# Dirac Fermions in HgTe

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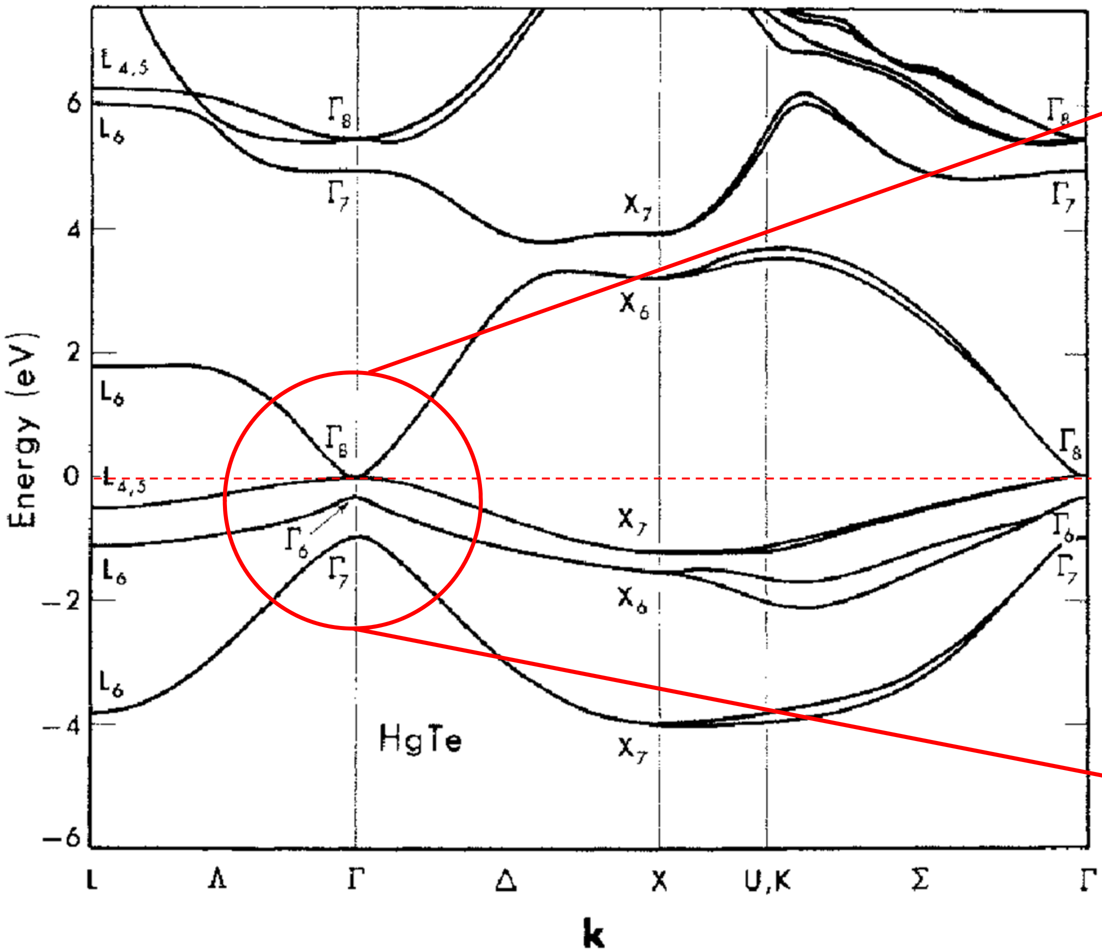
# Overview

- HgTe/CdTe bandstructure, quantum spin Hall effect
- HgTe as a Dirac system
- Dirac surface states of strained bulk HgTe

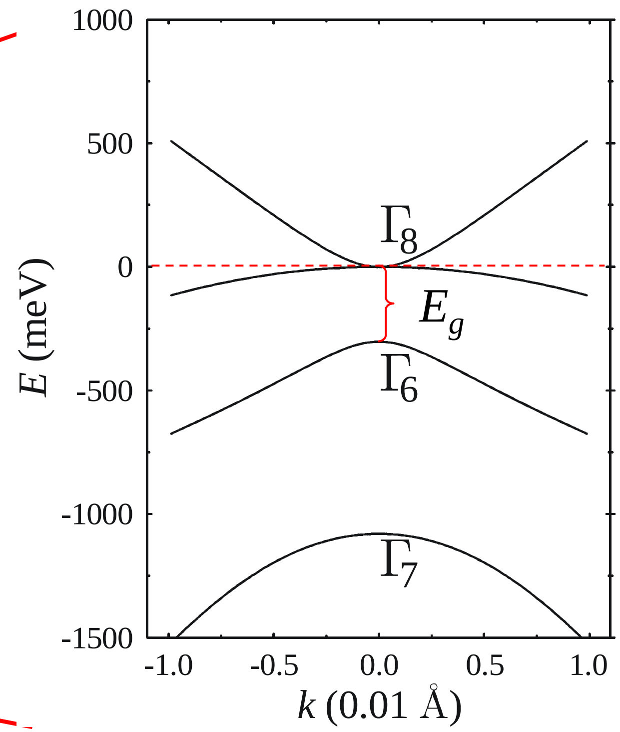
# HgTe

## band structure




D.J. Chadi et al. PRB, 3058 (1972)

