Tuning and probing symmetry breaking in graphene quantum Hall ferromagnets

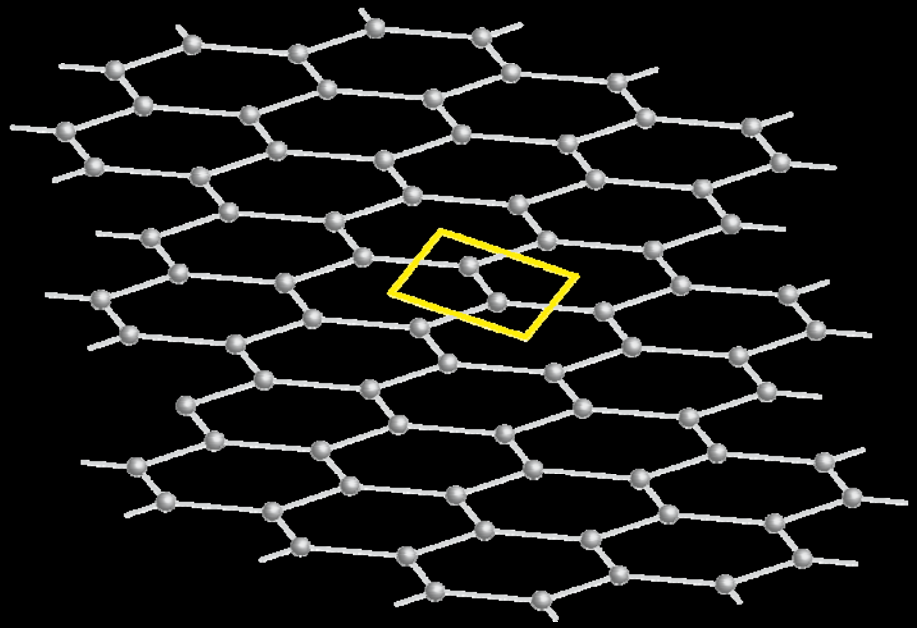
Andrea Young

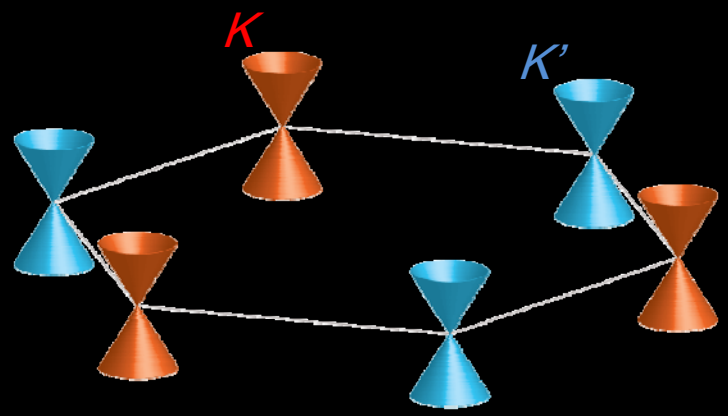
MIT/UCSB

Outline

- Quantum spin Hall effect in monolayer graphene (*Nature* 505, 528532)
- Capacitive probe of layer ferromagnetism in bilayer graphene *(unpublished)*

Graphene band structure





$$\hat{H} = v_F \hat{\sigma} \cdot \mathbf{p}$$

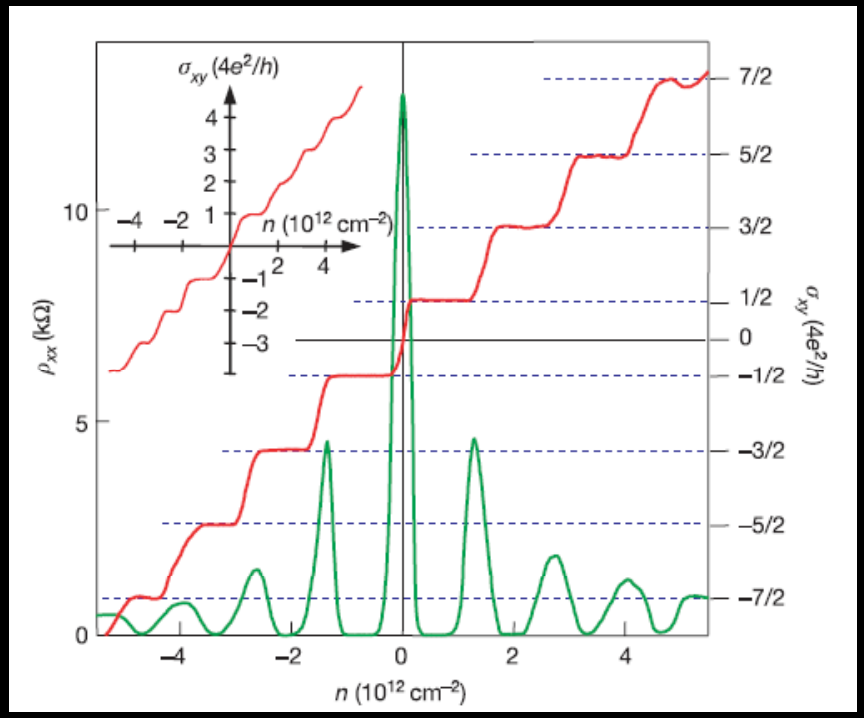
$$\varepsilon_p = \pm v_F |p|$$

Two Dirac valleys: with spin, 4x degeneracy
Massless, chiral quasiparticles in each valley
Not much correlated physics at B=0

Wallace (1947)

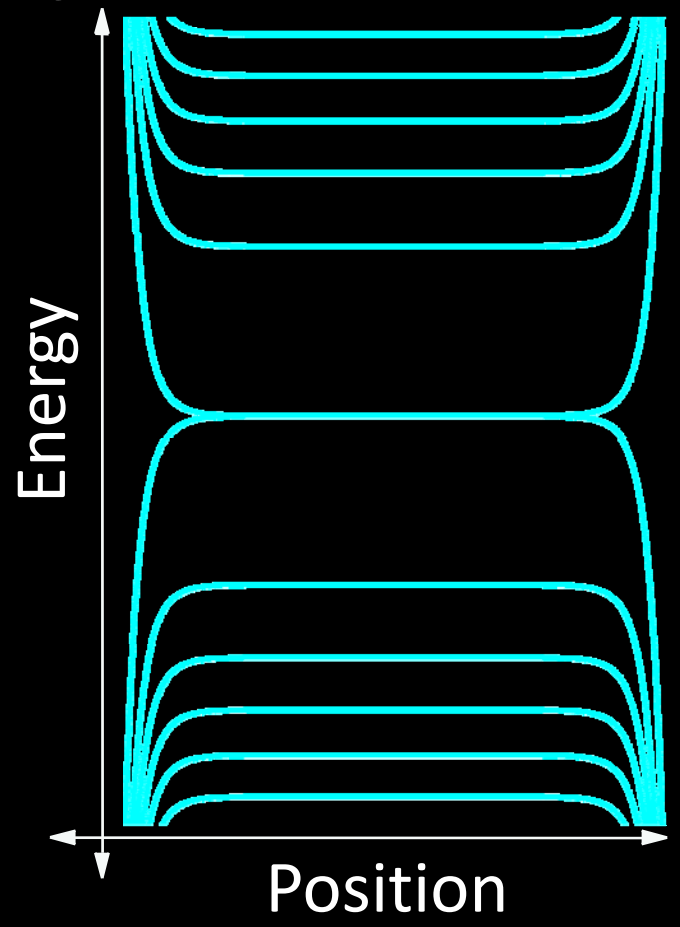
Graphene quantum Hall effect

Massless, 4x degenerate electrons



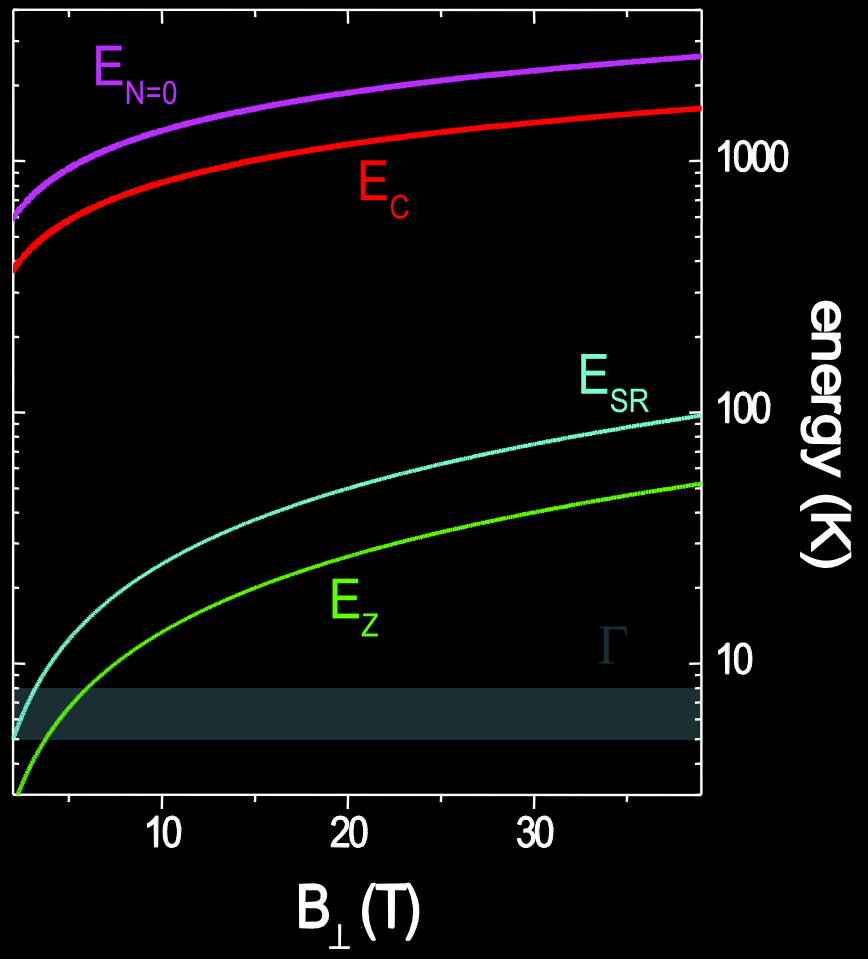
Novoselov et al., *Nature* (2005)
Zhang et al., *Nature* (2005)

$$\sigma_{xy} = \pm \frac{4e^2}{h}\left(N - \frac{1}{2}\right), \quad N \in Z^+$$

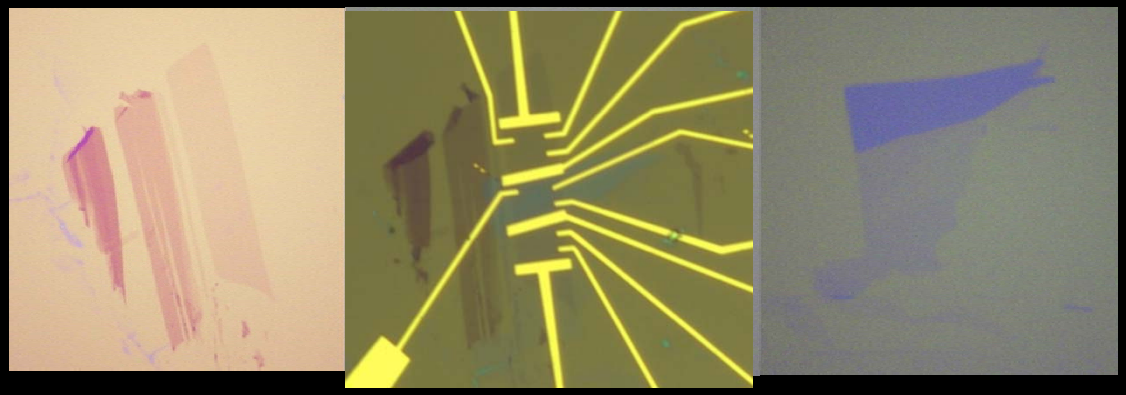


Electronic interactions

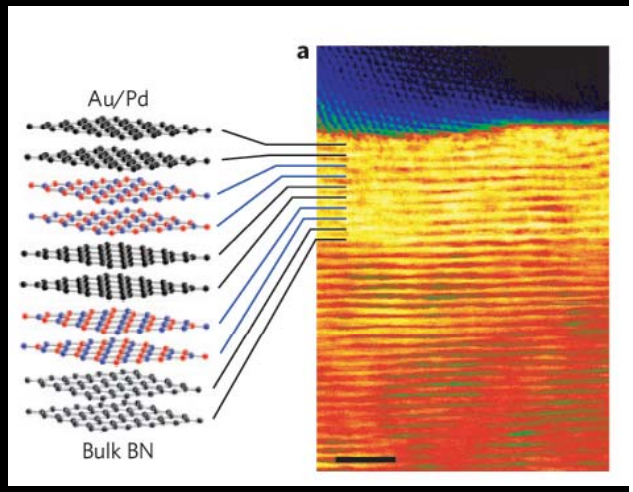
- Flat Landau Bands
  - Quenched kinetic energy
  - FQHE, QHFM, Wigner crystal, Nonabelions…
  - 1980s, 1990s, 2000s…
- How is graphene unique?
  - Lattice
  - Energetics



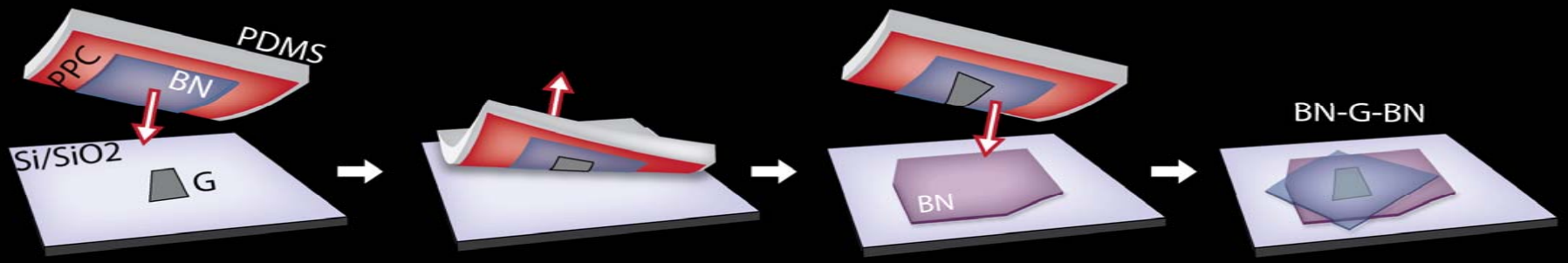
van der Waals heterostructures: graphene on hBN



hBN: crystalline insulator

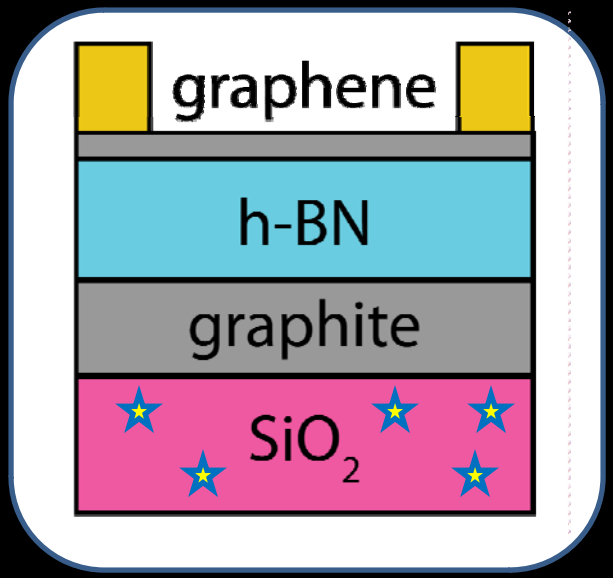


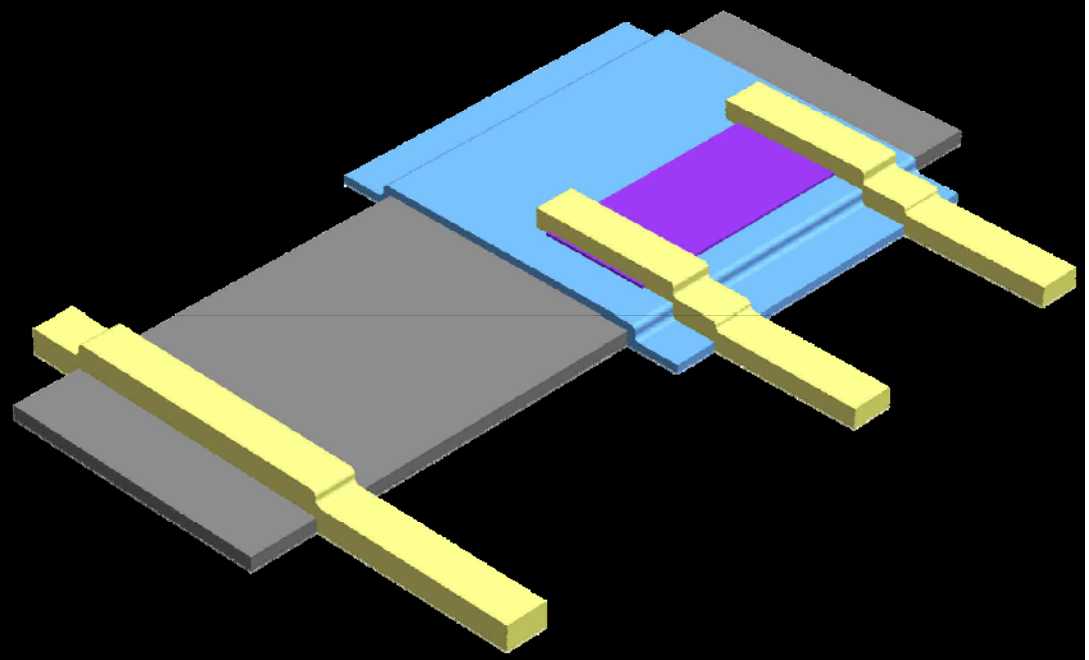
Haigh *Nature Materials (2012)*



CR Dean, **AFY** et al. *Nature Nano.* (2010)
Zomer et al., (Groningen) APL 2011
L. Wang et al (Columbia), *Science* (2013)

