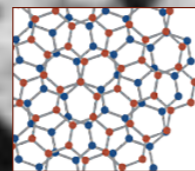


Towards UQM in experiments

Leon Balents, KITP



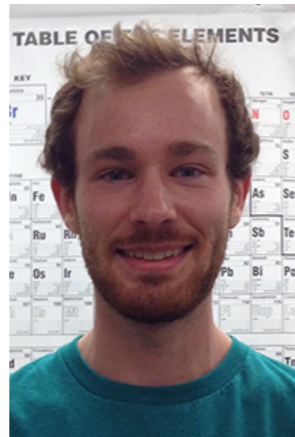
Simons Collaboration on
Ultra-Quantum Matter



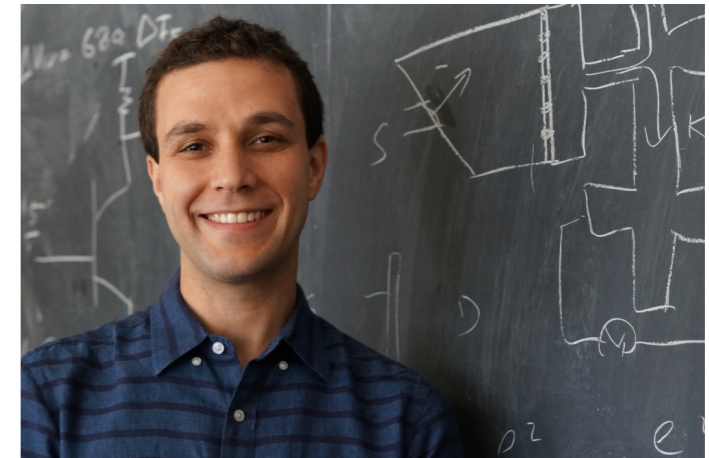
People



Stephen Wilson



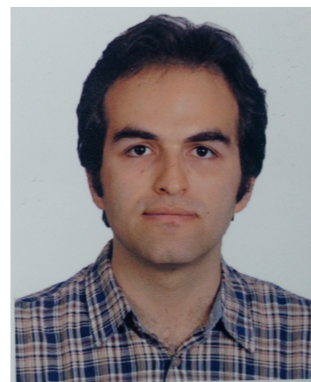
Mitchell Bordelon



Andrea Young



Chunxiao Liu



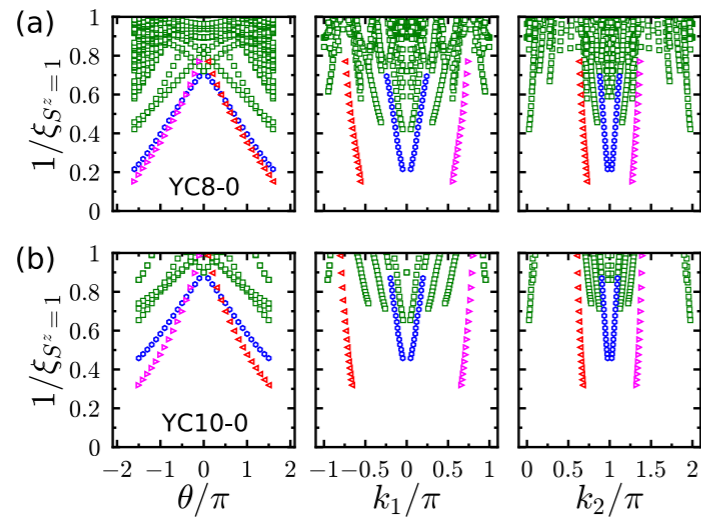
Kasra Hejazi

Outline

- NaYbO₂: 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

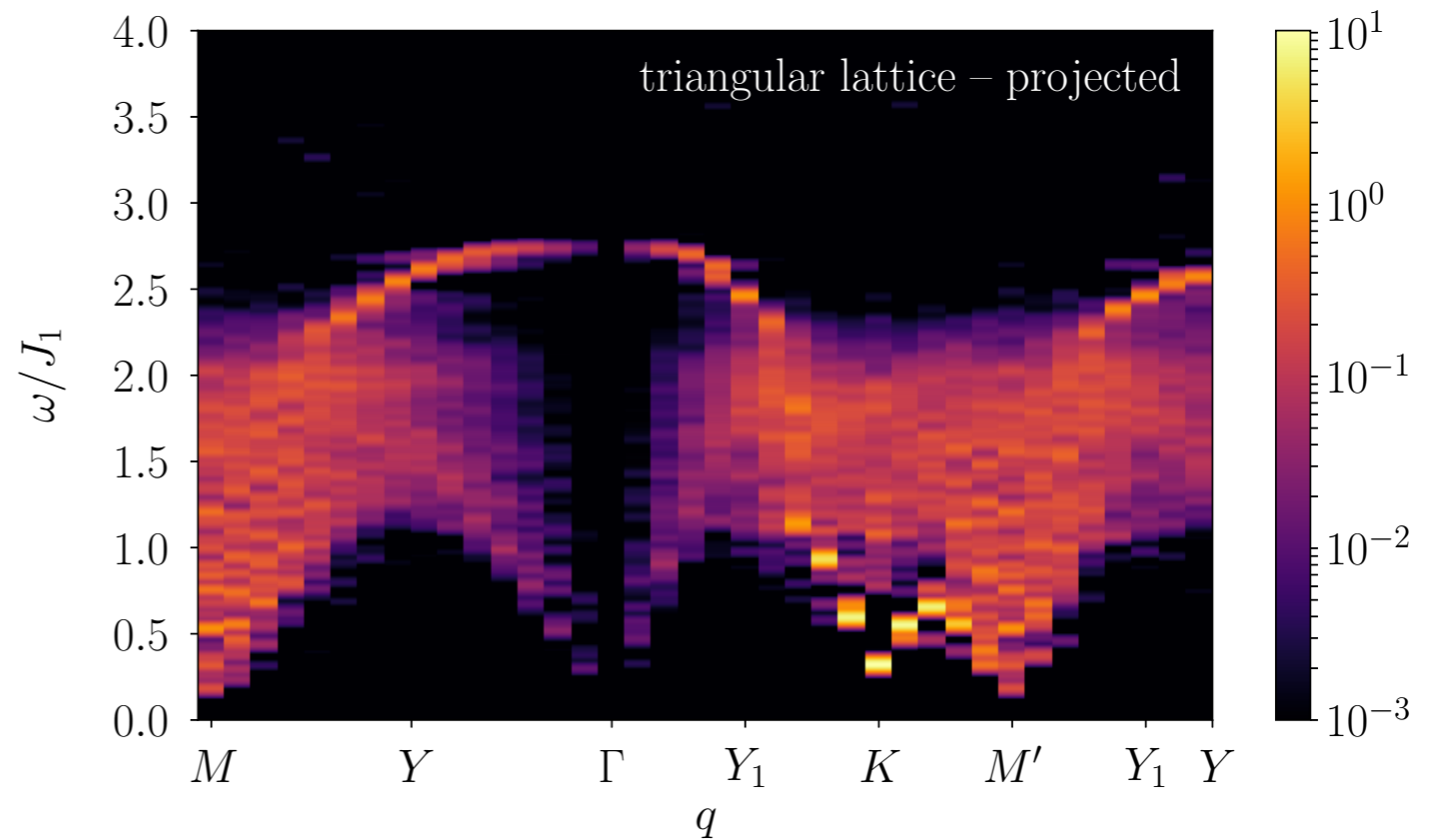
- Possible U(1) Dirac QSL on the triangular lattice (J_1 - J_2)



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}	$-M_{i1}$	-
Φ_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
Φ_2^\dagger	$e^{i\frac{2\pi}{3}}\Phi_2^\dagger$	$e^{i\frac{\pi}{3}}\Phi_2^\dagger$	Φ_2^\dagger	$-\Phi_3$	Φ_2
Φ_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

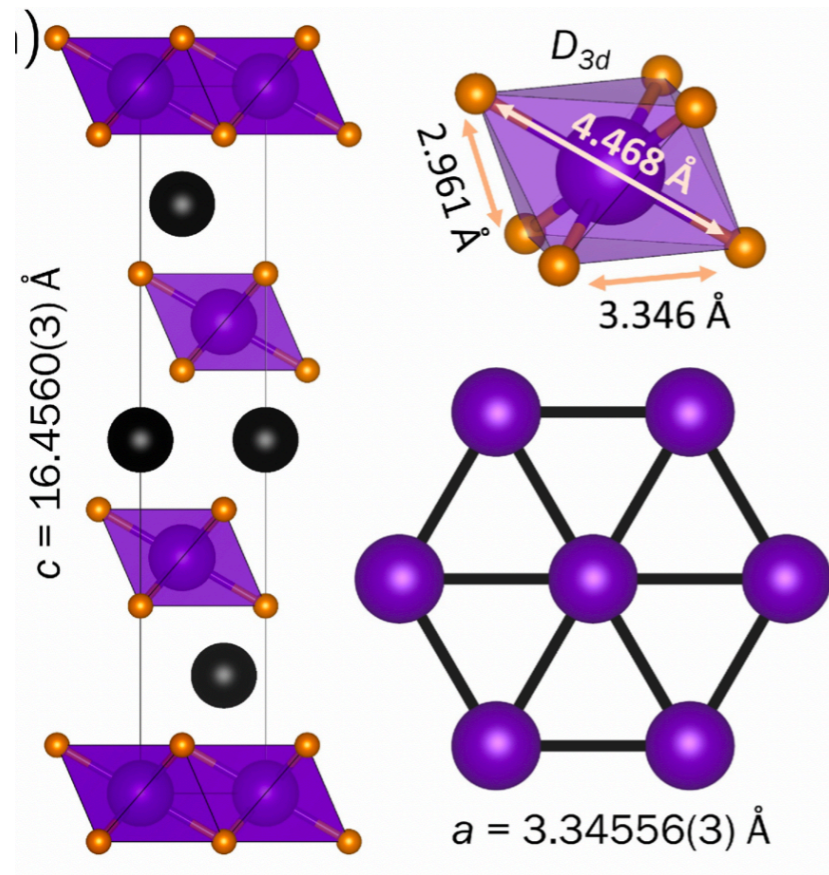


Federico Becca, unpublished

Spin Liquids?

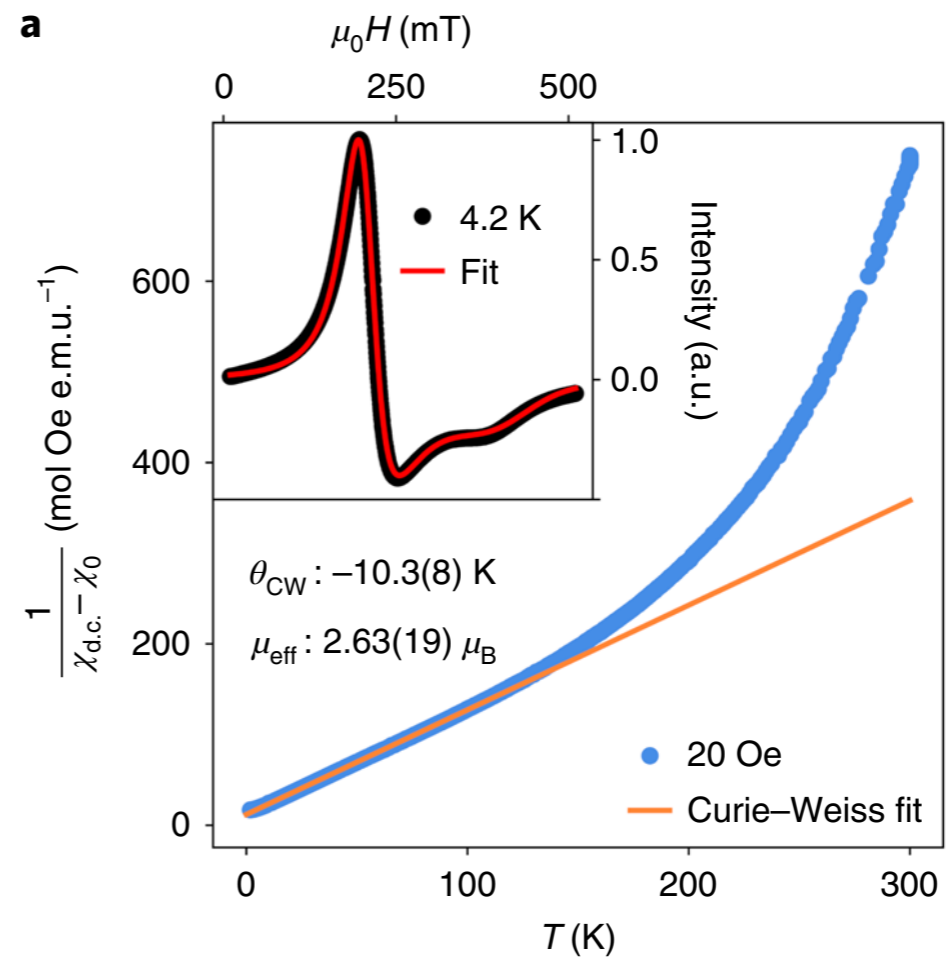
Model	QSL	Material	Issue
Kagome Heisenberg	U(1) Dirac	Herbertsmithite	Interlayer disorder
Kitaev honeycomb	Gapless Z2/Ising	α -RuCl ₃	Un-reproduced key result
Triangular Hubbard	U(1) Fermi surface	k-(ET), dmit organics	Interlayer disorder/ unreproduced result
Triangular J1-J2 Heisenberg	U(1) Dirac?	YbMgGaO ₄ ?	Random alloy Mg/Ga disorder

NaYbO₂



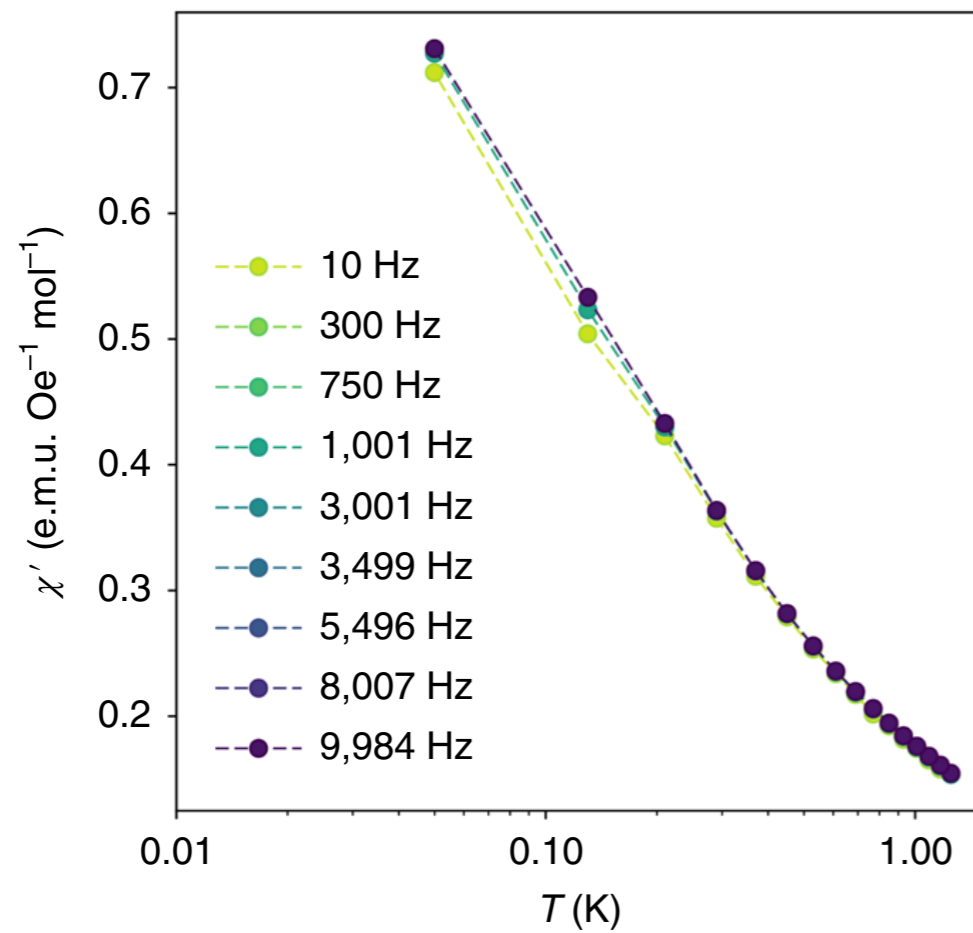
Isotropic triangular lattice of Yb³⁺
effective S=1/2 moments

