Spin Current:

A Probe of Quantum Materials

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International Center for Quantum Materials, PKU

Outline

I. Introduction to Spin current and Quantum materials

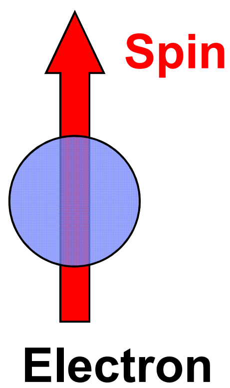
II. Spin current as a probe of quantum materials

- Spin dynamics in FM/superconductors
- Spin superfluidity in canted AFM:

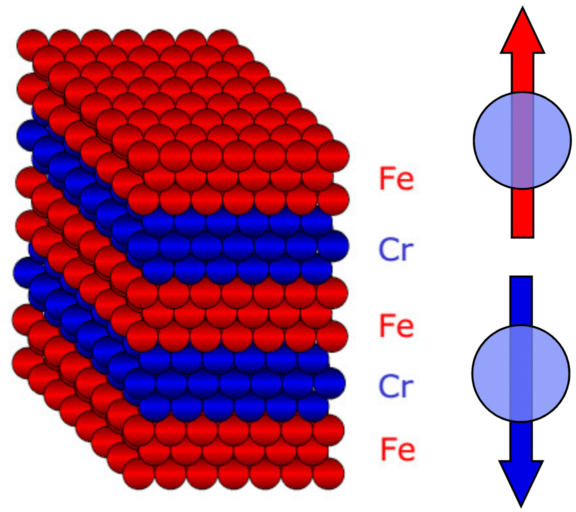
  Cr_2O_3 (Yes), Fe_2O_3 and $MnPS_3$ (No)

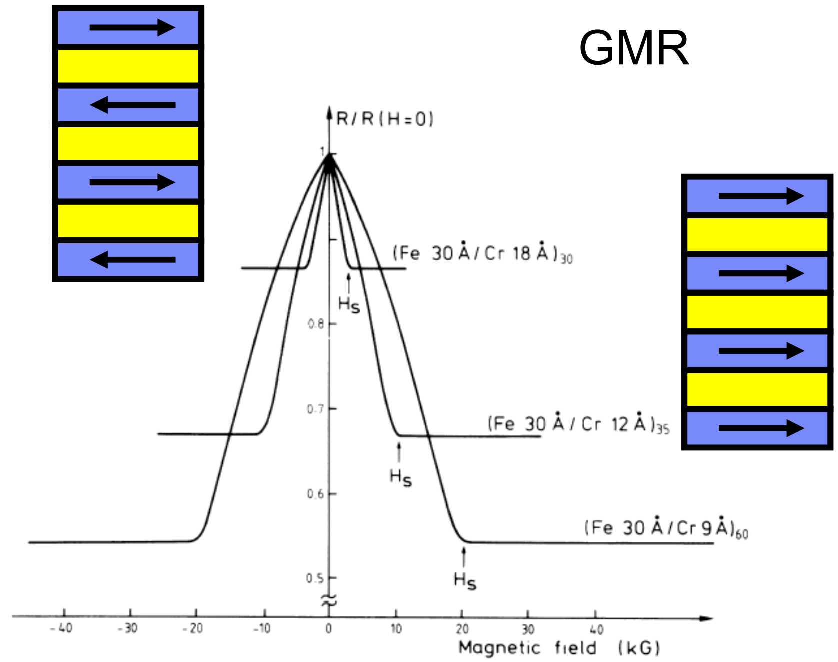
III. Summary and outlook

Introduction to spin current

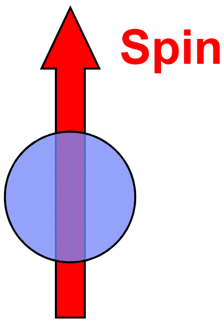


Magnetic structure

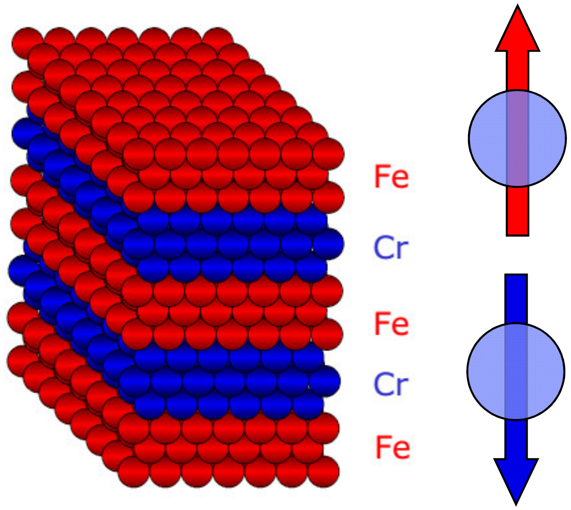


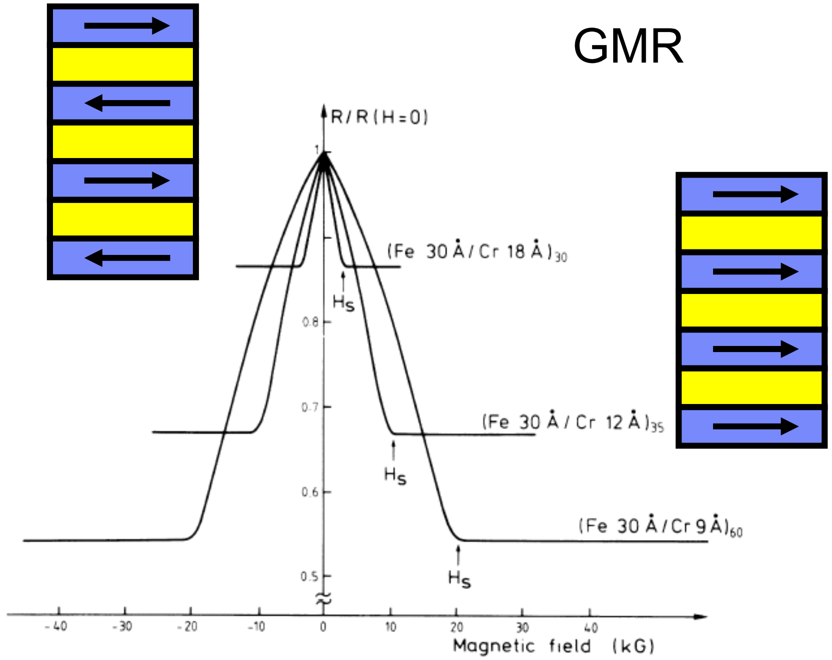


Introduction to spin current



Magnetic structure



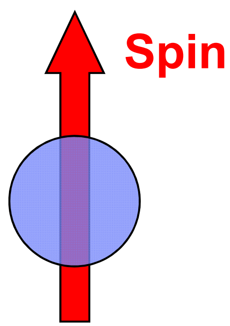


Albert Fert

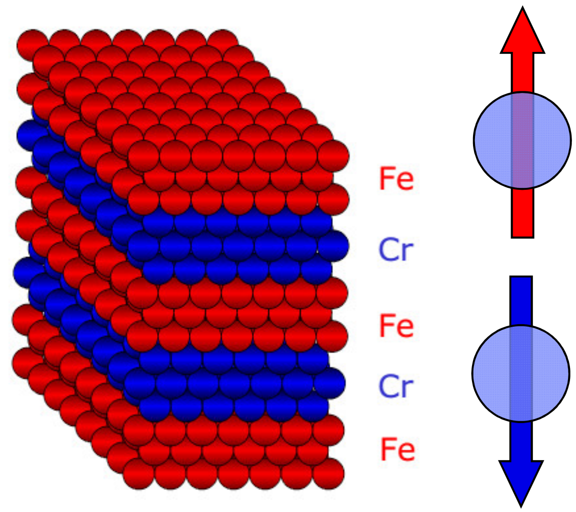
Peter Grunberg

Stuart Parkin

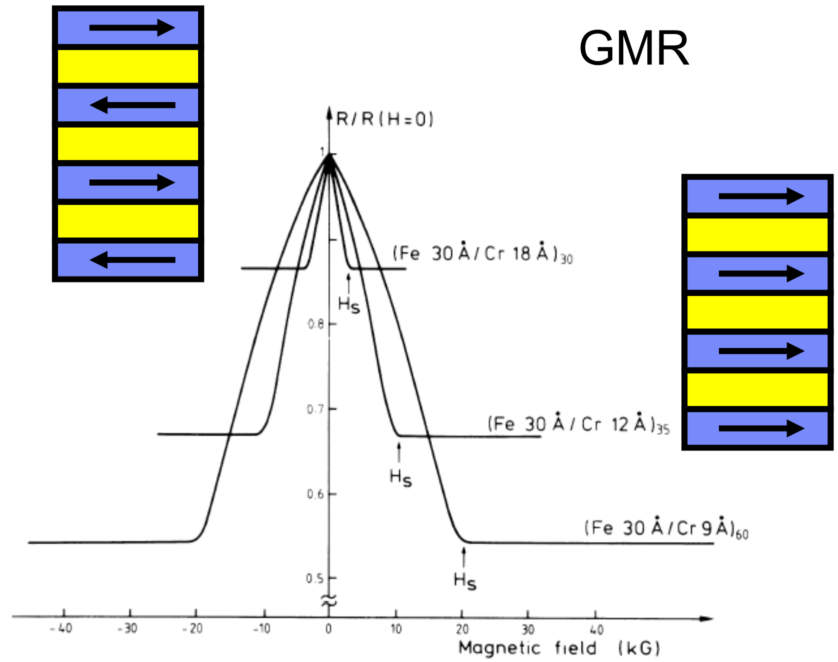
Introduction to spin current



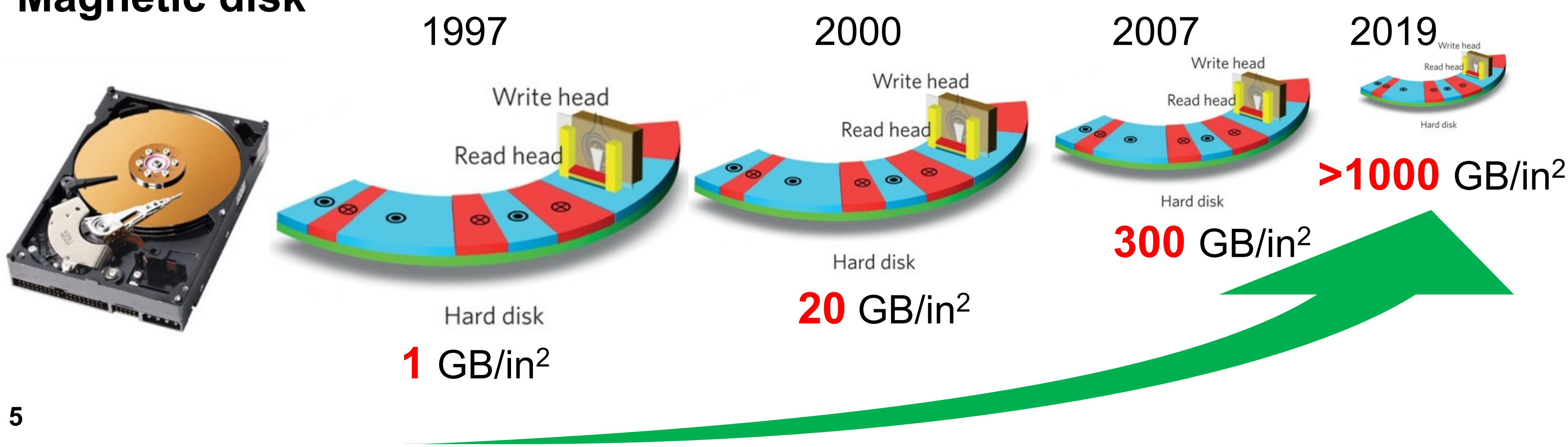
Magnetic structure



GMR



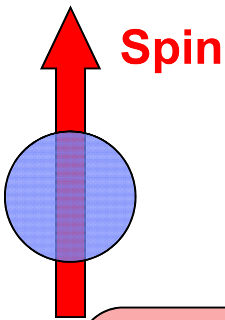
Magnetic disk

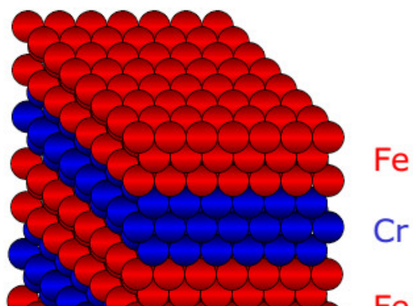


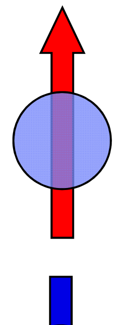
Introduction to spin current

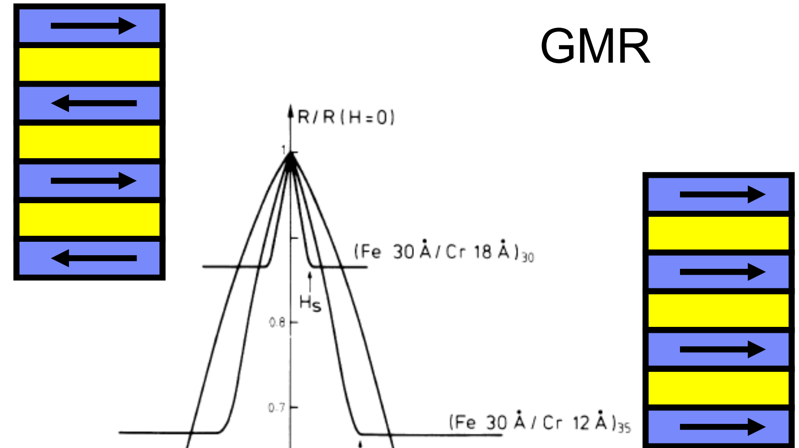
Magnetic structure

GMR



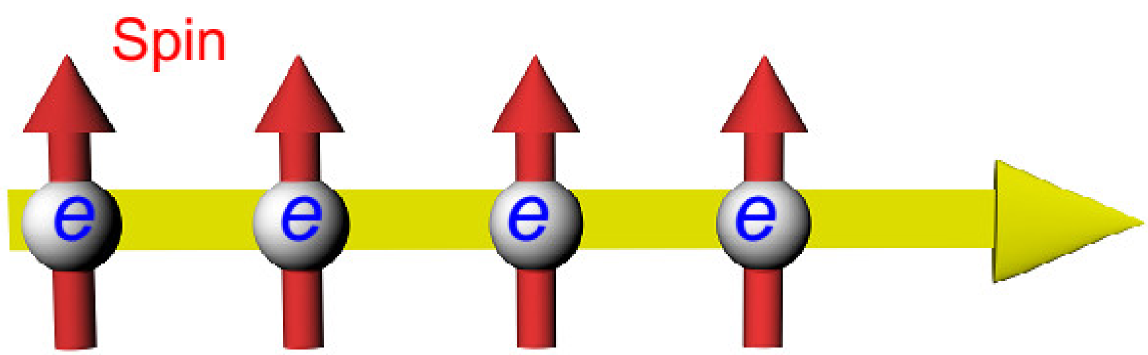






Ele

The Birth of Spintronics



Spin-electronics: Spin angular momentum carried by electrons

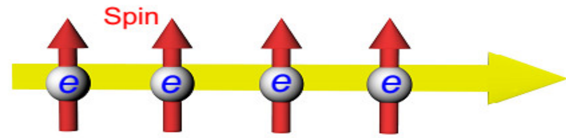
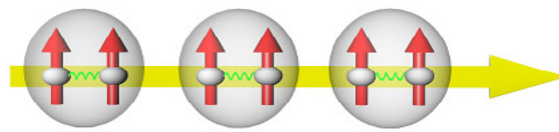
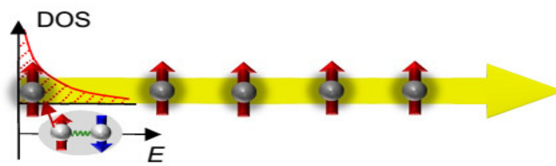
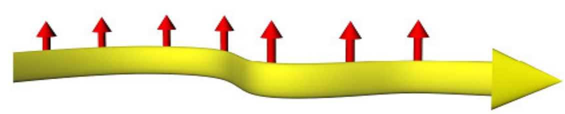
Quantum materials:

Quantum properties stem from a complex interplay between factors such as *reduced dimensionality, quantum confinement, quantum fluctuations, topology of wavefunctions,* etc.