Our experiments: ultraclean

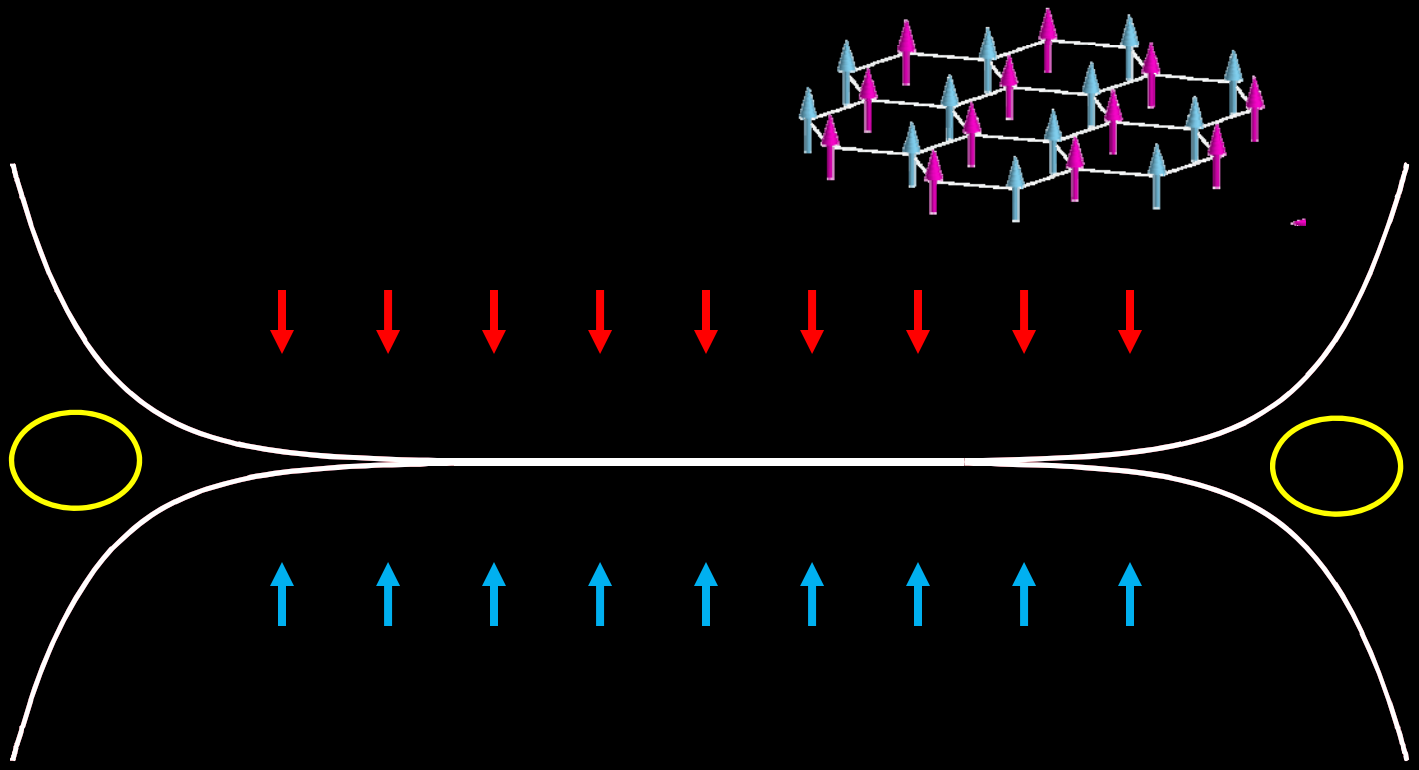




- Graphene/hBN/graphite
  - Screens impurities – lowest disorder, most uniform graphene
  - Screen interactions (partially)
  - Local gate electrode
    - change charge carrier density
    - capacitance (density of electronic states)

Quantum Spin Hall effect in the zLL

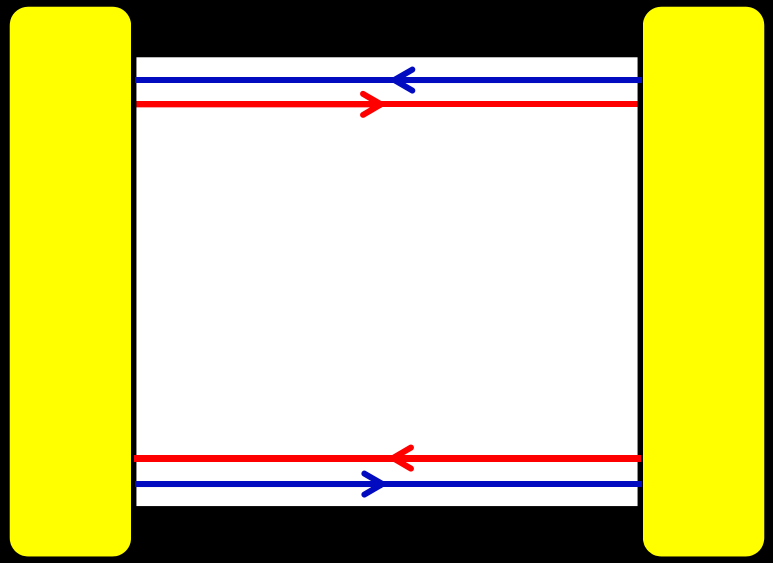
- Zeeman splitting: the “right” kind of gap



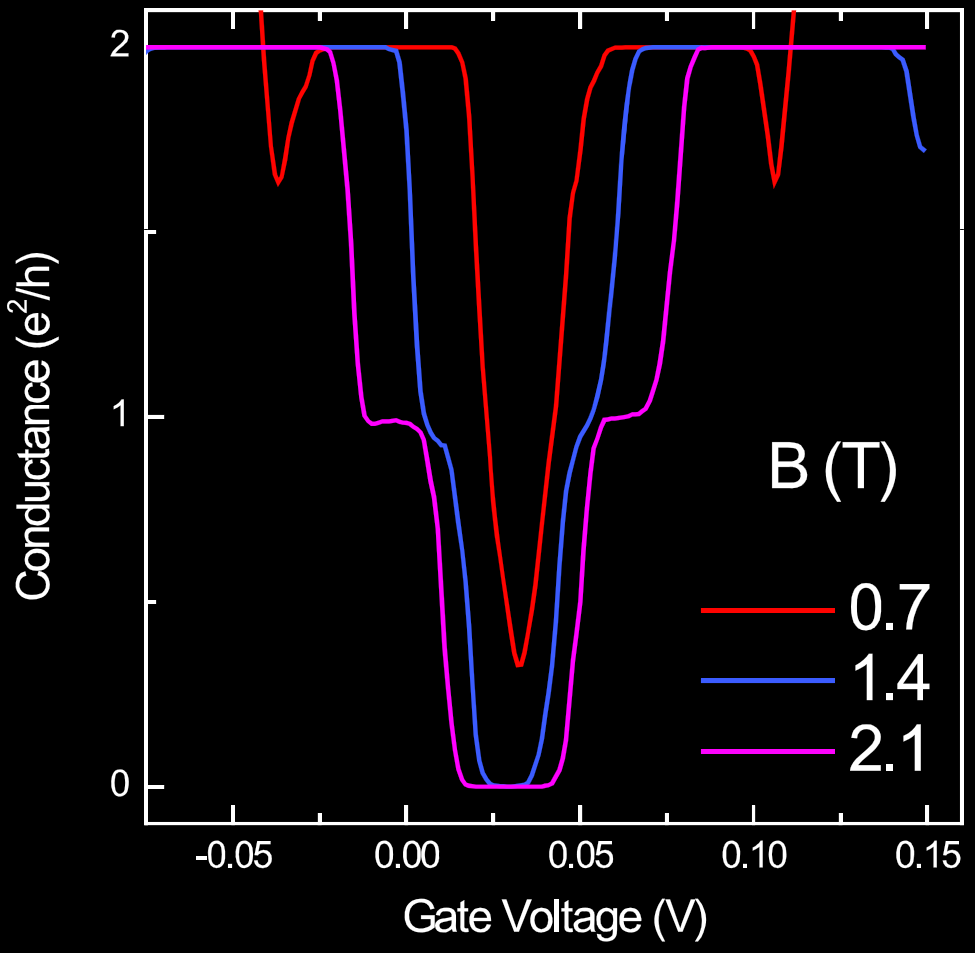
- Counterpropagating spin filtered edge states
- Opposite QHE for each spin (Not Z_2, 2 x Z)

Experiments: the ν=0 insulator

- Prediction: G=2e^2/h @ ν=0 (but σ_{xy}=0)
  - Fertig & Brey(2006), Abanin, Lee, Levitov(2006)

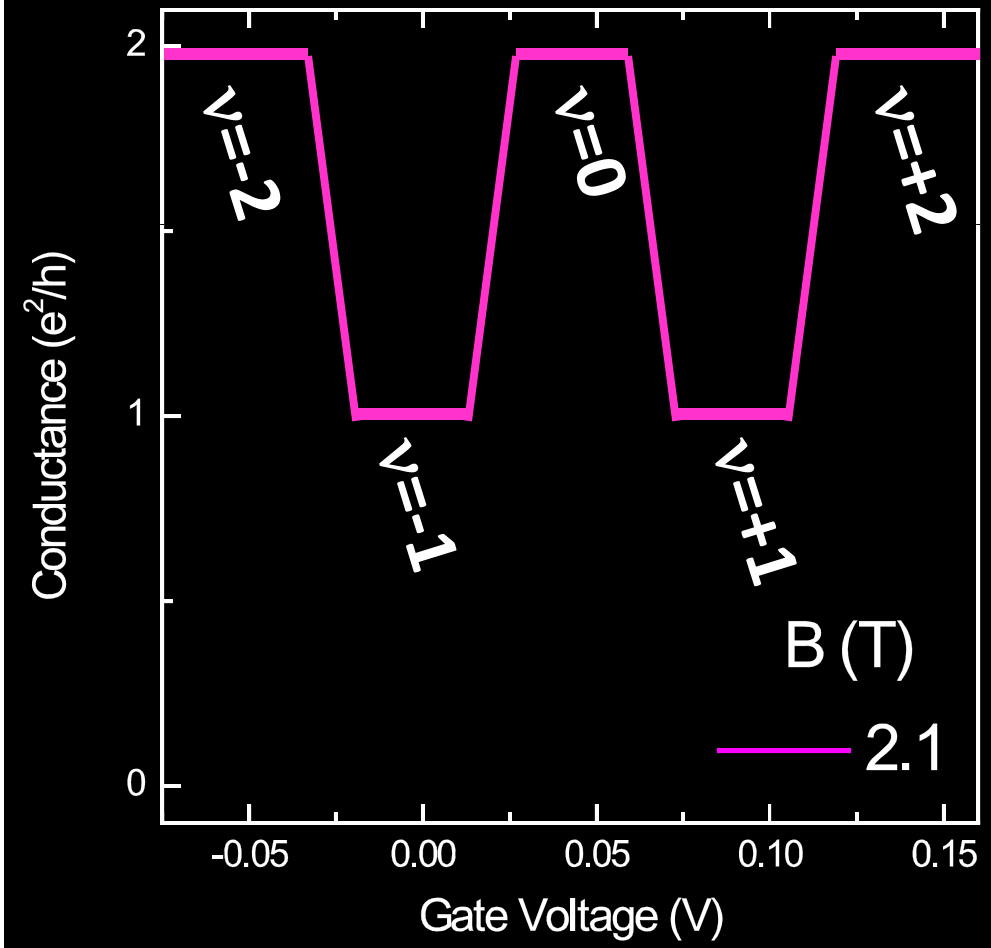


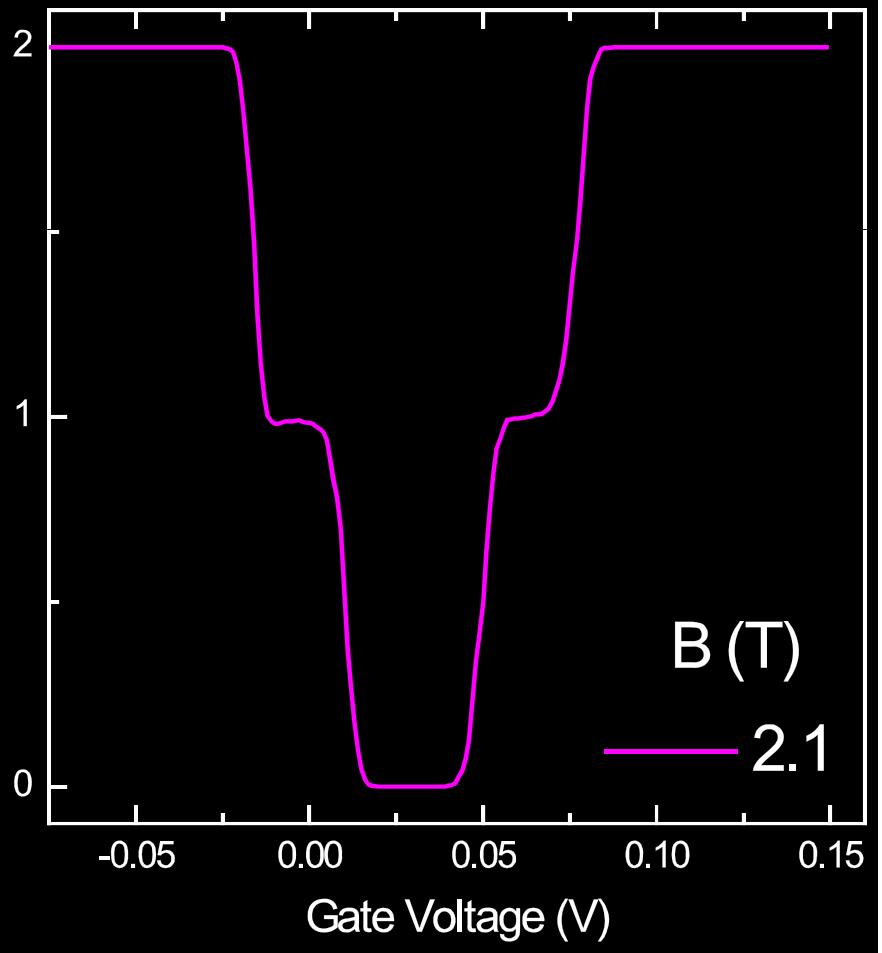
- Insulator!



