Exotic Spin transport in two-dimensional topological materials

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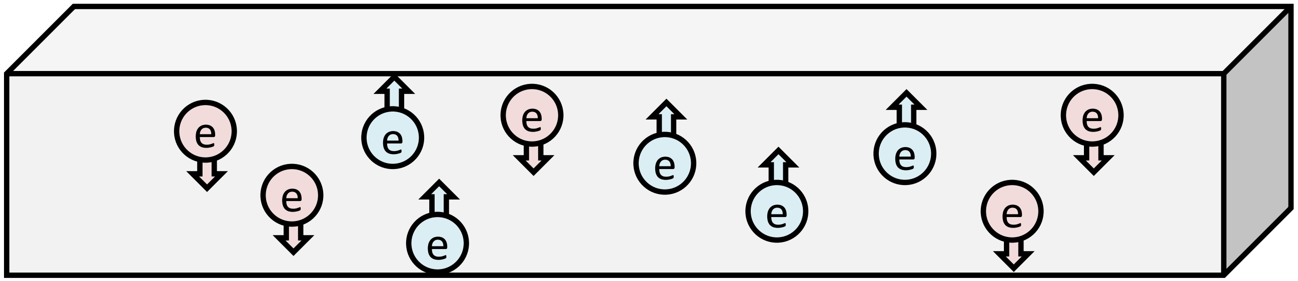
Why Spintronics?

Power dissipation



$$I = I_{\uparrow} + I_{\downarrow} \qquad\qquad P = I\,V$$

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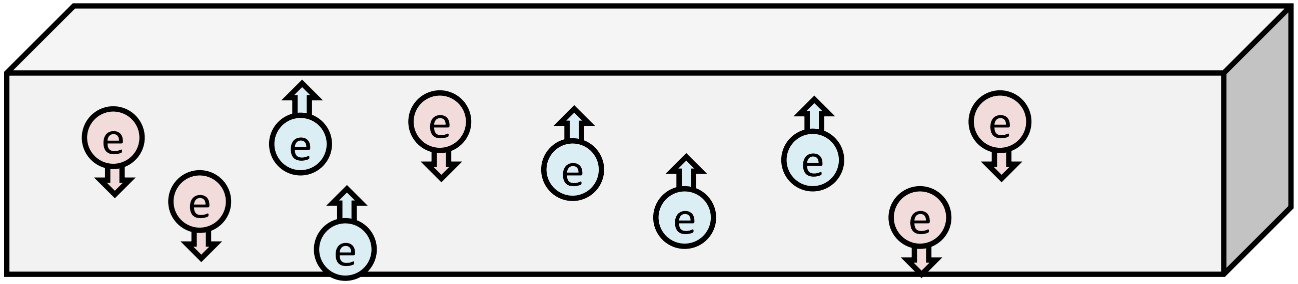
Why Spintronics?

Efficient information transport

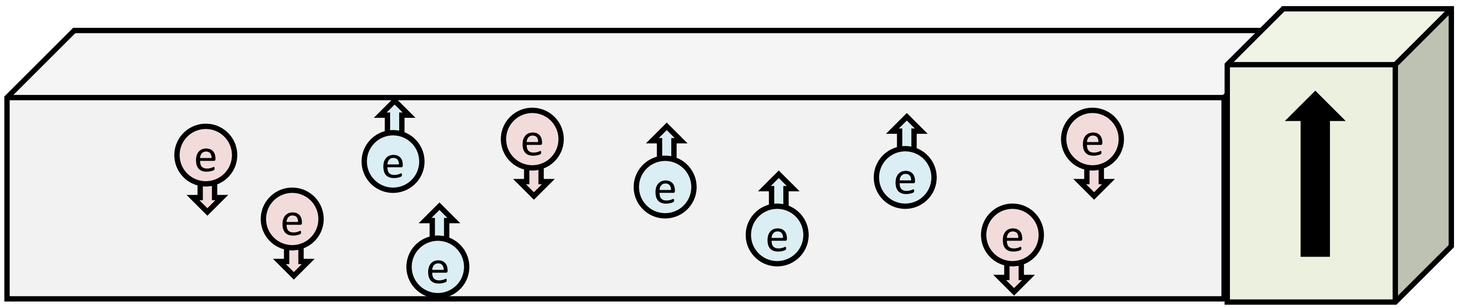
and...



$$I = I_{\uparrow} + (-I_{\downarrow}) = 0 \qquad \boldsymbol{P} = \mathbf{0}$$

Why Spintronics? Next-Gen memories!

Efficient magnetization control



How to create such spin current?

