Tunable magnetic properties in Heusler materials

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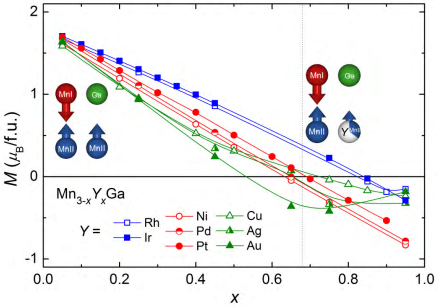
INTERNATIONAL CENTER FOR NANO-SYSTEMS

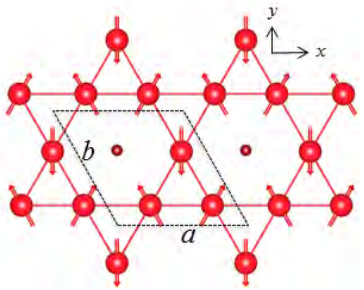
NANO-SYSTEMS FROM IONS, SPINS AND ELECTRONS

Plan of talk

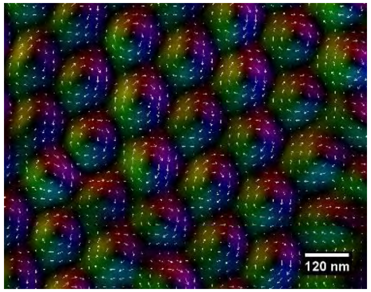
- A short introduction to Heusler materials
- Compensated ferrimagnets and giant exchange bias



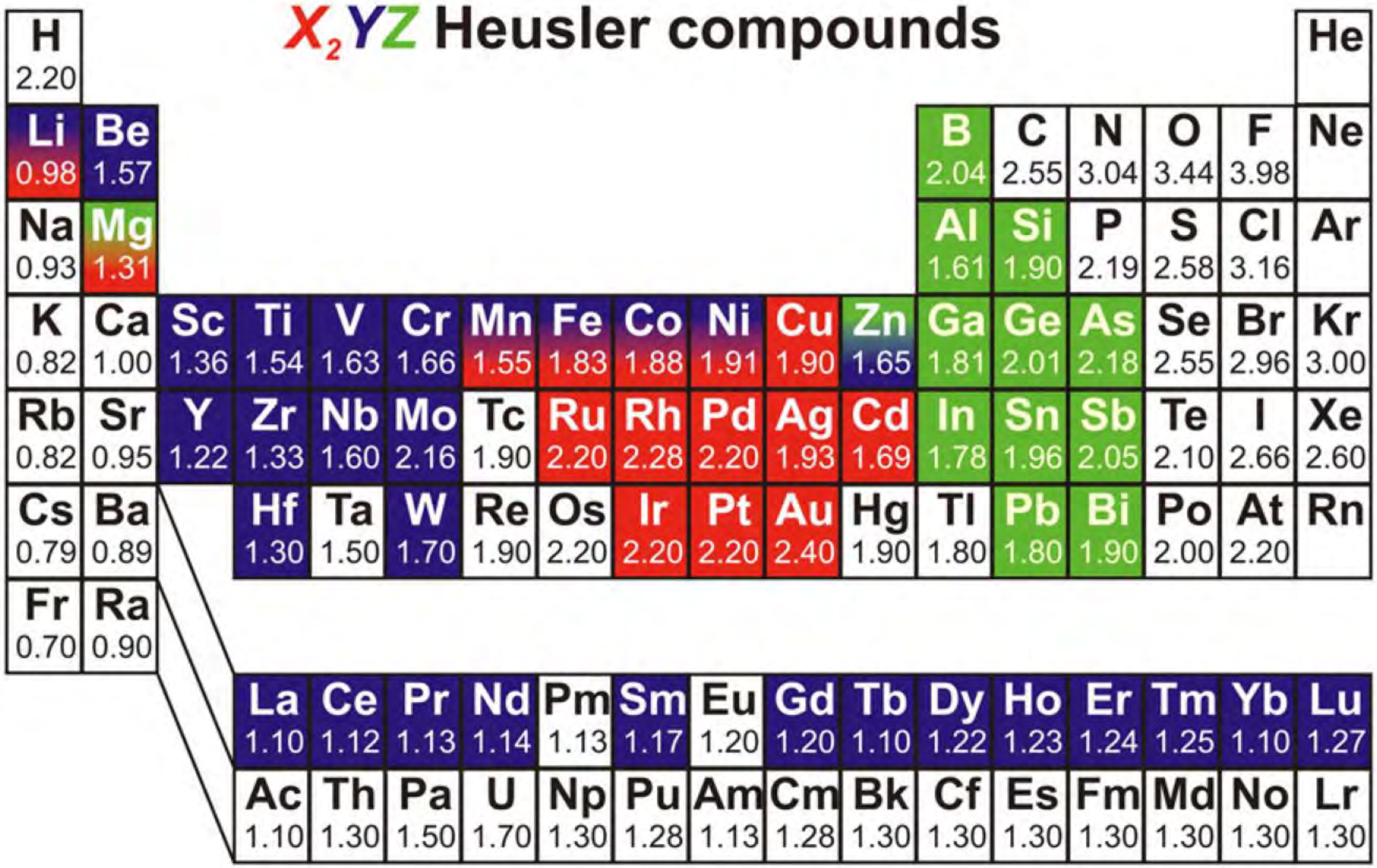
- Anomalous Hall effect in non-collinear antiferromagnets



- Non collinear spin structure and skyrmions in Heuslers



What is Heusler materials: X_2YZ

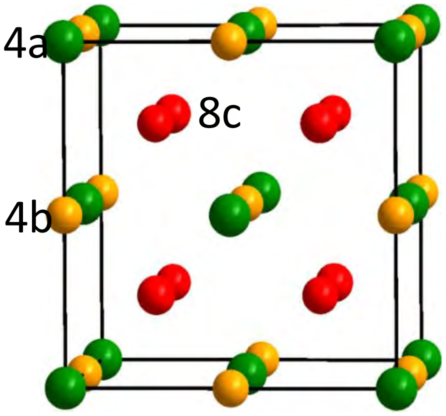


X_2YZ Heusler compounds

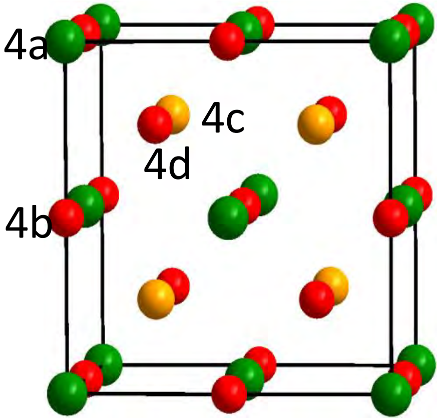
H 2.20																	He
Li 0.98	Be 1.57											B 2.04	C 2.55	N 3.04	O 3.44	F 3.98	Ne
Na 0.93	Mg 1.31											Al 1.61	Si 1.90	P 2.19	S 2.58	Cl 3.16	Ar
K 0.82	Ca 1.00	Sc 1.36	Ti 1.54	V 1.63	Cr 1.66	Mn 1.55	Fe 1.83	Co 1.88	Ni 1.91	Cu 1.90	Zn 1.65	Ga 1.81	Ge 2.01	As 2.18	Se 2.55	Br 2.96	Kr 3.00
Rb 0.82	Sr 0.95	Y 1.22	Zr 1.33	Nb 1.60	Mo 2.16	Tc 1.90	Ru 2.20	Rh 2.28	Pd 2.20	Ag 1.93	Cd 1.69	In 1.78	Sn 1.96	Sb 2.05	Te 2.10	I 2.66	Xe 2.60
Cs 0.79	Ba 0.89		Hf 1.30	Ta 1.50	W 1.70	Re 1.90	Os 2.20	Ir 2.20	Pt 2.20	Au 2.40	Hg 1.90	Tl 1.80	Pb 1.80	Bi 1.90	Po 2.00	At 2.20	Rn
Fr 0.70	Ra 0.90																
			La 1.10	Ce 1.12	Pr 1.13	Nd 1.14	Pm 1.13	Sm 1.17	Eu 1.20	Gd 1.20	Tb 1.10	Dy 1.22	Ho 1.23	Er 1.24	Tm 1.25	Yb 1.10	Lu 1.27
			Ac 1.10	Th 1.30	Pa 1.50	U 1.70	Np 1.30	Pu 1.28	Am 1.13	Cm 1.28	Bk 1.30	Cf 1.30	Es 1.30	Fm 1.30	Md 1.30	No 1.30	Lr 1.30

Structure:X$_2$YZ

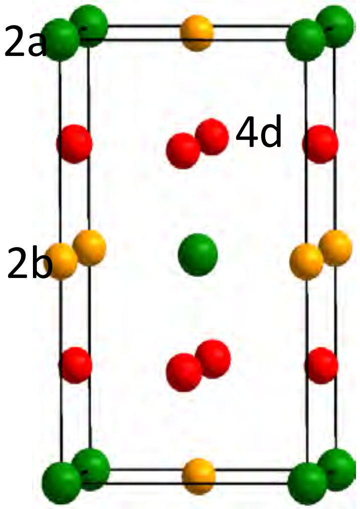
Designing magnetic properties from flexible structure:



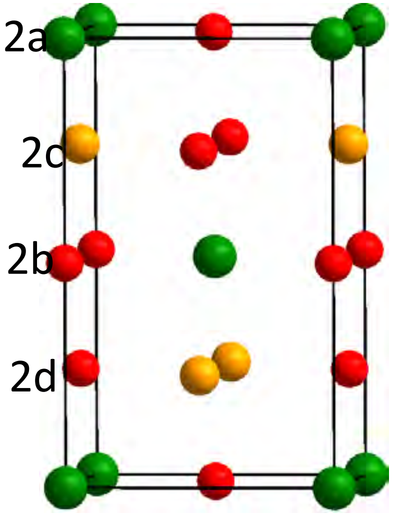
Fm-3*m*, centrosymmetric



F-43*m*, noncentrosymmetric

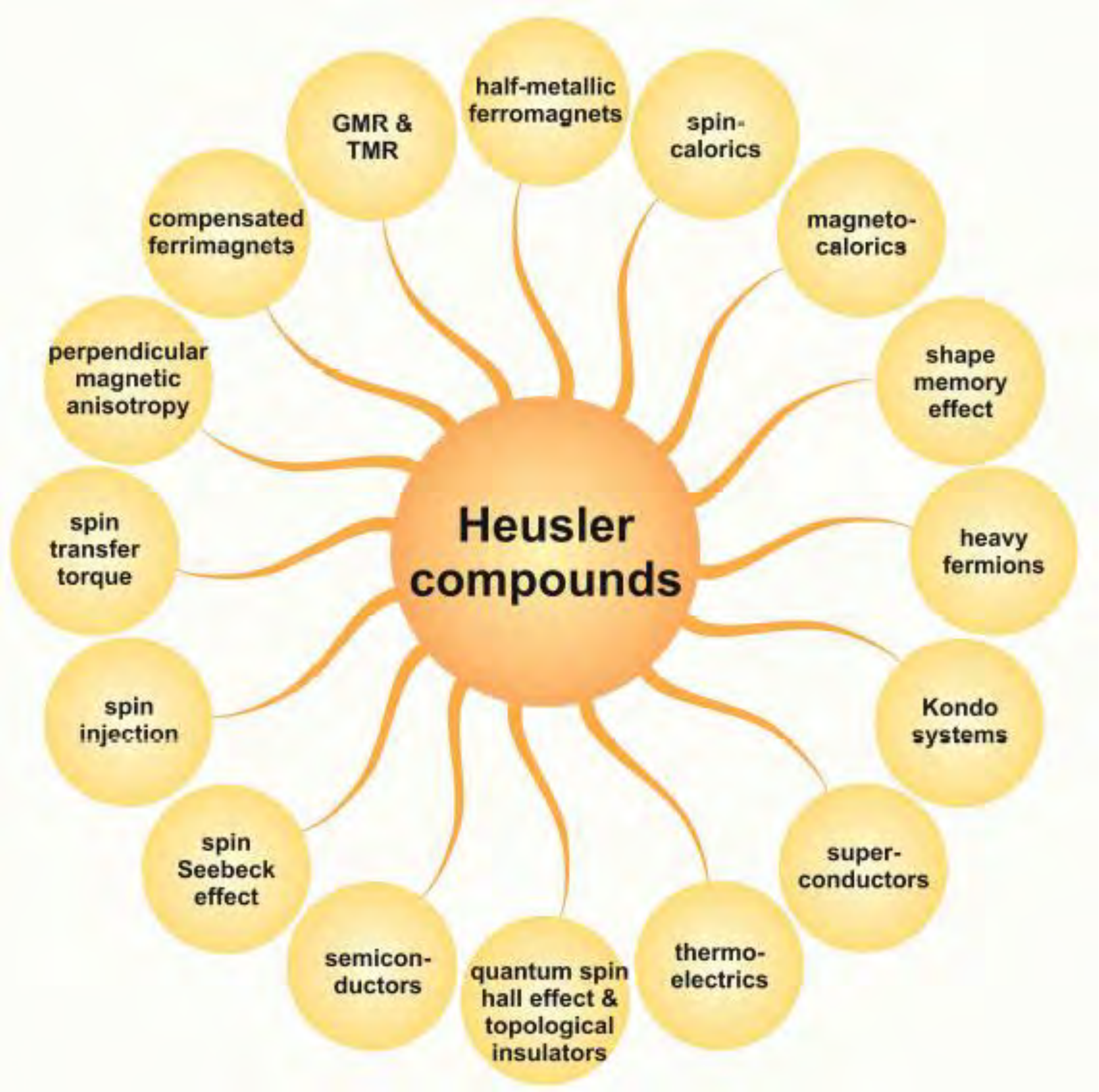


*I*4/*mmm*, centrosymmetric



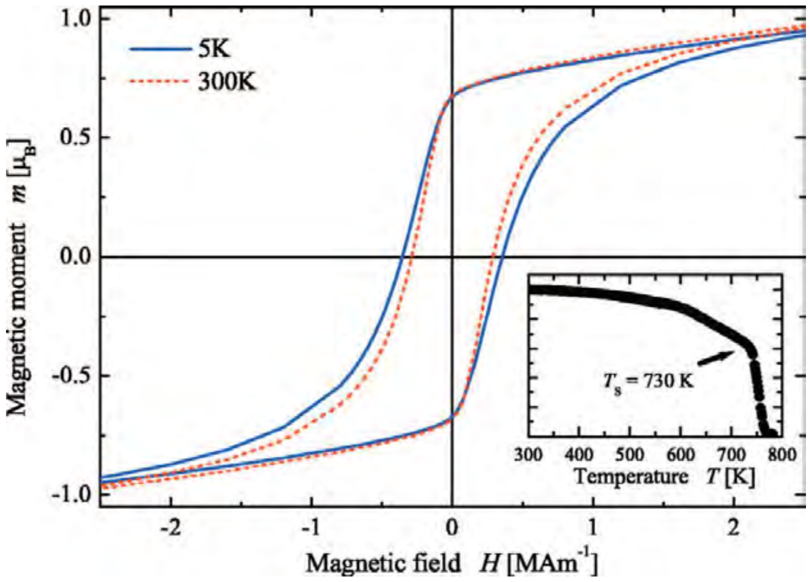
I-4*m*2, noncentrosymmetric

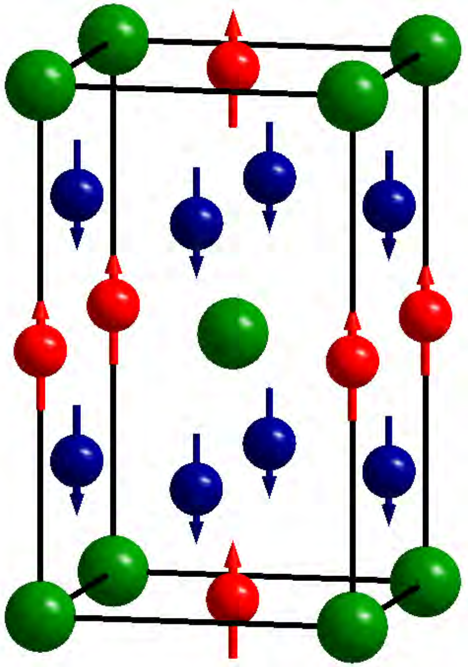
Why Heusler materials:



Tetragonal Heuslers for spintronics:

Mn_3Ga: Mn_2MnGa:Tetragonal material with large magnetic anisotropy





$MnI=3.1\mu_B$

$MnII+MnII=2.1\mu_B+2.1\mu_B$

$M=4.2-3.1=1.1\mu_B$

B. Balke, C. Felser et al., APL ***90****, 152504 (2007).*

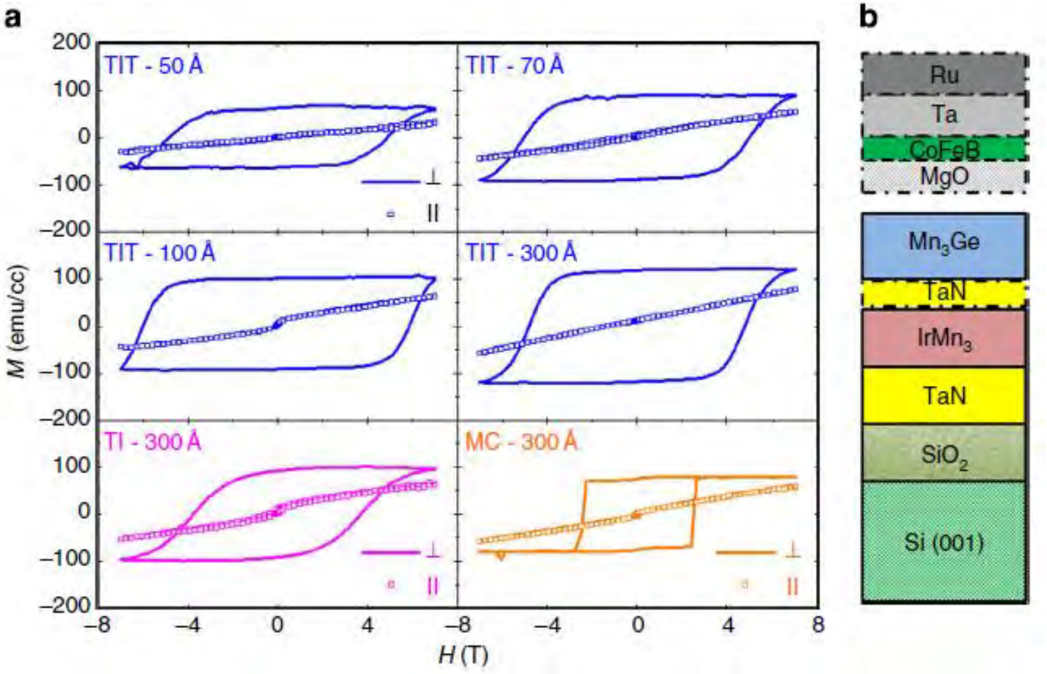
Low magnetic moment and large perpendicular magnetic anisotropy.

