Spontaneous anomalous Hall effect arising from an unconventional compensated magnetic phase in a semiconductor

Ruben D. Gonzalez Betancourt, Jan Zubáč, Rafael J. Gonzalez-Hernandez, Kevin Geishendorf, Zbynek Šobáň, Gunther Springholz, Kamil Olejník, Libor Šmejkal, Jairo Sinova, Tomas Jungwirth, Sebastian T. B. Goennenwein, Andy Thomas, Helena Reichlová, Jakub Železný, Dominik Kriegner

FZU Fyzikální ústav Akademie věd České republiky

TECHNISCHE UNIVERSITÄT DRESDEN

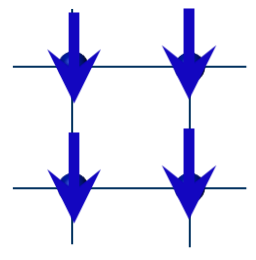
UNIVERSIDAD DEL NORTE

JG|U

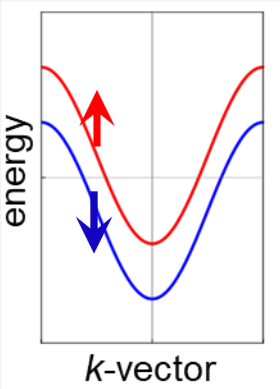
Magnetically ordered collinear materials

classification without spin orbit coupling

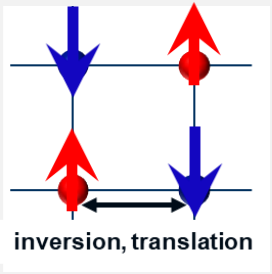
Ferromagnets



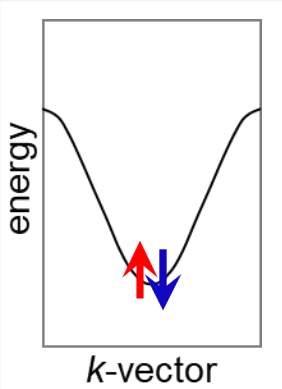
- net magnetization
- exchange splitting
- breaking $\mathcal{T}$ symmetry in electronic band structure
- industry favorite (GMR)



Antiferromagnets

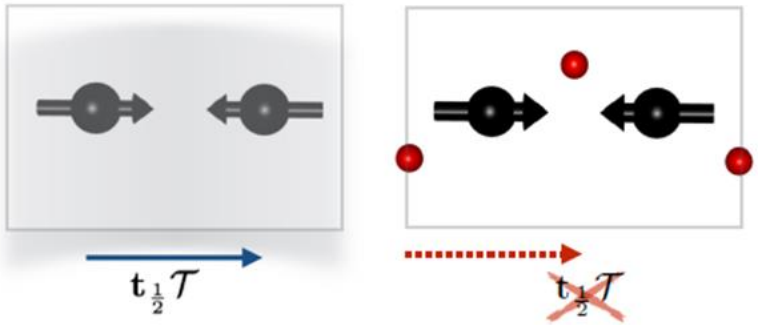


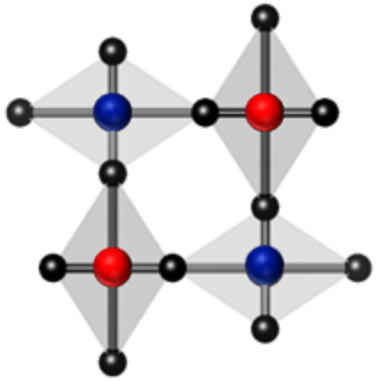
- no net magnetization
- no spin splitting
- **no breaking $\mathcal{T}$ symmetry** in electronic band structure
- application potential (speed...)



Additional class combining properties of antiferromagnets and ferromagnets

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



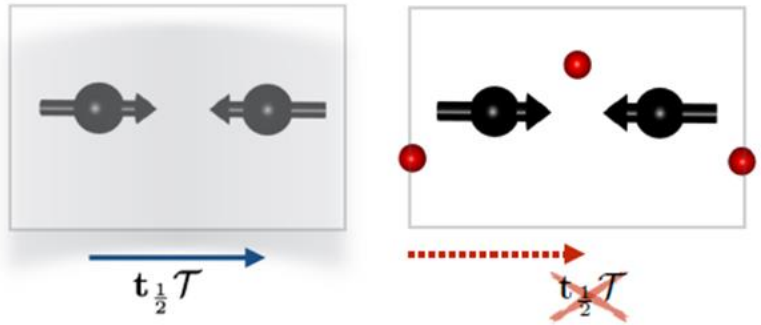


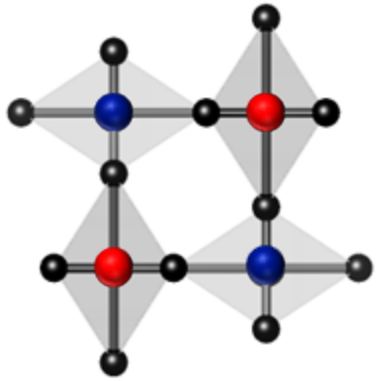
- Smejkal et al. Sci Adv (2020)
- Smejkal et al. arXiv:2105.05820
- Smejkal, Nat Rev.Mat (2022)
- González-Hernández et al. PRL (2021)
- On-line SPICE-SPIN+X Seminar: Tomas Jungwirth

- Helena Reichlova, Spice talk

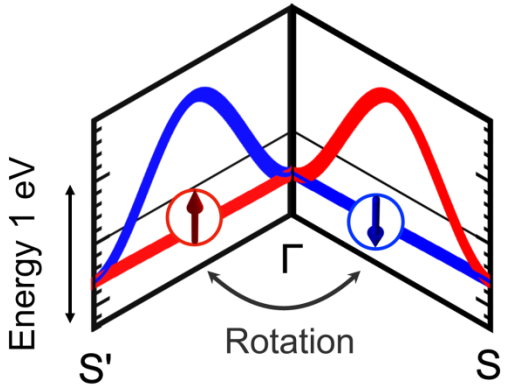
Additional material class
combining properties of antiferromagnets and ferromagnets

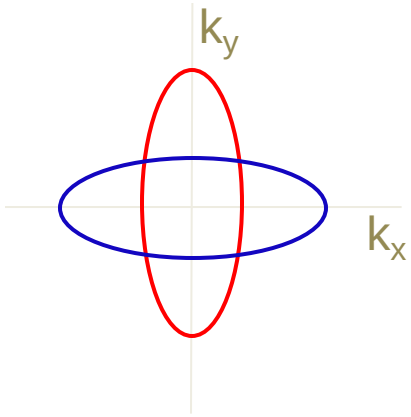
- real space – $t_{1/2}\mathcal{T}$ breaking by **non-magnetic atoms**





- momentum space





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

Smejkal et al. Sci Adv (2020)
Smejkal et al. arXiv:2105.05820
Smejkal, Nat Rev.Mat (2022)
González-Hernández et al. PRL (2021)
On-line SPICE-SPIN+X Seminar: Tomas Jungwirth

