

**Multiple-stable
anisotropic magnetoresistance memory
in antiferromagnetic semiconductor MnTe**

Dominik Kriegner, et al.

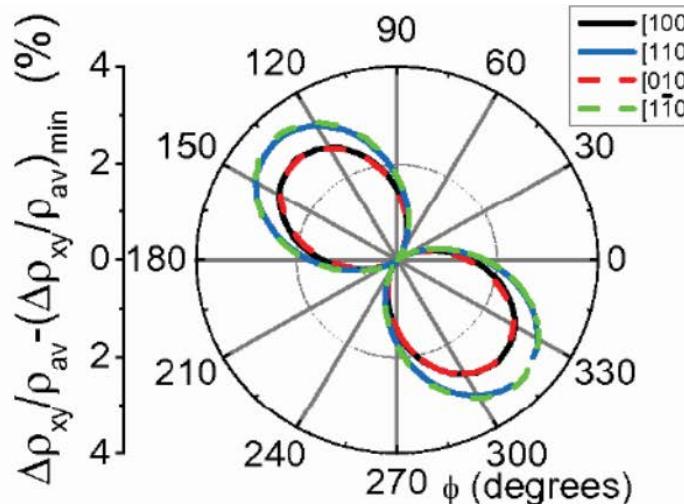
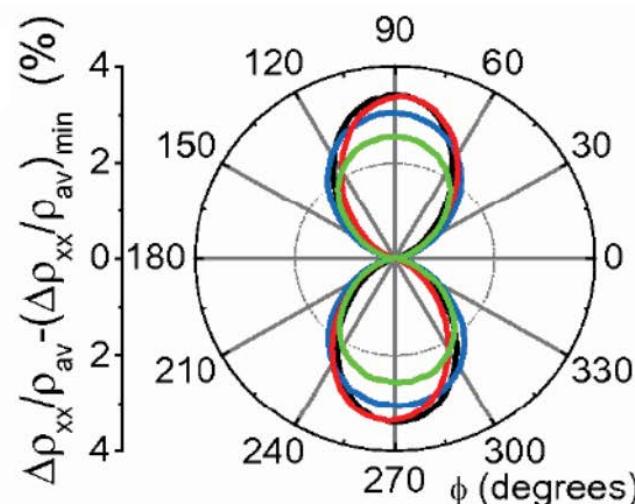
Mainz
September 30th, 2016

outline

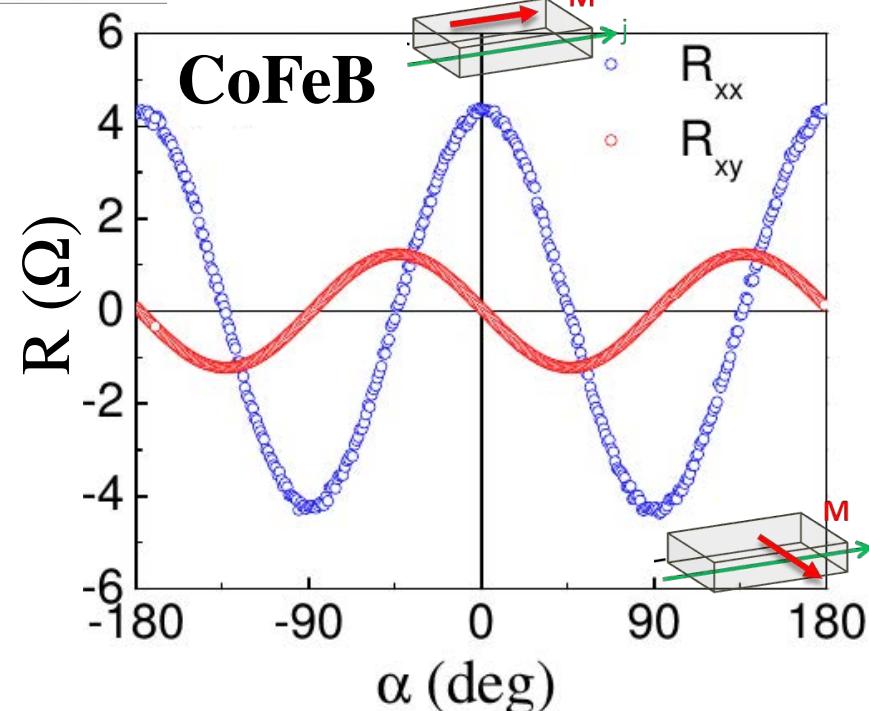
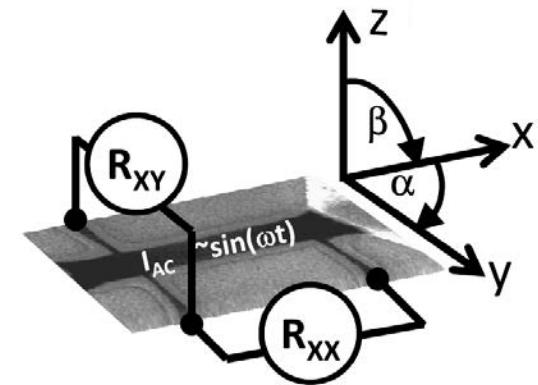
- AMR in ferromagnets
- AMR in antiferromagnets (FeRh, IrMn, CuMnAs)
- antiferromagnetic semiconductor MnTe
 - saturated anisotropic magnetoresistance
 - spin flop transition
 - harmonic AMR above spin-flop
- multiple stable AMR memory states

AMR in ferromagnets

GaMnAs



A. W. Rushforth, et al. PRL 99, 147207 (2007)

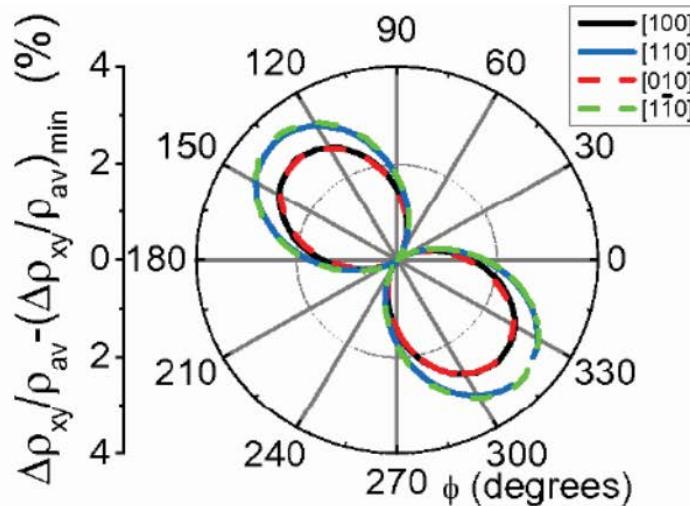
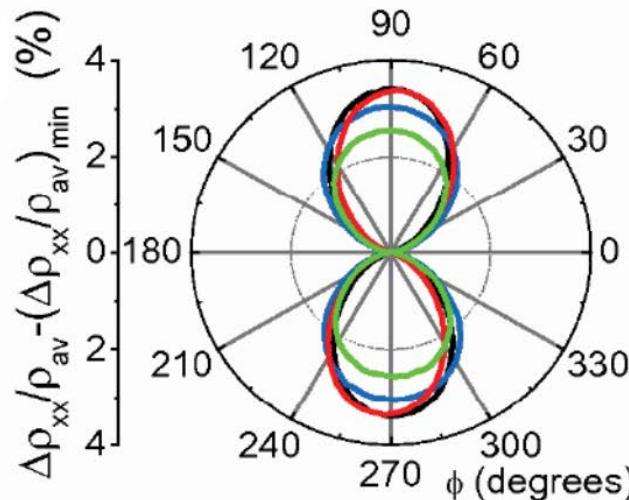


H. Reichlова, PRB 92, 165424 (2015)

Dominik Kriegner, September 30, 2016

AMR in ferromagnets

GaMnAs



A. W. Rushforth, et al. PRL 99, 147207 (2007)

- non-crystalline AMR:
- $\Delta R_{xx} \sim \cos(2\phi)$, $\Delta R_{xy} \sim \sin(2\phi)$
- more general (cubic!):

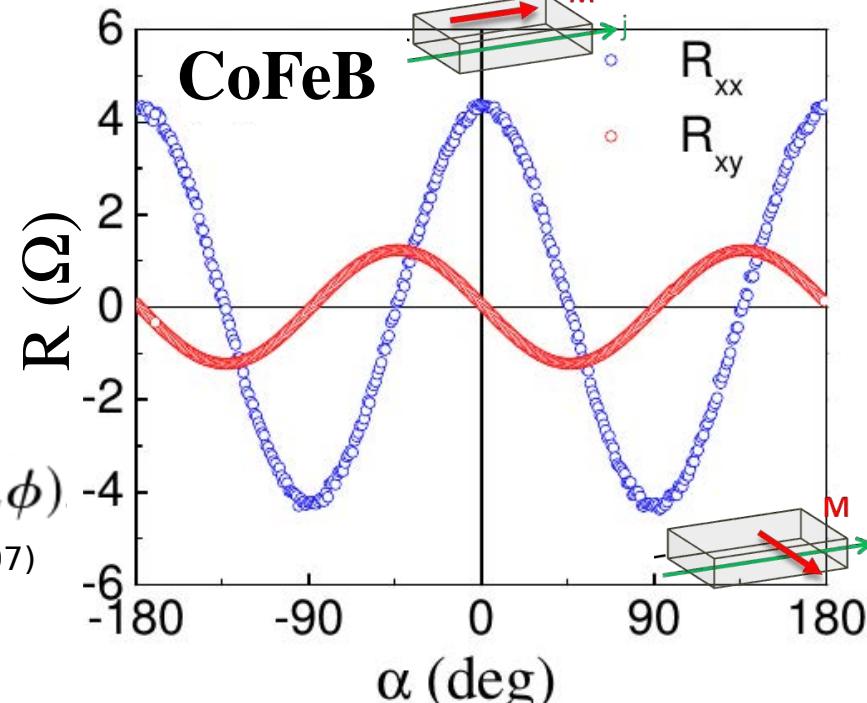
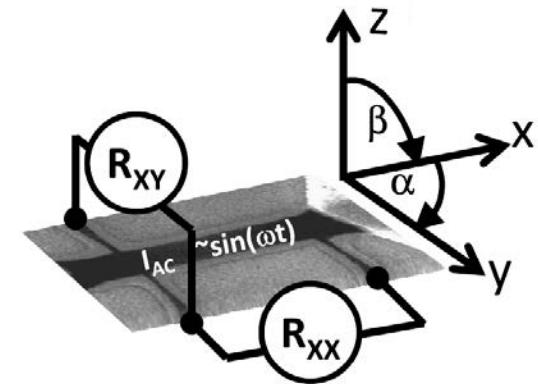
$$\Delta \rho_{xx}/\rho_{av} =$$

$$C_I \cos 2\phi + C_U \cos 2\psi + C_C \cos 4\psi + C_{I,C} \cos(4\psi - 2\phi)$$

A. W. Rushforth, et al. PRL 99, 147207 (2007)

$$\phi = \Delta(\mathbf{M}, \mathbf{j})$$

$$\psi = \Delta(\mathbf{M}, \text{cryst})$$



H. Reichlова, PRB 92, 165424 (2015)

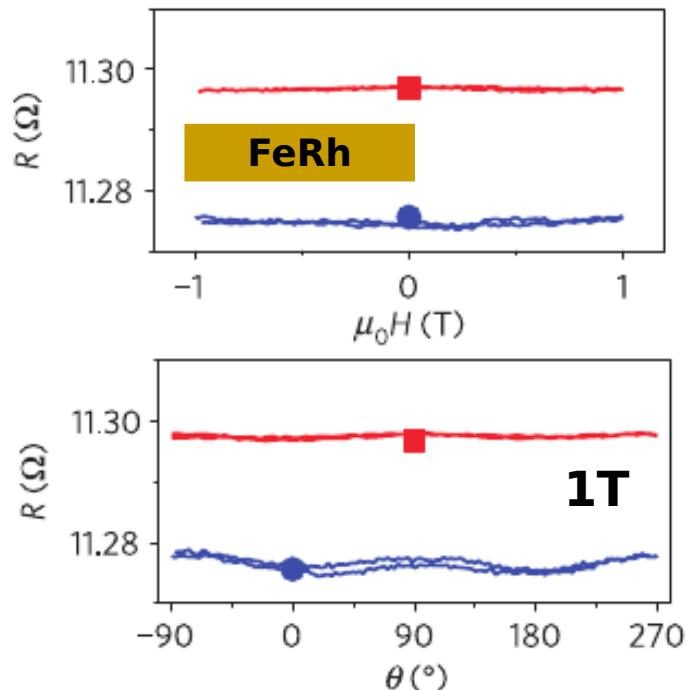
Dominik Kriegner, September 30, 2016

AMR in antiferromagnets

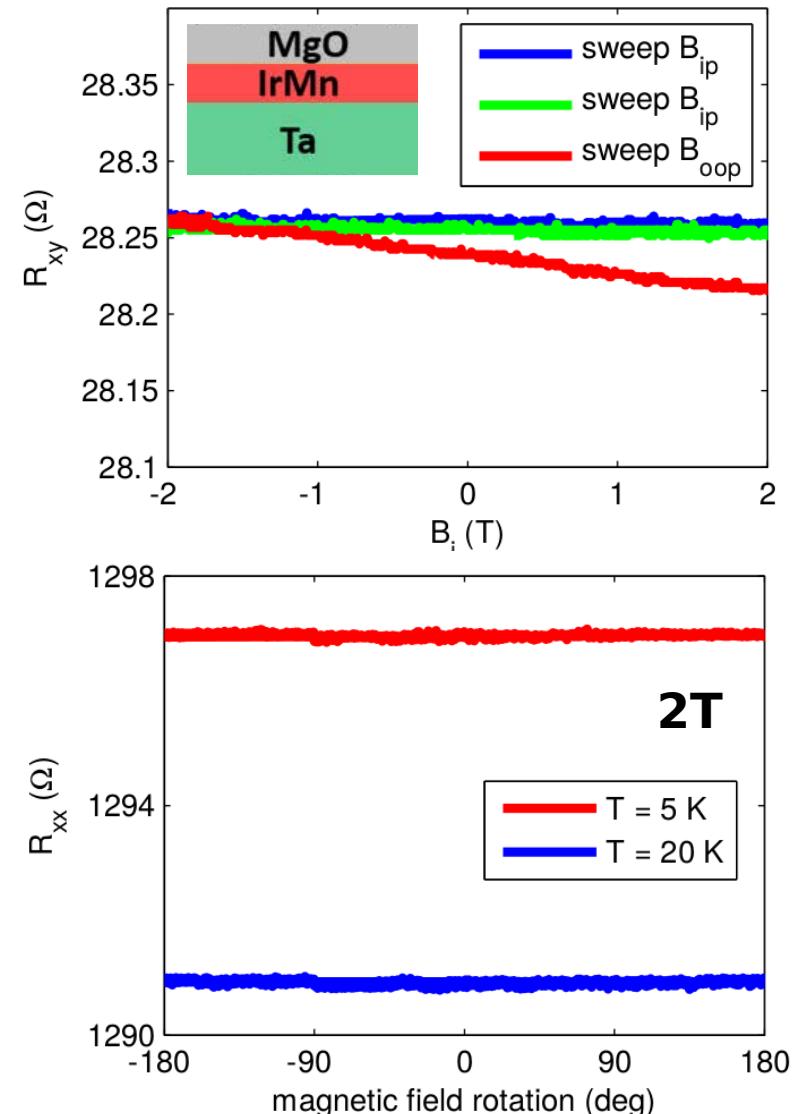
- L. Néel: “Effects in antiferromagnets depending on the square of the spontaneous magnetization should show the same variation as in ferromagnetic substances”

AMR in antiferromagnets

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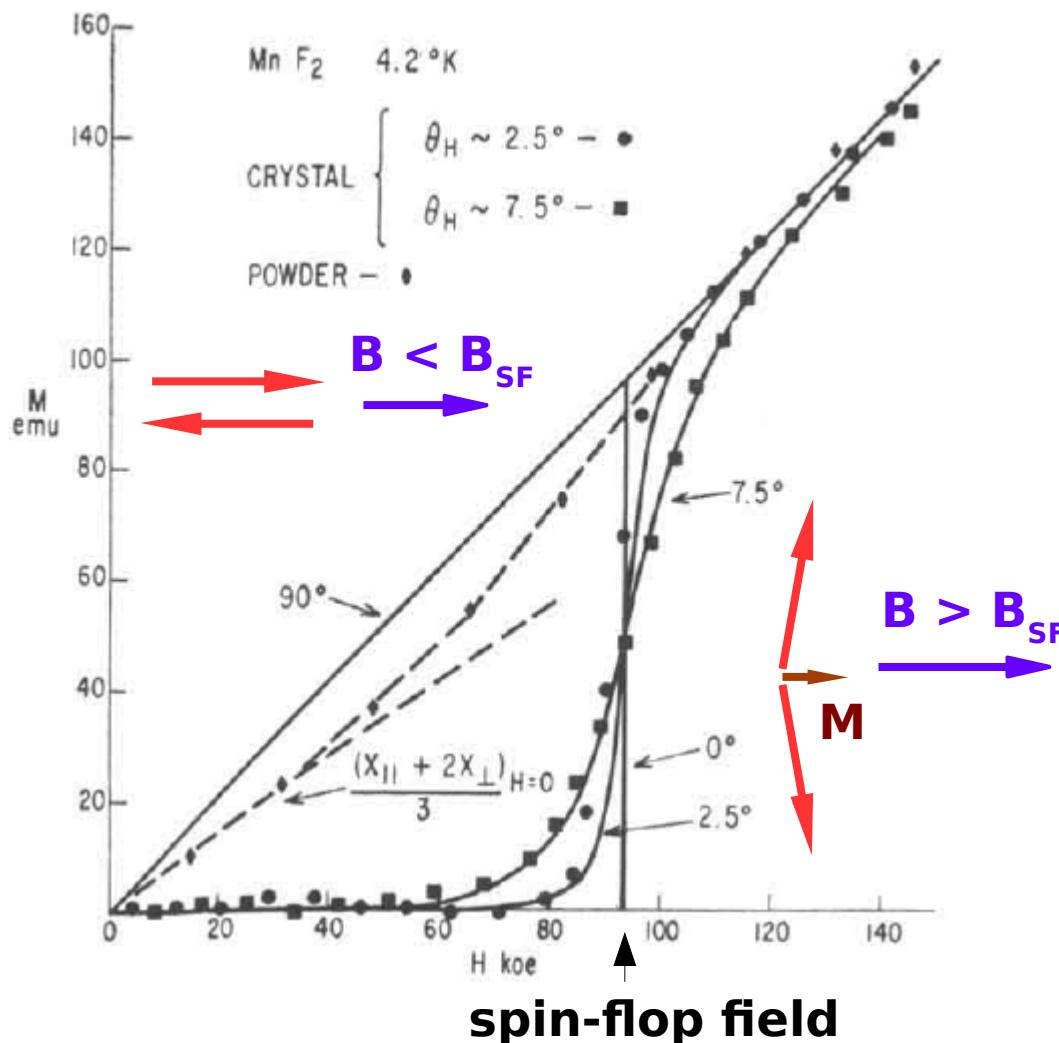
X. Marti, et al. Nat. Mat. 13, 367 (2014)



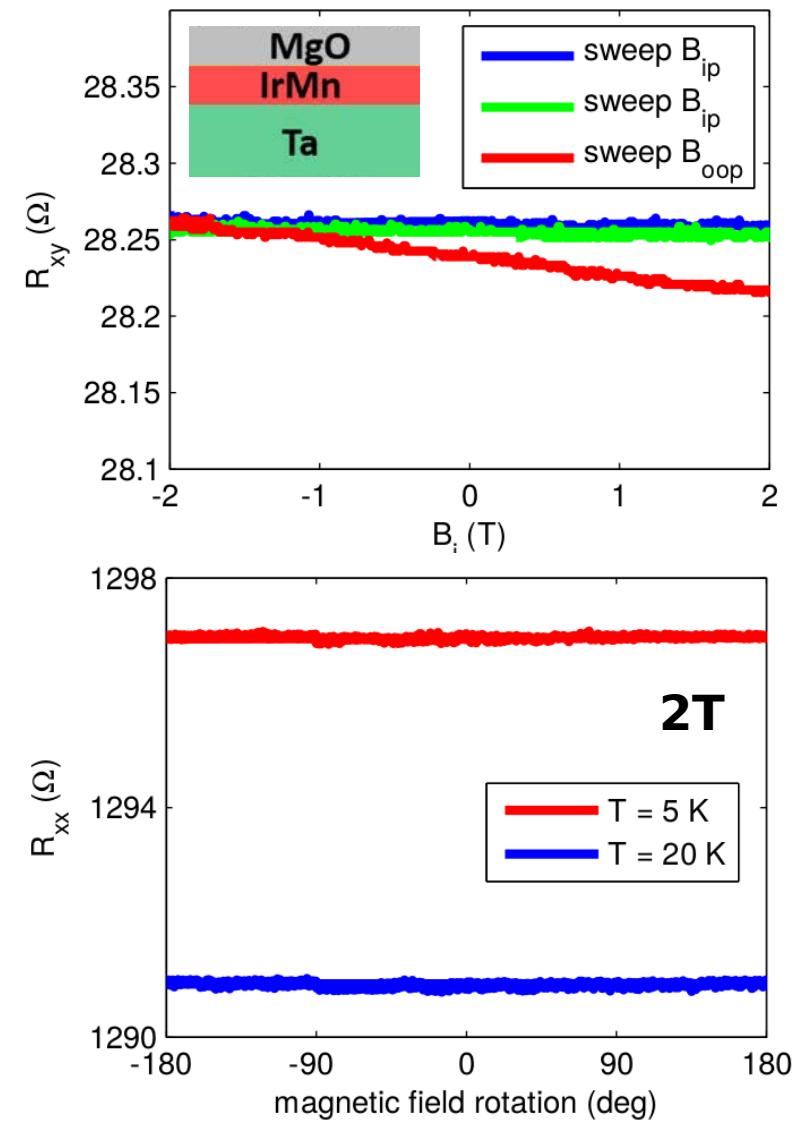
H. Reichlova, private comm.
Dominik Kriegner, September 30, 2016

AMR in antiferromagnets

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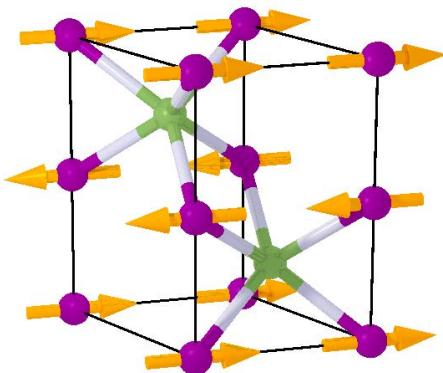


I. S. Jacobs, J. Appl Phys. 32, 61S (1961)



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Dominik Kriegner, September 30, 2016

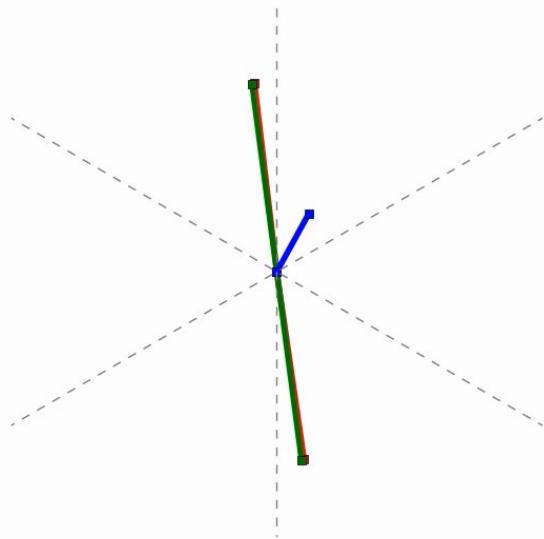


AFM field rotation

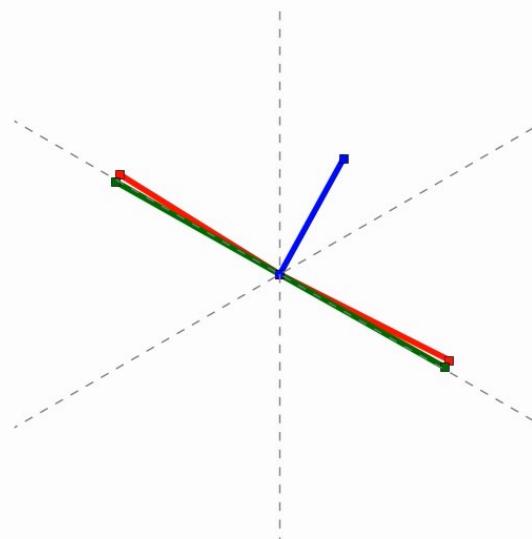
— field
— L
— M_1, M_2

for triaxial system (MnTe)

