

ZERO-MAGNETISATION SPIN-SOURCES

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The Leverhulme Trust



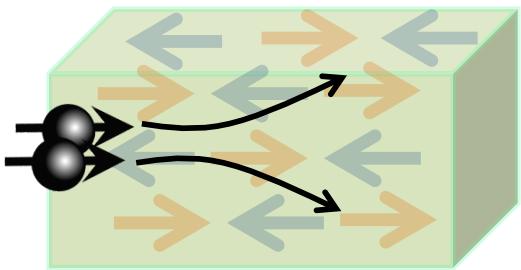
Winton Programme for the Physics of Sustainability
Department of Physics

SPICE workshop on anti-ferromagnetic spintronics
26-30 September 2016

ZERO MAGNETISATION SPIN-SOURCES

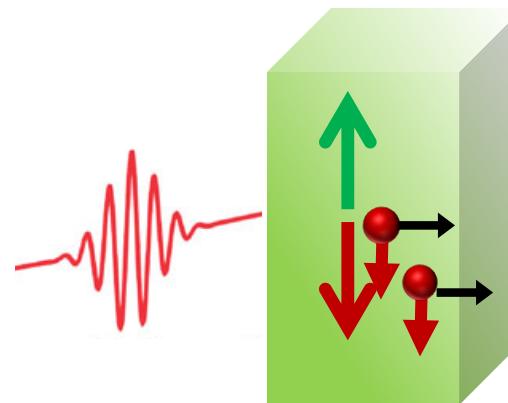
1

Spin-Hall effect in anti-ferromagnets



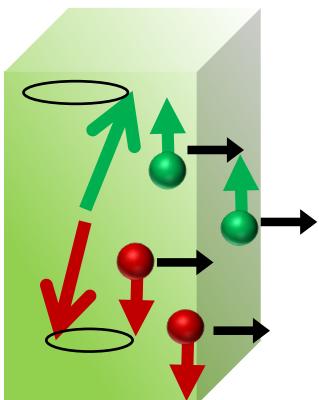
2

Element-selective spin-emission



3

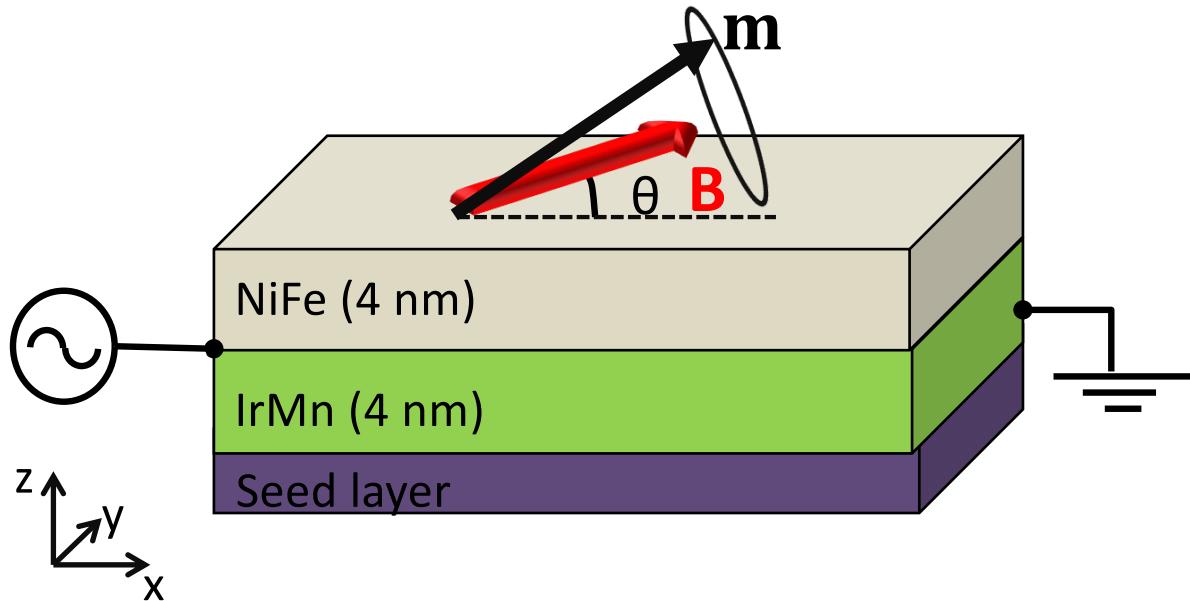
Spin-pumping from an anti-ferromagnet



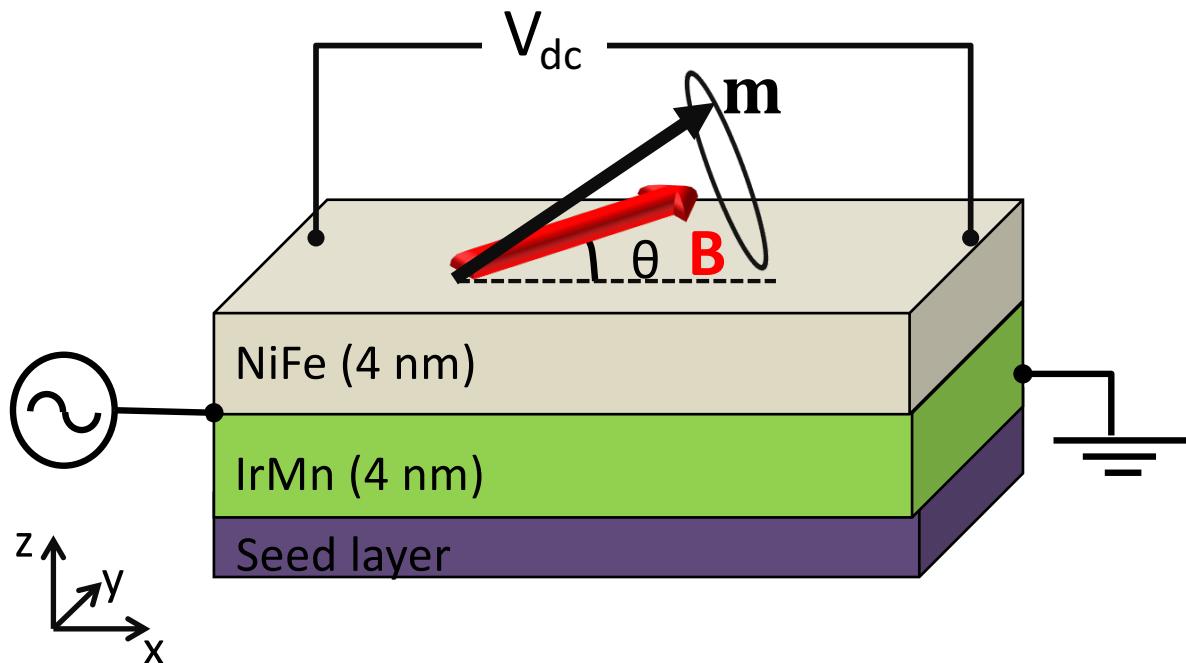
EXPERIMENT 1

The Spin-Hall effect in anti-ferromagnets

We determine the current-induced fields by FMR



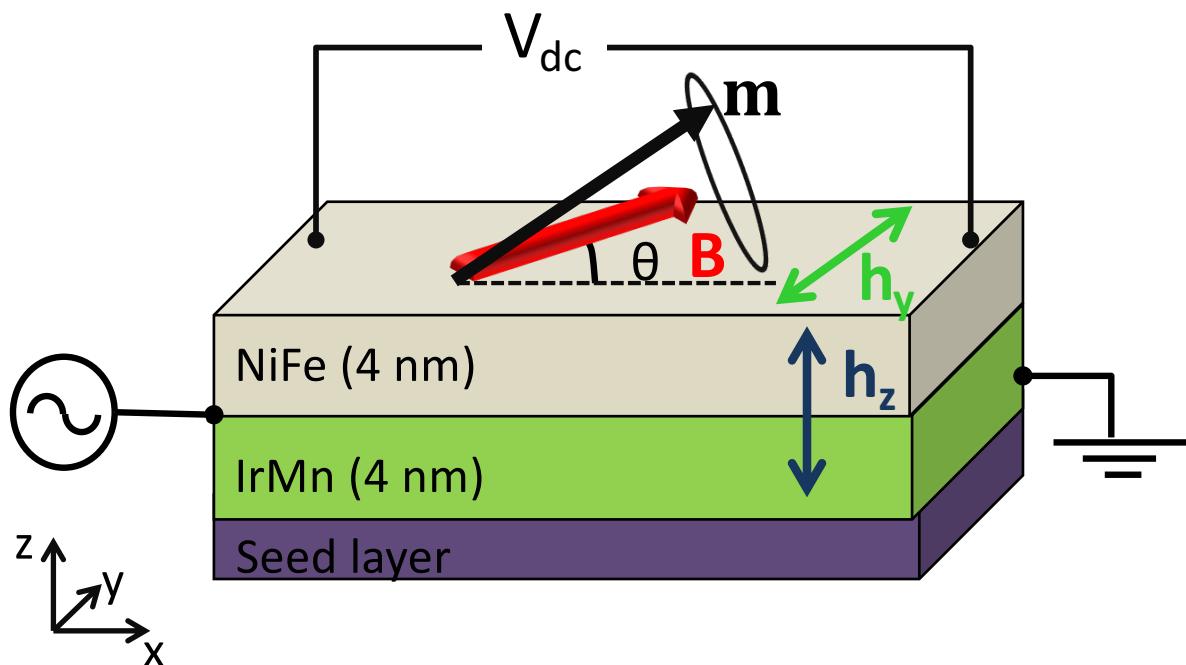
We determine the current-induced fields by FMR



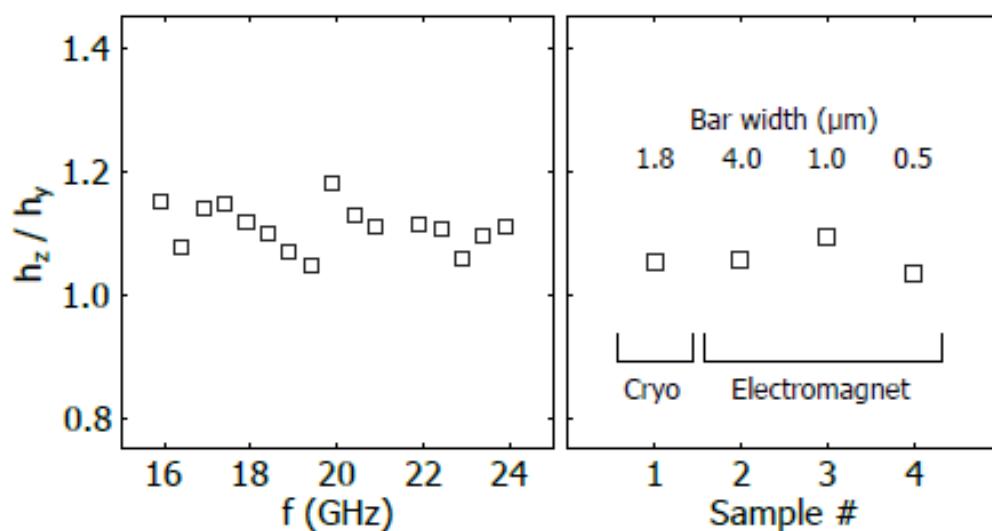
$$\begin{aligned} V(t) &= R(\omega t) \times I(\omega t) = \\ &= V_{dc} + V(2\omega t) \end{aligned}$$

