WMI

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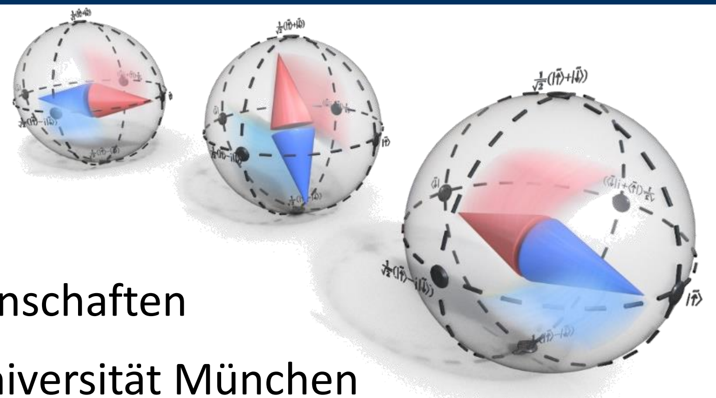
TUM
Technische Universität München

# All-electrical angular momentum transport in antiferromagnetic insulators and isolated ferromagnetic metals


**Matthias Althammer**


DFG Deutsche Forschungsgemeinschaft
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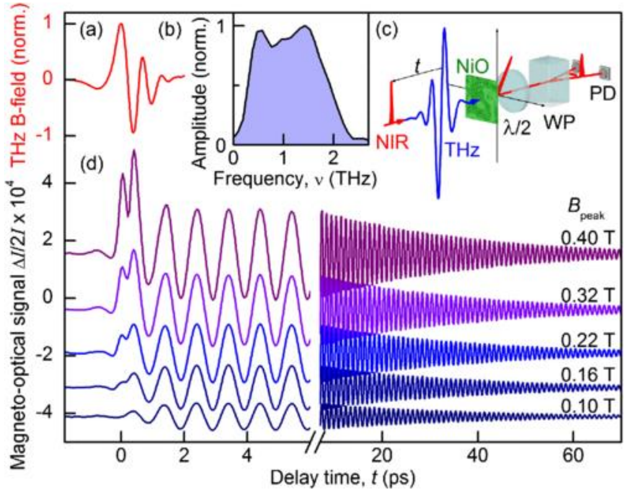
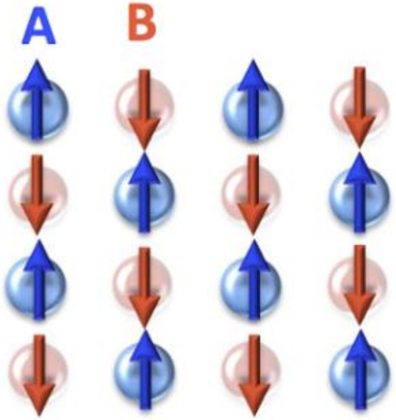
Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften
TUM School of Natural Sciences, Physik Department, Technische Universität München

# Antiferromagnetic Spintronics

## THz Dynamics



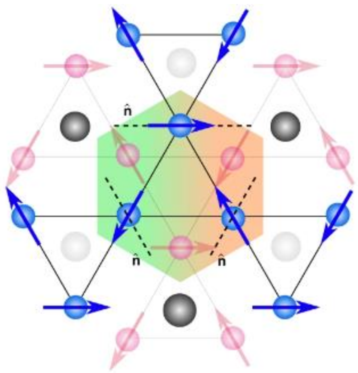

Baierl, S. *et al*., *Phys. Rev. Lett*. **117**, 197201 (2016).




**Reviews:**

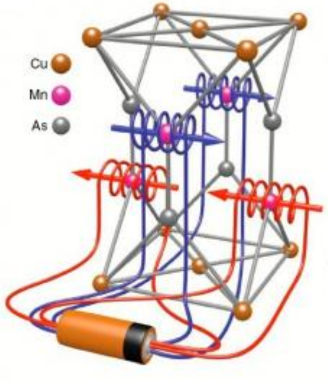
T. Jungwirth *et al., Nature Nanotechnology* **11**, 231 (2016).
V. Baltz *et al., Rev. Mod. Phys* **90,** 015005 (2018).
L. Šmejkal *et al., Nature Physics* **14**, 242 (2018).
J. Han *et al., Nature Materials* (2023).

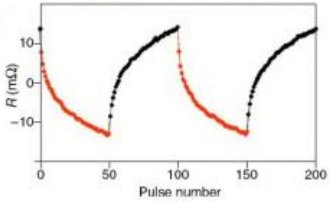
## Non-collinear Antiferromagnets



S. Nakatsuji *et al., Nature* **527**, 212 (2015)
M. Kimata *et al., Nature* **565**, 627 (2019).
M. Ikhlas *et al., Nature Physics* **18,** 1086 (2022).
Quin *et al., Nature* **613,** 485 (2023).

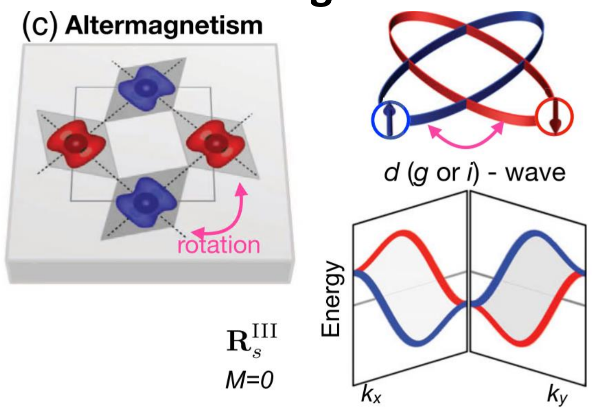
## Electrical Switching



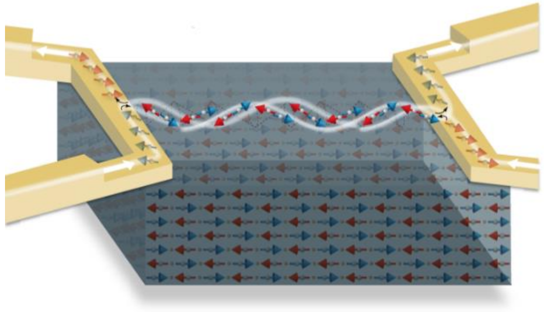

P. Wadley *et al., Science* **351**, 6273 (2016).
T. Jungwirth *et al., Nature Physics* **14,** 200 (2018).

## Altermagnetism



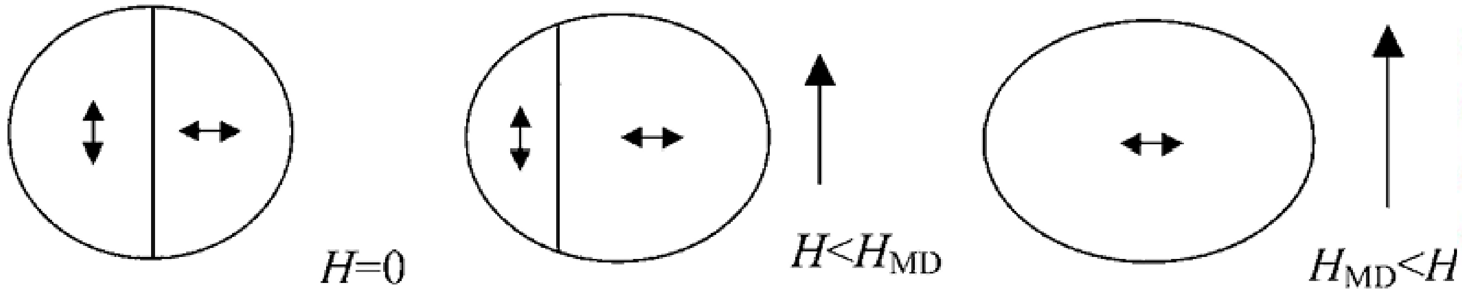

L. Šmejkal *et al., Sci. Adv.* 6, eaaz8809 (2020)
Z. Feng *et al., Nature Electronics* **5,** 735 (2022).
L. Šmejkal *et al., Phys. Rev. X* **12**, 040501 (2022).

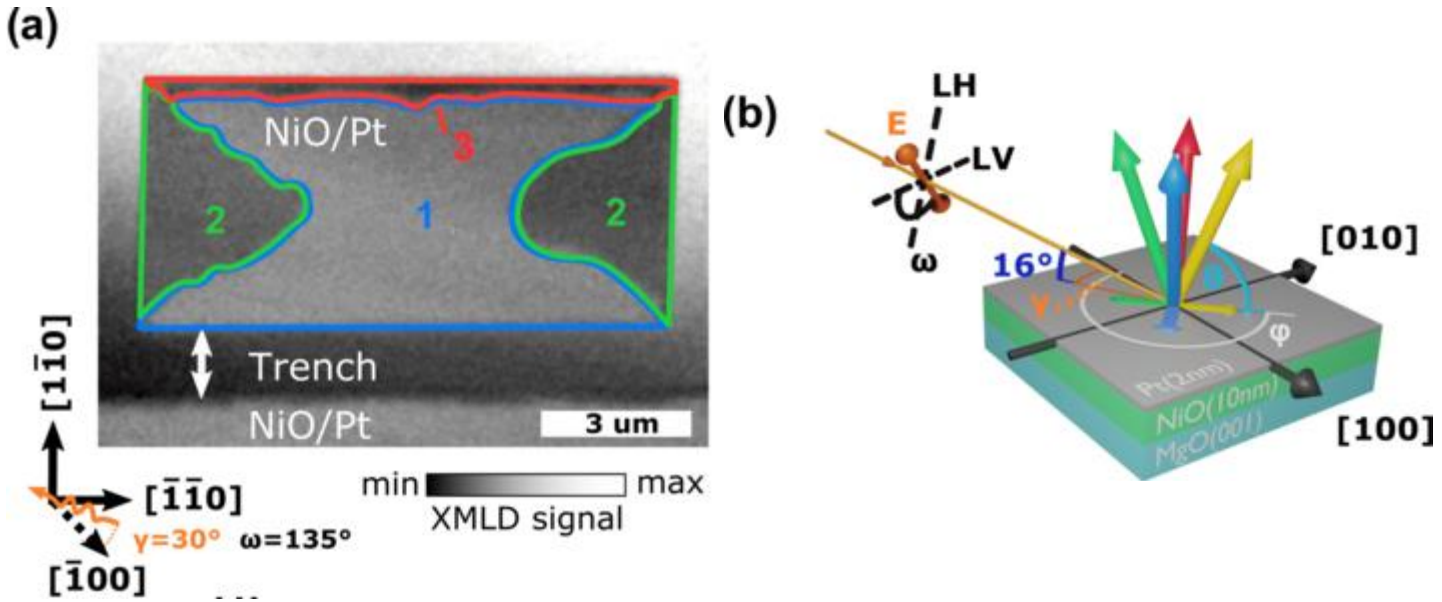
## Magnon Spin Transport

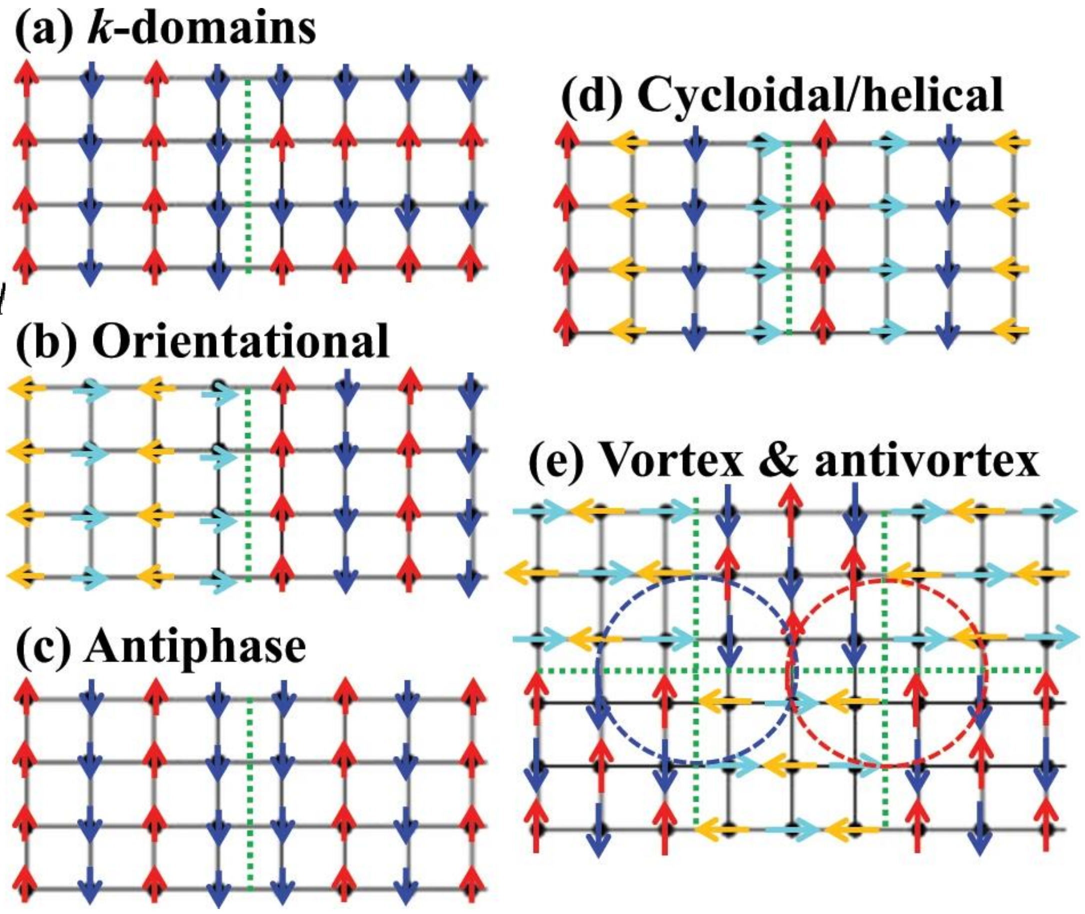


R. Lebrun *et al., Nature* **561**, 222 (2018).
Wimmer, *et al.*, Phys. Rev. Lett. **125** , 247204 (2020).

# Strain and magnetic domains



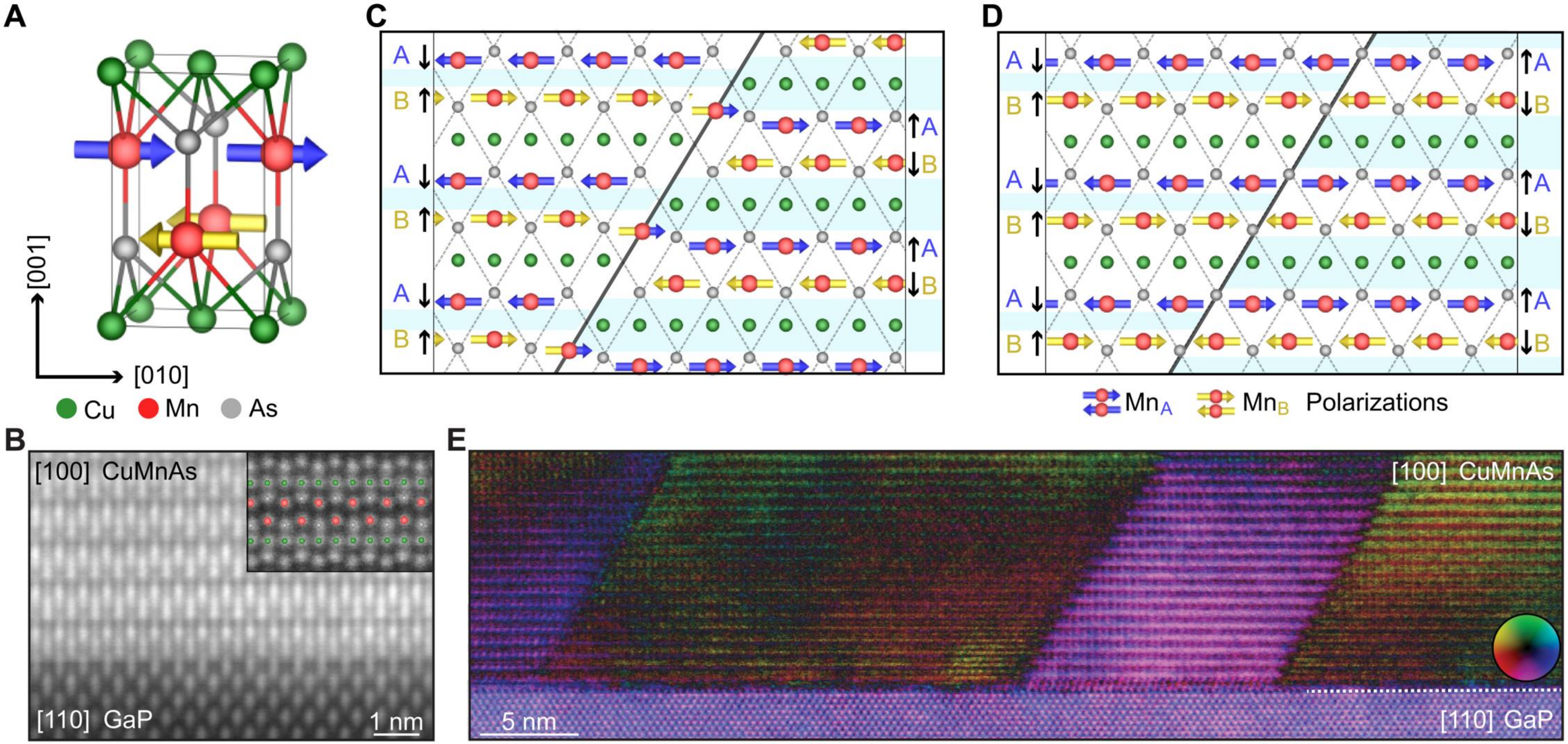




H. Gomonay and V.M. Loktev J. Phys.: Condens. Matter **14**, 3959 (2002).
J. Fischer *et al.*, Phys. Rev. B **97**, 014417 (2018)
H. Meer et al., Phys. Rev. B **106**, 094430 (2022)

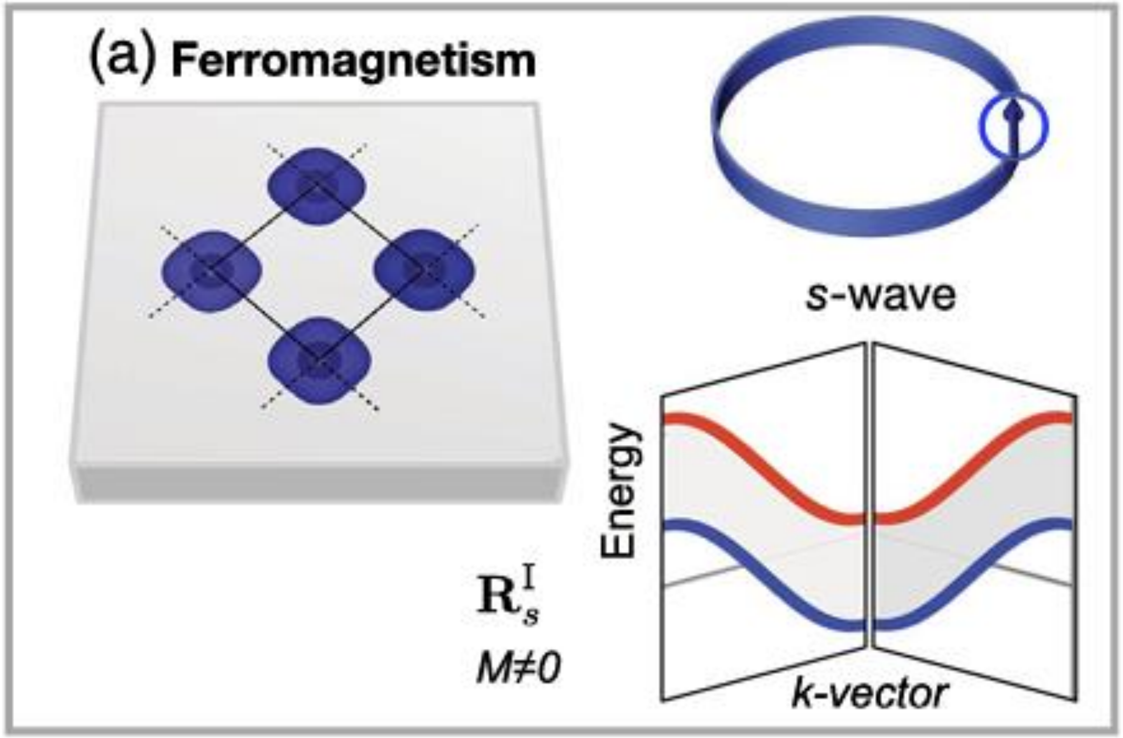
S.W. Cheong *et al., npj Quantum Mater.* **5**, 3 (2020)

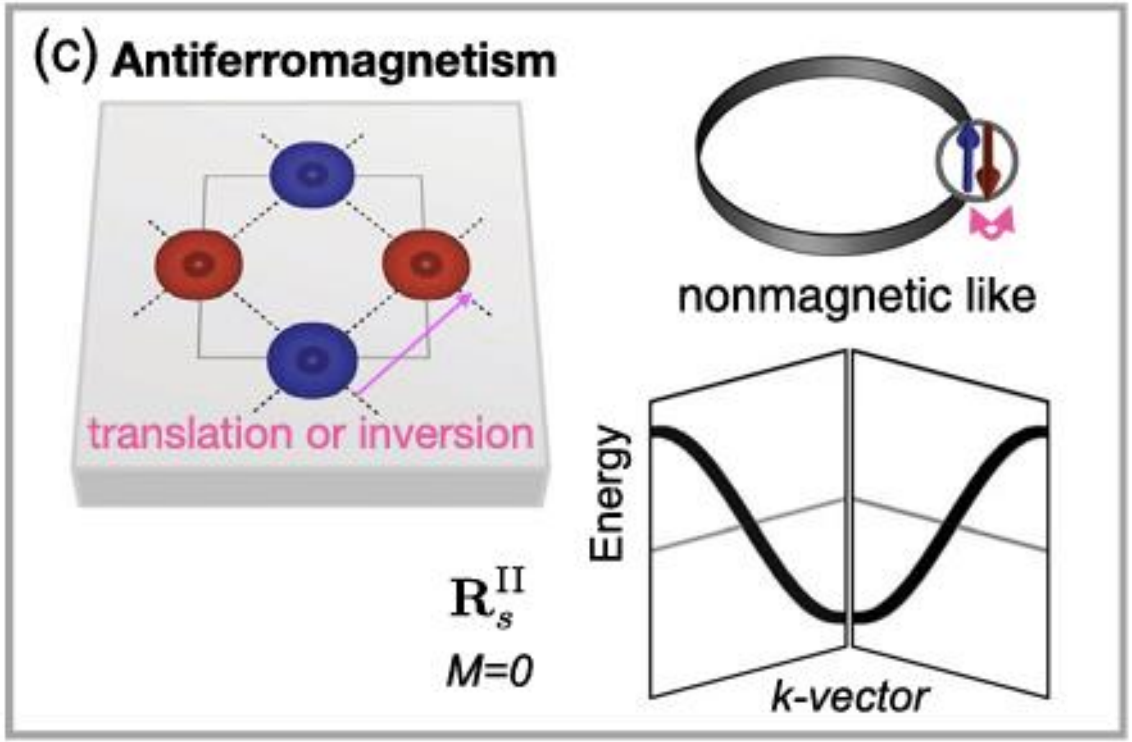
# Atomically sharp domain walls in CuMnAs




F. Krizek *et al., Sci. Adv.***8**, eabn3535 (2022)

# Spin degeneracy in antiferromagnets




time-reversal ($\mathcal{T}$) symmetry broken via magnetization

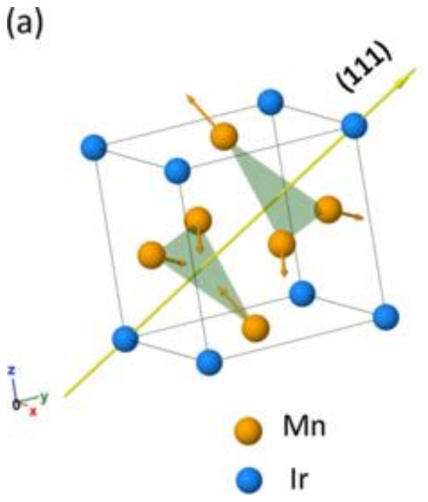
$\mathcal{T}$-symmetry

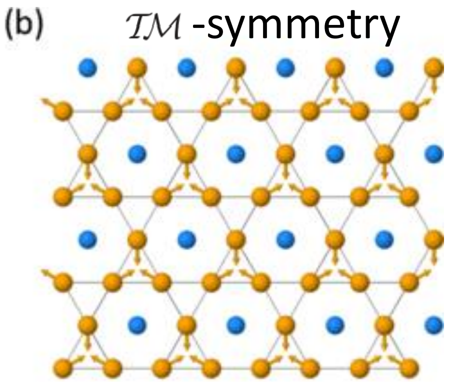
Kramers spin degeneracy

Spin-orbit interaction allows for spin splitting
→ Other more robust effects?

L. Šmejkal *et al., Phys. Rev. X* **12**, 040501 (2022).

# Non-collinear Antiferromagnets



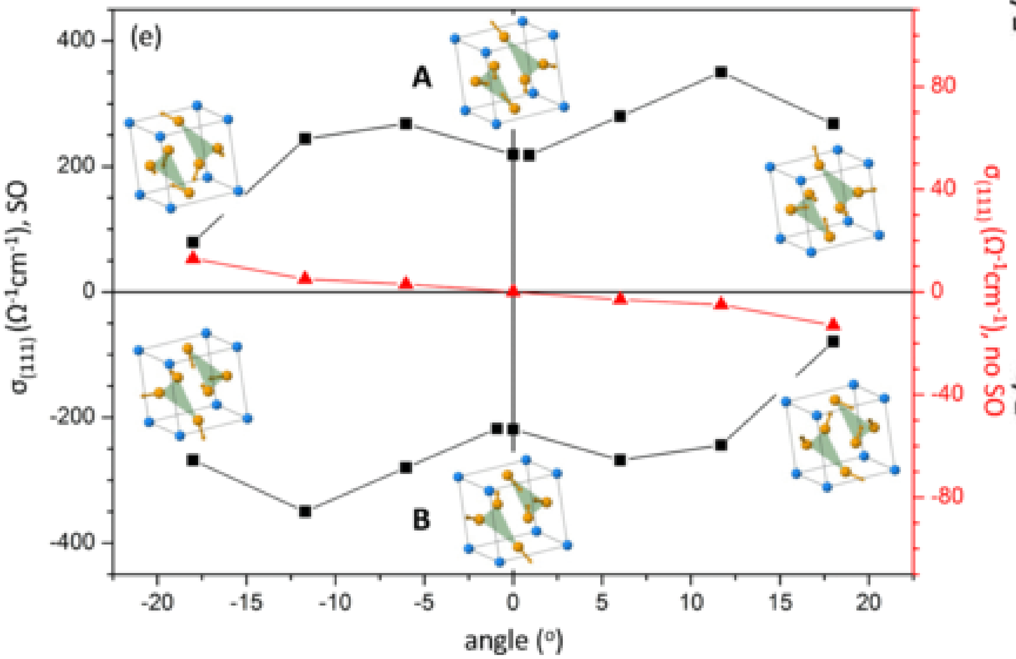




Berry curvature: $= i\langle \nabla_{\boldsymbol{k}} u_{n\boldsymbol{k}}| \times |\nabla_{\boldsymbol{k}} u_{n\boldsymbol{k}}\rangle$

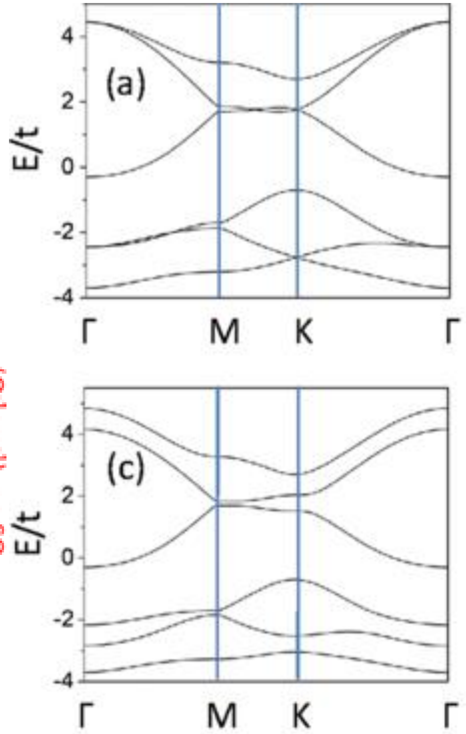
$\mathcal{T}$-symmetry $\Omega_n(\boldsymbol{k}) = -\Omega_n(-\boldsymbol{k})$

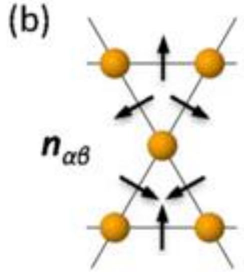
$\mathcal{I}$-symmetry: $\Omega_n(\boldsymbol{k}) = \Omega_n(-\boldsymbol{k})$

