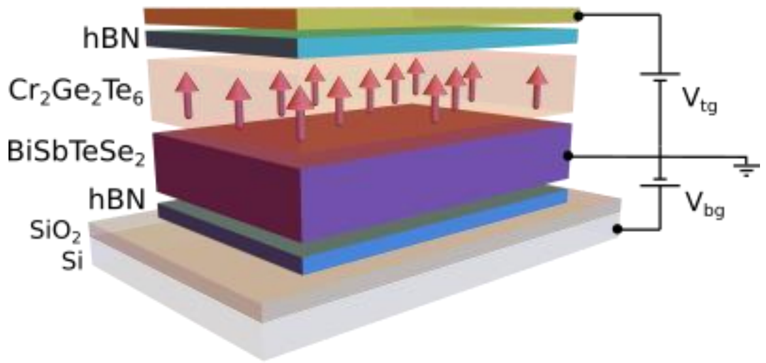
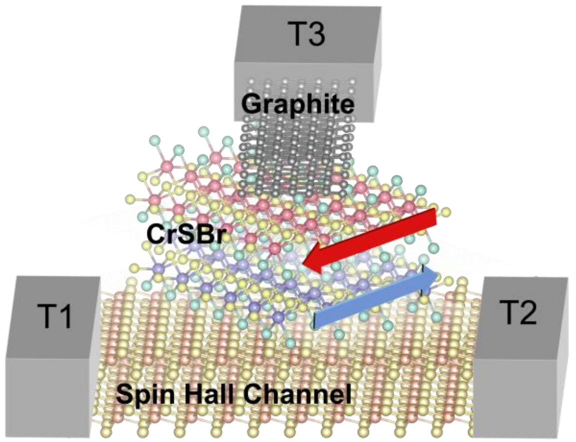
van der Waals Magnets and Antiferromagnets Interacting with Electron Spins

Cornell University



Rakshit Jain, Matthew Roddy, Vishakha Gupta, Benjamin Huang, Hasan M. Sayeed, Husain F. Alnaser, Amit Vashist, Kenji Watanabe, Takashi Taniguchi, Vikram V. Deshpande, Taylor D. Sparks, DCR

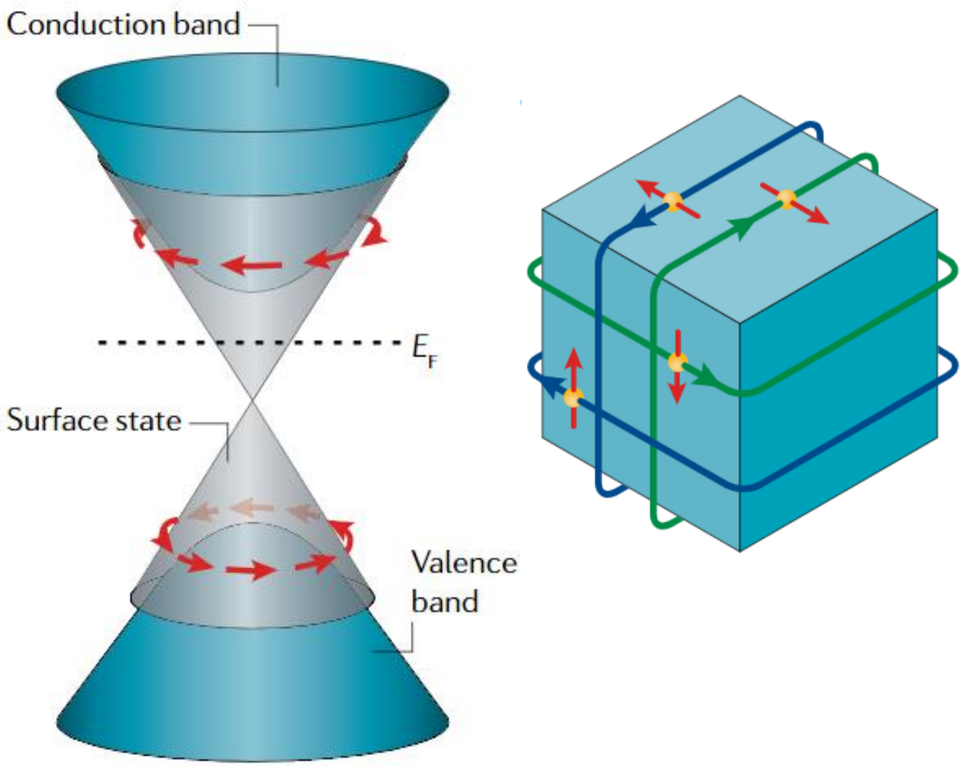
Thow Min Jerald Cham, Daniel G. Chica, Xiaoxi Huang, Kenji Watanabe, Takashi Taniguchi, Xavier Roy, **Yunqiu Kelly Luo**, DCR



Two Stories Today:

- Mechanically-assembled topological insulator/magnet structures can give much stronger exchange gaps in the topological surface state compared to deposited structures – quantized anomalous Hall effects above 10 K.
- Detection of antiferromagnetic resonance dynamics in micron-scale structures with control by spin-orbit torque.

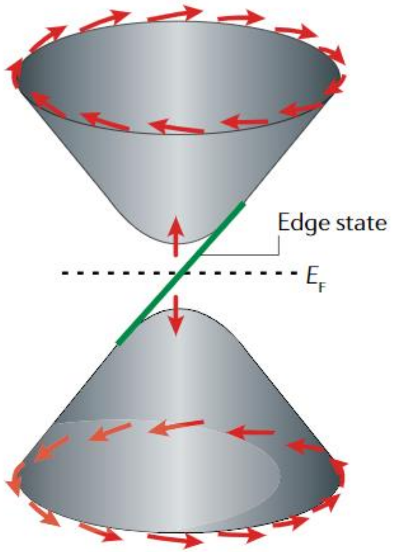
3D Topological Insulators



Tokura, Y., Yasuda, K. & Tsukazaki, A.
Nat Rev Phys **1**, 126 (2019)

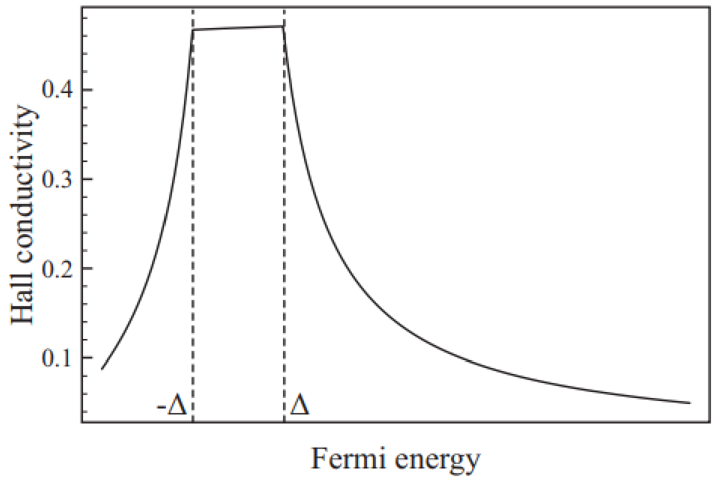
- If E_F lies in the bulk bandgap, topological insulator is insulating in the bulk but has conducting surface states
- These topological surface states have massless Dirac dispersion, spin-momentum locking

3D Topological Insulators with Magnetic Interactions

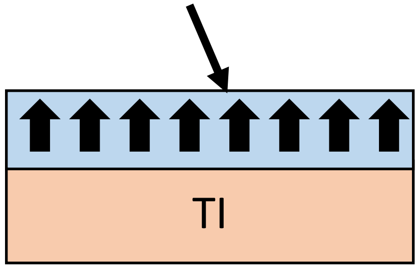


Coupling of a topological surface state to out-of-plane oriented magnetization opens an exchange gap and induces Berry curvature with an associated anomalous Hall effect.

If Fermi level is within the exchange gap and k_BT is less than the exchange gap width, have a quantized Hall conductivity.



Can be done with magnetic dopants or proximity coupling to an adjacent magnetic layer



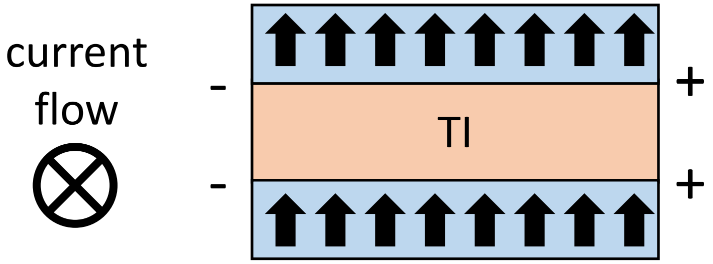
“parity anomaly state”

For a magnetic layer on **<u>one side</u>** of the TI,

$$\sigma_{xy} = \frac{e^2}{2h}$$

Longitudinal conductivity is not zero, due to conductance in the other, ungapped surface of the TI.

Quantized Anomalous Hall Effects With Two Magnetic Layers



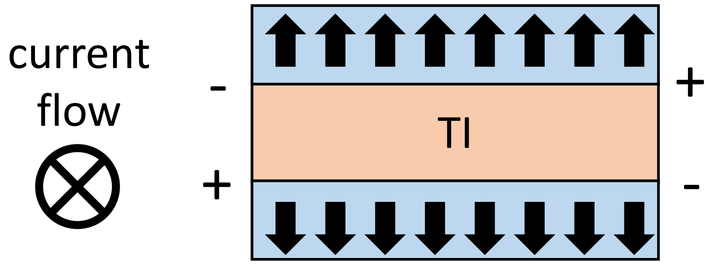
Magnetic layers on both sides, oriented parallel:

Quantized Hall conductance $\sigma_{xy} = 2 \times \frac{e^2}{2h} = \frac{e^2}{h}$

Can have zero longitudinal conductivity and resistance.

Dissipationless chiral edge states.

Properties analogous to quantum Hall effect, but at zero applied magnetic field.



Magnetic layers on both sides, oriented antiparallel:

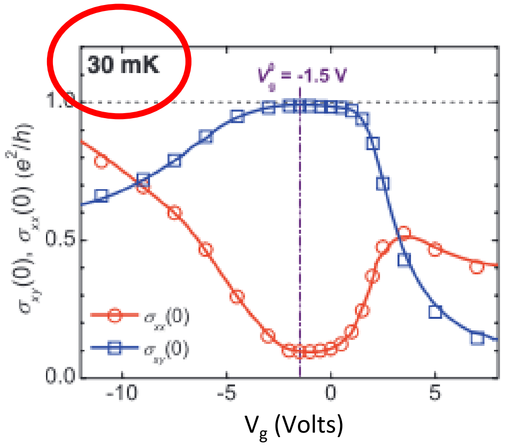
Hall conductance = 0

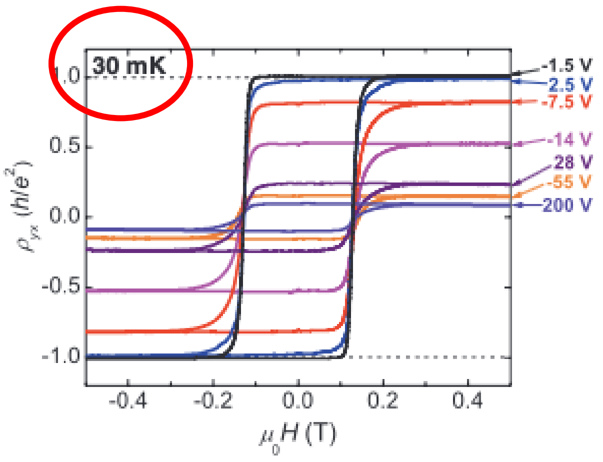
Very high resistance. Magnetoresistance ratio ~ 10^5 - 10^7% at low T.

"Axion insulator" state.

Previous Realizations: Quantization at zero magnetic field observed only at temperatures below 4.2 K.

First demonstration: C.-Z. Chang et al., *Science* **340**, 167 (2013); in uniformly Cr-doped topological-insulator films





First experiments, quantization only below 100 mK, later improvements in sample quantity allow up to ~ 4 K.

Other realizations: intrinsic topological antiferromagnet $MnBi_2Te_4$, moiré graphene and $MoTe_2/WSe_2$ layers (fractional quantum anomalous Hall effect also observed recently in moiré systems), but all at less than ~2 K.

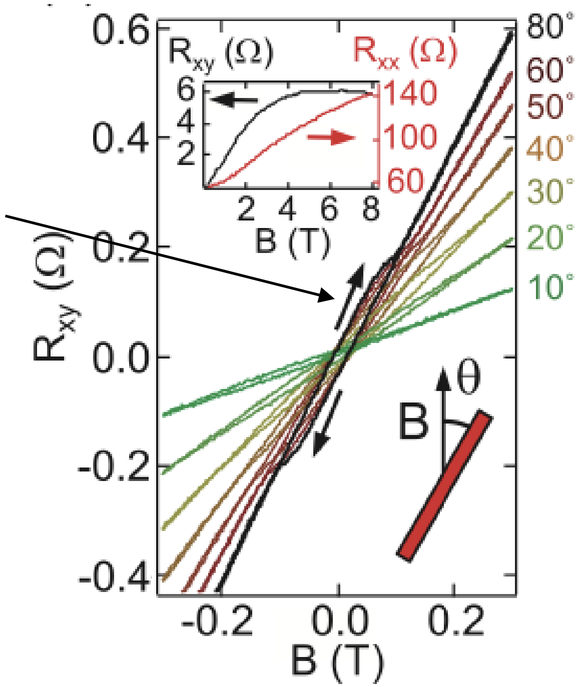
Proximity-coupled topological insulator/magnet systems: Attempts with deposited heterostructures

Coupling a topological insulator to a separate magnetic layer is attractive for going to higher temperatures. However, achieving strong coupling of a topological surface state to a separate magnet using top-down deposition has been frustrating.