First seen: Checkelsky *PRL (2008)*

No QSH state at ν=0

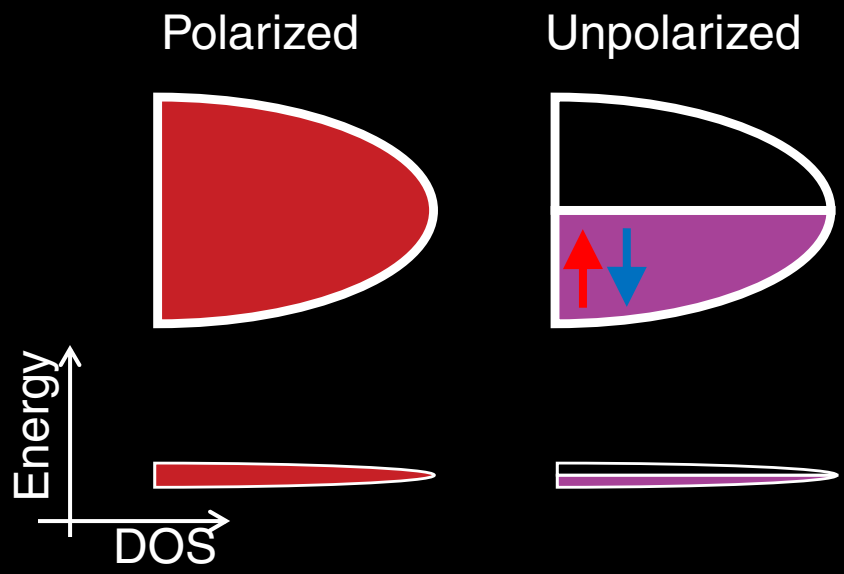


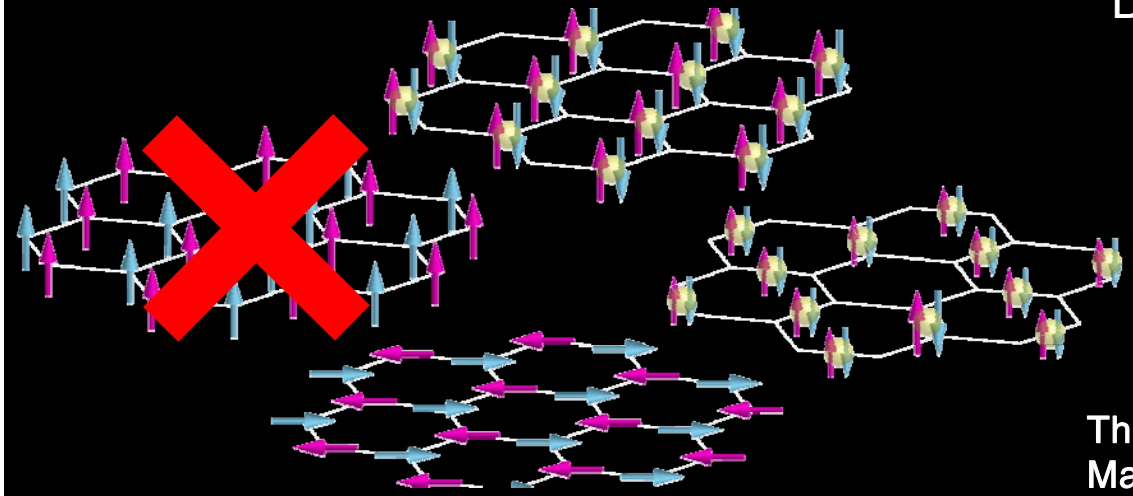


First seen: Checkelsky *PRL (2008)*

Quantum Hall ferromagnetism

- Exchange: symmetric *isospin* wavefunctions
- In which (SU(4)…) direction?
  - Spin/Valley anisotropies?



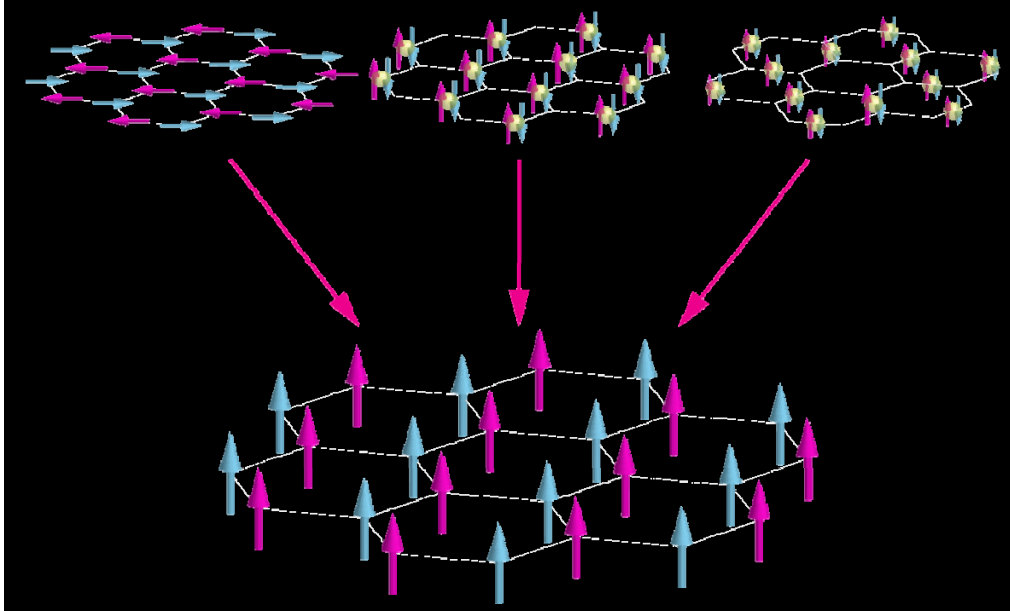


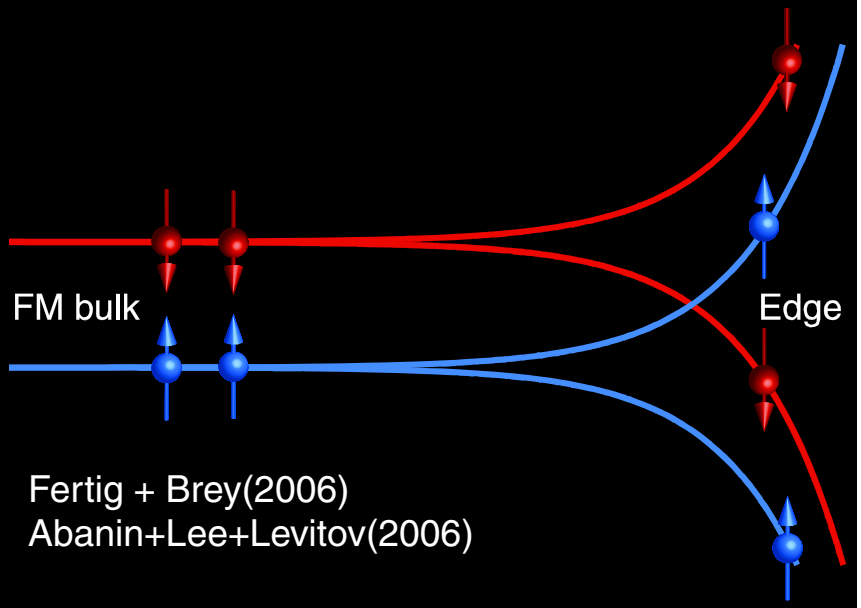
Expt. says:
ν=0 not QSH

Theory: 50+ papers, MPA Fisher, I Herbut, A Macdonald, LS Levitov, H Fertig, D.H. Lee, M Kharitonov…and more

Good news

- Ferromagnet is GS in limit of large Zeeman
  - Need *very* clean samples
  - Very big field

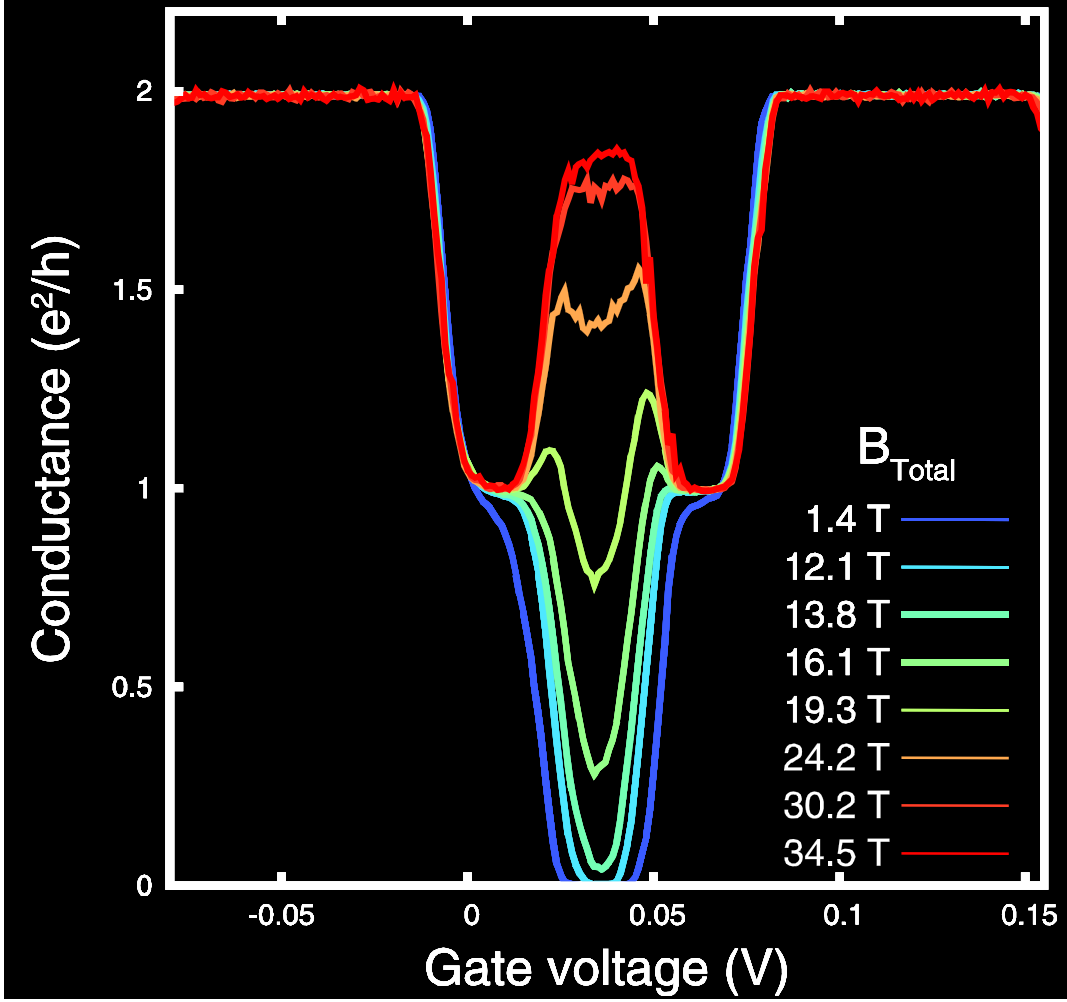


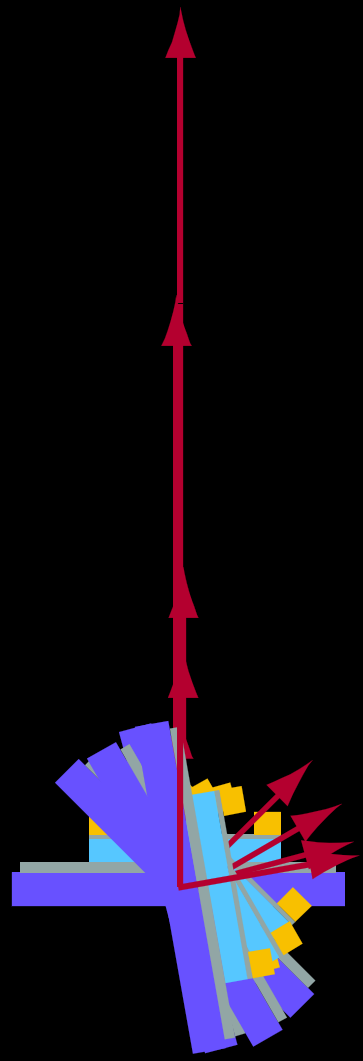


Fertig + Brey(2006)
Abanin+Lee+Levitov(2006)

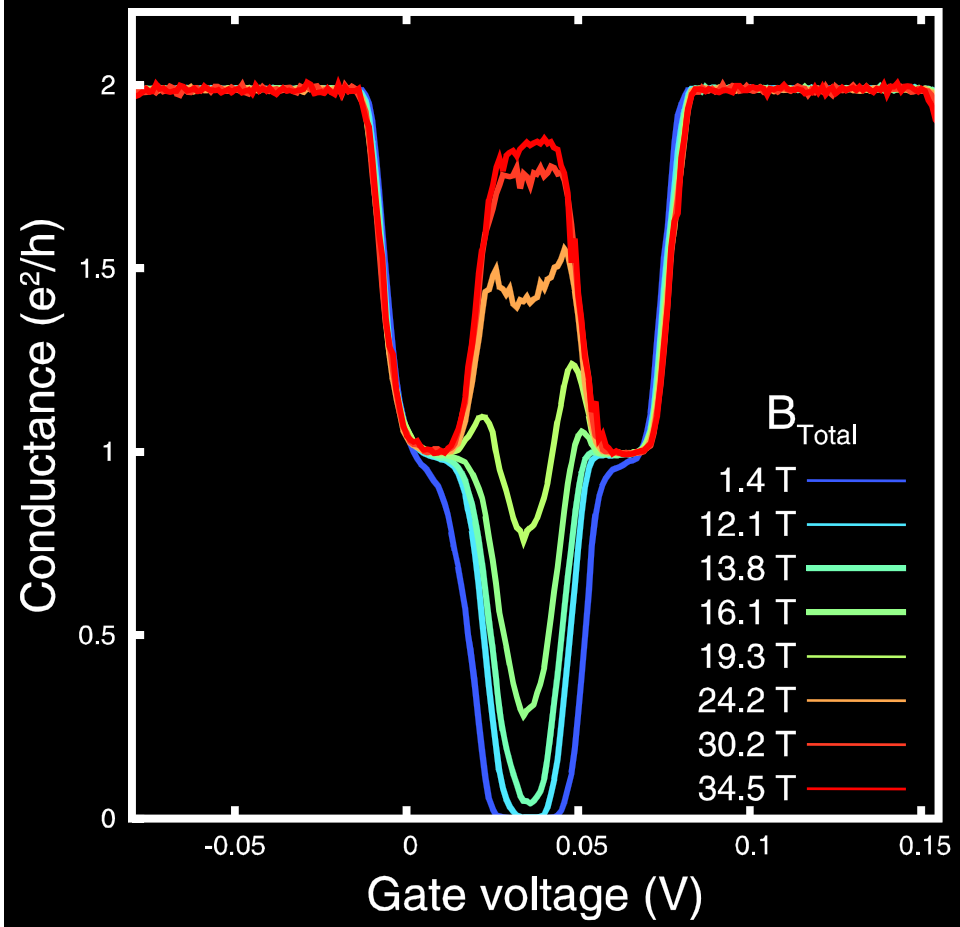
- Insulating bulk
- $2e^2/h$ edge conductance

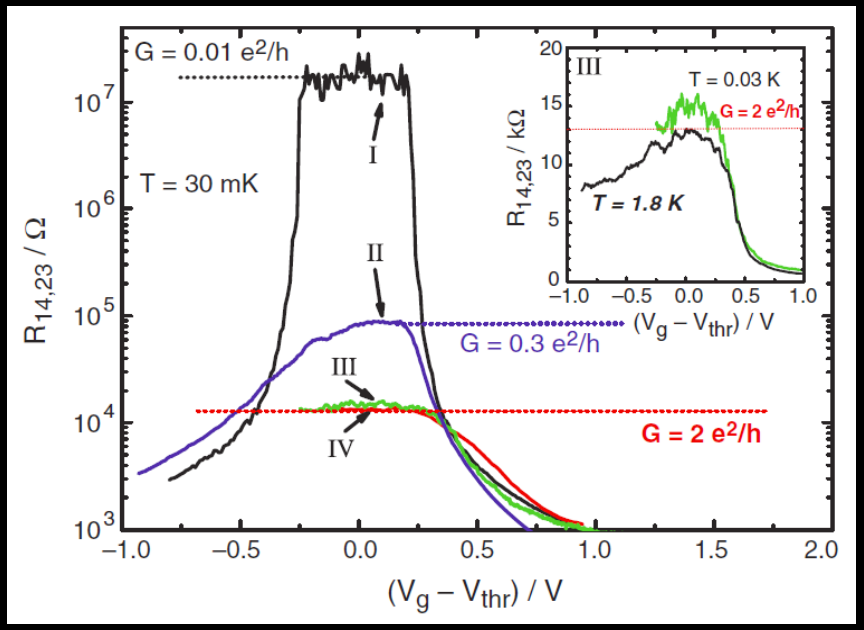
ν=0 state in tilted field





A quantum spin Hall effect?