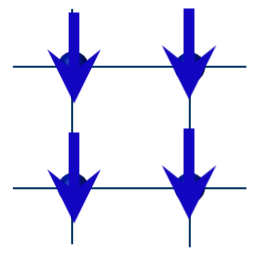
Alternating spin splitting = *altermagnets*

Helena Reichlova, Spice talk

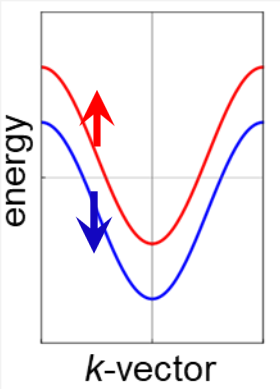
Magnetically ordered collinear materials

classification without spin orbit coupling

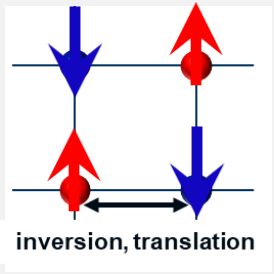
Ferromagnets



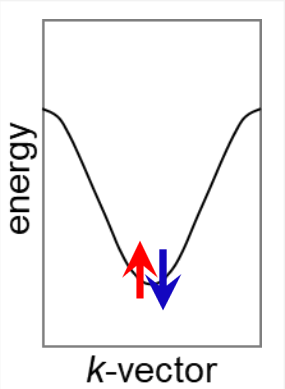
- net magnetization
- exchange splitting
- breaking $\mathcal{T}$ symmetry in electronic band structure
- industry favorite (GMR)



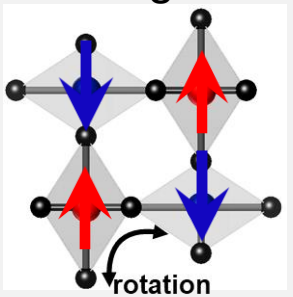
Antiferromagnets



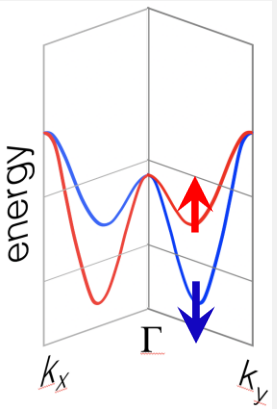
- no net magnetization
- no spin splitting
- **no breaking $\mathcal{T}$ symmetry** in electronic band structure
- application potential (speed...)



Altermagnets



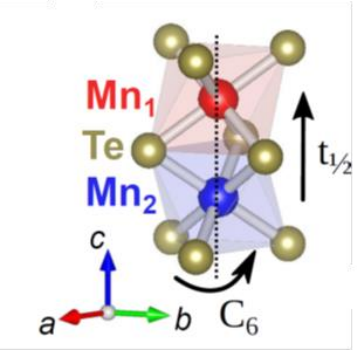
- no net magnetization
- anisotropic spin splitting
- **breaking $\mathcal{T}$ symmetry** in electronic band structure
- high speed, GMR potential...

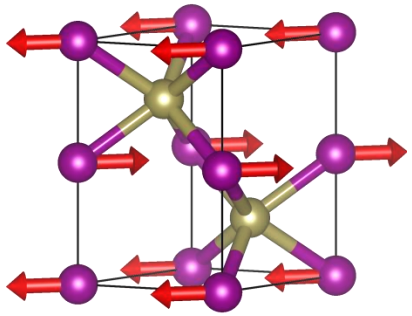


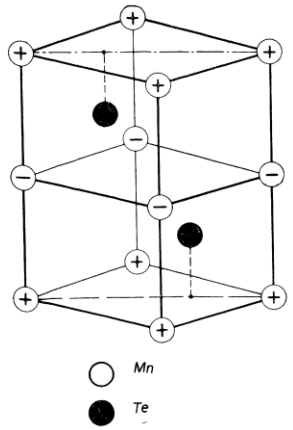
🕮 Helena Reichlova, Spice talk

Altermagnet MnTe

- Magnetic sublattices connected by rotation/screw axis





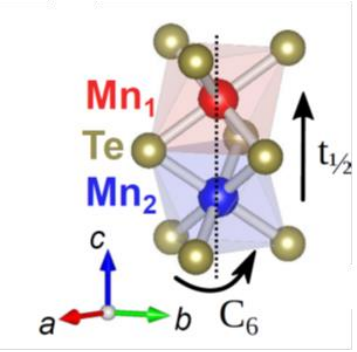


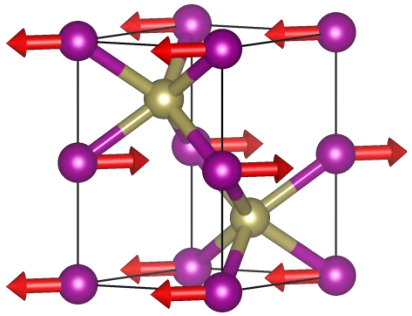
🕮 Kunitomi, et al., Journal de Physique, 25, 568 (1964)

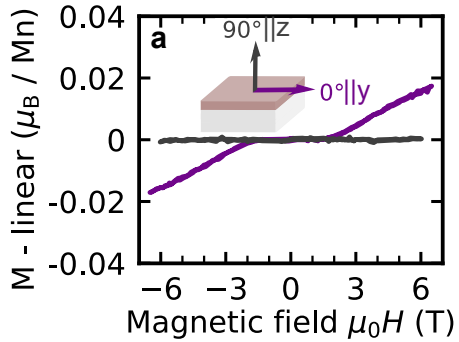
- Te atoms surround magnetic Mn atoms at non-centrosymmetric positions

Altermagnet MnTe

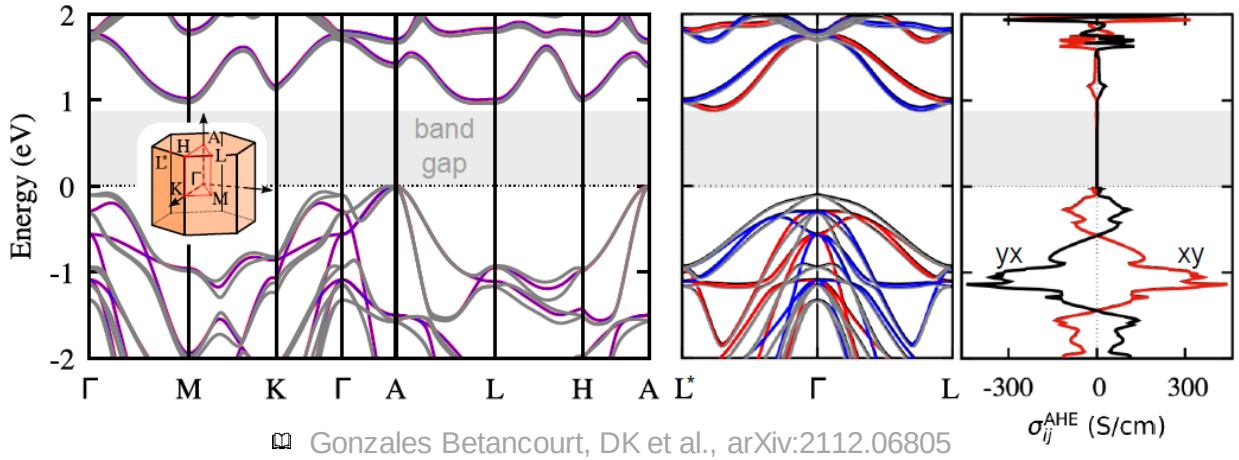
- Magnetic sublattices connected by rotation/screw axis







