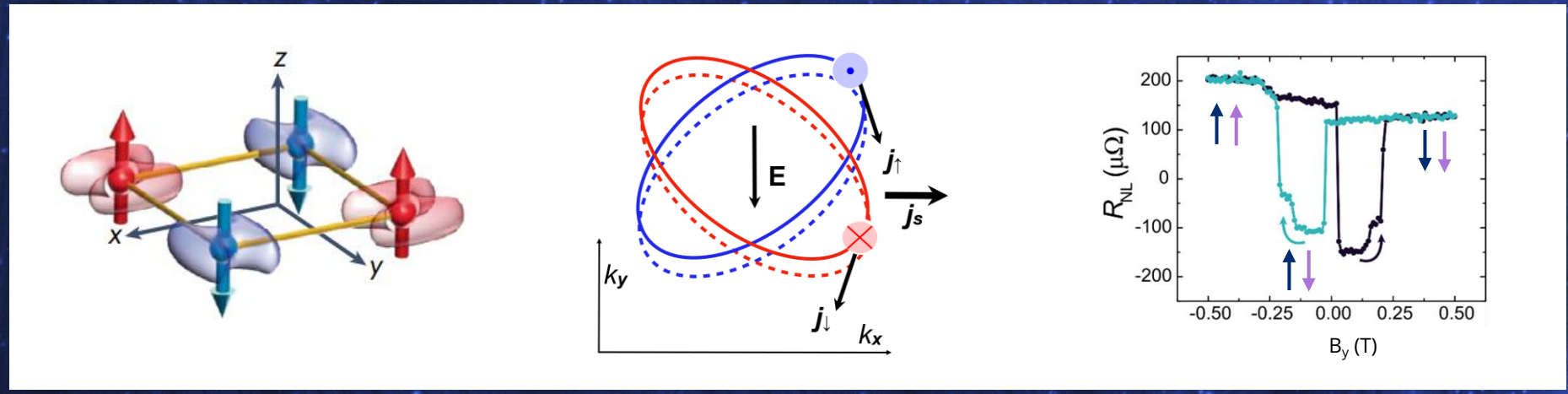
Experimental Signatures of Altermagnetism in Spintronic Devices

Helena Reichlova



FZU Institute of Physics of the Czech Academy of Sciences
DIOSCURI CENTRE FOR SPINCALORITRONICS AND MAGNONICS
Co-funded by the European Union
MINISTRY OF EDUCATION, YOUTH AND SPORTS

Experimental Signatures of Altermagnetism in Spintronic Devices

Helena Reichlova

DIOSCURI
CENTRE FOR SPINCALORITRONICS AND MAGNONICS

M. Leiviskä, A. Badura, R. Gonzalez-Betancourt,
J. Solano, D. Golub, Z. Šobáň, B. Gut, H. Martínek

CINaM
L. Michéz
I. Kounta

FZU
T. Jungwirth
D. Kriegner

CIC nanoGUNE
J. Mencos
F. Casanova

mpipks
W. Campos
L. Šmejkal

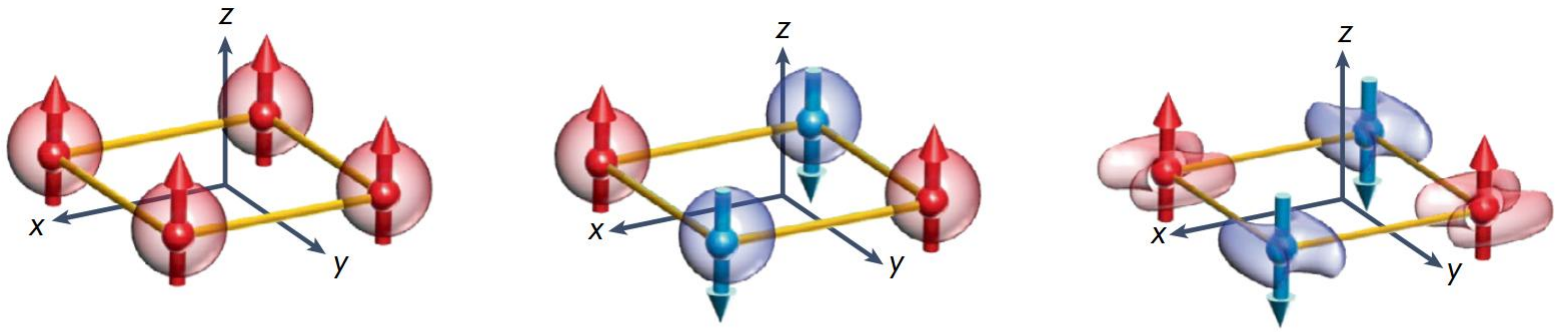
spintec
SPIN IN ELECTRONICS
J. Rial
C. Pfaff
V. Baltz

DIPC
S. Bergeret
N. Sigales
T. Kokkeler

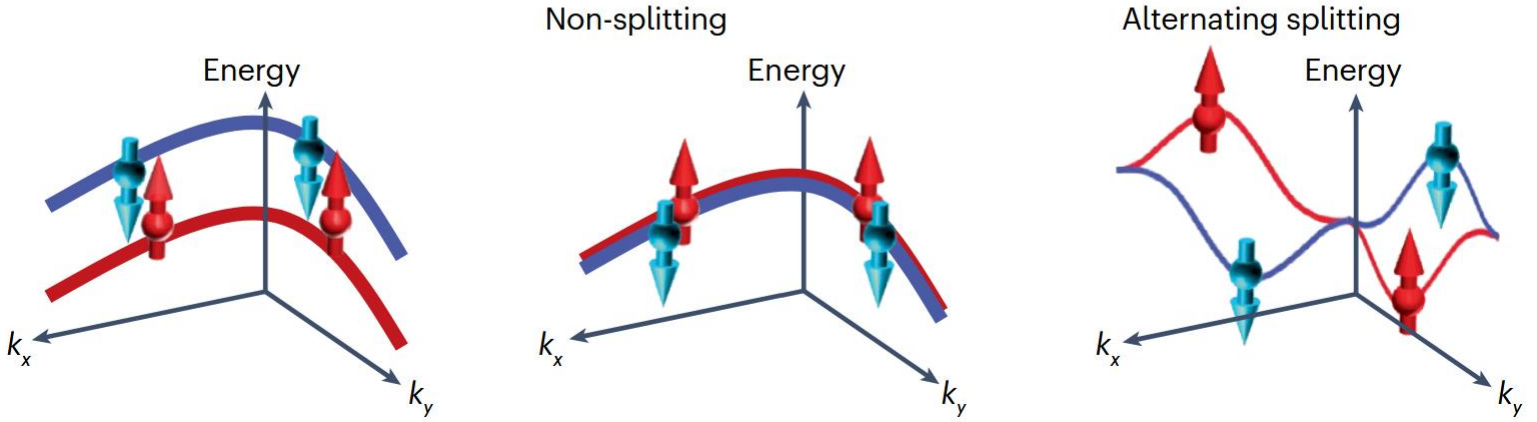
JG|U
J. Sinova
O. Gomonay
R. Gonzalez-Hernandez

Altermagnets – alternating spin splitting

Real space



Momentum space



Altermagnetic splitting:

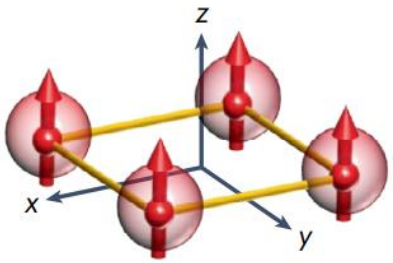
- ✓ Large
- ✓ Spin up/down not mixed
- ✓ Unprecedent anisotropy

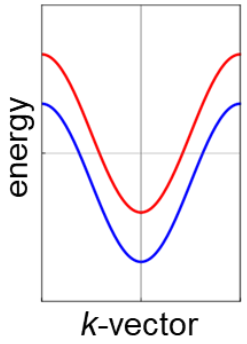
FZU Institute of Physics of the Czech Academy of Sciences

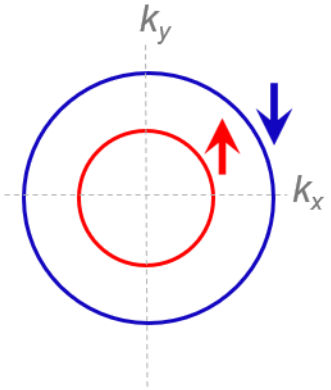
DIOSCURI CENTRE FOR SPINCALORITRONICS AND MAGNONICS

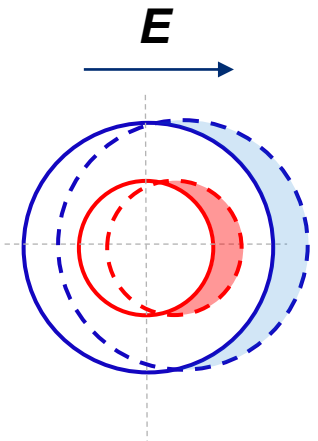
Spin splitting in spintronics

Ferromagnets



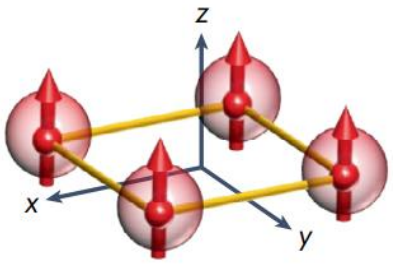


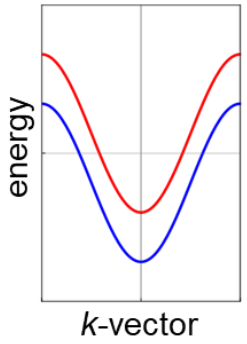


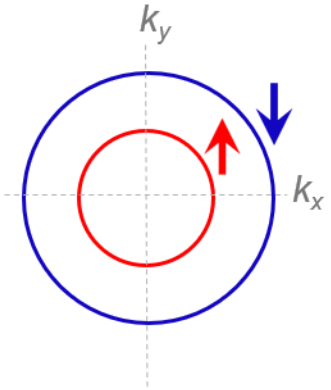


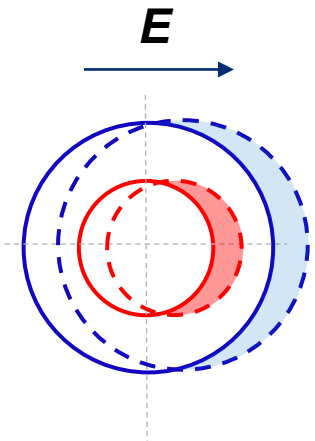
Spin splitting in spintronics

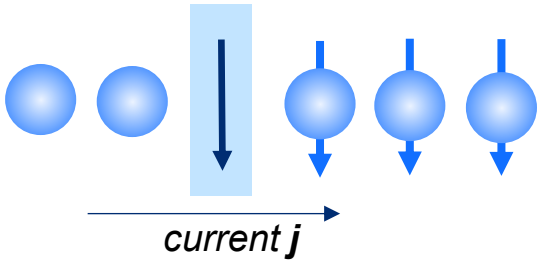
Ferromagnets

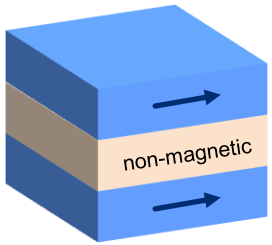


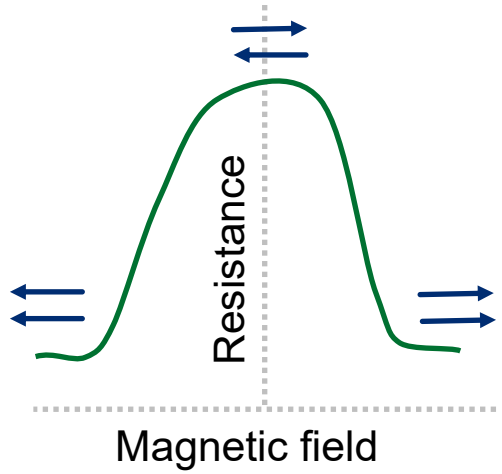




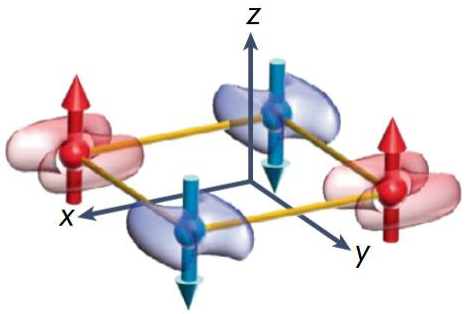


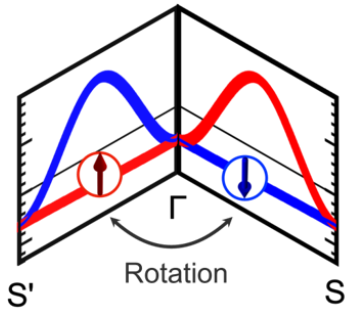


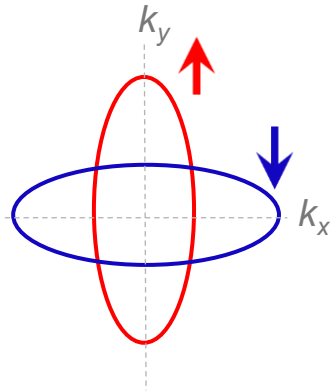




Spin splitting of altermagnets

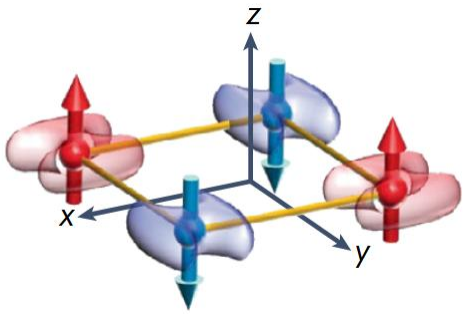


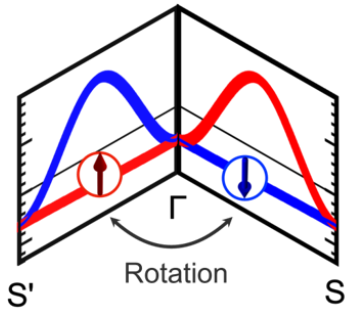


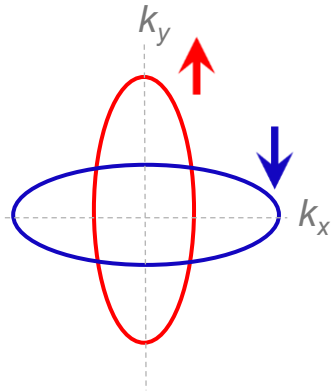


🕮 Gonzalez-Hernandez et al. PRL 126, 127701 (2021)
🕮 Smejkal et al. PRX 12, 011028 (2022)

