Crystal Hall Effects in Collinear Antiferromagnets

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3rd Antiferromagnetic Spintronics Workshop

https://www.researchgate.net/profile/Libor_Smejkal

Jairo Sinova

Tomáš Jungwirth

Abundant collinear antiferromagnets may exhibit a new type of Hall effect:
***Crystal Hall effect**.*

Libor Šmejkal, Rafael Gonzales-Hernandez,Tomáš Jungwirth, and Jairo Sinova, arXiv 1901.00445 (2019)

Crystal Hall Effects in Collinear Antiferromagnets

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INTERDISCIPLINARY SPINTRONICS RESEARCH

1. **Topological antiferromagnetic spintronics and spontaneous Hall effects intro**

LS, TJ, JS, Rapid.Res.Lett. (2017)
LS, Zelezny, JS, TJ, Phys.Rev.Lett. (2017)
LS, Y.Mokrousov, B.Yan, A.H.MacDonald, Nat.Phys.(2018)
LS & T.Jungwirth, Topology in magnetism, Springer (2018)

2. Spontaous Hall effect in collinear antiferromagnets?

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

3. Classification, material candidates and applications of crystal Hall effect

Gonzalez-Hernandez, Zelezny, LS et al. (2019)

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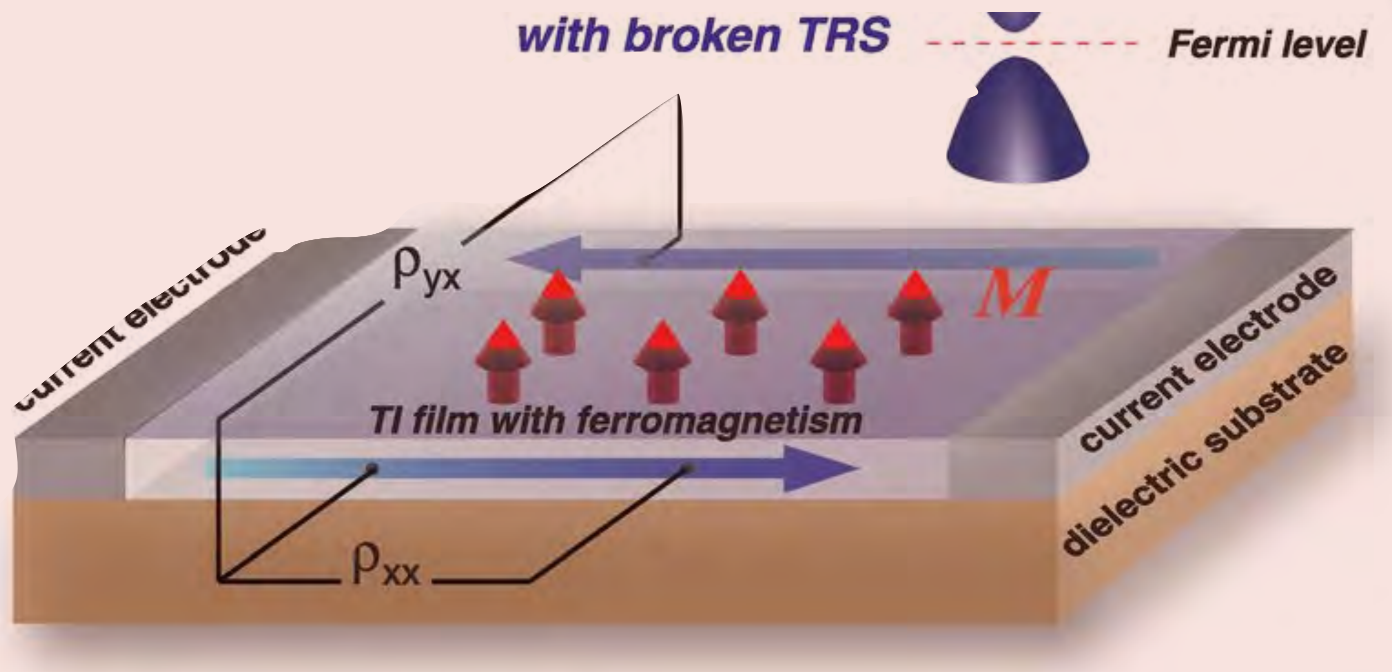
Magnetically doped topological insulators



Fragile magnetism and critical temperatures

Unaticipated effects
Large signal/noise
Low dissipation

Antiferromagnetic spintronics

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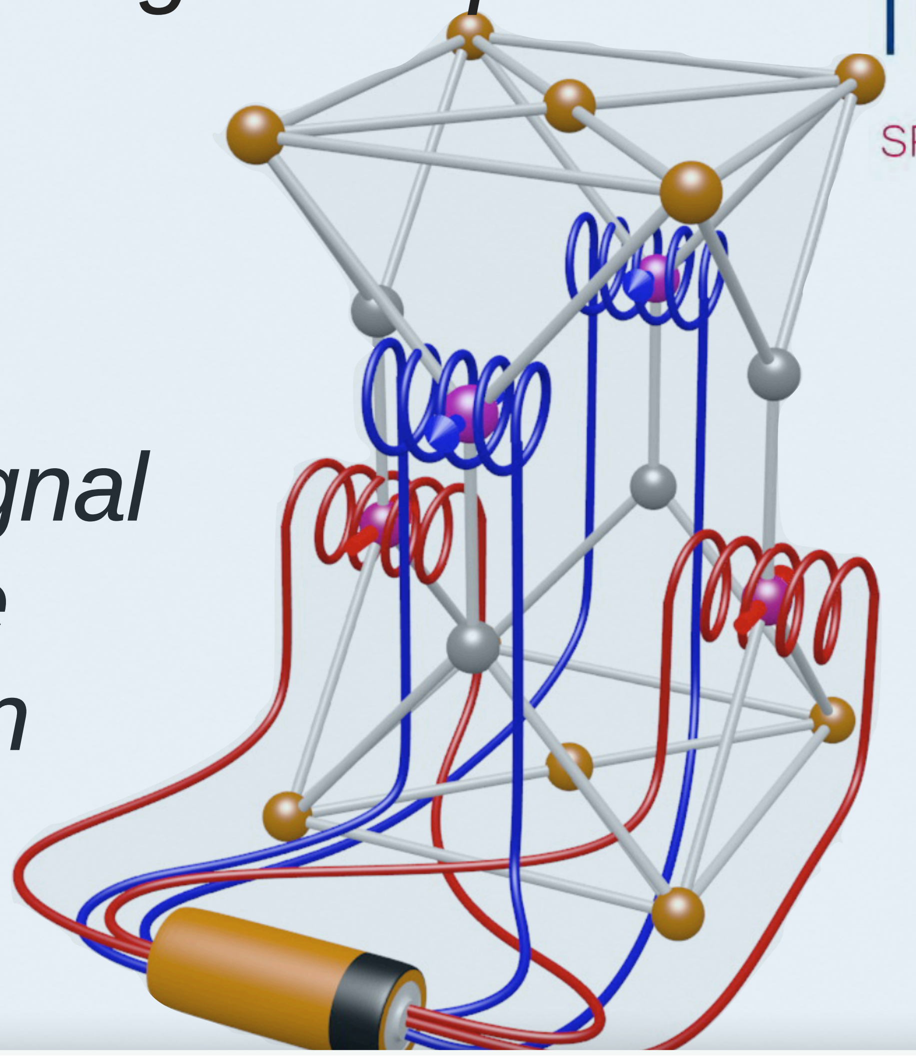
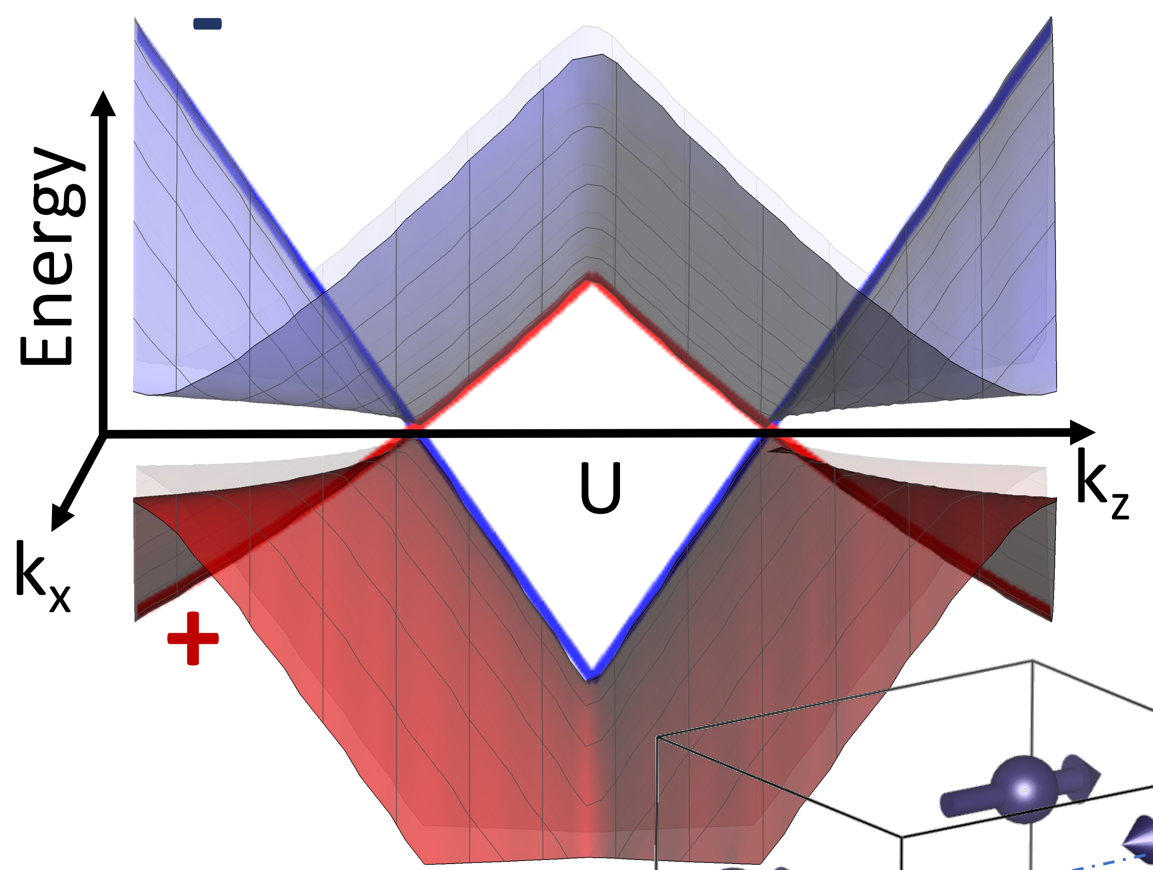


Limited signal magnitude
Dissipation

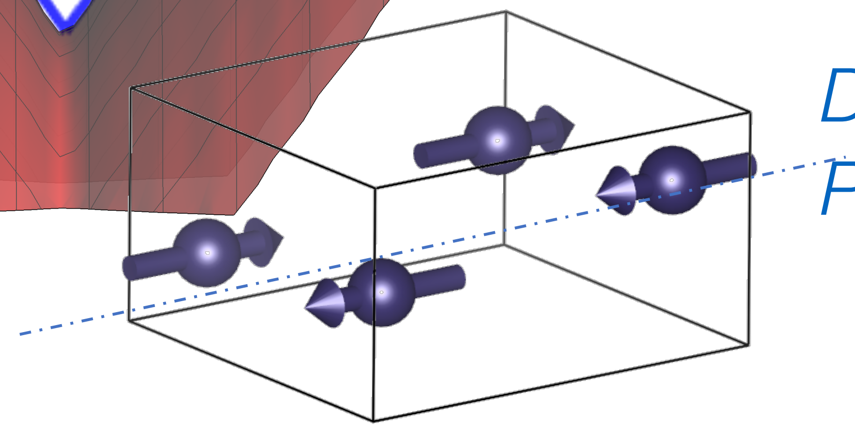
Topological antiferromagnetic spintronics: m



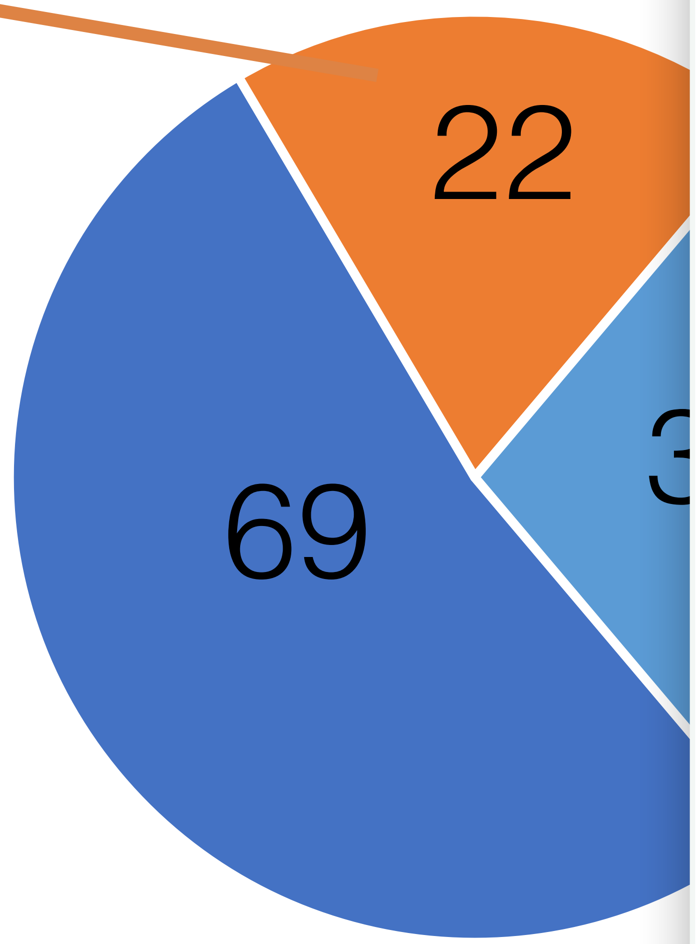
Dirac antiferromagnets

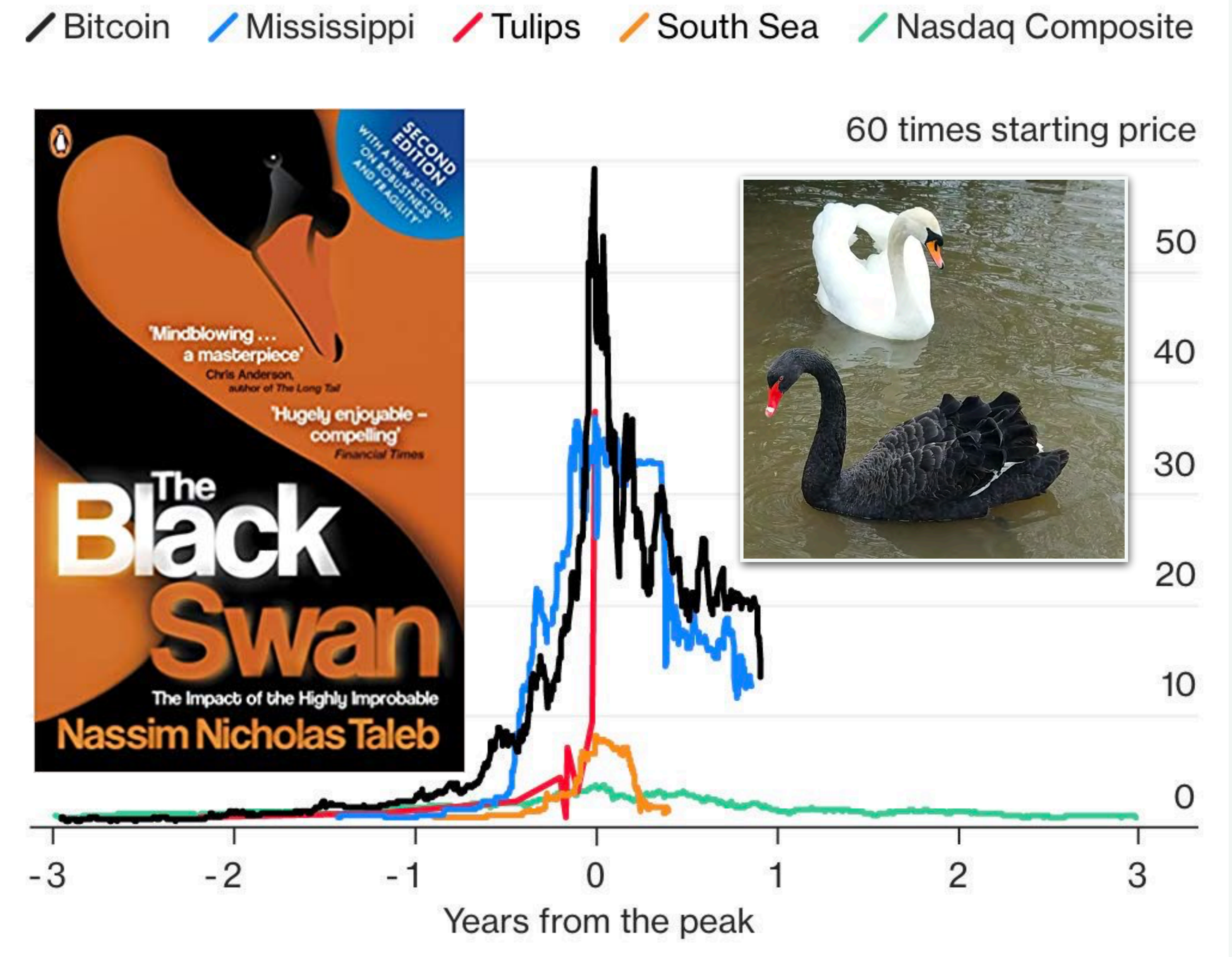
LŠ, Zelezny, JS, TJ, Phys.Rev.Lett. (2017)

