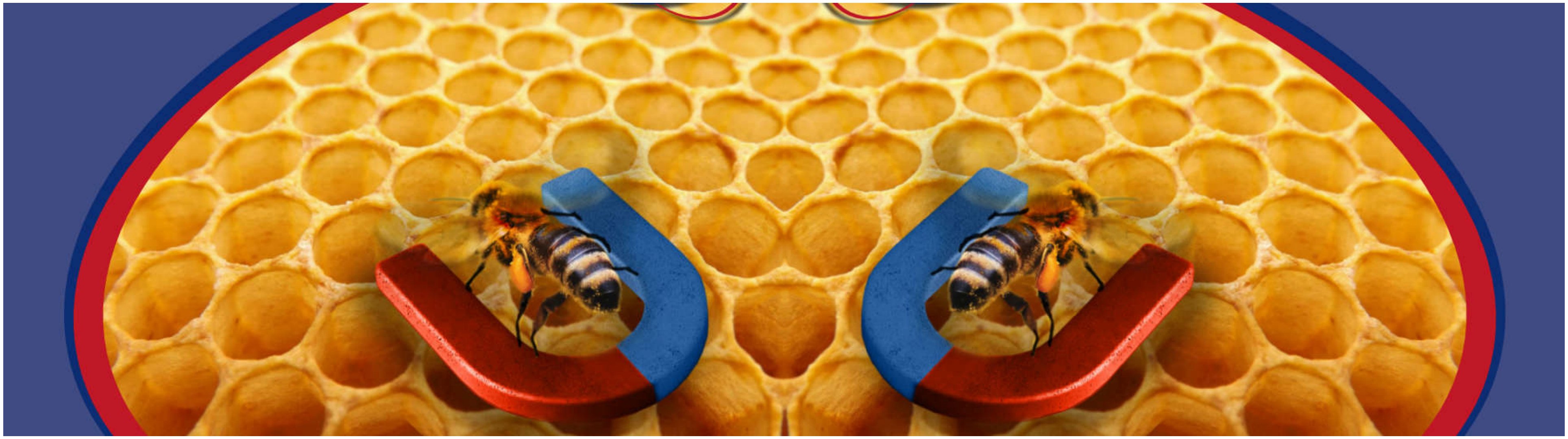


Spin Transport in Magnetic 2D Materials and Heterostructures

Wei Han

2D VAN DER WAALS
SPIN SYSTEMS
SPICE || August 4th 2020

北京大学量子材料科学中心
International Center for Quantum Materials, PKU

Outline

I. Introduction to Magnetic 2D Materials

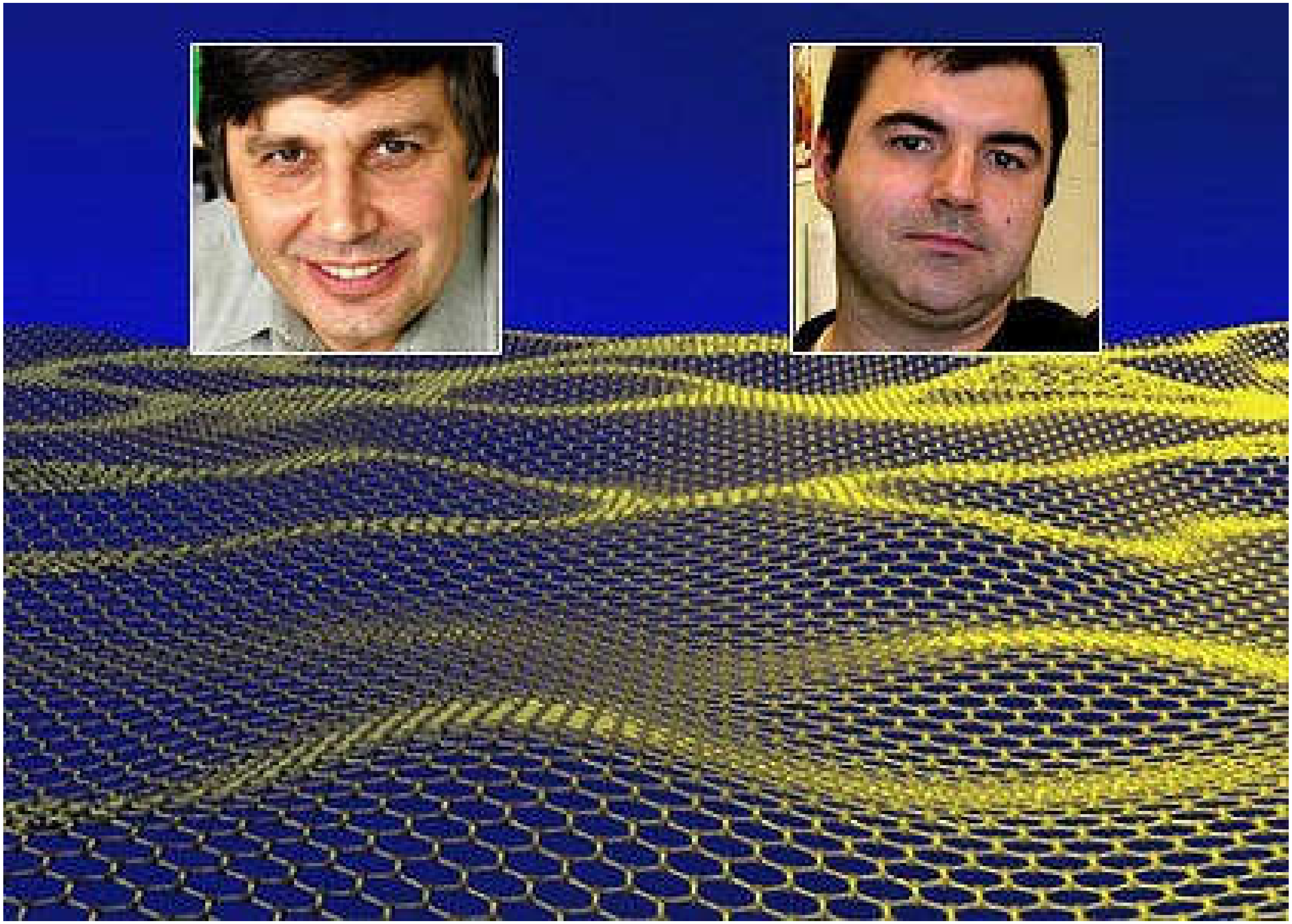
II. Spin (Magnon) Transport in Insulating $MnPS_3$ Flakes

III. Spin (Electron) Transport in Metallic $FeTaS_2$ Flakes

- Spin scattering mechanisms in $FeTaS_2$
- Spin transport in $FeTaS_2$/SC junctions

IV. Summary

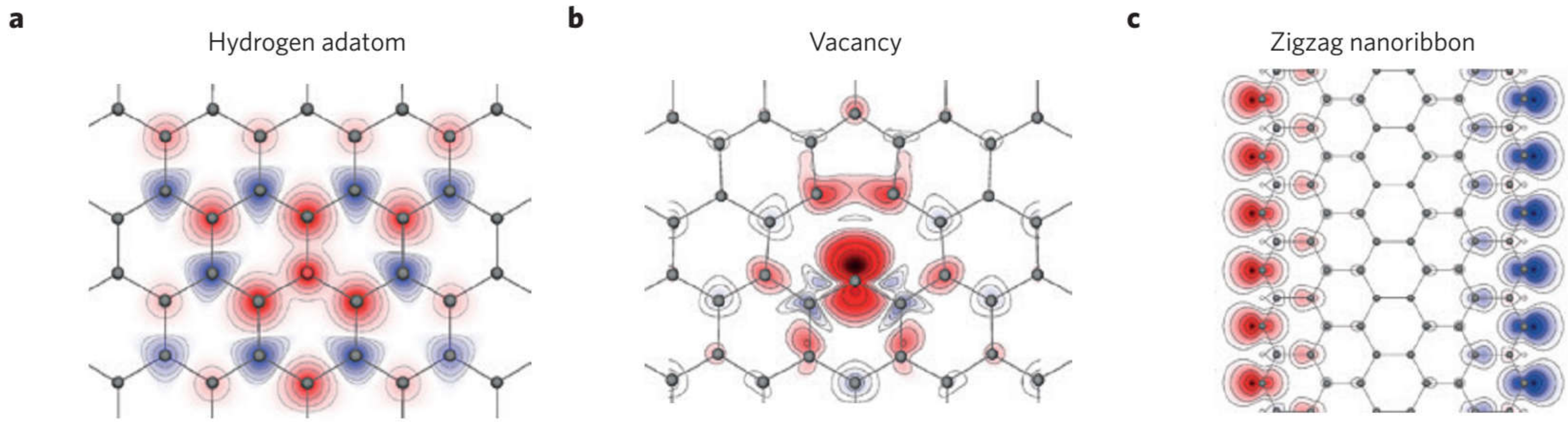
Introduction to Magnetic 2D Materials



Nobel Prize in physics (2010)

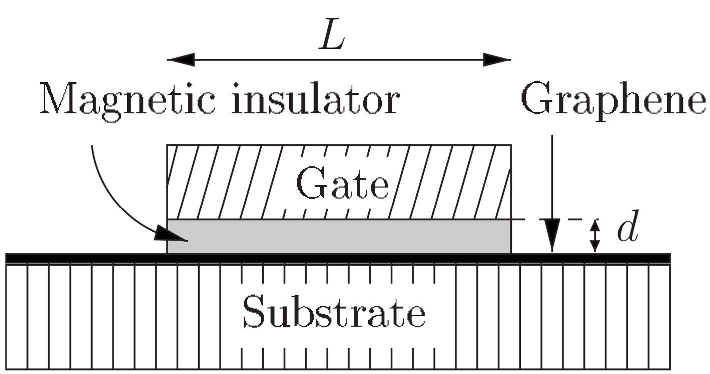
Making Graphene Magnetic

Doping of magnetic impurity



Yazyev and Helm, PRB (2007)
Han, et al, Nature Nanotech (2014)

Magnetic proximity effect



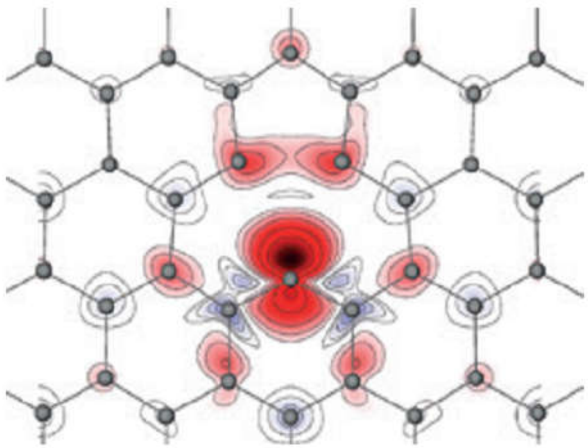
FM insulator: YIG ($Y_3Fe_5O_{18}$), EuO

AFM insulator: $BiFeO_3$

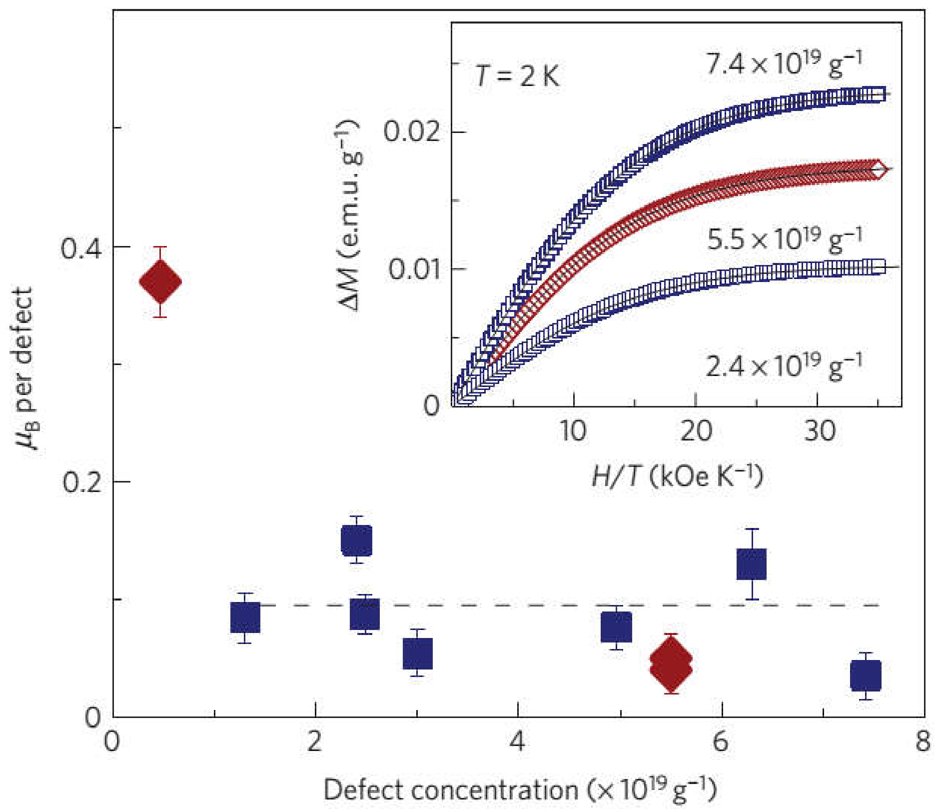
Haugen, et al, PRB (2008)
Qiao, et al, PRL (2010)
Wei, et al, Nature Materials (2016)
Wang, et al, PRL (2015)

Making graphene magnetic

Doping of magnetic impurity



$$M = NgJ\mu_B \left[\frac{2J}{2J+1} \operatorname{ctnh}\left(\frac{(2J+1)z}{2J} \right) - \frac{1}{2J} \operatorname{ctnh}\left(\frac{z}{2J} \right) \right]$$

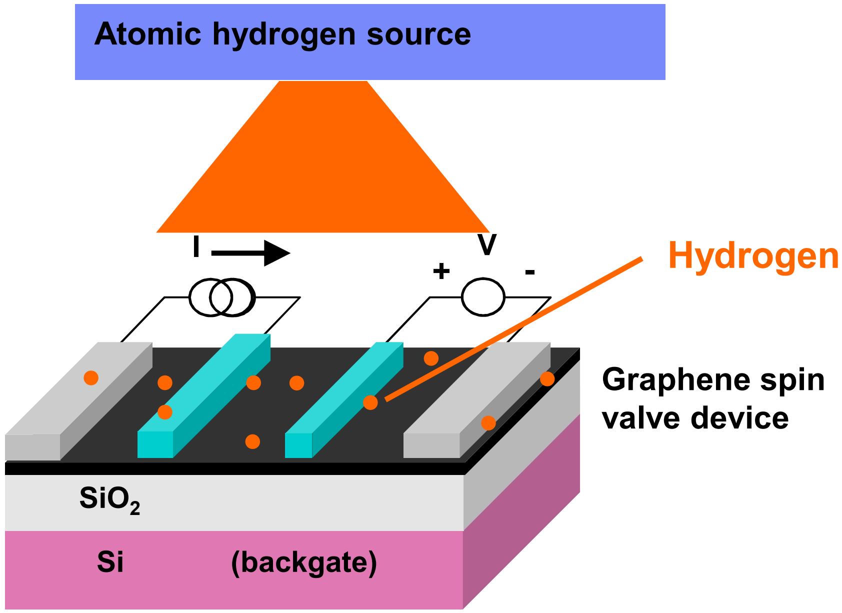


Paramagnetic

Nair, et al, Nature Physis (2010)

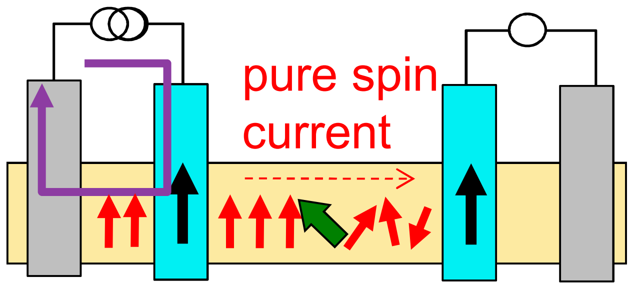
Making graphene magnetic

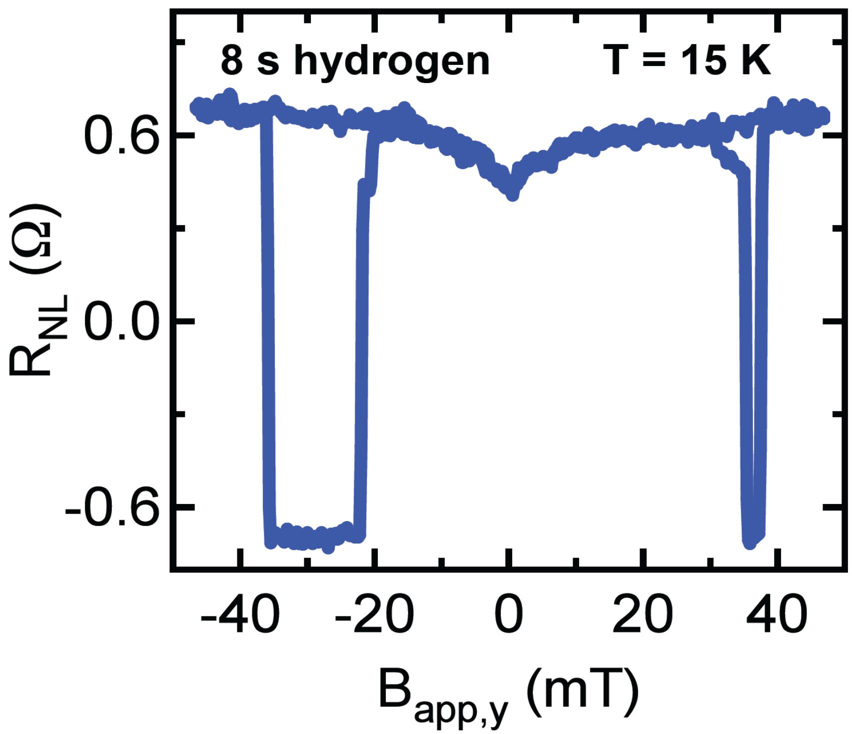
Doping of magnetic impurity



$$H_{ex} = A_{ex}\, \vec{S}_e \cdot \vec{S}_M$$

Paramagnetic

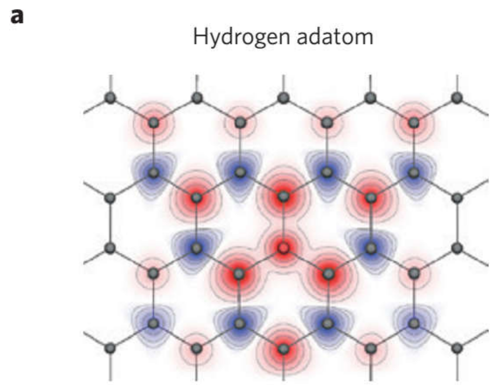




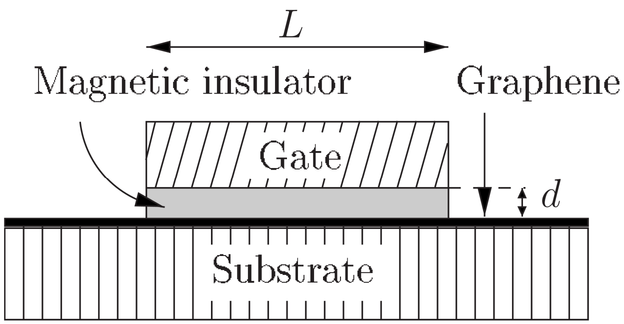
McCreary, et al, PRL (2012)

Introduction to Magnetic 2D Materials

Doping of magnetic impurity



Magnetic proximity effect

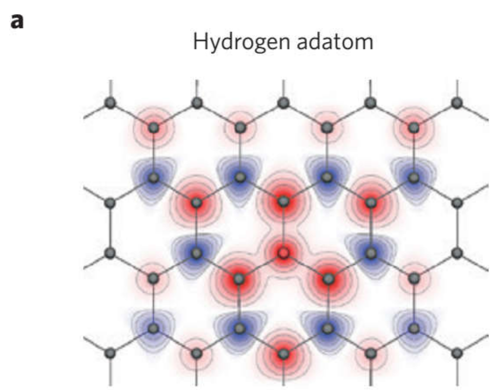


Extrinsic ferromagnetism

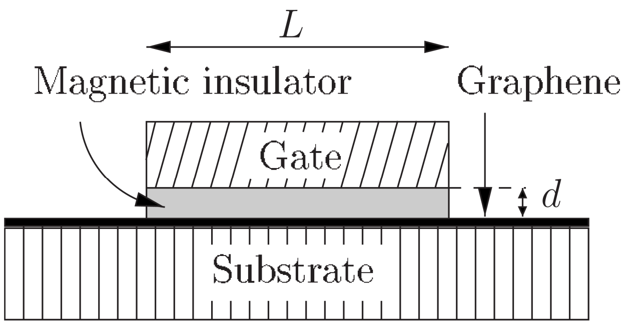
How about intrinsic 2D ferromagnetism?

