Spin transport at the multiferroic altermagnet/heavy metal interfaces

Dr. Miina Leiviskä[1],

R. Firouzmandi[2], K. Ahn[1], P. Kubaščik[3], S. Sailler[4], Z. Soban[1], S. Prakash Bommanaboyena[1], C. Müller[1], B. Gut[4], K. Uhlířová[4], D. Kriegner[1], M. Hývl[1], M. Lammel[5], K. K. Bestha[2], L. Šmejkal[6,7,1], J. Zelezny[2], A. U. B. Wolter[2], M. Scheufele[8,9], J. Fischer[10], M. Opel[8], S. Geprägs[8], M. Althammer[8], B. Buechner[2,11,12], T. Jungwirth[1,13], L. Nadvornik[3], S. T. B. Goennenwein[5], V. Kocsis[2], and H. Reichlova[1]

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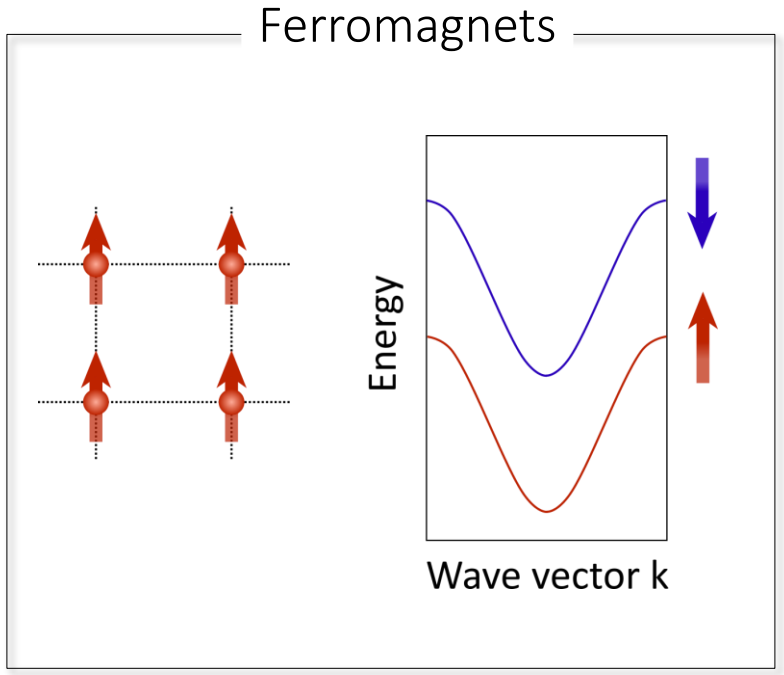
10 Universite Grenoble Alpes, CEA, CNRS, Spintec, Grenoble, France
11 Institute of Solid State and Materials Physics and Wurzburg-Dresden Cluster of Excellence ct.qmat, TU Dresden, Dresden, Germany
12 Center for Transport and Devices, Technische Universität Dresden, 01069 Dresden, Germany
13 School of Physics and Astronomy, University of Nottingham, Nottingham, UK

FZU Institute of Physics of the Czech Academy of Sciences

Division of Solid State Physics

Young Research Leaders Group workshop | leiviska@fzu.cz

Classifying collinear magnets



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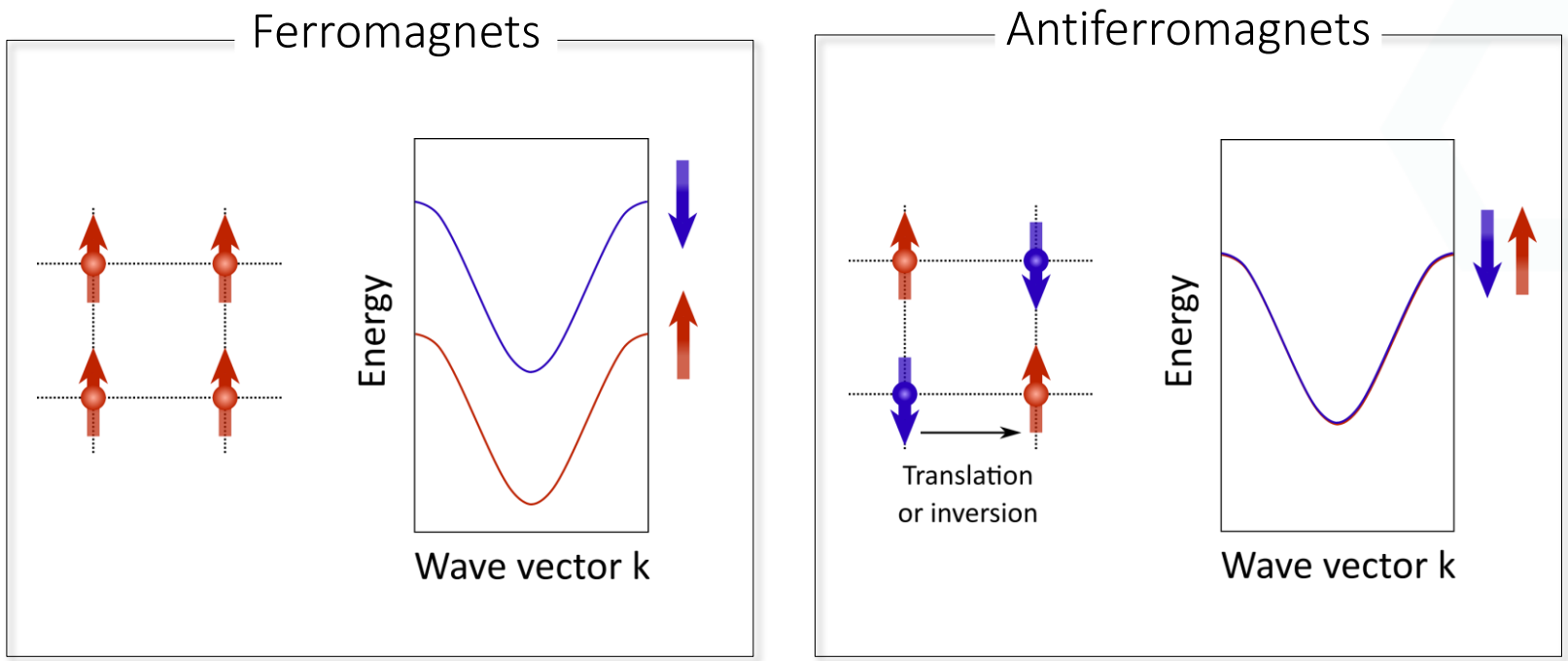
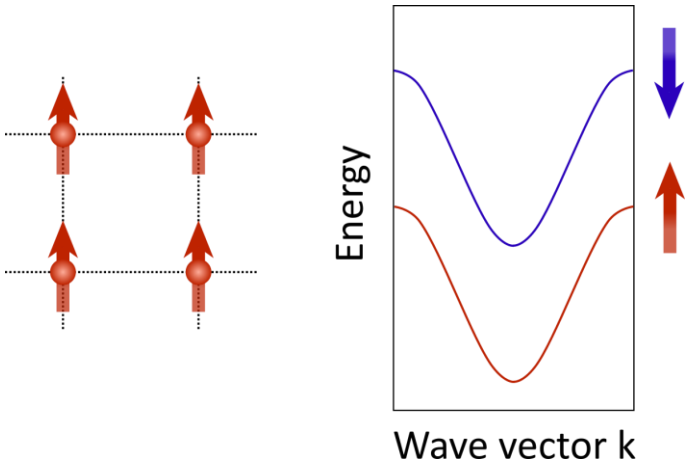
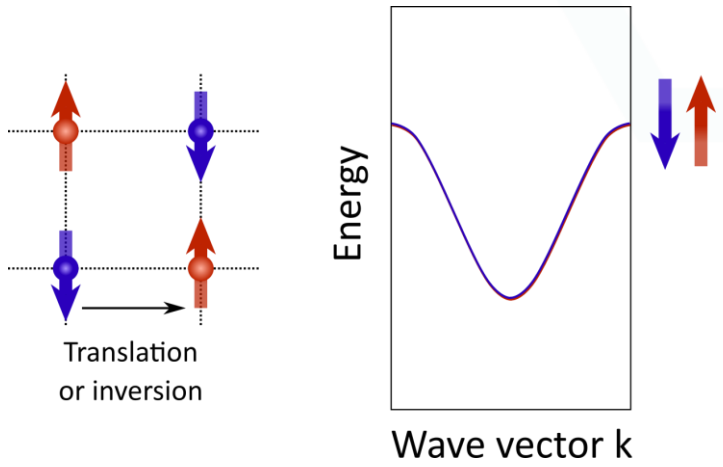


Classifying collinear magnets

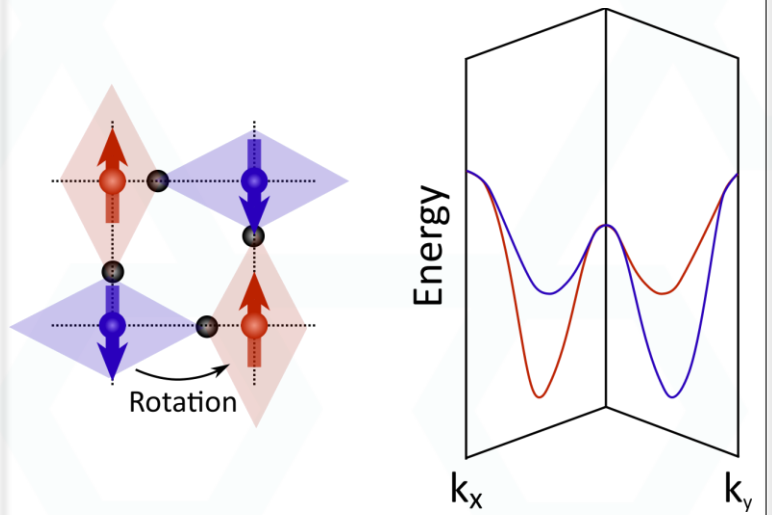
Ferromagnets



Antiferromagnets

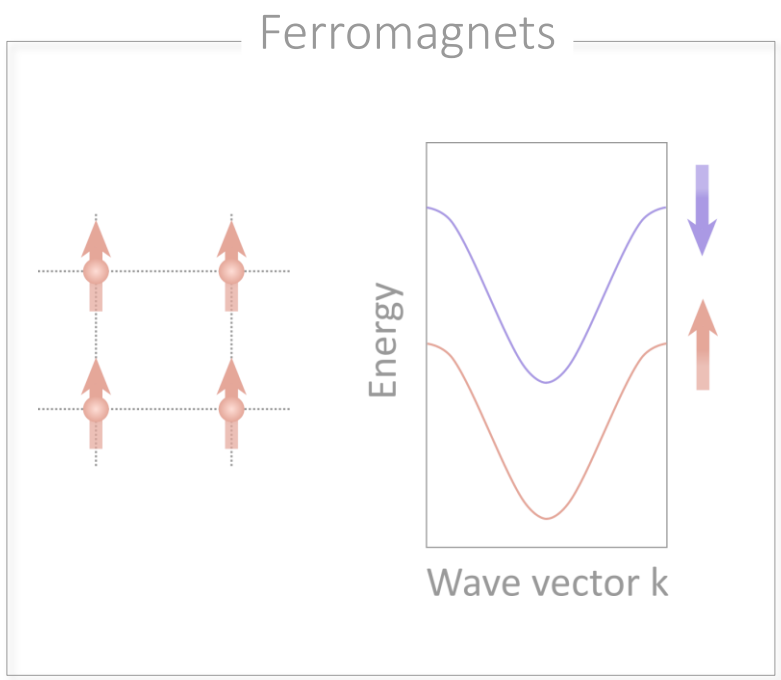


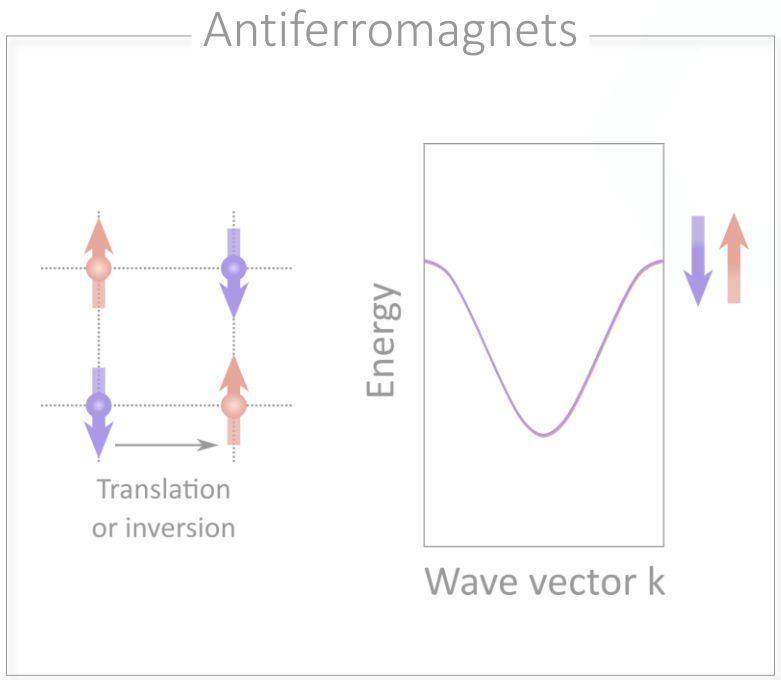
Altermagnets

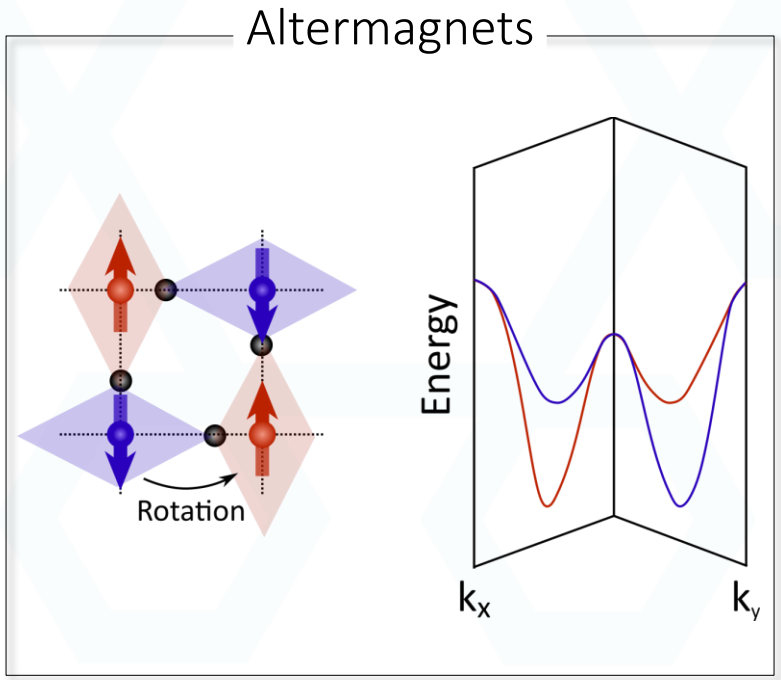


Phys. Rev. X **12**, 031042 (2022)
Phys. Rev. X **12**, 021016 (2022)

