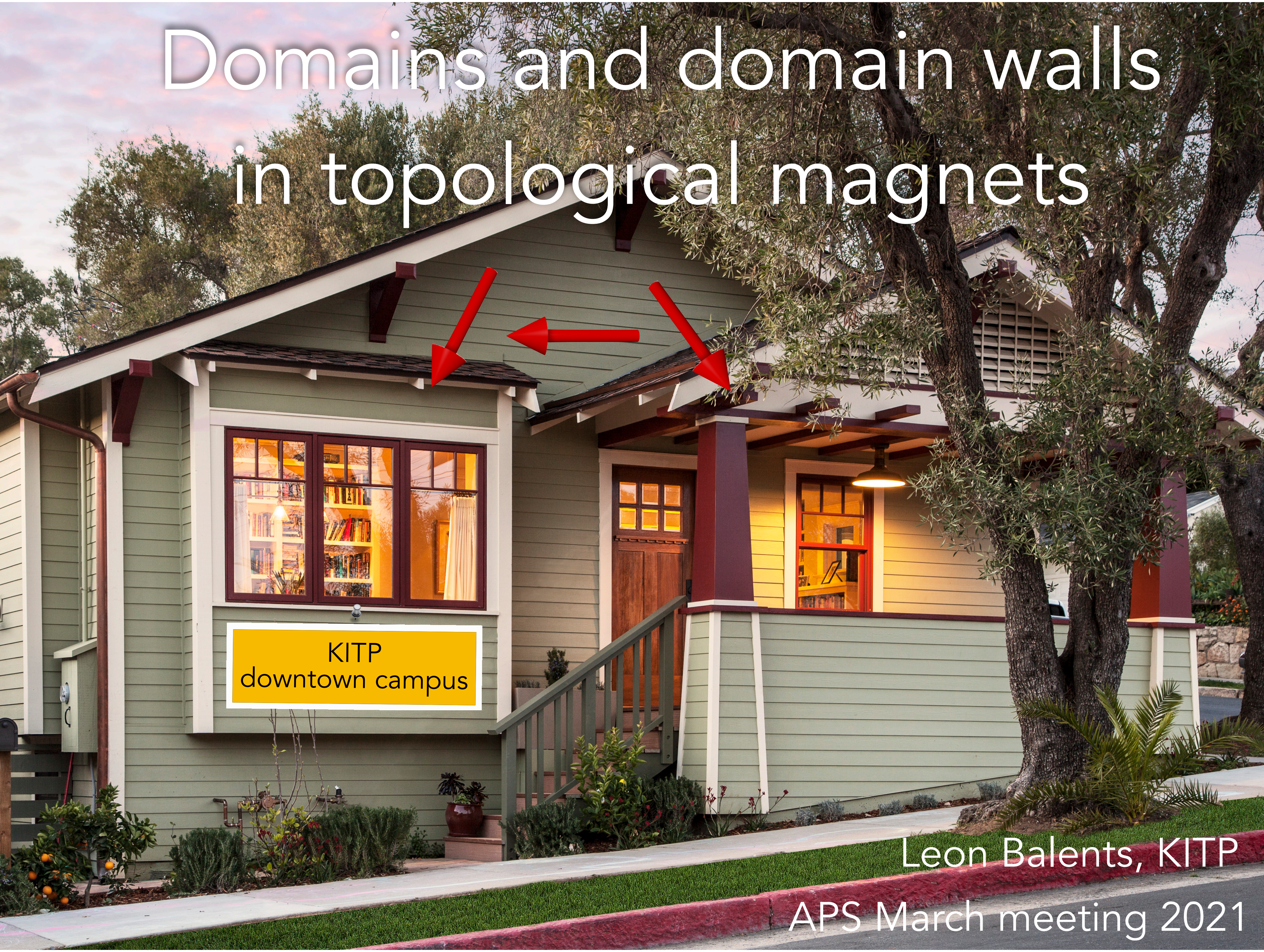
Domains and domain walls in topological magnets



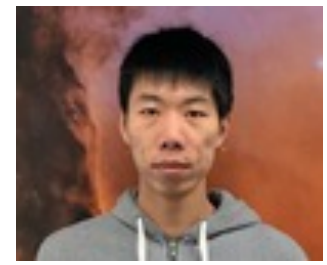
Leon Balents, KITP

APS March meeting 2021

Collaborators

Kamran Behnia

Mengxing Ye



Xuzhe Ying

Outline

- This talk: Back in 2019 I had in mind some general discussion but now I decided to just discuss two aspects of anomalous Hall physics in topological magnetsMain classes

- Planar Hall effect in Mn_3Sn, what it tells us about domain walls, and what is still unclear

- Control of valley ferromagnetic domains in twisted bilayer graphene

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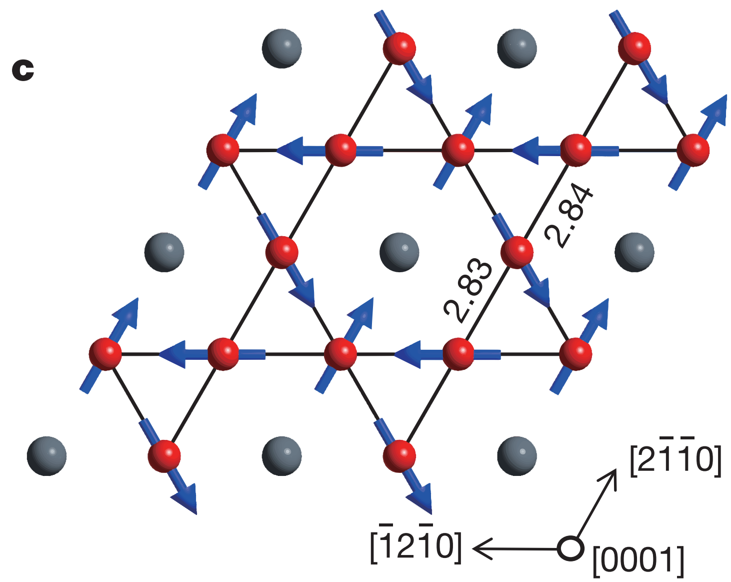
- Control of valley ferromagnetic domains in twisted bilayer graphene

Mn_3Sn family



two kagomé layers of Mn, related by inversion

large ordered *antiferromagnetic* moment

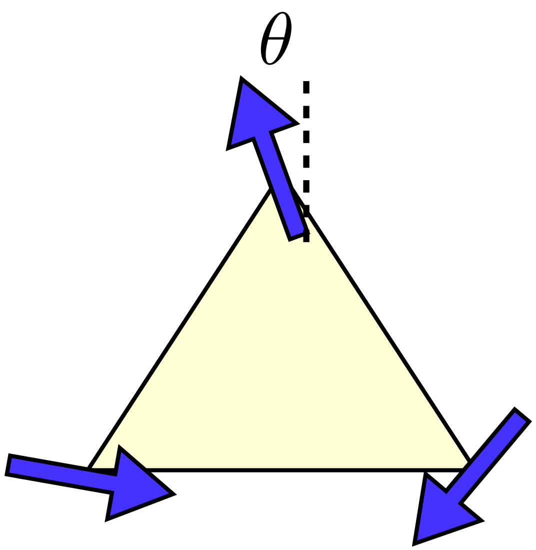
~ 2 μ_B /Mn

tiny FM moment: .002 μ_B/Mn

T_N ~ 420K

Nagamiya *et al*, 1982

Energetics: triangle



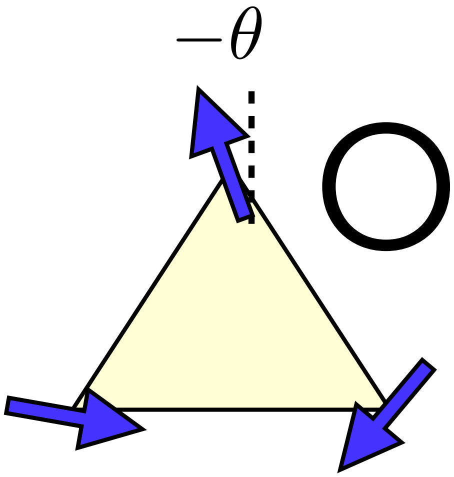
$$E = J\left(\boldsymbol{S}_1 \cdot \boldsymbol{S}_2 + \boldsymbol{S}_2 \cdot \boldsymbol{S}_3 + \boldsymbol{S}_3 \cdot \boldsymbol{S}_1\right)$$

$$+D\hat{\boldsymbol{z}} \cdot \left(\boldsymbol{S}_1 \times \boldsymbol{S}_2 + \boldsymbol{S}_2 \times \boldsymbol{S}_3 + \boldsymbol{S}_3 \times \boldsymbol{S}_1\right)$$

$$-K \sum_i \left(\hat{n}_i \cdot \boldsymbol{S}_i\right)^2$$

$J \gg D \gg K$ **Hierarchy of interactions**

- J: spins at 120° angles and M=0
- D: spins are "anti-chiral" in XY plane
- K: weak canting toward easy axes creates tiny moment and fixes in-plane angle



Order parameter

$$\psi = |\psi| e^{i\theta}$$

J. Liu + L.B., 2017

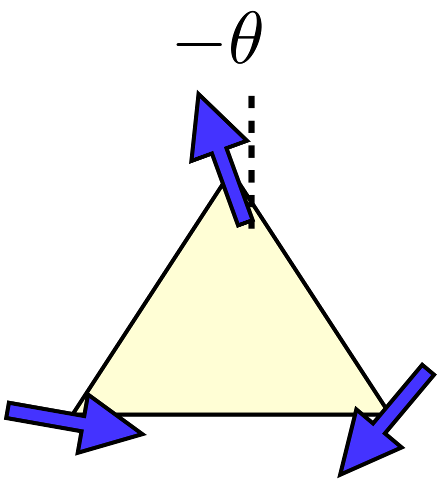
$$\mathbf{S}_a^{(0)} = m_s \begin{pmatrix} \cos(\theta - \frac{2\pi a}{3}) \\ \sin(-\theta - \frac{2\pi a}{3}) \\ 0 \end{pmatrix}$$

"octupole"

$$\boldsymbol{m} = \frac{K}{J} g m_s \begin{pmatrix} \cos\theta \\ \sin\theta \\ 0 \end{pmatrix}$$

"dipole"

For practical purposes, can view *direction* of magnetization as order parameter, even though it is small in magnitude.



