Spontaneous anomalous Hall effect in MnTe

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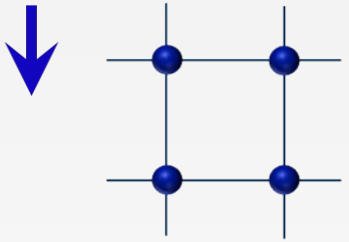
9.5.2023

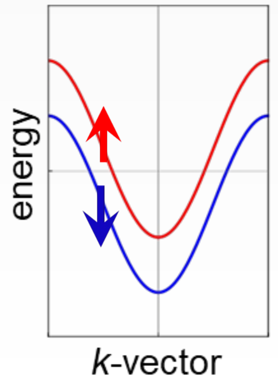
Magnetically ordered collinear materials

classification without spin orbit coupling

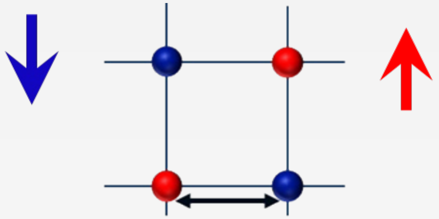
Ferromagnets



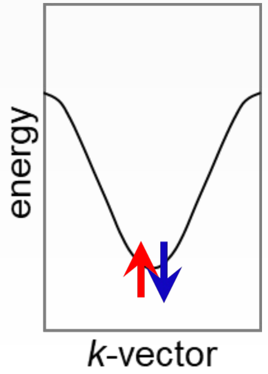
- net magnetization
- exchange splitting
- breaking $\mathcal{T}$ symmetry in electronic band structure



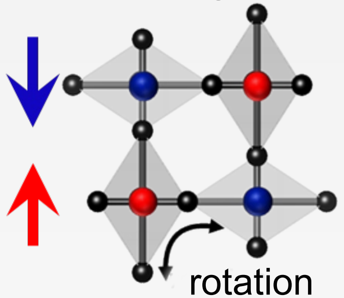
Antiferromagnets



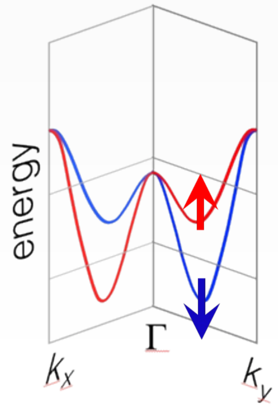
- no net magnetization
- no spin splitting
- **no breaking $\mathcal{T}$ symmetry** in electronic band structure



Altermagnets



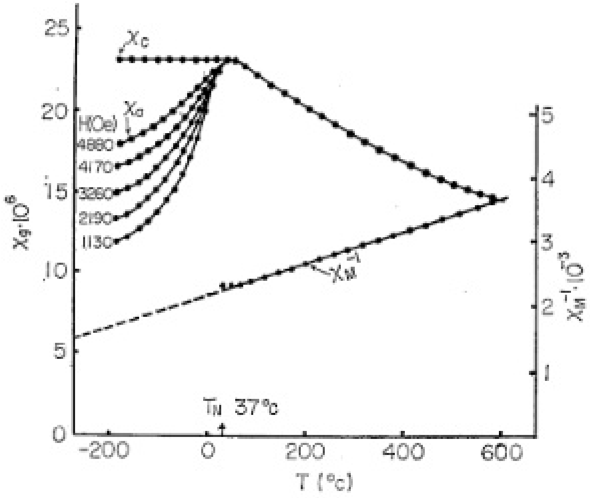
- no net magnetization
- anisotropic spin splitting
- **breaking $\mathcal{T}$ symmetry** in electronic band structure



Libor Šmejkal, et al. Phys. Rev. X 12, 031042 (2022)

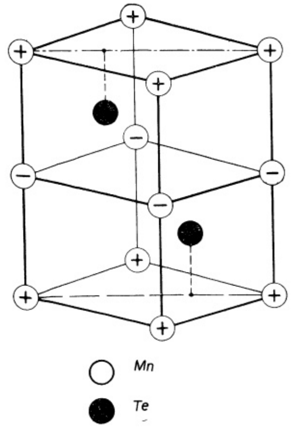
What about MnTe?: magnetic structure

Susceptibility

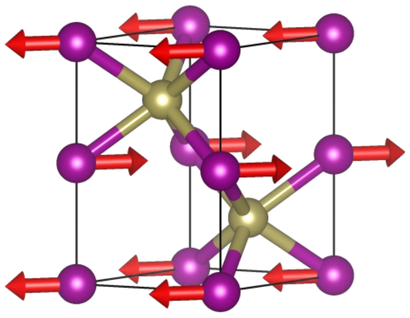


📖 Komatsubara et al. J. Phys. Soc. Jpn. 18, 356 (1964)

Neutron diffraction



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

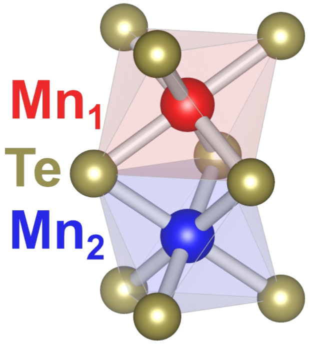


Magnetic space group

$$Cm'c'm$$

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

Building block of the structure



Is MnTe an altermagnet?

How to identify:

- The opposite-spin sublattices have to be connected by crystallographic rotation transformation, possibly combined with translation or inversion Transformation
- (but not by translation or inversion)

🕮 Libor Šmejkal, et al. Phys. Rev. X 12, 040501 (2022)

Is MnTe an altermagnet?

$[C_2||t_{1/2}]$ $\mathcal{T}t$

How to identify:

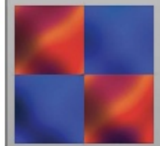
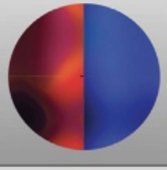
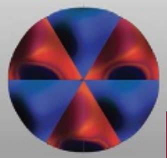
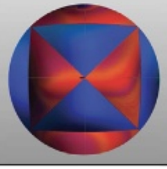
- The opposite-spin sublattices have to be connected by crystallographic rotation transformation, possibly combined with translation or inversion Transformation
- (but not by translation or inversion)

$\mathcal{P}$ at Mn site

screw axis

$[C_2||C_6t_{1/2}]$

📖 Libor Šmejkal, et al. Phys. Rev. X 12, 040501 (2022)