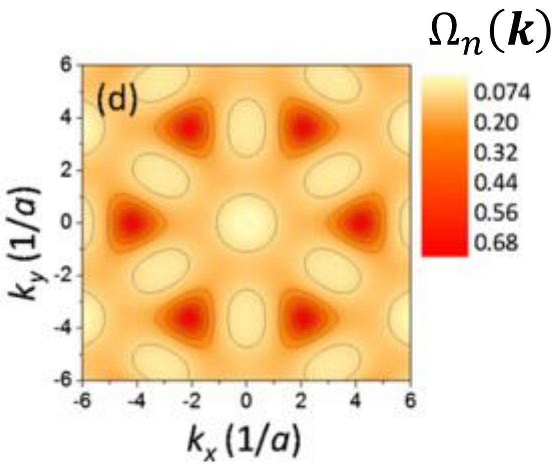
With spin-orbit coupling




Without spin-orbit coupling

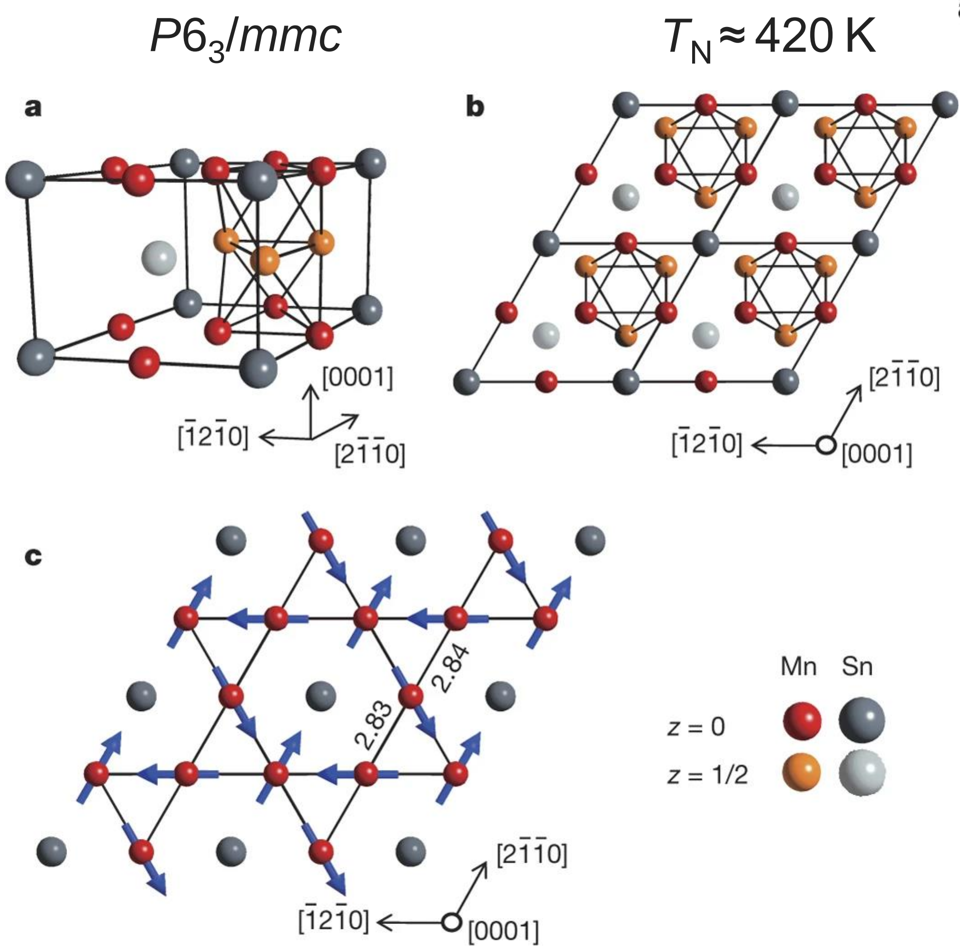


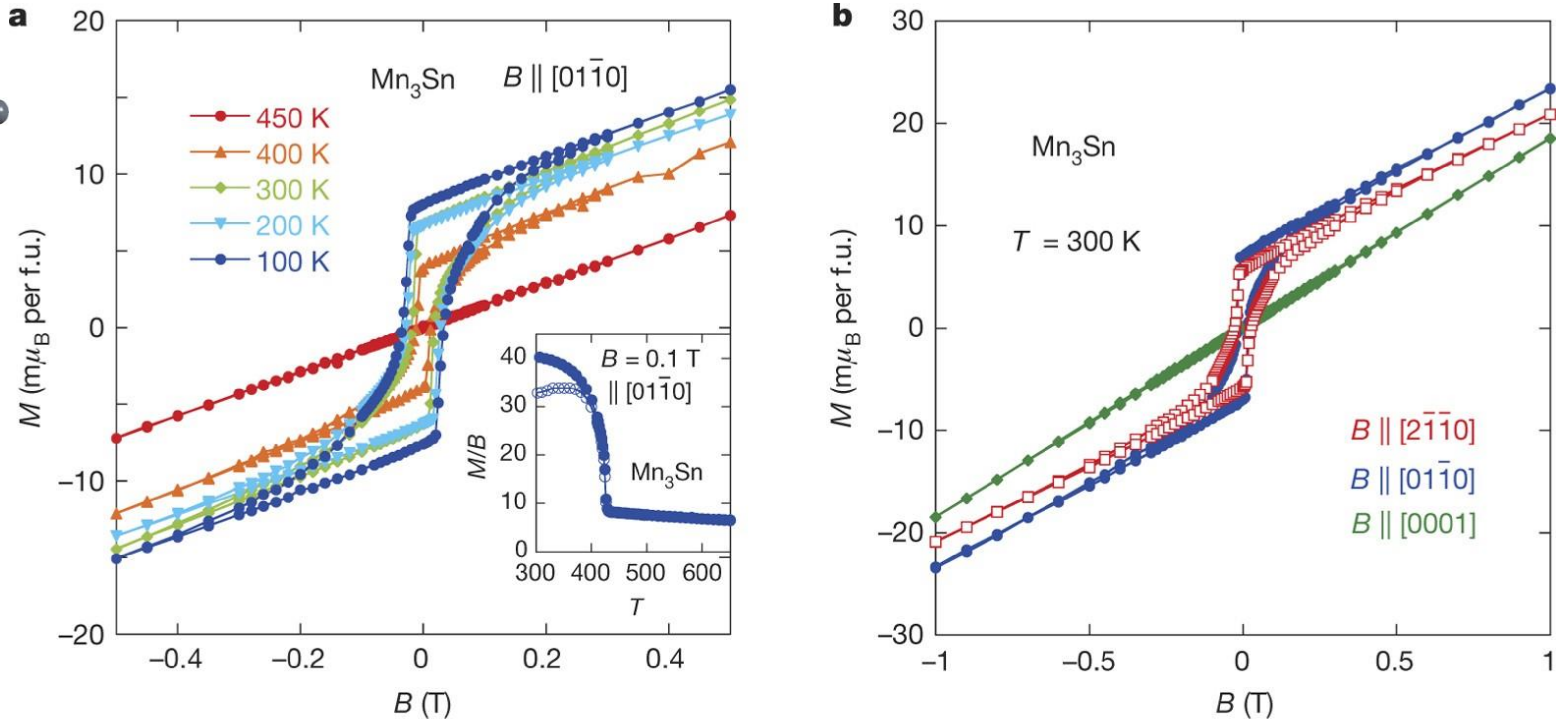




H. Chen et al., PRL **112**, 017205 (2014)
SHE: J. Železný *et al.*, PRL **119**, 187204 (2017)

# Anomalous Hall effect in non-collinear $Mn_3Sn$

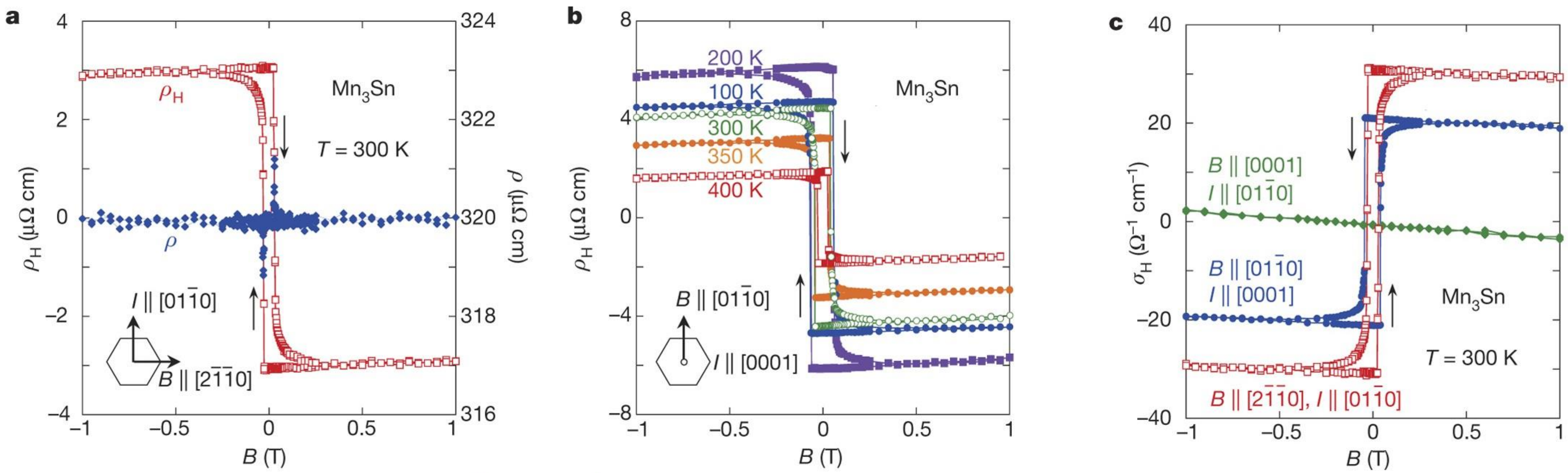


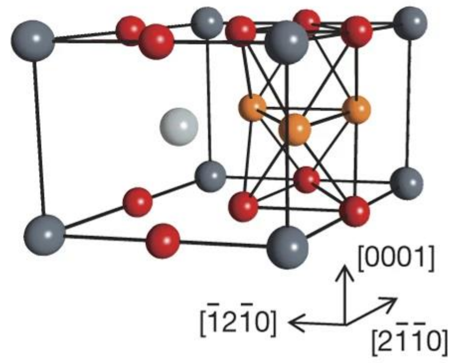



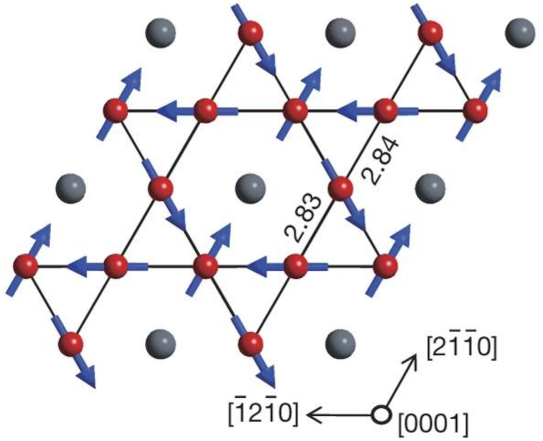

Finite net magnetic moment controlled via external magnetic field

S. Nakatsuji *et al., Nature* **527**, 212 (2015)

# Anomalous Hall effect in non-collinear $Mn_3Sn$



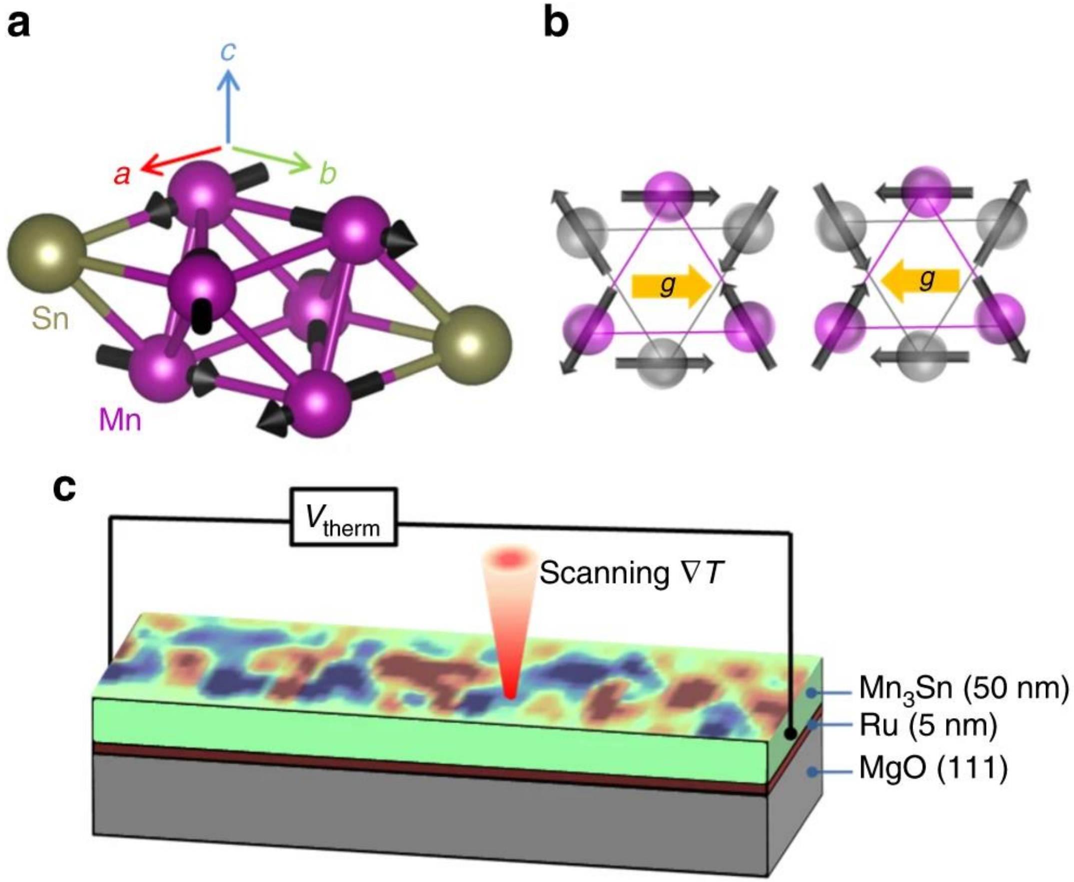



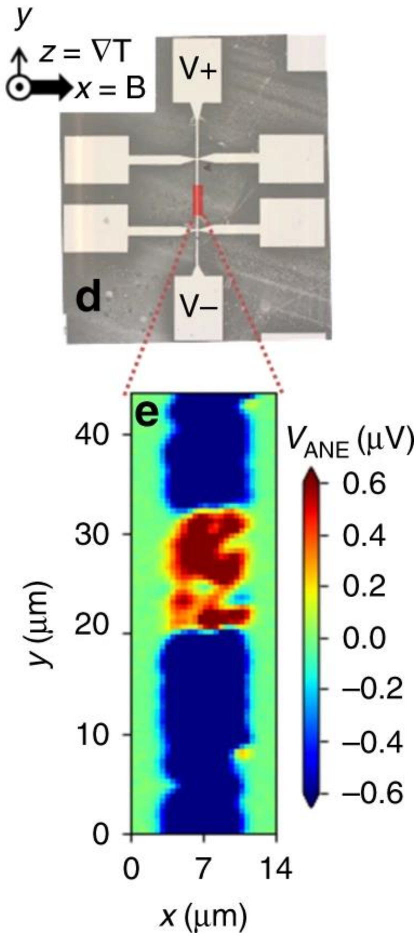

Finite and sizeable anomalous Hall conductivity

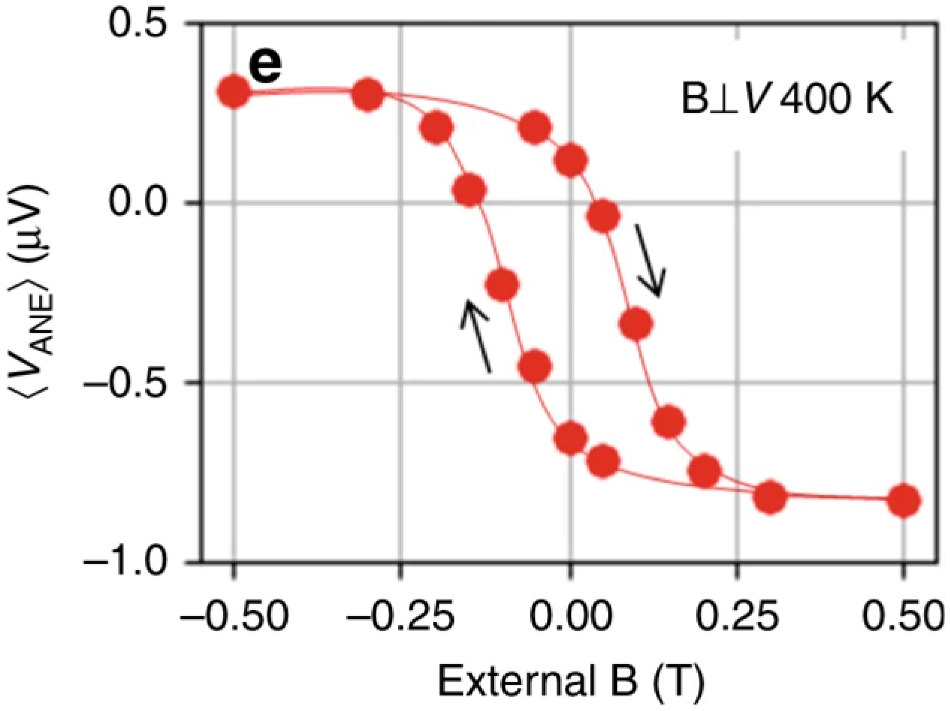
Hysteresis due to control of spin orientation by external magnetic field

S. Nakatsuji *et al., Nature* **527**, 212 (2015)

# Anomalous Nernst effect (ANE) $Mn_3Sn$



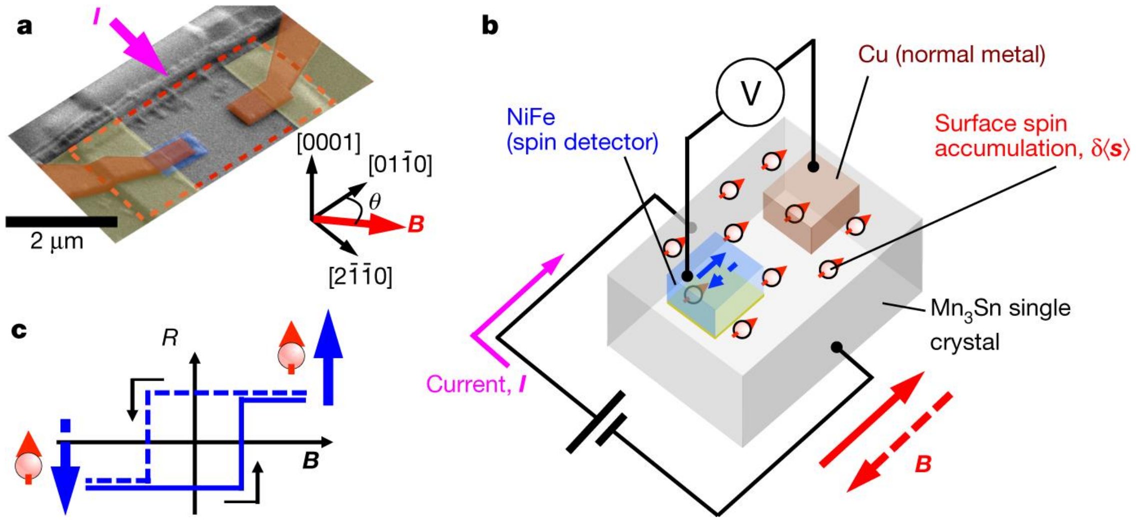



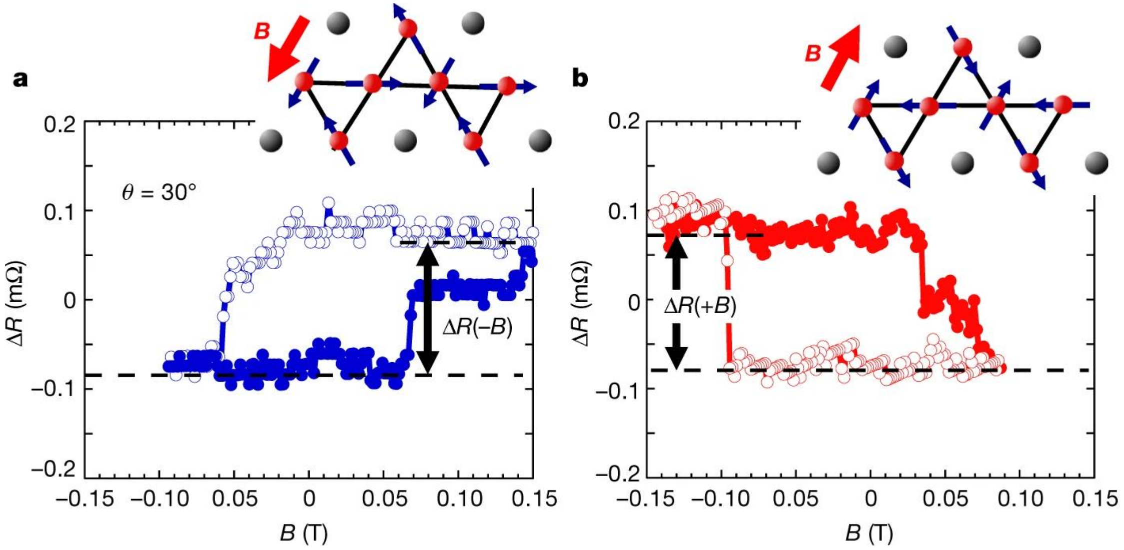

Finite ANE

Weiler *et al.*, Phys. Rev. Lett. **108**, 106602 (2012)
Reichlova *et al.*, Nature Communications **10**, 5459 (2019)

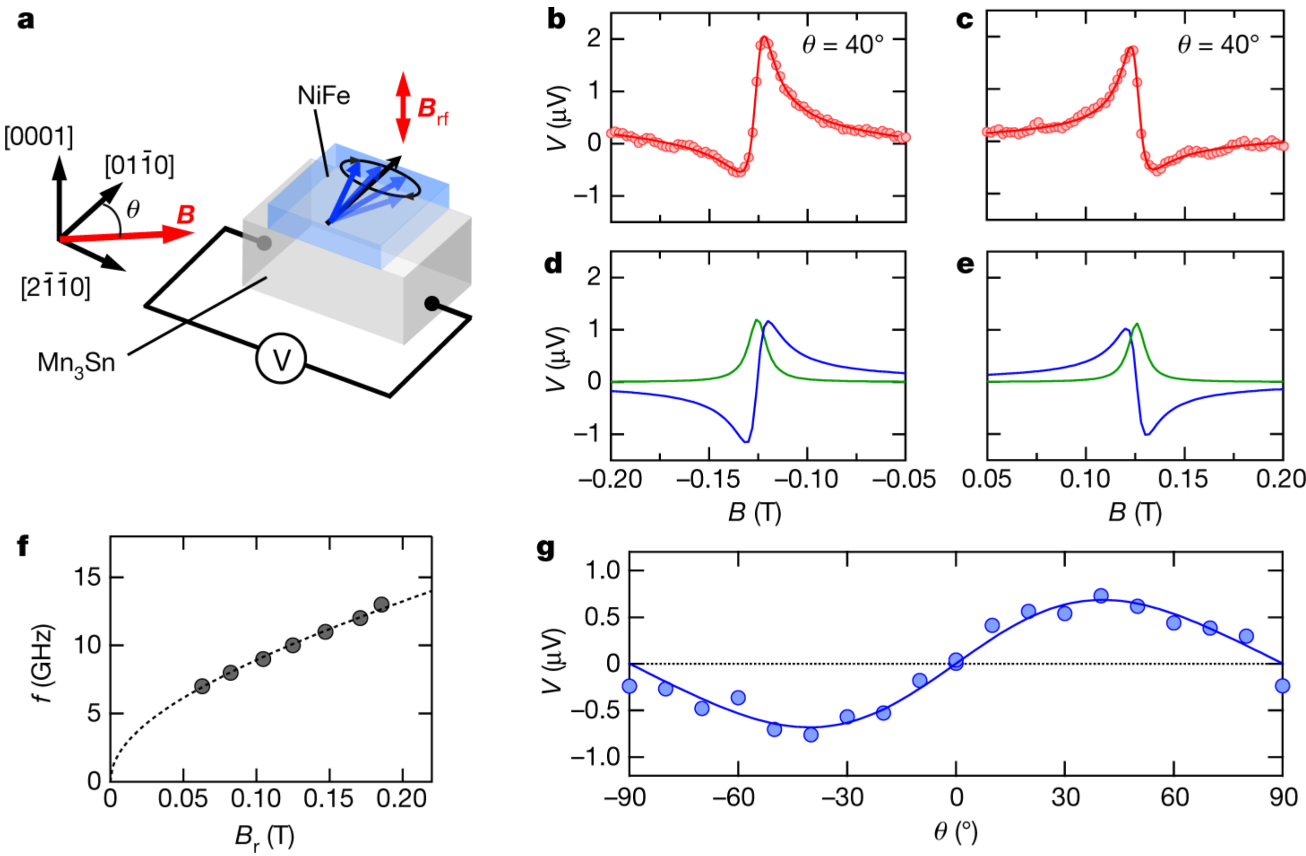
# Charge to Spin current conversion $Mn_3Sn$

## Charge to Spin current



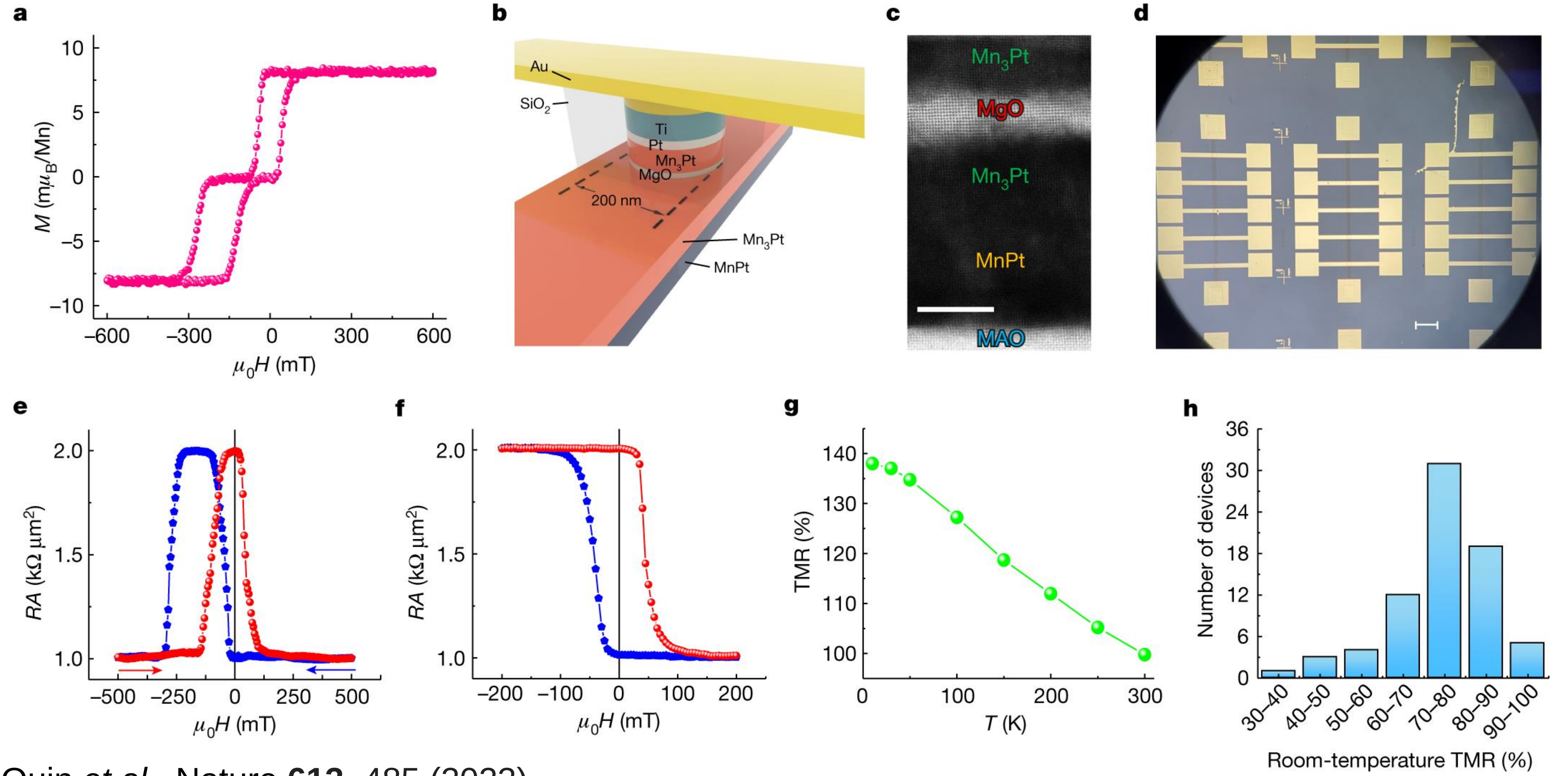




## Spin to Charge current



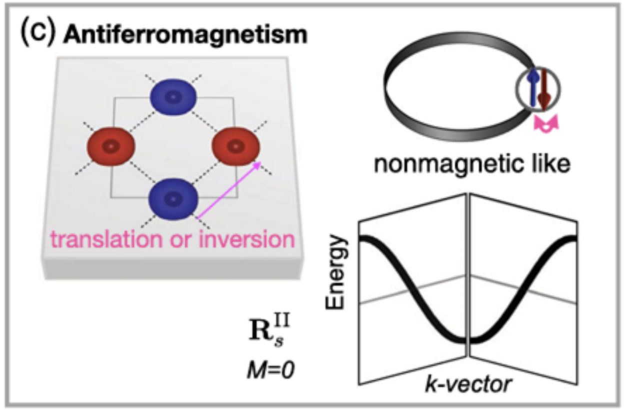

M. Kimata *et al., Nature* **565**, 627 (2019).

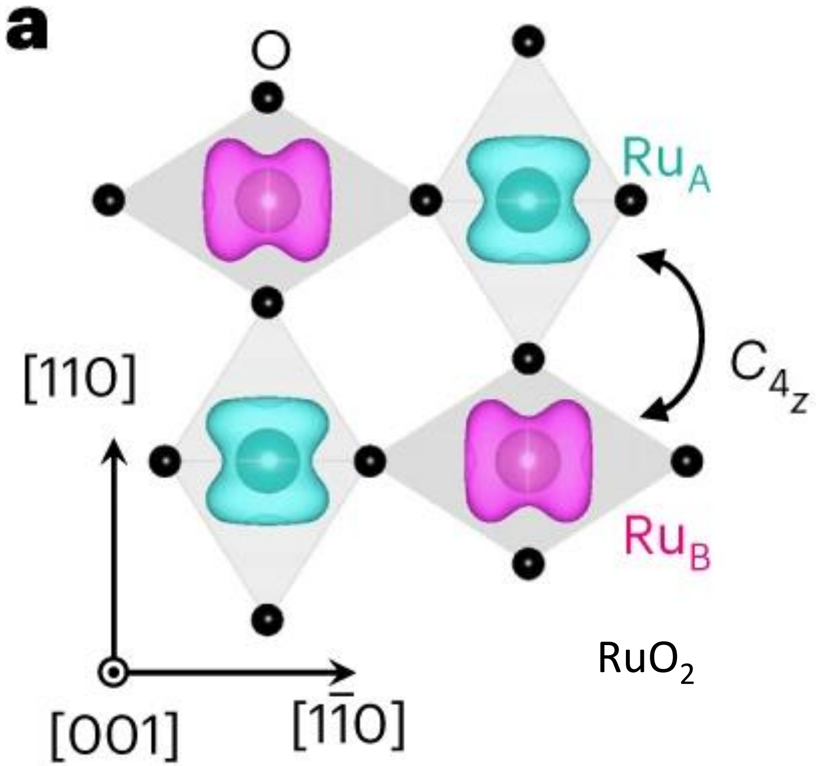
# Tunneling Magnetoresistance $Mn_3Pt$




Quin *et al.*, Nature **613**, 485 (2023).