Spin injection **Spin Hall effect**

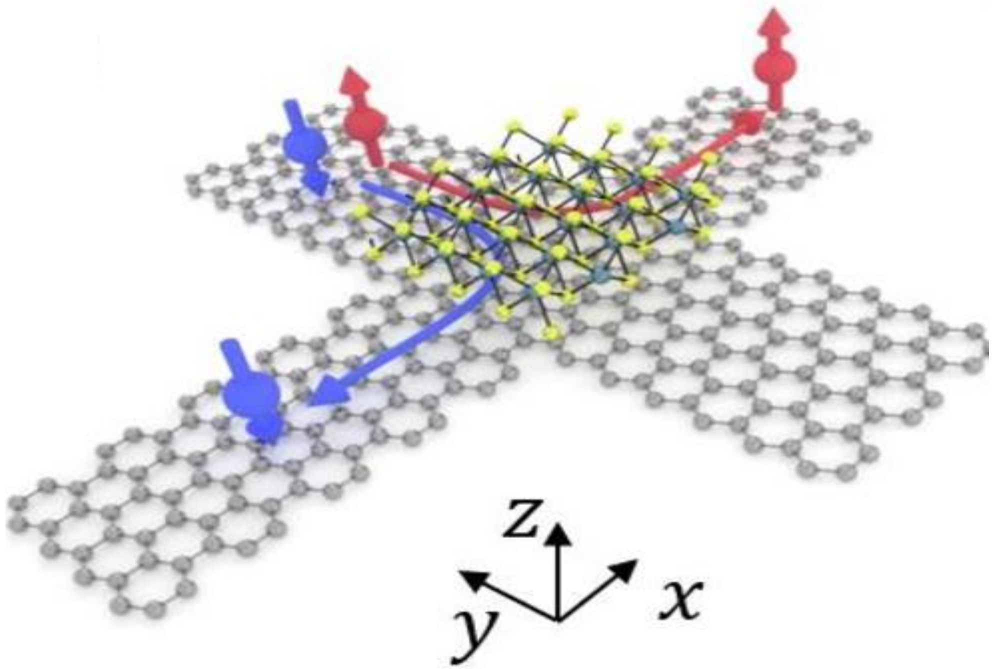
Spin-orbit coupling ⟹ Spinorbitronics

Spin Hall effect

σ_{xy}^{α} spin Hall conductivity

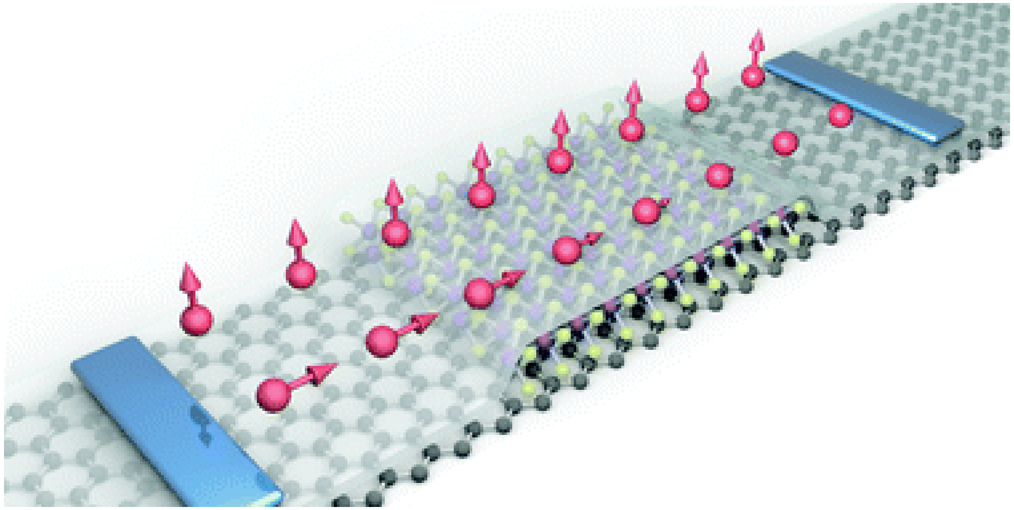
θ_{xy}^{α} spin Hall angle

θ_{xy}^{α} >100%



The downside of the spin-orbit

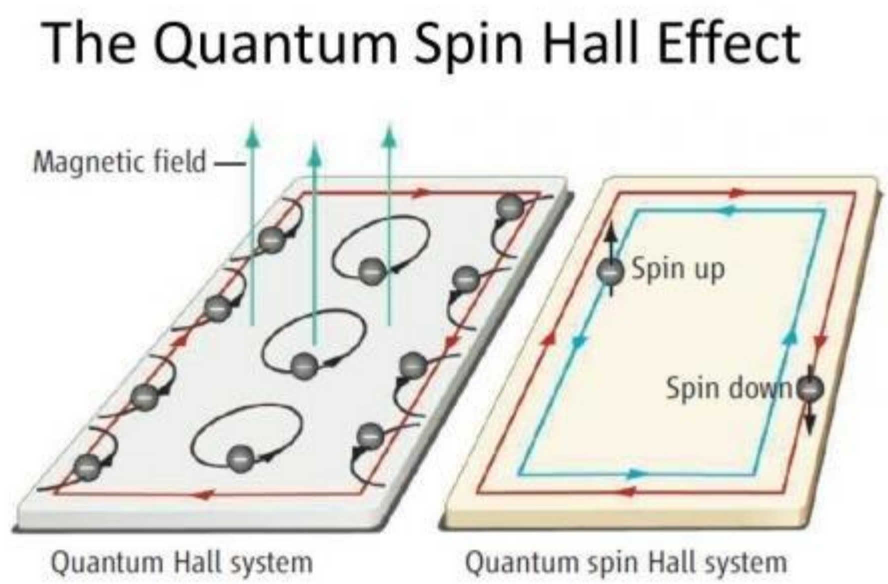
In real life the
electron loose
its spin information
while moving



Long spin relaxation lengths!

Can we have efficient spin-to-charge interconversion and long spin relaxation length?

YES!



C.L. Kane, E.J. Mele Phys. Rev. Lett. **95**, 226801 (2005)

Naoto Nagaosa Science **318**, 5851, pp. 758-759 (2007)

1T-WTe_2 a Quantum Spin Hall insulator

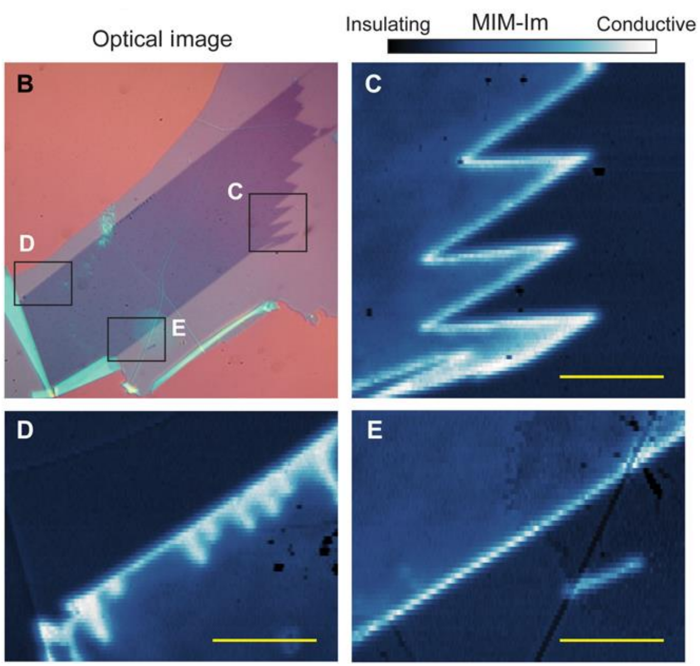
Prediction in 2014

Quantum spin Hall effect in two-dimensional transition metal dichalcogenides

Xiaofeng Qian,[1*] Junwei Liu,[2*] Liang Fu,[2†] Ju Li[1†]

Imaging quantum spin Hall edges in monolayer WTe_2

Yanmeng Shi[1,*], Joshua Kahn[2,*], Ben Niu[1,3,*], Zaiyao Fei[2], Bosong Sun[2], Xinghan Cai[2], Brian A. Francisco[1], Di Wu[3], Zhi-Xun Shen[4], Xiaodong Xu[2,†], David H. Cobden[2,†] and Yong-Tao Cui[1,†]

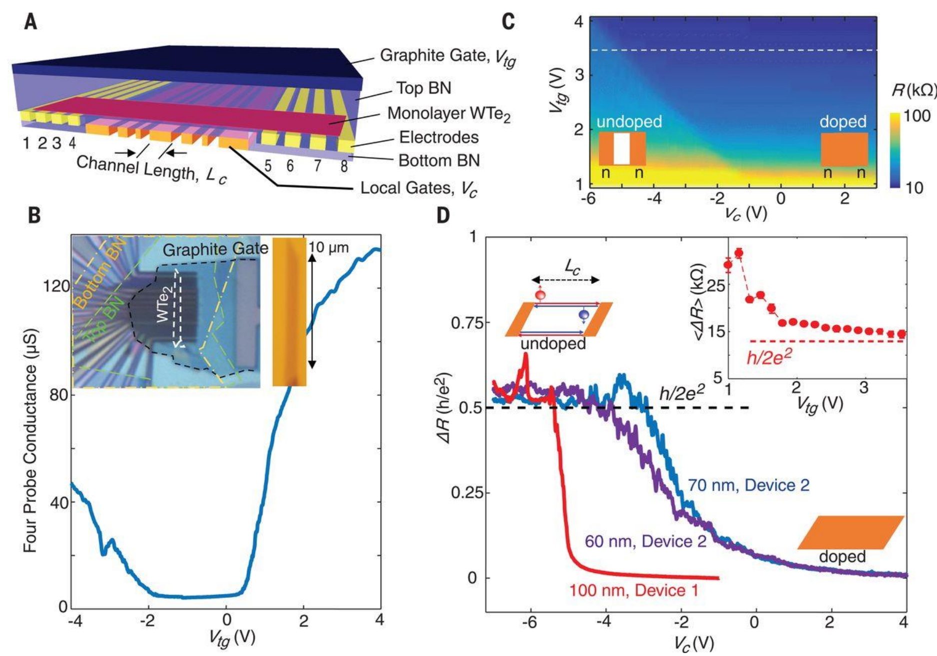


No transport measurements

Observation of the quantum spin Hall effect up to 100 kelvin in a monolayer crystal