ESR shows $g_{xy}=3.3$, $g_z=1.7$: expect
XY-like spins (common for Yb³⁺)

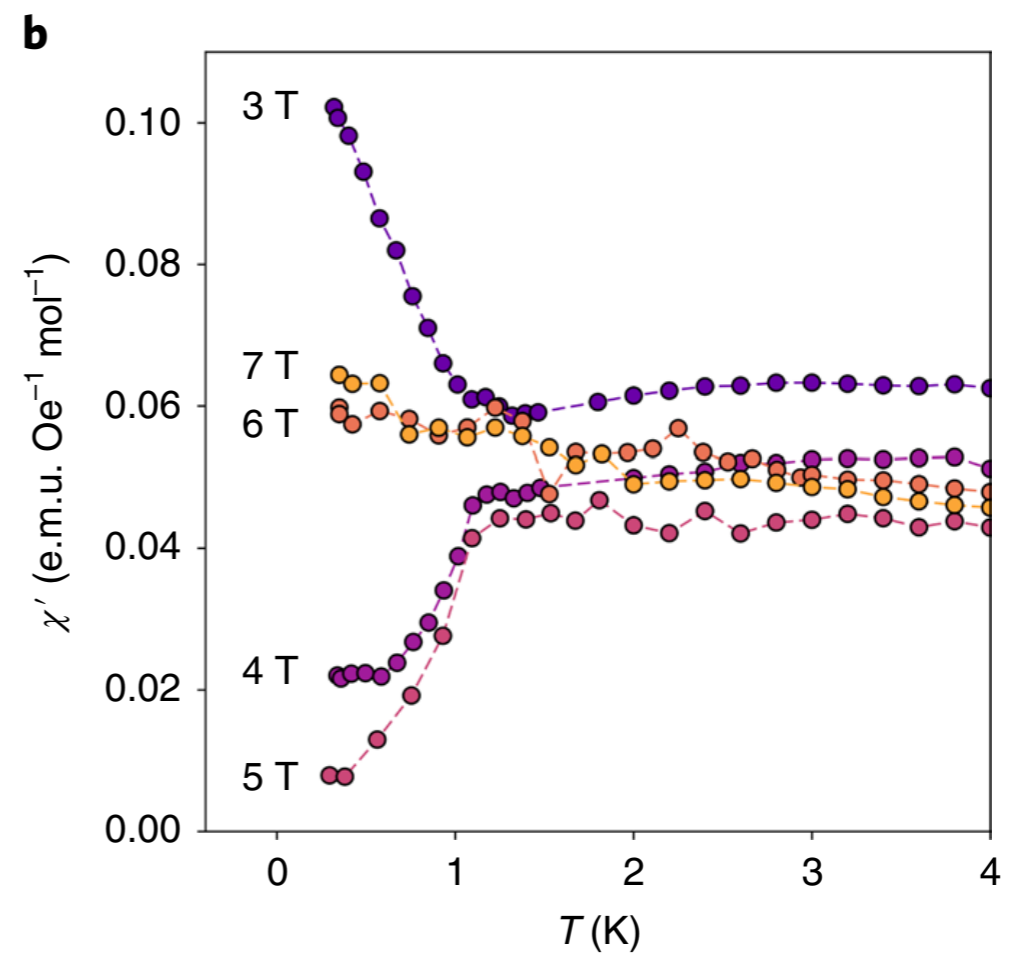


Susceptibility shows antiferromagnetic
exchange with ~10K scale

NaYbO₂



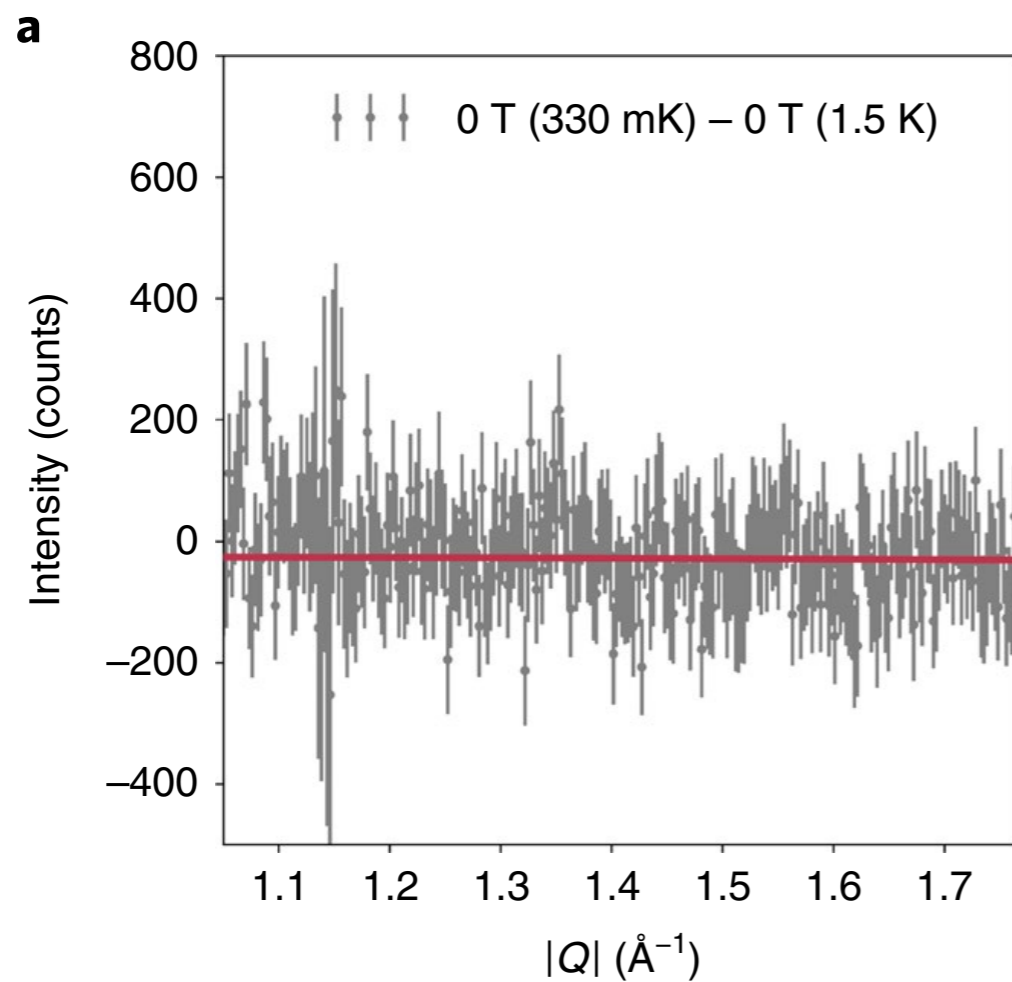
No ordering or freezing at $B=0$



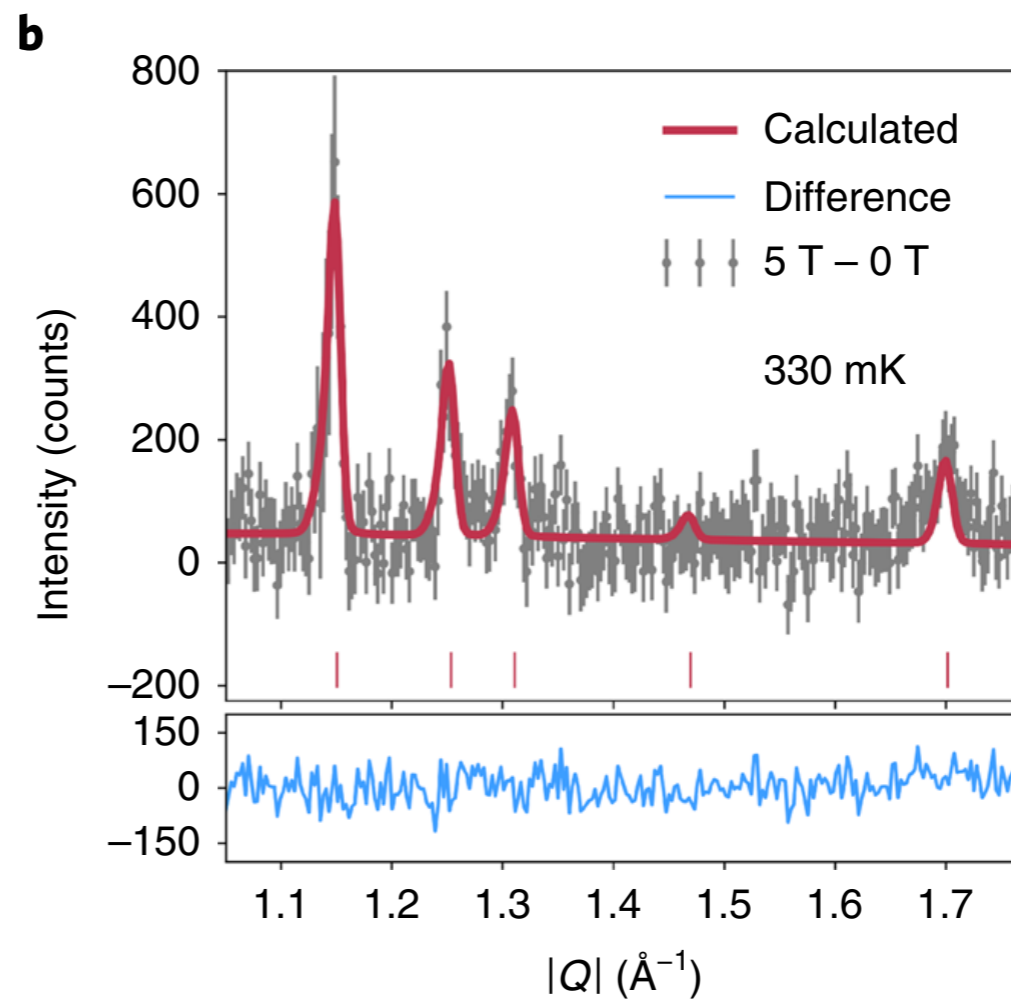
"action" in $B > 2T$.