Textures

J. Liu + L.B., 2017

$$\psi = |\psi| e^{i\theta} \qquad F \sim \int d^3x \left\{ \frac{\rho}{2}(\nabla\theta)^2 - \lambda \cos 6\theta \right\}$$

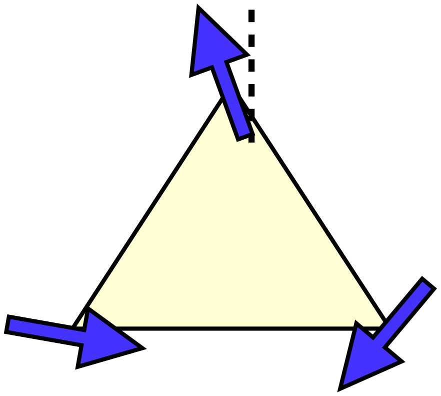
sine-Gordon model with 6-fold anisotropy

$$\rho \sim \frac{J}{a} \qquad \lambda \sim \frac{K^3}{J^2 a^3}$$

n.b. reduced by frustration

$$\frac{\sigma_{ij} - \sigma_{ji}}{2} = \sigma^H \epsilon_{ijk} \hat{m}_k$$

$$\hat{m} = (\cos\theta, \sin\theta, 0)$$

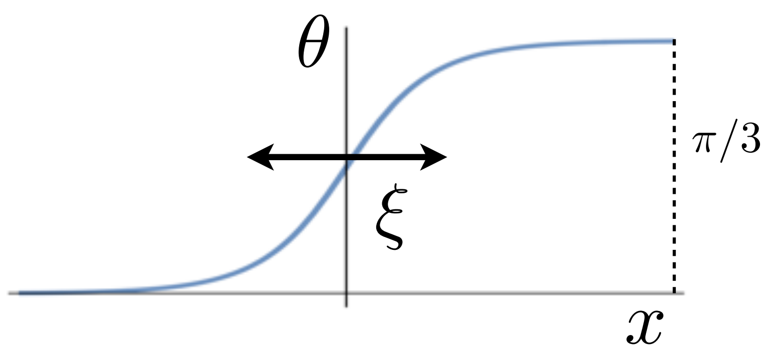


Textures

$$\psi = |\psi| e^{i\theta}$$

$$F \sim \int d^3x \left\{ \frac{\rho}{2} (\nabla\theta)^2 - \lambda \cos 6\theta \right\}$$

soliton = domain wall connecting *neighboring* minima of cosine



$$\xi = \frac{1}{6}\sqrt{\frac{\rho}{\lambda}}$$

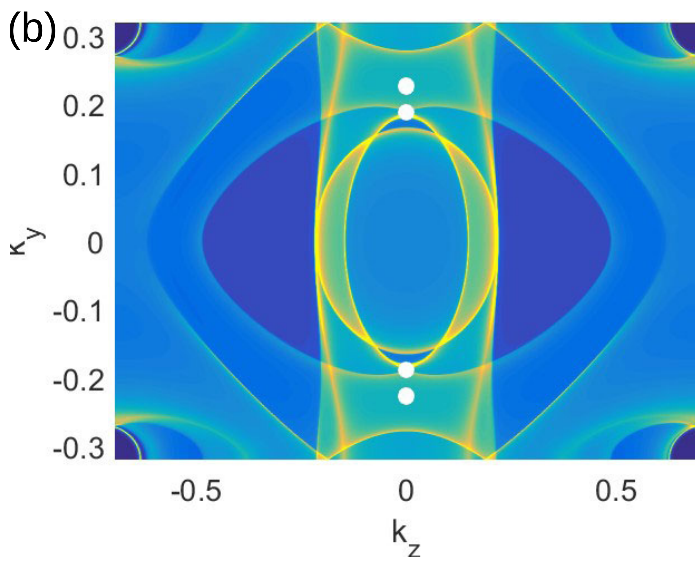
wide DWs

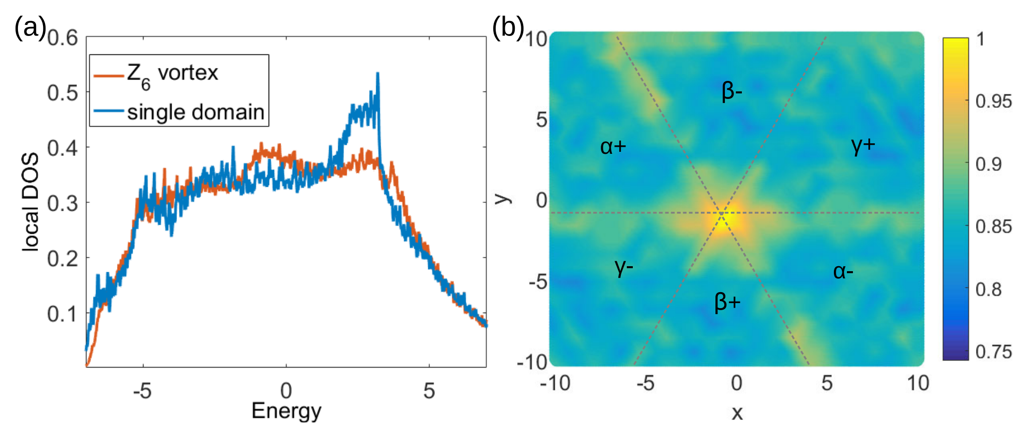
$$\theta(x) = \frac{2}{3} \tan^{-1} \exp(x/\xi)$$

Electronic states at DWs

Theoretically: domain walls host bound/topological modes

J. Liu + L.B., 2017

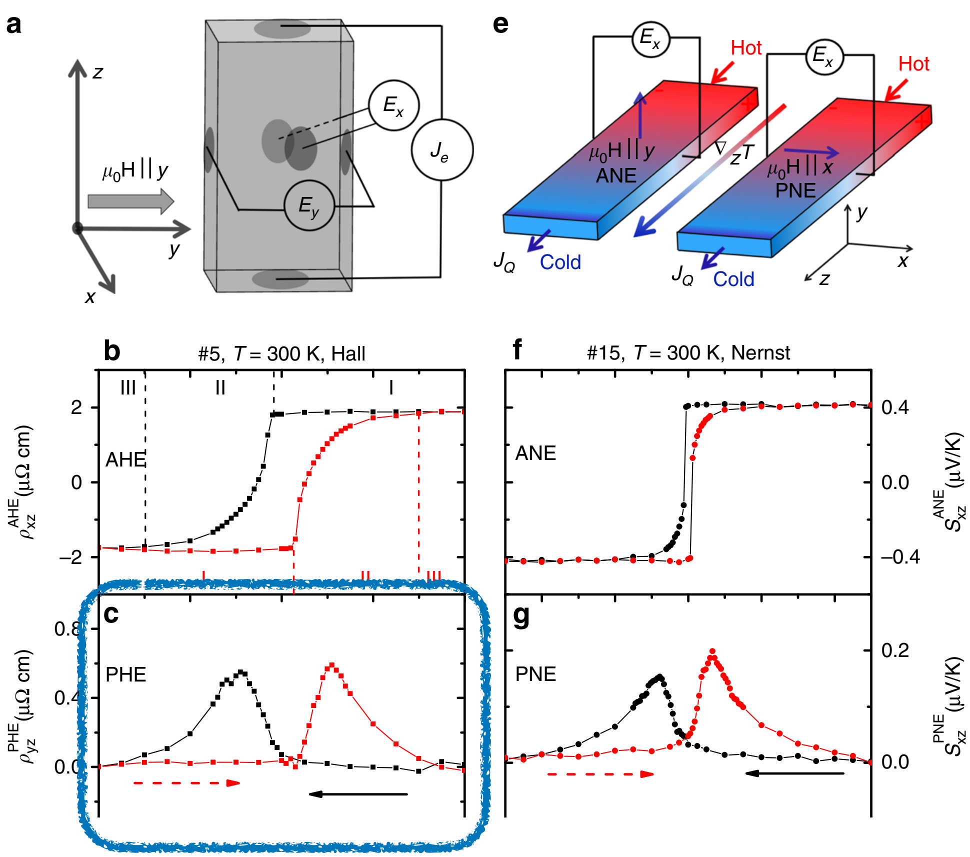




Many other calculations

Reality check?