[Tulapurkar, Nature 2005](#)
[Fang, Nature Nano 2011](#)

We determine the current-induced fields by FMR



$$\mathbf{h}_z \sim \sigma \times \mathbf{m}$$



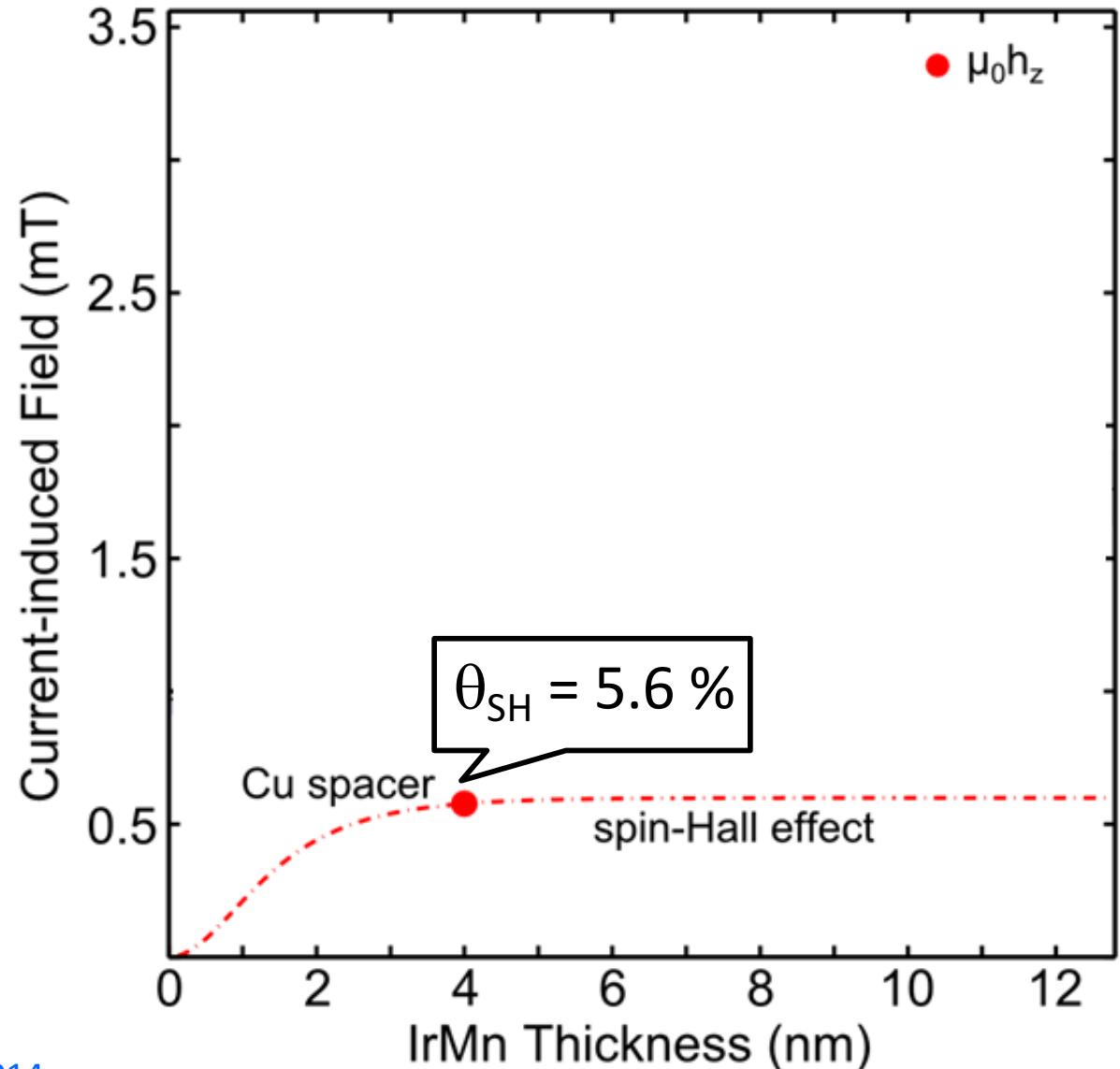
@ 10^7 A/cm^2

	@ 10^7 A/cm^2
h_z	$1.13 \pm 0.05 \text{ mT}$
h_y	$1.04 \pm 0.03 \text{ mT}$
h_{Oe}	$1.09 \pm 0.07 \text{ mT}$

SHE-STT or ELSE?



$$\theta_{SH} = \frac{2e\mu_0 M_s d_F}{\hbar J_{IrMn}} h_z$$

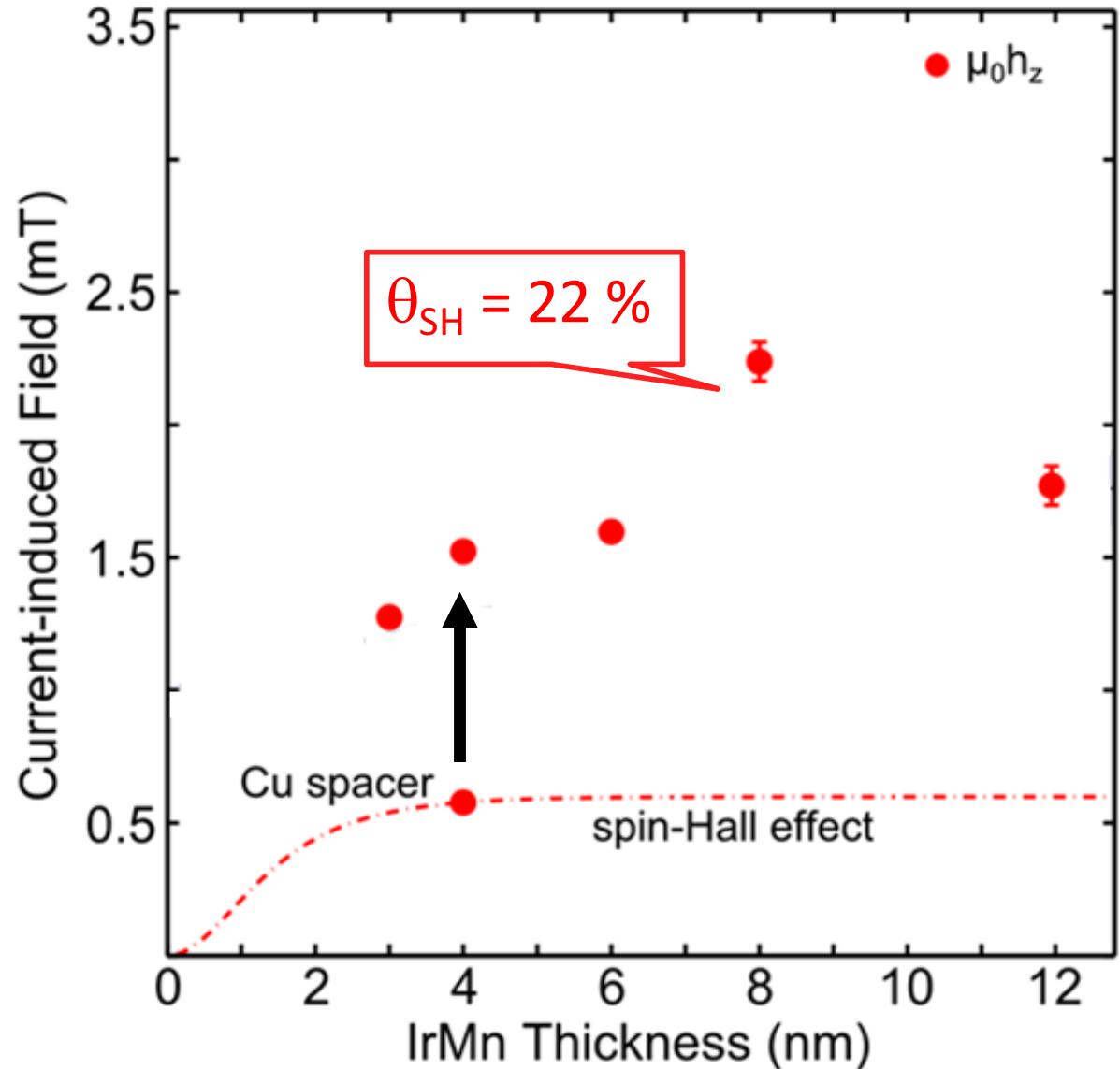


$\theta_{SH}(Ir_{20}Mn_{80}) \sim 0.8\theta_{SH}(Pt)$ [Mendes, 2014](#)

