/film, …

Digital: Hard-disks, DVDs,…

Gutenberg (1400-1468)

Analog to Digital





Hilbert et al. Science (2011)

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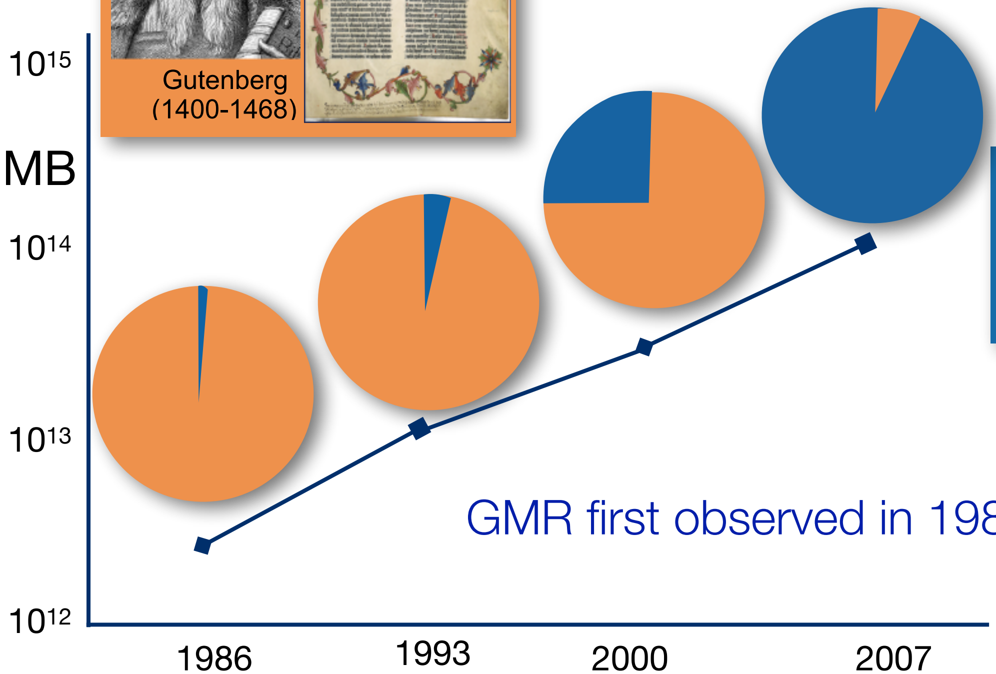
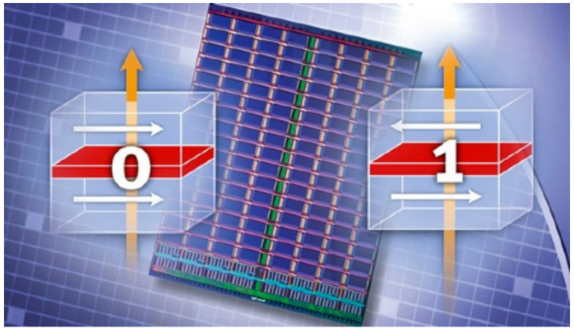


Hilbert et al. Science (2011)

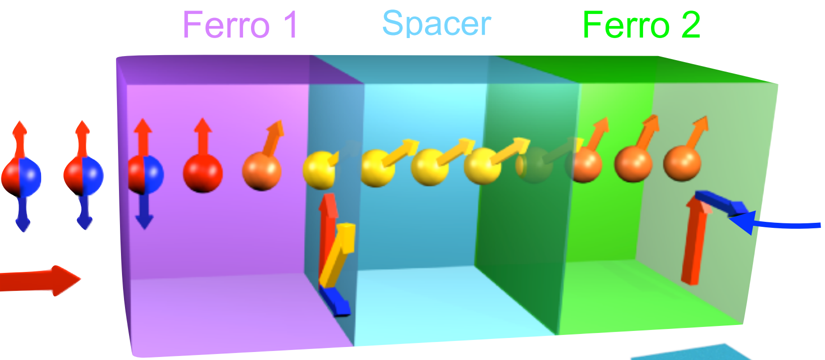
What is next in memory storage?

Spin-Transfer MRAM

(2015)

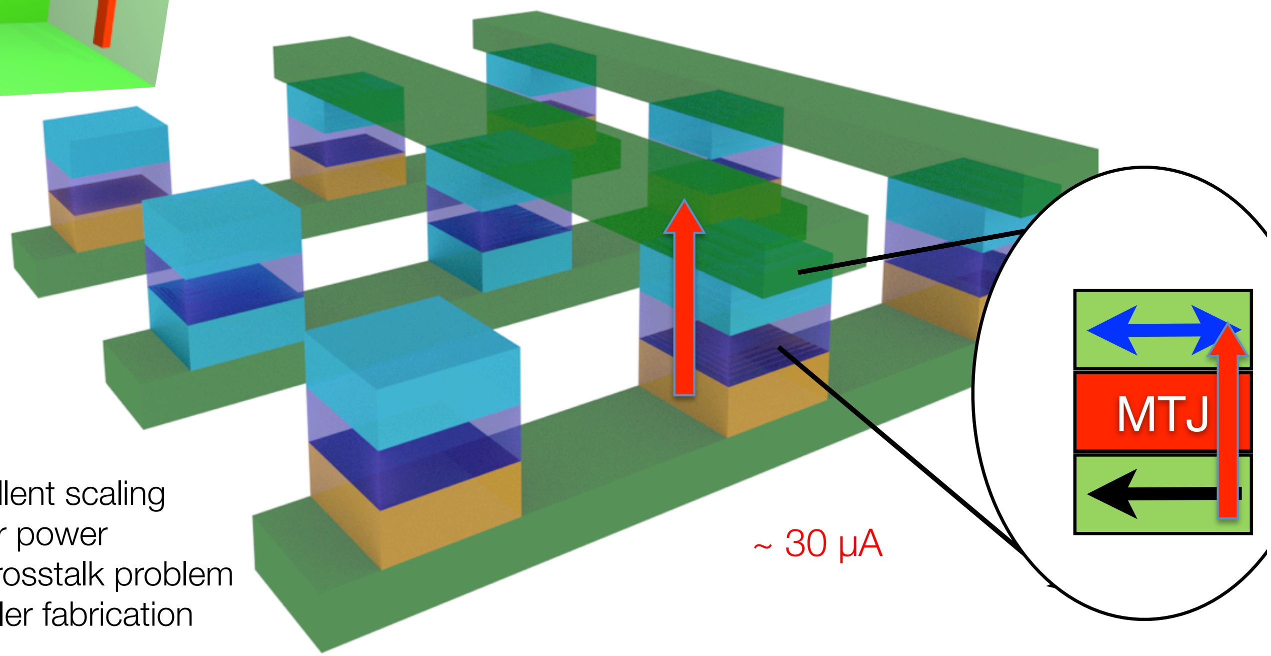


Spin-Transfer-Torque MRAM

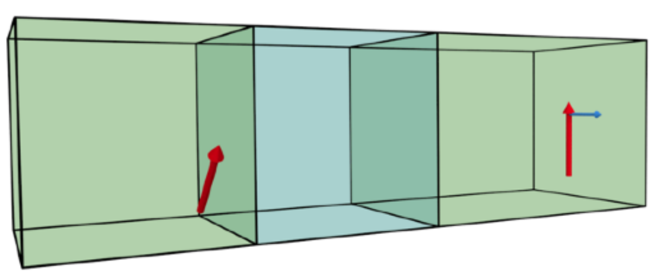


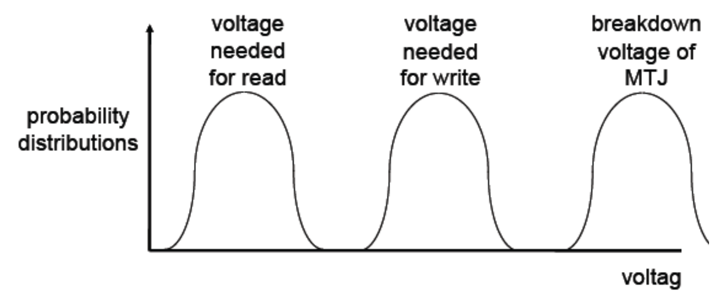
Torque

$$\frac{d\hat{M}}{dt} = \boxed{-\gamma \hat{M} \times \vec{H}_{eff}} \boxed{+ \alpha \hat{M} \times \frac{d\hat{M}}{dt}} \boxed{+ \frac{\hbar P J}{2e} (\hat{M} \times \hat{M}_0) \times \hat{M}}$$

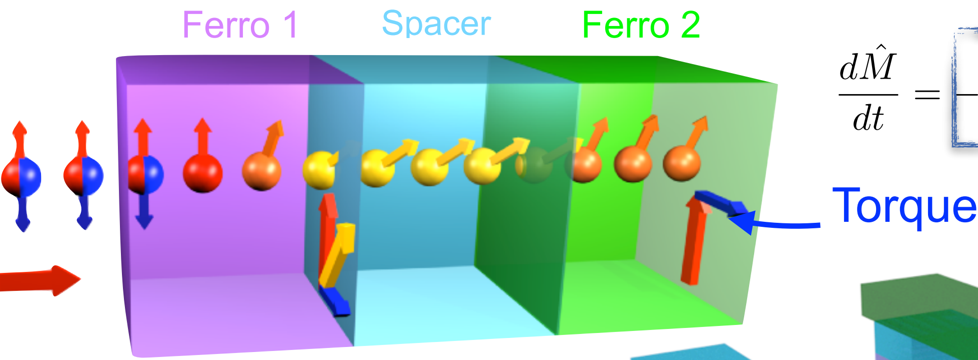


- excellent scaling
- lower power
- no crosstalk problem
- simpler fabrication

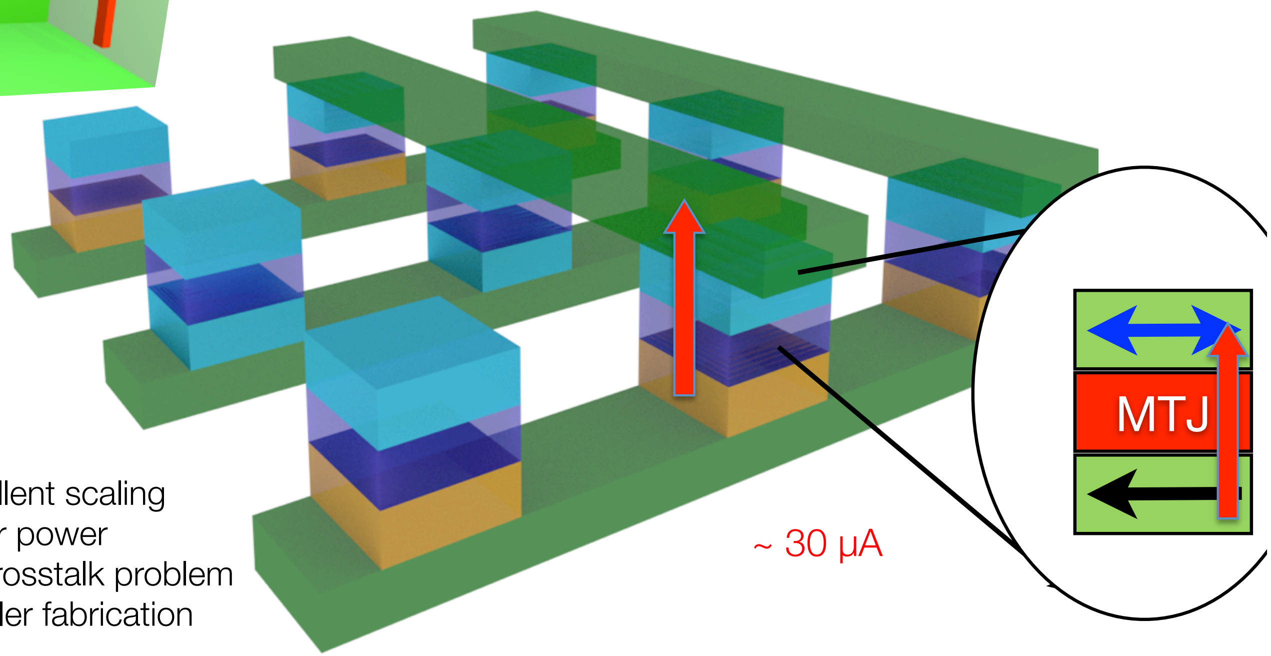




Spin-Transfer-Torque MRAM



$$\frac{d\hat{M}}{dt} = \boxed{-\gamma \hat{M} \times \vec{H}_{eff}} \boxed{+ \alpha \hat{M} \times \frac{d\hat{M}}{dt}} \boxed{+ \frac{\hbar P J}{2e} (\hat{M} \times \hat{M}_0) \times \hat{M}}$$



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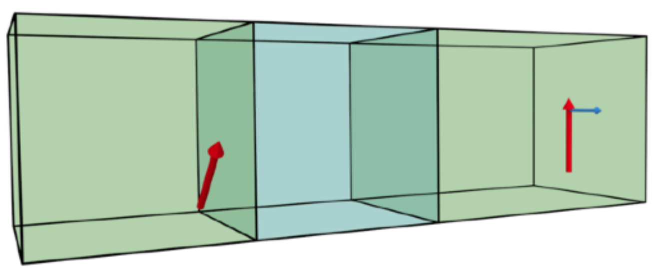
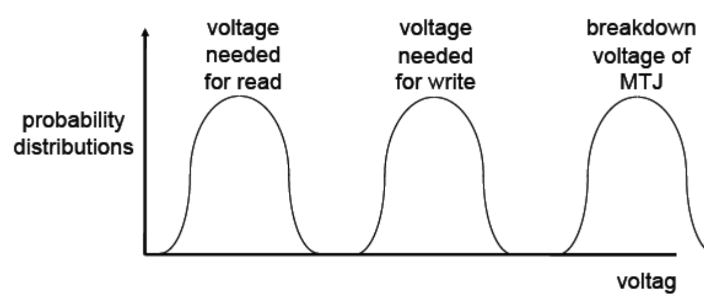
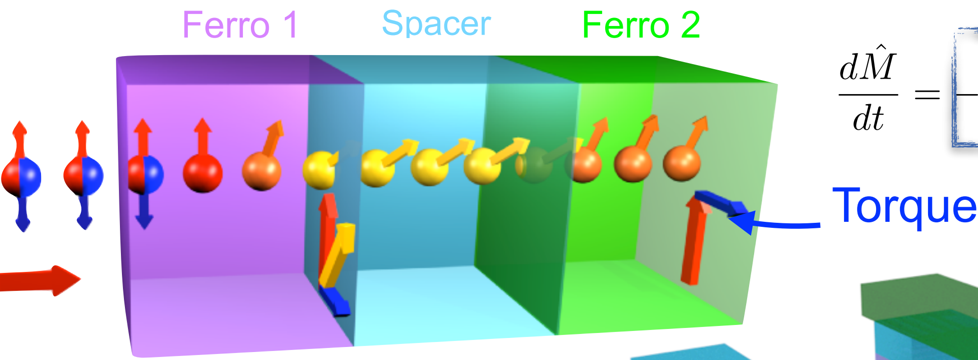




Spin-Transfer-Torque MRAM



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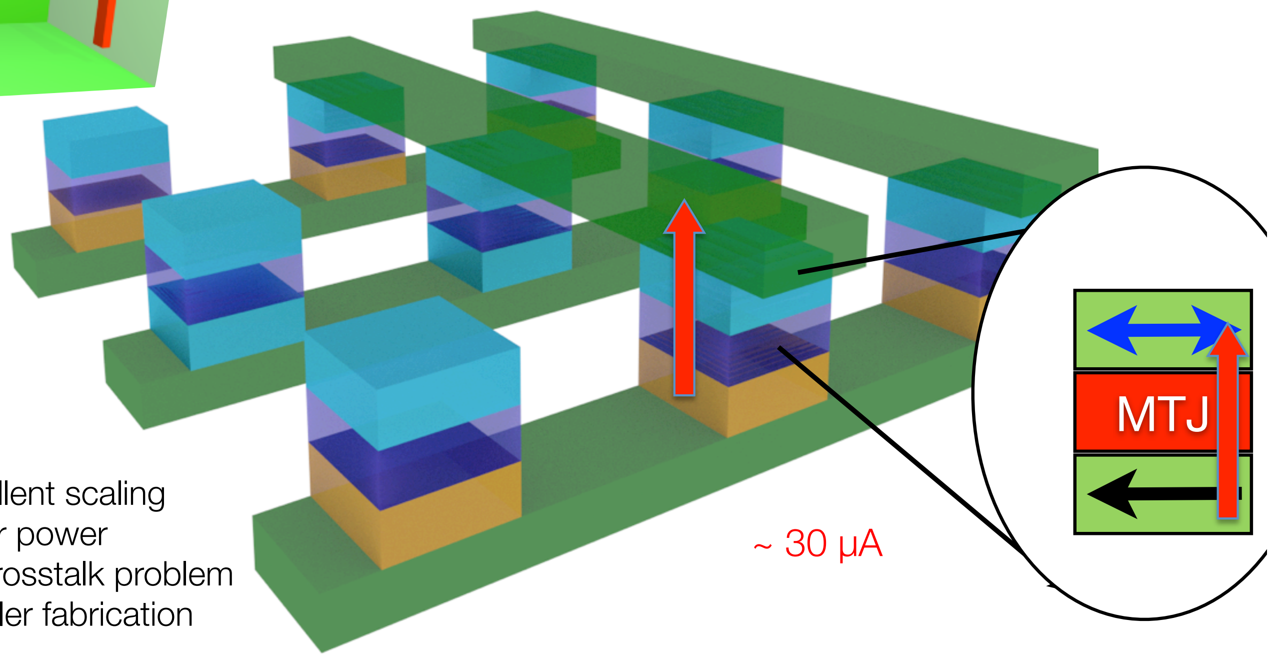

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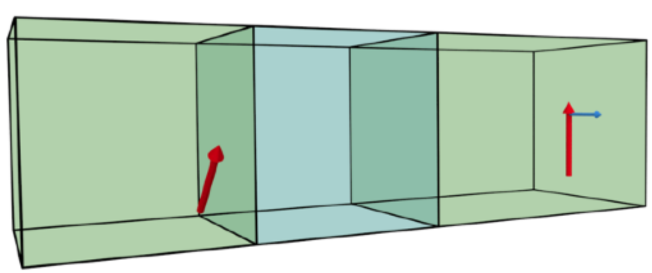
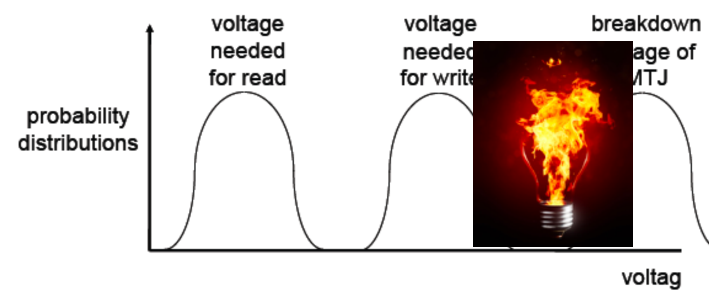
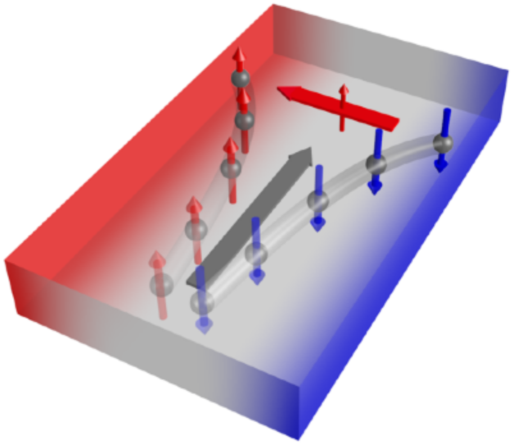
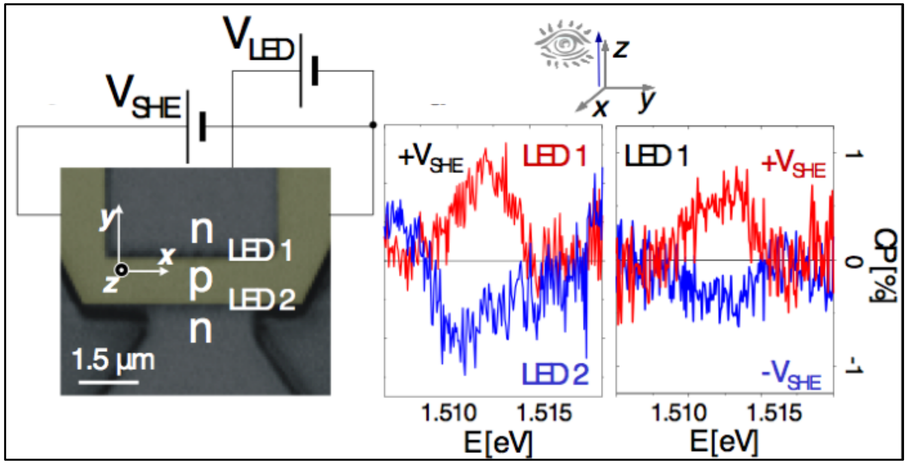




Spin Hall Effect in p-GaAs

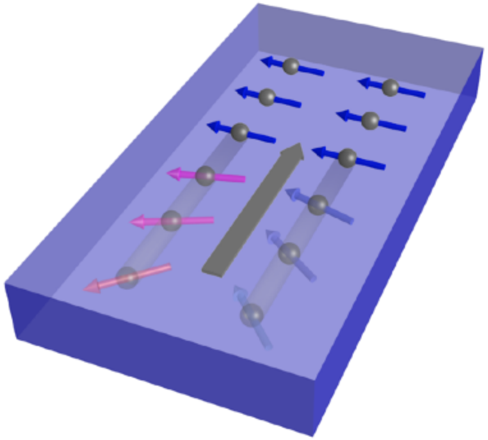


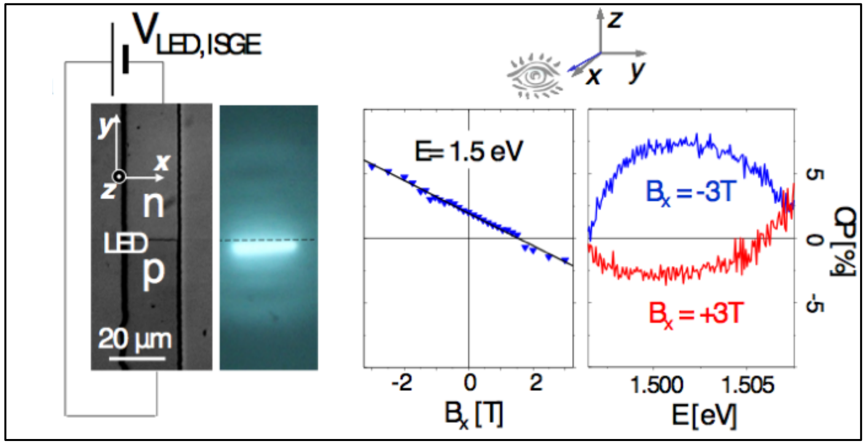


Wunderlich et at. arXiv '04, PRL '05

Inverse Spin Galvanic Effect or Edelstein Effect

(Reverse process of circular photo-galvanic effect,   Ganichev et al., 2001)





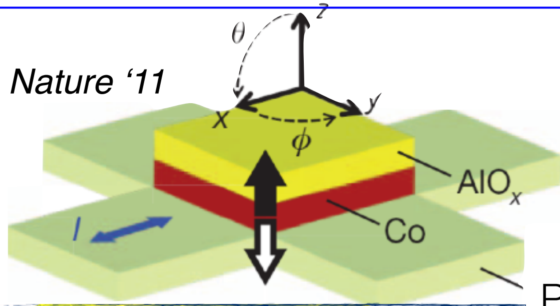
Experiments of in-plane current magnetic switching

