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ARTICLES

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There are amendments to this paper

Interacting topological edge channels

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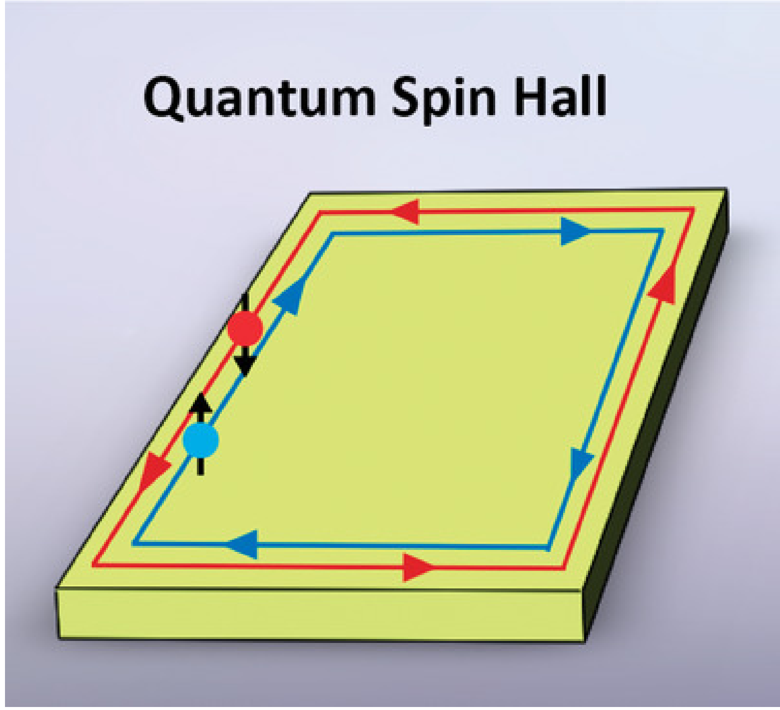
Electrical currents in a quantum spin Hall insulator are confined to the boundary of the system. The charge carriers behave as massless relativistic particles whose spin and momentum are coupled to each other. Although the helical character of those states is already established by experiments, there is an open question regarding how those edge states interact with each other when they are brought into close spatial proximity. We employ an inverted HgTe quantum well to guide edge channels from opposite sides of a device into a quasi-one-dimensional constriction. Our transport measurements show that, apart from the expected quantization in integer steps of $2e^2/h$, we find an additional plateau at e^2/h. We combine band structure calculations and repulsive electron–electron interaction effects captured within the Tomonaga–Luttinger liquid model and Rashba spin–orbit coupling to explain our observation in terms of the opening of a spin gap. These results may have direct implications for the study of one-dimensional helical electron quantum optics, and for understanding Majorana and para fermions.

Zumbühl Group journal club 29.01.2021

Henok Weldeyesus

$$G_0 = \frac{2e^2}{h}$$



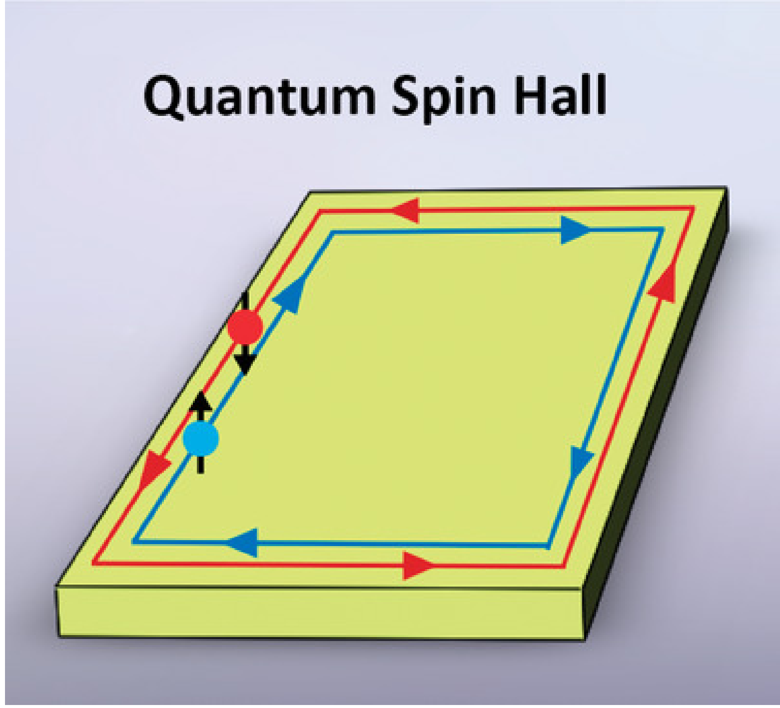
Quantum spin hall effect

Cao, C. and Chen, J.-H. (2019); Adv. Quantum Technol.; 2

Quantum Spin Hall Effect

- No magnetic field needed
  - Conserves time revearsal symmetry
- Edgestates come in pairs of opposit spin and chirality (helical)

- Examples:
  - HgTe quantum wells
  - InAs/GaSb double quantum wells
  - WTe2
  - Bismuthene



Cao, C. and Chen, J.-H. (2019); Adv. Quantum Technol.; 2

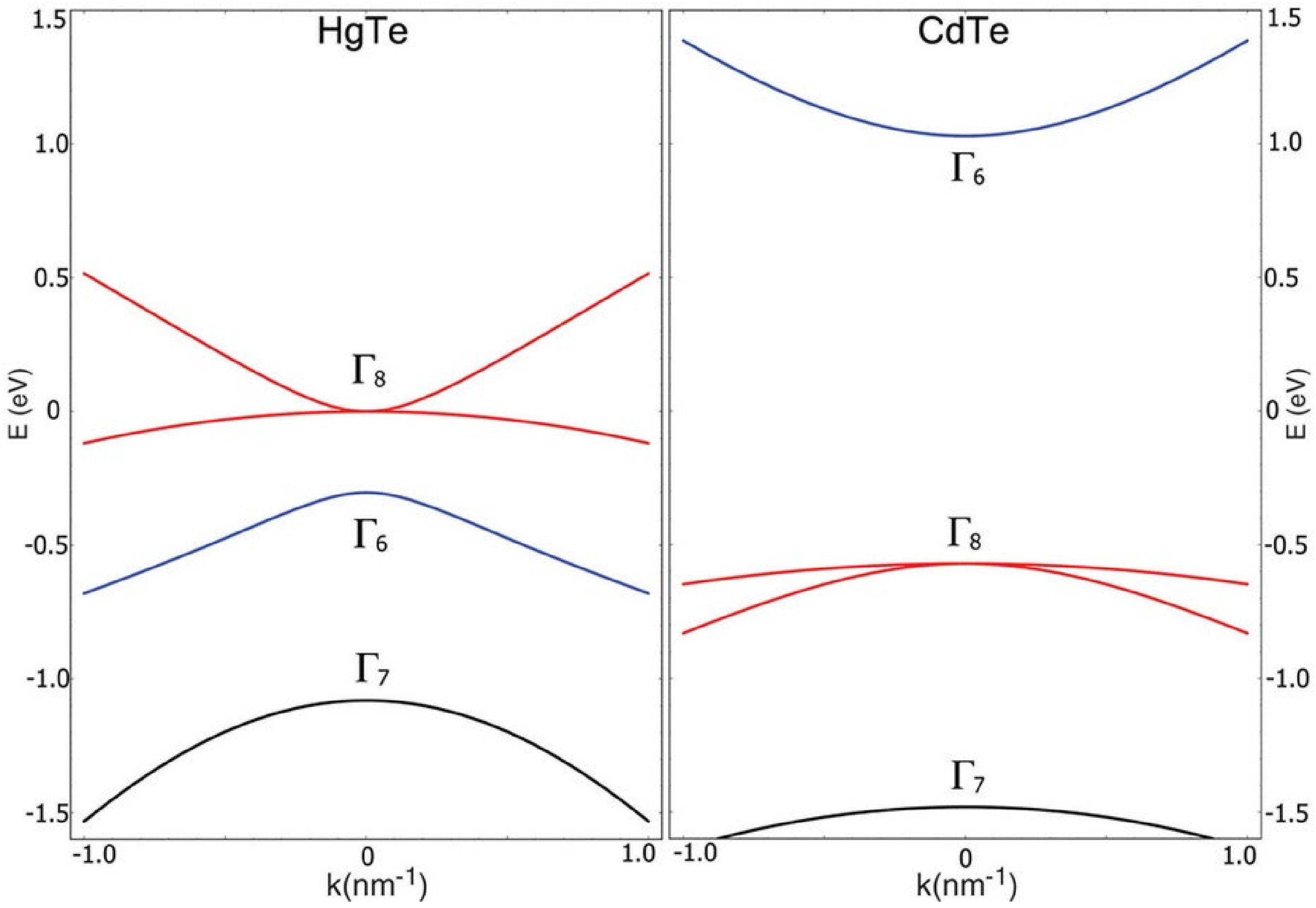
Quantum Spin Hall Effect: HgTe/CdTe Quantum Wells