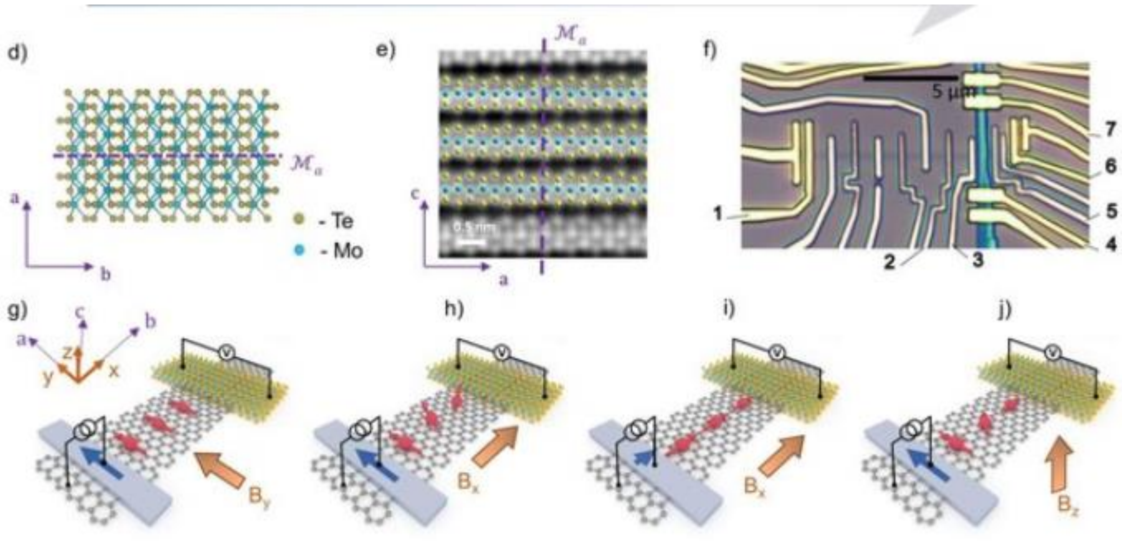
Sanfeng Wu[1,*,†], Valla Fatemi[1,*,†], Quinn D. Gibson[2], Kenji Watanabe[3], Takashi Taniguchi[3], Robert J. Cava[2], Pabl...
+ See all authors and affiliations

Science 05 Jan 2018:
Vol. 359, Issue 6371, pp. 76-79
DOI: 10.1126/science.aan6003



Purely electrical measurements

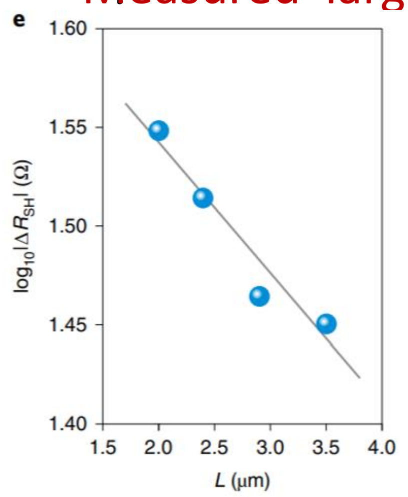
Low-symmetry materials (TMD-1T_d)



MoTe$_2$

C. K. Safeer, N. Ontoso, et al. *Nano Letters* **19** (12), 8758-8766, 2019

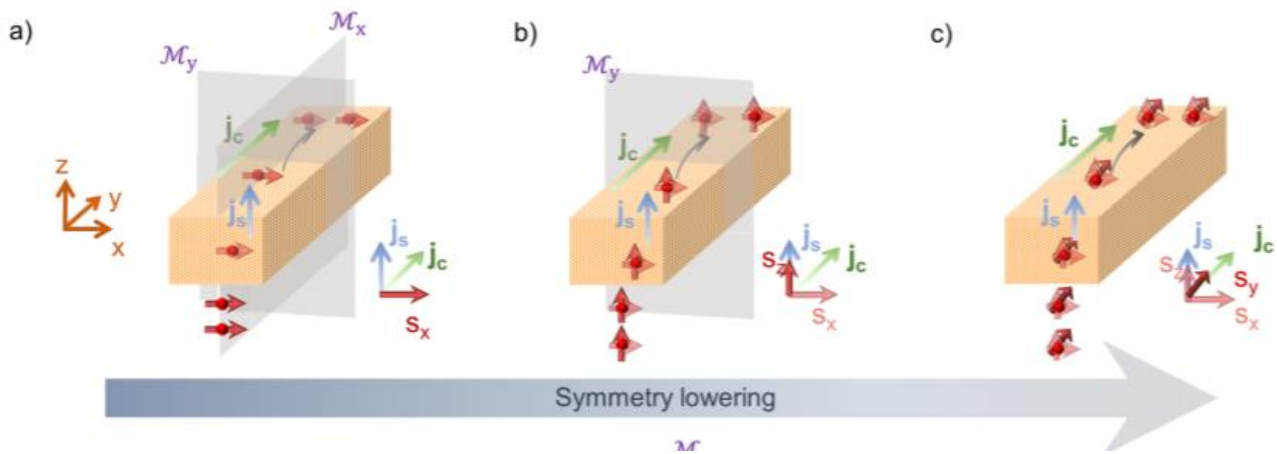
Measured large multidirectional spin-to-charge conversion in MoTe2



Large multidirectional spin-to-charge conversion and spin relaxation length over μm

P. Song, Chuang-Han Hsu, Kian Ping Loh, et al
Nat. Mater. **19,** 292–298 (2020).

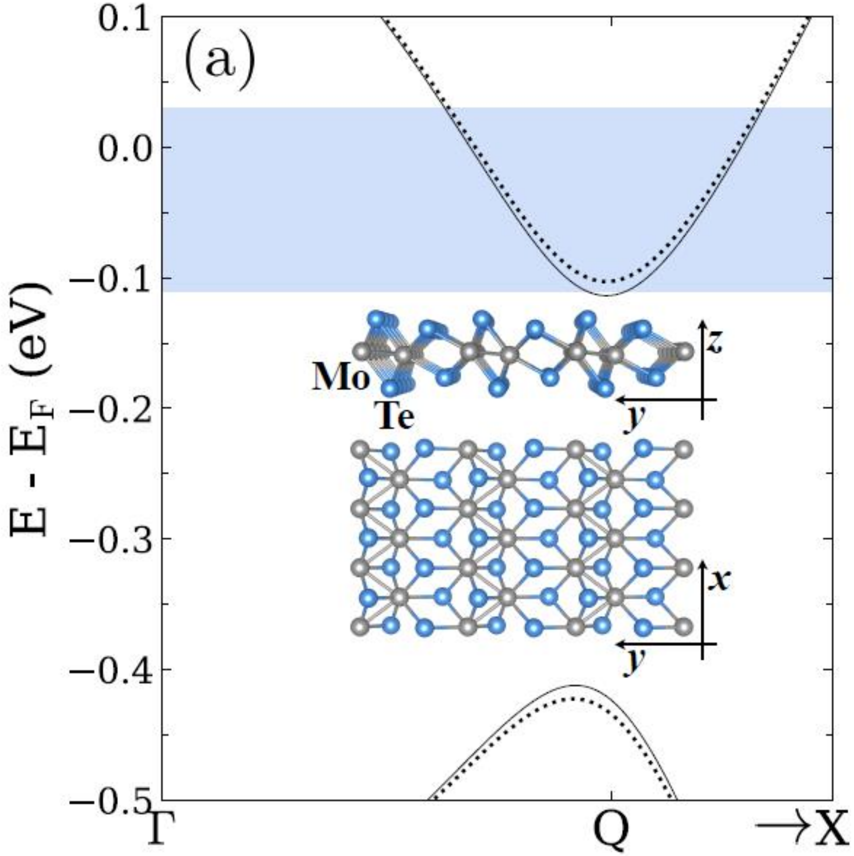
Bulk TMD-1T_d ($MoTe_2$)



Belongs to $Pmn2_1$ layer group

$$\begin{pmatrix} \sigma^x_{xx} & 0 & 0 \\ 0 & \sigma^x_{yy} & \sigma^x_{yz} \\ 0 & \sigma^x_{zy} & \sigma^x_{zz} \end{pmatrix} \quad \begin{pmatrix} 0 & \sigma^y_{xy} & \sigma^y_{xz} \\ \sigma^y_{yx} & 0 & 0 \\ \sigma^y_{zx} & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & \sigma^z_{xy} & \sigma^z_{xz} \\ \sigma^z_{yx} & 0 & 0 \\ \sigma^z_{zx} & 0 & 0 \end{pmatrix}$$

Monolayer TMD-1T_d ($MoTe_2$)