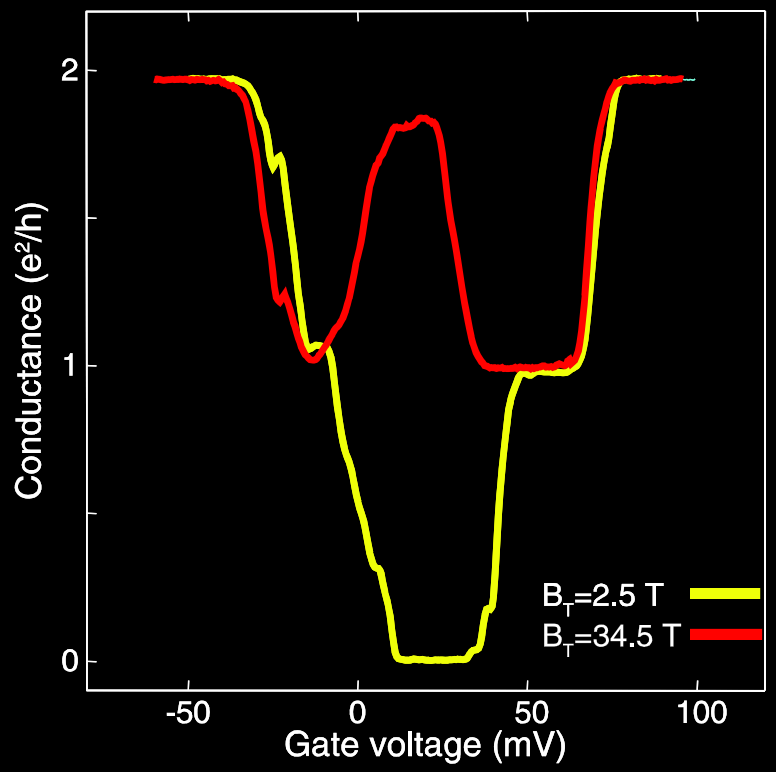


Konig (2007)

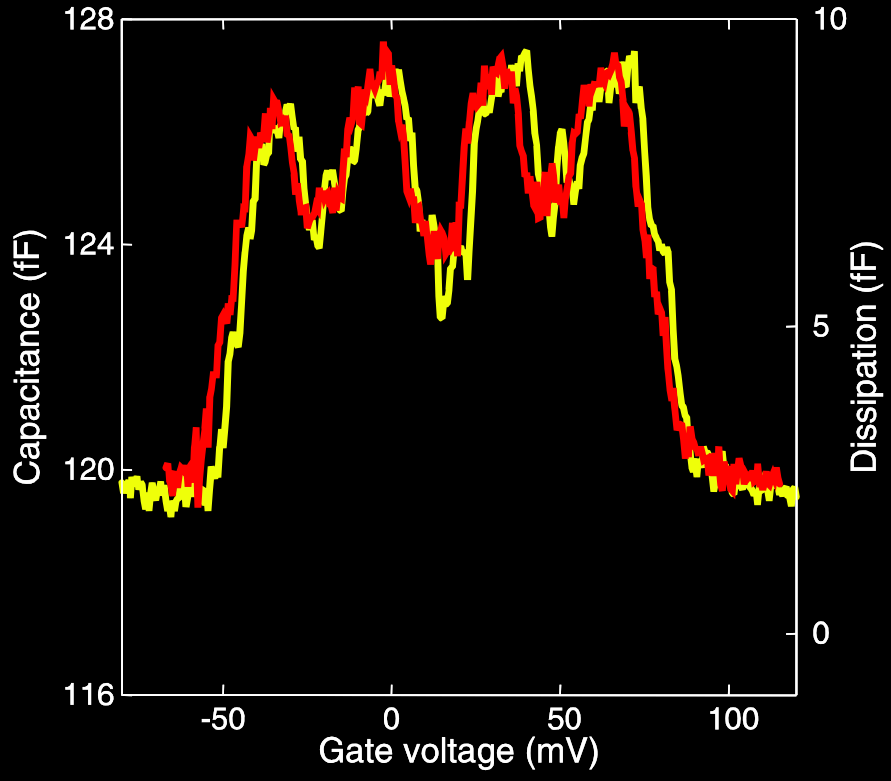
- Different microscopics—same phenomenology?

Probing the bulk DOS

EDGE || BULK



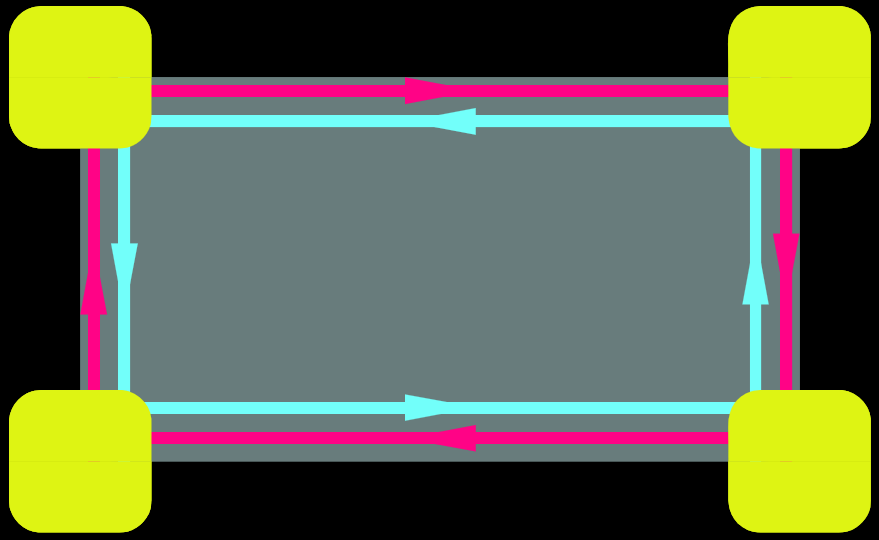
BULK ONLY

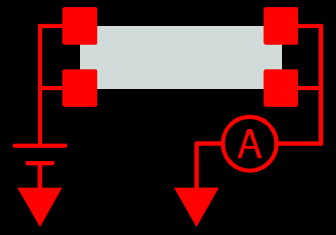


This is an edge effect!

