Electrical switching of spin and valley in spin-orbit coupled graphene multilayers

Shubhayu Chatterjee
Carnegie Mellon University

SPICE Workshop
Hybrid Correlated States and Dynamics in Quantum Materials
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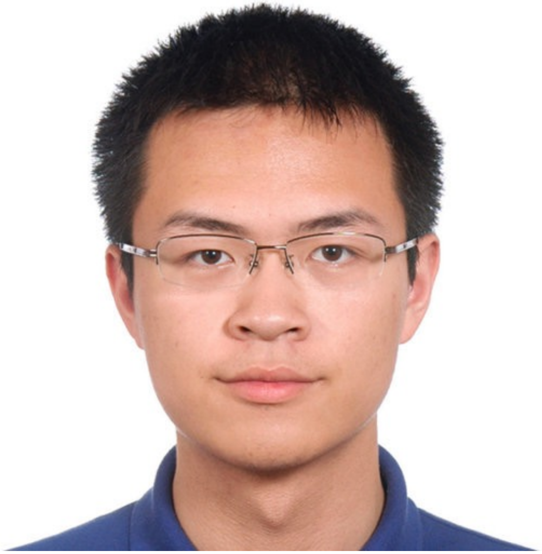
<P|Q|I>

In collaboration with:



Taige Wang
UC Berkeley

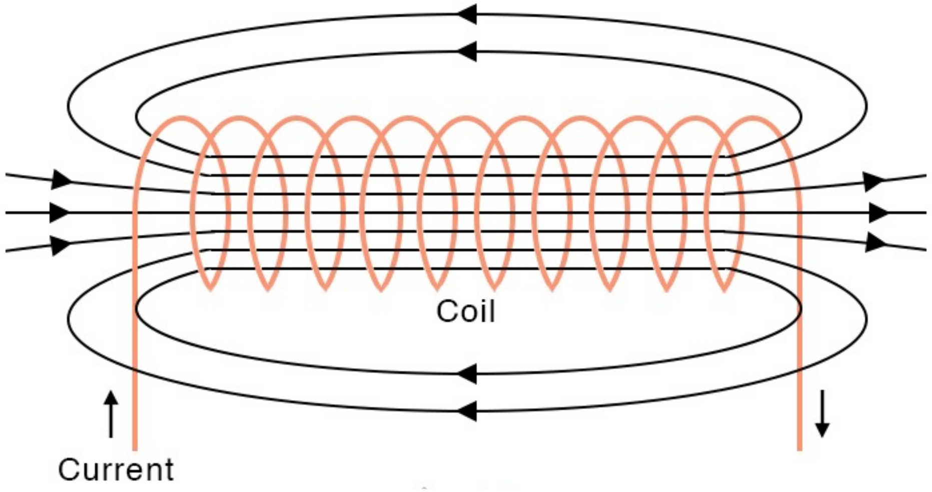
Marc Vila Tusell
UC Berkeley

Mike Zaletel
UC Berkeley

T. Wang*, M. Vila Tusell*, M. P. Zaletel and SC, PRL **132**, 116504 (2024)

Electric field control of magnetism

- Magnetism in materials is typically controlled by magnetic fields, sourced by currents in a solenoid

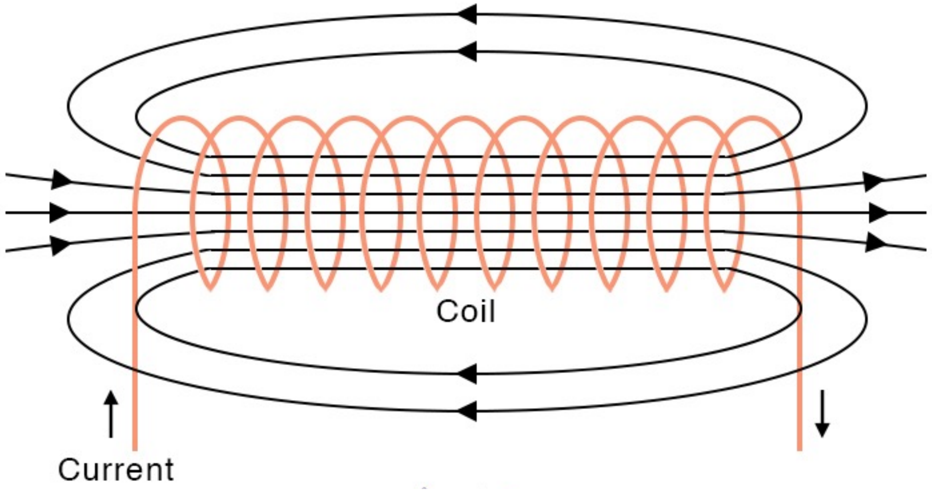


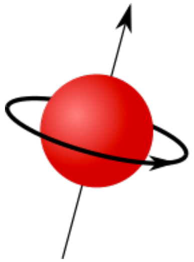
Electric field control of magnetism

- Magnetism in materials is typically controlled by magnetic fields, sourced by currents in a solenoid

- Electrical control of magnetism – longstanding goal of the spintronics community

- Promise for energy-efficient next generation devices





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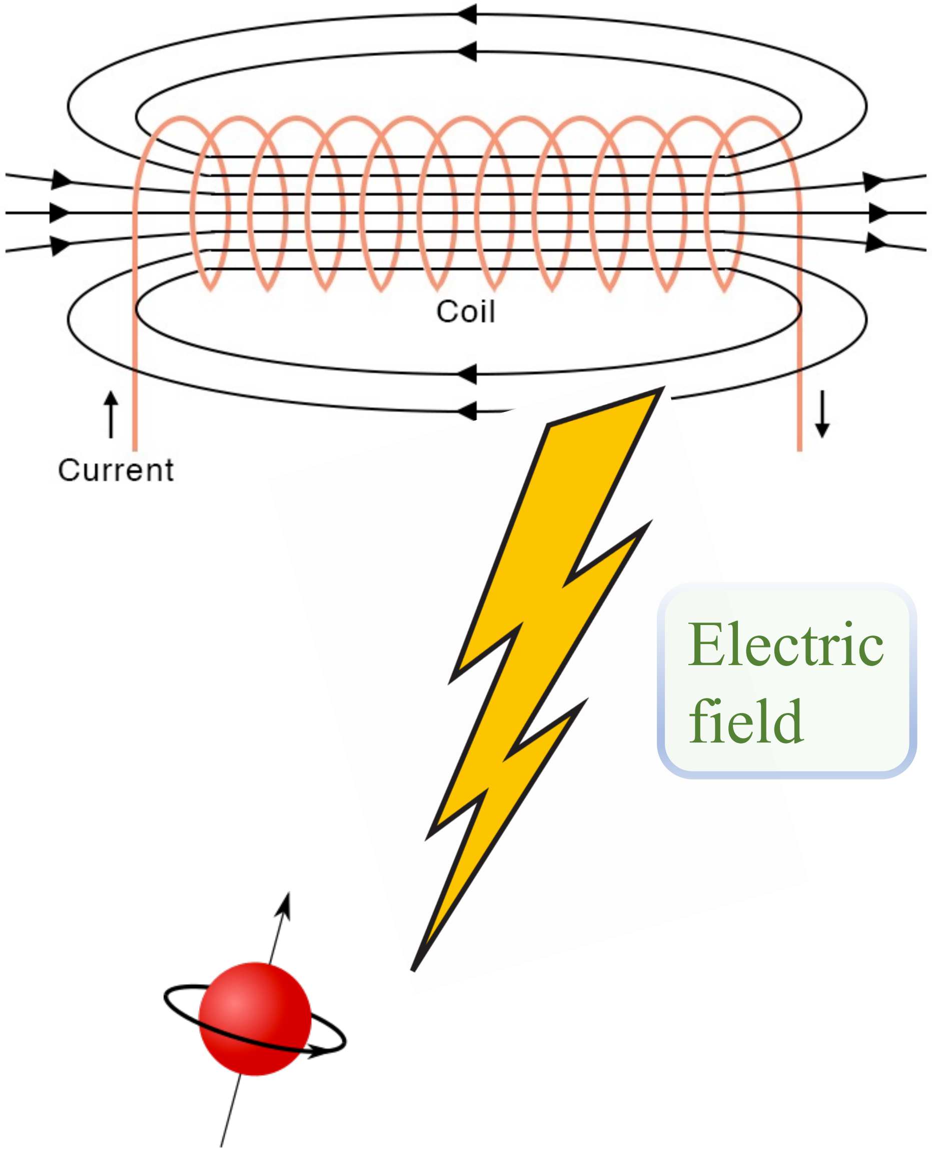

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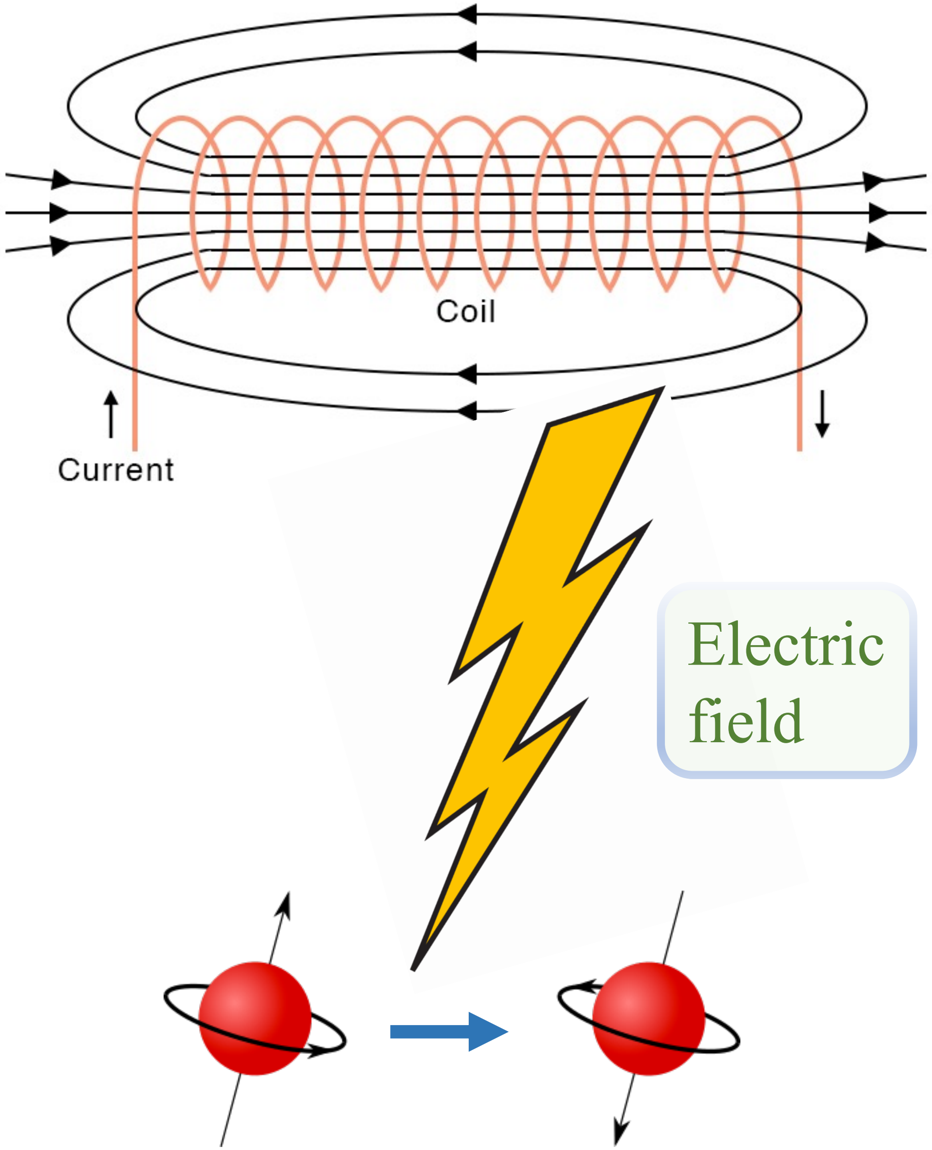

Electric field control of magnetism

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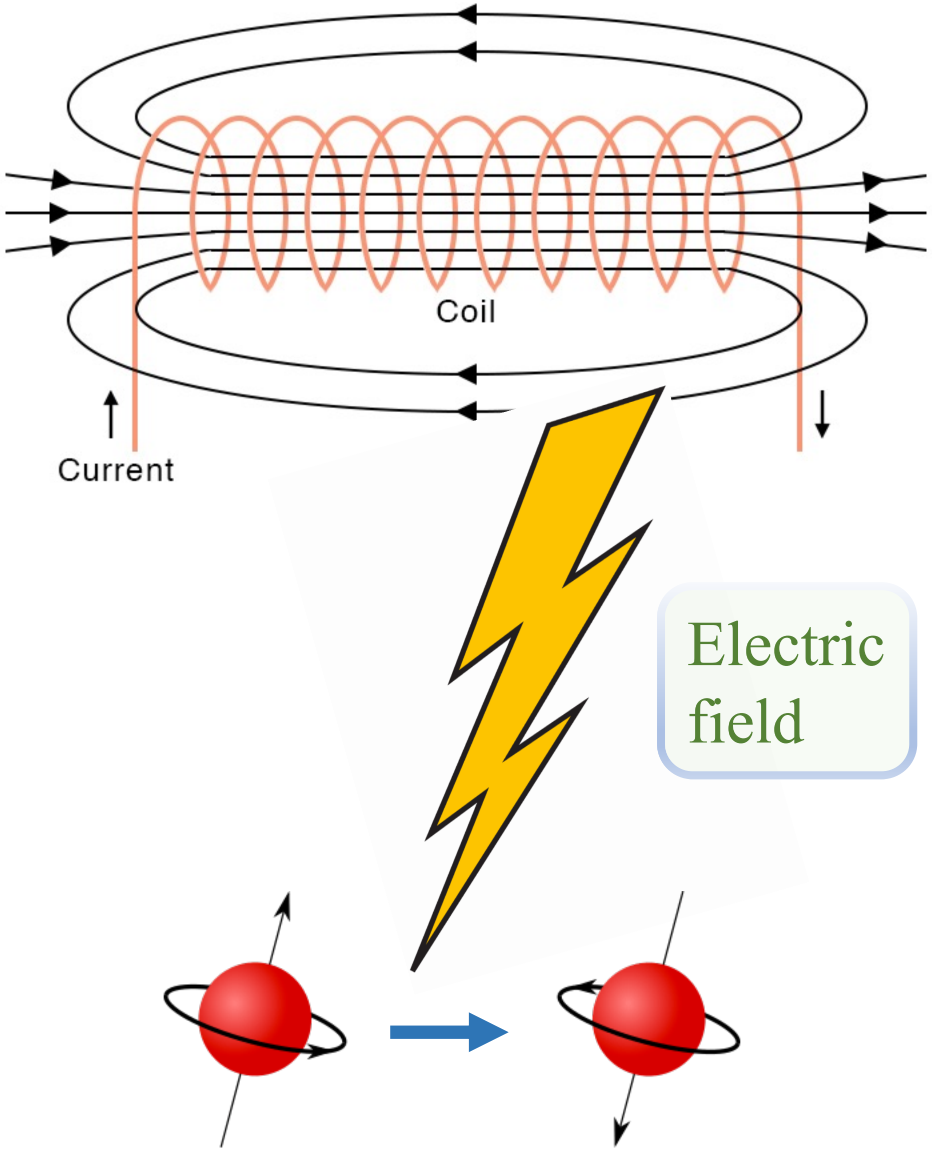
- Electrical control of magnetism – longstanding goal of the spintronics community
- Promise for energy-efficient next generation devices
- Potential barrier – Magnetism originates in materials from a combination of Fermi statistics and repulsive Coulomb interaction
- Difficult to control *directly* via electric fields



