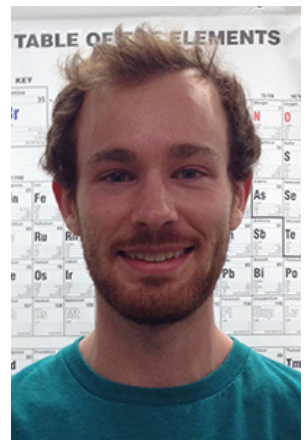
Towards UQM in experiments

Leon Balents, KITP

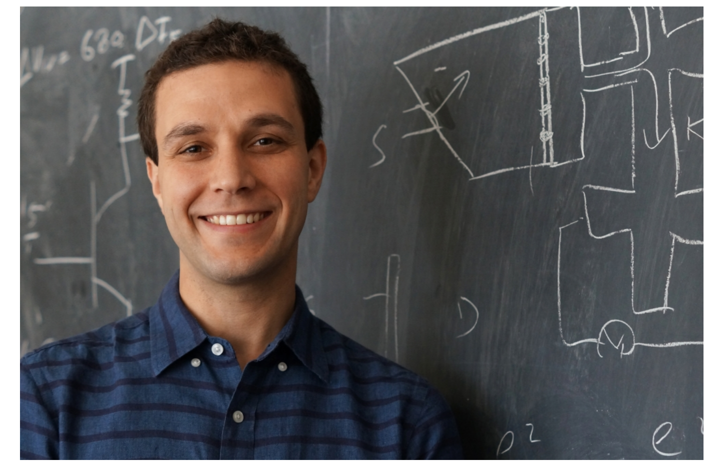
Simons Collaboration on Ultra-Quantum Matter

Collaborators

Stephen Wilson



Mitchell Bordelon



Andrea Young

Chunxiao Liu

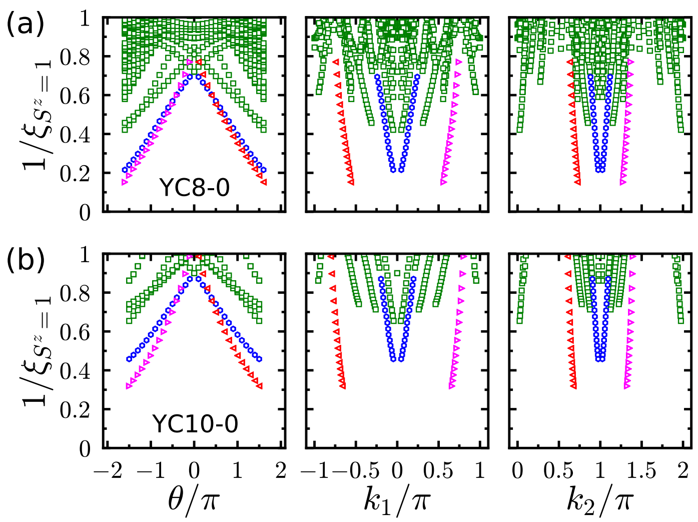
Kasra Hejazi

Outline

- $NaYbO_2$: a possible new quantum spin liquid
- Continuum model for twisted bilayer graphene for dummies
- Quantum anomalous Hall effect in TBG: controlling the order parameter with current

Spin Liquids

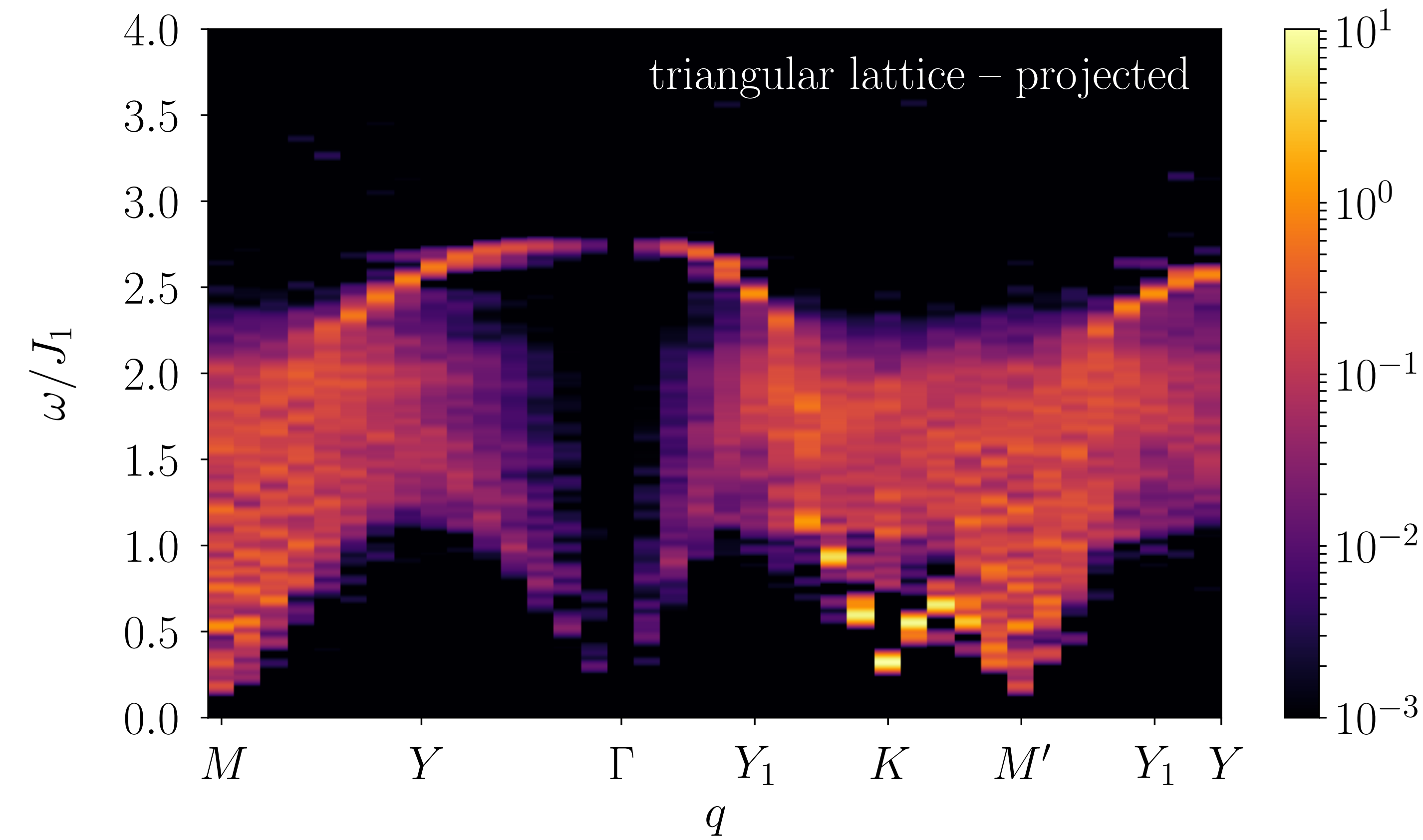
- Possible U(1) Dirac QSL on the triangular lattice (J_1-J_2)



Shijie Hu *et al*, 2019

	T_1	T_2	R	C_6	$\mathcal{T}$
M_{00}	$+$	$+$	$-$	$+$	$-$
M_{i0}	$+$	$+$	$+$	$-$	$+$
M_{01}	$-$	$-$	$-M_{03}$	$-M_{02}$	$+$
M_{02}	$+$	$-$	M_{02}	M_{03}	$+$
M_{03}	$-$	$+$	$-M_{01}$	M_{01}	$+$
M_{i1}	$-$	$-$	M_{i3}	M_{i2}	$-$
M_{i2}	$+$	$-$	$-M_{i2}$	$-M_{i3}$	$-$
M_{i3}	$-$	$+$	M_{i1}	$-M_{i1}$	$-$
$\Phi_1^\dagger$	$e^{-i\frac{\pi}{3}}\Phi_1^\dagger$	$e^{i\frac{\pi}{3}}\Phi_1^\dagger$	$-\Phi_3^\dagger$	Φ_2	Φ_1
$\Phi_2^\dagger$	$e^{i\frac{2\pi}{3}}\Phi_2^\dagger$	$e^{i\frac{\pi}{3}}\Phi_2^\dagger$	$\Phi_2^\dagger$	$-\Phi_3$	Φ_2
$\Phi_3^\dagger$	$e^{i\frac{-\pi}{3}}\Phi_3^\dagger$	$e^{i\frac{-2\pi}{3}}\Phi_3^\dagger$	$-\Phi_1^\dagger$	$-\Phi_1$	Φ_3
$\Phi_{4/5/6}^\dagger$	$e^{i\frac{2\pi}{3}}\Phi_{4/5/6}^\dagger$	$e^{-i\frac{2\pi}{3}}\Phi_{4/5/6}^\dagger$	$\Phi_{4/5/6}^\dagger$	$-\Phi_{4/5/6}$	-$\Phi_{4/5/6}$

X-Y Song *et al*, 2018

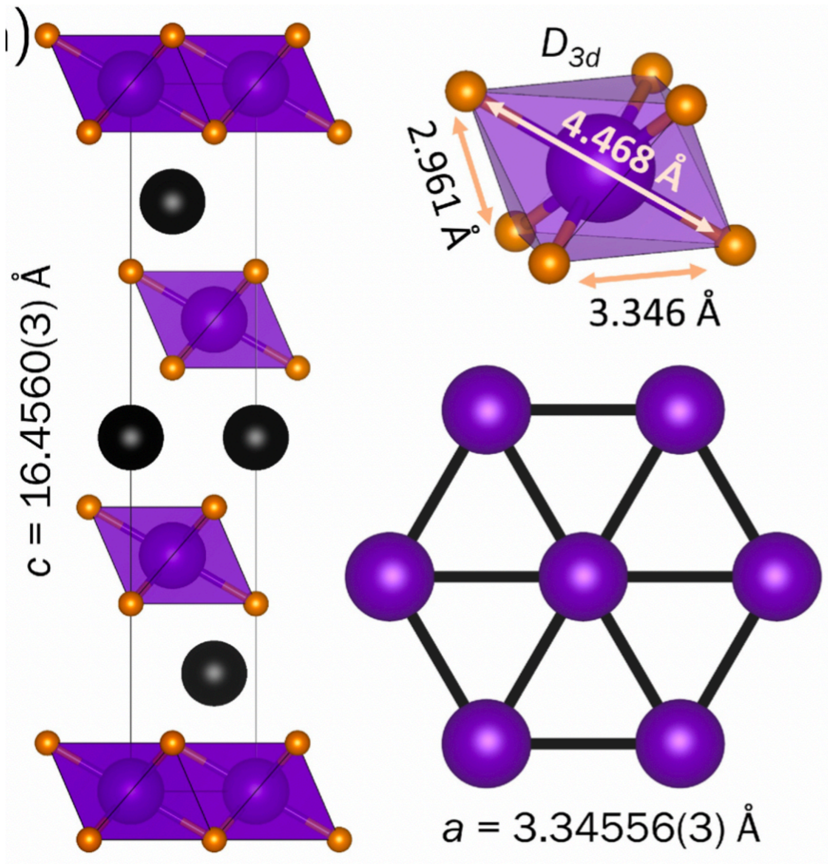


Federico Becca, unpublished

Spin Liquids?

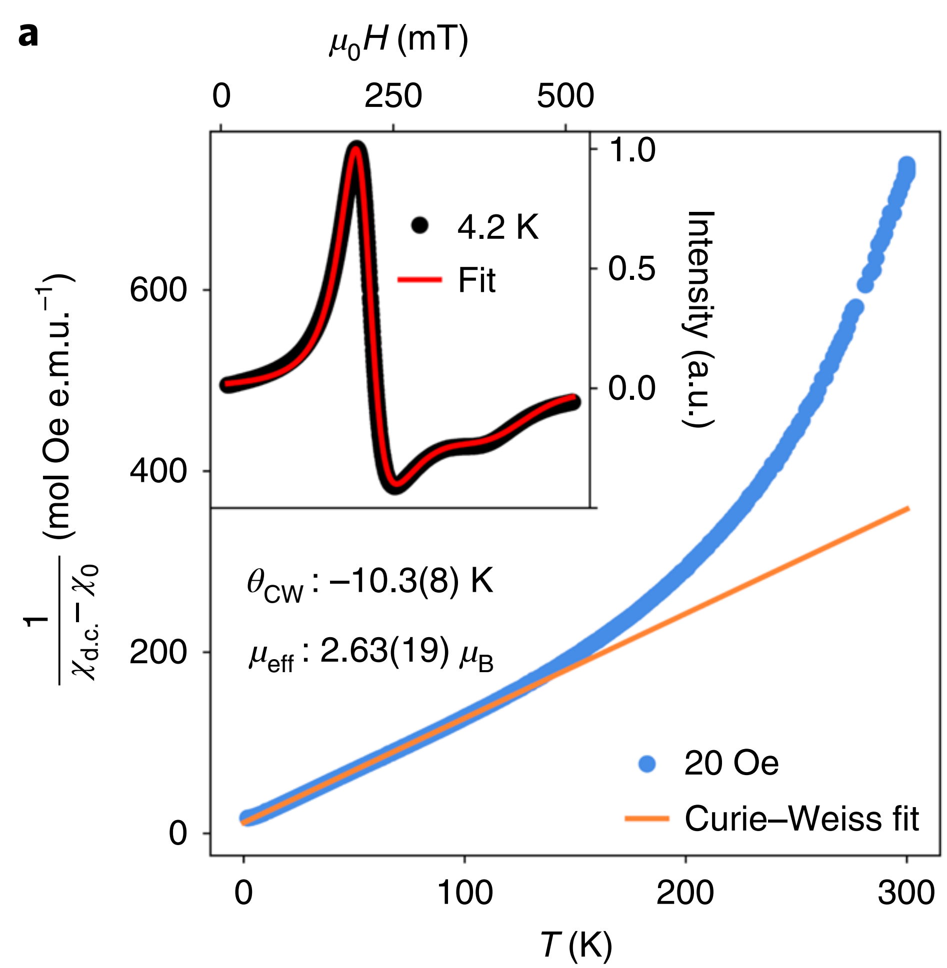
Model	QSL	Material	Issue
Kagome Heisenberg	U(1) Dirac	Herbertsmithite	Interlayer disorder
Kitaev honeycomb	Gapless Z2/Ising	α-$RuCl_3$	Un-reproduced key result
Triangular Hubbard	U(1) Fermi surface	k-(ET),dmit organics	Interlayer disorder/ unreproduced result
Triangular J_1-J_2 Heisenberg	U(1) Dirac?	$YbMgGaO_4$?	Random alloy Mg/Ga disorder

$NaYbO_2$



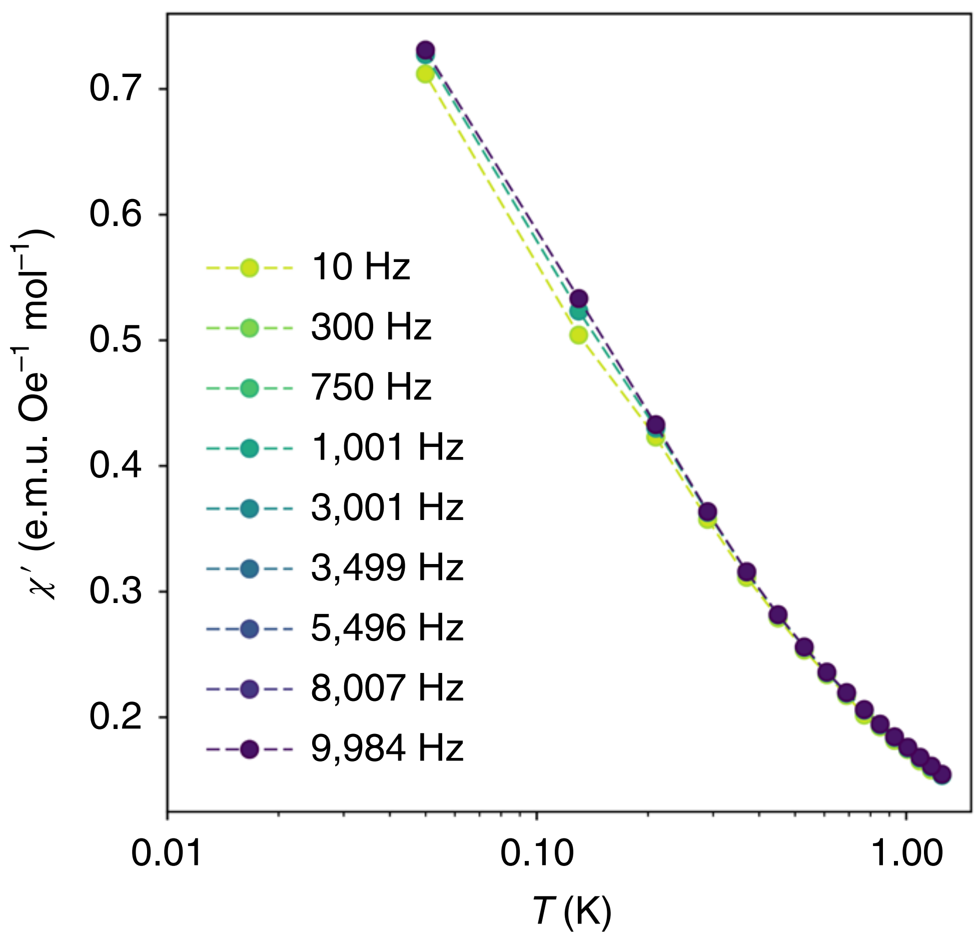
Isotropic triangular lattice of Yb^{3+} effective S=1/2 moments

ESR shows g_{xy}=3.3, g_z=1.7: expect XY-like spins (common for Yb^{3+})