Spin-momentum locking			$\mathbf{G}$	$\mathbf{R}_s^{\mathrm{III}}$	$\mathbf{H}$	A	Candidate
Bulk 	B-2 *d*-wave		$2/m$	$^22/^2m$ (4)	$\bar{1}$	C_{2z}	CuF_2
	B-4 *g*-wave		$\bar{3}m$	$^1\bar{3}^2m$ (12)	$\bar{3}$	C_{21}	CoF_3, FeF_3, Fe_2O_3
			$6/m$	$^26/^2m$ (12)		C_{6z}	
			$6/mmm$	$^26/^2m^2m^1m$ (24)	$\bar{3}m$	C_{6z}	CrSb, MnTe, VNb_3S_6
	B-6 *i*-wave		$m\bar{3}m$	$^1m^1\bar{3}^2m$ (48)	$m\bar{3}$	C_{4z}	

Type of spin splitting symmetry in band structure:

d- , g-, i- wave

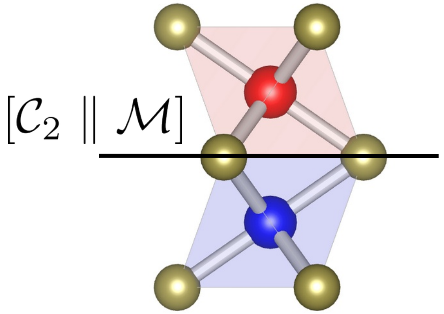
$$^26/^2m^2m^1m$$

Band structure of MnTe

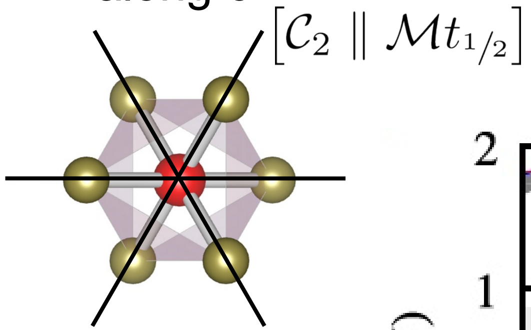
Mirror planes combined with spin space rotation cause spin degeneracy

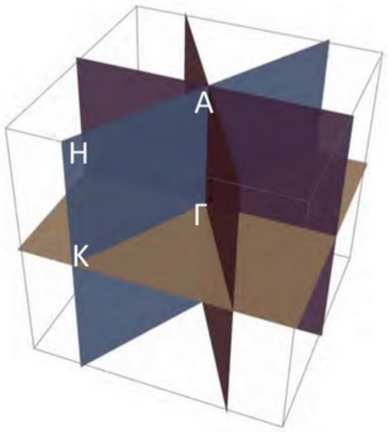
$$^{2}6/^{2}m^{2}m^{1}m$$

View along a

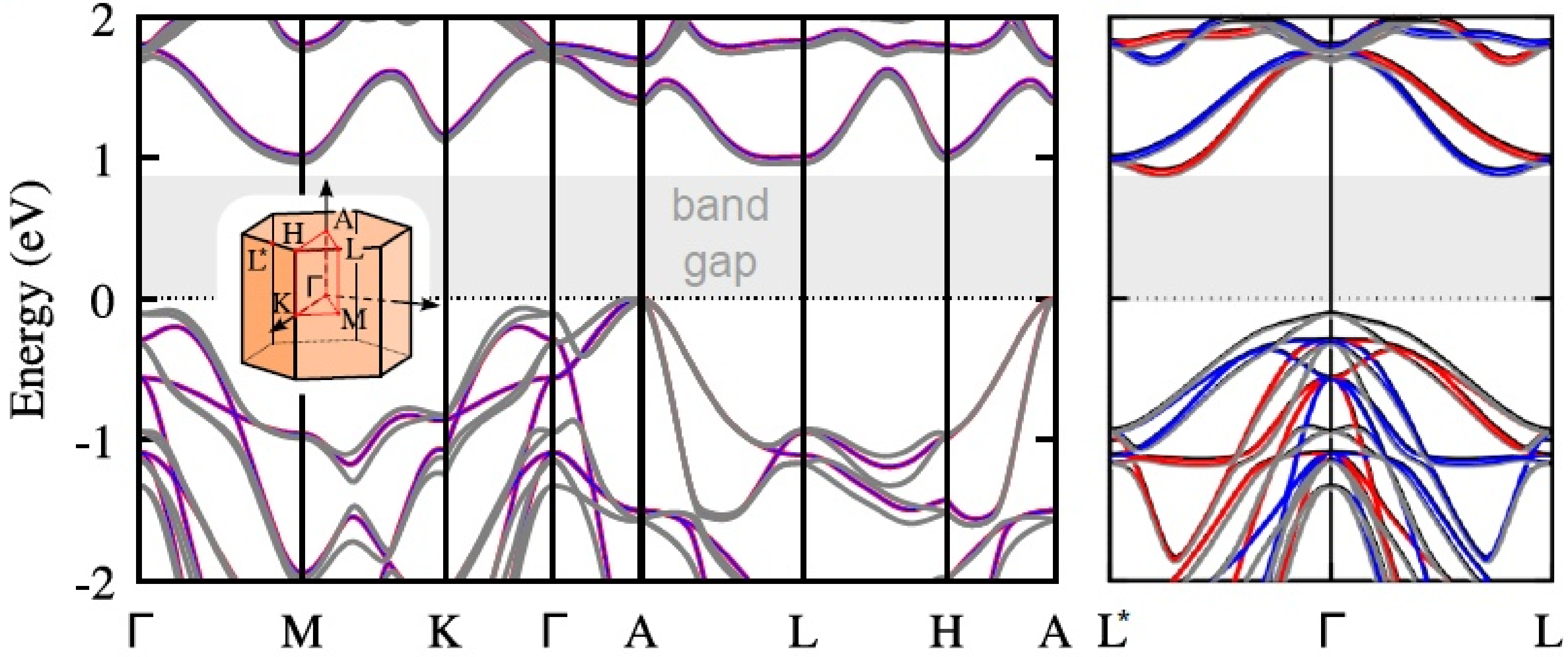


along c





Directions outside high symmetry lines are anisotropically spin split



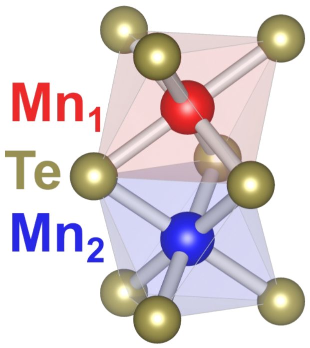
Anomalous Hall effect: symmetries

Can a time reversal odd
Hall pseudo vector **h** exist?