Quantum Materials

Keimer, B. & Moore, J. E. Nat. Phys. (2017)
Basov, D. N., Averitt, R. D. & Hsieh, D. Nat. Mater. (2017)
Tokura, Y., Kawasaki, M. & Nagaosa, N. Nat. Phys. (2017)

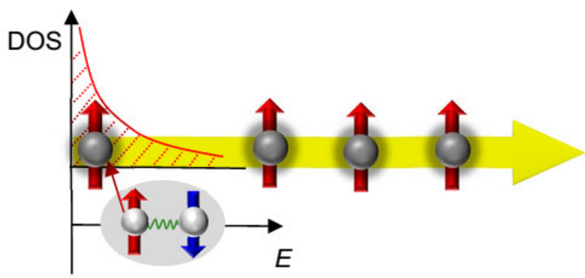
New-types of spin current in quantum materials

	Materials	Illustration of spin current
Electron (hole) (S = 1/2)	Metals, semiconductors, and topological insulators, etc	
Spin-triplet pair (S = 1)	Superconductors	
Quasiparticle (S = 1/2)	Superconductors	
Spinon (S = 1/2)	Quantum spin liquids	
Magnon (S = 1)	Magnetic insulators	
Electron-hole pair or magnon (S = 1)	Spin superfluids	

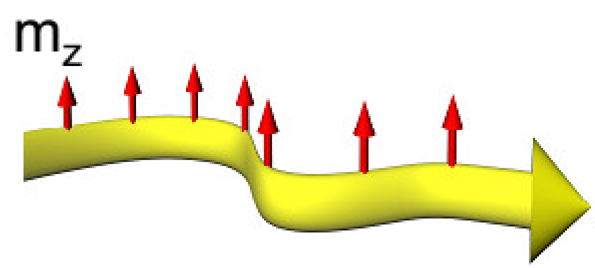
Spin current in Quantum materials

Angular momentum:

Quasiparticles in SC



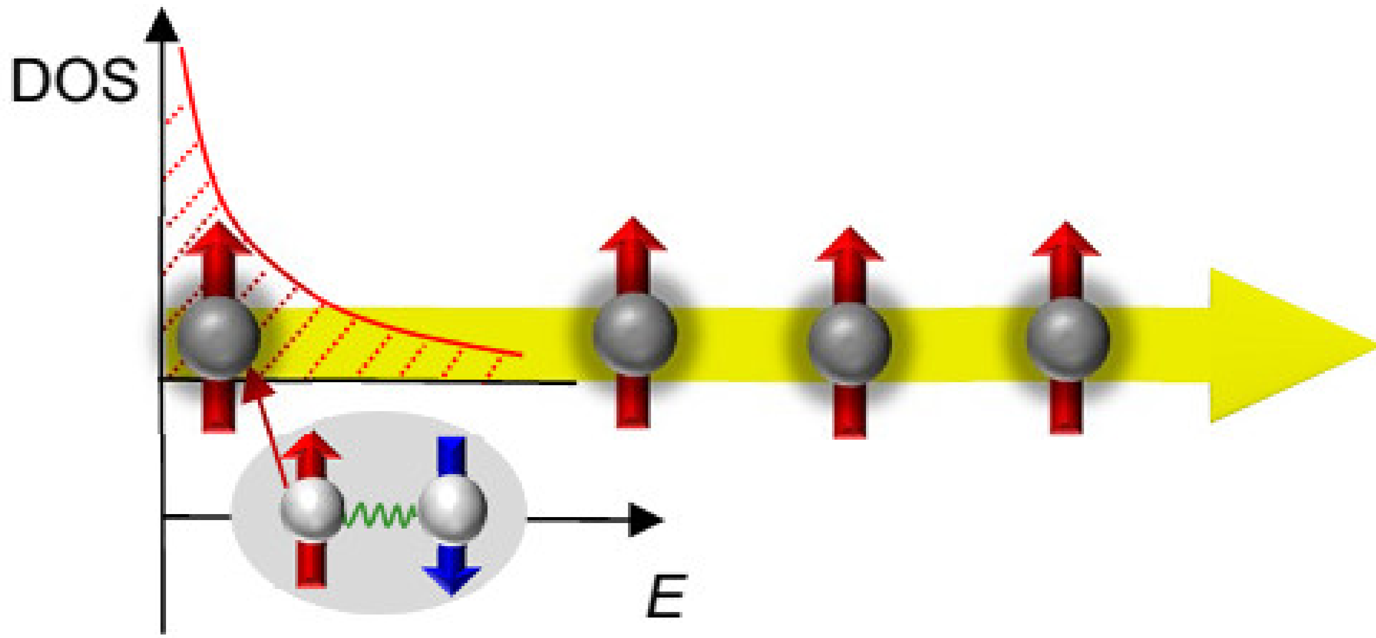
Spin Superfluidity



- Spin dynamics in FM/superconductors
- Spin superfluidity in canted AFM: Cr_2O_3

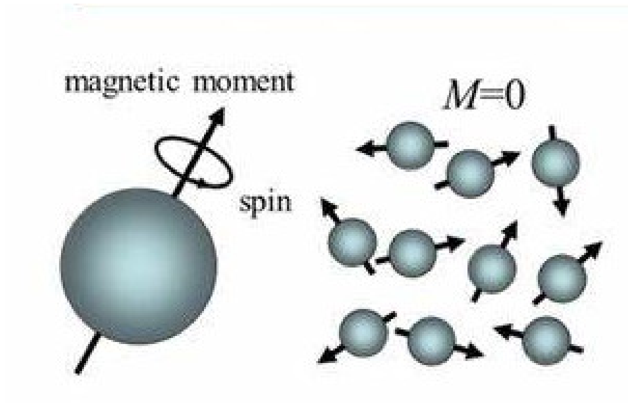
Angular momentum:

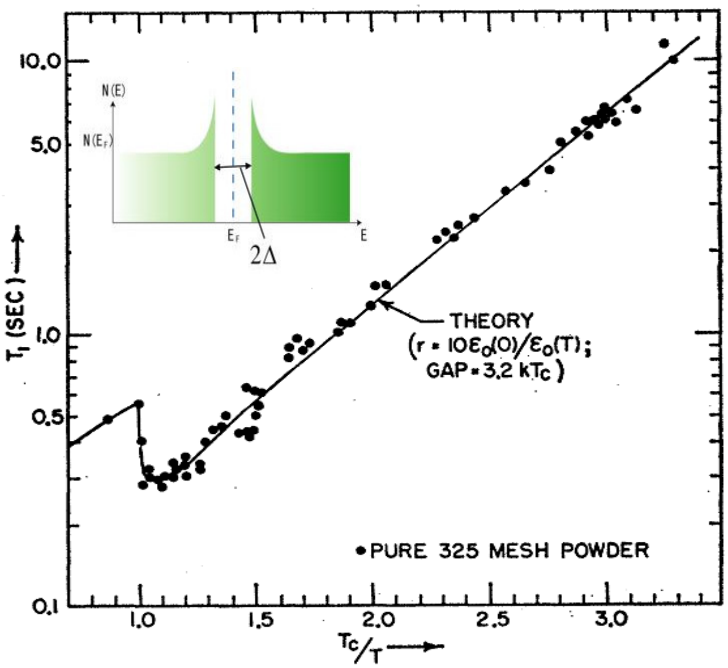
Quasiparticles in SC

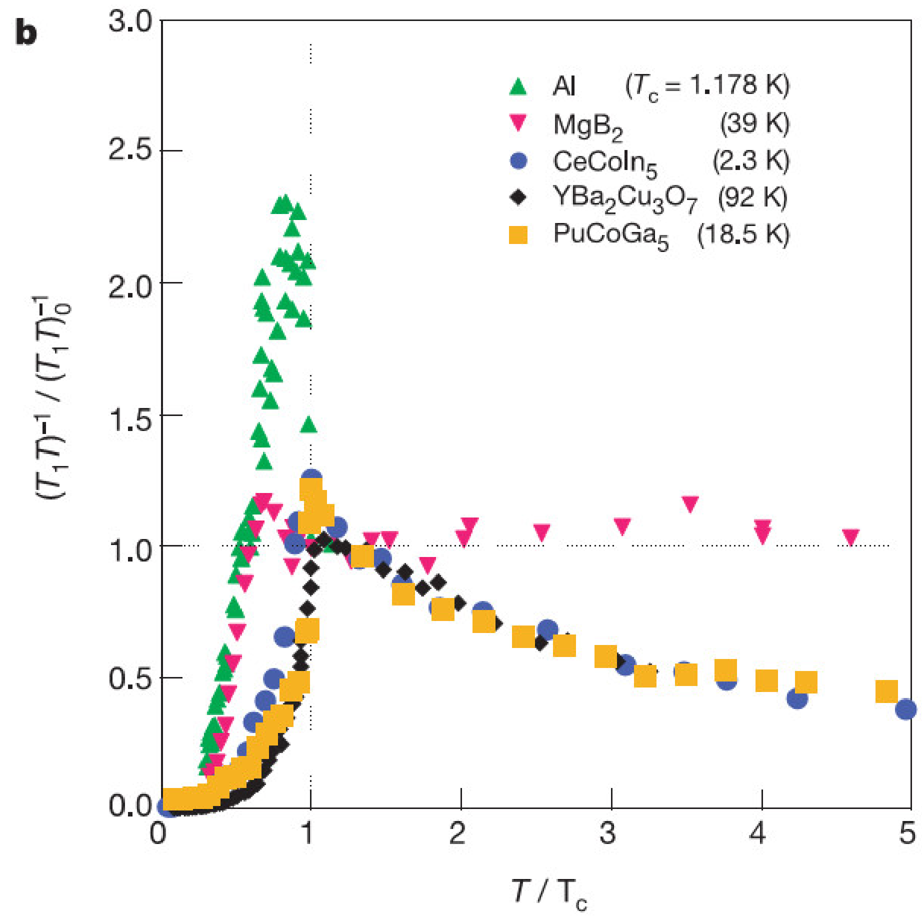


Spin susceptibility in s-SC

NMR measurement



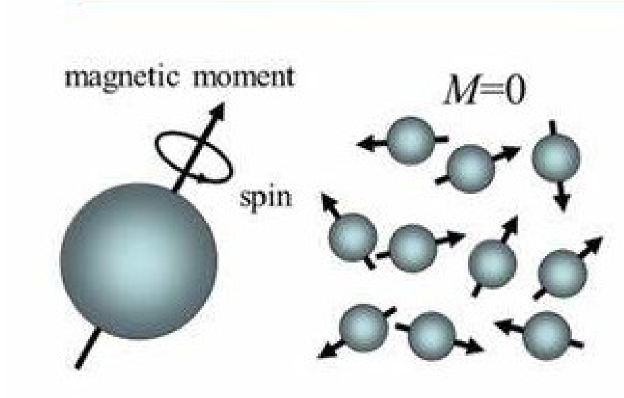


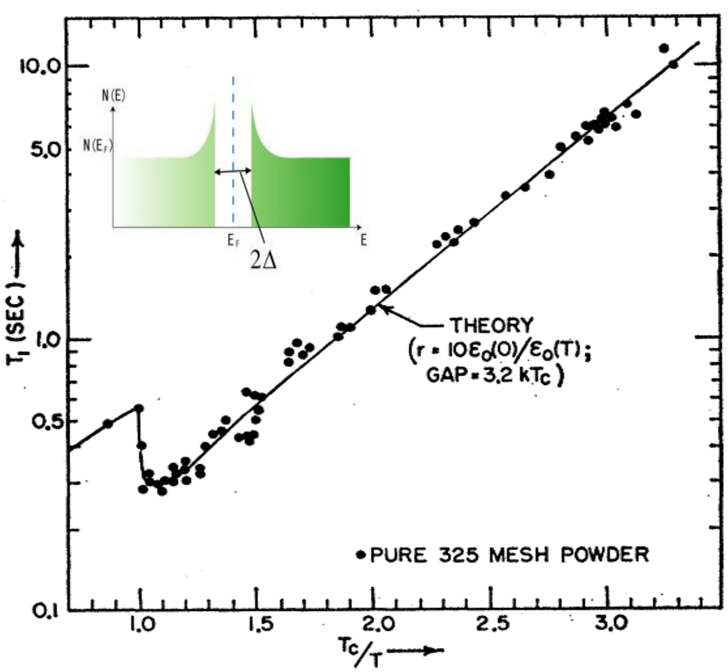


Masuda & Redfield, Phys. Rev. (1962)
Tinkham, Introduction to superconductivity
Curro, et al, Nature (2005)

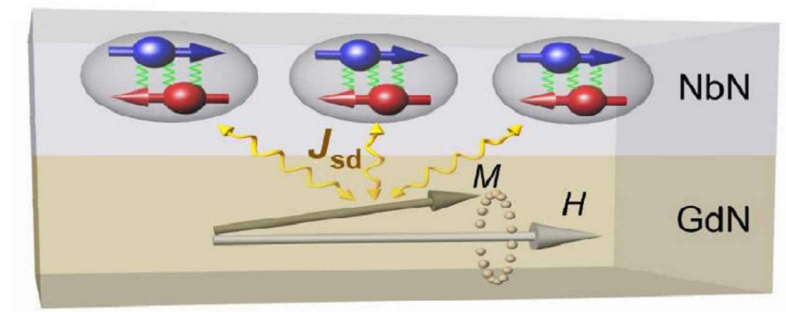
Spin susceptibility in s-SC

NMR ➔ Ferromagnetic FMR in FM/SC

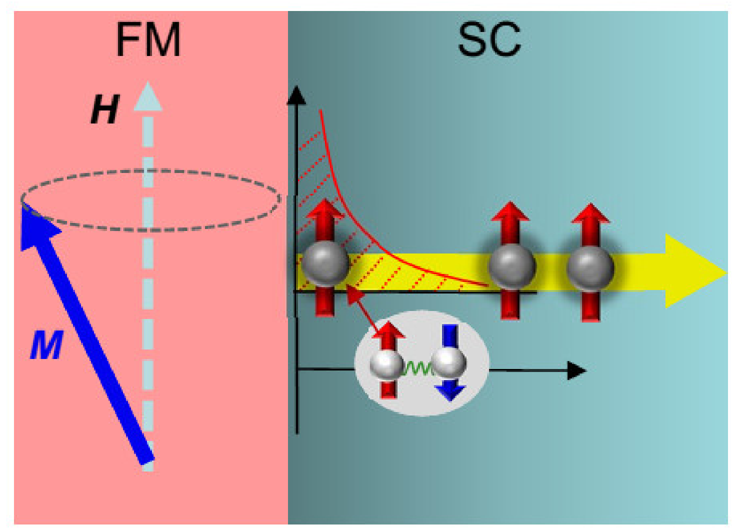




SC films

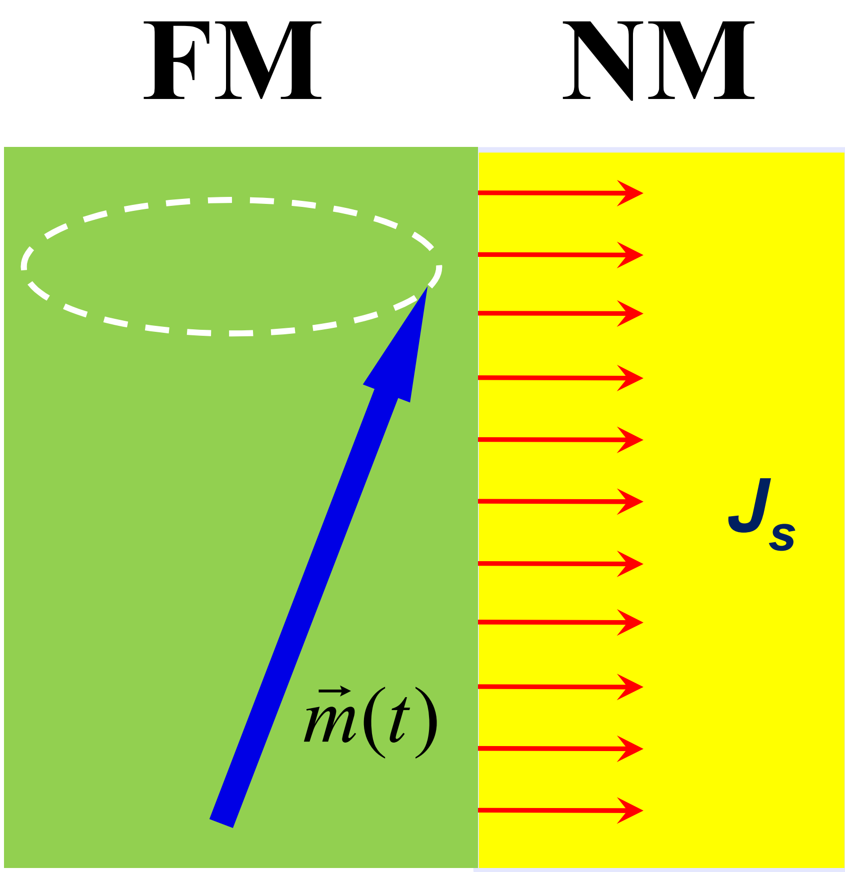


FM films



$$\delta\alpha \propto J_{sd}^2 \sum_q \mathrm{Im}\, x_q^R(\varpi)$$

Introduction of spin pumping

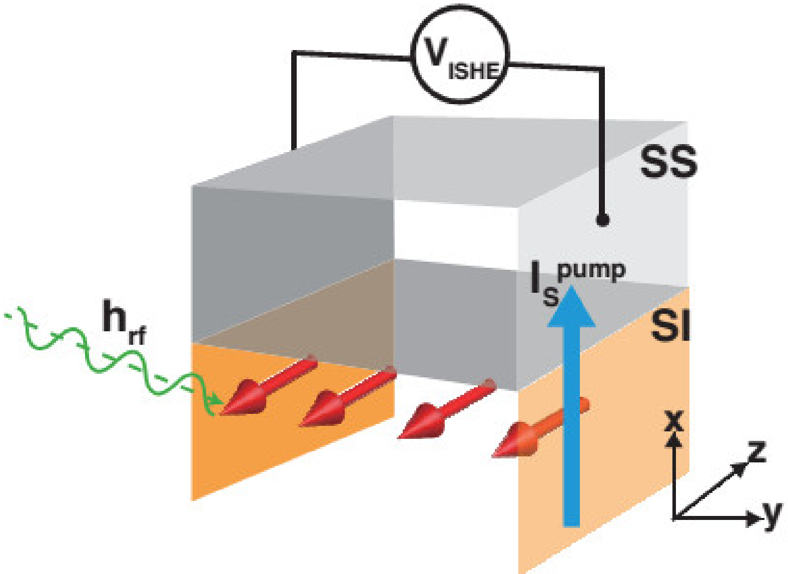


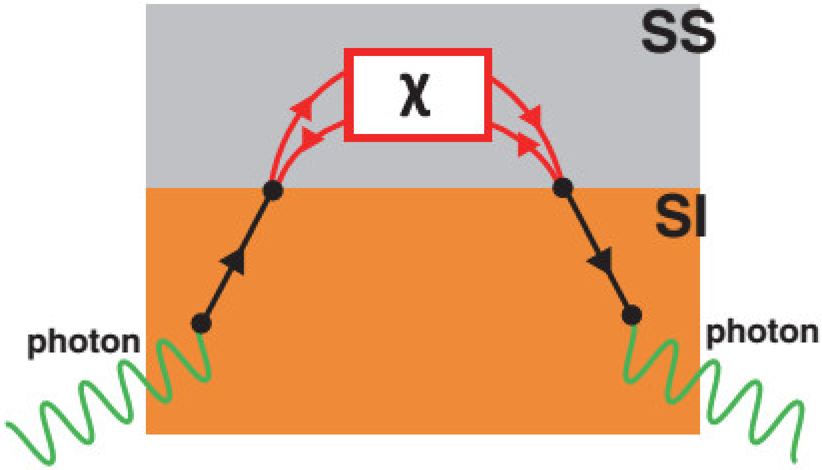
$$\vec{J}_S = \frac{\hbar g_r^{\uparrow\downarrow}}{4\pi M^2}\left(\vec{M} \times \frac{\partial \vec{M}}{\partial t}\right)$$