Introduction to Magnetic 2D Materials

Doping of magnetic impurity



Magnetic proximity effect

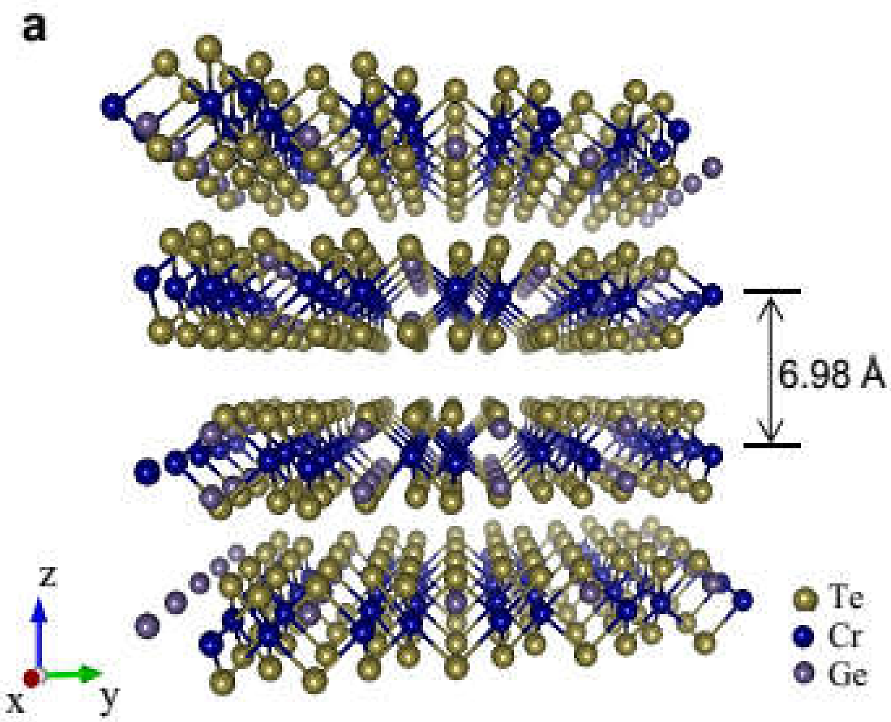


Extrinsic ferromagnetism

How about intrinsic 2D ferromagnetism?

Ferromagnetic 2D materials

Bulk $Cr_2Ge_2Te_6$

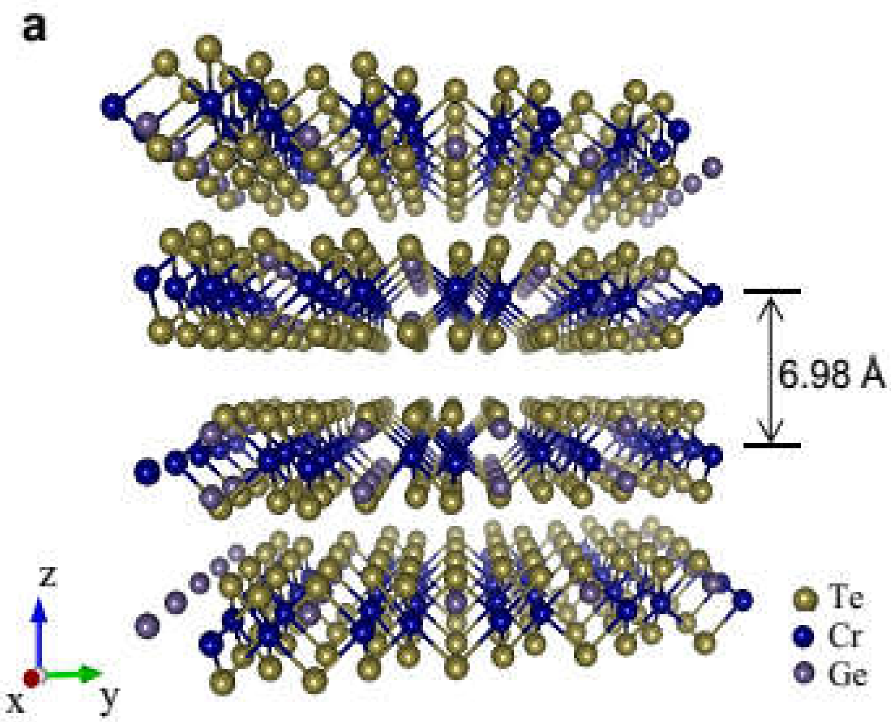


Layered structure

V. Carteaux, et al, J. Phys.: Condens. Matter 7, 69 (1995);
H. Ji, et al, J. Appl. Phys. (2013)

Ferromagnetic 2D materials

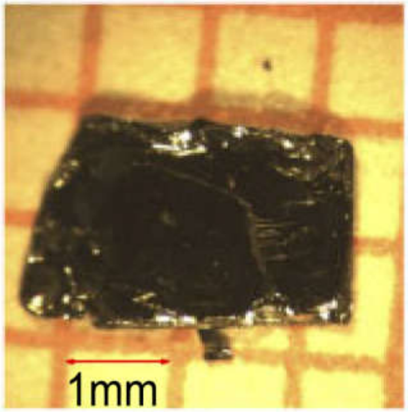
Bulk $Cr_2Ge_2Te_6$



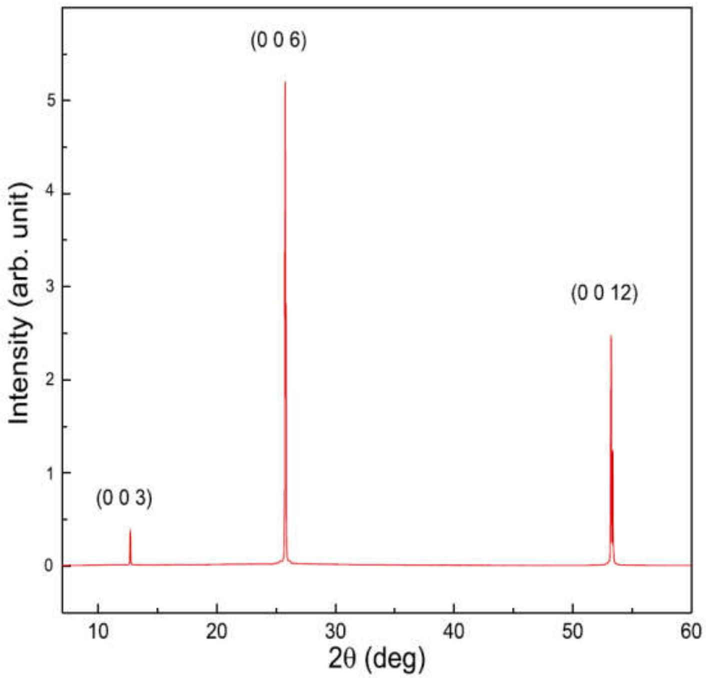
Layered structure

V. Carteaux, et al, J. Phys.: Condens. Matter 7, 69 (1995);
H. Ji, et al, J. Appl. Phys. (2013)

Flux method



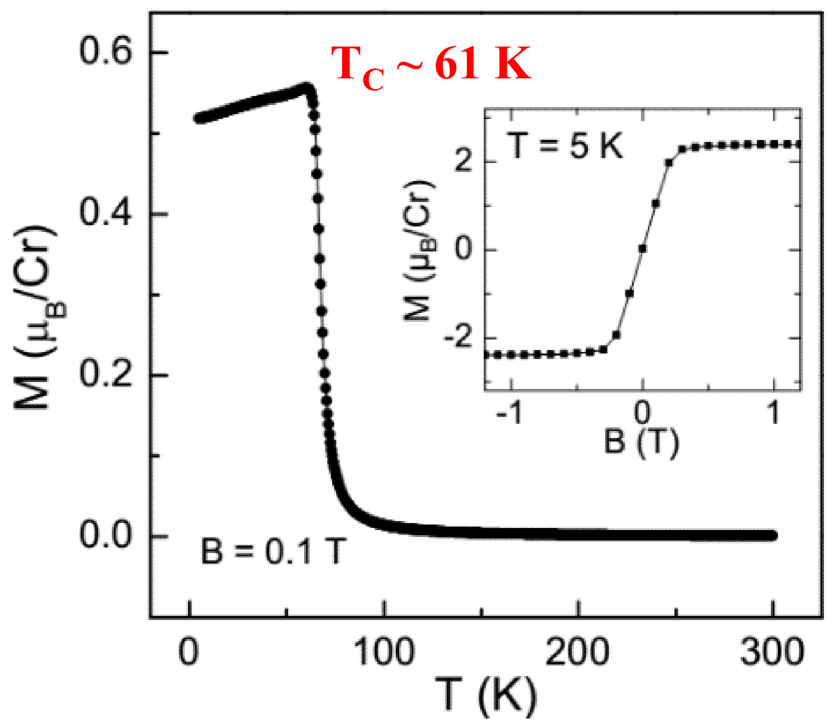
XRD

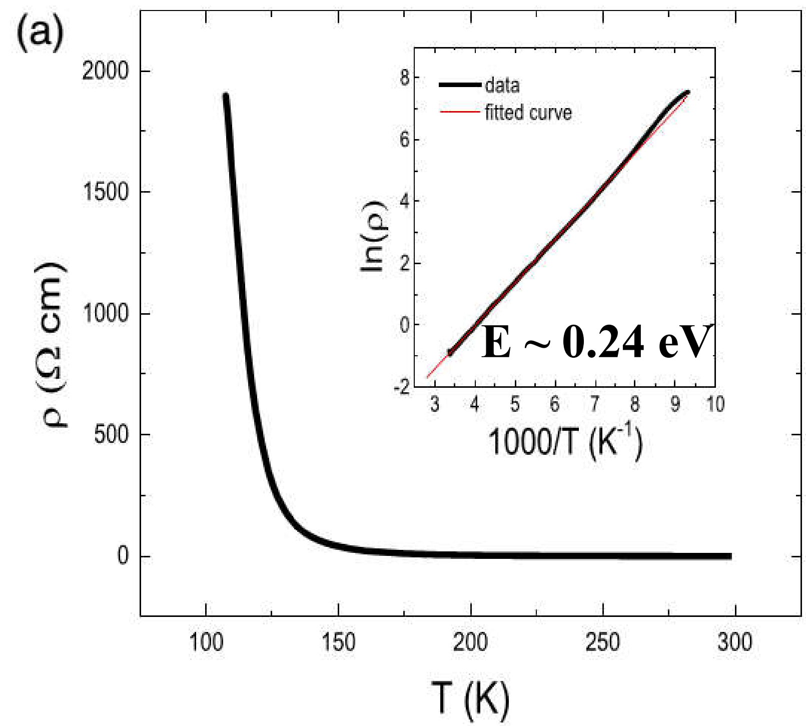


Ferromagnetic 2D materials

Ferromagnetic

Semiconducting



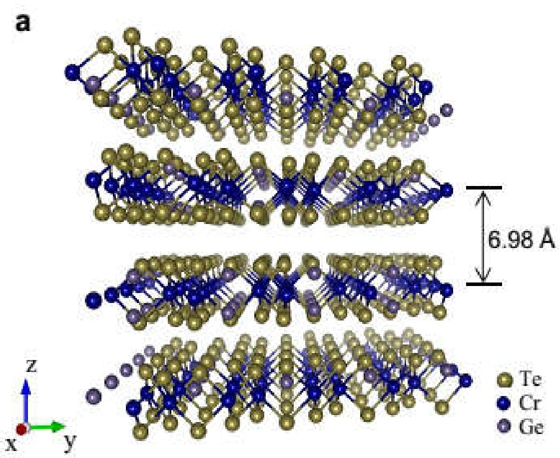


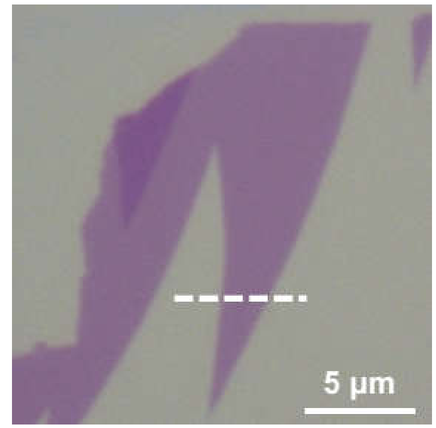
Ferromagnetic semiconductor

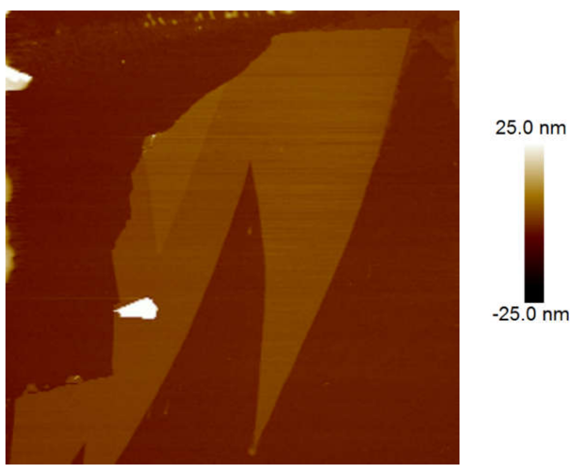
X. Zhang, Y. Zhao, Q. Song, S. Jia, J. Shi, and W. Han*, **Jpn. J. Appl. Phys. 55, 033001 (2016)**

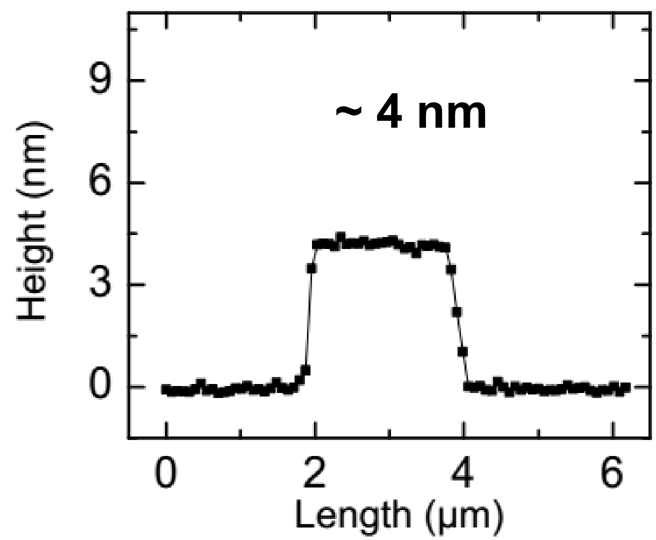
Ferromagnetic 2D flakes

2D flakes: Mechanical exfoliation





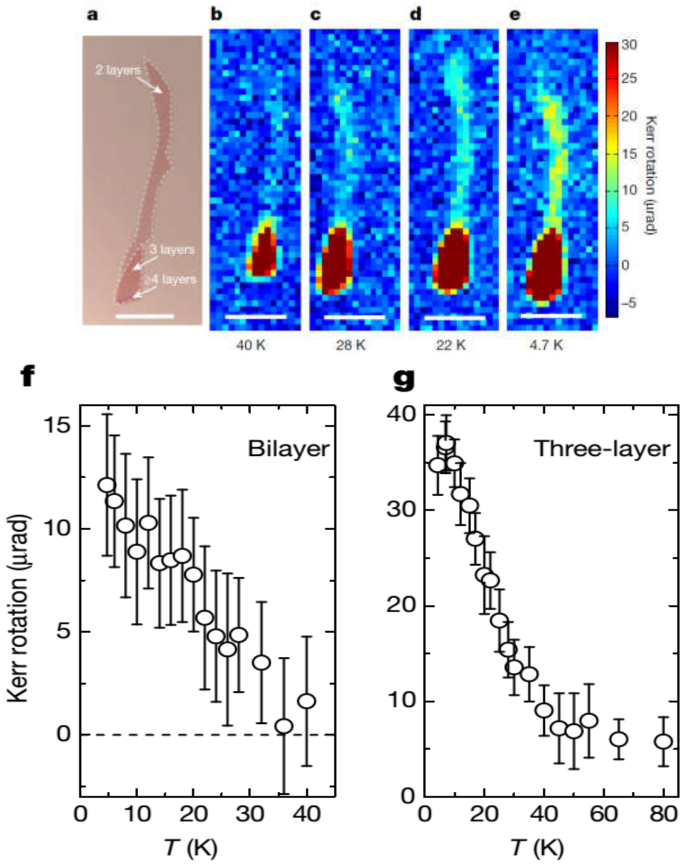




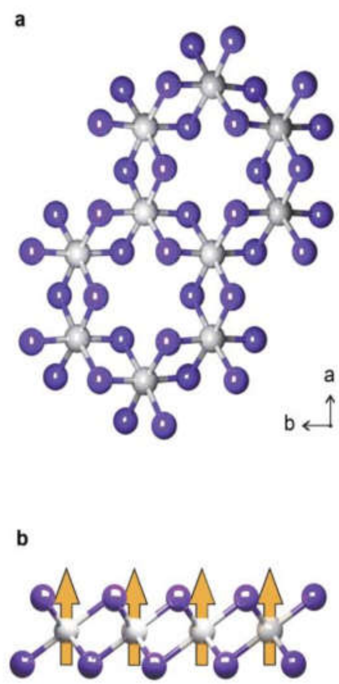
W. Xing, Y. Chen, P. Odenthal, X. Zhang, W. Yuan, T. Su, Q. Song, T. Wang, S. Jia, X. C. Xie, Y. Li, and W. Han*, **2D Materials, 4, 024009 (2017)**

