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SPIN IN ELECTRONICS

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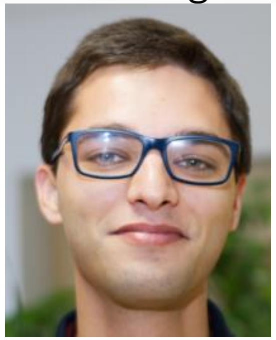
SPICE SPIN PHENOMENA

SPIN+X SFB/TRR 173

Spin And Charge Transport In Antiferromagnets

R. L. Seeger



M. Leiviskä

F. van Duijn

P. Merodio
now Poli. Uni. Spain

L. Frangou
Kings Uni. UK

O. Gladii
HZDR Germany

G. Forestier
ST-micro. France

Outline

1. The lab’ and antiferromagnetic spintronics
2. Spin transport to reveal antiferro. properties
3. The self-induced spin-charge conversion
4. Cooper pair transport to reveal antiferro. properties
5. Replicating spin textures in antiferros.

1. The lab' and today's talk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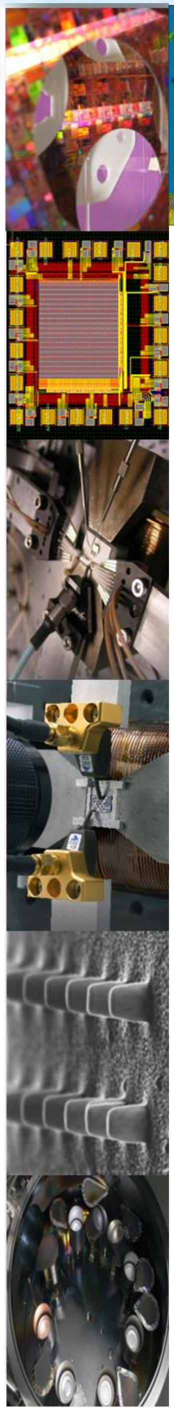
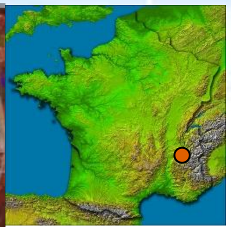
Credit photo: esrf.fr





The lab' and antiferromagnetic spintronics

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SPIN IN ELECTRONICS

Head L. Prejbeanu, O. Fruchart

Board
L. Prejbeanu, O. Fruchart
V. Baltz, M. Jamet, K. Garello, M. Chshiev
I. Joumard, C. Broisin

Administrative support
C. Broisin. A. Stoenescu, C. Conche$^{1/2}$

Council
L. Prejbeanu, O. Fruchart, O. Klein, B. Dieny, A. Masseboeuf, C. Vergnaud, H. Béa, G. DiPendina, P. Sabon, S. Manceau, E. Clot

Concepts Group — V. Baltz, M. Jamet

- **Spin-orbitronics**: G. Gaudin, O. Boulle, M. Miron
- **Topological spintronics**: J.-Ph. Attané, L. Vila, R. Giraud
- **Spin-insulatronics**: O. Klein
- **Antiferromagnetic spintronics**: V. Baltz
- **Spin-textures**: A. Masseboeuf, O. Fruchart
- **2D spintronics**: M. Jamet, F. Bonell, A. Marty, C. Vergnaud

Device Group — K. Garello

- **MRAM**: R. Sousa, L. Prejbeanu, K. Garello, B. Dieny$^{1/2}$
- **Integrated circuit design**: G. Prenat, G. Di Pendina, L. Anghel$^{1/2}$
- **Artificial intelligence**: L. Anghel$^{1/2}$, P. Talatchian
- **Radiofrequency spintronics**: U. Ebels
- **Sensors**: C. Baraduc, H. Béa
- **Biology, Health**: B. Dieny$^{1/2}$, H. Joisten, R. Morel

Theory Group — M. Chshiev

- **Theory**: M. Chshiev, L. Buda-Prejbeanu, D. Gusakova

Support Group — I. Joumard

- **Materials**: M. Rubio-Roy, A. Brenac, S. Auffret, P. Warin$^{1/2}$, J. Faure-Vincent
- **Instrumentation**: I. Joumard, N. Mollard, E. Billiet, E. Gautier
- **Nanofabrication**: P. Sabon, N. Chaix, C. Lemonias, N. Marini

Antiferromagnetic spintronics in the lab'

Some literature reviews:

T. Jungwirth *et al*, Nat. Nanotechnol. **11**, 231 (2016)

V. Baltz *et al*, Rev. Mod. Phys. **90**, 015005 (2018)

L. Šmejkal *et al*, Nat. Phys. **14**, 242 (2018)

V. Bonbien *et al*, arXiv:2102.01632

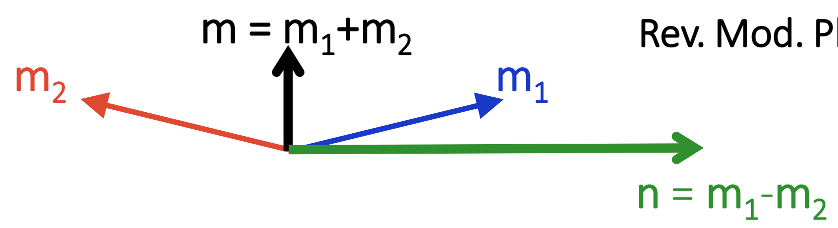
S.-W. Cheong *et al*, npj Quantum Mater. **5**, 3 (2020)

Antiferromagnetic spintronics in the lab'

Specificities of antiferromagnetic materials

2 sublattices m_1 and m_2 → net **m** and Néel vector **n**

Global vs. local property



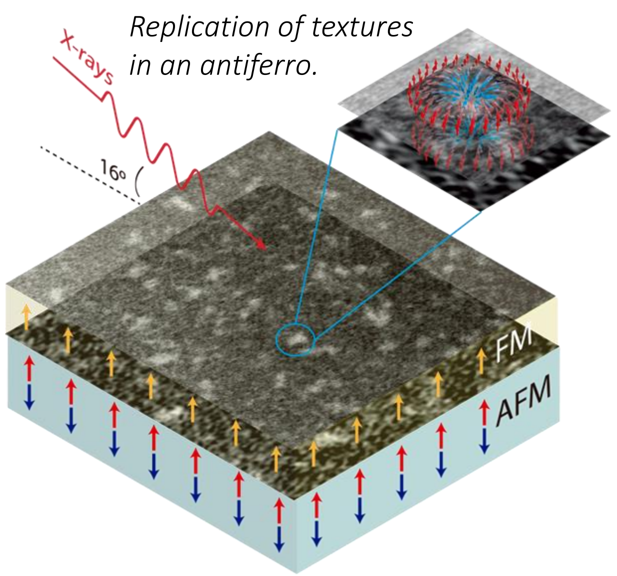
Rev. Mod. Phys. 90, 015005 (2018)

1 Nanomagnetism

Interfacial frustrations
Phys. Rev. B 81, 052404 (2010)

poly-MnX X=Fe,Pd,Ir,Pt , NiO

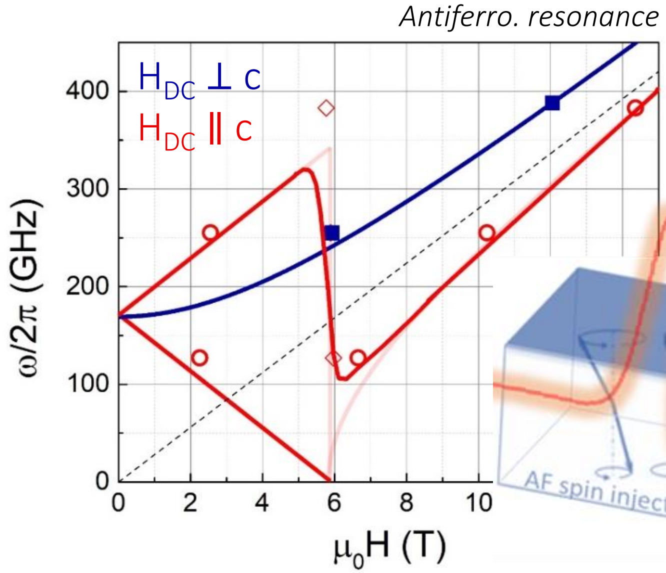
Spin textures
arXiv:2009.14796

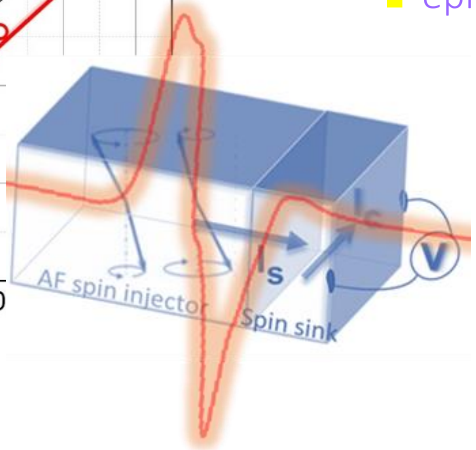


2 Dynamics

Sub-THz resonance and transport
Nat. Comm. 11, 6332 (2020)

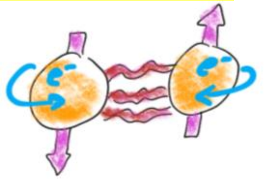
bulk-α-Fe_2O_3





3 Electronic transport

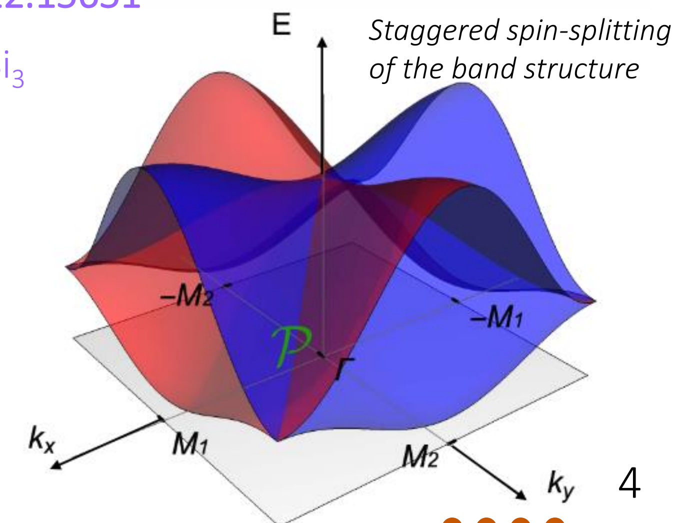
Spin injection, propagation, conversion
Phys. Rev. Lett. 116, 077203 (2016)
Phys. Rev. B 98, 094422 (2018)
arXiv:2102.03425



poly-MnX X=Fe,Pd,Ir,Pt , and MnX/NbN hybrids

Spontaneous charge Hall effects
arXiv:2012.15651

épi-Mn_5Si_3



2. Spin transport to reveal antiferro. properties

Some literature papers:

H. Wang *et al*, Phys. Rev. Lett. **113**, 097202 (2014)

C. Hahn *et al*, Europhys. Lett. **108**, 57005 (2014)

P. Merodio *et al*, Appl. Phys. Lett. **104**, 032406 (2014)

J. B. S. Mendes *et al*, Phys. Rev. B **89**, 140406 (2014)

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

L. Frangou *et al*, Phys. Rev. Lett. **116**, 077203 (2016)

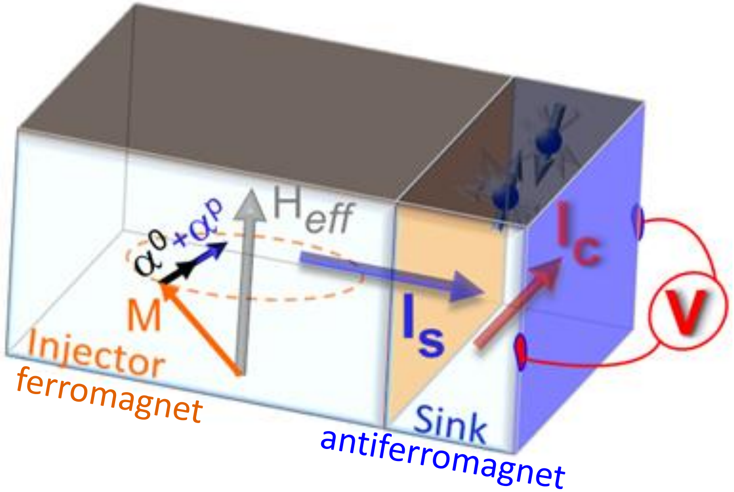
Z. Qiu *et al*, Nat. Commun. **7**, 12670 (2016)

… and many more

Spin transport to reveal antiferro. properties

Ferromagnetic resonance for pumping spins
in a 'static' antiferromagnet far from $T_{Néel}$

Appl. Phys. Lett. 104, 032406 (2014)
Rev. Mod. Phys. 90, 015005 (2018)



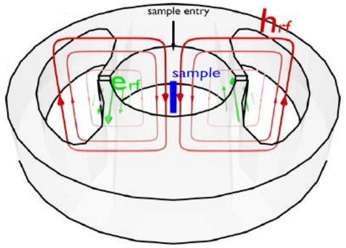
$$\boldsymbol{j}_s^0 = \frac{\hbar}{4\pi}\left(G_{\uparrow\downarrow,\mathcal{Re}}^{AF/F}\,\boldsymbol{m}\times\frac{d\boldsymbol{m}}{dt} + G_{\uparrow\downarrow,\Im m}^{AF/F}\,\frac{d\boldsymbol{m}}{dt}\right)$$

transfer by STT
spin relaxation

spin-orbit

$$\alpha^F = \alpha^0 + \frac{\gamma\hbar}{4\pi d^F}G_{\uparrow\downarrow,\mathcal{Re}}^{AF/F}$$

$$V_{ISHE} = \rho_{ISHE}^{AF\,*}d^*\frac{2e}{\hbar}j_s^0$$

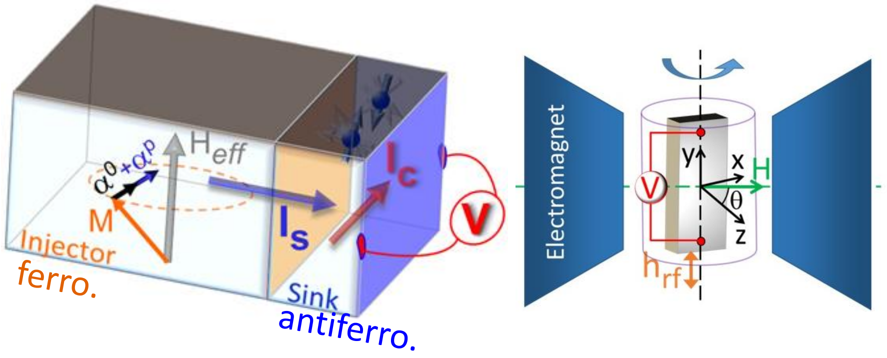


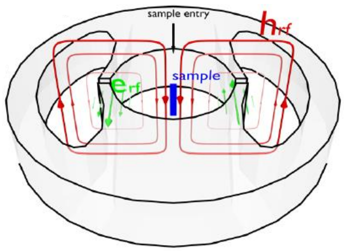
3 loop - 2 gap resonator ~ mode TE_{102}

Opened perspectives for the study of spin transport in antiferromagnetics, electronic and magnonic regimes

Y. Tserkovnyak *et al* RMP (2005)
K. Ando *et al* JAP (2011)
R. Igushi *et al* J. Phys. Soc. Jpn. (2017)

Ferromagnetic resonance for pumping spins in antiferromagnets

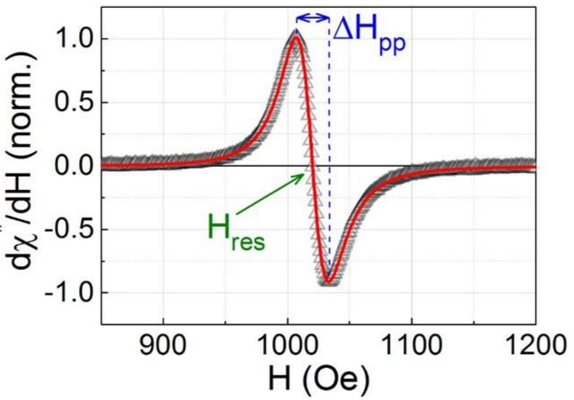


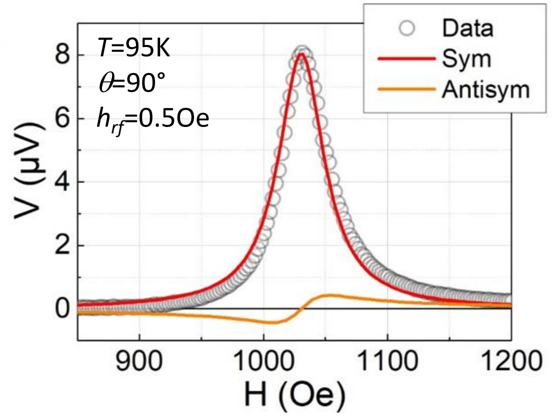


3 loop - 2 gap resonator ~ mode TE_{102}

fixed f=9.6 GHz - Variable hrf, H, T and θ

complementary stripline data with variable f





$$\Delta H_{pp} = \frac{2}{\sqrt{3}}\frac{\omega}{\gamma}\left(\alpha^0 + \underbrace{\frac{\gamma\hbar}{4\pi M_S^F d^F} G_{\uparrow\downarrow,\mathcal{R}e}^{AF/F}}\right) + \Delta H_0$$

α^p, spin absorption

$$V = \underbrace{V_{sym}} \frac{\Delta H^2}{\Delta H^2 + (H - H_{res})^2} + V_{antisym} \frac{-\Delta H (H - H_{res})}{\Delta H^2 + (H - H_{res})^2}$$

$$V_{sym,ISHE} = injection\left(G_{\uparrow\downarrow,\mathcal{R}e}^{AF/F}\right) \times conversion(\Theta_{ISHE} l_{sf})$$

Spin transport to reveal antiferro. properties

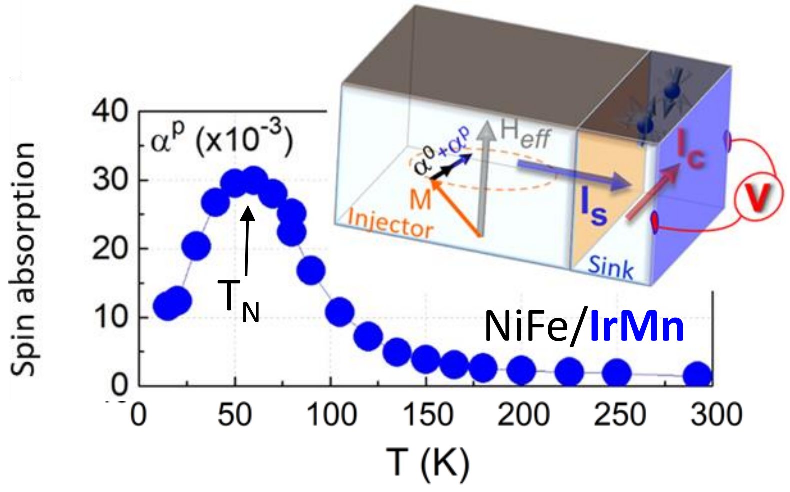
'Dynamic' antiferromagnet near $T_{Néel}$

L. Frangou *et al*, Phys. Rev. Lett. 116, 077203 (2016)

$$m = m_0 + \chi^{(0)} h + \cdots$$

$$\chi^{(0)} \propto G^{AF/F}_{\uparrow\downarrow,\mathcal{R}e}(T)$$

Y. Ohnuma *et al* PRB (2014)



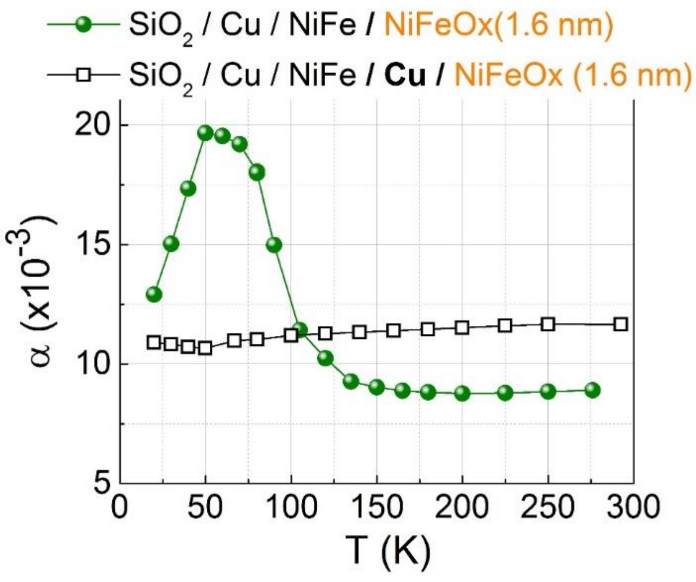
Access to linear spin fluctuations in thin films of antiferromagnets

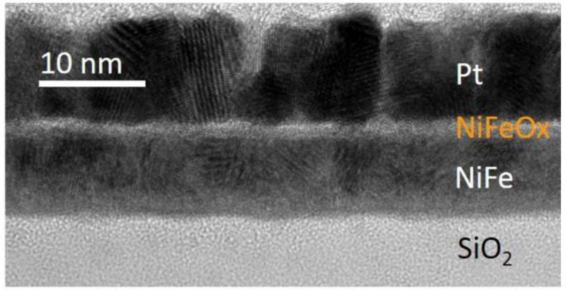
Opened perspectives for the study of phase transitions at low thicknesses, electronic and magnonic regimes