# Altermagnetism



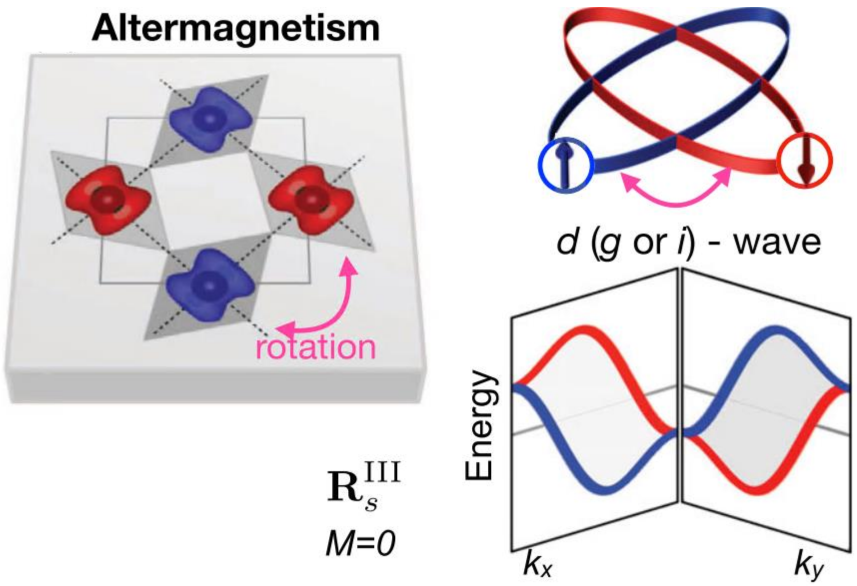




$RuO_2$

Swan-dancer
L. Šmejkal

Duck-hunter
J. Sinova

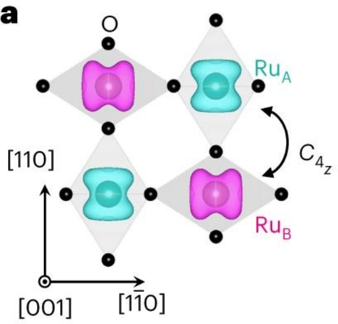
Fly Eagles Fly
T. Jungwirth

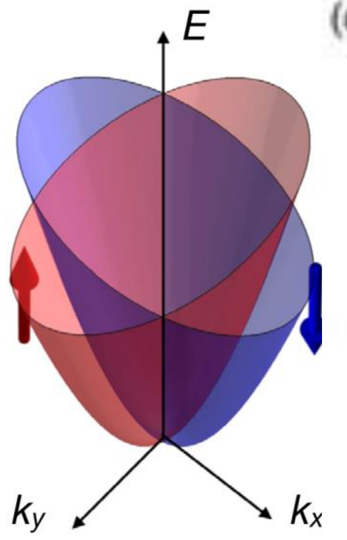


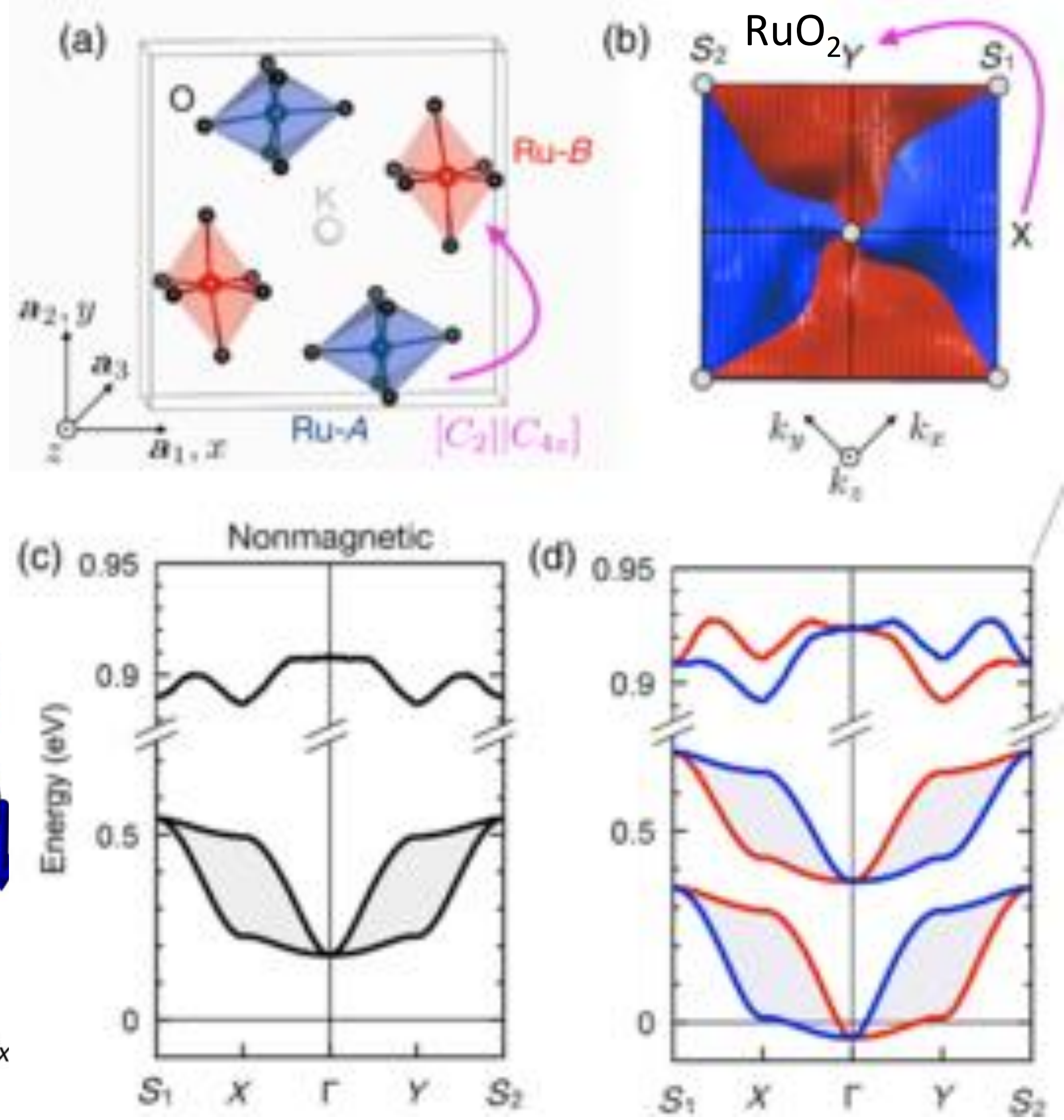

Z. Feng *et al., Nature Electronics* **5**, 735 (2022)

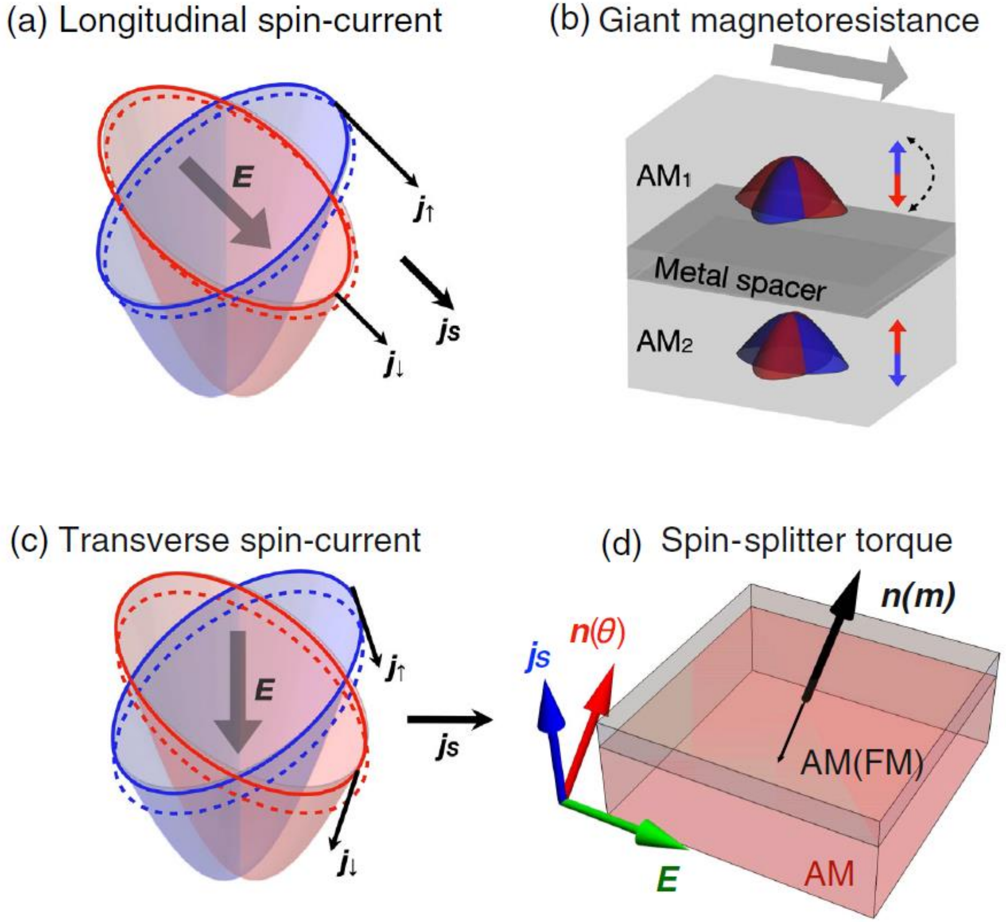
L. Šmejkal, J. Sinova, and T. Jungwirth, Phys. Rev. X **12**, 031042 (2022) & Phys. Rev. X **12**, 040501 (2022)

# Altermagnetism



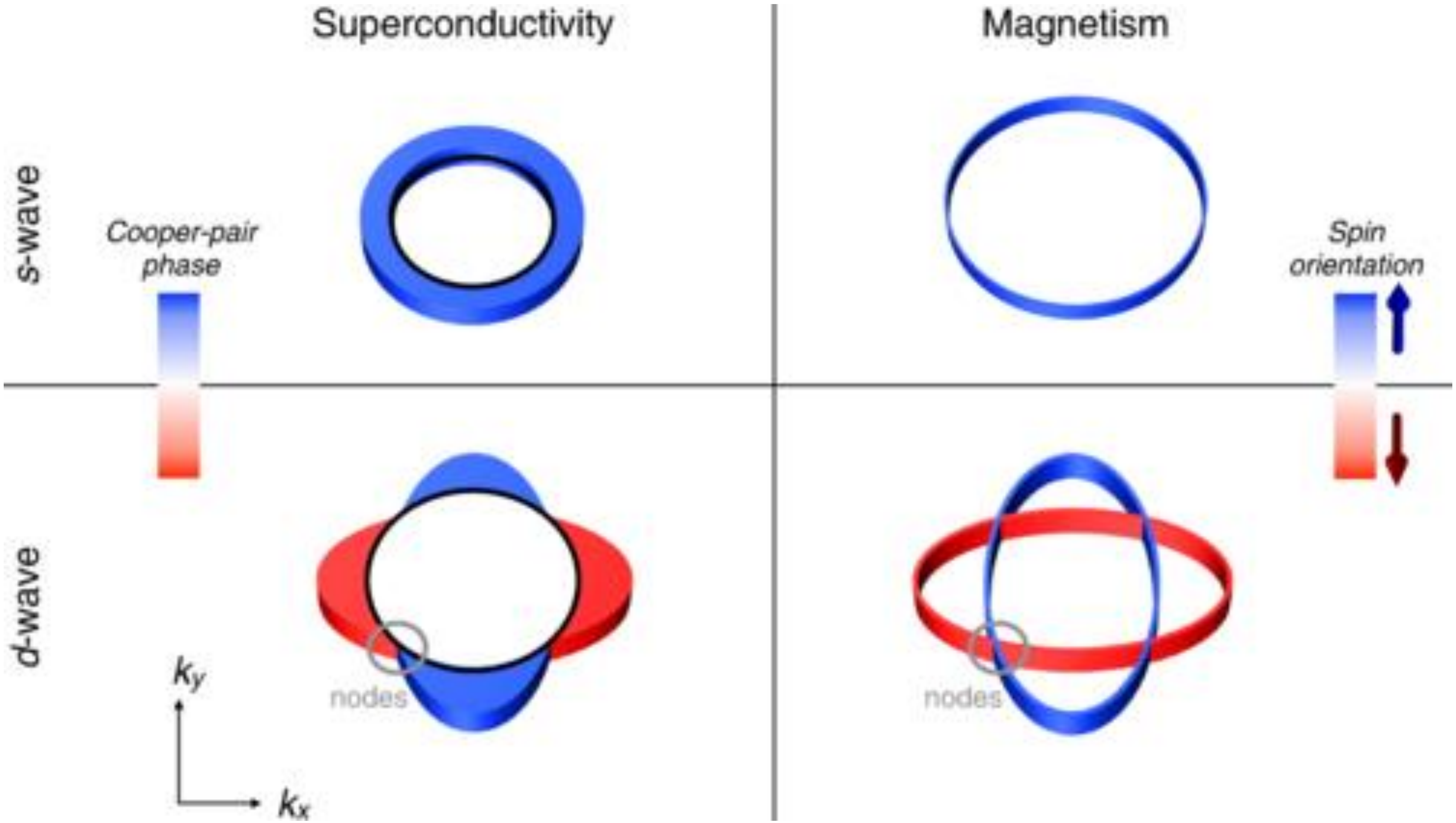



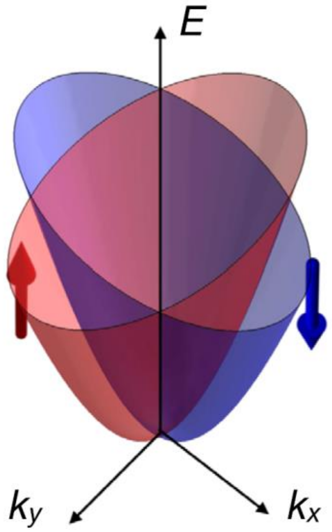




L. Šmejkal, J. Sinova, and T. Jungwirth, Phys. Rev. X **12**, 031042 (2022) & Phys. Rev. X **12**, 040501 (2022)

# Altermagnets and d-wave superconductivity






L. Šmejkal, J. Sinova, and T. Jungwirth, Phys. Rev. X **12**, 040501 (2022)

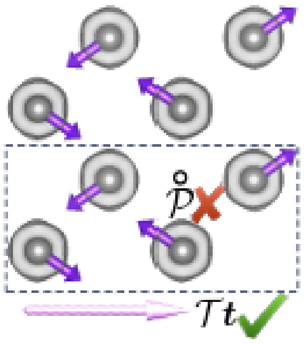
# Node symmetries

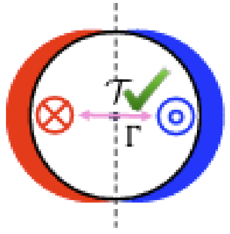
| Spin-momentum locking | | G | $\mathbf{R}_s^{\mathrm{III}}$ | H | $\mathcal{A}$ | Candidate |
|---|---|---|---|---|---|---|
| Planar $(k_{x/y}, k_z)$ | P-2 *d*-wave $(k_x, k_y)$ | $mmm$ | ${}^2m^2m^1m$ (8) | $2/m$ | $C_{2x}$ | $La_2CuO_4$, $FeSb_2$ |
| | | $4/m$ | ${}^24/{}^1m$ (8) | | $C_{4z}$ | $KRu_4O_8$ |
| | | $4/mmm$ | ${}^24/{}^1m^2m^1m$ (16) | $mmm$ | $C_{4z}$ | $RuO_2$, $MnO_2$, $MnF_2$ |
| | P-4 *g*-wave | | ${}^14/{}^1m^2m^2m$ (16) | $4/m$ | $C_{2x}$ | $KMnF_3$ |
| | P-6 *i*-wave | $6/mmm$ | ${}^16/{}^1m^2m^2m$ (24) | $6/m$ | $C_{21}$ | |

| Spin-momentum locking | | G | $\mathbf{R}_s^{\mathrm{III}}$ | H | $\mathcal{A}$ | Candidate |
|---|---|---|---|---|---|---|
| Bulk | B-2 *d*-wave | $2/m$ | ${}^22/{}^2m$ (4) | $\bar{1}$ | $C_{2z}$ | $CuF_2$ |
| | B-4 *g*-wave | $\bar{3}m$ | ${}^1\bar{3}^2m$ (12) | $\bar{3}$ | $C_{21}$ | $CoF_3$, $FeF_3$, $Fe_2O_3$ |
| | | $6/m$ | ${}^26/{}^2m$ (12) | | $C_{6z}$ | |
| | | $6/mmm$ | ${}^26/{}^2m^2m^1m$ (24) | $\bar{3}m$ | $C_{6z}$ | CrSb, MnTe, $VNb_3S_6$ |
| | B-6 *i*-wave | $m\bar{3}m$ | ${}^1m^1\bar{3}^2m$ (48) | $m\bar{3}$ | $C_{4z}$ | |

L. Šmejkal, J. Sinova, and T. Jungwirth, Phys. Rev. X **12**, 031042 (2022)

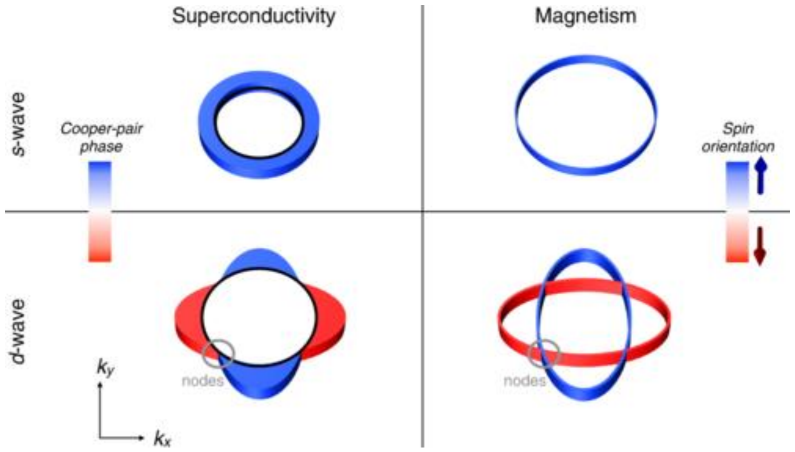
P-wave magnets



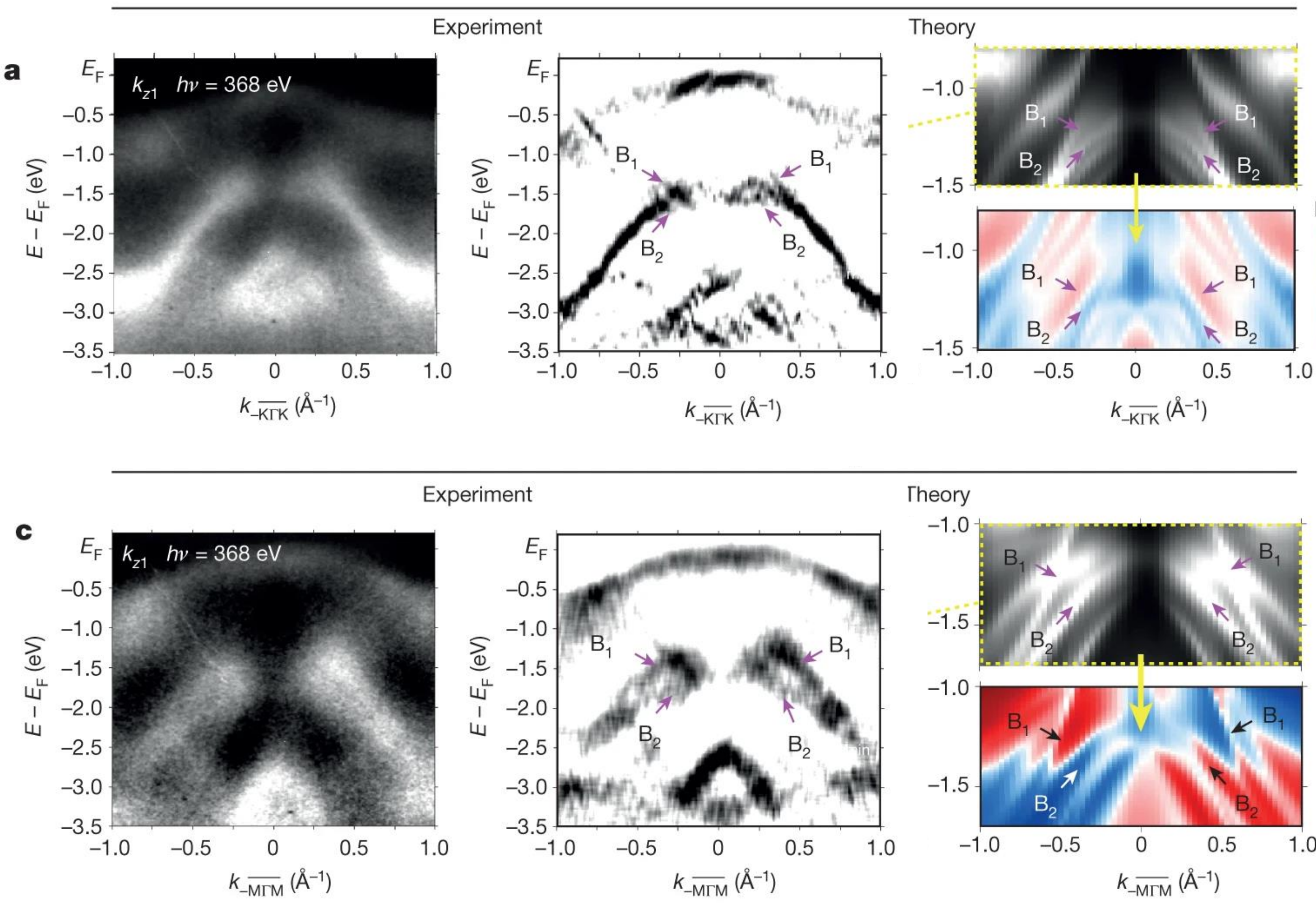

l=1 p-wave

He-3 superfluids

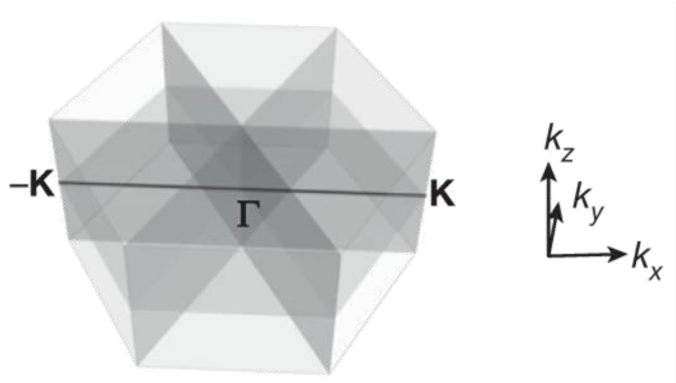


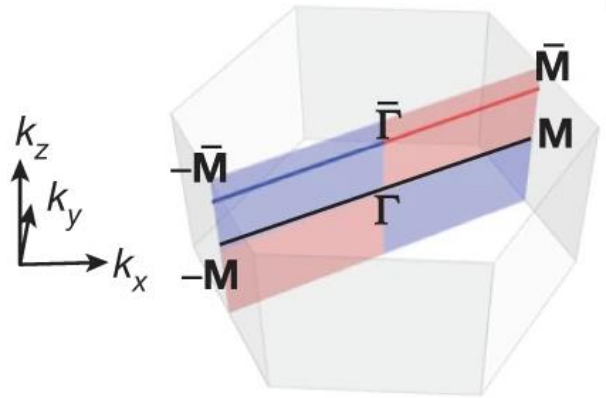

A.B. Hellenes, arXiv 2309.01607 (2023)

# Angle-resolved photoelectron emission spectroscopy MnTe




| Bulk | B-4 g-wave | | $\bar{3}m$ | $^1\bar{3}^2m$ (12) | $\bar{3}$ | $C_{2\parallel}$ | $CoF_3$, $FeF_3$, $Fe_2O_3$ |
|---|---|---|---|---|---|---|---|
|  | |  | 6/m | $^26/^2m$ (12) | | $C_{6z}$ | |
| | | | 6/mmm | $^26/^2m^2m^1m$ (24) | $\bar{3}m$ | $C_{6z}$ | CrSb, MnTe, $VNb_3S_6$ |