Belongs to $Pmn2_1$ layer group

$$\begin{pmatrix} \sigma^x_{xx} & 0 & 0 \\ 0 & \sigma^x_{yy} & \cancel{\sigma^x_{yz}} \\ 0 & \cancel{\sigma^x_{zy}} & \cancel{\sigma^x_{zz}} \end{pmatrix} \quad \begin{pmatrix} 0 & \boxed{\sigma^y_{xy}} & \cancel{\sigma^y_{xz}} \\ \sigma^y_{yx} & 0 & 0 \\ \cancel{\sigma^y_{zx}} & 0 & 0 \end{pmatrix}$$

$$\begin{pmatrix} 0 & \boxed{\sigma^z_{xy}} & \cancel{\sigma^z_{xz}} \\ \sigma^z_{yx} & 0 & 0 \\ \cancel{\sigma^z_{zx}} & 0 & 0 \end{pmatrix}$$

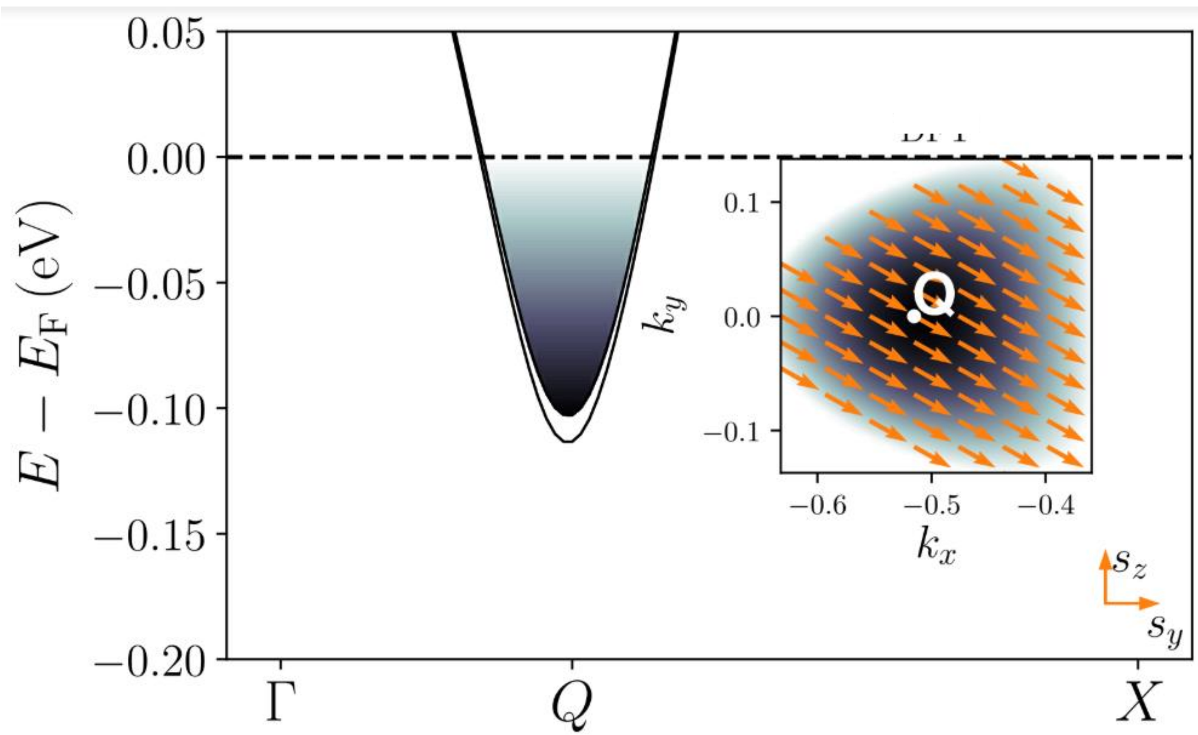
Two charge pocket Q, Q’ related by time-reversal symmetry

4-band symmetry-based model TMD-1T$_d$

Describes the two dominant orbitals of the valence bands,
d and p [τ_i], and the **spins** [σ_i]

$$H = k^2(m_p\tau_0 + m_d\tau_z) + \beta k_y\tau_y + \eta\tau_x + H_{SOC}$$

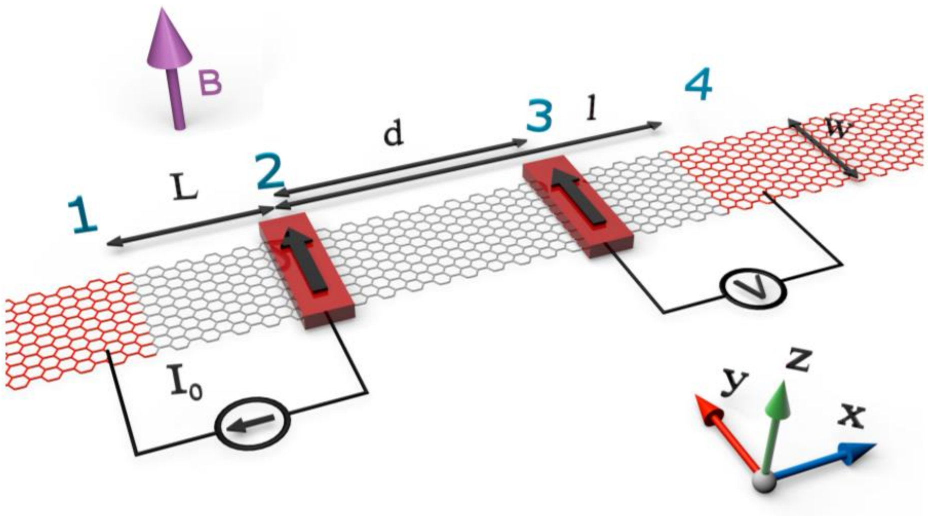
$$H_{SOC} = \cancel{\Lambda_x k_y\sigma_x\tau_x} + (\Lambda_y\sigma_y + \Lambda_z\sigma_z)k_x\tau_x$$



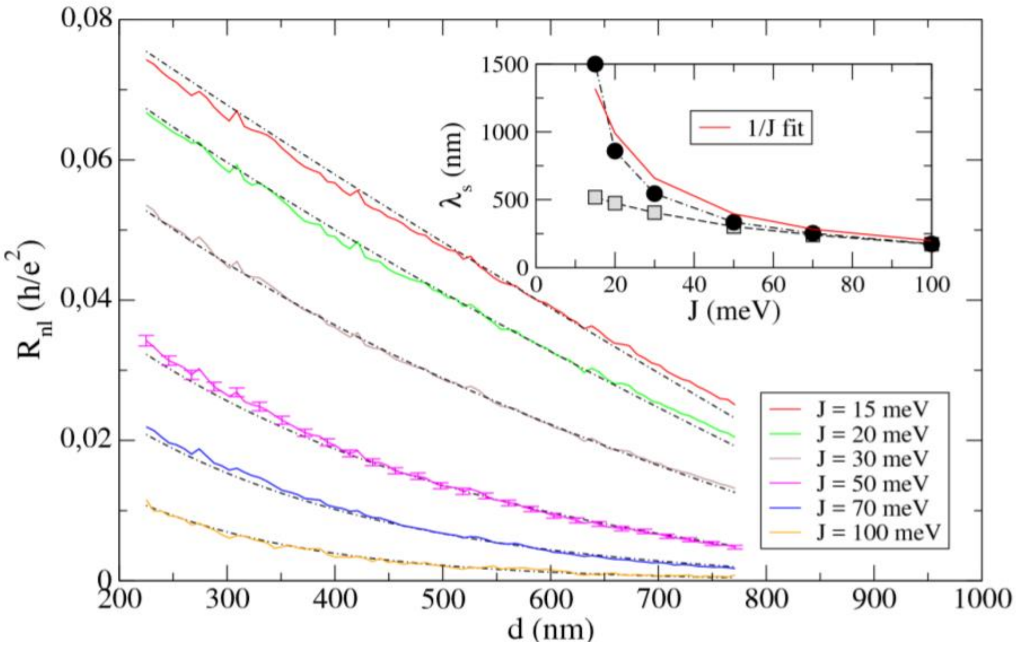
Persistent spin texture

$$\langle\vec{s}\rangle_{E_F} \approx \langle S_0\rangle_{E_F}\,\hat{u}(\theta)$$