Precessing magnetization in FM layer pump spin current into NM layer (Angular momentum conservatoin)

Tserkovnyak, et al, PRB (2002)
Tserkovnyak, et al, Rev. Mod. Phys. (2005)

Recent development of spin pumping theory





Ohnuma, et al, Phys. Rev. B (2014)
Inoue, et al, Phys. Rev. B (2017)

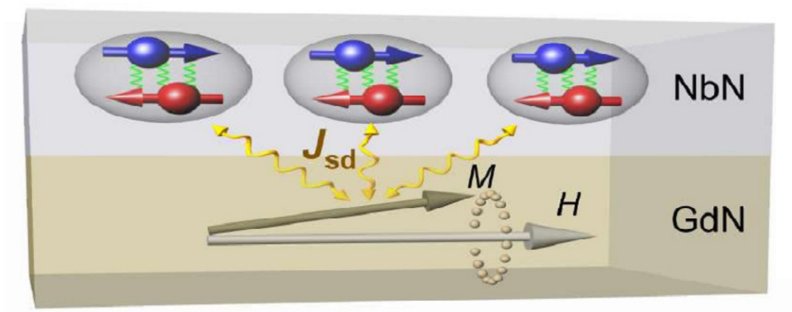
$$\delta\alpha = \left(\frac{J_{sd}}{\hbar}\right)^2 S_0 \frac{N_{int}}{N_{FM}} \frac{1}{\omega_0} \int_q I_m \chi_q^{+-}(\omega_0),$$

Enhanced Gilbert Damping

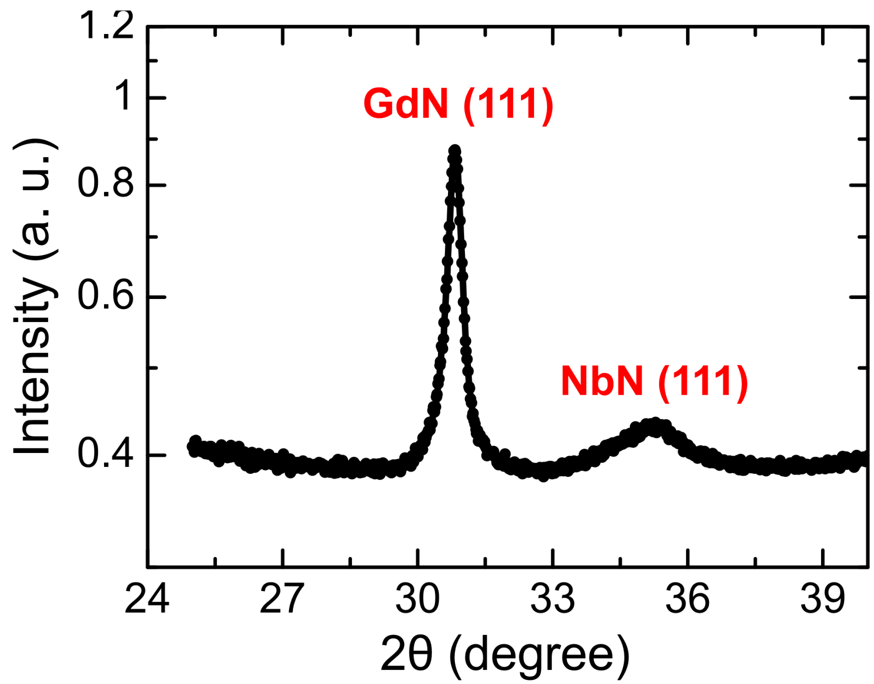
Dynamic Spin Susceptibility

Dynamic Spin susceptibility in s- wave SC

NbN/GdN/NbN trilayer



$$\delta\alpha \propto J_{sd}^2 \sum_q \mathrm{Im}\, x_q^R(\varpi)$$



NbN:

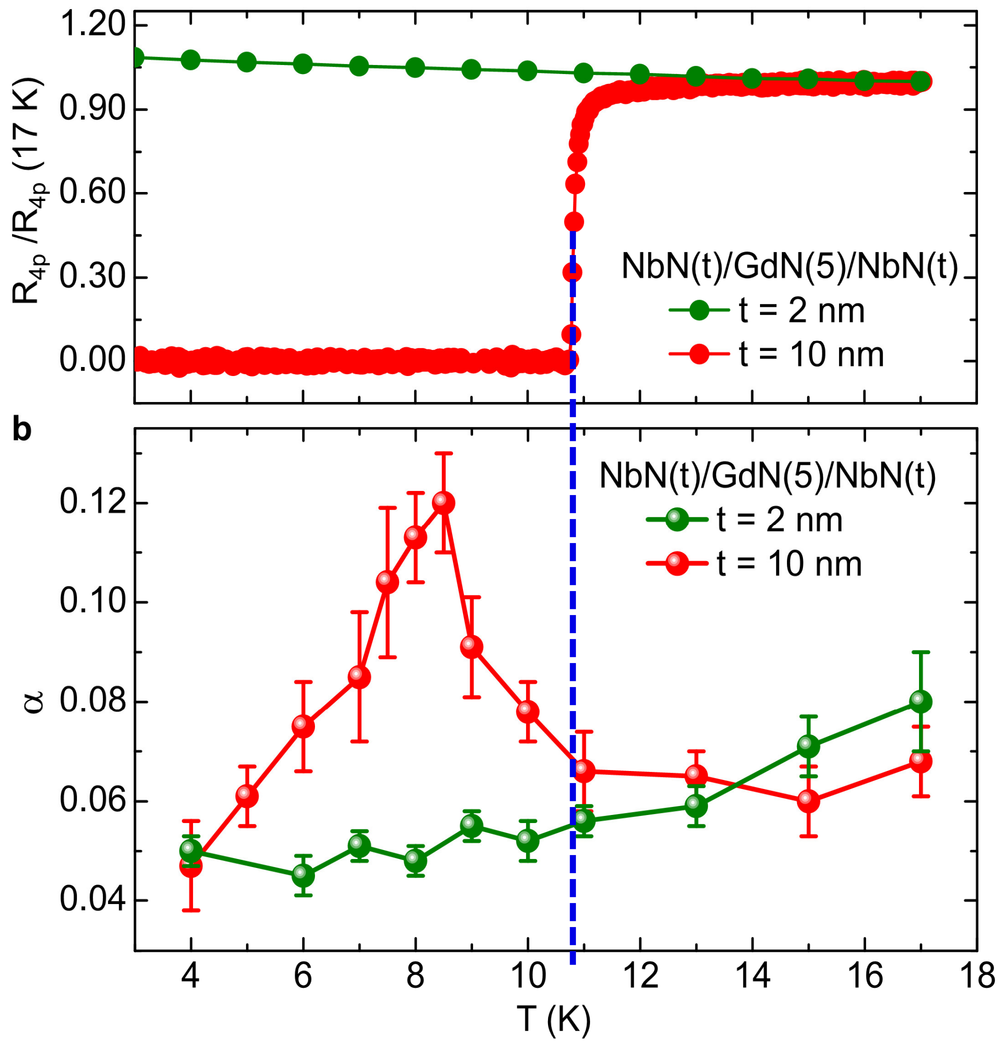
Spin diffusion length: ~ 7 nm

Coherence length: ~ 5 nm

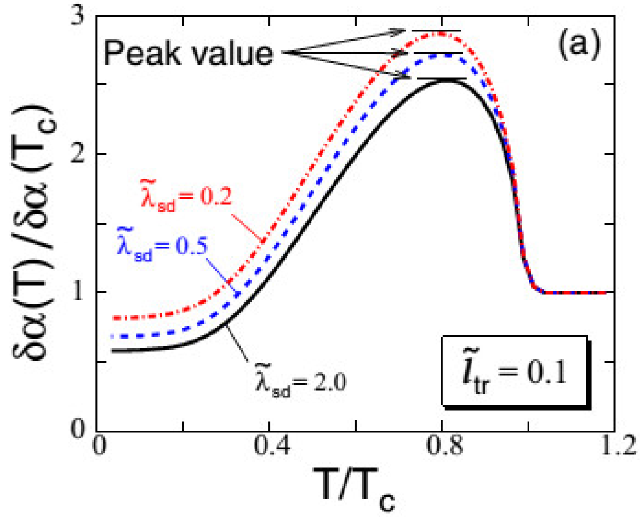
Samples from MIT **(Yota Takamura, Prof. J. Moodera)**

Dynamic Spin susceptibility in s- wave SC

NbN/GdN/NbN trilayer



Y. Yao, et al, **Phys. Rev. B 97, 224414 (2018)**

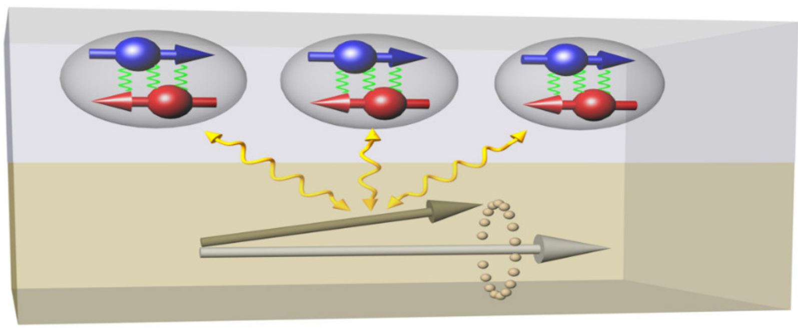


Inoue, et al, Phys. Rev. B (2017)

Yunyan Yao

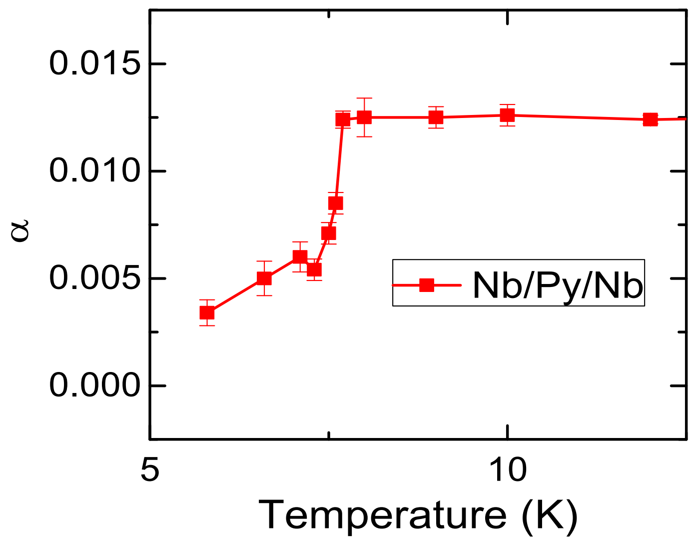
Spin current as a probe

1) Interface SC gap at the FM/SC interface

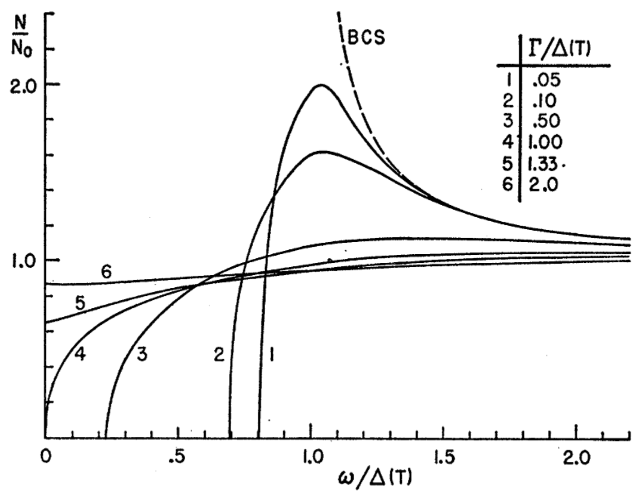


non-Abelian Majorana fermions using ($p_x + ip_y$)

Sau, et al, Phys. Rev. Lett. (2010)



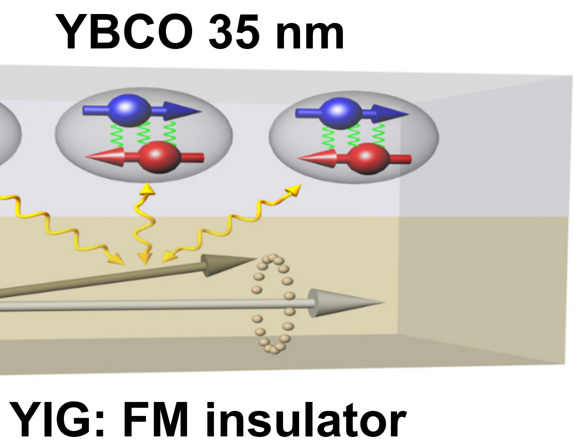
Similar to previous results:
Bell, et al, Phys. Rev. Lett. (2008)

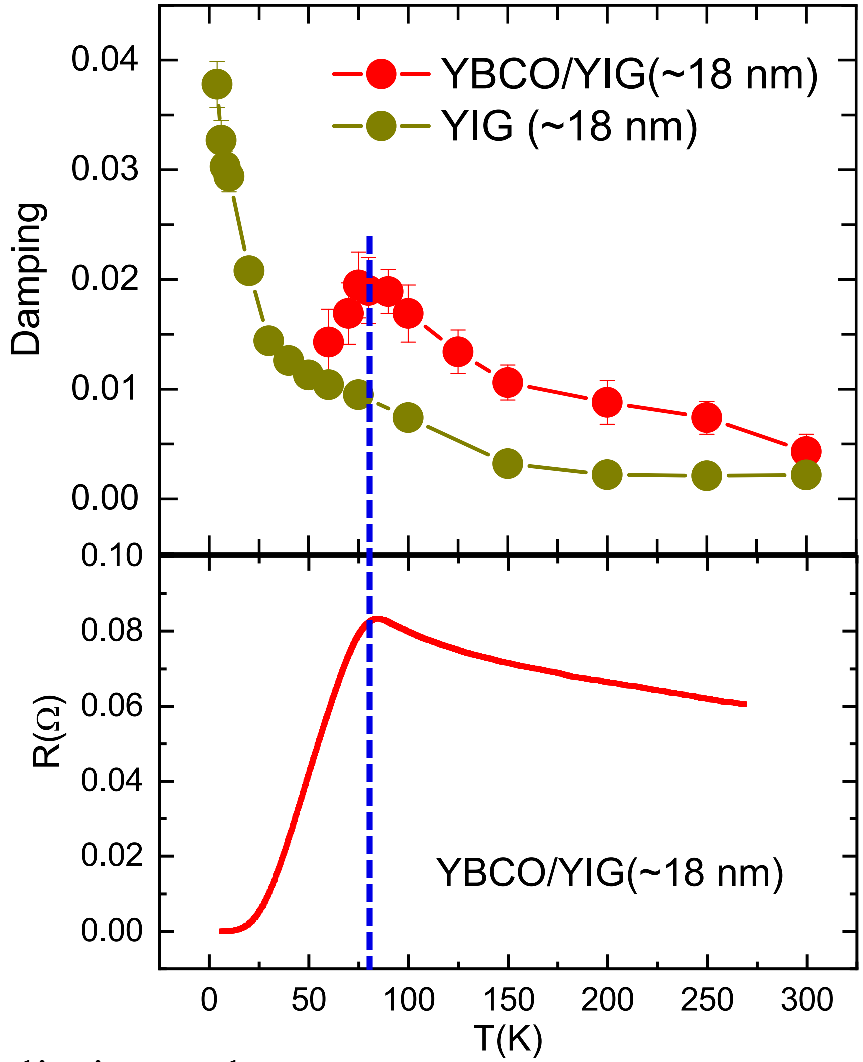


Skalski, et al, Phys. Rev. (1964)