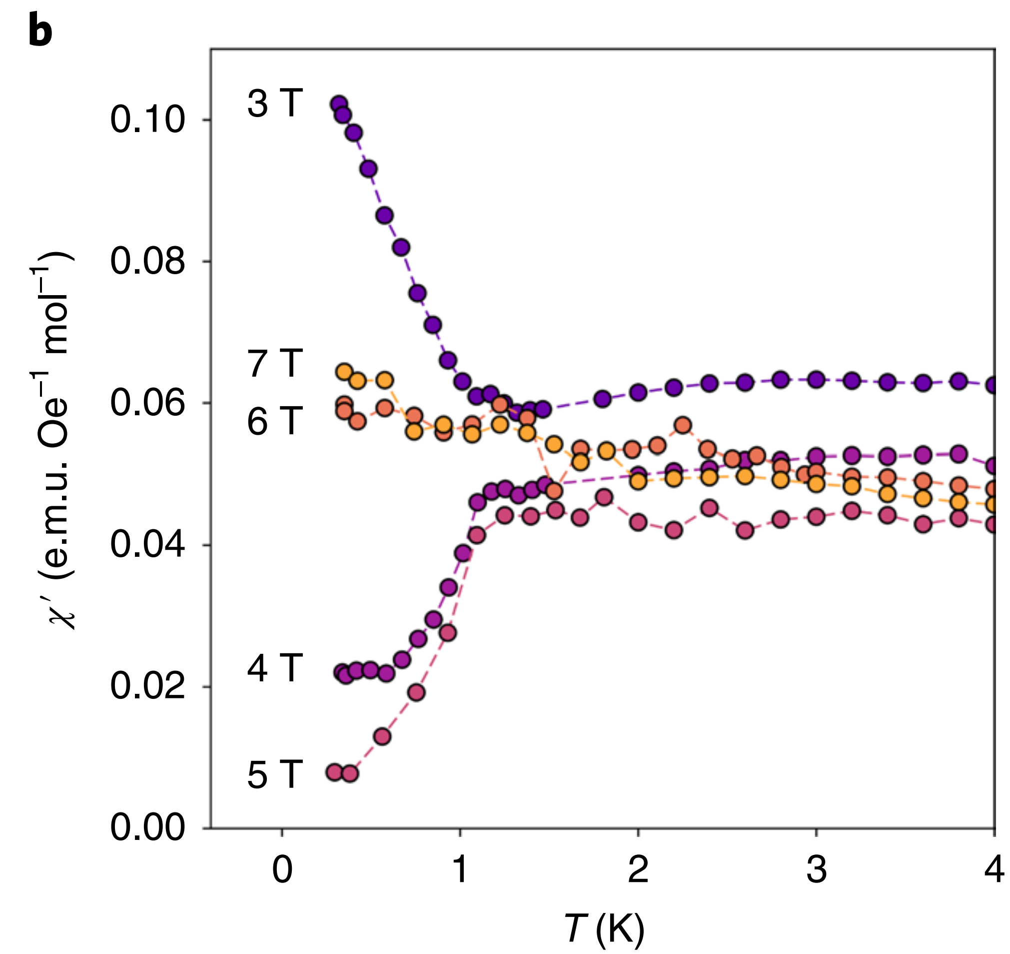


Susceptibility shows antiferromagnetic exchange with ~10K scale

$NaYbO_2$



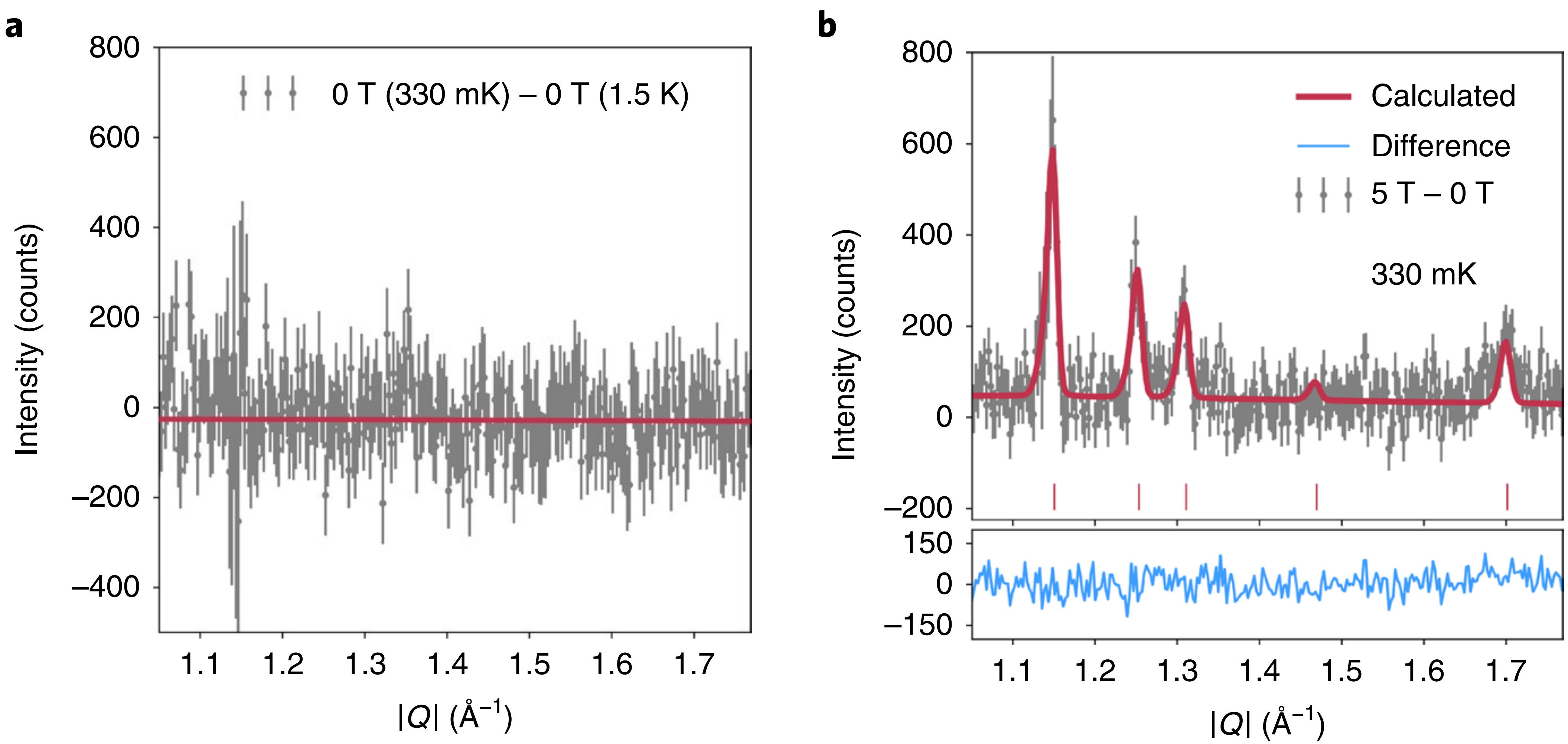
No ordering or freezing at B=0



“action” in B>2T.

NaYbO$_2$

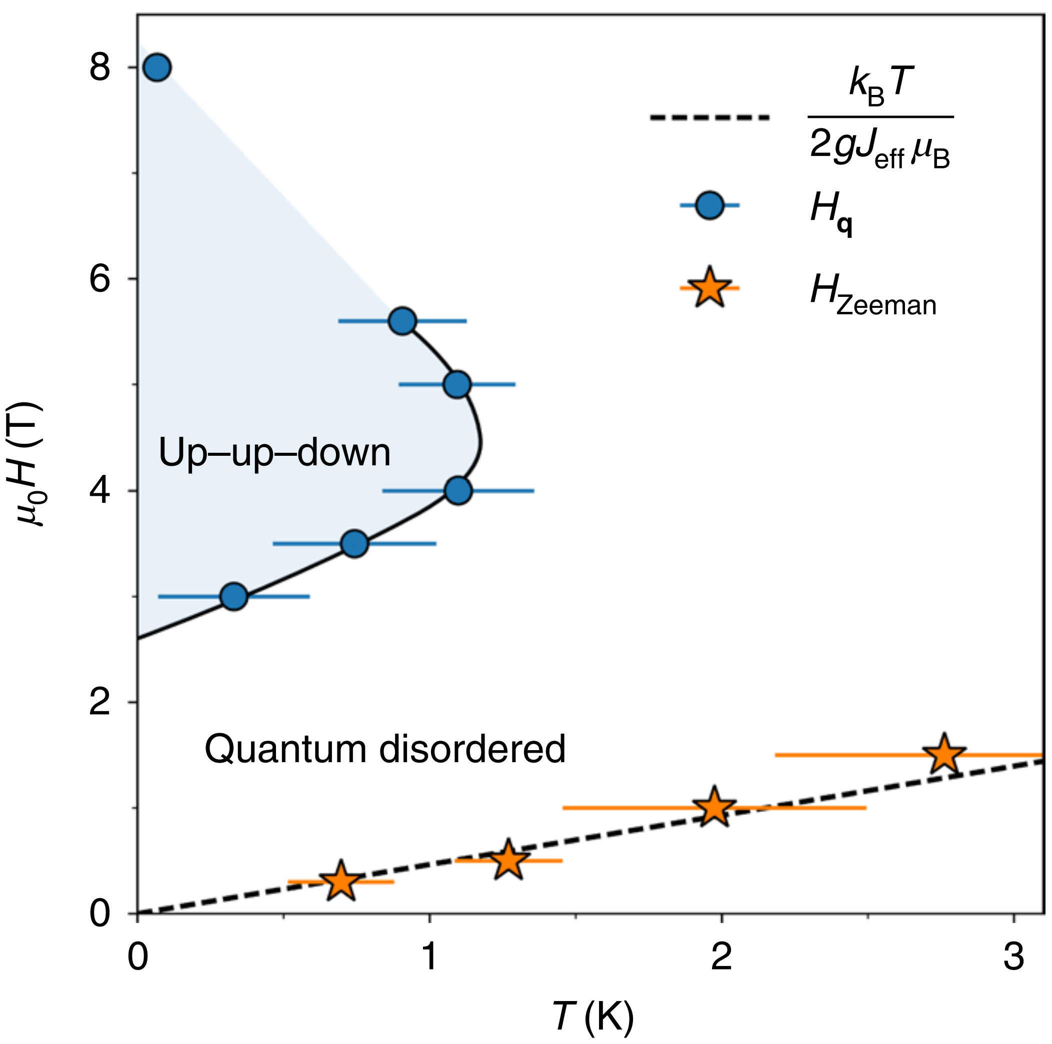
Neutron scattering



Featureless at B=0

Field-induced order

$NaYbO_2$



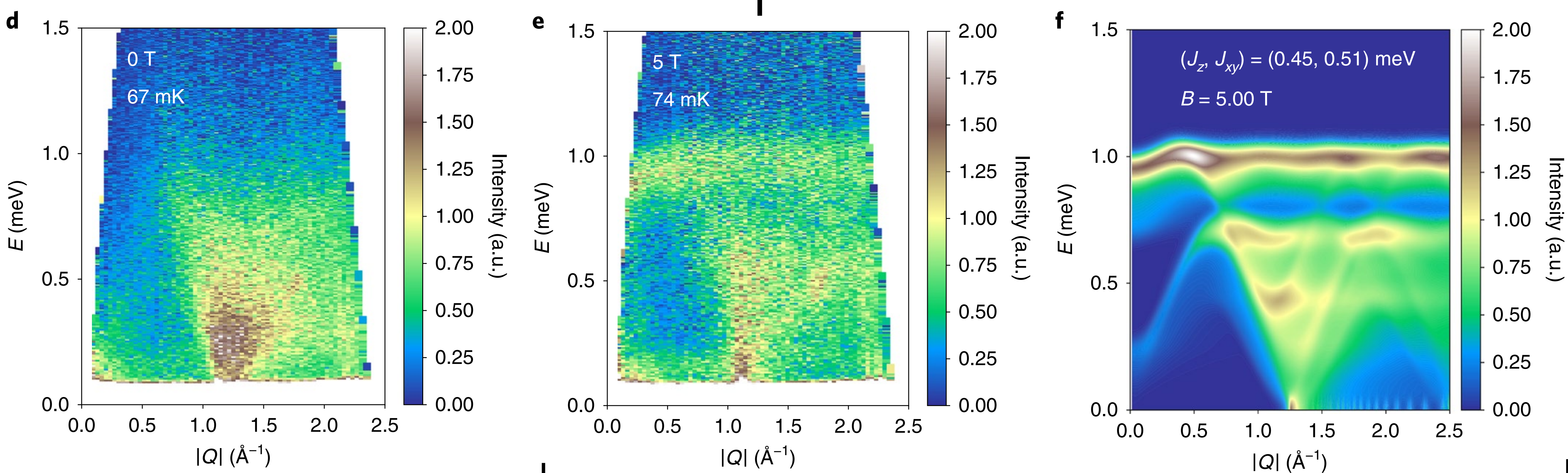
Field-induced 3-sublattice order

$NaYbO_2$

Powder INS

expt

SWT

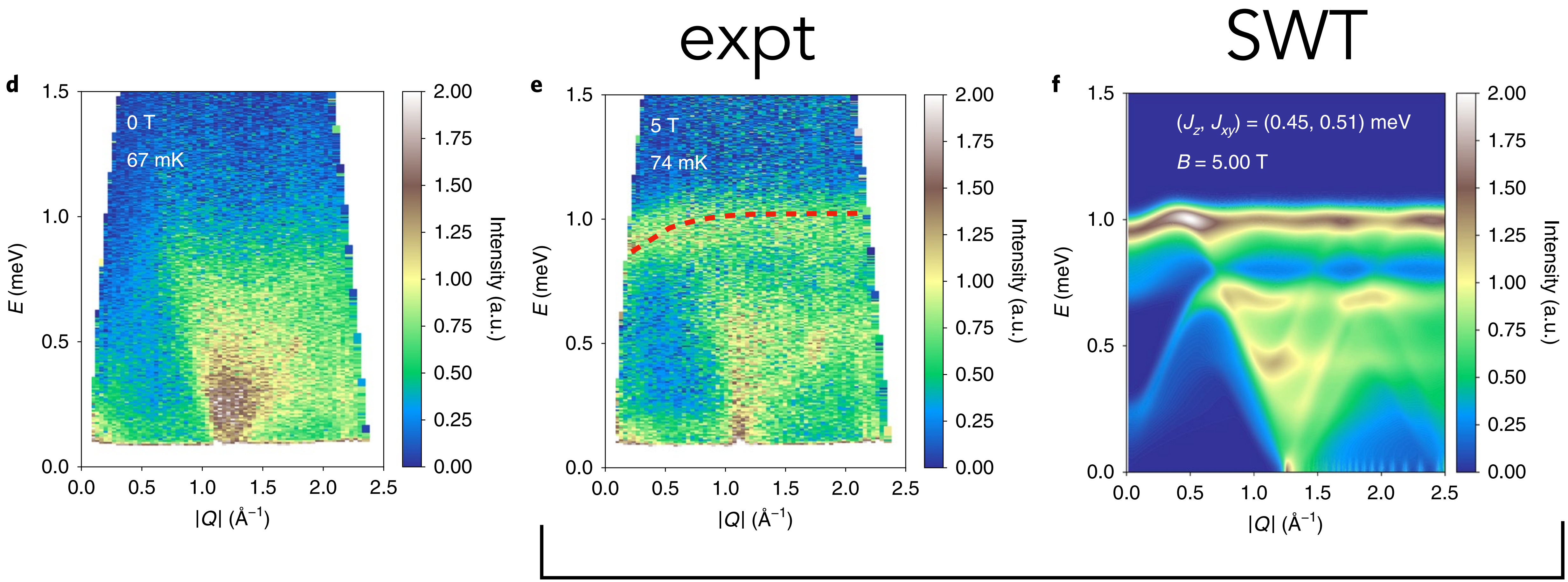


QSL?

In the ordered state

$NaYbO_2$

Powder INS

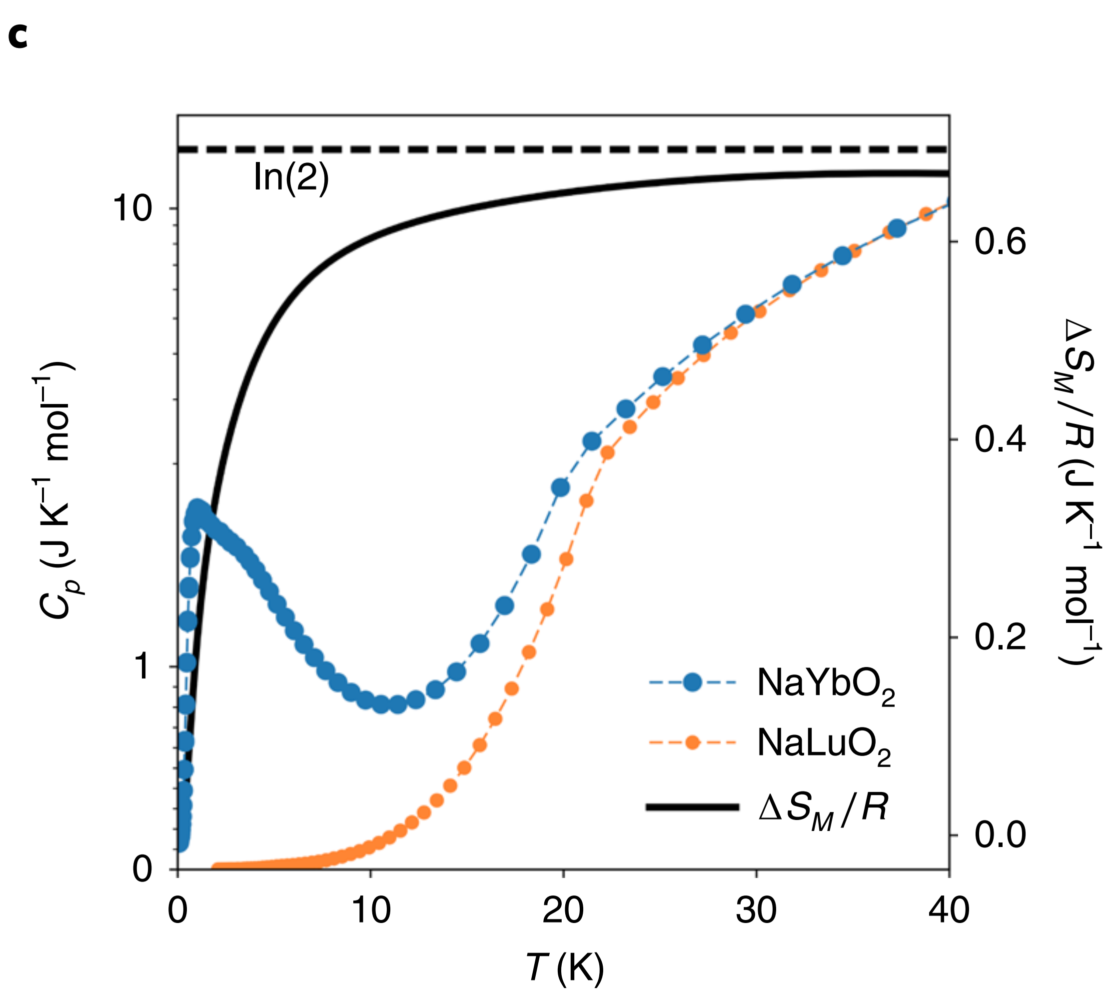


QSL?

