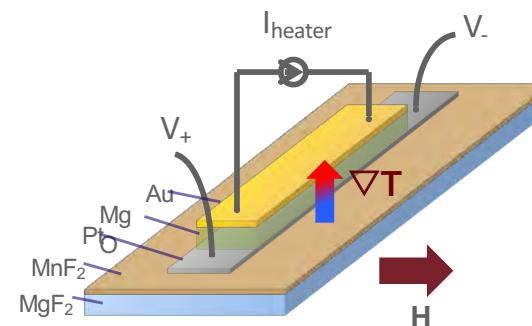
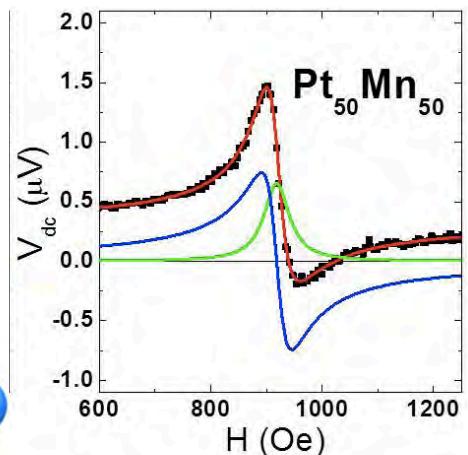
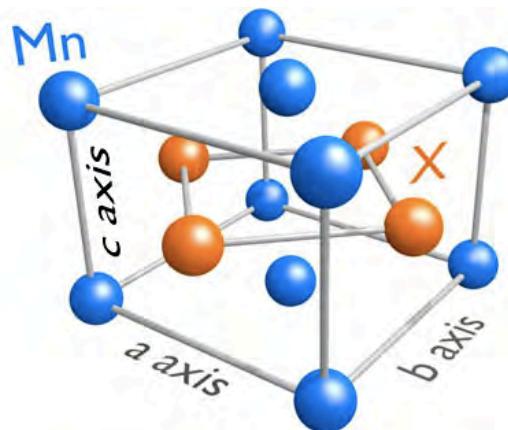
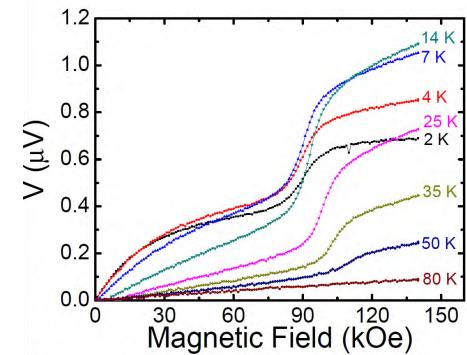


# Spin Currents in Antiferromagnets



Axel Hoffmann

Materials Science Division  
Argonne National Laboratory



# Outline

## ■ Metallic Antiferromagnets

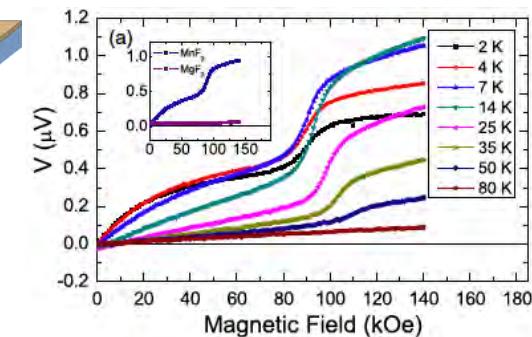
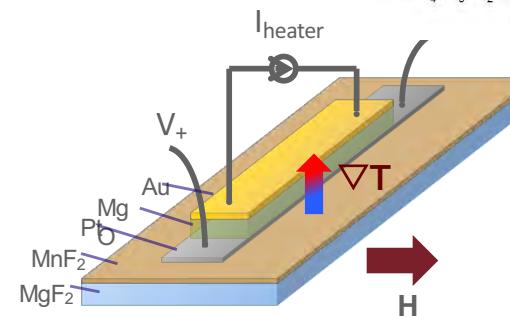
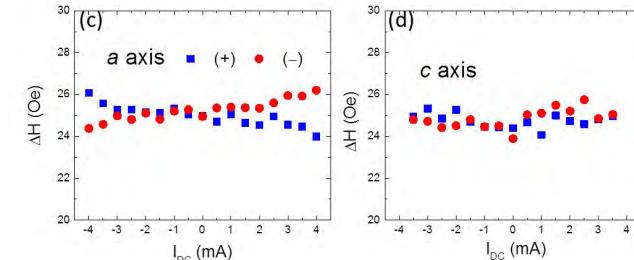
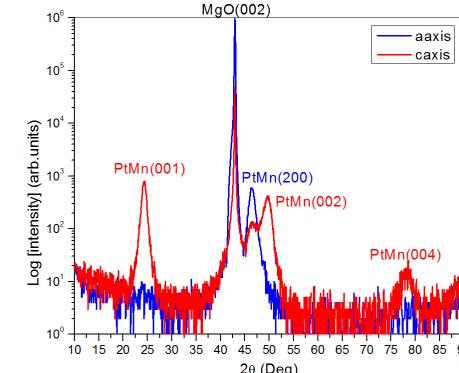
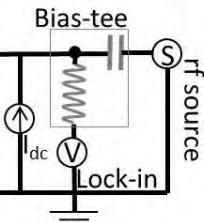
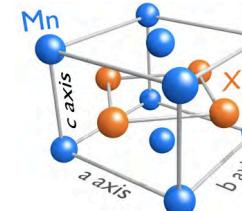
### ■ Spin Torque measured by Ferromagnetic Resonance

### ■ Anisotropy of Spin Hall Effects

## ■ Insulating Antiferromagnets

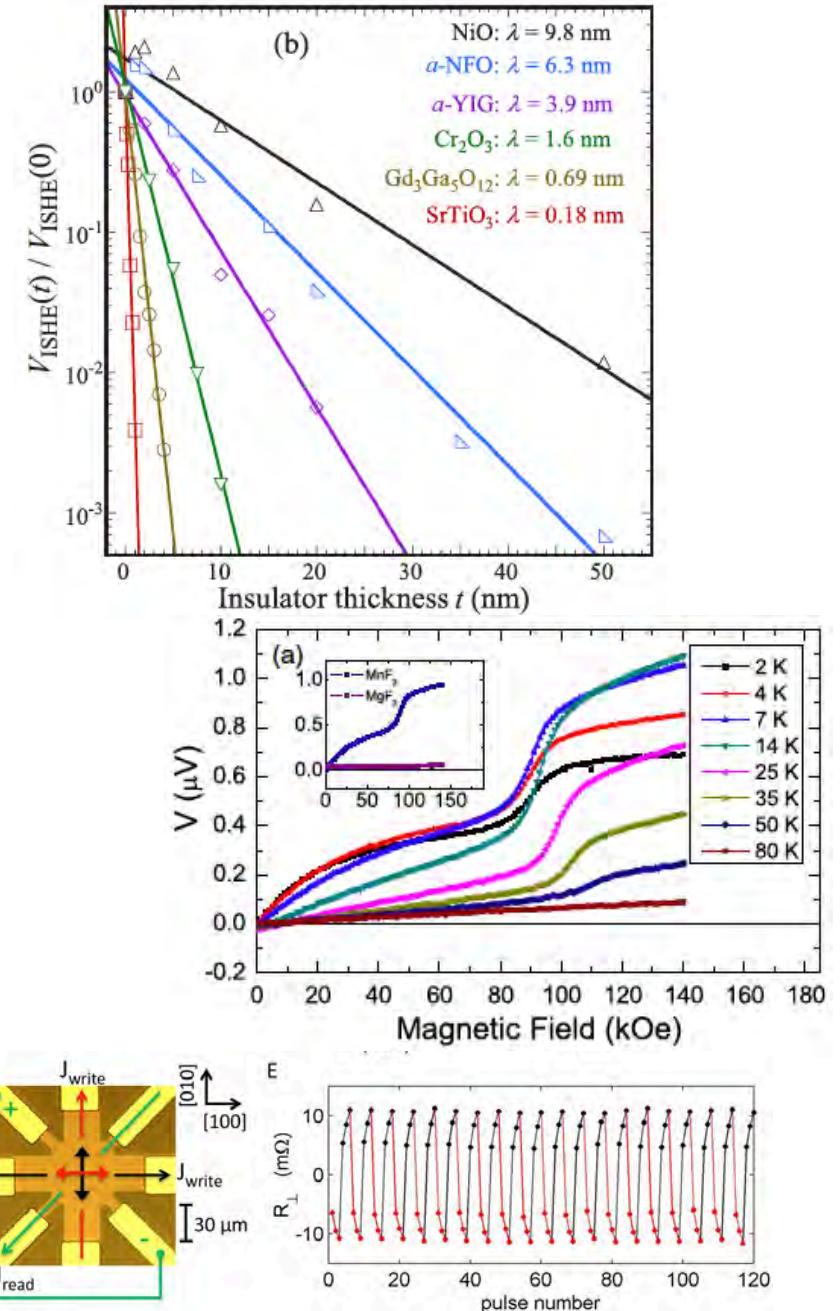
### ■ Spin Seebeck

## ■ Conclusions



# Why Antiferromagnets?

- Can be efficient spin current conductors
  - Wang *et al.*, Phys. Rev. Lett. **113**, 097202 (2014)
  - Hahn *et al.*, Europhys. Lett. **108**, 57005 (2014)
- Can be efficient sources for spin currents
  - Metallic: Spin Hall Effect
    - Zhang et al., Phys Rev. Lett. **113**, 196602 (2014)
  - Insulating Spin Seebeck Effect
    - Wu *et al.*, Phys. Rev. Lett. **116**, 097204 (2016)
- Antiferromagnetic magnetization can be switched electrically
  - Wadley *et al.*, Science, **351**, 587 (2016)
- Potential advantages
  - No stray field; minimize cross coupling
  - Small response to external magnetic fields
  - Fast dynamics in THz-range



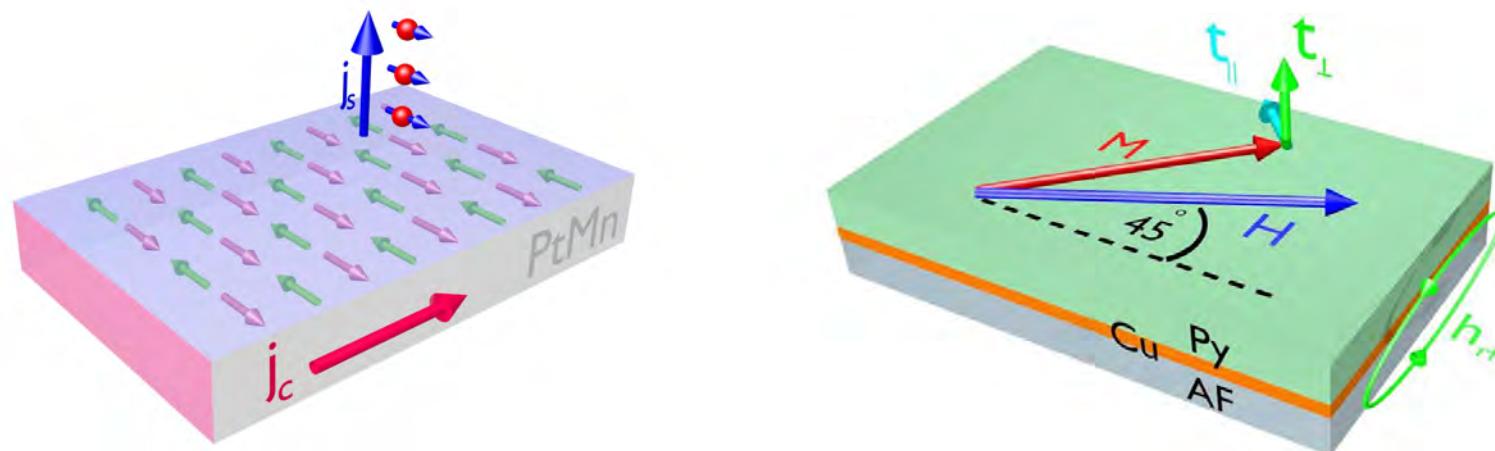
# Spin Hall Effects in Metallic Antiferromagnets