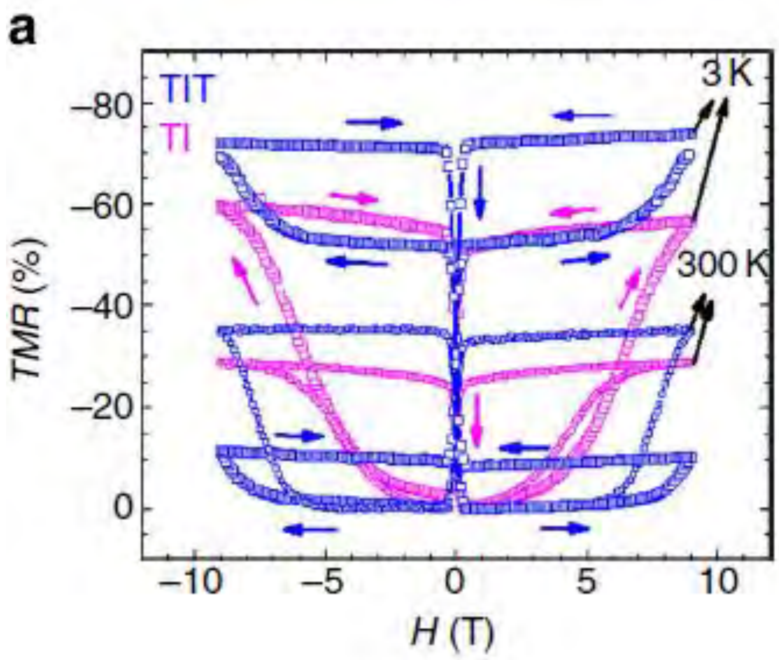
⇓

Ideal for spintronic application

Tetragonal structure and ferrimagnetic ordering

Tetragonal Heuslers for spintronics: Large TMR in Mn_3Ge

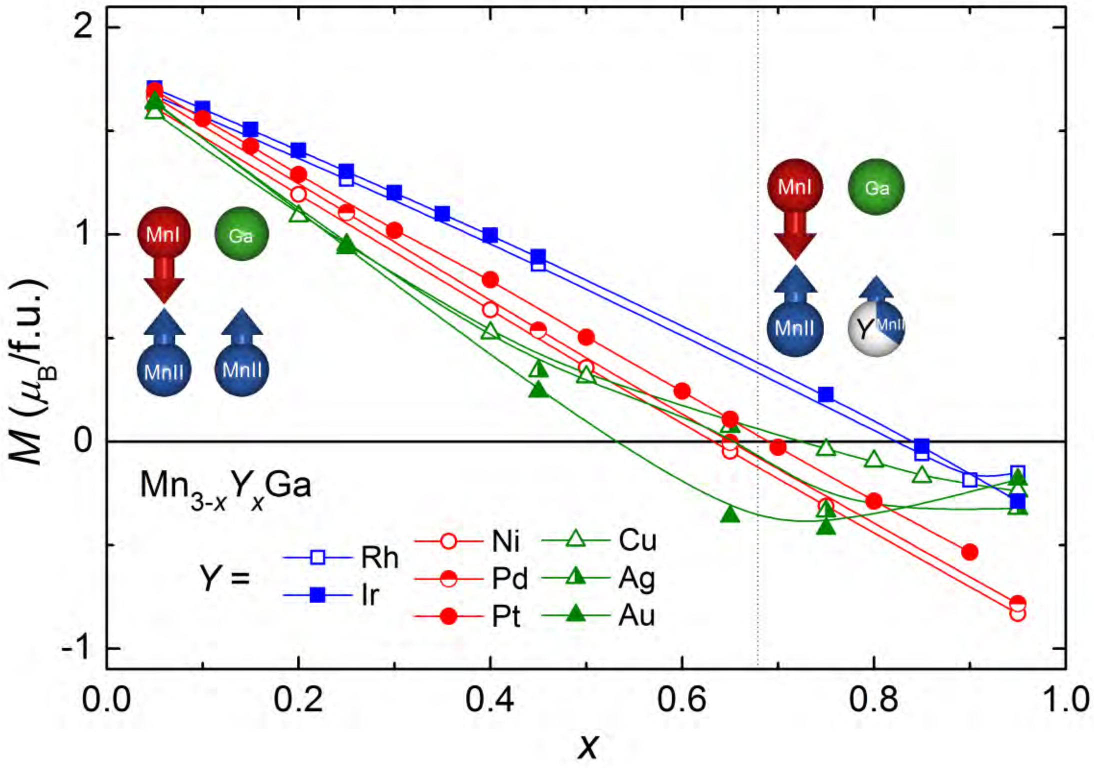




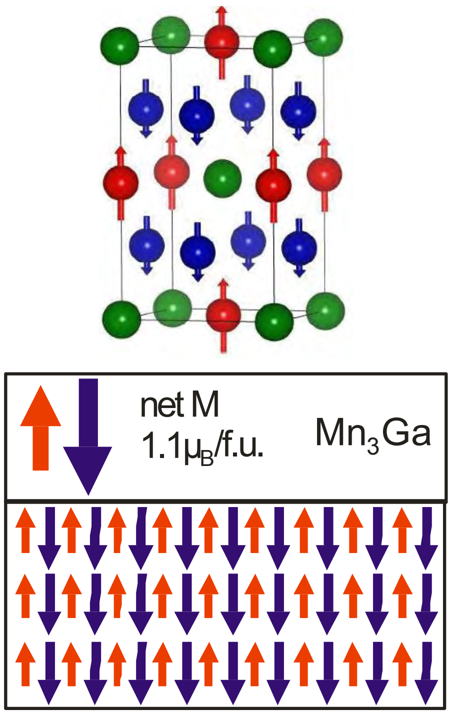
Jeong and Parkin et al., Nature Comm. 7, 10276 (2016).

- ✓ Extremely large perpendicular magnetic anisotropy in Mn_3Ge thin films.
- ✓ TMR up to 80 % has been observed in Mn3Ge based TMR device.

Compensated ferrimagnets and giant exchange bias

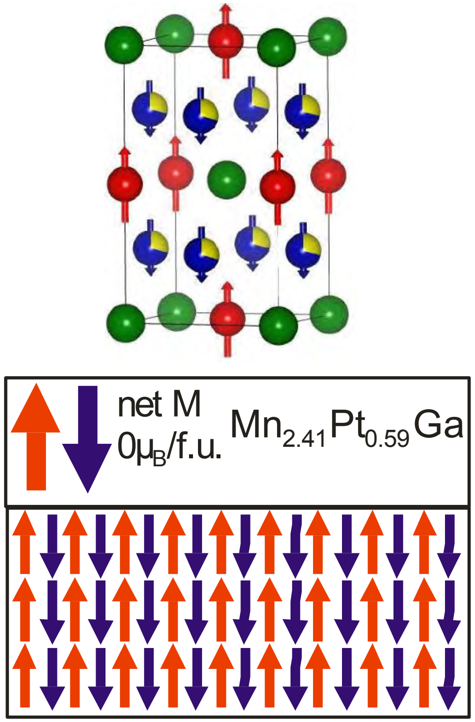


Designing compenstad magnetic state in Mn-Pt-Ga



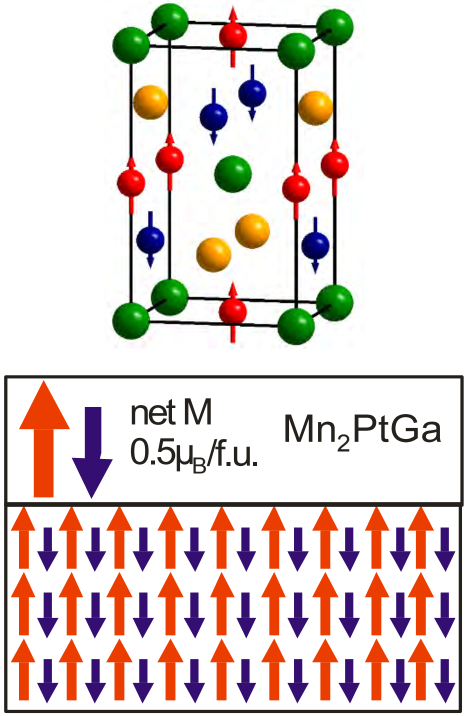
net M $1.1\mu_B$/f.u.

Mn_3Ga



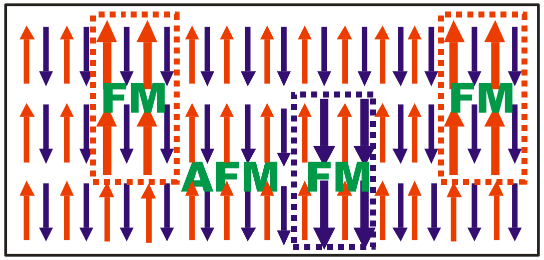
net M $0\mu_B$/f.u.

$Mn_{2.41}Pt_{0.59}Ga$



net M $0.5\mu_B$/f.u.

Mn_2PtGa



FM

AFM

FM

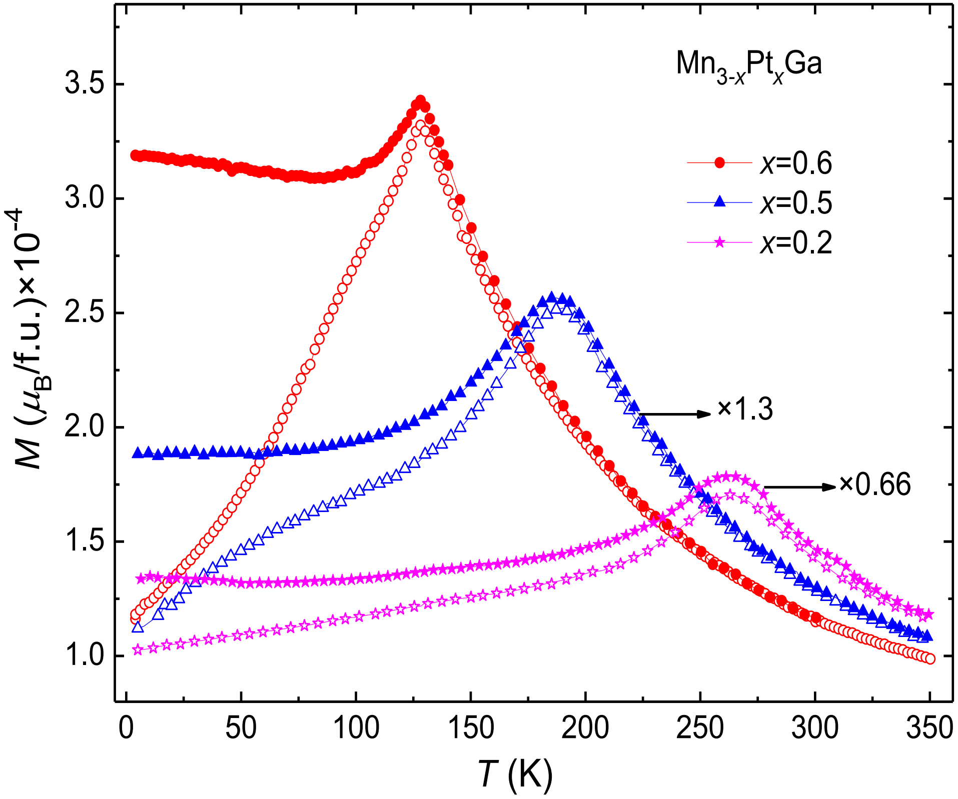
FM

FM clusters in AFM background

Nayak et al., Nature Mater. ***14****, 679 (2015).*

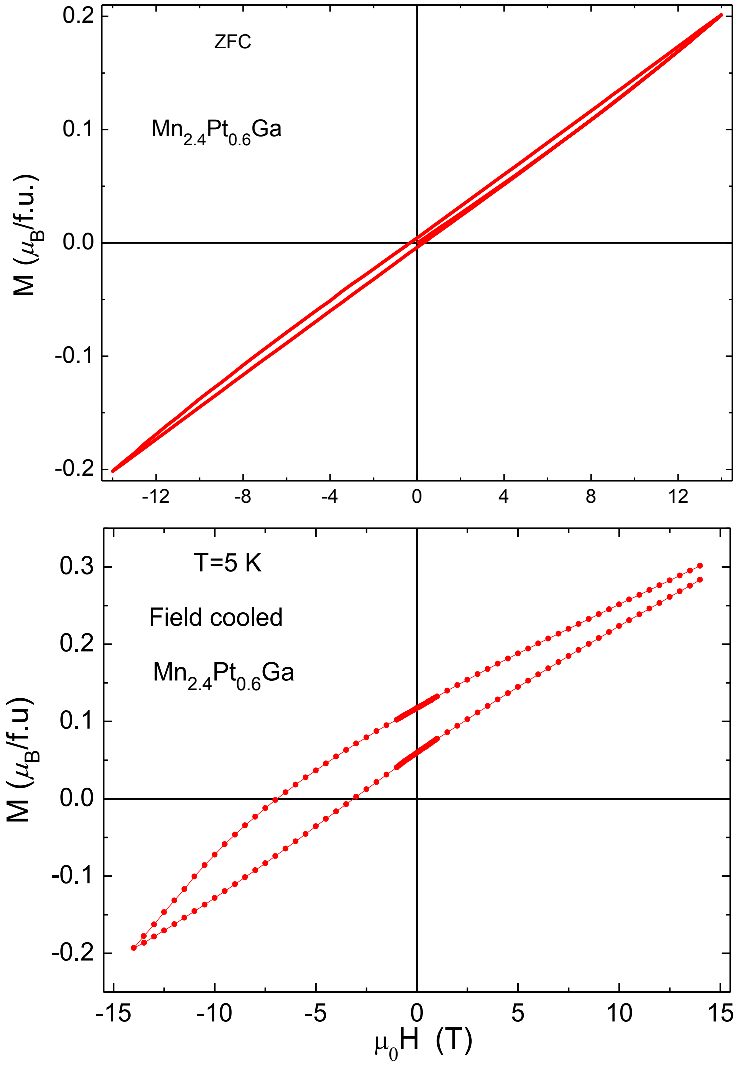
By combining two ferrimagnetic compounds with opposite spin alignment we can design a compensated magnetic state.

