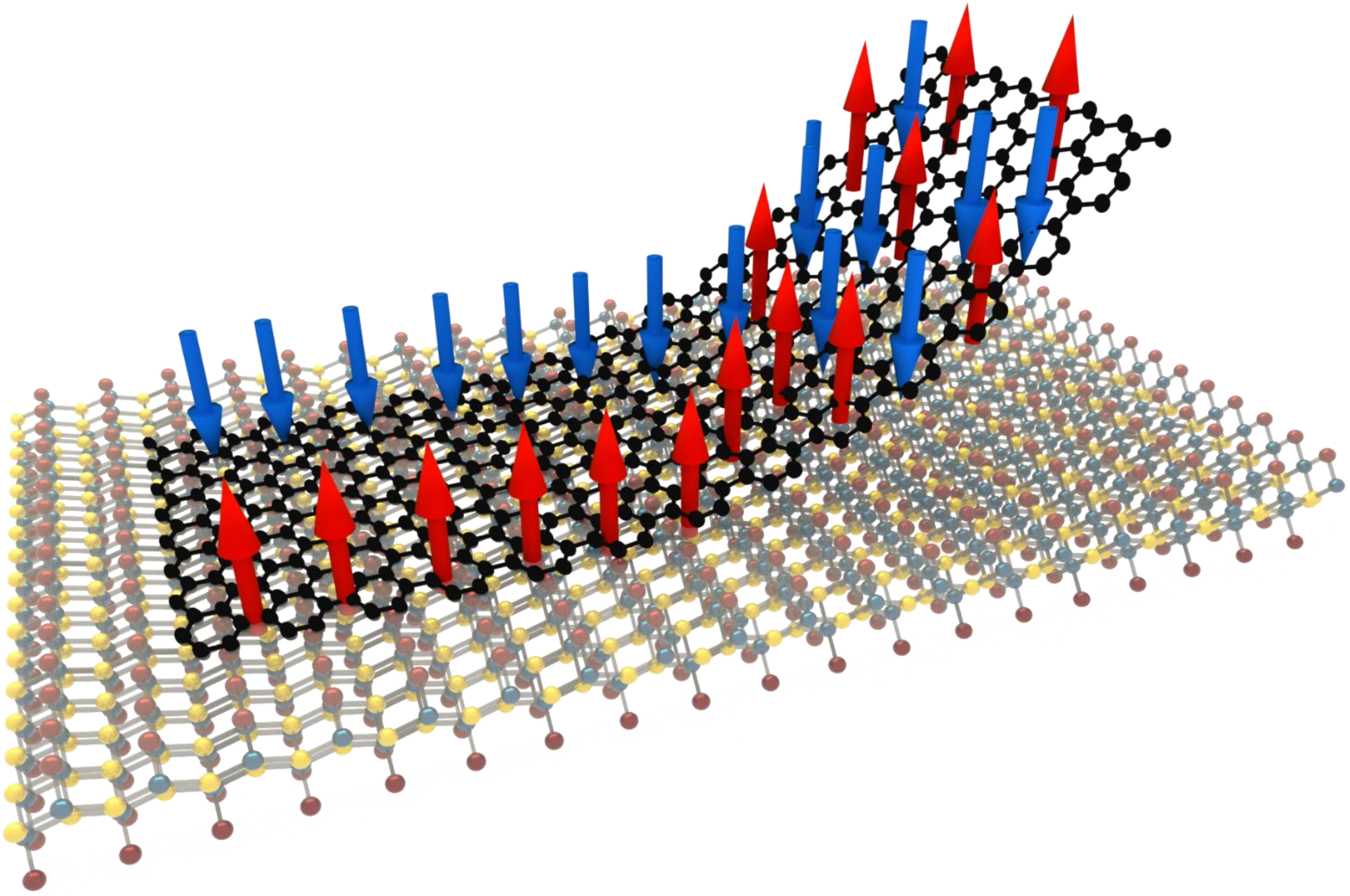
Graphene-based magnetic heterostructures for spintronic devices

Talieh Ghiasi

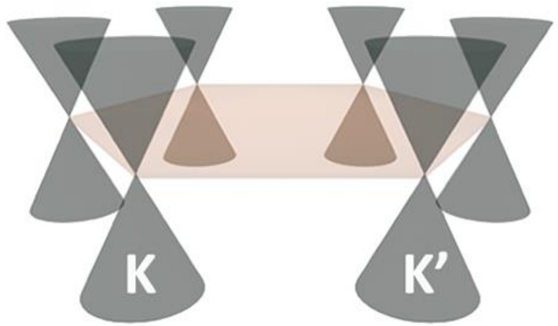
HARVARD UNIVERSITY

Delft University of Technology

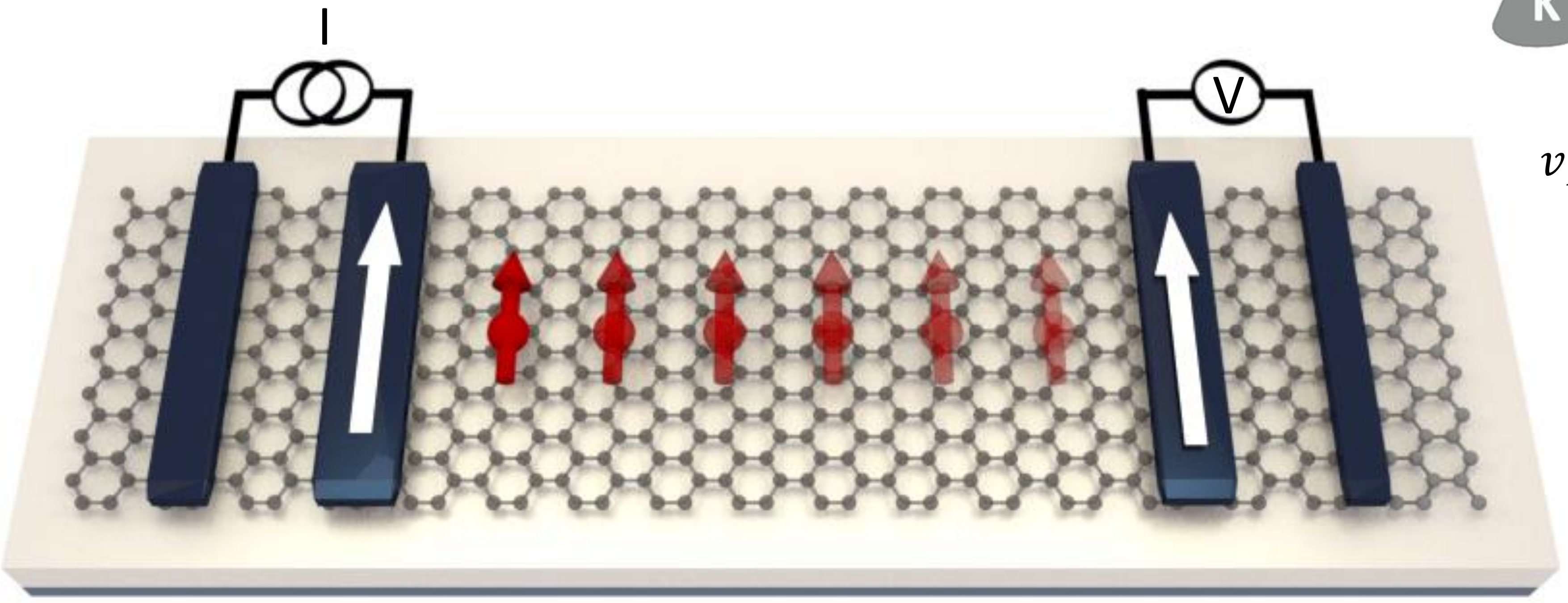
University of Groningen



Spintronic devices



$$E = \hbar v_F k$$
$$v_F = 10^6 \text{ m/s}$$



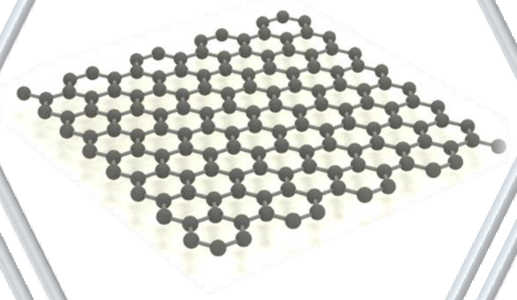
Injection Transport Detection

spin relaxation length $\sim 30\ \mu m$

M. Drögeler, et al. *Nano letters* 16. 3533 (2016)

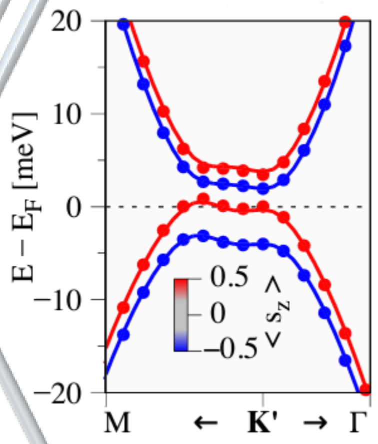
Tailoring graphene band structure

Gr



Spin-orbit coupling

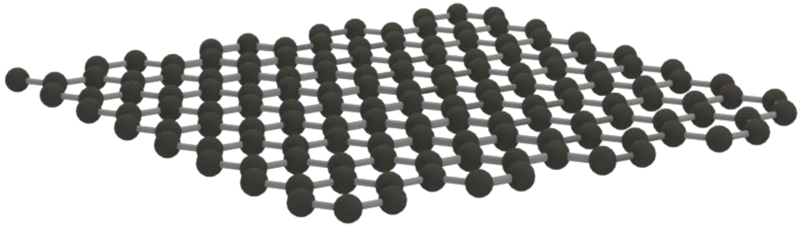
Exchange Interaction

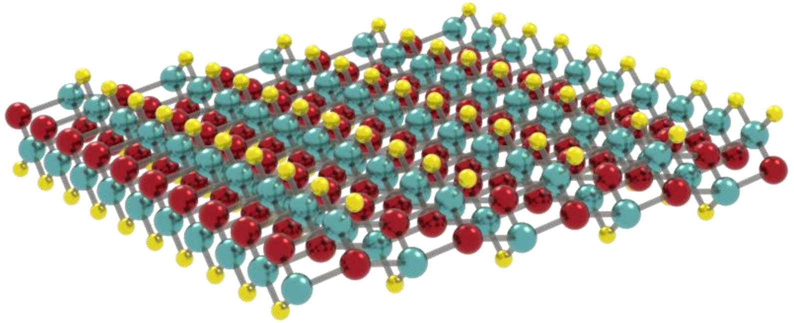


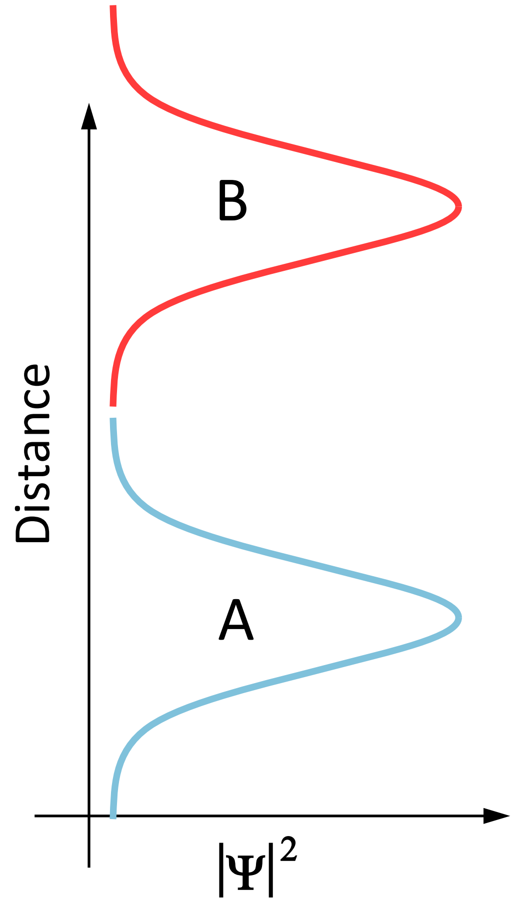
K Zollner, et al. *PRL* 125, 196402 (2020)

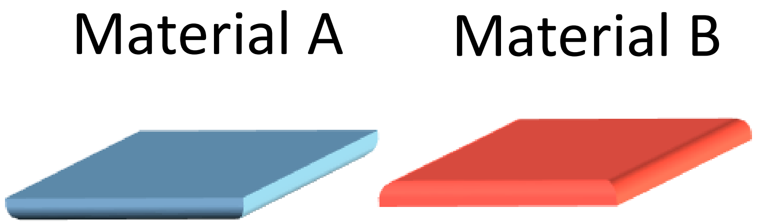
Proximity effect

Van der Waals heterostructures









K. S. Novoselov et al., *Science* 353, 9439 (2016)

J.F. Sierra, et al. *Nat. Nano.* 16.8 (2021)

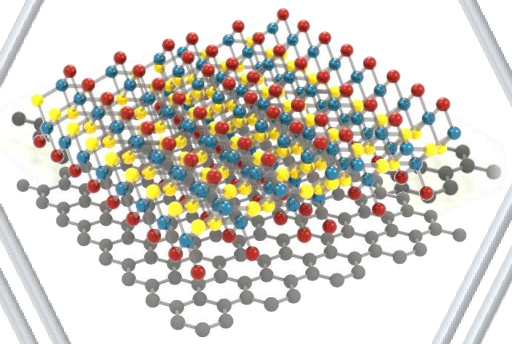
Proximity-induced magnetism in graphene

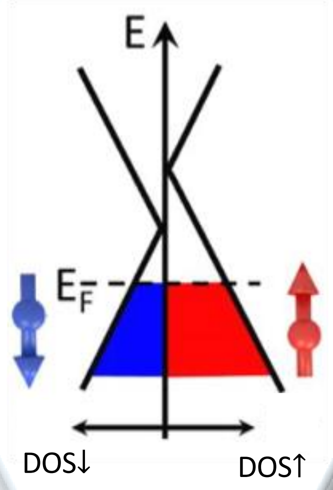
Anomalous Hall effect

Quantum anomalous Hall effect

Spin-orbit coupling

Gr/magnet





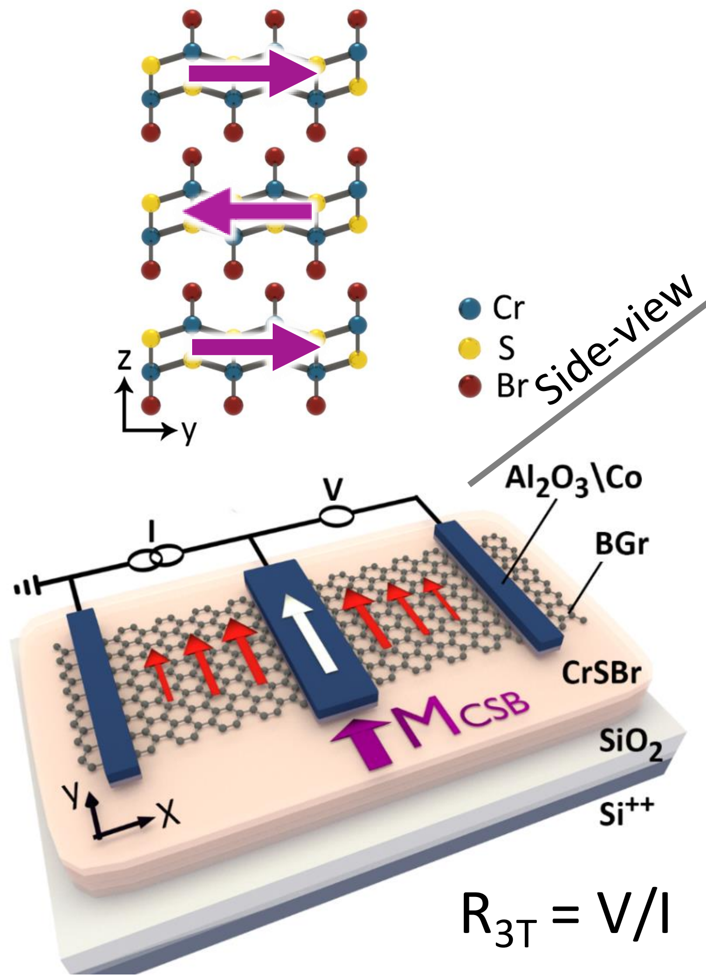
Exchange Interaction

Spin-dependent conductivity

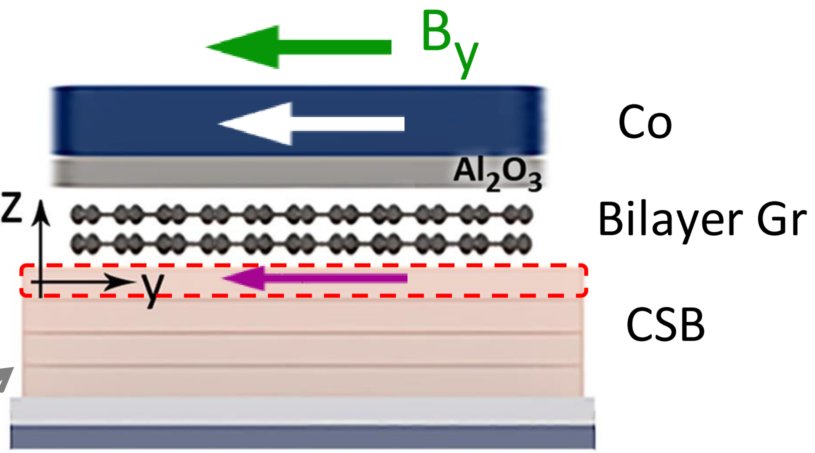
Spin-dependent Seebeck effect

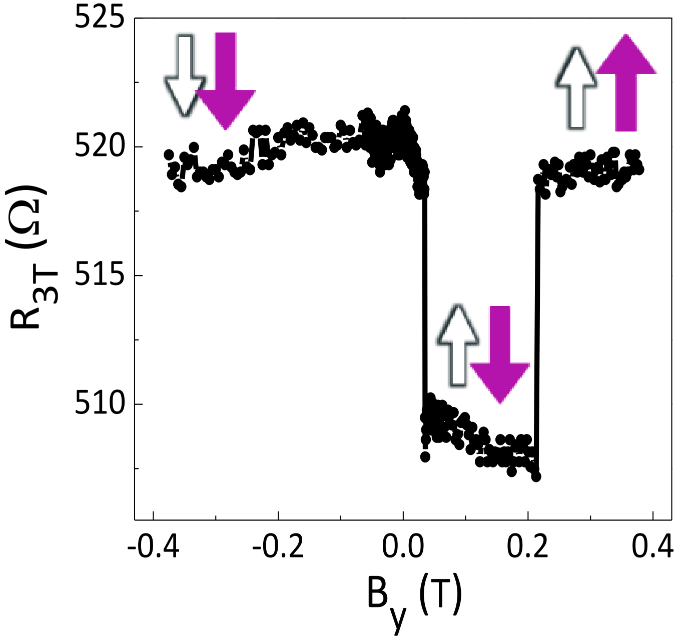
Proximity-induced magnetism

CrSBr (CSB)

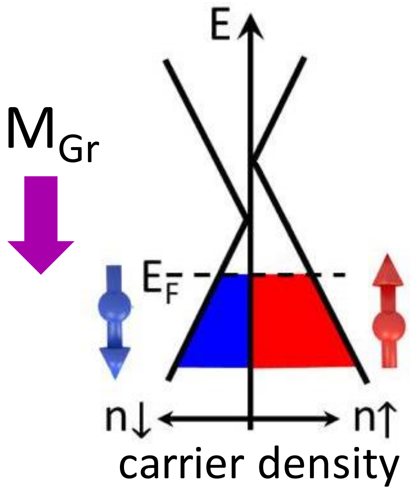


R_{3T} = V/I





"3-terminal Spin-valve"



