Chapter 8

Spintronics in Antiferromagnets

韩伟

量子材料科学中心

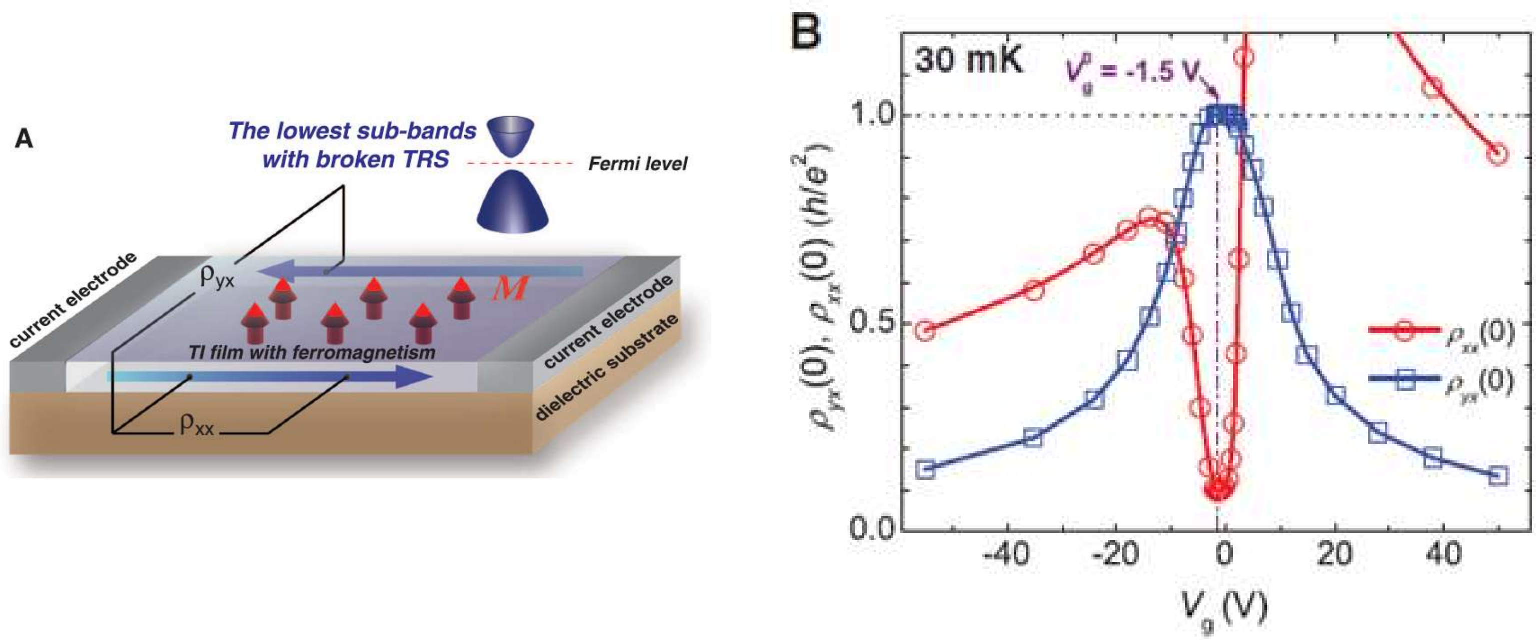
2018年12月14日

Review of last class

1. **Topology**
2. **Quantum anomalous Hall effect**
3. **Skyrmions**
4. **Spin-momentum locking of 3D TI**
   - **Spin injection**
   - **Spin orbit torque**
   - **Spin Seebeck effect**

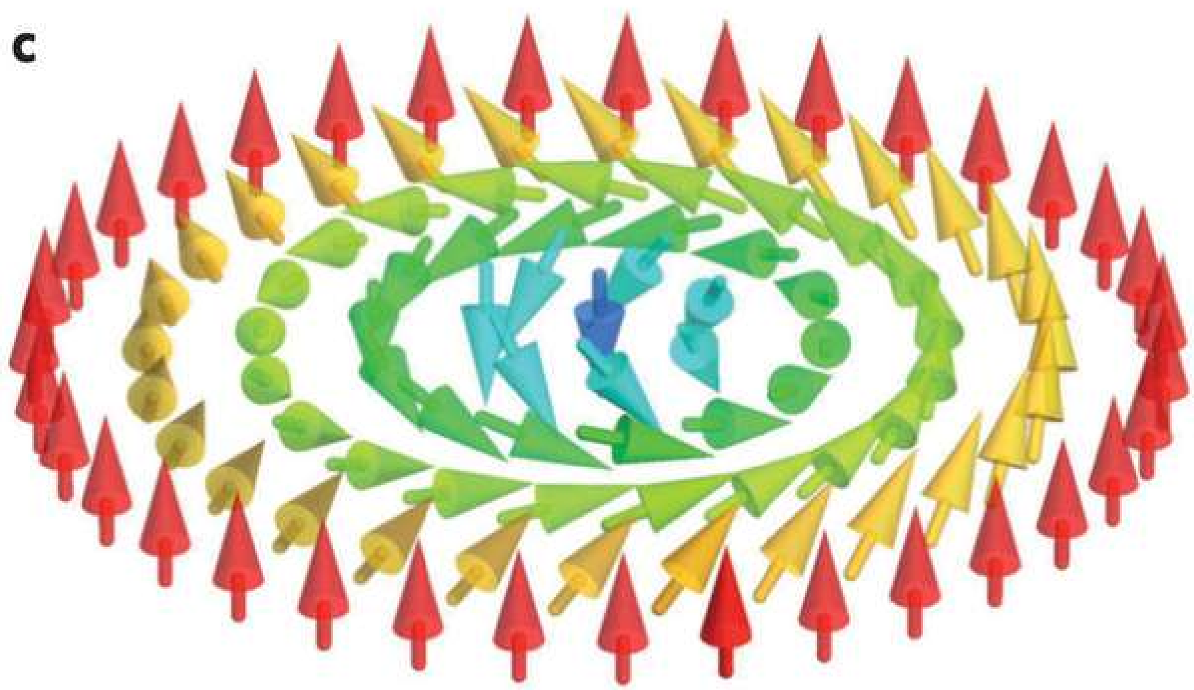
Review of last class

2. Quantum anomalous Hall effect



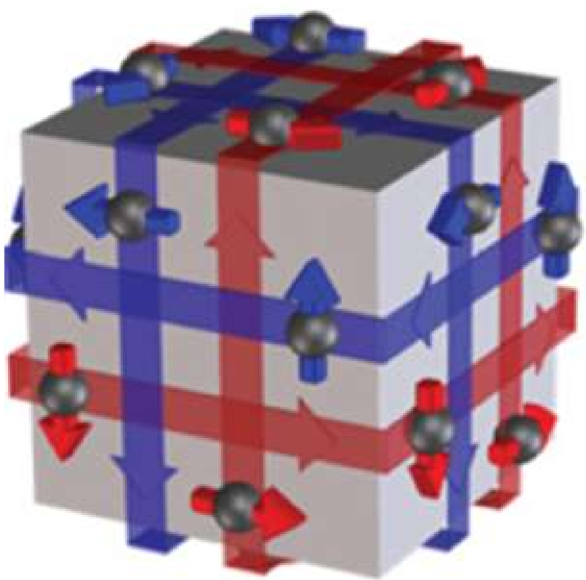
Review of last class

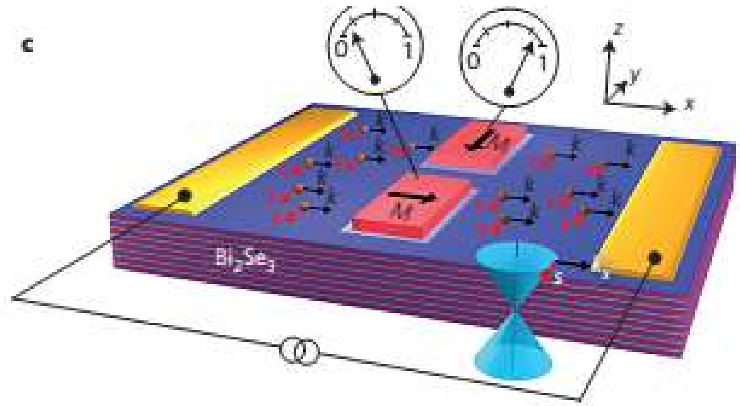
3. Skyrmions

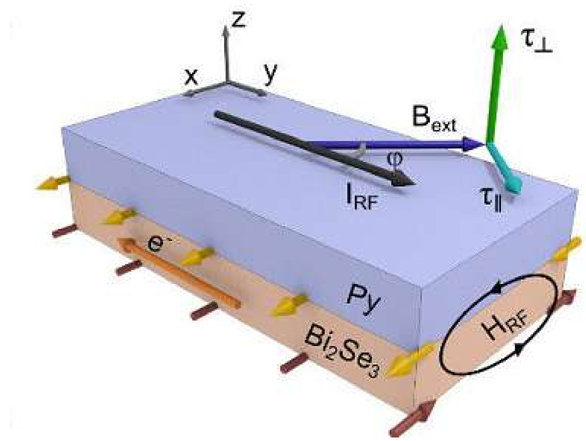


Review of last class

4. Spin-momentum locking of 3D TI





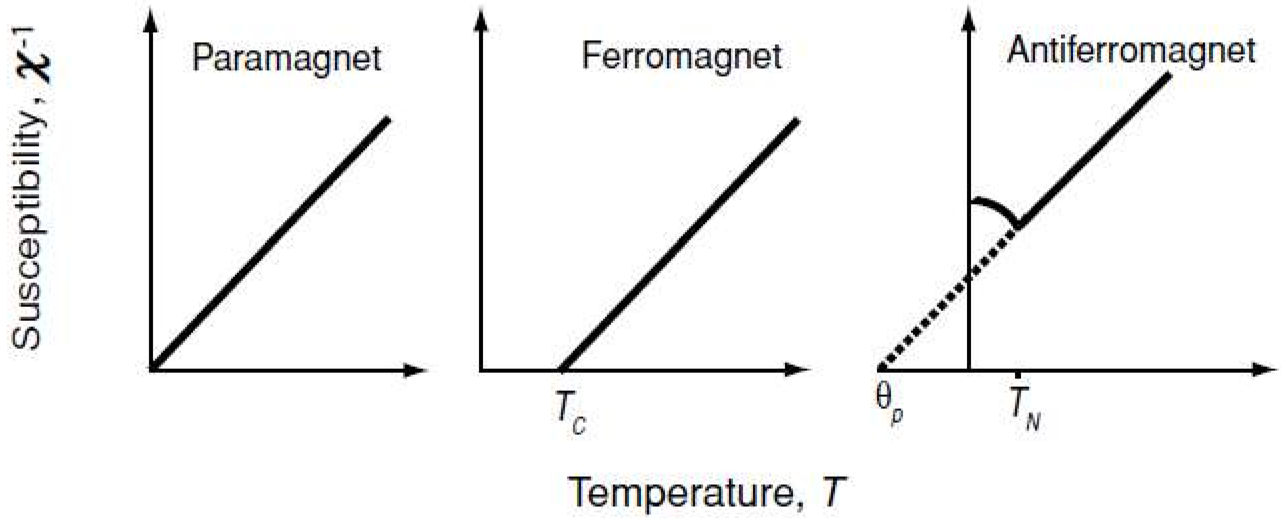


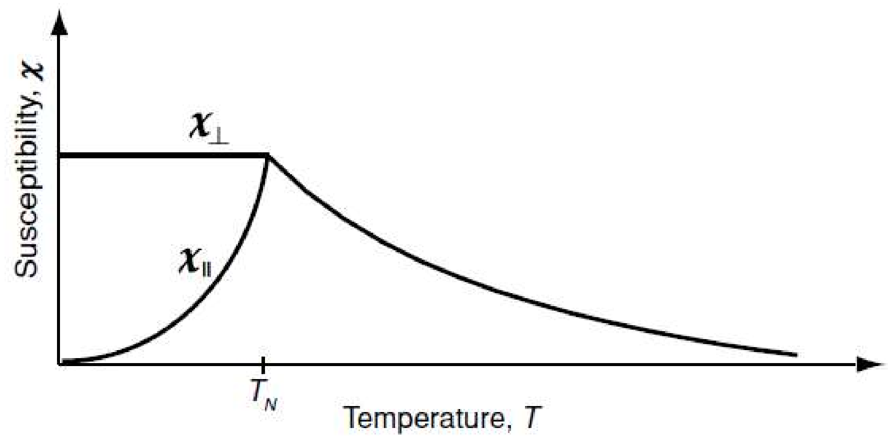
Outline

1. **Antiferromagnetism and Exchange bias**
2. **Spin Seebeck effect in AFM**
3. **AMR of AFM**
4. **Switching of AFM**
5. **Anomalous Hall effect in AFM**
6. **Spin orbit torque in AFM**
7. **Spin current in AFM**

1. Antiferromagnetism and Exchange bias

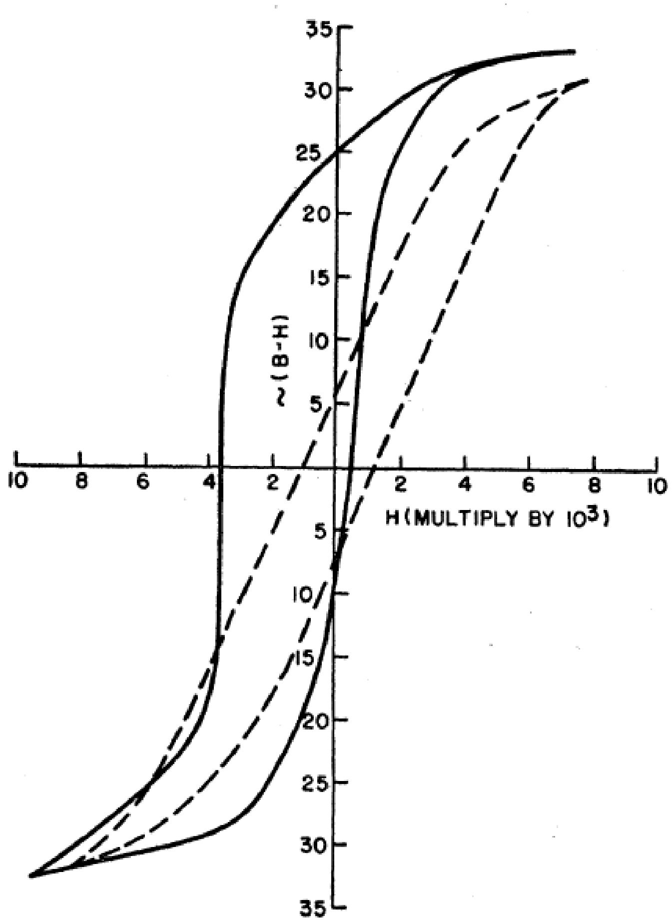
Antiferromagnetism and Exchange bias



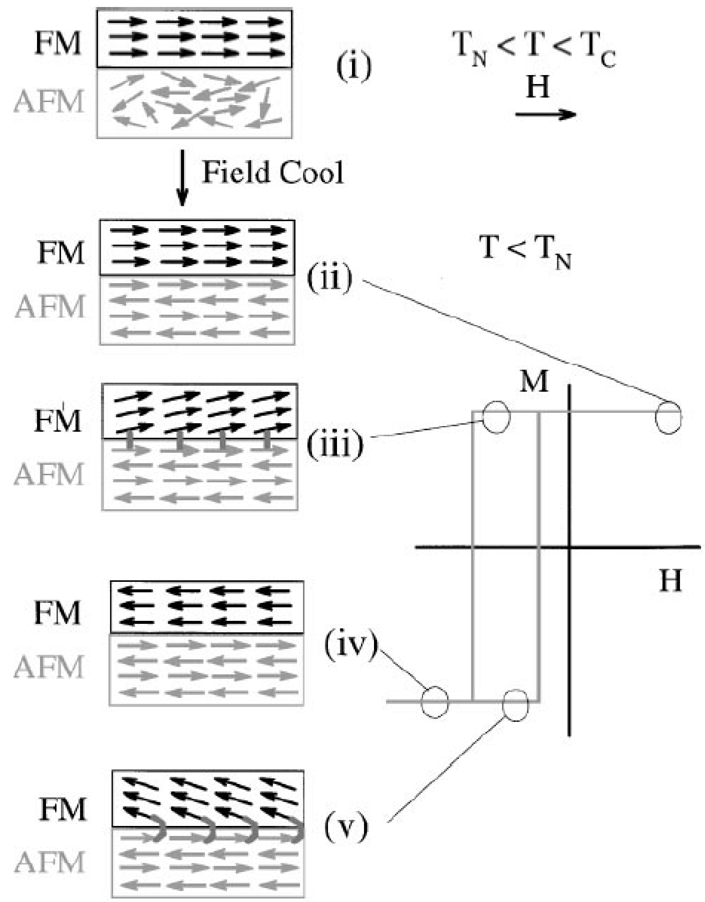


Coey, Book Magnetism and Magnetic Materials (2009)

Antiferromagnetism and Exchange bias

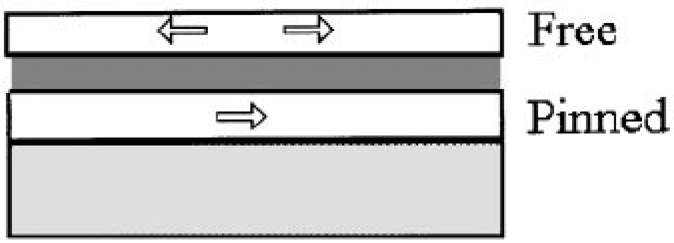


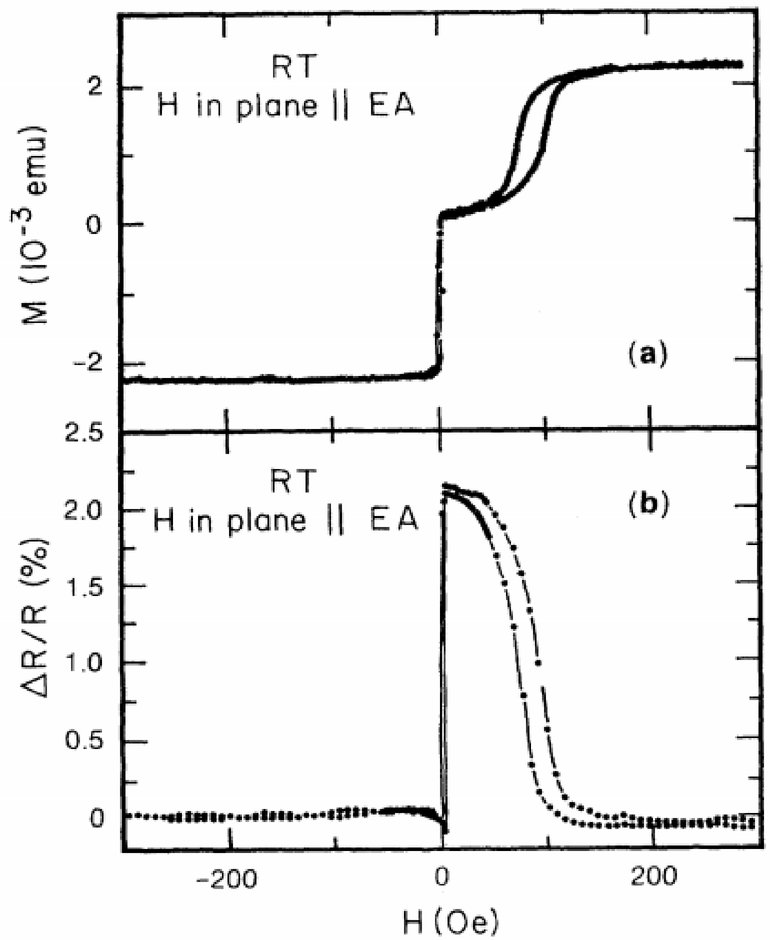
W. H. Meiklejohn and C. P. Bean
Physical Review **102**, 1413 (1956).



J. Nogue and I. K. Schuller JMMM **192**, 203 (1999).

Antiferromagnetism and Exchange bias





NiFe(15nm)/Cu(2.6nm)/
NiFe(15nm)/FeMn(10nm)

B. Dieny et al PRB, **43** 1297 (1991).

Antiferromagnetism and Exchange bias

A

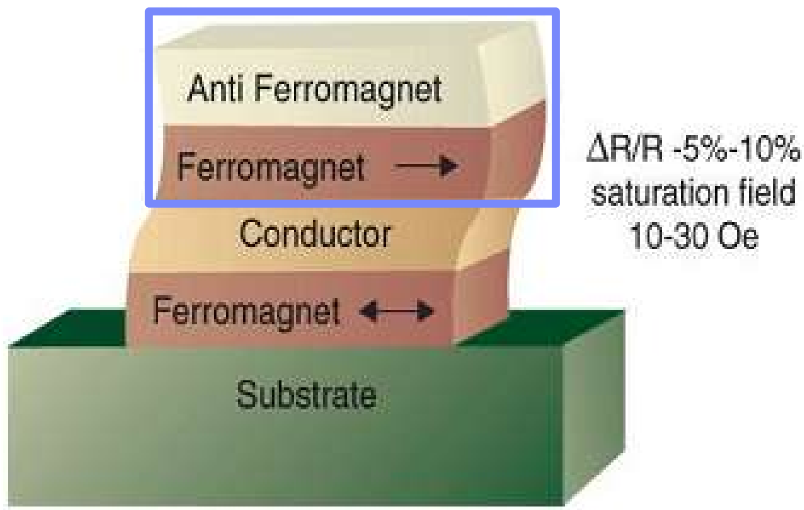


Fig. 1. Spin-dependent transport structures. **(A)** S

Yang & Parkin, Nature Nanotech (2014)

Antiferromagnetism and Exchange bias

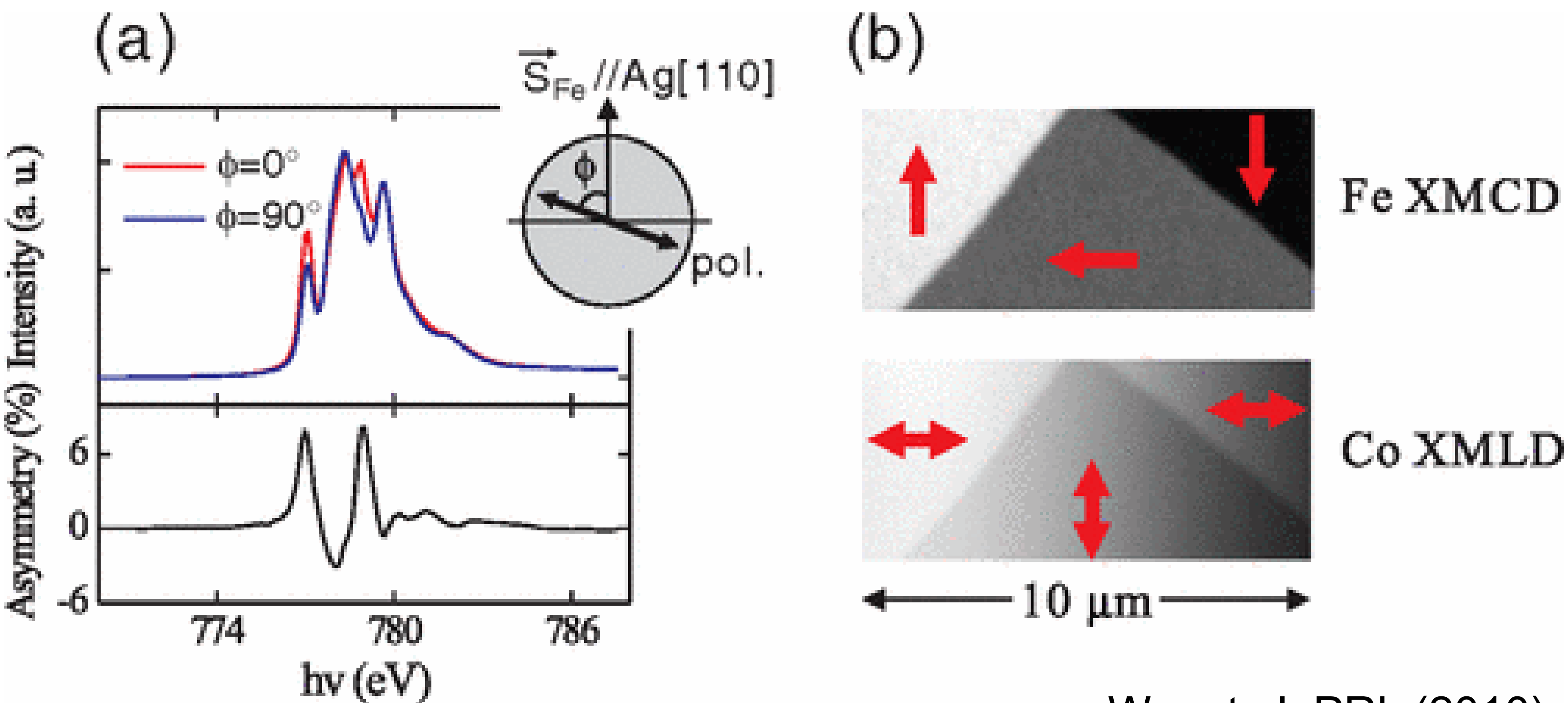
Table 6.1. Some common antiferromagnets

	Structure	T_N (K)	θ_p (K)	$\mu_0 M_\alpha$ (T)
Cr	sdw	311		0.20
Mn	Complex	96	~ -2000	0.20
NiO	Néel	524	-1310	0.54
αFe_2O_3	Canted	958	-2000	0.92
MnF_2	Néel	67	-80	0.78
FeMn	Néel	510		0.53
$IrMn_3$	Néel	690		0.50

sdw – spin density wave; Néel – two collinear sublattices.

Exchange bias

Antiferromagnetic CoO spins are 90° coupled to Fe spins.