$\mathbf{j}_{\mathrm{H}} = \mathbf{h} \times \mathbf{E}$

Antisymmetric components of transverse conductivity

$\mathbf{h} = (-\sigma^{\mathrm{a}}_{yz}, \sigma^{\mathrm{a}}_{xz}, -\sigma^{\mathrm{a}}_{xy})$



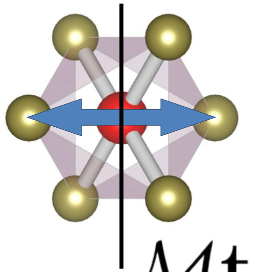
α-MnTe

~~$\mathcal{PT}$~~

~~$\mathcal{T}t$~~

$\mathcal{P}$

$\mathcal{C}_2\mathbf{t}_{1/2}$

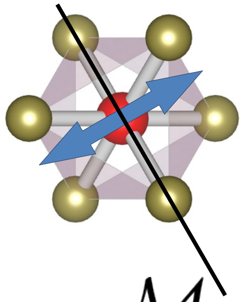


$\mathcal{M}\mathbf{t}_{1/2}\mathcal{T}$

$\mathbf{h} \parallel c$ ✓

$\mathcal{P}$

$\mathcal{C}_2\mathbf{t}_{1/2}$



$\mathcal{M}$

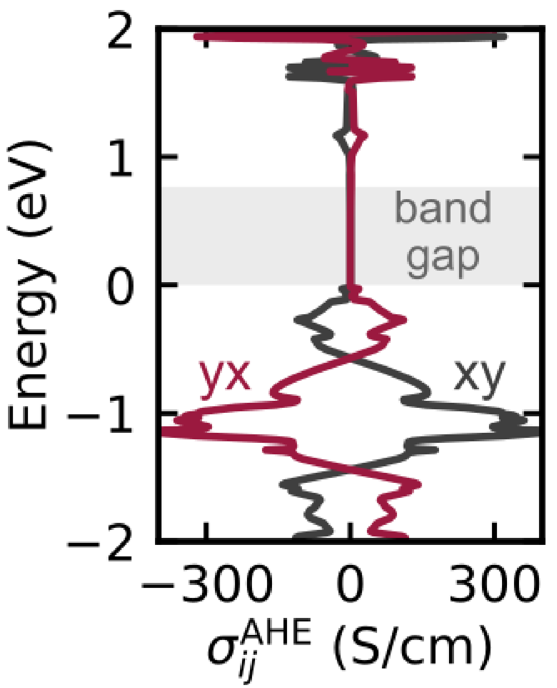
~~$\mathbf{h}$~~

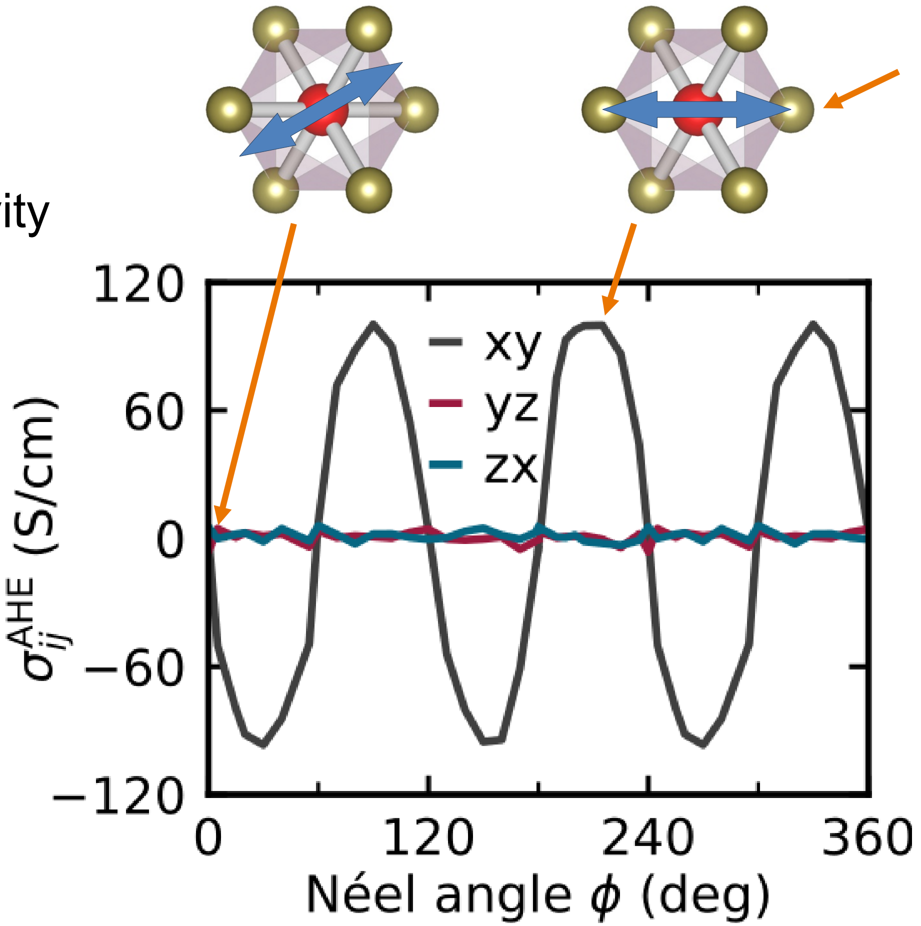
Depends on moment orientation!

AHE intrinsically anisotropic in altermagnets

Anomalous Hall effect: calculations

anomalous Hall conductivity





Easy axis orientation!

$$\mathbf{h} = (-\sigma^{\mathrm{a}}_{yz}, \sigma^{\mathrm{a}}_{xz}, -\sigma^{\mathrm{a}}_{xy})$$