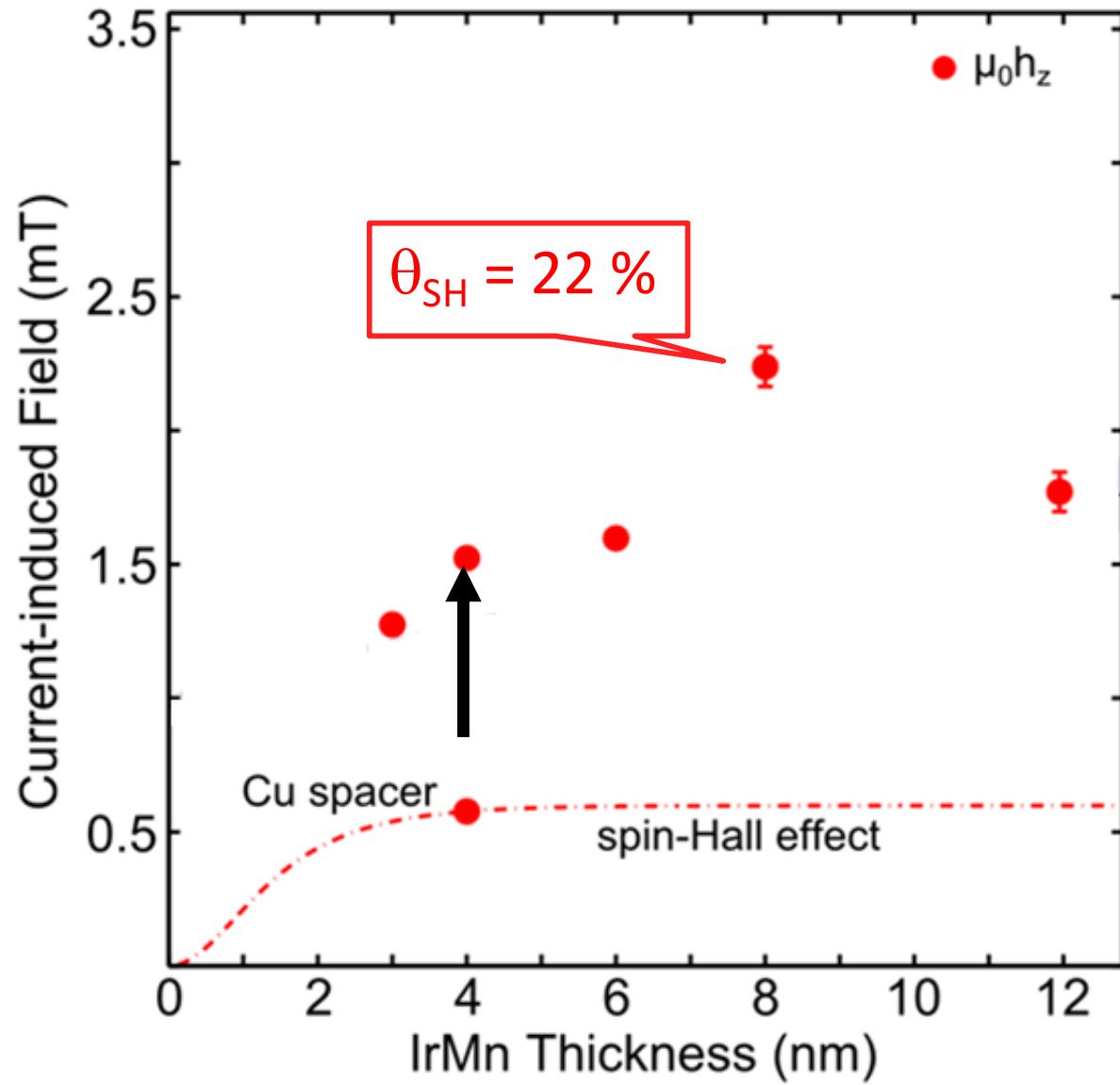
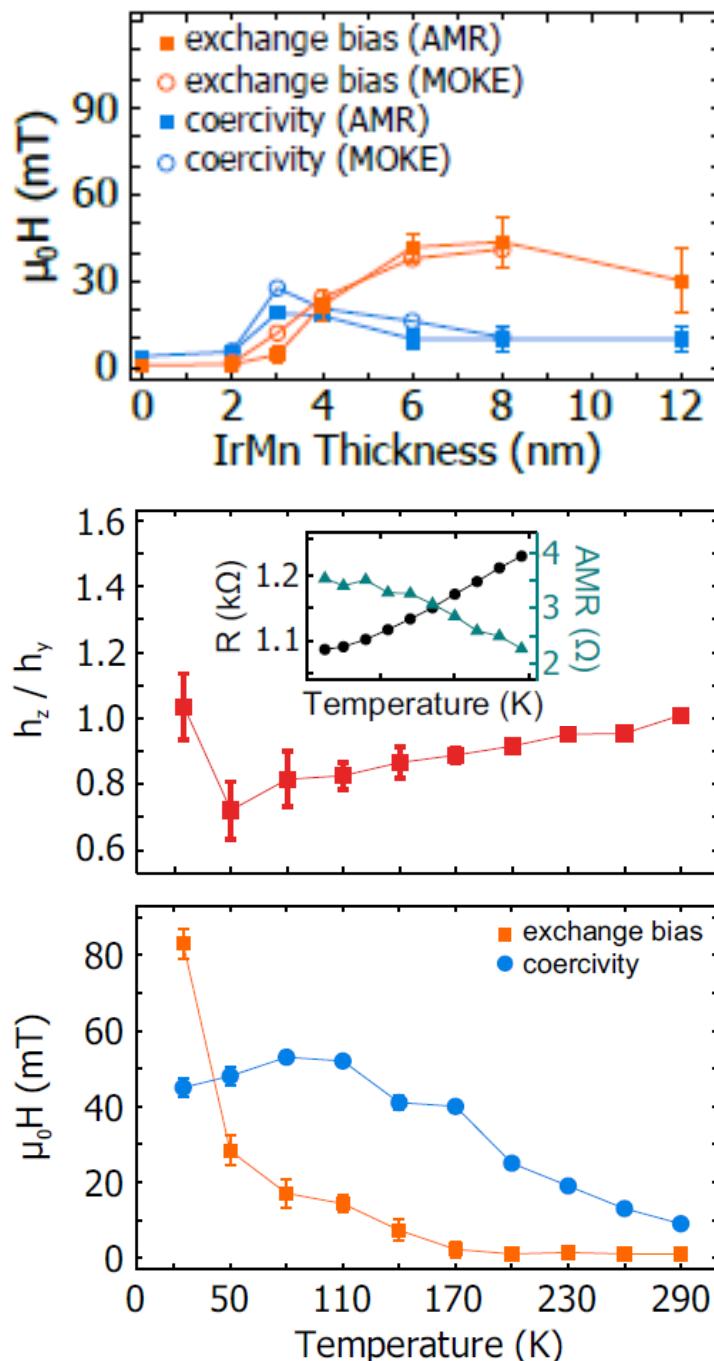
$\theta(Ir_{50}Mn_{50}) \sim 2\%$ [Zhang, 2014](#)

Tshitoyan, PRB 2015

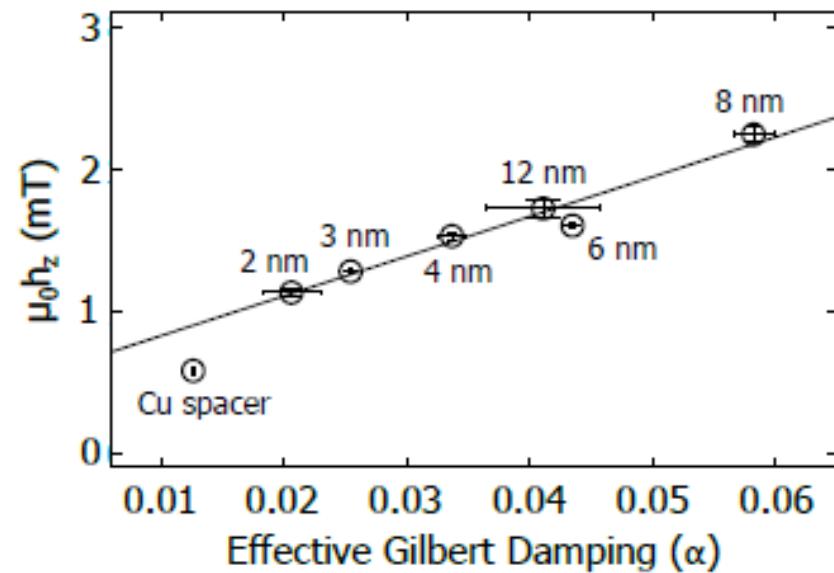
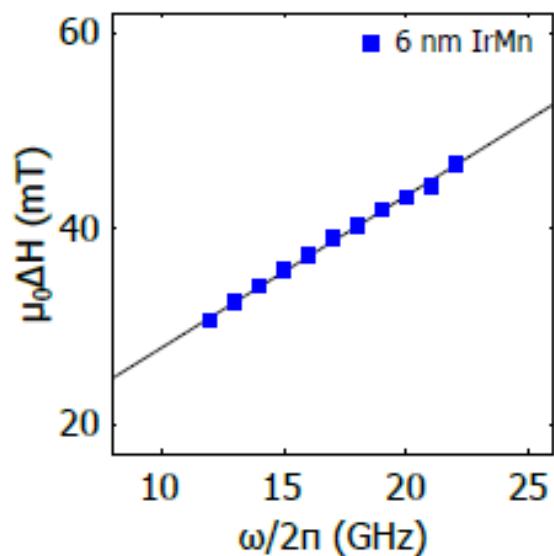
SHE-STT or ELSE?



The SH angle is correlated to the exchange field

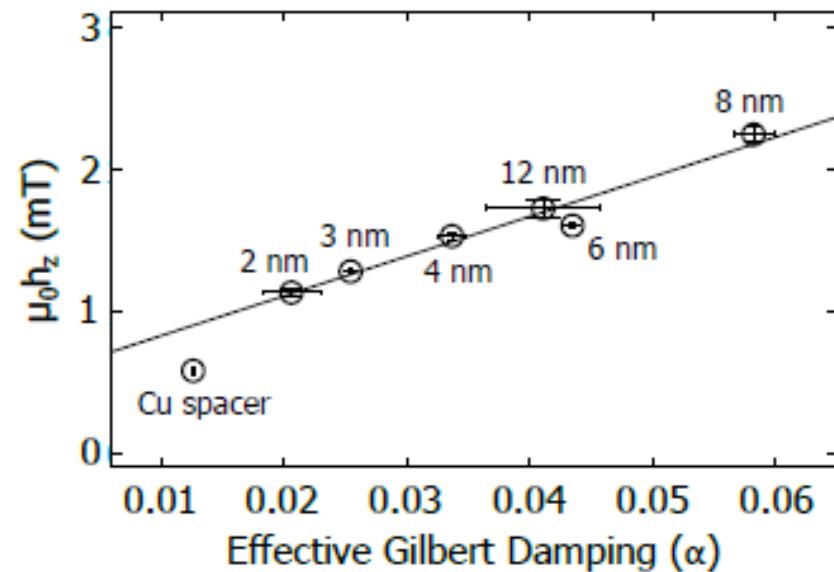
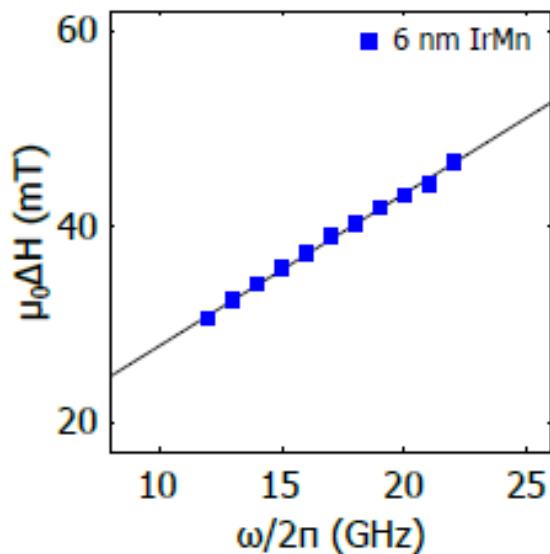