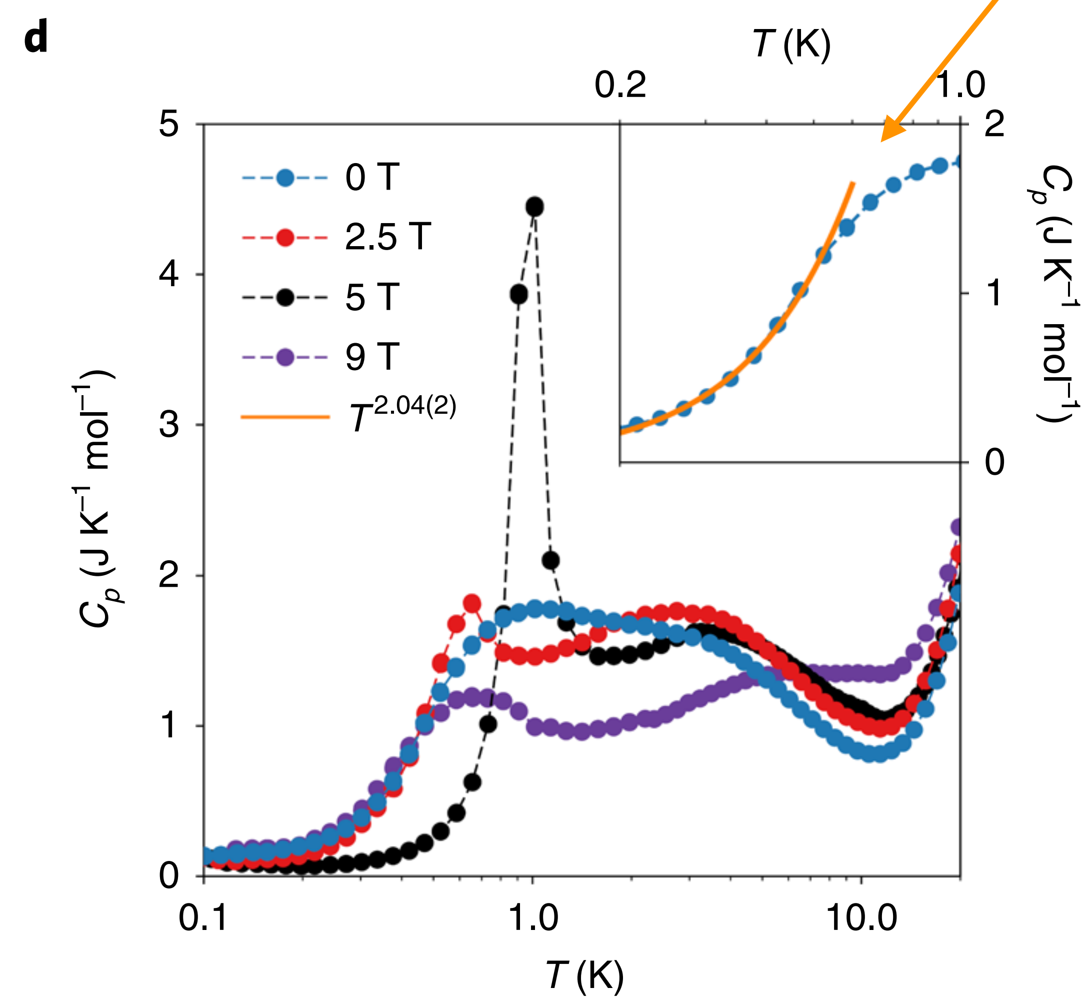
In the ordered state

$NaYbO_2$

$C \sim T^2$?



Entropy confirms S=1/2



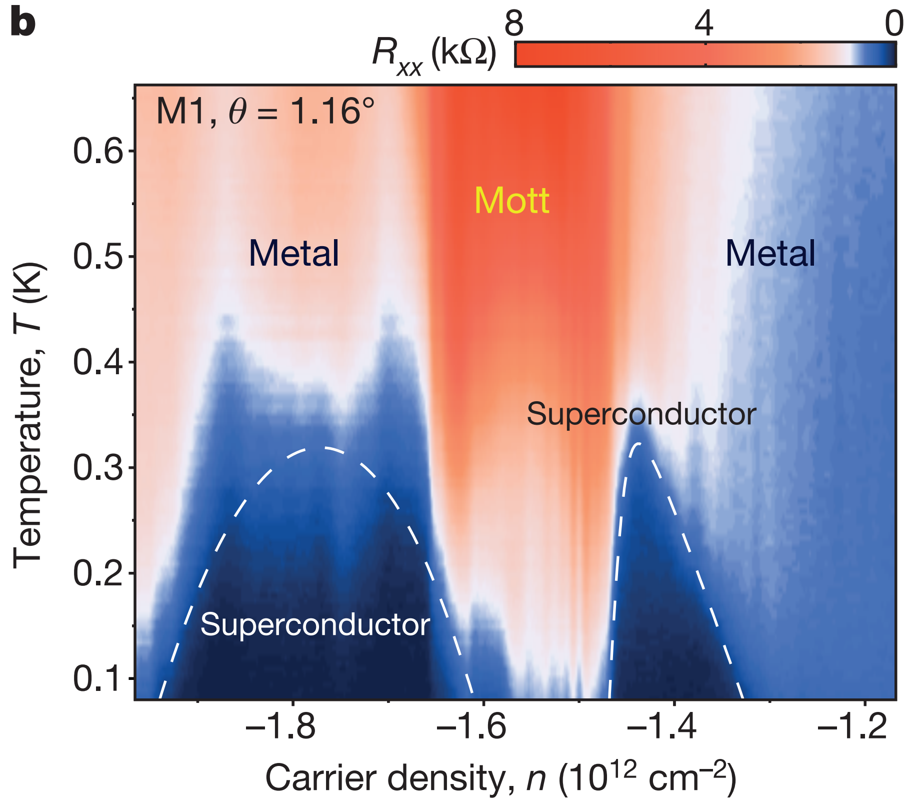
So far consistent with U(1) Dirac

Magic angle graphene

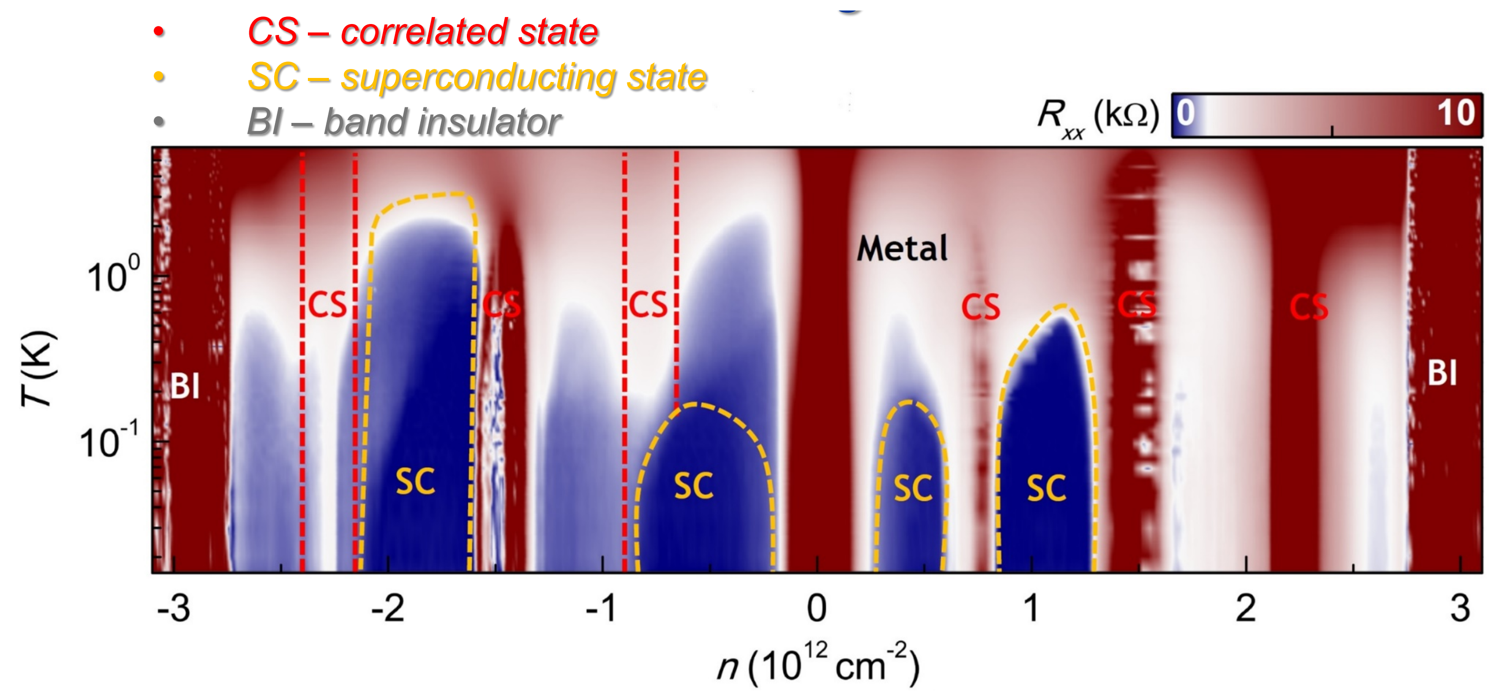
Pablo Jarillo-Herrero
(MIT)

Physics World
Breakthrough of the year,
2018

Dimitri Efetov
(Barcelona)