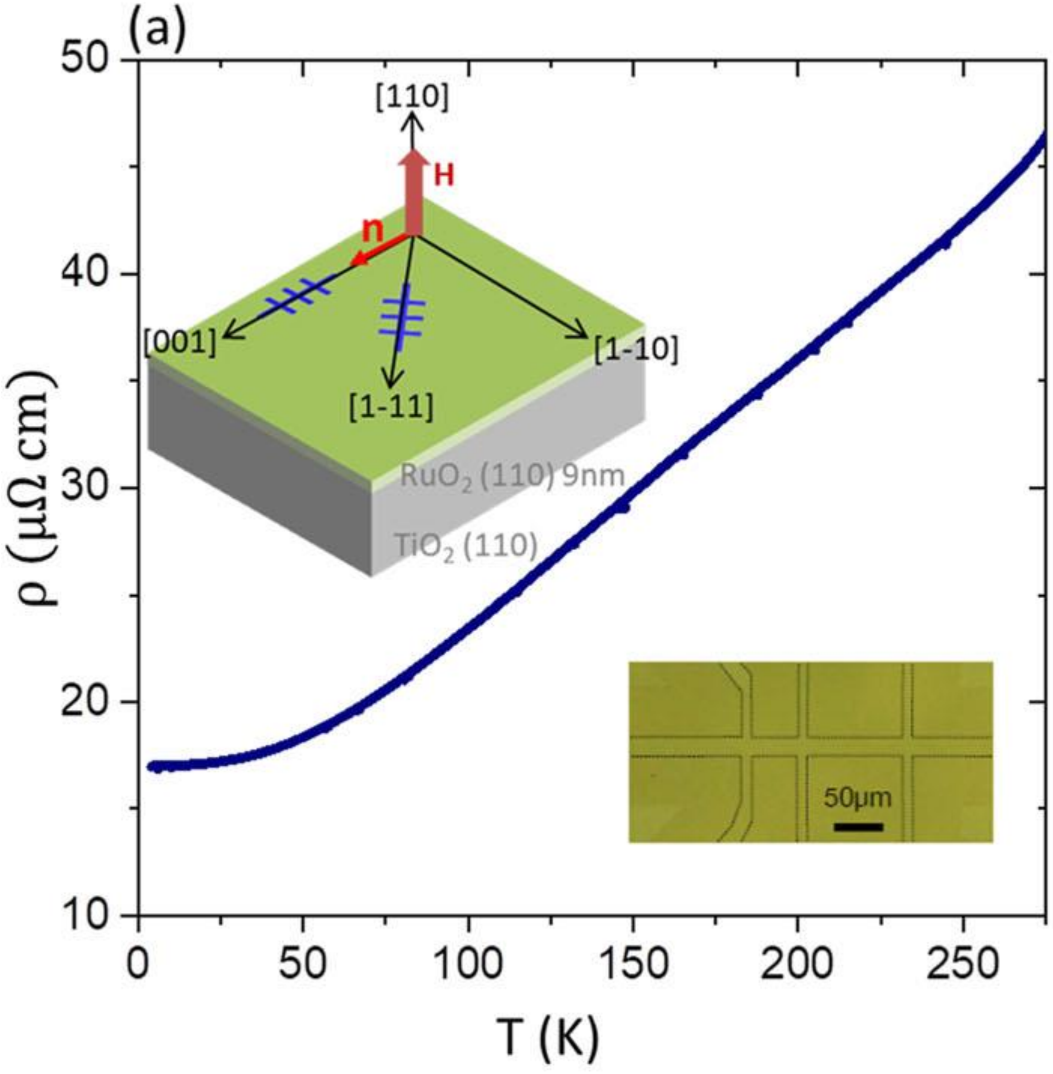


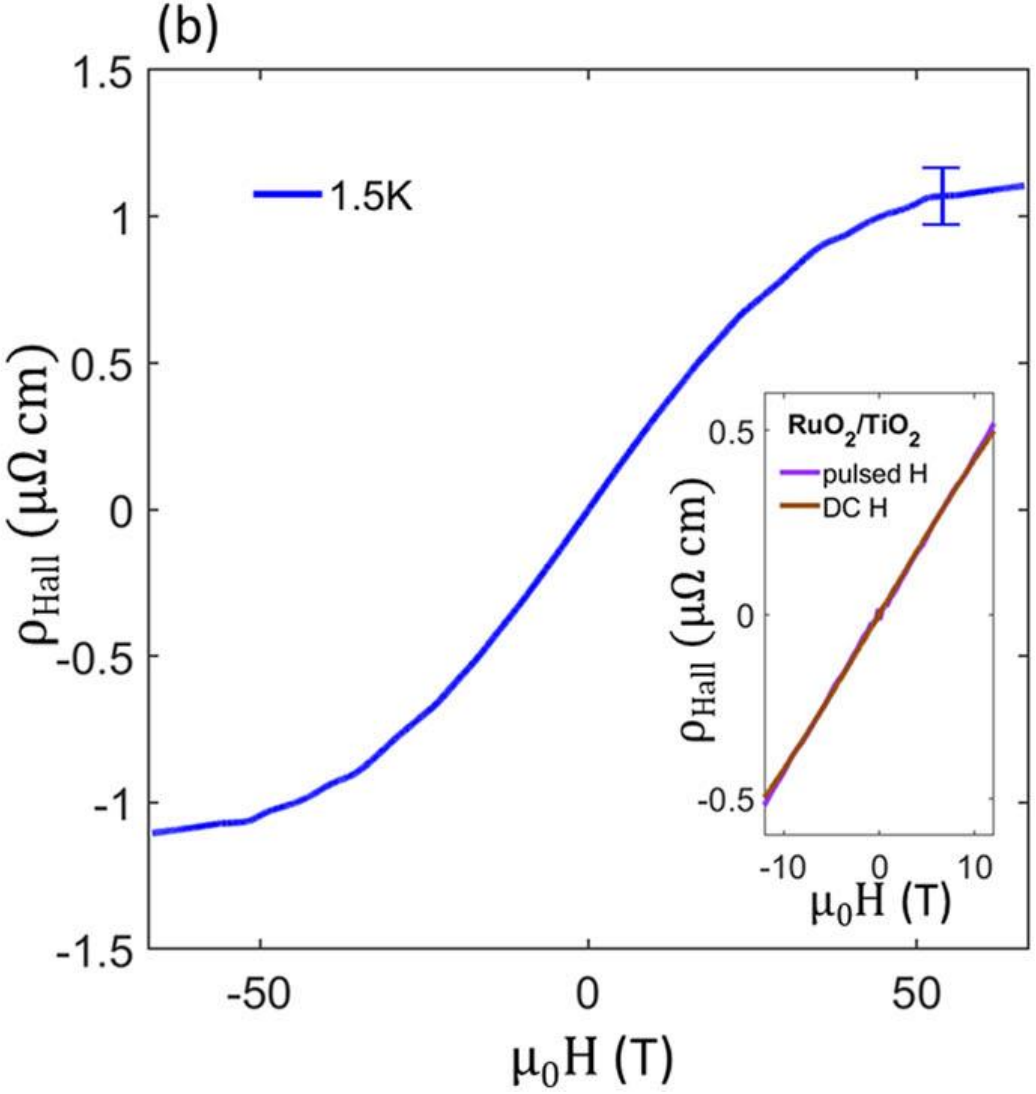






J. Krempaský *et al., Nature* **626**, 517 (2024)

# Anomalous Hall effect in RuO2

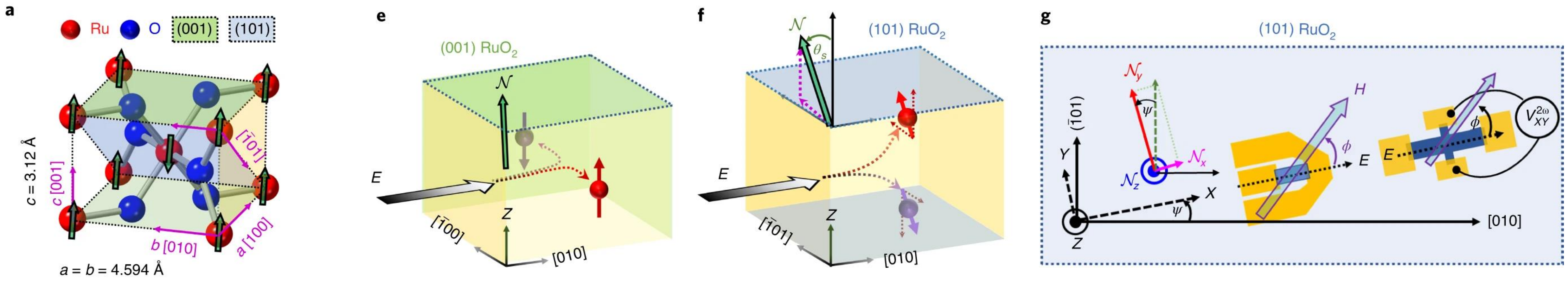


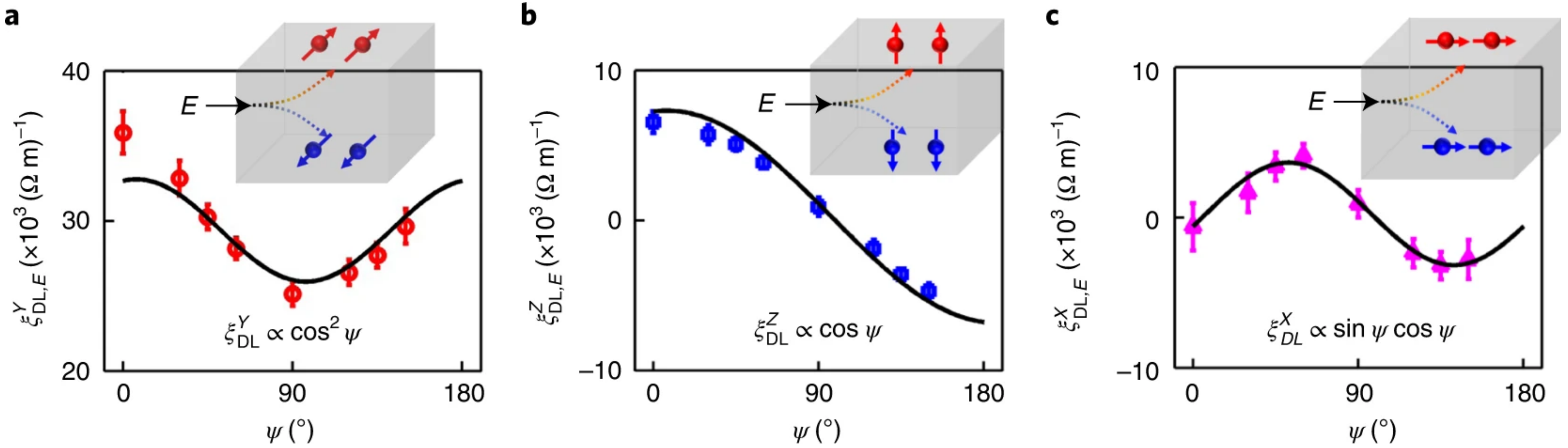




Z. Feng *et al., Nature Electronics* **5**, 735 (2022)

T. Tschirner *et al.*, *APL Mater.* **11**, 101103 (2023)

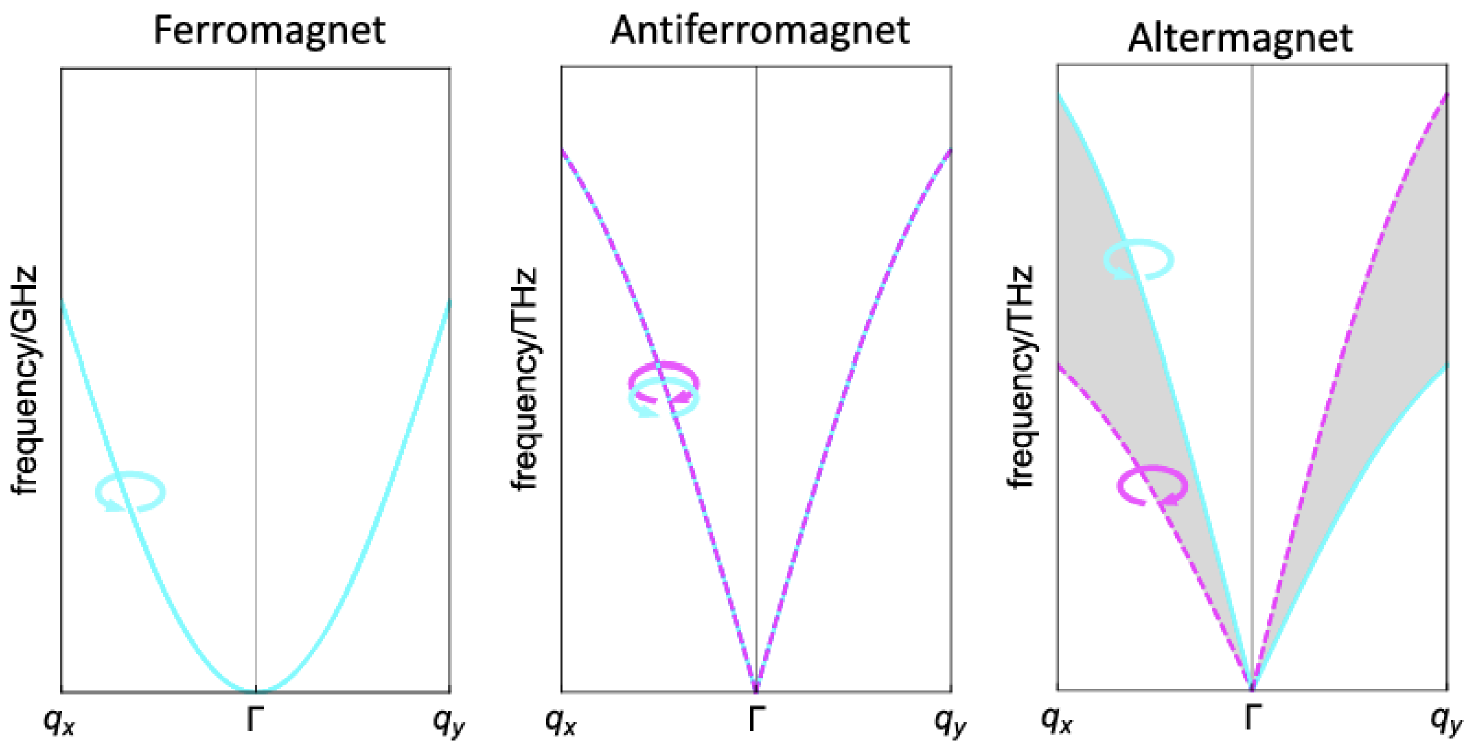
# Charge-to-Spin current conversion $RuO_2$

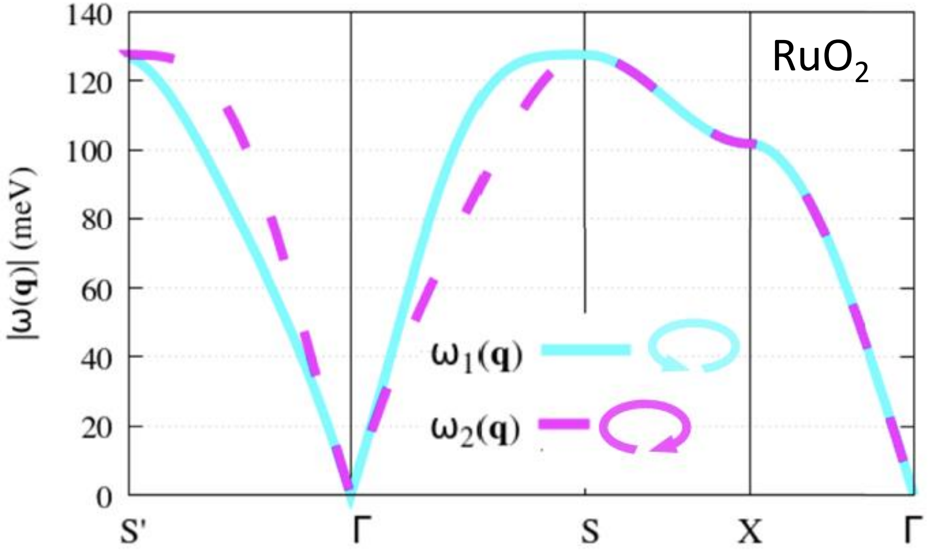



A. Bose *et al.*, *Nature Electronics* **5**, 267 (2022)

# Altermagnetic magnons



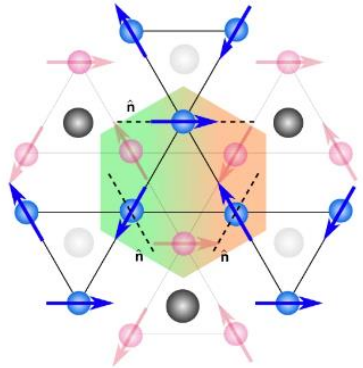

Splitting of magnon bands

Other excitations?

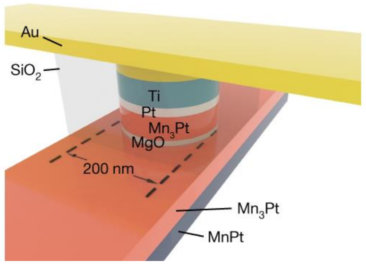
L. Šmejkal *et al.*, Phys. Rev. Lett. **131**, 256703 (2023)

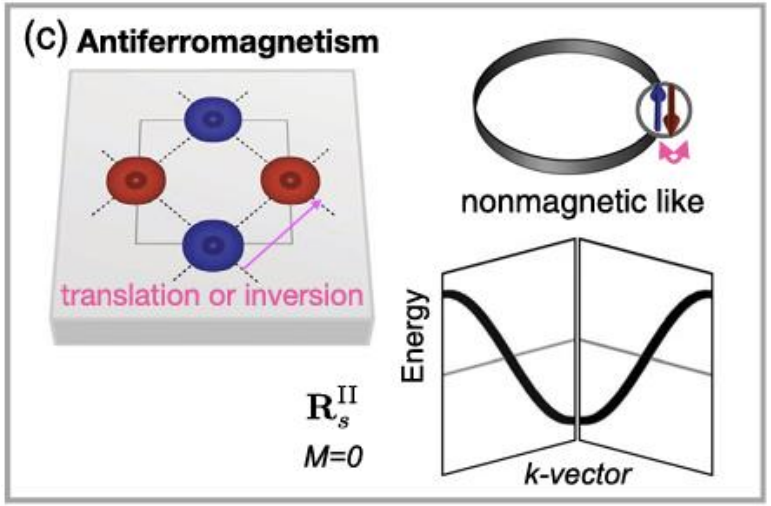
# Appetizer

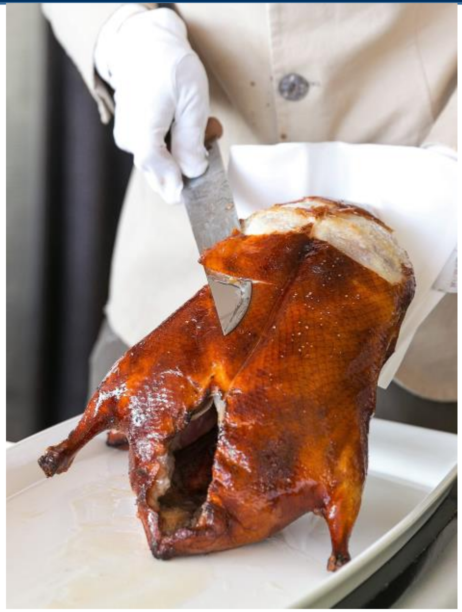
Find the duck!



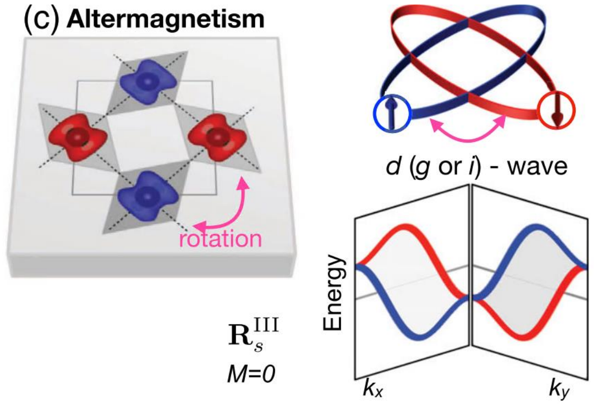

b

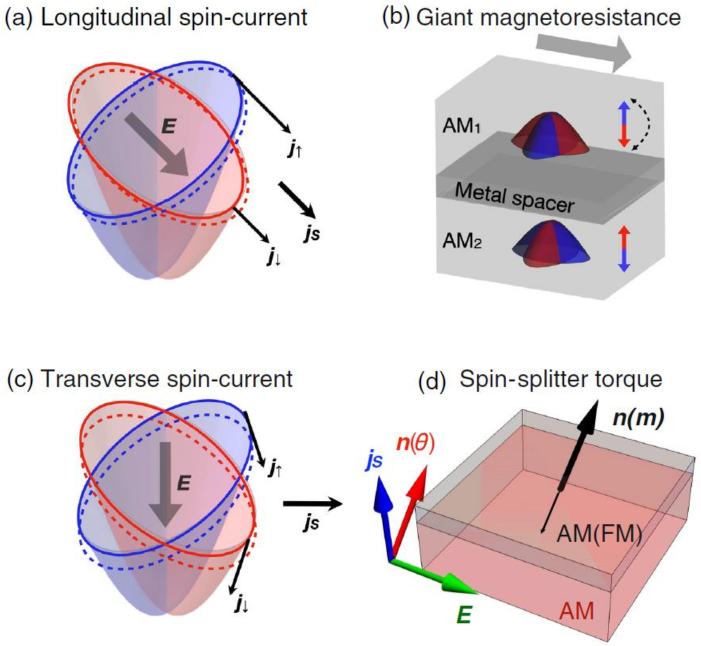


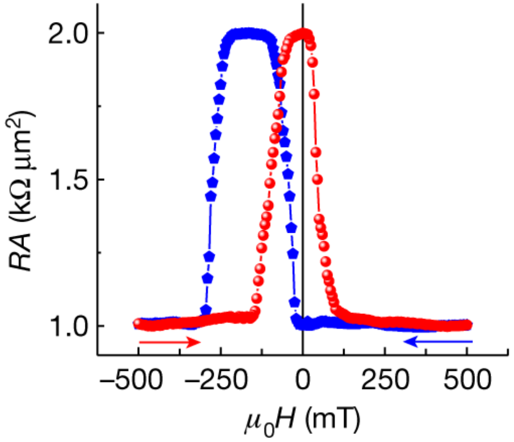



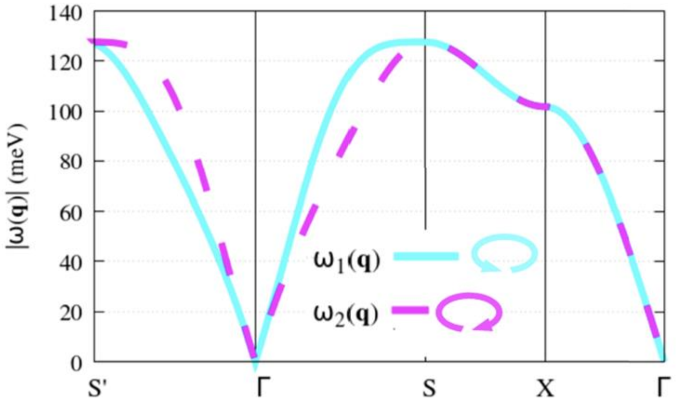



By City Foodsters - Cutting the Peking Duck skin tableside auf flickr, CC BY 2.0,
https://commons.wikimedia.org/w/index.php?curid=59070550



# Acknowledgements

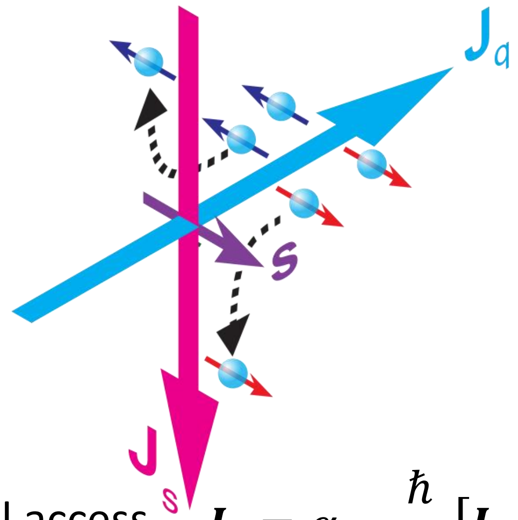

Theory support from
Akashdeep Kamra

J. Gückelhorn, T. Wimmer, M. Scheufele, M. Grammer, E. Karadza, L. Flacke,
S. Geprägs, H. Huebl, M. Opel, R. Gross,
R. Schlitz, S.T.B Goennenwein (U. Konstanz)

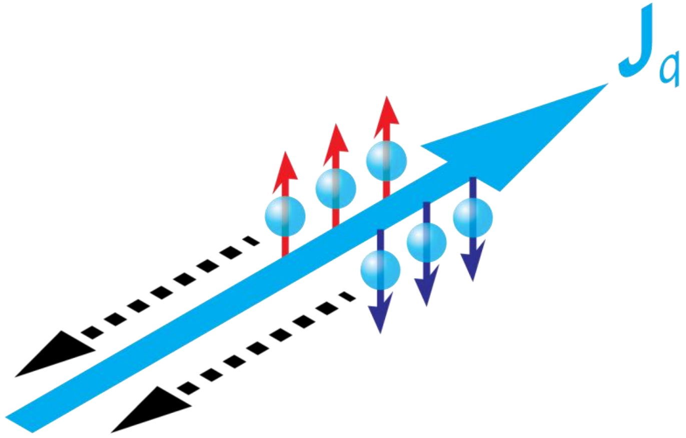
Universität Konstanz

# All-electrical Spin Current Generation and Detection

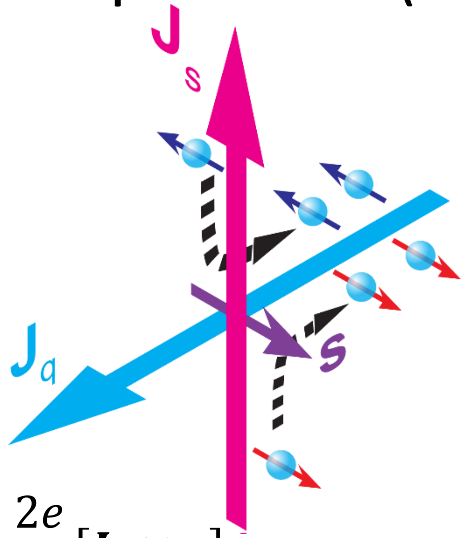
**direct spin Hall effect (SHE)**




**pure charge current**

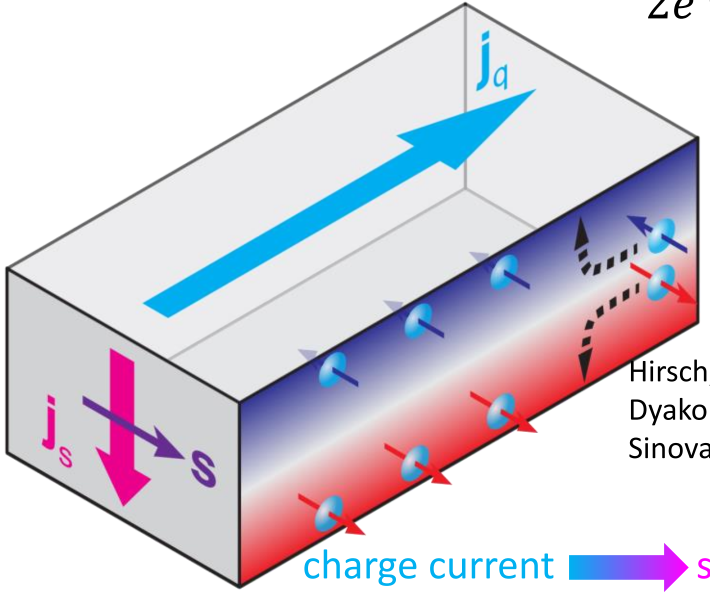



**inverse spin Hall effect (ISHE)**

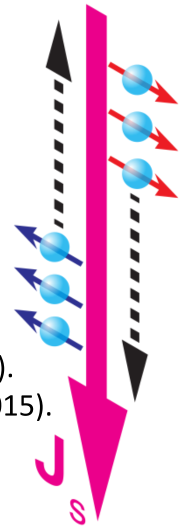


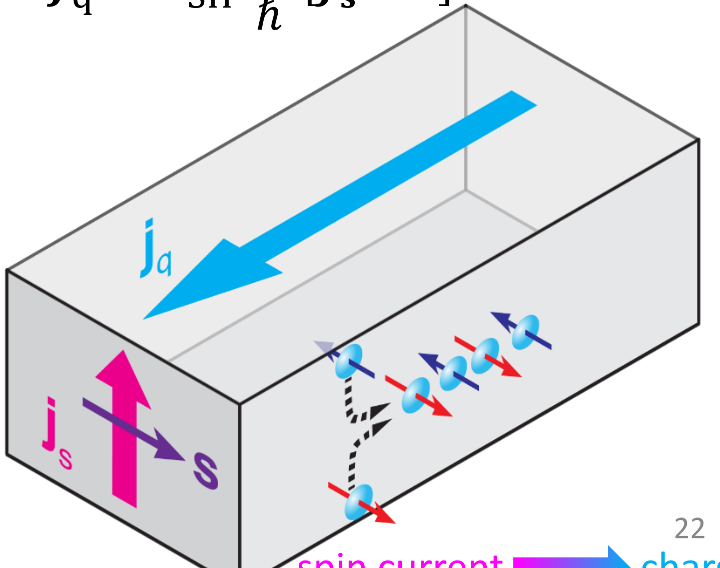

electrical access $J_{\mathbf{s}} = \alpha_{\mathrm{SH}} \frac{\hbar}{2e} [J_{\mathrm{q}} \times \boldsymbol{s}]$

$J_{\mathrm{q}} = \alpha_{\mathrm{SH}} \frac{2e}{\hbar} [J_{\mathbf{s}} \times \boldsymbol{s}]$




**pure spin current**



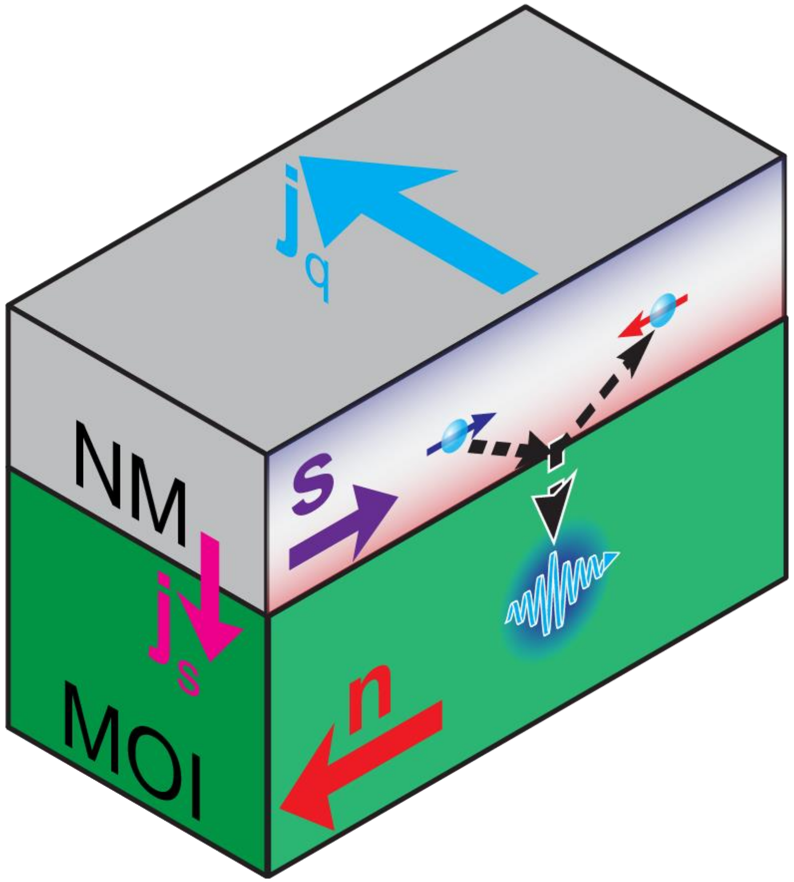




Hirsch, PRL **83**, 1834 (1999).
Dyakonov, Perel, JETP Lett.. **13**, 467 (1971).
Sinova et al., Rev. Mod. Phys. 87, 1213 (2015).

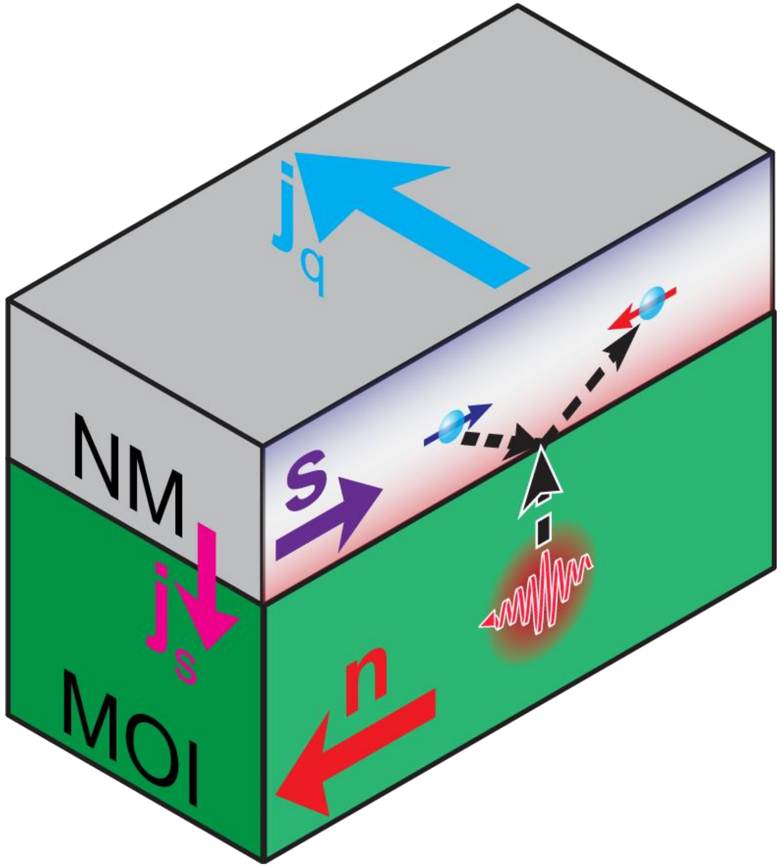
charge current → spin current

spin current → charge current

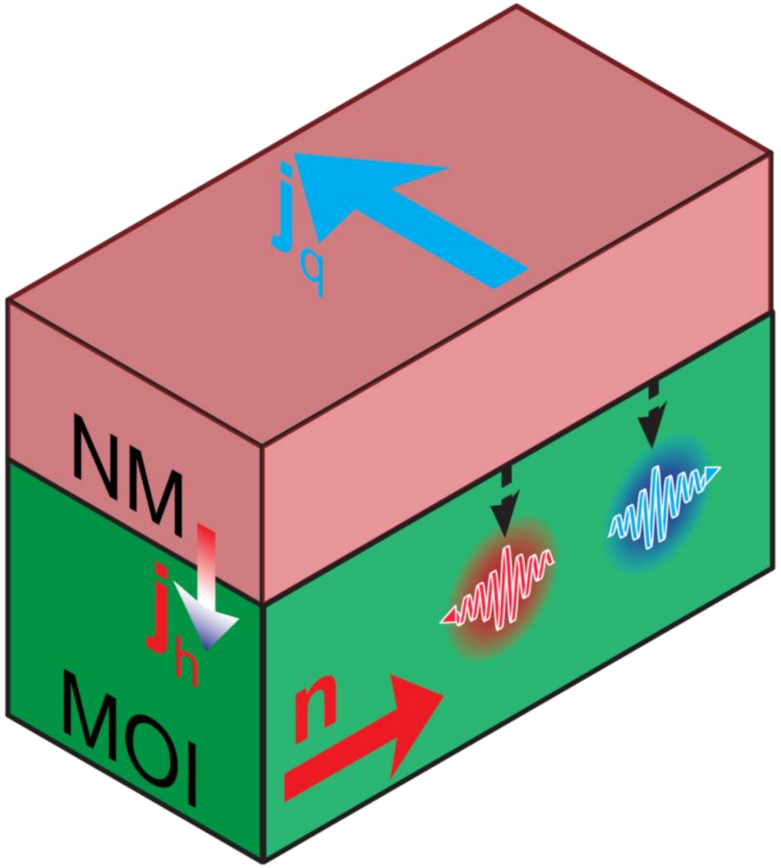
# All-Electrical Magnon Transport




SHE induced magnon generation




SHE induced magnon absorption




Joule heating induced magnon generation


Bender and Tserkovnyak, PRB **91**, 140402 (2015).
Cornelissen *et al*., Nat. Phys. **11**, 1022 (2015).
Goennenwein *et al*., APL **107**, 172405 (2015).
Cornelissen et al., PRB **94**, 014412 (2016).
Lebrun *et al*., Nature **561**, 222 (2018).




Electrically controlled magnon accumulation/depletion in thermal magnon gas

# All-Electrical Magnon Transport

**Reviews:**
Althammer, Phys Stat Sol RRL **15**, 2100130 (2021).
Althammer, J. Phys. D: Appl. Phys. **51** , 313001 (2018).