Electronic and magnonic transport regimes

Insulator

no magnonic transport through Cu

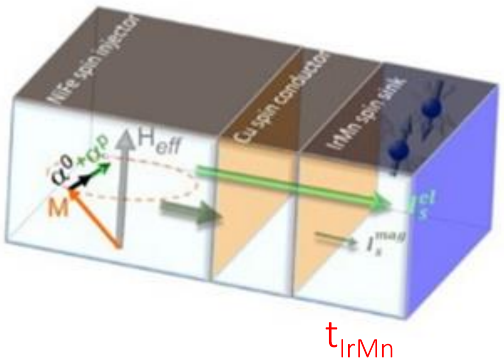


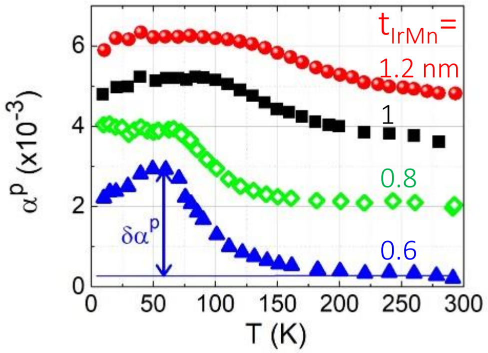


Metal

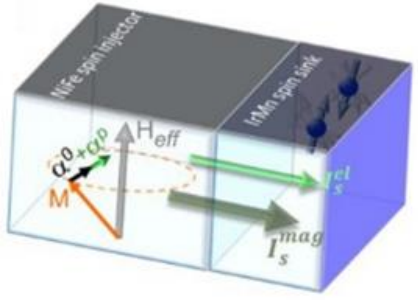
O. Gladii *et al*, Phys. Rev. B 98, 094422 (2018)

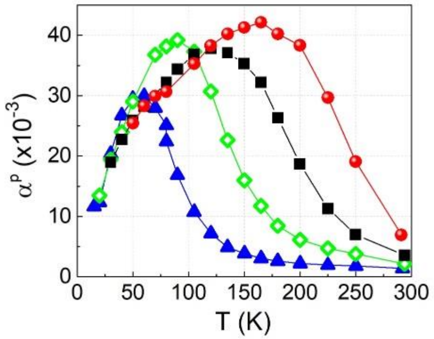
With Cu spacer
electronic transport prevails
~no magnonic transport

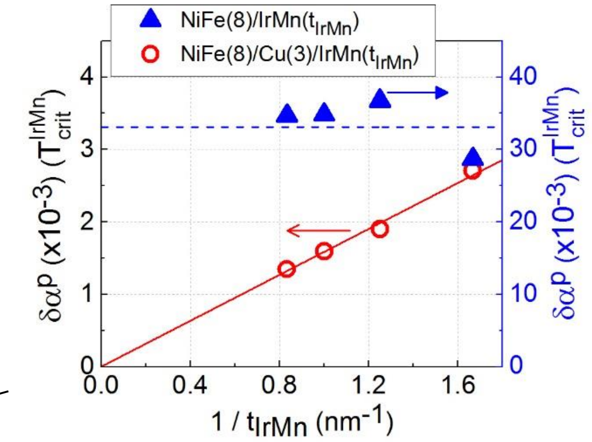




Without Cu spacer
magnonic transport prevails





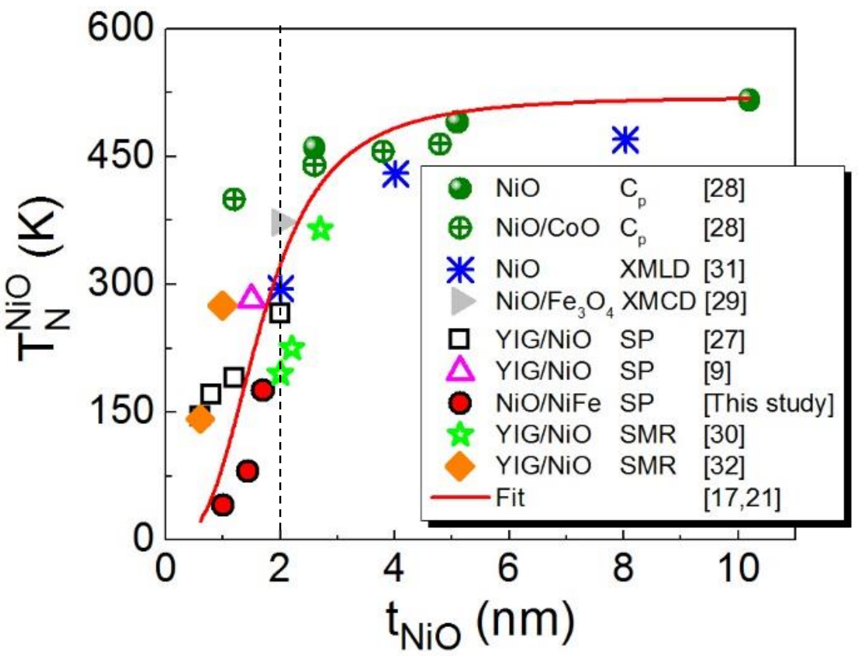


$\lambda_{magnons} \gg t_{IrMn} \sim \lambda_{e^-} = 0.7$ nm

see also
S. Jenkins *et al* JAP (2020), theory
H. Saglam *et al* PRB (2016), FeMn

Phase transitions at low thicknesses

O. Gladii *et al*, Appl. Phys. Exp. 12, 023001 (2019)



Universality class

$$(T_{N,bulk} - T_N(t_{NiO}))/T_N(t_{NiO}) = (t_{NiO}/\xi_0)^{-\lambda_{eff}}$$

M. Henkel *et al* PRL (1998)

TABLE II. Field theory predictions [22] from the three-dimensional $O(n)$ vector model of some critical exponents. The numbers in brackets estimate the error on the last given digits.

Model	n	Δ_1	$1/\nu$	$(1+2\Delta_1)/\nu = \lambda_{eff}$
Ising	1	0.50(2)	1.586(4)	3.17(6)
XY	2	0.53(2)	1.492(7)	3.07(11)
Heisenberg	3	0.555(25)	1.413(9)	2.98(13)

Spin transport to reveal antiferro. properties

'Dynamic' antiferromagnet near $T_{Néel}$

$$m = m_0 + \chi^{(0)} h + \chi^{(1)} h^2 + \chi^{(2)} h^3$$

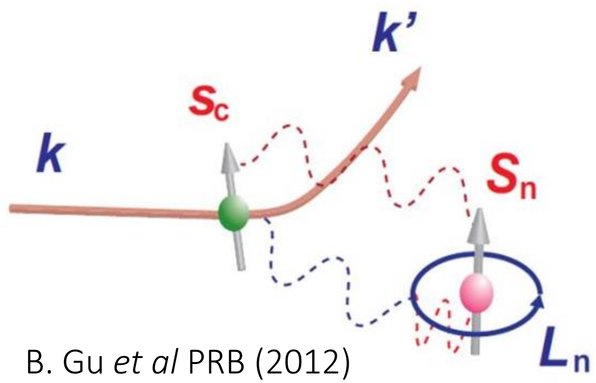
$$\chi^{(0)} \propto G^{AF/F}_{\uparrow\downarrow,\mathcal{R}e}(T)$$

Y. Ohnuma *et al* PRB (2014)

L. Frangou *et al*, Phys. Rev. Lett. 116, 077203 (2016)
O. Gladii *et al*, Phys. Rev. B 98, 094422 (2018)

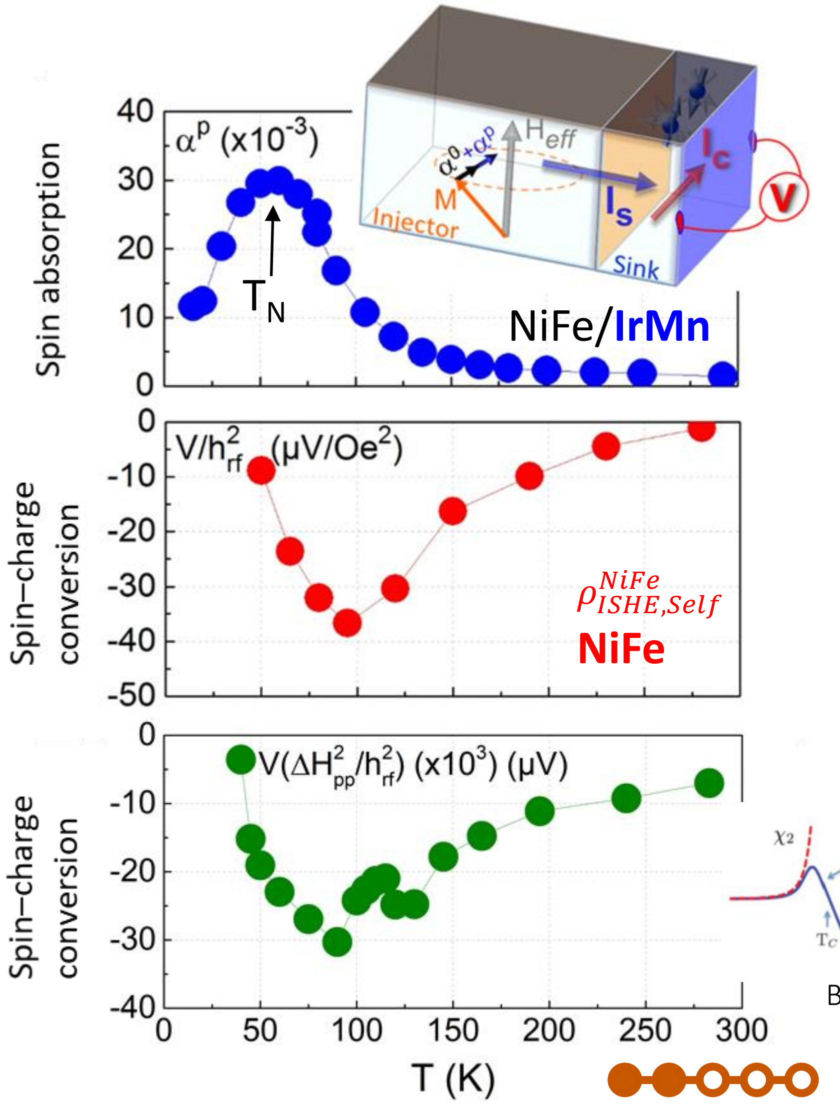
Access to linear spin fluctuations in thin films of antiferromagnets

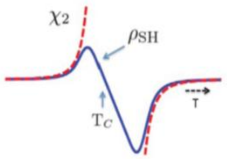
Opened perspectives for the study of phase transitions at low thicknesses, electronic and magnonic regimes



B. Gu *et al* PRB (2012)
D. H. Wei *et al* Nat. Com. (2012)

$$\chi^{(2)} \propto \rho^{AF}_{ISHE}(T) \propto V_{sym}\ (+\ \rho^{F}_{ISHE,self})$$





B. Gu *et al*

What about non-linear fluctuations !