$\sigma = ne\mu$

$n_\uparrow > n_\downarrow \Rightarrow \sigma_\uparrow > \sigma_\downarrow$

$$P_{Gr} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

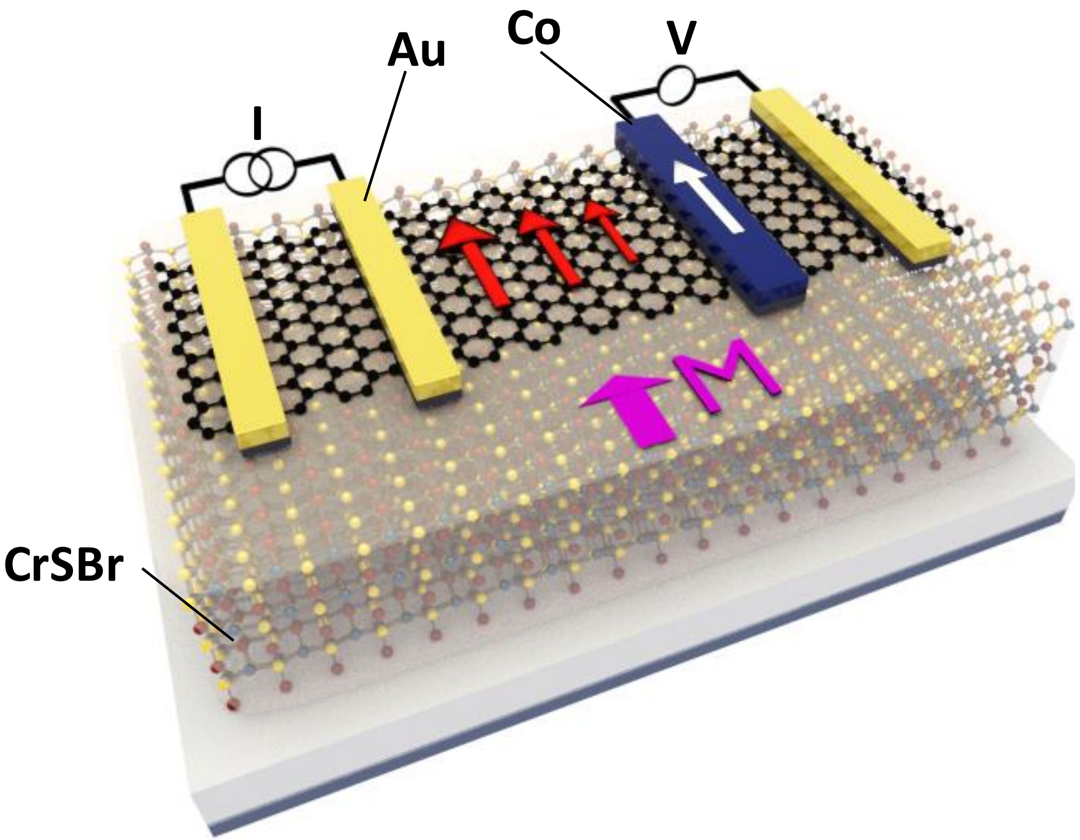
Spin-polarization of conductivity

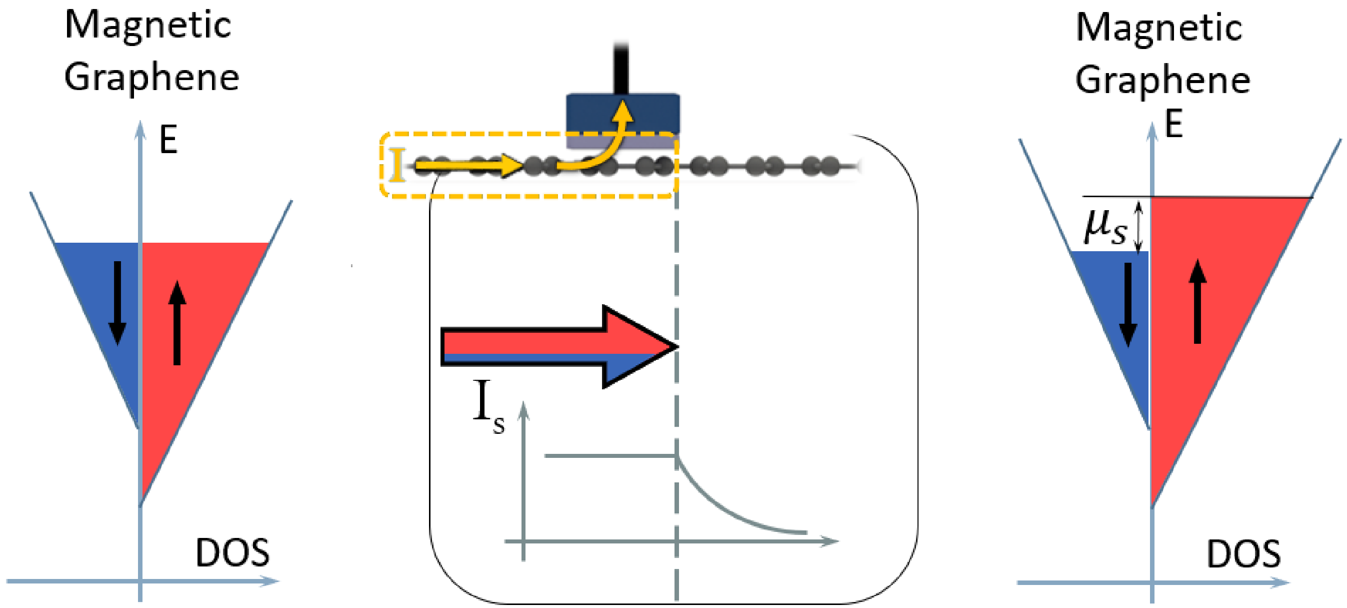
$\Delta R_{3T} \propto P_{Gr} . P_{Co}$ ➡ P_{Gr} = 14%

P_{Co} = 24%

TS Ghiasi, et al. *Nat. Nano.* 16, 788 (2021)

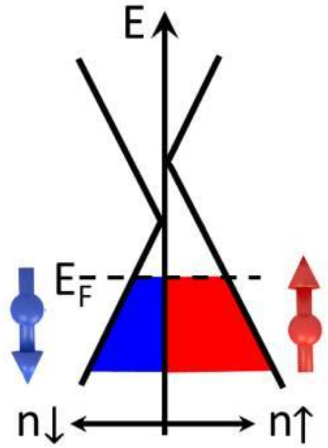
Spin-injection by magnetic graphene





AA Kaverzin, TS Ghiasi, et al., *2D Mater.* 9 045003 (2022)

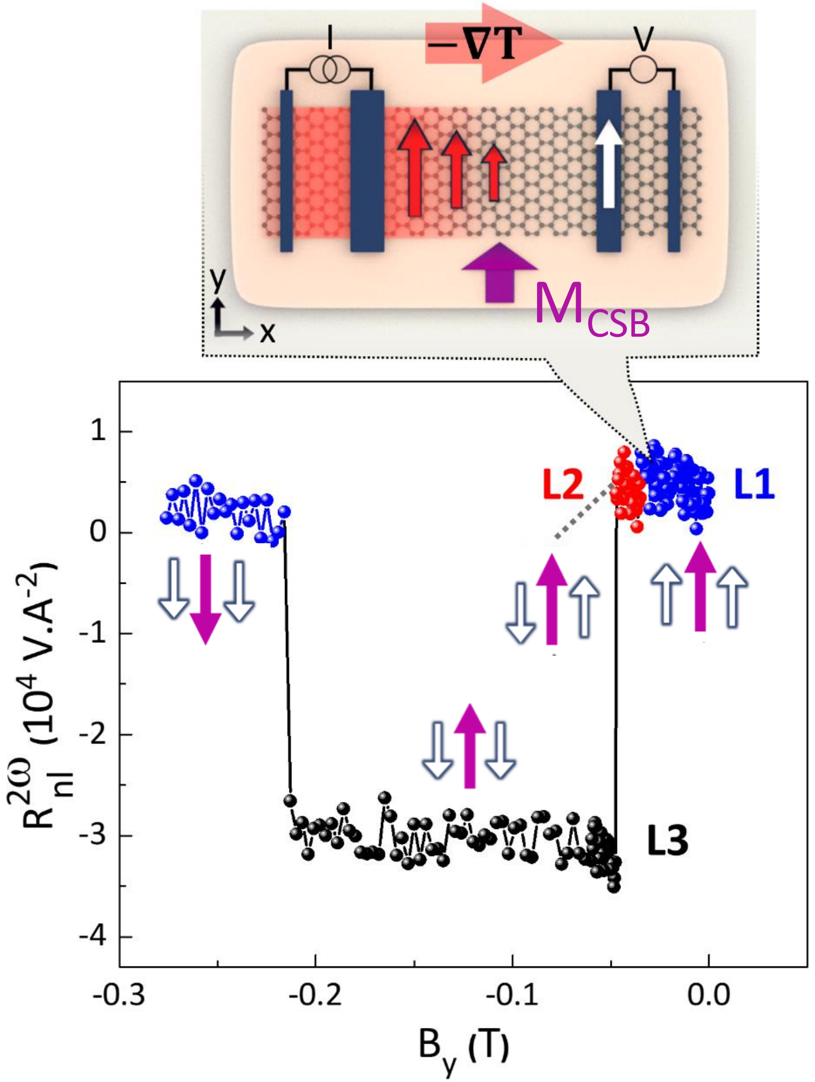
Spin-dependent Seebeck effect



Joule heating

$$\Delta T \propto I^2$$

$$R_{\text{nl}}^{2\omega} = V^{2\omega}/I^2$$



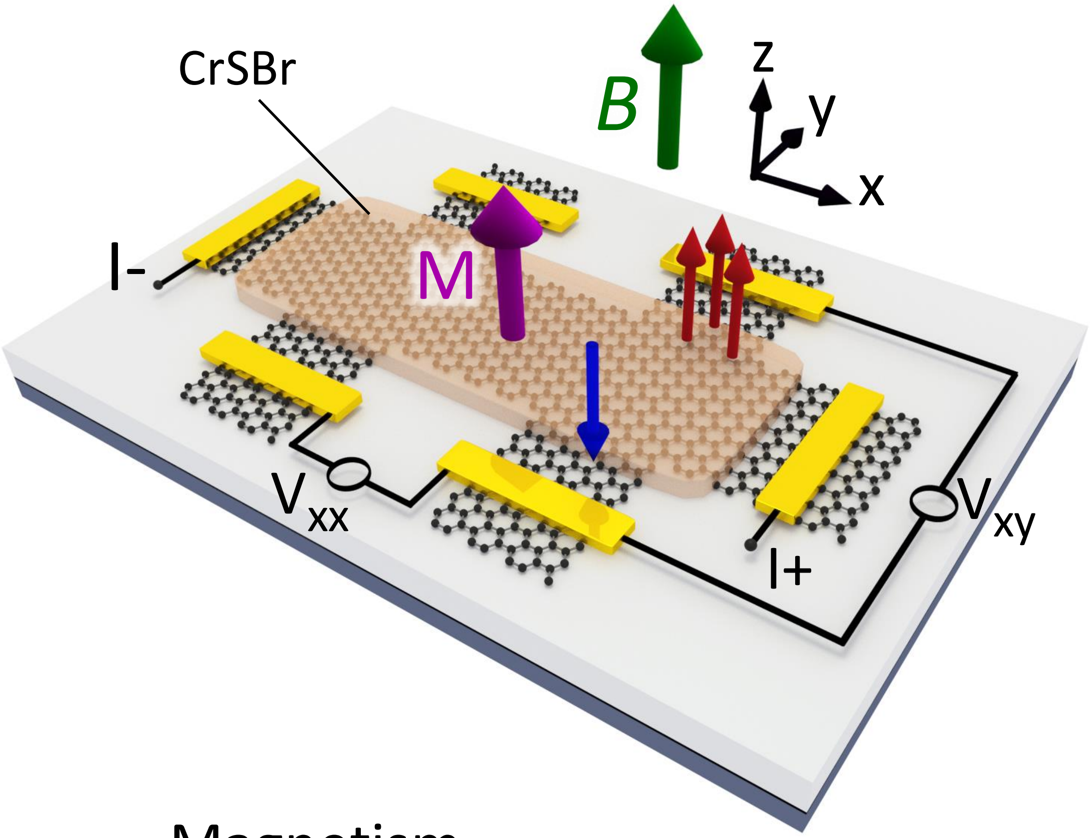
Electrical and thermal

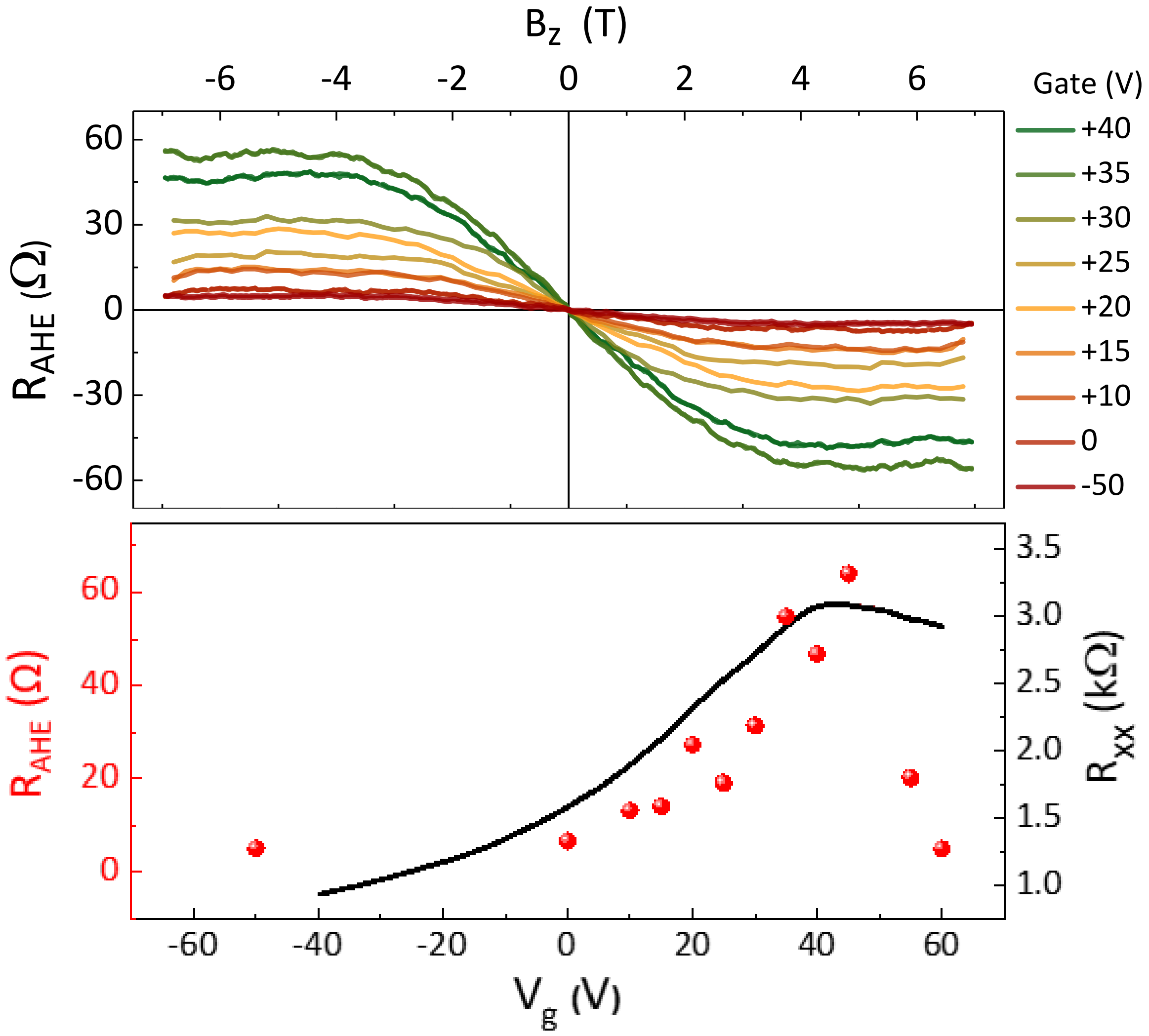
generation of spin currents

by the magnetic graphene

TS Ghiasi, et al. *Nat. Nano.* 16, 788 (2021)

Anomalous Hall effect





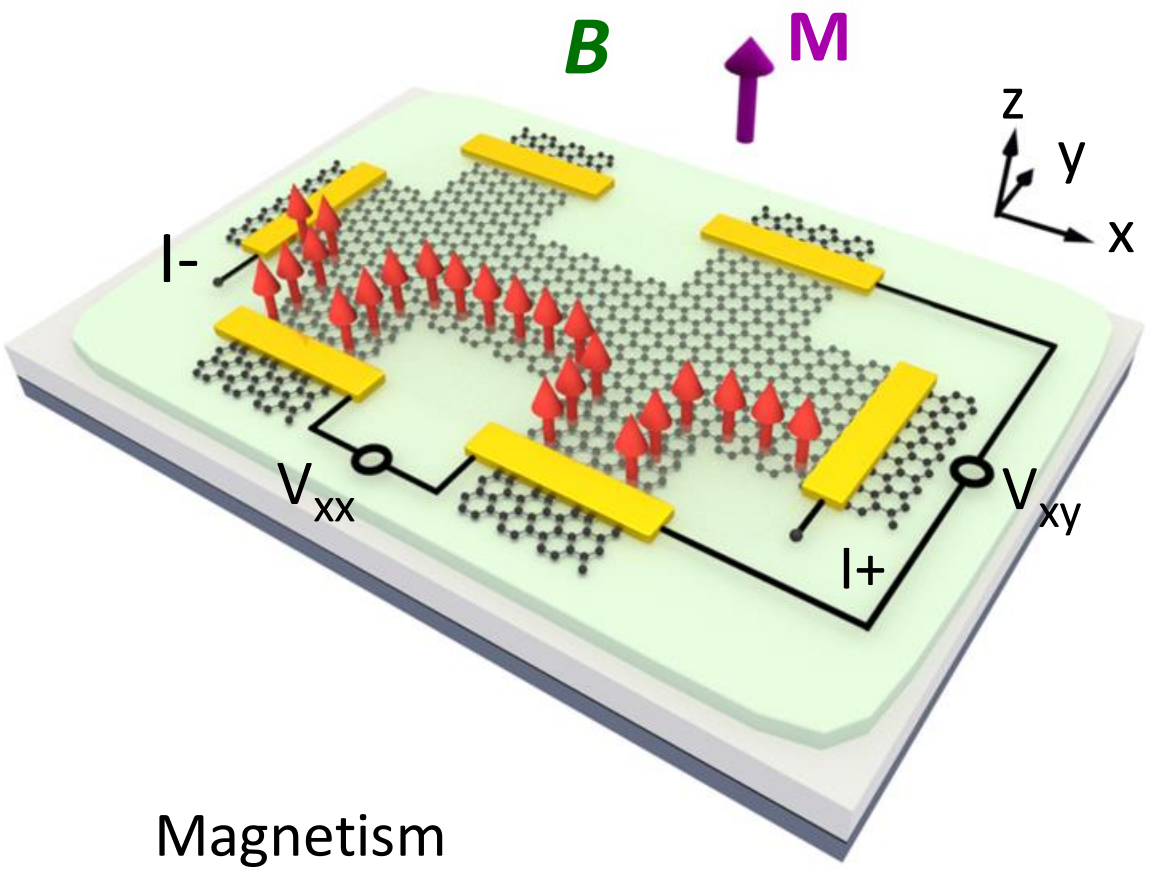
Magnetism

\+ => AHE

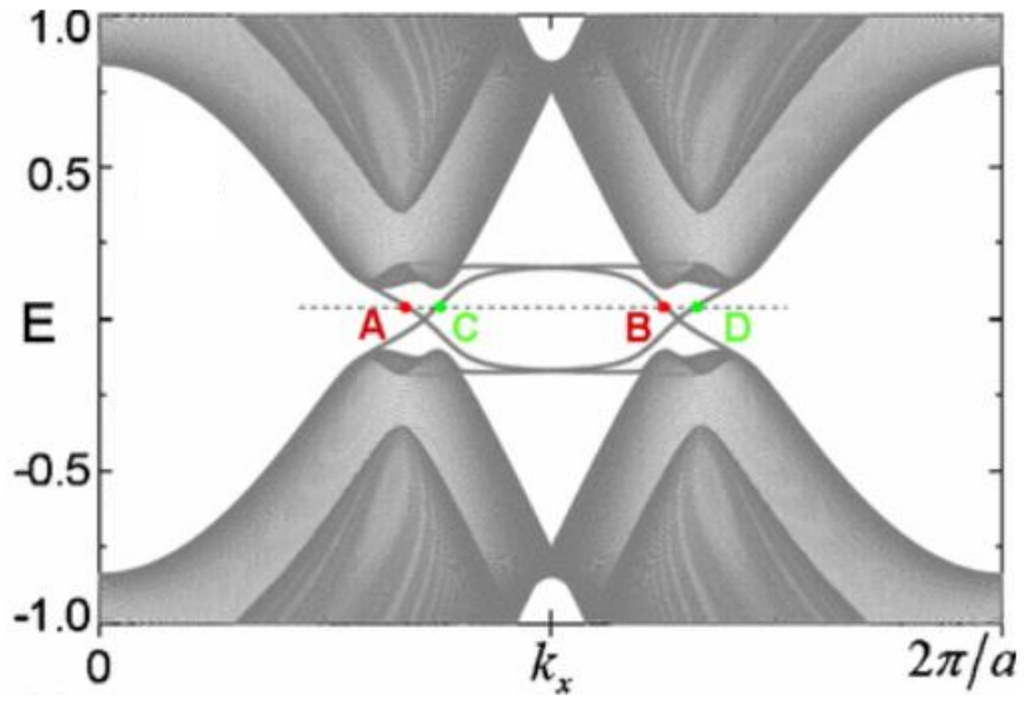
Spin-orbit coupling

TS Ghiasi, et al. *Nat. Nano.* 16, 788 (2021)

Quantum anomalous Hall effect?