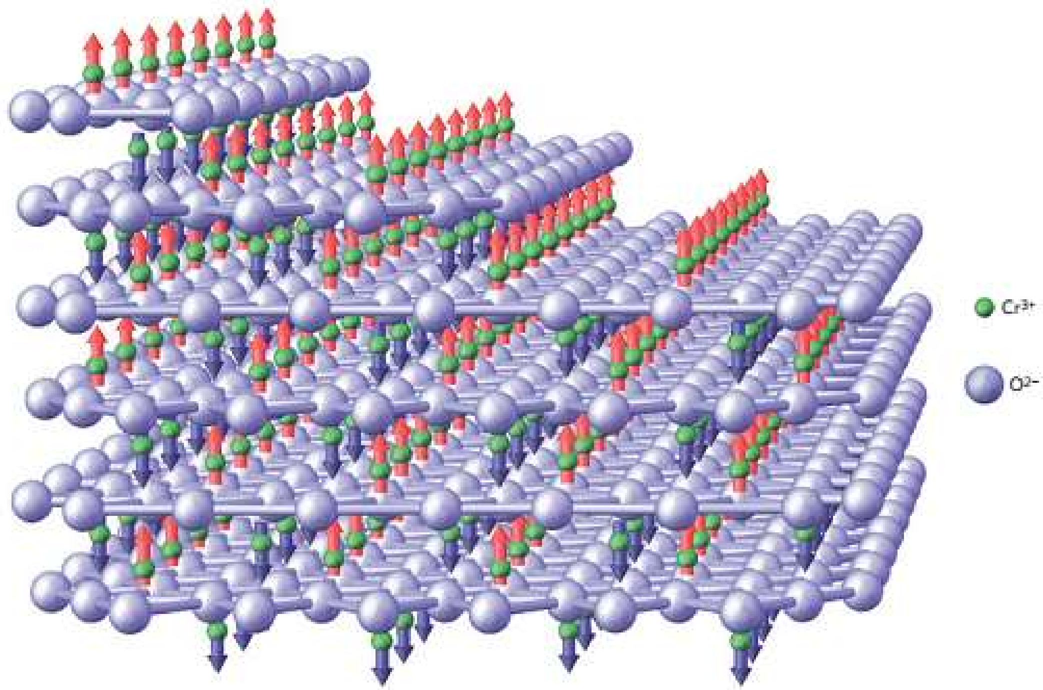


Wu, et al, PRL (2010)

Exchange bias

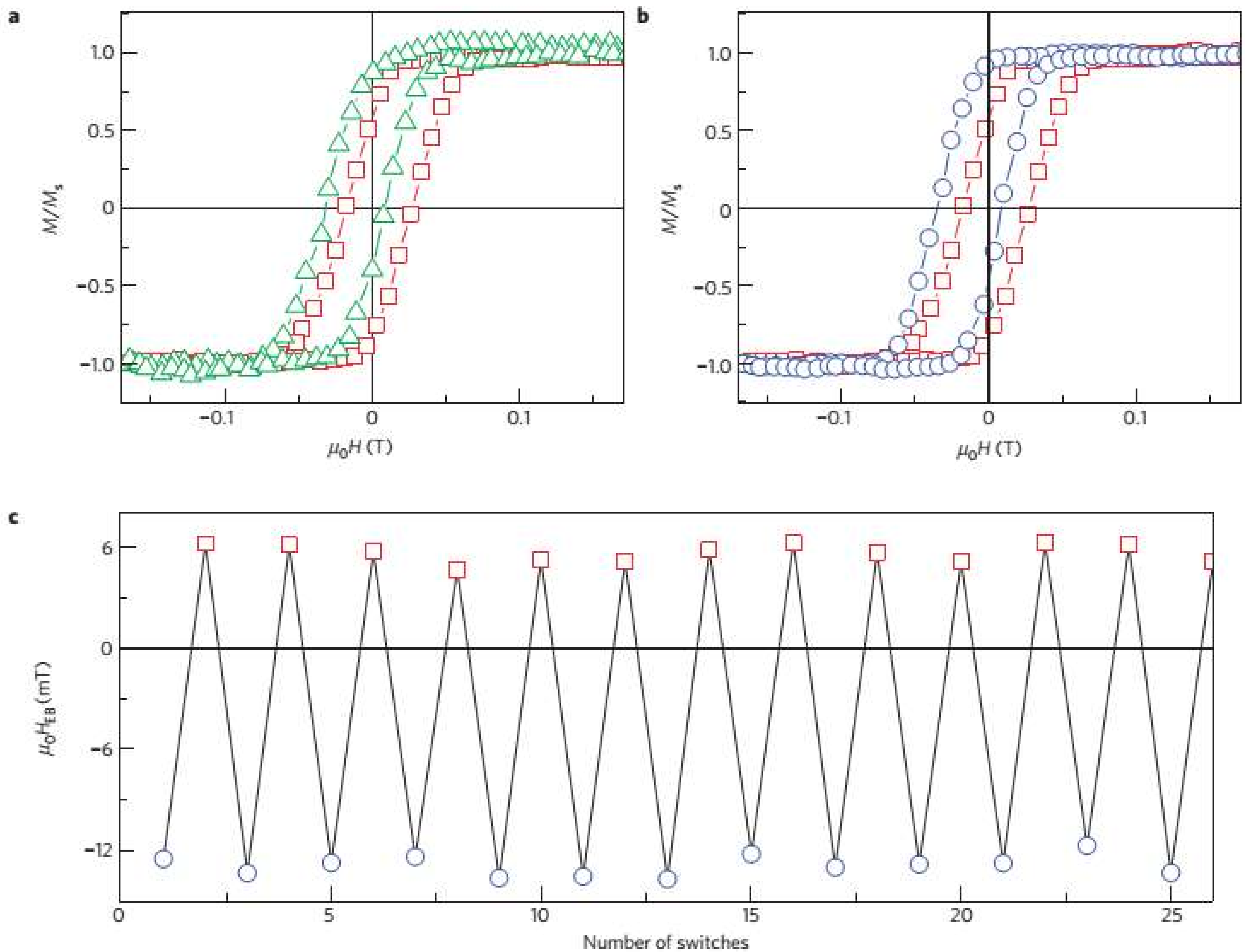
Collinear exchange coupling

Cr_2O_3



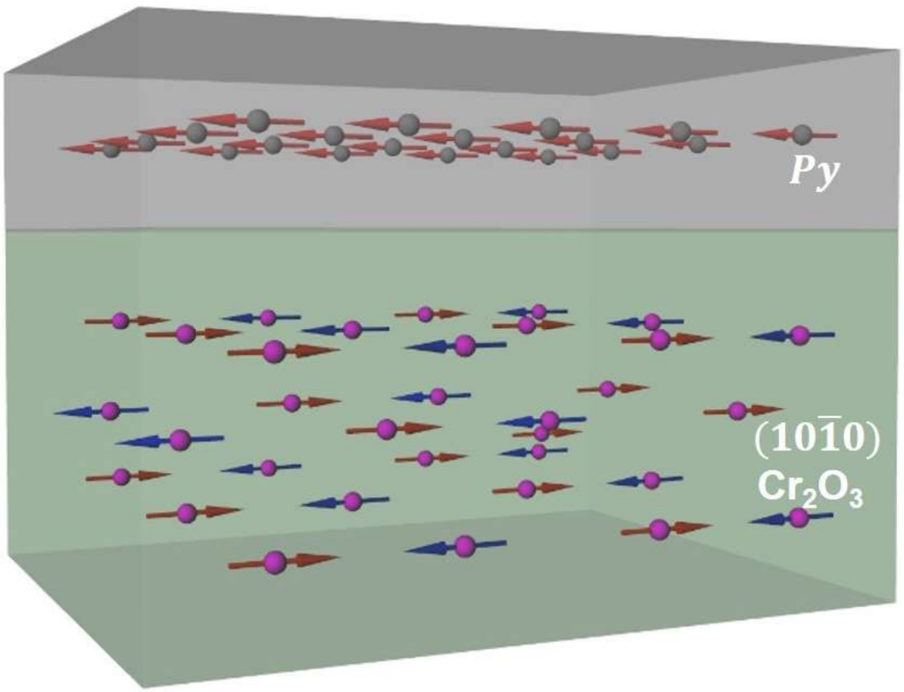
He, et al, Nature Materials (2010)

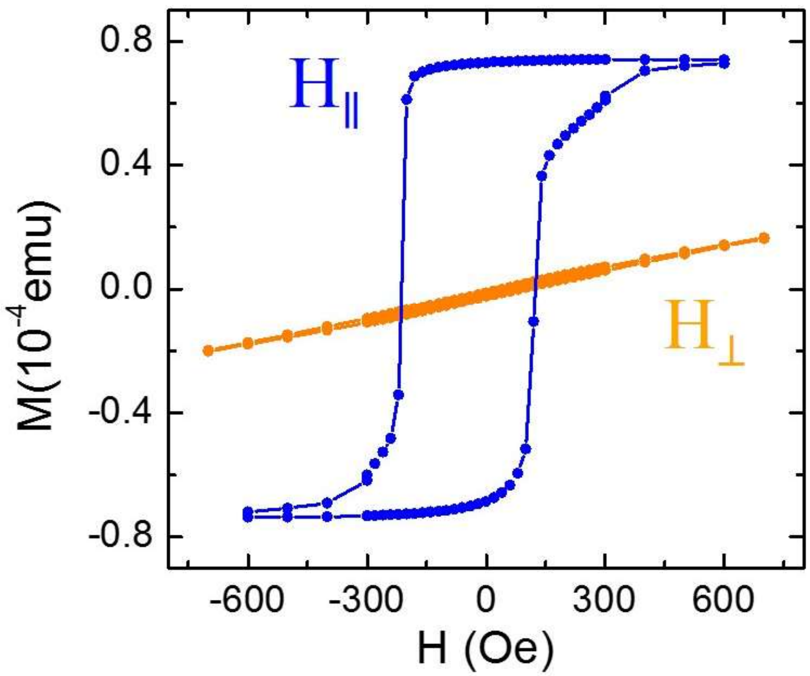
Electric field to tune Exchange bias



Exchange bias

Collinear exchange coupling



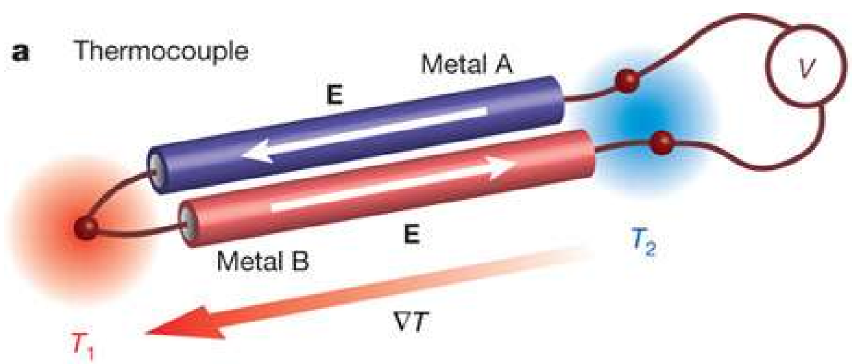


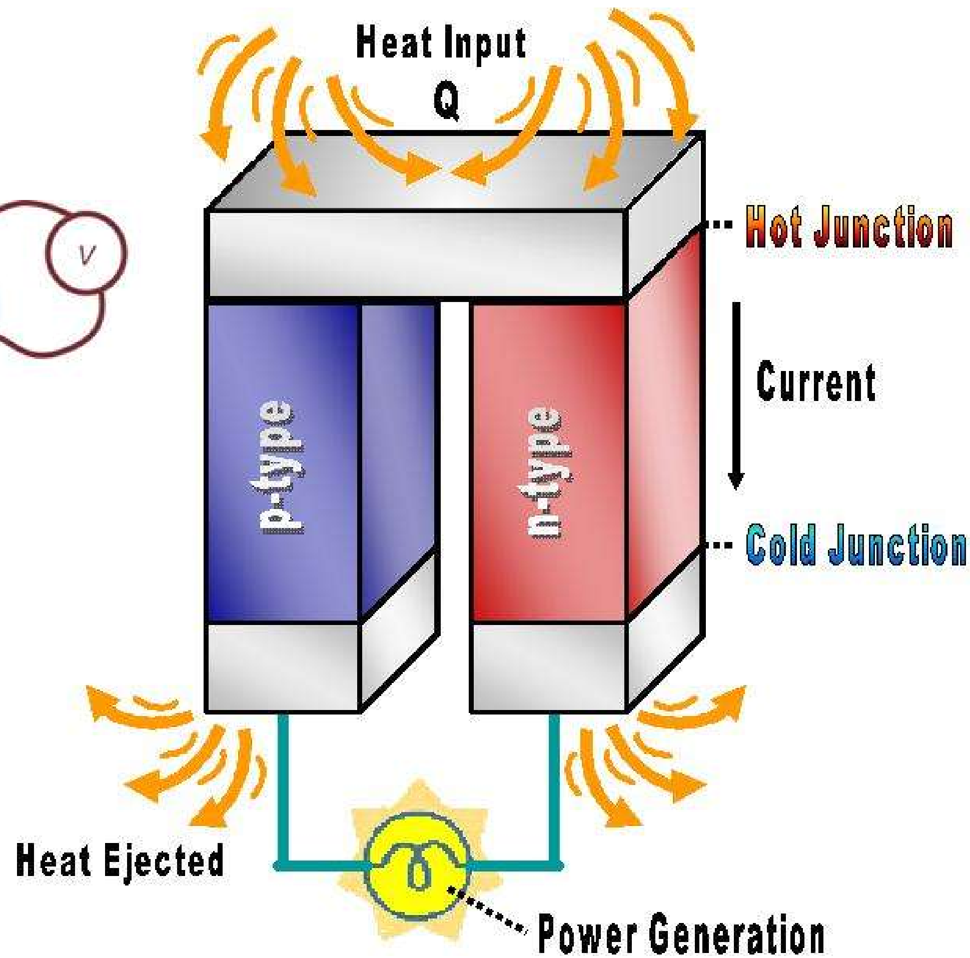
Yuan, et al, Scientific Reports (2016)

Outline

2. Spin Seebeck effect in AFM

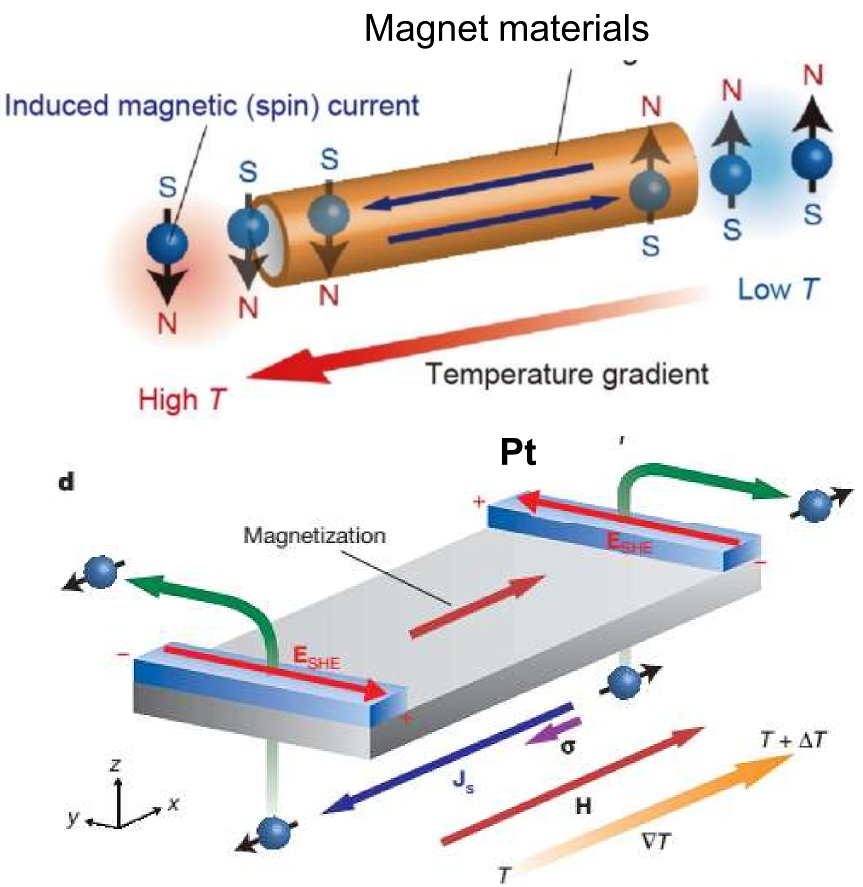
Seebeck effect

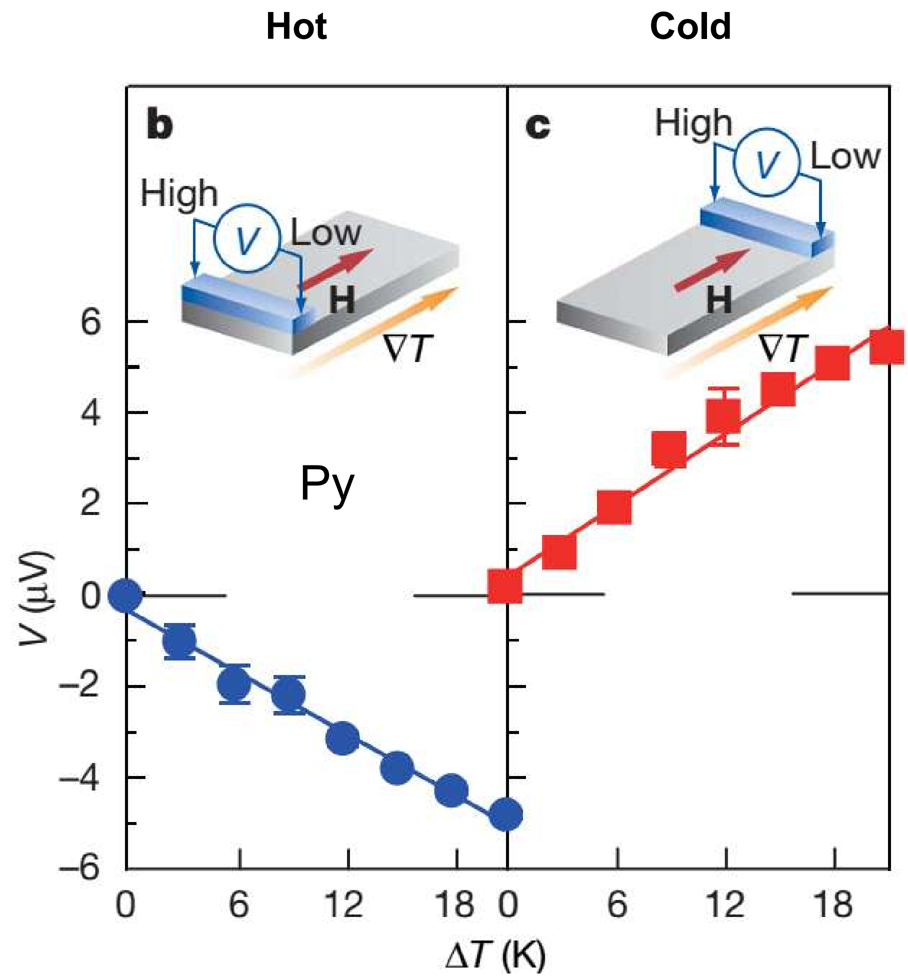




Spin Seebeck effect

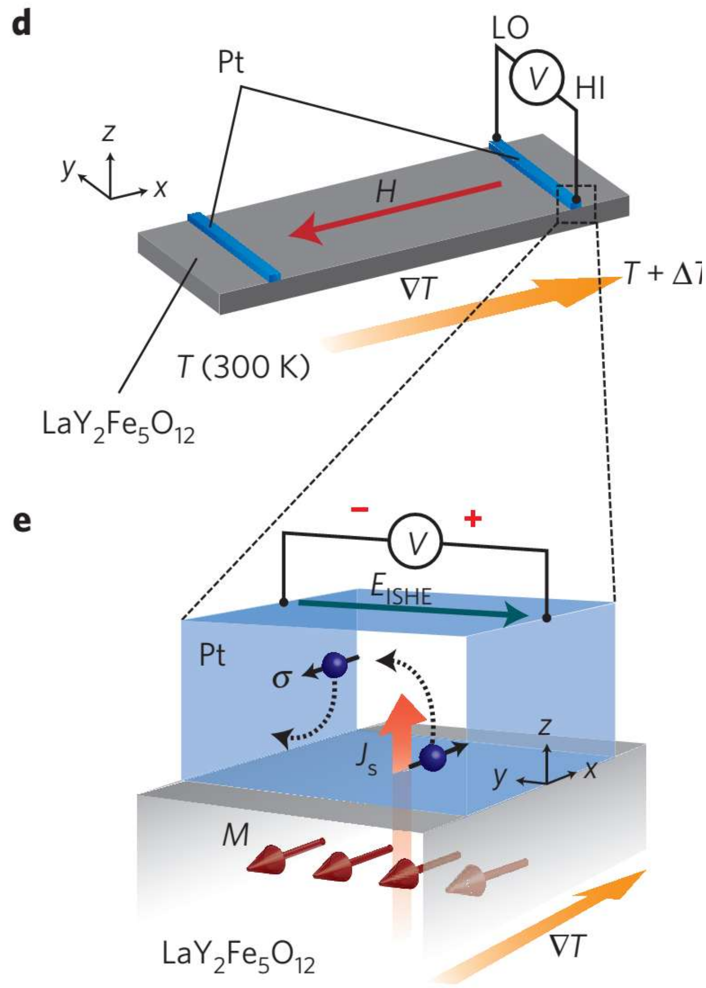
Spin Seebeck effect in FM metal





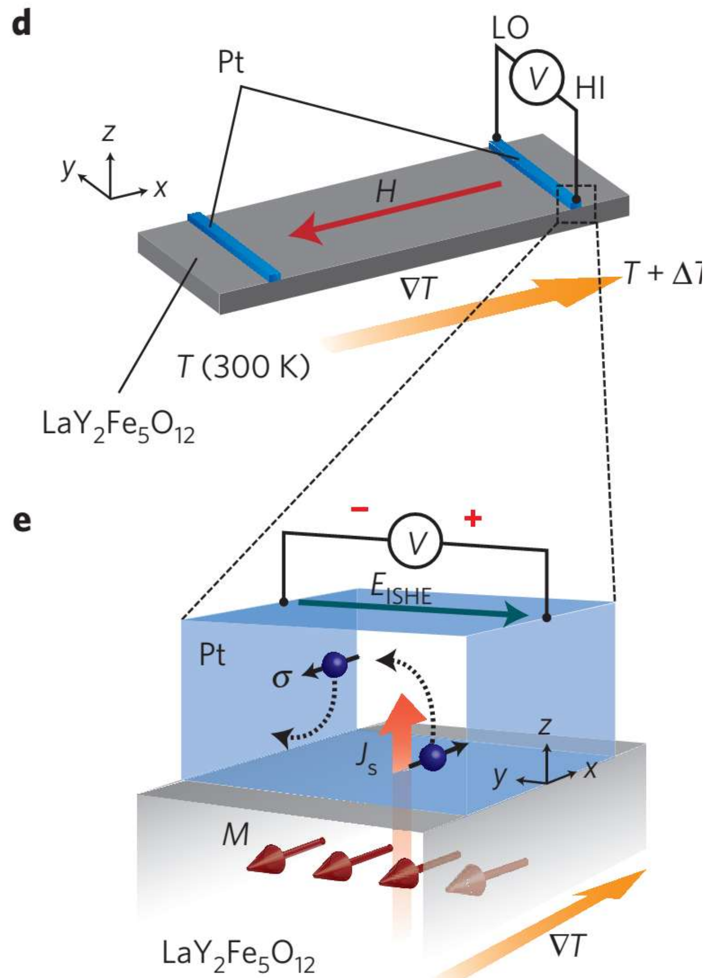
Uchida, et al. Nature (2008)

Spin Seebeck effect



Question:
How about AFM insulator?

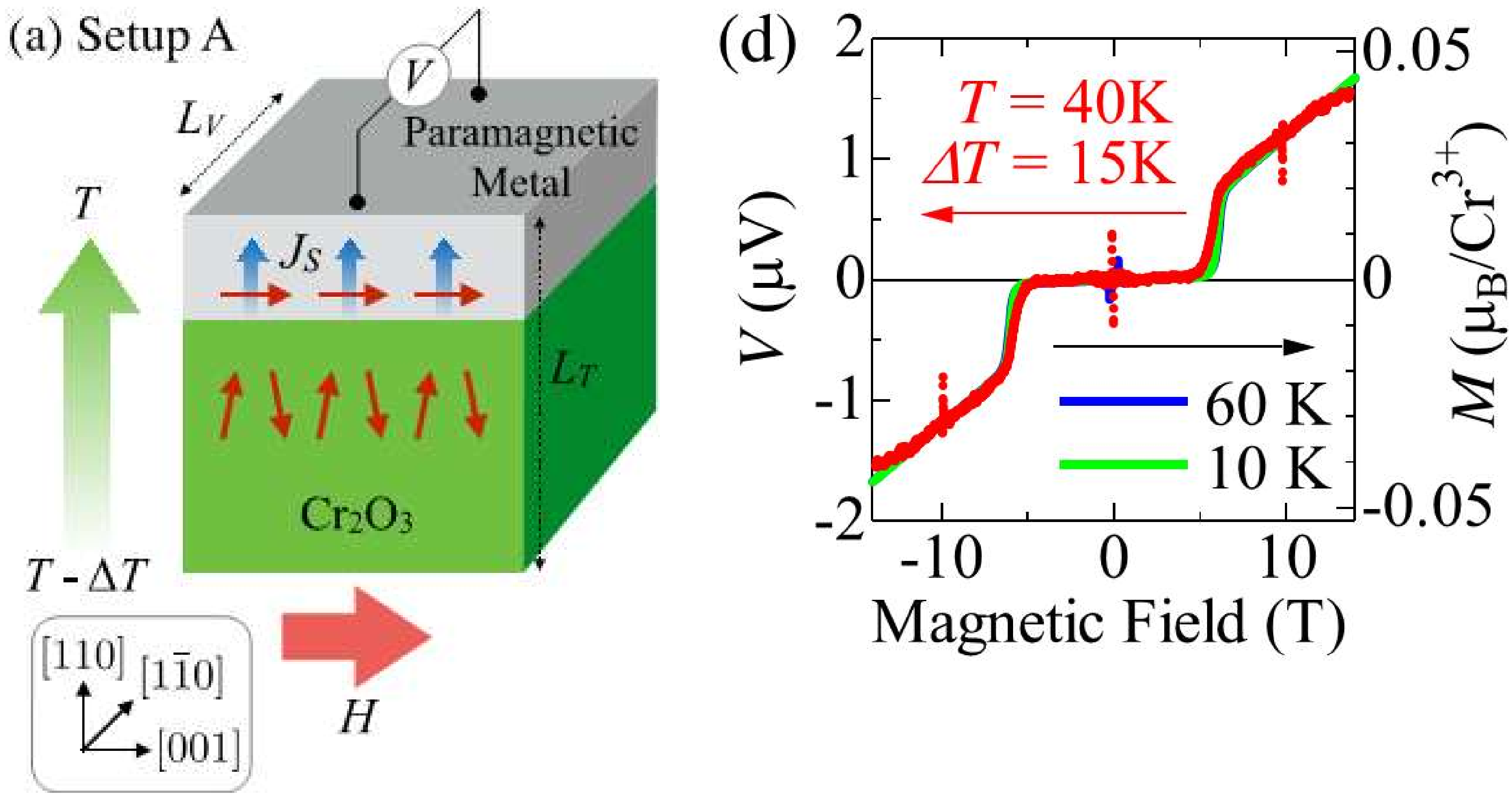
Spin Seebeck effect



Question:
How about AFM insulator?

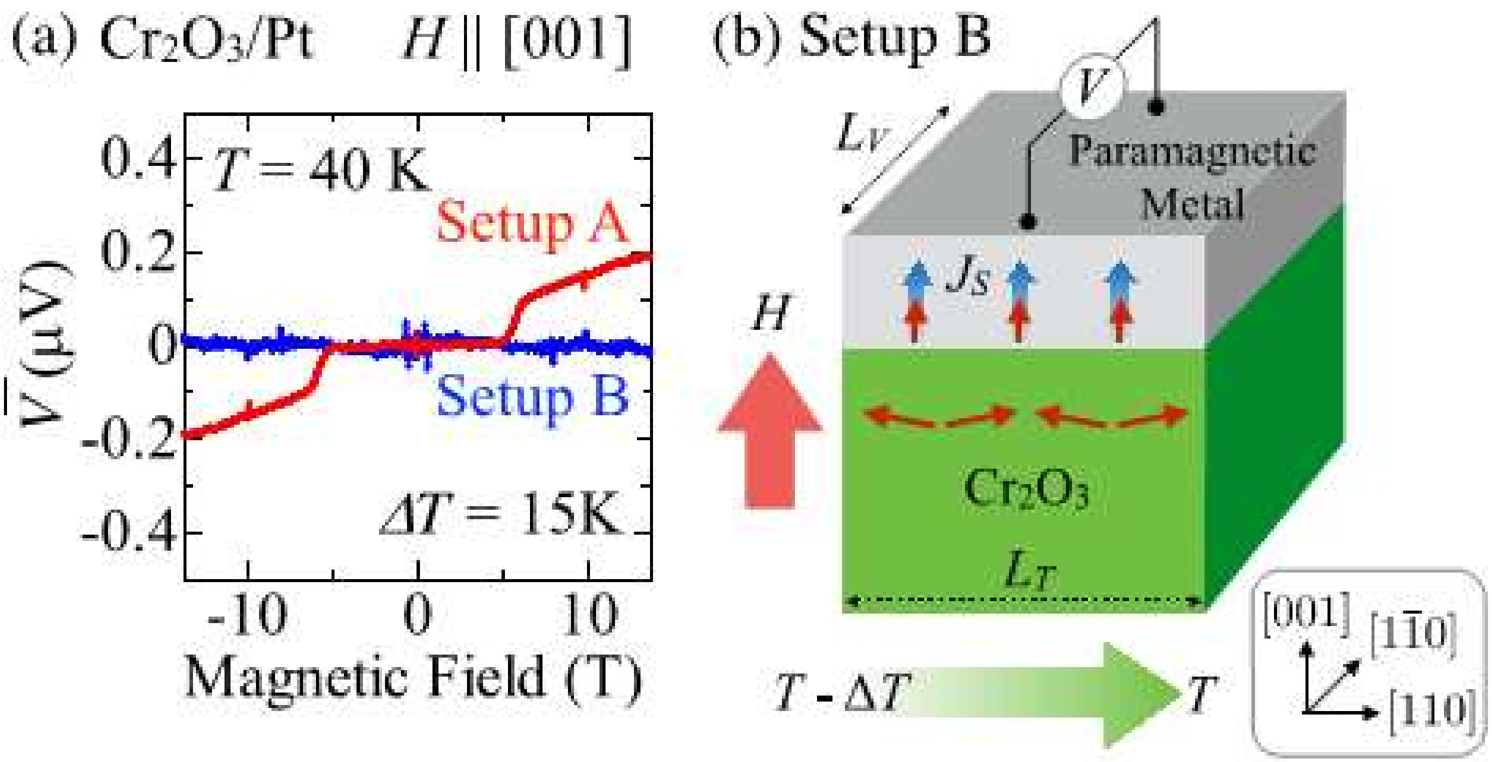
YES!