Coupled dynamics might be at the origin of the increase in h_z



$$\mu_0 \nabla H(\omega) = \mu_0 \nabla H_{\text{inh}} + \alpha_{\text{eff}} \frac{\omega}{\gamma}$$

Coupled dynamics might be at the origin of the increase in h_z



$$\mu_0 \nabla H(\omega) = \mu_0 \nabla H_{\text{inh}} + \alpha_{\text{eff}} \frac{\omega}{\gamma}$$

$$G_{\text{mix}} = \frac{G_{\text{eff}}}{1 - 2G_{\text{eff}}\lambda_{SD}/\sigma_{\text{IrMn}}} \quad \left. \right\}$$

$$G_{\text{eff}} = \frac{e^2}{h} \frac{4\pi M_s d_F}{g\mu_B} (\alpha - \alpha_0)$$

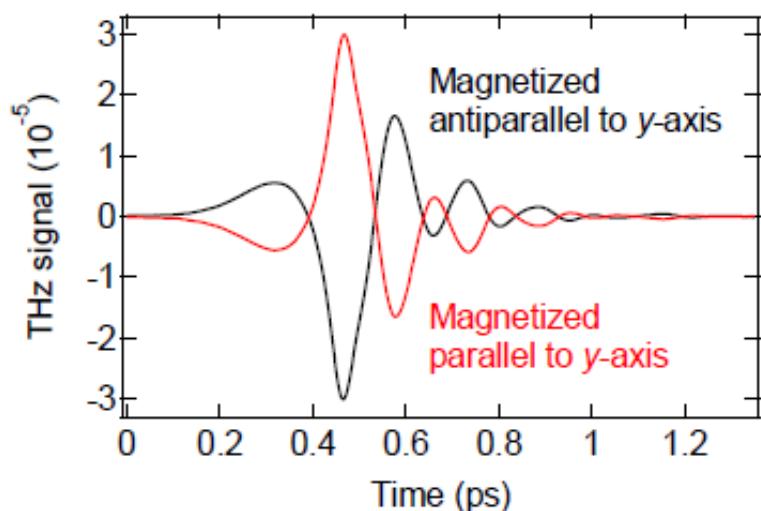
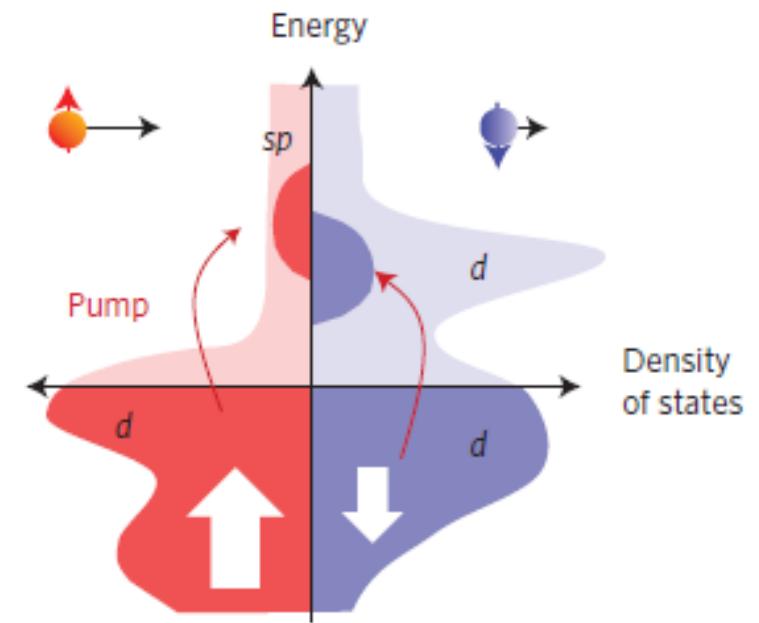
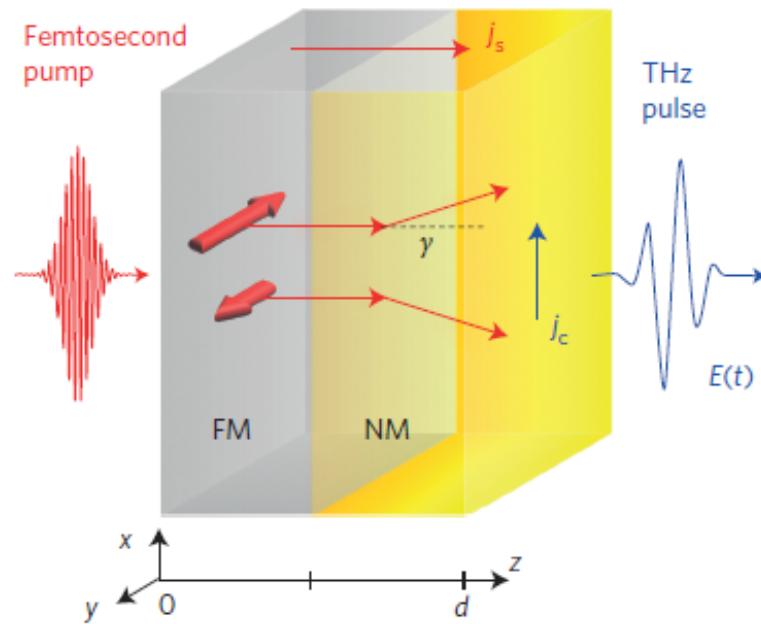
We get a negative value of G_{mix}
Unphysical

➡ $\alpha_{\text{eff}} = \alpha_{\text{sp}} + \alpha_{\text{ex}}$

EXPERIMENT 2

Element-selective spin emission from a
ferrimagnet

Ultra-fast spin emission in magnetic bilayers



In this case the emitted spin current is aligned with the net magnetisation.

Is it possible to have zero-magnetisation spintronic emitters of THz radiation?

3d-4f alloys

Periodic Table of the Elements

Legend:

- Alkali Metal
- Alkaline Earth
- Transition Metal
- Basic Metal
- Metalloid
- Nonmetal
- Halogens
- Noble Gas
- Lanthanide
- Actinide

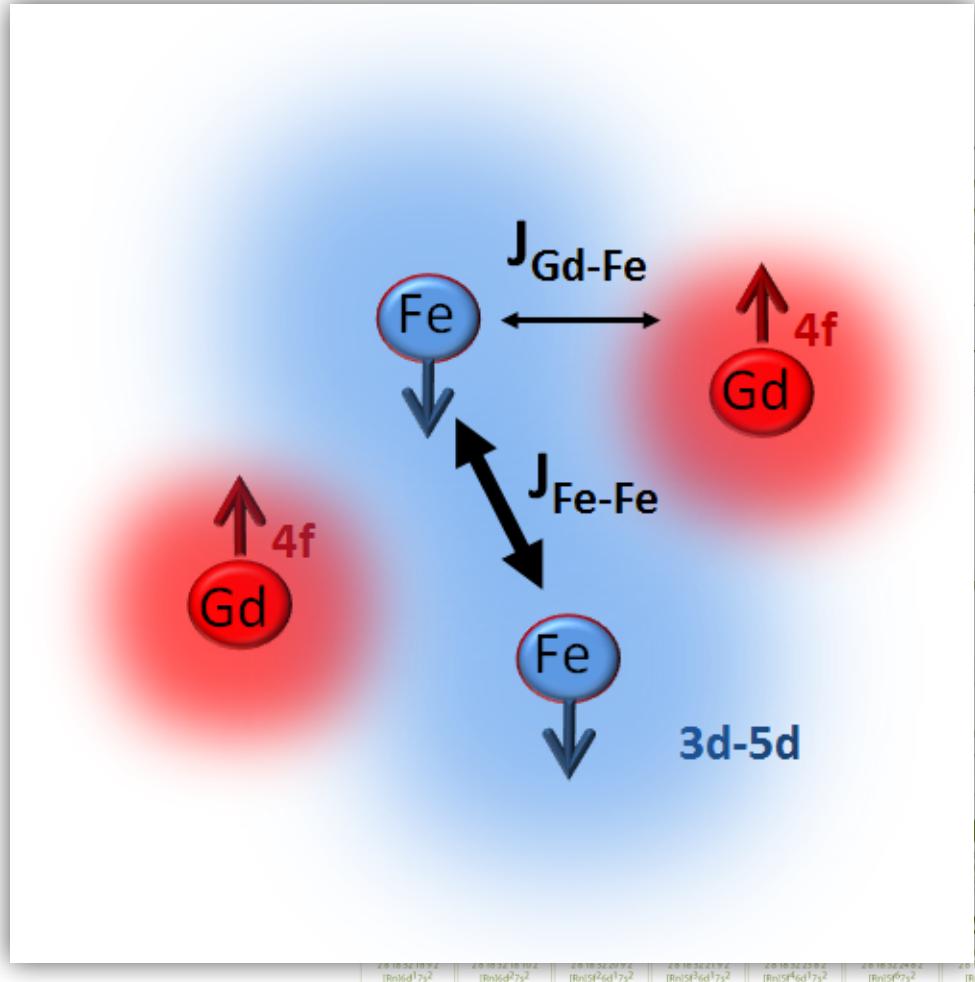
Elements highlighted in red circles:

- Iron (Fe)
- Cobalt (Co)
- Gadolinium (Gd)

Periodic Table Labels:

- Periods:** 1, 2, 3, 4, 5, 6, 7
- Groups:** IA, IIA, IIIA, IVA, VA, VIA, VIIA, VIIIA, 8A
- Elements:** H, He, Li, Be, Na, Mg, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Kr, Rb, Sr, Y, Zr, Nb, Mo, Tc, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, I, Xe, Cs, Ba, Hf, Ta, W, Re, Os, Ir, Pt, Au, Hg, Tl, Pb, Bi, Po, At, Rn, Fr, Ra, Rf, Db, Sg, Bh, Hs, Mt, Ds, Rg, Cn, Uut, Fl, Uup, Lv, Uus, Uuo.
- Series:** Lanthanide Series, Actinide Series.