NaYbO₂

Neutron scattering

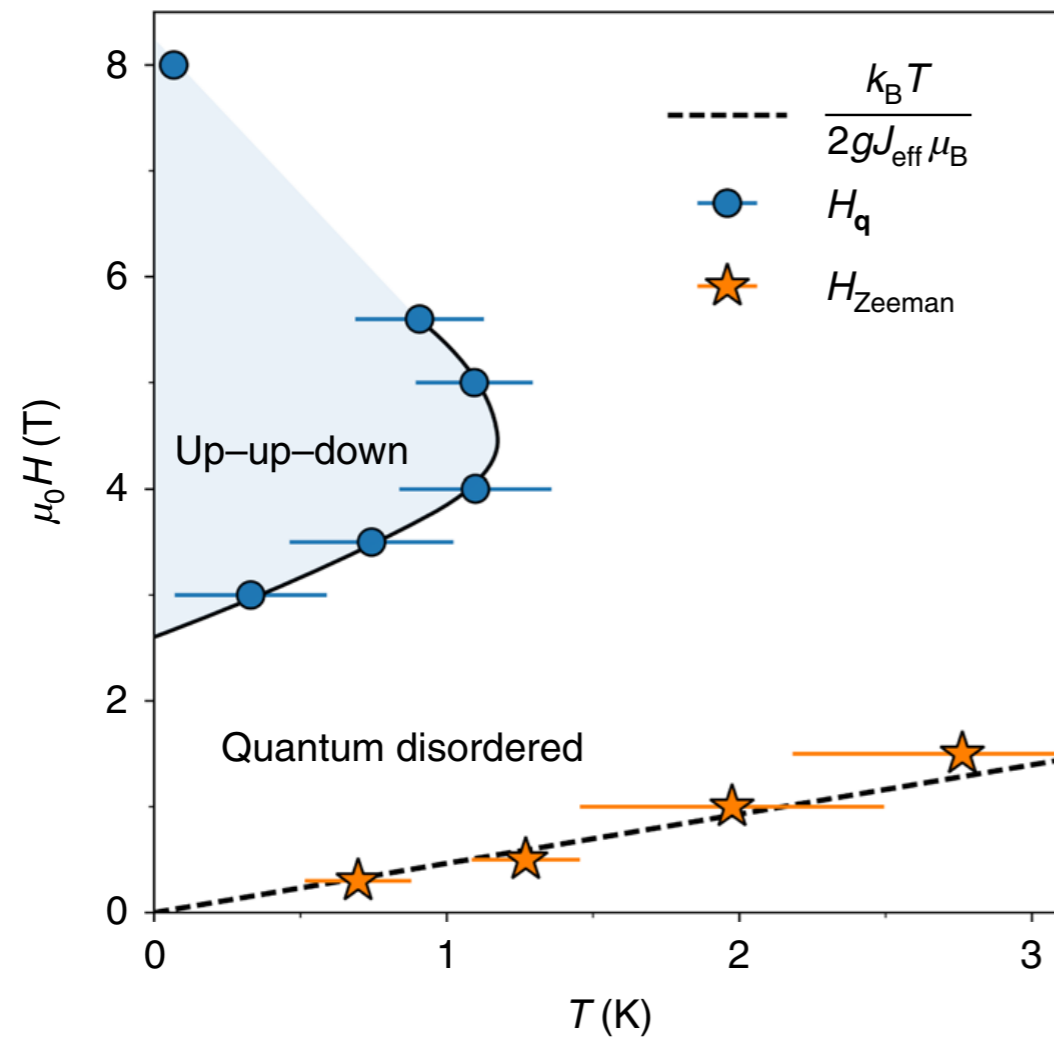


Featureless at B=0



Field-induced order

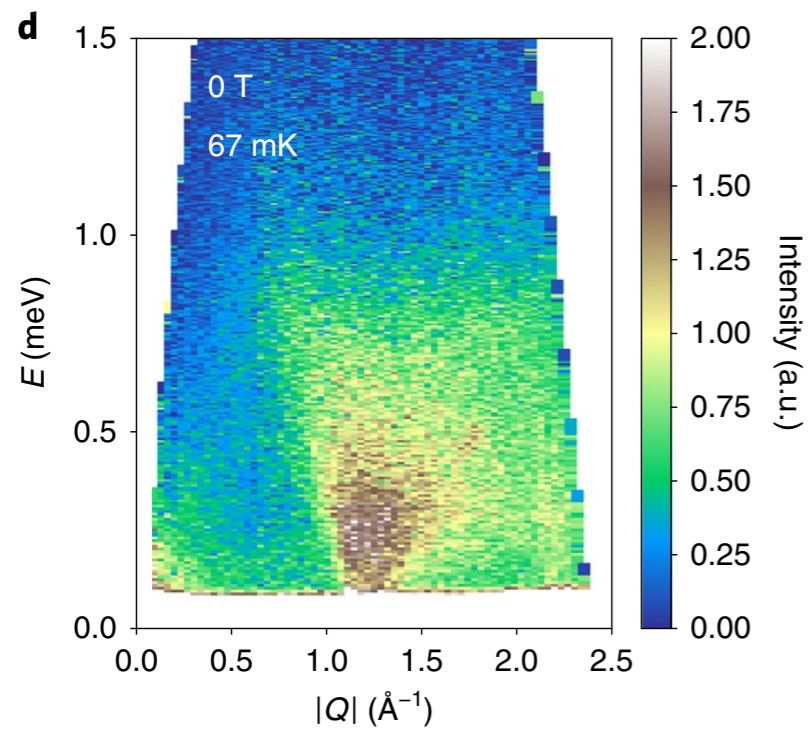
NaYbO₂



Field-induced
3-sublattice
order

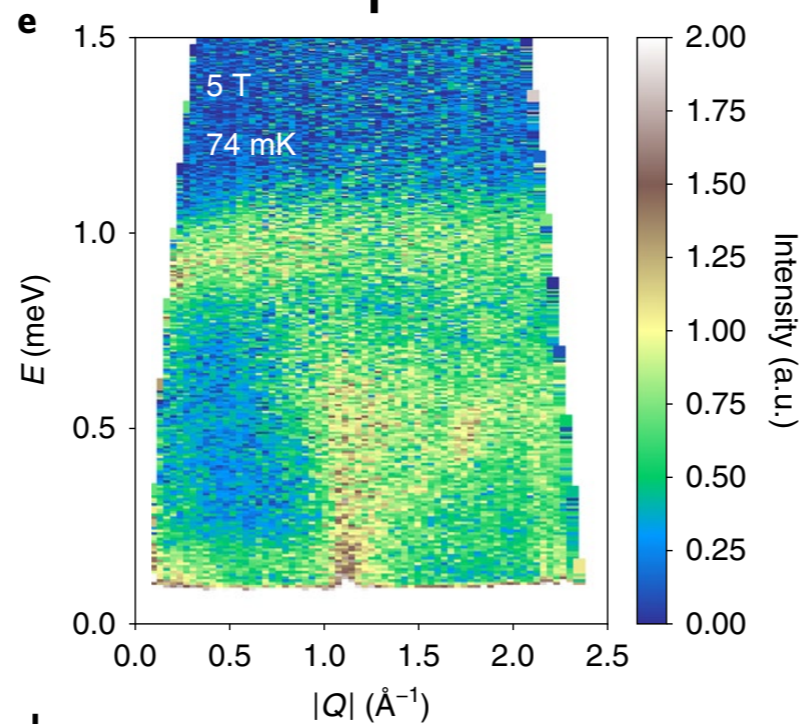
NaYbO₂

Powder INS

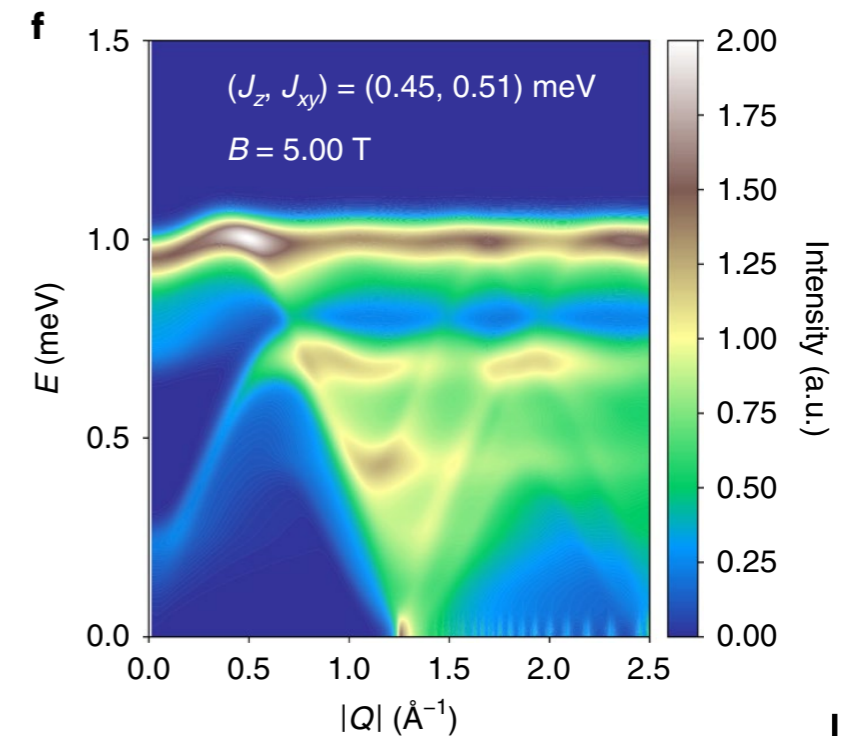


QSL?

expt



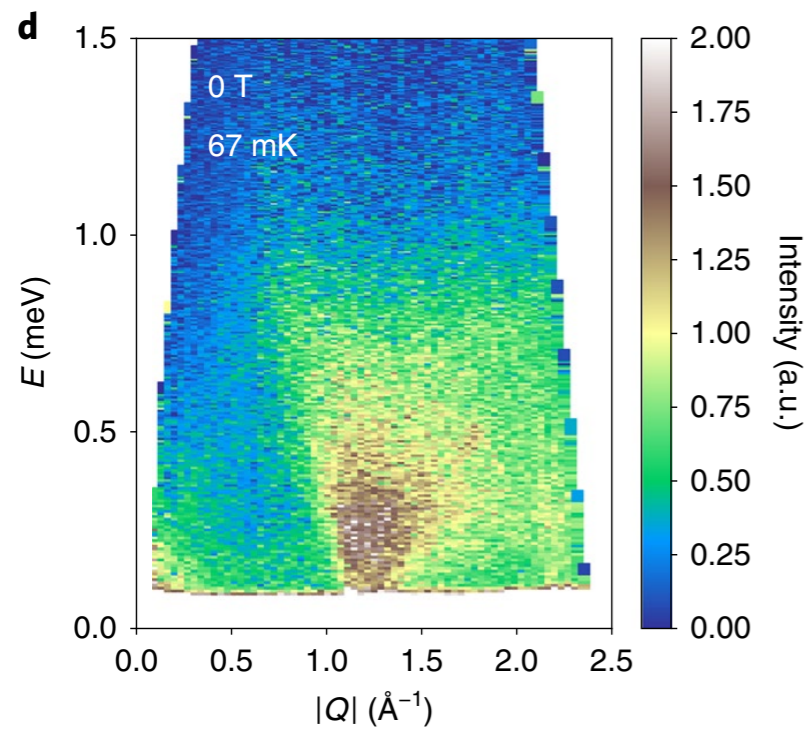
SWT



In the ordered state

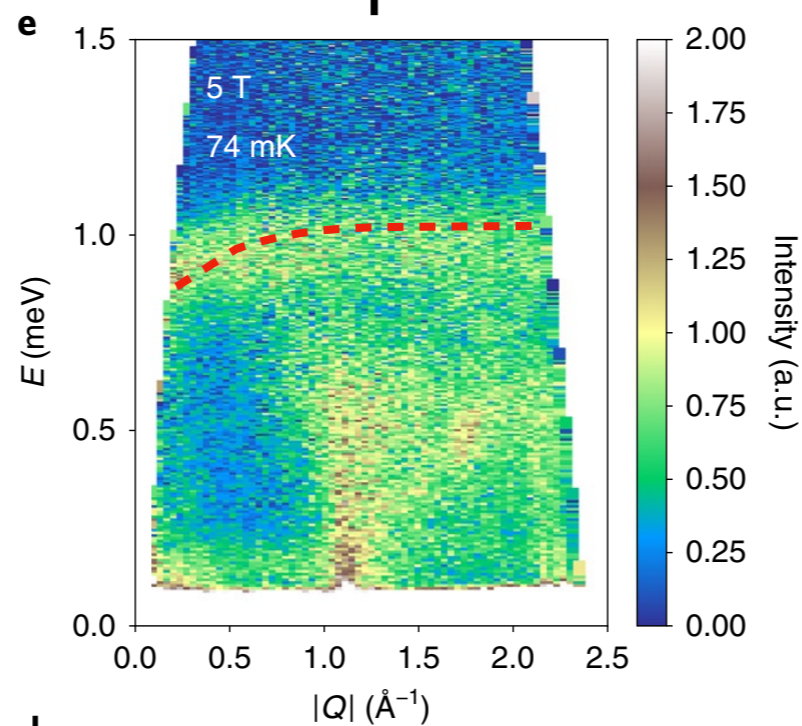
NaYbO₂

Powder INS

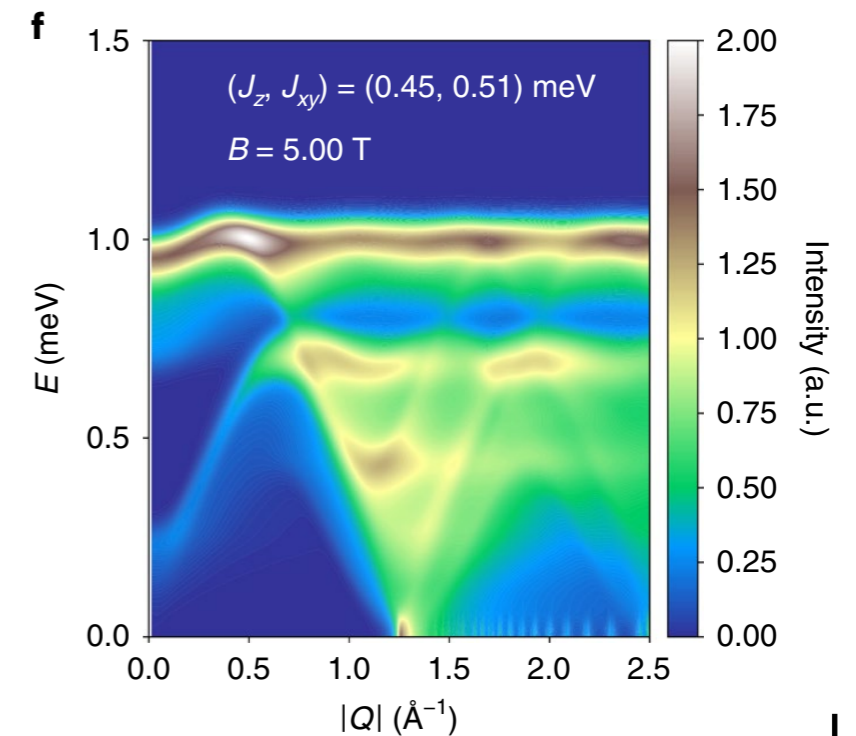


QSL?