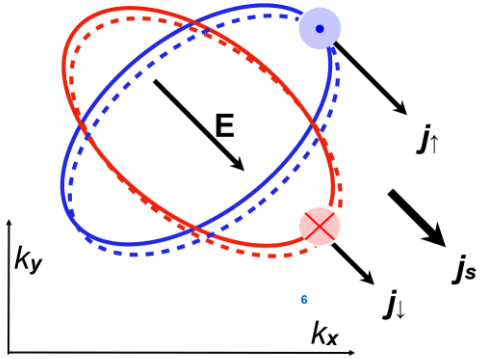
Spin splitting of altermagnets





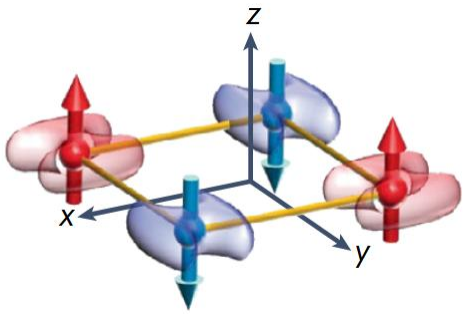


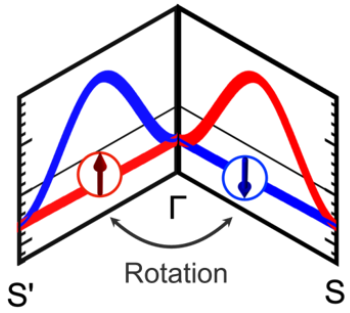
Longitudinal spin-current

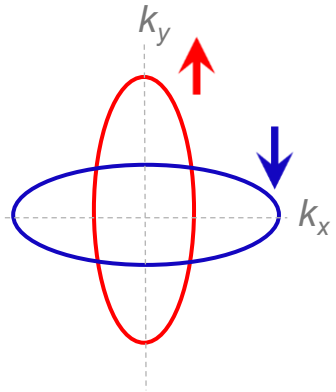


Gonzalez-Hernandez et al. PRL 126, 127701 (2021)
Smejkal et al. PRX 12, 011028 (2022)

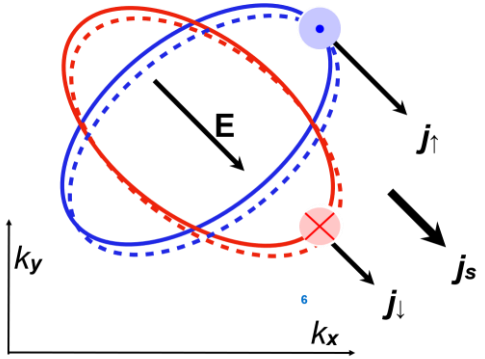
Spin splitting of altermagnets



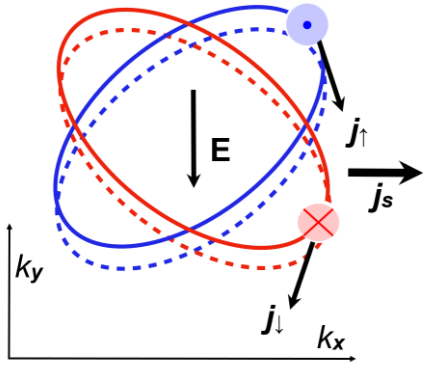




Longitudinal spin-current

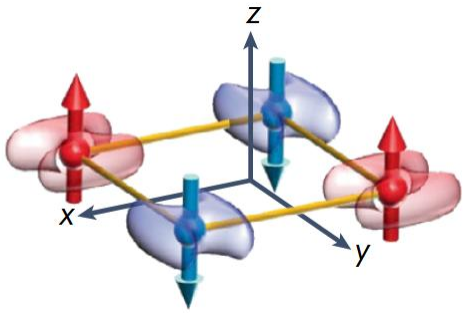


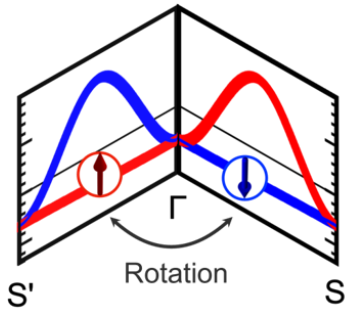
Transverse spin-current

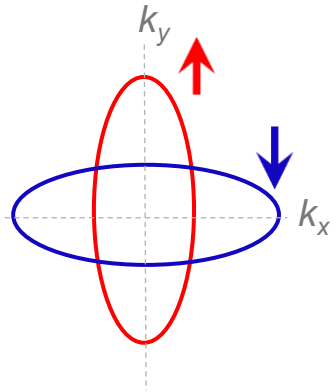


- Gonzalez-Hernandez et al. PRL 126, 127701 (2021)
- Smejkal et al. PRX 12, 011028 (2022)

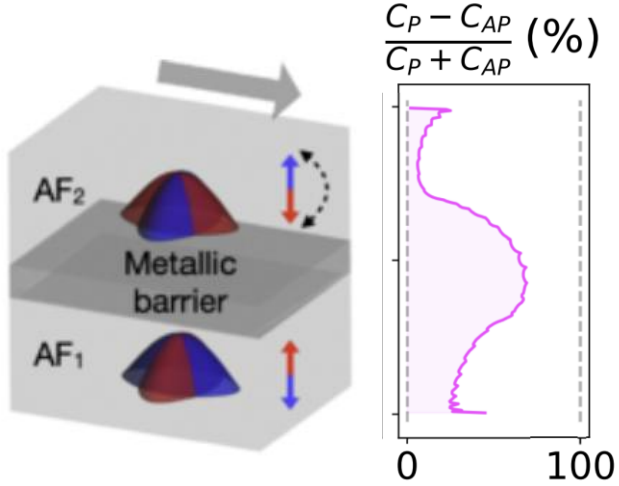
Spin splitting of altermagnets



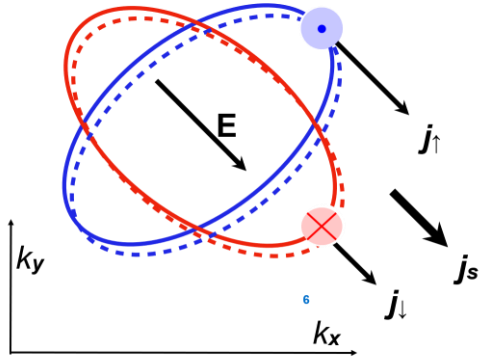




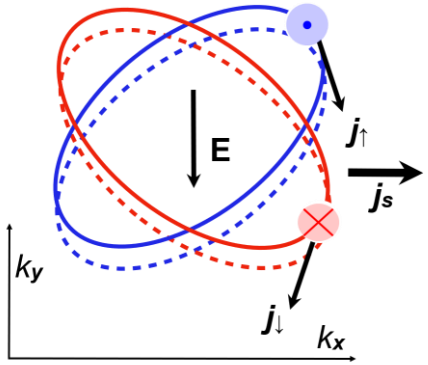
Altermagnetic spin valve?



Longitudinal spin-current



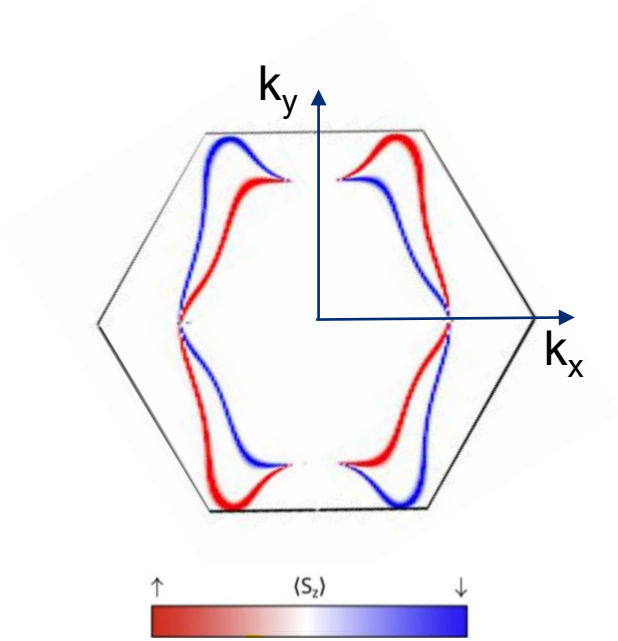
Transverse spin-current

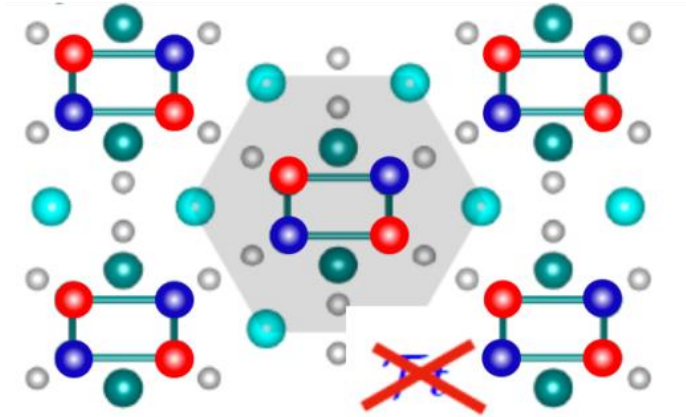


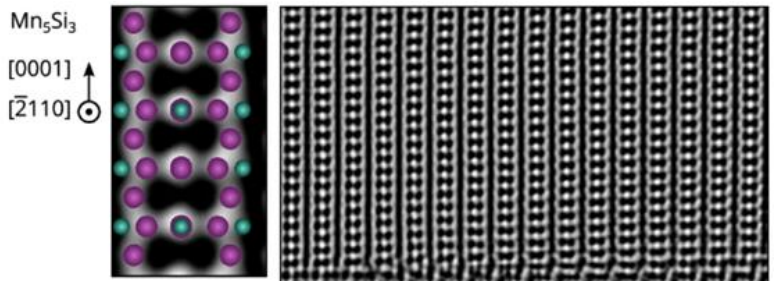
Gonzalez-Hernandez et al. PRL 126, 127701 (2021)
Smejkal et al. PRX 12, 011028 (2022)

Mn_5Si_3 thin films

- Metallic d-wave candidate
- epitaxial constrains of Si(111)
- T_N ~ 240 K







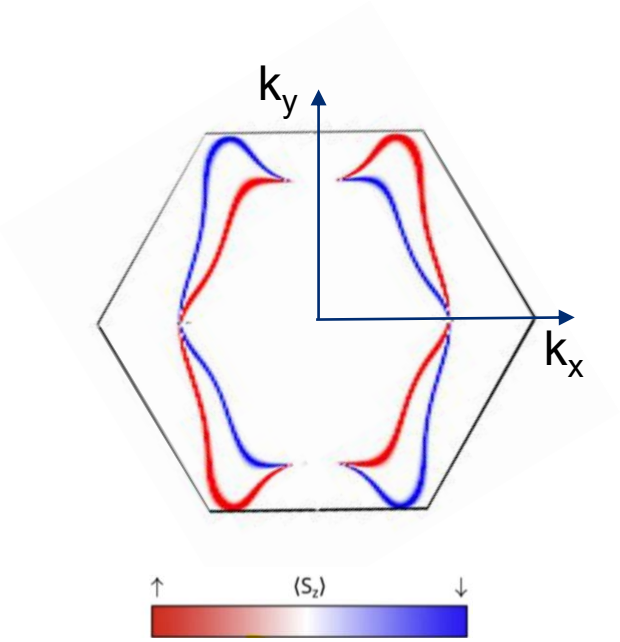
- Kounta, HR et al. Phys. Rev. Materials 7, 024416 (2023)
- Reichlova et al. Nature Comm. (2024)
- Rial et al. Phys. Rev. B 110, L220411 (2024)
- Han et al. Science Adv. 10, eadn0479 (2024)