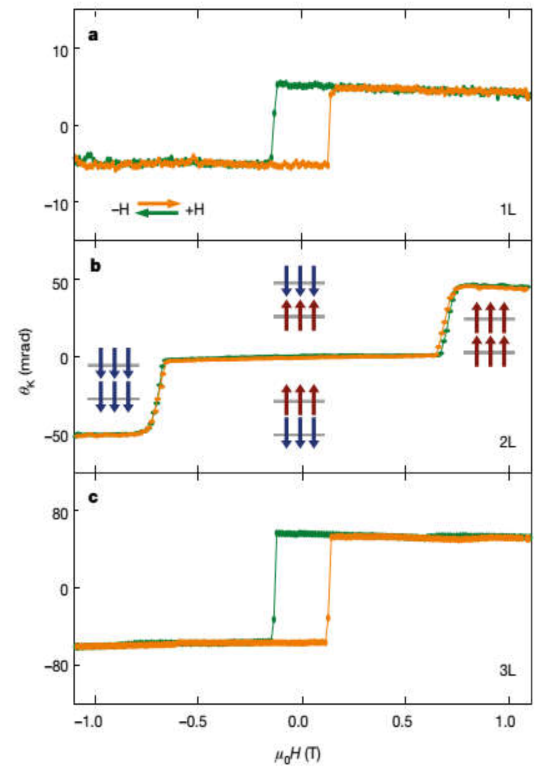
Ferromagnetic 2D materials

$Cr_2Ge_2Te_6$

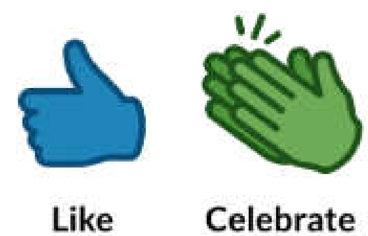


CrI_3





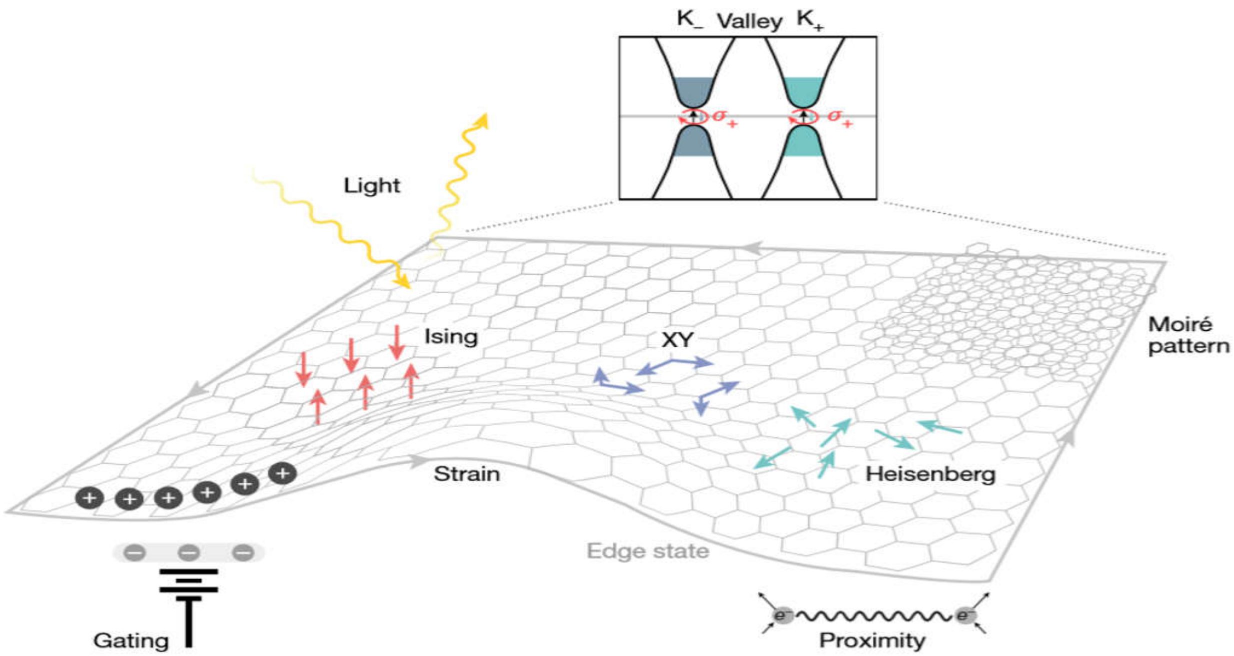
2D Ferromagnetism discovered!



Gong, et al, Nature (2017); Huang, et al, Nature (2017)

Introduction to Magnetic 2D Materials

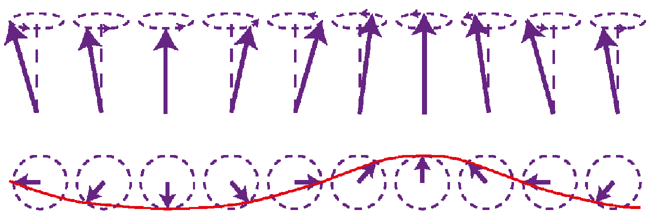
Chalcogenides	$Cr_2Ge_2Te_6$, $Cr_2Si_2Te_6$, Fe_3GeTe_2, VSe_2*, $MnSe_x$*	$Fe_2P_2S_6$, $Fe_2P_2Se_6$, $Mn_2P_2S_6$, $Mn_2P_2Se_6$, $Ni_2P_2S_6$, $Ni_2P_2Se_6$, $CuCrP_2Se_6$*, $AgVP_2S_6$, $AgCrP_2S_6$, $CrSe_2$, $CrTe_3$, $Ni_3Cr_2P_2S_9$, $MnBi_2Te_4$*, $MnBi_2Se_4$*	$CuCrP_2S_6$
Halides	CrI_3*, $CrBr_3$, GdI_2	$CrCl_3$, $FeCl_2$, $FeBr_2$, FeI_2, $MnBr_2$, $CoCl_2$, $CoBr_2$, $NiCl_2$, VCl_2, VBr_2, VI_2, $FeCl_3$, $FeBr_3$, CrOCl, CrOBr, CrSBr, $MnCl_2$*, VCl_3*, VBr_3*	$CuCl_2$, $CuBr_2$, $NiBr_2$, NiI_2, CoI_2, MnI_2 α-$RuCl_3$
Others	VS_2, InP_3, GaSe, GaS	MnX_3 (X = F, Cl, Br, I), FeX_2 (X = Cl, Br, I), MnSSe, $TiCl_3$, VCl_3	SnO, GeS, GeSe, SnS, SnSe, GaTeCl, CrN, CrB_2

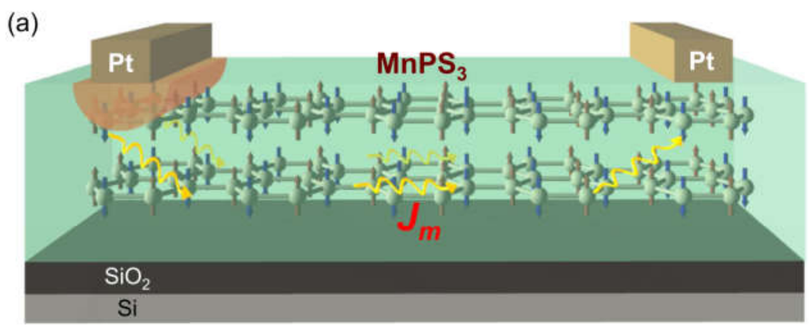


Burch, et al., Nature (2018); Gong, et al., Science (2019)

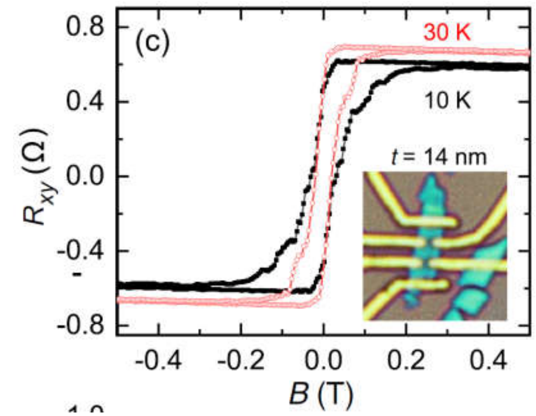
This Talk: Spin Transport in 2D Magnets

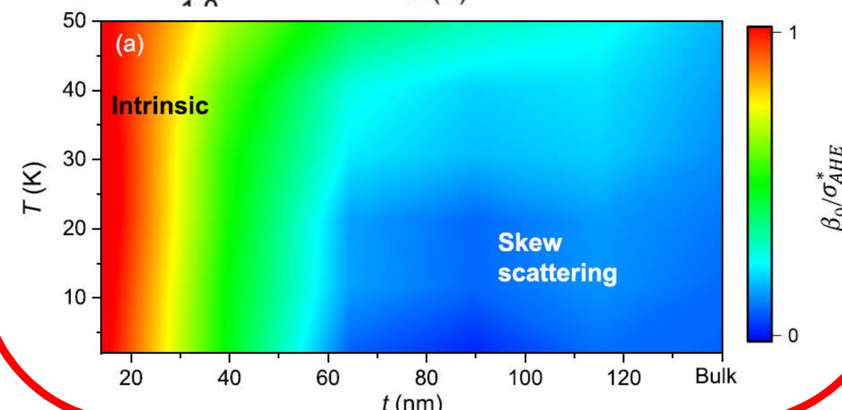
Magnon spin transport in **Insulating** $MnPS_3$ Flakes





Electron spin Transport in **Metallic** $FeTaS_2$ Flakes

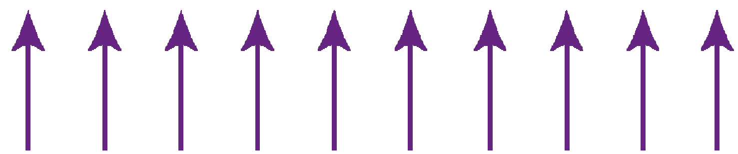




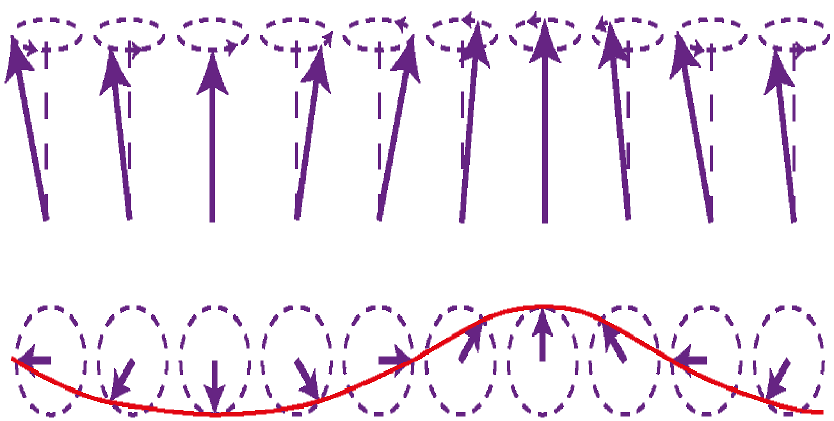
Magnon for information computing

Magnons in FM-ordered materials

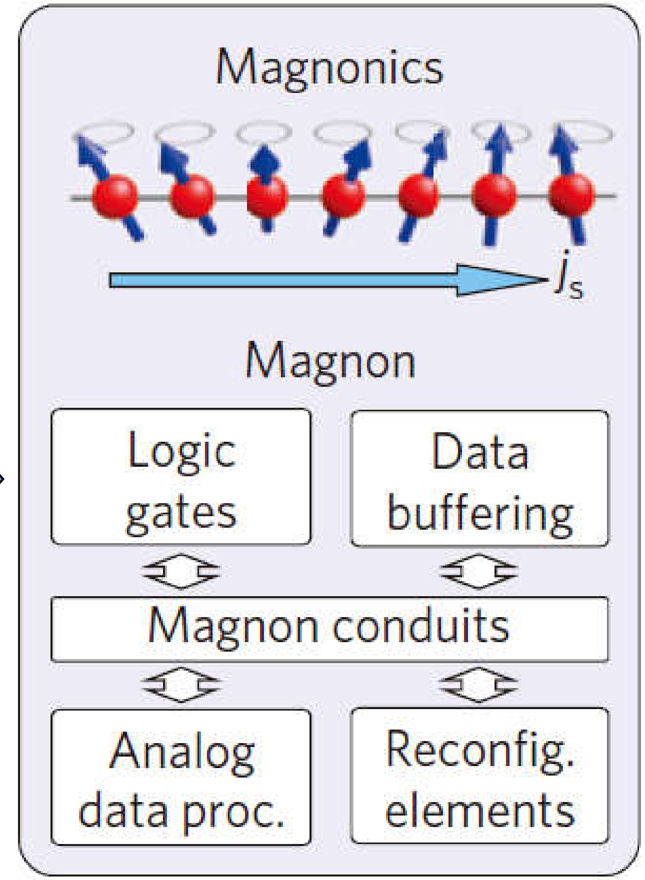
FM



Magnon (Charge 0, Spin-1 boson)

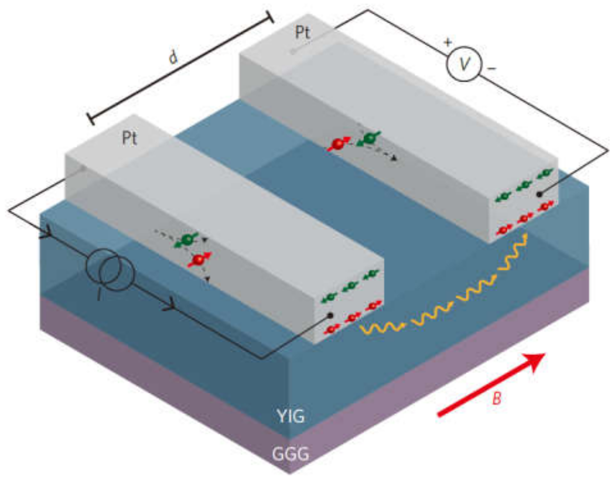


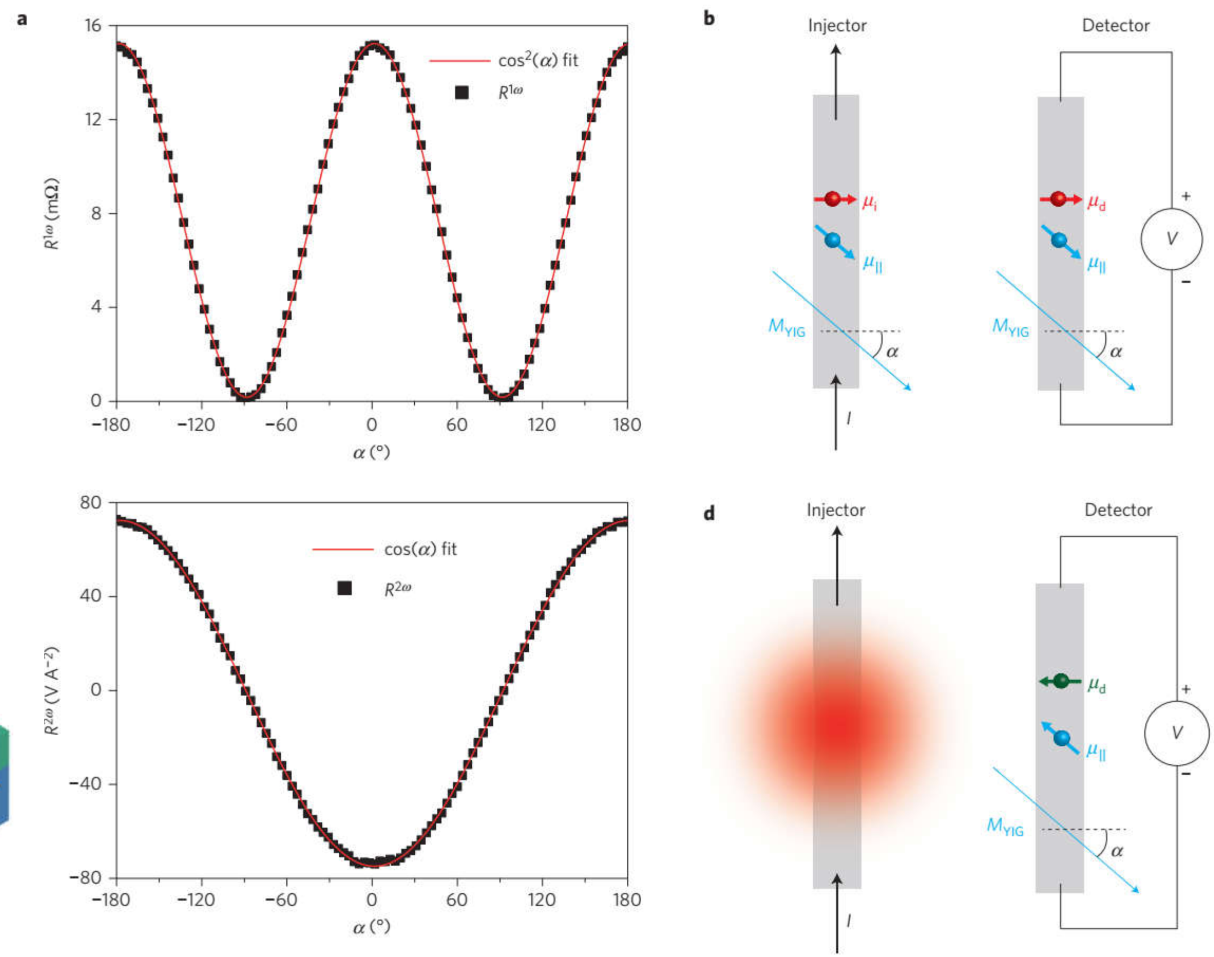
Magnon Spintronics

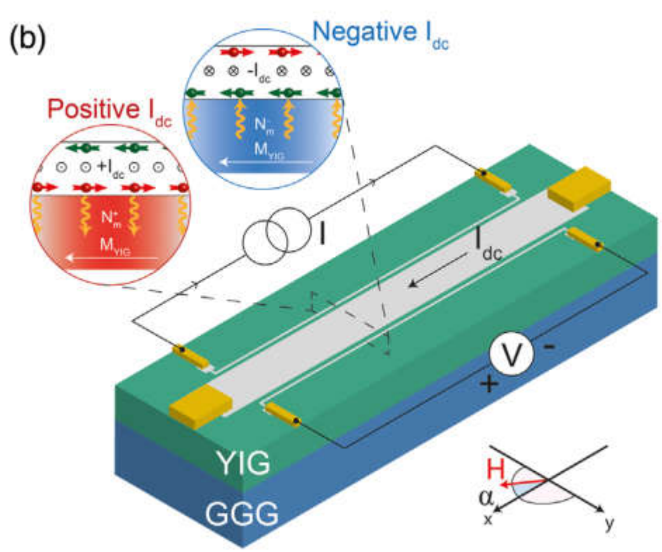


Chumak, et al., Nature Physics (2015)