expt



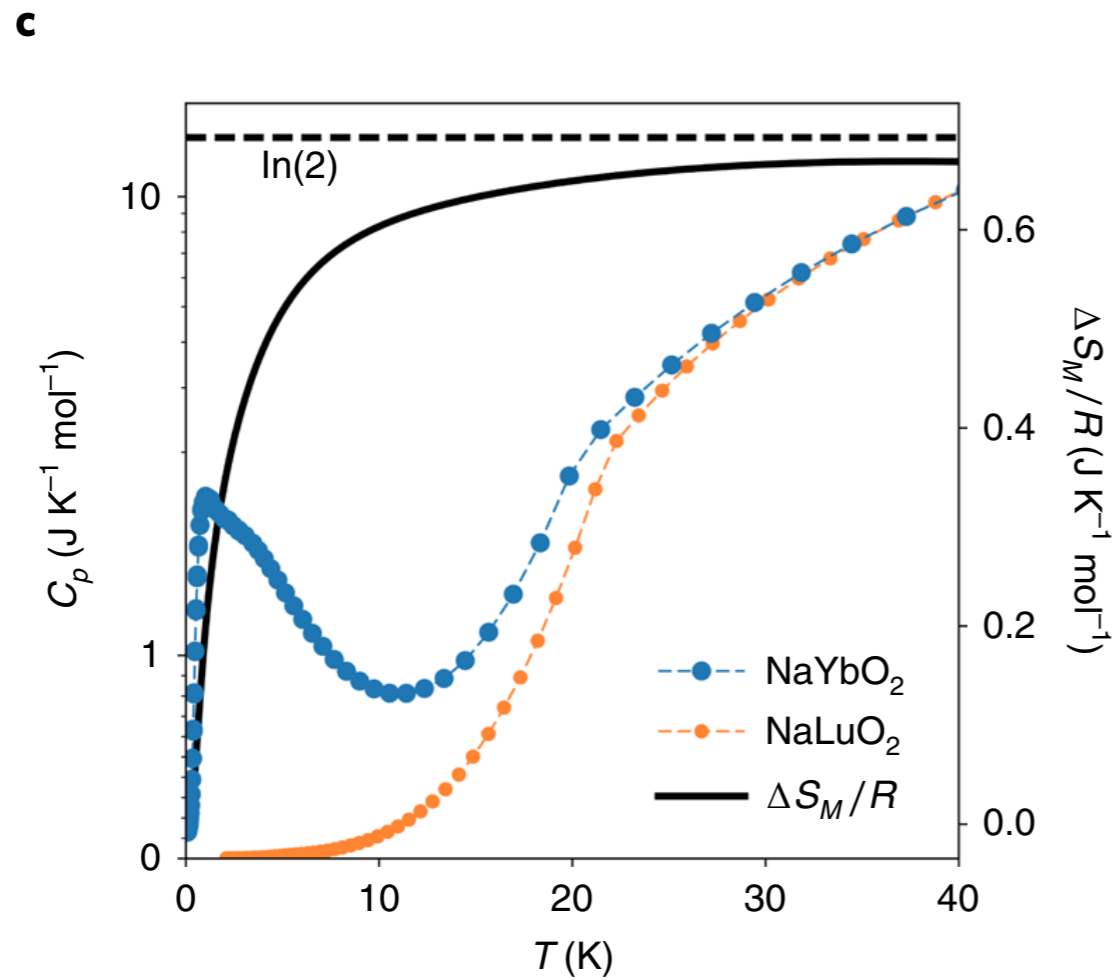
SWT



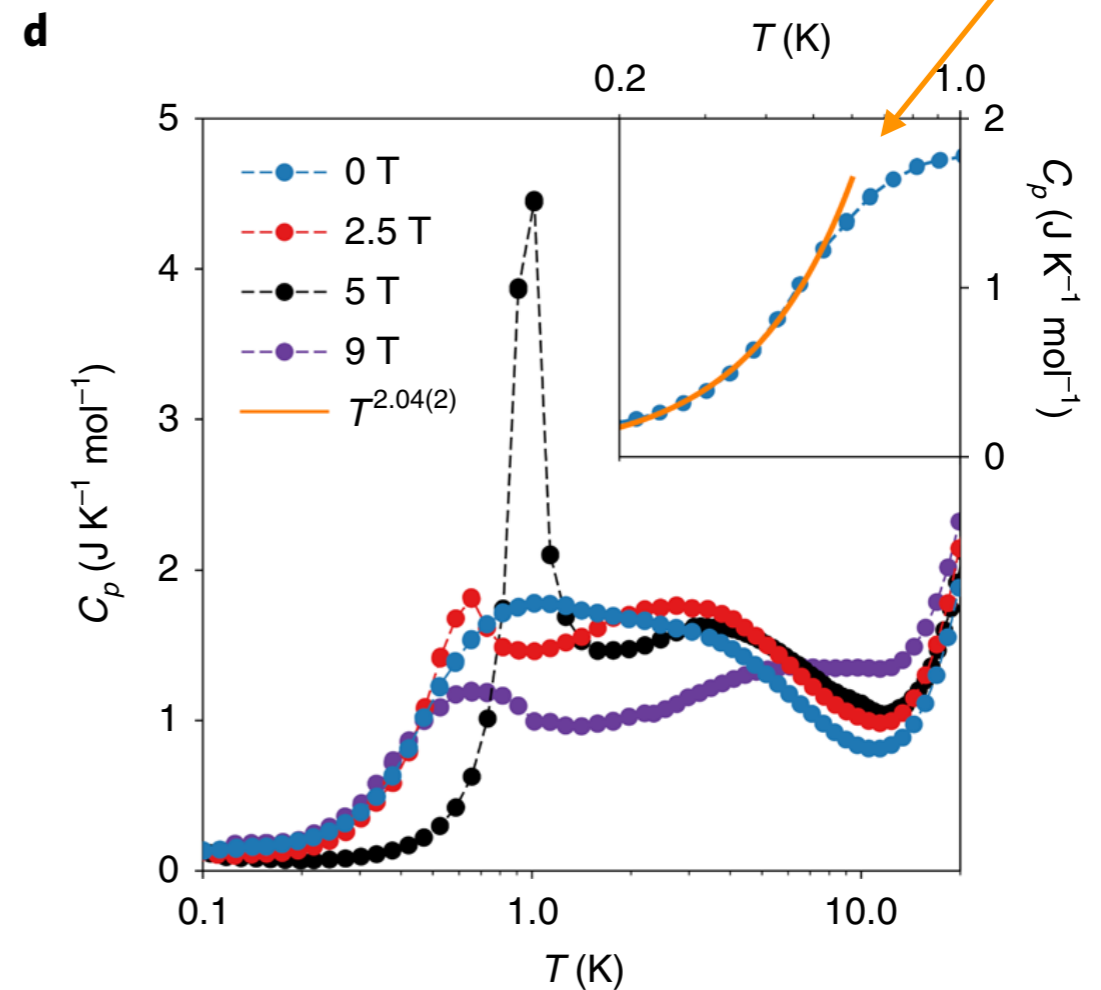
In the ordered state

NaYbO₂

$C \sim T^2?$



Entropy confirms $S=1/2$



So far consistent with U(1) Dirac

Magic angle graphene

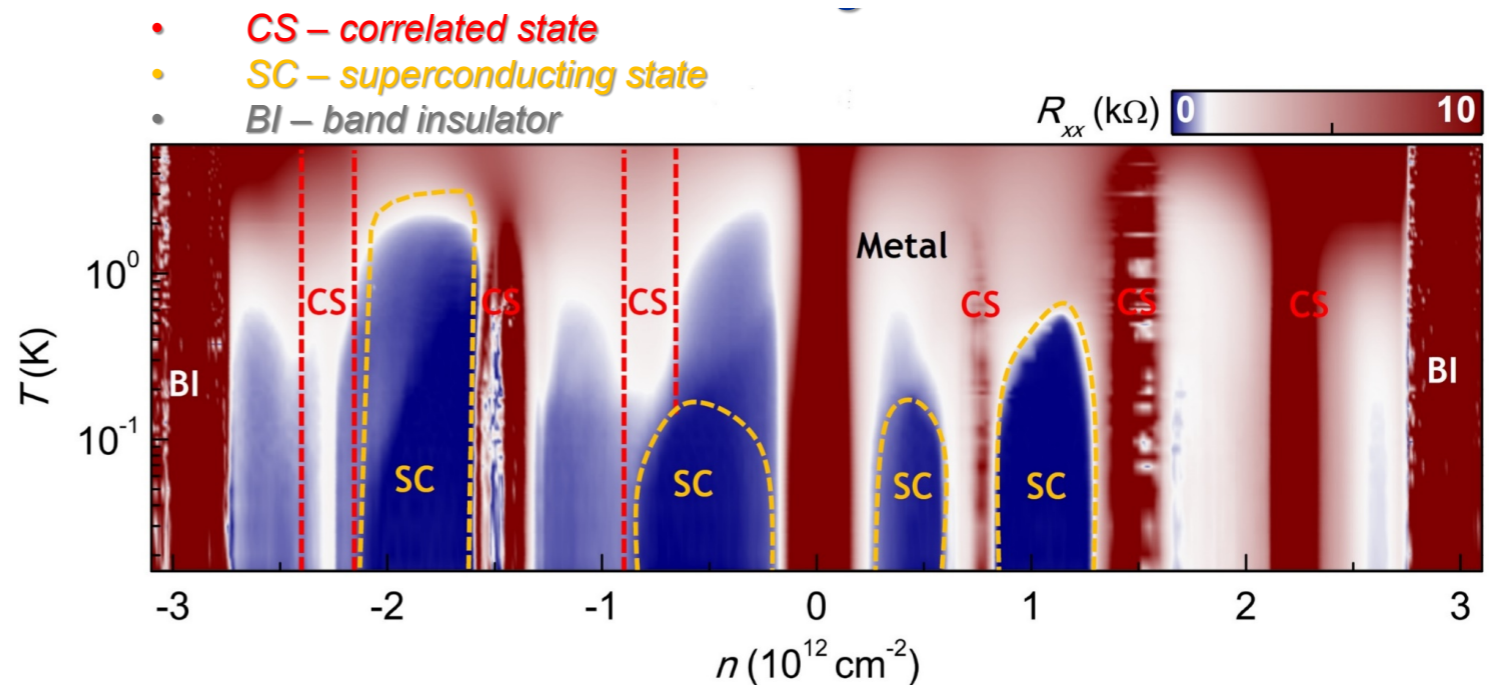
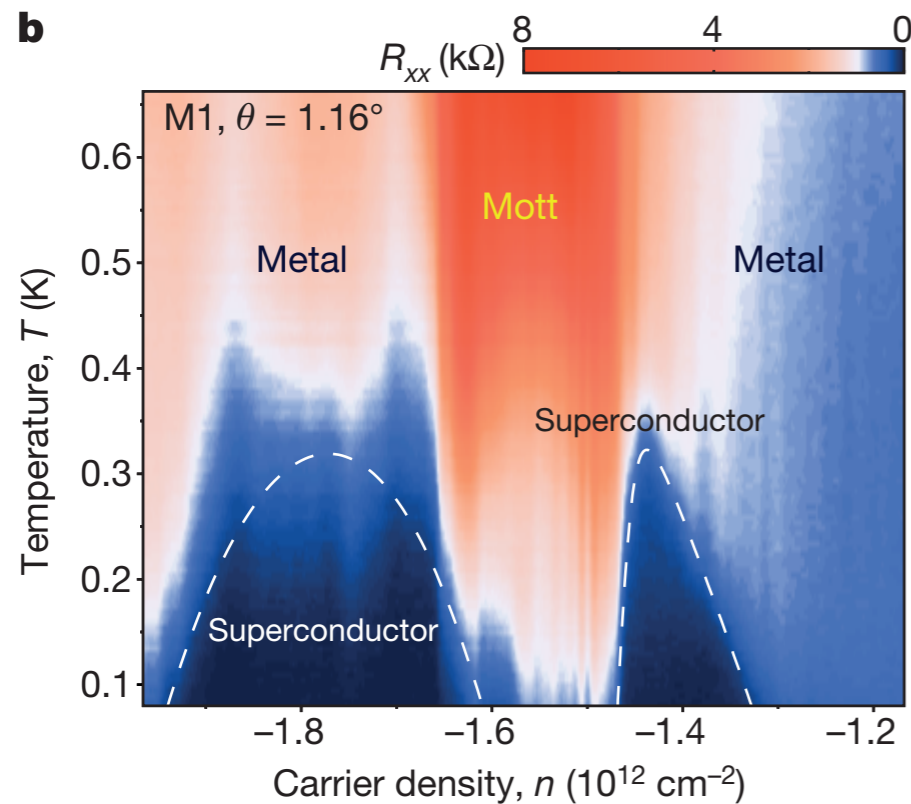


Pablo Jarillo-Herrero
(MIT)

Physics World
Breakthrough of the year,
2018

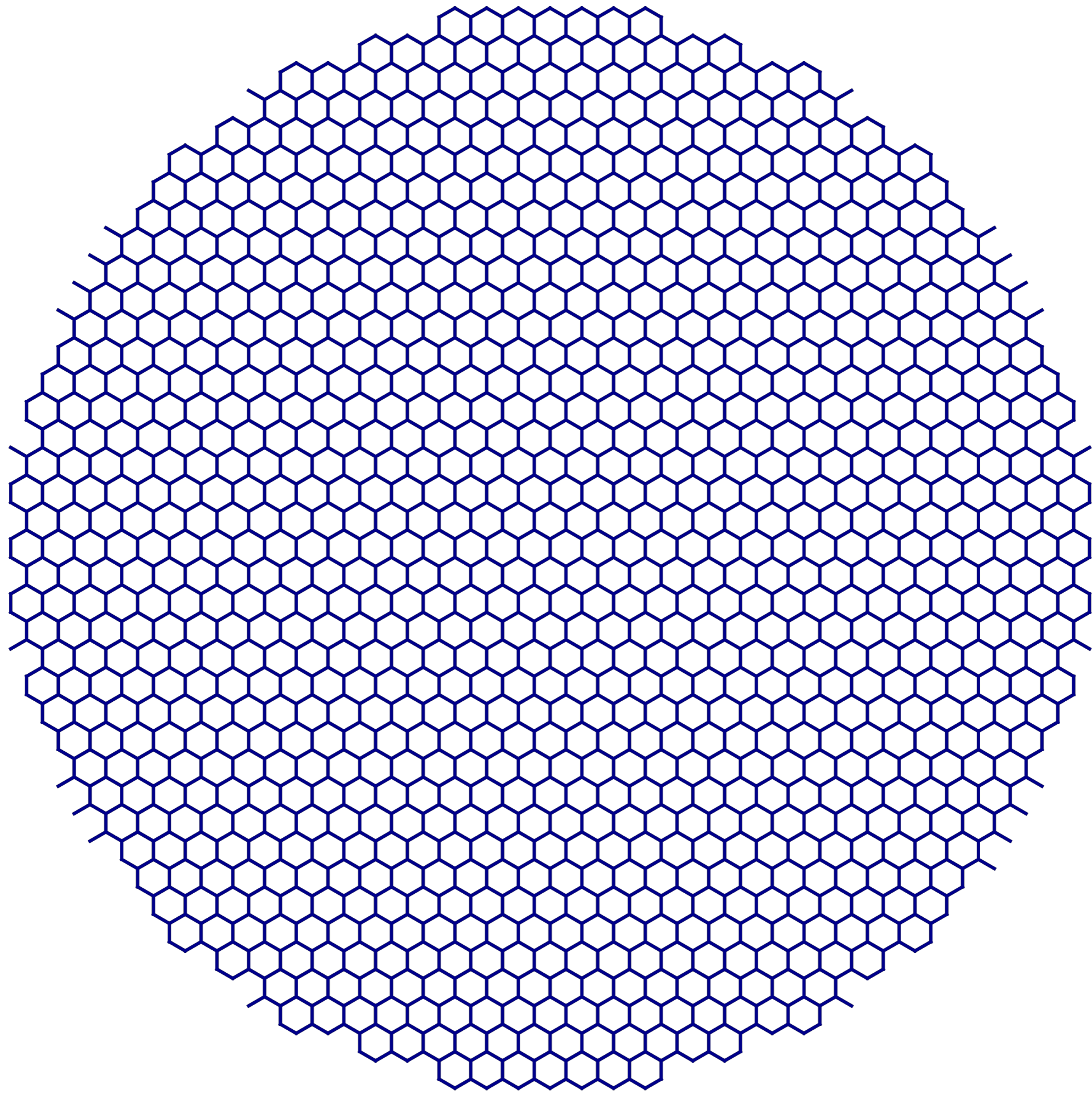


Dimitri Efetov
(Barcelona)