(Nice review by S. Bhattacharyya et al., *Adv. Mater*. **33**, 2007795 (2021).)

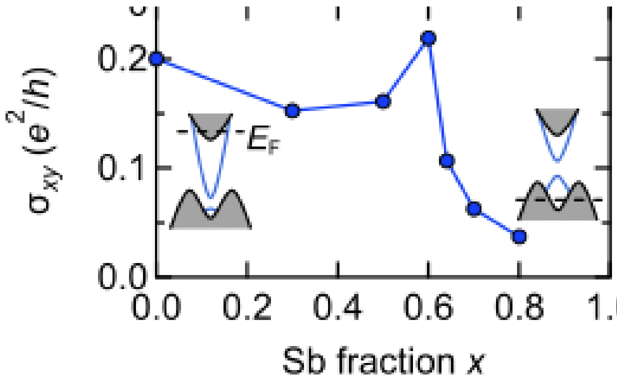
MBE $Bi_2Te_3/Cr_2Ge_2Te_6$

far below quantized value



Appl. Phys. Lett. **105**, 053512 (2014)

MBE $Cr_2Ge_2Te_6/(Bi_{1-x}Sb_x)_2Te_3/Cr_2Ge_2Te_6$

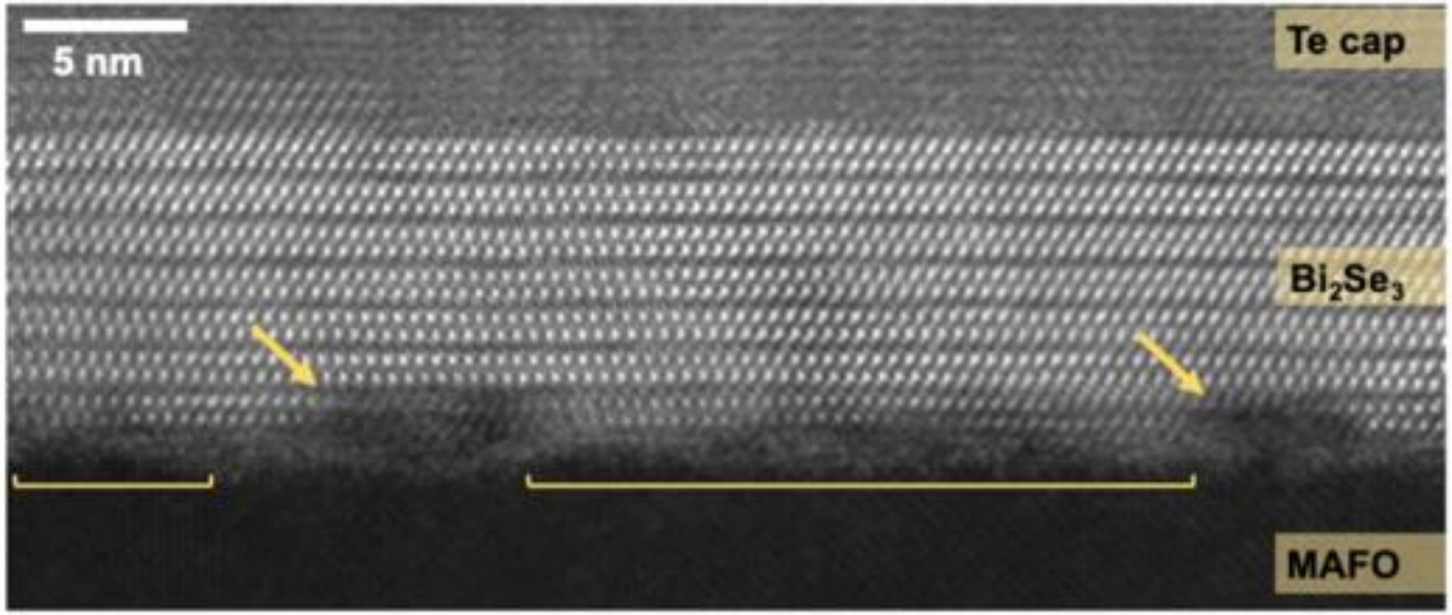


1/5 of quantized value at 2 K

Phys. Rev. Lett. ***123***, *016804 (2019)*

A quantized Hall signal has been measured only once in a deposited proximity TI/magnet sample, below 0.1 K in $Zn_{1-x}Cr_xTe/(Bi,Sb)Te_3/ Zn_{1-x}Cr_xTe$

Why is This So Difficult?



L. J. Riddiford et al.,
Phys. Rev. Lett. **128**, 126802 (2022)

- Interdiffusion and interface disorder are very difficult to avoid at interfaces within deposited heterostructures.

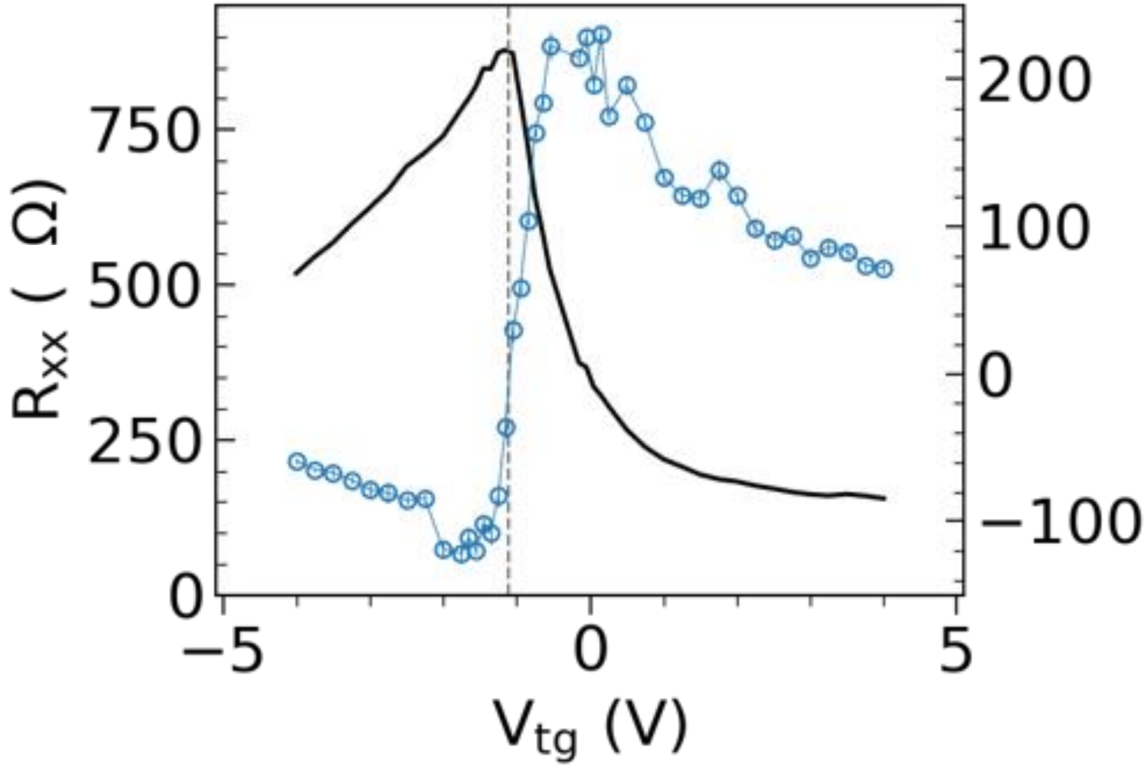
- Disorder at a TI/magnet interface will push a topological surface state toward the bulk of the TI and suppress the exchange coupling to an adjacent magnet.

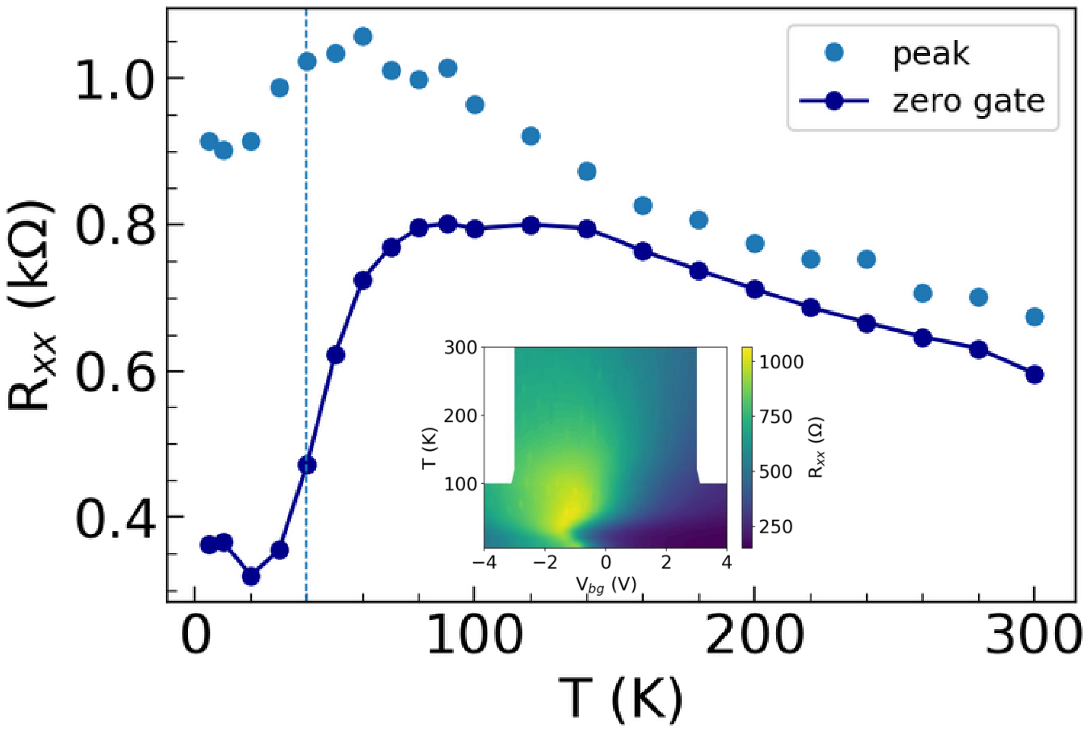
Can we do better by mechanical stacking of exfoliated layers?

