Spintronics with Compensated Magnets

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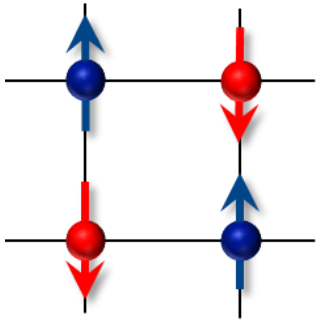
Spintronics with antiferromagnets



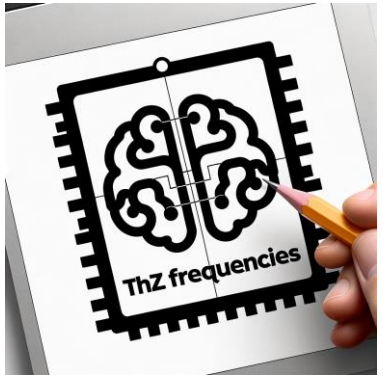
Antiferromagnetic materials for spintronics
- growing research field of last 15 years

🕮 Reichlova, PhD thesis (2016):
Nanostructure and Materials for Antiferromagnetic Spintronics

- General curiosity: Which effects work also without net magnetization ?
- Limits of ferromagnets: Replace ferromagnet by antiferromagnet?

	Ferromagnet	**Compensated magnet**
Density of integration	Stray field	No stray field
Speed	~ GHz	~ THz
Robustness	Sensitive to H_{ext}	Insensitive to H_{ext}
Versatility	Limited materials	More materials

🕮 Shick et al., PRB (2010)

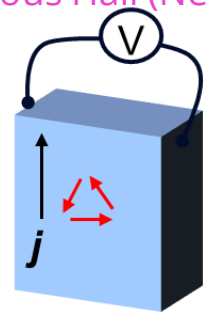


processing-in-memory & THz

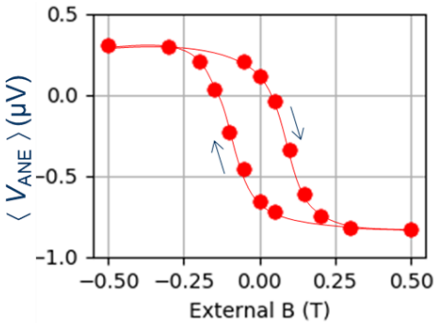
Spintronic effects in antiferromagnets?

Spintronic effects in antiferromagnets

✓ Anomalous Hall (Nernst) effect



Mn_3Sn, Mn_3Ge, Mn_3NiN...



- Nakatsuji et al. Nature (2015)
- Nayak et al., Sci Adv (2016)
- Ikhlas et al. Nat. Phys. (2017)
- Reichlova et al. Nat. Comm. (2019)
- Beckert , HR et al. PRB (2023)

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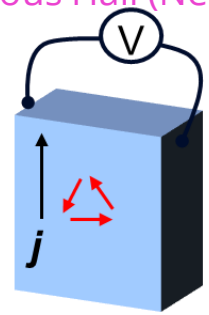

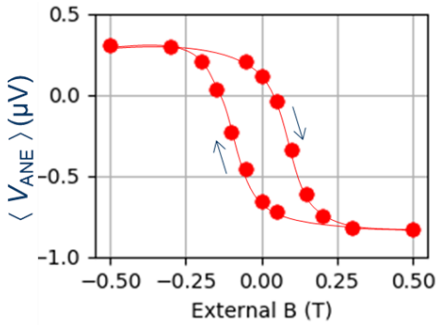

- Nakatsuji et al. Nature (2015)
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- Ikhlas et al. Nat. Phys. (2017)
- Reichlova et al. Nat. Comm. (2019)
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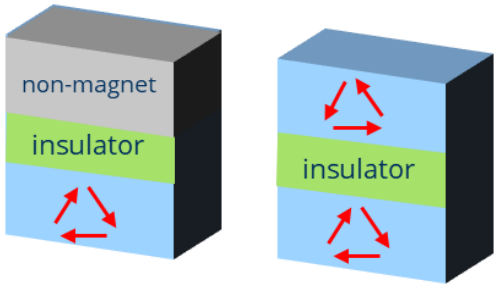
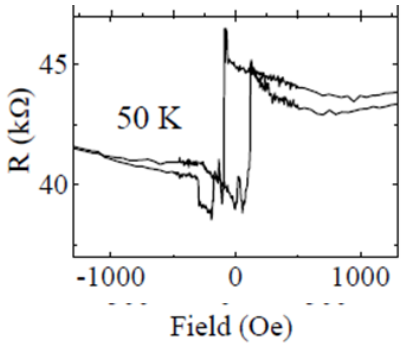
✓ Tunneling (anisotropic) magnetorestistance

IrMn, Mn_3Sn, Mn_3Pt ...





- Park et al. Nat Mat. (2012)
- Marti, HR et al. PRL (2012)
- Reichlova et al. MRX (2015)

- Chen et al. Nature (2023)
- Qin et al. Nature (2023)

Spintronic effects in antiferromagnets

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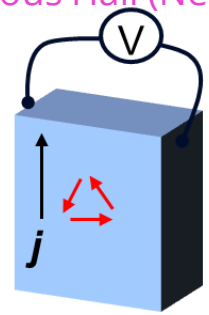

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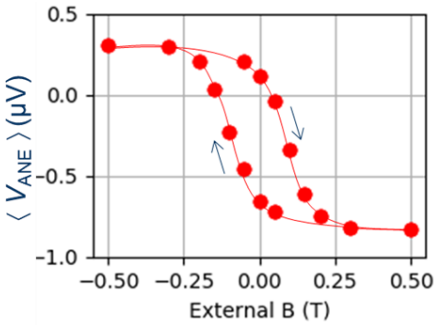

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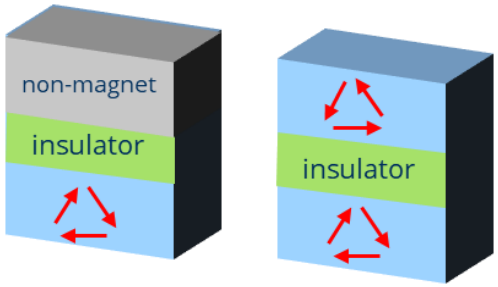

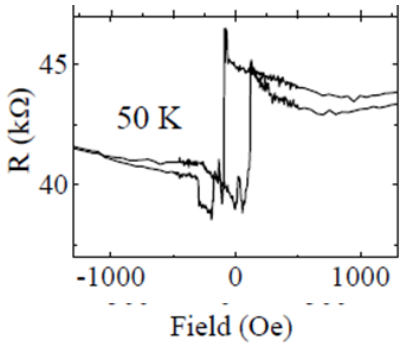

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- Chen et al. Nature (2023)
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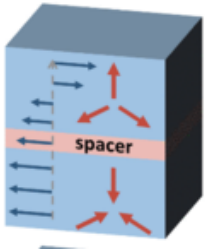
? Gigantic magnetoresistance



theory

- Zelezny et al. PRL (2017)

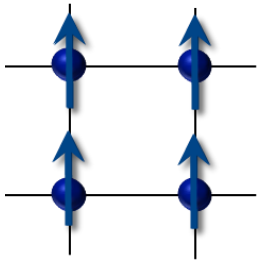
experimentally difficult

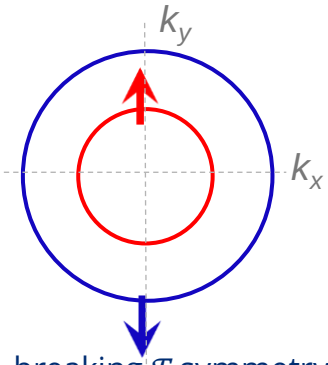
+ low spin current coherence

Magnetically ordered collinear materials

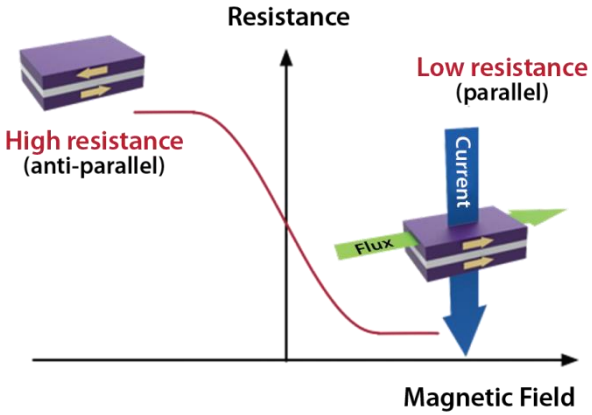
classification without spin orbit coupling

Ferromagnets





- breaking $\mathcal{T}$ symmetry
- spin polarization
- industry favorite (GMR)
- net magnetization
- mostly metals



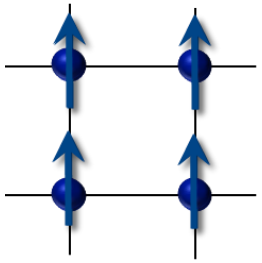
🕮 Resker, Electronic Products

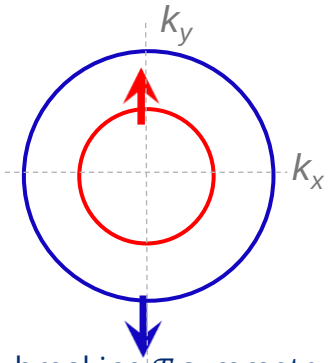
Libor Smejkal
Jairo Sinova
Tomas Jungwirth

Magnetically ordered collinear materials

classification without spin orbit coupling

Ferromagnets





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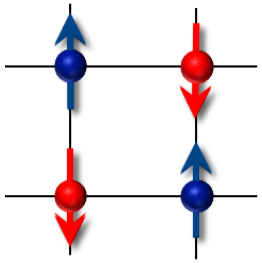
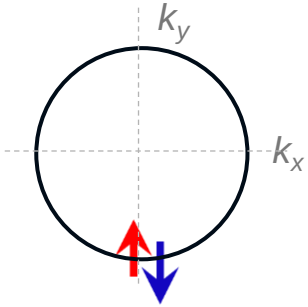
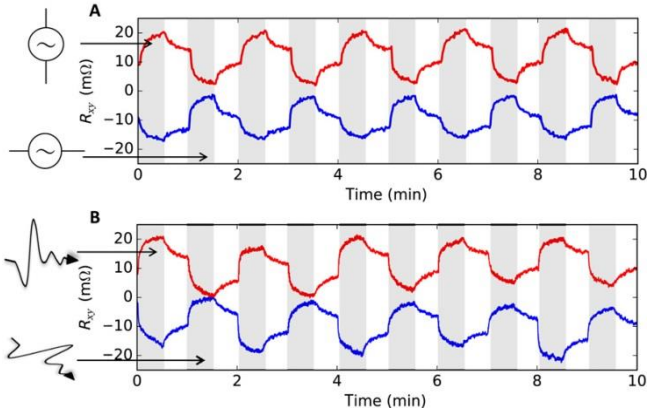
Antiferromagnets





- ✗ no breaking $\mathcal{T}$ symmetry
- ✗ no spin polarization
- ✓ application potential (THz)
- ✓ no net magnetization
- ✓ wide materials choice



🕮 Olejnik et al. Sci. Adv. (2018)

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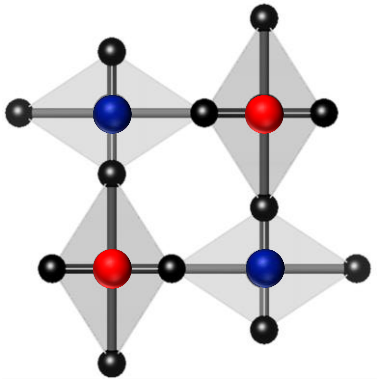
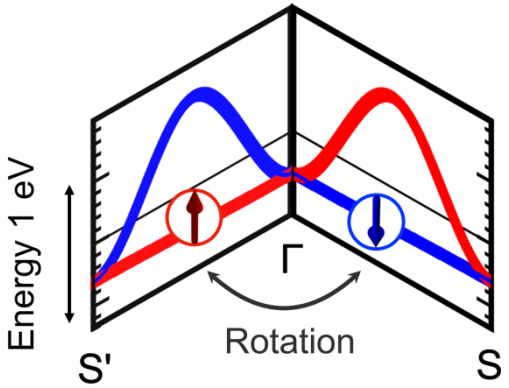
Class combining properties of antiferromagnets and ferromagnets