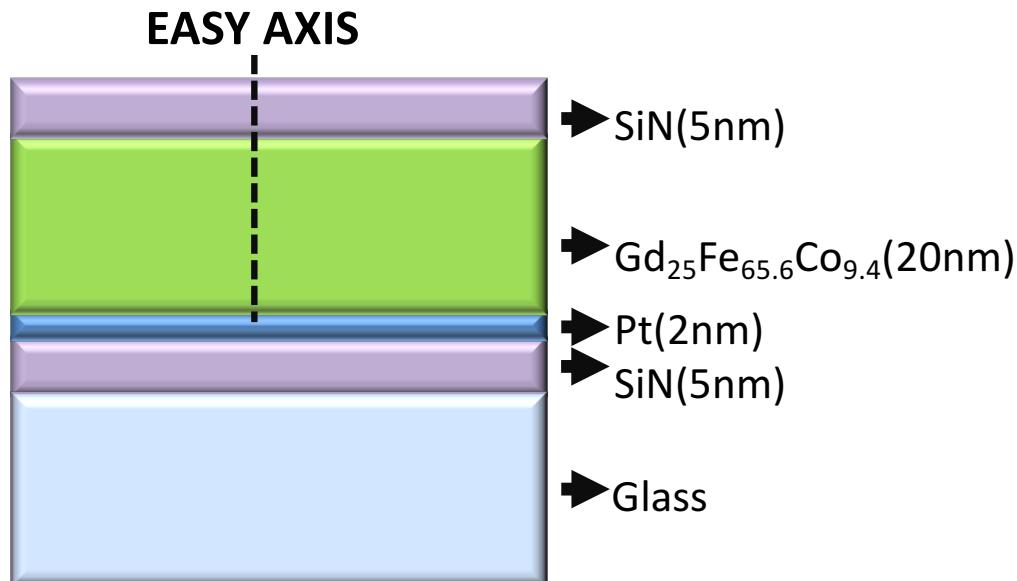
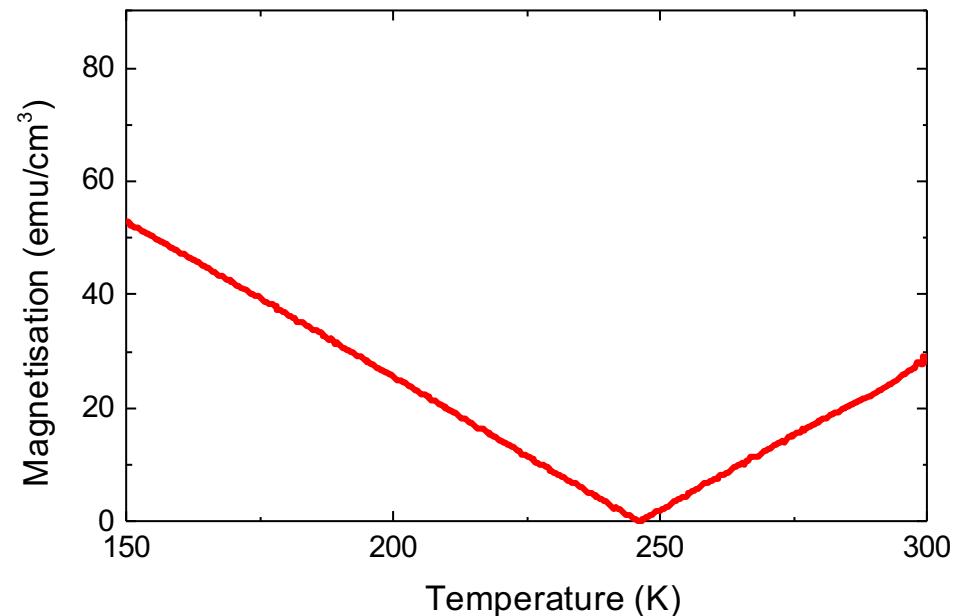
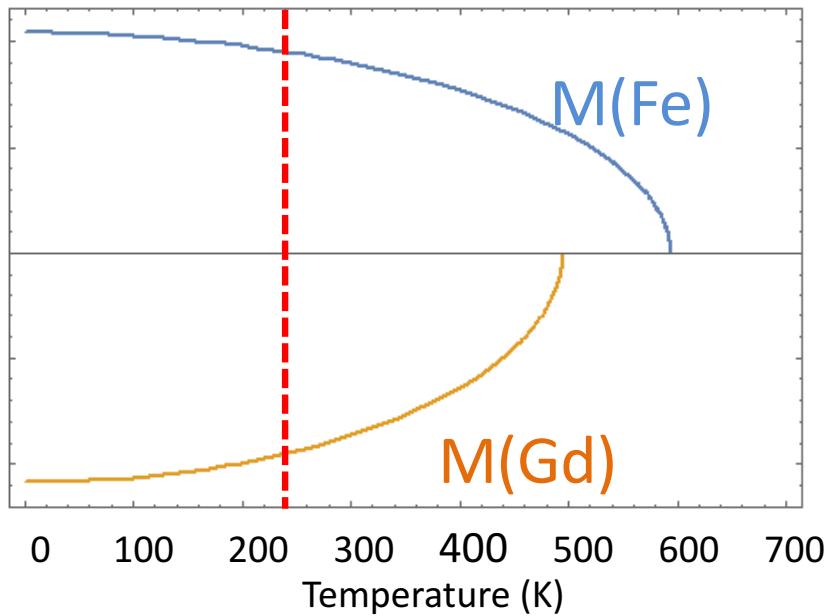
3d-4f alloys



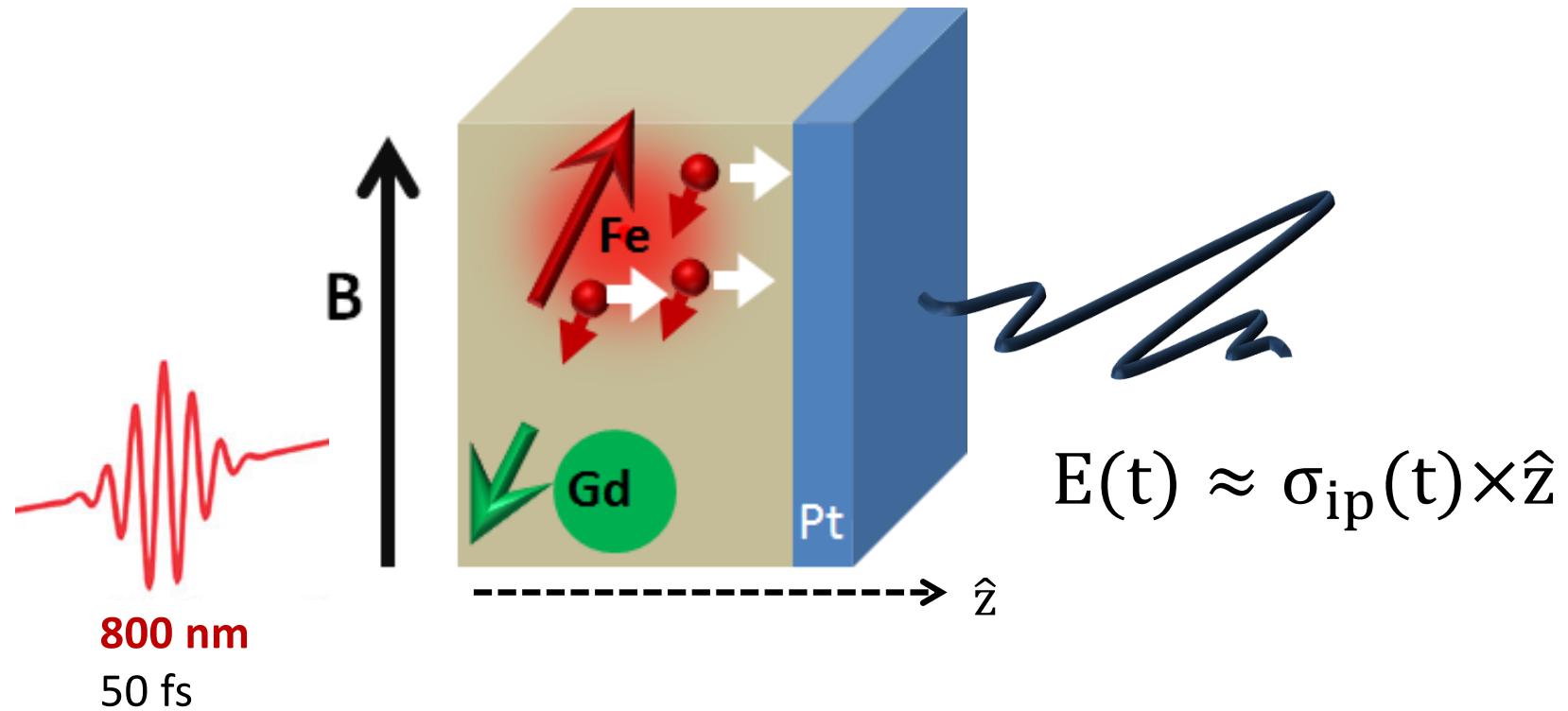
of the Elements									
Atomic Mass	Symbol	Name	Group	Period	Element	Atomic Mass	Symbol	Name	Group
Configuration									
2	He	Helium	VIIIA 8A	4.003					
10	Ne	Neon	VIIIA 8A	20.180					
11	Ar	Argon	VIIIA 8A	39.948					
12	Cl	Chlorine	VIIA 7A	35.453					
13	S	Sulfur	VIA 6A	32.066					
14	P	Phosphorus	VIA 5A	30.974					
15	N	Nitrogen	VIA 5A	14.007					
16	O	Oxygen	VIA 6A	15.999					
17	F	Fluorine	VIIA 7A	18.998					
18	Kr	Krypton	VIIIA 8A	84.798					
19	Br	Bromine	VIIA 7A	79.904					
20	I	Iodine	VIIA 7A	126.904					
21	Xe	Xenon	VIIIA 8A	131.249					
22	Rn	Radon	VIIIA 8A	222.018					
23	Pt	Platinum	VIIIA 8A	195.085					
24	Au	Gold	VIIIA 8A	196.967					
25	Hg	Mercury	VIIIA 8A	200.592					
26	Tl	Thallium	VIIIA 8A	204.383					
27	Pb	Lead	VIIIA 8A	207.2					
28	Sb	Antimony	VIIIA 8A	112.631					
29	Te	Tellurium	VIIIA 8A	127.6					
30	Se	Selenium	VIIIA 8A	78.971					
31	Ge	Germanium	VIIIA 8A	74.922					
32	As	Arsenic	VIIIA 8A	34.000					
33	Ge	Gallium	VIIIA 8A	32.066					
34	In	Inium	VIIIA 8A	30.974					
35	Sn	Tin	VIIIA 8A	28.086					
36	Ge	Germanium	VIIIA 8A	26.982					
37	Cd	Cadmium	VIIIA 8A	26.982					
38	Ag	Silver	VIIIA 8A	26.982					
39	Cu	Copper	VIIIA 8A	26.982					
40	Ni	Nickel	VIIIA 8A	26.982					
41	Pd	Palladium	VIIIA 8A	26.982					
42	Al	Aluminum	VIIIA 8A	26.982					
43	Zn	Zinc	VIIIA 8A	26.982					
44	Ge	Gallium	VIIIA 8A	26.982					
45	As	Arsenic	VIIIA 8A	26.982					
46	Se	Selenium	VIIIA 8A	26.982					
47	Br	Bromine	VIIIA 8A	26.982					
48	I	Iodine	VIIIA 8A	26.982					
49	Xe	Xenon	VIIIA 8A	26.982					
50	Pt	Platinum	VIIIA 8A	26.982					
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188	Sb	Antimony	VIIIA 8A	26.982					
189									