→ **Pristine Interfaces with no intermixing**

Characterization of $BiSbTeSe_2$ flakes

from the group of Taylor Sparks, Univ. of Utah

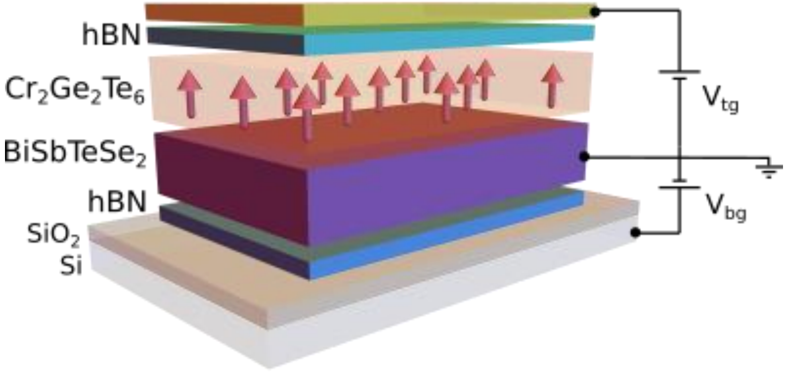


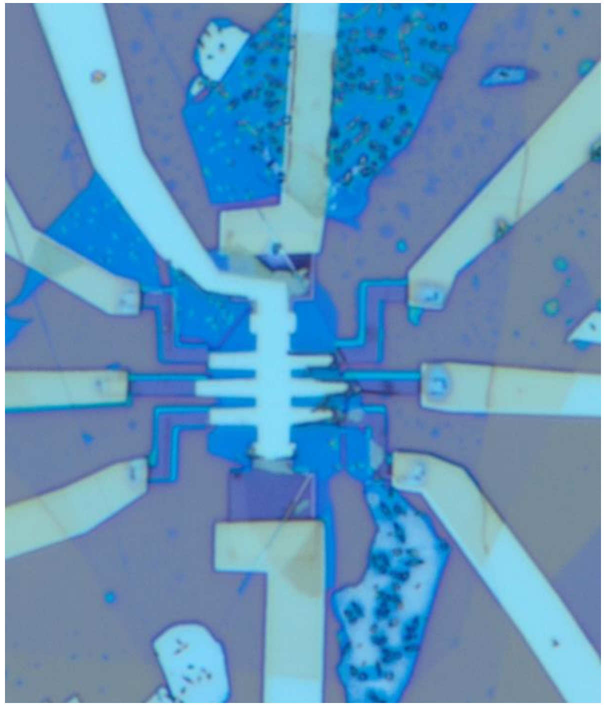


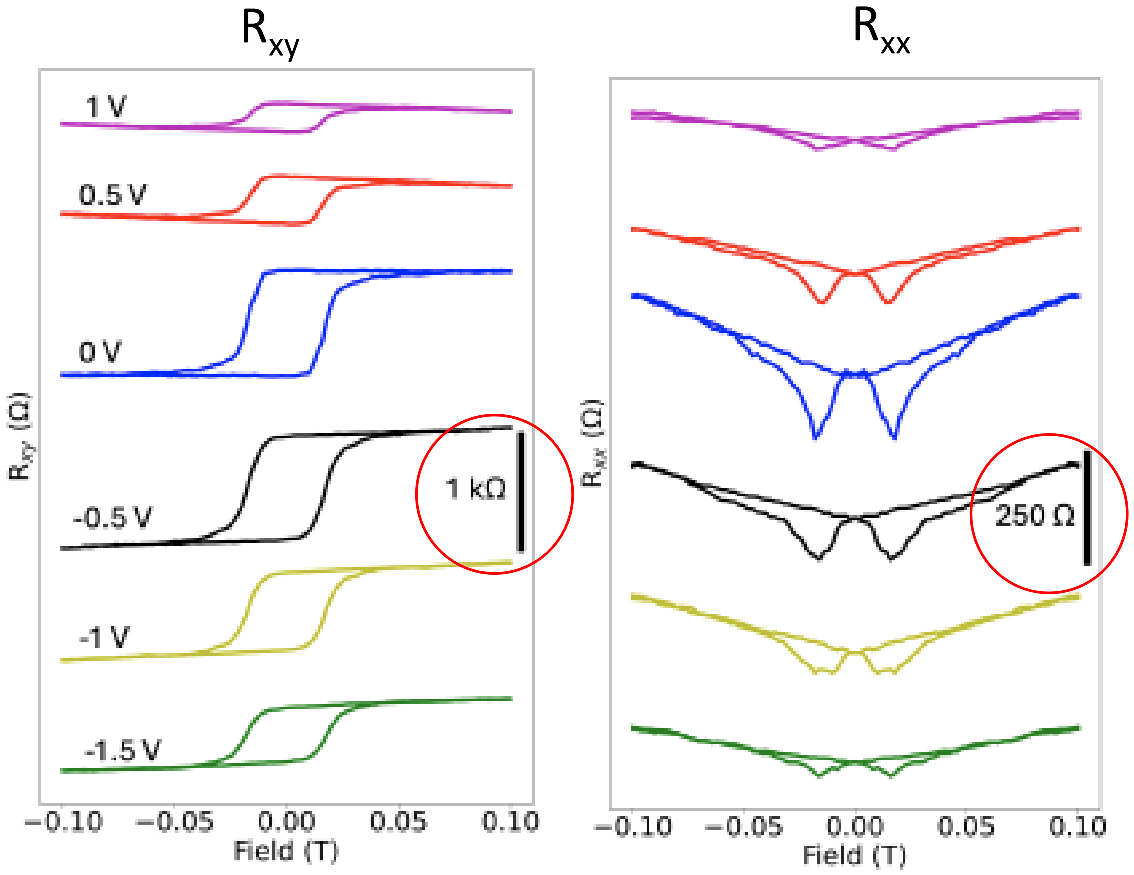
- Fermi level lies in the bulk gap, close to Diract point. Ambipolar transport accessed by electrostatic gate.

- Transport dominated by metallic surfaces below 40-60 K with **mobilities 100 times more than epitaxial magnetically-doped samples.**

Measurements of $BiSbTeSe_2/Cr_2Ge_2Te_6$ in well-defined Hall bars







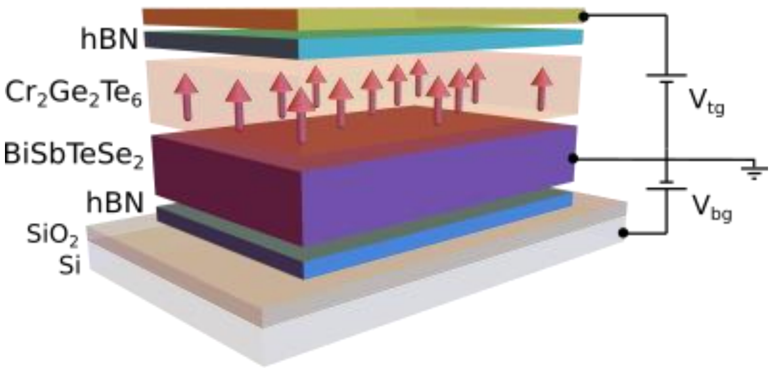
4.2 K

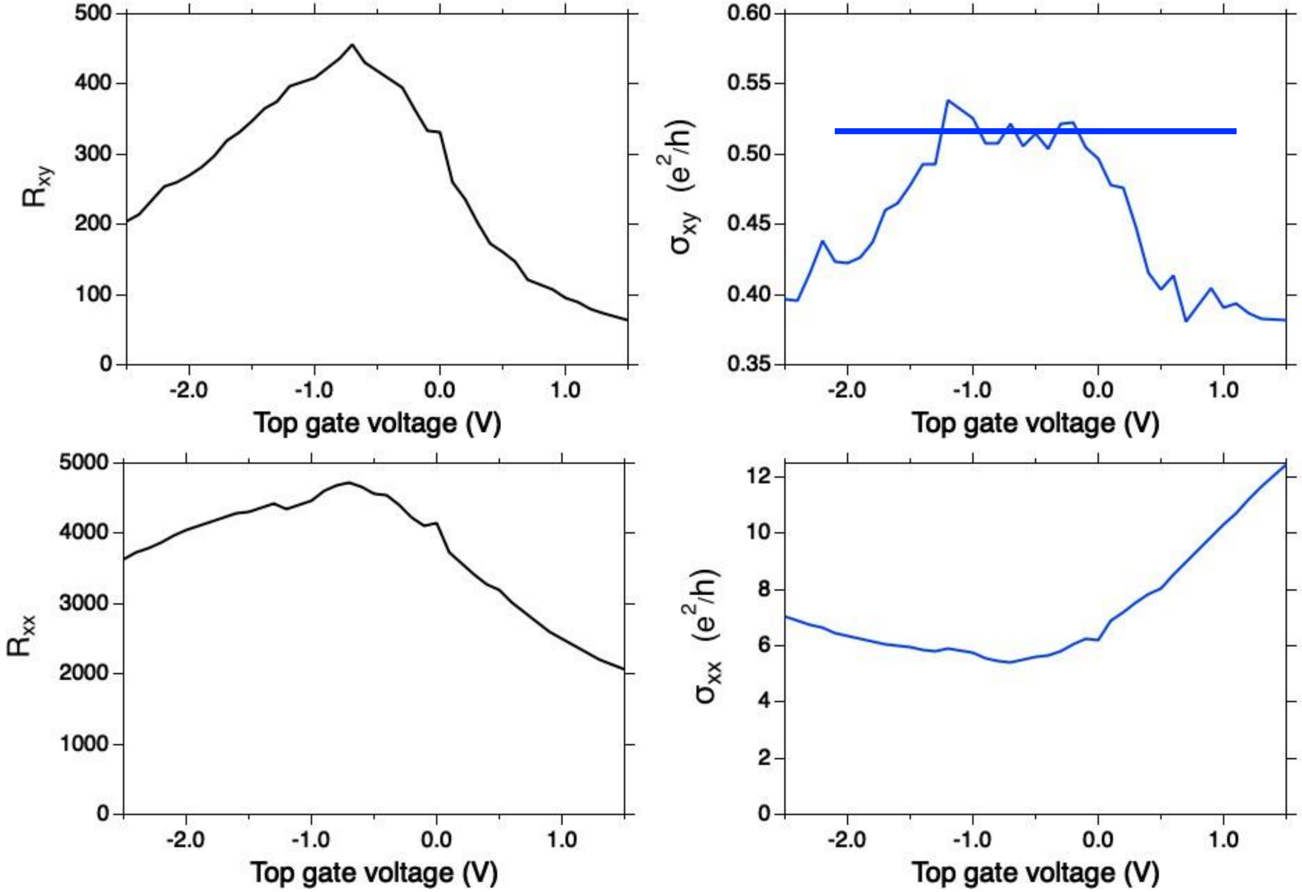
R. Jain et al., arXiv:2412.05380

Quantitative measurements on mechanically-assembled $BiSbTeSe_2/Cr_2Ge_2Te_6$ samples

$$\sigma_{xy} = \frac{\rho_{xy}}{\rho_{xy}^2 + \rho_{xx}^2}; \sigma_{xx} = \frac{\rho_{xx}}{\rho_{xy}^2 + \rho_{xx}^2}.$$

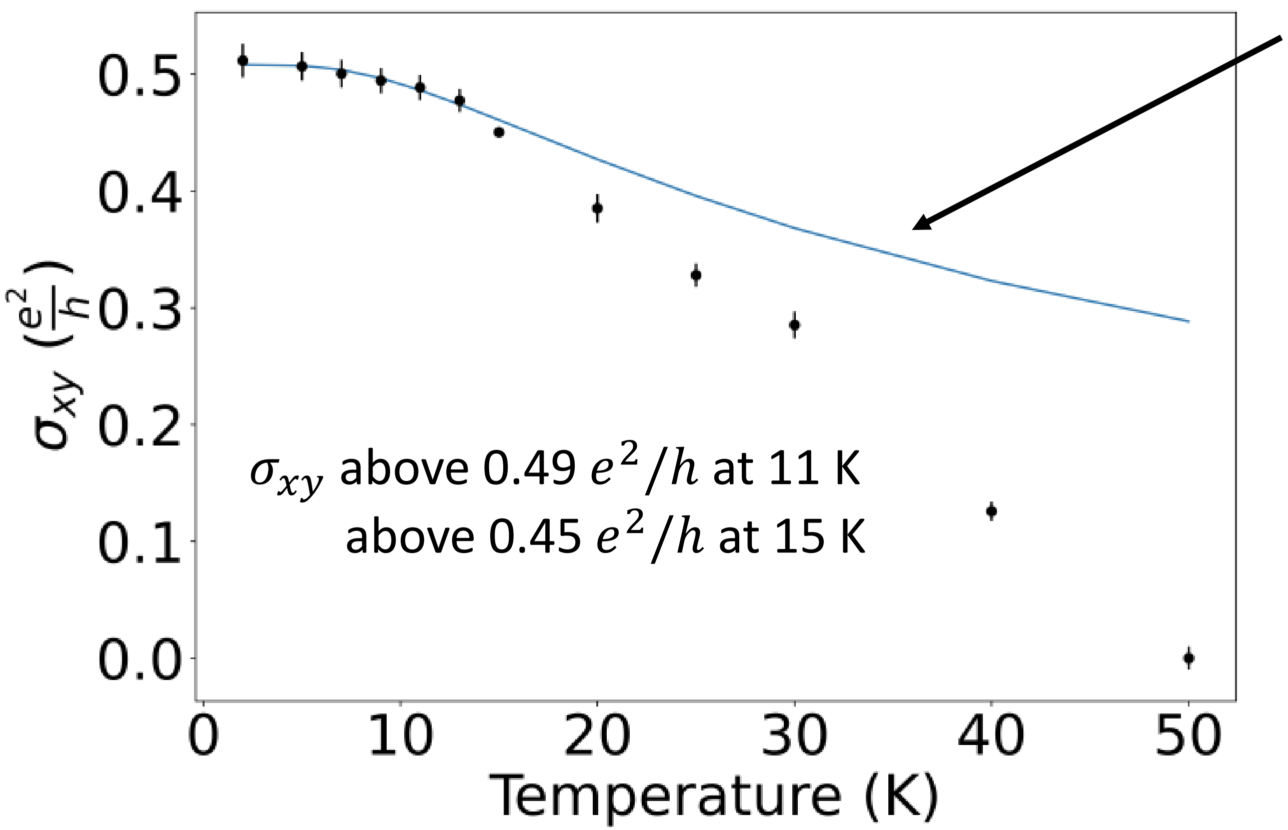
4.2 K





R. Jain et al., arXiv:2412.05380

Measured Temperature Dependence of Hall Conductivity



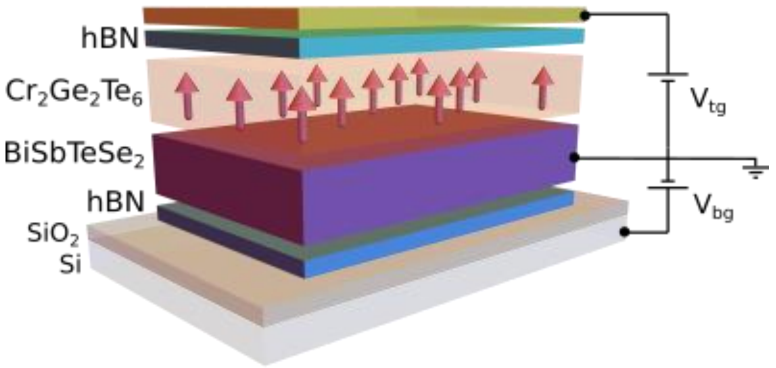
Fit to thermal activation across a fixed exchange gap.

Lesson: Exchange gap appears to be decreasing with increasing temperature in the range where the Hall conductivity is temperature-dependent.