Spin Seebeck effect in AFM

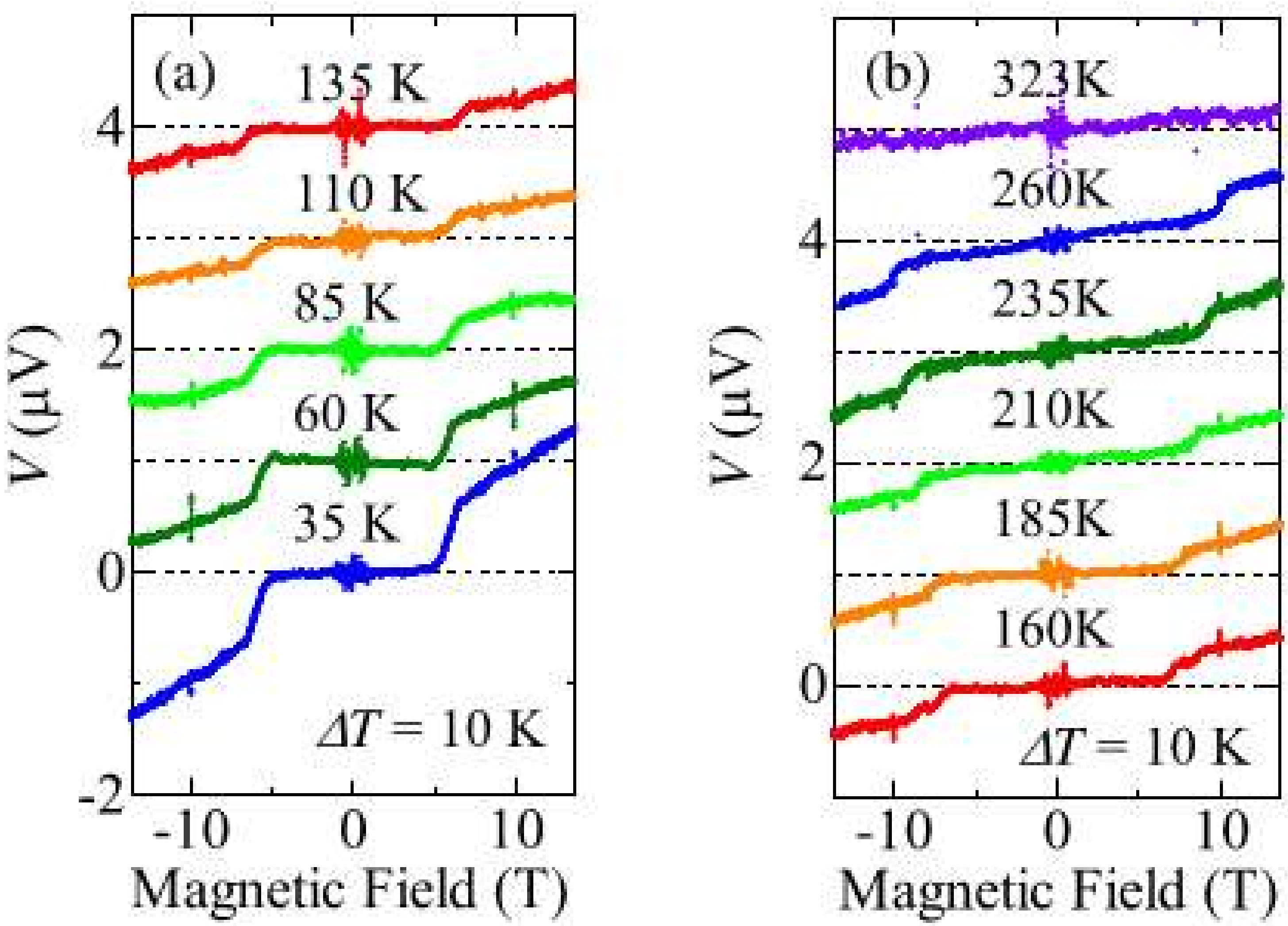


Seki et al, PRL (2015).

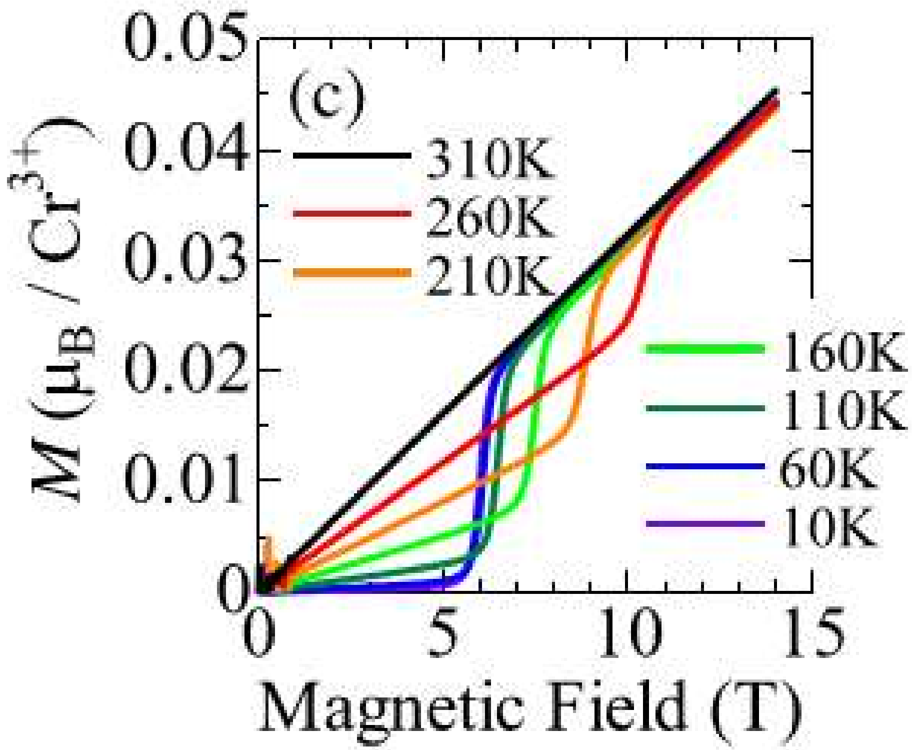
Spin Seebeck effect in AFM

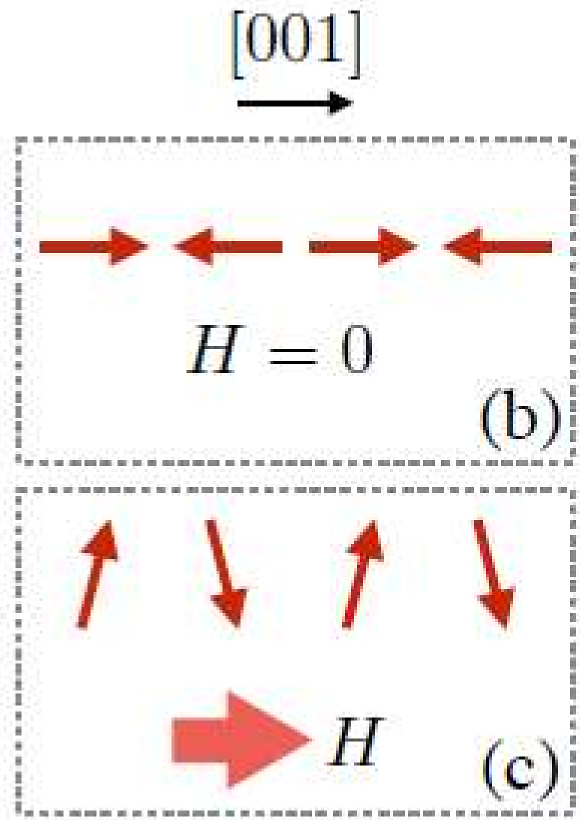


Spin Seebeck effect in AFM

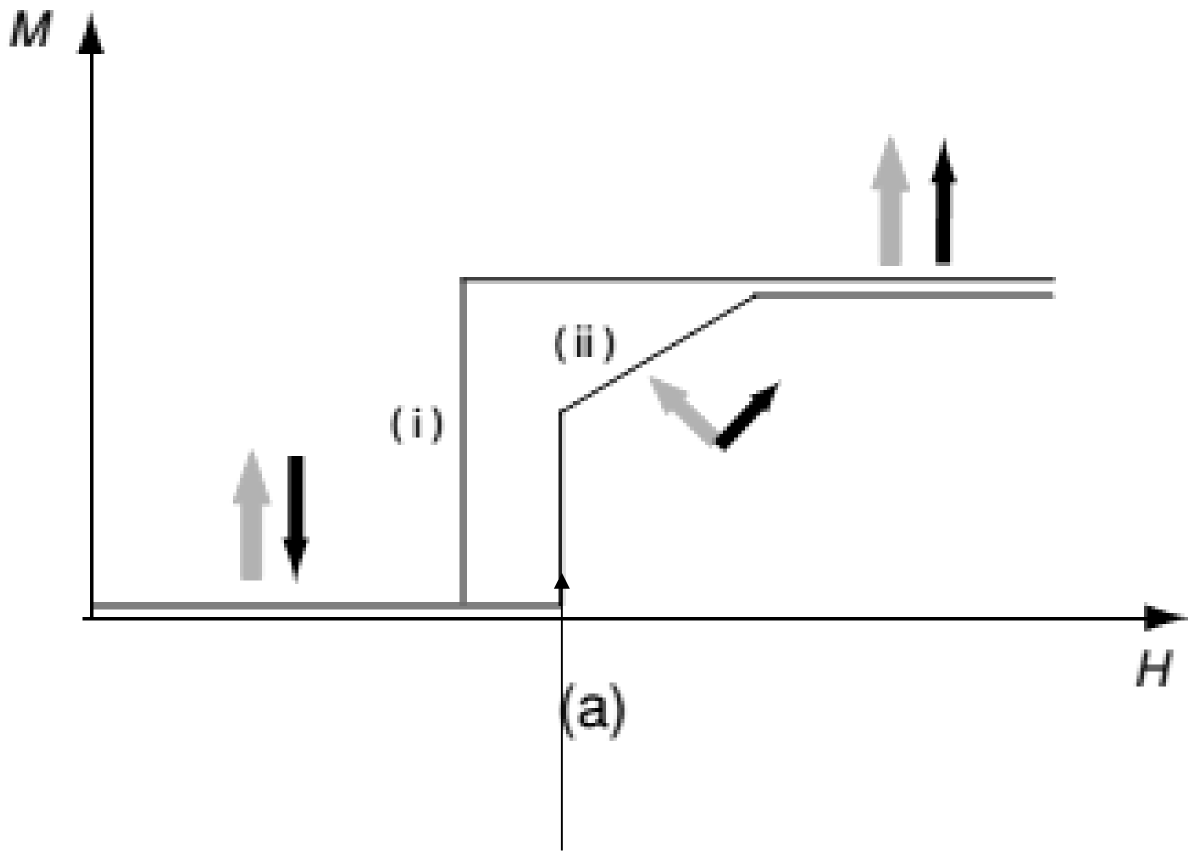


Spin Seebeck effect in AFM



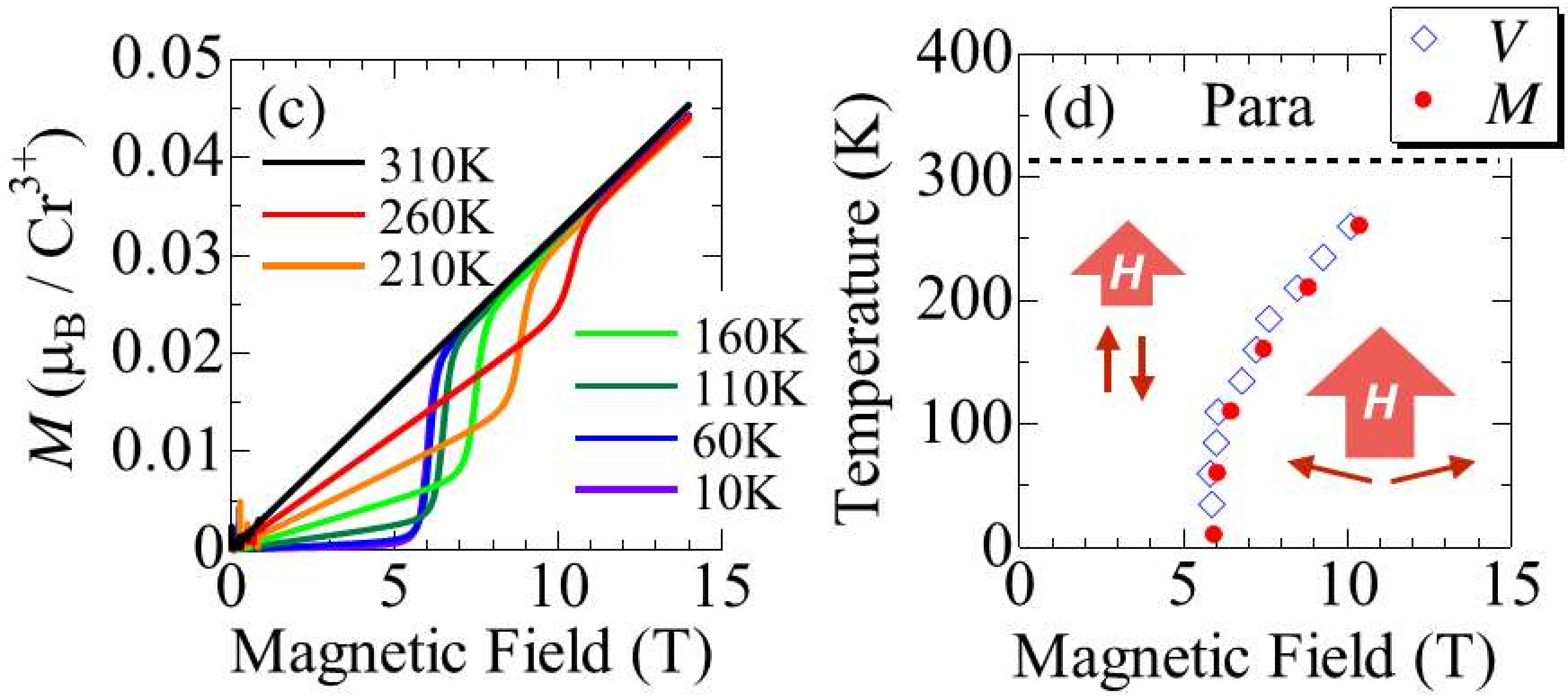


Spin Seebeck effect in AFM

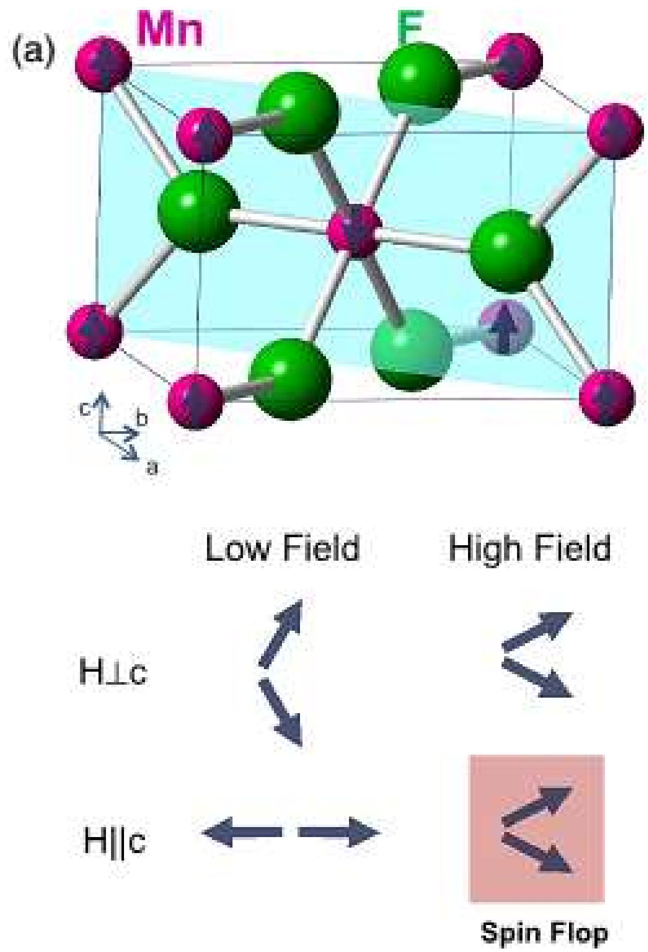


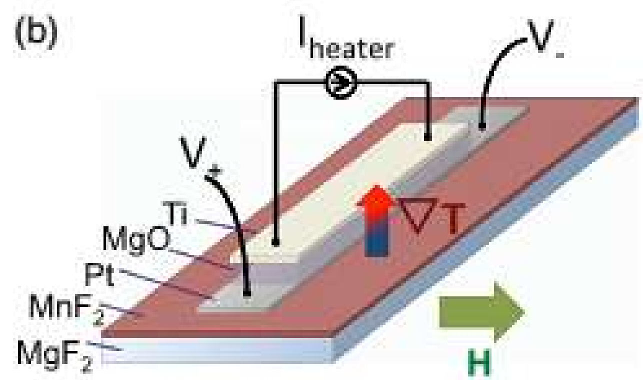
Spin flop field

Spin Seebeck effect in AFM



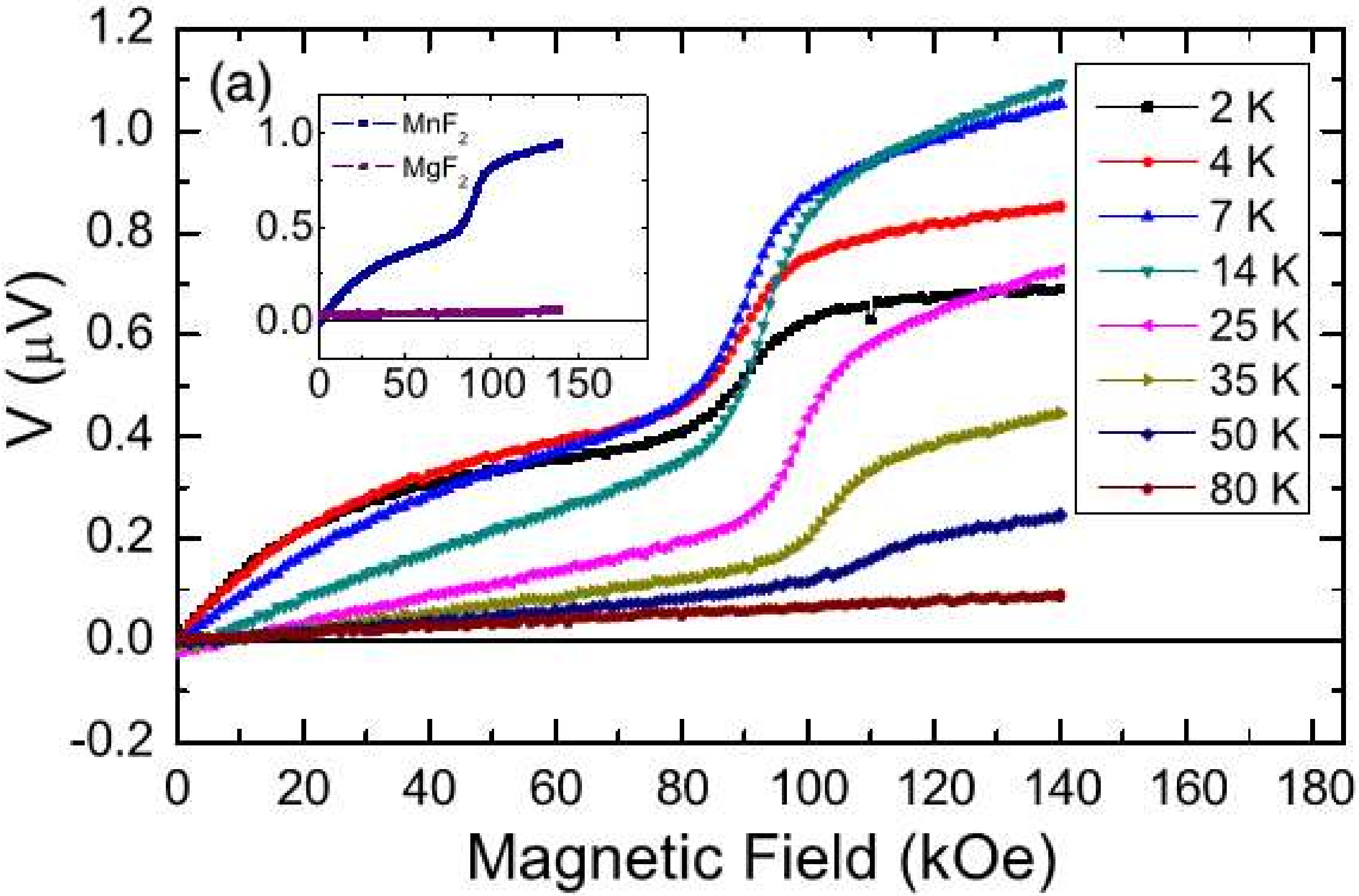
Spin Seebeck effect in AFM





Wu, et al, PRL (2016)

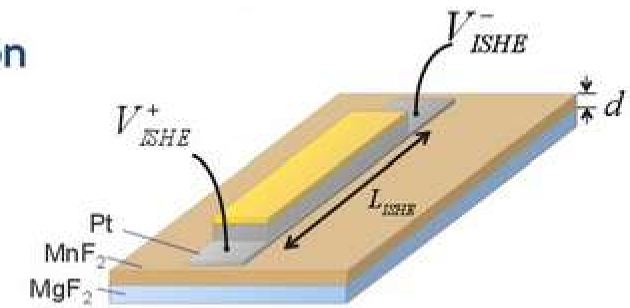
Spin Seebeck effect in AFM

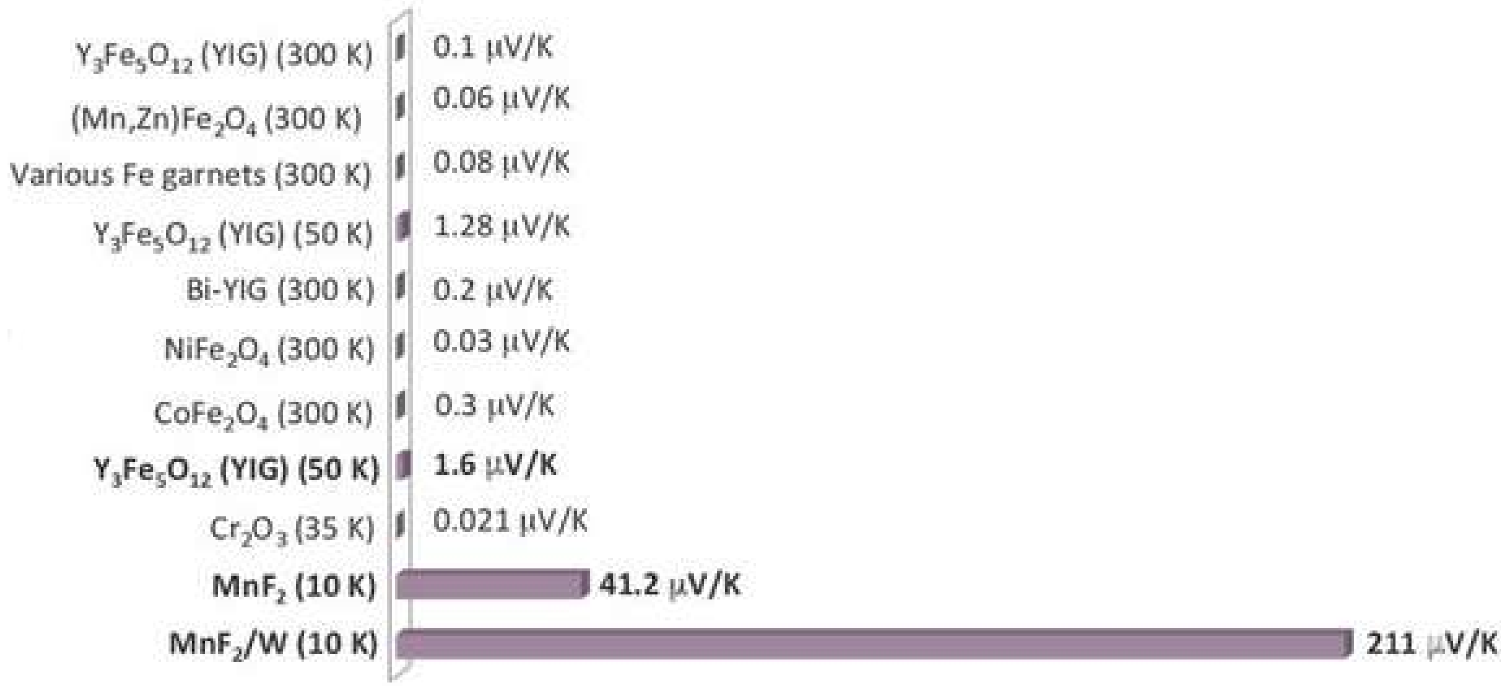


Spin Seebeck effect in AFM

Magnitude comparison

$$S = \frac{E_{ISHE}}{\nabla T} = \frac{V_{ISHE} / L_{ISHE}}{\Delta T / d}$$





1.6 μV/K ⟶ 211 μV/K

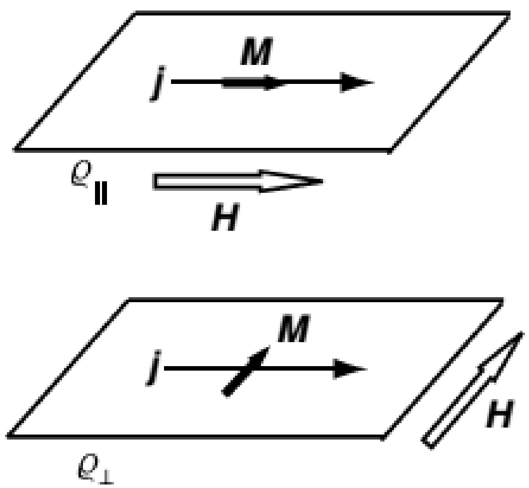
Outline

3. AMR of AFM

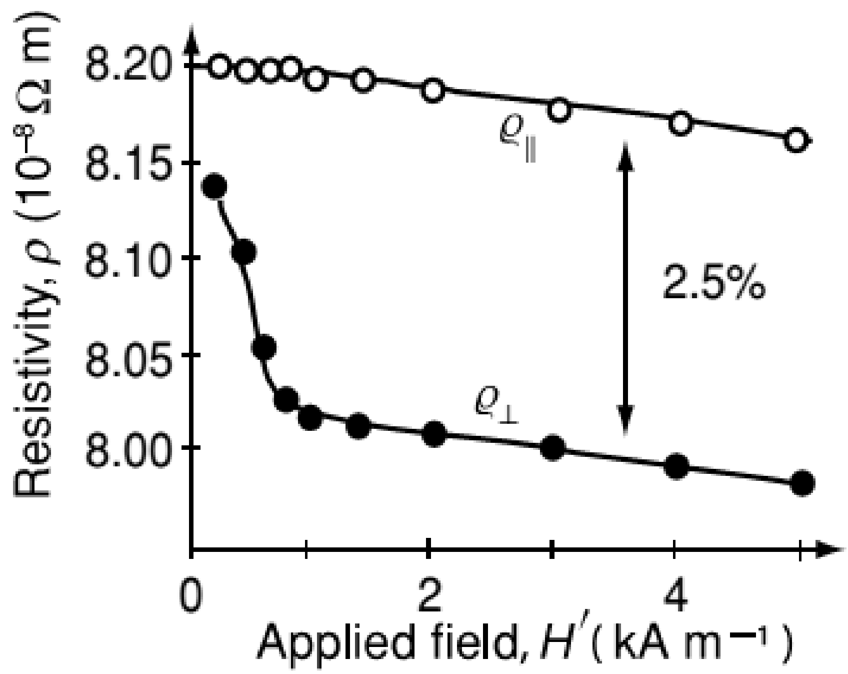
AMR in FM

AMR of a Nickel

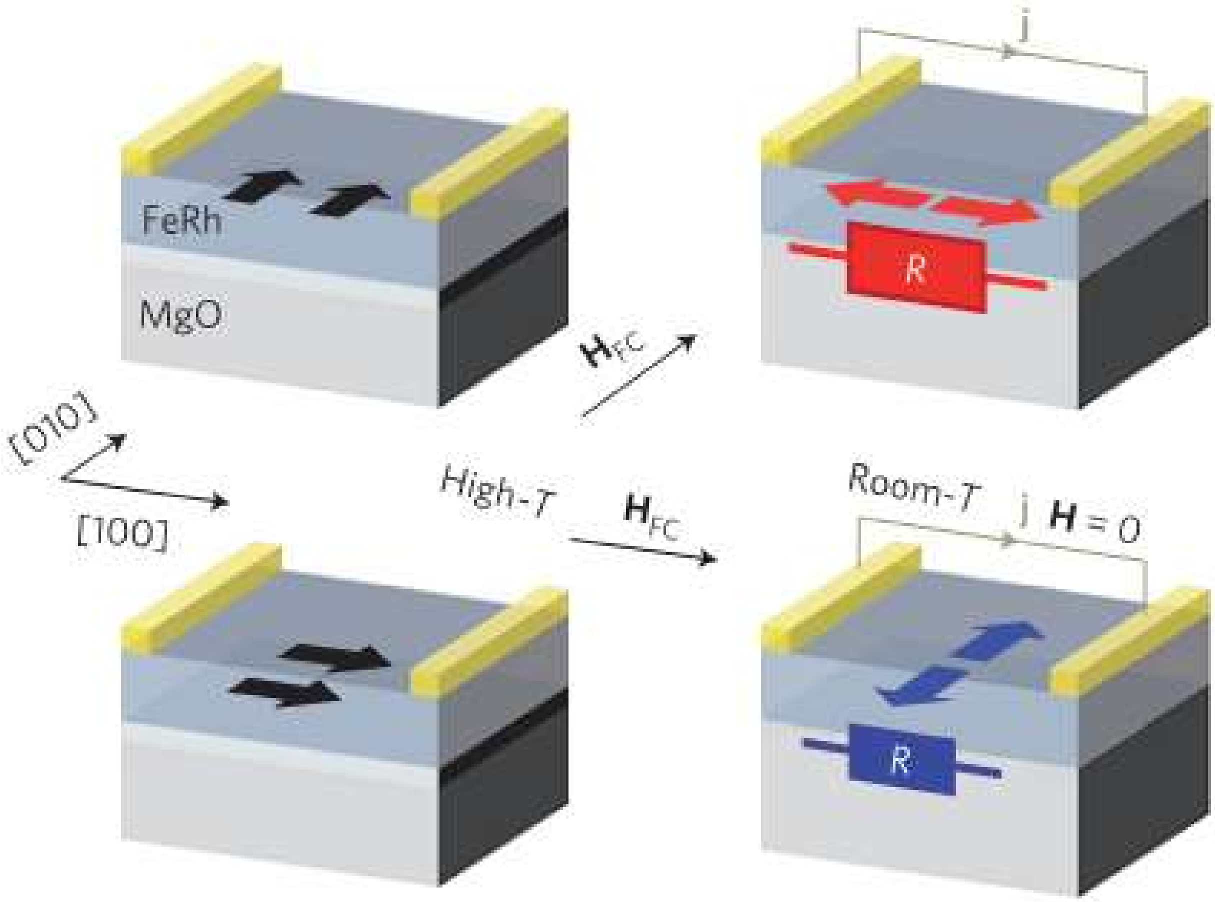
Discovered by William Thompson (1857)



Measurement of AMR for a thin film.