C.D. Stanciu et al., PRB 2006
J. Becker, PhD thesis, 2016

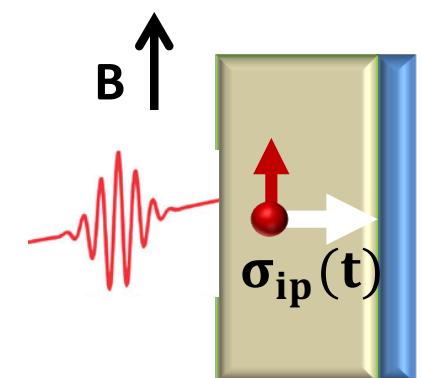
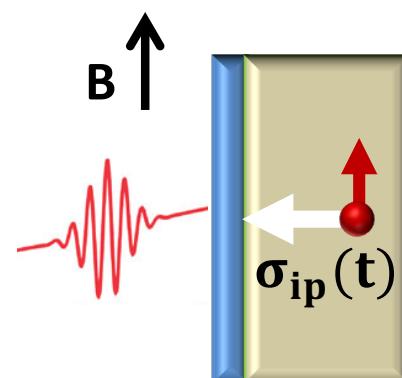
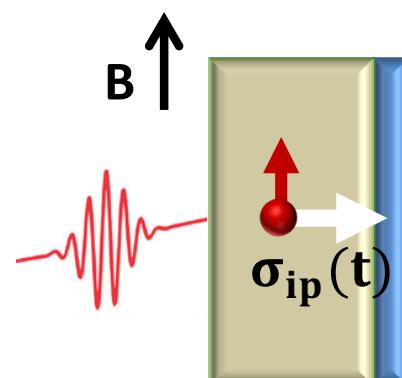
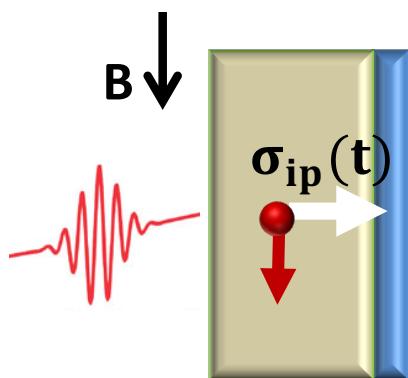
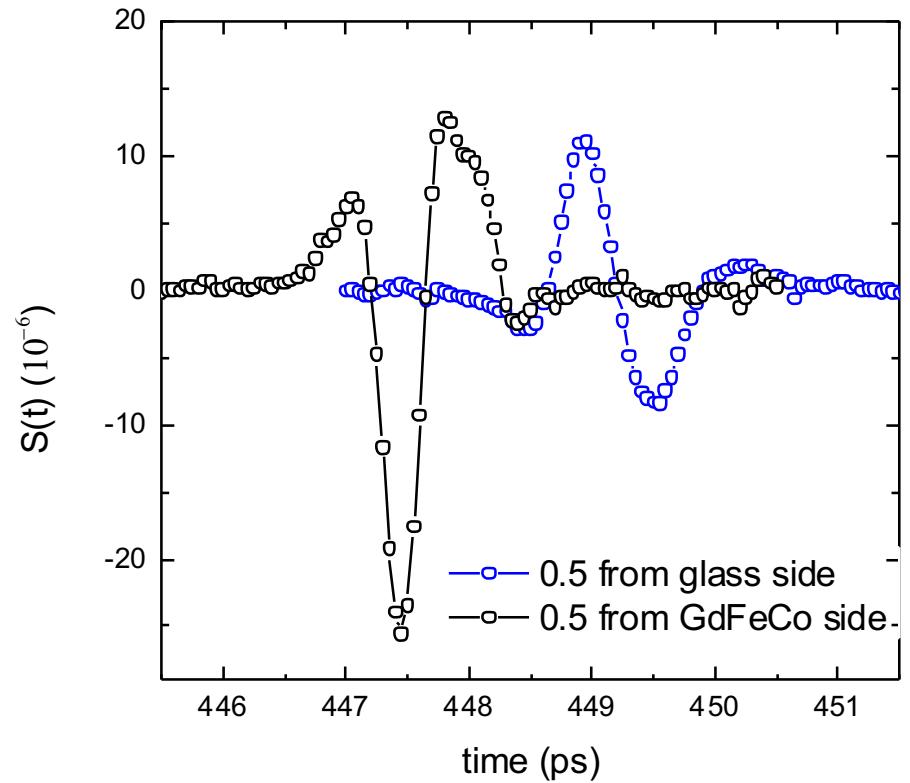
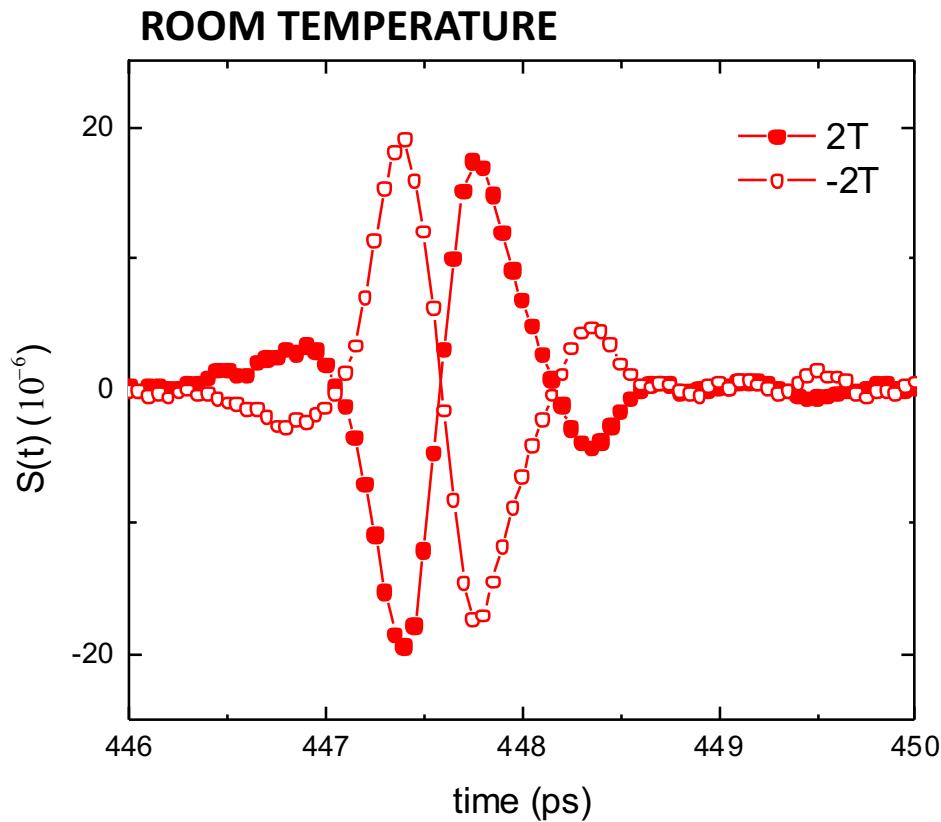
GdFeCo has a compensation temperature at which $M=0$



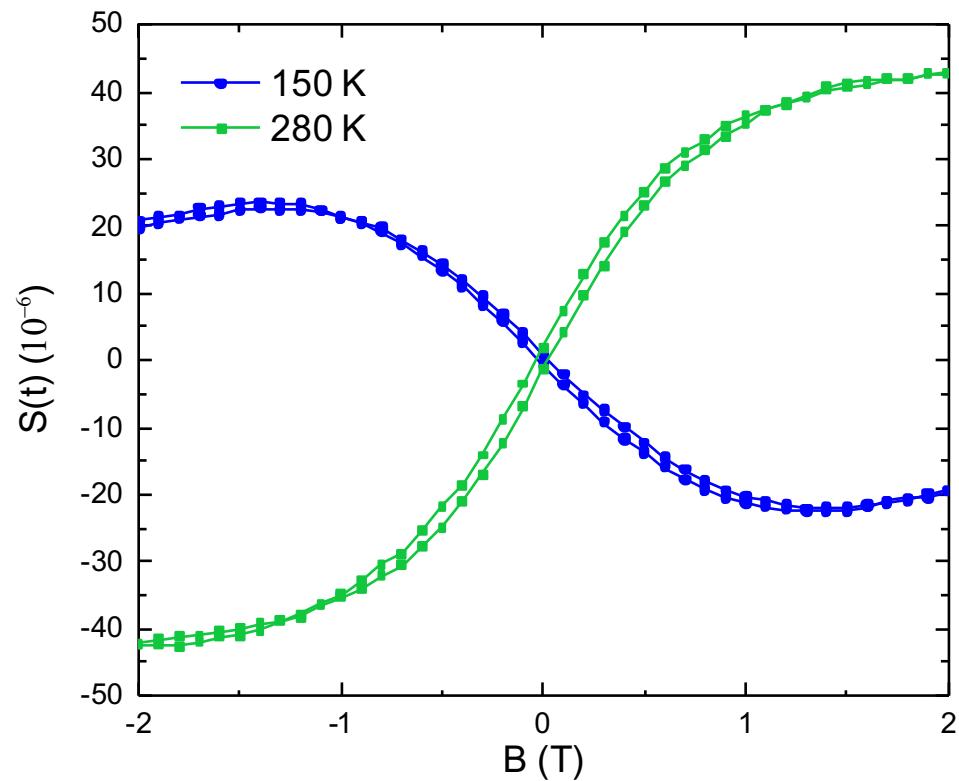
We use THz emission spectroscopy to measure spin-emission



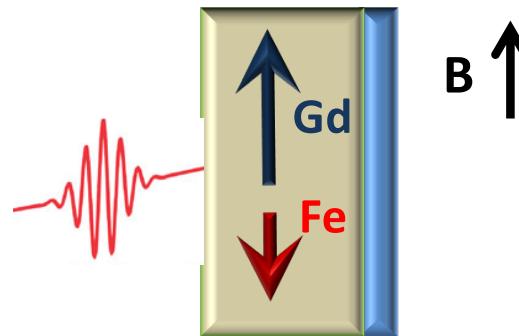
The emitted THz radiation has the symmetry of the ISHE



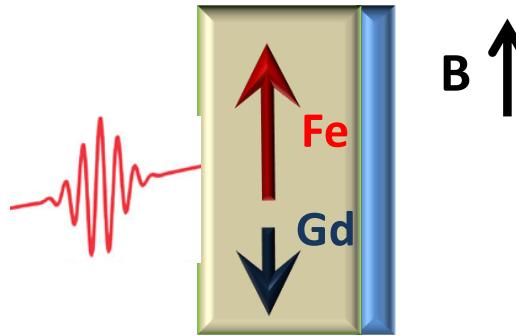
The emitted THz radiation is sensitive to the Fe spin only