Electric field

2D materials: A Quantum Lego kit

- Atomically thin two dimensional materials have recently emerged as highly tunable and versatile platforms

- Distinct material properties from different stacking

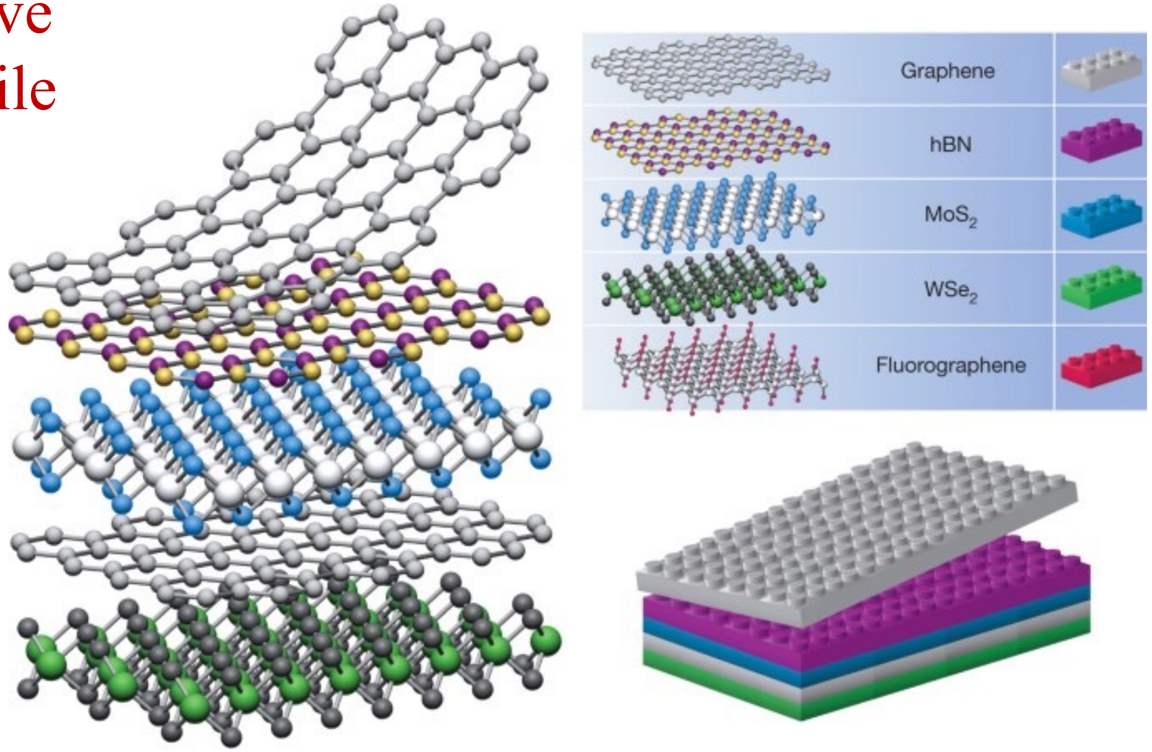
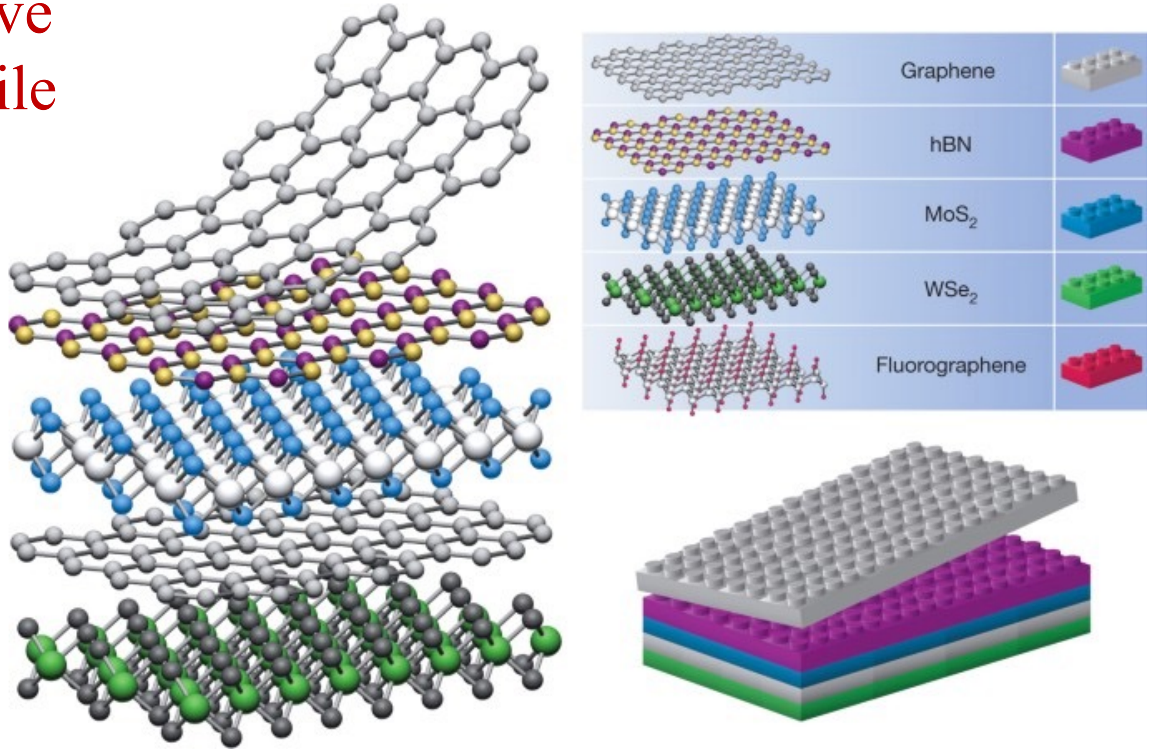


Figure: Geim, Grigorieva, Nature (2019)

2D materials: A Quantum Lego kit

- Atomically thin two dimensional materials have recently emerged as highly tunable and versatile platforms

1. Vary carrier density via metallic gate
2. Vary interaction strength by dielectric substrate



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3. *Twist angle* between layers – moiré materials (e.g., twisted bilayer graphene)

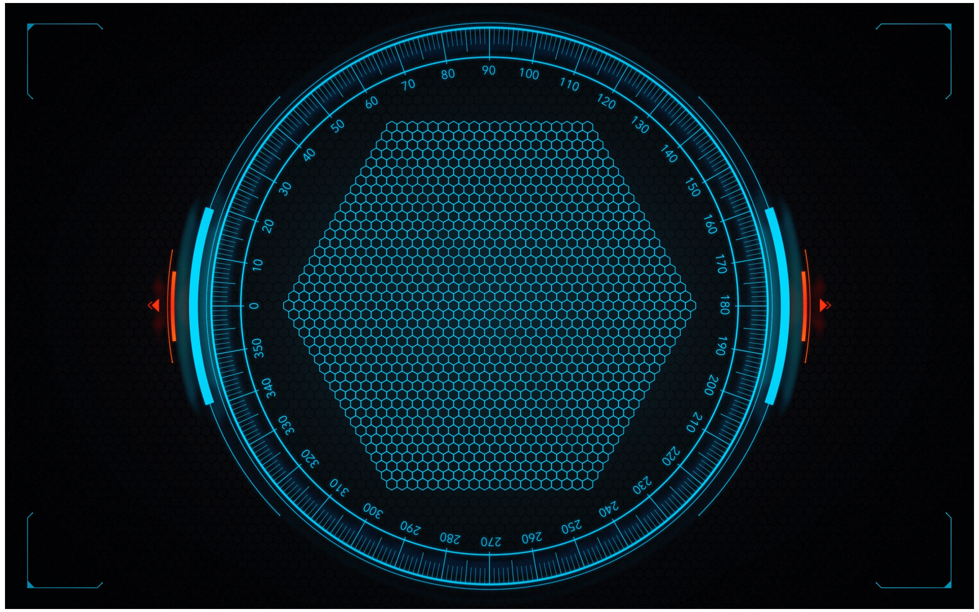

Figure: Quanta Magazine

2D materials: A Quantum Lego kit

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1. Vary carrier density via metallic gate
2. Vary interaction strength by dielectric substrate
3. *Twist angle* between layers – moiré materials (e.g., twisted bilayer graphene)
4. Perpendicular **E** fields (*displacement fields*) to flatten bands (e.g., ABC trilayer graphene)

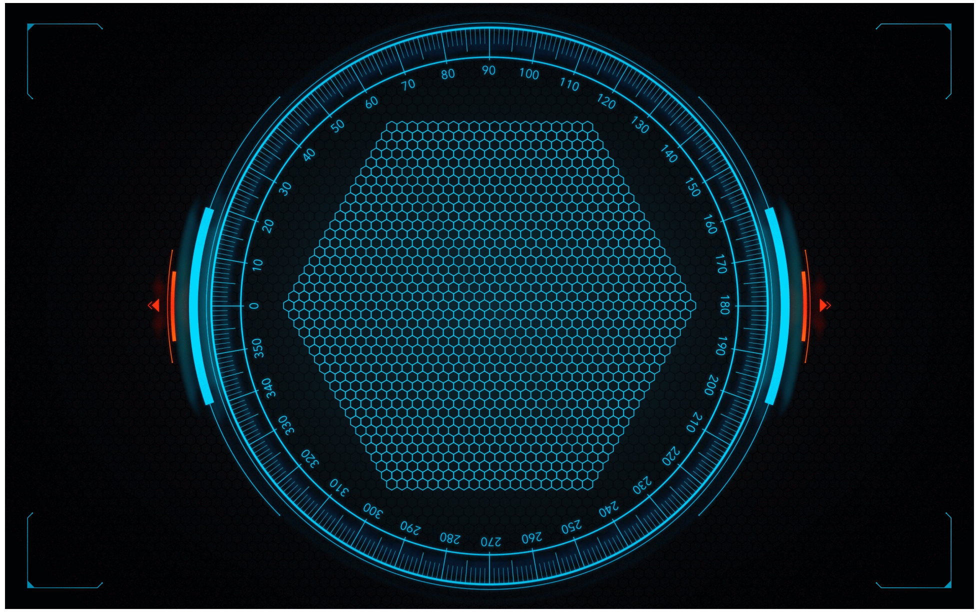


Figure: Quanta Magazine

Ferromagnets in Van der Waals materials

- Interaction is enhanced relative to bandwidth (t/U ≪ 1)
- Different forms of *hybrid correlated states* present, e.g., orbital (Chern) ferromagnets, spin polarized ferromagnets

Cao *et al*, (Nature 2018)^2
Choi *et al*, Nat. Physics (2019)
Sharpe *et al*, Science (2019)
Arora *et al*, Nature (2020)
Serlin *et al*, Science (2020)
Park *et al*, Nature (2021)
Hao *et al*, Science (2021)
Choi *et al*, Nat. Physics (2021)
Kim *et al*, Nature (2022)
Many many others…