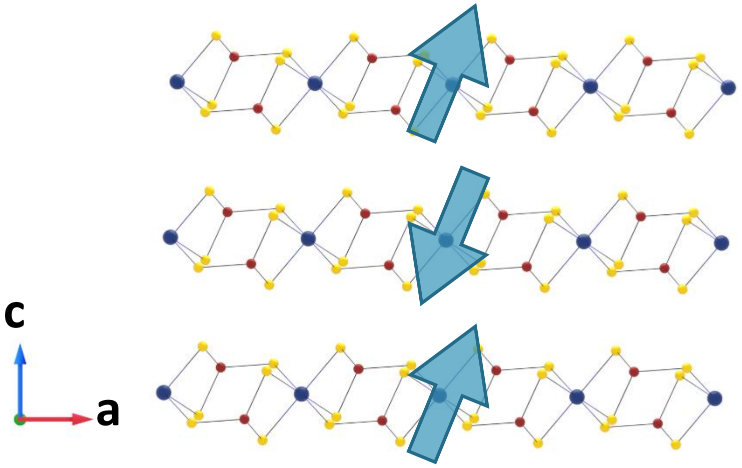
Magnetism
+ => AHE
Spin-orbit coupling



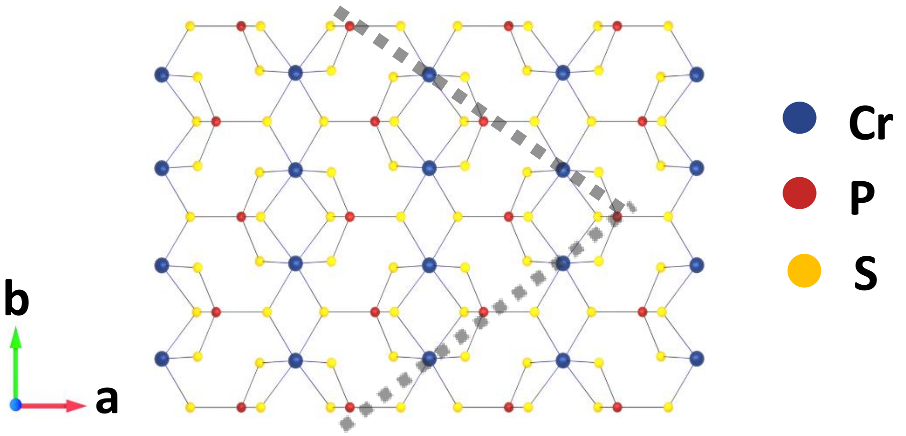
Z. Qiao, et al. *PRB,* 82. 161414 (2010)
Y. Yang, Y., et al. *PRL*, *107*. 066602 (2011)

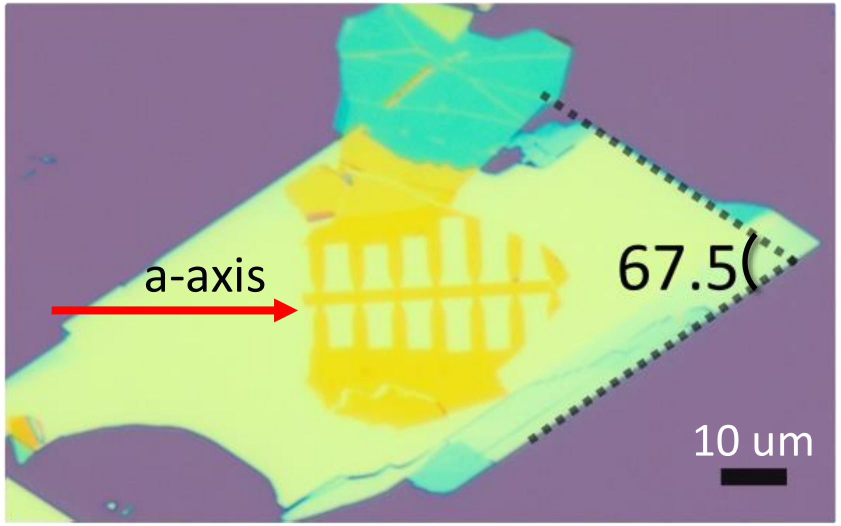
2D magnet: $CrPS_4$ (CPS)

