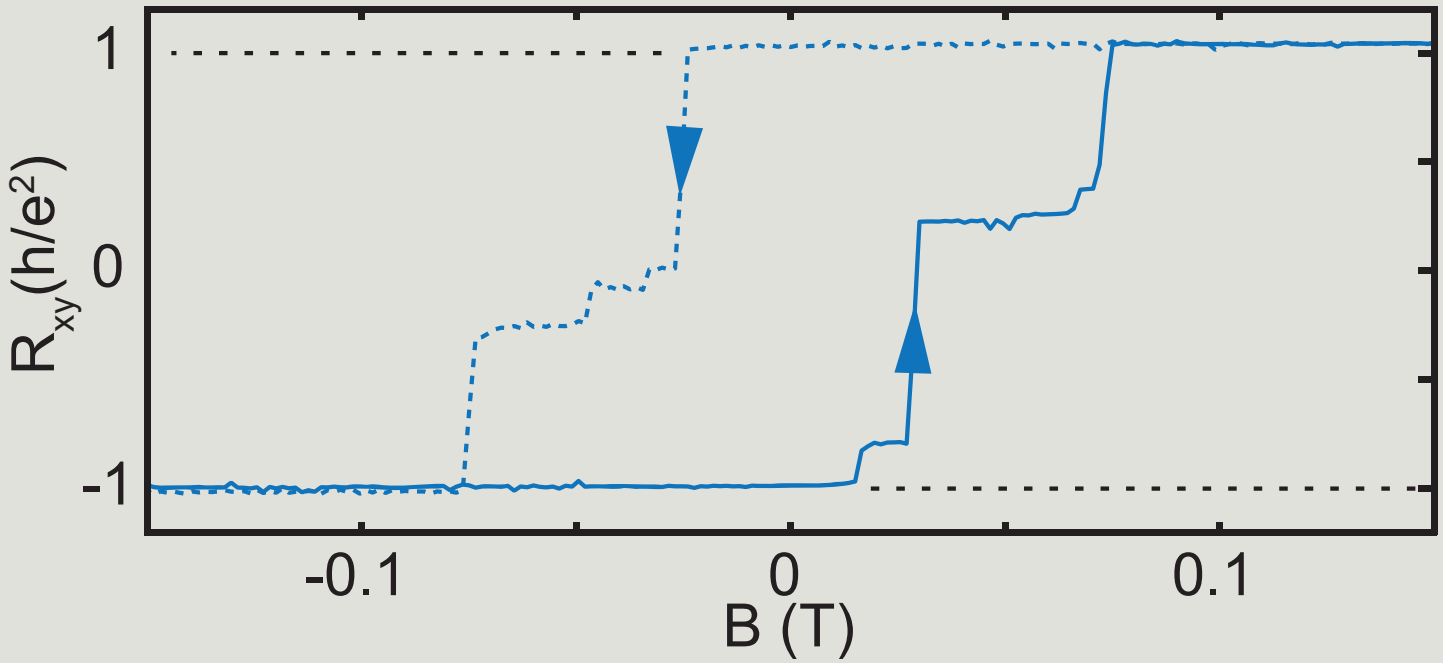
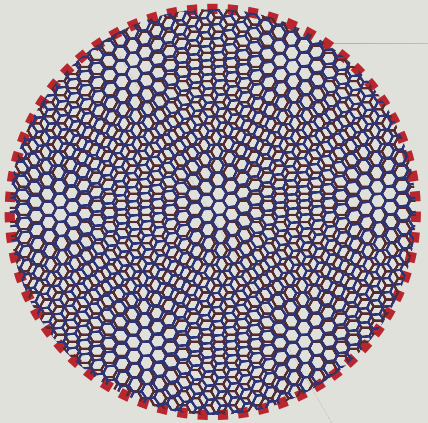


Quantum Anomalous Hall Effect in twisted bilayer graphene

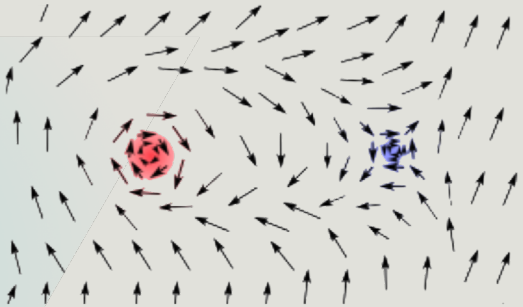
FLAT CLUB, LOUK RADEMAKER, 11 OCTOBER 2019

Context & Relevance

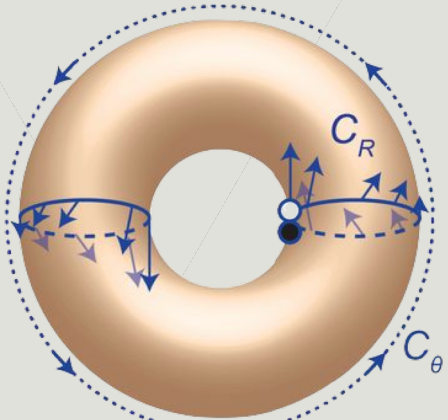
Moiré patterns
in Twisted Heterostructures



Two-dimensional
Magnetism

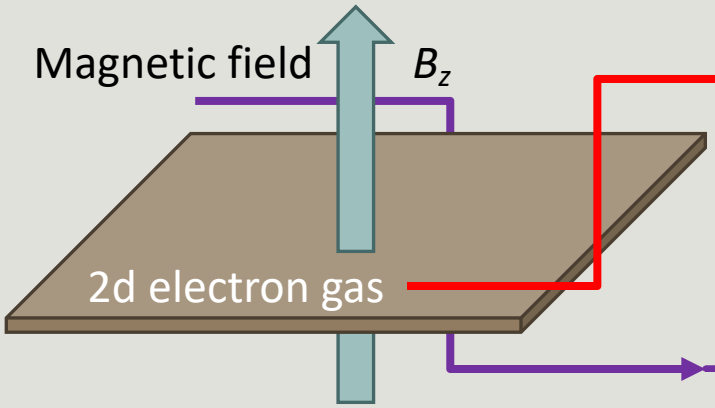


**Quantum Anomalous
Hall effect in
Twisted Bilayer graphene**



Band
Topology

Quantum Hall effect



$$H = \frac{k^2}{2m}$$

$$H = \frac{(k - eA)^2}{2m}$$ Peierls substitution

$$A = (0, Bx, 0)$$ Landau gauge

$$H = \frac{\mathbf{k}_x{}^2}{2m} + \frac{1}{2m}(k_y - eB\mathbf{x})^2$$

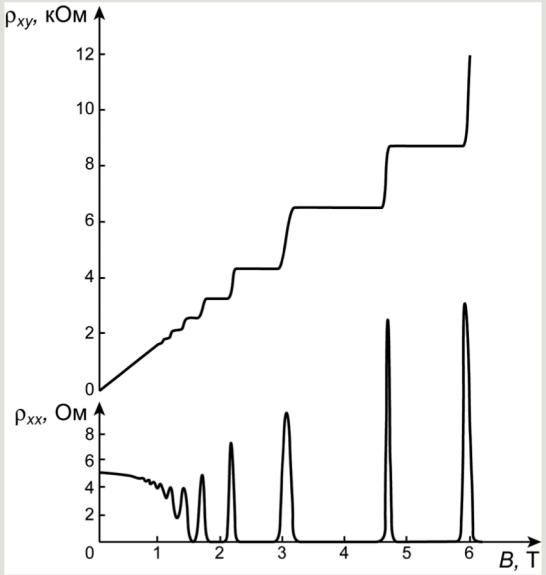
Shifted harmonic oscillator for each k_y