Spin current as a probe

2) Spin dynamics in d-wave superconductor films



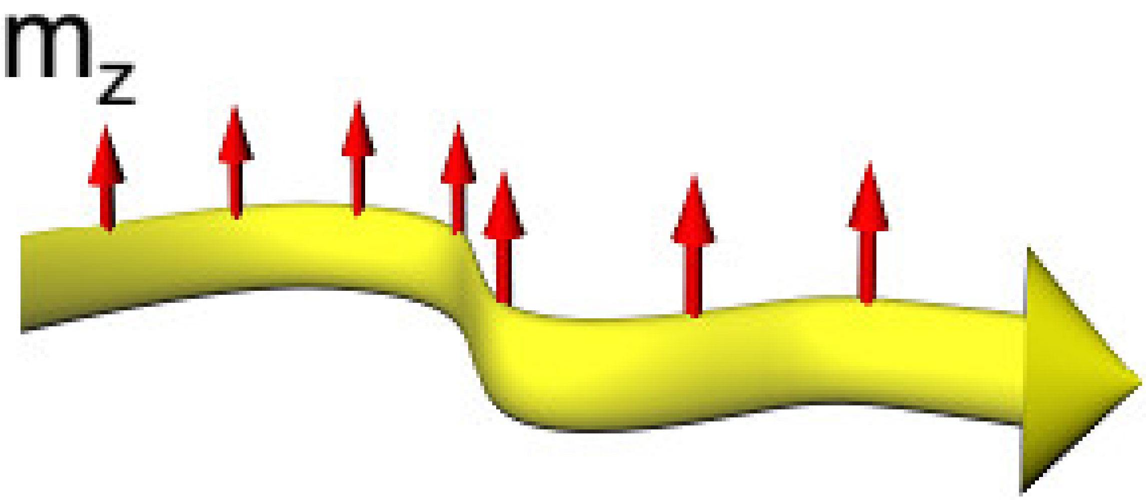


Samples from Nanjing University, China **(Prof. Di Wu, Siyu Xia)**

Y. Yao, et al, preliminary data.

Angular momentum:

Spin superfluidity

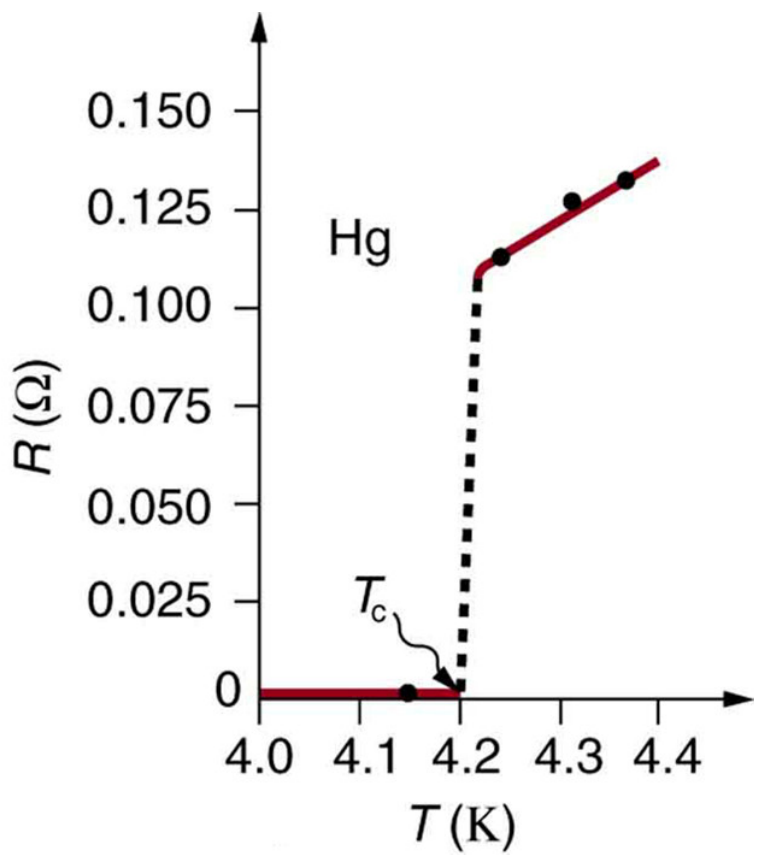


Spin superfluidity:

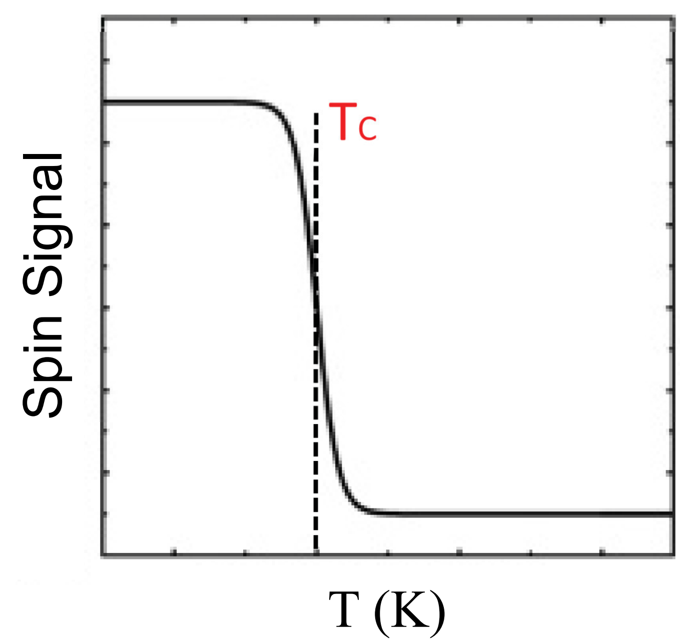
Spin analogue of superconductivity

Spin superfluidity: Spin analogue of superconductivity

Charge superconductivity:
Zero resistance



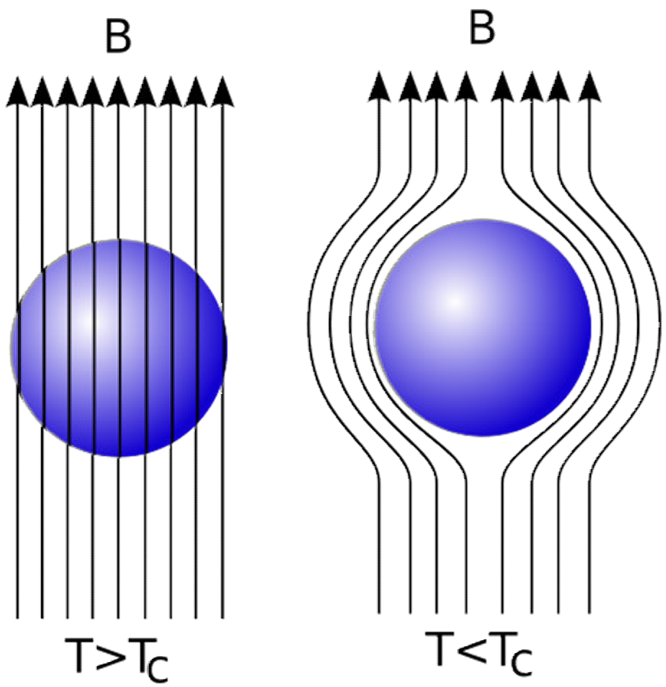
Spin superfluidity:
Zero spin resistance



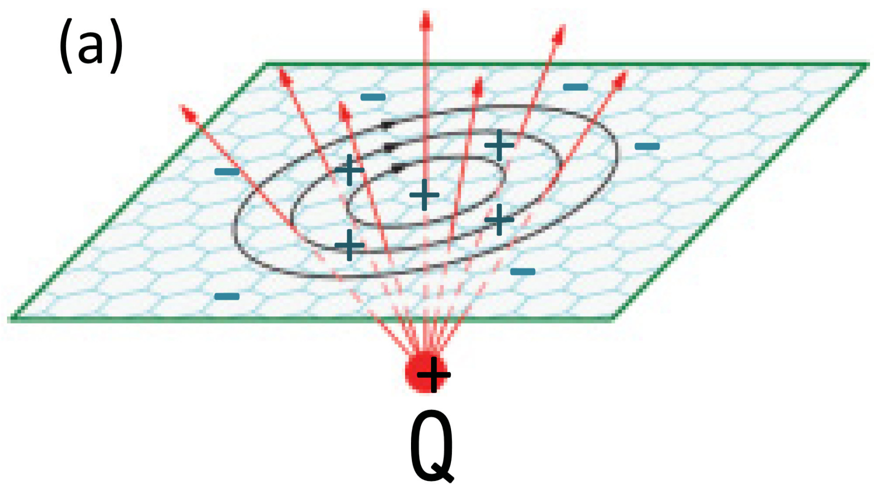
Sonin, JETP (1978)
Q. Sun and X. C. Xie, PRB (2011), PRB (2012), Nature Comm. (2014)

Spin superfluidity: Spin analogue of superconductivity

Charge superconductivity:
Meissner effect (B)



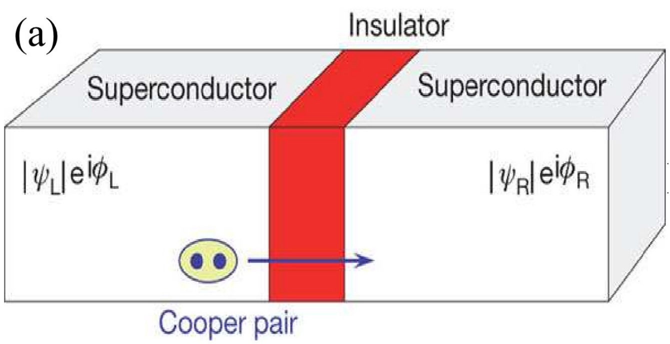
Spin superfluidity:
Meissner effect (E)

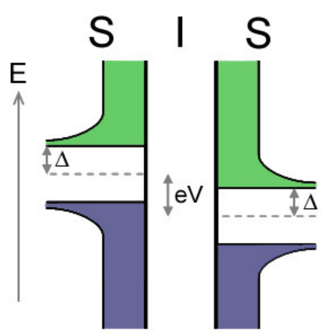


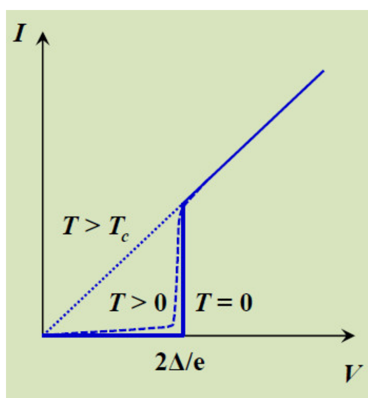
Q. Sun and X. C. Xie, PRB (2011), PRB (2012), Nature Comm. (2014)

Spin superfluidity: Spin analogue of superconductivity

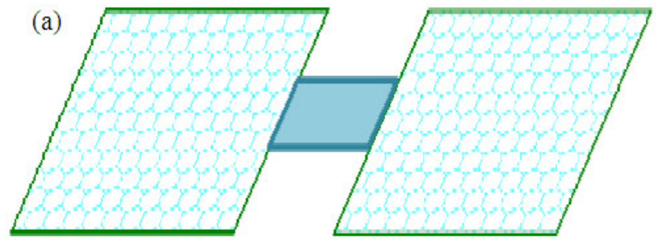
Charge superconductivity:
Josephson effect

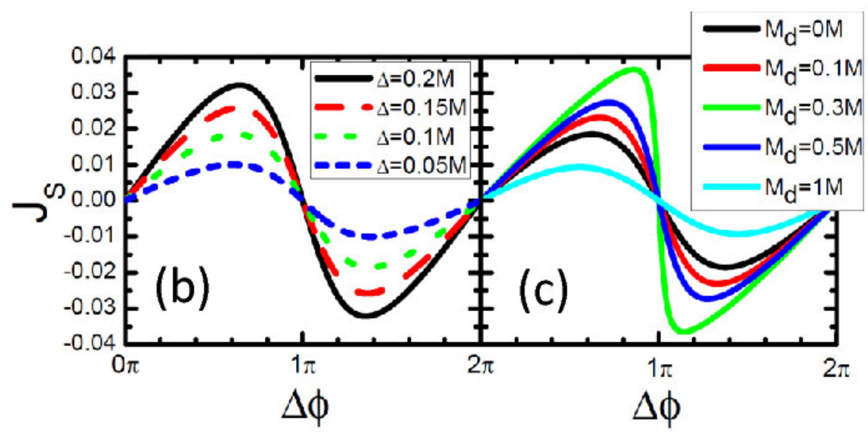






Spin superfluidity:
Spin-Josephson effect





Sun and Xie, PRB (2011), PRB (2012)
Liu, et al, PRB (2014)
Chen, Kent, MacDonald, PRB (2014).

Spin superfluidity: Spin analogue of superconductivity

Analogs of superfluid currents for spins and electron-hole pairs

É. B. Sonin

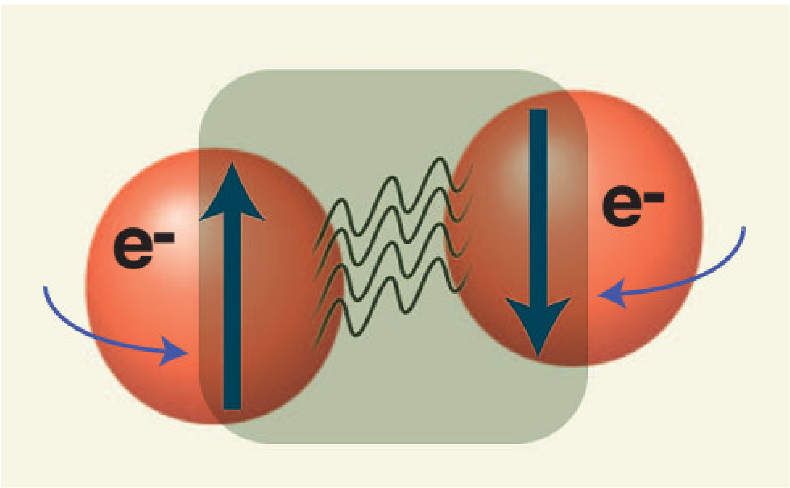
A. F. Ioffe Physico-technical Institute, USSR Academy of Sciences
(Submitted 20 October 1977)
Zh. Eksp. Teor. Fiz. **74**, 2097–2111 (June 1978)

States analogous to those with superfluid currents in an ordinary superfluid can exist in a Bose-condensed electron-hole liquid as well as an easy-plane antiferromagnet. For easy-plane antiferromagnets these states are metastable helicoidal structures with an antiferromagnetic vector that rotates inside the easy plane. These structures are investigated with the aid of the usual phenomenological theory based on the Landau-Lifshitz equations to which some dissipative terms are added. The metastable helicoidal structures can be produced by injecting spins into the antiferromagnet. This gives rise to magnetization far from the point of injection, a manifestation of a real spin transport in these states. For a ~~band~~ antiferromagnet, the stationary phenomenological equations are the Ginzburg-Landau equations, which are derived by using an excitonic-state model with extrema that do not coincide in k-space.

PACS numbers: 75.10.–b

Spin superfluidity: Spin analogue of superconductivity

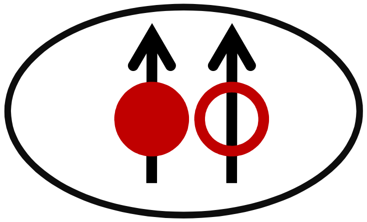
Charge superconductivity:



ie, Wang, et al, Science (2011)

Spin superfluidity:

e-h BEC
Charge: 0
Spin pairs: (1/2 + 1/2)



Magnon BEC
Charge: 0
Magnon: Spin-1

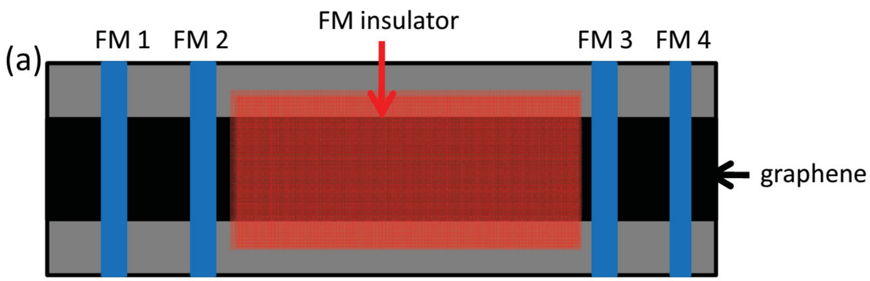
Sonin, JETP (1978)
Q. Sun and X. C. Xie, PRB (2011), PRB (2012), Nature Comm. (2014)
Takei, et al, PRB (2014)

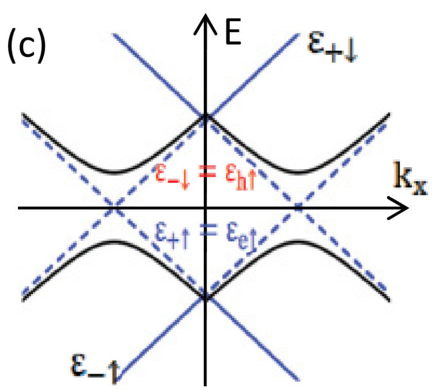
Material candidates

1) Spin superfluidity in FM graphene

e-h BEC
Charge: 0
Spin pairs: (1/2 + 1/2)

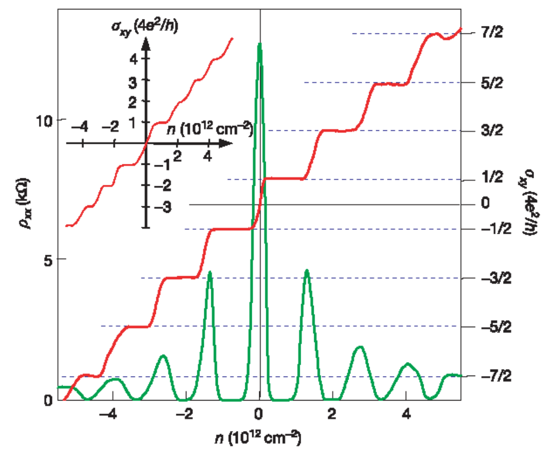
Proximity-induce FM graphene



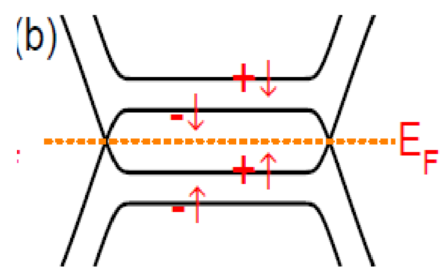


Q. Sun and X. C. Xie, PRB (2011)

v = 0 quantum state of graphene



Novoselov et al., Nature (2005)
Zhang et al., Nature (2005)