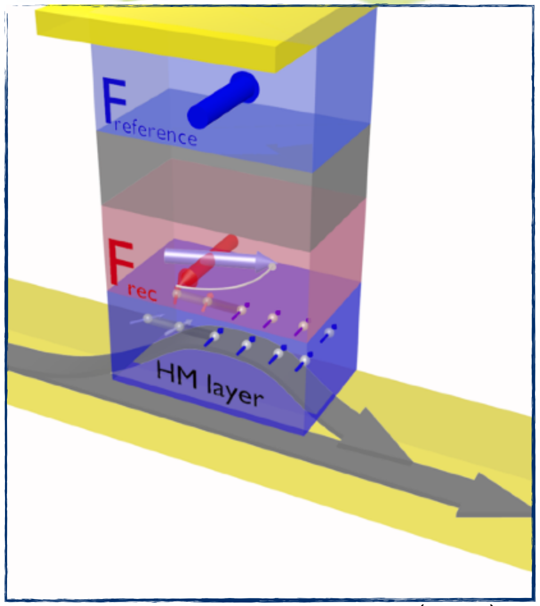
INSP/RE group INTERDISCIPLINARY SPINTRONICS RESEARCH

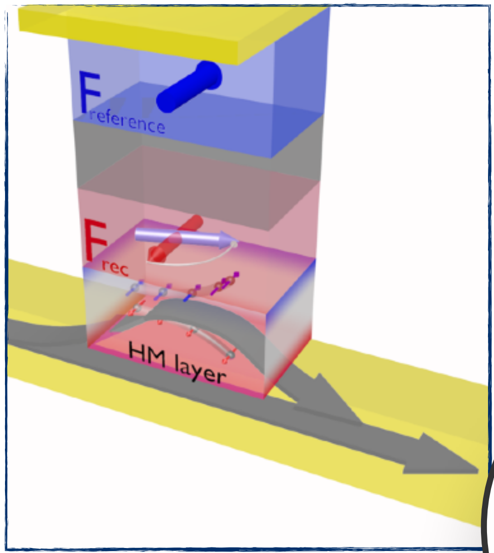
spin-orbit torque at PM/FM interface

SHE as spin-current generator + STT

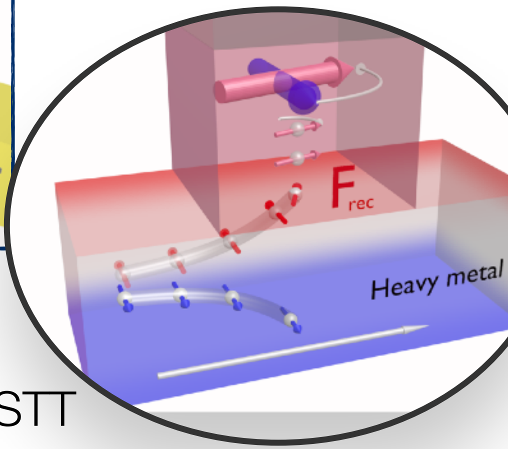
Miron et al., Nature '11







Buhrman,et al., Science '12



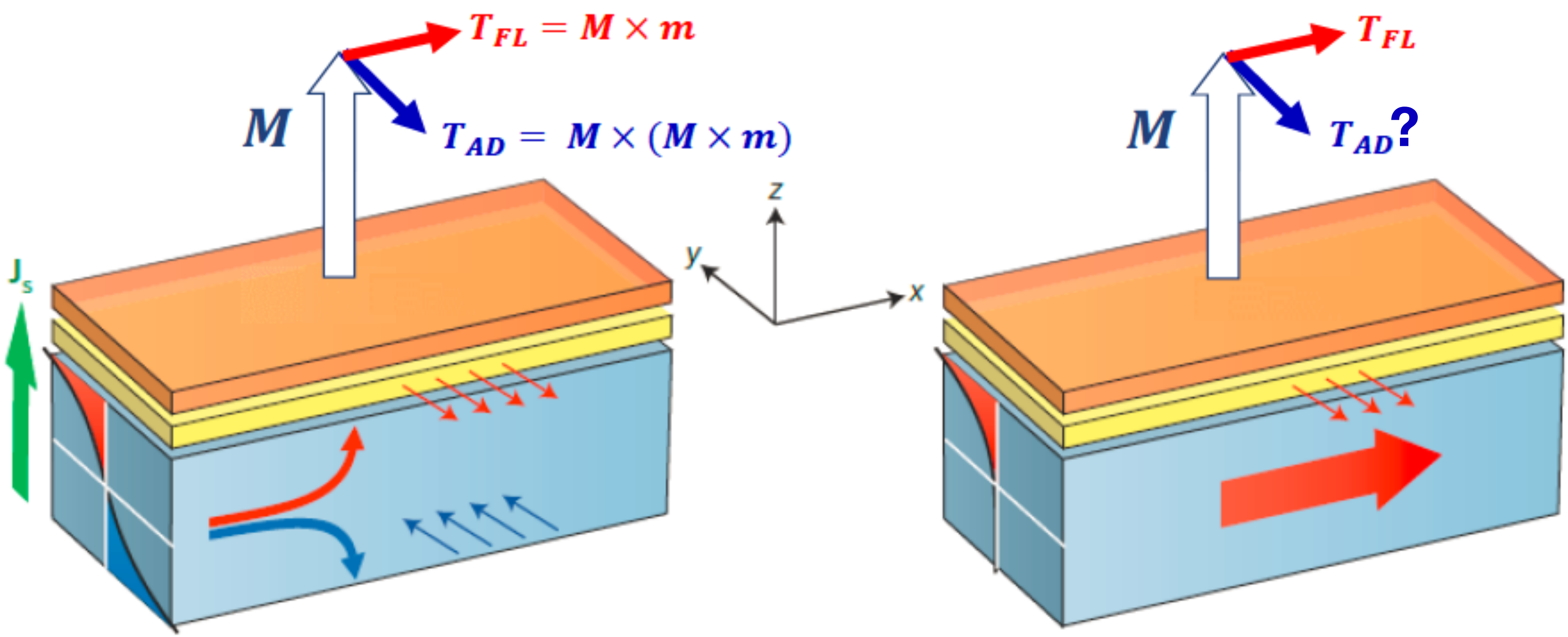
intrinsic SHE + STT

$$\left(\frac{d\vec{M}}{dt}\right)_{SHE-STT} = P\hat{M} \times (\hat{n} \times \hat{M})$$

$$H_{ex} = J_{ex}\vec{M} \cdot \delta\vec{s} \qquad \left(\frac{d\vec{M}}{dt}\right)_{SOT} = \frac{J_{ex}}{\hbar}\vec{M} \times \delta\vec{s}$$

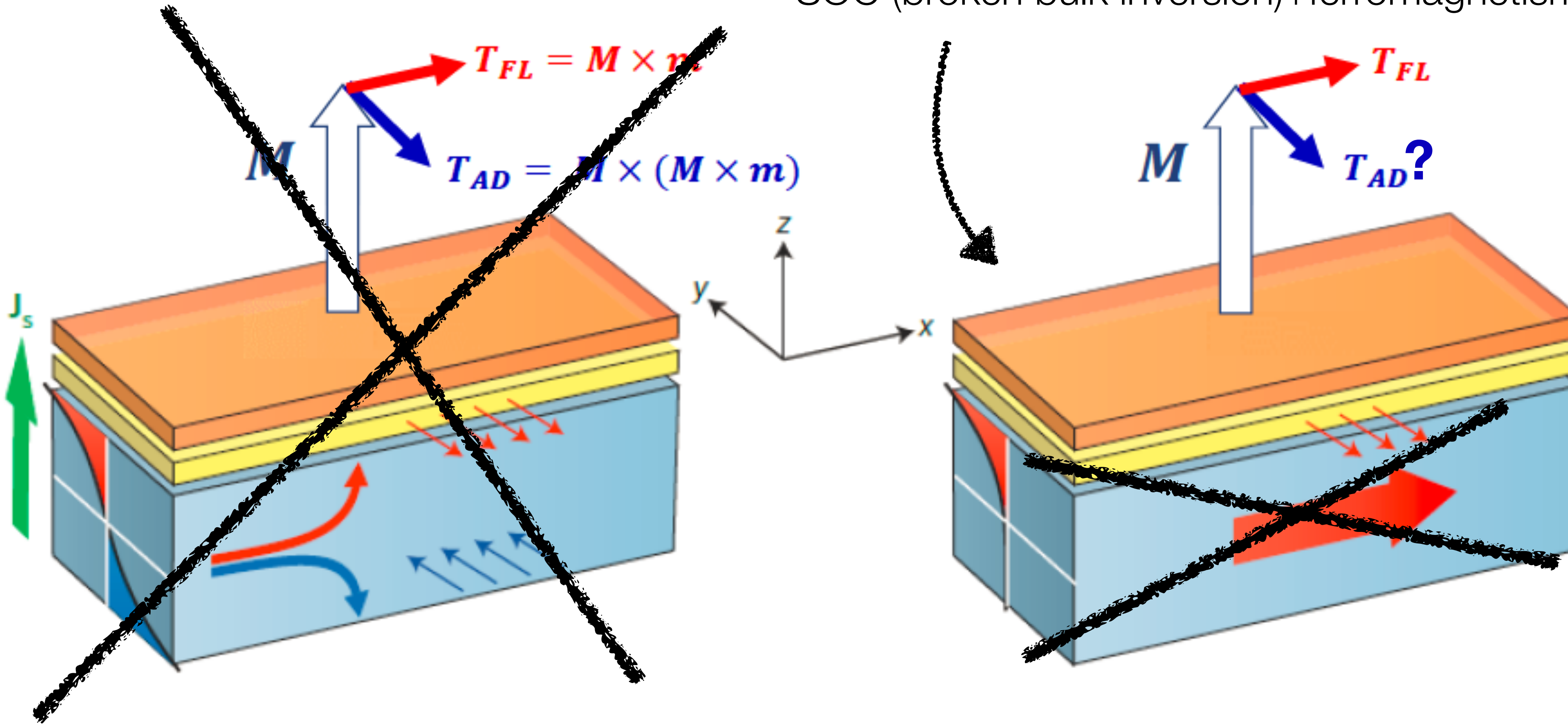
$h_{SOT} \parallel z \times J$

Jairo Sinova and Tomas Jungwirth, Physics Today (2017)

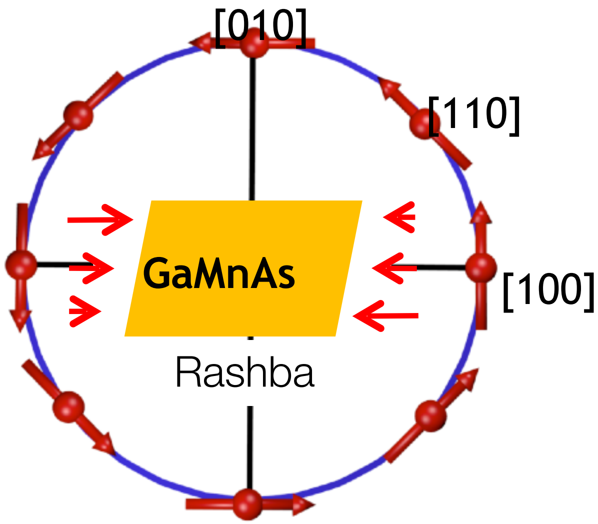


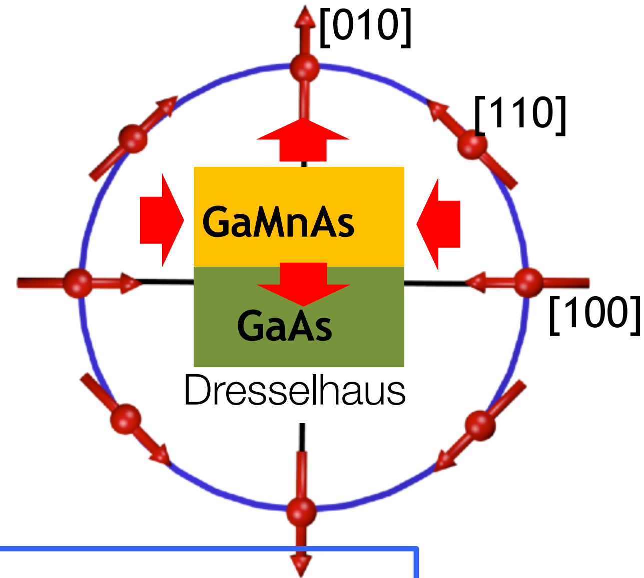
$T_{FL} = M \times m$
M
$T_{AD} = M \times (M \times m)$
J_s
z
y
x
M
T_{FL}
T_{AD}?

Make a ferromagnet behave like a cat:
SOC (broken bulk inversion)+ferromagnetism



Intrinsic (Berry phase) spin-orbit torque in GaMnAs





$$\left(\frac{d\hat{M}}{dt}\right)_{SOT} = \hat{M} \times \delta s_z(\theta_{\mathbf{M}-\mathbf{E}})\hat{z}$$

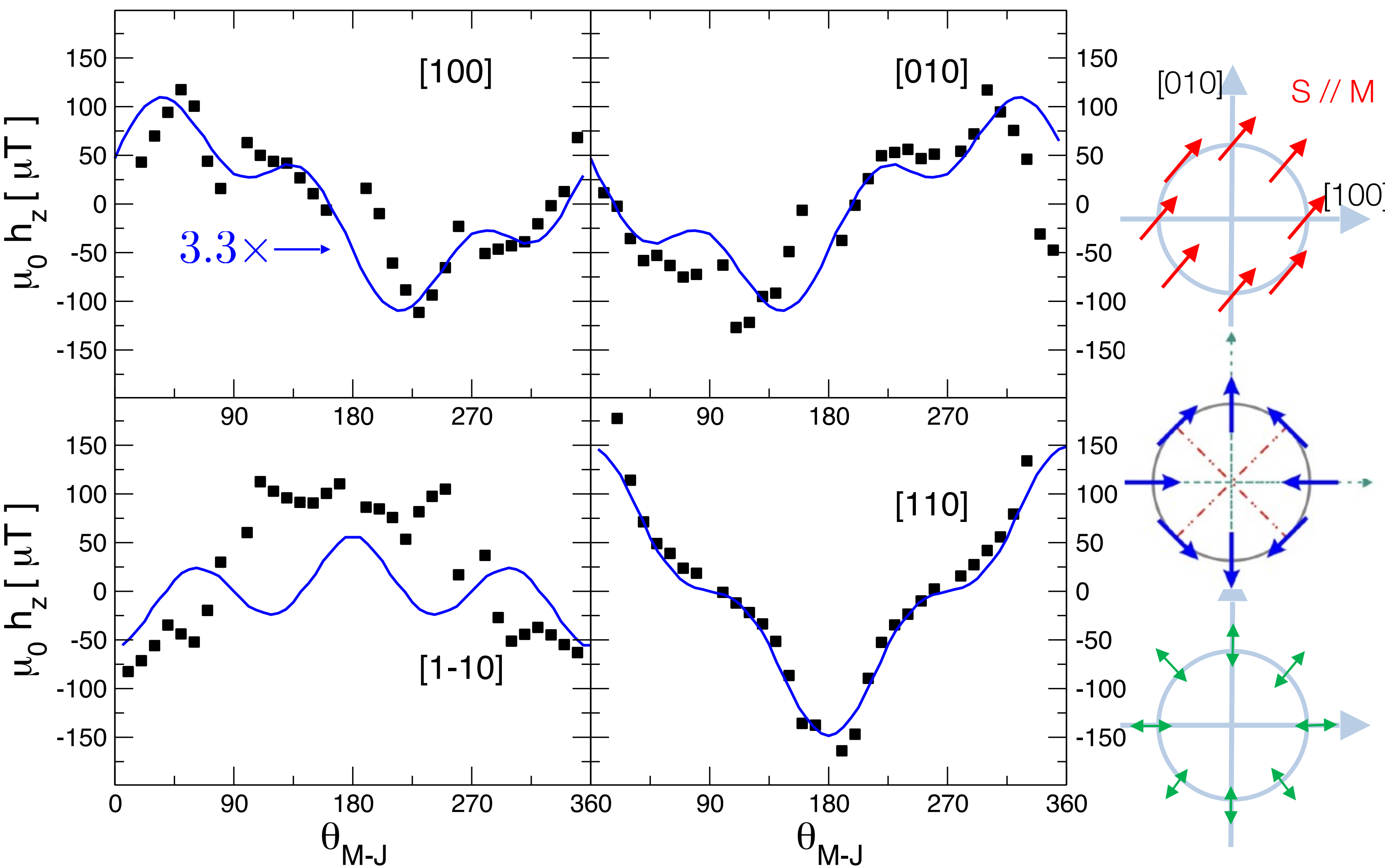
angle between **M** and current direction

Kurebayashi, JS, et al., Nat. Nanot. (2014)

current direction	Rashba: $\delta s_{z,\mathbf{M}} \sim$	Dresselhaus: $\delta s_{z,\mathbf{M}} \sim$
$\mathbf{E} \parallel [100]$	$\cos\theta_{\mathbf{M}-\mathbf{E}}$	$\sin\theta_{\mathbf{M}-\mathbf{E}}$
$\mathbf{E} \parallel [010]$	$\cos\theta_{\mathbf{M}-\mathbf{E}}$	$-\sin\theta_{\mathbf{M}-\mathbf{E}}$
$\mathbf{E} \parallel [110]$	$\cos\theta_{\mathbf{M}-\mathbf{E}}$	$\cos\theta_{\mathbf{M}-\mathbf{E}}$
$\mathbf{E} \parallel [1-10]$	$\cos\theta_{\mathbf{M}-\mathbf{E}}$	$-\cos\theta_{\mathbf{M}-\mathbf{E}}$

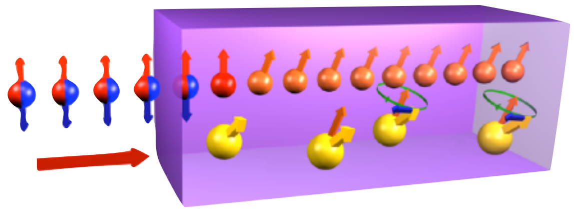
Discovery of anti-damping spin-orbit torques

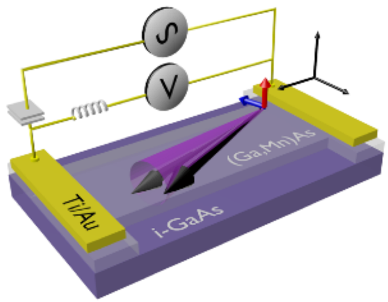
Solid line: Calculations with H_{KL} (captures higher harmonics)

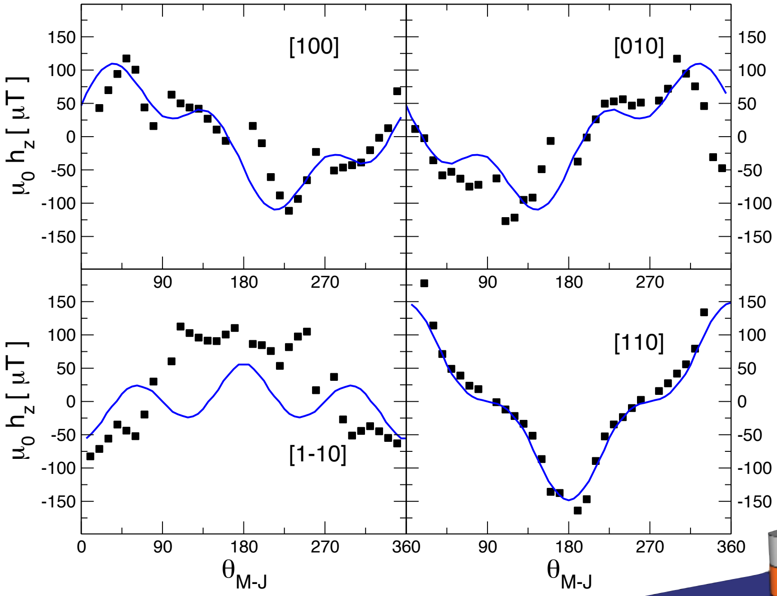


Kurebayashi, JS, et al., Nat. Nanot. (2014)

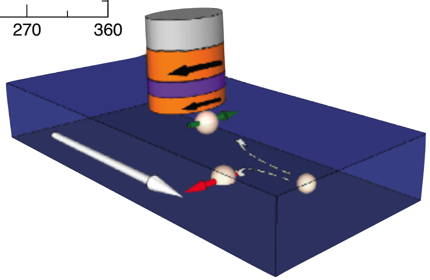
We have achieved a “cat” magnet







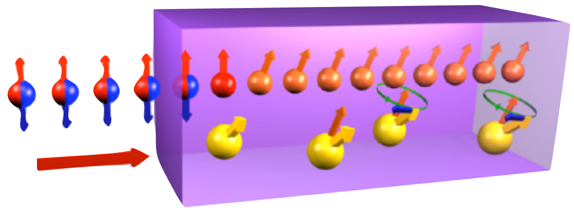
Kurebayashi, JS, et al., Nat. Nanot. (2014)

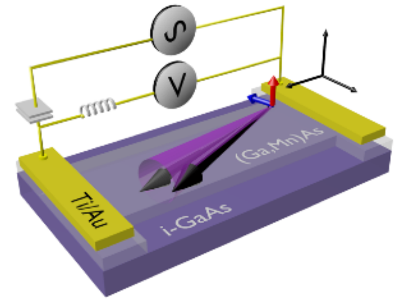


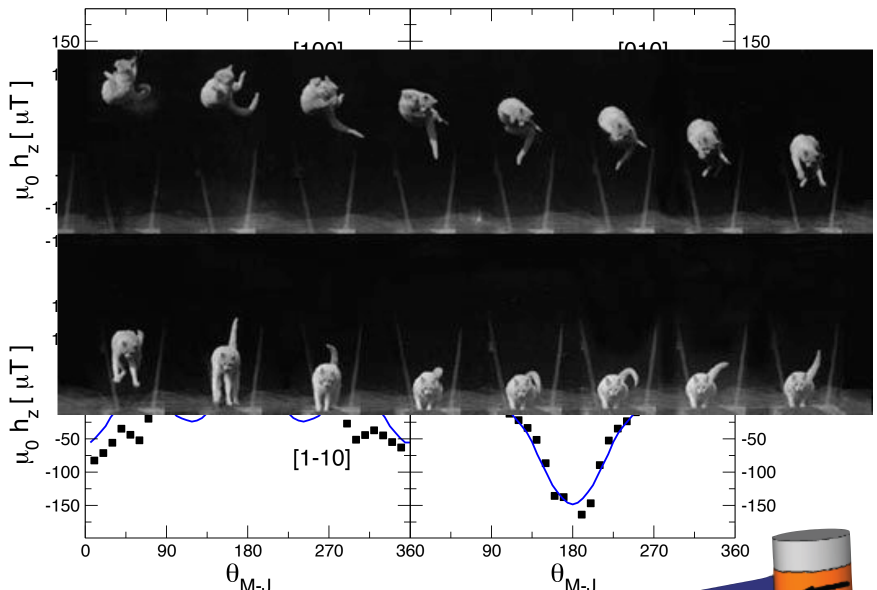
MRAMs without melting

2011-2014

We have achieved a "cat" magnet

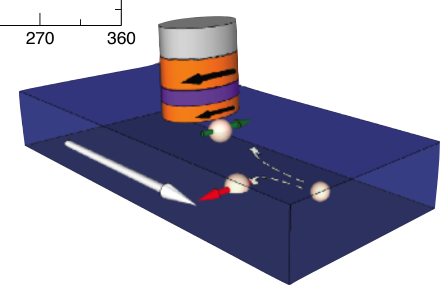






Kurebayashi, JS, et al., Nat. Nanot. (2014)

