Engineering topological flat bands with a superlattice potential

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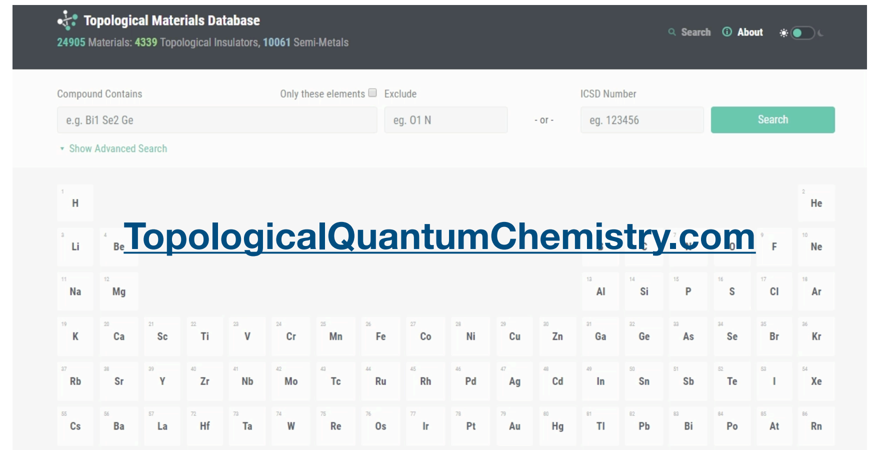
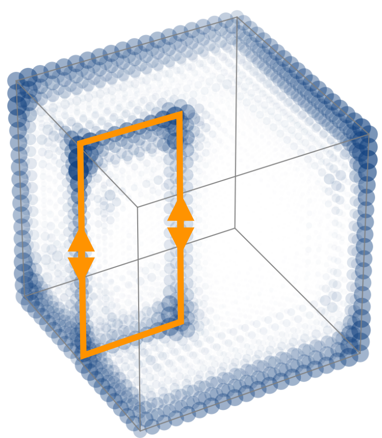
ALFRED P. SLOAN FOUNDATION

Cano group: topological materials

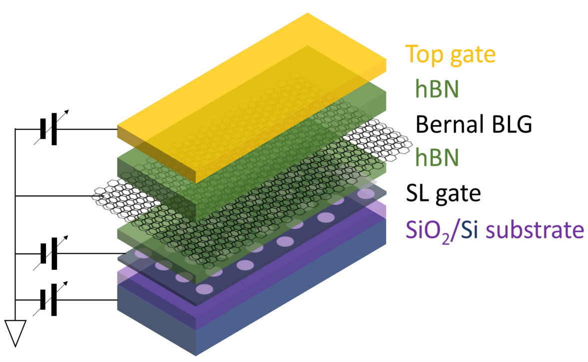


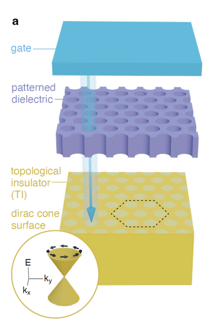
Topological quantum chemistry:
classify and predict topological materials

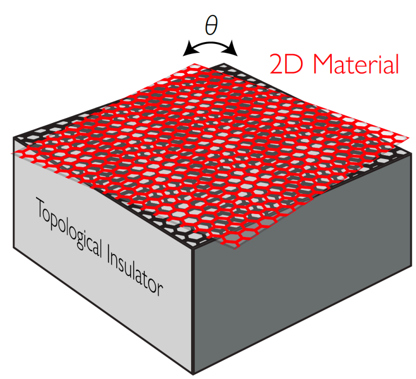


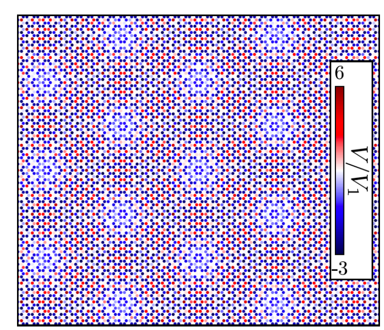
Higher order topology:
new materials and new probes

Moiré and superlattice heterostructures: topology by design









Engineering topological flat bands with a superlattice potential: outline

1. Bilayer graphene in a superlattice potential yields topological flat bands

Ghorashi, Dunbrack, Abouelkomsan, Sun, Du, **JC**
PRL 130, 196201 (2023);
Ghorashi and **JC** PRB 107, 195423 (2023);

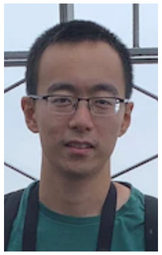
Sayed Ghorashi

Aaron Dunbrack

2. Spontaneous symmetry breaking: preliminary evidence

(a) Quantum anomalous Hall effect at integer filling

(b) Fractional Chern insulator at ν = 1/3



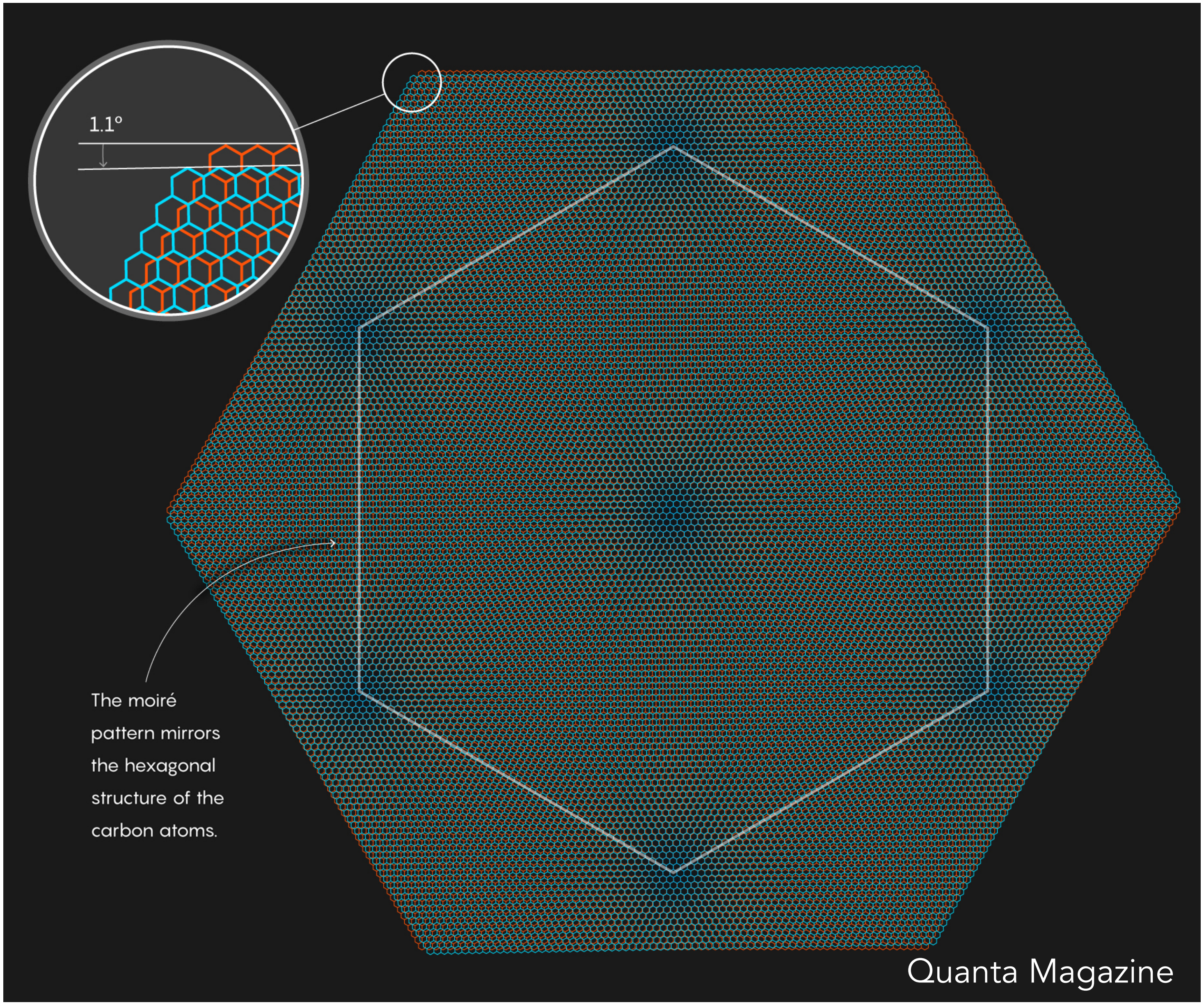
Yongxin Zeng
(Austin → Columbia)

3. Experimental data

Sun, Ghorashi, Watanabe, Taniguchi, Camino,
JC, Du ArXiv 2306.06848

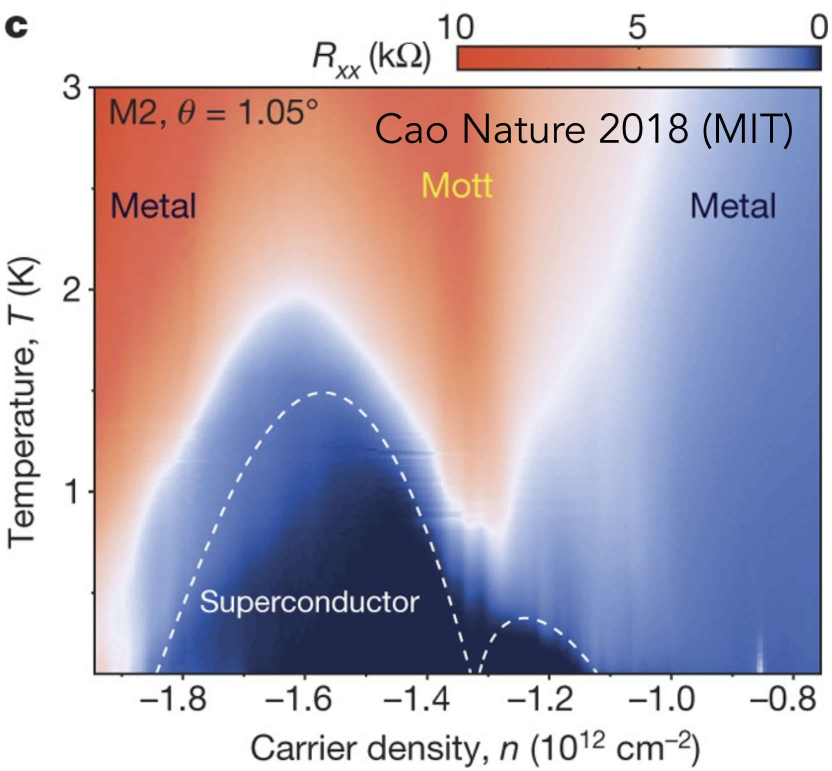
Ahmed Abouelkomsan
(Stockholm → MIT)