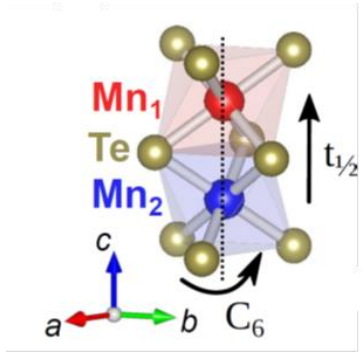
- Te atoms surround magnetic Mn atoms at non-centrosymmetric positions
- -> spin polarization in band structure is allowed: found between Γ and L

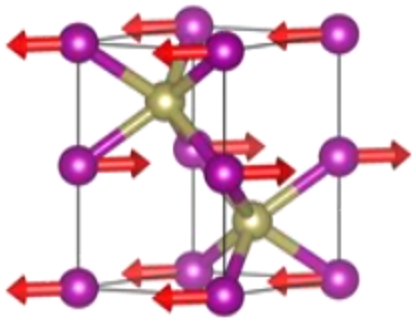


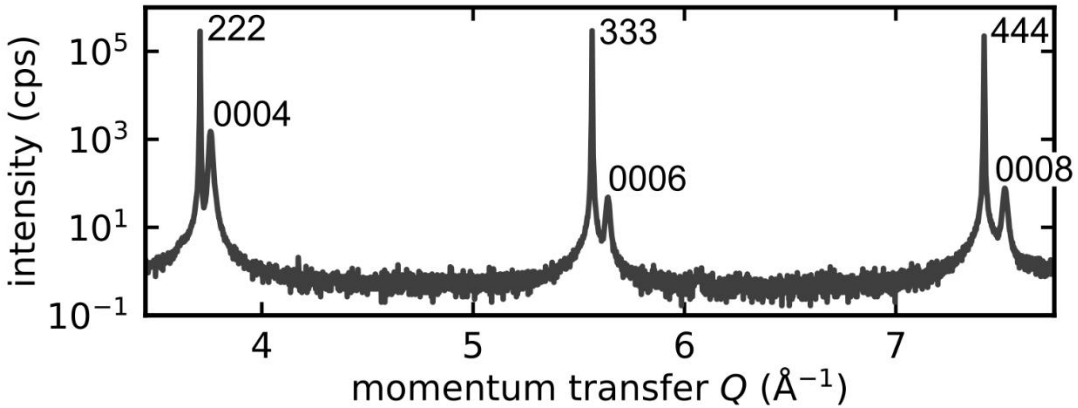
📖 Gonzales Betancourt, DK et al., arXiv:2112.06805

Altermagnet MnTe

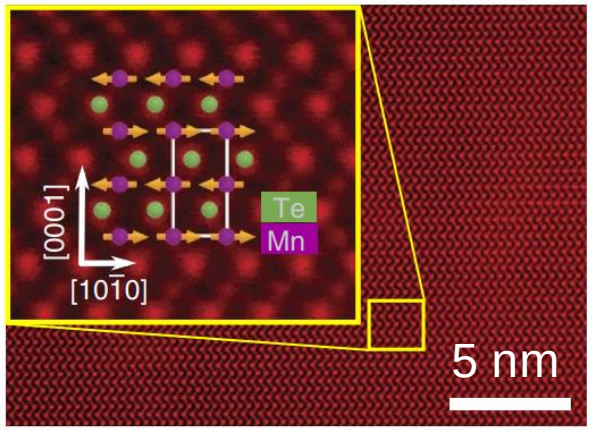
- Magnetic sublattices connected by rotation/screw axis

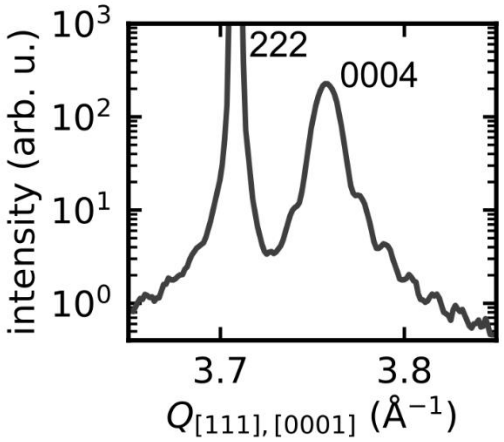






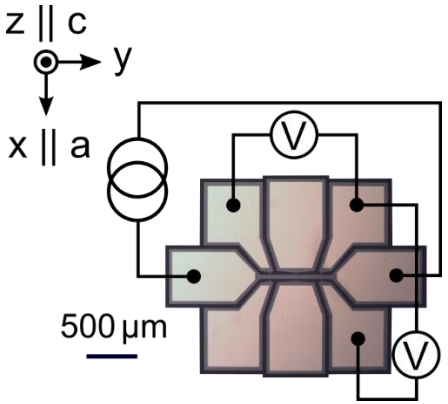
- Thin film growth by molecular beam epitaxy (JKU Linz)
  -> high quality single crystalline films
  - epitaxial orientation
    (0001) $[1\text{-}100]_{MnTe}$ || (111) $[11\text{-}2]_{InP}$
  - Semiconducting band gap ~1.4eV



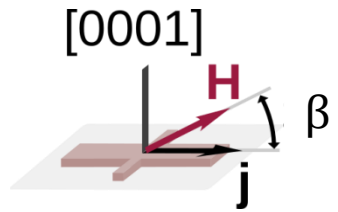


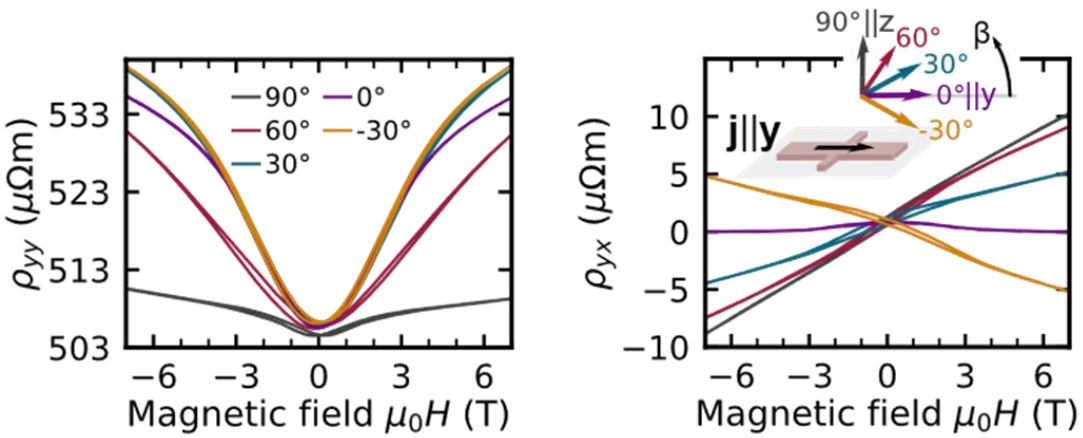
DK et al Nat. Comm. 7, 11623 (2016)

