Spontaneous anomalous Hall response and altermagnetism explored in MnTe and Mn_5Si_3

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Institut für Festkörper- und Materialphysik, TU Dresden

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- Sebastain T. B. Goennenwein, Ruben D. Gonzalez Betancourt, Rafael Lopez Seeger, Vincent Baltz, Lisa Michez, Ismaila Kounta, Gunter Springholz, Richard Schlitz, Eva Schmoranzerova, Antonin Badura, Zbynek Soban, Kamil Olejnik, Jan Zubac, Philipp Ritzinger, Andy Thomas, Sebastian Beckert, Michaela Lammel, Miina Leiviska, Vaclav Petricek, Dominik Kriegner

Outline

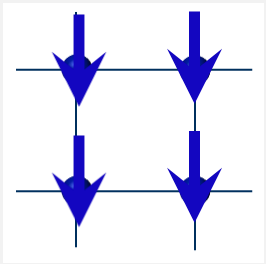
- Magnetically ordered materials
- Anomalous Hall effect in materials with vanishing magnetization
- Anomalous Hall effect in semiconducting MnTe
- Anomalous Hall effect in spin d-wave candidate Mn_5Si_3
- Discussion and Outlook

🕮 Reichlova et al., arXiv:2012.15651
🕮 Gonzalez Betancourt et al., arXiv:2112.06805
🕮 González-Hernández et al. PRL (2021)
🕮 Smejkal et al. Sci Adv (2020)
🕮 Smejkal et al. Nat Rev Mat. (2022)

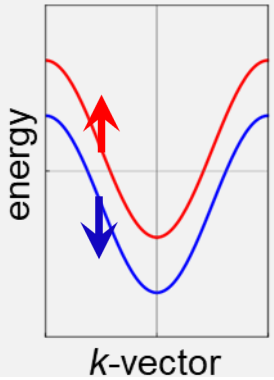
Magnetically ordered collinear materials

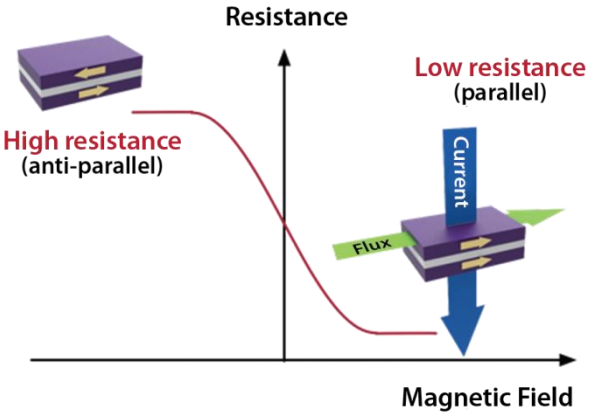
classification without spin orbit coupling

Ferromagnets



- net magnetization
- exchange splitting
- breaking $\mathcal{T}$ symmetry in electronic band structure
- industry favorite (GMR)





🕮 Resker, Electronic Products

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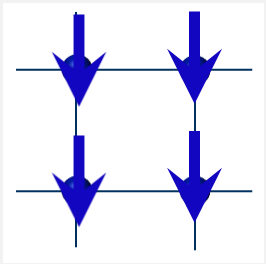

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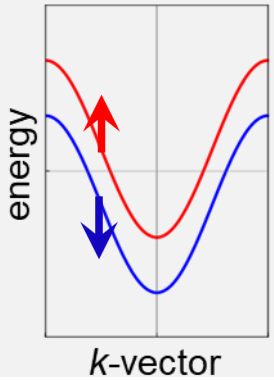

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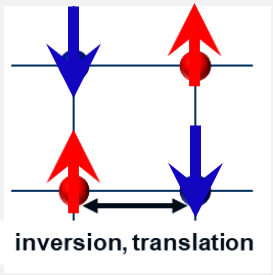
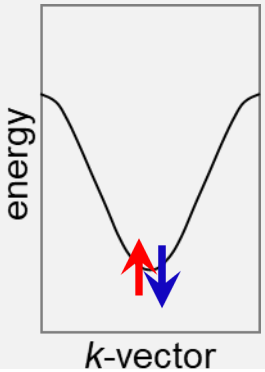
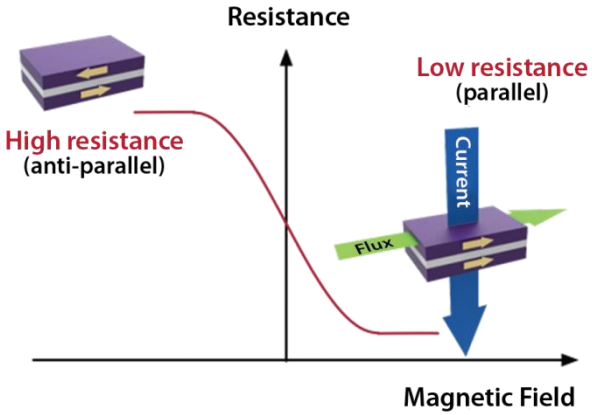


- no net magnetization
- no spin splitting
- no breaking $\mathcal{T}$ symmetry in electronic band structure
- application potential (speed...)





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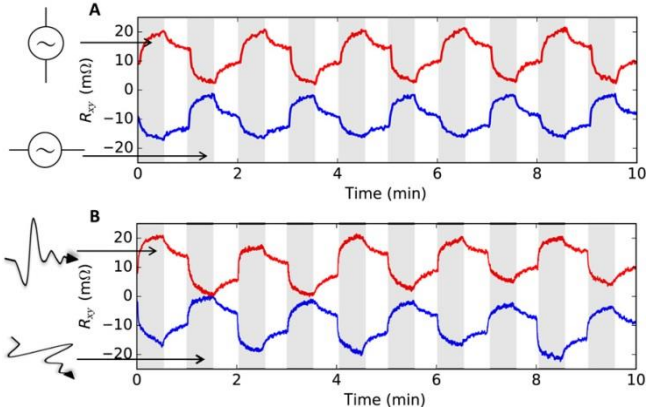
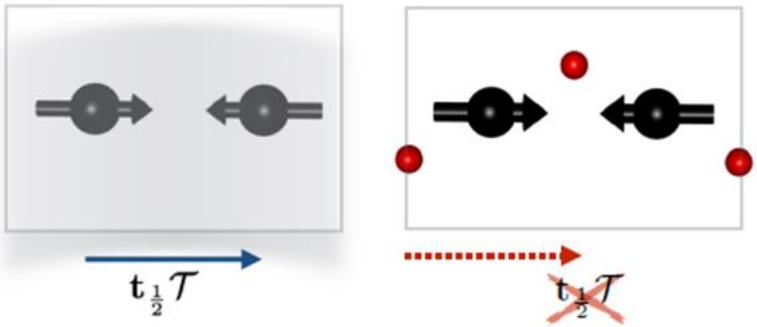


🕮 Olejnik et al. Sci. Adv. (2018)

Class combining properties of antiferromagnets and ferromagnets

1) real space – $t_{1/2}\mathcal{T}$ breaking by **non-magnetic atoms**



- Smejkal et al. Sci Adv (2020)
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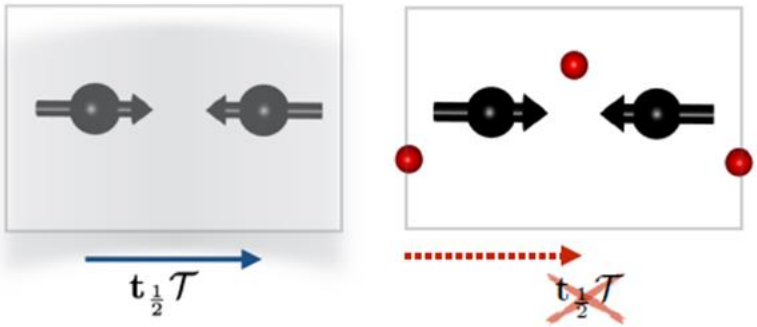
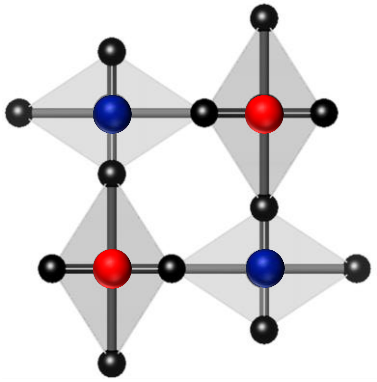
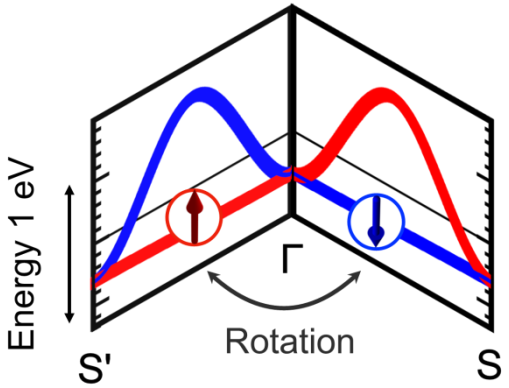




2) momentum space



- opposite spin splitting of two sub-lattices

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Alternating spin splitting = *altermagnets*

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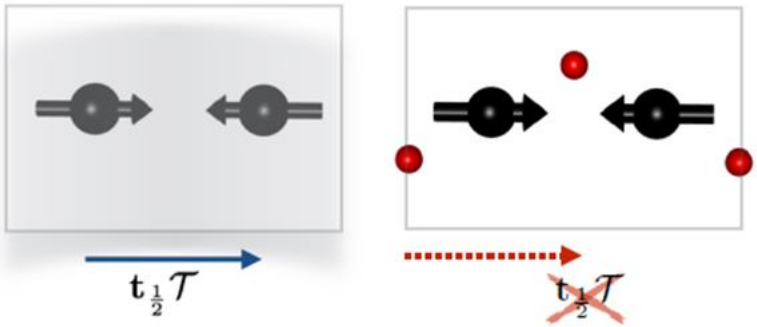

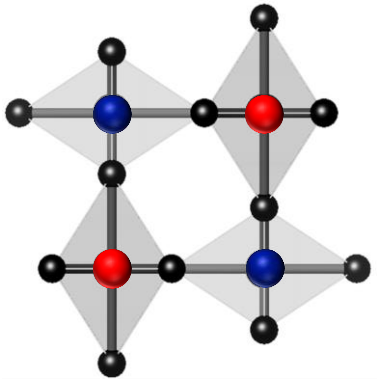

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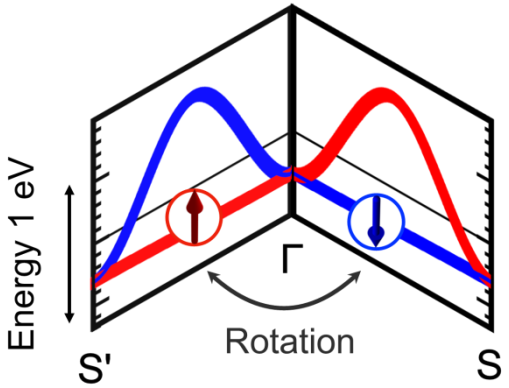

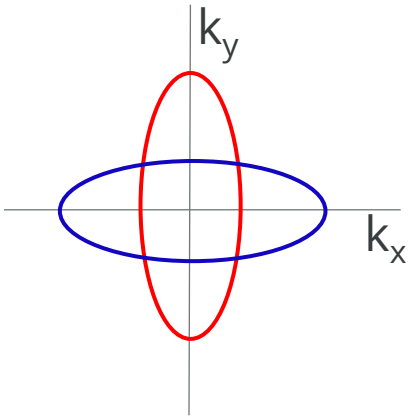

- opposite spin splitting of two sub-lattices
- anisotropic splitting in the band structure
- conserved spin

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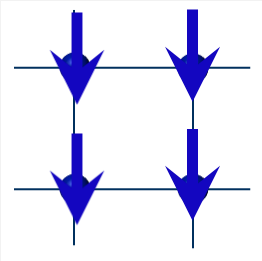

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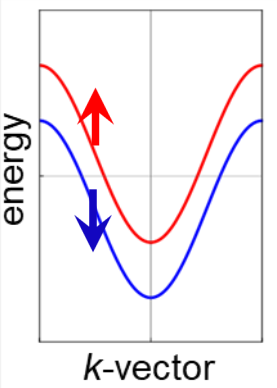

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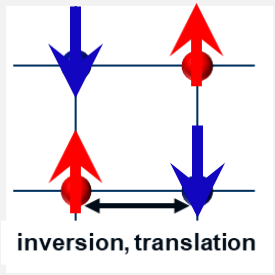

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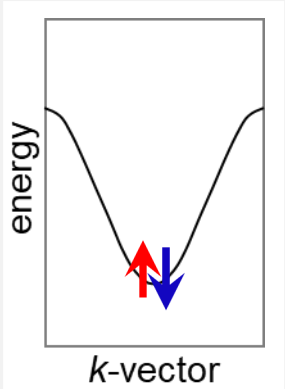

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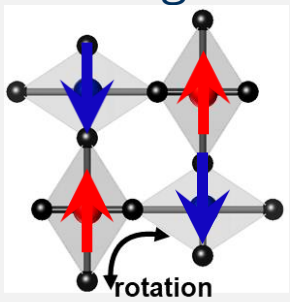
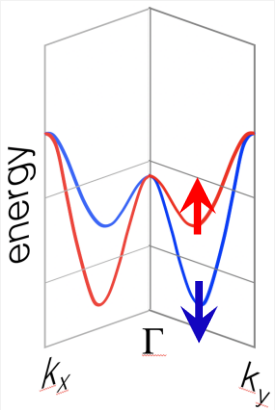
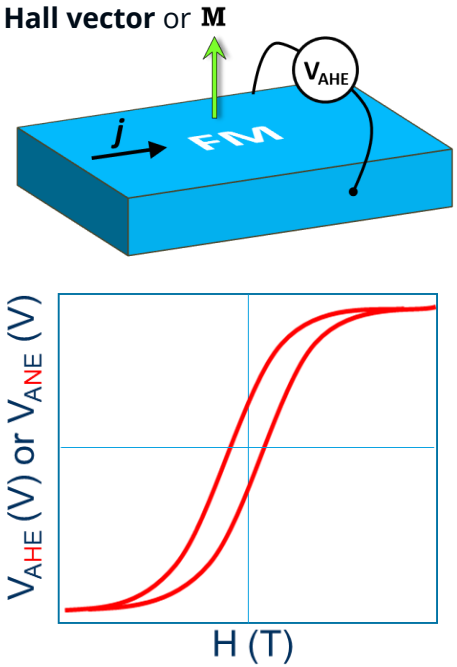


- no net magnetization
- anisotropic spin splitting
- breaking $\mathcal{T}$ symmetry in electronic band structure
- high speed, GMR potential...



Breaking $\mathcal{T}$ symmetry in band structure
=> anomalous Hall effect



1881: empirical relation $\rho_H \sim R_0 B + R_S M_z$

from 50' discussing the exact origin...

2010: AHE in a spin liquid candidate

2014: AHE predicted for non-collinear magnets

2015: AHE in non-collinear Mn_3X

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- Nagaosa et al. Rev. Mod. Phys. (2010)
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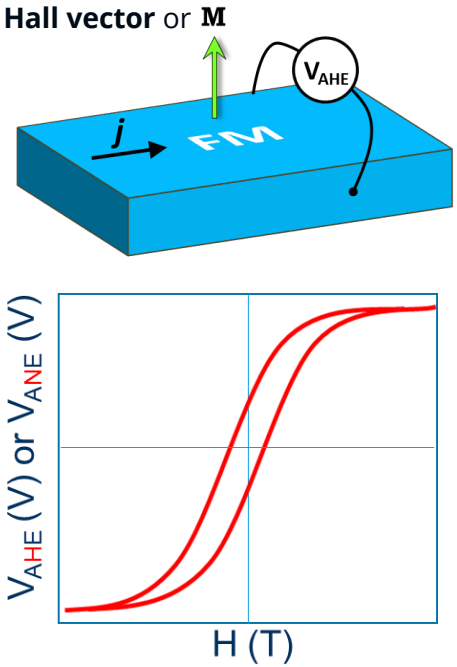

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- not spontaneous AHE

2022: Mn_5Si_3 and MnTe **this talk**

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Semiconducting altermagnet MnTe

- seminconductor, gap 1.4 eV
- MBE growth InP (111) / MnTe
- Mn hexagonal planes + Te atoms at non-centrosymmetric positions

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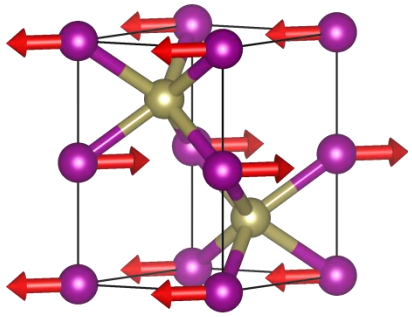