Motivation: twisted bilayer graphene

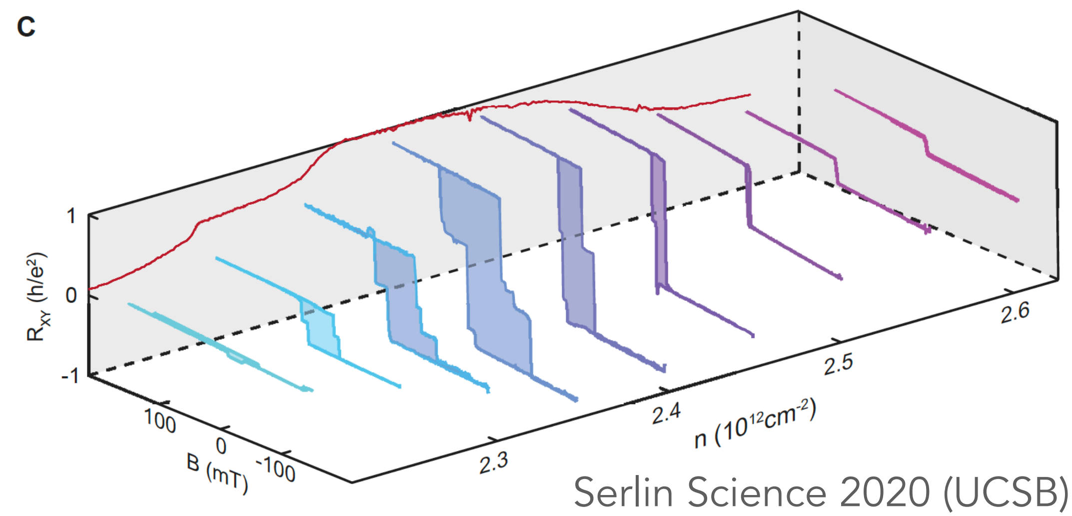


Motivation: twisted bilayer graphene

Superconductivity



Quantum anomalous Hall

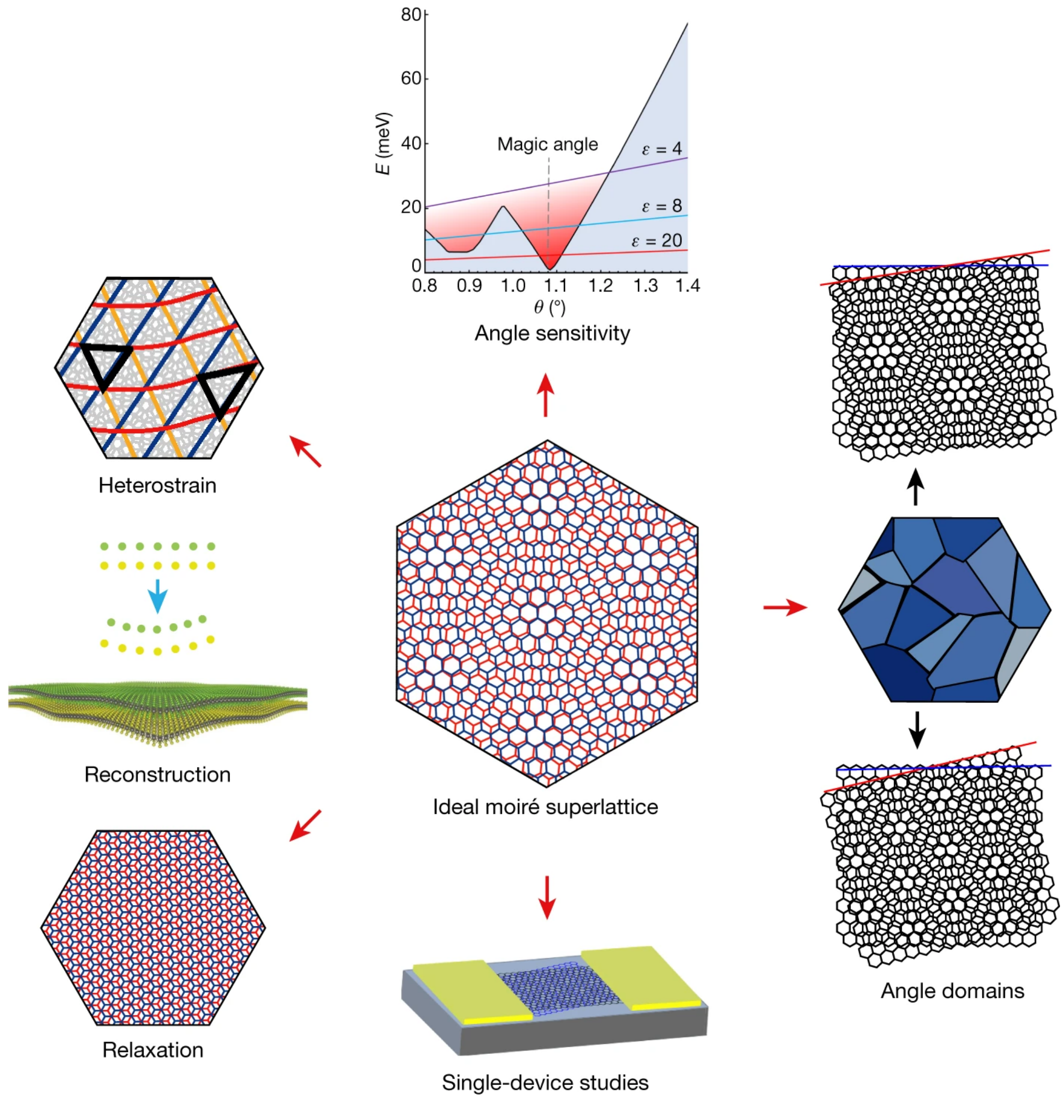


Serlin Science 2020 (UCSB)

The whole is greater than the sum of its parts

Twisted bilayer graphene also comes with challenges

Lau, Bockrath, Mak, Zhang Nature 602, 41 (2022)

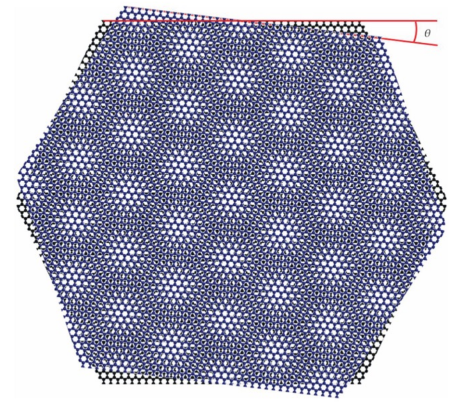


Motivates investigation into alternative platforms

What are the defining features?

Two layers of graphene

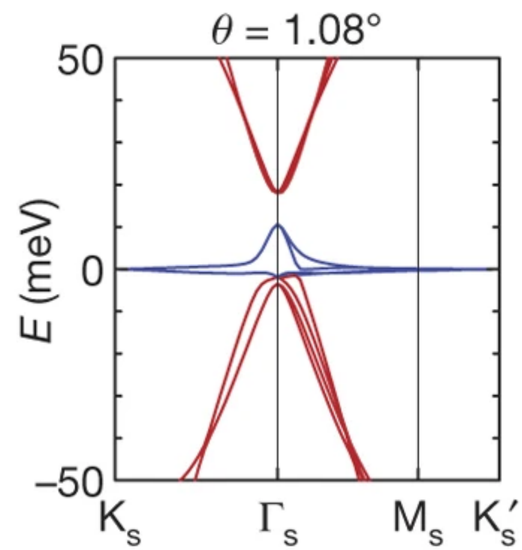
Large superlattice



$\Downarrow$

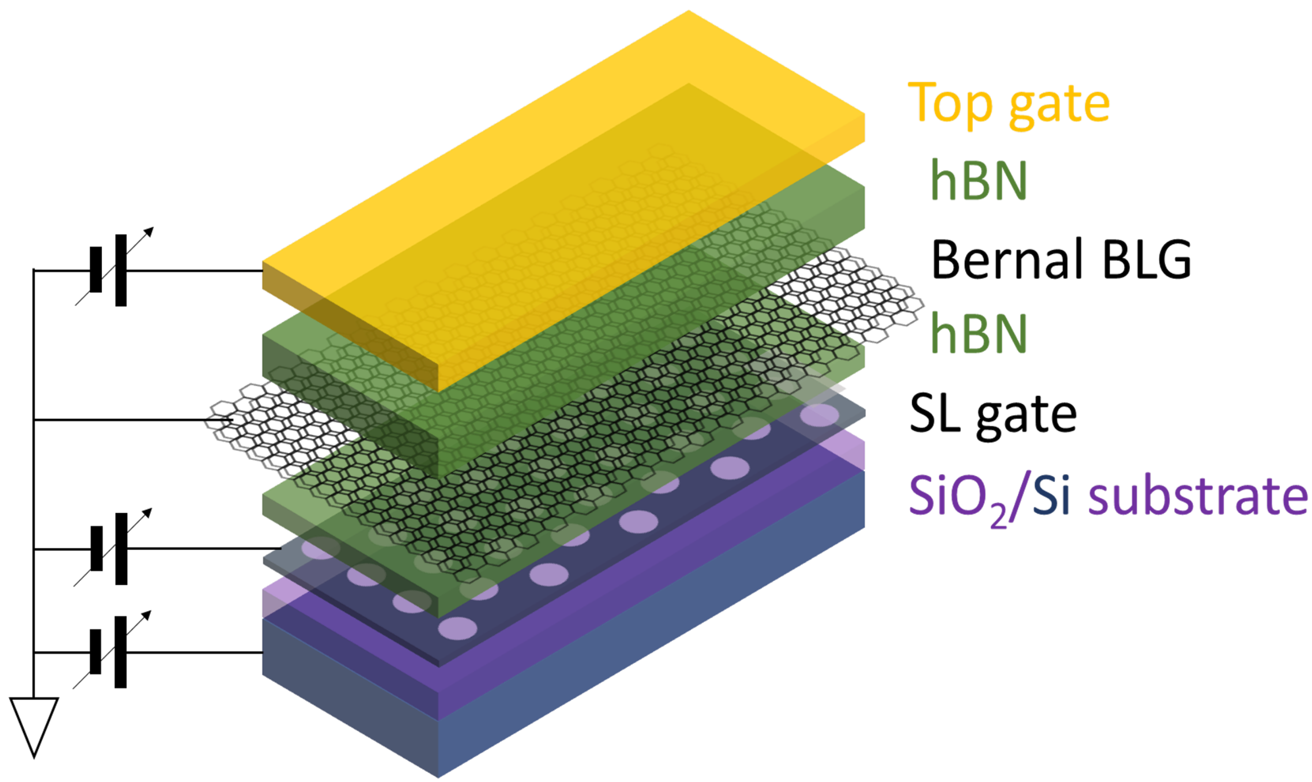
Dispersionless electrons

"flat bands"