3. The self-induced spin-charge conversion

Some literature papers:

C. Ciccarelli *et al*, Nat. Nanotechnol. **10**, 50 (2014)

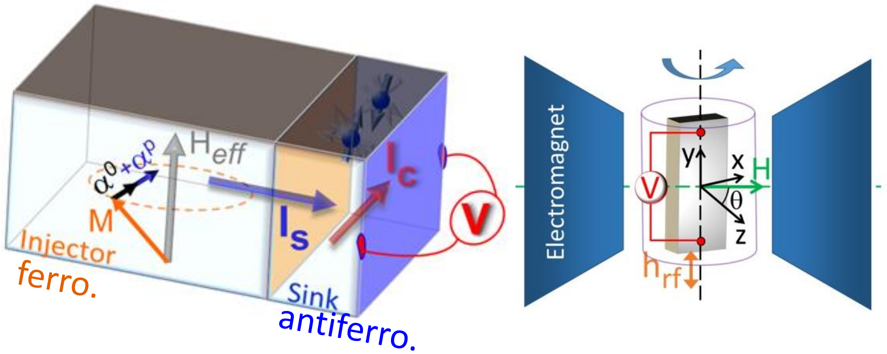
A. Azevedo *et al*, Phys. Rev. B **92**, 024402 (2015)

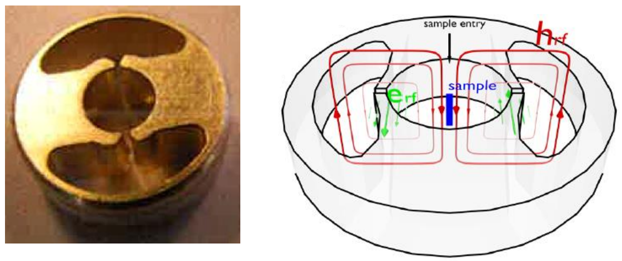
A. Tsukahara *et al*, Phys. Rev. B **89**, 235317 (2014)

K. Kanagawa *et al*, AIP Adv. **8**, 055910 (2018)

O. Gladii *et al*, Phys. Rev. B **98**, 094422 (2018)

Spin charge conversion in IrMn for the full T-range ?

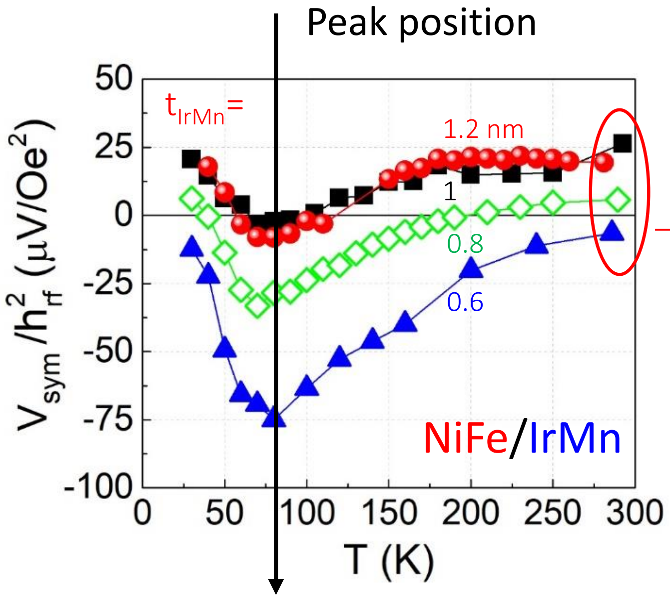




3 loop - 2 gap resonator ~ mode TE_{102}

fixed f=9.6 GHz - Variable hrf, H, T and θ

complementary stripline data with variable f



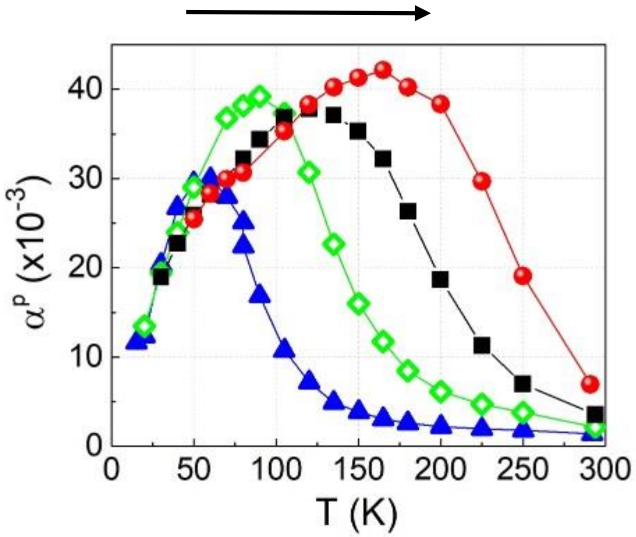
At 300K
conversion mainly in IrMn

$\lambda_{IrMn}\tanh(\frac{t_{IrMn}}{2\lambda_{IrMn}})$

See also

J. B. S. Mendes *et al* PRB (2014)

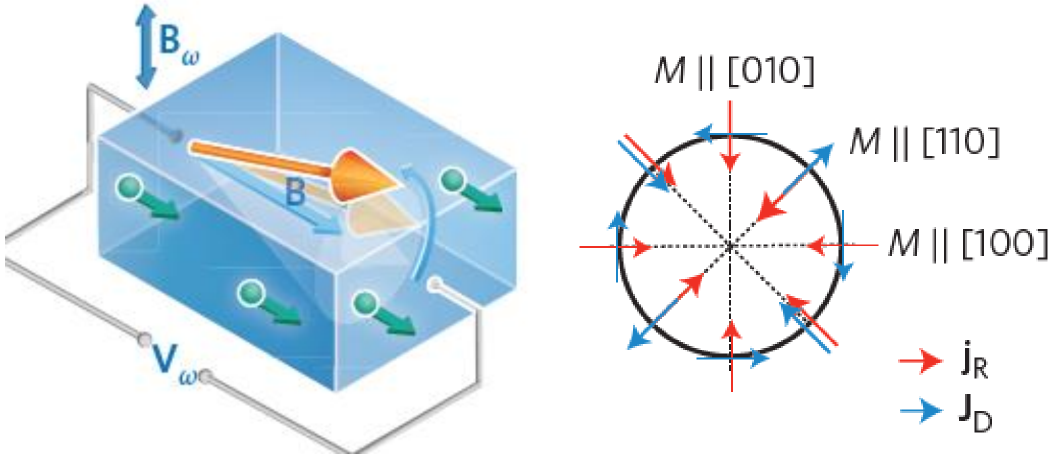
W. Zhang *et al* PRL (2014)

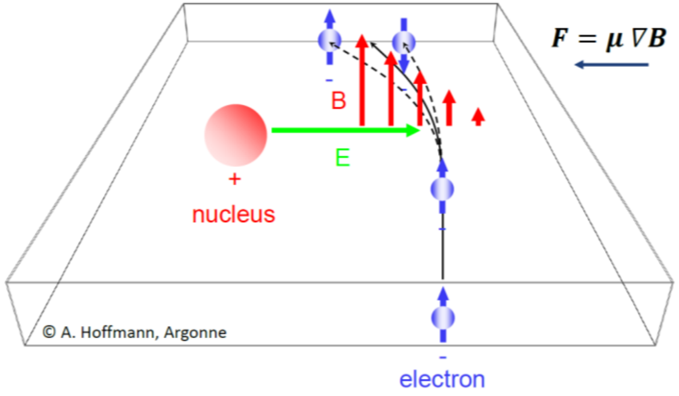


At low-T
conversion mainly somewhere else

The self-induced spin-charge conversion

Conversion in ferromagnets triggered by several mechanisms





magnonic charge-pumping (MCP), also called inverse spin-orbit torque (ISOT) effect

dictated by lack of spatial inversion symmetry

C. Ciccarelli *et al* Nat. Nano (2014)	(Ga,Mn)As	300K
A. Azevedo *et al* PRB (2015)	NiFe/Ox	300K

ISHE, subsequent to spin-current generation based on spin-dependent scattering at the different interfaces

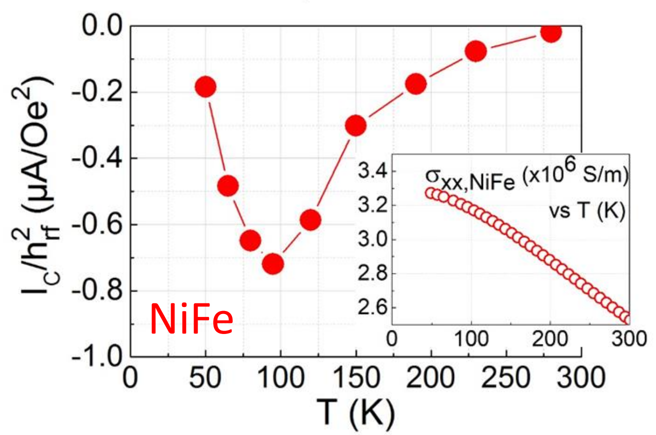
A. Tsukahara *et al* PRB (2014)	NiFe	300K
K. Kanagawa *et al* AIP Adv. (2018)	Co, Fe	300K

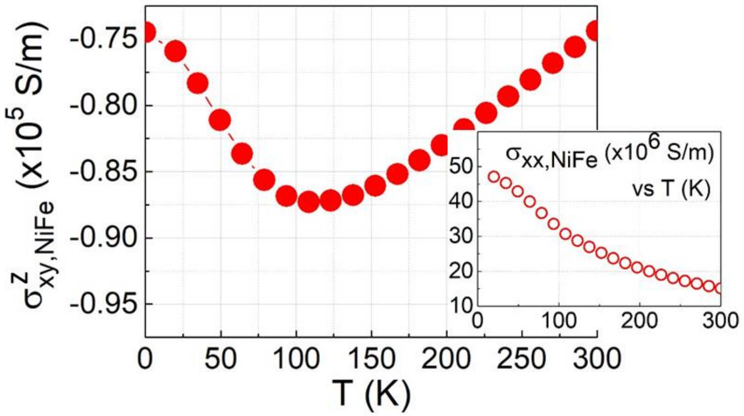
The self-induced spin-Hall effect

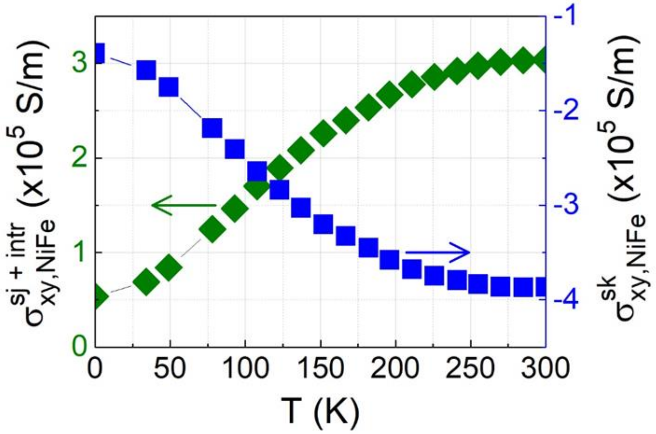
O. Gladii *et al*, Phys. Rev. B 98, 094422 (2018)

Experiments

Theory







Approach using the scaling behavior:

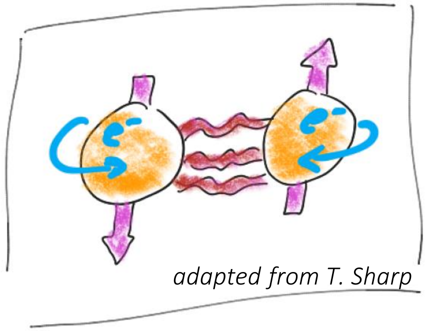
$$\sigma^{z}_{xy,NiFe} = \sigma^{sk}_{xy,NiFe} + \sigma^{sj+intr}_{xy,NiFe} = \sigma_{xx,NiFe} S + \sigma^{sj+intr}_{xy,NiFe}$$

The skewness factor, S is determined in the $Ni_{0.85}Fe_{0.15}$ - $Ni_{0.7}Fe_{0.3}$ range.