Side-view

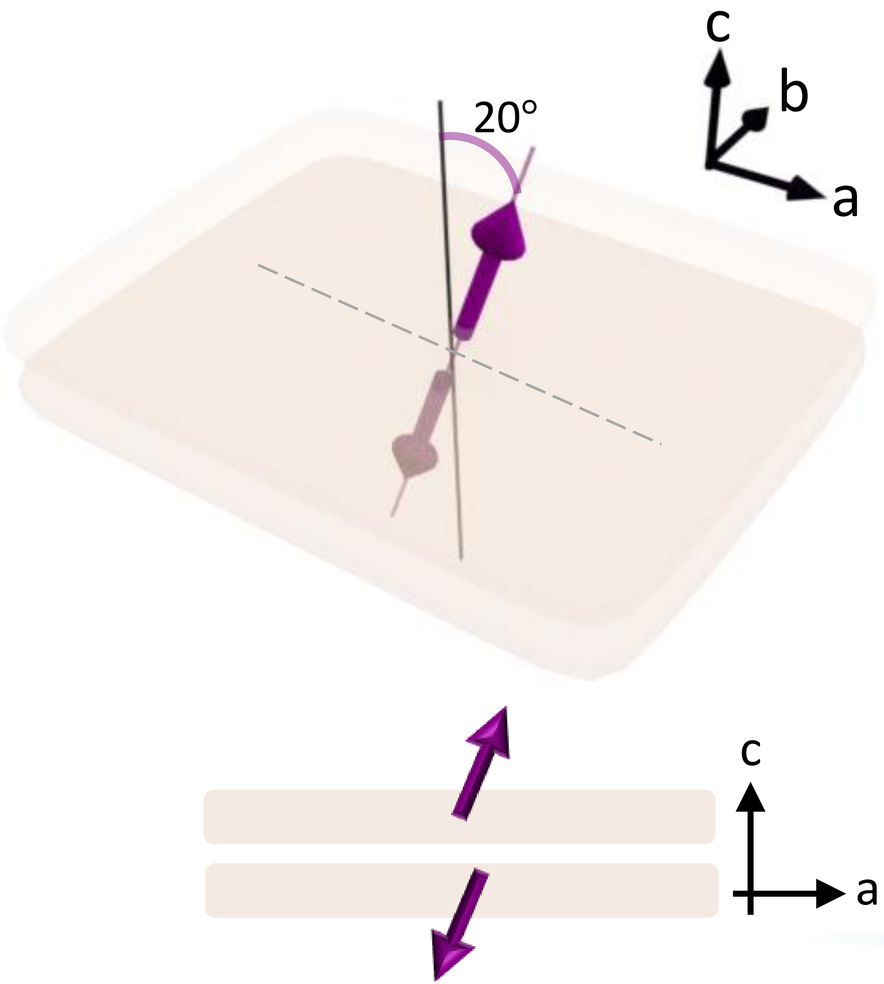


Top-view



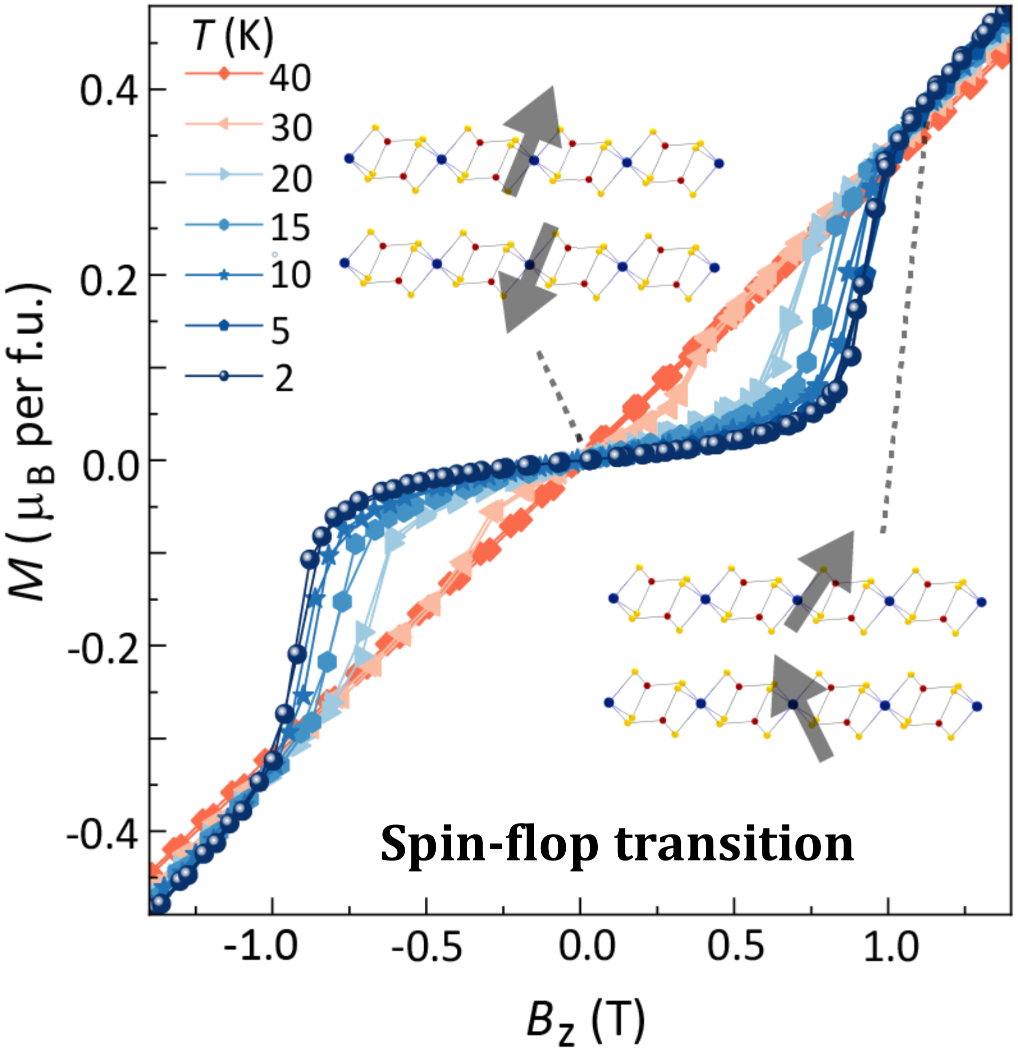


Magnetic behavior of $CrPS_4$



Side view

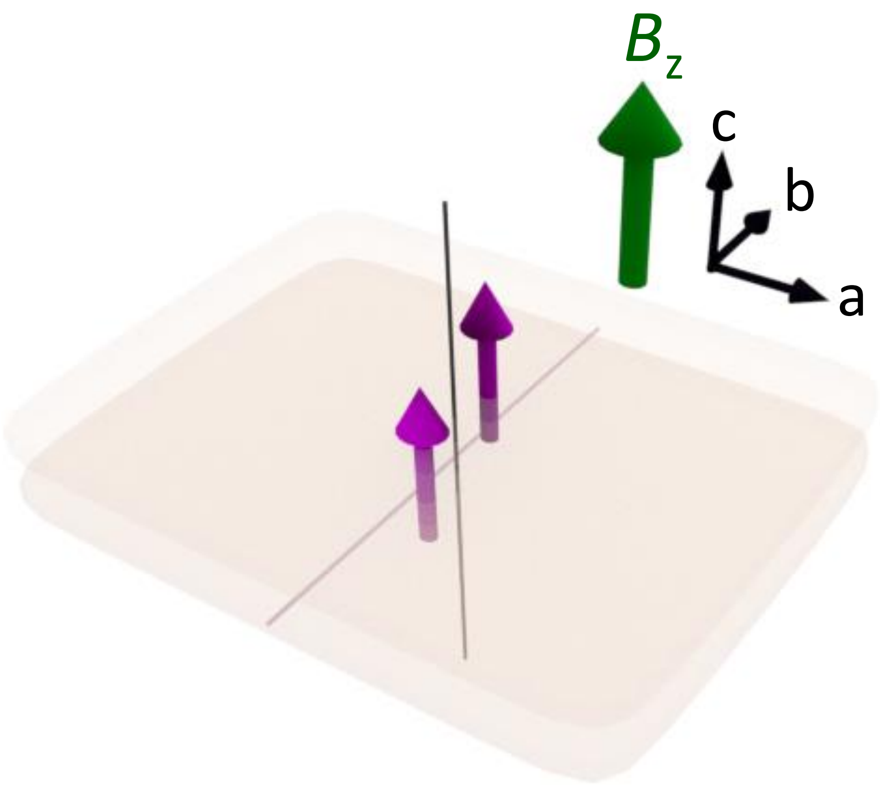
SQUID magnetometry



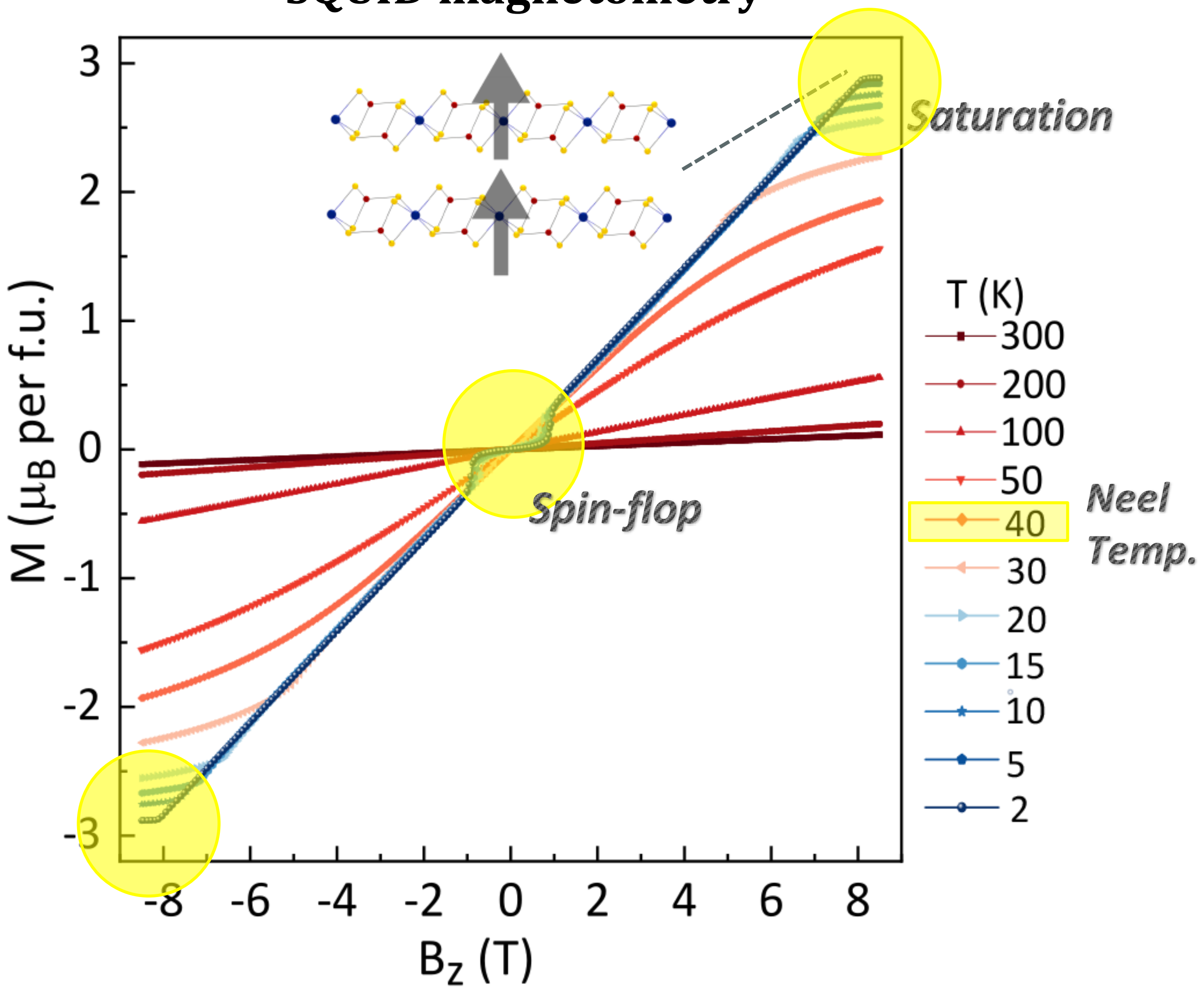
Spin-flop transition

Y. Peng, et al. *Adv. Mater,* 32. 2001200 (2020).

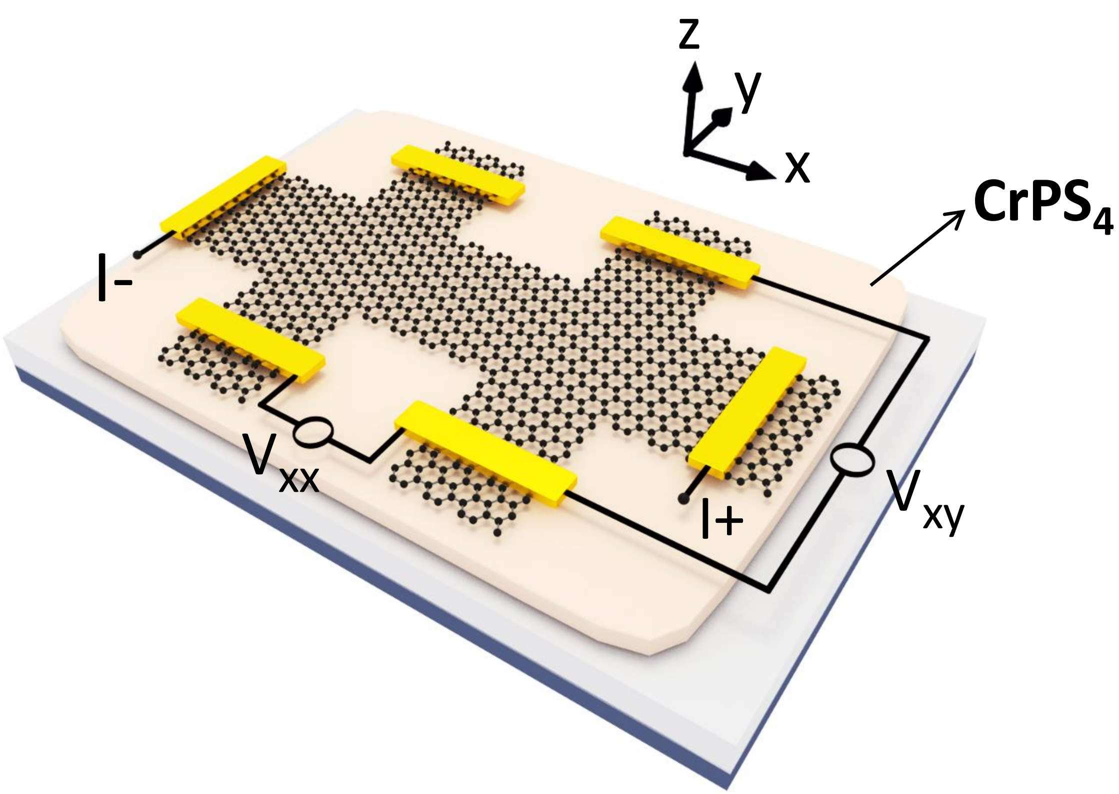
Magnetic behavior of $CrPS_4$

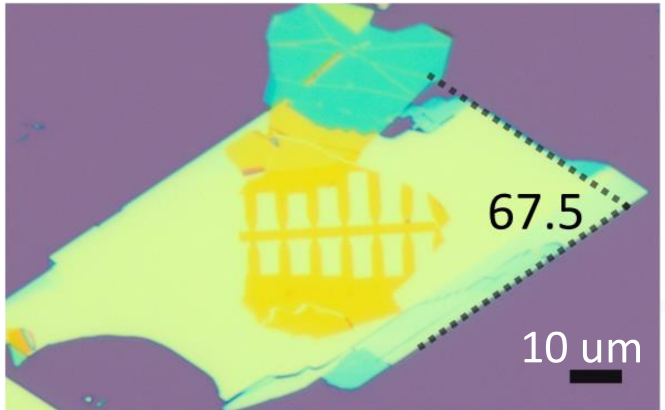


SQUID magnetometry

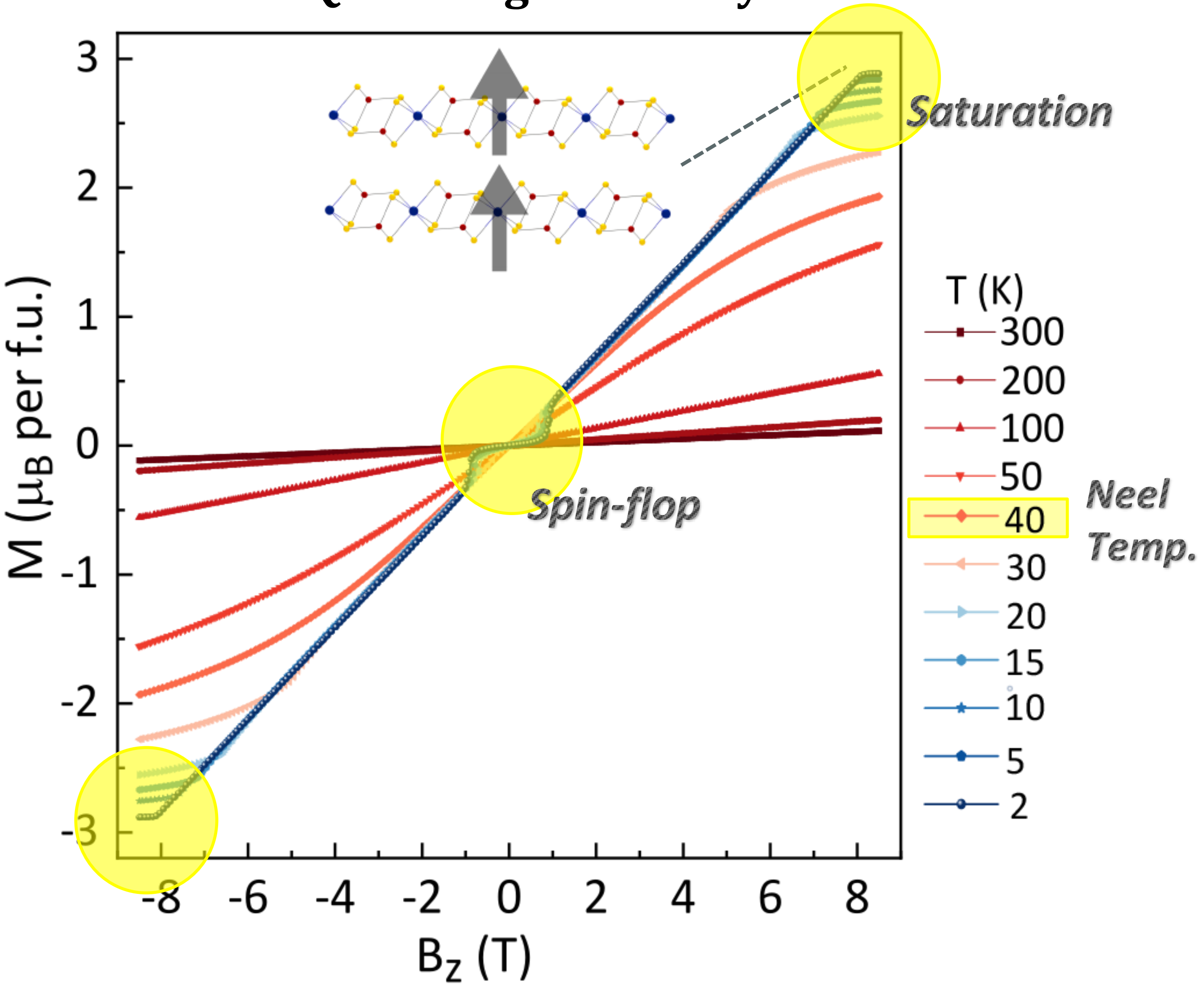


Magnetic behavior of $CrPS_4$

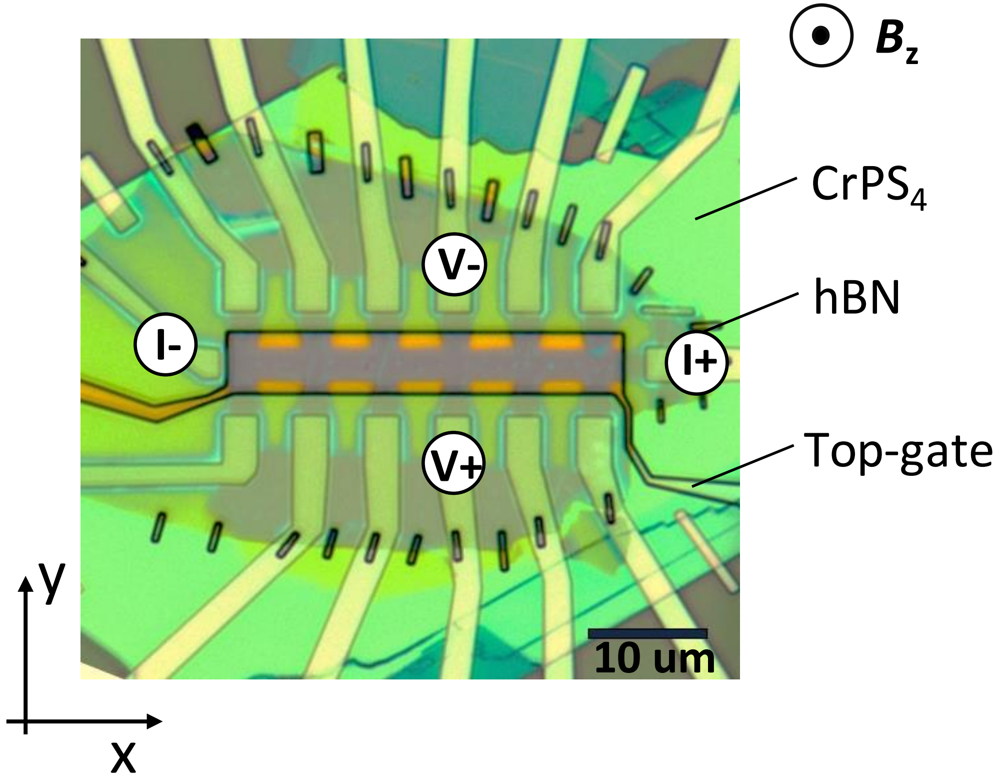


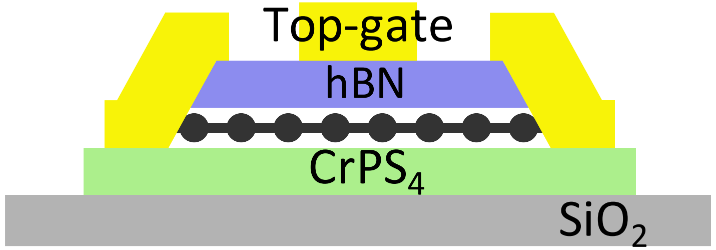


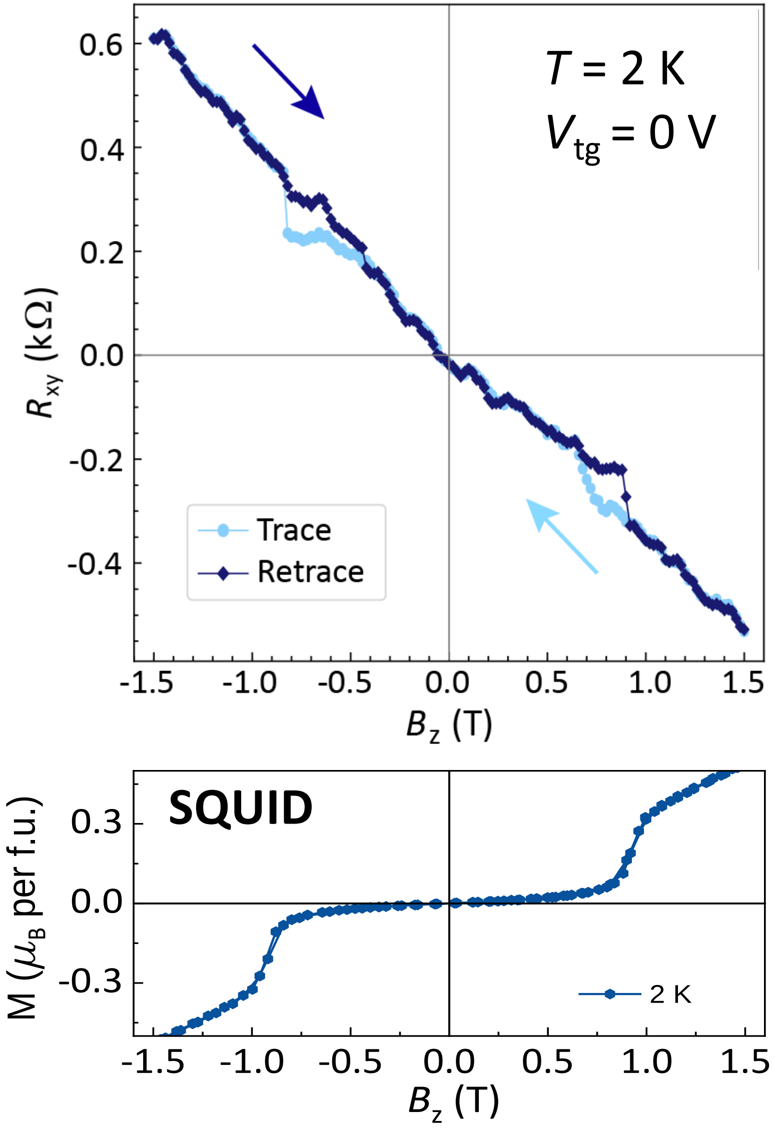
SQUID magnetometry



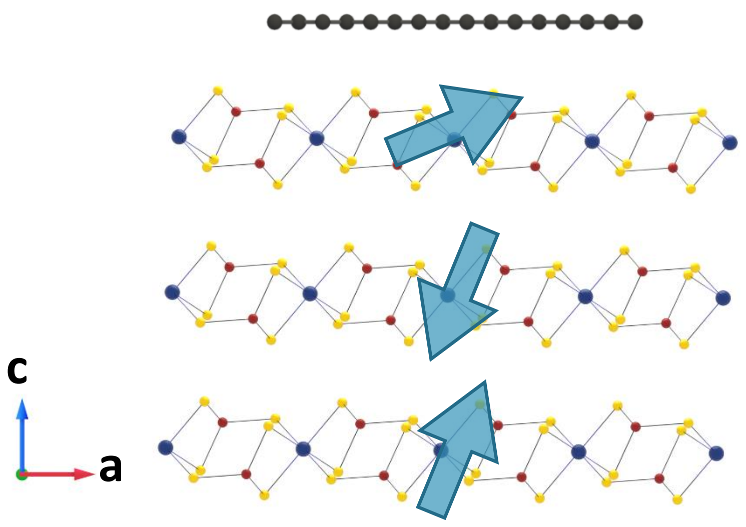
Spin-flop detection by graphene!

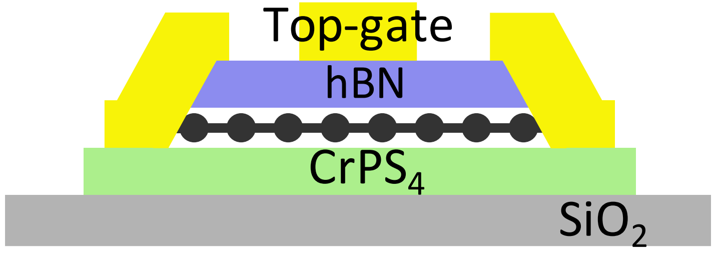


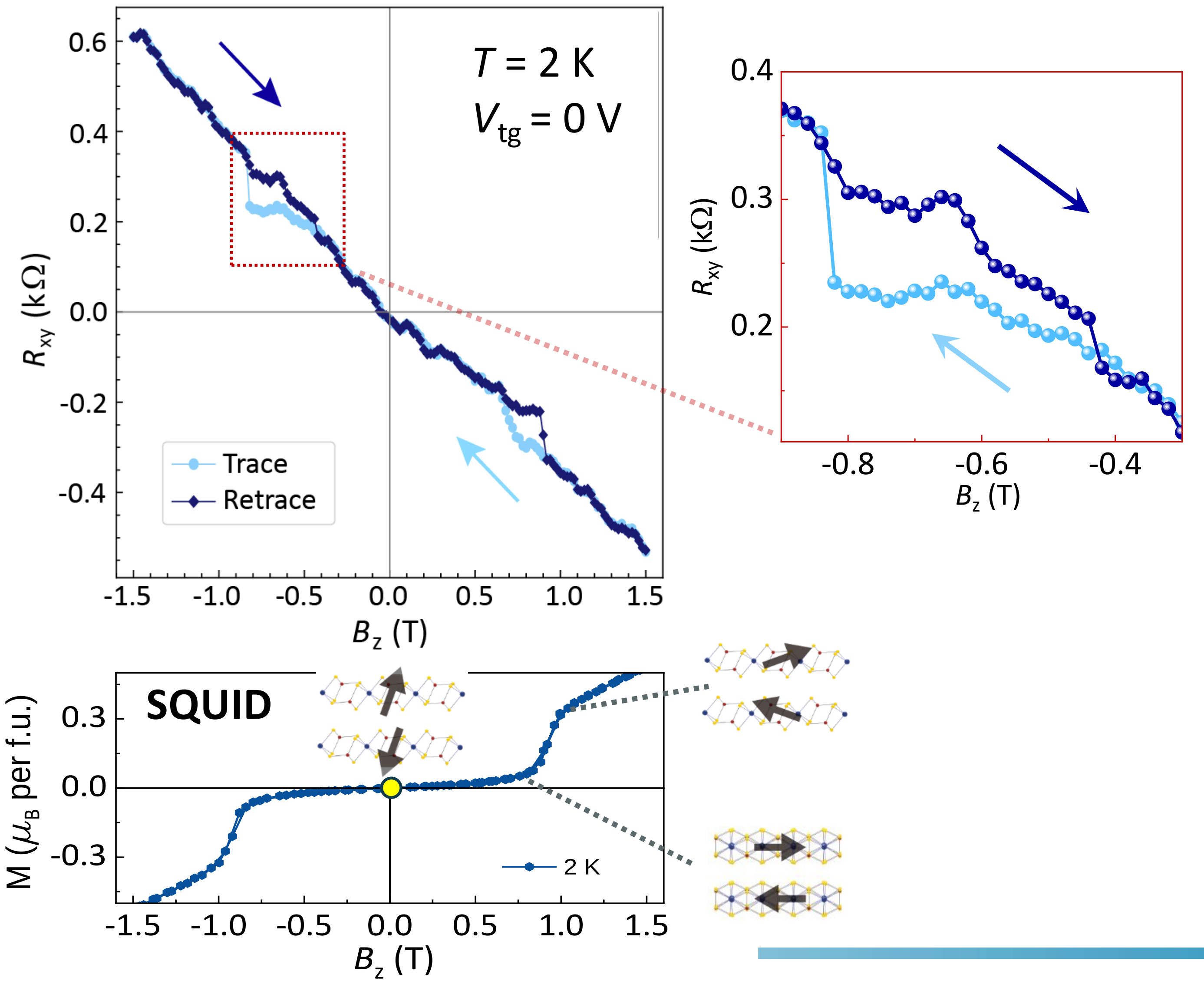




Spin-flop detection by graphene! ...through the anomalous Hall effect $R_{AHE} \propto M_z$

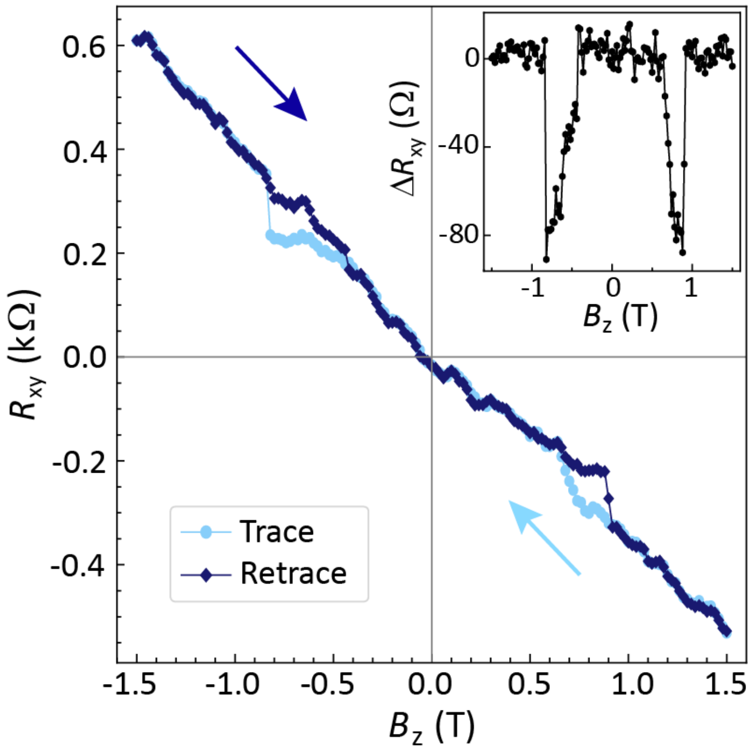


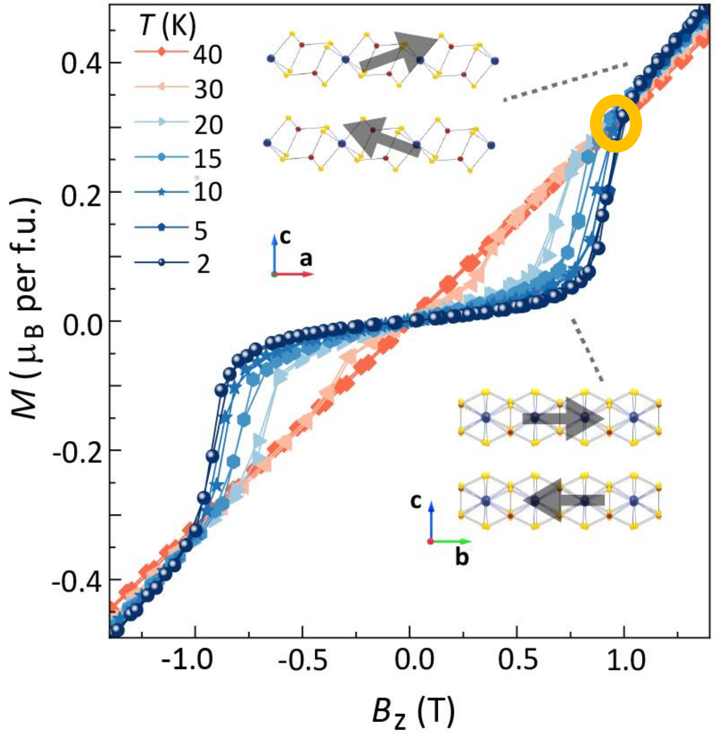


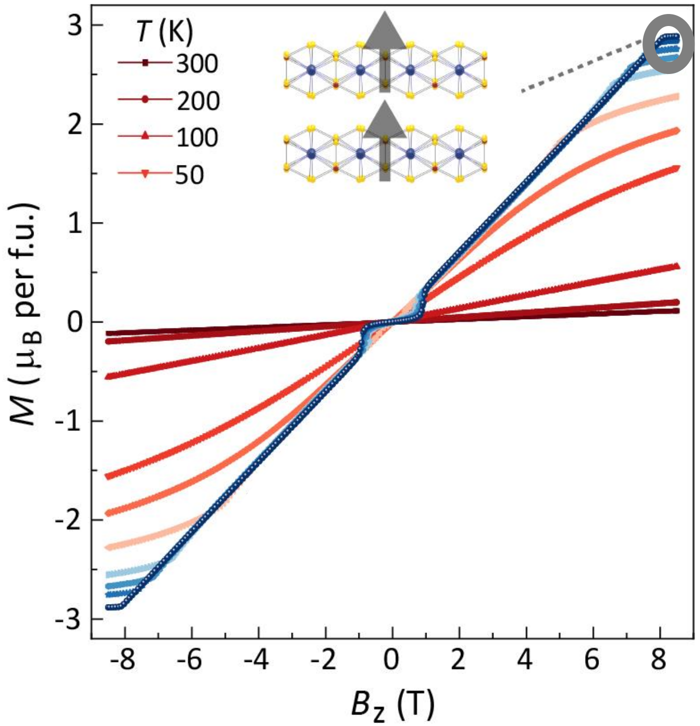


Anomalous Hall effect in magnetized graphene

($R_{AHE} \propto M_z$)

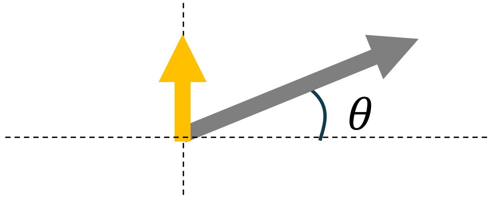






6° canted $\vec{M}$: 80 Ω AHE

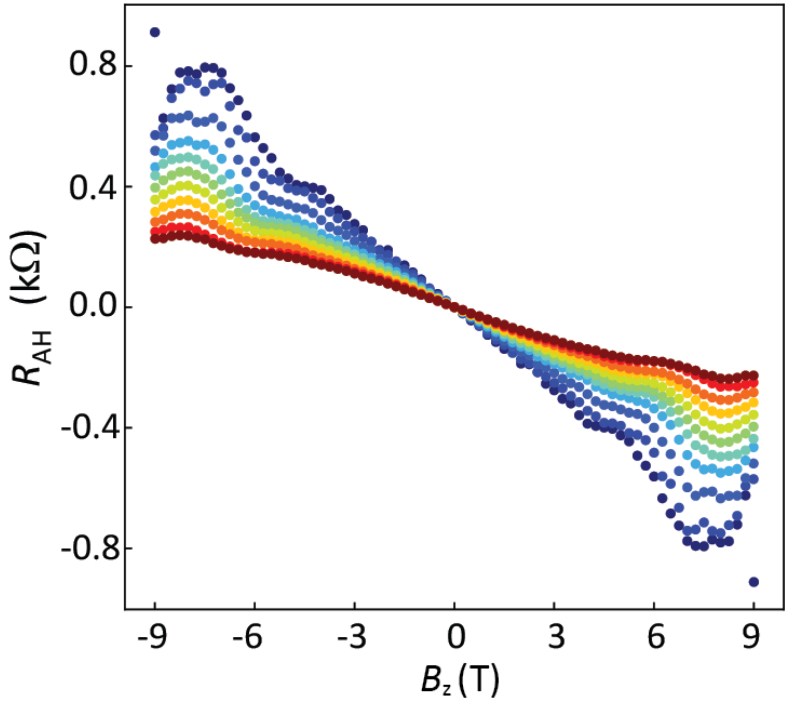
90° canted $\vec{M}$: 700 Ω AHE

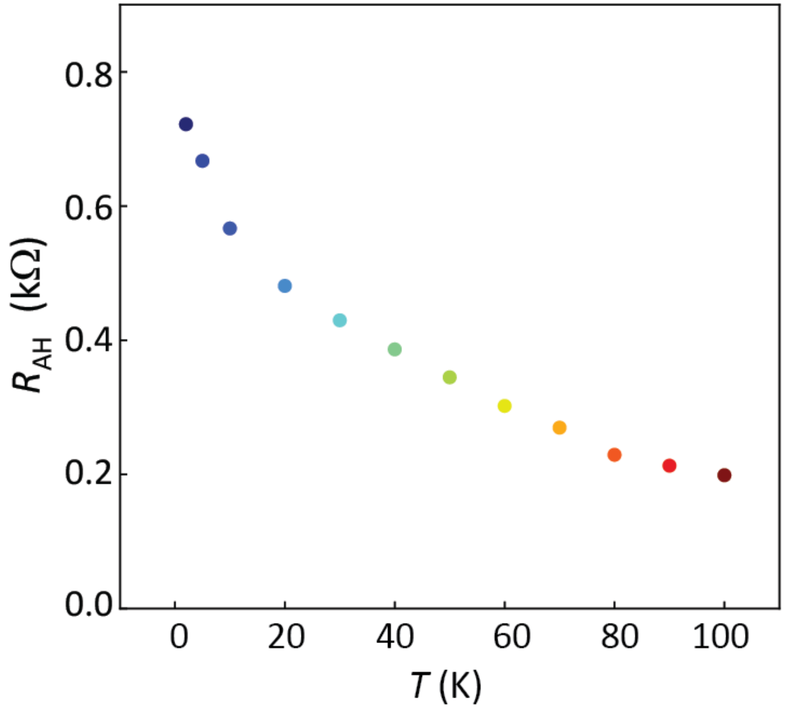


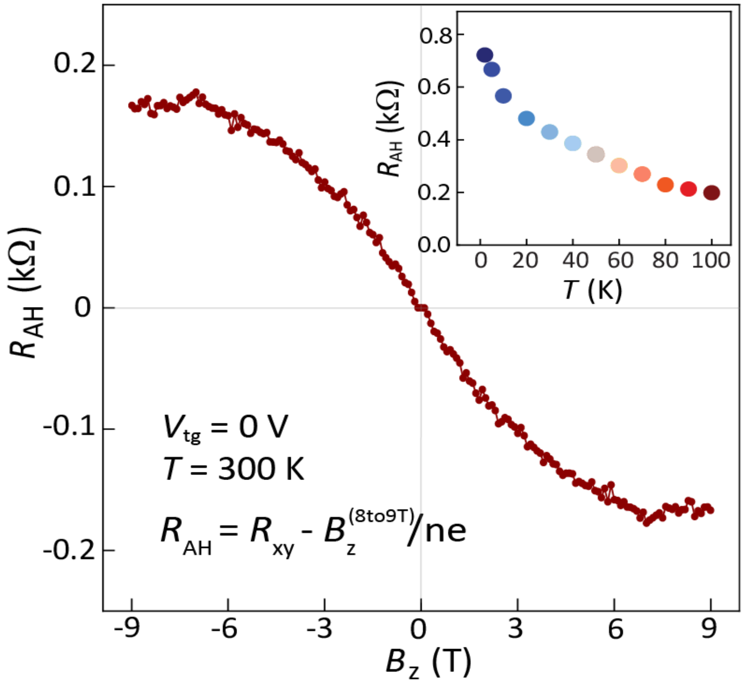
$$\theta = Arcsin\left(\frac{0.3}{2.87}\right) = 6°$$

Anomalous Hall effect in magnetized graphene

Room temperature magnetism?!