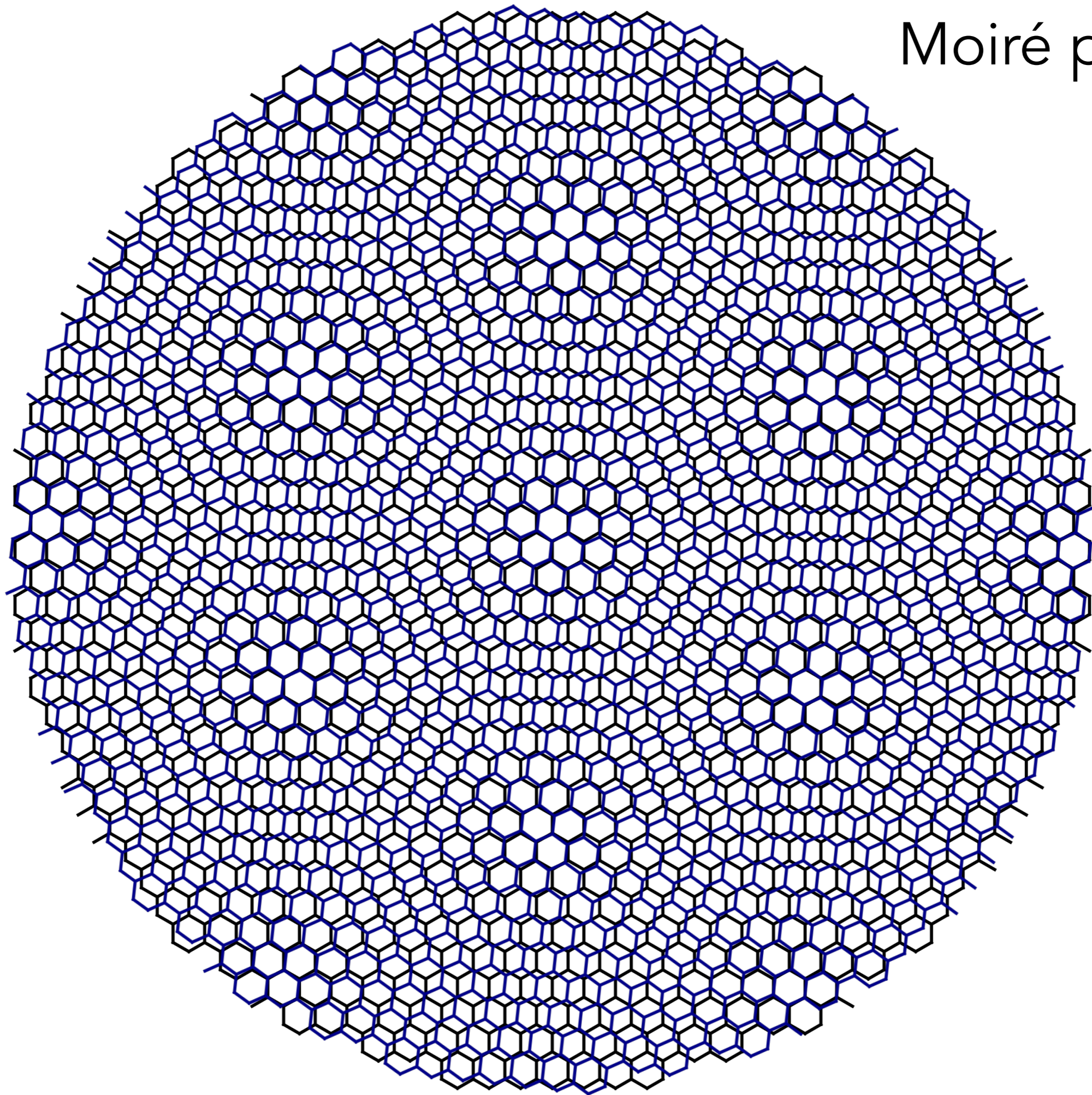
Two topics in TBG

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



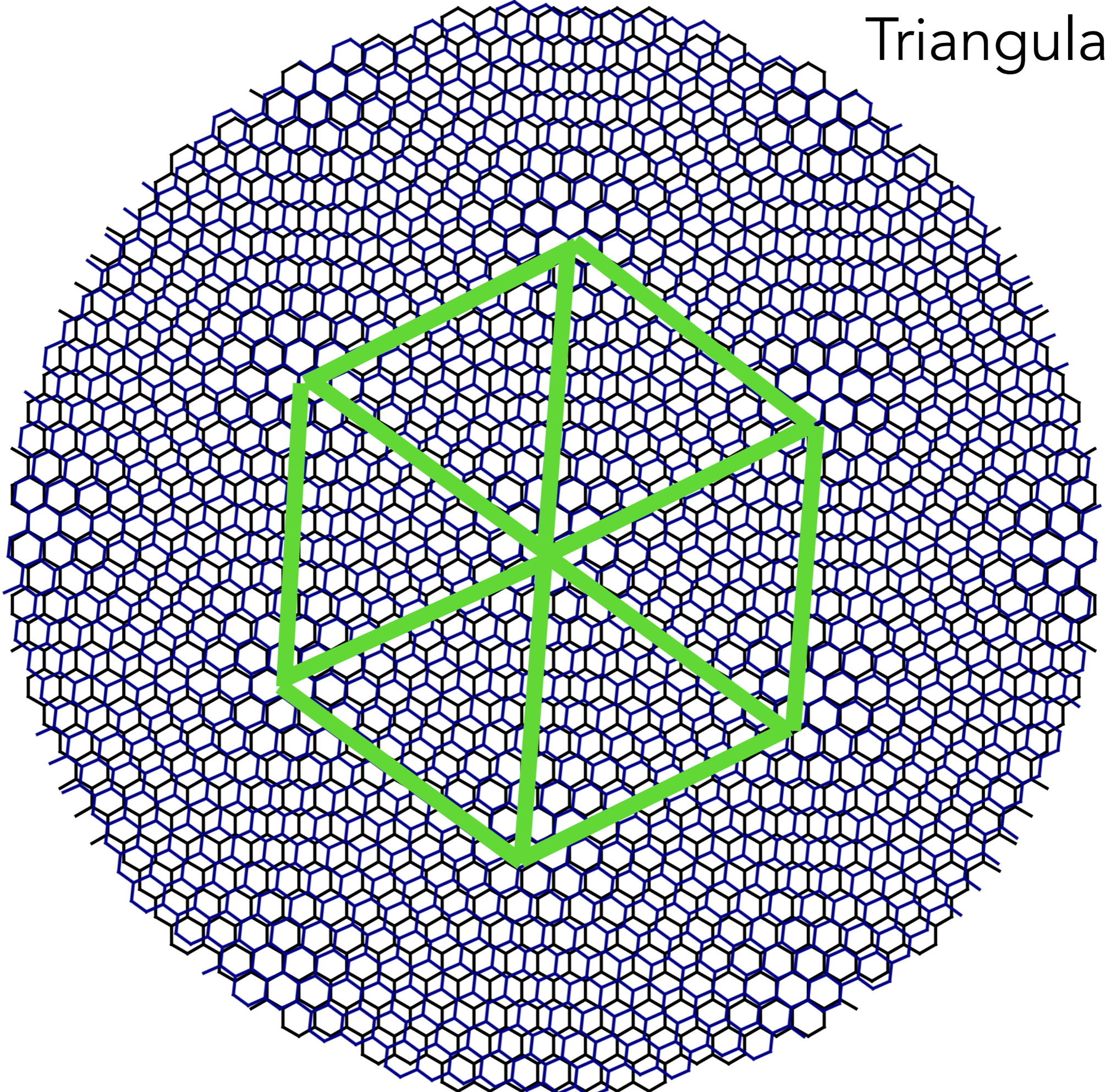
Moiré pattern

6°

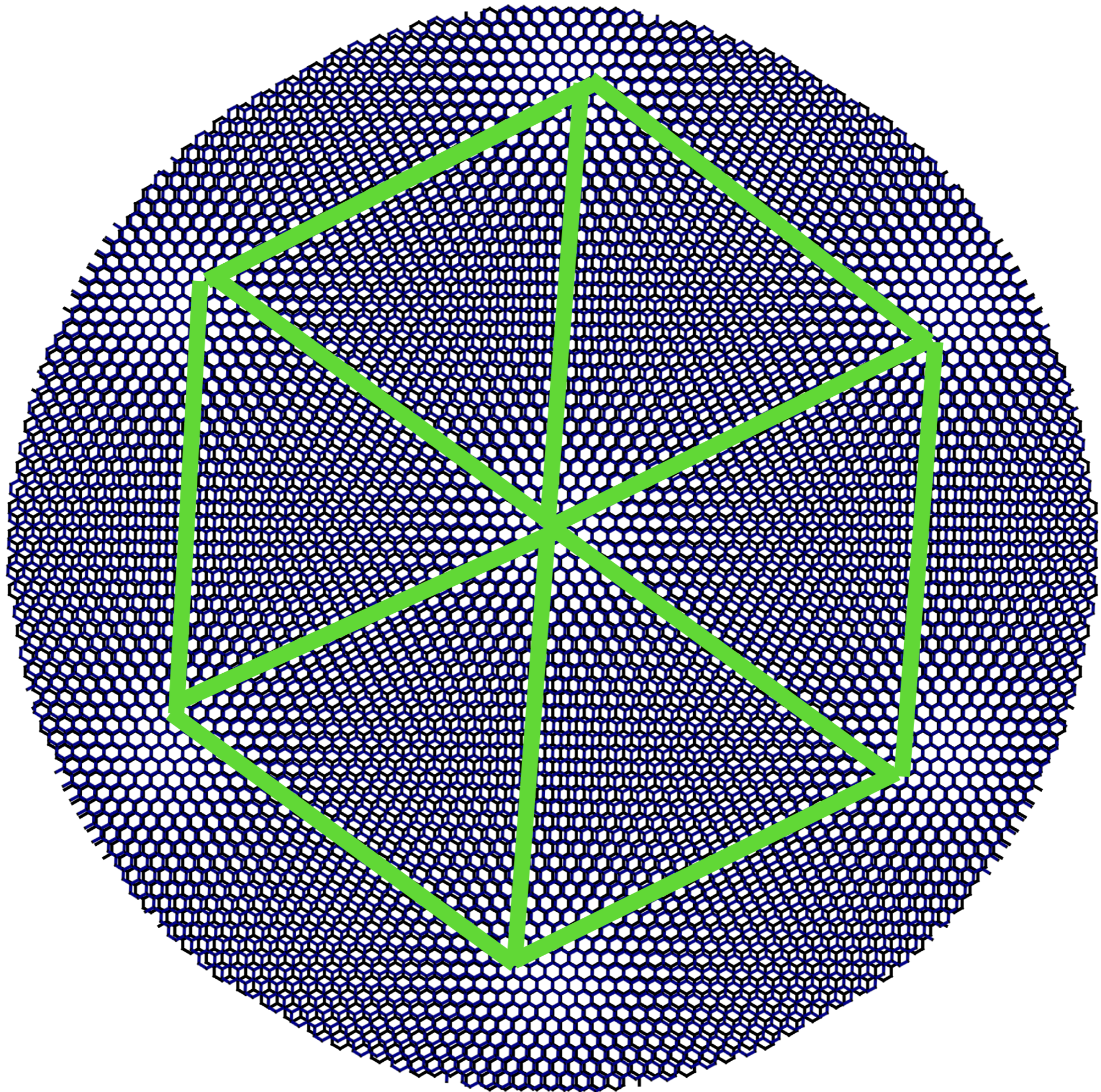


Triangular lattice

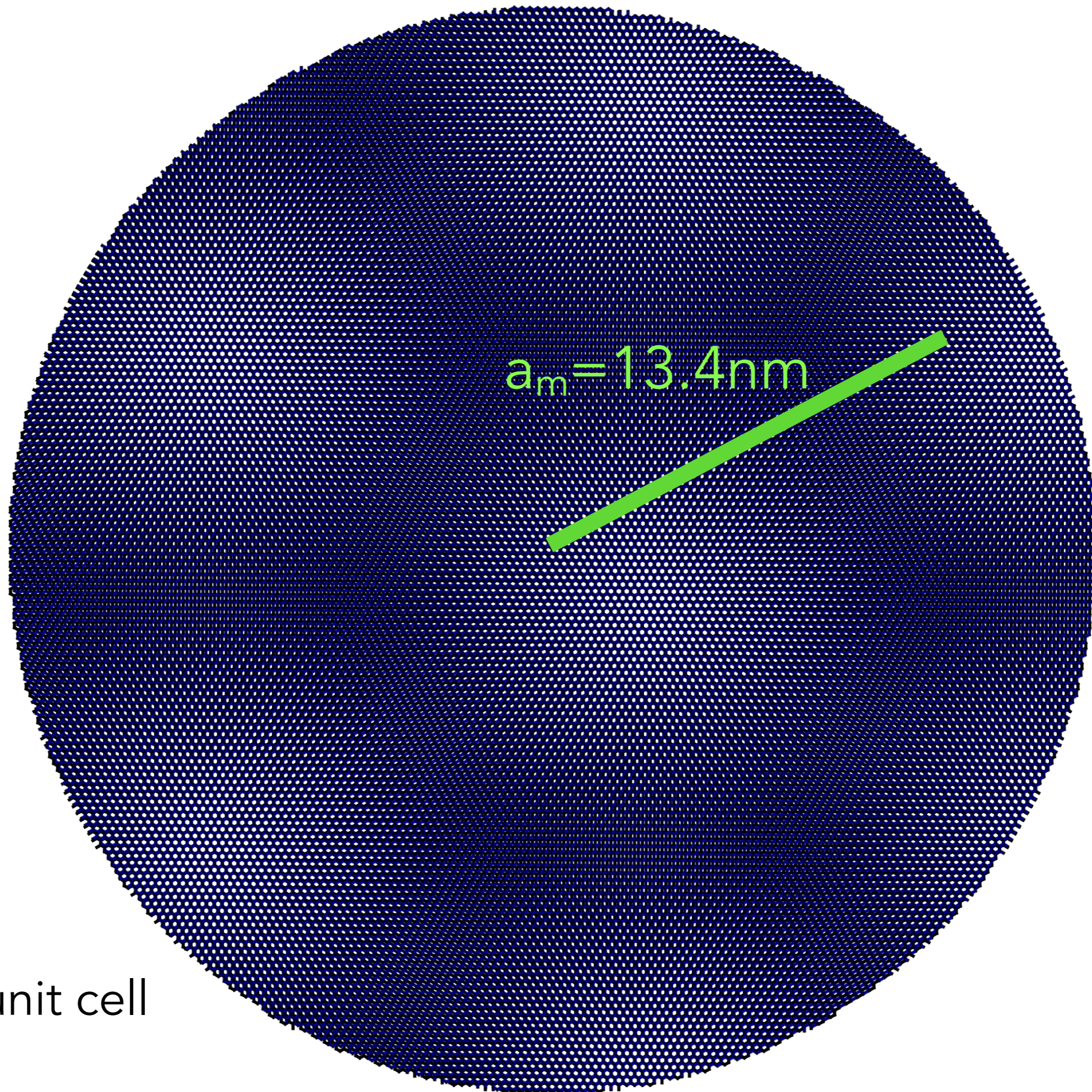
6°



2°

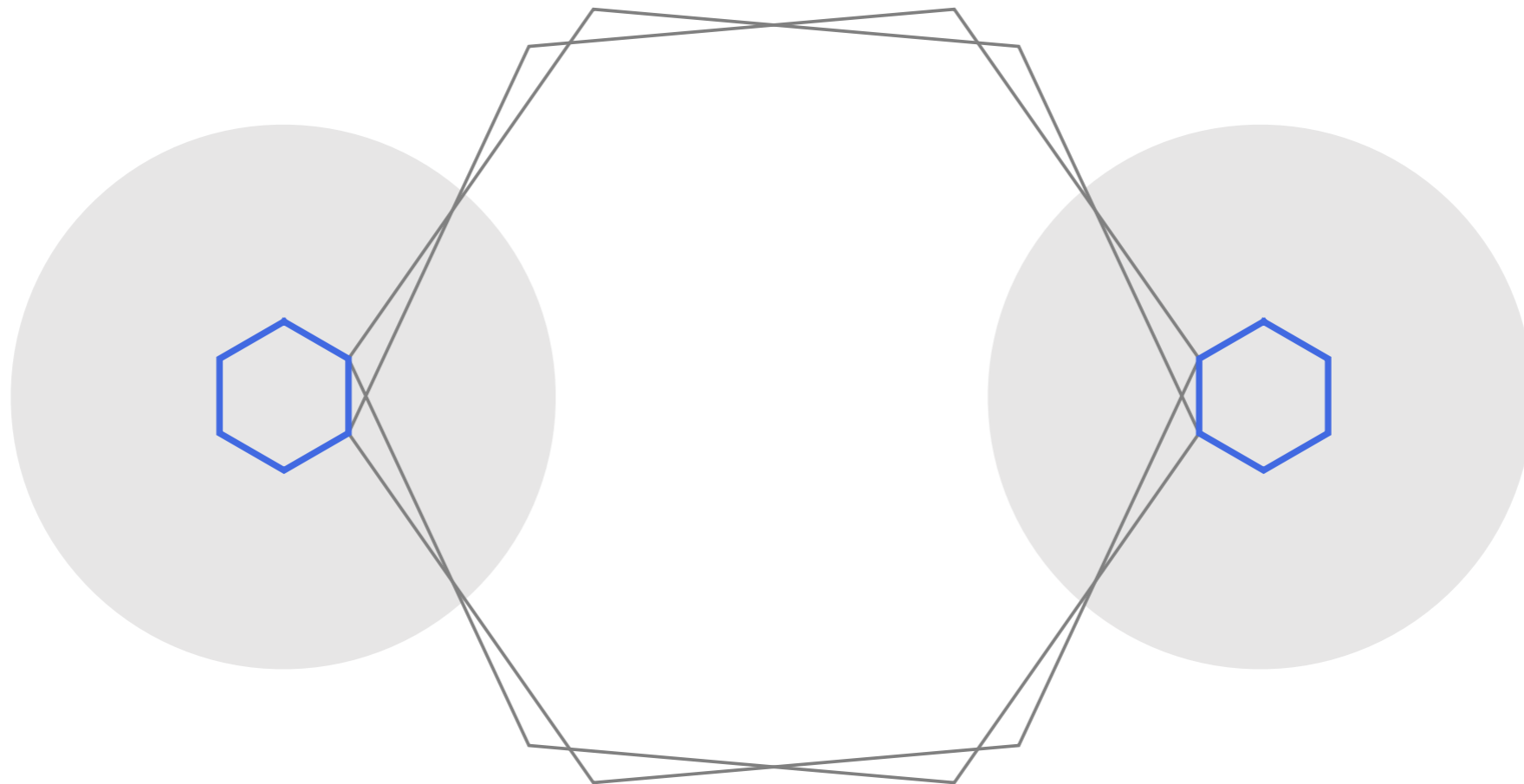


1°



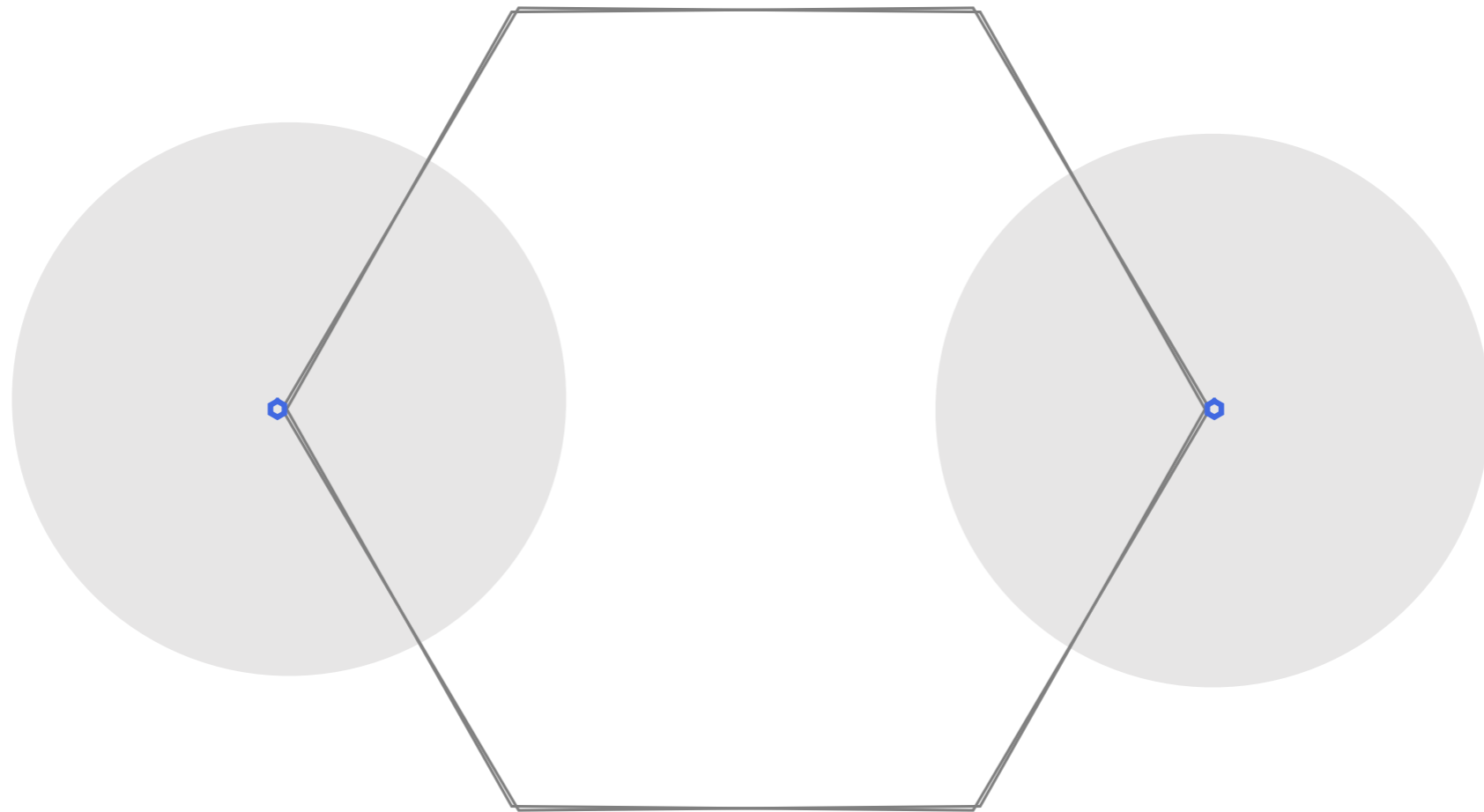
huge unit cell

Continuum model



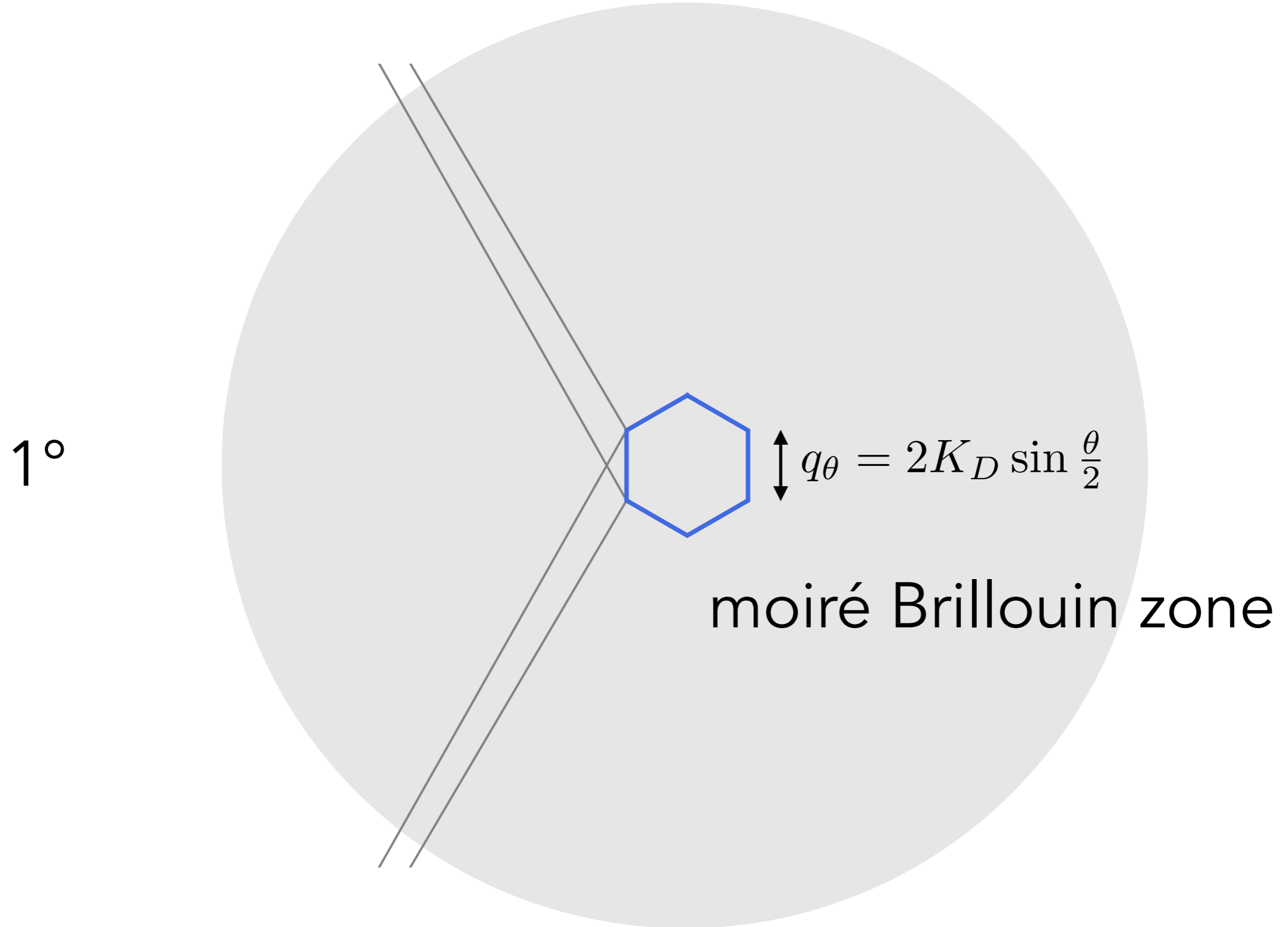
approximate single layer as Dirac cone
no mixing from one valley to the other

Continuum model



1°

One valley



Continuum model

Bistritzer+MacDonald (2011)

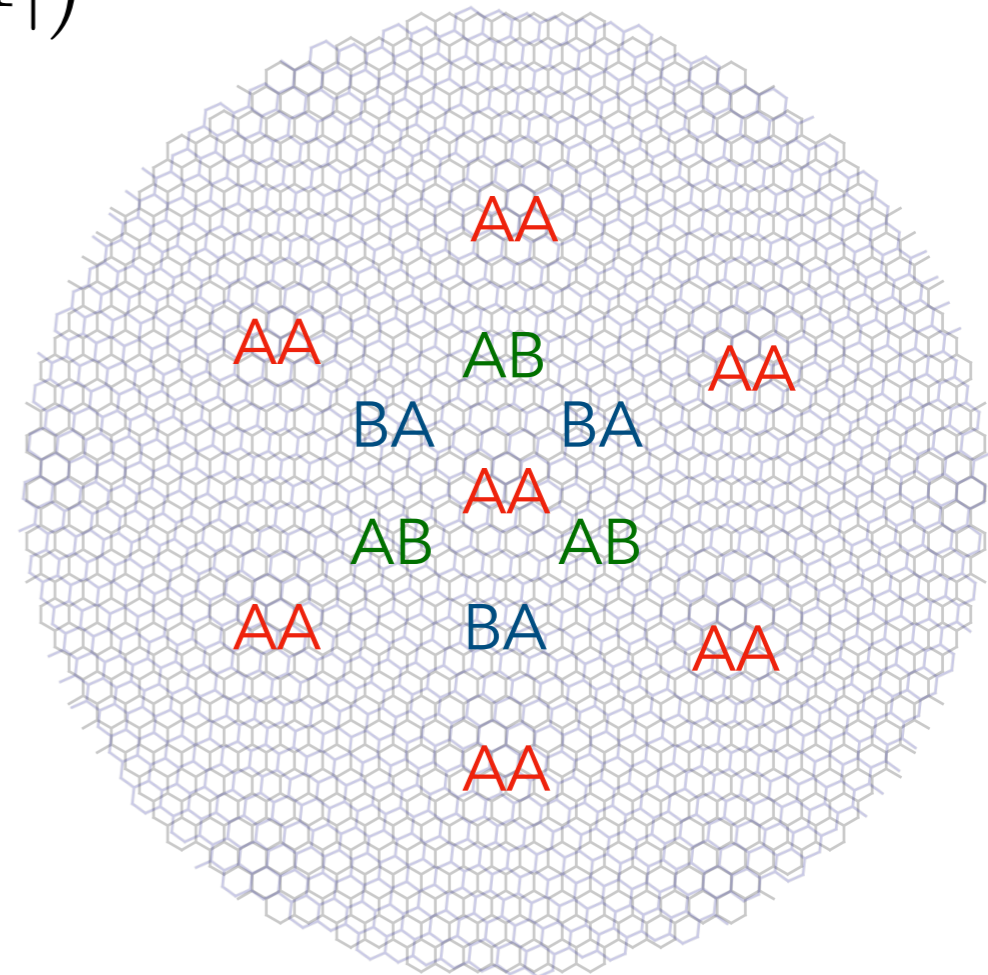
$$H = H_{\text{kin}} + H_{\text{tun}}$$

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

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

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

$$T_{\mathbf{k}\mathbf{p}'}^{\alpha\beta} = \langle \Psi_{\mathbf{k}\alpha}^{(1)} | H_T | \Psi_{\mathbf{p}'\beta}^{(2)} \rangle \quad [1]$$

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

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

and

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

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

$$\langle \mathbf{R} + \tau_\alpha | H_T | \mathbf{R}' + \tau'_\beta \rangle = t(\mathbf{R} + \tau_\alpha - \mathbf{R}' - \tau'_\beta), \quad [4]$$

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

$$T_{\mathbf{k}\mathbf{p}'}^{\alpha\beta} = \sum_{\mathbf{G}_1 \mathbf{G}_2} \frac{t_{\bar{\mathbf{k}}+\mathbf{G}_1}}{\Omega} e^{i[\mathbf{G}_1\tau_\alpha - \mathbf{G}_2(\tau_\beta - \tau) - \mathbf{G}'_2\mathbf{d}]} \delta_{\bar{\mathbf{k}}+\mathbf{G}_1, \bar{\mathbf{p}}'+\mathbf{G}'_2}. \quad [5]$$

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

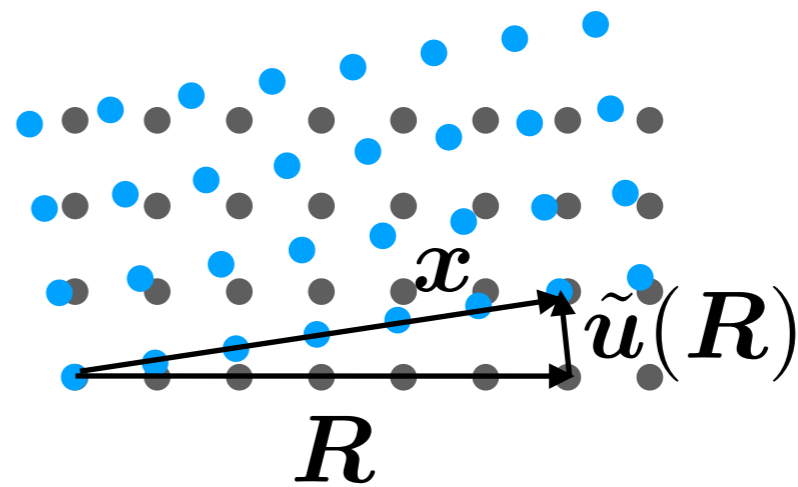
Here:

- 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

$$\theta = \frac{1}{2} (\partial_x u_y - \partial_y u_x)$$

$$\tilde{\boldsymbol{u}} = \theta \hat{\boldsymbol{z}} \times \boldsymbol{R}$$

Twisting is just a subset of elastic
deformations of two layers

Effective field theory

Locality:

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