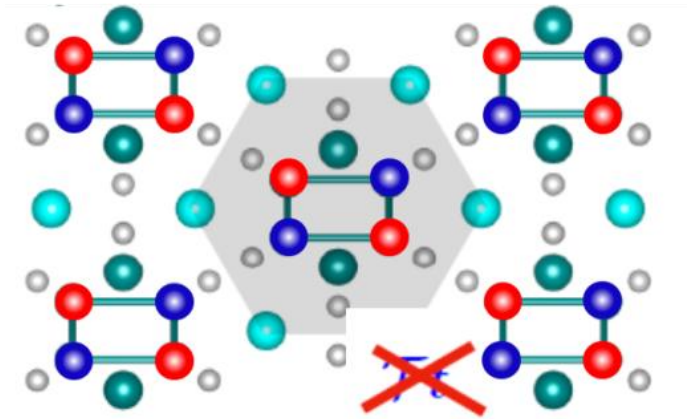
FZU Institute of Physics of the Czech Academy of Sciences

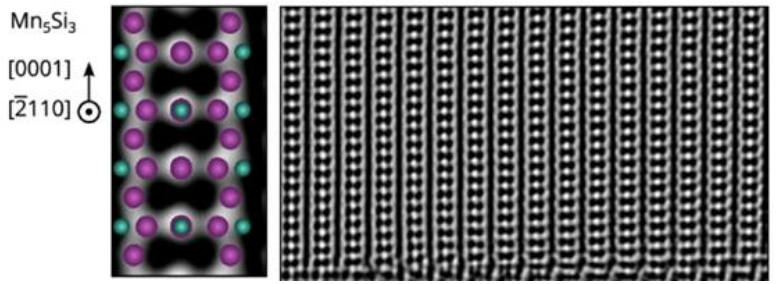
DIOSCURI CENTRE FOR SPINCALORITRONICS AND MAGNONICS

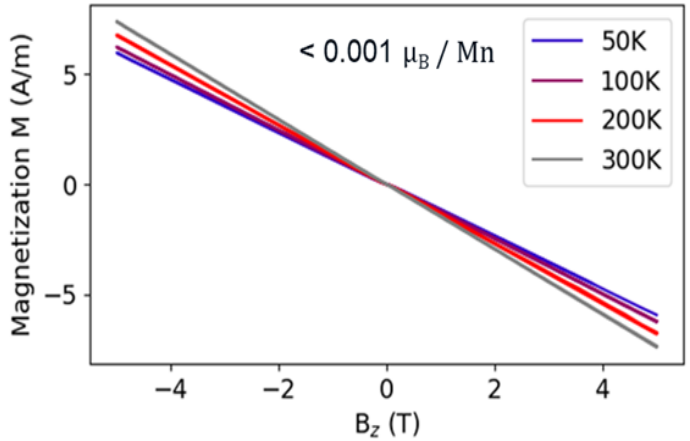
Mn_5Si_3 thin films

- Metallic d-wave candidate
- epitaxial constrains of Si(111)
- T_N ~ 240 K
- Vanishing magnetization





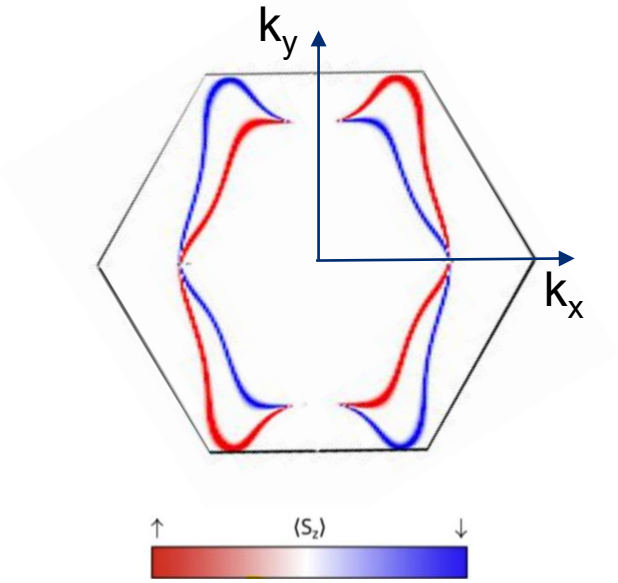


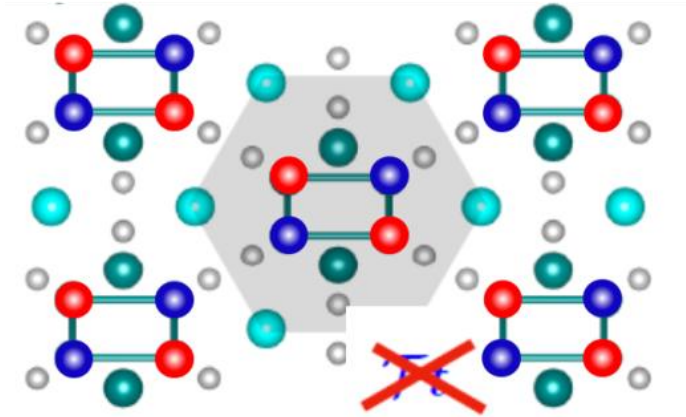


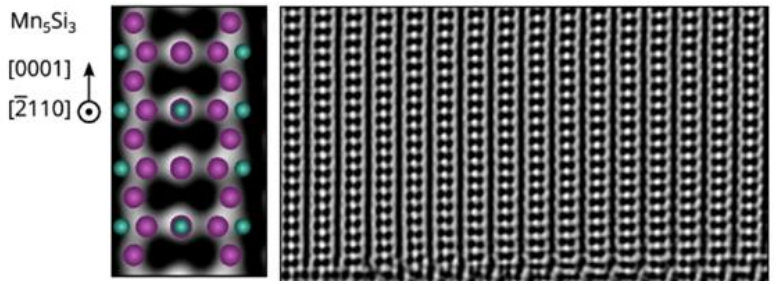
- Kounta, HR et al. Phys. Rev. Materials 7, 024416 (2023)
- Reichlova et al. Nature Comm. (2024)
- Rial et al. Phys. Rev. B 110, L220411 (2024)
- Han et al. Science Adv. 10, eadn0479 (2024)

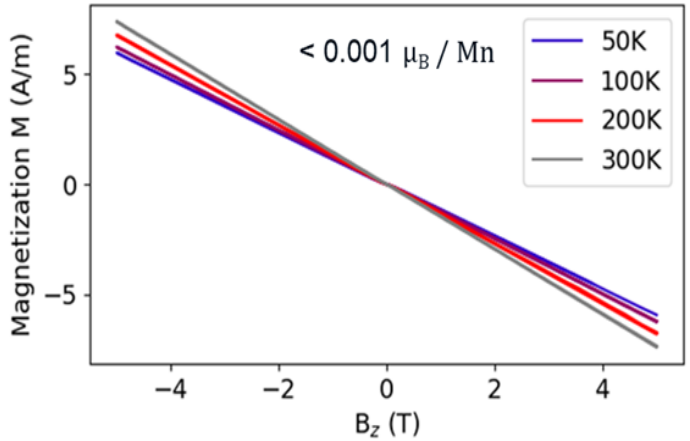
Mn_5Si_3 thin films

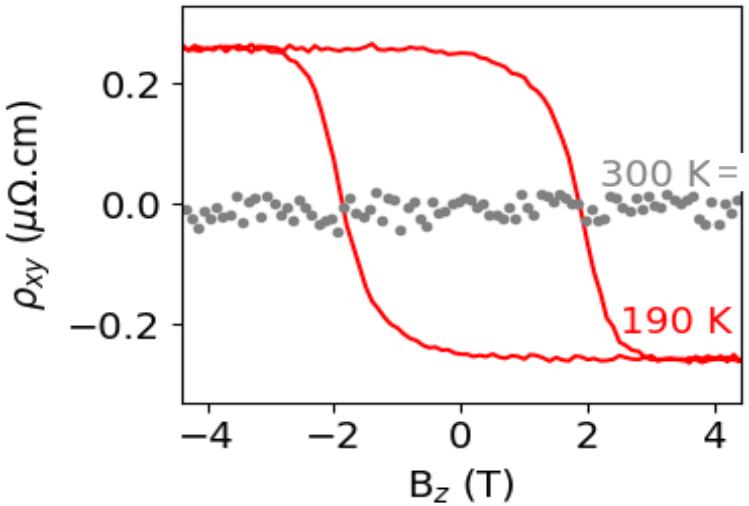
- Metallic d-wave candidate
- epitaxial constrains of Si(111)
- T_N ~ 240 K
- Vanishing magnetization
- Anomalous Hall effect reversal











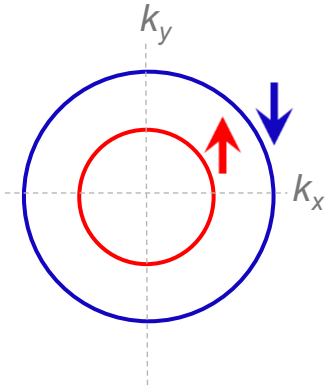
- Kounta, HR et al. Phys. Rev. Materials 7, 024416 (2023)
- Reichlova et al. Nature Comm. (2024)
- Rial et al. Phys. Rev. B 110, L220411 (2024)
- Han et al. Science Adv. 10, eadn0479 (2024)

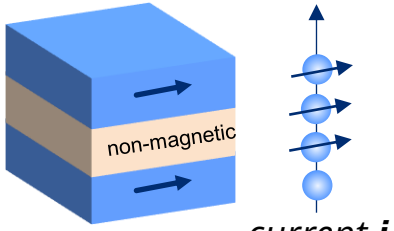
FZU Institute of Physics of the Czech Academy of Sciences