MRAMs without melting



2011-2014

Antiferromagnetic Spintronics

INSP/RE group
INTERDISCIPLINARY SPINTRONICS RESEARCH

Last issue of the International Technologica Roadmap for Semiconductors in 2016

Ordered spins
Non-volatile

Spin not charge based
Radiation-hard

No net moment
Insensitive to magnetic fields, no fringing stray fields

THz dynamics
Ultra-fast switching

Multiple-stable domain configurations
Memory-logic bit cells

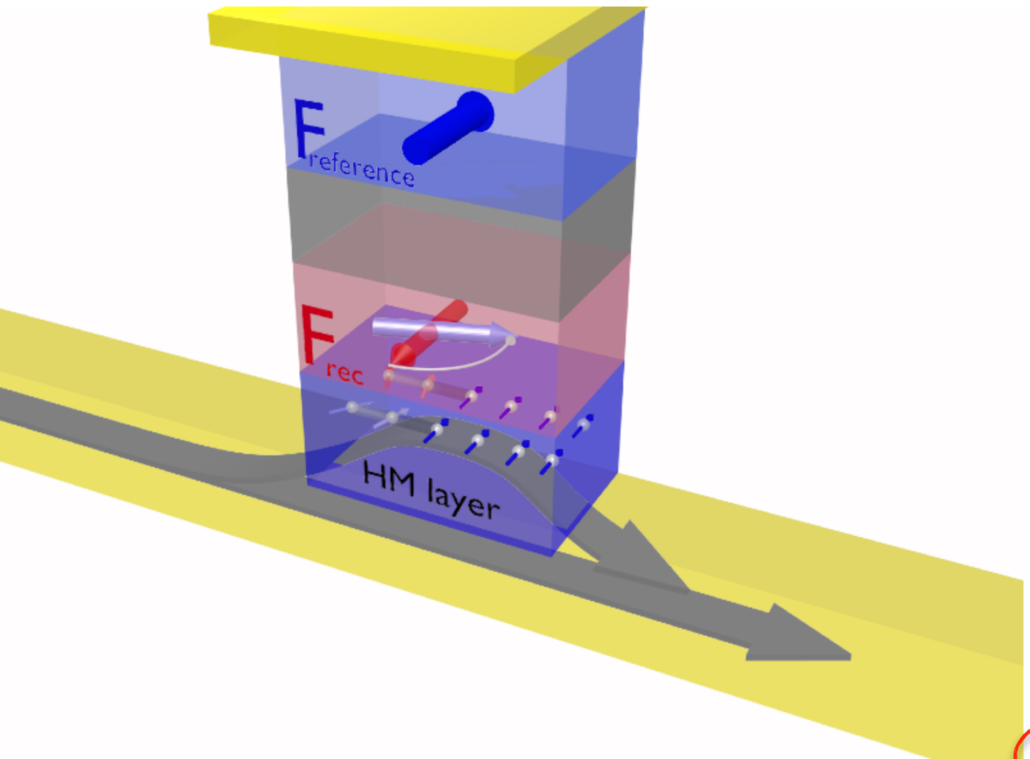
Materials range
Insulators, semiconductors, semimetals, metals, superconductors

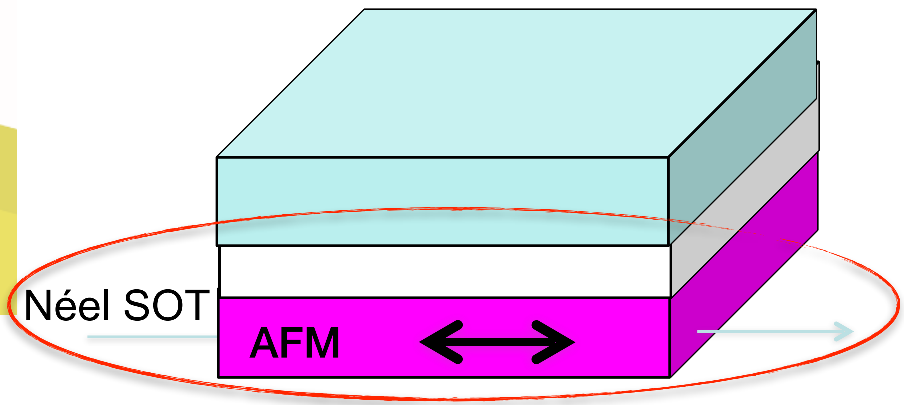
SP/CE

Antiferromagnetic Spin-orbitronics

Writing by spin-orbit torque in a single-layer ferromagnet

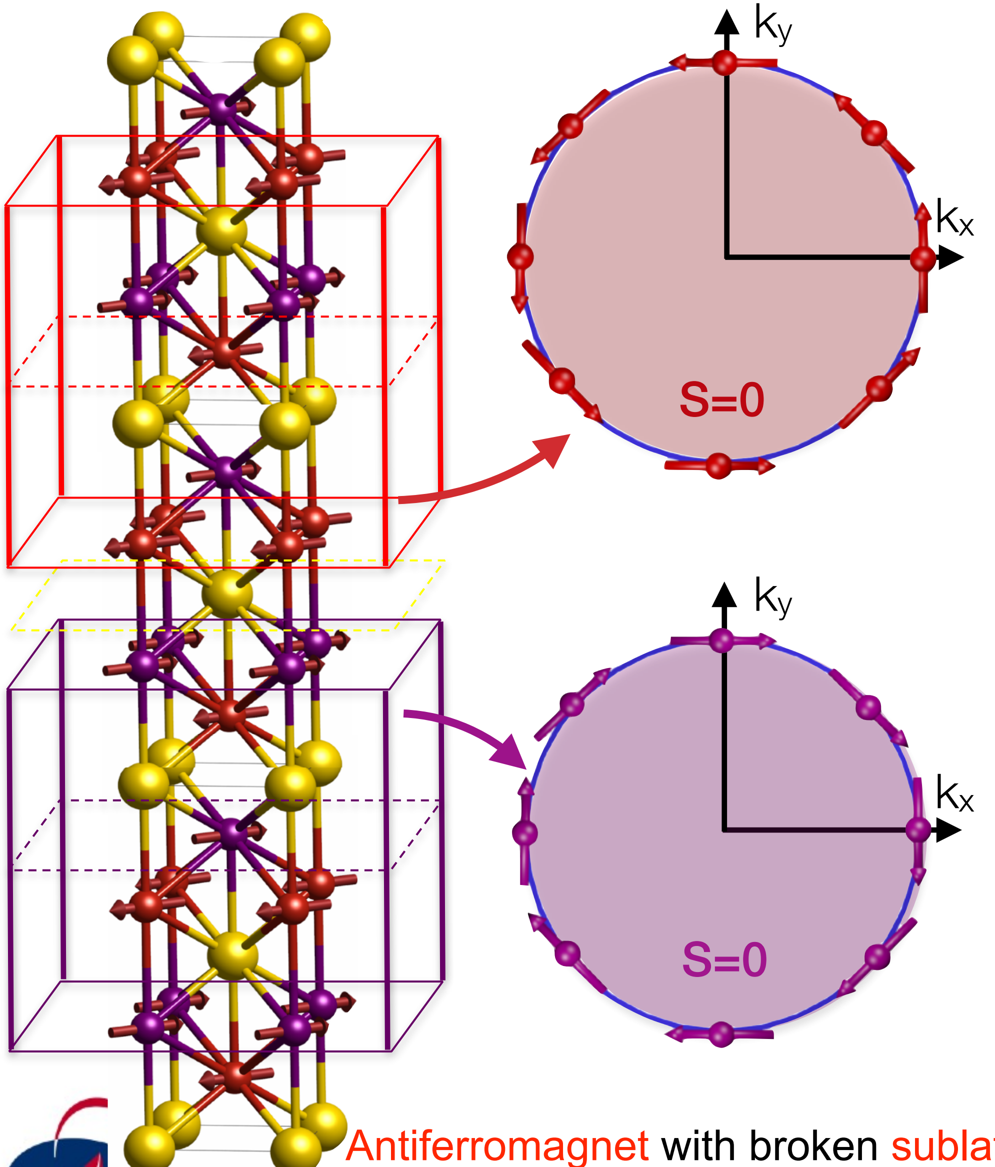
Magnet reversing itself : SOT

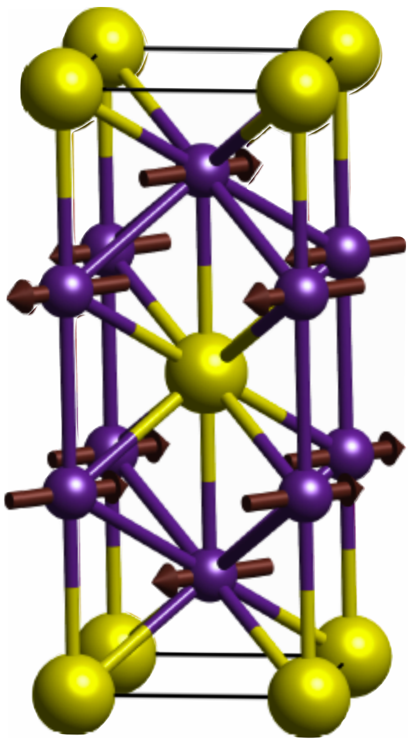




J. Zelezny, H. Gao, K. Vyborny, J. Masek, J. Zemen, A. Manchon, J. Sinova, and T. Jungwirth, *PRL (2014)*

Writing by **Néel spin-orbit torque** in a single-layer **antiferromagnet**

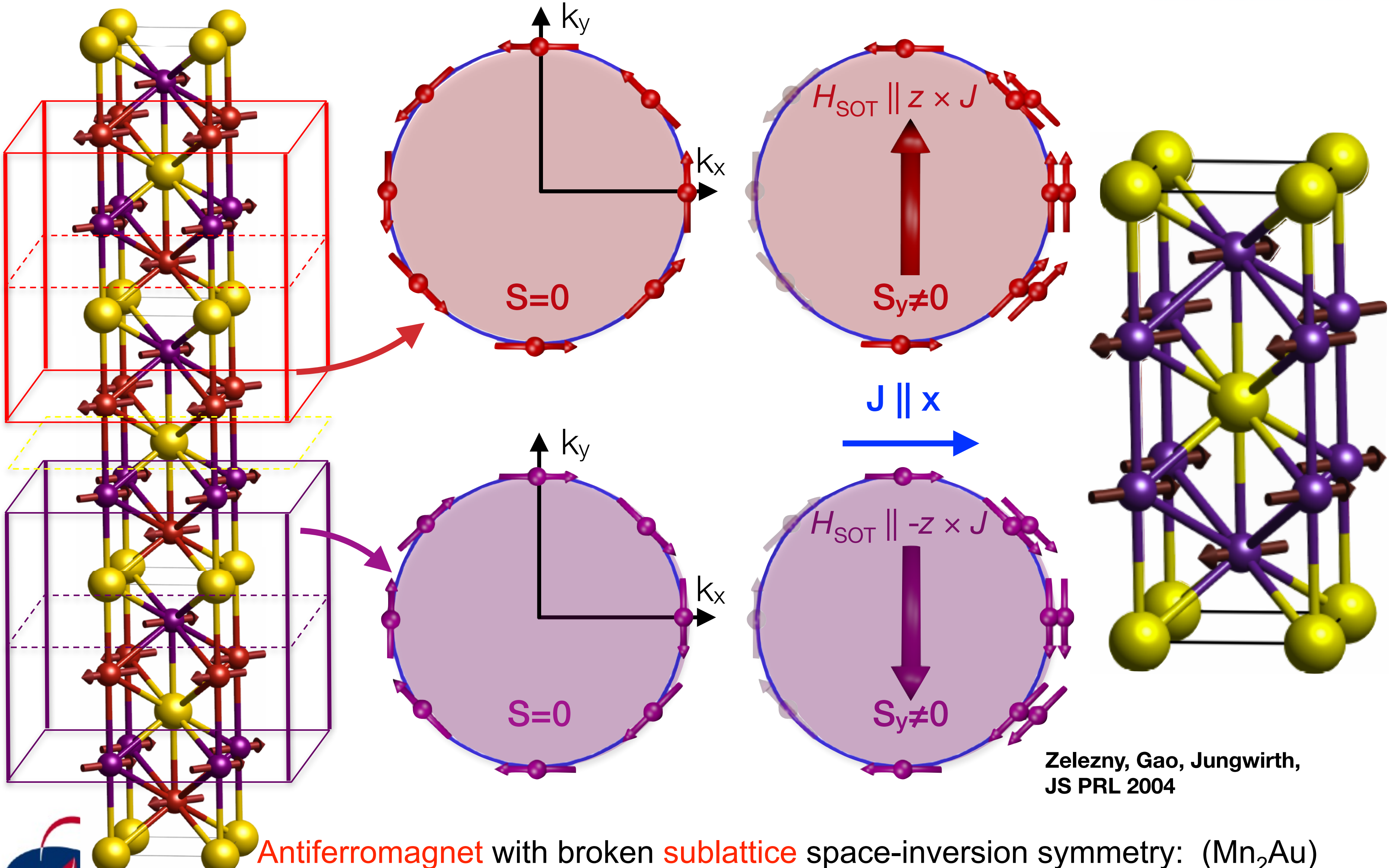




Zelezny, Gao, Jungwirth, JS PRL 2004

Antiferromagnet with broken sublattice space-inversion symmetry: (Mn_2Au)

Writing by **Néel spin-orbit torque** in a single-layer **antiferromagnet**



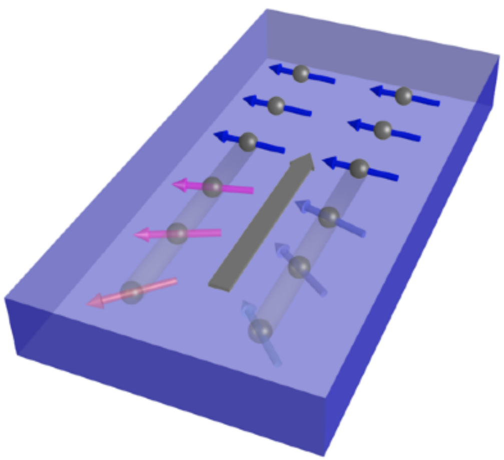
Zelezny, Gao, Jungwirth, JS PRL 2004

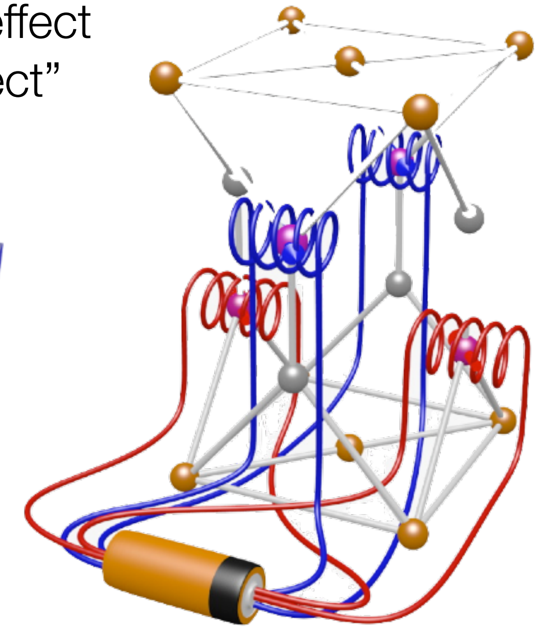
Antiferromagnet with broken sublattice space-inversion symmetry: (Mn_2Au)

Antiferromagnetic Spin-orbitronics: Néel spin-orbit torque

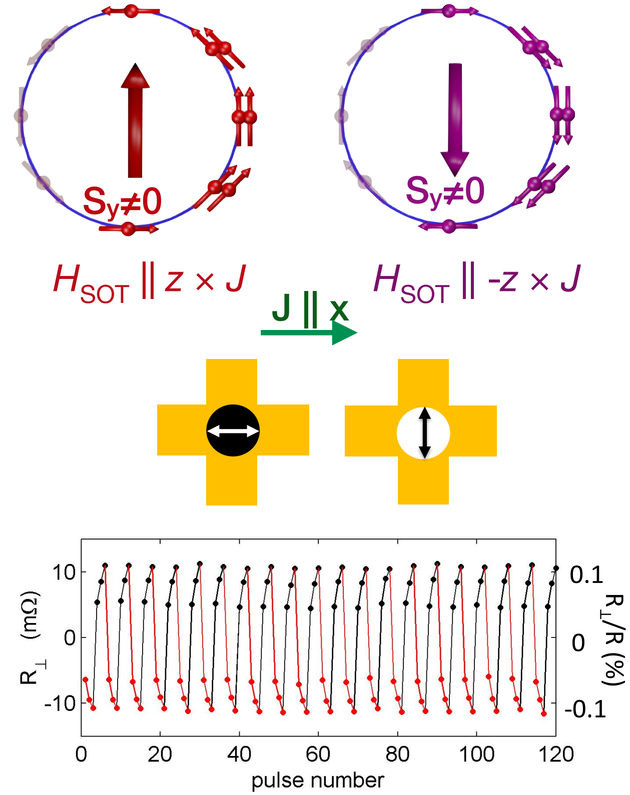
INSP/RE group
INTERDISCIPLINARY SPINTRONICS RESEARCH

Inverse spin galvanic effect (ISGE) "Edelstein effect"





J.Zelezny, J.Sinova, T.Jungwirth et al., Phys.Rev.Lett.(2014)

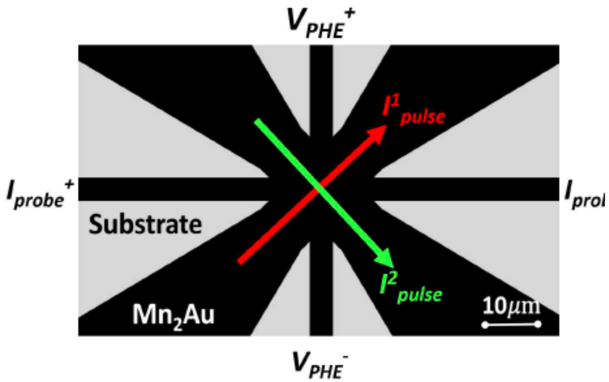


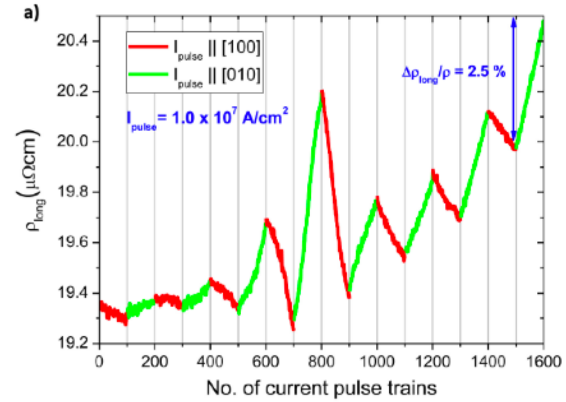
P..Wadley. TJ, et al., Science (2016)
Bodnar, Smajkal, TJ, JS, et al. Nat. Comm. (2018),

Functionalities based on electrical manipulation of antiferromagnetic order

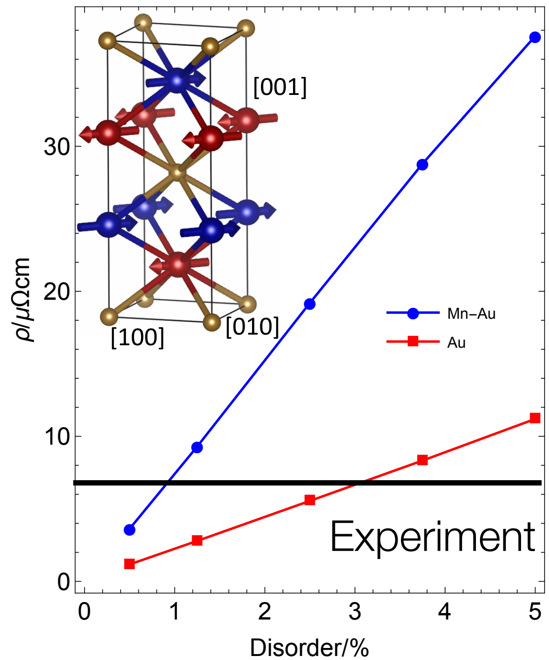
SP/CE

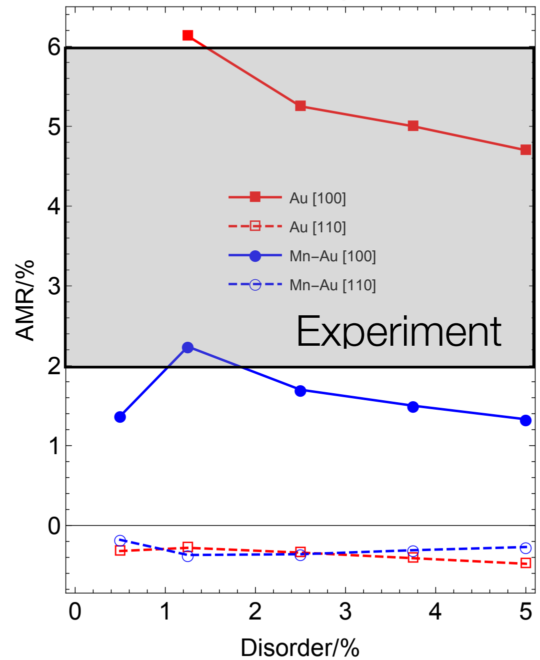
Experimental Observation of Néel SOT in Mn_2Au





Relativistic DFT:





- Experiment:
- *S.Bodnar et al.**, **(2.5-6 %)**,
- *M.Meinert et al, arXiv.1706.06983* (**5 %***D: App.Phys*)
- *M.Jourdan et al., JoP . (2015):* **8 μΩcm**
- H.Wu et al., AFM (2016) (**1-2.5 %**)

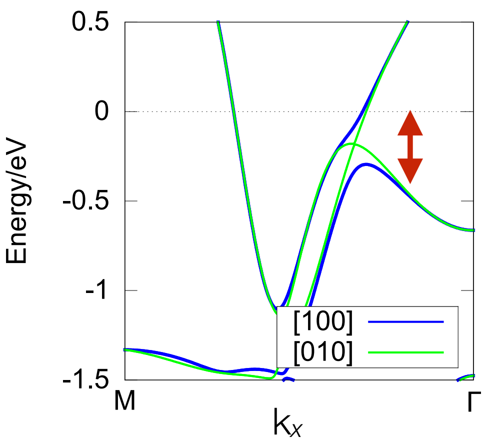
0.6+-0.3% Au rich, Mn-Au <5%

Bodnar, Smejkal, Jourdan, Kläui, Jungwirth, JS, et al, Nature Communications (2018)

Anisotropic spectral function and stability of Dirac points

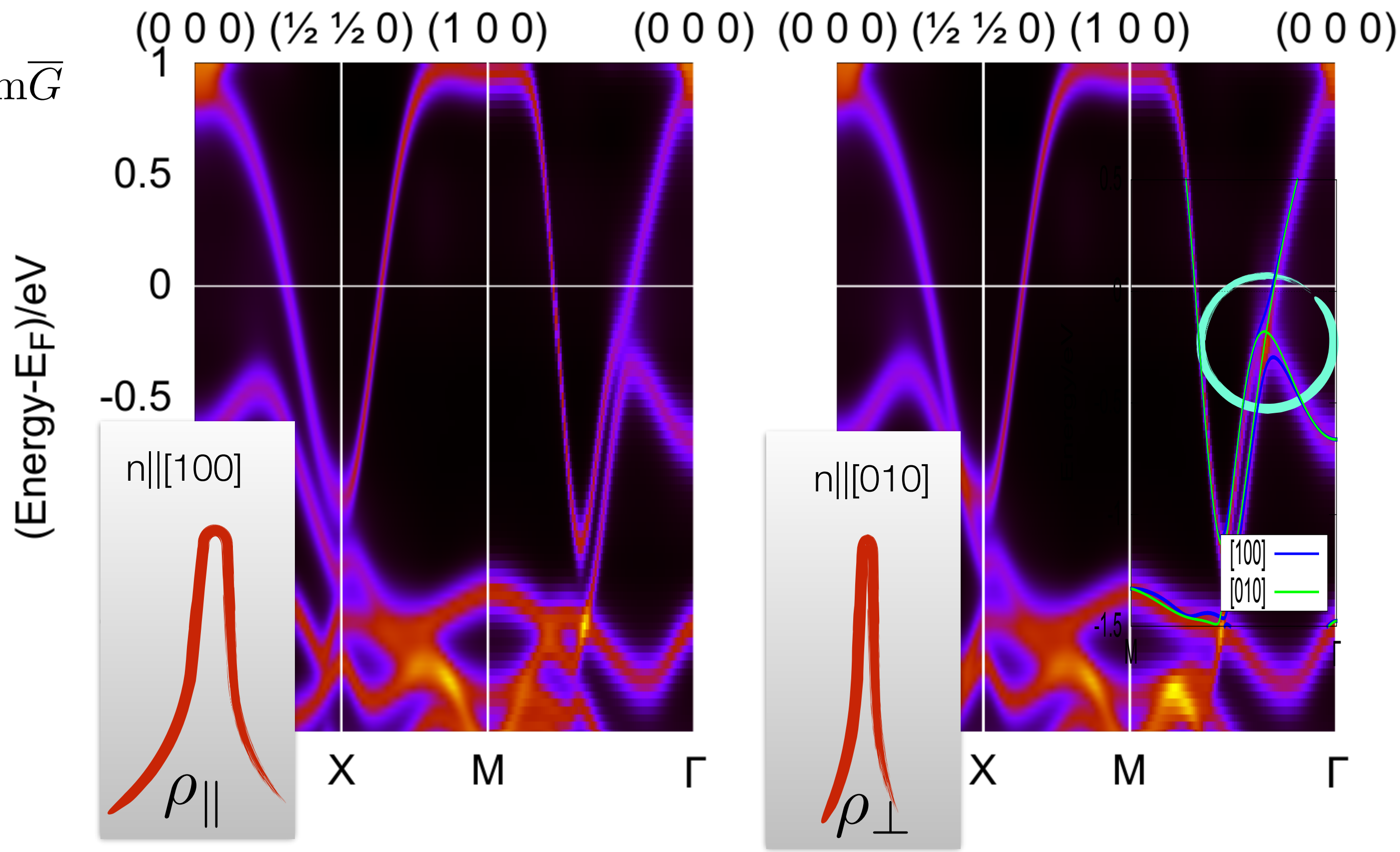
INSP/RE group
INTERDISCIPLINARY SPINTRONICS RESEARCH

$$E(\mathbf{k}) \rightarrow A(E, \mathbf{k}) = -\frac{1}{\pi}\mathrm{Im}\overline{G}$$



$$\rho_{||} > \rho_{\perp}$$

$$\mathrm{AMR} > 0$$



Angular dependence of Bloch spectral function

- ***CPA preserves the symmetry prevented hybridisations***
- ***Disorder propagates Dirac point to Fermi level and shifts the Fermi level***