Classifying collinear magnets







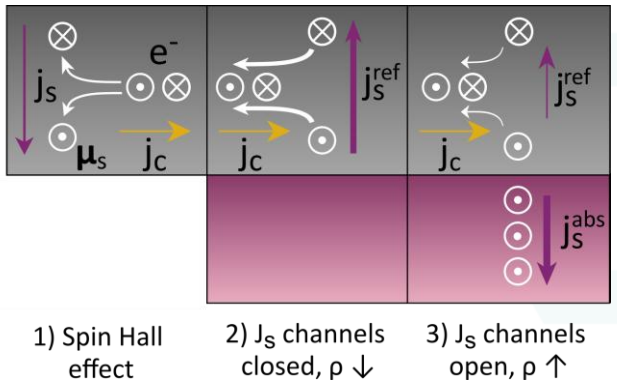
Phys. Rev. X **12**, 031042 (2022)
Phys. Rev. X **12**, 021016 (2022)

Spin Hall Magnetoresistance

Magnetization of the MI layer modulates the resistivity of the NM layer

Heavy metal (HM)

Magnetic insulator (MI)



Spin Hall effect
+ inverse spin Hall effect
+ spin current channels

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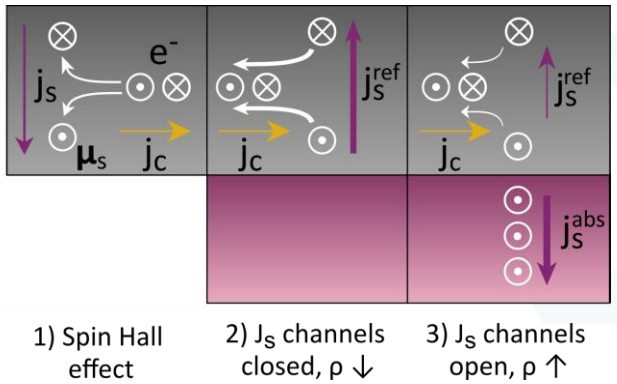

Spin Hall effect
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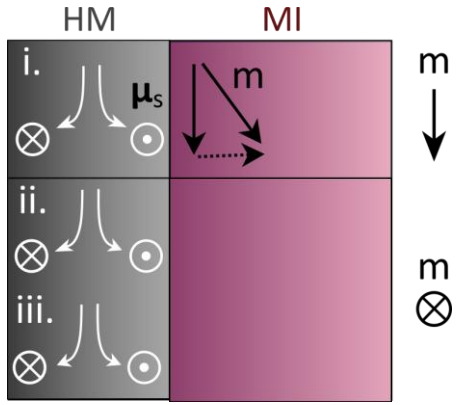
Phys. Rev. B. 104, 024415 (2021)



Transversal $\mathbf{m} \perp \boldsymbol{\sigma}$

i. Spin transfer torque

Spin Hall Magnetoresistance

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Heavy metal (HM)

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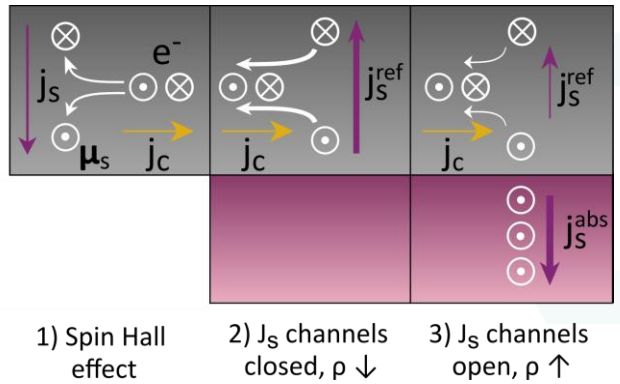

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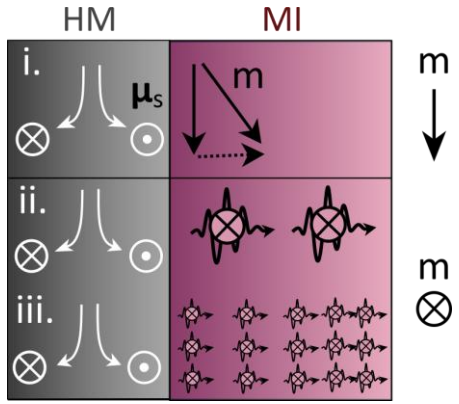
Phys. Rev. B. 104, 024415 (2021)



Transversal $\mathbf{m} \perp \boldsymbol{\sigma}$ — i. Spin transfer torque

Longitudinal $\mathbf{m} \parallel \boldsymbol{\sigma}$ — ii. Incoherent thermal magnon creation/annihilation; iii. Magnon capacitance/propagation

Spin Hall Magnetoresistance

PHYSICAL REVIEW B **102**, 094437 (2020)

Microscopic theory of spin Hall magnetoresistance

T. Kato,[1] Y. Ohnuma,[2] and M. Matsuo[2,3,4,5]
[1]*Institute for Solid State Physics, The University of Tokyo, Kash*
[2]*Kavli Institute for Theoretical Sciences, University of Chinese Academy of*
[3]*CAS Center for Excellence in Topological Quantum Computation, University of Chinese*
[4]*RIKEN Center for Emergent Matter Science, Wako, Saitama*
[5]*Advanced Science Research Center, Japan Atomic Energy Agency,*

PHYSICAL REVIEW B **104**, 024415 (2021)

Theory of spin-Hall magnetoresistance in the ac terahertz regime

David A. Reiss,[1] Tobias Kampfrath,[2,3] and Piet W. Brouwer[1]
tems and Physics Department, Freie Universität Berlin, Arnimallee 14, 14195 Berlin, Germany
ıent, Freie Universität Berlin, Arnimallee 14, 14195 Berlin, Germany
ıl Chemistry, Fritz-Haber Institut, Faradayweg 4–6, 14195 Berlin, Germany

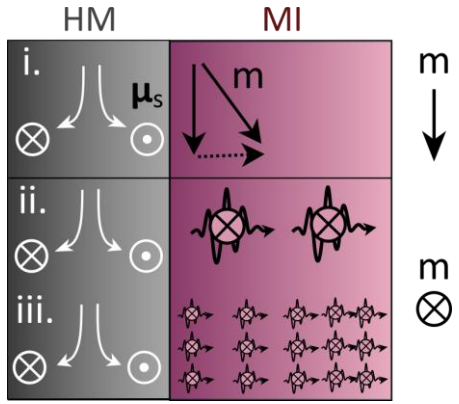
Resolving Ultrafast Coherent and Incoherent Spin Torque Contributions via Terahertz Spin-Hall Magnetoresistance

Peter Kubaščík[1], Richard Schlitz[2], Oliver Gueckstock[3], Oliver Franke[3], Miina Leiviska[4], Martin Borchert[5], Gerhard Jakob[6], Kamil Olejník[4], Andrej Farkaš[1,4], Zdenek Kašpar[1,4], Jiří Jechumtál[1], Martin Bušina[1], Eva Schmoranzerová[1], Petr Němec[1], Yicheng Z. Wu[7,8], Georg Woltersdorf[9], Mathias Kläui[6], Piet W. Brouwer[3], Sebastian T. B. Goennenwein[2], Tobias Kampfrath[3], Lukáš Nádvorník[1,*]

arXiv 2507.02498v2

and more …

Phys. Rev. B. 104, 024415 (2021)



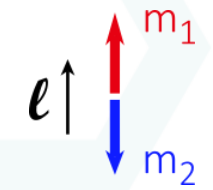
Transversal $\mathbf{m} \perp \boldsymbol{\sigma}$

i. Spin transfer torque

Longitudinal $\mathbf{m} \parallel \boldsymbol{\sigma}$

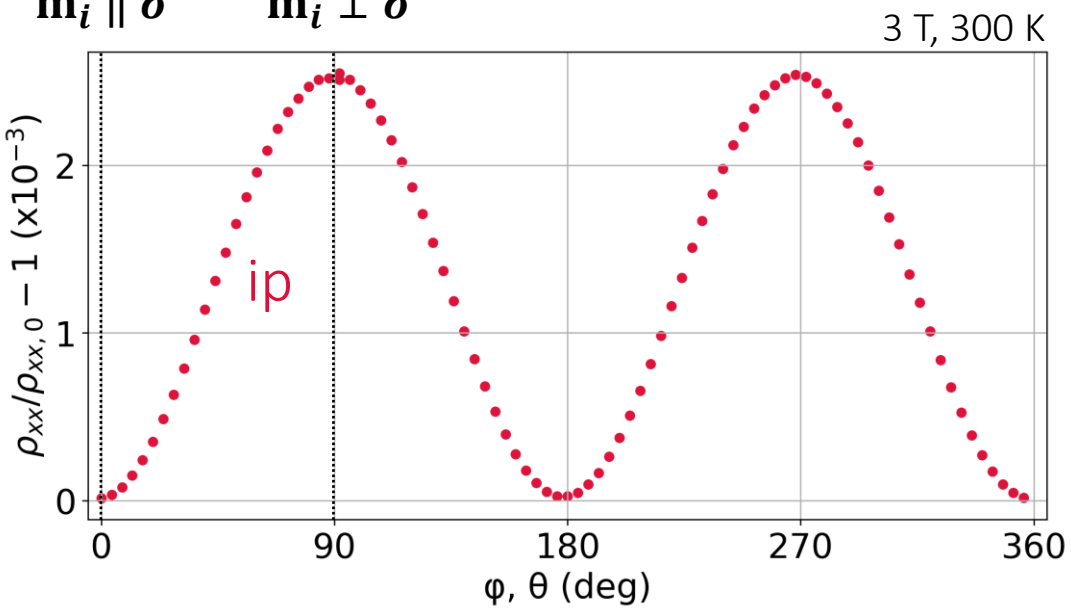
ii. Incoherent thermal magnon creation/annihilation
iii. Magnon capacitance/propagation

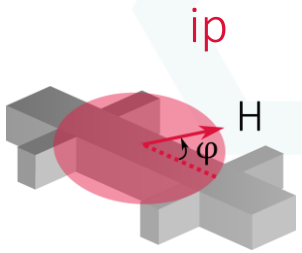
Spin Hall Magnetoresistance – example of α-Fe_2O_3



More spin current reflected $\mathbf{m}_i \parallel \boldsymbol{\sigma}$

More spin current absorbed $\mathbf{m}_i \perp \boldsymbol{\sigma}$





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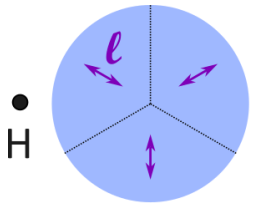