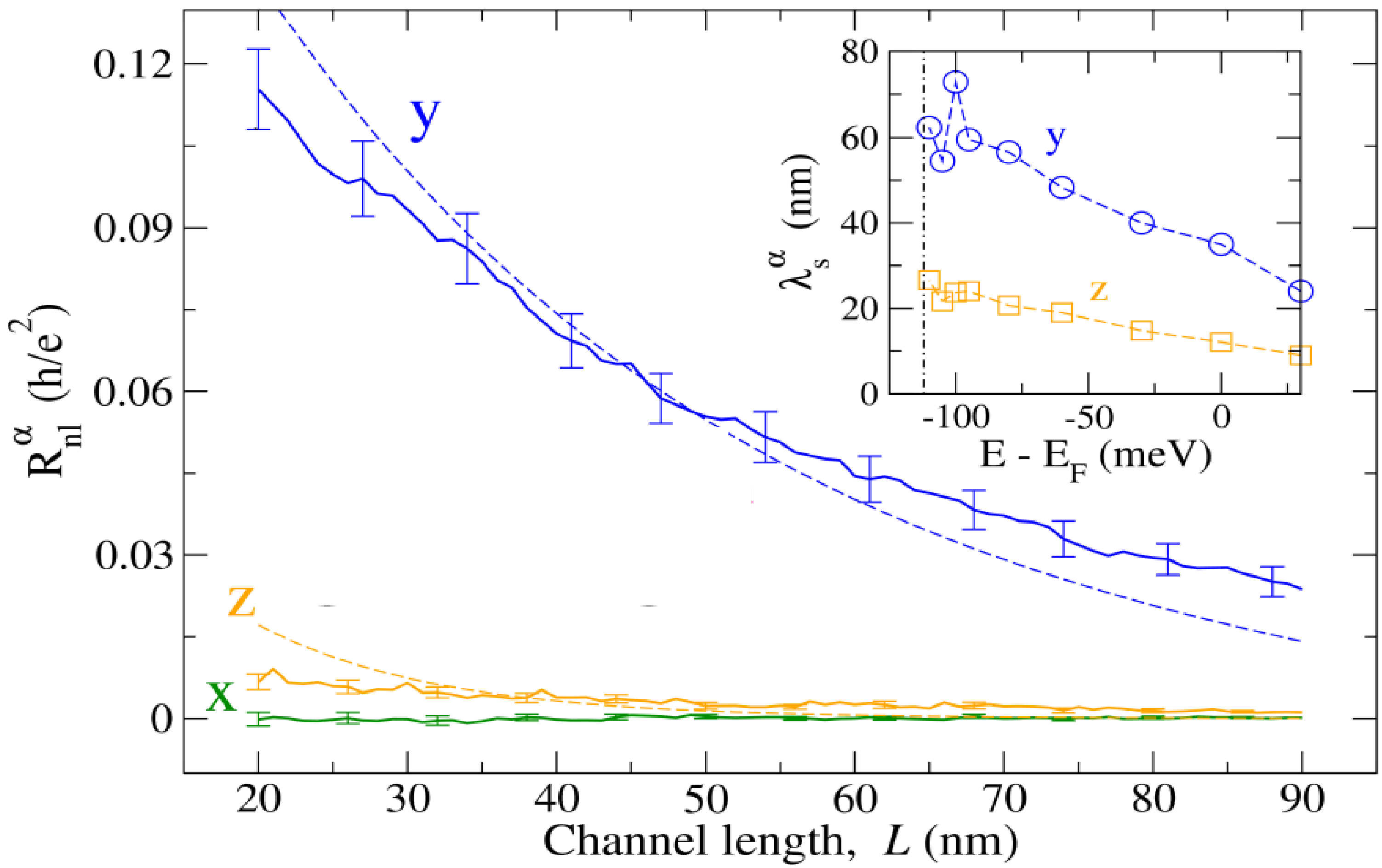
Nonlocal spin valves



kwant

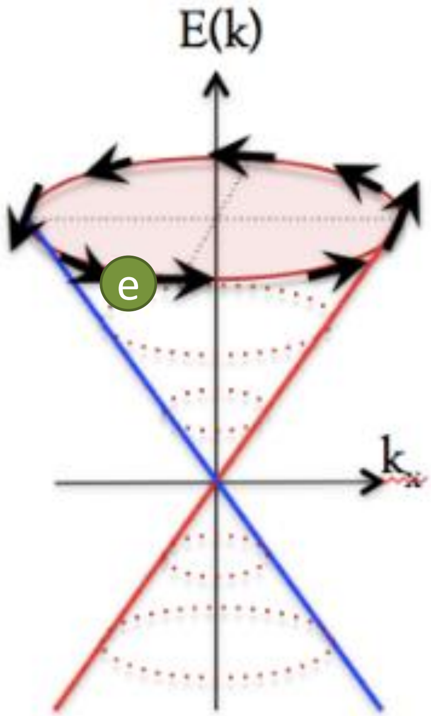


Anisotropic spin dynamics in $MoTe_2$



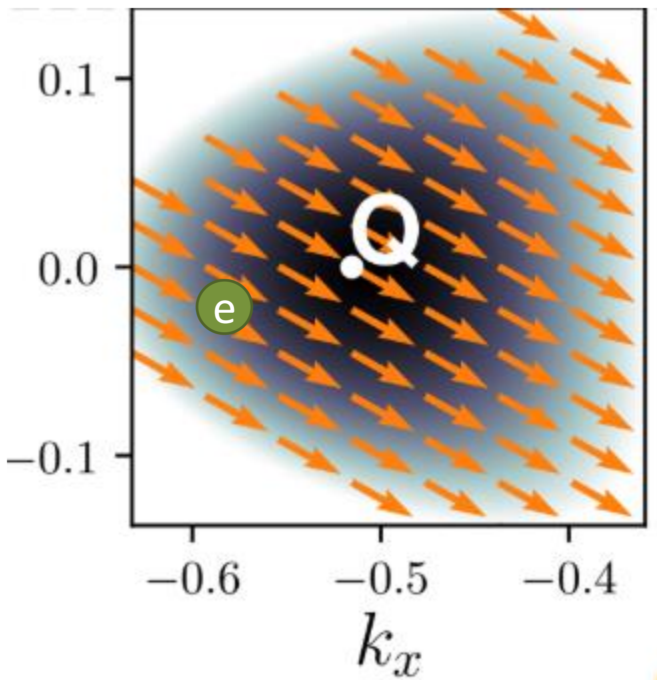
$$\langle \vec{s} \rangle_{E_F} \approx \langle S_0 \rangle_{E_F} \, \hat{u}(\theta)$$