Anisotropy of AHE manifests in sin(3Φ) dependence of σ_{xy}

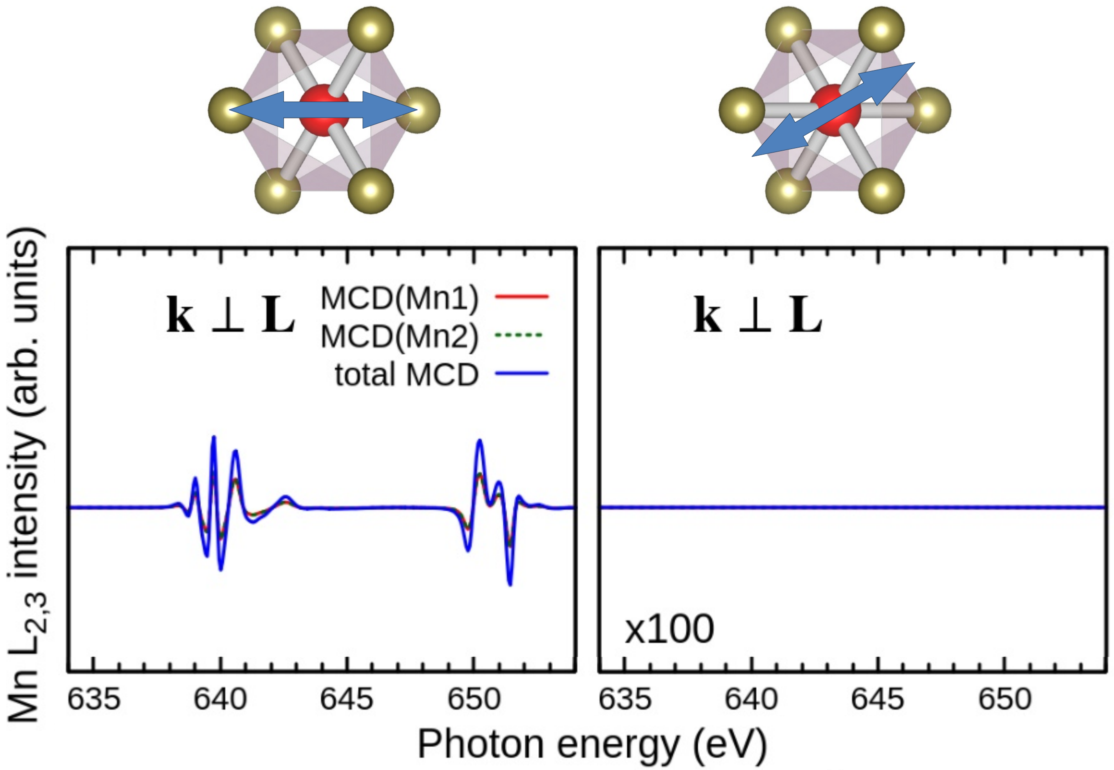
Φ defined between Neel vector and a-axis

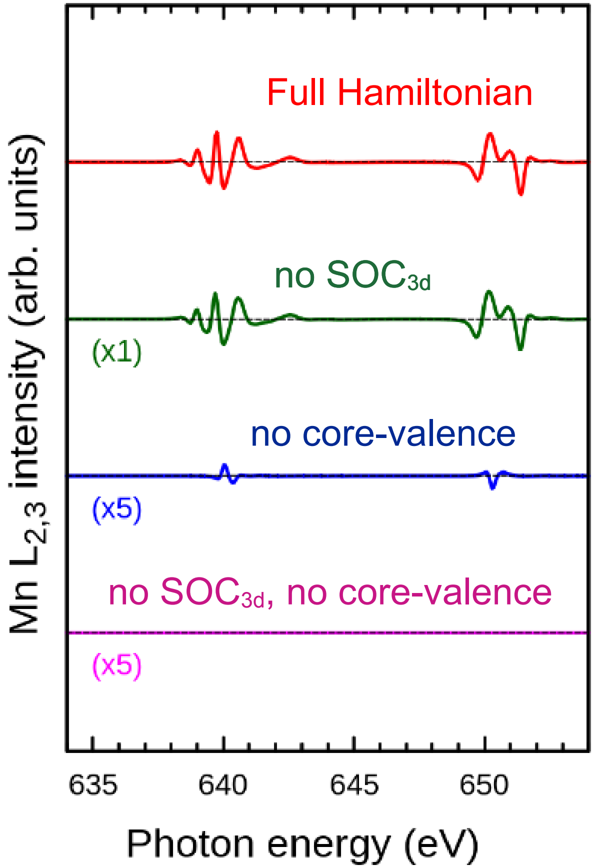
E_F = VB - 0.25 eV

X-ray magnetic circular dichroism: calculations

Circular dichroism governed by same pseudo-vector: $\mathbf{h} = (-\sigma^{\mathrm{a}}_{yz}, \sigma^{\mathrm{a}}_{xz}, -\sigma^{\mathrm{a}}_{xy})$

- AHE: only valence electronic states → valence SOC
- XMCD: also atomic core levels
  → core SOC + core/valence exchange



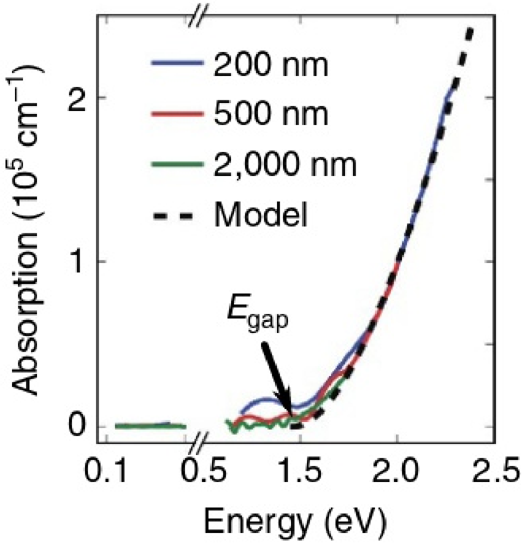


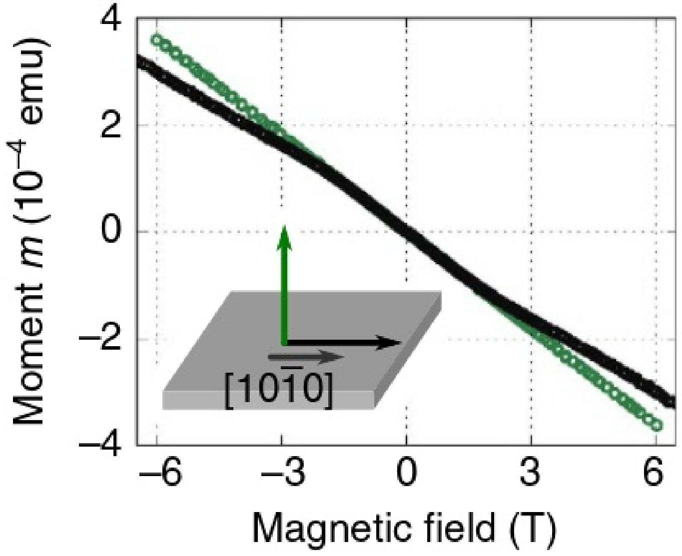
Atsushi Hariki, DK et al., arXiv:2305.03588