Compenstad magnetic state in $Mn_{3-x}Pt_xGa$



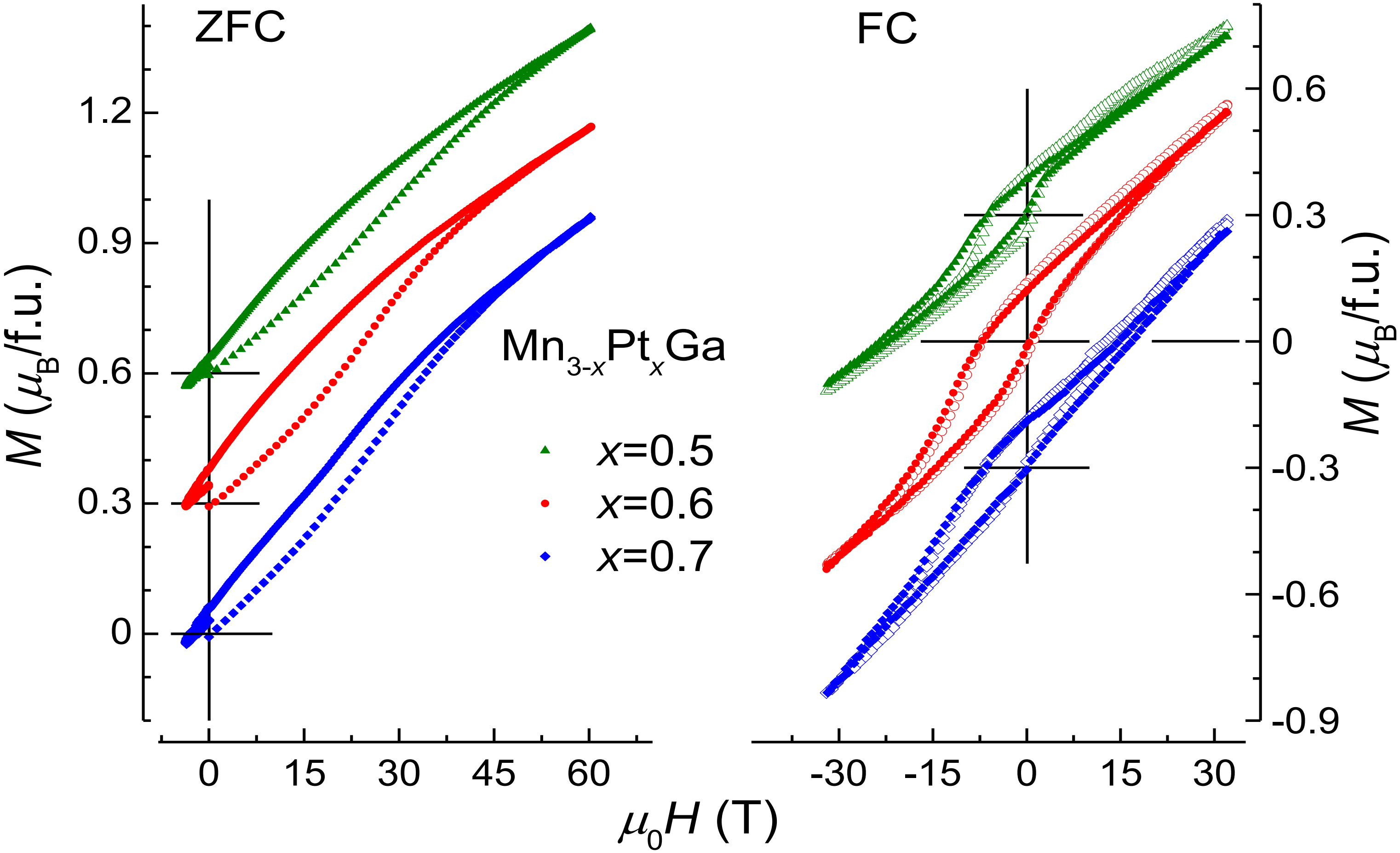
❖ A compensated magnetic state is achieved in Mn-Pt-Ga

Nayak et al., Nature Mater. ***14****, 679 (2015).*



Large hysteresis indicates FM components inside AFM background

Large EB in $Mn_{3-x}Pt_xGa$

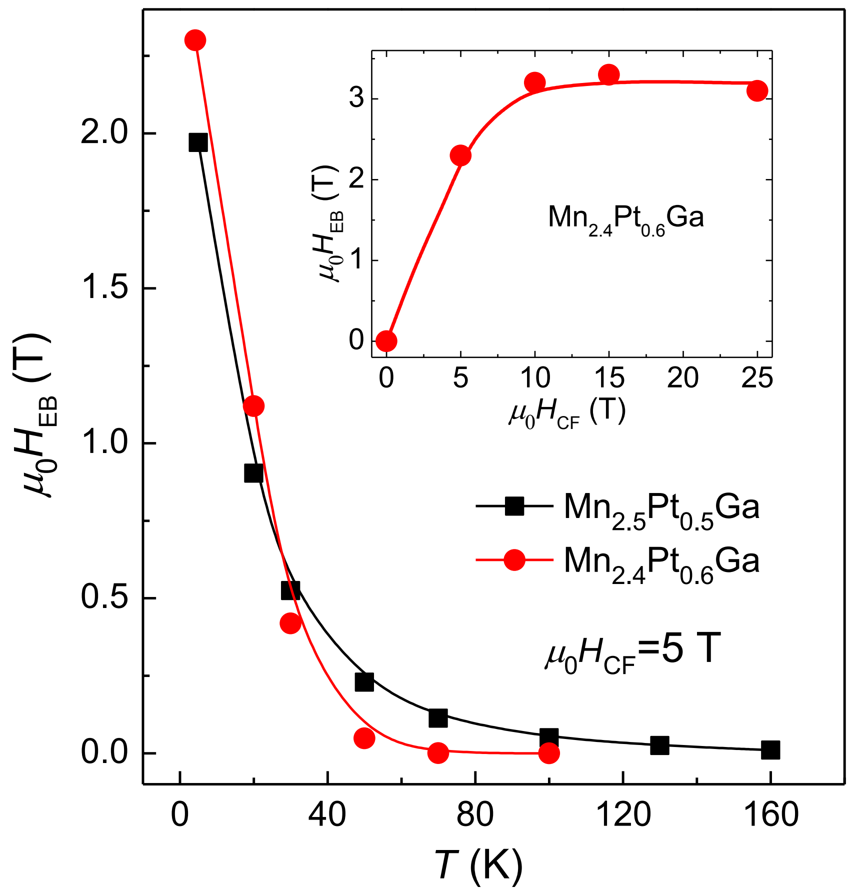


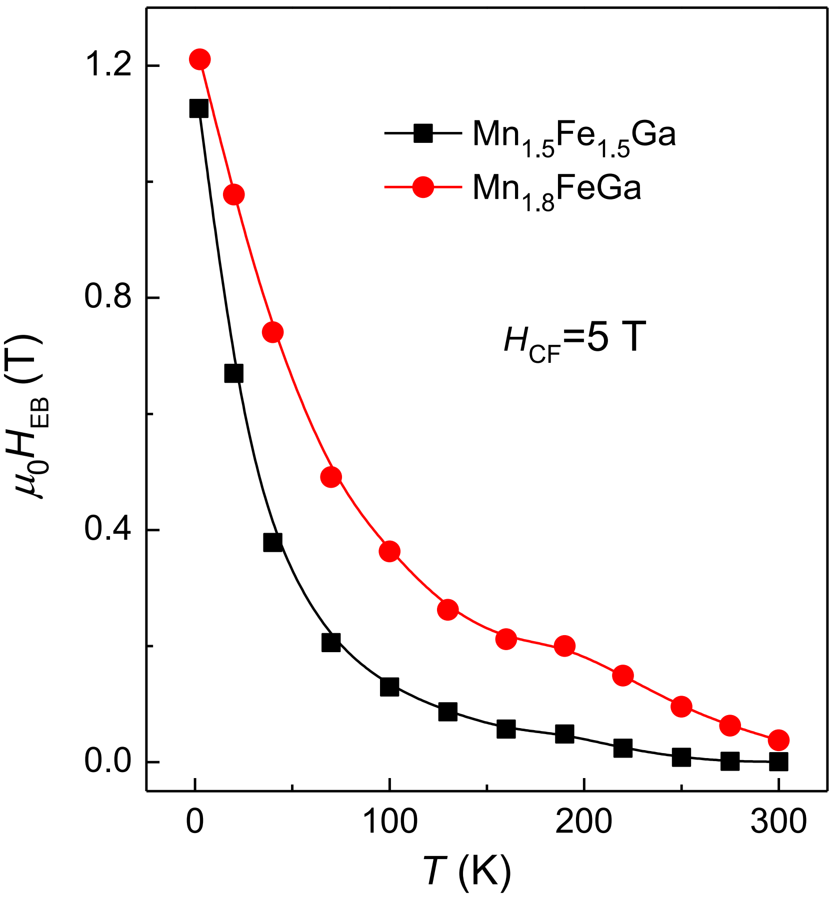
Nayak et al., Nature Mater. **14**, 679 (2015).

EB > 3 T is achieved

- Pulsed field magnetization measurements display a close hysteresis loop with coercivity around 3.5 T.
- Field cooled MH loops measured in a dc magnetic field of 32 T confirms the presence of an extremely large EB.

Large EB in $Mn_{3-x}Pt_xGa$





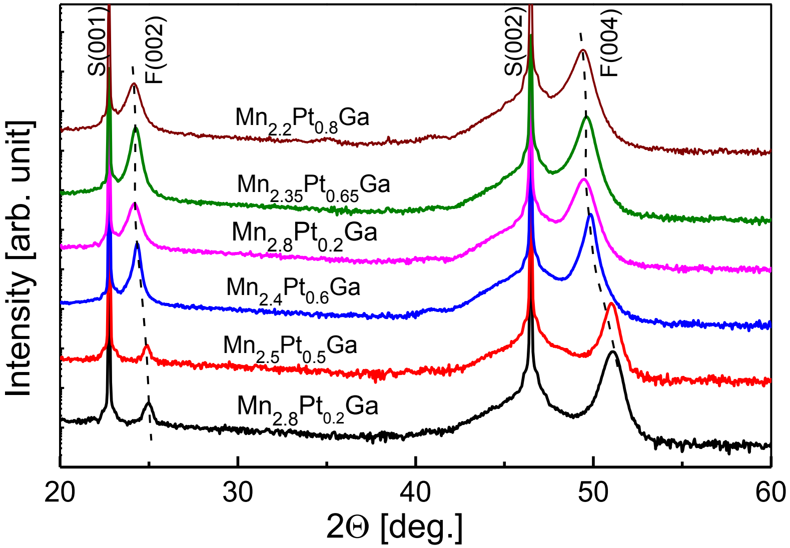
- EB monotonically decreases with temperatures.

- EB vanishes around 150 K.

EB up to room temperature in Mn-Fe-Ga system.

Nayak et al., Nature Mater. ***14****, 679 (2015).*

Mn-Pt-Ga thin films:



Successful growth of tetragonal Mn-Pt-Ga thin films by dc magnetron sputtering.

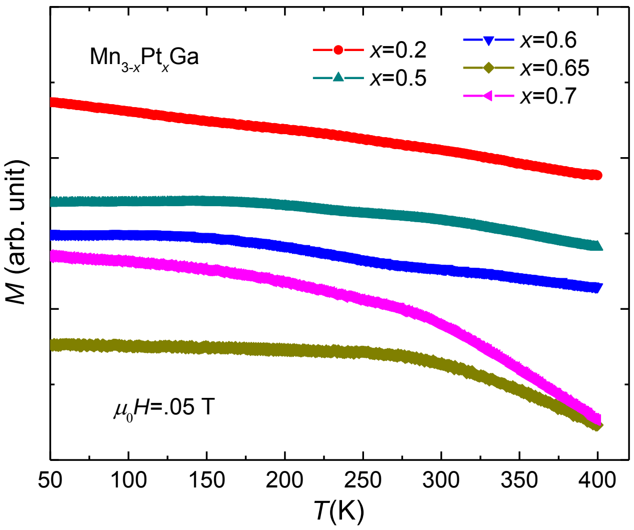
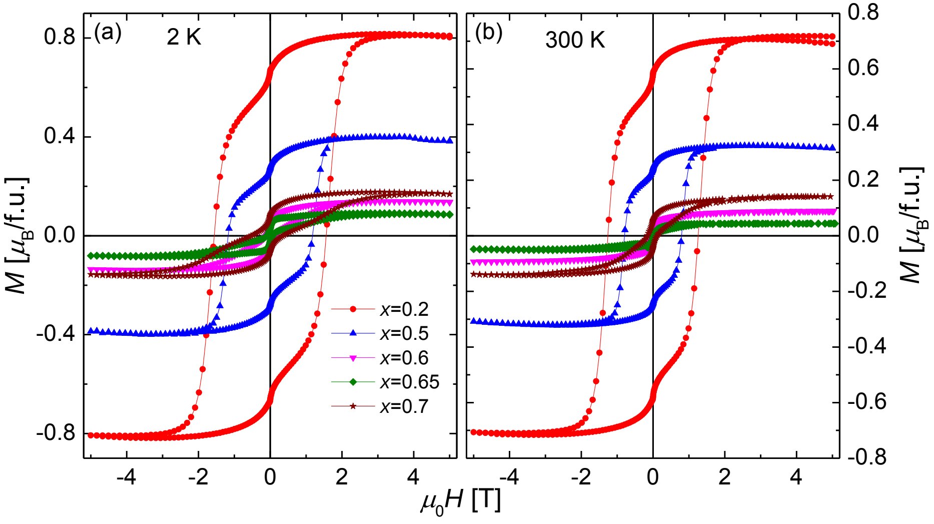


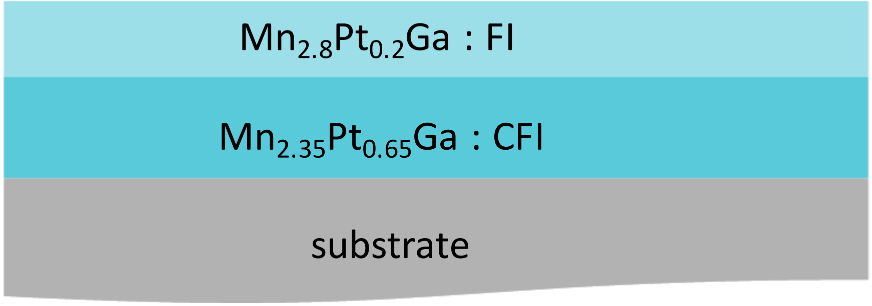
Exhibit high ordering temperatures.



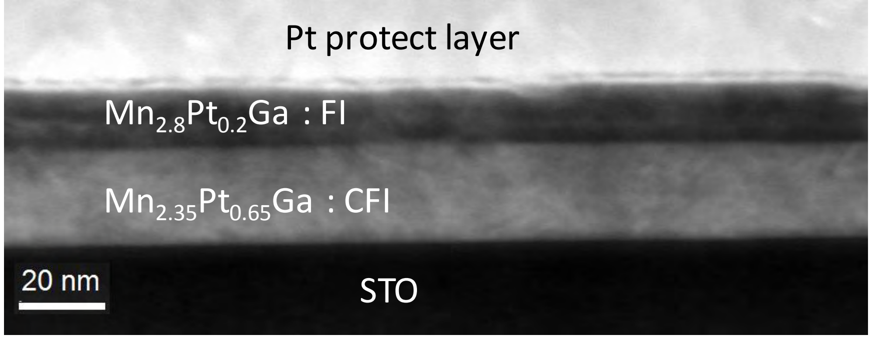
✓ Tunable magnetic anisotropy and compensated magnetic state is achieved.

Sahoo et al., Adv. Mater. 2016.