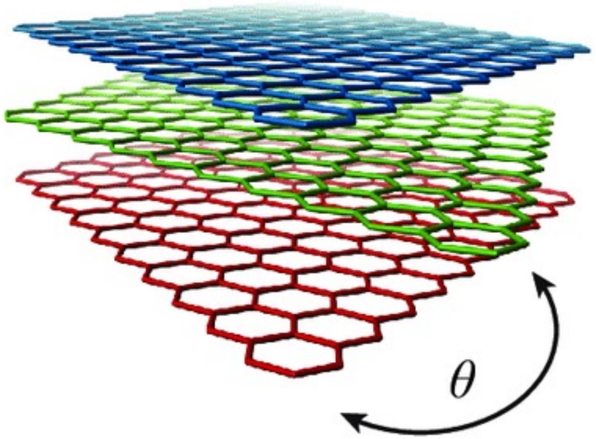
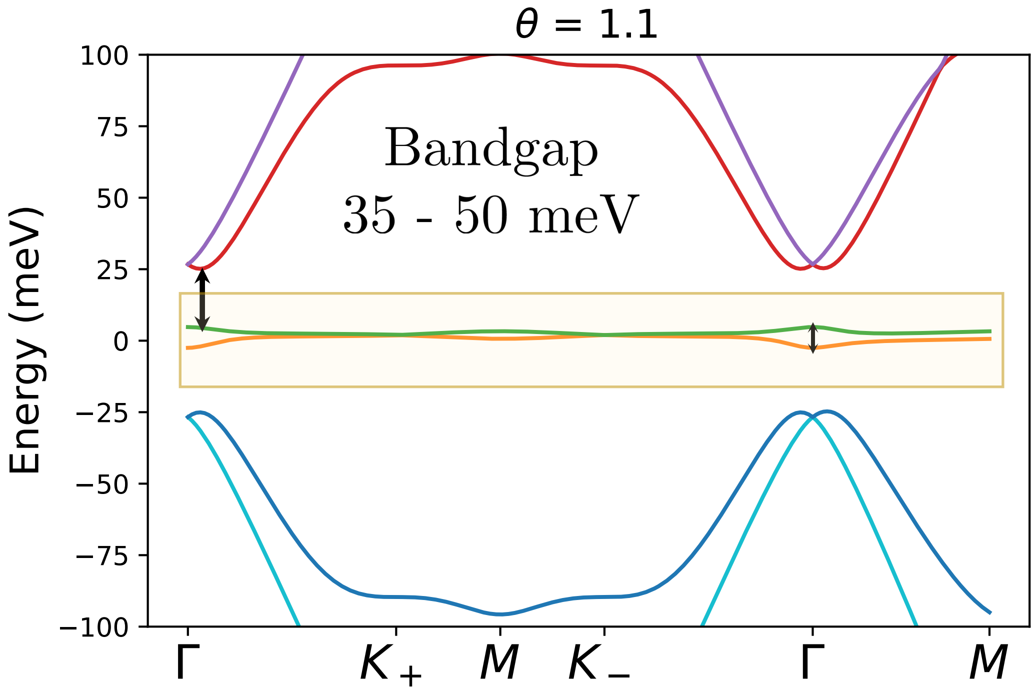


Figure: Khalaf *et al*, PRB 2019



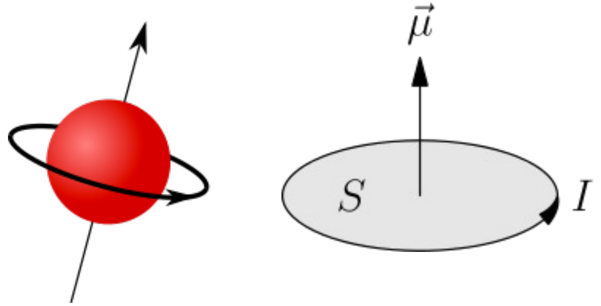
Bandwidth
5 - 15 meV

Bistritzer, Macdonald, PNAS 2011,
Los Santos *et al*, PRL 2007
Tarnospolsky *et al*, PRL 2019
Khalaf *et al*, PRB 2019
Bernevig *et al*, PRB 2021 (TBG I-VI)

2D materials for electrical switches

- Can we exploit the tunability of Van der Waals heterostructures to design an electrical switch of magnetism?

- Can we *selectively* control spin and valley degrees of freedom?



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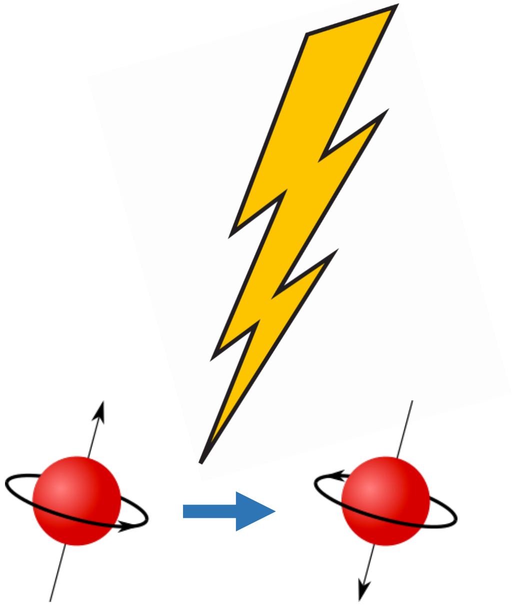

Outline

- Substrate induced spin-orbit coupling in chiral few-layered graphene
- Design principles of an electrical spin or valley switch
- Conclusion and outlook

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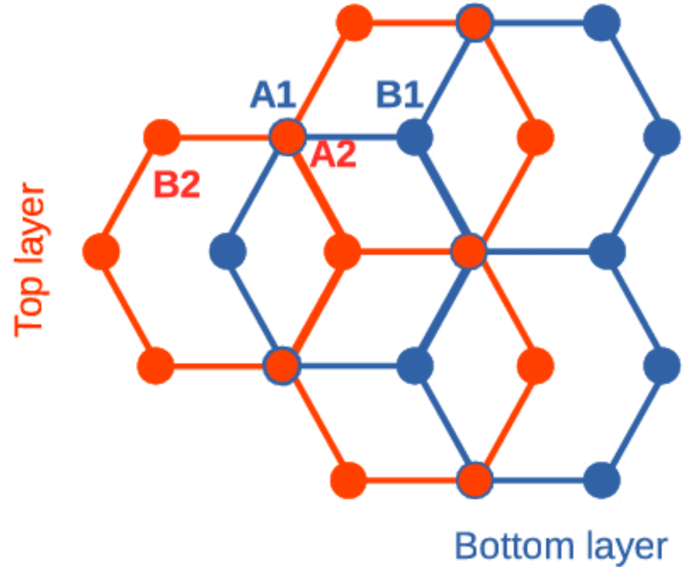
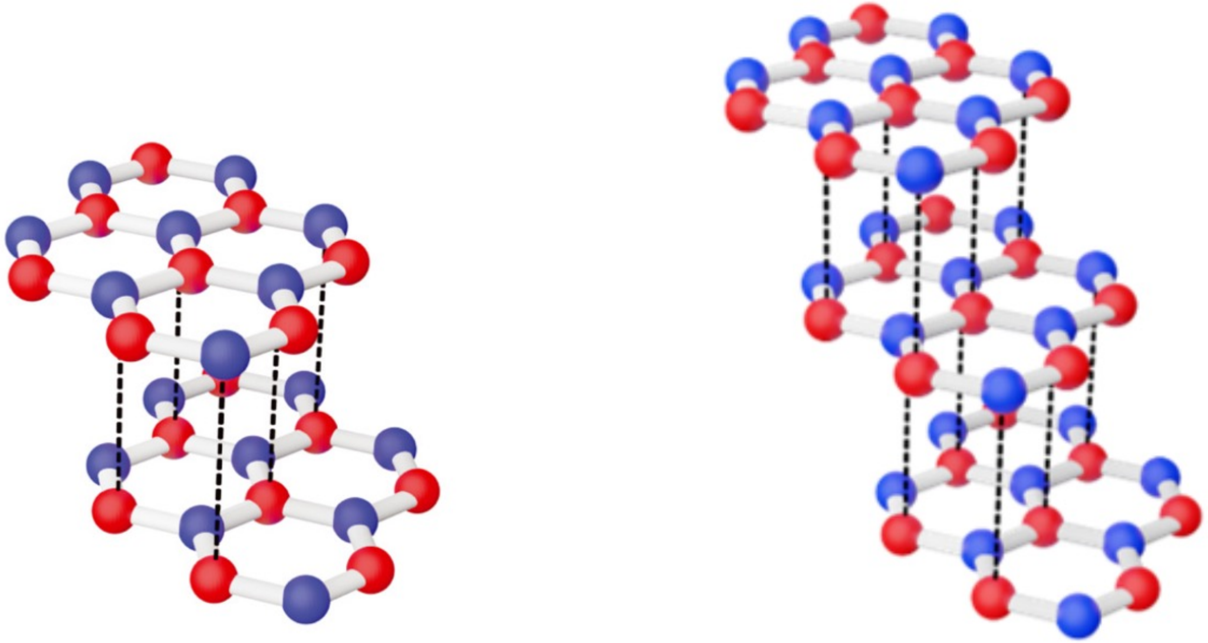
Chiral multilayered graphene

- Chirally stacked graphene multilayers





N = 2
Bernal bilayer graphene
(BBG)

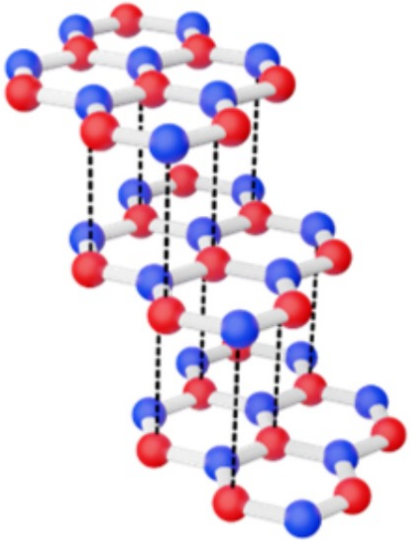
N = 3
Rhombohedral trilayer
graphene (RTG)

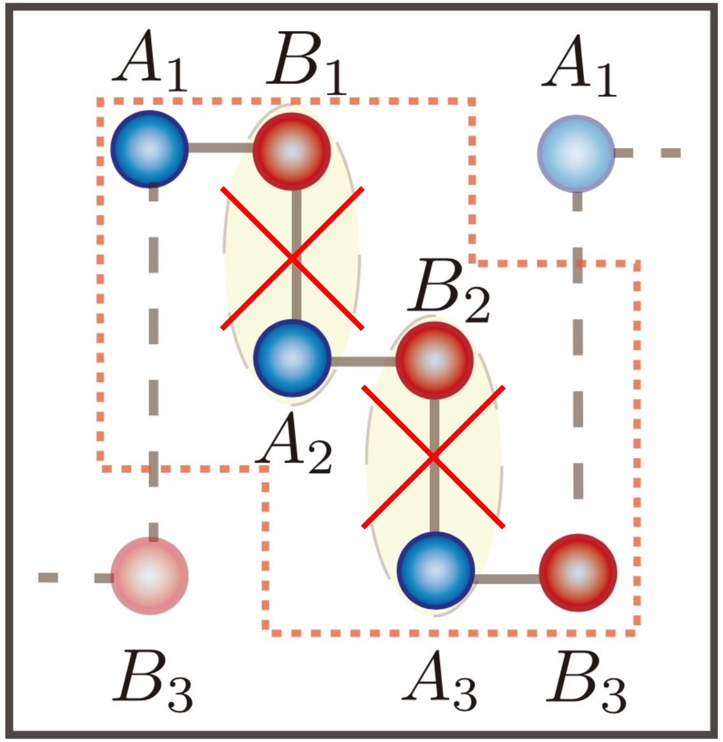
Figure: Zhou *et al*, Science (2022)

Chiral multilayered graphene

- Active sites for low-energy physics: A_1 and B_N

RTG

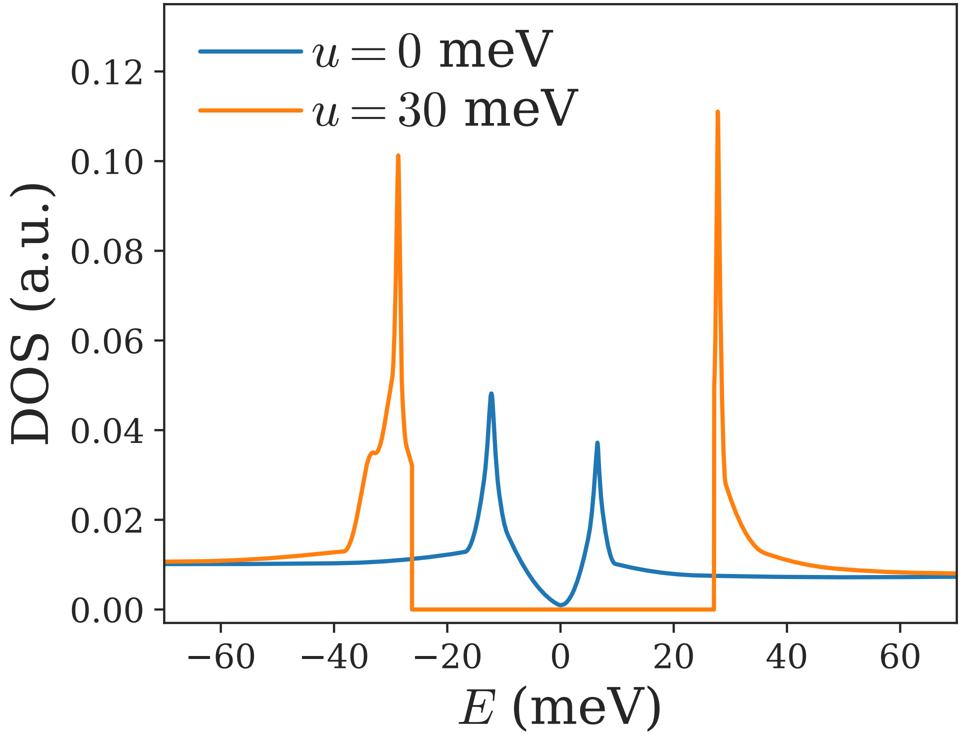


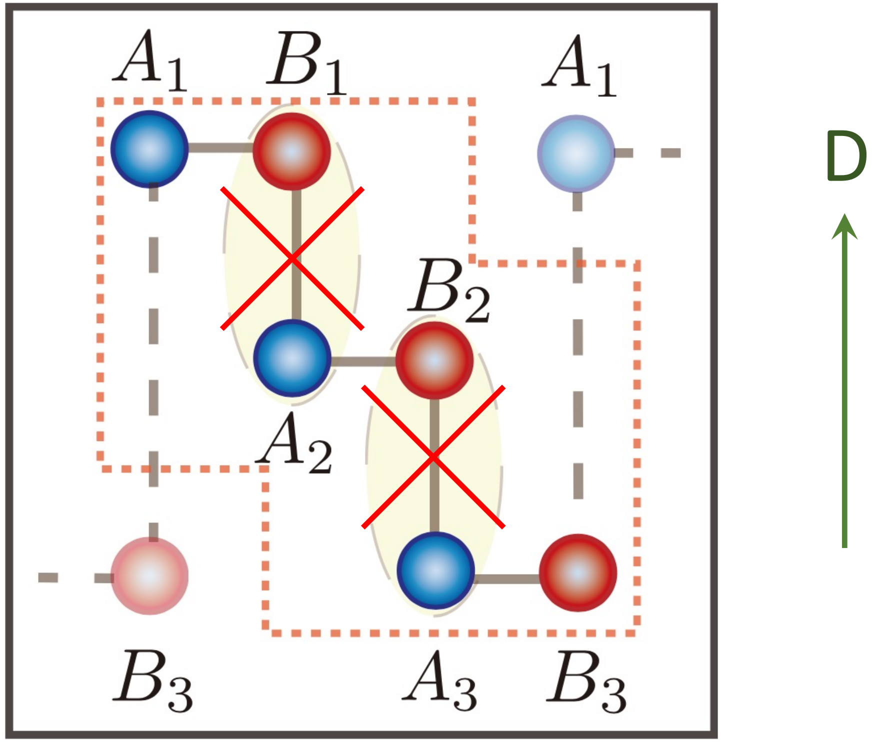


Chiral multilayered graphene

- Active sites for low-energy physics: A_1 and B_N
- Perpendicular displacement field D enhances DOS

$$H_{\text{eff}}(\tau, k) \approx \begin{pmatrix} u & \frac{(vk_-)^N}{t_\perp^{N-1}} \\ \frac{(vk_+)^N}{t_\perp^{N-1}} & -u \end{pmatrix}$$