Dynamical axions



D. J. E. Marsh, LŠ, and M. N. Al
Phys. Rev. Lett. (2019)





Sources: Bloomberg, International Center for Finance at Yale School of Management, Peter Garber

LŠ & Tomáš Jungwirth, Topology in Magnetism, Springer (2018),
LŠ, Y.Mokrousov, B.Yan, A.H.MacDonald, Nat.Phys.(2018)

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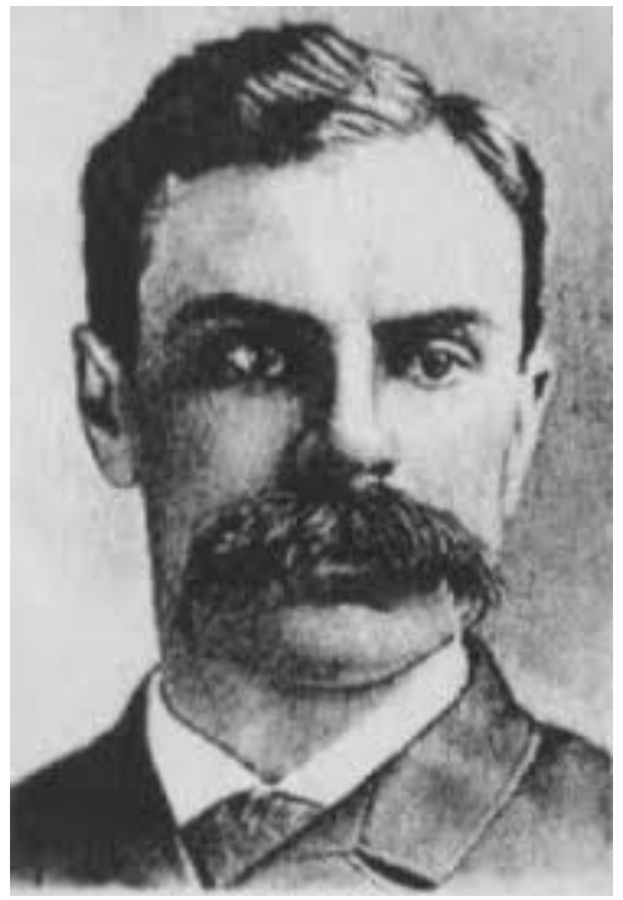
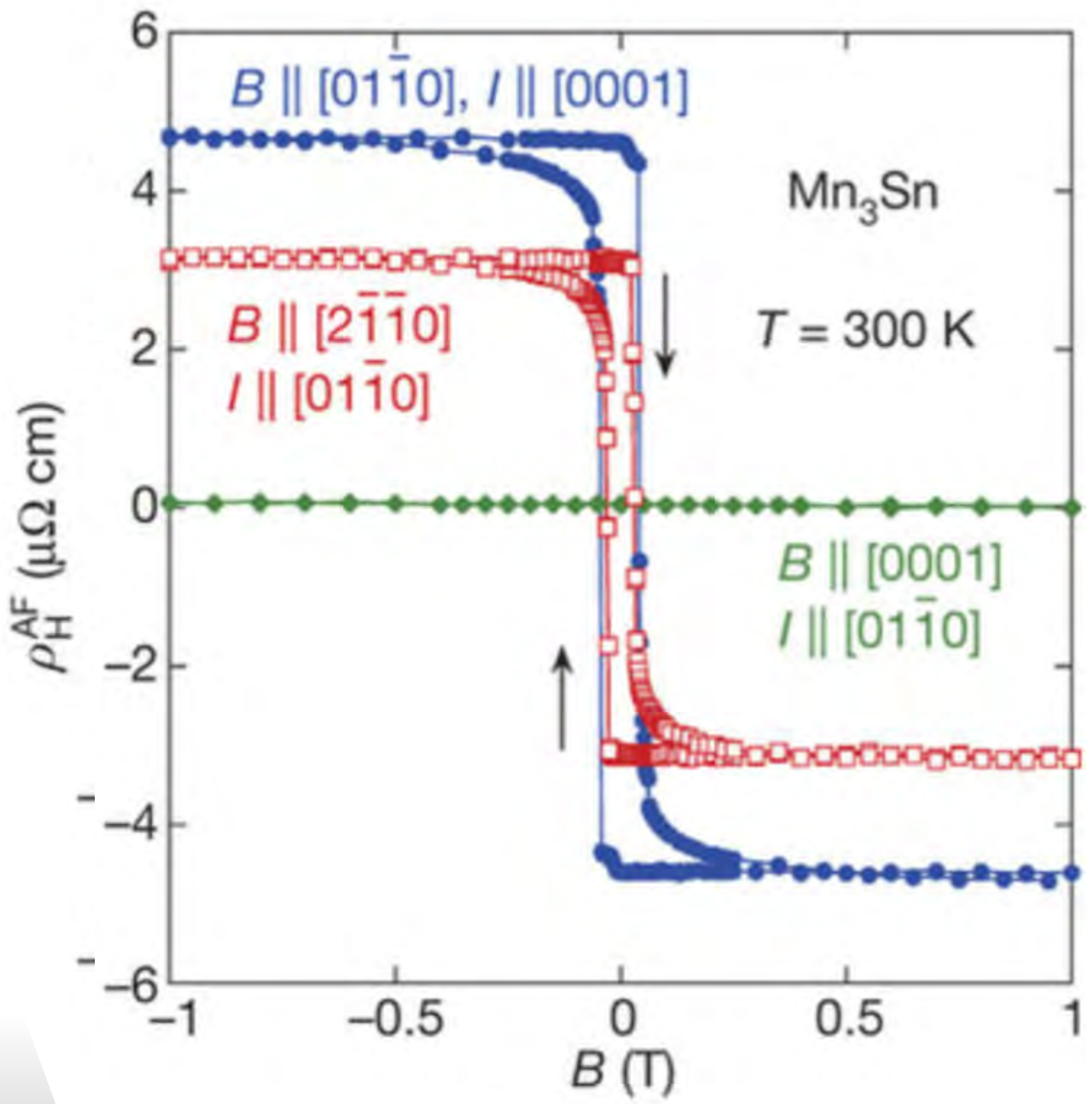
Spontaneous Hall effect



$$\rho_{ab}(\mathbf{m}) = (E_a/j_{\mathrm{H},b} - E_b/j_{\mathrm{H},a})/2$$

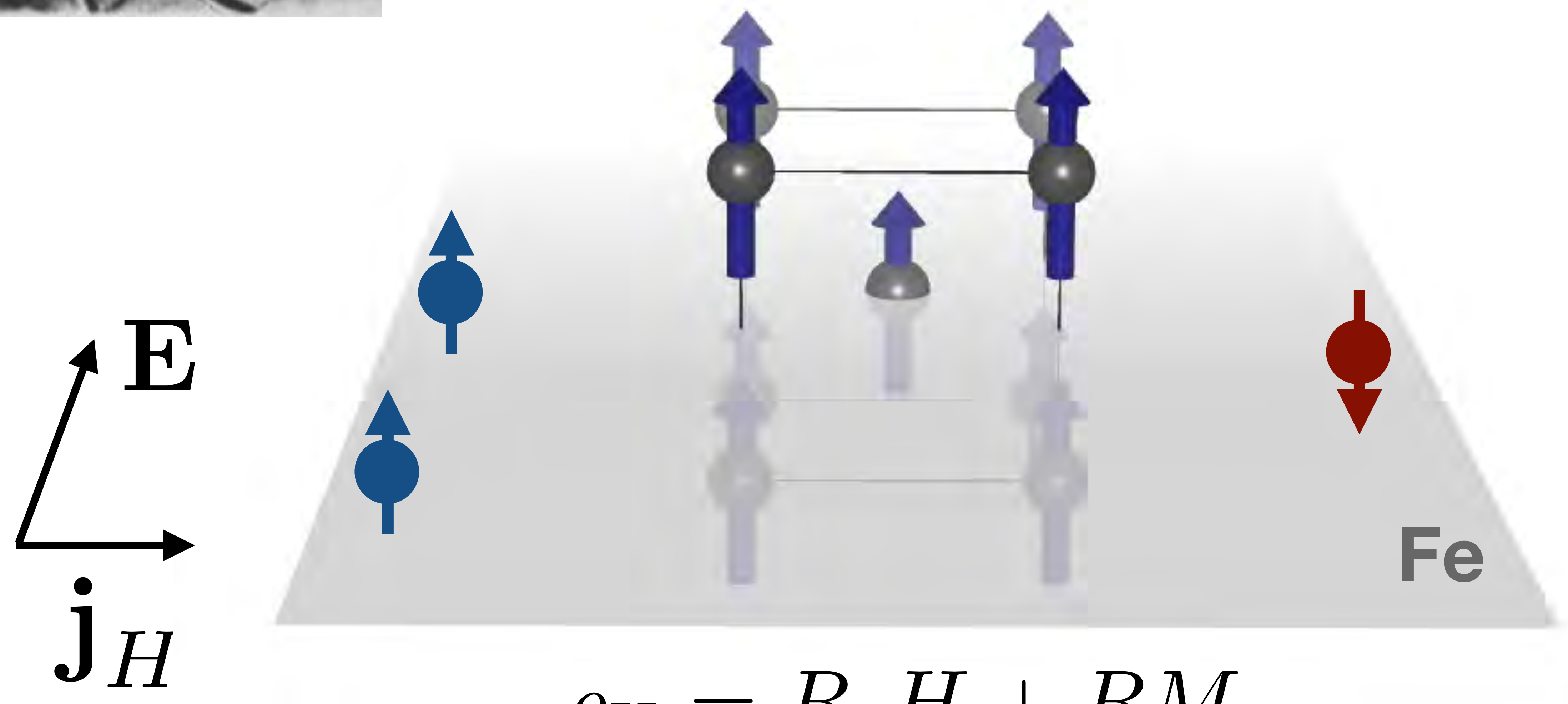
Hall vector $\boldsymbol{\sigma} \sim \mathbf{E} \times \boldsymbol{j}_H$

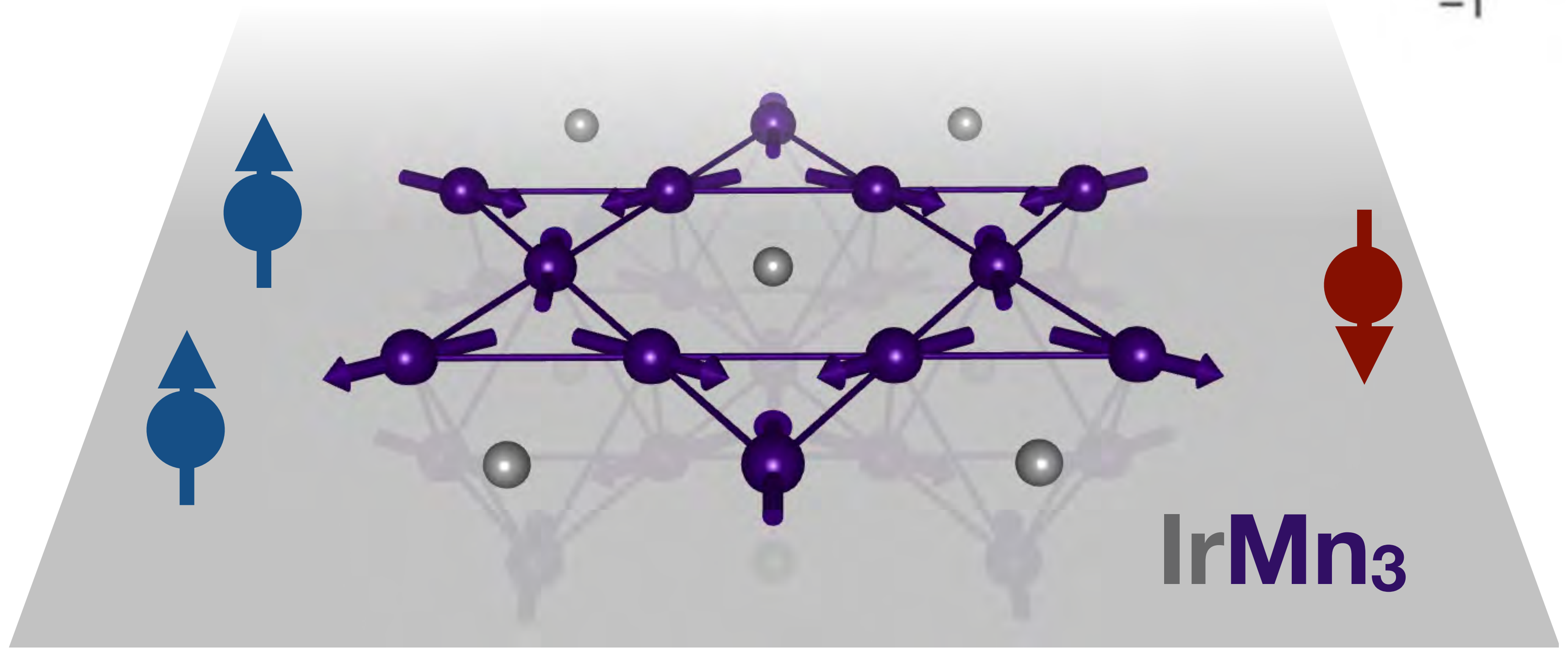


magnetisation

magnetic chirality

$$\chi^{(M)} \sim \mathbf{S}_i \times \mathbf{S}_j$$





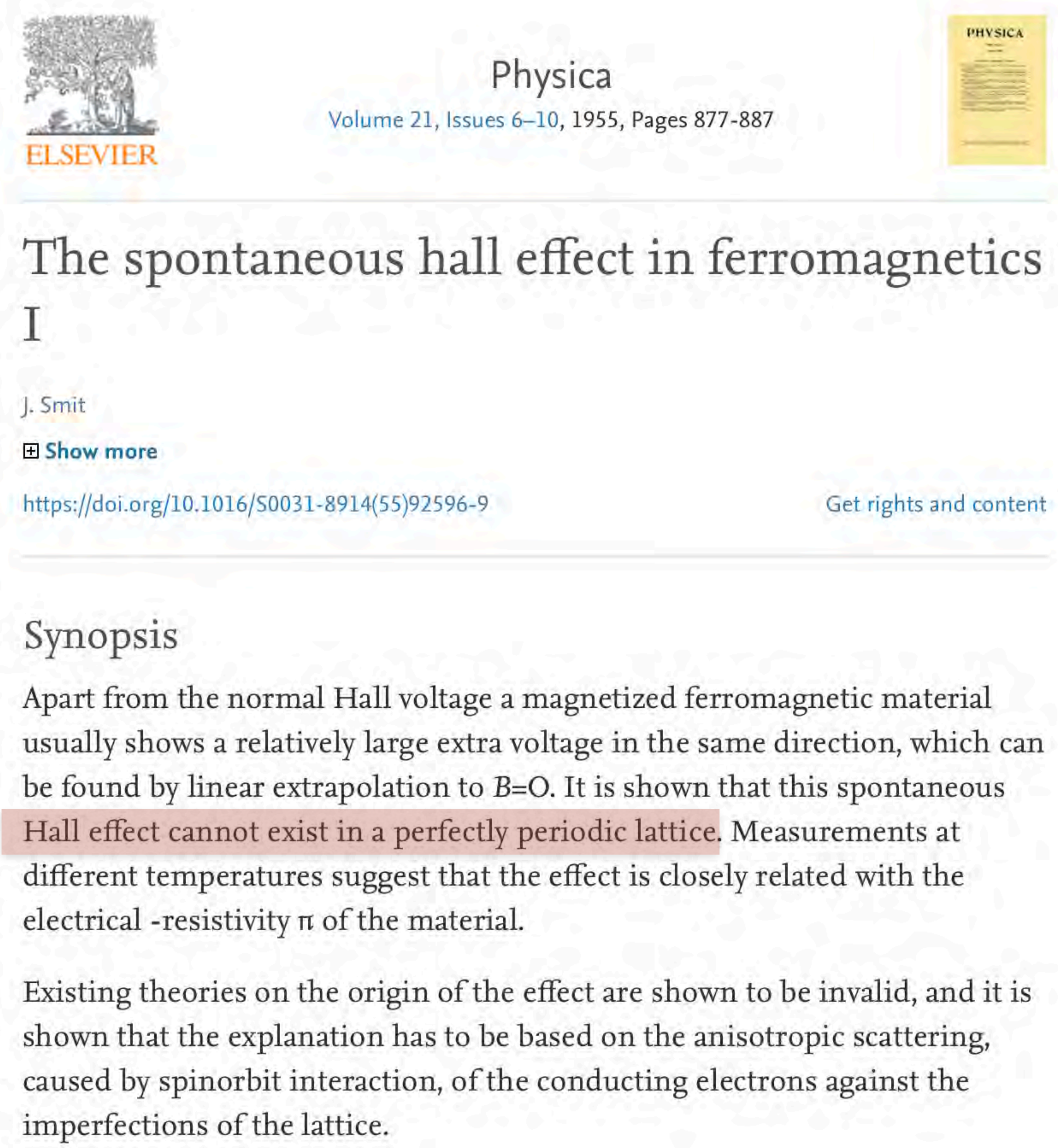
$$\rho_{\mathrm{H}} = R_0 H + RM$$

$$\rho_{\mathrm{H}} = R_0 H + RM + \rho^{\mathrm{AF}}$$

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

Hua Chen et al., PRL (2014), Falser & Kubler, EPL (2014)
Nakatsuji et al., Nature (2015), Nayak, Felser, Parkin et al., Sci. Adv. (2016)