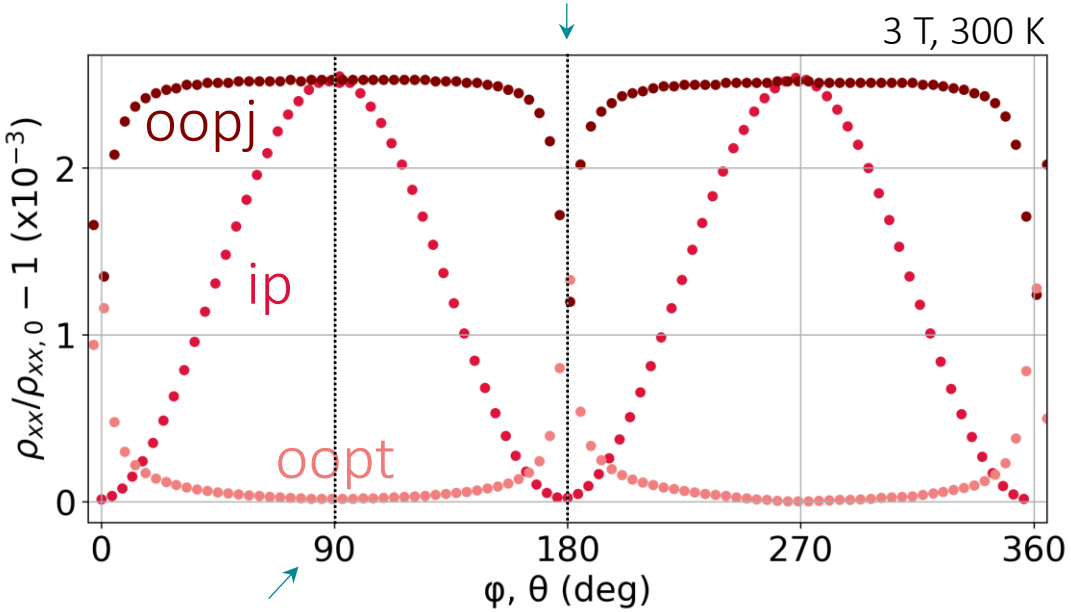

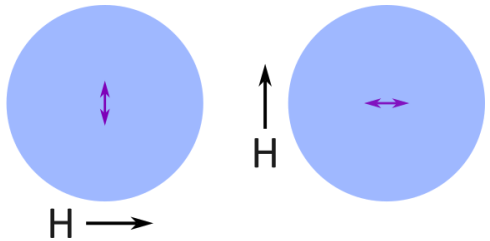

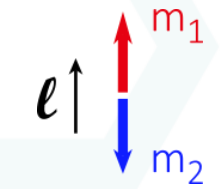

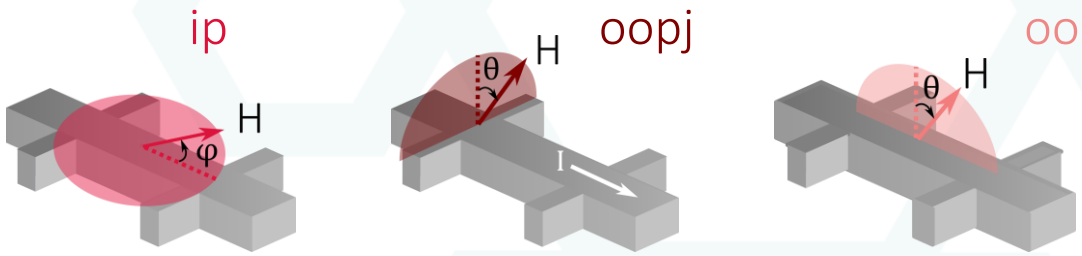

Out-of-plane scans reflect changes in domain population

Phys. Rev. Applied **13**, 014019 (2020)

Spin Hall Magnetoresistance in collinear magnets

	Order	t_{Pt} (nm)	Interface	Temperature (K)	SMR (10^{-4})	Ref
YIG/Pt	FI	2.5	*in situ*	300	16	PRB 87, 224401 (2013)
YIG/Pt	FI	6	*ex situ*	300	3.48	APL 110, 012403 (2017)
$CoGe_2O_4$/Pt	FI	2	*in situ*	300	6	APL 105, 142402 (2014)
GdIG/Pt	FI	5.5	*ex situ*	295	2.3	J. Phys.: Cond. Matt. 30, 035802 (2018)
NiO/Pt	AF	3.5	*in situ*	300	8	PRB 97, 014417 (2018)
NiO/Pt	AF	5	*ex situ*	300	2.7	APL 111, 052409 (2017)
$SrMnO_3$/Pt	AF	7	-	300	3	PRB 90, 144431 (2014)
$BiFeO_3$/Pt	AF	5	*ex situ*	300	0.8	Chin. Phys. Lett. 40, 117402 (2023)
α-Fe_2O_3/Pt	AM	3	*in situ*	300	25	PRA 13, 014019 (2020)

Spin Hall Magnetoresistance in collinear magnets

Altermagnet

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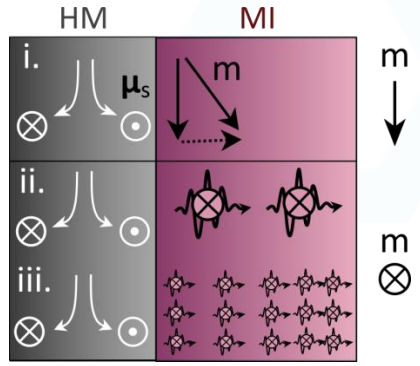
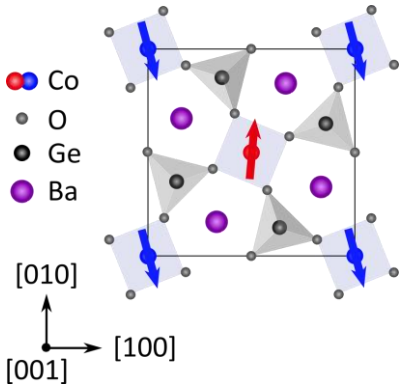
Does the magnetic ordering of MI influence the SMR?

Suppression/enhancement of spin channels?

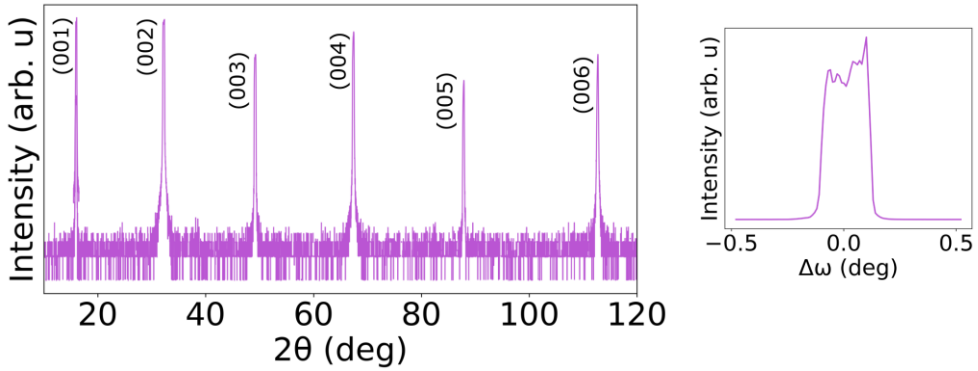


Bulk $Ba_2CoGe_2O_7$ as an altermagnetic candidate material



Multiferroic:
Ferroelectric
+ Altermagnetic

High-quality single crystals, (001) orientation



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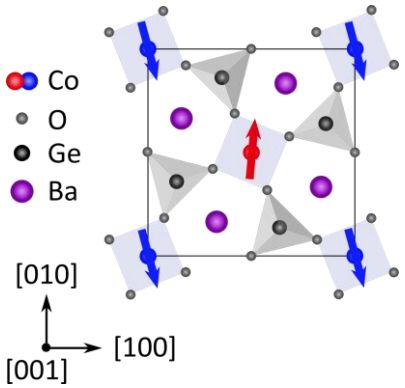

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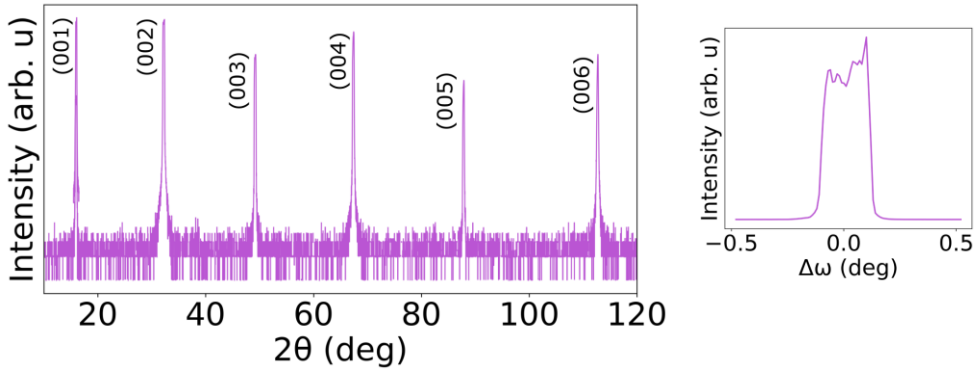
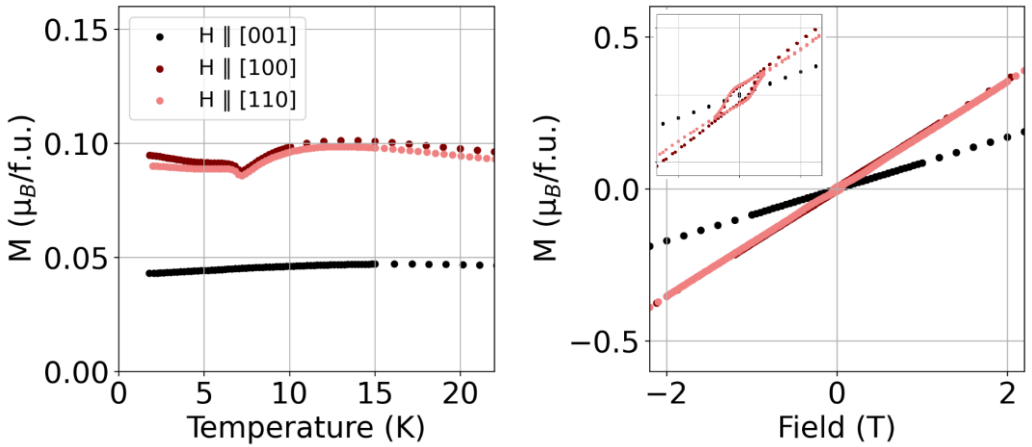
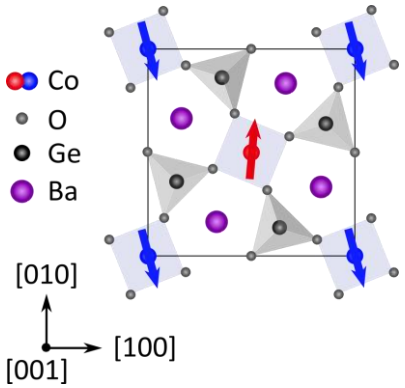


T_N ~ 6.7 K, small net moment in-plane due to canting



M. Leiviskä *et al*, Phys. Rev. Materials **9**, 084403 (2025)

Bulk $Ba_2CoGe_2O_7$ as an altermagnetic candidate material



Multiferroic:
Ferroelectric
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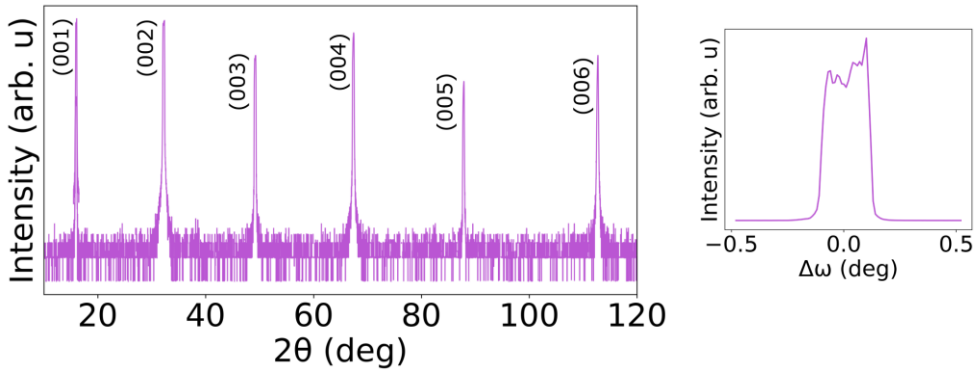
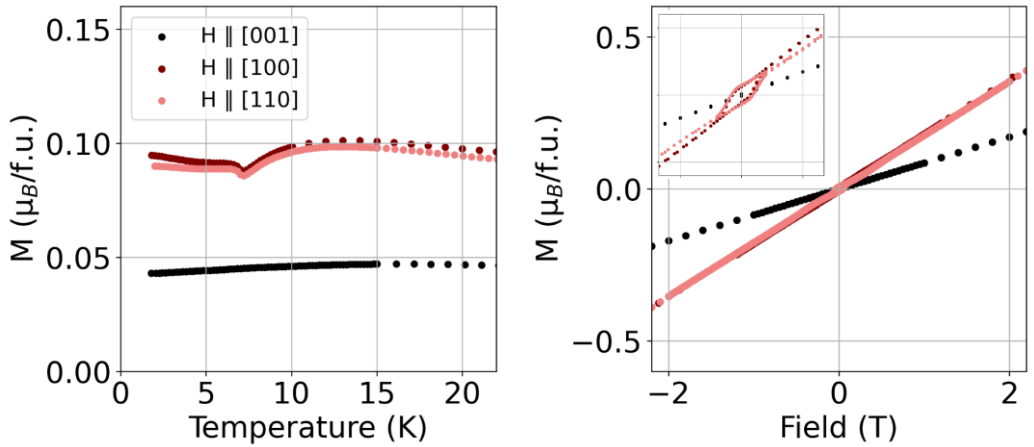
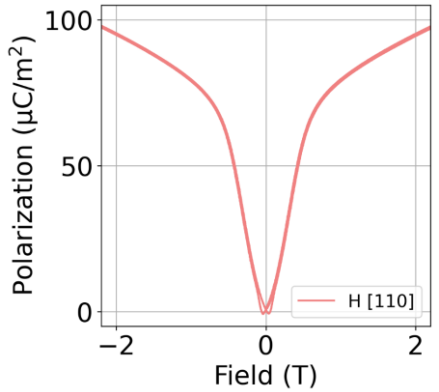
High-quality single crystals, (001) orientation