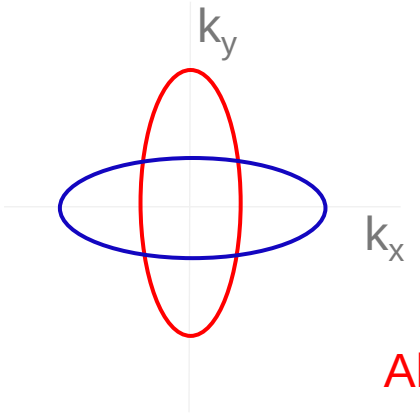
1) real space – $t_{1/2}\mathcal{T}$ breaking by **non-magnetic atoms**

- reflected magnetic order of real space
- opposite spin polarization of two sub-lattices
- anisotropic spin polarization
- conserved spin



2) momentum space





🕮 Smejkal et al. Phys. Rev. X 12, 031042 (2022)
🕮 González-Hernández et al. PRL (2021)
🕮 On-line SPICE-SPIN+X Seminar: Tomas Jungwirth

Alternating spin splitting = *altermagnets*

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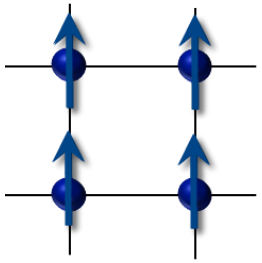
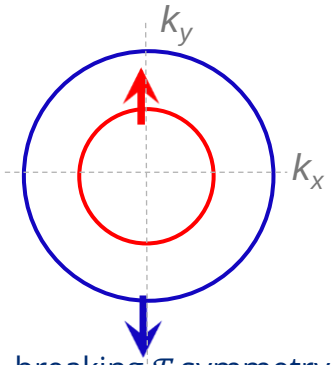
Magnetically ordered collinear materials

classification without spin orbit coupling

Ferromagnets





- ✓ breaking $\mathcal{T}$ symmetry
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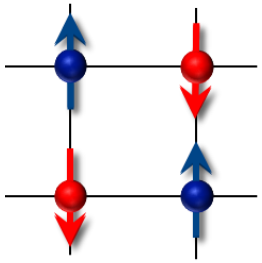
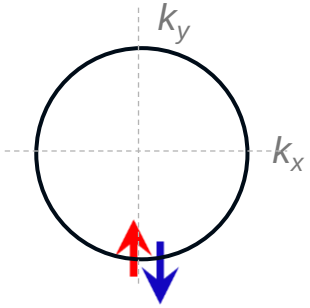
Antiferromagnets





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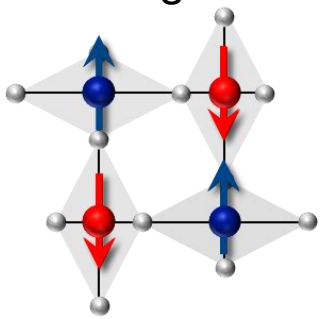
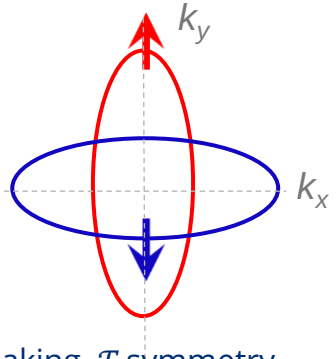
Altermagnets





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JGU FZU

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Many directions of altermagnetic experiments..

Spectroscopy

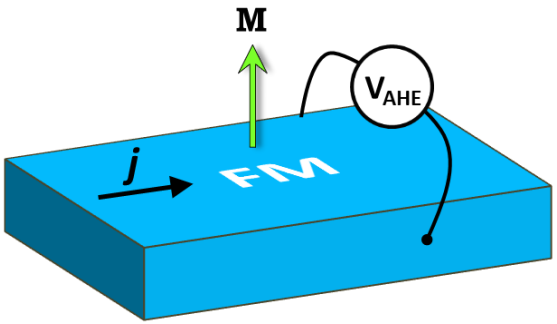
- Fedchenko et al. Sci. Adv.10,eadj4883 (2024)
- Krempasky et al., Nature 626, 517–522 (2024)
- Lee at al., Phys. Rev. Lett. **132**, 036702 (2024)
- Lin et al. arXiv:2402.04995

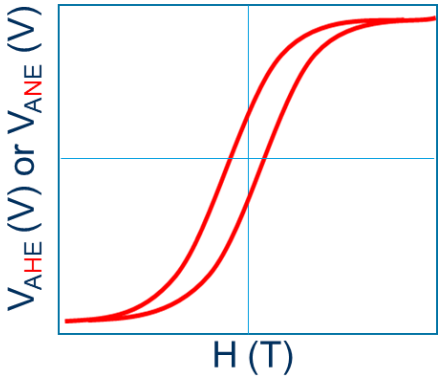
Anomalous Hall effect

Anomalous Nernst effect

- Feng et al. Nat. Elect. (2022)
- **Gonzalez Betancourt et al. PRL (2023)**
- **Reichlova et al. arXiv:2012.15651 (2020), Nat. Comm. (in press)**
- **Tschirner et al. APL Mater. 11, 101103 (2023)**
- **Leiviska et al., arXiv:2401.02275 (2024)**
- **Badura et al. arXiv:2403.12929 (2024)**

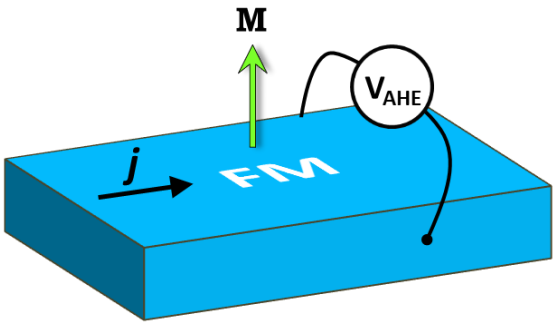
Anomalous Hall Effect

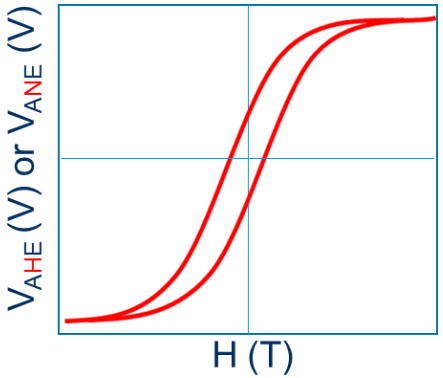




- requires $\mathcal{T}$ breaking in electronic bands
- historically: only ferromagnets
- intrinsic contribution: non-collinear antiferromagnets

Anomalous Hall Effect





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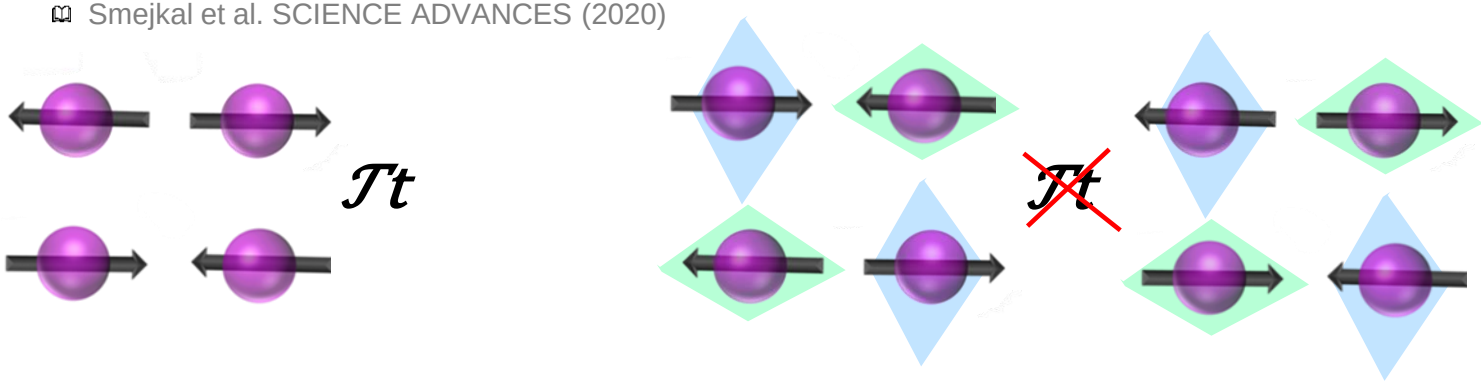
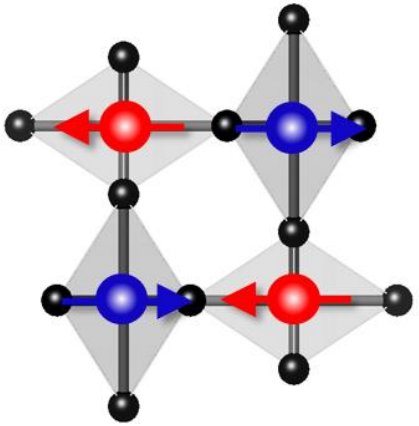
- historically: only ferromagnets
- intrinsic contribution: non-collinear antiferromagnets
- 2020: collinear magnets with particular symmetry: altermagnets
  - Smejkal et al. SCIENCE ADVANCES (2020)



- not allowed for every Neel vector orientation

Anomalous Hall Effect in Altermagnets

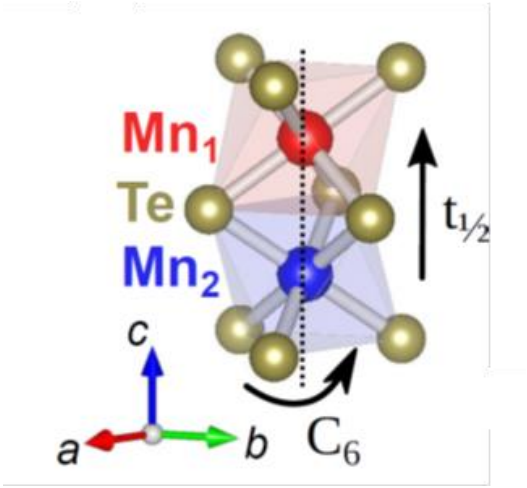
Metallic altermagnet RuO_2



$\mathcal{Tt}$

🕮 Tschirner et al. *APL Mater.* 11, 101103 (2023)

Semiconducting altermagnet MnTe

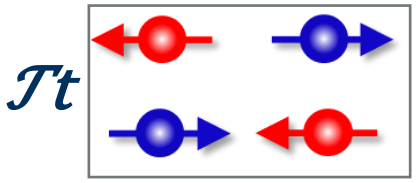


$\mathcal{Tt}$

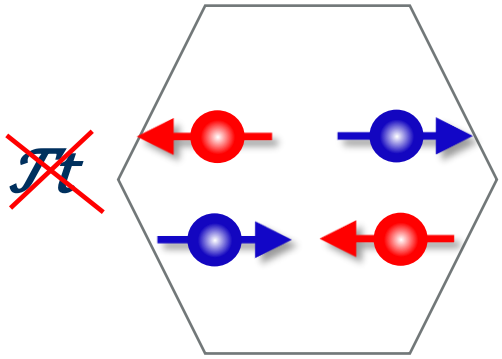
🕮 Gonzalez Betancourt et al. PRL (2023)