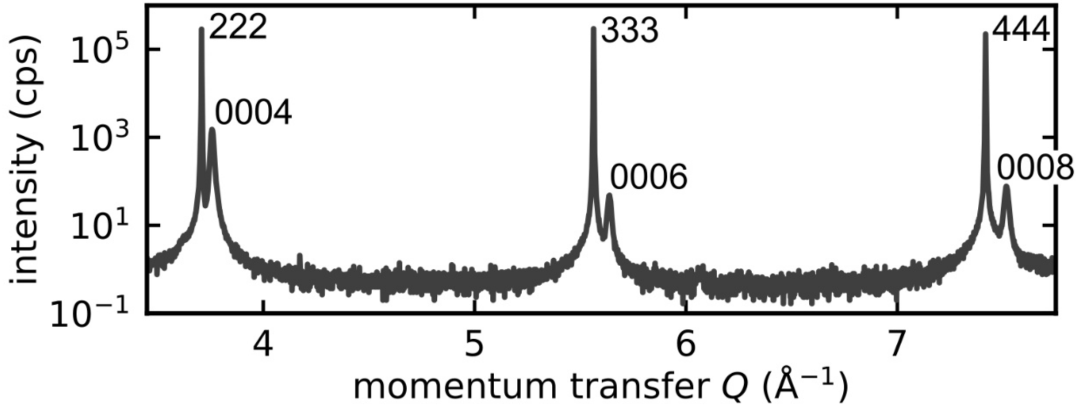
(finally) experiments: MnTe thin films

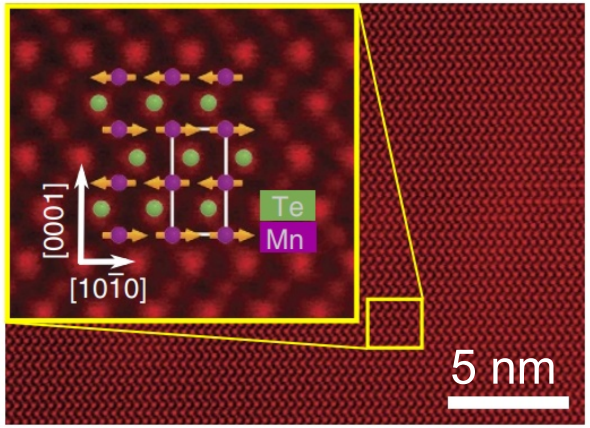
single crystalline epitaxial growth by molecular beam epitaxy (JKU Linz)

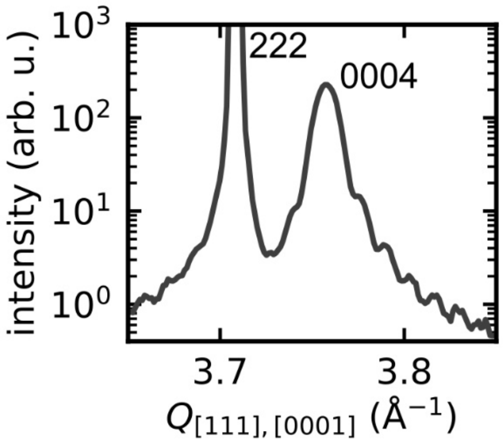
- Orientation (0001) $[1\text{-}100]_{MnTe}$ || (111) $[11\text{-}2]_{InP}$
- Unintentional p-type doping
- Semiconducting band gap ~1.4eV









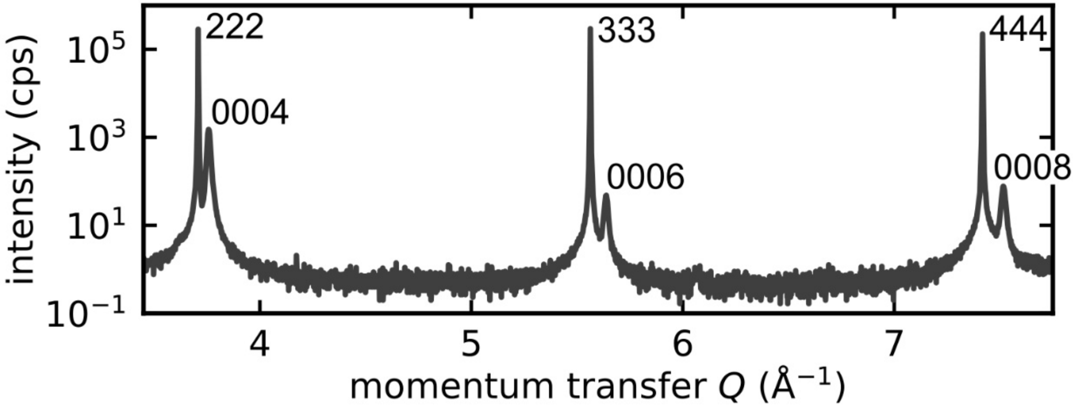


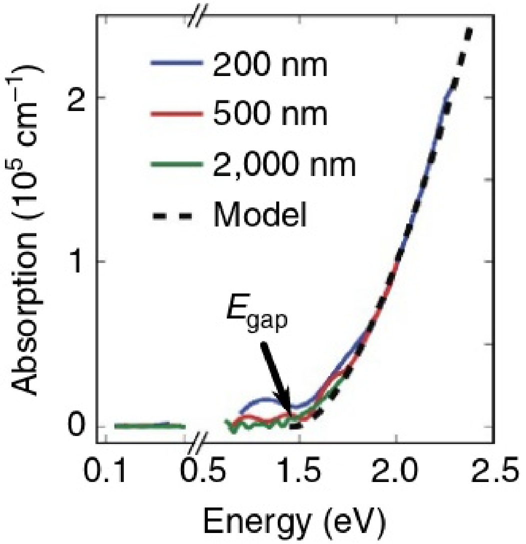
DK et al Nat. Comm. 7, 11623 (2016)