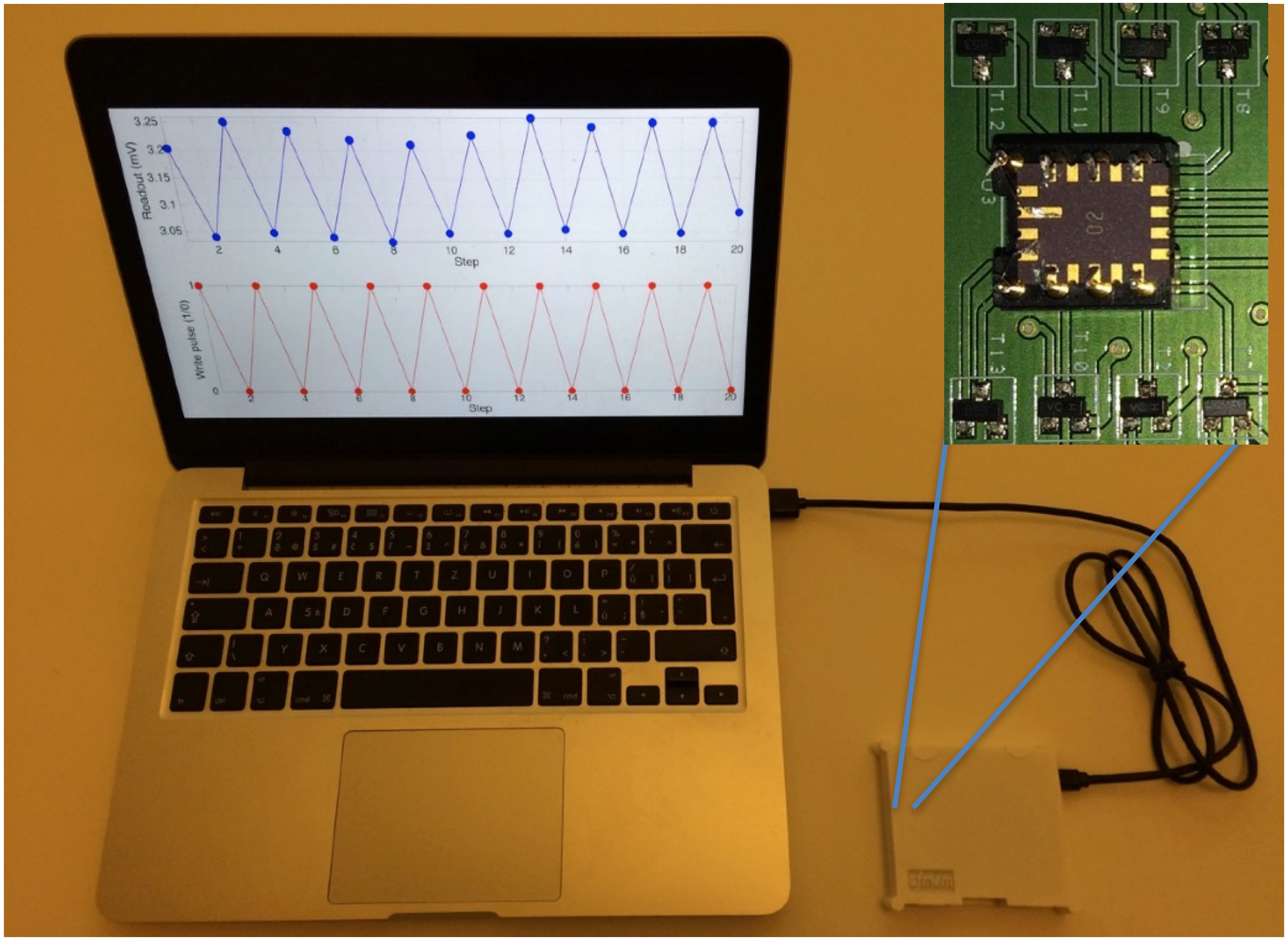
5% Au-rich **AMR 6%**

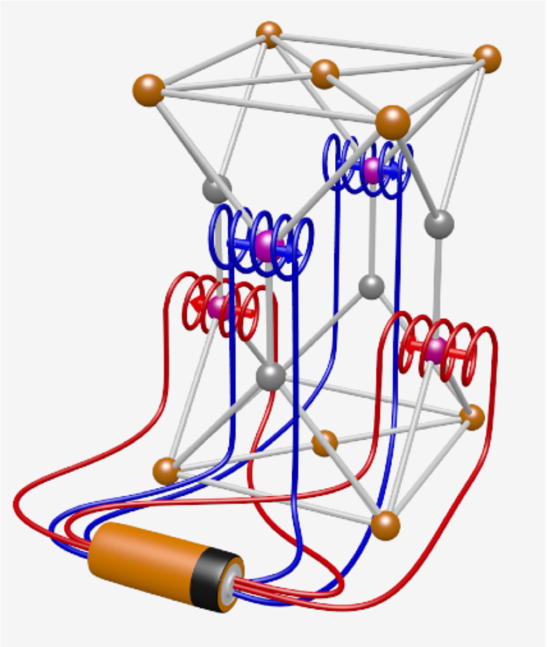
S. Y. Bodnar, L. Smajkal, T.Jungwirth, J.Sinova, M.Kläui, M.Jourdan, et al, Nat. Comm. (2018)

SP/CE

From prediction, to observation, to device in 1 one year!!

INSP/RE group
INTERDISCIPLINARY SPINTRONICS RESEARCH





Works like this but not done like this

Electrical read/write antiferromagnetic memory

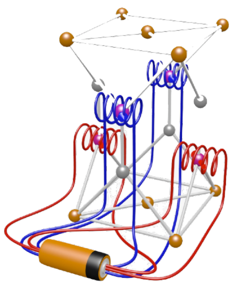
Wadley, Jungwirth et al. Science '16, Jungwirth, Marti, Wadley, Wunderlich, Nature Nanotech. '16

SP/CE

Topological antiferromagnetic spintronics and the crystal Hall effect

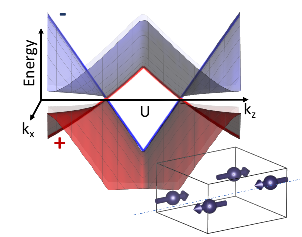
INSP/RE group
INTERDISCIPLINARY SPINTRONICS RESEARCH

I. Néel Spin-Orbit Torques in Antiferromagnets:



Zelezny, Gao, JS, Jungwirth PRL (2014)
Zelazny, Gao, et al. PRB (2016)
Bodnar, Smejkal, Jourdan, Kläui, Jungwirth, JS, et al, Nat. Com. (2018)

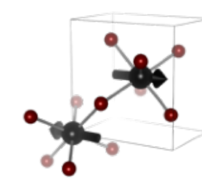
II. Topological Dirac Fermion + Antiferromagnets + Neel SOTs



Smejkal, Zelezny, Sinova, Jungwirth PRL (2017)
Smejkal, Jungwirth, Sinova PSS (2017)

III. AHE in collinear AFMs: Crystal Hall Effect

Jungwirth, JS, et al, Nature Physics (AFM spintronics Reviews) (2018)
Surprises of the Spin Hall Effect, Physics Today 70, 7, 38 (2017)
Smejkal, Gonzales, Jungwirth, JS, arXiv 1901.00445 (2019)

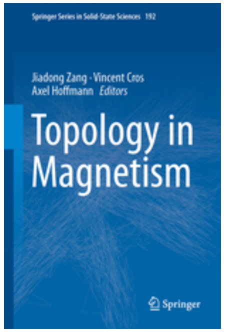


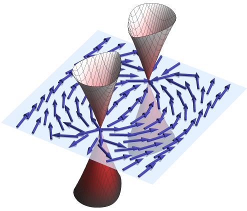
SP/CE

Can we control the relativistic fermions electrically?

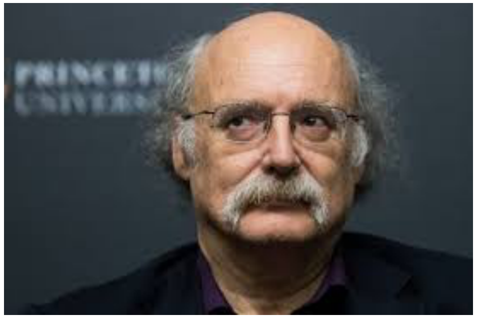
?

+





"Just knowing the correct laws of quantum mechanics does not mean that we understand all the strange phenomena that it allows"
Haldane, Nobel Lecture 2016



Libor Smejkal, Zelezny, Sinova, Jungwirth PRL (2017)

Can we control the relativistic fermions electrically?

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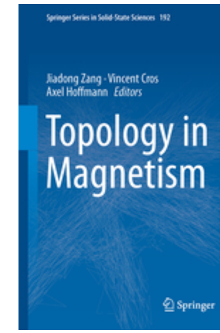
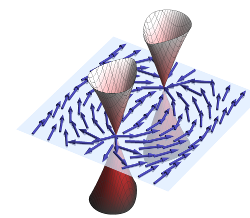
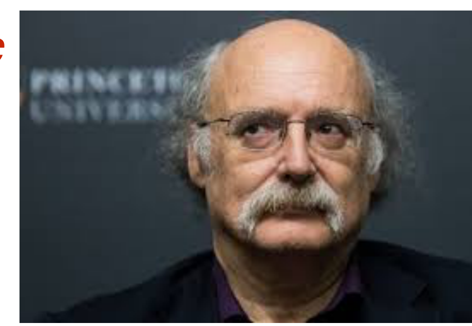
+



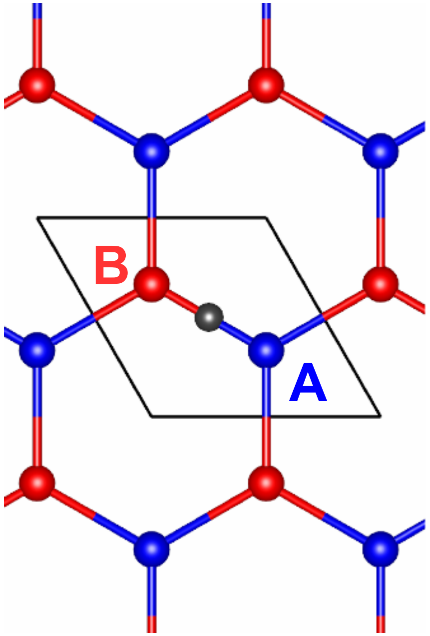


"Just knowing the correct laws of" ***relativistic*** *"quantum mechanics does not mean that we understand all the strange"* ***and useful*** *"phenomena that it allows"*



Libor Smejkal, Zelezny, Sinova, Jungwirth PRL (2017)

Model of AFM topological semimetal



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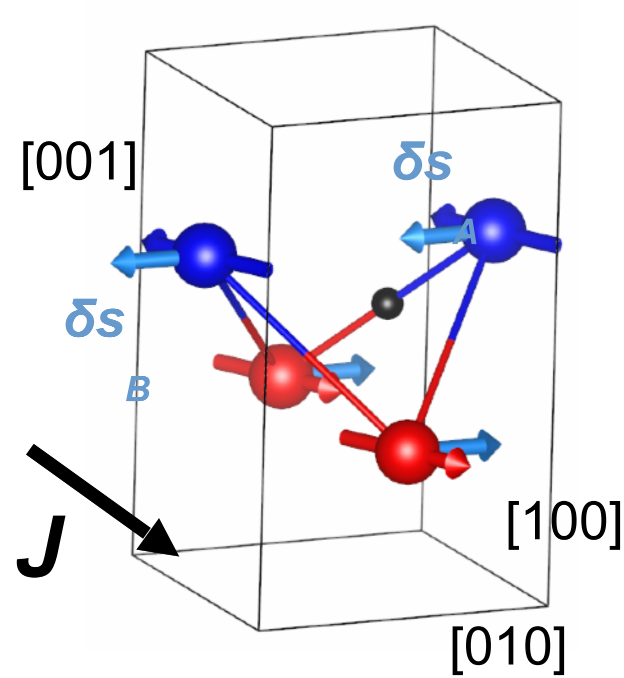
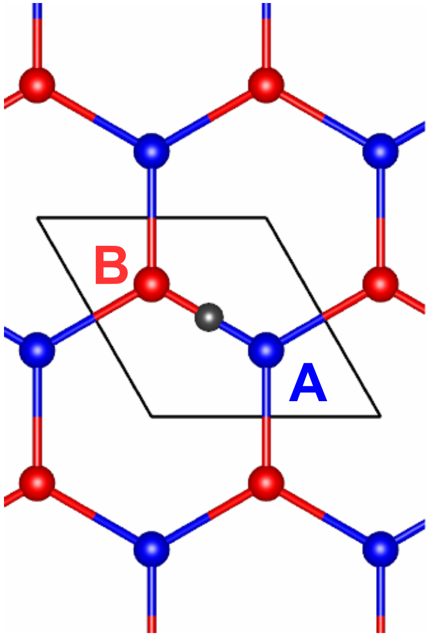
Dirac fermions + AF spintronics



Model of AFM topological semimetal

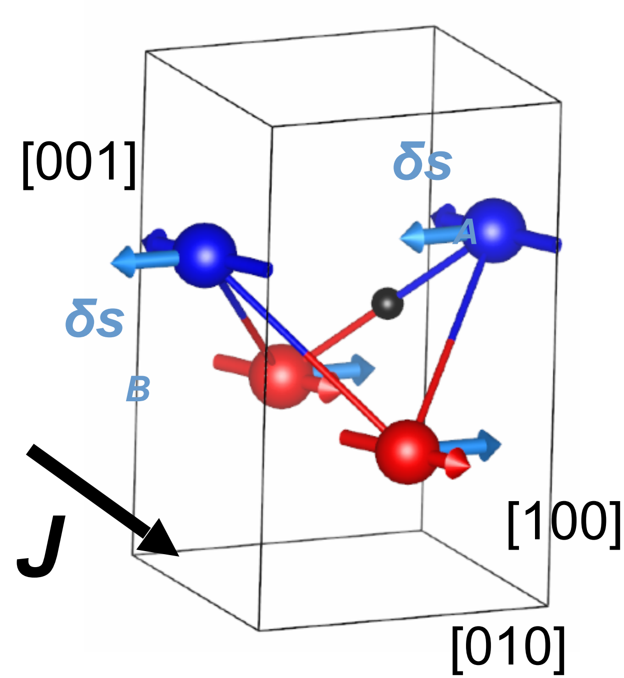


?

Dirac fermions + AF spintronics

YES!

Overlap of symmetry conditions



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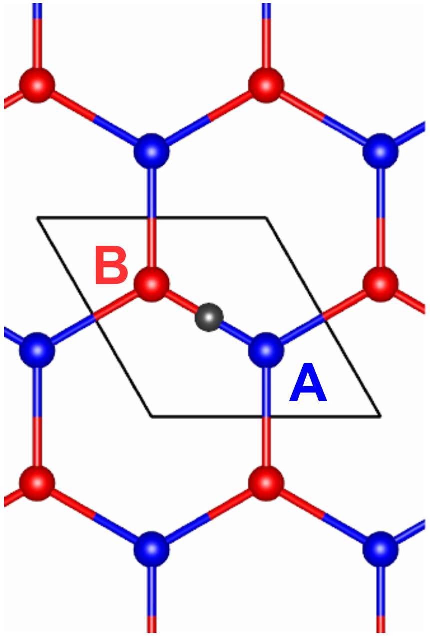


?

Dirac fermions + AF spintronics

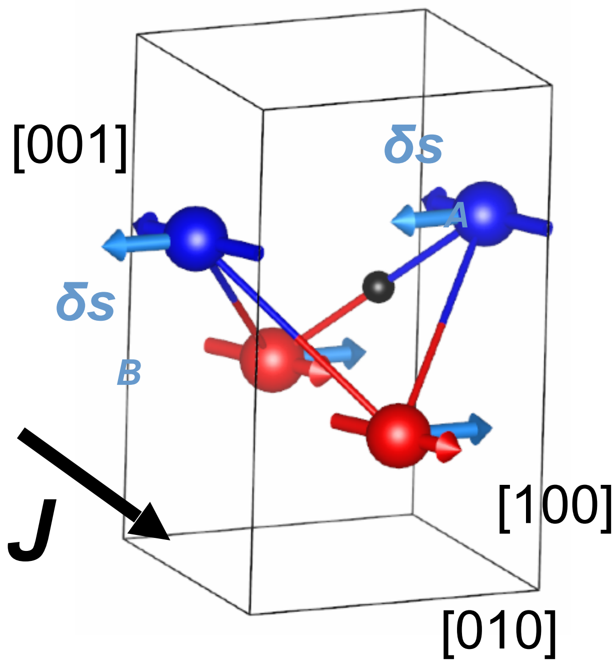
YES!

Overlap of symmetry conditions

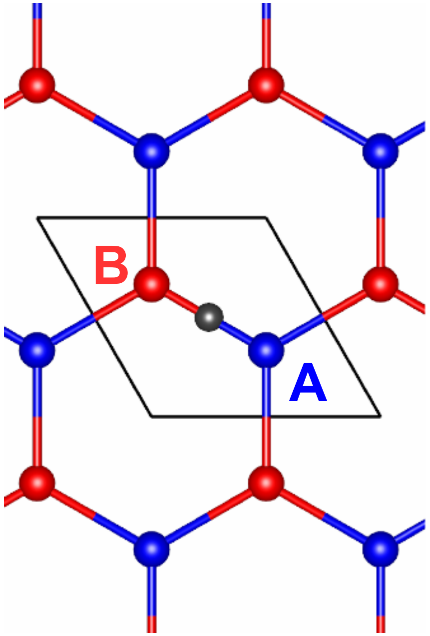
1. Two sites in unit cell

band crossing

inversion-partner sites → staggered field



Model of AFM topological semimetal



?
Dirac fermions + AF spintronics
YES!

Overlap of symmetry conditions

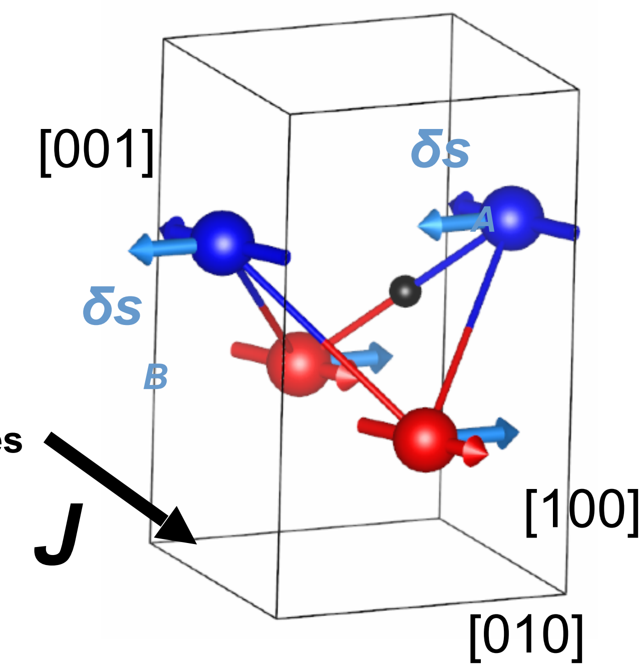
1. Two sites in unit cell

band crossing **inversion-partner sites → staggered field**

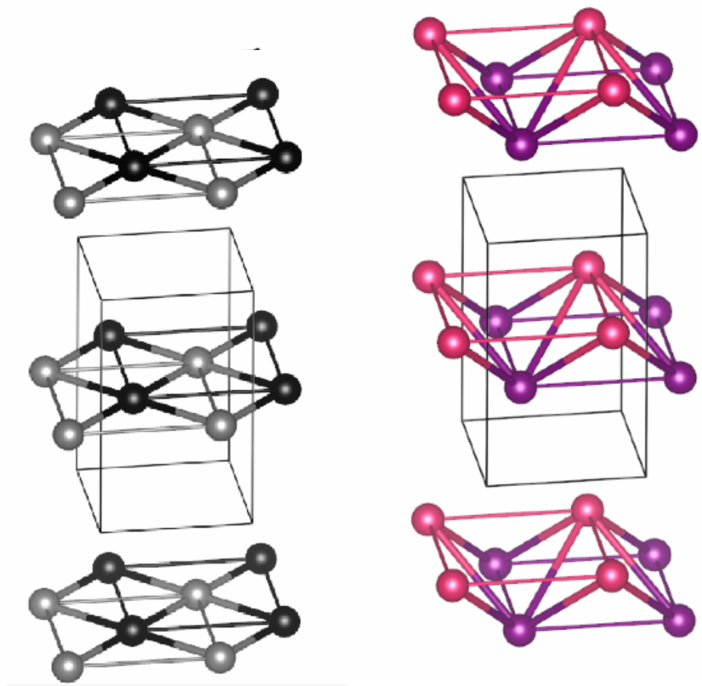
2. $\mathcal{PT}$ symmetry

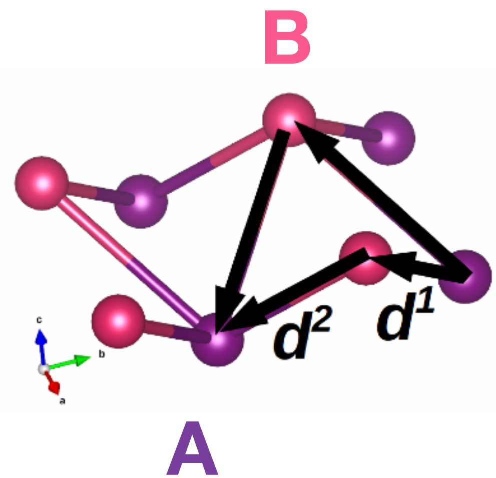
Double band degeneracy → Dirac point

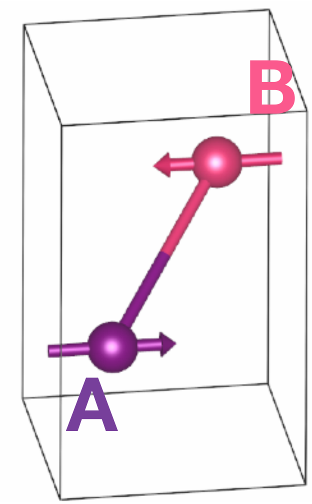
AF spin-sublattices at inversion partner sites