$T_N \sim 6.7$ K, small net moment in-plane due to canting



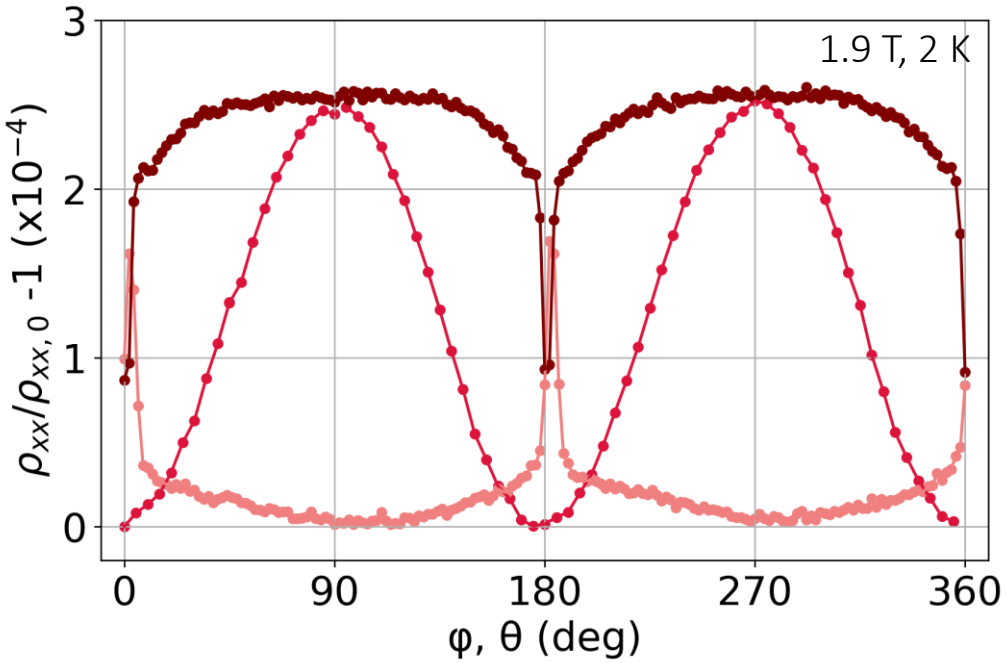


Finite polarization due to p-d hybridization between O^{2-} and Co^{2+} ions

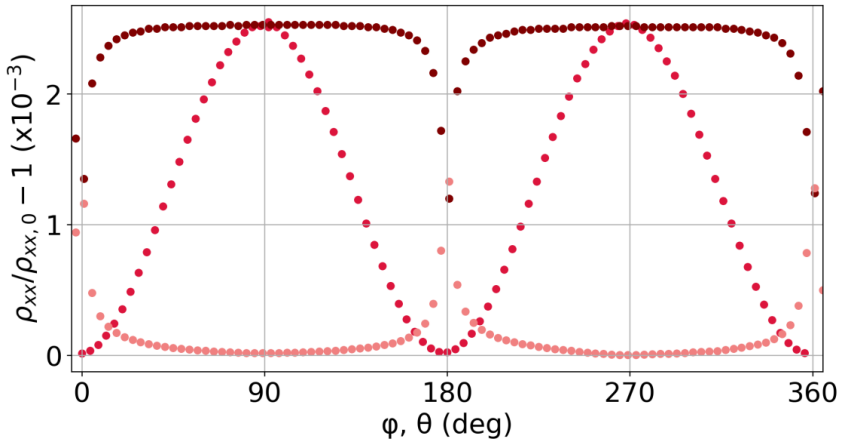
PRL 105, 137202 (2010)

M. Leiviskä *et al*, Phys. Rev. Materials **9**, 084403 (2025)

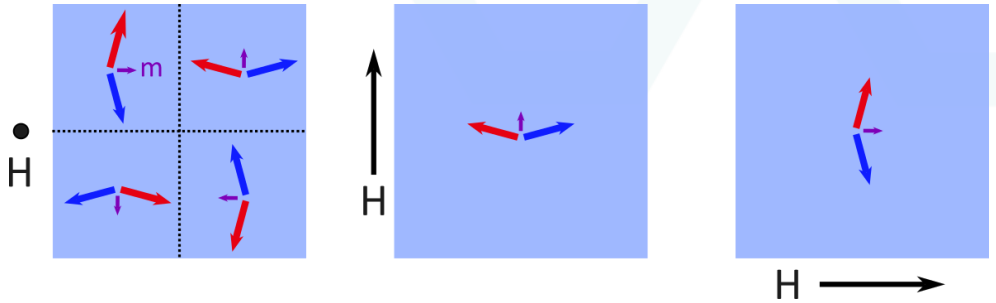
SMR in $Ba_2CoGe_2O_7$



Recall α-Fe_2O_3!



Qualitatively similar behavior



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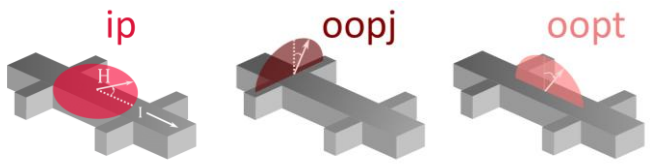
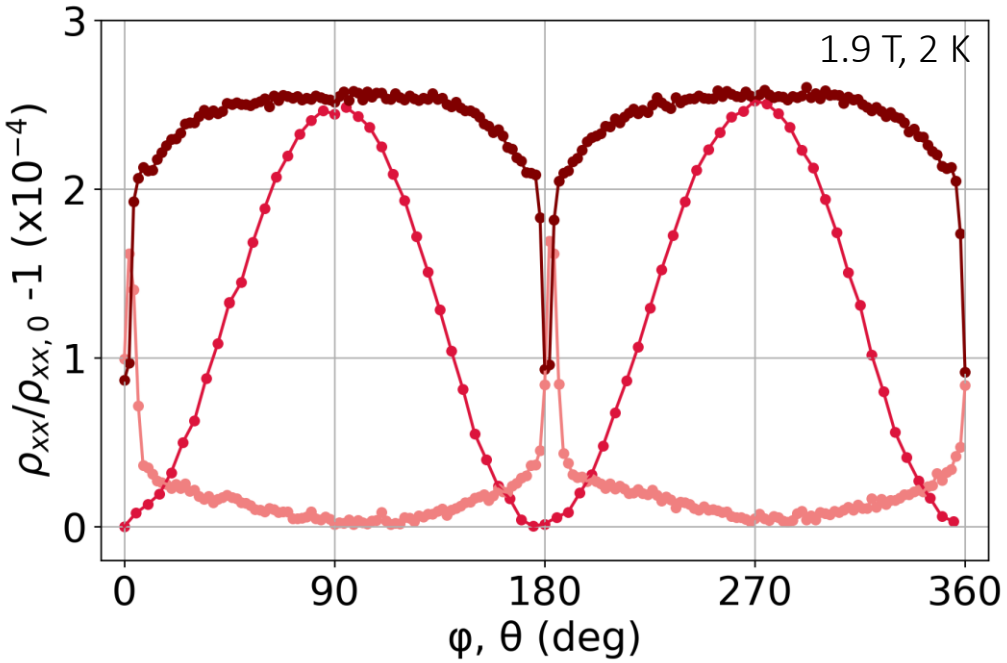
SMR in $Ba_2CoGe_2O_7$



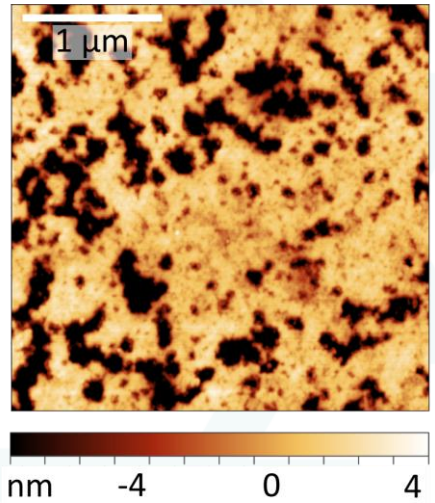


Surprisingly large amplitude!

Non-optimal interface

Non-optimal Pt thickness (~15 nm)

Low temperature



	Order	t_{Pt} (nm)	Interface	Temperature (K)	SMR (10^{-4})	Ref
YIG/Pt	FI	2.5	*in situ*	300	16	PRB 87, 224401 (2013)
YIG/Pt	FI	6	*ex situ*	300	3.48	APL 110, 012403 (2017)
$CoGe_2O_4$/Pt	FI	2	*in situ*	300	6	APL 105, 142402 (2014)
GdIG/Pt	FI	5.5	*ex situ*	295	2.3	J. Phys.: Cond. Matt. 30, 035802 (2018)
NiO/Pt	AF	3.5	*in situ*	300	8	PRB 97, 014417 (2018)
NiO/Pt	AF	5	*ex situ*	300	2.7	APL 111, 052409 (2017)
$SrMnO_3$/Pt	AF	7	-	300	3	PRB 90, 144431 (2014)
$BiFeO_3$/Pt	AF	5	*ex situ*	300	0.8	Chin. Phys. Lett. 40, 117402 (2023)
α-Fe_2O_3/Pt	AM	3	*in situ*	300	25	PRA 13, 014019 (2020)

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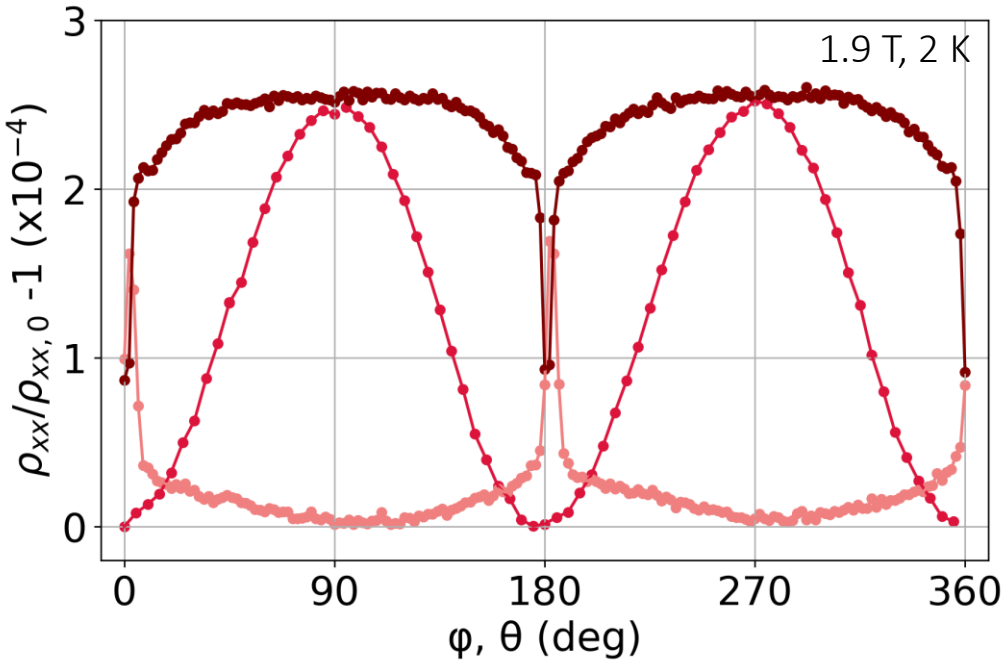
SMR in $Ba_2CoGe_2O_7$



Surprisingly large amplitude!