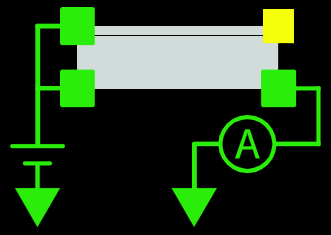
QSH Nonlocal transport

- Contact equilibration
- “edge” = quantum R

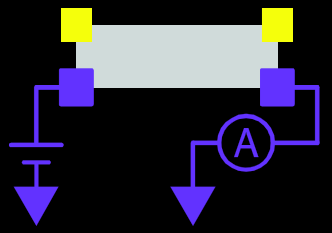




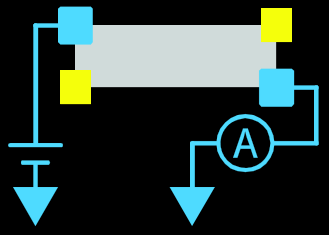
$$G = 2\frac{e^2}{h}$$



$$G = \frac{3}{2}\frac{e^2}{h}$$



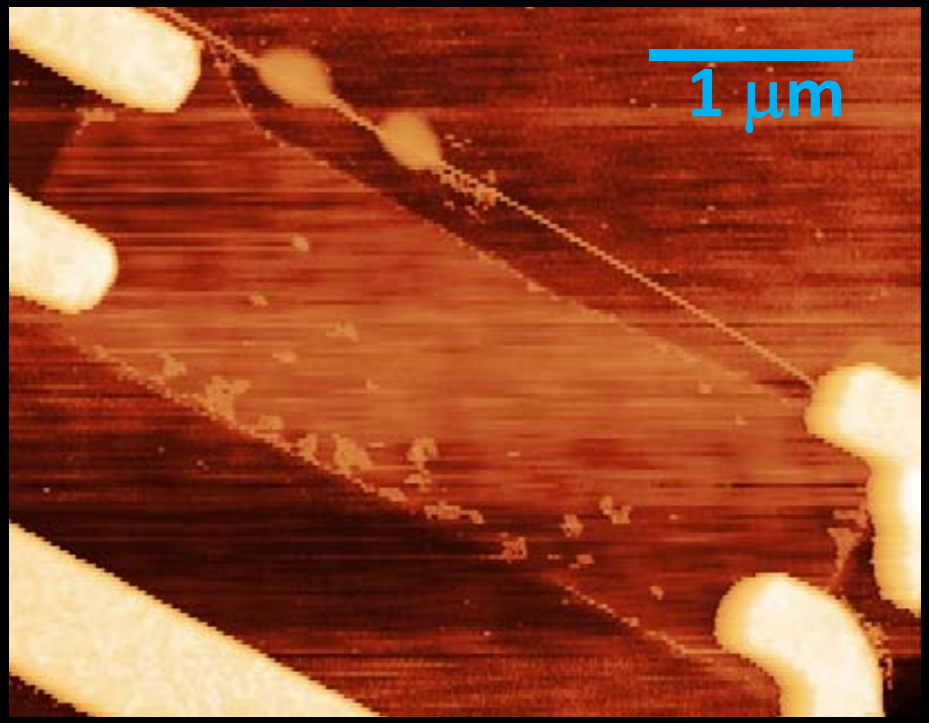
$$G = \frac{4}{3}\frac{e^2}{h}$$

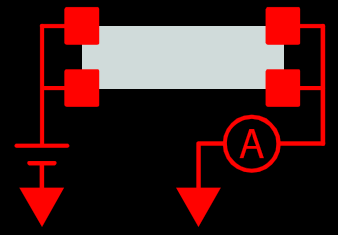


$$G = \frac{e^2}{h}$$

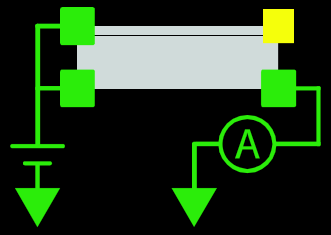
QSH Nonlocal transport

- Contact equilibration
- “edge” = quantum R

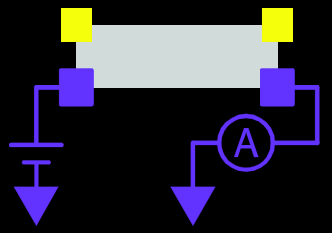




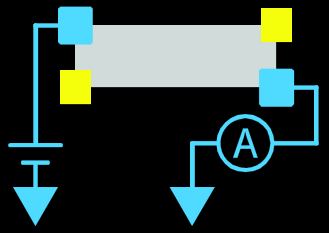
$$G = 2\frac{e^2}{h}$$



$$G = \frac{3}{2}\frac{e^2}{h}$$

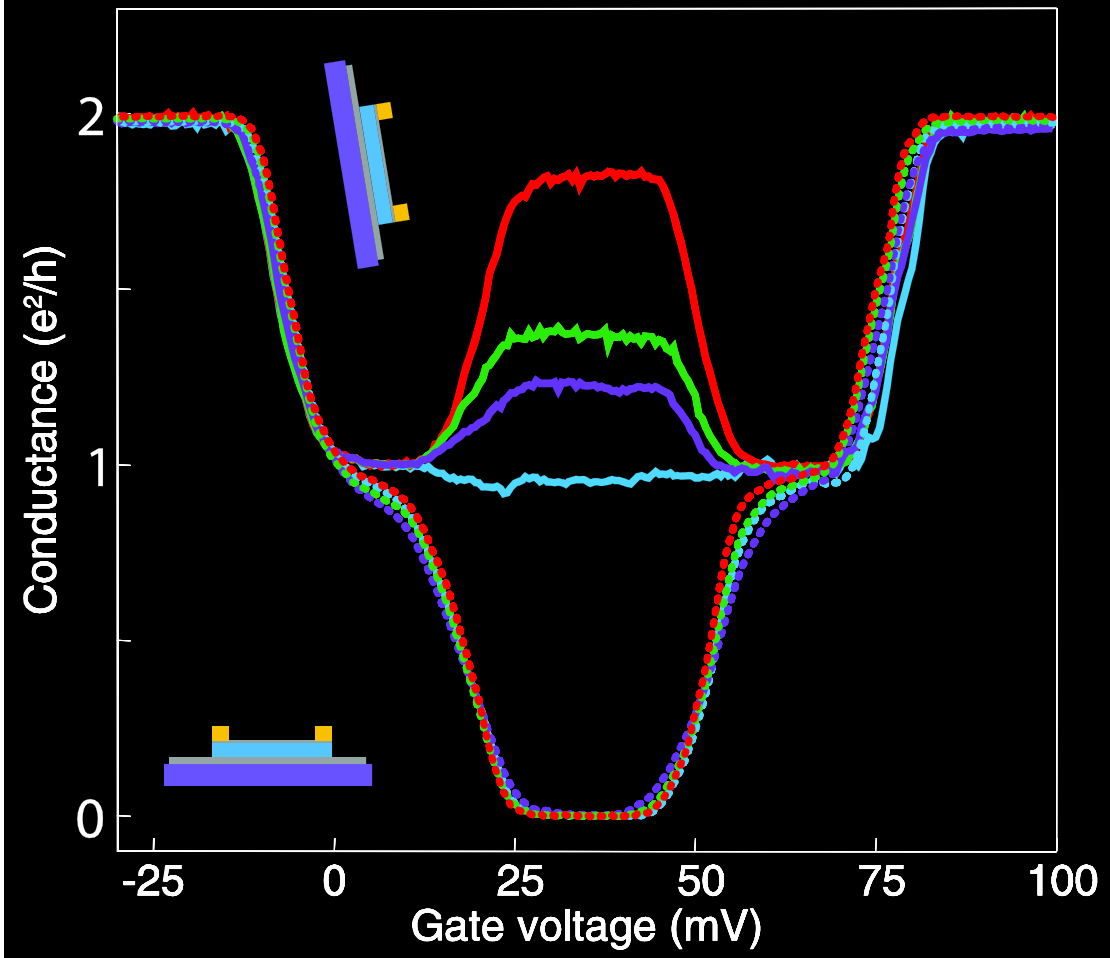


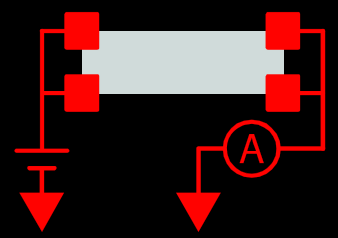
$$G = \frac{4}{3}\frac{e^2}{h}$$



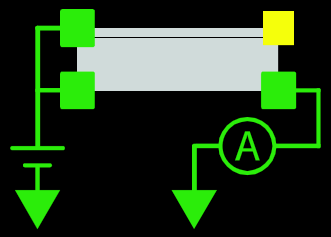
$$G = \frac{e^2}{h}$$

QSH Nonlocal transport

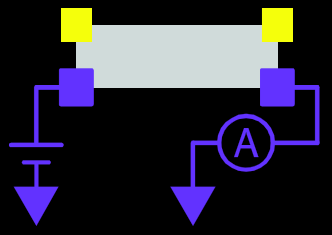




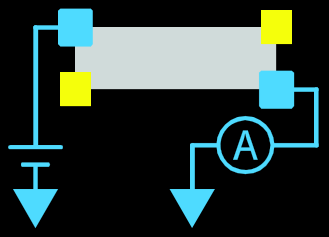
$$G = 2\frac{e^2}{h}$$



$$G = \frac{3}{2}\frac{e^2}{h}$$



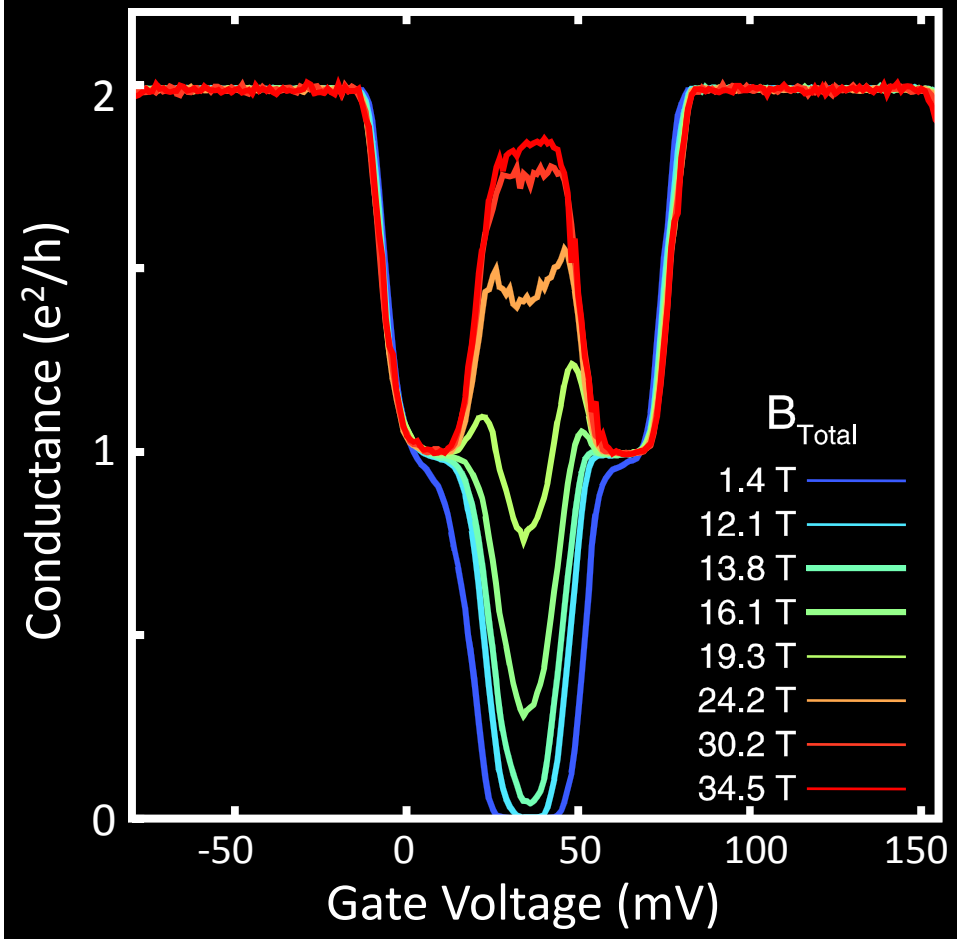
$$G = \frac{4}{3}\frac{e^2}{h}$$

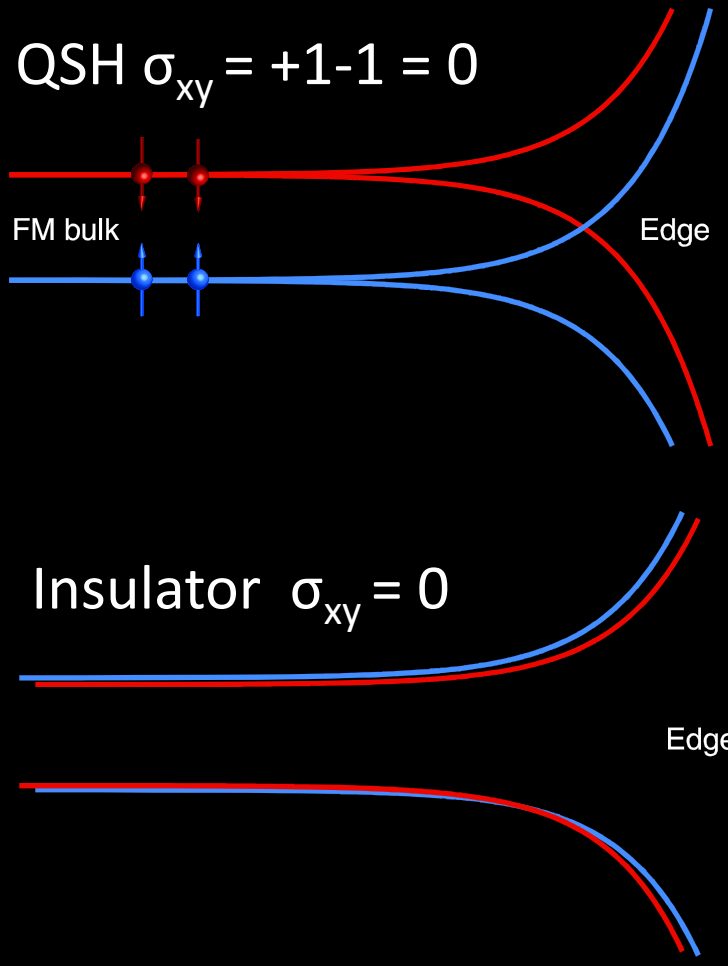


$$G = \frac{e^2}{h}$$

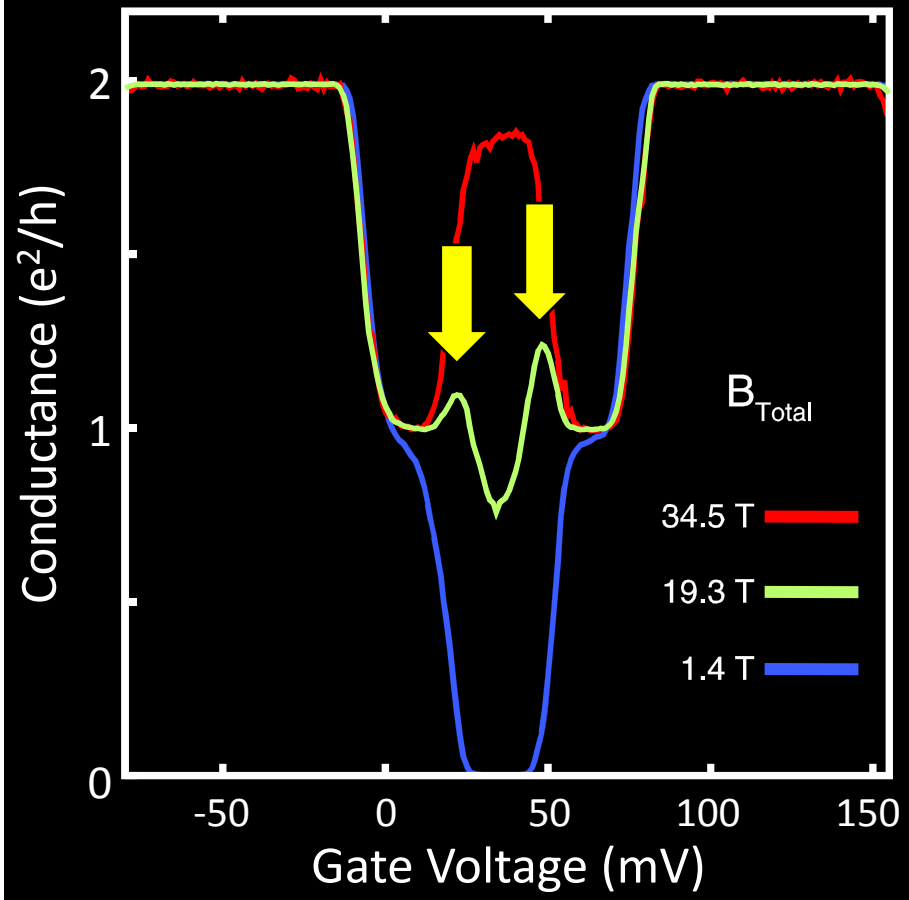
Spin symmetry protected QSH

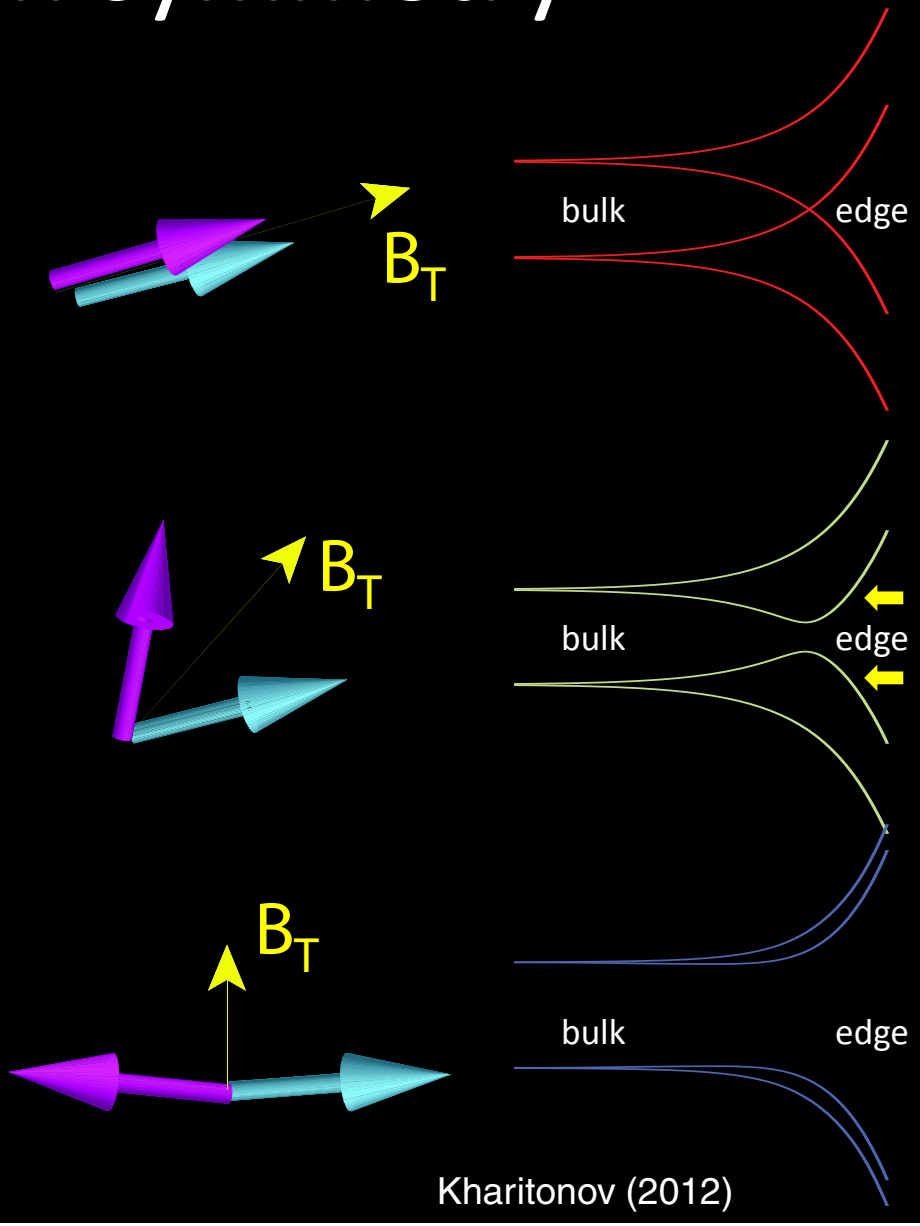
Two copies of the QHE, protected by a *spin symmetry*





Breaking spin symmetry

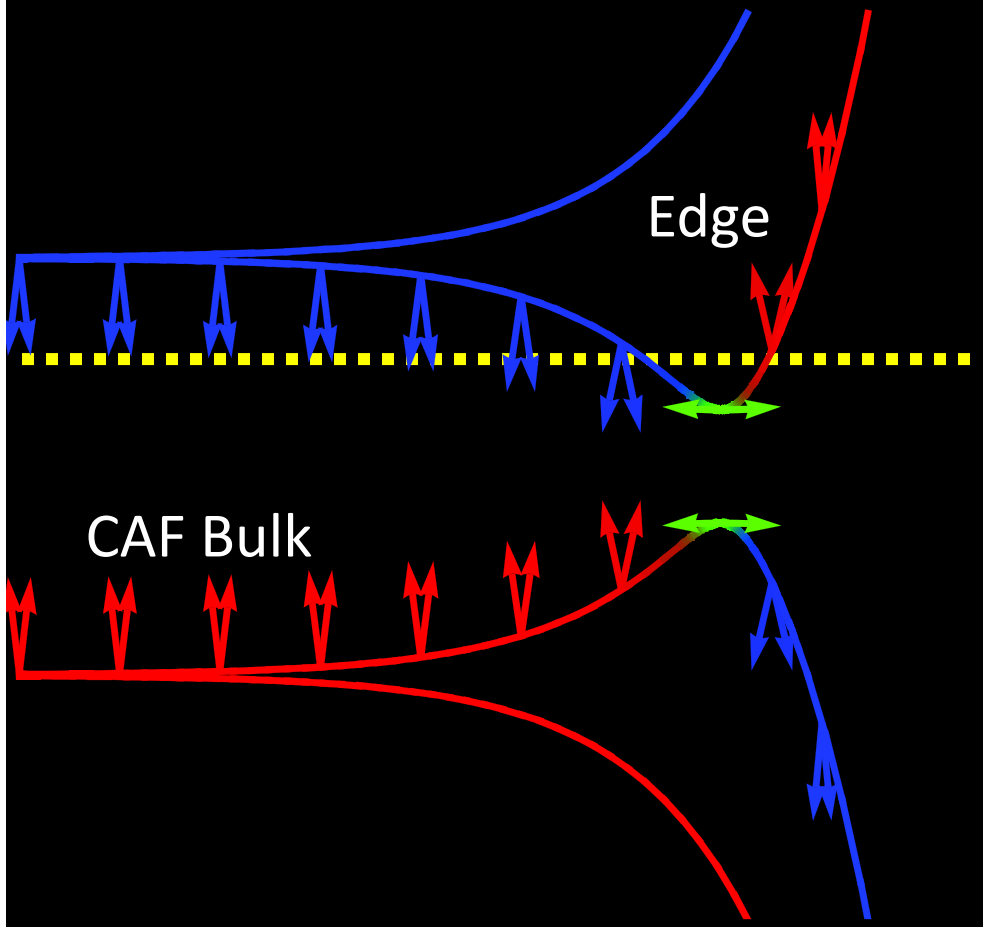




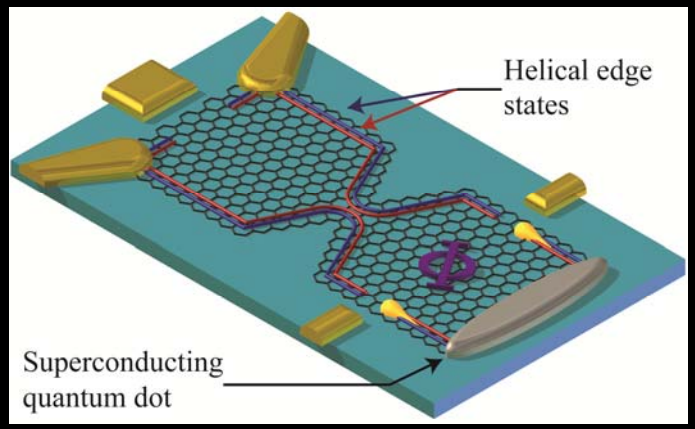
Metallic lobes
Nonlocal transport
Bulk gap never closes (capacitance)