Axel Hoffmann, MSD, Argonne National Laboratory

[hoffmann@anl.gov](mailto:hoffmann@anl.gov)

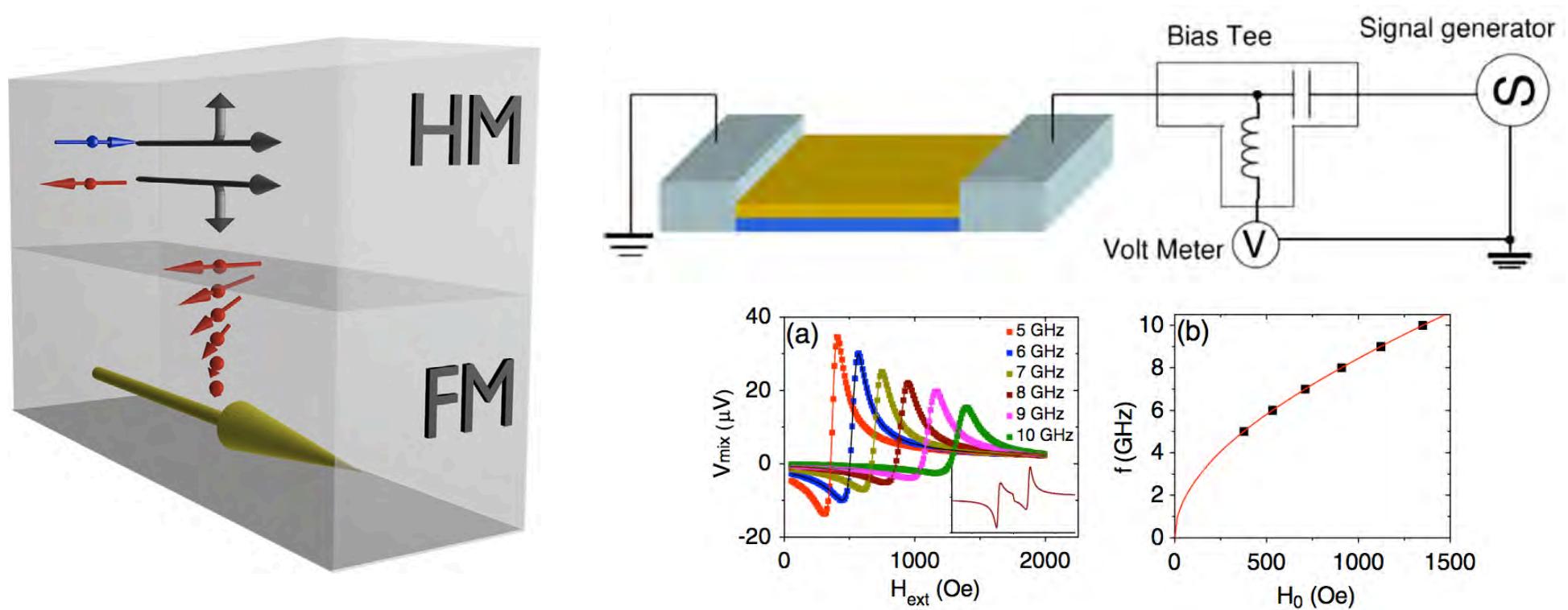


# Spin Torque Ferromagnetic Resonance



# Spin-Torque Ferromagnetic Resonance

- Excitation of spin dynamics by Oersted field and SHE torques.
- Mixing of anisotropic magnetoresistance (AMR) in Py with microwaves lead to *dc* rectification.
- Lineshape analysis can quantify spin Hall angle.



L. Liu *et al.*, Phys. Rev. Lett. **106**, 036601 (2011)

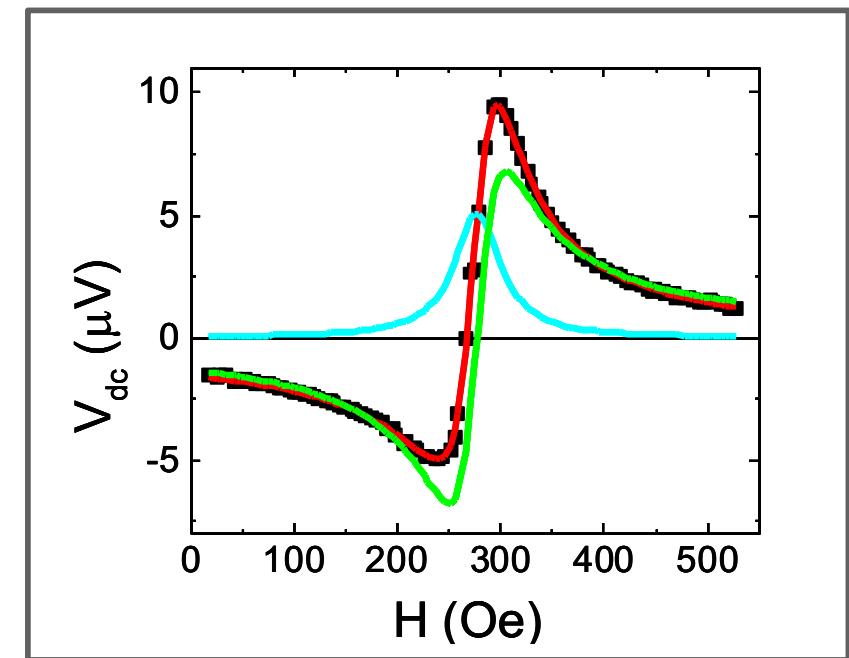
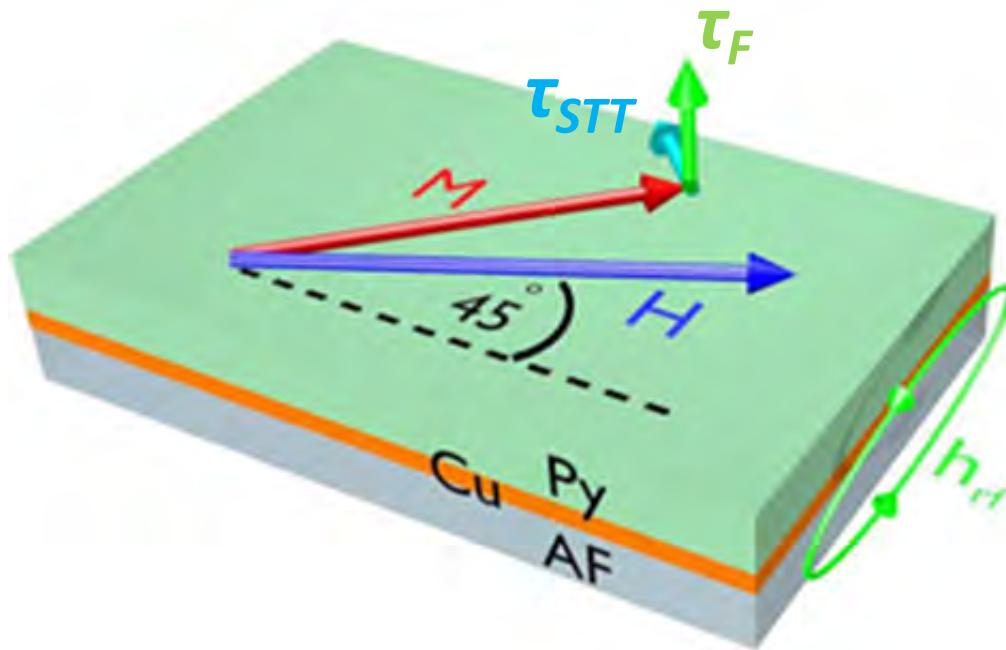
Axel Hoffmann, MSD, Argonne National Laboratory

hoffmann@anl.gov

# Spin-Torque Ferromagnetic Resonance

Landau–Lifshitz–Gilbert equation (LLG)

$$\frac{d\hat{\mathbf{m}}}{dt} = -|\gamma| \hat{\mathbf{m}} \times \mathbf{H}_{eff} + \alpha \hat{\mathbf{m}} \times \frac{d\hat{\mathbf{m}}}{dt} + |\gamma| \tau_{STT} \hat{\mathbf{m}} \times (\hat{\mathbf{y}} \times \hat{\mathbf{m}}) + |\gamma| \tau_F \hat{\mathbf{m}} \times \hat{\mathbf{y}}$$



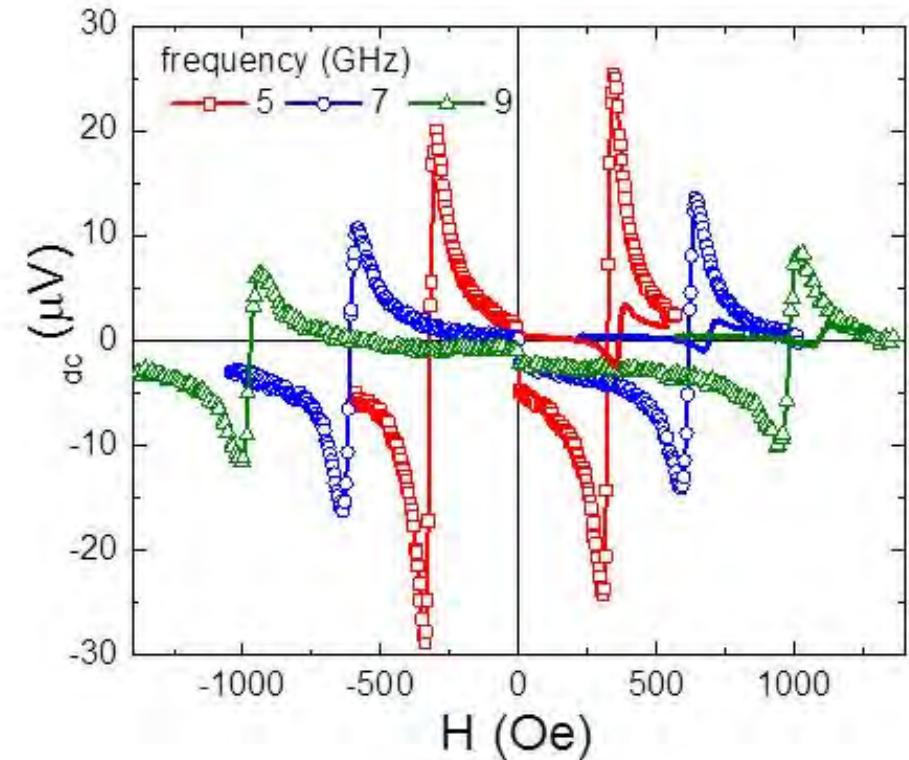
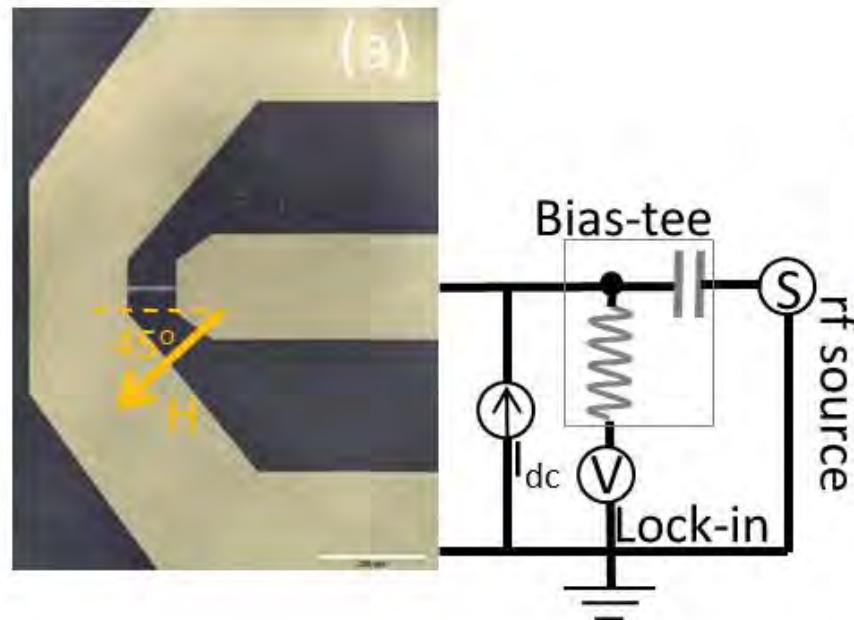
$$V_{dc} = \frac{S * \Delta}{(H^2 - H_{FMR}^2)^2 + \Delta^2} + \frac{A * (H^2 - H_{FMR}^2)}{(H^2 - H_{FMR}^2)^2 + \Delta^2}$$