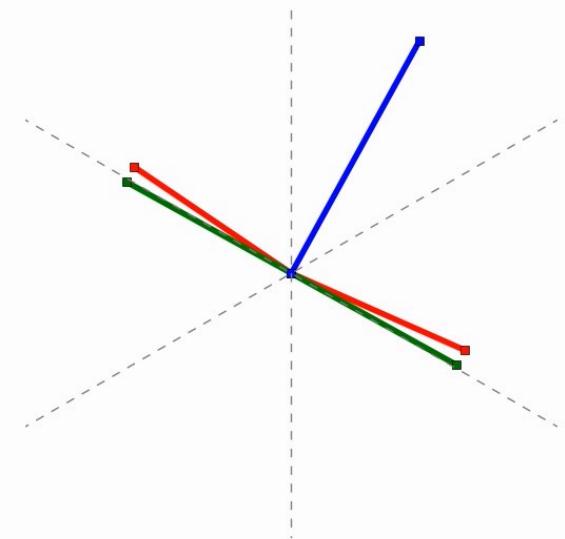
field < spin-flop



$\sim 2 \times$ spin-flop



$\sim 4 \times$ spin-flop



Néel-order:

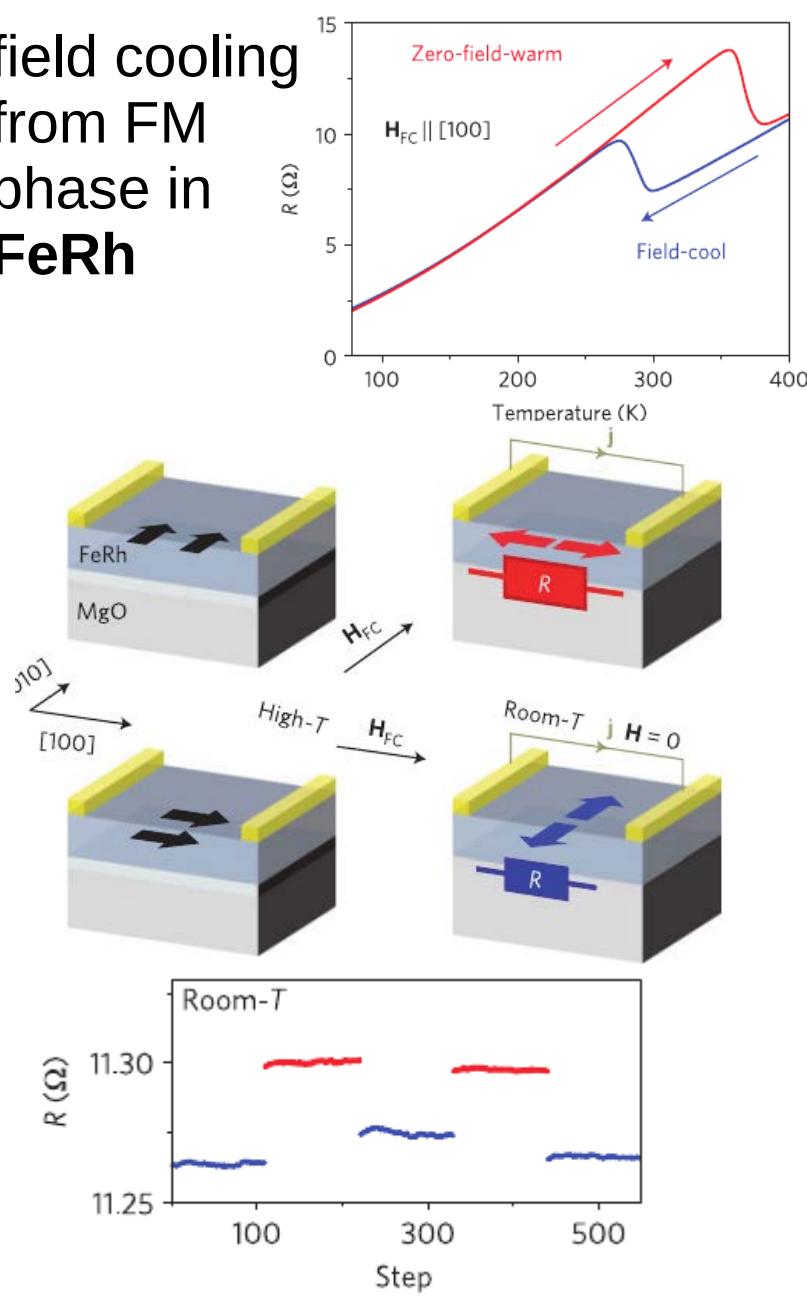
wobbling around
easy axis

rotating, but
“skipping” of hard axis

following perpendicular
to the applied field

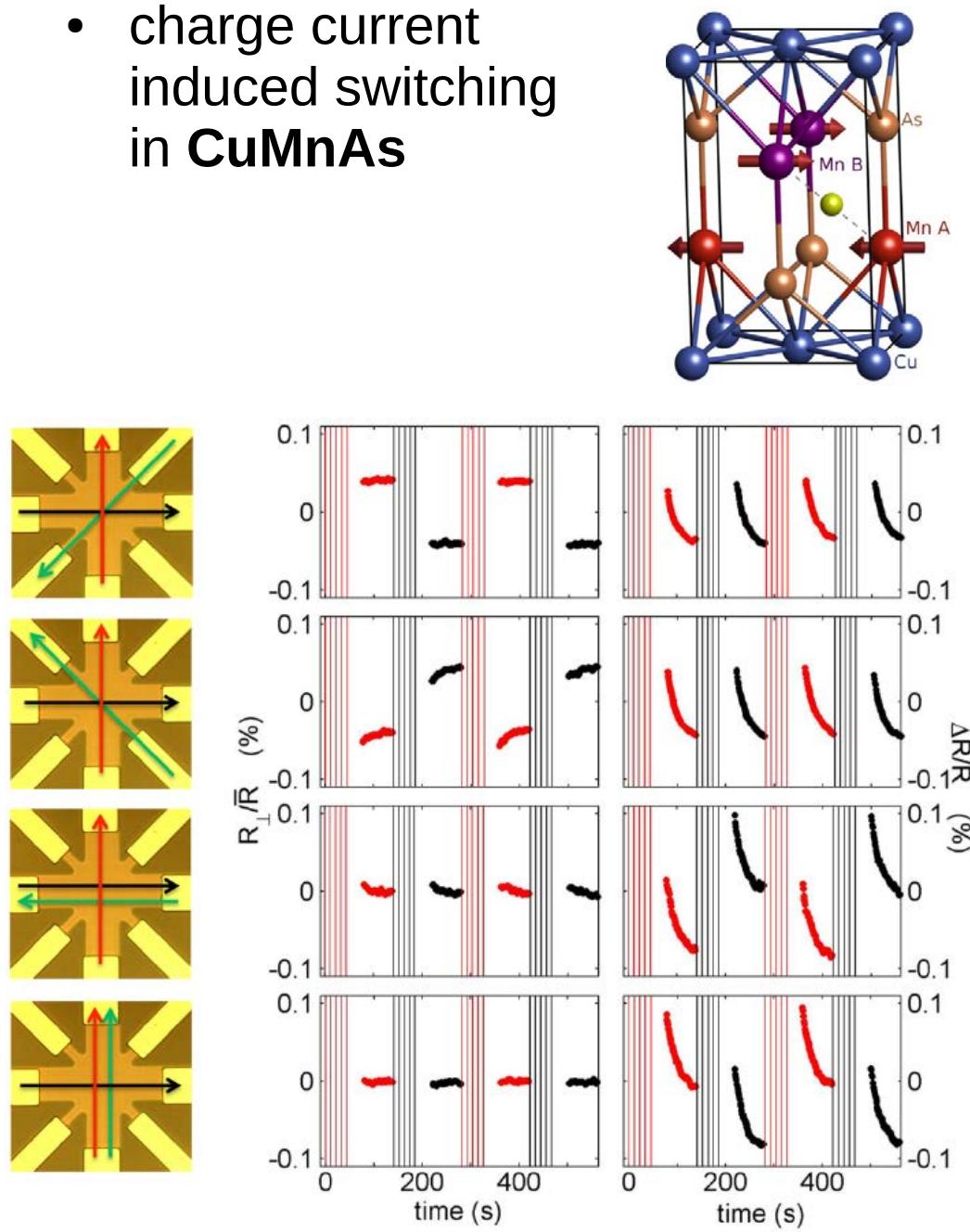
AMR in antiferromagnets (II)

- field cooling from FM phase in FeRh



X. Marti, et al. Nat. Mat. 13, 367 (2014)

- charge current induced switching in CuMnAs

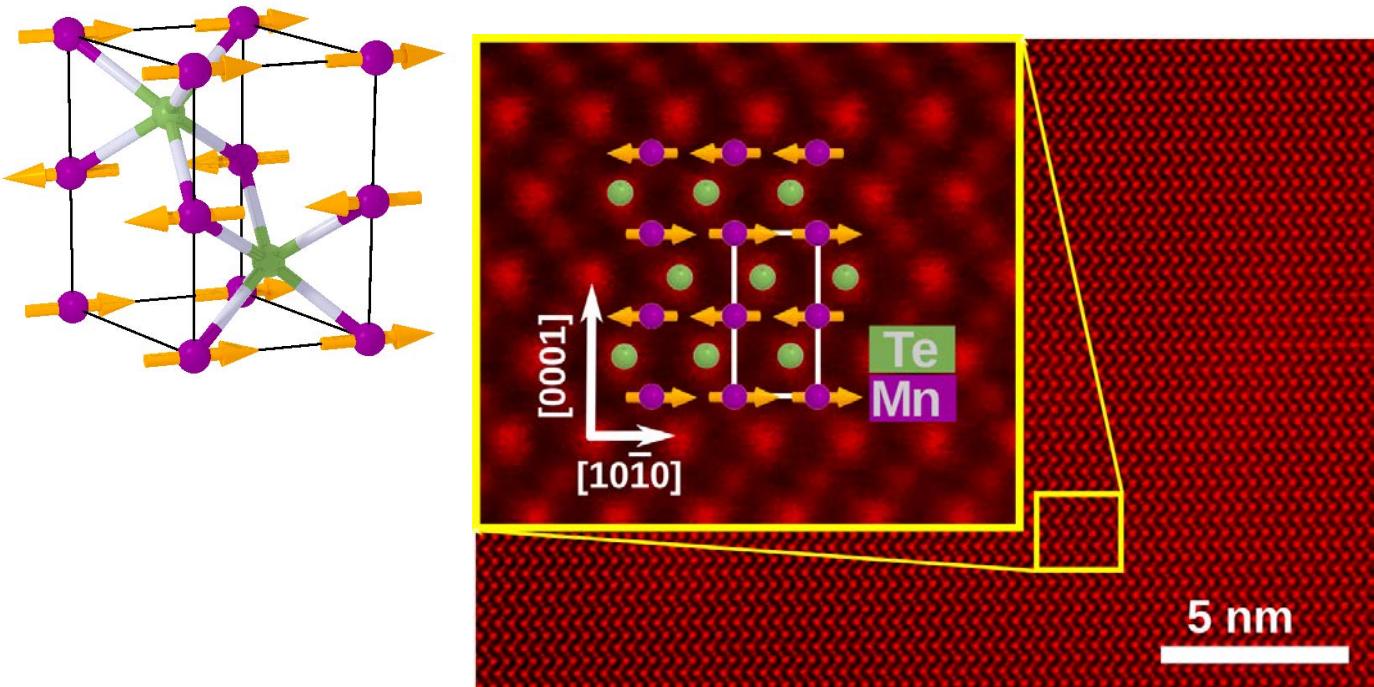


P. Wadley et al., Science 351, 587 (2016)

field cooling of IrMn: D. Petti et al. Appl. Phys. Lett. 102, 192404 (2013)

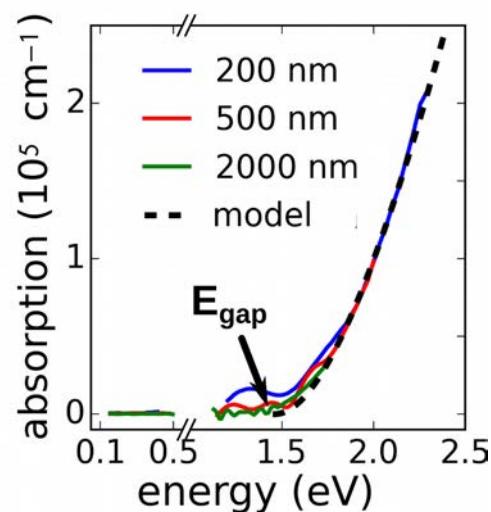
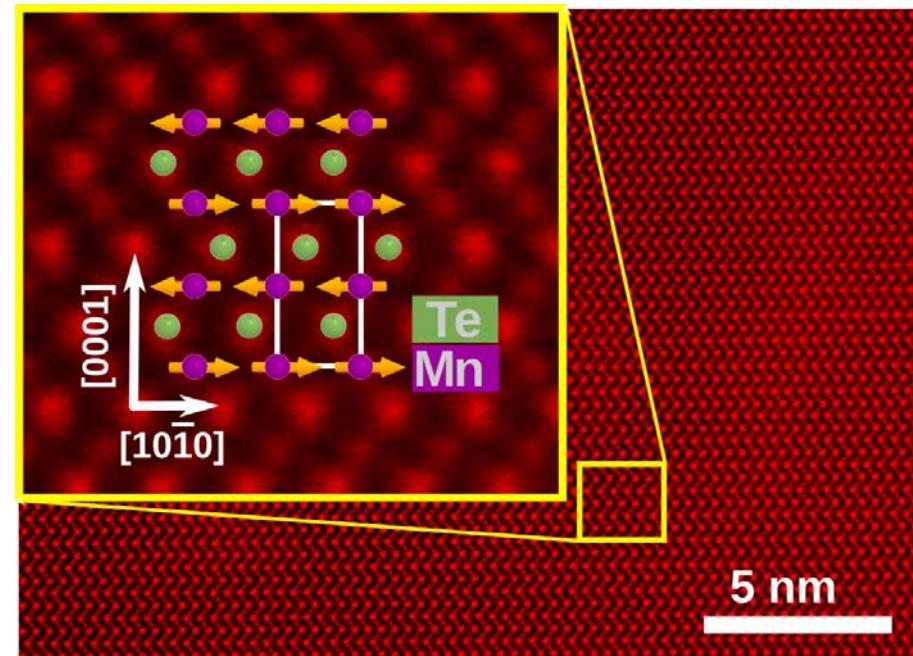
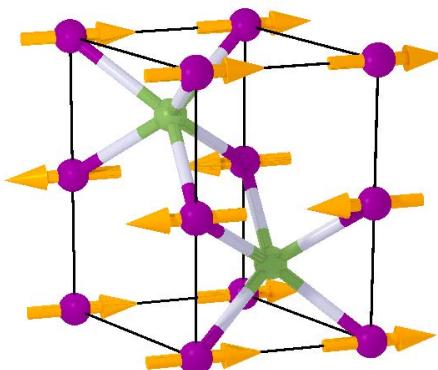
antiferromagnetic semiconductor MnTe

- epitaxial single crystalline thin films (MBE)
- hexagonal structure
 - FM c-planes
- bulk $T_N=310\text{K}$



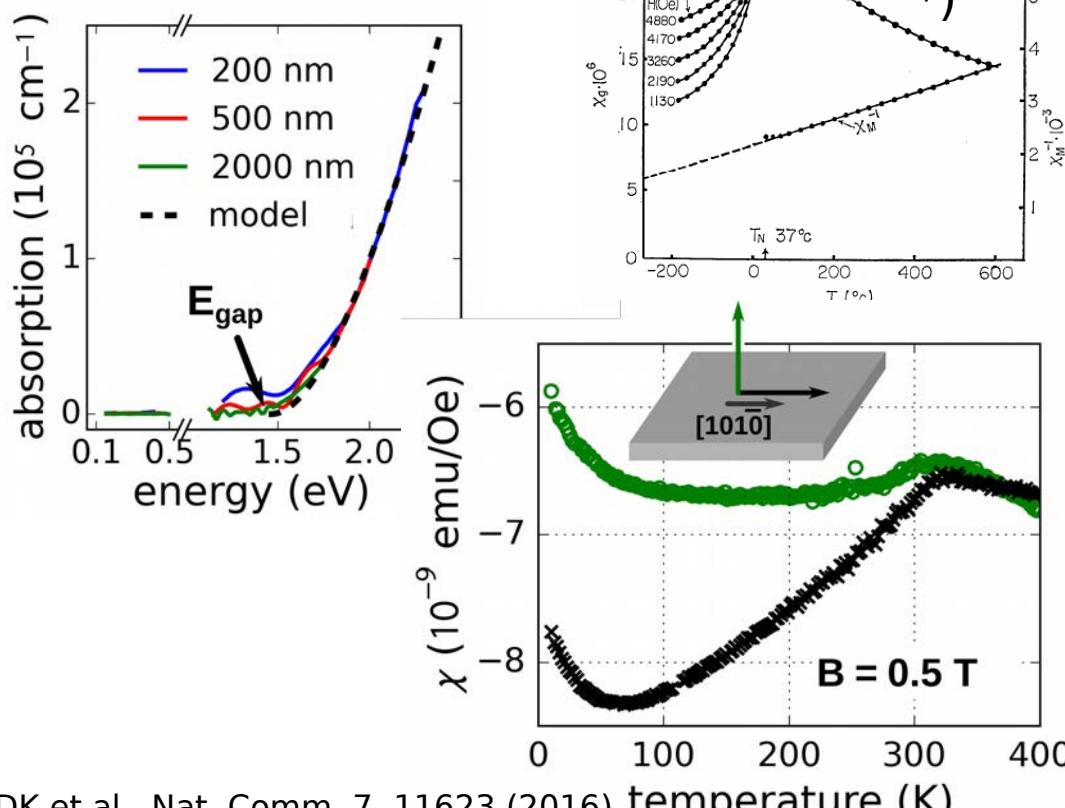
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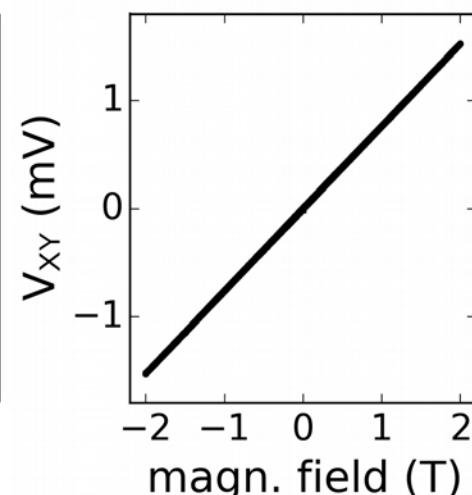
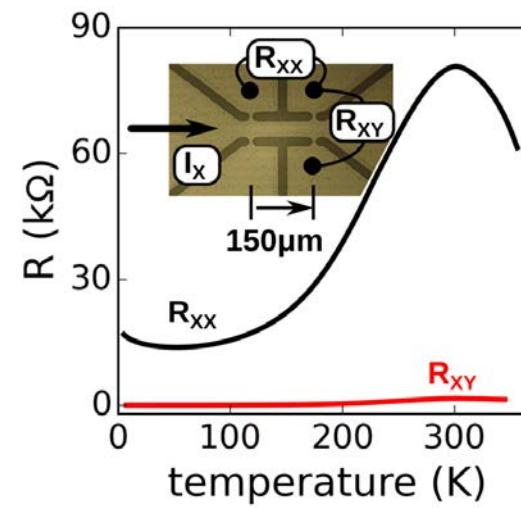
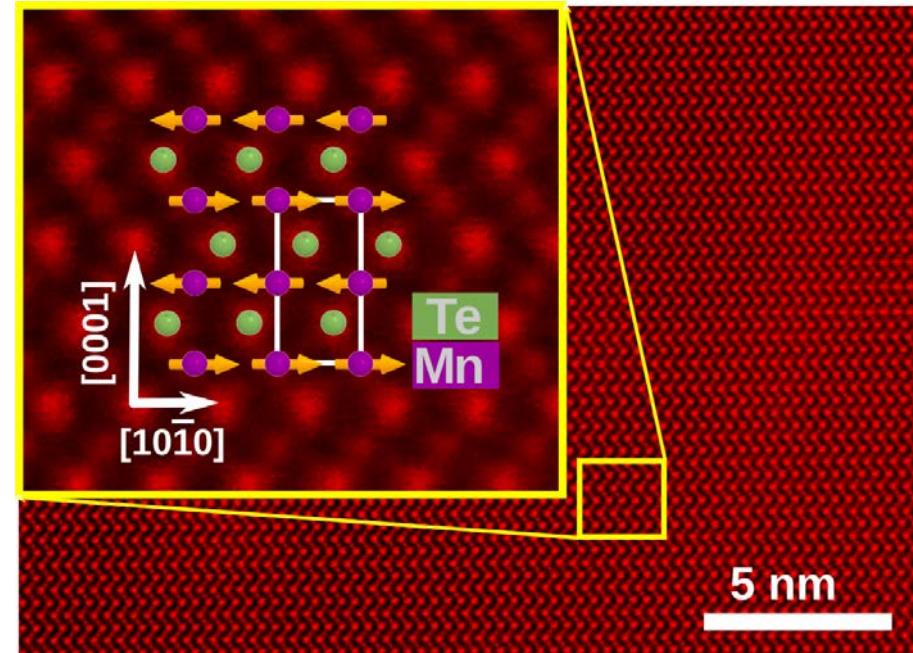
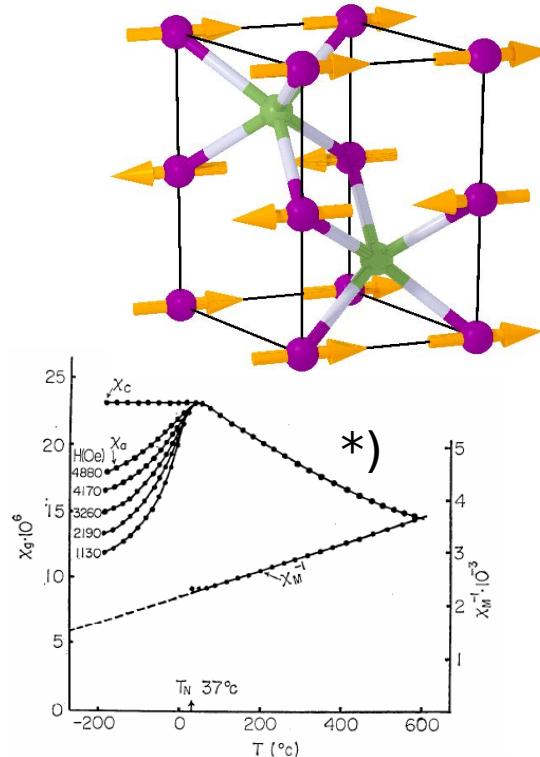
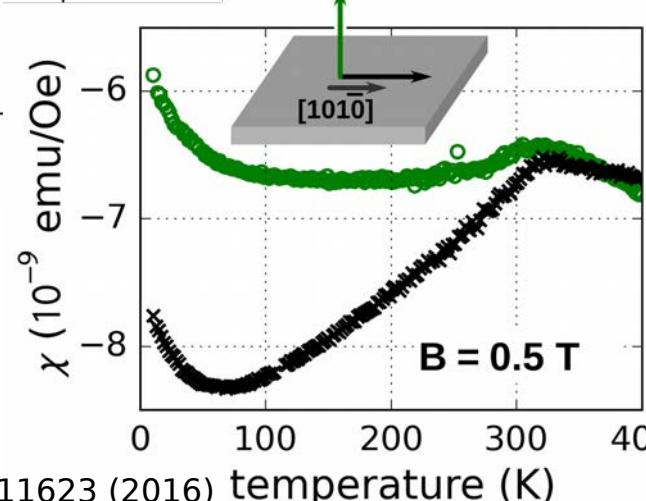
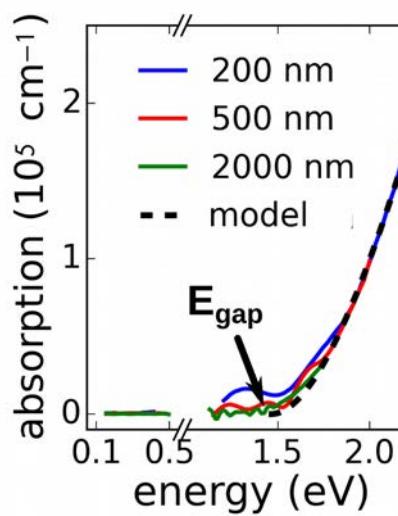
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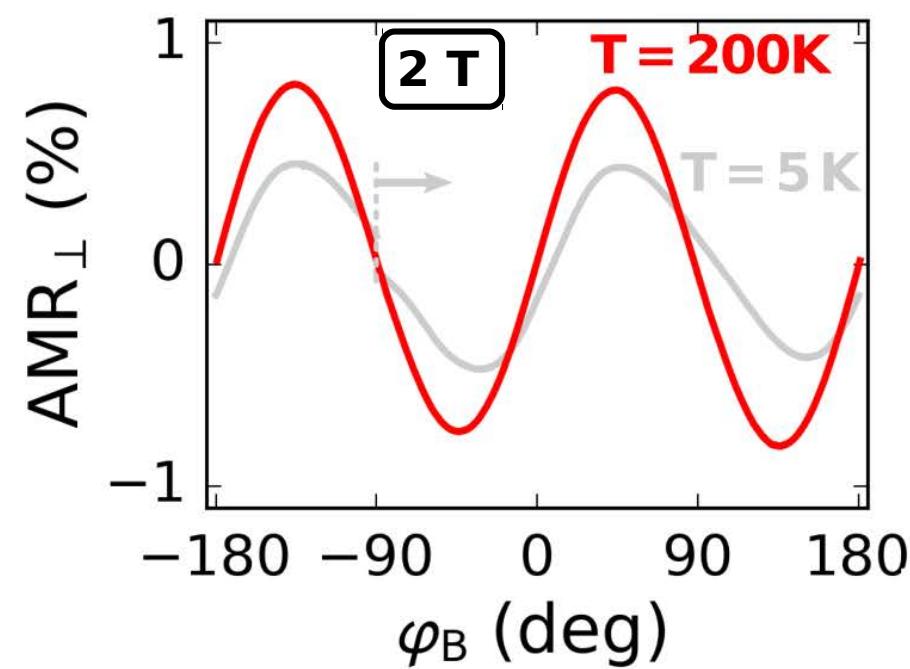
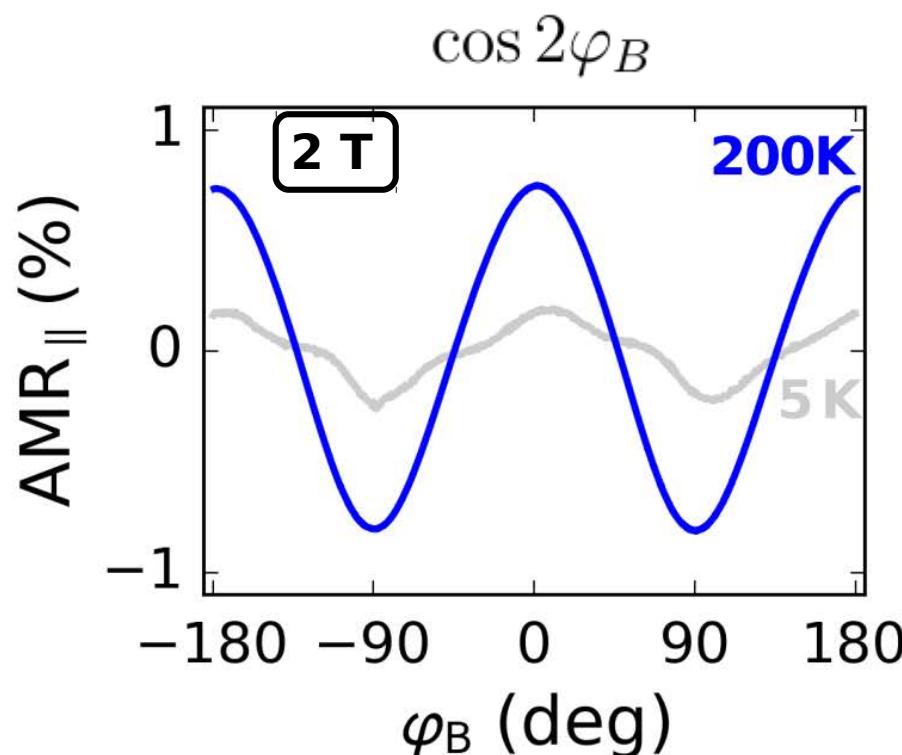
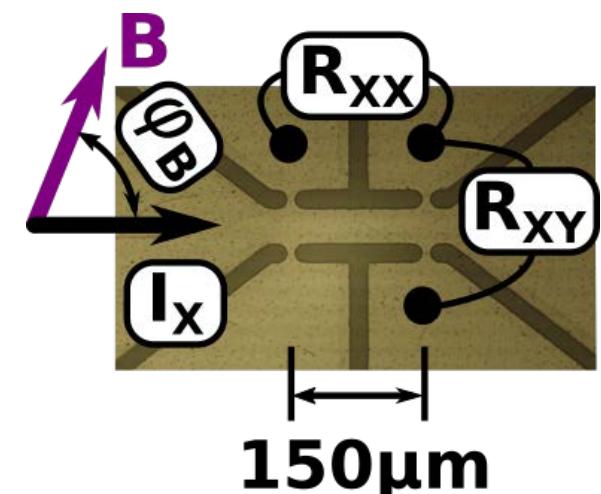
- epitaxial single crystalline thin films (MBE)
- hexagonal structure
 - FM c-planes
- bulk $T_N=310\text{K}$
 - $\rho=1.8\times10^{-4} \Omega\text{m}$
 - $p \sim 6\times10^{18} \text{ cm}^{-3}$
 - $\mu \sim 43 \text{ cm}^2/\text{Vs}$