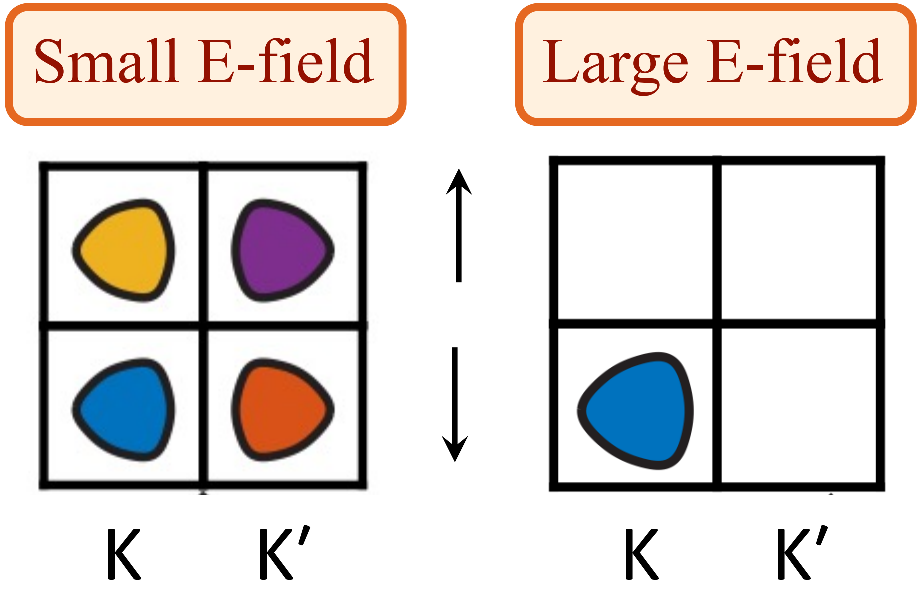


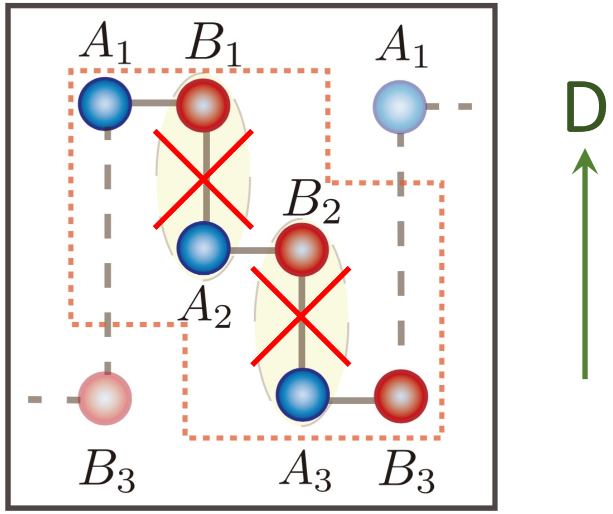


Chiral multilayered graphene

- Active sites for low-energy physics: A_1 and B_N
- Perpendicular displacement field D enhances DOS
- Enhanced DOS leads to interaction-driven flavor polarization

Zhou *et al*, Nature^2 (2021), Science (2022)
Seiler *et al*, Nature (2022), arXiv:2308.00827
Han, Lu *et al*, Science (2024)
Liu, Zheng *et al*, arXiv:2306.11042





Induced spin-orbit coupling

- Encapsulation by TMDs induces spin-orbit coupling (SOC) in chiral graphene

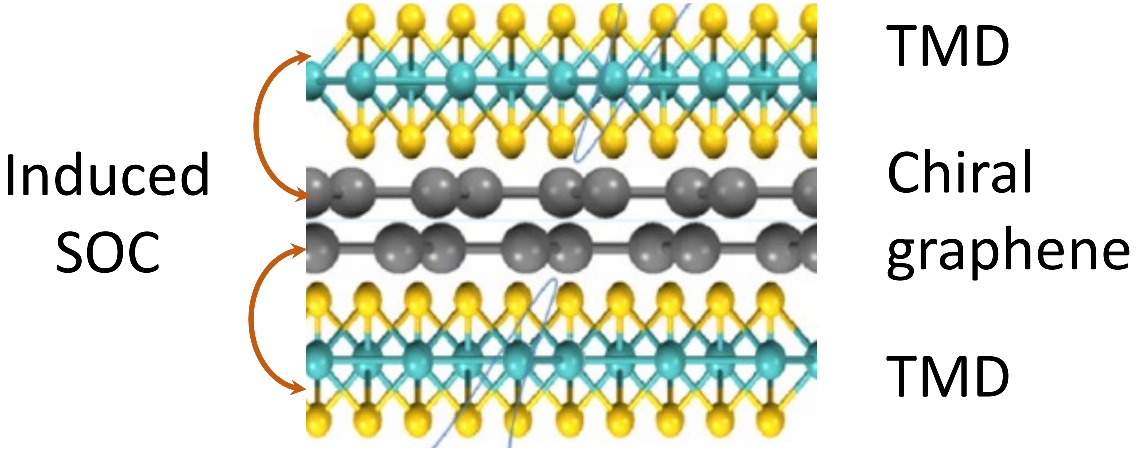
- On the adjacent monolayer – major contributions are:

$$H_{\mathrm{Ising-SOC}} = \lambda_I \, \tau^z s^z$$

Reduces spin-rotation symmetry from SU(2) to U(1)

$$H_{\mathrm{Rashba-SOC}} = \lambda_R \left(\tau^z \sigma^x s^y - \sigma^y s^x \right)$$

Breaks spin-rotation completely



Gmitra, Fabian, PRB (2015)
Zollner *et al*, PRB (2022)

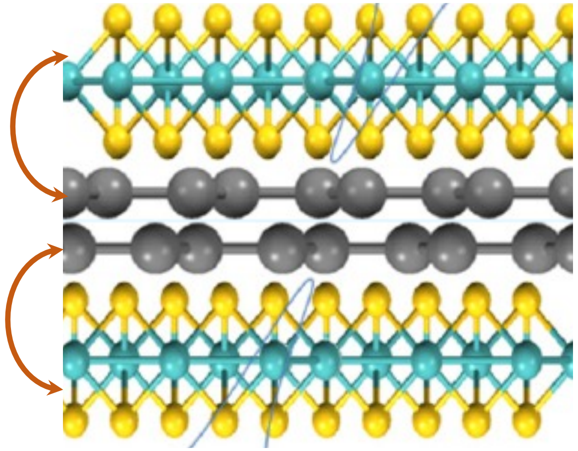
Induced spin-orbit coupling

- Encapsulation by TMDs induces spin-orbit coupling (SOC) in chiral graphene
- In chiral multilayers, the Rashba term is suppressed, only Ising SOC is important

$$H_{\text{Ising}-\text{SOC}} = \lambda_I\, \tau^z s^z$$

$$\cancel{H_{\text{Rashba}-\text{SOC}} = \lambda_R \left(\tau^z \sigma^x s^y - \sigma^y s^x\right)}$$

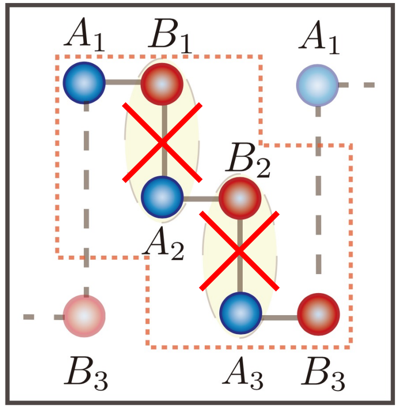
Induced SOC



TMD

Chiral graphene

TMD



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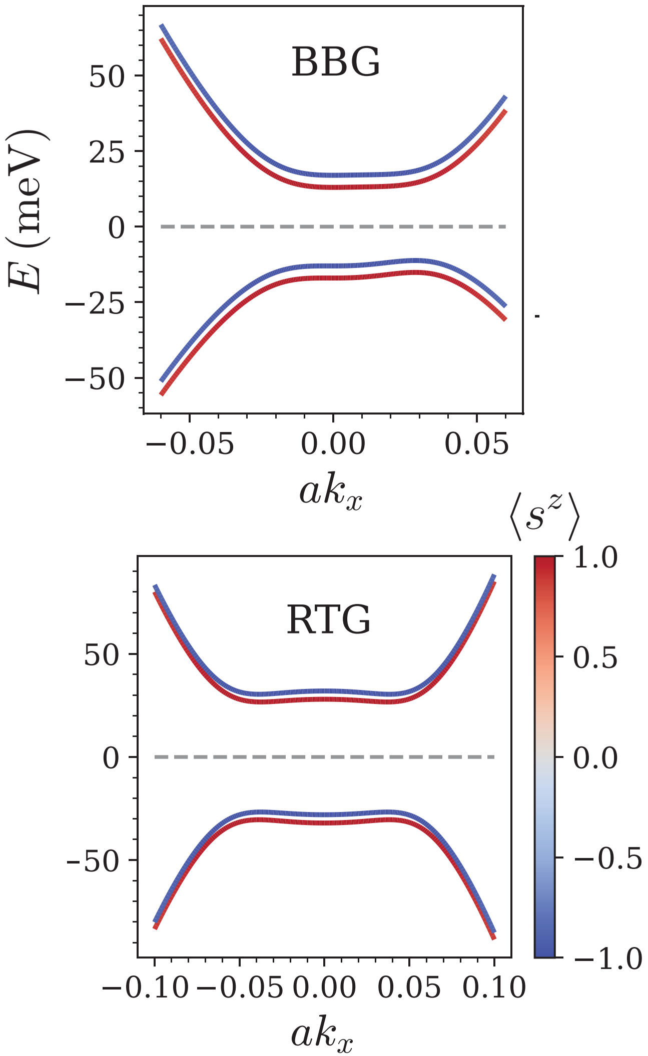
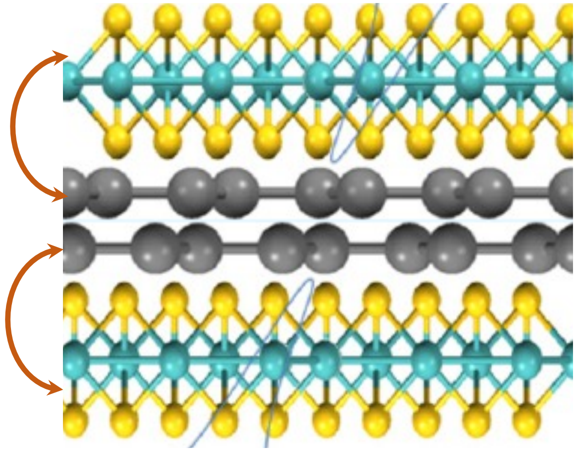
- Effective Hamiltonian in (A_1 , B_N) basis:

$$H_{\text{eff}}(\tau, k) \approx \begin{pmatrix} u + \lambda_I^{\text{top}} s^z \tau^z & \frac{(v k_-)^N}{t_\perp^{N-1}} \\ \frac{(v k_+)^N}{t_\perp^{N-1}} & -u + \lambda_I^{\text{bot}} s^z \tau^z \end{pmatrix}$$





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- If TMDs are *aligned*, we expect the same sign of Ising SOC on the top and bottom layers

$$\lambda_I^{\text{top}} = \lambda_I^{\text{bot}}$$

Zaletel, Khoo, arXiv:1901.01294

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- If TMDs are *anti-aligned*, inversion symmetry is preserved (at $u = 0$)