Anisotropic spin dynamics in $MoTe_2$



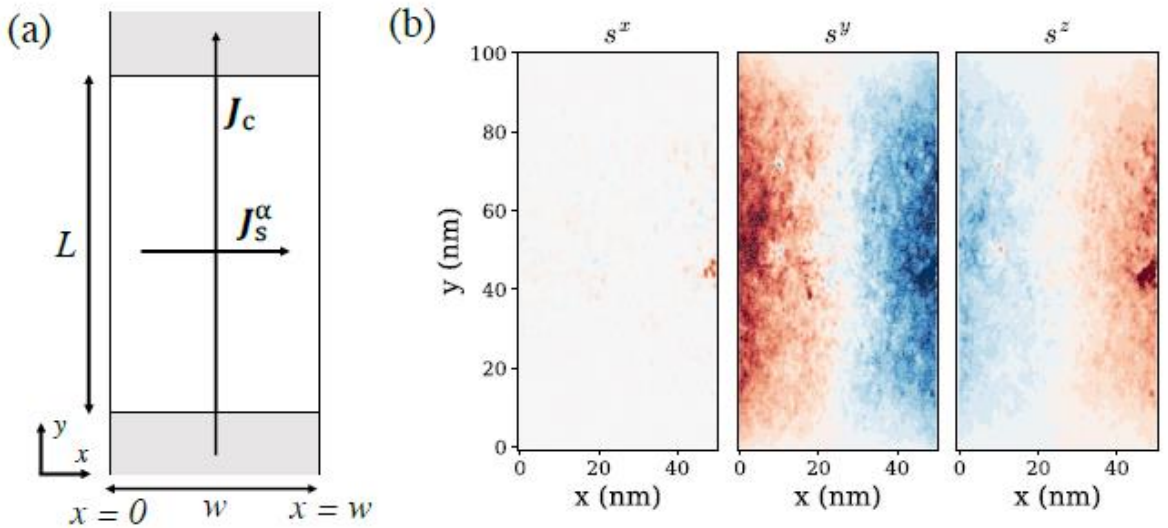
Scattering changes
the effective magnetic field randomly
(Relaxation)

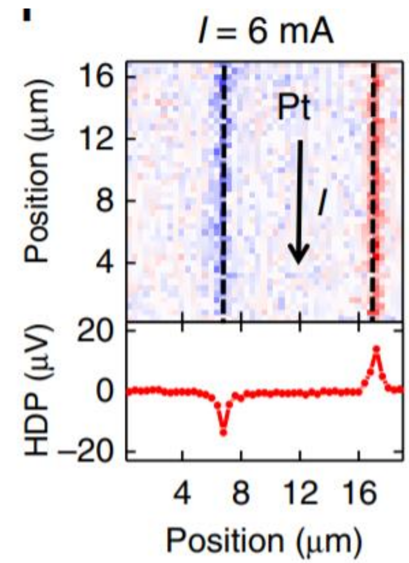
$$\langle \vec{s} \rangle_{E_F} \approx \langle S_0 \rangle_{E_F}\, \hat{u}(\theta)$$



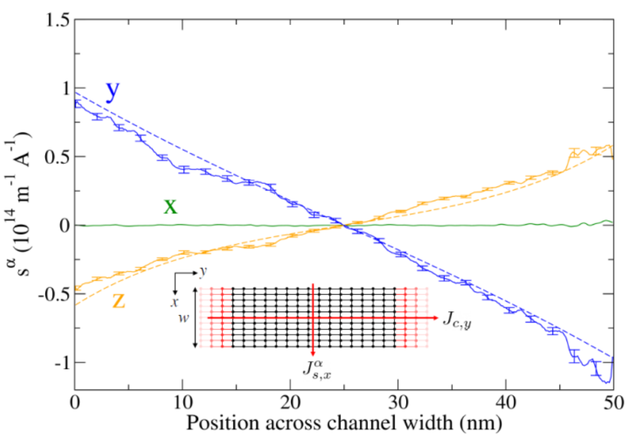
The effective magnetic field is fixed
(Dephasing)