Non-optimal interface

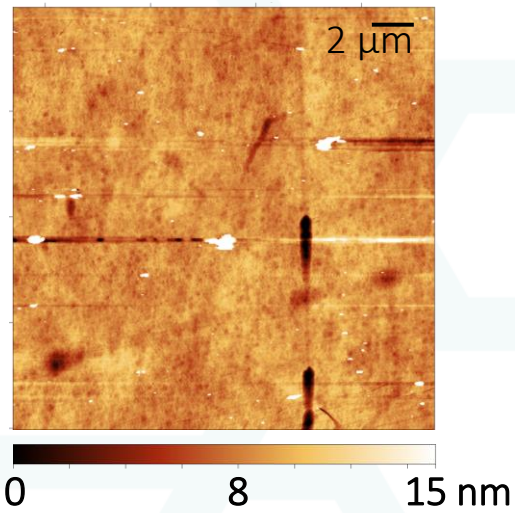
Non-optimal Pt thickness (~15 nm)

Low temperature

Update:

Better surface quality + thinner Pt

⟶ SMR amplitude **doubled**



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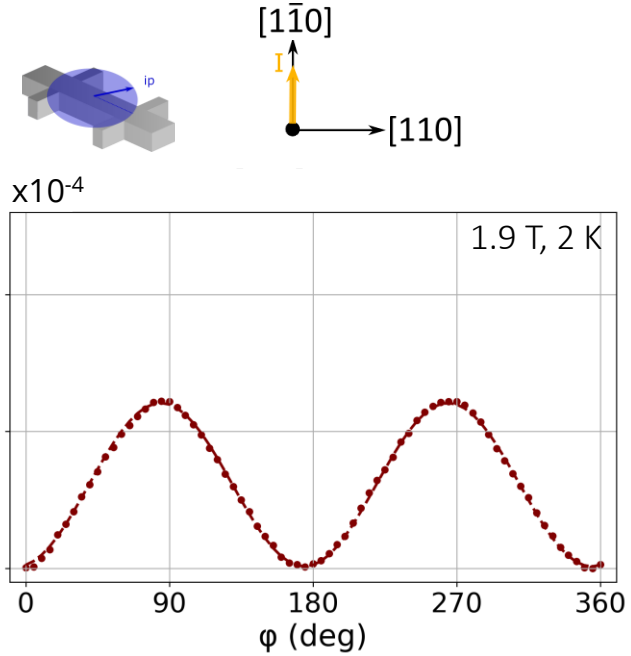
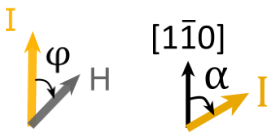
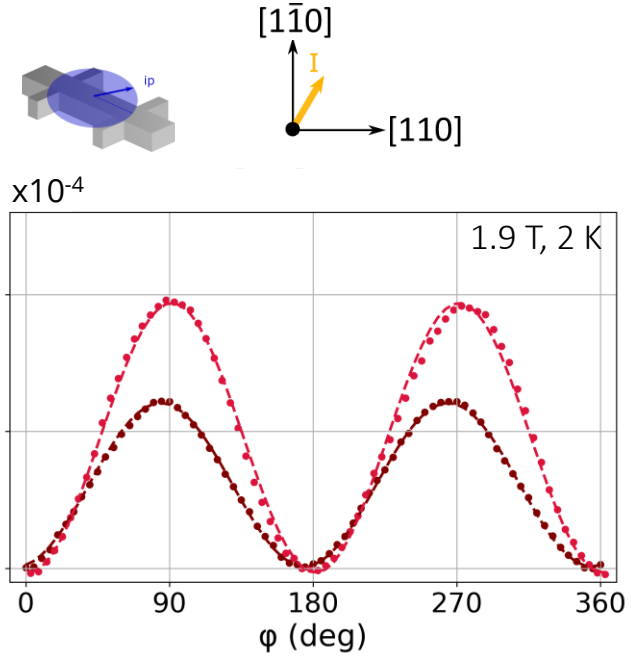
SMR in $Ba_2CoGe_2O_7$ - anisotropy with current direction

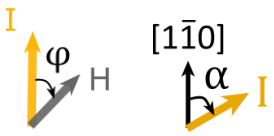




M. Leiviskä *et al*, Phys. Rev. Materials **9**, 084403 (2025)

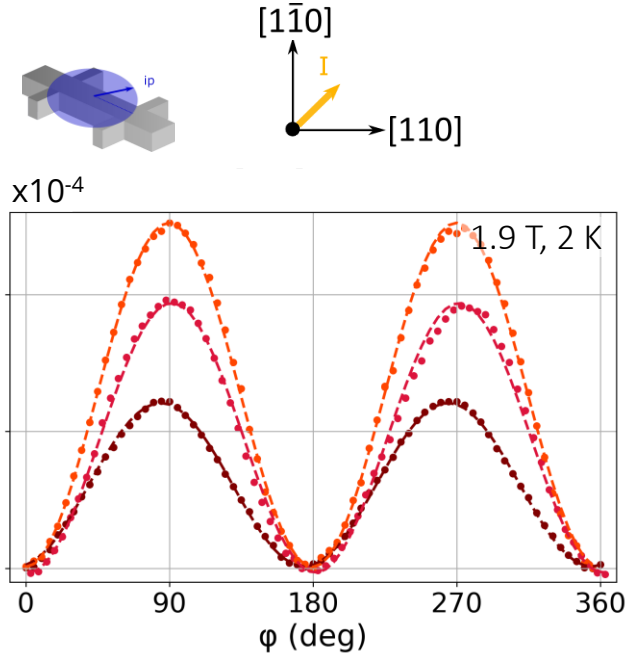
SMR in $Ba_2CoGe_2O_7$ - anisotropy with current direction

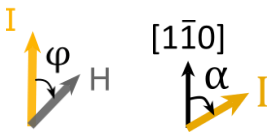




M. Leiviskä *et al*, Phys. Rev. Materials **9**, 084403 (2025)

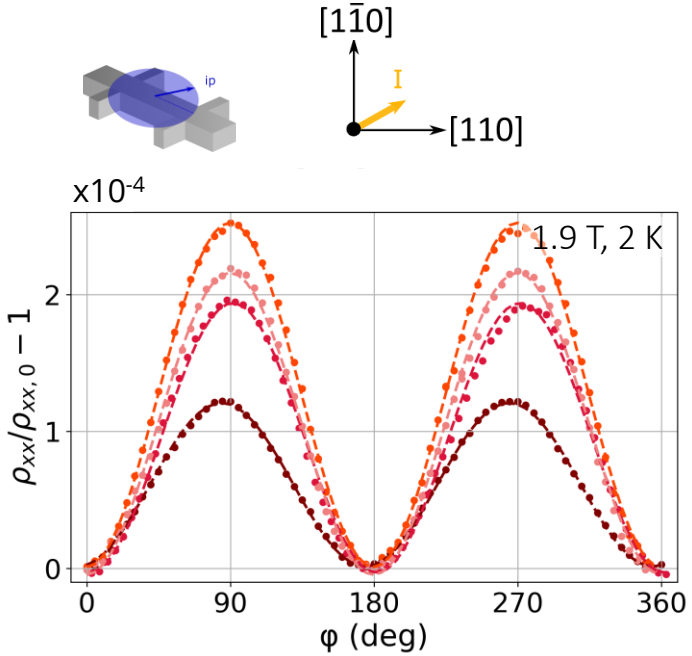
SMR in $Ba_2CoGe_2O_7$ - anisotropy with current direction

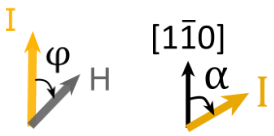




M. Leiviskä *et al*, Phys. Rev. Materials **9**, 084403 (2025)

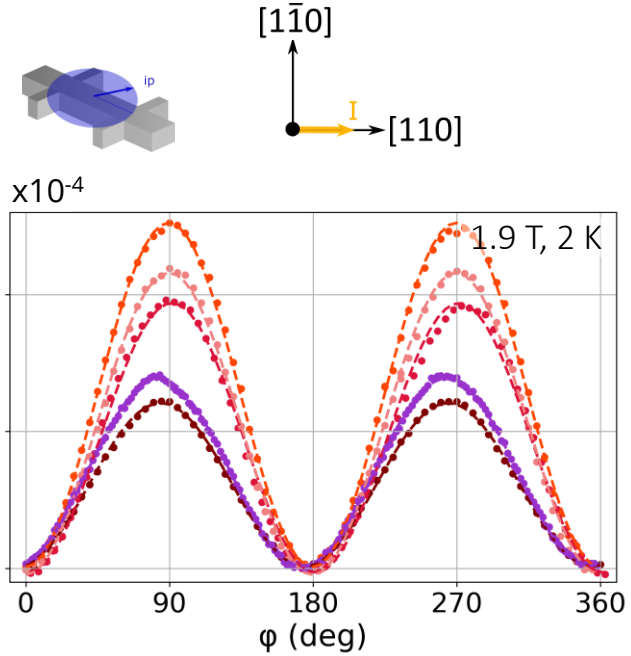
SMR in $Ba_2CoGe_2O_7$ - anisotropy with current direction

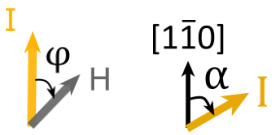




M. Leiviskä *et al*, Phys. Rev. Materials **9**, 084403 (2025)

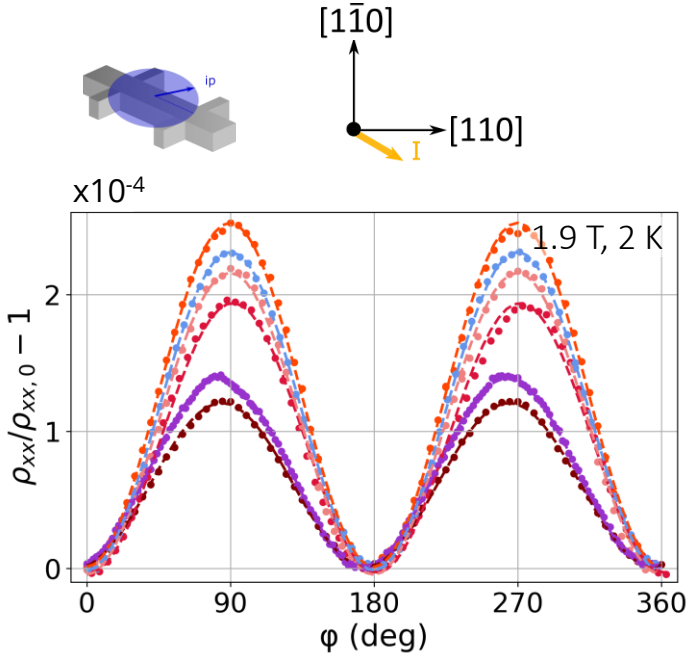
SMR in $Ba_2CoGe_2O_7$ - anisotropy with current direction

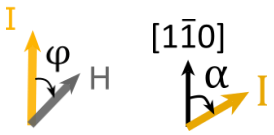




M. Leiviskä *et al*, Phys. Rev. Materials **9**, 084403 (2025)

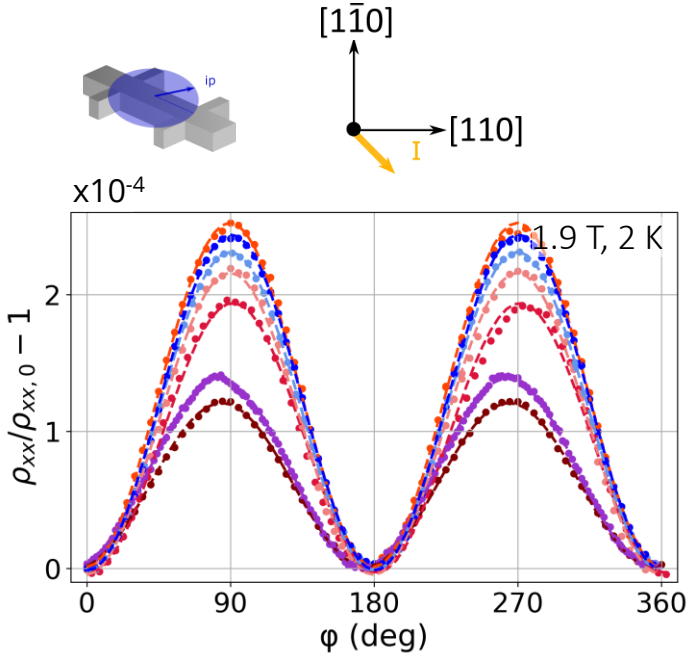
SMR in $Ba_2CoGe_2O_7$ - anisotropy with current direction

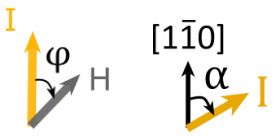




M. Leiviskä *et al*, Phys. Rev. Materials **9**, 084403 (2025)

SMR in $Ba_2CoGe_2O_7$ - anisotropy with current direction





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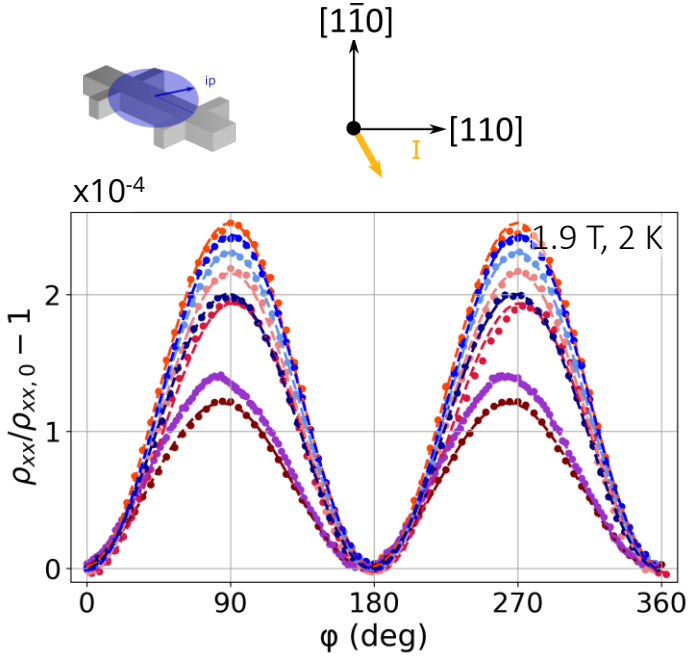