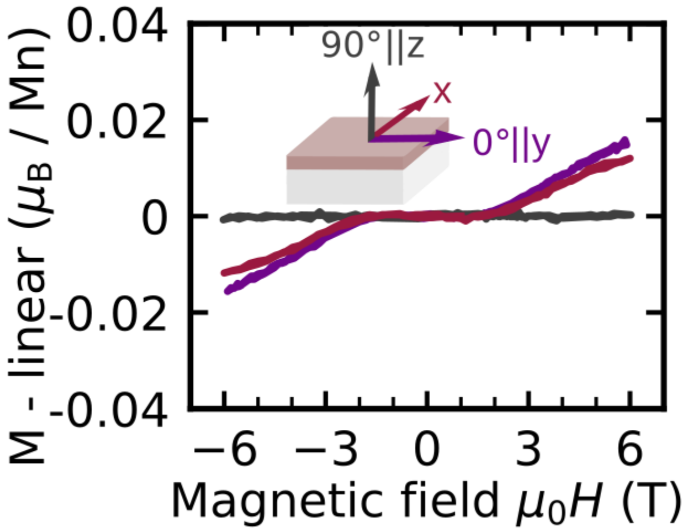
(finally) experiments: MnTe thin films

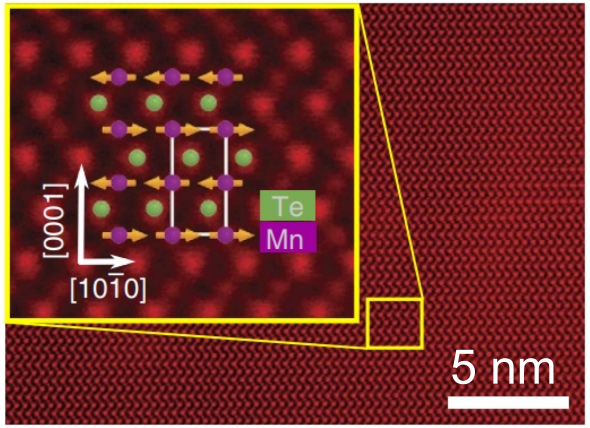
single crystalline epitaxial growth by molecular beam epitaxy (JKU Linz)

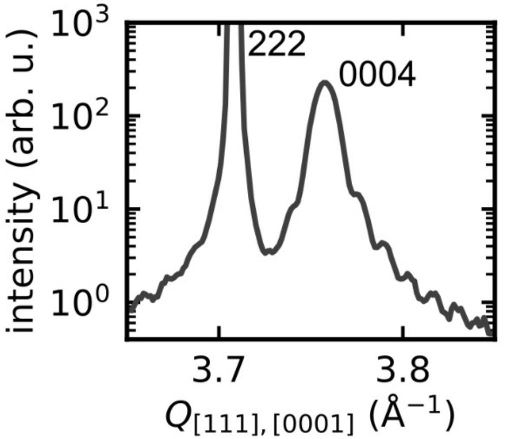
- Orientation (0001) $[1\text{-}100]_{MnTe}$ || (111) $[11\text{-}2]_{InP}$
- Unintentional p-type doping
- Semiconducting band gap ~1.4eV
- No detectable spontaneous moment







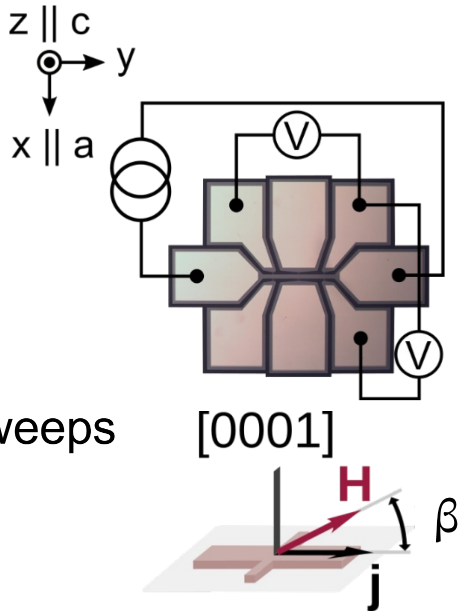


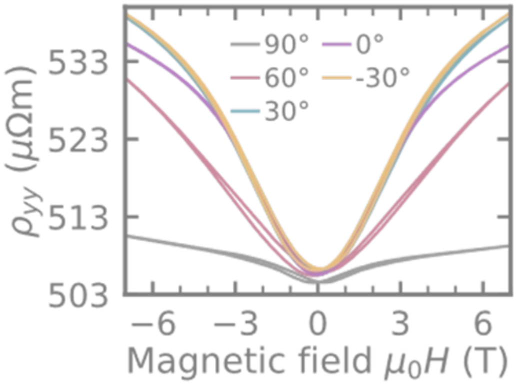


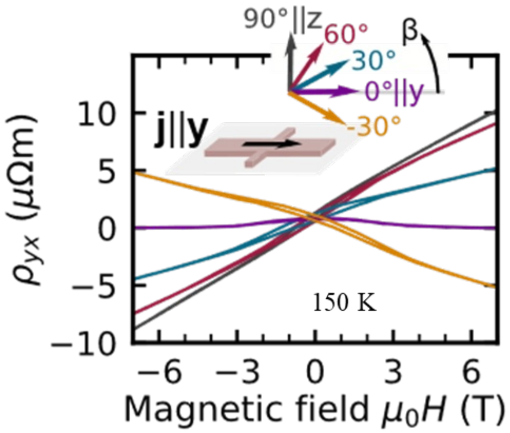
📖 DK et al Nat. Comm. 7, 11623 (2016)