Kharitonov (2012)

CAF Edge state spin texture

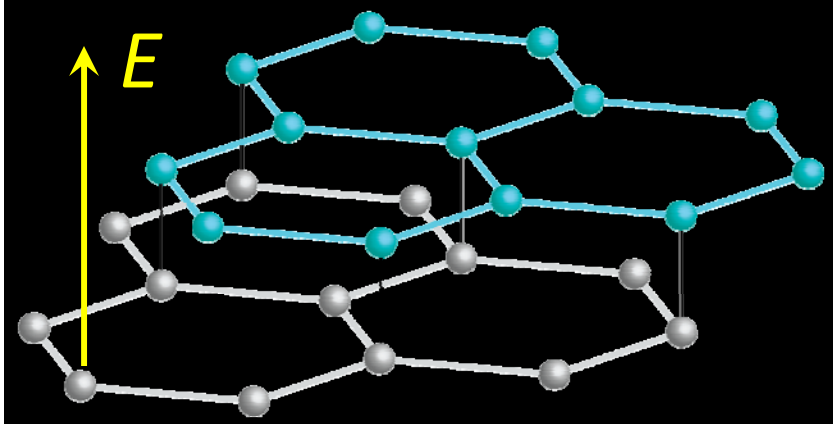


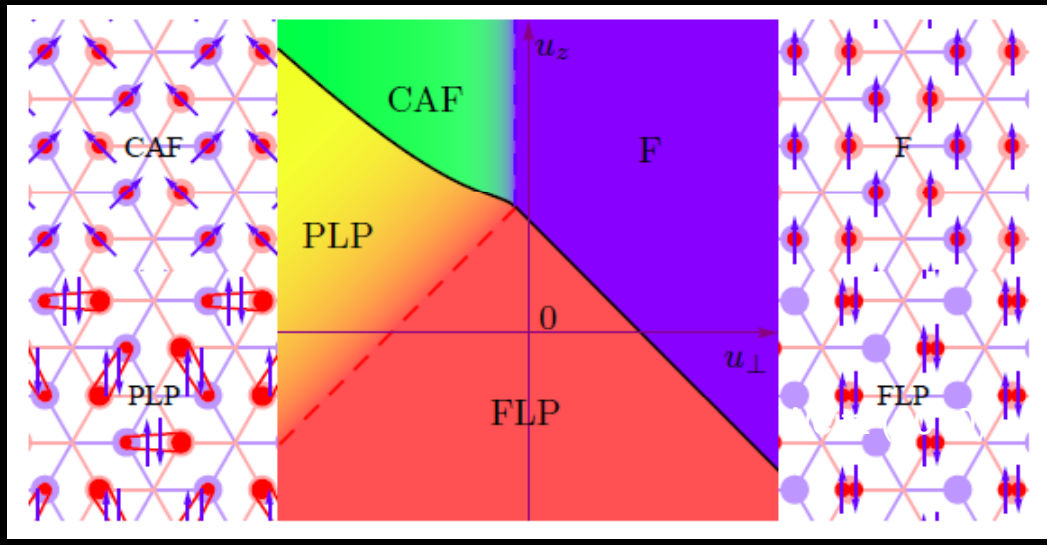
- CAF texture protects from backscattering (partially)
- Depletable
- Proximity effect ➔ Majoranas?



Fu *PRL* (2011)

Bilayer graphene



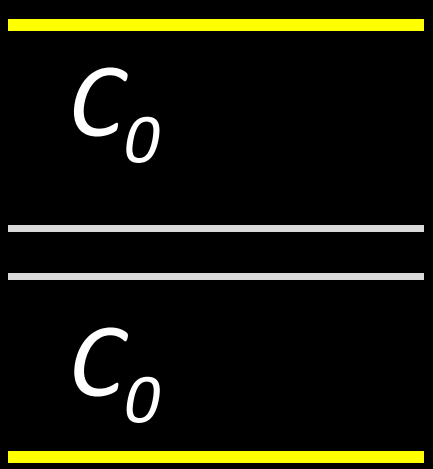


Kharitonov (2011)

- Control layer polarization via E field (sublattice in ZLL for Bernal)
- Most studies: vary E, watch
- Motivation: a direct probe?

Bilayer capacitance

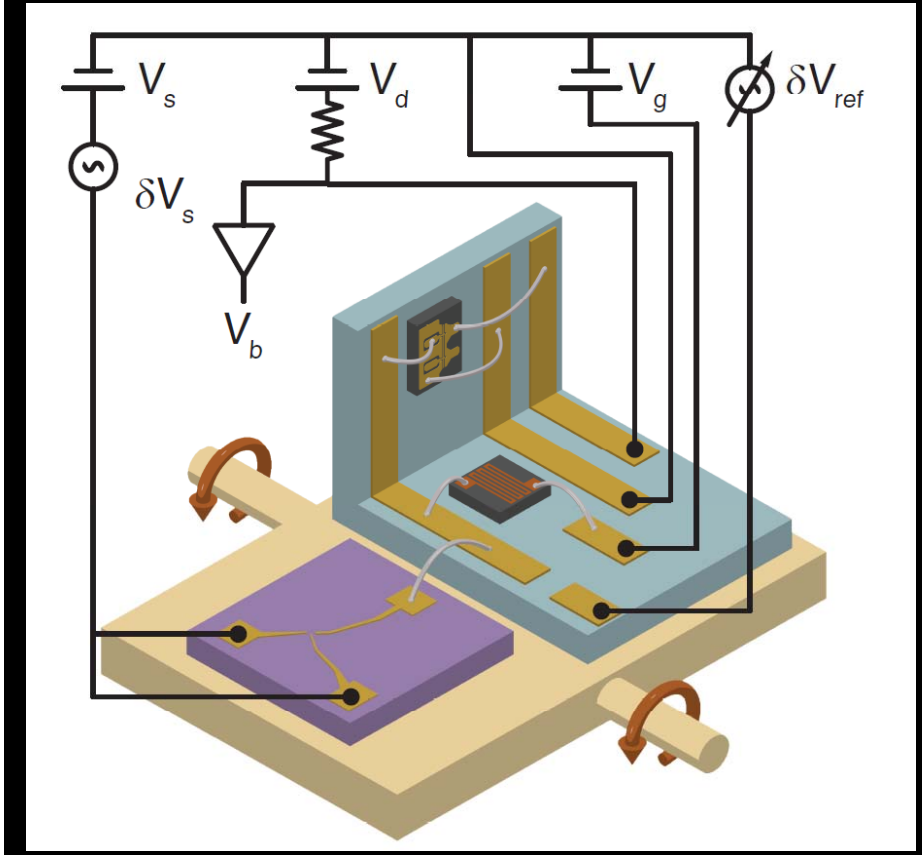
- Charge localized on one of two layers
- Strongly coupled, but layers screen each other
  - Three "compressibilities"
    - total DOS : ν_{++}
    - layer polarization: ν_{-+}
    - Polarizability: ν_{--}



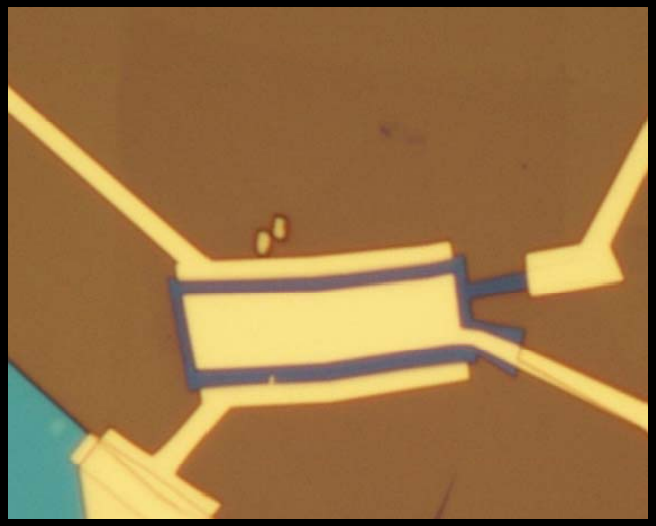
Young and Levitov *PRB* 2011
Young et al., PRB 2012

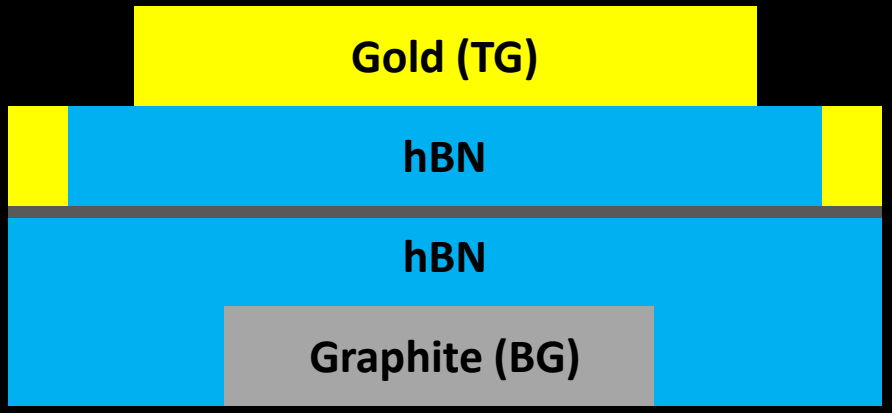
$$C_T - C_B \simeq \frac{C_0^2}{C_{BLG}(2C_0 + \nu_{++})}\nu_{-+}$$