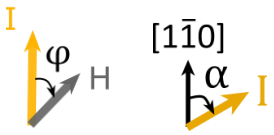

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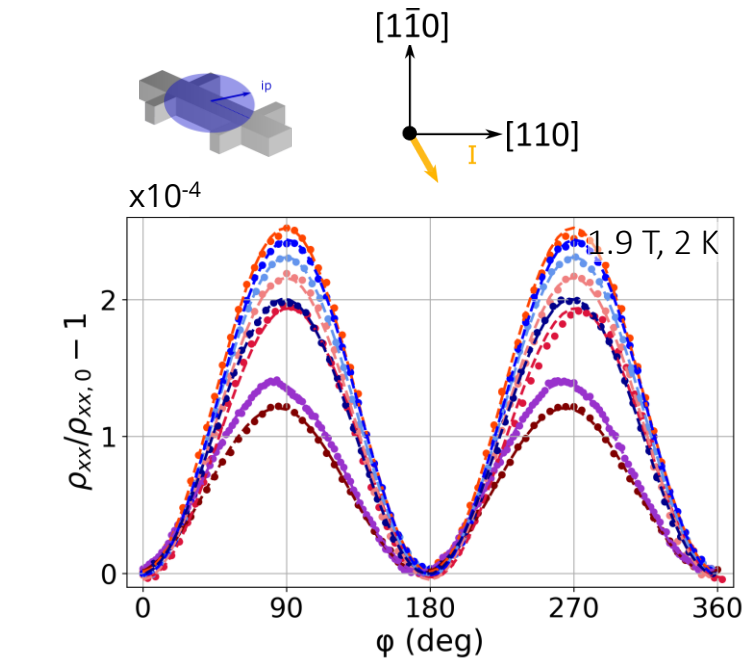
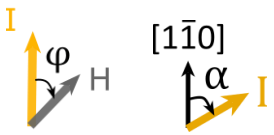
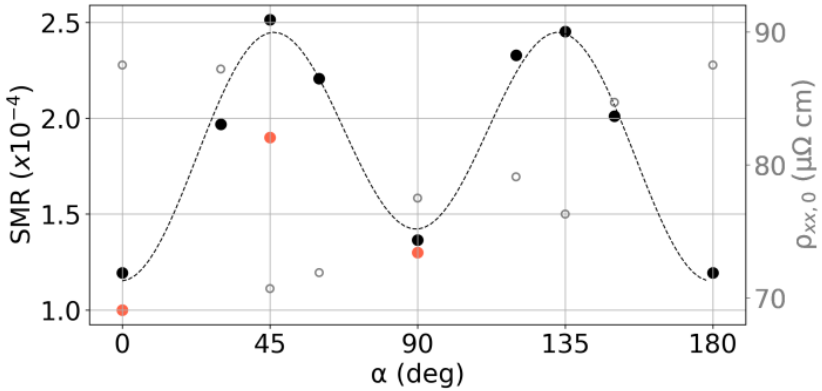
SMR in $Ba_2CoGe_2O_7$ - anisotropy with current direction

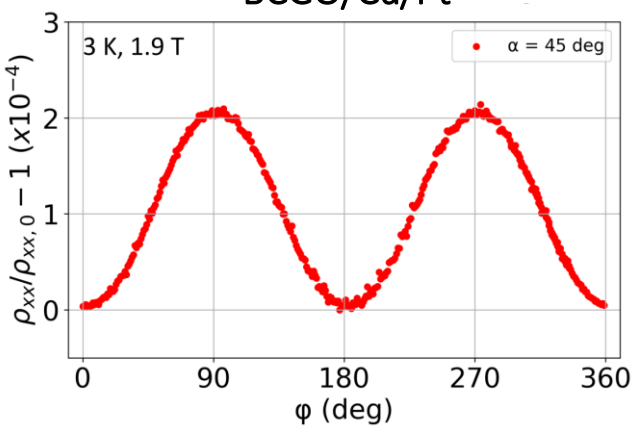




The SMR ratio is anisotropic with the current direction

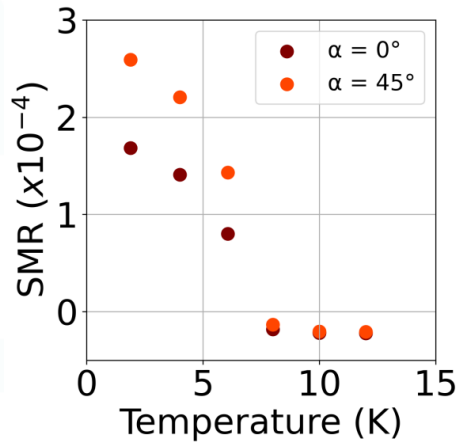


BCGO/Cu/Pt



Not related to Pt proximity effect

Does **not** correlate with device resistivity

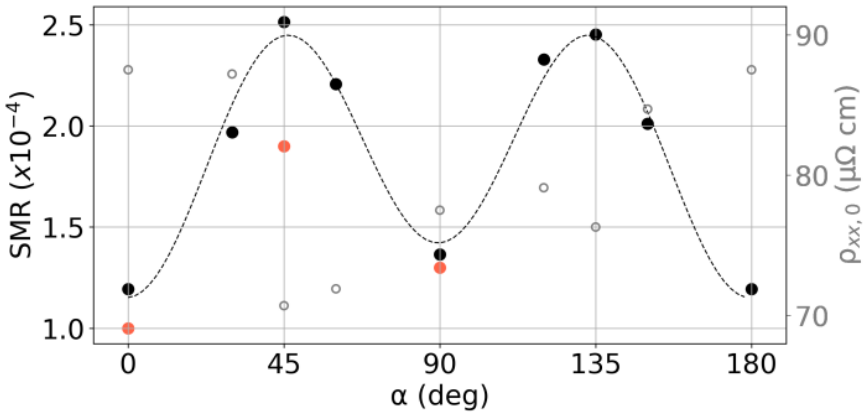


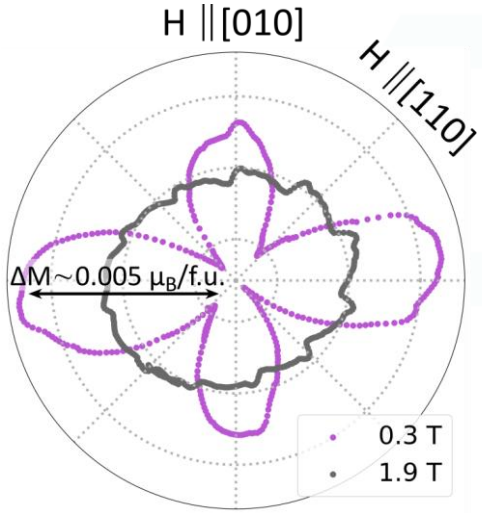
Correlates with the **altermagnetic** phase

M. Leiviskä *et al*, Phys. Rev. Materials **9**, 084403 (2025)

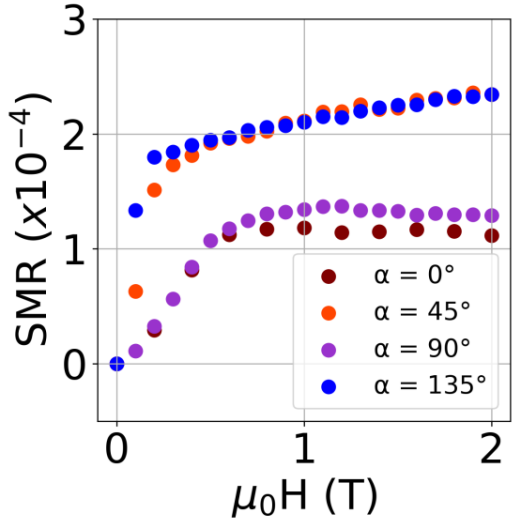
SMR in $Ba_2CoGe_2O_7$ - anisotropy with current direction

The SMR ratio is anisotropic with the current direction





Does **not** correlate with magnetocrystalline anisotropy

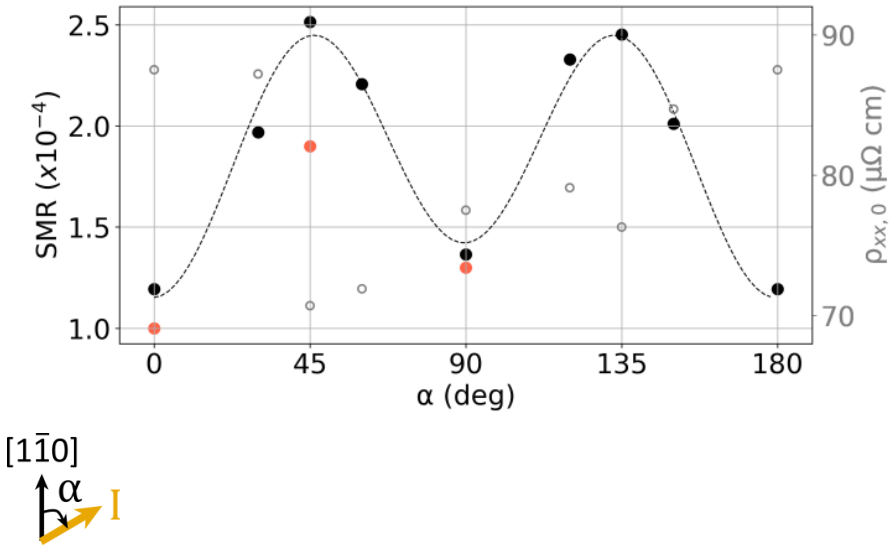


Likely **monodomain** state

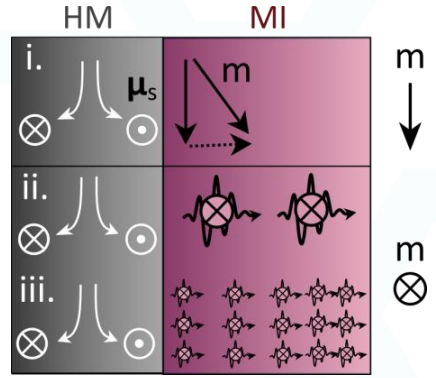
M. Leiviskä *et al*, Phys. Rev. Materials **9**, 084403 (2025)

SMR in $Ba_2CoGe_2O_7$ - anisotropy with current direction

The SMR ratio is anisotropic with the current direction



Intrinsic anisotropy of the spin current channels?



Anisotropic spin mixing conductance?

PHYSICAL REVIEW B **96**, 144434 (2017)

Crystal field effects on spin pumping

Adam B. Cahaya,[1] Alejandro O. Leon,[1] and Gerrit E. W. Bauer[1,2,3]

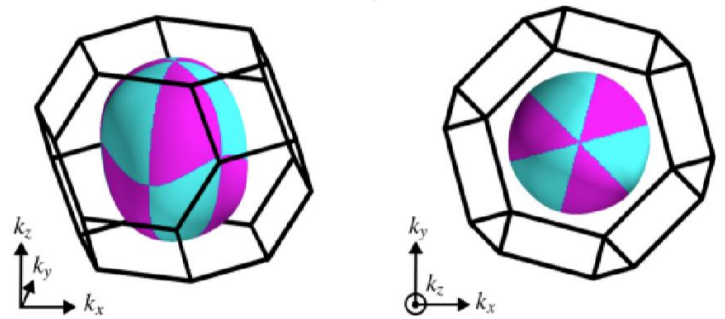
[1]*Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan*

[2]*WPI-AIMR & CSRN, Tohoku University, Sendai 980-8577, Japan*

[3]*Zernike Institute for Advanced Materials, Groningen University, The Netherlands*

(Received 7 September 2017; published 26 October 2017)

Anisotropic magnon dispersion?



Example of α-Fe_2O_3 - PRB 112, 064425 (2025)

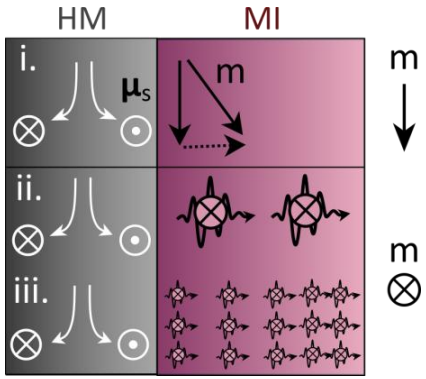
Relativistic vs. non-relativistic effects

SMR in $Ba_2CoGe_2O_7$ - anisotropy with current direction

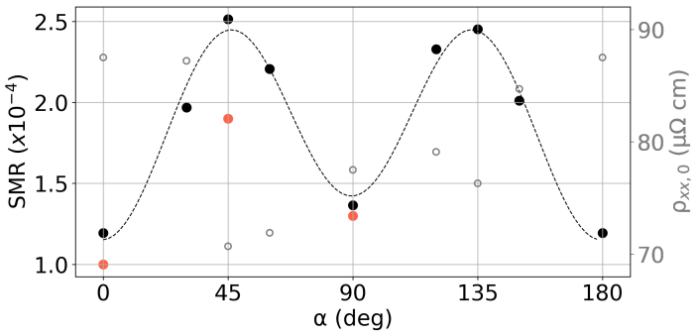
Intrinsic anisotropy of the spin current channels?

Spin mixing conductance?

Magnon dispersion?

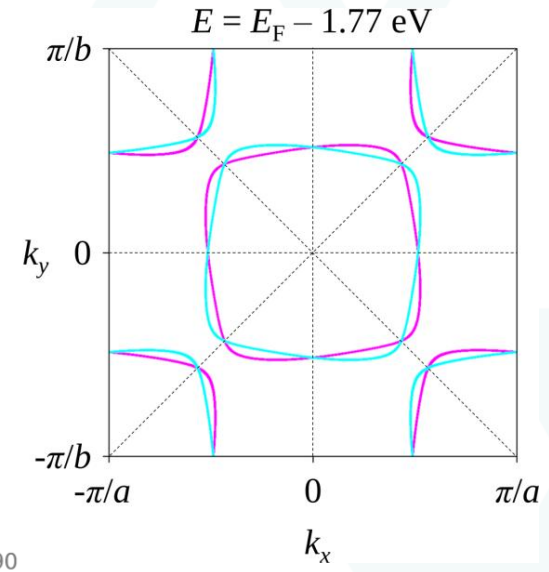


Symmetry matching?