Magnetic field sweep measurements



- Hall bars defined by lithography
- Analysis of longitudinal and transversal resistance during oblique field sweeps

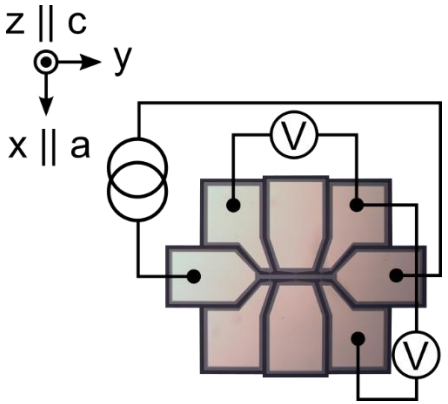




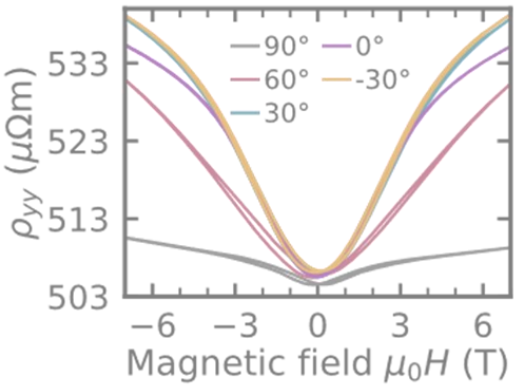
- Longitudinal signal dominated by AMR
- Transversal signal by the ordinary Hall effect

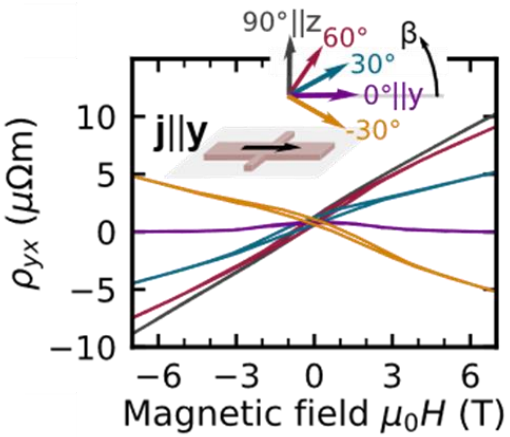
Gonzales Betancourt, DK et al., arXiv:2112.06805

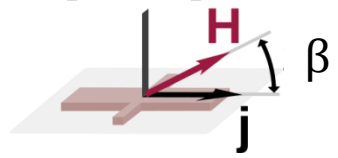
Magnetic field sweep measurements

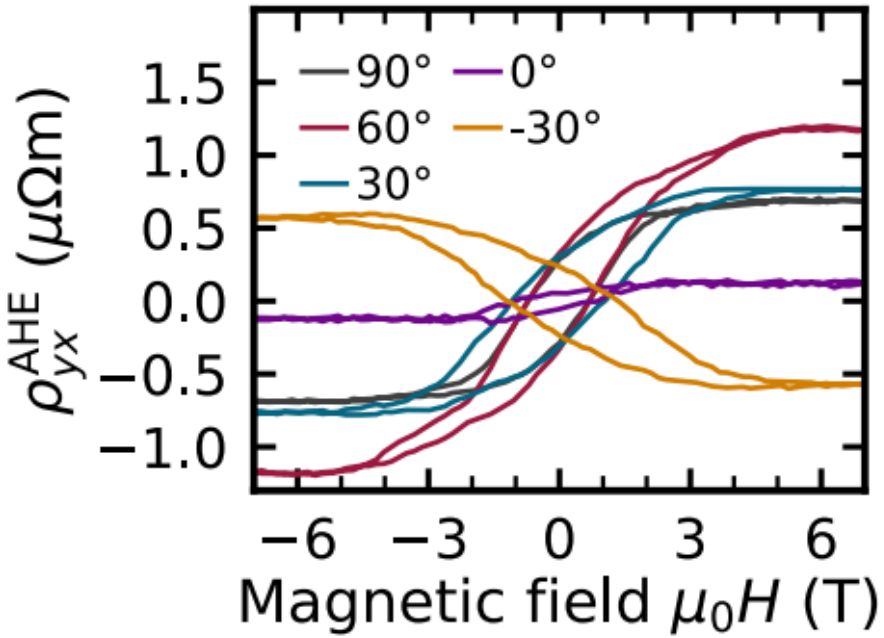


- Hall bars defined by lithography
- Analysis of longitudinal and transversal resistance during oblique field sweeps