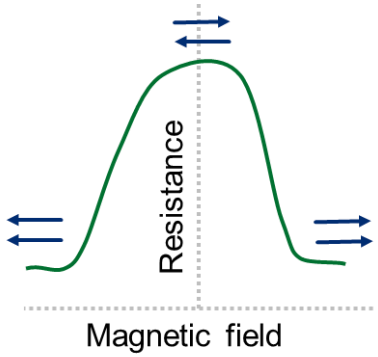
DIOSCURI CENTRE FOR SPINCALORITRONICS AND MAGNONICS

Spin current from Mn_5Si_3 thin films

Ferromagnets

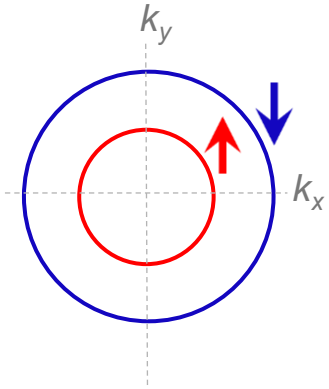


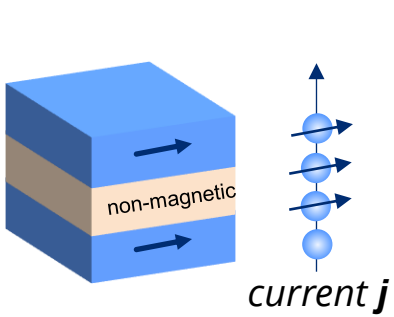


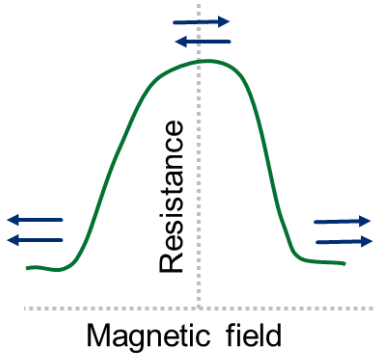


Spin current from Mn_5Si_3 thin films

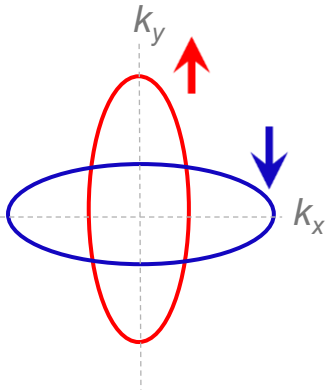
Ferromagnets

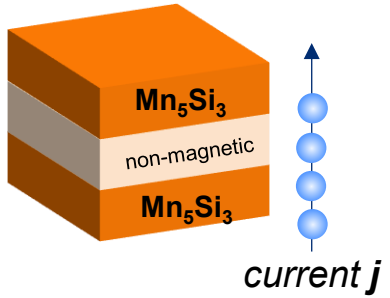




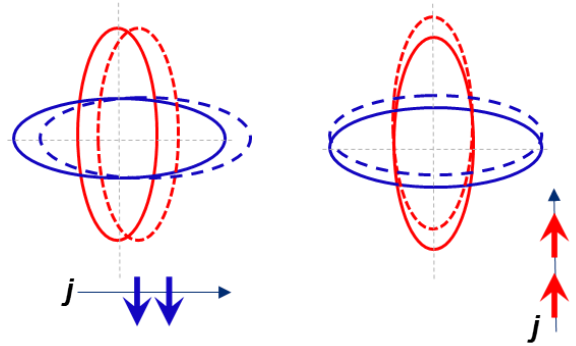


Altermagnets





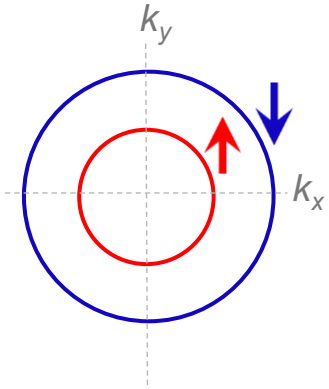
- Anisotropic spin polarization

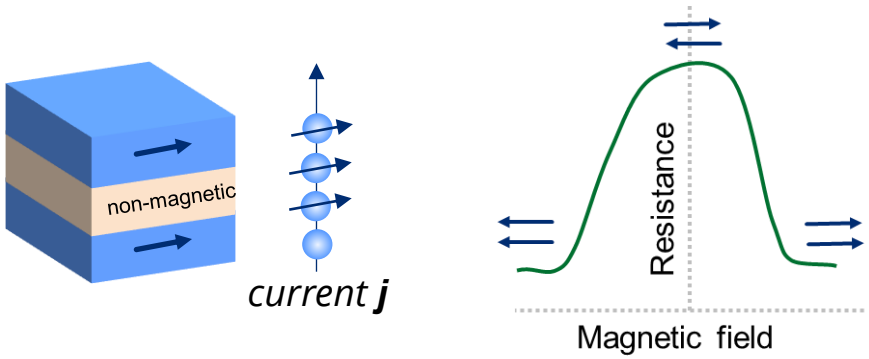


- Mn_5Si_3 films: no polarization in z- direction

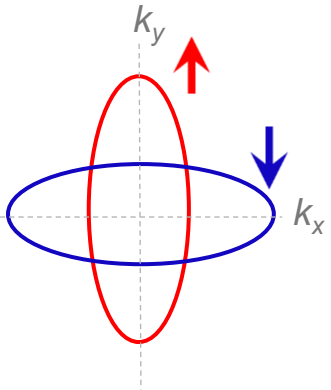
Spin current from Mn_5Si_3 thin films

Ferromagnets

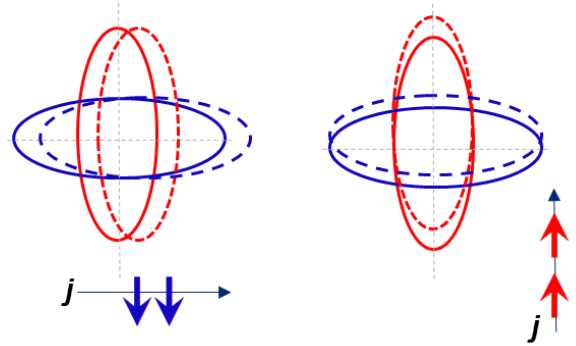




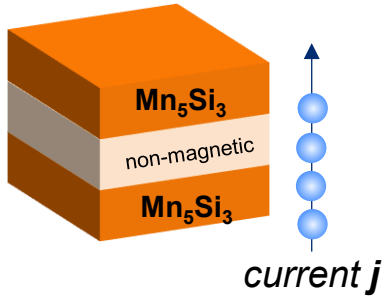
Altermagnets

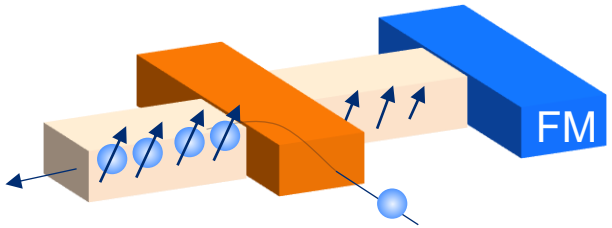


- Anisotropic spin polarization



- Mn_5Si_3 films: no polarization in z- direction
- Lateral spin injection & detection

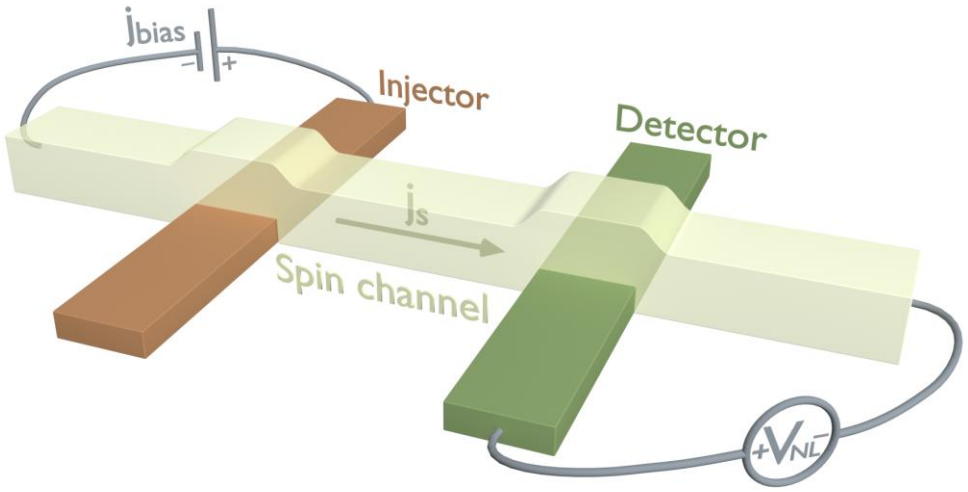




FZU Institute of Physics of the Czech Academy of Sciences

DIOSCURI CENTRE FOR SPINCALORITRONICS AND MAGNONICS

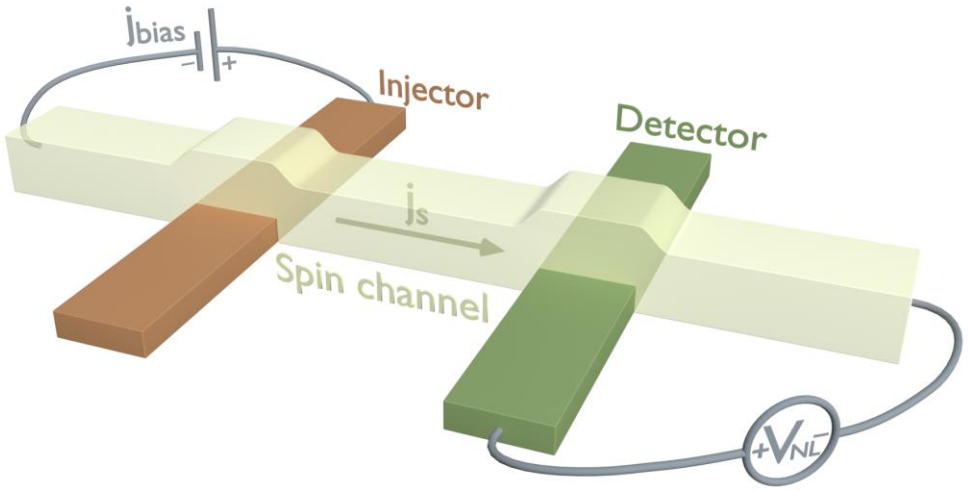
Lateral spin valves - principle

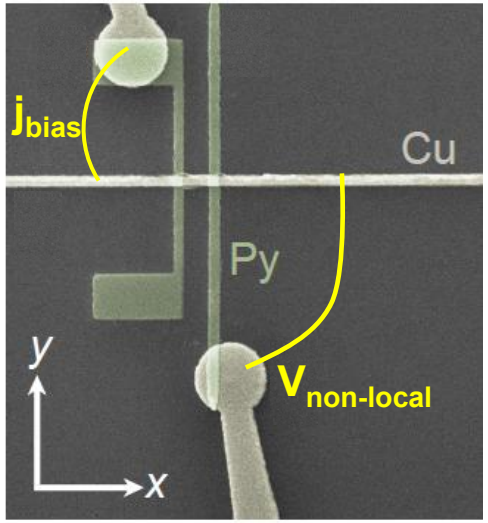


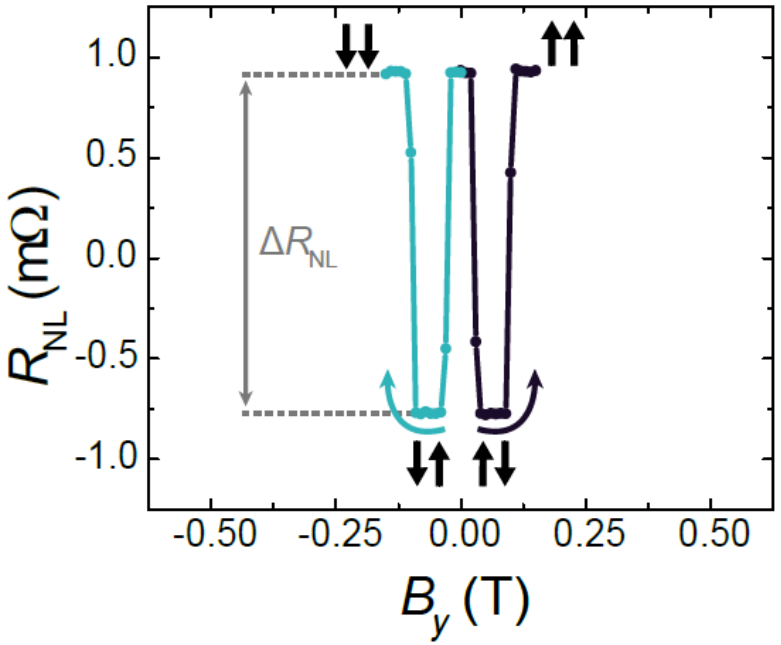
- Elegant design to separate charge and spin current

🕮 Mencos et al. arXiv:2512.17427v1

Lateral spin valves – ferromagnets



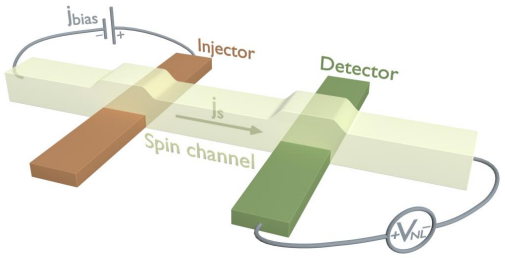


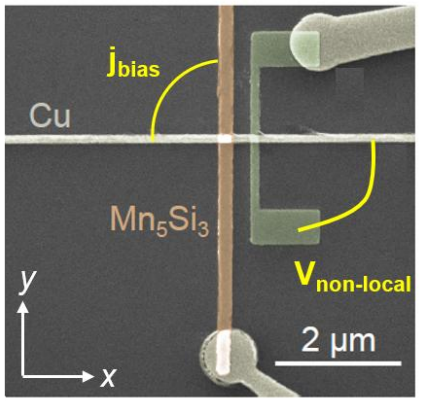


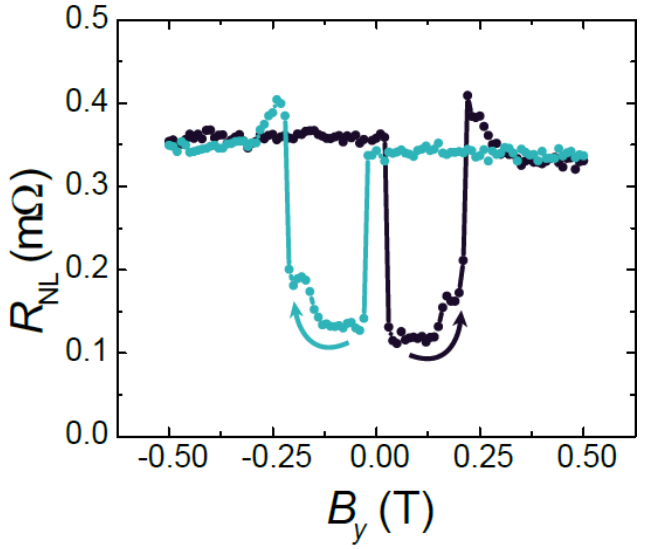
- Elegant design to separate charge and spin current
- Conventional ferromagnet reference – non-local signal as expected

🕮 Mencos et al. arXiv:2512.17427v1

Lateral spin valves with Mn_5Si_3 injector



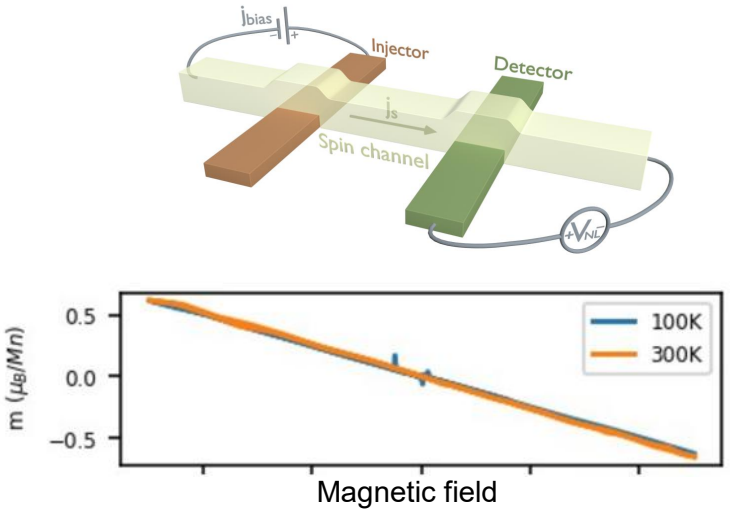


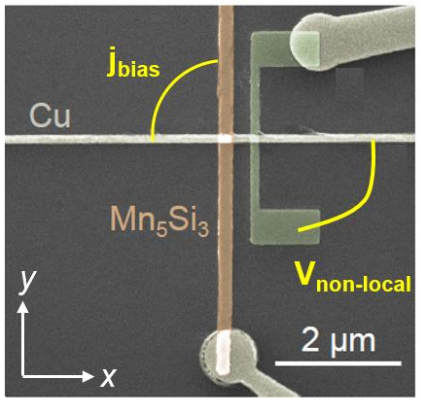


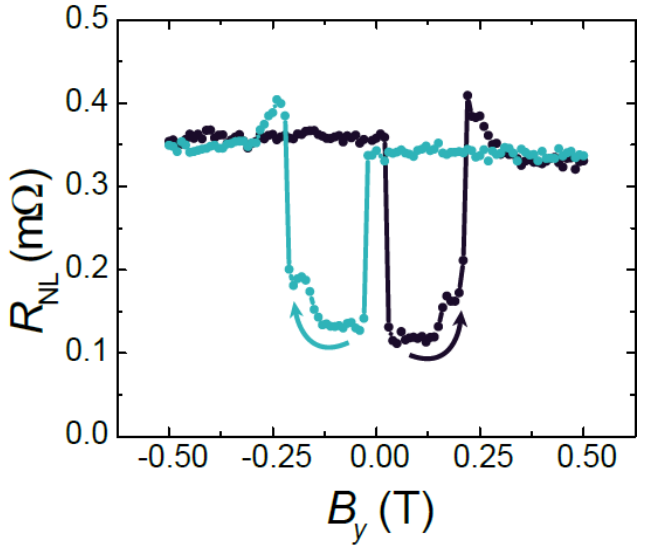
- Spin current generated and detected non-locally