Qualitative agreement
with *ab-initio* calculations of SH conductivity in bulk permalloy

Non-monotonic T-dependence
skew and side-jump + intrinsic diffusions of opposite signs and of similar amplitudes

4. Cooper pair transport to reveal antiferro. properties



adapted from T. Sharp

Some literature papers:

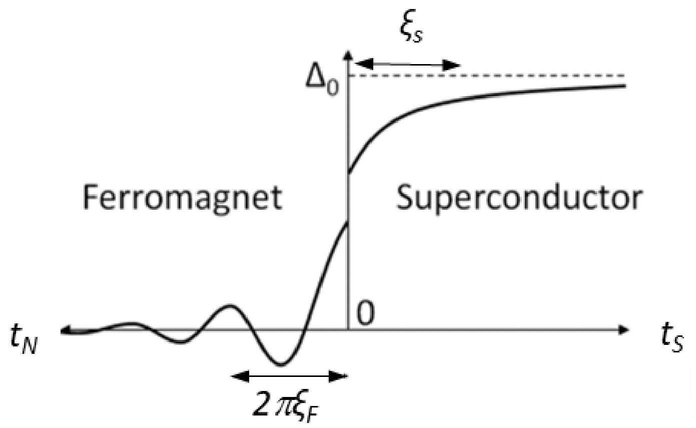
C. Bell *et al*, Phys. Rev. B **68**, 144517 (2003)
B. M. Andersen *et al*, Phys. Rev. Lett. **96**, 117005 (2006)
B. L. Wu *et al*, Appl. Phys. Lett. **109**, 152602 (2013)
M. F. Jakobsen *et al*, Phys. Rev. B **102**, 140504(R) (2020)
R. L. Seeger *et al*, arXiv:2102.03425

Cooper pair transport to reveal antiferro. properties

spintec SPIN IN ELECTRONICS

Principle of the proximity effect in ferro/super bilayers

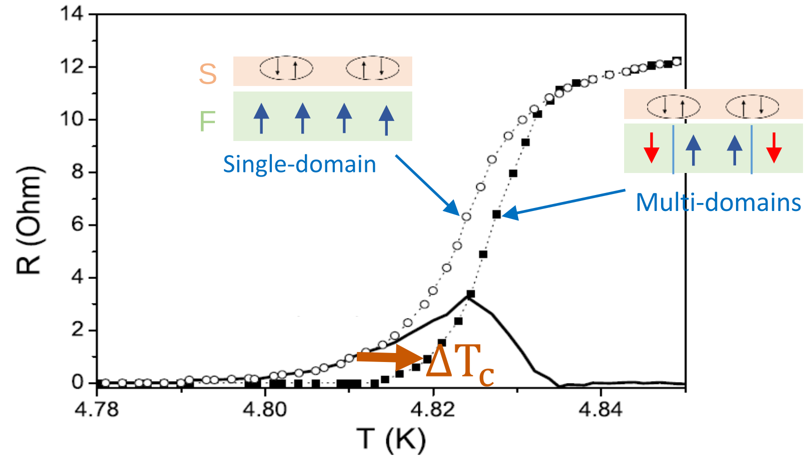
Review
A. I. Buzdin RMP (2005)



Saturated ferro.	suppression of supercond.	loss of T_C
Multi-domain ferro.	suppression partially alleviated	partial recovery ΔT_C
	(a Cooper pair samples different directions of h_{ex})	

A broad set of parameters

supercond. coherence length (ξ_s) vs the layers' thicknesses (t_S, t_N, t_F)
vs the domain & domain wall sizes (D, d)



L. Y. Zhu et al PRL (2008)

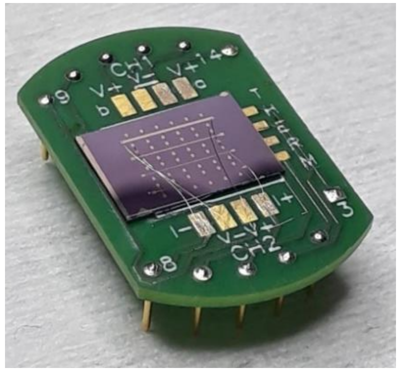
Max. recovery of $\Delta T_C/T_C$~0.6% reported preventing investigation of

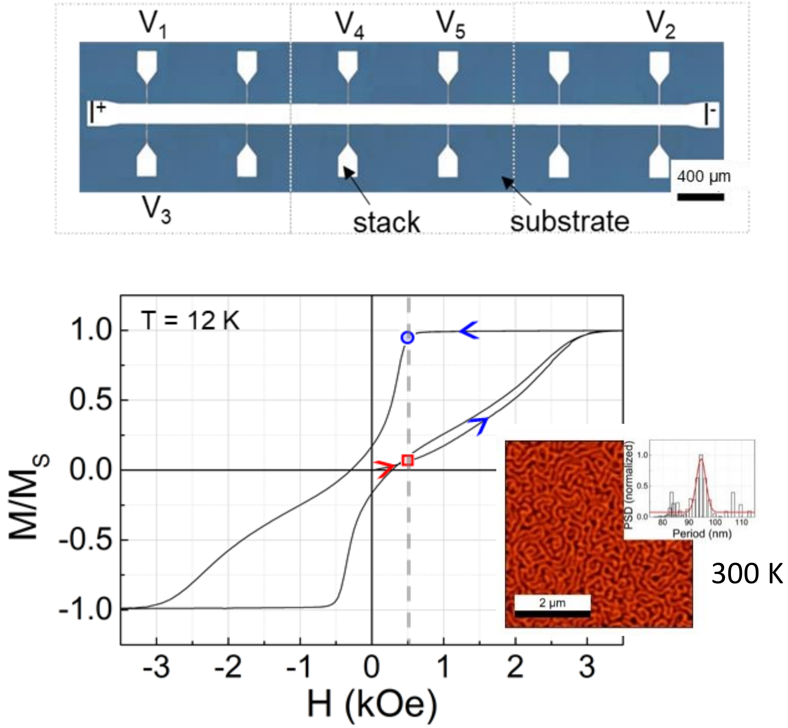
1. the intermediate magnetic configurations
2. inserting an interlayer, eg antiferromagnets

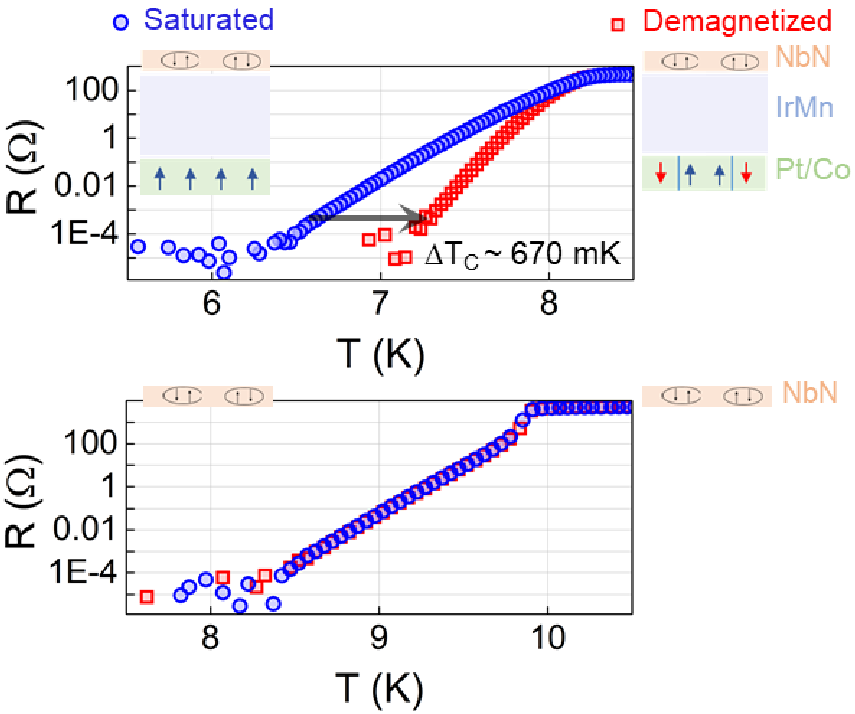
Cooper pair transport to reveal antiferro. properties

Optimization of the proximity effect

R. L. Seeger *et al*, arXiv:2102.03425







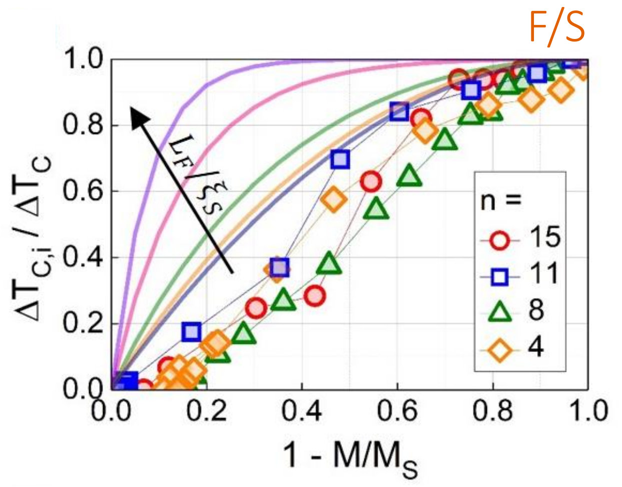
$[Pt/Co]_{x15}$/IrMn/NbN stacks with $\xi_s(T_C)$ ~ d ~ t_S ~ t_F ~15 nm < D ~50 nm

Tenfold improvement compared to literature data, $\Delta T_C/T_C$~10%

Opened the way for novel experimental and theoretical investigations

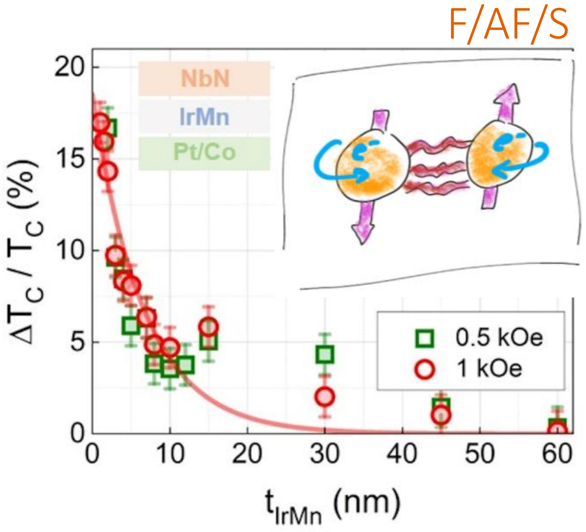
Novel experimental and theoretical investigations