Genealogy of Hall effects


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

The spontaneous hall effect in ferromagnetics I

J. Smit

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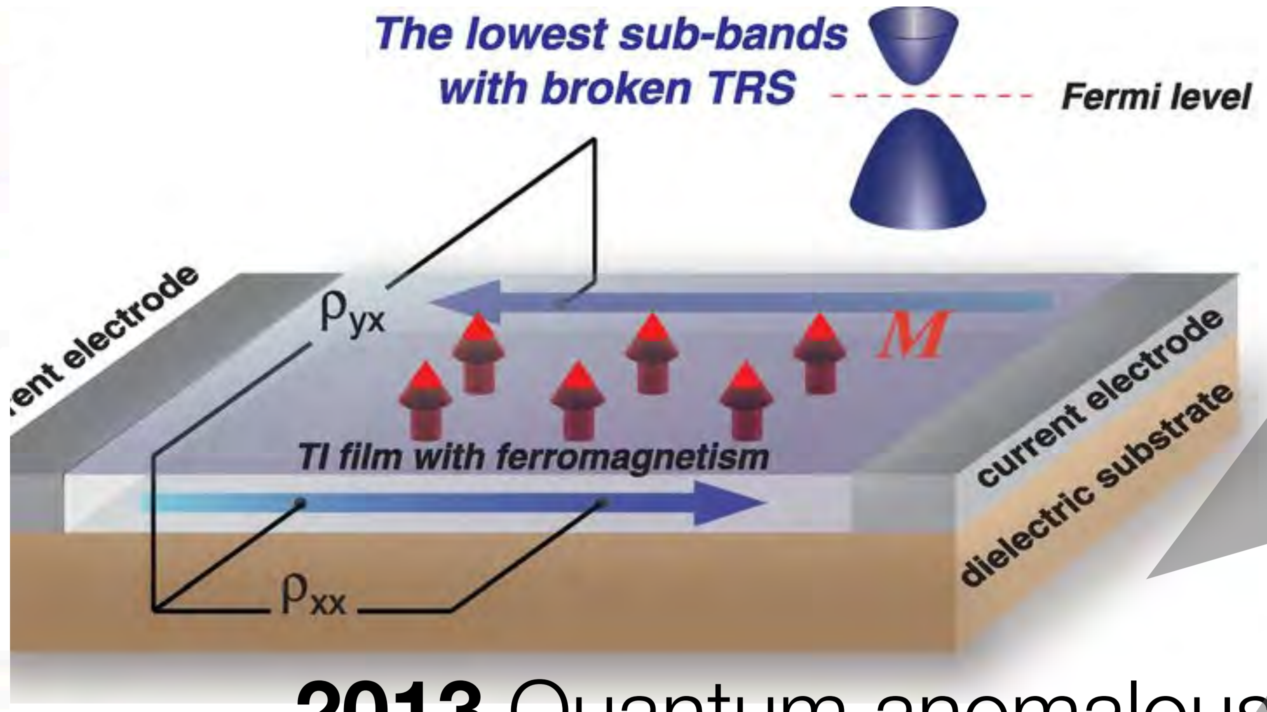
Synopsis

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.



Spontaneous Hall effect without complicated antiferromagnetism?

2015 Anomalous Hall effect in non collinear antiferromagnets **without magnetization**
Nakatsuji, Nature (2015)
Felser and Parkin, Sci.Adv.(2016)

2013 Quantum anomalous Hall in topological insulators

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

2010 **without dipolar-magnetic order**
Machida, Nature (2010)

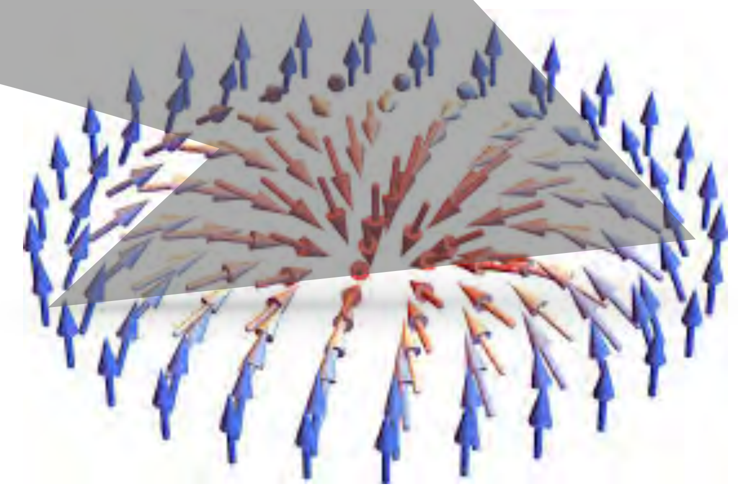
2002 Berry curvature - **topological properties of wave functions**
Jungwith et al. PRL (2002), Nagaosa et al., PRL (2002)

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
Microscopically: spin-polarisation and spin-orbit coupling

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



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

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Spontaneous Hall effect from collinear antiferromagnetism?

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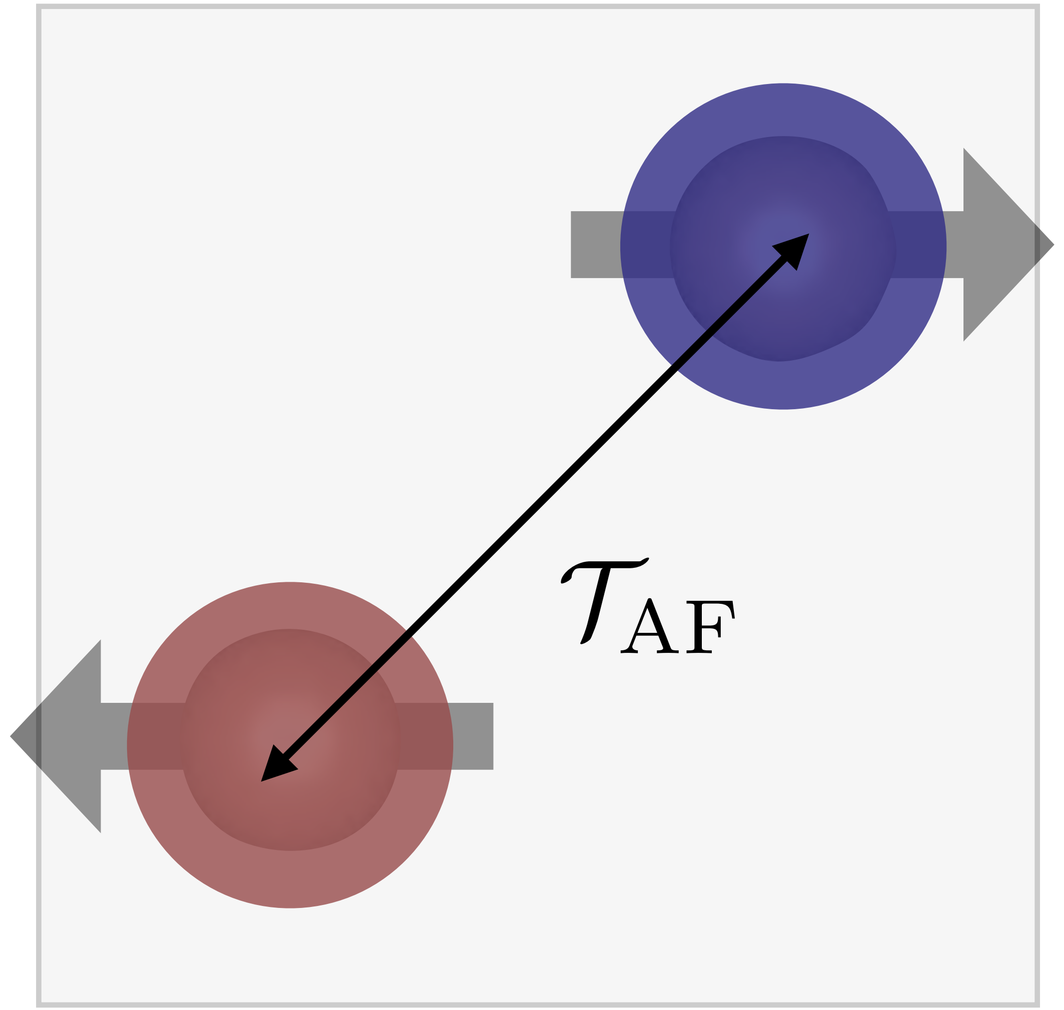
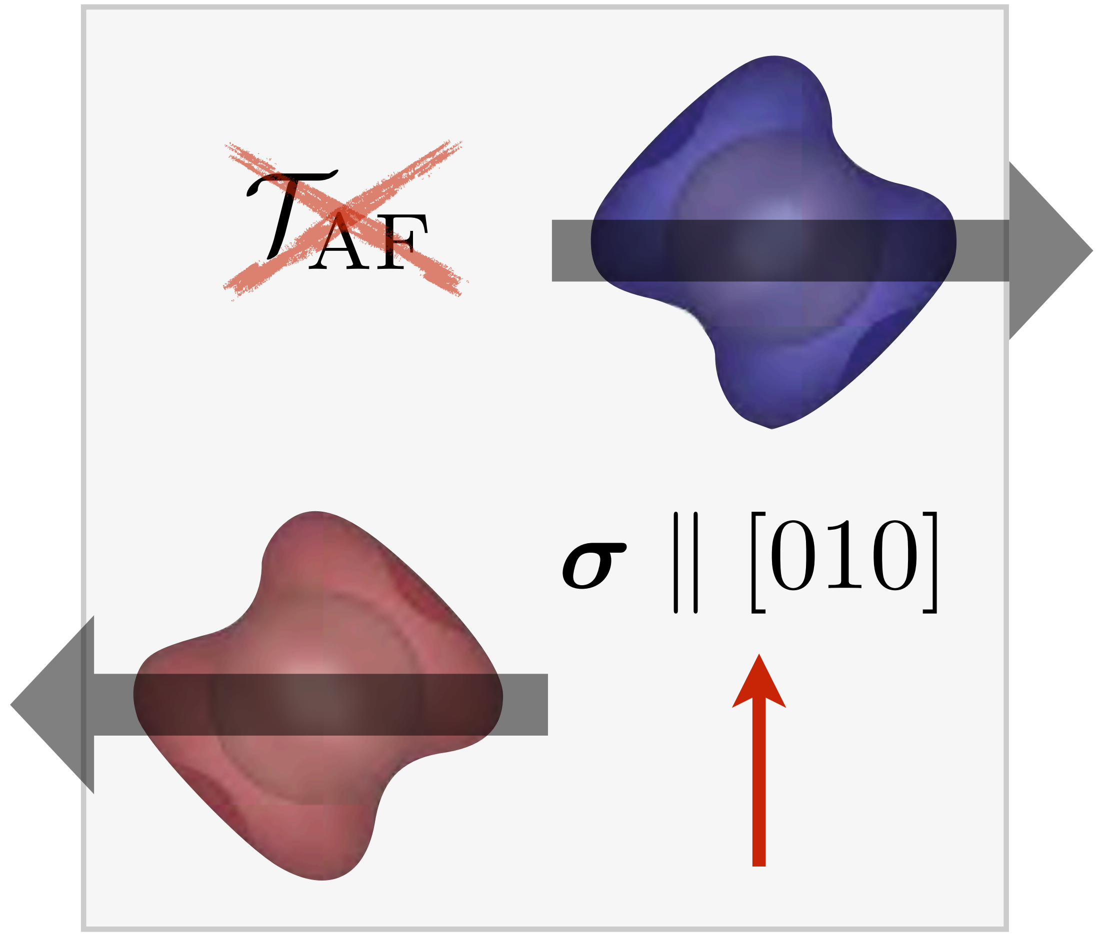
spin degenerate bands
($IrMn$, $CuMnAs$, Mn_2Au, …)

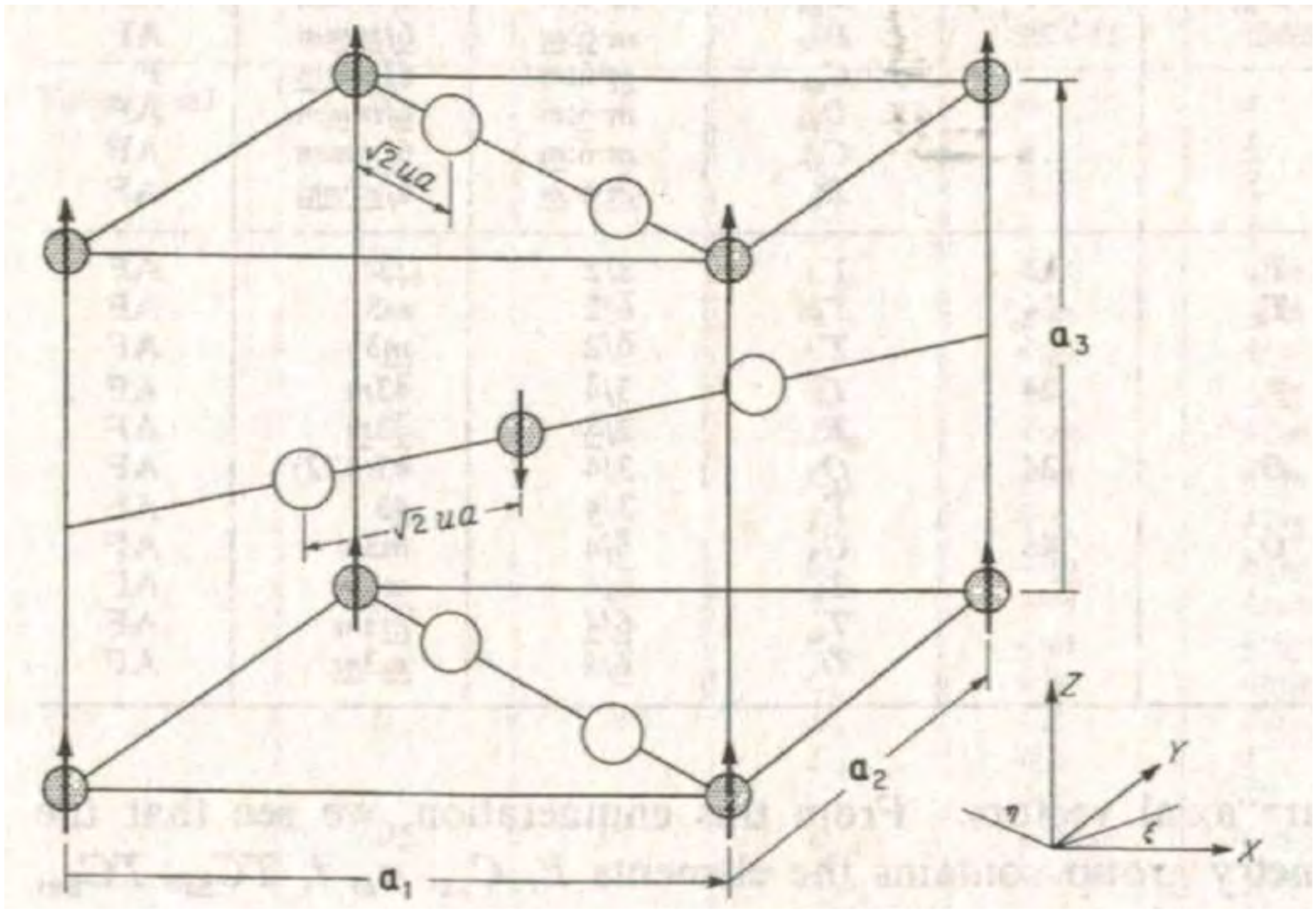
Magnetisation density spontaneously breaks symmetries and allows Hall vector! (RuO_2, …)