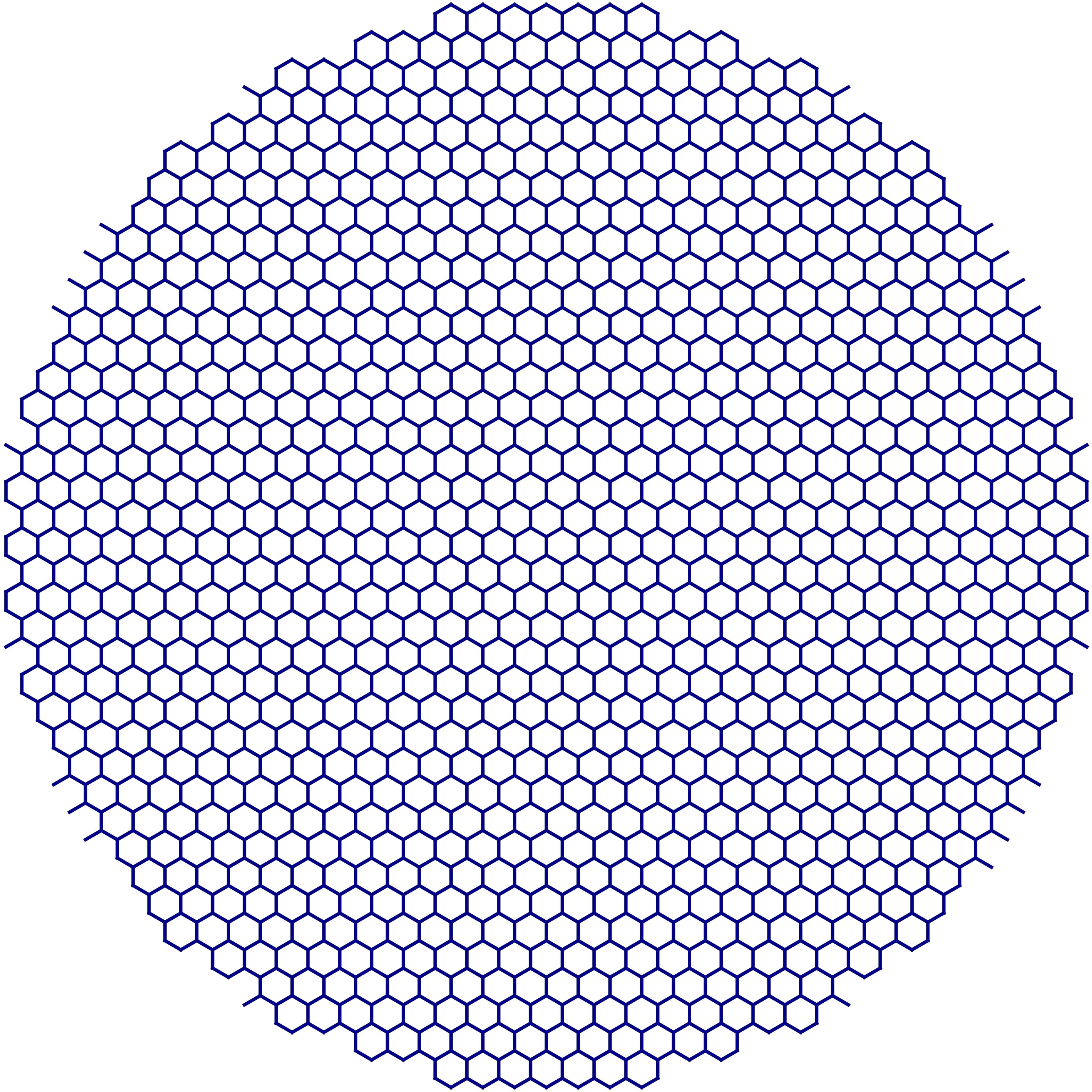
Y. Cao *et al*, 2018



YX. Lu *et al*, 2019

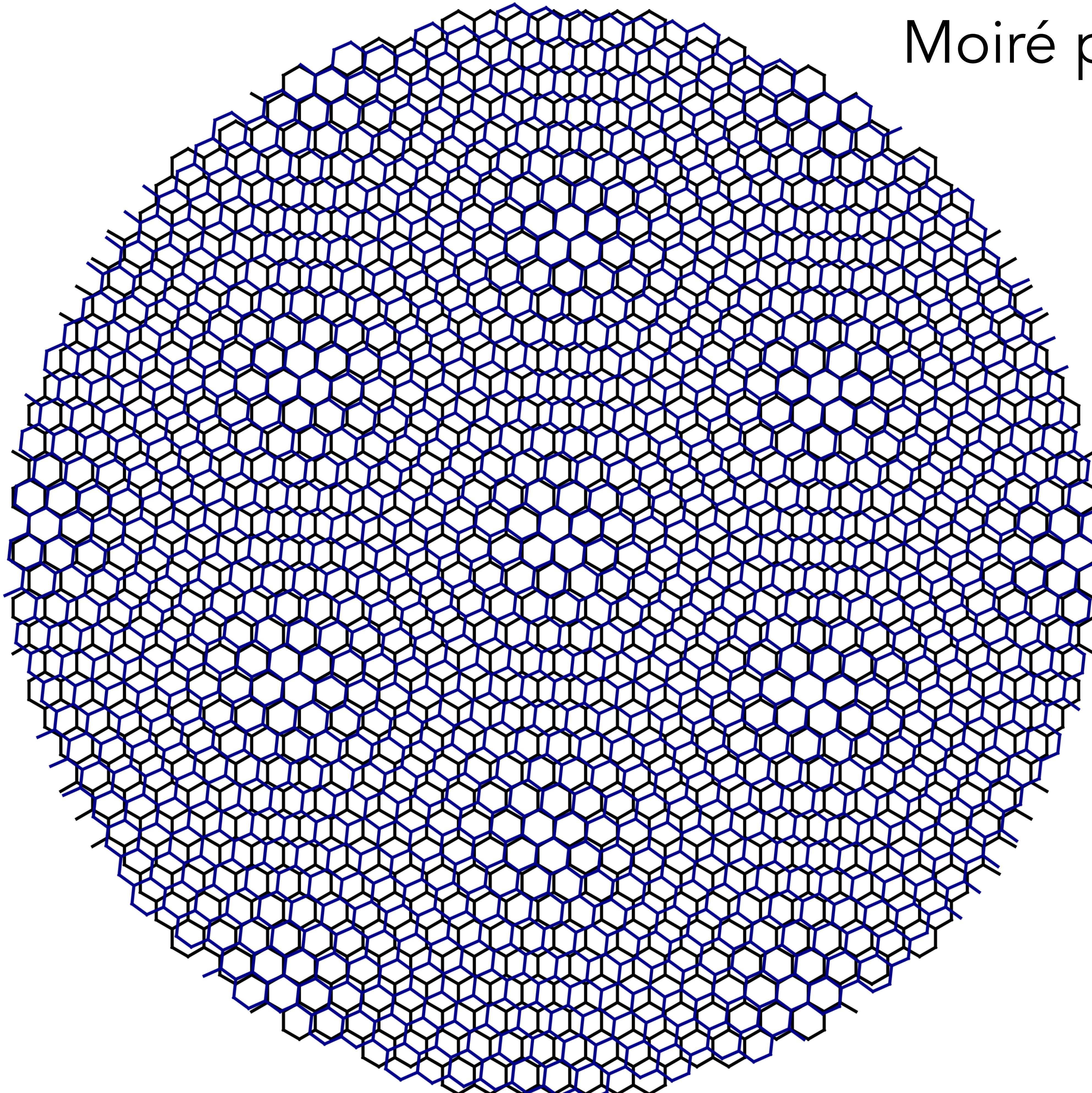
Two topics in TBG

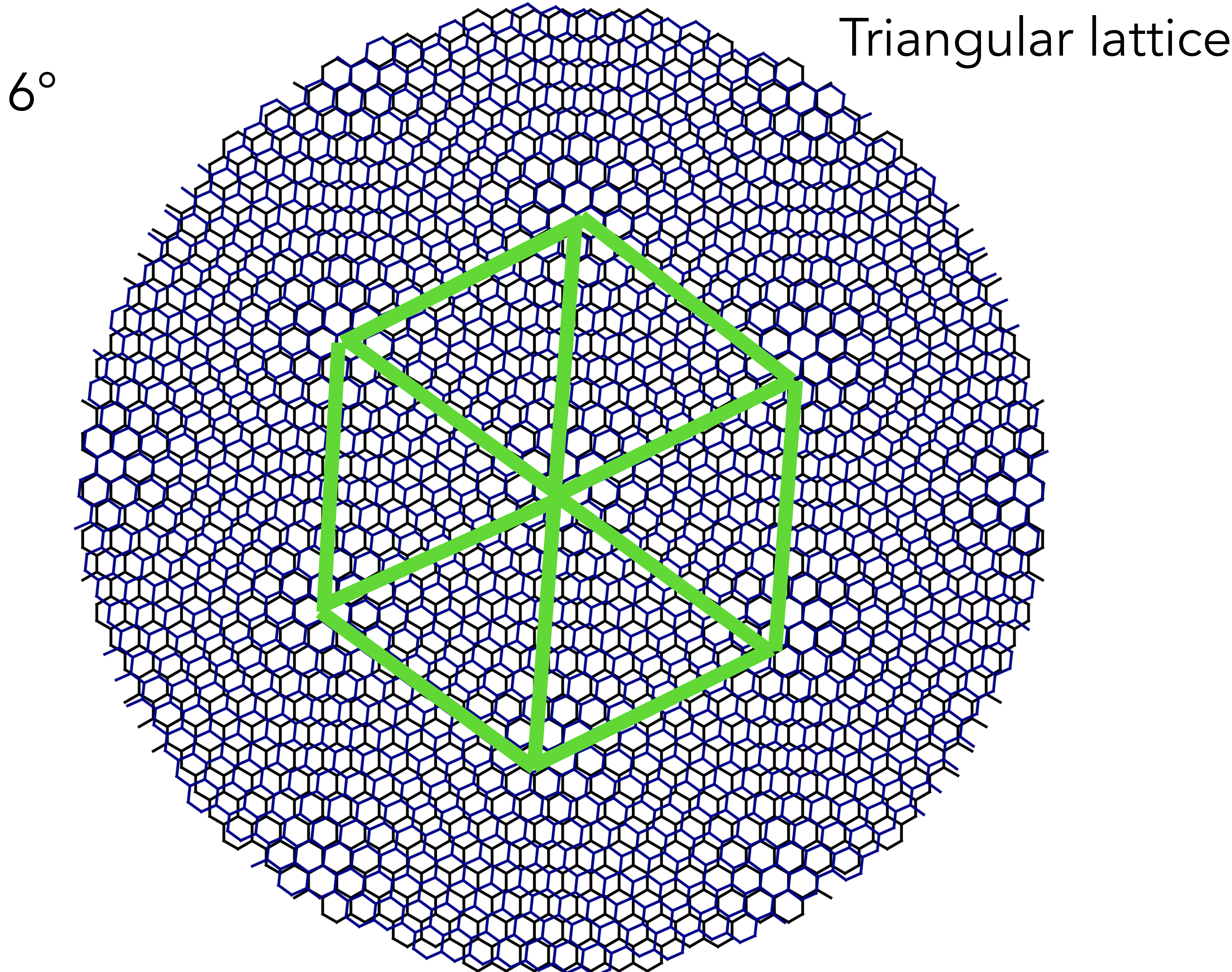
1. Continuum model for TBG as effective field theory
2. Non-equilibrium driving a QAHE state