Mencos et al. arXiv:2512.17427v1

Lateral spin valves with Mn_5Si_3 injector



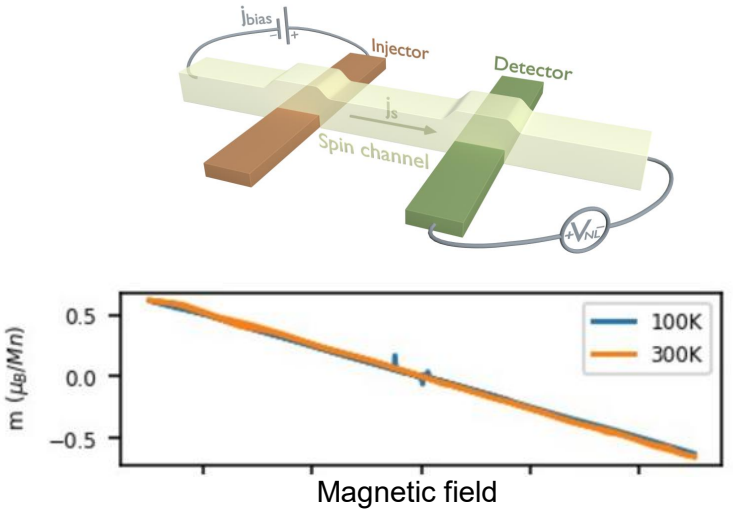


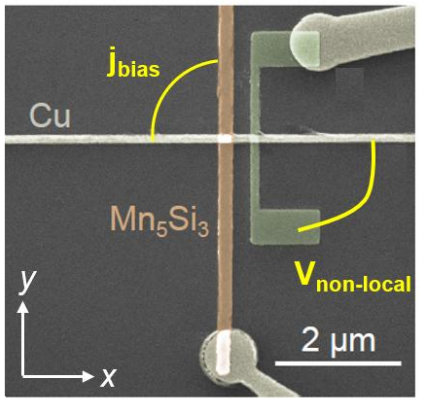


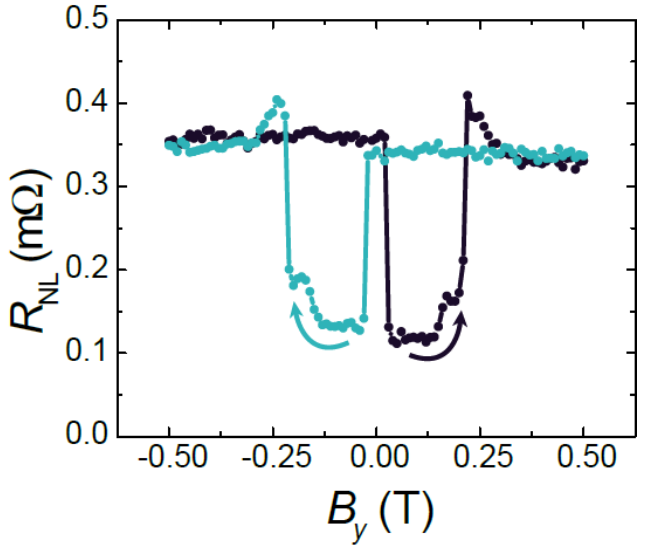
- Spin current generated and detected non-locally despite **vanishing net magnetization**

Mencos et al. arXiv:2512.17427v1

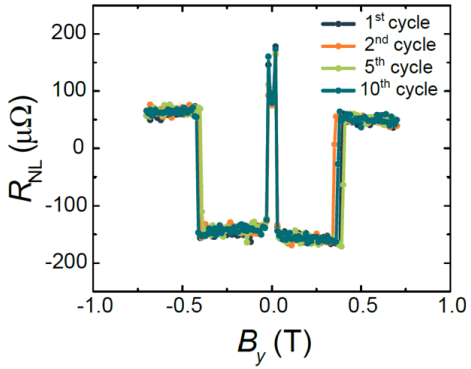
Lateral spin valves with Mn_5Si_3 injector





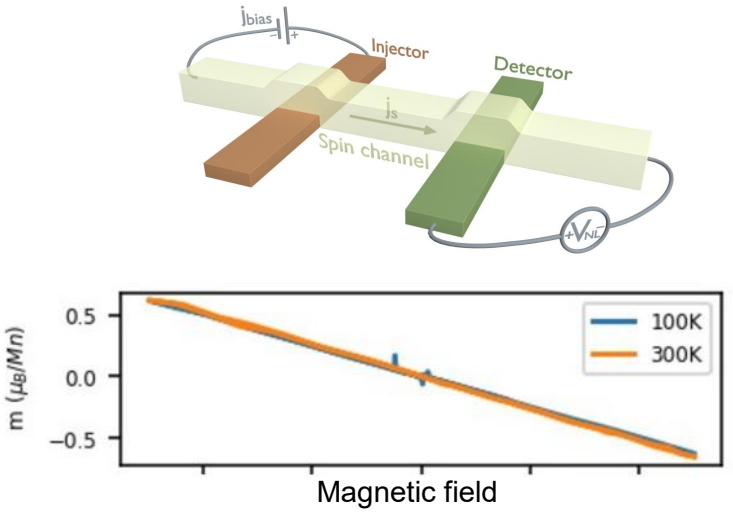


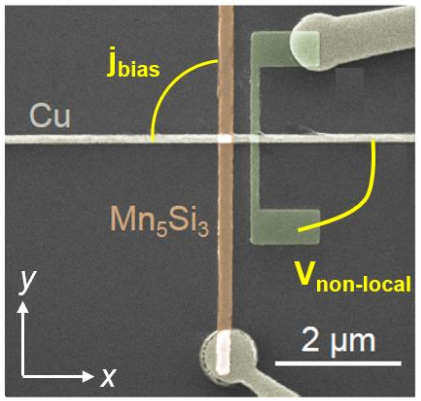
- Spin current generated and detected non-locally despite **vanishing net magnetization**
- Robust for cycling

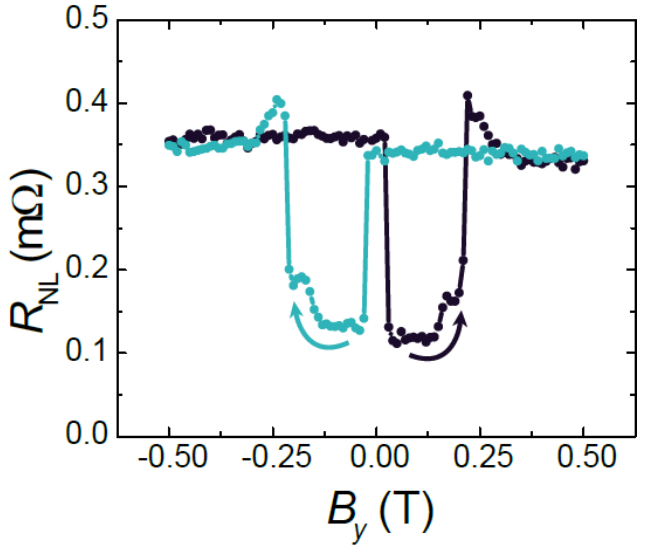


Mencos et al. arXiv:2512.17427v1

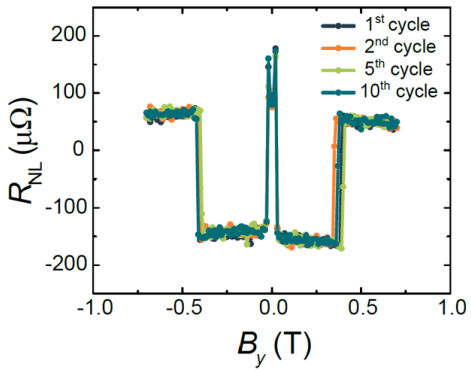
Lateral spin valves with Mn_5Si_3 injector

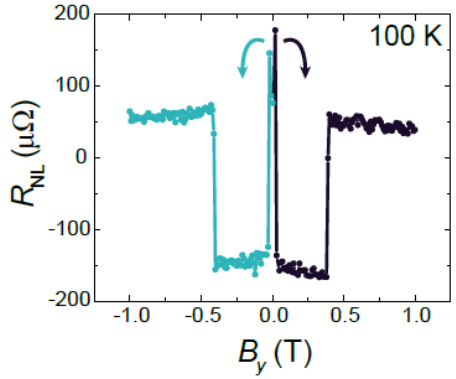


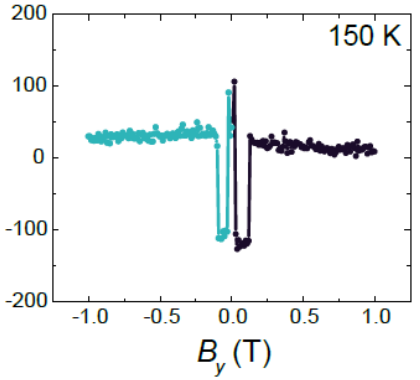


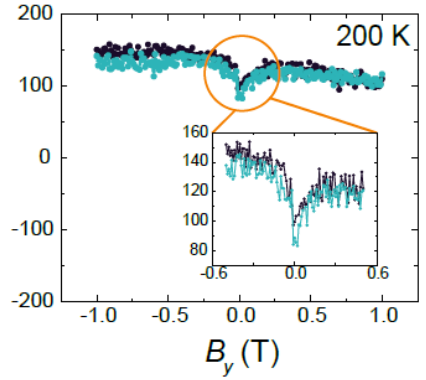


- Spin current generated and detected non-locally despite **vanishing net magnetization**
- Robust for cycling
- Vanishing ~T_N