Spin Hall Effect induced spin accumulation



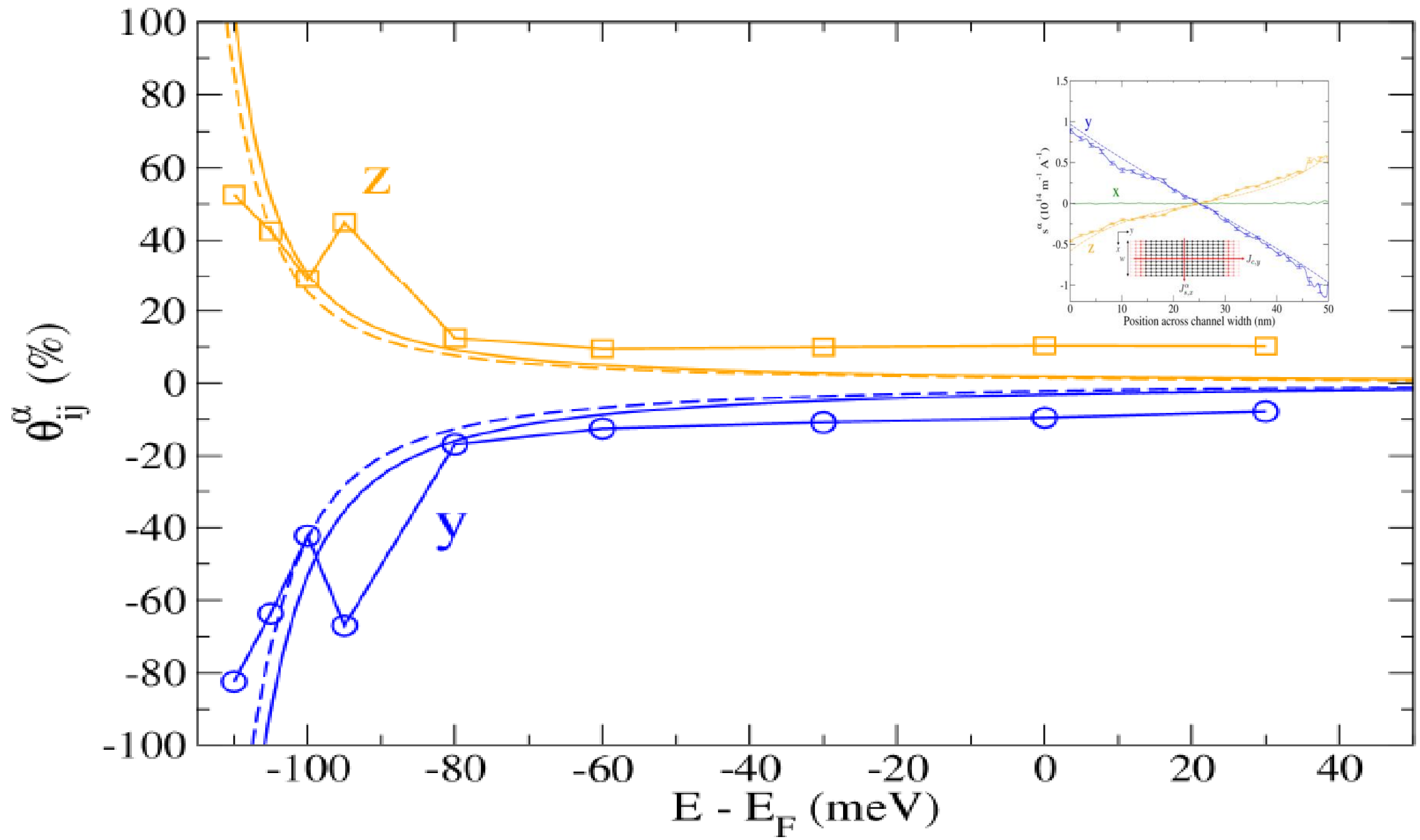


DOI: 10.1038/s41467-018-04939-6 OPEN
Hyunsoo Yang's group



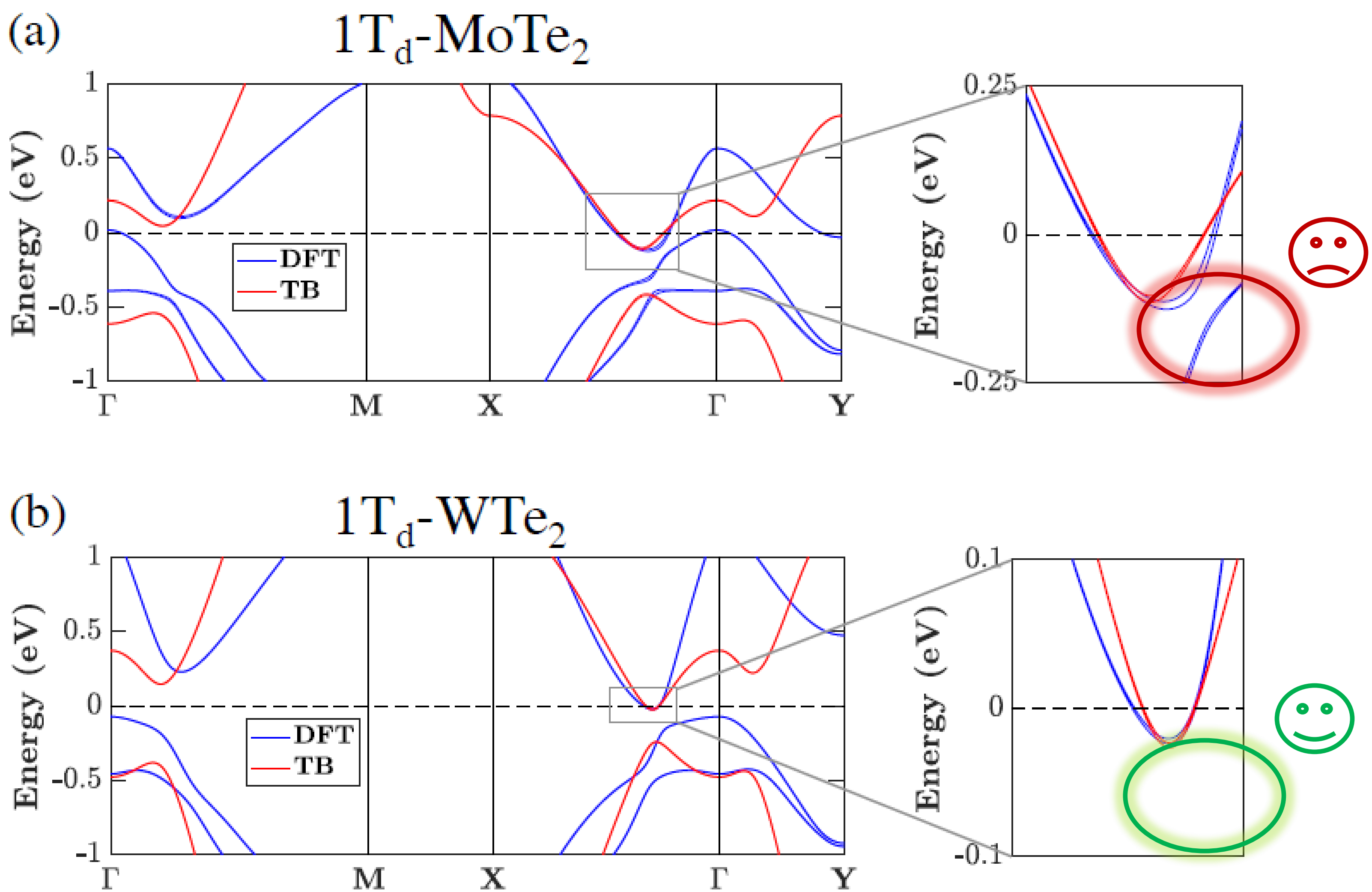
Multidirectional spin
Hall effect in the MONOLAYER

Enormous Spin Hall Angle 80%

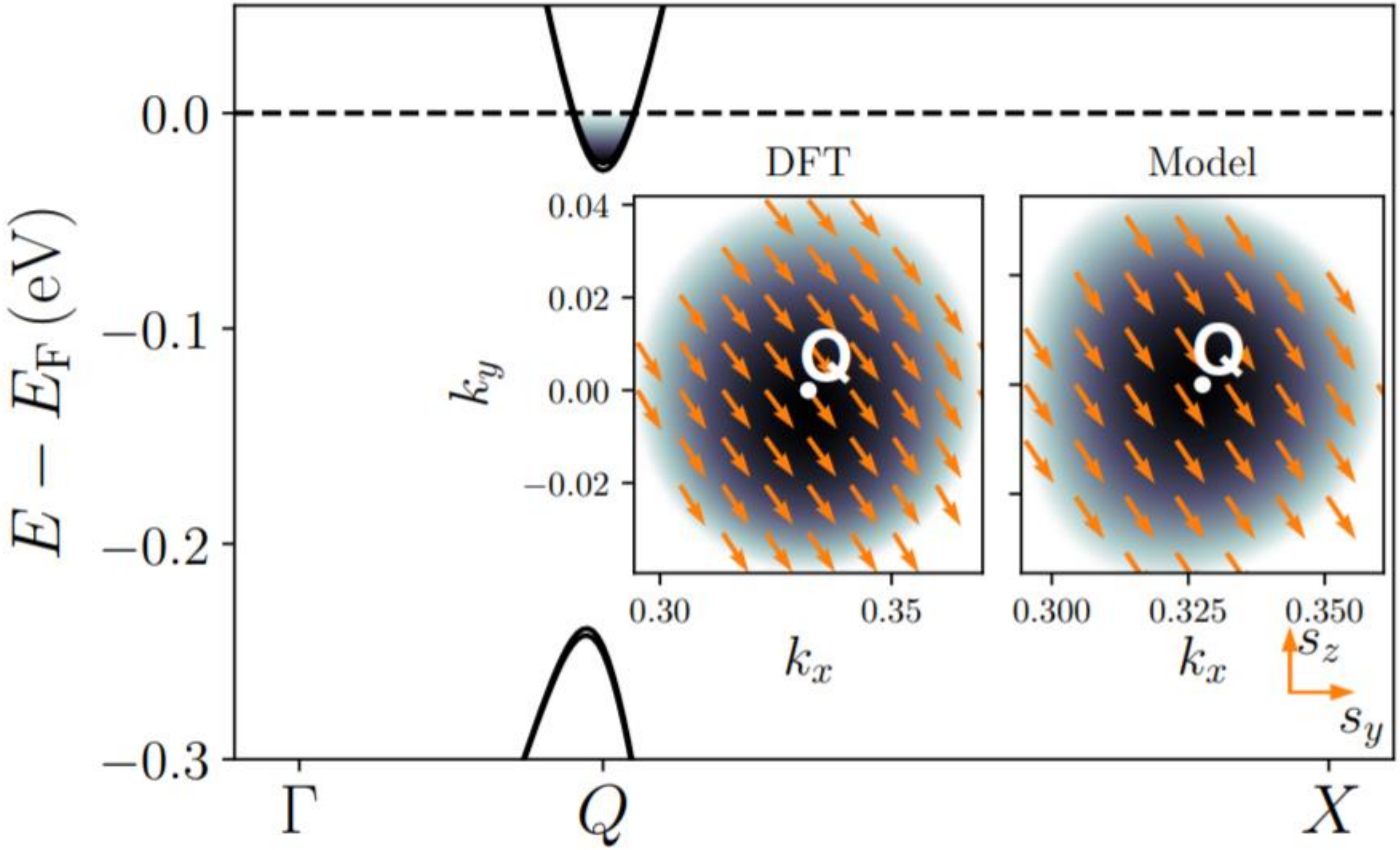


- Lines are Berry curvature component computed through Kubo.
- Symbols are device results.
- Dashed xy-> yx results