Nonlocal spin transport and magnon transistor



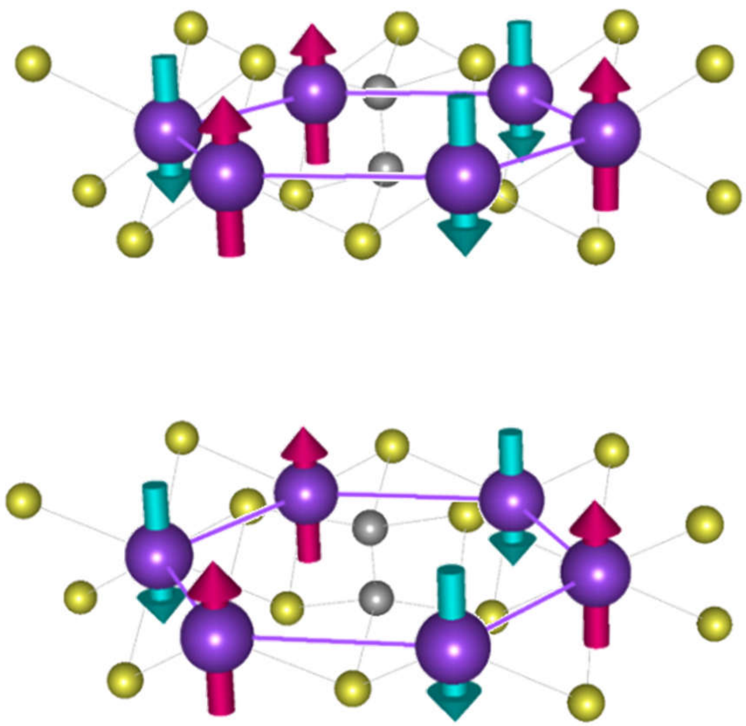


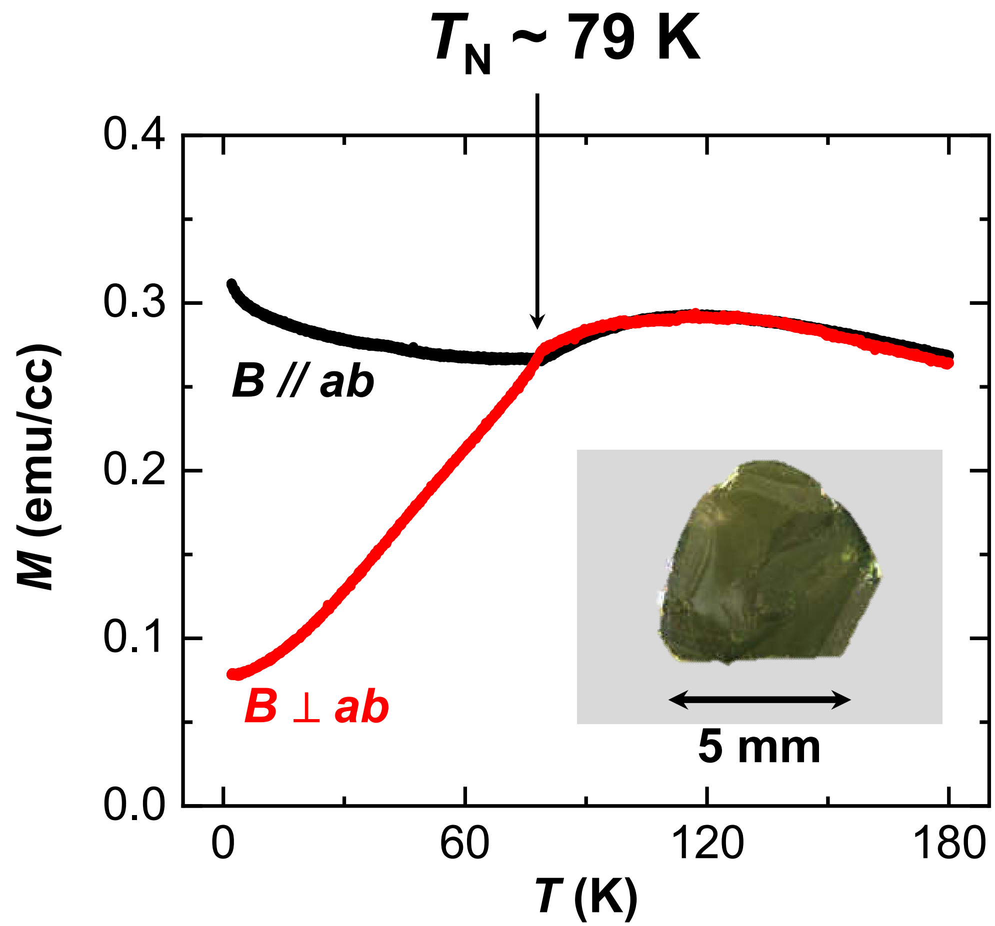


Cornelissen, et al., Nature Physics (2015)
Cornelissen, et al., PRL (2018)