We propose an alternative to twisted bilayer graphene:

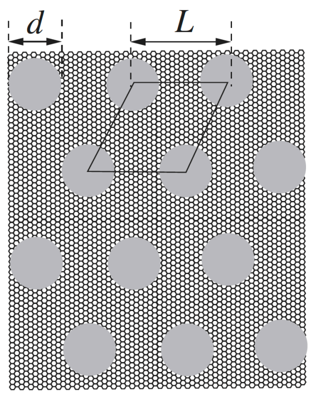
bilayer graphene with a superlattice potential

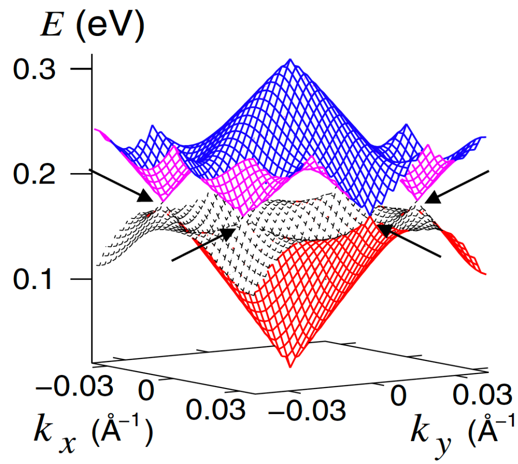


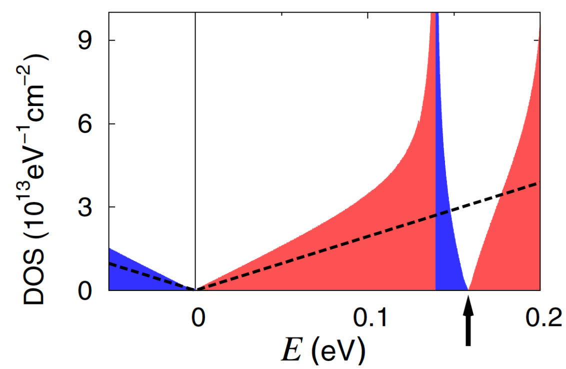
Ghorashi, Dunbrack, Abouelkomsan, Sun, Du, **JC** PRL 130, 196201 (2023)

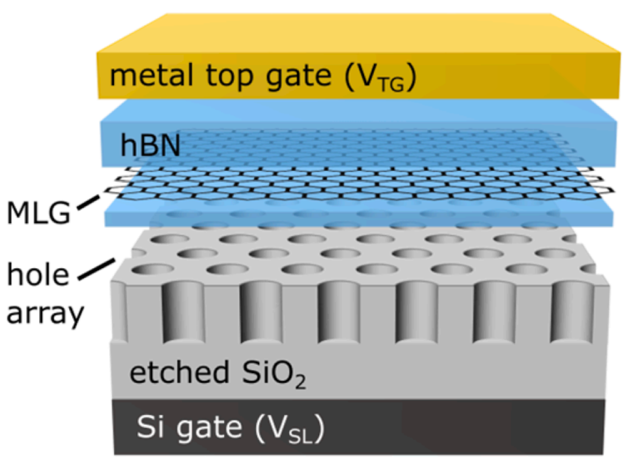
Previously: superlattice on monolayer graphene

Park et al, Cohen/Louie group: Nat. Phys. 4, 213 (2008); PRL 101, 126804 (2008)

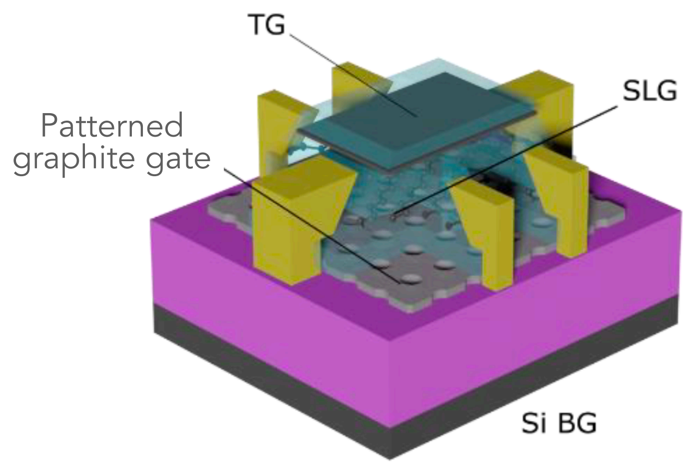








Dielectric patterning: L ~ 35nm
Dean group, *Nat. Nanotech* (2018)

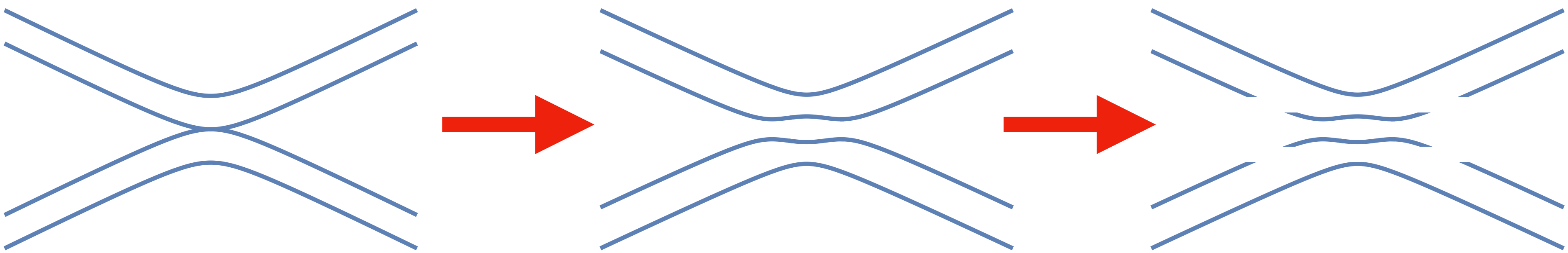


Patterned graphite gate: L ~ 18nm
Koppens group, ArXiv: 2207.14027

Spoiler:

Superlattice on BLG drives topological flat bands

Bilayer graphene + Electric field + Superlattice potential

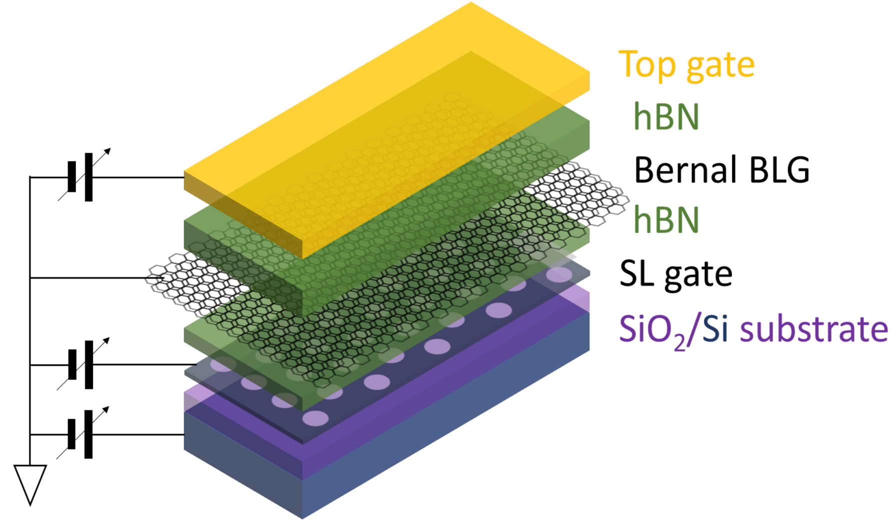


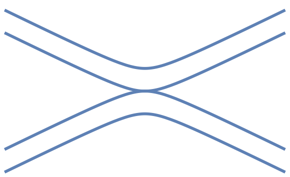
Semimetal — Topological bands — Topological flat bands

Ghorashi, Dunbrack, Abouelkomsan, Sun, Du, **JC** PRL 130, 196201 (2023)

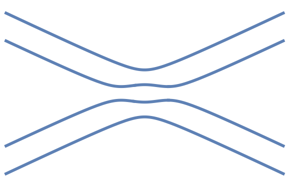
Continuum model

$$\hat{H} = \hat{H}_{BLG} + \hat{H}_{V_0} + \hat{H}_{SL}$$

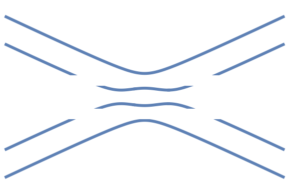




$$H_{BLG}(\mathbf{r}) = \hbar v \tau^0(-i\partial_x\sigma^1 - i\partial_y\sigma^2) + \frac{t}{2}(\tau^1\sigma^1 - \tau^2\sigma^2)$$