Planar Hall effect



Hall effect in plane perpendicular to field

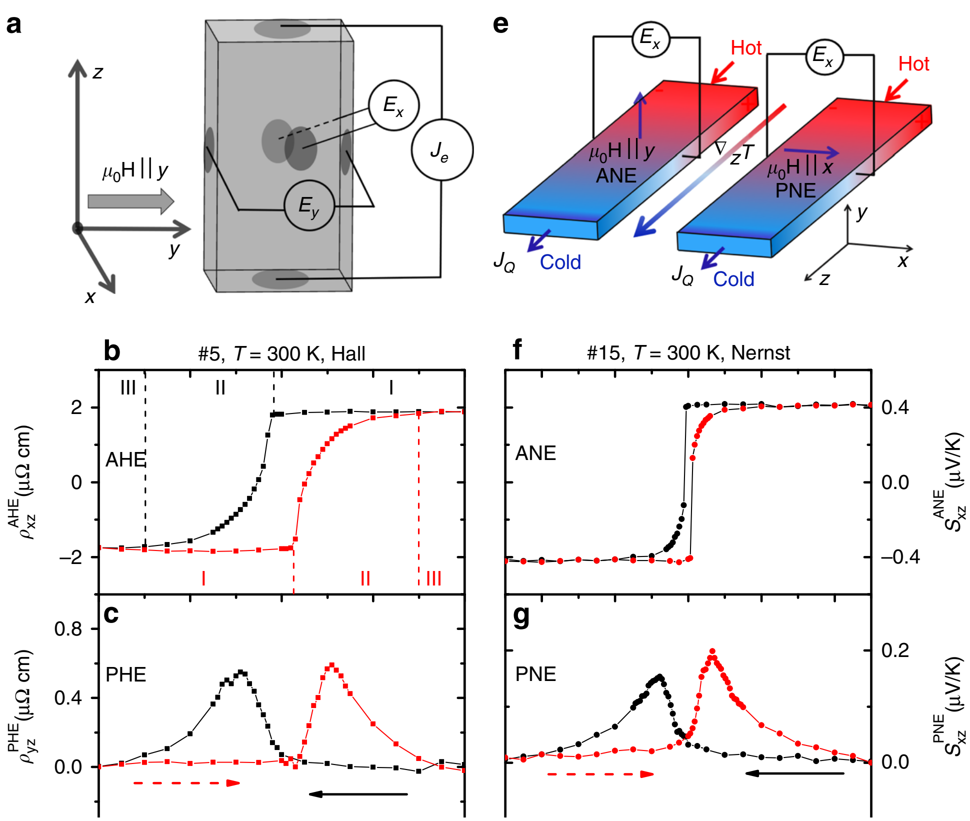
ARTICLE

https://doi.org/10.1038/s41467-019-10815-8 OPEN

Chiral domain walls of Mn_3Sn and their memory

Xiaokang Li[1,2], Clément Collignon[2,3], Liangcai Xu[1], Huakun Zuo[1], Antonella Cavanna[4], Ulf Gennser[4], Dominique Mailly[4], Benoît Fauqué[3], Leon Balents[5], Zengwei Zhu[1] & Kamran Behnia[2,6]

Planar Hall effect



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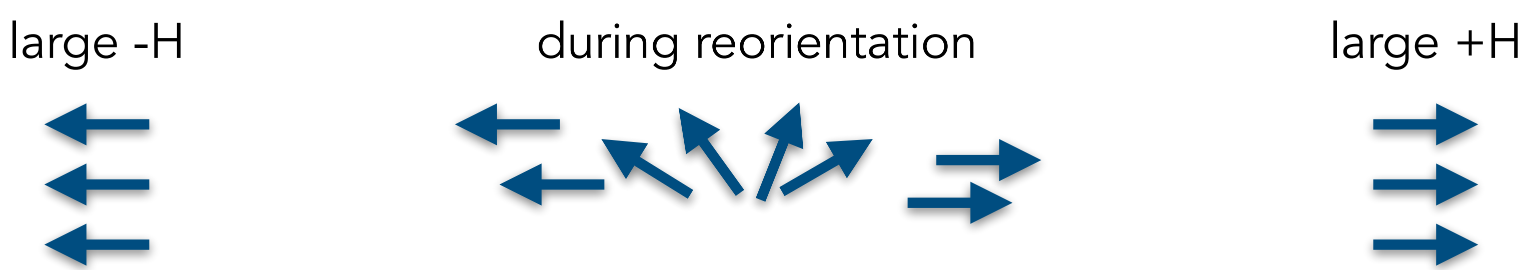
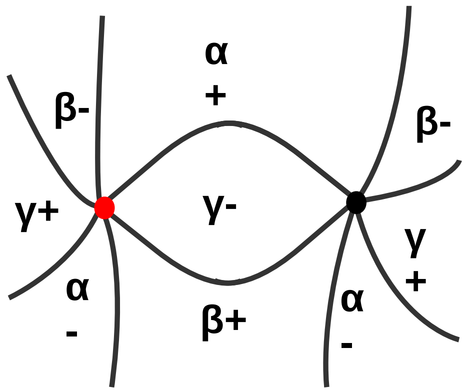
Explanation: order parameter rotates in the ab plane (as predicted)



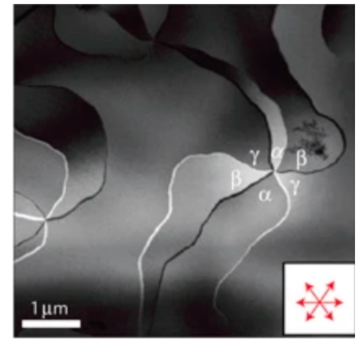
6 domains or 2 domains?



6-fold domains

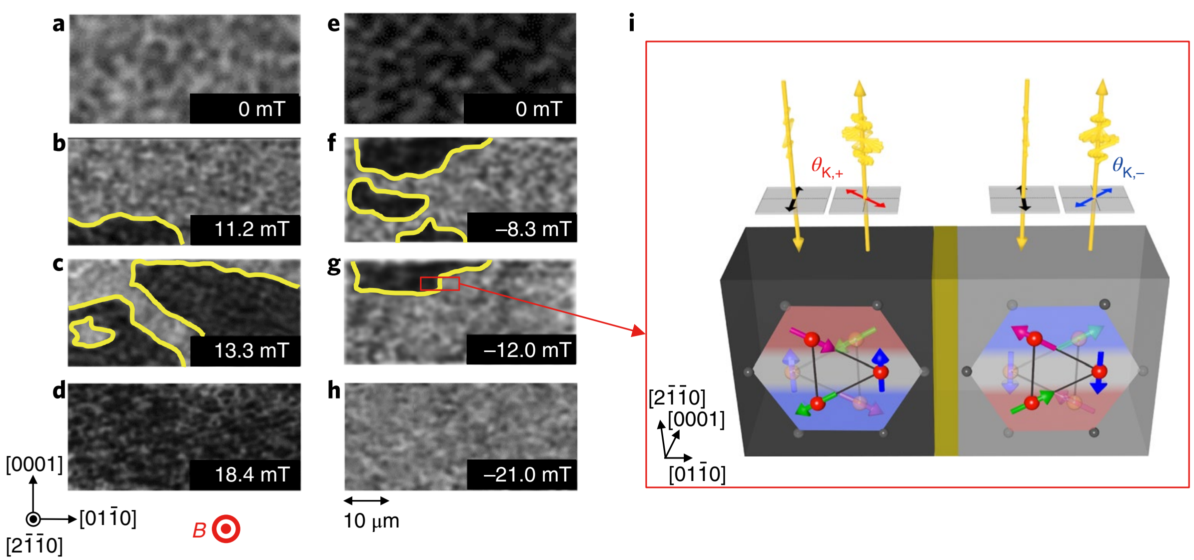
Required by C_3 + TR symmetries

J. Liu + L.B., 2017



c.f. structural Z_6 vortex in $YMnO_3$

(T. Choi *et al*, 2010)



nature photonics

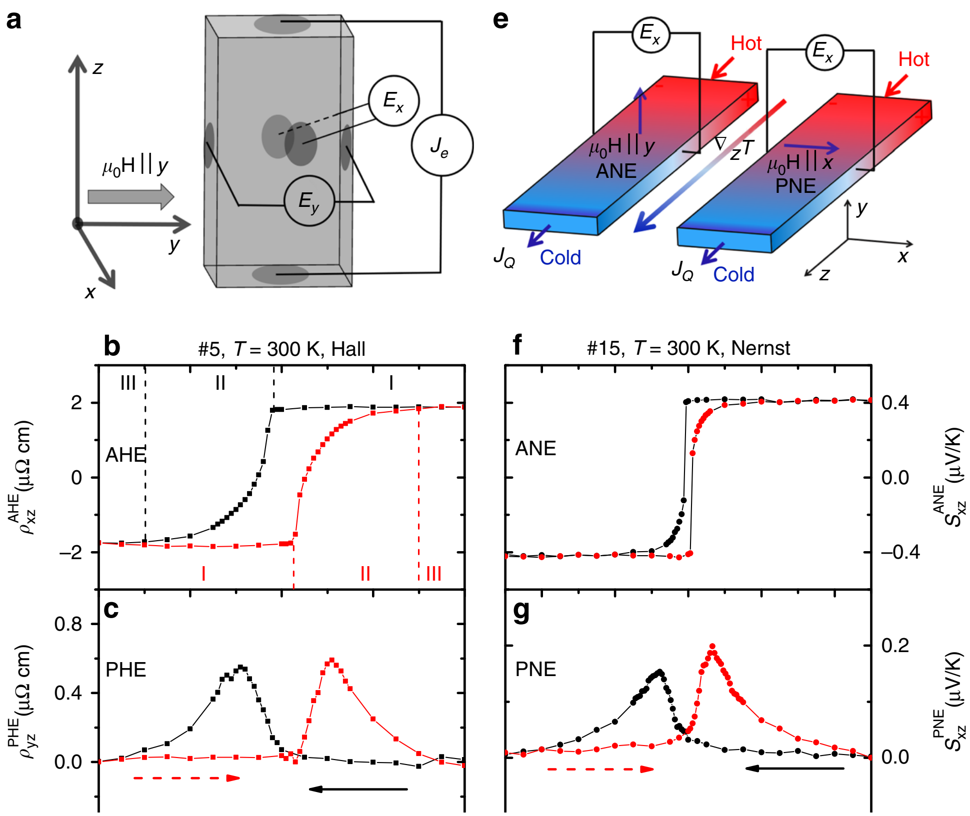
LETTERS

https://doi.org/10.1038/s41566-017-0086-z

Large magneto-optical Kerr effect and imaging of magnetic octupole domains in an antiferromagnetic metal