L. Liu *et al.*, Phys. Rev. Lett. **106**, 036601 (2011)



# Ferromagnetic Resonance Driven by Spin Hall Spin Transfer Torques

FeMn (10 nm) / Cu (1 nm) / Ni<sub>80</sub>Fe<sub>20</sub> (5 nm)



- Sufficiently large spin Hall effect even for FeMn to drive magnetization dynamics

W. Zhang *et al.*, Phys. Rev. B **92**, 144405 (2015)

# Quantifying Spin Hall Angles

## Ratio analysis

$$\theta_{\text{SH}} = \frac{V_s}{V_a} \frac{e\mu_0 M_s t_{\text{AFTPy}}}{\hbar} \left[ 1 + \frac{4\pi M_{\text{eff}}}{H} \right]^{\frac{1}{2}}$$

## Amplitude analysis

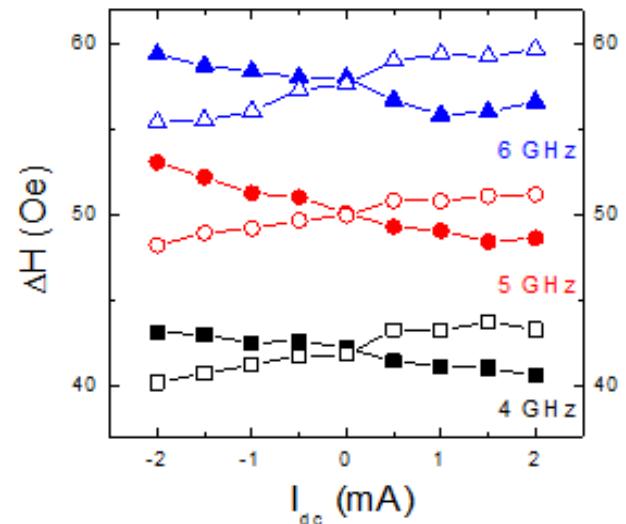
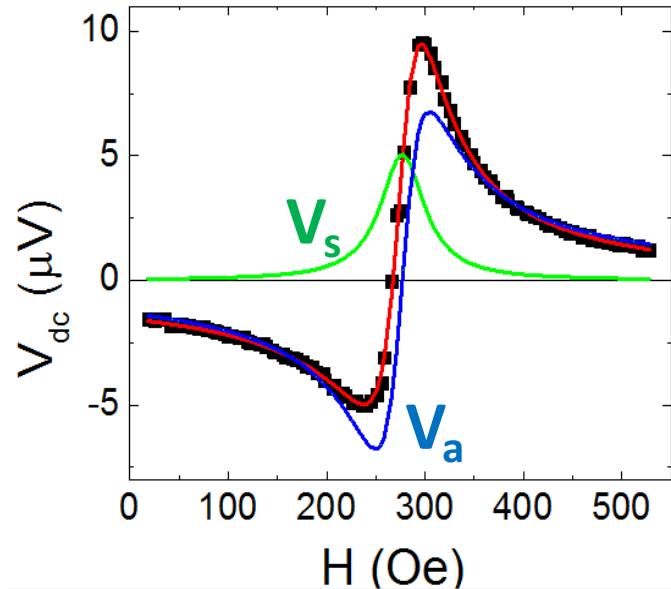
$$V_a = -\frac{I_{\text{rf}}\gamma \cos\phi}{4} \frac{dR}{d\phi} \tau_{\perp} \frac{\left(1 + \frac{\mu_0 M_{\text{eff}}}{H}\right)^{\frac{1}{2}}}{\Delta} F_{\text{asym}}(H),$$

$$V_s = -\frac{I_{\text{rf}}\gamma \cos\phi}{4} \frac{dR}{d\phi} \tau_{\parallel} \frac{1}{\Delta} F_{\text{sym}}(H)$$

## DC Modulation

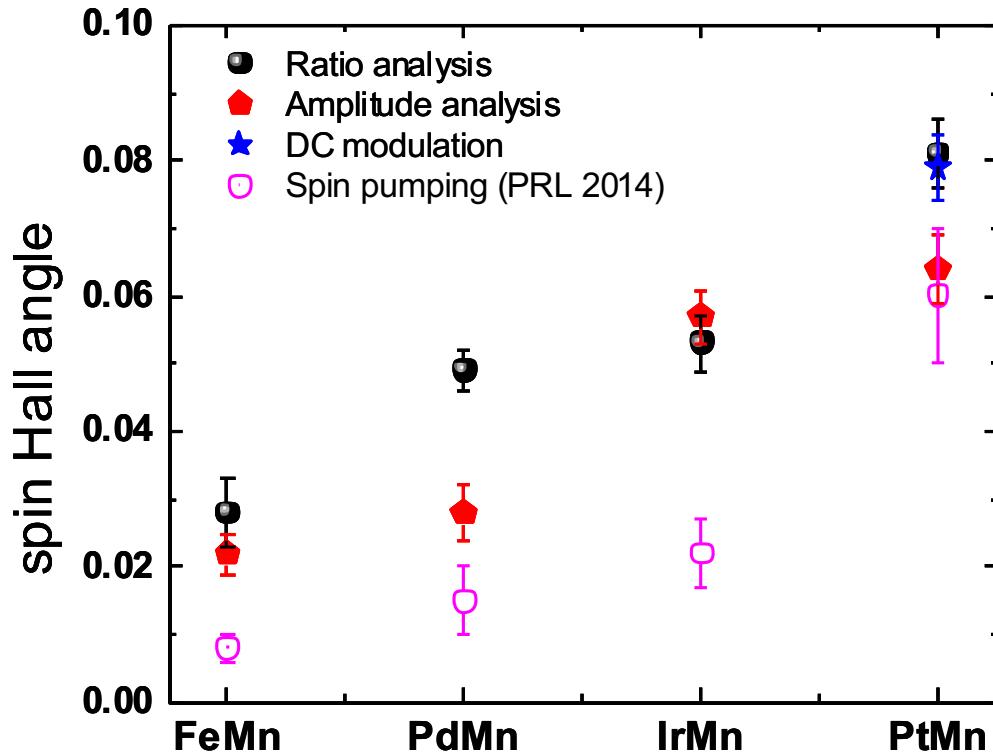
$$|\theta_{\text{DL}}| = \frac{2e}{\hbar} \frac{(H_{\text{res}} + \frac{M_{\text{eff}}}{2})\mu_0 M_s t_{\text{Py}}}{\sin\phi} \left| \frac{\Delta\alpha_{\text{eff}}}{\Delta J_{\text{dc}}} \right|$$

$$|\theta_{\text{FL}}| = \frac{2e\mu_0 M_s t_{\text{Py}}}{\hbar} \left| \frac{H_{\text{FL}}}{J_{\text{dc,PtMn}}} \right|$$



W. Zhang et al., Phys. Rev. B 92, 144405 (2015)

# ST-FMR Lineshape and Spin Hall Angle

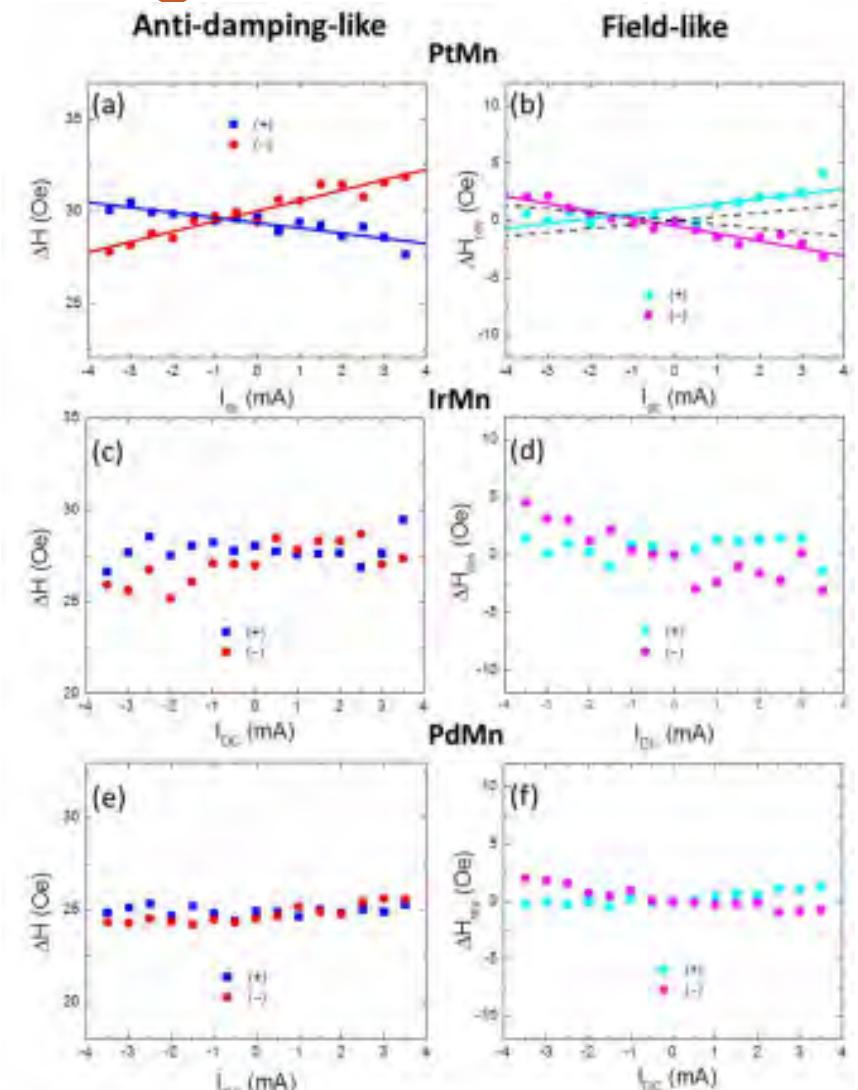


$$\text{Re}[G_{\uparrow\downarrow}^{\text{eff}}] = (3.9 \pm 0.5) \times 10^{14} \Omega^{-1} m^{-2}$$

$$\text{Im}[G_{\uparrow\downarrow}^{\text{eff}}] = (1.0 \pm 0.2) \times 10^{14} \Omega^{-1} m^{-2}$$