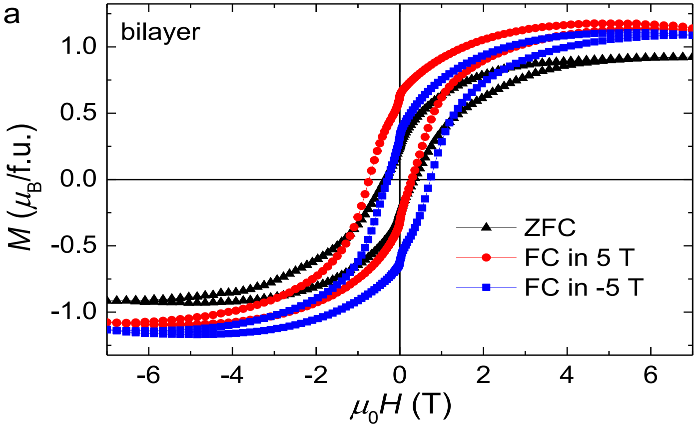
Mn-Pt-Ga bilayers:

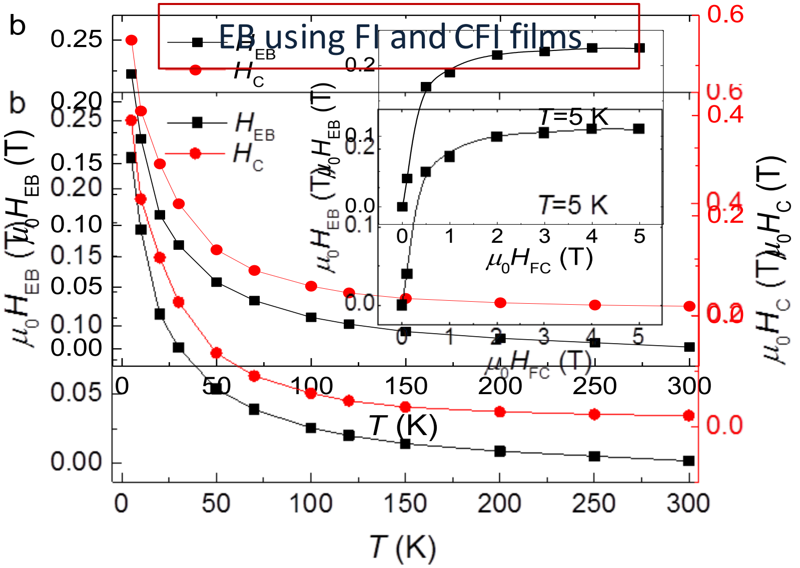


Designing bilayers of FI and CFI films



- Crossectional TEM view shows two distinct layers.



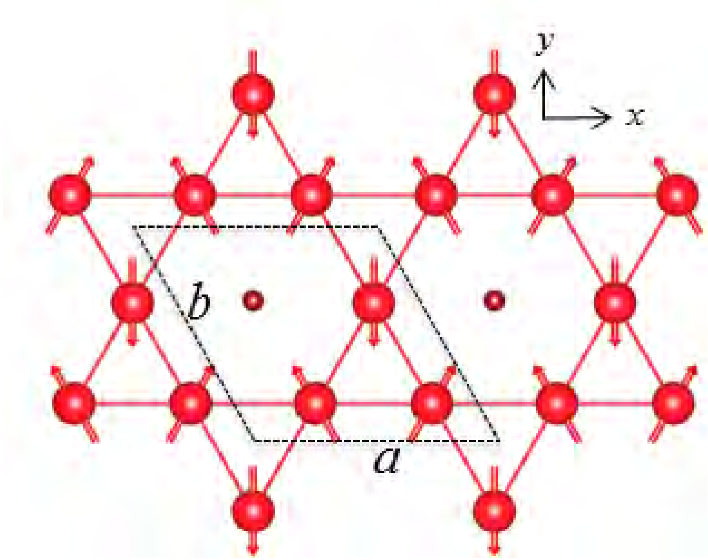


EB using FI and CFI films

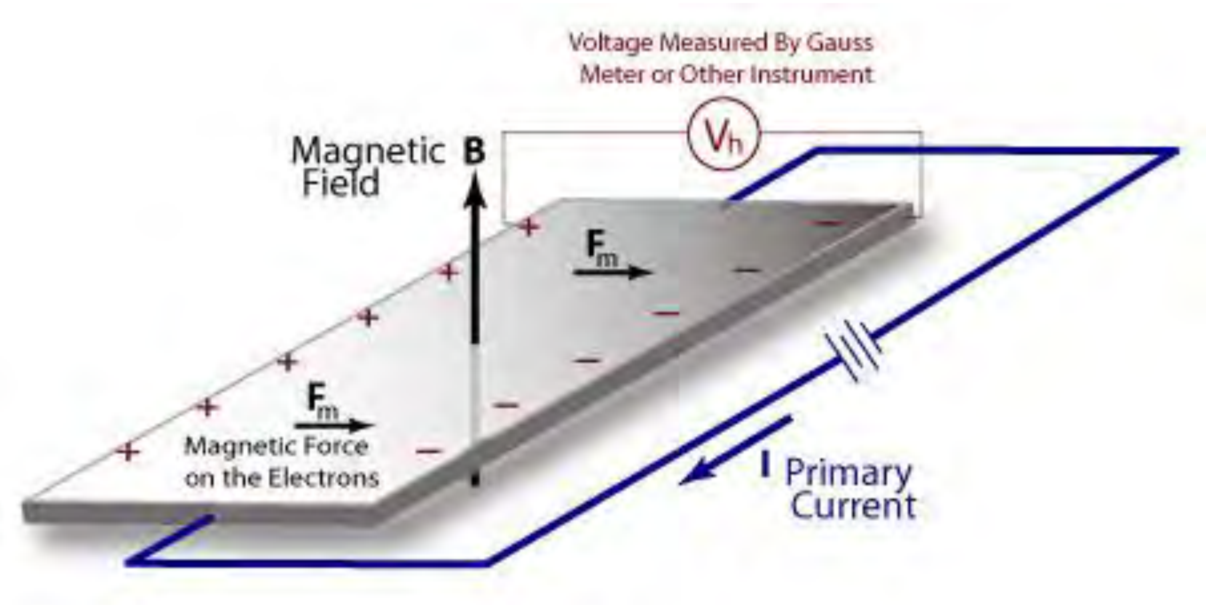
Similar compositions and identical crystal and electronic structures ensures high thermal stabilities.

Sahoo et al., Adv. Mater. 2016.

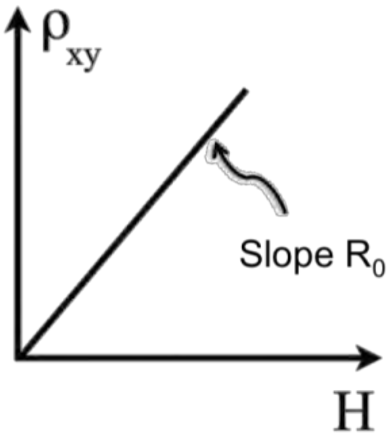
Anomalous Hall effect in non-collinear antiferromagnets



Hall effect

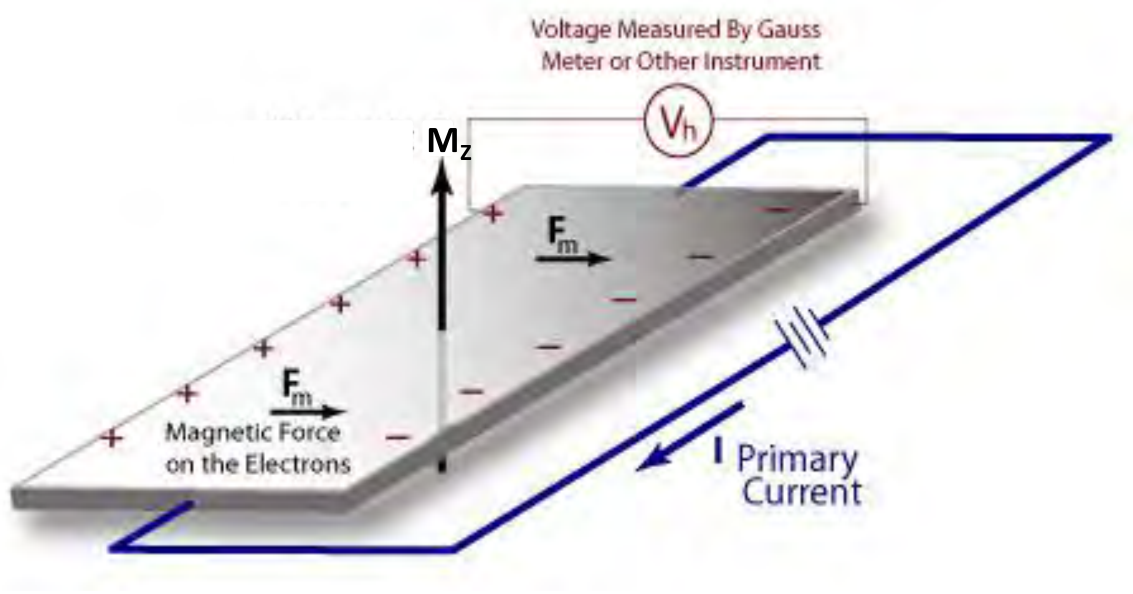


Normal conductor

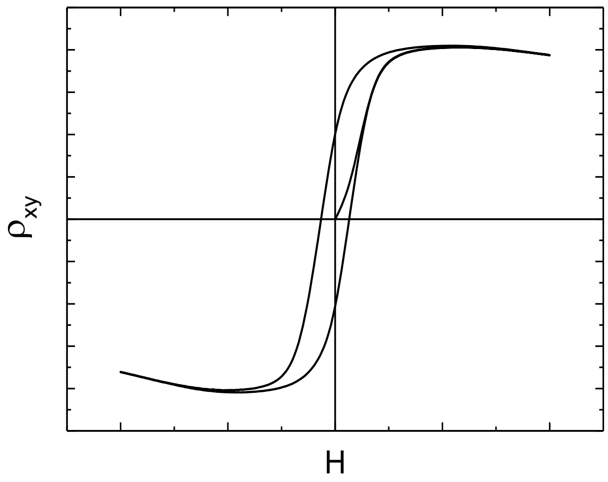


- ✓ Deflection of charge carriers in a presence of external magnetic field.
- ✓ Hall voltage linearly proportional to magnetic field.

Anomalous Hall effect



Ferromagnetic conductor

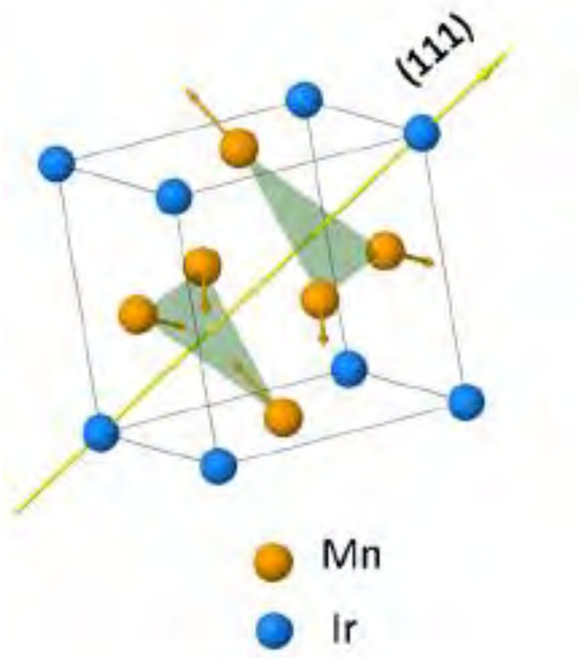


Anomalous Hall effect

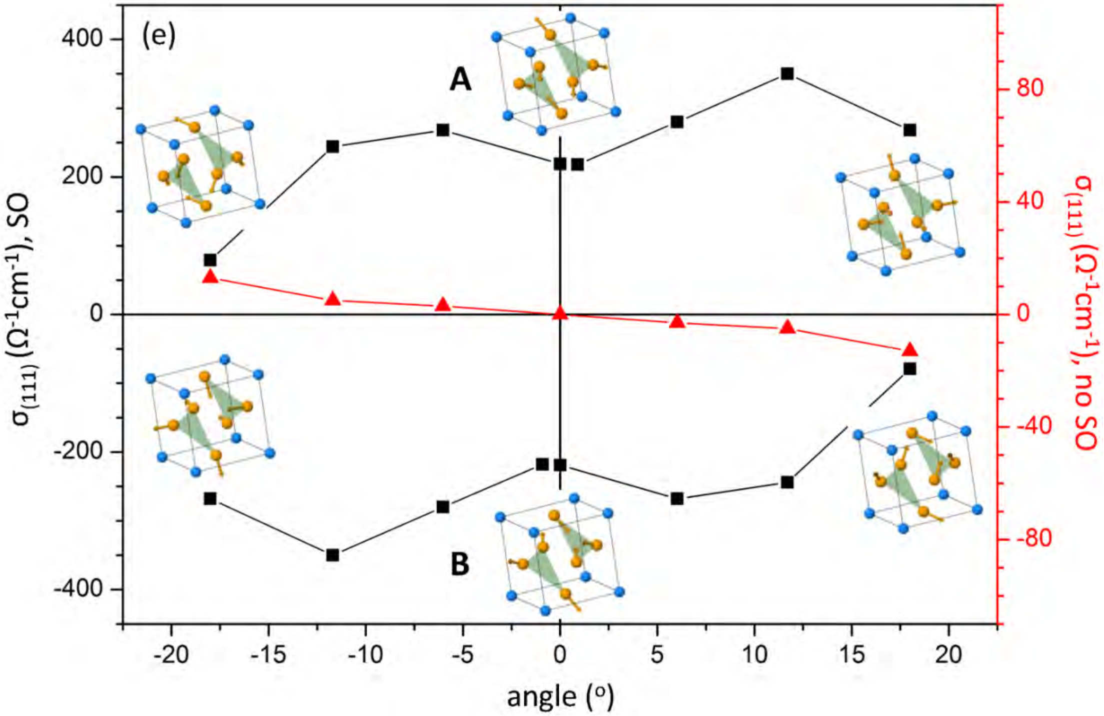
$$\rho_{xy} = R_0 H_z + R_s M_z,$$

- ✓ No need of magnetic fields.
- ✓ Intrinsic to all ferromagnetic materials.
- ✓ ρ_{xy}^{A} roughly scale with the magnetization.

Anomalous Hall effect in noncollinear antiferromagnet Mn_3Ir

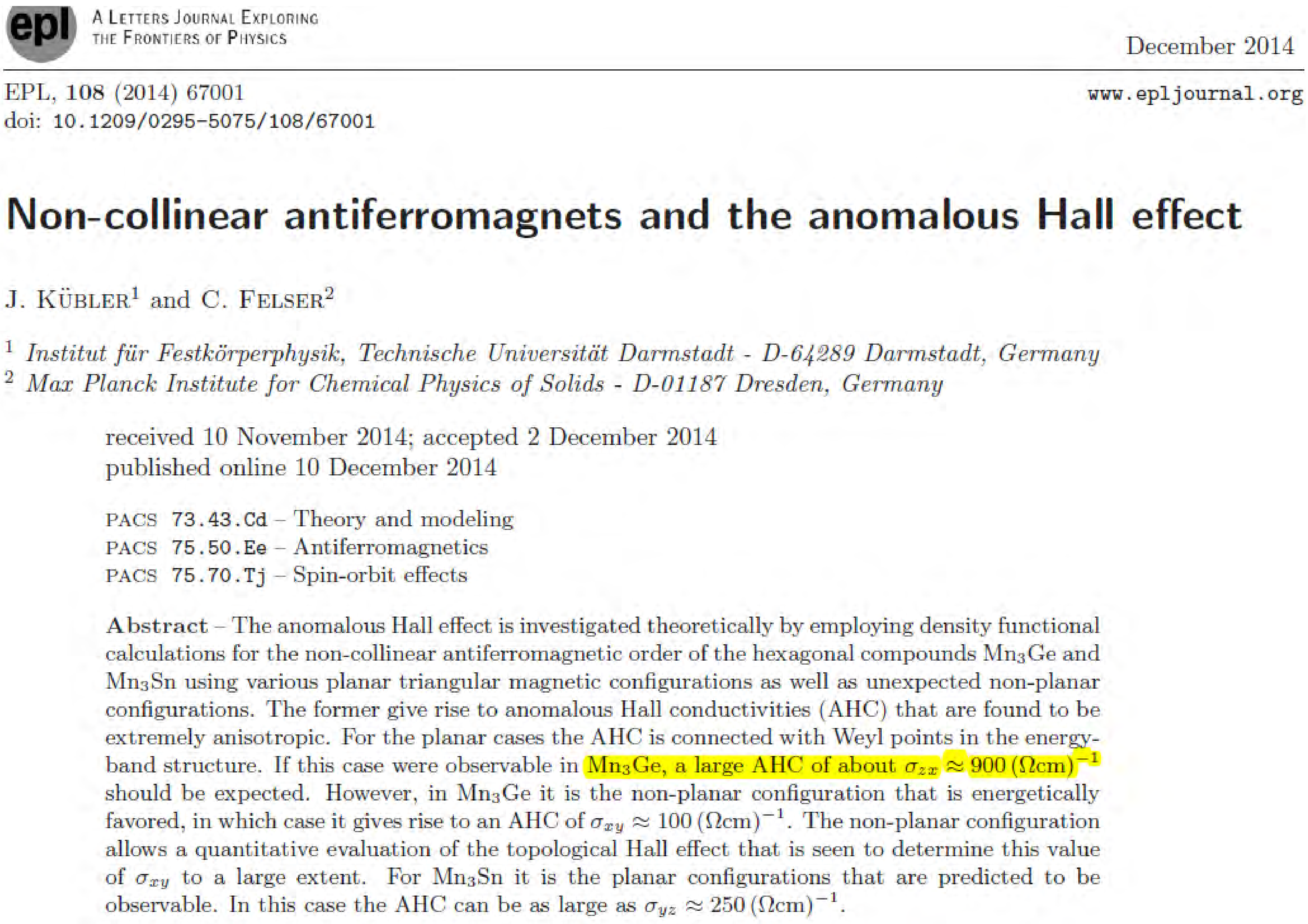


Non-collinear AFM spin arrangement



Chen et al., Phys. Rev. Lett. 112, 017205 (2014).