- CdTe: normal ordering of Band;

  valence band Heavy holes
  conduction band Electrons

- HgTe: inverse ordering of bands;

  valence band Electrons
  conduction band Heavy Holes



B. Bernevig, T. Hughes, S. Zhang; Science 2006; 314

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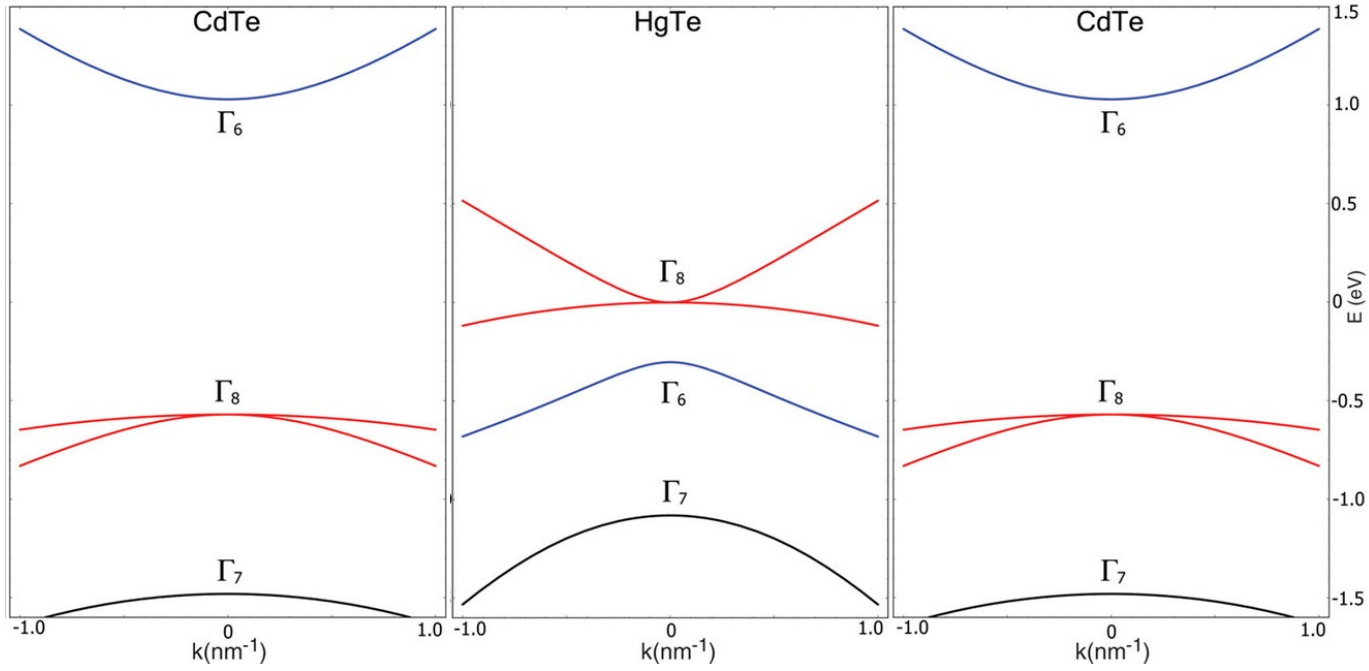
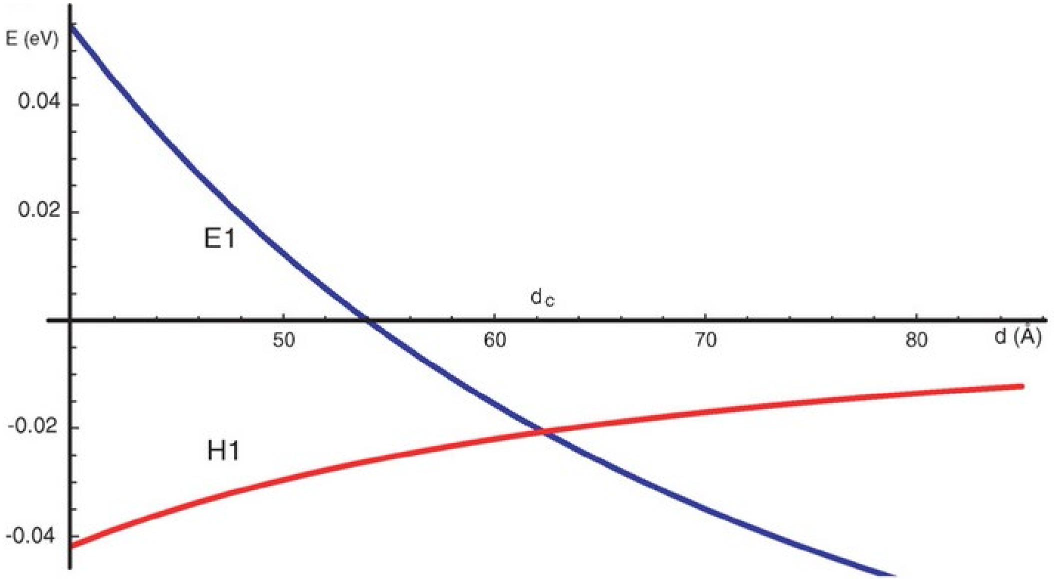
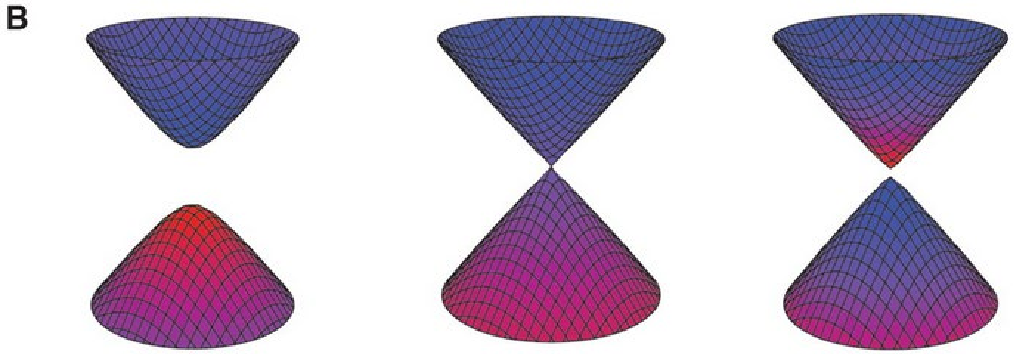


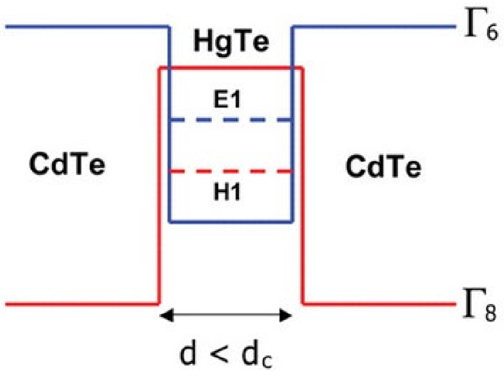
B. Bernevig, T. Hughes, S. Zhang; Science 2006; 314

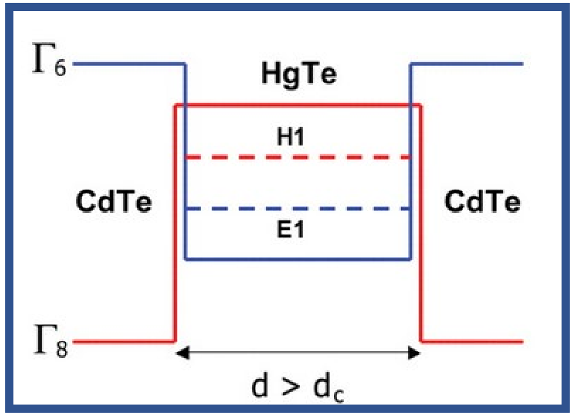
Quantum Spin Hall Effect: HgTe/CdTe Quantum Wells

- Band order in quantum well depends on thicknes
- Band inversion at d_c~63nm







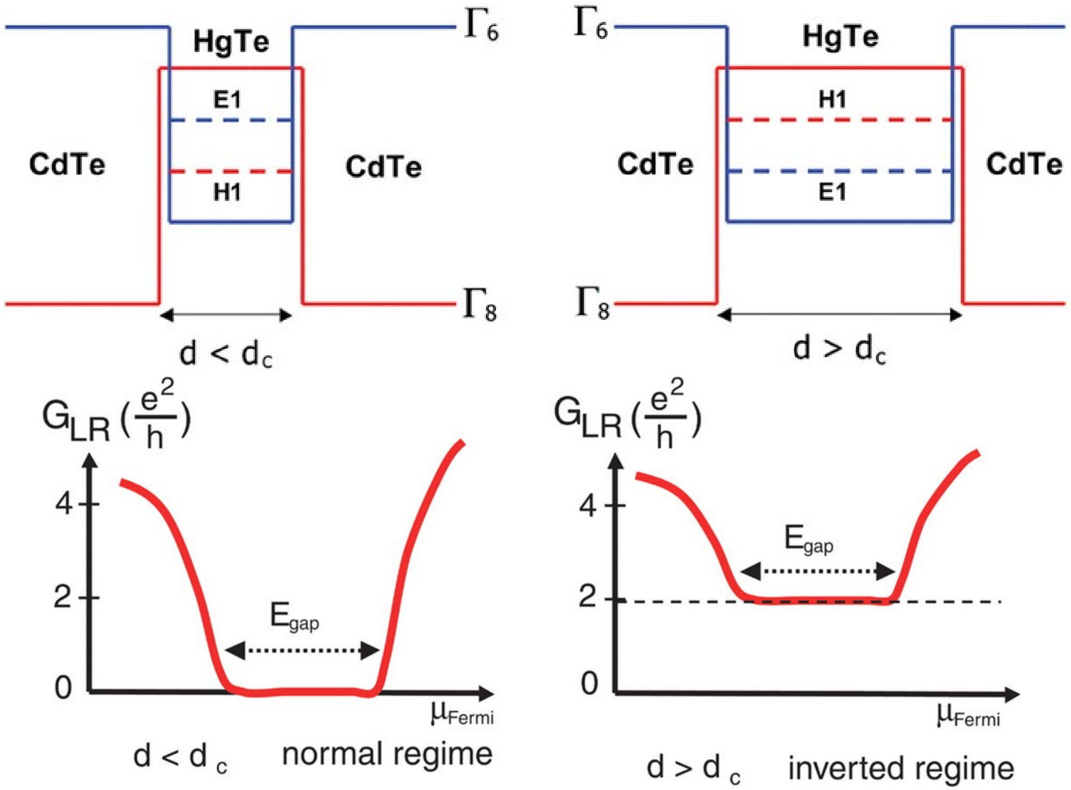


Inverted/"topological" regime

B. Bernevig, T. Hughes, S. Zhang; Science 2006; 314

Quantum Spin Hall Effect

- Normal regime: Expect $\sigma = 0$ when μ is in gap
- Inverted regime: Expect $\sigma = 2e^2/h$ when μ is in gap (edge states)