"internal spin Hall angle" of PtMn ~

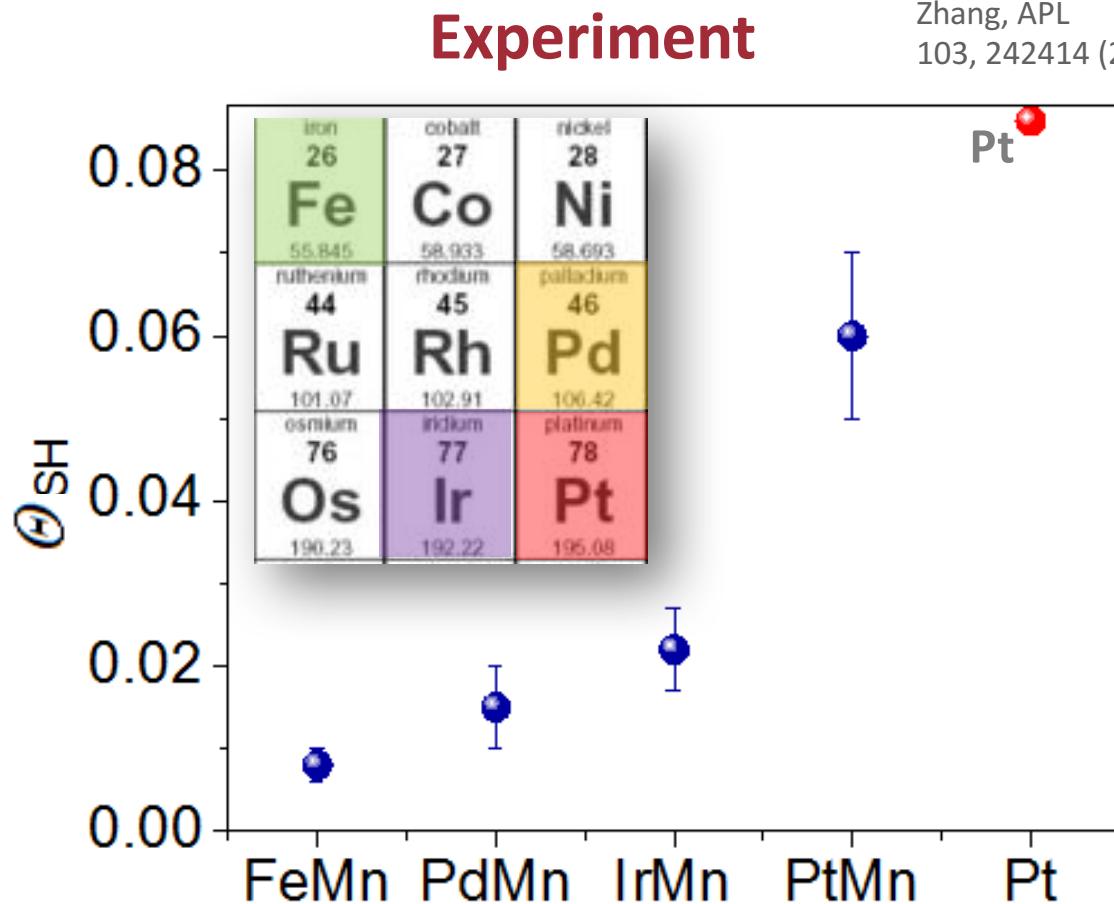
**12.5%**



W. Zhang et al., Phys. Rev. B 92, 144405 (2015)



# Comparison to Ab-Initio Theory

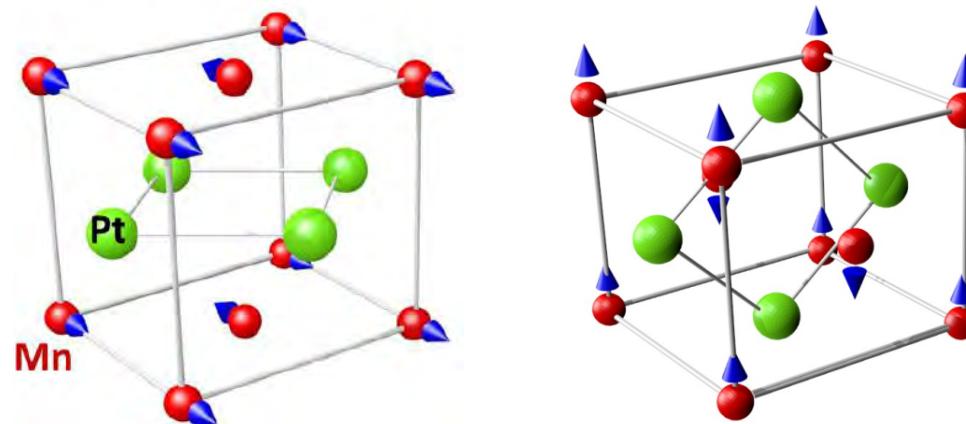
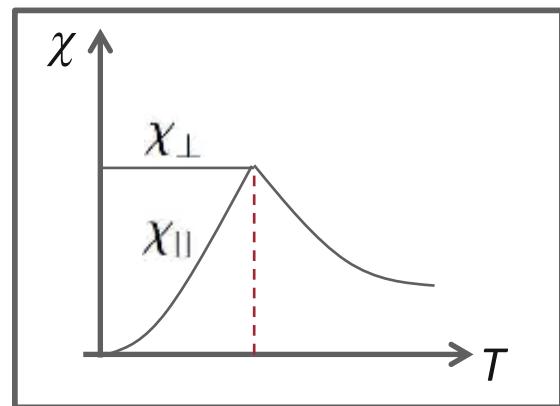


**Ab-initio theory**

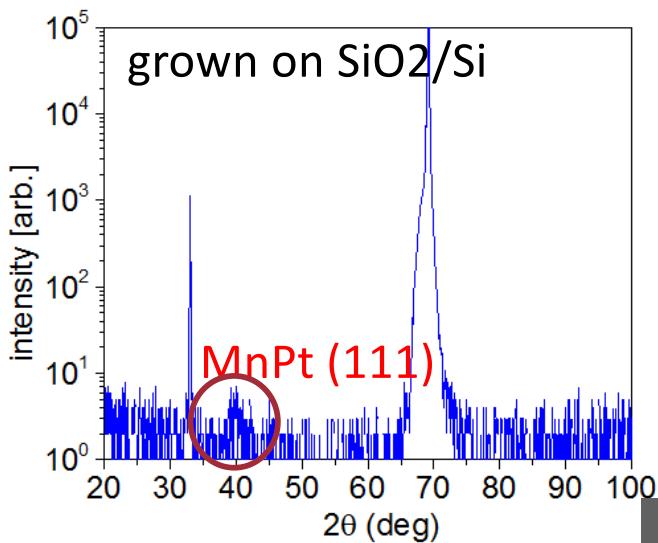
	$\sigma_{theo}^{av}$ ( $\text{h/e S/m}$ )	$\sigma_{exp}$ ( $\text{h/e S/m}$ )
PtMn	125.2	182.9
IrMn	41.6	40.8
PdMn	3.9	33.6
FeMn	-59.0	23.9

W. Zhang et al, Phys. Rev. Lett. **113**, 196602 (2014)

# Anisotropic Spin Hall Effect



# Spin Hall Effect and Anisotropy

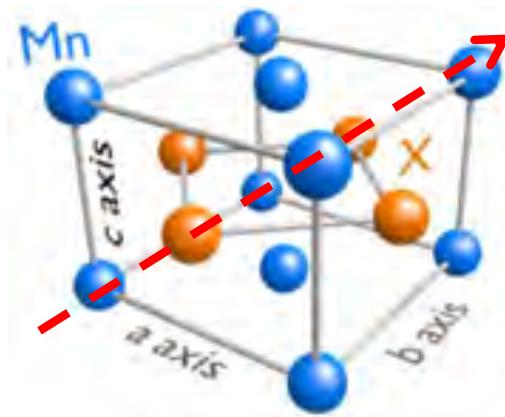


(111) Textured

Individual crystallines rotated randomly around (111)

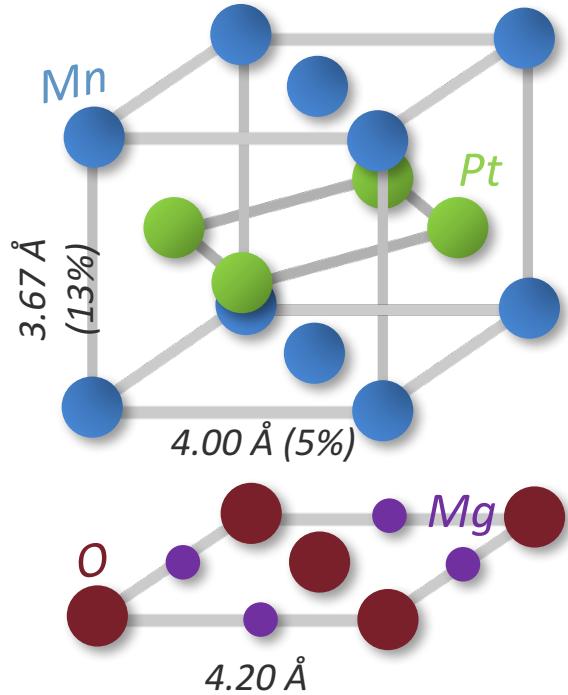
Mn magnetization along **a** and/or **c** axes

Mn magnetization within crystallines is random



		$\sigma_{yz}^x$	$\sigma_{xy}^z$	$\bar{\sigma}$	$\sigma_{av}$	$\sigma_{exp}$
PtMn	<i>c</i> axis	303.9	60.3	194.7	125.2	182.9
	<i>a</i> axis	30.4	92.5	90.5		
IrMn	<i>c</i> axis	372.8	40.9	157.8	41.6	40.8
	<i>a</i> axis	-21.3	-325.1	-16.5		
PdMn	<i>c</i> axis	69.5	17.8	34.8	3.9	33.6
	<i>a</i> axis	0.0	-70.8	-11.6		
FeMn	<i>c</i> axis	51.9	-100.3	-48.6	-59.0	23.9
	<i>a</i> axis	-82.6	-121.6	-64.2		

# Epitaxial Growth



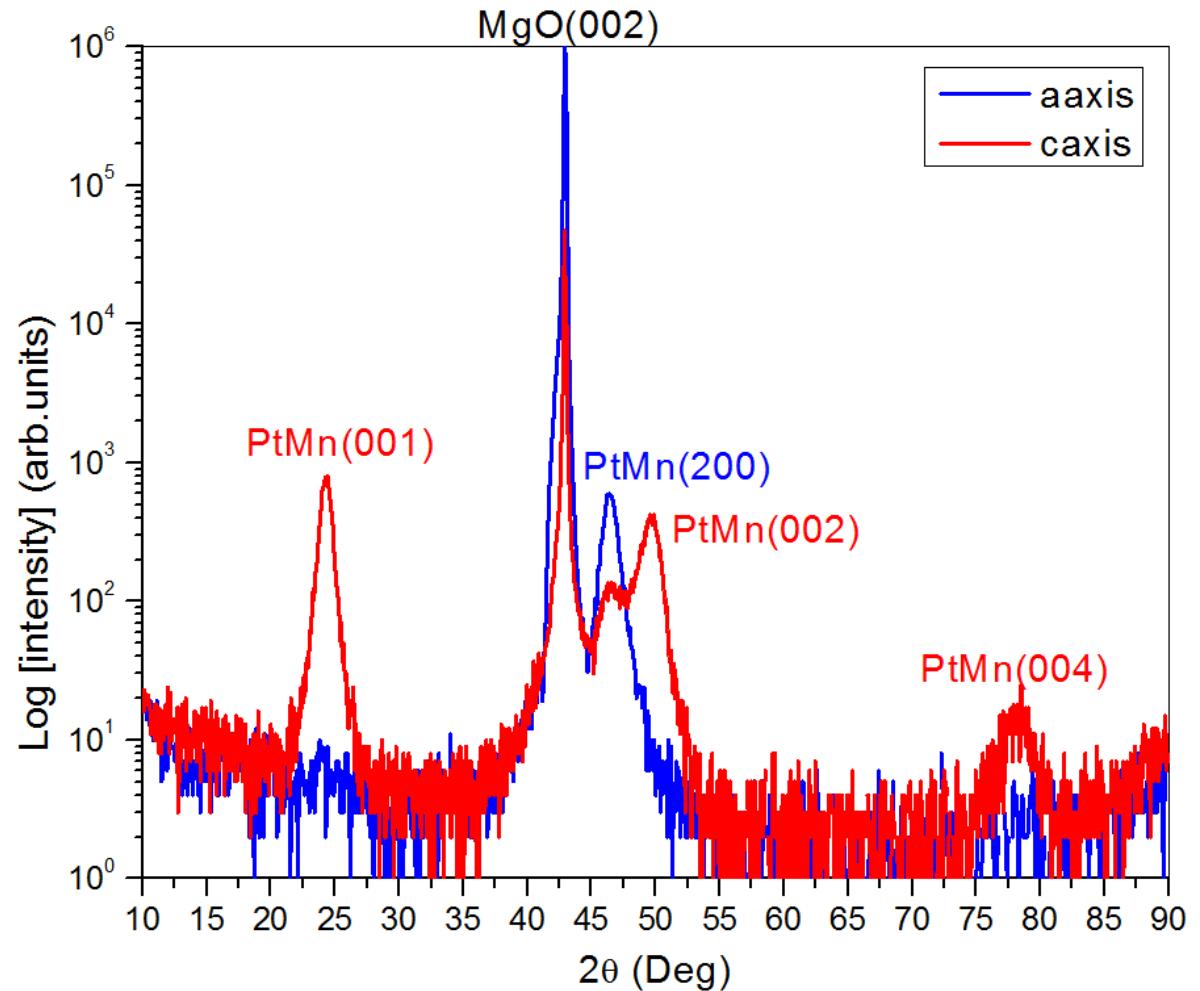
Cheng *et al.*, JAP (01')  
Krishnan *et al.*, J. Mater. Sci. (06')