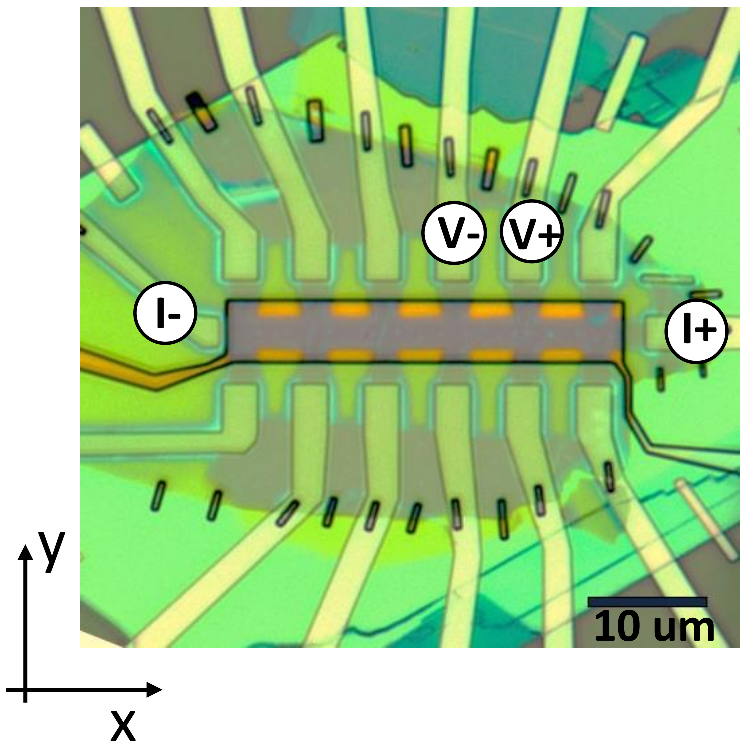


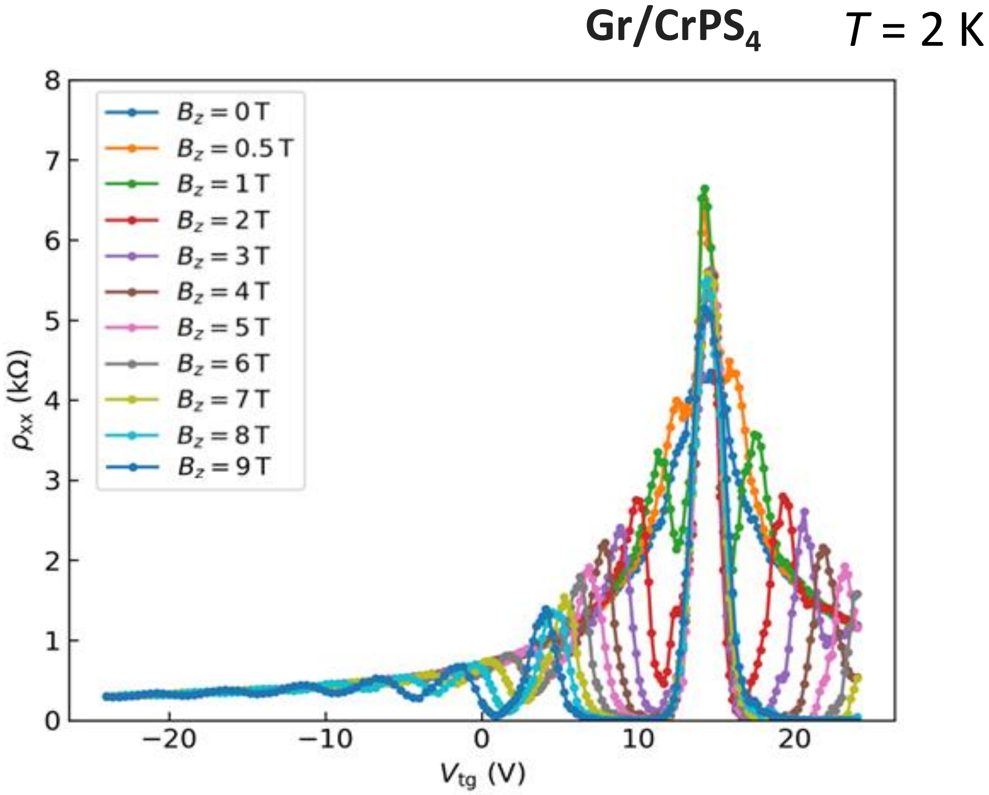
90° canted $\vec{M}$: 700 Ω AHE

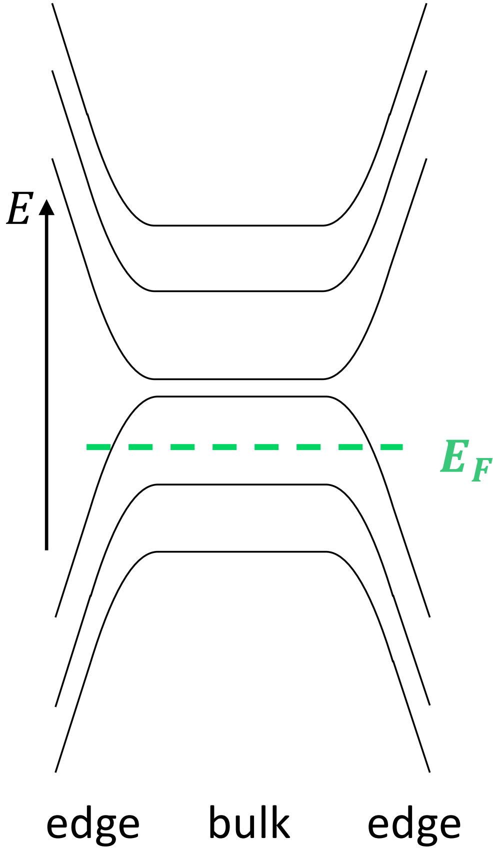
W Zhu, et al. "**Interface-enhanced room-temperature Curie temperature** in CrPS4/graphene van der Waals heterostructure." *PRB* 108, L100406 (2023).

T Ghiasi, et al. *arXiv:2312.07515* (2023)

Quantum transport in magnetic graphene

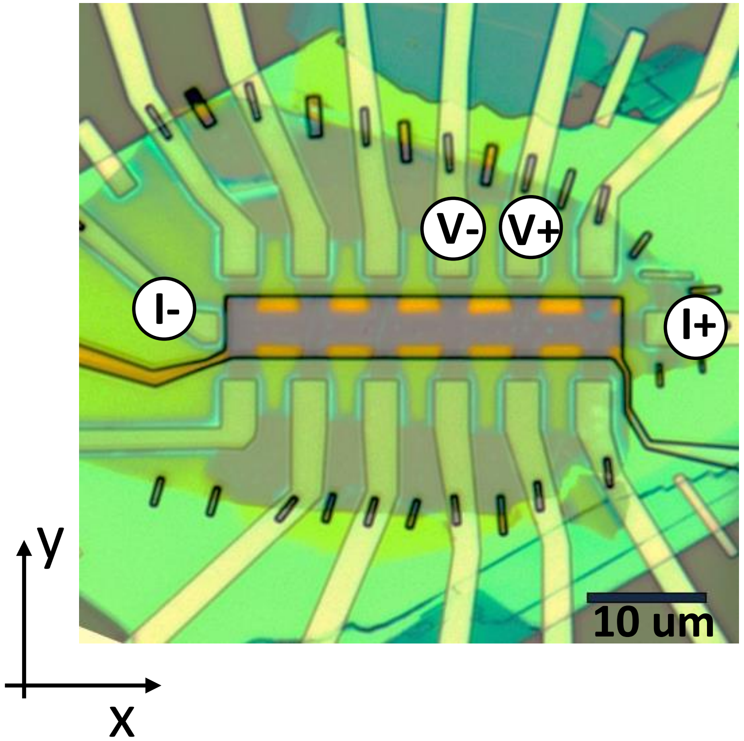


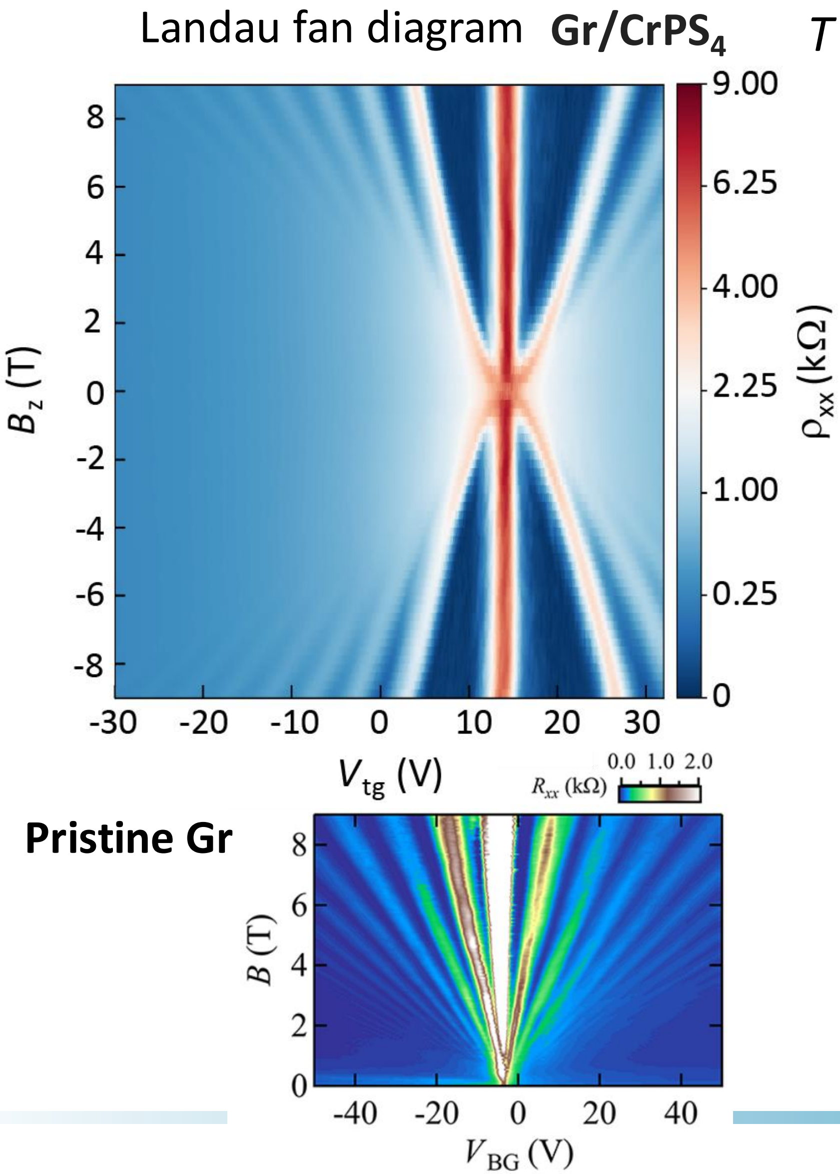


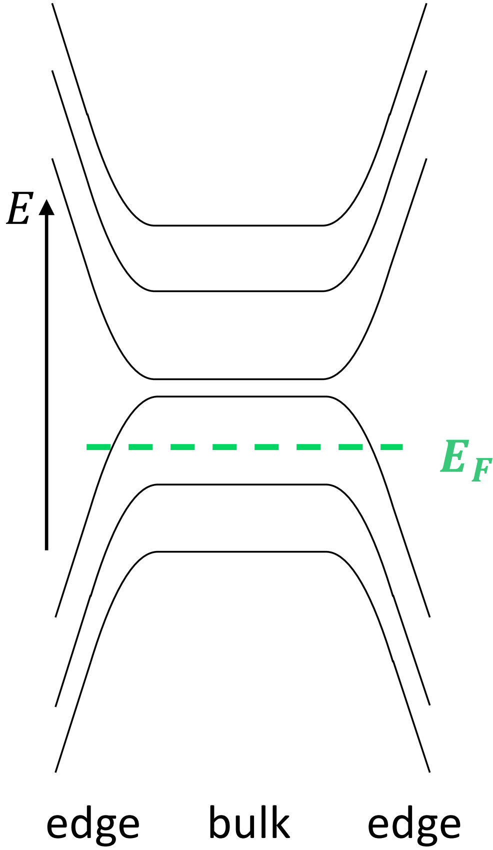


T Ghiasi, et al. *arXiv:2312.07515* (2023)

Quantum transport in magnetic graphene



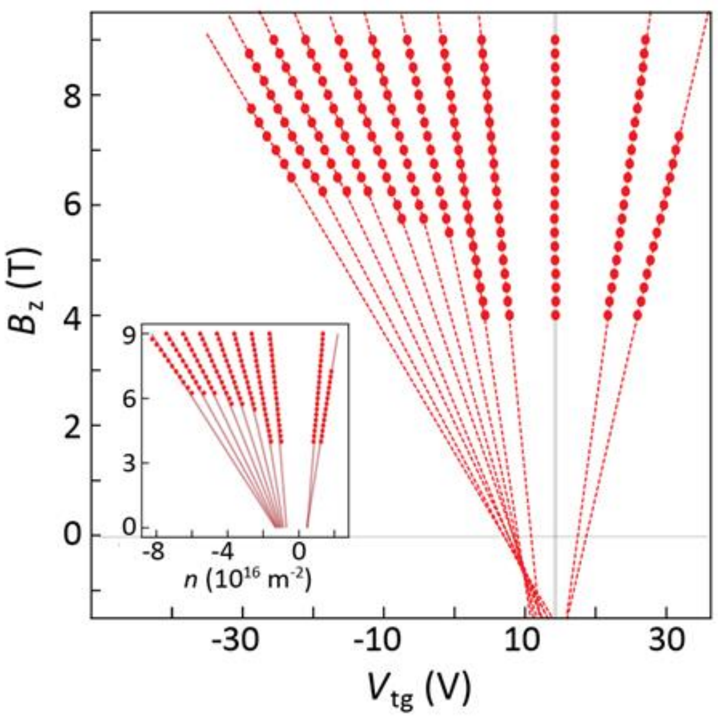




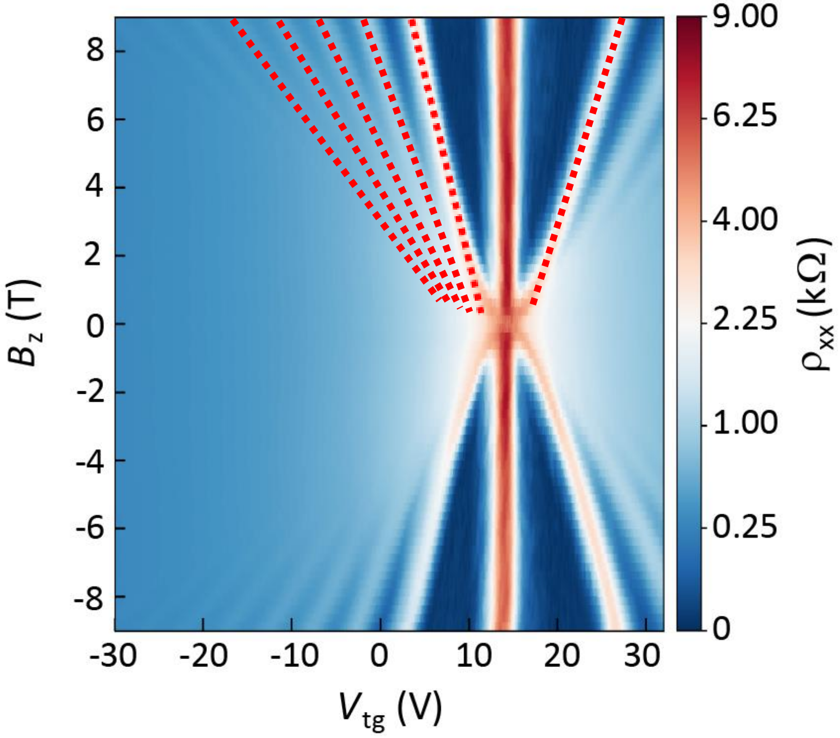
T Ghiasi, et al. *arXiv:2312.07515* (2023)

M Onodera, et al. *Nano Lett.* 19, 7282 (2019)

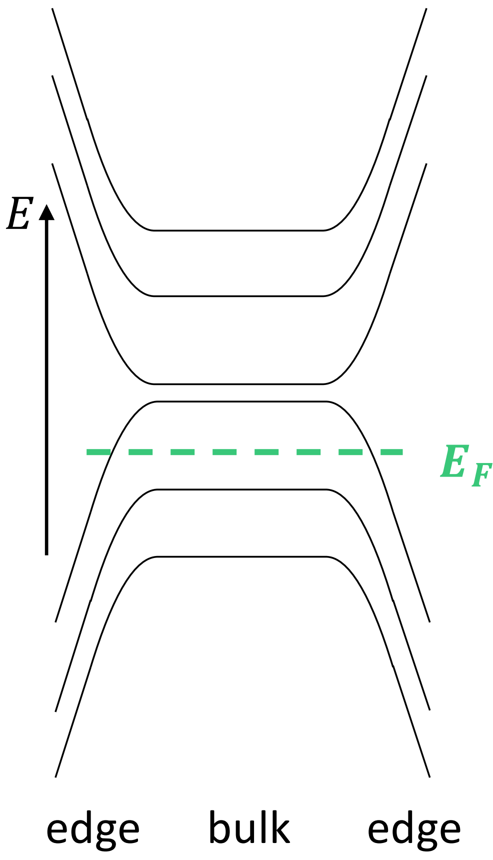
Quantum transport in magnetic graphene



Landau fan diagram **Gr/CrPS$_4$** T = 2 K



Pristine Gr



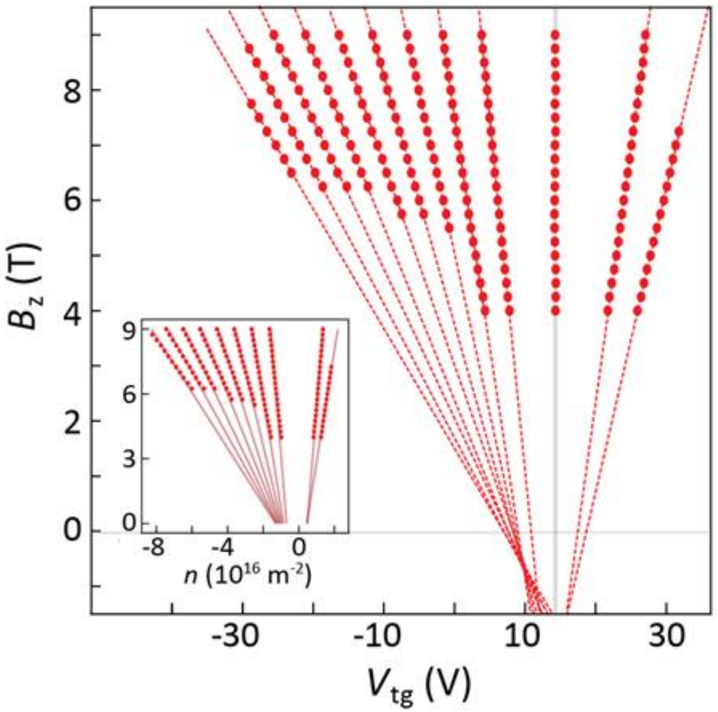
$$E_N = \sqrt{\alpha |N_{\mathrm{LL}}| B} \qquad N\text{: LL number}$$

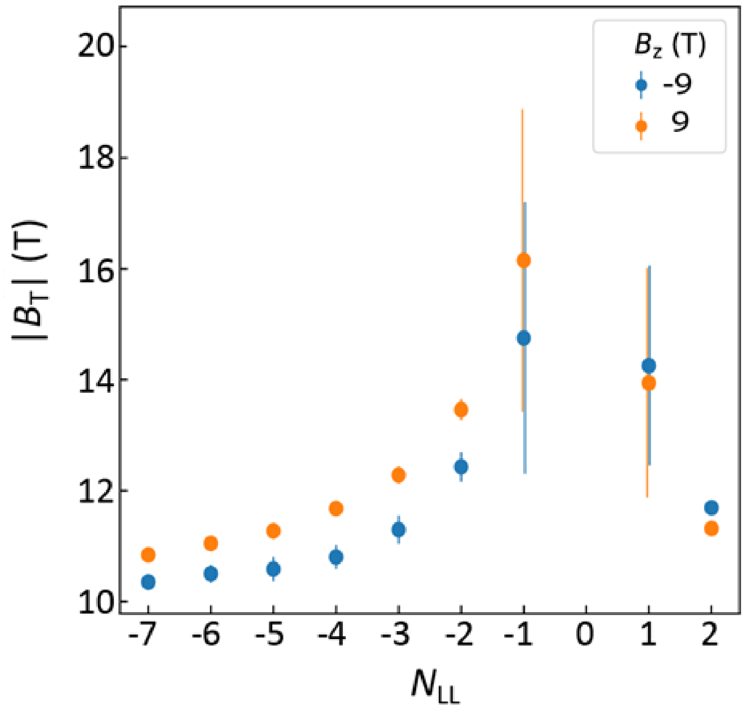
$$E^2 \propto n \propto V_{tg} \propto B$$