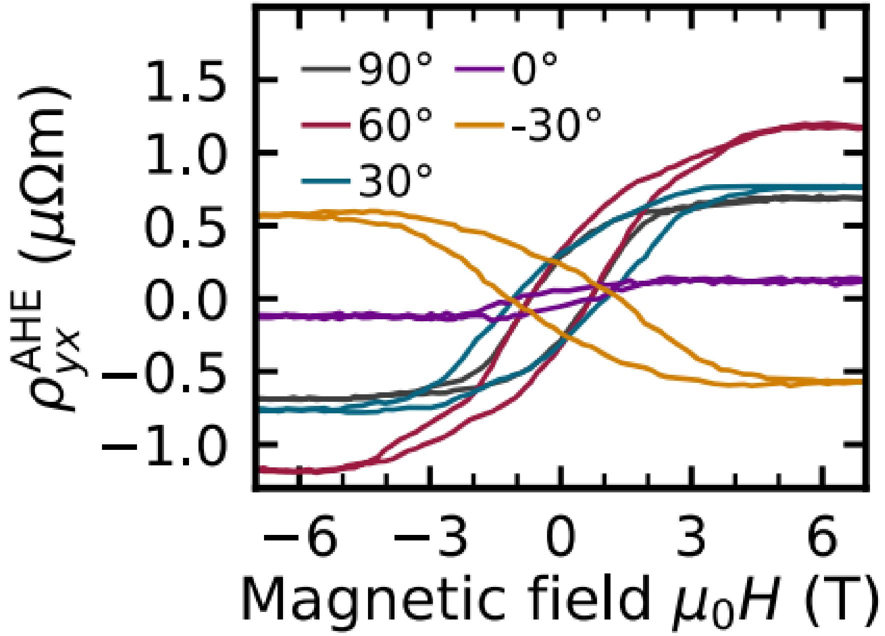
Magnetic field sweep measurements

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







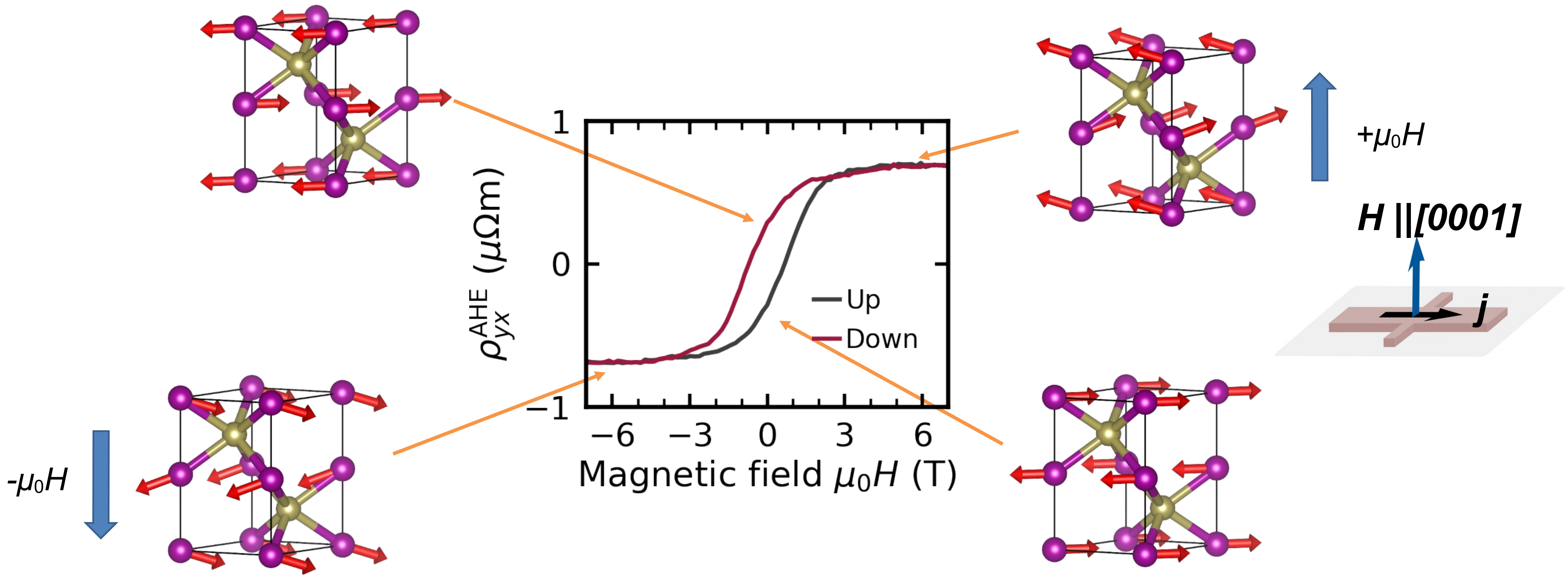


- Isolation of the hysteretic signal
  - -> spontaneous hysteretic signal
  - Depends on out of plane field component

Magnetic field sweep interpretation

- Out of plane field component determines inplane magnetic order orientation

$\mu_0 \boldsymbol{H} \rightarrow$ weak $\mathbf{M_z} \rightarrow$ change inplane $\mathbf{L} \rightarrow$ Hall pseudovector

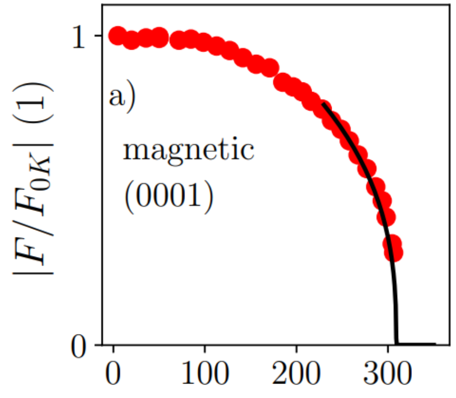


Note: moment's tilt heavily exaggerated

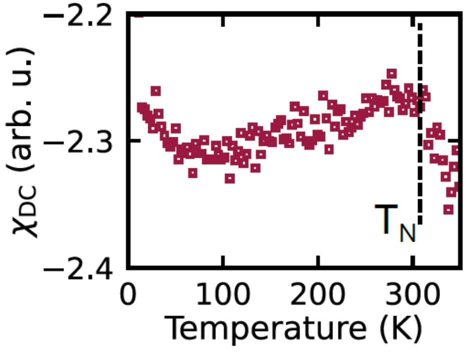
Temperature dependence of the AHE

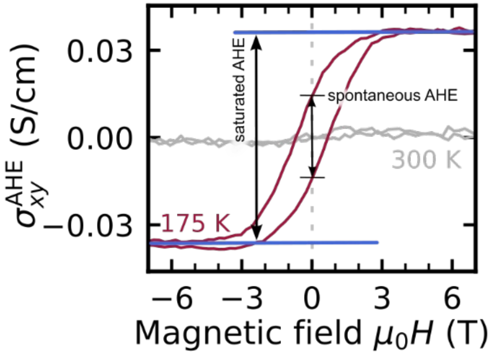
- Neutron diffraction / susceptibility show magnetic transition
- AHE vanishes with the magnetic order