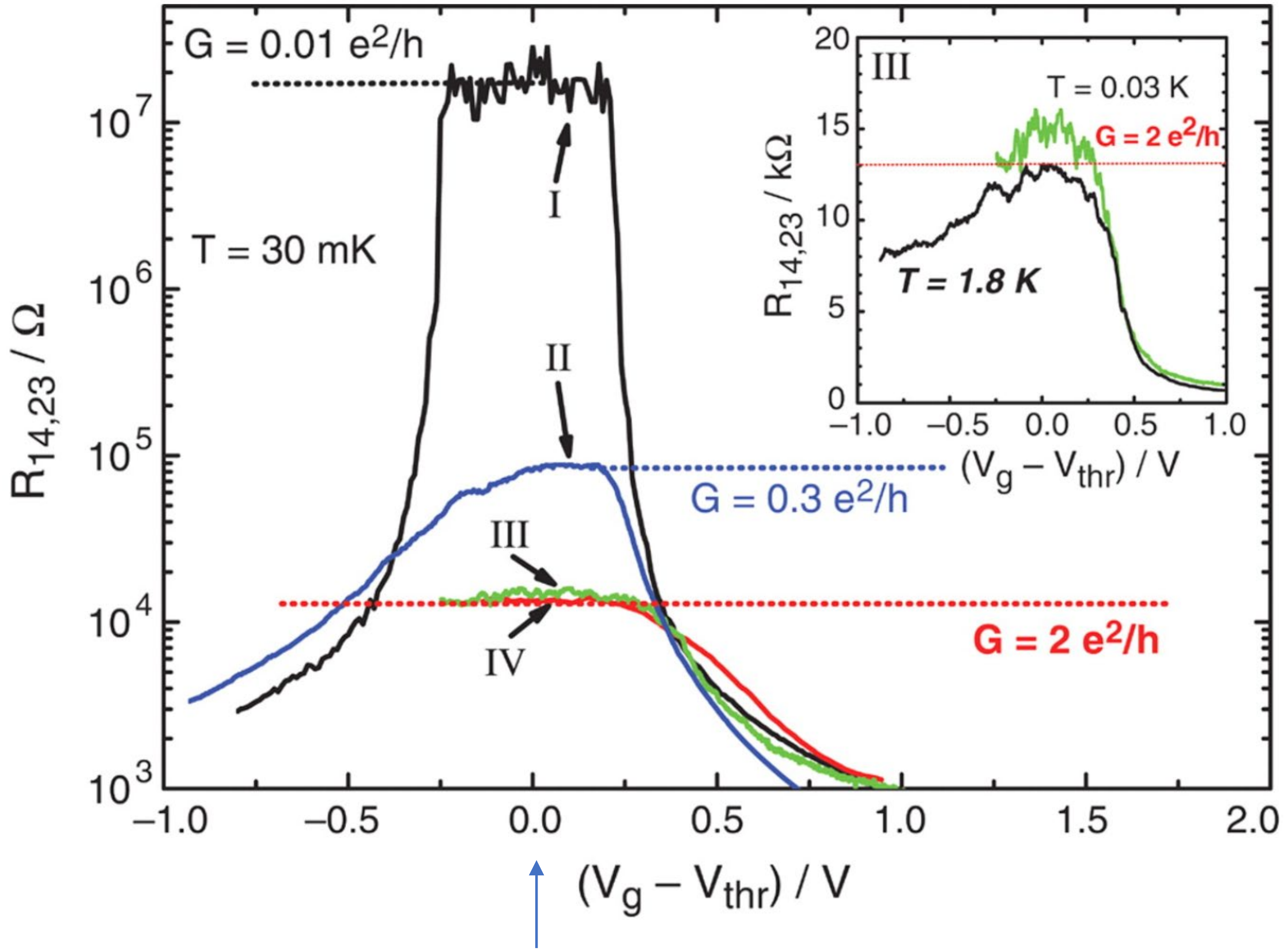


B. Bernevig, T. Hughes, S. Zhang; Science 2006; 314

First measurement

- I L = 13 µm
  II L = 13 µm
  III L = 1 µm
  IV L = 0.5 µm
- Inelastic mean freepath >1µm

Black: non inverted (5.5nm)
Blue; **Green**; **Red**: inverted (7.3)



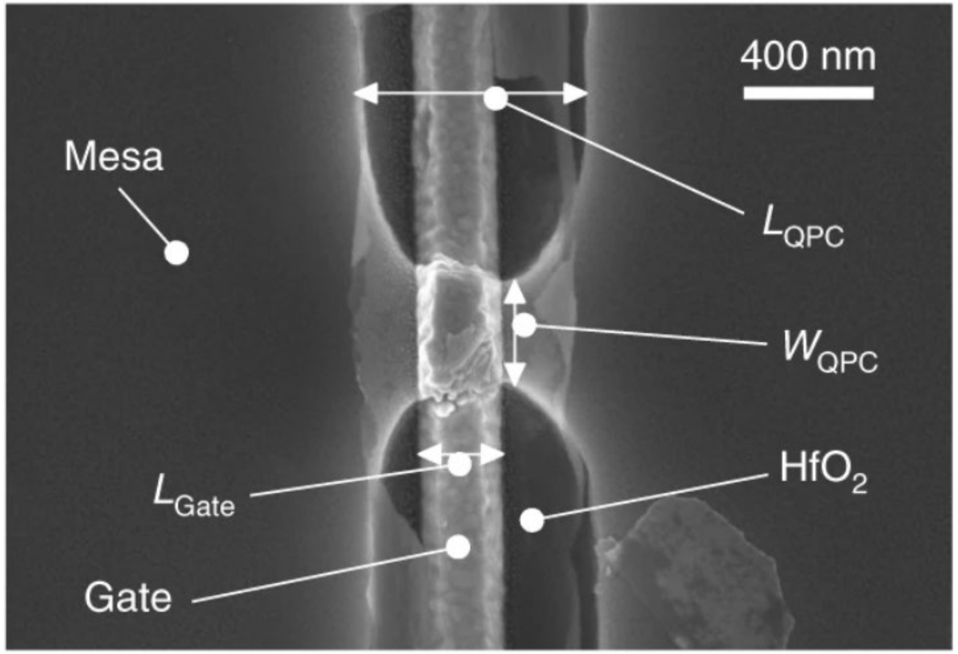
Center of bandgap

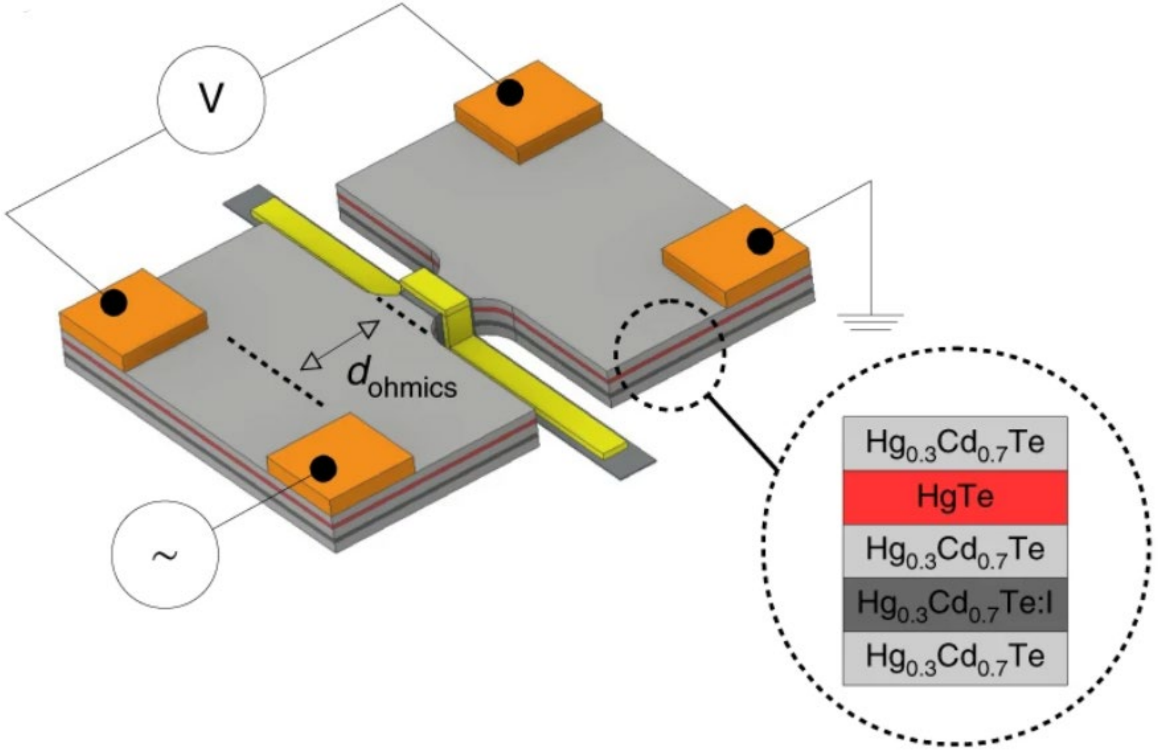
M. König, S. Wiedmann, L.W. Molenkamp; Science 2007;318