$$H = \omega_C \left(\mathbf{n} + \frac{1}{2}\right)$$

Landau levels

$$\omega_C = \frac{eB}{m}$$

Cyclotron frequency

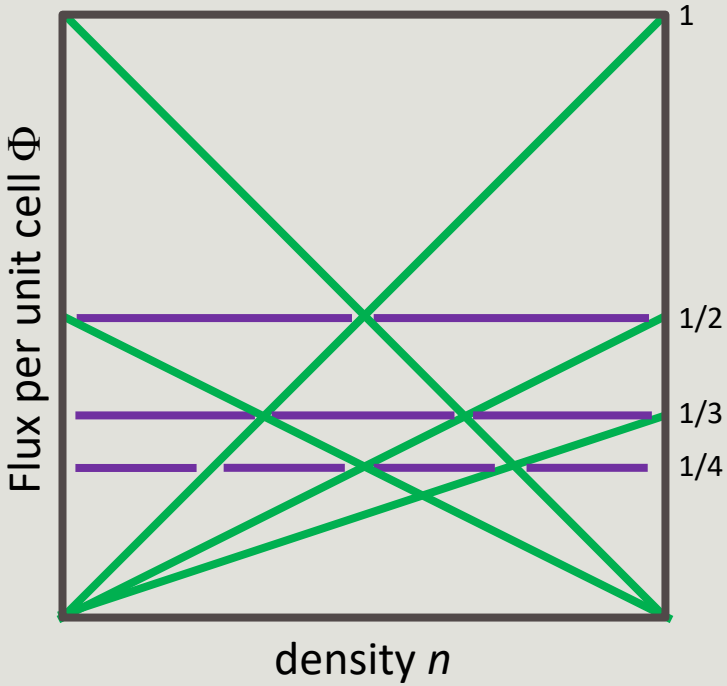


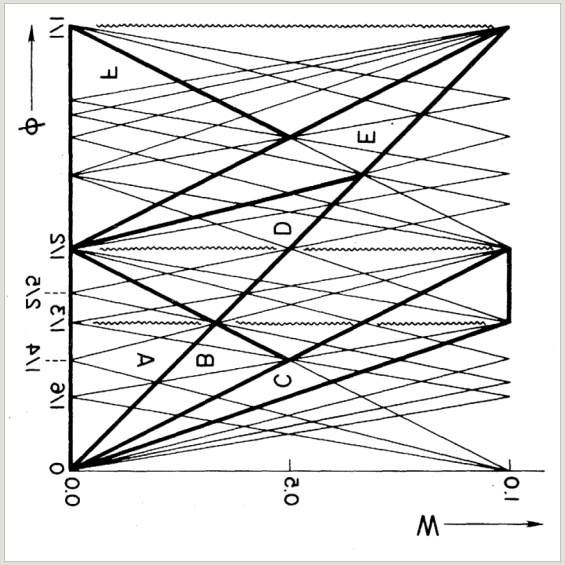
Field vs. density

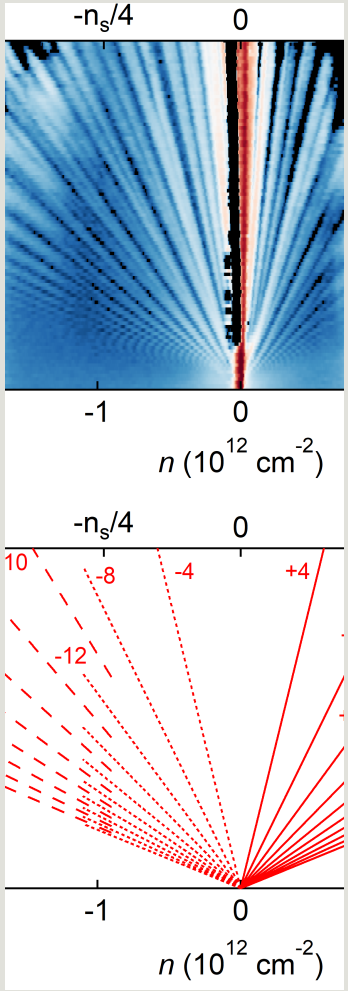
Number of states per Landau level: Φ/Φ_0

→ Insulating state when filled a Landau level

Claro-Wannier diagram (PRB 1979)







Yankowitz
Science 2019

One Φ_0 per unit cell:
- 40,000 T for graphene
- 16 T for twisted bilayer graphene

Streda formula

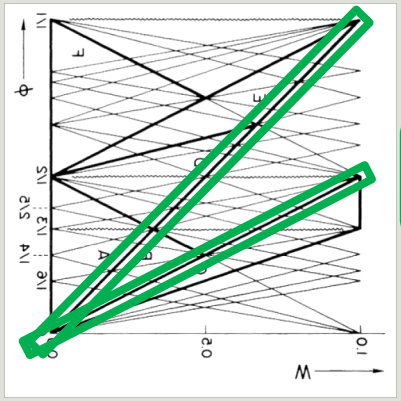
Hall response of an insulator: $\sigma = \begin{pmatrix} 0 & \sigma_{xy} \\ \sigma_{xy} & 0 \end{pmatrix}$ with $j = \sigma E$

Use the **continuity** & **Maxwell-Faraday** equations:
(*practically:* tune B field and gate voltage such that you remain insulating)

$$\frac{\partial n}{\partial t} = -\nabla \cdot j = -\sigma_{xy}(\partial_x E_y - \partial_y E_x) = \sigma_{xy} \frac{\partial B}{\partial t}$$