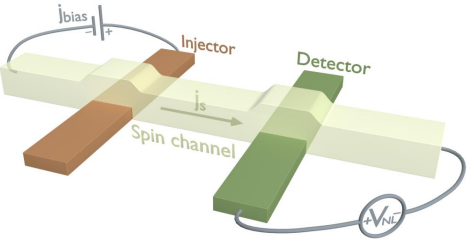


FZU Institute of Physics of the Czech Academy of Sciences

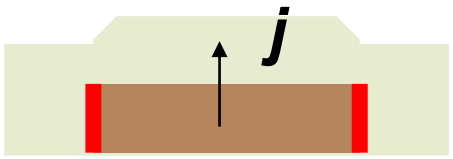
DIOSCURI CENTRE FOR SPINCALORITRONICS AND MAGNONICS

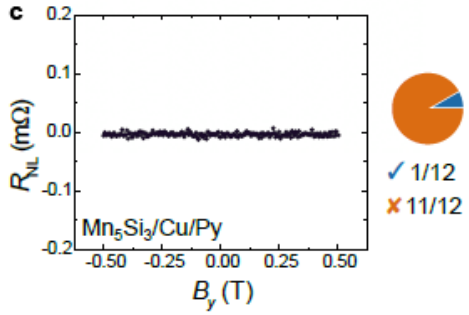
Mencos et al. arXiv:2512.17427v1

Role of the side injection



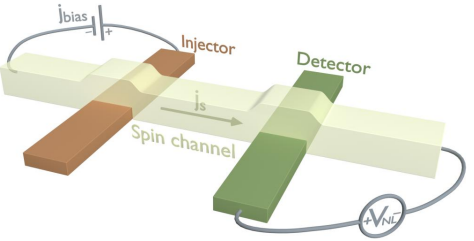
Side edge blocked



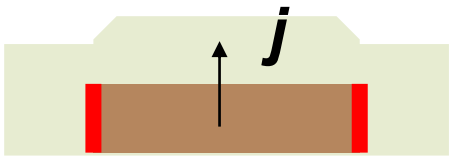


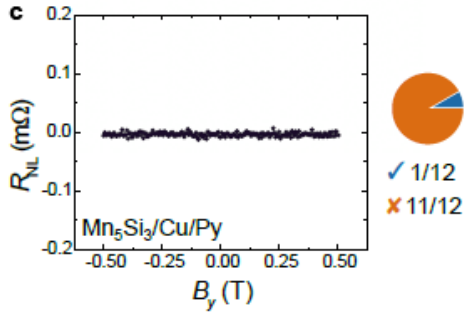
- Key role of edge cleaning

Role of the side injection



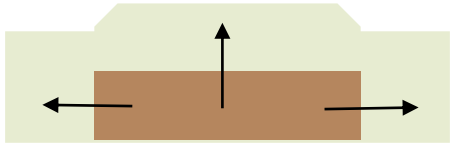
Side edge blocked

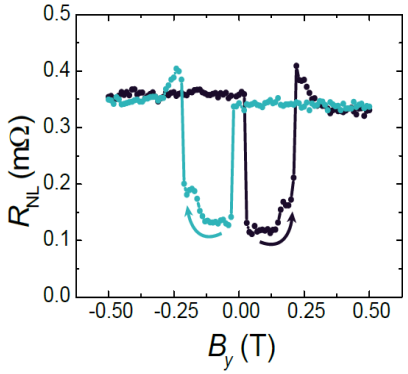




✓ 1/12
✘ 11/12

Side edge cleaned

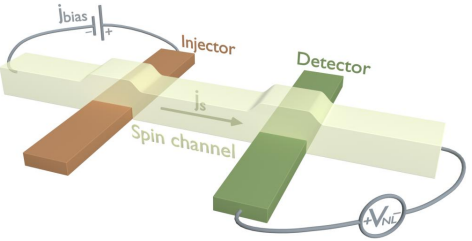




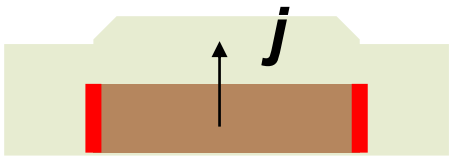
✓ 8/10
✘ 2/10

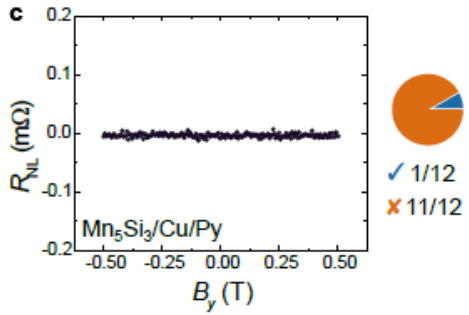
- Key role of edge cleaning

Role of the side injection

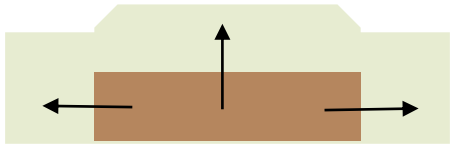


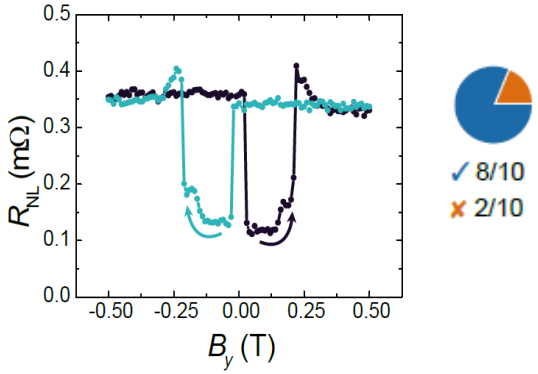
Side edge blocked



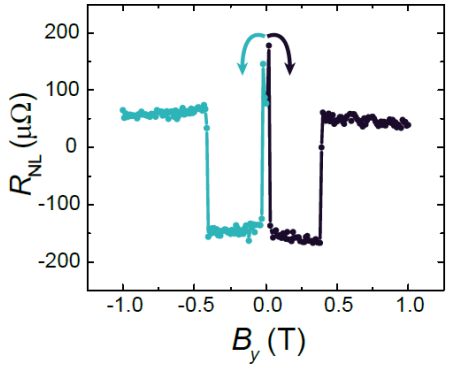


Side edge cleaned





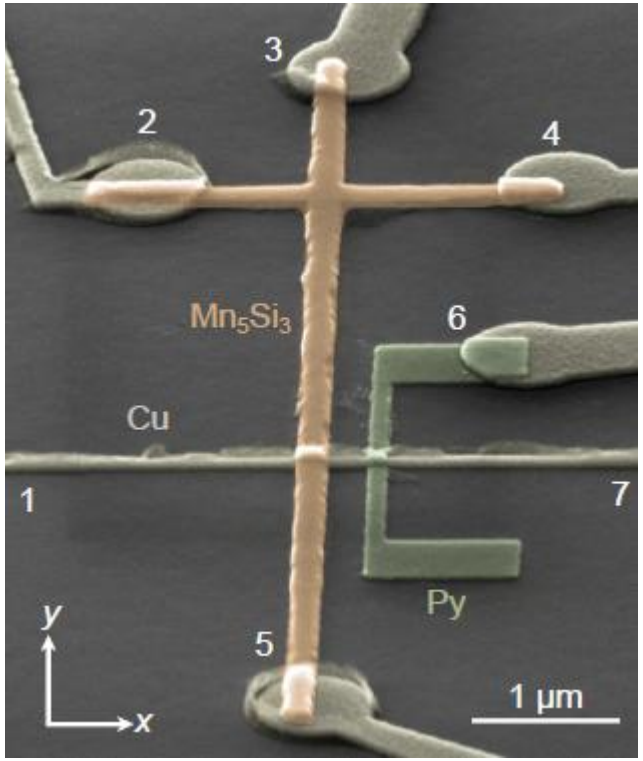
Top surface blocked

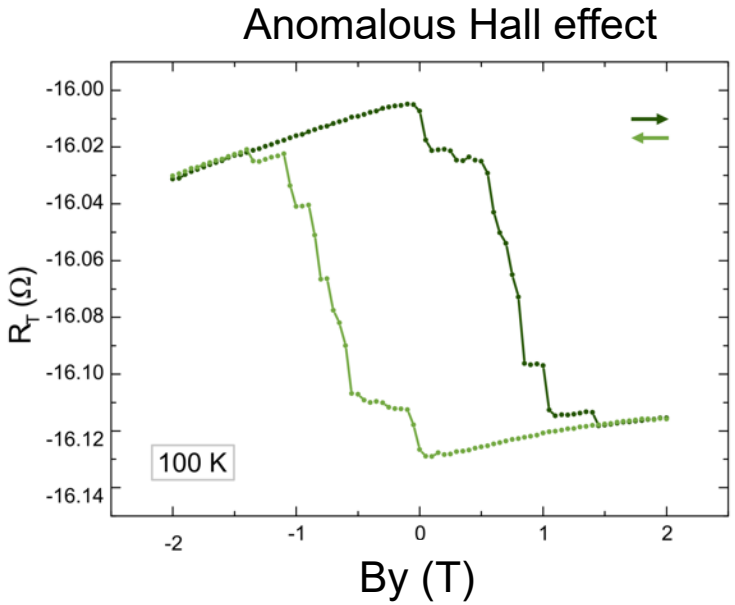


Consistently working

- Key role of edge cleaning
- Signal remains if top surface blocked

Lateral spin valves with Mn_5Si_3 injector

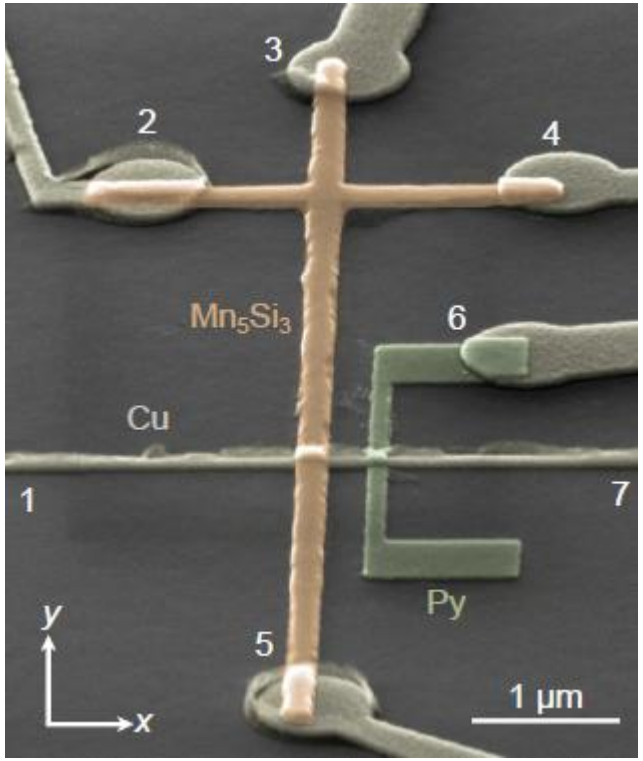




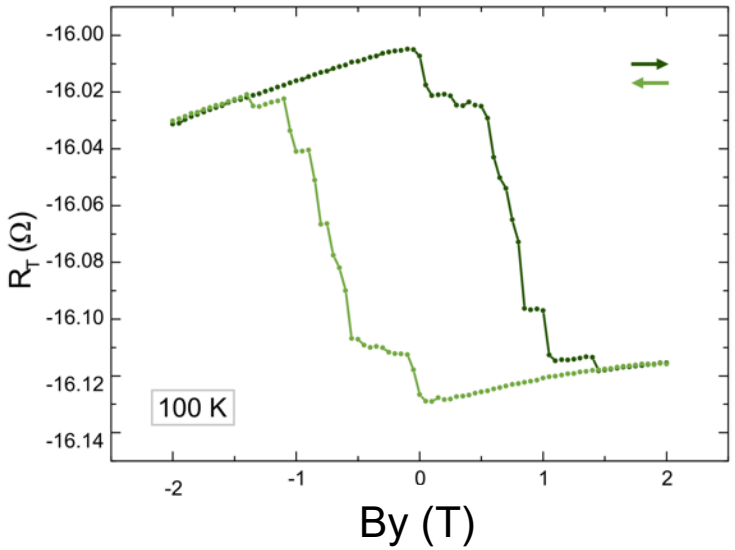
- Anomalous Hall effect measurements on the Mn_5Si_3 electrode

🕮 Mencos et al. arXiv:2512.17427v1

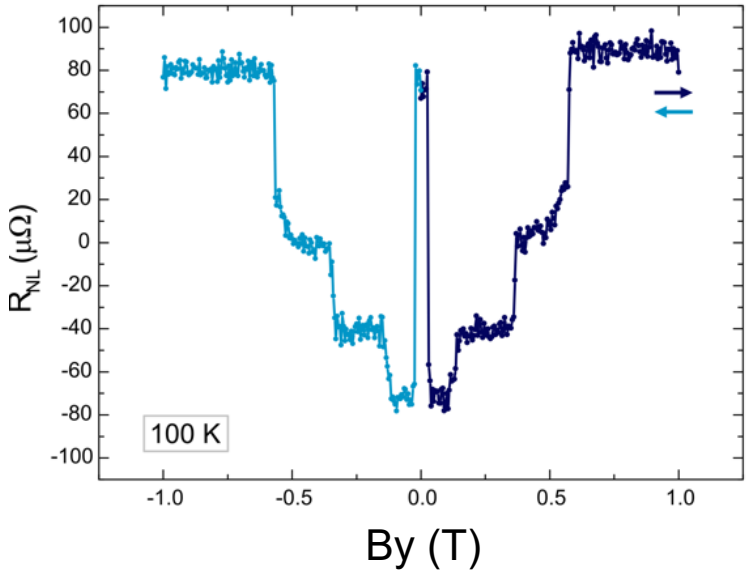
Lateral spin valves with Mn_5Si_3 injector



Anomalous Hall effect



Non-local spin current

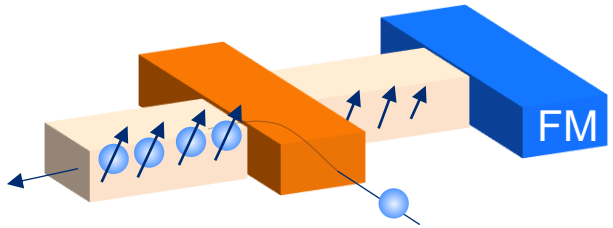


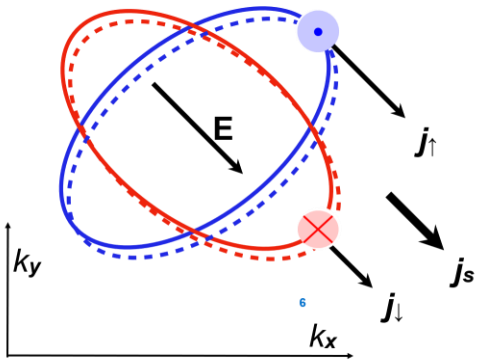
- Anomalous Hall effect measurements on the Mn_5Si_3 electrode
- Similar steps in non-local signal