Silicon compatible altermagnet Mn_5Si_3

bulk



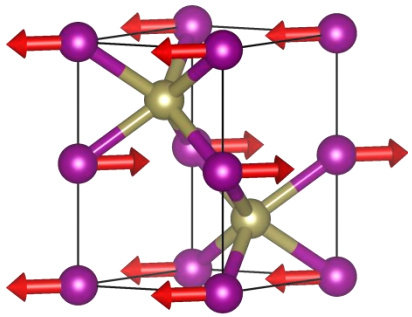
thin films

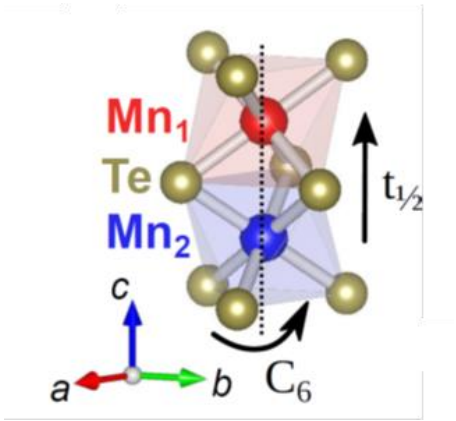


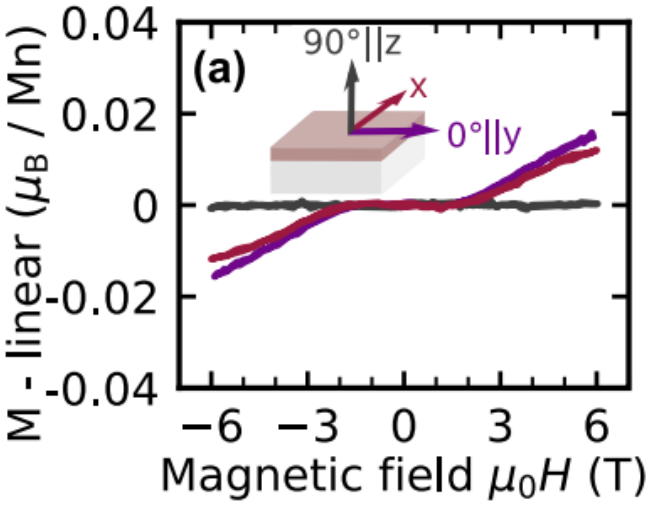
🕮 Reichlova et al. Nat.Comm., in press
🕮 Leiviska et al., arXiv:2401.02275 (2024)

Semiconducting altermagnet MnTe

- MBE growth InP (111) / MnTe
- Mn hexagonal planes + Te atoms at non-centrosymmetric positions





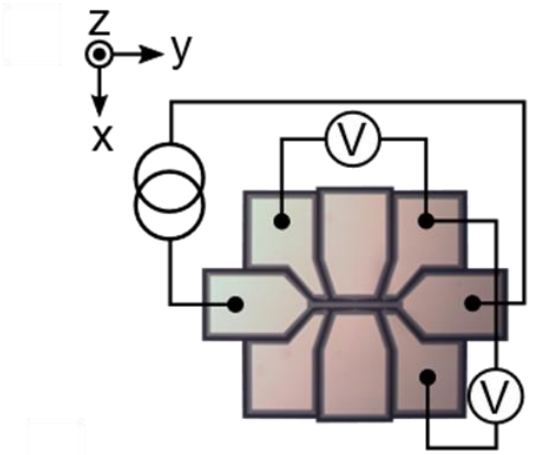


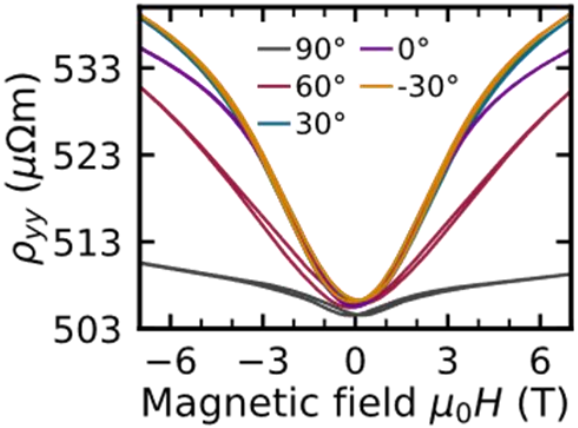
- spin degenerate along high symmetry directions
- spin splitting between Γ and L
- AHE theoretically allowed

🕮 Allen at al. Solid State Comm (1977)
🕮 Kunitomi et al. J Phys France (1964)
🕮 Kriegner at al., Nat. Comm. (2016)

Magnetic field sweeps

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





🕮 Gonzalez Betancourt et al., PRL (2023)

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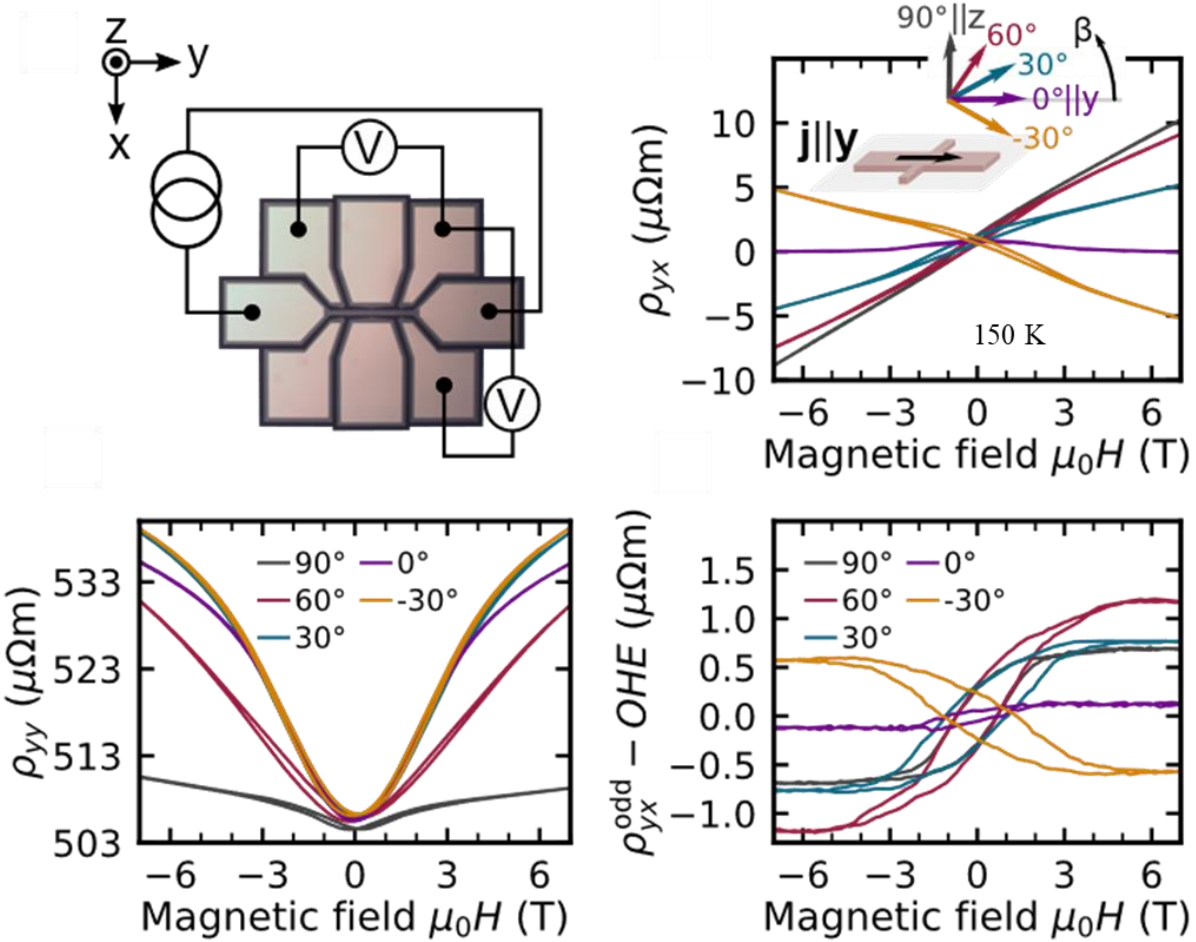
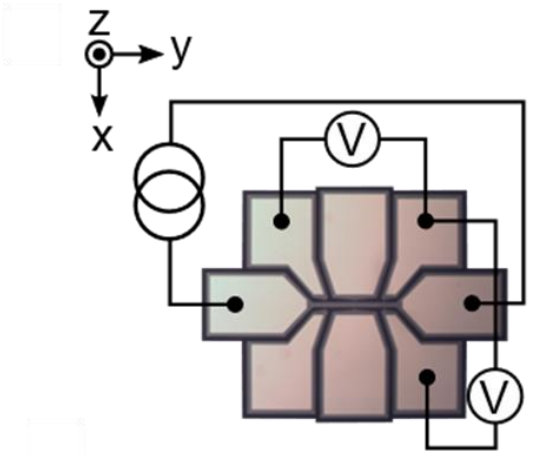
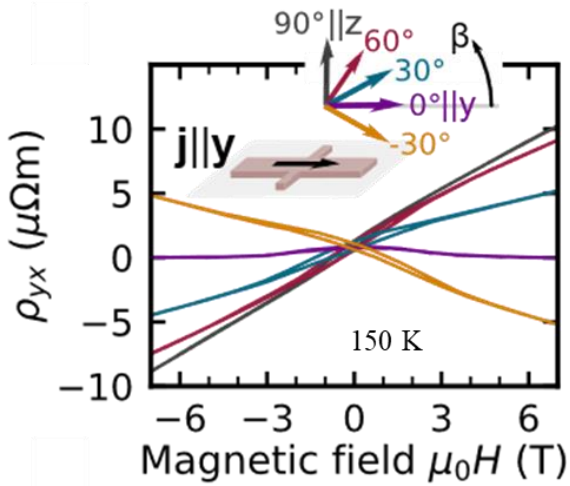


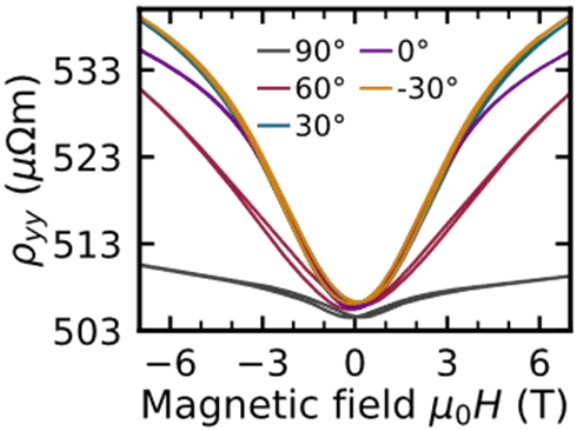
🕮 Gonzalez Betancourt et al., PRL (2023)

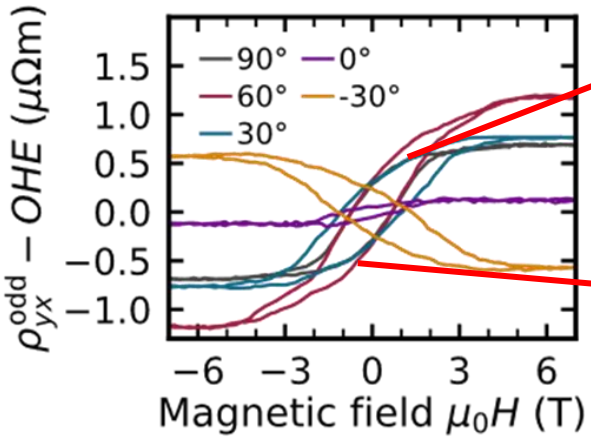
Magnetic field sweeps

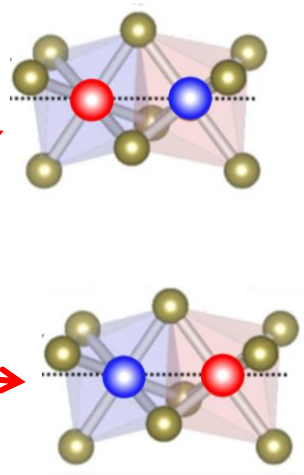
- out-of plane Hall vector linked to in-plane compensated moments
- magnetic field induced reversal of the Hall vector







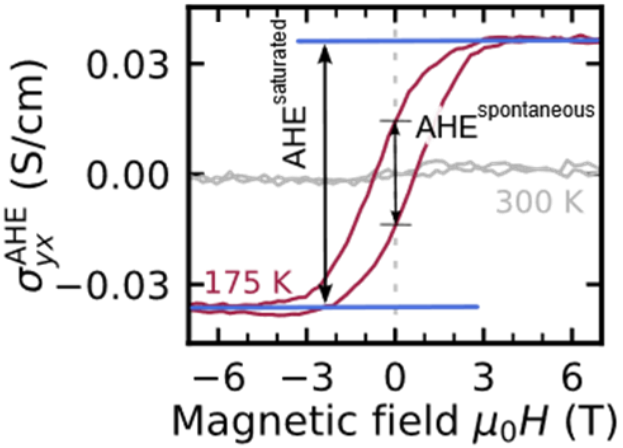




🕮 Gonzalez Betancourt et al., PRL (2023)