## semi-metal or semiconductor



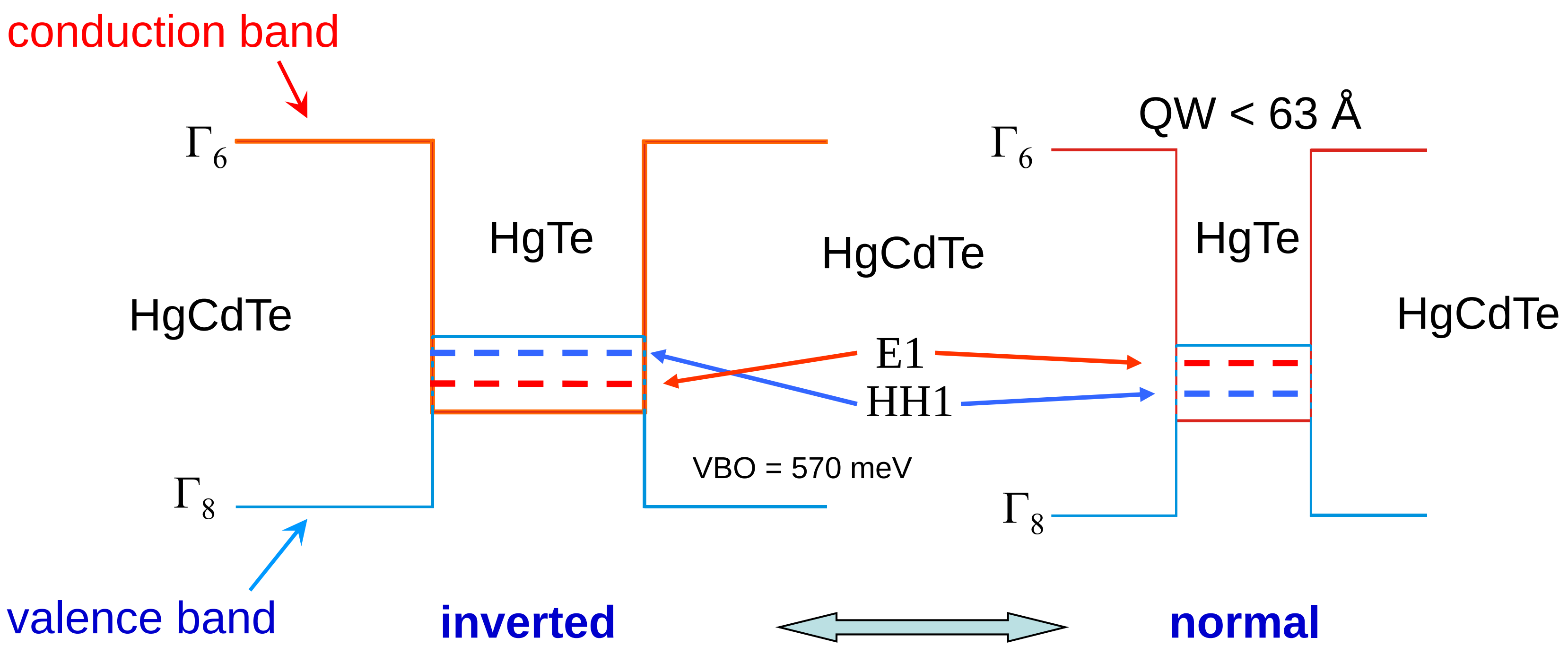

**fundamental energy gap**

$$E^{\Gamma 6} - E^{\Gamma 8} \approx -300\,\text{meV}$$

# HgTe-Quantum Wells



Type-III QW

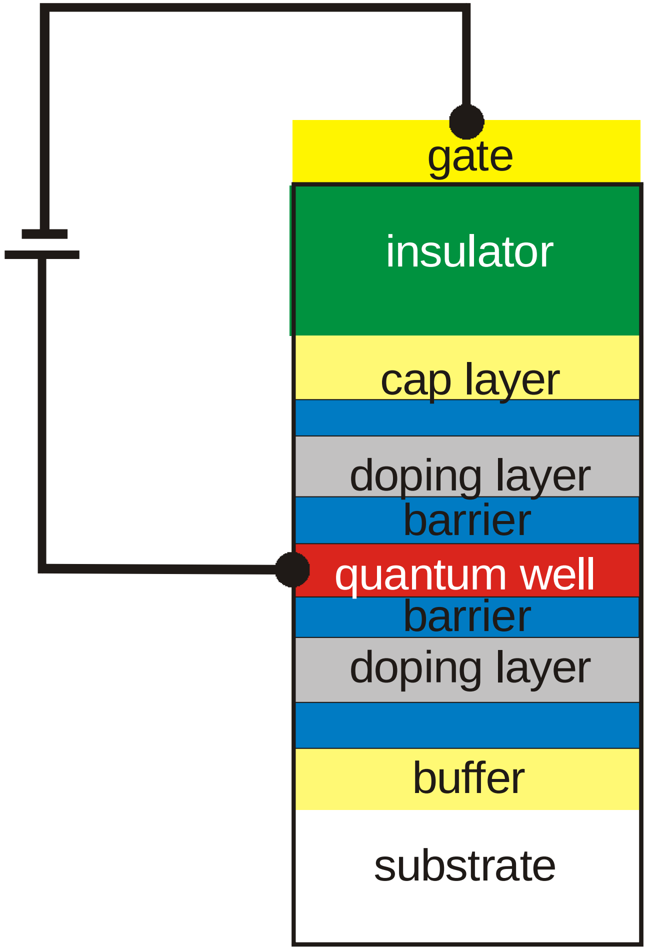



band structure

# Layer Structure

Carrier densities: $n_s = 1x10^{11} \dots 2x10^{12}\ cm^{-2}$

Carrier mobilities: $\mu = 1x10^5 \dots 1.5x10^6\ cm^2/Vs$




Au

100 nm $Si_3N_4/SiO_2$

25 nm CdTe