Tomoya Higo[1,2], Huiyuan Man[1], Daniel B. Gopman[3], Liang Wu[4,5,6], Takashi Koretsune[2,7,8], Olaf M. J. van 't Erve[9], Yury P. Kabanov[3,10], Dylan Rees[4,5], Yufan Li[11], Michi-To Suzuki[2,8], Shreyas Patankar[4,5], Muhammad Ikhlas[1,2], C. L. Chien[11], Ryotaro Arita[2,8], Robert D. Shull[3], Joseph Orenstein[4,5] and Satoru Nakatsuji[1,2]*

Planar Hall effect



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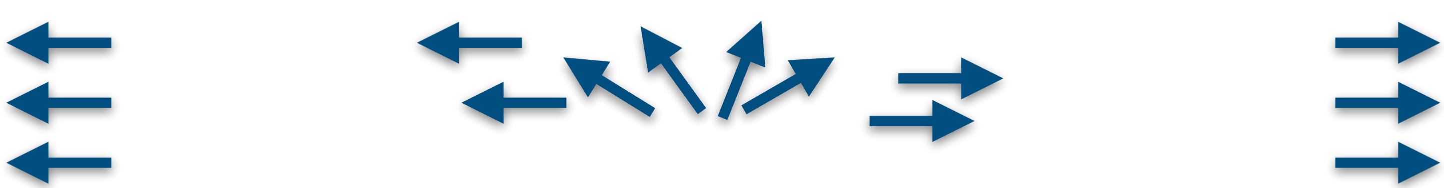
[Rotation inside DWs or in metastable domains?]

large -H

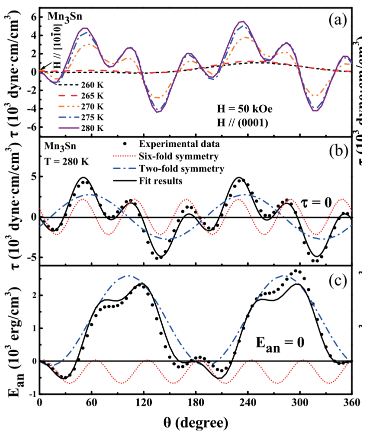
during reorientation

large +H



6 domains or 2 domains?

T. Duan *et al* *Appl. Phys. Lett. 107, 082403 (2015)*



Torque suggests some other source of two-fold anisotropy contributes.

Indicates breaking of lattice C_3 symmetry

Proposal: spin-lattice coupling

$$\mathcal{H}_{s-l} = -\alpha u_{ij} \hat{m}_i \hat{m}_j \qquad \hat{m} = (\cos\theta, \sin\theta)$$

effective 2-fold anisotropy

magnitude of spin-lattice coupling can be measured by magnetostriction

$$u_{xx} = -u_{yy} = \frac{\alpha}{2\mu}\cos 2\theta, \qquad u_{xy} = \frac{\alpha}{2\mu}\sin 2\theta$$

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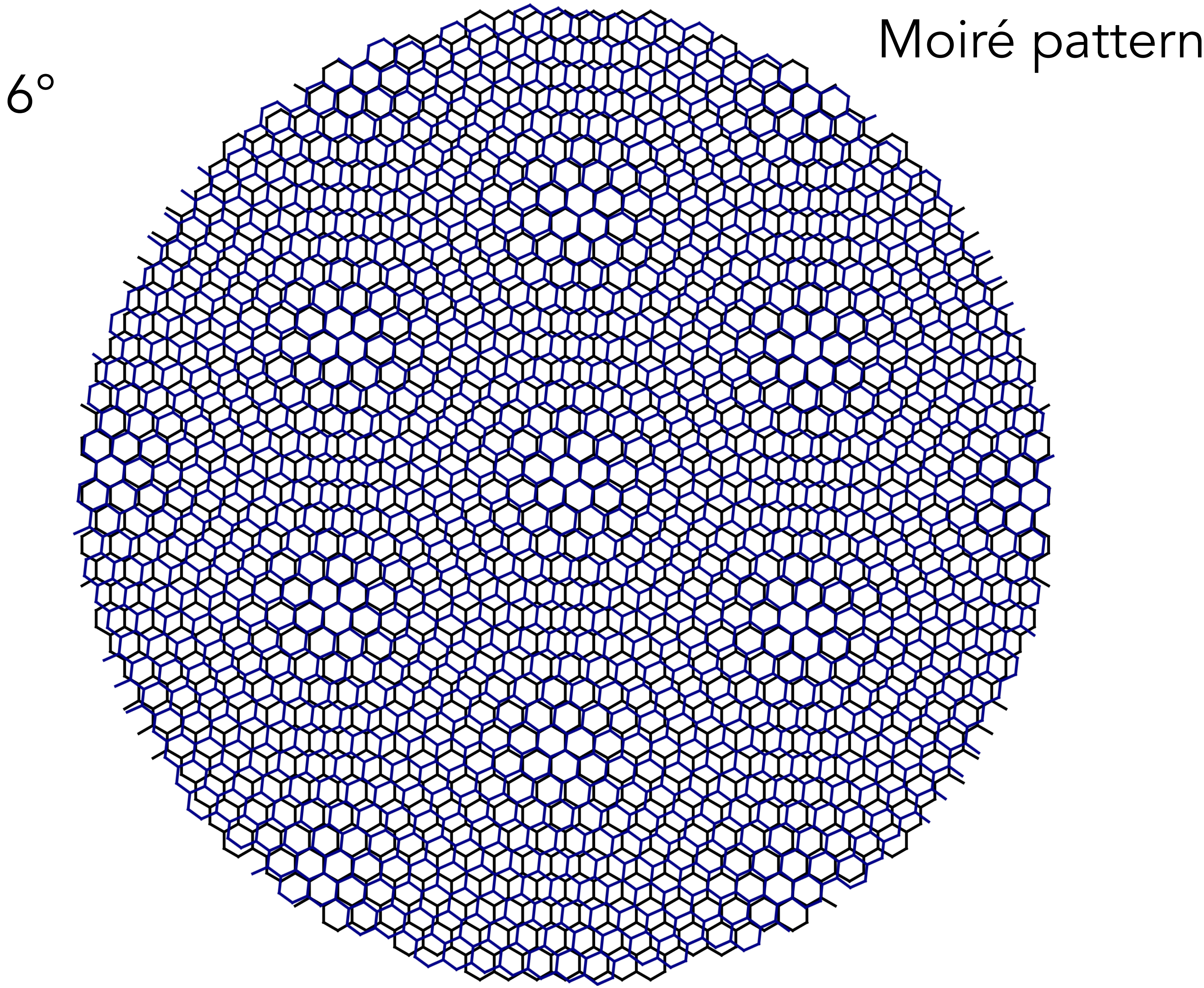
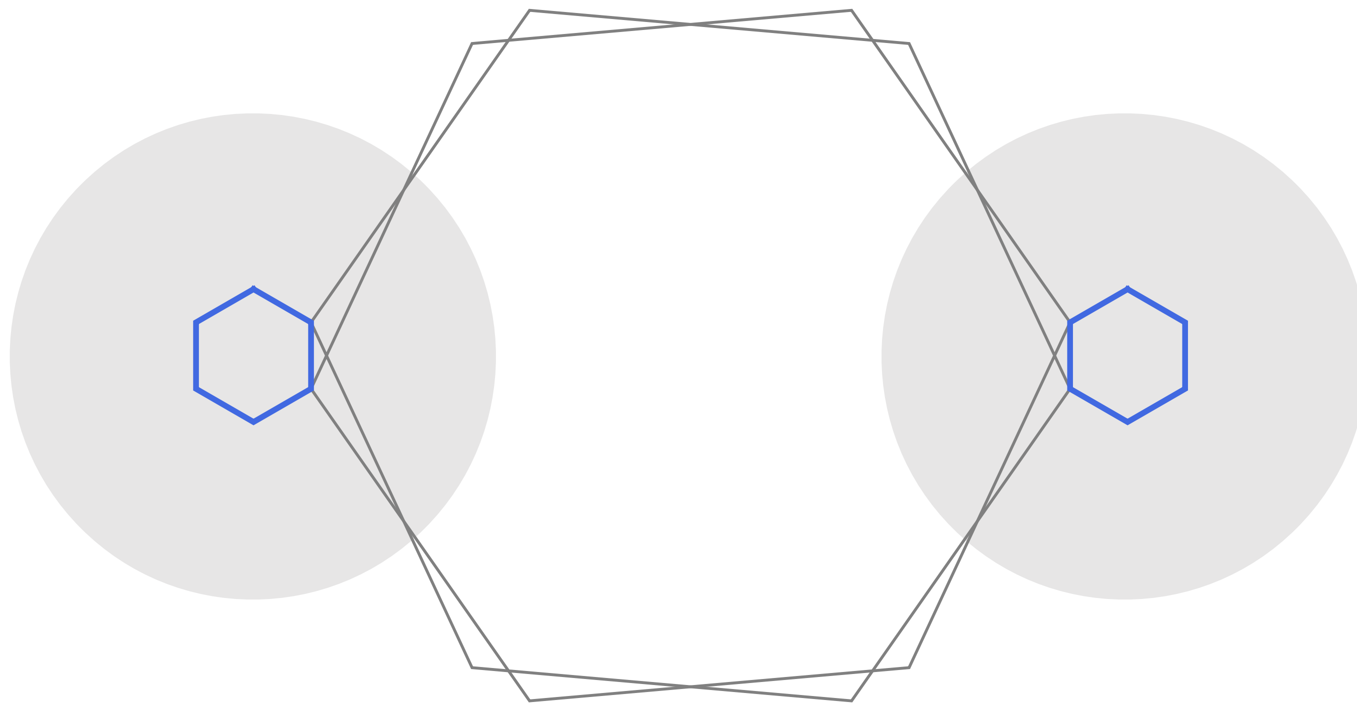