$MoTe_2$ vs WTe_2



A model for WTe_2

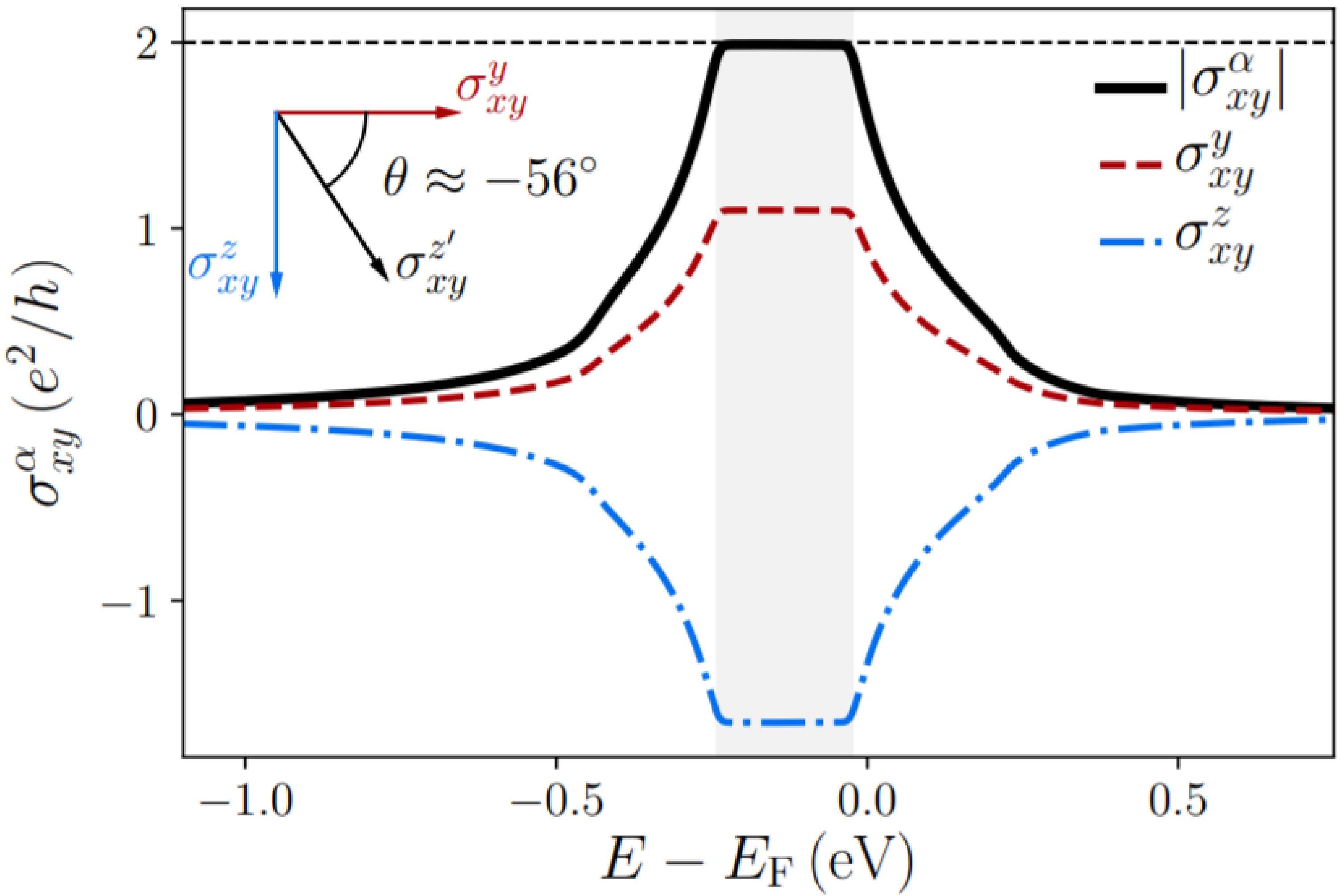


$\langle \vec{s} \rangle_{E_F} \approx \langle S_0 \rangle_{E_F} \, \hat{u}(\theta)$

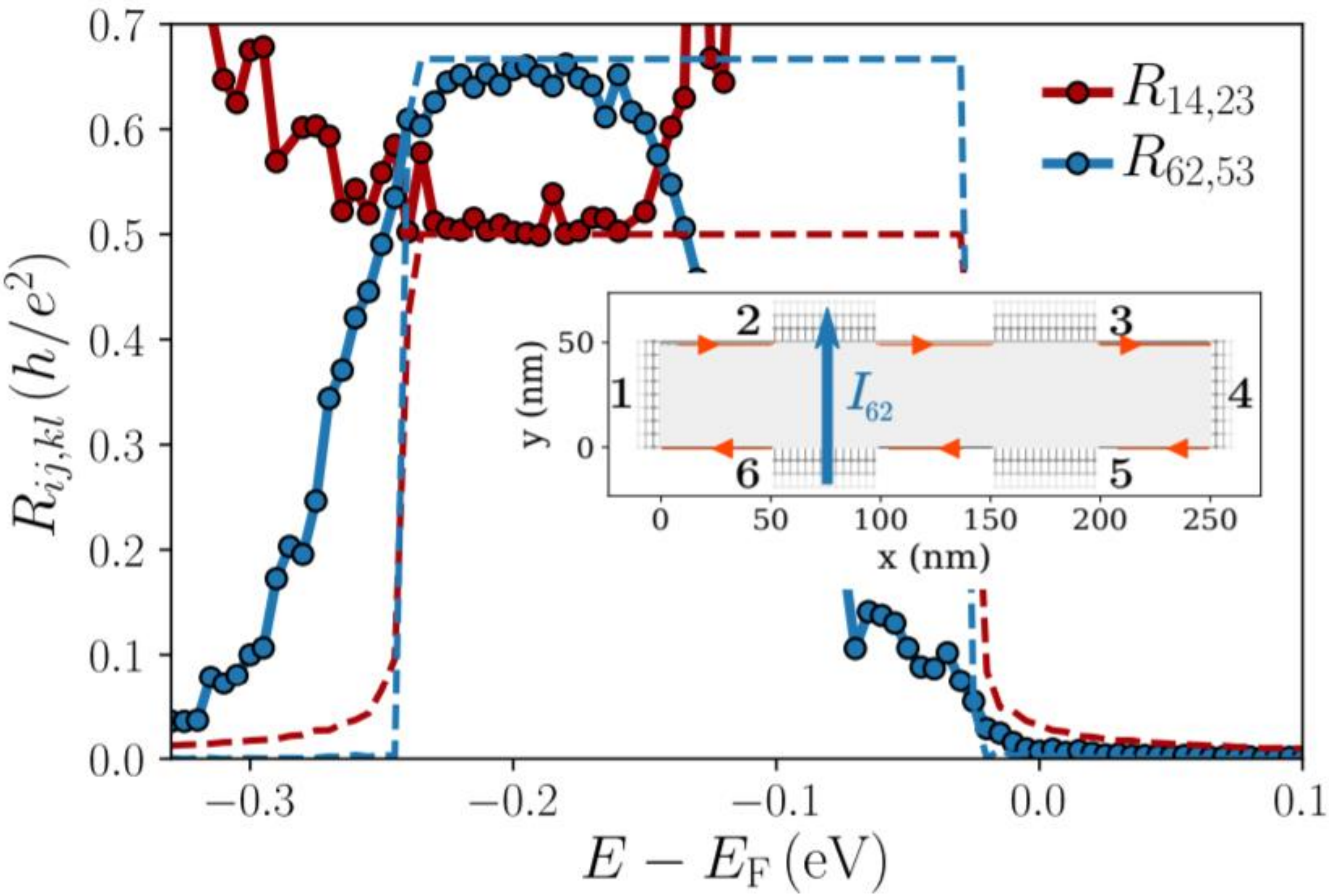
$\theta \equiv \arctan\left(\Lambda_z / \Lambda_y\right) \approx -56^\circ$

Canted Quantum Spin Hall Effect in WTe_2

$\langle \vec{s} \rangle_{E_F} \approx \langle S_0 \rangle_{E_F} \, \hat{u}(\theta)$ $\theta \equiv \arctan(\Lambda_z/\Lambda_y) \approx -56°$



Topologically protected edge-states



Disorder 1eV (Experimentally worst-case 100 meV)

1/3 and 2/6 implies it is topological

Conclusions

arXiv:2007.05626
arXiv:2007.02053
Phys. Rev. Lett. 124, 196602 (2020)

- The monolayers of TMDs in 1Td phases can sustain huge multidirectional spin Hall effect, and simultaneously a long spin relaxation length.
- Part of the origin of the spin relaxation length is a persistent spin texture.
- The huge spin Hall angle is due to hotspot of the Berry curvature and may also protect against relaxation processes.
- A canted Quantum spin Hall effect is allowed do to the low symmetries of the materials

Questions?

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