Minimal lattice model







$$\mathcal{H}_{\mathrm{SOC}}(r) = i \sum_{\langle\langle i,j \rangle\rangle, \langle k \rangle} \lambda_{ij} \hat{c}_i^\dagger \left(\mathbf{d}_{ik}^1 \times \mathbf{d}_{kj}^2 \right) \cdot \boldsymbol{\sigma} \hat{c}_j$$

$$\mathcal{H} = \sum_{\langle i,j \rangle, \langle\langle i,j \rangle\rangle} t_{ij} \hat{c}_i^\dagger \hat{c}_j + \sum_i J_i \hat{c}_i^\dagger \mathbf{n} \cdot \boldsymbol{\sigma} \hat{c}_i$$

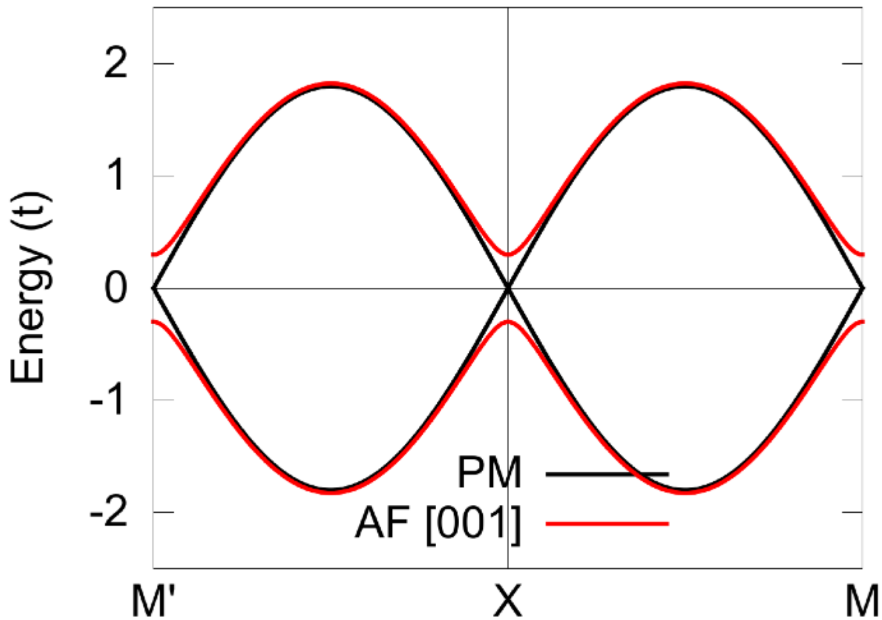
Kane-Mele spin-orbit coupling

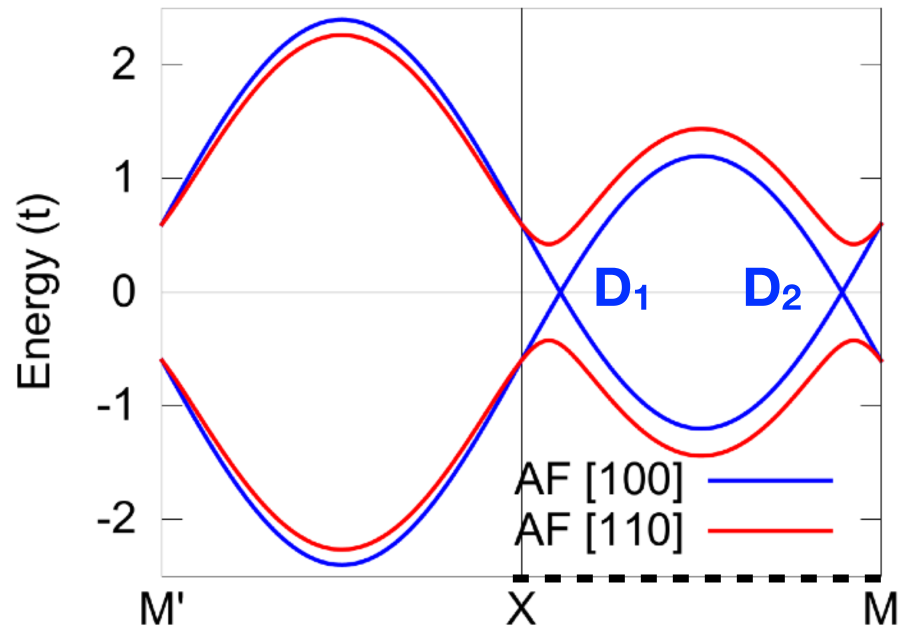
Young, Kane, Phys.Rev.Lett.(2015)

L.Smejkal, J.Zelezny, J.Sinova, and T.Jungwirt, Phys.Rev.Lett. (2017)

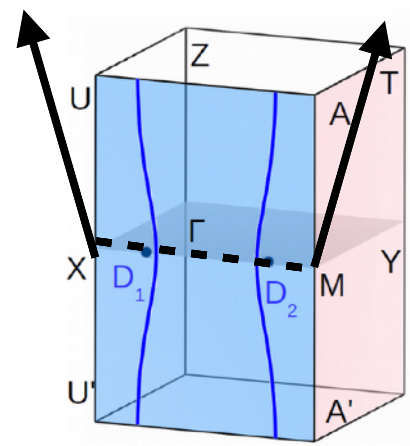
Minimal lattice model: band structure

Antiferromagnetic Dirac semimetal





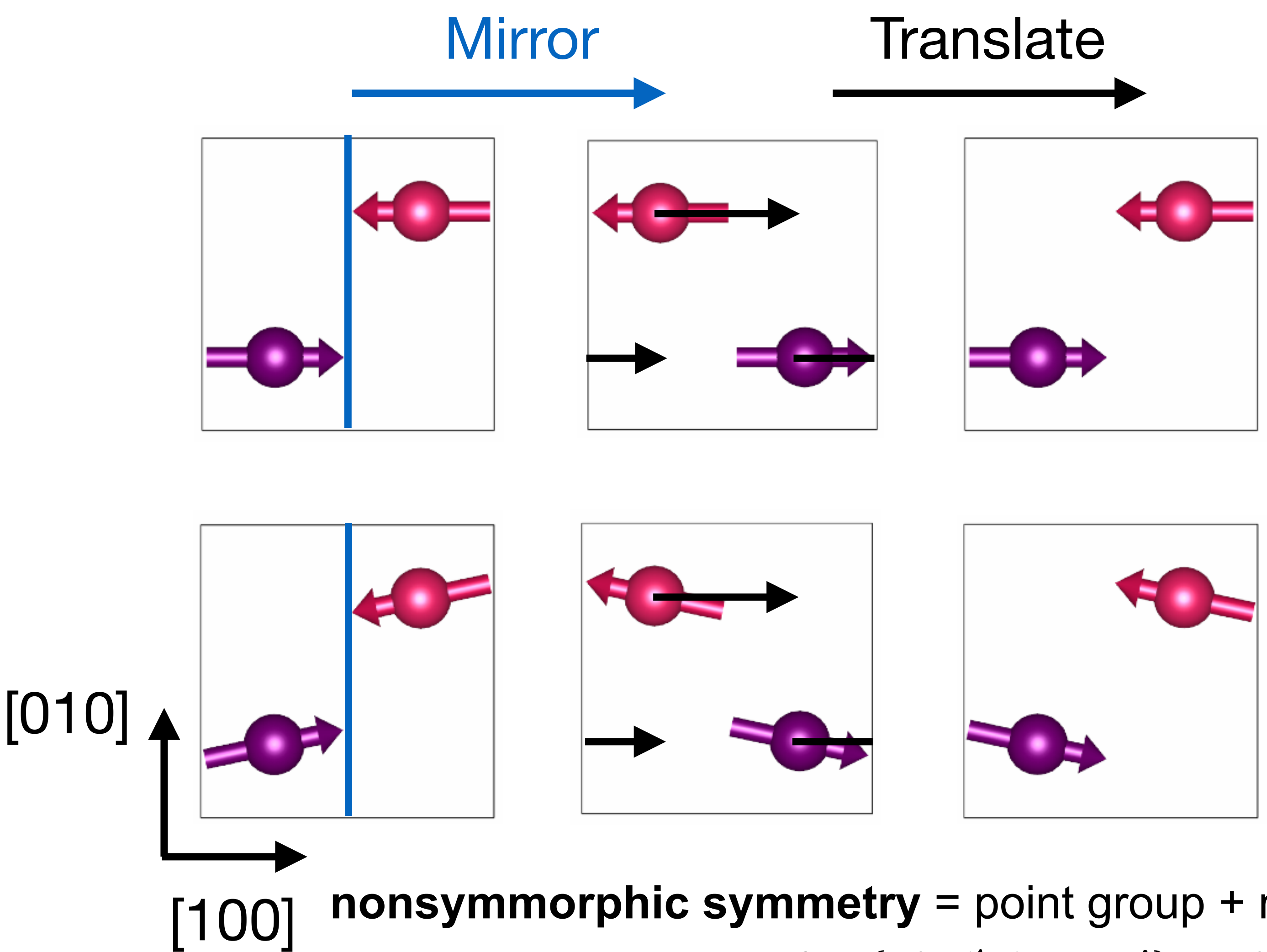
$$H_{\mathbf{k}} = -2t\tau_x \cos\frac{k_x}{2}\cos\frac{k_y}{2} - t'\left(\cos k_x + \cos k_y\right) + \lambda\tau_z\left(\sigma_y \sin k_x - \sigma_x \sin k_y\right) + \tau_z J_n \boldsymbol{\sigma}\cdot\mathbf{n}$$



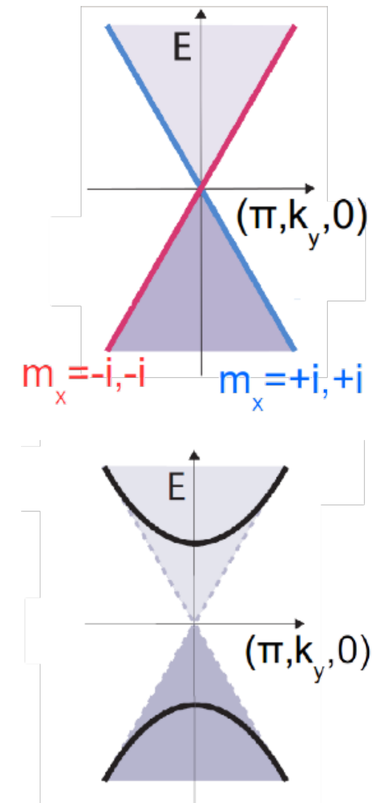
Renormalization: 2D Dirac points —> 3D nodal lines

L.Smejkal, J.Zelezny, JS, and T.Jungwirt, Phys.Rev.Lett. (2017)

Symmetry protection of Dirac points



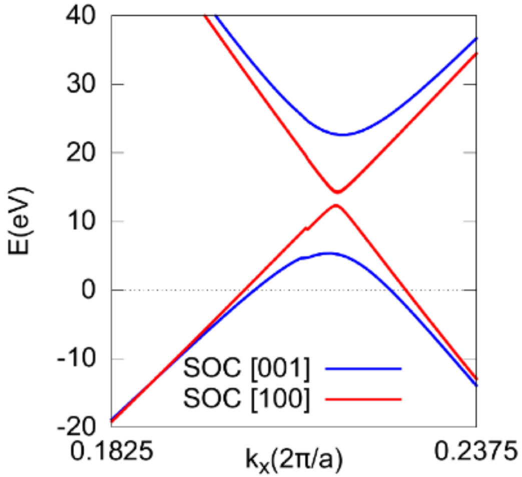
at $\mathcal{G}_x$ invariant subspace

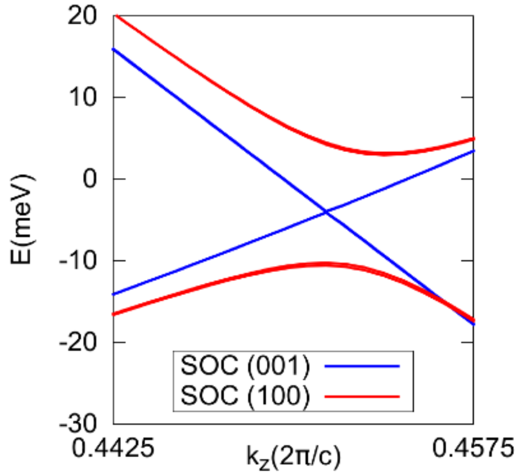


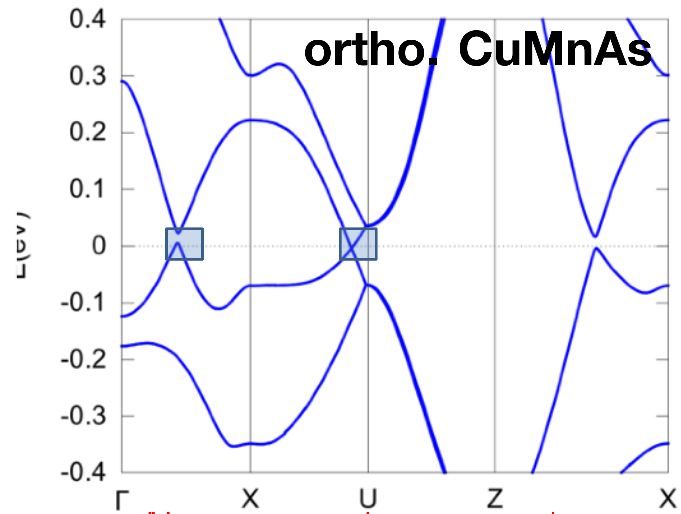
nonsymmorphic symmetry = point group + nontrivial translation

glide mirror plane $\mathcal{G}_x = \{M_x/(1/2,0,0)\}$ $M_x = i\sigma_x\tau_z$

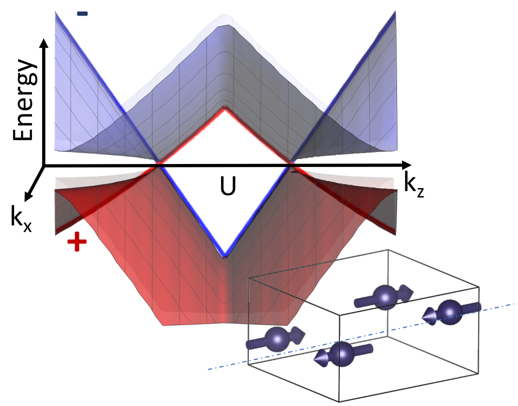
Electrical control of Dirac fermions



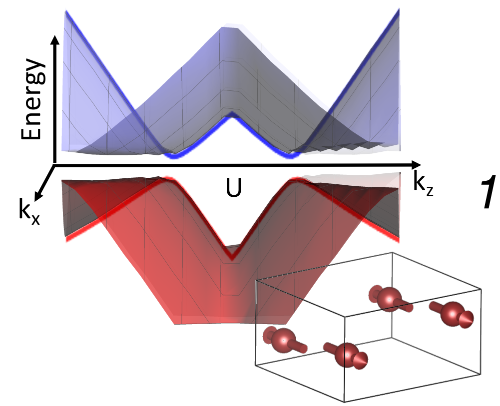




Nonsymmorphic symmetry:
Screw axis+Glide plane



[001] Pn’m’a’ $\left\{C_{2z}|\left(\frac{1}{2},0,\frac{1}{2}\right)\right\}$

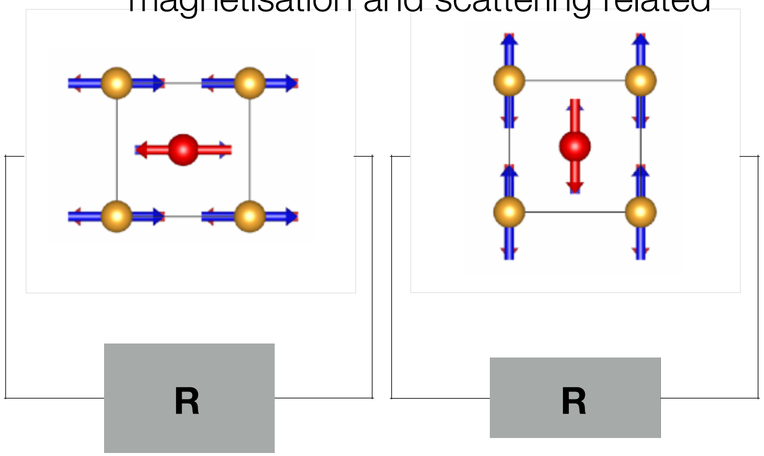


10 meV

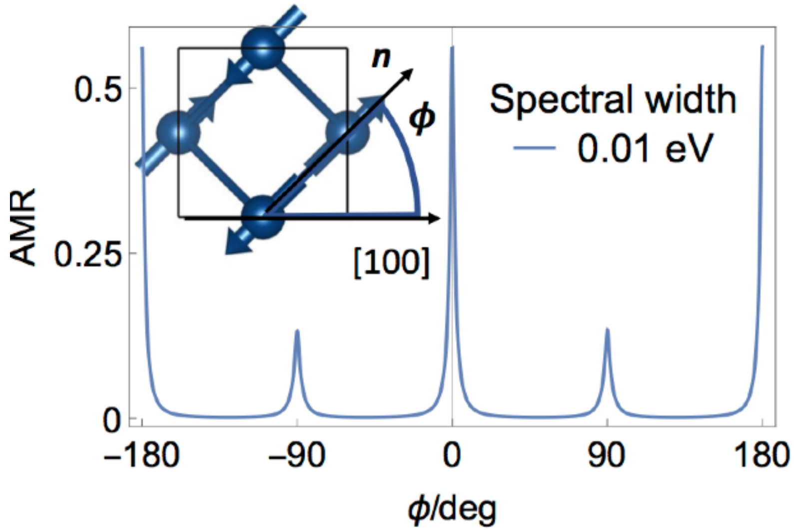
[100] Pnm’a $\left\{C_{2z}|\cancel{\left(\frac{1}{2},0,\frac{1}{2}\right)}\right\}$

Topological anisotropic magnetoresistance

Anisotropic magnetoresistance is even in magnetisation and scattering related



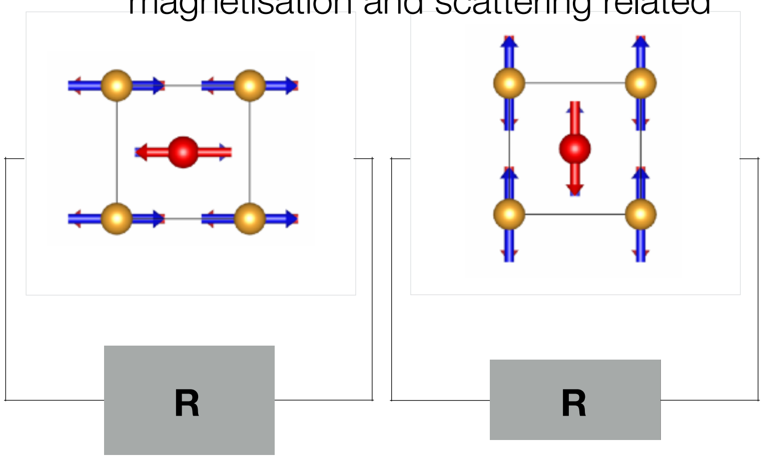
Marti, Jungwirth et al. Nat.Mat.(2014)



$$\Lambda_{100} \equiv \frac{\rho_{L,100}(\phi=0)-\rho_{L,100}(\phi=90^\circ)}{\overline{\rho}}$$

Topological anisotropic magnetoresistance

Anisotropic magnetoresistance is even in magnetisation and scattering related



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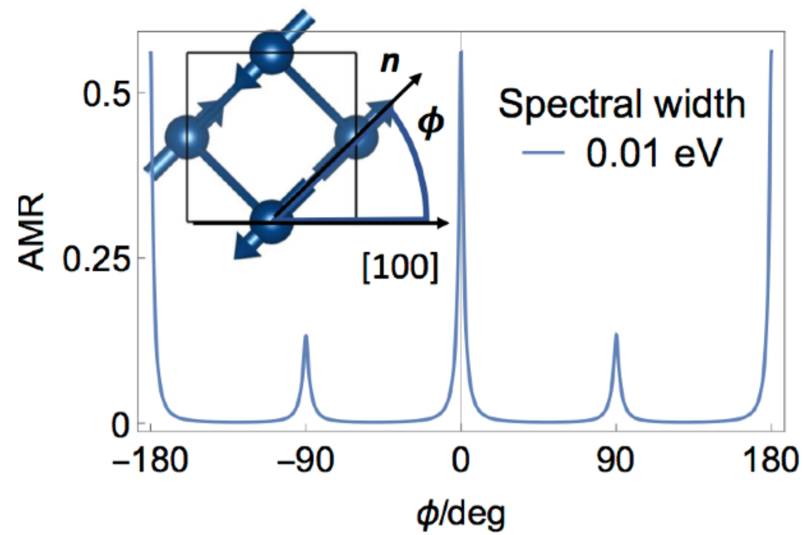
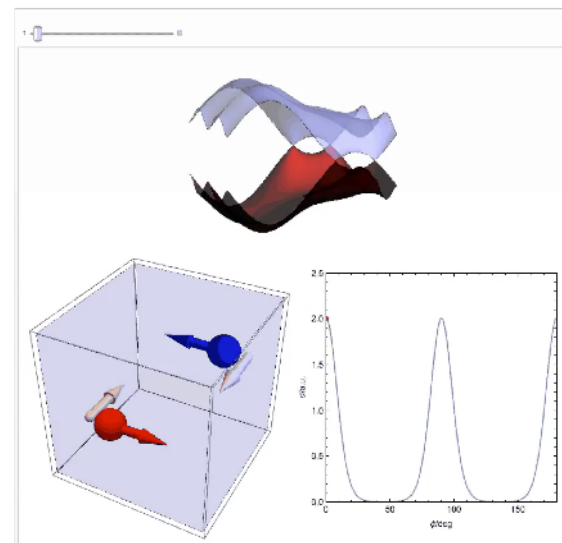
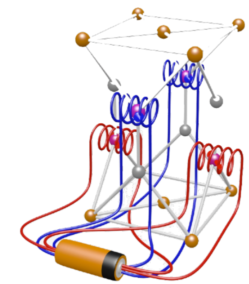




Topological antiferromagnetic spintronics and the crystal Hall effect

INSP/RE group
INTERDISCIPLINARY SPINTRONICS RESEARCH

I. Néel Spin-Orbit Torques in Antiferromagnets:



Zelezny, Gao, JS, Jungwirth PRL (2014)
Zelazny, Gao, et al. PRB (2016)
Bodnar, Smejkal, Jourdan, Kläui, Jungwirth, JS, et al, Nat. Com. (2018)

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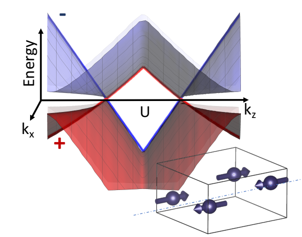

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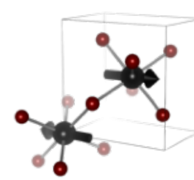
III. AHE in collinear AFMs: Crystal Hall Effect

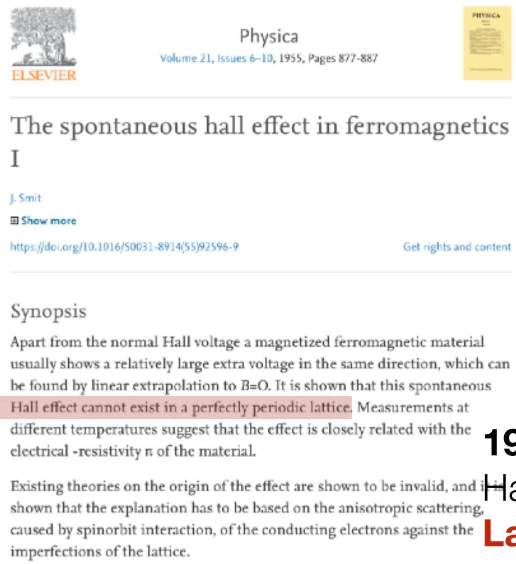


Jungwirth, JS, et al, Nature Physics (AFM spintronics Reviews) (2018)
Surprises of the Spin Hall Effect, Physics Today 70, 7, 38 (2017)
Smejkal, Gonzales, Jungwirth, JS, arXiv 1901.00445 (2019)

SP/CE

INSP/RE group
INTERDISCIPLINARY SPINTRONICS RESEARCH

Spontaneous Hall effect without complicated antiferromagnetic order?