Anomalous Hall effect in noncollinear antiferromagnet Mn_3Ge



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Non-collinear antiferromagnets and the anomalous Hall effect

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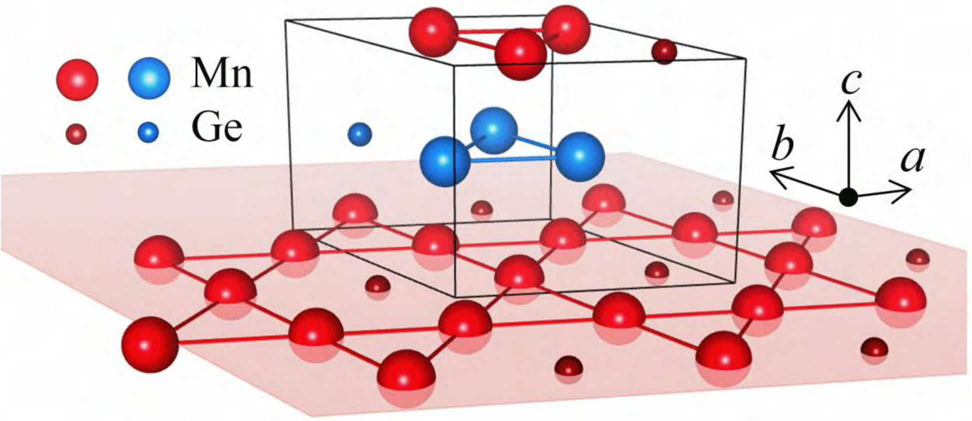
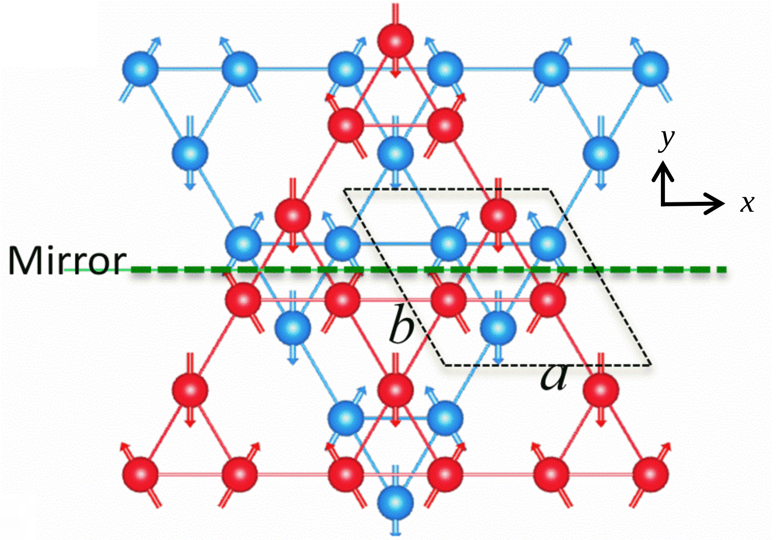
PACS 73.43.Cd – Theory and modeling
PACS 75.50.Ee – Antiferromagnetics
PACS 75.70.Tj – Spin-orbit effects

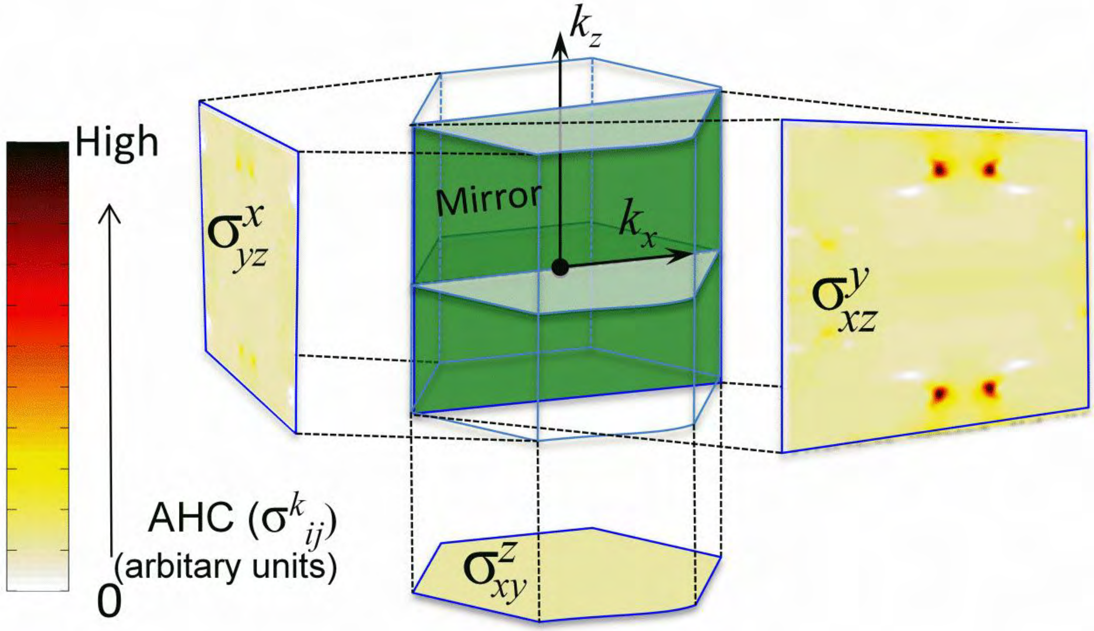
Abstract – The anomalous Hall effect is investigated theoretically by employing density functional calculations for the non-collinear antiferromagnetic order of the hexagonal compounds Mn_3Ge and Mn_3Sn using various planar triangular magnetic configurations as well as unexpected non-planar configurations. The former give rise to anomalous Hall conductivities (AHC) that are found to be extremely anisotropic. For the planar cases the AHC is connected with Weyl points in the energy-band structure. If this case were observable in Mn_3Ge, a large AHC of about $\sigma_{zx} \approx 900\,(\Omega\text{cm})^{-1}$ should be expected. However, in Mn_3Ge it is the non-planar configuration that is energetically favored, in which case it gives rise to an AHC of $\sigma_{xy} \approx 100\,(\Omega\text{cm})^{-1}$. The non-planar configuration allows a quantitative evaluation of the topological Hall effect that is seen to determine this value of σ_{xy} to a large extent. For Mn_3Sn it is the planar configurations that are predicted to be observable. In this case the AHC can be as large as $\sigma_{yz} \approx 250\,(\Omega\text{cm})^{-1}$.

Anomalous Hall effect in noncollinear antiferromagnet Mn_3Ge



- ➢ Two layers of Mn triangles stacked along the c axis.

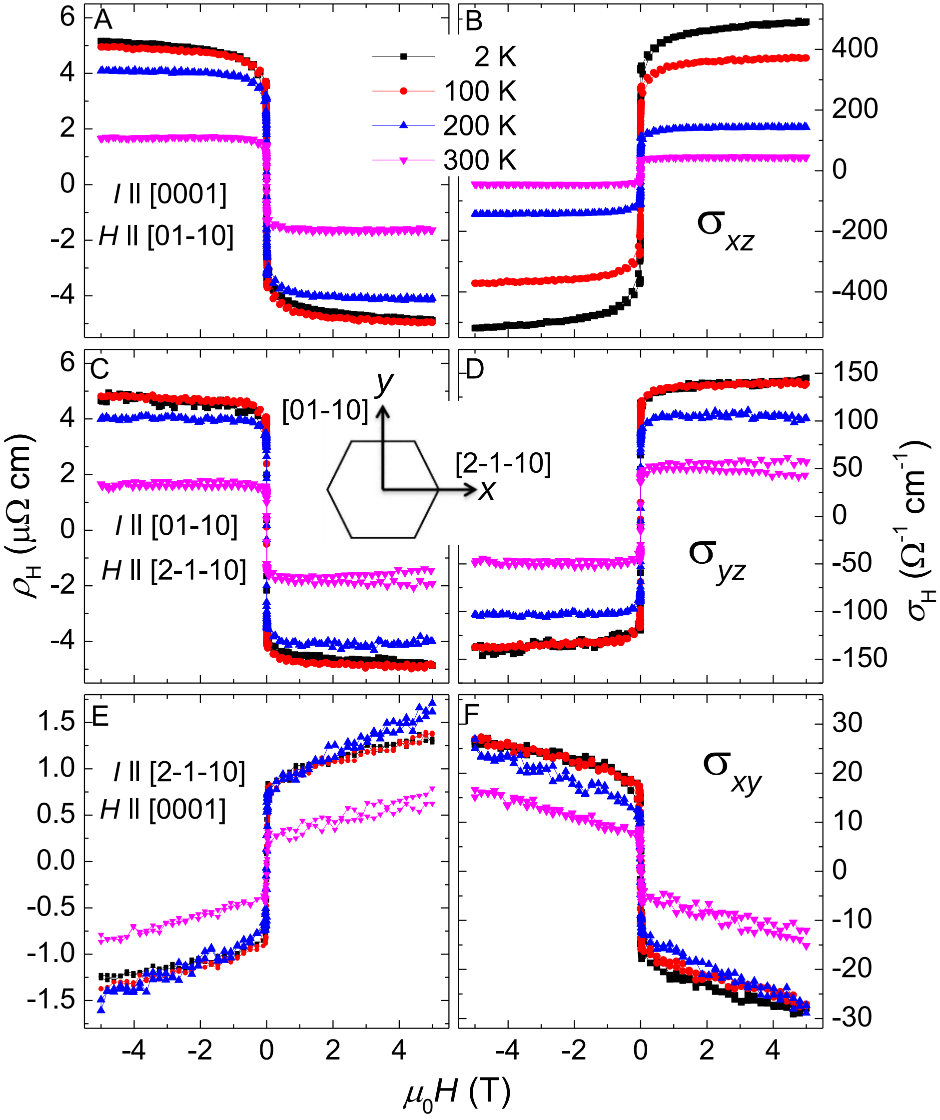




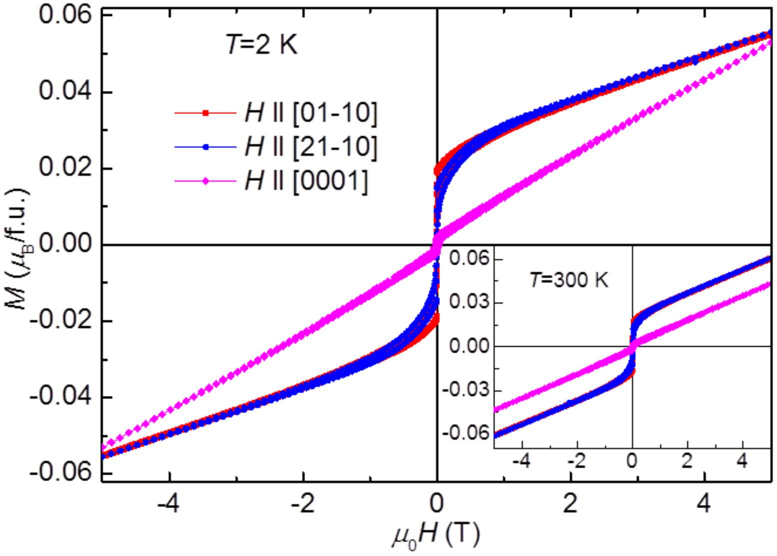
- ✓ Two spin triangles can be transformed into each other by a mirror reflection with respect to the xz plane.
- ✓ σ^k_{ij} vanish if they align parallel to the mirror plane due to mirror symmetry.
- ✓ A non zero σ^y_{xz} ~330 $(\text{ohmcm})^{-1}$ is expected.

Science Advances 2, e1501870 (2016).

Anomalous Hall effect in noncollinear antiferromagnet Mn_3Ge



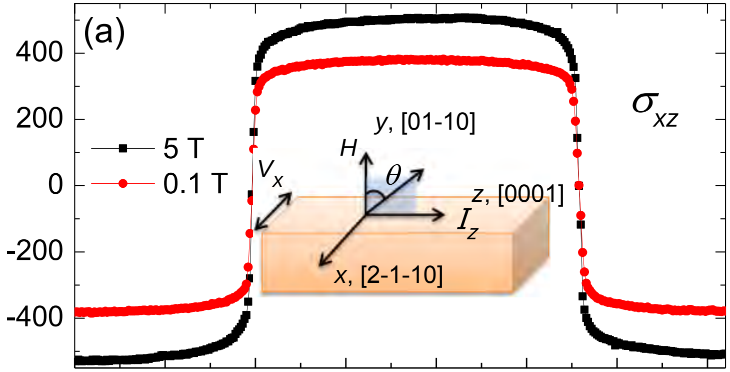
- ✓ A large anomalous Hall conductivity is found in the xz plane.



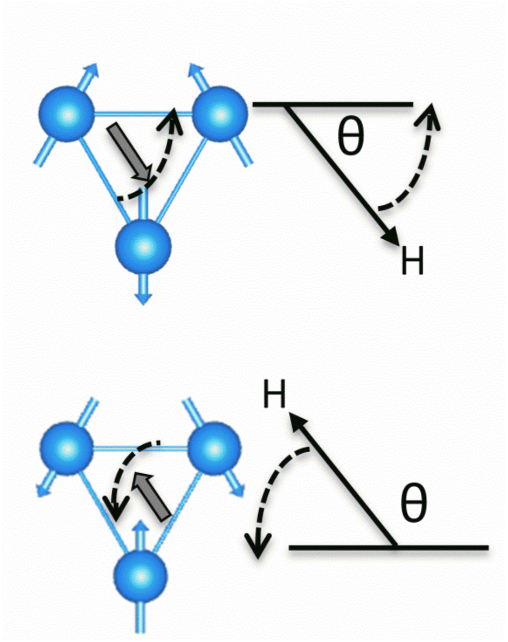
- ✓ A small residual in-plane moment can perturb the mirror symmetry.
- ✓ As predicted by theory the σ_{xy} is al most zero.

Science Advances 2, e1501870 (2016).

Anomalous Hall effect in noncollinear antiferromagnet Mn_3Ge



- ✓ Angle dependent measurements show that even when field is applied along the ab-plane, σ_{xy} is almost zero.
- ✓ No effect of magnetic field on the observed AHE.
- ✓ Magnetic field only helps to change the sign of the AHE.



Science Advances 2, e1501870 (2016).