Gives us the **Streda formula**

$$\boxed{\sigma_{xy} = \frac{\partial n}{\partial B}}$$

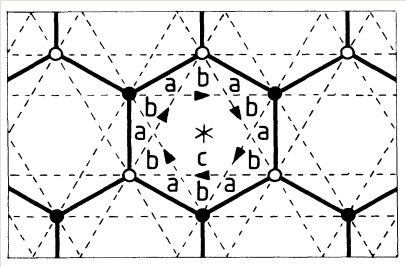


$$\boxed{\Phi/\Phi_0 = \tfrac{1}{\nu} n/A} \longrightarrow \boxed{\sigma_{xy} = \nu \frac{e^2}{h}}$$

Integer Quantum Hall Effect

Haldane model (1988)

Can you have **QHE without a magnetic field** on a **lattice?**



$$t_{ij} c_i^\dagger c_j \rightarrow t_{ij} c_i^\dagger c_j e^{i \int_j^i \vec{A}\cdot d\vec{r}}$$

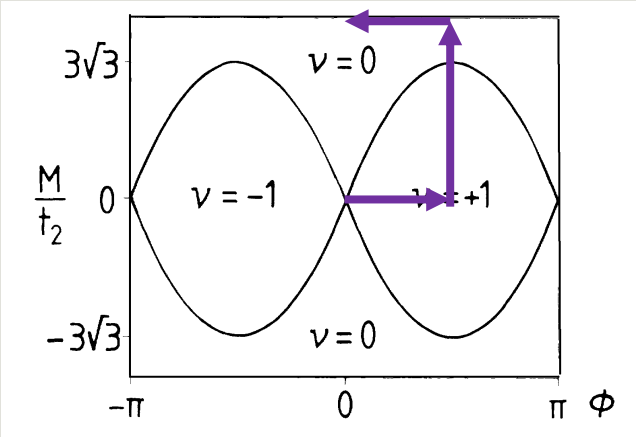
No net flux but the next-nearest-neighbor hopping acquires a phase

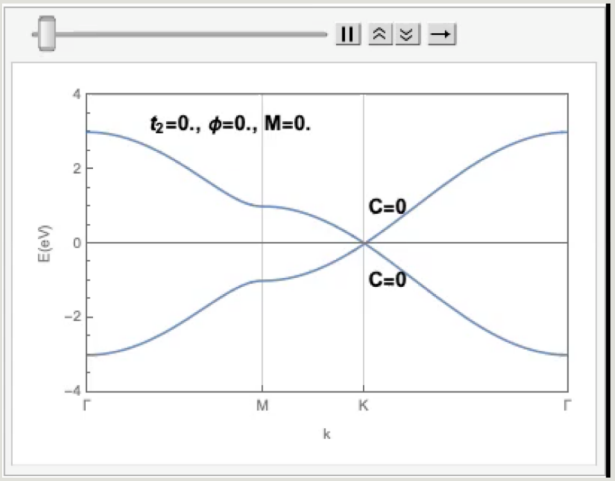
$$\mathbf{H}(\mathbf{k}) = 2t_2 \cos\phi \left(\sum_i \cos(\mathbf{k}\cdot\mathbf{b}_i)\right)\mathbf{I} + t_1 \left(\sum_i [\cos(\mathbf{k}\cdot\mathbf{a}_i)\sigma^1 + \sin(\mathbf{k}\cdot\mathbf{a}_i)\sigma^2]\right) + \left[M - 2t_2 \sin\phi \left(\sum_i \sin(\mathbf{k}\cdot\mathbf{b}_i)\right)\right]\sigma^3$$

NNN hopping with phase

"graphene"