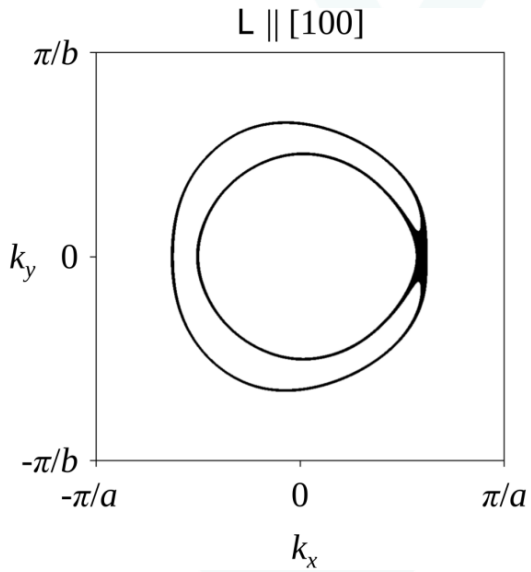


Looking for more clues:

i. Theory



Non-Relativistic



Relativistic

Kyohoon Ahn

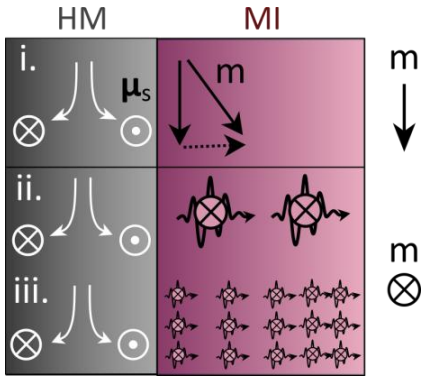
FZU

FZU Institute of Physics of the Czech Academy of Sciences

Division of Solid State Physics

SMR in $Ba_2CoGe_2O_7$ - anisotropy with current direction

Intrinsic anisotropy of the spin current channels?
Spin mixing conductance?
Magnon dispersion?



Looking for more clues:
i. Theory
ii. Frequency-dependence

Lukas Nadvornik
Peter Kubaščik

arXiv 2507.02498v2

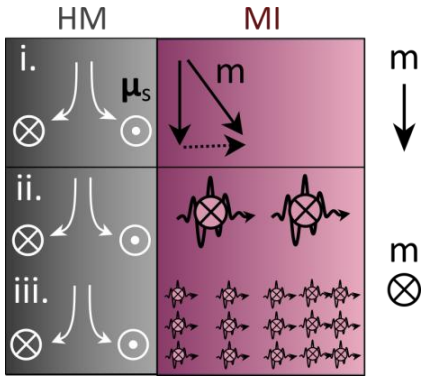
Resolving Ultrafast Coherent and Incoherent Spin Torque Contributions via Terahertz Spin-Hall Magnetoresistance

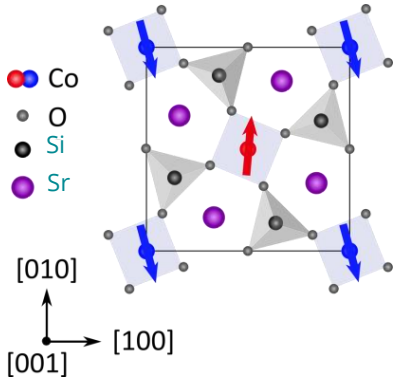
Peter Kubaščík[1], Richard Schlitz[2], Oliver Gueckstock[3], Oliver Franke[3], Miina Leiviska[4], Martin Borchert[5], Gerhard Jakob[6], Kamil Olejník[4], Andrej Farkaš[1,4], Zdenek Kašpar[1,4], Jiří Jechumtál[1], Martin Bušina[1], Eva Schmoranzerová[1], Petr Němec[1], Yicheng Z. Wu[7,8], Georg Woltersdorf[9], Mathias Kläui[6], Piet W. Brouwer[3], Sebastian T. B. Goennenwein[2], Tobias Kampfrath[3], Lukáš Nádvorník[1,*]

Resolving the spin current channels with frequency-dependence?

SMR in $Ba_2CoGe_2O_7$ - anisotropy with current direction

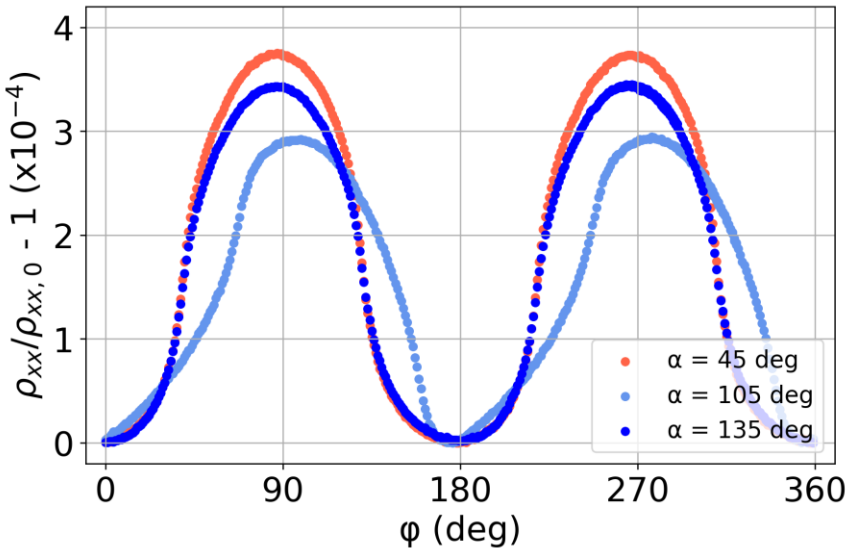
Intrinsic anisotropy of the spin current channels?
Spin mixing conductance?
Magnon dispersion?





Looking for more clues:

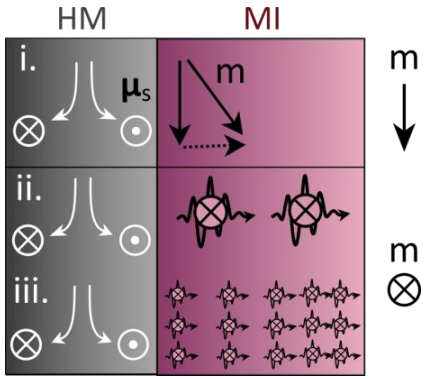
i. Theory
ii. Frequency-dependence
iii. Universality?



Large, anisotropic SMR present also in the sister compound $Sr_2CoSi_2O_7$

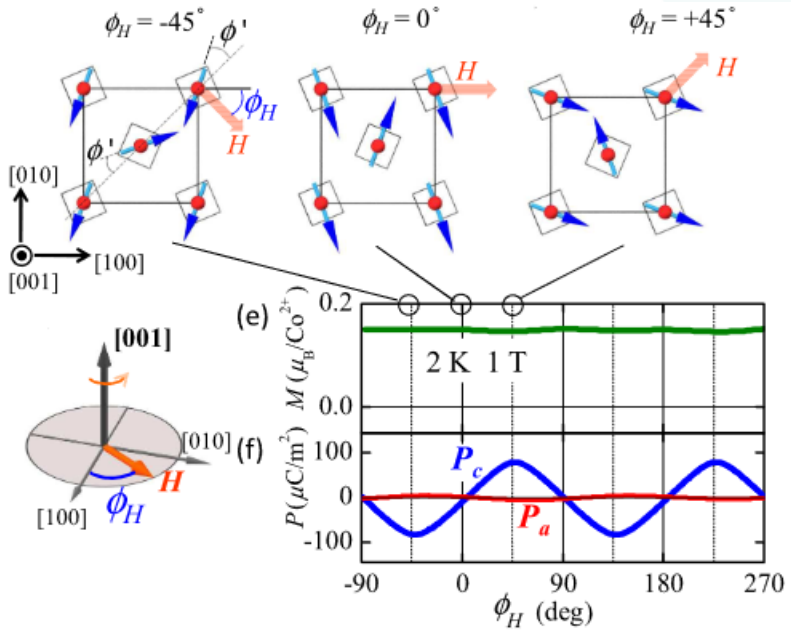
SMR in $Ba_2CoGe_2O_7$ - anisotropy with current direction

Intrinsic anisotropy of the spin current channels?
Spin mixing conductance?
Magnon dispersion?

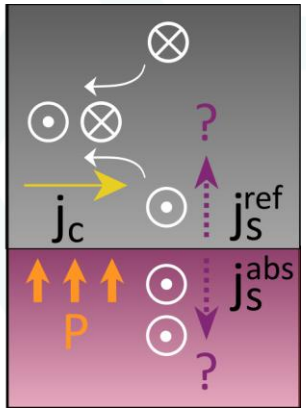


Looking for more clues:

i. Theory
ii. Frequency-dependence
iii. Universality?
iv. Polarization?



Phys. Rev. Lett 105, 137202 (2010)



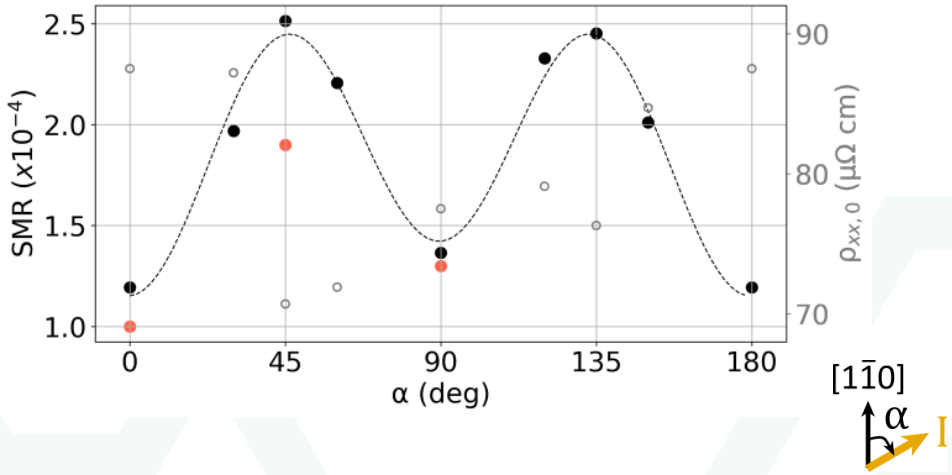
What is the effect of finite polarization?

Gerrit Bauer
Olena Gomonay
Joseph Barker

Conclusions

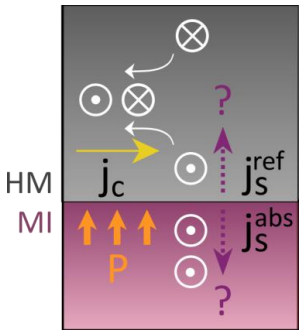
We observe sizable spin Hall magnetoresistance in multiferroic altermagnet/Pt heterostructures

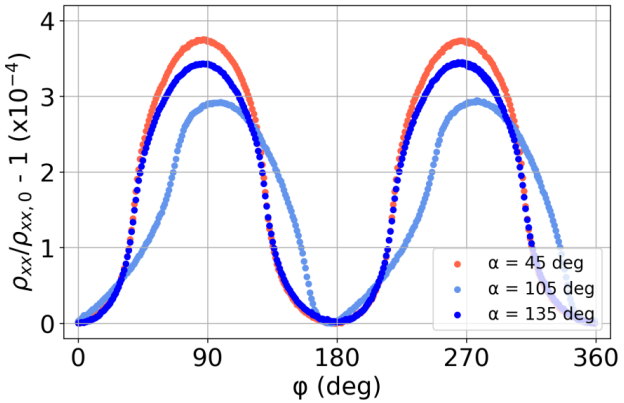
→ Another example of large SMR in an altermagnet



The SMR amplitude is anisotropic with the crystal direction of the current

→ Attributed to intrinsic anisotropy of the spin current channels across the interface





Work in progress!