Low-T growth 120°C + anneal 250°C → **a**

High-T growth 550°C → **c**

**Very different exchange bias effects:**

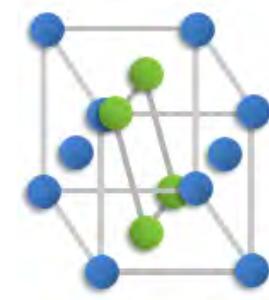
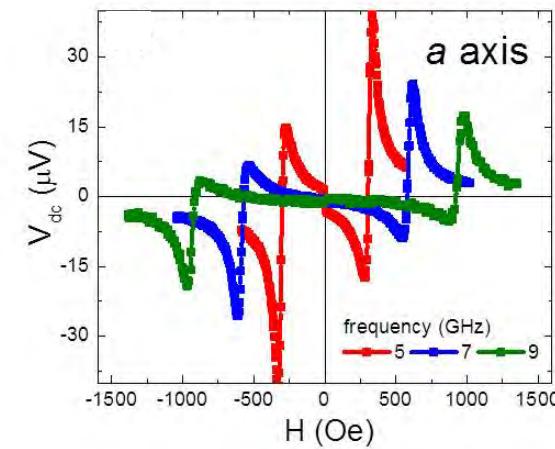
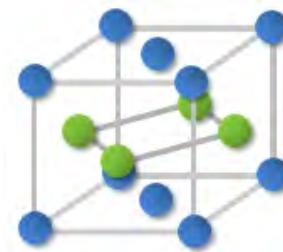
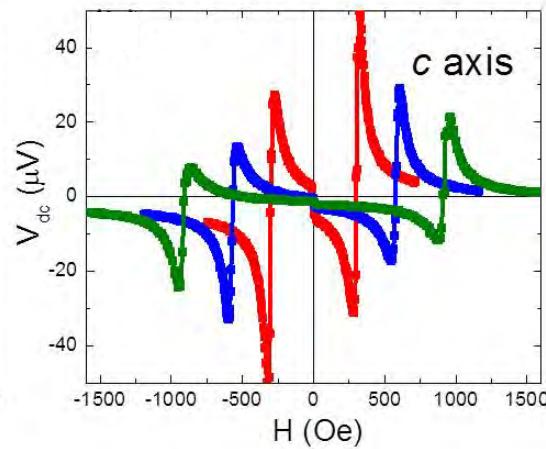
Zhang&Krishnan, PRB (11')(12')(13')



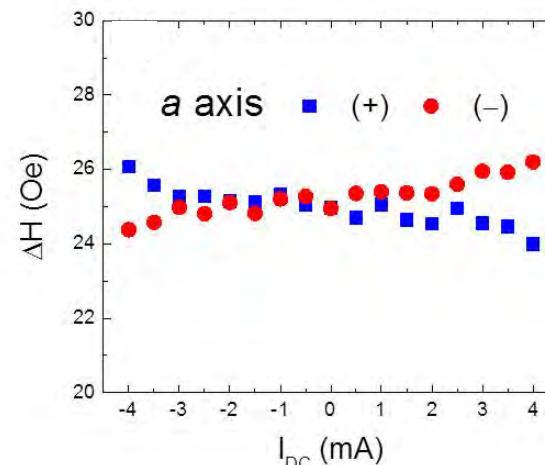
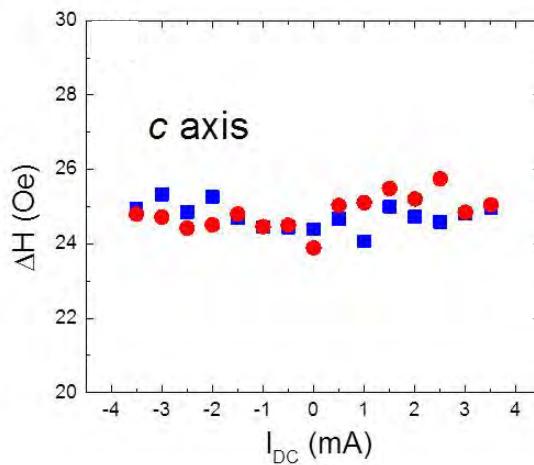
W. Zhang *et al.*, Phys. Rev. B **92**, 144405 (2015)



# Spin Transfer Torque - Ferromagnetic Resonance



PtMn



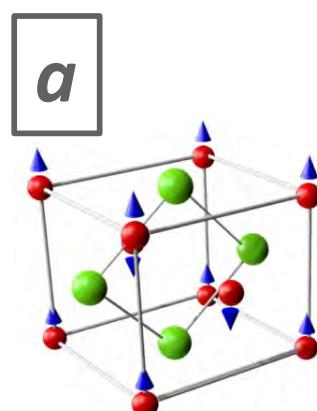
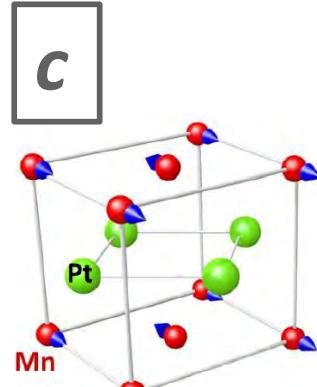
$\theta_{SH}$	PtMn	IrMn	PdMn
$c$ axis	$0.052 \pm 0.002$	$0.050 \pm 0.005$	$0.032 \pm 0.006$
$a$ axis	$0.086 \pm 0.002$	$0.023 \pm 0.005^a$	$0.039 \pm 0.005$

W. Zhang *et al.*,  
Phys. Rev. B 92, 144405 (2015)



# Comparison to Ab-Initio Calculations

Theo Exp



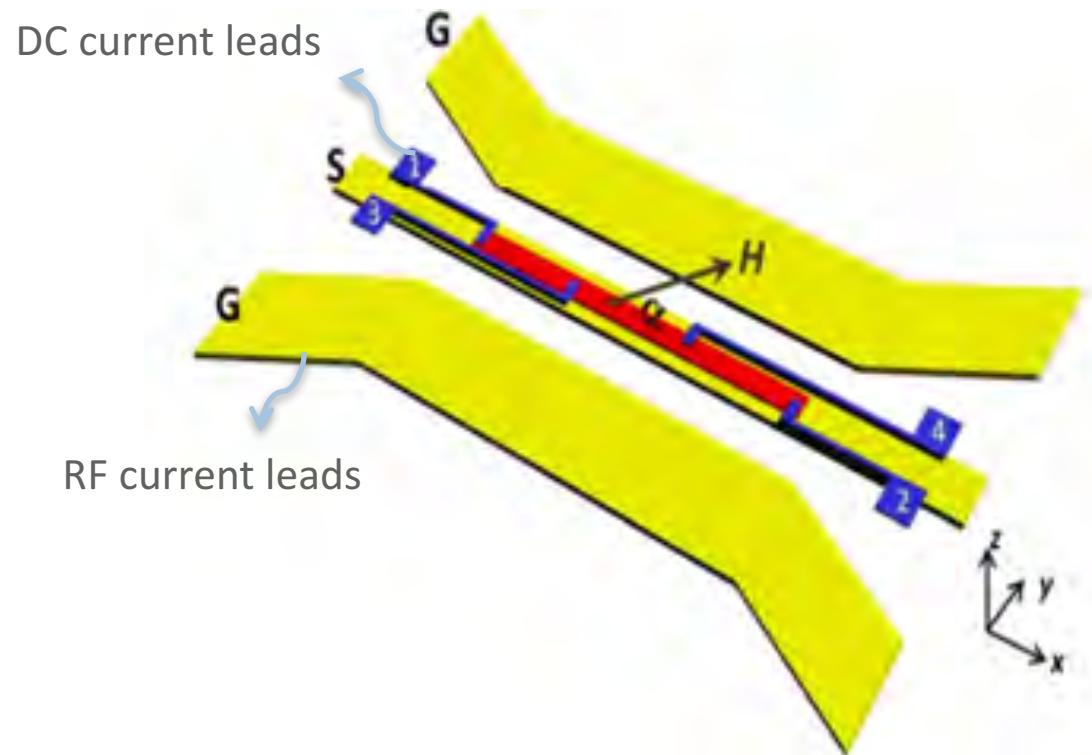
	Growth	$d_0$ (Å)	$M_{\text{stag}}$	$\sigma^{\text{SHE}}$	$\sigma_{\text{av}}^{\text{SHE}}$	$\sigma_{\text{exp}}^{\text{SHE}}$	$\rho$ ( $\mu\Omega \text{ cm}$ )
PtMn	c axis	3.67	c	219.9	94.2	144	180.3
	c axis		$a/b$	31.4			
	a axis		c	182			
IrMn	a axis	4.00	$a/b$	120	141	263	163.4
	c axis		c	59.7			
	c axis		$a/b$	3.64			
PdMn	c axis	3.64	$a/b$	110.4	93.5	77.9	320.8
	a axis		c	207			
	a axis		$a/b$	3.86			
PdMn	c axis	3.86	c	-80	16	53.2	216.3
	c axis		$a/b$	3.58			
	a axis		c	17.0			
PdMn	c axis	4.07	$a/b$	2.0	7.0	59.2	270.5
	a axis		c	44			
	a axis		$a/b$	-18			

Units for  
 $\sigma^{\text{SHE}}$   
 $(\hbar/e \text{ S/m})$

W. Zhang *et al.*, Phys. Rev. B **92**, 144405 (2015)



# How About Magnons in Metallic Antiferromagnets?



Negative sign of voltage



the spin current reaches W

W: 4 nm

FeMn: 0-12 nm

Py: 12 nm

Spin Hall angles

W :  $\sim 0.1$  (-)

FeMn:  $\sim 0.01$  (+)