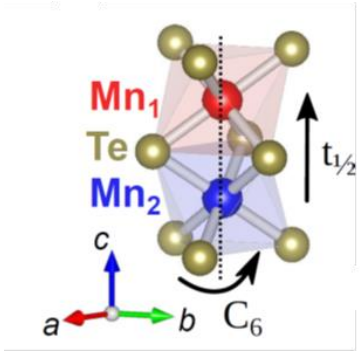

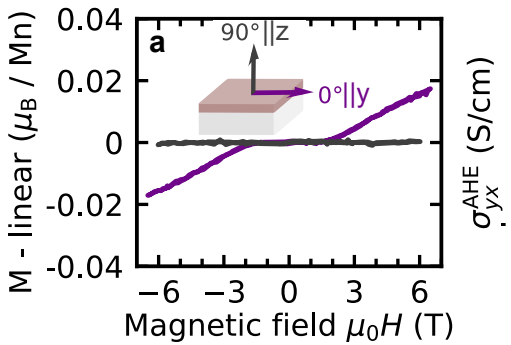

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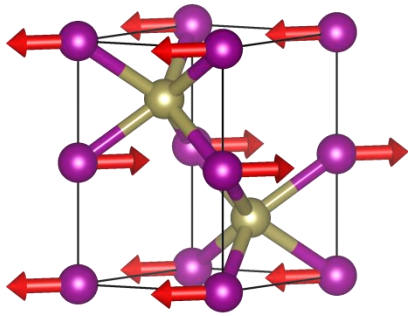
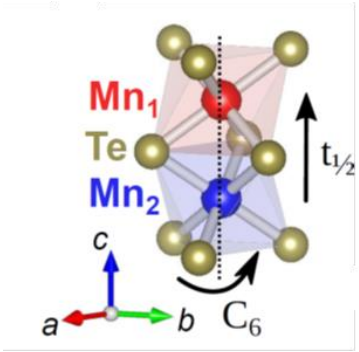
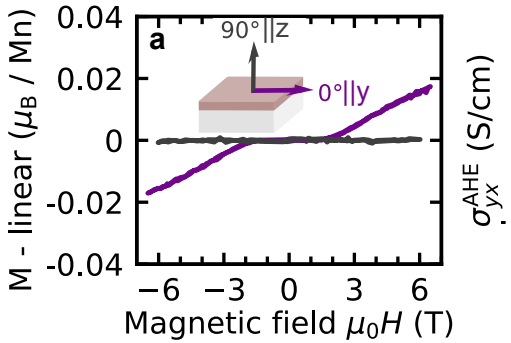
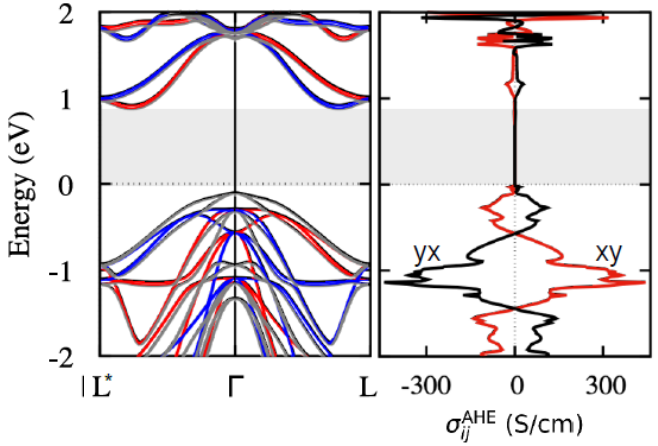


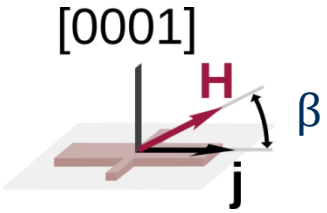


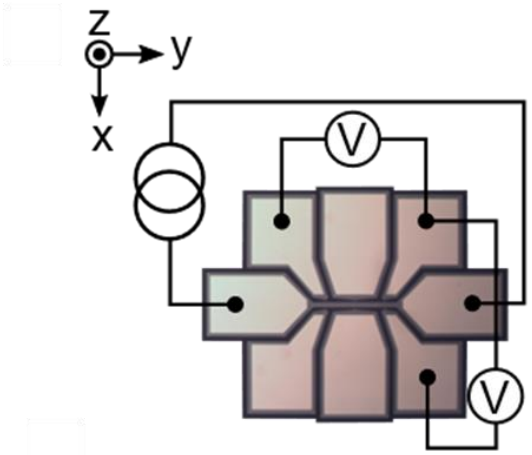


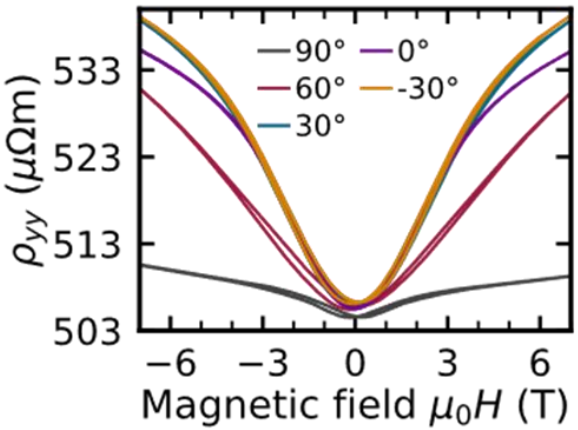
- spin degenerate along high symmetry directions
- spin splitting between Γ and L
- AHE theoretically allowed



Magnetic field sweeps







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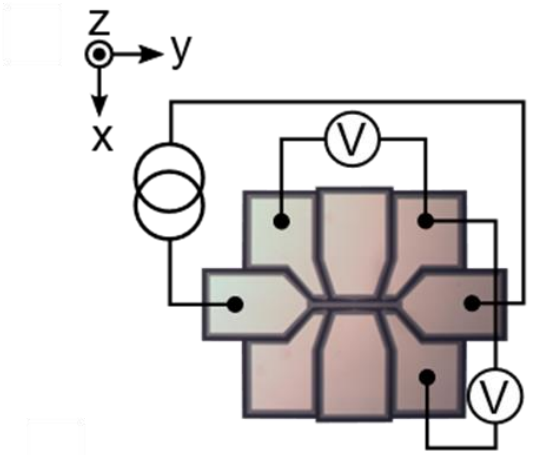
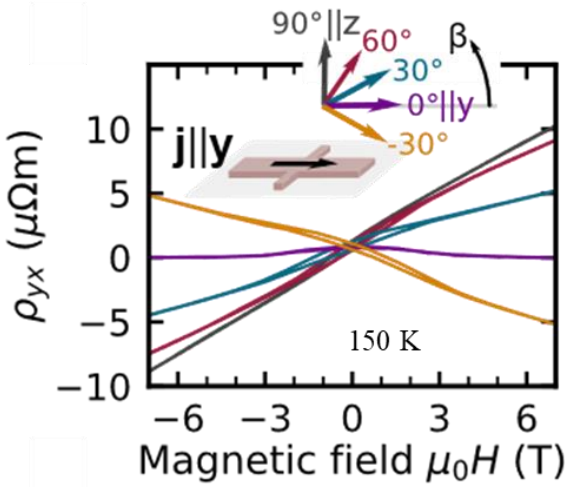
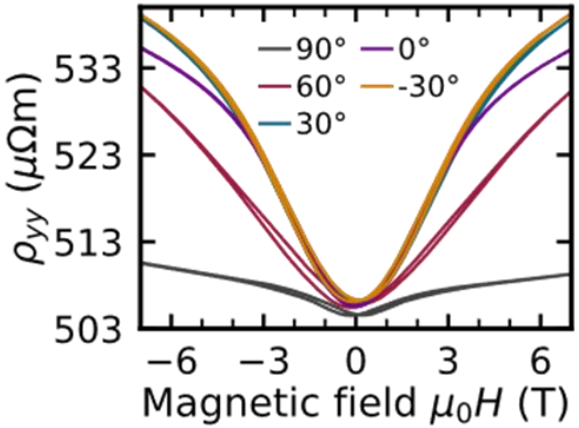
Magnetic field sweeps

- out-of plane Hall vector linked to in-plane compensated moments







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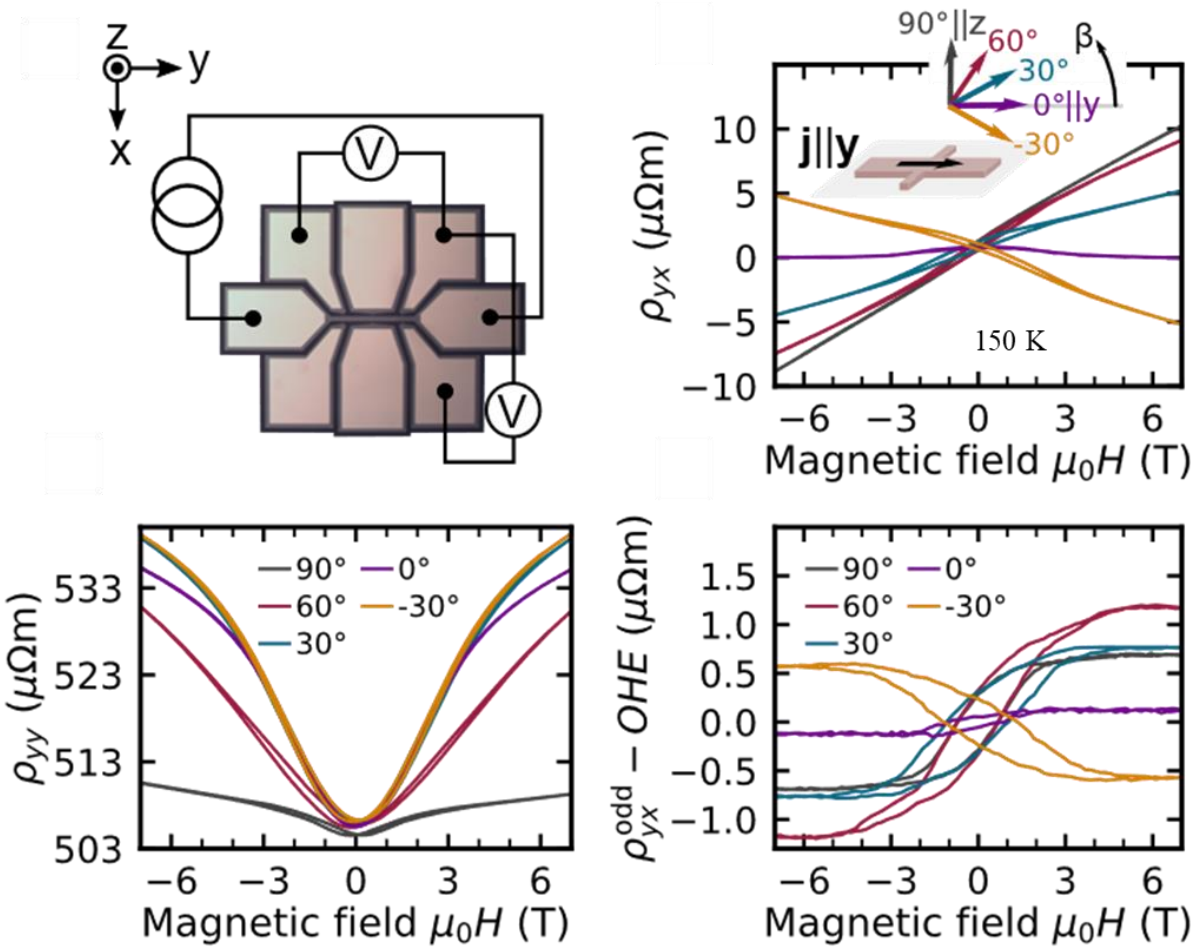
- out-of plane Hall vector linked to in-plane compensated moments
- magnetic field induced reversal of the Hall vector



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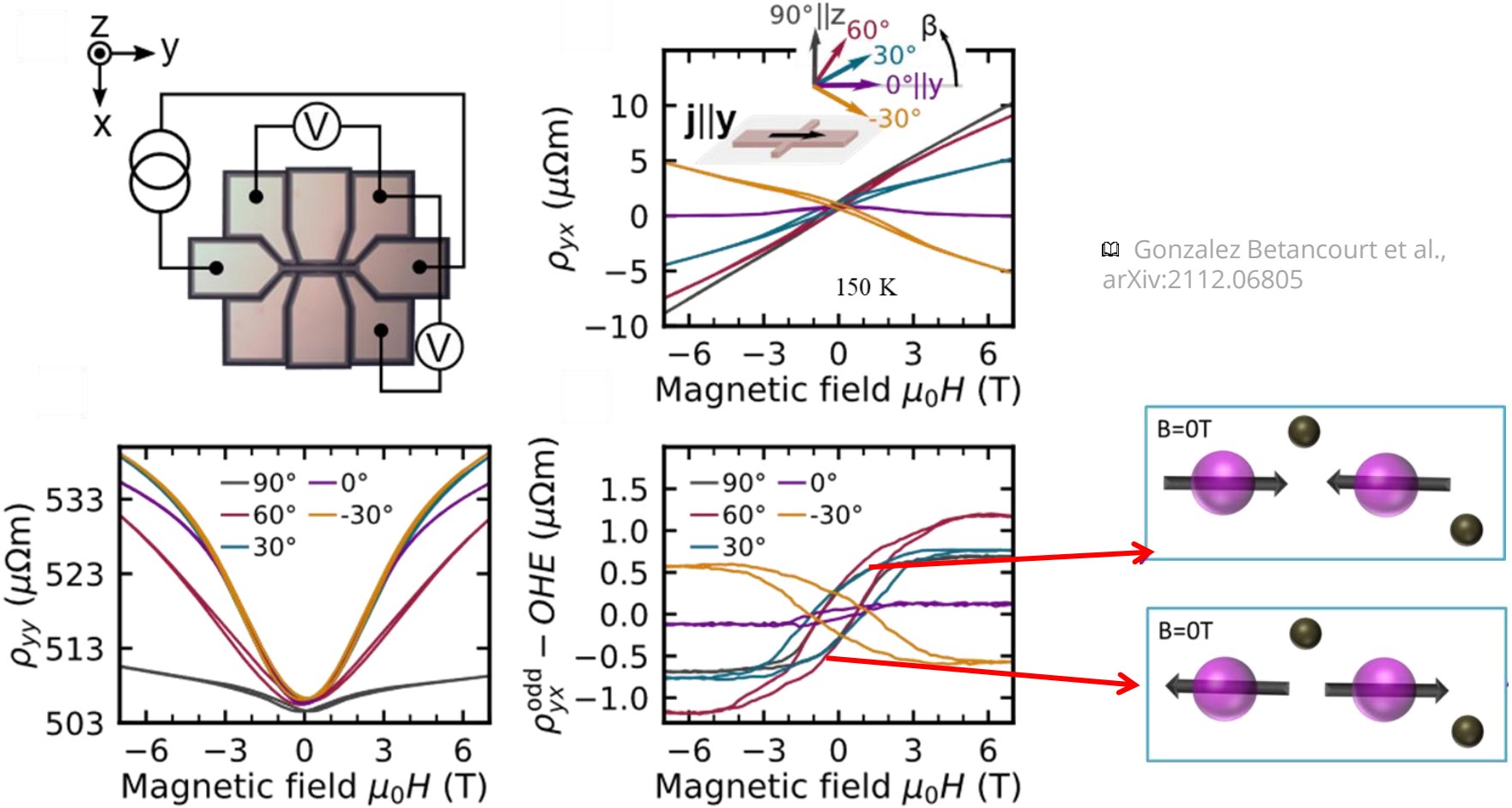

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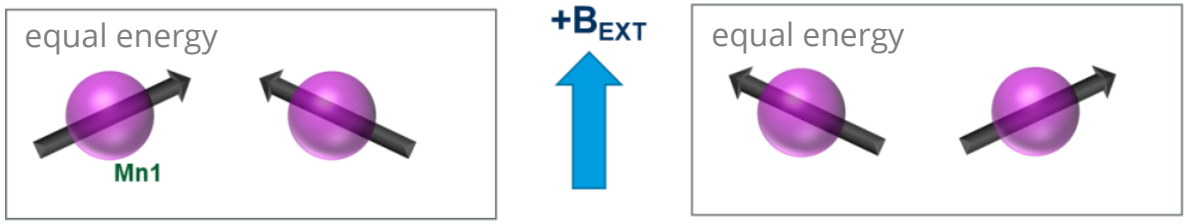
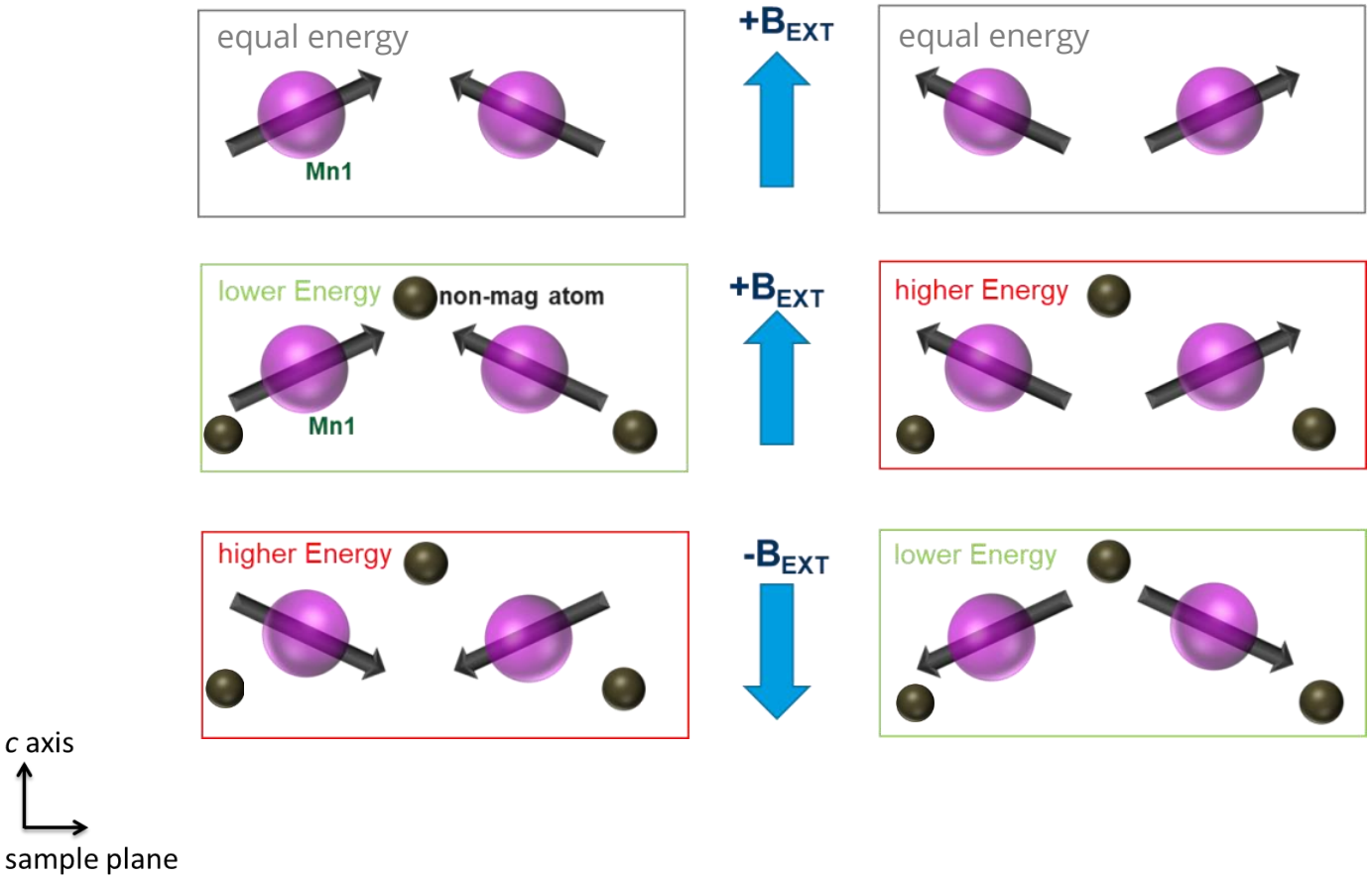
Magnetic order reversal - cartoon