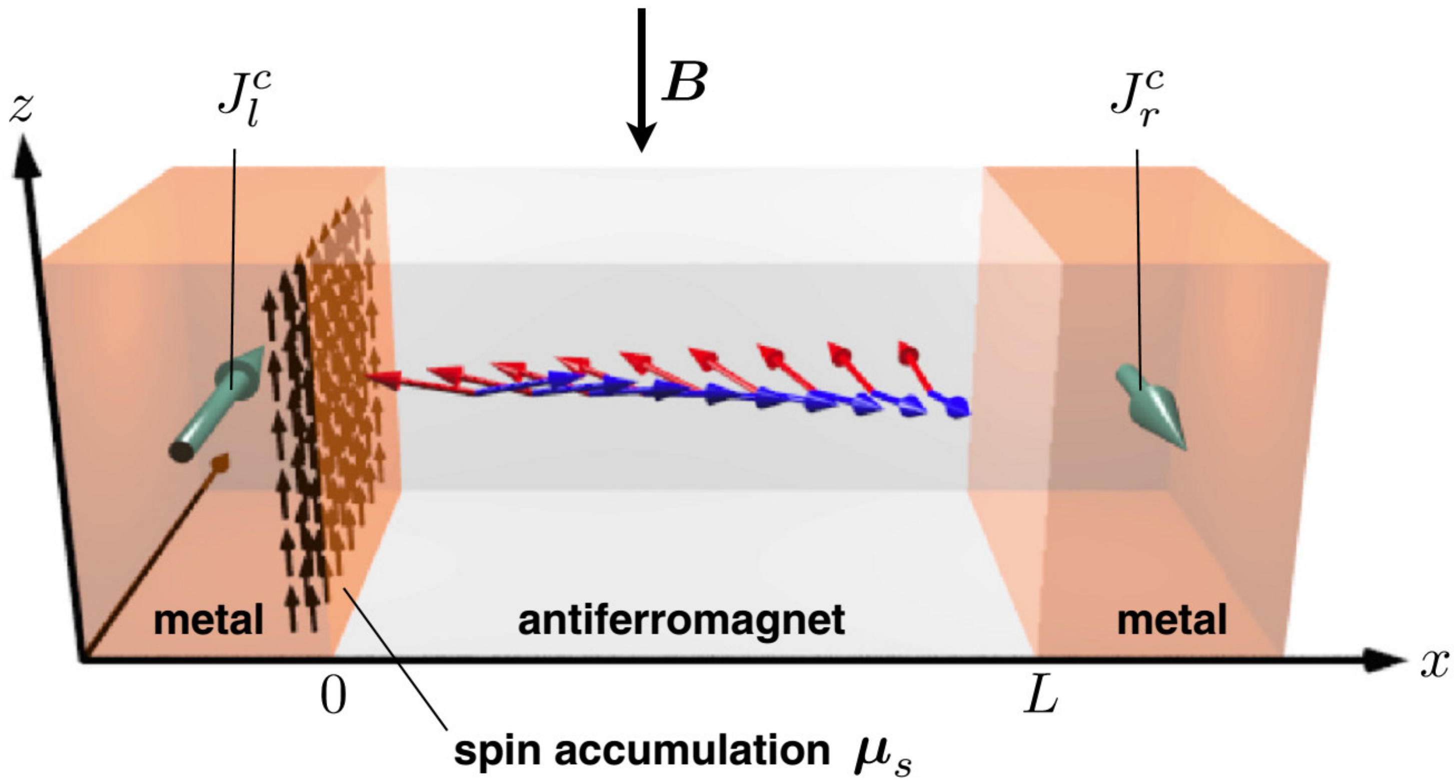


Q. Sun and X. C. Xie, PRB (2013)
Takei, et al, PRL (2016)

Material candidates

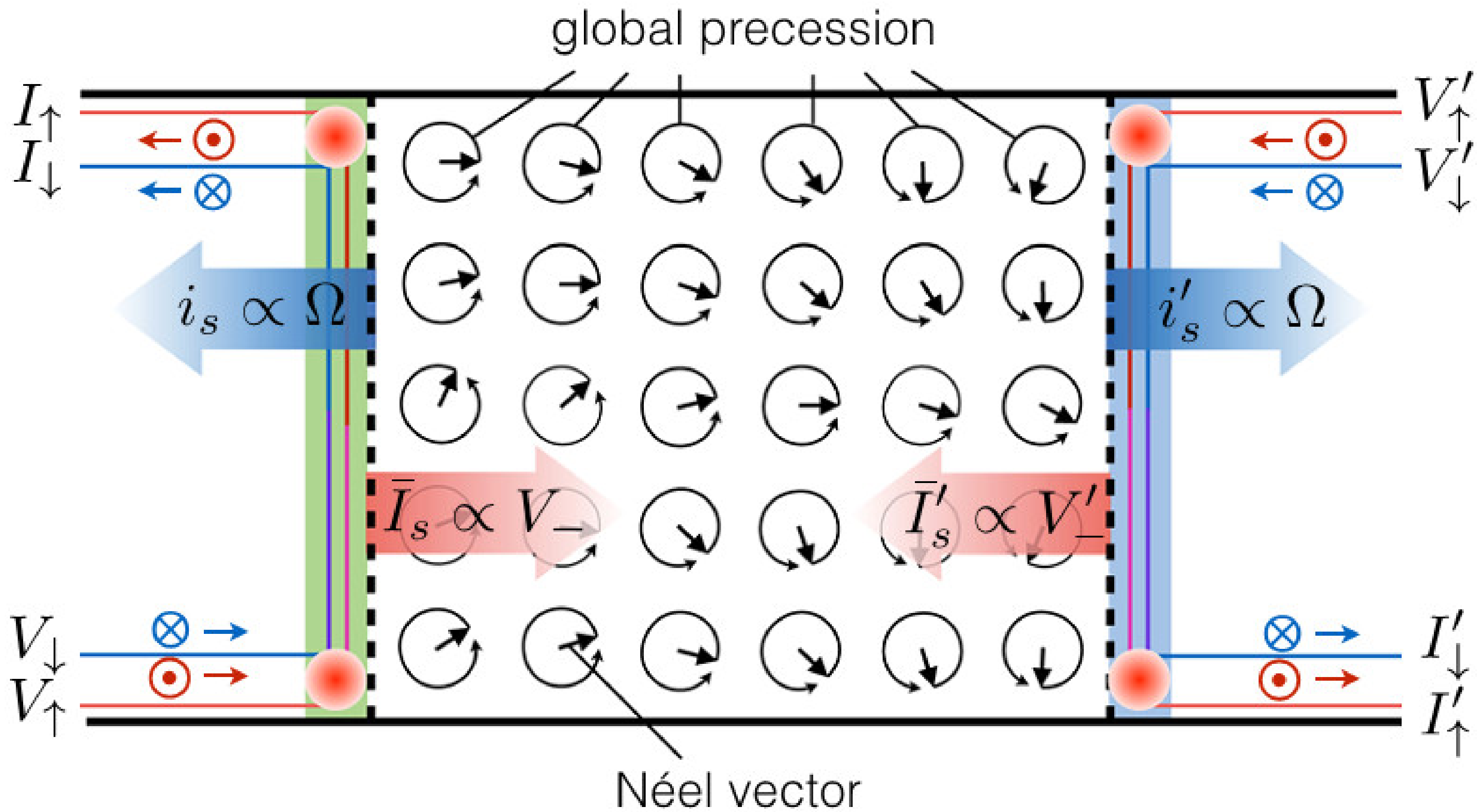
2) Spin superfluidity in canted AFM

Magnon
Charge: 0
Magnon: Spin-1 boson



Takei, et al, PRB (2014)

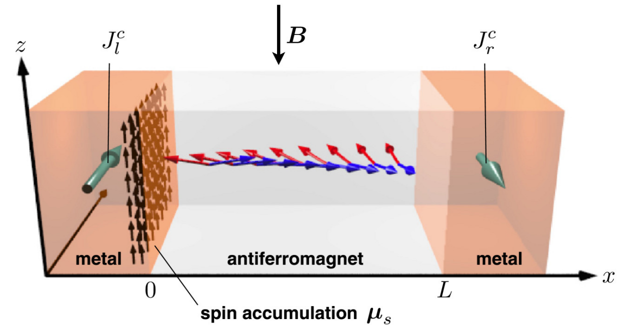
Spin current as a probe for spin superfluidity



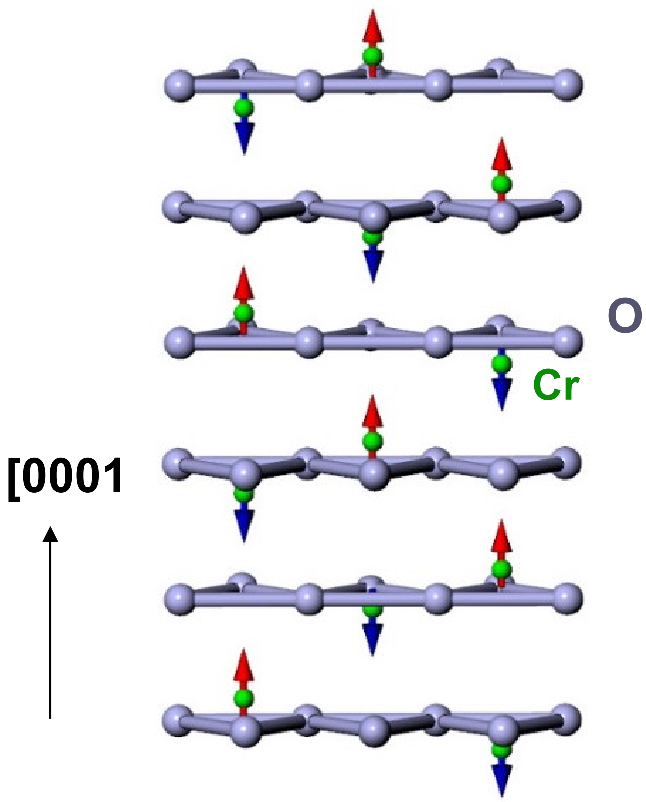
Takei, et al, PRL (2015)

Our experimental approach

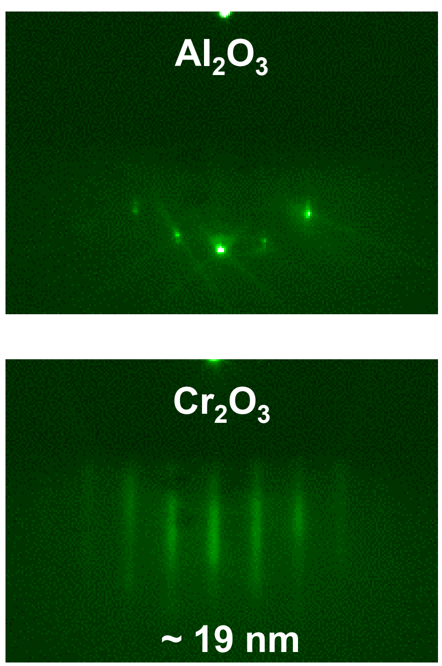
Cr_2O_3 AFM insulator

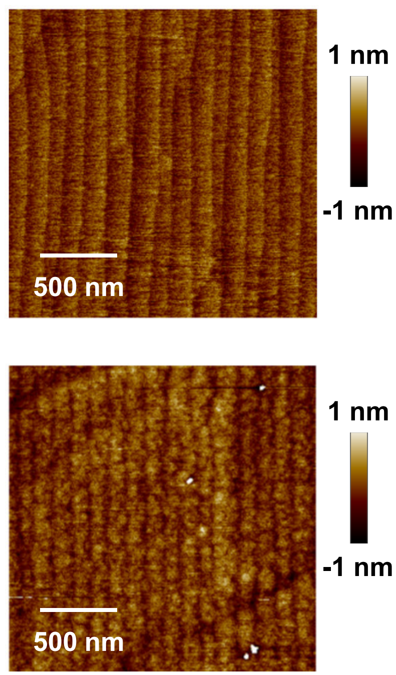


(0001)-oriented Cr_2O_3



Atomic flat (0001)-Cr_2O_3 AFM films

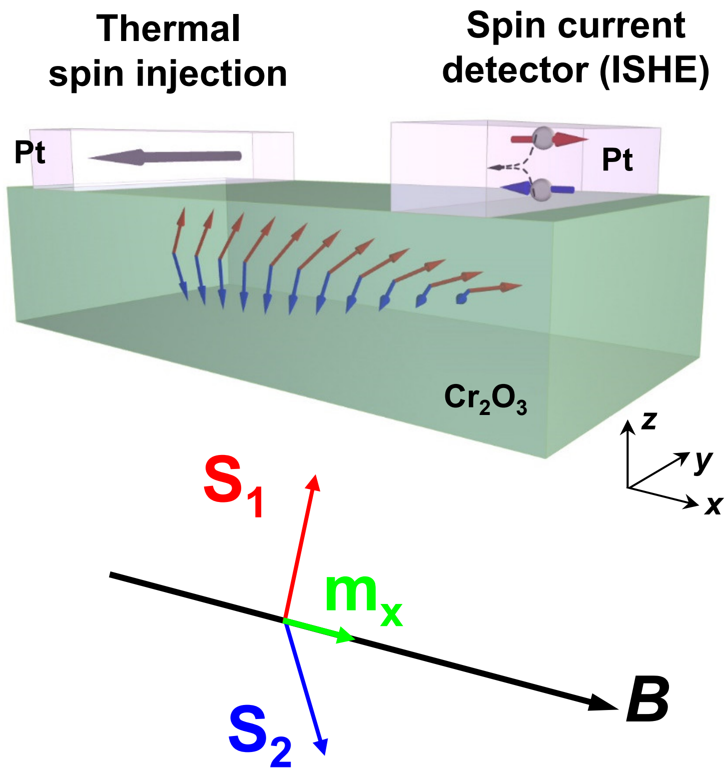




Pulsed Laser deposition

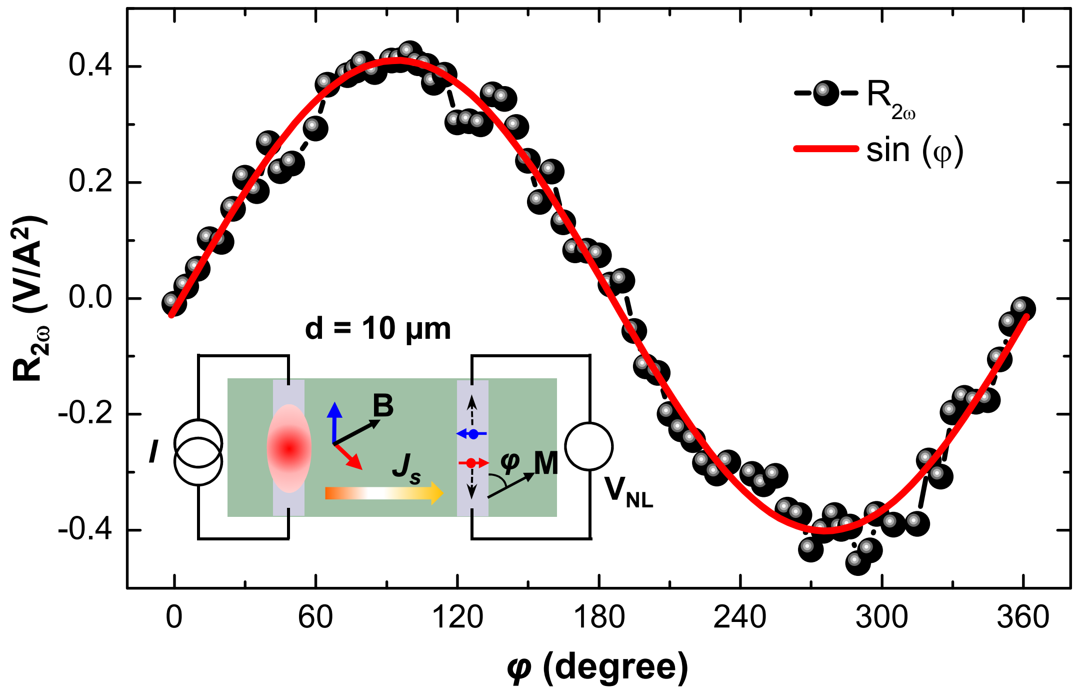
Experimental signatures for spin superfluidity