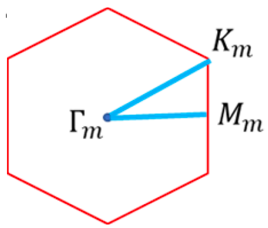


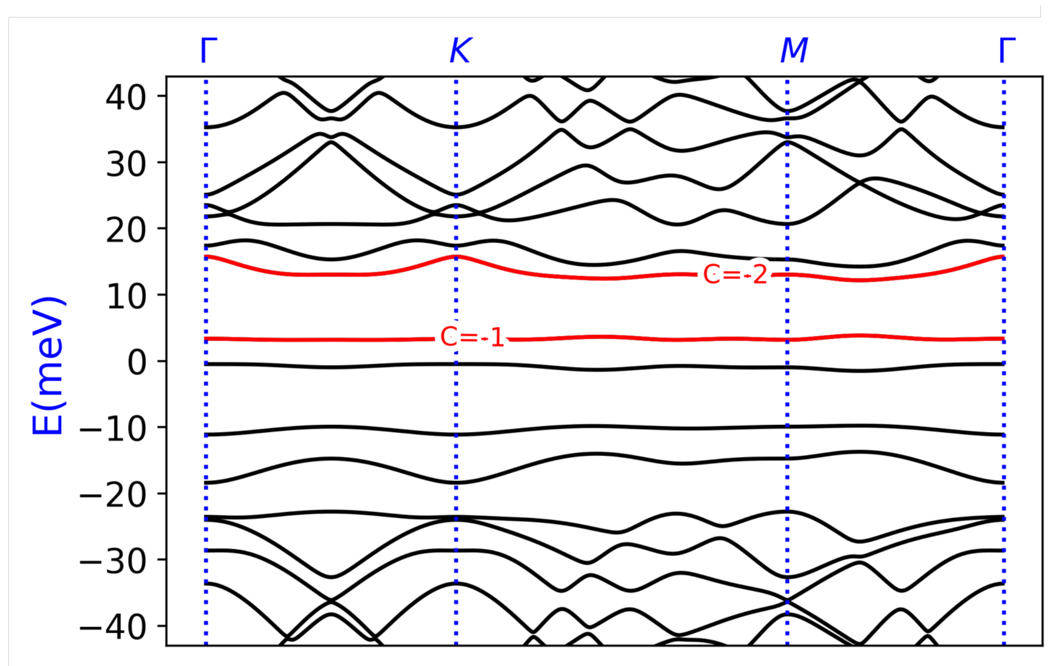
$$H_{V_0}(\mathbf{r}) = V_0\tau^3\sigma^0$$



$$H_{SL}(\mathbf{r}) = V_{SL}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \alpha & 0 \\ 0 & 0 & 0 & \alpha \end{pmatrix}\sigma^0 \sum_n \cos(\mathbf{Q}_n \cdot \mathbf{r})$$

Results: verify topological flat band





Higher Chern number C=2 band

Flat Chern band

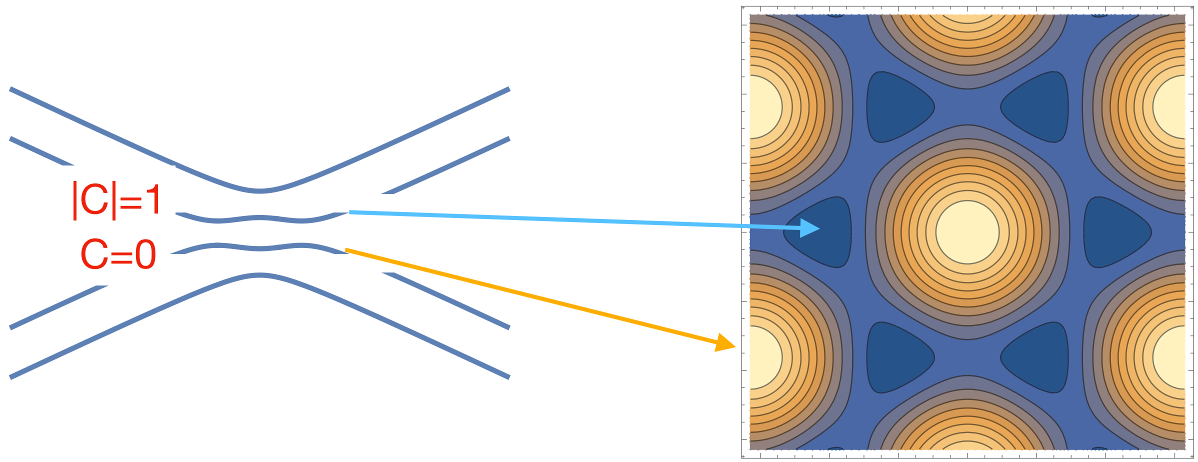
$L = 50$ nm

$V_0 = -5$ meV

$V_{SL} = 10$ meV

Ghorashi, Dunbrack, Abouelkomsan, Sun, Du, **JC** PRL 130, 196201 (2023)

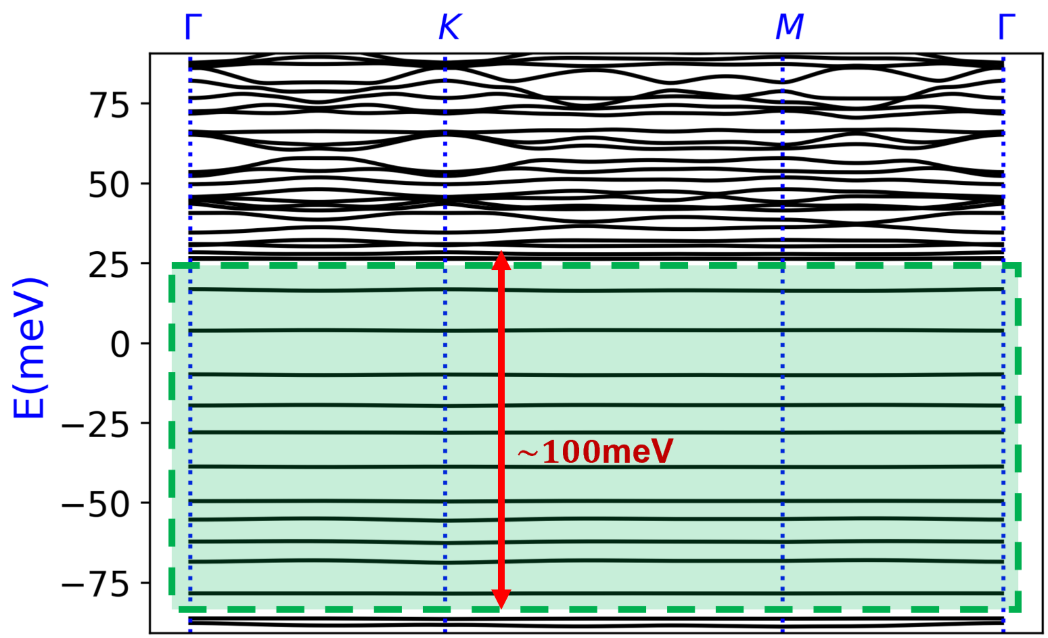
Particle-hole asymmetry from triangular superlattice



Conduction electrons localized near potential minima → honeycomb lattice

Valence band holes localized near potential maxima → triangular lattice

Larger fields: stack of (trivial) flat bands



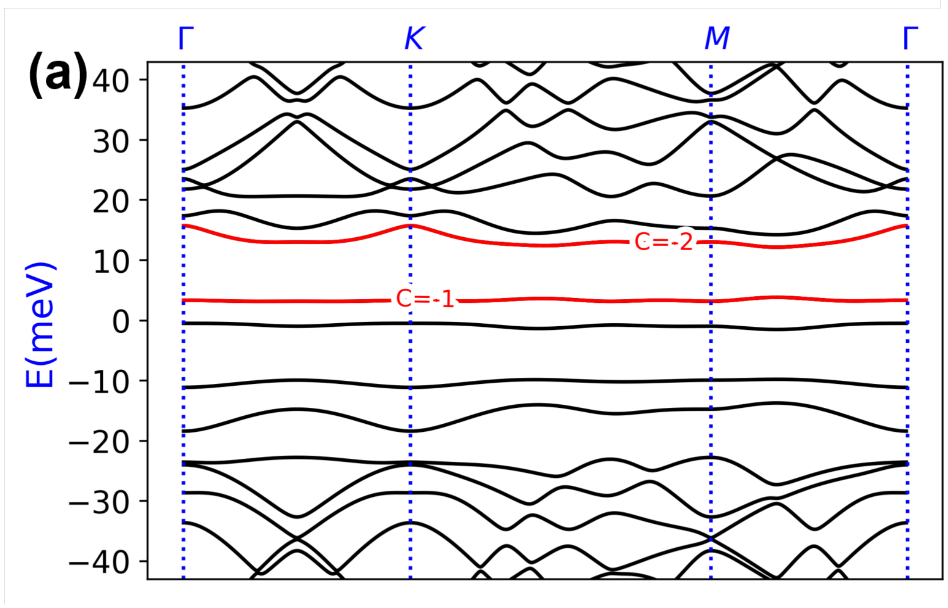
$$L = 50 \text{ nm}$$

$$V_0 = -70 \text{ meV}$$

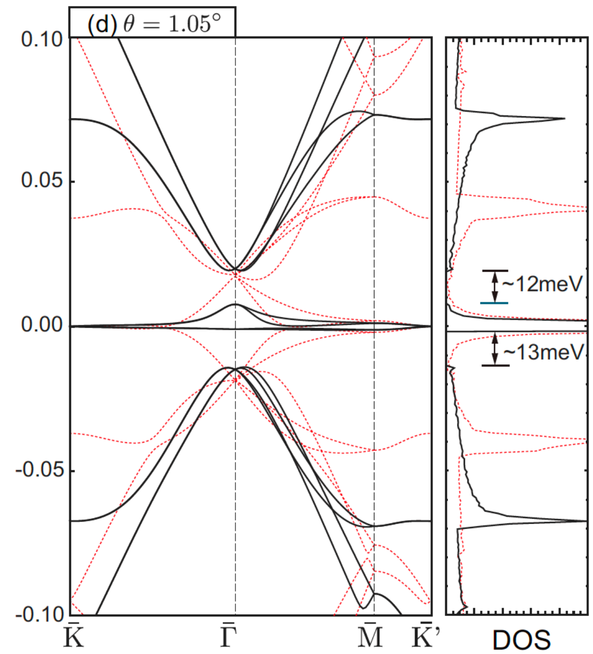
$$V_{SL} = 50 \text{ meV}$$

Ghorashi, Dunbrack, Abouelkomsan, Sun, Du, **JC** PRL 130, 196201 (2023)

Comparison: BLG w/ superlattice potential vs TBG



Ghorashi, Dunbrack, Abouelkomsan, Sun, Du, **JC** PRL 130, 196201 (2023)



Nam and Koshino, PRB 96, 075311 (2017)

Flat-ish Chern bands robust over region of potentials
Requires order over large length scales
Superlattice engineering: flexibility in geometry / length

Fine-tune to magic angle
Twist angle disorder
Naturally hits a sweet spot!