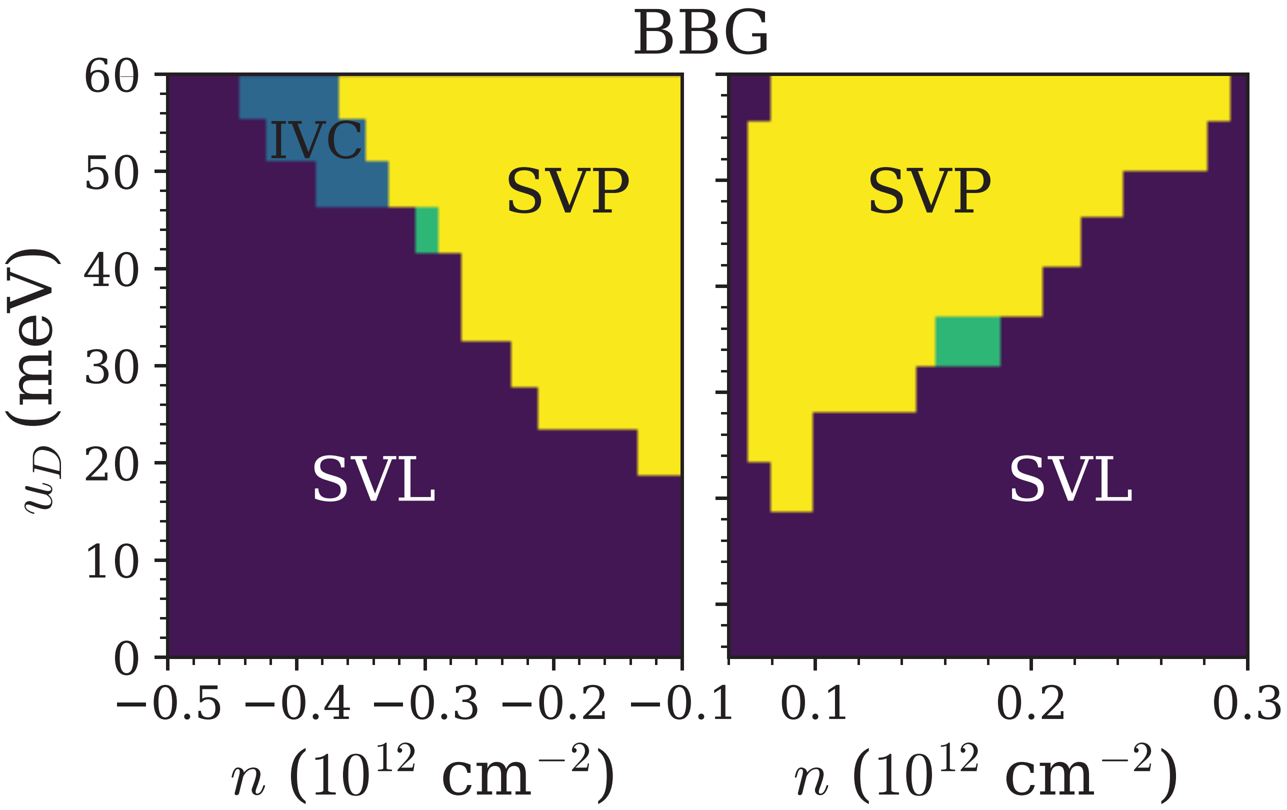
- Inversion *requires* opposite signs of Ising SOC on top and bottom layers

$$\lambda_I^{\text{top}} = -\lambda_I^{\text{bot}}$$

Zaletel, Khoo, arXiv:1901.01294

Interactions cause flavor polarization

- Requires finite D in BBG/RTG, seen at D = 0 in rhomohedral pentalayer graphene (RPG)



Phase diagram at $\lambda_I = 2$ meV, $\lambda_R = 0$, aligned device

Experiments:
Zhang *et al*, Nature (2023)
Seiler et al, arXiv:2403.17140

BBG on WSe_2

Han *et al*, Science (2024)

RPG on WS_2

Theory:
Wang, SC *et al*, PRL (2024)
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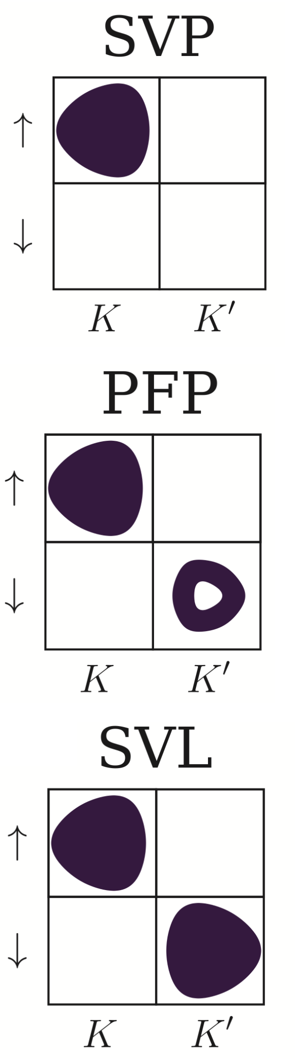

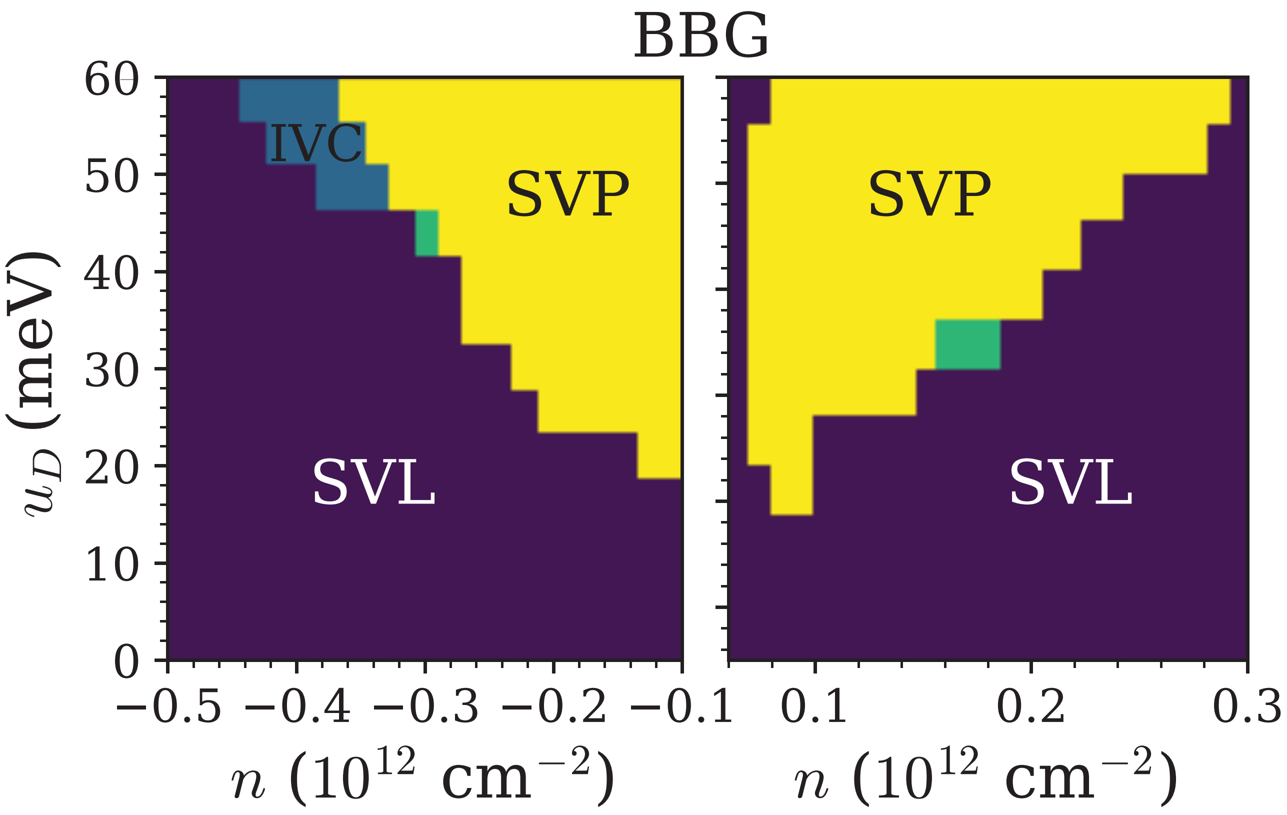

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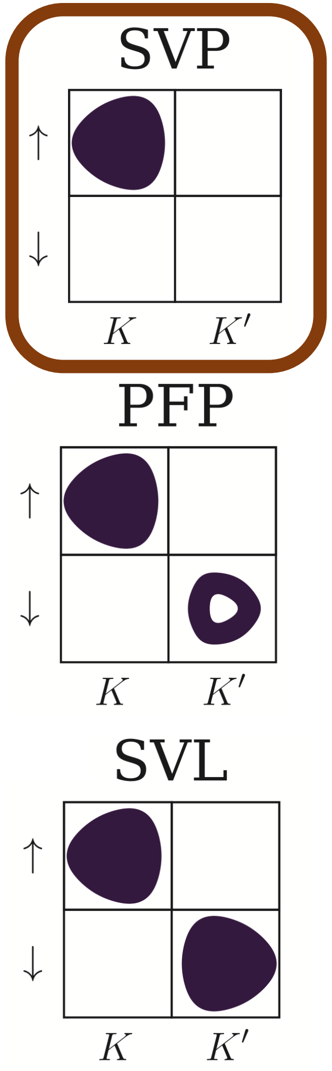

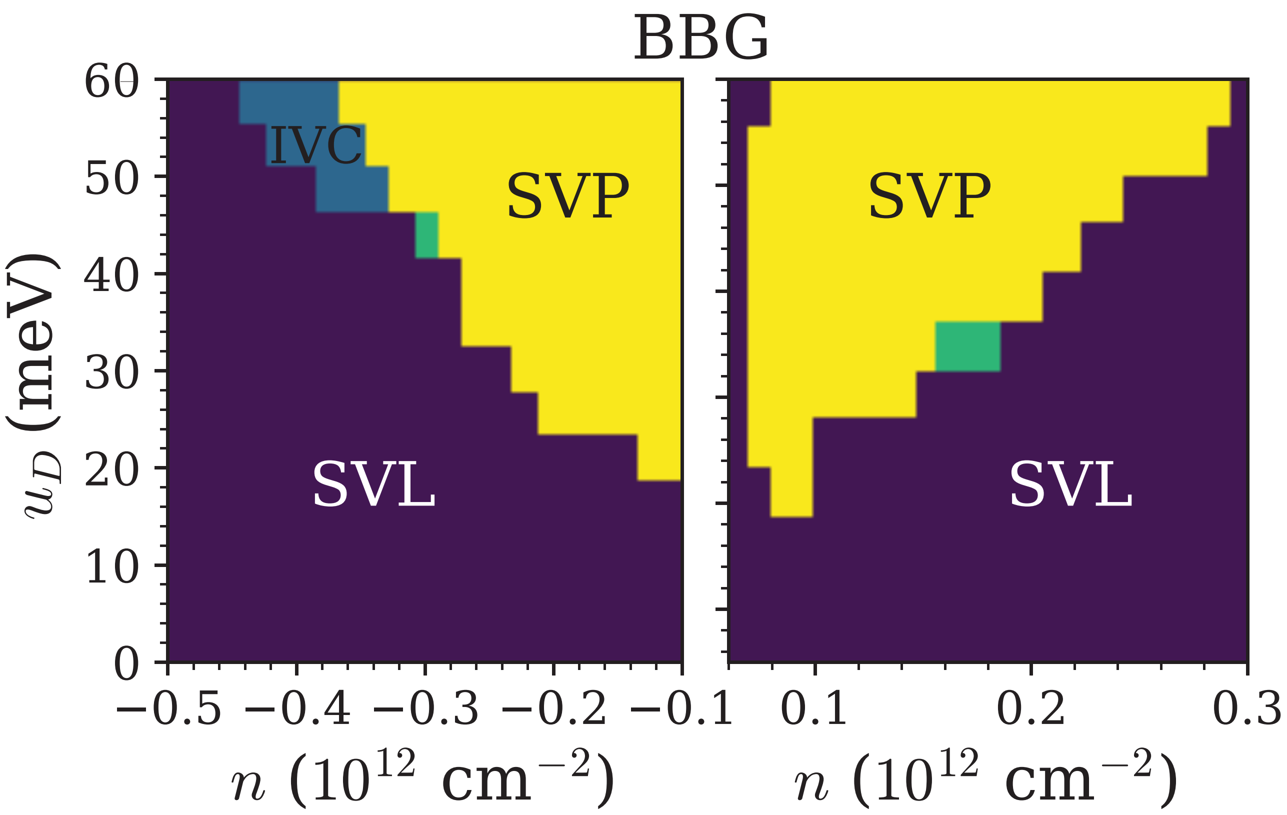

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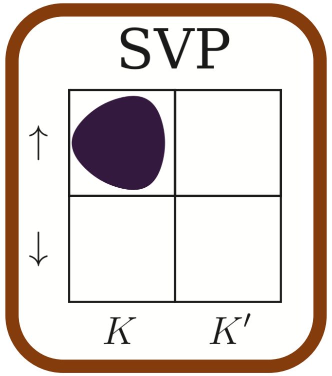