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)

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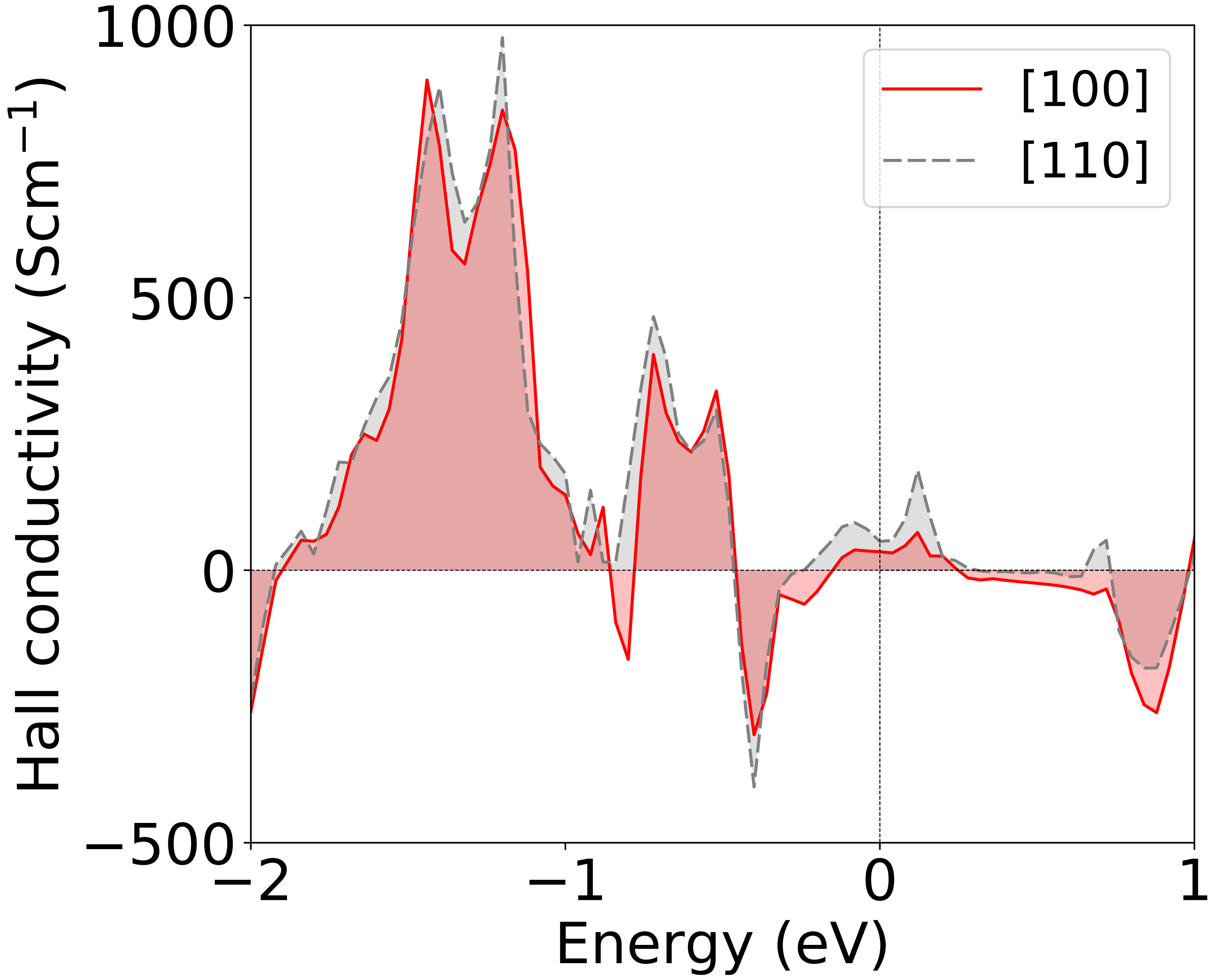
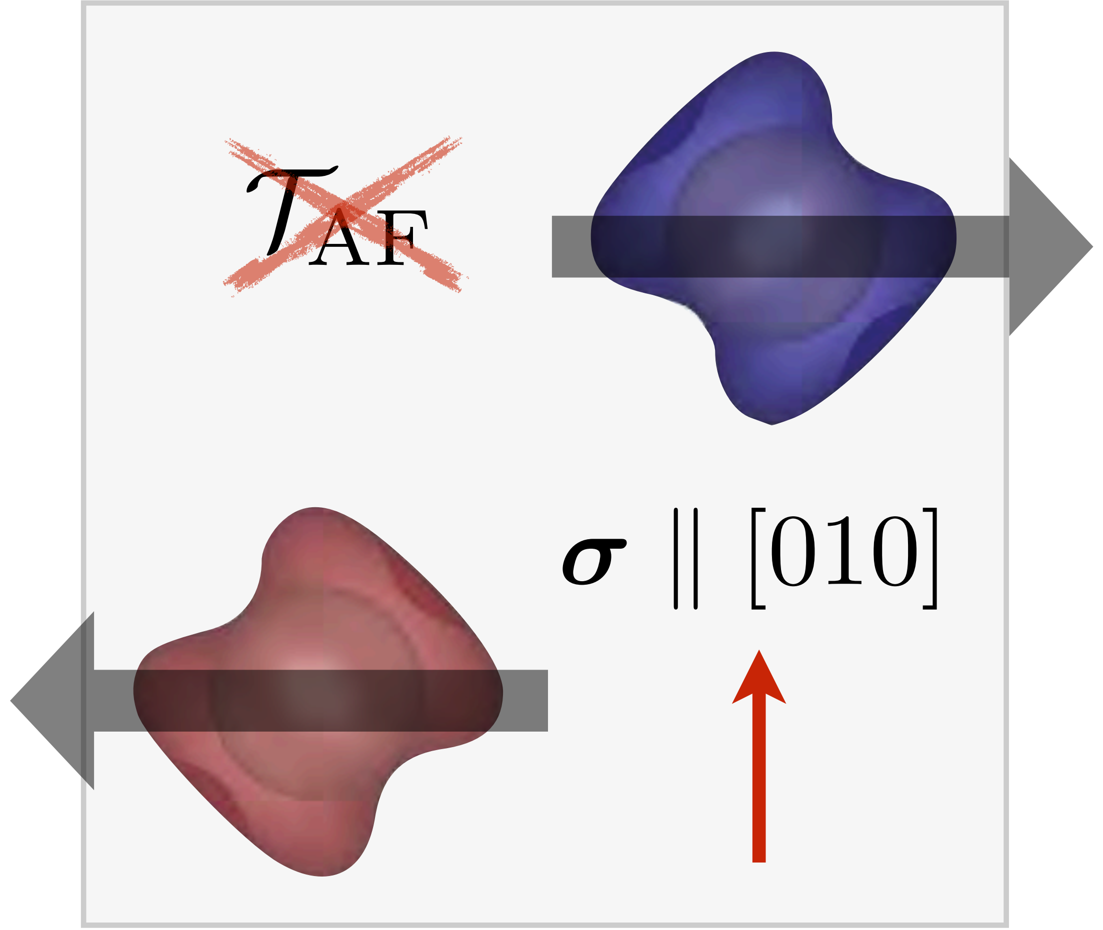
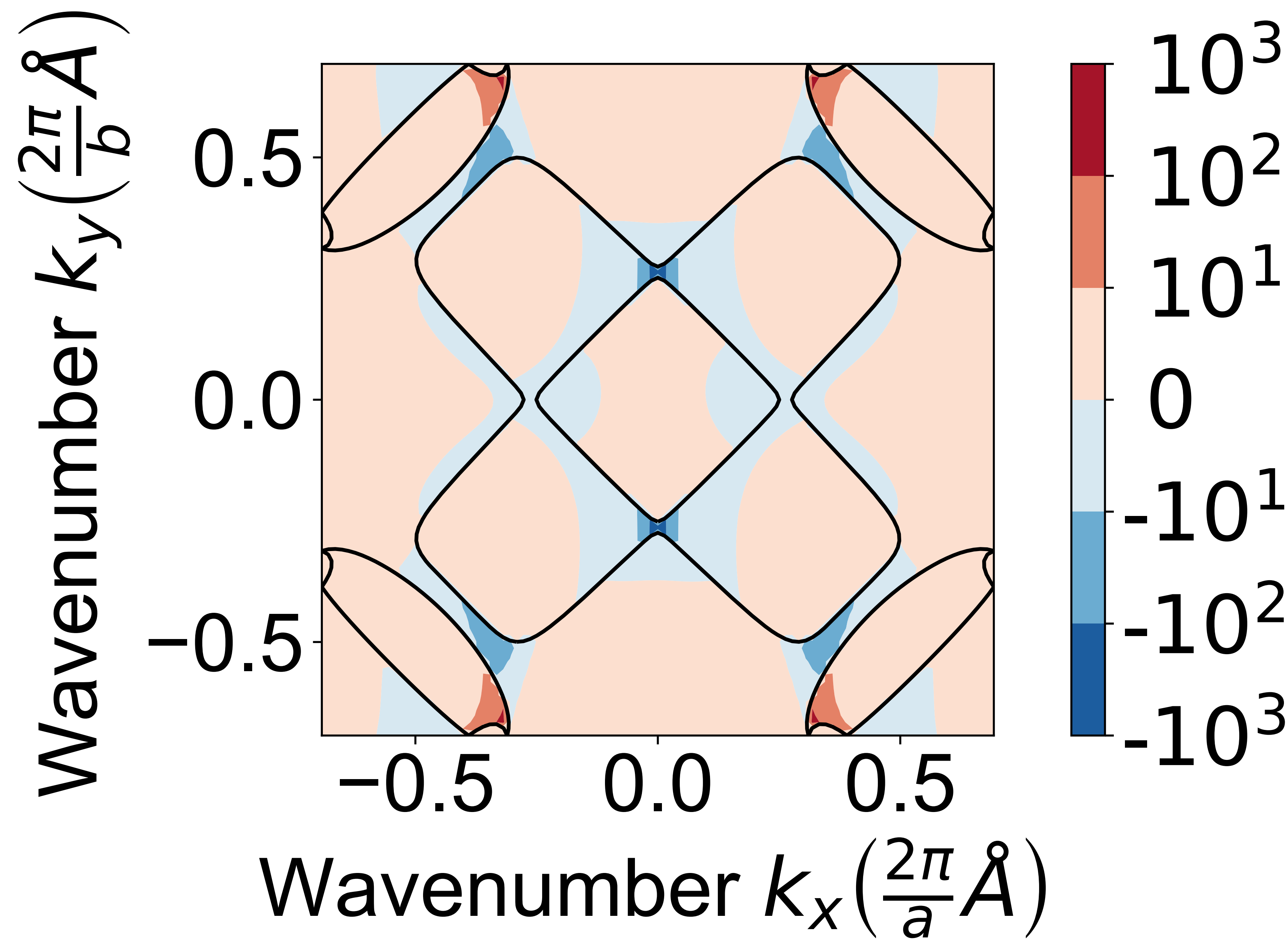
Giant spontaneous Hall effect from collinear antiferromagnetism?

Spontaneous symmetry breaking is strong already without SOC!



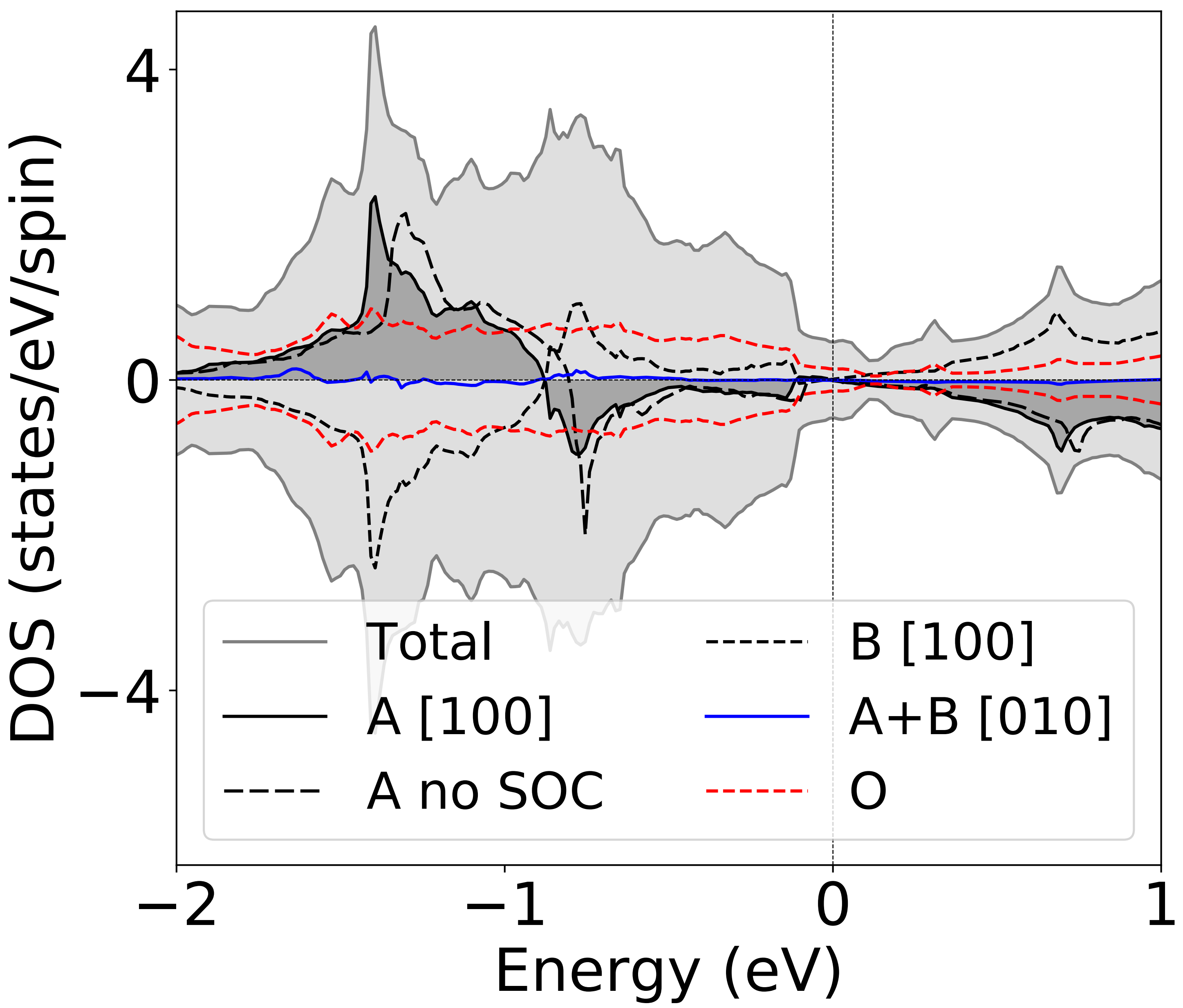
$$\sigma_{xy} = \frac{e^2}{h} \int_{BZ} \frac{d\mathbf{k}}{(2\pi)^3} \sum_n f(\mathbf{k}) b_z^n(\mathbf{k})$$