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:

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

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:

$$\mathbf{x} = \mathbf{R} + \tilde{\mathbf{u}}(\mathbf{R}) \quad \mathbf{R} \text{ is not the actual real space location - physics is local in } \mathbf{x} \text{ not } \mathbf{R}$$

Effective field theory

Locality:

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

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

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

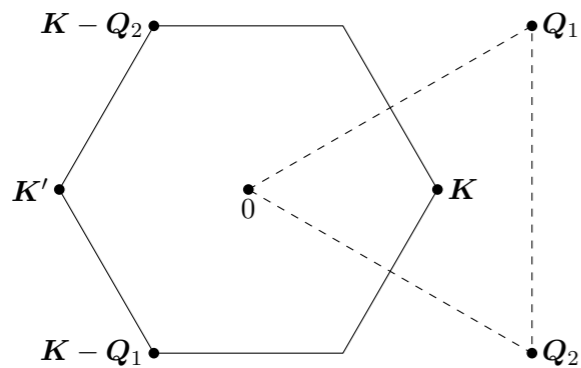
Effective field theory

- 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

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

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



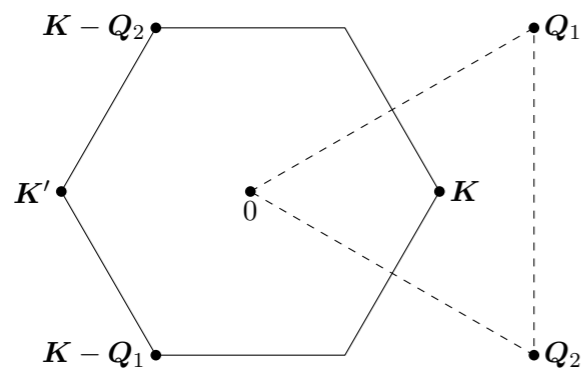
Correct to first order in strain gradients and hopping

Result

coordinate change

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

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



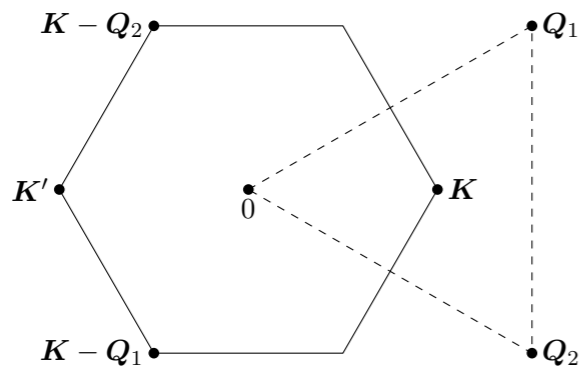
Correct to first order in strain gradients and hopping

Result

Strain gauge field

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

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

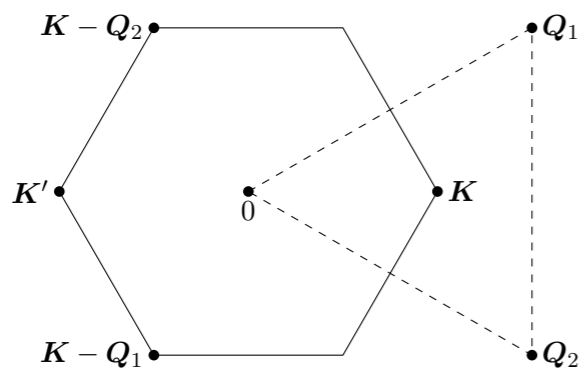


Correct to first order in strain gradients and hopping

Result

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

$$+ \sum_j \left[e^{-i\mathbf{Q}_j \cdot (\mathbf{u}_1 - \mathbf{u}_2)} \psi_2^\dagger \mathsf{T}_j \psi_1 + \text{h.c.} \right] \leftarrow \text{tunneling. Form fixed by space group symmetries}$$



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

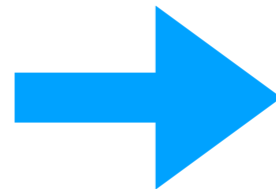
Correct to first order in strain gradients and hopping

Apply to rigid twist

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

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

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



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

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

Exactly the BM model.

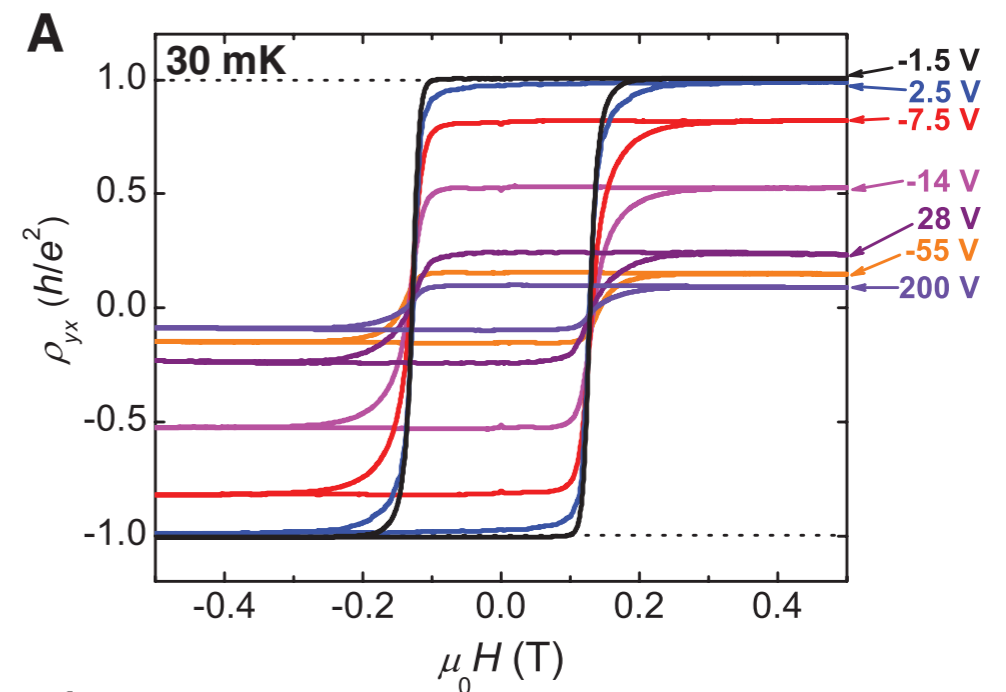
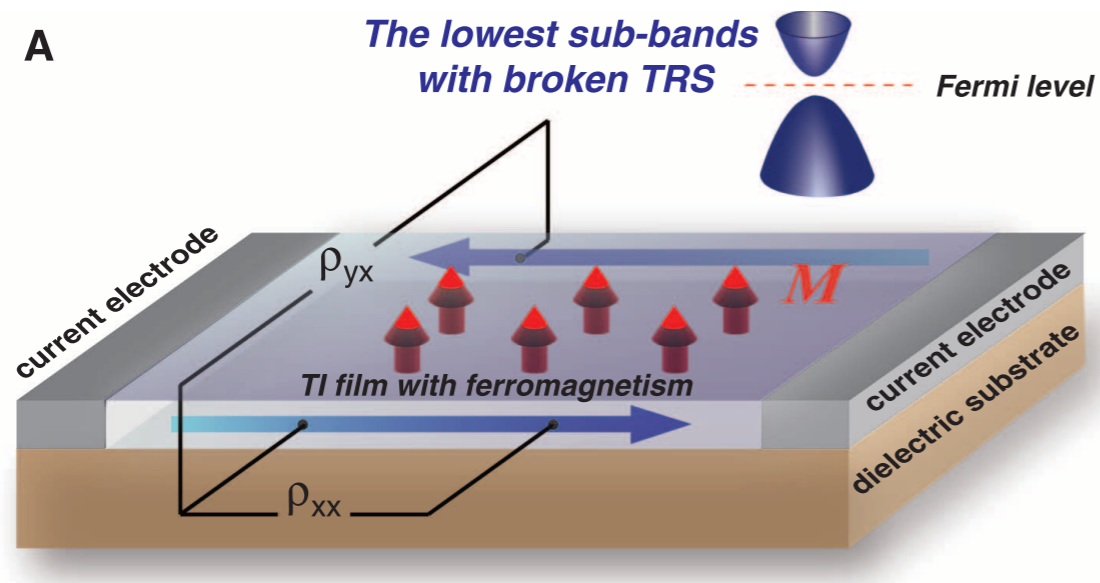
Result