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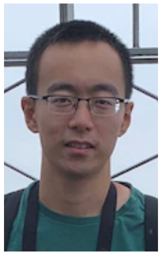
(a) Quantum anomalous Hall effect at integer filling

(b) Fractional Chern insulator at $\nu = 1/3$



Yongxin Zeng
(Austin → Columbia)

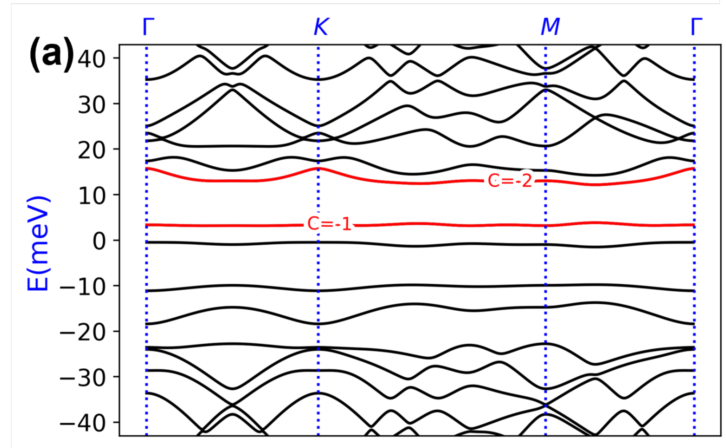
3. Experimental data

Sun, Ghorashi, Watanabe, Taniguchi, Camino,
JC, Du ArXiv 2306.06848

Ahmed Abouelkomsan
(Stockholm → MIT)

What happens at integer filling?

Spin and valley degenerate flat bands ⇒ 4x degeneracy



K ↑, C=-1 K ↓, C=-1 K′ ↑, C=+1 K′ ↓, C=+1

At $\boldsymbol{\nu}$ = 1: expect "spin-valley ferromagnet" ⇒ quantum anomalous Hall

K ↑, C=-1 K ↓, C=-1 K′ ↑, C=+1

K′ ↓, C=+1

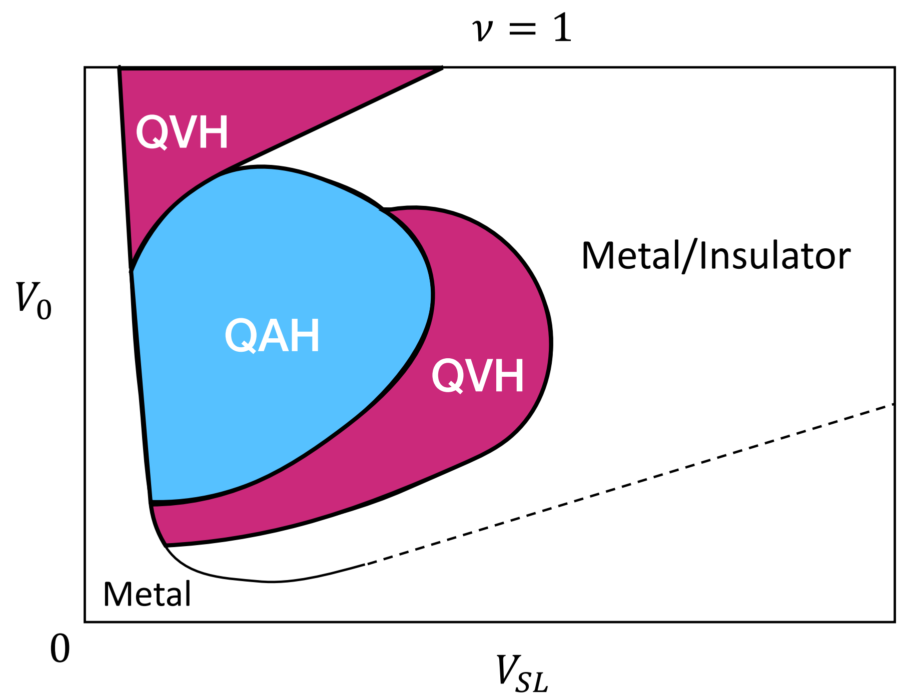
Spontaneous symmetry breaking @ ν = 1 → quantum anomalous Hall

K ↑, C=-1

K ↓, C=-1

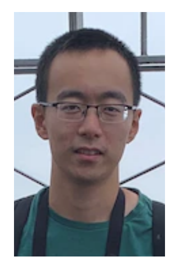
K’ ↑, C=+1

K’ ↓, C=+1

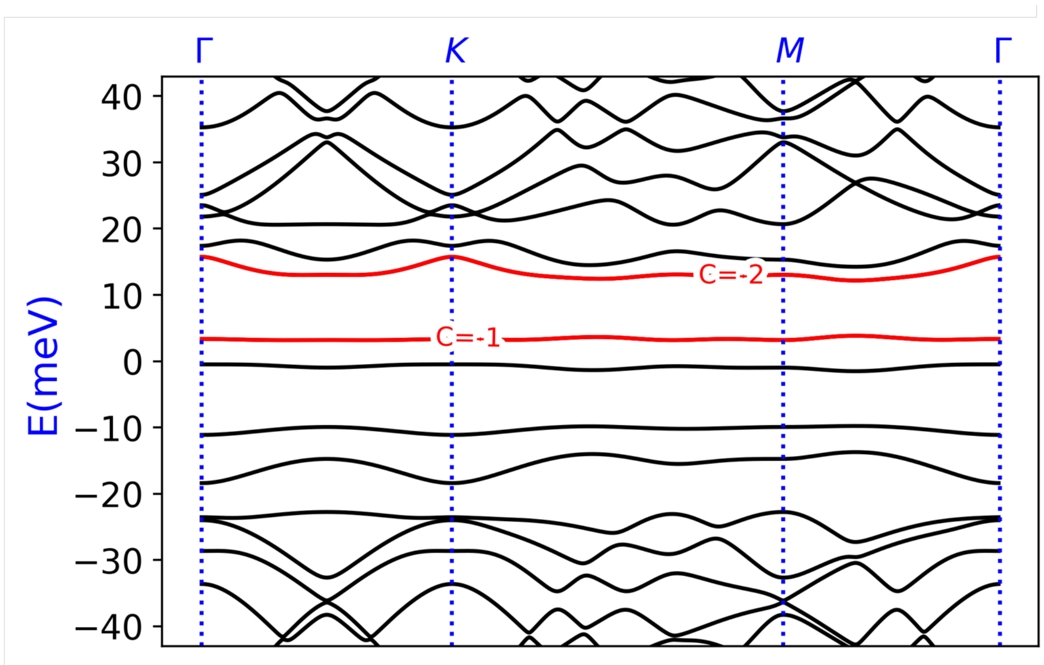


Gate-tunable topological phase transition

Preliminary Hartree-Fock phase diagram
By Yongxin Zeng, UT Austin/Flatiron Institute



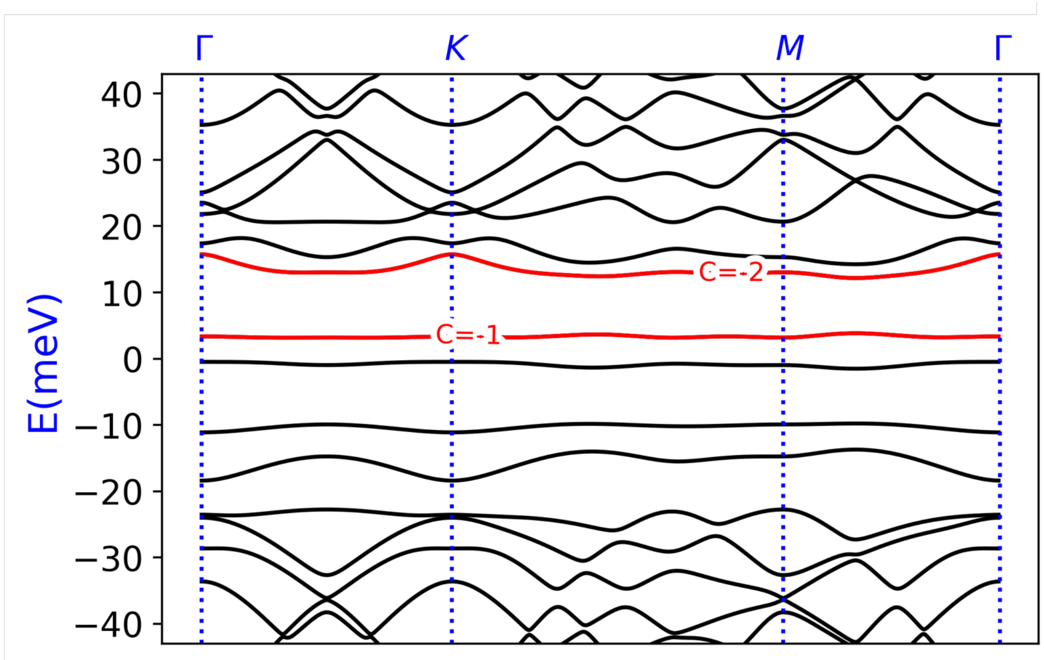
What happens when Chern band is fractionally filled?



… is the ground state a fractional Chern insulator?

“Indicators” for a fractional Chern insulator

- **Small bandwidth** ✅
- Small Berry curvature fluctuations
- Near-“ideal” band geometry



“Indicators” for a fractional Chern insulator

- Small bandwidth ✅
- Small Berry curvature fluctuations
- **Near-“Ideal” band geometry** ✅

$$T(\boldsymbol{k}) = \mathrm{tr}\, g(\boldsymbol{k}) - |\Omega(\boldsymbol{k})|$$

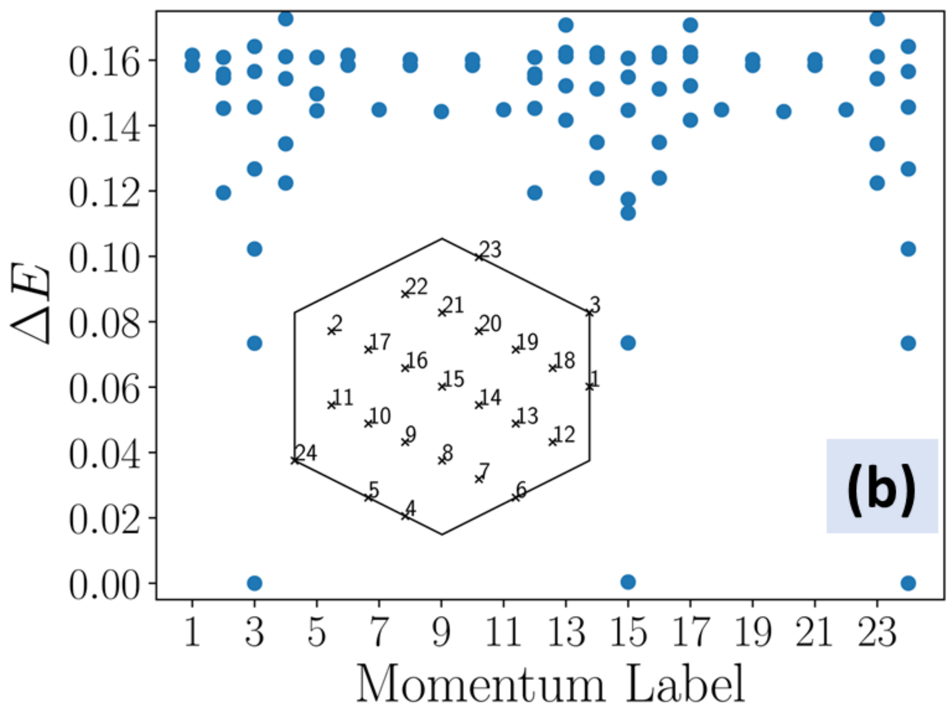
$\bar{T} = \langle T(\mathbf{k}) \rangle_{BZ} = 0$: defines an “ideal” Chern band