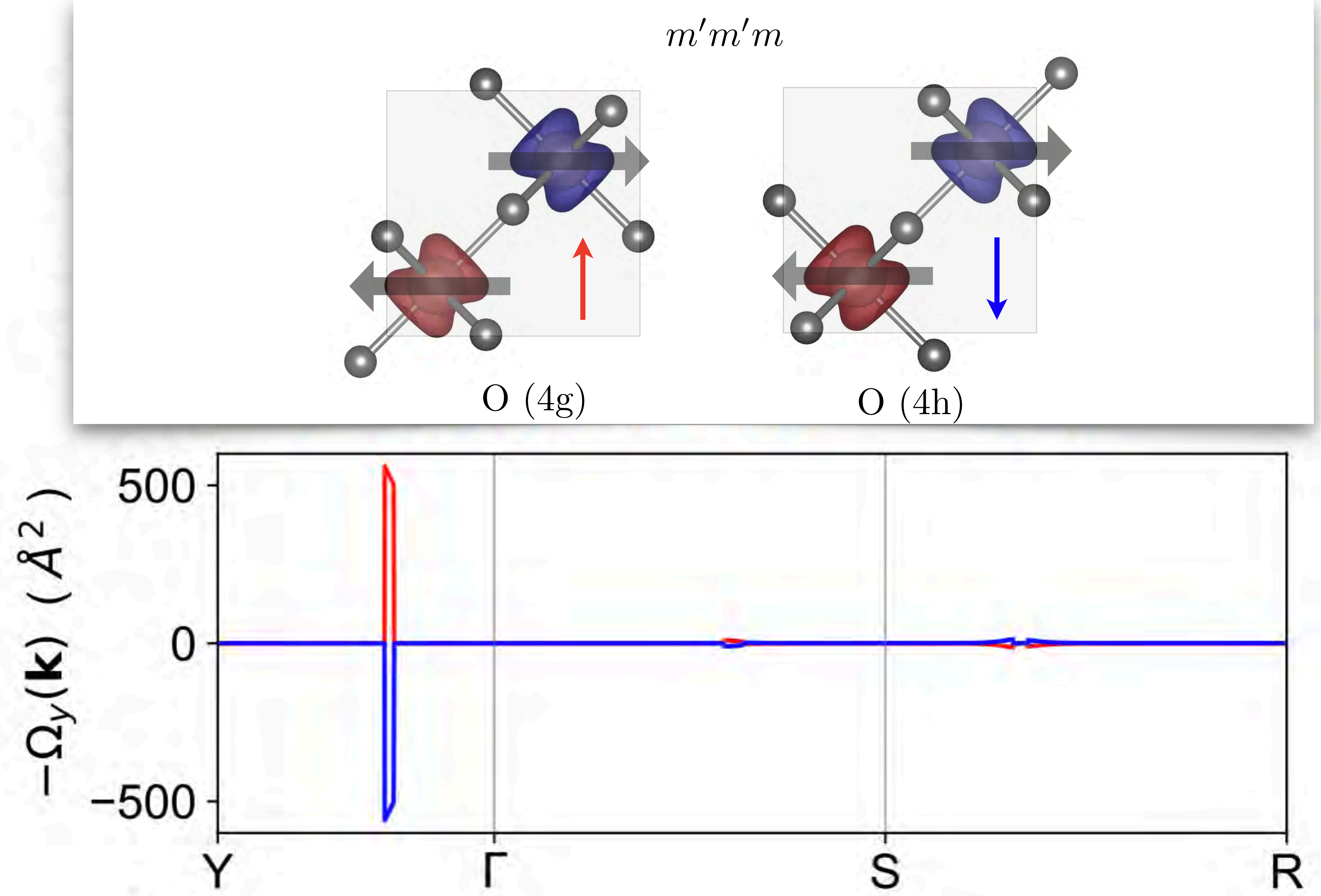




LŠ, R.H.Gonzales, JS, TJ, arXiv 1901.00445 (2019)

Magnitude can as large as record values in ferromagnets

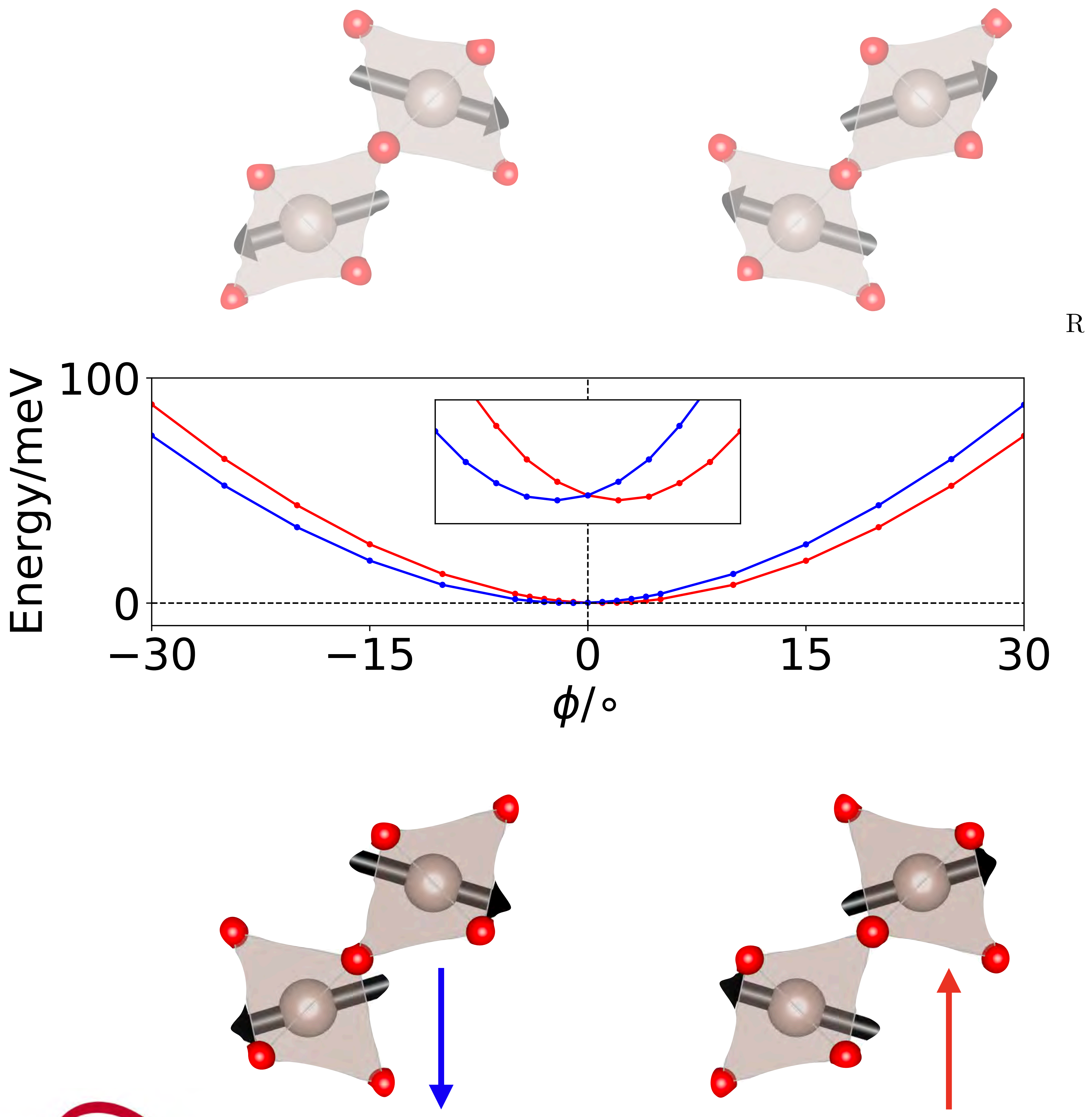


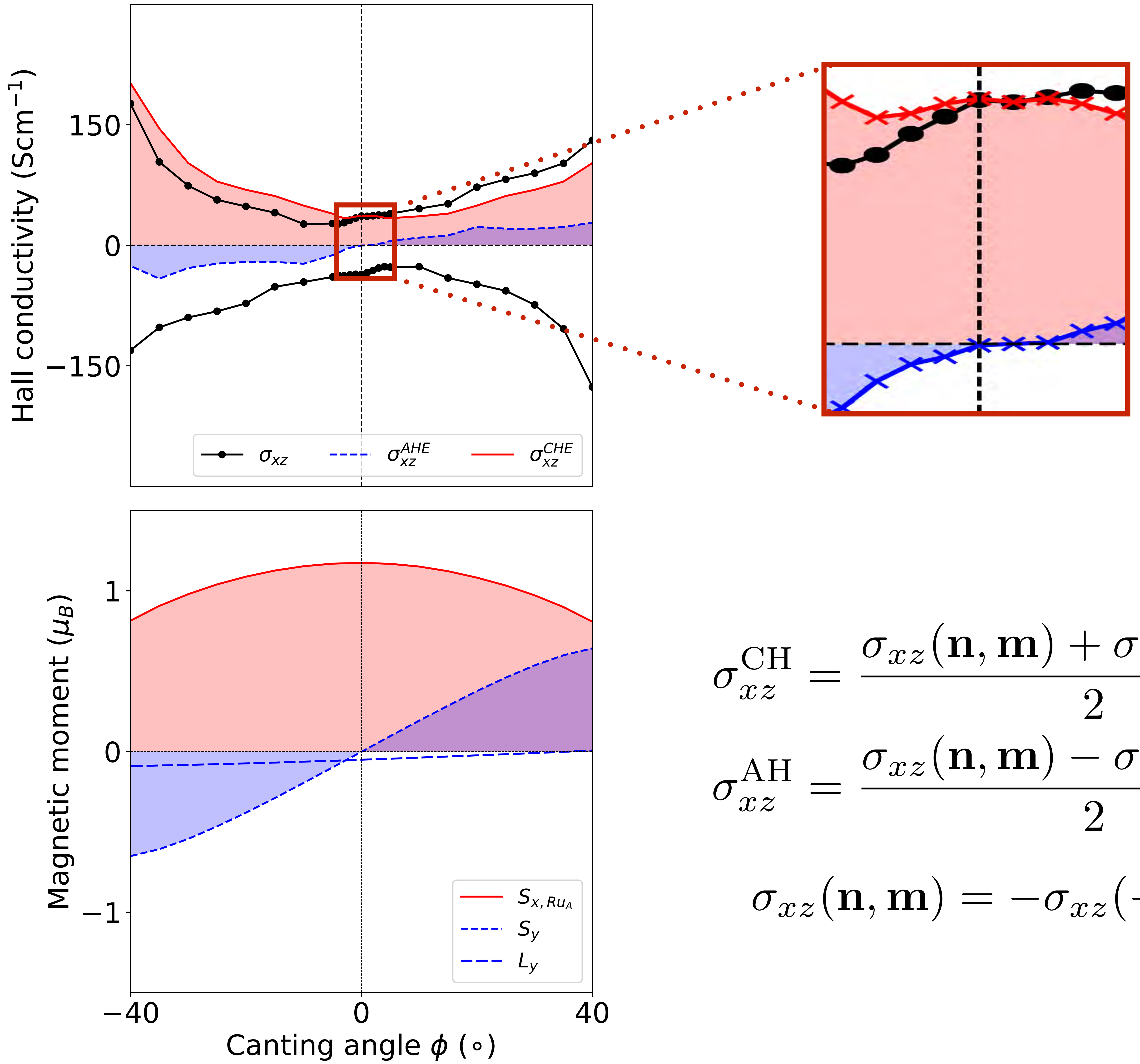


Correlations stabilise antiferromagnetism

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

Crystal Hall .VS. anomalous Hall from canting





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

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

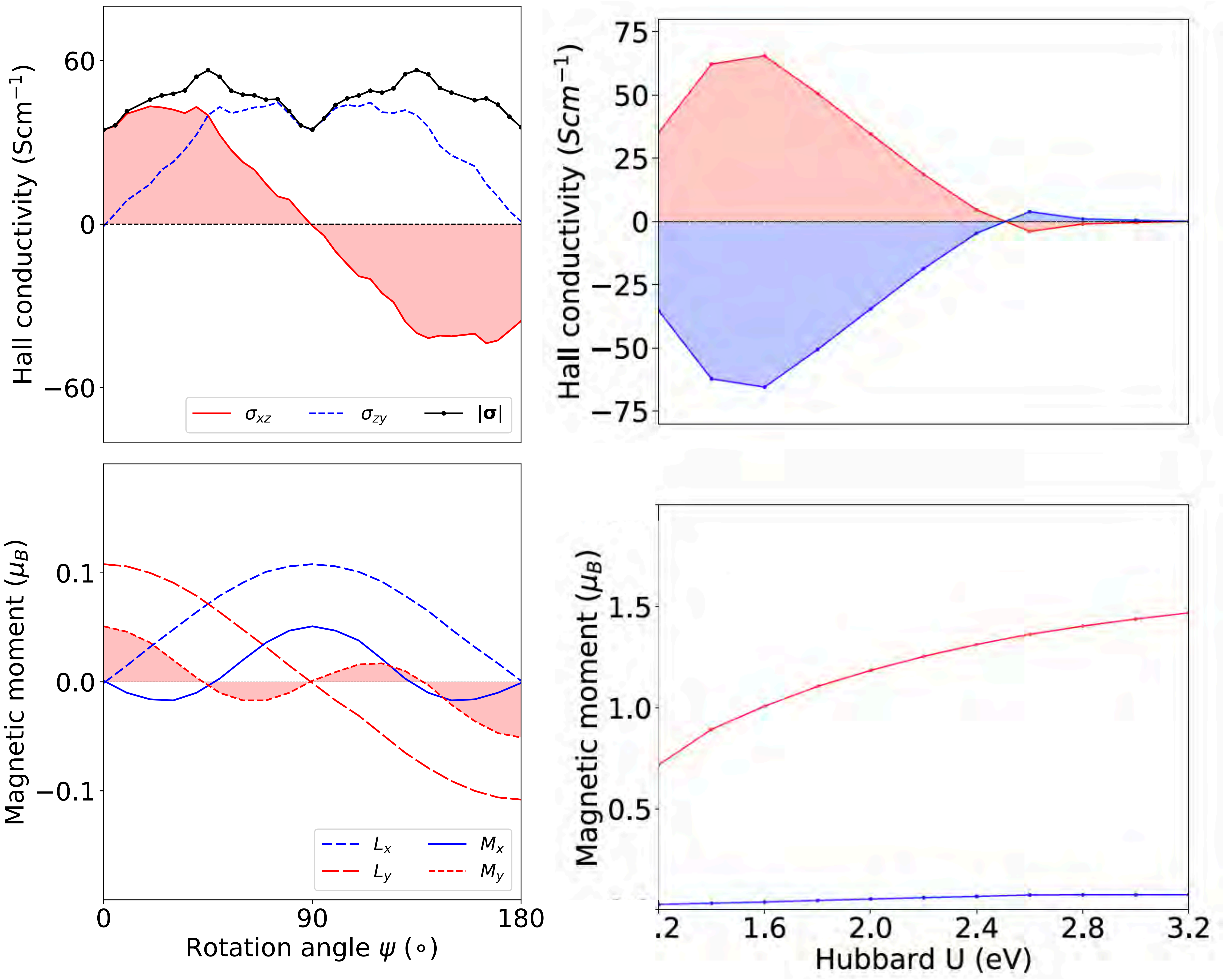
$$\sigma_{xz}(\mathbf{n},\mathbf{m}) = -\sigma_{xz}(-\mathbf{n},\textbf{-m})$$