R. L. Seeger *et al*, arXiv:2102.03425



1. Impact of a gradual change of the ferromagnetic state from single- to multi-domain, corroborated by a quasiclassical diffusive model

$$\frac{T_{C0}-T_C}{T_{C0}} = 2\pi T_{C0} \sum_{\omega>0} \left[\frac{1}{\tilde{\tau}\omega^2} + \frac{\tilde{h}_0^2}{\omega^3} + \sum_{q\neq 0} \frac{|\tilde{h}_q|^2}{\omega^2[\omega + D_S q^2/2]} \right]$$



2. Probe of the penetration depth (ξ_{AF}) of Cooper pairs in antiferromagnets

data fitting with $\Delta T_C/T_C \propto \exp[-t_{spacer}/\xi_{spacer}]$, returned ξ_{IrMn} = (6.7±1) nm.
for comparison, we obtained ξ_{Pt} = (12.4±2) nm
$\Delta T_C/T_C$ independent on the IrMn state due to its transparency for Cooper pairs

5. Replicating spin textures in antiferros.

Some literature papers:

N. B. Weber *et al*, Phys. Rev. Lett. **91**, 237205 (2003)

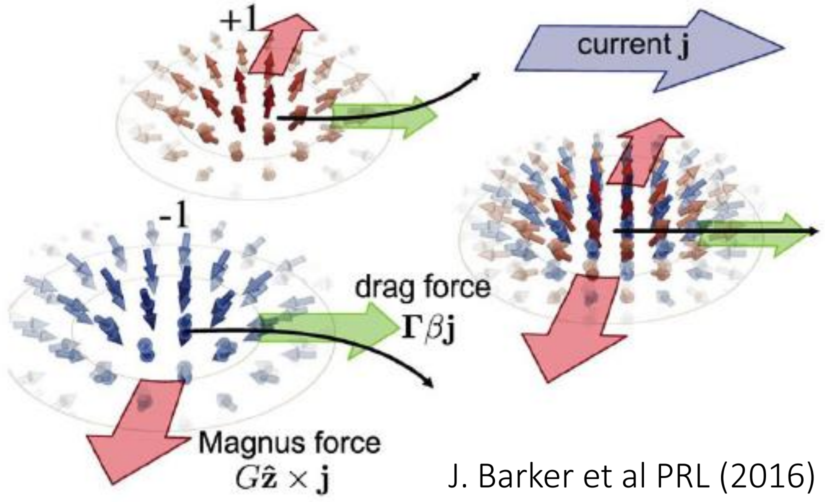
M. Bode *et al*, Nat. Mater. **5**, 477 (2006)

J. Barker *et al*, Phys. Rev. Lett. **116**, 147203 (2016)

S. Brück *et al*, Adv. Mater. **17**, 2978 (2005)

J. Wu *et al*, Nat. Phys. **7**, 303 (2011)

K. G. Rana, R. L. Seeger *et al*, arXiv:2009.14796



J. Barker et al PRL (2016)

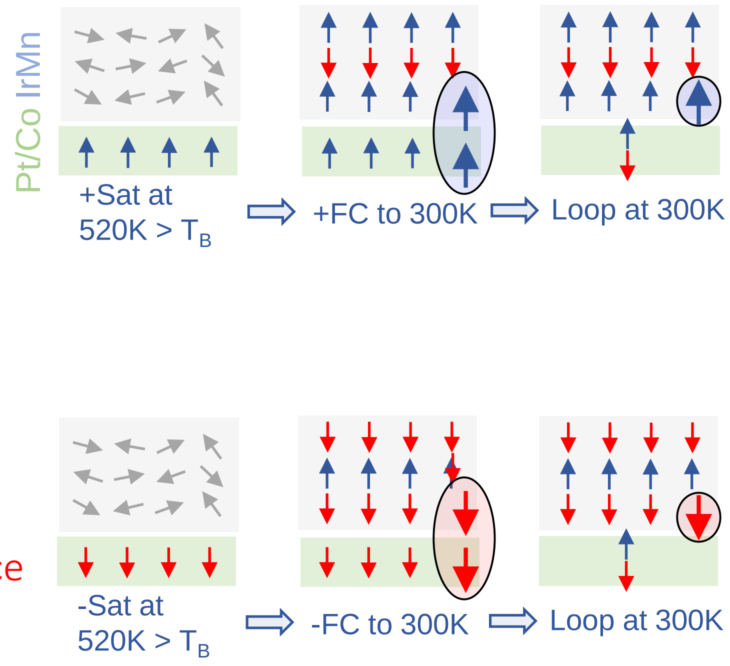
Advantages of textures in antiferros over their ferromagnetic analogs

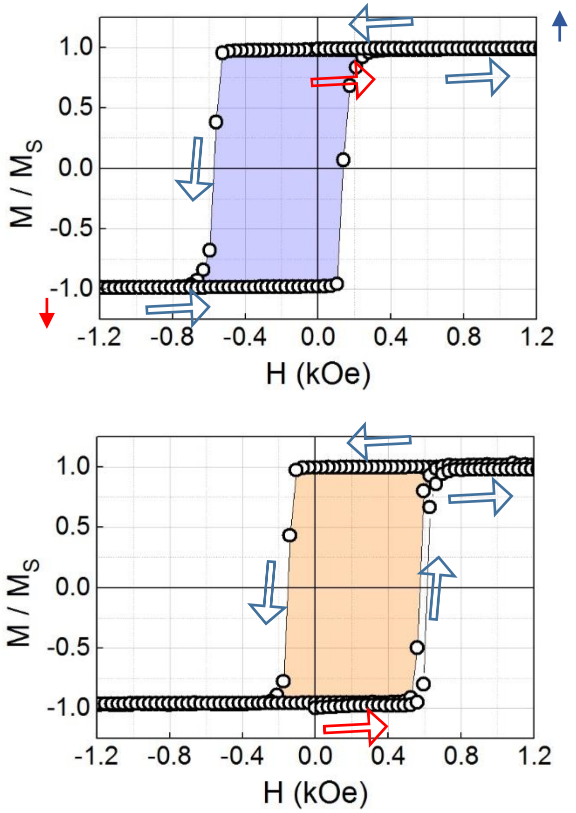
Domain wall	ultrafast dynamics not limited by the Walker breakdown
Vortex	new type of divergent textures
Skyrmion	straight trajectory due to compensation of the Sk-HE

How to create these spin textures ?

Replicating spin textures in antiferros.

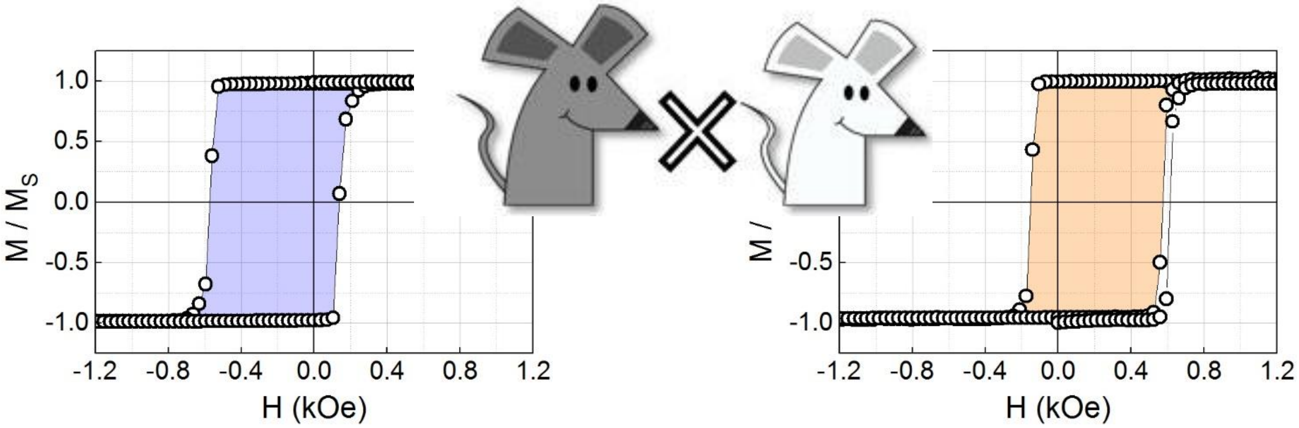
Domain impression through ferro/antiferro exchange bias coupling



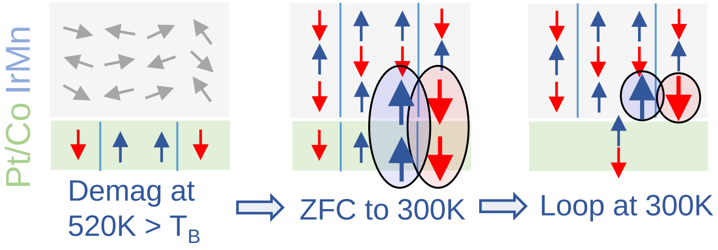


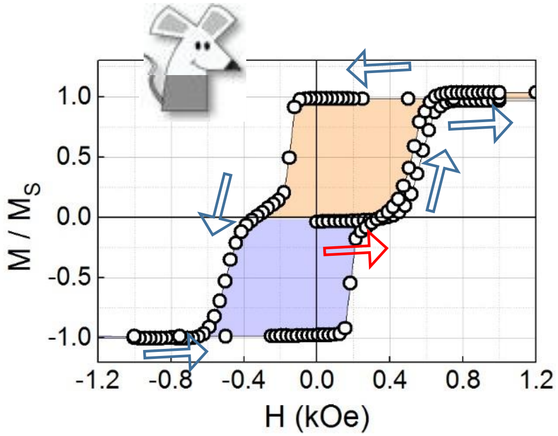
Opposite remanence

S. Brück *et al*, Adv. Mater. 17, 2978 (2005)



Demagnetized remanence



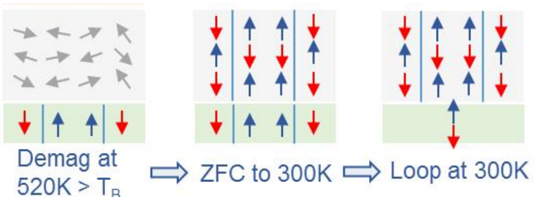


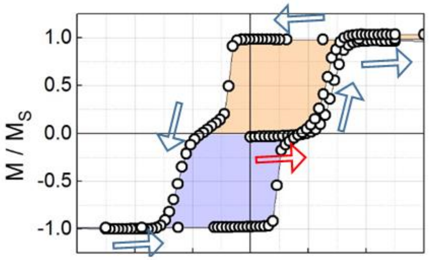
Replicating spin textures in antiferros.