harmonic AMR in MnTe

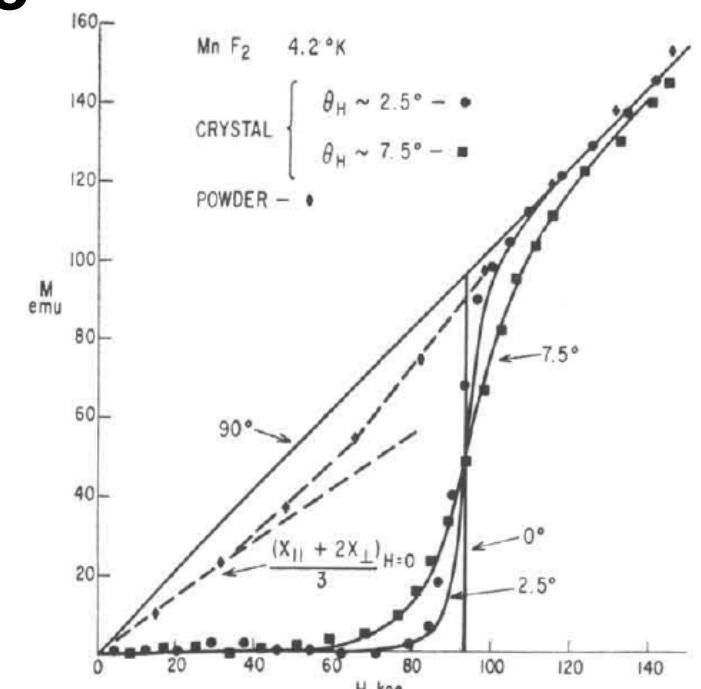
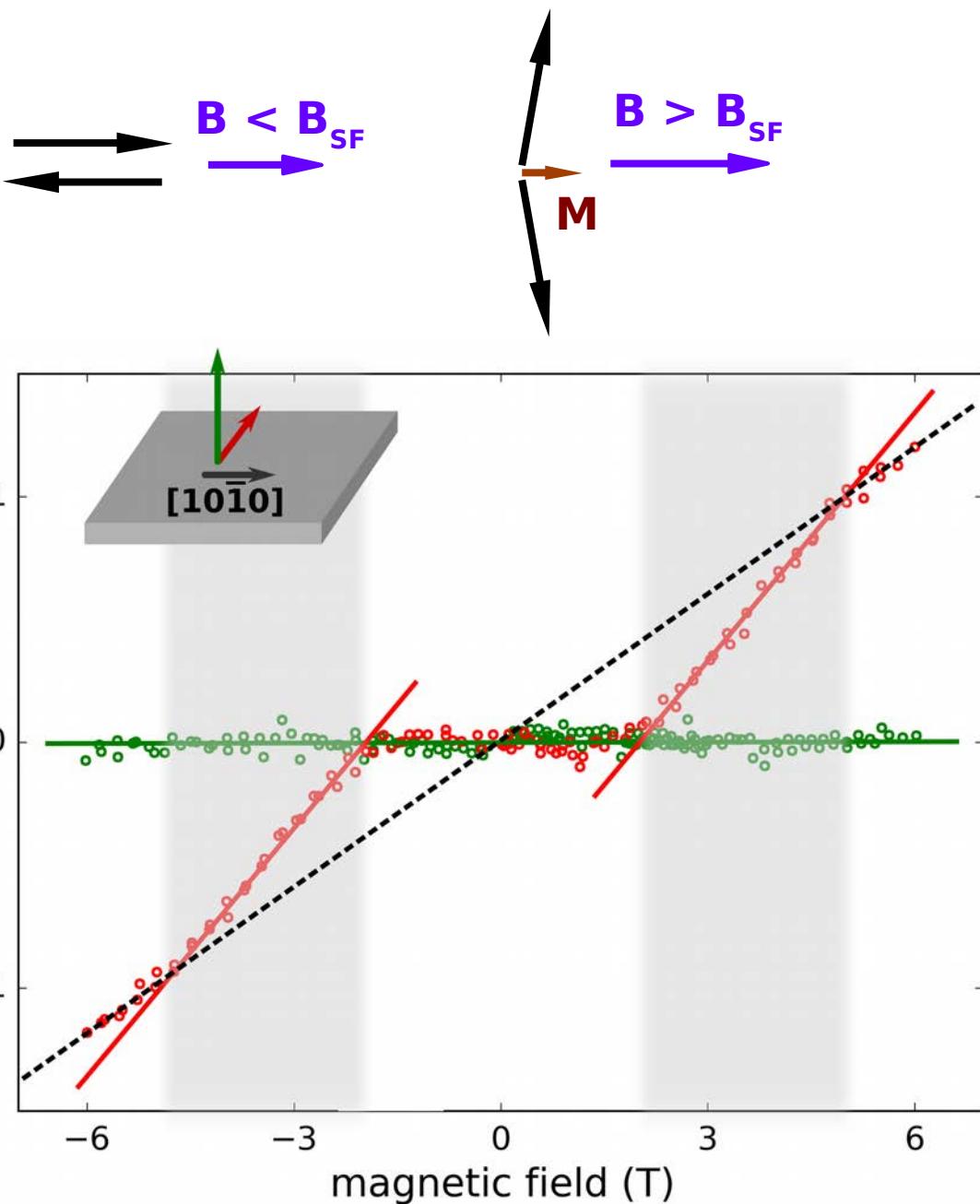
$$AMR_{\parallel}(\varphi_B) \equiv \frac{R_{XX}(\varphi_B) - \langle R_{XX} \rangle}{\langle R_{XX} \rangle}$$

$$AMR_{\perp}(\varphi_B) \equiv \frac{R_{XY}(\varphi_B) - \langle R_{XY} \rangle}{\langle R_{XX} \rangle} n$$

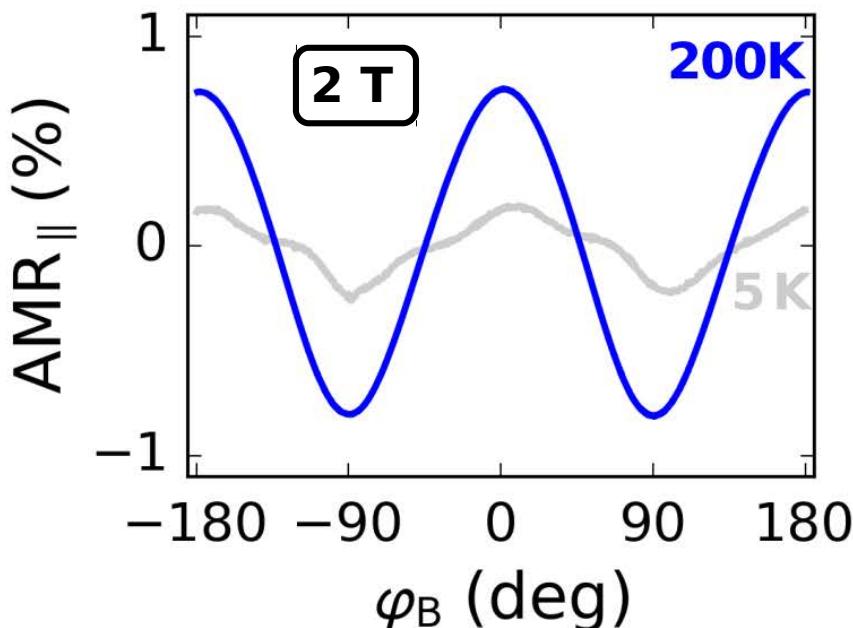


spin flop in MnTe

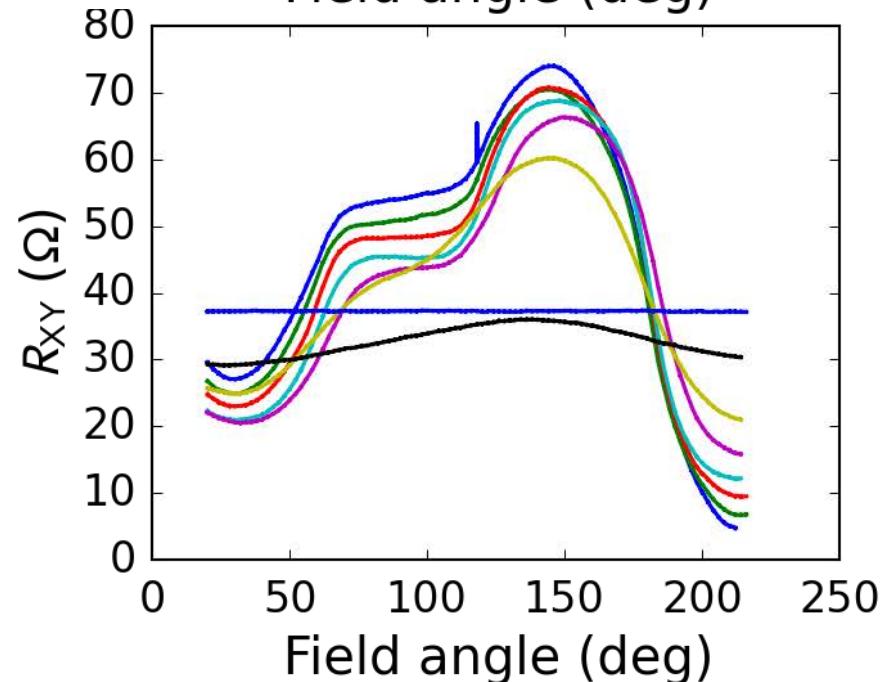
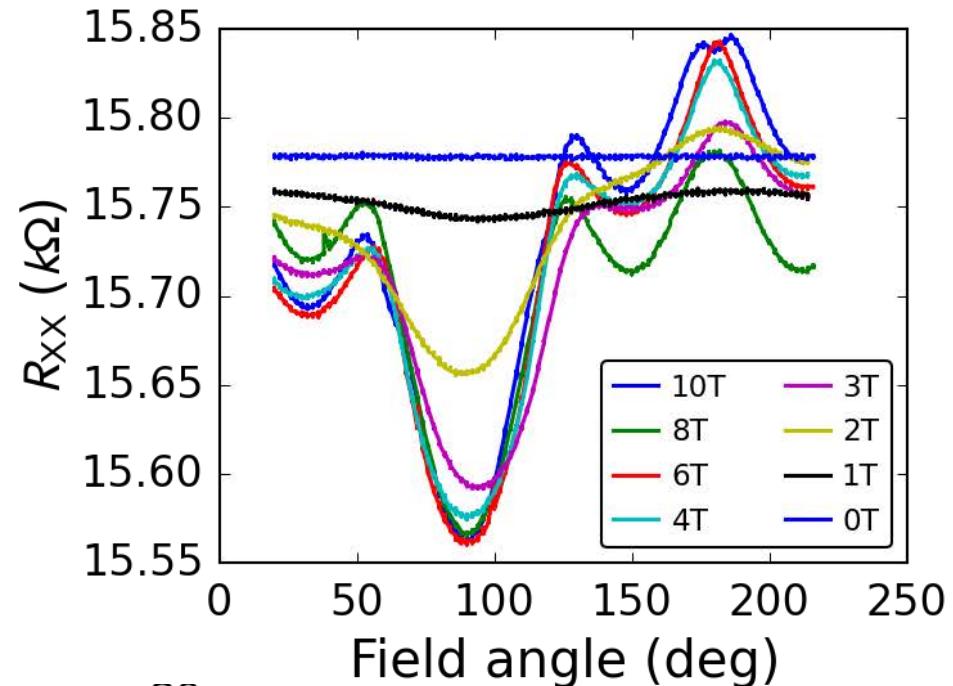
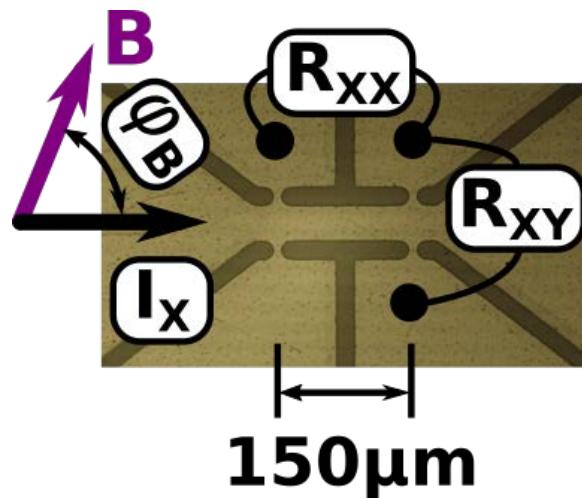
- spin-flop field at 200K $< 2\text{T}$



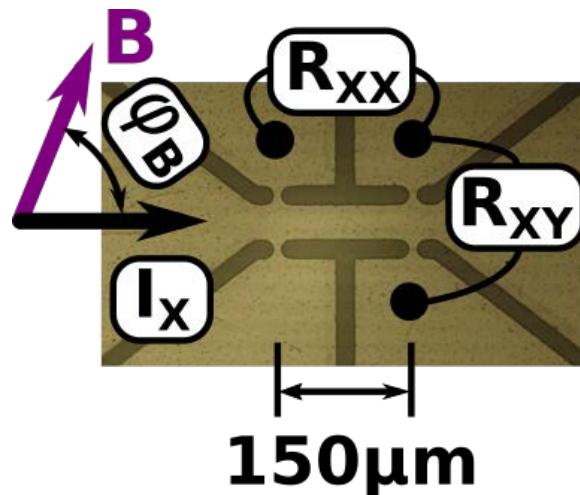
I. S. Jacobs. J. Appl Phys. 32, 61S (1961)



field rotations at T=5K



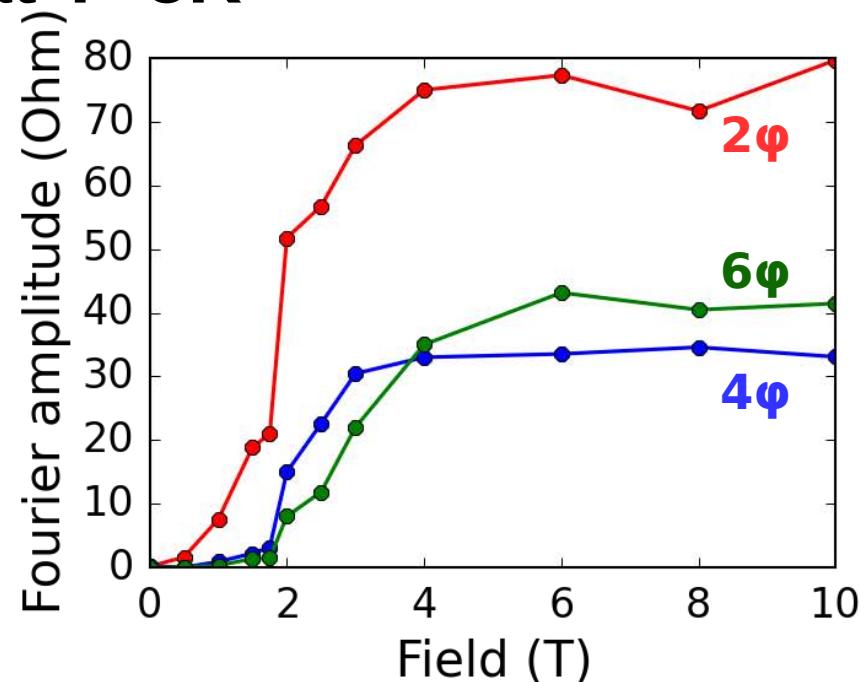
field rotations at T=5K



- R_{xx} shows
 - “cos”(2ϕ)
 - “cos”(4ϕ)
 - “cos”(6ϕ)
 - ncAMR $\sim 0.5\%$
- R_{xy} shows
 - “sin”(ϕ) (ordinary Hall)
 - “sin”(2ϕ)
 - “sin”(4ϕ)

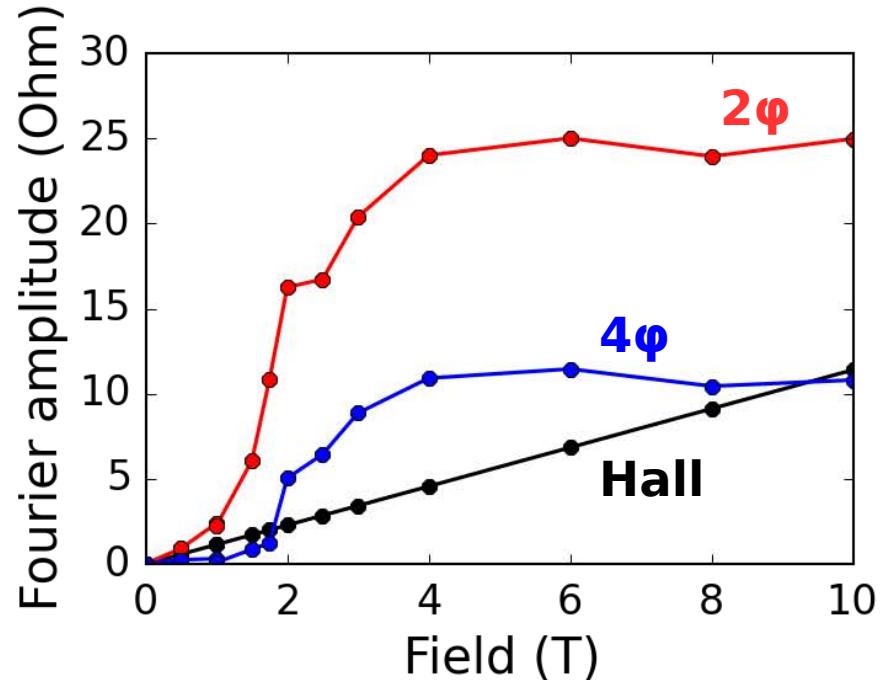
R_{xx}

non-cryst
+
cryst.