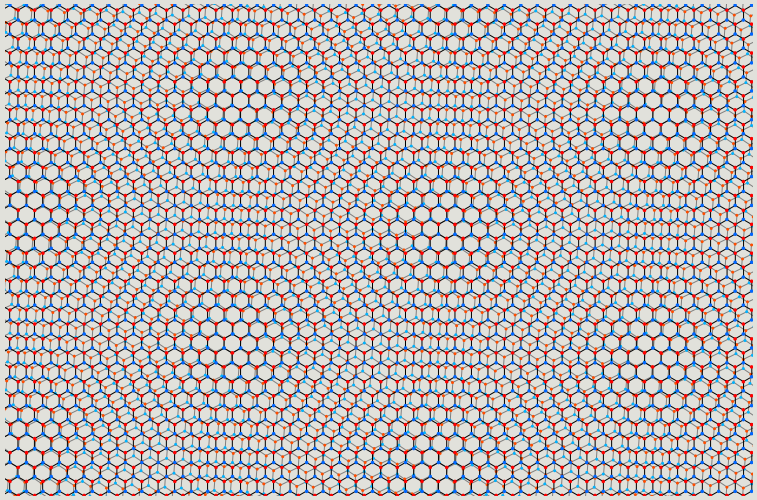
trivial gap

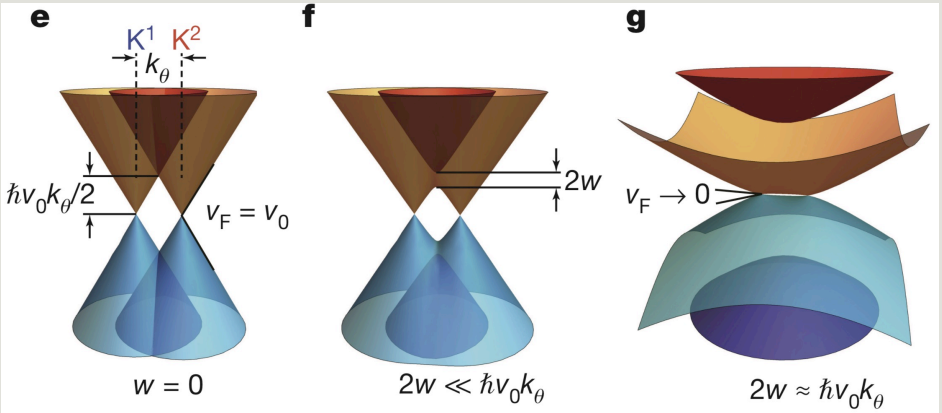


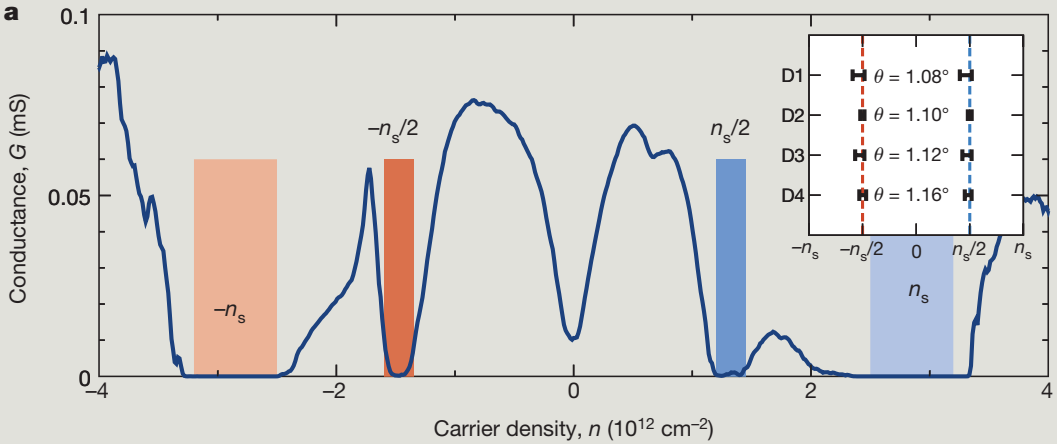


Twisted Bilayers

Quick recap of twisted bilayer physics

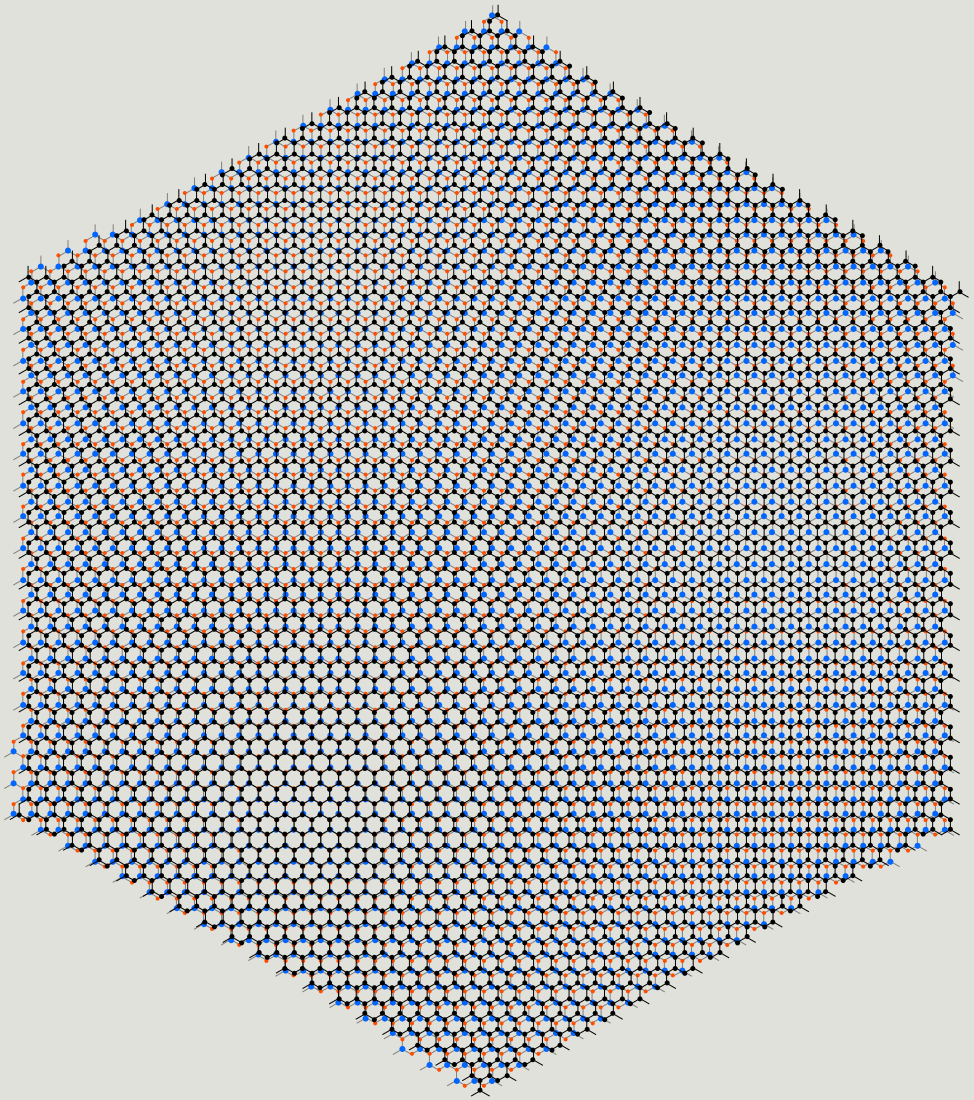






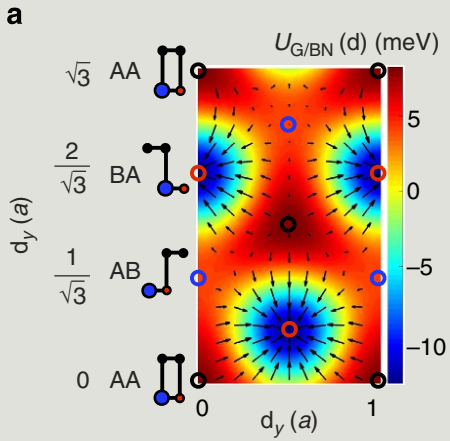
(Cao Nature 2018)

hBN alignment with graphene



hBN substrate is hexagonal but **has 1.6% larger lattice constant**

When **graphene** is placed on top, structural relaxation favors BA stacking



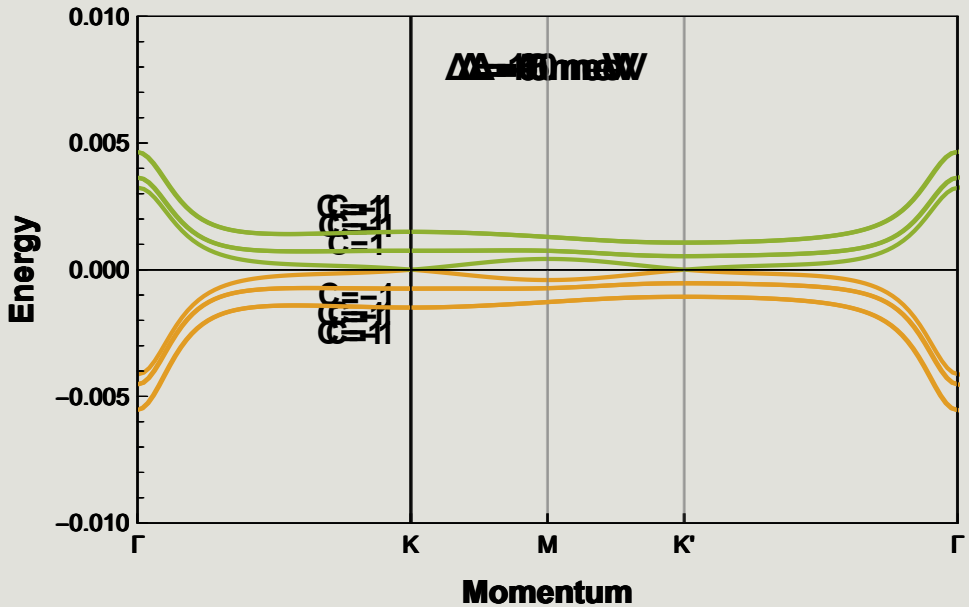
Leading in graphene to **sublattice symmetry breaking**