Nonlocal spin transport



Field induced Canted AFM

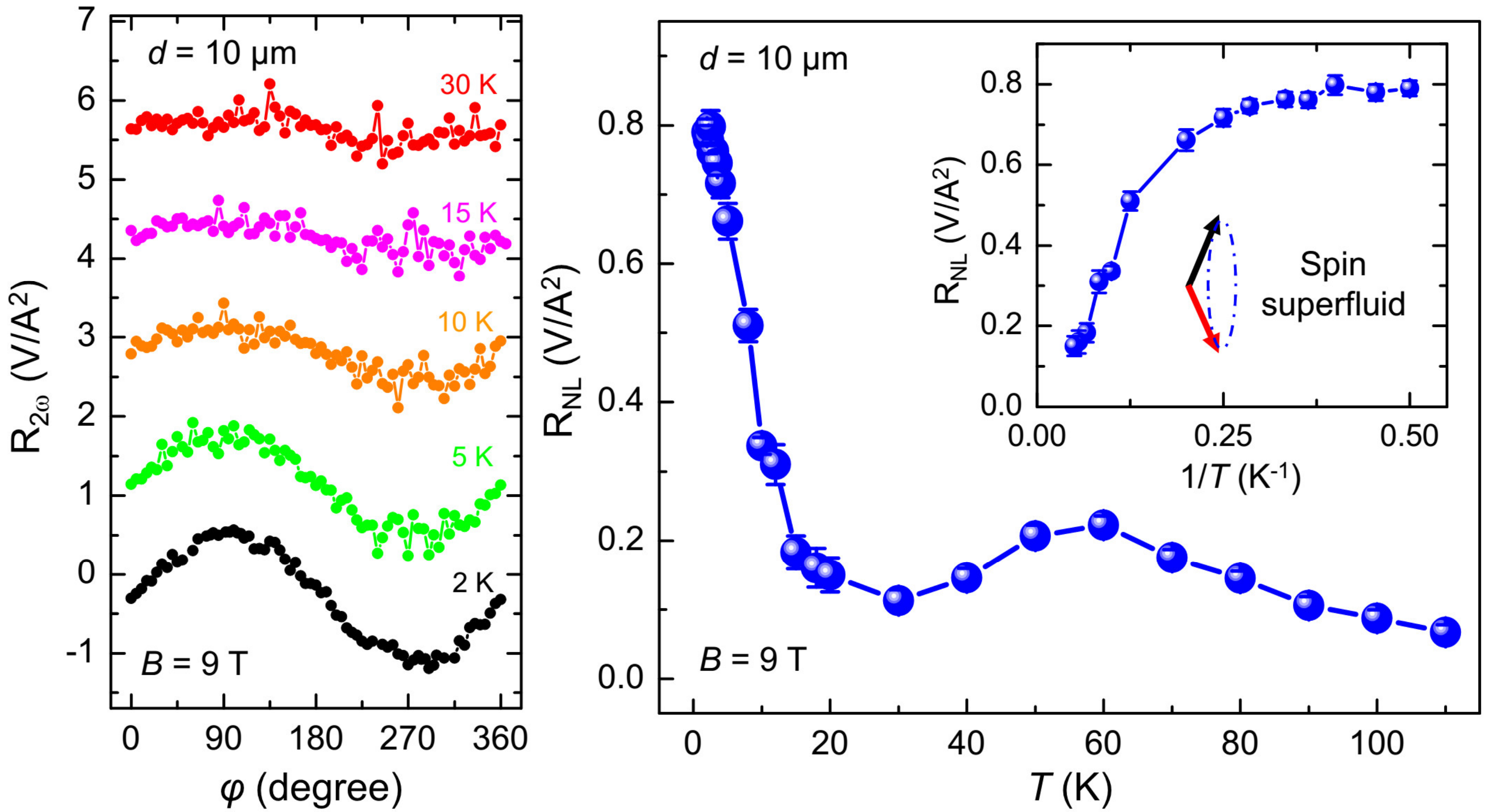
R_{NL} detects spin conductance



Nonlocal technique previously used to study Magnon diffusion in ferromagnetic insulator YIG: Cornelissen, et al, Nat. Phys. (2015)

Experimental signatures for spin superfluidity

Saturation of the nonlocal spin signal

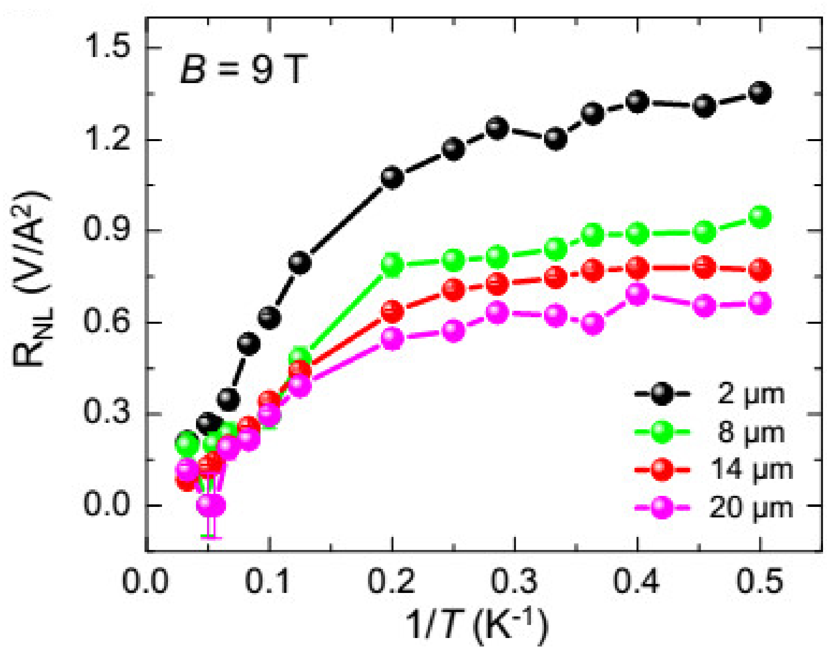


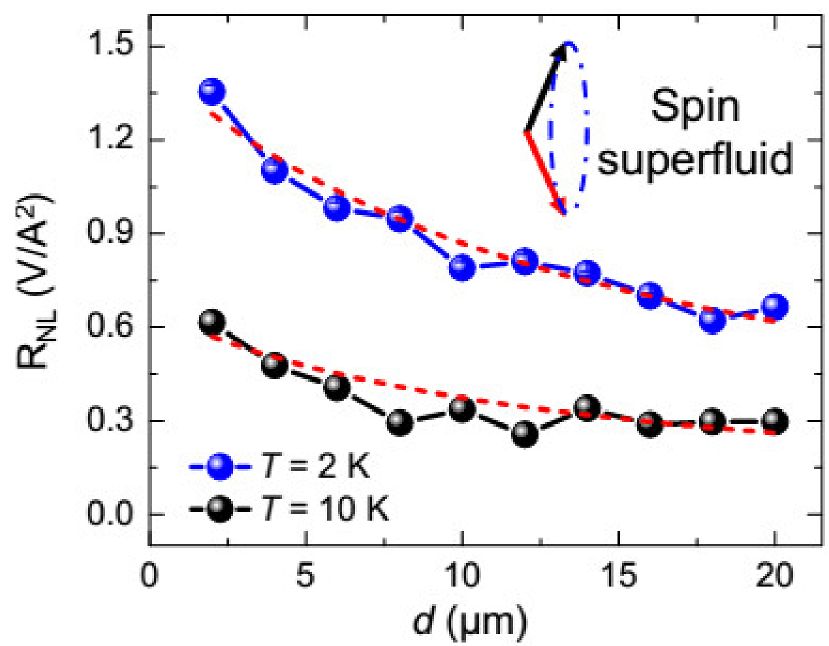
Saturation of the nonlocal spin signal (spin conductance)

→ Spin superfluidity in canted AFM

Experimental signatures for spin superfluidity

Long distance spin transport





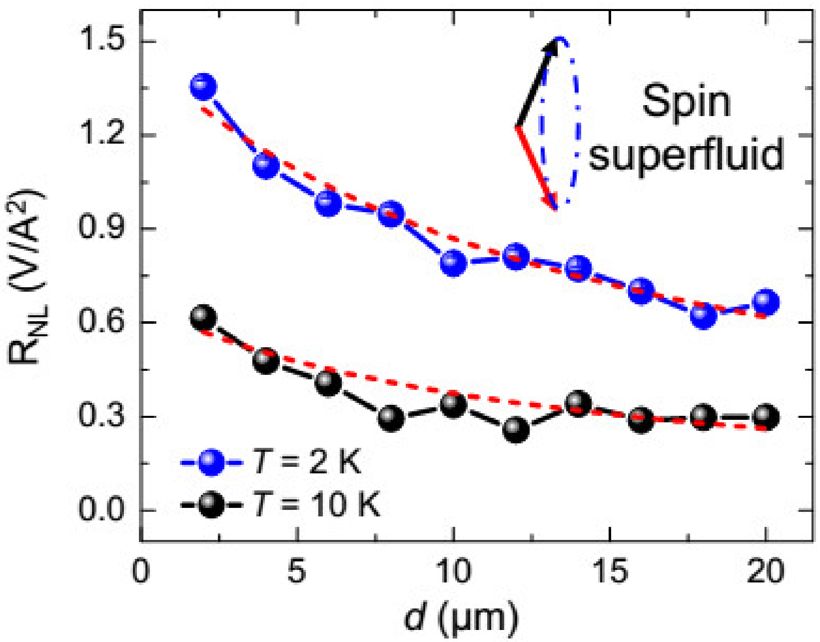
Slow decay: $R_{NL} \sim \frac{L_\alpha}{d + L_\alpha}$

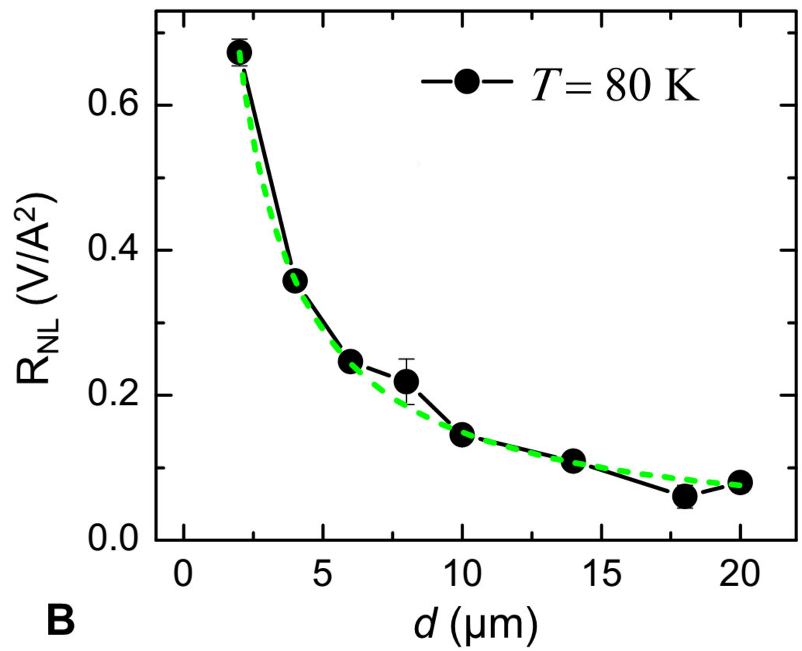
L_α related to the damping of AFM

Sonin, Advances in physics (2010)
Takei, et al, PRB (2014)

Experimental signatures for spin superfluidity

Comparison with incoherent magnons





Slow decay: $R_{NL} \sim \dfrac{L_\alpha}{d + L_\alpha}$

L_α related to the damping of AFM

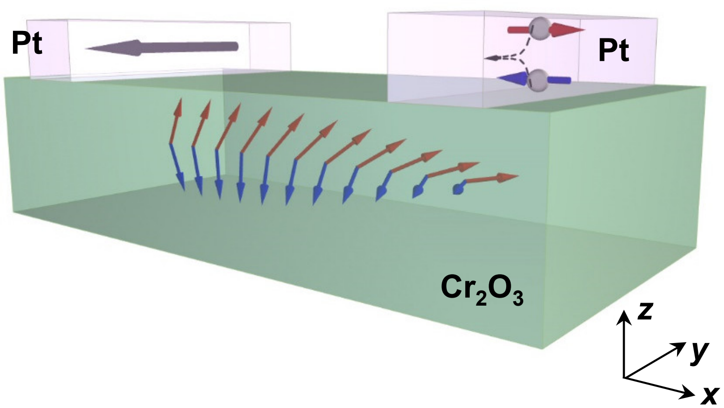
Fast decay (magnon diffusion):

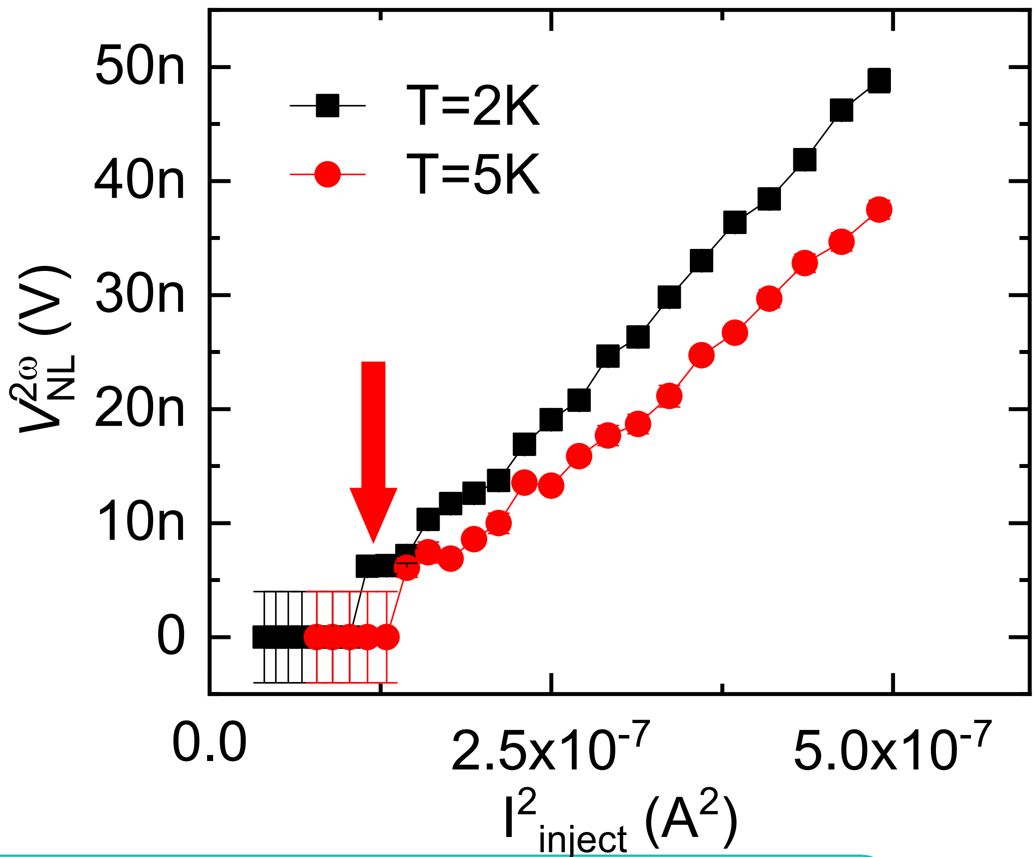
$$R_{NL} \sim \frac{\exp(d/\lambda)}{1 - \exp(2\,d/\lambda)}$$

Similar to incoherent magnons in YIG: Cornelissen, et al, Nat. Phys. (2015)

Experimental signatures for spin superfluidity

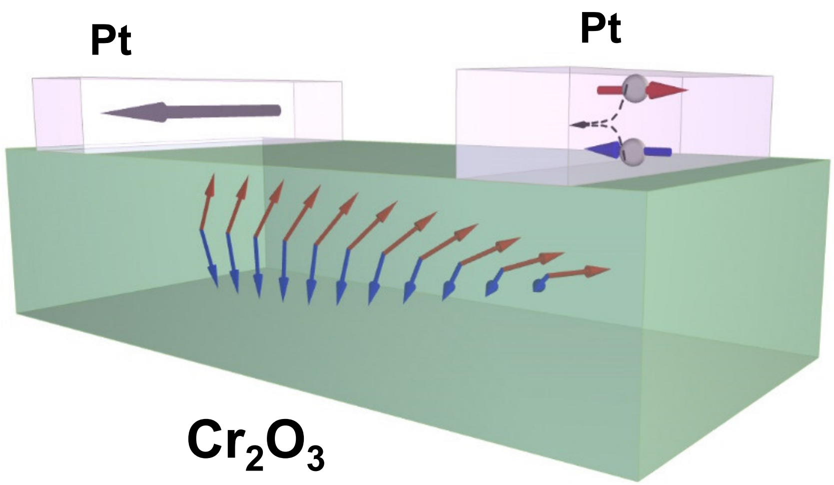
Critical current density





A critical spin current (I_S) density is needs to overcome AFM pinning (anisotropy)

Experimental signatures for spin superfluidity



Wei Yuan

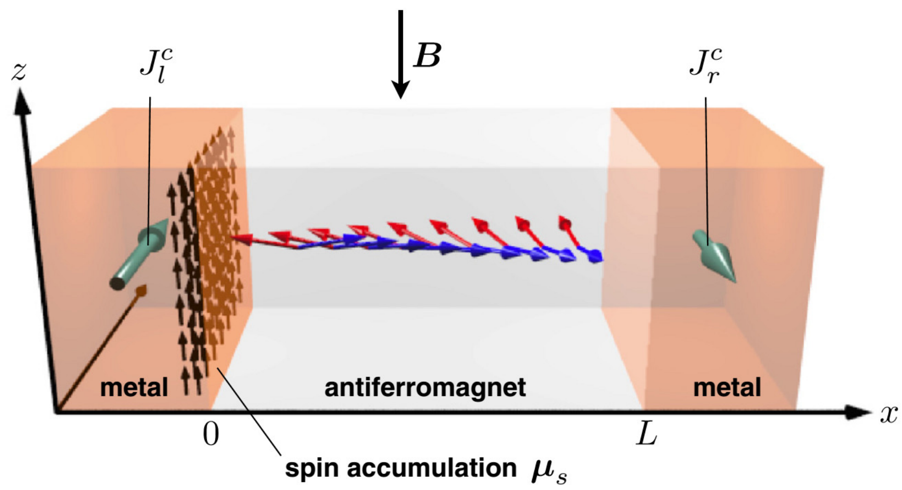
Tang Su

Wenyu Xing

- Saturation of the nonlocal spin signal at LT
- Spacing dependence of the spin transport
- Critical current for spin superfluidity
- Edge scattering

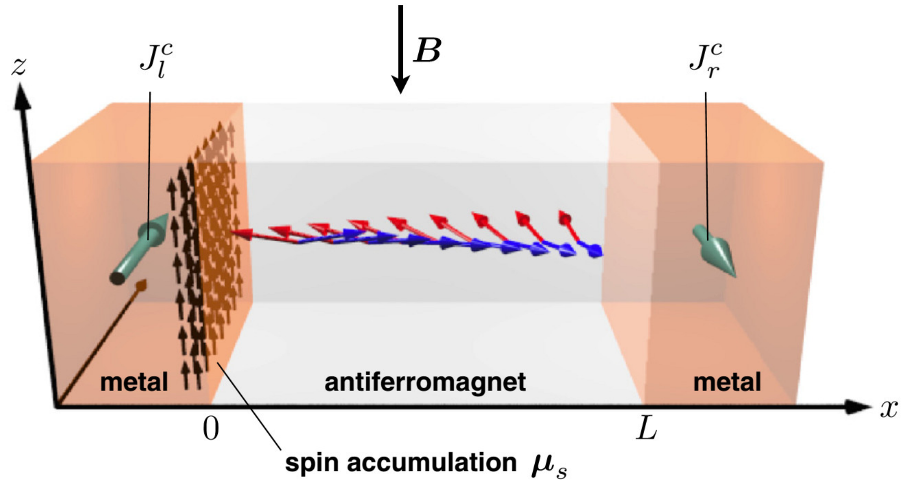
W. Yuan, Q. Zhu, T. Su, Y. Yao, W. Xing, Y. Chen, Y. Ma, X. Lin, J. Shi*, R. Shindou, X. C. Xie*, and Wei Han*, ***Science Advances*, 4: eaat1098 (2018).**

Spin superfluidity in canted AFM



Question: Does spin superfluidity exist in all canted AFM?