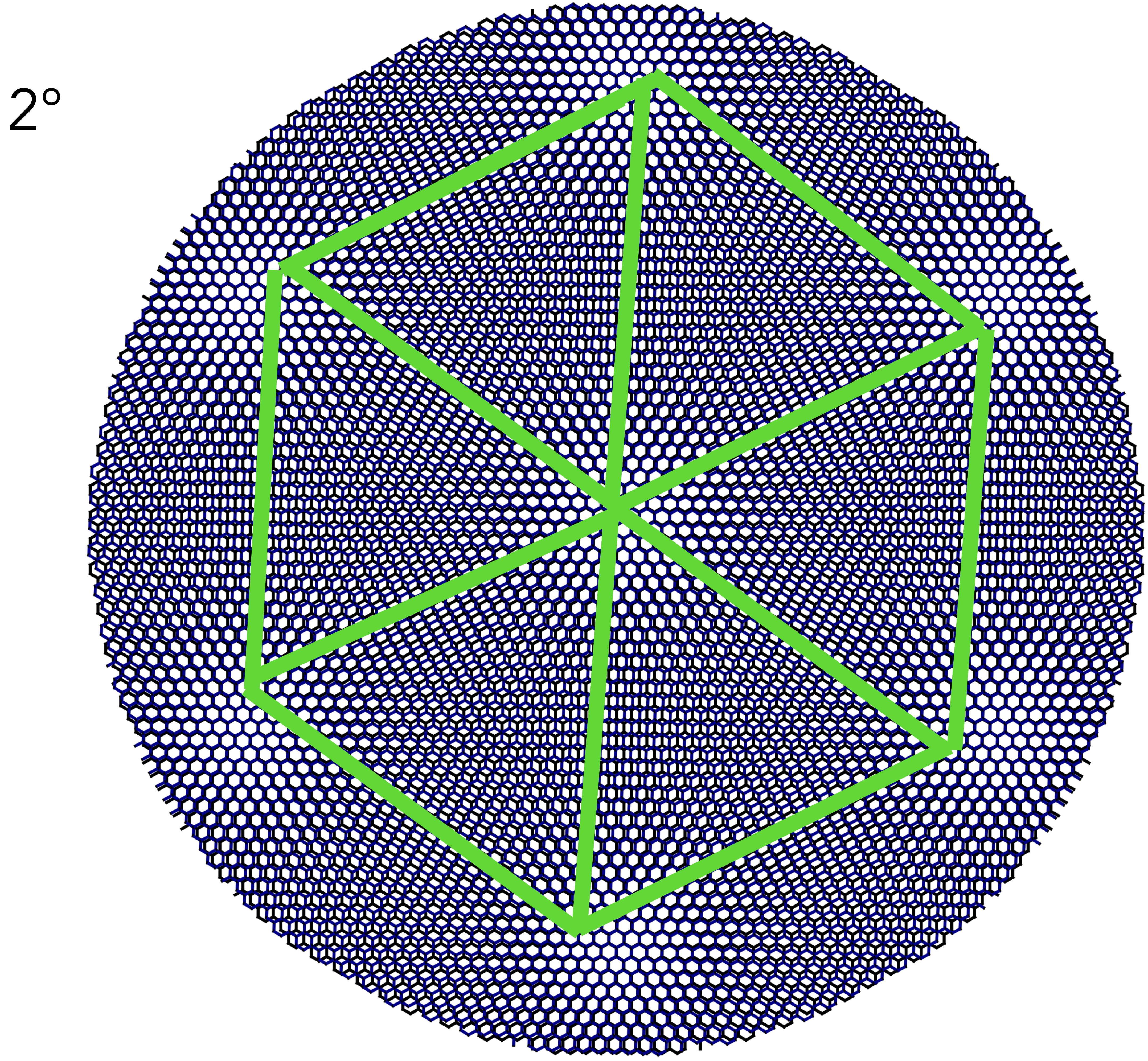


Moiré pattern

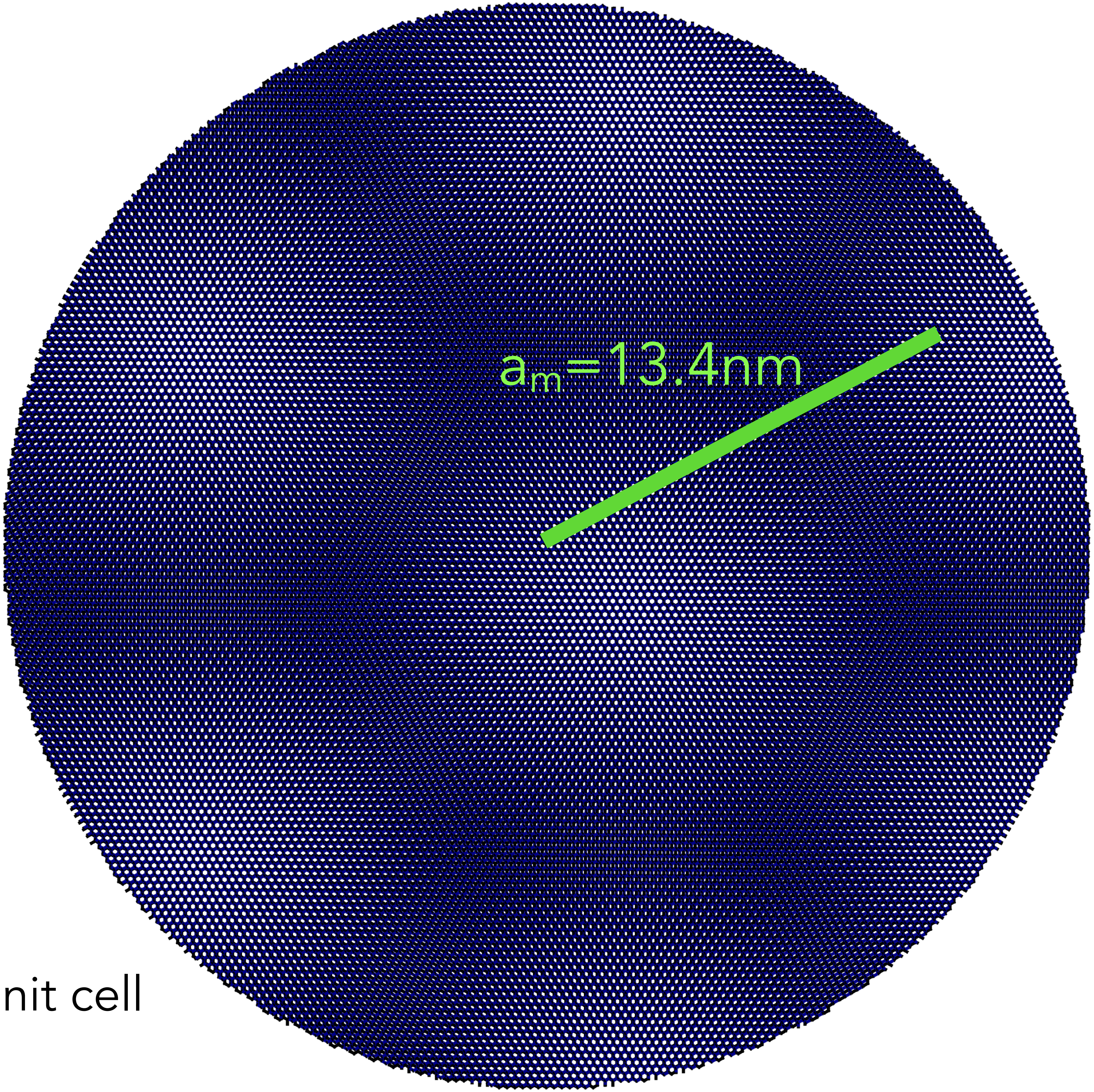
6°




6°
Triangular lattice

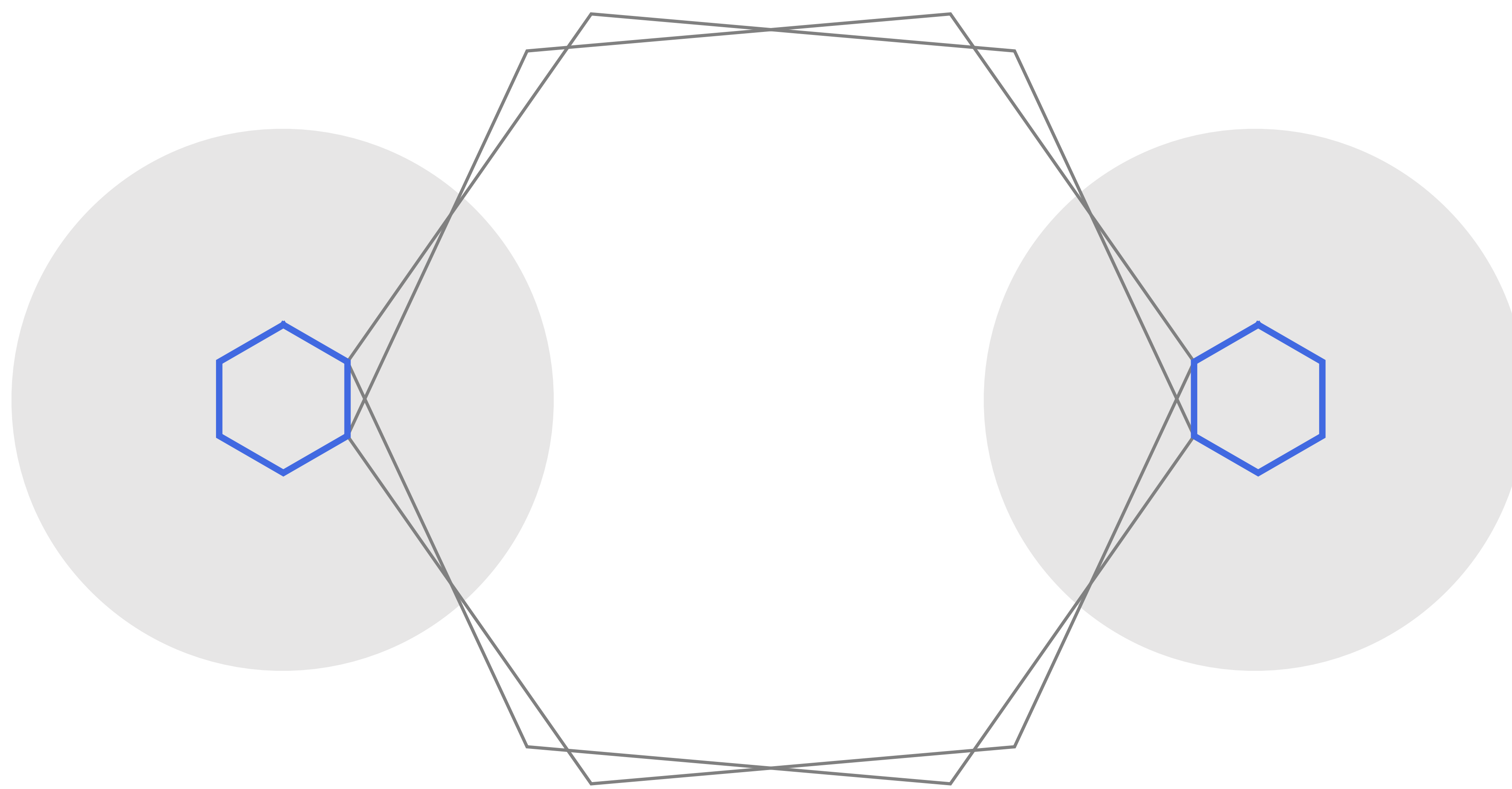

2°

1°



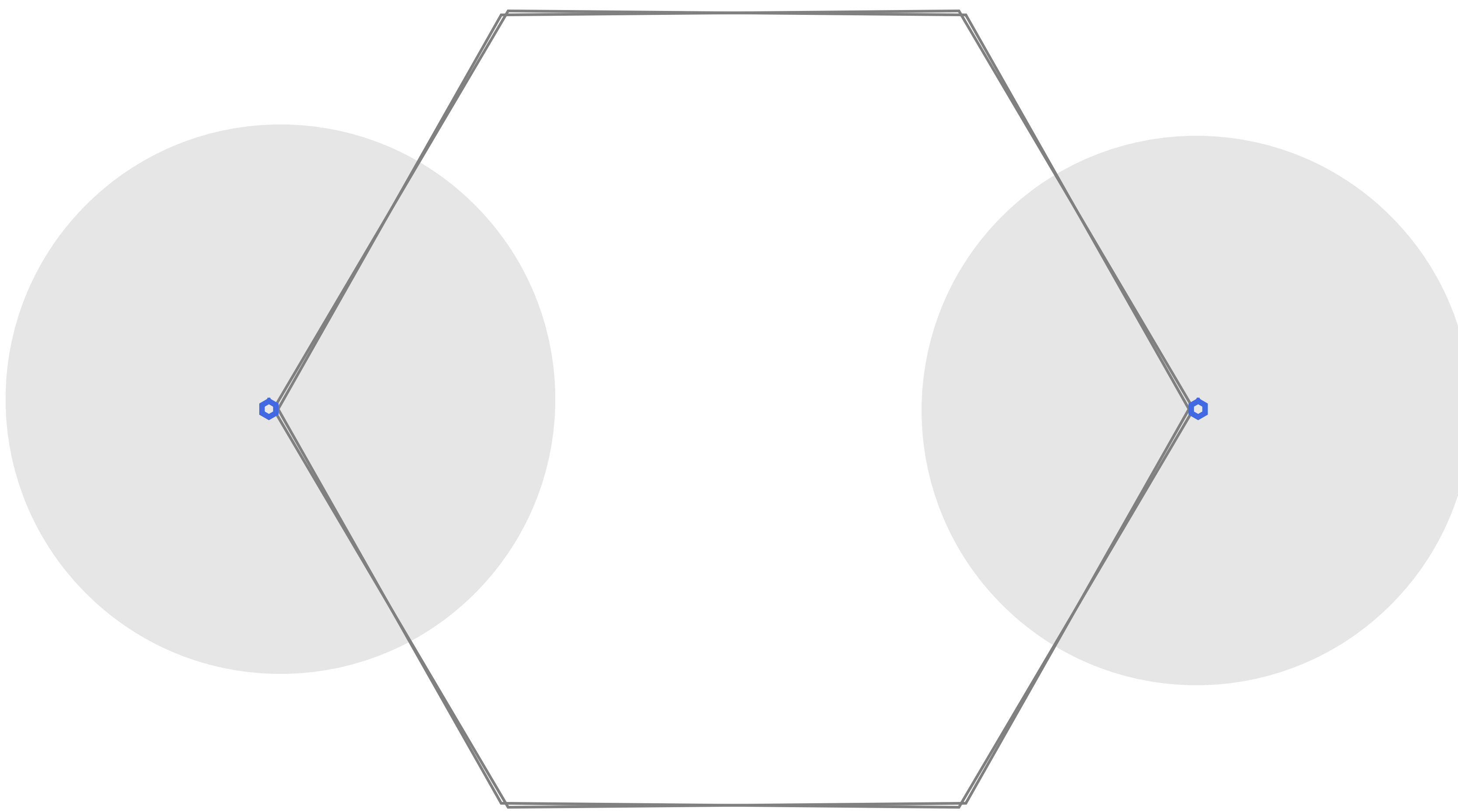
huge unit cell

Continuum model



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

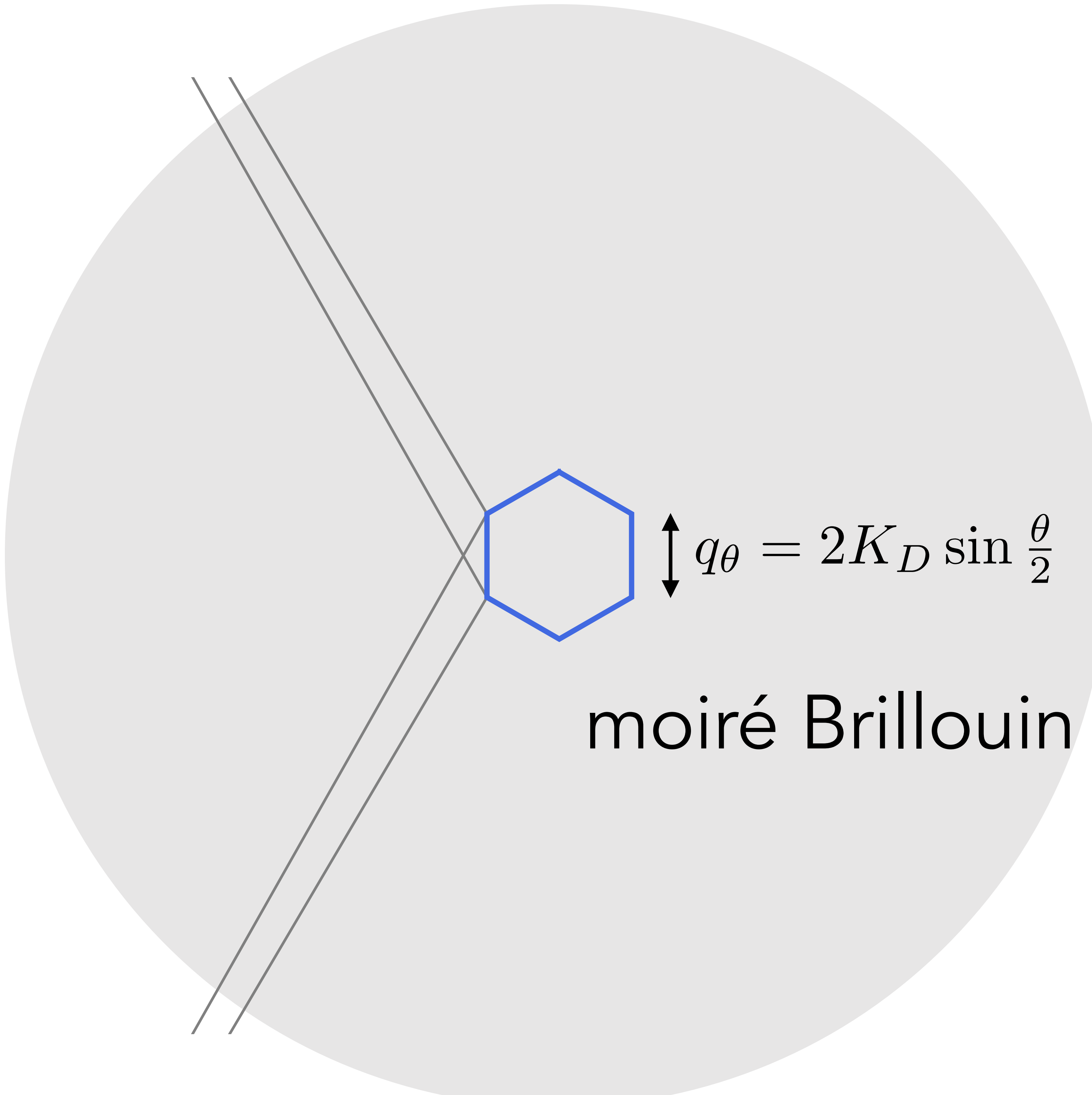
Continuum model



1°

One valley

1°



Continuum model

Bistritzer+MacDonald (2011)

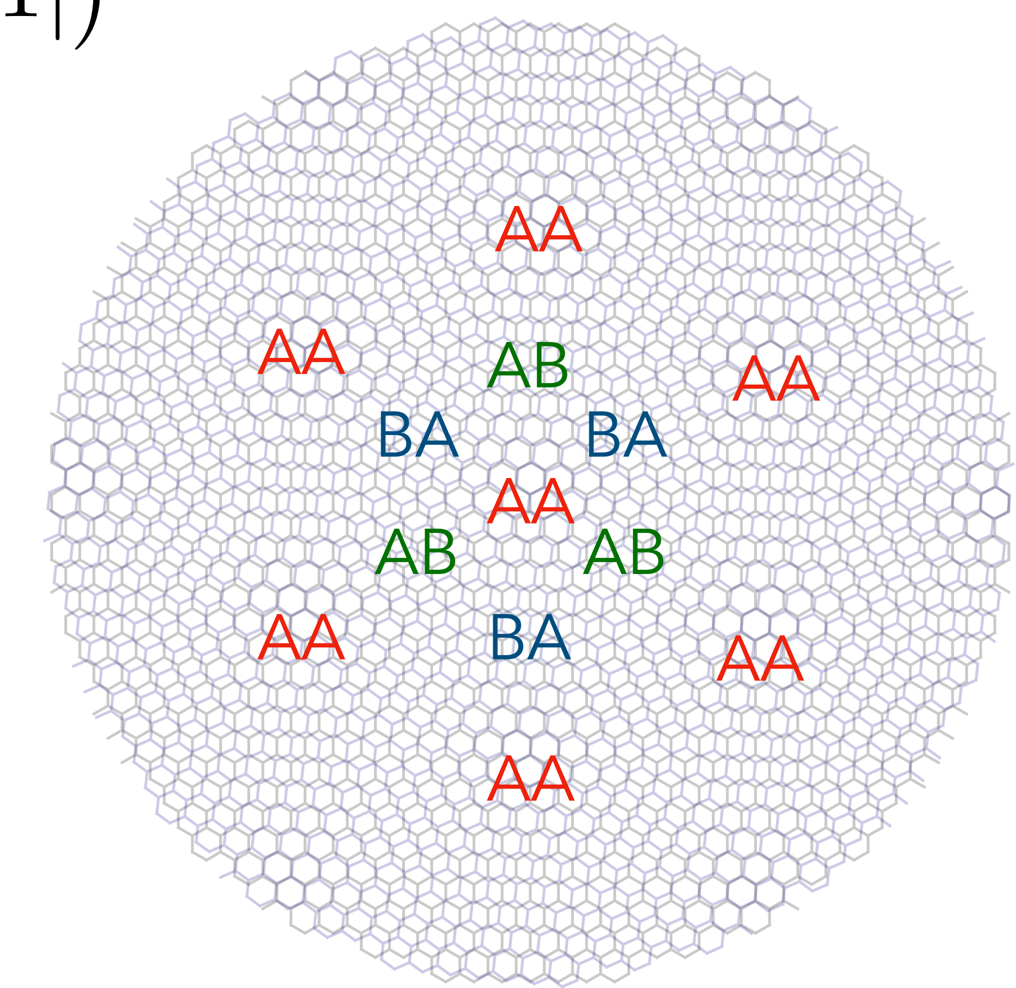
$$H = H_{\rm kin} + H_{\rm tun}$$

$$H_{\rm kin} = v(\boldsymbol{k} - \boldsymbol{K}_1) \cdot \boldsymbol{\sigma}_{\theta/2}|1\rangle\langle 1| + v(\boldsymbol{k} - \boldsymbol{K}_2) \cdot \boldsymbol{\sigma}_{-\theta/2}|2\rangle\langle 2|$$

$$H_{\rm tun} = w\left(\mathsf{T}(\boldsymbol{x})|1\rangle\langle 2| + \mathsf{T}^\dagger(\boldsymbol{x})|2\rangle\langle 1|\right)$$

periodic hopping matrix: smoothly interpolates hopping of uniform AA/AB/BA bilayers

- Restores periodicity
- Reveals dimensionless parameter, w/vk_θ
- Predicts flat bands at magic angles



BM Derivation

We derive a continuum model for the tunneling term by assuming that the interlayer tunneling amplitude between π-orbitals is a smooth function $t(r)$ of spatial separation projected onto the graphene planes. The matrix element

$$T^{\alpha\beta}_{\mathbf{kp}'} = \langle \Psi^{(1)}_{\mathbf{k}\alpha} | H_{\mathrm{T}} | \Psi^{(2)}_{\mathbf{p}'\beta} \rangle \qquad \textbf{[1]}$$

of the tunneling Hamiltonian H_{T} describes a process in which an electron with momentum $\mathbf{p}' = M\mathbf{p}$ residing on sublattice β in one layer hops to a momentum state $\mathbf{k}$ and sublattice α in the other layer. In a π-band tight-binding model the projection of the wave functions of the two layers to a given sublattice are

$$|\psi^{(1)}_{\mathbf{k}\alpha}\rangle = \frac{1}{\sqrt{N}} \sum_{\mathbf{R}} e^{i\mathbf{k}(R+\tau_\alpha)} |\mathbf{R} + \tau_\alpha\rangle \qquad \textbf{[2]}$$

and

$$|\psi^{(2)}_{\mathbf{p}\beta}\rangle = \frac{1}{\sqrt{N}} \sum_{\mathbf{R}'} e^{i\mathbf{p}(R'+\tau'_\beta)} |\mathbf{R}' + \tau'_\beta\rangle. \qquad \textbf{[3]}$$

Here $\tau_{\mathrm{A}} = 0$, $\tau_{\mathrm{B}} = \tau$, and $\mathbf{R}$ is summed over the triangular Bravais lattice. Substituting Eqs. **2** and **3** in Eq. **1** and invoking the two-center approximation,

$$\langle \mathbf{R} + \tau_\alpha | H_{\mathrm{T}} | \mathbf{R}' + \tau'_\beta \rangle = t(\mathbf{R} + \tau_\alpha - \mathbf{R}' - \tau'_\beta), \qquad \textbf{[4]}$$

for the interlayer hopping amplitude in which t depends on the difference between the positions of the two carbon atoms we find that

$$T^{\alpha\beta}_{\mathbf{kp}'} = \sum_{\mathbf{G}_1\mathbf{G}_2} \frac{t_{\bar{\mathbf{k}}+\mathbf{G}_1}}{\Omega} e^{i[\mathbf{G}_1\tau_\alpha - \mathbf{G}_2(\tau_\beta - \tau) - \mathbf{G}'_2\mathbf{d}]} \delta_{\bar{\mathbf{k}}+\mathbf{G}_1, \bar{\mathbf{p}}'+\mathbf{G}'_2}. \qquad \textbf{[5]}$$

Here Ω is the unit cell area, $t_{\mathbf{q}}$ is the Fourier transform of the tunneling amplitude $t(\mathbf{r})$, the vectors $\mathbf{G_1}$ and $\mathbf{G_2}$ are summed over reciprocal lattice vectors, and $\mathbf{G}'_2 = M\mathbf{G_2}$. The bar notation over momenta in Eq. **5** indicates that momentum is measured relative to the center of the Brillouin zone and not relative to the Dirac point. Note that crystal momentum is conserved by the tunneling process because t depends only on the difference between lattice positions.*

Directly calculate overlap of every C orbital in layer 1 with every C orbital in layer 2

Assume rigid rotation of layers

Obtain hopping matrix in momentum space by Poisson resummation formula

At the end of the calculation Fourier transform back to obtain simple real space formula

Effective field theory

Describes low energy, long wavelength physics, can include effects of any perturbations that are small and slowly varying

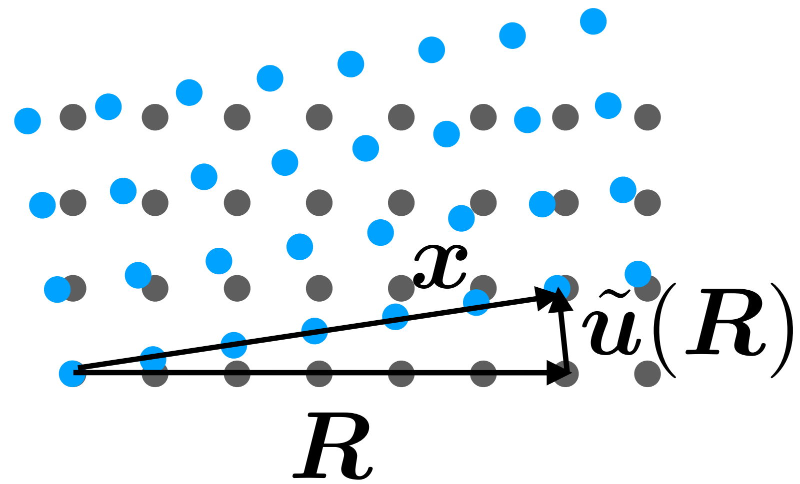
Here:

- Unperturbed system: isolated graphene layers
- Perturbations:
  - Interlayer tunneling
  - Slowly varying displacements of the layers

Rotation ⊂ Displacement Gradient

Ashcroft-Mermin: phonons

$$\boldsymbol{x} = \boldsymbol{R} + \tilde{\boldsymbol{u}}(\boldsymbol{R})$$



Rotation

$$\theta = \frac{1}{2}\left(\partial_x u_y - \partial_y u_x\right) \qquad \tilde{\boldsymbol{u}} = \theta \hat{\boldsymbol{z}} \times \boldsymbol{R}$$

Twisting is just a subset of elastic deformations of two layers

Effective field theory

Locality:

$$H = \int d^2x\, \mathcal{H}[\psi, \boldsymbol{u}, w]$$

Hamiltonian density is a *local* functional of the fields, *analytic*, and expandable in powers of small parameters — here field gradients and hopping strength

Effective field theory

Locality:

$$H = \int d^2x\, \mathcal{H}[\psi, \boldsymbol{u}, w]$$

Hamiltonian density is a ***local*** functional of the fields, *analytic*, and expandable in powers of small parameters — here field gradients and hopping strength

Small problem:

$$\boldsymbol{x} = \boldsymbol{R} + \tilde{\boldsymbol{u}}(\boldsymbol{R})$$

R is not the actual real space location - physics is local in **x** not **R**

Effective field theory

Locality:

$$H = \int d^2x \, \mathcal{H}[\psi, \boldsymbol{u}, w]$$

Hamiltonian density is a ***local*** functional of the fields, *analytic*, and expandable in powers of small parameters — here field gradients and hopping strength

Solution: Eulerian coordinates

$$\boldsymbol{x} = \boldsymbol{R} + \boldsymbol{u}(\boldsymbol{x})$$

Effective field theory

- Three effects:

  1. Coordinate change: transformation of local frames to global one

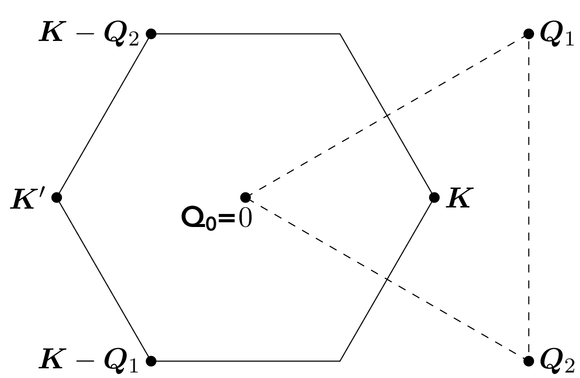
  2. Strains: modification of energetics of each layer due to changes in electron hopping

  3. Tunneling: strong dependence of relative *local* alignment

Result

$$\mathcal{H} = \sum_l \psi_l^\dagger \left[-iv \left(\tau^\mu + \frac{\partial u_{l,\mu}}{\partial x_\nu} \tau^\nu \right) \frac{\partial}{\partial x_\mu} + v \left(\boldsymbol{K} \cdot \partial_\mu \boldsymbol{u}_l + \boldsymbol{\mathcal{A}}_l \right) \tau^\mu \right] \psi_l$$

$$+ \sum_j \left[e^{-i\boldsymbol{Q}_j \cdot (\boldsymbol{u}_1 - \boldsymbol{u}_2)} \psi_2^\dagger \mathsf{T}_j \psi_1 + \text{h.c.} \right]$$



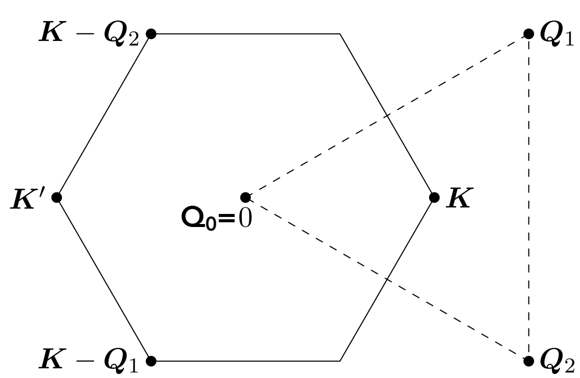
Correct to first order in strain gradients and hopping

Result

coordinate change

$$\mathcal{H} = \sum_l \psi_l^\dagger \left[-iv \left(\tau^\mu + \frac{\partial u_{l,\mu}}{\partial x_\nu} \tau^\nu \right) \frac{\partial}{\partial x_\mu} + v \left(\boldsymbol{K} \cdot \partial_\mu \boldsymbol{u}_l + \boldsymbol{\mathcal{A}}_l \right) \tau^\mu \right] \psi_l$$

$$+ \sum_j \left[e^{-i\boldsymbol{Q}_j \cdot (\boldsymbol{u}_1 - \boldsymbol{u}_2)} \psi_2^\dagger \mathsf{T}_j \psi_1 + \text{h.c.} \right]$$