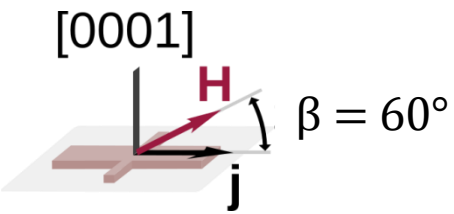
- Isolation of the hysteretic signal

  -> spontaneous hysteretic signal

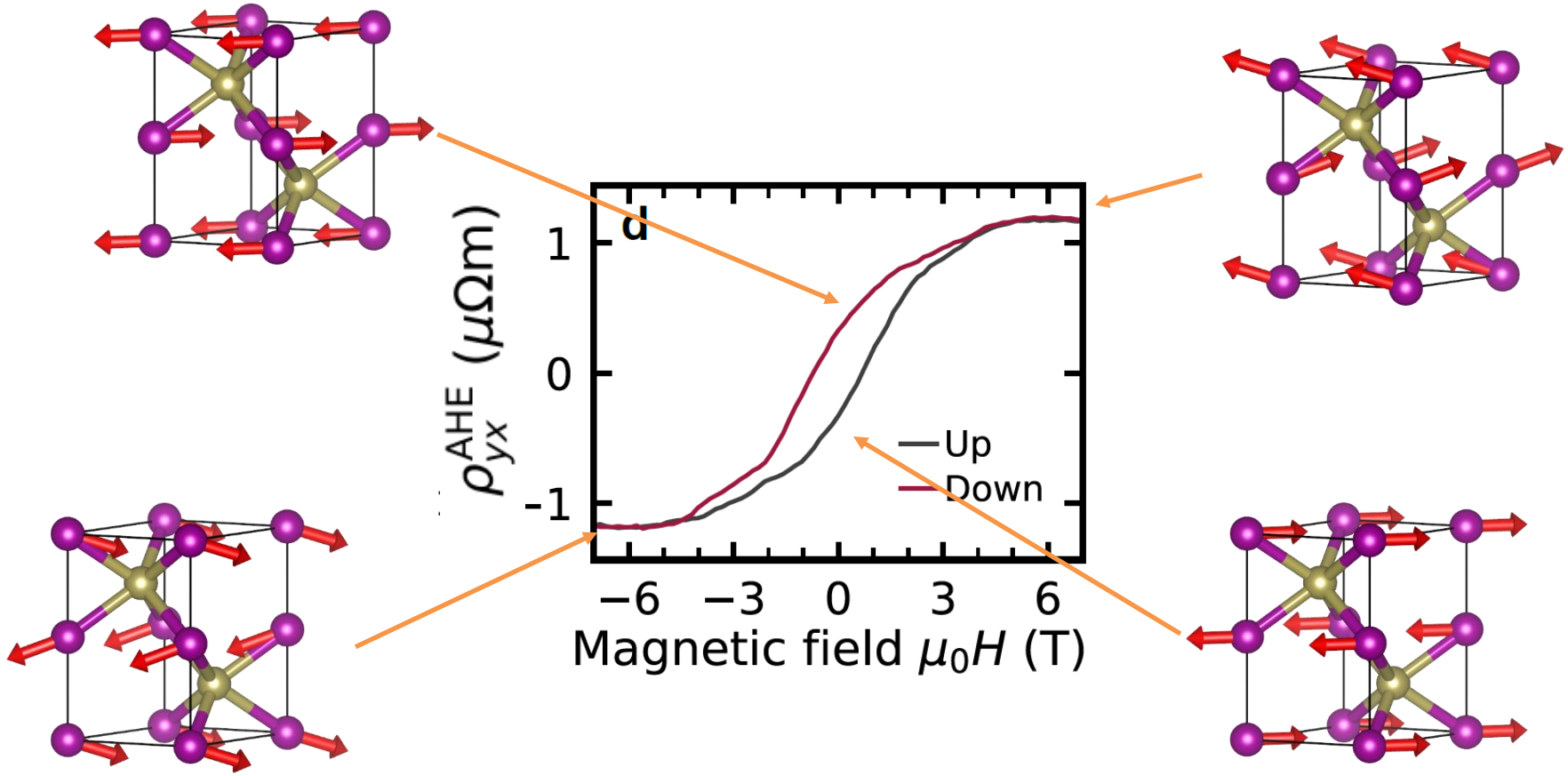
  Depends on out of plane field component

Gonzales Betancourt, DK et al., arXiv:2112.06805

Magnetic field sweep interpretation



- Out of plane field component determines inplane magnetic order orientation

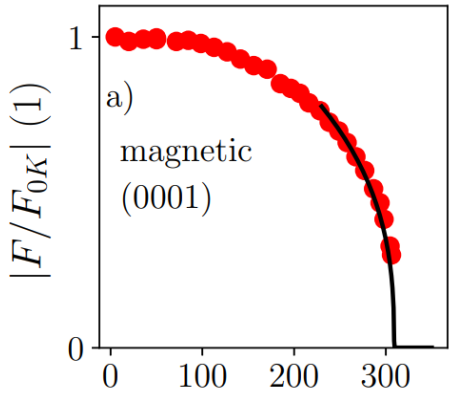


Note: moment's tilt heavily exaggerated

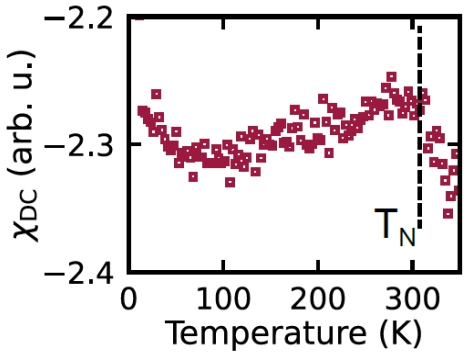
Temperature dependence of the AHE

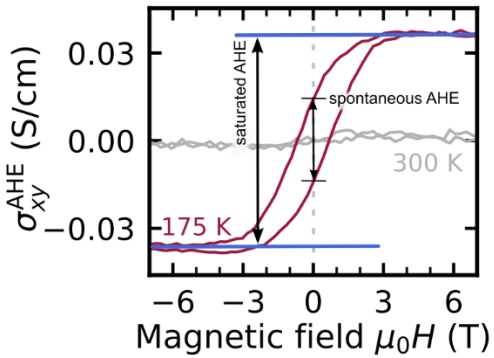
- Neutron diffraction / susceptibility show magnetic transition
- AHE vanishes with the magnetic order

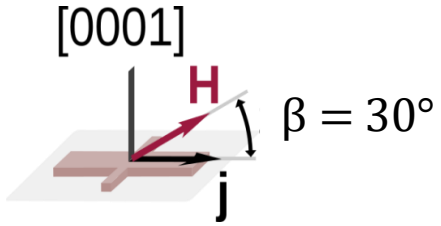
thin film neutron diffraction

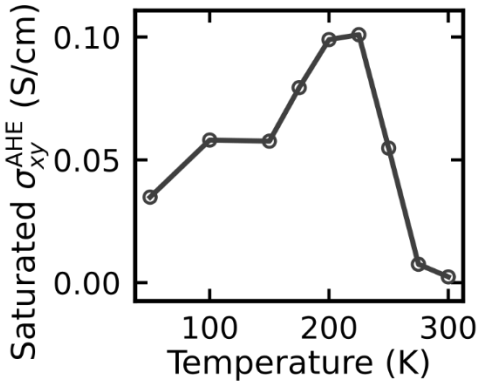


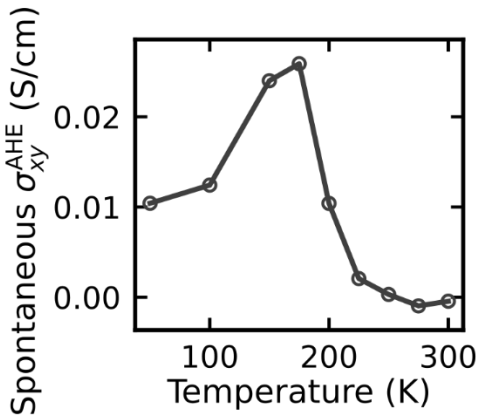
susceptibility









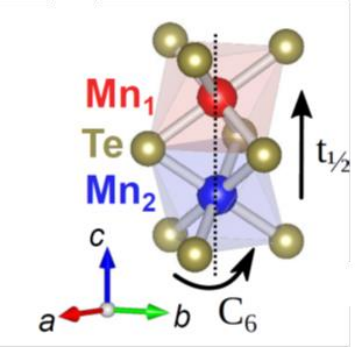


DK et al., Phys. Rev. B 96, 214418 (2017)