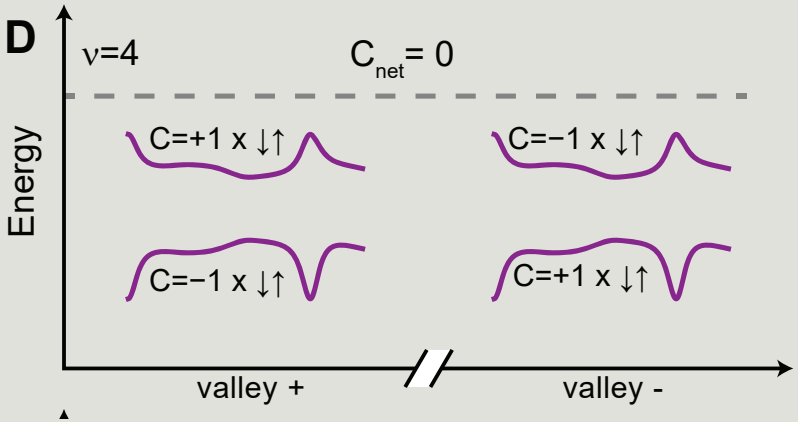
(Jung Nature Comm. 2015)

hBN alignment on TBG

Very beautiful result for TBG:

- Include the sublattice breaking **on one of the layers**
- Leads to a **gap** at K and K' point





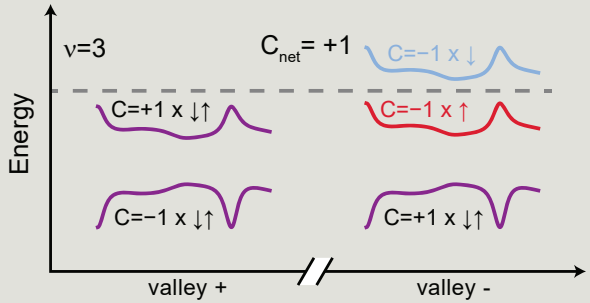
Above: bandstructure for a single valley.

(Bultinck arXiv:1901.08110)

(Serlin arXiv:1907.00261)

Ferromagnetism

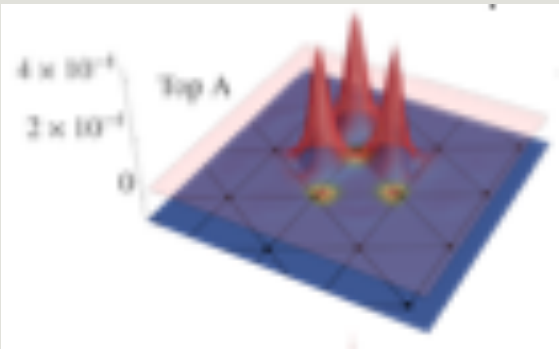
Imagine at **ν=3** filling you have a **spin & valley polarized state**



Insulator
Net nonzero Chern number
Breaks time-reversal symmetry
Quantum Anomalous Hall effect!

But **why would you expect ferromagnetism?**

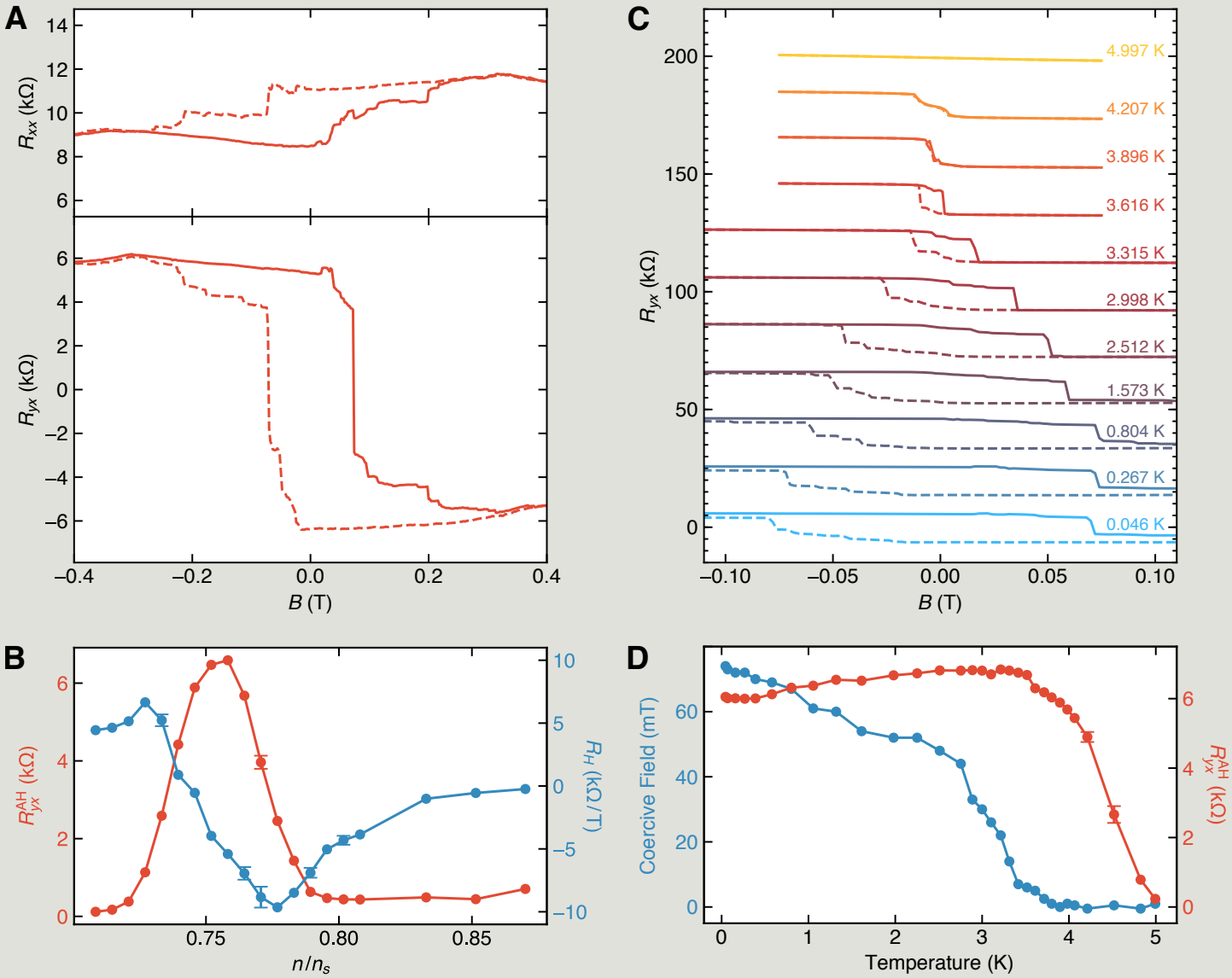
- Superexchange typically gives antiferromagnetic coupling
- **Direct exchange** between **Wannier orbitals** gives ferromagnetic coupling