Lower bound on exchange gap = 4.5 meV

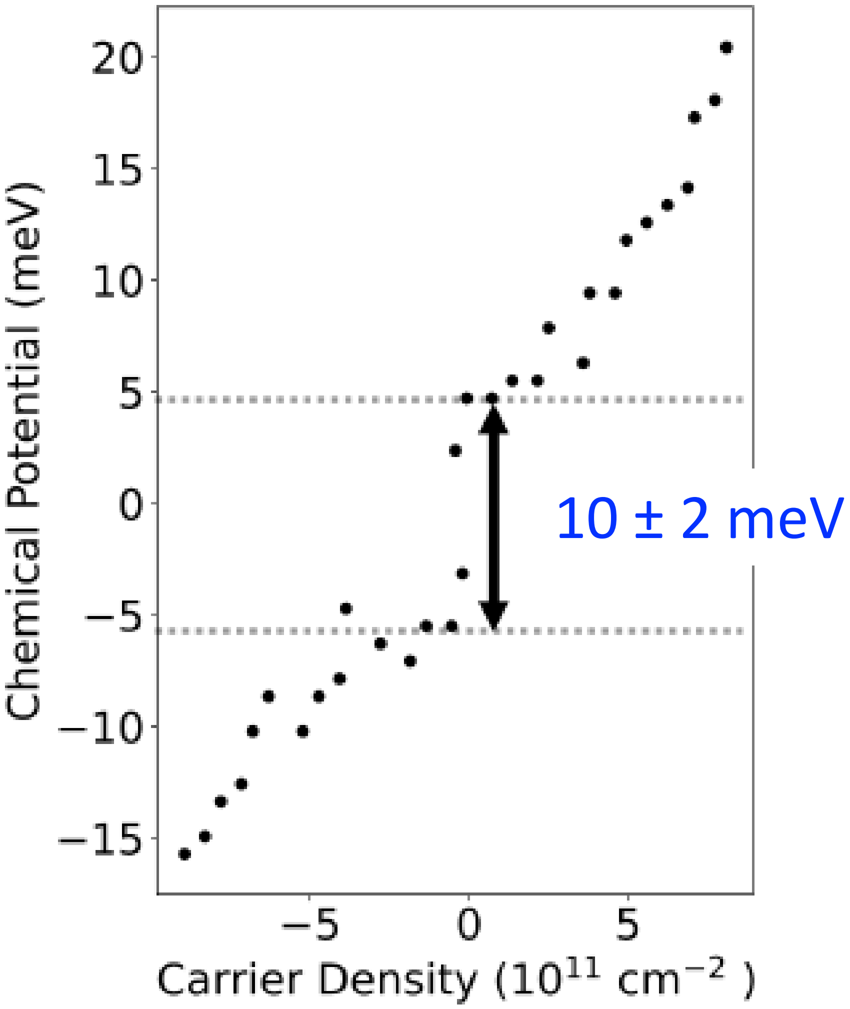
R. Jain et al., arXiv:2412.05380

Direct capacitive sensing of the exchange gap



$$\mu_{top} = -\frac{C_B}{C_{TI}} e V_{BG}'$$

$$n_{top} = \frac{C_T}{e}\left(V_{TG}' + \left(\frac{1}{C_T} + \frac{1}{C_{TI}}\right) C_B V_{BG}'\right).$$

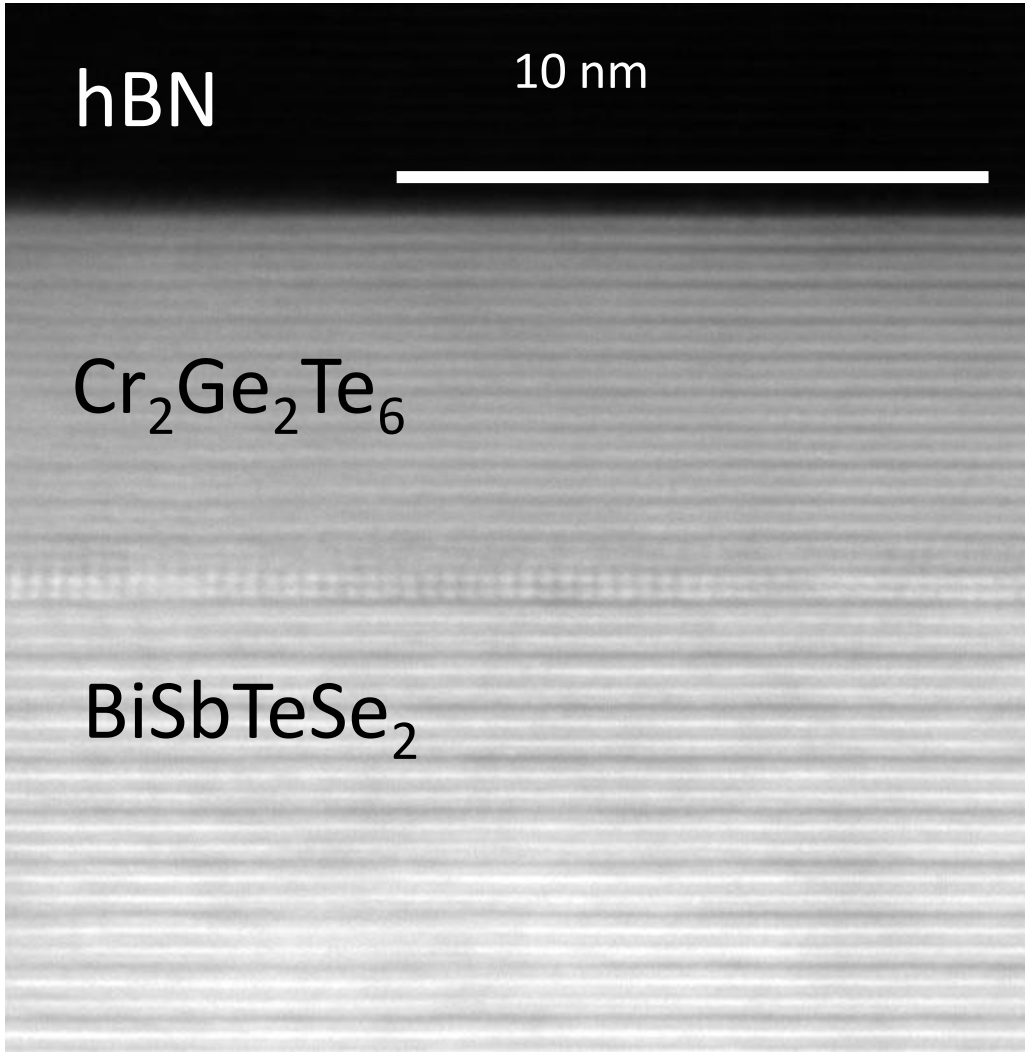


Value similar to DFT predictions for Bi_2Se_3/CrI_3 (Sci. Adv. **5**, eaaw1874 (2019)).

Much larger compared to gaps measured by thermal activation of R_{xx} in other systems: 0.06 meV in a Cr-doped magnetic topological insulator and 0.6 meV in $MnBi_2Te_4$.

R. Jain et al., arXiv:2412.05380

Why are Top-Down-Deposited and Mechanically-Assembled Samples So Different?



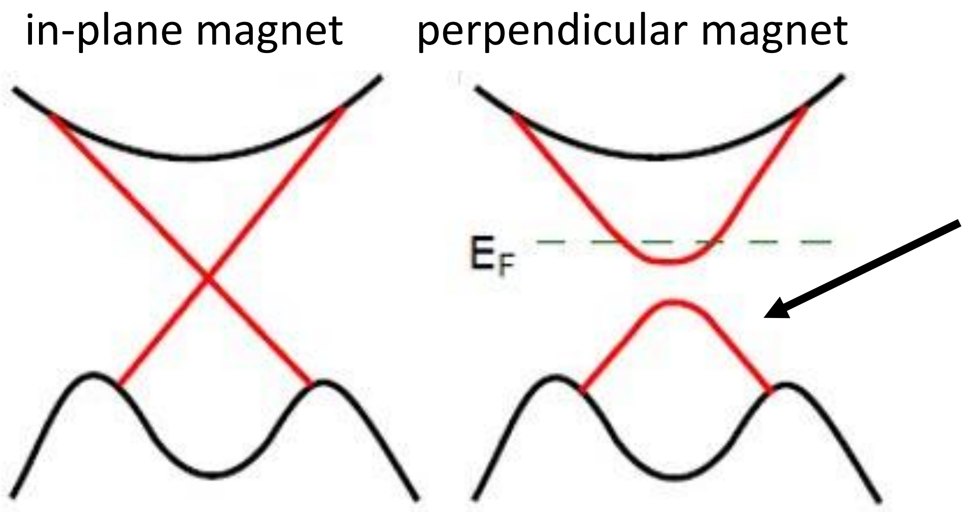
- A pristine interface enhances proximity coupling between a topological surface state and a separate magnet. Interface disorder will push the surface state away from the interface, and might also cause a magnetic dead layer.
- Mechanically-assembled samples also have much higher mobility – even with the magnetic layer, ~10x higher mobility than magnetically-doped TIs.

Bottom Line: ~100x higher temperature scale for quantum anomalous Hall effect compared to deposited TI/magnet samples

Working now on magnetic layers both above and below a TI layer to investigate Chern insulator and axion insulator states.

Effect of the Topological Surface State on the Magnetic Layer

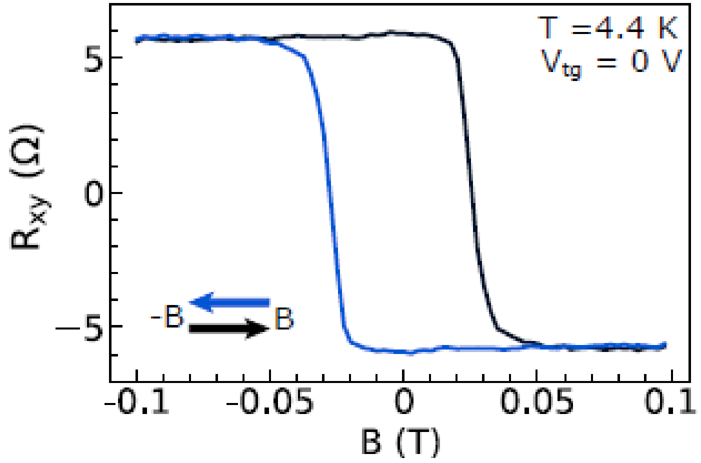
Increased perpendicular magnetic anisotropy?

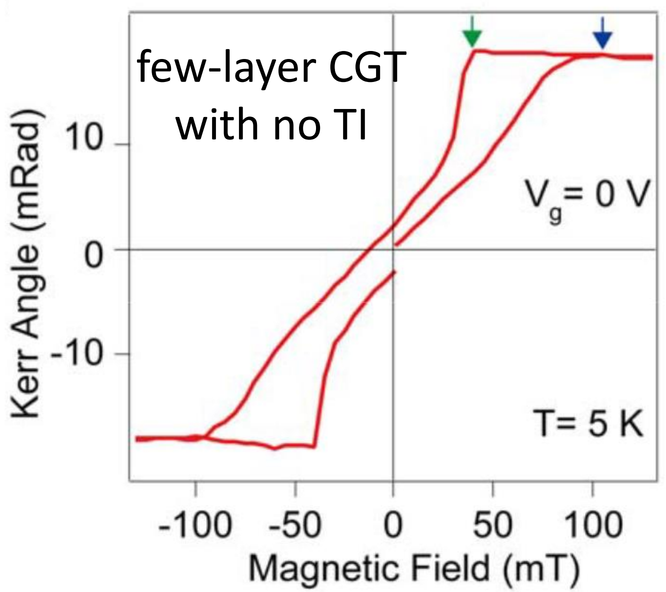


When the Fermi energy is near the exchange gap, the lowered energy of the filled electronic states in the case of a perpendicular magnet should favor perpendicular magnetic anisotropy

Effect of the Topological Surface State on the Magnetic Layer

BSTS/CGT (10 nm/2 nm)

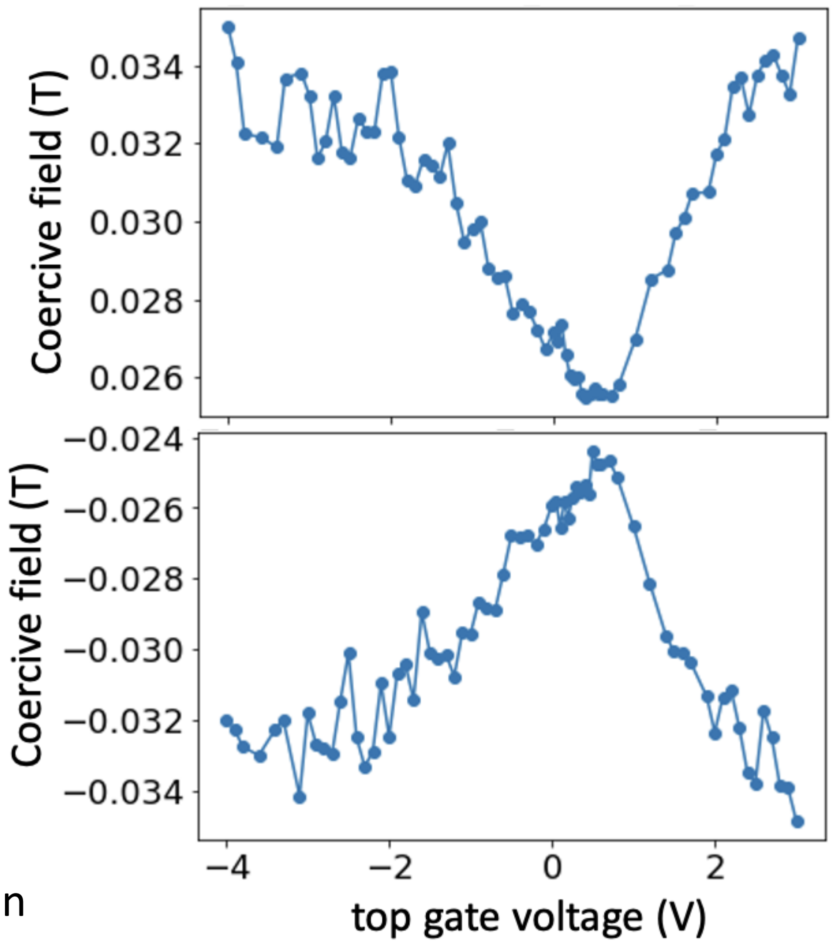




Coercive field of a $Cr_2Ge_2Te_6$ film on the TI is increased relative to a similar film with no TI.

But the gate dependence of the coercive field is opposite to what is expected for the magnetic anisotropy.