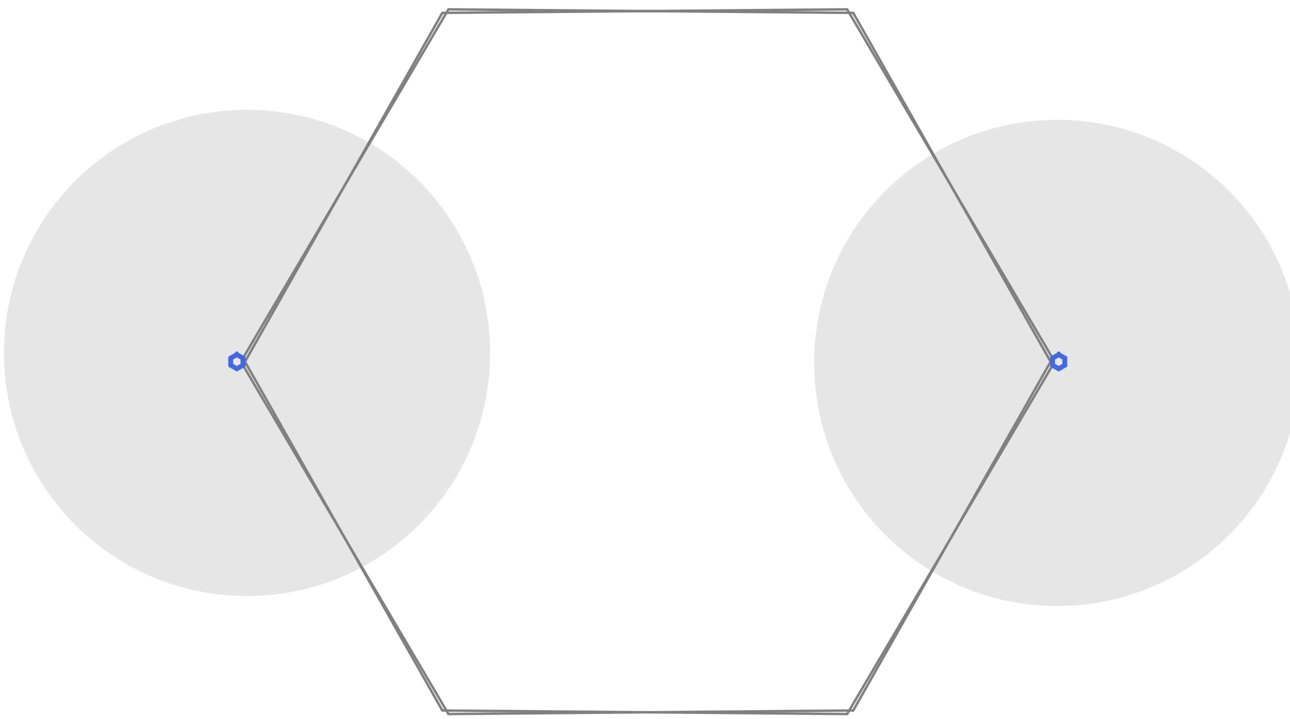
6°
Moiré pattern

Continuum model



approximate single layer as Dirac cone
no mixing from one valley to the other

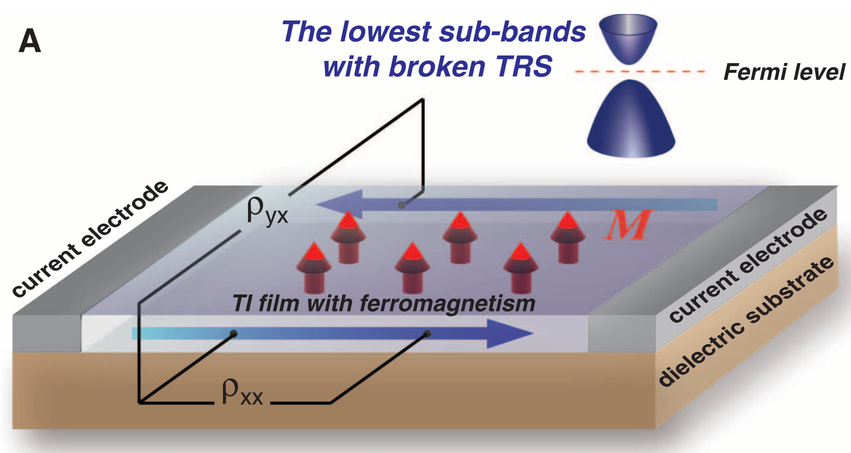
Continuum model

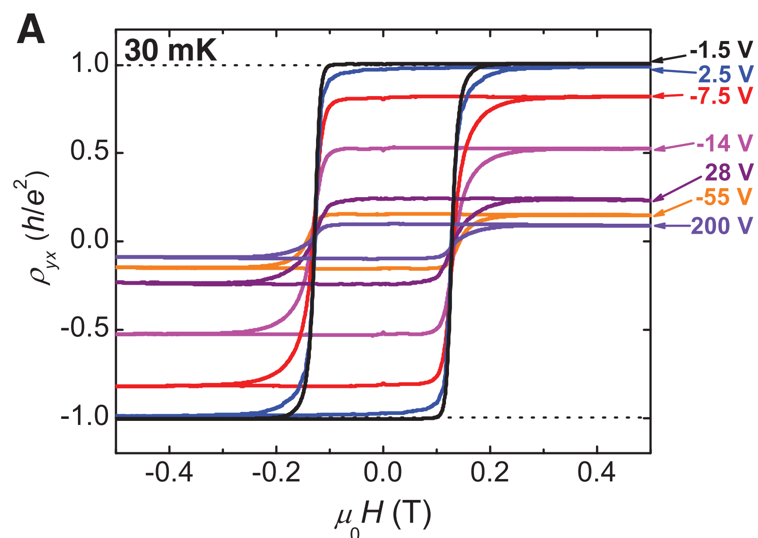


1°

Quantum Anomalous Hall Effect

This is just the appearance of QHE in zero magnetic field by spontaneous breaking of time-reversal symmetry