Temperature dependence of the AHE

- AHE vanishes in paramagnetic state



Temperature dependence of the AHE

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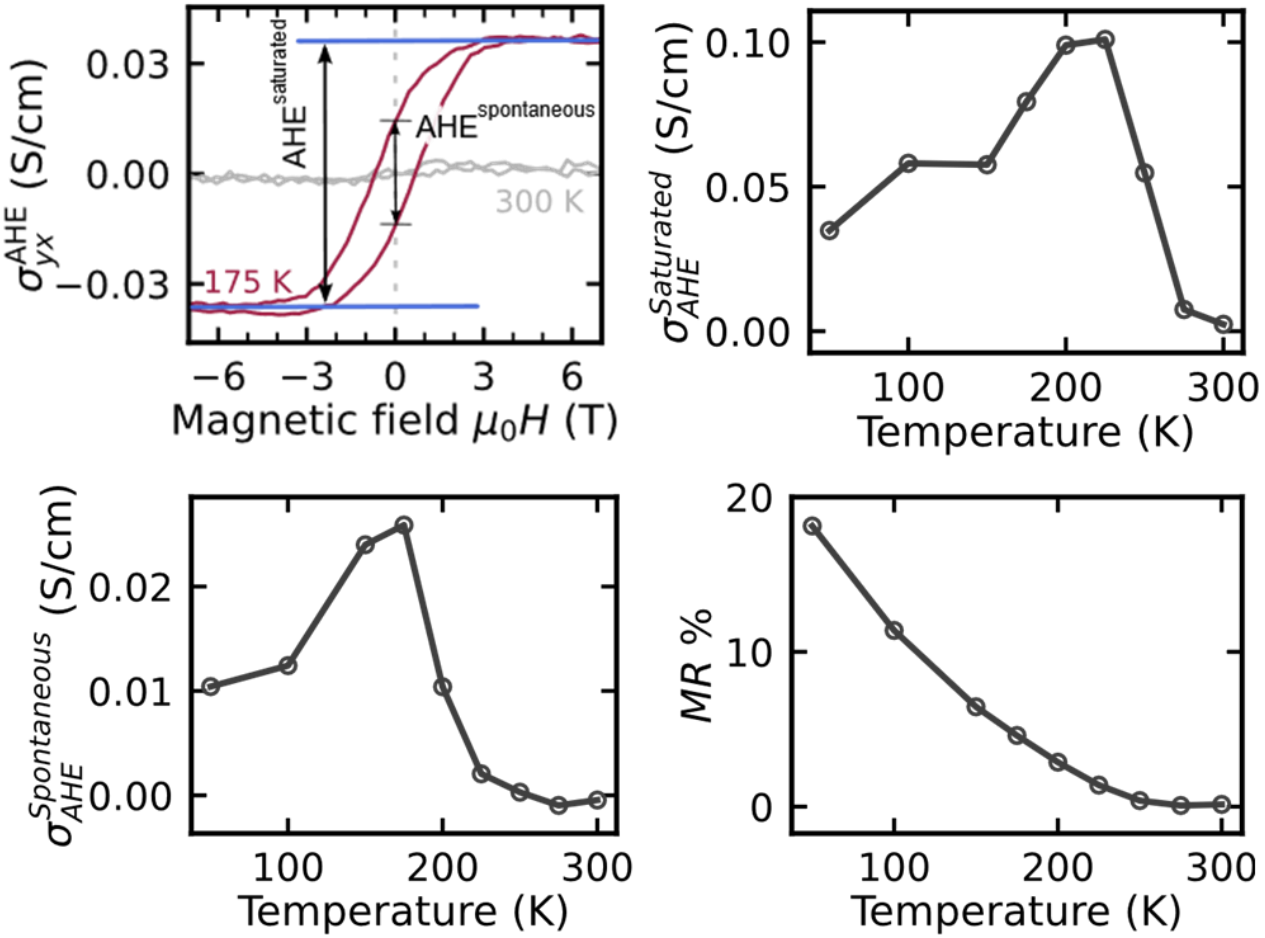
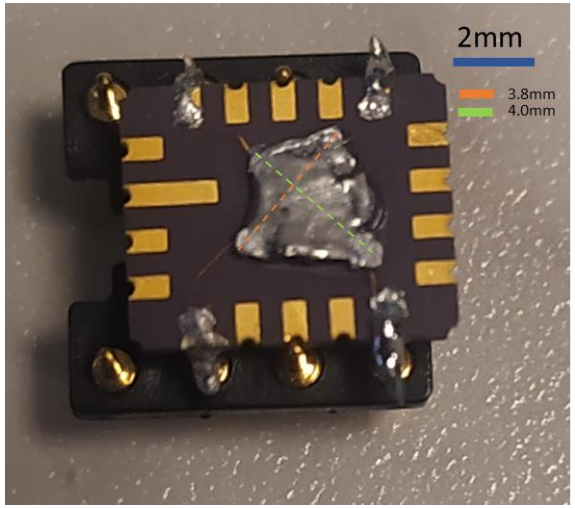
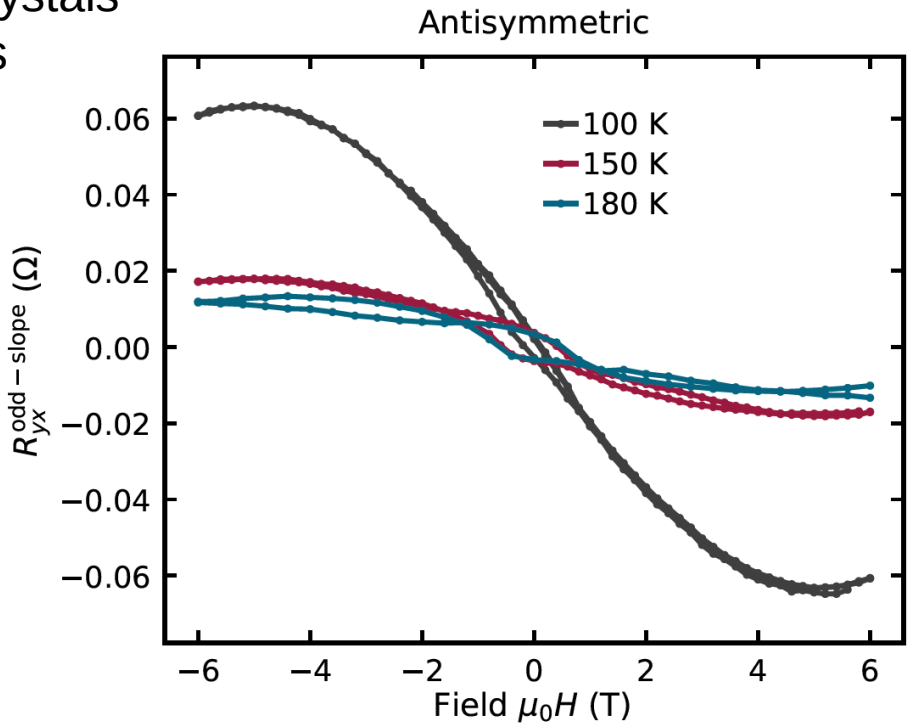
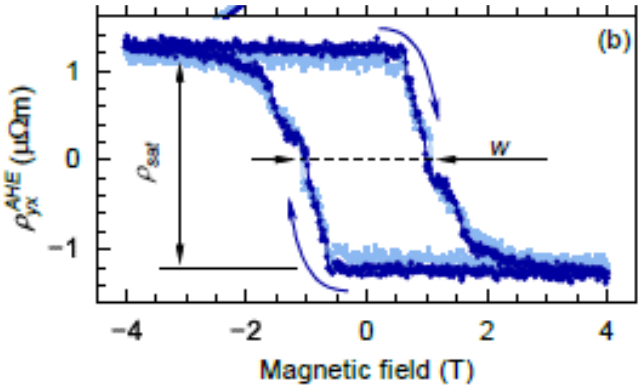


Semiconducting altermagnet MnTe

- AHE present also in bulk crystals
- observed by several groups



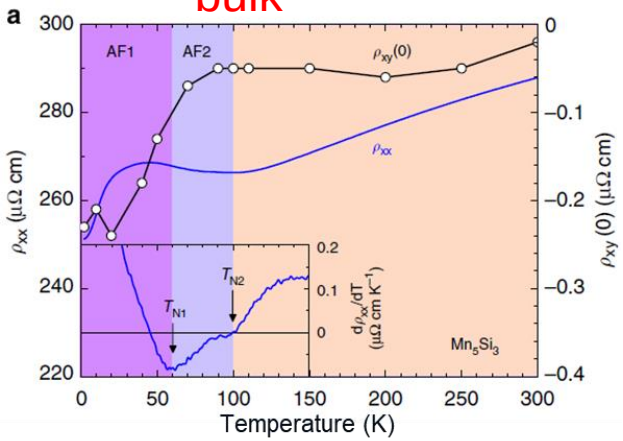




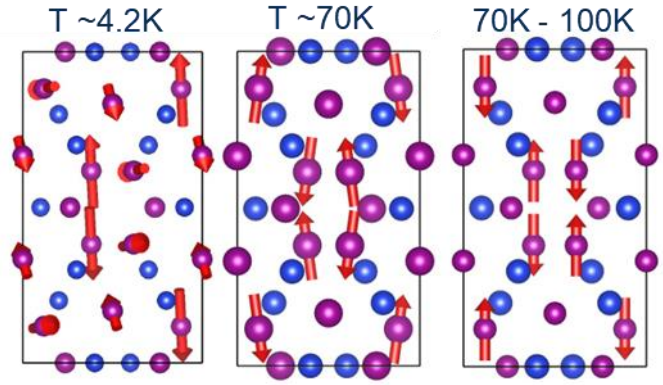
- Gonzalez-Betancourt et al, unpublished
- Kluczyk et al. arXiv:2310.09134

Mn_5Si_3 films

bulk

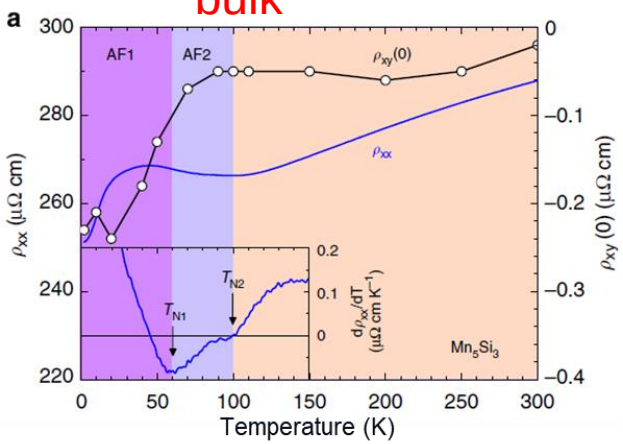


- Suergers et al, Nat Comm (2013)
- Brown et al., J. Phys Cond. Matt (1992)
- Brown et al., J. Phys Cond. Matt (1995)