Physica
Volume 21, Issues 6–10, 1955, Pages 877-887

The spontaneous hall effect in ferromagnetics I

J. Smit

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https://doi.org/10.1016/S0031-8914(55)92596-9

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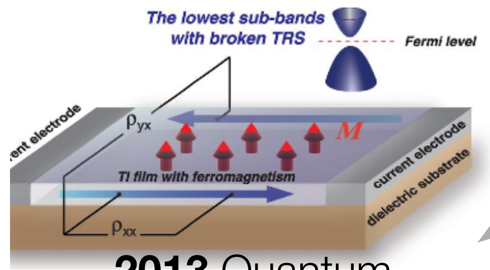
Synopsis

Apart from the normal Hall voltage a magnetized ferromagnetic material usually shows a relatively large extra voltage in the same direction, which can be found by linear extrapolation to B=O. It is shown that this spontaneous Hall effect cannot exist in a perfectly periodic lattice. Measurements at different temperatures suggest that the effect is closely related with the electrical -resistivity π of the material.

Existing theories on the origin of the effect are shown to be invalid, and it is shown that the explanation has to be based on the anisotropic scattering, caused by spinorbit interaction, of the conducting electrons against the imperfections of the lattice.



2013 Quantum anomalous Hall in topological insulators

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

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

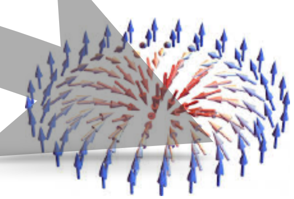
2002 Berry curvature - **topological properties of wave functions**

1980 Quantum Hall effect

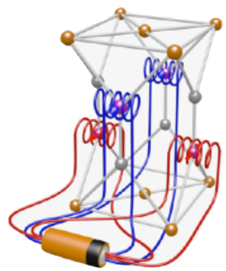
1879 Hall effect from field
1881 Hall effect from magnetisation

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

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

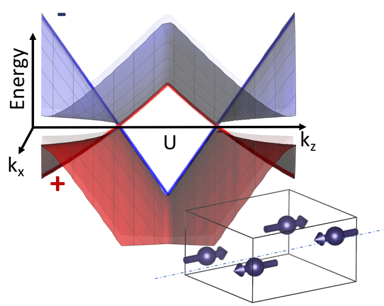


Symmetry considerations of AFM spintronics



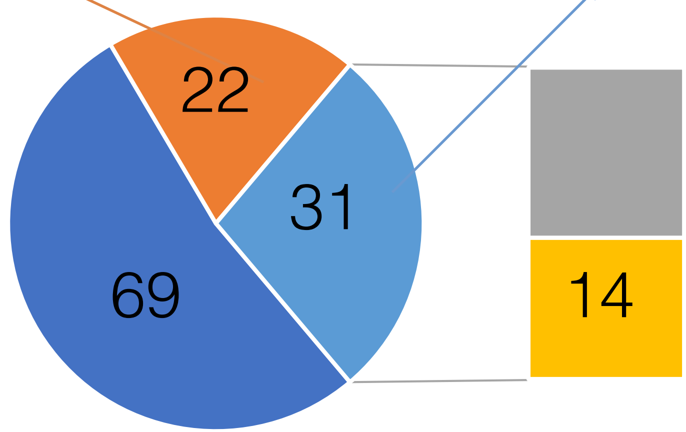
magnetic symmetries: 122/1651

Dirac antiferromagnets



Šmejkal, Zelezny, JS, TJ, Phys.Rev.Lett. (2017)

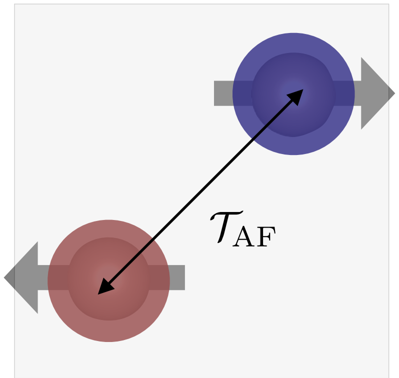
Spontaneous Hall antiferromagnets



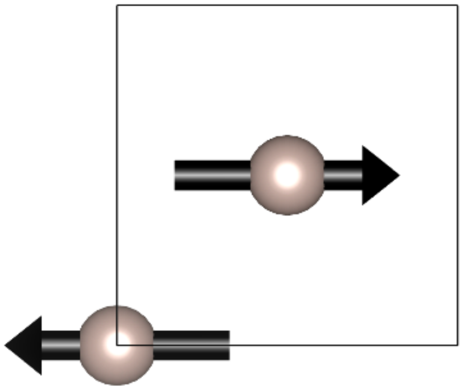
collinear antiferromagnets

Spontaneous Hall effect from collinear AFM

spin degenerate bands
(IrMn,CuMnAs,Mn_2Au, …)



LŠ, J.Železny, JS, TJ, Phys.Rev.Lett. (2017)



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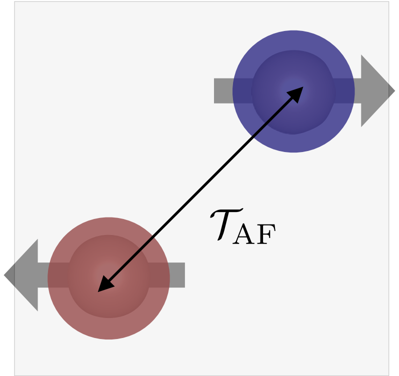
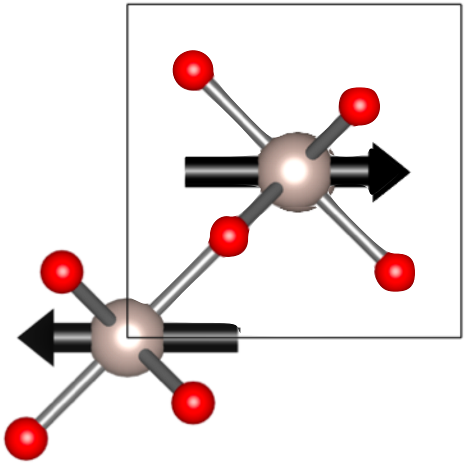


LŠ, J.Železny, JS, TJ, Phys.Rev.Lett. (2017)



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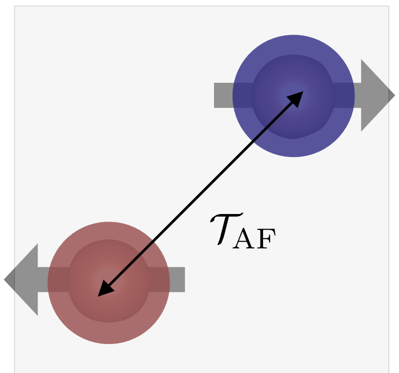
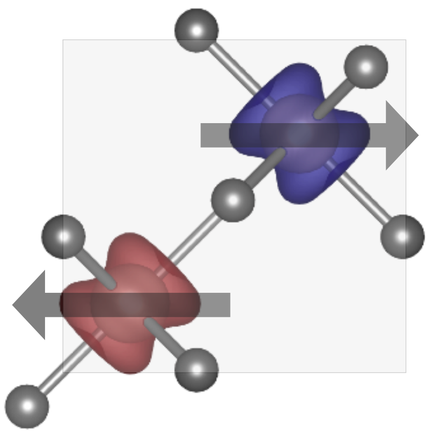
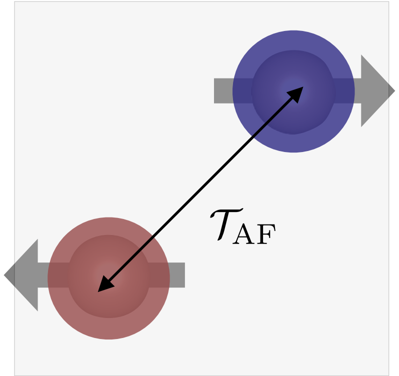


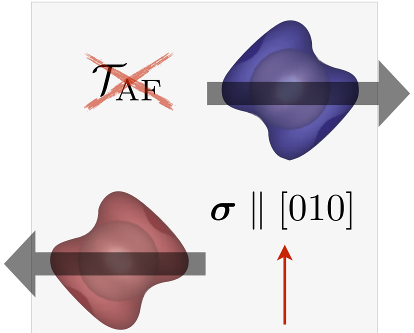


LŠ, J.Železny, JS, TJ, Phys.Rev.Lett. (2017)

Spontaneous Hall effect from collinear AFM

spin degenerate bands
(IrMn,CuMnAs,Mn_2Au, …)

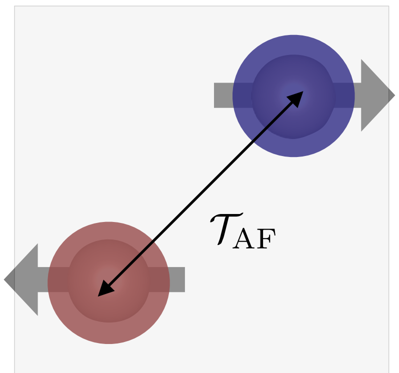




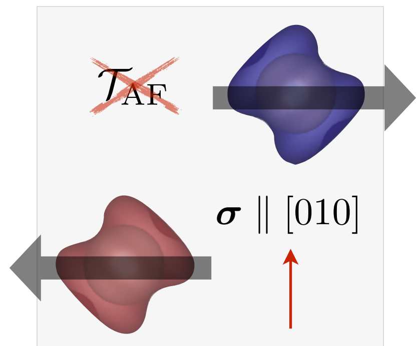
LŠ, J.Železny, JS, TJ, Phys.Rev.Lett. (2017)

spin degenerate bands
(IrMn,CuMnAs,Mn_2Au, …)

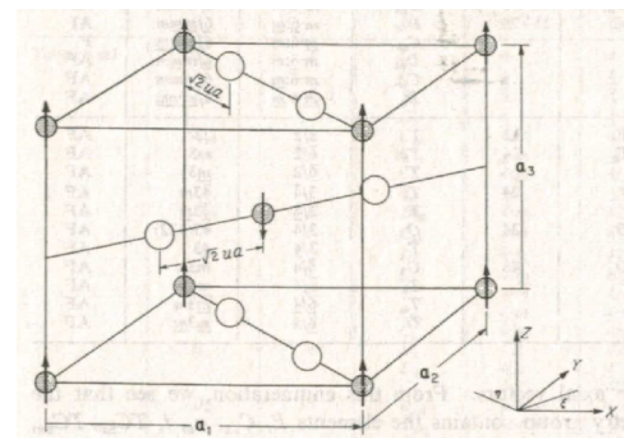
Magnetisation density spontaneously breaks symmetries and allows Hall vector! (RuO_2, …)



LŠ, J.Železny, JS, TJ, Phys.Rev.Lett. (2017)



LŠ, R.H.Gonzales, JS, TJ, arXiv 1901.00445 (2019)



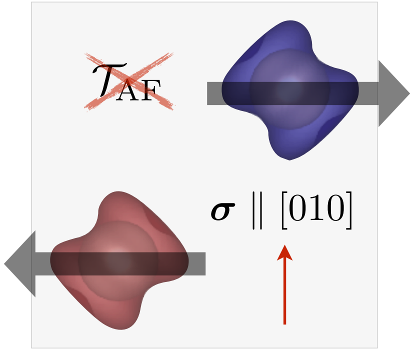
Notorious antiferromagnets

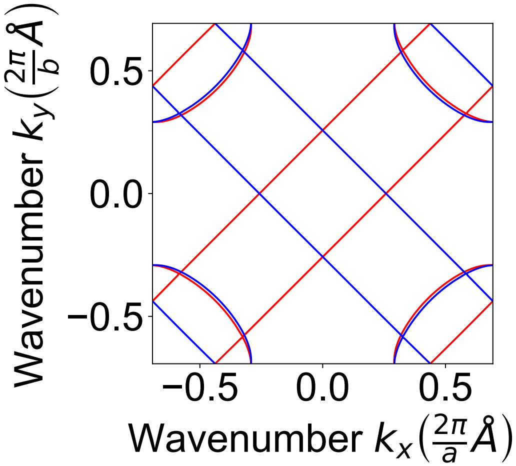
Bradley & Cracknell, The Mathematical Theory of Symmetry in Solids (1972)

Tinkham, Group theory and quantum mechanics (1964)

Analysing magnetisation projection vectors (black arrows) is incomplete!
Landau, Lifshitz, Electrodynamics of Continuous Media (1972)

Spontaneous symmetry breaking is strong already without SOC!





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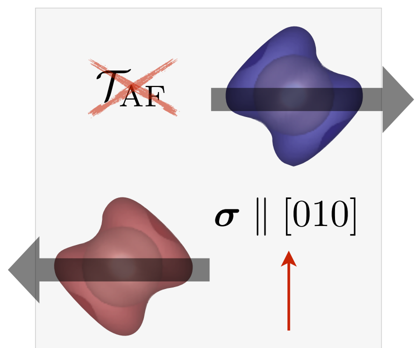

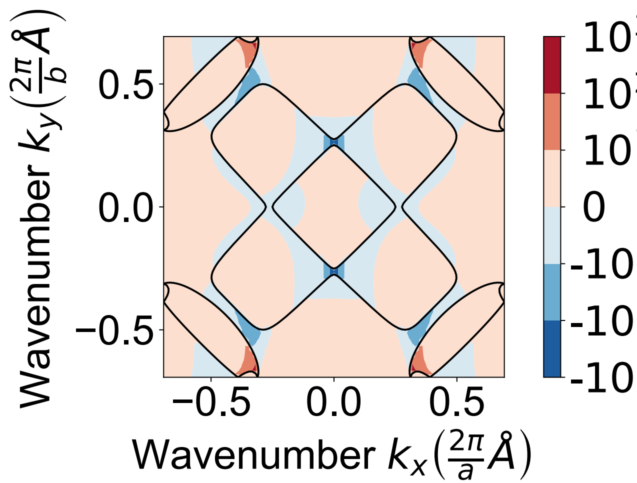

LŠ, R.H.Gonzales, JS, TJ, arXiv 1901.00445 (2019)

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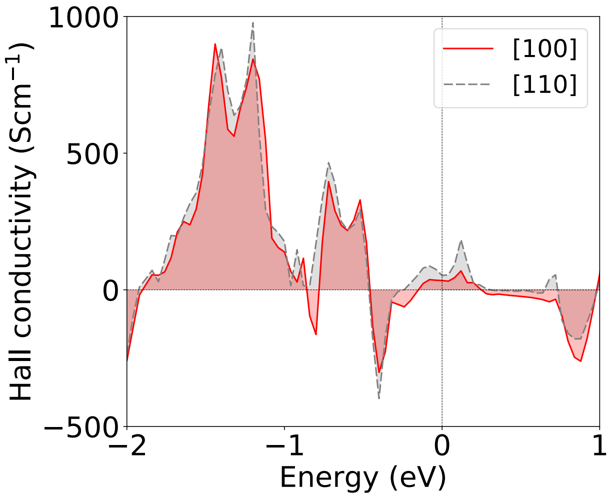
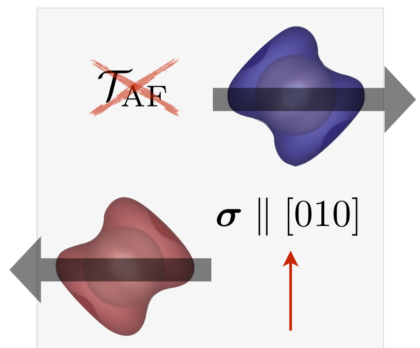
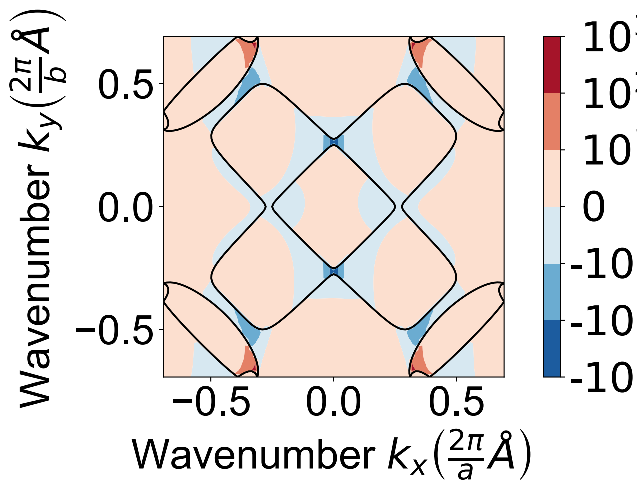


$$\sigma_{xy} = \frac{e^2}{h} \int_{BZ} \frac{d\mathbf{k}}{(2\pi)^3} \sum_n f(\mathbf{k}) b_z^n(\mathbf{k})$$





LŠ, R.H.Gonzales, JS, TJ, arXiv 1901.00445 (2019)

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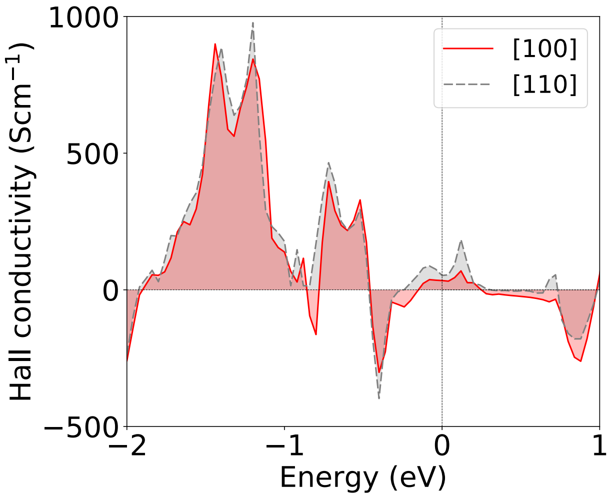

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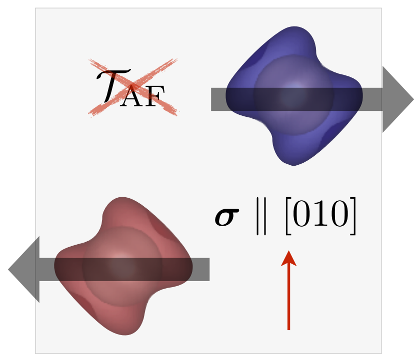
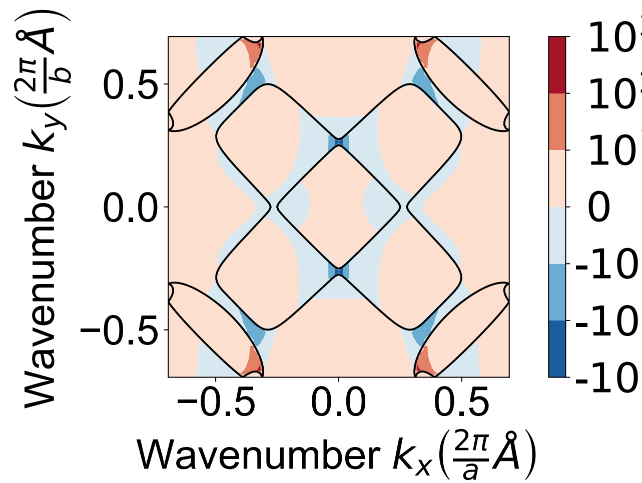
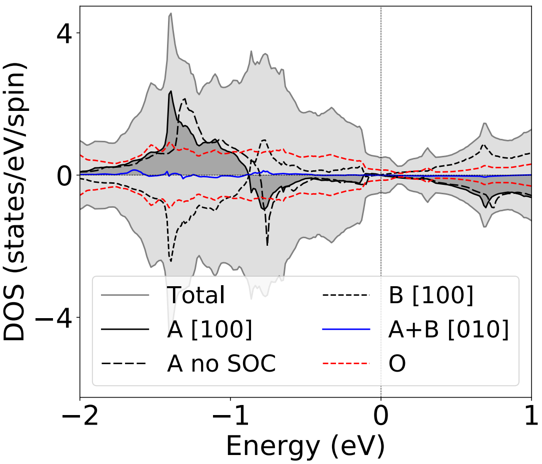




LŠ, R.H.Gonzales, JS, TJ, arXiv 1901.00445 (2019)

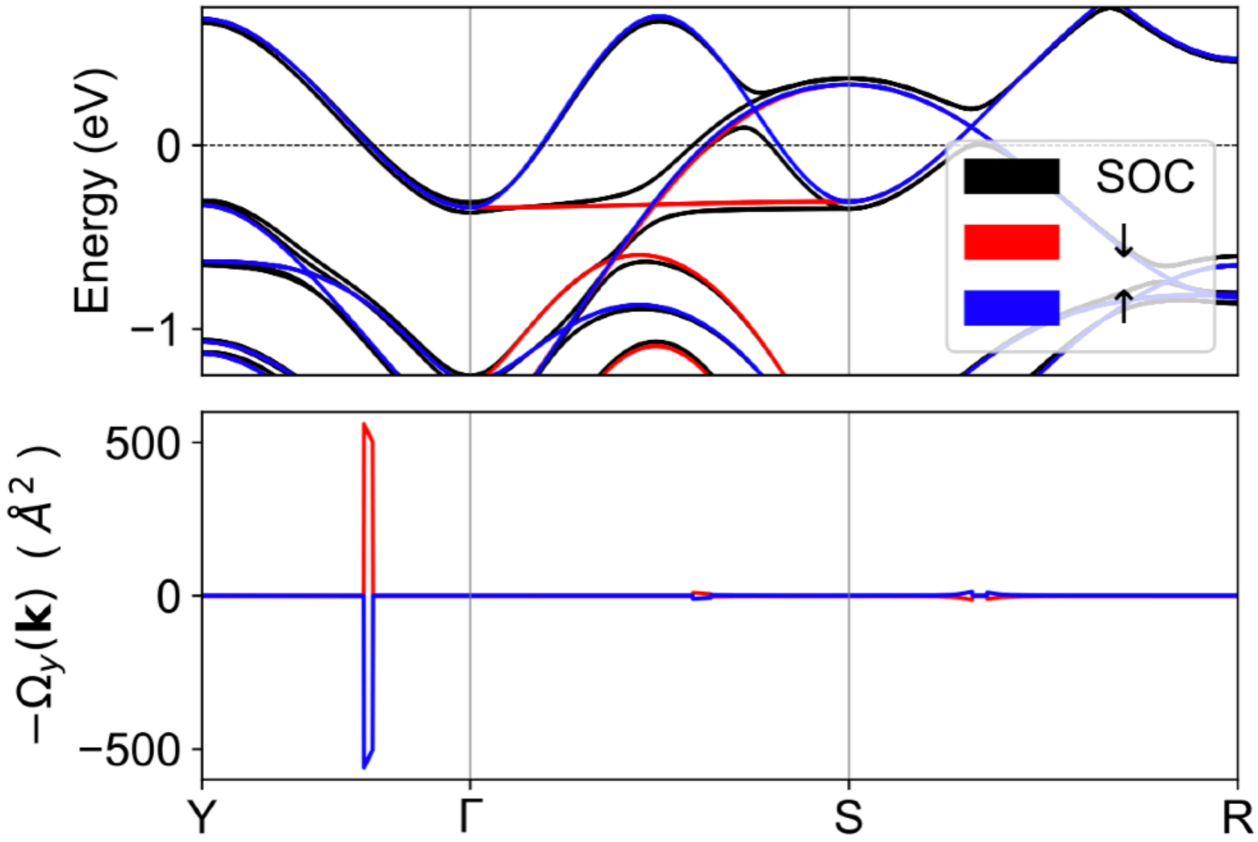
Magnitude can be as large as record values in ferromagnets