10 nm HgCdTe x = 0.7

9 nm HgCdTe with I

10 nm HgCdTe x = 0.7

4 - 12 nm HgTe

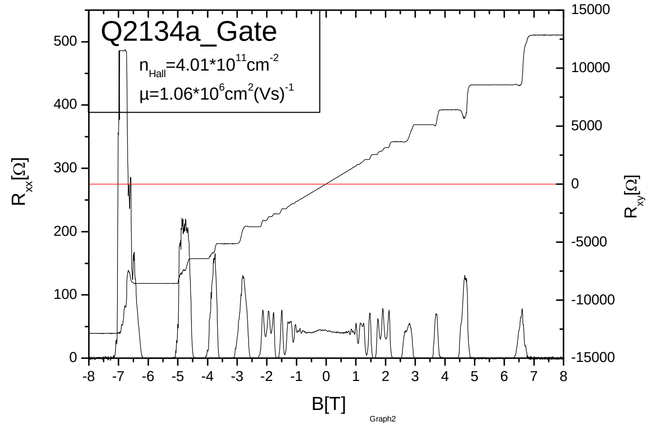
10 nm HgCdTe x = 0.7

9 nm HgCdTe with I

10 nm HgCdTe x = 0.7

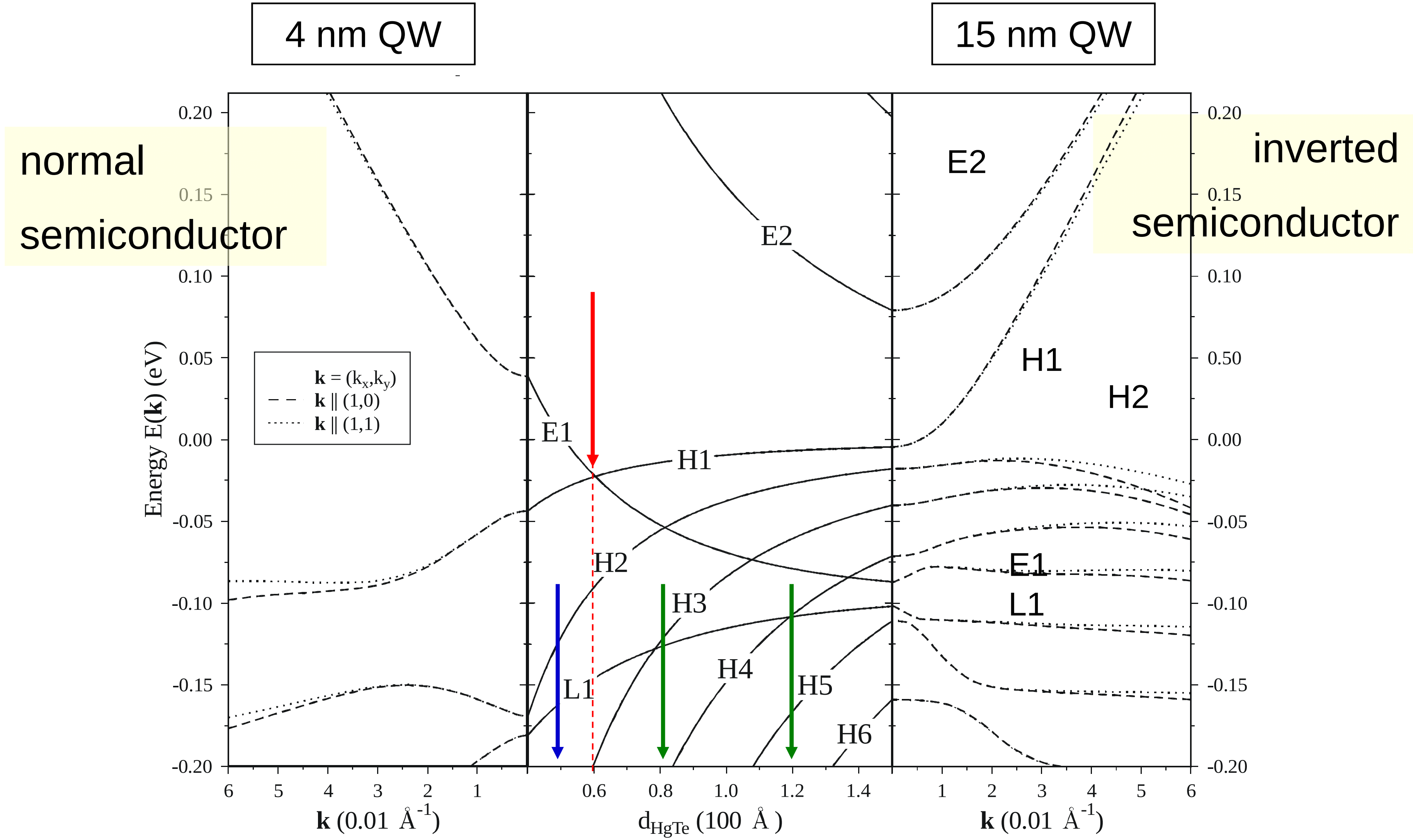
25 nm CdTe

CdZnTe(001)




symmetric or asymmetric doping

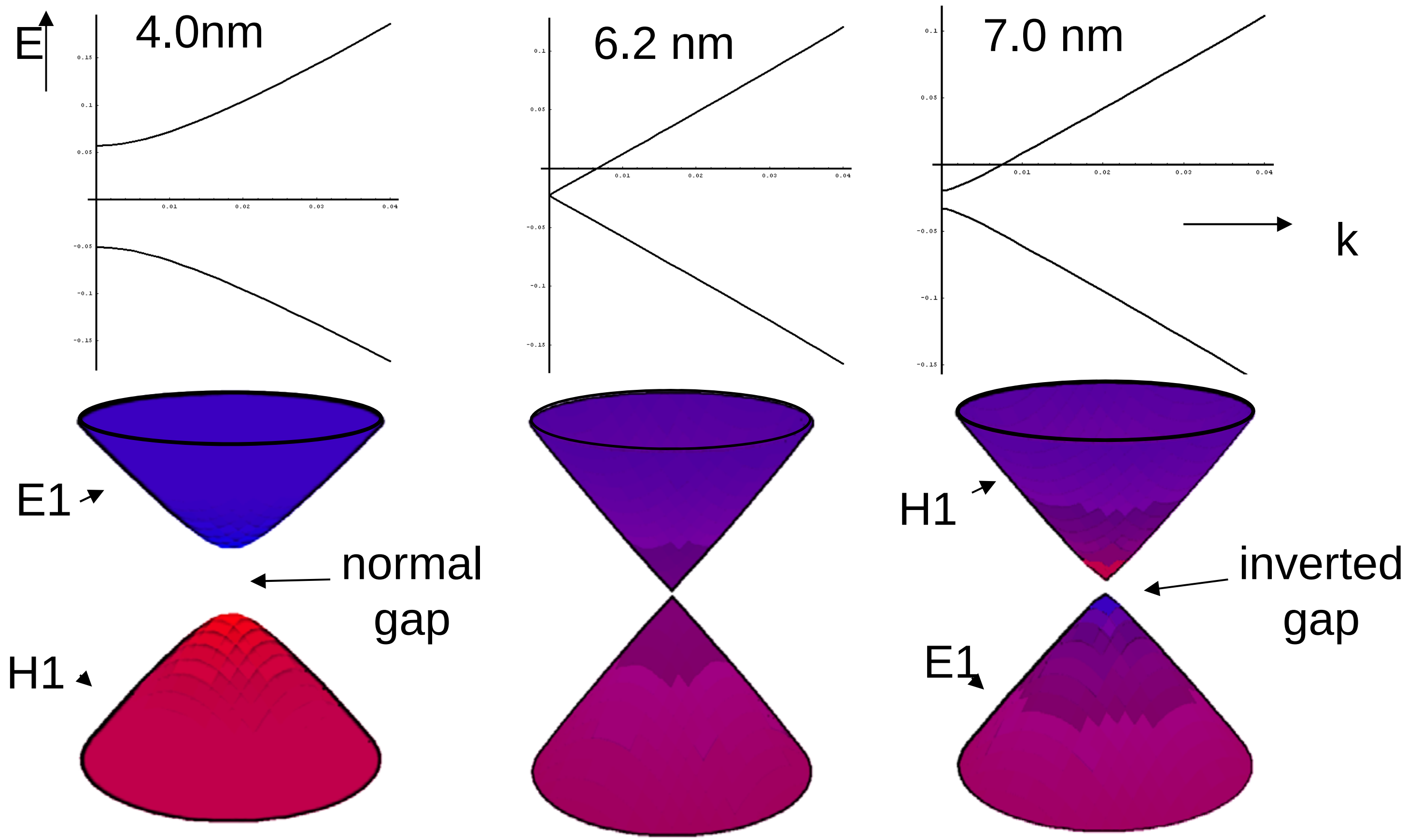
# Band Gap Engineering



# Bandstructure HgTe



B.A Bernevig, T.L. Hughes, S.C. Zhang, Science **314**, 1757 (2006)