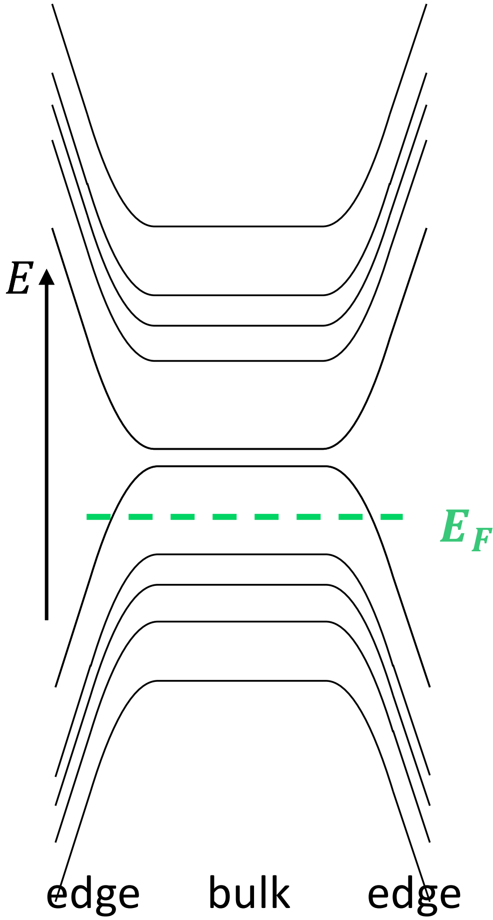
T Ghiasi, et al. *arXiv:2312.07515* (2023)

M Onodera, et al. *Nano Lett.* 19, 7282 (2019)

Quantum transport in magnetic graphene







$$E_N = \sqrt{\alpha |N_{LL}| B_T}$$ N: LL number

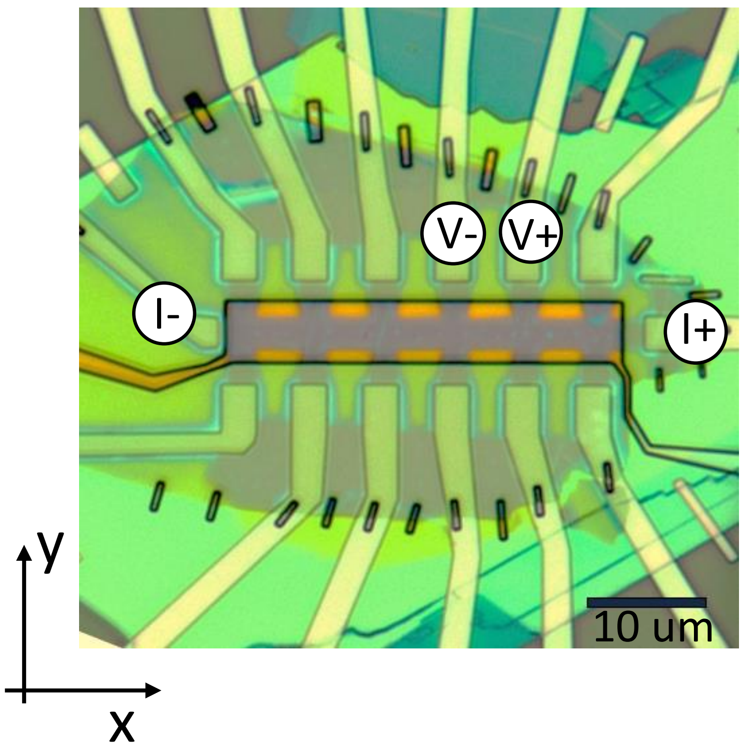
Dipolar magnetic field…(strain?)

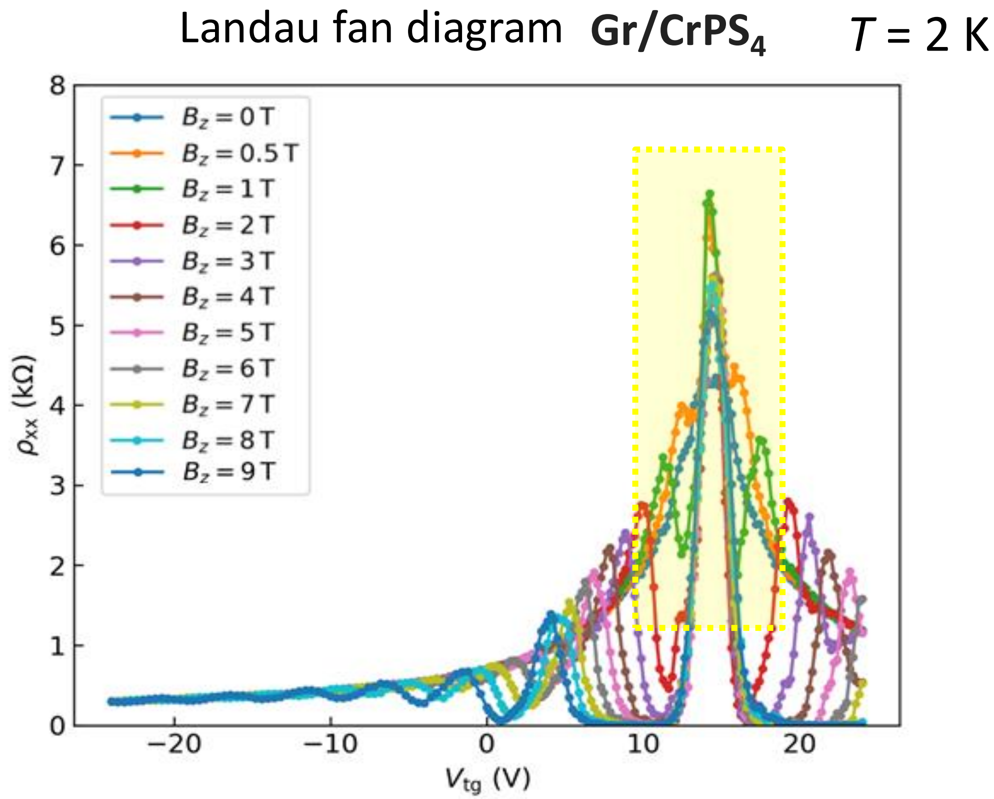
$$E^2 \propto n \propto V_{tg} \propto B_T$$

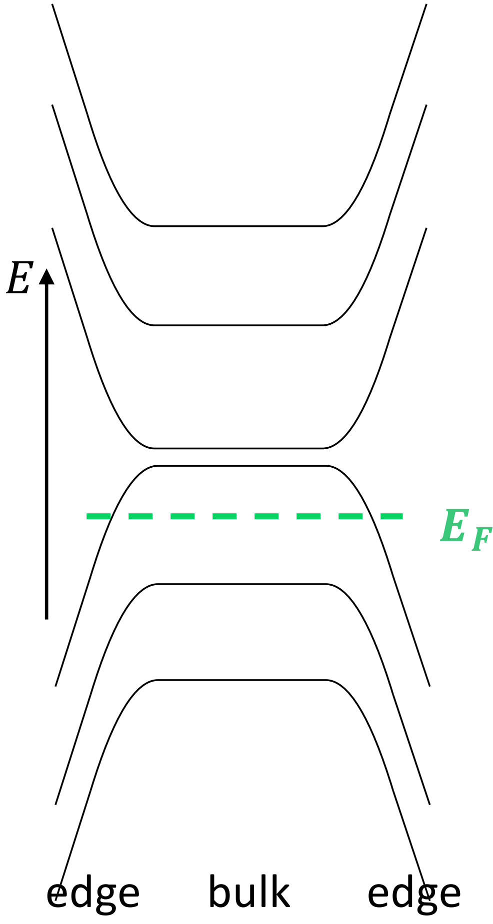
$$B_T = B_z + B_{ps}$$

Houmes, et al., "Highly Anisotropic Mechanical Response of the Van der Waals Magnet $CrPS_4$" *Adv. Funct. Mater.* 34.3 (2024): 2310206. *15* (2023)