Experiment:
Cornelissen *et al*., Nat. Phys. **11**, 1022 (2015).
Goennenwein, MA *et al.*, APL **107**, 172405 (2015).
Cornelissen et al., PRB **94**, 014412 (2016).
Ganzhorn *et al.*, APL **109**, 022405 (2016).
Liu *et al.*, PRB **95**, 140402 (2017).
Ganzhorn *et al.*, AIP Advances **7**, 085102 (2017).
Cornelissen *et al.*, PRL **120**, 097702 (2018).
Lebrun *et al*., Nature **561**, 222 (2018).
Wimmer, MA *et al.*, PRL **123** , 257201 (2019).
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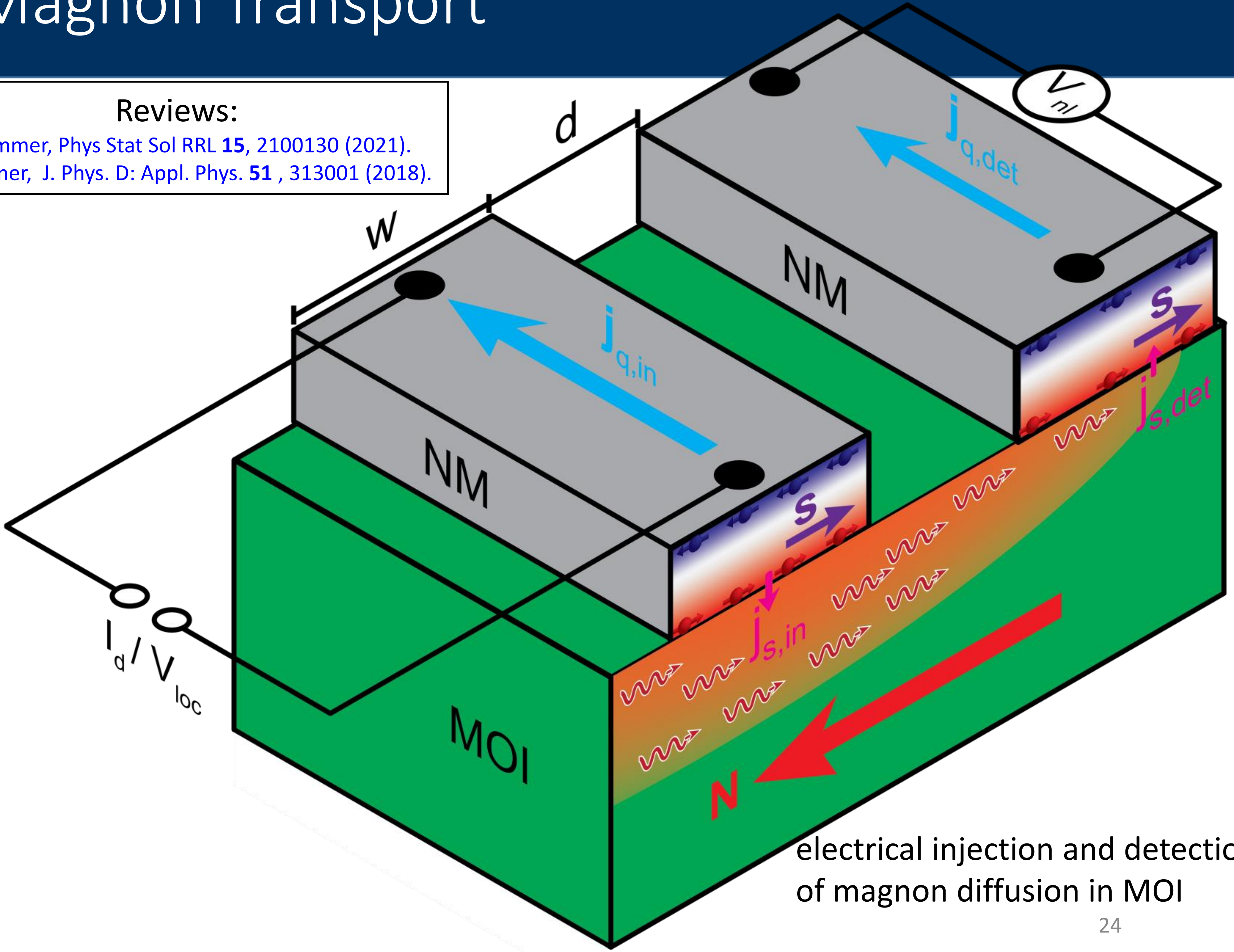
Ross et al., Nano Lett. **20**, 306 (2020).
J. Han et al., Nat. Nano. **15**, 1748 (2020).
Gückelhorn, MA et al., APL **117** , 182401 (2020).
Wimmer, MA, et al., PRL **125** , 247204 (2020).
R. Schlitz et al., PRL **126**, 257201 (2021).
Gückelhorn, MA et al., PRB **104**, L180410 (2021).
Gückelhorn, MA et al., PRB **105**, 094440 (2022).
X-Y. Wei et al., Nat. Mater. **21**, 1352 (2022).
J. Gao et al., Phys. Rev. Research **4**, 043214 (2022).
Gückelhorn, MA et al., PRL **130**, 216703 (2023).

Theory:
Zhang and Zhang, PRL **109**, 096603 (2012).
Zhang and Zhang, PRB **86**, 214424 (2012).
Bender and Tserkovnyak, PRB **91**, 140402 (2015).
Takei, PRB **100**, 134440 (2019).
Kamra, MA, et al., PRB **102** , 174445 (2020).


electrical injection and detection of magnon diffusion in MOI

# Antiferromagnetic Magnons

**2** magnon modes in AFMs

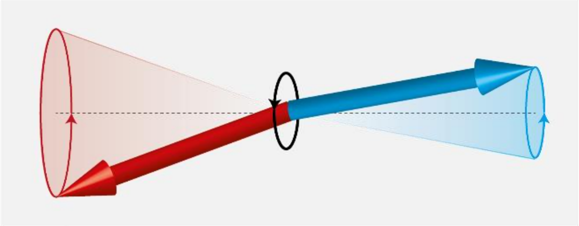
**Easy axis antiferromagnet**

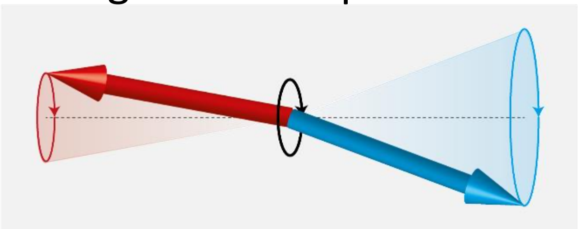
β-mode

α-mode

Left-circular polarized

Right-circular polarized

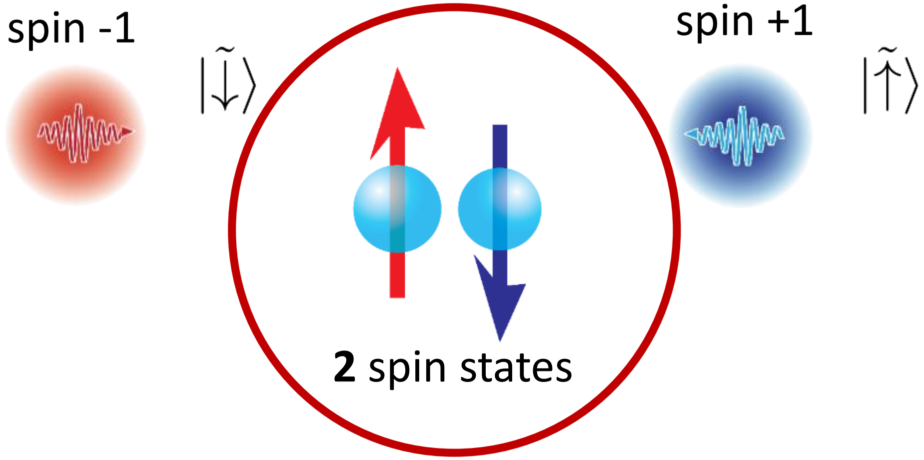


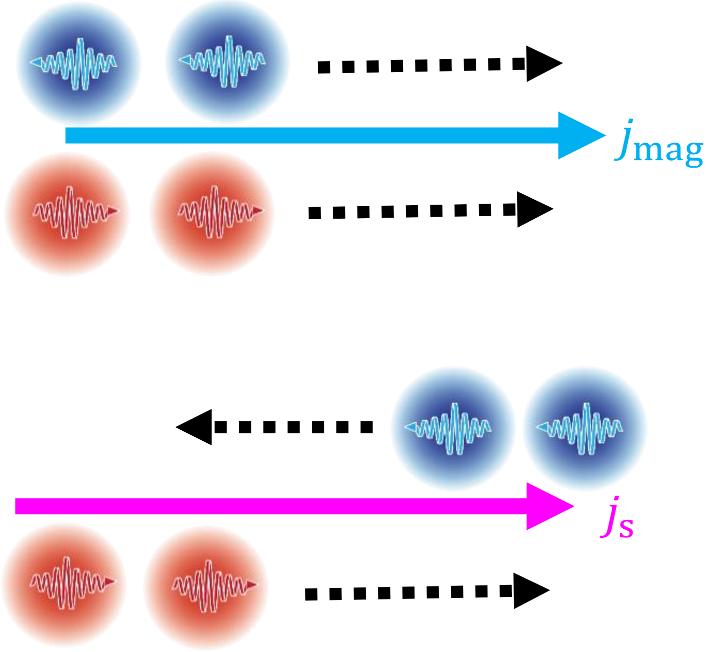


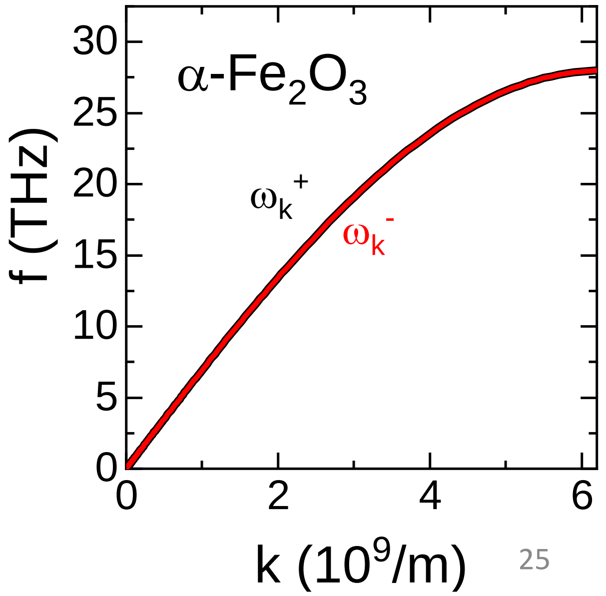
**Easy plane antiferromagnet**

linear polarized

linear polarized

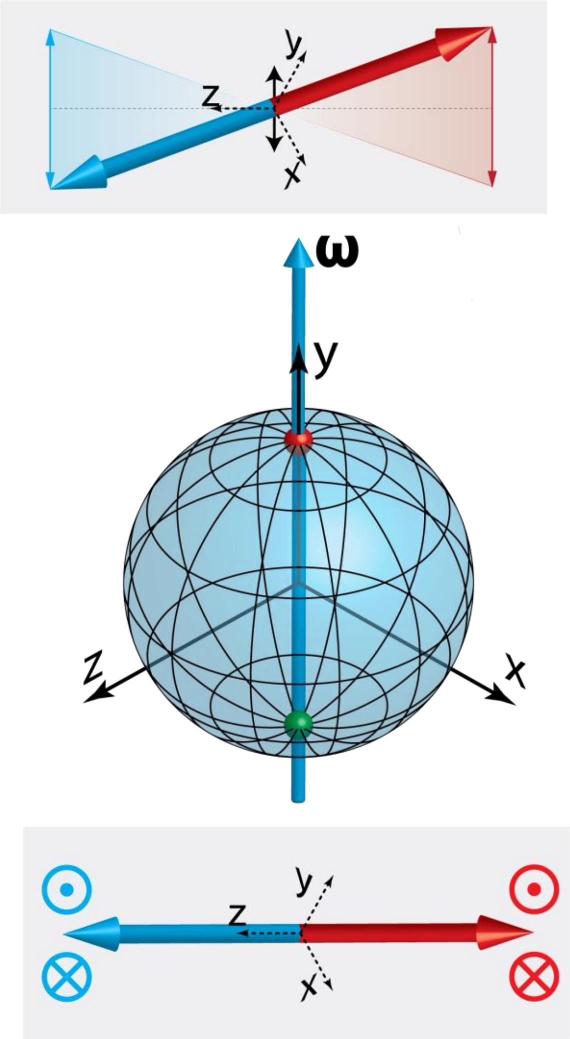


R. Cheng *et al.*, Sci. Rep. **6**, 24223 (2016).
Rezende *et al.*, JAP **126**, 151101 (2019).
K. Nakata *et al.*, J. Phys. D **50**, 114004 (2017).
M.W. Daniels *et al.*, Phys. Rev. B **98**, 134450 (2018).
K Shen, JAP **129**, 223906 (2021).
J. Han *et al.,* Nat. Mater. (2023).

# Antiferromagnetic Magnons Described via Pseudospin

A. Kamra

Pseudospin **S**




T. Wimmer *et al.*, Phys. Rev. Lett. **125** , 247204 (2020).
A. Kamra *et al.,* Phys. Rev. B **102**, 174445 (2020).

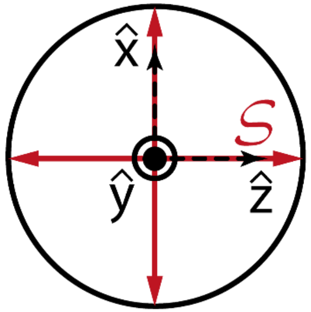


General concept also applicable to other bosonic systems, e.g. photons, phonons

# Antiferromagnetic Magnons Described via Pseudospin

A. Kamra

Pseudospin **S**



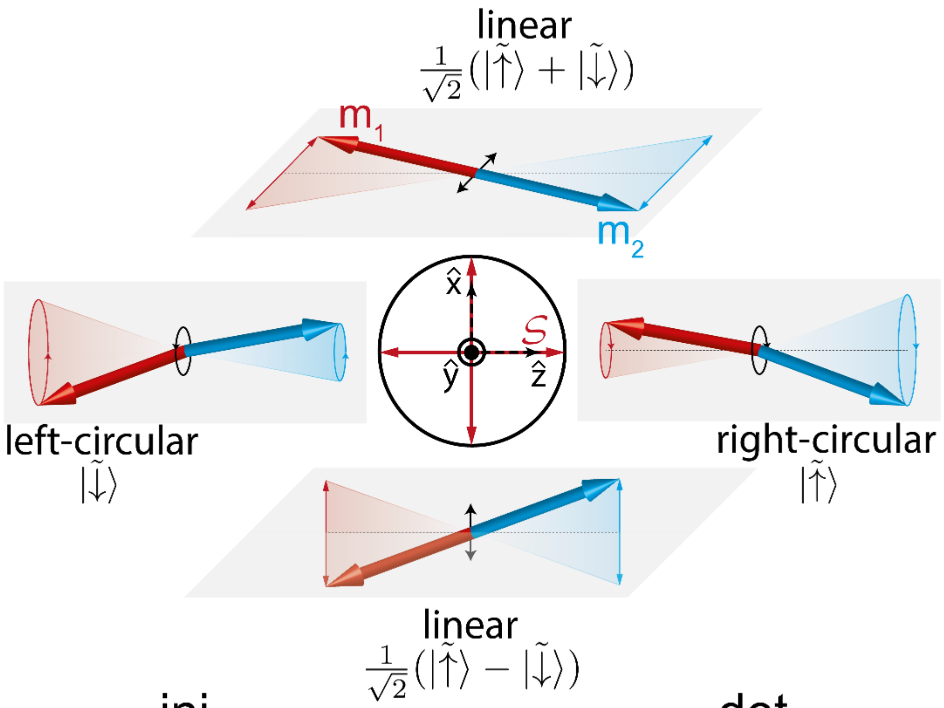

- Pseudospin **S** direction determines the polarization state of the magnon modes and their superpositions
- Finite magnon spin is given by z component of **S**
- Mapping of up- and down-spin states similar to Bloch sphere description of a two-level system

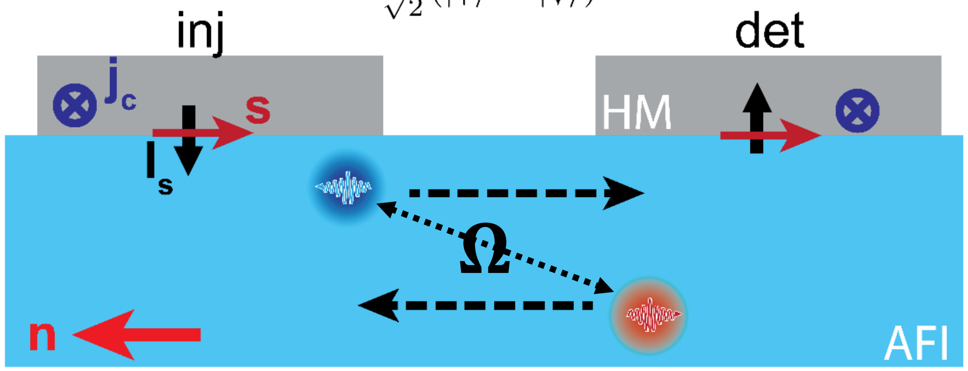
T. Wimmer *et al.*, Phys. Rev. Lett. **125** , 247204 (2020).
A. Kamra *et al.,* Phys. Rev. B **102**, 174445 (2020).



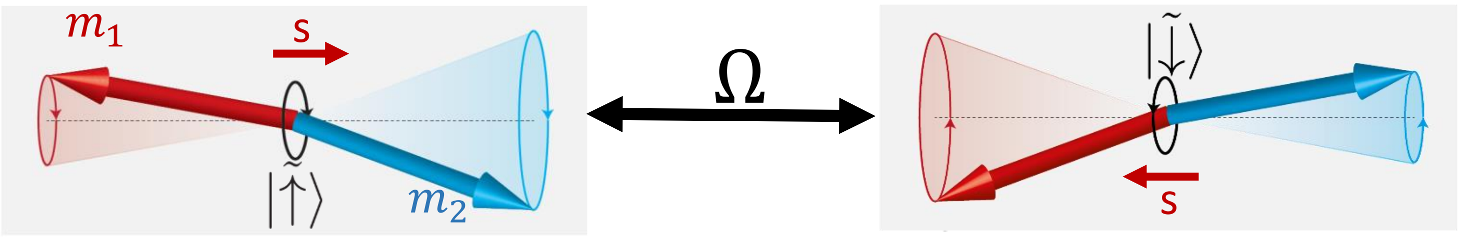
General concept also applicable to other bosonic systems, e.g. photons, phonons

# Mode Coupling Ω and Pseudospin Diffusion Equation




What happens when they couple?




Mode coupling Ω induced via breaking of rotational symmetry about the Neel vector $\boldsymbol{n}$

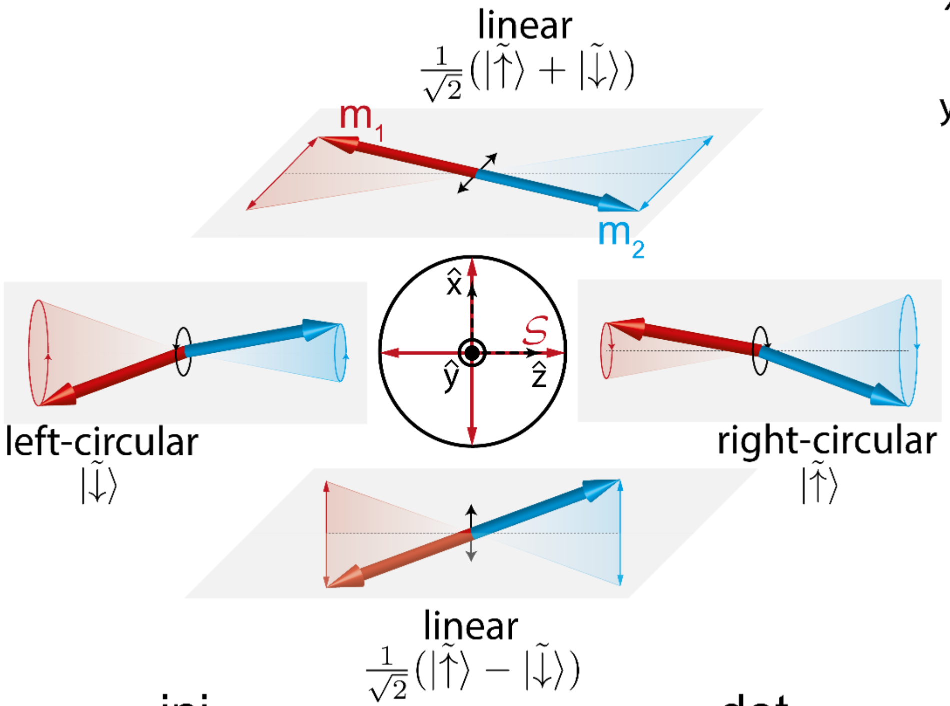
## Diffusive pseudospin transport equation:

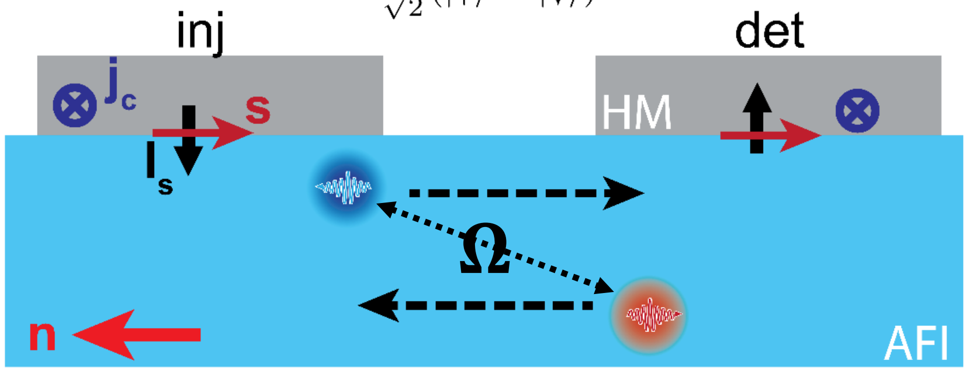
$$\frac{\partial \mathcal{S}}{\partial t} = D\nabla^2 \mathcal{S} - \frac{\mathcal{S}}{\tau_s} + \mathcal{S} \times \Omega\, \hat{\mathbf{y}}$$

**S** : pseudospin density vector
$D$: diffusion constant
$\tau_s$: spin lifetime
Ω: coherent coupling between ‘spin-up’ and ‘spin-down’ modes → precession frequency of pseudospin

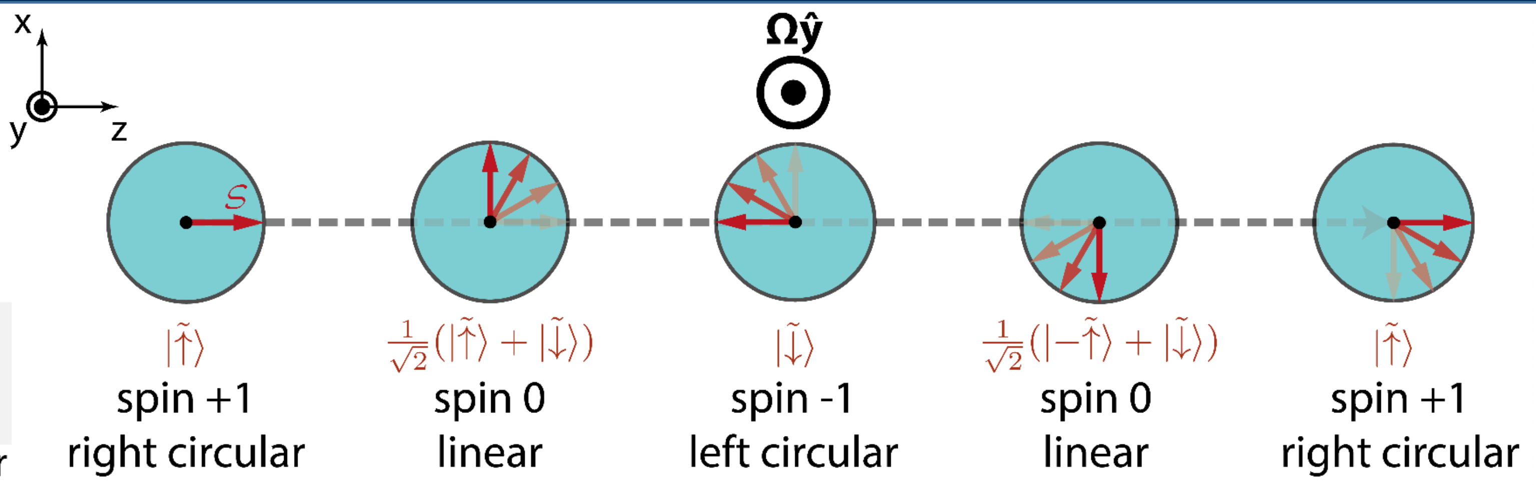
T. Wimmer *et al.*, Phys. Rev. Lett. **125** , 247204 (2020).
A. Kamra *et al.,* Phys. Rev. B **102**, 174445 (2020).

# Mode Coupling Ω and Pseudospin Diffusion Equation




What happens when they couple?




Diffusive pseudospin transport equation:

$$\frac{\partial \mathcal{S}}{\partial t} = D\nabla^2 \mathcal{S} - \frac{\mathcal{S}}{\tau_s} + \mathcal{S} \times \Omega\,\hat{\mathbf{y}}$$

**S** : pseudospin density vector

$D$: diffusion constant

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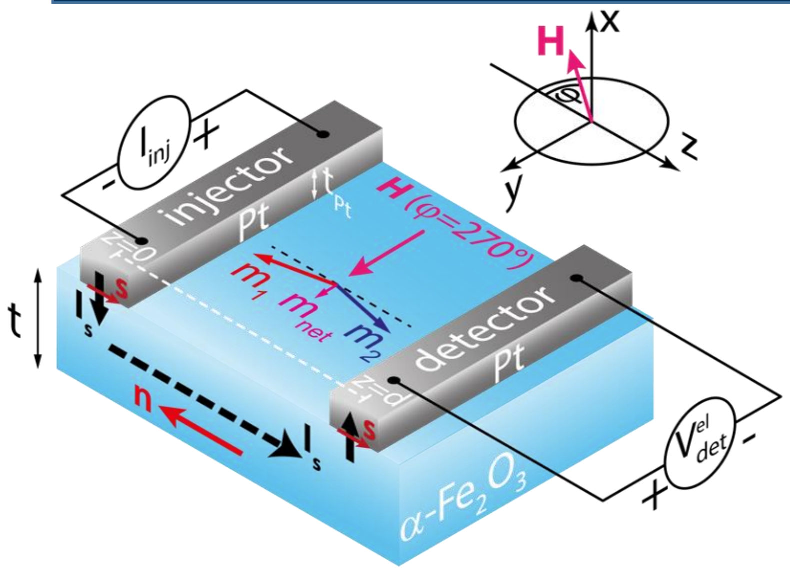
Ω: coherent coupling between 'spin-up' and 'spin-down' modes → precession frequency of pseudospin

T. Wimmer *et al.*, Phys. Rev. Lett. **125** , 247204 (2020).
A. Kamra *et al.,* Phys. Rev. B **102**, 174445 (2020).

# Pseudospin Precession Frequency in Hematite and 1D Solution of Pseudospin Diffusion Equation




In hematite: coupling Ω determined by easy-plane anisotropy and DMI induced canting

Pseudospin precession frequency:

$$\hbar\Omega = \hbar\widetilde{\omega}_{an} - \mu_0 m_{net0} H$$

$m_{net0}$: canted magnetic moment at zero external field
→ DMI-induced canting
$\omega_{an}$: easy-plane anisotropy energy

$$\frac{\partial \mathcal{S}}{\partial t} = D\nabla^2\mathcal{S} - \frac{\mathcal{S}}{\tau_s} + \mathcal{S} \times \Omega\,\hat{\mathbf{y}}$$

Boundary condition at injector ($z = 0$): $-D\frac{\partial \mathcal{S}_z}{\partial z} = j_{s0}$

Steady state solution in 1-D:

$$s_z(z) = \frac{j_{s0}\lambda_s}{D(a^2+b^2)} e^{\frac{-az}{\lambda_s}} \left(b\cos\left(\frac{b\,z}{\lambda_s}\right) - a\sin\left(\frac{b\,z}{\lambda_s}\right)\right)$$

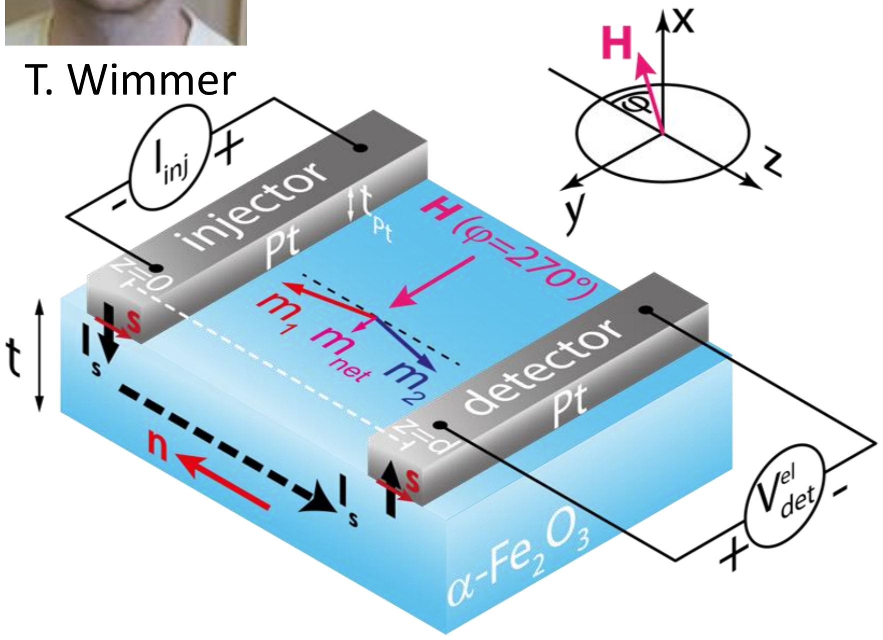
with $a = \frac{1}{\sqrt{2}}\sqrt{1+\sqrt{1+\Omega^2\tau_s^2}}$ and b $= \frac{1}{\sqrt{2}}\sqrt{-1+\sqrt{1+\Omega^2\tau_s^2}}$
and $\lambda_s = \sqrt{D\tau_s}$ spin Diffusion Length


T. Wimmer *et al.*, Phys. Rev. Lett. **125** , 247204 (2020).
A. Kamra *et al.,* Phys. Rev. B **102**, 174445 (2020).

# Sample Layout and Properties: Pt/$\alpha$-$Fe_2O_3$(hematite)

T. Wimmer

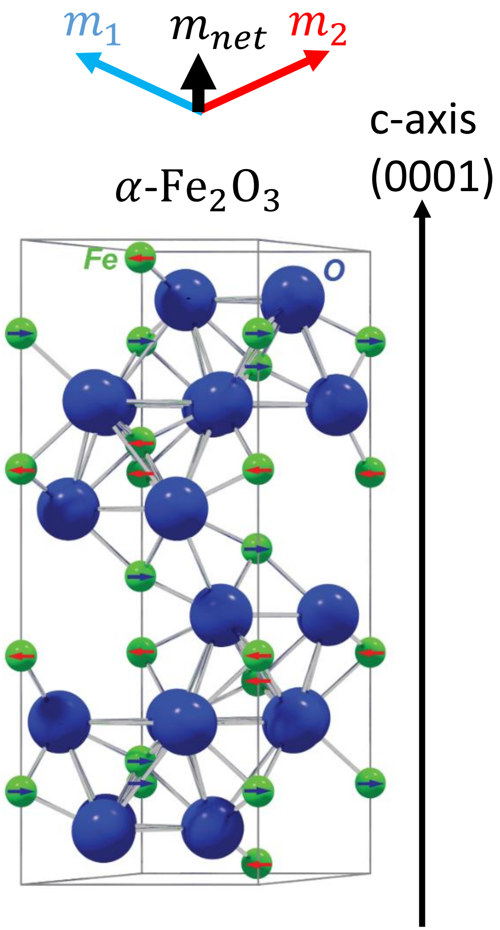
$t_{\mathrm{Pt}} = 5$ nm
$t_{\mathrm{Fe_2O_3}} = 15$ nm




$$V_{\mathrm{det}}^{\mathrm{el}} = \frac{V_{\mathrm{det}}(+I) - V_{\mathrm{det}}(-I)}{2}$$