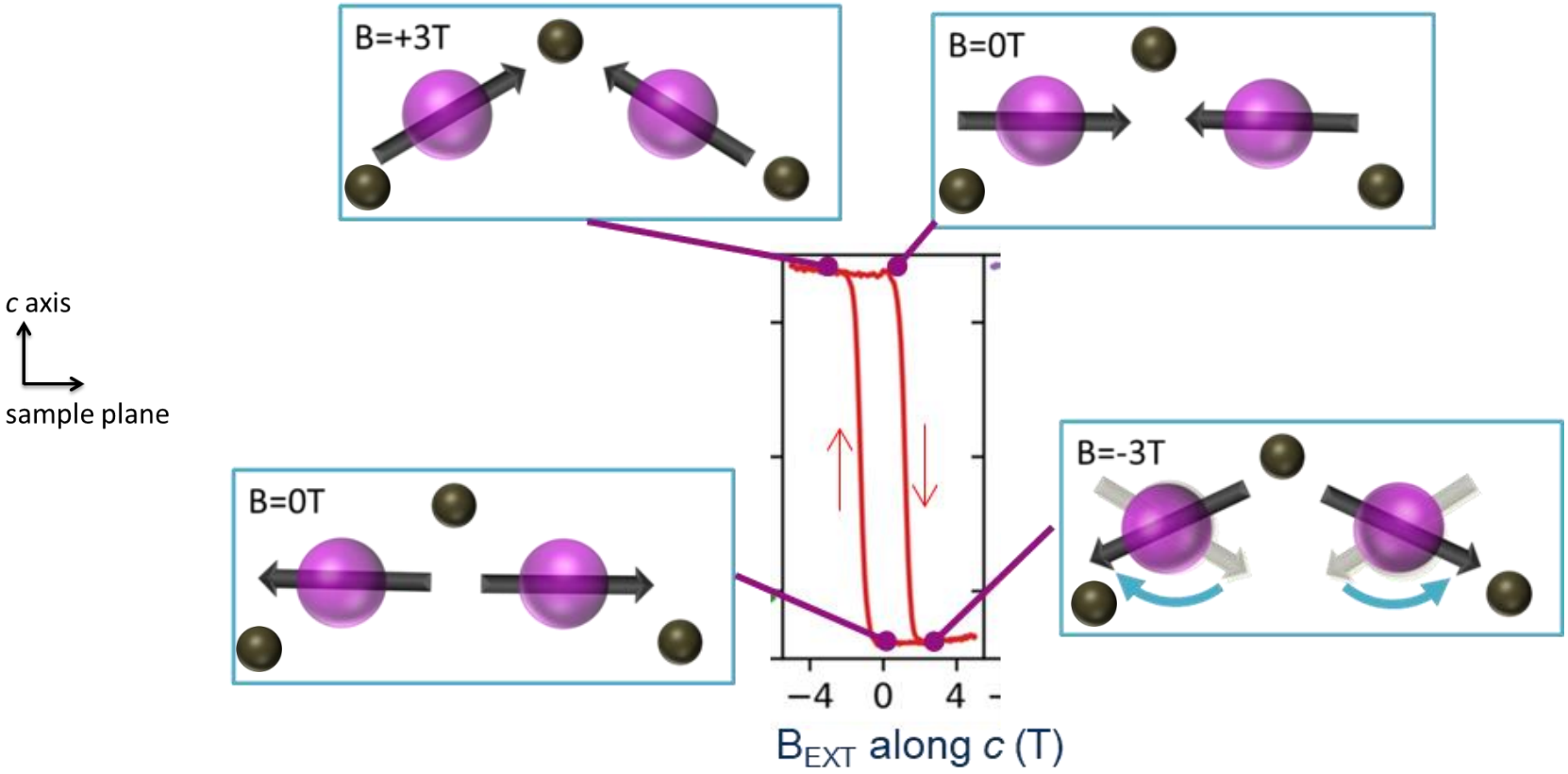
Magnetic order reversal - cartoon

- considering also the non-magnetic atoms
- preferred only one orientations of spins



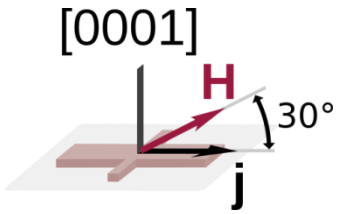
Magnetic order reversal – simplified cartoon

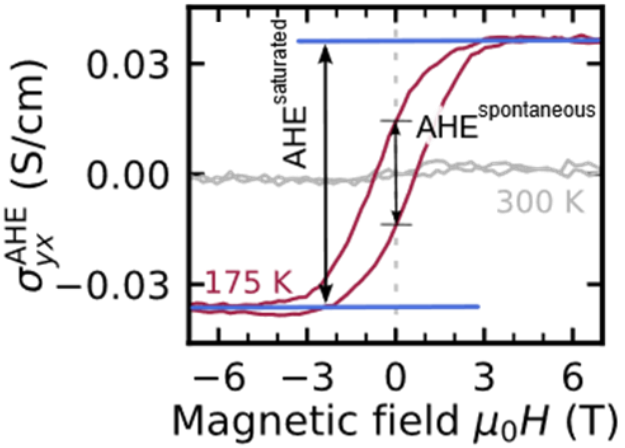
- why hysteresis?
- preferred only one orientations of spins
- spontaneous – remnant in B = 0T



canting of moments heavily exaggerated!

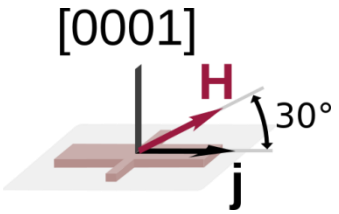
Temperature dependence of the AHE

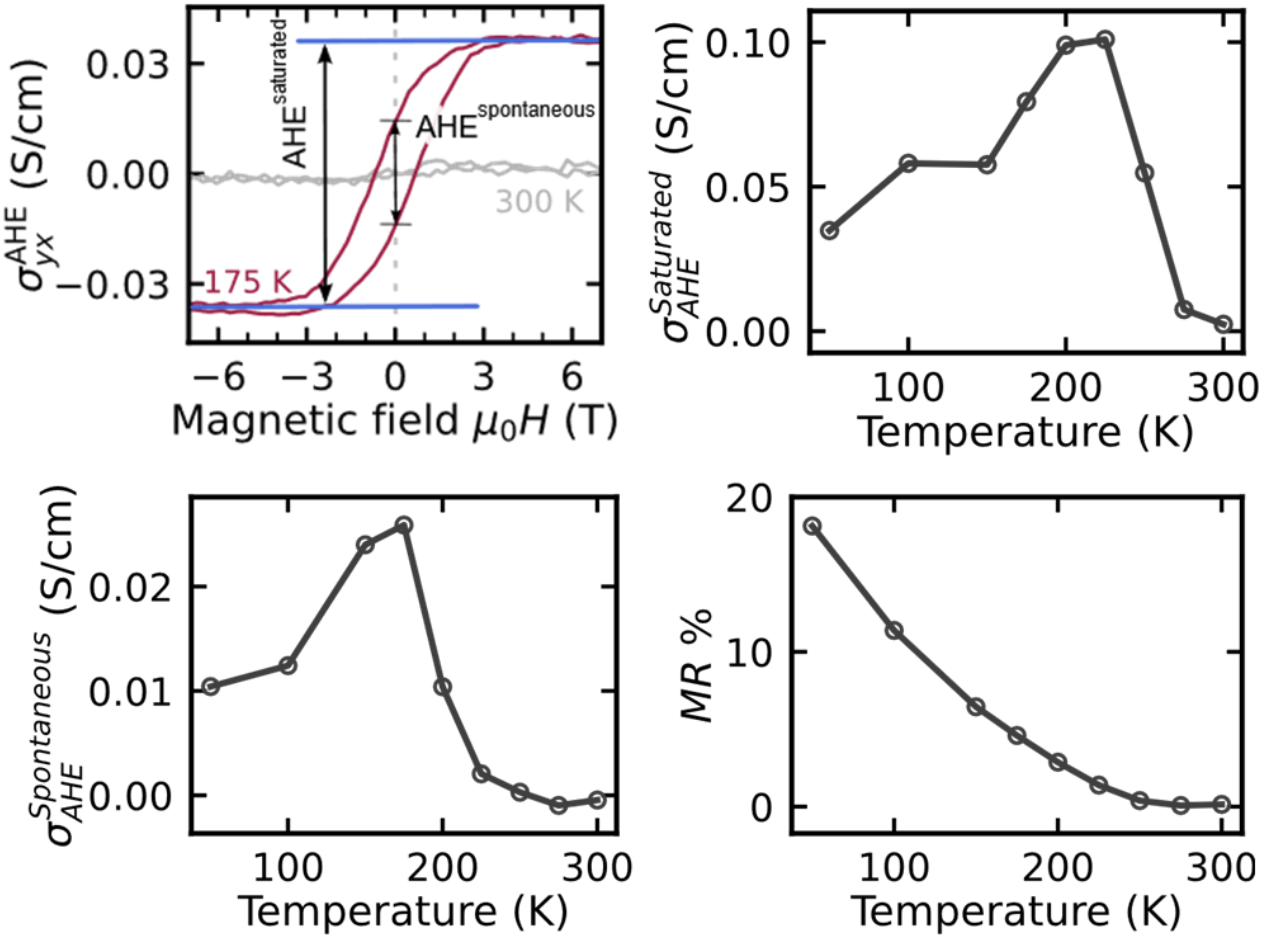




Temperature dependence of the AHE

- AHE vanishes in paramagnetic state

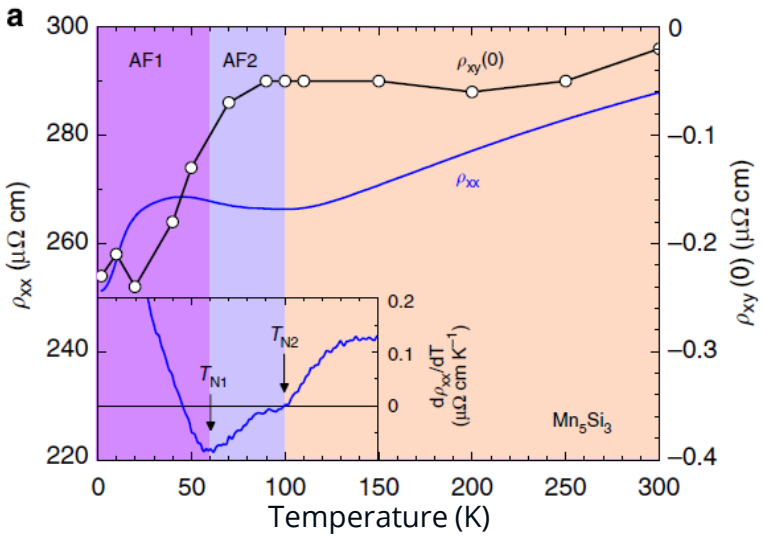


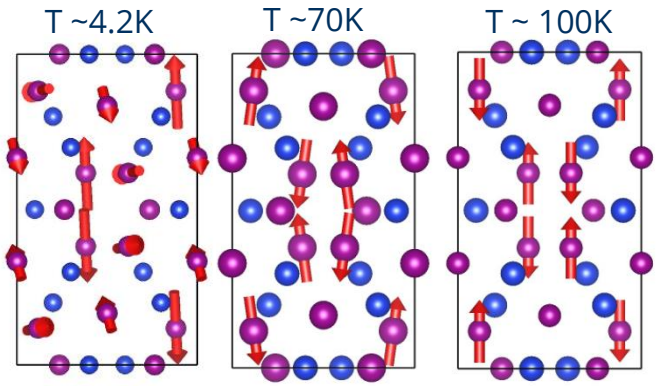


helena.reichlova@tu-dresden.de

Mn_5Si_3 bulk material

- bulk and polycrystalline material: magnetic phase transitions ~ 60K and 100K





- Suergers et al, Nat Comm (2013)
- Brown et al., J. Phys Cond. Matt (1992)
- Brown et al., J. Phys Cond. Matt (1995)

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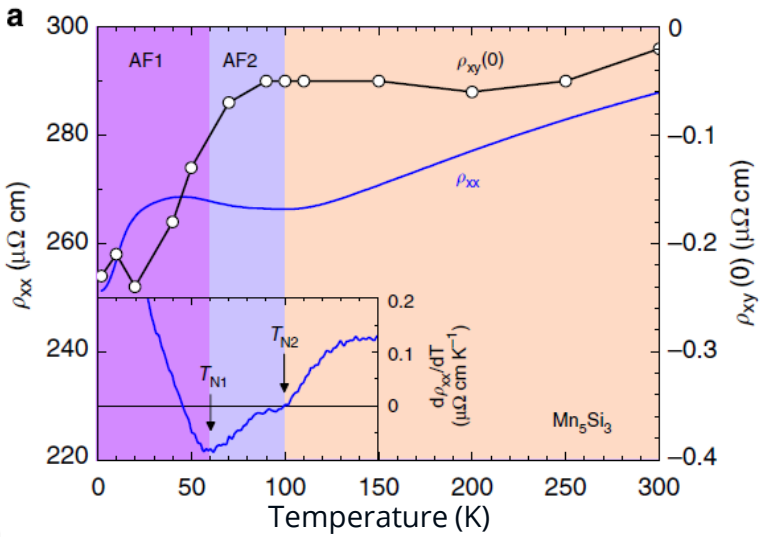

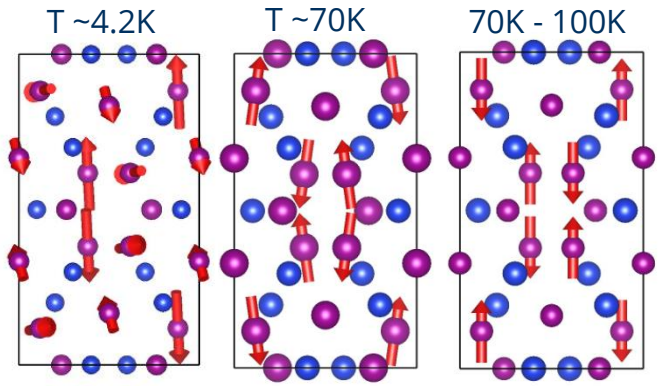

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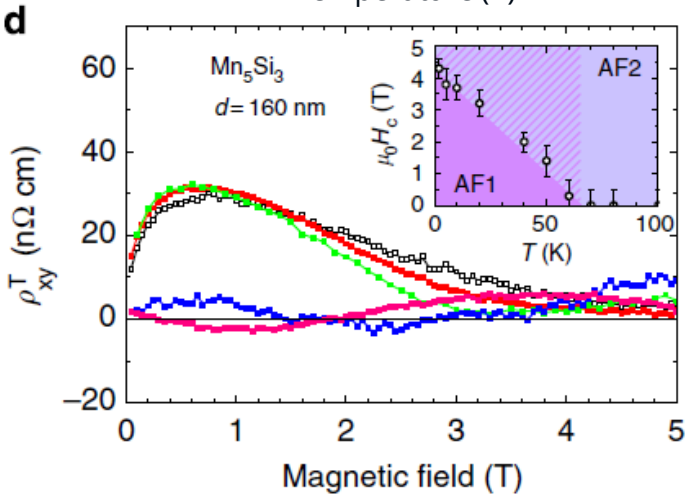
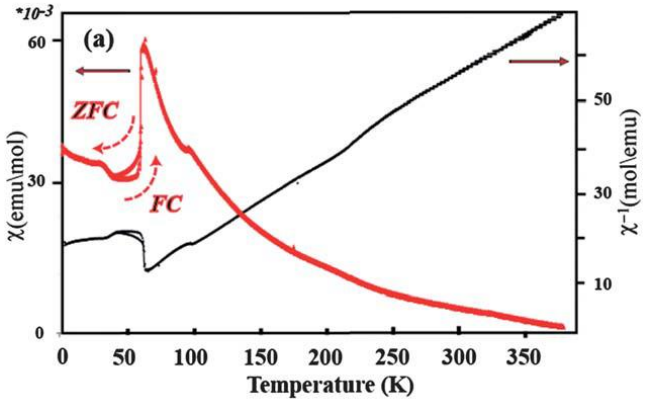


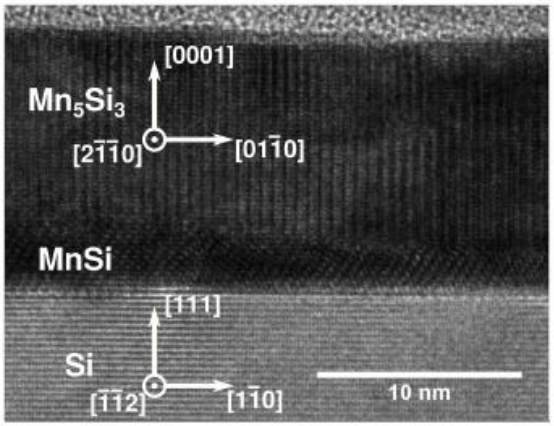


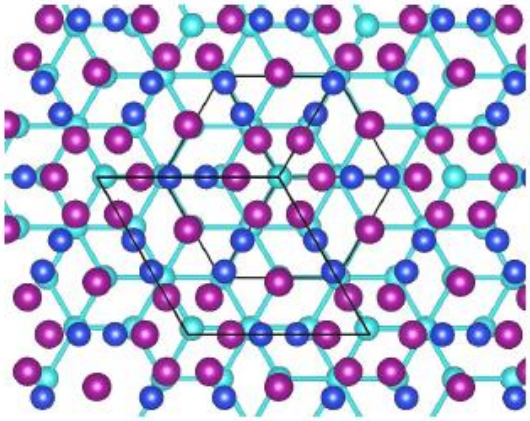
- Gottschilch et al, J. Mat. Chem. (2012)

Compare bulk and films Mn_5Si_3

- MBE grown on Si(111)
- epitaxial constraints stabilize the hexagonal unit cell

🕮 Kounta, Michez et al., in prep.