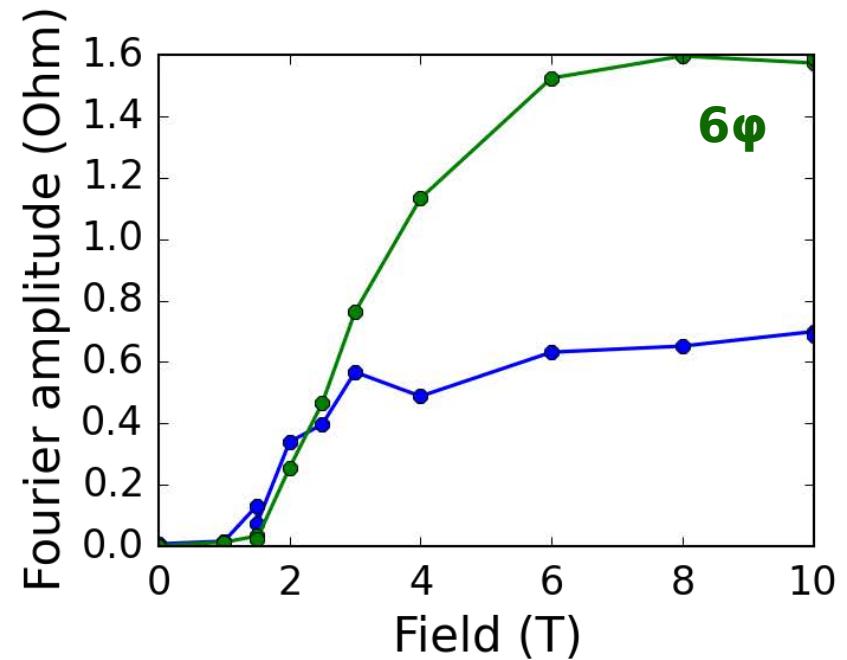
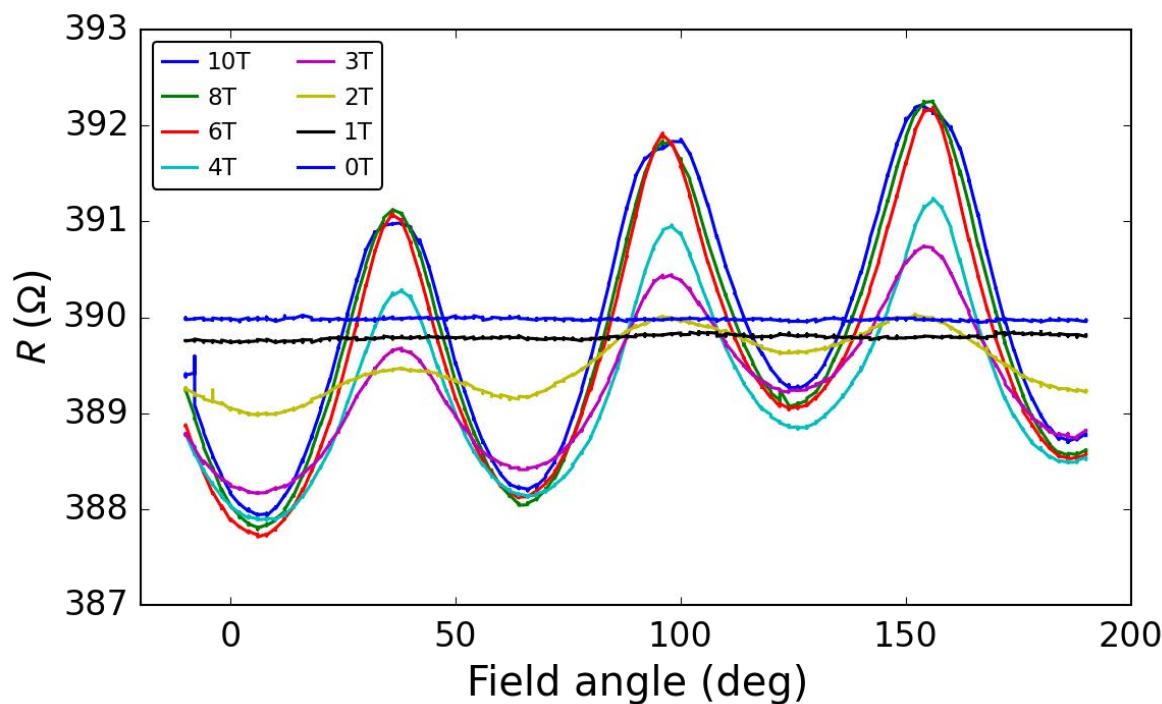
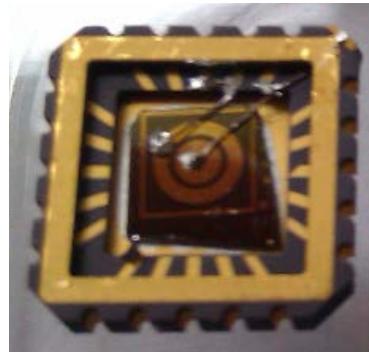
non-cryst
+
Hall

R_{xy}



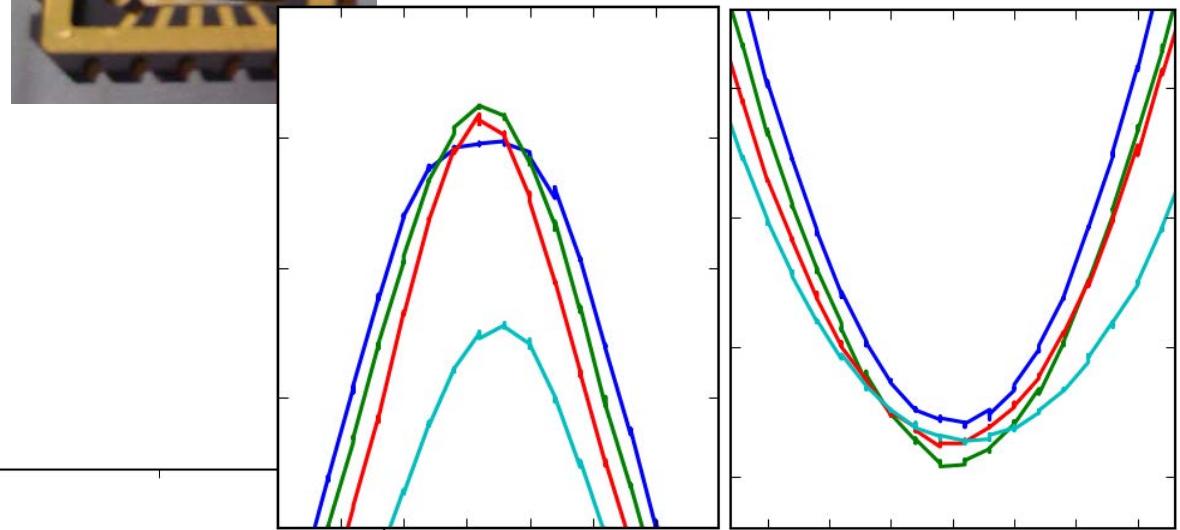
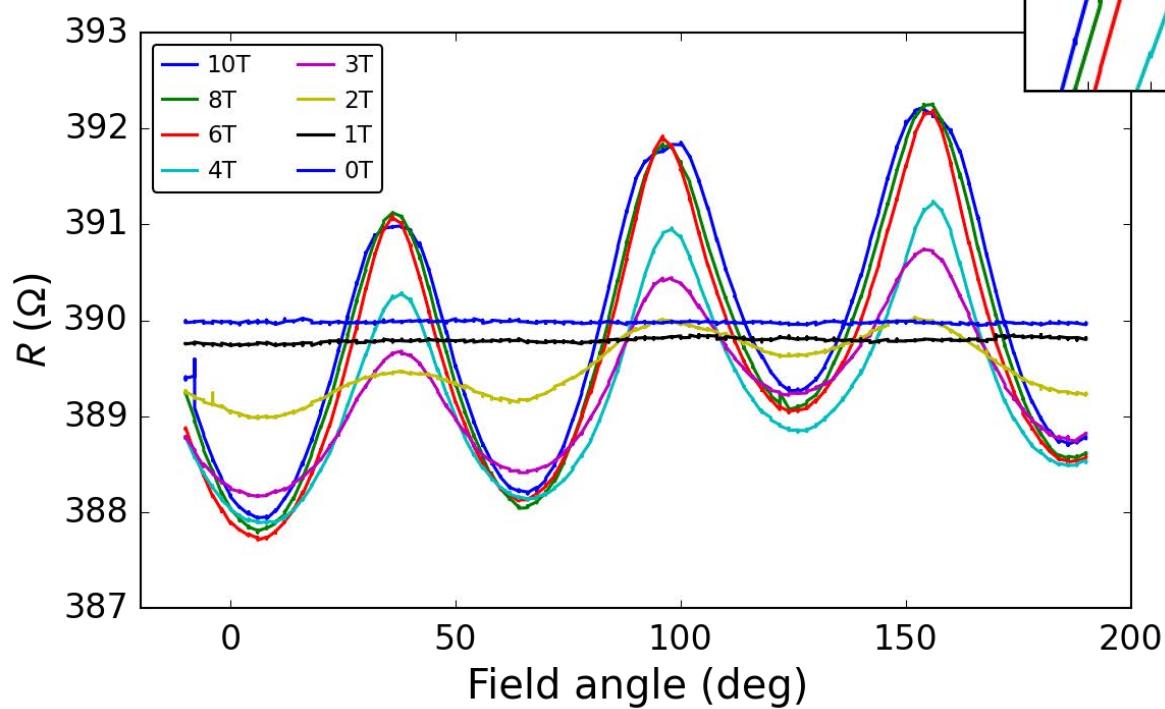
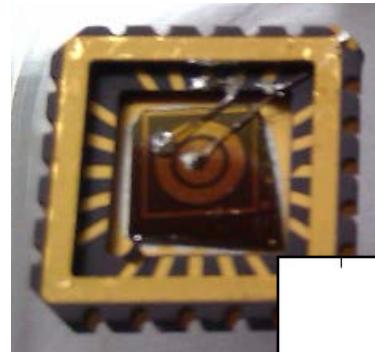
isolation of crystalline AMR

- Corbino disk geometry
- dominantly 6-fold signal

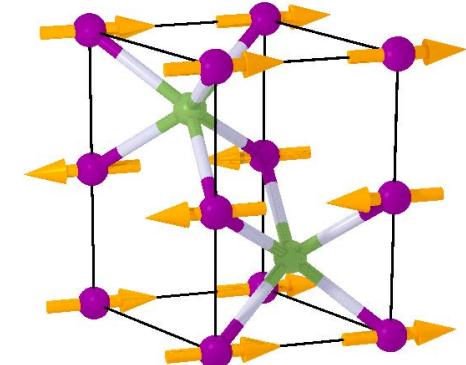


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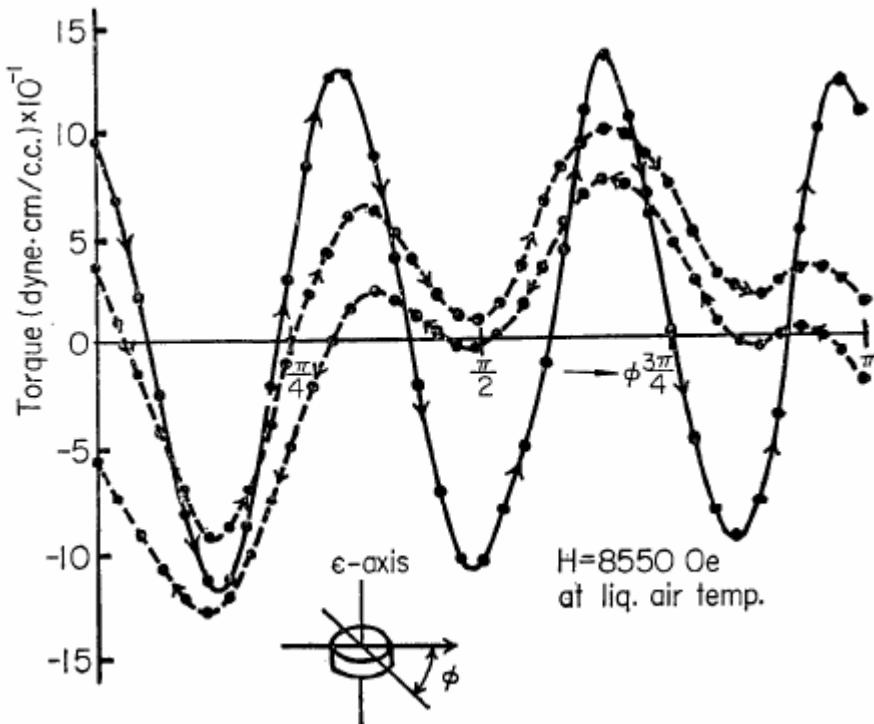


easy axis:
field = [11-20] →
Néel vector
[10-10]

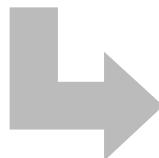


field cooling of MnTe

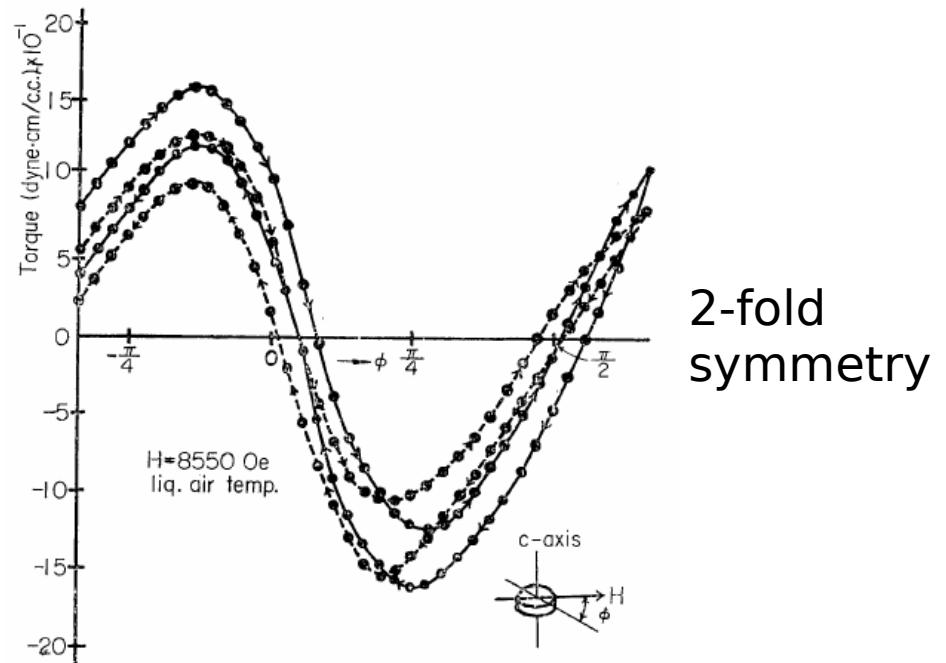
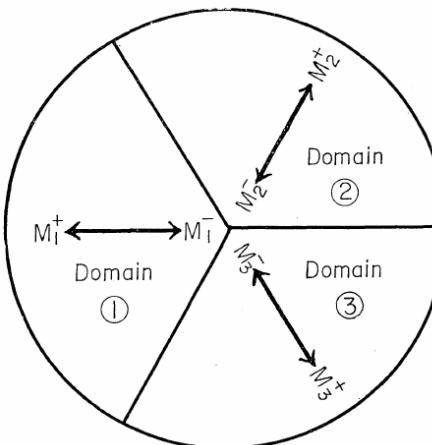
- Komatsubara et al., J. Phys. Soc. Jap. 18, 356 (1963)
- **1cm³** single crystalline sample



predominantly 6-fold symmetry



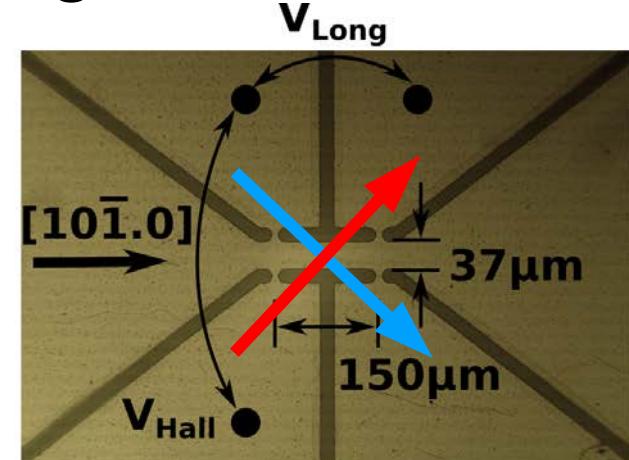
field cooling from
above T_N



2-fold
symmetry

field cooling (FC) \leftrightarrow “writing”

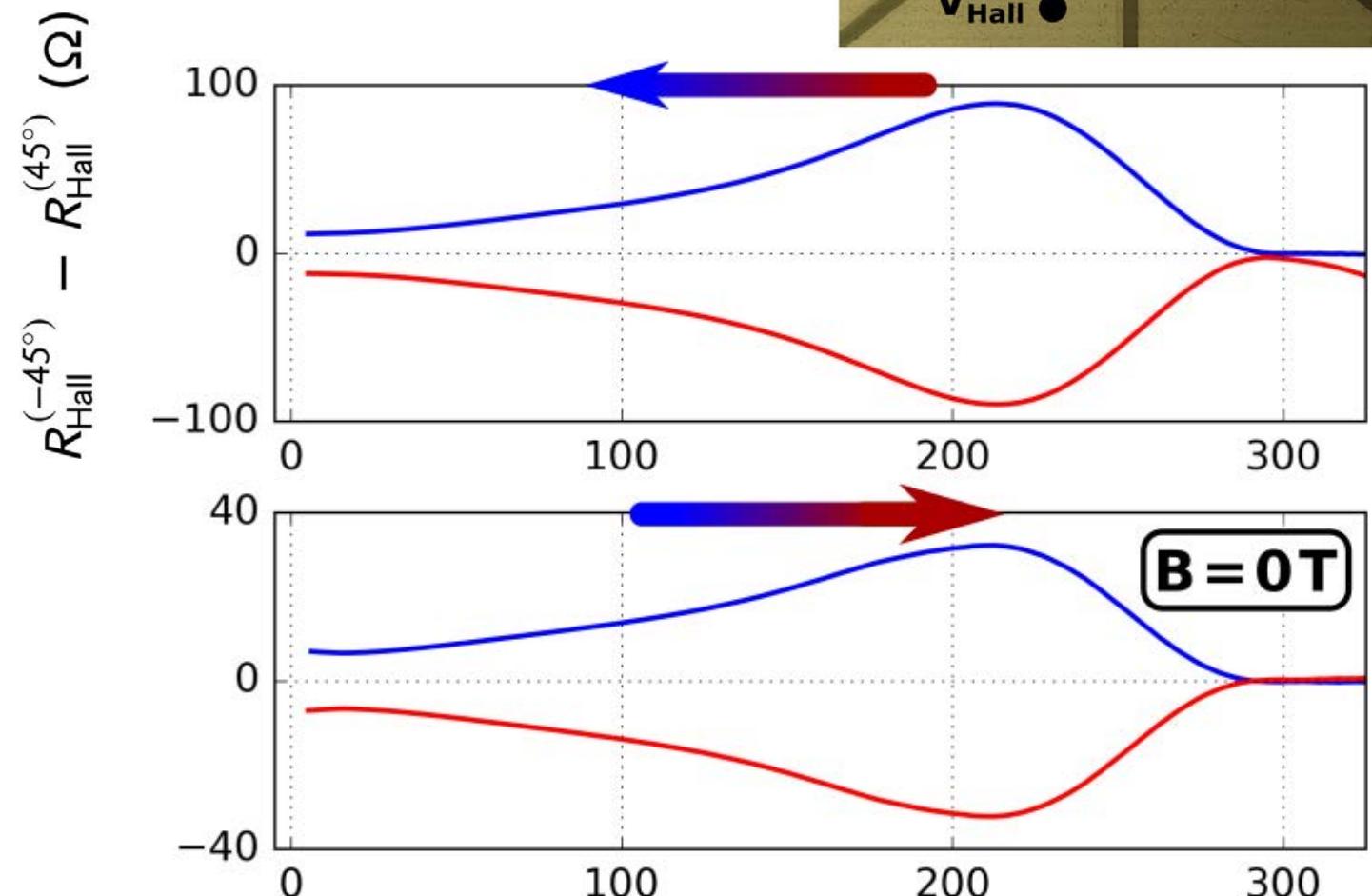
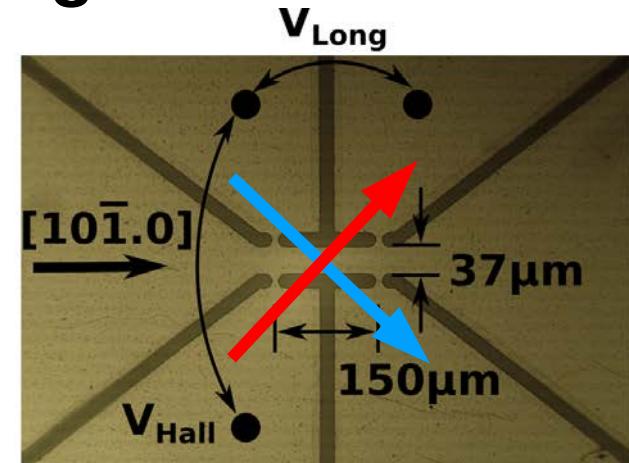
- procedure:
 - apply magn. field at $T > T_N$
 - cool to 5K



expect maximum splitting for FC in
blue/red directions:
 $\Delta R_{XY} \propto \sin(2\angle_{inp}(\mathbf{L}, \mathbf{j}))$

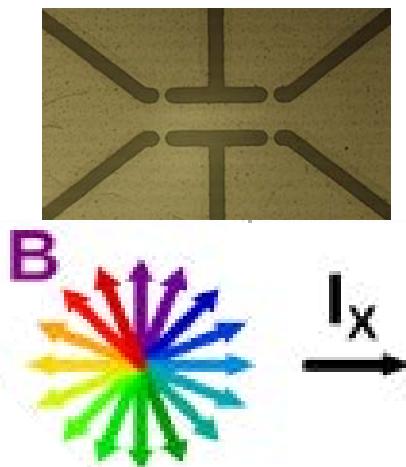
field cooling (FC) \leftrightarrow “writing”

- procedure:
 - apply magn. field at $T > T_N$
 - cool to 5K
 - remove field
 - heat in **zero field**



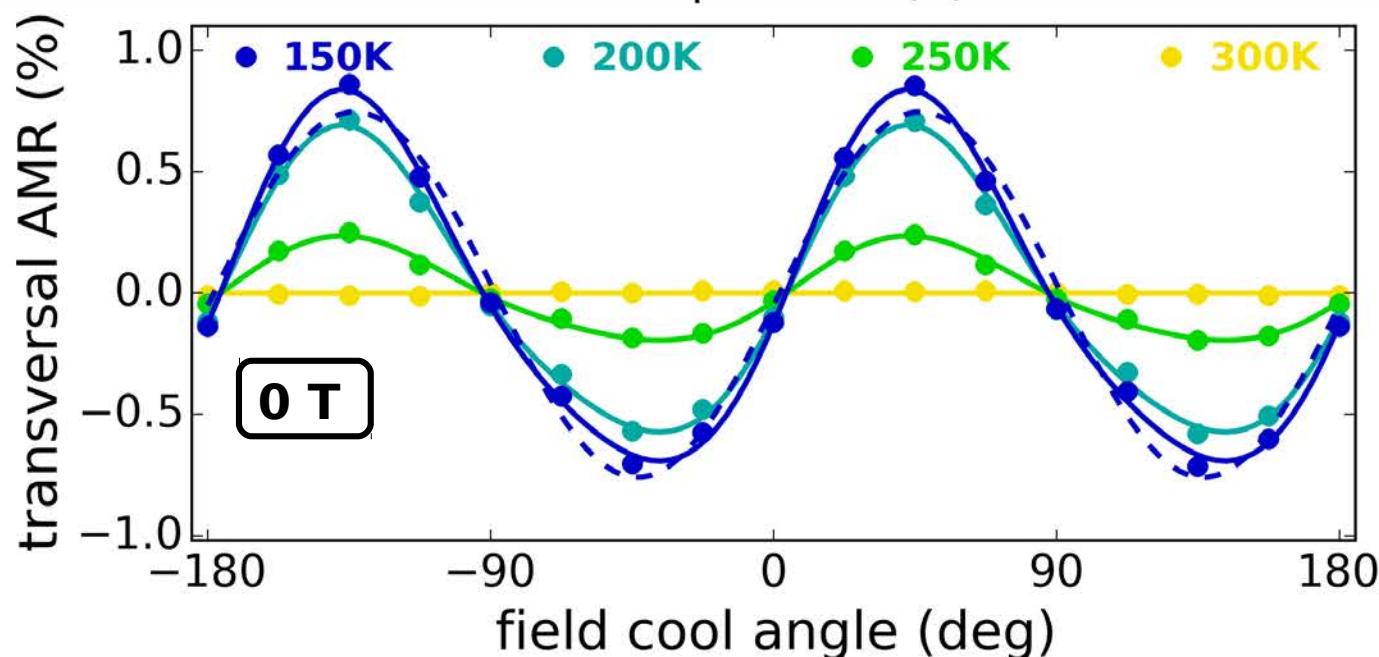
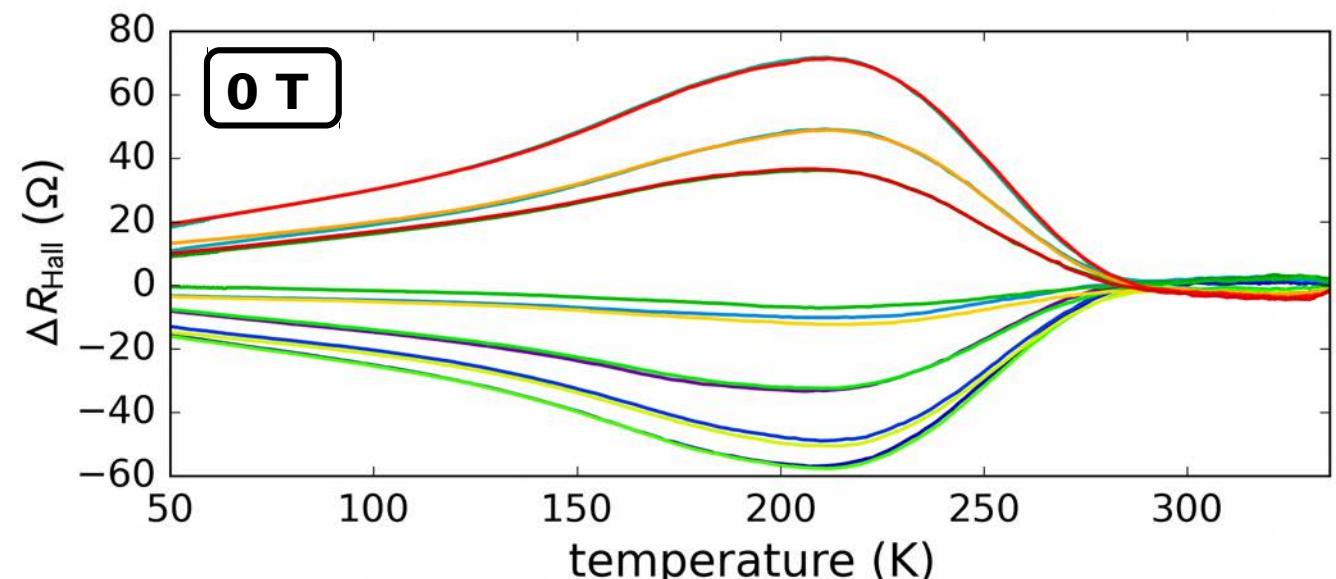
setting of multiple states