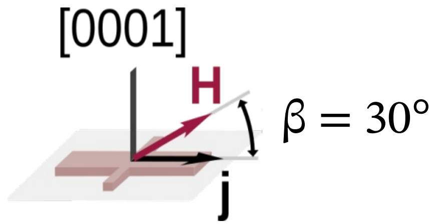
thin film neutron diffraction

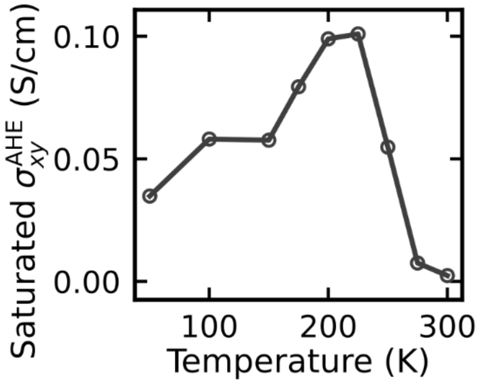


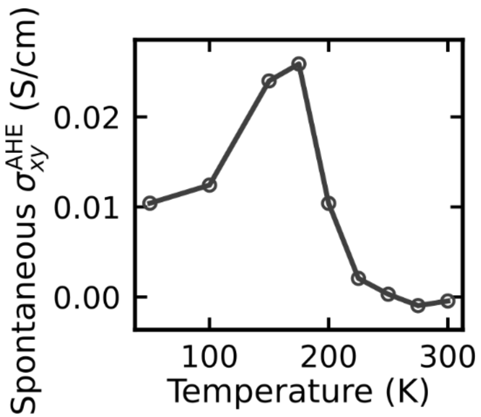
susceptibility







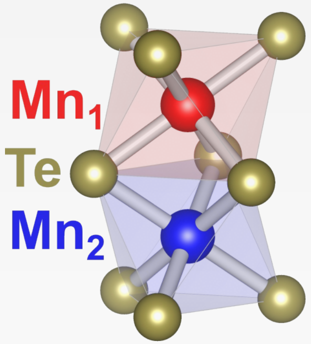




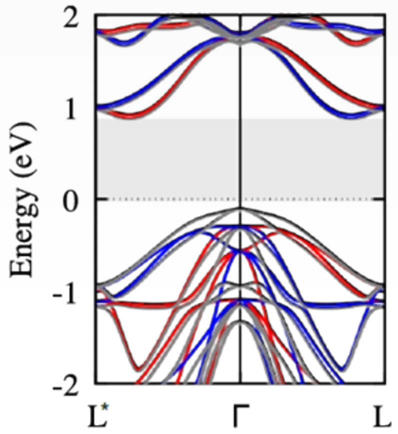
DK et al., Phys. Rev. B 96, 214418 (2017)

Altermagnets with AHE

MnTe
semiconductor



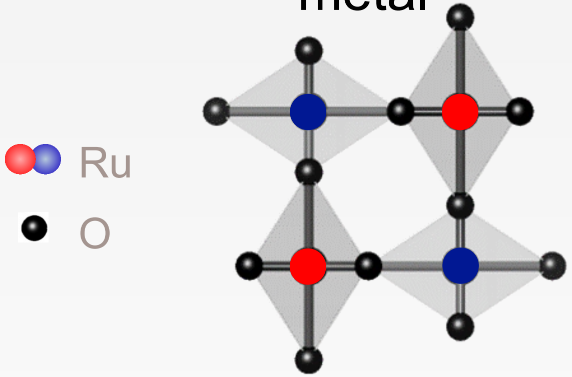
- Symmetry breaking by **Te - octahedra**
- **g-wave**



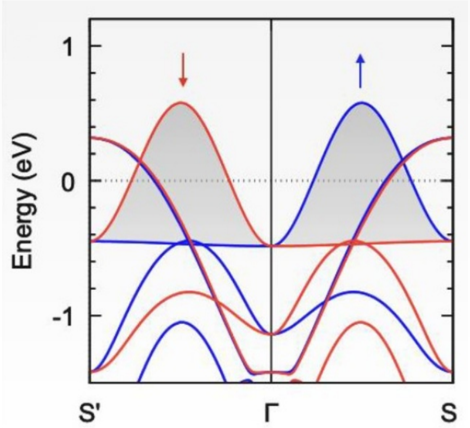
- **spontaneous anomalous Hall effect**

See also talk by Pete Wadley

RuO_2
metal



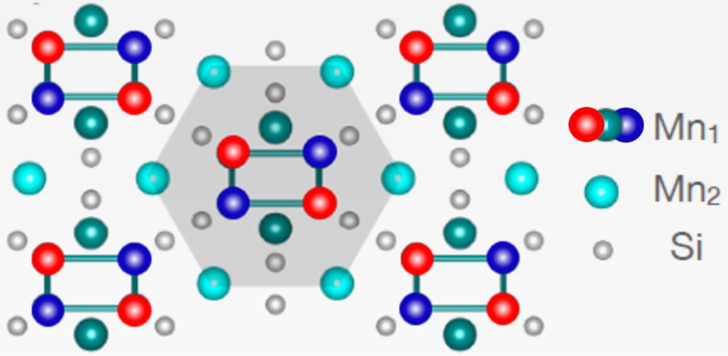
- Symmetry breaking by **O-octahedra**
- **d-wave**



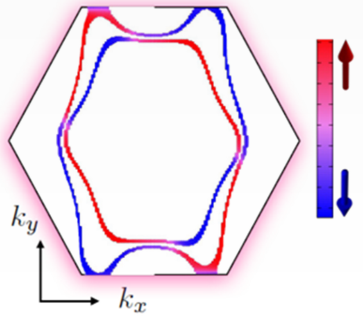
- Large spin splitting
- **No** spontaneous anomalous Hall effect

Talk by Helena Reichlova

Mn_5Si_3
Thin films!



- Symmetry breaking by **multiple magnetic sublattices**
- **d-wave**



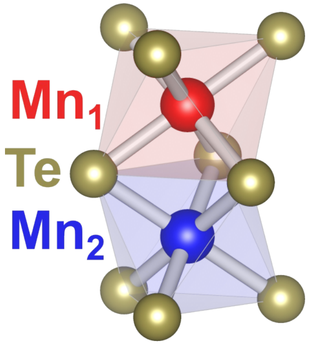
spin polarized Fermi surfaces

- **spontaneous anomalous Hall effect**

Talk by Sebastian Goennenwein

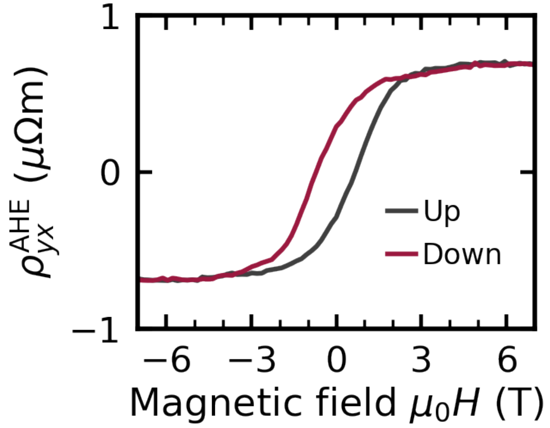
📖 Gonzales Betancourt, DK et al., PRL 130, 036702 (2023)
📖 Feng et al. Nat. Electron. 5, 735–743 (2022)
📖 Reichlova, DK, et al., arXiv:2012.15651

Summary



- MnTe is an altermagnet
- Easy axis Neel vector orientation allows for AHE and circular dichroism
- Experimentally detected AHE in field sweep measurements -> spontaneous nature

📖 Gonzales Betancourt, DK et al., PRL 130, 036702 (2023)



Thank you for your attention