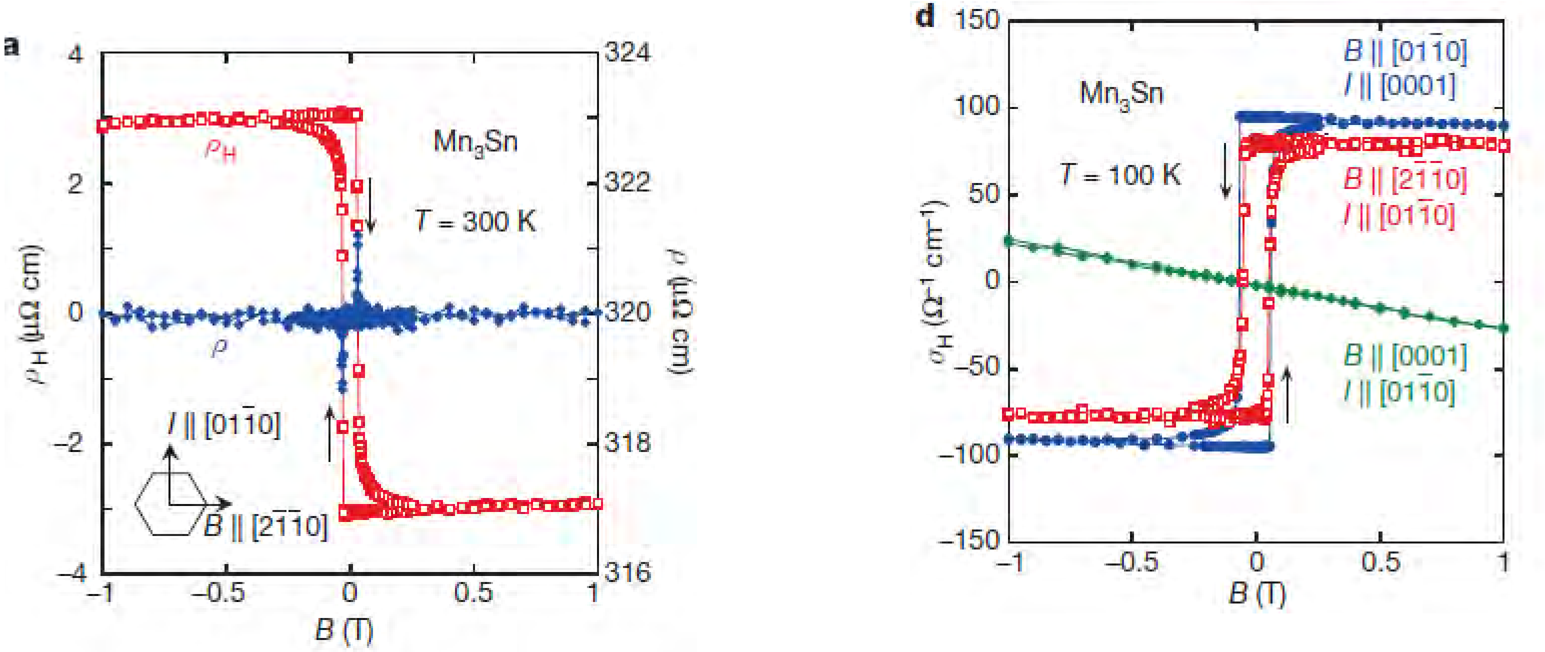
Anomalous Hall effect in noncollinear antiferromagnet Mn_3Sn

LETTER

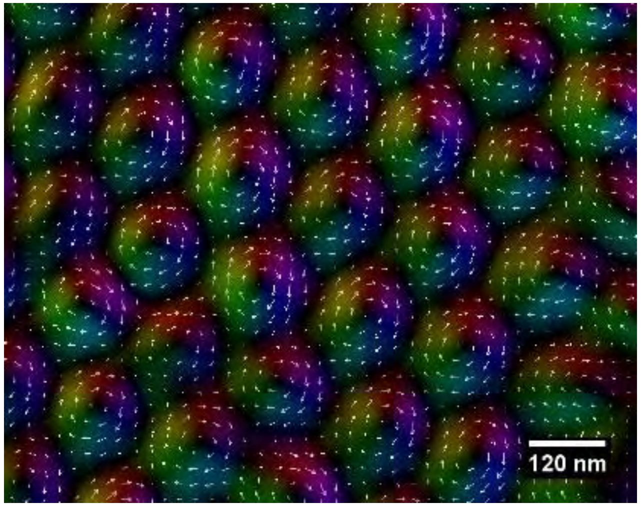
doi:10.1038/nature15723

Large anomalous Hall effect in a non-collinear antiferromagnet at room temperature

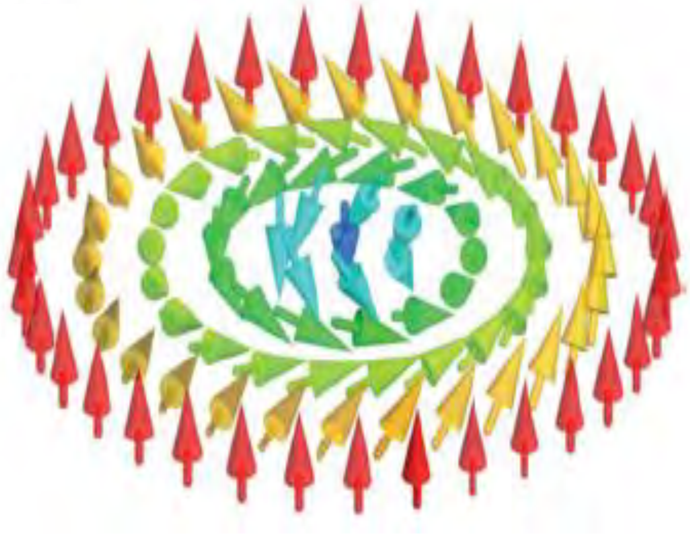
Satoru Nakatsuji[1,2], Naoki Kiyohara[1] & Tomoya Higo[1]

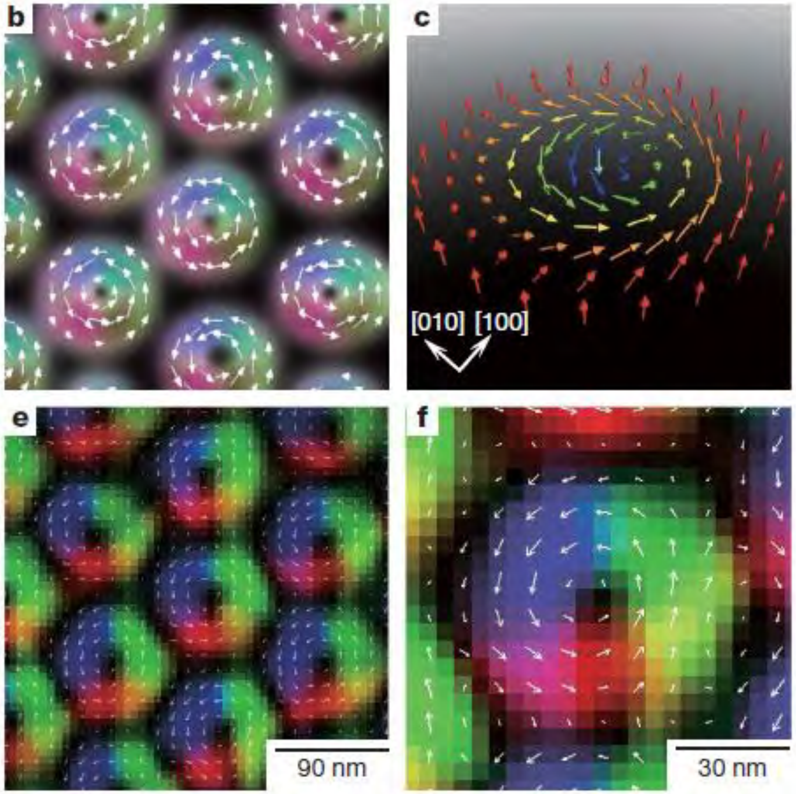


Non collinear spin structure and skyrmions in Heuslers



Why non-collinear magnetic structure:



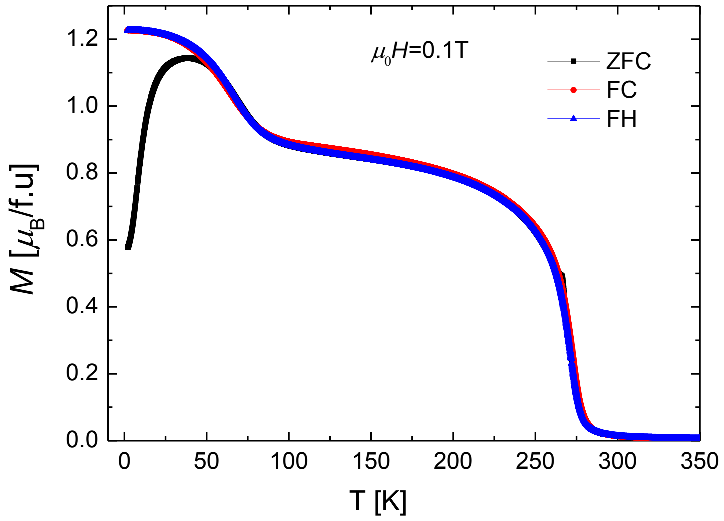


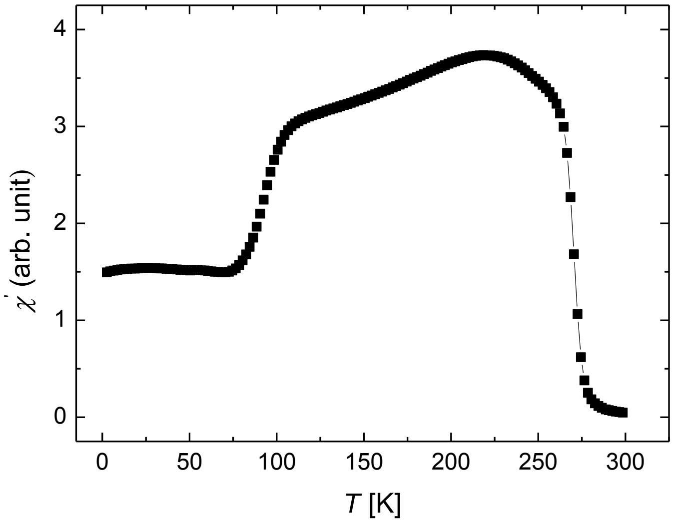
Nature 465, 901 (2010).

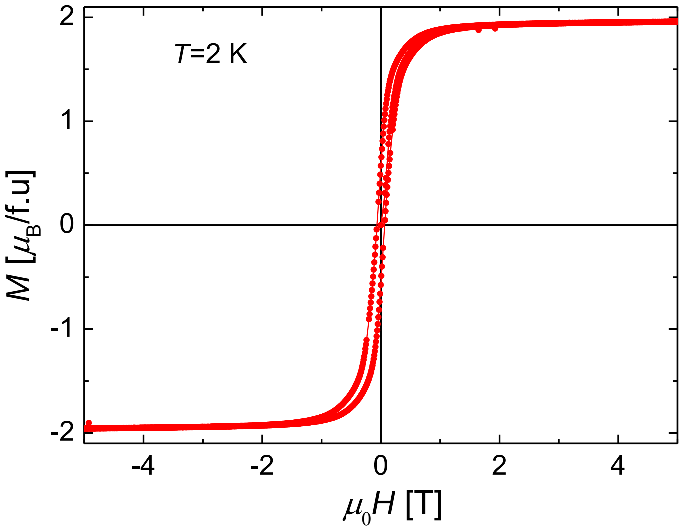
- ✓ A magnetic skyrmion is a vortex like topological object with a circular chiral spin configuration.
- ✓ Breaking of the inversion symmetry and D-M interaction for skyrmion.
- ✓ The competition between the direct exchange ($-J_{ij}\, s_i.s_j$) and the Dzyaloshinskii-Moriya exchange ($D_{ij}.(s_i \times s_j)$) gives rise to skyrmion.
- ✓ Good candidates for future data storage.

- ✓ Lorentz TEM image of skyrmions

Non-collinear magnetic structure in Mn_2RhSn



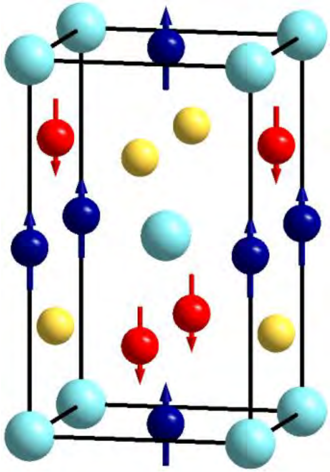




- First time observed a spin-reorientaion transition in the Heusler tetragonal compound Mn_2RhSn.
- Total magnetic moment of 2μB/f.u indicates a non-collinear magnetic structure in Mn_2RhSn.

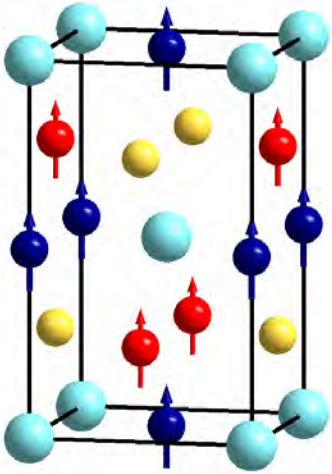
Meshcheriakova et al., Phys. Rev. Lett. 113, 087203 (2014).

Non-collinear magnetic structure in Mn_2RhSn



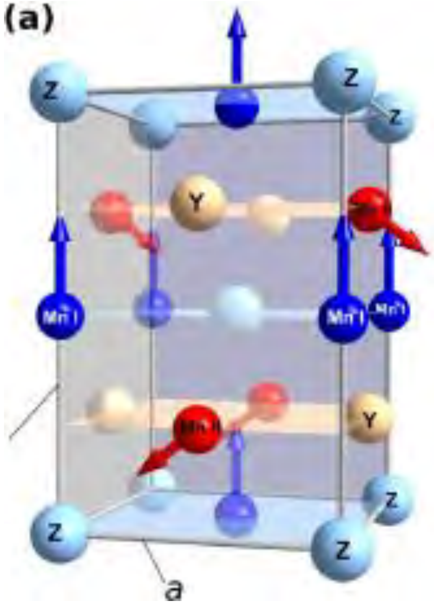
$M= 3.5-\xcancel{3.0\mu_B}=0.5\mu_B$

FI ordering does not hold with experimental result



$M= 3.5+\xcancel{3.0\mu_B}=6.5\mu_B$

FM ordering does not hold with experimental result

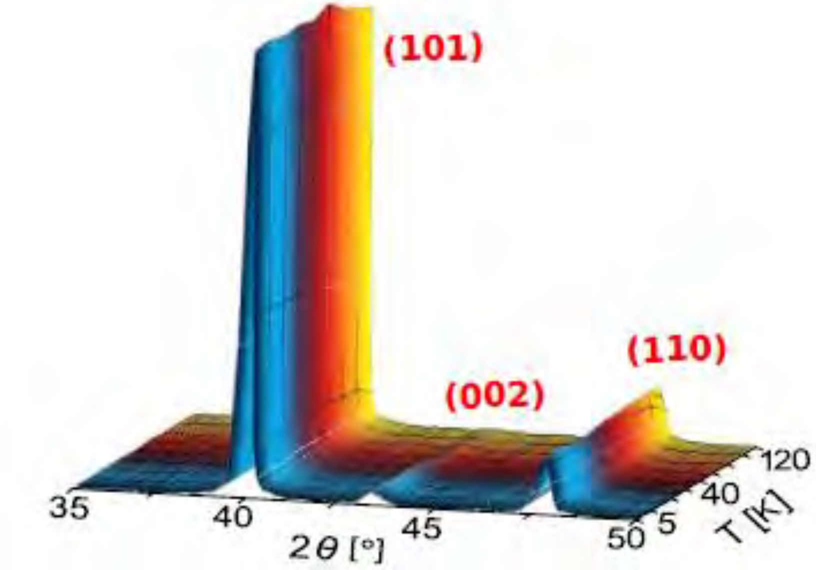


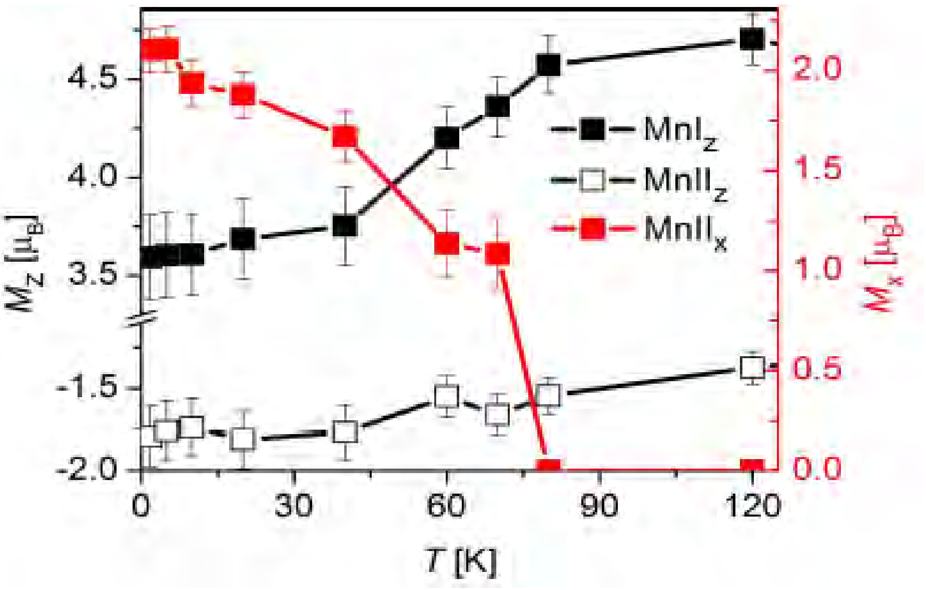
$M= MnI_z-MnII_z=$
$3.5-1.5\mu_B=2\mu_B$

Noncollinear ordering due to competing FM and AFM interactions.

Meshcheriakova et al., Phys. Rev. Lett. 113, 087203 (2014).