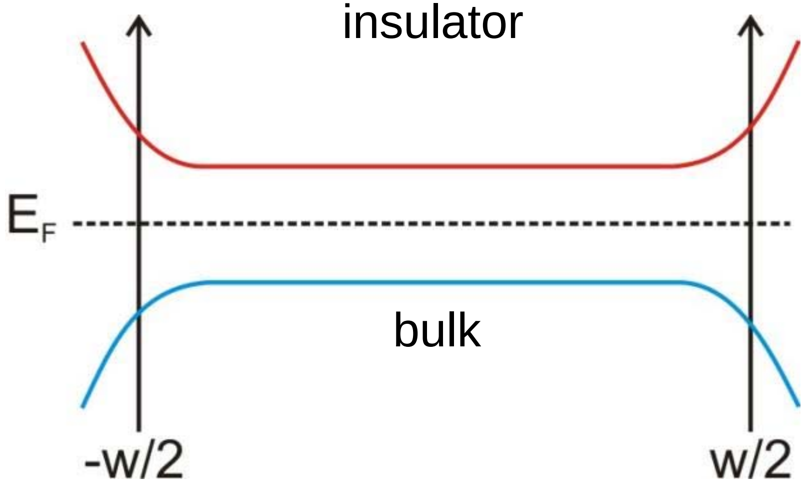


# QSH insulator

# QSHE, Simplified Picture

**m > 0**

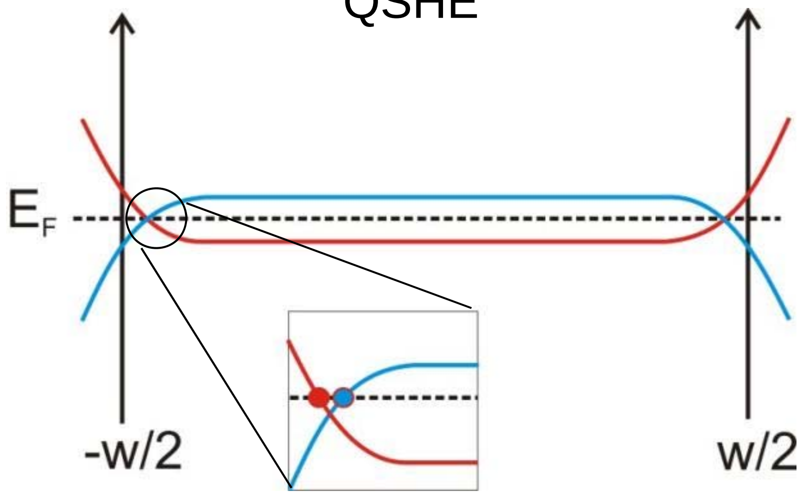
normal
insulator

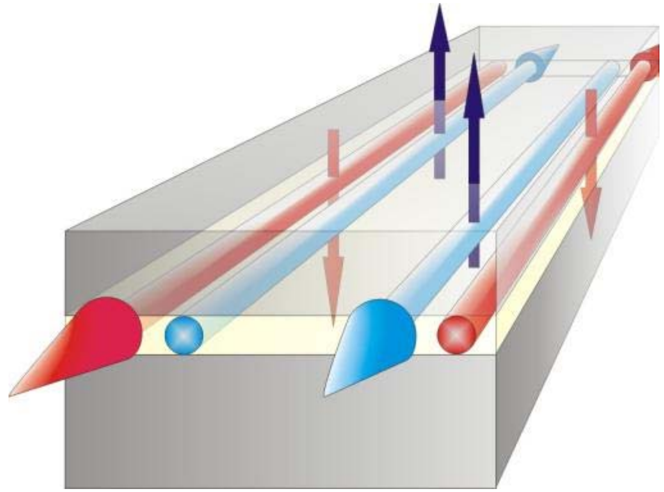




**m < 0**

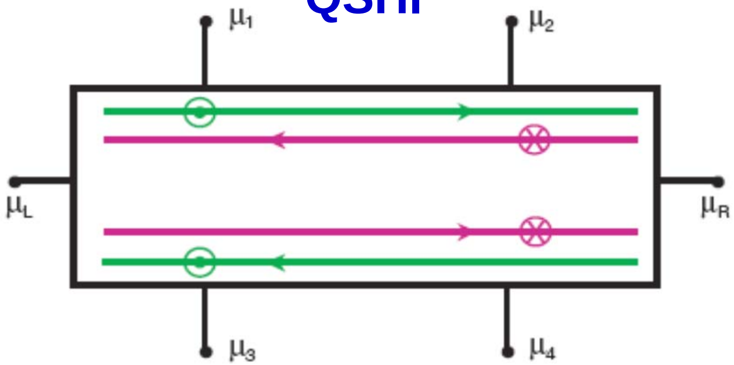
QSHE



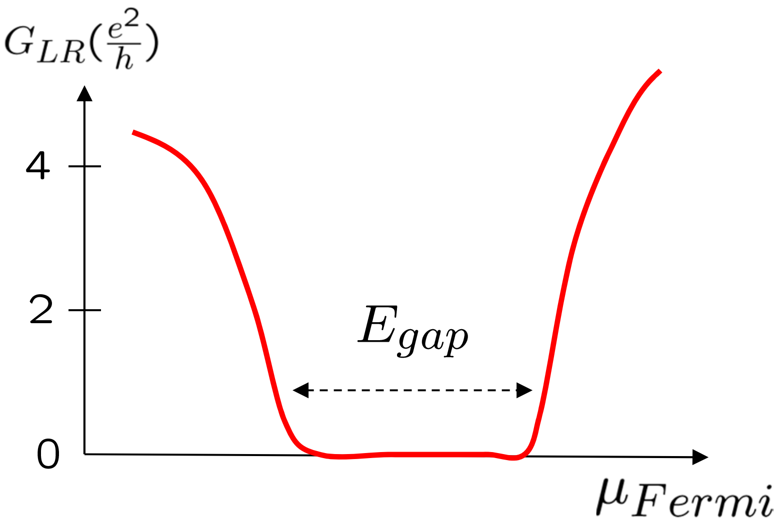



# Experimental Signature

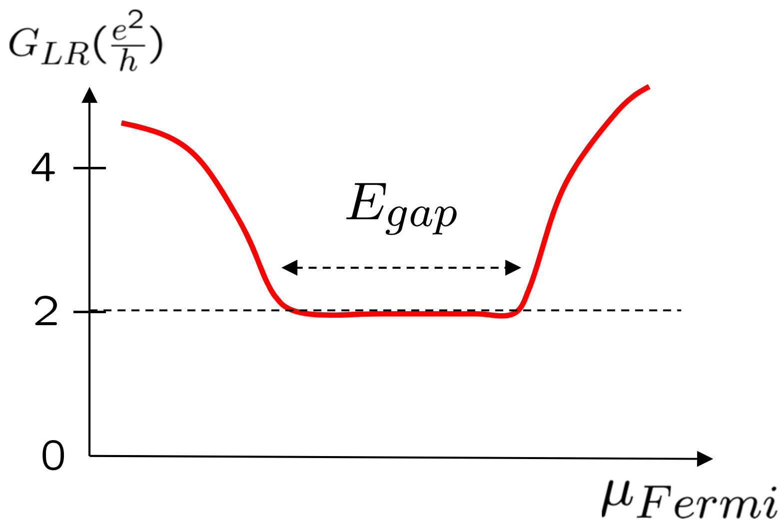
QSHI




normal insulator state

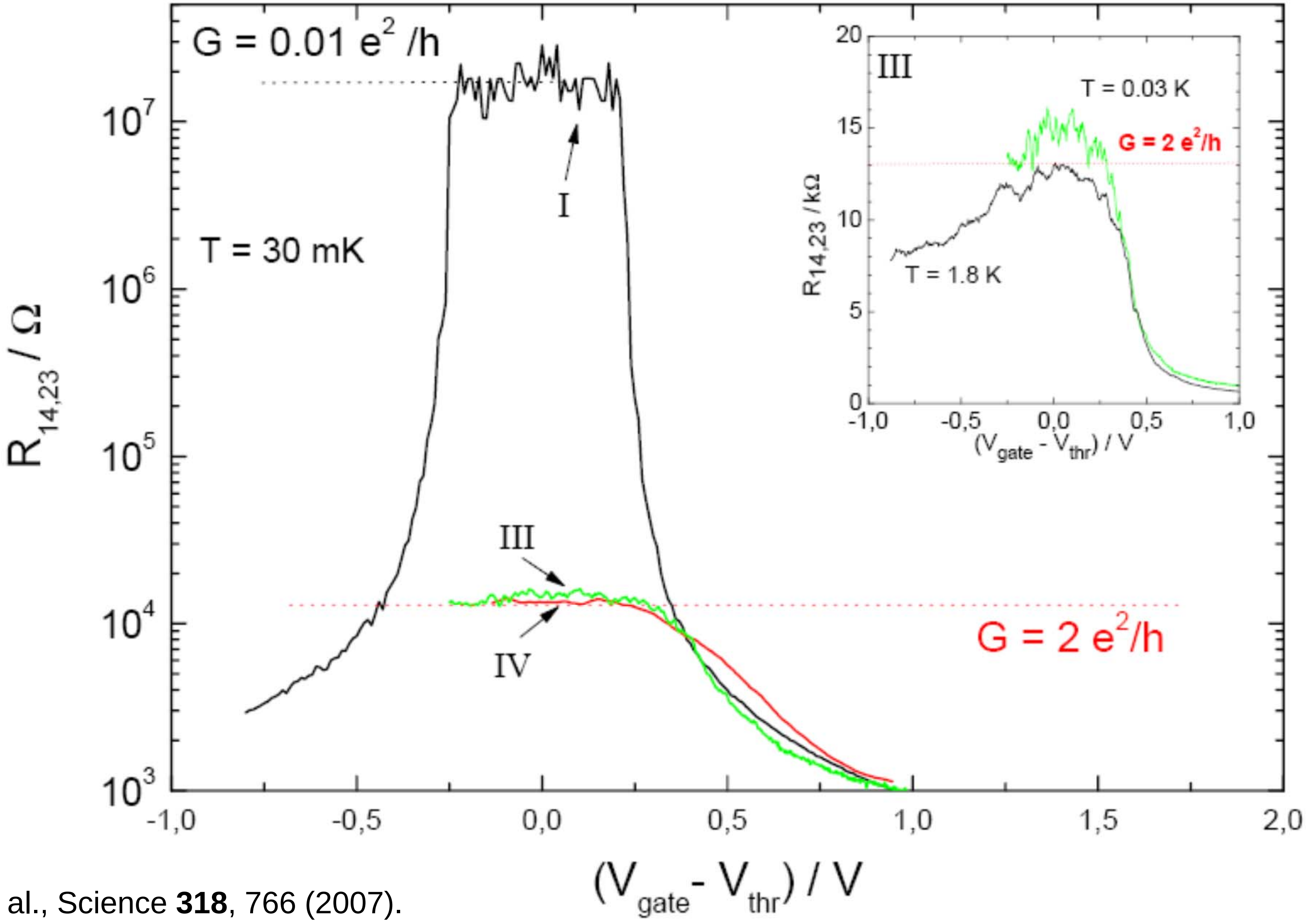