See Poster  
from Hilal Saglam  
On Thursday

# Spin Seehock

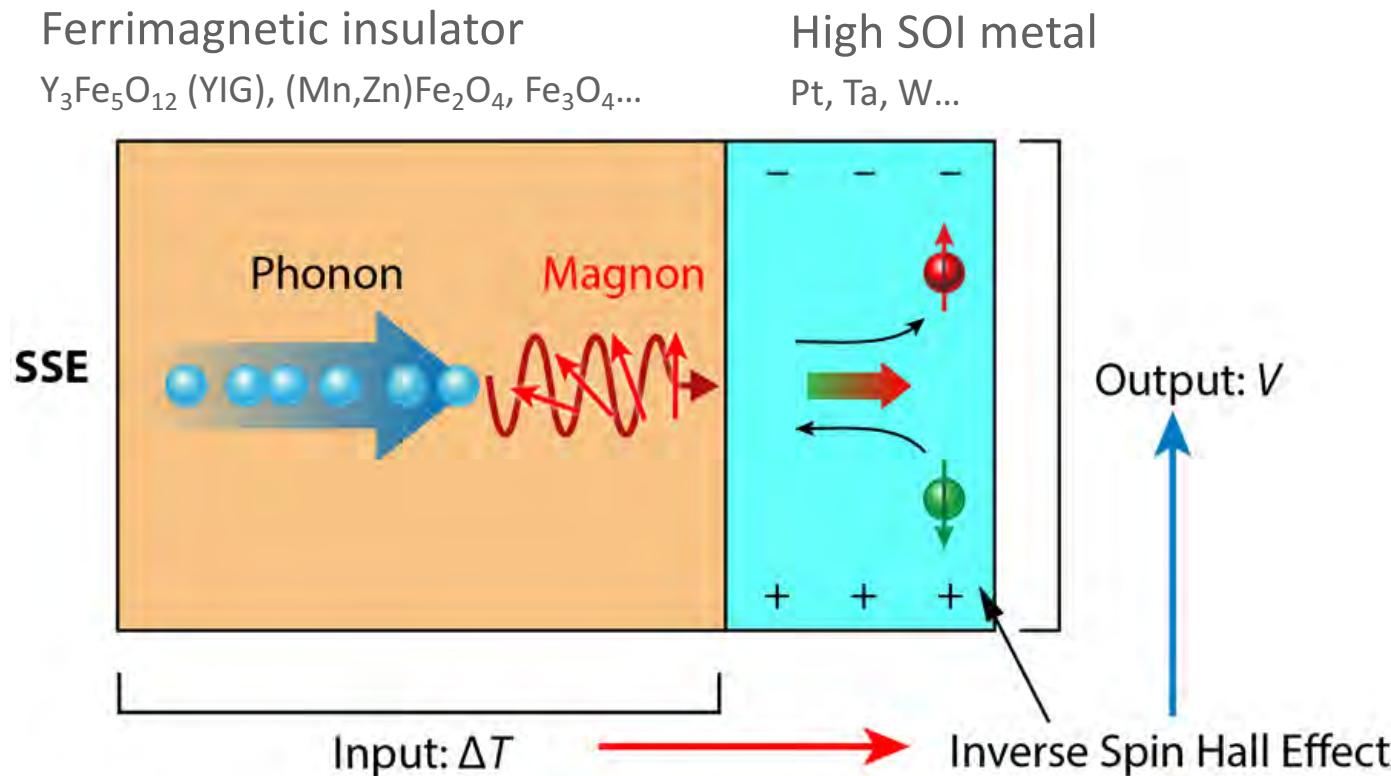
Axel Hoffmann, MSD, Argonne National Laboratory

[hoffmann@anl.gov](mailto:hoffmann@anl.gov)



# Spin Seebeck Effect

Generate spin current from the spin Seebeck effect while detecting using the ISHE

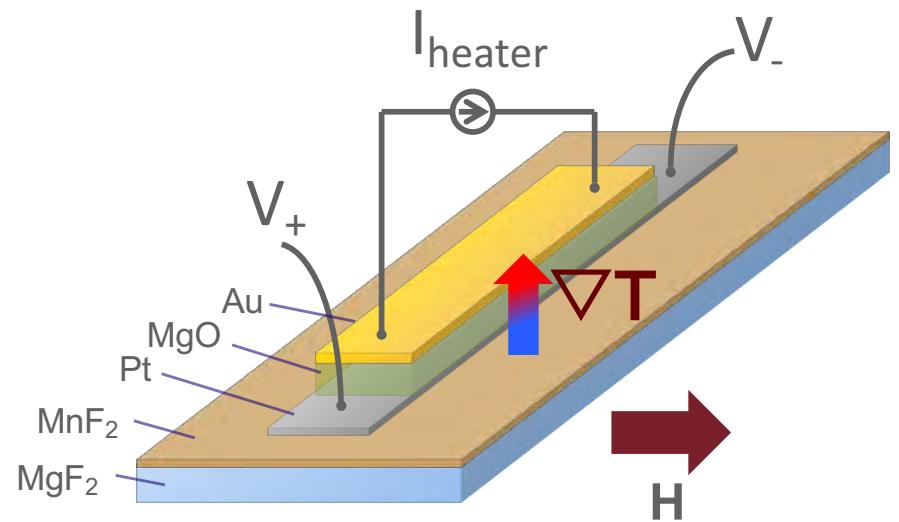
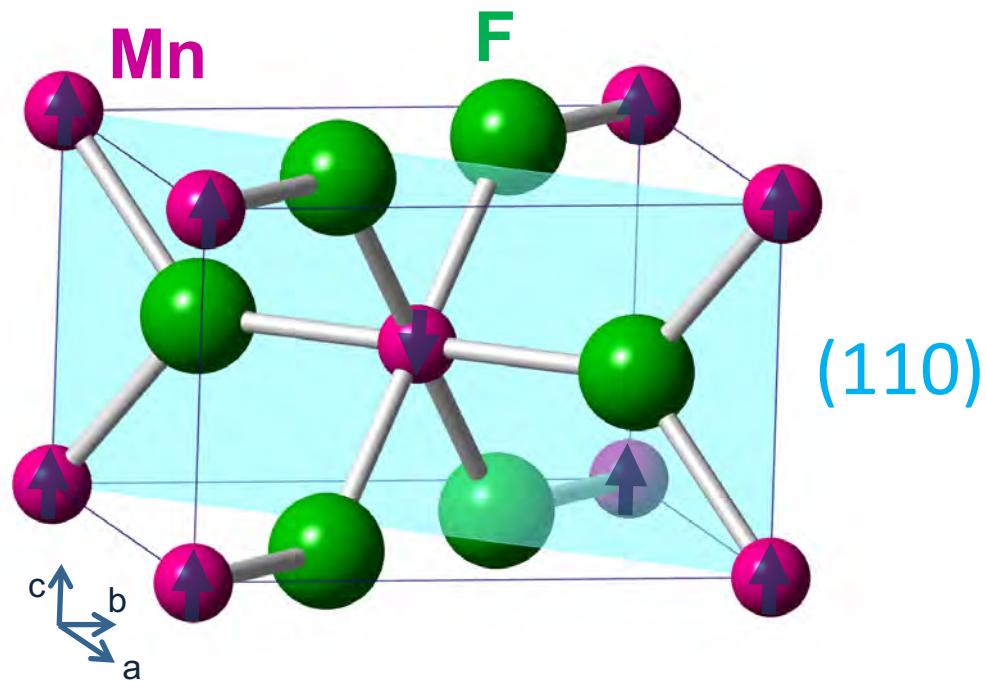


J. P. Heremans and S. R. Boona, Physics 7, 71 (2014)

**Not just limited to Ferro- or Ferrimagnets!**

# Spin Seebeck in Antiferromagnetic Insulators

Antiferromagnetic insulator:  $\text{MnF}_2$



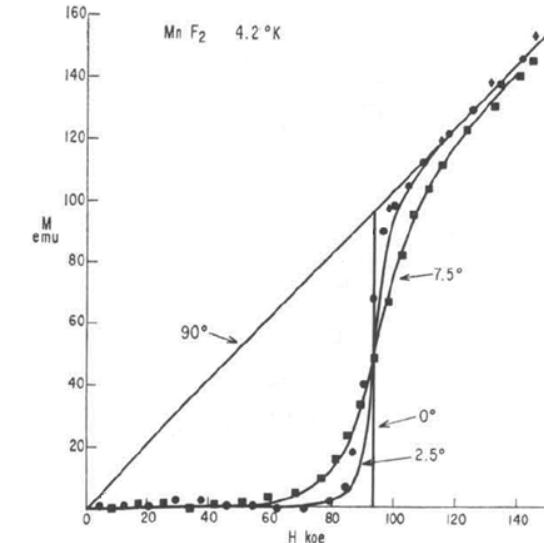
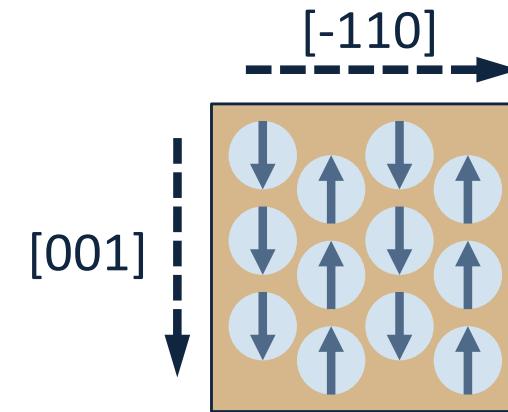
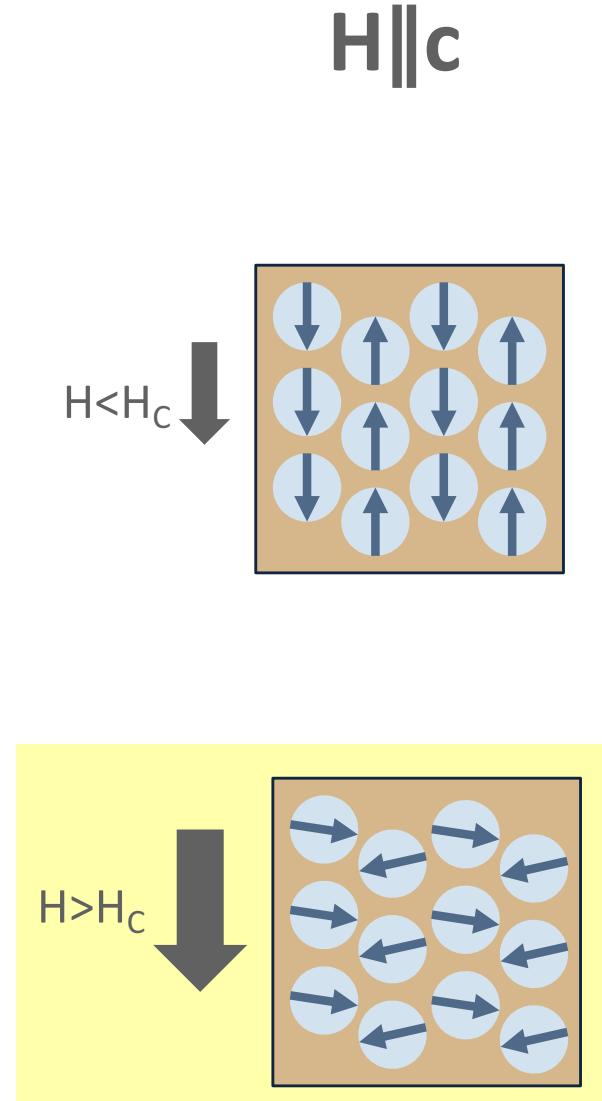
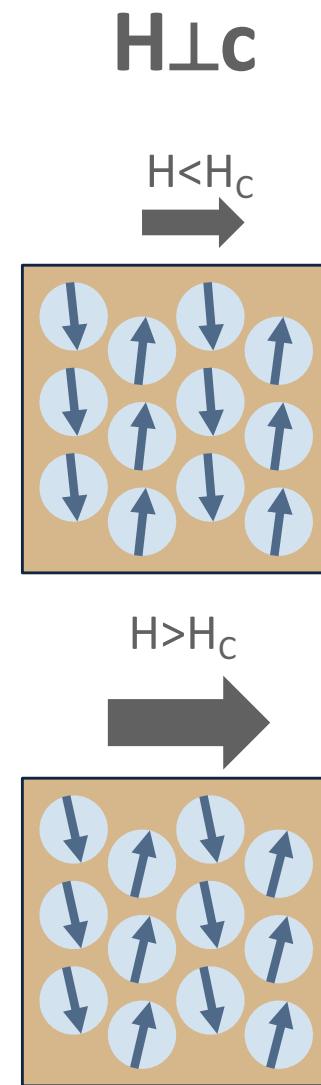
MBE grown thin film  $\text{MnF}_2$  (110)(30 nm) on  $\text{MgF}_2$  (110)  
4 nm Pt deposited ex-situ