Device and measurement schematic



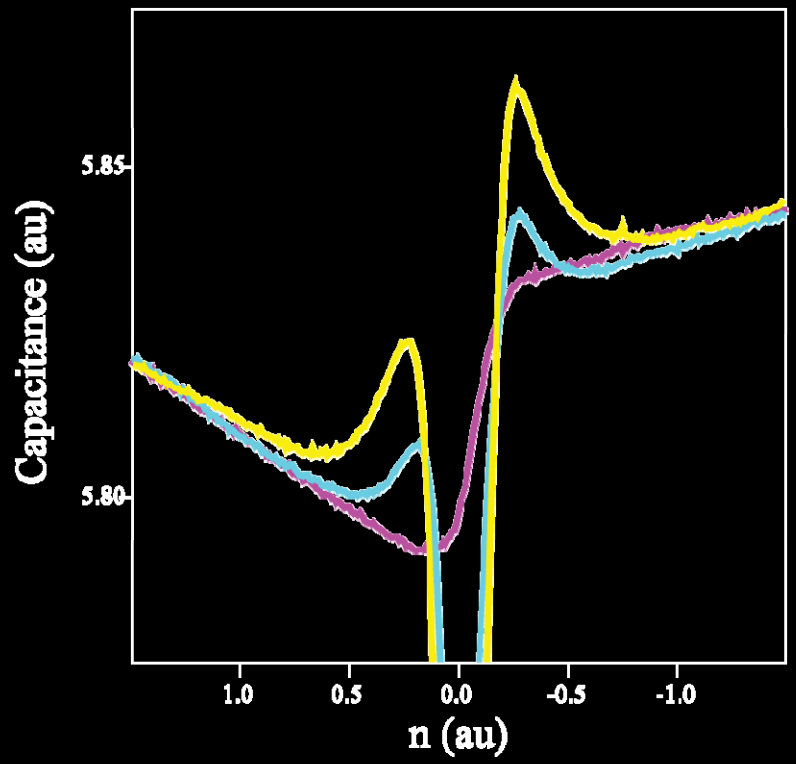
HEMT Cryogenic amplifiers



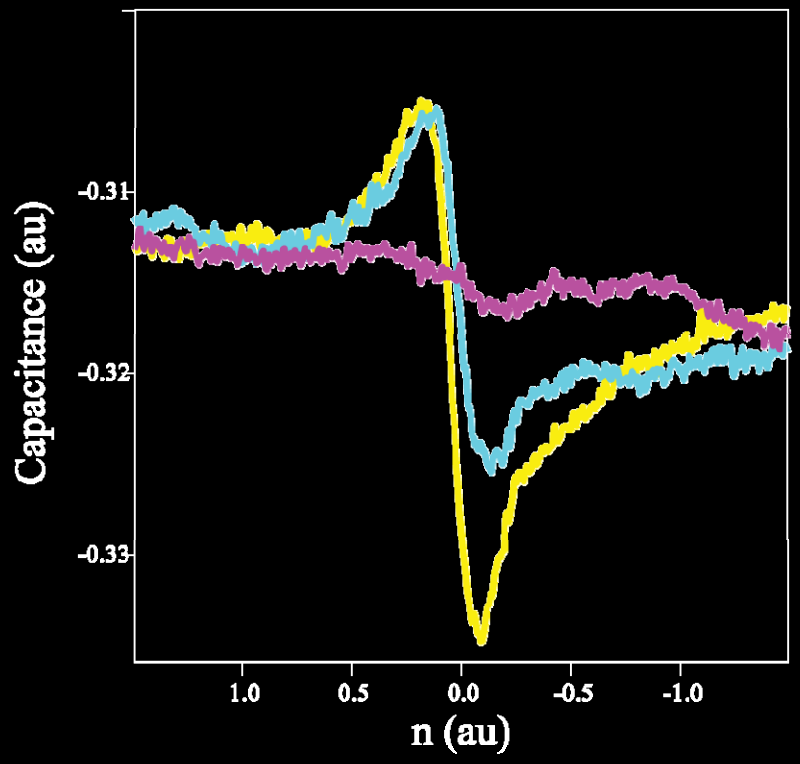


B=0 capacitance: ph asymmetry and 1D vHs

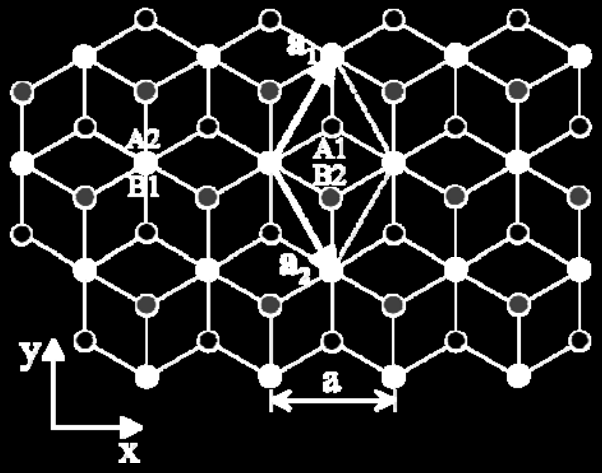
Symmetric: CT+CB

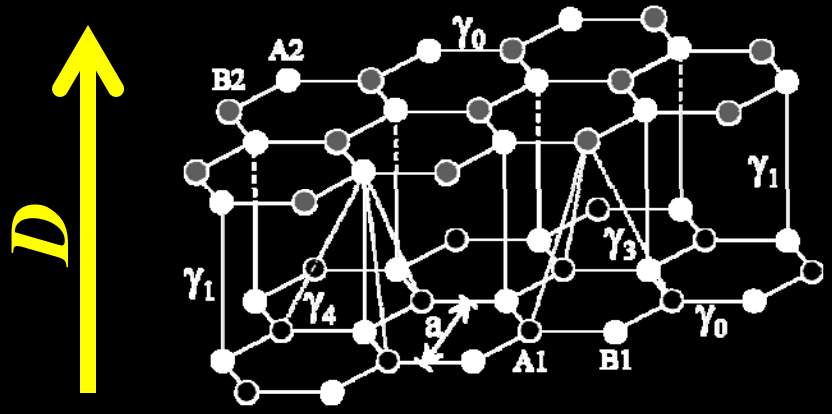


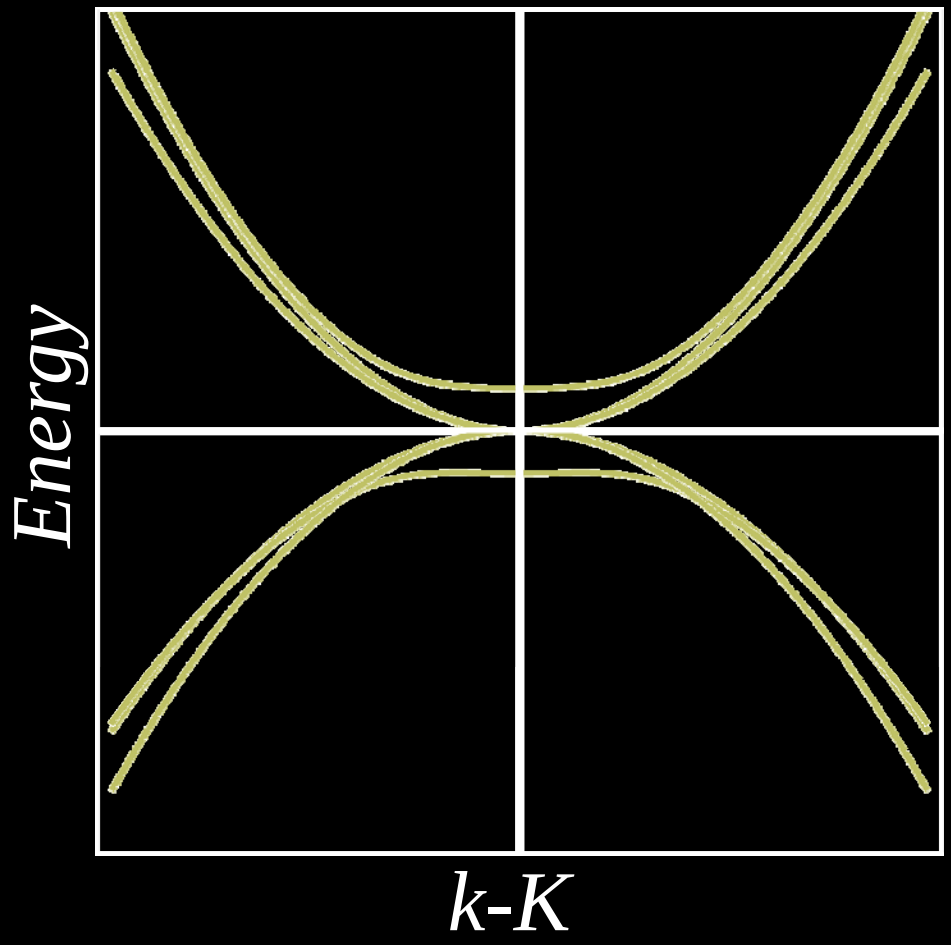
Asymmetric: CT-CB



Bilayer graphene: layers and isospins

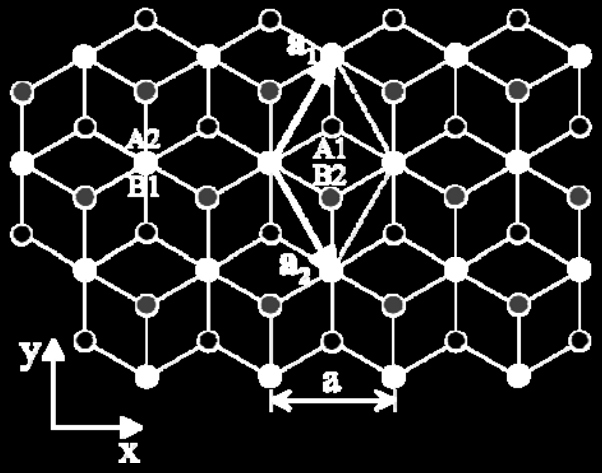


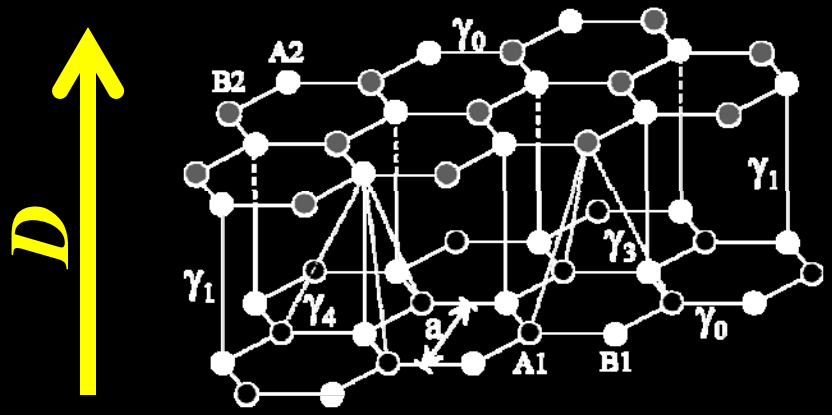


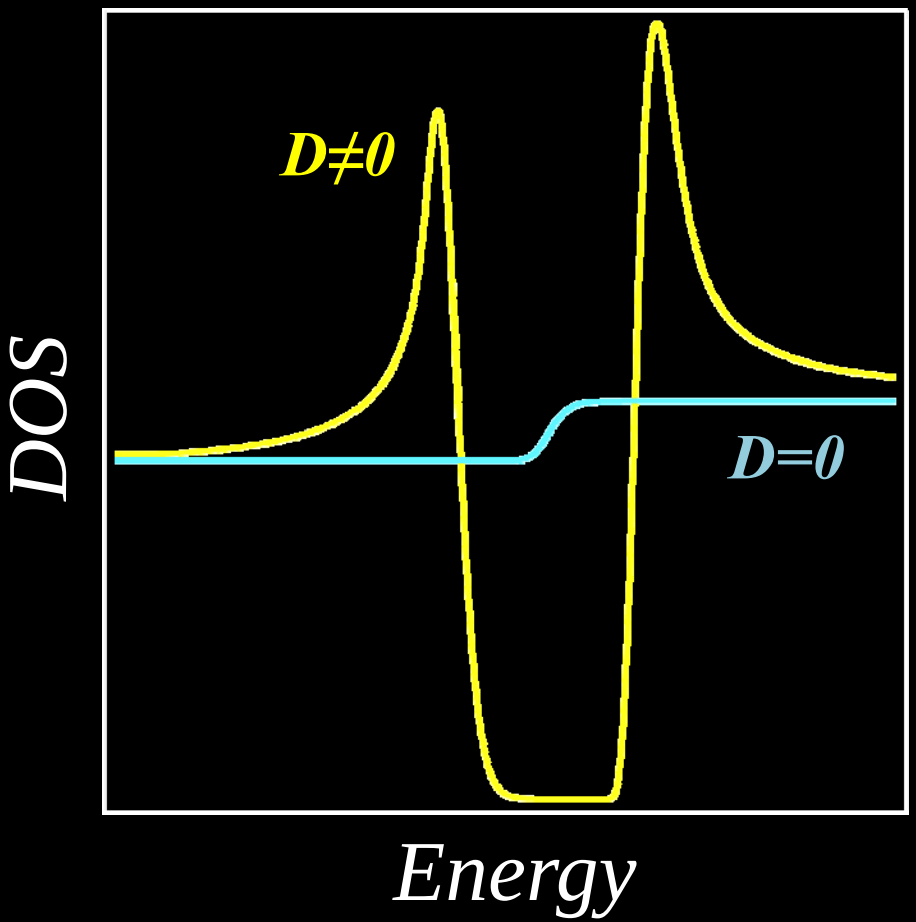


Adapted from Koshino+McCann (2013)

Bilayer graphene density of states

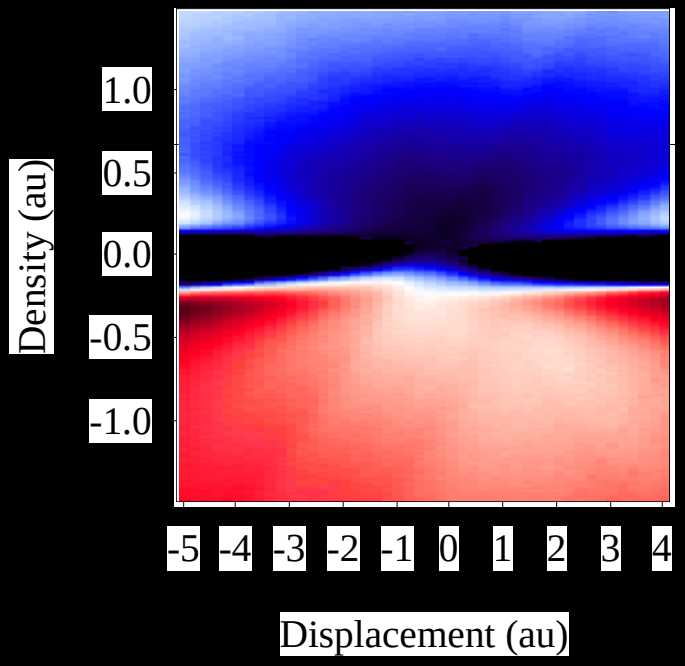


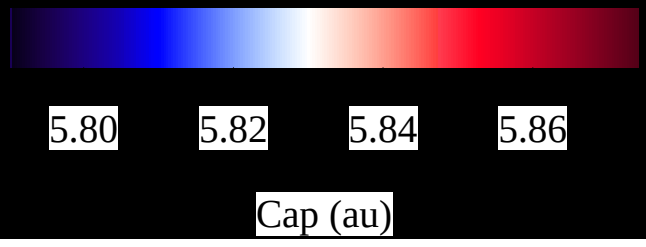




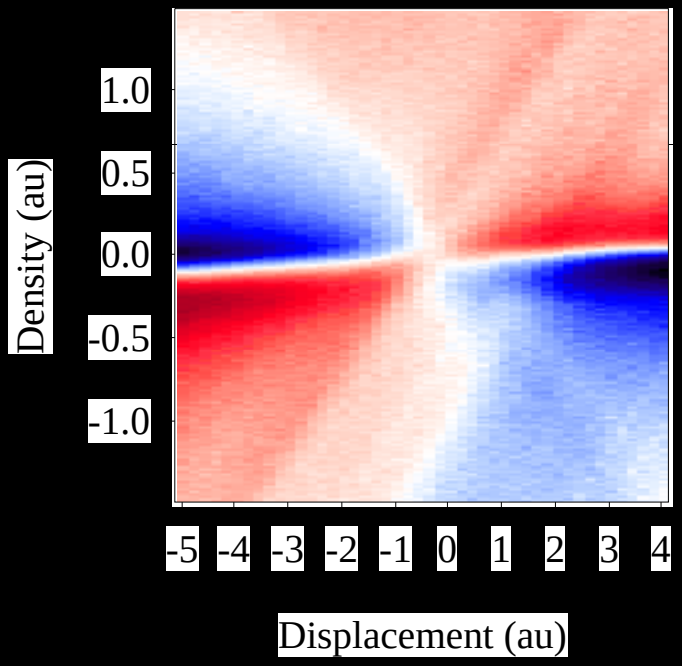
B=0 capacitance: ph asymmetry and 1D vHs