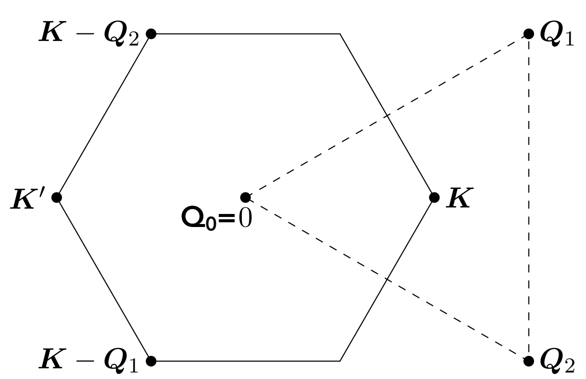
Correct to first order in strain gradients and hopping

Result

Strain gauge field

$$\mathcal{H} = \sum_l \psi_l^\dagger \left[-iv \left(\tau^\mu + \frac{\partial u_{l,\mu}}{\partial x_\nu} \tau^\nu \right) \frac{\partial}{\partial x_\mu} + v \left(\boldsymbol{K} \cdot \partial_\mu \boldsymbol{u}_l + \boldsymbol{\mathcal{A}}_l \right) \tau^\mu \right] \psi_l$$

$$+ \sum_j \left[e^{-i\boldsymbol{Q}_j \cdot (\boldsymbol{u}_1 - \boldsymbol{u}_2)} \psi_2^\dagger \mathsf{T}_j \psi_1 + \mathrm{h.c.} \right]$$



Correct to first order in strain gradients and hopping

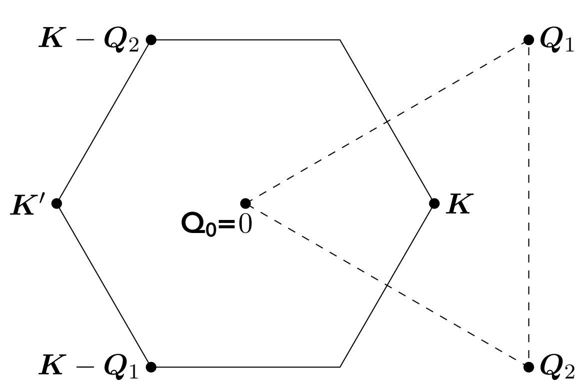
Result

$$\mathcal{H} = \sum_l \psi_l^\dagger \left[-iv \left(\tau^\mu + \frac{\partial u_{l,\mu}}{\partial x_\nu} \tau^\nu \right) \frac{\partial}{\partial x_\mu} + v \left(\boldsymbol{K} \cdot \partial_\mu \boldsymbol{u}_l + \boldsymbol{\mathcal{A}}_l \right) \tau^\mu \right] \psi_l$$

$$+ \sum_j \left[e^{-i\boldsymbol{Q}_j \cdot (\boldsymbol{u}_1 - \boldsymbol{u}_2)} \psi_2^\dagger \, \mathsf{T}_j \psi_1 + \text{h.c.} \right]$$

← tunneling. Form fixed by space group symmetries

$$\mathsf{T}_j = u\,\mathbb{I} + w\left(\bar{\zeta}^j \tau^+ + \zeta^j \tau^- \right), \qquad j = 0, 1, 2,$$



Correct to first order in strain gradients and hopping

Apply to rigid twist

$$\mathcal{H} = \sum_l \psi_l^\dagger \left[-iv \left(\tau^\mu + \frac{\partial u_{l,\mu}}{\partial x_\nu} \tau^\nu \right) \frac{\partial}{\partial x_\mu} + v \left(\boldsymbol{K} \cdot \partial_\mu \boldsymbol{u}_l + \boldsymbol{\mathcal{A}}_l \right) \tau^\mu \right] \psi_l$$

$$+ \sum_j \left[e^{-i\boldsymbol{Q}_j \cdot (\boldsymbol{u}_1 - \boldsymbol{u}_2)} \psi_2^\dagger \mathsf{T}_j \psi_1 + \text{h.c.} \right]$$

Evaluate for $\boldsymbol{u}_1 = -\boldsymbol{u}_2 = \frac{\theta}{2} \hat{\boldsymbol{z}} \times \boldsymbol{x}.$

$$\mathcal{H} = \psi_1^\dagger \left[-iv\boldsymbol{\tau}(\tfrac{\theta}{2}) \cdot \boldsymbol{\nabla} - \frac{vk_\theta}{2} \tau^y \right] \psi_1 + \psi_2^\dagger \left[-iv\boldsymbol{\tau}(-\tfrac{\theta}{2}) \cdot \boldsymbol{\nabla} + \frac{vk_\theta}{2} \tau^y \right] \psi_2$$

$$+ \sum_j \left[e^{-i\boldsymbol{q}_j \cdot \boldsymbol{x}} \psi_2^\dagger \mathsf{T}_j \psi_1 + \text{h.c.} \right] \qquad \boldsymbol{q}_j = -\theta \hat{\boldsymbol{z}} \times \boldsymbol{Q}_j$$

Exactly the BM model.

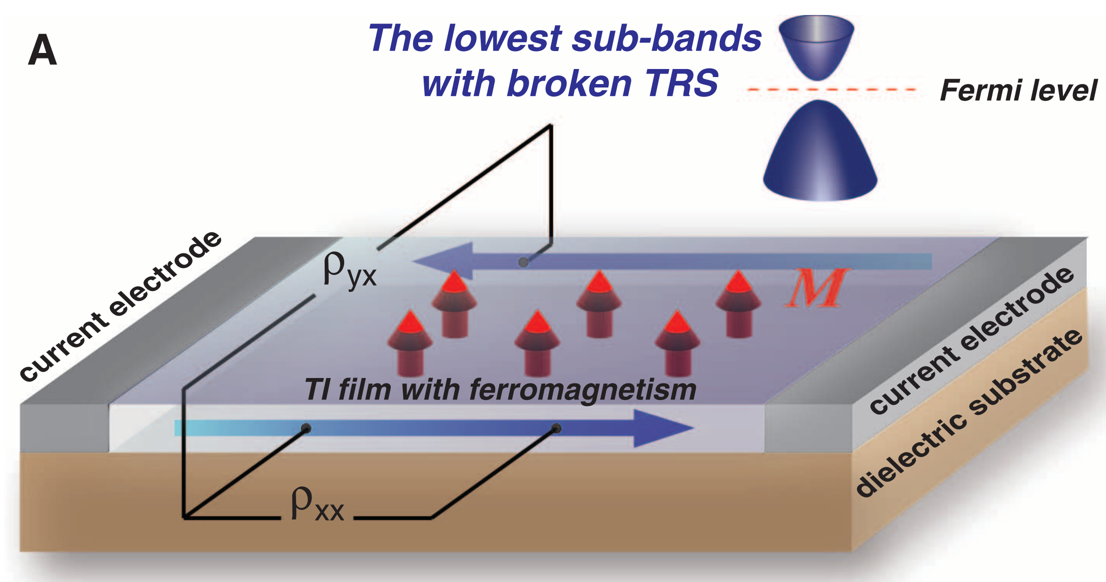
Result

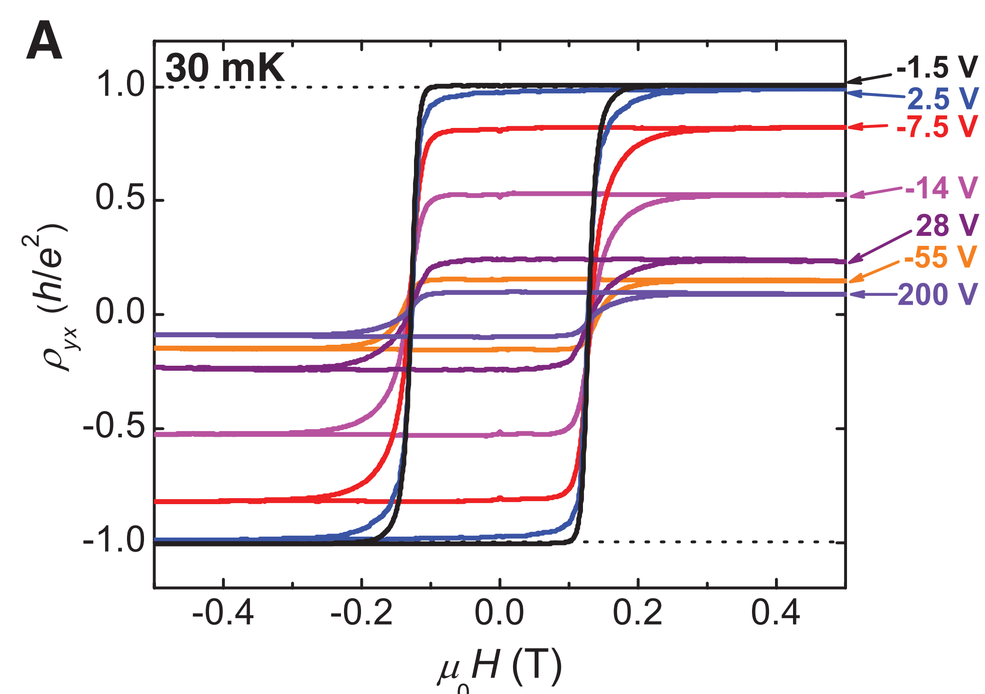
$$\mathcal{H} = \sum_l \psi_l^\dagger \left[-iv \left(\tau^\mu + \frac{\partial u_{l,\mu}}{\partial x_\nu} \tau^\nu \right) \frac{\partial}{\partial x_\mu} + v \left(\boldsymbol{K} \cdot \partial_\mu \boldsymbol{u}_l + \boldsymbol{\mathcal{A}}_l \right) \tau^\mu \right] \psi_l$$
$$+ \sum_j \left[e^{-i\boldsymbol{Q}_j \cdot (\boldsymbol{u}_1 - \boldsymbol{u}_2)} \psi_2^\dagger \mathsf{T}_j \psi_1 + \text{h.c.} \right]$$

- Recovers BM result intuitively
- Subsumes other extensions of BM (Nam+Koshino, Bi,Yuan+Fu…)
- Includes coupling of acoustic phonons
- Can handle arbitrary inhomogeneous strains
- All these things together
- Easy to add more layers
- Very nice for teaching

Quantum Anomalous Hall Effect

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



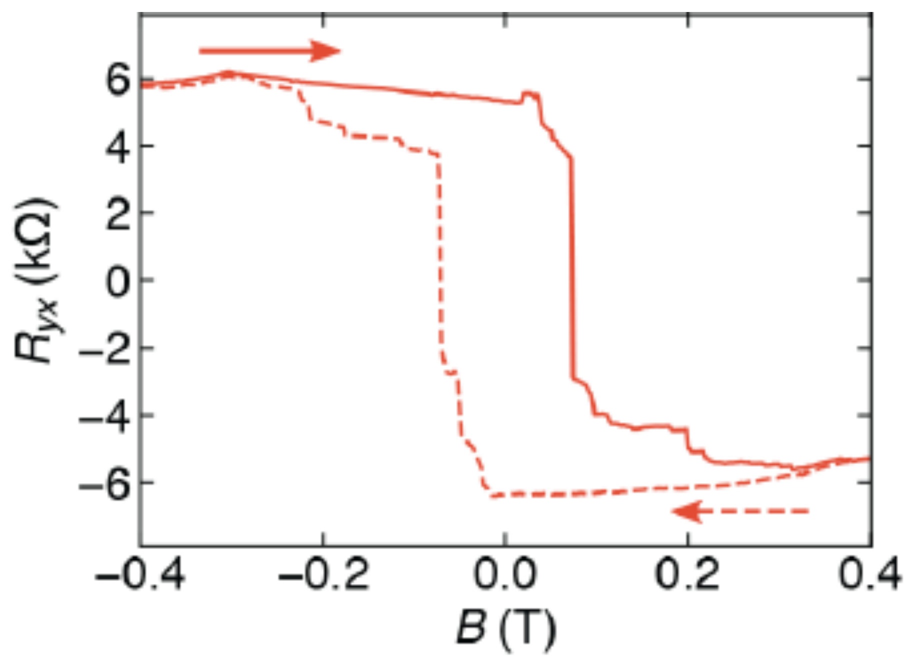


C.-Z. Zhang *et al*, 2013

Cr-doped $(Bi/Sb)_2Te_3$

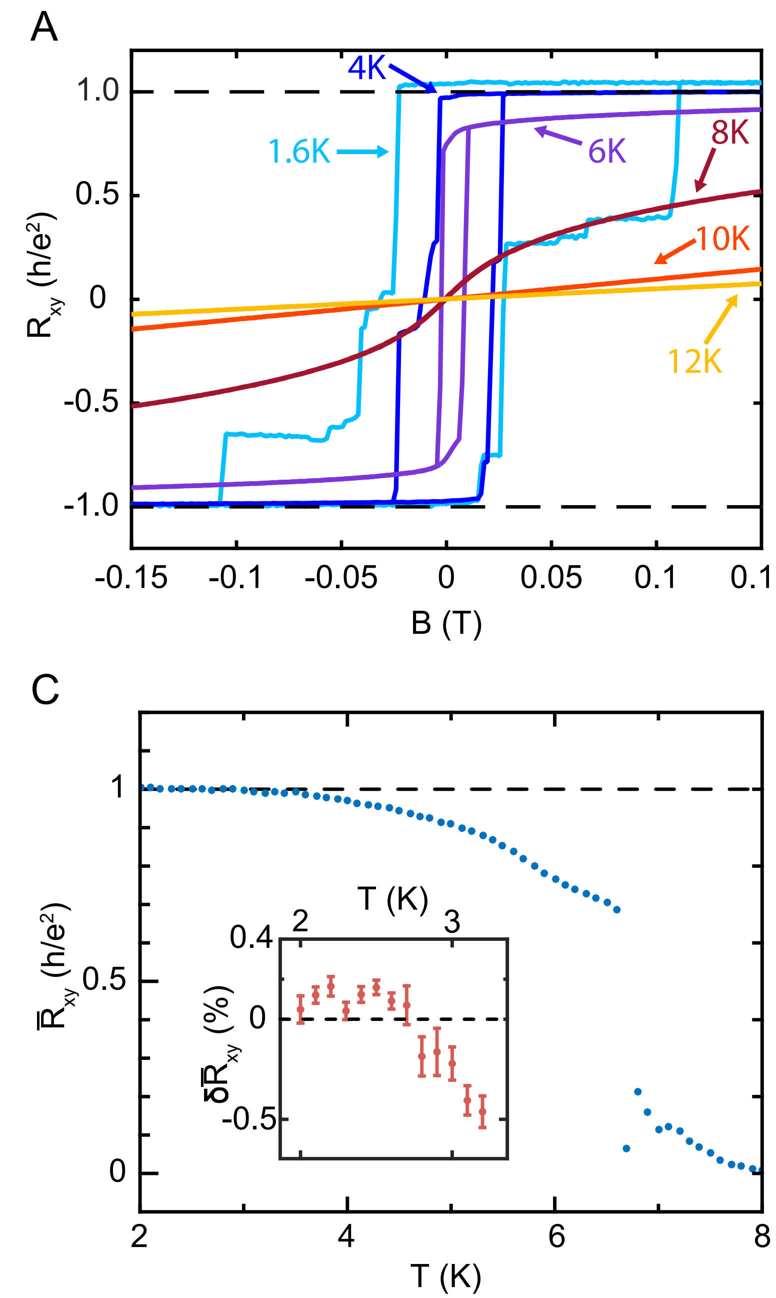
QAHE in TBG

3 e-'s per moiré unit cell



A. Sharpe, et. al. ***Science (2019)****;*

Spontaneous AHE - not quite quantized

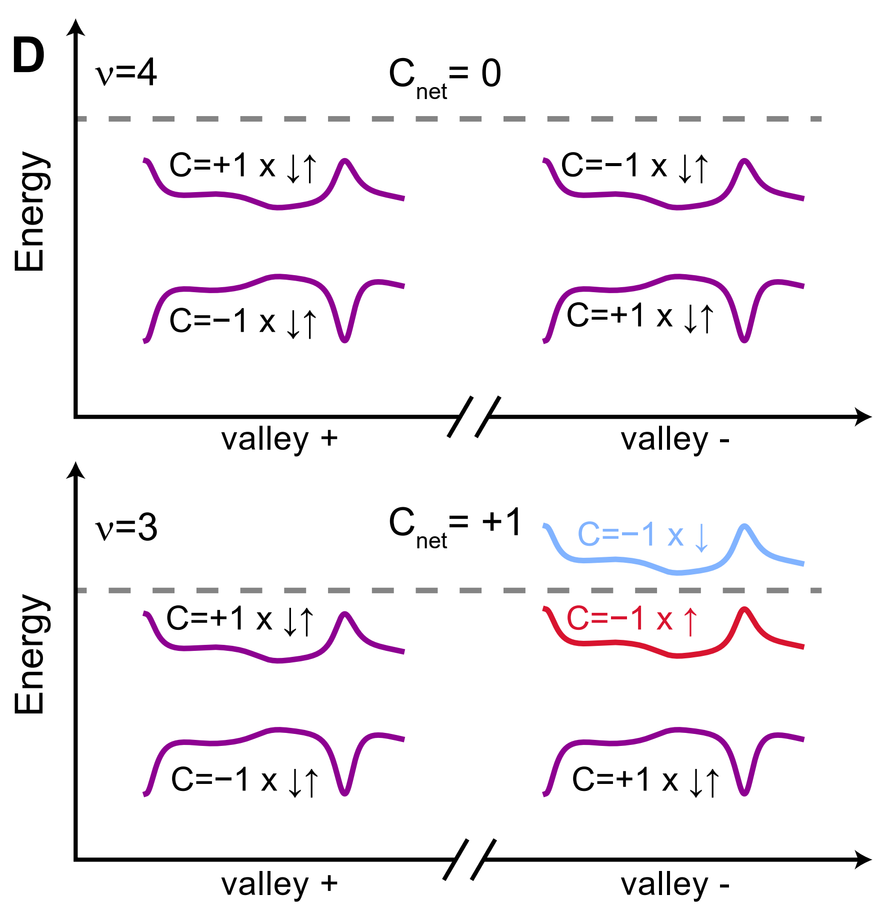


M. Serlin *et al*, unpublished

QAHE to 1/1000 accuracy

Theoretical remarks

- Underlying Dirac fermions of graphene have large incipient Berry curvature
- Curvature is realized by breaking C_2T symmetry
- Valley polarization gives non-zero AHE.
- Quantization occurs if gap is complete - needs spin polarization