Anisotropic Crystal Hall effect

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

Hall vector can be switched on-off
Ultimate anisotropy of Hall effect

Hall vector is not proportional to
Sublattice magnetisation
Net magnetisation



Antiferromagnetic minimal model: crystal chirality and topology

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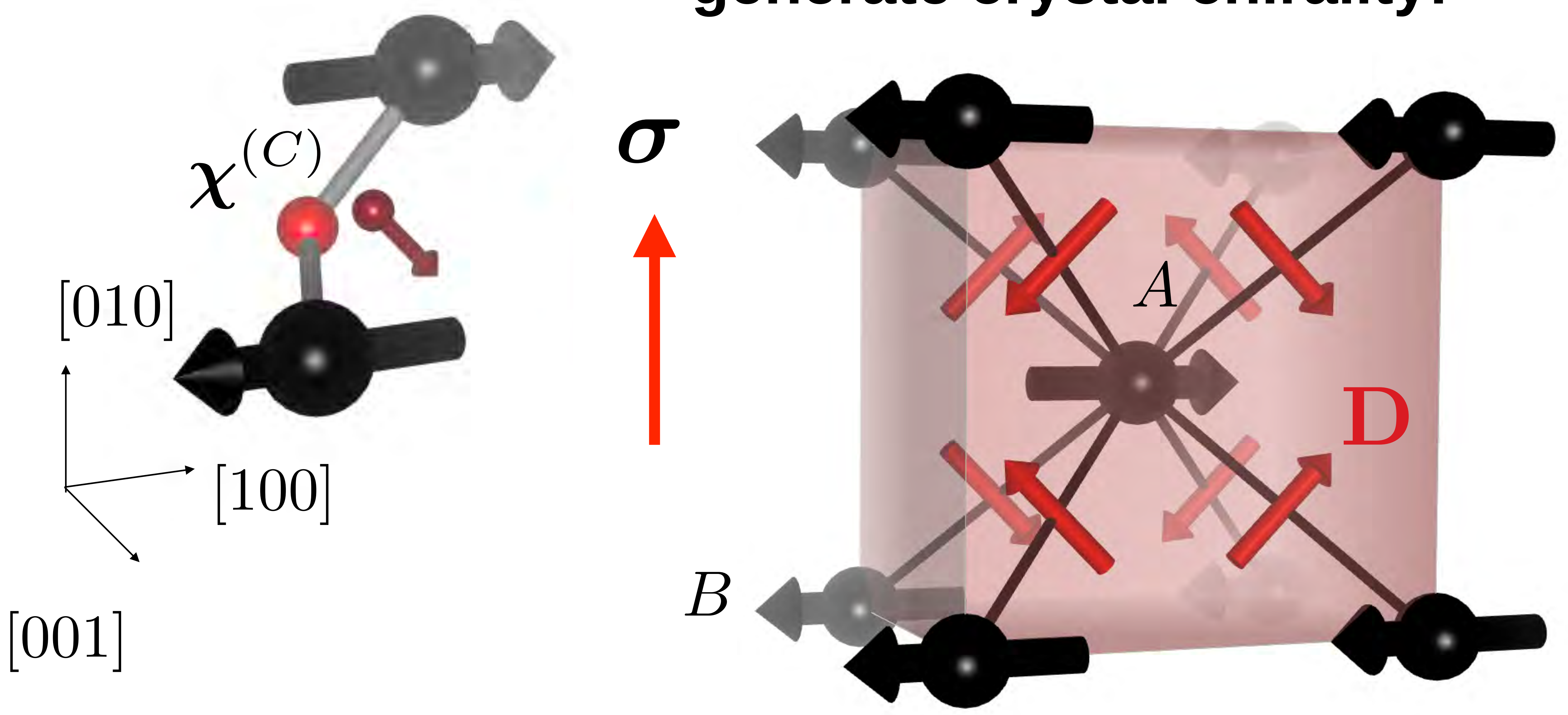
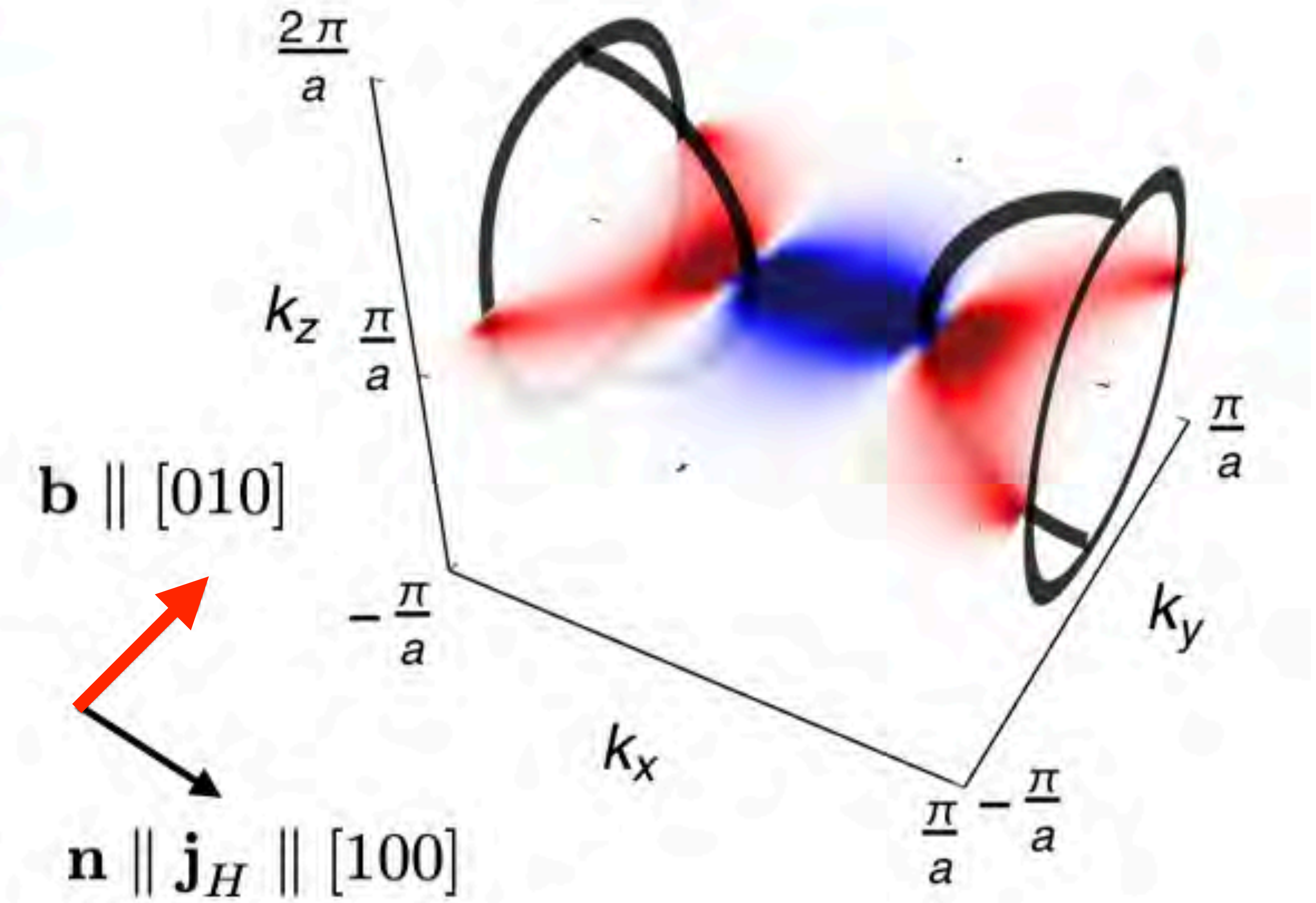
Nonmagnetic atoms at noncetrosymmetric positions generate crystal chirality!





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

Multiple mirrors stabilise nodal chains.

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

$$\chi^{(C)} = \mathrm{sign}\left(\mathbf{d}_{k,A} \times \mathbf{d}_{k,B}\right)$$

Asymmetric spin-orbit coupling:
swap <-> swap Hall vector

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Crystal Hall Effects in Collinear Antiferromagnets

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3. **Classification, material candidates and applications of crystal Hall effect**

    Gonzalez-Hernandez, Zelezny, LS et al. (2019)

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Noncollinear vs collinear antiferromagnets

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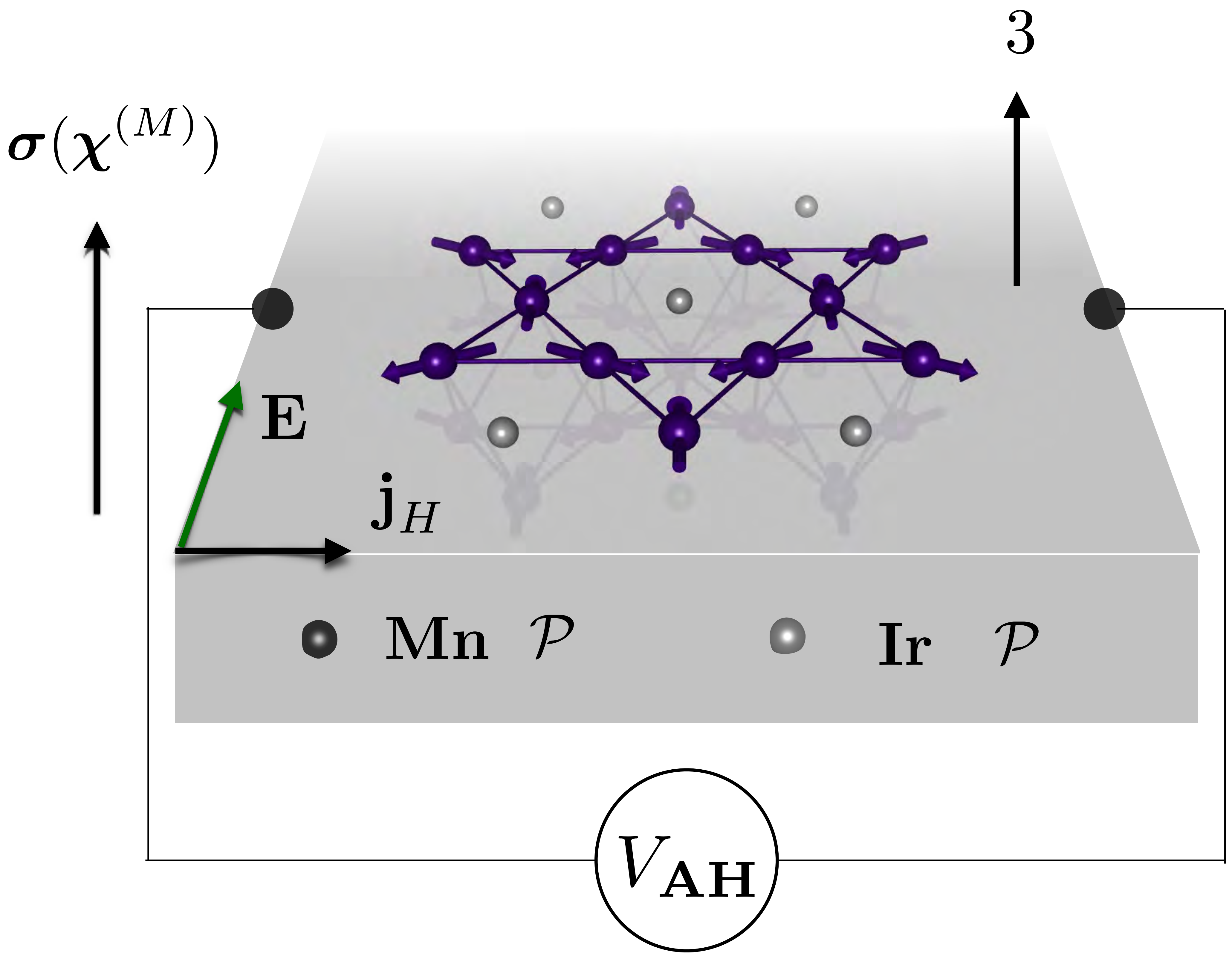
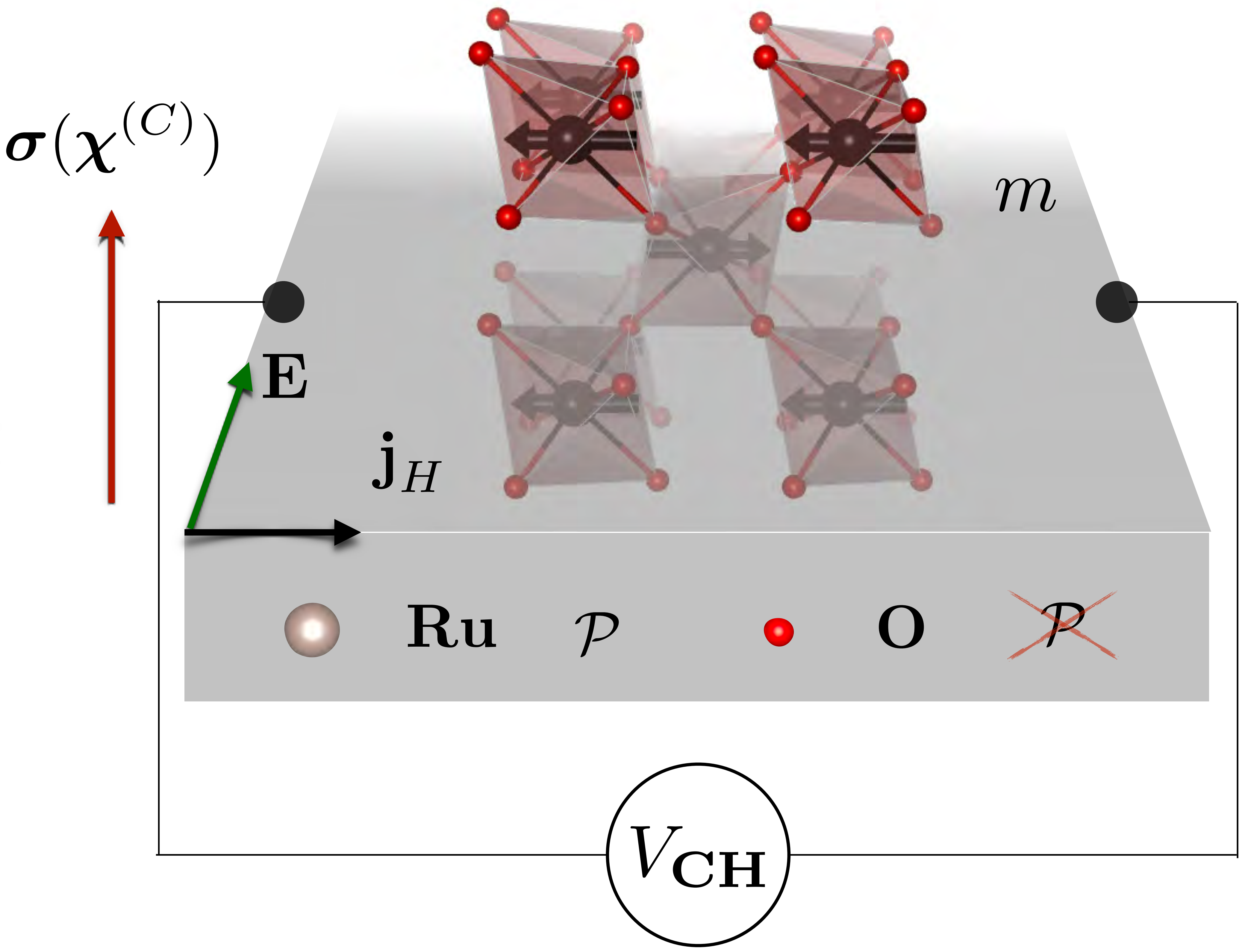
Centrosymetric Wyckoff
Magnetic chirality



Non-censtotrymetric Wyckoff
Crystal chirality



Simple collinear antiferromangetism not compatible with 3, 4, 6 symmetries!

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Classification of crystal Hall antiferromagnets

Centrosymmetric MPG	$\boldsymbol{\sigma}$	Noncentrosymmetric MPG	$\boldsymbol{\sigma}$	Tensor	
$\bar{1}$	arb.	1	arb.	$\begin{pmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{xz} & \sigma_{zy} & \sigma_{zz} \end{pmatrix}$	
$2/m$	$\parallel \mathbf{a}_{C_2}$ $\perp \mathcal{M}$	2 m	$\parallel \mathbf{a}_{C_2}$ $\perp \mathcal{M}$	$\begin{pmatrix} \sigma_{xx} & 0 & \sigma_{xz} \\ 0 & \sigma_{yy} & 0 \\ \sigma_{xz} & 0 & \sigma_{zz} \end{pmatrix}$	
$\bar{3}$ $4/m$ $6/m$	$\parallel \mathbf{a}_{C_2}$	$3\ 4\ 6\ \bar{4}\ \bar{6}$	$\parallel \mathbf{a}_{C_2}$	$\begin{pmatrix} \sigma_{xx} & \sigma_{xy} & 0 \\ -\sigma_{xy} & \sigma_{xx} & 0 \\ 0 & 0 & \sigma_{zz} \end{pmatrix}$	
$2'/m'$	$\perp \mathbf{a}_{\mathcal{T}C_2}$ $\in \mathcal{T}\mathcal{M}$	$2'$ m'	$\perp \mathbf{a}_{\mathcal{T}C_2}$ $\in \mathcal{T}\mathcal{M}$	$\begin{pmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ -\sigma_{xy} & \sigma_{yy} & \sigma_{yz} \\ -\sigma_{xz} & -\sigma_{yz} & \sigma_{zz} \end{pmatrix}$	
$m'm'm$	$\parallel \mathbf{a}_{C_2}$ $\perp \mathcal{M}_z$	$2'2'2\ m'm'2$ $m'm2'$	$\parallel \mathbf{a}_{C_2}$ $\perp \mathcal{M}_y$	$\begin{pmatrix} \sigma_{xx} & \sigma_{xy} & 0 \\ -\sigma_{xy} & \sigma_{yy} & 0 \\ 0 & 0 & \sigma_{zz} \end{pmatrix}$	RuO_2 $CoNb_3S_6$ $CaMnO_3$*
$\bar{3}m'$ $4/m'm'm$ $6/m'm'm$	$\parallel \mathbf{a}_{C_n}$	$42'2'\ 4m'm'\ \bar{4}2'm'$ $32'\ 3m'\ 62'2'$ $6m'm'\ \bar{6}m'2'$	$\parallel \mathbf{a}_{C_n}$	$\begin{pmatrix} \sigma_{xx} & \sigma_{xy} & 0 \\ -\sigma_{xy} & \sigma_{xx} & 0 \\ 0 & 0 & \sigma_{zz} \end{pmatrix}$	Mn_3Pt