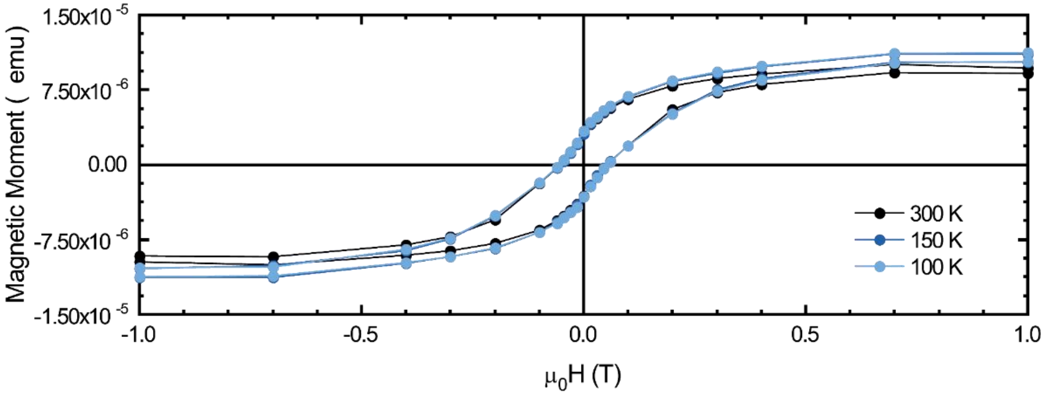
Normalization: $R_{\mathrm{det}}^{\mathrm{el}} = \frac{V_{\mathrm{det}}}{I_{\mathrm{inj}}} \cdot \frac{A_{\mathrm{inj}}}{A_{\mathrm{det}}}$

magnetic easy-plane (c-plane) with slight canting due to DMI




- hexagonal (0001) orientation
- grown via pulsed laser deposition (PLD) on sapphire $Al_2O_3$
- 15nm thick
- shows NO Morin transition

→ Spins oriented in-plane for all temperatures
→ magnetic easy-plane film



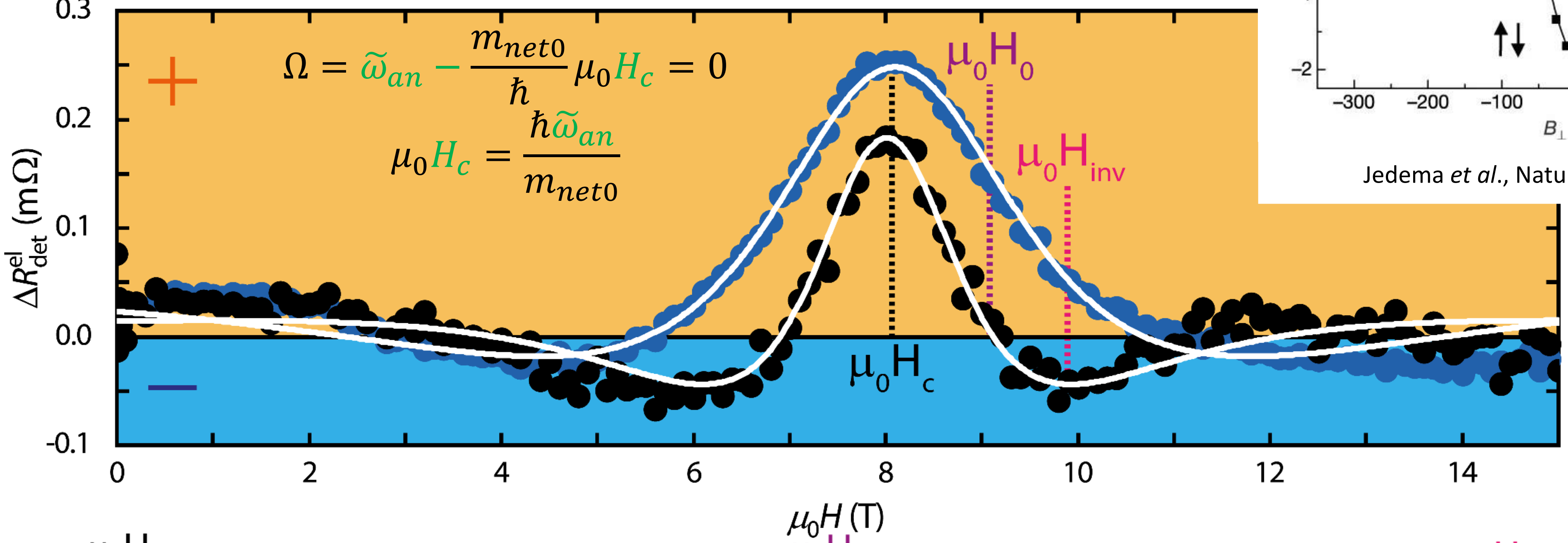

ferromagnetic behaviour due to canted moment and easy plane anisotropy

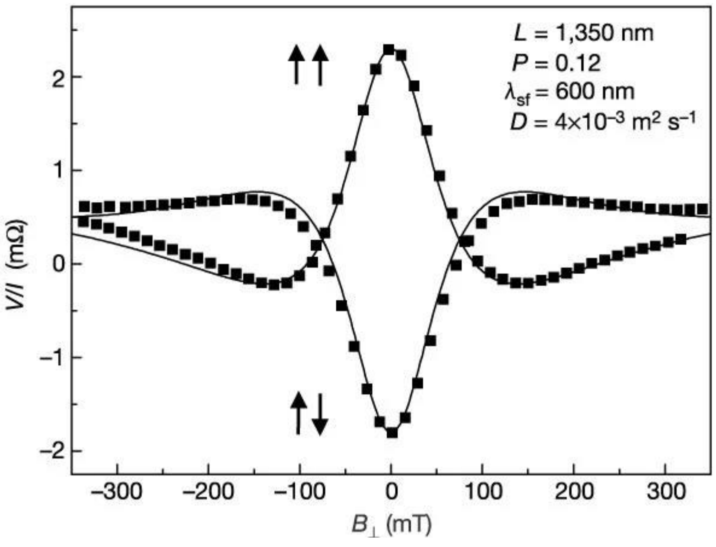
vanishing Morin transition observed for thin hematite also in:
J. Han *et al.*, Nature Nanotechnology **15**, 1748-3395 (2020).

# Antiferromagnetic Magnon Hanle Effect

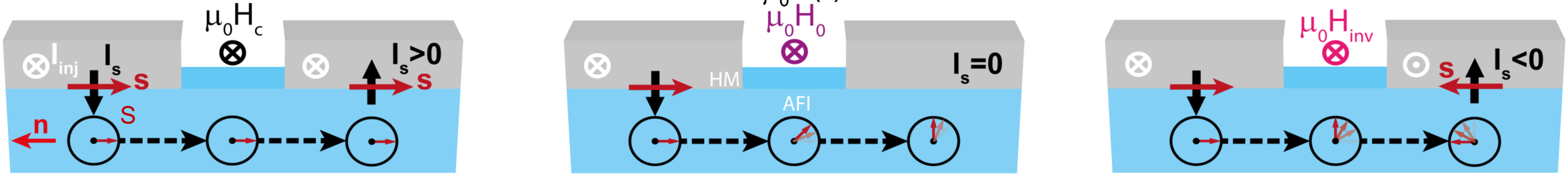
T. Wimmer *et al.*, Phys. Rev. Lett. **125** , 247204 (2020).
A. Kamra *et al.*, Phys. Rev. B **102**, 174445 (2020).
A. Ross *et al.,* Appl. Phys. Lett. **117**, 242405 (2020).
K. Shen, Journal of Applied Physics **129**, 223906 (2021).
V. Brehm *et al.*, Phys. Rev.. B **107**, 184404 (2023).

$$\Delta R^{\mathrm{el}}_{\mathrm{det}} \propto s_z(z)$$




Jedema *et al.*, Nature **416**, 713 (2002).




$\Omega = 0$
$s_z > 0$

$\Omega_0 > 0$
$s_z = 0$

$\Omega > \Omega_0$
$s_z < 0$

# Nonreciprocal Pseudospin Diffusion Equation

A. Kamra

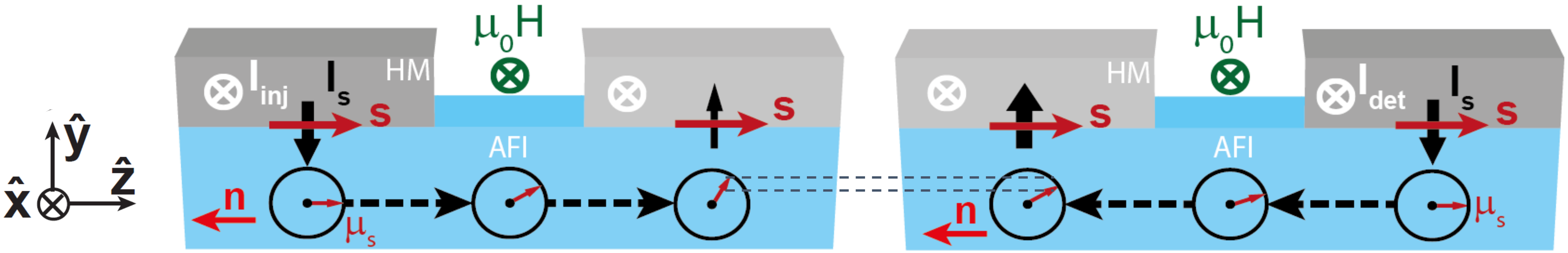
Diffusive pseudospin transport equation:

$$\frac{\partial \boldsymbol{\mu}_s}{\partial t} = D\nabla^2 \boldsymbol{\mu}_s - \frac{\boldsymbol{\mu}_s}{\tau_s} + \boldsymbol{\mu}_s \times \omega \hat{\boldsymbol{x}} - l \frac{\partial \boldsymbol{\mu}_s}{\partial z} \times \delta\omega \hat{\boldsymbol{x}}$$

Antisymmetric component of the k-resolved pseudofield $\boldsymbol{\omega}(\boldsymbol{k})$

$$\boldsymbol{\mu}_s(z) = \boldsymbol{\mu}_s^{\mathrm{sym}}(z) + \boldsymbol{\mu}_s^{\mathrm{asym}}(z)$$

$$\mu_{sz}(+d) = \mu_{sz}^{\mathrm{sym}}(d) + \mu_{sz}^{\mathrm{asym}}(d) \qquad \mu_{sz}(-d) = \mu_{sz}^{\mathrm{sym}}(d) - \mu_{sz}^{\mathrm{asym}}(d)$$

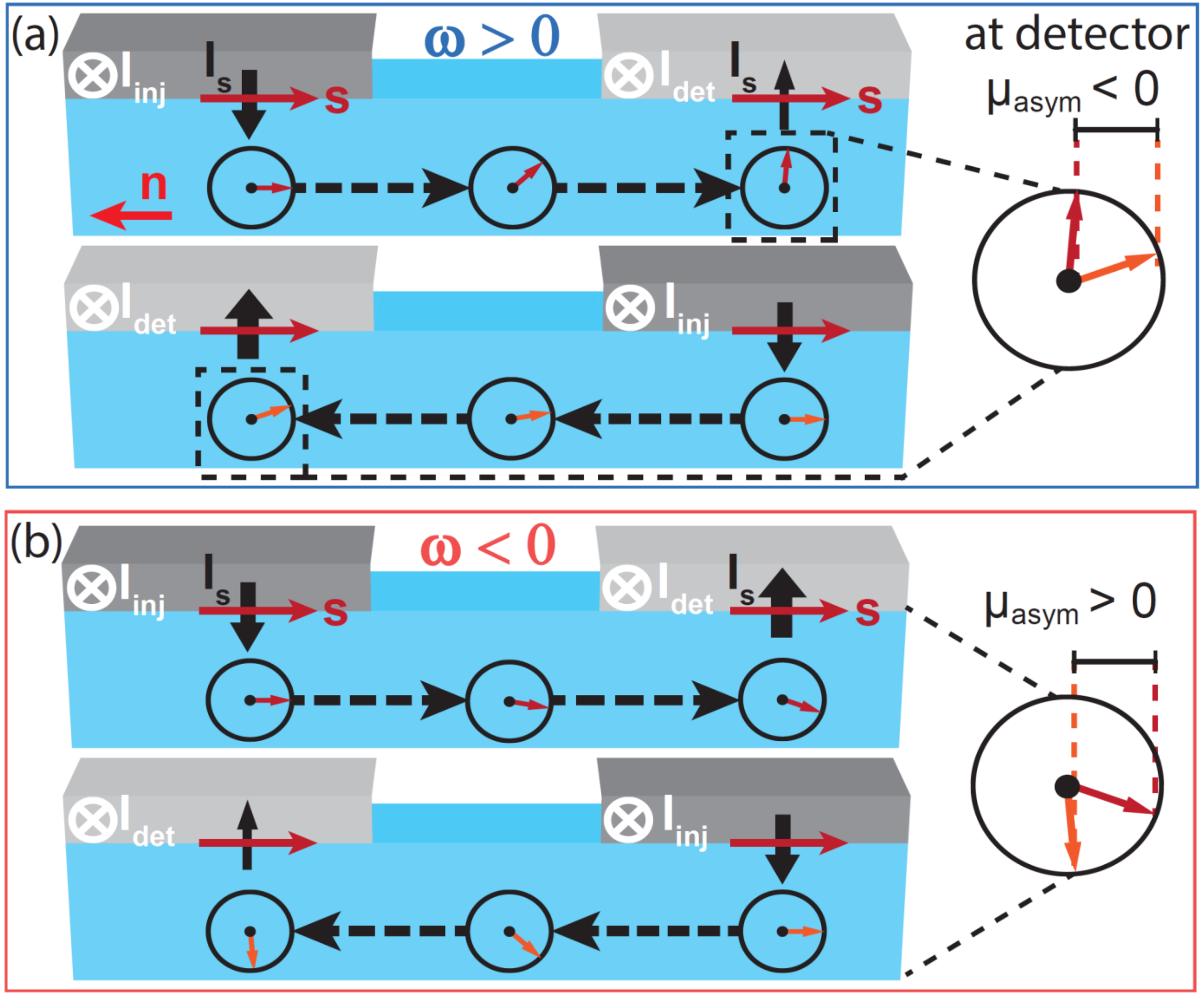


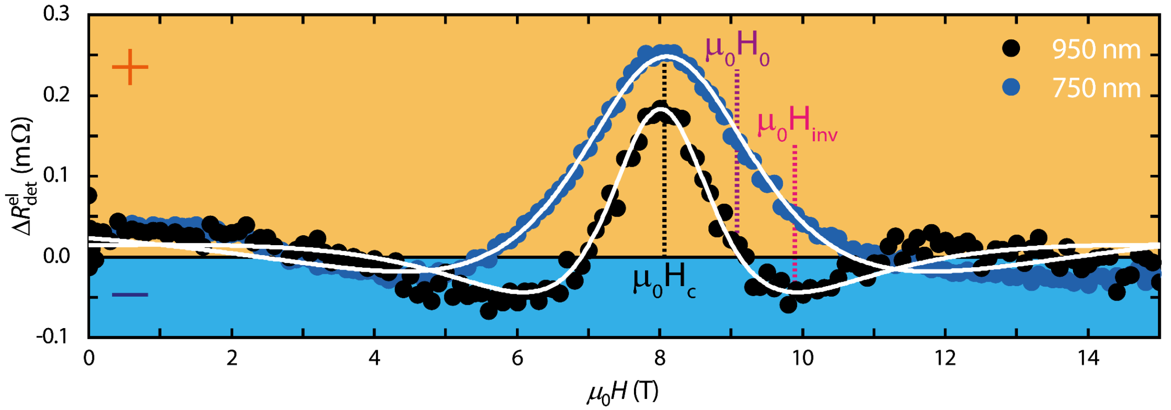

Inj → Det

Det → Inj

J. Gückelhorn, et al., PRL **130**, 216703 (2023).

# Magnetic Field Dependence




$\mu_0 H < \mu_0 H_c$

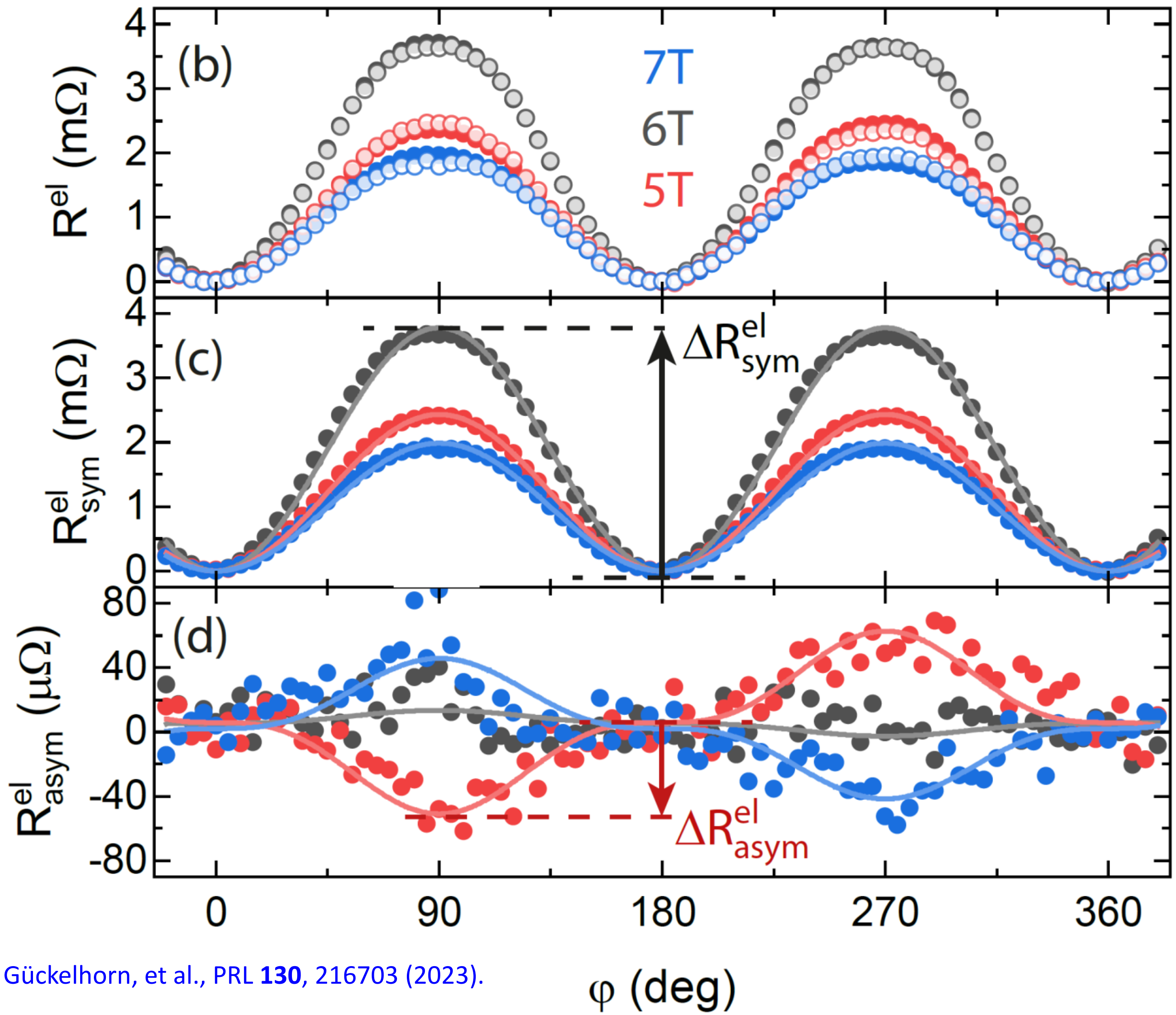
$$\boldsymbol{\mu}_s(z) = \boldsymbol{\mu}_s^{\text{sym}}(z) + \boldsymbol{\mu}_s^{\text{asym}}(z)$$

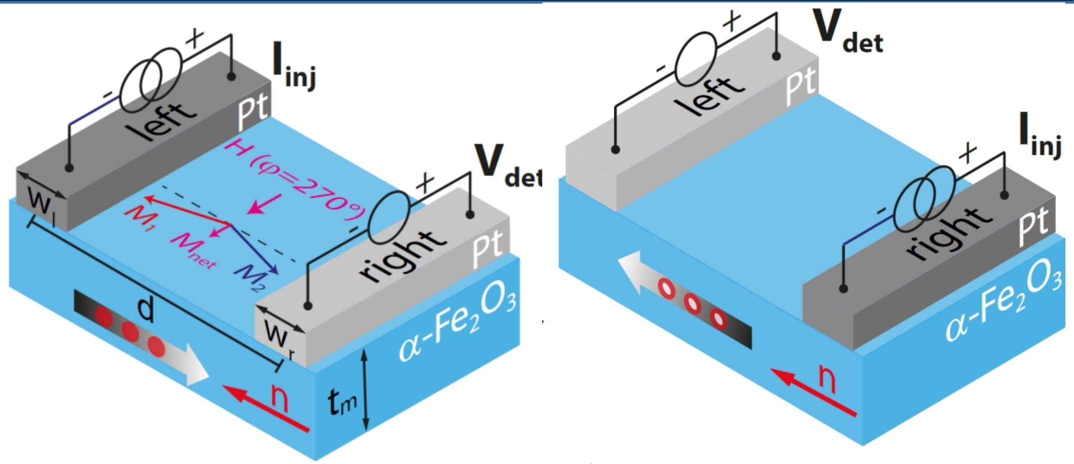
**Symmetric signal has maximum at $\boldsymbol{\mu_0 H_c}$**
**Antisymmetric signal changes sign at $\boldsymbol{\mu_0 H_c}$**

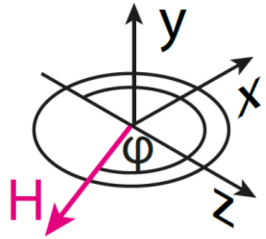
$\mu_0 H > \mu_0 H_c$

J. Gückelhorn, et al., PRL **130**, 216703 (2023).

# Symmetric/Antisymmetric Spin Signal




$$R^{el}_{sym} = \left[R^{el}(+d) + R^{el}(-d)\right]/2$$
$$R^{el}_{asym} = \left[R^{el}(+d) - R^{el}(-d)\right]/2$$

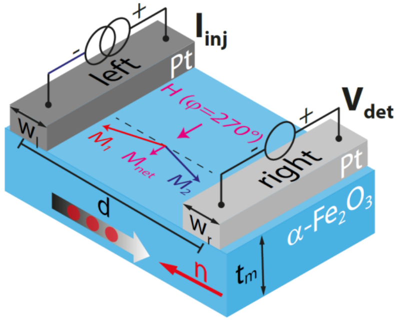
Extract amplitudes via fit:

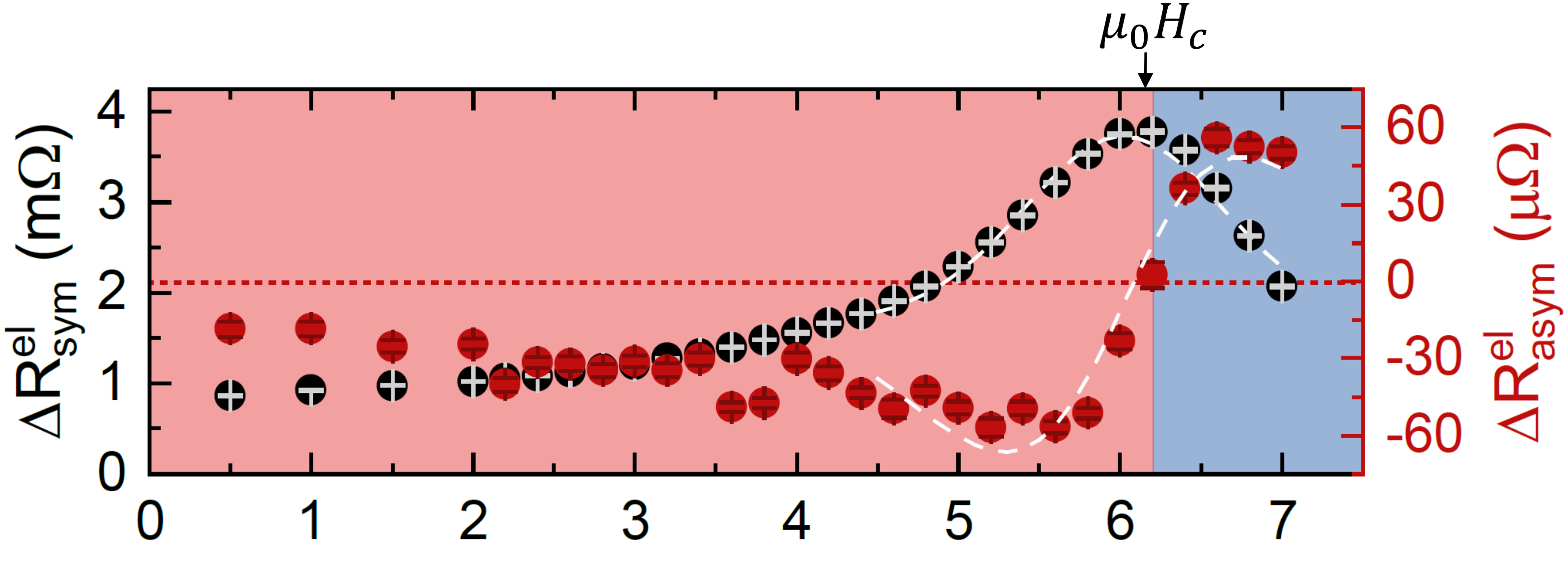
$$R^{el}_{sym} = \Delta R^{el}_{sym} \sin^2 \varphi$$
$$R^{el}_{asym} = \Delta R^{el}_{asym} \sin^3 \varphi$$

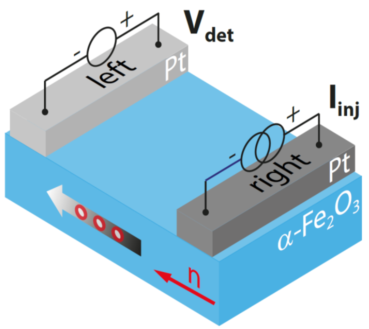
J. Gückelhorn

J. Gückelhorn, et al., PRL **130**, 216703 (2023).

# Magnetic Field Dependence

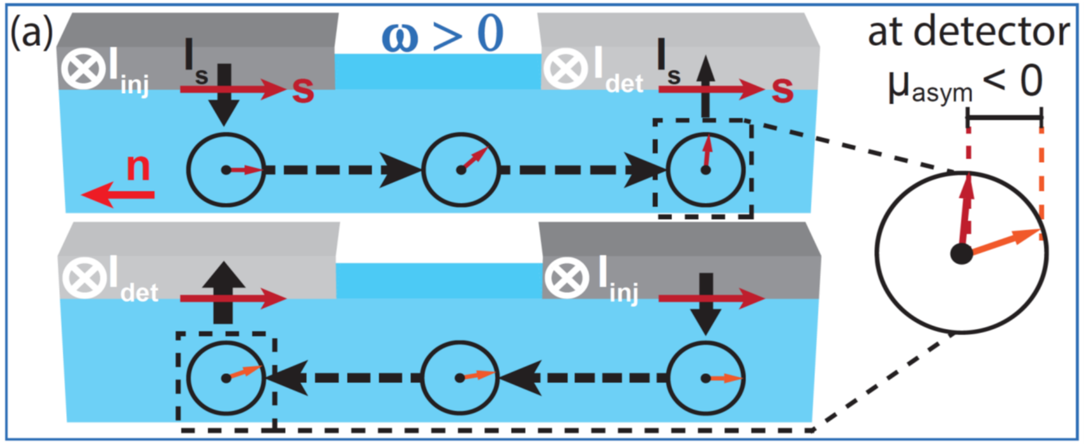


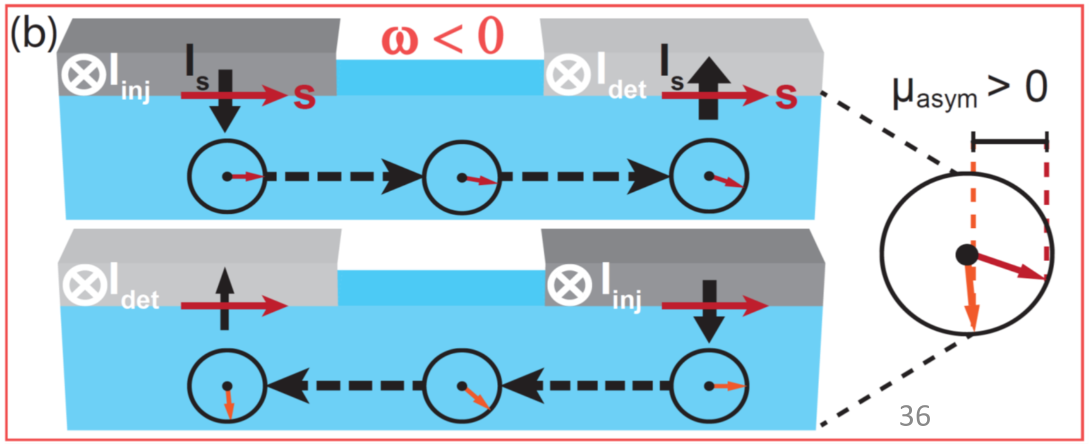




Role of low energy magnons: J. Gückelhorn *et al.,* Phys. Rev. B **105**, 094440 (2022).

$\mu_0 H < \mu_0 H_c$ Good agreement between theory and experiment $\mu_0 H > \mu_0 H_c$



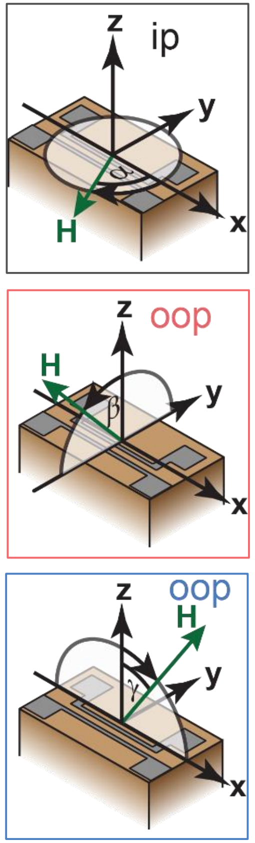

Microscopic Origin?