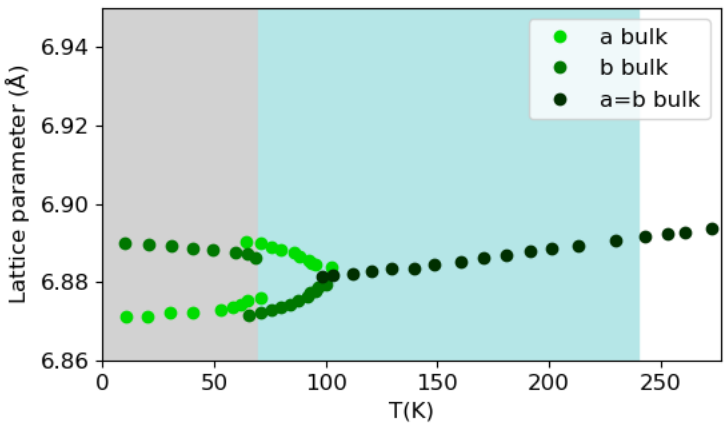


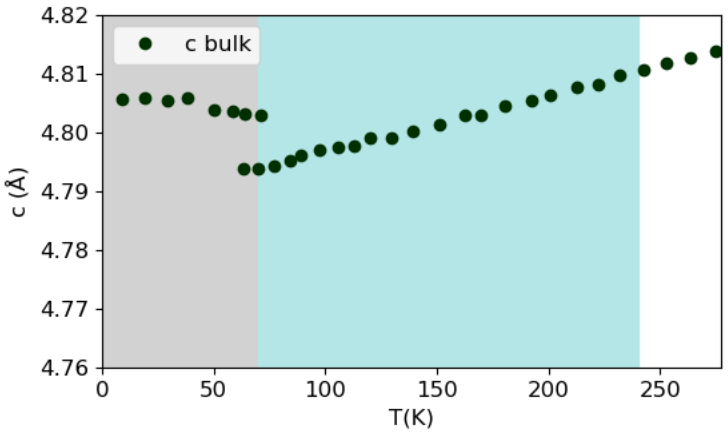
✓ increase of T_N ~ 240K

✓ symmetry allowing altermagnetism

- confirmed by synchrotron measurements (Soleil, Lisa Michez)

🕮 bulk data: Brown et al., J. Phys Cond. Matt





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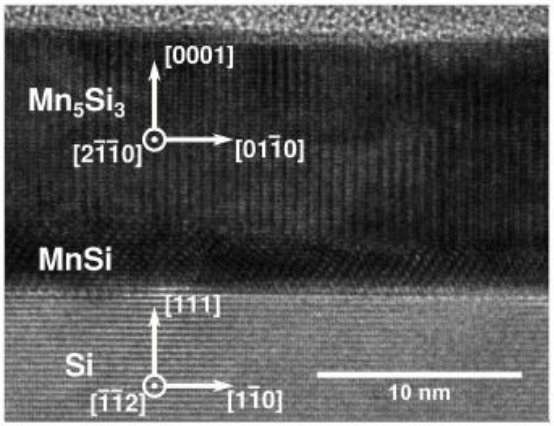

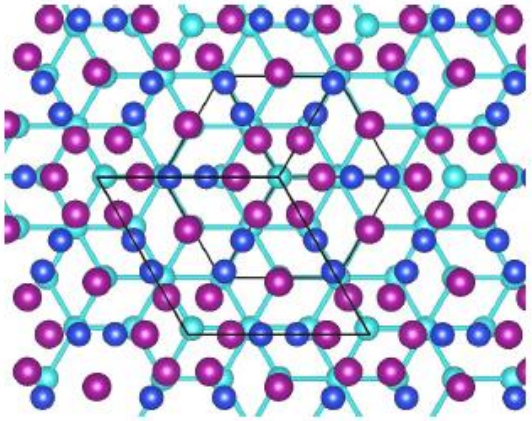

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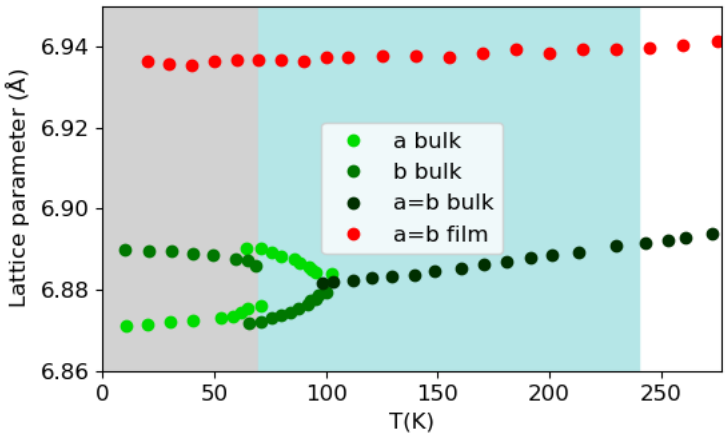
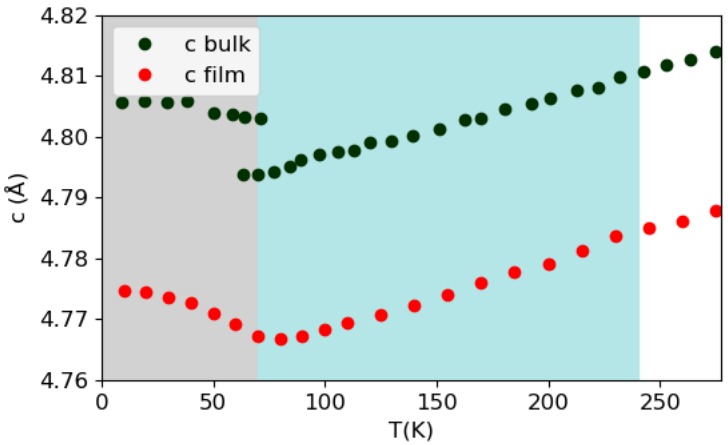
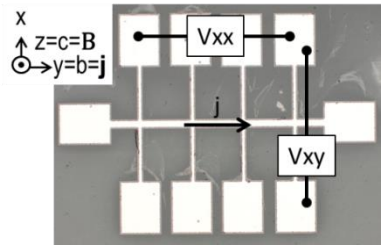
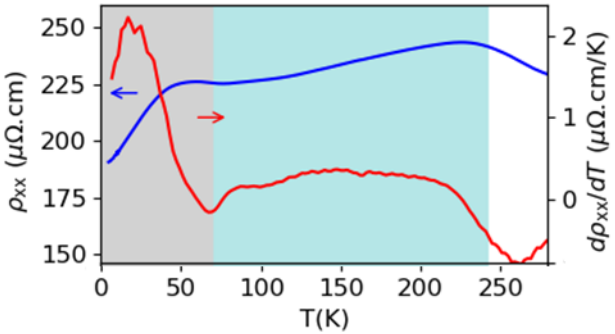




Mn_5Si_3 thin films

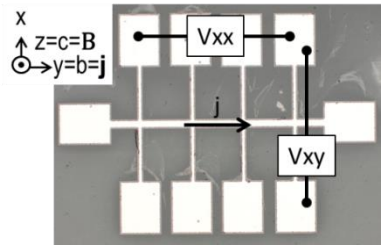


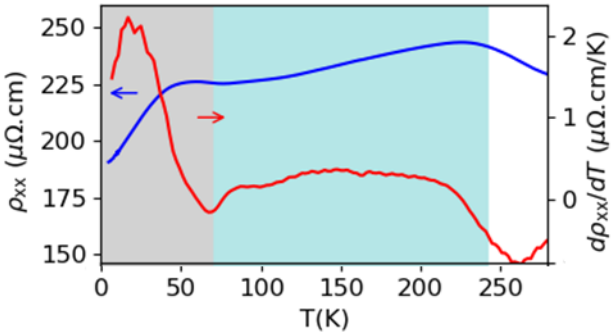


- shifted T_N ~240K

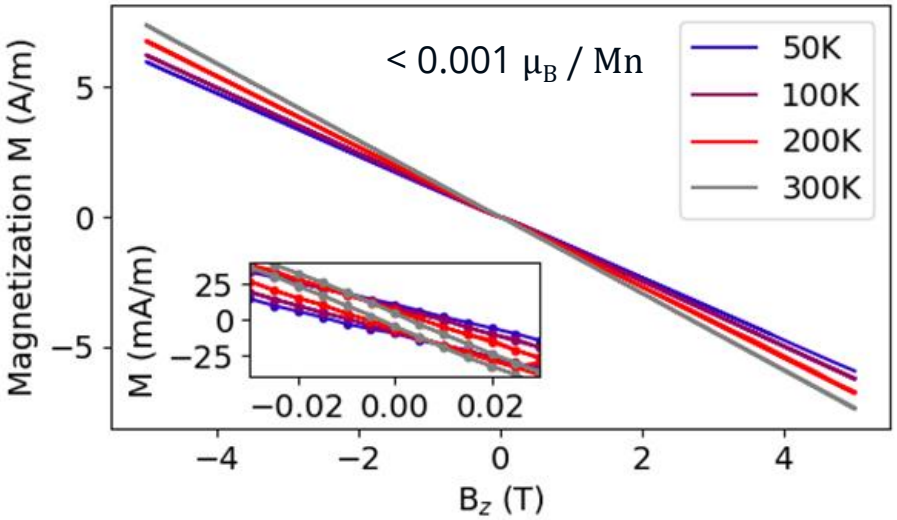
🕮 Reichlova et al., arXiv:2012.15651

Mn_5Si_3 thin films





- shifted T_N ~240K
- vanishing magnetization



🕮 Reichlova et al., arXiv:2012.15651

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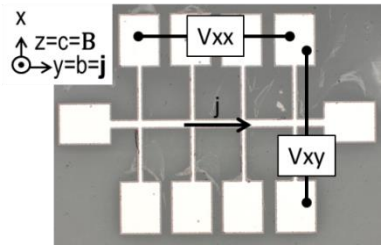
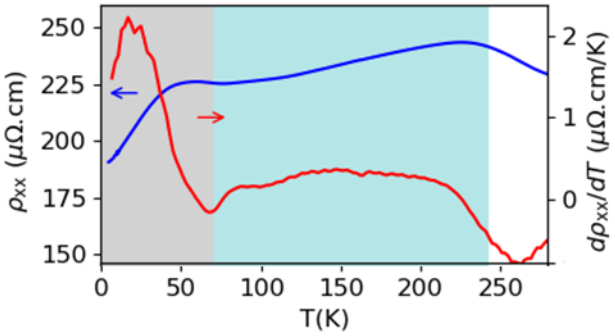
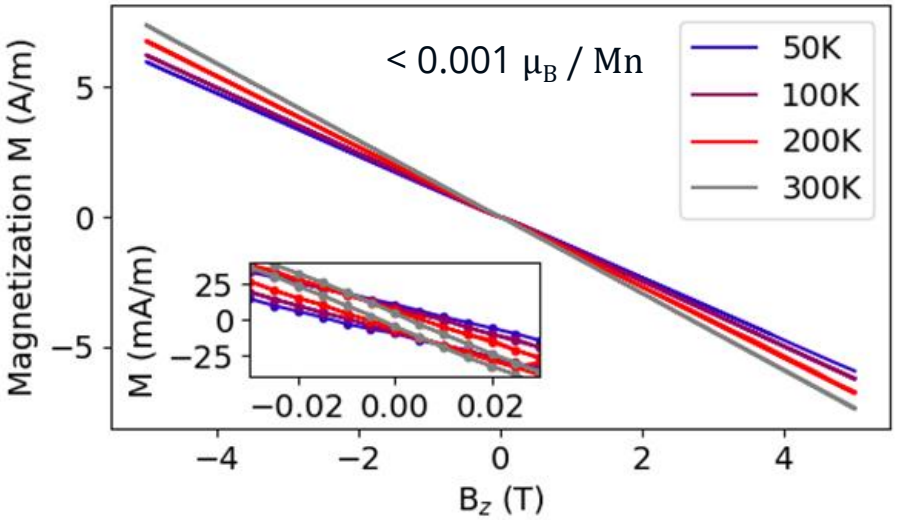
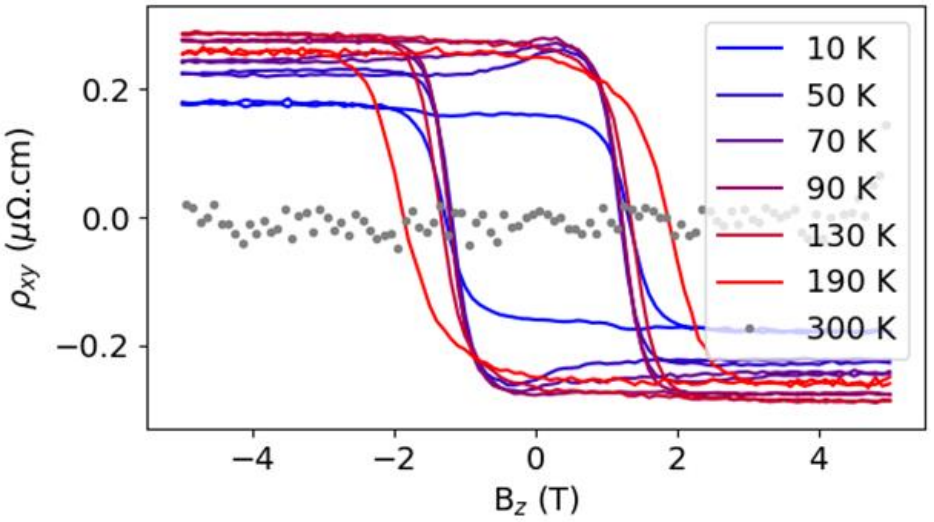




- shifted T_N ~240K
- vanishing magnetization
- spontaneous AHE

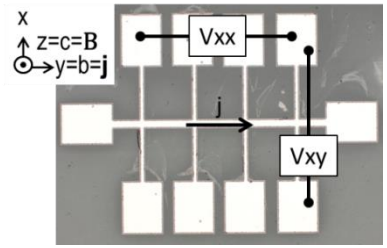


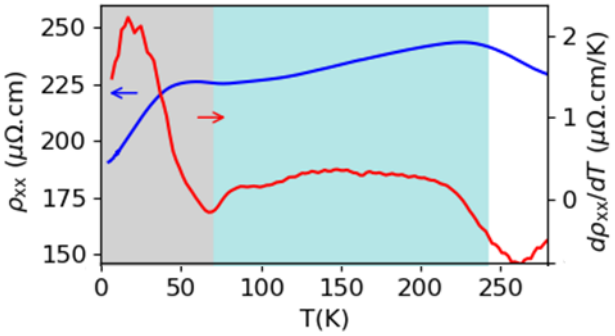


✓ Breaking $\mathcal{T}$ symmetry in the band structure

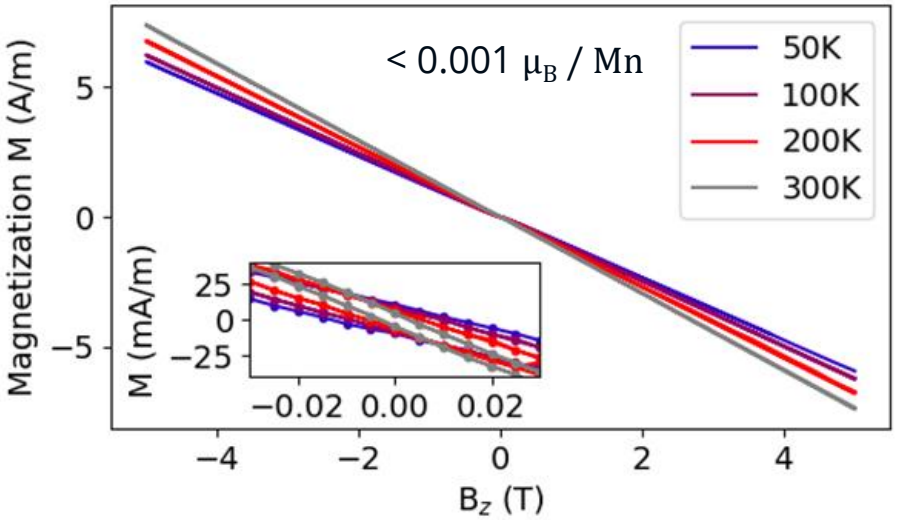
🕮 Reichlova et al., arXiv:2012.15651

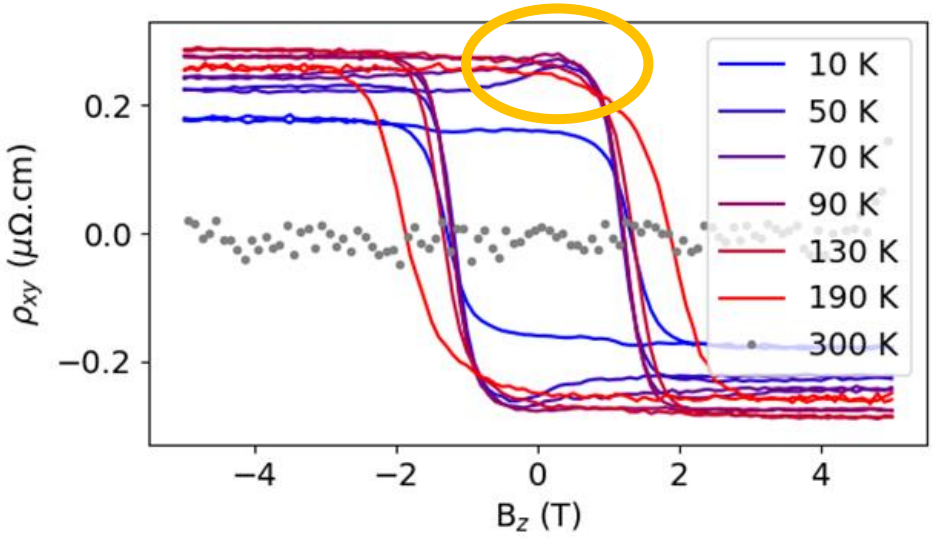
Mn_5Si_3 thin films





- shifted T_N ~240K
- vanishing magnetization
- spontaneous AHE
- absent above T_N
- H_c ~ 2T
- topological feature below 70K