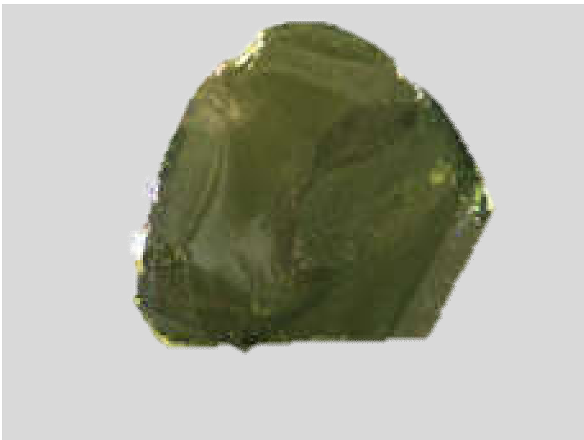
$MnPS_3$ properties

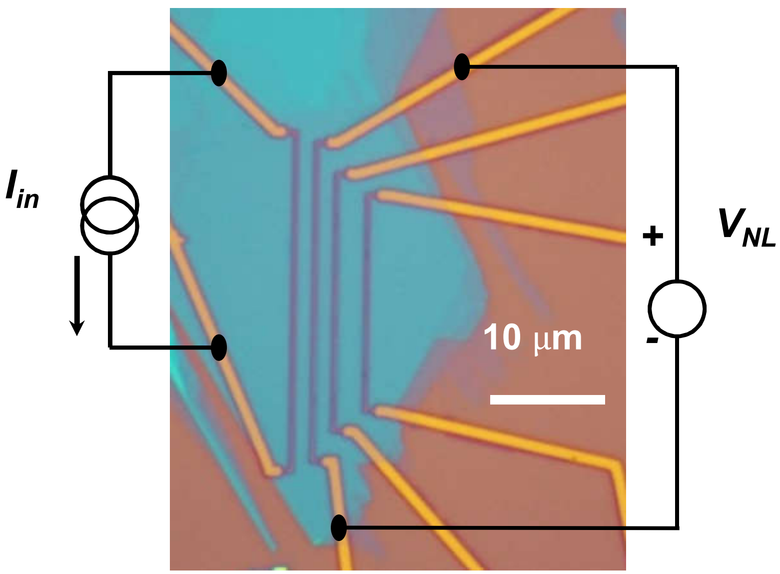
Crystal and spin structures

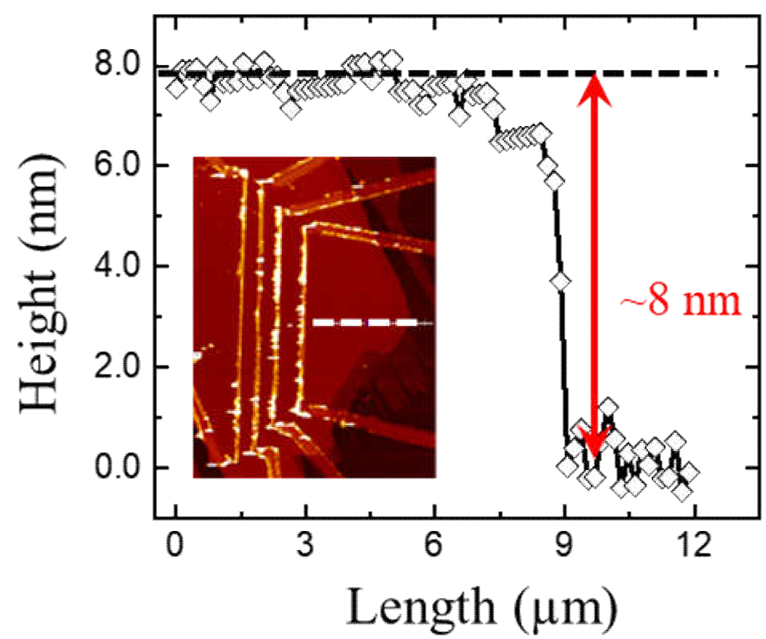




Device fabrication



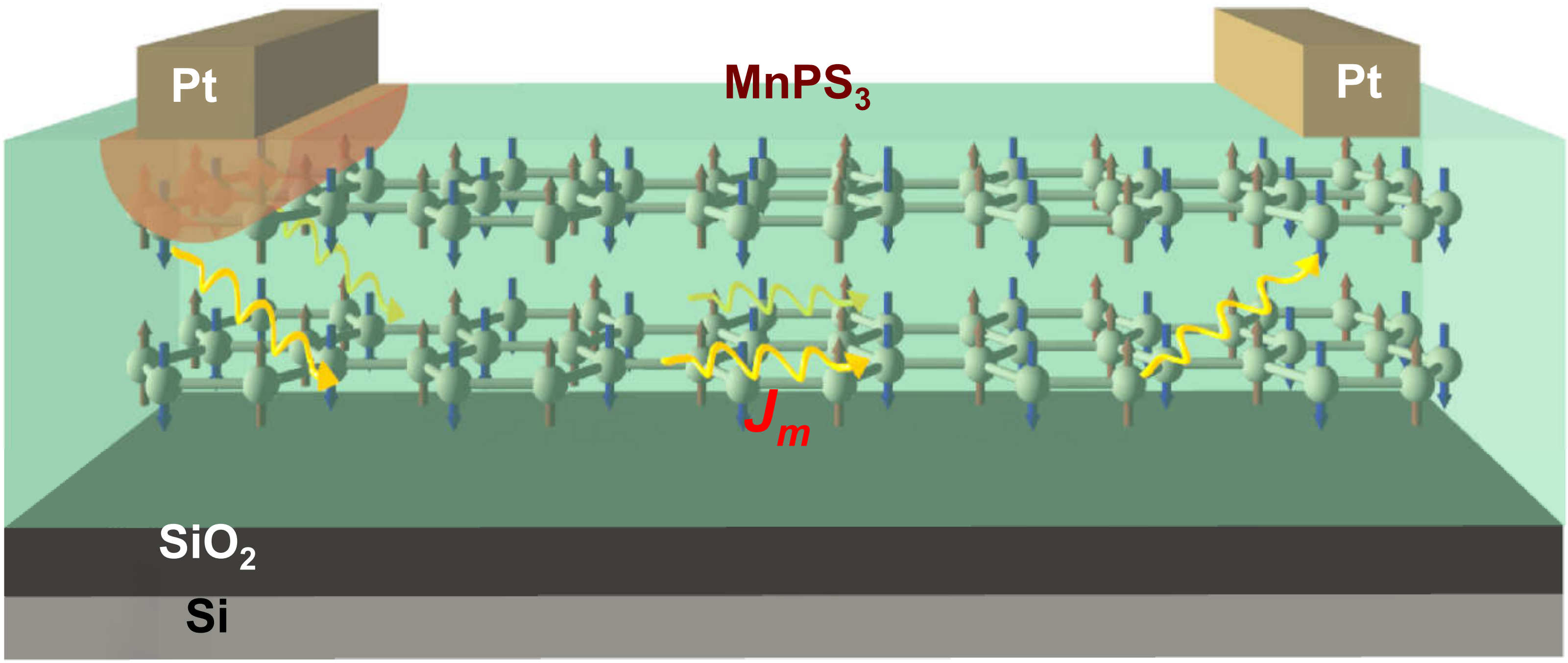




Nonlocal Magnon transport

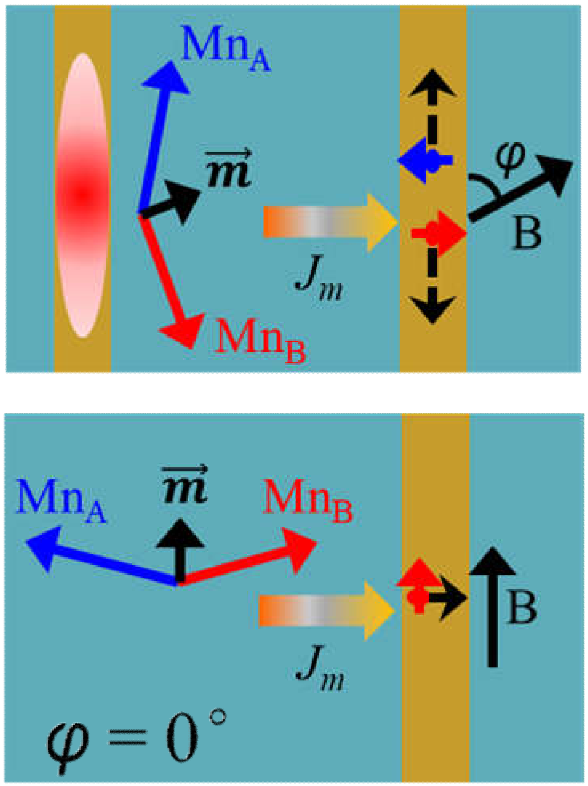
Injector:
Thermal spin injection

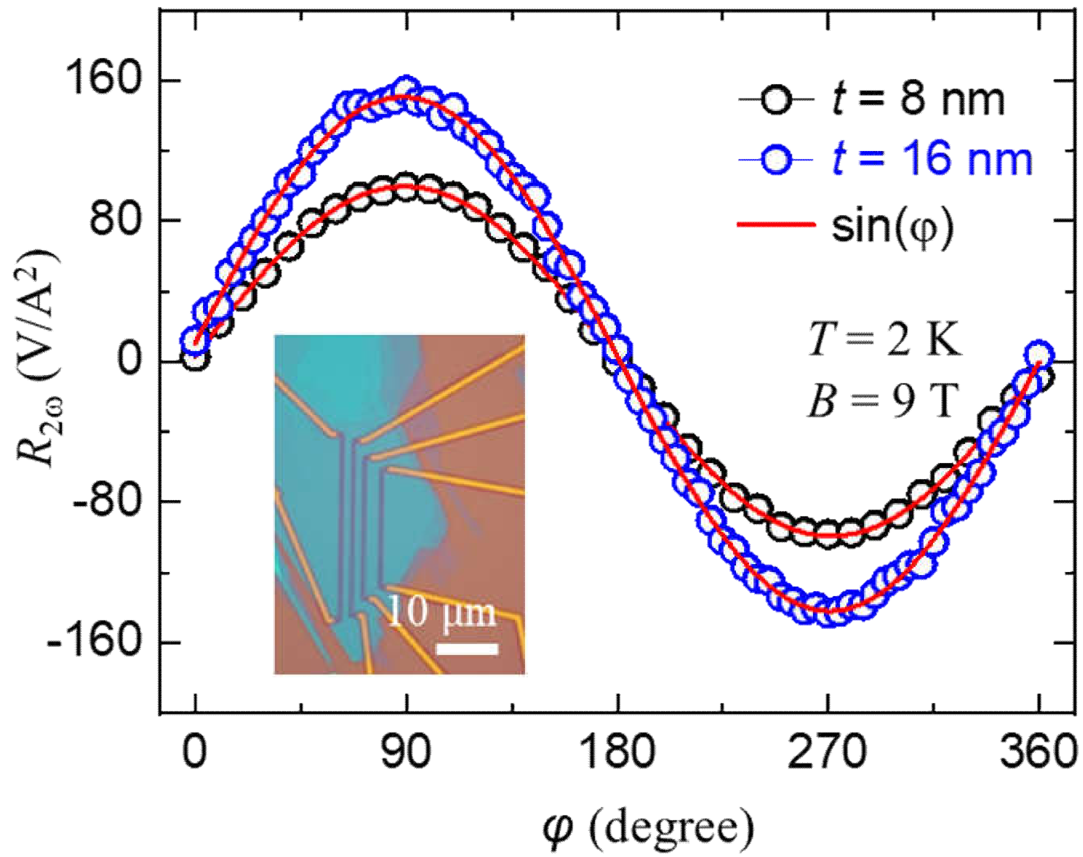
Detector:
Inverse spin Hall effect



Thermal magnons

Magnon transport in 2D $MnPS_3$

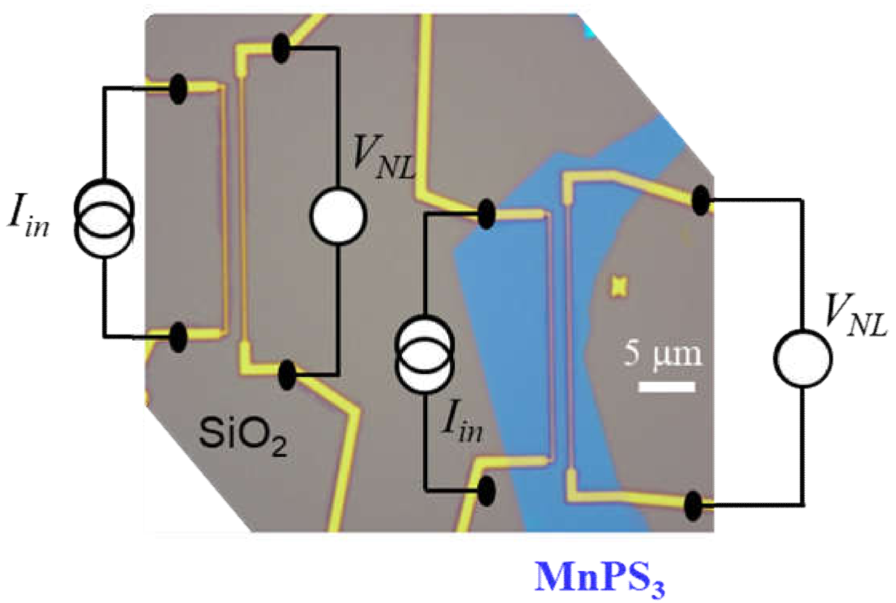


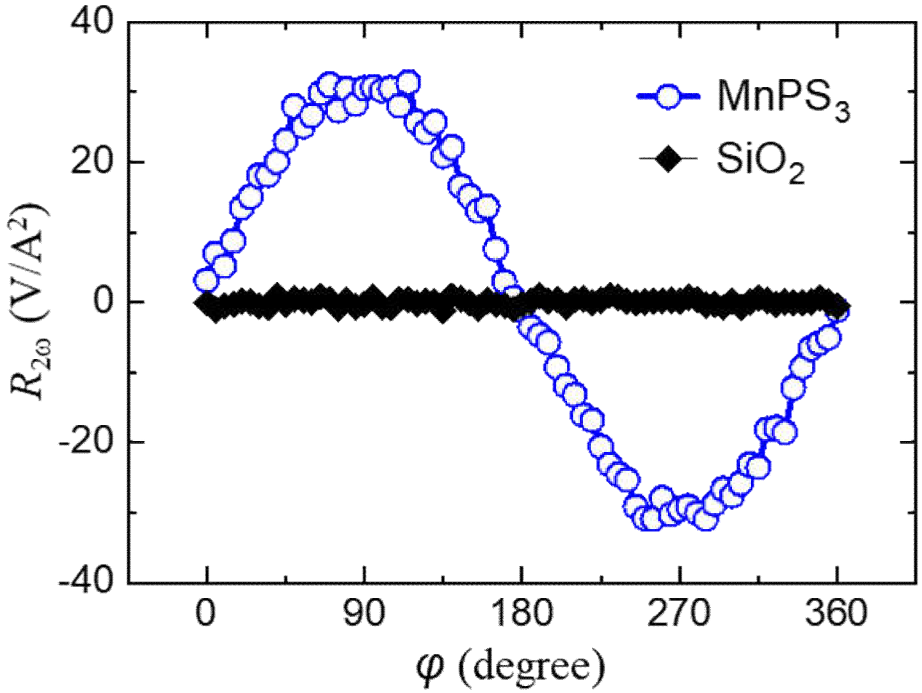


$$R_{2\omega} = R_{\mathrm{NL}} \sin(\varphi)$$

Magnon transport in 2D $MnPS_3$

Control device fabricated on SiO_2/Si substrates

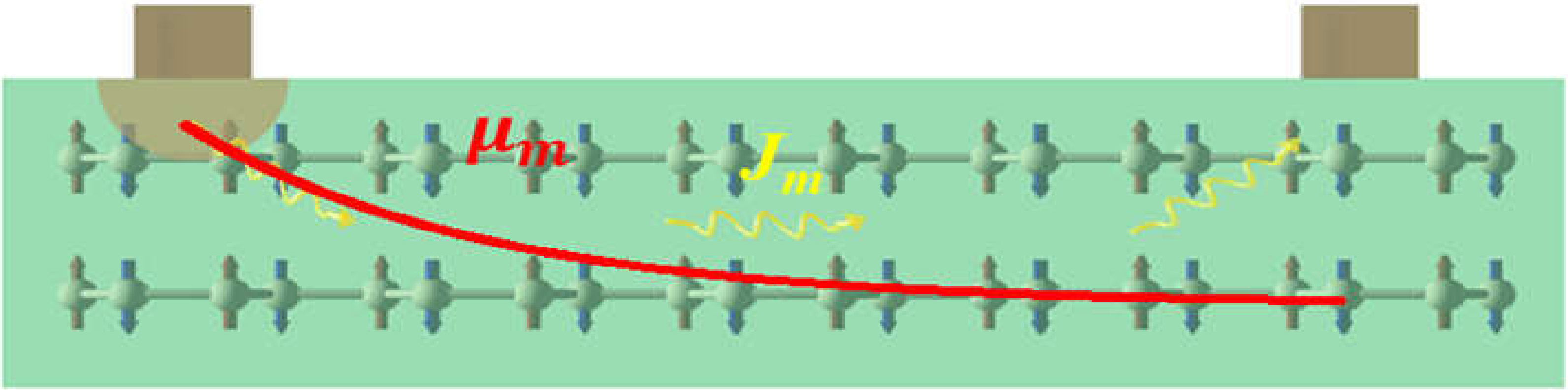


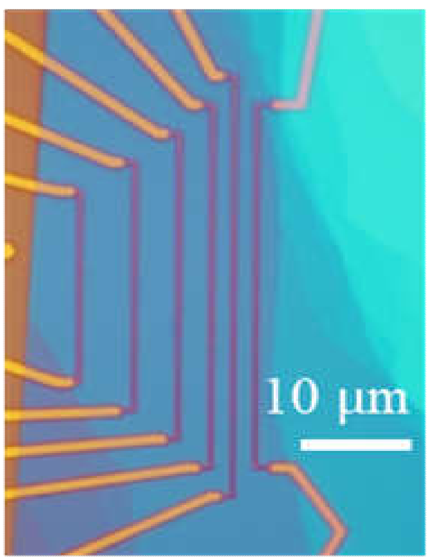


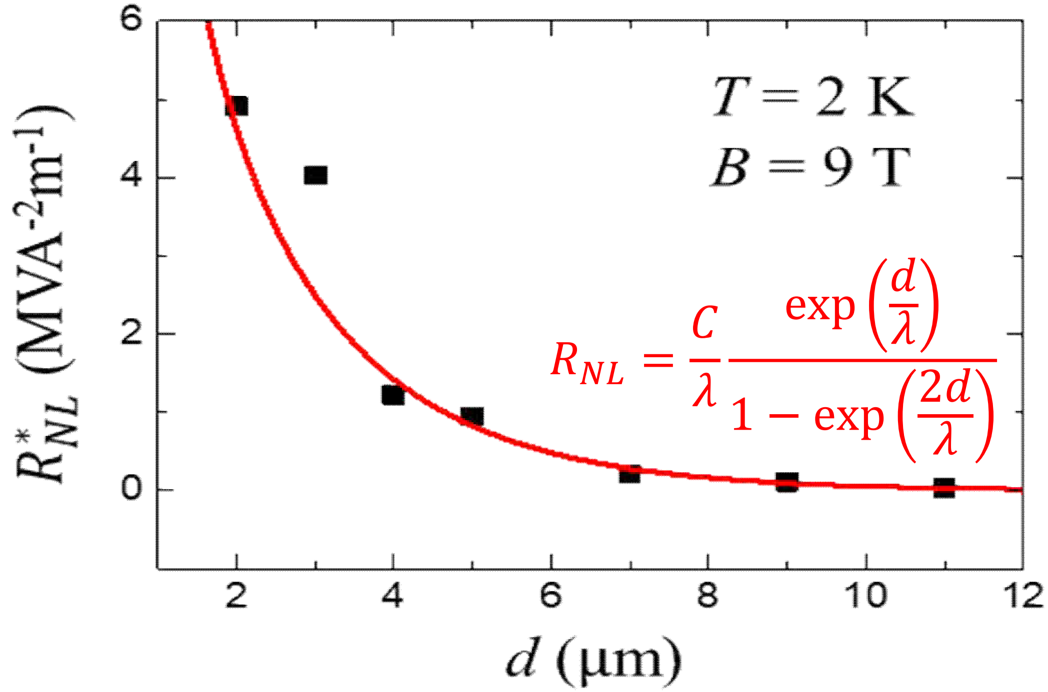
The absence of spin signal on the control device rules out the possibility of signals from the SiO_2/Si substrate.

Magnon transport in 2D $MnPS_3$

Magnon signal – Exponential decay



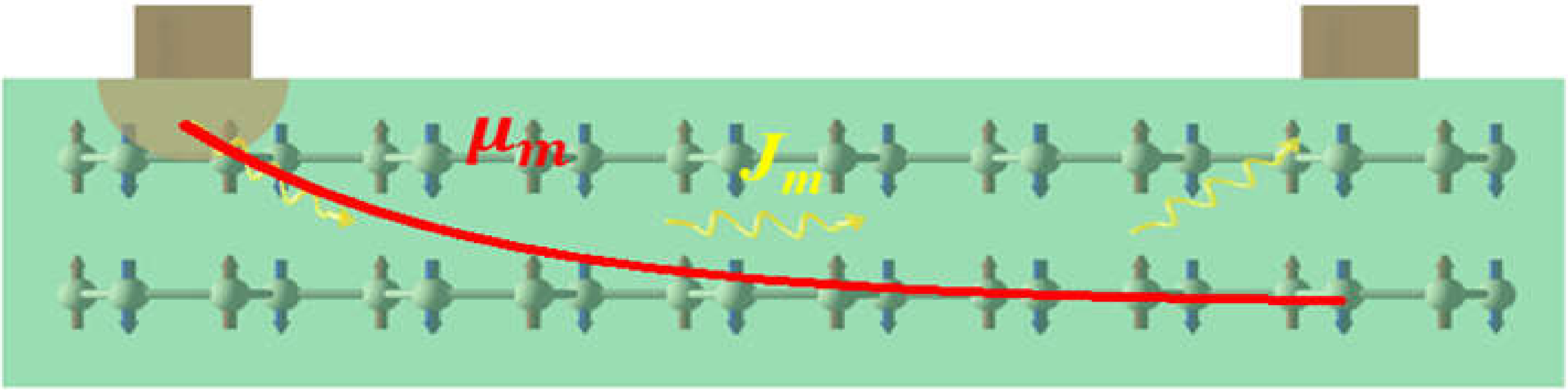


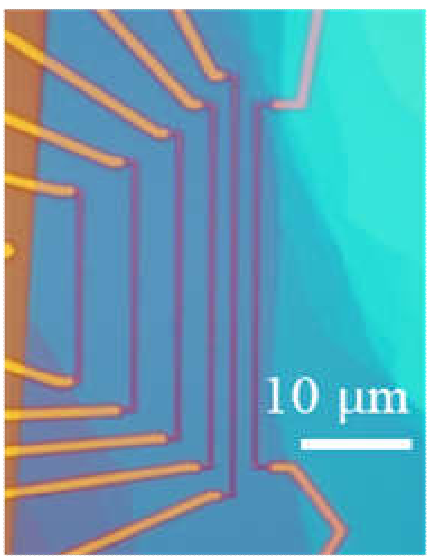


13 nm $MnPS_3$

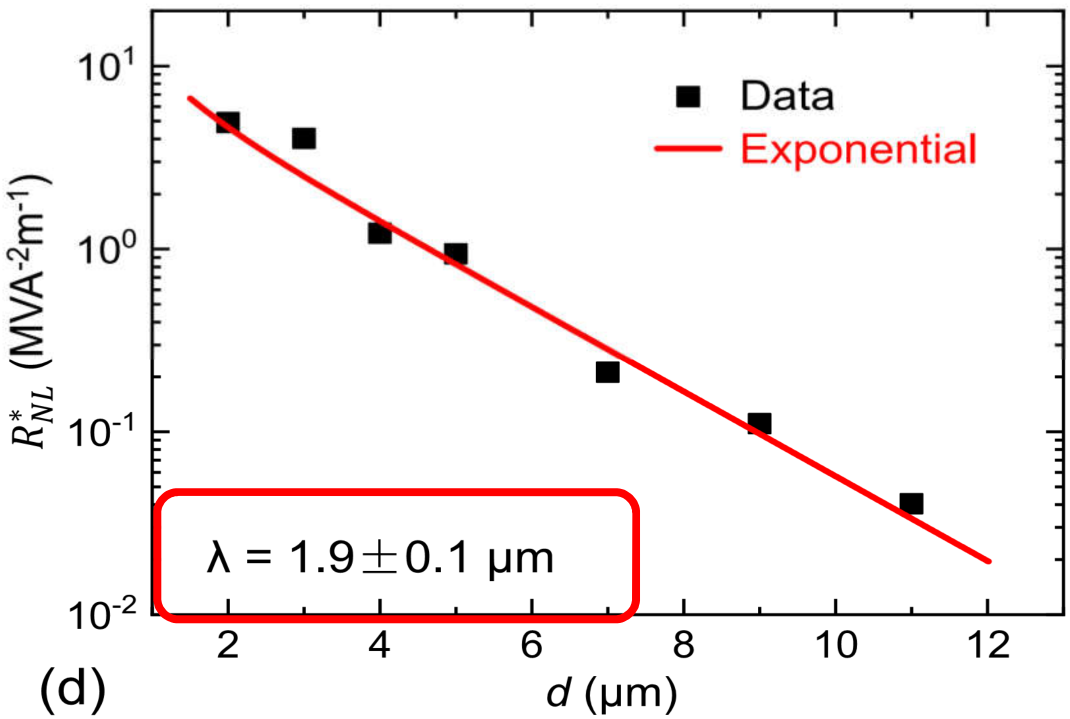
Magnon transport in 2D $MnPS_3$

Magnon signal – Exponential decay





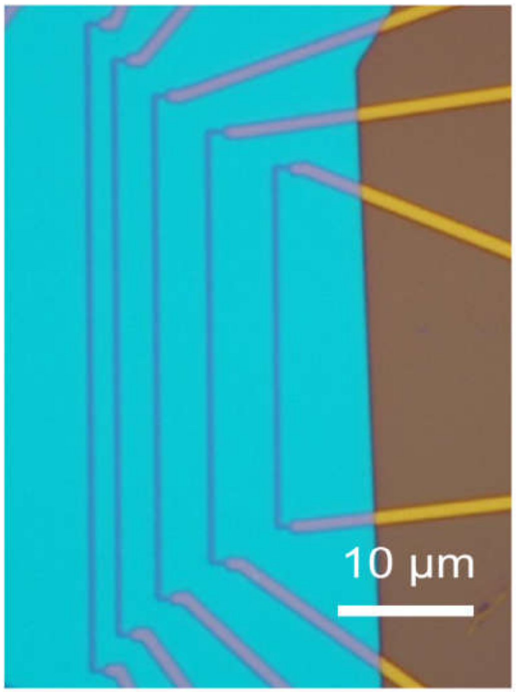
13 nm $MnPS_3$



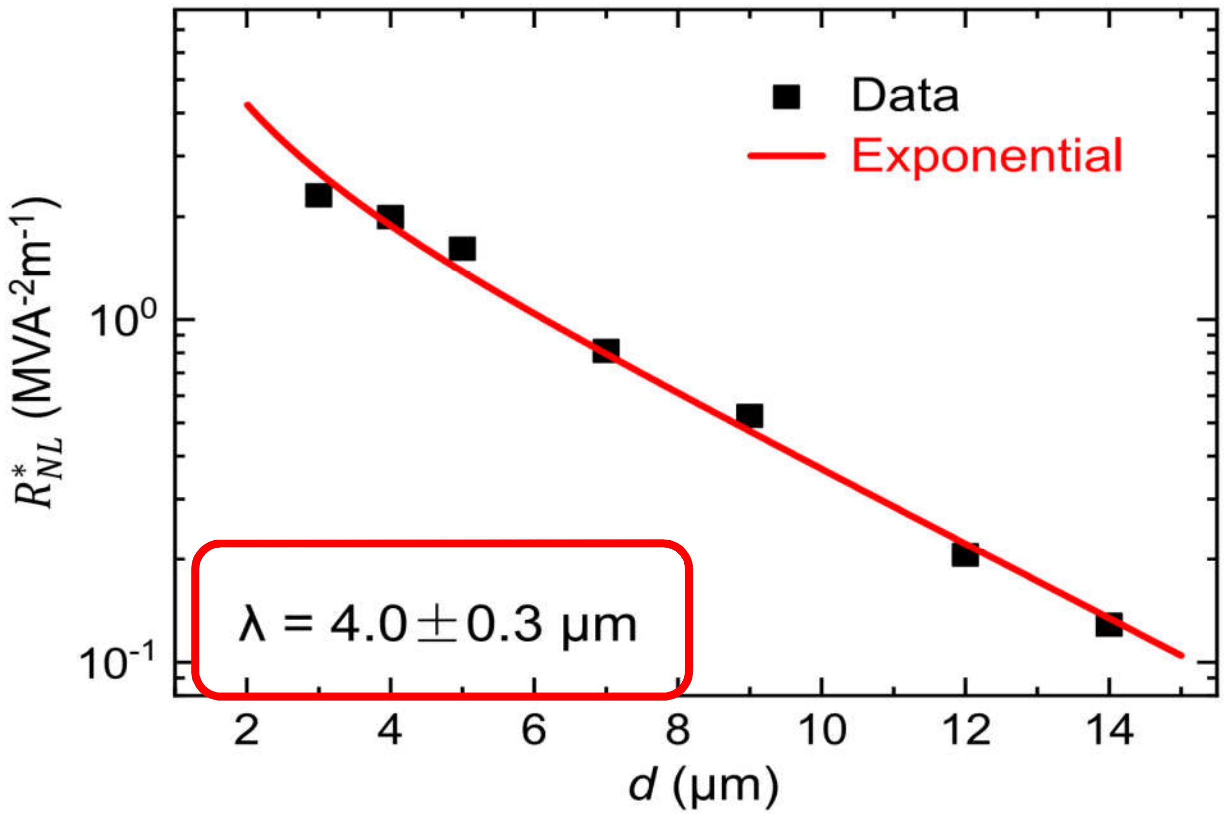
(d)