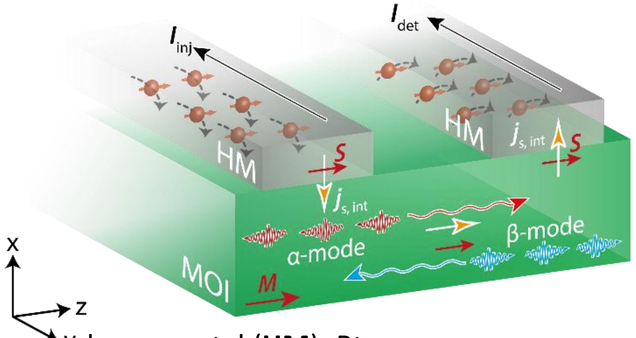




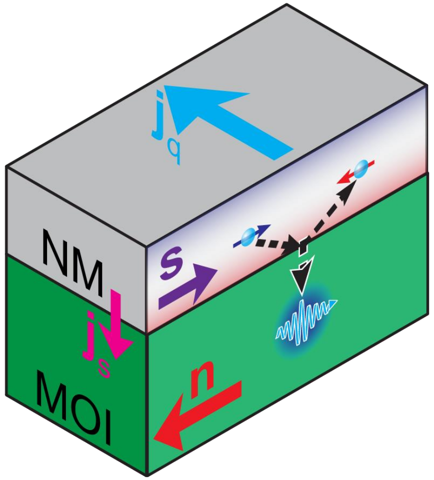

J. Gückelhorn, et al., PRL **130**, 216703 (2023).

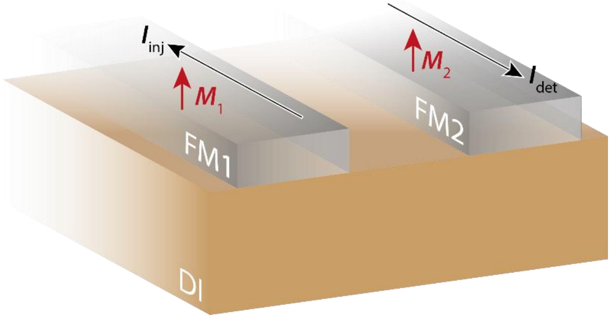
# Angular momentum transport metallic FMs




heavy metal (**HM**): Pt
magnetically ordered insulator (**MOI**): YIG

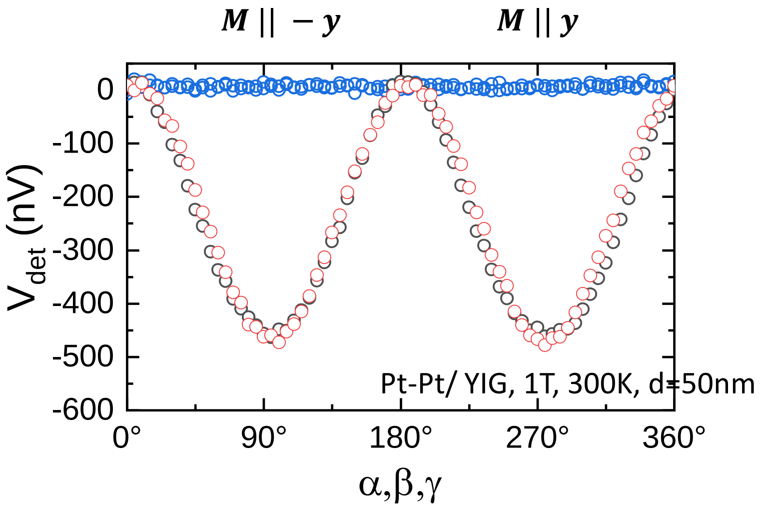


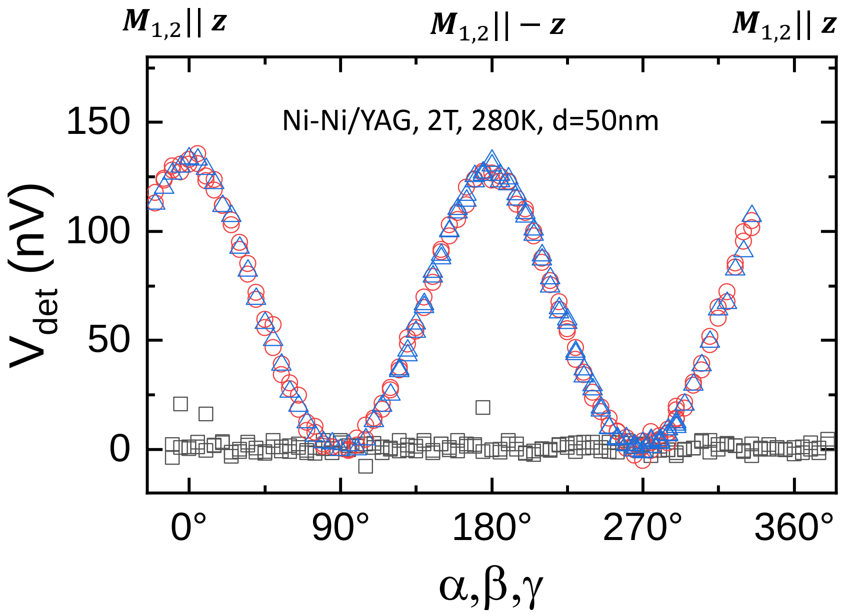




**FM1**: Ni
**FM2**: Ni
**Diamagnetic insulator (DI)**: YAG

current reversal:

$$V_{\mathrm{det}} = \frac{V_{\mathrm{det}}(+I) - V_{\mathrm{det}}(-I)}{2}$$

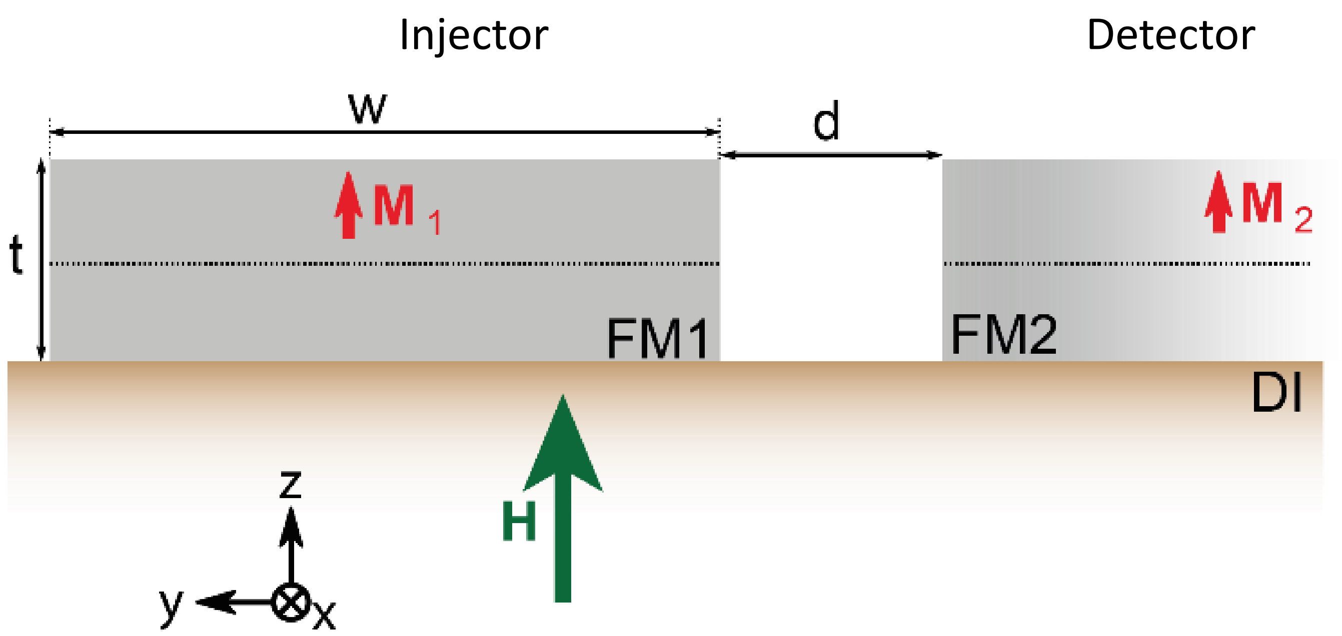


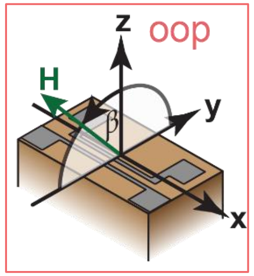

S.T.B. Goennenwein *et al.*, APL **107**, 172405 (2015).
K. Ganzhorn. PhD Thesis (2018).

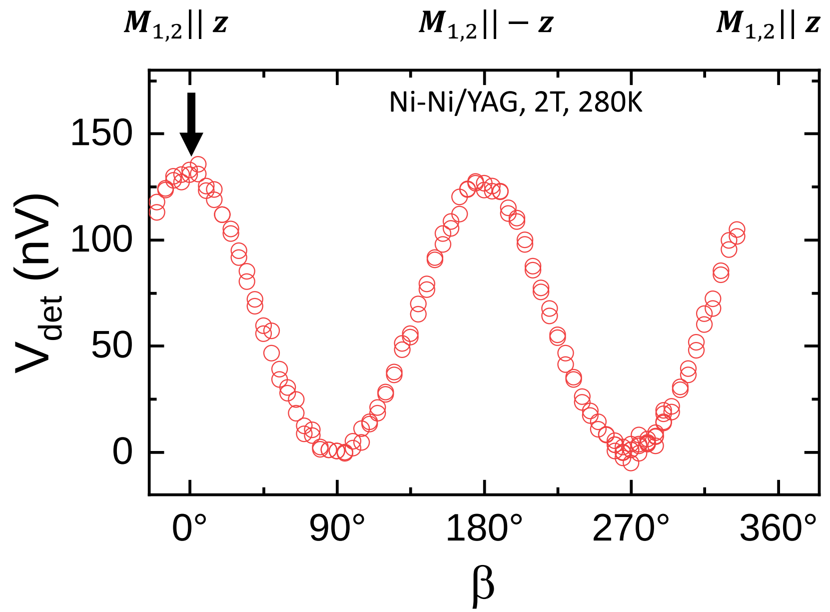
R. Schlitz *et al.*, arXiv:2311.05290 (Accepted in PRL 2024).

# Model




- Magnetization defines the two spin states

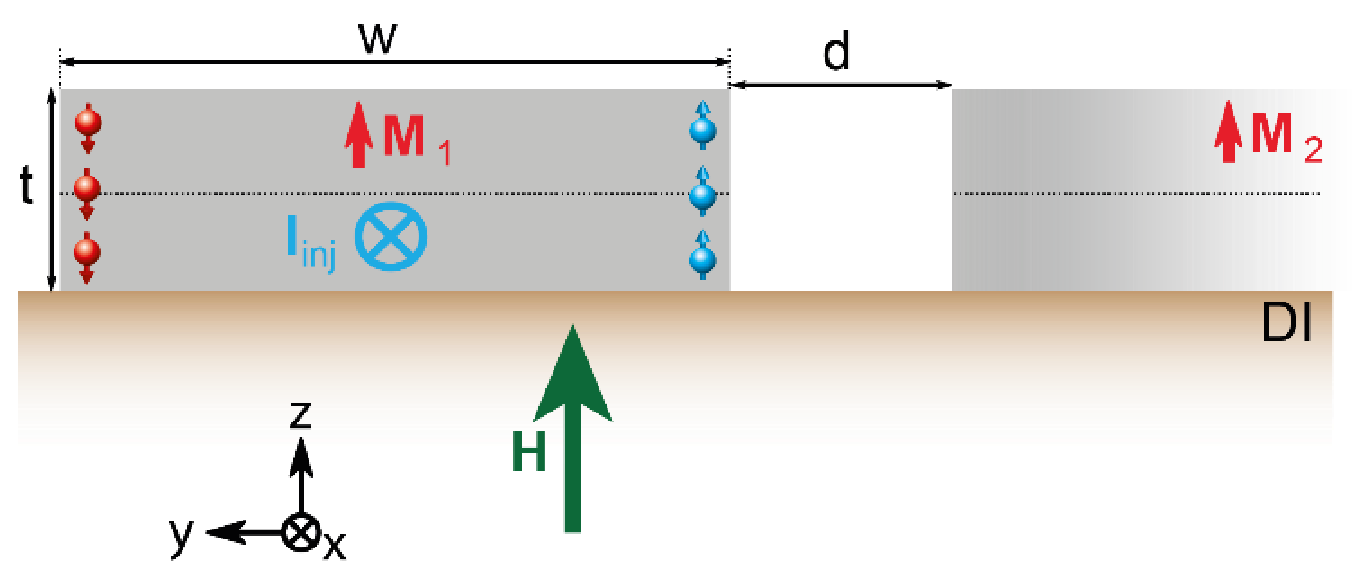


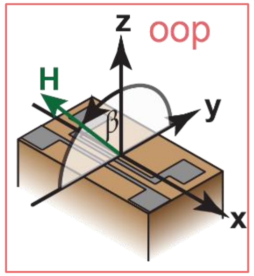



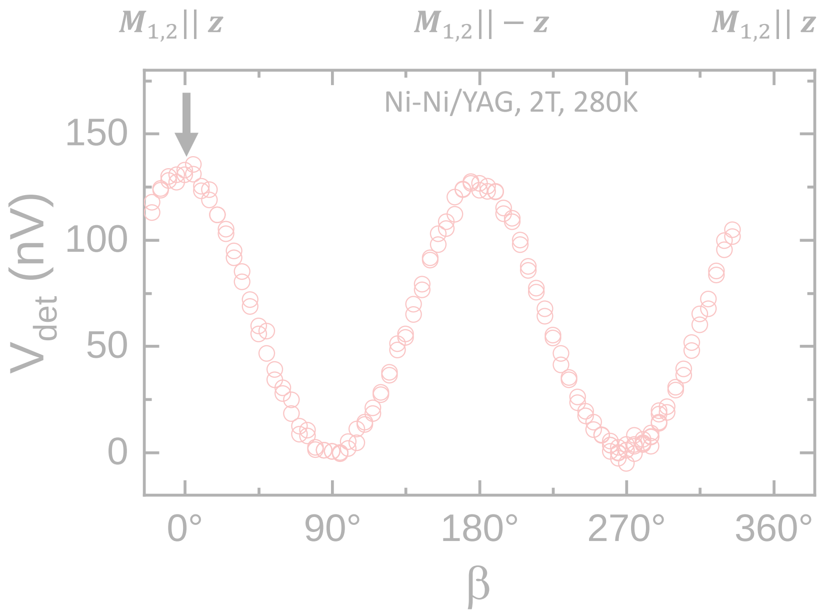



R. Schlitz *et al.*, arXiv:2311.05290 (Accepted in PRL 2024).

# Model



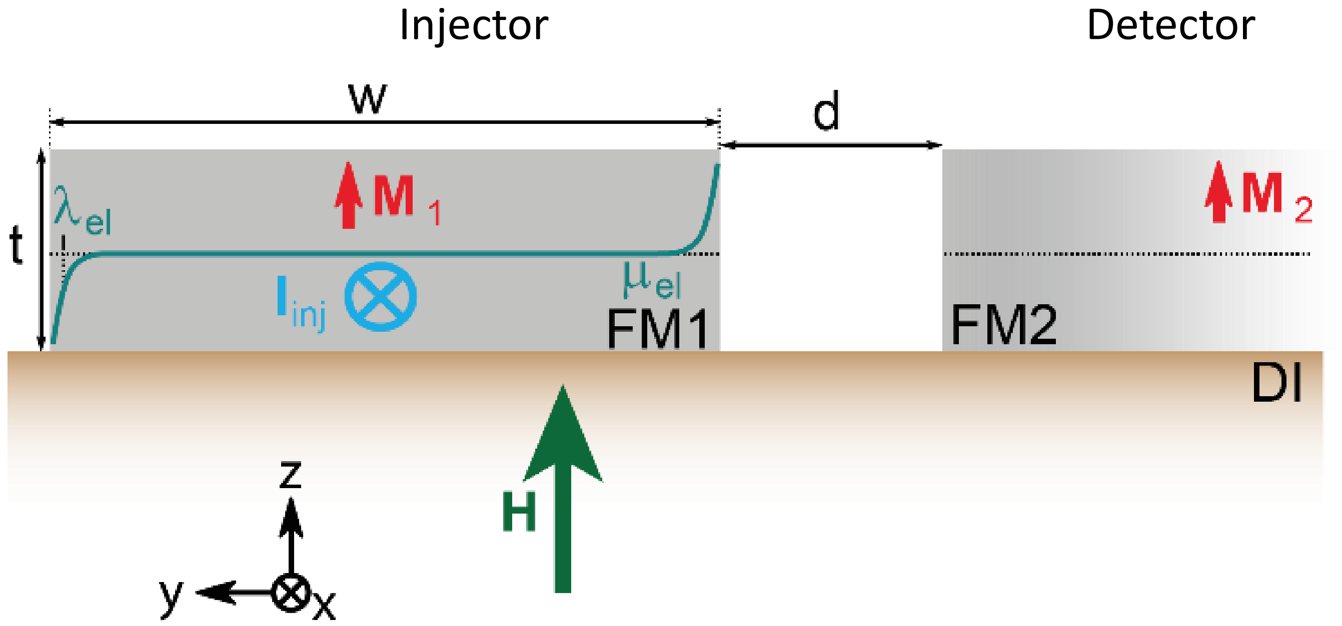



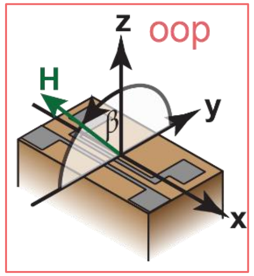

- Inherent magnetization eliminates all spin accumulation transverse to it

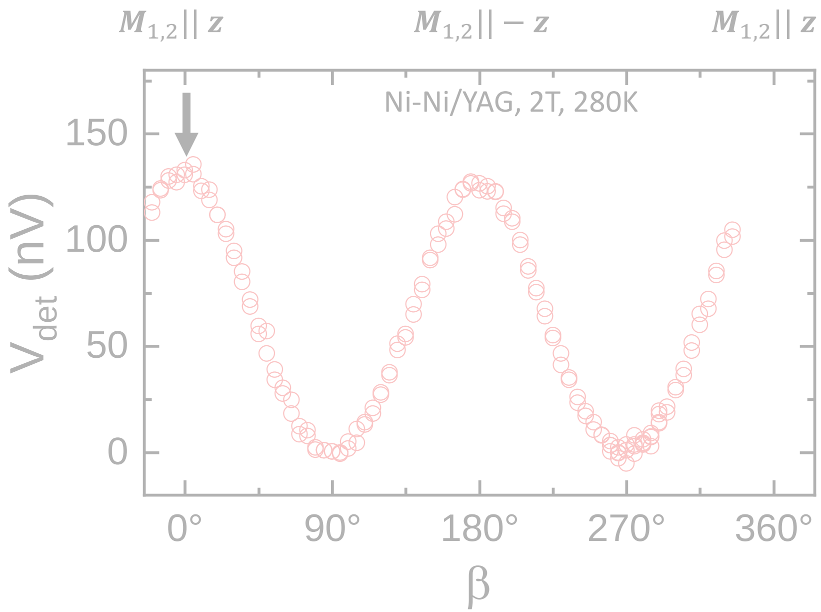
R. Schlitz *et al.*, arXiv:2311.05290 (Accepted in PRL 2024).

# Model



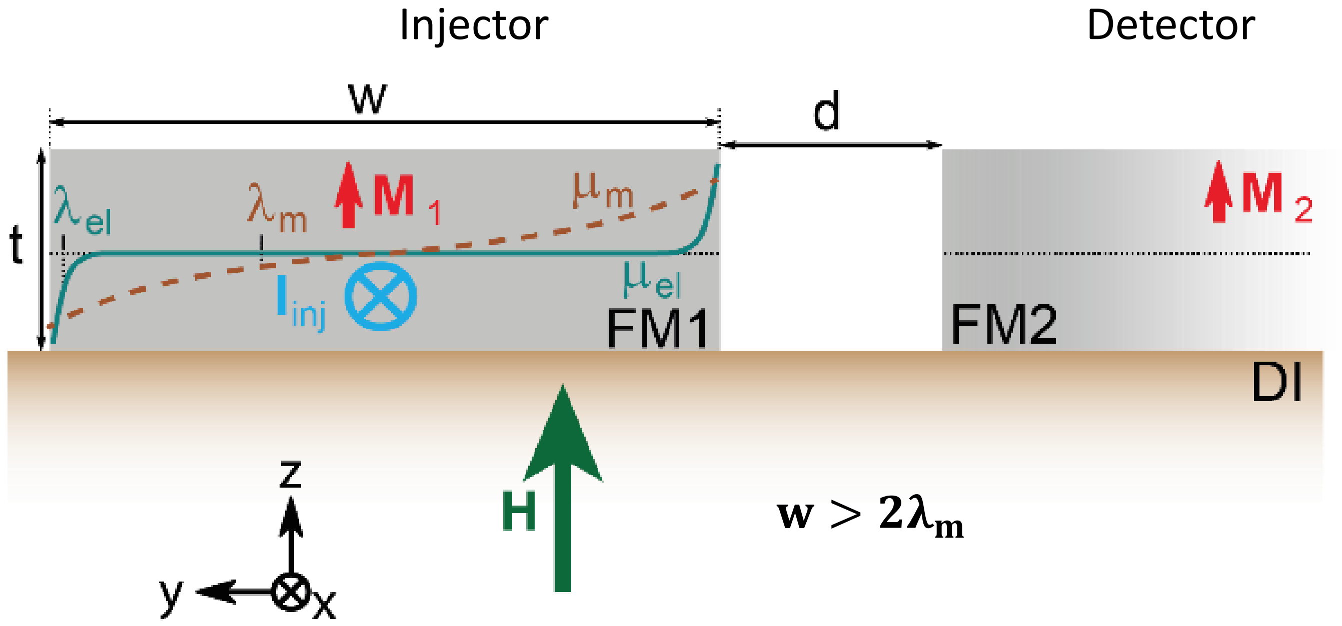

$\mu_{el}$: electron spin chemical potential
$\lambda_{el}$: electron spin decay length



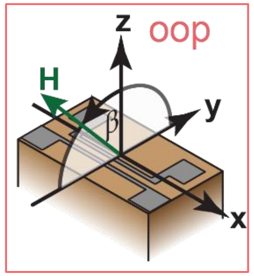



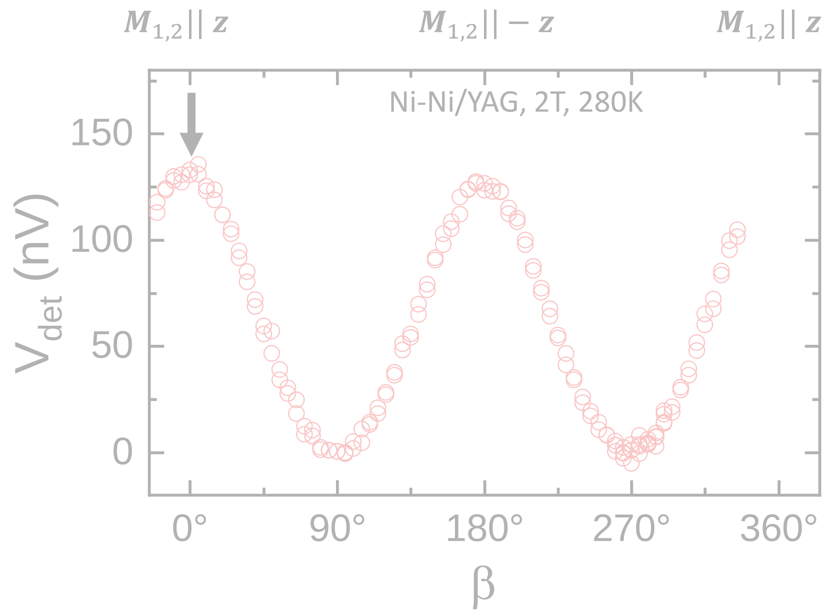

R. Schlitz *et al.*, arXiv:2311.05290 (Accepted in PRL 2024).

# Model




$\mathbf{w > 2\lambda_m}$

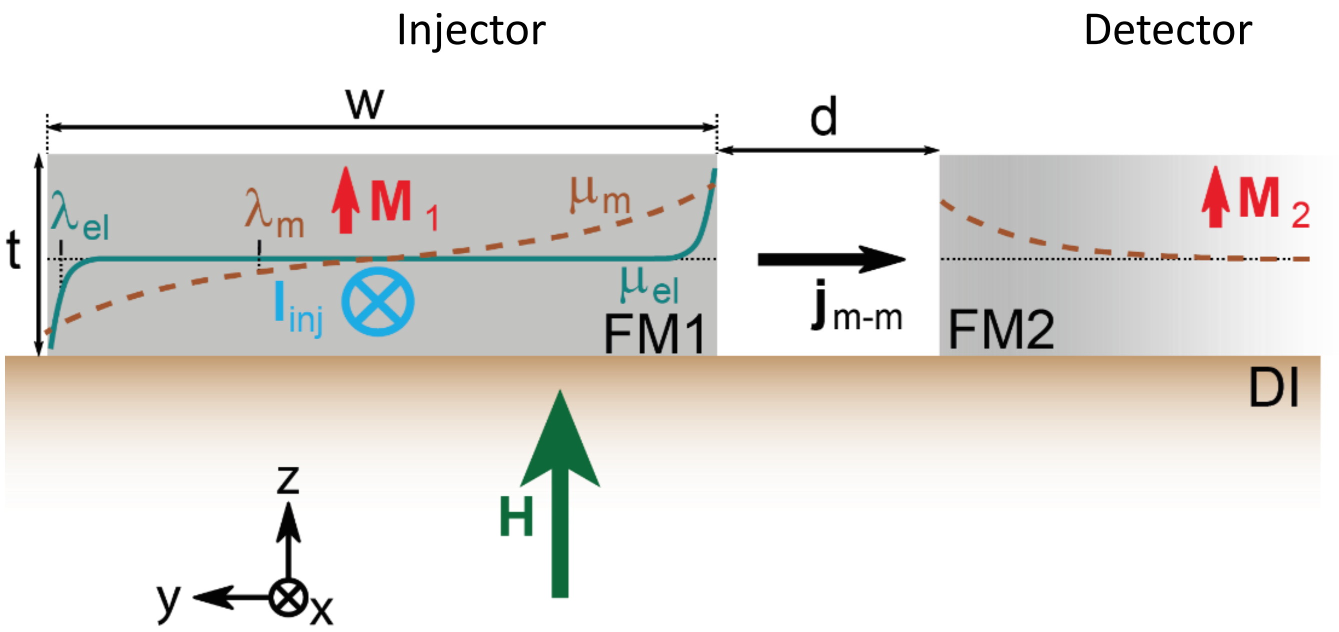


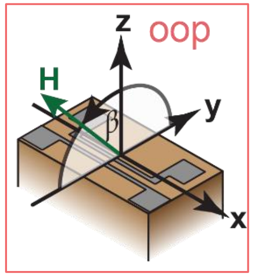

$\mu_{el}$: electron spin chemical potential
$\lambda_{el}$: electron spin decay length
$\mu_m$: magnon chemical potential
$\lambda_m$: magnon decay length

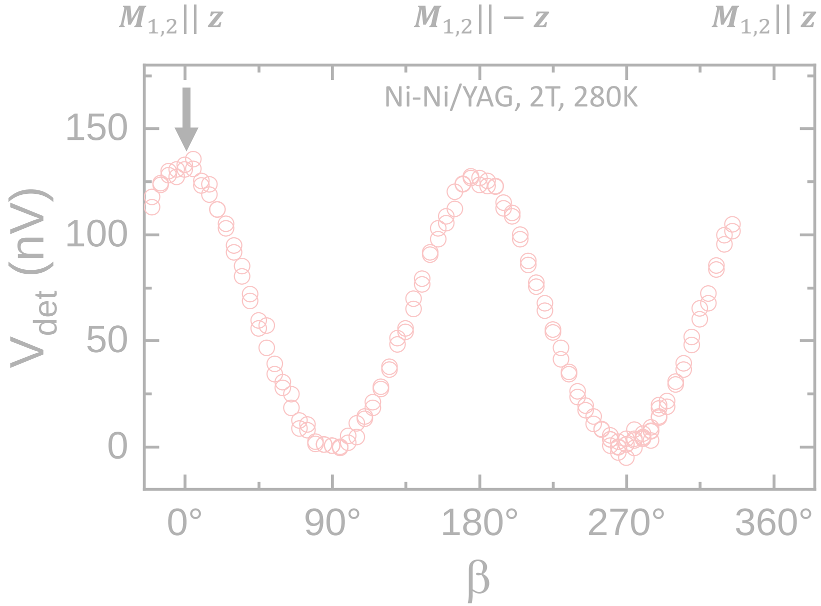
R. Schlitz *et al.*, arXiv:2311.05290 (Accepted in PRL 2024).