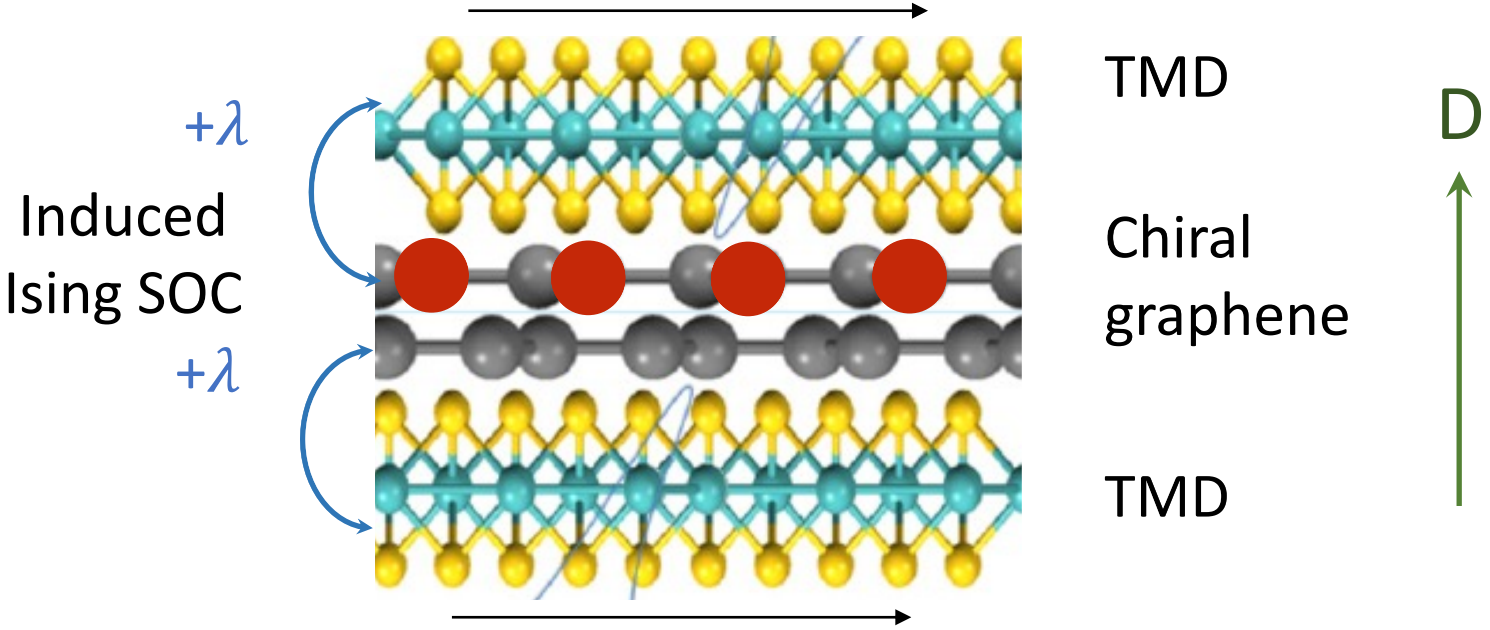

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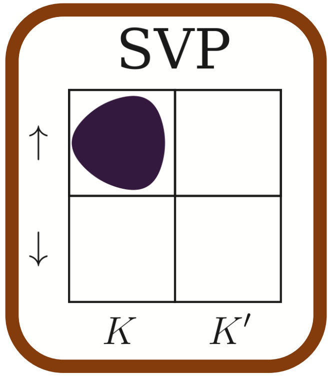
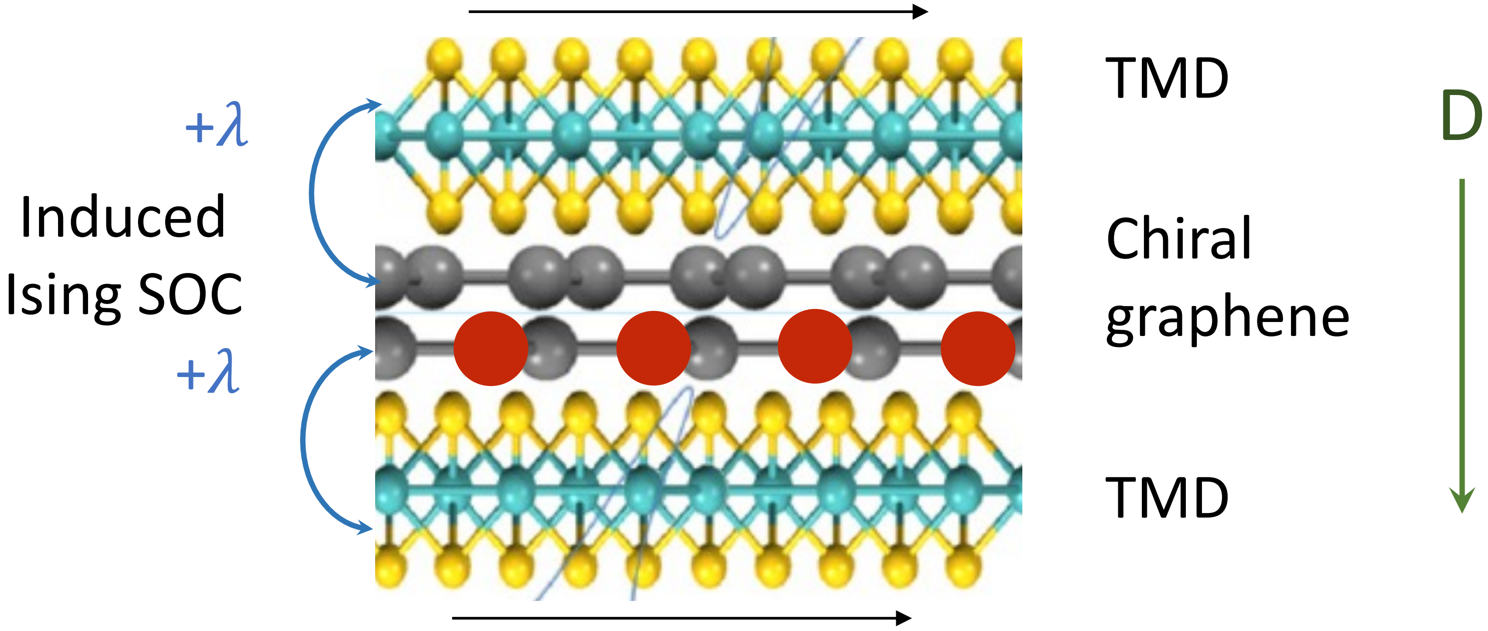
- Flipping D moves electrons to opposite layer, preserves $\tau^z s^z = 1$ in aligned device

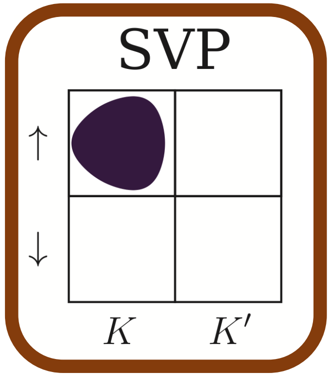


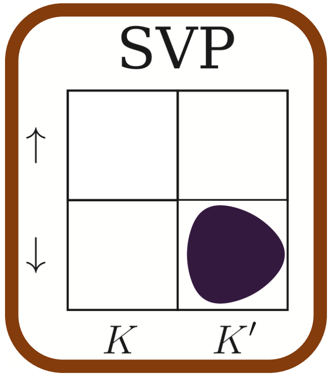


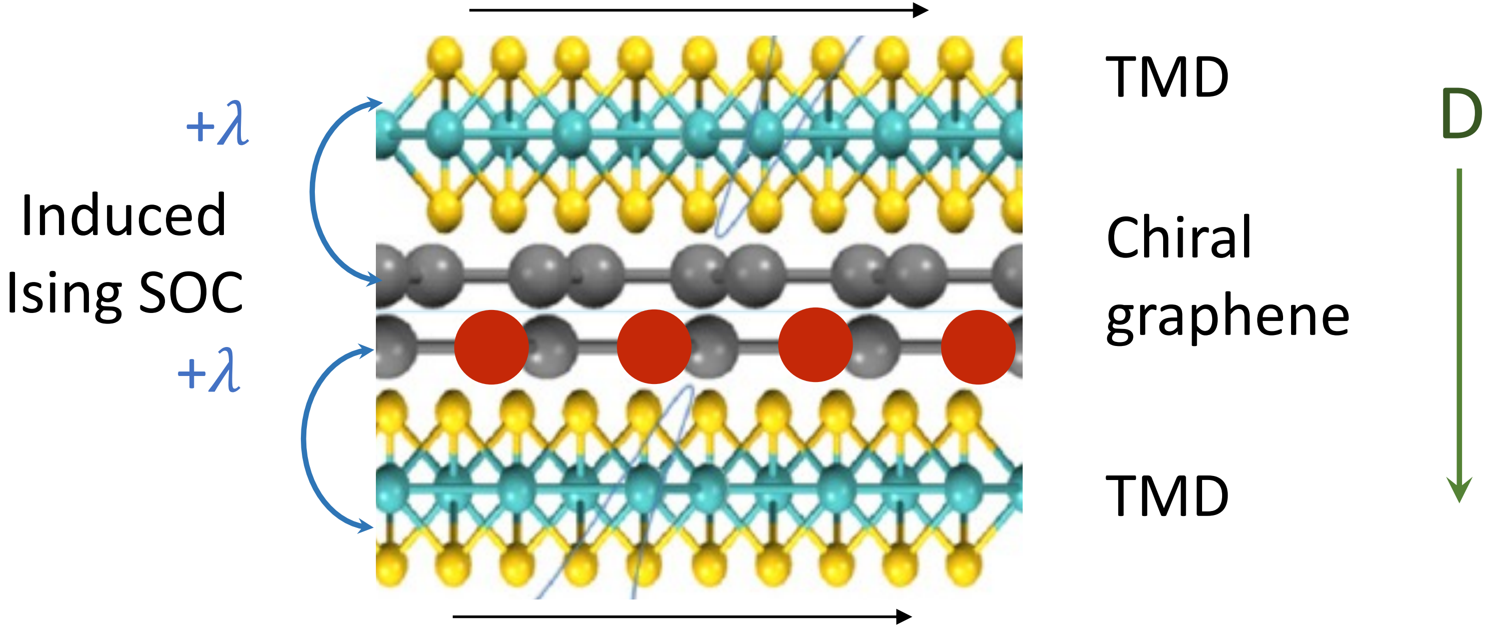
Interactions cause flavor polarization

- D fixes whether the low-energy electrons (or holes) lie on the top or bottom layer
- Reversing D also flips the orbital magnetic moment (arising from Berry phase effects) in each valley
- Fully isospin polarized phase with $\tau^z s^z = 1$ (or -1) still allows for two possibilities for a given direction of the electric field:

1. $\tau^z = 1, s^z = 1$ (K, ↑)
2. $\tau^z = -1, s^z = -1$ (K′, ↓)







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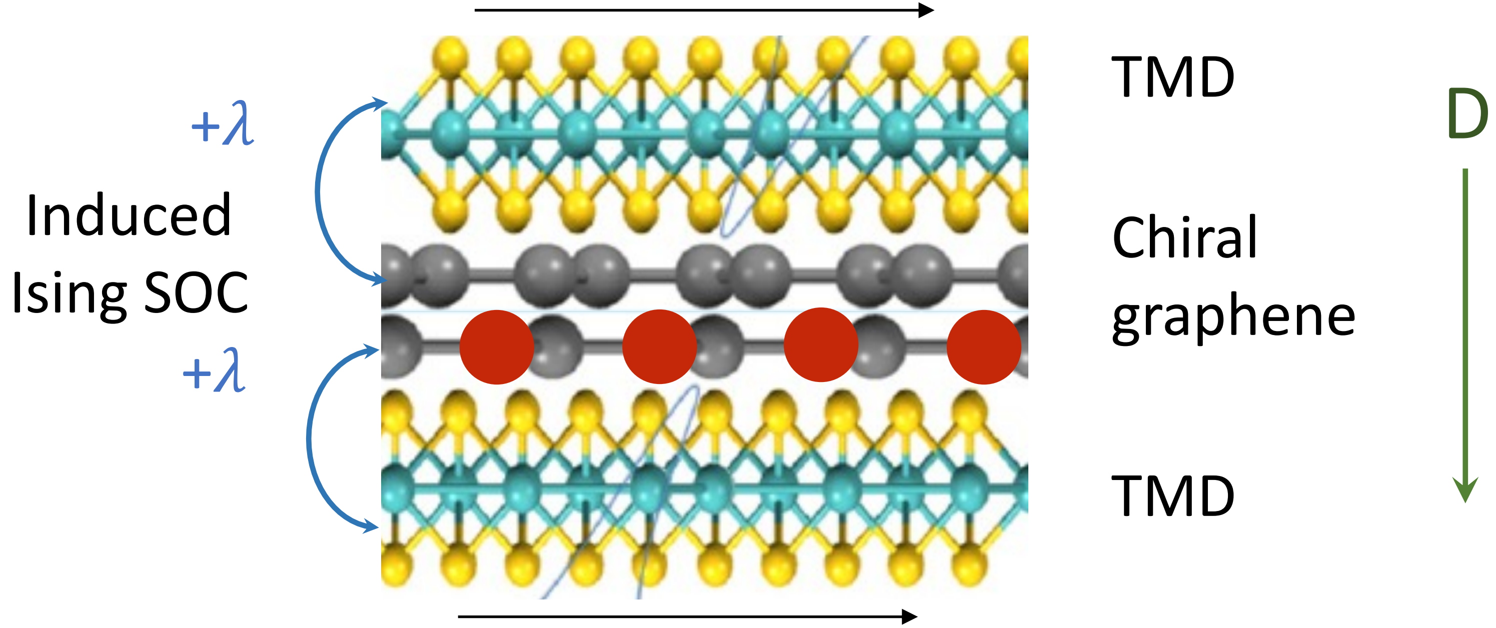
Would like to flip valley and spin on demand



Outline

- Substrate induced spin-orbit coupling in chiral few-layered graphene
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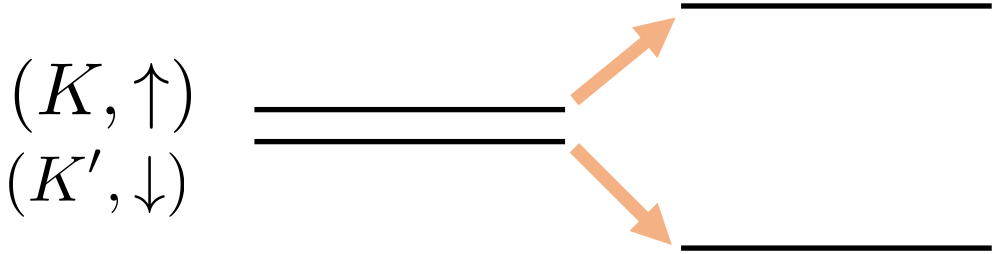
- Conclusion and outlook

Resolution: Static magnetic field

- Need to split degeneracy between (K, ↑) and (K′, ↓)