Magnon transport in 2D $MnPS_3$

Magnon signal – Exponential decay

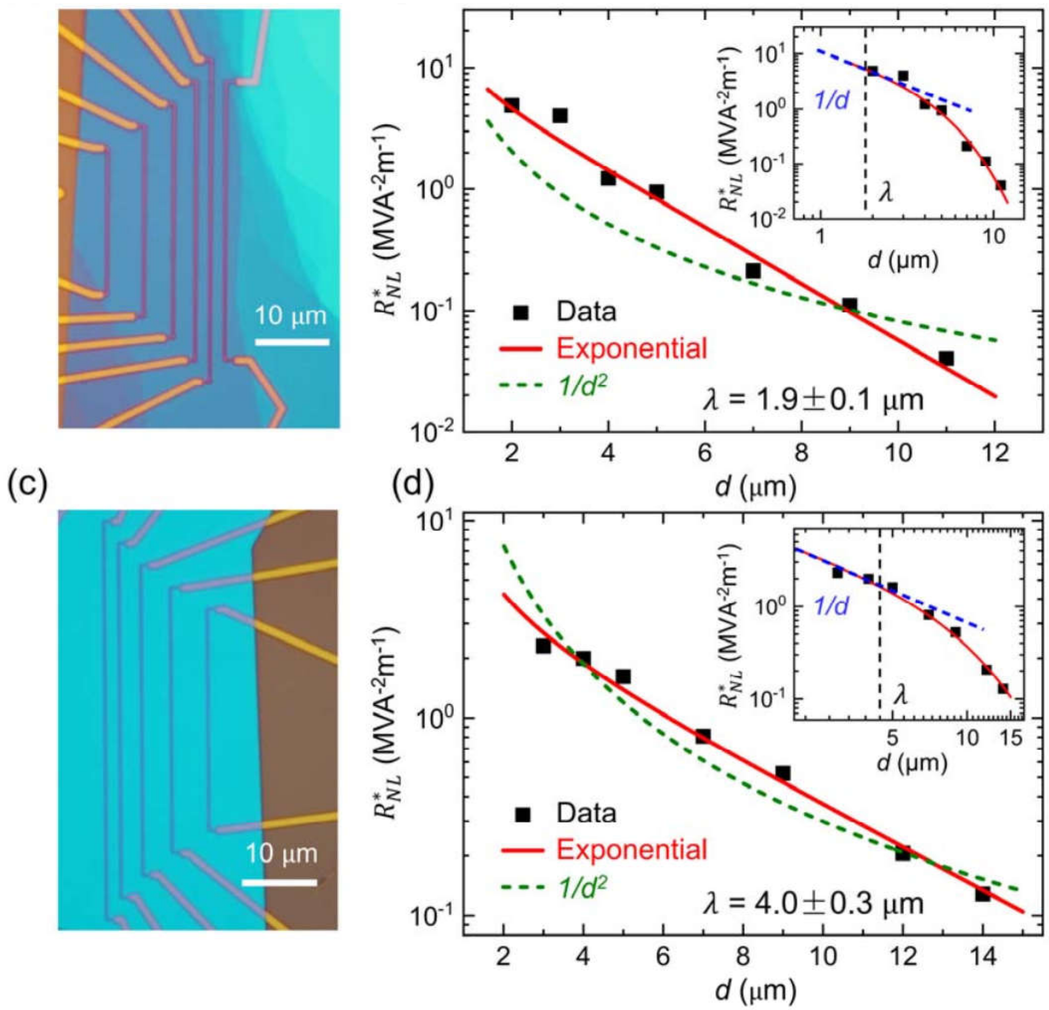


24 nm $MnPS_3$



Magnon transport in 2D $MnPS_3$

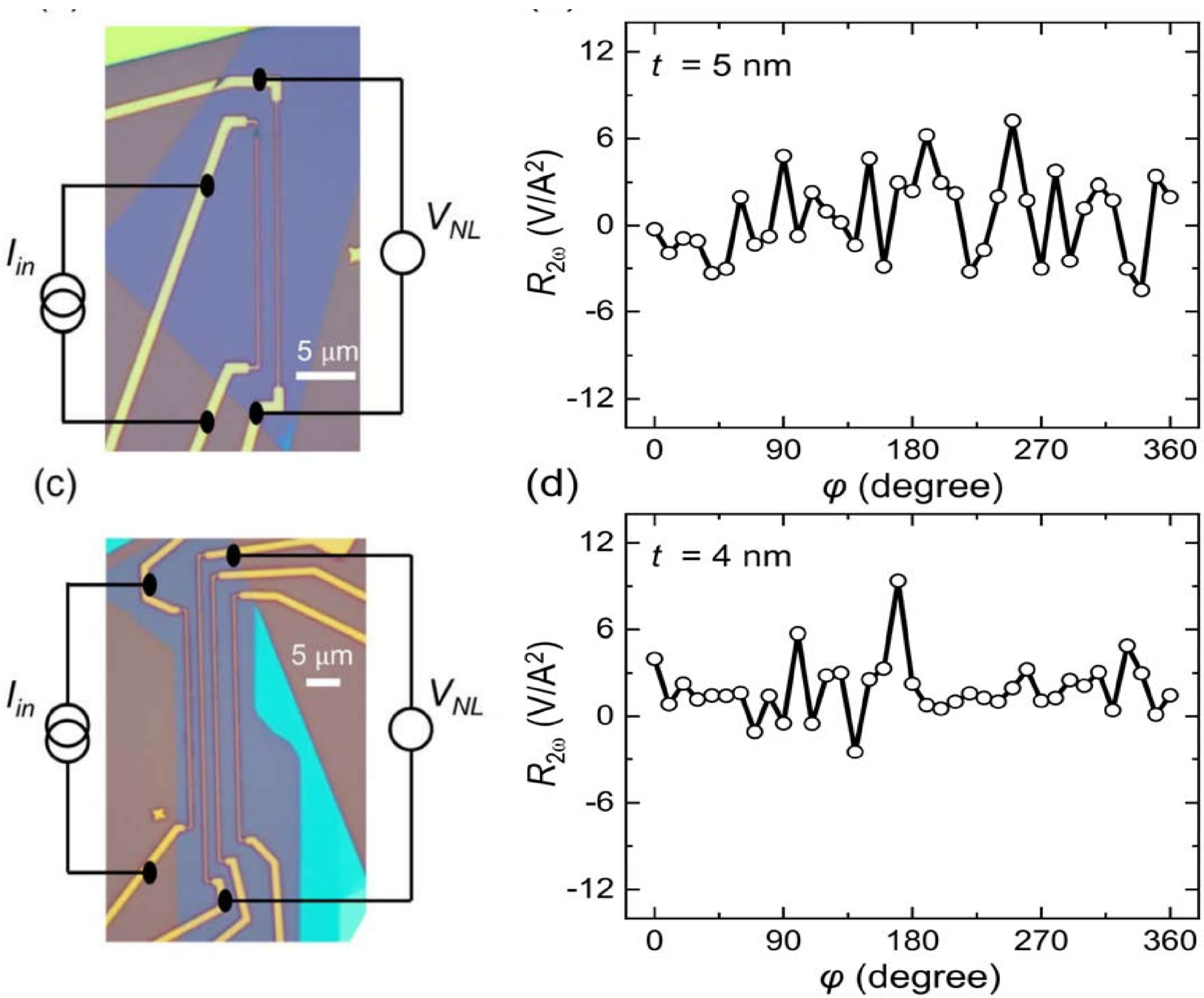
Magnon signal – Exponential decay



The Criteria (exponential vs. $1/d^2$): Shan, et al., PRB (2017)

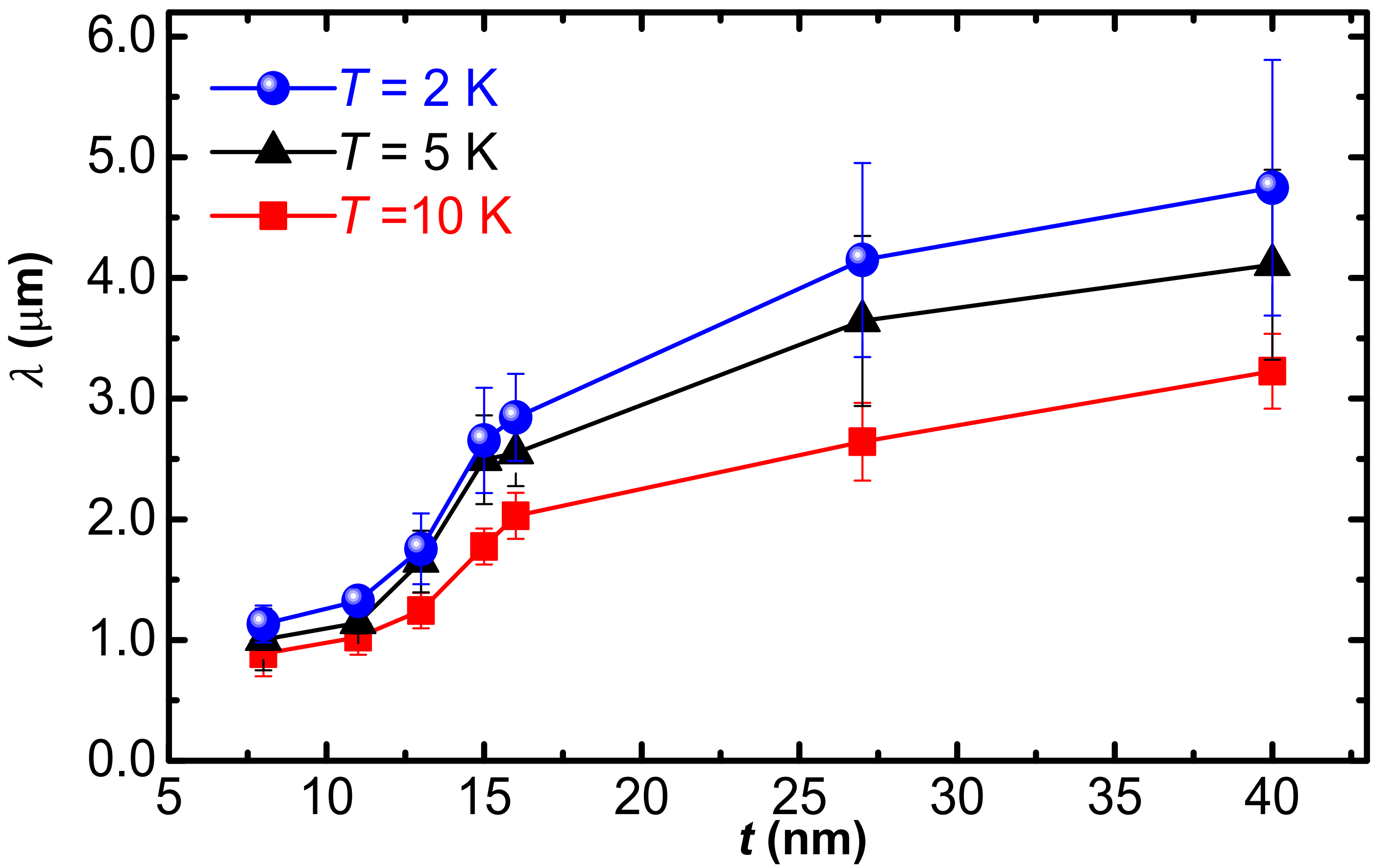
Magnon transport in 2D $MnPS_3$

Absence of magnon signals in thin $MnPS_3$



Magnon transport in 2D $MnPS_3$

Magnon relaxation length in 2D $MnPS_3$

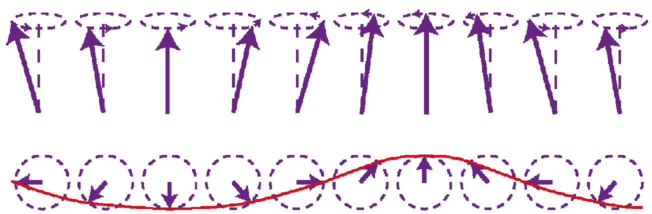


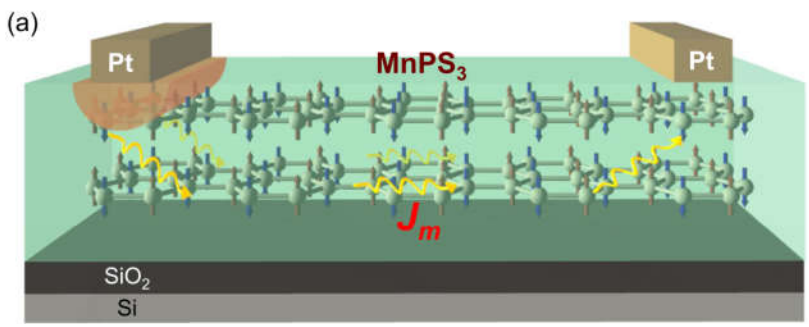
Wenyu Xing

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

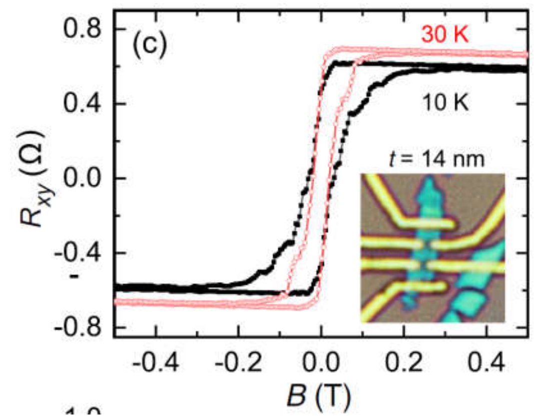
This Talk: Spin Transport in 2D Magnets

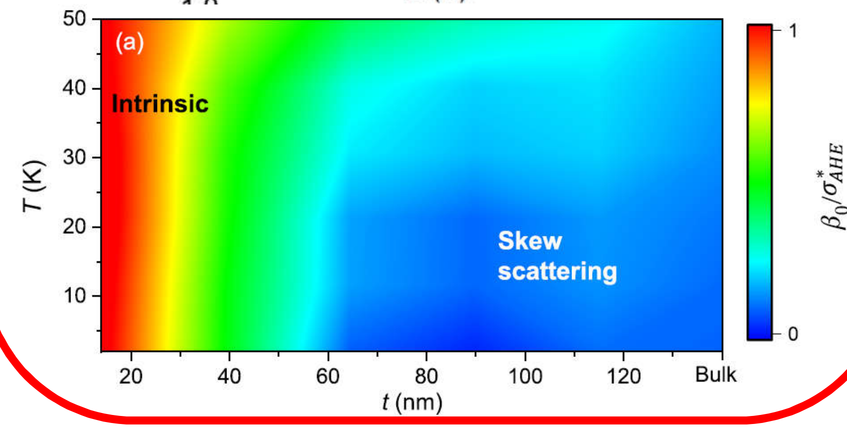
Magnon spin transport in **Insulating** $MnPS_3$ Flakes





Electron spin Transport in **Metallic** $FeTaS_2$ Flakes



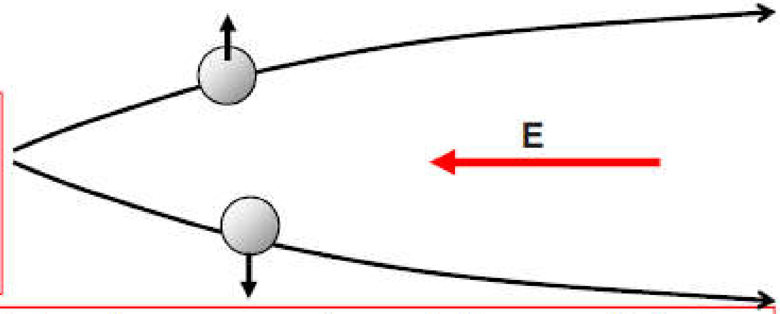


Electron spin scattering in metallic $FeTaS_2$ flakes

Anomalous Hall effect Mechanisms in FM

a) Intrinsic deflection

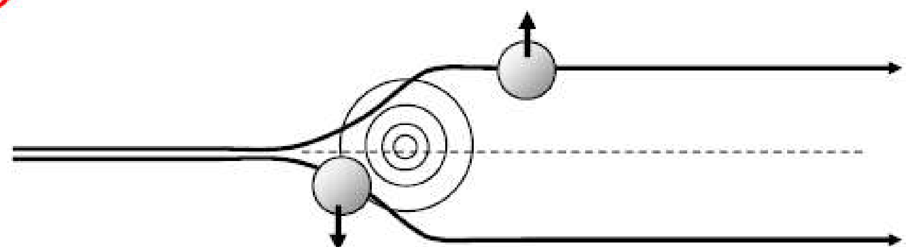
Interband coherence induced by an external electric field gives rise to a velocity contribution perpendicular to the field direction. These currents do not sum to zero in ferromagnets.



$$\frac{d\langle\vec{r}\rangle}{dt} = \frac{\partial E}{\hbar\partial\vec{k}} + \frac{e}{\hbar} E \times b_n$$

Electrons have an anomalous velocity perpendicular to the electric field related to their Berry's phase curvature

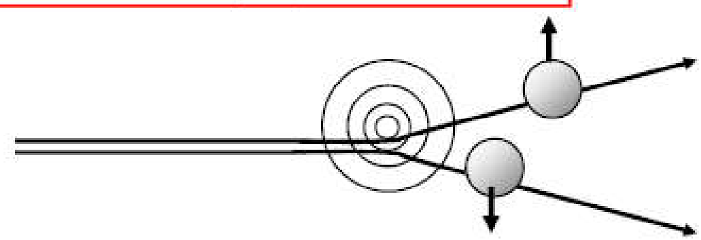
b) Side jump



The electron velocity is deflected in opposite directions by the opposite electric fields experienced upon approaching and leaving an impurity. The time-integrated velocity deflection is the side jump.

c) Skew scattering

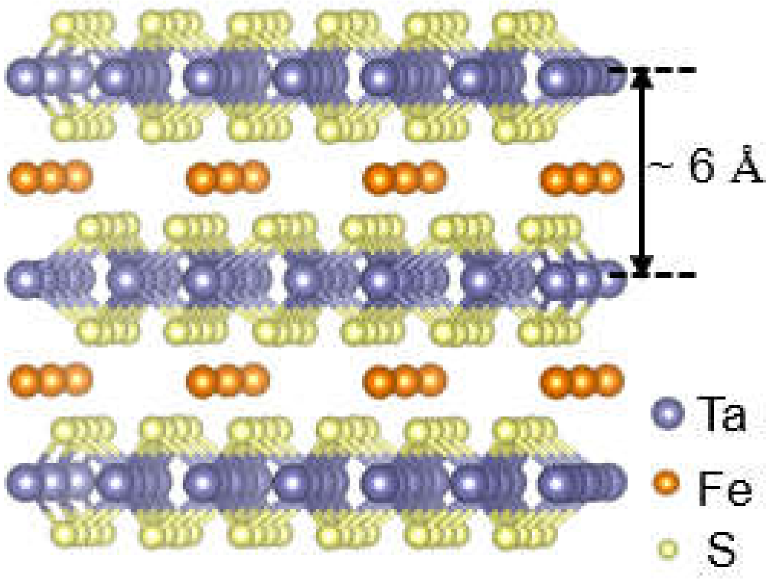
Asymmetric scattering due to the effective spin-orbit coupling of the electron or the impurity.