Interacting topological edgechannels

Sample

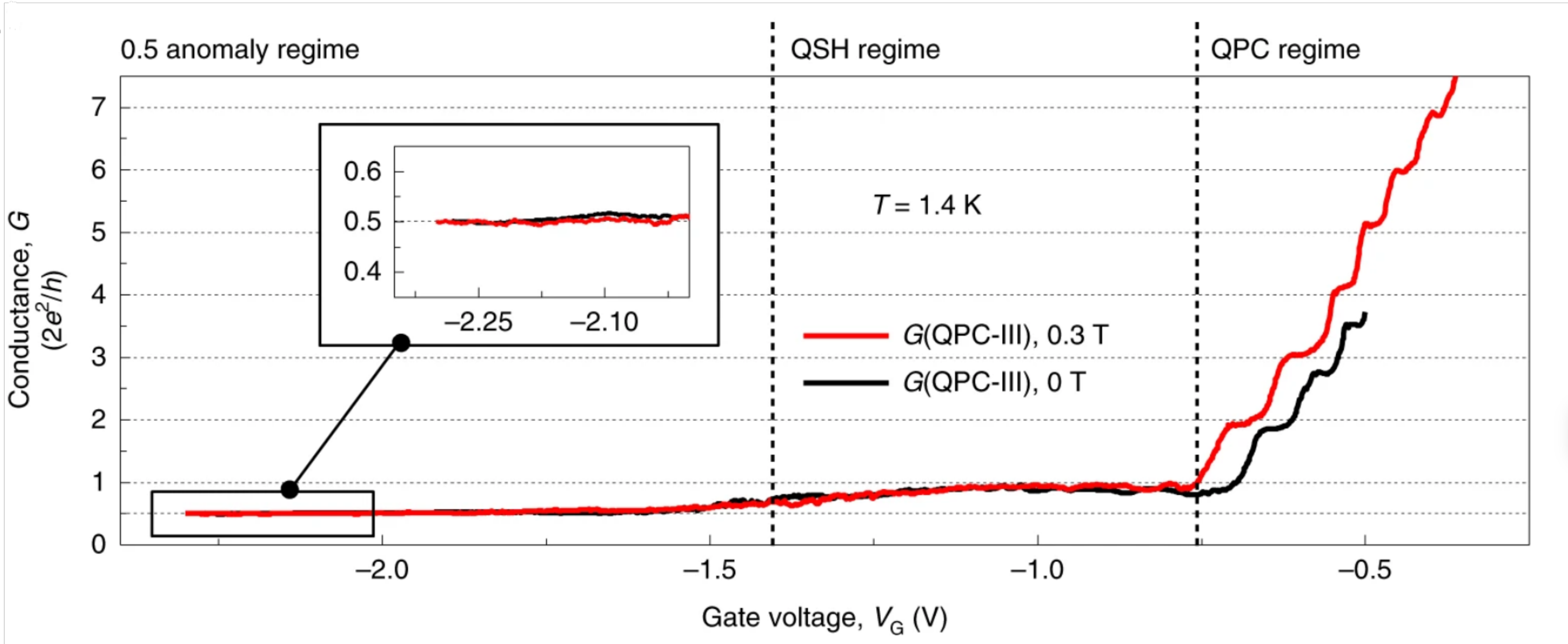
- HgTe/CdTe Quantum Well (7nm or 10.5nm wide)
- Iodine doping layer 70nm below QW
- QPC width 25nm – 250nm | QPC length 200-300nm





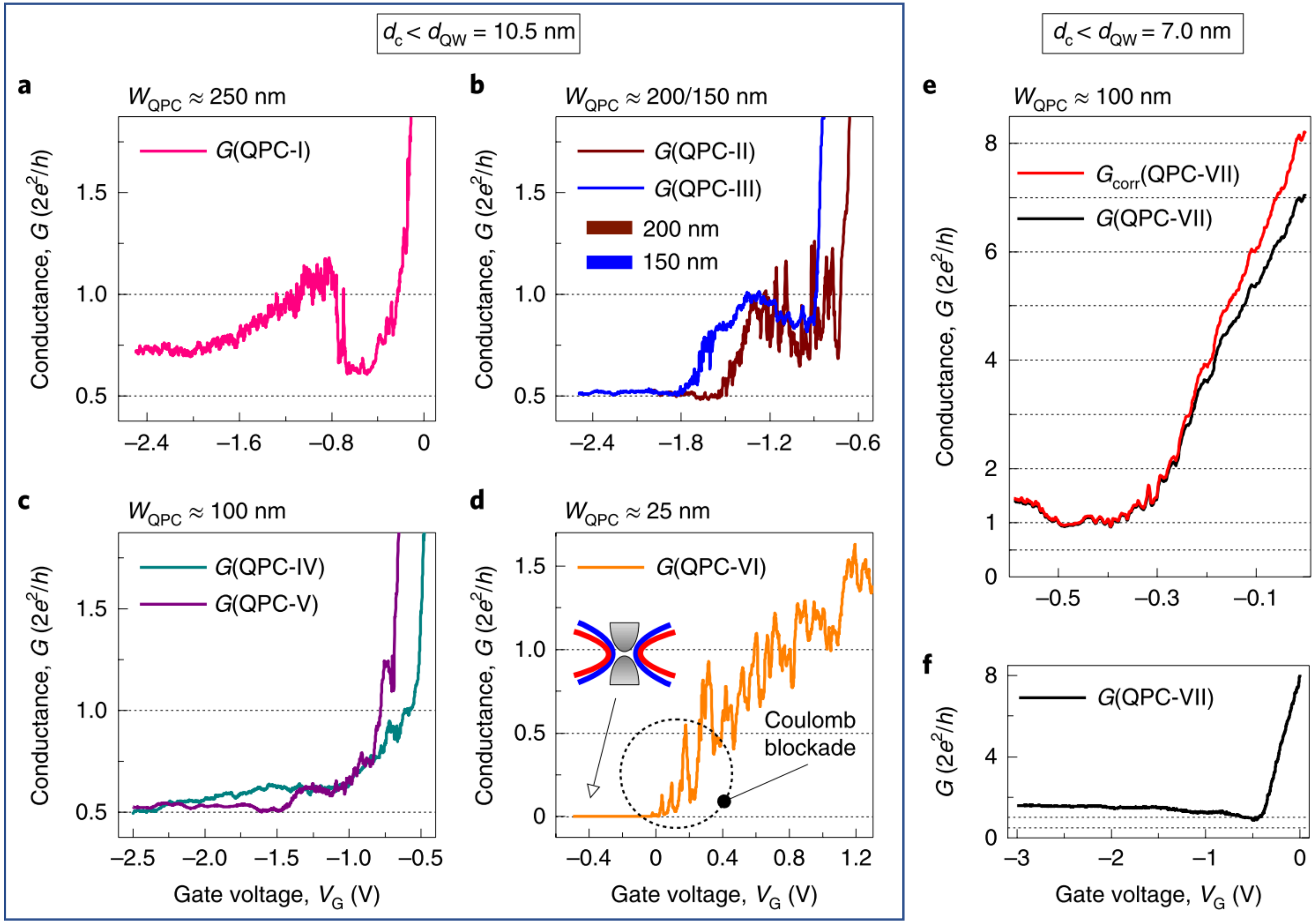
Gate trace

- QPC regime: standard QPC behaviour, steps of G_0
- QSH regime: quantized conduction of G_0;
  much longer step than QPC regime
- 0.5 anamoly regime