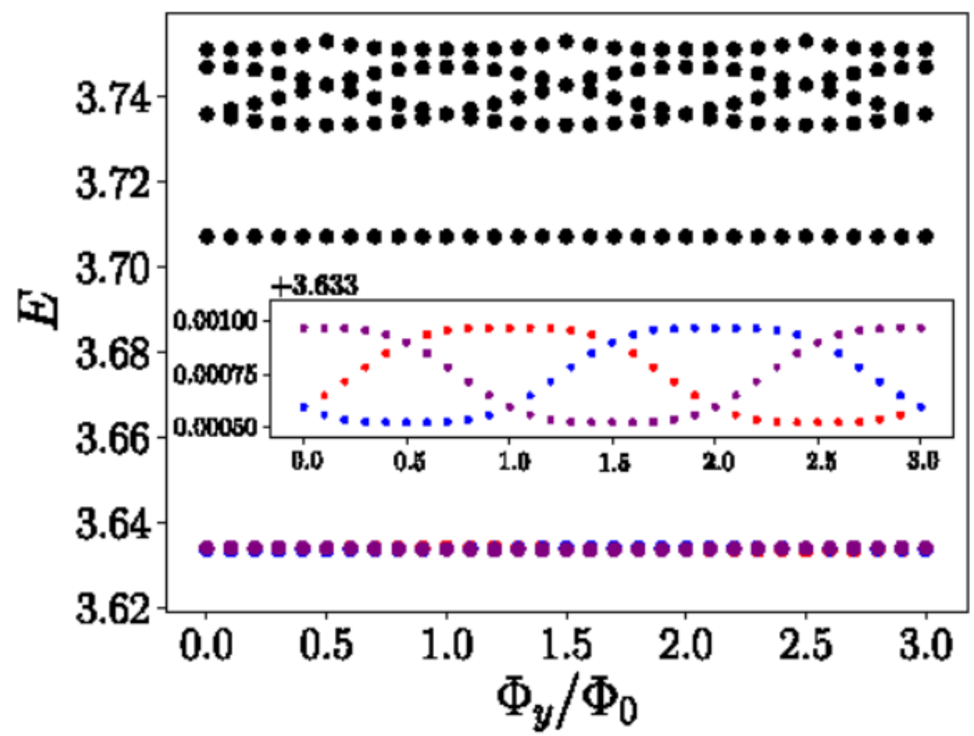
Chiral TBG	**“Realistic” TBG**	**BLG with SL**
$\bar{T} = 0$	$\bar{T} = 3 - 4$	$\bar{T} = 2.15$

Refs: Ledwith, Tarnopolski, Khalaf, Vishwanath PRR 2020
Wang, **JC**, Millis, Liu, Yang PRL 2021

Exact diagonalization reveals fractional Chern insulator at $\nu = 1/3$

(Preliminary)





Preliminary calculation by Ahmed Abouelkomsan (Stockholm U)

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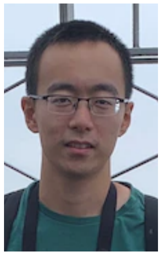

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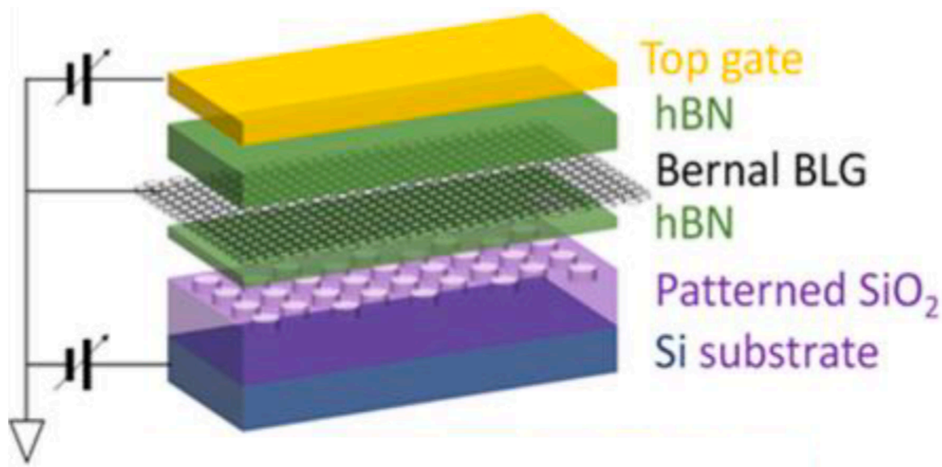
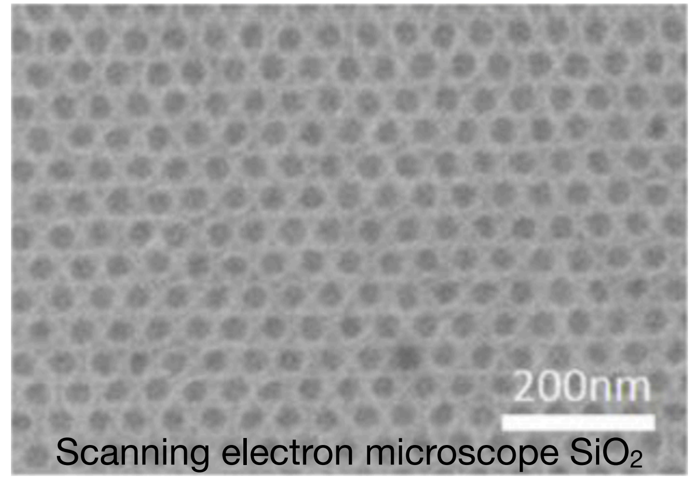
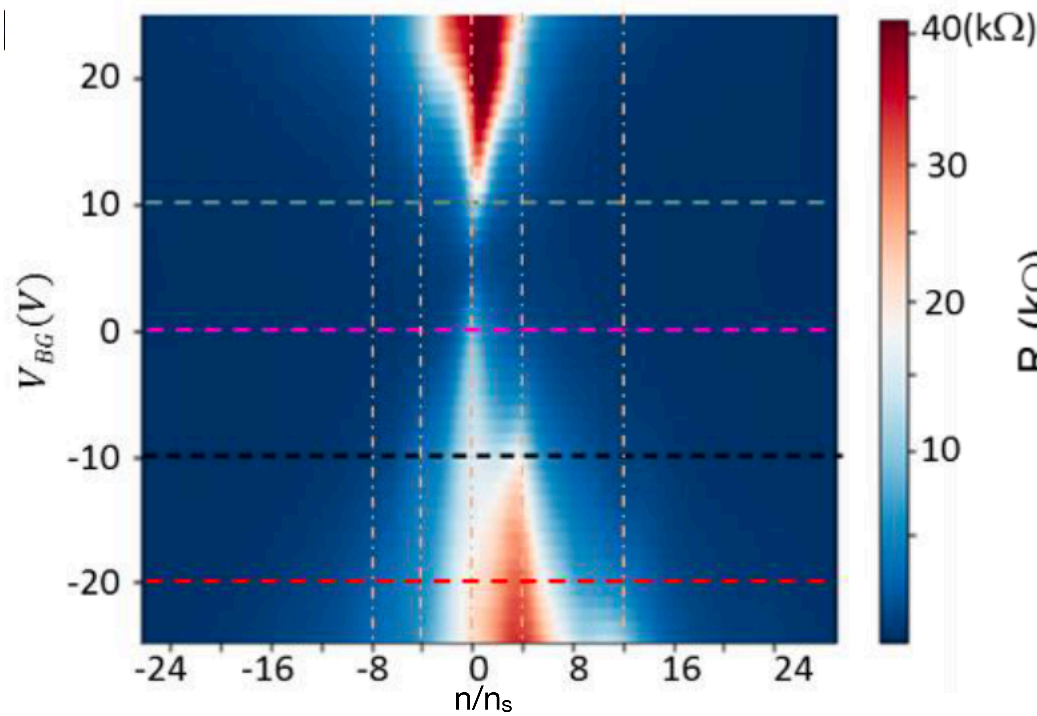
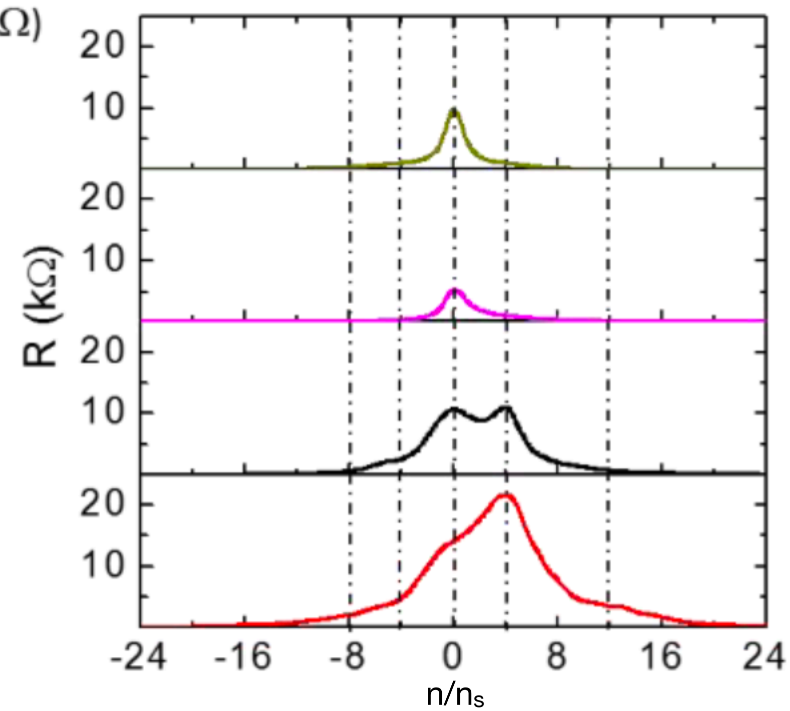
First experimental realization of superlattice on BLG