Domains and domain walls in IrMn

S. Brück *et al*, Adv. Mater. 17, 2978 (2005)

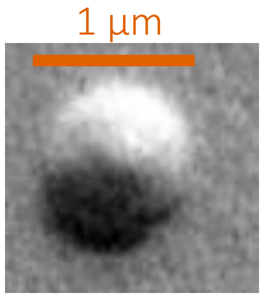
double shifted hysteresis loops



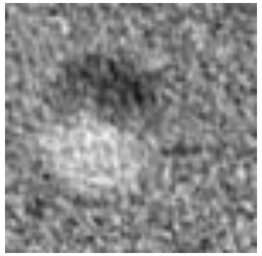


Curling vortex in IrMn

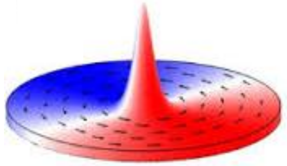
circular dichroism
uncompensated interface



Fe-edge



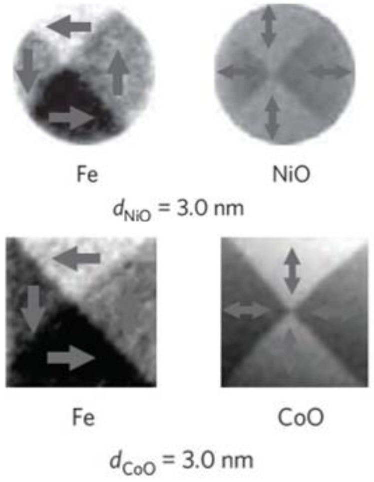
Mn-edge

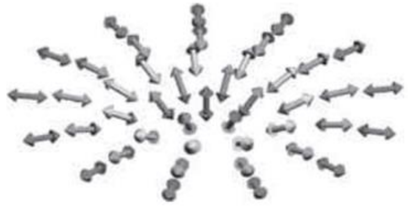


G. Salazar-Alvarez *et al*
Appl. Phys. Lett. 95, 012510 (2009)

Divergent vortices in NiO and CoO

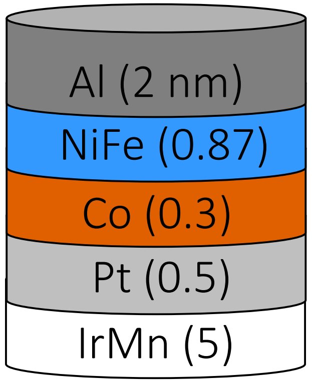
linear dichroism
compensated 'volume'





J. Wu *et al*
Nat. Phys. 7, 303 (2011)

K. G. Rana, R. L. Seeger *et al*, arXiv:2009.14796
Collab' AF spintronics and skyrmions s-o teams



MOKE-oop

H_{EB} ~ 50 mT

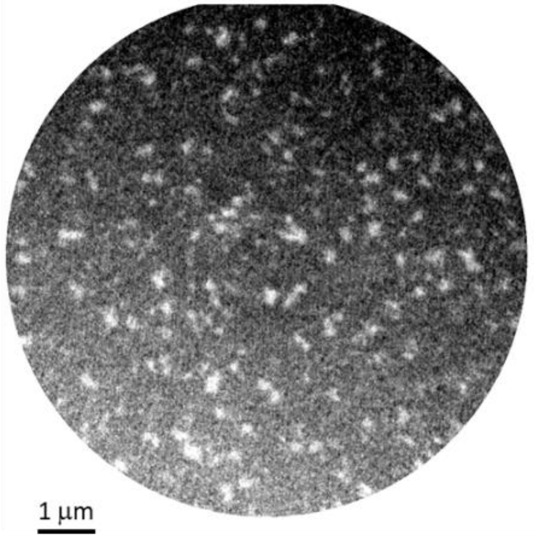
BLS

D = -0.30 $mJ.m^{-2}$

$|D| > D_{Bloch\text{->}Néel} = 0.16\ mJ.m^{-2}$

Left-handed Néel walls & skyrmions

XMCD-PEEM Fe L-edge, ALBA

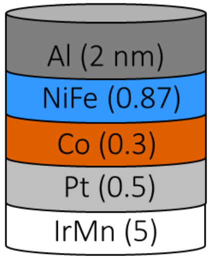


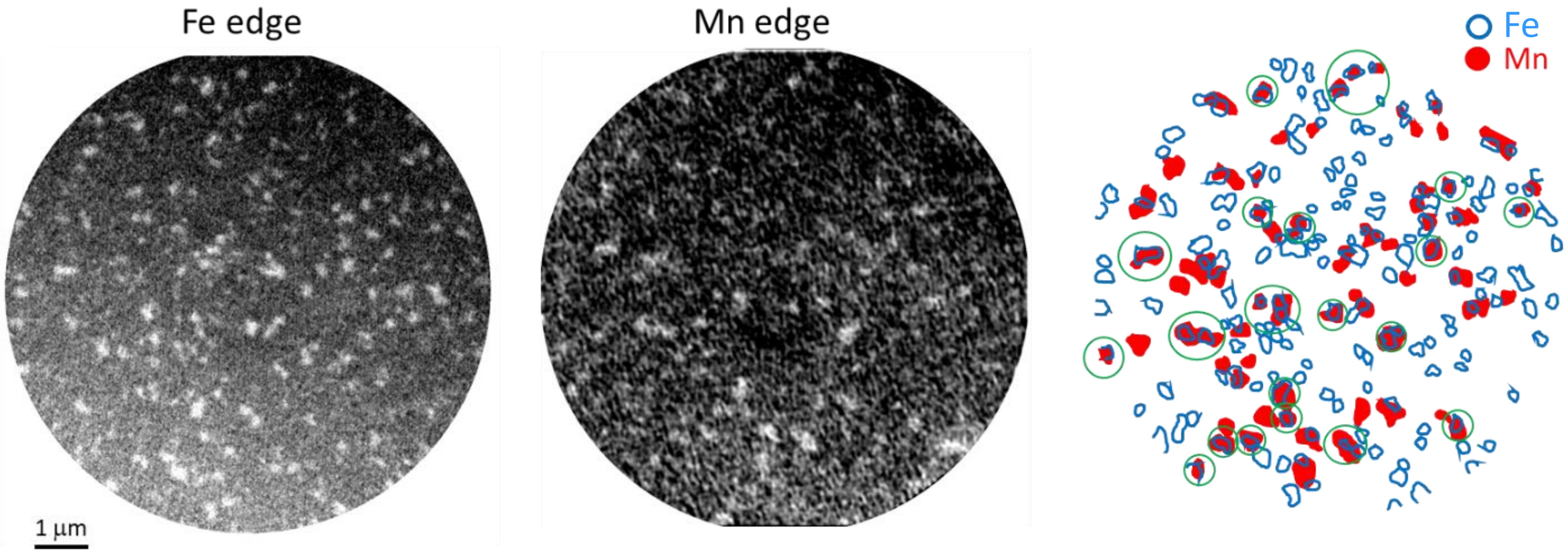
spin textures in the ferromagnet

Replicating spin textures in antiferros.

K. G. Rana, R. L. Seeger *et al*, arXiv:2009.14796

XMCD-PEEM L-edges, ALBA

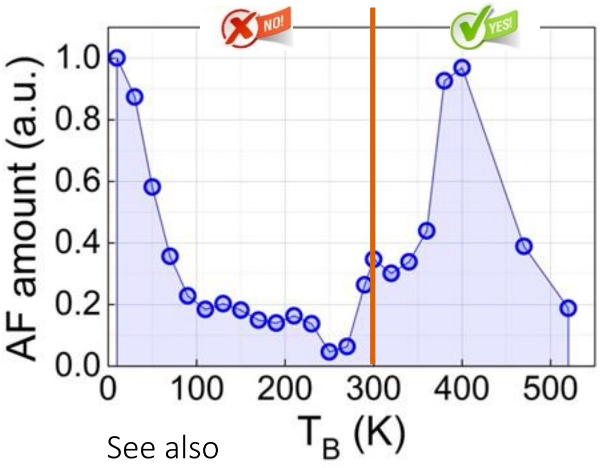




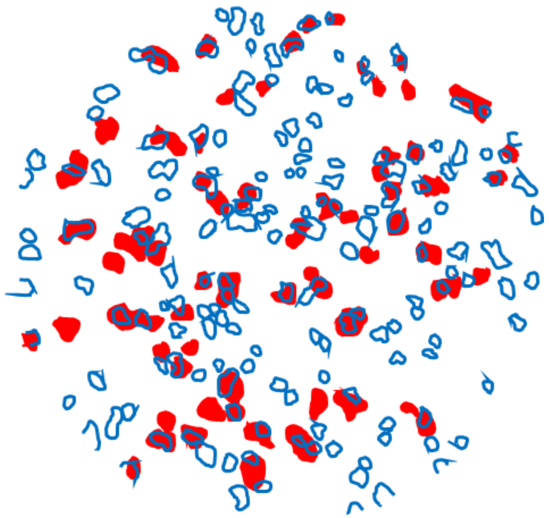
Ferro. Fe-edge spin textures replicated in the antiferro. Mn-edge - see green circles

Lack of conformity in some areas

Replicating spin textures in antiferros.



See also
S. Soeya *et al* J. Appl. Phys. (1997)
V. Baltz *et al* Phys. Rev. B (2010)



K. G. Rana, R. L. Seeger *et al*, arXiv:2009.14796

Lack of conformity in some areas

due to the spatial distribution of blocking temperature

areas where $T_B \geq 300$ K

the ferro. configuration can be stabilized in the antiferro. at 300 K by a cooling procedure from T_B to 300 K

areas where $T_B < 300$ K

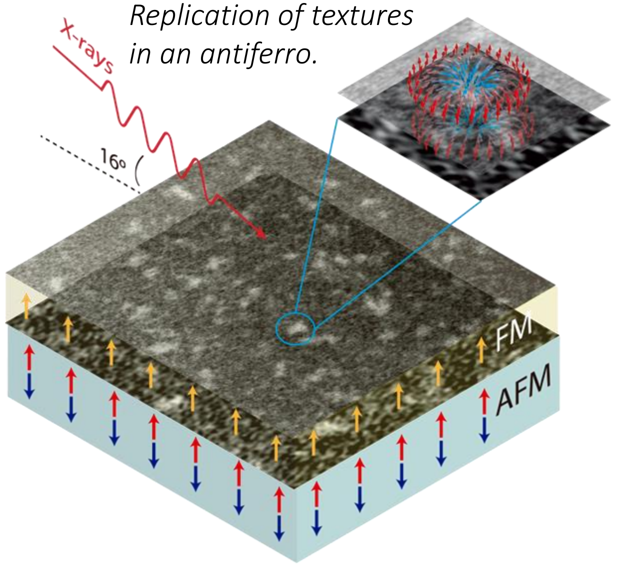
textures cannot be stabilized at 300K in the antiferro.

Conclusion

Nanomagnetism

Interfacial frustrations
Spin textures
poly-MnX X=Fe,Pd,Ir,Pt , NiO

Replication of textures in an antiferro.