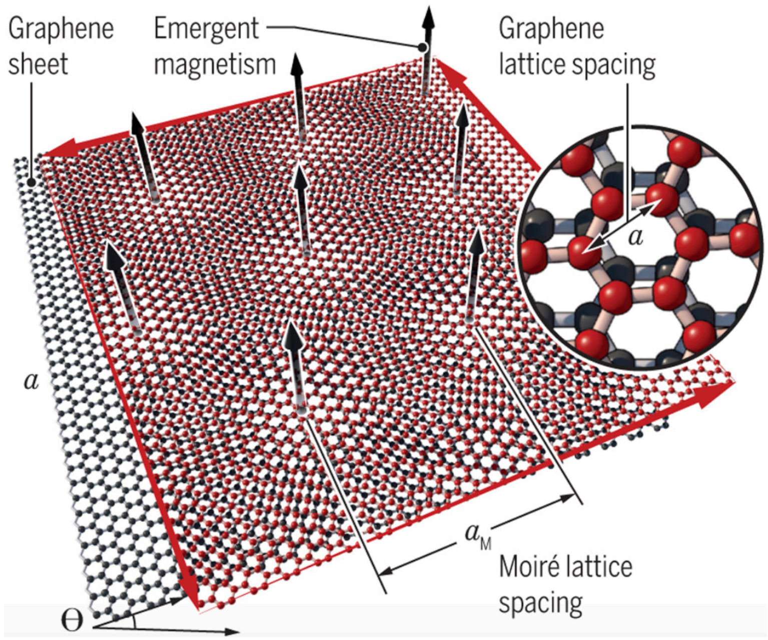


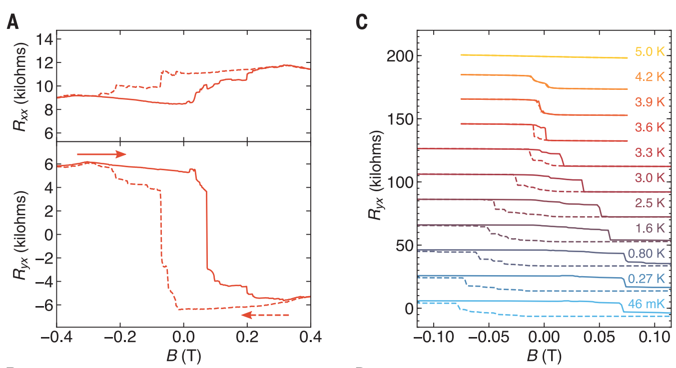


C.-Z. Zhang *et al*, 2013

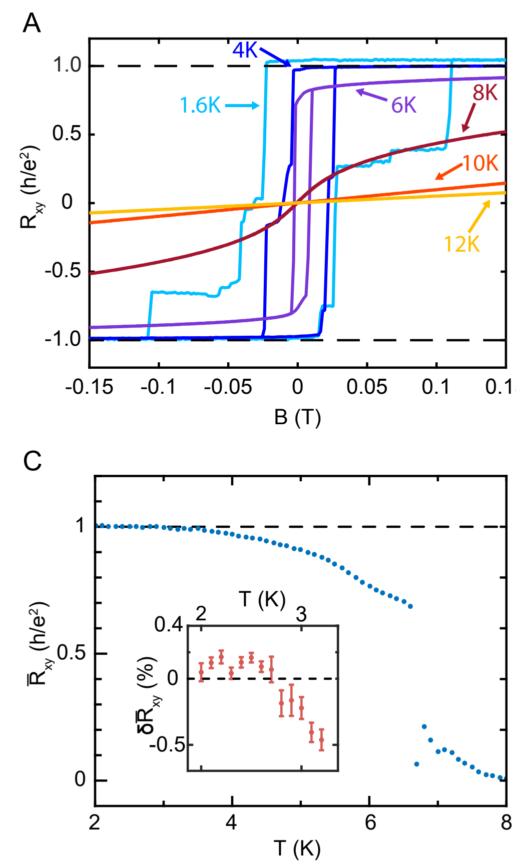
Cr-doped $(Bi/Sb)_2Te_3$

QAHE in graphene





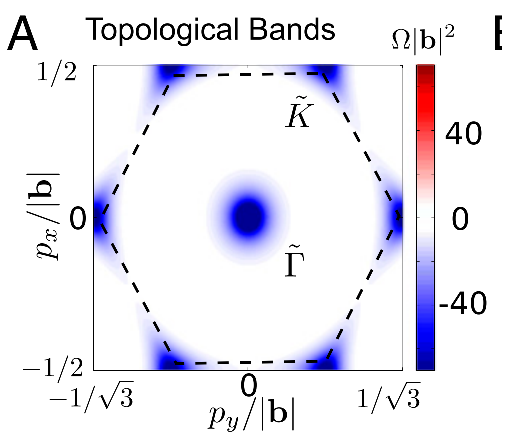
A. Sharpe *et al*, 2019



M. Serlin *et al*, 2019

Origin of QAHE?

- Underlying Dirac fermions of graphene have large incipient Berry curvature
- Curvature is realized by breaking C_2T symmetry



Topological Bloch bands in graphene superlattices

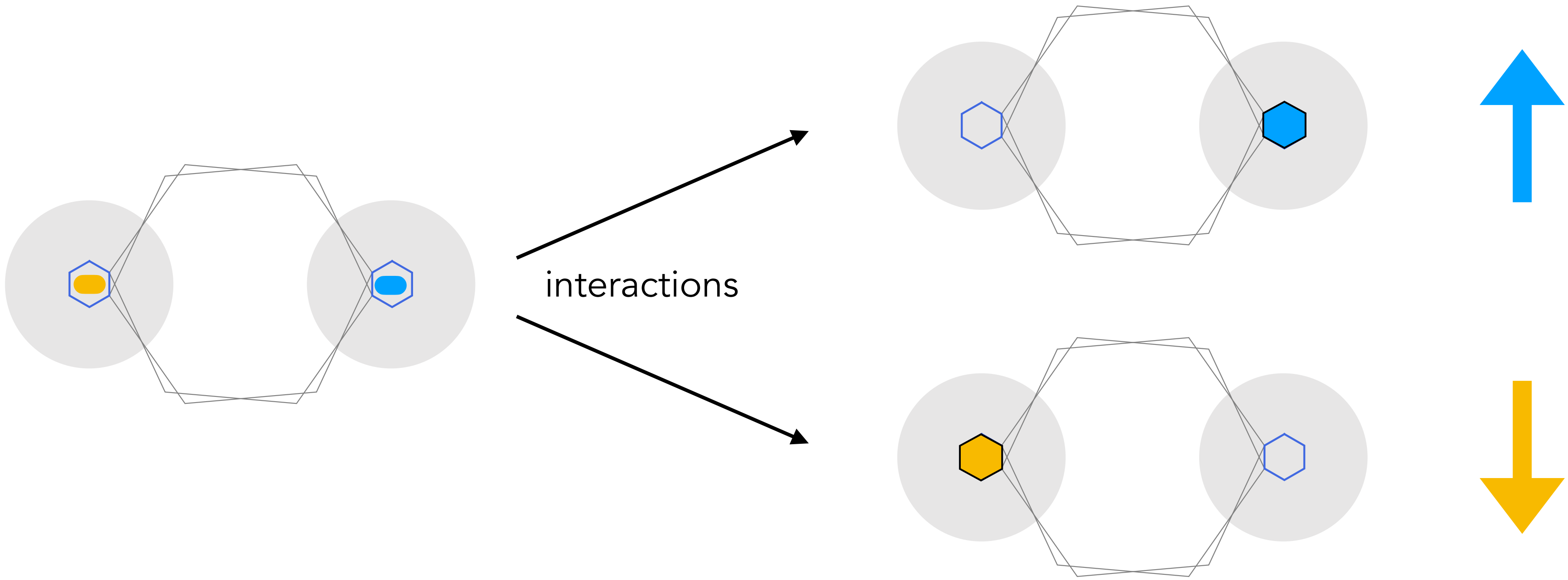
Justin C. W. Song[a,b,c,1], Polnop Samutpraphoot[c], and Leonid S. Levitov[c,1]

[a]Walter Burke Institute for Theoretical Physics, California Institute of Technology, CA 91125; [b]Institute for Quantum Information and Matter, and Department of Physics, California Institute of Technology, CA 91125; and [c]Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139

Edited by Subir Sachdev, Harvard University, Cambridge, MA, and approved June 24, 2015 (received for review December 30, 2014)

No interactions needed - just coupling to hBN - to generate Dirac mass and form valley Chern bands

Valley ferromagnetism



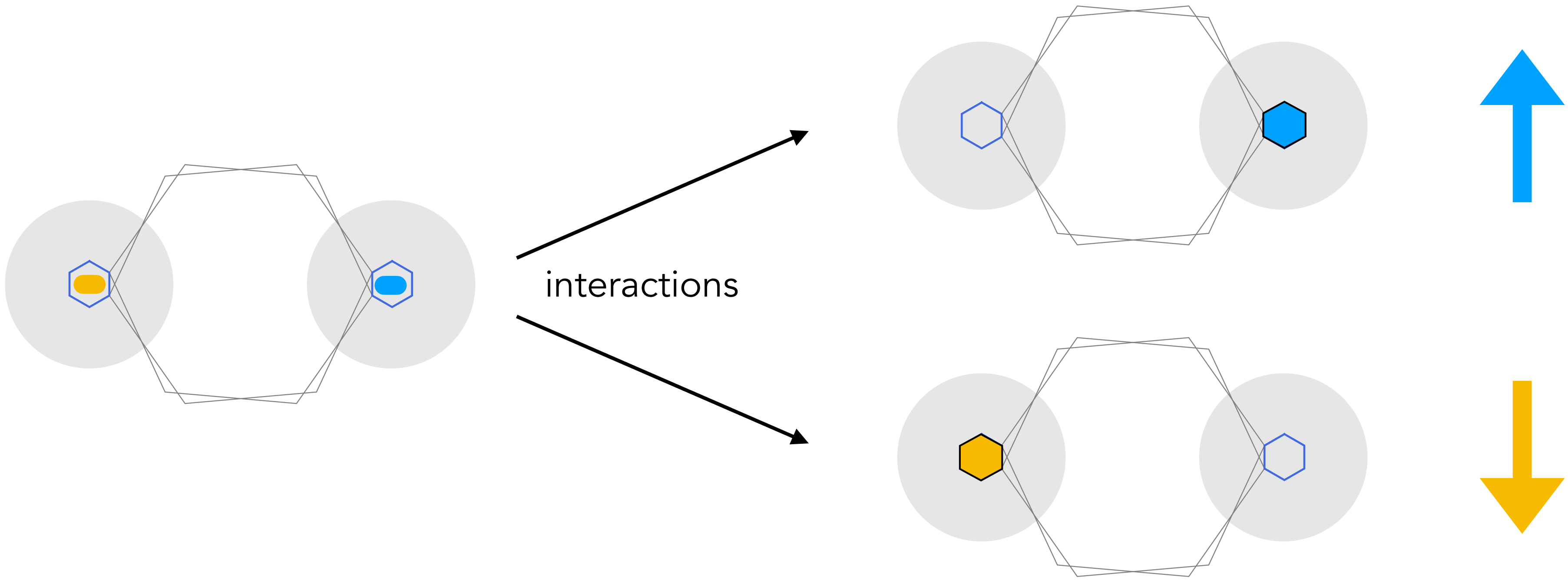
Valley polarization $\phi = n_K - n_{K'}$