Mn_5Si_3 bulk vs. thin films

bulk



- Suergers et al, Nat Comm (2013)
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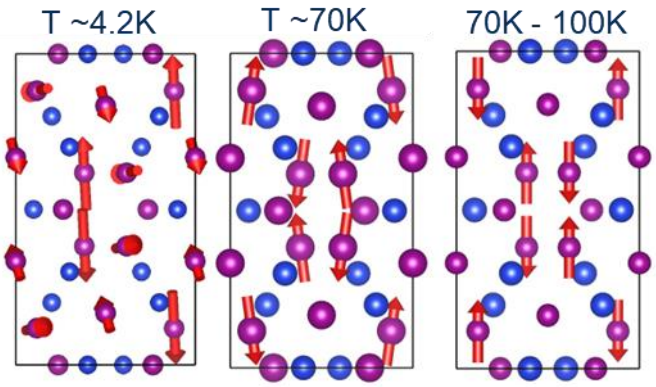
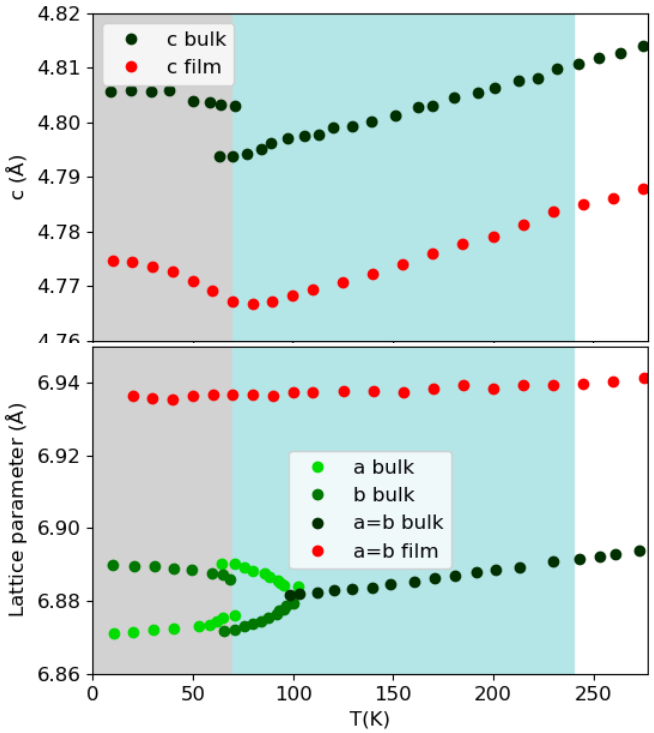


thin films

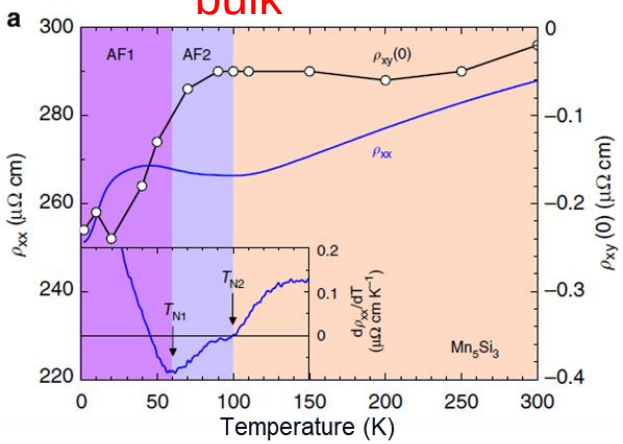
- epitaxial constrains of Si(111)
- altermagnetic
- shift of T_N

- Kounta et al. Phys. Rev. Materials 7, 024416 (2023)



Mn_5Si_3 bulk vs. thin films

bulk



- Suergers et al, Nat Comm (2013)
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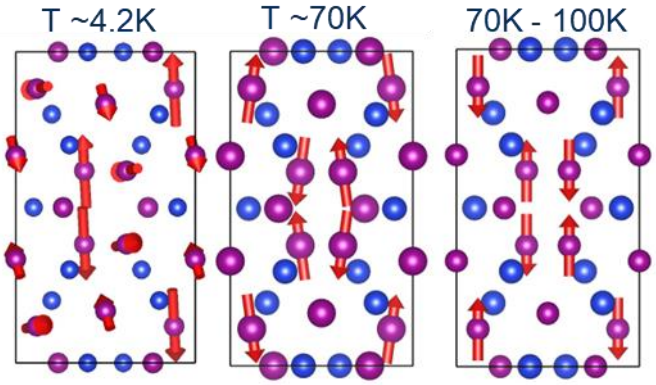
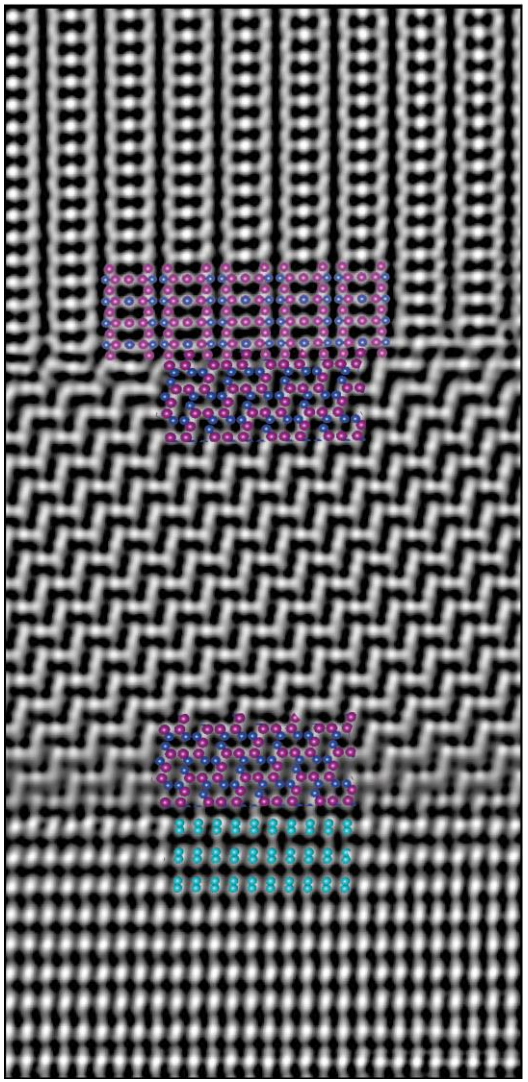


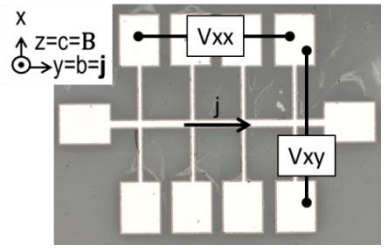
thin films

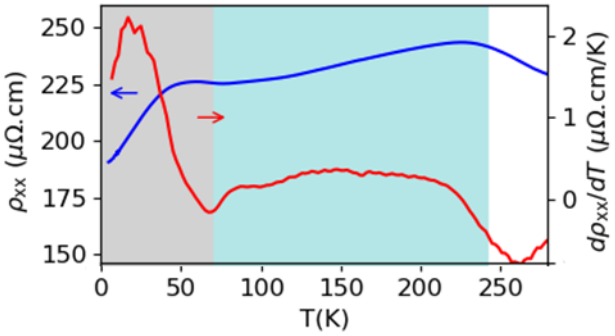
- epitaxial constrains
- altermagnetic
- shift of T_N



TEM: Filip Krizek, ETH (unpublished)

Mn_5Si_3 thin films

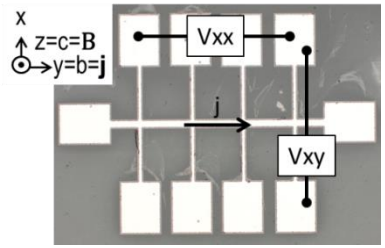


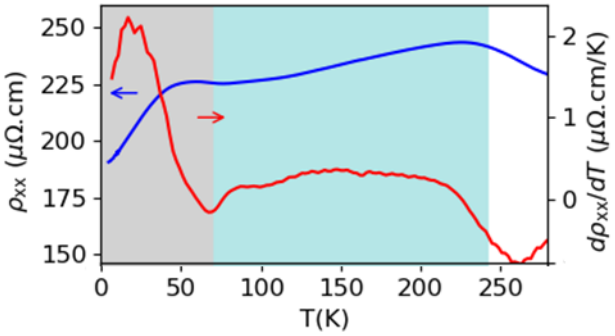


- shifted T_N ~240K

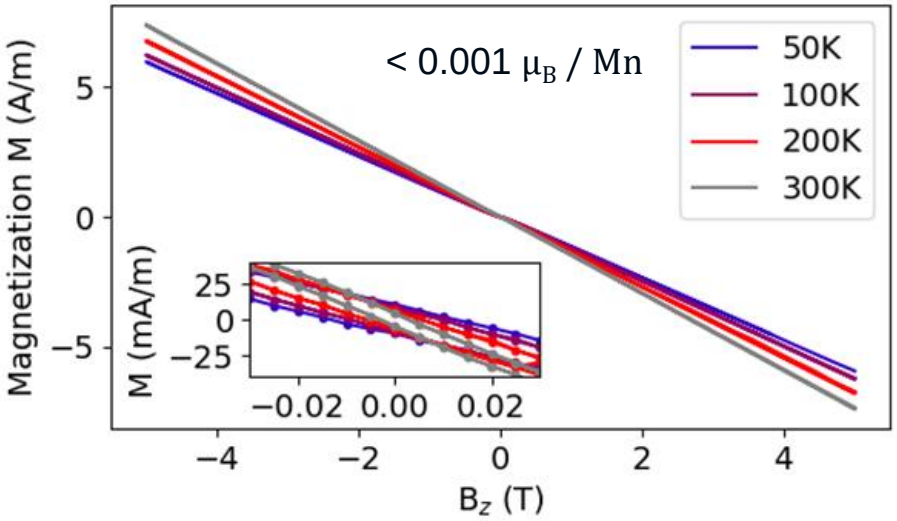
🕮 Reichlova et al., Nat Comm (in press)

Mn_5Si_3 thin films



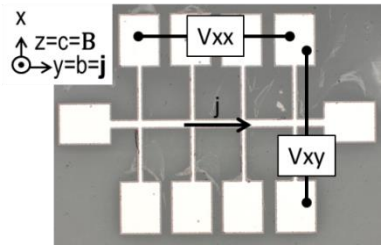


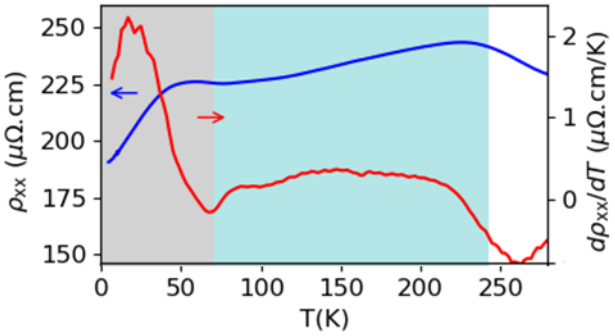
- shifted T_N ~240K
- vanishing magnetization



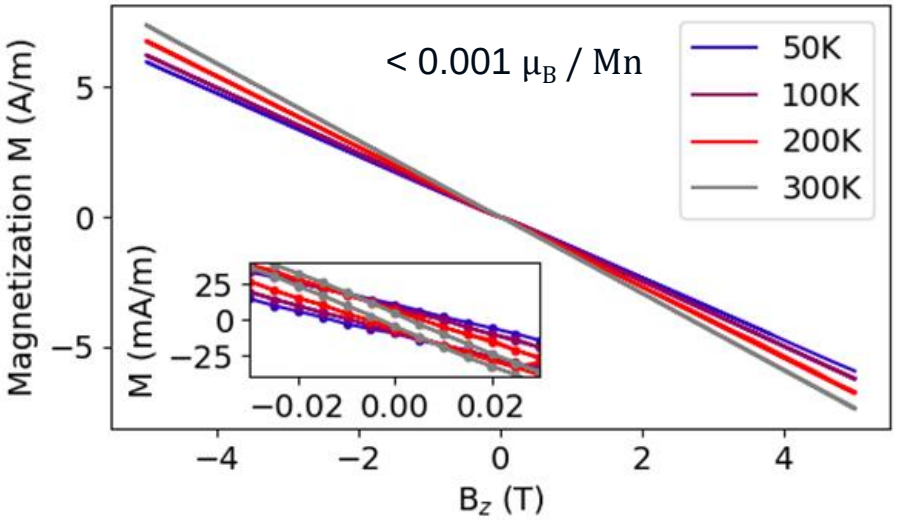
🕮 Reichlova et al., Nat Comm (in press)