FC in various directions



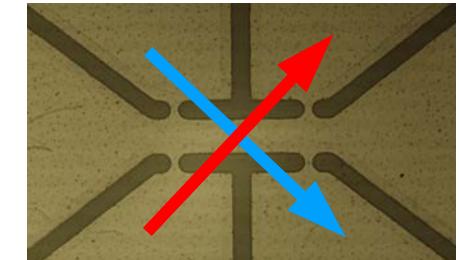
continuous AMR:

$$\Delta R_{XY} \sim \propto \sin(2\Delta_{\text{inp}}(\mathbf{L}, \mathbf{j}))$$

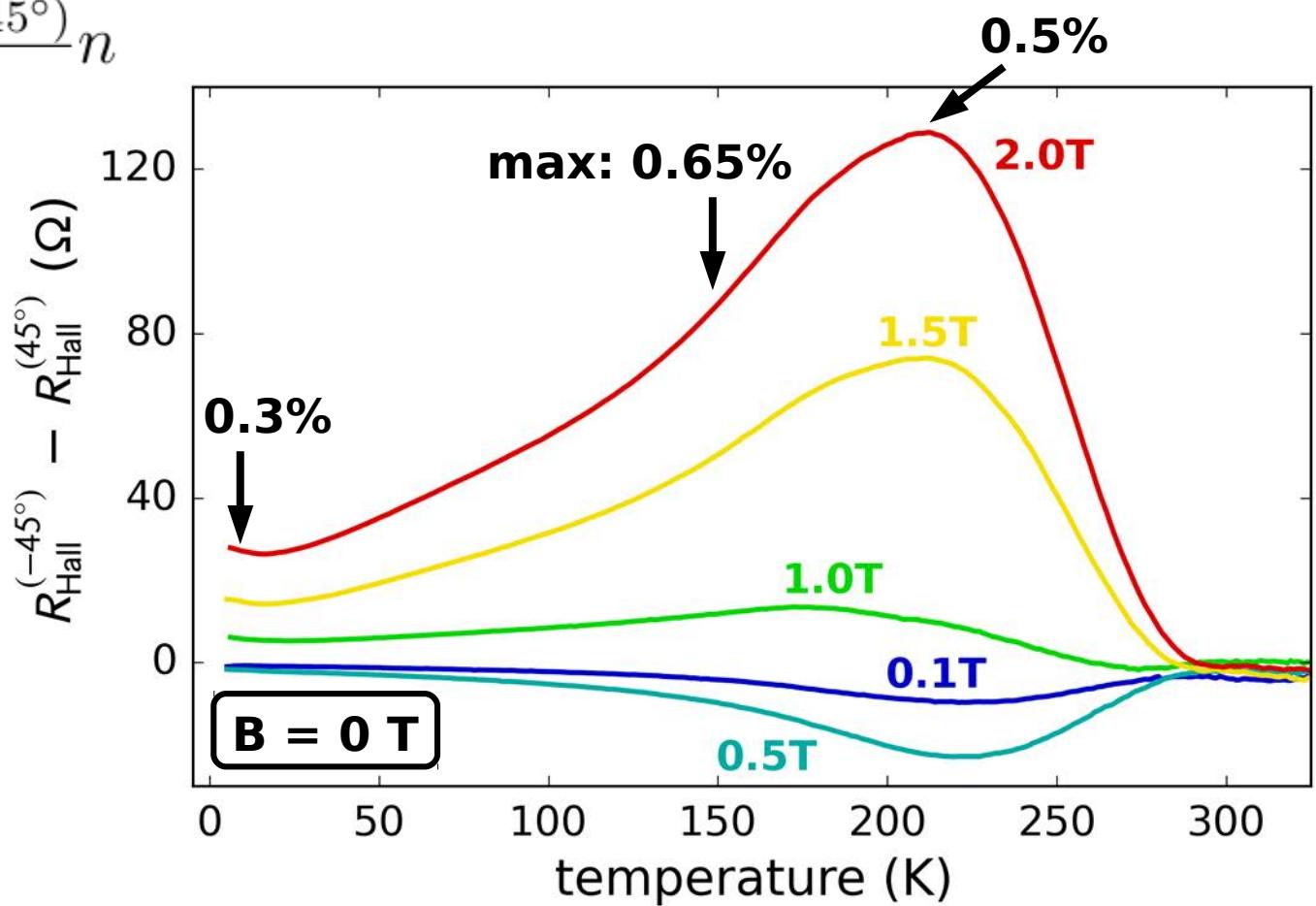
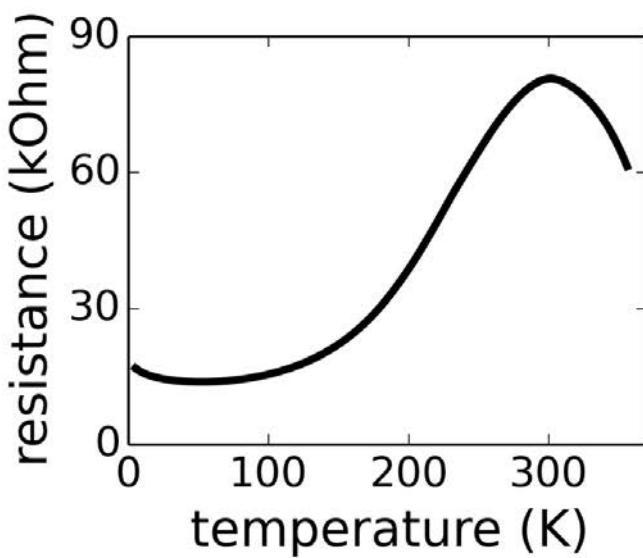


FC magnitude dependence

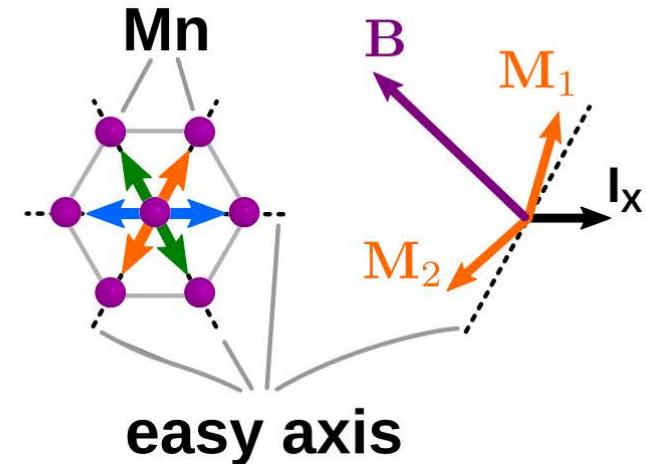
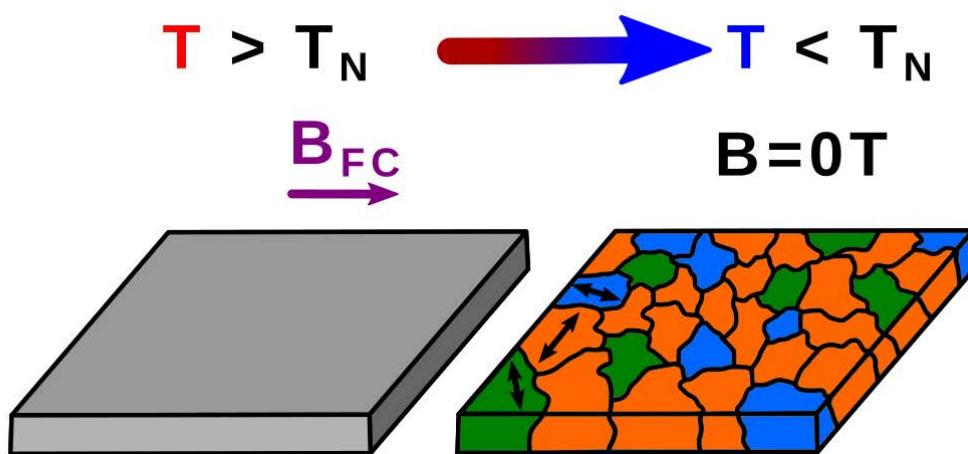
- FC with different field strength
- AMR splitting increases (**no** saturation up to 2T)
- **negative** effect in small fields?!



$$\text{AMR}_{\text{ampl}} = \frac{R_{XY}(45^\circ) - R_{XY}(-45^\circ)}{\langle R_{XX} \rangle} n$$



model for field cooling



1) get \mathbf{L} direction based on Stoner-Wohlfarth:

$$E = E_{\text{Zeeman}} + E_{\text{anisotropy}} + E_{\text{exchange}}$$

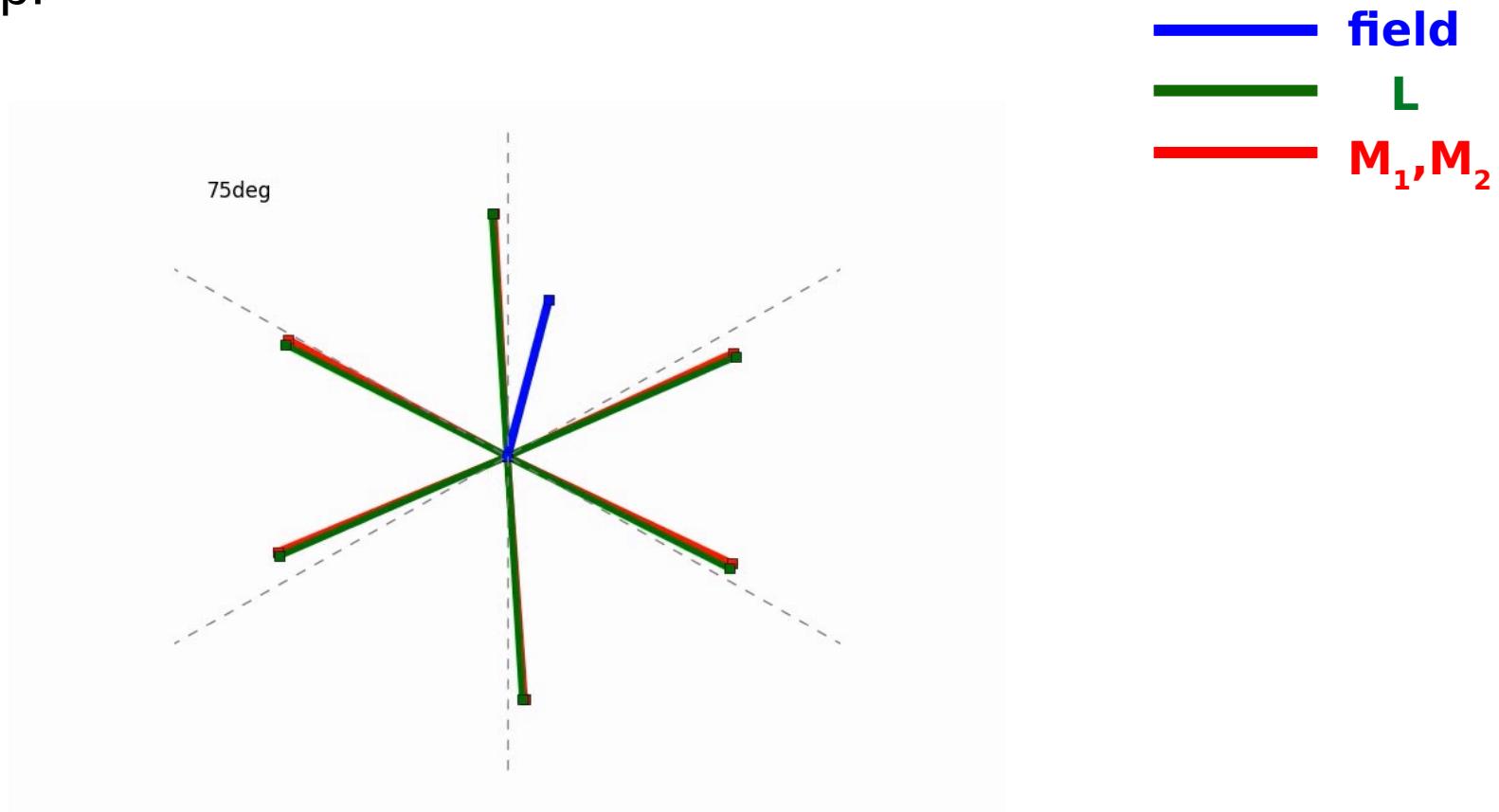
2) calculate domain occupation by Boltzmann distribution

3) use

- $\Delta R_{XX,\text{AMR}} = n R_{\text{NC}} \cos(2\phi(\mathbf{L}, \mathbf{j}))$
- $\Delta R_{XY,\text{tAMR}} = R_{\text{NC}} \sin(2\phi_{\text{inp}}(\mathbf{L}, \mathbf{j}))$

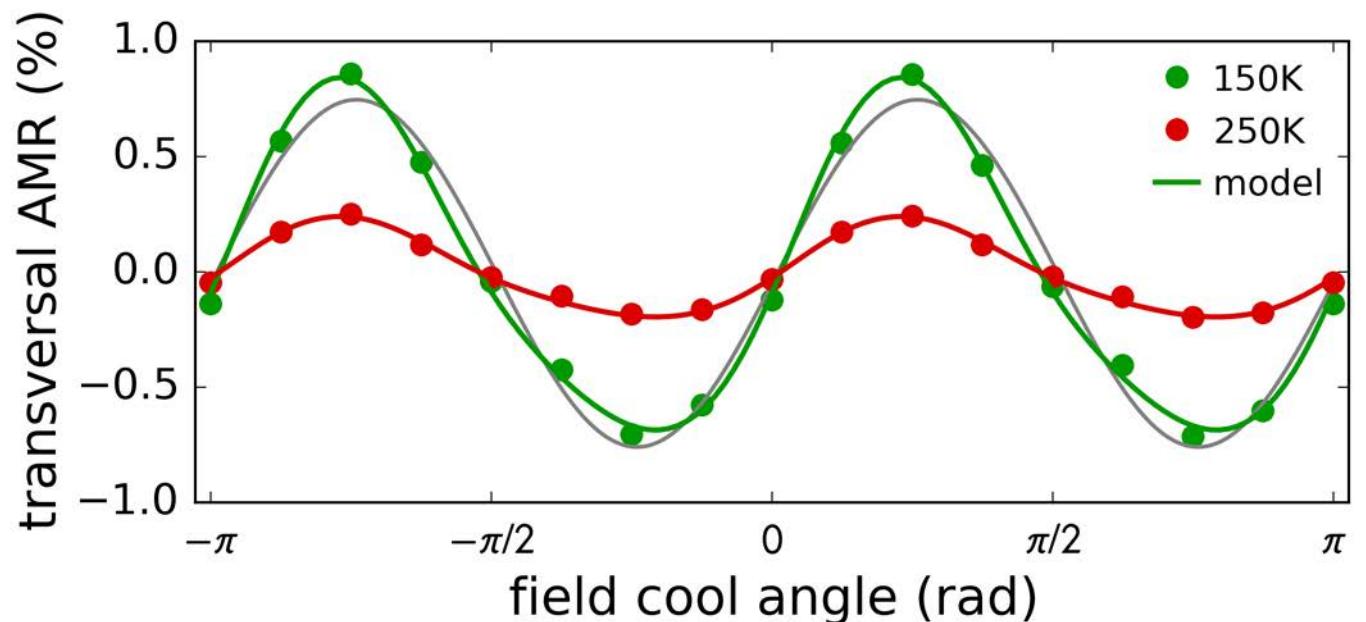
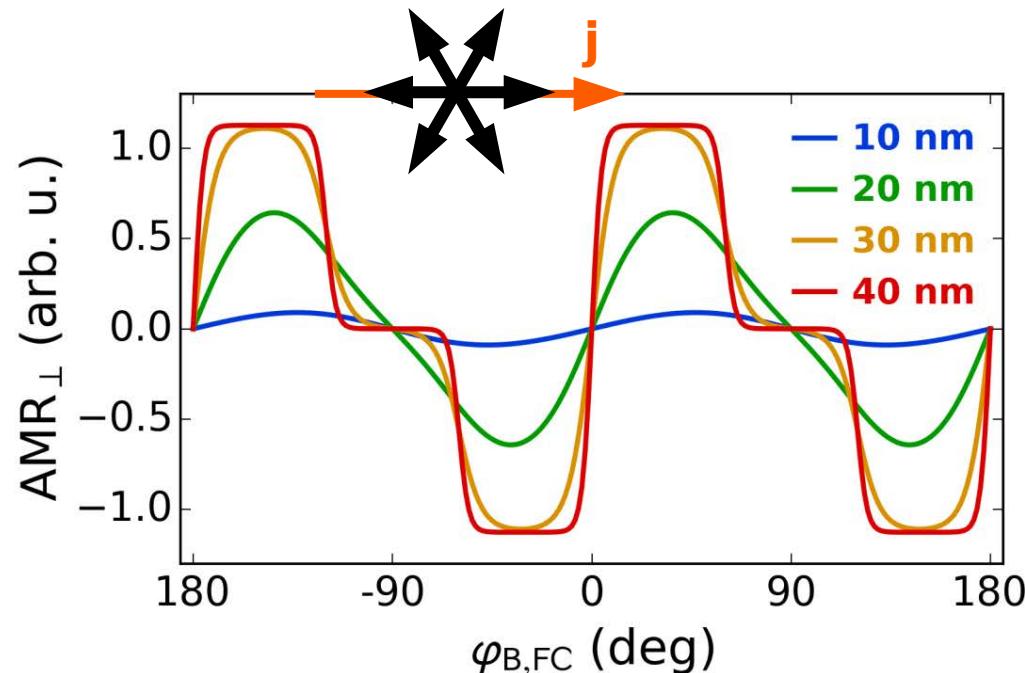
multidomain AFM field rotation

- all three domains populated
- below spin-flop:



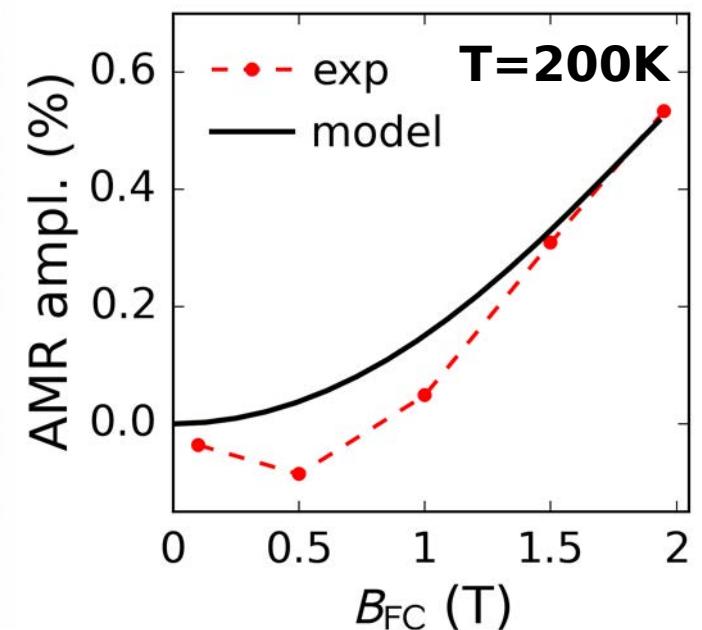
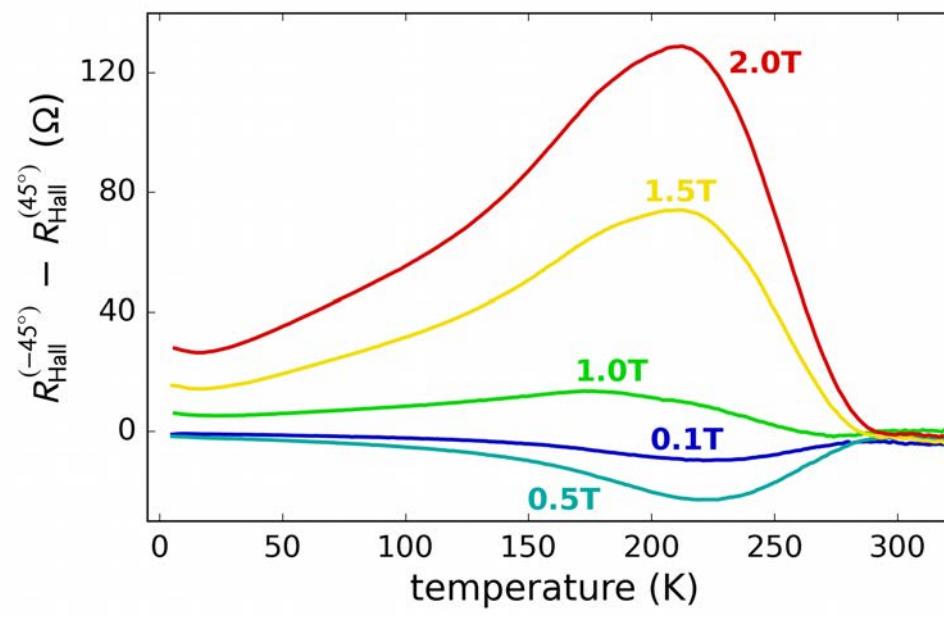
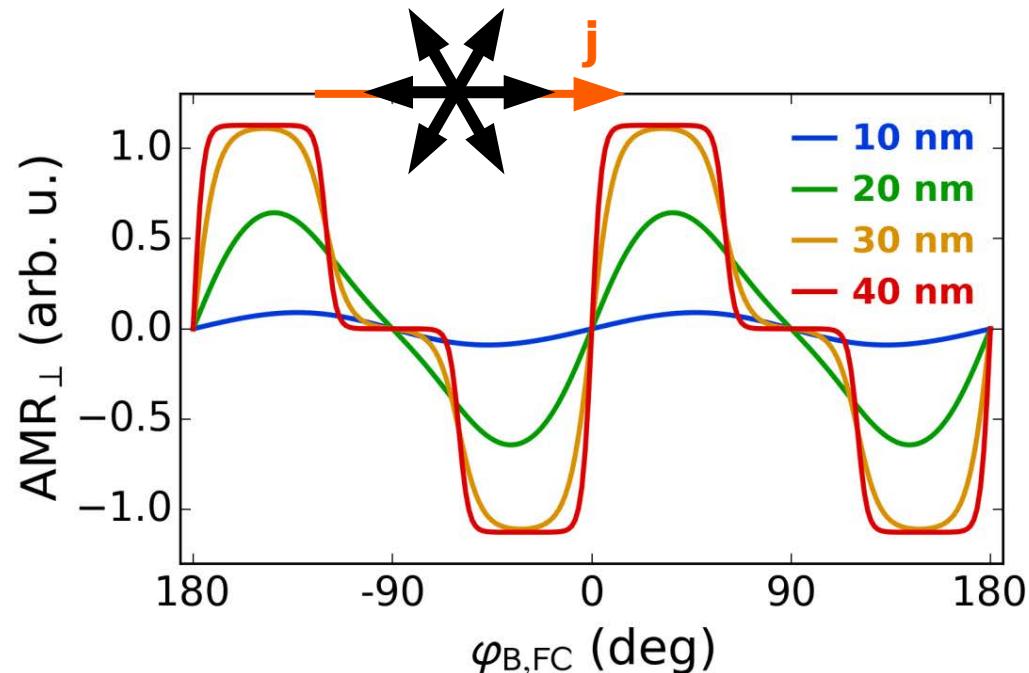
shape of zero-field AMR

- known FC strength
- deduced exchange/anisotropy
- easy axis direction
- fit parameter:
 - AMR ampl.
 - domain size