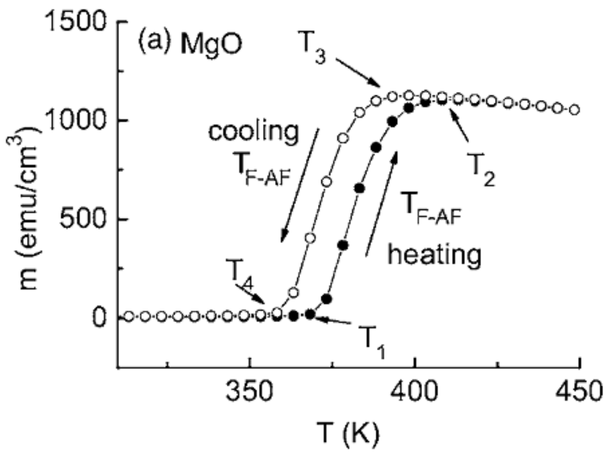


AMR in AFM

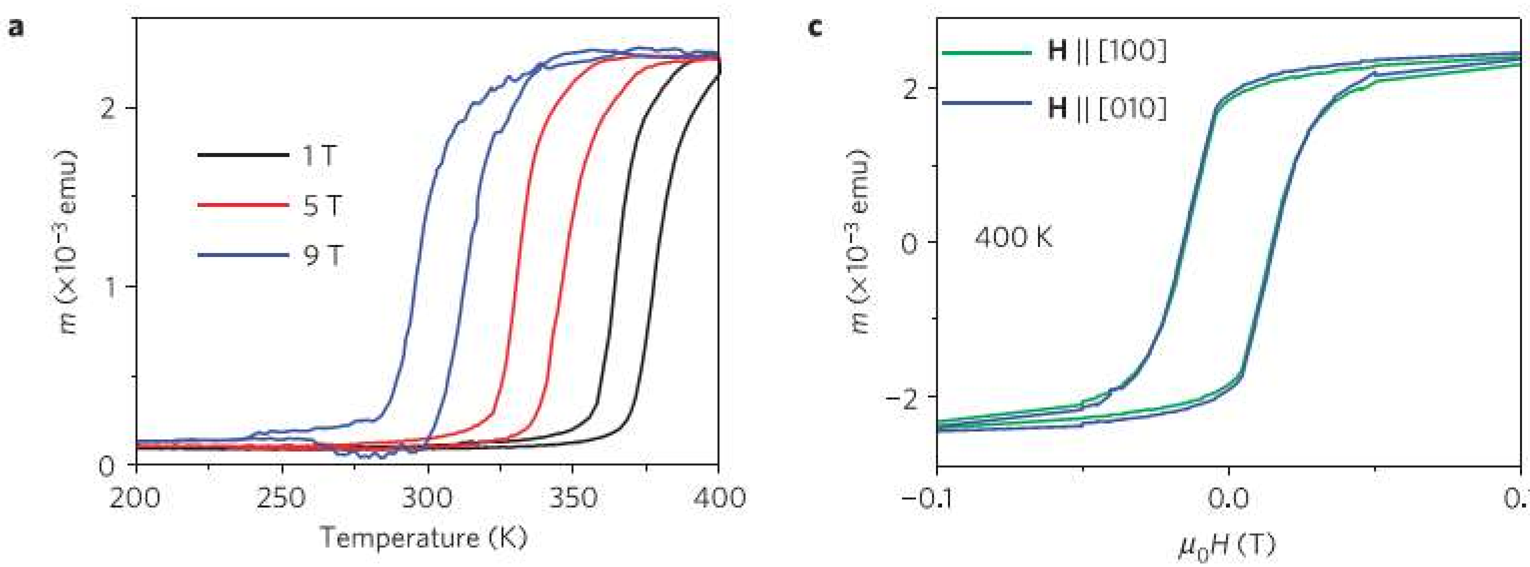


Marti, et al, Nature Materials (2014)

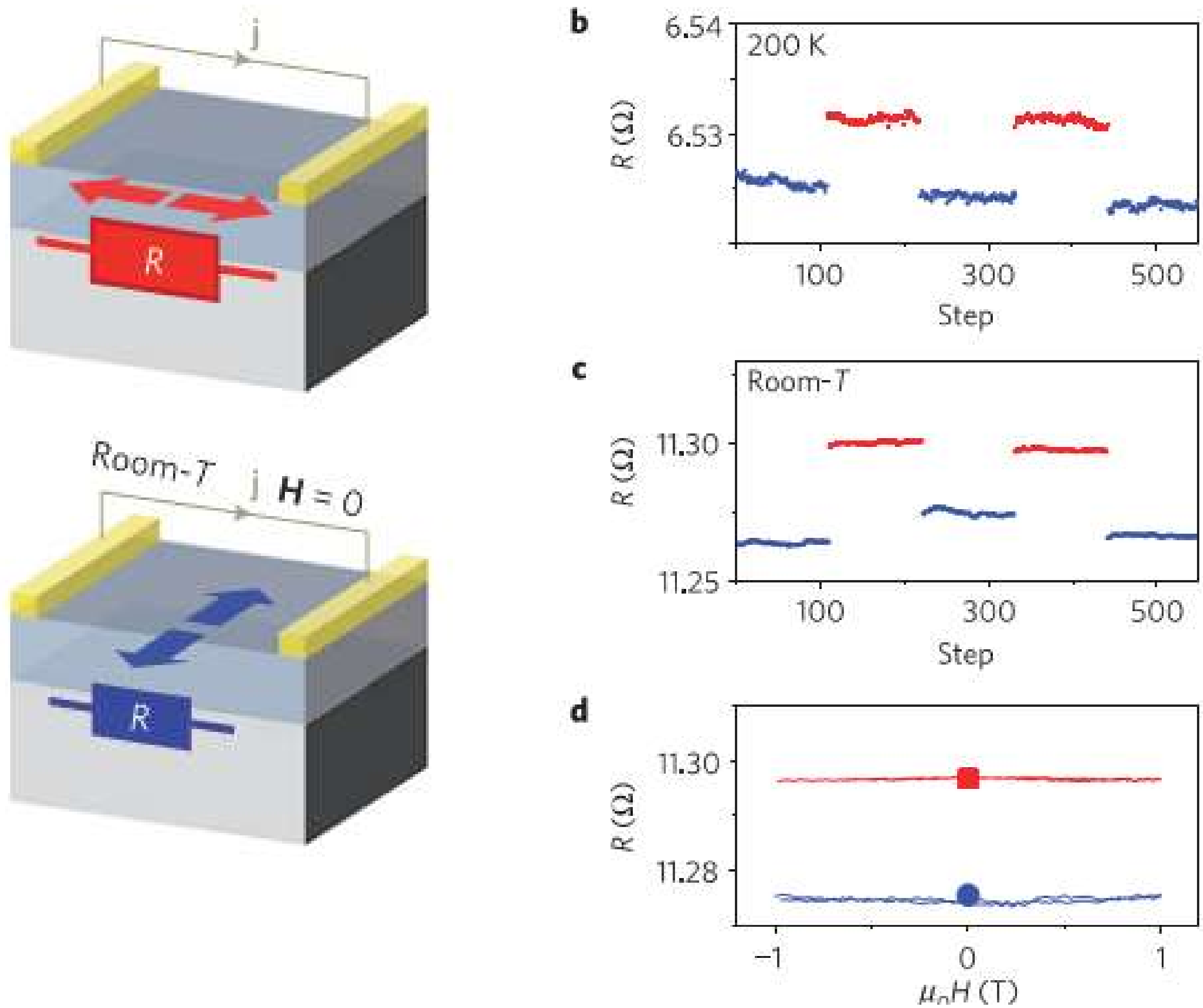
AMR in AFM



Maat, et al, PRB (2006)



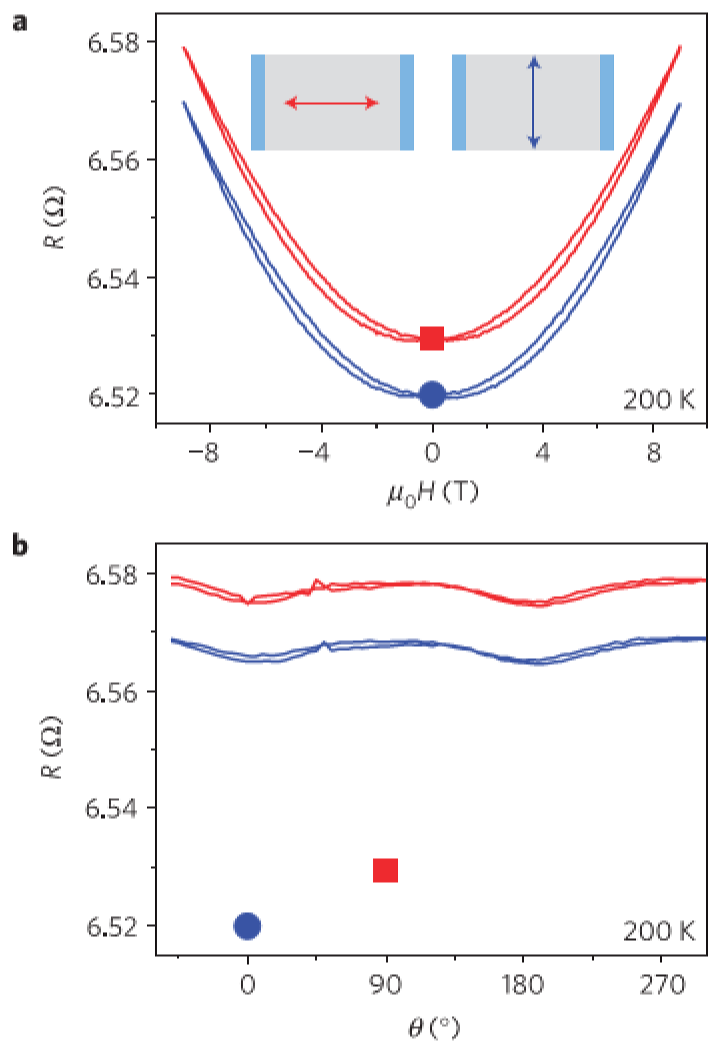
AMR in AFM



j
R
Room-T
j
H = 0
R
b
6.54
200 K
6.53
R (Ω)
100
300
500
Step
c
Room-T
11.30
R (Ω)
11.25
100
300
500
Step
d
11.30
R (Ω)
11.28
−1
0
1
μ0H (T)

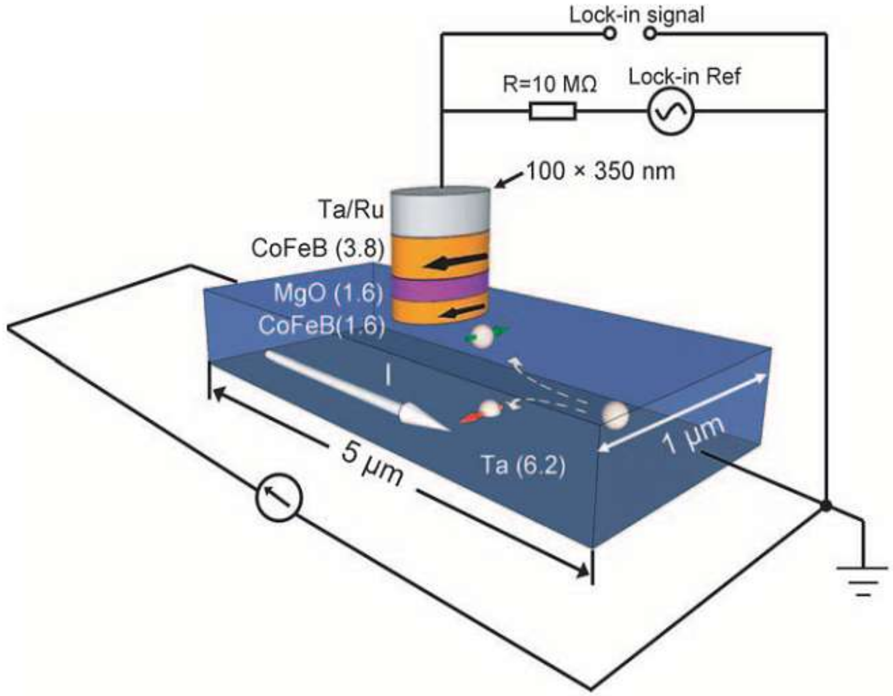
AMR in AFM

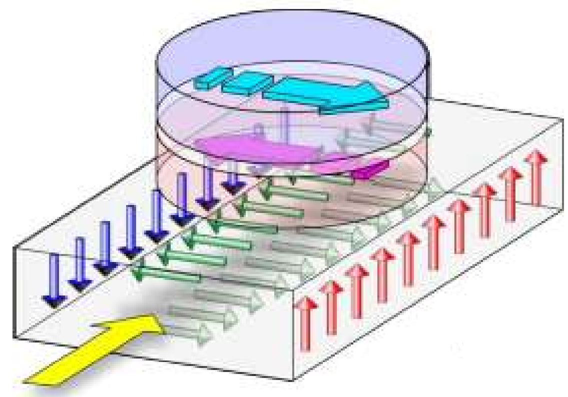
Advantage: Signal robust in magnetic field

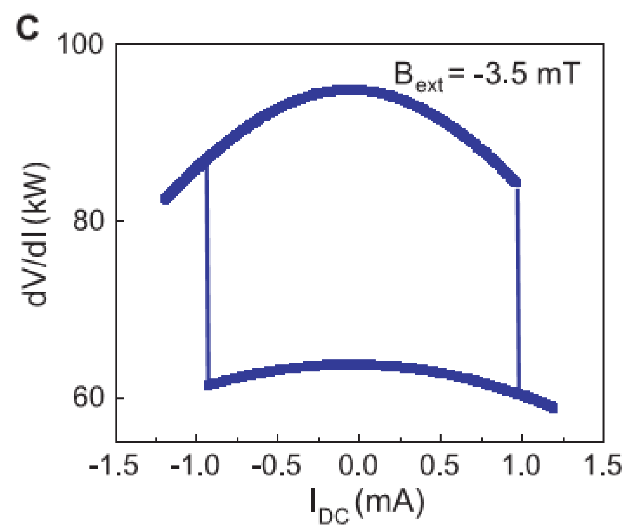


4. Switching of AFM

Switching of FM by spin torque

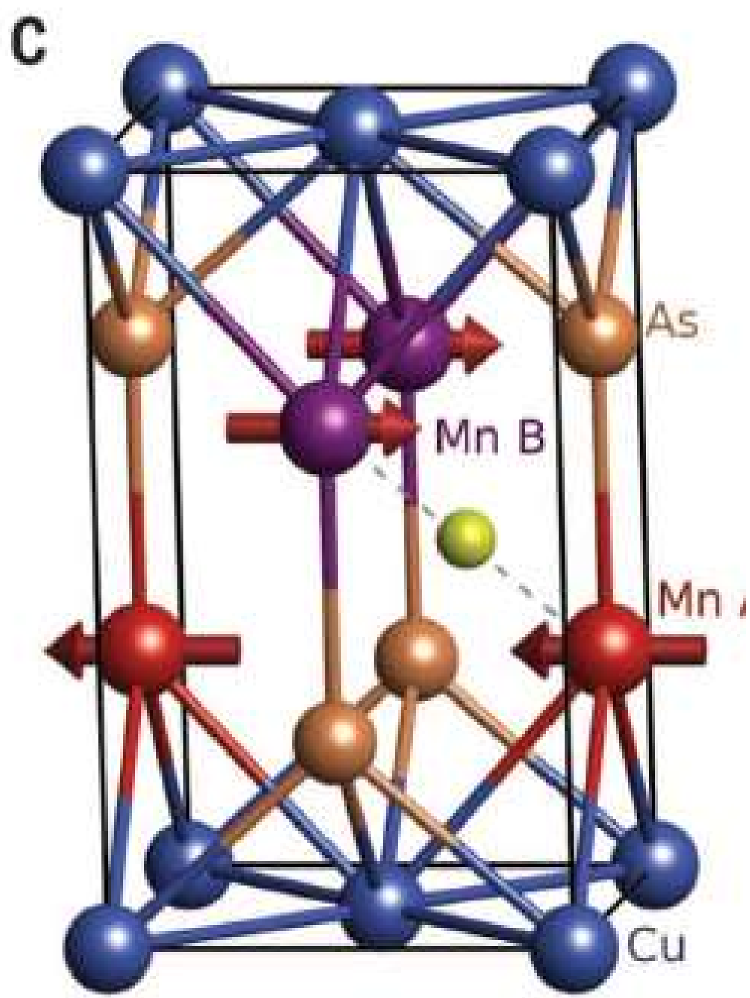


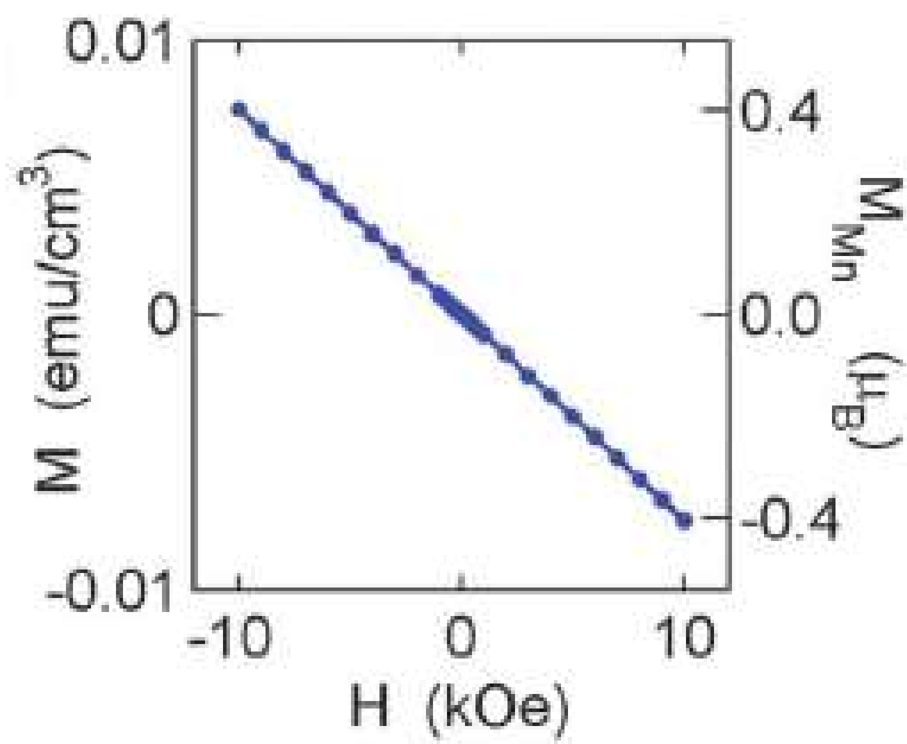




Liu, et al., Science (2012)

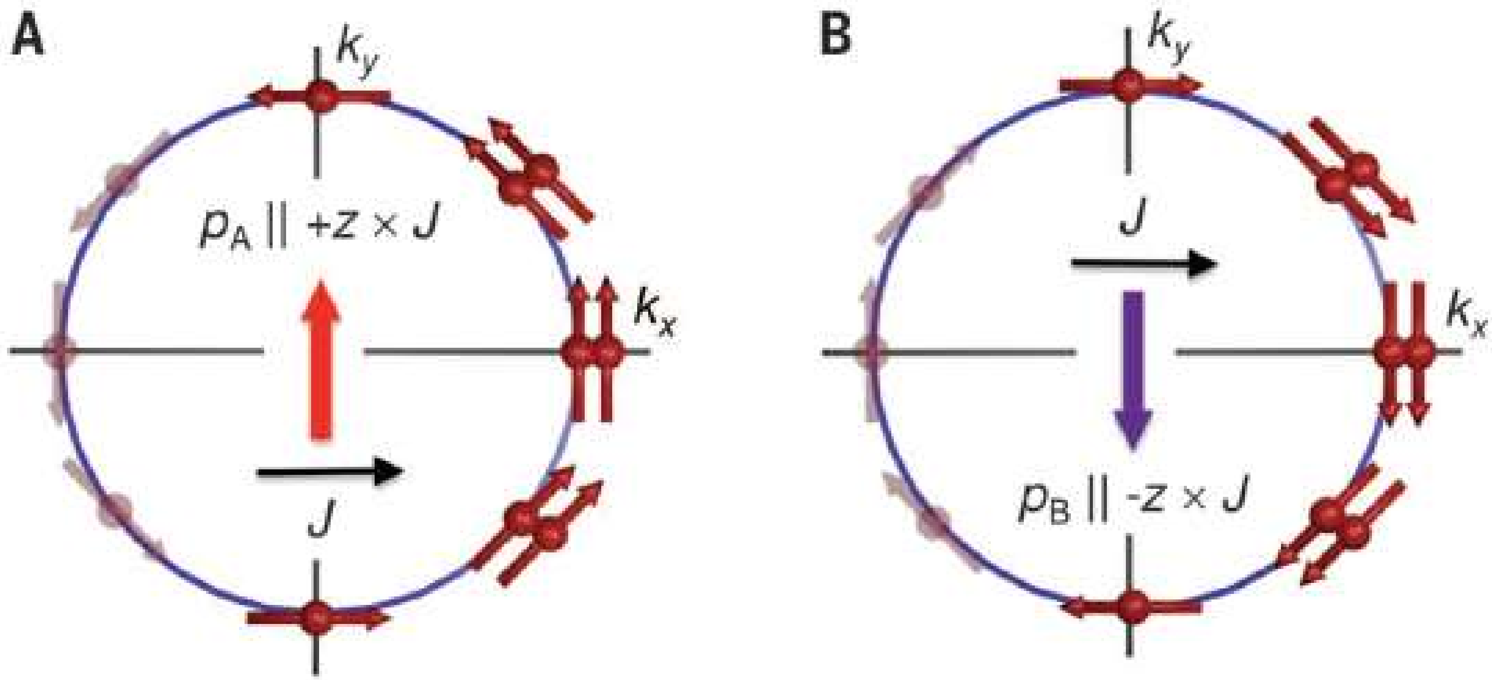
Switching of AFM





Wadley et al, science **351**, 587(2016)