Need to take into account gate-dependent changes in magnetization as well as magnetic anisotropy?



Antiferromagnetic Dynamics

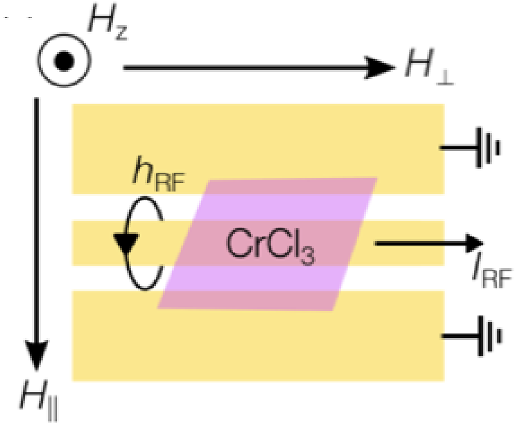
Challenge: Can we make progress toward using antiferromagnetic dynamics for something useful?

Need:

1. Ability to detect the dynamics directly in the time or frequency domains using microscopic samples.
2. Ability to manipulate the dynamics electrically

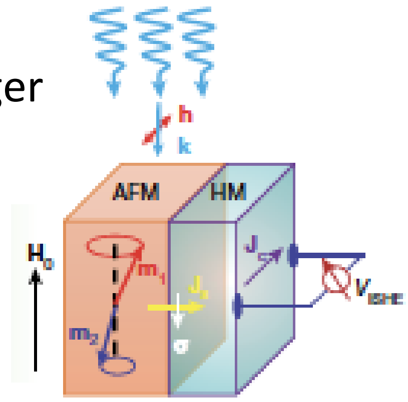
(one potential goal – a high-frequency antiferromagnetic nanoscale oscillator)

<u>Previous techniques for detecting antiferromagnetic resonances</u>

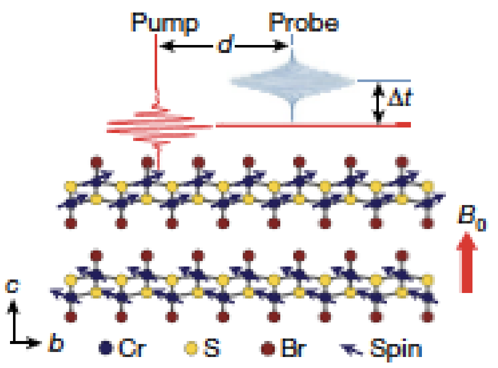


Resonant absorption

millimeter or larger samples

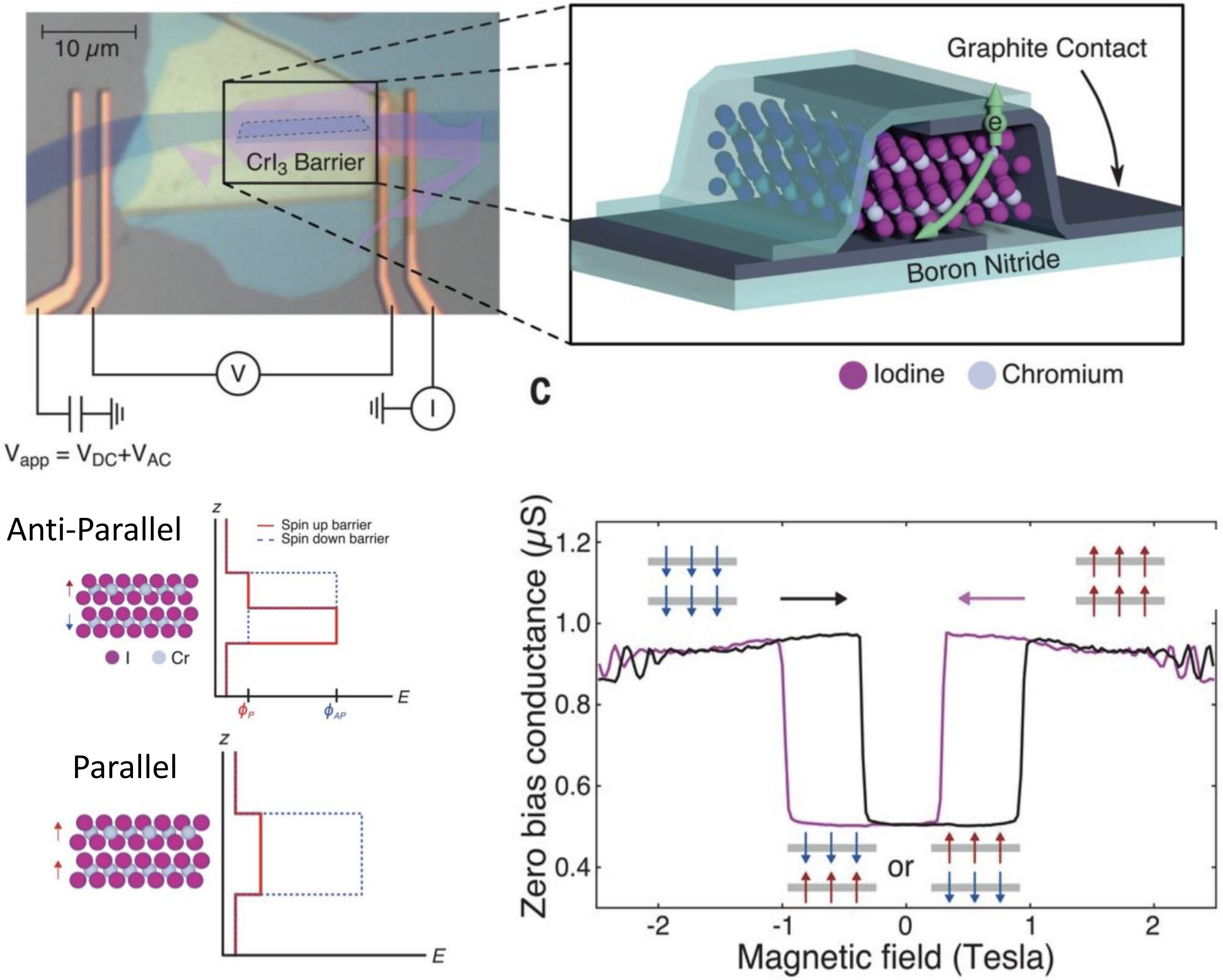


Spin Pumping

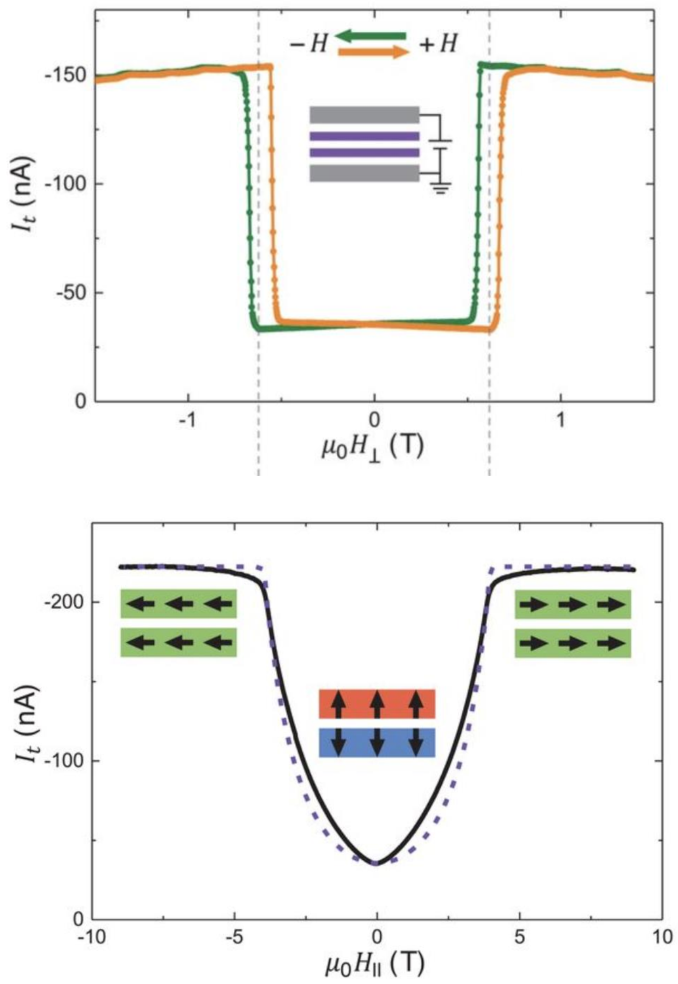


Optical Probes

Scheme: Use magnetoresistance of few-layer vdW antiferromagnets

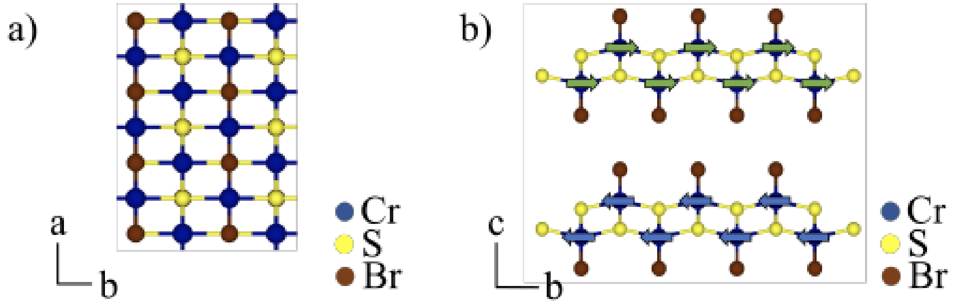


Klein, D. R. et al. *Science* **360**, 1218 (2018)

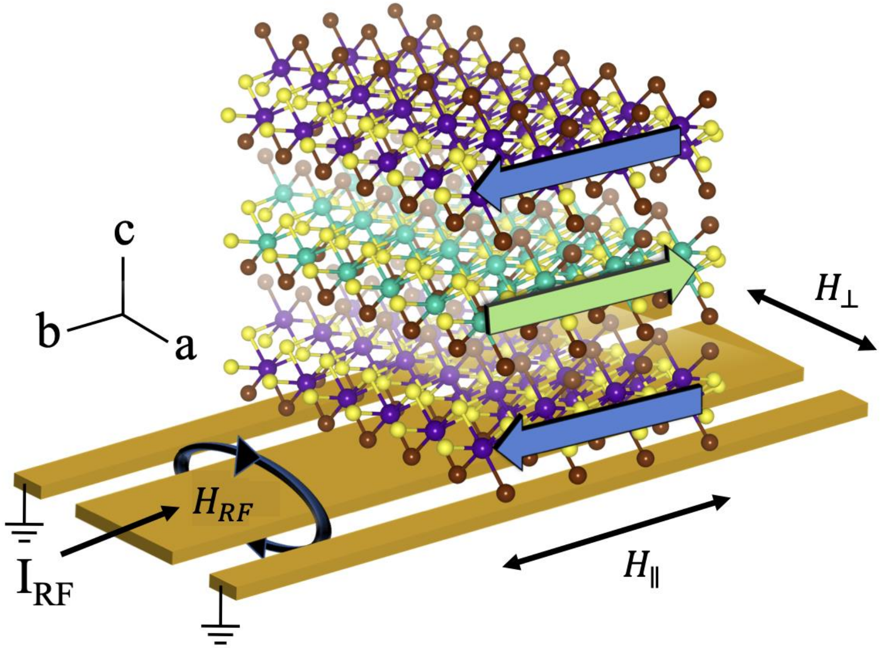


Song, T. et al. *Science*, **360**, 1214 (2018)

What are the antiferromagnetic resonance modes of CrSBr?