$\mathcal{T}$ time inversion

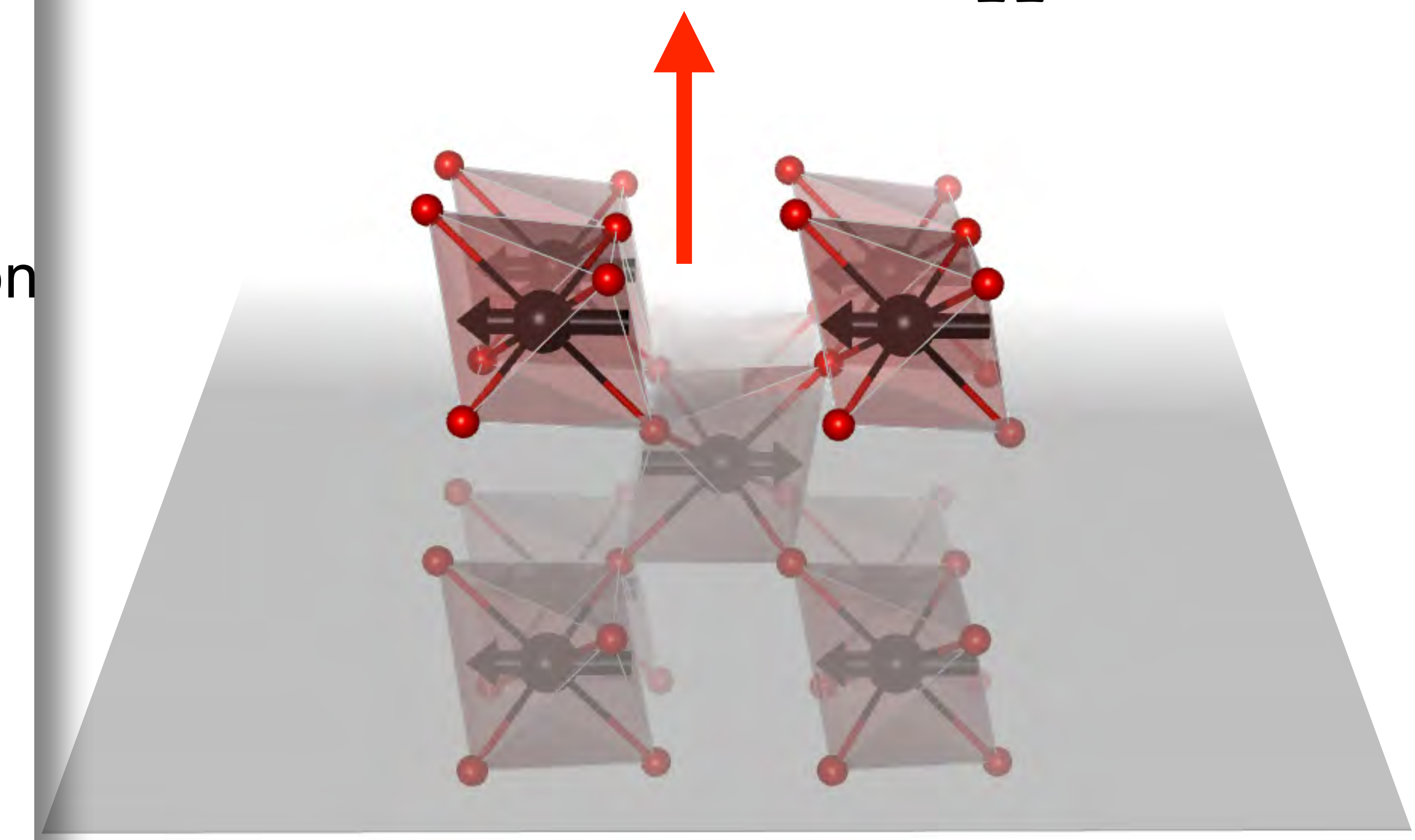
$\bar{1} = \mathcal{P}$ space inversion

$m = \bar{2}$ mirror

$\bar{1}' = \mathcal{P}\mathcal{T}$

Hall plane does not have to be given by symmetry!

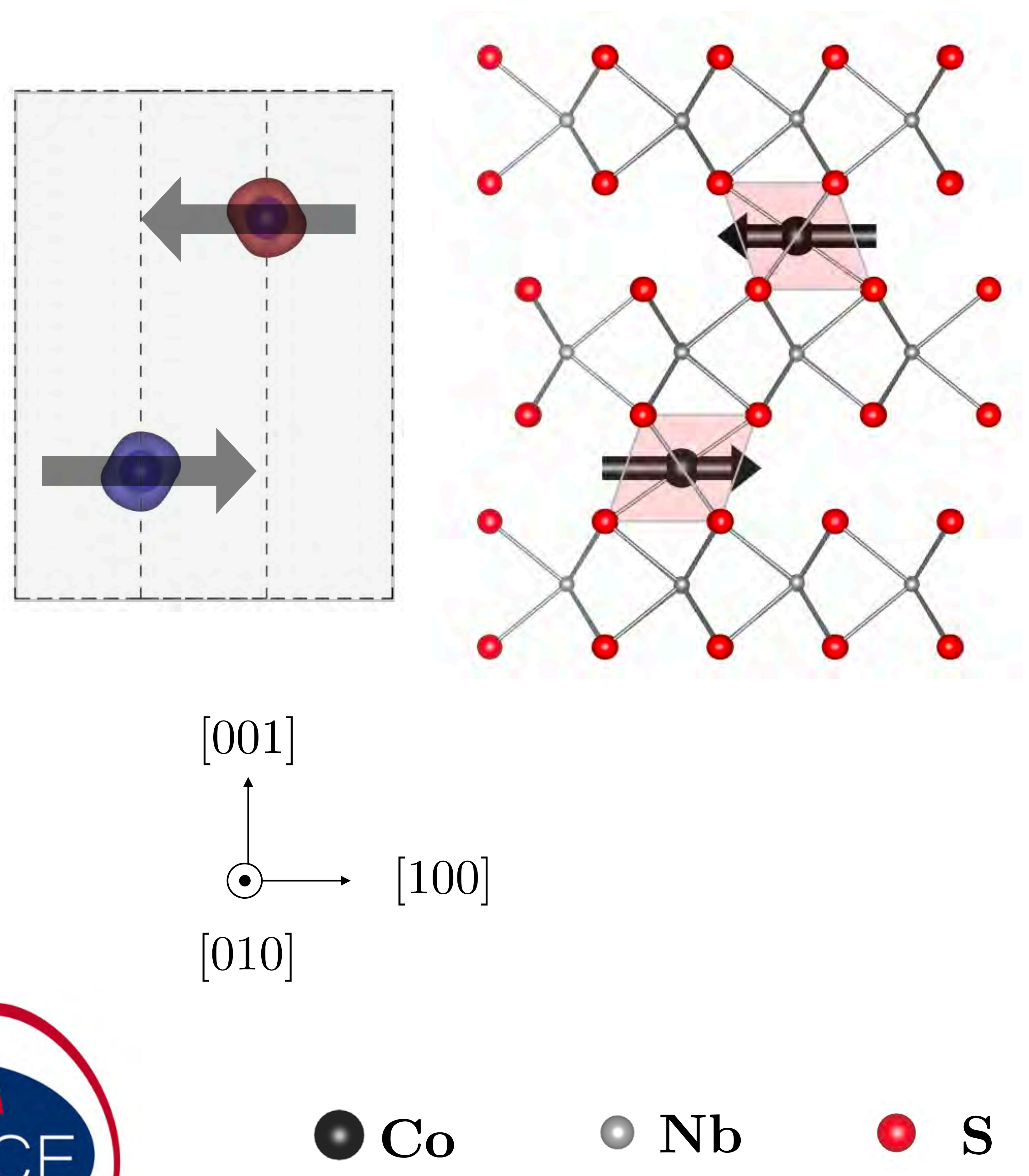
$$\boldsymbol{\sigma} \sim \mathbf{E} \times \boldsymbol{j}_H$$

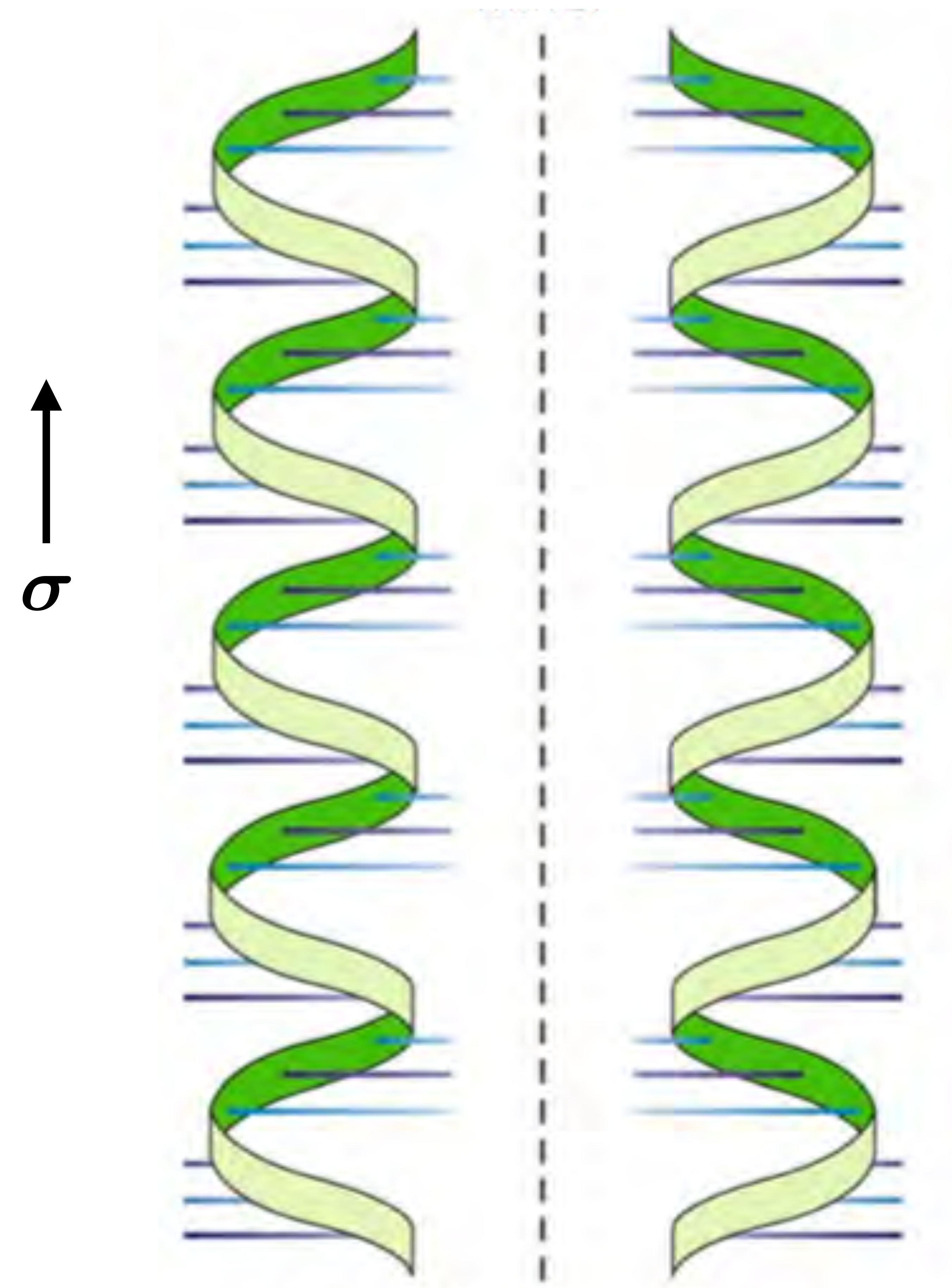


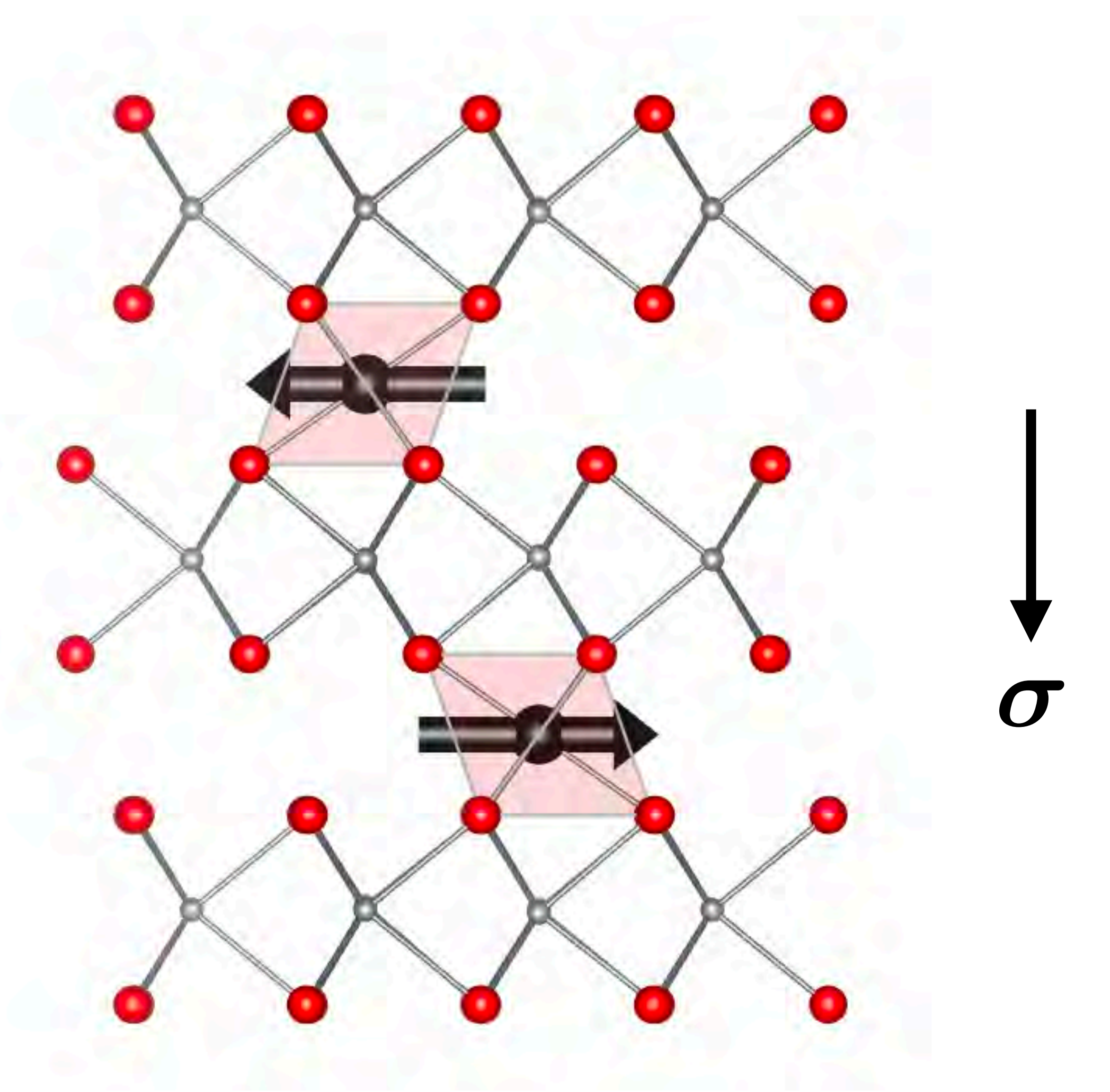
~5/10 ferromagnetic Laue point groups
~1/10 of magnetic material database **are** crystal Hall antiferromagnets!

Global chirality in $CoNb_3S_6$ antiferromagnet

left-handed | Mirror | right-handed







Experiment: ~**27 S/cm**

Ghimire et al. Nat. Comm. (2018)

Our theory: ~80 S/cm

Global crystal chirality controls Hall sign!