S. M. Wu, et al., Phys. Rev. Lett. 116, 097204 (2016)



# Spin Seebeck in Antiferromagnetic Insulators

Spin flop transition exists at high magnetic fields



I. S. Jacobs, J. Appl. Phys. 32, S61 (1961)

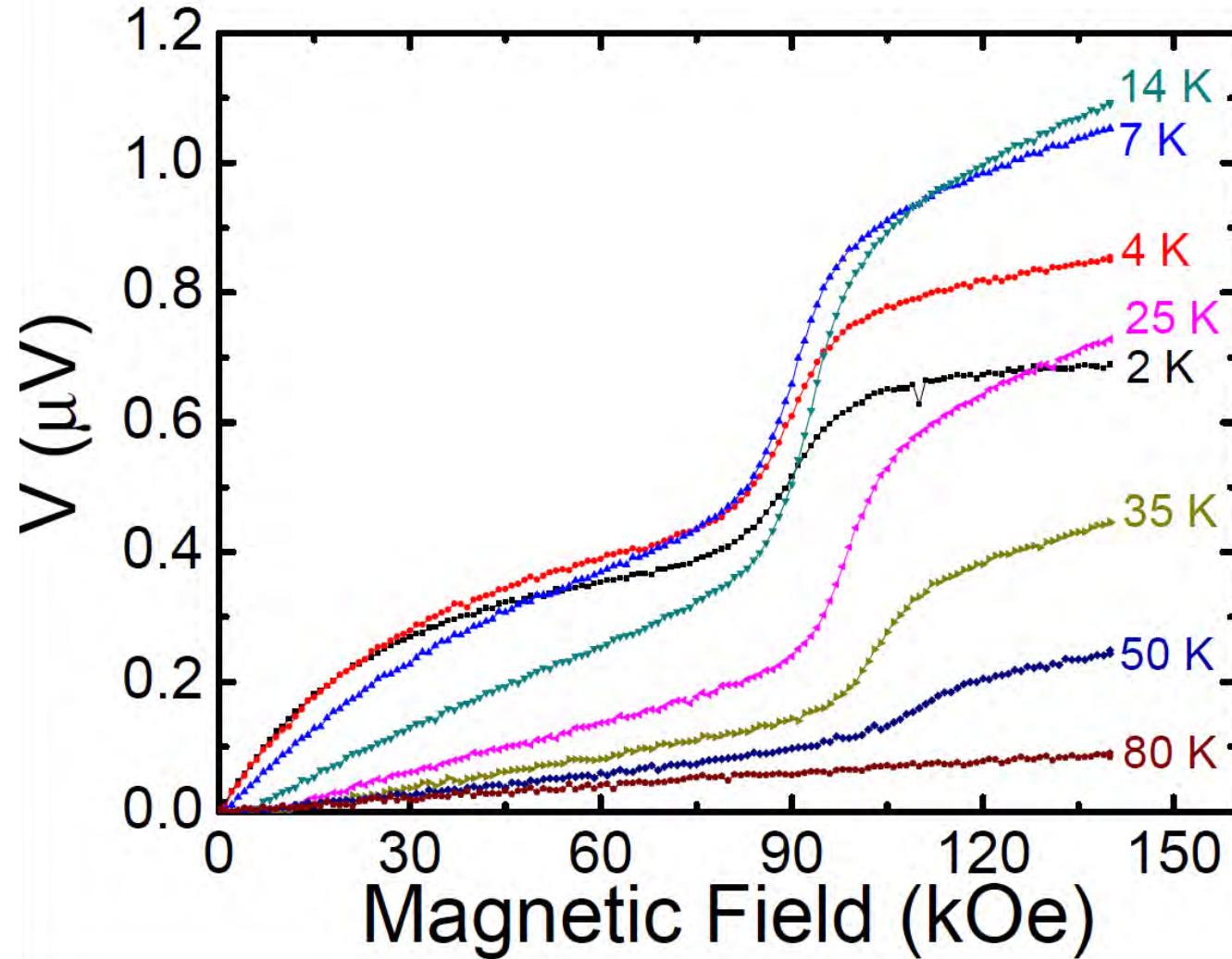
S. M. Wu, et al., Phys. Rev. Lett. 116, 097204 (2016)



# Antiferromagnetic SSE in $\text{MnF}_2$ along Spin Flop Axis

$H \parallel c$

0.16 mW<sub>rms</sub>, 3 Hz

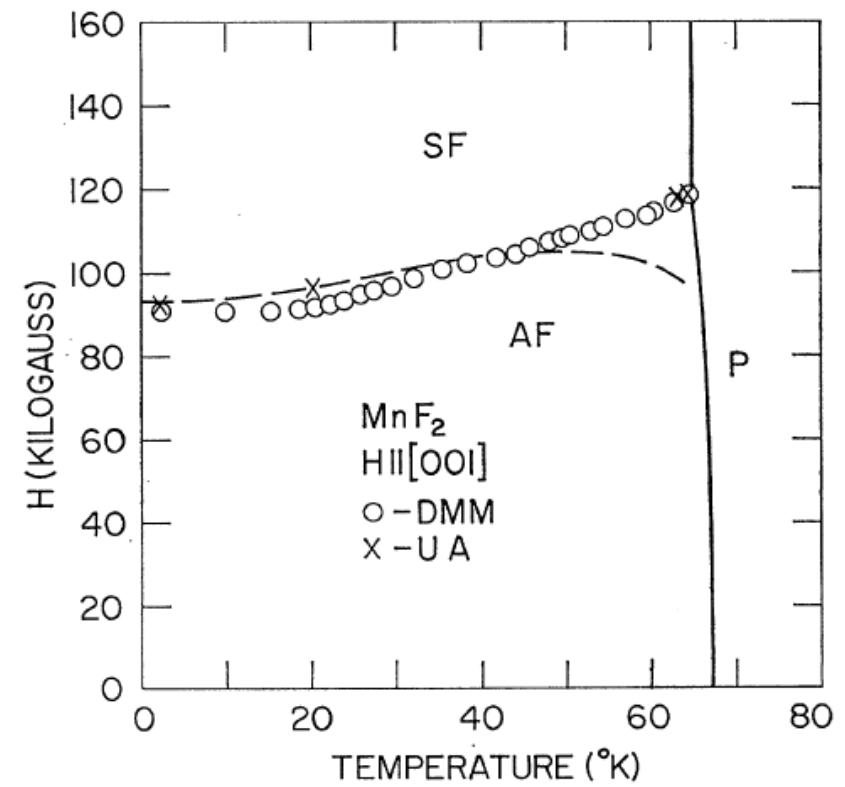
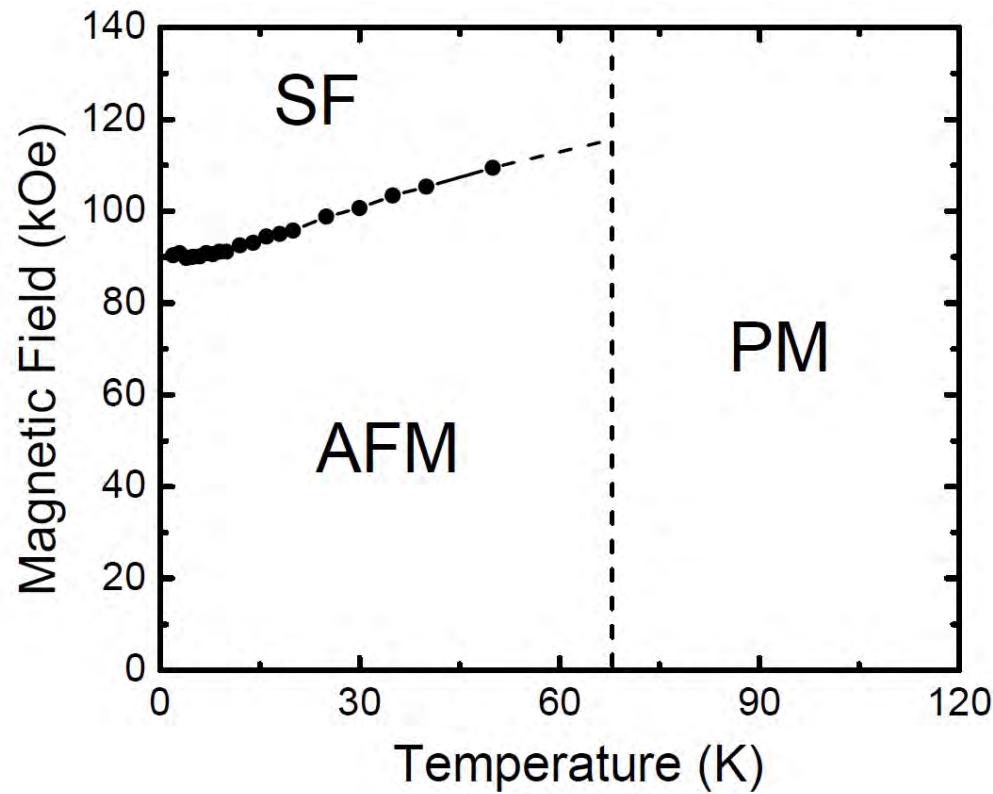