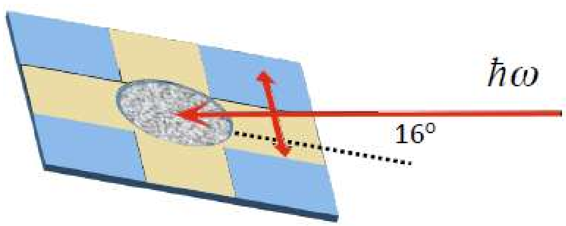
Switching of AFM

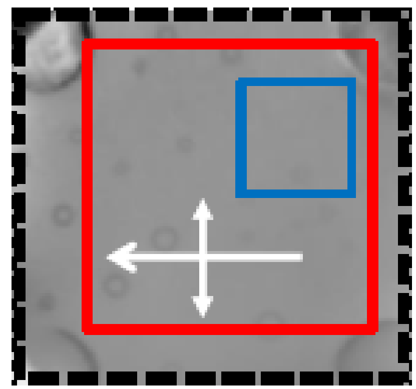


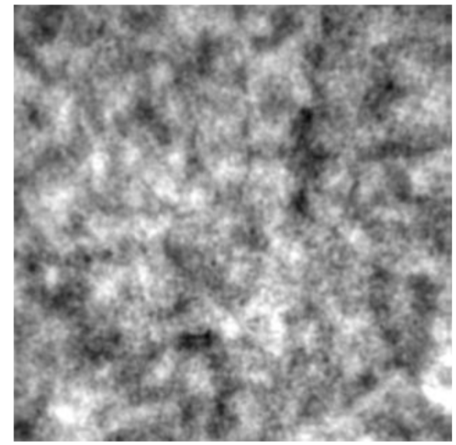
Inverse spin-galvanic effect

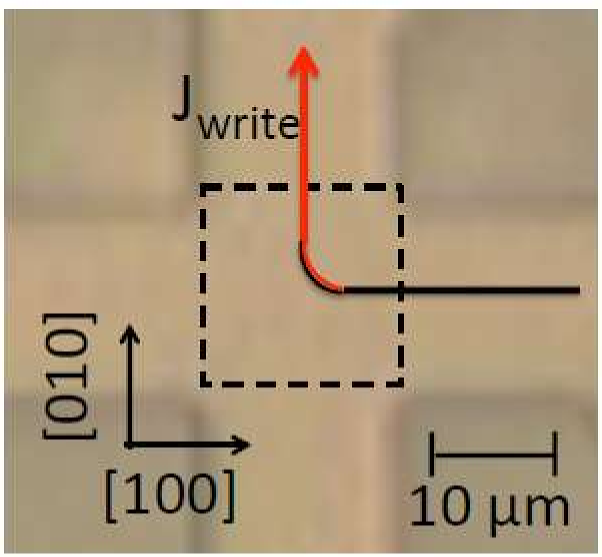
Switching of AFM

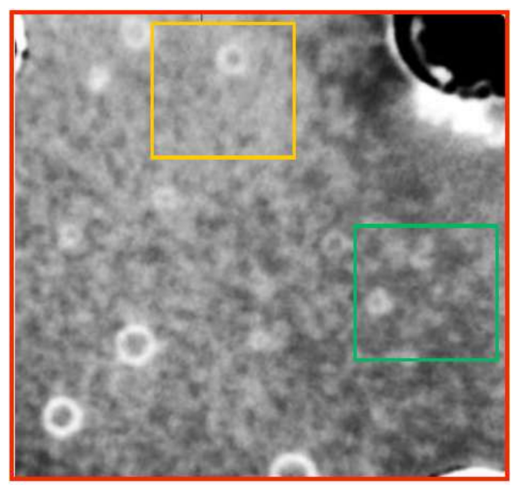
Before writing pulses

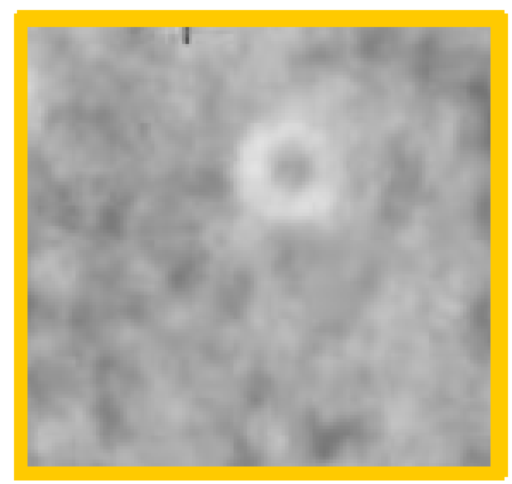






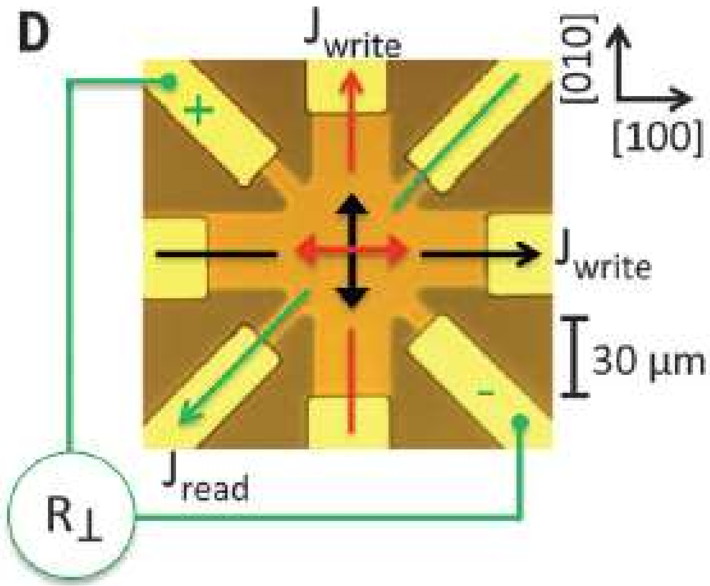




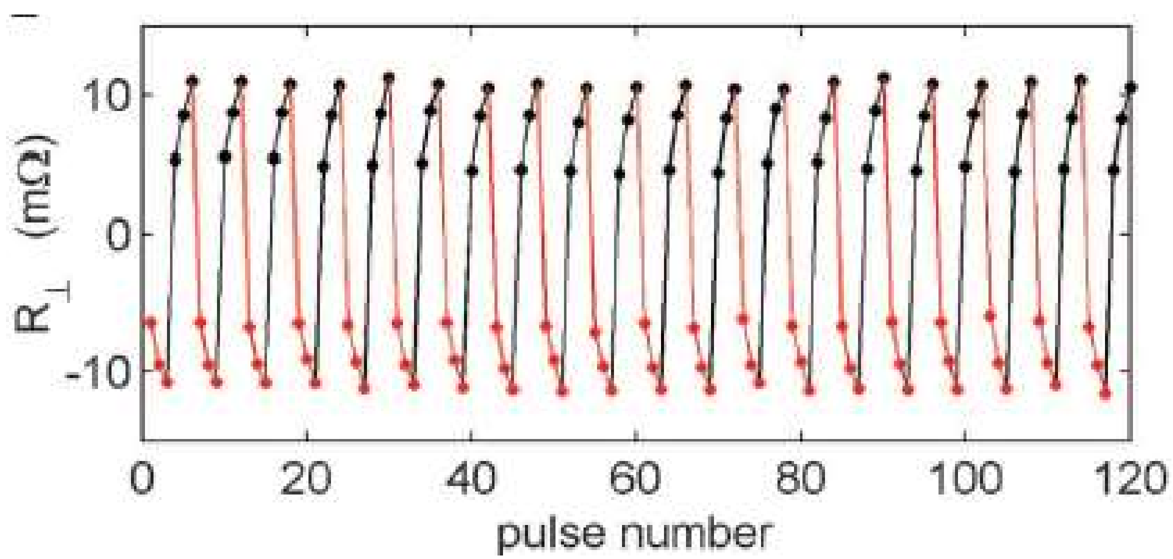


After writing pulses

Switching of AFM

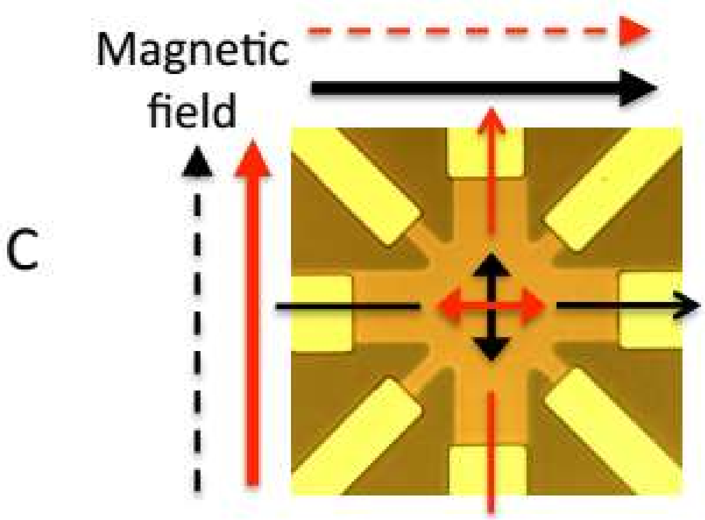


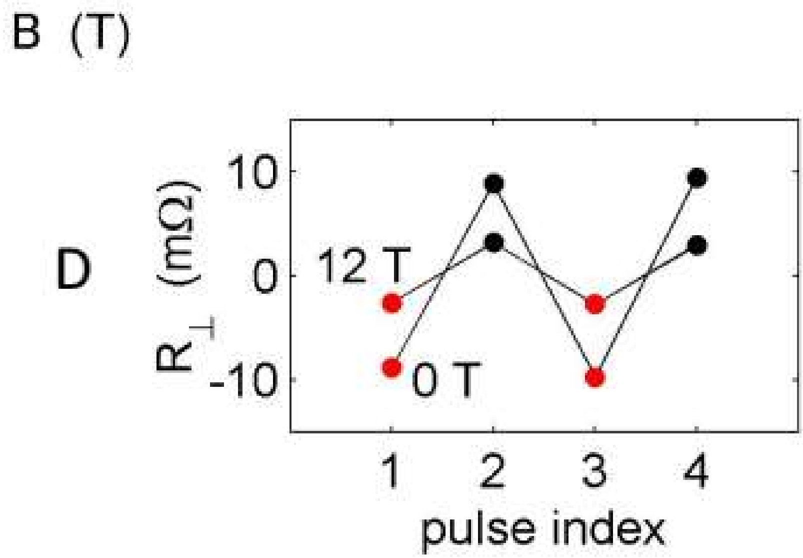
Writing current: during time=50ms, amplitude=$4*10^{-6}$ Acm^{-2}.



Switching of AFM

Advantage: Signal robust in magnetic field





休息10分钟

5. Anomalous Hall effect in AFM

AHE in AFM

PRL **112,** 017205 (2014) PHYSICAL REVIEW LETTERS week ending 10 JANUARY 2014

Anomalous Hall Effect Arising from Noncollinear Antiferromagnetism

Hua Chen, Qian Niu, and A. H. MacDonald
Department of Physics, University of Texas at Austin, Austin, Texas 78712, USA
(Received 3 October 2013; published 10 January 2014)

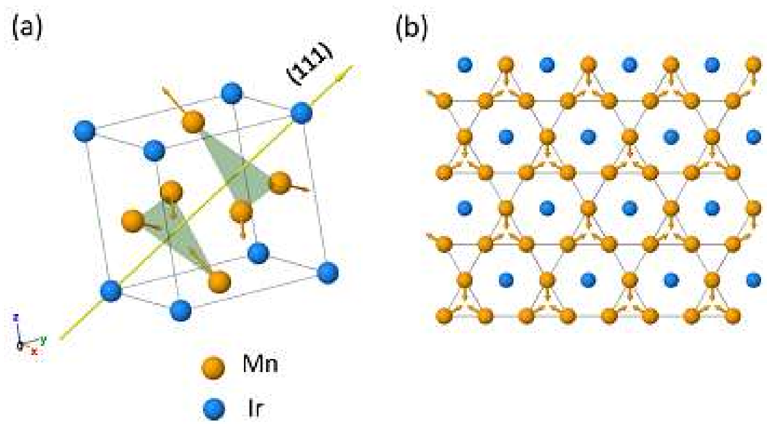


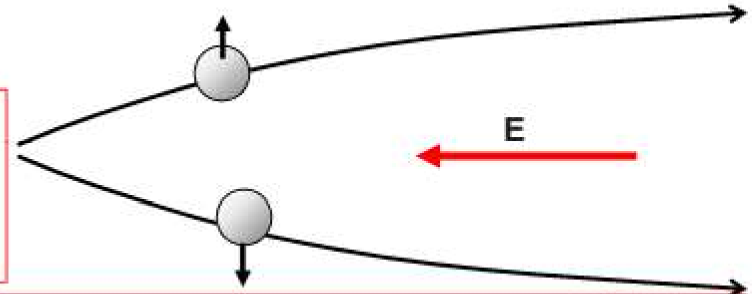
FIG. 1 (color online). Structure of Mn_3Ir. (a) Unit cell of Mn_3Ir with triangular antiferromagnetic order. (b) An individual (111) plane of Mn_3Ir. The Mn atoms form a kagome lattice.

- **Large spin orbit coupling of Ir transfer to Mn.**
- **Non-collinear antiferromagnetism**

AHE in AFM

a) Intrinsic deflection

Interband coherence induced by an external electric field gives rise to a velocity contribution perpendicular to the field direction. These currents do not sum to zero in ferromagnets.

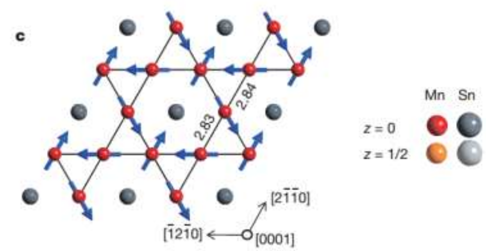


$$\frac{d\langle \vec{r} \rangle}{dt} = \frac{\partial E}{\hbar \partial \vec{k}} + \frac{e}{\hbar} E \times b_n$$

Electrons have an anomalous velocity perpendicular to the electric field related to their Berry's phase curvature

$$\sigma_{\ell m} = \frac{e^2}{\hbar} \int \frac{d\mathbf{k}}{(2\pi)^3} \Omega_p(\mathbf{k}) f(\mathbf{k}),$$

$$\Omega_n(\boldsymbol{k}) = i \langle \nabla_{\boldsymbol{k}} u_{n\boldsymbol{k}} | \times | \nabla_{\boldsymbol{k}} u_{n\boldsymbol{k}} \rangle$$



Non-collinear antiferromagnetic structure

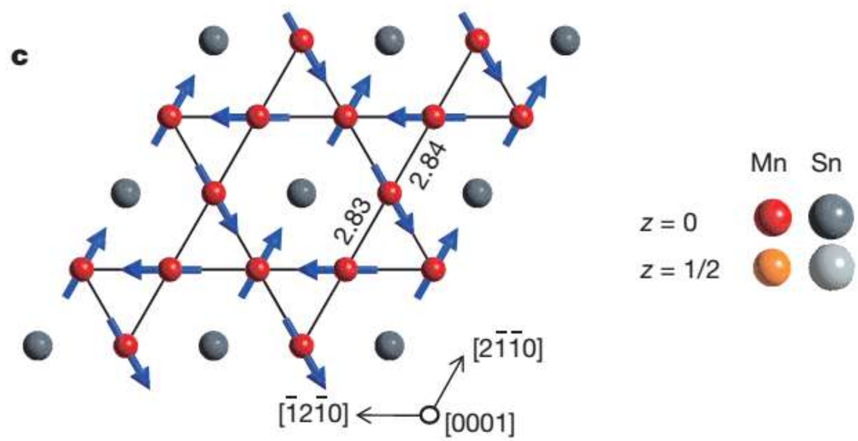
AHE in AFM

LETTER

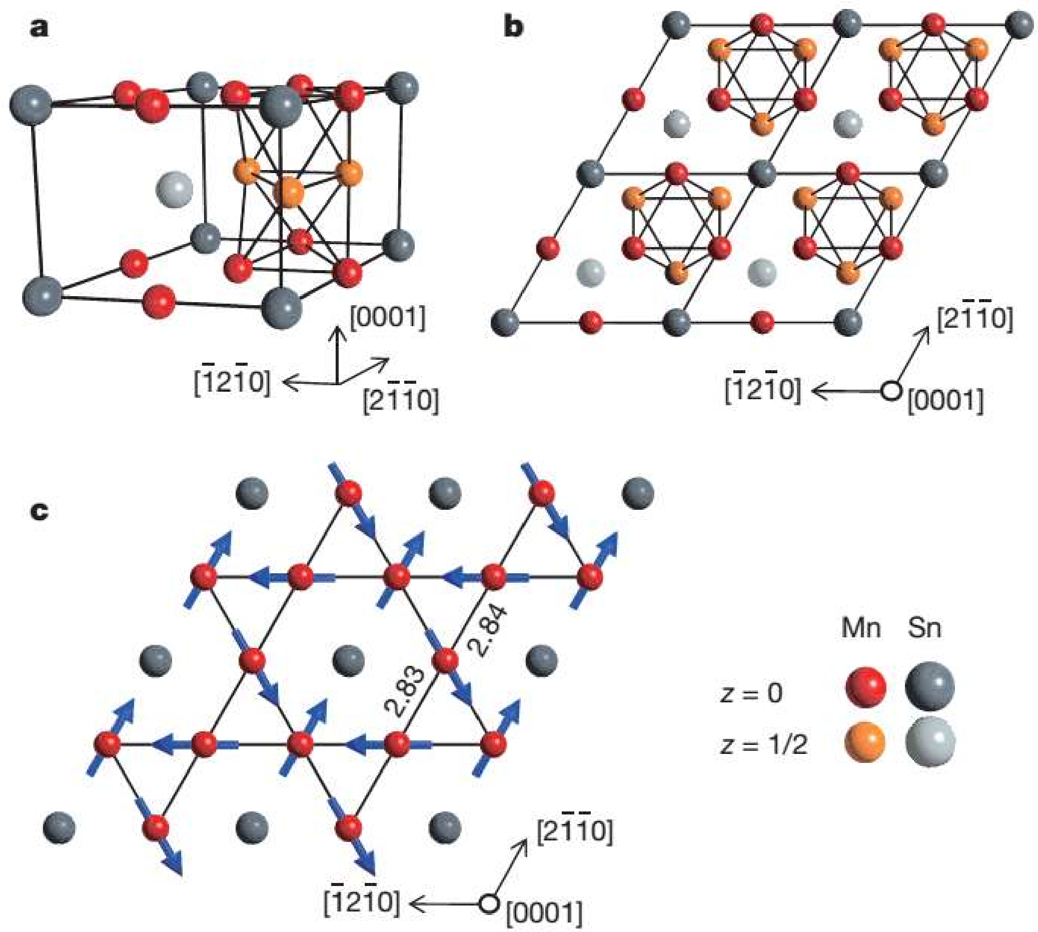
doi:10.1038/nature15723

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

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



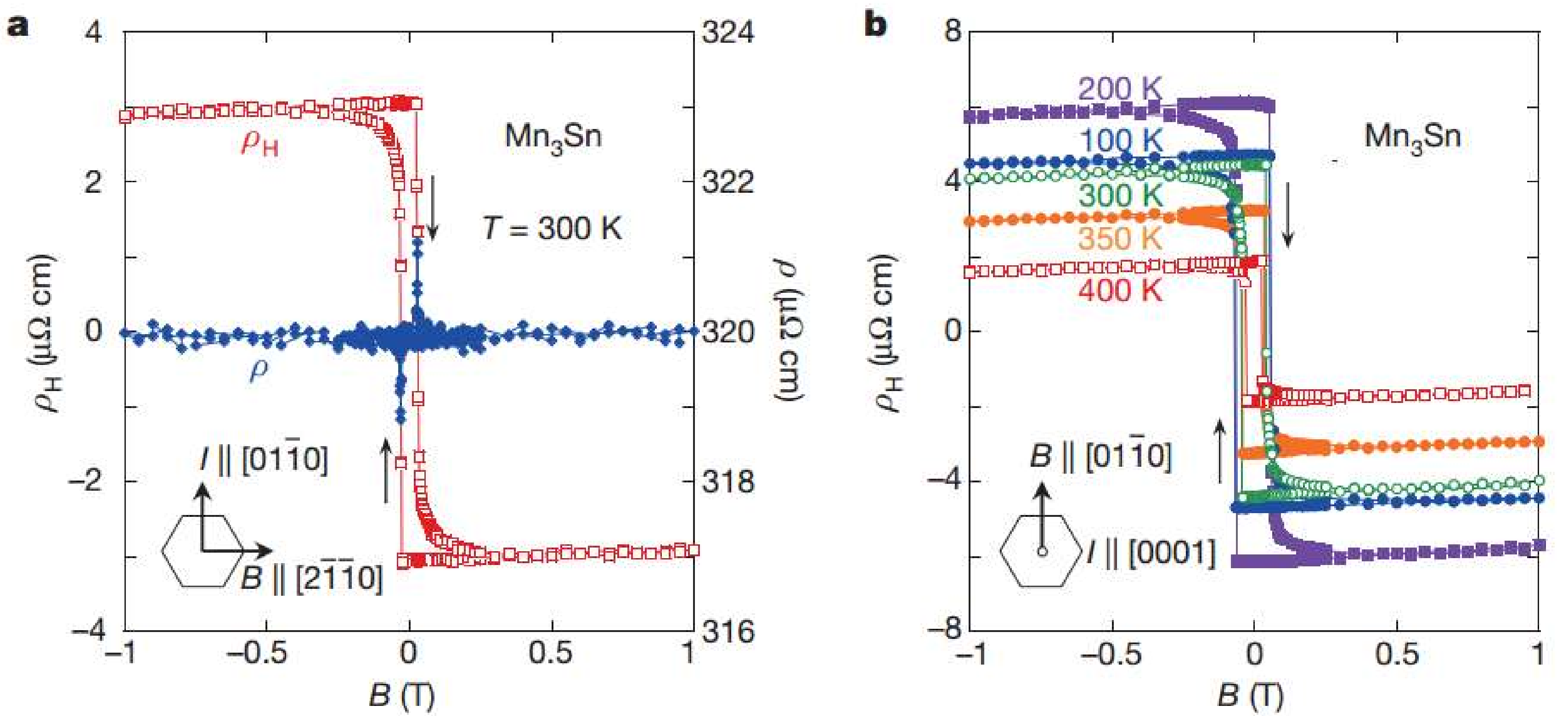
AHE in AFM



Mn_3Sn is a hexagonal antiferromagnet (AFM) that exhibits noncollinear ordering of Mn magnetic moments at the Néel temperature of $T_N \approx 420$ K

The canting of the other two spins towards the local easy-axis is considered to be the origin of the weak ferromagnetic moment.

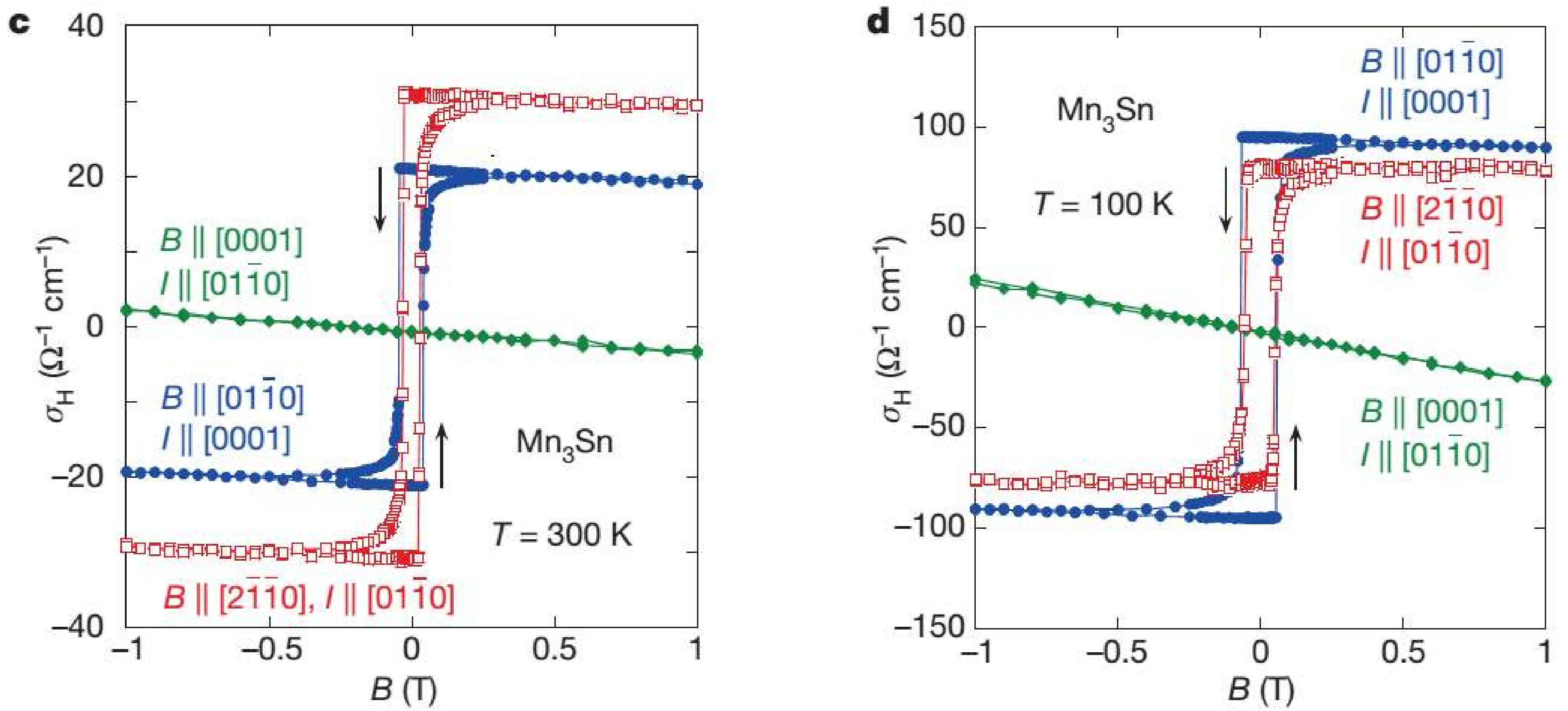
AHE in AFM



$|\Delta\rho_{\mathrm{H}}| \approx 6\,\mu\Omega\ \mathrm{cm}$

a small field of ~300 Oe

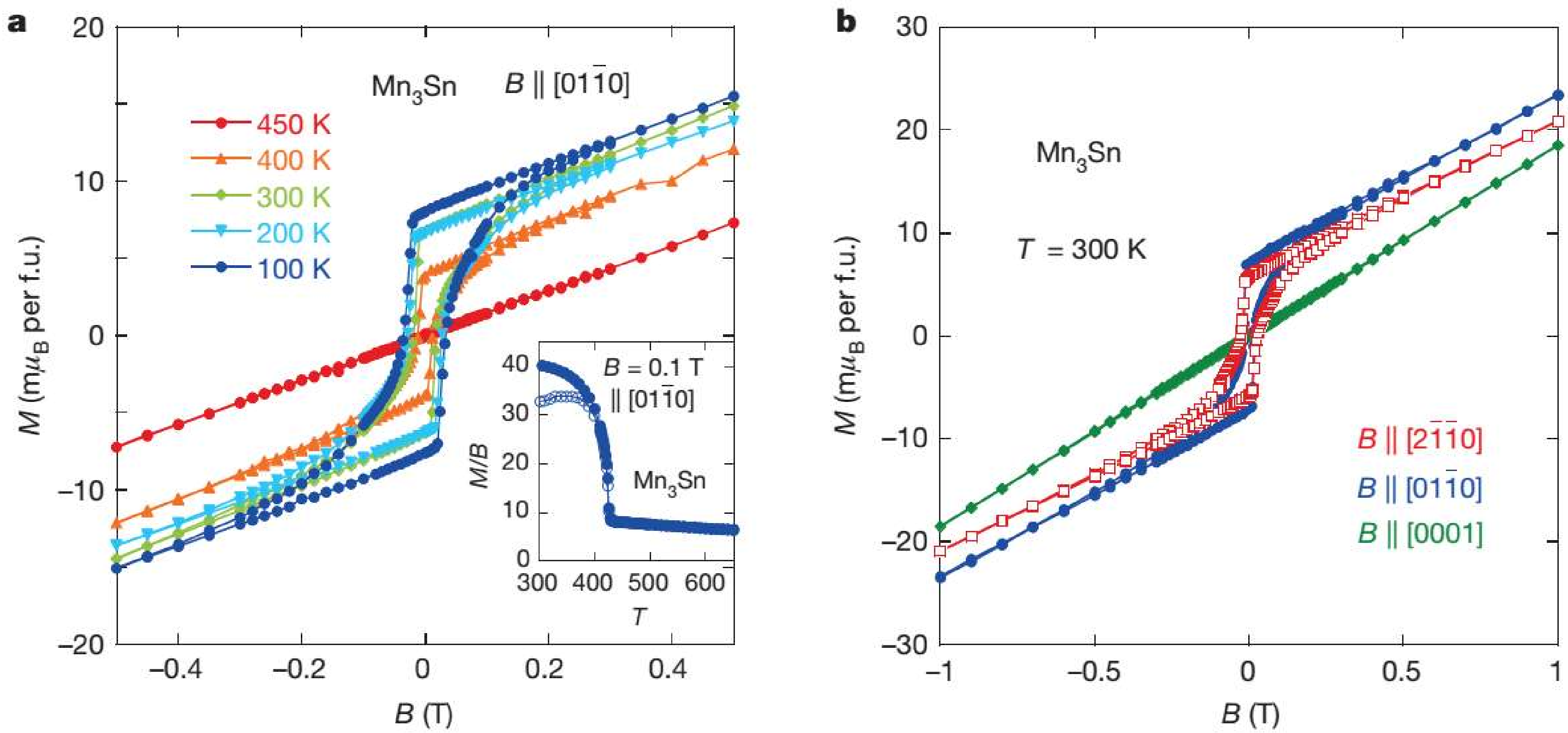
AHE in AFM



$\sigma_{\mathrm{H}} = -\rho_{\mathrm{H}}/\rho^2$

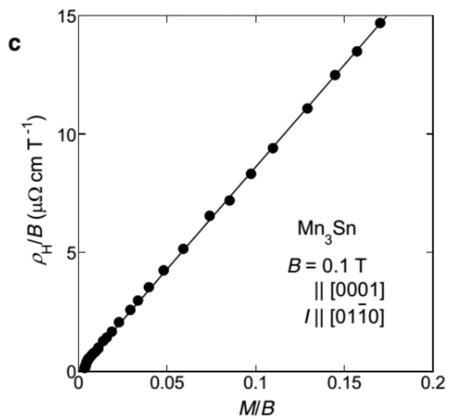
Hysteresis for *H* || [01-11] and *H* || [2-1-10]
Linear for *H* || [0001]

AHE in AFM



The similar anisotropic and hysteretic behaviours found in both ρ_H(B) and *M*(B) indicate that the existence of the small and soft ferromagnetic component allows us to switch the sign of the Hall effect.