Spontaneous symmetry breaking

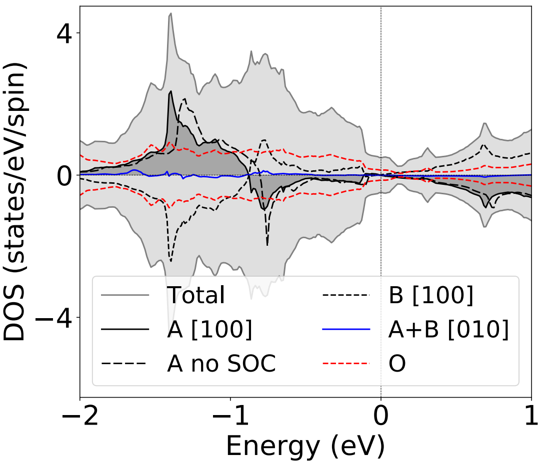


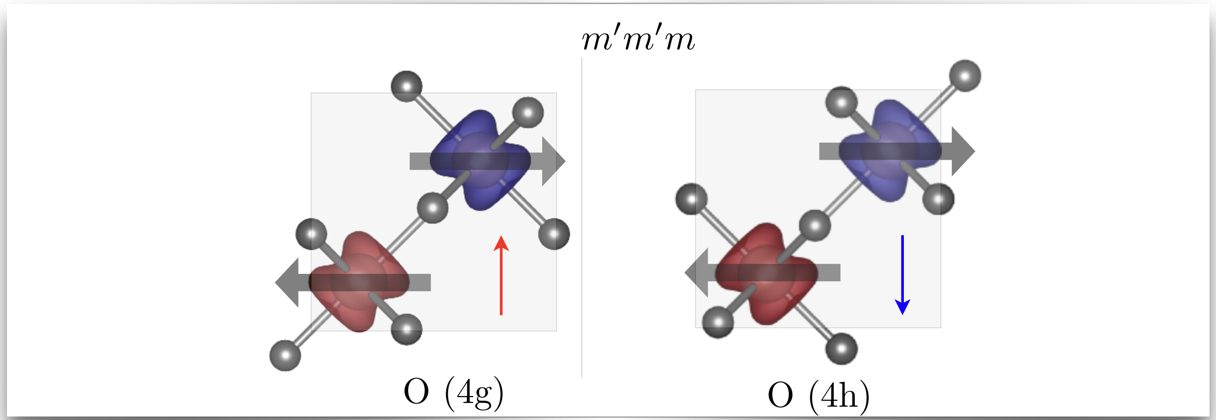
Correlations stabilise antiferromagnetism

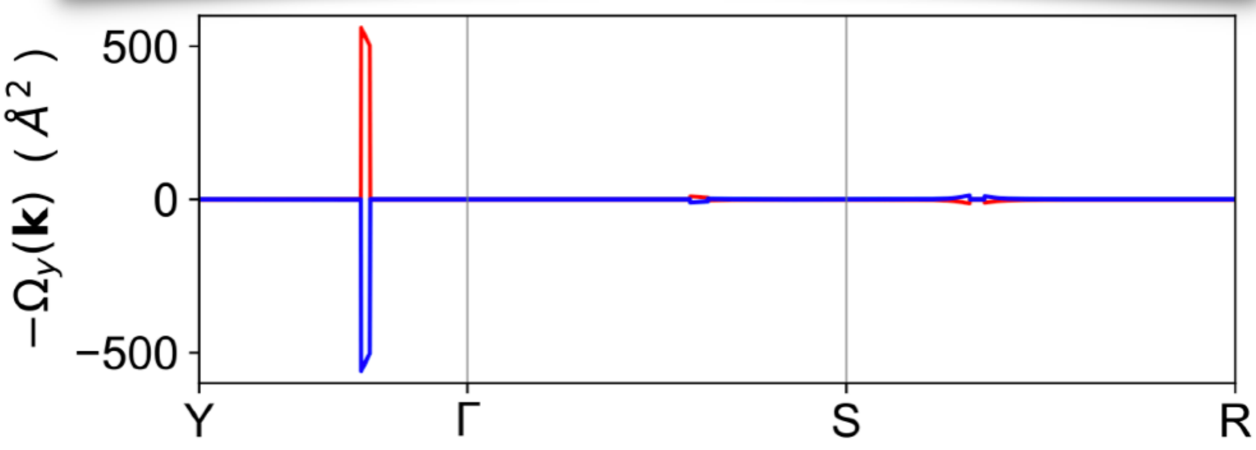
Berlijn et al., Phys. Rev. Lett. (2017)



Spontaneous symmetry breaking



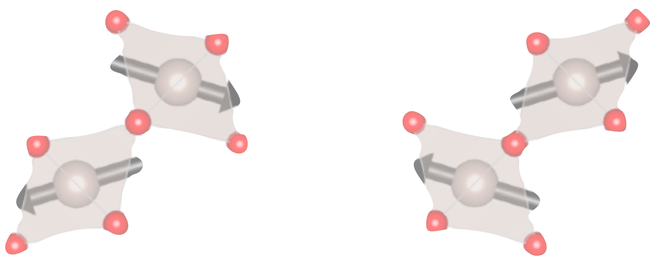




Correlations stabilise antiferromagnetism

Berlijn et al., Phys. Rev. Lett. (2017)

Crystal Hall .VS. anomalous Hall from canting



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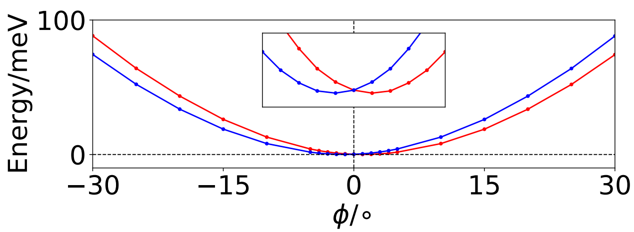

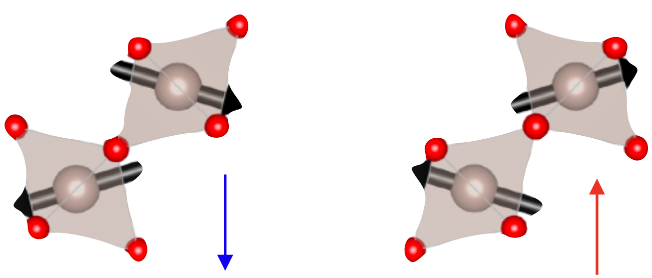

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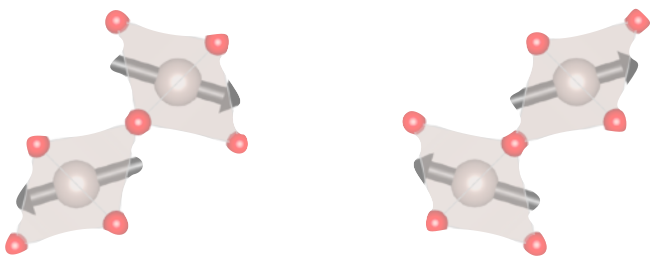
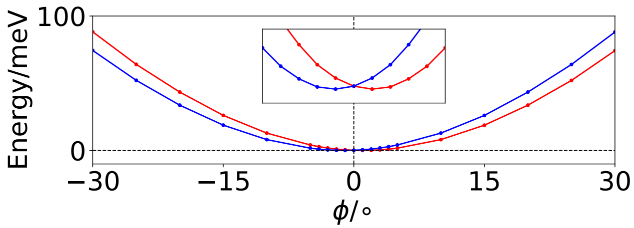
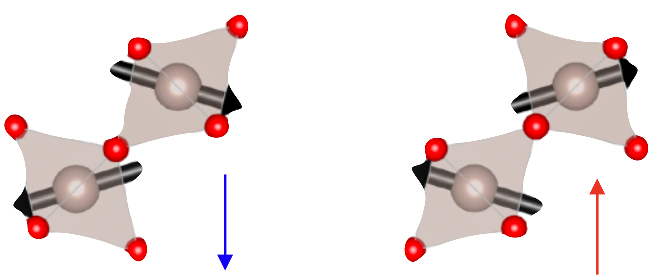
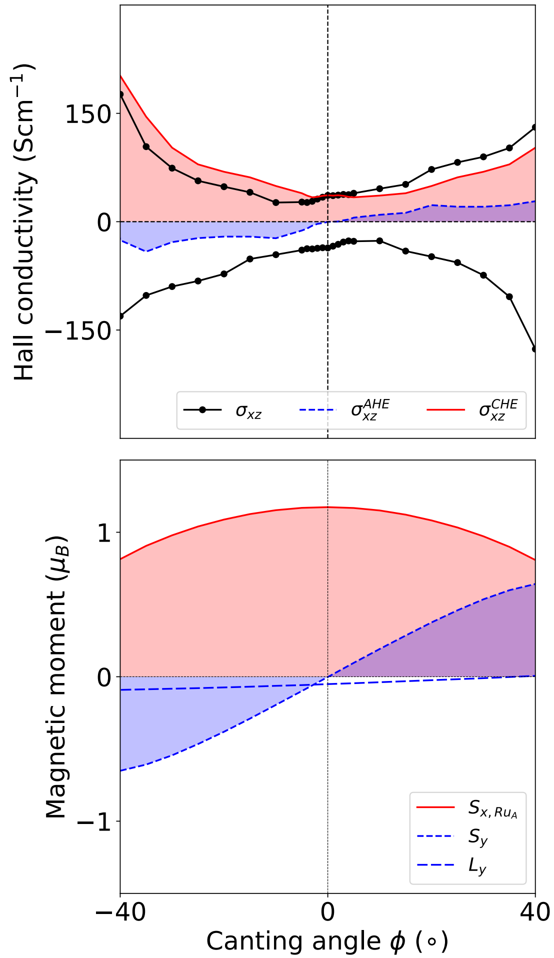






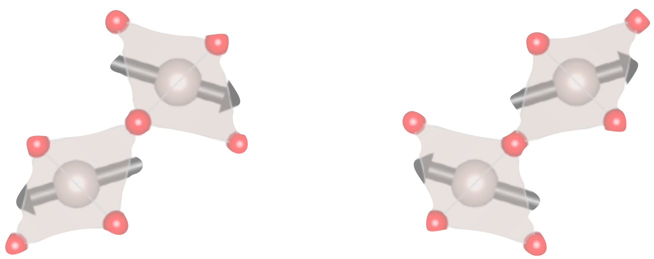


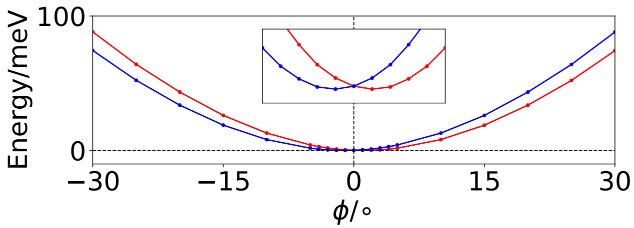
$$\sigma_{xz}^{\mathrm{CH}} = \frac{\sigma_{xz}(\mathbf{n},\mathbf{m}) + \sigma_{xz}(\mathbf{n},\textbf{-m})}{2}$$

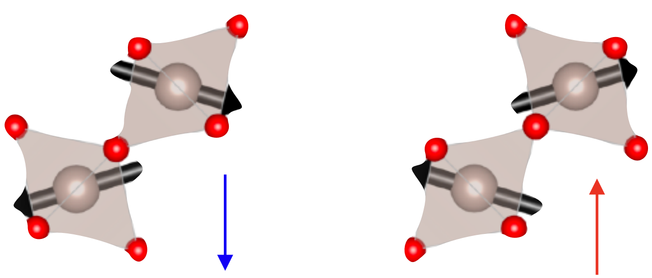
$$\sigma_{xz}^{\mathrm{AH}} = \frac{\sigma_{xz}(\mathbf{n},\mathbf{m}) - \sigma_{xz}(\mathbf{n},\textbf{-m})}{2}$$

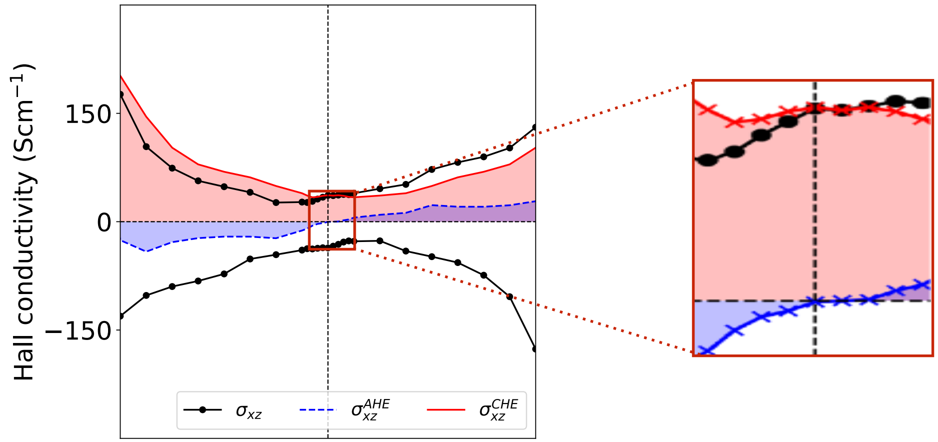
$$\sigma_{xz}(\mathbf{n},\mathbf{m}) = -\sigma_{xz}(-\mathbf{n},\textbf{-m})$$

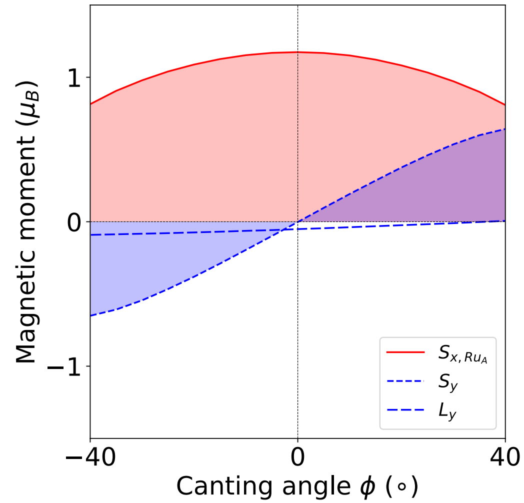
Crystal Hall .VS. anomalous Hall from canting











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Anisotropic Crystal Hall effect

$\mathbf{n}$	MSG	$\mathbf{m}$ (μ_B)	σ_H (Scm^{-1})
[001]	$P4_2'/mnm'$	0	0
[100]	$Pnn'm'$	$\parallel$ [010] 0.05	36
[110]	$Cmm'm'$	$\parallel$ $[\bar{1}10]$ 0.0075	58

Anisotropic Crystal Hall effect

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Anisotropic Crystal Hall effect

INSP/RE group
INTERDISCIPLINARY SPINTRONICS RESEARCH

$\mathbf{n}$	MSG	$\mathbf{m}$ (μ_B)	σ_{H} (Scm^{-1})
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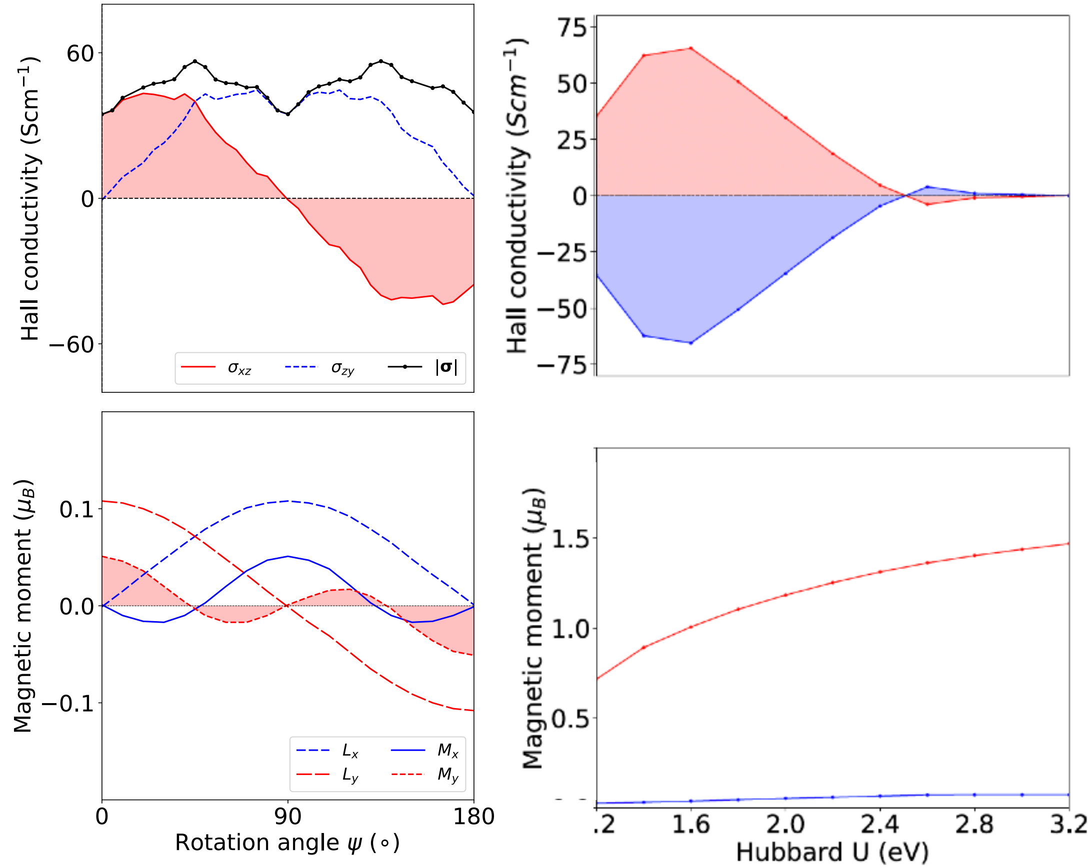
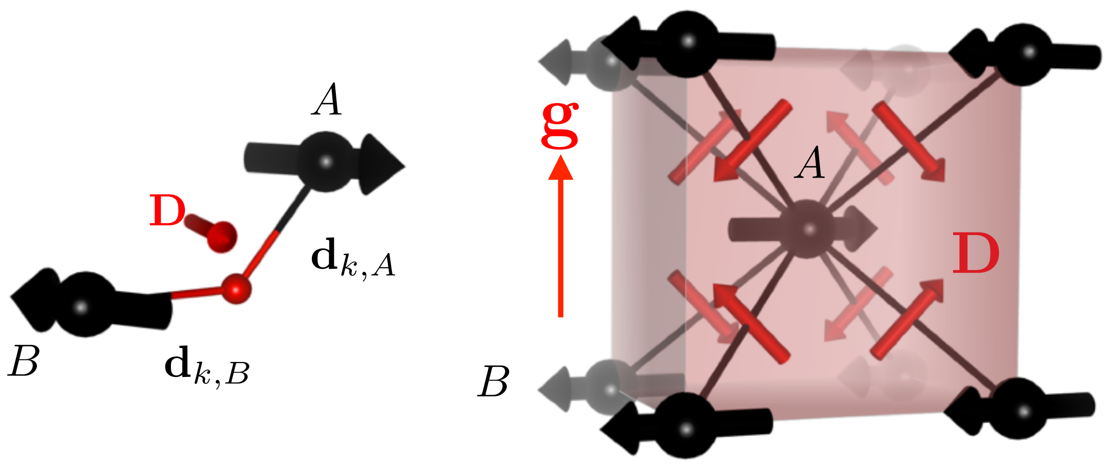
[110]	$Cmm'm'$	$\parallel$ $[1\bar{1}0]$ 0.0075	58

Hall vector is not proportional to Sublattice magnetisation Net magnetisation

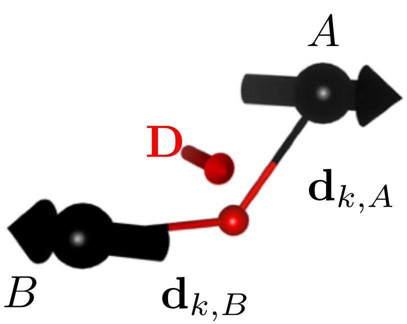


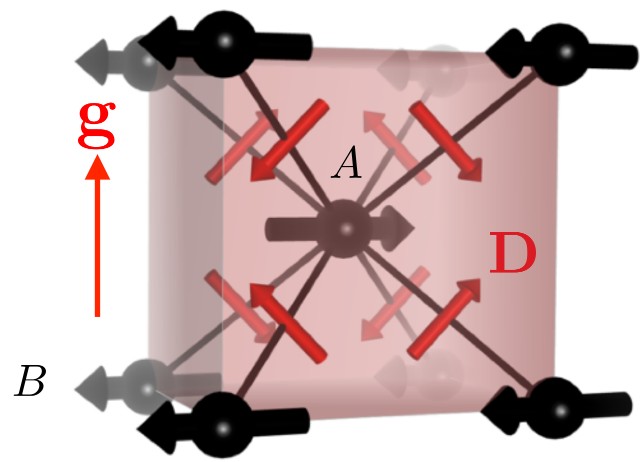


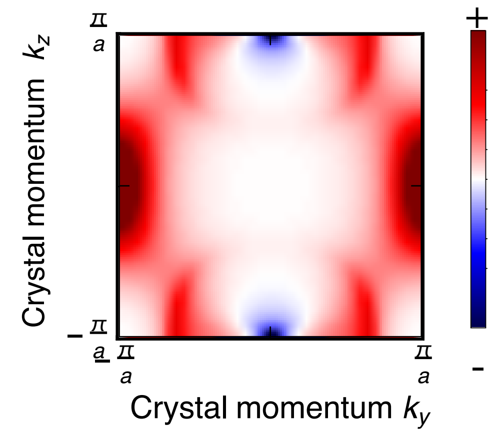
$$H = t\sum_{ij} c_i^\dagger c_j + J_n \sum_i \mathbf{u}_i \cdot \mathbf{s} c_i^\dagger c_i + \boxed{\lambda \sum_{ij,k} \mathbf{D}_{ij}^k \cdot \mathbf{s} c_i^\dagger c_j}$$

asymmetric spin-orbit coupling

AFM minimal model: crystal chirality and topology







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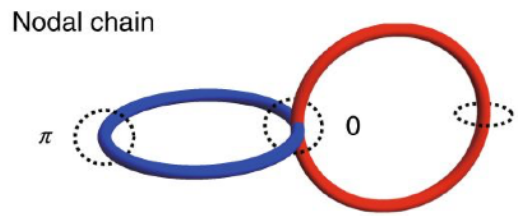
$$H_{\mathbf{k}} = -4t\tau_x \cos\frac{k_x}{2}\cos\frac{k_y}{2}\cos\frac{k_z}{2} + \tau_z J_n \boldsymbol{\sigma}\cdot\mathbf{n} + \boxed{4i\lambda \sin\frac{k_z}{2}\left[\sigma_{xy}^{(-)}\sin\frac{k_x+k_y}{2} + \sigma_{xy}^{(+)}\sin\frac{k_x-k_y}{2}\right]}$$

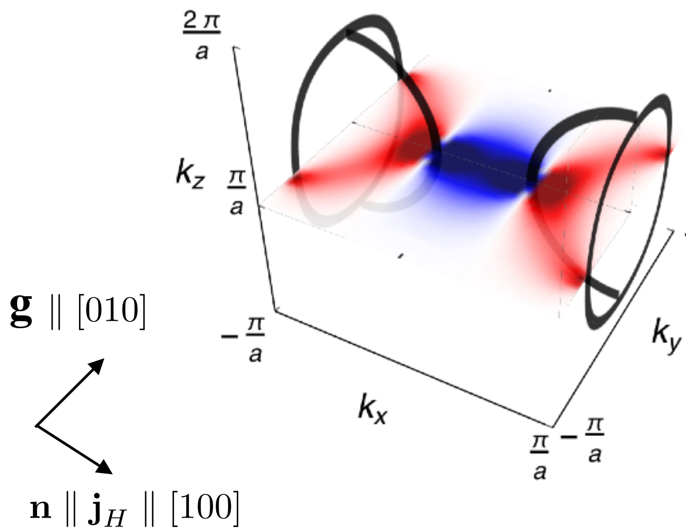
asymmetric spin-orbit coupling

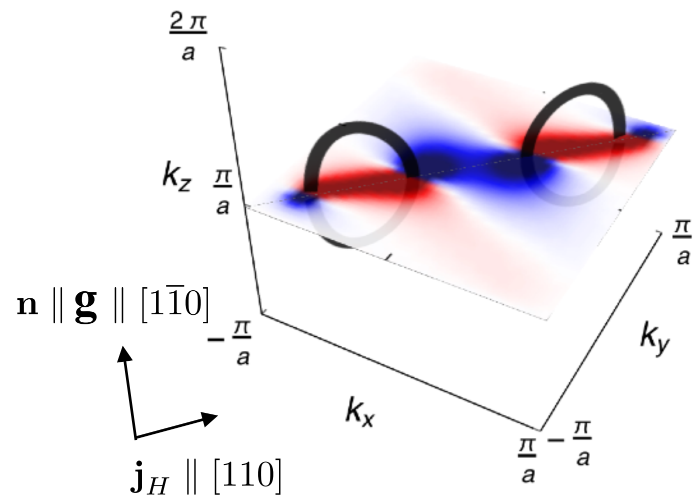
Antiferromagnetic nodal chain metals

Bzdusek et al., Nature (2016)
Yan et al., Nat. Phys. (2018)