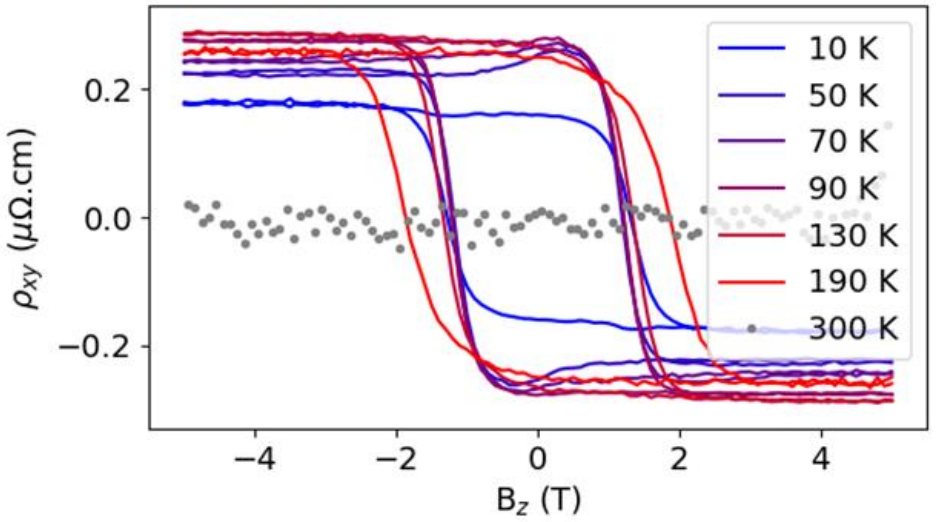
Mn_5Si_3 thin films





- shifted T_N ~240K
- vanishing magnetization
- spontaneous AHE
- absent above T_N
- H_c ~ 2T

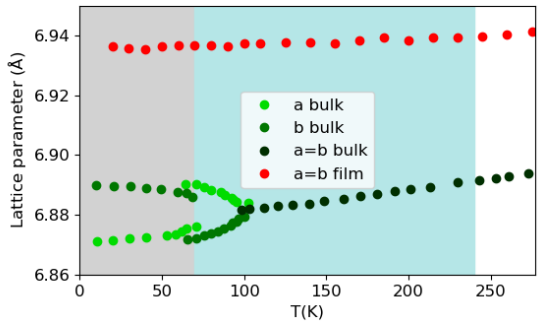




🕮 Reichlova et al., Nat Comm (in press)

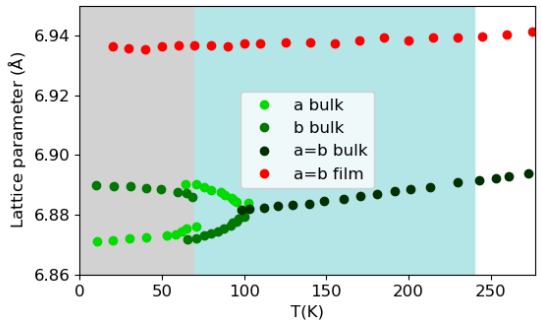
Mn_5Si_3 thin films

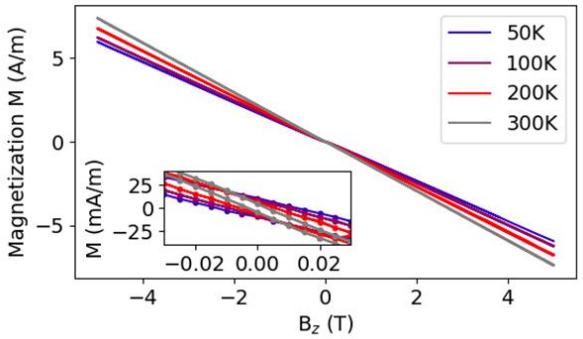
- ✓ hexagonal crystal unit cell



Mn_5Si_3 thin films

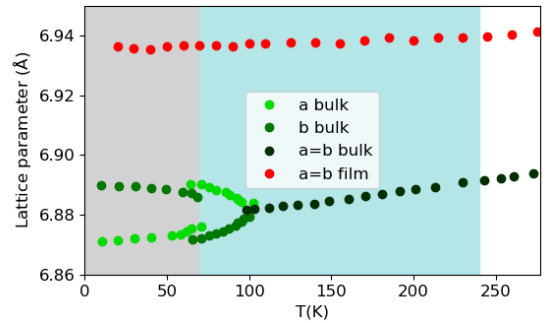
- ✓ hexagonal crystal unit cell
- ✓ vanishing magnetization

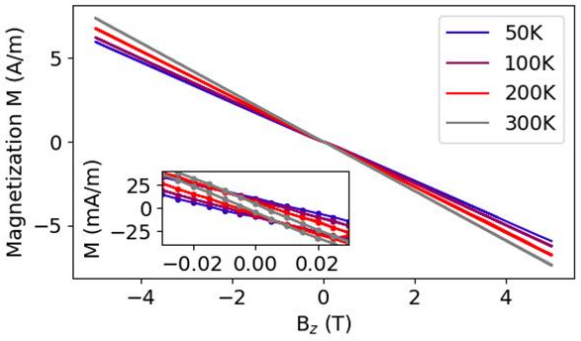


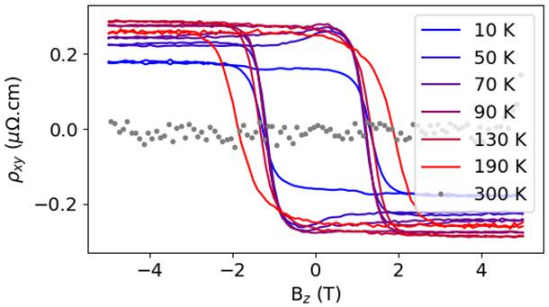


Mn_5Si_3 thin films

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

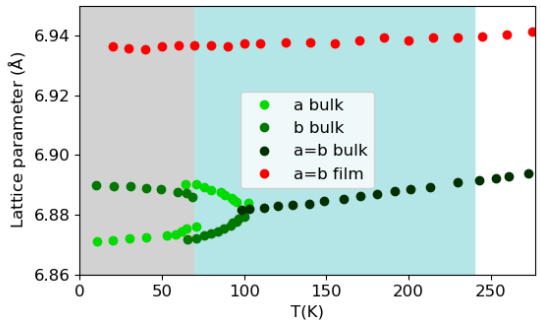


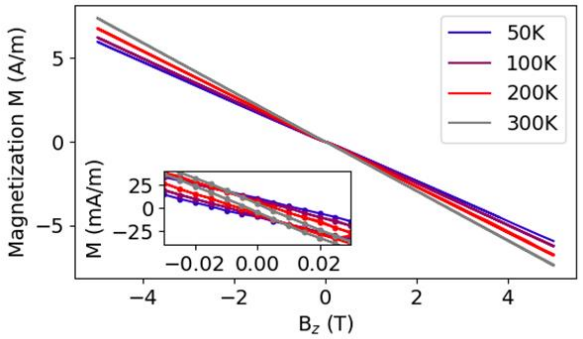


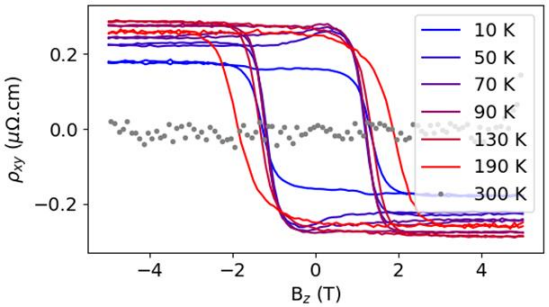


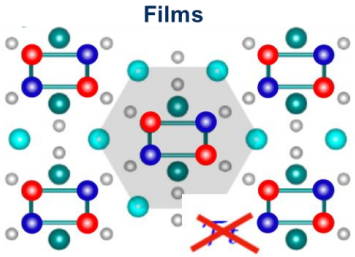
Mn_5Si_3 thin films

- ✓ hexagonal crystal unit cell
- ✓ vanishing magnetization
- ✓ spontaneous $\mathcal{T}$ breaking in band structure
- ✓ no frustration (reason for non-collinearity)







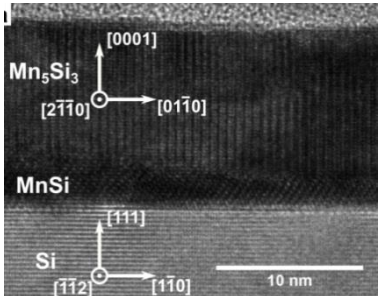


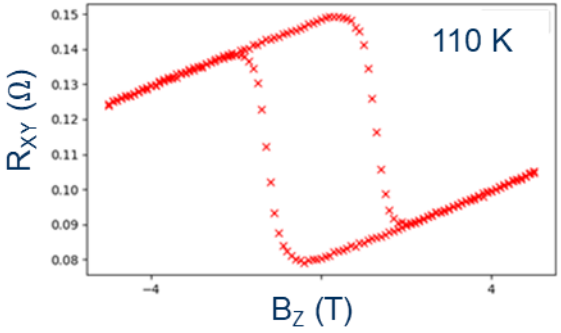
spontaneous anomalous Hall effect originating from altermagnetism

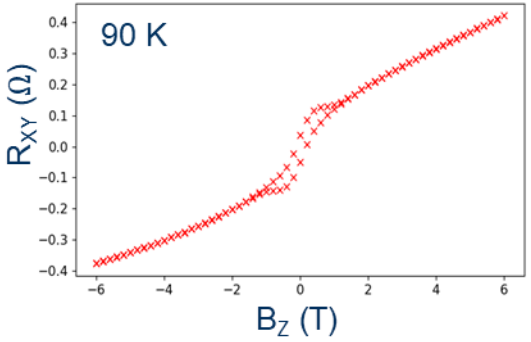
🕮 Reichlova et al., Nat Comm (in press)

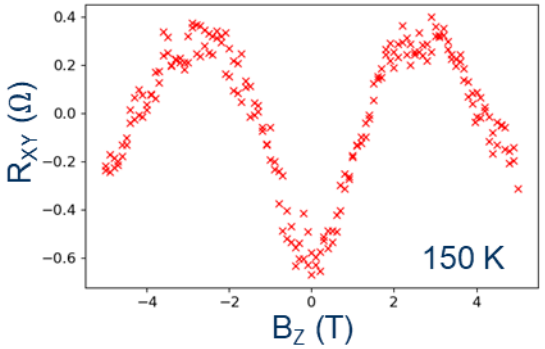
Crystal purity importance

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

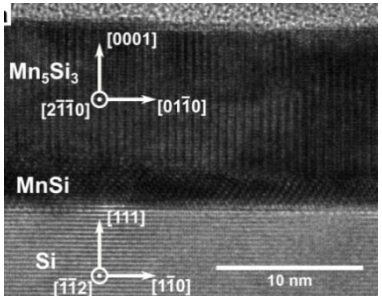




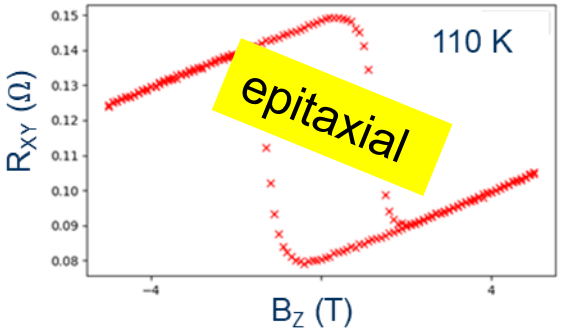


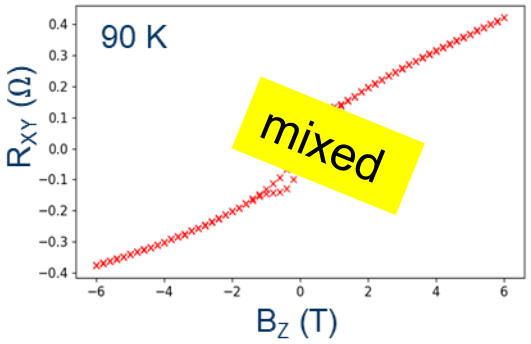


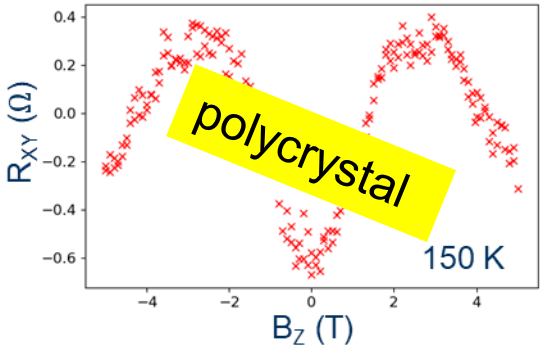
Crystal purity importance



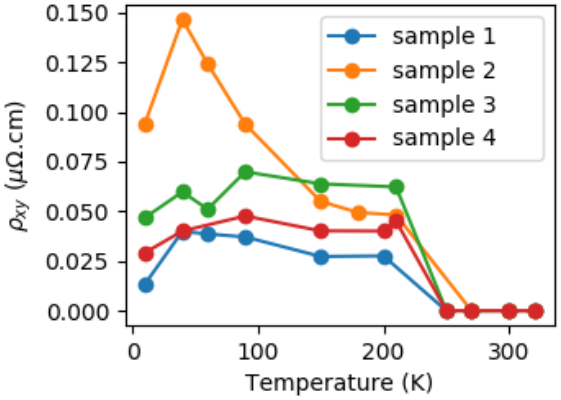
- anisotropic polarization – crystal quality!
- many samples studied
- very different on a first look