✓ Breaking $\mathcal{T}$ symmetry in the band structure

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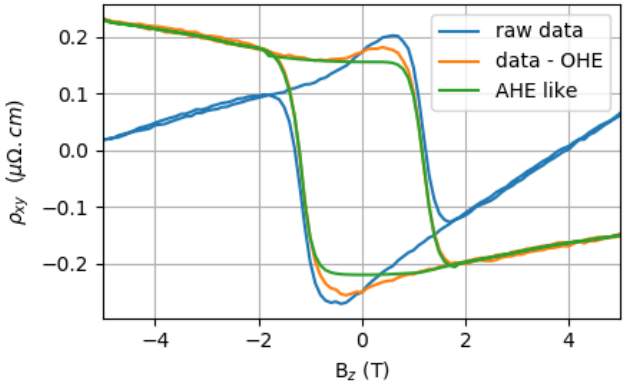
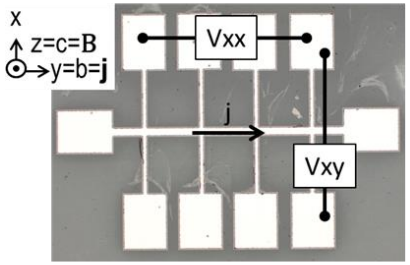
Mn_5Si_3 – anomalous Hall effect



- subtracted background



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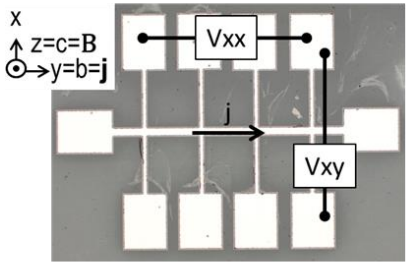
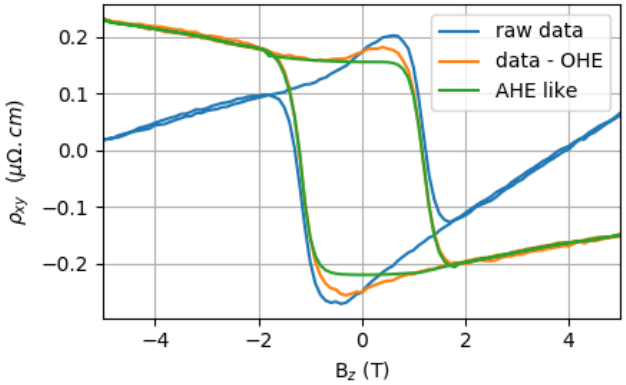
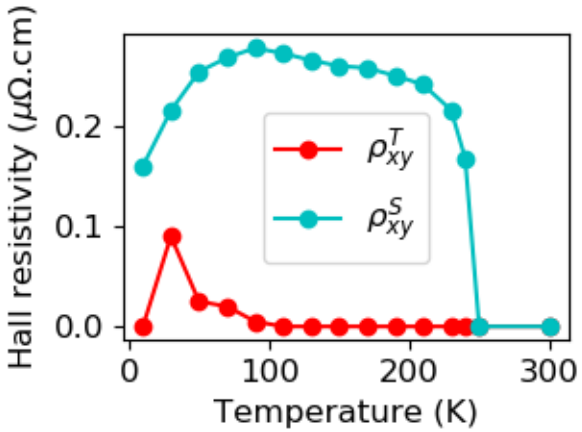




- subtracted background
- extracted topological Hall effect



✓ topological Hall consistent with Suergers et al, Nat Comm (2013)

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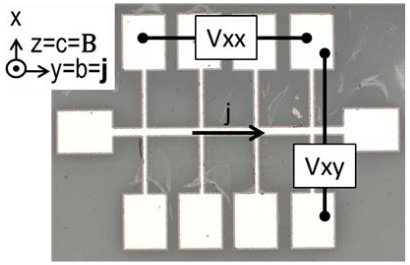
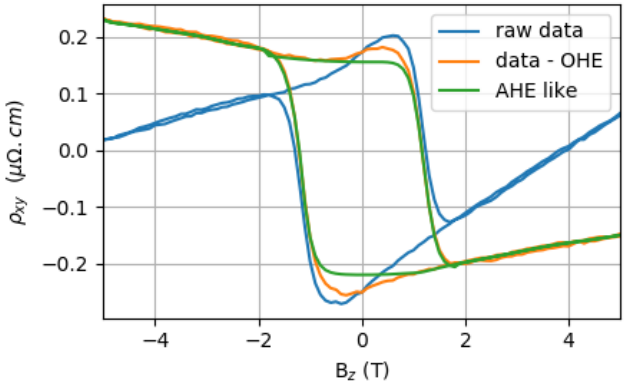
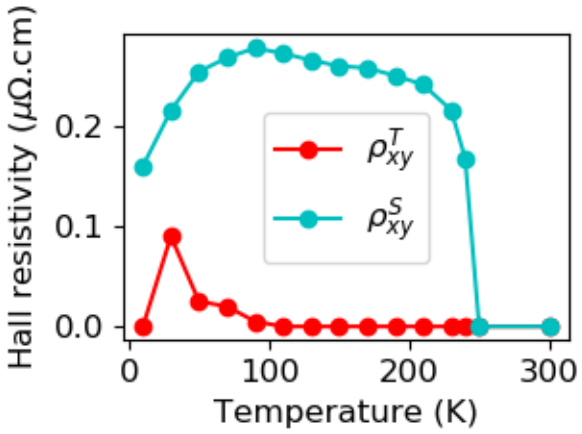
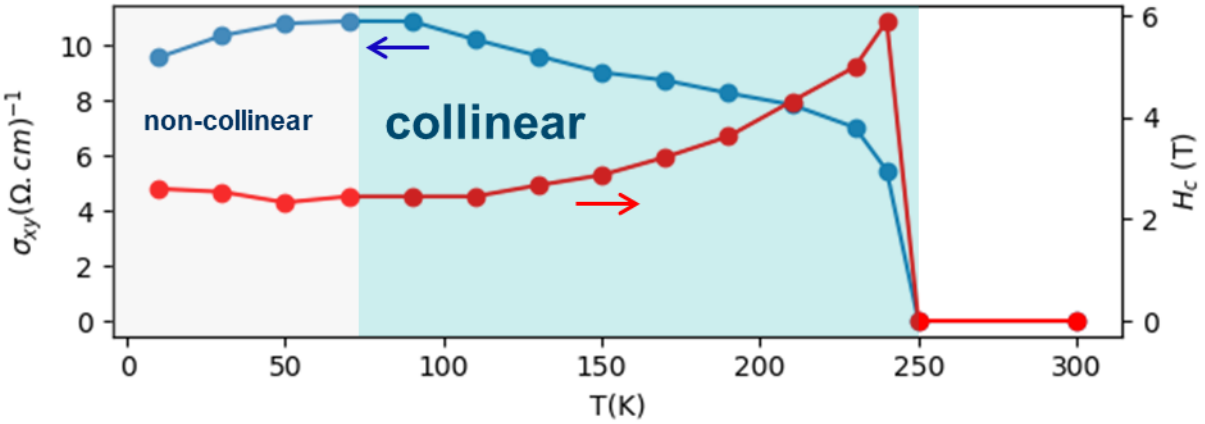




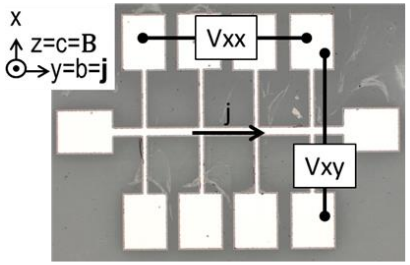
- subtracted background
- extracted topological Hall effect
- AHE and H_c in whole temperature range
- H_c broadening

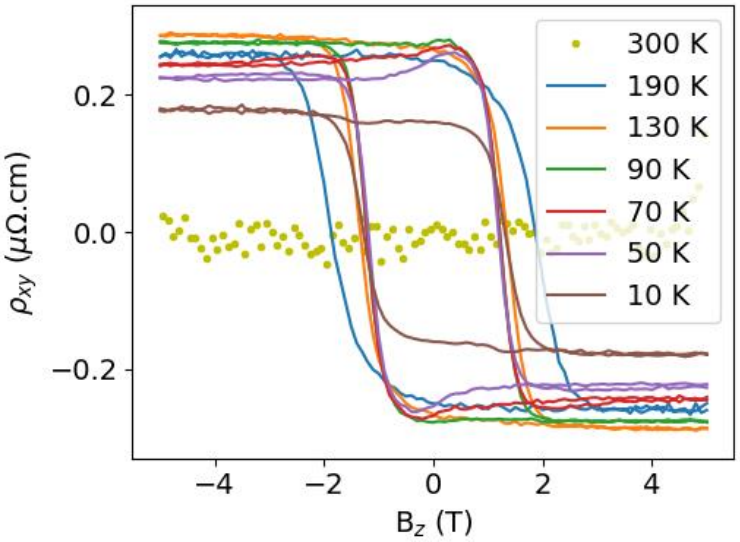


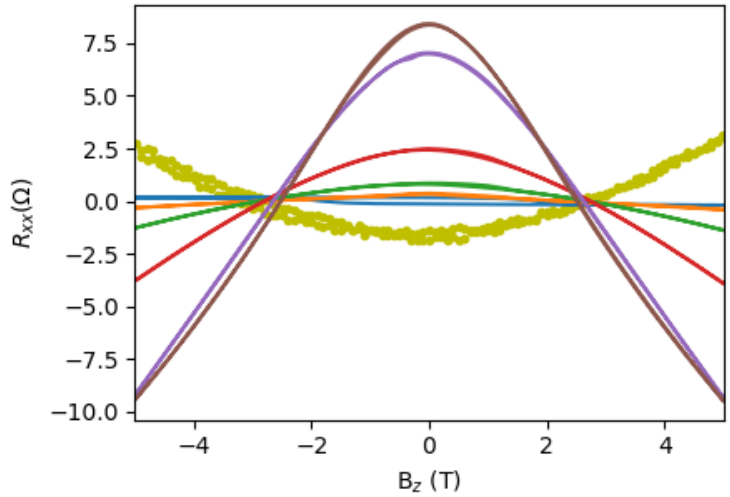


✓ topological Hall consistent with Suergers et al, Nat Comm (2013)
✓ anomalous Hall conductivity ~ 5-10 S/cm

Mn_5Si_3 – magnetoresistance

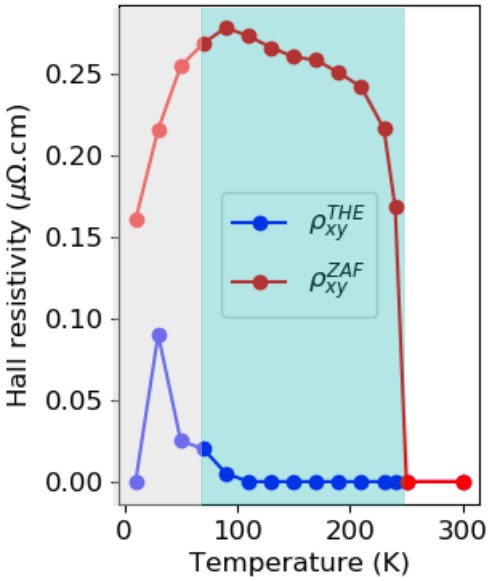


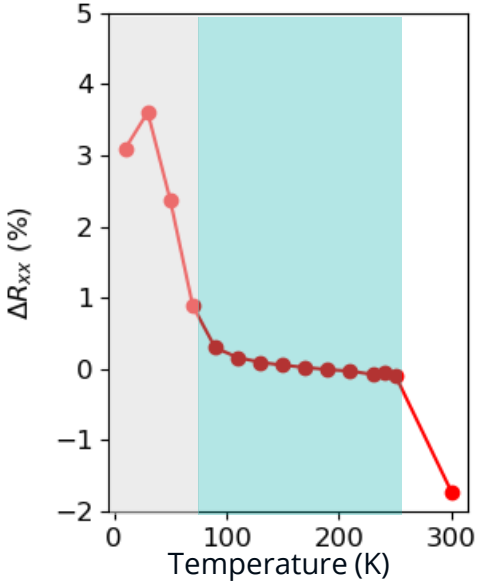




- MR strong in low temperature phase
- supporting co-planar order above 70K

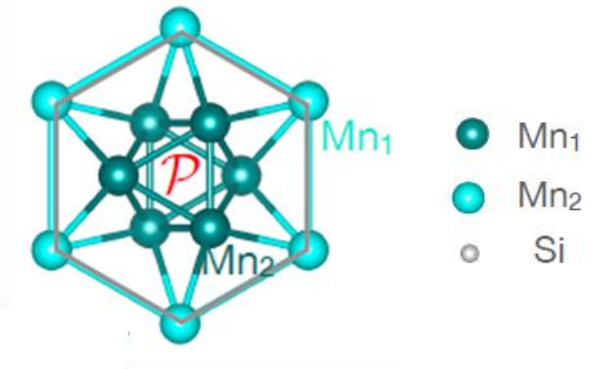
🕮 Usami et al. J.Phys Soc (1978)
🕮 Suerges et al, Nat Comm (2013)



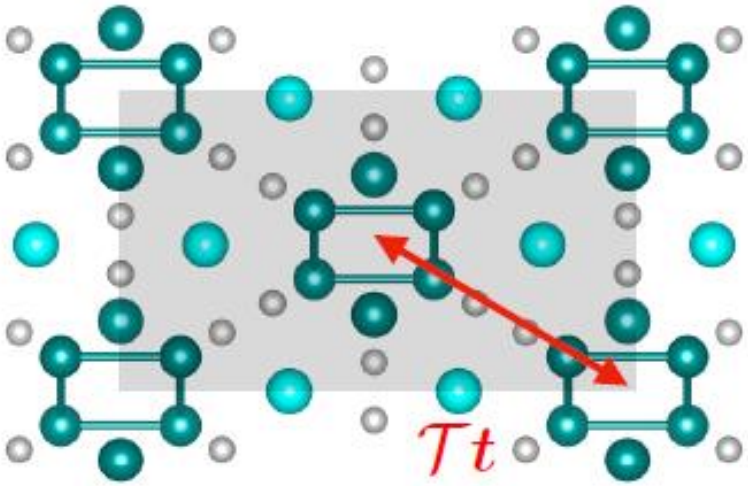


Multi-sublattice spin splitting

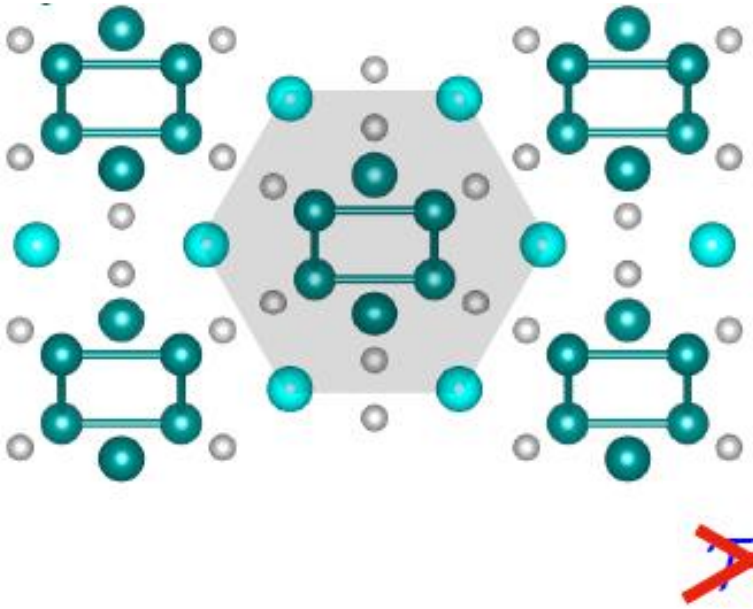
- ✓ hexagonal crystal unit cell
- ✓ vanishing magnetization
- ✓ spontaneous $\mathcal{T}$ breaking in band structure
- ✓ unlikely non-coplanar



Bulk



Films



🕮 Gottschilch et al, J. Mat. Chem. (2012)

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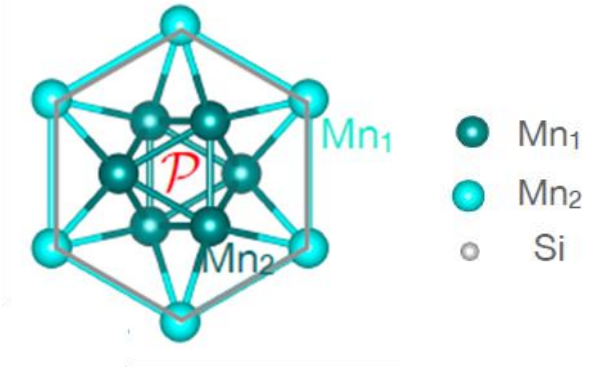