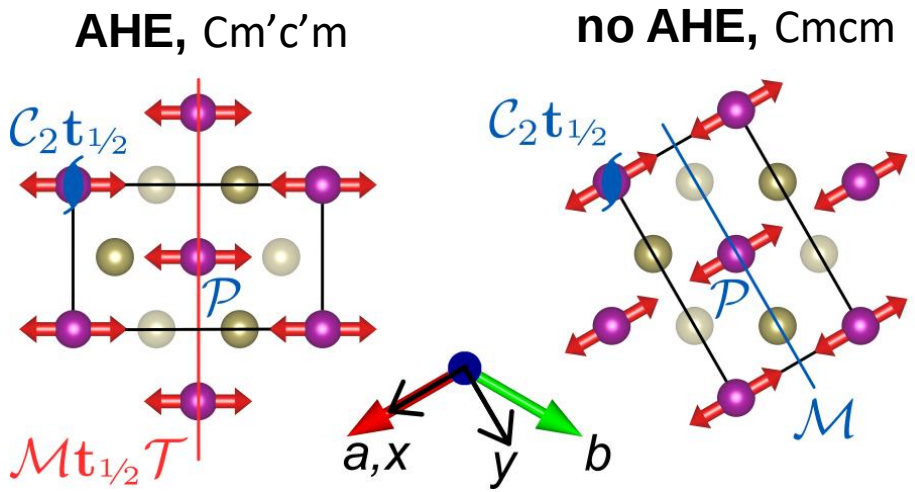
Gonzales Betancourt, DK et al., arXiv:2112.06805

Dependence on inplane Néel vector orientation

- All antiparallel moment orientations allow spin polarization in the band structure

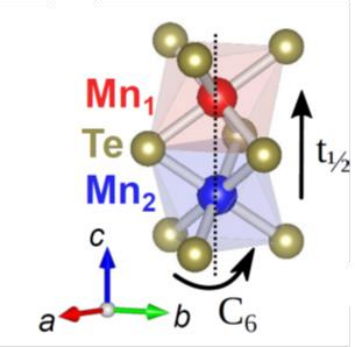


- AHE depends on existence of pseudovector

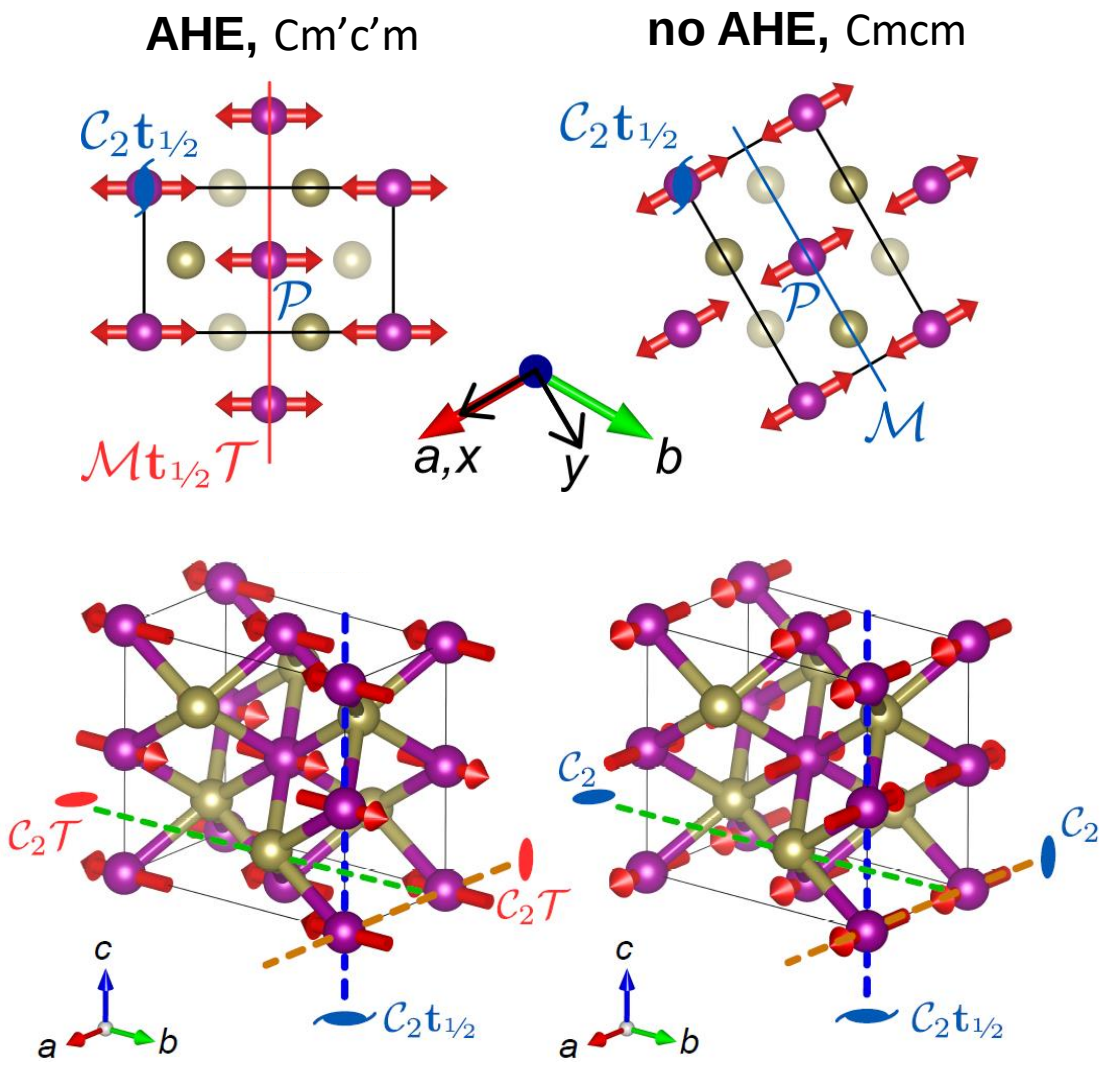


Dependence on inplane Néel vector orientation

- All antiparallel moment orientations allow spin polarization in the band structure