(Ochi, arXiv:1805.09606; Kang, arXiv:1810.08642)

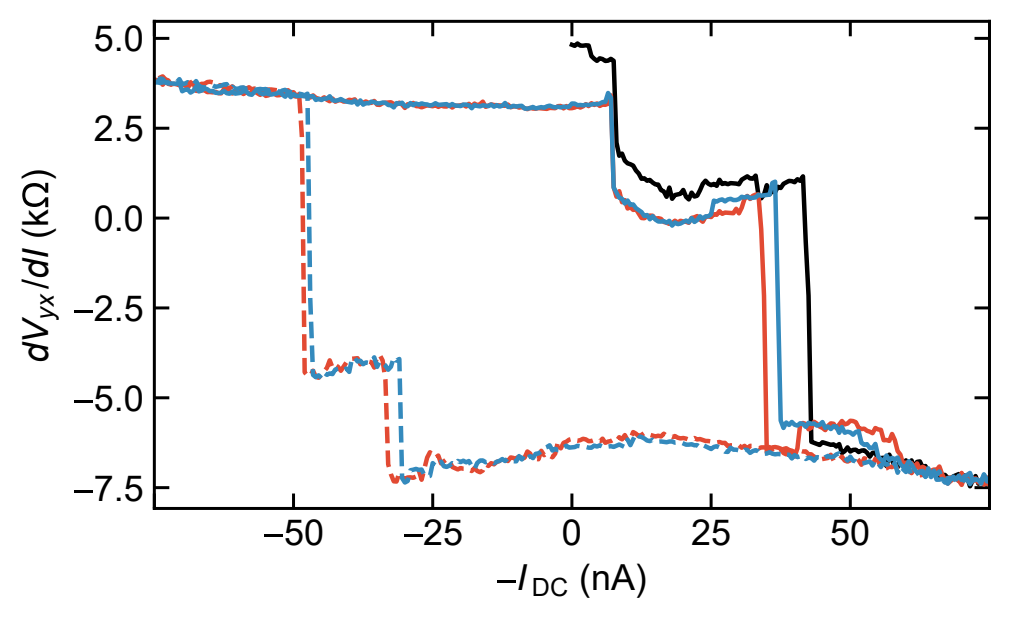
Stanford Experiment (1)

(Sharpe arXiv:1901.03520)



Stanford Experiment (2)

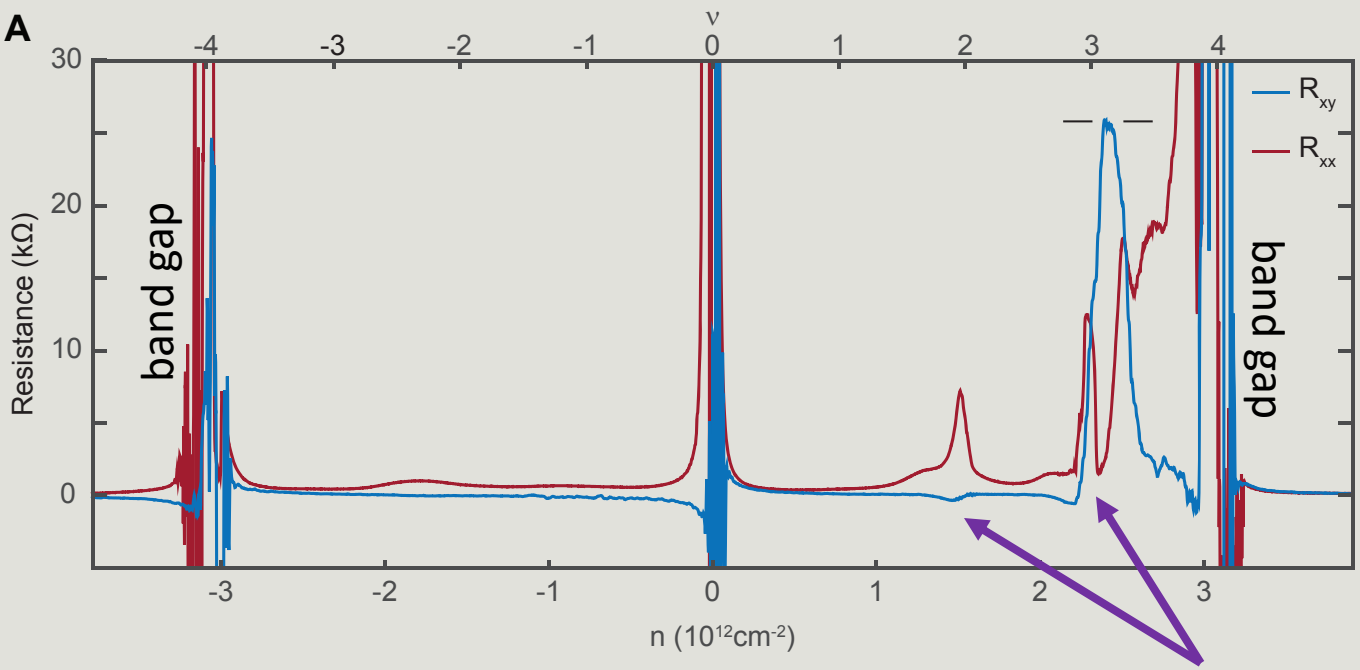
Applying a **DC current** in the plane can switch the polarized state



Santa Barbara Experiment (1)

Measure **longitudinal and transverse** resistivity as a function of **doping**

(done at weak field of 150 mT and low T=1.6 K)