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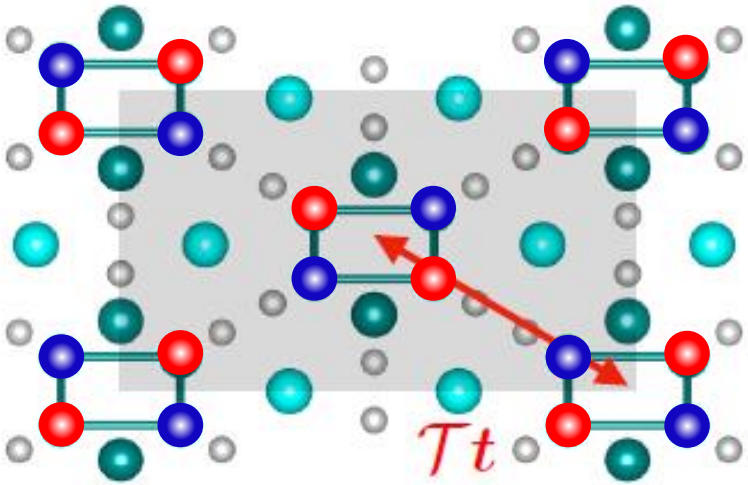
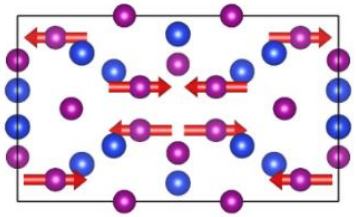
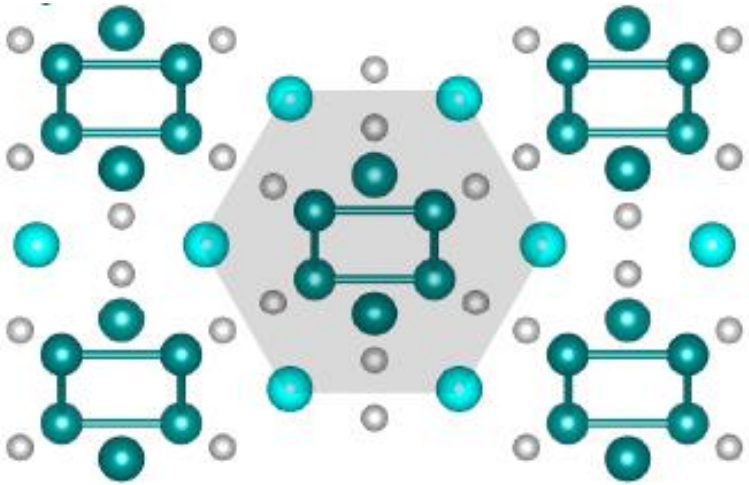




Films



🕮 Gottschilch et al, J. Mat. Chem. (2012)

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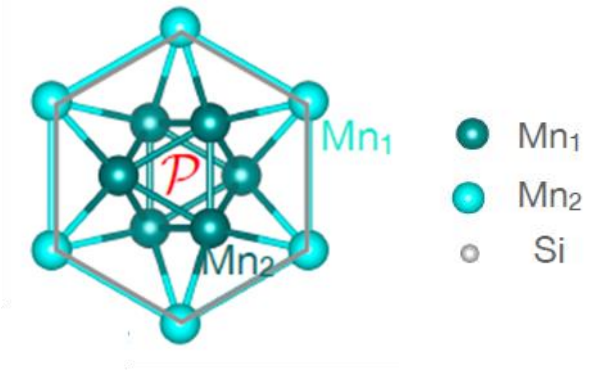

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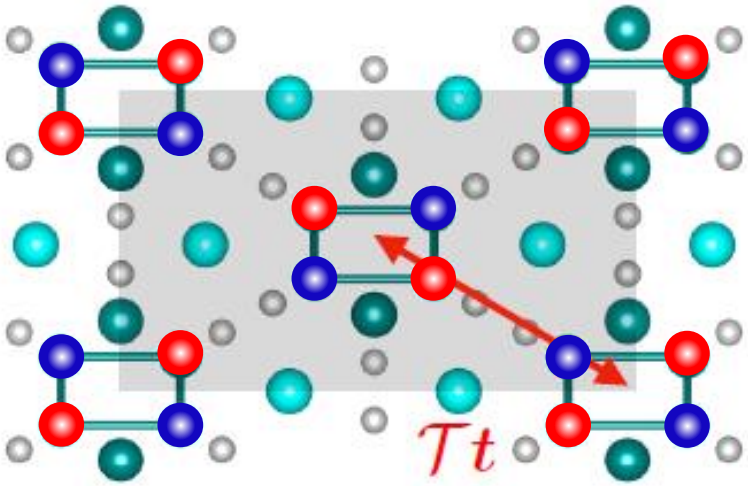
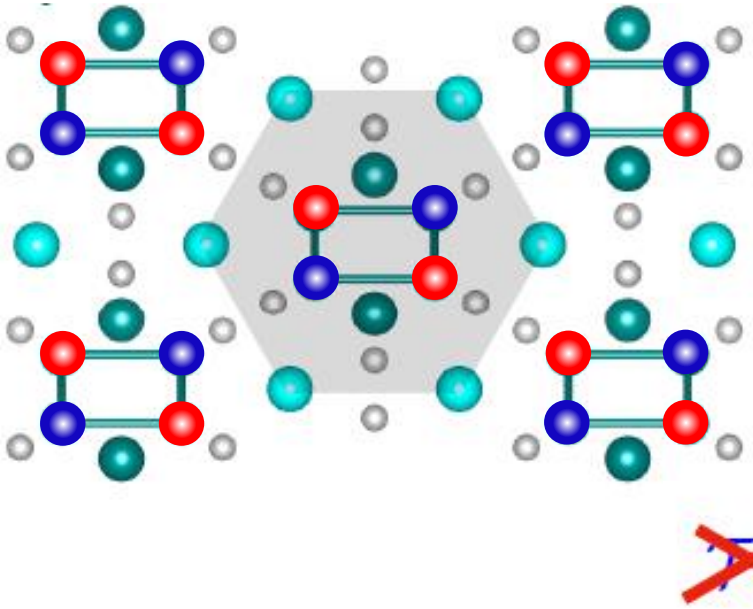


Films



🕮 Gottschilch et al, J. Mat. Chem. (2012)

Origin of the anomalous Hall effect in Mn5Si3

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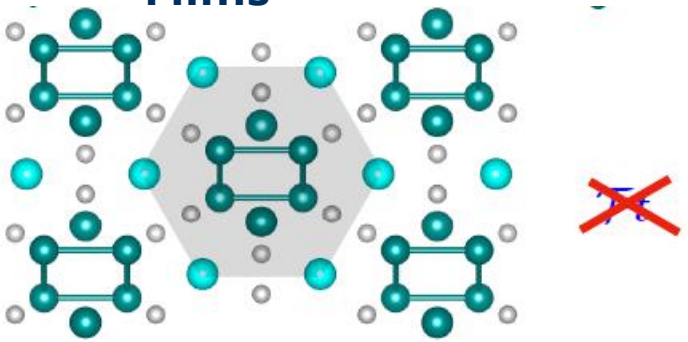
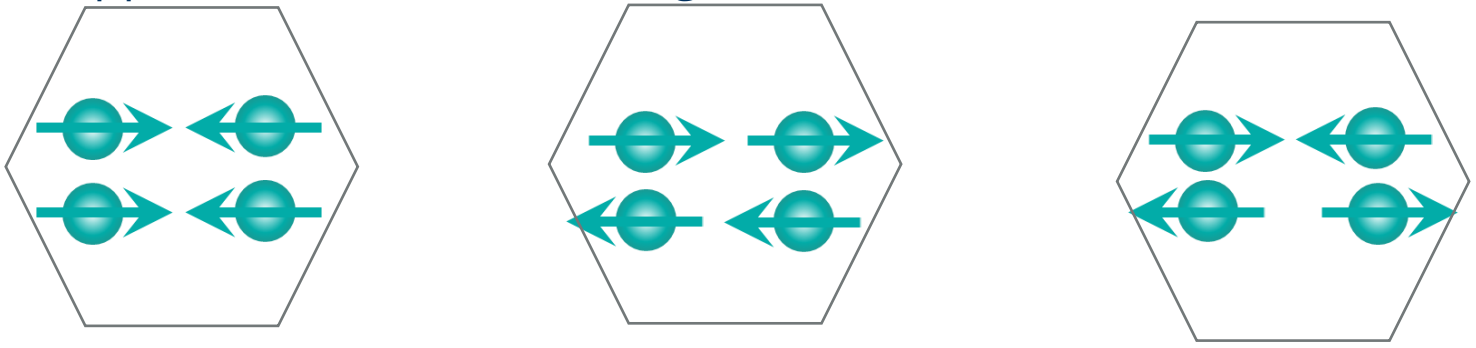
- ✓ vanishing magnetization
- ✓ spontaneous $\mathcal{T}$ breaking in band structure
- ✓ unlikely non-coplanar

Films



- 3 possible compensated spin arrangement of 4 Mn
- only checkerboard allows AHE
- DFT supports checkerboard as a ground state

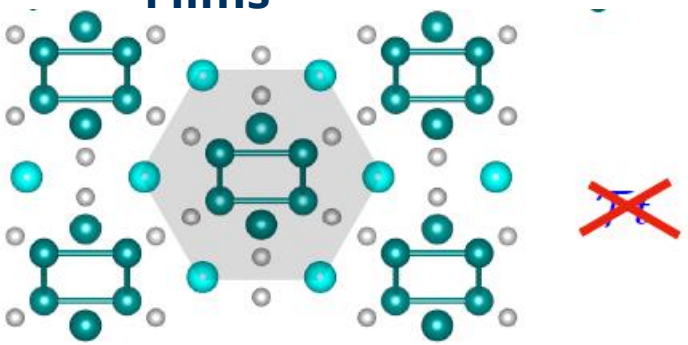


🕮 Gottschilch et al, J. Mat. Chem. (2012)

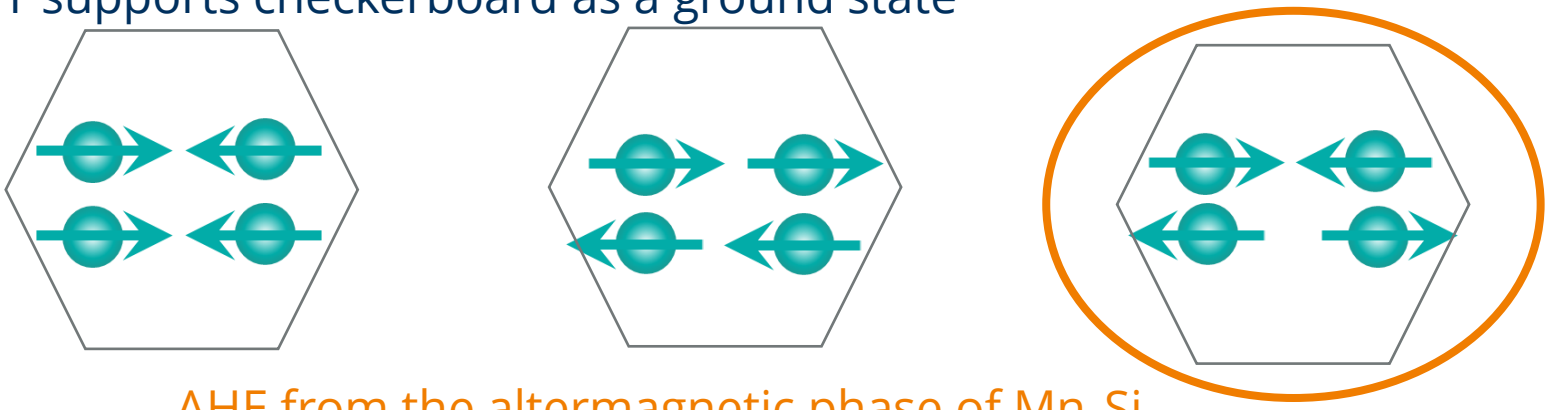
Origin of the anomalous Hall effect in Mn5Si3

- ✓ hexagonal crystal unit cell
- ✓ vanishing magnetization
- ✓ spontaneous $\mathcal{T}$ breaking in band structure
- ✓ unlikely non-coplanar

Films



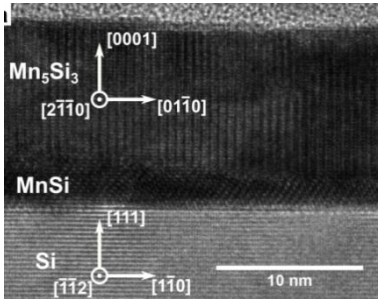
- 3 possible compensated spin arrangement of 4 Mn
- only checkerboard allows AHE
- DFT supports checkerboard as a ground state

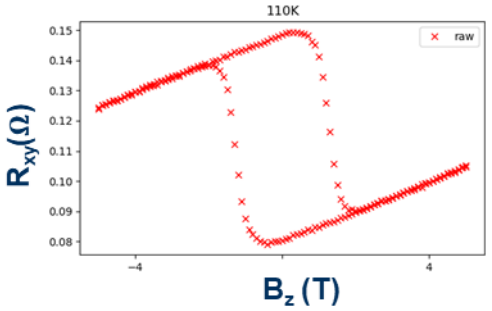


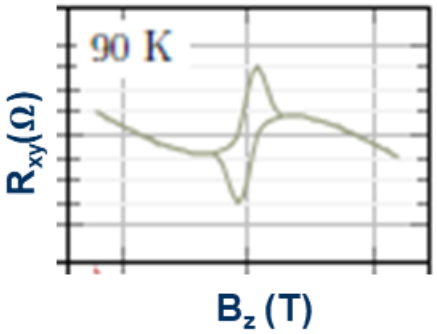
AHE from the altermagnetic phase of Mn_5Si_3
corresponding calculated AHE ~ 5-20 S/cm ✓ experiment

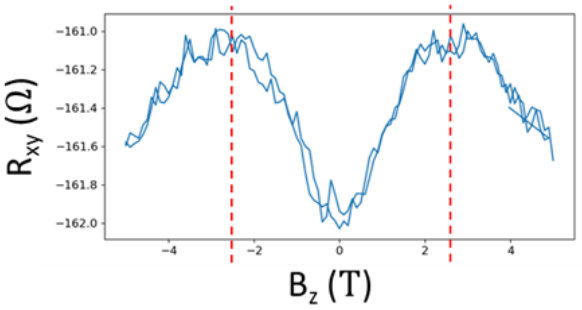
Crystal purity importance

- anisotropic splitting – crystal quality!
- many samples studied
- very different on a first look









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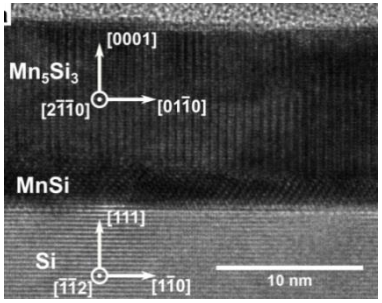
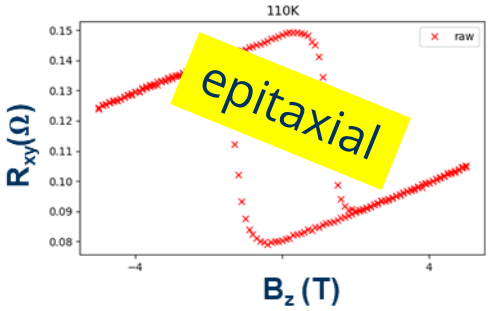
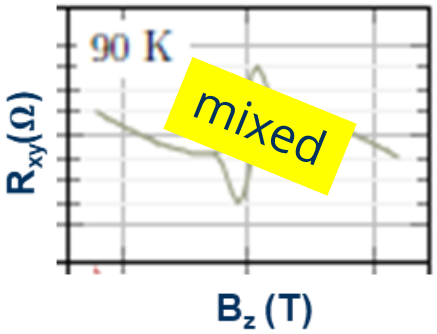
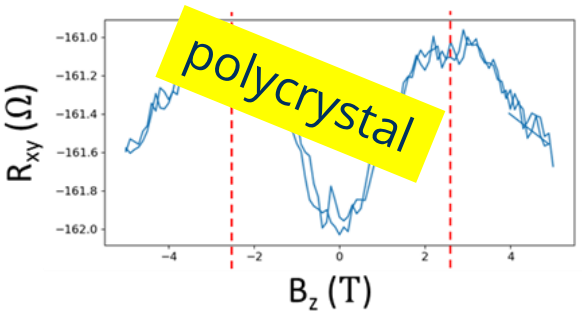
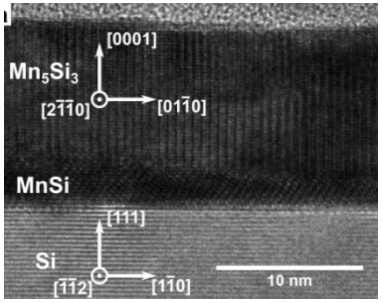








Crystal purity importance



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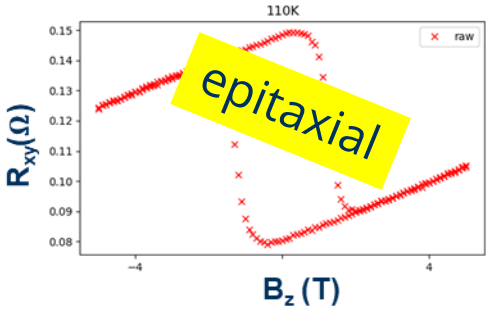