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

- 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

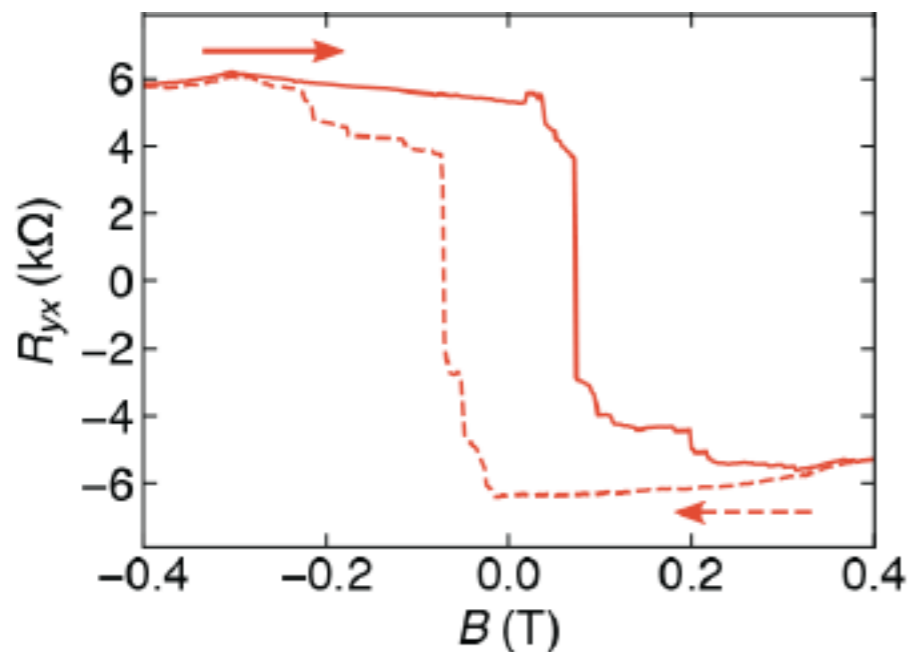


C.-Z. Zhang et al, 2013

Cr-doped $(\text{Bi/Sb})_2\text{Te}_3$

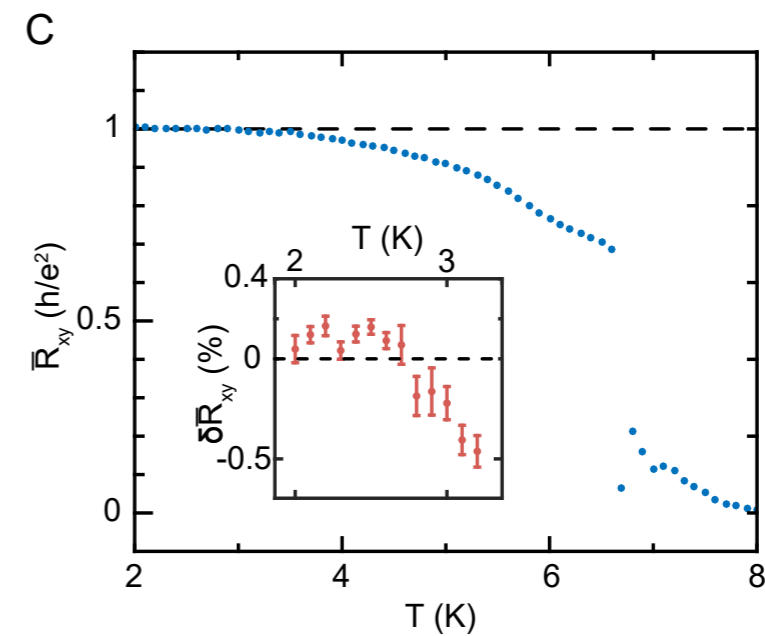
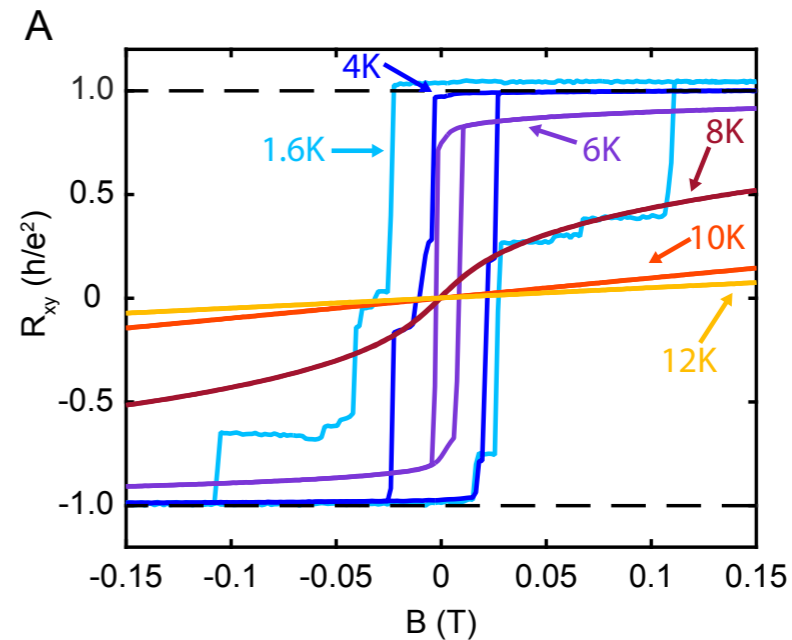
QAHE in TBG

3 e^- 's per moiré unit cell



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

Spontaneous AHE - not quite quantized

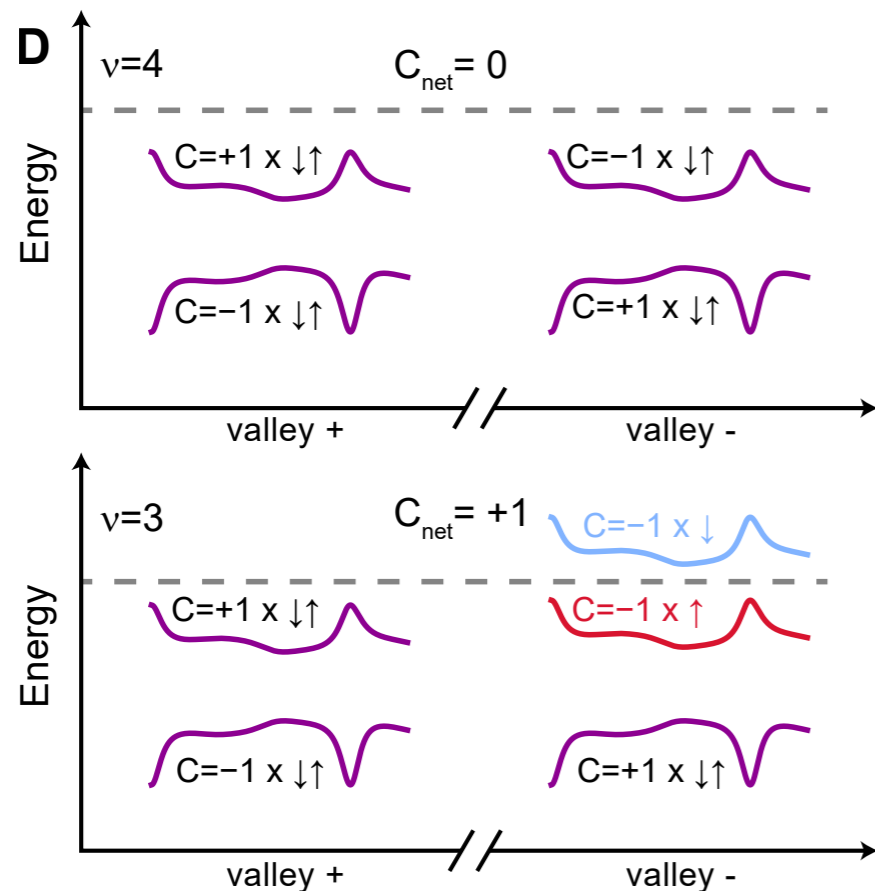


QAHE to 1/1000 accuracy

M. Serlin et al, unpublished

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)
 \times
 $SU(2)$ (spin)

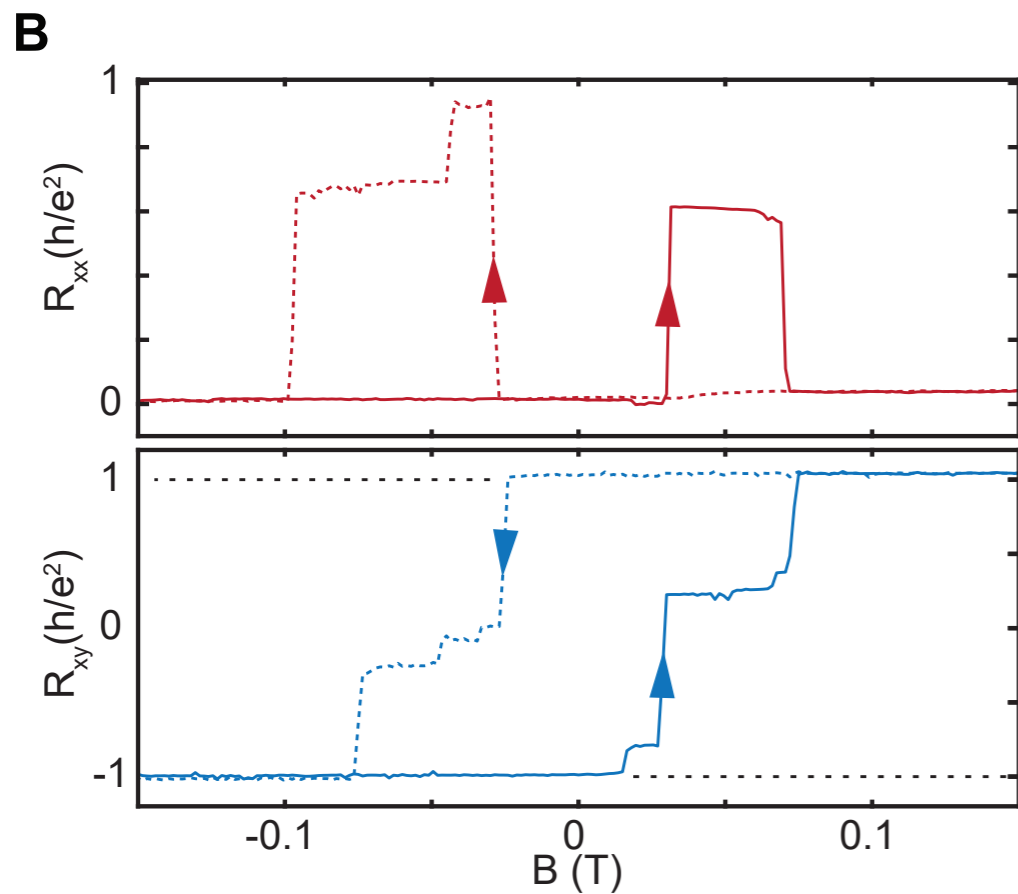
If you have any more questions...



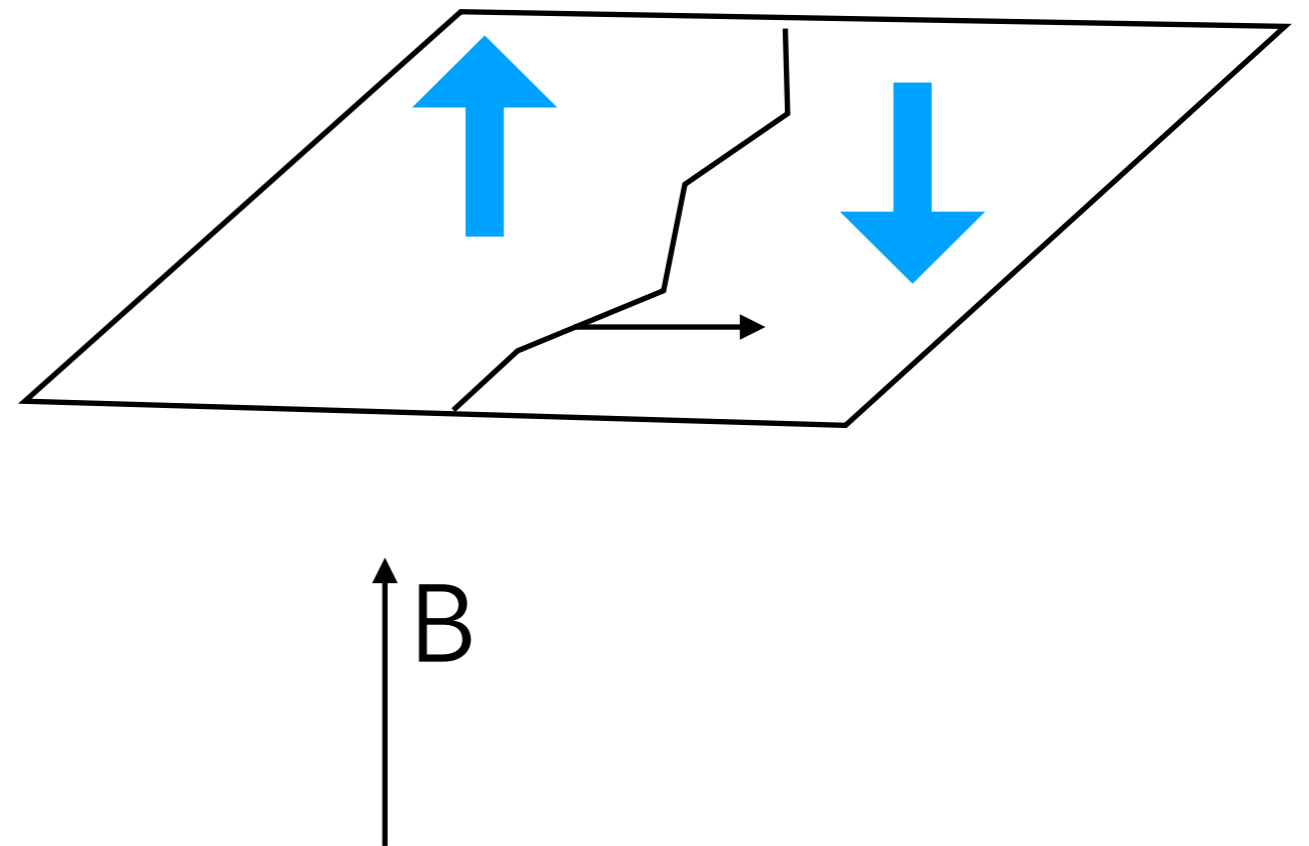
1. arXiv:1907.06282 [pdf, other] [cond-mat.str-el](#) [cond-mat.mes-hall](#)
Derivation of Wannier orbitals and minimal-basis tight-binding hamiltonians for twisted bilayer graphene: a first-principles approach
Authors: Stephen Carr, Shang Fang, Hoi Chun Po, Ashvin Vishwanath, Efthimos Kaxiras
Abstract: Twisted bilayer graphene (TBG) 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 TBG 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 mot... [View 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, Shang Jong 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 ϵ_0 in... [View 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 (tern double) bilayer graphene (TDBLG), consisting of (tern two) Bernal stacked bil... [View 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.str-el](#) [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 stabiliz... [View 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](#) [DOI](#)
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 coexist... [View More](#)
Submitted: 12 August, 2019; v1 submitted 29 January, 2019; **originally announced:** January 2019.
Comments: 5.5 pages, 4 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](#) [DOI](#)
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... [View 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](#) [DOI](#)
Faithful Tight-binding Models and Fragile Topology of Magic-angle Bilayer Graphene
Authors: Hoi Chun Po, Lijun 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... [View More](#)
Submitted: 2 June, 2018; 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](#) [DOI](#)
Band Structure of Twisted Bilayer Graphene: Emergent Symmetries, Commensurate Approximants and Wannier Obstructions
Authors: Lijun 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. $\theta \approx 1.05^\circ$). In this regime, correlated insulating states and superconductivity have been experimentally observed. A microscopic description of these phenomena requires an understanding of univ... [View 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 approximation... [View 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/PhysRevB.8.031089](#) [DOI](#)
Origin of Mott insulating behavior and superconductivity in twisted bilayer graphene
Authors: Hoi Chun Po, Lijun 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... [View More](#)
Submitted: 22 May, 2018; v1 submitted 26 March, 2018; **originally announced:** March 2018.
Comments: Main text (17 pages, 4 figures, 1 table) + Appendix; 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: Gaurav Cheri, Aaron L. Sharpe, Eli J. Fox, Ya-Hui Zhang, Shaolin Wang, Lili Jiang, Bosai Lyu, Hongyuan Li, Kenji Watanabe, Takashi Taniguchi, Zhewen 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 \mathcal{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... [View 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](#) [DOI](#)
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... [View 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, Ivan Mias, 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 $\frac{1}{2}$ 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... [View 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, Deliang Chowdhury, Daniel Rodan-Legrain, Oriol Rubies-Bigorda, 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 Z — linear resistivity above a small, density dependent, crossover temperature — for... [View 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](#) [DOI](#)
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 (TGH-BN) provides an interesting system where both the bandwidth and the topology can be tuned by an applied perpendicular electric field D_\perp . Thus the TGH-BN system can simulate both Hubbard model physics and nearly flat Chern band physics within one sample. We derive lattice models... [View More](#)
Submitted: 1 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](#) [DOI](#)
Faithful Tight-binding Models and Fragile Topology of Magic-angle Bilayer Graphene
Authors: Hoi Chun Po, Lijun 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... [View More](#)
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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](#) [DOI](#)
Band Structure of Twisted Bilayer Graphene: Emergent Symmetries, Commensurate Approximants and Wannier Obstructions
Authors: Lijun Zou, Hoi Chun Po, Ashvin Vishwanath, T. Senthil
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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