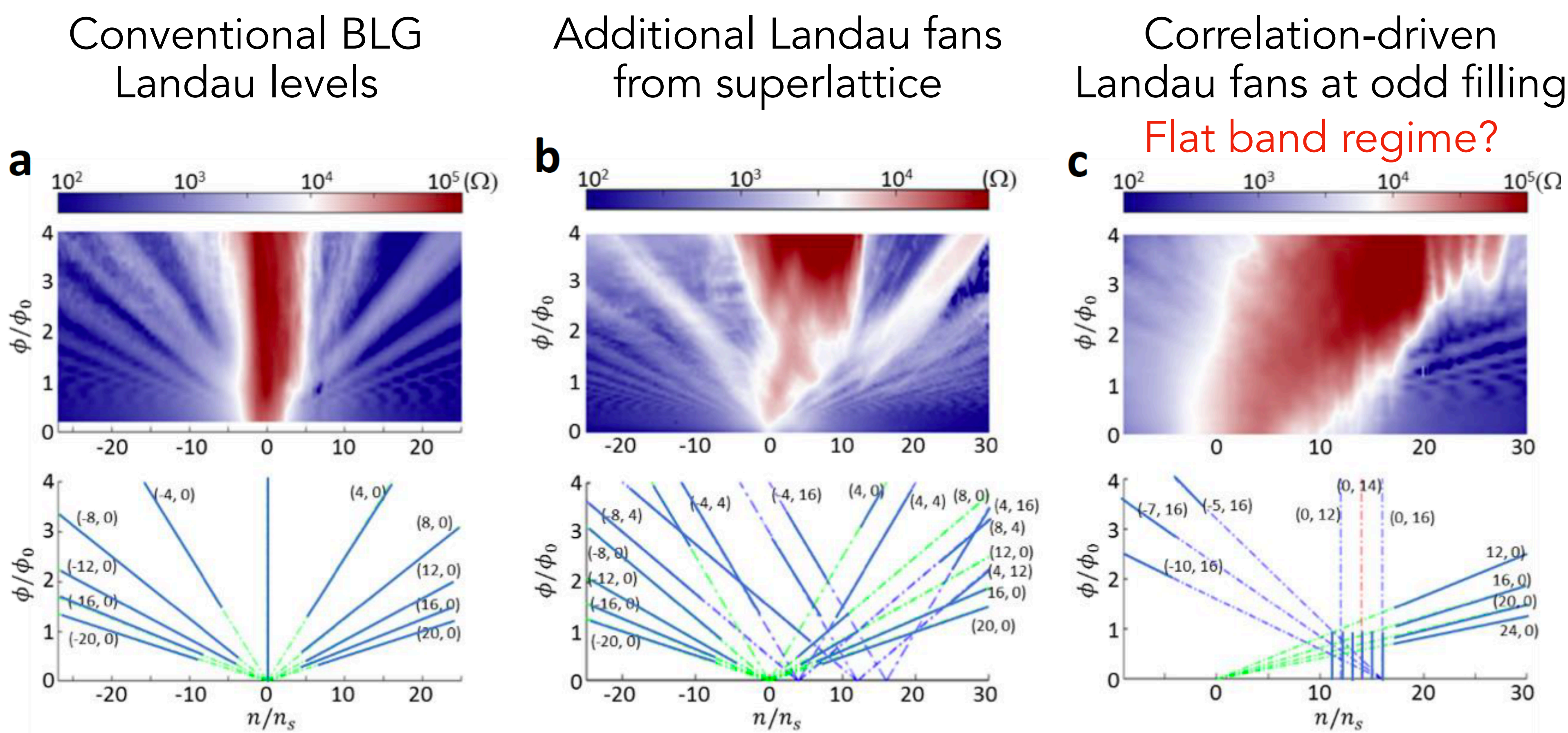






Sun, Ghorashi, Watanabe, Taniguchi, Camino, **JC**, Du ArXiv 2306.06848

Landau fans reveal correlation-driven physics

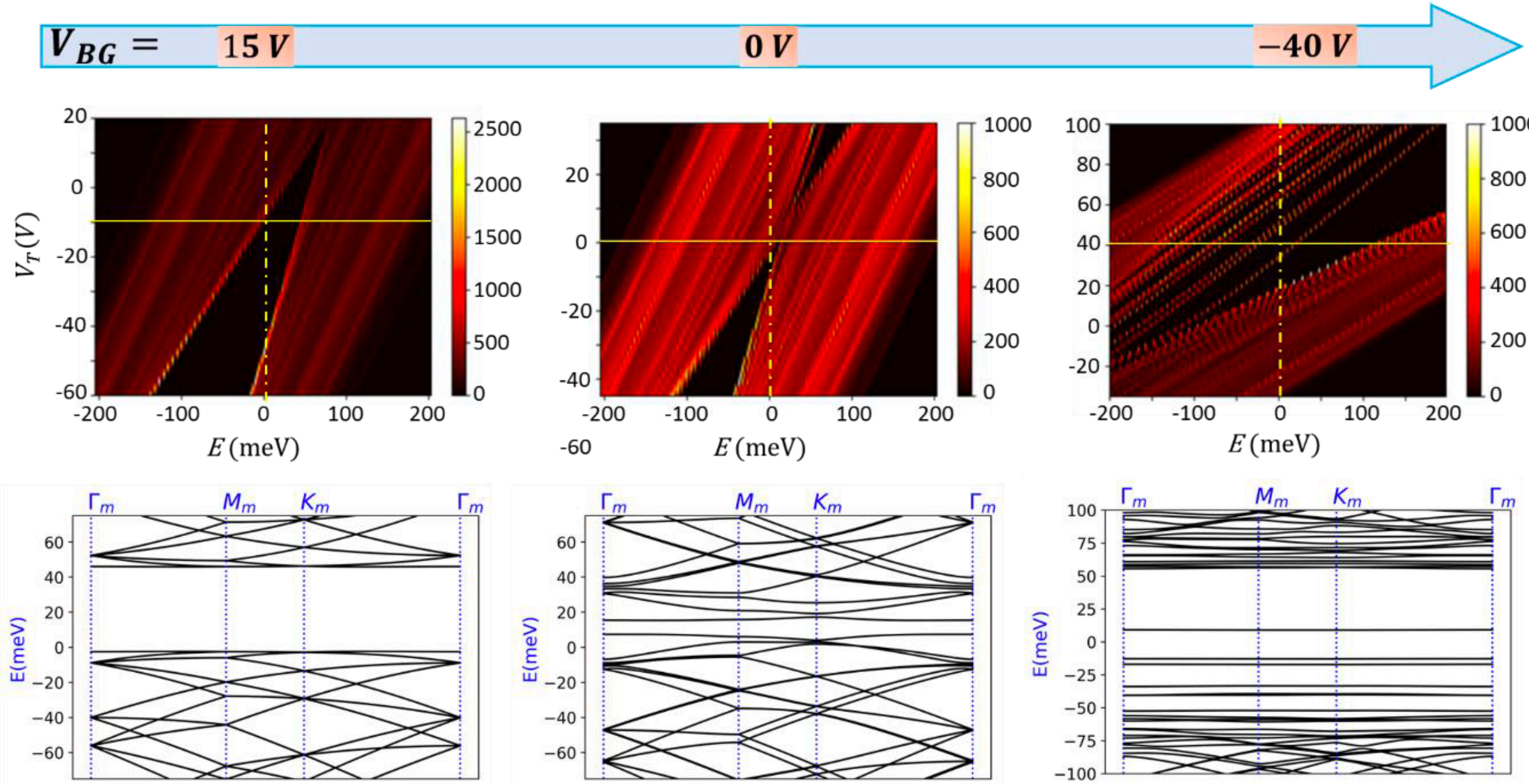


$$\frac{n}{n_s} = t\frac{\phi}{\phi_0} + s$$

V_{BG}

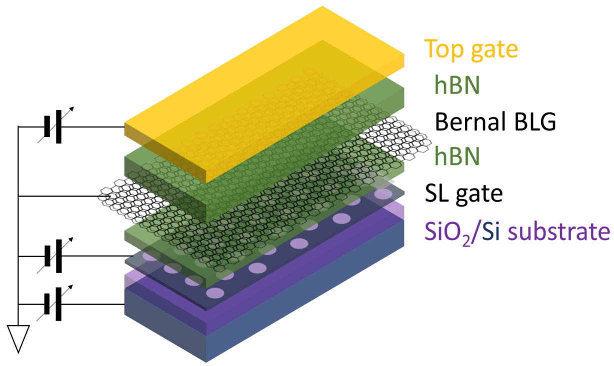
Sun, Ghorashi, Watanabe, Taniguchi, Camino, **JC**, Du ArXiv 2306.06848

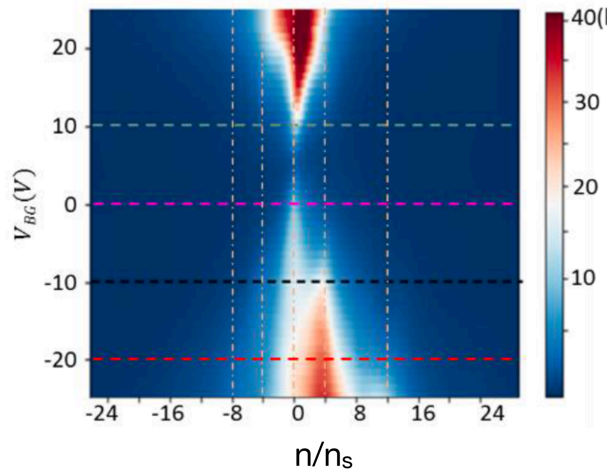
Landau levels consistent with flat band regime

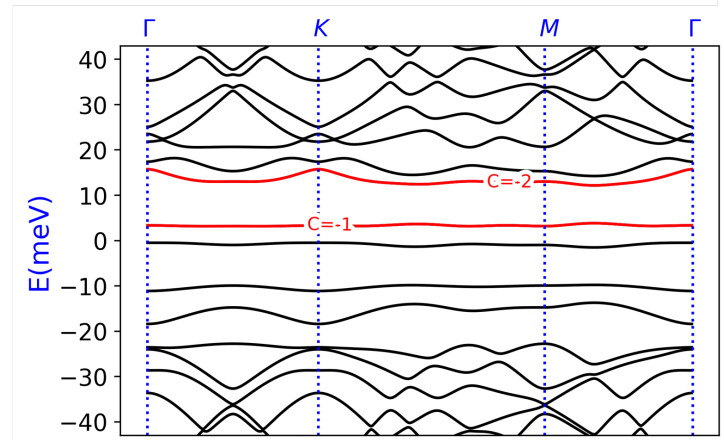


Sun, Ghorashi, Watanabe, Taniguchi, Camino, **JC**, Du ArXiv 2306.06848

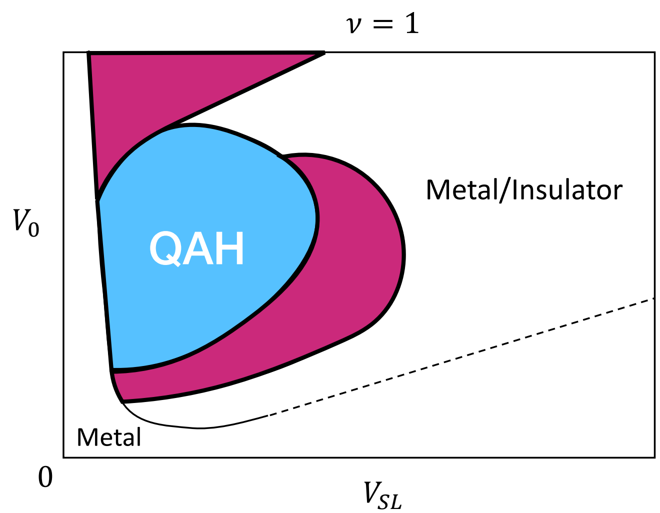
Bilayer graphene in a superlattice potential: realistic, tunable platform for topological phases