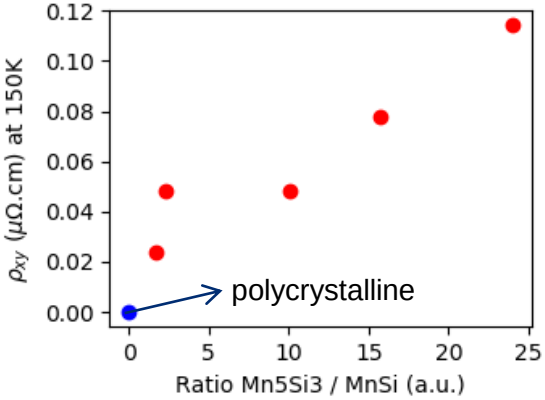


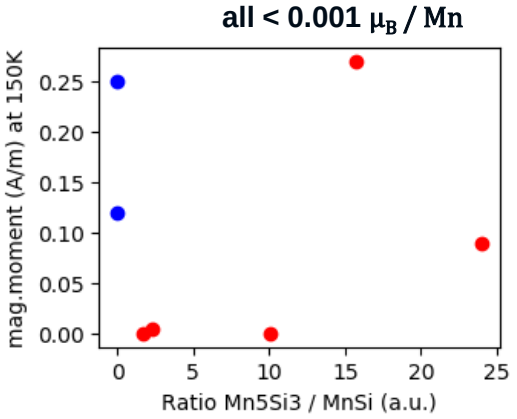




- correlates with sample's phase purity
- does not correlate with "SQUID signal"

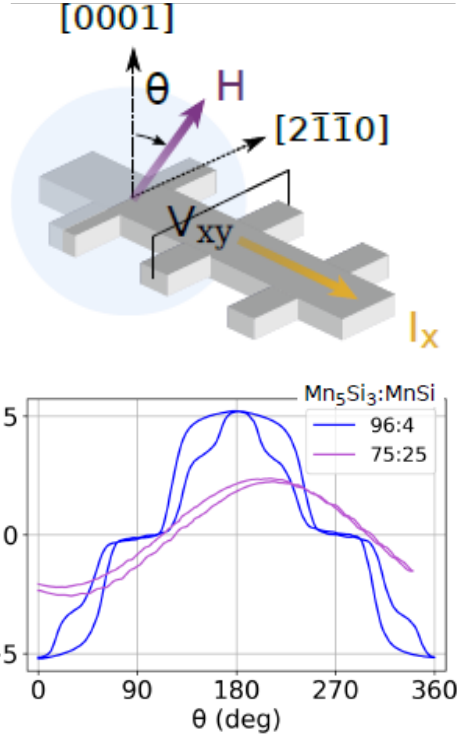


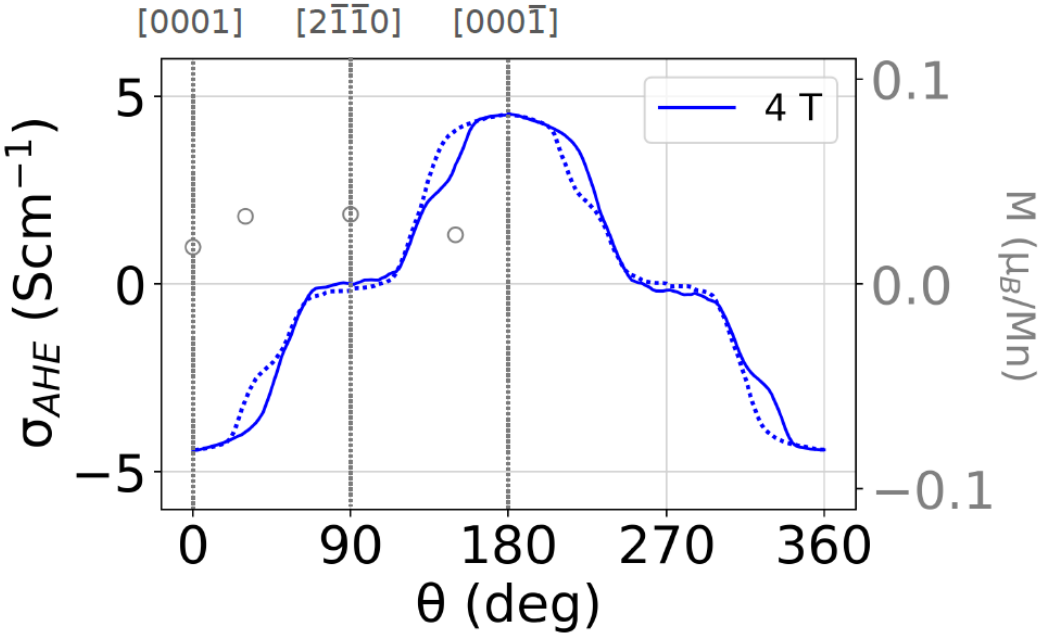




Anisotropic altermagnetic AHE

- ferromagnetic AHE ~ cosine
- altermagnetic AHE ~ spin and crystal symmetry of material
- does not correspond to SQUID data
- modelling by introducing DMI from epitaxial strain
- asymmetry in traces: only if the Neel vector assumed in AHE paper considered

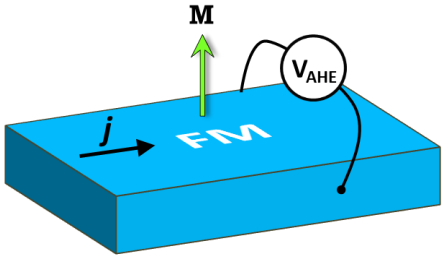




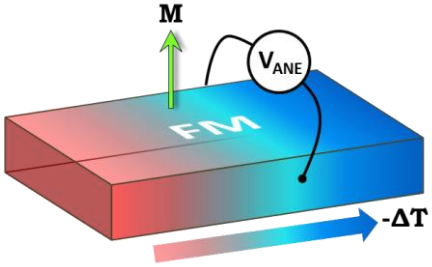
🕮 Kounta et al. PRM (2023)
🕮 Leiviska et al., arXiv:2401.02275 (2024)
🕮 Rial, Gomonay et al., in preparation

Anomalous Nernst effect in altermagnets?

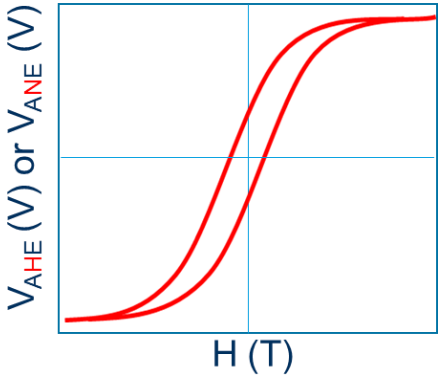
Thermoelectric counterpart of the anomalous Hall effect



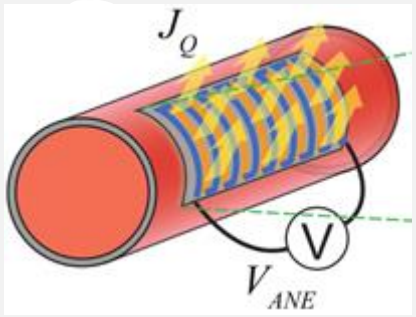
anomalous Hall effect



anomalous Nernst effect



Elegant way of heat harvesting

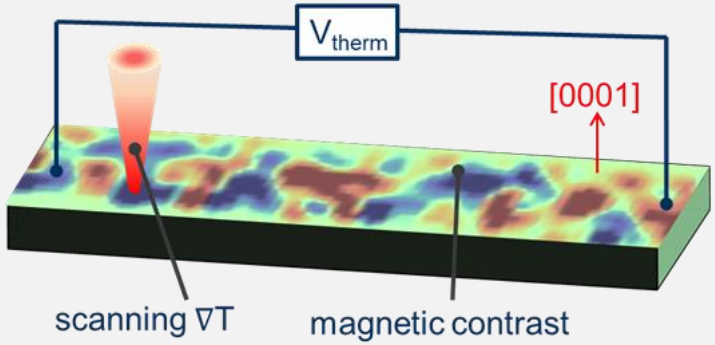


$$\boldsymbol{E_{ANE} \sim N.\nabla T \times M}$$

- simple
- dissipation less
- flexible, scalable

🕮 Zhou et al. APE 043001 (2020)
🕮 Uchida et al. APL (2021)

Magnetic microscopy tool

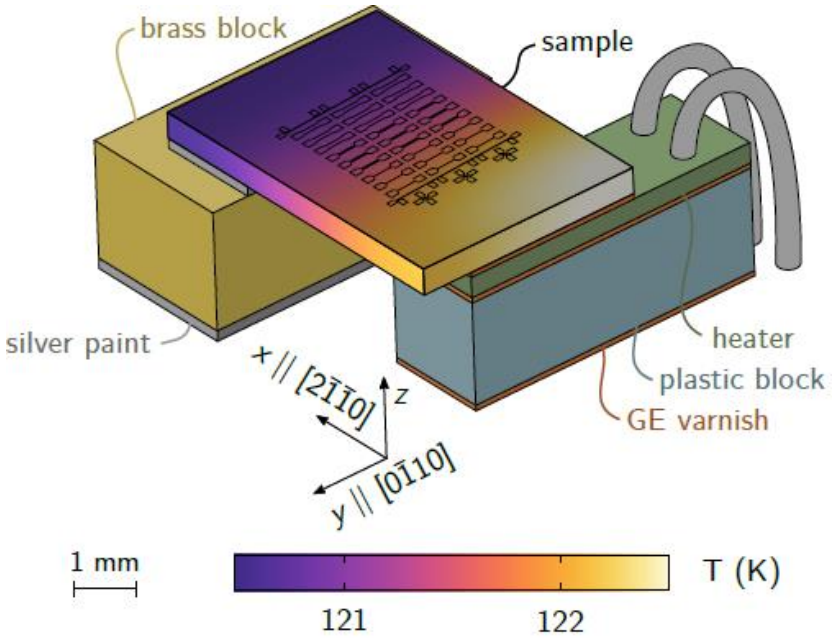


🕮 Weiler et al., PRL (2012)
🕮 Reichlova et al. Nat Comm (2019)

Anomalous Nernst effect in collinear compensated magnets

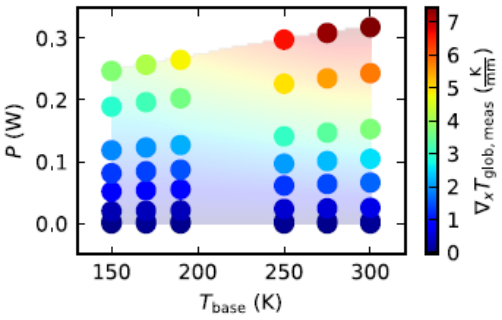
- Collinear antiferromagnets: does not exist
- Predicted to exist in altermagnets 🕮 Zhou et al. PRL (2024)
- Altermagnets: relies on altermagnetic $\mathcal{T}$ breaking
  no need of heavy elements

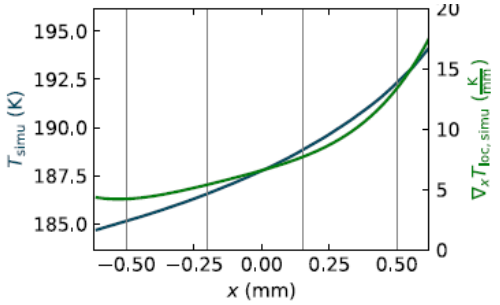
Test ANE in Mn5Si3 films:
- collinear compensated order
- abundant light elements
- silicon compatible