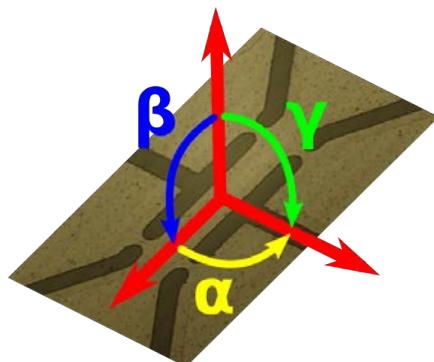
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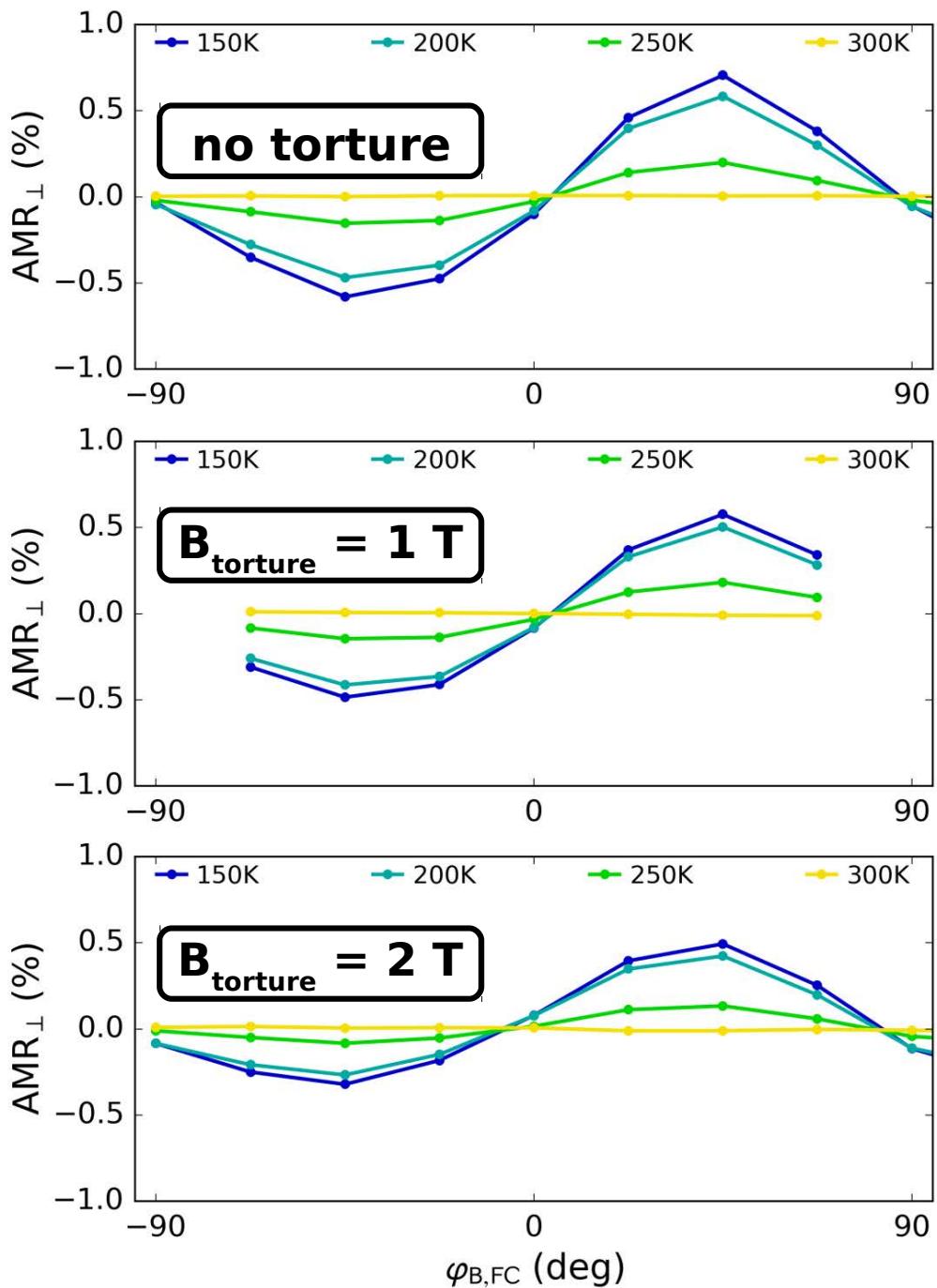


stability of the continuous state

- FC in 2T
in various directions
- torture by field rotations

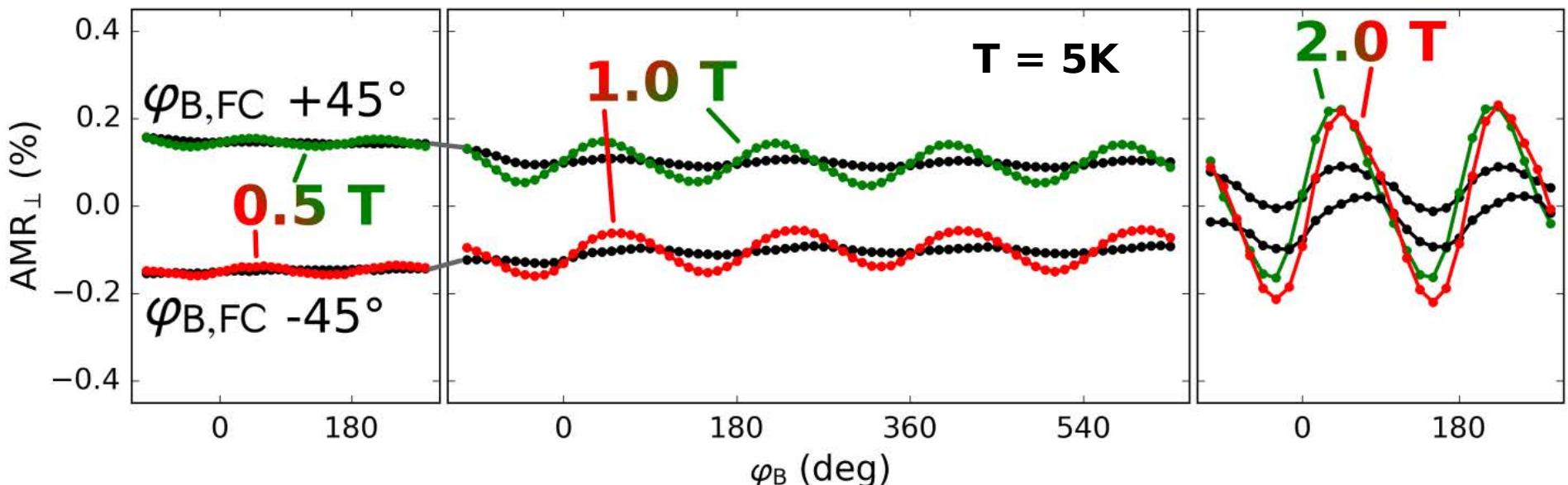
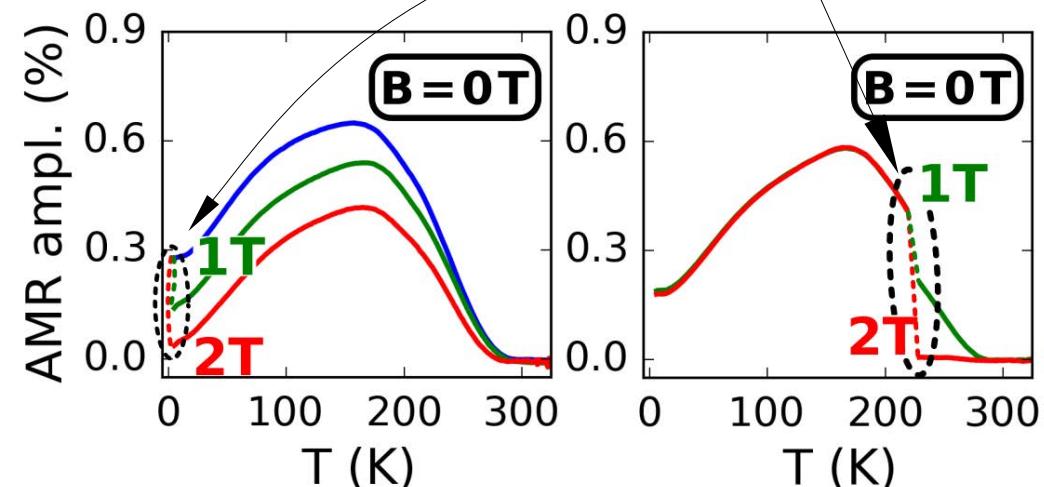
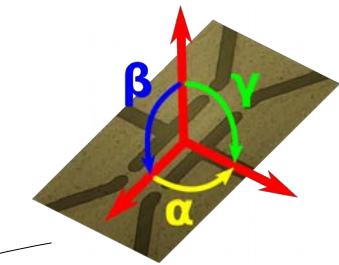


- measure zero field AMR
while heating



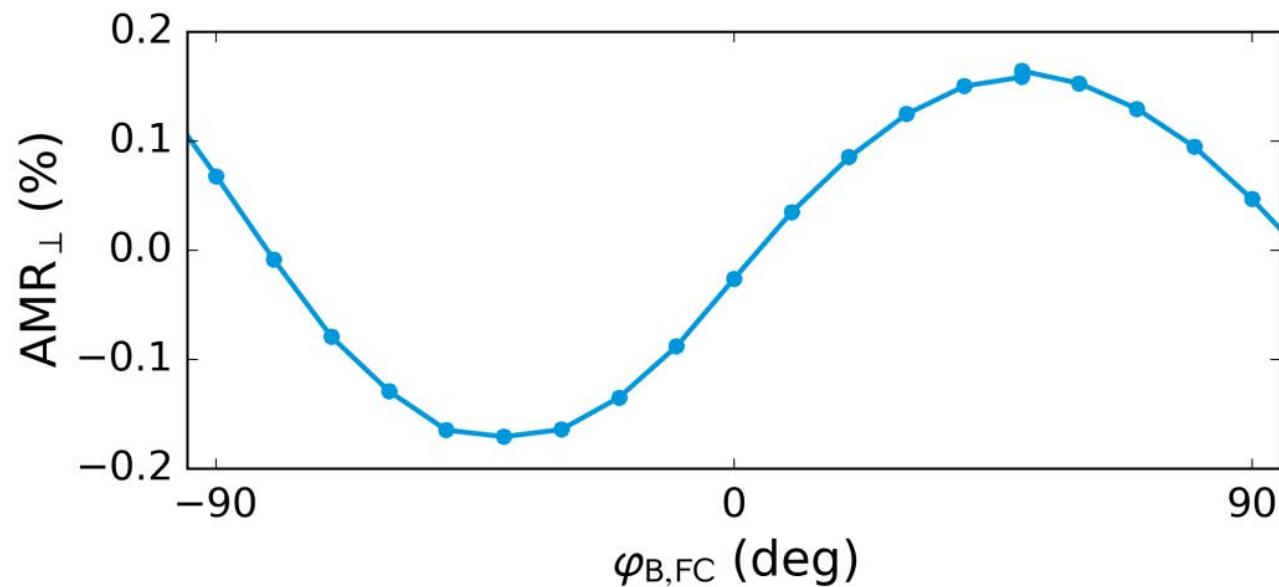
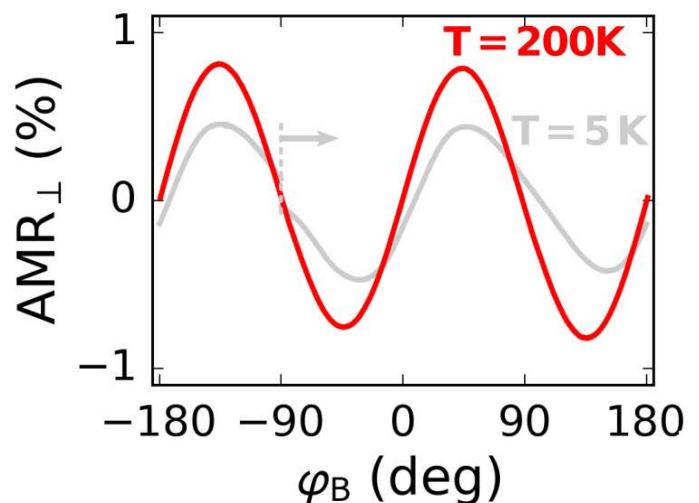
stability of the memory

- AMR splitting can not be removed at 5K (with 2T)
- **@200K: 2 T destroys memory**
- memory states stay distinct also in applied fields (<2T)



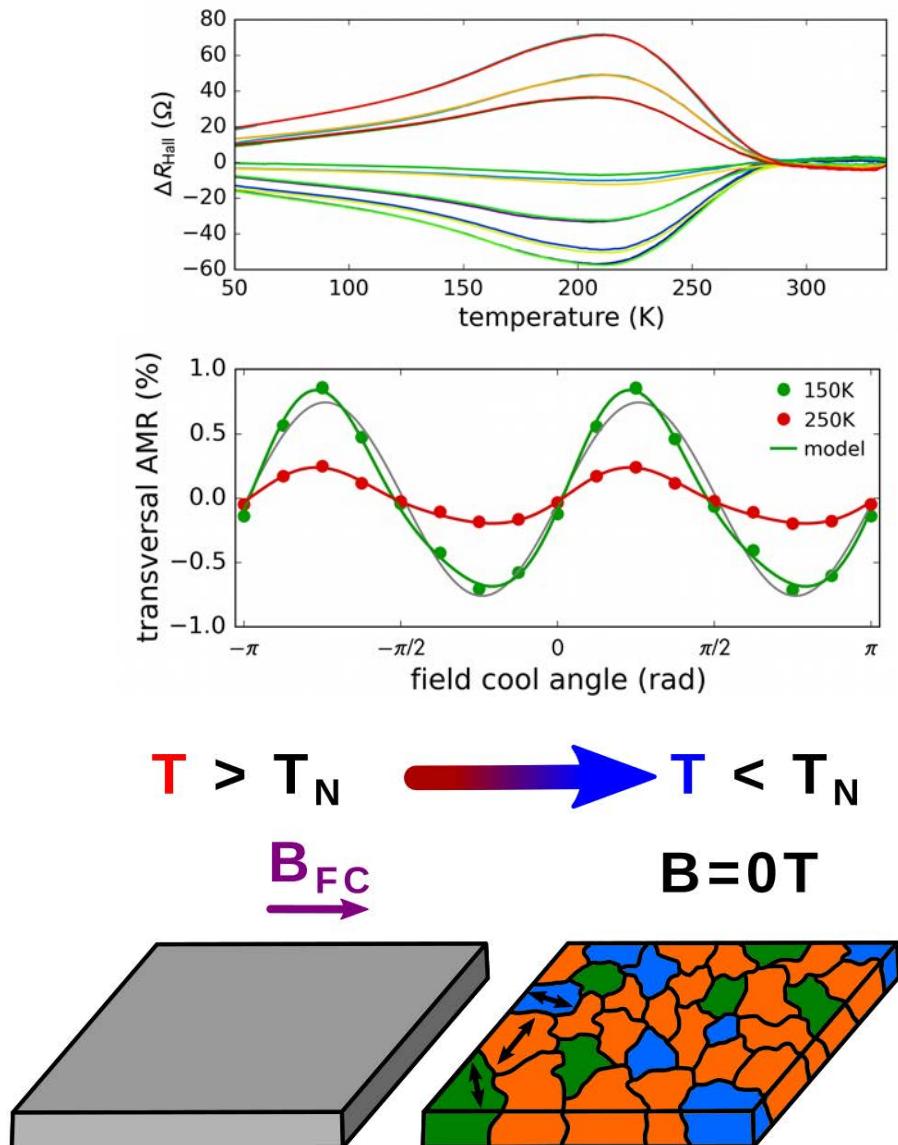
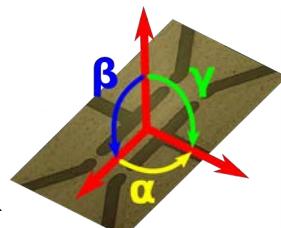
isothermal field writing

- $T=200\text{K}$
- apply field in certain direction ($2T$)
- remove field
- measure R_{XY}



summary

- antiferromagnetic semiconductor MnTe
 - band gap 1.46eV
 - p-type: $\rho=1.8\times 10^{-4} \Omega\text{m}$, $p \sim 6\times 10^{18} \text{ cm}^{-3}$
- AMR in AFM above spin-flop field
- splitting of states upon field cooling
 - FC in Y gives low R_{xx} state
- multiple stability in zero field
 - continuous zero field AMR
 - **0.65%@150K**
- stability of the frozen state
 - “undestructable” at 5K
 - destroyed above spin-flop field



thanks for your attention



Kamil Olejnik
Karel Vyborny
Helena Reichlova
Vit Novak
Xavier Marti
Tomas Jungwirth



Vaclav Holy
Vit Saidl
Petr Nemec



Valentine V. Volobuev
Gunther Springholz

CAMBRIDGE

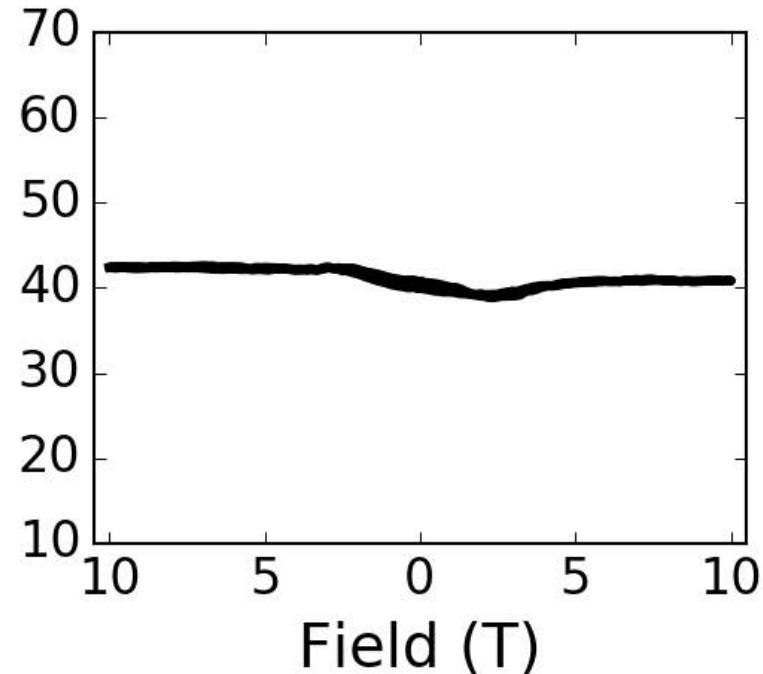
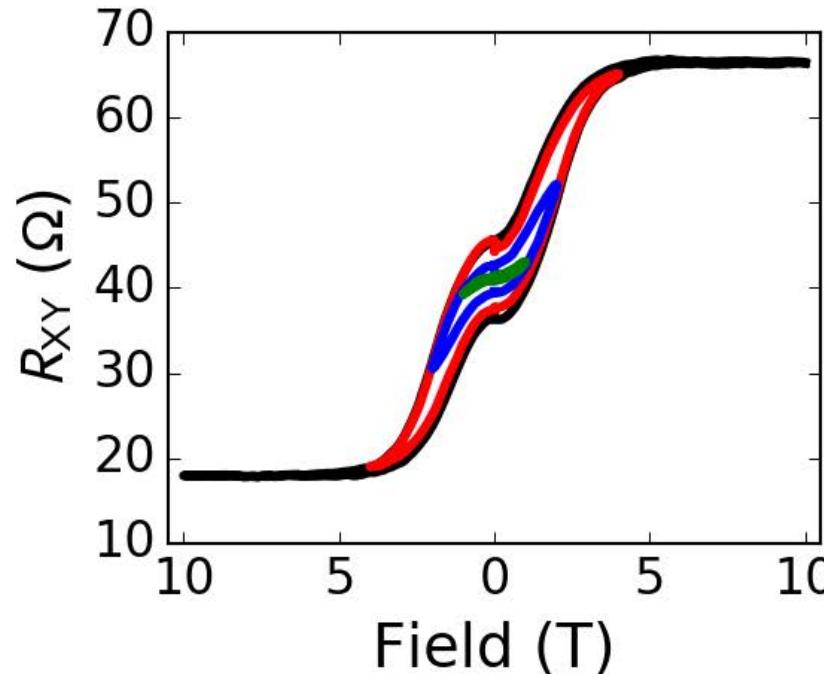
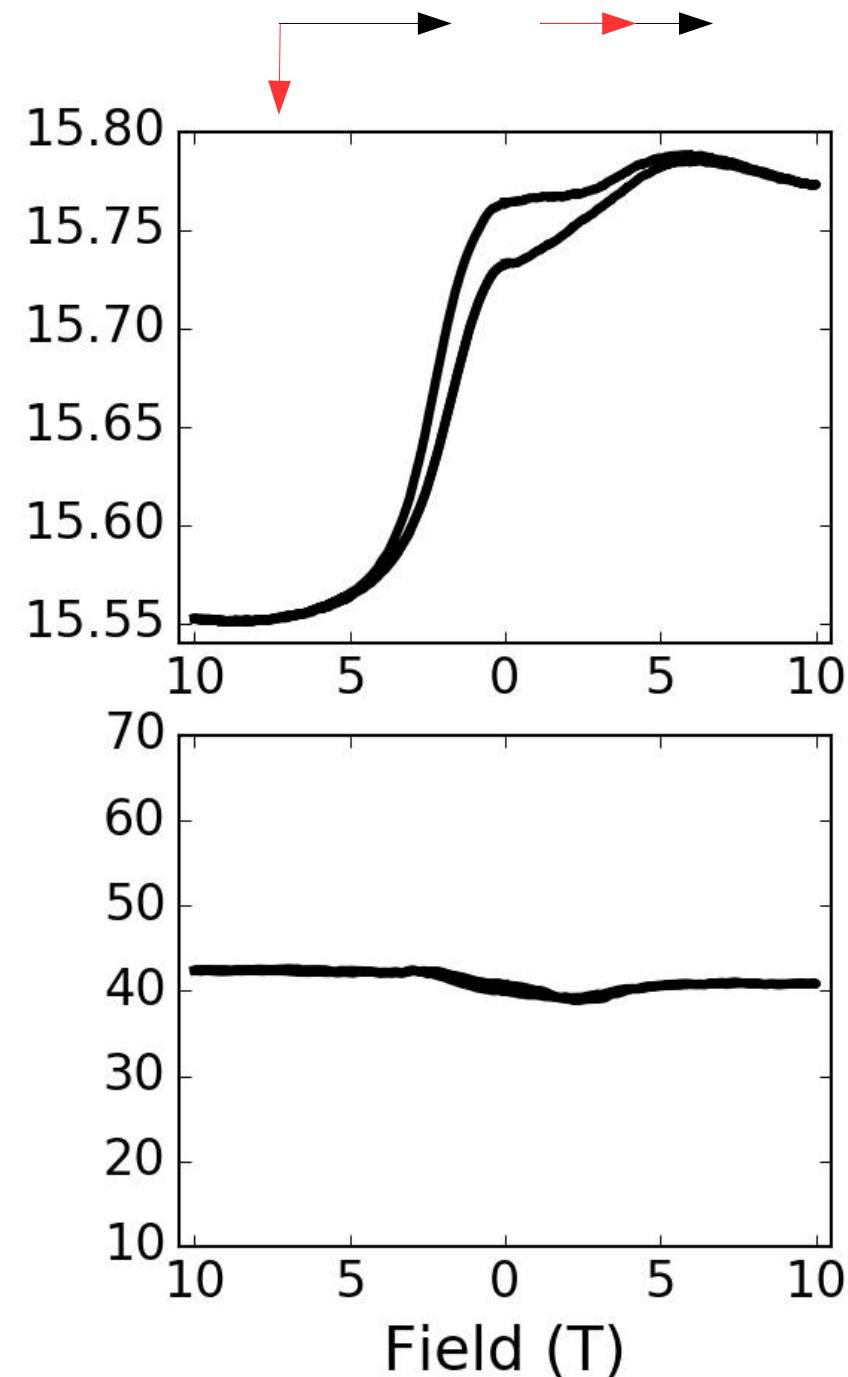
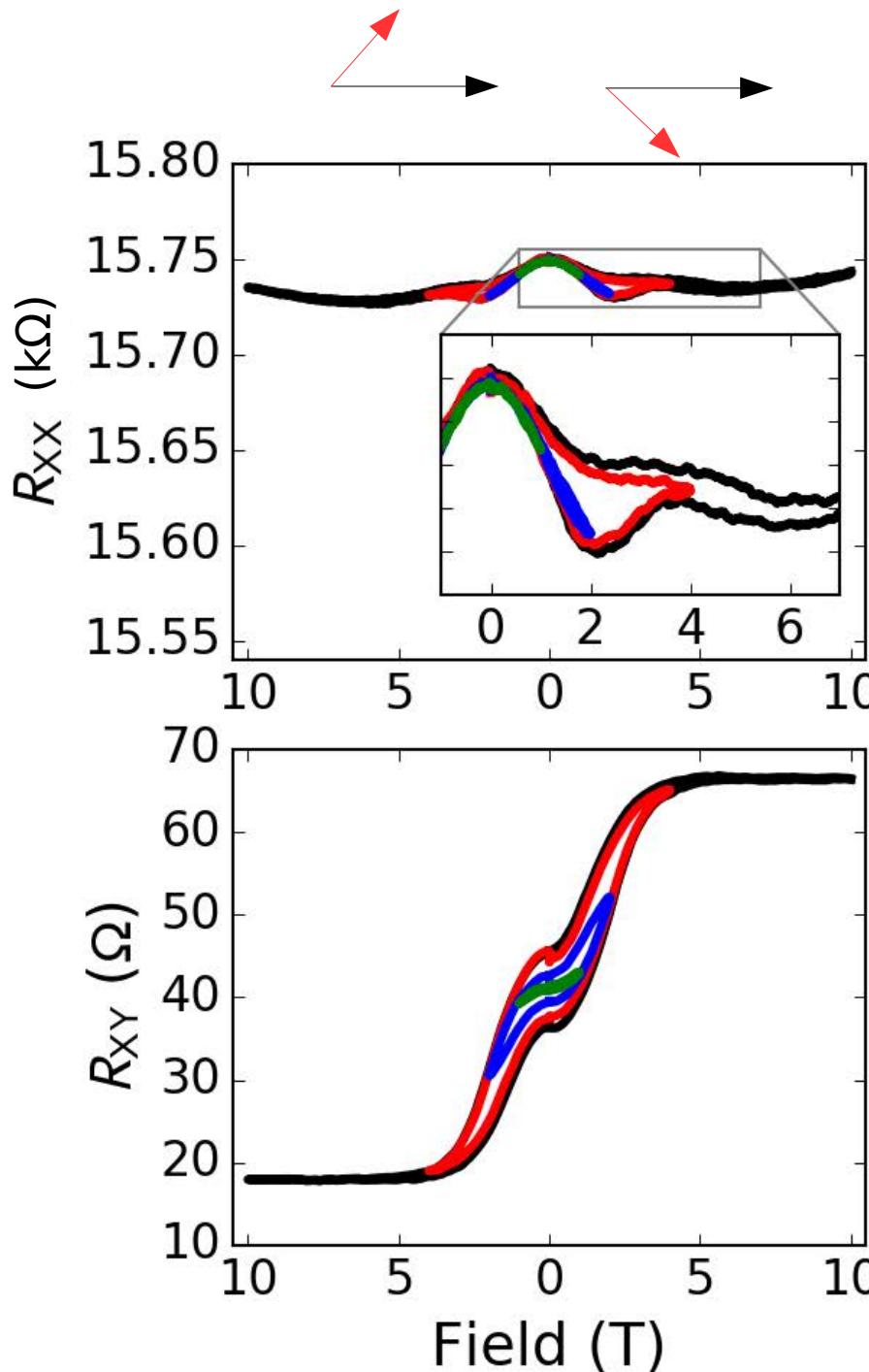
HITACHI