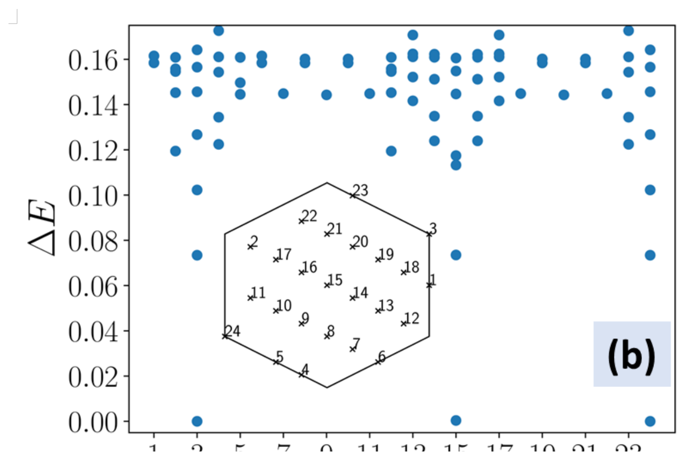




Flat Chern bands



QAH + gate-tunable topology



Evidence for FCI @ $\nu = 1/3$

Ghorashi, Dunbrack, Abouelkomsan, Sun, Du, **JC** PRL 130, 196201 (2023); PRB 107, 195423 (2023);
Sun, Ghorashi, Watanabe, Taniguchi, Camino, **JC**, Du ArXiv 2306.06848;
Zeng, Abouelkomson in prep

Theoretical outlook

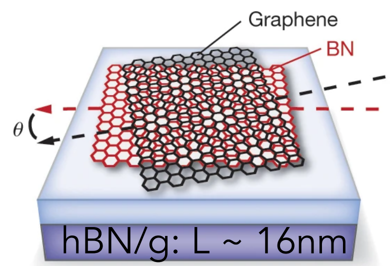
1. **Improve model:**

   (a) Is continuum model adequate?

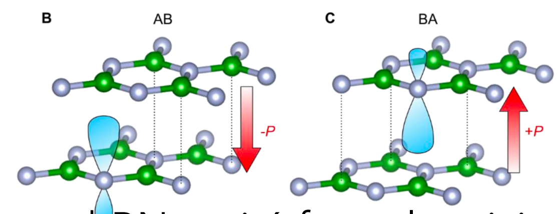
   (b) Is cosine reasonable for superlattice?

2. **Theory is agnostic to the platform: what is the best platform?**

Moire heterostructures?

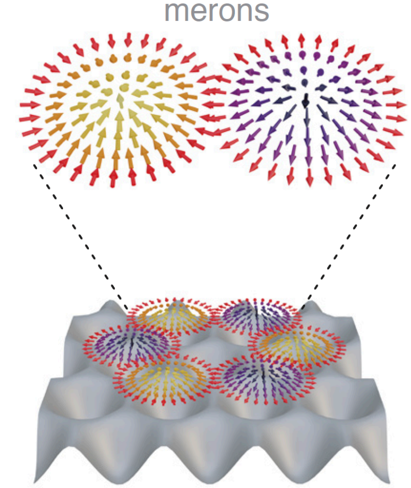


Dean, et al, Kim *Nature* (2013)

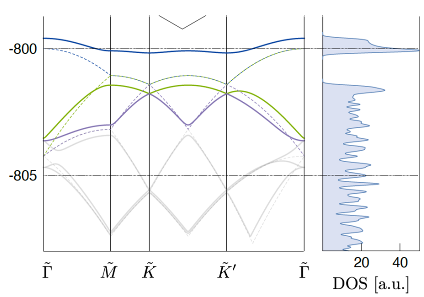


hBN moiré ferroelectricity
Jarillo-Herrero group *Science* (2021)

3. **New/optimal lattice geometry?**



4. **Apply superlattice to other 2D materials?**



TMDs: Shi, Ma, Song 1904.07877

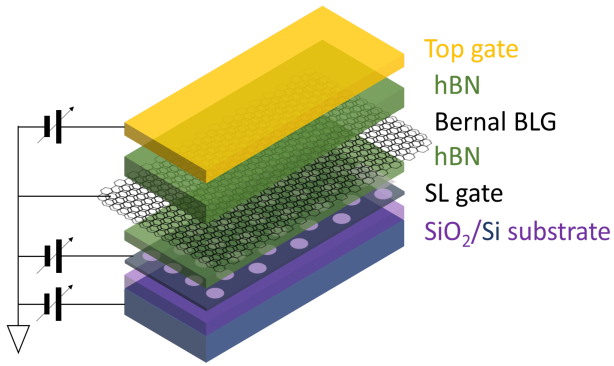
Manipulate topological insulator surface states

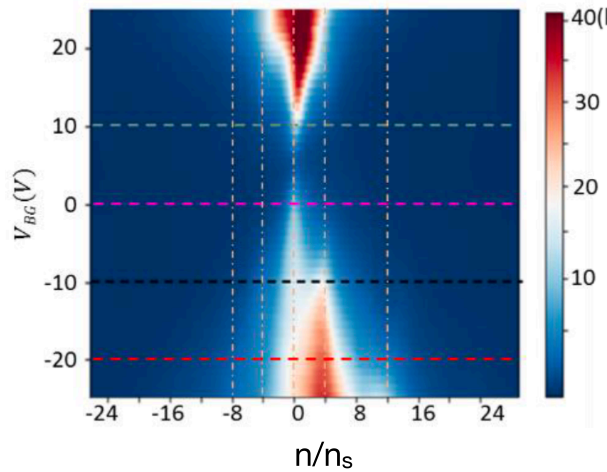
JC, Fang, Pixley, Wilson, PRB 103, 155157 (2021)

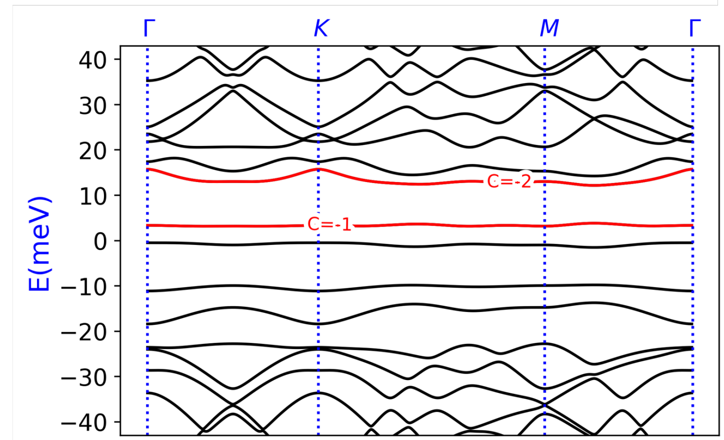
Guerci, Wang, Pixley, **JC**, PRB 106, 245417 (2022)

Dunbrack and **JC**, PRB 106, 075142 (2022)

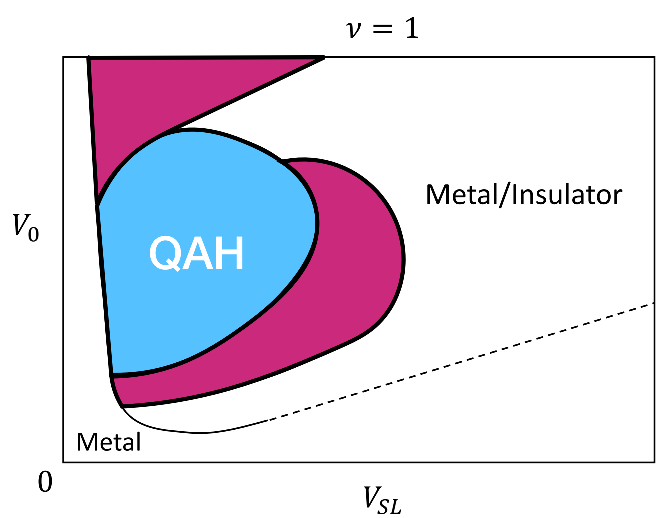
Bilayer graphene in a superlattice potential: realistic, tunable platform for topological phases



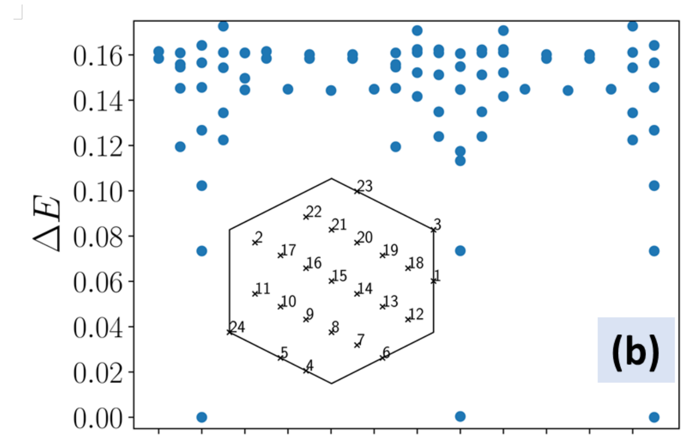




Flat Chern bands



QAH + gate-tunable topology



Evidence for FCI @ ν = 1/3

Ghorashi, Dunbrack, Abouelkomsan, Sun, Du, **JC** PRL 130, 196201 (2023); PRB 107, 195423 (2023);
Sun, Ghorashi, Watanabe, Taniguchi, Camino, **JC**, Du ArXiv 2306.06848;
Zeng, Abouelkomson in prep