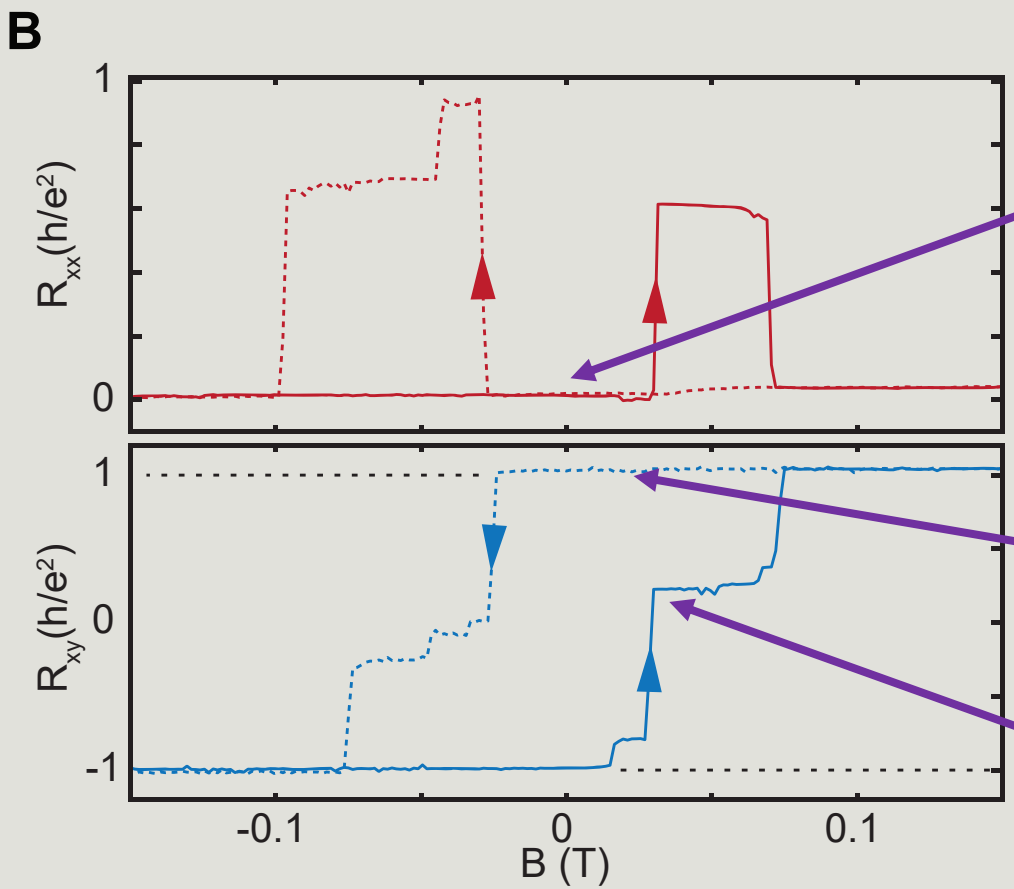
gapped at
charge neutrality

correlated
insulator only
at ν=2 and ν=3

Serlin, arXiv:1907.00261

Santa Barbara Experiment (2)

At **ν=3** filling and T=1.6 K, get **hysteresis** and a perfect **Quantum Anomalous Hall effect**



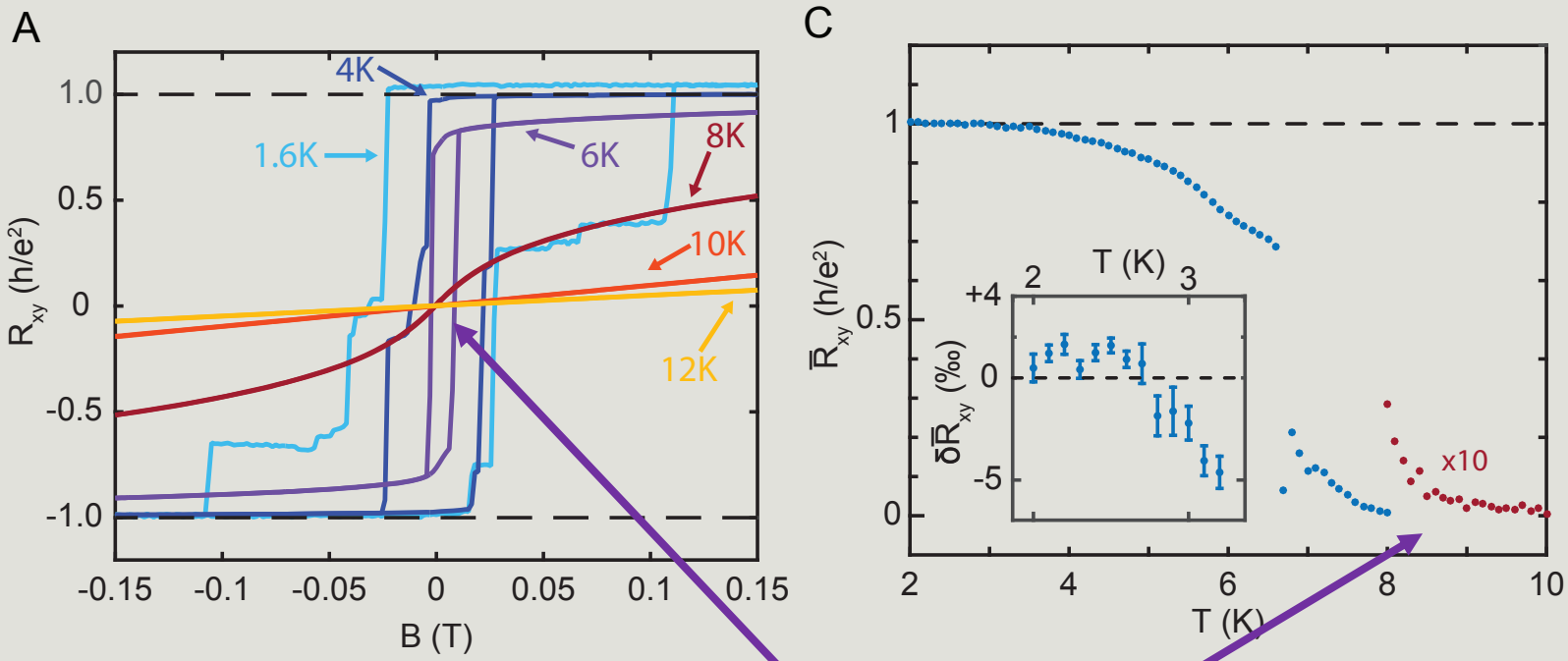
Really insulating at zero field

Quantized to within 0.1% of h/e^2

Steps are likely caused by ferromagnetic domains

Santa Barbara Experiment (3)