Spin and valley split

Symmetry breaking =
Z_2 (valley)
x
SU(2) (spin)

If you have any more questions…

1. arXiv:1907.06282 [pdf, other] cond-mat.str-el cond-mat.mes-hall
   Derivation of Wannier orbitals and minimal-basis tight-binding hamiltonians for twisted bilayer graphene: a first-principles approach
   Authors: Stephen Carr, Shiang Fang, Hoi Chun Po, Ashvin Vishwanath, Efthimios Kaxiras
   Abstract: Twisted bilayer graphene (TBLG) has emerged as an important platform for studying correlated phenomena, including unconventional superconductivity, in two-dimensional systems. The complexity of the atomic-scale structures in TBLG has made even the study of single-particle physics at low energies around the Fermi level, quite challenging. Our goal here is to provide a convenient and physically moti… ▽ More
   Submitted 14 July, 2019; **originally announced** July 2019.
   Comments: 12 pages, 5 figures, 1 table

2. arXiv:1905.07409 [pdf, other] cond-mat.str-el cond-mat.mes-hall
   Nematic topological semimetal and insulator in magic angle bilayer graphene at charge neutrality
   Authors: Shang Liu, Eslam Khalaf, Jong Yeon Lee, Ashvin Vishwanath
   Abstract: We report on a fully self-consistent momentum space Hartree-Fock calculation of interaction effects on the Moiré flat bands of twisted bilayer graphene, tuned near the magic angle. We focus on the charge neutrality point, where experiments have variously reported either insulating or semimetallic behavior. We find three types of self-consistent solutions with competitive ground state energy (i) in… ▽ More
   Submitted 17 May, 2019; **originally announced** May 2019.
   Comments: 5 pages, 4 figures

3. arXiv:1903.08685 [pdf, other] cond-mat.str-el cond-mat.supr-con
   Theory of correlated insulating behaviour and spin-triplet superconductivity in twisted double bilayer graphene
   Authors: Jong Yeon Lee, Eslam Khalaf, Shang Liu, Xiaomeng Liu, Zeyu Hao, Philip Kim, Ashvin Vishwanath
   Abstract: Two monolayers of graphene twisted by a small `magic' angle exhibit nearly flat bands leading to correlated electronic states and superconductivity, whose precise nature including possible broken symmetries, remain under debate. Here we theoretically study a related but different system with reduced symmetry - twisted {\em double} bilayer graphene (TDBLG), consisting of {\em two} Bernal stacked bi… ▽ More
   Submitted 3 September, 2019; **v1** submitted 20 March, 2019; **originally announced** March 2019.
   Comments: main 15 pages, appendix 11 pages

4. arXiv:1903.08130 [pdf, other] cond-mat.mes-hall cond-mat.str-el cond-mat.supr-con
   Spin-polarized Correlated Insulator and Superconductor in Twisted Double Bilayer Graphene
   Authors: Xiaomeng Liu, Zeyu Hao, Eslam Khalaf, Jong Yeon Lee, Kenji Watanabe, Takashi Taniguchi, Ashvin Vishwanath, Philip Kim
   Abstract: Ferromagnetism and superconductivity typically compete with each other since the internal magnetic field generated in a magnet suppresses the formation of spin-singlet Cooper pairs in conventional superconductors. Only a handful of ferromagnetic superconductors are known in heavy fermion systems, where many-body electron interactions promoted by the narrow energy bands play a key role in stabilizi… ▽ More
   Submitted 25 March, 2019; **v1** submitted 19 March, 2019; **originally announced** March 2019.
   Comments: 13 pages, 3 figures and supplementary information

5. arXiv:1901.10485 [pdf, other] cond-mat.str-el cond-mat.mes-hall doi 10.1103/PhysRevB.100.085109
   Magic Angle Hierarchy in Twisted Graphene Multilayers
   Authors: Eslam Khalaf, Alex J. Kruchkov, Grigory Tarnopolsky, Ashvin Vishwanath
   Abstract: When two monolayers of graphene are stacked with a small relative twist angle, the resulting band structure exhibits a remarkably flat pair of bands at a sequence of 'magic angles' where correlation effects can induce a host of exotic phases. Here, we study a class of related models of n-layered graphene with alternating relative twist angle $\pm\theta$ which exhibit magic angle flat bands coexistin… ▽ More
   Submitted 12 August, 2019; **v1** submitted 29 January, 2019; **originally announced** January 2019.
   Comments: 5.5 pages, 6 figures; published version
   Journal ref: Phys. Rev. B 100, 085109 (2019)

6. arXiv:1808.05250 [pdf, ps, other] cond-mat.str-el cond-mat.mes-hall doi 10.1103/PhysRevLett.122.106405
   Origin of Magic Angles in Twisted Bilayer Graphene
   Authors: Grigory Tarnopolsky, Alex J. Kruchkov, Ashvin Vishwanath
   Abstract: Twisted Bilayer graphene (TBG) is known to feature isolated and relatively flat bands near charge neutrality, when tuned to special magic angles. However, different criteria for the magic angle such as the vanishing of Dirac speed, minimal bandwidth or maximal band gap to higher bands typically give different results. Here we study a modified continuum model for TBG which has an infinite sequence… ▽ More
   Submitted 15 August, 2018; **originally announced** August 2018.
   Comments: 7 pages, 4 figures
   Journal ref: Phys. Rev. Lett. 122, 106405 (2019)

7. arXiv:1808.02482 [pdf, other] cond-mat.str-el cond-mat.mtrl-sci cond-mat.supr-con doi 10.1103/PhysRevB.99.195455
   Faithful Tight-binding Models and Fragile Topology of Magic-angle Bilayer Graphene
   Authors: Hoi Chun Po, Liujun Zou, T. Senthil, Ashvin Vishwanath
   Abstract: Correlated insulators and superconductivity have been observed in "magic-angle" twisted bilayer graphene, when the nearly flat bands close to neutrality are partially filled. While a momentum-space continuum model accurately describes these flat bands, interaction effects are more conveniently incorporated in tight-binding models. We have previously shown that no fully symmetric tight-binding mode… ▽ More
   Submitted 2 June, 2019; **v1** submitted 7 August, 2018; **originally announced** August 2018.
   Comments: (9+10) pages, (6+5) figures, (3+4) tables; v3: close to published version
   Journal ref: Phys. Rev. B 99, 195455 (2019)

8. arXiv:1806.07873 [pdf, other] cond-mat.str-el cond-mat.mes-hall cond-mat.mtrl-sci doi 10.1103/PhysRevB.98.085435
   Band Structure of Twisted Bilayer Graphene: Emergent Symmetries, Commensurate Approximants and Wannier Obstructions
   Authors: Liujun Zou, Hoi Chun Po, Ashvin Vishwanath, T. Senthil
   Abstract: A remarkable feature of the band structure of bilayer graphene at small twist angle is the appearance of isolated bands near neutrality, whose bandwidth can be reduced at certain magic angles (eg. $\theta \sim 1.05^\circ$). In this regime, correlated insulating states and superconductivity have been experimentally observed. A microscopic description of these phenomena requires an understanding of univer… ▽ More
   Submitted 29 August, 2018; **v1** submitted 20 June, 2018; **originally announced** June 2018.
   Comments: 14 pages + appendices; v3: published version
   Journal ref: Phys. Rev. B 98, 085435 (2018)

9. arXiv:1805.06867 [pdf, other] cond-mat.str-el cond-mat.supr-con
   Superconductivity from Valley Fluctuations and Approximate SO(4) Symmetry in a Weak Coupling Theory of Twisted Bilayer Graphene
   Authors: Yi-Zhuang You, Ashvin Vishwanath
   Abstract: We develop a weak coupling approach to superconductivity in twisted bilayer graphene, starting from the Fermi liquid regime. A key observation is that near half filling, the fermiology consists of well nested Fermi pockets derived from opposite valleys, leading to enhanced valley fluctuation, which in turn can mediate superconductivity. This scenario is studied within the random phase approximatio… ▽ More
   Submitted 29 March, 2019; **v1** submitted 17 May, 2018; **originally announced** May 2018.
   Comments: 13 pages, 8 figures, 3 tables

10. arXiv:1803.09742 [pdf, other] cond-mat.str-el cond-mat.mtrl-sci cond-mat.supr-con doi 10.1103/PhysRevX.8.031089
   Origin of Mott insulating behavior and superconductivity in twisted bilayer graphene
   Authors: Hoi Chun Po, Liujun Zou, Ashvin Vishwanath, T. Senthil
   Abstract: A remarkable recent experiment has observed Mott insulator and proximate superconductor phases in twisted bilayer graphene when electrons partly fill a nearly flat mini-band that arises a `magic' twist angle. However, the nature of the Mott insulator, origin of superconductivity and an effective low energy model remain to be determined. We propose a Mott insulator with intervalley coherence that s… ▽ More
   Submitted 22 May, 2018; **v1** submitted 26 March, 2018; **originally announced** March 2018.
   Comments: Main text (17 pages, 4 figures, 1 table) + Appendices; v2: Schematic (Fig. 1) updated; typos fixed and notational consistency improved
   Journal ref: Phys. Rev. X 8, 031089 (2018)

1. arXiv:1905.06535 [pdf] cond-mat.mes-hall cond-mat.mtrl-sci cond-mat.str-el
   Tunable Correlated Chern Insulator and Ferromagnetism in Trilayer Graphene/Boron Nitride Moiré Superlattice
   Authors: Guorui Chen, Aaron L. Sharpe, Eli J. Fox, Ya-Hui Zhang, Shaoxin Wang, Lili Jiang, Bosai Lyu, Hongyuan Li, Kenji Watanabe, Takashi Taniguchi, Zhiwen Shi, T. Senthil, David Goldhaber-Gordon, Yuanbo Zhang, Feng Wang
   Abstract: Studies on two-dimensional electron systems in a strong magnetic field first revealed the quantum Hall (QH) effect, a topological state of matter featuring a finite Chern number (C) and chiral edge states. Haldane later theorized that Chern insulators with integer QH effects could appear in lattice models with complex hopping parameters even at zero magnetic field. The ABC-trilayer graphene/hexago… ▽ More
   Submitted 16 May, 2019; **originally announced** May 2019.
   Comments: 16 pages, 4 figures, and 2 extended figures

2. arXiv:1904.10452 [pdf, other] cond-mat.str-el cond-mat.mes-hall cond-mat.supr-con doi 10.1103/PhysRevB.100.125104
   Landau Level Degeneracy in Twisted Bilayer Graphene: Role of Symmetry Breaking
   Authors: Ya-Hui Zhang, Hoi Chun Po, T. Senthil
   Abstract: The degeneracy of Landau levels flanking charge neutrality in twisted bilayer graphene is known to change from eight-fold to four-fold when the twist angle is reduced to values near the magic angle of $\approx 1.05^\circ$. This degeneracy lifting has been reproduced in experiments by multiple groups, and is known to occur even in devices which do not harbor the correlated insulators and supercondu… ▽ More
   Submitted 23 April, 2019; **originally announced** April 2019.
   Comments: 12 pages, 10 figures
   Journal ref: Phys. Rev. B 100, 125104 (2019)

3. arXiv:1901.08209 [pdf, other] cond-mat.str-el
   Twisted Bilayer Graphene Aligned with Hexagonal Boron Nitride: Anomalous Hall Effect and a Lattice Model
   Authors: Ya-Hui Zhang, Dan Mao, T. Senthil
   Abstract: A recent experiment reported a large anomalous Hall effect in Magic Angle Twisted Bilayer Graphene (TBG) aligned with a hexagonal boron nitride(h-BN) substrate at $\frac{3}{4}$ filling of the conduction band. In this paper we study this system theoretically, and propose explanations of this observation. We emphasize that the physics for this new system is qualitatively different from the pure TBG… ▽ More
   Submitted 23 January, 2019; **originally announced** January 2019.
   Comments: 5 pages, 2 figures + appendix

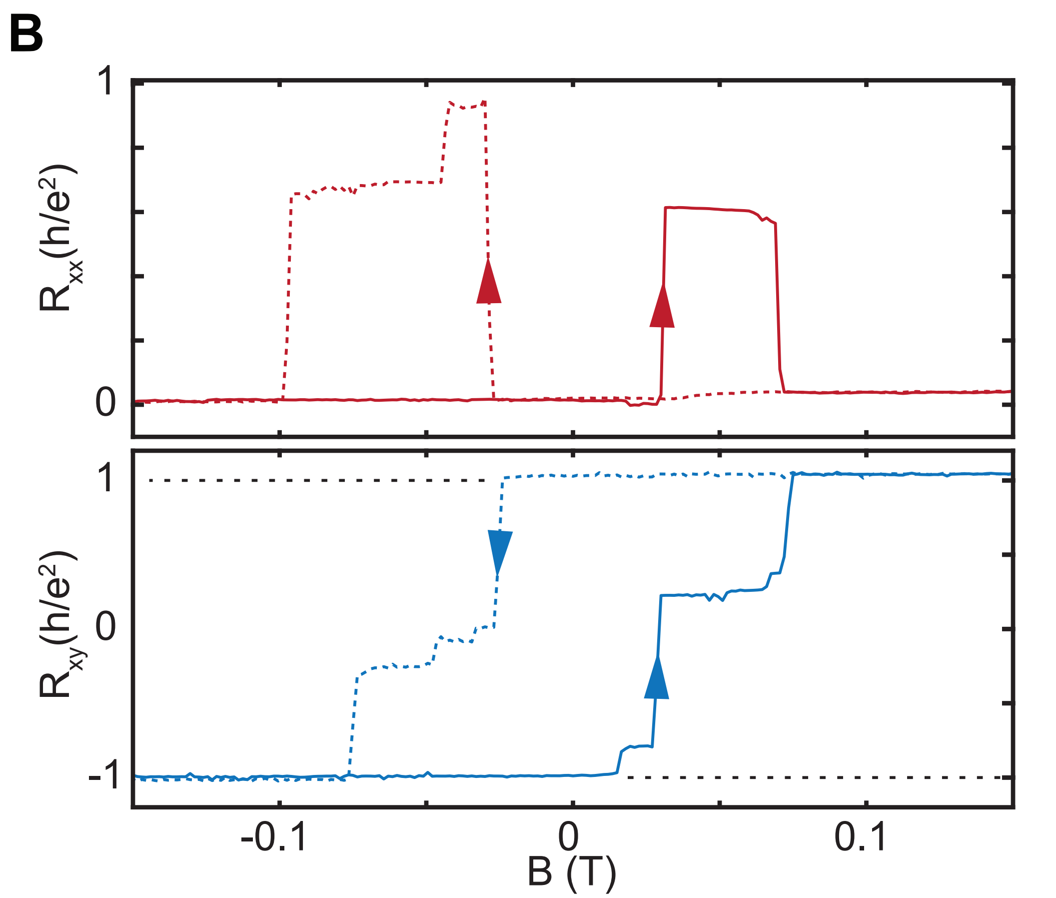
4. arXiv:1901.03710 [pdf, other] cond-mat.str-el cond-mat.mes-hall cond-mat.supr-con
   Strange metal in magic-angle graphene with near Planckian dissipation
   Authors: Yuan Cao, Debanjan Chowdhury, Daniel Rodan-Legrain, Oriol Rubies-Bigordà, Kenji Watanabe, Takashi Taniguchi, T. Senthil, Pablo Jarillo-Herrero
   Abstract: Recent experiments on magic-angle twisted bilayer graphene have discovered correlated insulating behavior and superconductivity at a fractional filling of an isolated narrow band. In this paper we show that magic-angle bilayer graphene exhibits another hallmark of strongly correlated systems --- a broad regime of $T-$linear resistivity above a small, density dependent, crossover temperature--- for… ▽ More
   Submitted 11 January, 2019; **originally announced** January 2019.
   Comments: 7 pages, 3 figures. (Supplementary material: 3 pages, 2 figures)

5. arXiv:1809.05110 [pdf, other] cond-mat.str-el cond-mat.mes-hall doi 10.1103/PhysRevB.99.205150
   Bridging Hubbard Model Physics and Quantum Hall Physics in Trilayer Graphene/h-BN moiré superlattice
   Authors: Ya-Hui Zhang, T. Senthil
   Abstract: The moiré superlattice formed by ABC stacked trilayer graphene aligned with a hexagonal boron nitride substrate (TG/h-BN) provides an interesting system where both the bandwidth and the topology can be tuned by an applied perpendicular electric field D. Thus the TG/h-BN system can simulate both Hubbard model physics and nearly flat Chern band physics within one sample. We derive lattice models… ▽ More
   Submitted 4 December, 2018; **v1** submitted 13 September, 2018; **originally announced** September 2018.
   Comments: 20 pages, 13 figures
   Journal ref: Phys. Rev. B 99, 205150 (2019)