$d < d_c$, normal regime



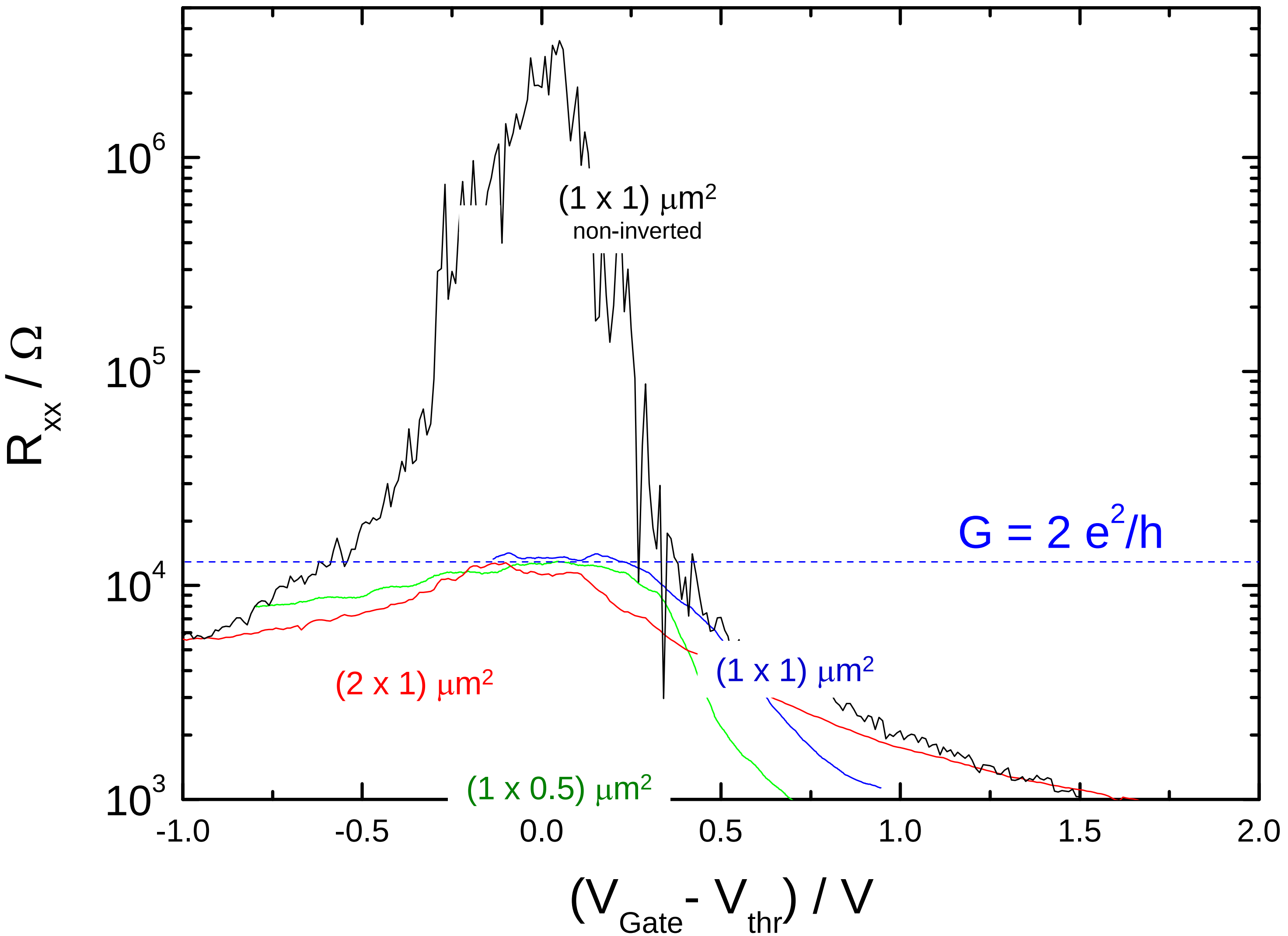

$d > d_c$, inverted regime

# Observation of QSHI state



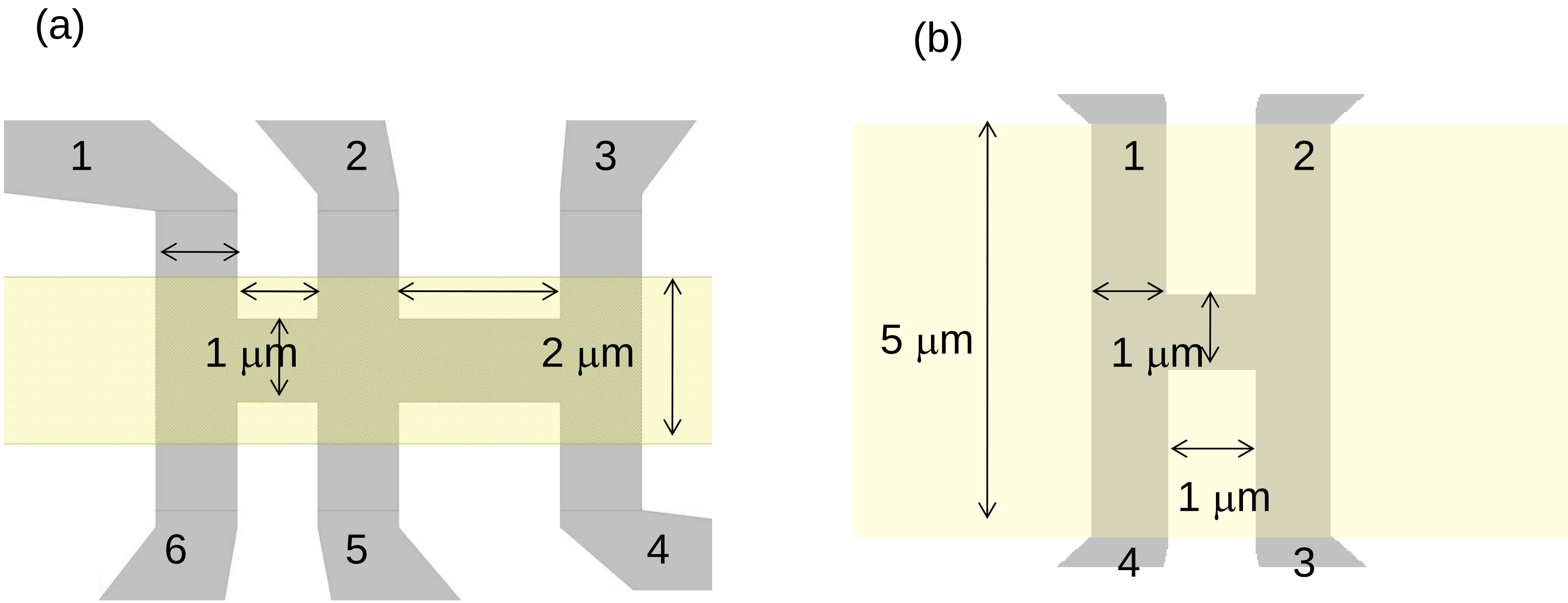

M. König et al., Science **318**, 766 (2007).

# Observation of QSH Effect




M. König et al., Science **318**, 766 (2007).

# Verify helical edge state transport

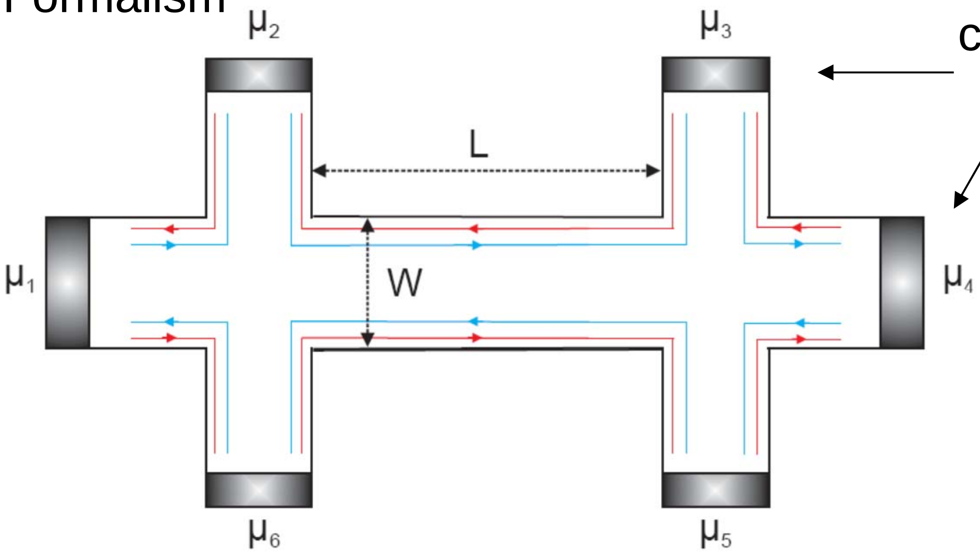



Multiterminal /Non-local transport samples

# Multi-Terminal Probe



Landauer-Büttiker Formalism




normal
conducting contacts
➔ no QSHE

$$T = \begin{pmatrix} -2 & 1 & 0 & 0 & 0 & 1 \\ 1 & -2 & 1 & 0 & 0 & 0 \\ 0 & 1 & -2 & 1 & 0 & 0 \\ 0 & 0 & 1 & -2 & 1 & 0 \\ 0 & 0 & 0 & 1 & -2 & 1 \\ 1 & 0 & 0 & 0 & 1 & -2 \end{pmatrix} \Rightarrow \begin{cases} G_{2t} = \dfrac{I_{14}}{\mu_4 - \mu_1} = \dfrac{2}{3}\dfrac{e^2}{h} \\ G_{4t} = \dfrac{I_{14}}{\mu_3 - \mu_2} = \dfrac{2e^2}{h} \end{cases}$$