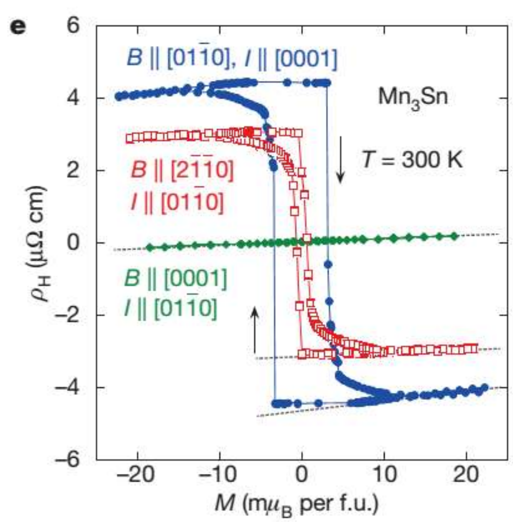
AHE in AFM

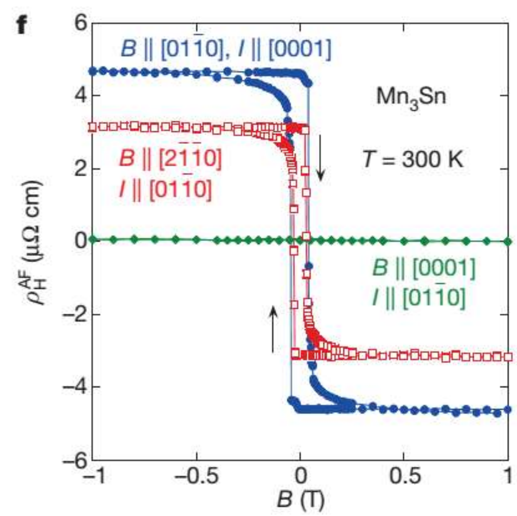


$$\rho_{\mathrm{H}} = R_0 B + R_s \mu_0 M$$

R_0 and R_s are the ordinary and anomalous Hall coefficients, and μ_0 is the permeability.

R_0= 3.0×10^{-4} cm^3 C^{-1} indicates that R_0B is negligibly small

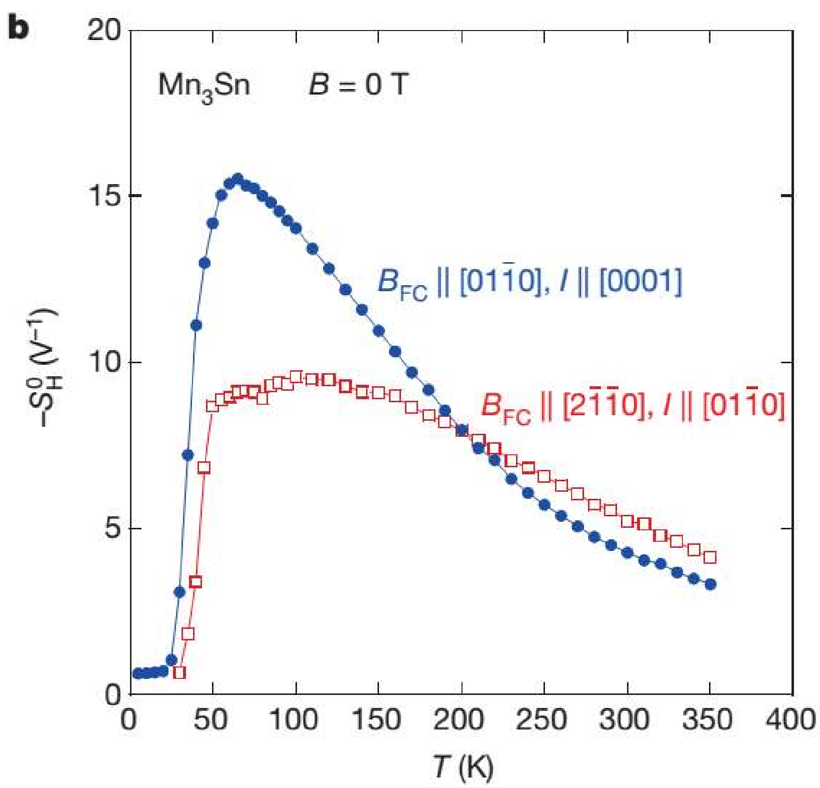




$$\rho_{\mathrm{H}} = R_0 B + R_s \mu_0 M + \rho_{\mathrm{H}}^{\mathrm{AF}}$$

the large AHE $\rho_{\mathrm{H}}^{\mathrm{AF}}$, must have a distinct origin driven by the antiferromagnetic order.

AHE in AFM



$$S_H^0$$

$$S_H = \mu_0 R_s / \rho^2$$

$$\sigma_H = -\rho_H / \rho^2$$

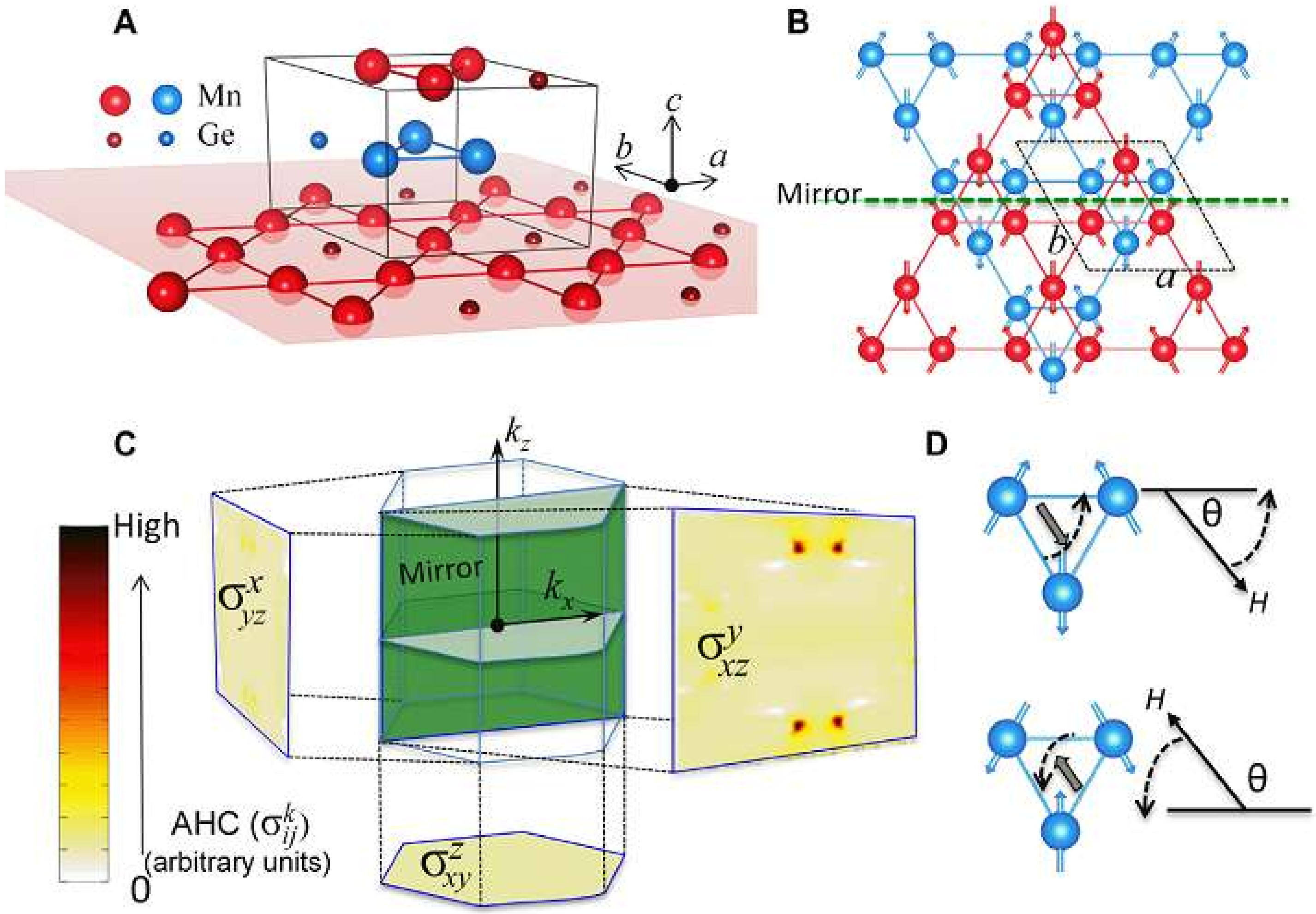
$$\rho_H = R_0 B + R_s \mu_0 M$$

$$S_H^0 = -\sigma_H(B=0) / M(B=0)$$

In a magnetic conductor with relatively high resistivity, the AHE is dominated by S_H.

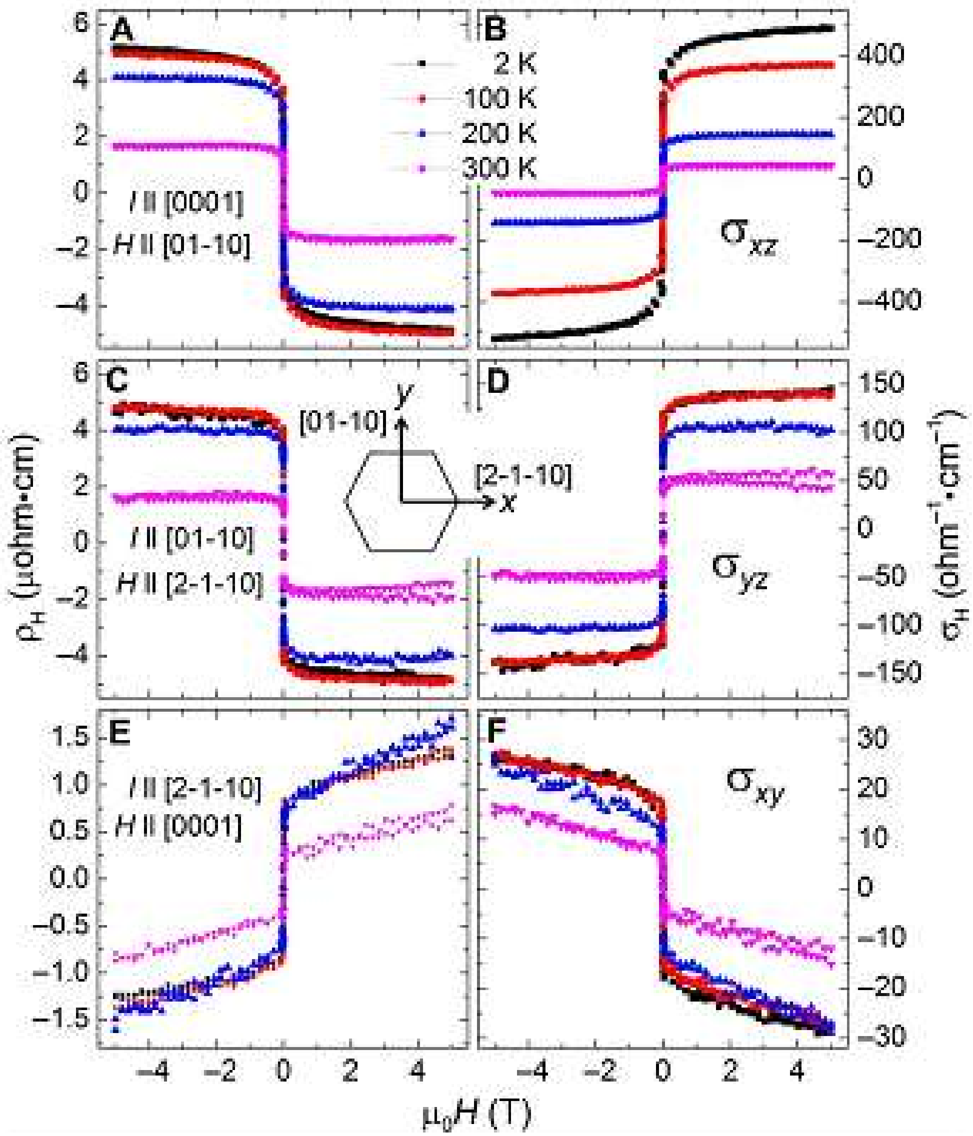
14 V^{-1} (Mn_3Sn) at 100 K >> 0.01–0.1 V^{-1}(like Fe, Ni, Co...)

AHE in AFM Mn_3Ge



Nayak, et al, Science Advances 2, e1501870 (2016)

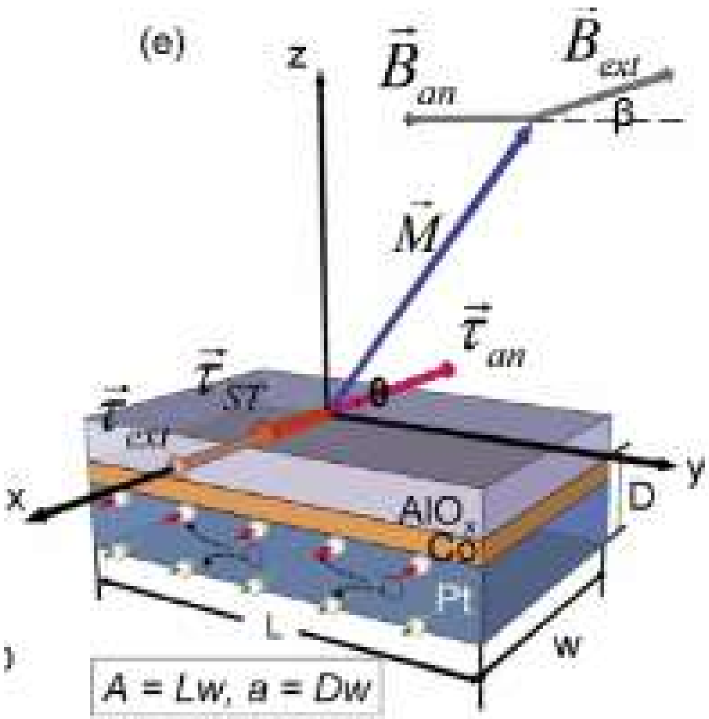
AHE in AFM $MnGe_3$

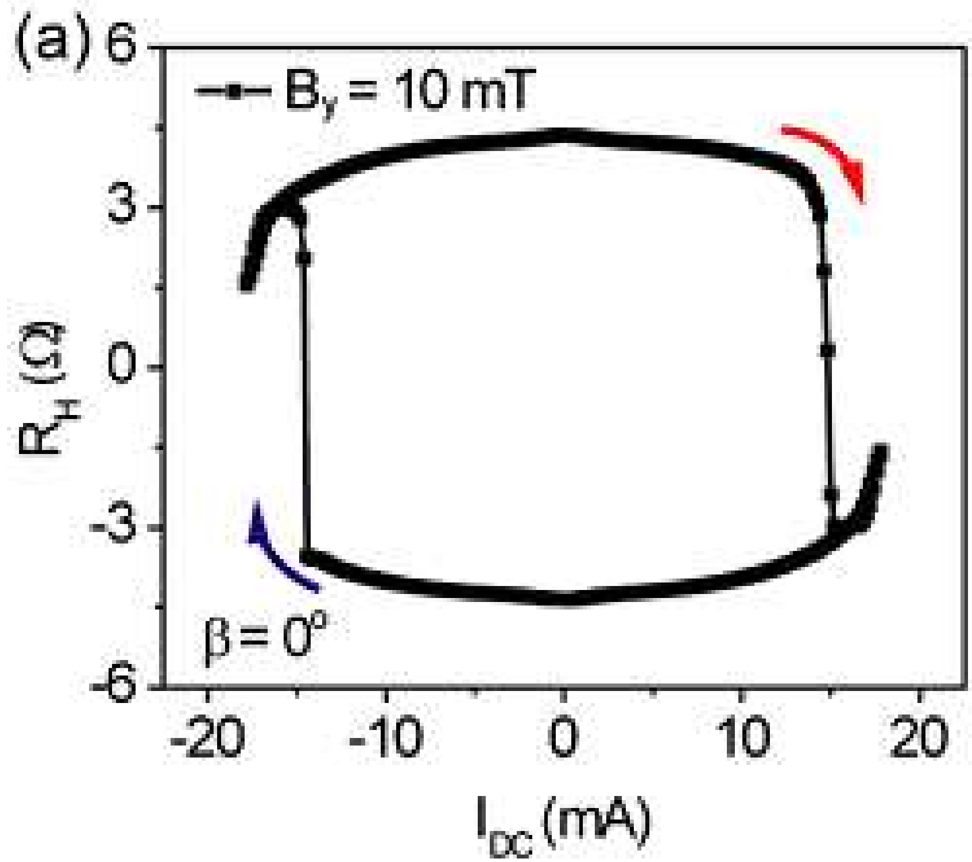


6. Spin orbit torque in AFM

Spin orbit torque in AFM

Spin Hall orbit torque to FM





Liu et al., PRL 109, 096602 (2012)

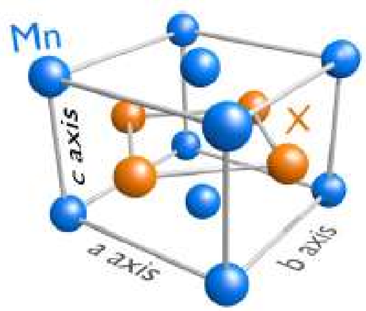
Spin orbit torque in AFM

PRL **113,** 196602 (2014) PHYSICAL REVIEW LETTERS week ending 7 NOVEMBER 2014

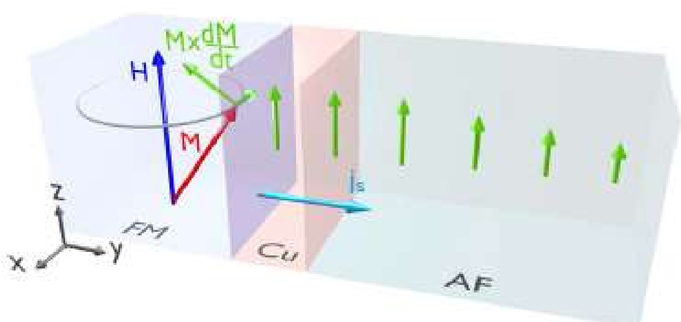
Spin Hall Effects in Metallic Antiferromagnets

Wei Zhang, Matthias B. Jungfleisch, Wanjun Jiang, John E. Pearson, and Axel Hoffmann
Materials Science Division, Argonne National Laboratory, Argonne, Illinois 60439, USA

Frank Freimuth and Yuriy Mokrousov
Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, D-52425 Jülich, Germany
(Received 12 August 2014; published 4 November 2014)

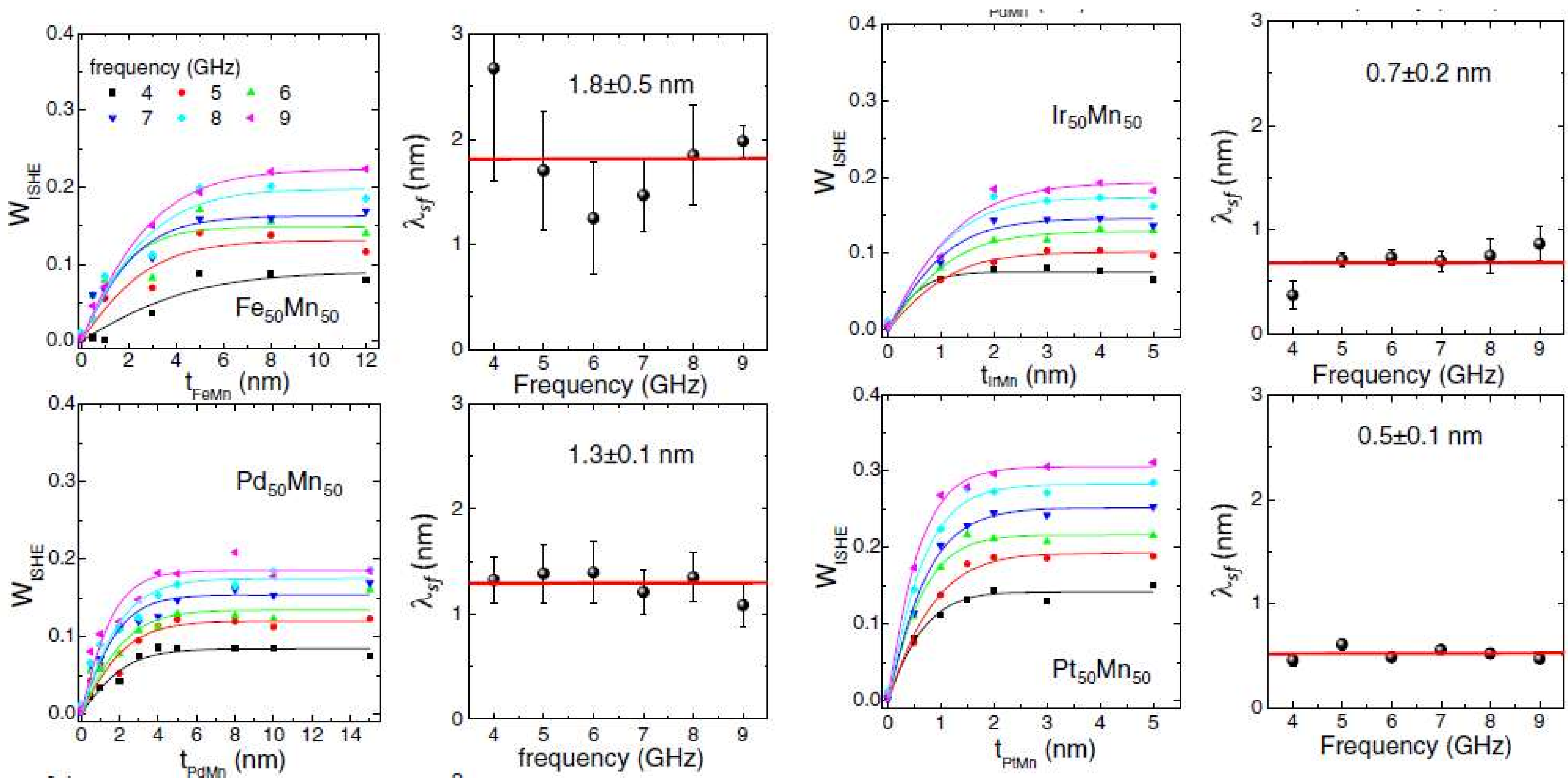


Crystal structure of CuAu-Ⅰ-type Afs



Schematic of spin pumping and spin Hall effect

Spin orbit torque in AFM



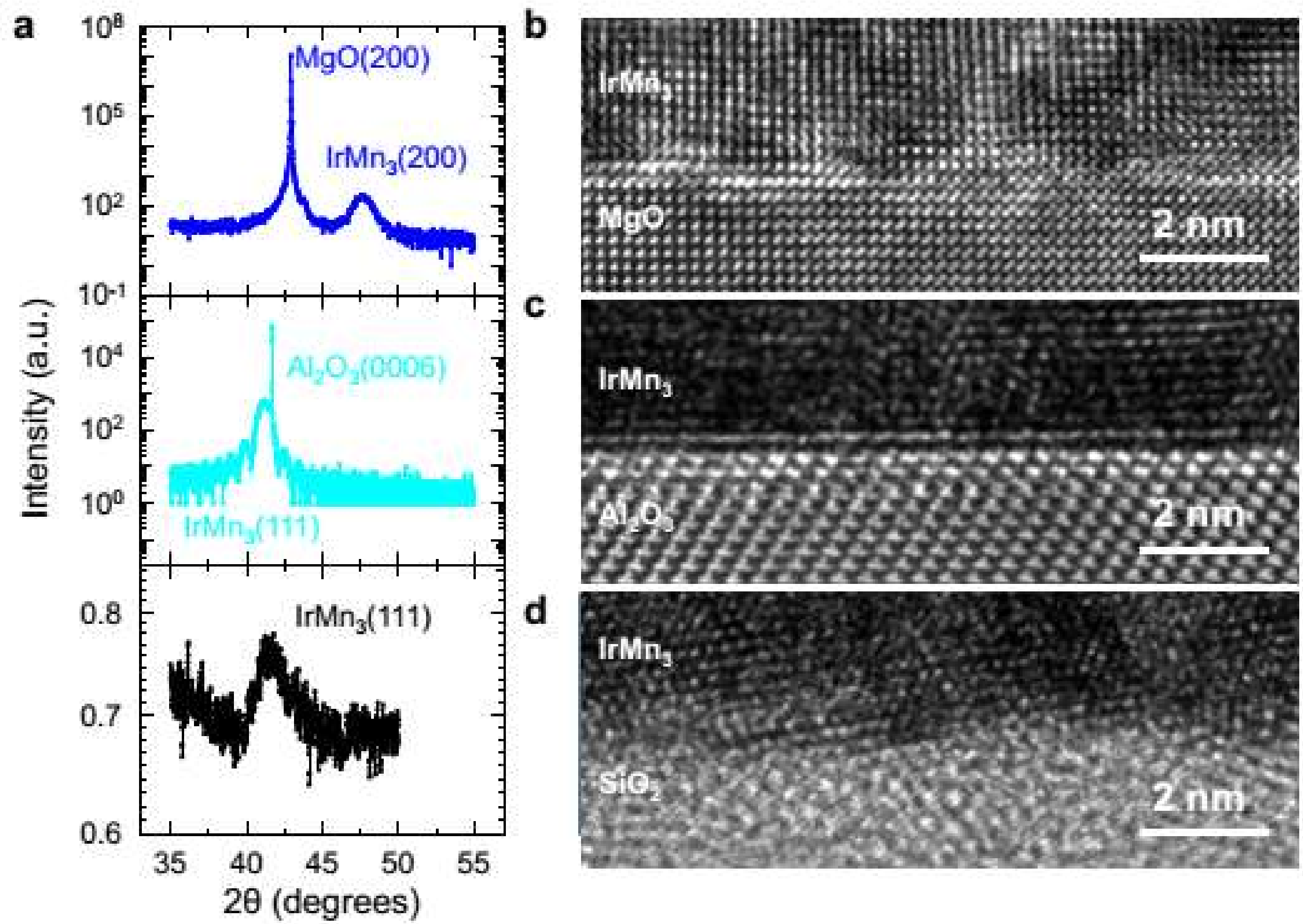
Thickness dependence shows spin diffusion length to be short ~1nm