→ More theory, more materials, frequency dependence …

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Olena Gomonay

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Michaela Lammel
Sebastian Goennenwein

Johanna Fischer

Spin Hall Magnetoresistance at the Altermagnetic Insulator/Pt Interface

Dr. Miina Leiviskä[1],

R. Firouzmandi[2], K. Ahn[1], P. Kubaščik[3], S. Sailler[4], Z. Soban[1], S. Prakash Bommanaboyena[1], C. Müller[1], B. Gut[4], K. Uhlířová[4], D. Kriegner[1], M. Hývl[1], M. Lammel[5], K. K. Bestha[2], L. Šmejkal[6,7,1], J. Zelezny[2], A. U. B. Wolter[2], M. Scheufele[8,9], J. Fischer[10], M. Opel[8], S. Geprägs[8], M. Althammer[8], B. Buechner[2,11,12], T. Jungwirth[1,13], L. Nadvornik[3], S. T. B. Goennenwein[5], V. Kocsis[2], and H. Reichlova[1]

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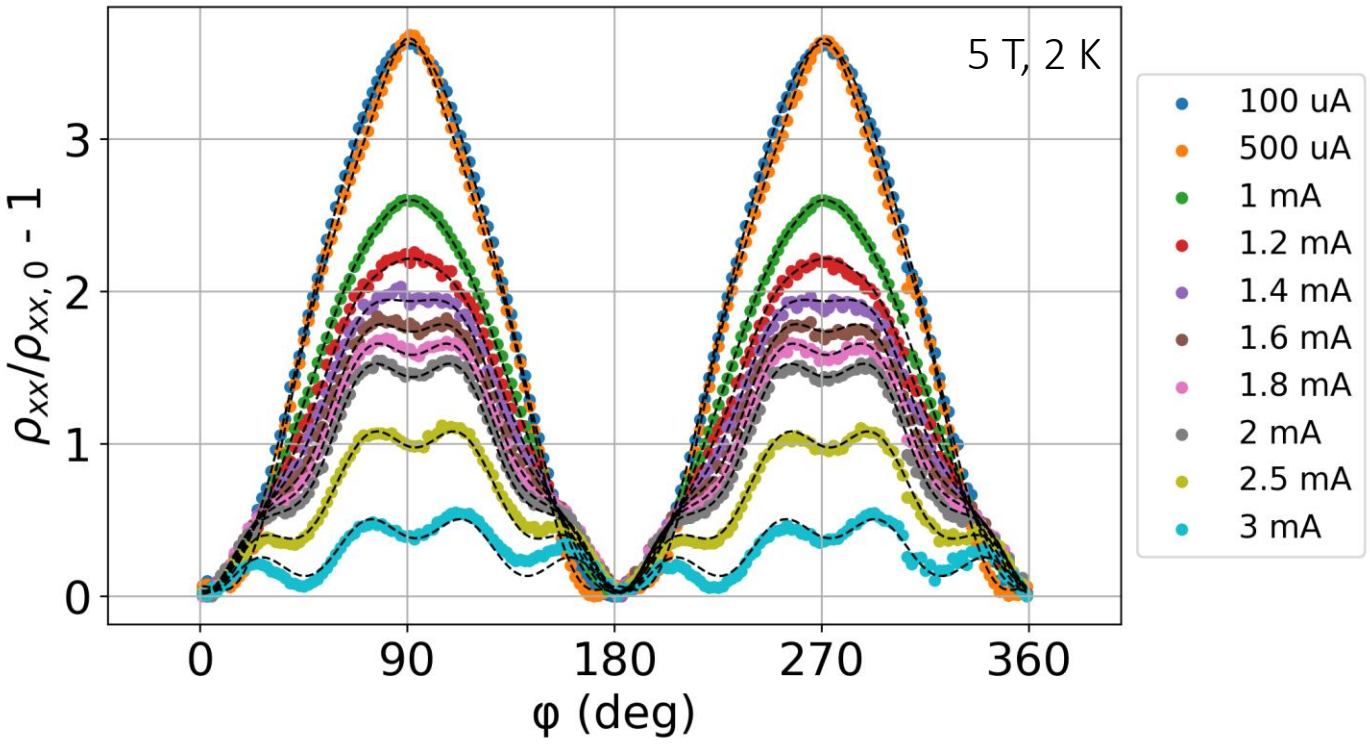
Division of Solid State Physics

Supplementary slides

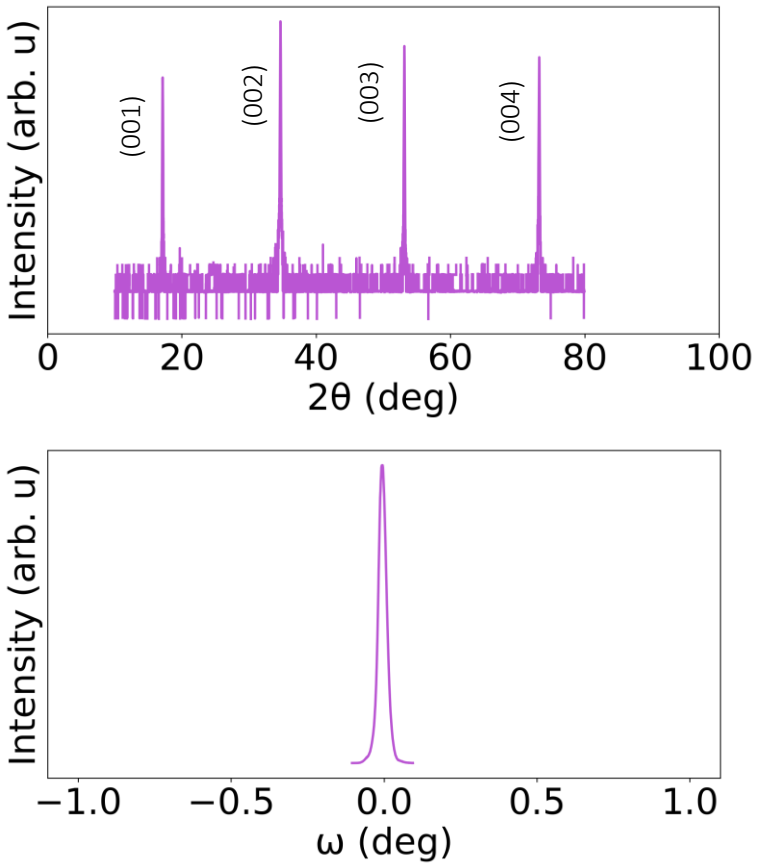
Bonus: Higher order harmonics in SMR?

Increasing magnetic field strength + increasing current density

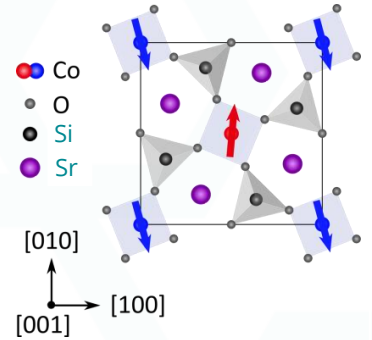


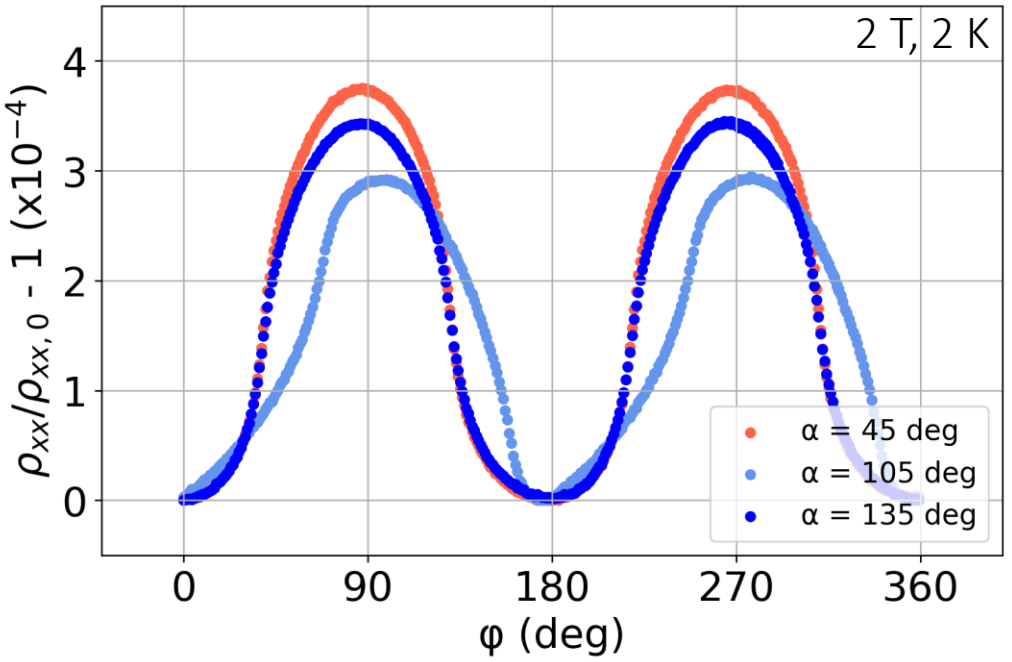
Non-linear effects? Origin?

Bonus: Sister compound $Sr_2CoSi_2O_7$



Better crystal quality,
better surface quality

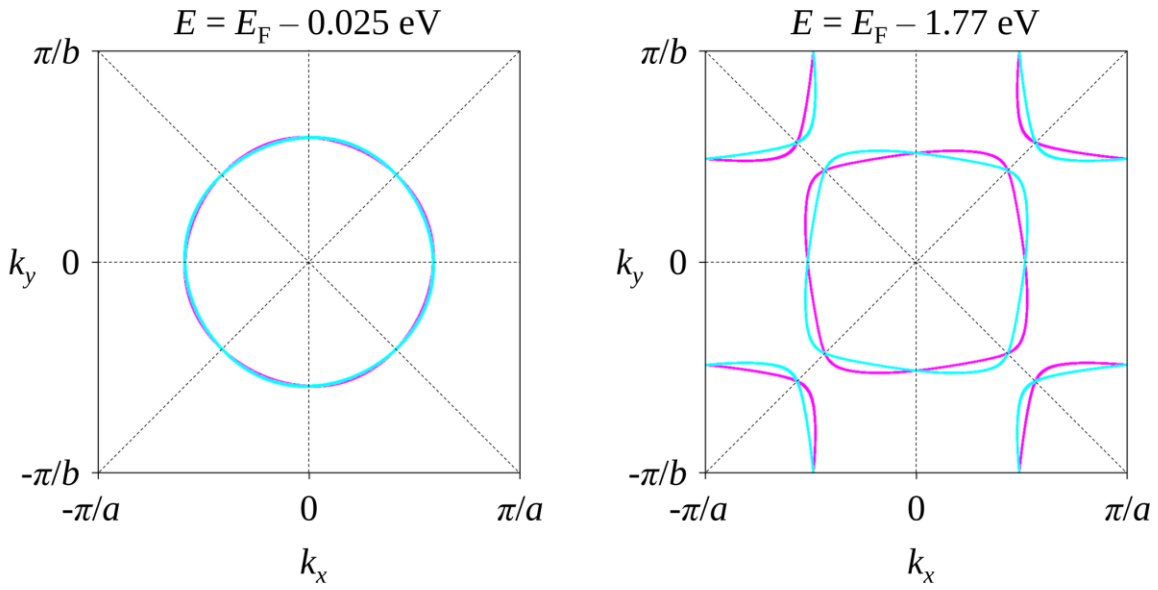




Even larger SMR amplitude with same anisotropy as BCGO
Deviation from $\cos 2\varphi$? → Ongoing Master thesis

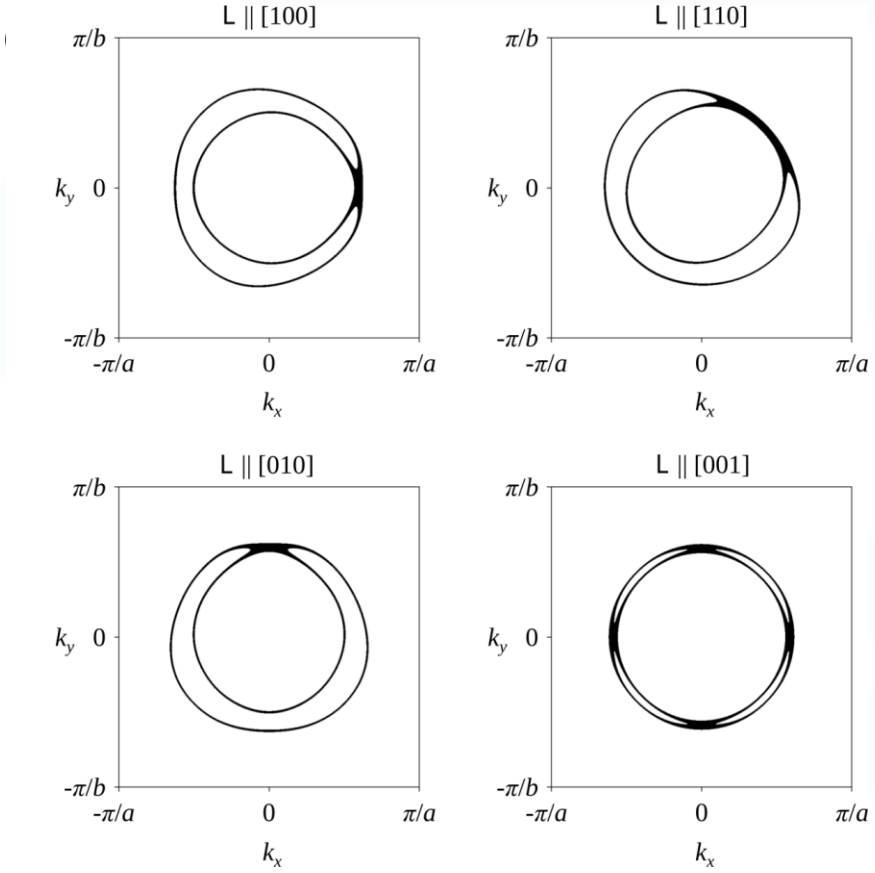
Band structure calculations on BCGO

Non-relativistic



Altermagnetic spin splitting is very small
Spin point group ${}^{1}4^{2}m^{2}m$

Relativistic



$\mathrm{m}_i \parallel \{110\}$ → magnetic space group is $\mathrm{Cm'm2'}$
$\mathrm{m}_i \parallel \{100\}$ → magnetic space group is $\mathrm{P2_12_1'2'}$