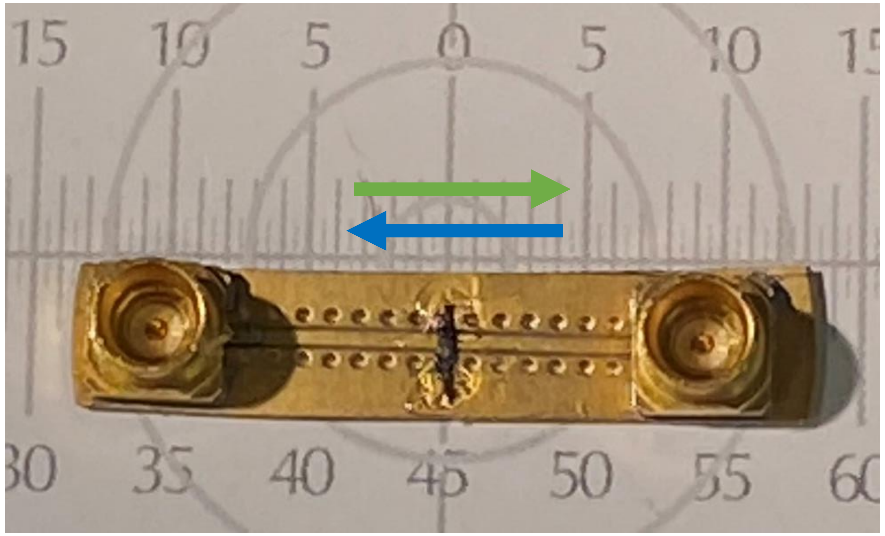


In-plane magnetic easy axis along b



(not to scale)

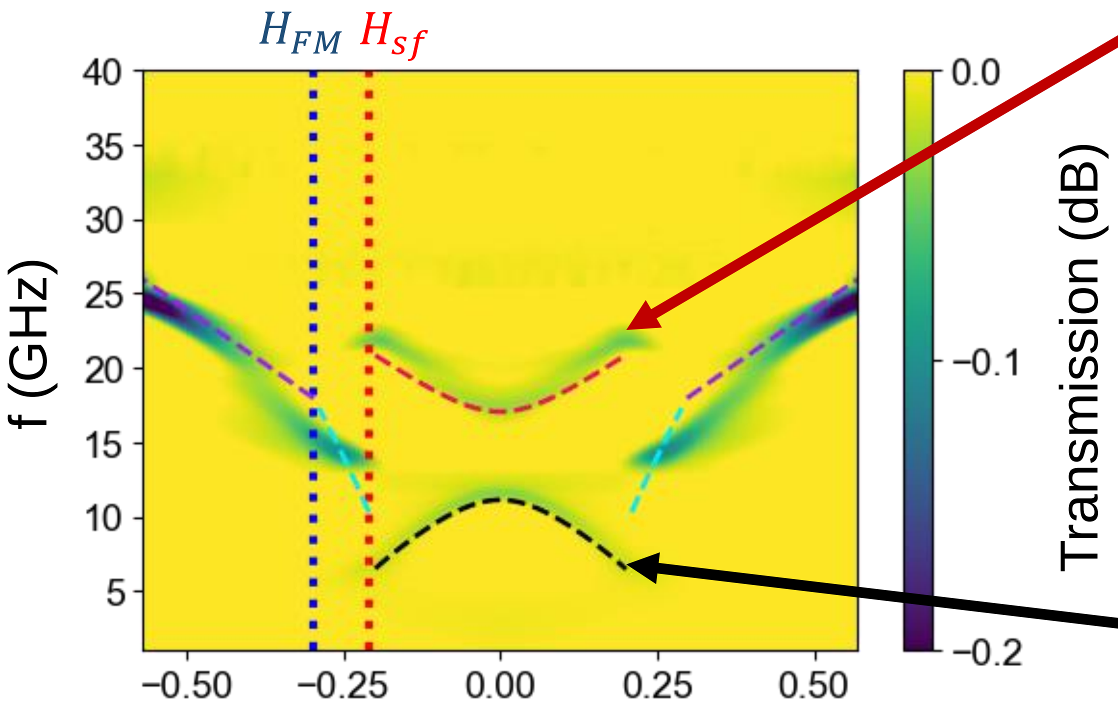
CrSBr from the group of Xavier Roy, Columbia

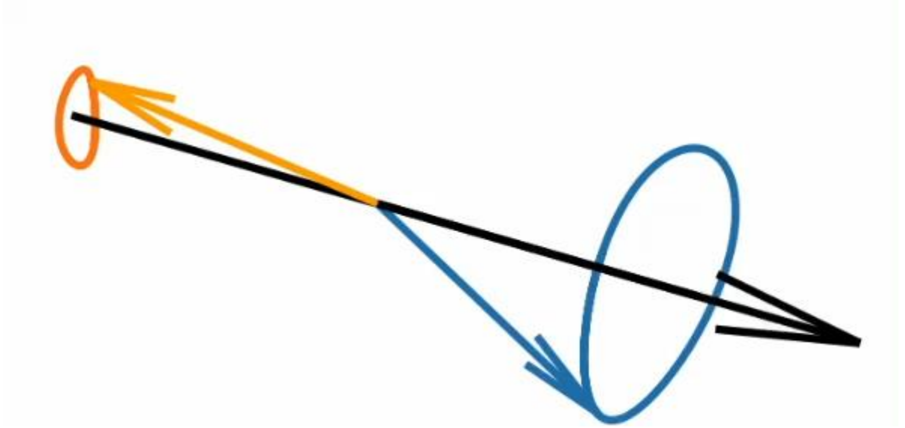


Followed MacNeill, D., Liu, L. et al. *Phys. Rev. Lett. 123*, 047204 (2019).

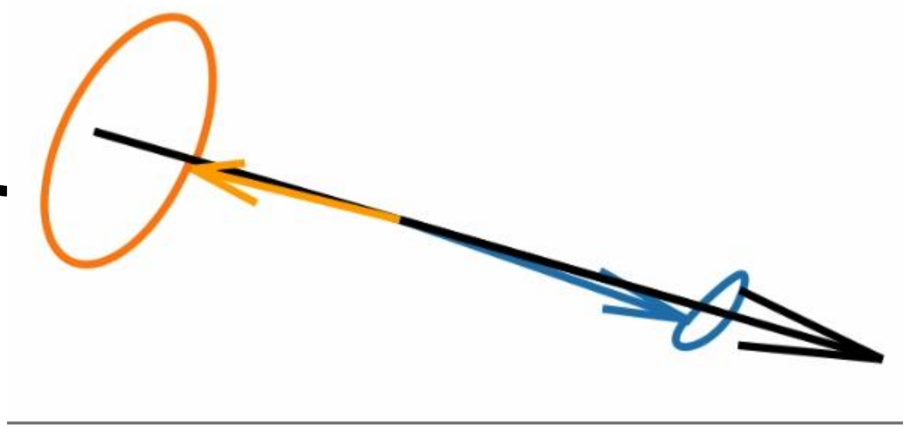
T. M. J. Cham et al. *Nano Letters* **22**, 6716 (2022)

External Field ‖ to in-plane easy axis



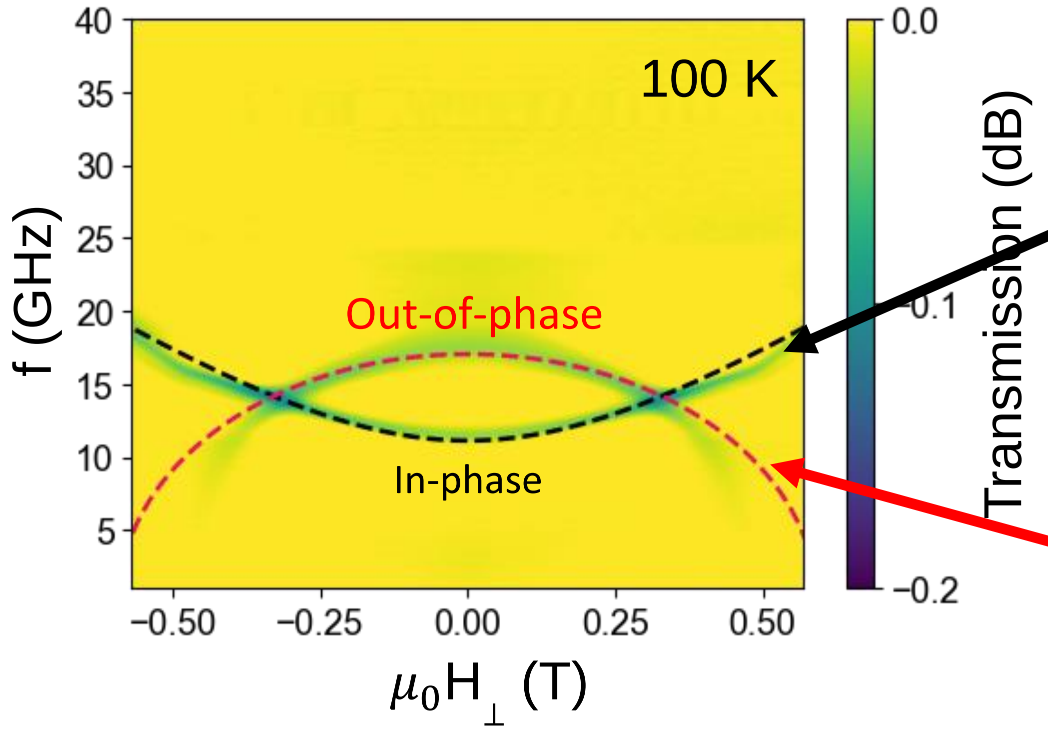


“RH Mode”

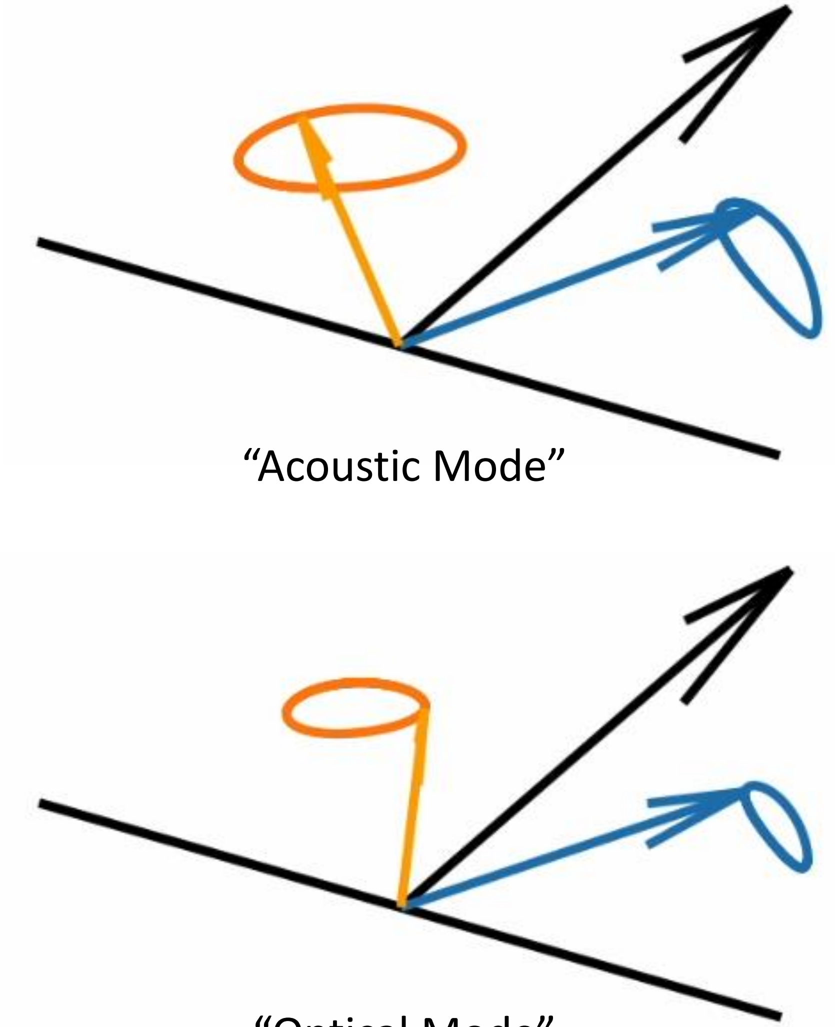


Left-Handed/Right-Handed chiral modes

External Field ⊥ to in-plane easy axis



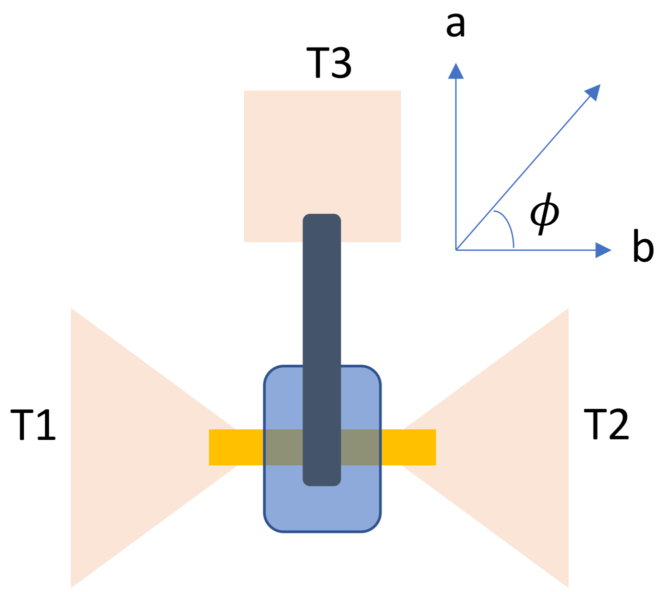
Out-of-phase and In-phase modes

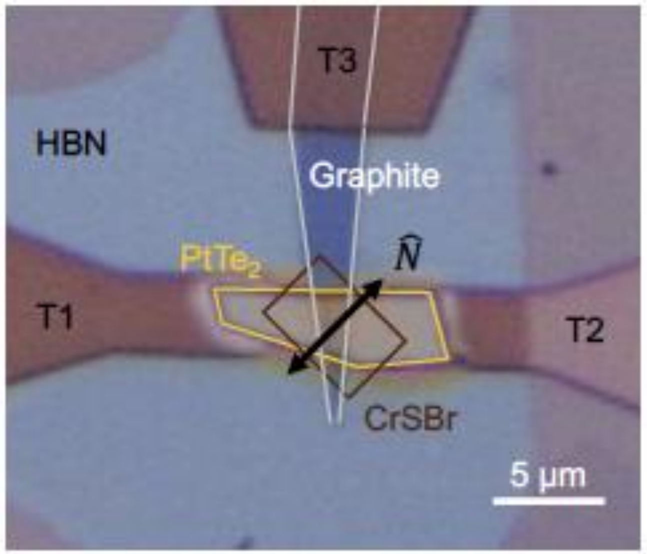


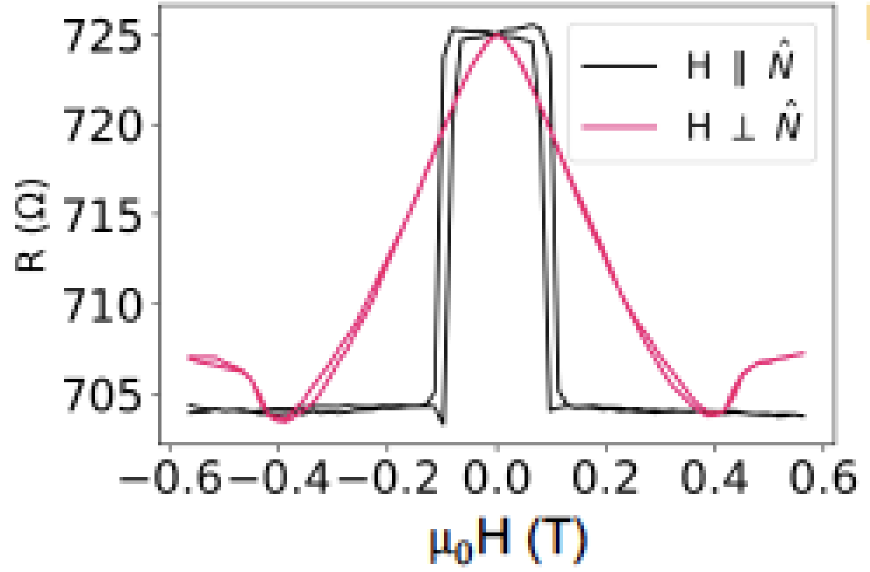
“Acoustic Mode”