$Fe_{50}Mn_{50}$
$Pd_{50}Mn_{50}$

$Ir_{50}Mn_{50}$
$Pt_{50}Mn_{50}$

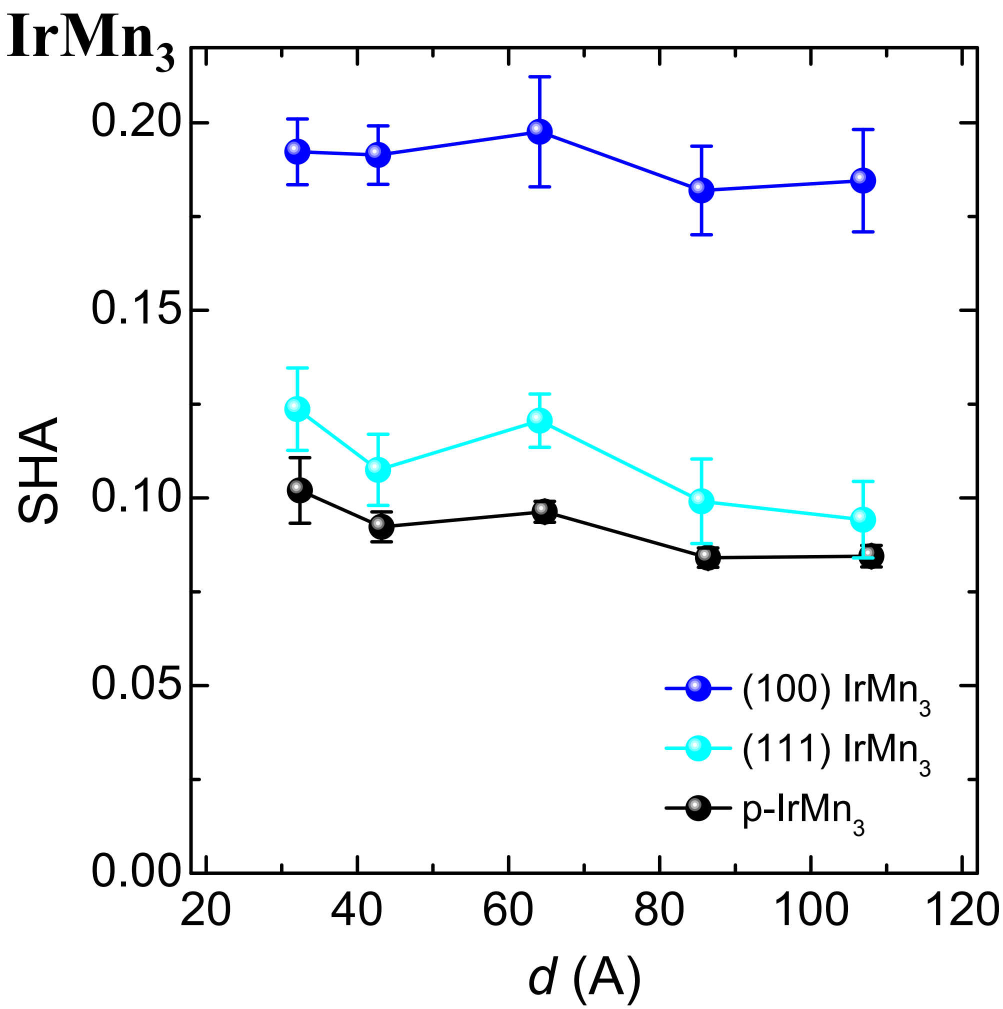
Spin orbit torque in AFM

$IrMn_3$



- **(100) on MgO**
- **(111) on Al2O3**
- **Grown by magneton sputtering**

Spin orbit torque in AFM

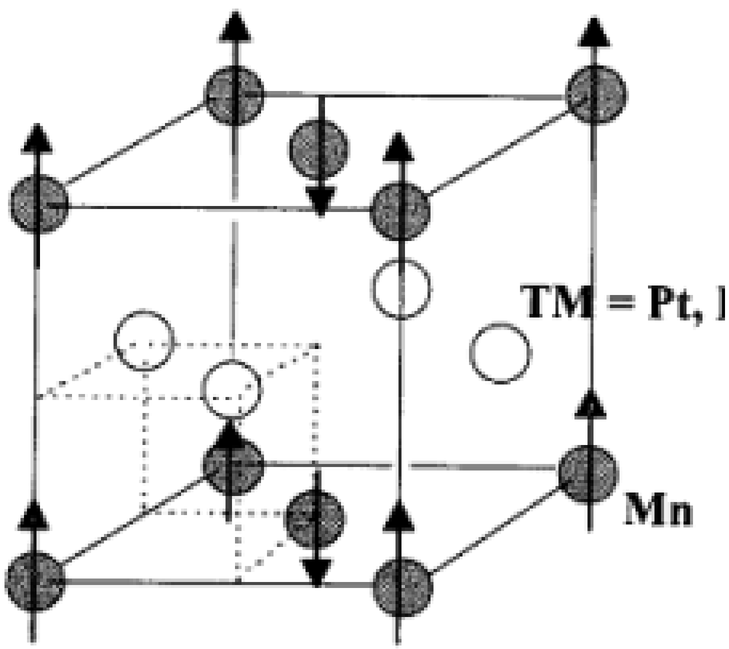


- **The effective SHA is the largest for (100) $IrMn_3$**
- **(111) and polycrystalline IrMn3 show similar SHA.**

Zhang, Han, et al, Science Advances (2016)

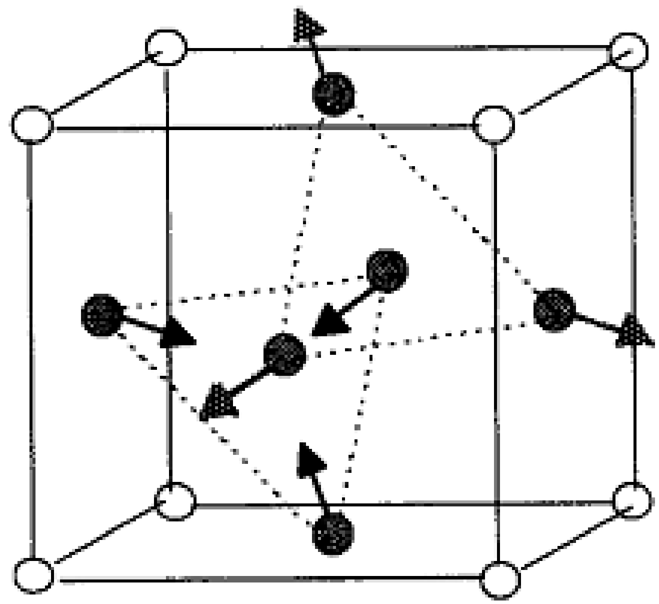
Spin orbit torque in AFM

IrMn



- **Collinear AFM**

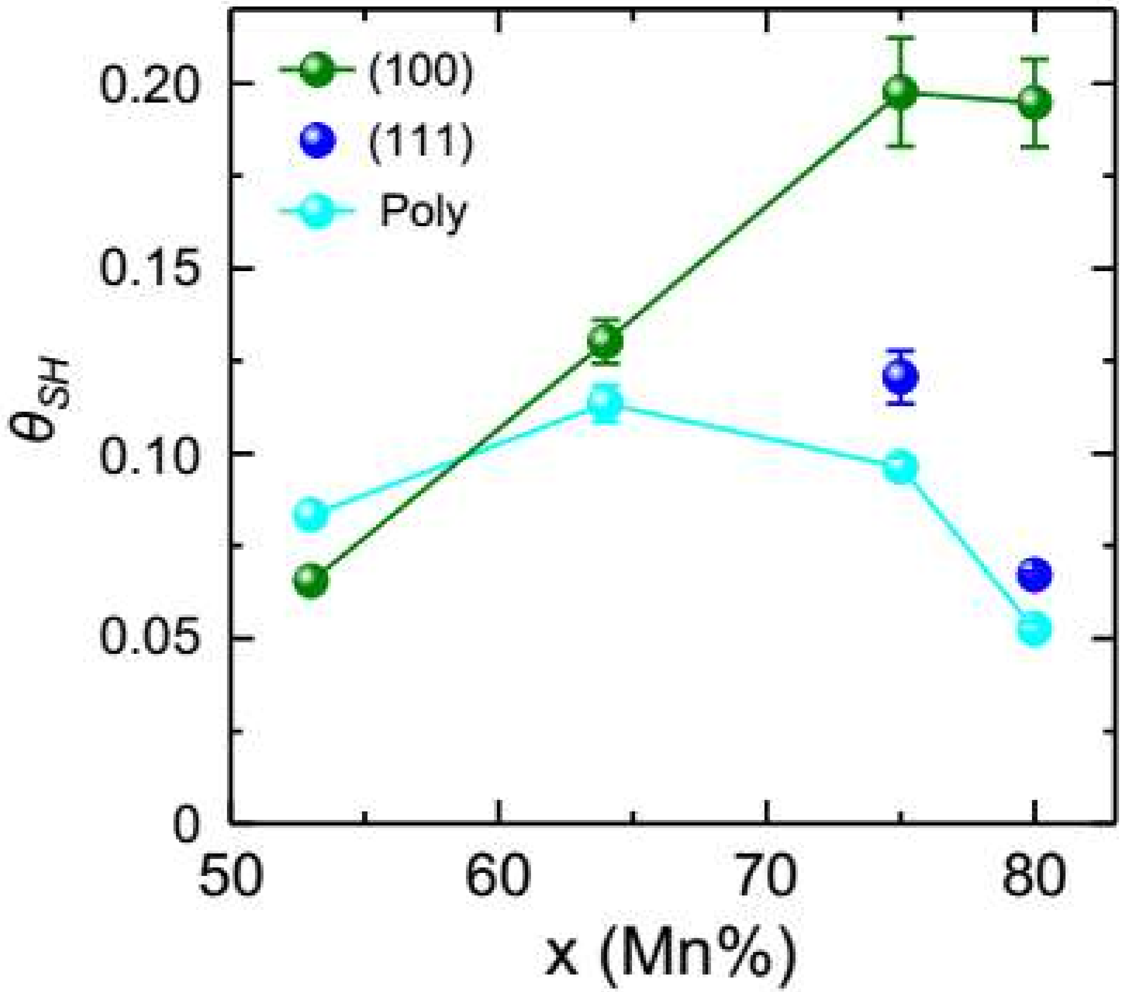
$IrMn_3$



- **Non-Collinear AFM**

Non-collinear AFM spin structure

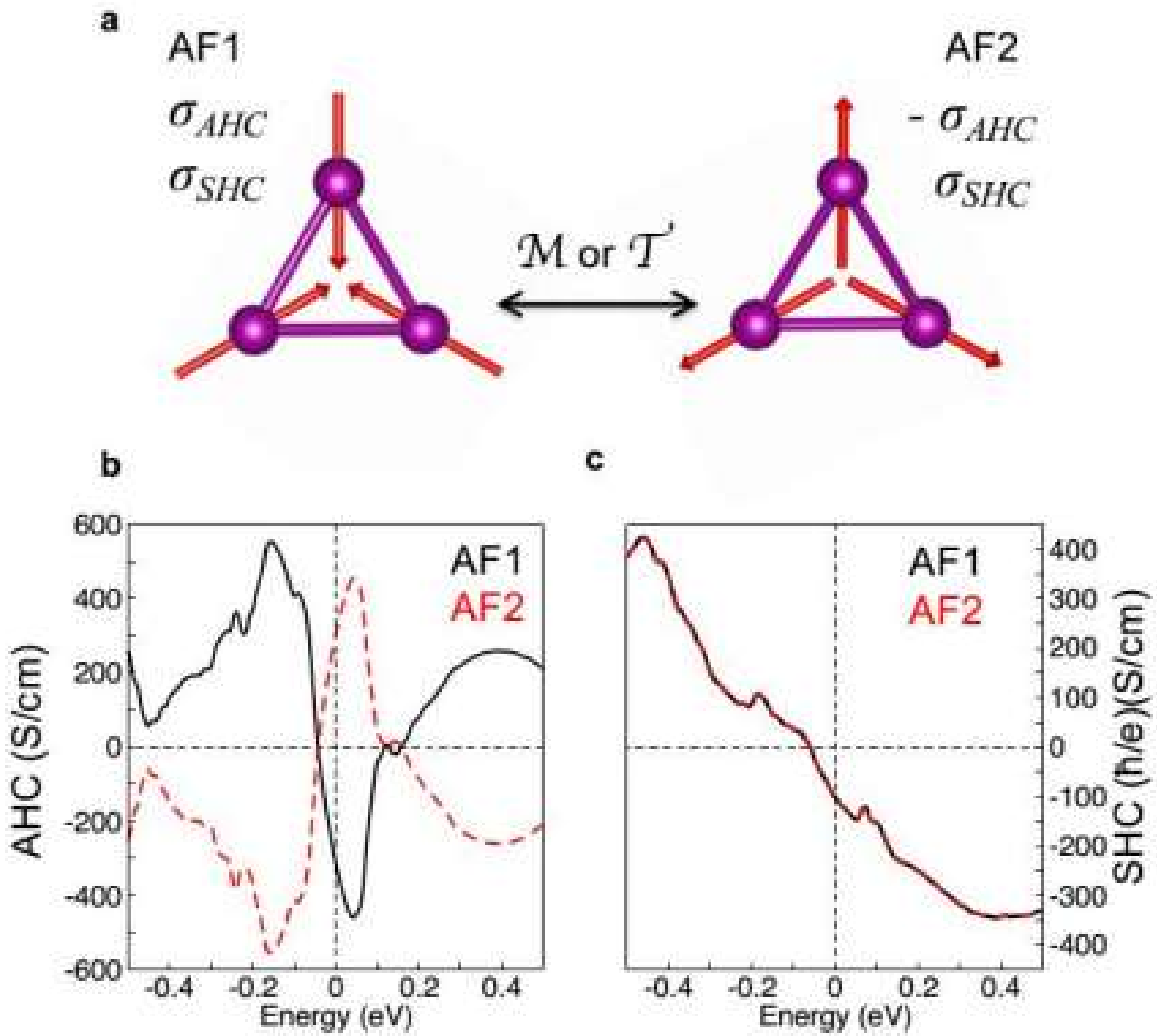
Spin orbit torque in AFM



- Little facet dependence in collinear AFM

- Strong Facet dependence in non-collinear AFM

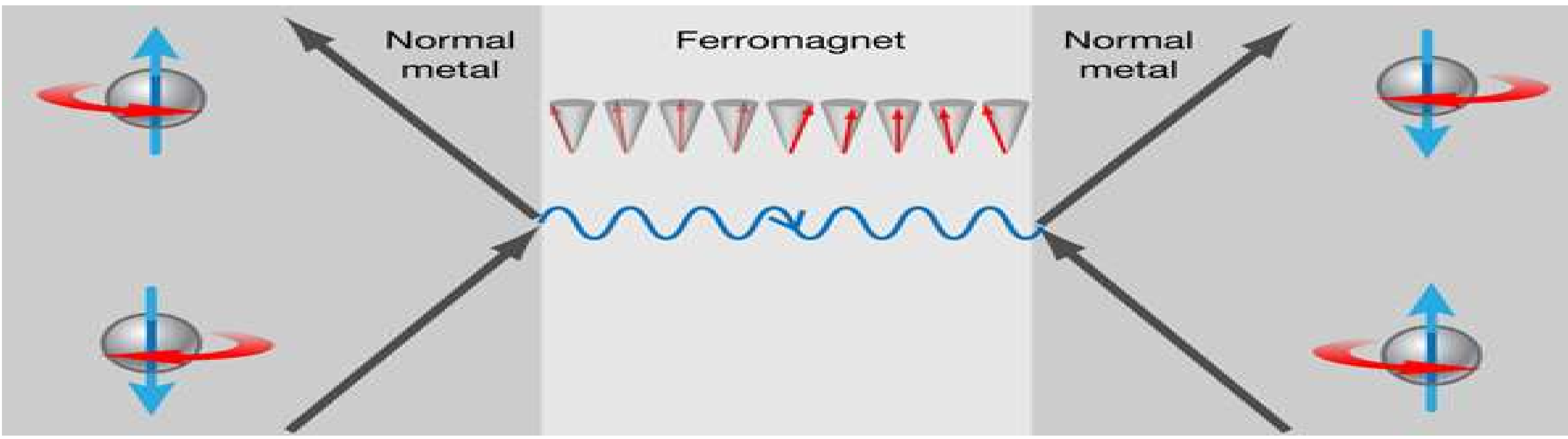
Spin orbit torque in AFM



Zhang, Han, et al, Science Advances (2016)

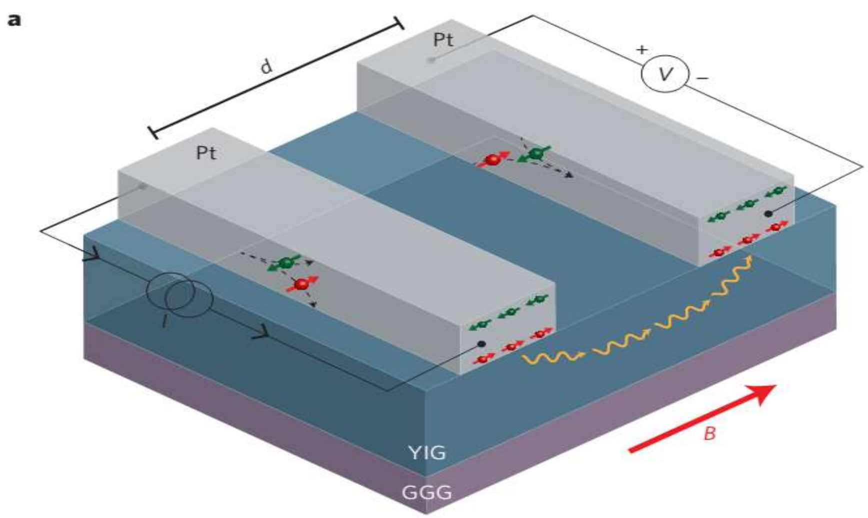
7. Spin current in AFM

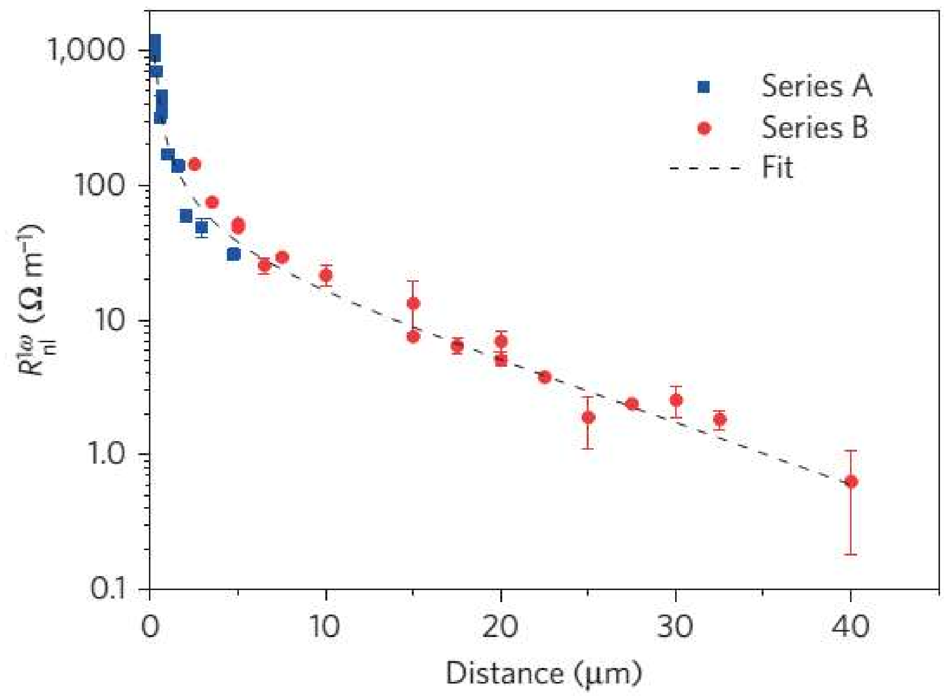
Magnon-mediated spin current



Magnon: s = 1

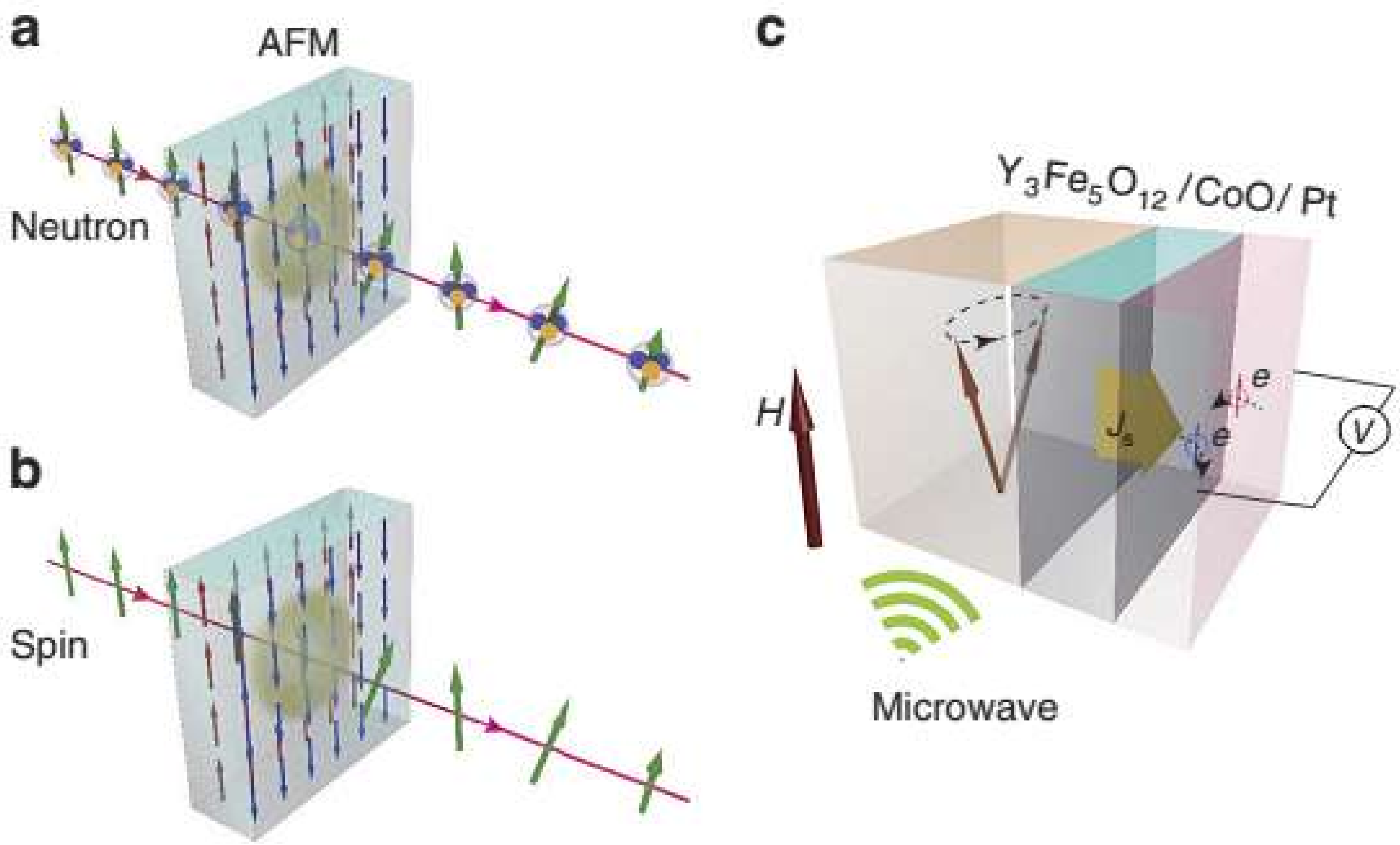
Magnon-mediated spin current





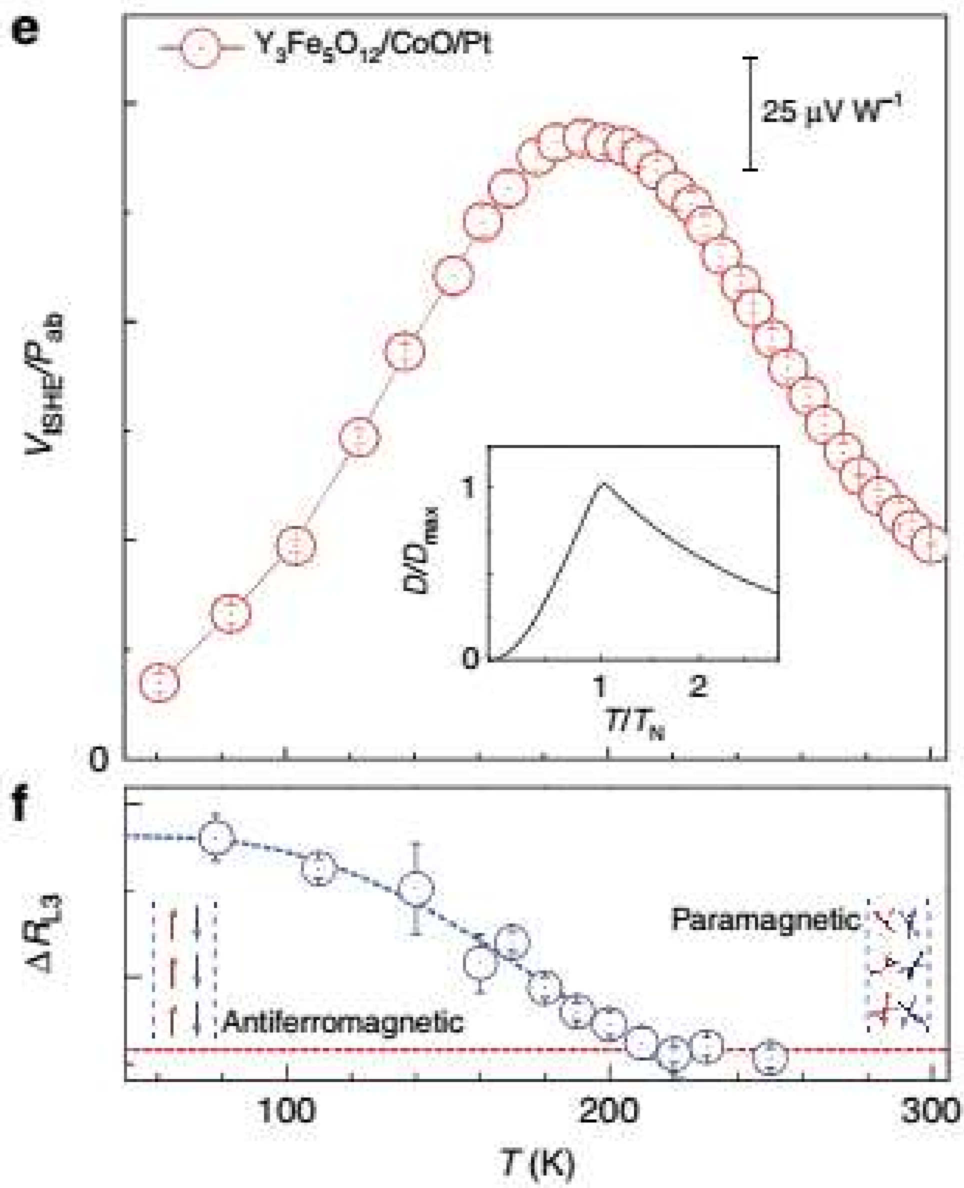
Cornelissen, et al, Nat. Phys. (2015)

Spin current through AFM

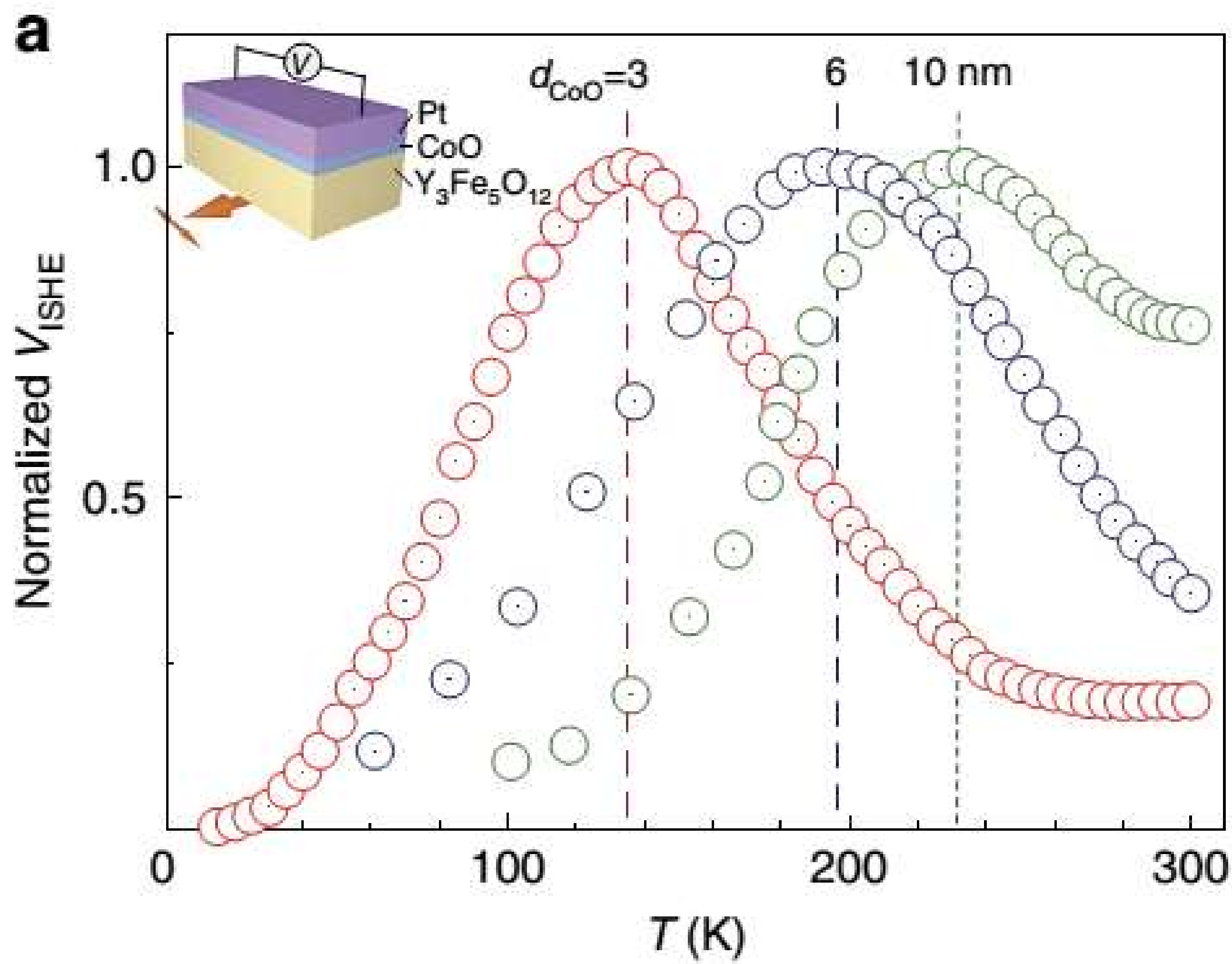


Qiu, et al, Nat. Commun. 7, 12670 (2016)