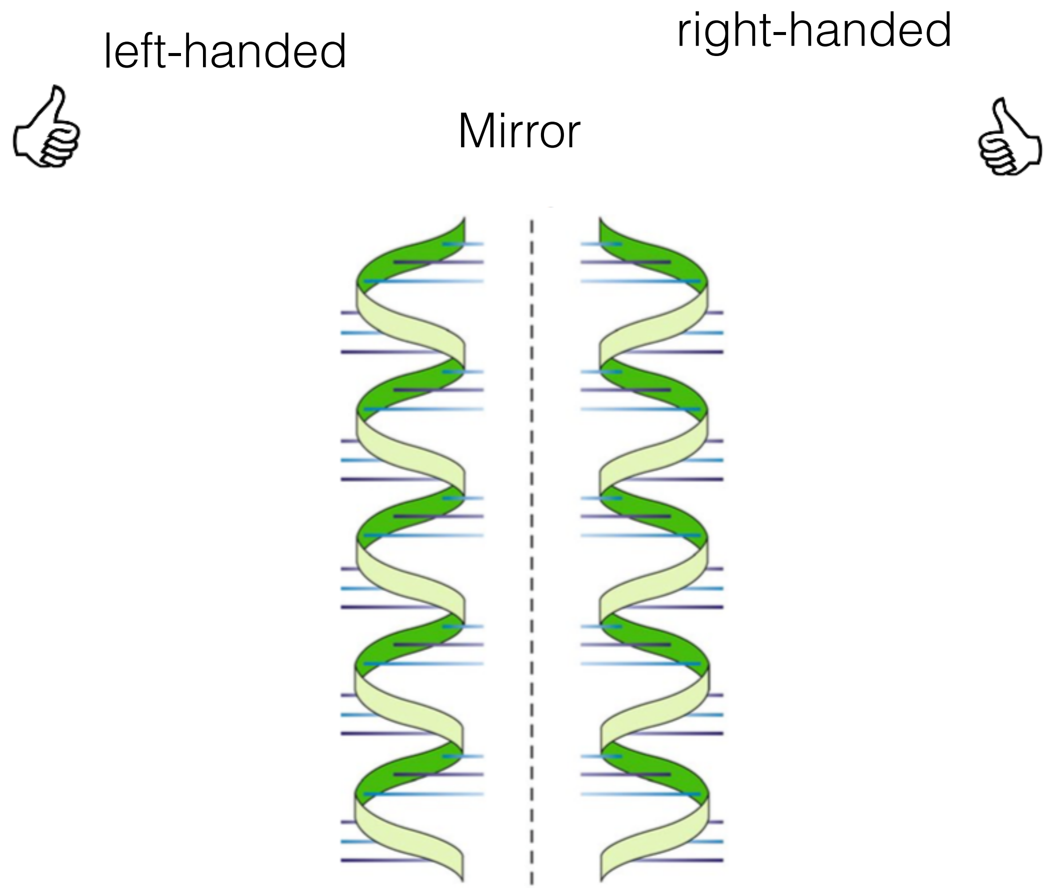
multiple mirror symmetries





If Néel vector points in high symmetry lines, nodal chains are allowed by symmetry, giving rise to high Berry's phase contribution to the crystal Hall effect

Global chirality in $CoNb_3S_6$ antiferromagnet



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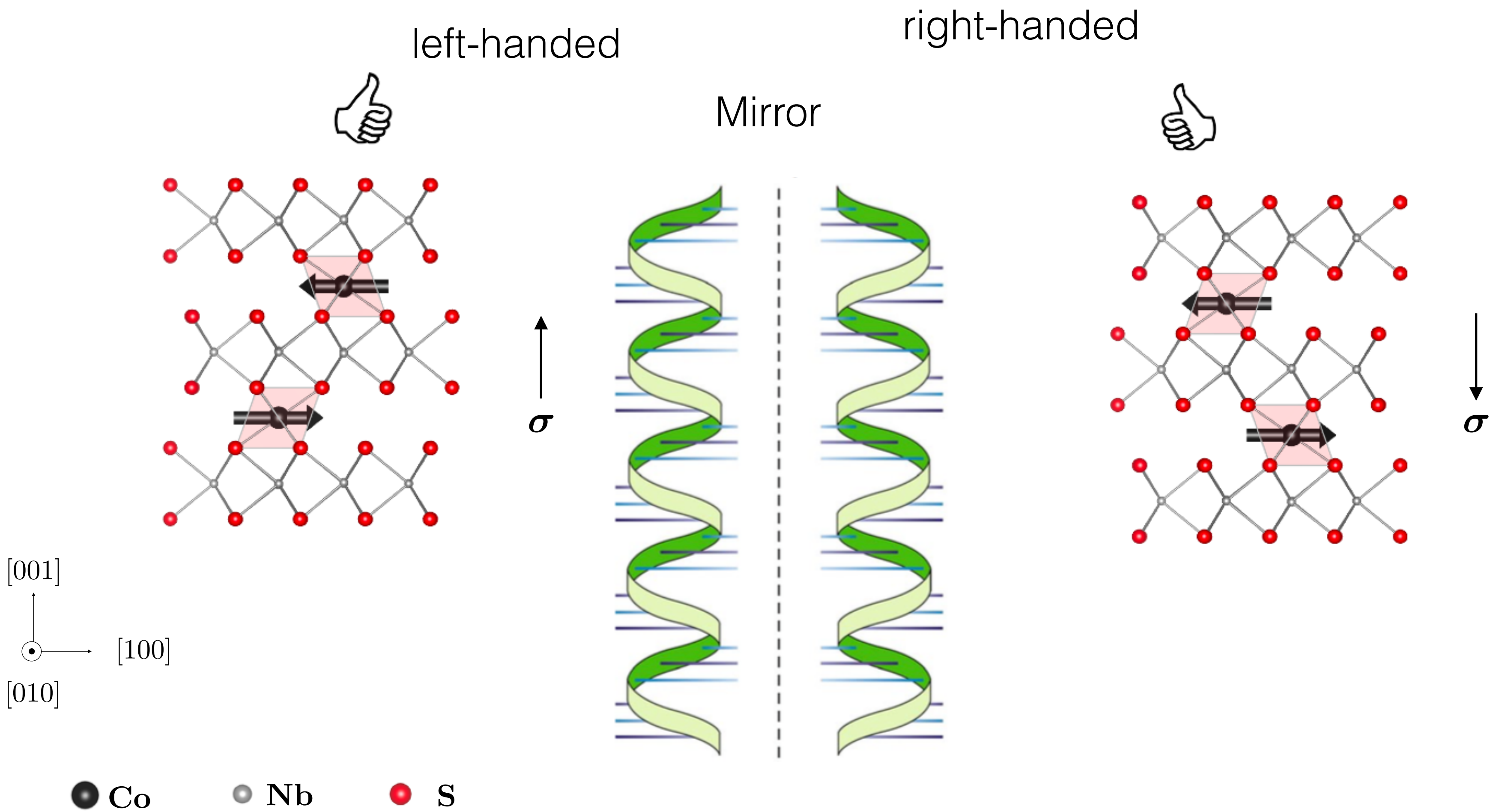

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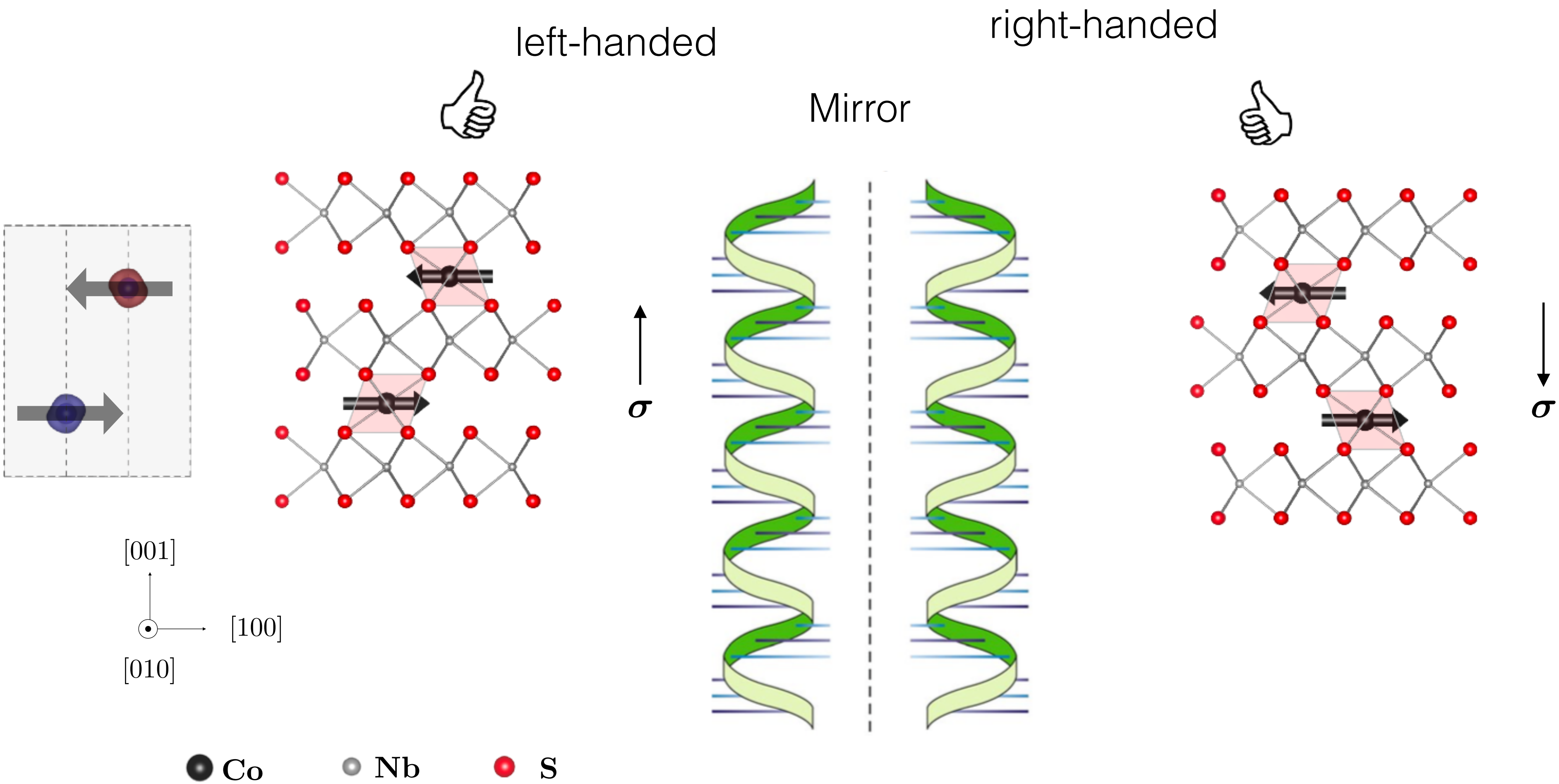

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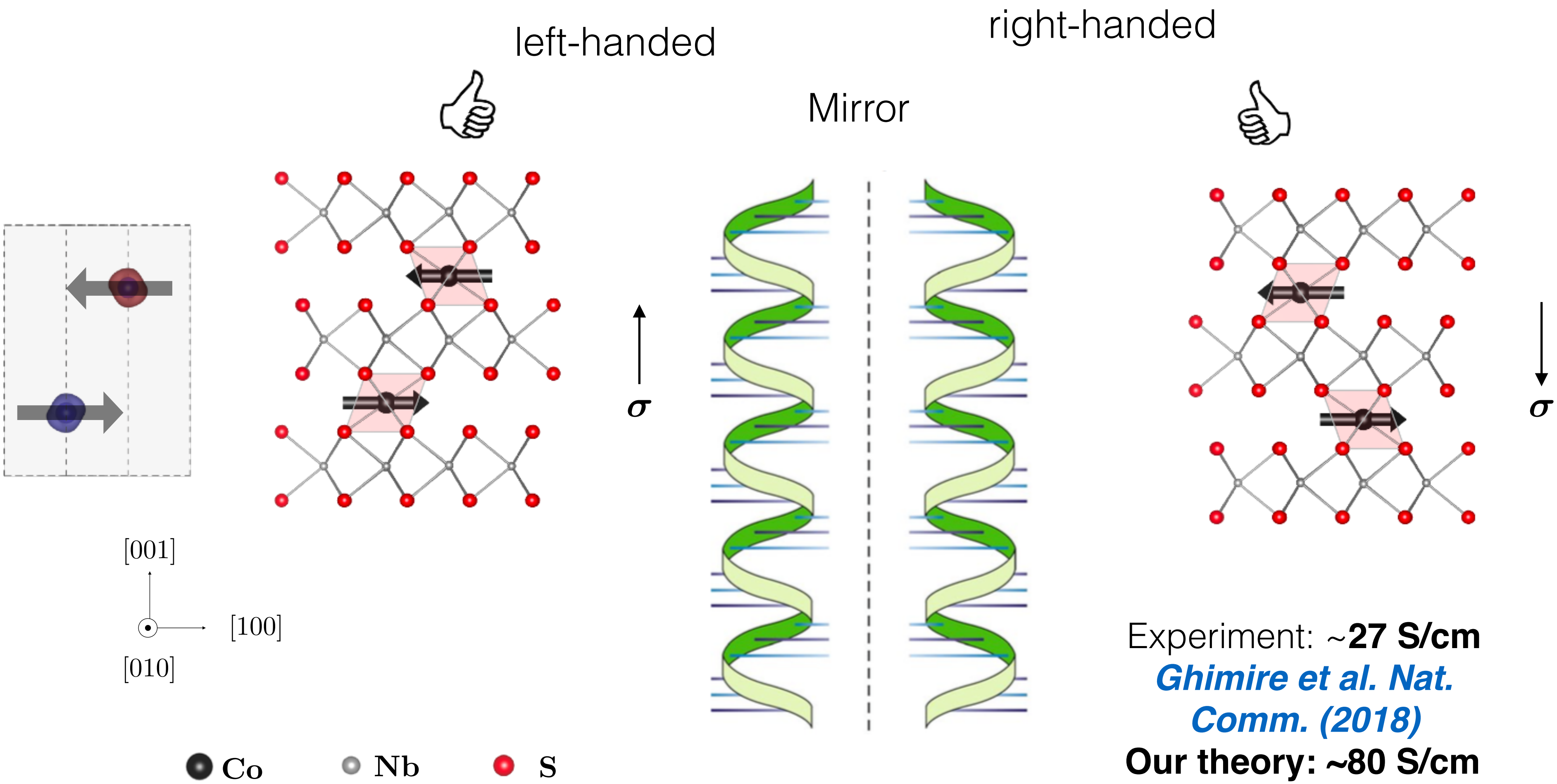

Experiment: ~**27 S/cm**

Ghimire et al. Nat. Comm. (2018)

Our theory: ~80 S/cm

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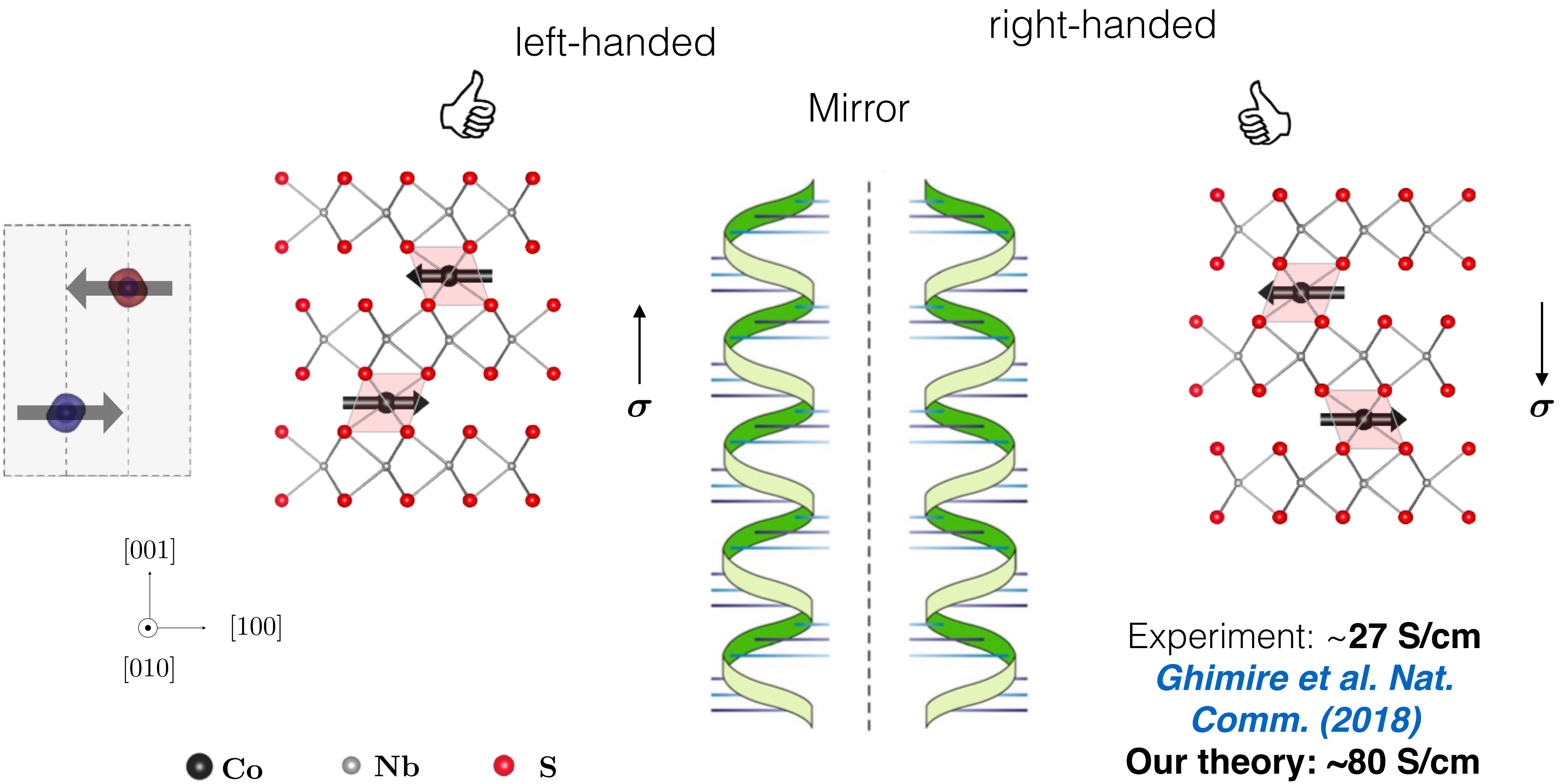
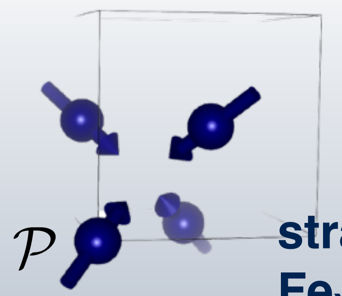


Experiment: ~**27 S/cm**
Ghimire et al. Nat. Comm. (2018)
Our theory: ~80 S/cm

Global crystal chirality controls Hall sign!

Spontaneous Hall antiferromagnets

"topological" Hall effect

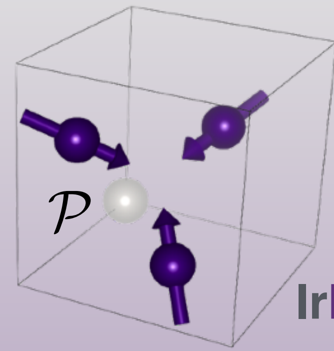


strained Fe_xMn_{1-x}

Onode et al. PRL (2001)
J.P. Hanke et al. Sci.Rep. (2017)

noncoplanar+spin-chirality

anomalous Hall effect

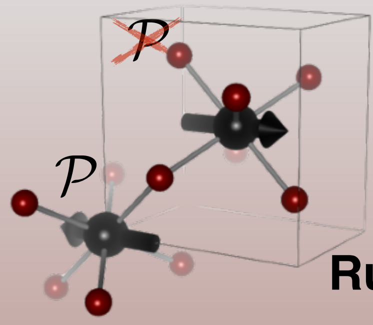


$IrMn_3$

Hua Chen et al. PRL(2014)

noncollinear+symmetric SOC

crystal Hall effect



RuO_2

Smejkal, Hernandez-Gonzales, TJ, JS, arXiv 1901.00445 (2019)

collinear+asymmetric SOC

spin-orbit coupling complexity →

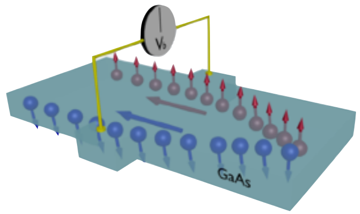
← **magnetic order complexity**

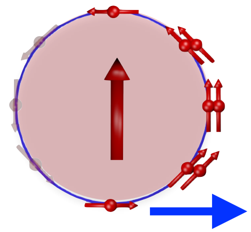
Key signature of CHE:
The sign will change if the broken inversion symmetry (arising from the non-magnetic SOC atoms) is reversed - while retaining the same magnetic order

NCAF candidates quite rare but CHE in 1/10 of magnetic database materials!

SUMMARY

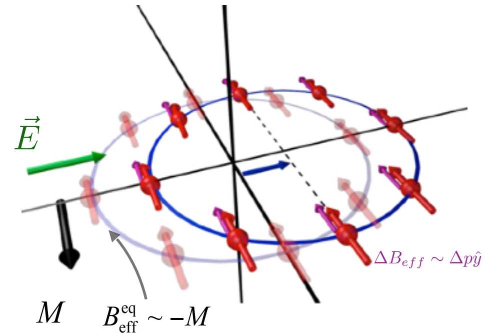
SHE and ISGE





JS,Valenzuela, Wunderlich, Back, Jungwirth RMP (2015)

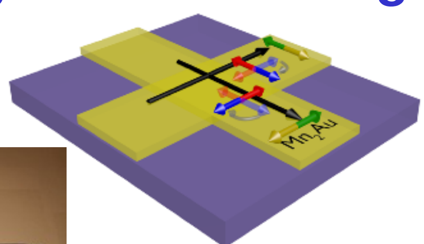
SOT in a single-layer ferromagnet

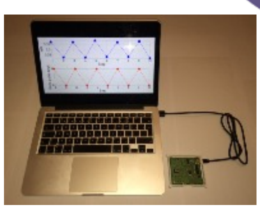


Kurebayashi, et al., Nature Nanotech (2014)

Kurebayashi, et al., Nature Physics (2016)

Néel SOT in a single-layer antiferromagnet



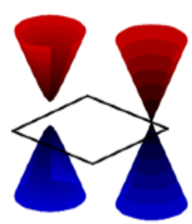


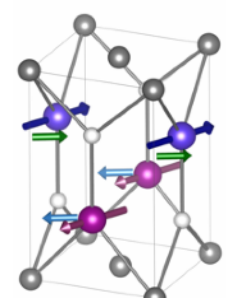
J. Zelezny, et al, PRL (2014)
J. Zelezny, et al, PRB (2016)
O. Gomonay, et al, PRL (2016)
Yu, et al. arXiv: 1706.02482 (2017)
Wadley, et al Science (2016)

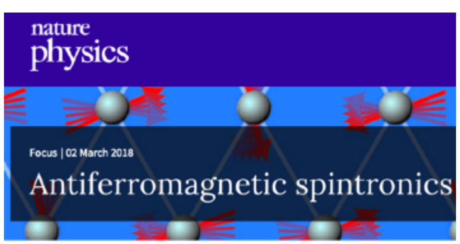
Topological Antiferromagnetic Spin-orbitronics

Topological Dirac Semi Metal+ AFM (i)

Neel SOT physics (ii)
AHE in RuO2 (col-AFM)(iii)







Libor Smejkal, et al PRL (2017) and PSS (2017)

Jungwirth, JS, et al, Nature Physics (AFM spintronics Reviews) (2018)

Kläui, **Gomonay**

Jungwirth

Zelezny

Institute of Physics Prague

Univ. of Nottingham

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