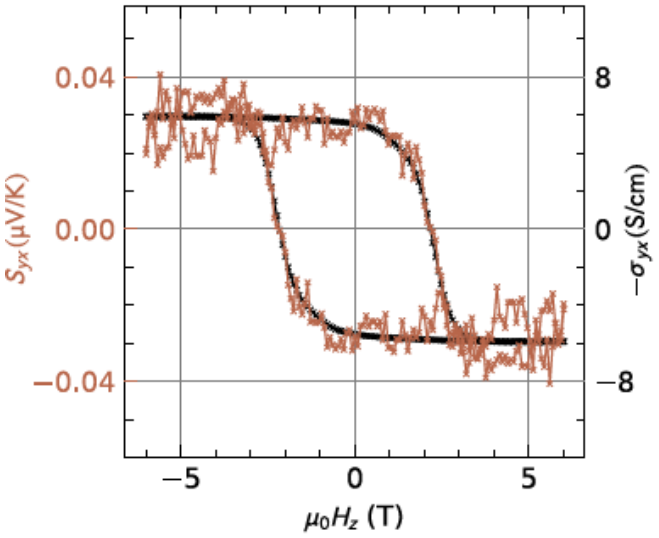
Quantification of ANE

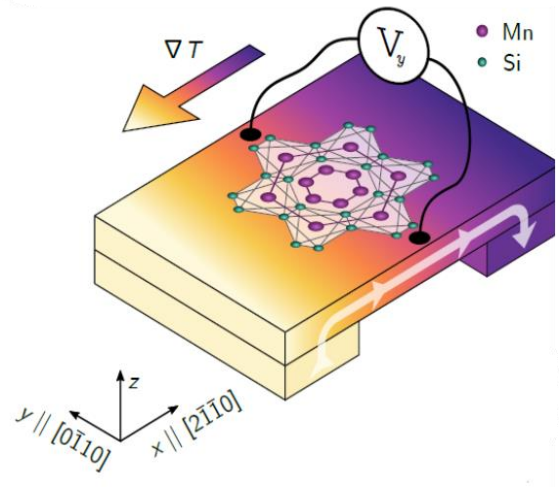
1) calibrate thermometers
2) at each base temperature measure ΔT
3) vary power on heater
4) feed into FEM
5) create a spatial temperature map

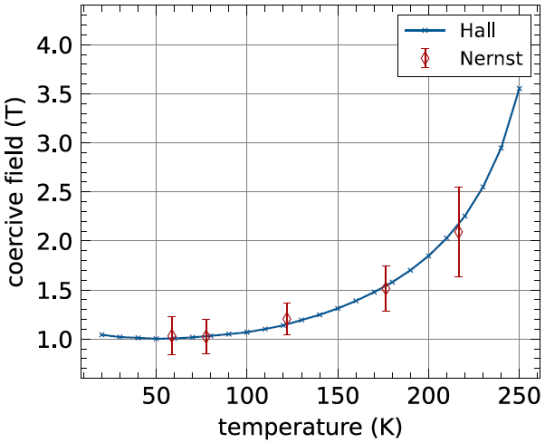




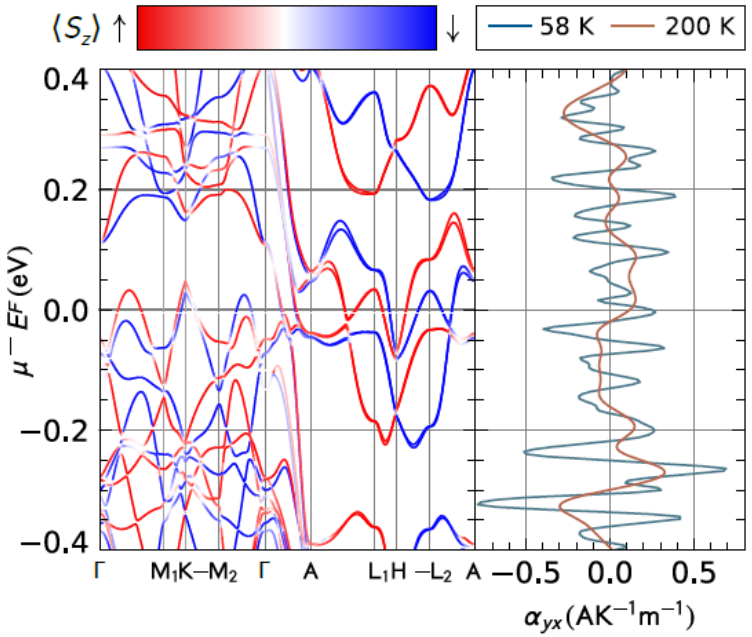
Anomalous Nernst Effect in Mn5Si3







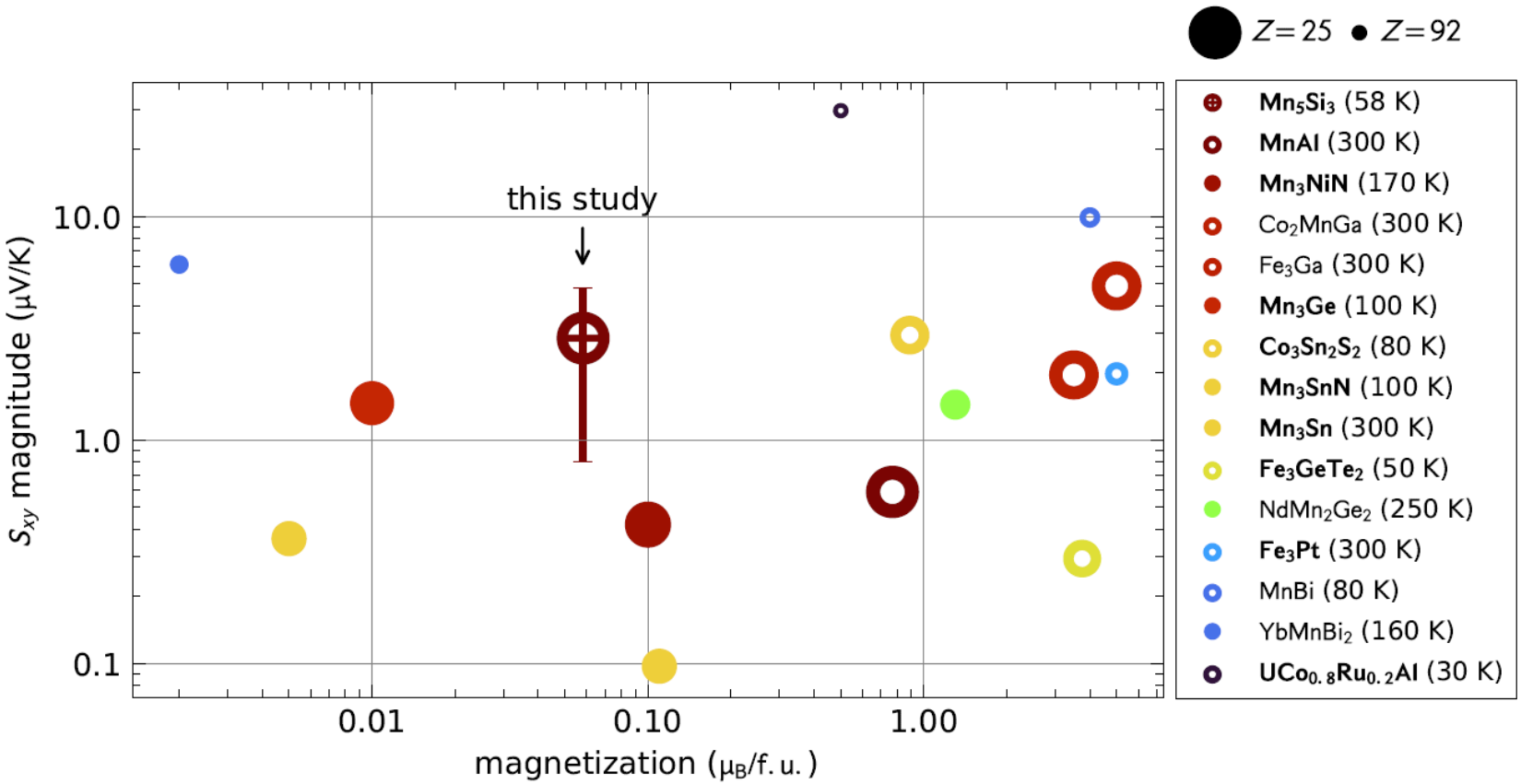
- Robust spontaneous ANE
- Anisotropy as AHE
- Value in agreement with theory



Anomalous Nernst Effect in Mn5Si3

- first ANE in collinear compensated magnet
- comparable magnitude to other materials
- Si compatible film, vanishing magnetization, metallic

🕮 Badura et al. arXiv:2403.12929
🕮 Han et al. arXiv:2403.13427



Many directions of altermagnetic experiments..

few examples

Spectroscopy

- Hariki et al. arxiv.org/abs/2305.03588
- Fedchenko et al. Sci.Adv. (2024)
- Krempansky et al. Nature (2024)
- Lin et al. arXiv:2402.04995

Anomalous Hall effect

Anomalous Nernst effect

- Feng et al. Nat. Elect. (2022)
- **Gonzalez Betancourt et al. PRL (2023)**
- **Reichlova et al. Nat. Comm. in press**
- **Tschirner et al. APL Mater. 11, 101103 (2023)**
- **Leiviska et al., arXiv:2401.02275 (2024)**
- **Badura et al., arXiv:2403.12929**

Spin torques

- Bose et al. Nat. Electr. (2022)
- Bai et al. PRL (2022)
- Karube et al., PRL (2023)
- Han et al. Sci. Adv. 10, eadn0479 (2024)

Magneto-optics

- Hariki et al. arxiv.org/abs/2305.03588
- Zhou et al. PRB 024401 (2021)
- Mazin et al. PNAS (2021)
- Samanta et al. J.App.Phys. (2020)

Magnons

- Smejkal et al. Phys. Rev. Lett. **131**, 256703 (2023)

(anomalous) thermal Hall effect

- Zhou et al. Phys. Rev. Lett. **132**, 056701 (2024)

van der Waals systems

- Mazin et al. arXiv:2309.02355 (2023)

...

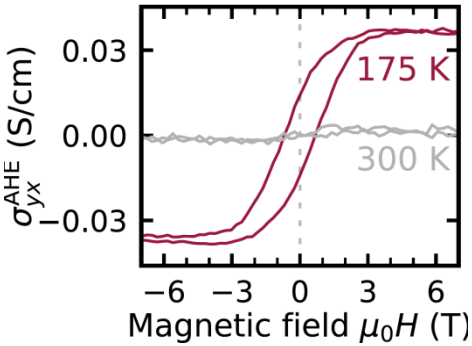
Conclusion

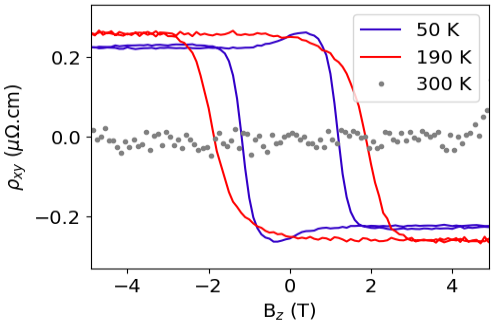
- Revised classification of collinear magnets

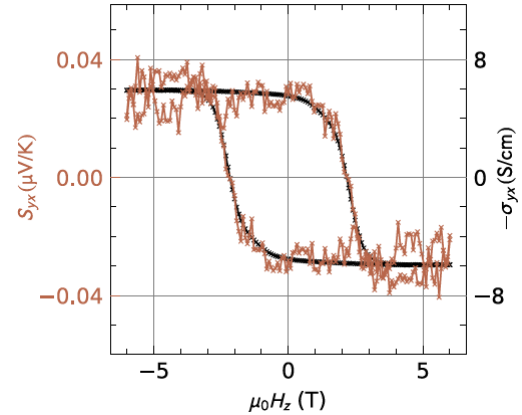
- AHE in **MnTe altermagnet**
  - intrinsic semiconductor
  - local crystal field environment

- AHE in **Mn_5Si_3 films**
  - metallic and silicon compatible
  - epitaxial constrains induced altermagnetism

- **Anomalous Nernst effect** in altermagnets
  - abundant and light elements







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