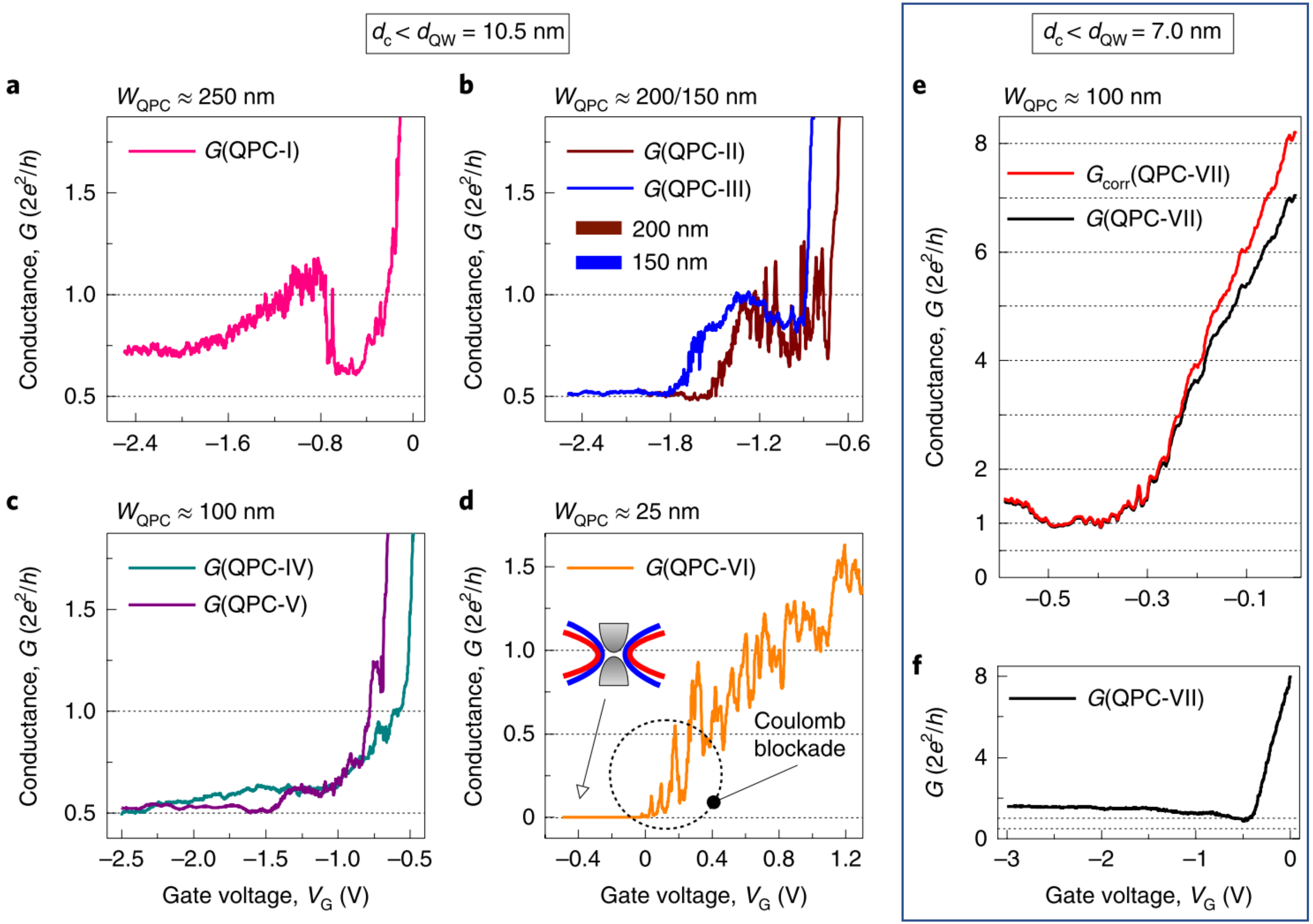
Width dependence

- To observe 0.5 anomaly:
  QPC width 200nm-100nm
  Quantum well width 10.5nm
- No G_0 step for w_qpc <150nm
- Localization for w_qpc <25nm



Width dependence

- Thin QWs show no 0.5 anomaly
- Explanation by band structure

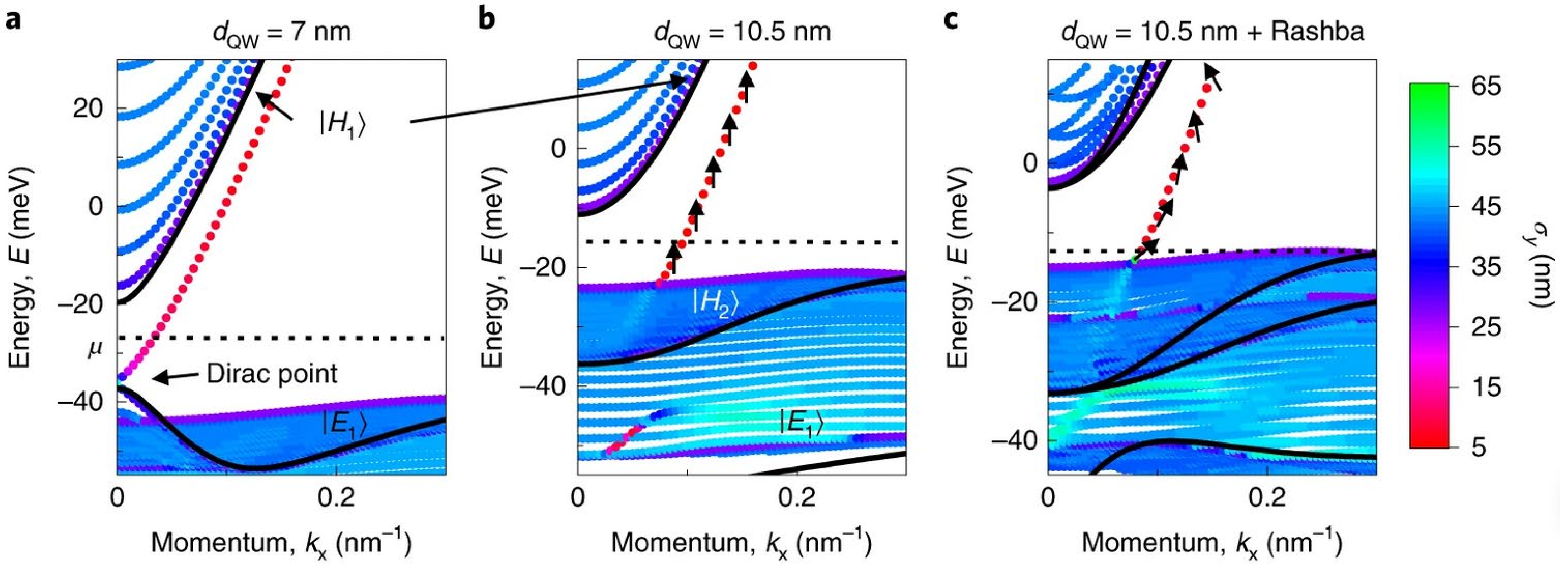


Band structure

Color = wavefunction width (std dev) ; Black = Bulk calculations

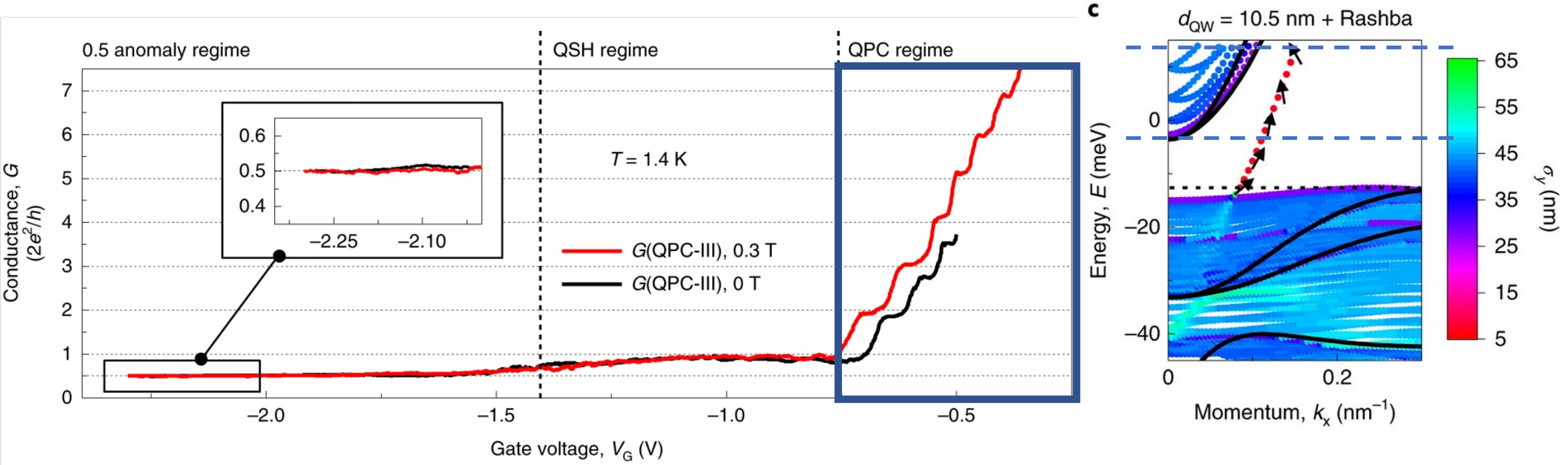
Bandgap between |H1> and |E1>
Dirac point in bandgap

Bandgap between |H1> and |H2>
Dirac point deep in valence band



Obeservation

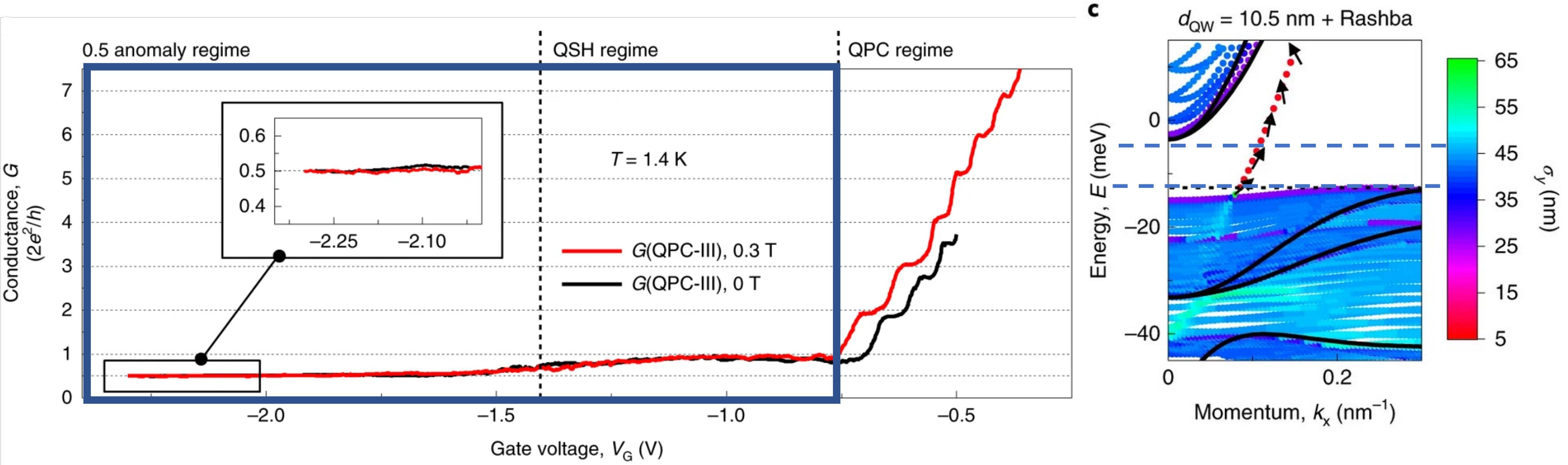
QPC behavior when μ sits in conduction band sub bands