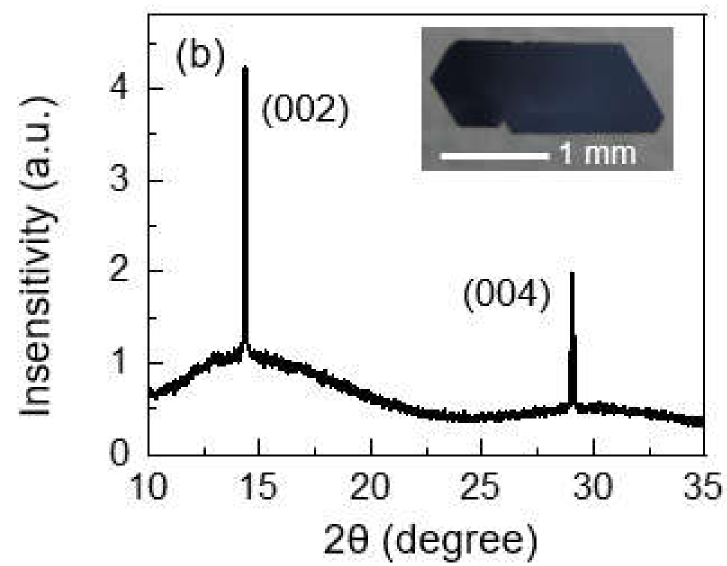
Nagaosa, et.al., Rev. Mod. Phys. (2010)

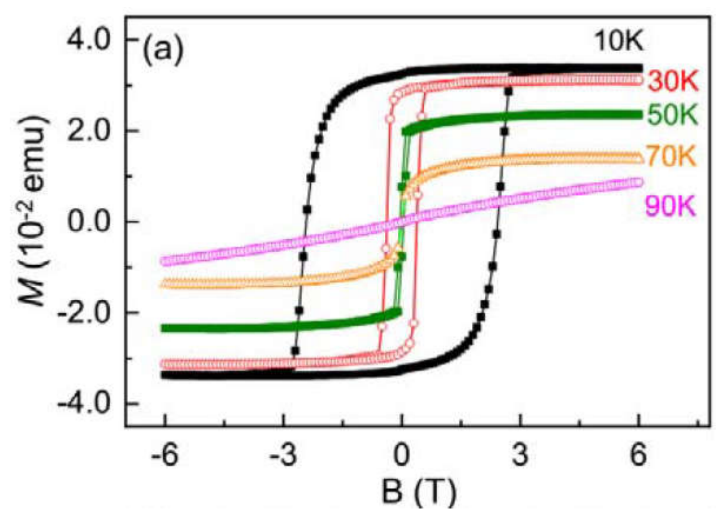
Electron spin Transport in Metallic $FeTaS_2$ Flakes

Layered $FeTaS_2$



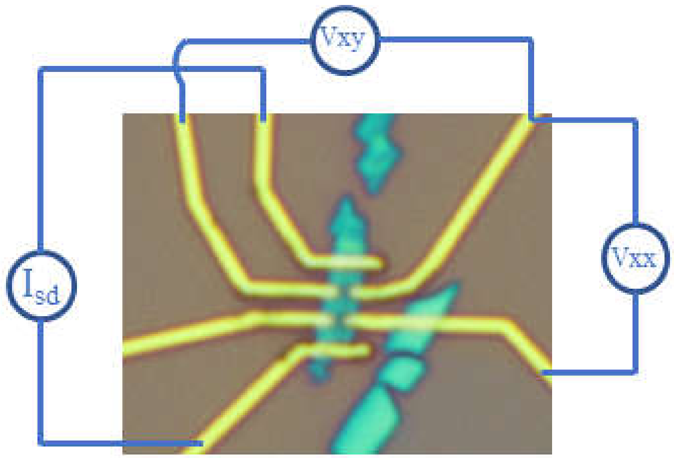
$Fe_{0.29}TaS_2$

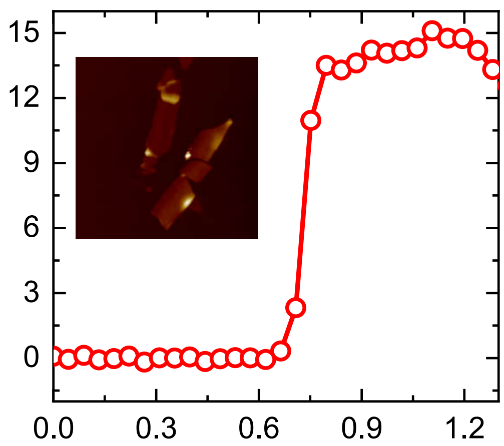


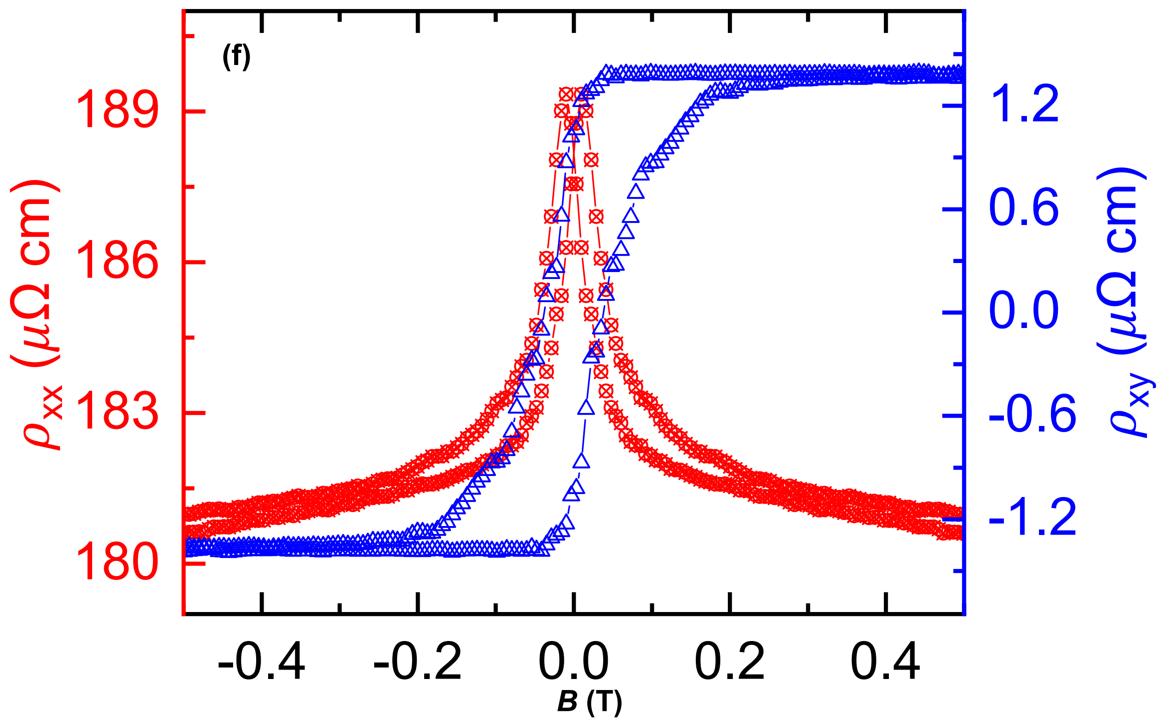


Anomalous Hall resistance in 2D $Fe_{0.29}TaS_2$

Device fabrication and AHE measurement

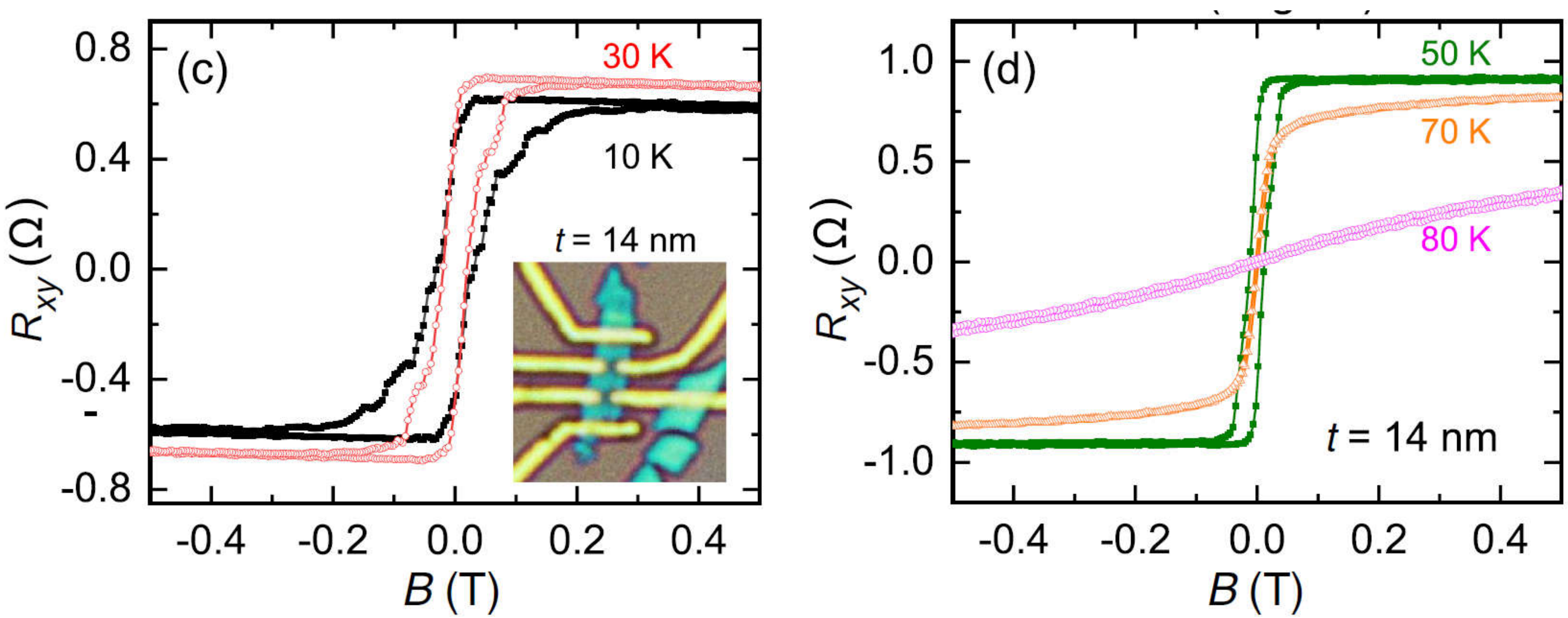






Anomalous Hall resistance in 2D $Fe_{0.29}TaS_2$

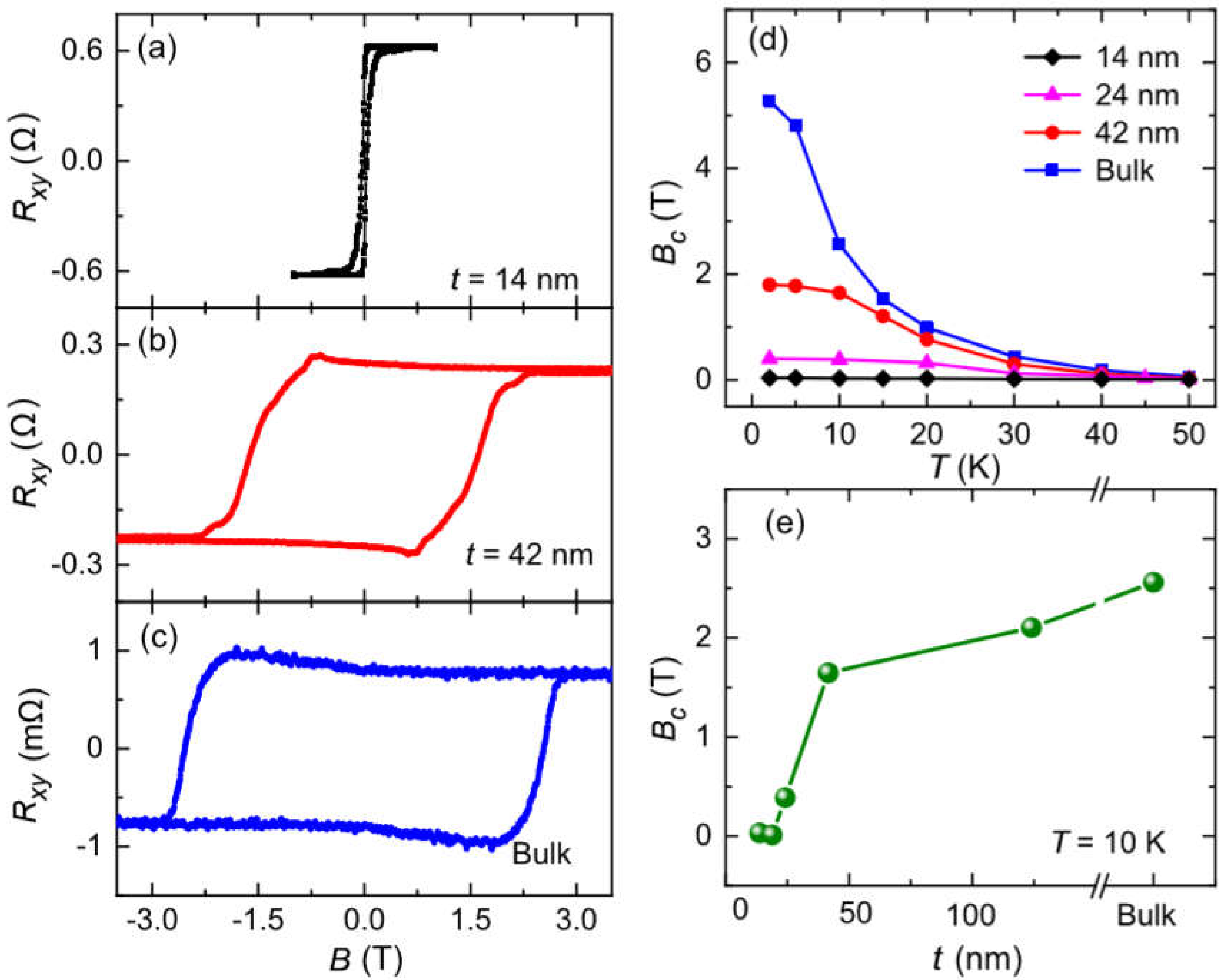
Device fabrication and AHE measurement



T_C ~ 80 K, similar to bulk

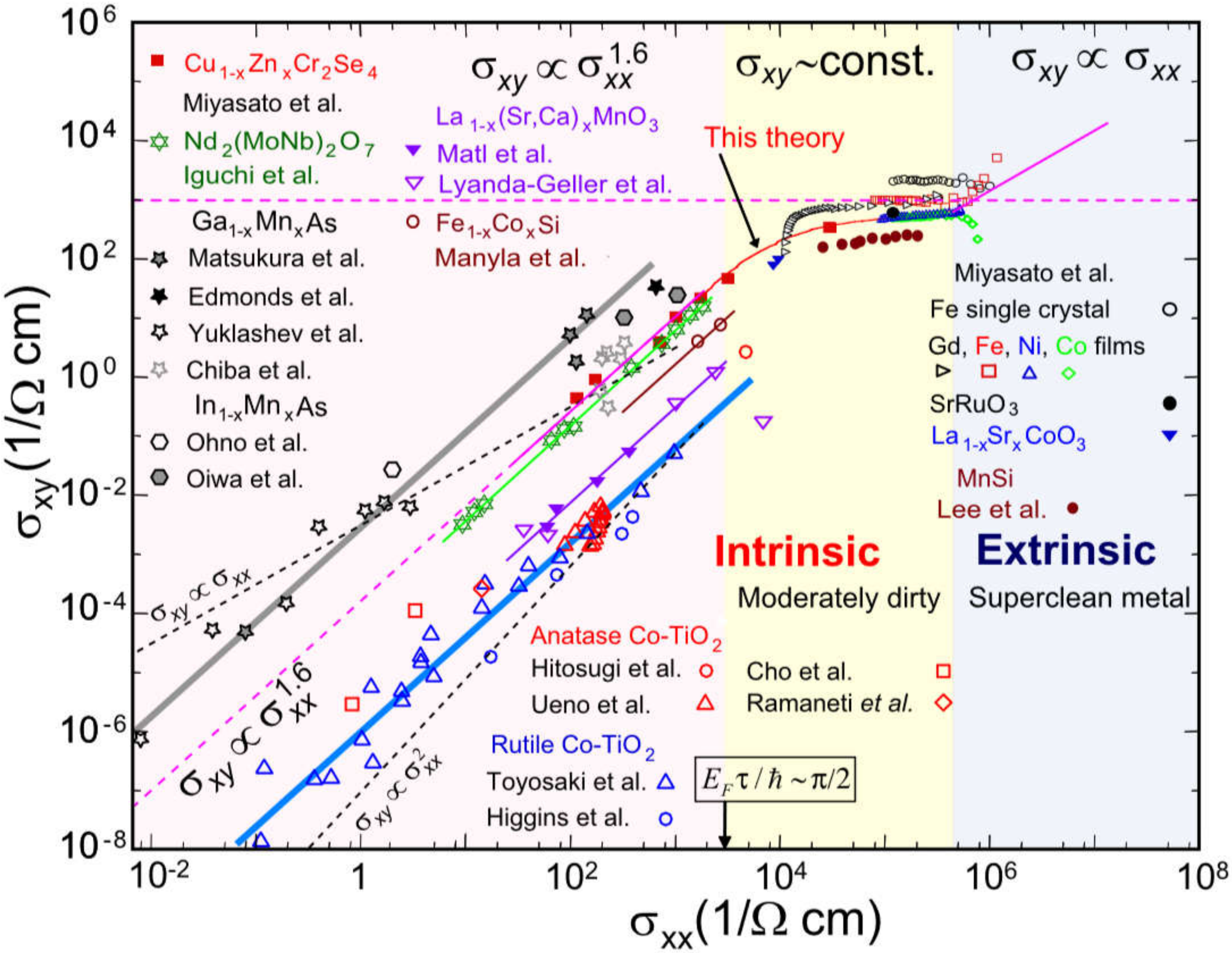
Anomalous Hall resistance in 2D $Fe_{0.29}TaS_2$

Thickness dependence of B_c of $Fe_{0.29}TaS_2$



Anomalous Hall mechanism in FM

Scaling relationship

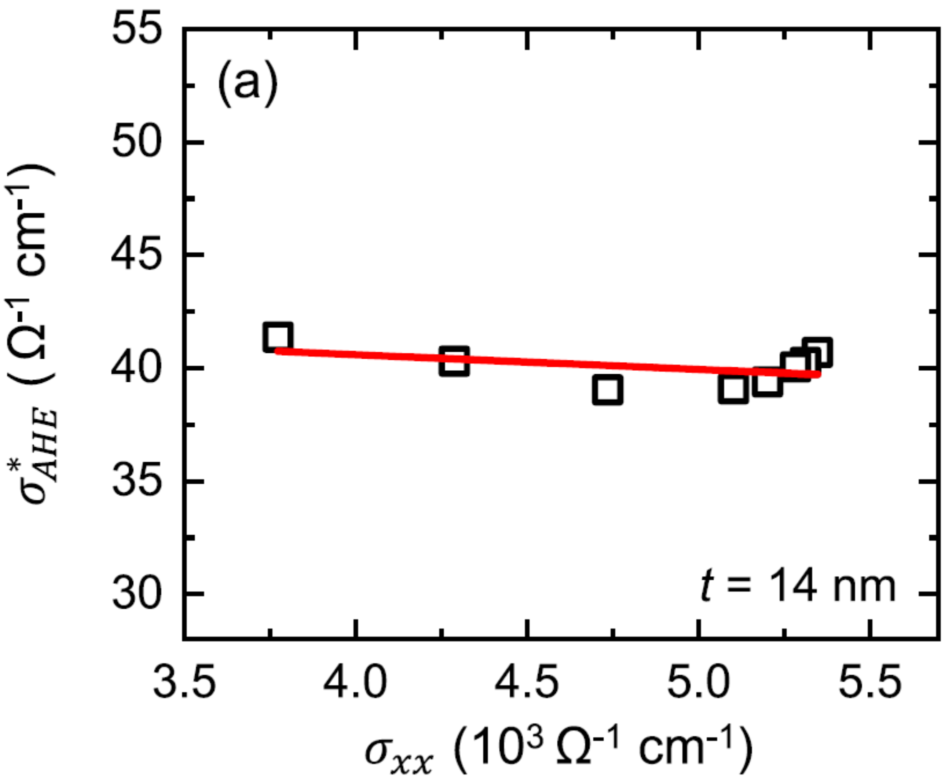


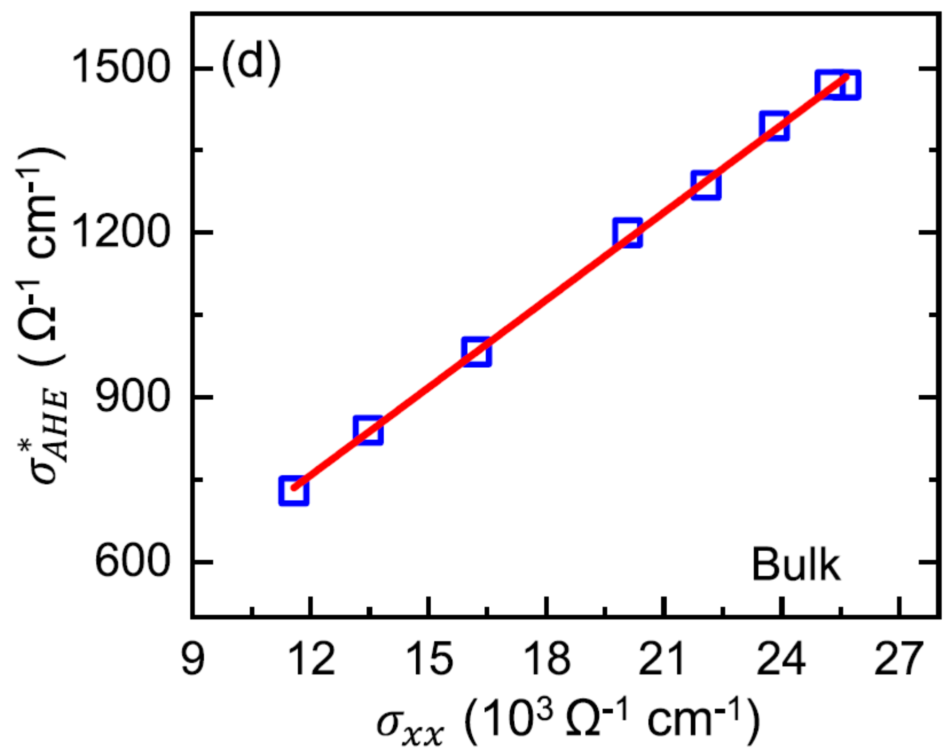
Nagaosa, et.al., Rev. Mod. Phys. (2010); Onoda, et.al., Phys. Rev. B. (2008)