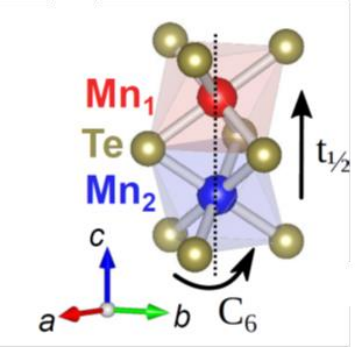


- AHE depends on existence of pseudovector

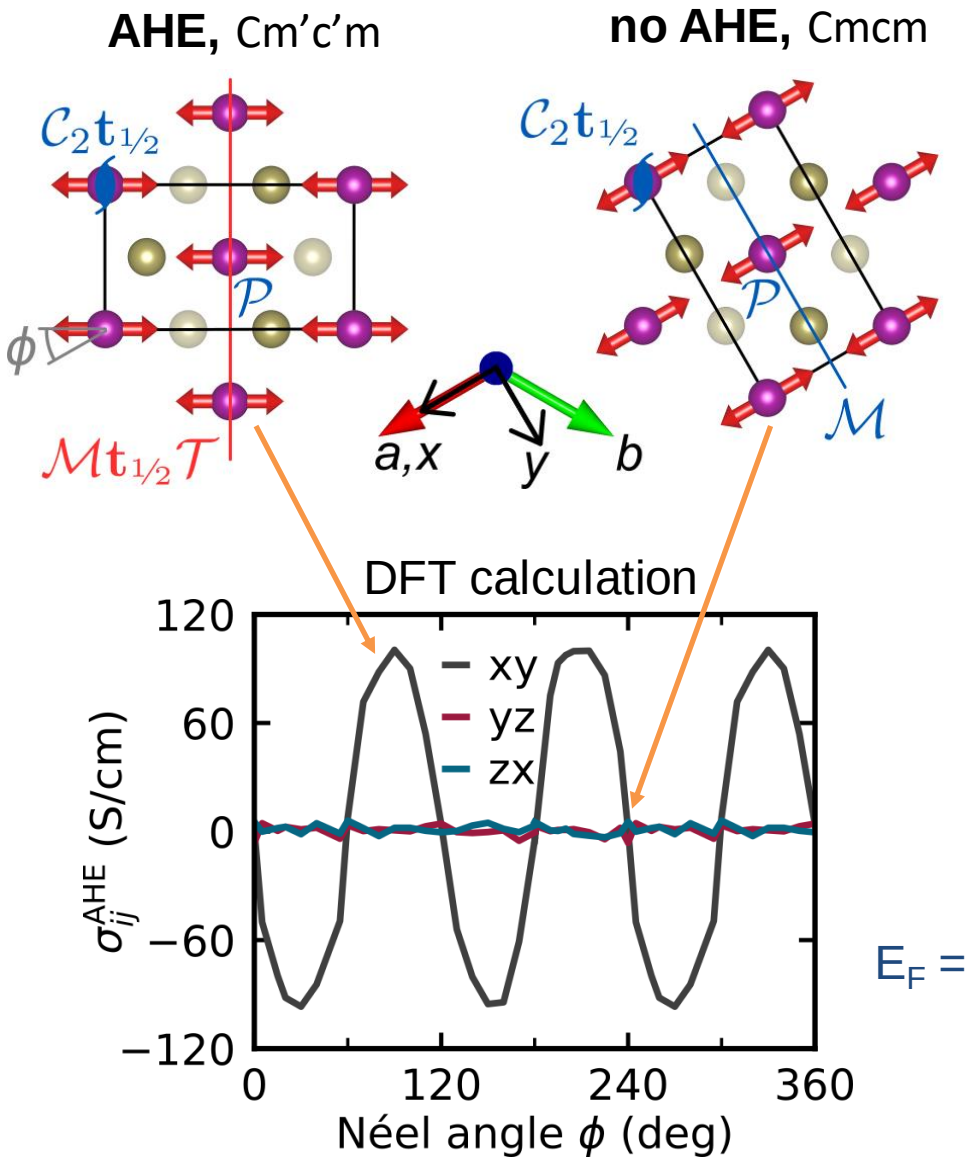


Dependence on inplane Néel vector orientation

- All antiparallel moment orientations allow spin polarization in the band structure



- AHE depends on existence of pseudovector



E_F = VB - 0.25 eV

Experimental magnetic field rotations

- Complex traces with many AMR components
- Theory predicts

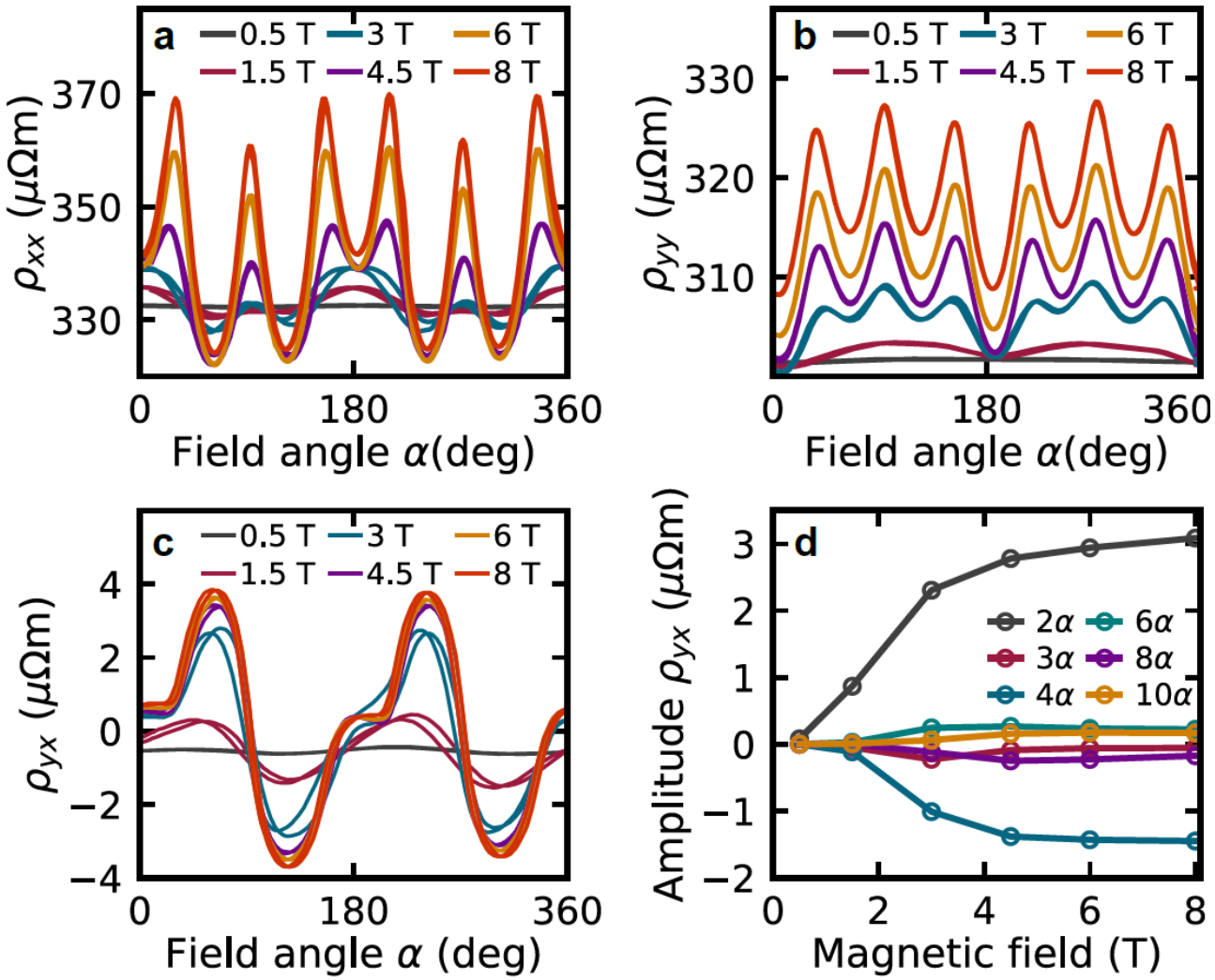
$$\sigma_{yy} = \sigma^{(0)} + \sigma^{(2)}\cos(2\phi) + \sigma^{(4)}\cos(4\phi) + \sigma^{(6)}\cos(6\phi),$$

$$\sigma_{yx} = \sigma^{(2)}\sin(2\phi) + \sigma^{(3)}\sin(3\phi) - \sigma^{(4)}\sin(4\phi),$$

AHE

In experiment also higher order terms (anisotropy?)