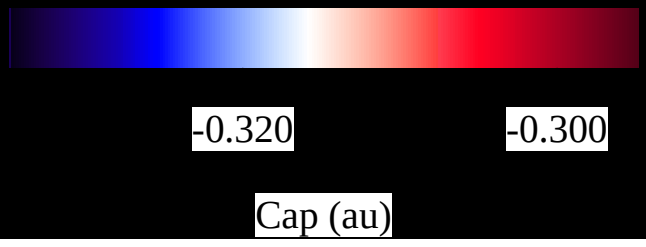
Symmetric: CT+CB



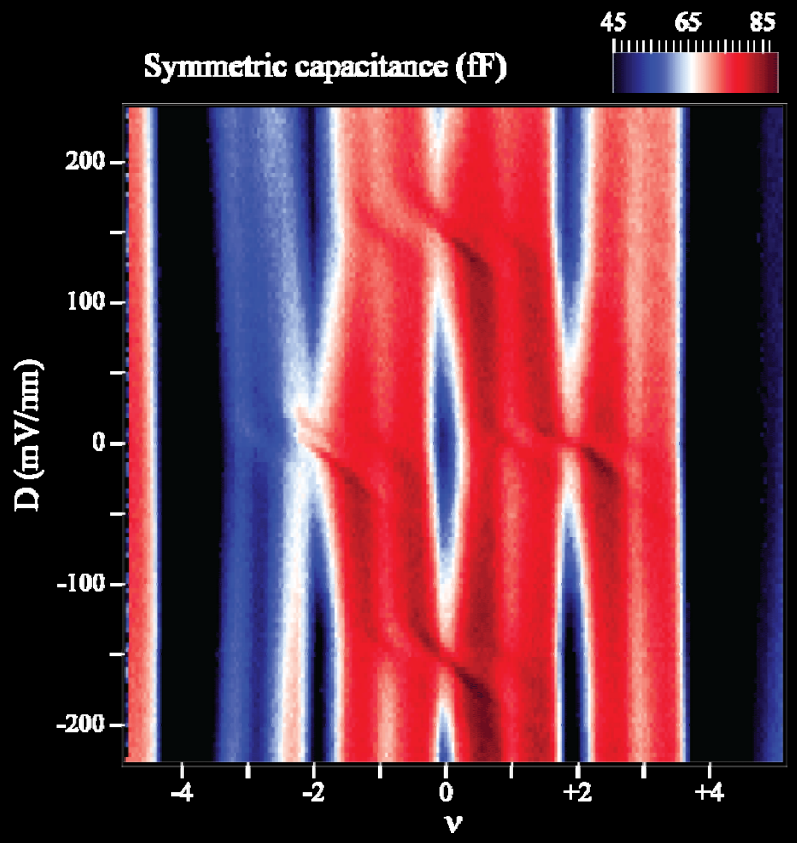


Asymmetric: CT-CB



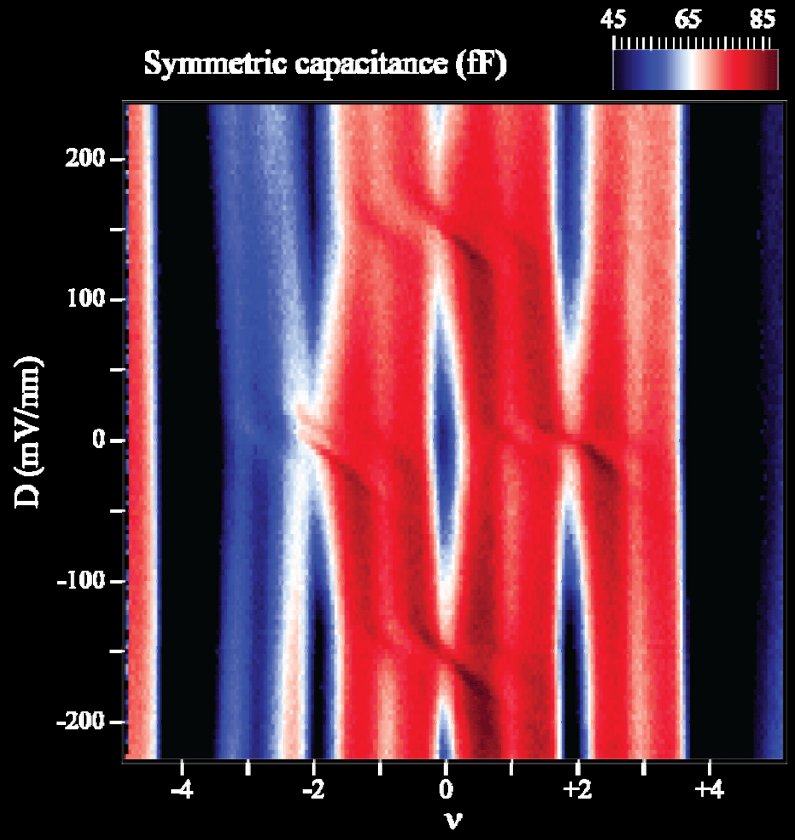


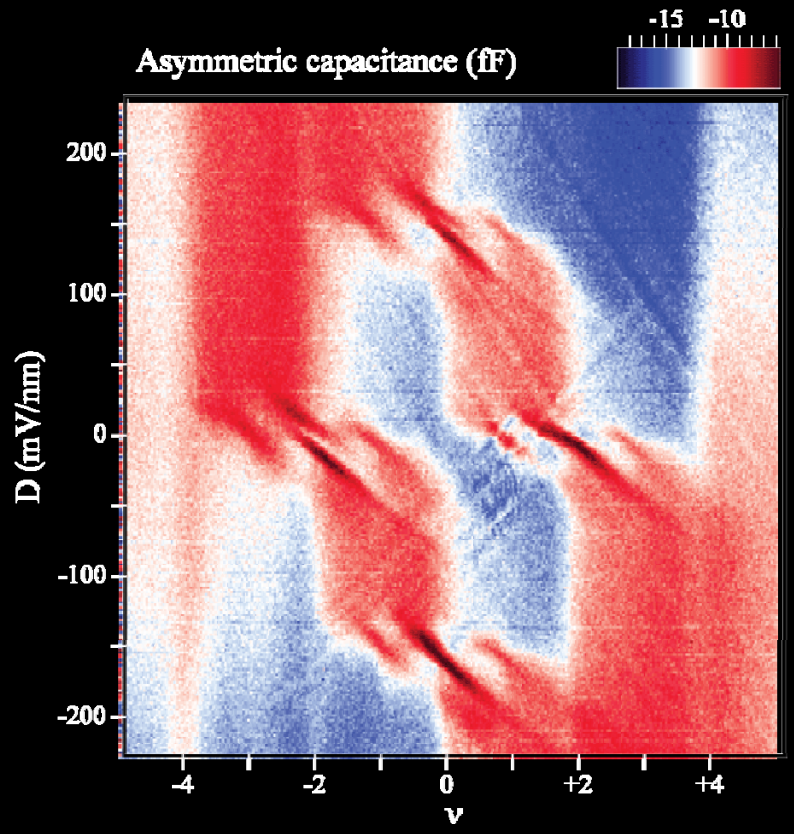
High field: full symmetry breaking



- Spin, valley, and *orbital* degeneracy
- What kind of order characterizes the different gapped phases?
- We will probe *layer polarization*

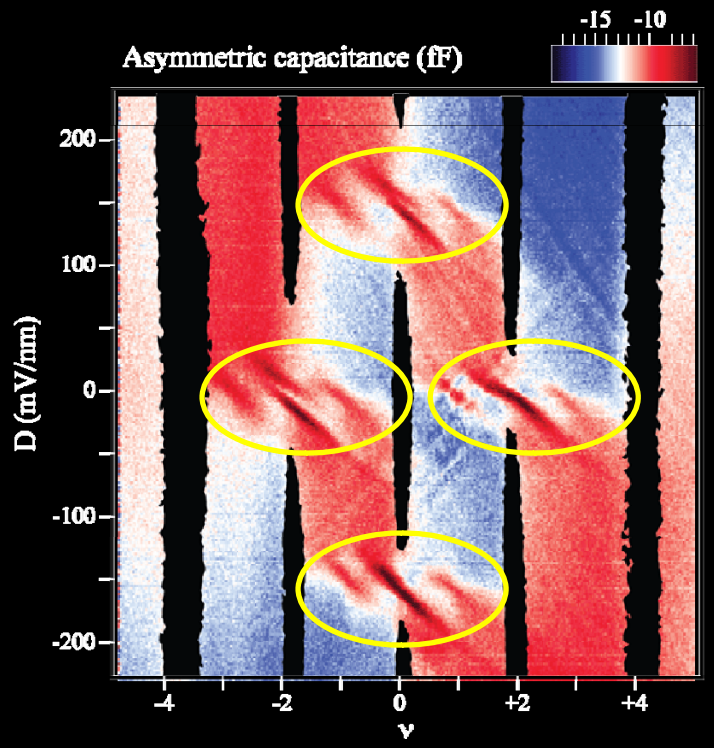
High field: full symmetry breaking



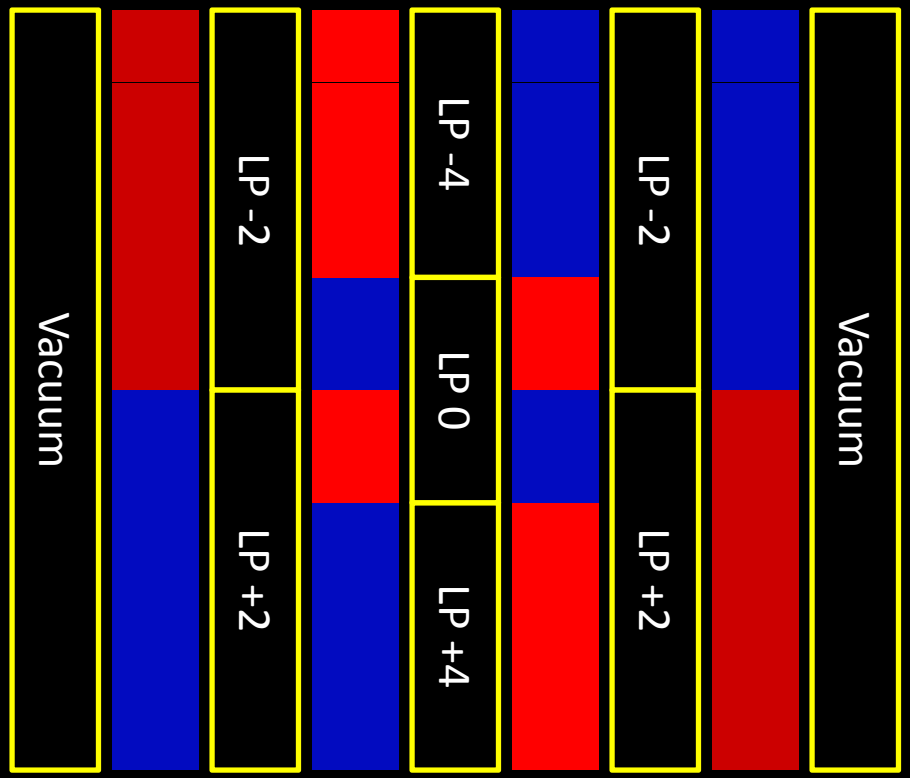


High field: full symmetry breaking

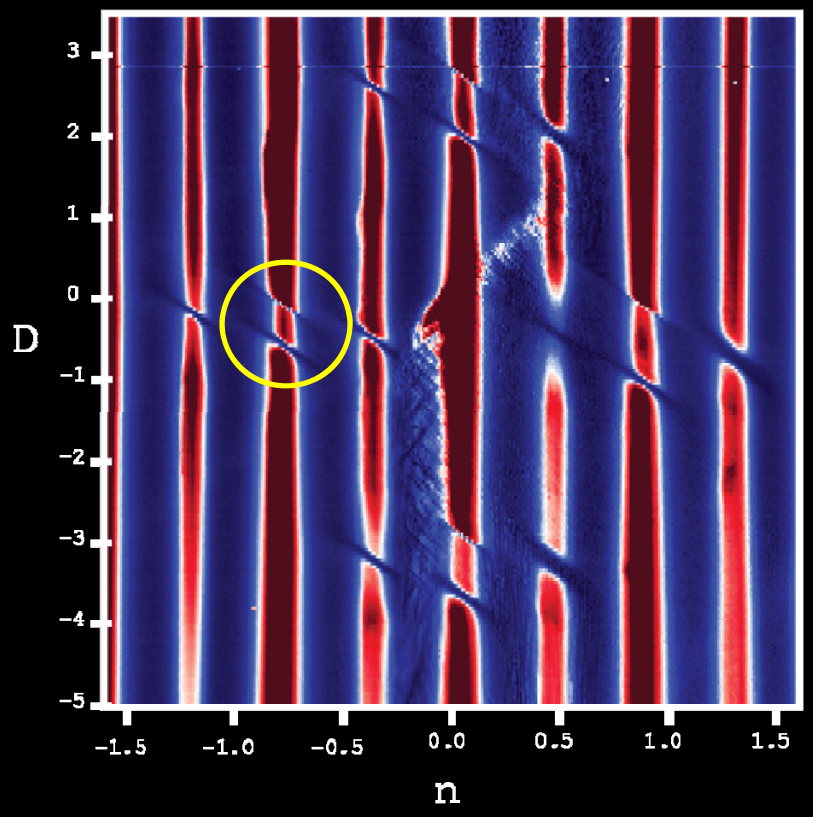
Red/blue ~ fill top/bottom layer



Orbital degeneracy "breaks last"



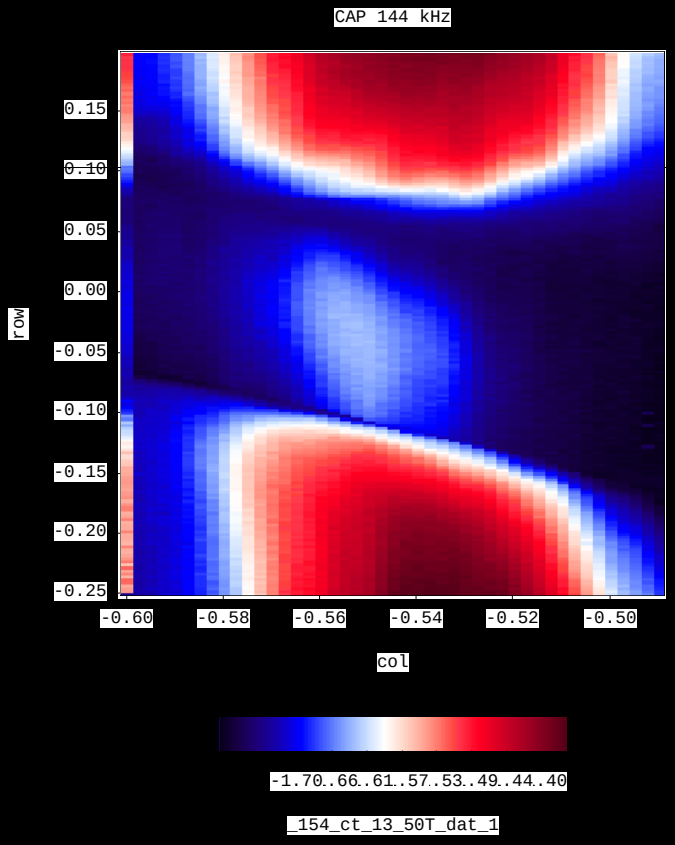
High field: full symmetry breaking



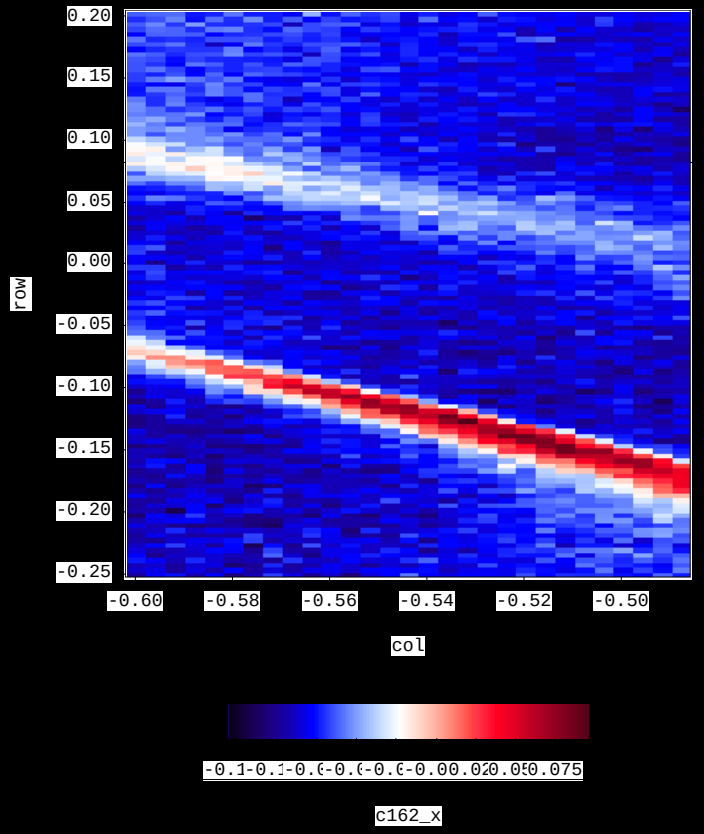
- Precise order not known
- BUT: transitions in layer polarization

Phase transitions

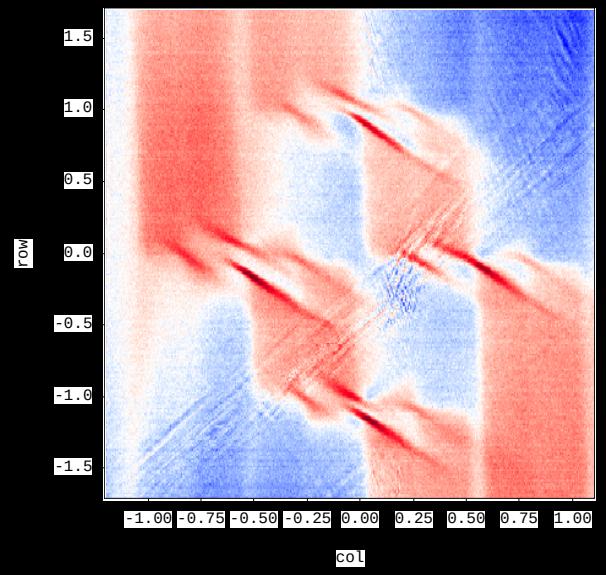
Symmetric

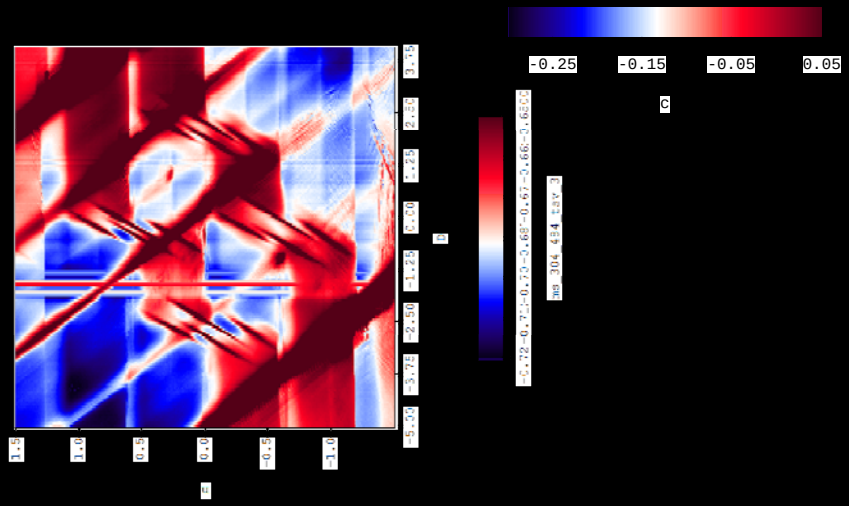


Asymmetric



Phase transitions





- Why slope?
- Why sign asymmetry?
- Why so strong?

- Macroscopic polarization reversal
- Asymmetric gates?

Collaborators

Quantum Spin Hall effect

- MIT
  - **B. Hunt, J. Sanchez Yamagishi, S. Choi,** P. Jarillo-Herrero, R. Ashoori
- NIMS
  - T. Taniguchi, K. Watanabe

Layer Polarization

- MIT
  - B. Hunt, R. Ashoori
- Columbia
  - L. Wang, C. Dean, J. Hone
- NIMS
  - T. Taniguchi, K. Watanabe