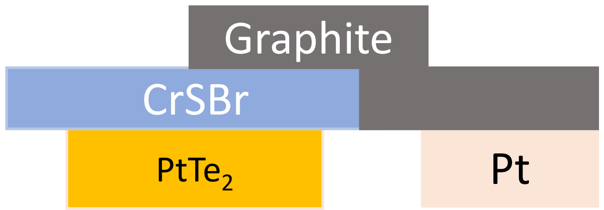
“Optical Mode”

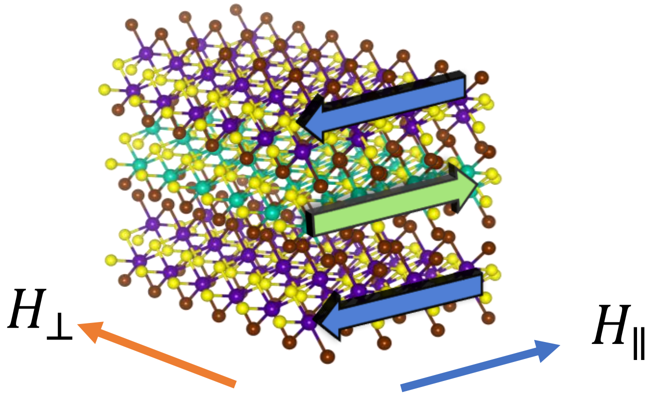
Electrical readout of DC antiferromagnetic order in CrSBr









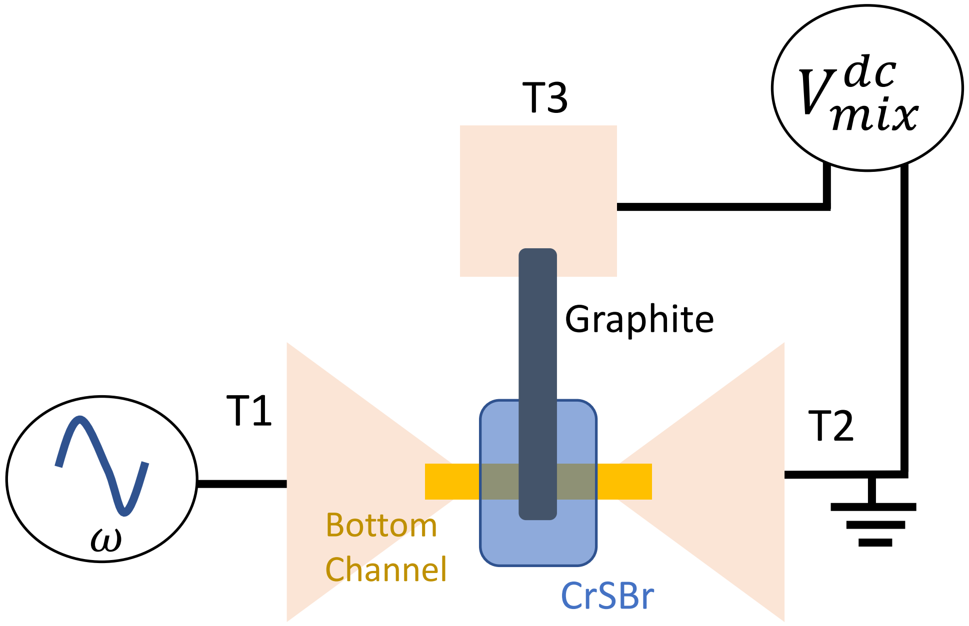


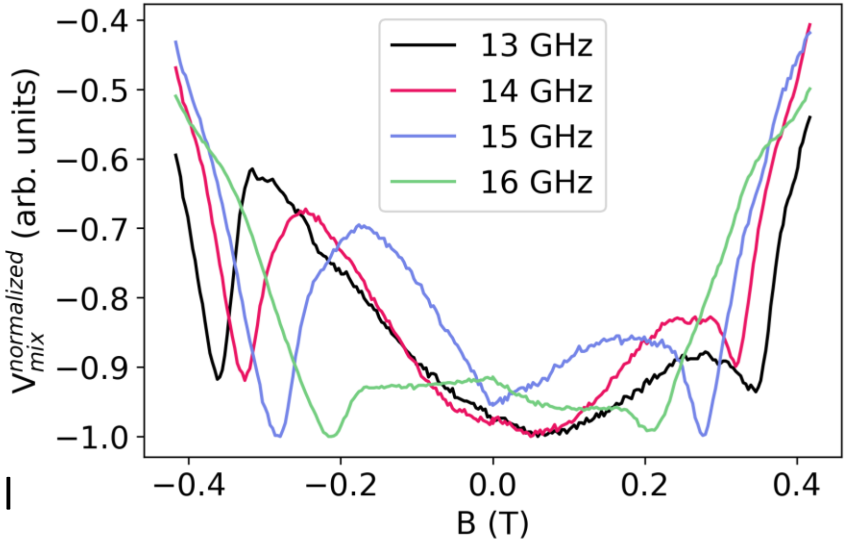
T. M. J. Cham et al., arXiv:2407.09462, to appear in *Science*

Antiferromagnetic Resonance in a vdW heterostructure

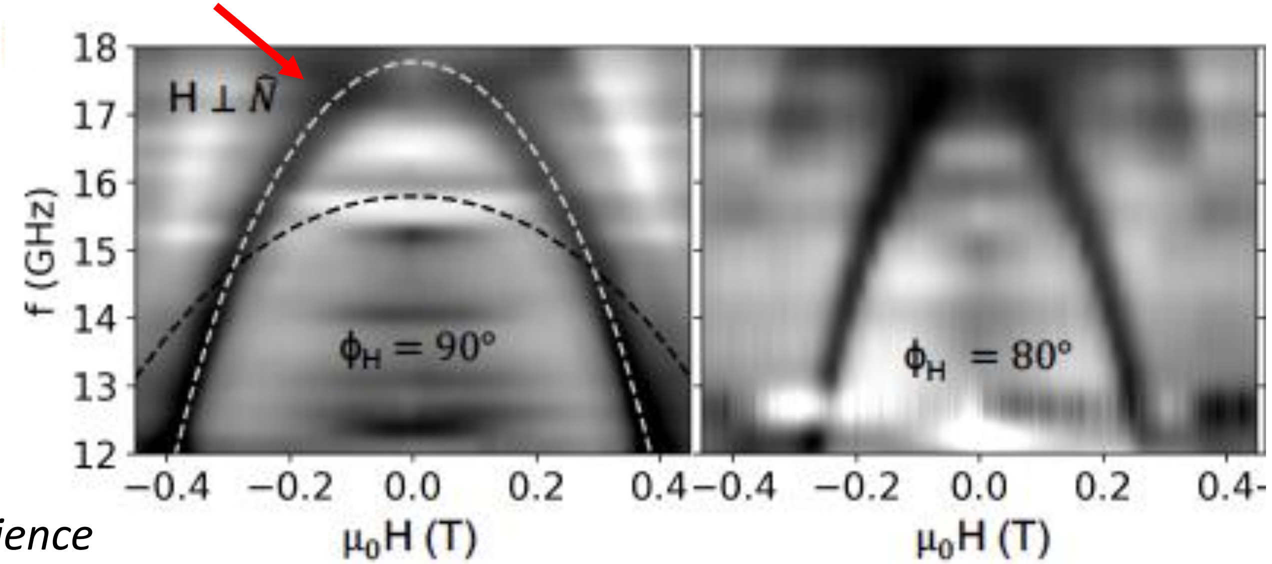
$$V_{mix}(t) = \underbrace{I_0 \sin(\omega t)}_{\text{RF Current}}\underbrace{(R_0 + \Delta R \sin(\omega t))}_{\text{MR Response}}$$

$$V_{mix}^{dc} = \frac{\Delta R I_0}{2}$$





Only the optical mode produces a resistance signal



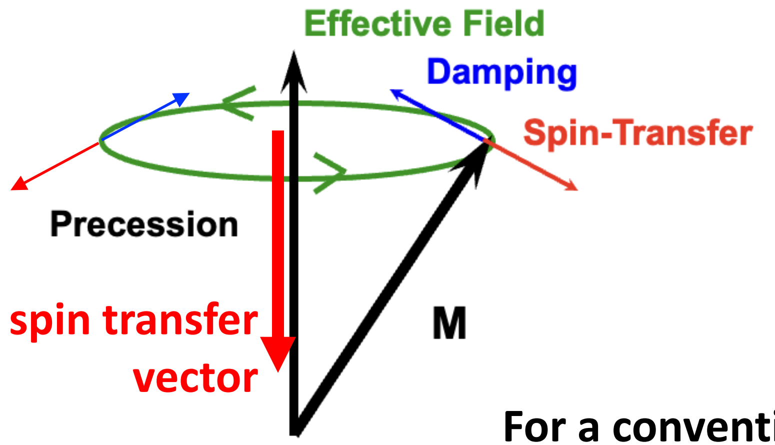
Bilayer: H_a = 0.33 T , H_c = 0.77 T, H_E = 0.096 T

Bulk: H_a = 0.22 T , H_c = 0.75 T, H_E = 0.27 T

T. M. J. Cham et al., arXiv:2407.09462, to appear in *Science*

Background: Spin-orbit-torque modulation ferromagnetic resonance linewidths

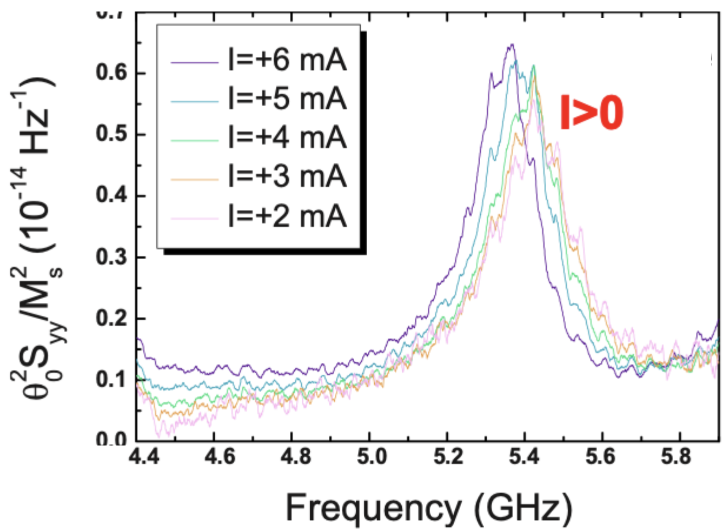
Spin-orbit torque from a heavy metal can act opposite to the intrinsic damping of a magnet, provide ”anti-damping”



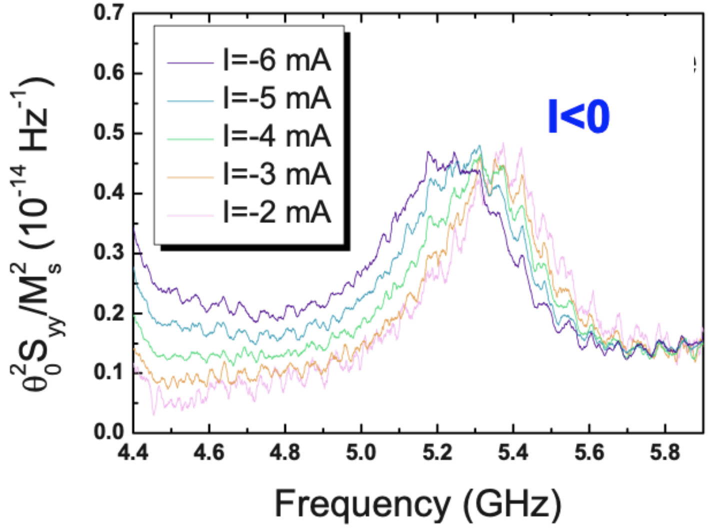
Maximum effect if the spin-transfer vector is antiparallel to the precession axis, $\propto \cos\theta$