generally

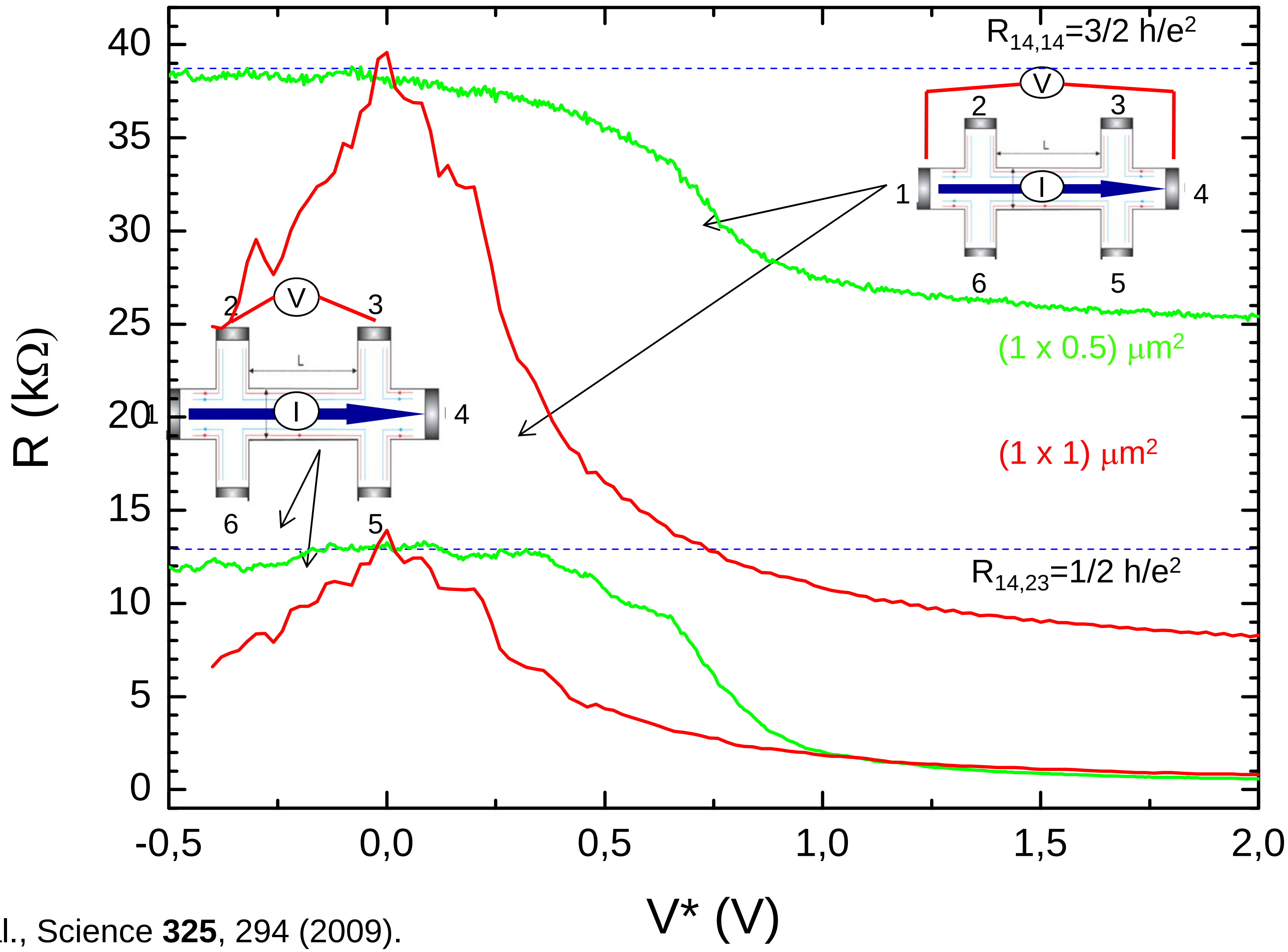
$$R_{2t} = \frac{(n+1)h}{2e^2}$$

$$G_{4t,\exp} \approx 2\frac{e^2}{h}$$

$$\left.\frac{R_{2t}}{R_{4t}}\right|_{\exp} \approx 3$$

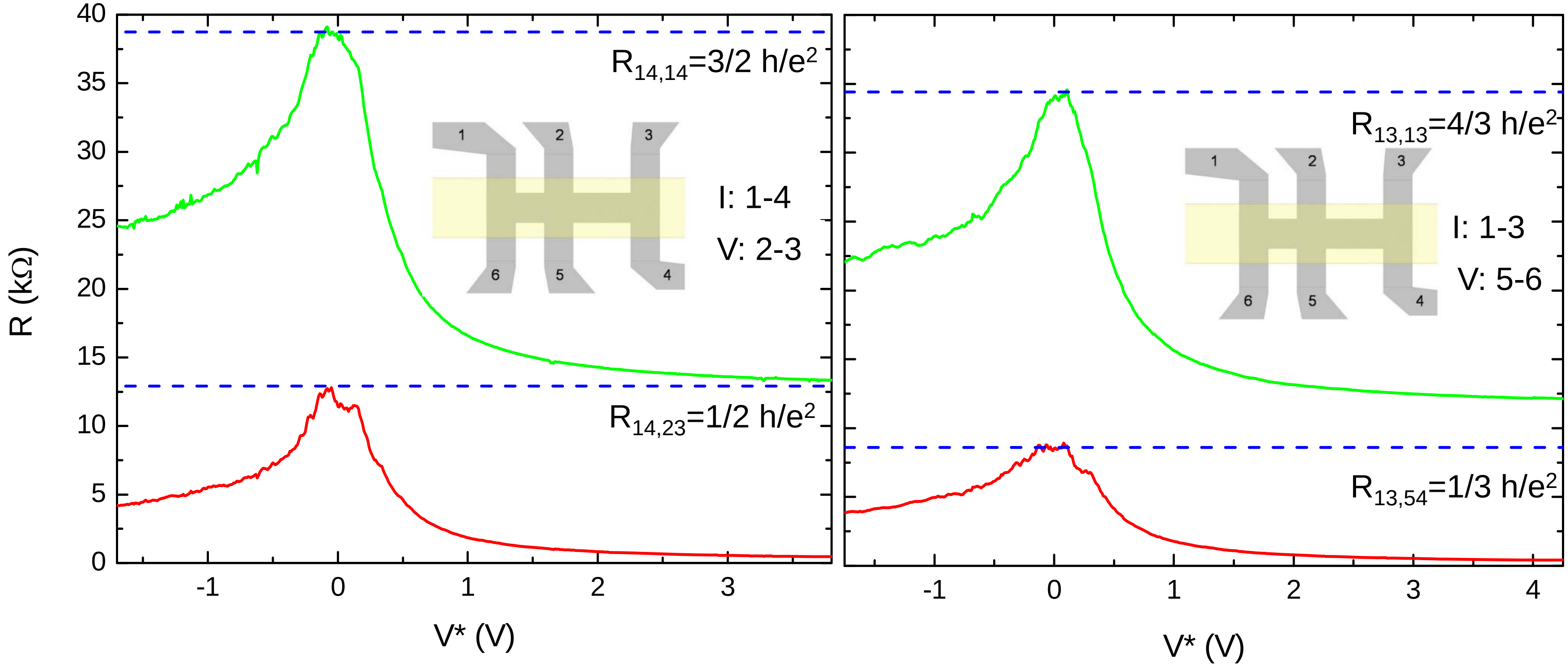
# Multi-Terminal Measurements






A. Roth et al., Science **325**, 294 (2009).