Obeservation

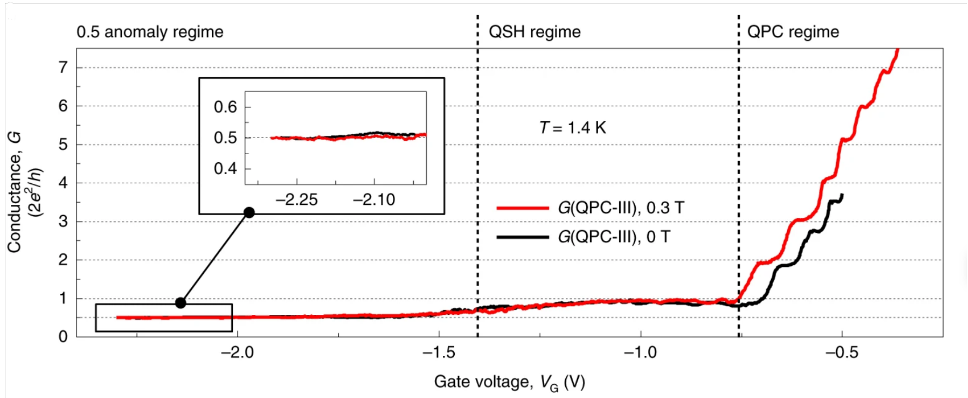
QSH and 0.5 anomaly behaviour in the band gap

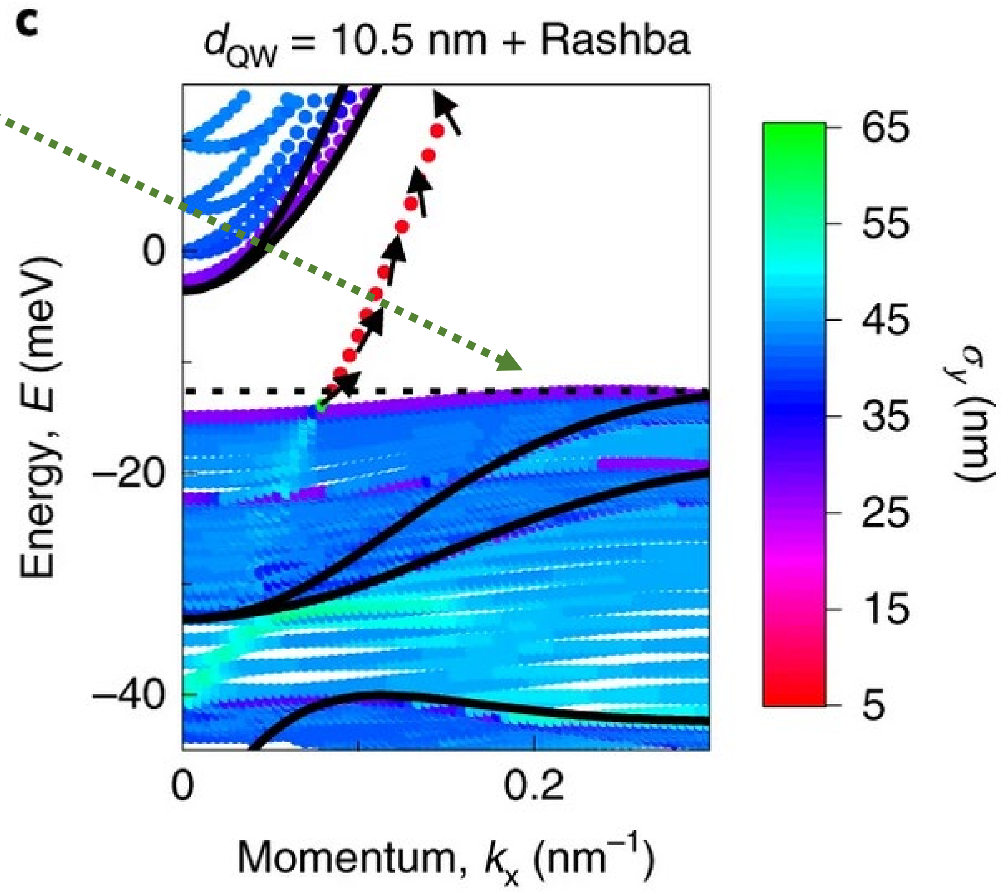
Band structure itself does not explain 0.5 anomaly!

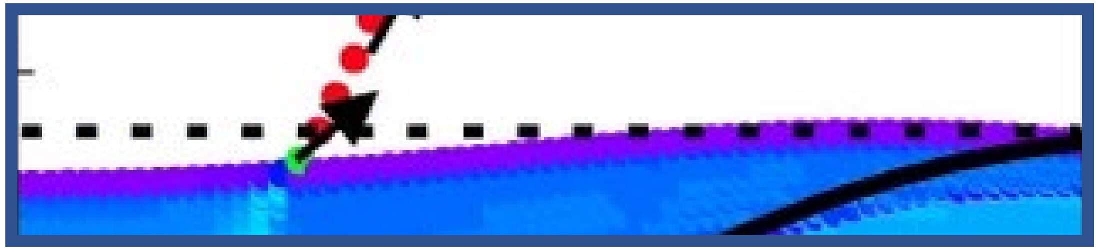


Band structure results

- Edgestate at fermi lvl ~10nm std deviation width
- Long plateaus(in Vg) due to fermi level pining
  - Making Vg more negative doesnt change μ



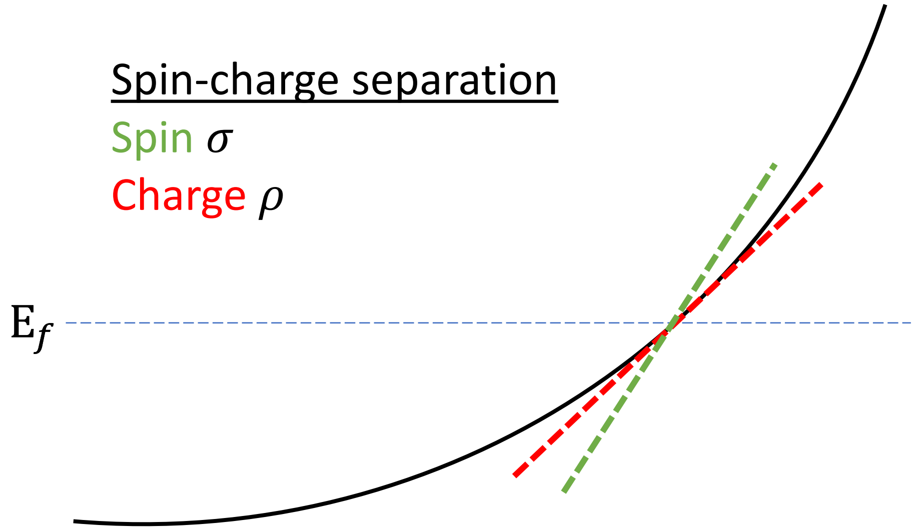




The 0.5 Anomaly

Luttinger Liquid

- Interacting electrons in 1d
- Spin-charge separation
  - Description in terms of independent bosonic modes for spin and charge



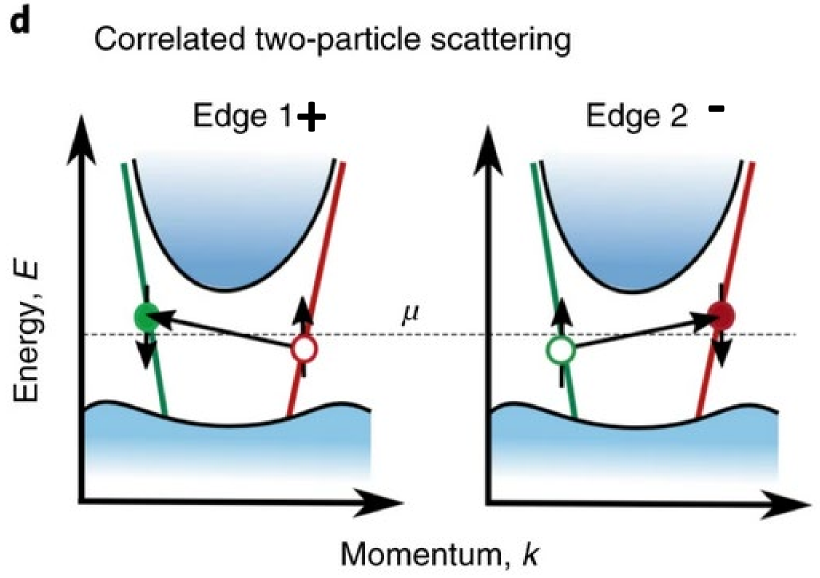
0.5 Anamoly

- Helical edge protected by time reversal symmetrie
  - But back scattering possible with e-e interaction and Rashba SIO

- Relevant scattering term $H_S = g_s \int_0^L dx[\hat{\chi}^\dagger_{R,+}(x)\hat{\chi}_{L,+}(x)\hat{\chi}^\dagger_{L,-}(x)\hat{\chi}_{R,-}(x) + h.c.]$

+ - *edge index*; **L R** *left/right mover (and spin)*

- R+ scatters into L+ (with spin flip)
  L- scatters into R- (with spin flip)



Luttinger Liquid

- Solve bosonized hamiltionian

$$H_{\text{eff}} = \frac{1}{2\pi}\int_0^{\mathrm{L}} \mathrm{d}x \sum_{\nu=\sigma,\rho}\left[\frac{u_\nu}{K_\nu}(\partial_x\phi_\nu)^2 + u_\nu K_\nu(\partial_x\theta_\nu)^2\right] + \tilde{g}_{\mathrm{s}}\cos(2\sqrt{2}\theta_\sigma)$$