For a conventional ferromagnet:

anti-damping narrows linewidth

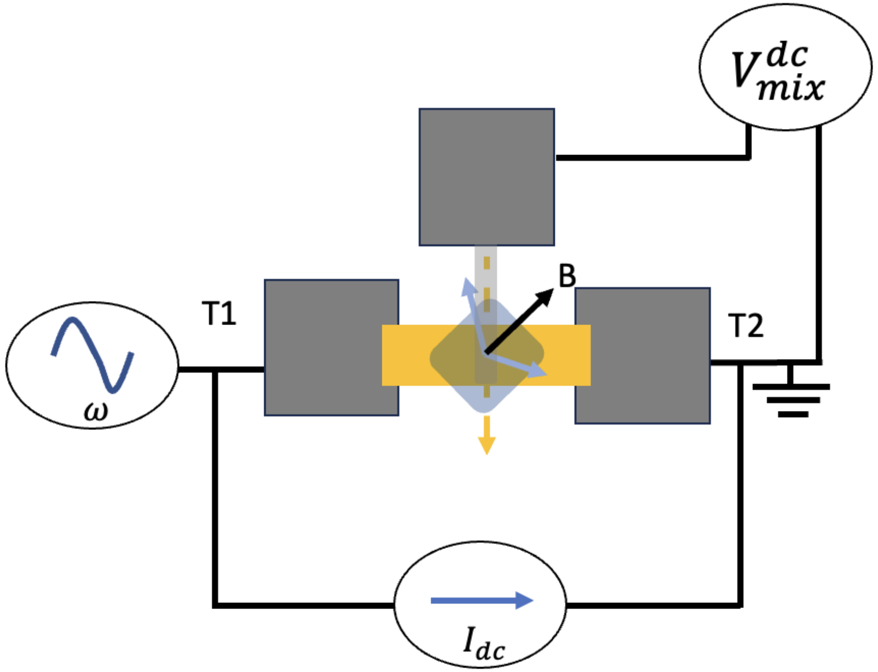


increased damping broadens linewidth

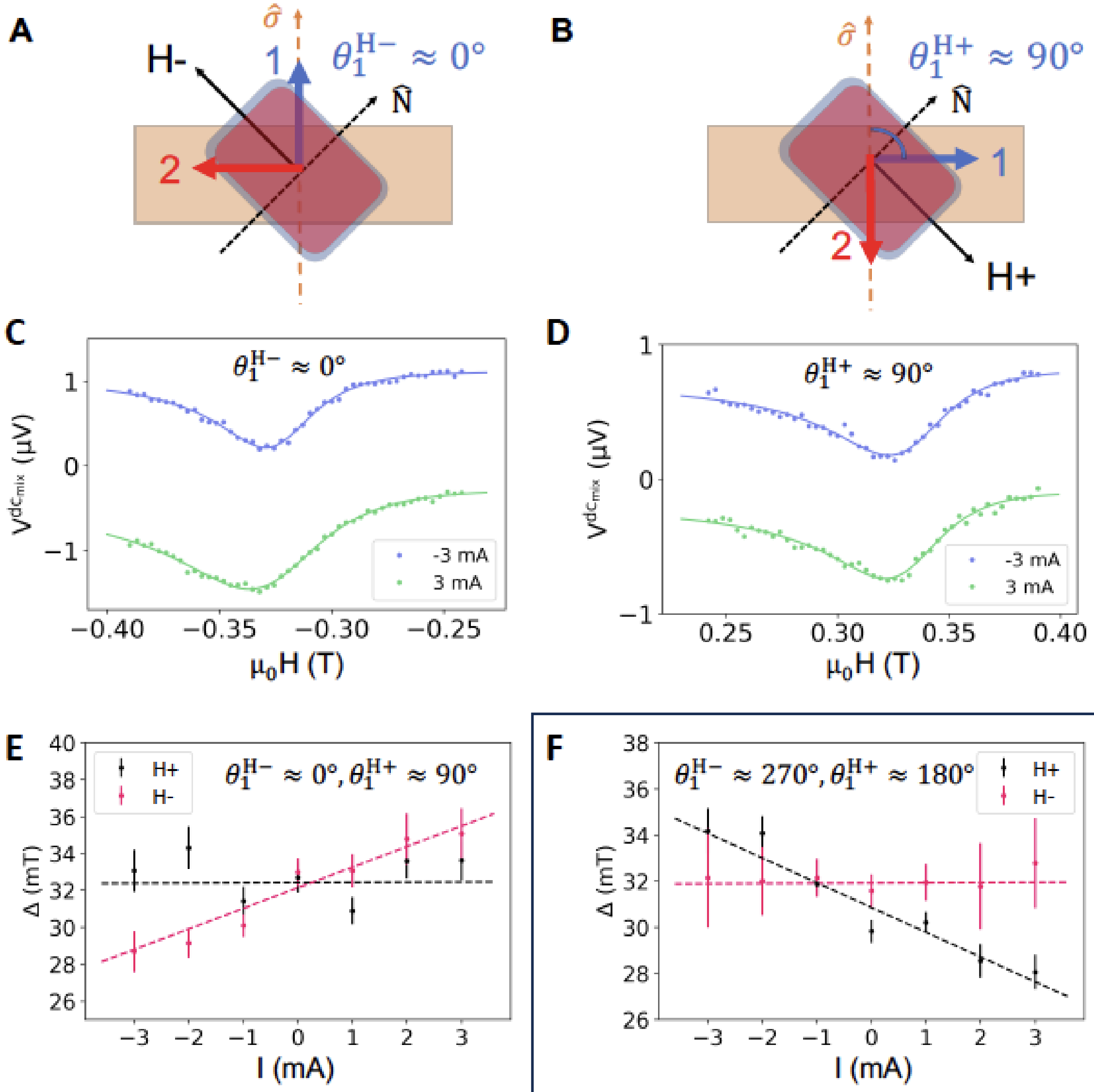


Data from S. Petit et al., Phys Rev. B. 78, 184420 (2008) Magnetic tunnel junction with $Ni_{80}Fe_{20}$ free layer.

Spin-orbit-torque modulation of the AFMR linewidth



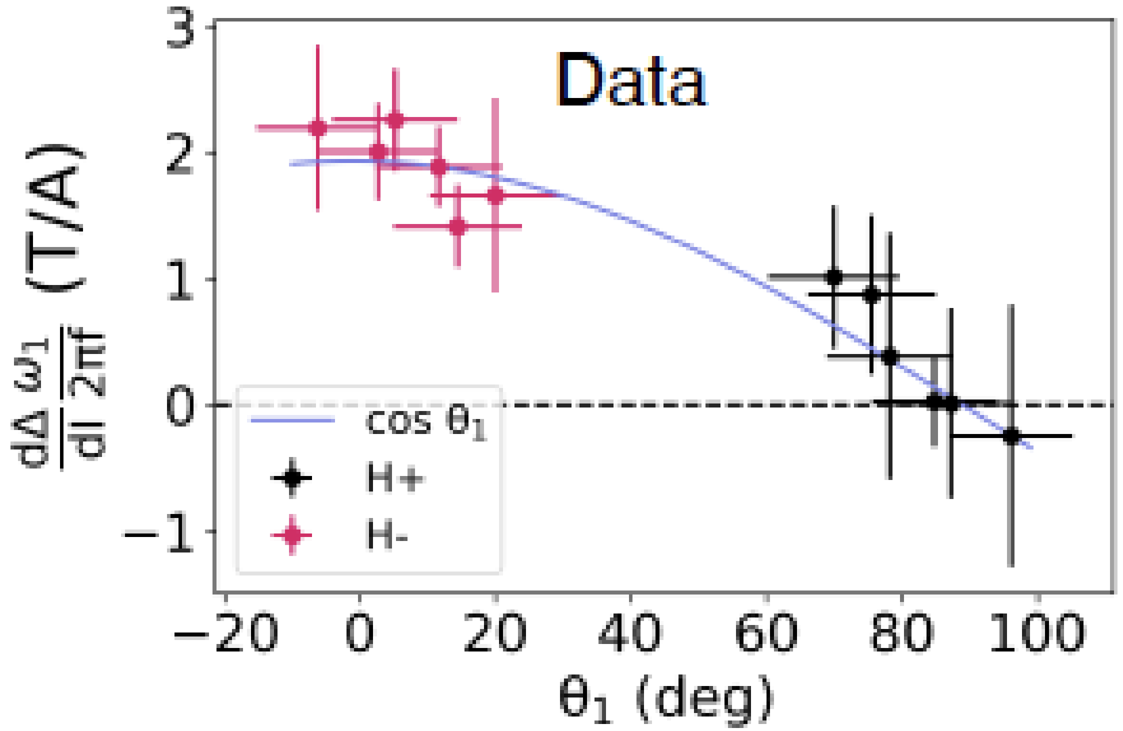
Current-induced changes in linewidth have an asymmetric dependence on the sign of magnetic field



spin sublattices reversed

T. M. J. Cham et al., arXiv:2407.09462, to appear in *Science*

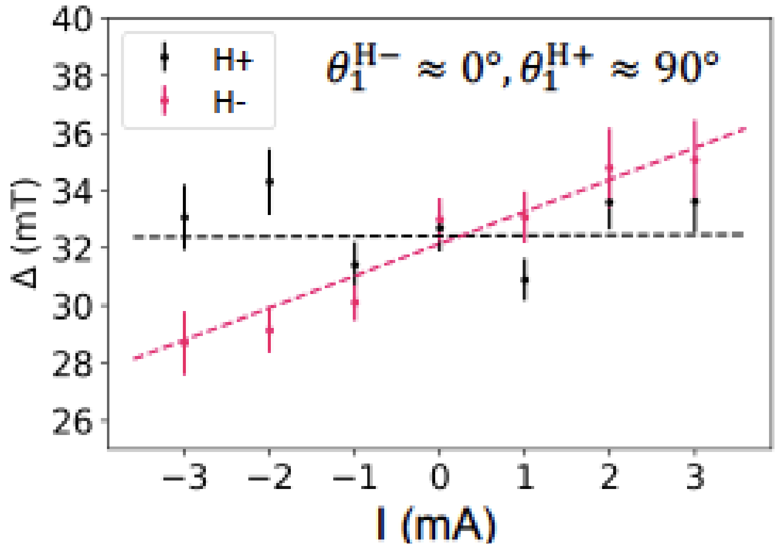
Current-induced linewidth changes depend only on the angle of one of the two spin sublattices



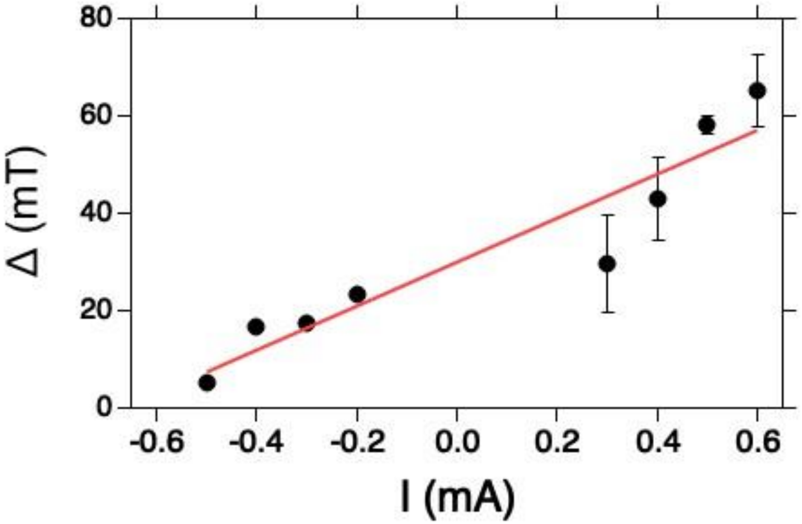
Spin-orbit torque acts only on the spin sublattice adjacent to the $PtTe_2$ with negligible penetration to the second layer.

T. M. J. Cham et al., arXiv:2407.09462 to appear in *Science*

Working toward negative effective damping – aiming to make antiferromagnetic nano-oscillators

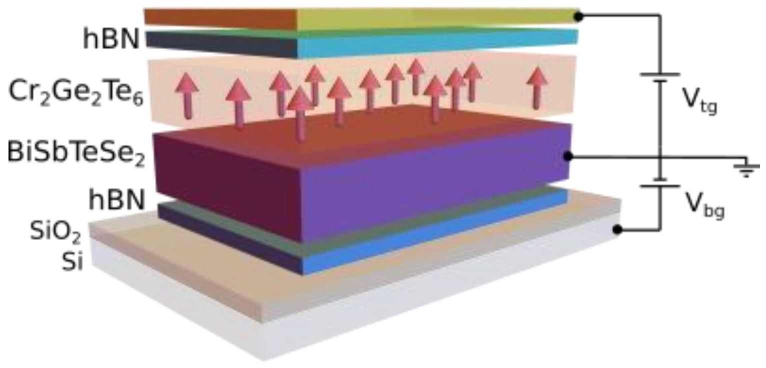


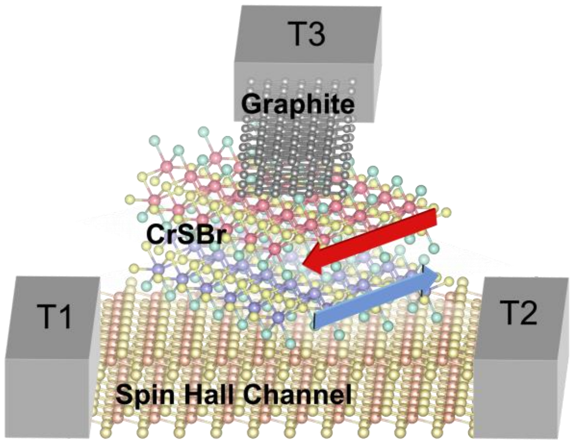
For our initial $PtTe_2$/CrSBr devices, we can reduce linewidth by ~ 12%, limited by heating.



With improvements in materials and device design, can now reduce damping by at least 85%. Measurements underway to try to detect dc-driven auto-oscillations.

Summary





- Mechanically-assembled topological insulator/magnet structures can give much stronger exchange gaps in the topological surface state compared to deposited structures – quantized anomalous Hall effects to > 10 K.

- We are beginning to develop capabilities to directly detect and control of antiferromagnetic resonance dynamics in micron-scale structures – and can selectively address just one spin sublattice using spin-orbit torque.

parity anomaly/QAHE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