Non-collinear magnetic structure in Mn_2RhSn

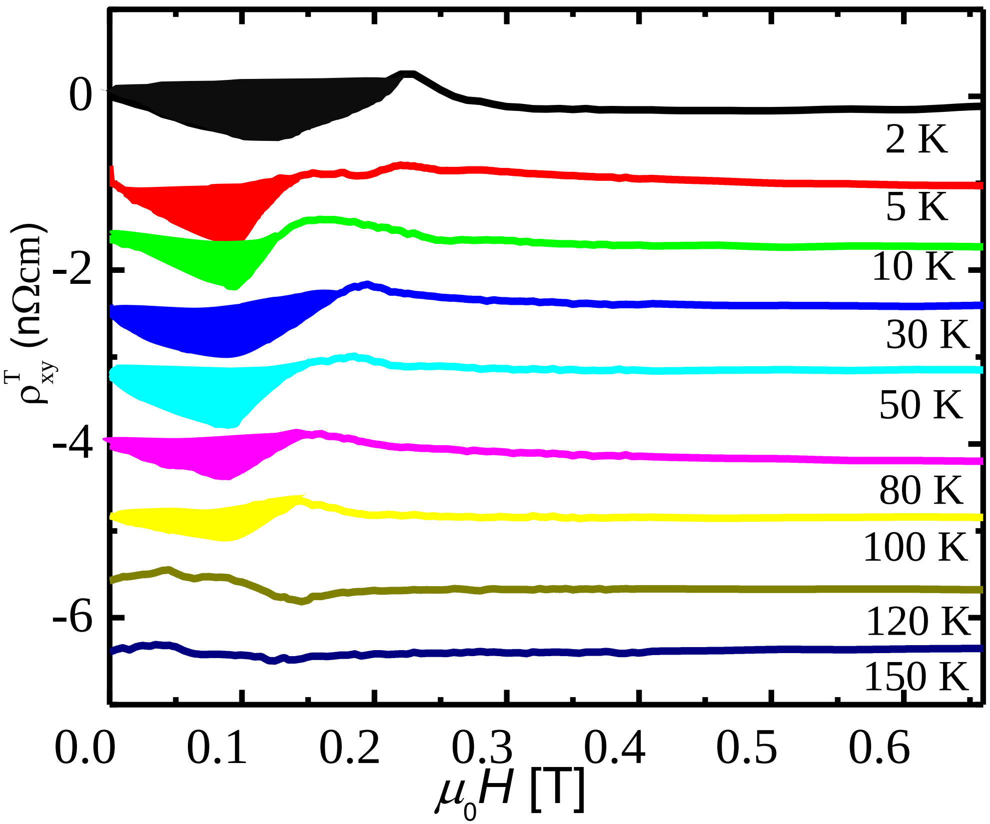




- Neutron diffraction study confirms the noncollinear ordering.
- In-plane component of the Mn moment completely disappears above the spin-reorientation transition.

Meshcheriakova et al., Phys. Rev. Lett. 113, 087203 (2014).

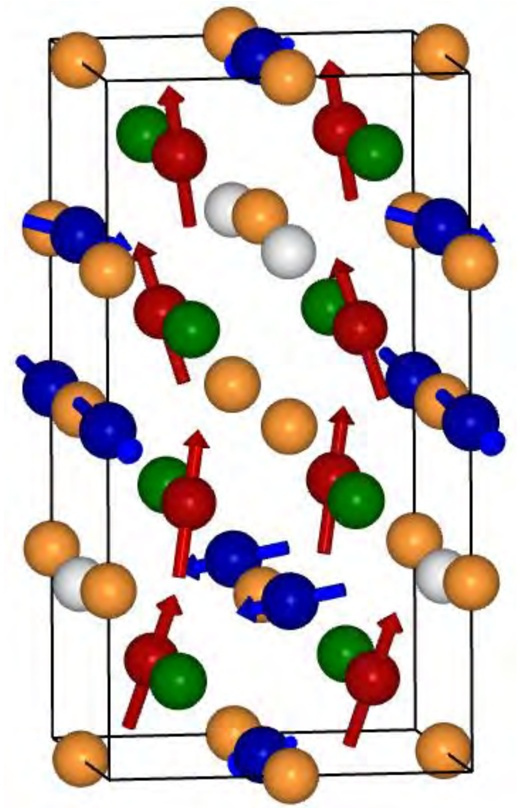
Topological Hall effect in Mn_2RhSn thin films

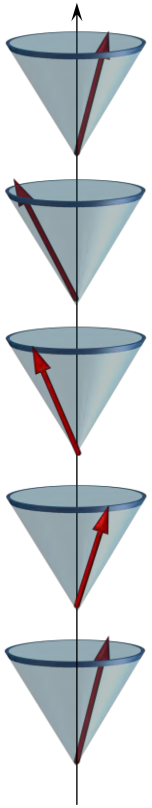


- Existence of topological Hall effect below the spin-reorientation transition indicates presence of skyrmion like structure.

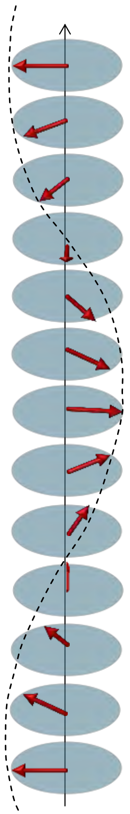
Rana et al., New J. Phys. 2016.

Non-collinear magnetic structure in Mn-Pt-Sn

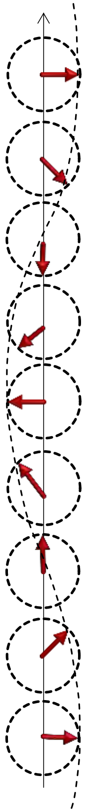




conical ll [001]

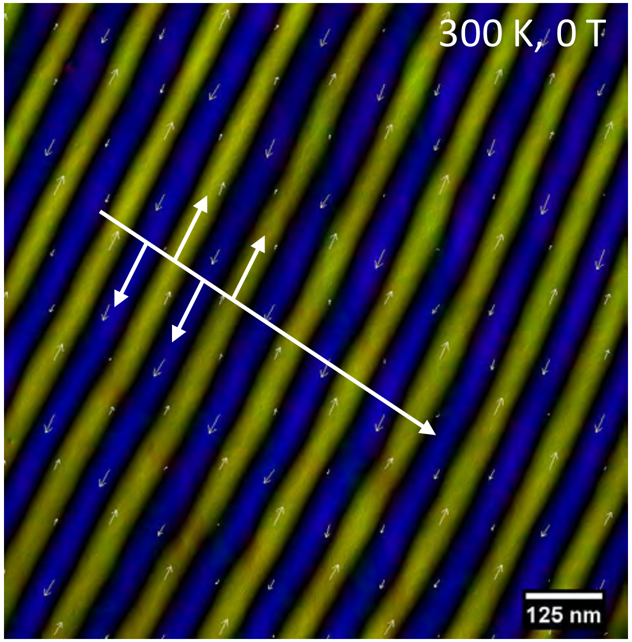


helical ll [012]

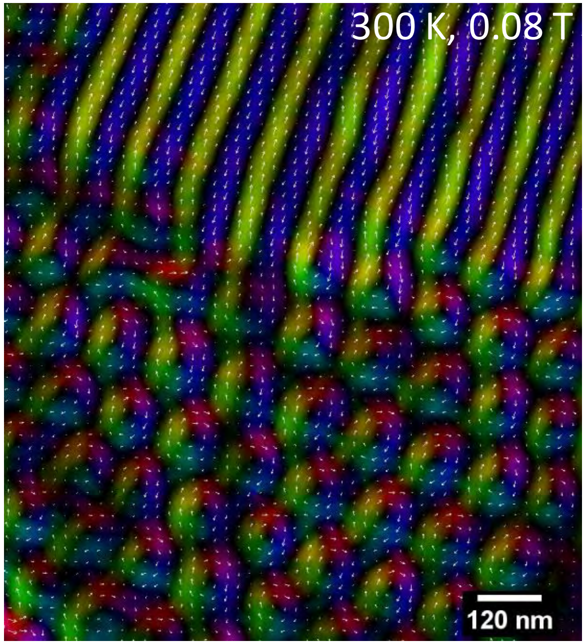


cycloid ll [012]

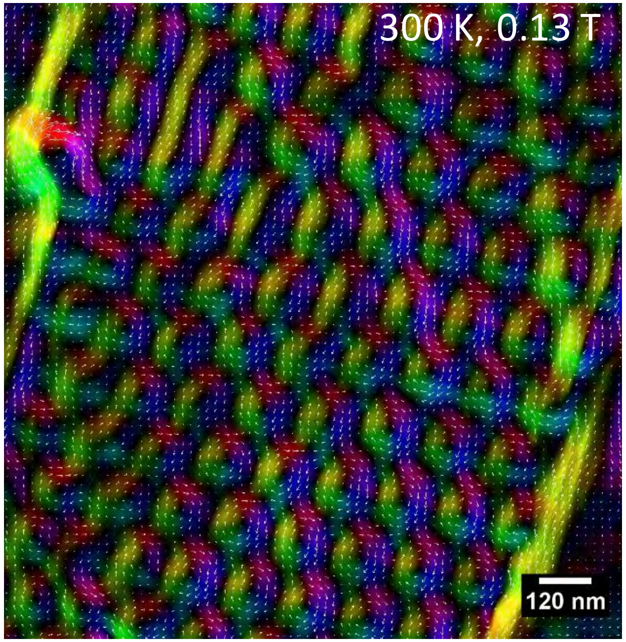
Skyrmions in Pd-doped Mn-Pt-Sn



Helimagnetic phase at zero field



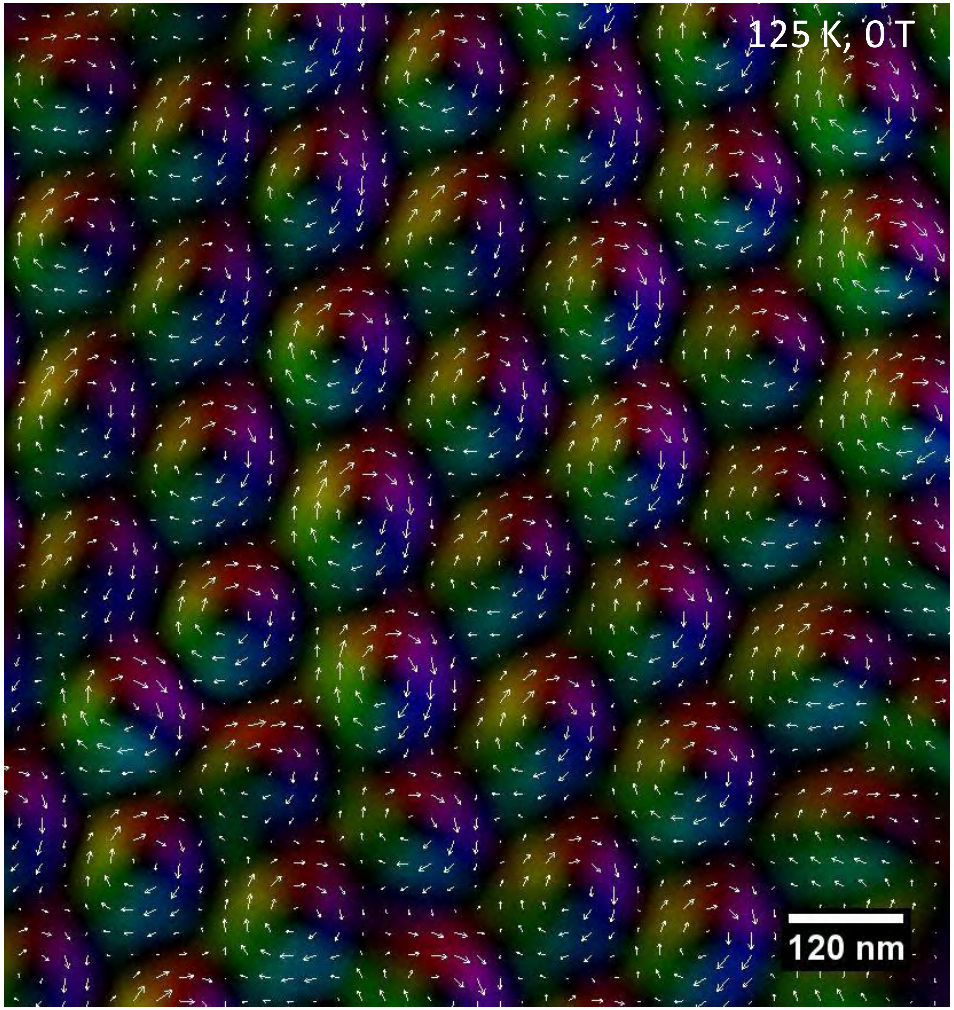
Helimagnetic and skyrmions in small field

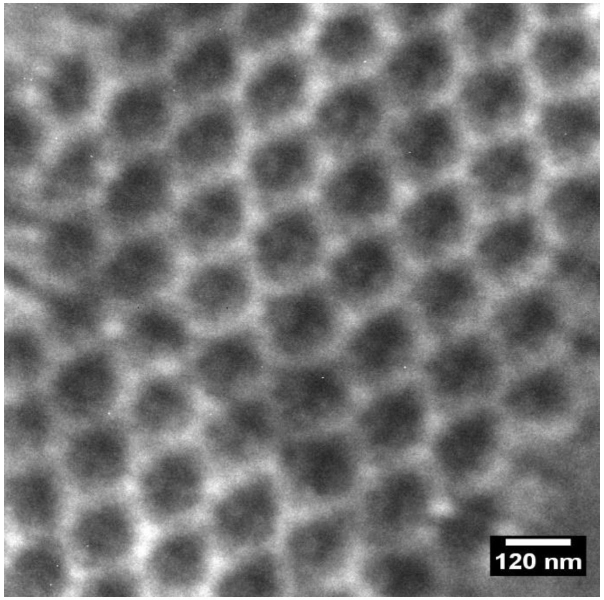


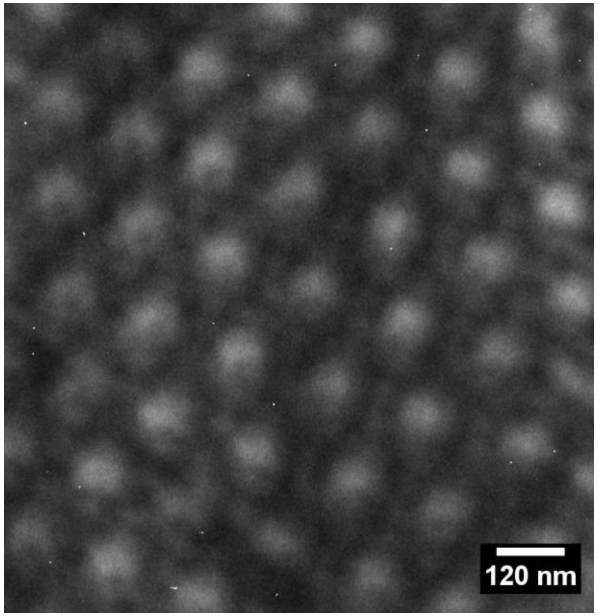
Skyrmions at higher field

The skyrmion phase can be stabilized up to 400 K, which is the T_C of the present material.

Skyrmions in Pd-doped Mn-Pt-Sn

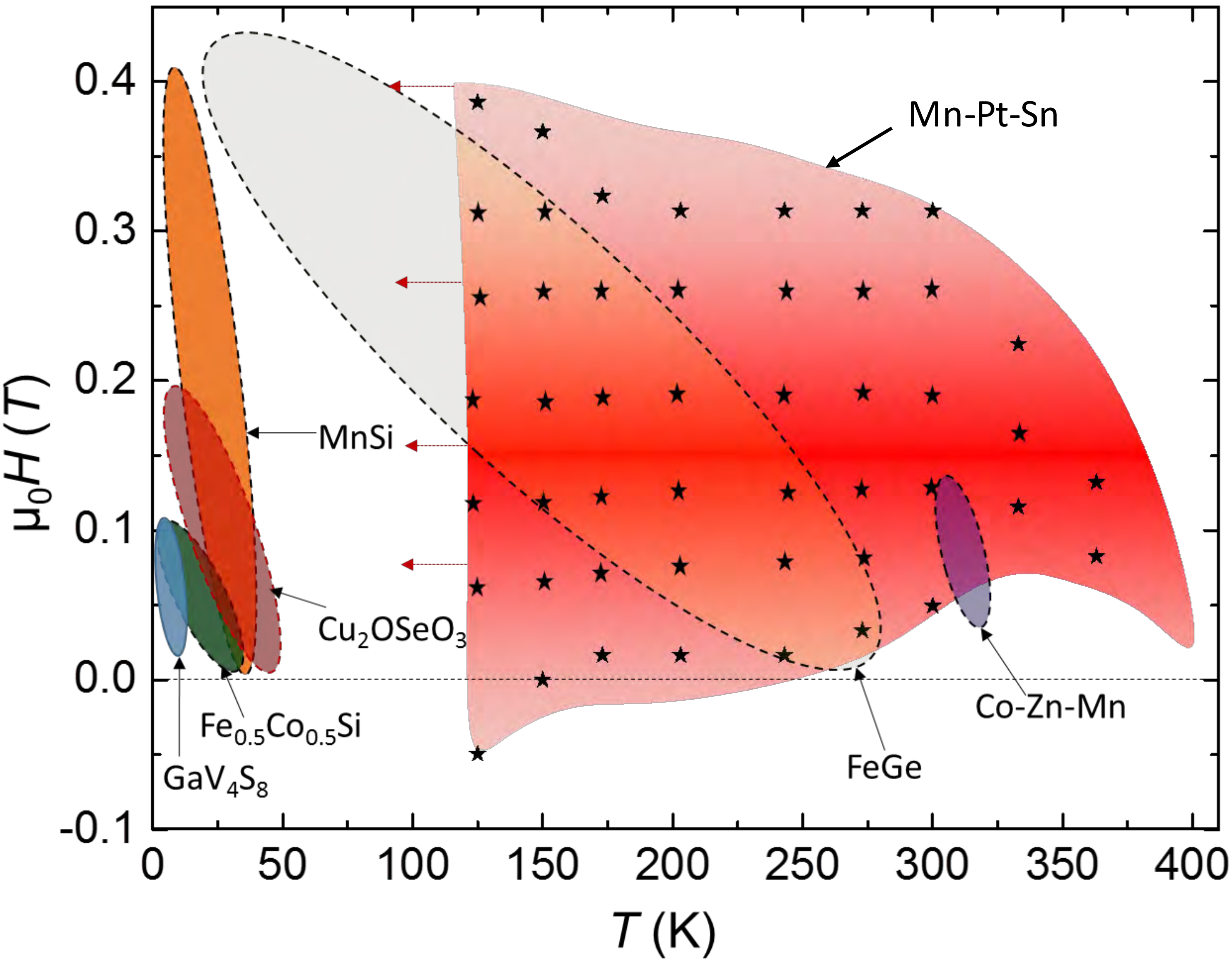






Skyrmion phase can be stabilized in zero magnetic field at low temperatures.