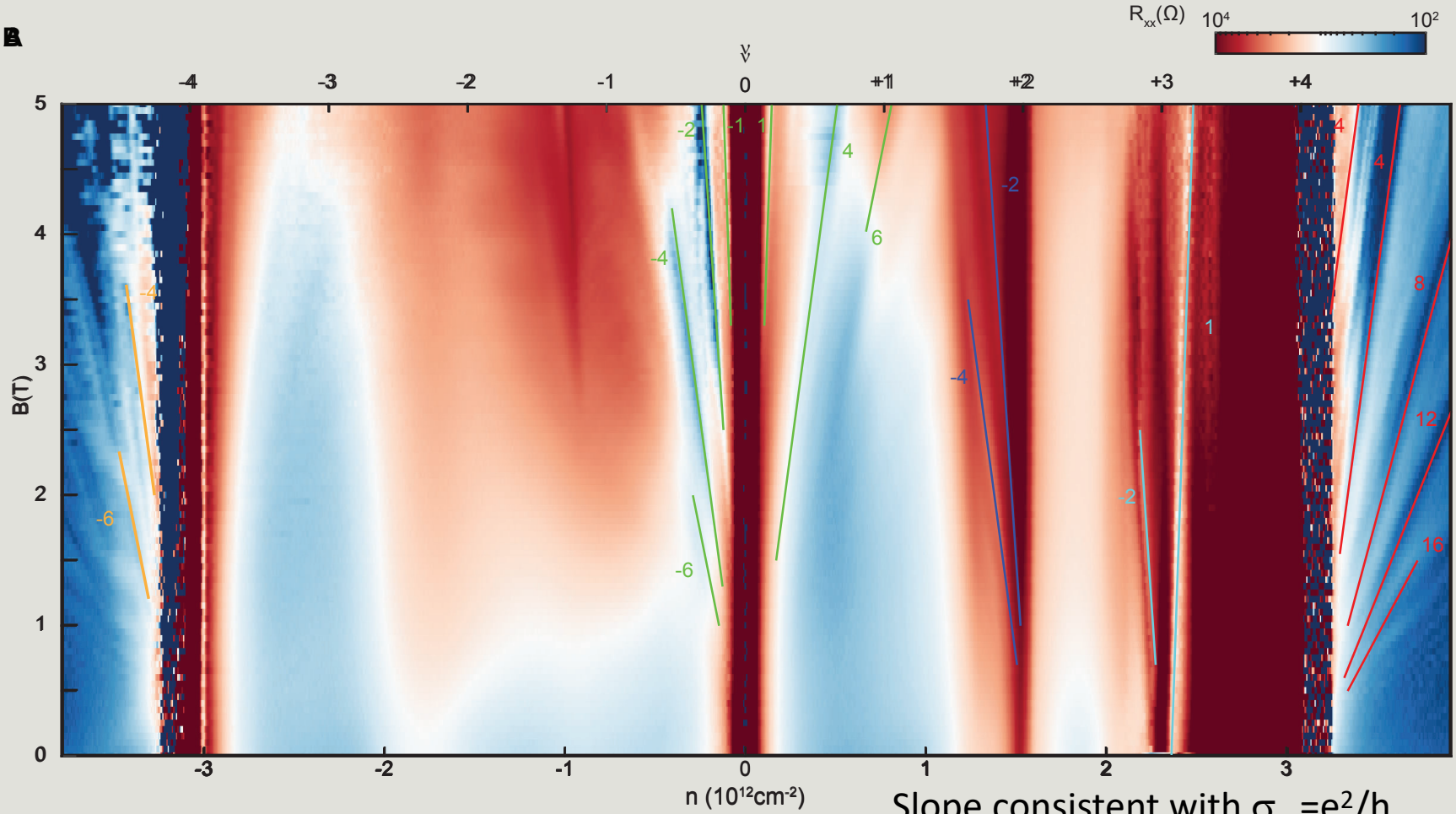
Same data, now as a function of **temperature**



Hysteresis loop disappears around 8-9 Kelvin

Santa Barbara Experiment (4)

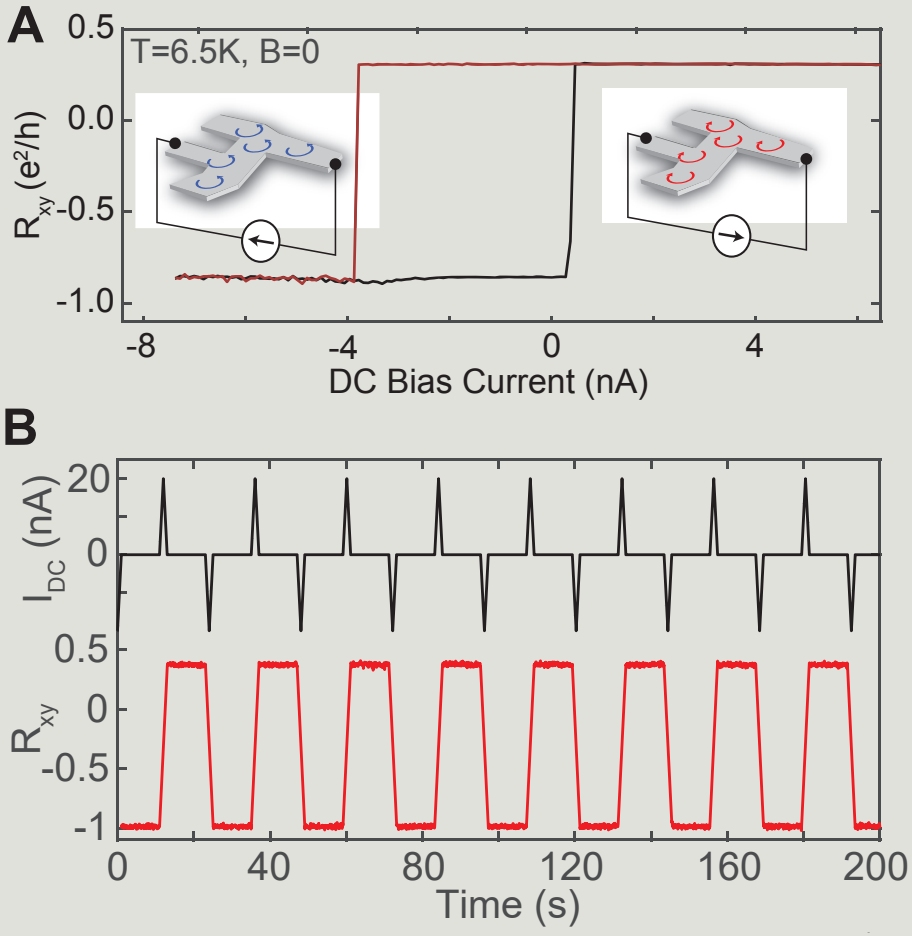
Same data, now as a function of **doping and field** to see Landau fans



Slope consistent with $\sigma_{xy}=e^2/h$

Santa Barbara Experiment (5)

Current-induced **switching** of magnetization at higher T



Note the offset in R_{xy}, because measurements are not "Onsager symmetrized" (?)

Open questions

- Why is the state spin/valley ferromagnetic?
- Why only the ν=3 filling – what about others?
- Why the current-switching of magnetization?
- Why does this effect only happen with aligned hBN?
- Why is there only QAH in California?