# Model



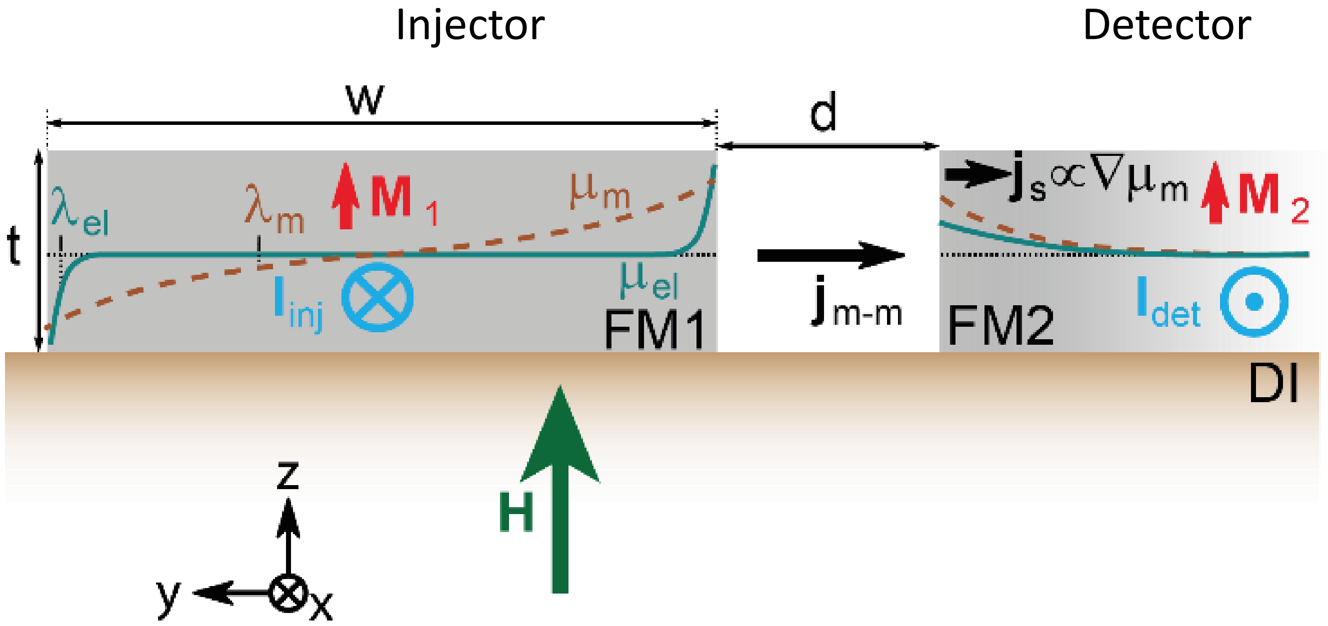

$\mu_{el}$: electron spin chemical potential
$\lambda_{el}$: electron spin decay length
$\mu_m$: magnon chemical potential
$\lambda_m$: magnon decay length
$j_{m-m}$: angular momentum transport



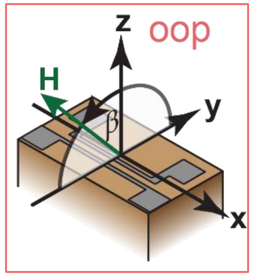



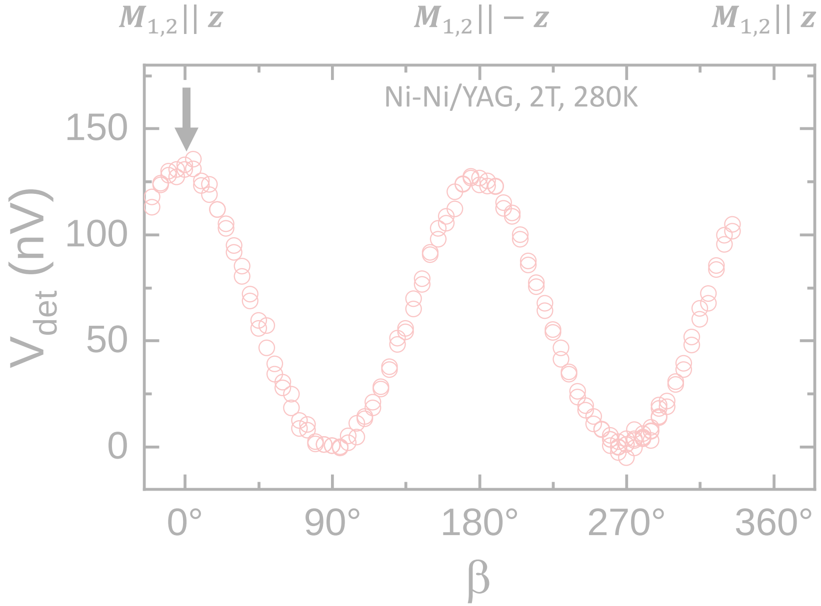

R. Schlitz *et al.*, arXiv:2311.05290 (Accepted in PRL 2024).

# Model



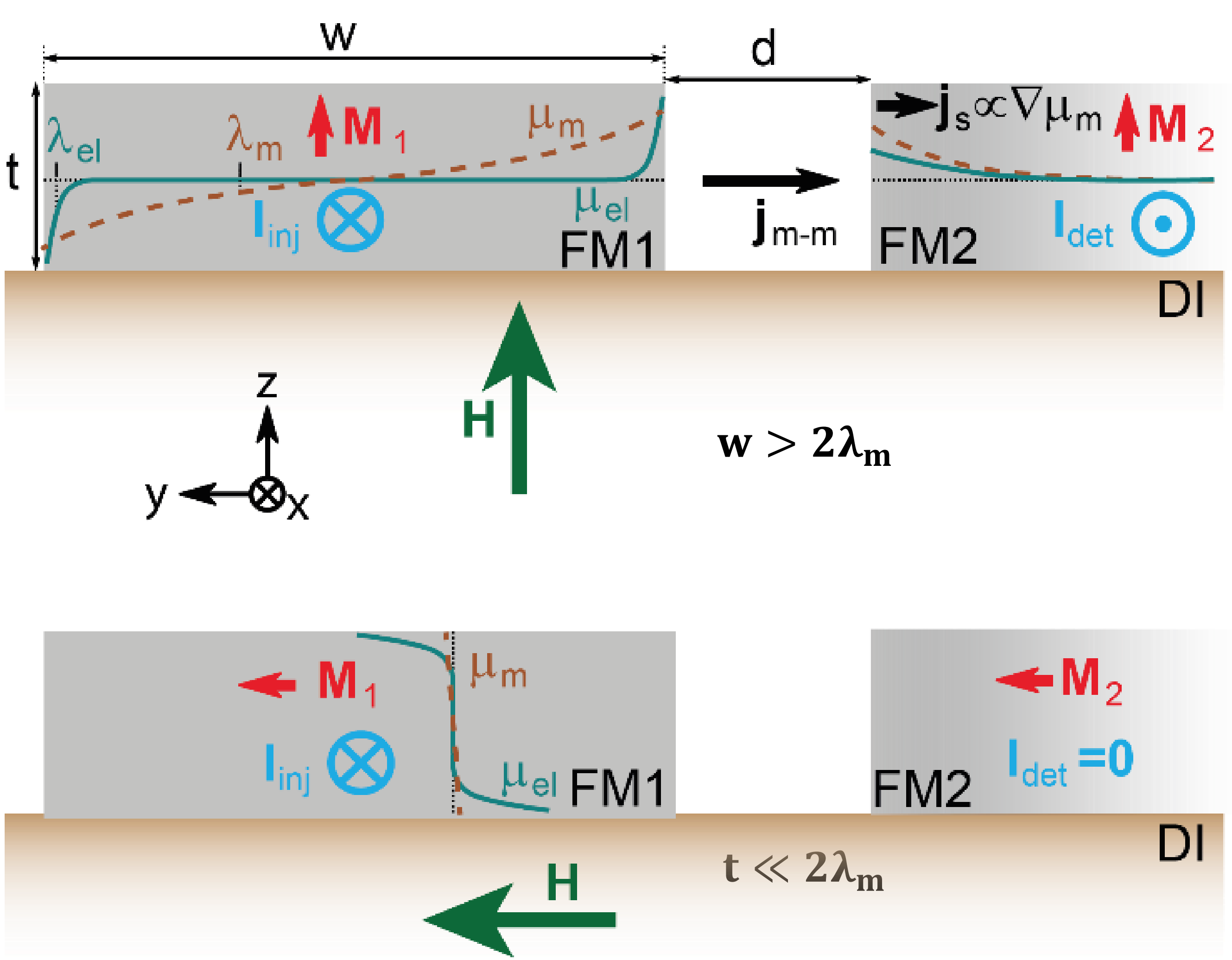

$\mu_{el}$: electron spin chemical potential
$\lambda_{el}$: electron spin decay length
$\mu_m$: magnon chemical potential
$\lambda_m$: magnon decay length
$j_{m-m}$: angular momentum transport
$j_s$: electron spin current

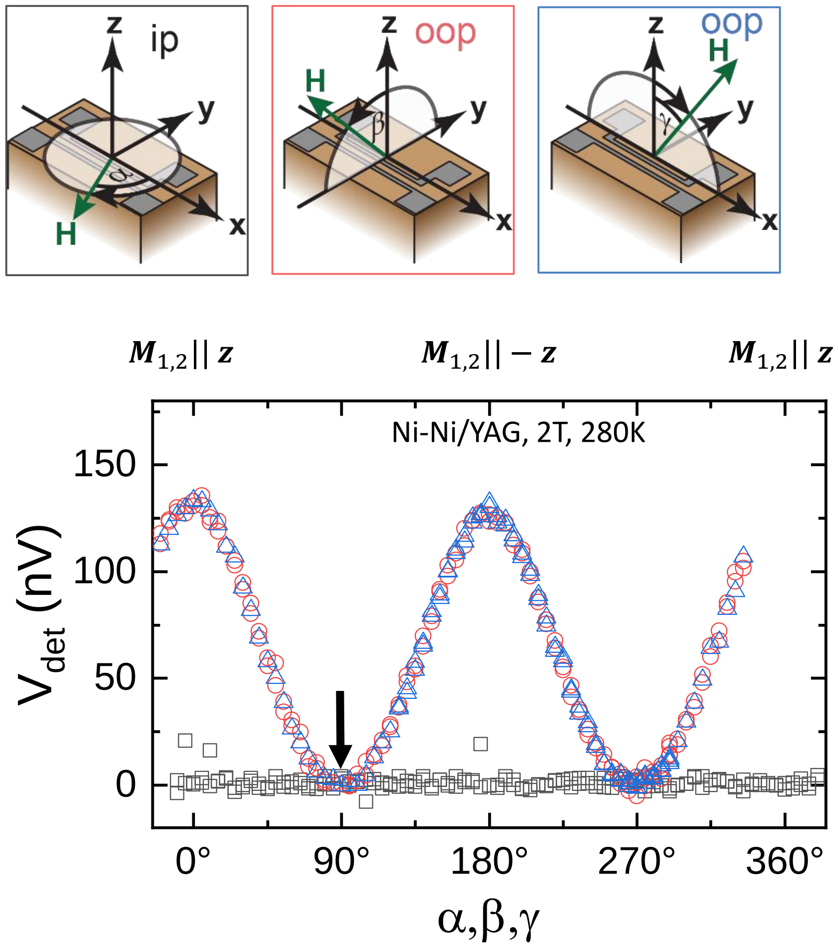



R. Schlitz *et al.*, arXiv:2311.05290 (Accepted in PRL 2024).

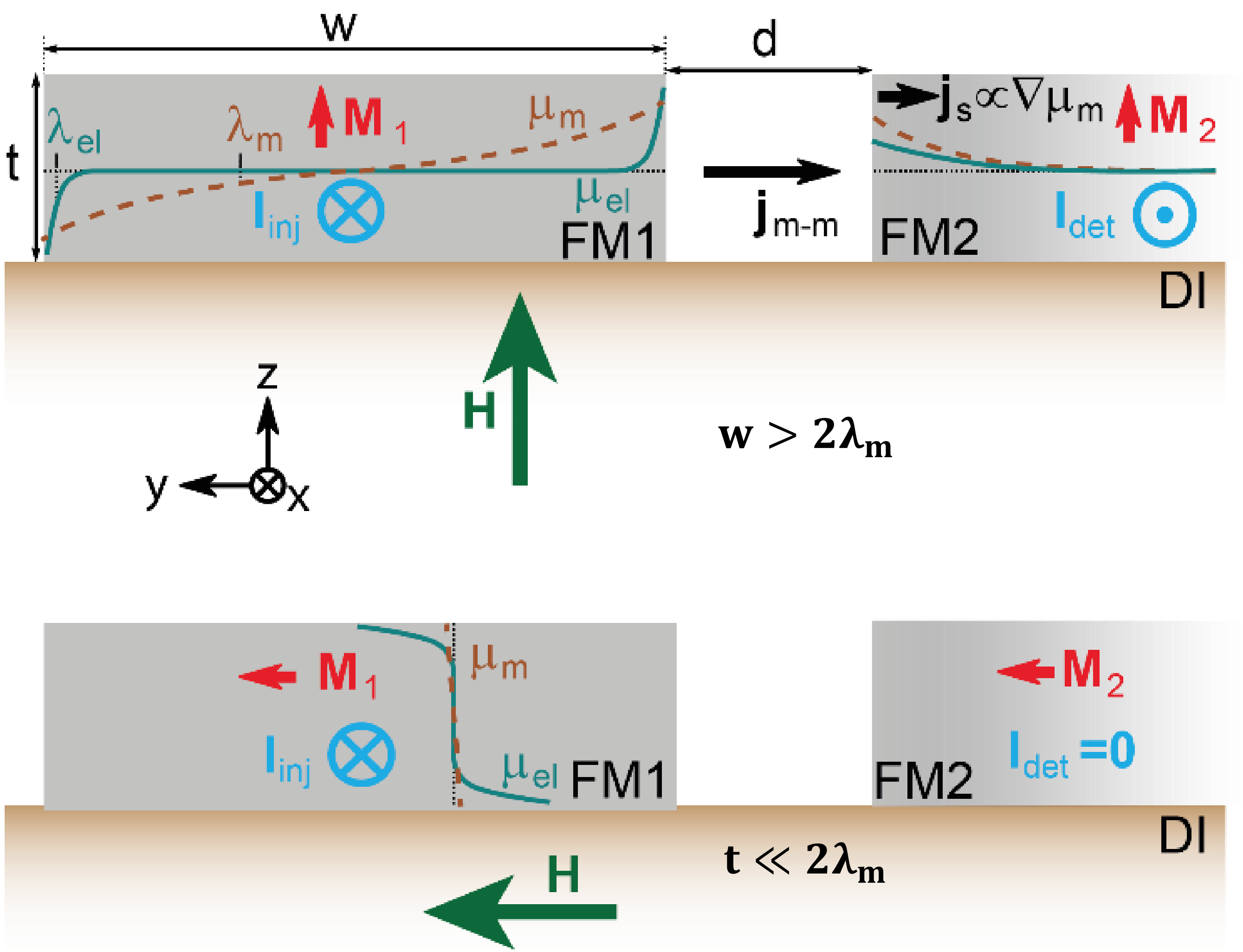
# Model

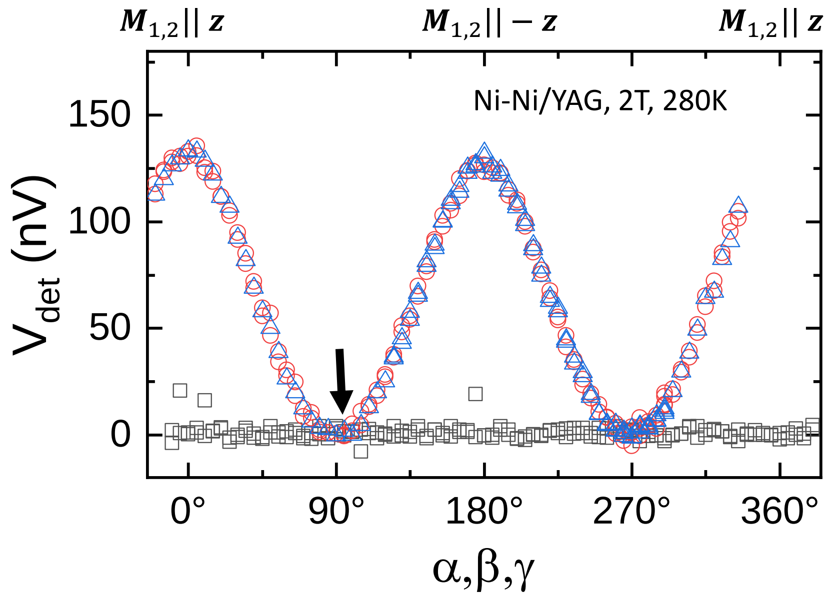



R. Schlitz *et al.*, arXiv:2311.05290 (Accepted in PRL 2024).

# Model




**Ferromagnetic materials**:
- Ni-Ni ✓
- Py($Ni_{80}Fe_{20}$)-Py ✓
- CoFe($Co_{25}Fe_{75}$)-CoFe✓

Mixed Configurations:
- Ni-Py✓
- CoFe-Py✓

**Non-Ferromagnetic materials**:
- Pt-Pt ×

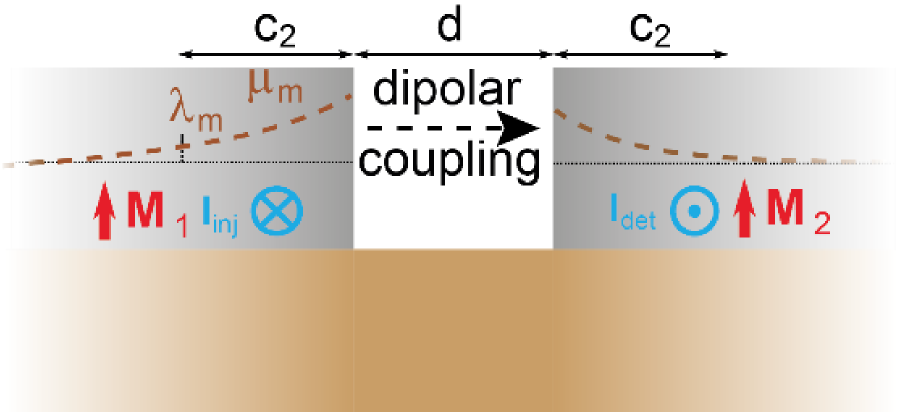
Mixed Configurations:
- CoFe-Pt×

➡ universal effect!

R. Schlitz *et al.*, arXiv:2311.05290 (Accepted in PRL 2024).

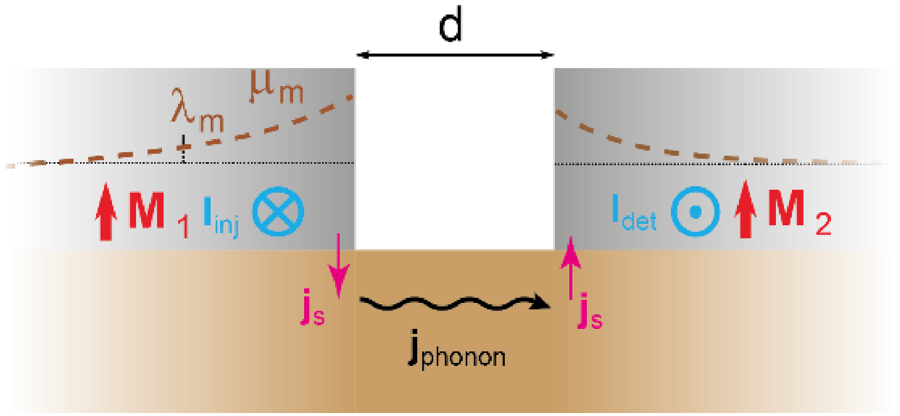
# Transport mechanism

**dipolar coupling**




$$\eta_s(d) = \frac{c_1}{d + c_2}$$

**phonon mediated coupling**

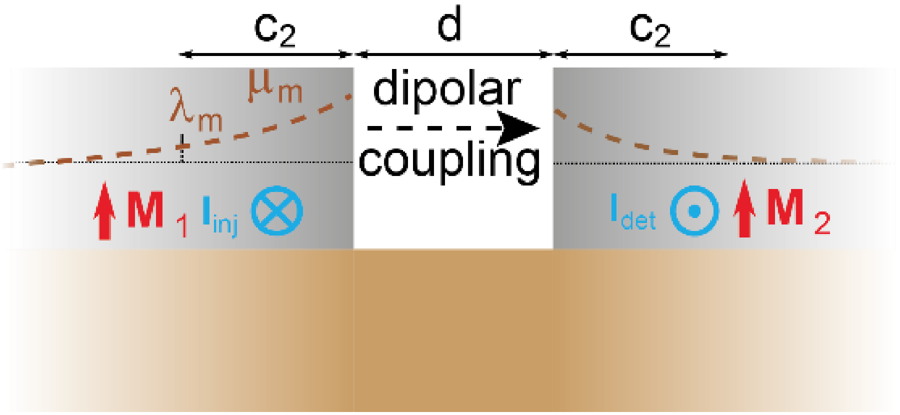



$$\eta_s(d) = c_1 e^{-\frac{d}{\lambda}}$$

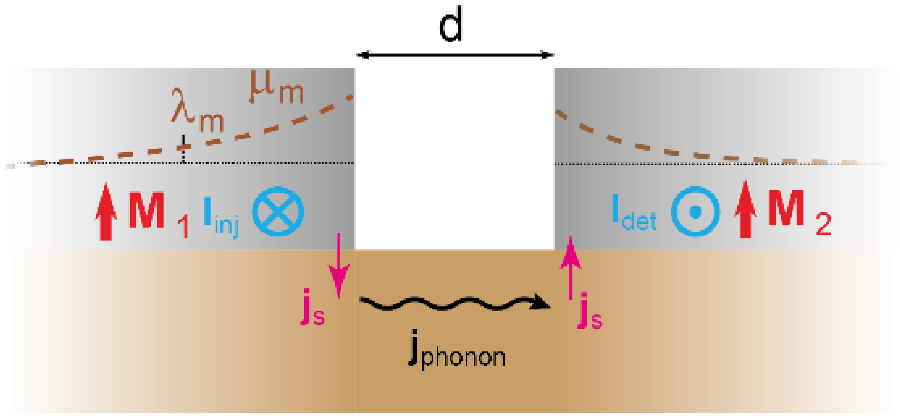
R. Schlitz *et al.*, arXiv:2311.05290 (Accepted in PRL 2024).

# Transport mechanism

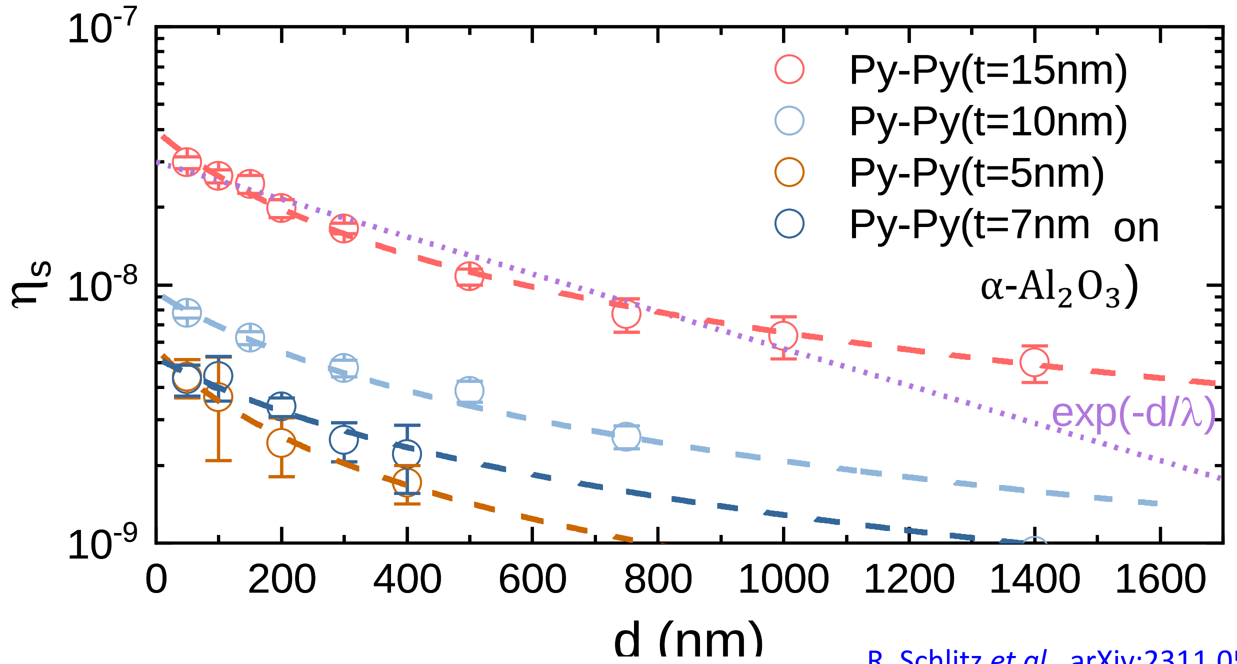
**dipolar coupling**




**phonon mediated coupling**




$$\eta_s(d) = \frac{c_1}{d + c_2}$$




$$\eta_s(d) = c_1 e^{-\frac{d}{\lambda}}$$

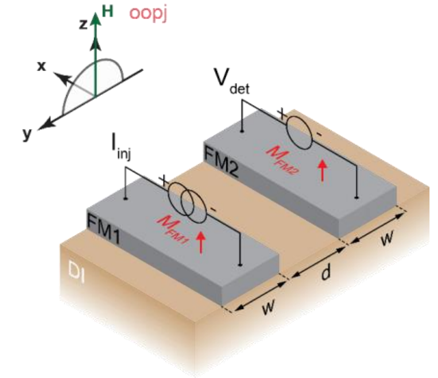
**spin transfer efficiency**

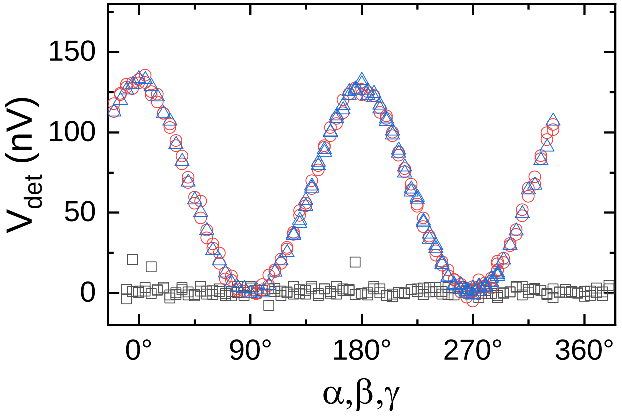
$$\eta_s(d) = \frac{I_{\mathrm{det}}}{I_{\mathrm{inj}}} = \frac{V_{\mathrm{det}}}{V_{\mathrm{inj}}}$$

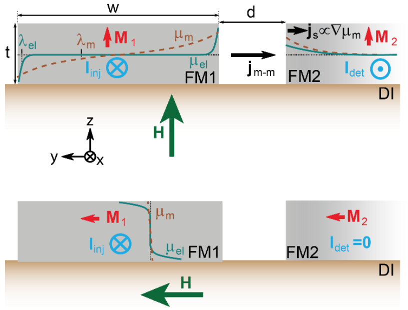
R. Schlitz *et al.*, arXiv:2311.05290 (Accepted in PRL 2024).

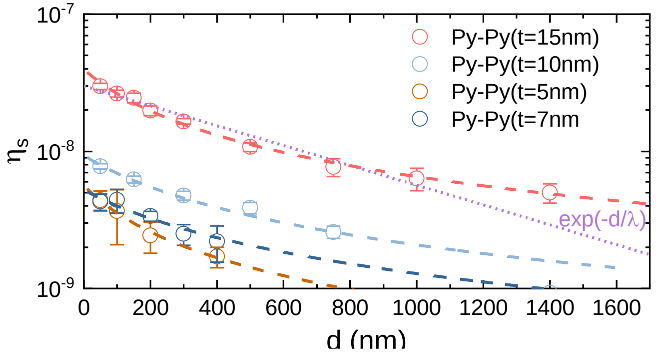
# Summary

## Angular momentum transport via magnons in metallic ferromagnets



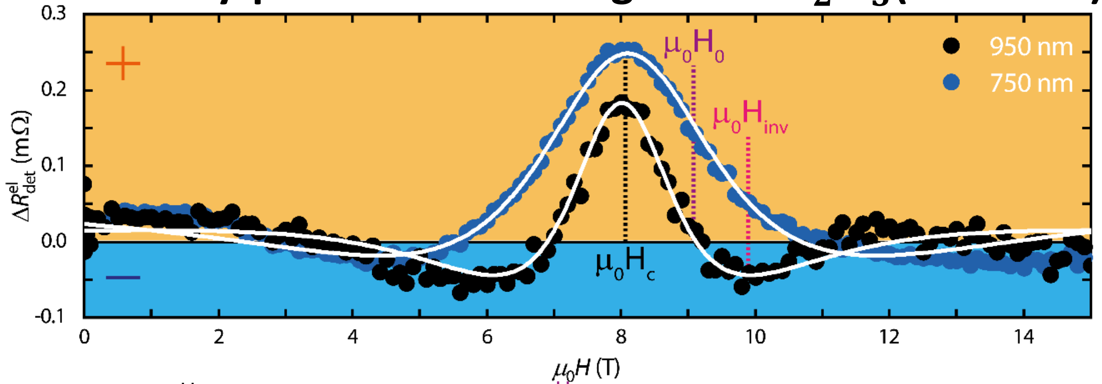



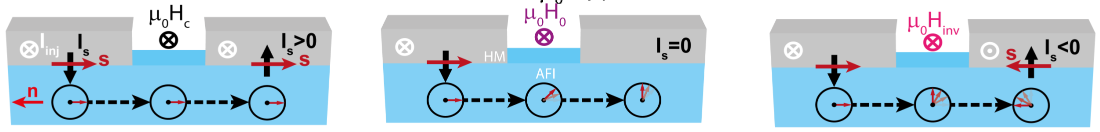



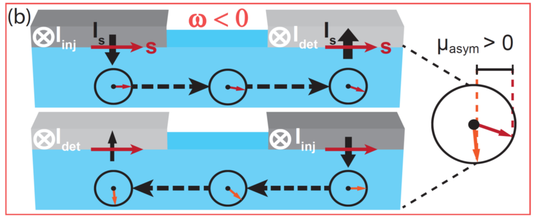

- Angular momentum transport between two separated FM strips
- Dipolar coupling between thermal magnons dominant mechanism

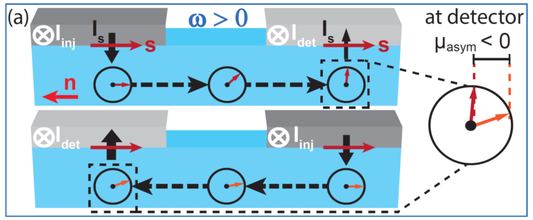
R. Schlitz *et al.*, arXiv:2311.05290 (accepted for publication in PRL 2024).

## Easy-plane antiferromagnet $\alpha$-$Fe_2O_3$(hematite)




- Pseudospin dynamics and antiferromagnetic magnon Hanle effect
- First observation of nonreciprocal spin transport in an antiferromagnet
- Influence of nonreciprocity on magnon Hanle and Pseudospin dynamics

T. Wimmer *et al.*, Phys. Rev. Lett. **125** , 247204 (2020).
A. Kamra *et al.,* Phys. Rev. B **102**, 174445 (2020).
J. Gückelhorn *et al.,* Phys. Rev. B **105**, 094440 (2022).
J. Gückelhorn *et al.,* PRL **130**, 216703 (2023).
M. Scheufele *et al.*, APL Materials (2023).

WMI

# Advertisement

## Upcoming Seminar 2024

### Hybrid Angular Momentum Transport and Dynamics

WE-Heraeus-Seminar
27 Oct - 31 Oct 2024, Physikzentrum Bad Honnef
Scientific organizers:
PD Dr. Timo Kuschel, U Bielefeld • PD Dr. Matthias Althammer, WMI Garching

### Invited Speakers

- **Christian H. Back**, TU München, Germany
- **Gerrit E. W. Bauer**, Tohoku University, Sendai, Japan
- **Chiara Ciccarelli**, Cambridge University, United Kingdom
- **Rembert A. Duine**, Utrecht University, The Netherlands
- **Benedetta Flebus**, Boston College, USA
- **Dongwook Go**, FZ Jülich, Germany
- **Sebastian T. B. Goennenwein**, University of Konstanz, Germany
- **Olena Gomonay**, Mainz University, Germany
- **Axel Hoffmann**, University of Illinois, Urbana-Champaign, USA
- **Hans Huebl**, Walther-Meißner-Institut, Garching, Germany
- **Akashdeep Kamra**, UAM Madrid, Spain
- **Takashi Kikkawa**, University of Tokyo, Japan
- **Mathias Kläui**, Mainz University, Germany
- **Silvia Viola Kusminsky**, RWTH Aachen, Germany
- **Romain Lebrun**, Université Paris-Saclay, France
- **Yuriy Mokrousov**, FZ Jülich, Germany
- **Markus Münzenberg**, Universität Greifswald, Germany
- **Helena Reichlova**, TU Dresden, Germany
- **Richard Schlitz**, ETH Zürich, Switzerland
- **Tom Seifert**, FU Berlin, Germany
- **Ka Shen**, Beijing University, China

https://www.we-heraeus-stiftung.de/veranstaltungen/hybrid-angular-momentum-transport-and-dynamics/