Quantum transport in magnetic graphene







Quantum transport in magnetic graphene

$$\mu\, B_\mathrm{T} \gg 1$$

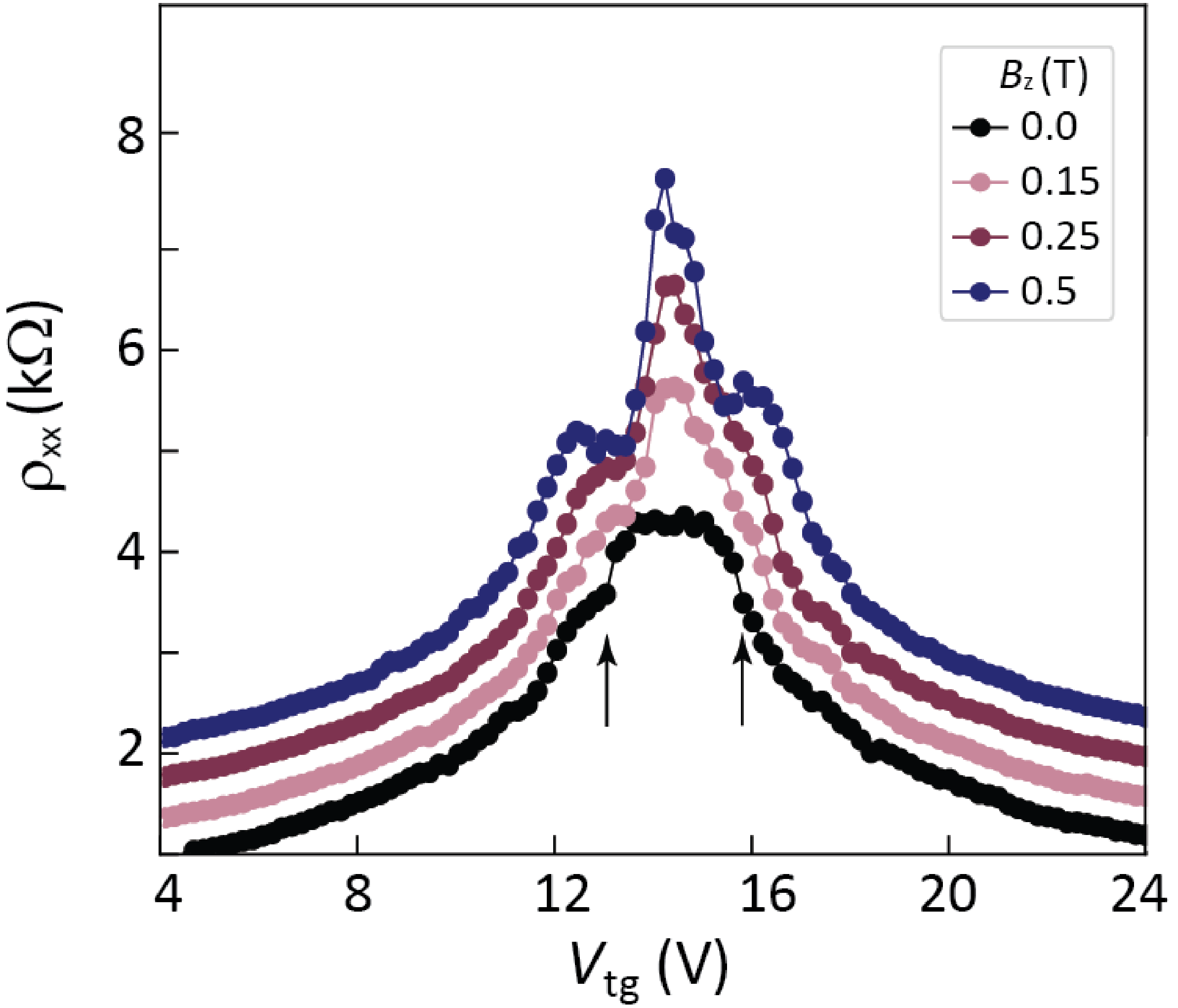
$$\mu \approx 2000\ \mathrm{cm^2/Vs}$$

$$\Downarrow$$

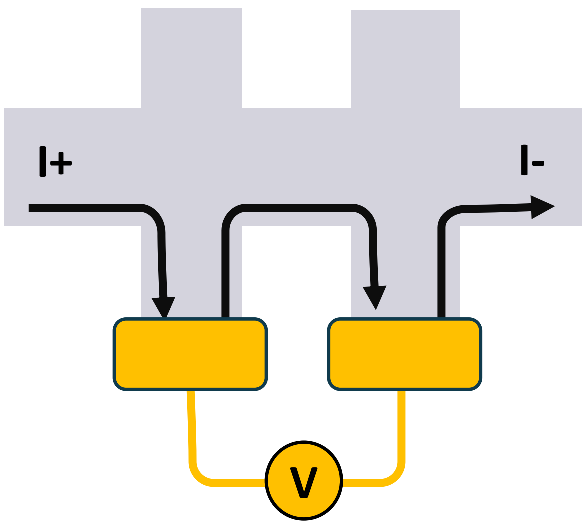
$$B_\mathrm{T} \gg 5\ \mathrm{T}$$

$$B_\mathrm{T} = B_\mathrm{z} + B_\mathrm{ps}$$

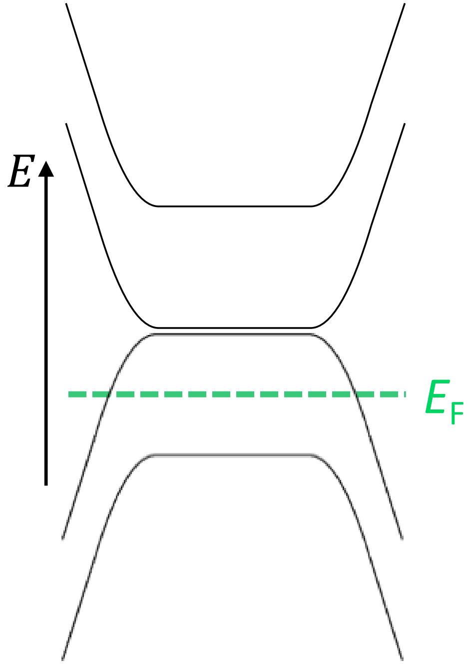
$$B_\mathrm{ps} \gg 5\ \mathrm{T}$$

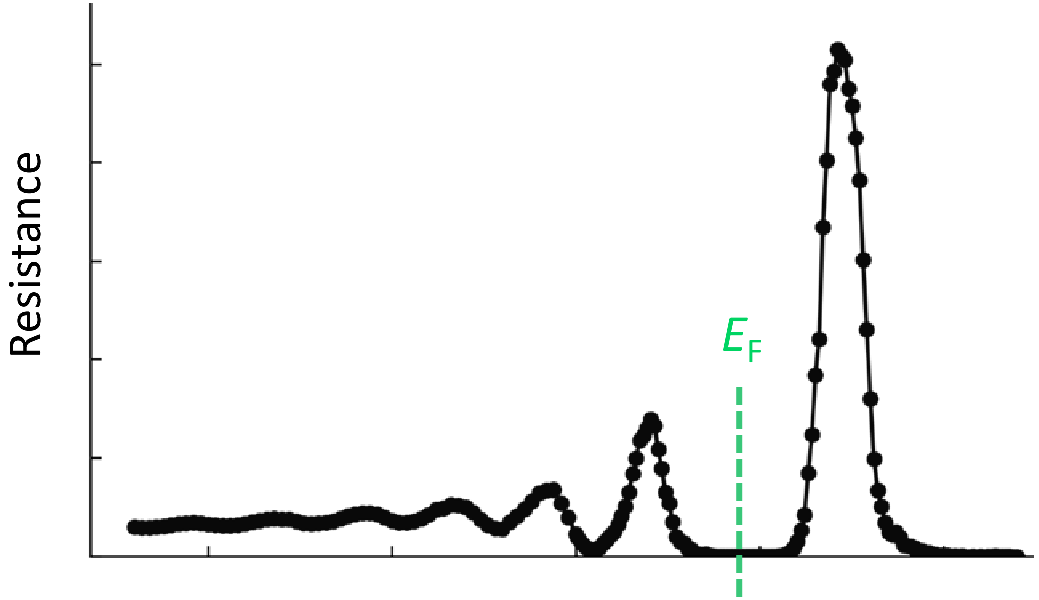


Chiral states



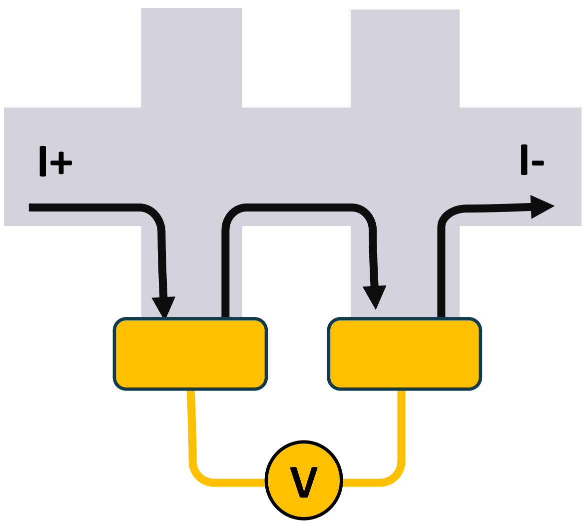
$R_{4T} = 0$



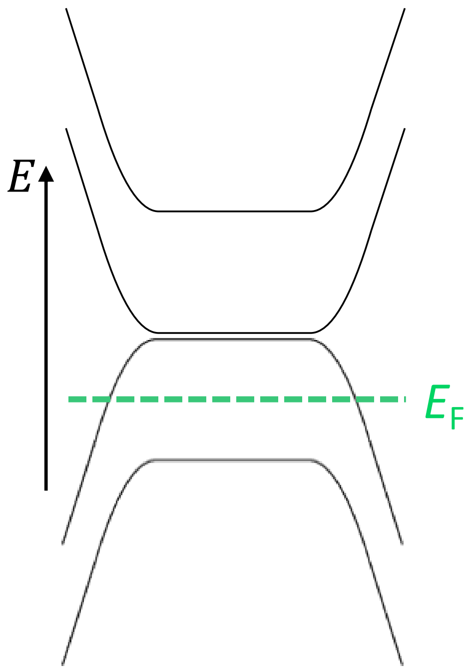


Chiral states vs. helical states

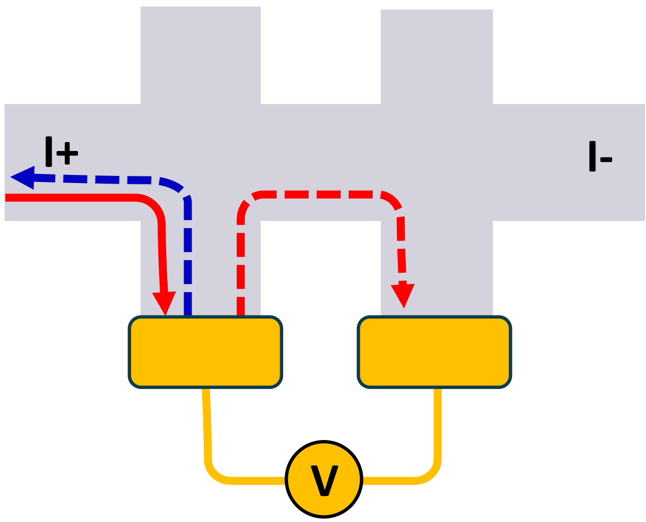
Chiral states



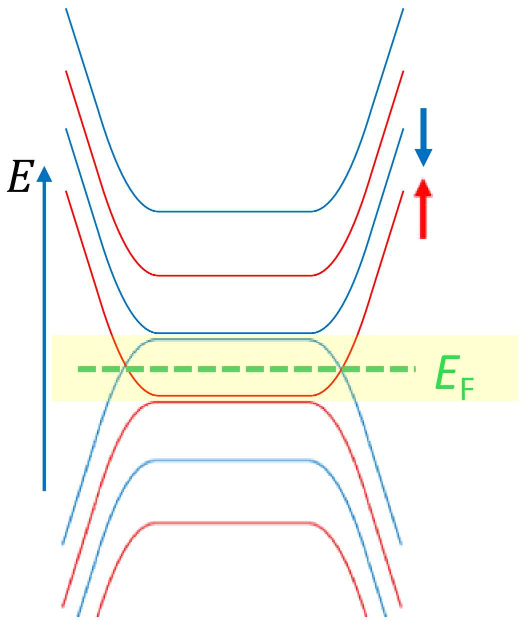
$R_{4T} = 0$



Helical states



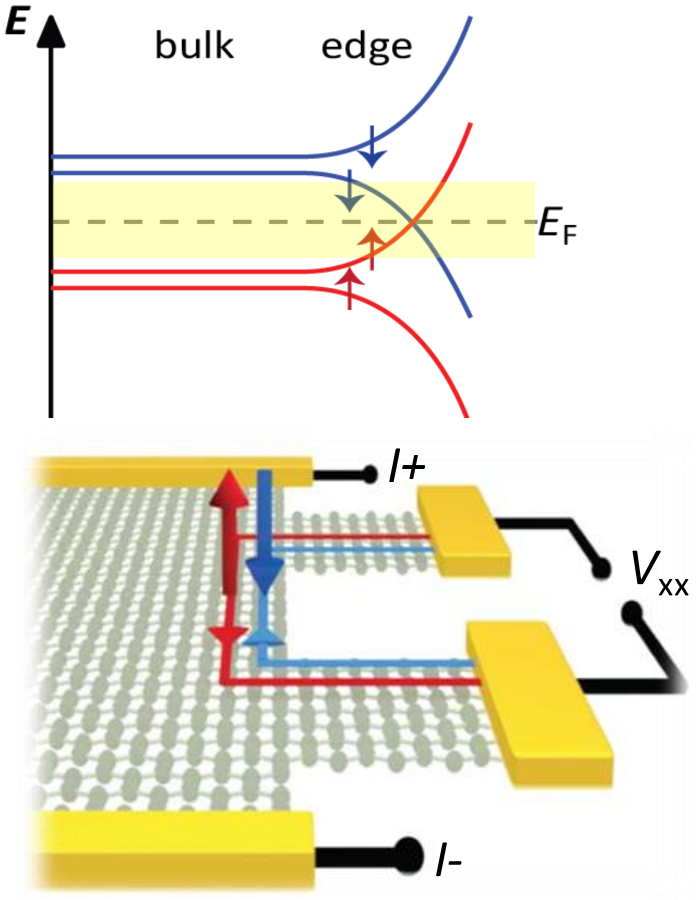
$R_{4T} \neq 0$



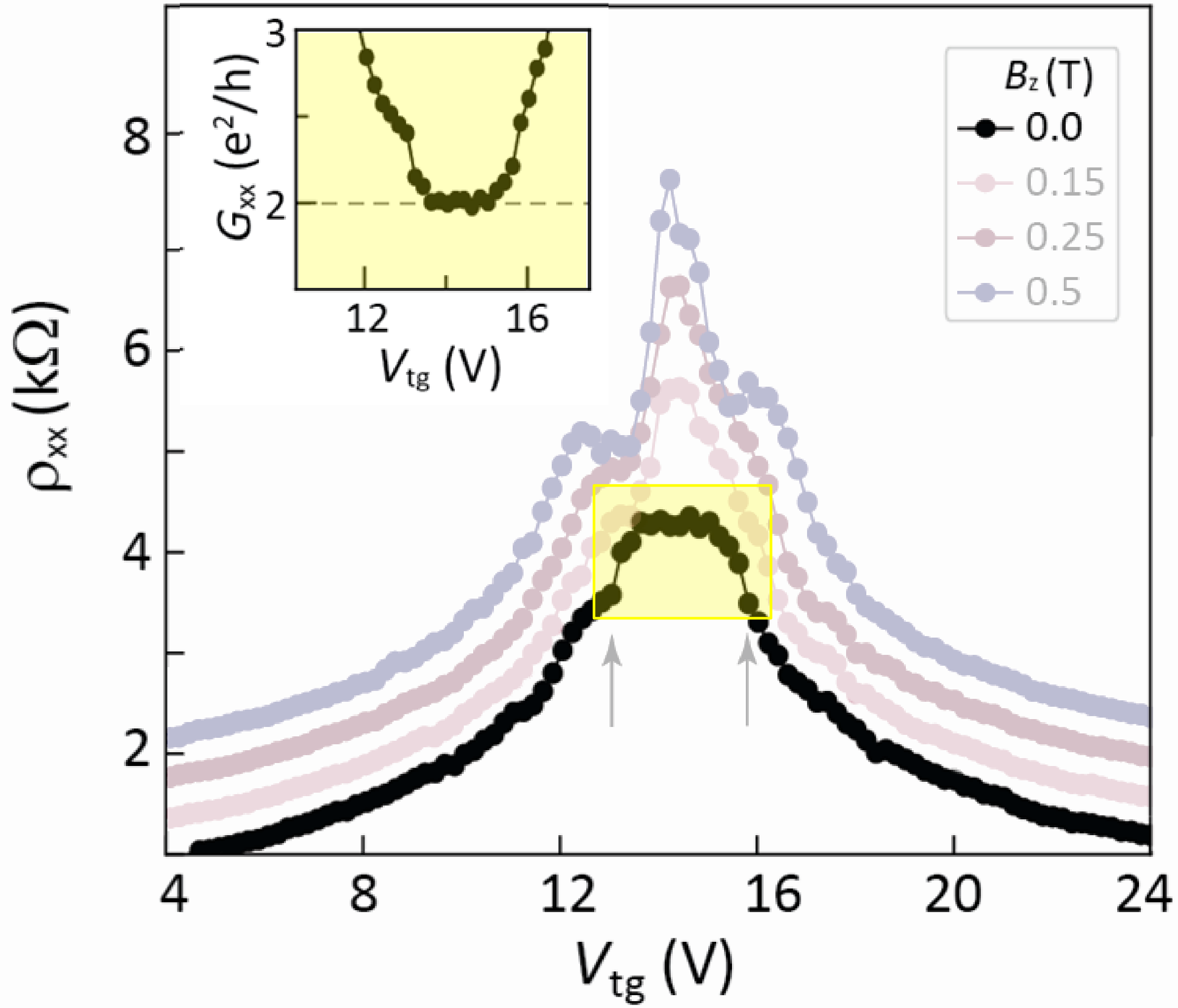
$$R_{2t} = \frac{h}{e^2}\left(\frac{1}{\mathrm{N_L}} + \frac{1}{\mathrm{N_R}}\right)^{-1}$$

$$R_{4t} = R_{2t}\frac{\mathrm{N_V}}{\mathrm{N_I}}$$

Quantum transport in magnetic graphene

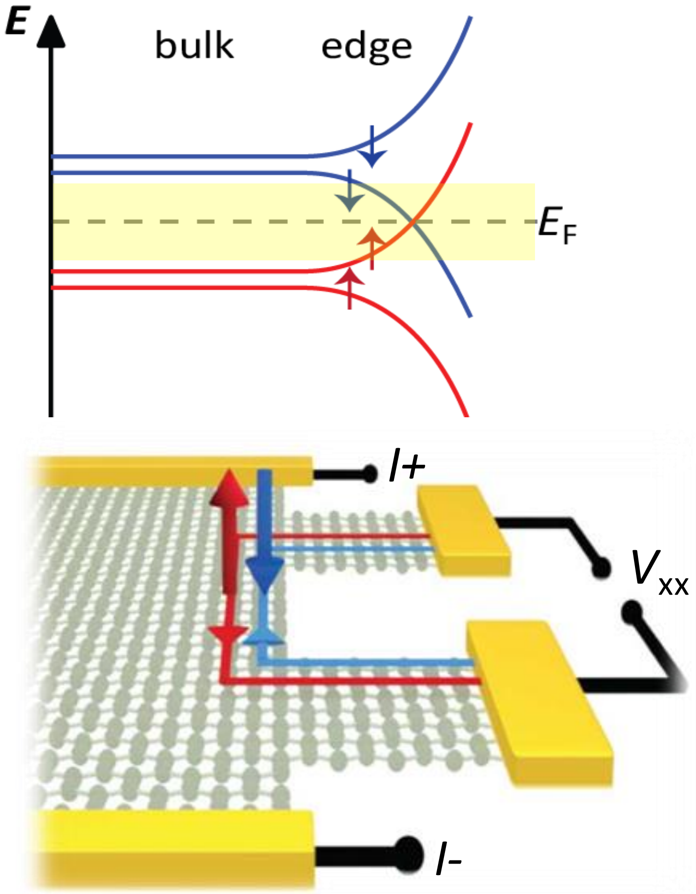


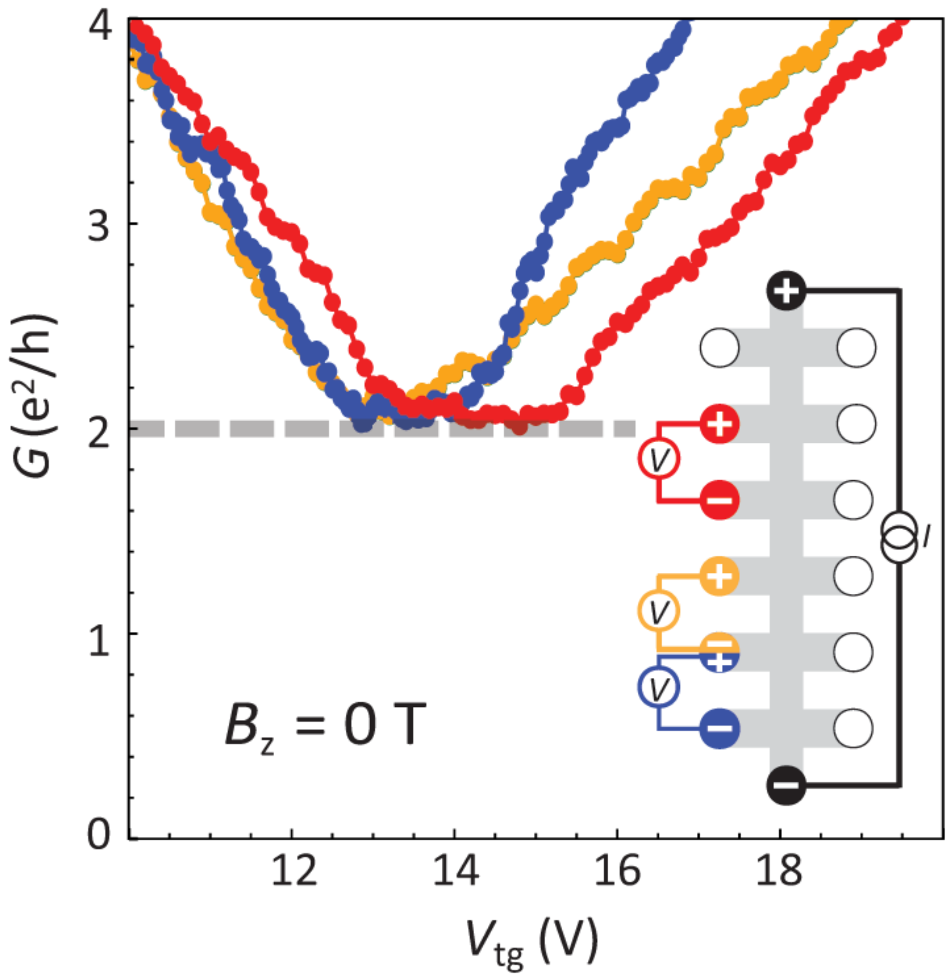
Spin-polarized (helical) quantum Hall states



T Ghiasi, et al. *arXiv:2312.07515* (2023)

Quantum anomalous spin Hall effect





Spin-polarized (helical) quantum Hall states

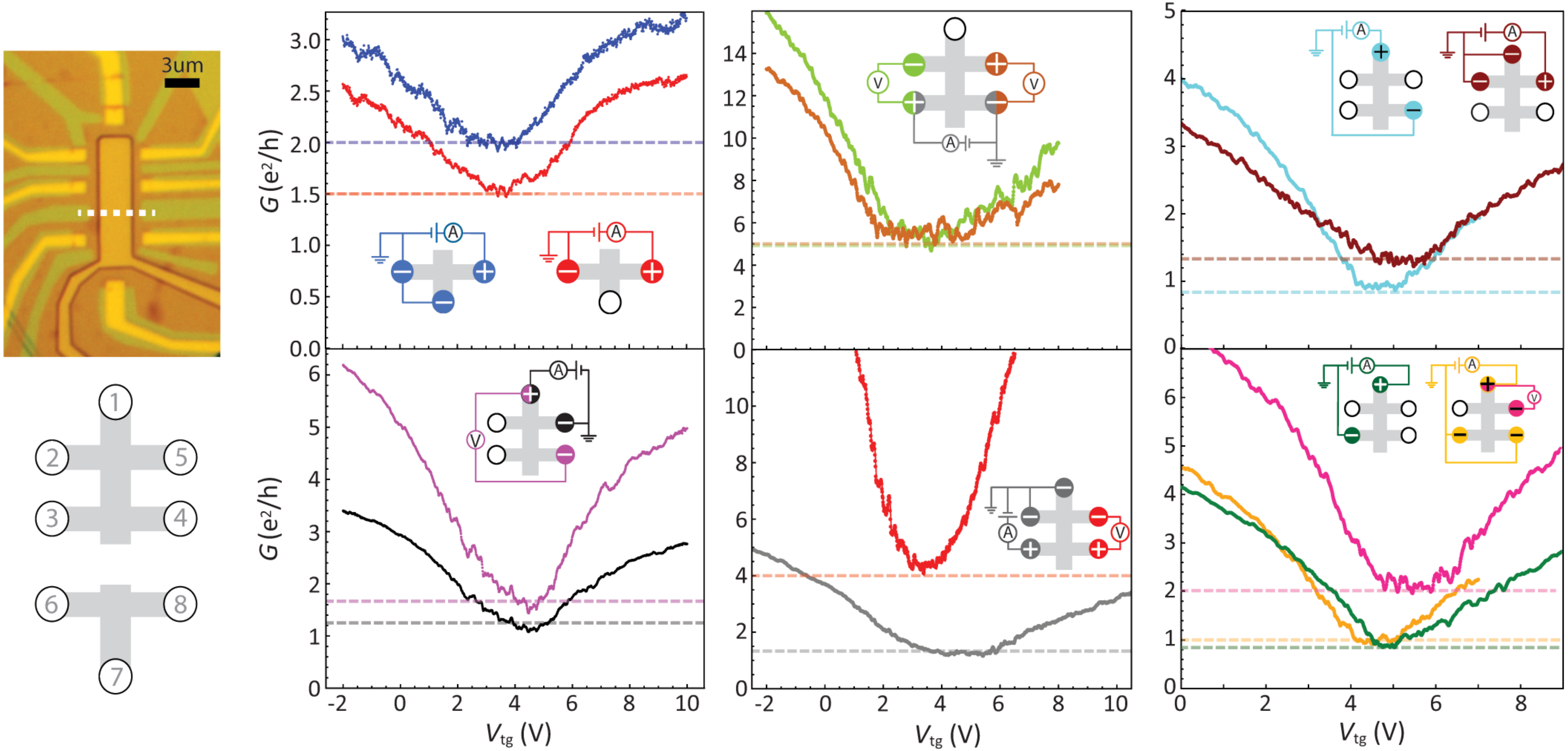
T Ghiasi, et al. *arXiv:2312.07515* (2023)

Quantum anomalous spin Hall effect

$B_z = 0$

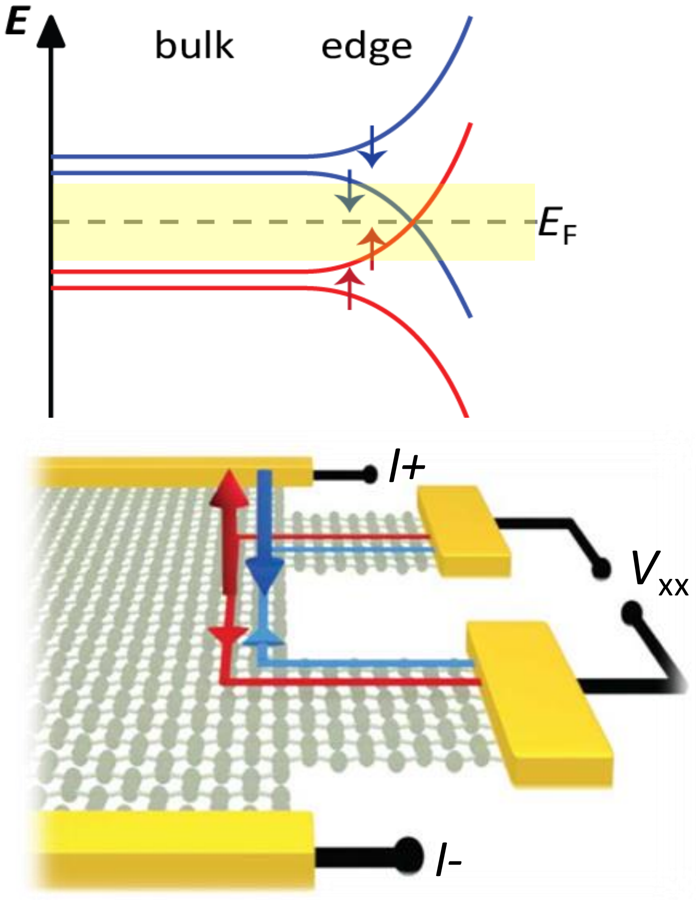
$$R_{2t} = \frac{h}{e^2}\left(\frac{1}{N_L} + \frac{1}{N_R}\right)^{-1}$$

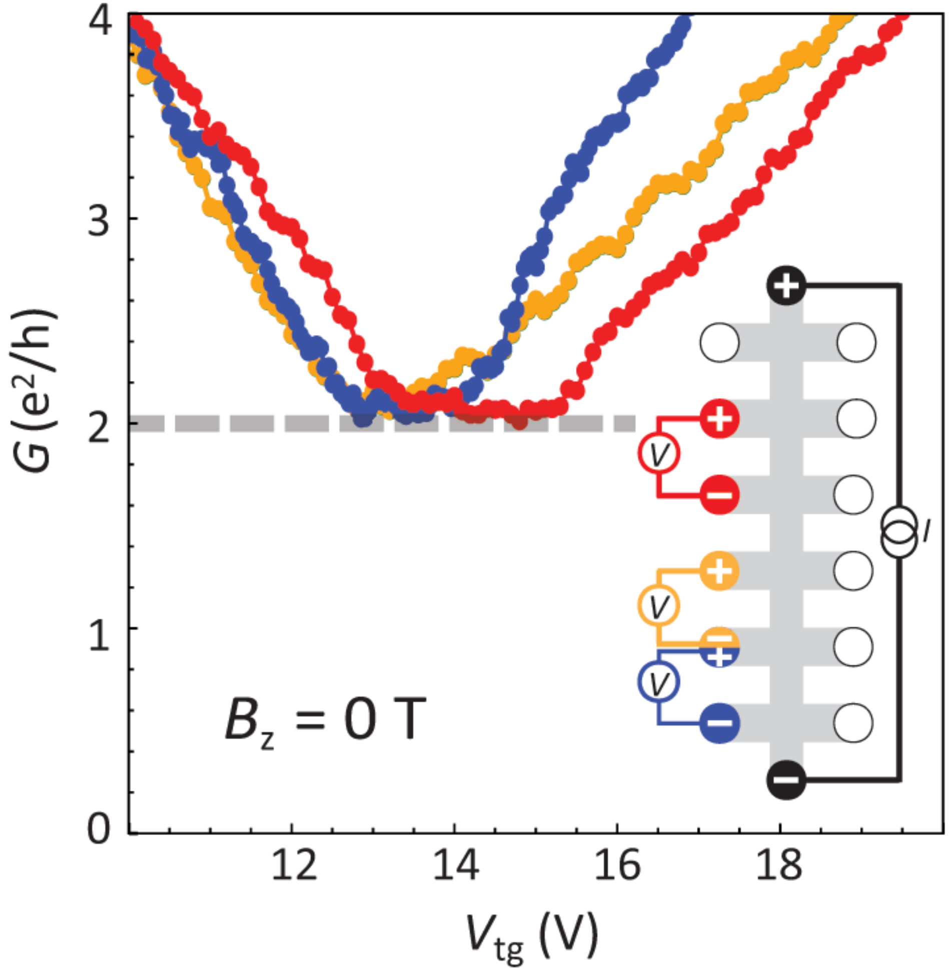
$$R_{4t} = R_{2t}\frac{N_V}{N_I}$$



T Ghiasi, et al. *arXiv:2312.07515* (2023)

Quantum anomalous spin Hall effect



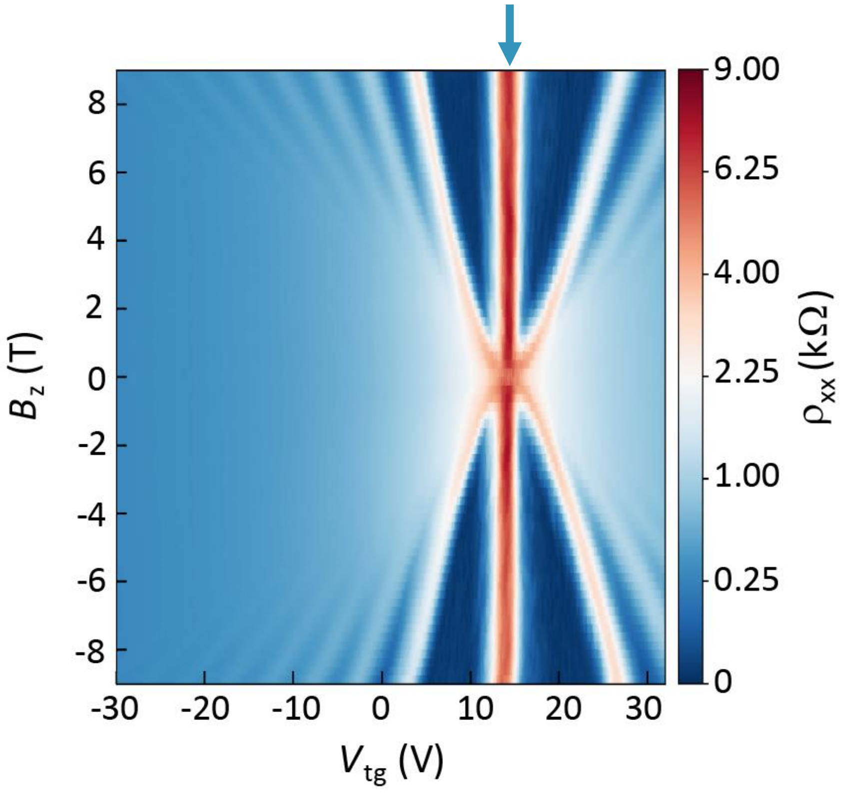


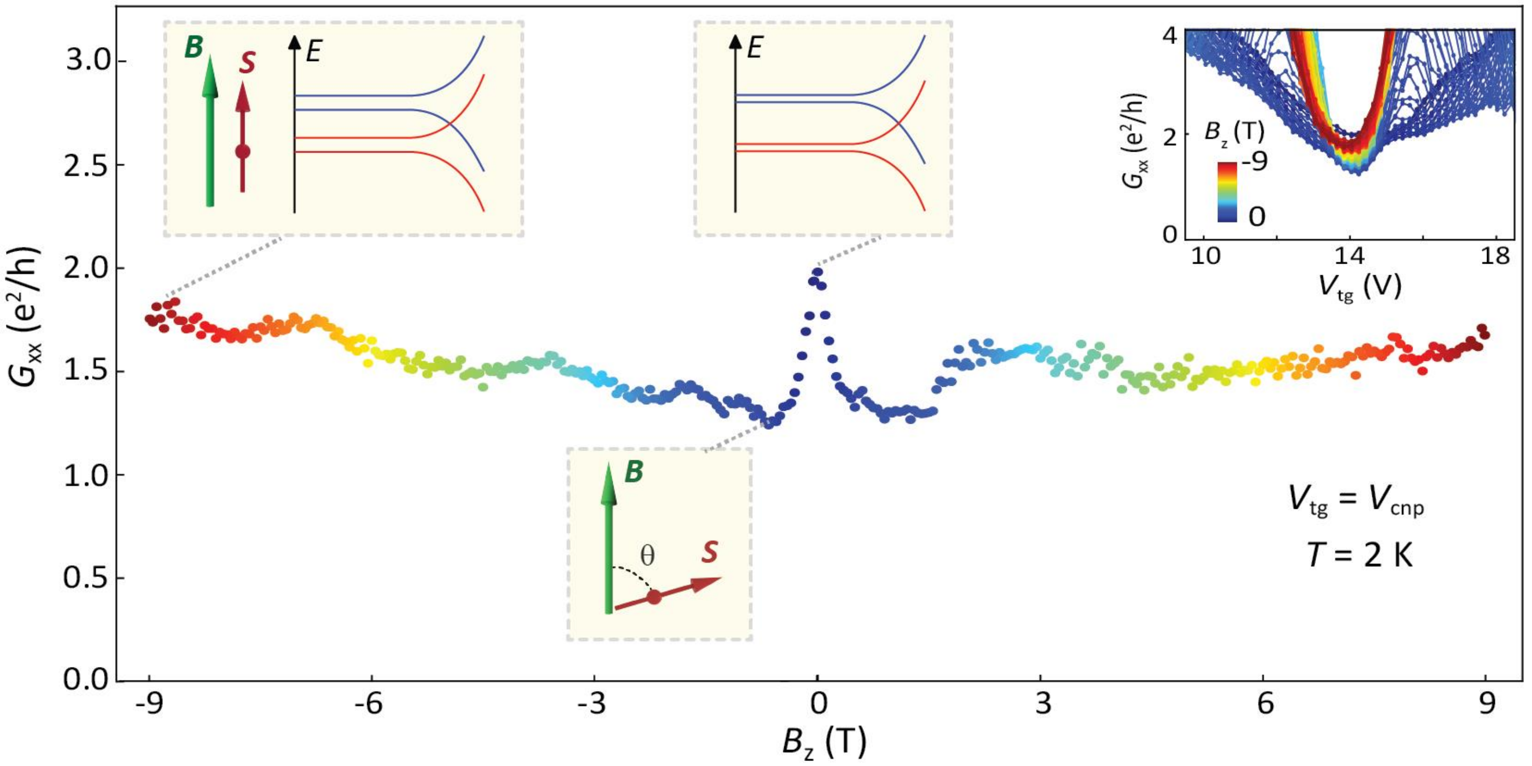
Spin-polarized (helical) quantum Hall states