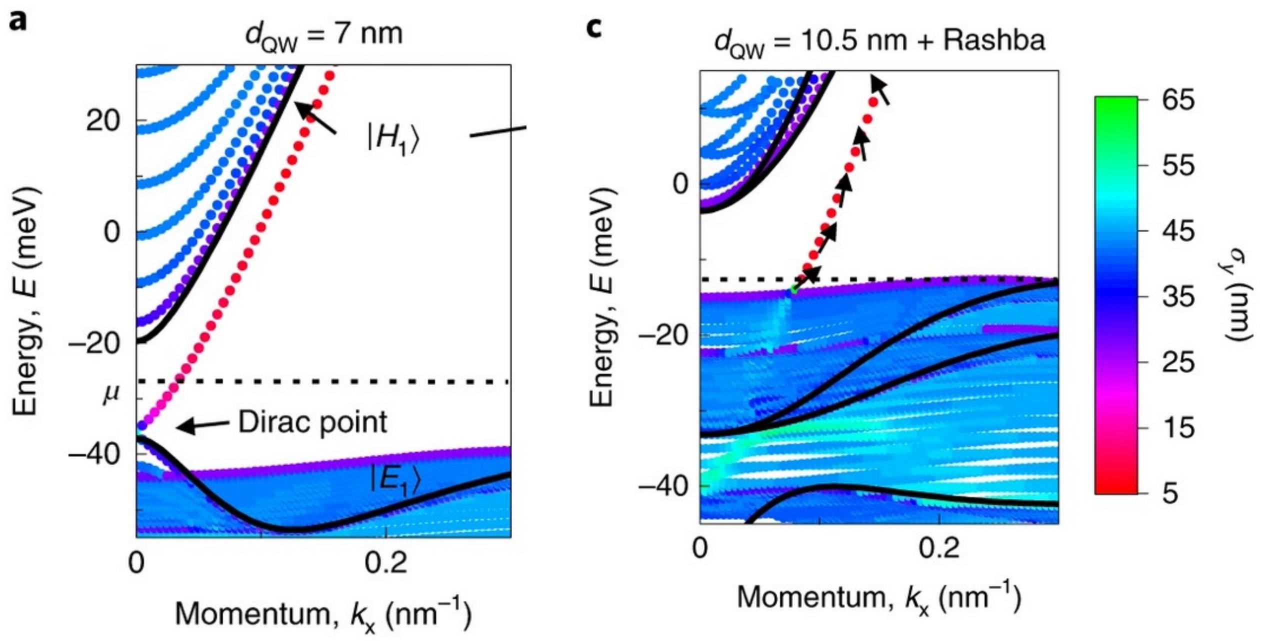
„standard“ Bosonization

Gap term

- Result: Conductance G_0 without spin gap and 0.5 G_0 with spin gap

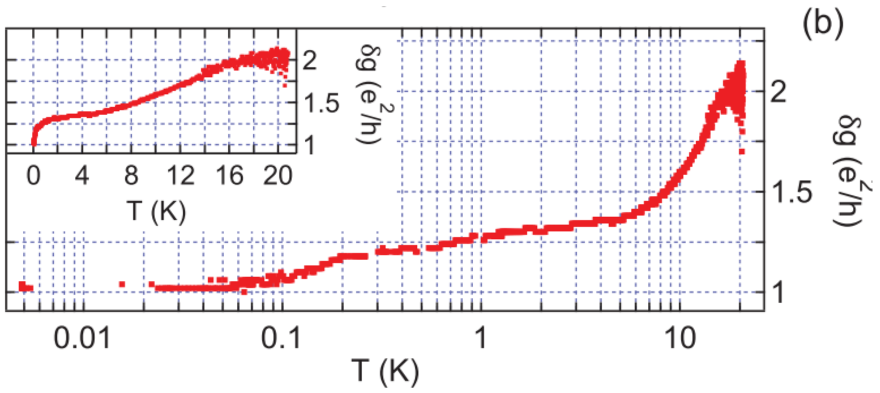
Importance of the "camelback"

- Interaction parameter depends on Rashba coupling strength α
- α grows with increasing electric field (gate voltage)
- Fermi level pinning allows for larger gate voltages
  → stronger interactions
- No 0.5 anomaly in thin QW
  due to "lack of Fermi level pinning"



Comparison with nuclear spin helix

- Nuclear spin helix might cause spin gap in GaAs quantum wire
- Small amount of nuclear spins would lead to very small spingap in HgTe