Measured Hall effects in antiferromagnets

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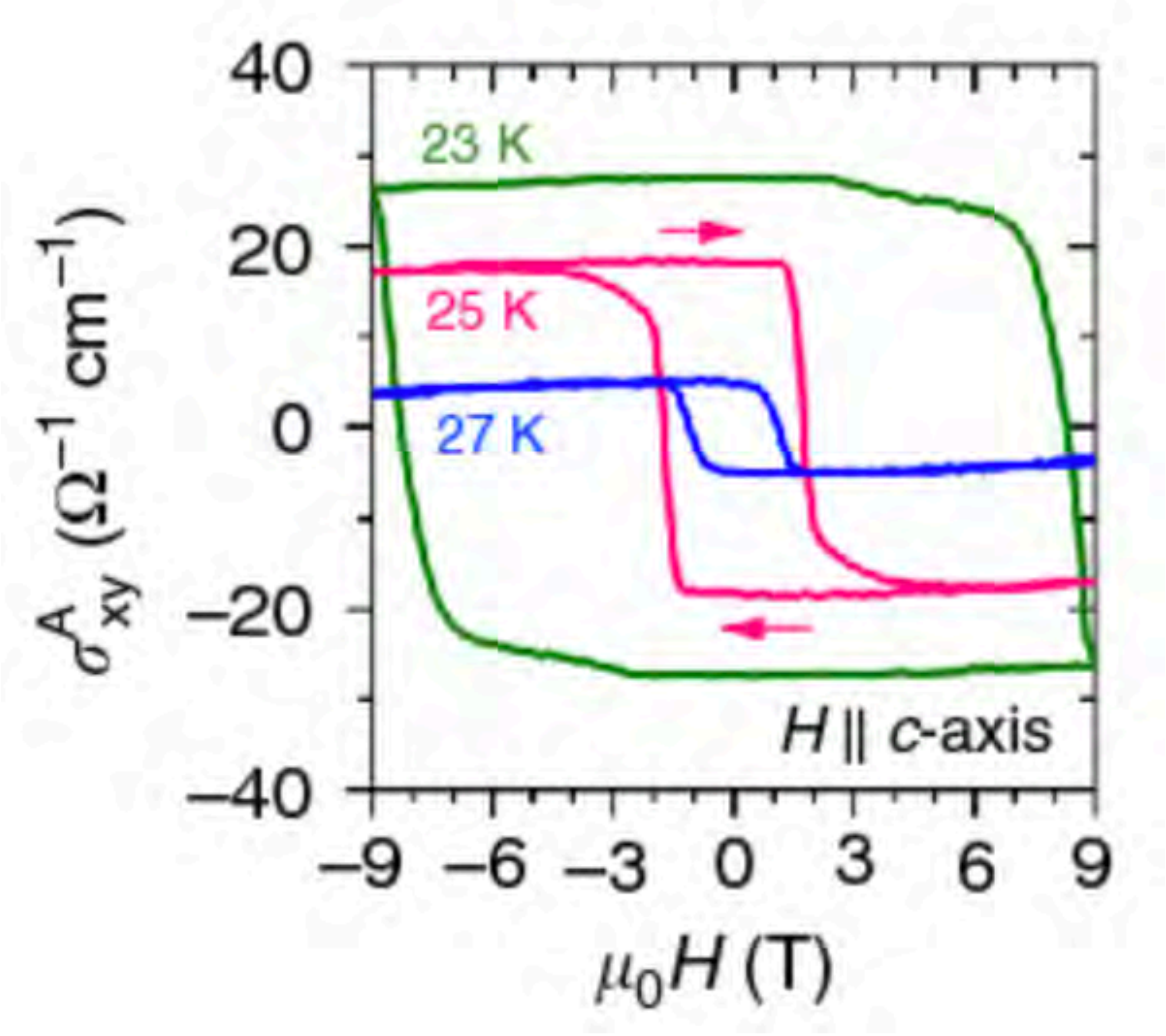
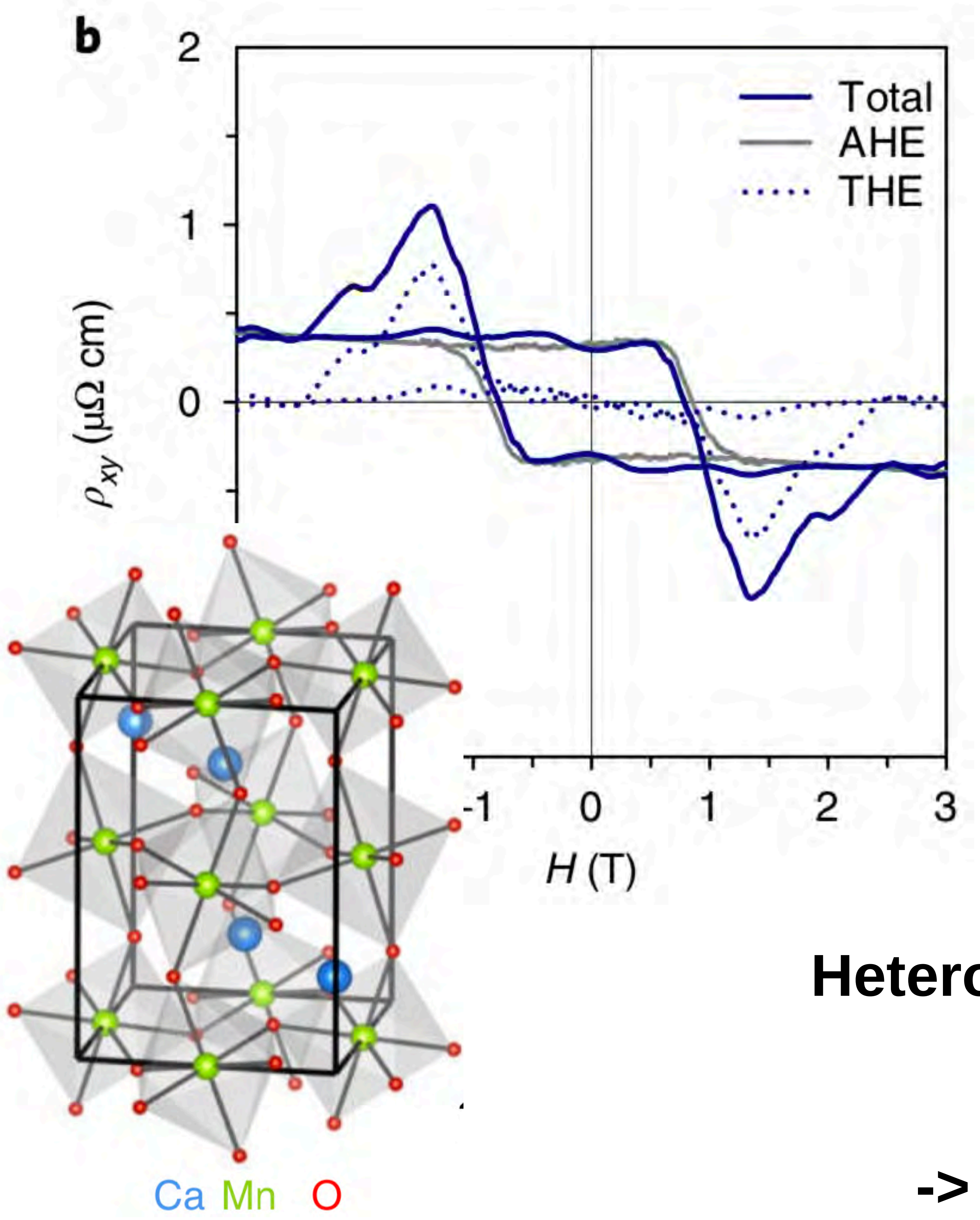
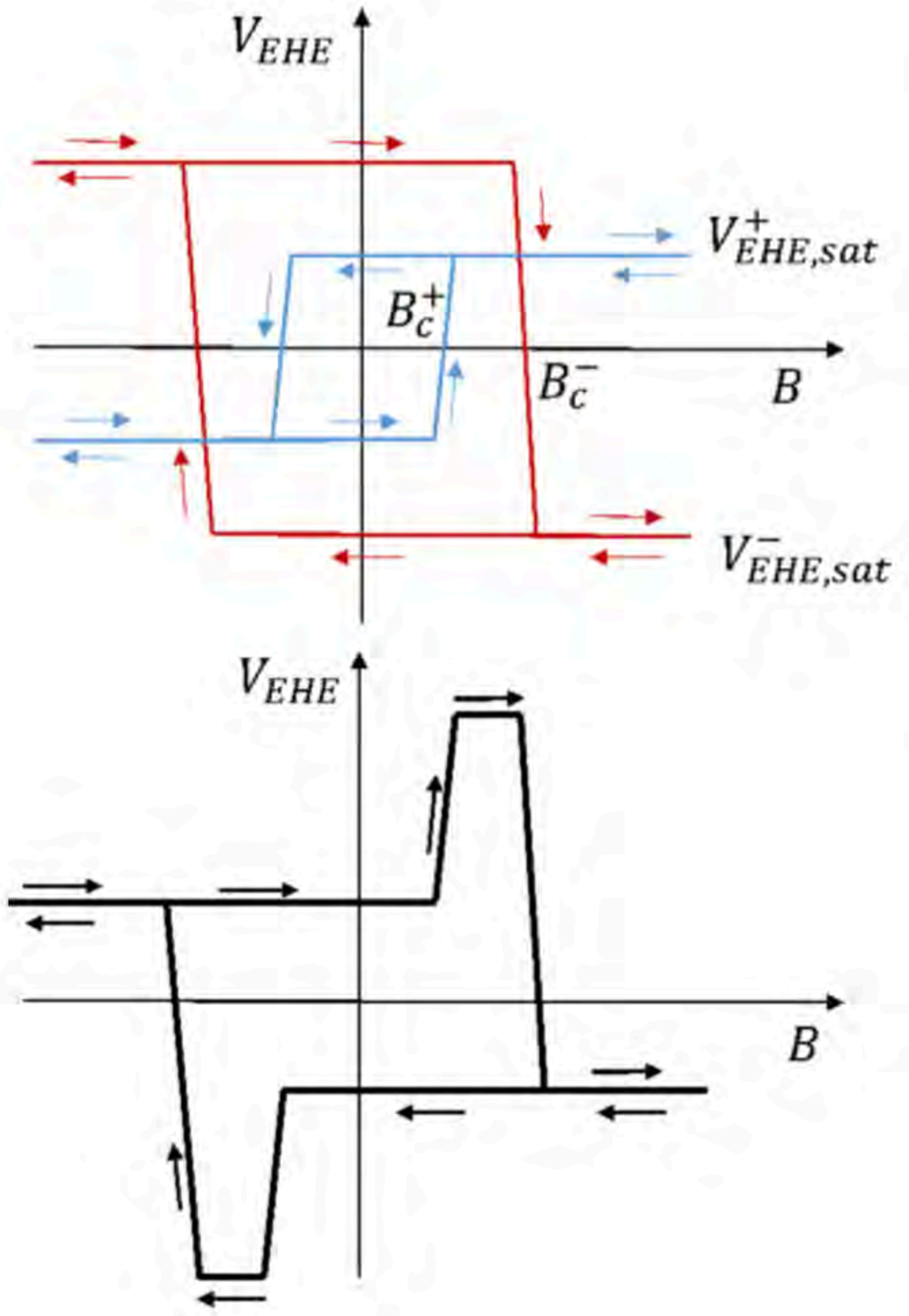
Experiment: ~**27 S/cm**
Ghimire et al. Nat. Comm. (2018)
Our theory: ~80 S/cm



Experiment
Bibes et al. Nat. Phys. (2018)
Topological Hall effect?





Heterogenous ferromagnets with anomalous Hall with opposite polarities
Gerber, PRB (2018)
-> crystal chiral domains —> Crystal Hall effect

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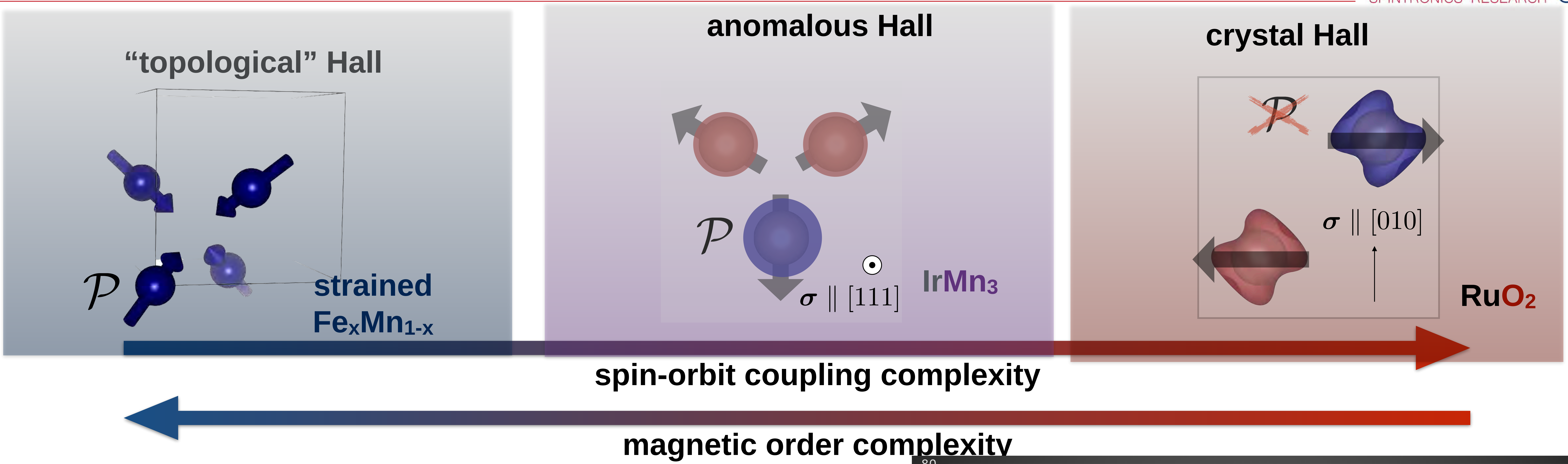
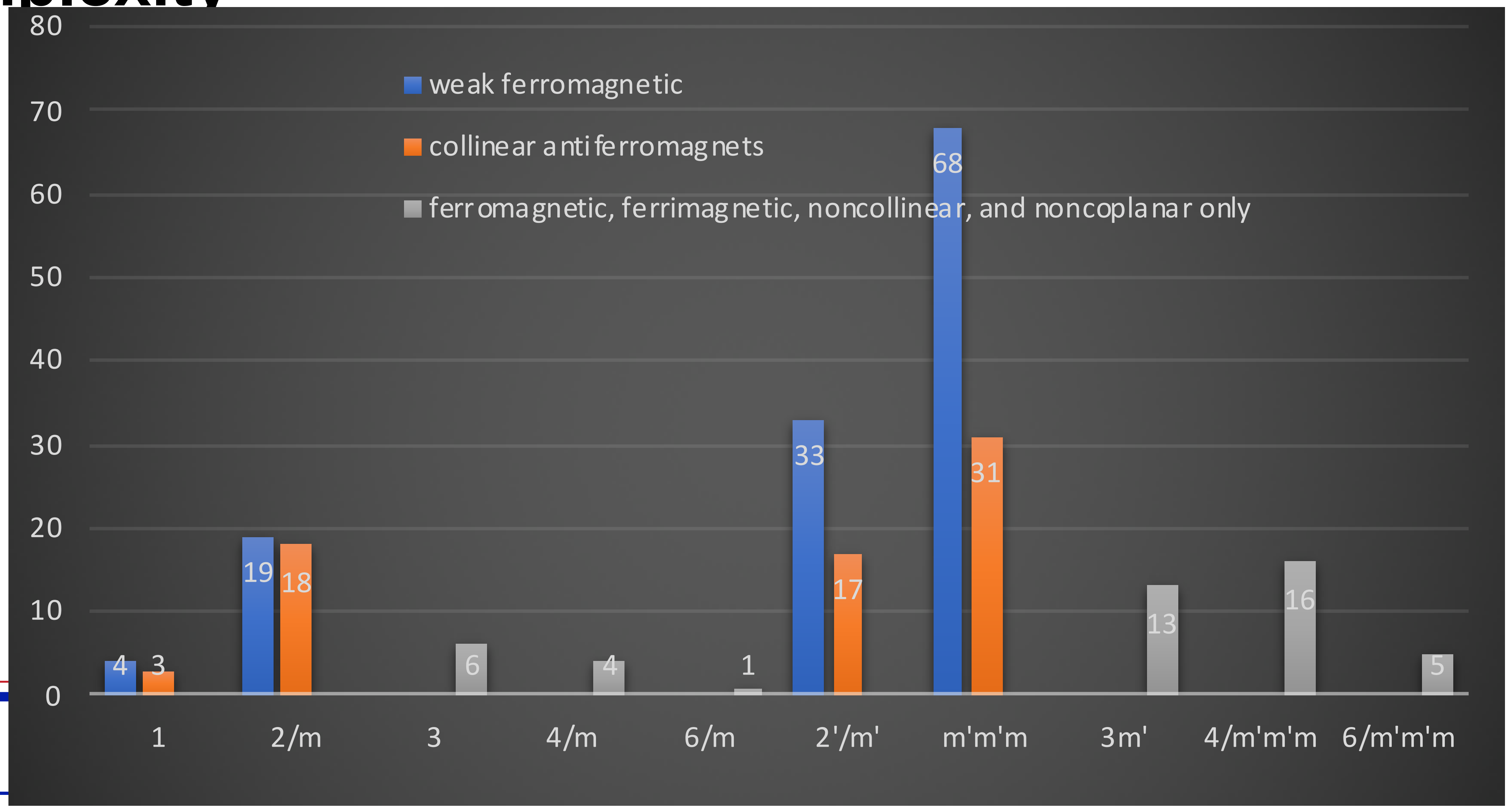
Spontaneous Hall antiferromagnets $\rho_H = \rho_{THE} + \rho_{AHE} + \rho_{CHE}$



A. Allows Hall effect in abundant collinear antiferromagnets ~1/10!
B. Fundamental understanding (anisotropy, orbital, spin-orbit)
C. Many more variants to come.

LS, R.Hernandez-Gonzales, TJ, JS, arXiv 1901.00445 (2019)



Thank you for your attention and looking forward for your questions!

Ilja Turek, Karel Carva, Jakub Železný (Prague)
Rafael Hernandez-Gonzalez, Kei Yamamoto, Olena Gomonay, Martin Jourdan, Stanislav Yu Bodnar, Mathias Kläui (Mainz)

Yuriy Mokrousov (Julich)
Helena Reichlova, Dominik Kriegner (Dresden)
Laura Mihalceanu (Kaiserslautern)
Mazhar Ali (Halle), David Marsch (Gottingen)

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