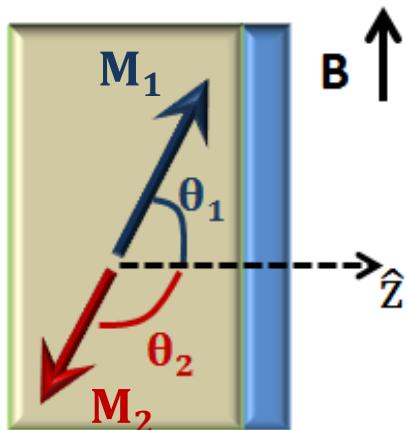
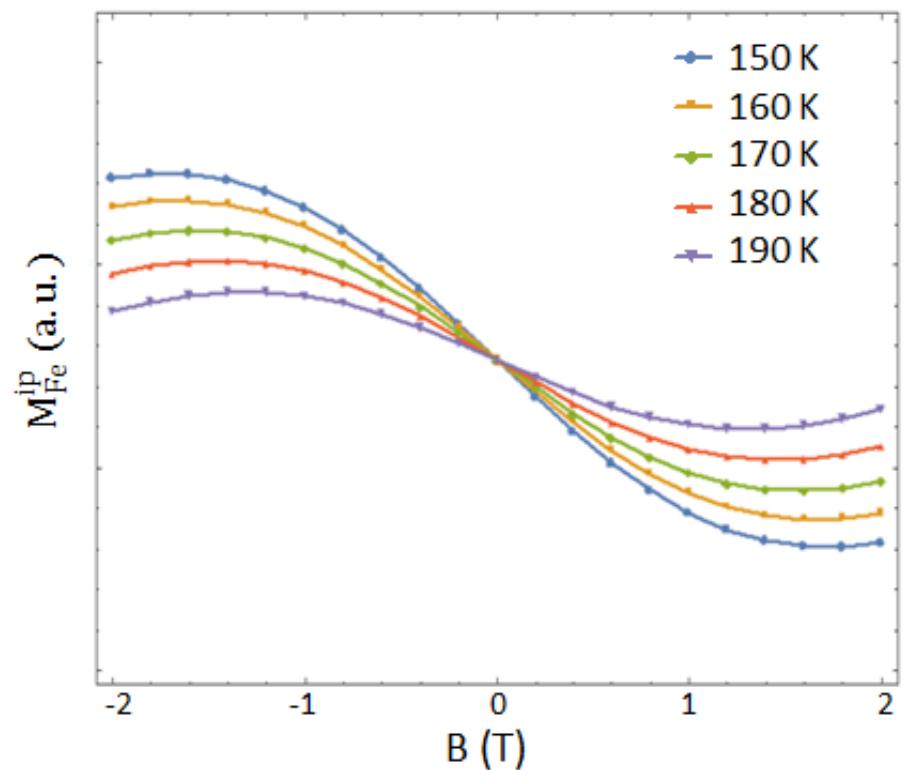
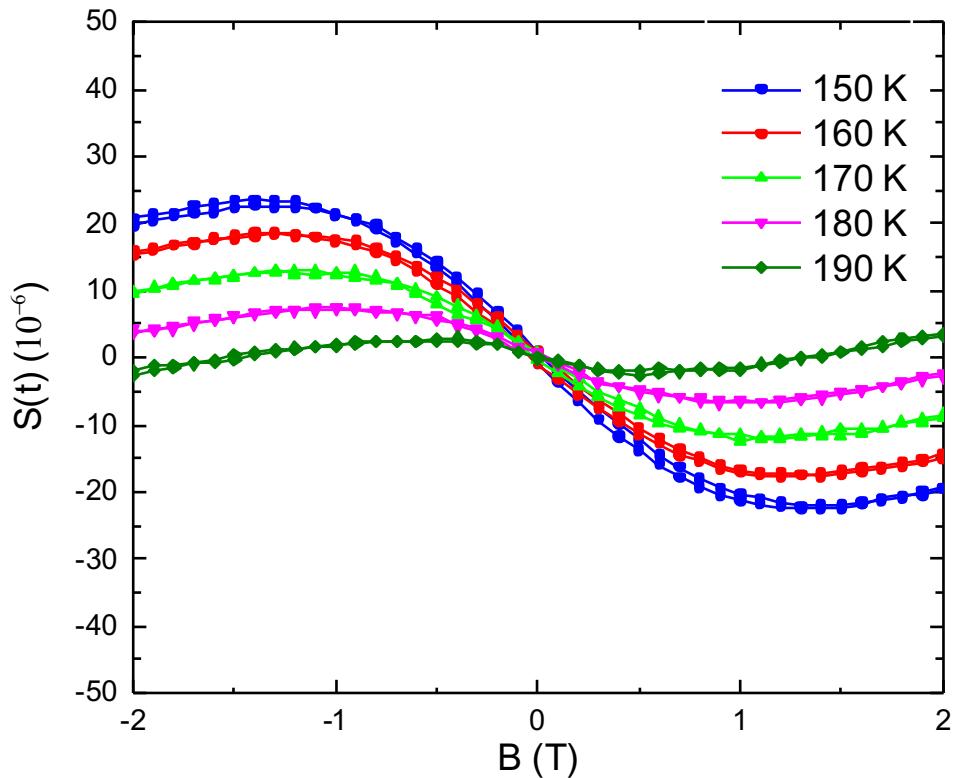
BELOW T_{comp}



ABOVE T_{comp}



The emitted THz radiation is sensitive to the Fe spin only



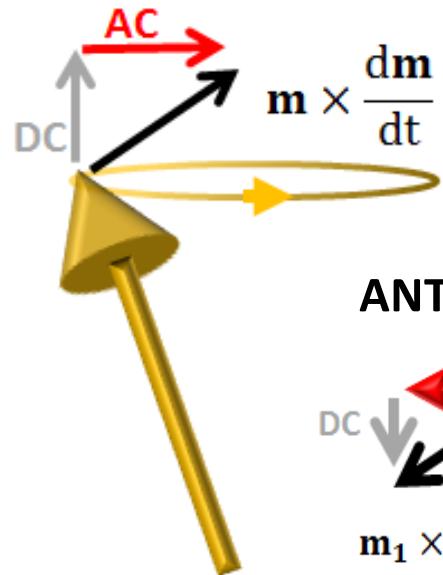
$$E = -M_1 B \sin(\theta_1) - M_2 B \sin(\theta_2) + JM_1 M_2 \cos(\theta_1 + \theta_2) - \frac{K}{2} M_1^2 \cos^2(\theta) - \frac{K}{2} M_2^2 \cos^2(\varphi)$$

EXPERIMENT 3

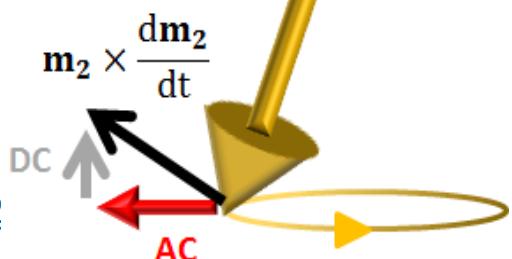
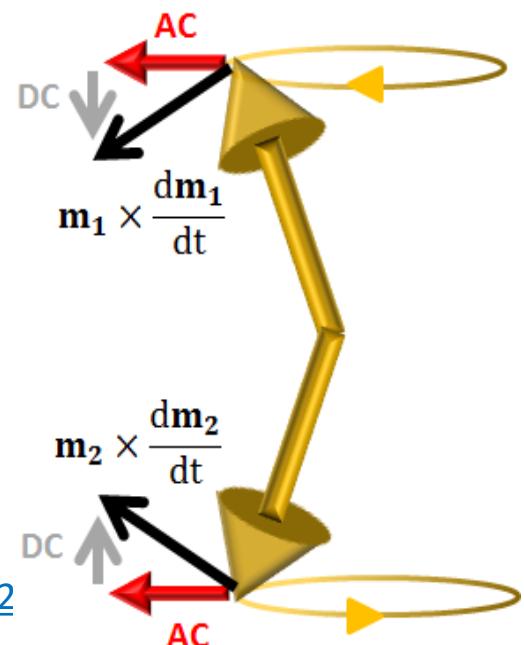
Spin-pumping from anti-ferromagnets

Spin-pumping from an AFM

FERROMAGNETS

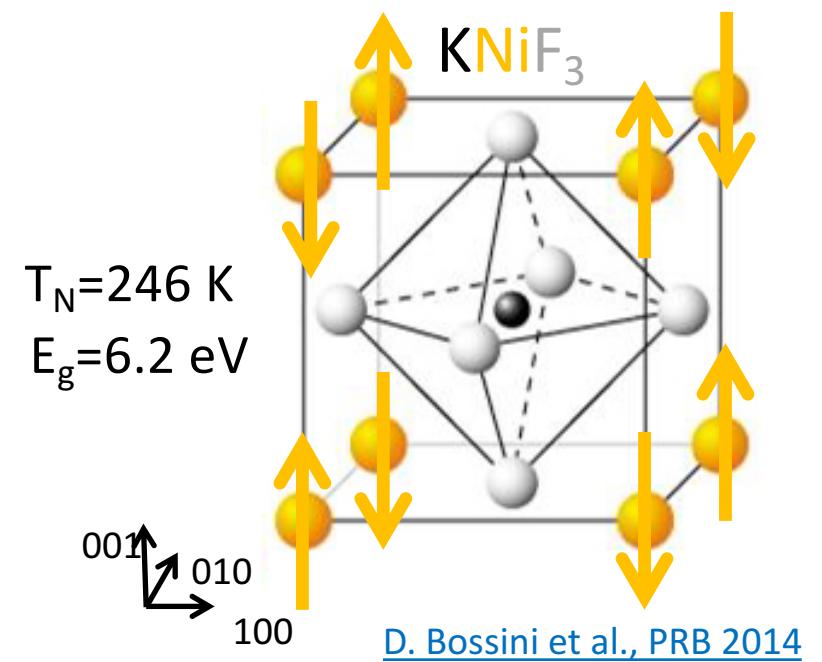
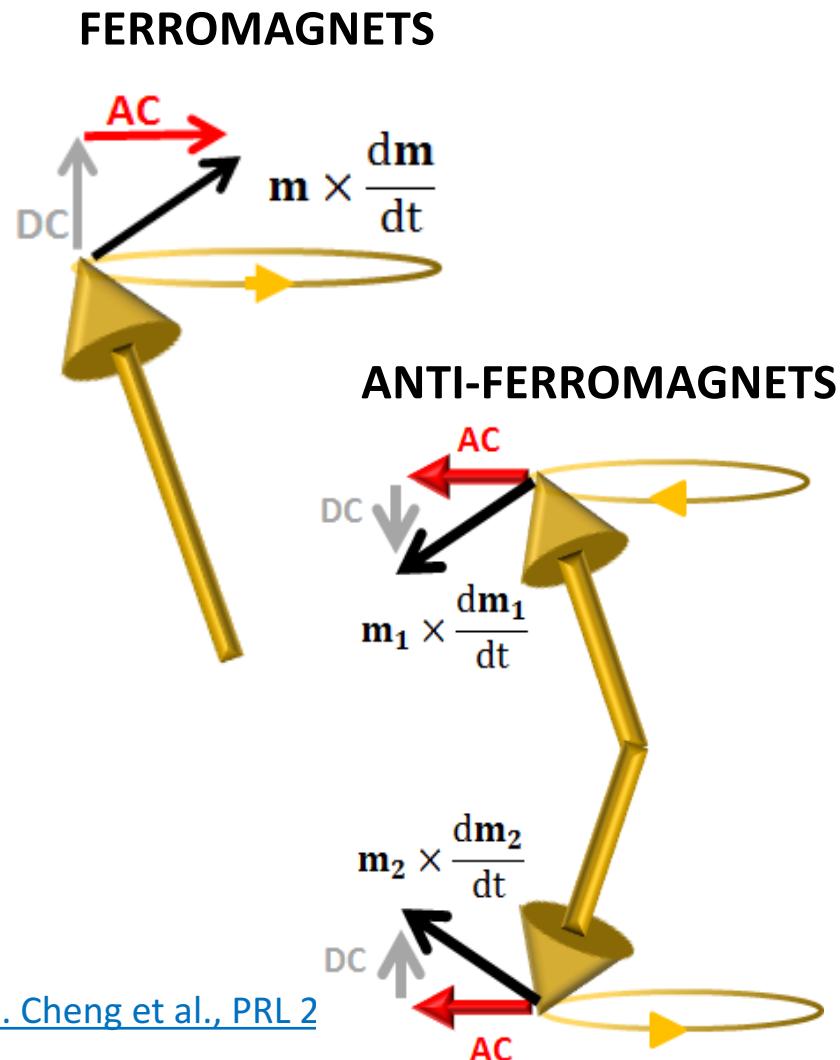