Orbital magnetization $m^{\mu}(\boldsymbol{k}) = \frac{-ie}{2}\epsilon_{\mu\nu\lambda}\left\langle \frac{\partial u_{n\boldsymbol{k}}}{\partial k_\nu} \right| (\mathcal{H}_{\boldsymbol{k}} - \epsilon_{n\boldsymbol{k}}) \left| \frac{\partial u_{n\boldsymbol{k}}}{\partial k_\lambda} \right\rangle$

Hall conductivity $\sigma_{xy} = \frac{e^2}{2\pi h} \sum_n \int d^2\boldsymbol{k}\, n_F(\epsilon_{n\boldsymbol{k}}) \Omega_n(\boldsymbol{k})$

In equilibrium $m_z \propto \sigma_{xy} \propto \phi$

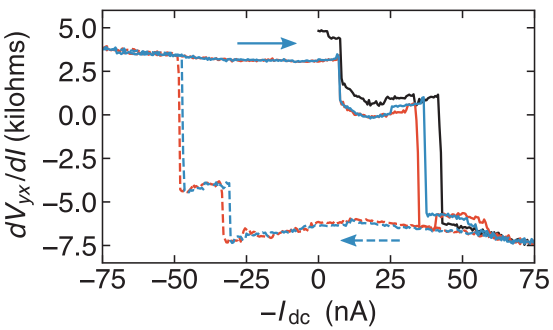
Valley ferromagnetism



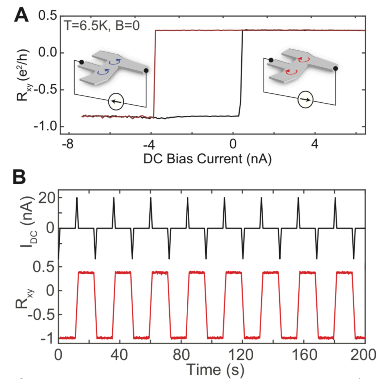
Differences from normal FMs:

- Two dimensional
- Dominant orbital moment
- Extreme Ising anisotropy
- Large Hall angle at low T

Current control

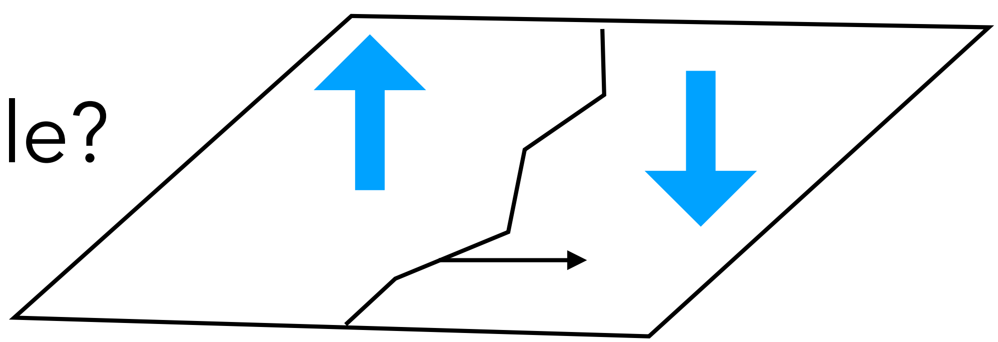


A. Sharpe *et al*, 2019



M. Serlin *et al*, 2019

How does the current couple?



Topological spintronics in a *pure* orbital ferromagnet

Quantized regime

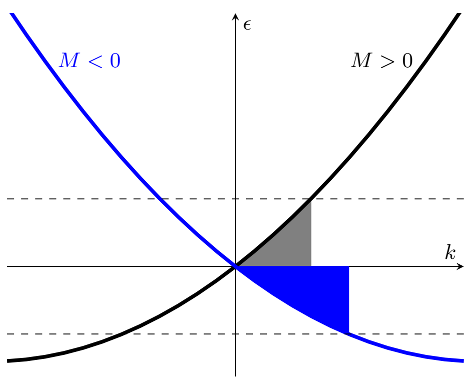
$$\rho_{xx} \ll \rho_{xy}$$

- no dissipation, only edge state transport
- Charge of each edge is separately conserved

✤ Can view current-carrying state as quasi-equilibrium ensemble where current determines edge occupation

Can formulate F(I,M)

$$\Delta F \sim \frac{\hbar^2}{me^3v^3} LI^3$$



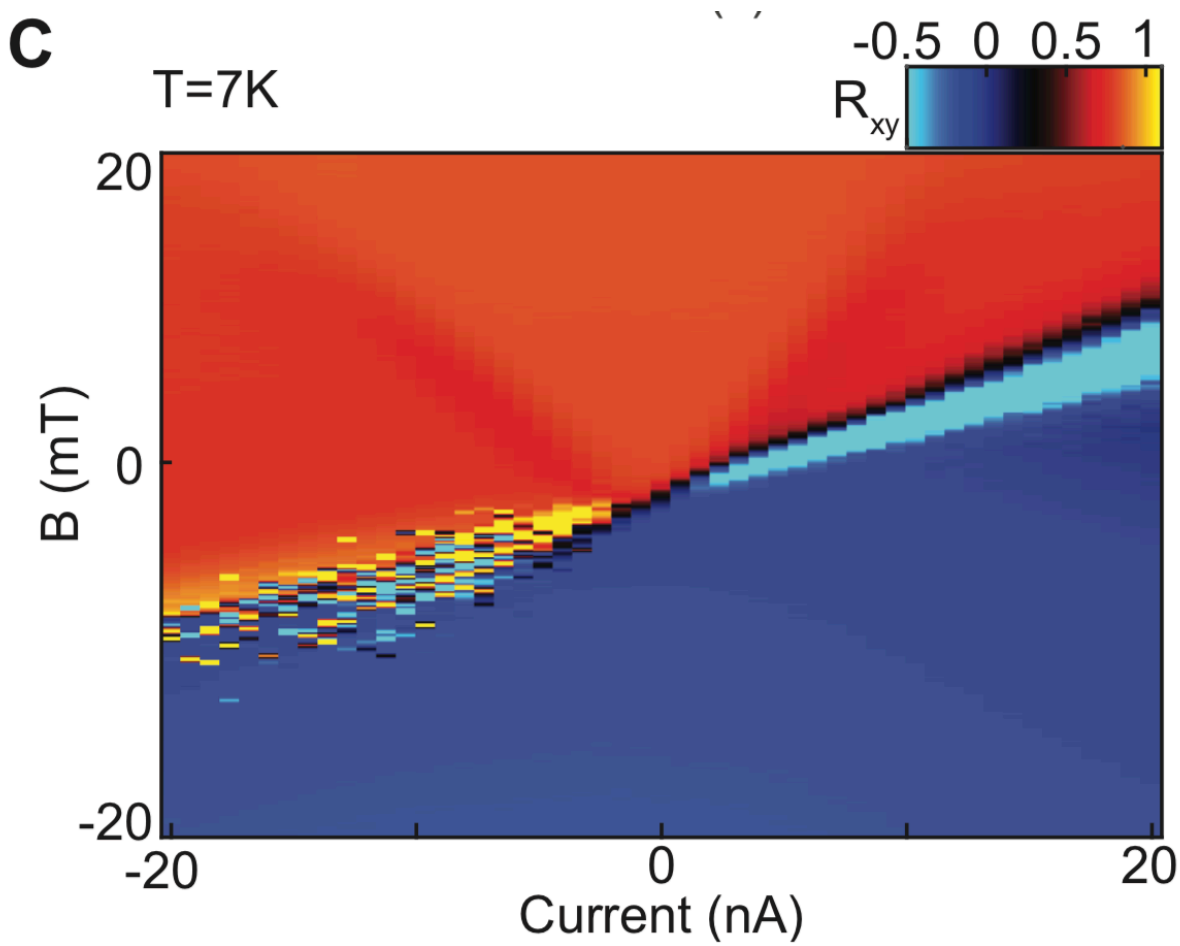
M. Serlin *et al*, 2019

another mechanism

Current Driven Magnetization Reversal in Orbital Chern Insulators

Chunli Huang, Nemin Wei, and Allan H. MacDonald
Department of Physics, University of Texas at Austin, Austin TX 78712
(Dated: September 22, 2020)

Dissipative Regime



A fully non-equilibrium problem, bulk 2d physics

Magneto-electric effect

ARTICLE

https://doi.org/10.1038/s41467-020-15473-9 OPEN

Giant orbital magnetoelectric effect and current-induced magnetization switching in twisted bilayer graphene

Wen-Yu He [1✉], David Goldhaber-Gordon [2,3] & K. T. Law [1✉]

$$M_i = \sum_{i,j} \alpha_{ij} E_j,$$

$$\alpha_{ij} = -\tau \frac{e}{\hbar} \int_{\mathbf{q}} \sum\nolimits_{s,\xi,\nu} M^i_{s,\xi,\nu}(\mathbf{q}) v^j_{s,\xi,\nu}(\mathbf{q}) f'(E_{s,\xi,\nu})$$

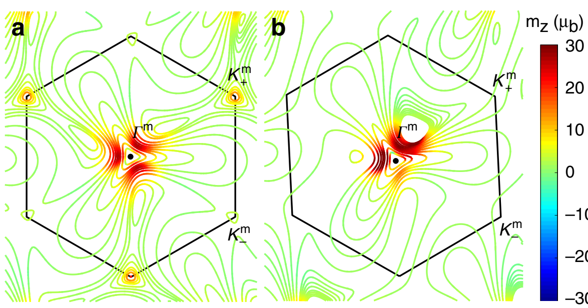
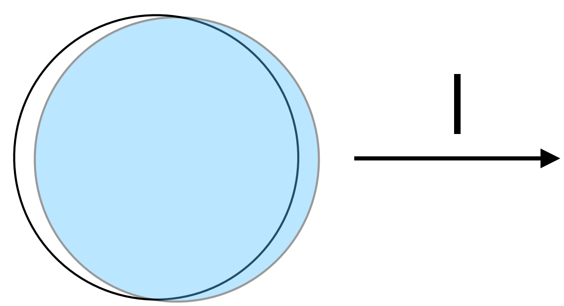


Fig. 2 The orbital magnetic moments of the Bloch electrons. a The orbital

Orbital moment induced by local change to electron distribution



Current Control

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Wen-Yu He[1✉], David Goldhaber-Gordon[2,3] & K. T. Law[1✉]

How to connect to I-induced force?