S. M. Wu, et al., Phys. Rev. Lett. **116**, 097204 (2016)



# MnF<sub>2</sub> Phase Diagram

H||c

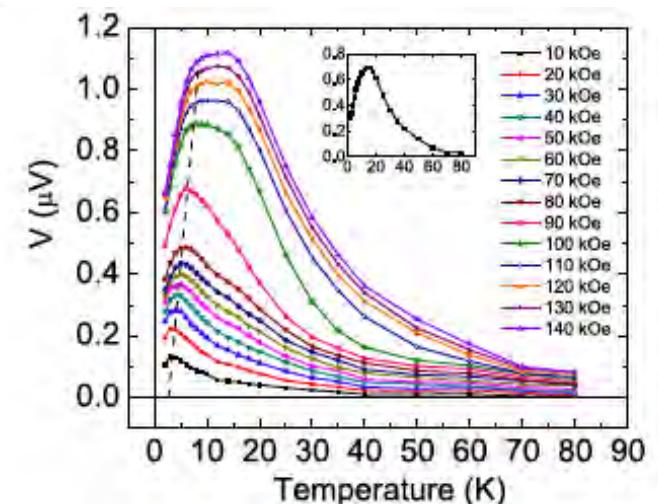
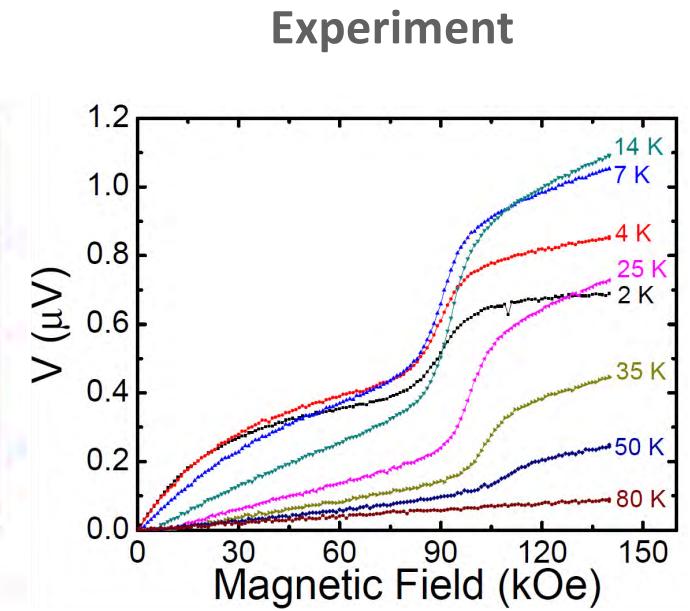
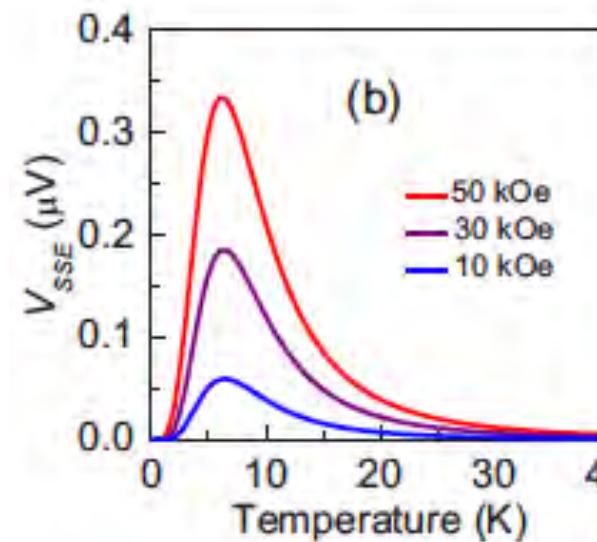
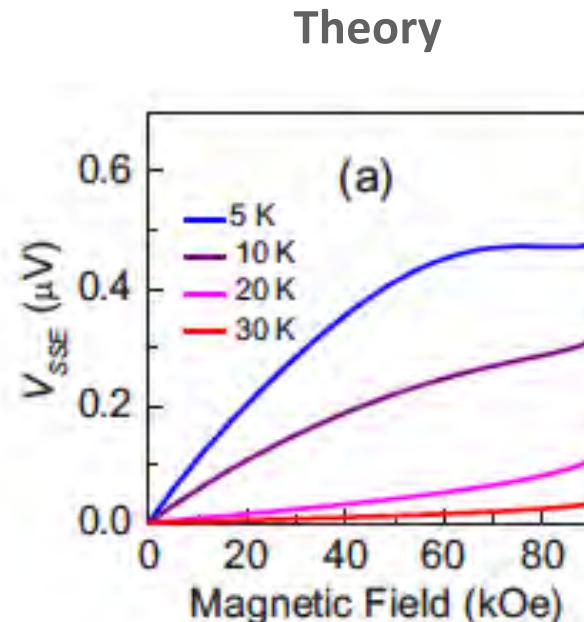
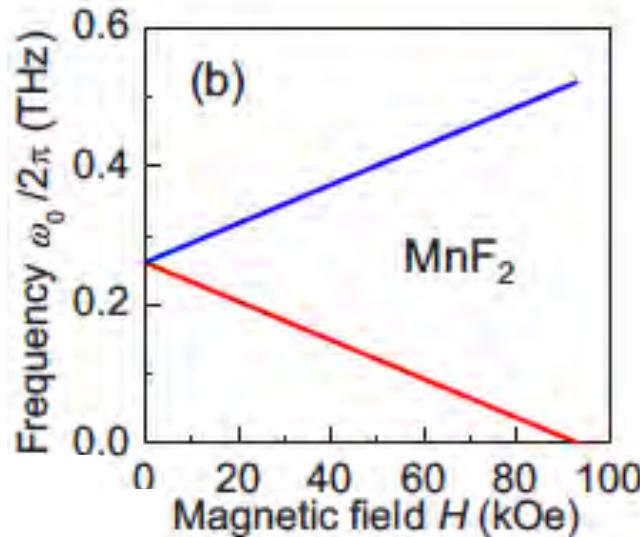
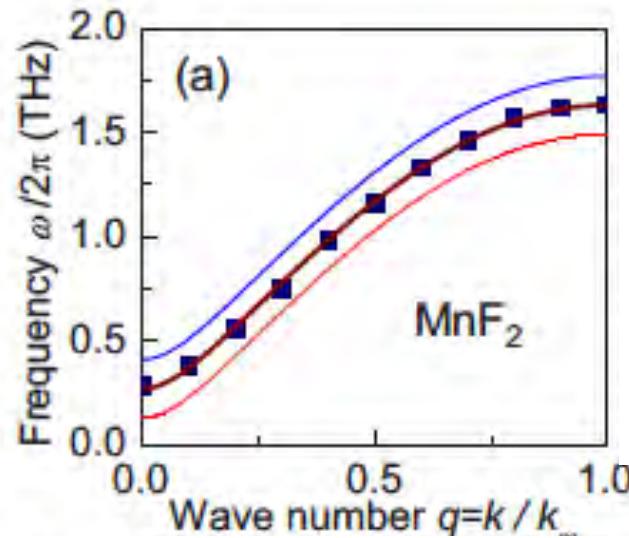


Y. Shapira, et al., Phys. Rev. B 1, 3083 (1970)

S. M. Wu, et al., Phys. Rev. Lett. 116, 097204 (2016)

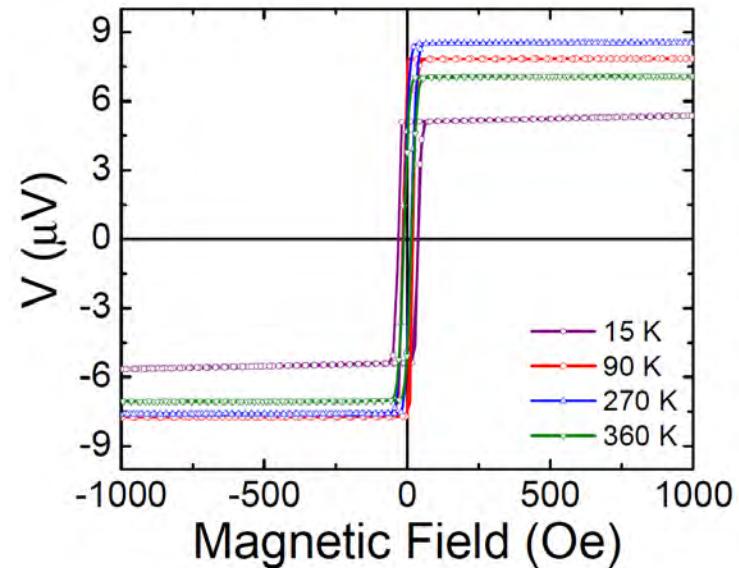
# Theoretical Model based Magnon Dispersion

S. M. Rezende, et al.,  
Phys. Rev. B 93, 014425 (2016)



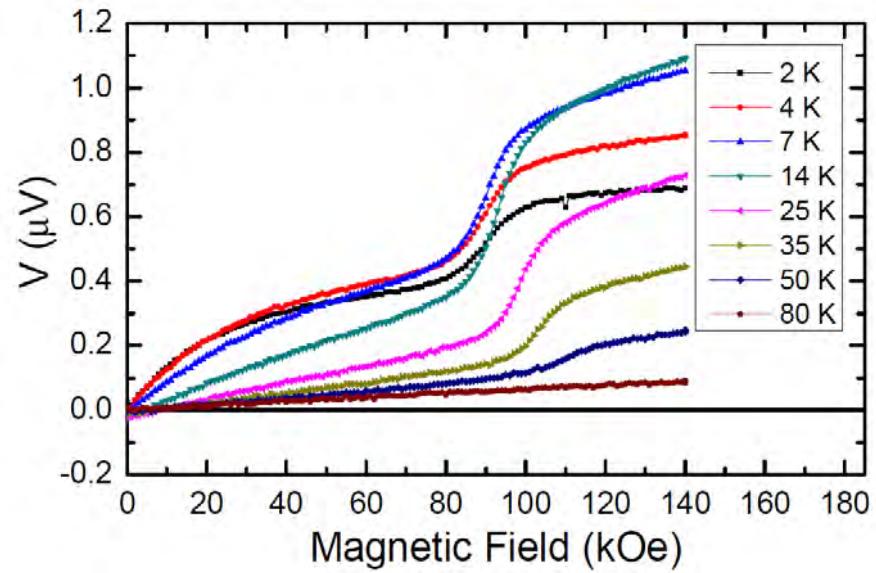
# Magnitude comparison

YIG/Pt



$37.3 \text{ mW}_{\text{rms}}$

$\text{MnF}_2/\text{Pt}$

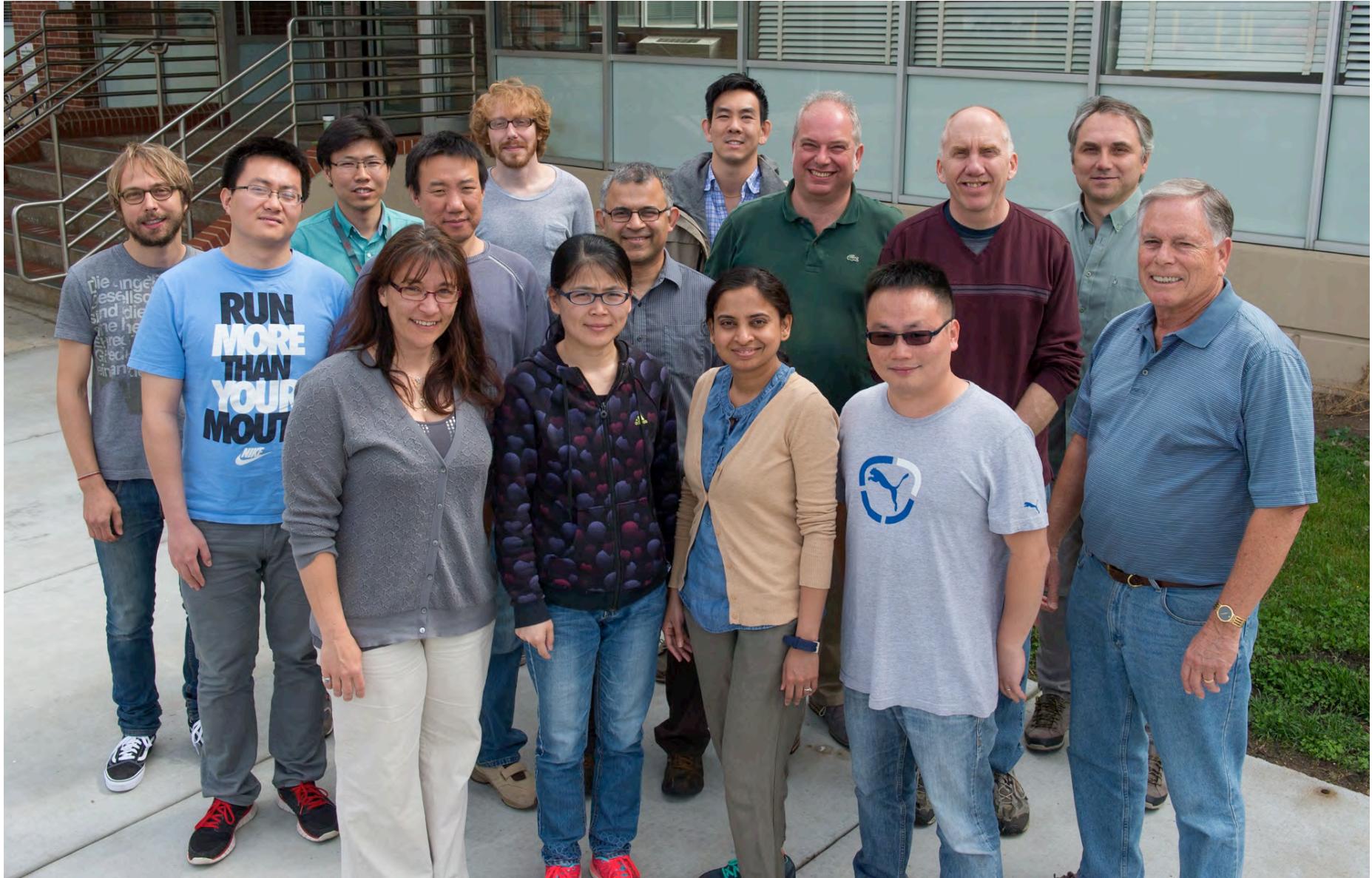


$0.16 \text{ mW}_{\text{rms}}$

$\sim 25x$  more signal for the same power



# Magnetic Films Group



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# Thanks to

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Argonne National Laboratory

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Northwestern University**

**Frank Freimuth and Yuriy Mokrousov  
Forschungszentrum Jülich and JARA**

**Amit KC, Pavel Borisov, and David Lederman  
West Virginia University**

**Financial Support  
DOE-BES Materials Science and Engineering Division**

# Conclusions

## Metallic Antiferromagnets

- Have sizeable spin Hall effects
- Spin Hall effect sufficiently large to drive ferromagnetic resonance
- Crystalline orientation matters