Spin superfluidity in canted AFM



Question: Does spin superfluidity exist in all canted AFM?

No

Spin transport in Fe_2O_3

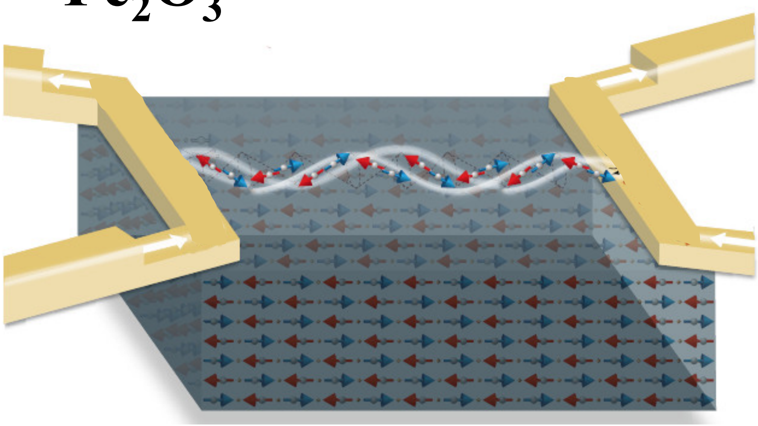
LETTER

https://doi.org/10.1038/s41586-018-0490-7

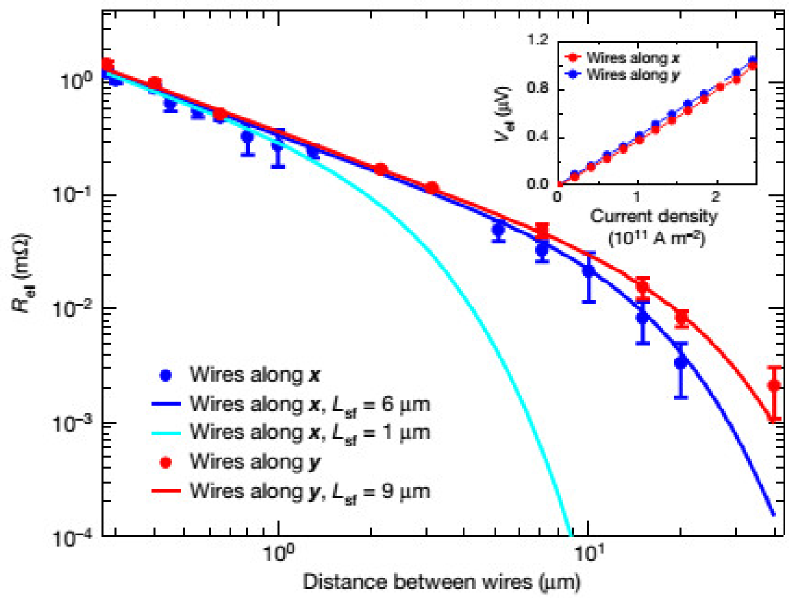
Tunable long-distance spin transport in a crystalline antiferromagnetic iron oxide

R. Lebrun[1,6]*, A. Ross[1,2,6], S. A. Bender[3], A. Qaiumzadeh[4], L. Baldrati[1], J. Cramer[1,2], A. Brataas[4], R. A. Duine[3,4,5] & M. Kläui[1,2,4]*

Fe_2O_3



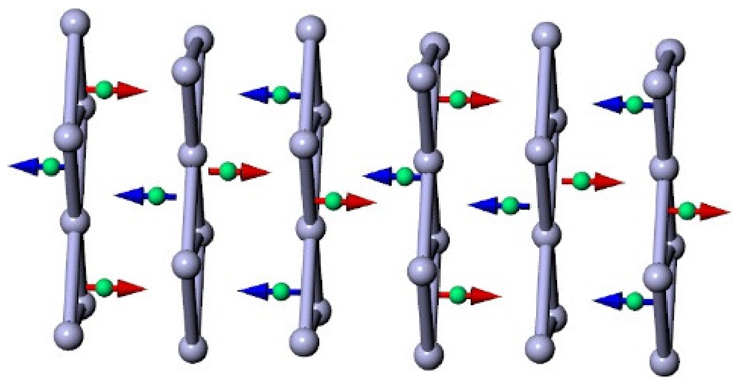
Incoherent magnon

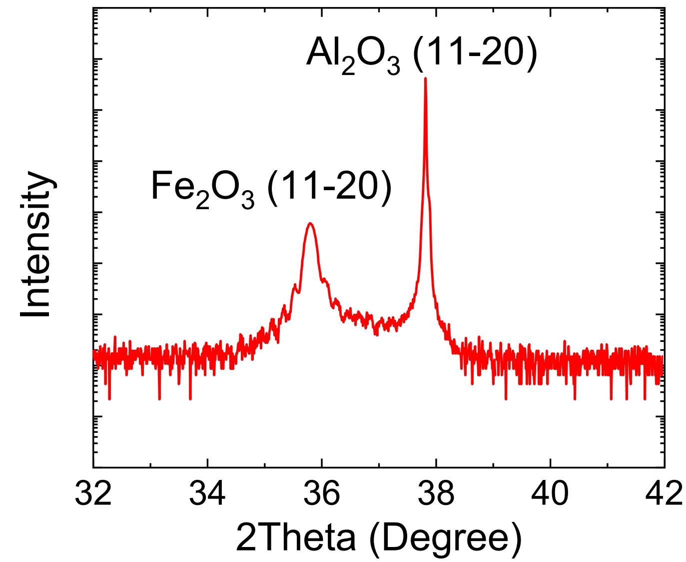


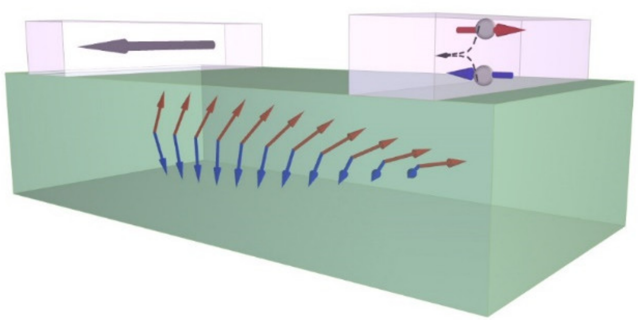
Klaui Group @Mainz, et al, Nature (2018)