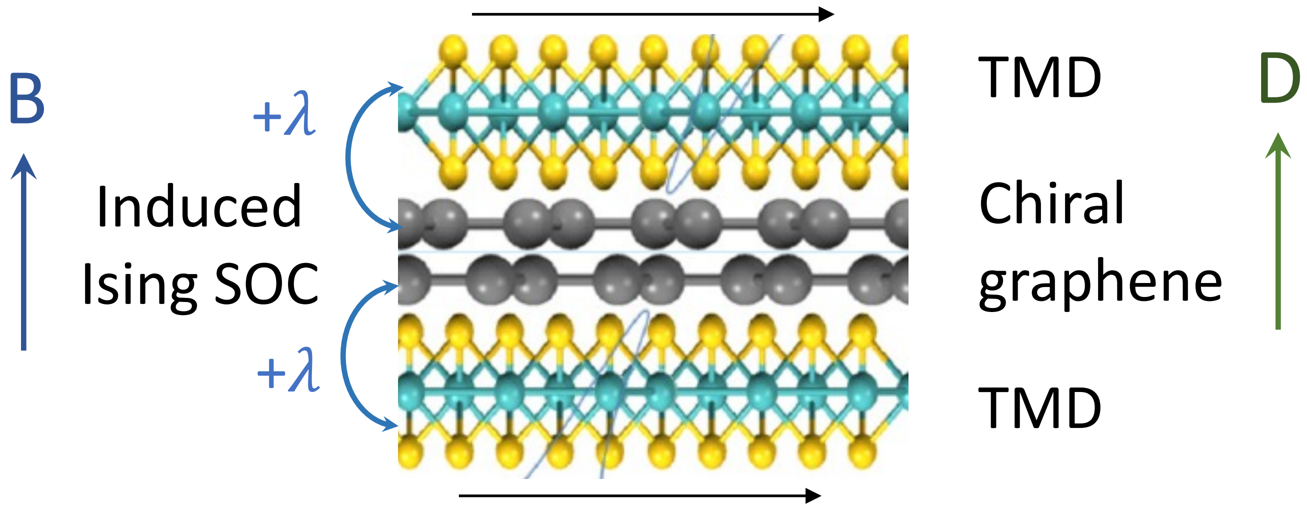


- Solution: add a constant perpendicular magnetic field B

- Couples to both orbital and spin magnetic moment:

$$H_B = -(g_s s^z + g_v \tau^z)B$$

$$g_v = |g_v|\mathrm{sign}(D)$$

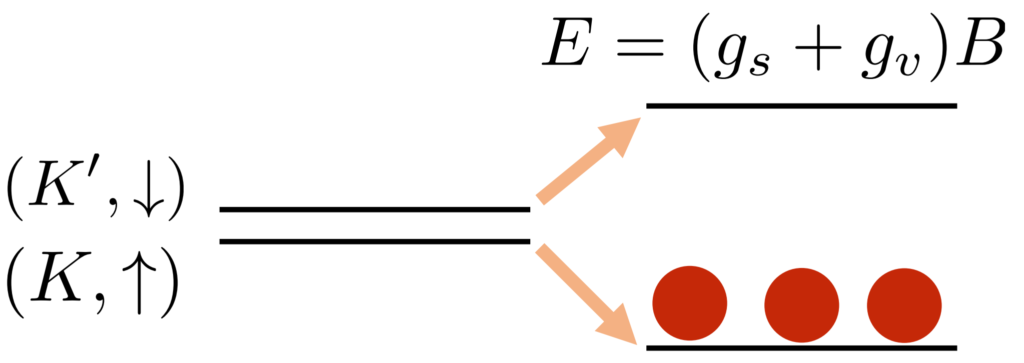


- If $g_s < g_v$, then orbital magnetization is pinned by B, hence valley and spin are both flipped

Resolution: Static magnetic field

Assume g_s , g_v are positive

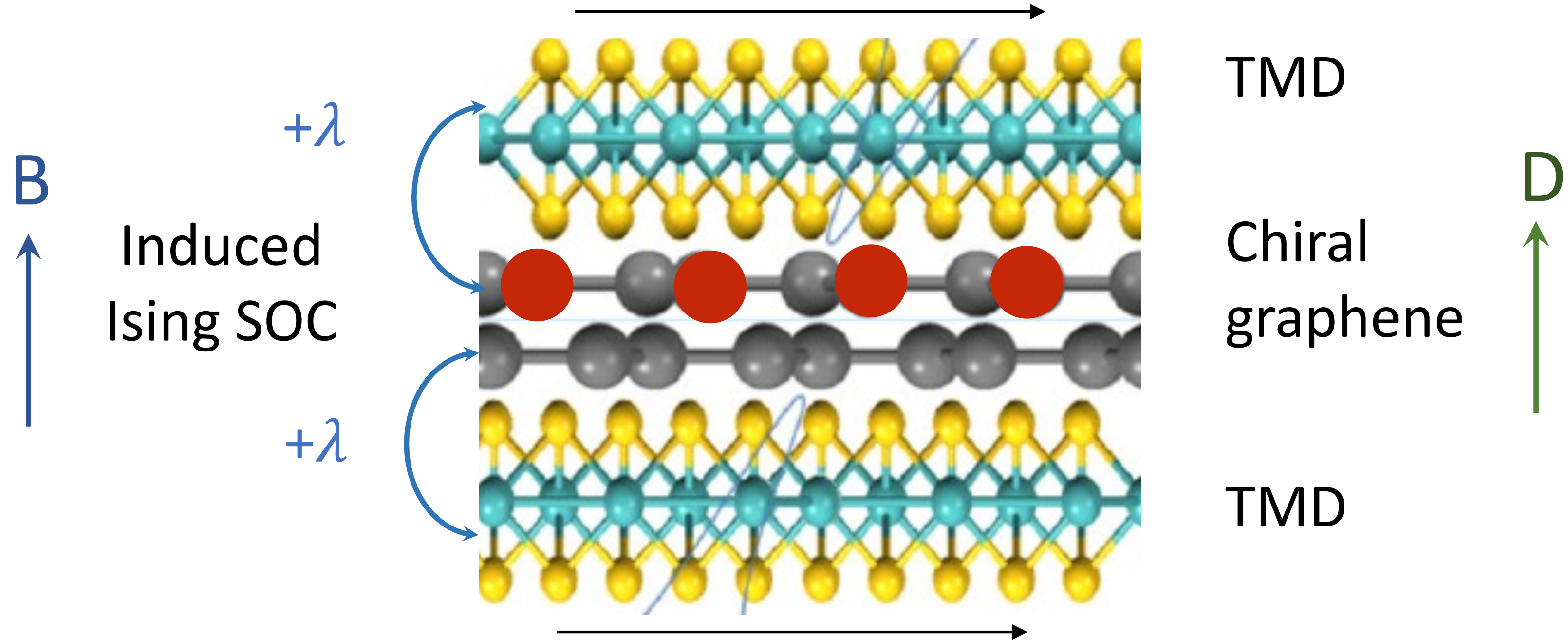
- (K,↑) is occupied when D points up


$E = (g_s + g_v)B$

$(K', \downarrow)$

$(K, \uparrow)$

$E = -(g_s + g_v)B$



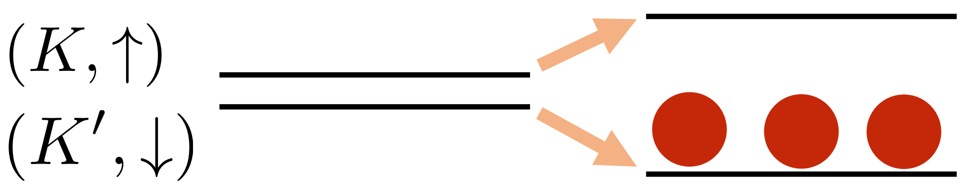
$$H_B = -(g_s s^z + g_v \tau^z)B \qquad g_v = |g_v| \mathrm{sign}(D)$$

Resolution: Static magnetic field

If $g_s < g_v$, orbital moment remains fixed, i.e., valley is flipped

- $(K', \downarrow)$ is occupied when D is reversed

$$E = (g_v - g_s)B$$



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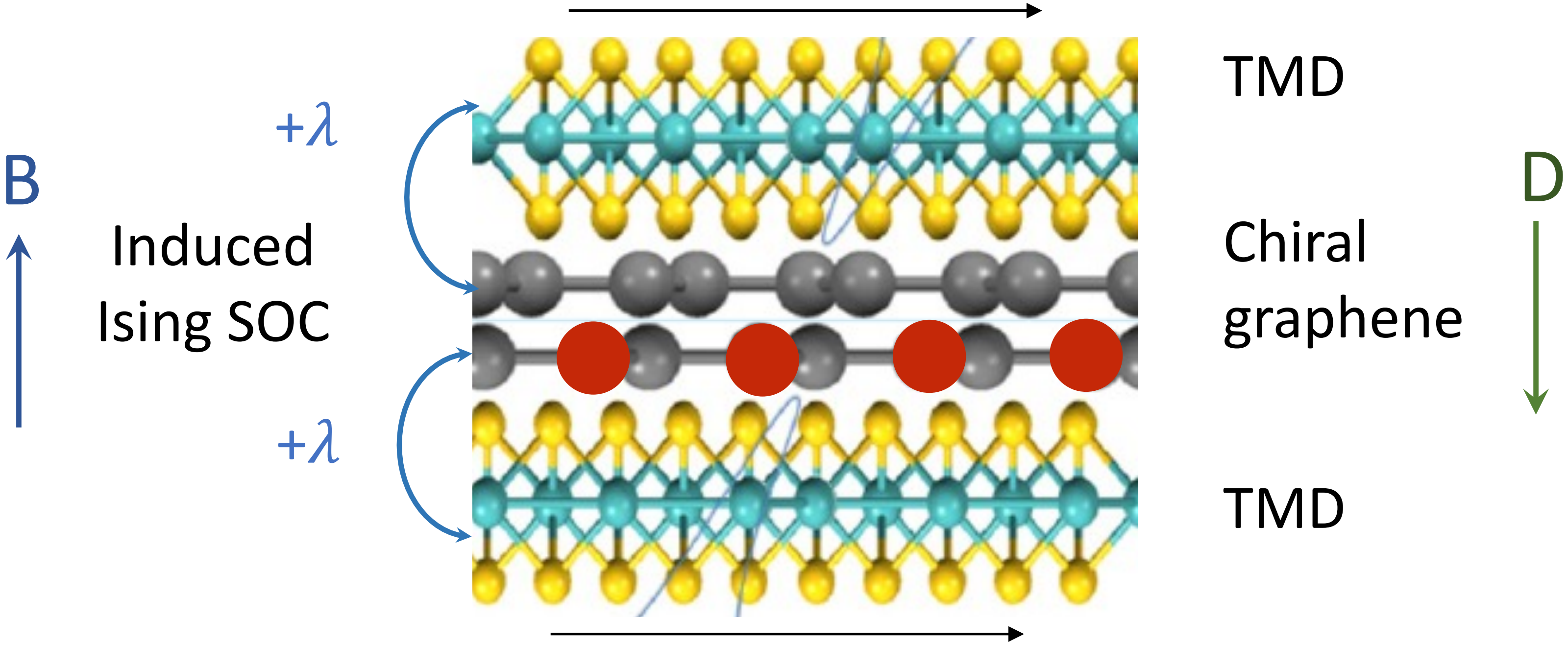


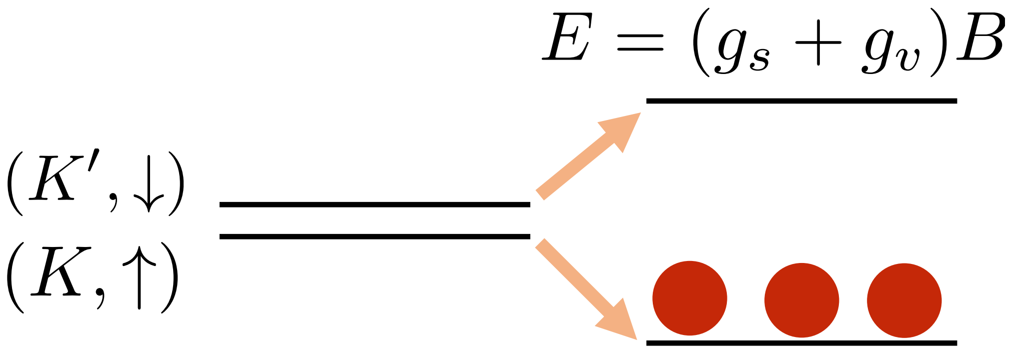
Electric field induced
spin + valley switch

$$H_B = -(g_s s^z + g_v \tau^z)B \qquad g_v = |g_v|\mathrm{sign}(D)$$

Device with anti-aligned TMDs

Assume g_s , g_v are positive

- (K,↑) is occupied when D points up



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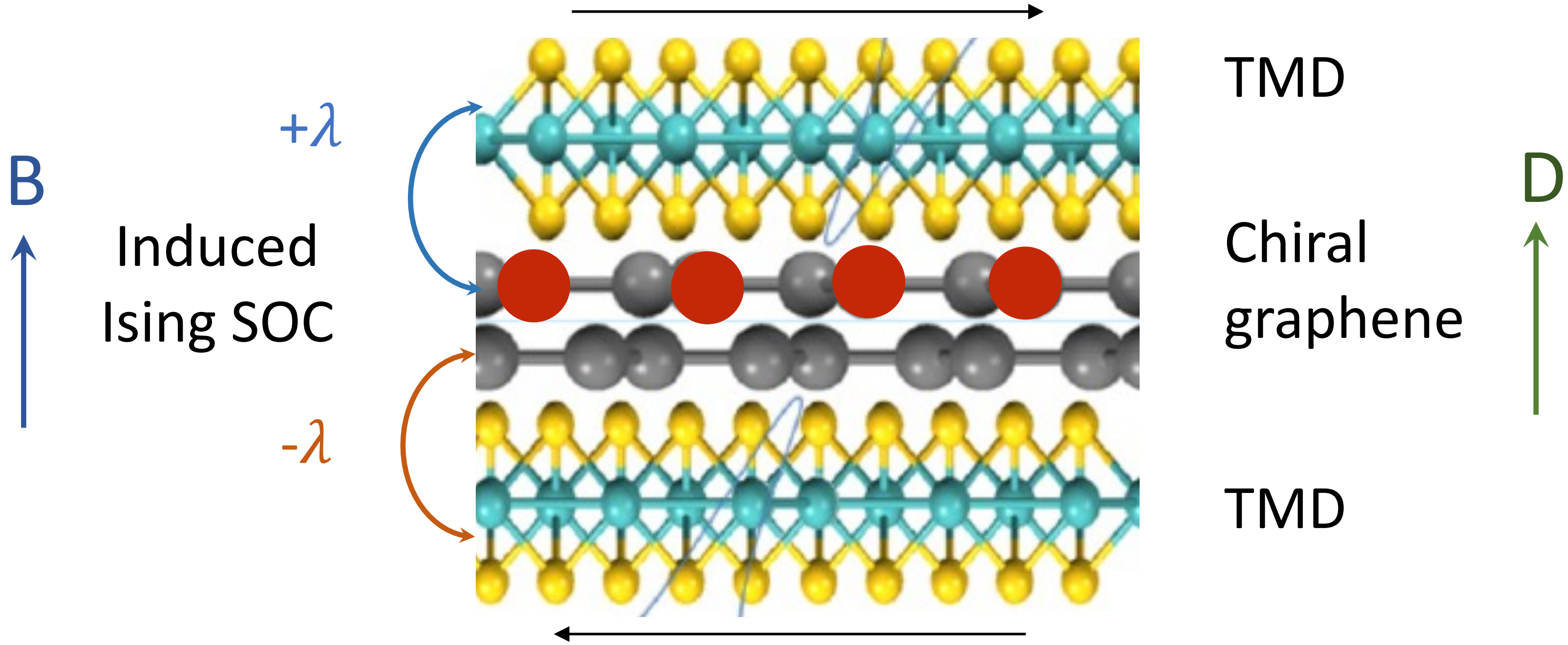
$(K, \uparrow)$