ANTI-FERROMAGNETS

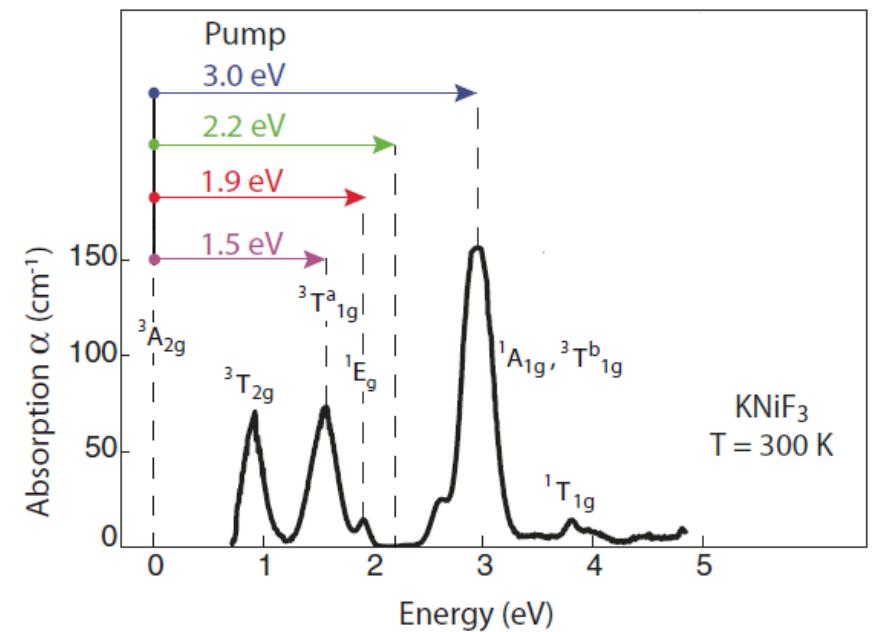
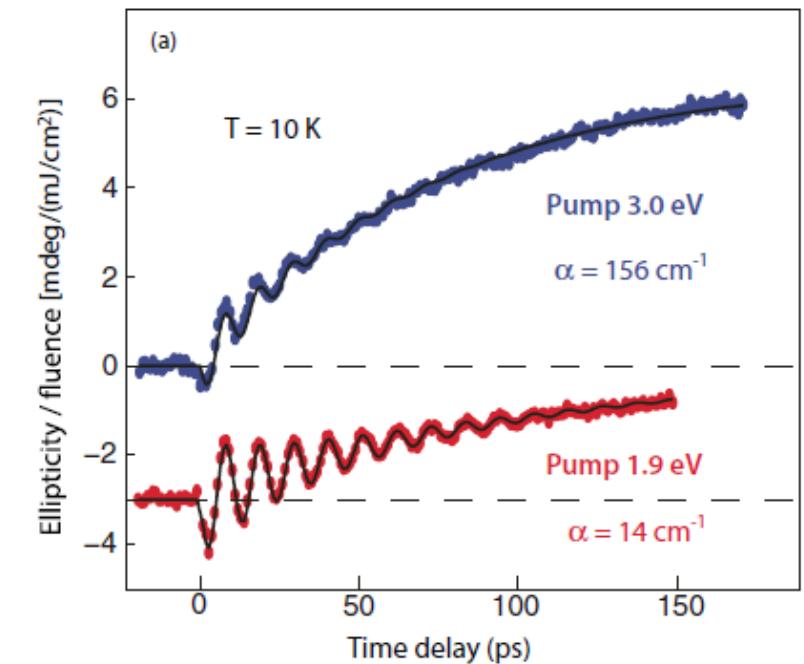
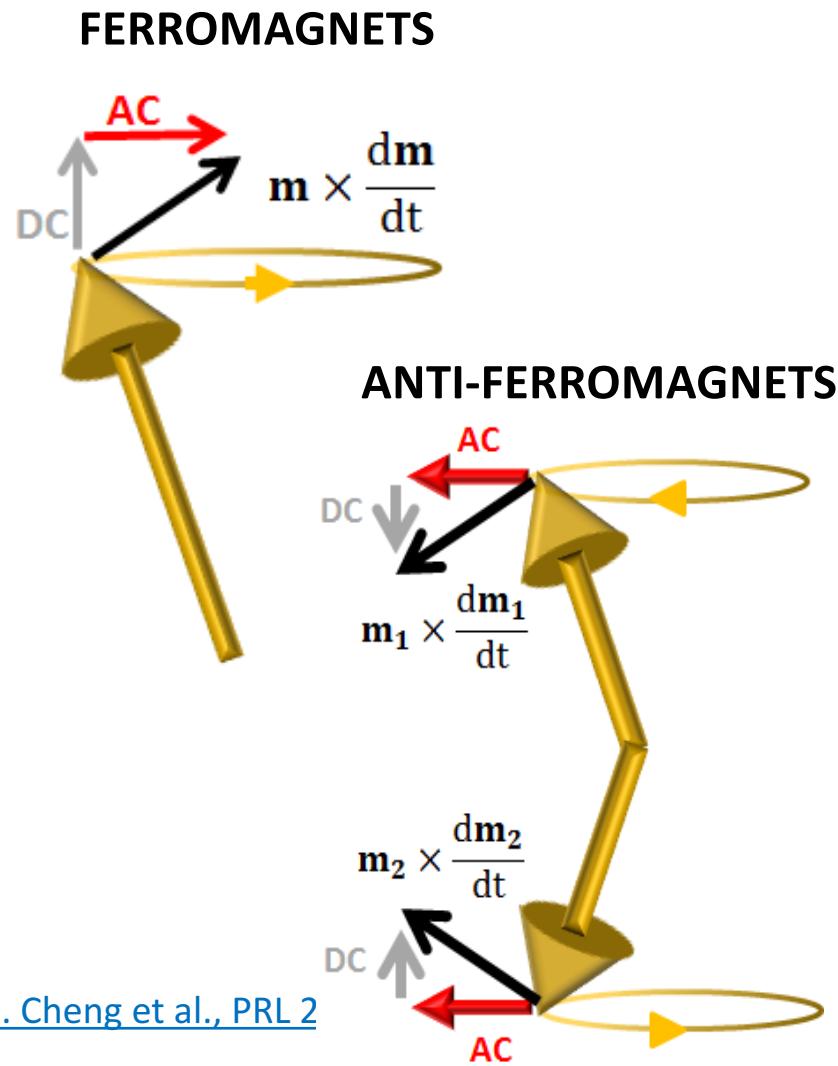


[R. Cheng et al., PRL 2](#)

Spin-pumping from an AFM



Spin-pumping from an AFM

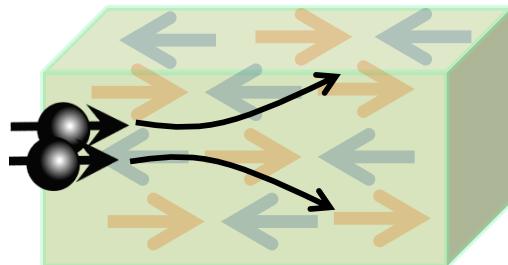


D. Bossini et al., PRB 2014

SUMMARY

1

Spin-Hall effect in anti-ferromagnets



Leeds

Tom Moore
Andrei Mihai,
Mannan Ali

Cambridge

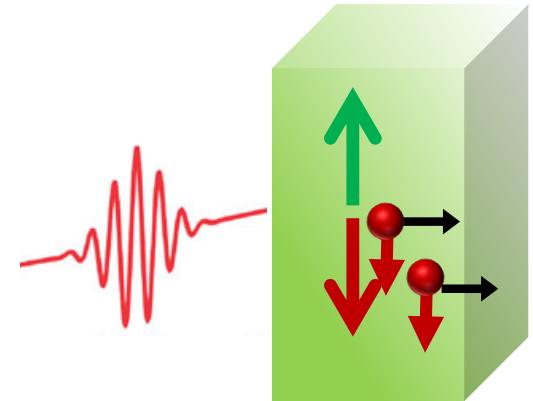
Vahe Tshytoyan
Andrew Irvine
Andrew Ferguson

Prague

Tomas Jungwirth

2

Element-selective spin-emission

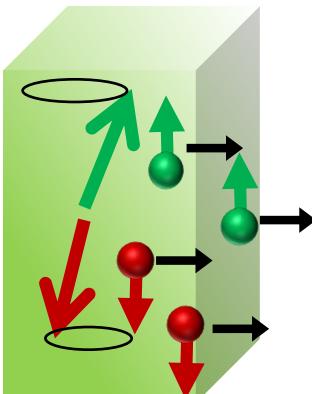


Nijmegen

Alexey Kimel
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3

Spin-pumping from an anti-ferromagnet



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