Mencos et al. arXiv:2512.17427v1

Anisotropic spin injection

- Longitudinal spin polarization

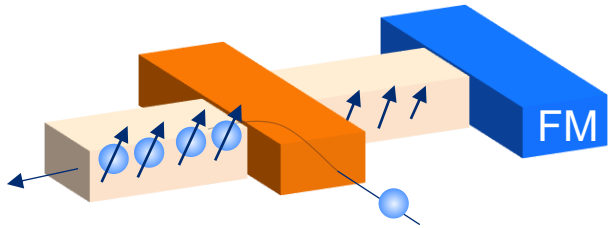


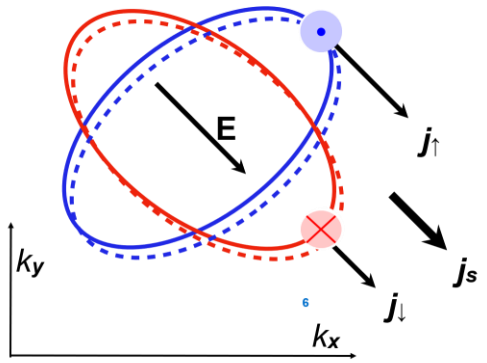


🕮 Mencos et al. arXiv:2512.17427v1

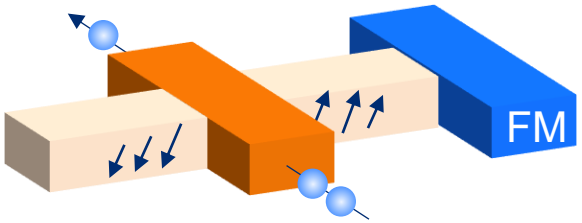
Anisotropic spin injection

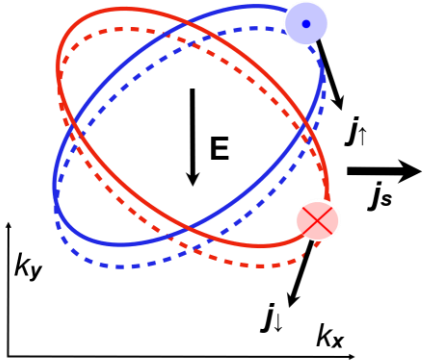
- Longitudinal spin polarization





- Transversal spin current

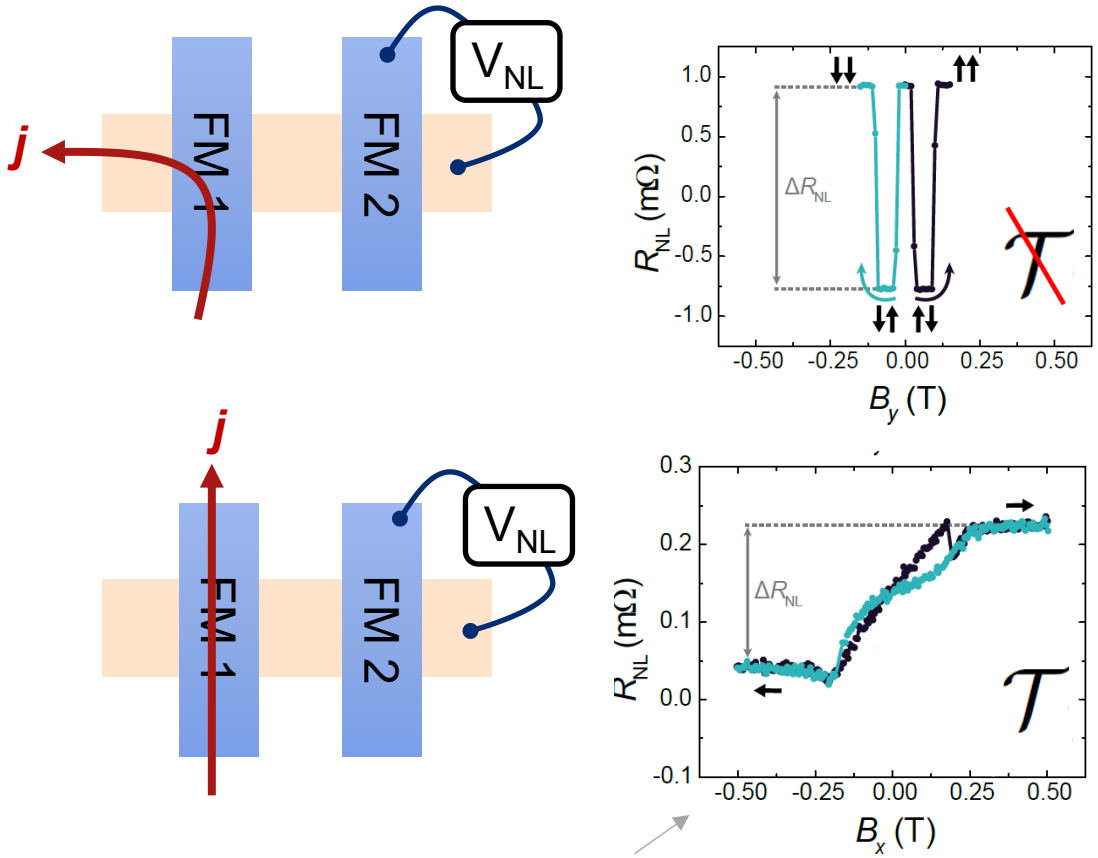




🕮 Mencos et al. arXiv:2512.17427v1

Anisotropic spin injection

- Compare to ferromagnetic lateral spin valves

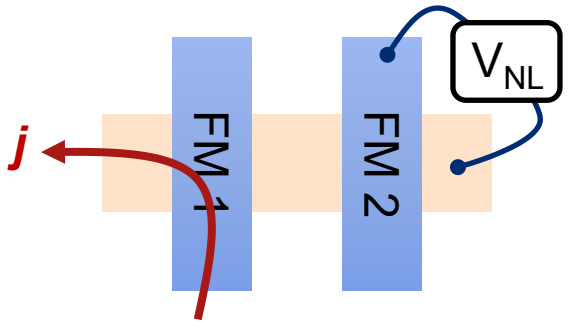


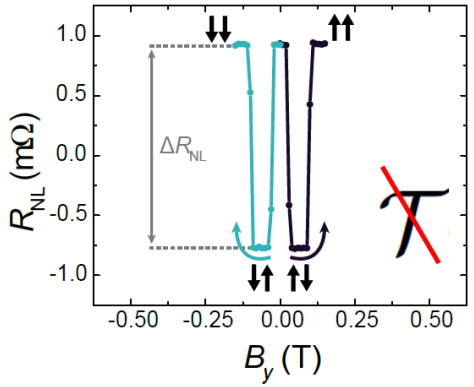
Spin Hall effect independent magnetization FM1

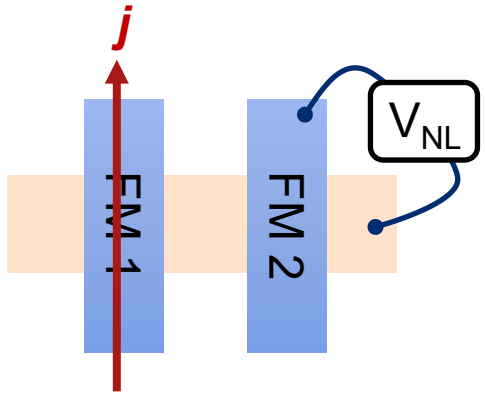
🕮 Mencos et al. arXiv:2512.17427v1

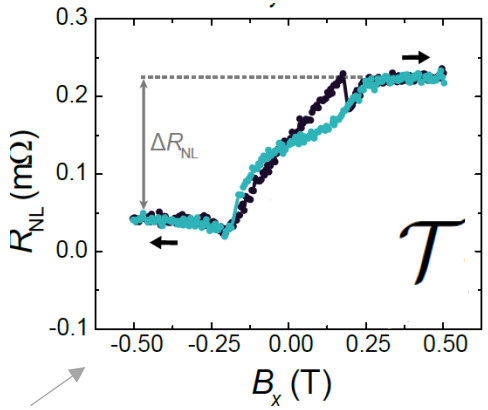
Anisotropic spin injection

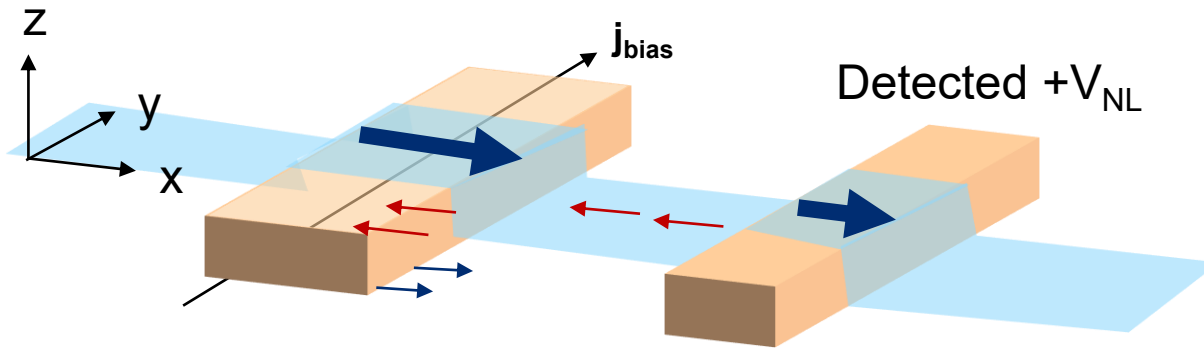
- Compare to ferromagnetic lateral spin valves

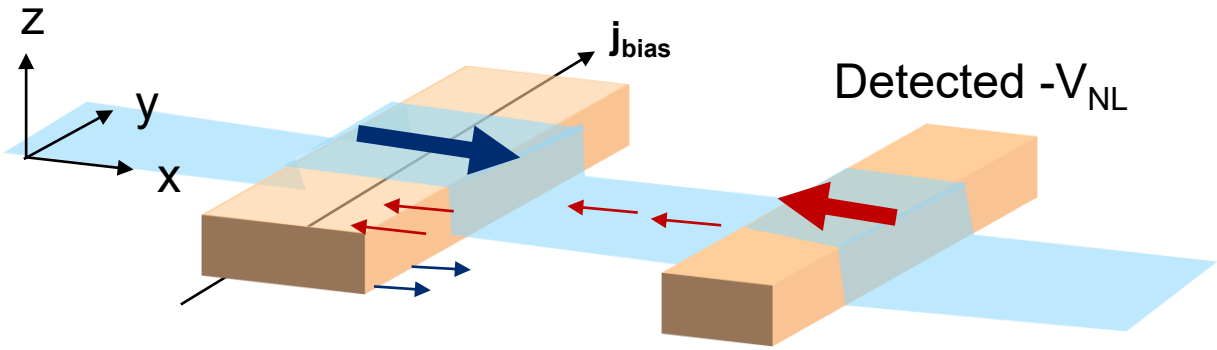










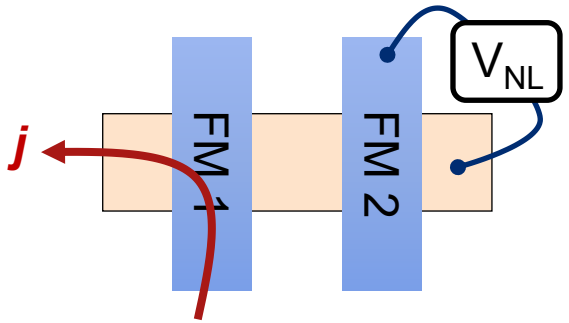


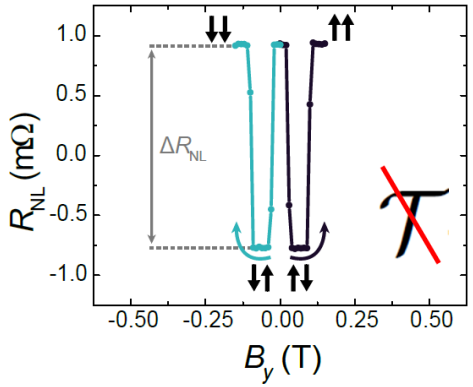
Spin Hall effect independent magnetization FM1

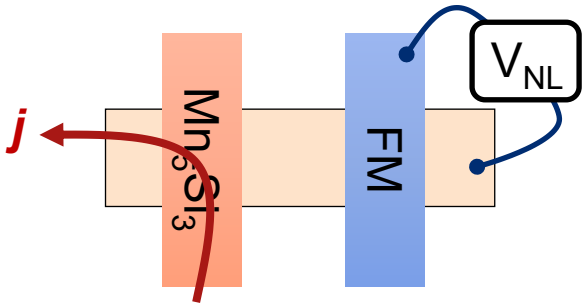
Mencos et al. arXiv:2512.17427v1

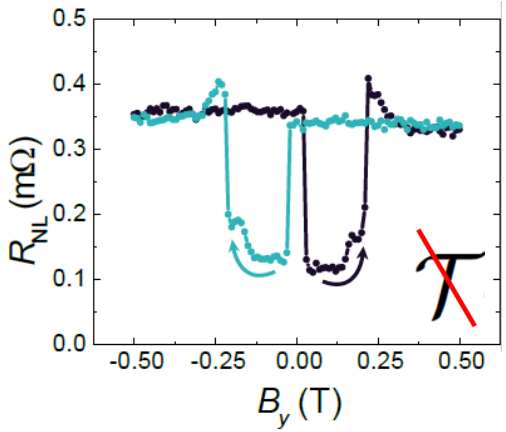
Anisotropic spin injection

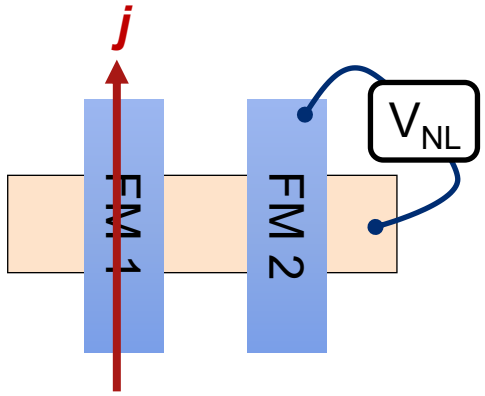
- Compare to ferromagnetic lateral spin valves
- Time reversal broken transversal spin current in Mn_5Si_3