Skyrmions in Pd-doped Mn-Pt-Sn



Summary:

✓ *Designing compensated magnetic state for antiferromagnetic spintronics.*

We have successfully designed compensated magnetic state in Mn-Pt-Ga system and use this to achieve a large exchange bias.

✓ *AHE in non-collinear antiferromagnets.*

We have shown that Mn_3Ge, which has a non-collinear antiferromagnetic spin structure can give a large AHE at room temperature.

✓ *Heuslers in terms of non-collinear magnetism.*

Existence of both non-collinear magnetic states and skyrmions have been shown in the Heusler system.

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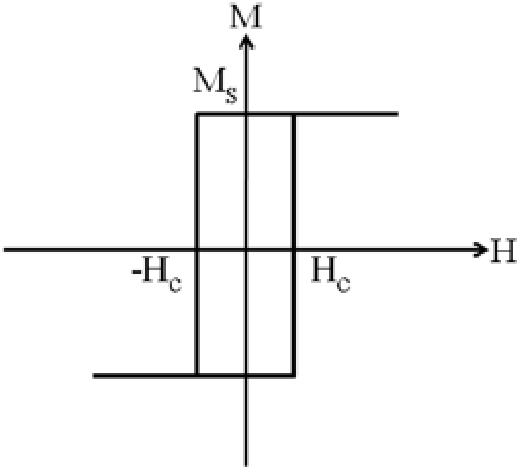
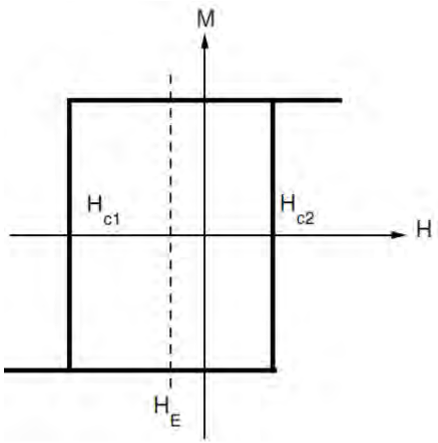
Thank You

What is exchange bias?



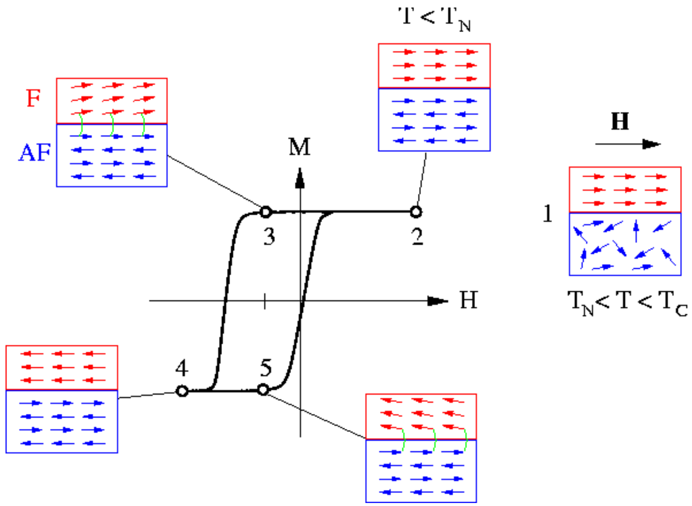
Conventional FM hysteresis loop



Exchange-biased hysteresis loop

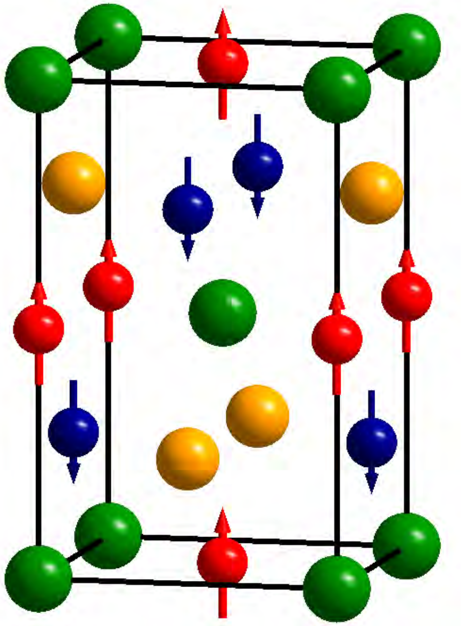
Technological importance:

- Extensively used in all GMR and TMR based devices
- Permanent magnet



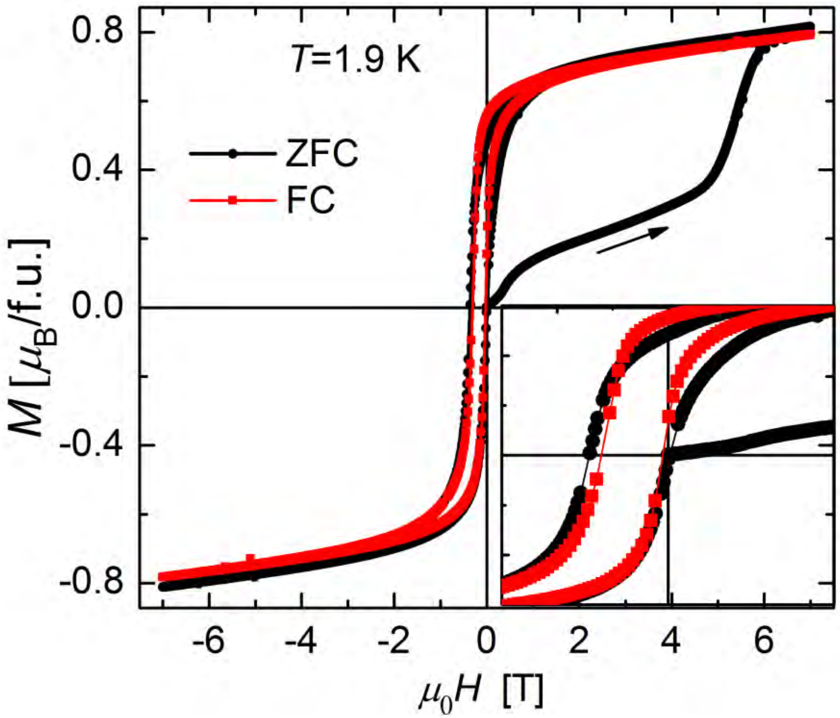
Interfacial exchange interaction between FM and AFM layers

Mn_2PtGa: ZFC exchange bias



MnI=3.65μ_B, MnII=3.1μ_B

M=3.65-3.1=0.55μ_B

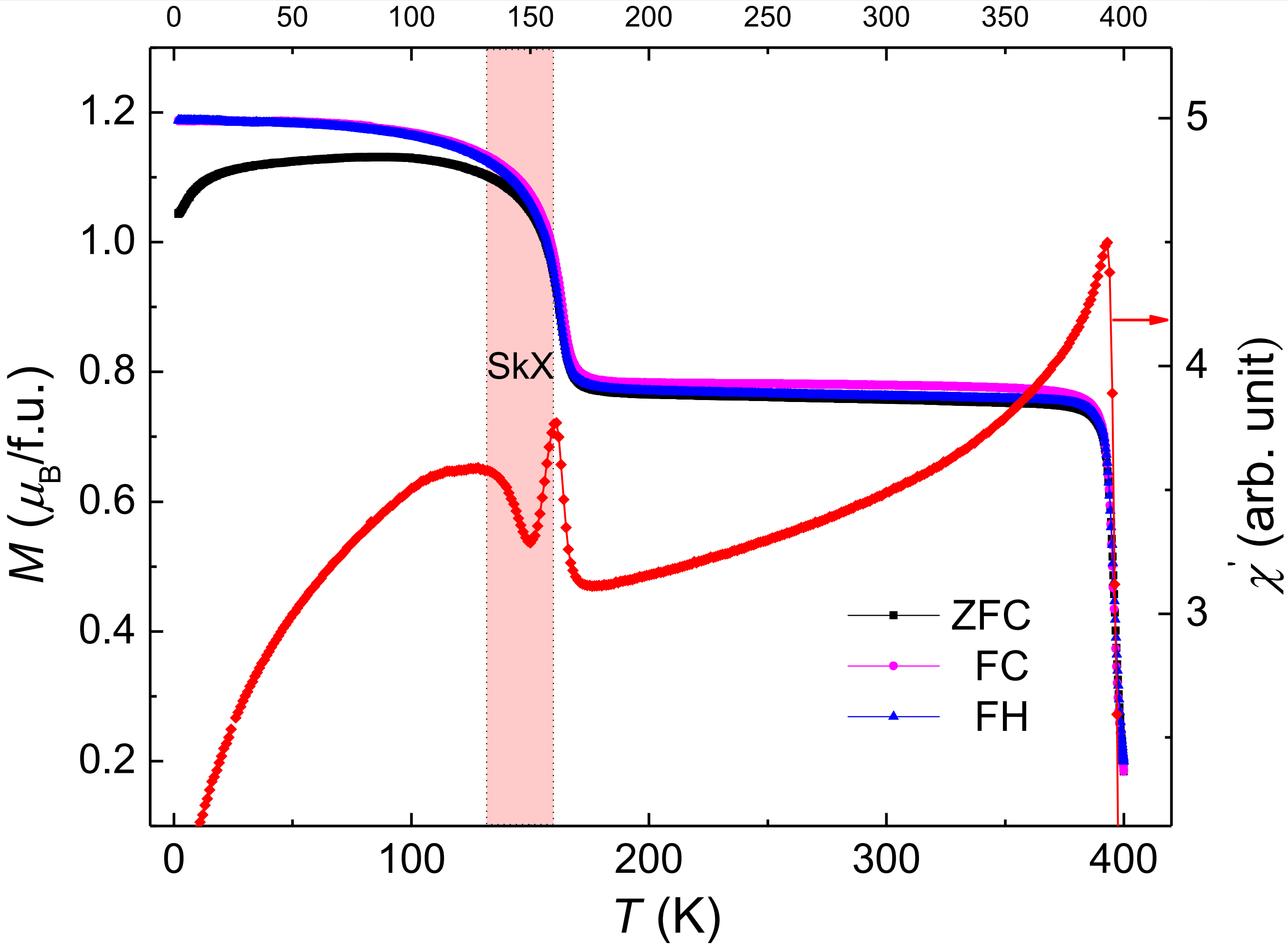


Tetragonal crystal structure and ferrimagnetic ordering

- ✓ A large EB of 0.2T both in ZFC and FC modes.

Nayak et al., Phys. Rev. Lett. 110, 127204 (2013).

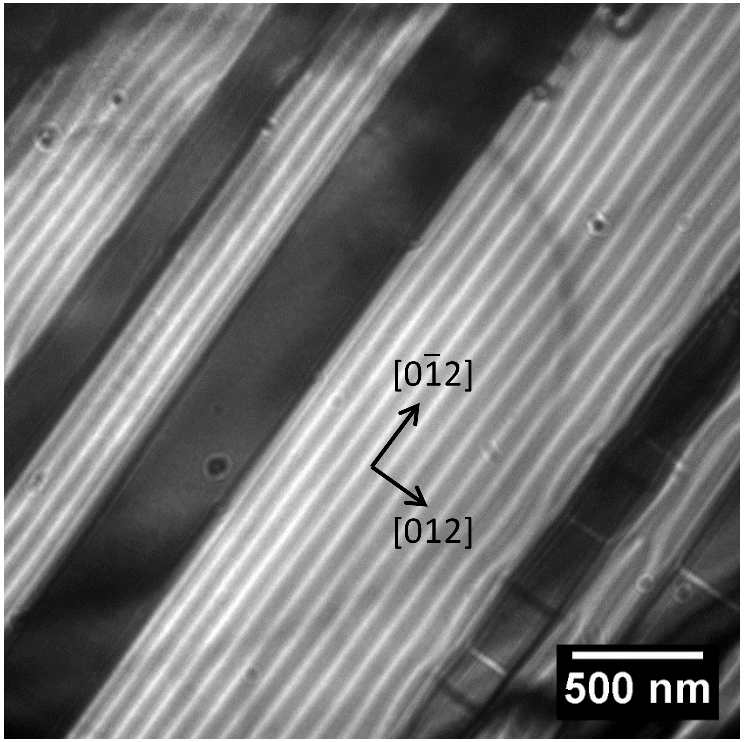
Non-collinear magnetic structure in Mn-Pt-Sn

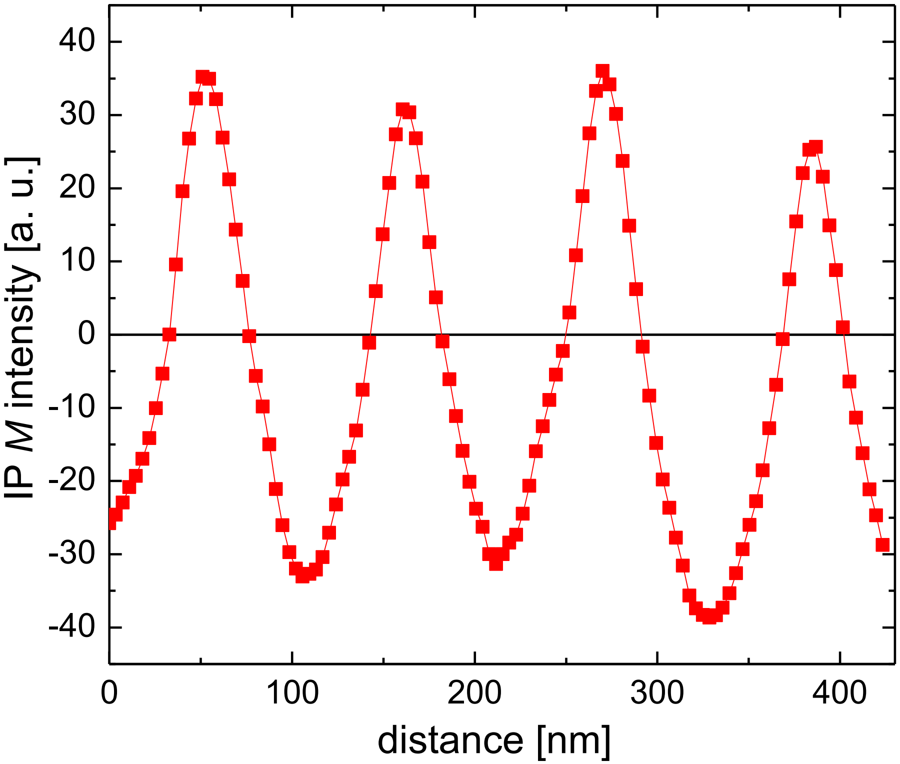


- A spin-reorientation transition is observed around 150 K in Mn-Pt-Sn .
- The ac-susceptibility measurements show the existence of a dip (in zero magnetic field) just below the spin-reorientation transition.

Nayak et al., Under review.

Non-collinear magnetic structure in Mn-Pt-Sn





- These stripes may correspond to the helicoid/cycloid magnetic structure with periods nearly 110 nm.

Nayak et al., Under review.