Anomalous Hall mechanism in 2D $Fe_{0.29}TaS_2$

Scaling relationship

$$\sigma^*_{AHE} = \sigma_{AHE}/M = \alpha_0\sigma_{xx} + \beta_0{}^*$$





$\sigma^*_{AHE} \sim const$:

Intrinsic AHE

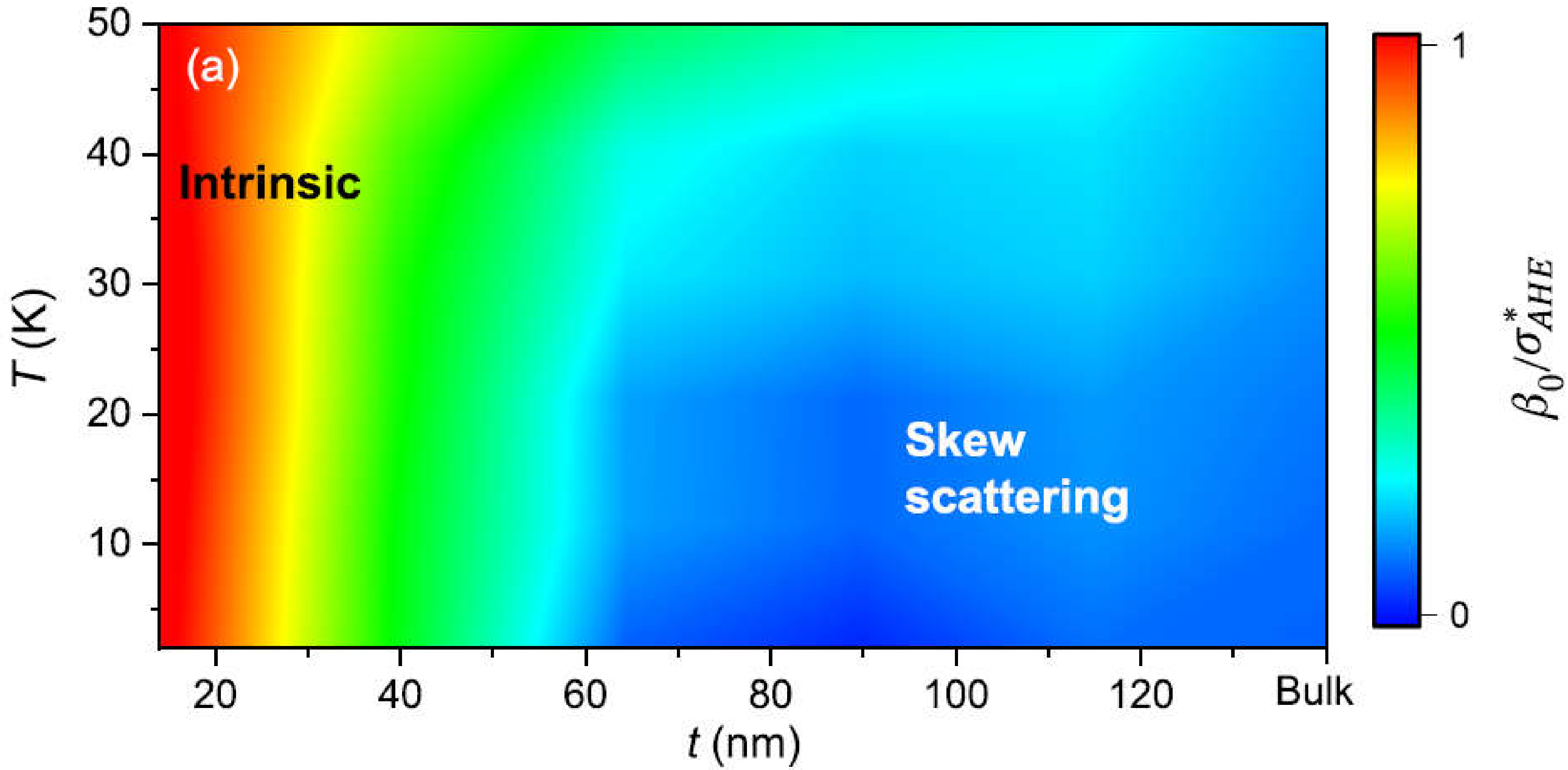
$\sigma^*_{AHE} \propto \sigma_{xx}$:

skew scattering

Anomalous Hall mechanism in 2D $Fe_{0.29}TaS_2$

Thickness dependent AHE Mechanisms

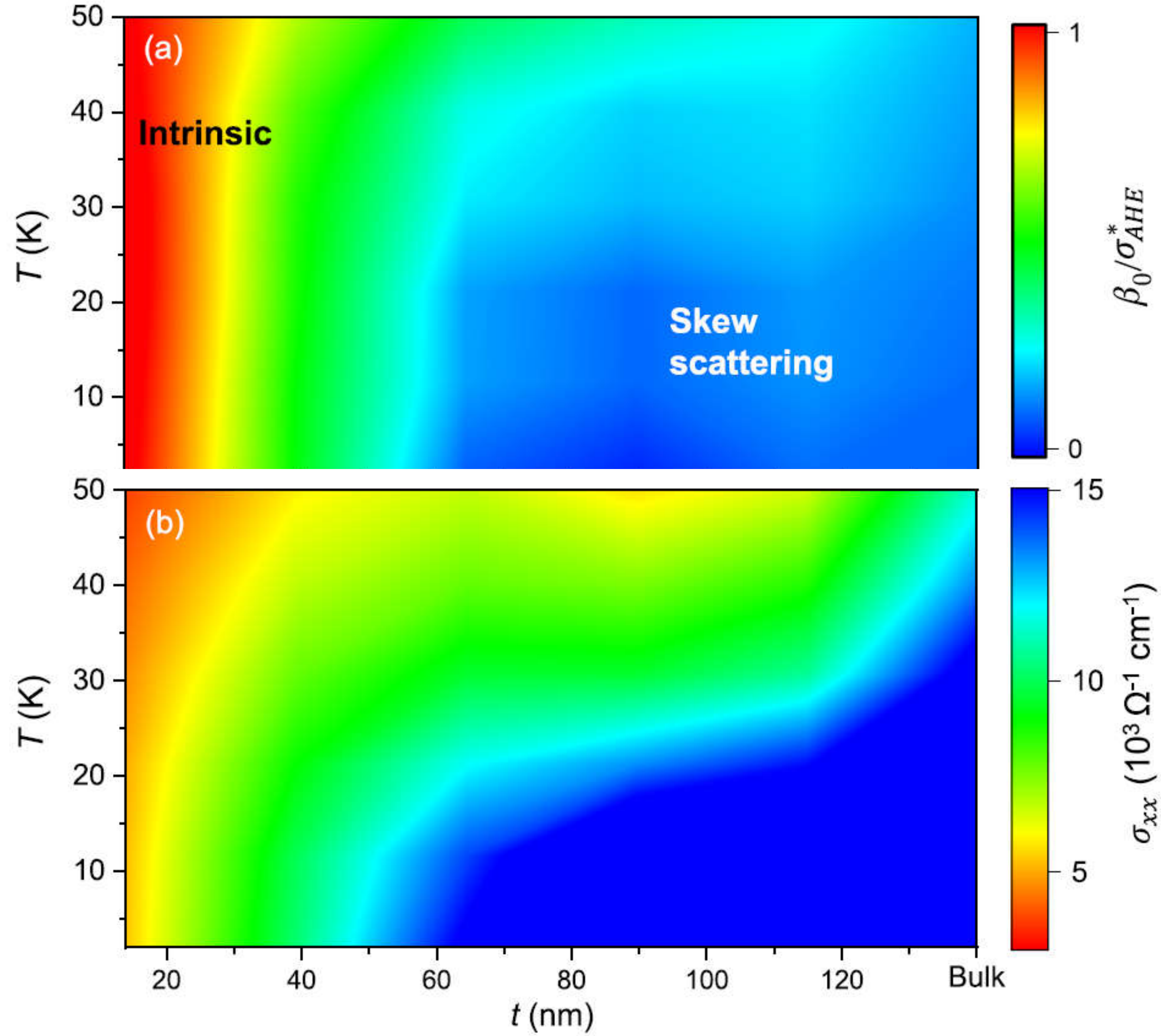
$$\sigma^*_{AHE} = \alpha_0 \sigma_{xx} + \beta_0{}^*$$



Anomalous Hall mechanism in 2D $Fe_{0.29}TaS_2$

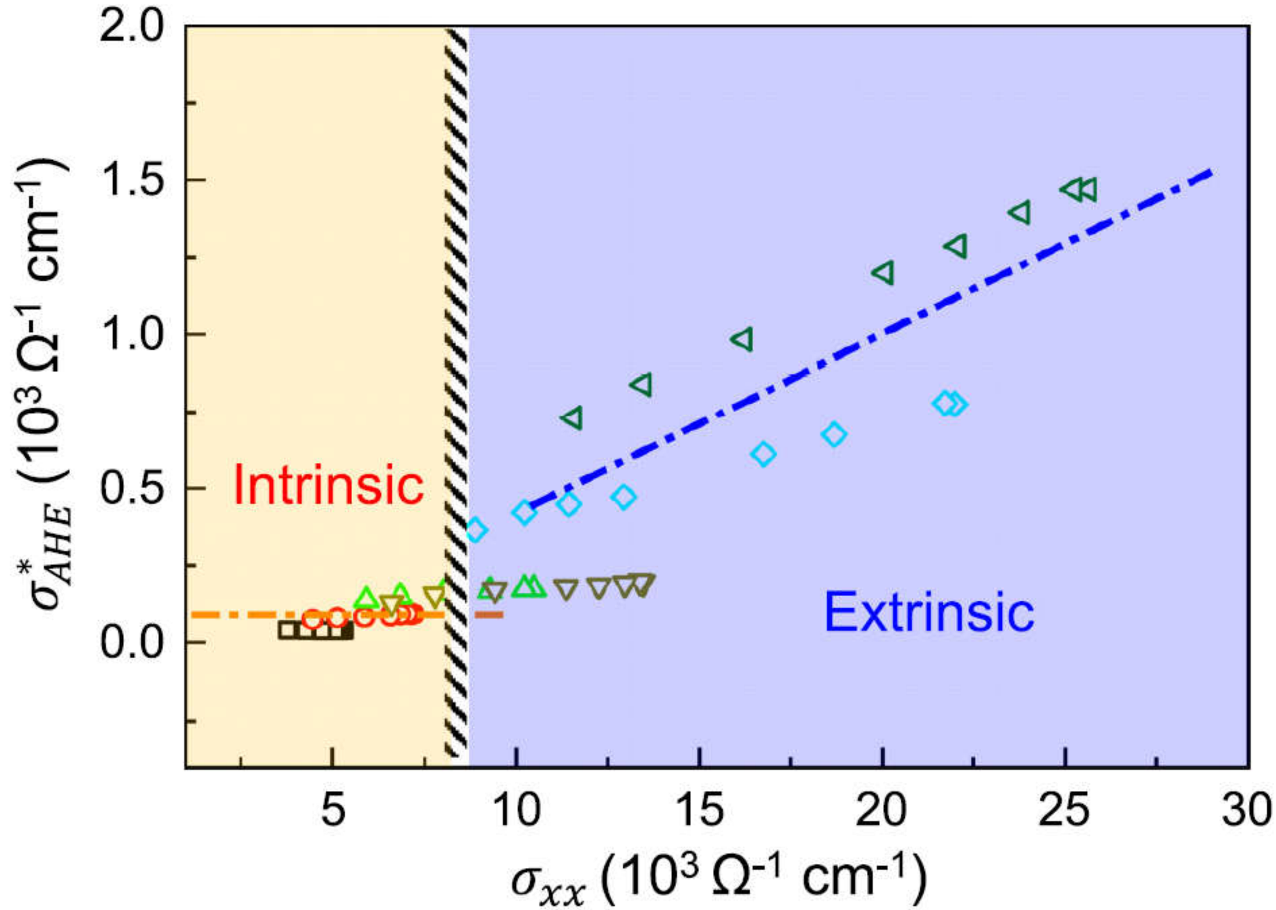
AHE Mechanisms *vs.* Channel conductivity

$$\sigma^*_{AHE} = \alpha_0\sigma_{xx} + \beta_0{}^*$$



Anomalous Hall mechanism in 2D $Fe_{0.29}TaS_2$

AHE Mechanisms *vs.* Channel conductivity

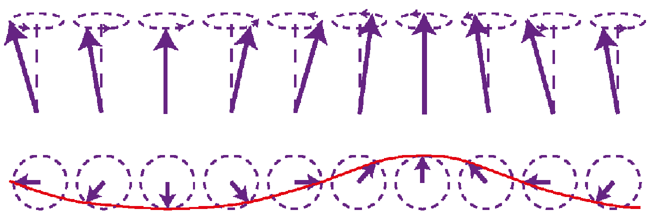


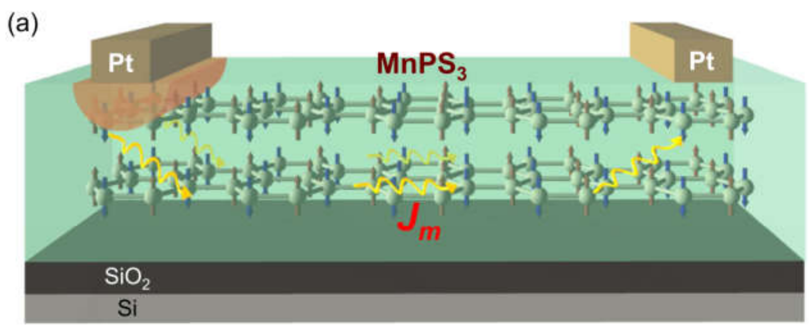
Ranran Cai

R. Cai, W. Xing, H. Zhou, B. Li, Y. Chen, Y. Yao, Y. Ma, X. C. Xie, S. Jia, and W. Han*, **Physical Review B, 100, 054430 (2019)**

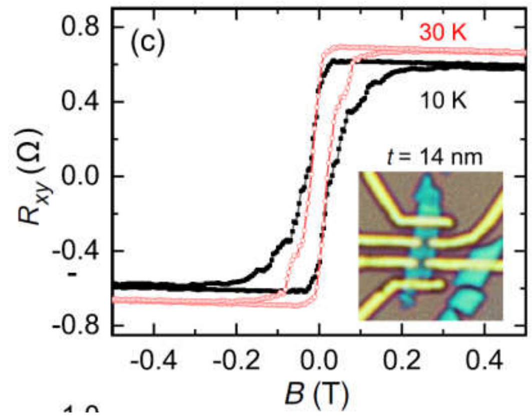
Summary: Spin Transport in 2D Magnets

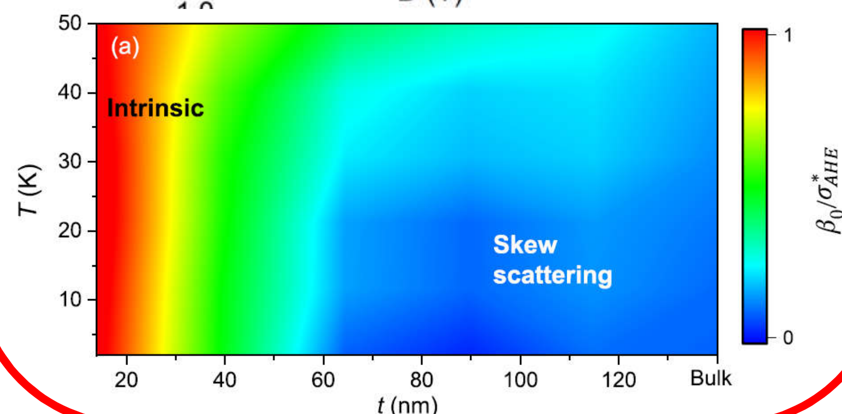
Magnon spin transport in **Insulating** $MnPS_3$ Flakes





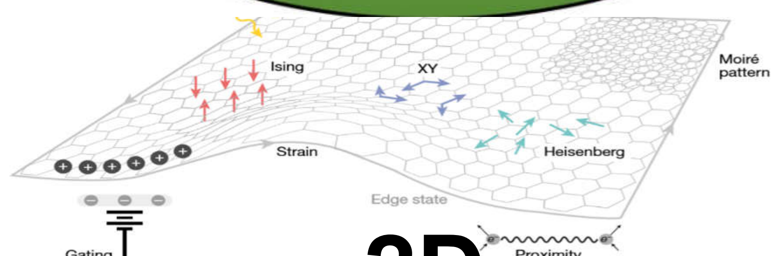
Electron spin scattering in **Metallic** $FeTaS_2$ Flakes





Outlook: Spin Transport in 2D Magnets

Quasi 2D



2D

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Wenyu Xing

Ranran Cai

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