Thomas Wagner
Sylvain Martin
Joerg Wunderlich

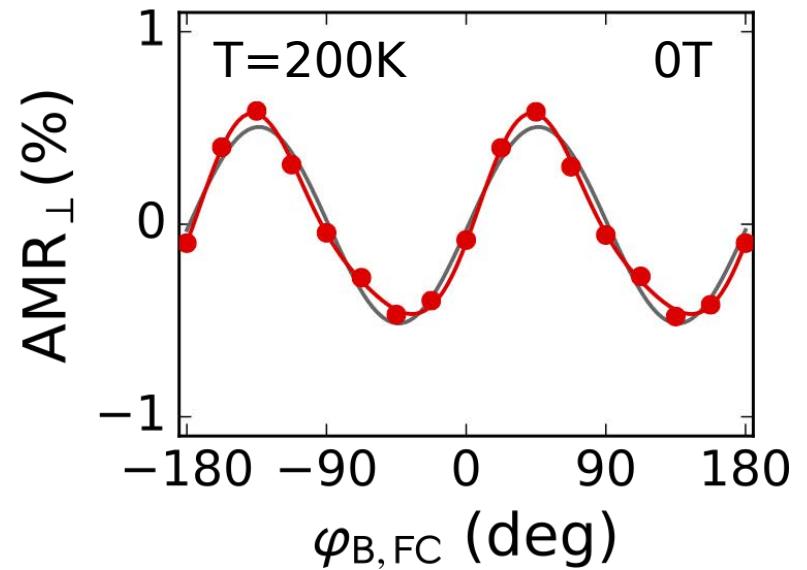
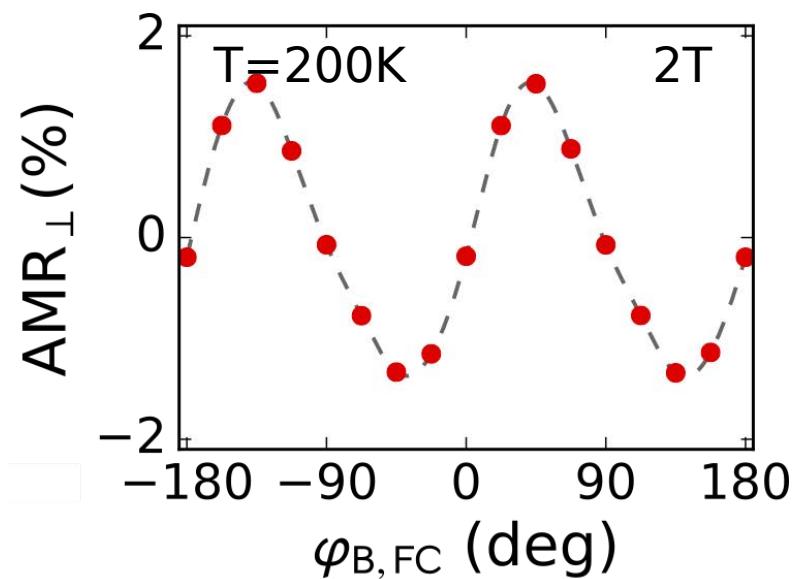
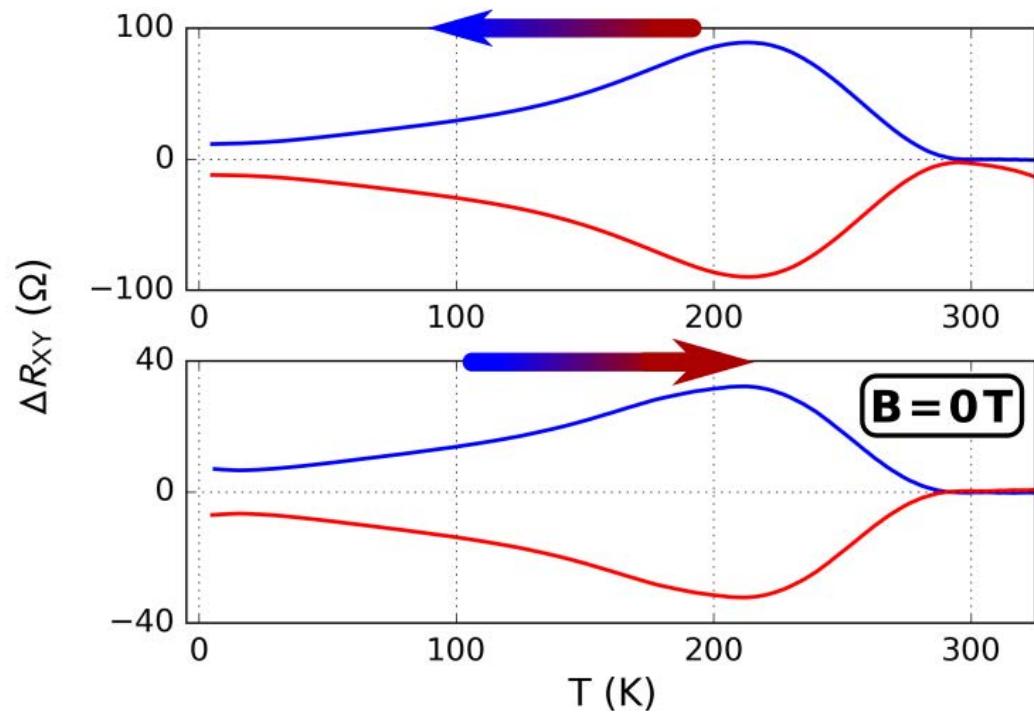


Jaume Gazquez

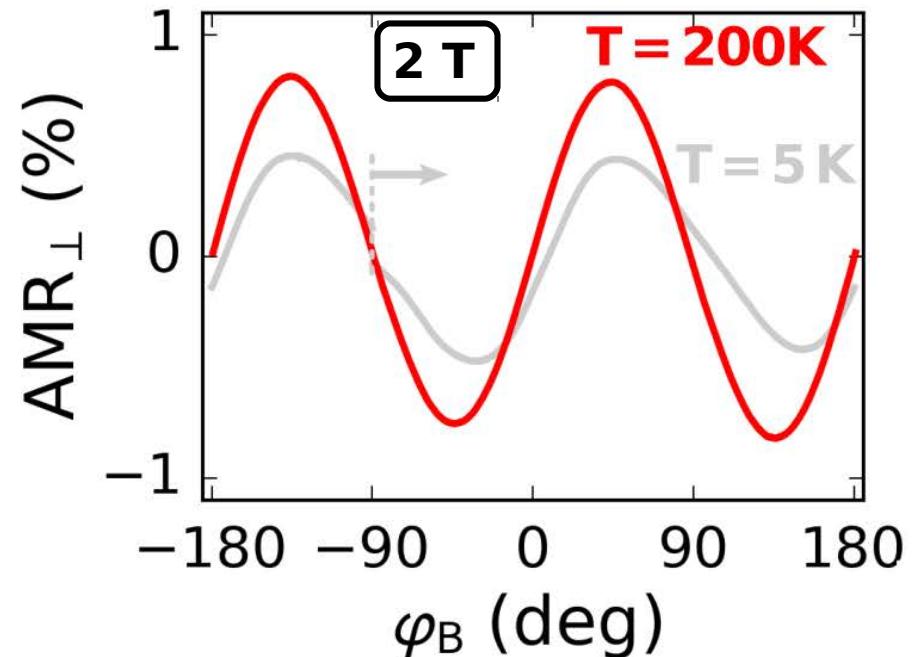
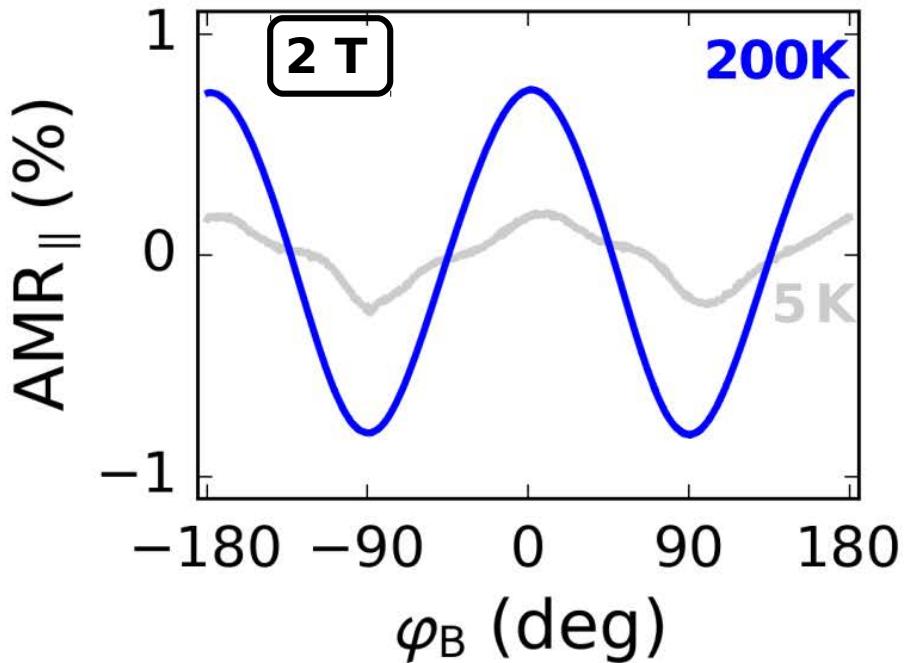
hysteresis in AFM



field cooling vs. zero field heating

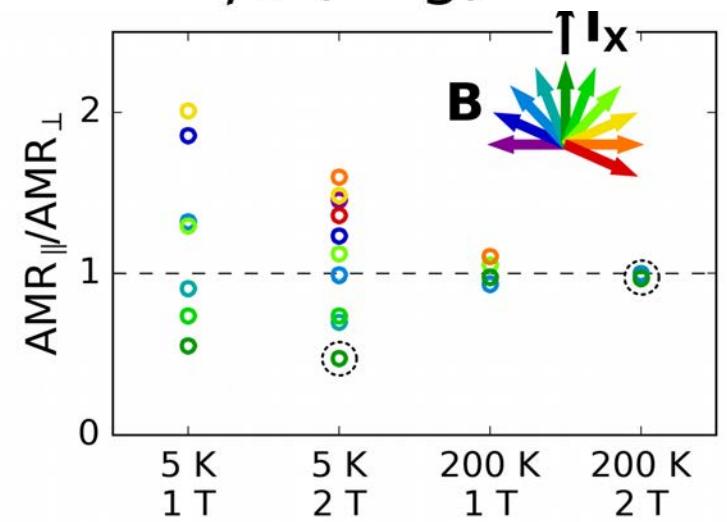


AMR-ratio vs. field & temperature

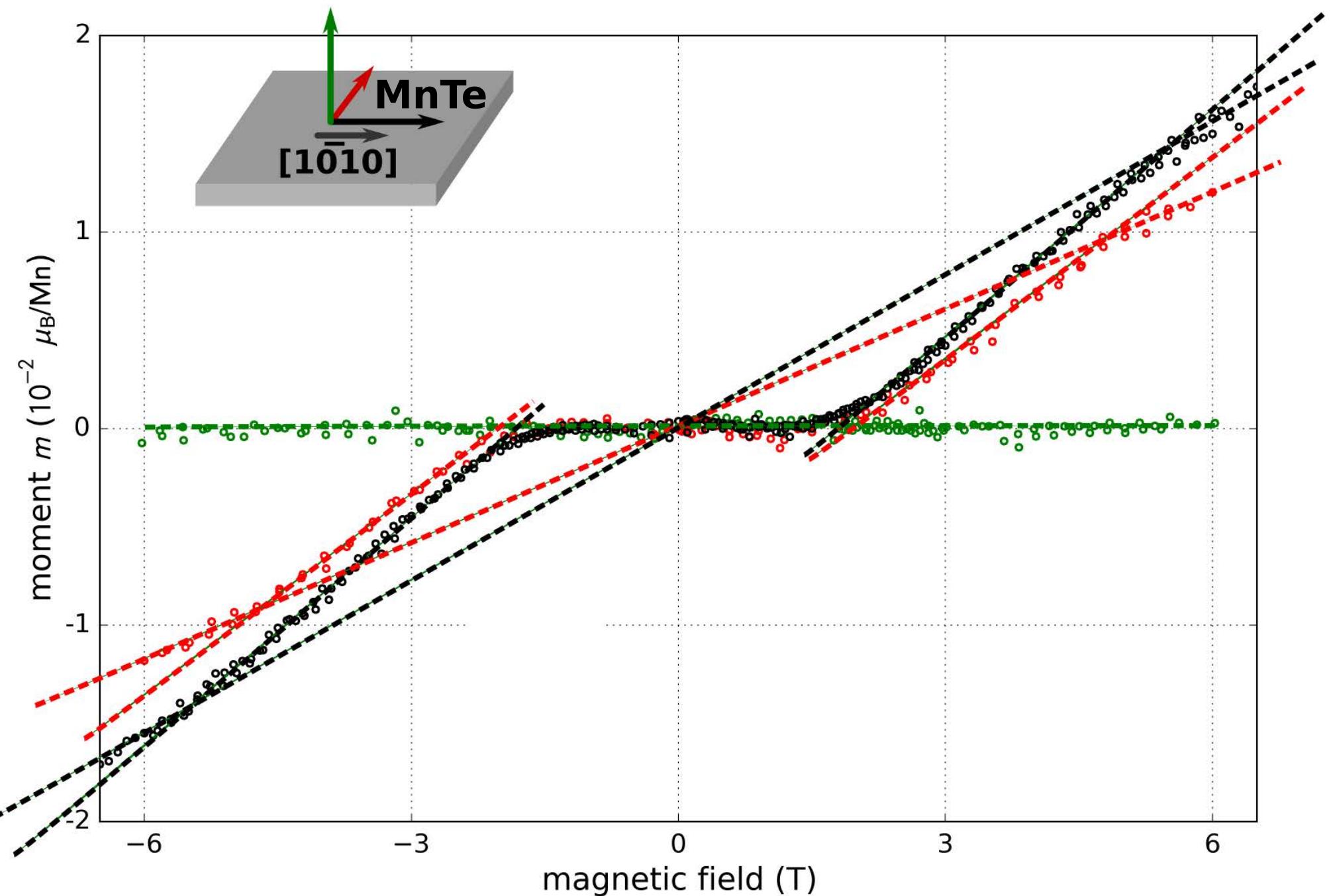


$$\text{AMR}_{\parallel}(\varphi_B) \equiv \frac{R_{XX}(\varphi_B) - \langle R_{XX} \rangle}{\langle R_{XX} \rangle}$$

$$\text{AMR}_{\perp}(\varphi_B) \equiv \frac{R_{XY}(\varphi_B) - \langle R_{XY} \rangle}{\langle R_{XX} \rangle} n$$

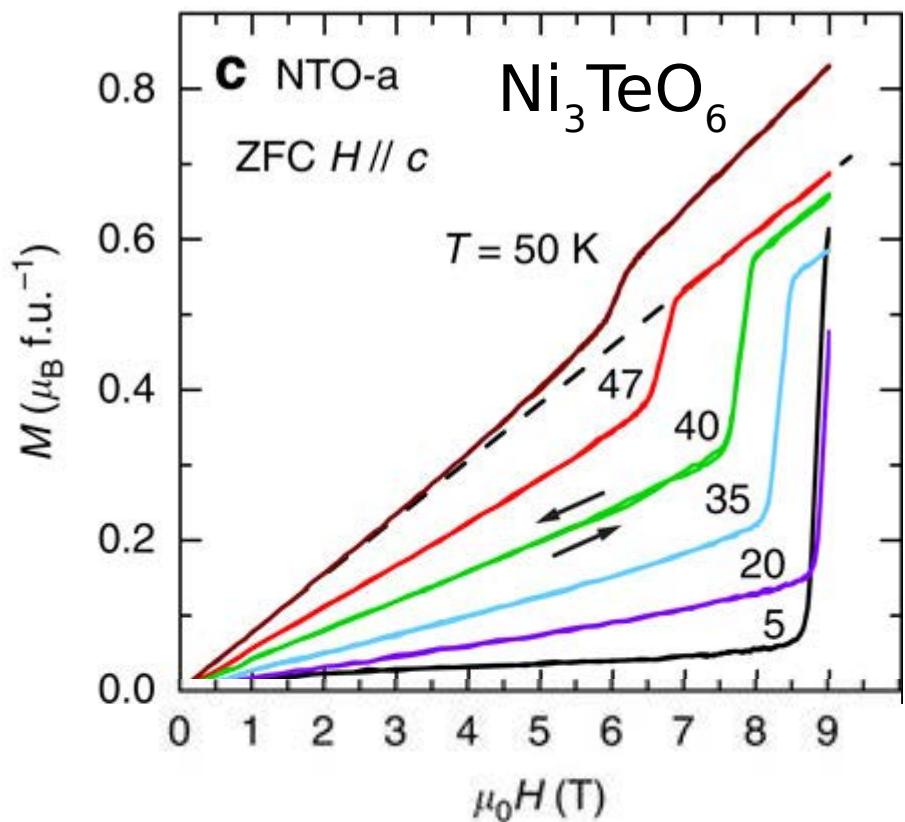


Note about spin-flop

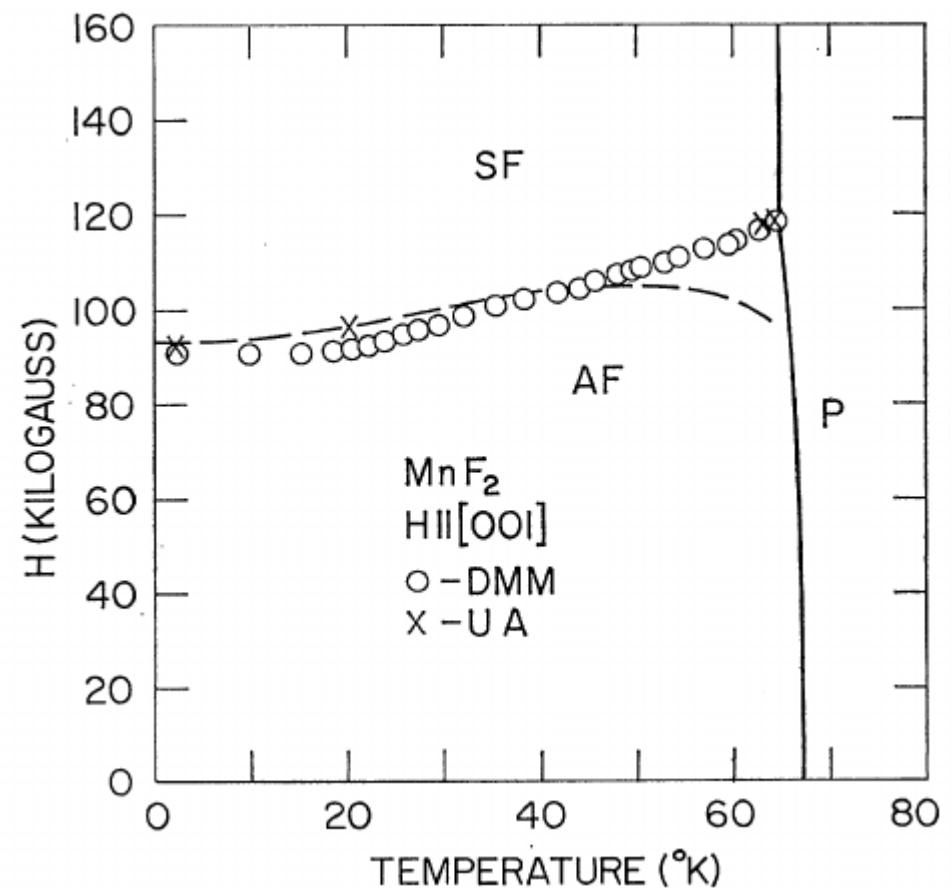


Note about spin-flop field vs. temperature

- temperature behavior complicated → anisotropy, magnetic moments



Yoon Seok Oh, et al. Nat Comm 5, 3201 (2014)