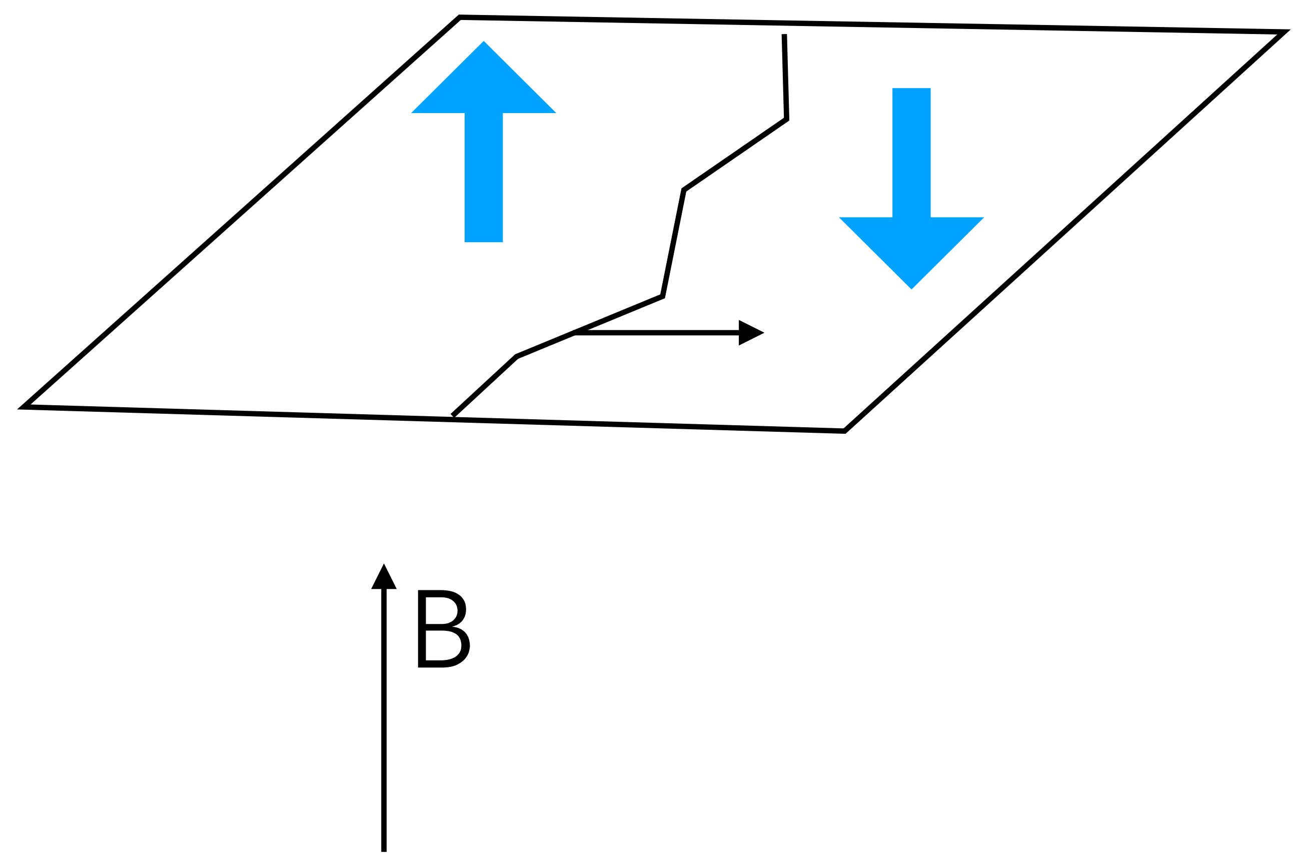
6. arXiv:1808.02482 [pdf, other] cond-mat.str-el cond-mat.mtrl-sci cond-mat.supr-con doi 10.1103/PhysRevB.99.195455
   Faithful Tight-binding Models and Fragile Topology of Magic-angle Bilayer Graphene
   Authors: Hoi Chun Po, Liujun Zou, T. Senthil, Ashvin Vishwanath
   Abstract: Correlated insulators and superconductivity have been observed in "magic-angle" twisted bilayer graphene, when the nearly flat bands close to neutrality are partially filled. While a momentum-space continuum model accurately describes these flat bands, interaction effects are more conveniently incorporated in tight-binding models. We have previously shown that no fully symmetric tight-binding mode… ▽ More
   Submitted 2 June, 2019; **v1** submitted 7 August, 2018; **originally announced** August 2018.
   Comments: (9+10) pages, (6+5) figures, (3+4) tables; v3: close to published version
   Journal ref: Phys. Rev. B 99, 195455 (2019)

7. arXiv:1806.07873 [pdf, other] cond-mat.str-el cond-mat.mes-hall cond-mat.mtrl-sci doi 10.1103/PhysRevB.98.085435
   Band Structure of Twisted Bilayer Graphene: Emergent Symmetries, Commensurate Approximants and Wannier Obstructions
   Authors: Liujun Zou, Hoi Chun Po, Ashvin Vishwanath, T. Senthil
   Abstract: A remarkable feature of the band structure of bilayer graphene at small twist angle is the appearance of isolated bands near neutrality, whose bandwidth can be reduced at certain magic angles (eg. $\theta \sim 1.05^\circ$). In this regime, correlated insulating states and superconductivity have been experimentally observed. A microscopic description of these phenomena requires an understanding of univer… ▽ More
   Submitted 29 August, 2018; **v1** submitted 20 June, 2018; **originally announced** June 2018.
   Comments: 14 pages + appendices; v3: published version
   Journal ref: Phys. Rev. B 98, 085435 (2018)

Domain manipulation



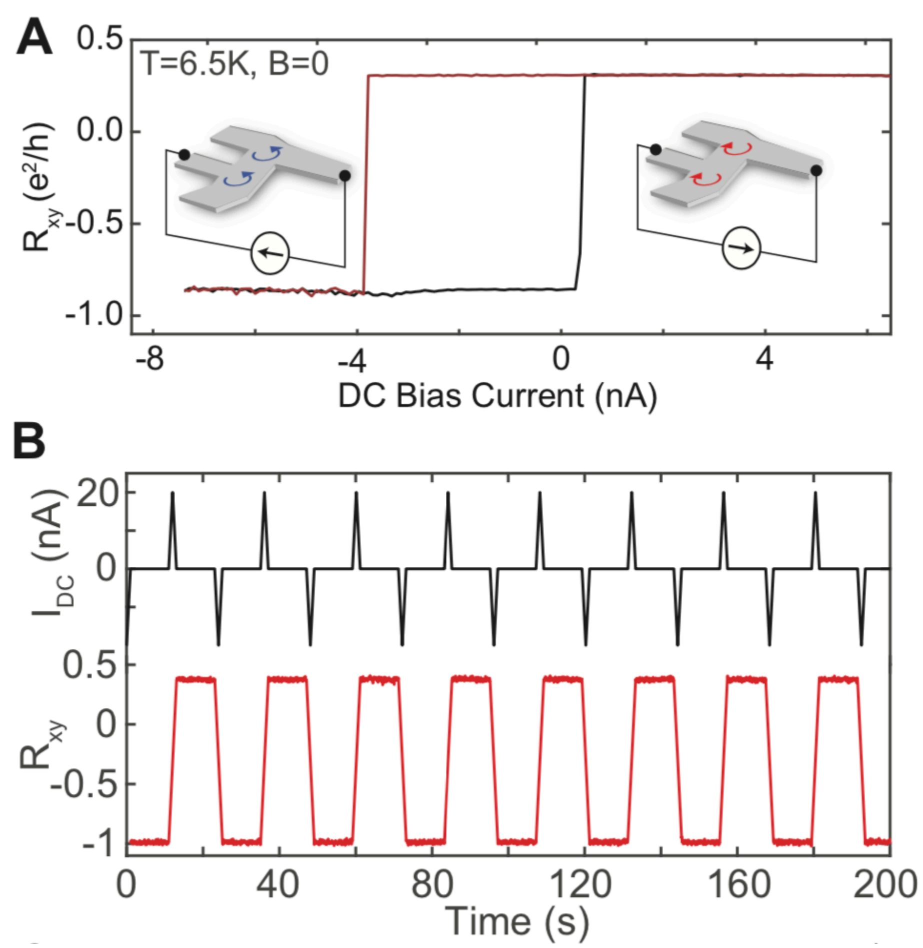
B field biases energy of domains



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

n.b. domains are *valley* domains

Domain manipulation



(tiny)

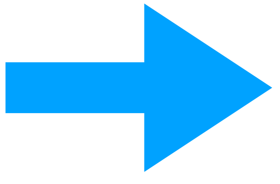
Current switches domains. How does this work?

Current

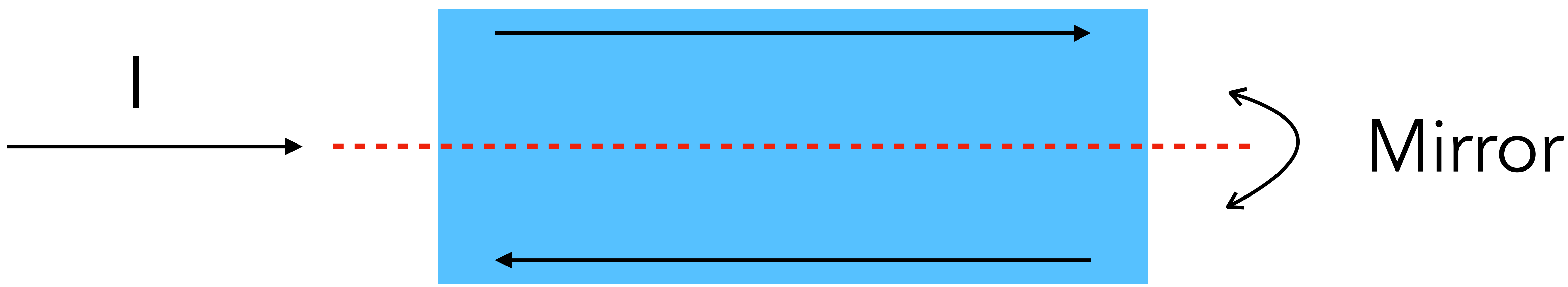
Well-developed IQHE:

- 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)

(A)symmetry



I → I vector

M → -M pseudovector

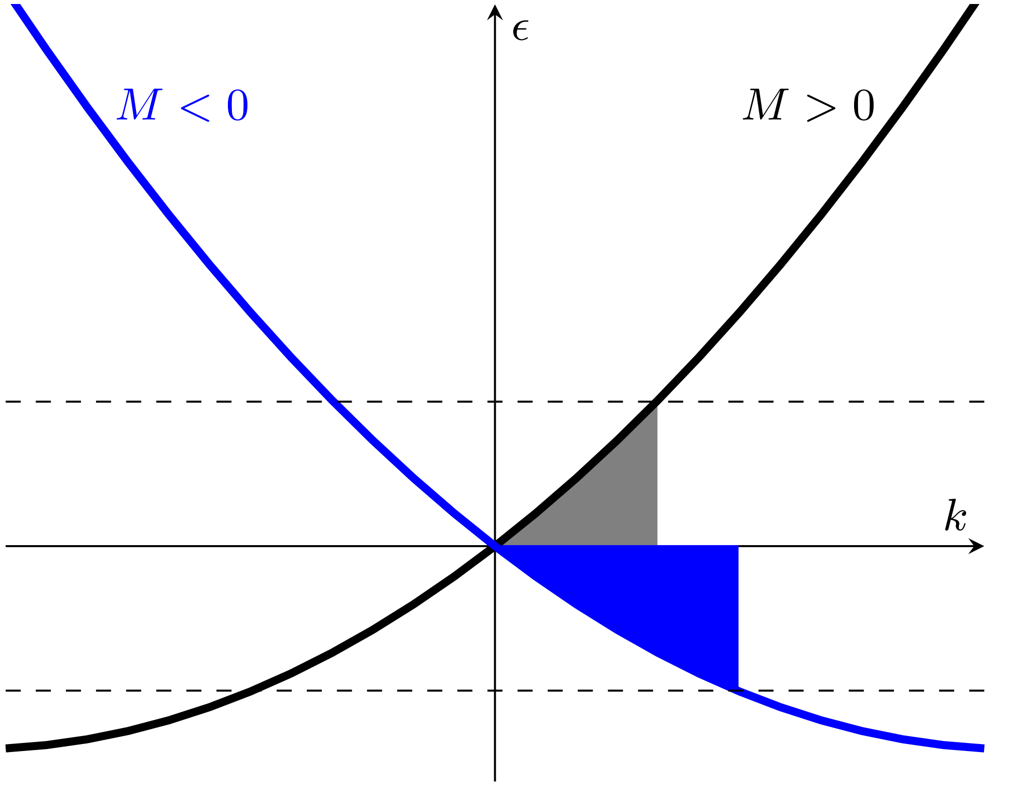
Energetics

Simple limit: one "fast" (costly) edge

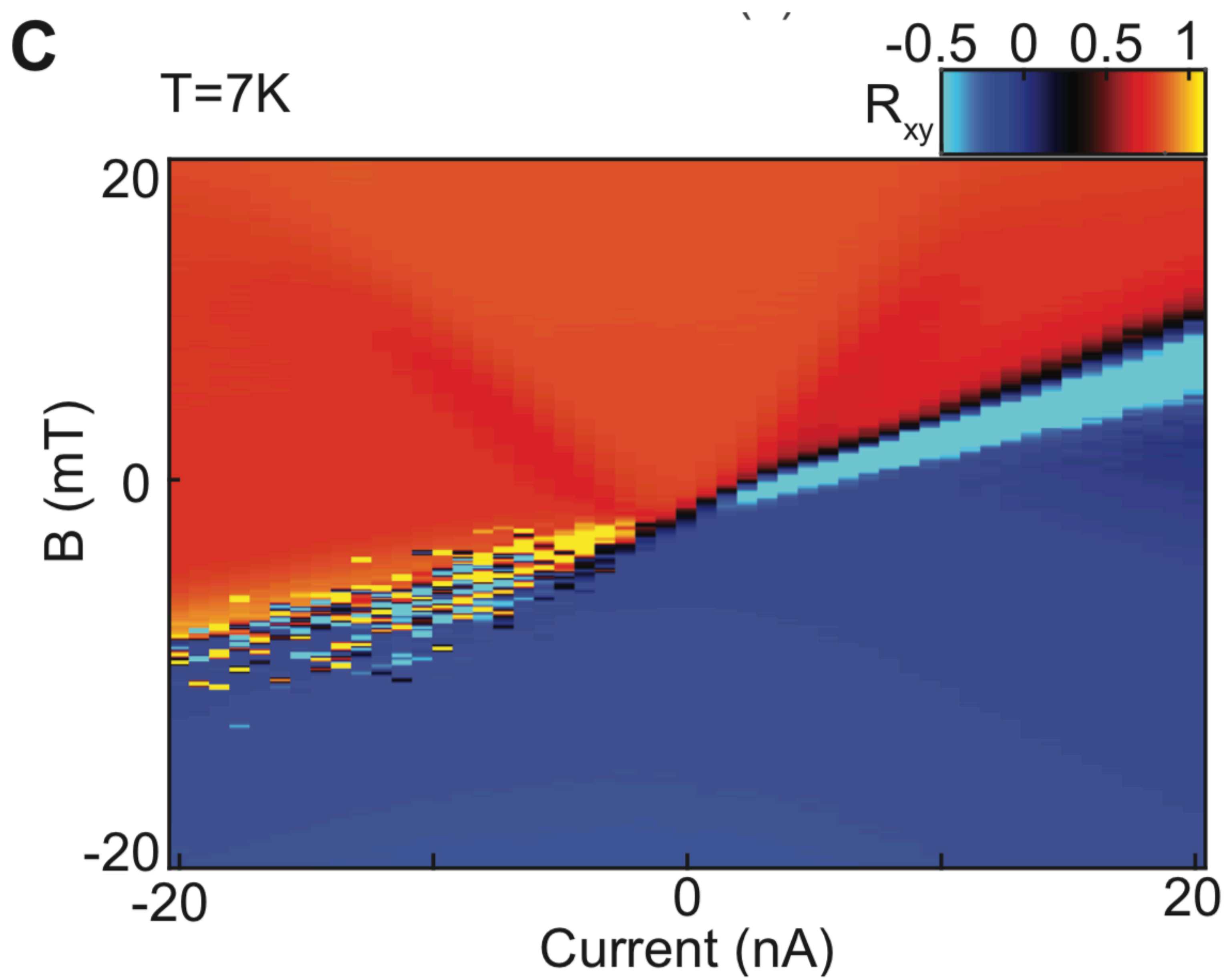
I>0:

- Add right-moving e-s
- Remove left-moving e-s

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

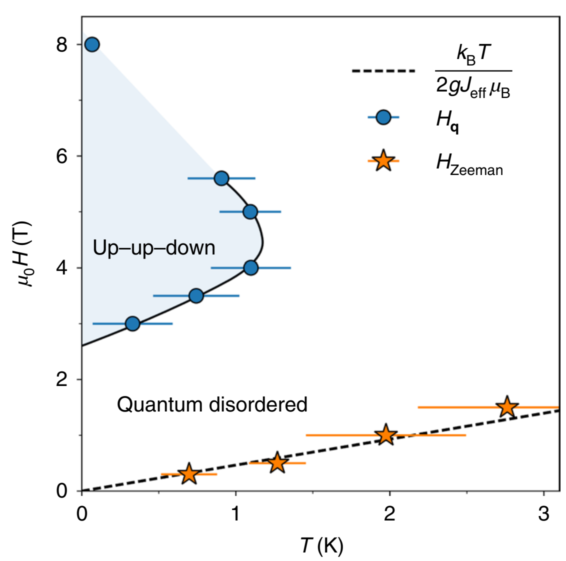


Dissipative Regime



A fully non-equilibrium problem, bulk 2d physics

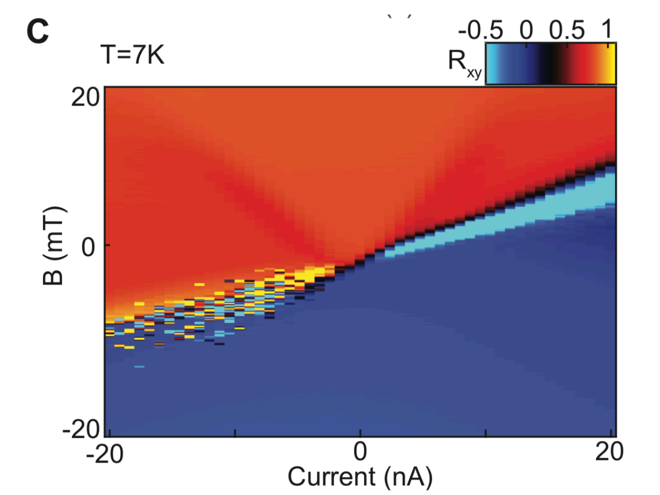
Thanks



M. Bordelon *et al*, Nat. Phys. (2019)

$$\mathcal{H} = \sum_l \psi_l^\dagger \left[-iv \left(\tau^\mu + \frac{\partial u_{l,\mu}}{\partial x_\nu} \tau^\nu \right) \frac{\partial}{\partial x_\mu} + v \left(\boldsymbol{K} \cdot \partial_\mu \boldsymbol{u}_l + \boldsymbol{\mathcal{A}}_l \right) \tau^\mu \right] \psi_l$$
$$+ \sum_j \left[e^{-i\boldsymbol{Q}_j \cdot (\boldsymbol{u}_1 - \boldsymbol{u}_2)} \psi_2^\dagger \mathsf{T}_j \psi_1 + \text{h.c.} \right]$$

L.B., arXiv:1909.01545



M. Serlin *et al*, arXiv:1907.00261