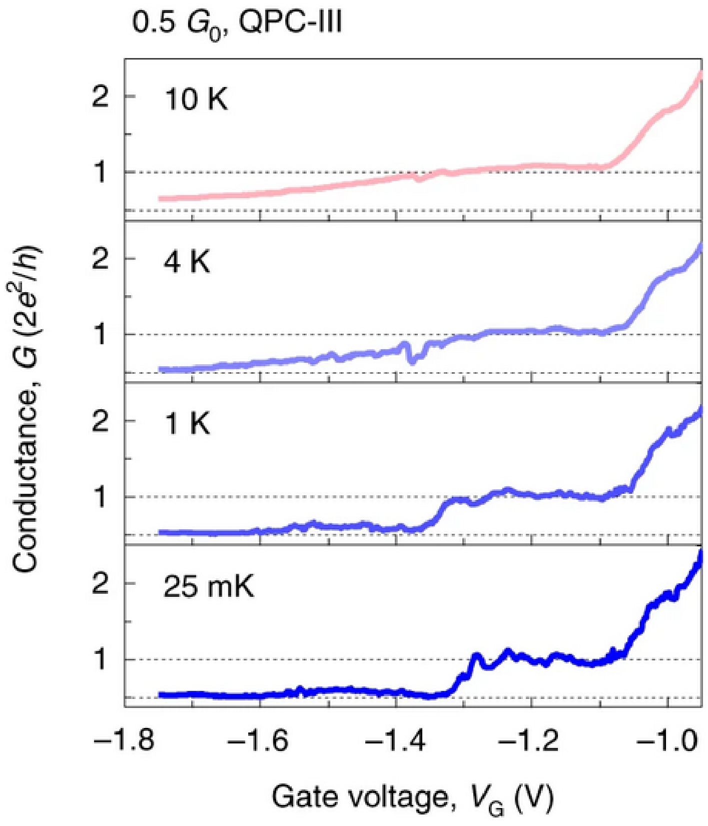


Scheller et al. (2014), PRL 112

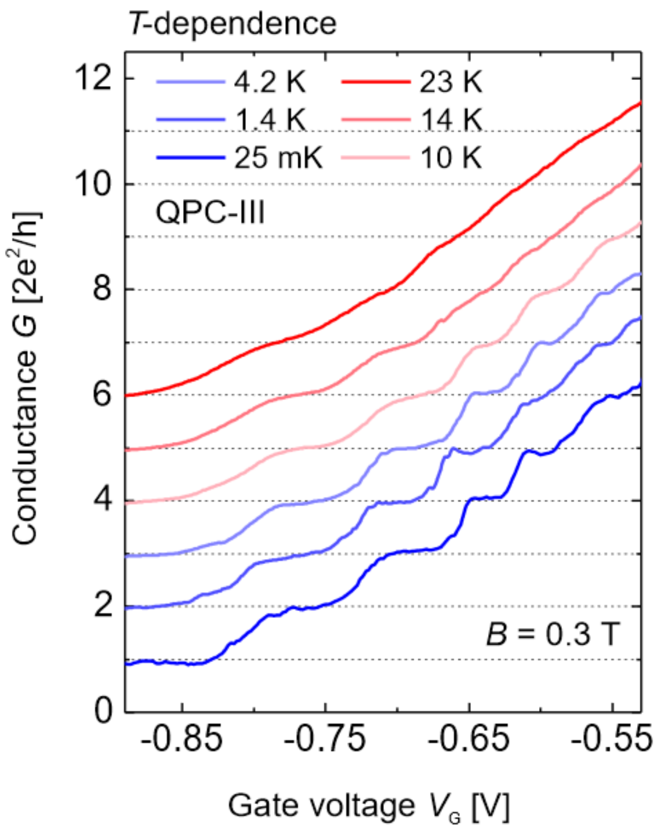
Characterisation of the spin gap

Temperature dependence

- 0.5 anomaly visible up to 1.4K
  - Estimate ΔE = 150-300 μeV



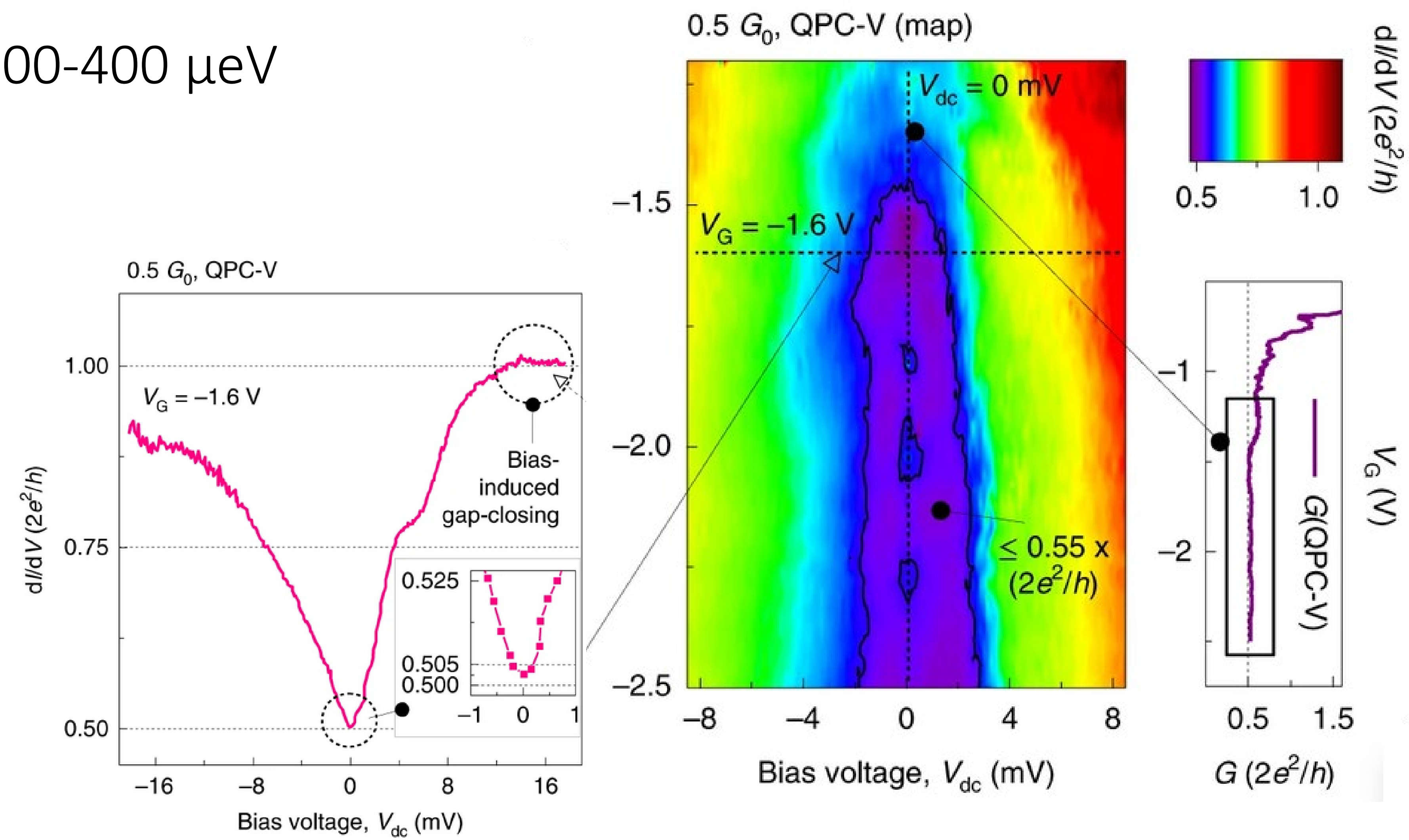
Quantum spin hall regime



QPC regime (offset for clarity)

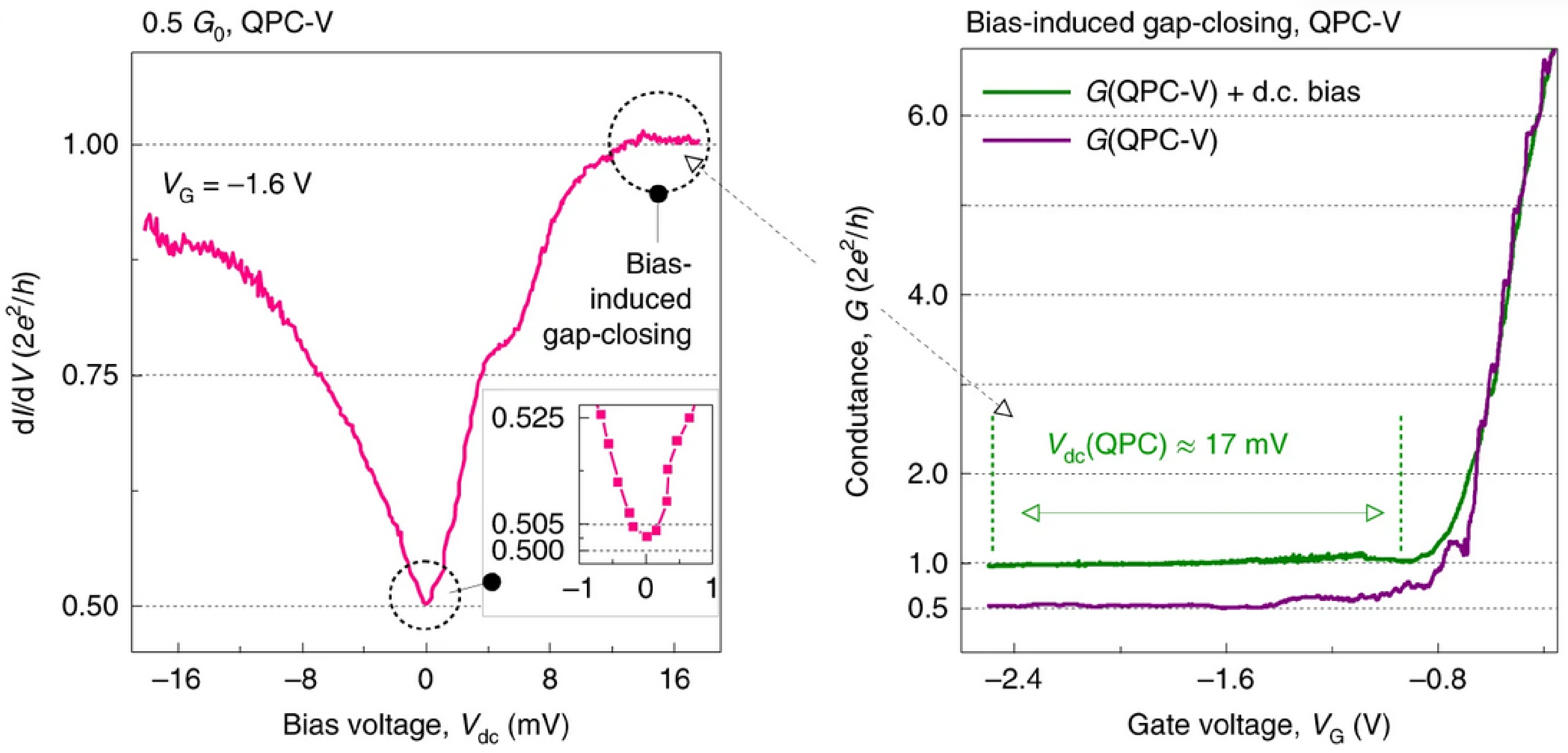
Source/drain Bias dependence

- Energy gap eV_{sd} = 200-400 μeV



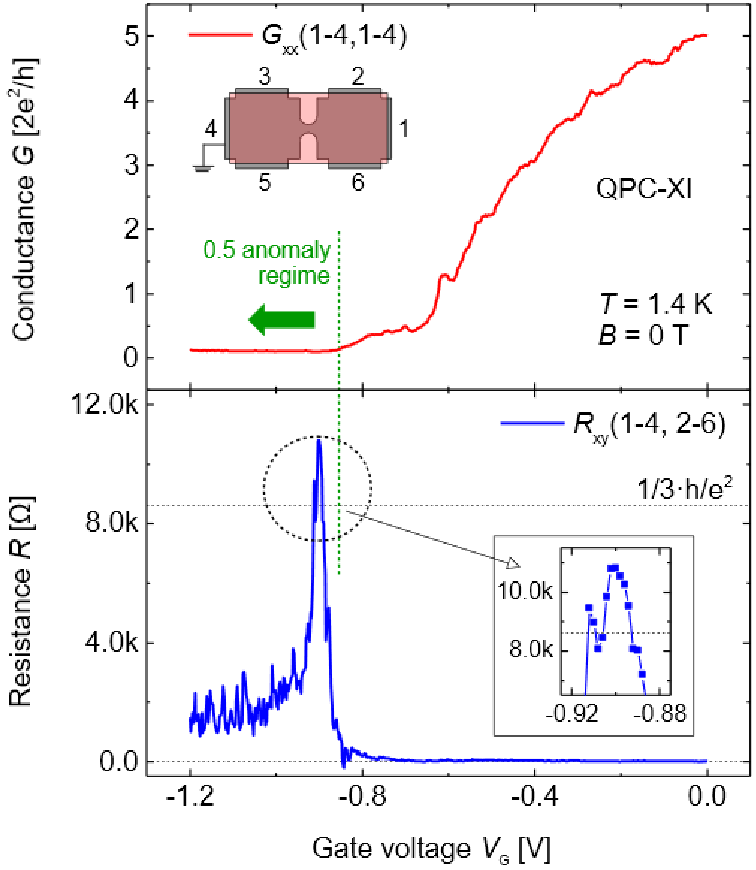
Source/drain Bias dependence

- Recovery of 2e^2/h plateau at large bias (12 mV)



Outlook: Multi terminal measurement

- Evidence for refelceted state from R_{xy} measurements
  - R_{xy} should be $\frac{1}{3}\frac{h}{e^2}$ when in the 0.5 Anaomly regime
- Some evidence seen,but
  Independent gating of leads and QPC needed



Summary

- QSH conductance reduces from G_0 to $0.5G_0$
  - Explained by coulomb interaction between edge channels
  - Coulomb interactions open spin gap
- Camel back valence band is important for the observation
- Spin gap ~ 200-300 μeV

Outlook

- Non local measurement of reflected channel

Appendix

Material parameters

QPC Nr.	W_{QPC}/nm	d_{QW} /nm	$n_e(0\,V)/(10^{11}\,cm^{-2})$	$\mu(0\,V)/(10^5\,cm^2V^{-1}s^{-1})$
I	250	10.5	5.9	3.2
II	200	10.5	5.9	3.2
III	150	10.5	5.9	3.2
IV	100	10.5	5.9	3.2
V	100	10.5	5.9	3.2
VI	25	10.5	5.9	3.2
VII	100	7.0	5.2	2.7
VIII	50	10.5	5.9	3.2
IX	150	7.0	5.2	2.7
X	200	7.0	5.2	2.7
XI	200	10.5	5.8	2.0