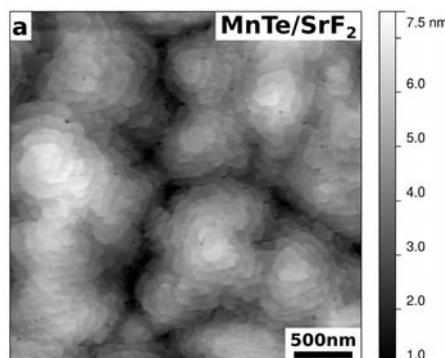


Y. Shapira and S. Foner, PRB 1, 3083 (1970)

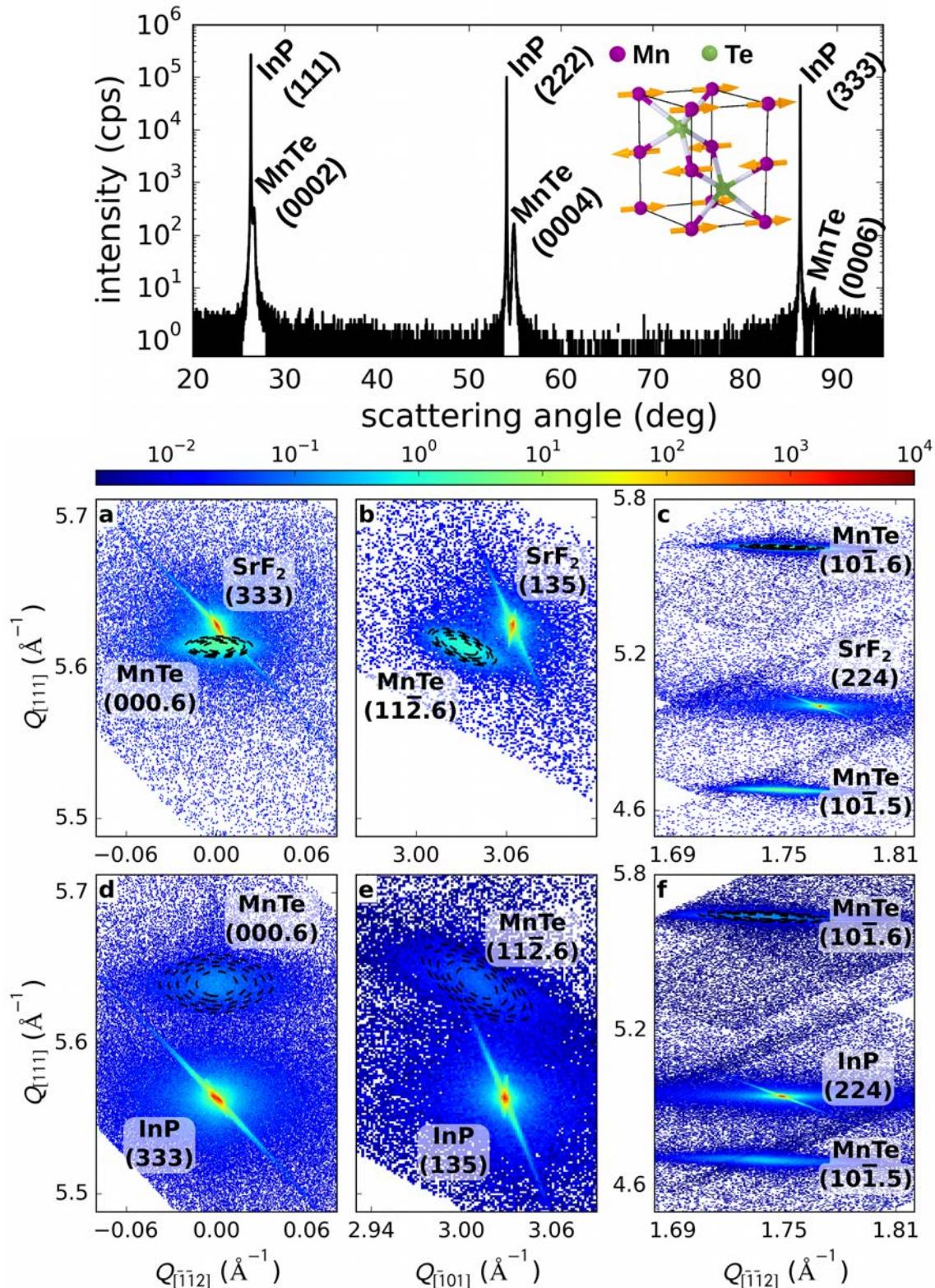
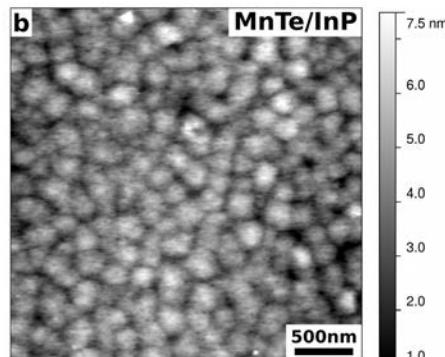
structural analysis

MnTe grows as mosaic thin film
block size ~20-30nm
rotation of domains:
Gaussian distribution
~0.2-0.3degree

200nm

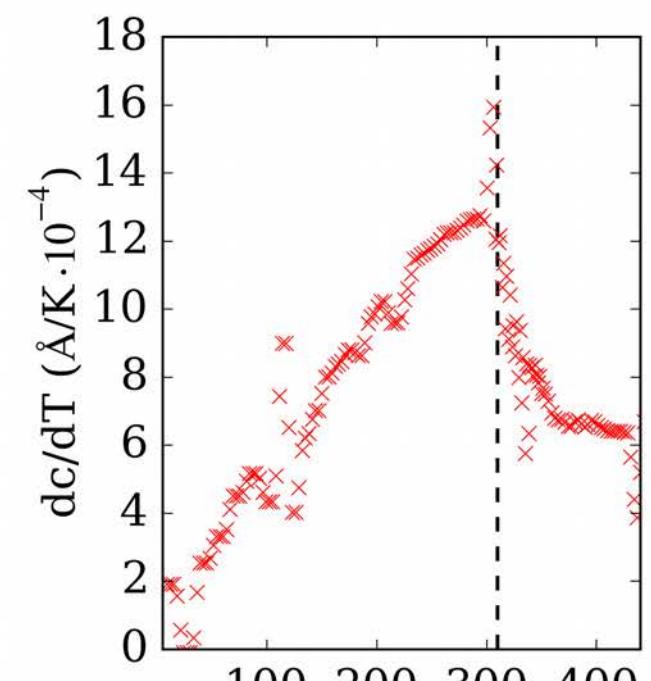
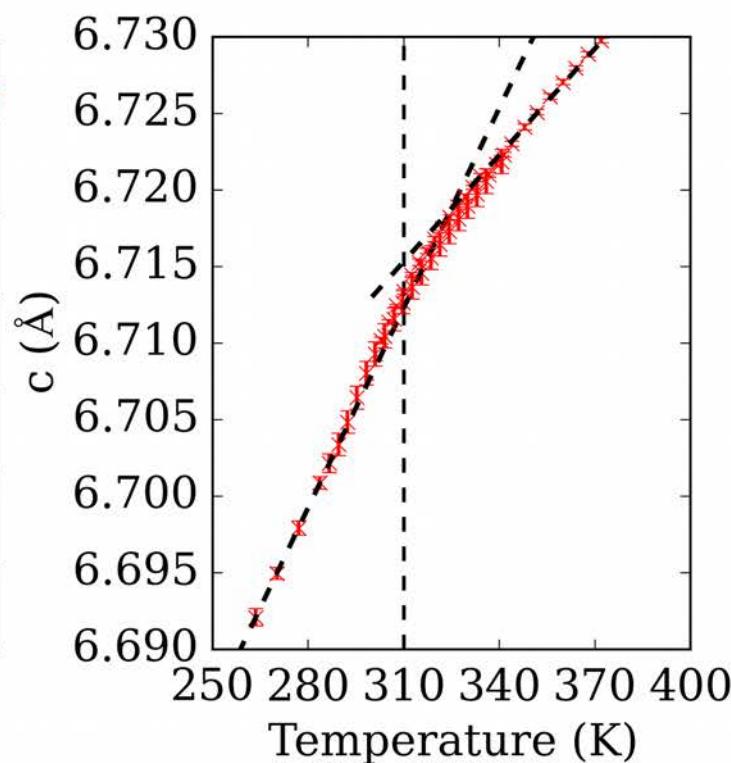
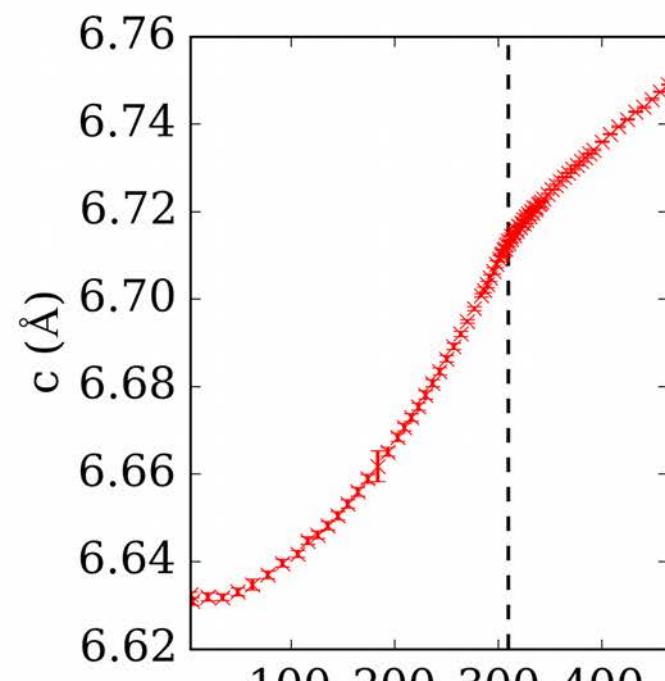
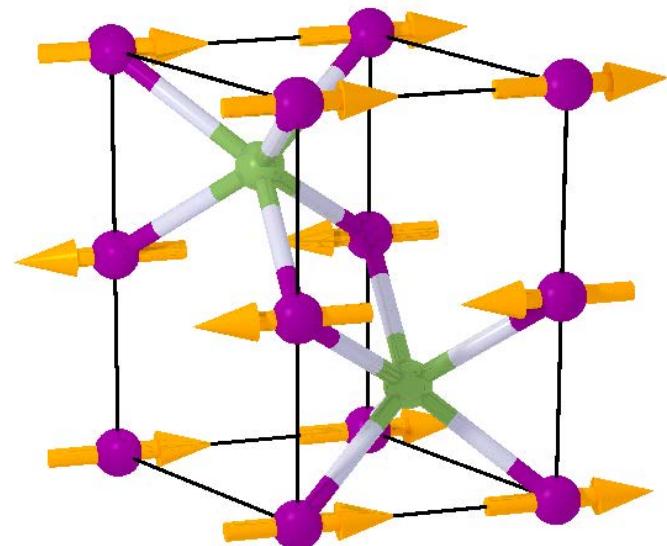


50nm



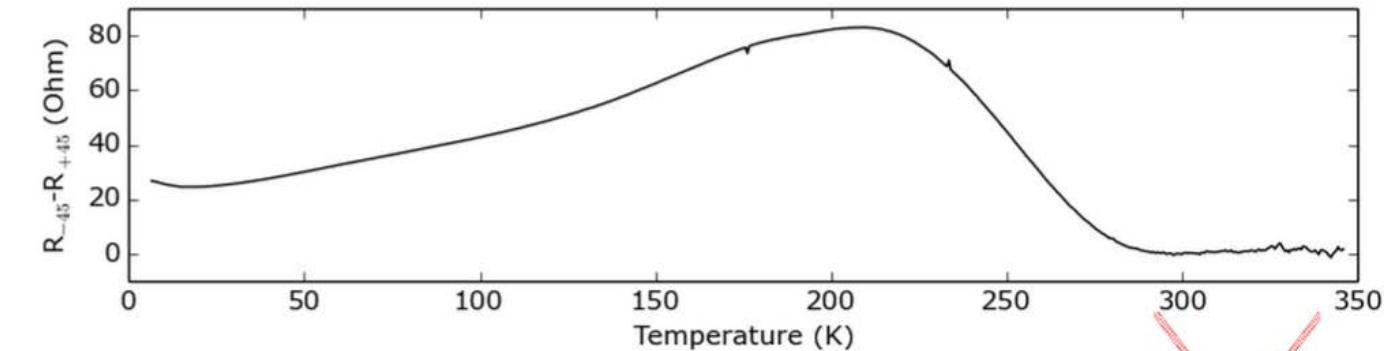
lattice parameter vs. temperature

- thermal expansion of distance of AFM stacked FM-ordered atomic planes is changing at T_N

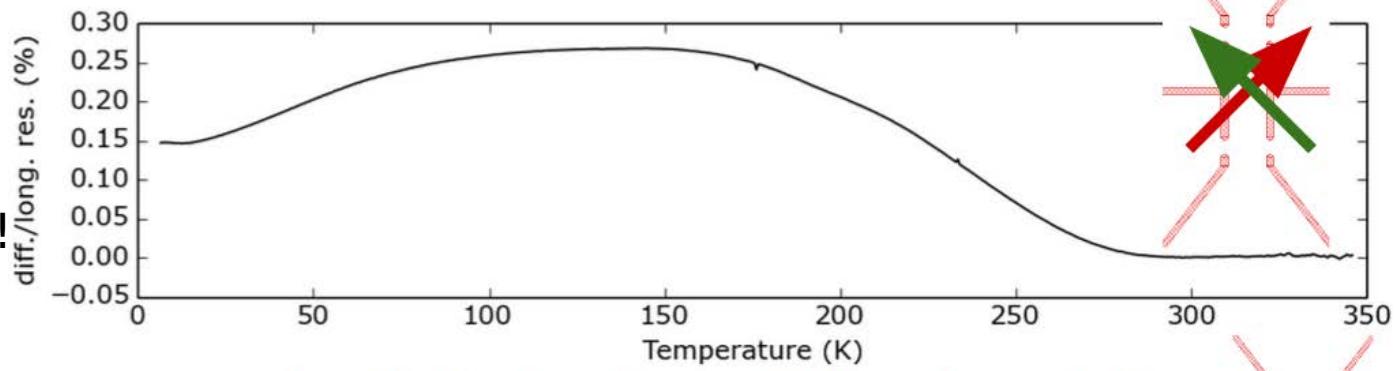


comparison longitudinal/transversal

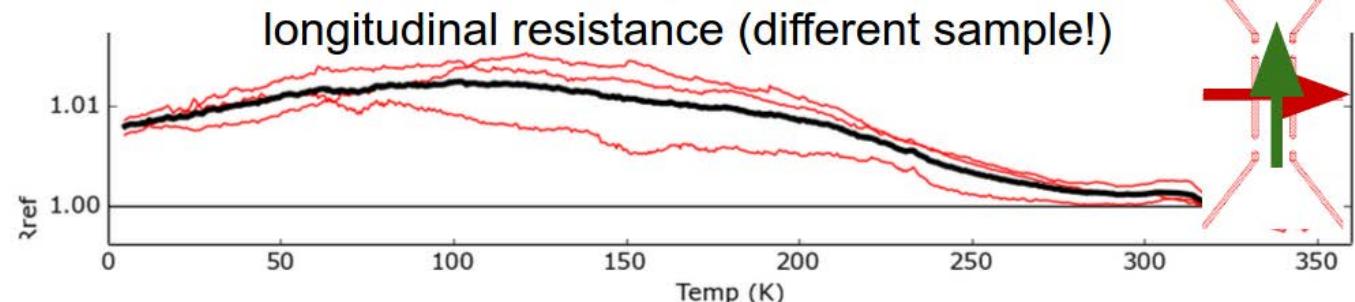
difference from Hall:



normalized by R_{xx} :
no aspect ratio considered!



difference of R_{xx} FC cycles:



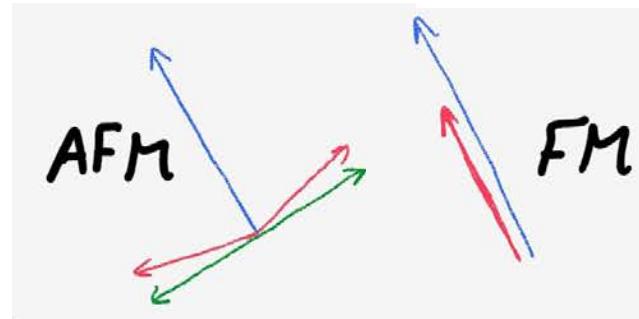
ingredients for a continuous state at *zero field*

— B
— L
— M
— easy axis

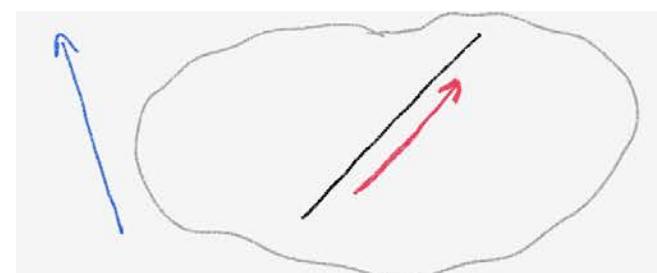
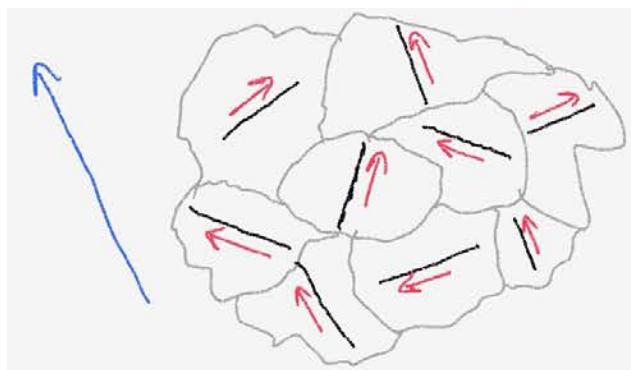
polycrystal

single crystal

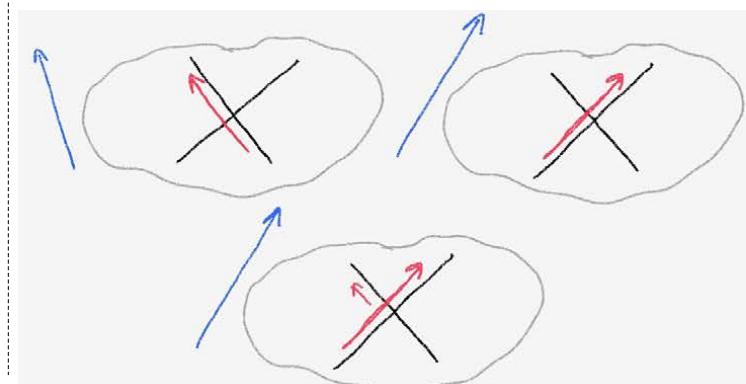
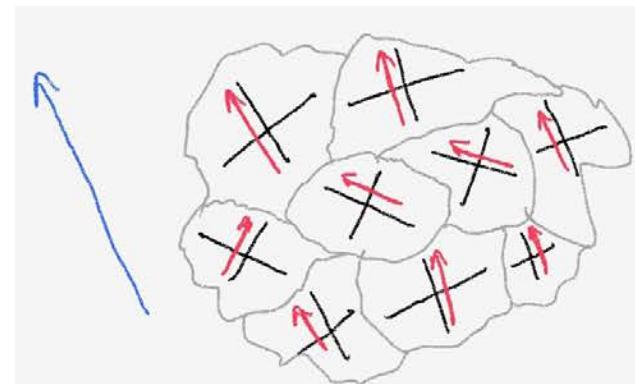
isotropic



uniaxial FM



biaxial FM



ingredients for a continuous state at zero field

continuous zero field AMR needs breaking into multiple magnetic domains upon the release of the field and at least biaxial anisotropy!

polycrystal



 B

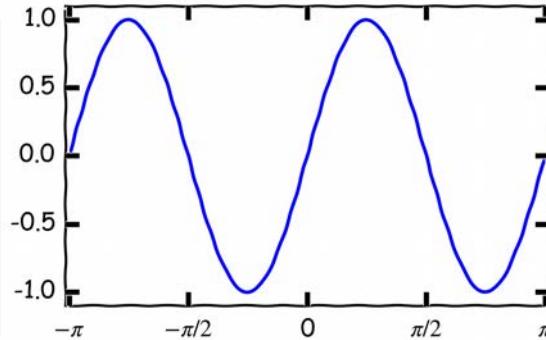
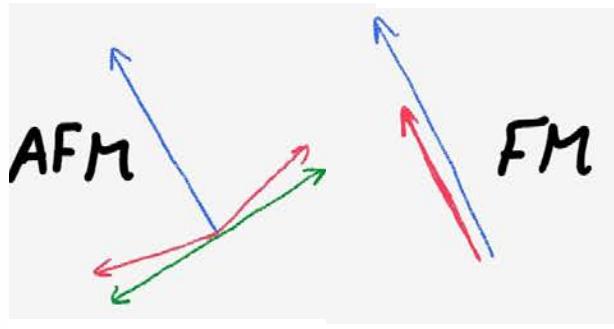
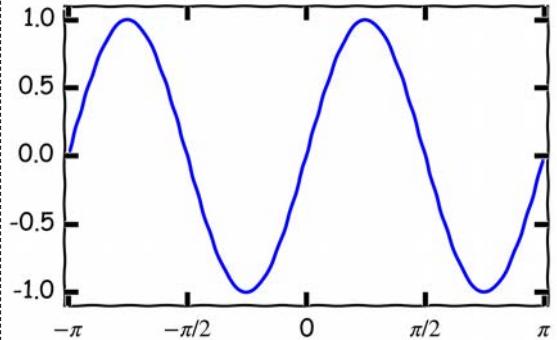
 L

 M

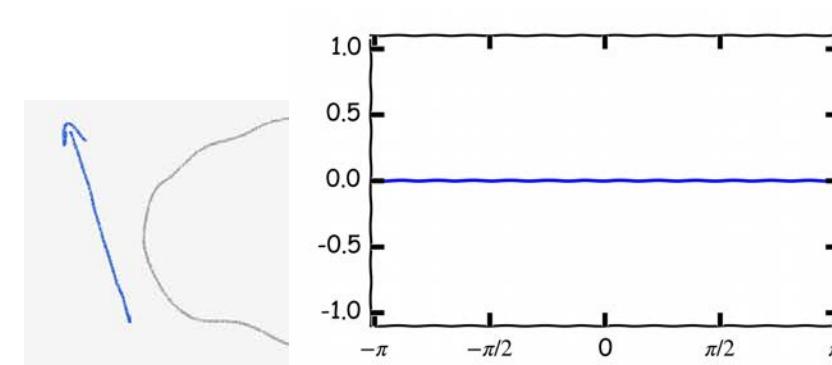
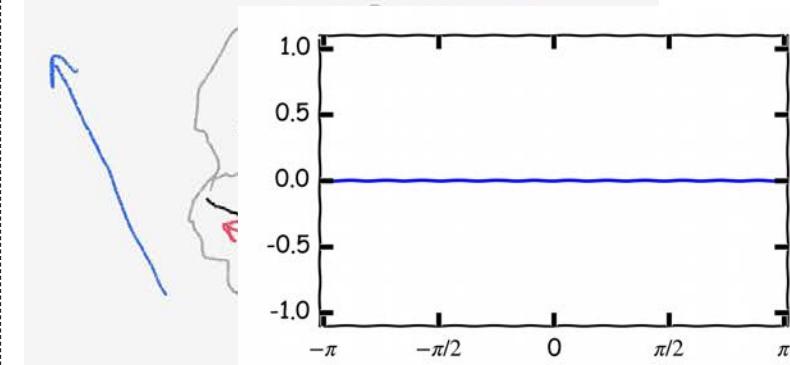
 easy axis

single crystal

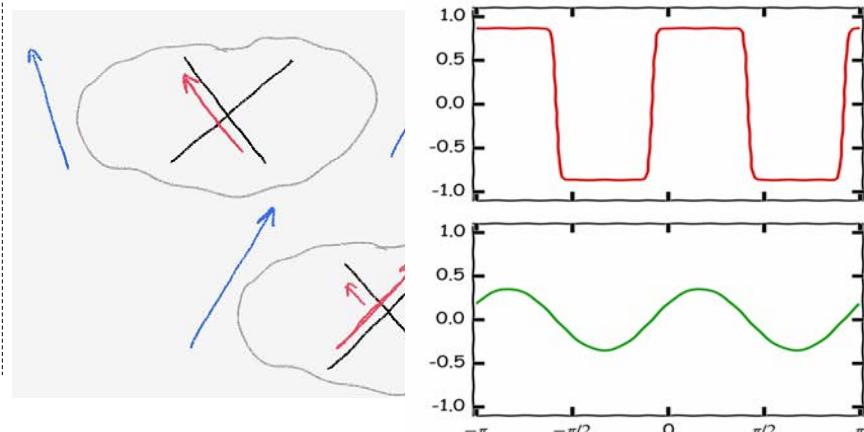
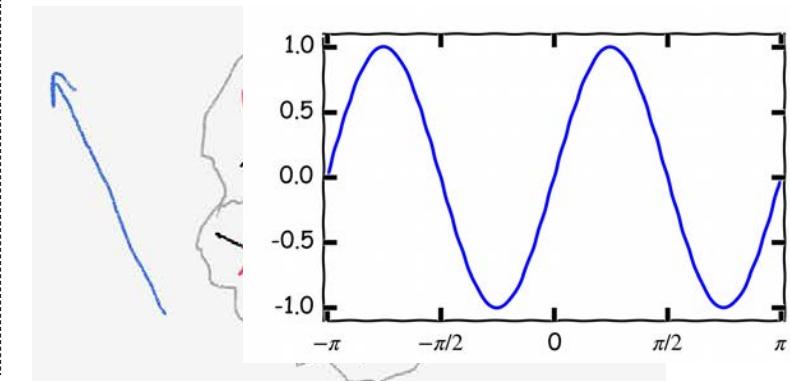
isotropic



uniaxial FM



biaxial FM



spin flop in SQUID

- for inplane field we find a kink in SQUID at $\sim 2\text{T}$
- similar kink found in longitudinal R
- spin flop field decreases at higher temp