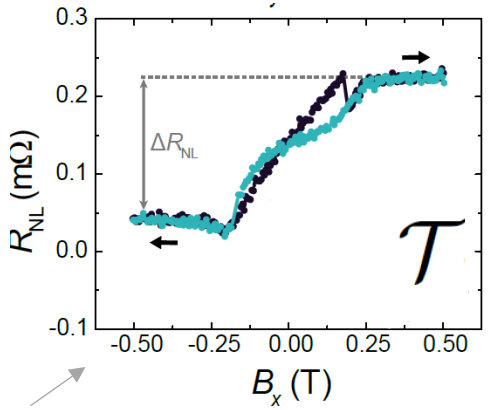










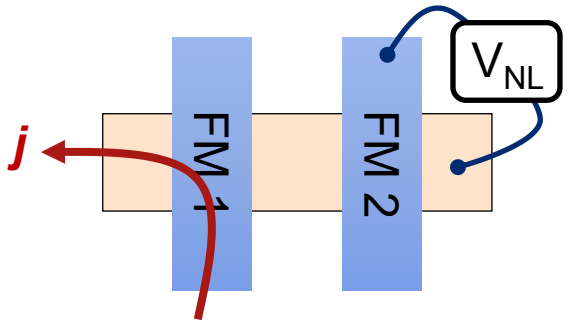


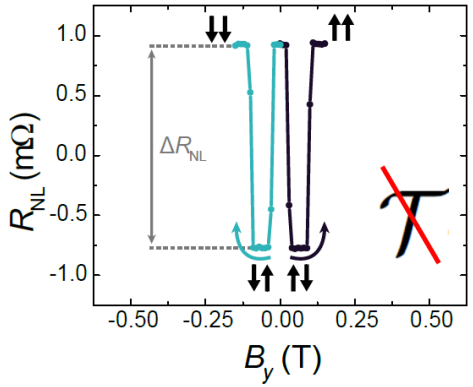
Spin Hall effect independent magnetization FM1

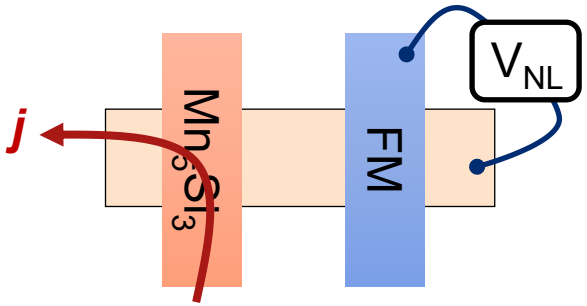
Mencos et al. arXiv:2512.17427v1

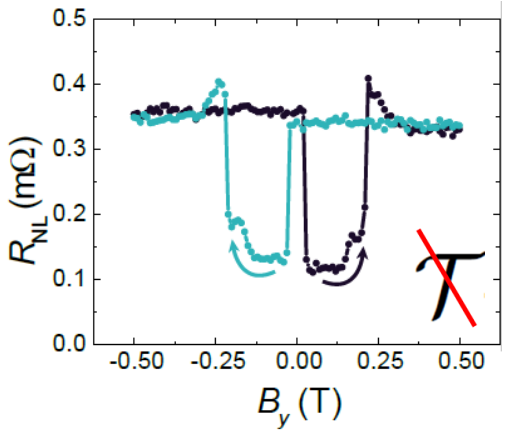
Anisotropic spin injection

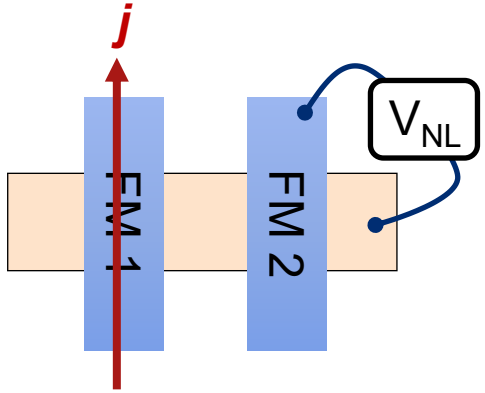
- Compare to ferromagnetic lateral spin valves
- Time reversal broken transversal spin current in Mn_5Si_3

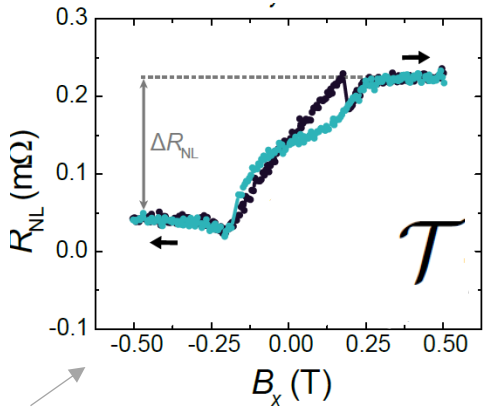


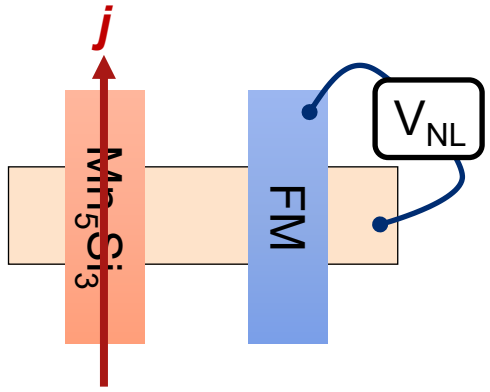


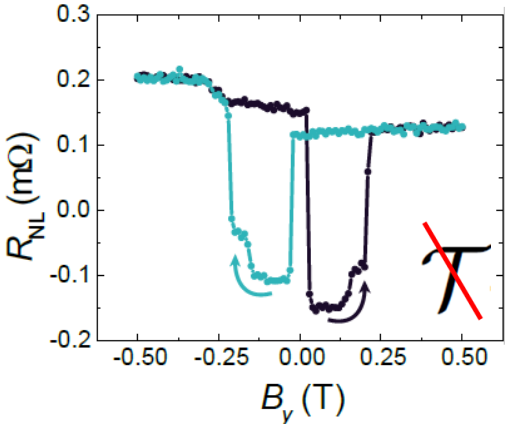








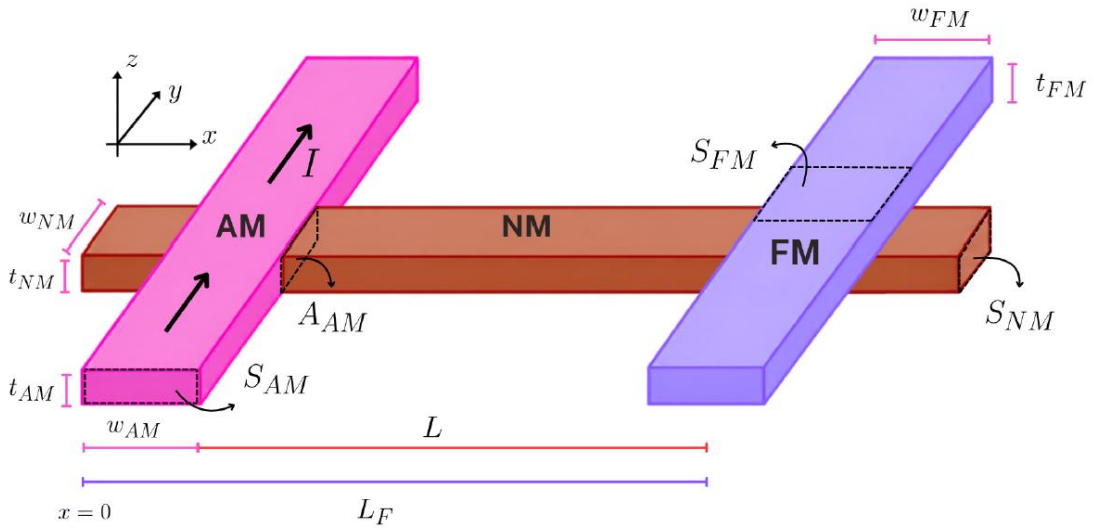




Spin Hall effect independent magnetization FM1

Mencos et al. arXiv:2512.17427v1

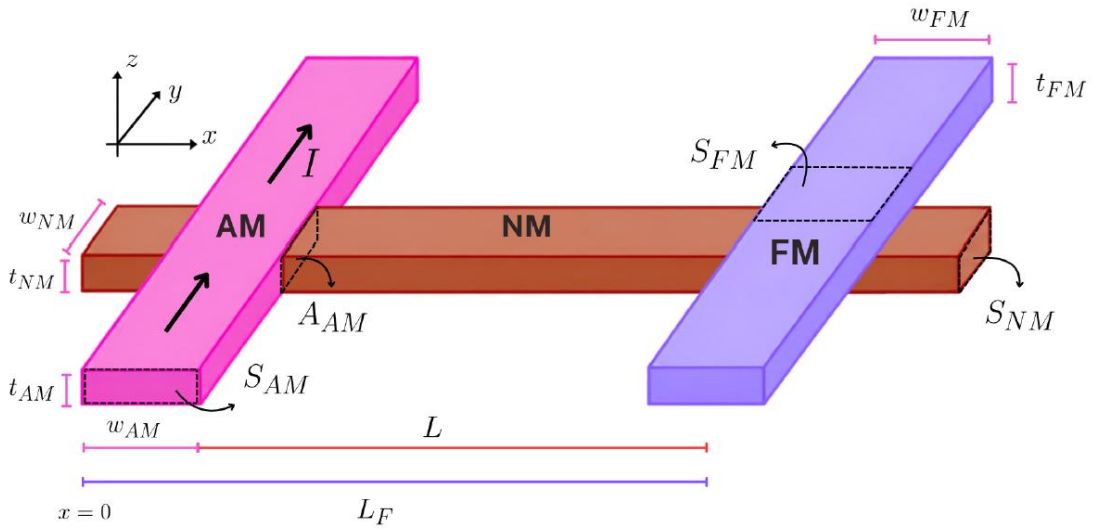
Estimate the efficiency

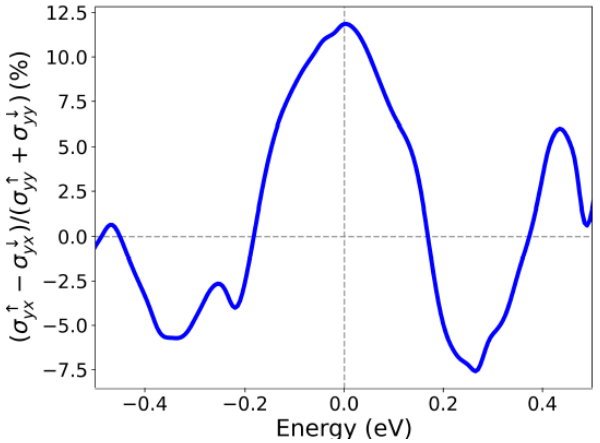


$$\Delta R_{NL} = \frac{4\,T_{xy}\,\ell_{\mathrm{AM}}\rho_{\mathrm{AM}}P_{\mathrm{eff}}\,r_F \mathrm{th}\frac{w_{\mathrm{AM}}}{\ell_{\mathrm{AM}}}\left[(1+r_B)\mathrm{th}\frac{w_{\mathrm{AM}}}{2\ell_{\mathrm{AM}}}+r_A\right](\hat{\mathbf{m}}\cdot\mathbf{N})\,e^{-L/\ell_{\mathrm{NM}}}}{S_{\mathrm{AM}}\left\{e^{\frac{-2L}{\ell_{\mathrm{NM}}}}\left[2r_Br_A-\mathrm{th}\frac{w_{\mathrm{AM}}}{\ell_{\mathrm{AM}}}(1-r_A^2-r_B^2)\right]+(1+2r_F)\left[2r_A(1+r_B)+\mathrm{th}\frac{w_{\mathrm{AM}}}{\ell_{\mathrm{AM}}}\left((1+r_B)^2+r_A^2\right)\right\}\right.}$$

Mencos et al. arXiv:2512.17427v1
Sigales et al. PRB 113, 184447 (2026)

Estimate the efficiency





$$\Delta R_{NL} = \frac{4\,T_{xy}\,\ell_{\mathrm{AM}}\rho_{\mathrm{AM}}P_{\mathrm{eff}}\,r_F \mathrm{th}\frac{w_{\mathrm{AM}}}{\ell_{\mathrm{AM}}}\left[(1+r_B)\mathrm{th}\frac{w_{\mathrm{AM}}}{2\ell_{\mathrm{AM}}}+r_A\right](\hat{\mathbf{m}}\cdot\mathbf{N})\,e^{-L/\ell_{\mathrm{NM}}}}{S_{\mathrm{AM}}\left\{e^{\frac{-2L}{\ell_{\mathrm{NM}}}}\left[2r_Br_A-\mathrm{th}\frac{w_{\mathrm{AM}}}{\ell_{\mathrm{AM}}}(1-r_A^2-r_B^2)\right]+(1+2r_F)\left[2r_A(1+r_B)+\mathrm{th}\frac{w_{\mathrm{AM}}}{\ell_{\mathrm{AM}}}\left((1+r_B)^2+r_A^2\right)\right]\right\}}$$

- Considering experimental parameters
- Considering DFT spin polarization

spin diffusion length in the Mn_5Si_3 ~ **50-130 nm**

FZU Institute of Physics of the Czech Academy of Sciences

DIOSCURI CENTRE FOR SPINCALORITRONICS AND MAGNONICS

Mencos et al. arXiv:2512.17427v1
Sigales et al. PRB 113, 184447 (2026)

Conclusion

- Altermagnetic spin splitting
  - → comparable to ferromagnets
  - → unprecedent anisotropic
- Mn_5Si_3 thin films
  - → altermagnetic candidate
  - → metallic d-wave
  - → vanishing magnetization
- Lateral spin valves with an altermagnet
  - → non-locally detected spin current
  - → time reversal symmetric
  - → unconventional spin-injection phenomenology

- Kounta et al. PRM (2023)
- Mencos et al. arXiv:2512.17427
- Sigales et al. PRB 113, 184447 (2026)
- Song et al. Nature Reviews Materials (2025)
- Jungwirth et al. Altermagnetic spintronics, Nature Physics (2026)

FZU Institute of Physics of the Czech Academy of Sciences
DIOSCURI CENTRE FOR SPINCALORITRONICS AND MAGNONICS
Co-funded by the European Union
MINISTRY OF EDUCATION, YOUTH AND SPORTS