T Ghiasi, et al. *arXiv:2312.07515* (2023)

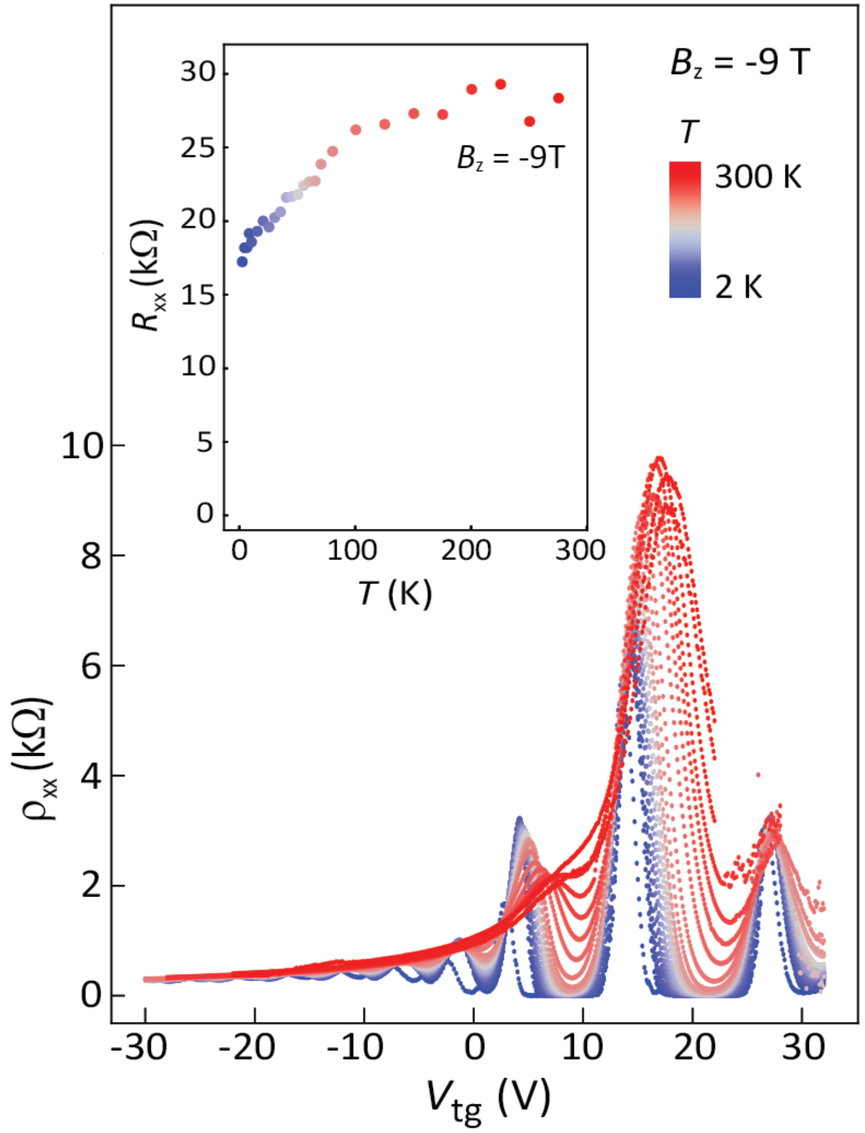
Quantum anomalous spin Hall effect

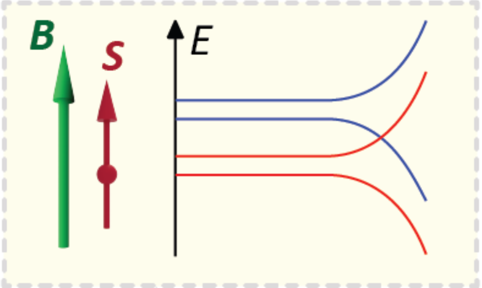
No considerable broadening



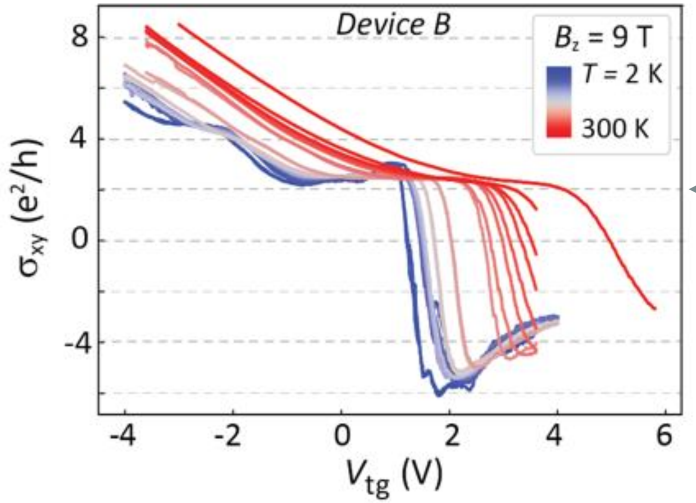


Quantum Hall transport in magnetic graphene



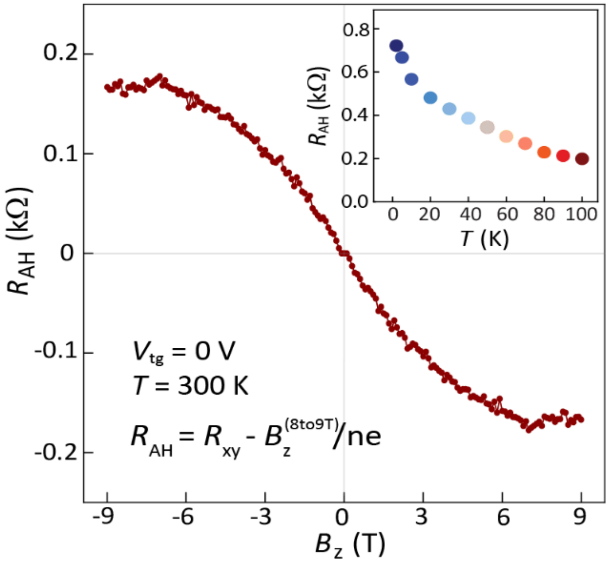


Room temperature QH transport



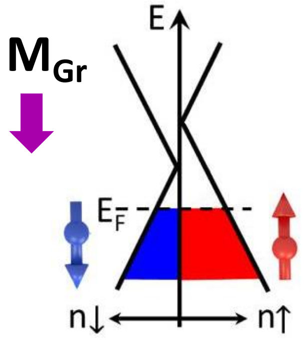
$2e^2/h$

Room temperature AHE



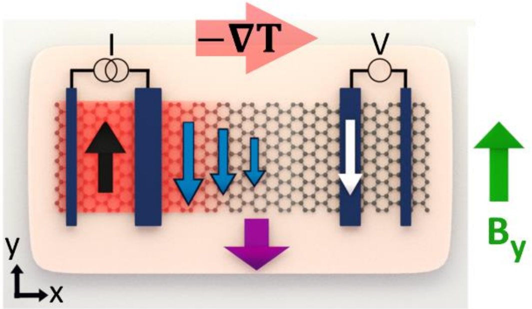
Graphene-based magnetic heterostructures for spintronic devices

- Strong spin-polarization of conductivity in graphene

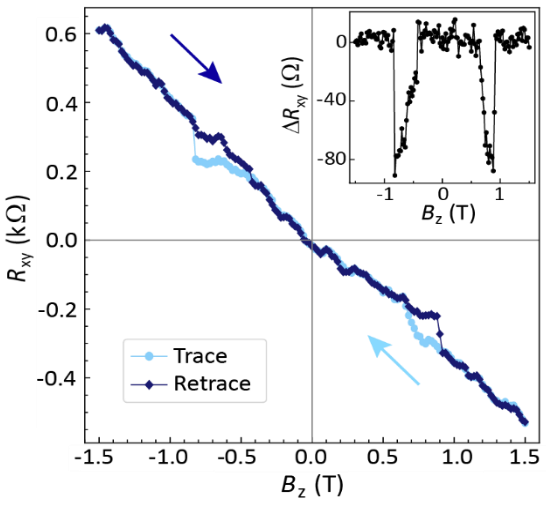


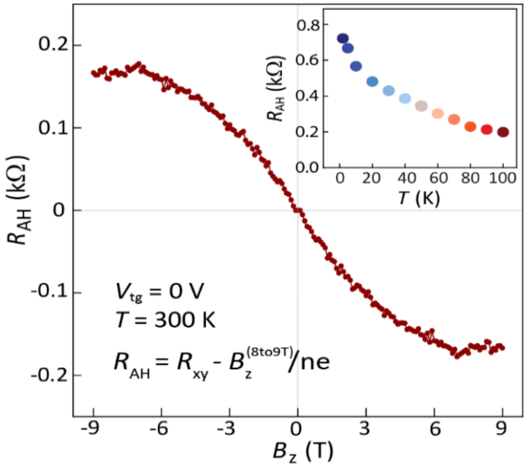
P_{Gr} = 14%

- Spin-dependent Seebeck effect

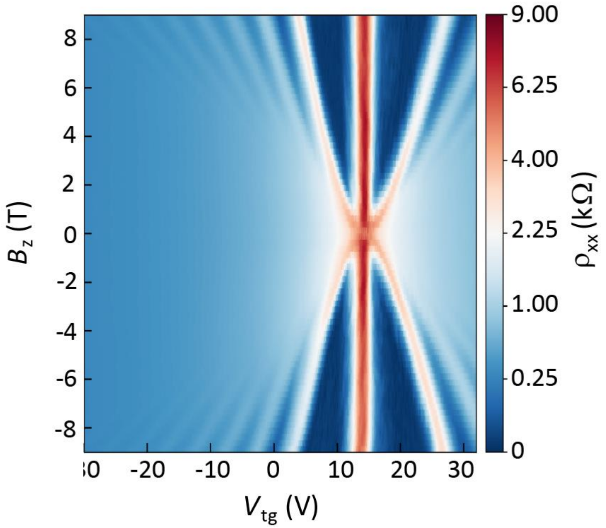


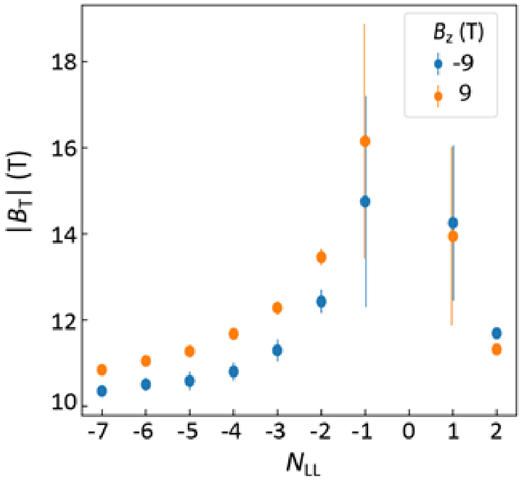
- Anomalous Hall effect



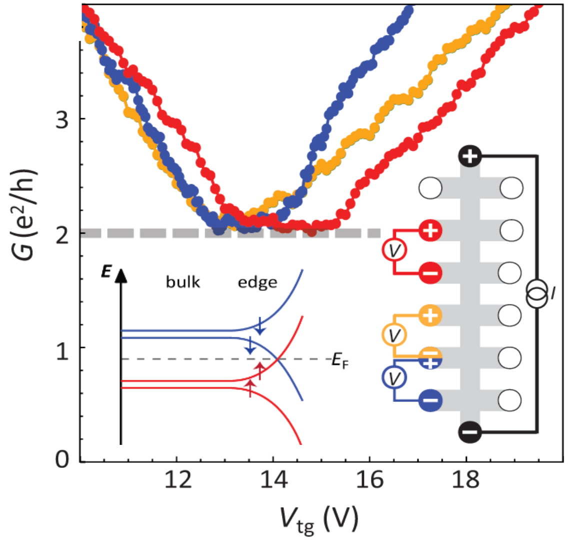


- Quantum Hall regime

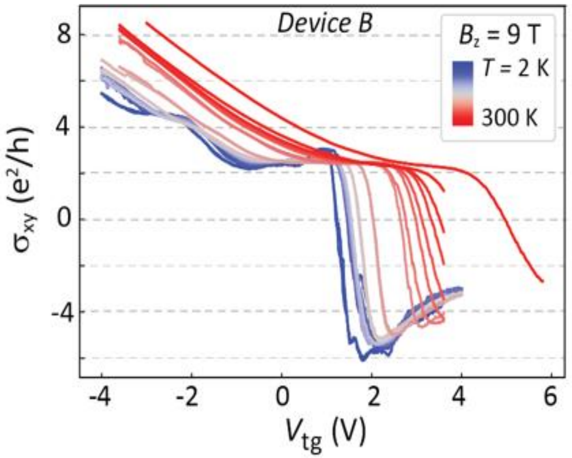




- Helical states at B = 0



- RT QH conductance



Acknowledgment

Alexey Kaverzin

Dennis de Wal

Bart van Wees

university of groningen

Davit Petrosyan

Josep Ingla Aynés

Herre van der Zant

TU Delft

Klaus Zollner

Jaroslav Fabian

UR Universität Regensburg

Avalon Dismukes

Xavier Roy

Columbia University in the City of New York

Samuel Mañas-Valero

Eugenio Coronado

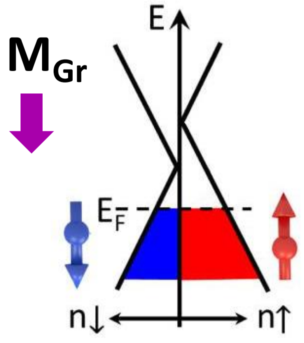
Vniversitat de València

Philip Kim

Harvard University

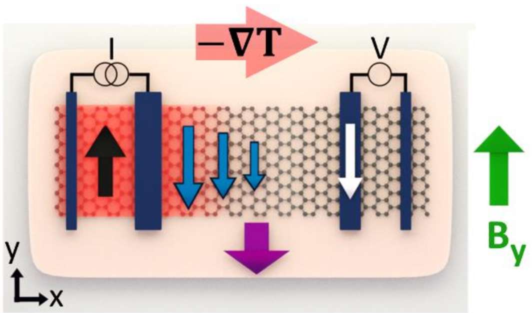
Graphene-based magnetic heterostructures for spintronic devices

- Strong spin-polarization of conductivity in graphene

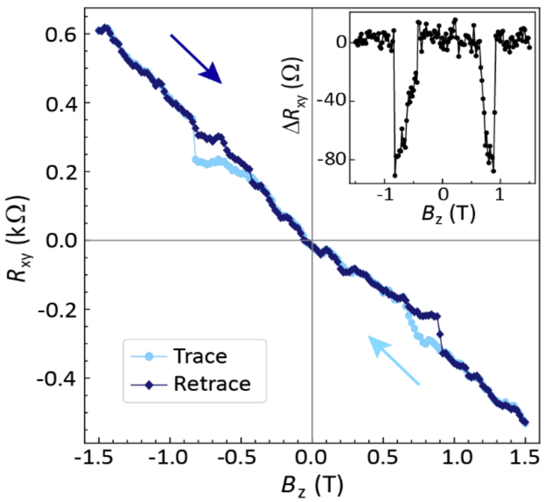


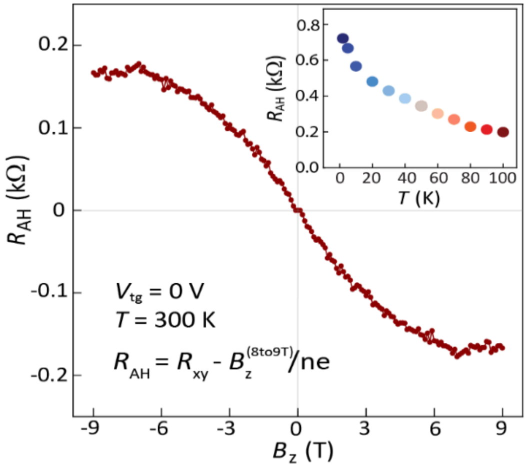
P_{Gr} = 14%

- Spin-dependent Seebeck effect

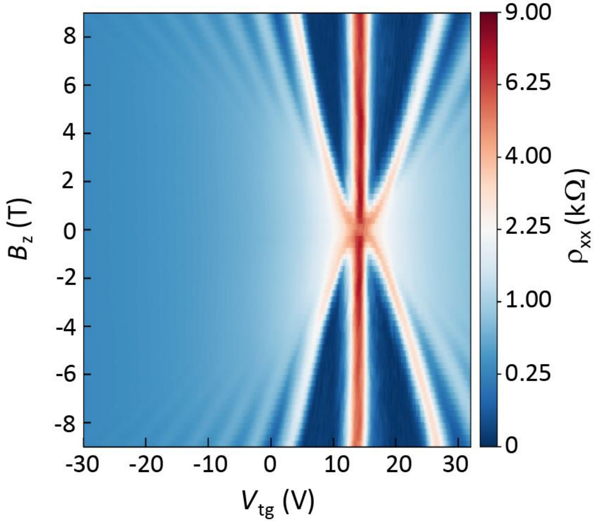


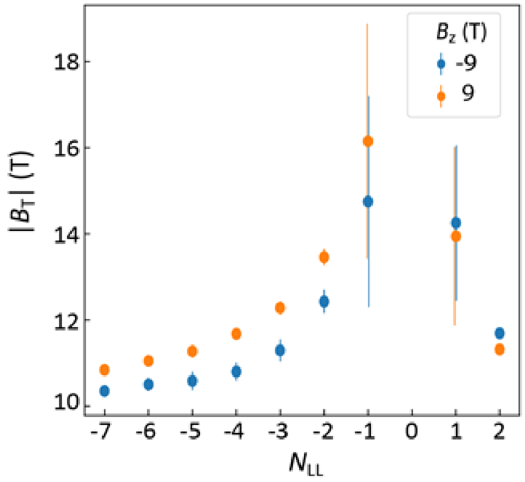
- Anomalous Hall effect



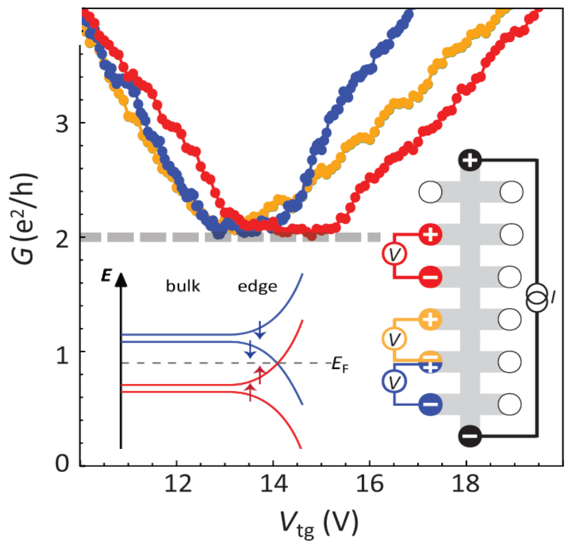


- Quantum Hall regime





- Helical states at B = 0



- RT QH conductance