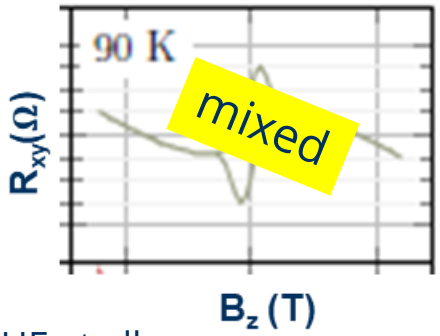

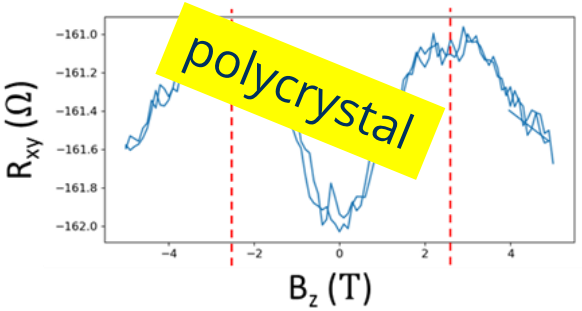

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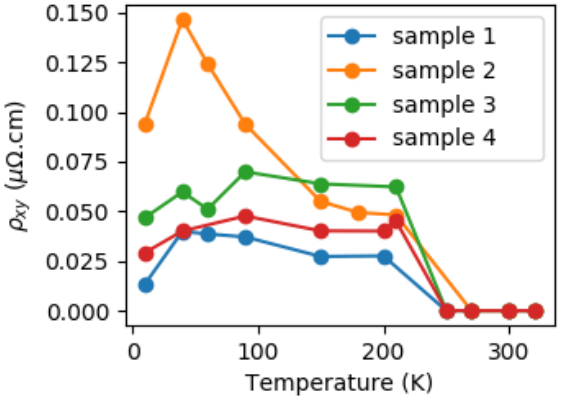
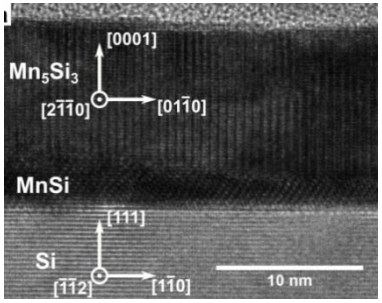


Crystal purity importance



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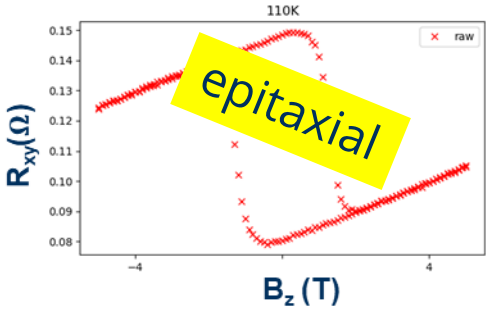

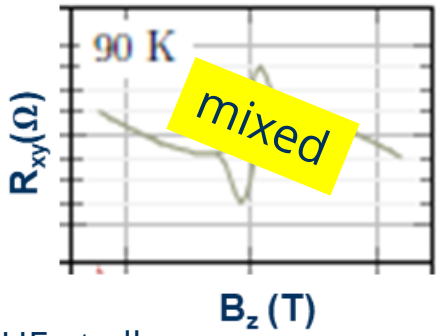

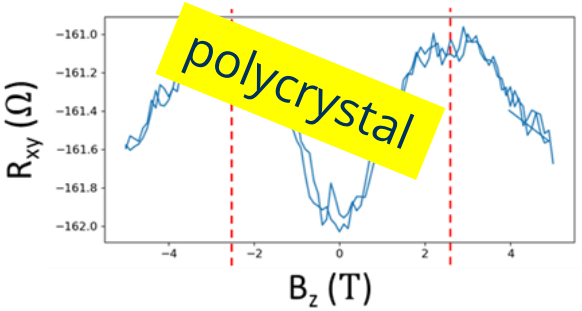

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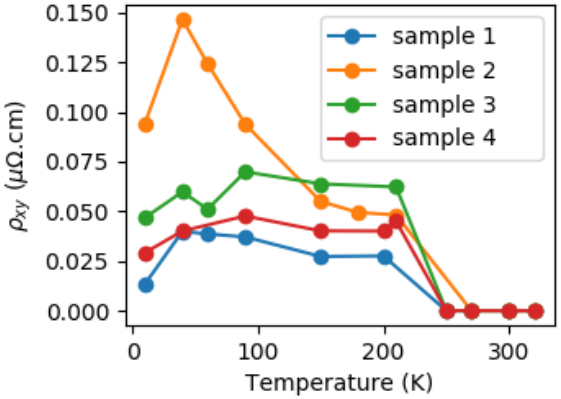

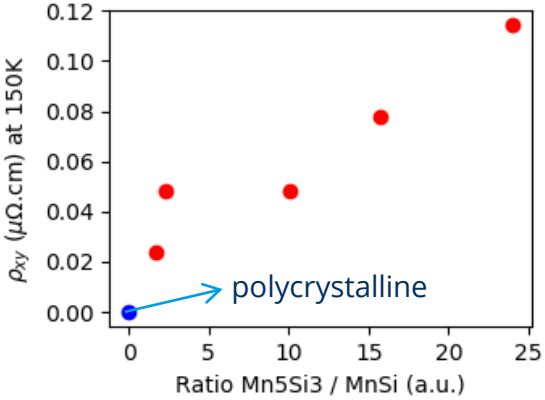

helena.reichlova@tu-dresden.de

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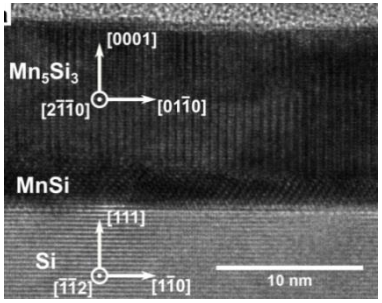

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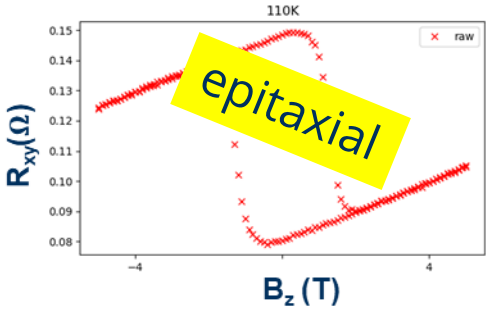
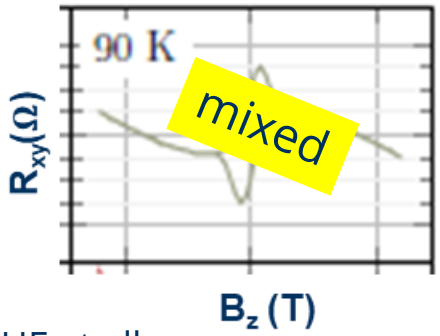
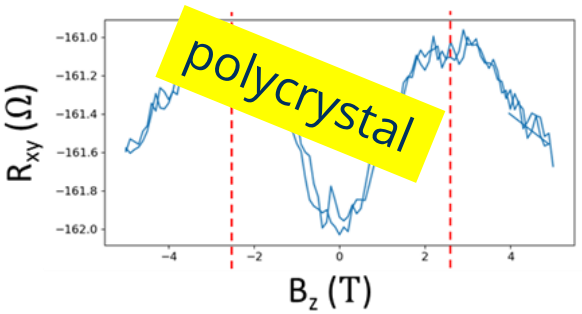
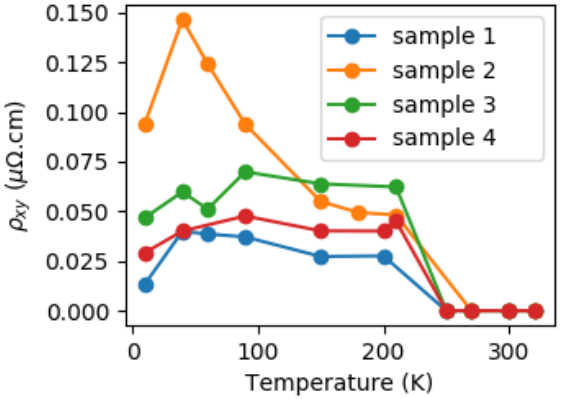
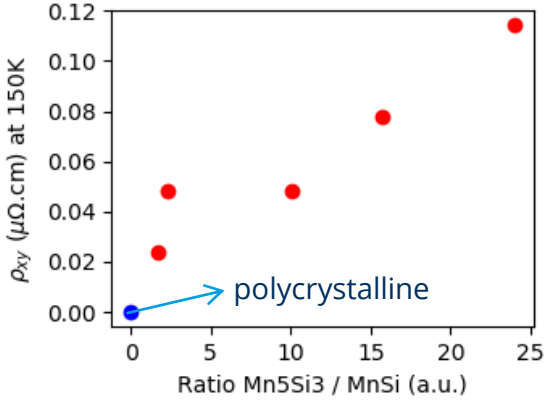


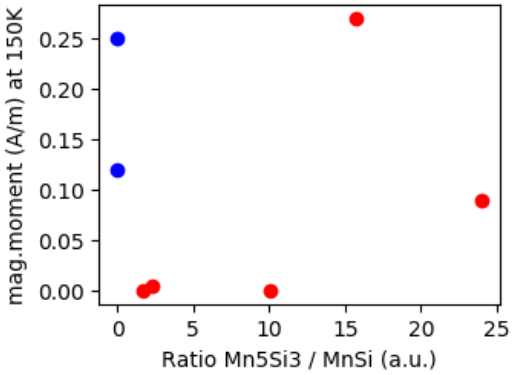




- some AHE up to ~240K or no AHE at all
- correlates with sample's phase purity
- does not correlate with "SQUID signal"

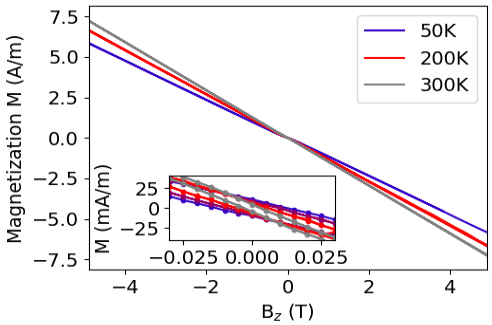


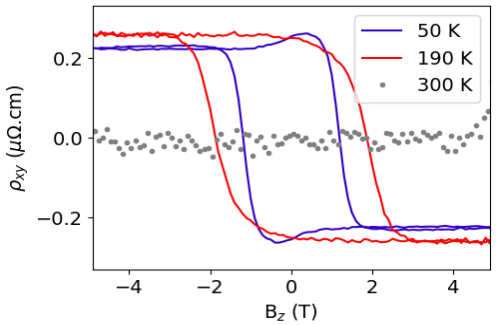




Discussion – Spin Splitting

- we focused on the AHE
- Mn_5Si_3 as an altermagnetic candidate





🕮 Bai et al. PRL (2022)
🕮 Bose et al. Nat. Electr. (2022)

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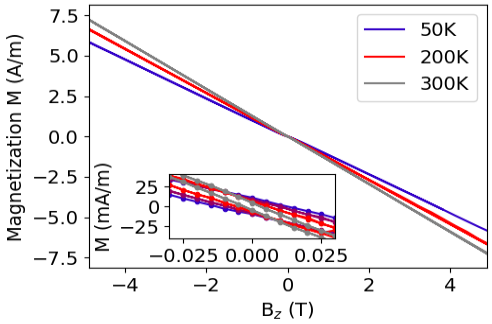
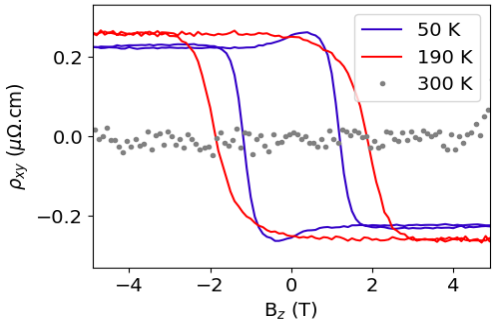
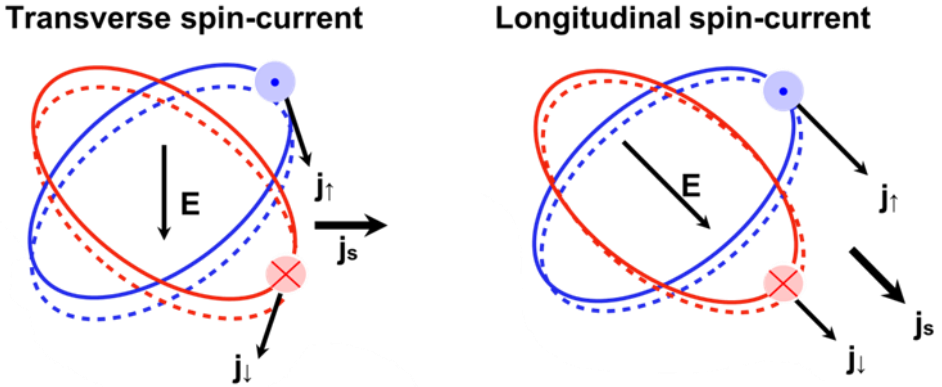




- anisotropic spin splitting – present in the whole BZ
- source of a coherent spin current



- González-Hernández et al. PRL (2021)
- Yuan et al., PRB (2020)
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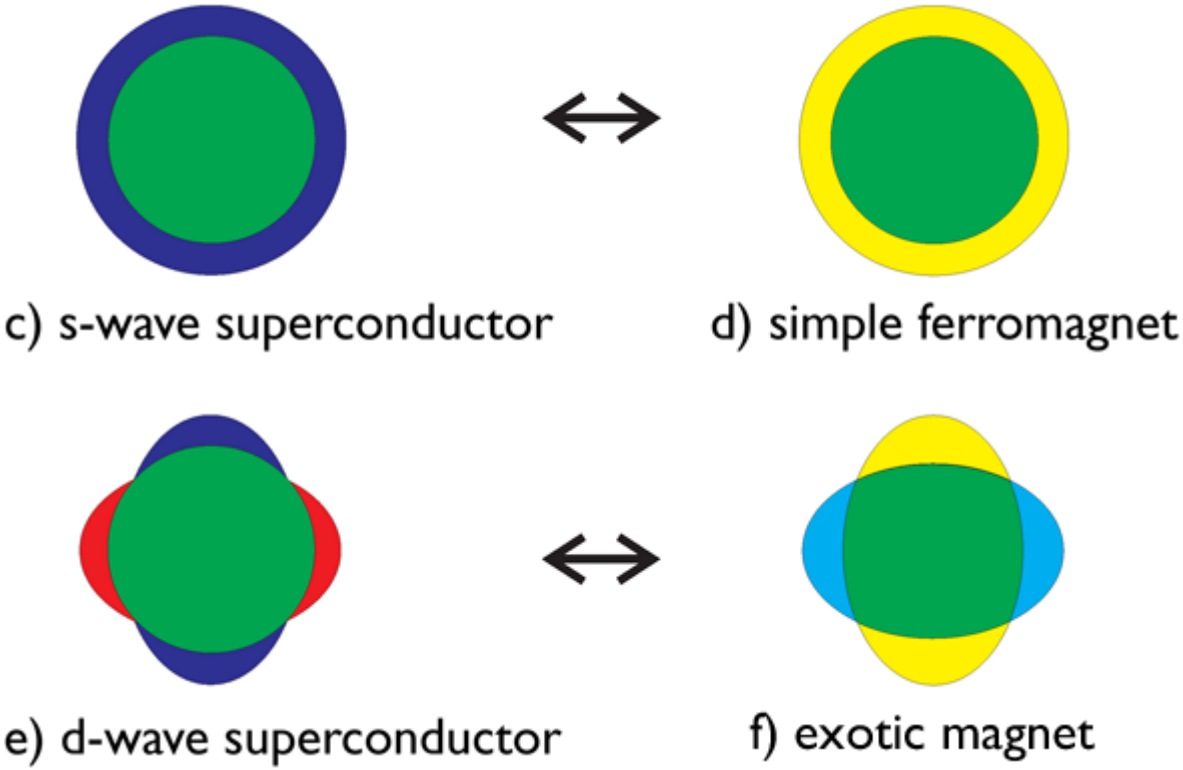
- Bai et al. PRL (2022)
- Karube et al., arXiv:2111.07487

- Smejkal et al., PRX (2022)
- Shao et al., Nat. Comm. (2021)

- many consequences: GMR, spin torques...