Spin transport in Fe_2O_3

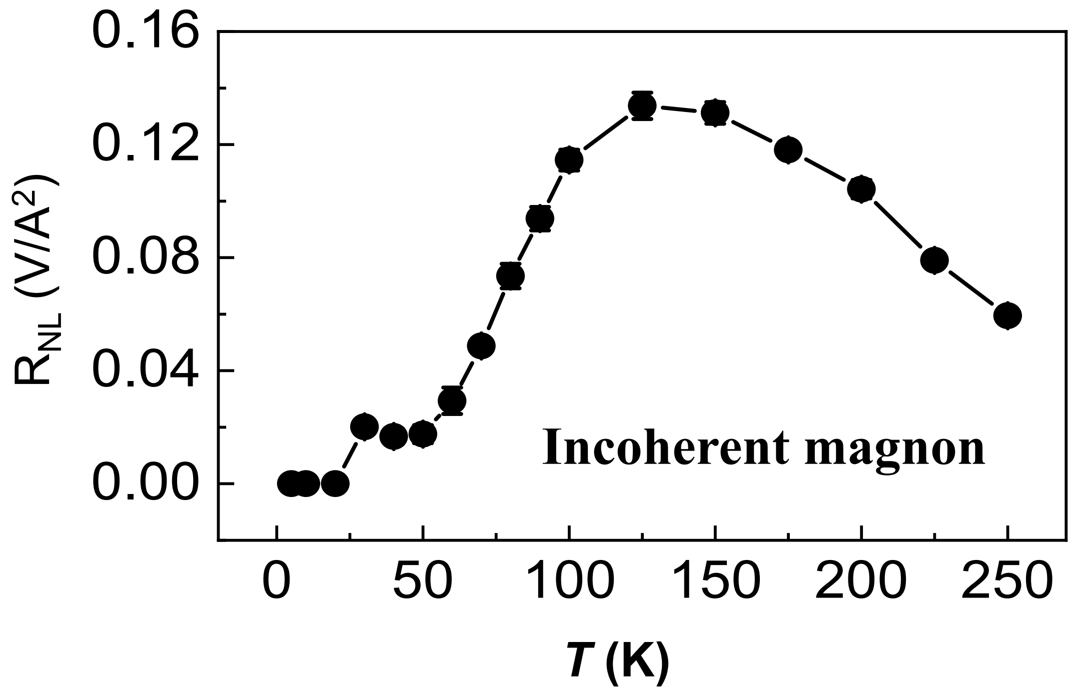
(11-20) Fe_2O_3 (50 nm) on Al_2O_3





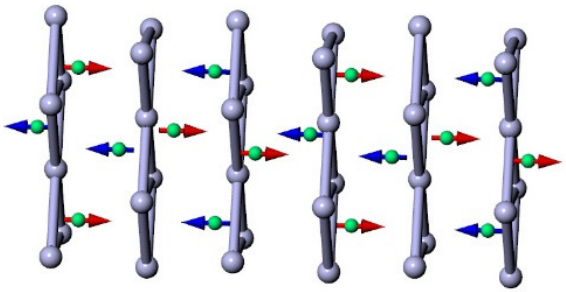


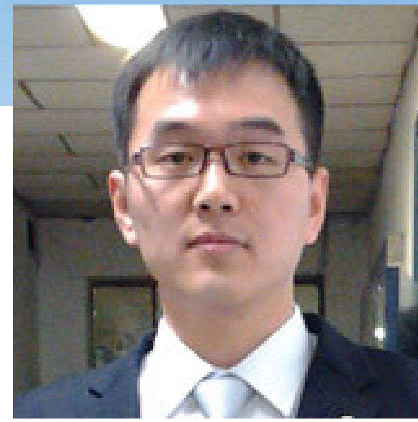
Fe_2O_3



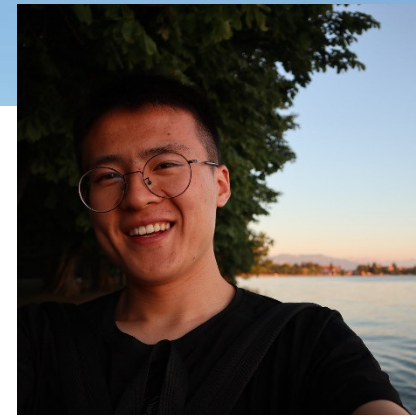
Spin transport in Fe_2O_3

Fe_2O_3

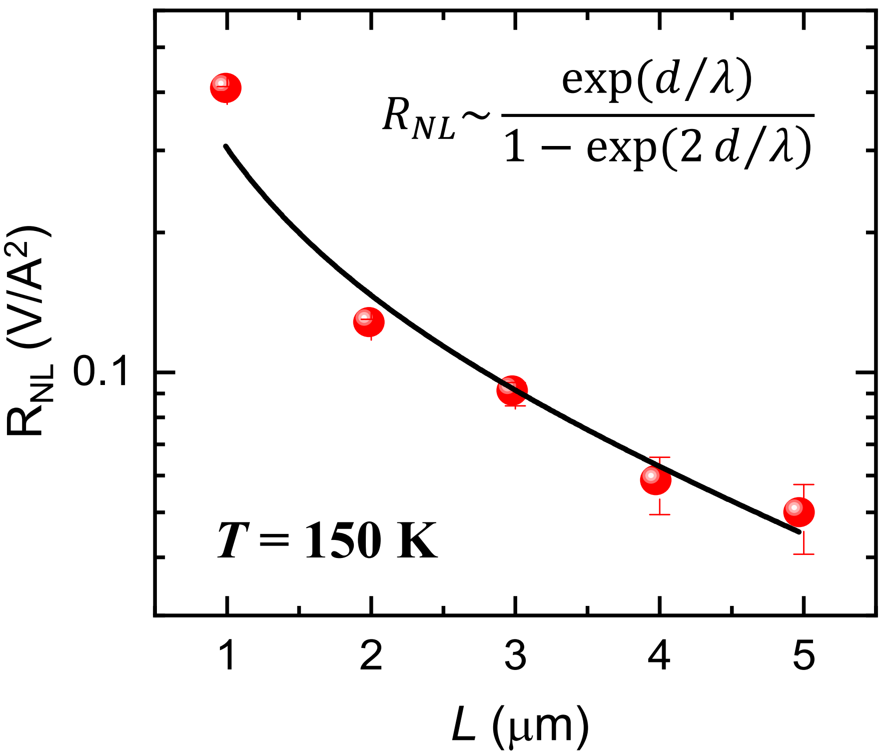


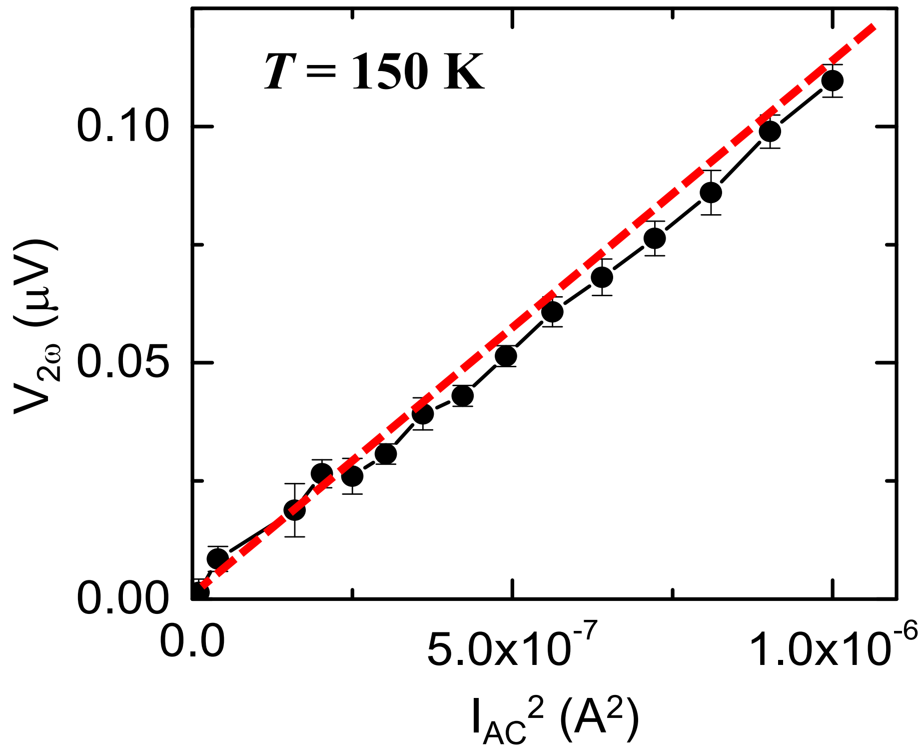


Wenyu Xing



Yang Ma

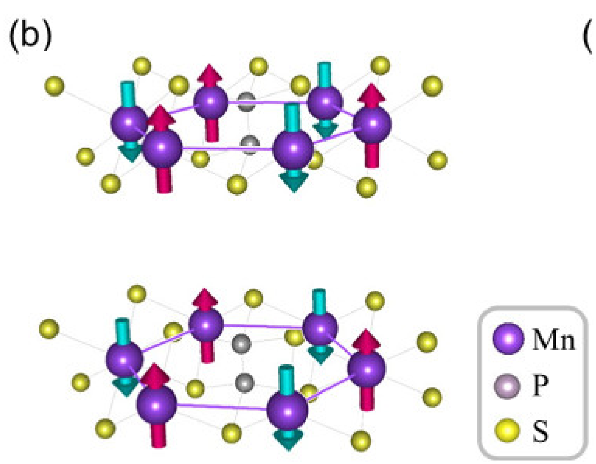




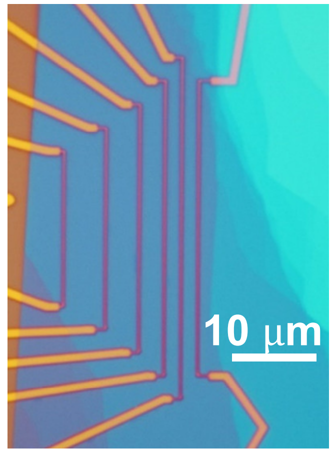
W. Xing, Y. Ma, et al, unpublished

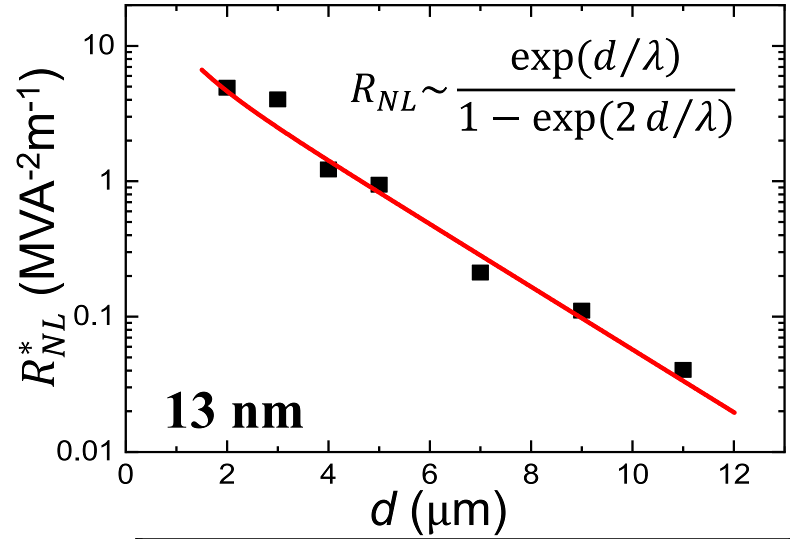
Magnon transport in 2D $MnPS_3$

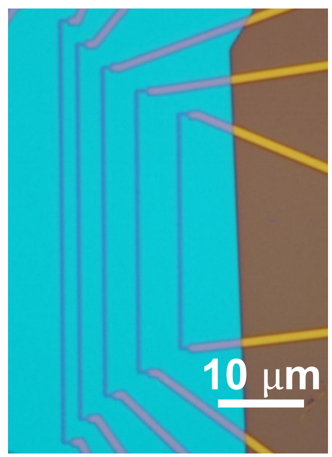
$MnPS_3$

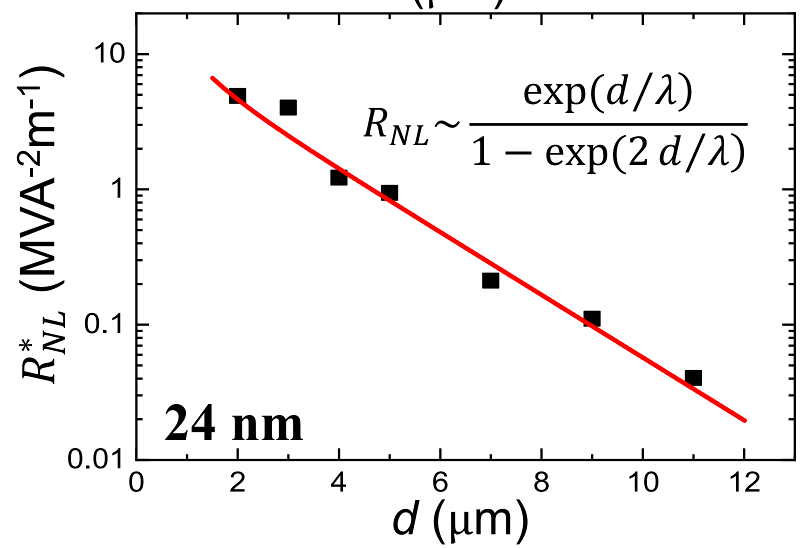


Wenyu Xing









W. Xing, L. Qiu, X. Wang, Y. Yao, Y. Ma, R. Cai, S. Jia, X. C. Xie, and Wei Han*, **Physical Review X 9, 011026 (2019)**

Outline

I. Introduction to spin current and quantum materials

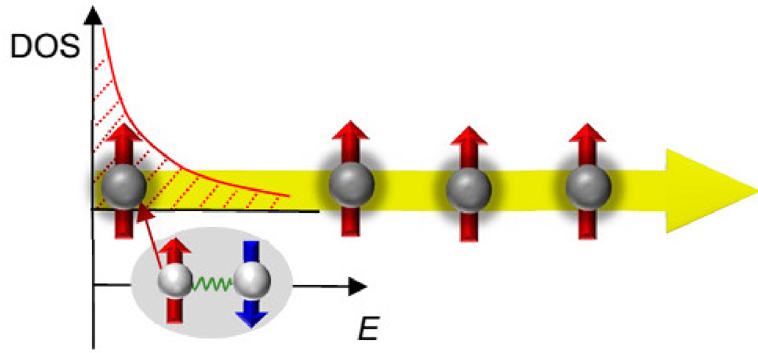
II. Spin current as a probe for quantum materials

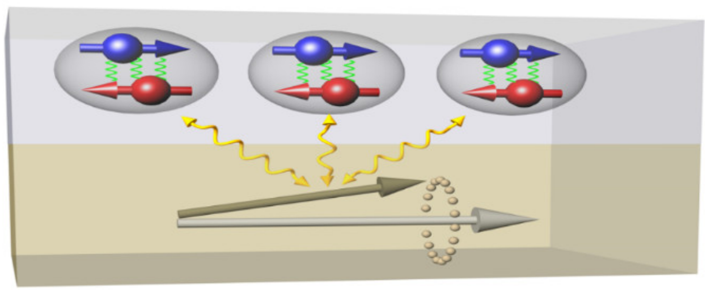
- Spin dynamics in FM/superconductors
- Spin superfluidity in canted AFM:
  Cr_2O_3 (Yes), Fe_2O_3 and $MnPS_3$ (No)

III. Summary and outlook

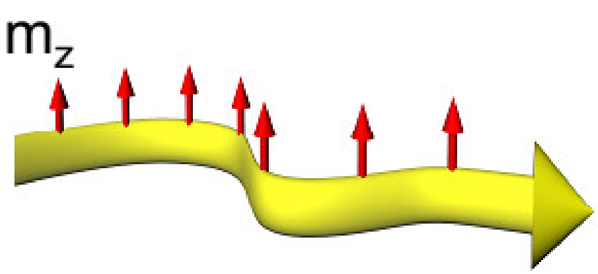
Spin current: a novel probe for Quantum Materials

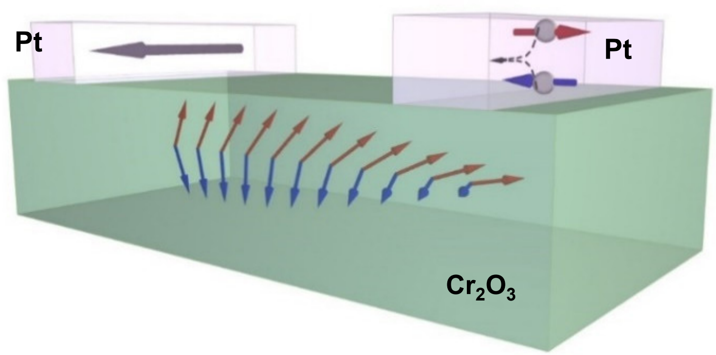
- **Spin dynamics in FM/SC**





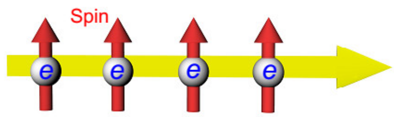
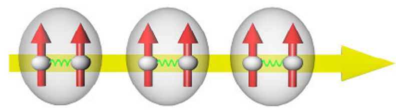
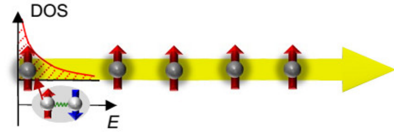
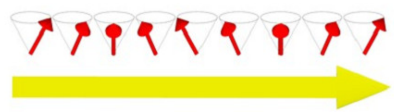
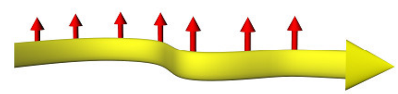
- **Signatures for Spin Superfluidity Ground State**

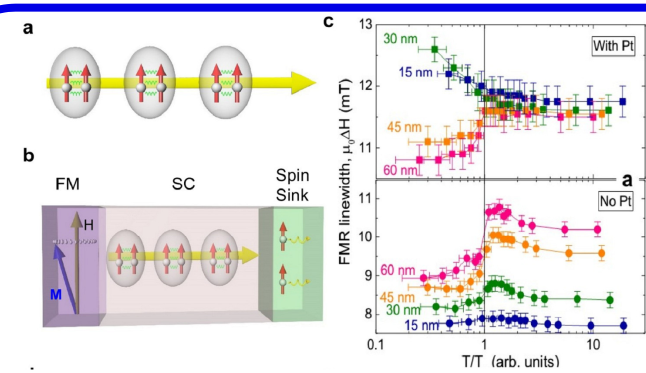




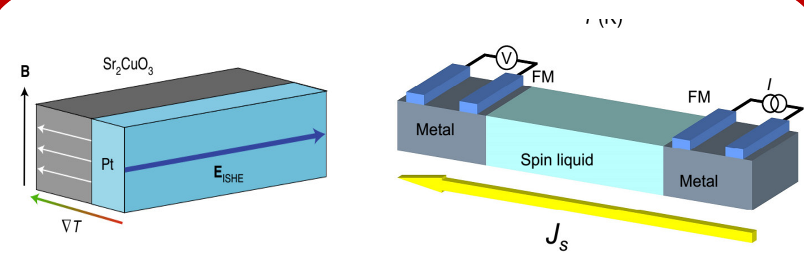
Cr_2O_3 (Yes), Fe_2O_3 and $MnPS_3$ (No)

Outlook: Spin current as a probe of Quantum Materials

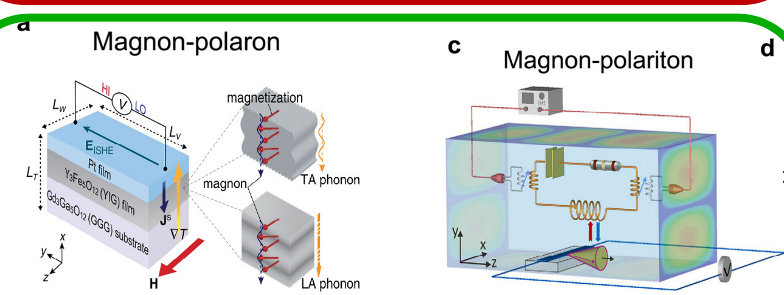
	Materials	Illustration of spin current
Electron (hole) (S = 1/2)	Metals, semiconductors, and topological insulators, etc	
Spin-triplet pair (S = 1)	Superconductors	
Quasiparticle (S = 1/2)	Superconductors	
Spinon (S = 1/2)	Quantum spin liquids	
Magnon (S = 1)	Magnetic insulators	
Electron-hole pair or magnon (S = 1)	Spin superfluids	



Jeon, et al, Nat. Mater. (2018)

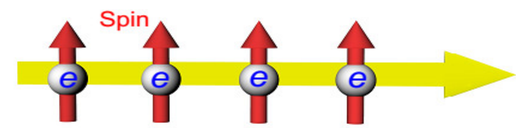
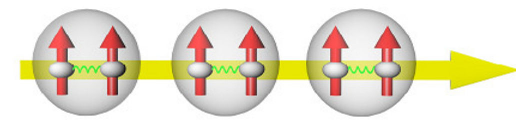
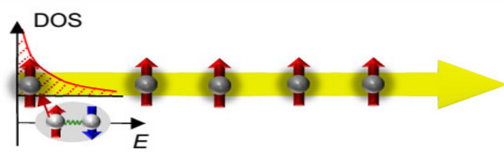
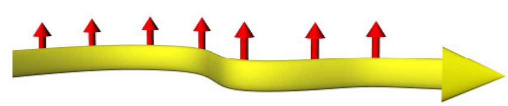


Hirobe, et al, Nat. Phys. (2016)
Chen, et al, PRB (2013)



Kikkawa, et al, PRL (2016)
Bai, et al, PRL (2015)

Outlook: Spin current as a probe of Quantum Materials

	Materials	Illustration of spin current
Electron (hole) (S = 1/2)	Metals, semiconductors, and topological insulators, etc	
Spin-triplet pair (S = 1)	Superconductors	
Quasiparticle (S = 1/2)	Superconductors	
Spinon (S = 1/2)	Quantum spin liquids	
Magnon (S = 1)	Magnetic insulators	
Electron-hole pair or magnon (S = 1)	Spin superfluids	

W Han*, S. Maekawa, and X. C. Xie, Nature Materials (2019)
https://doi.org/10.1038/s41563-019-0456-7

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Massachusetts Institute of Technology, USA

Prof. Jagadeesh S. Moodera, Prof. Yota Takamura (TIT, Japan)

Nanjing University, China

Prof. Di Wu, Ms. Siyu Yao

University of California, Riverside, USA

Prof. Jing Shi

RIKEN, Japan

Prof. Sadamichi Maekawa (KITS, Beijing)

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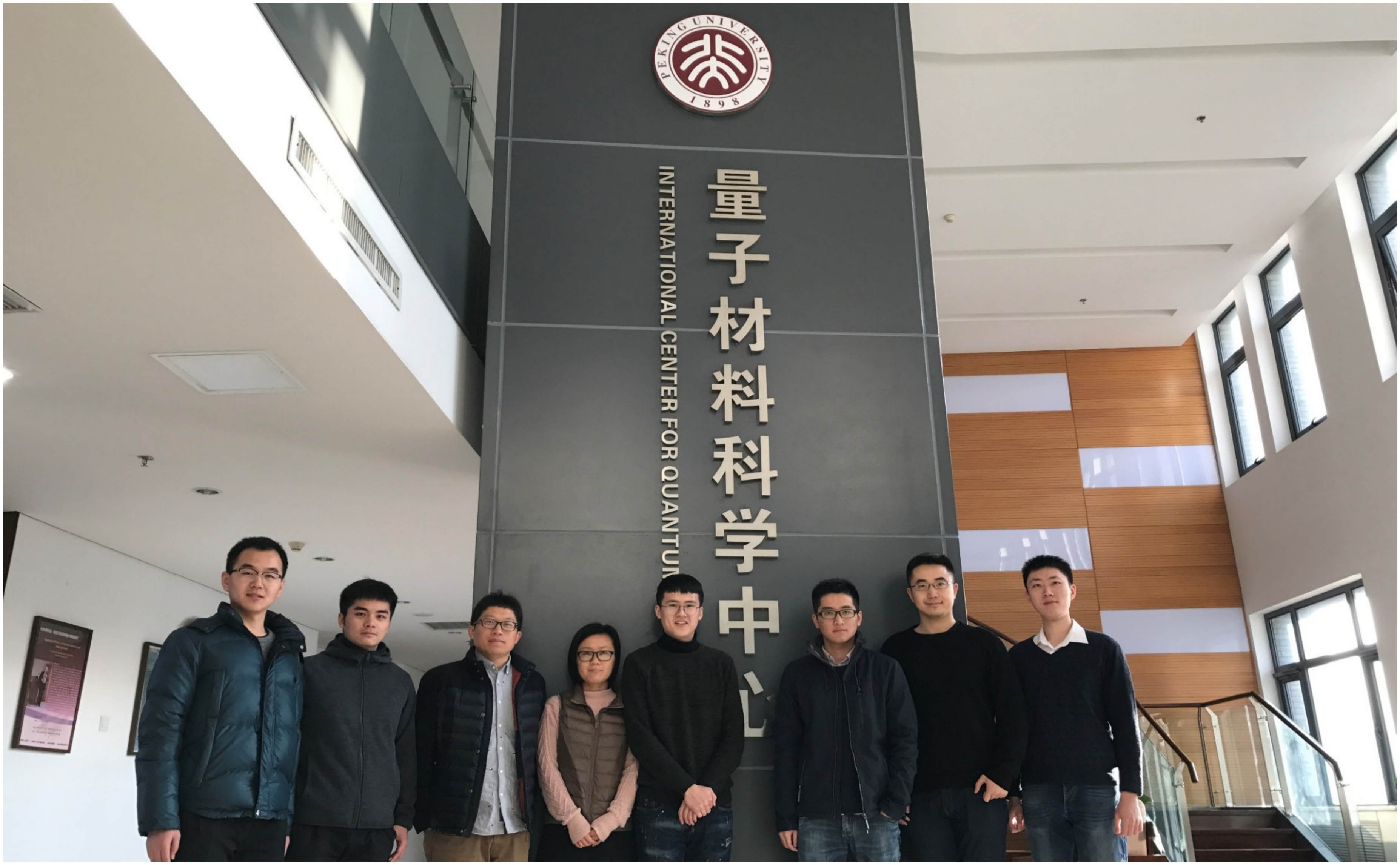
Theory: Prof. Xin-Cheng Xie, Prof. Ryuichi Shindou

Experiment: Prof. Shuang Jia, Prof. Xi Lin, Prof. Yuan Li

Acknowledgement—Students and funding



Funding: NSF of China, MOST (973)

Acknowledgement-audience

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Group: http://www.phy.pku.edu.cn/~LabSpin/home.html