$E = -(g_s + g_v)B$

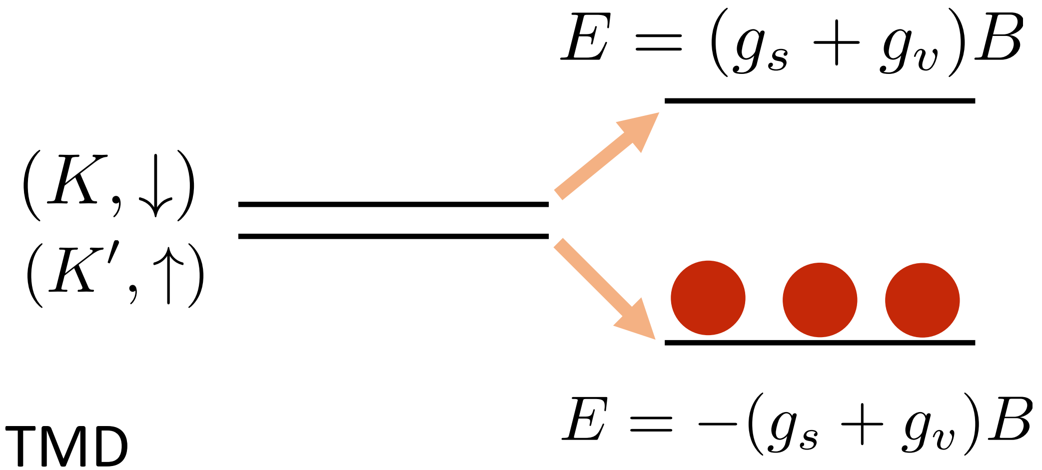


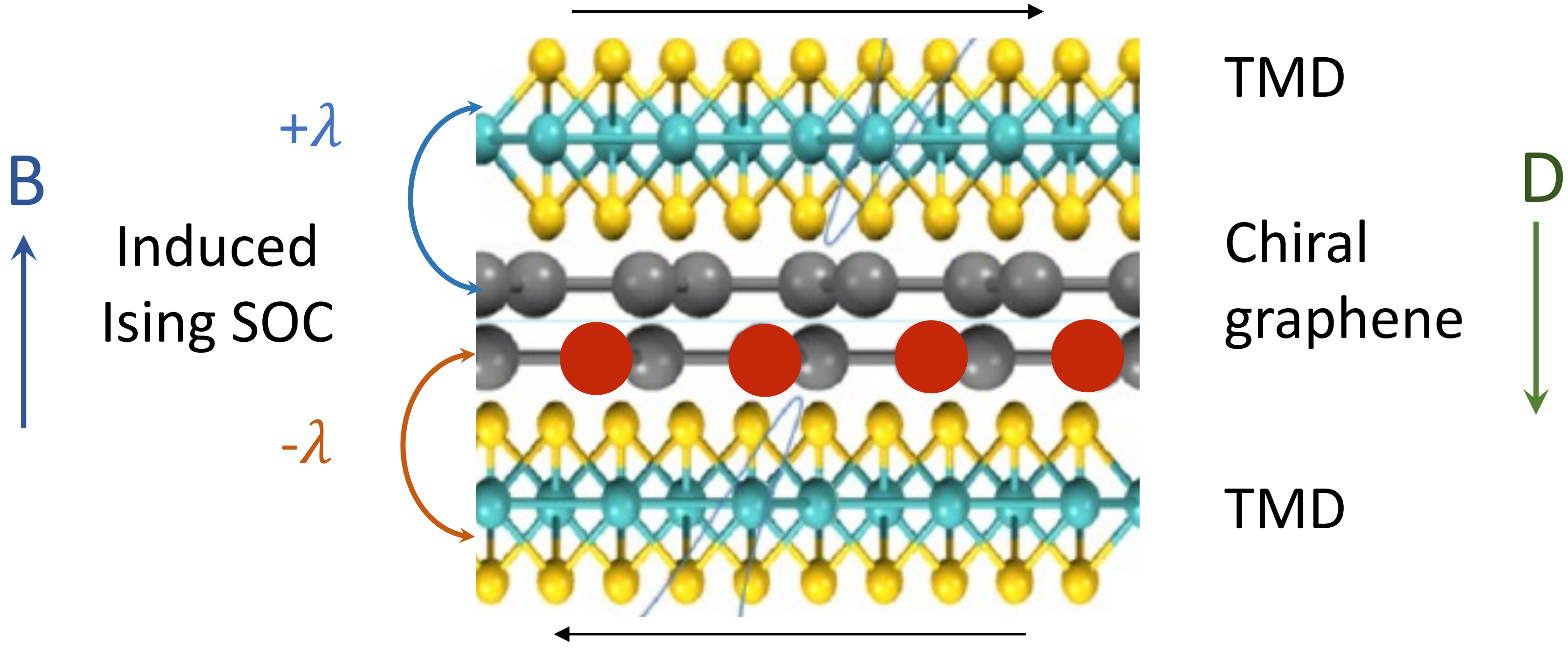
$$H_B = -(g_s s^z + g_v \tau^z)B \qquad g_v = |g_v|\text{sign}(D)$$

Device with anti-aligned TMDs

When D is reversed, low-lying manifold is different due to opposite sign of SOC

- (K′,↑) is occupied when D is reversed





Electric field induced **valley switch**

$$H_B = -(g_s s^z + g_v \tau^z)B$$

$$g_v = |g_v|\text{sign}(D)$$

Typical g_v/g_s is large in chiral graphene

- Finally, can control ratio of g_v to g_s by tuning D or no. of layers N
- Large D → localized orbitals → small Berry curvature → small g_v
- Large N → larger Berry curvature → large g_v

Niu *et al*, RMP (2010)
Thonhauser, Int. J. Mod. Phys (2011)

$$M = \frac{e}{\hbar}\int_{\mathbf{k}} n_F(\varepsilon_{n,\mathbf{k}})\Omega_{n,\mathbf{k}} \quad \text{if p-h symmetric}$$

Typically, $g_v \approx$ 15-30

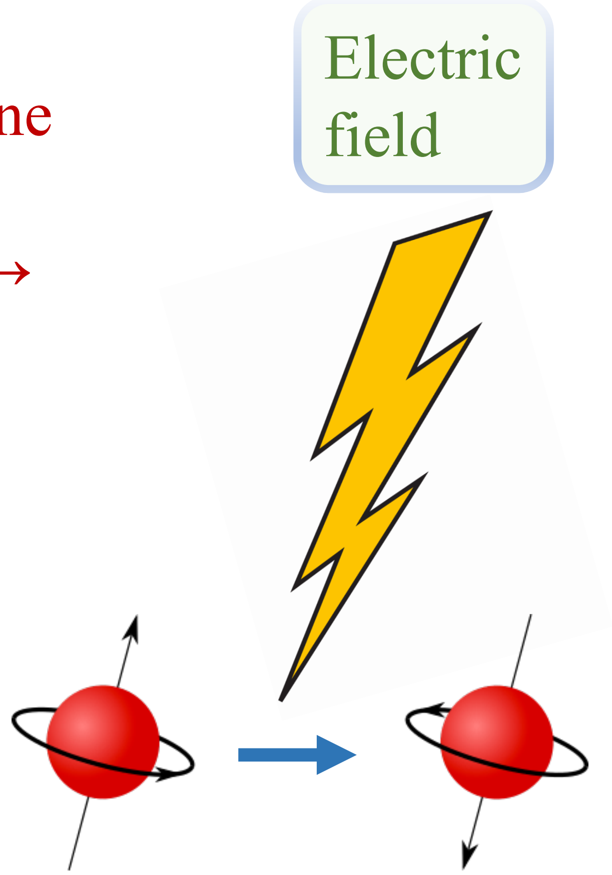
- Verified numerically by considering contributions from all bands that $g_v \gg g_s$
- Flipping only spin, without reversing valley, may be obtained by reversing chemical potential in the TMD aligned device

Outline

- Substrate induced spin-orbit coupling in chiral few-layered graphene
- Design principles of an electrical spin or valley switch
- Conclusion and outlook

Conclusions

- Discussed the effects of induced SOC in chirally stacked graphene
- Showed that induced SOC + electric field induced correlations → selective spin and/or valley switch



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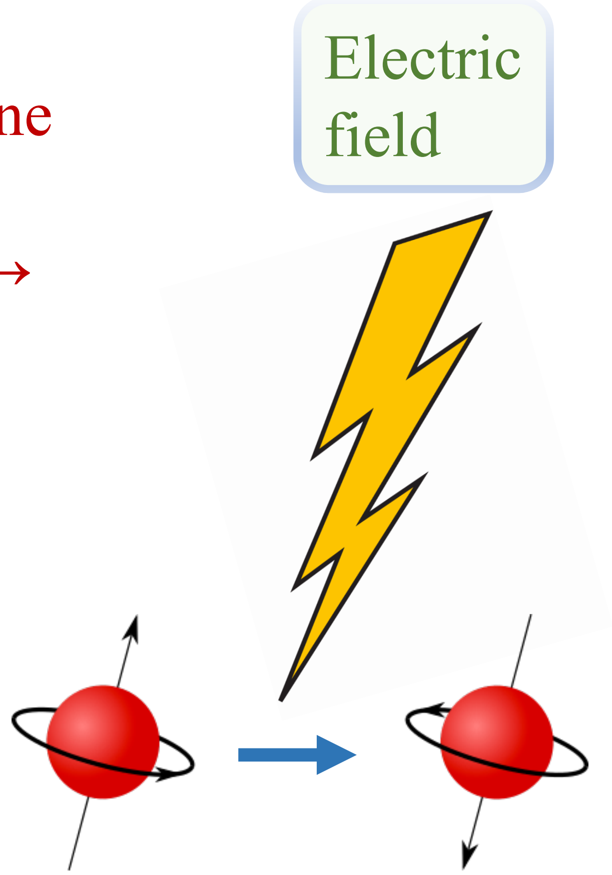
Electric field

Open questions:

1. How stable are these phases to thermal fluctuations?
2. Can one use correlations and induced SOC to create a stable magnetic memory?

Han et al, Science (2024)

3. Similar physics in moiré TMDs for higher tunability?

Abouelkomsan, Bergholtz and SC, arXiv:2210.14918

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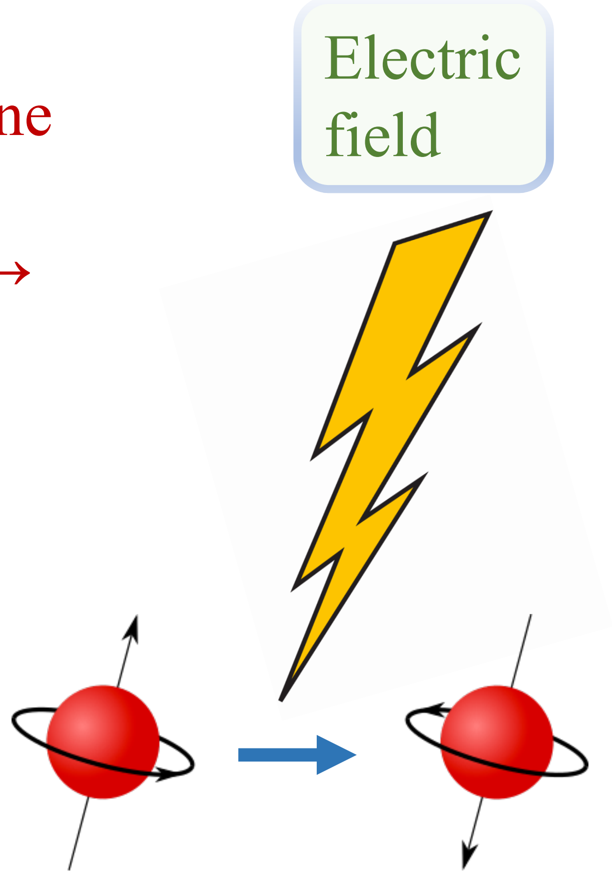

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Thank you for your attention!