Three-fold transversal term detected but weak compared to AMR



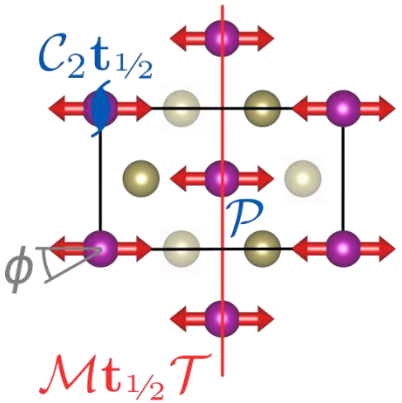
T = 50 K

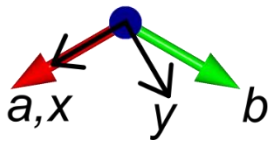
Experimental magnetic field rotations

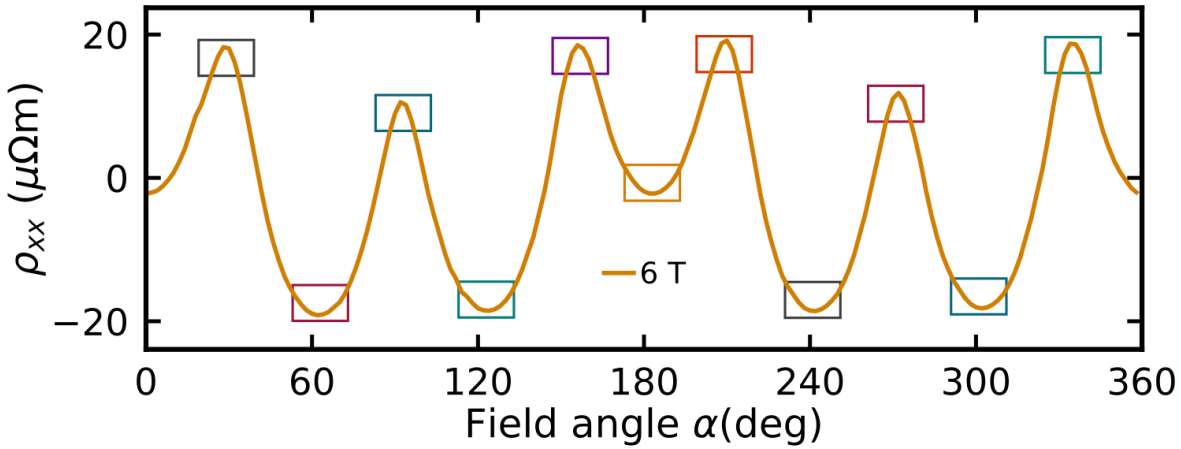
- Complex traces with many AMR components
- Anisotropy allows to determine easy axes orientation

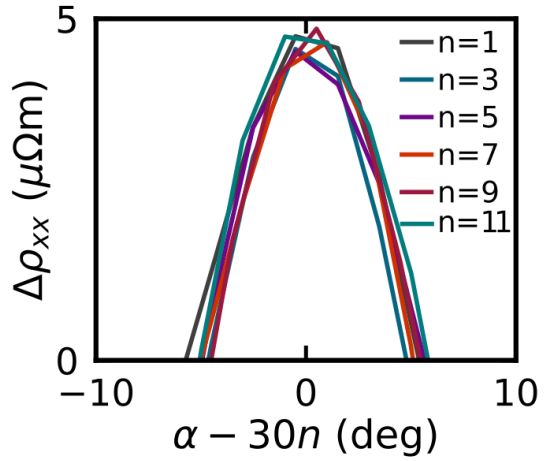
- Consistent with presence of spontaneous AHE

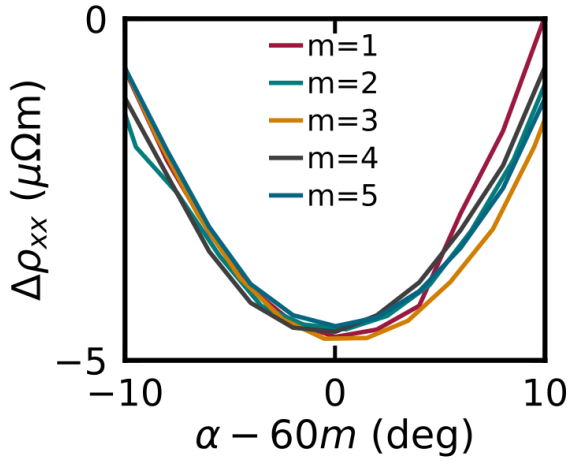
AHE, Cm’c’m







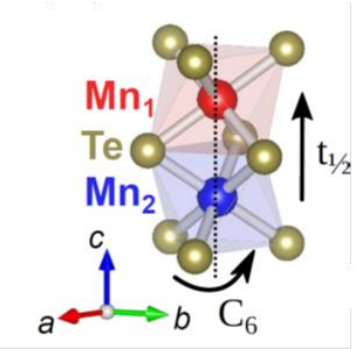


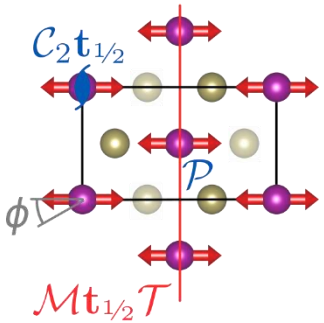


Note: Due to spin-flop moments arrange ~ perpendicular to the field

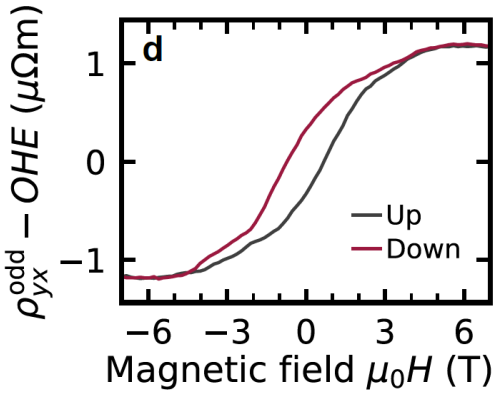
Summary

- Investigated single crystalline epitaxial thin films of MnTe
- Te atoms at non-centrosymmetric positions allow for spin polarization in the band structure
- Particular magnetic order enables AHE, allows a pseudovector





- Experimentally detected AHE in field sweep measurements -> spontaneous nature
- Rich angular dependent magnetoresistance traces



Gonzales Betancourt, DK et al., arXiv:2112.06805