Discussion: Spin d-wave magnetic phase candidate

- Fermi surface in k-space highly anisotropic
- resemblance with superconductivity



🕮 Schofield, APS Viewpoint (2009)

Discussion: Spin d-wave magnetic phase candidate

- Fermi surface in k-space highly anisotropic
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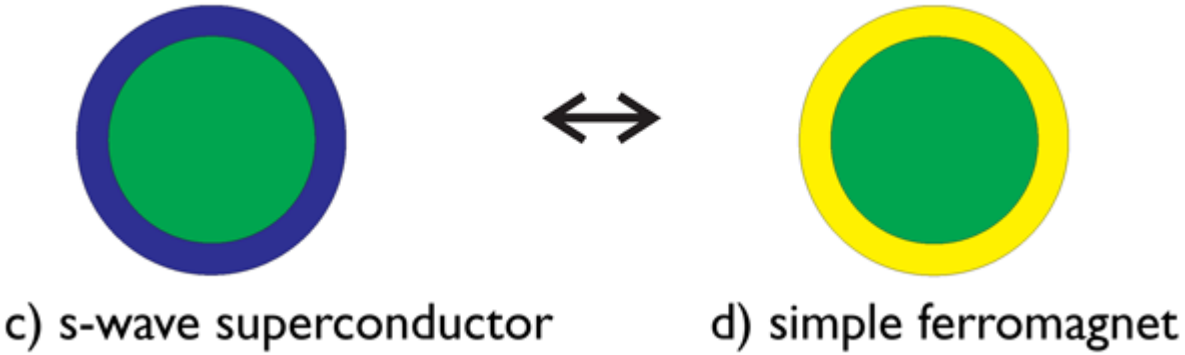
- spin d-wave magnetic equivalent missing



- Schofield, APS Viewpoint (2009)
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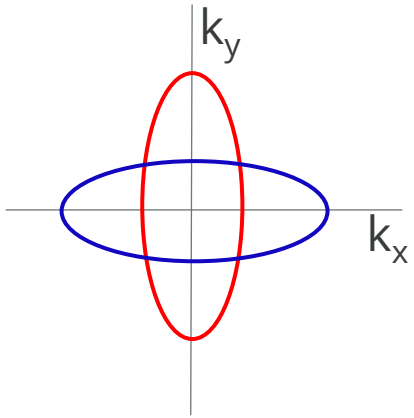

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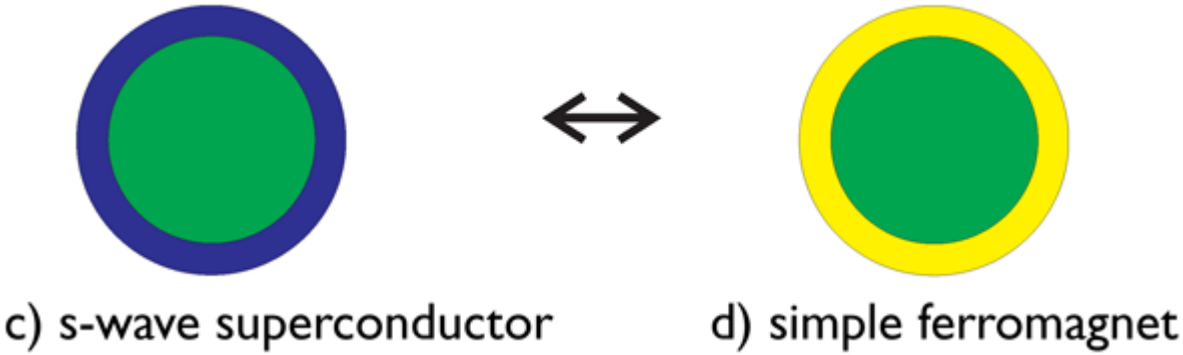

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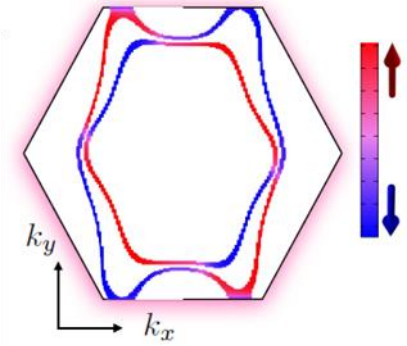
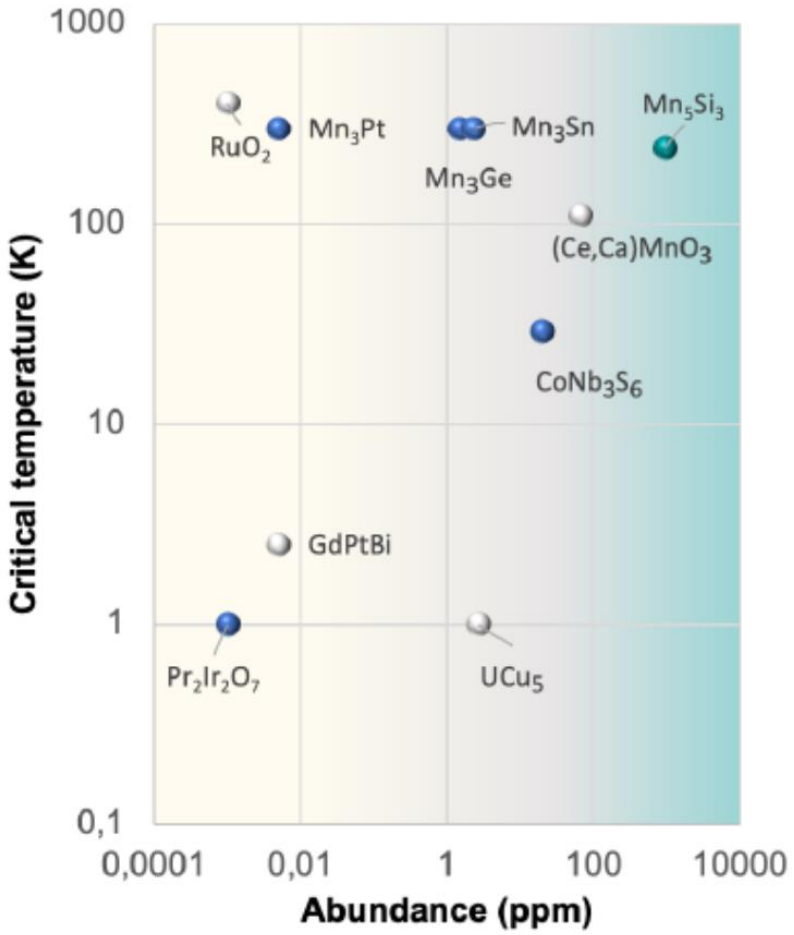


spin polarized Fermi surfaces of Mn_5Si_3

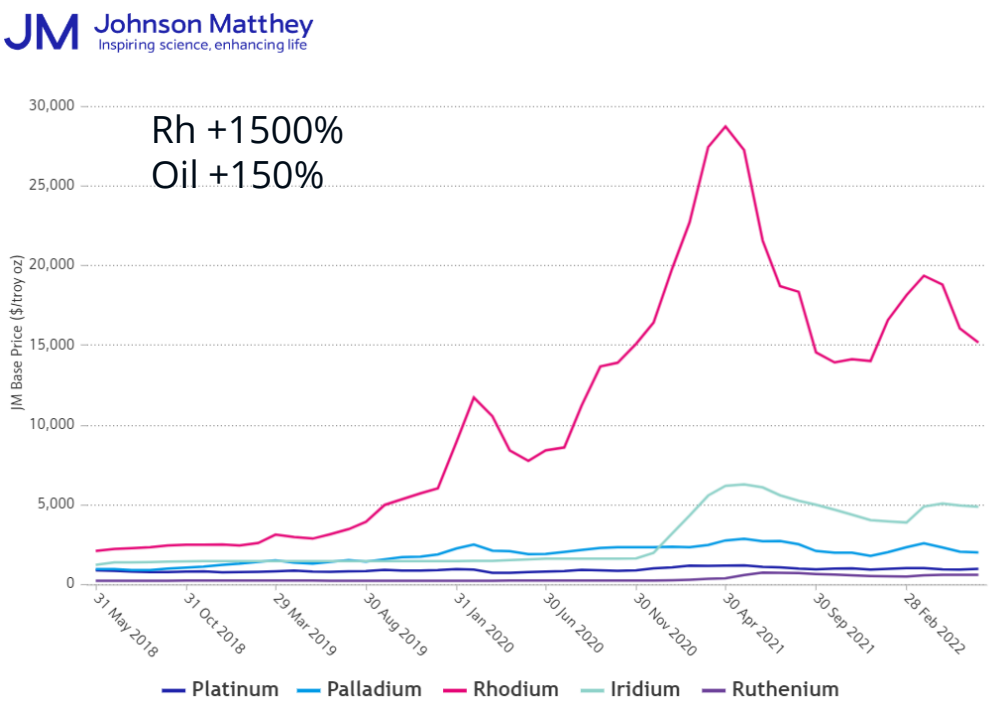
Mn_5Si_3 as an example that altermagnets can be:

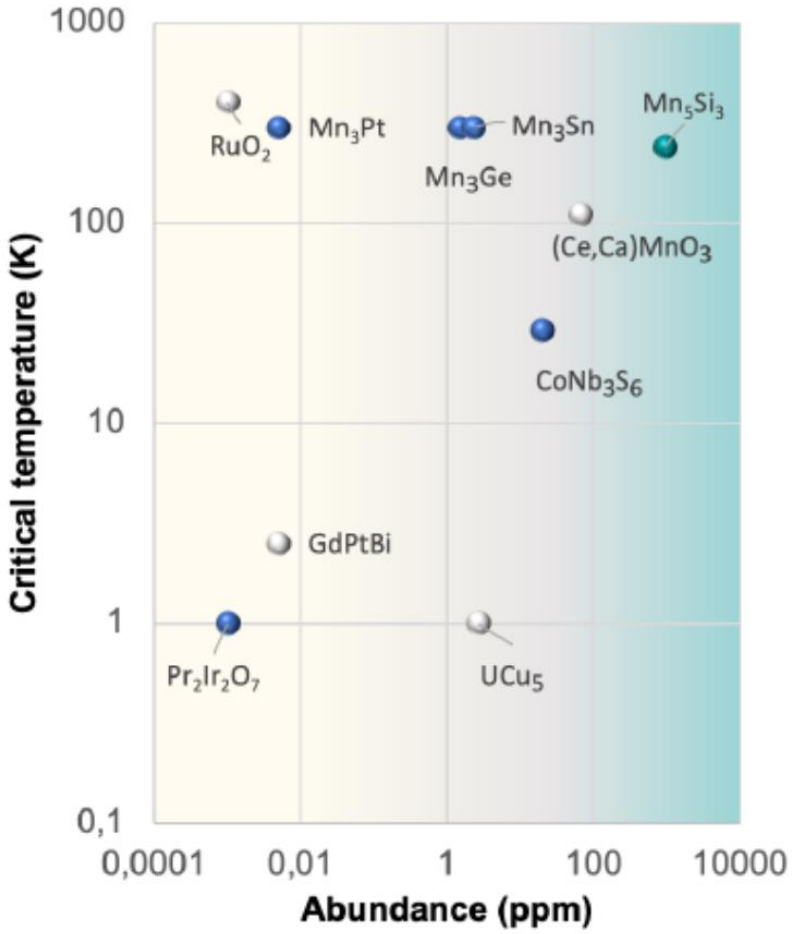
- light elements
- abundant
- non-toxic



Mn_5Si_3 as an example that altermagnets can be:

- light elements
- abundant
- non-toxic
- inexpensive
- sustainable

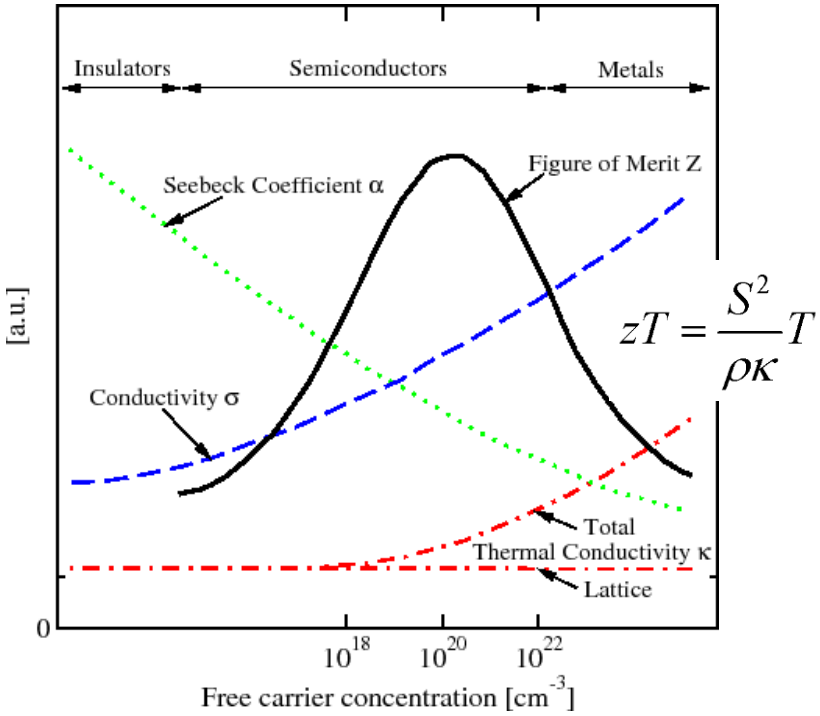


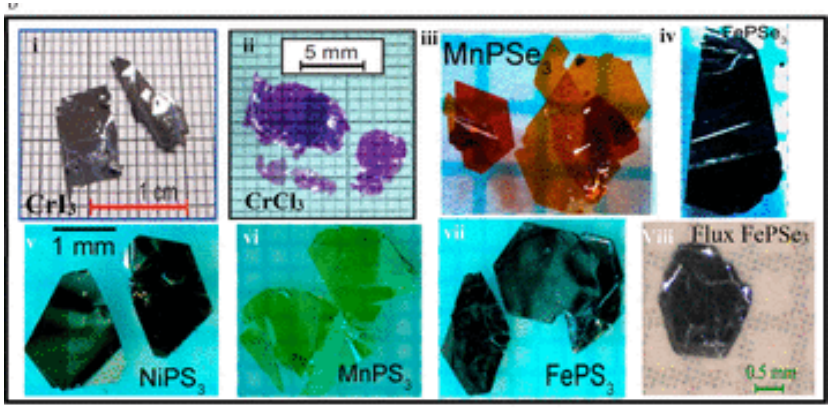


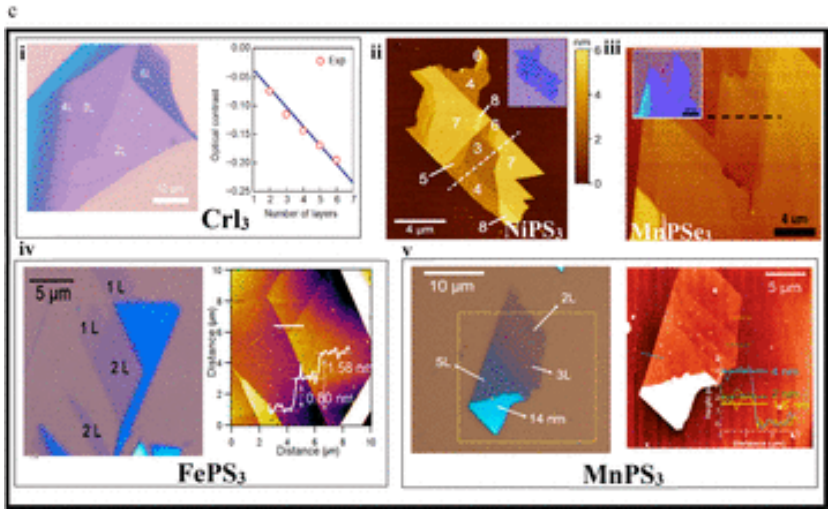
Outlook: new materials & spin-caloritronics

- semiconductors (as MnTe)

- many altermagnetic insulators...
- van der Waals systems...
- strain / dimension control...





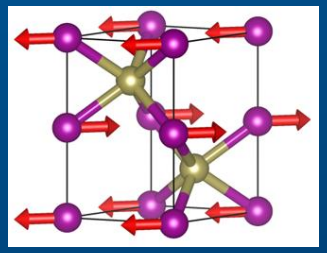


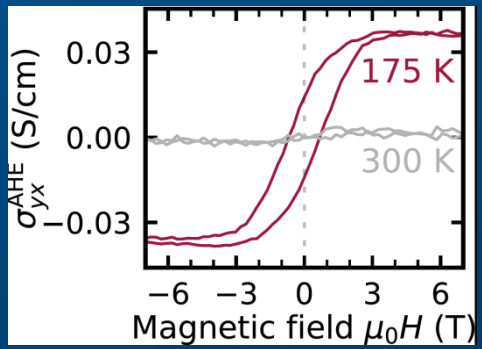
- Rahman et al. *ACS Nano (2021)*
- Bhandari and D. Rowe, , *CRC Handbook of Thermoelectrics* (1994)
- Smejkal et al. arXiv:2204.10844

Conclusion

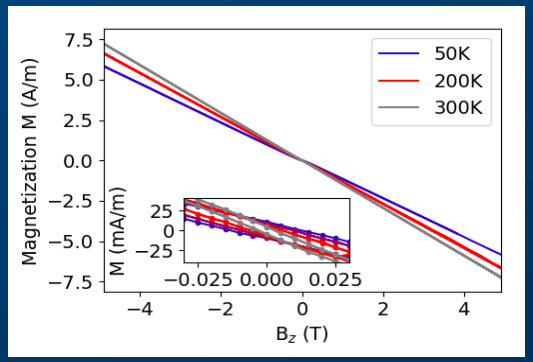
- Spontaneous AHE arising from altermagnetism

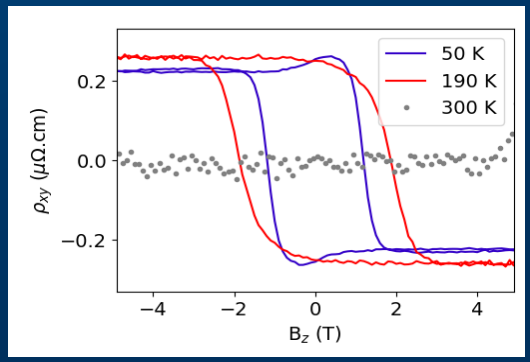
- AHE in **MnTe altermagnet**
  - local crystal field environment
    - Gonzalez Betancourt et al., arXiv:2112.06805





- AHE in **Mn_5Si_3 altermagnetic candidate**
  - multisublattice spin splitting
    - Reichlova et al., arXiv:2012.15651





Outlook & Acknowledgements

- **many materials & areas**
  - spintronics – spin splitting…
  - spincaloritronics - magnons to explore…
  - thermal transport – insulating altermagnets…
  - optics + ultrafast
  - superconductivity
  - ….

- Reichlova et al., arXiv:2012.15651
- Gonzalez Betancourt et al., arXiv:2112.06805

- González-Hernández et al. PRL (2021)
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- Mazin et al. PNAS (2021)

- Feng et al. arxiv2002.08712
- Bai et al. PRL (2022)
- Bose et al. Nat. Electr. (2022)
- Karube et al., arXiv:2111.07487
- …

- Libor Smejkal, Tomas Jungwirth, Jairo Sinova, Rafael Gonzales Hernandez, Jakub Zelezny

- Sebastain T. B. Goennenwein, Ruben D. Gonzalez Betancourt, Rafael Lopez Seeger, Vincent Baltz, Lisa Michez, Ismaila Kounta, Gunter Springholz, Richard Schlitz, Eva Schmoranzerova, Antonin Badura, Zbynek Soban, Kamil Olejnik, Jan Zubac, Philipp Ritzinger, Andy Thomas, Michaela Lammel, Miina Leiviska, Vaclav Petricek, Dominik Kriegner