Use ME effect in free energy?

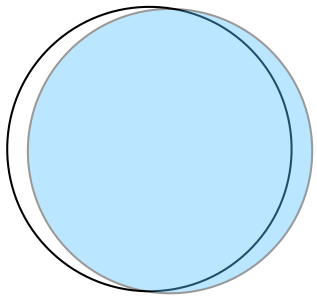
$$F = -a_0(M_z + \delta M_z)^2 + b_0(M_z + \delta M_z)^4$$
$$\approx -a_0 M_z^2 + b_0 M_z^4 - 2a_0 M_z(\alpha_{zx}E_x + \alpha_{zy}E_y)$$

c.f.

$$\Delta E = -\boldsymbol{B} \cdot \boldsymbol{M}$$

Should be cautious: not in equilibrium

Liouville Theorem



Semi-classical dynamics preserves phase space volume:
Valley polarization is **not** induced by this mechanism

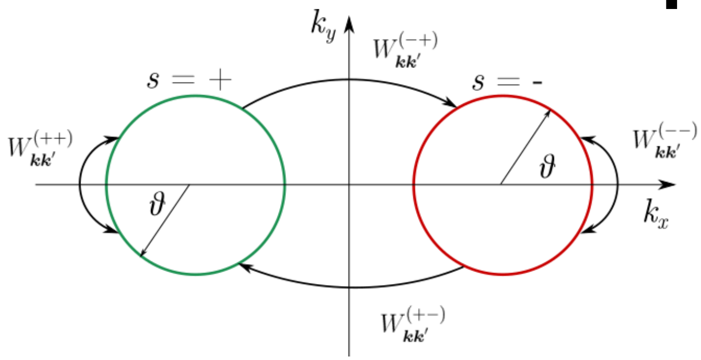
$$\partial_t f_{\boldsymbol{k}}^{(s)} + \boldsymbol{v}_{\boldsymbol{k}}^{(s)} \cdot \partial_{\boldsymbol{x}} f_{\boldsymbol{k}}^{(s)} + e\boldsymbol{E} \cdot \partial_{\boldsymbol{k}} f_{\boldsymbol{k}}^{(s)} = \sum_{s'=\pm} \int \mathrm{d}\Gamma' W_{\boldsymbol{k}\boldsymbol{k}'}^{(ss')} \left(f_{\boldsymbol{k}'}^{(s')} - f_{\boldsymbol{k}}^{(s)} \right) \delta(\epsilon_{\boldsymbol{k}'}^{(s')} - \epsilon_{\boldsymbol{k}}^{(s)})$$

In relaxation time approximation:

$M = \alpha E \sim \tau E \sim j$

$\phi = 0$ Valley polarization is <u>primary</u> order parameter, but not induced by ME mechanism (not in equilibrium)

Anisotropic scattering



anisotropic $W^{(+-)}_{\boldsymbol{k}\boldsymbol{k}'}$ needed

$$\partial_t f^{(s)}_{\boldsymbol{k}} + \boldsymbol{v}^{(s)}_{\boldsymbol{k}} \cdot \partial_{\boldsymbol{x}} f^{(s)}_{\boldsymbol{k}} + e\boldsymbol{E} \cdot \partial_{\boldsymbol{k}} f^{(s)}_{\boldsymbol{k}} = \sum_{s'=\pm} \int \mathrm{d}\Gamma' W^{(ss')}_{\boldsymbol{k}\boldsymbol{k}'} \left(f^{(s')}_{\boldsymbol{k}'} - f^{(s)}_{\boldsymbol{k}} \right) \delta(\epsilon^{(s')}_{\boldsymbol{k}'} - \epsilon^{(s)}_{\boldsymbol{k}})$$

e.g.

$$W^{(-+)}_{\boldsymbol{k}\boldsymbol{k}'} = W^{(+-)}_{\boldsymbol{k}'\boldsymbol{k}} = \frac{1}{\nu\tau'} \left(1 + a_1 \cos\theta_{\boldsymbol{k}} + b_1 \sin\theta_{\boldsymbol{k}} + a_1' \cos\theta_{\boldsymbol{k}'} + b_1' \sin\theta_{\boldsymbol{k}'}\right)$$

$$\Delta n_0 = n^{(+)} - n^{(-)} = \tfrac{1}{2}\nu v_{\mathrm{F}}\tau \left[eE_x\left(a_1 + a_1'\right) + eE_y\left(b_1 + b_1'\right)\right] \propto \frac{\tau}{\tau'}$$

$$\Delta n_0 = \frac{1}{2hv_{\mathrm{F}}} \frac{h}{e^2} \left[ej_x\left(a_1 + a_1'\right) + ej_y\left(b_1 + b_1'\right)\right]$$

Result

Rough estimate

$$\Delta n_0 \simeq \frac{1}{ev_{\mathrm{F}}} \boldsymbol{j} \cdot \boldsymbol{\delta}_\epsilon \propto \frac{\epsilon}{\theta_w} \frac{1}{hv_F} \frac{h}{e^2} ej$$

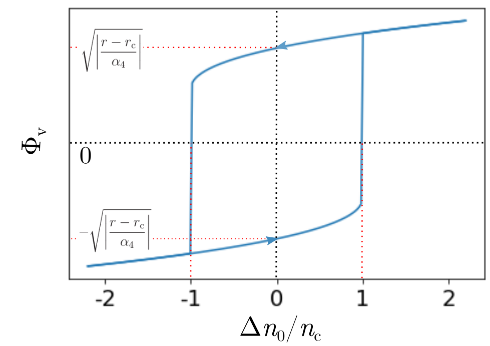
This is the "bare" response just from quasiparticle physics. Should be included in a TDGL-like formulation as a force, to take into account both QP physics and interactions.

Keldysh result:

$$(r - r_c)\Phi_{\mathrm{v}} - \alpha_4 \Phi_{\mathrm{v}}^3 = \Delta n_0$$

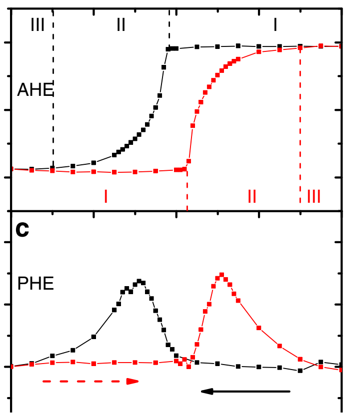
RHS acts as force on valley order parameter

n.b. result is parametrically larger than ME one near T_c

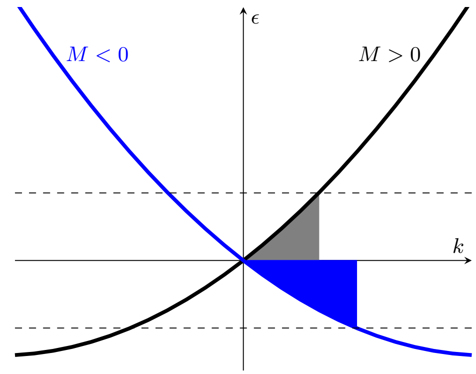


X. Ying, M. Ye, LB, arXiv:2101.01790

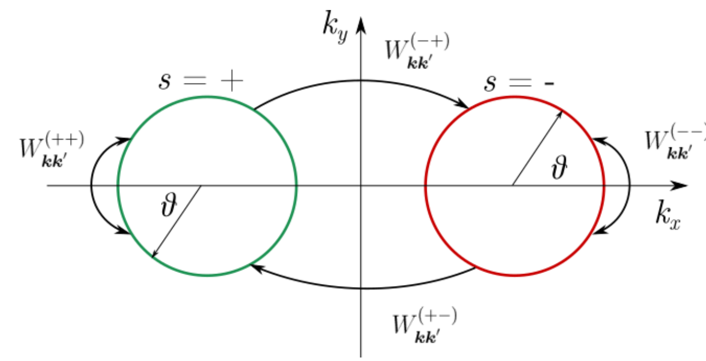
Thanks



X. Li *et al*, Nat. Comm. (2019)



M. Serlin *et al*, 2019



X. Ying, M. Ye, LB, arXiv:2101.01790

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