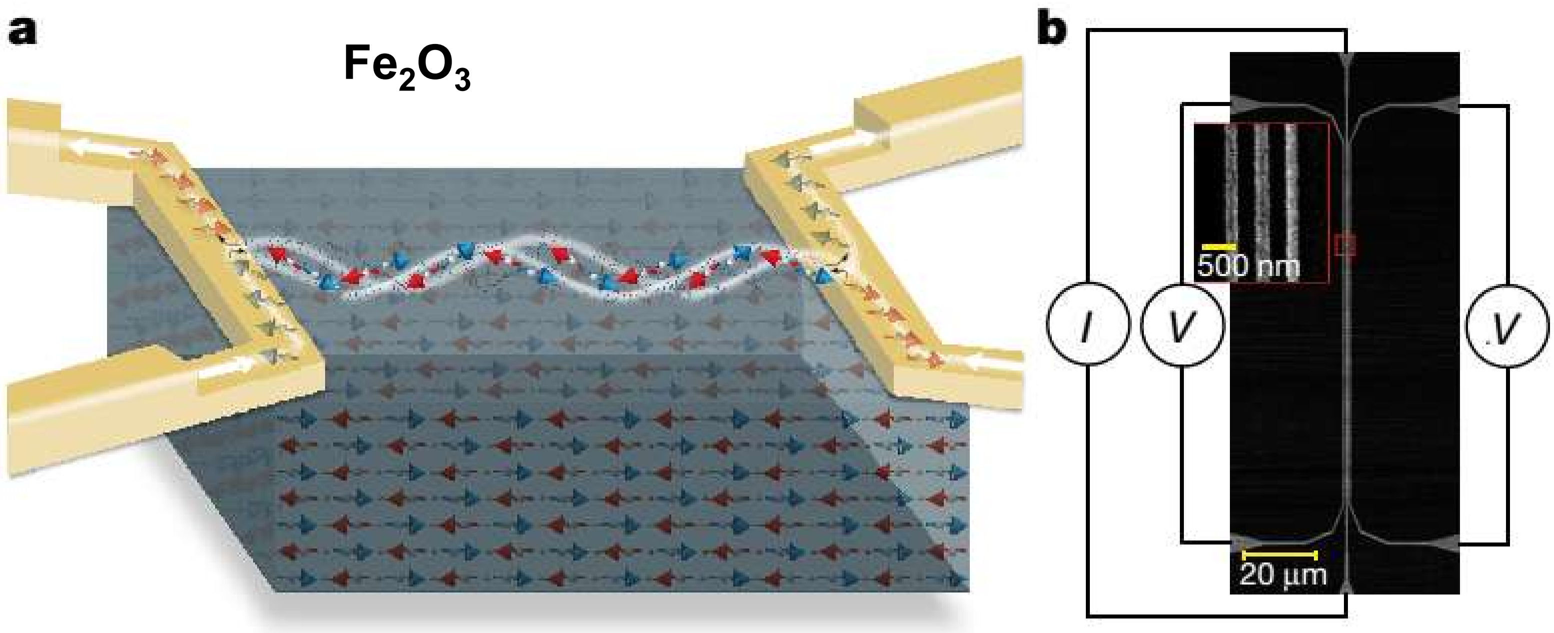
Spin current through AFM



Spin current through AFM

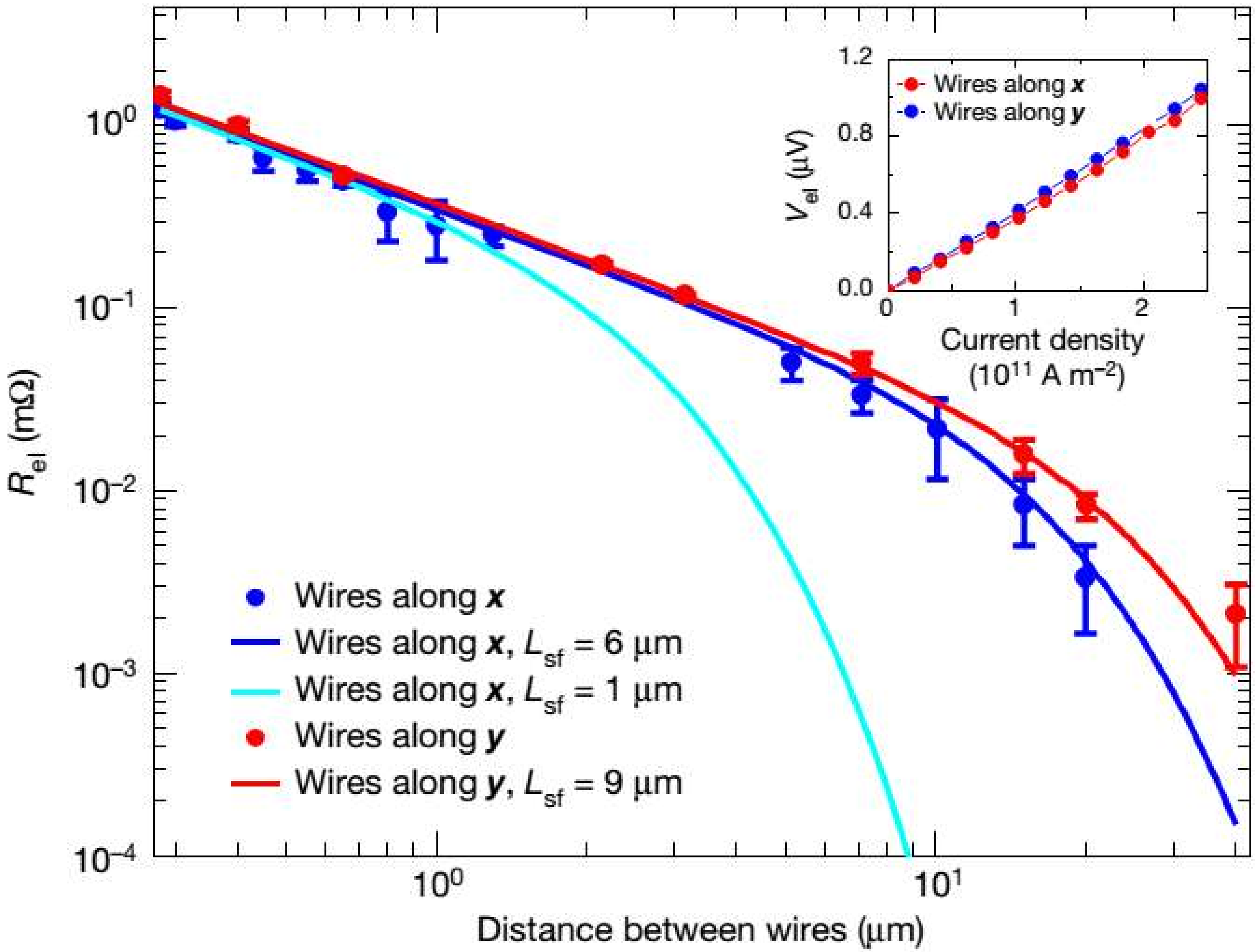


Spin current through AFM

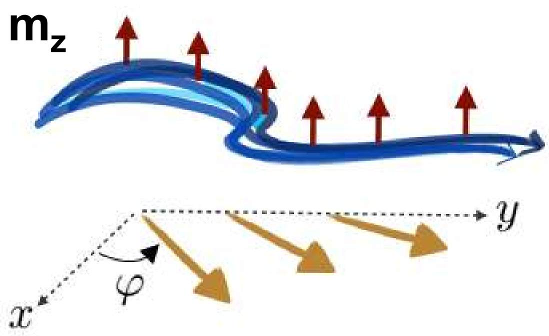


R. Lebrun, et al, Nature 561, 222 (2018).

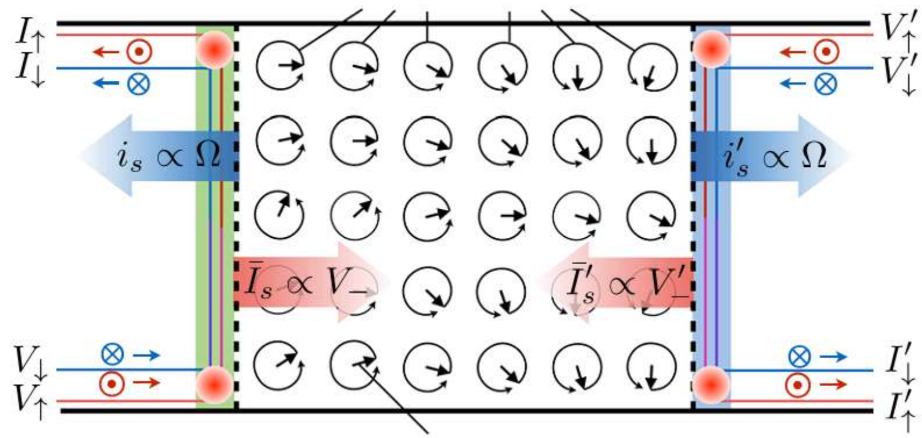
Spin current through AFM



From incoherent magnon to Spin superfluid

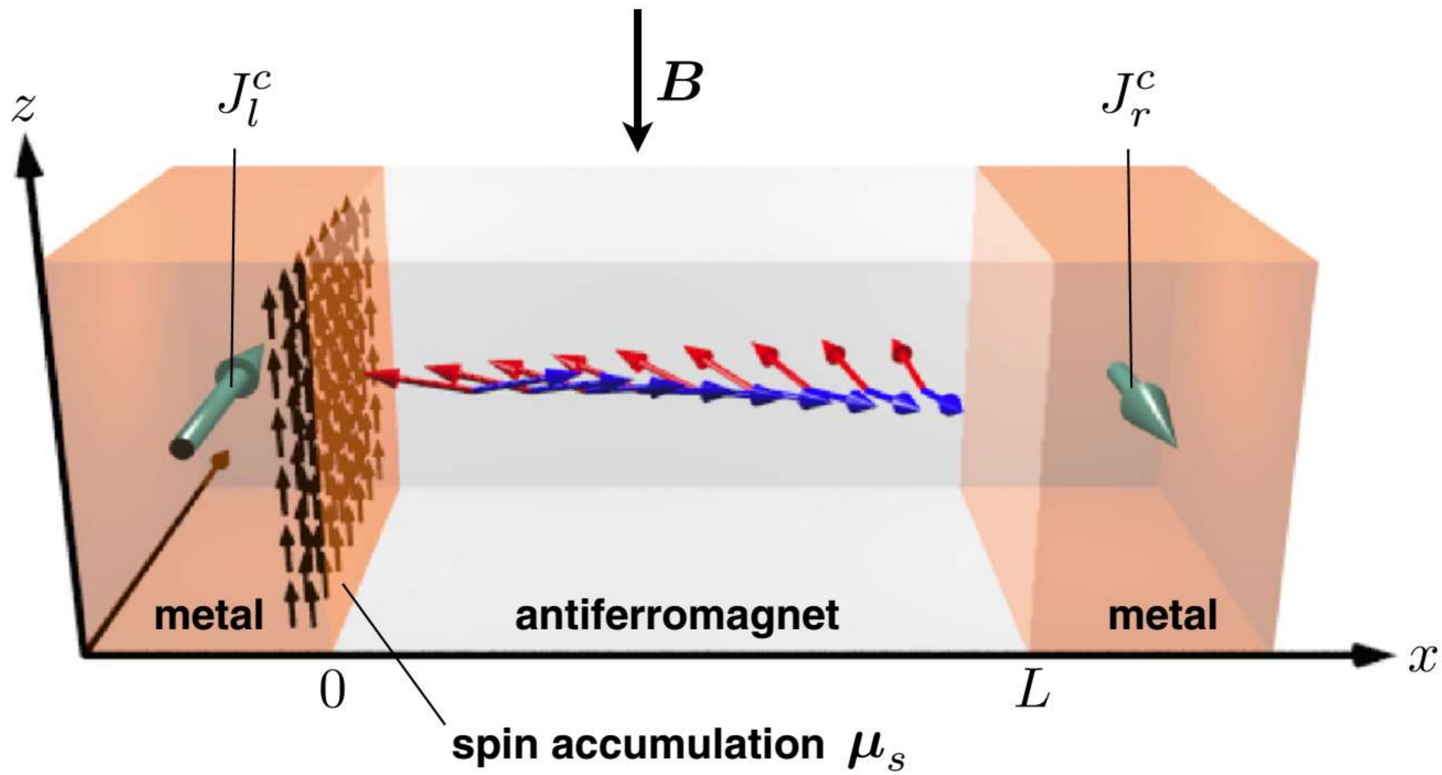


$$j_S \propto \nabla\varphi$$



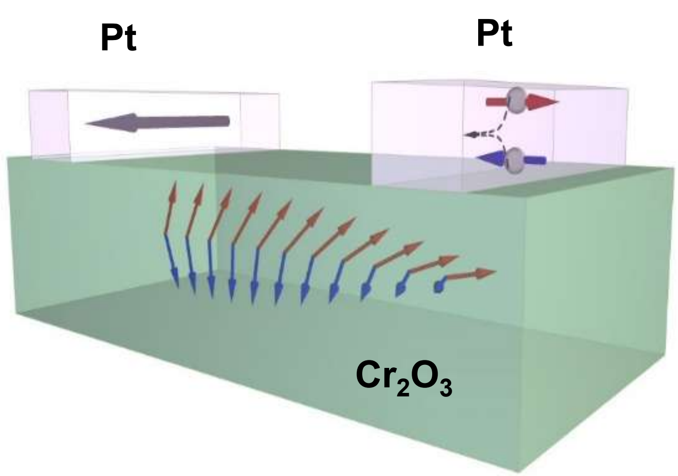
Sonin, JETP (1978)
Sun and Xie, PRB (2011), PRB (2012)
Liu, et al, PRB (2014)
Takei, et al, PRB (2014)
Chen, Kent, MacDonald, PRB (2014)

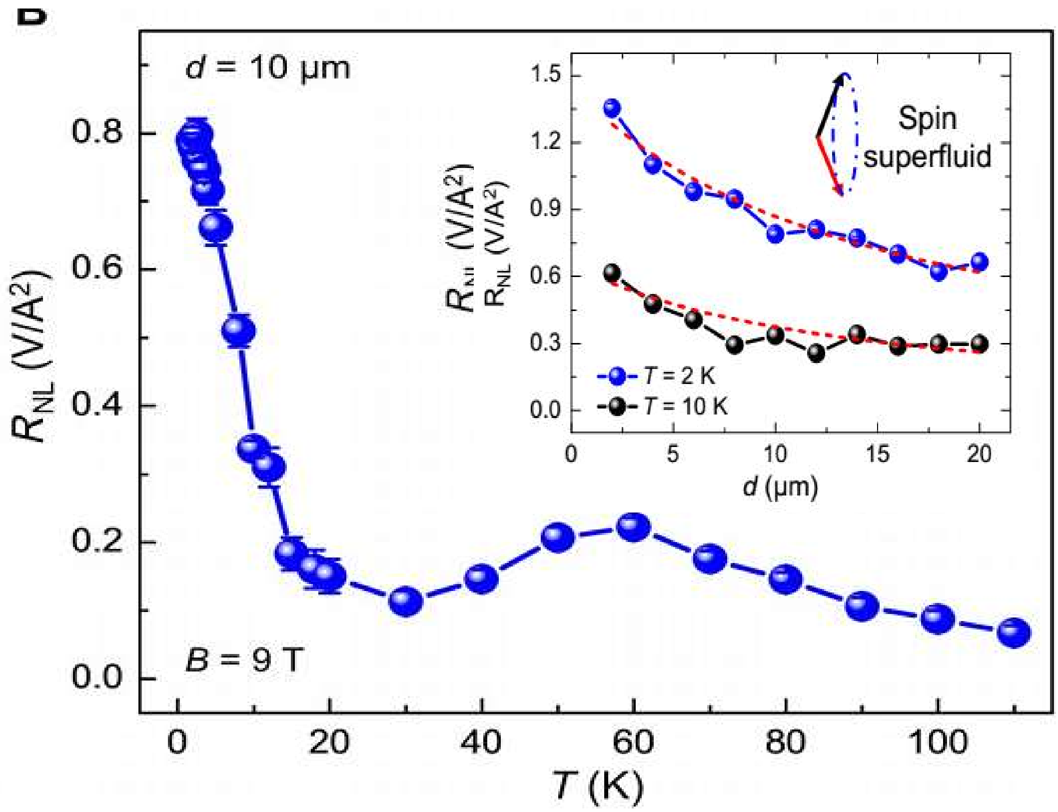
From incoherent magnon to Spin superfluid



Takei, et al, PRB (2014)
Takei, et al, PRL (2015)

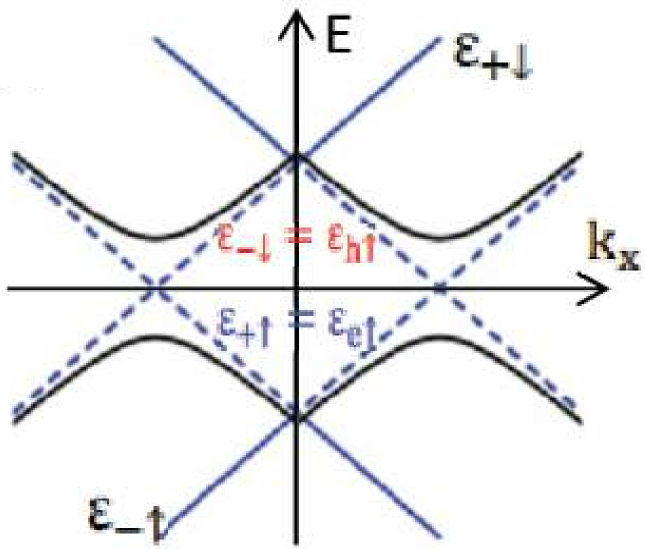
From incoherent magnon to Spin superfluid



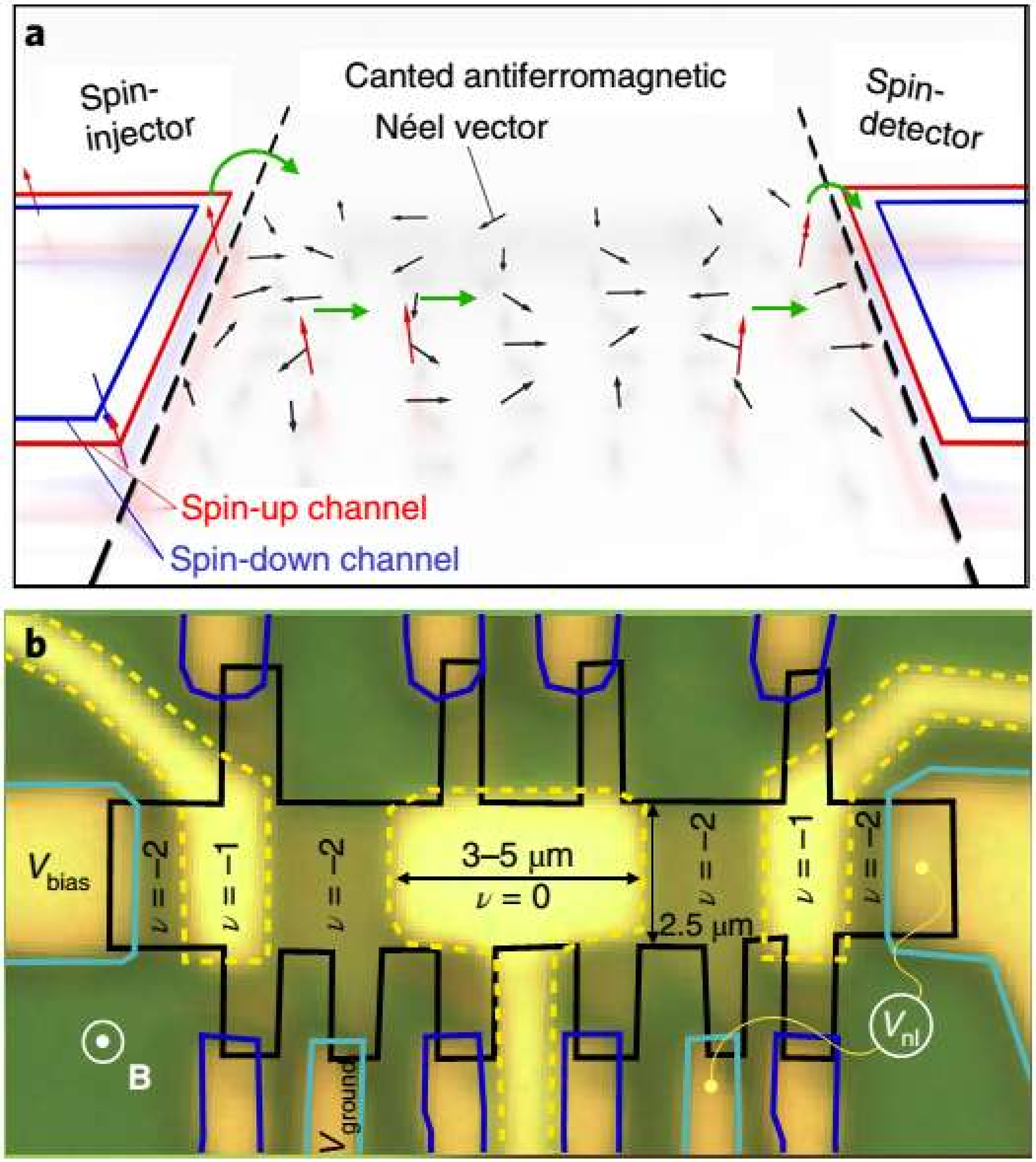


Yuan, W. et al. Science Advances (2018)

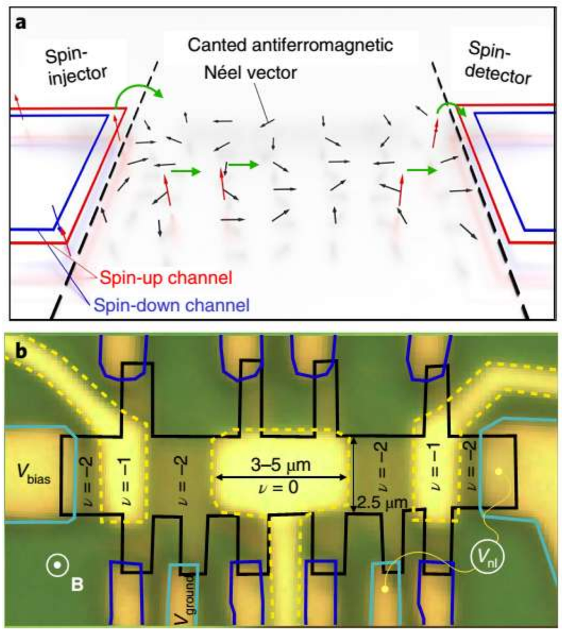
From incoherent magnon to Spin superfluid

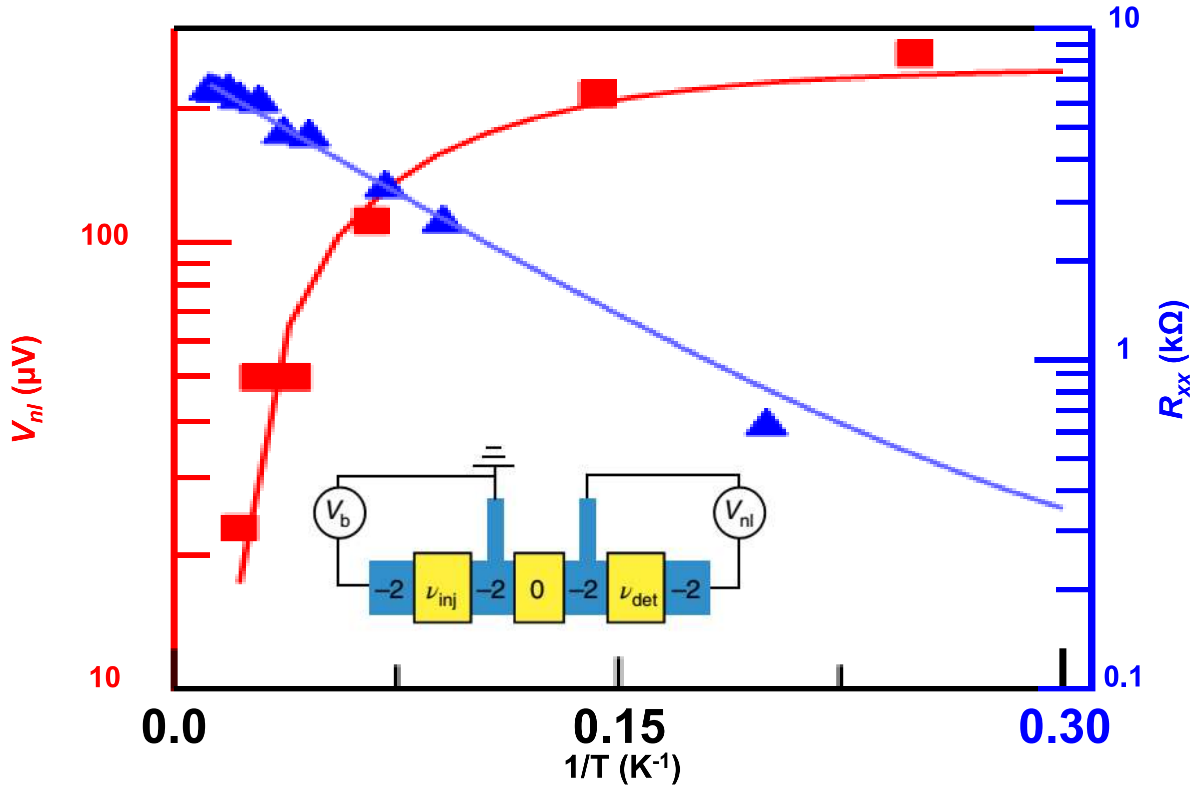


v = 0 Graphene



From incoherent magnon to Spin superfluid





Stepanov, et al, Nature Physics (2018)

Summary

1. Antiferromagnetism and Exchange bias

2. Spin Seebeck effect in AFM

3. AMR of AFM

4. Switching of AFM

5. Anomalous Hall effect in AFM

6. Spin orbit torque in AFM

7. Spin current in AFM

最后两节课: Dec. 21th

Date	Group
Dec. 21st 10:10 am- 11:00 am	Topic: Magnon BEC 何梦云、李思衡、李娜、孙慧敏、陈文杰
Dec. 21st 11:10 am- 12:00 pm	Topic: Spin FET 张仕雄、丁石磊、梁栋、杨洁、朱鹏飞、赵嘉佶

最后两节课: Dec. 28th

Date	Group
Dec. 28th 10:10 am-11:00 am	Topic: Quantum Spin liquids 吉源　孙恺伟　尚念梓　王一帆
Dec. 28th 11:10 am-12:00 pm	Topic: Anomalous hall effect/spin hall effect 赵利利，王善，闫姣婕，齐少勉，李龙飞，刘震