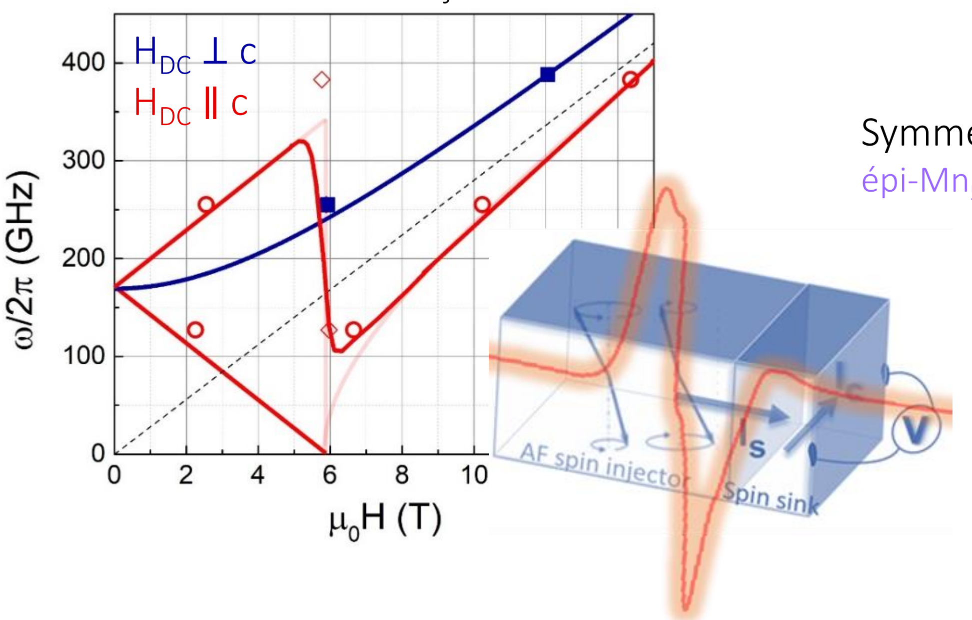


K. G. Rana, R. L. Seeger *et al*,
arXiv:2009.14796
SPINTEC, ALBA, LSPM

Dynamics

Sub-THz resonance and transport
bulk-α-Fe_2O_3

Antiferro. resonance



R. Lebrun *et al*,
Nat. Comm. 11, 6332 (2020)
CNRS/Thales, JGU, NTNU, SPINTEC, LNCMI

See also: J. Li *et al*, Nature 578, 70 (2020)
P. Vaidya *et al*, Science 368, 160 (2020)

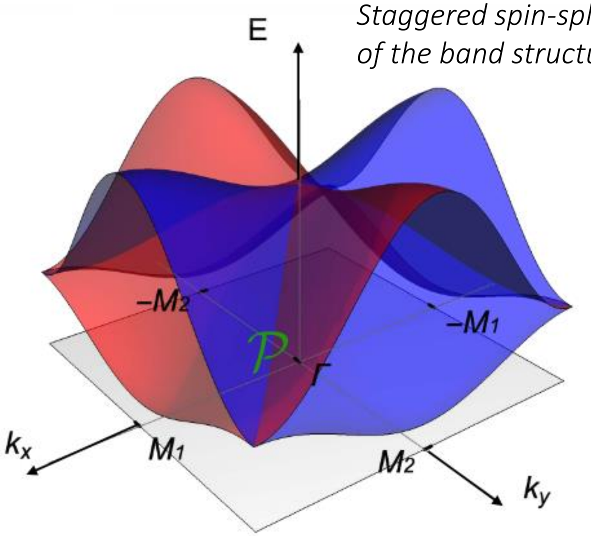
Electronic transport

Spin & charge injection, propagation, conversion
poly-MnX X=Fe,Pd,Ir,Pt & MnX/NbN hybrids

R. L. Seeger *et al*, arXiv:2102.03425
SPINTEC, PHELIQS, LOMA

Symmetry driven spontaneous charge Hall effect
épi-Mn_5Si_3

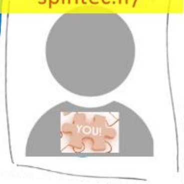
Staggered spin-splitting of the band structure



H. Reichlová, R. L. Seeger *et al* & L. Šmejkal,
arXiv:2012.15651
JGU, Prague, CINaM, SPINTEC, TUD, Konstanz

Open
Post-doc position
spintec.fr/

Post-doctoral position – Experimental antiferromagnetic spintronics



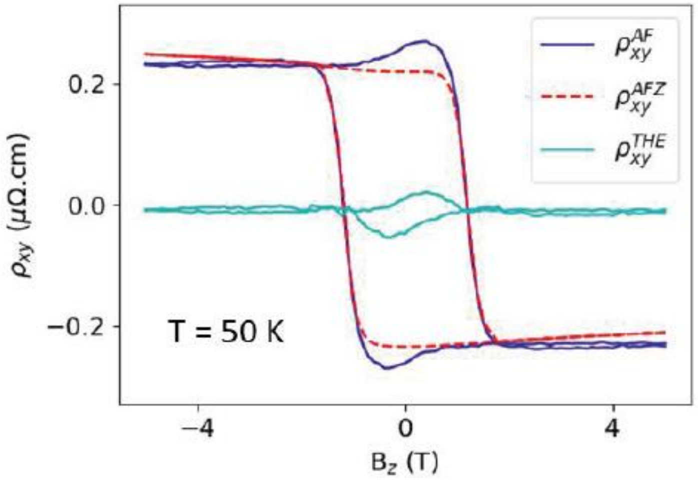
Spintec > Post-doctoral grants > Post-doctoral position – Experimental antiferromagnetic spintronics

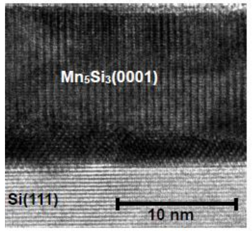
Subject and context:

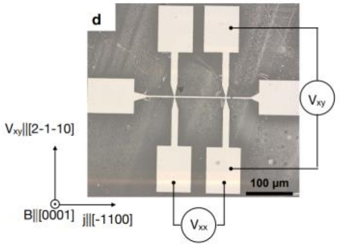
The candidate will work in the frame of the MATHEEIAS project. MATTHEIAS stands for MAgneto-THermo-Electric Effects In Antiferromagnetic Spintronics. It is a collaborative international project co-funded by the French ANR and the German DFG. The project relies on the following consortium: SPINTEC Grenoble, CINaM Marseille, TUD Dresden / Uni. Konstanz, and JGU Mainz, in close collaboration with FZU & Charles Uni. Prague. The aim of the project is to identify and exploit novel mechanisms in an emerging branch of spintronics based on transport phenomena governed by intrinsic crystal and magnetic symmetries and its interplay with the antiferromagnetic order, such as the newly demonstrated macroscopic time reversal symmetry breaking arising from the antiferromagnetic Zeeman effect – arXiv:2012.15651. The project will focus on the origins of the Hall effect and its thermal and optical counterparts (Nernst and Kerr effects) arising from time-reversal symmetry breaking.

The candidate will conduct nanofabrication, magnetotransport, and spin pumping experiments to study spin and charge transport in specific antiferromagnets called Zeeman antiferromagnets and also in related superconducting / antiferromagnets hybrids.

Experiment – 'antiferro' Hall effect ~ 20 S.cm^{-1}



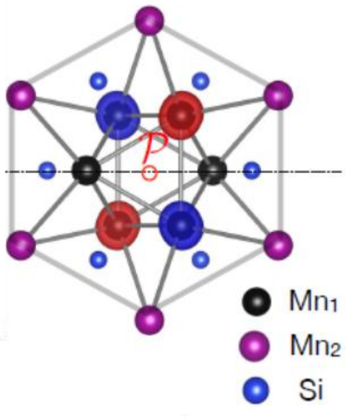


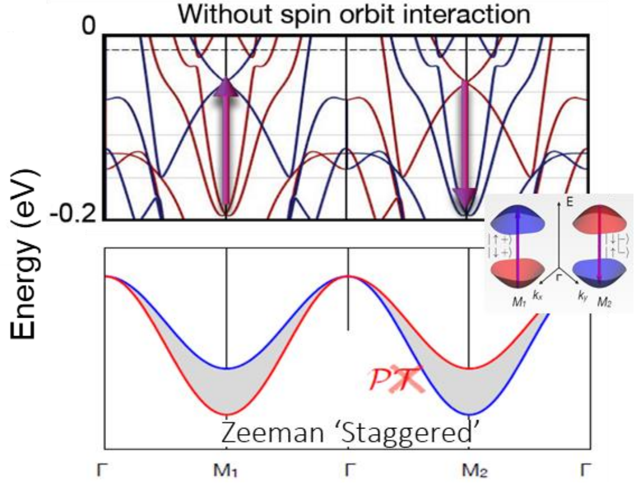


Spontaneous Hall effect in the Mn_5Si_3 antiferro. due to a novel $\mathcal{T}$-symmetry breaking mechanism with staggered spin-splitting

Low atomic numbers, collinear magnetism with weak spin-decoherence, and vanishing net magnetization

Theory – spin-symmetry group – $\sigma_{xy}^{AFZ} = -\frac{e^2}{\hbar}\int \frac{d\mathbf{k}}{2\pi} f(\epsilon_k)\boldsymbol{\Omega}_{\boldsymbol{k}}$





H. Reichlová, R. L. Seeger *et al* & L. Šmejkal, arXiv:2012.15651
JGU, Prague, CINaM, SPINTEC, TUD, Konstanz

See also: L. Šmejkal, J. Sinova, T. Jungwirth, arXiv:2105.05820

ANR JCJC, ASTRONICS
ANR DFG, MATHEEIAS
PE-BU
ELSA
CRG
KAUST-SPINTEC-UTEXAS

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S. Auffret, I. Joumard, O. Boulle, G. Gaudin,
M. Chshiev, B. Dieny, L. Vila, U. Ebels,
D. Gusakova, M. Rubio-Roy + see next slide

SYMMES Grenoble
S. Gambarelli

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S. Goennenwein, H. Reichlová, D. Kriegner *et al*

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E. Schmoranzerova & A. Bad'ura

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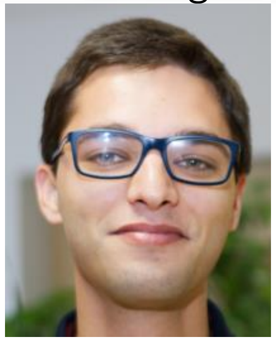
Spin And Charge Transport In Antiferromagnets

R. L. Seeger



M. Leiviskä

F. van Duijn

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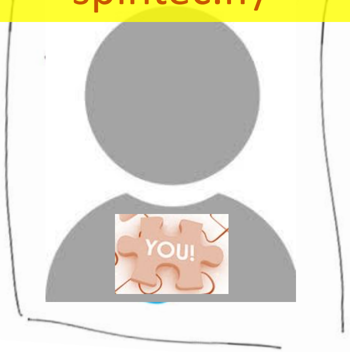

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L. Frangou
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O. Gladii
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