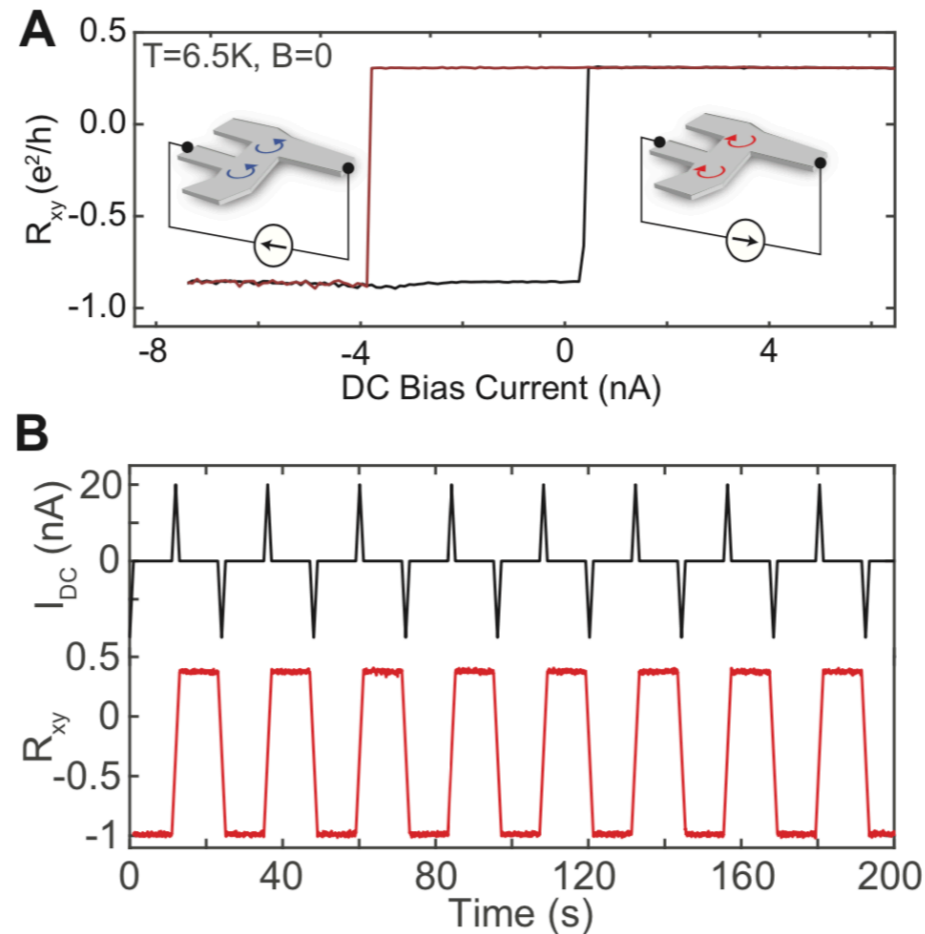
B field biases energy of domains



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

n.b. domains are *valley* domains

Domain manipulation



(tiny)

Current switches domains. How does this work?

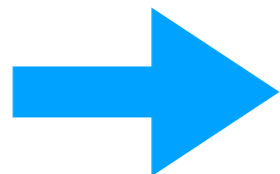
Current



Well-developed IQHE:

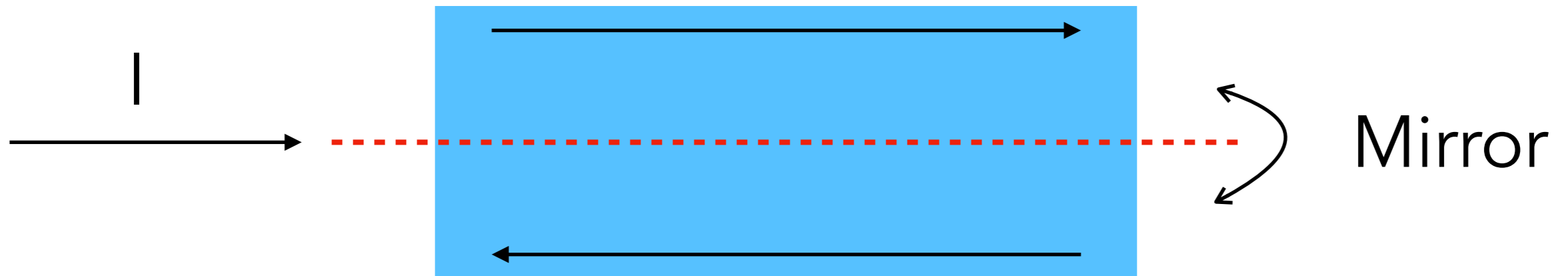
- no dissipation, only edge state transport
- Charge of each edge is separately conserved

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



Can formulate $F(I, M)$

(A)symmetry



$I \rightarrow I$ vector
 $M \rightarrow -M$ pseudovector

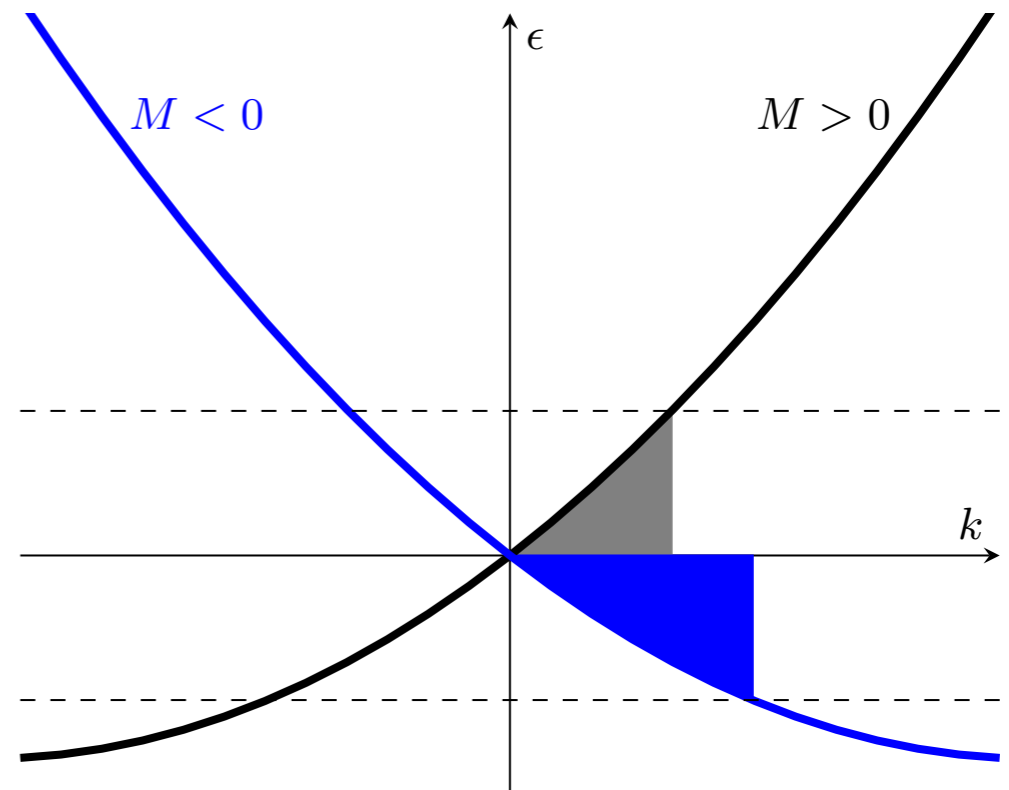
Energetics

Simple limit: one "fast" (costly) edge

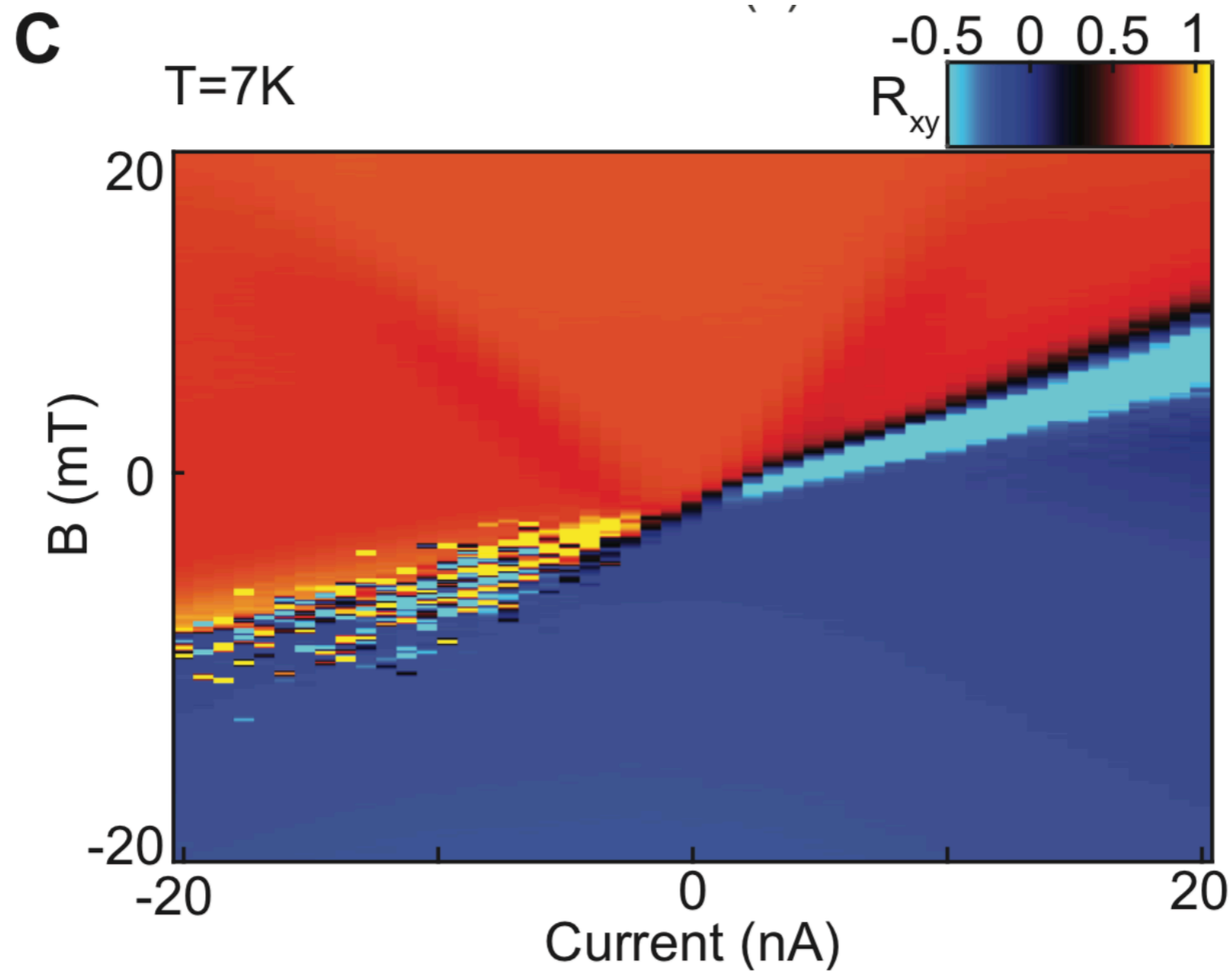
$I > 0$:

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

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

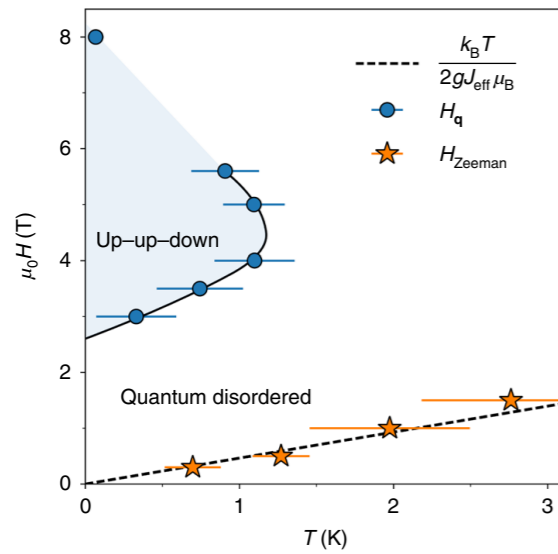


Dissipative Regime



A fully non-equilibrium problem, bulk 2d physics

Thanks

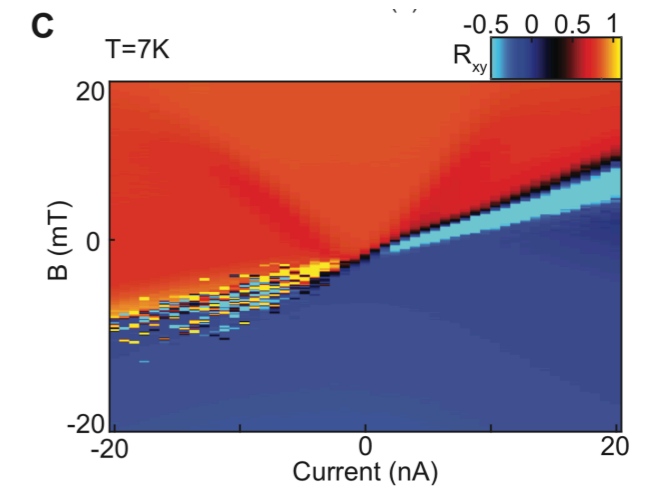


M. Bordelon et al, Nat. Phys. (2019)

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

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

L.B., arXiv:1909.01545



M. Serlin et al, arXiv:1907.00261