# Multi-Terminal Measurements

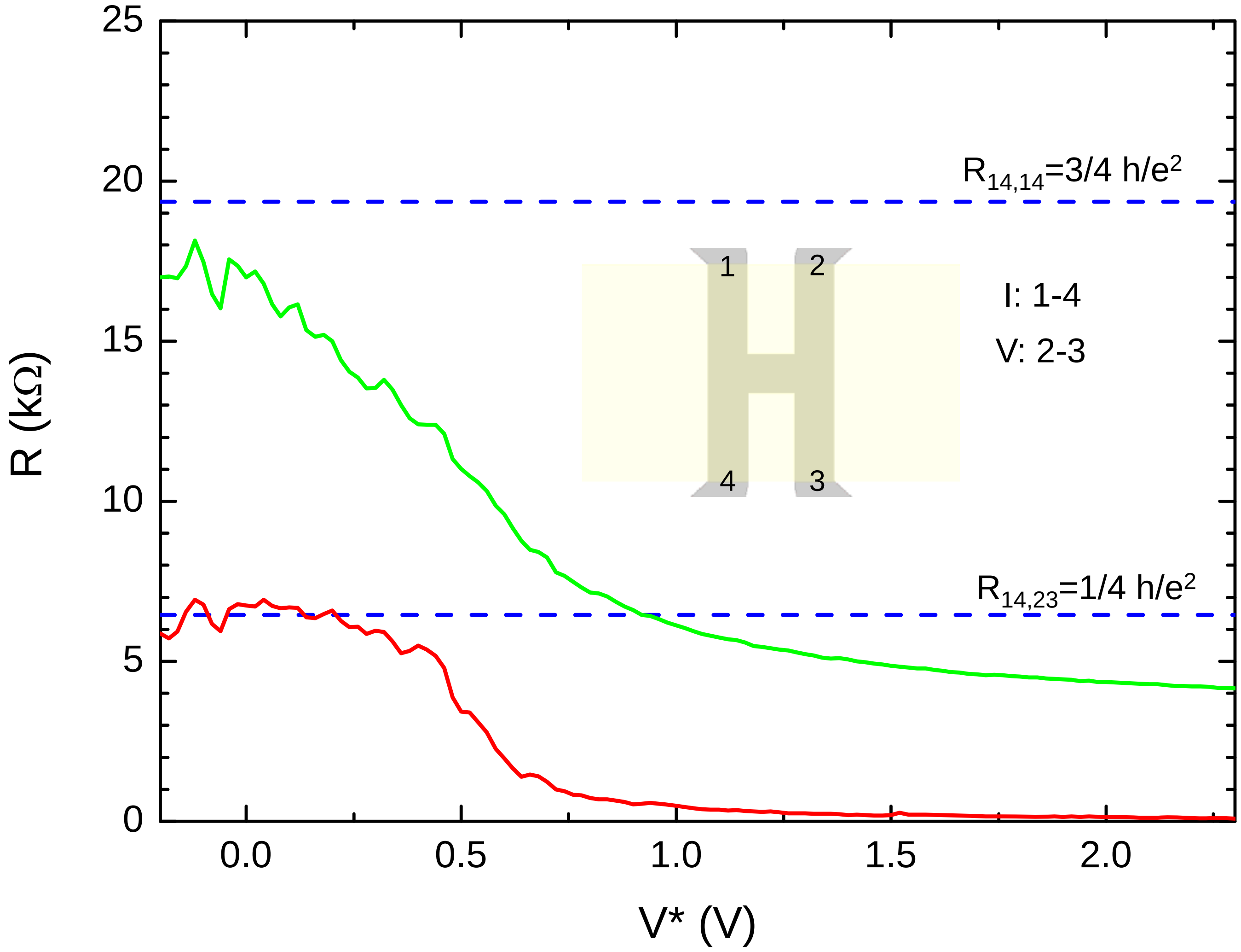



Configurations would be equivalent in quantum adiabatic regime

A. Roth et al., Science **325**, 294 (2009).

# Non-Local data on H-bar





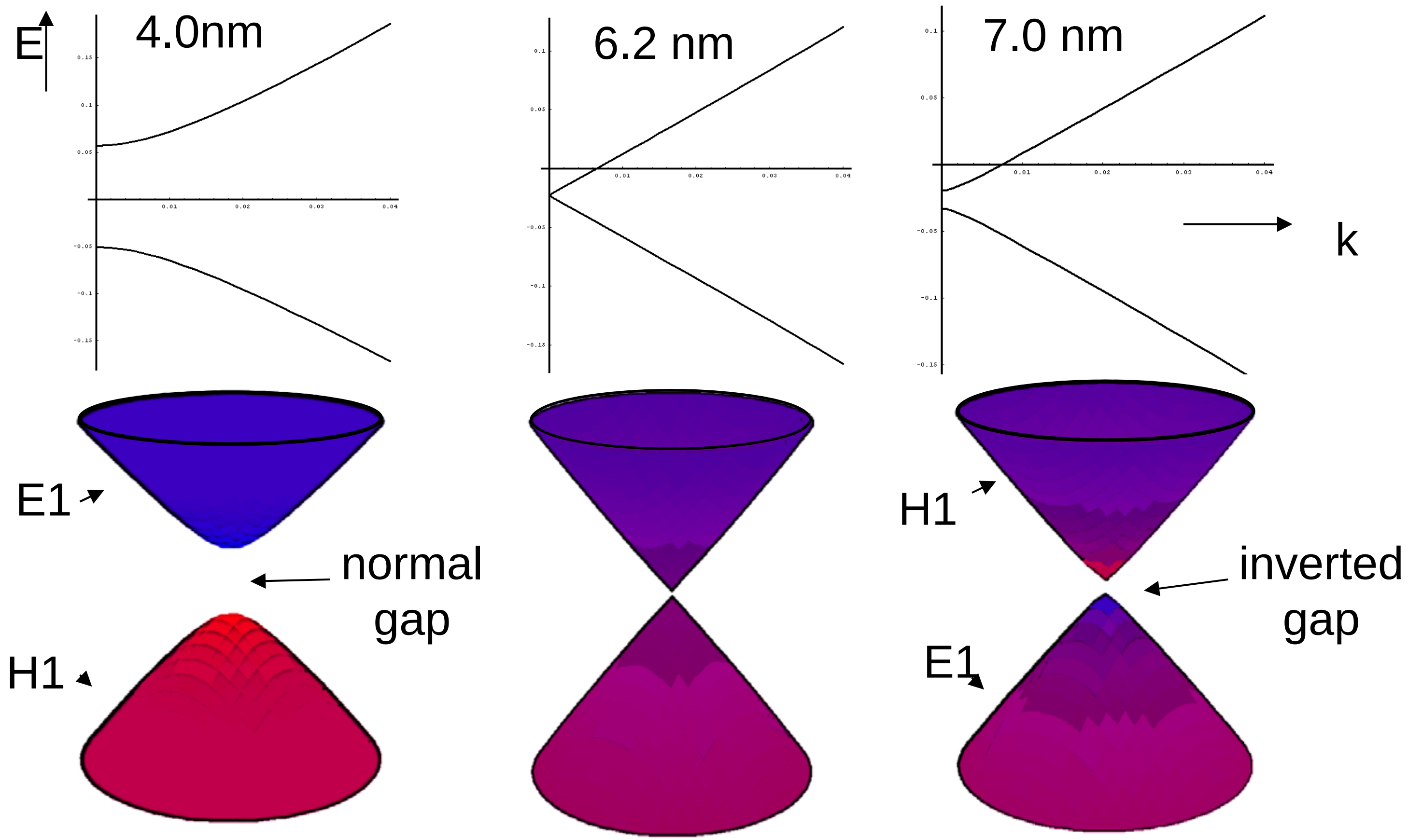

A. Roth et al., Science **325**, 294 (2009).

# Zero gap HgTe well as a Dirac system

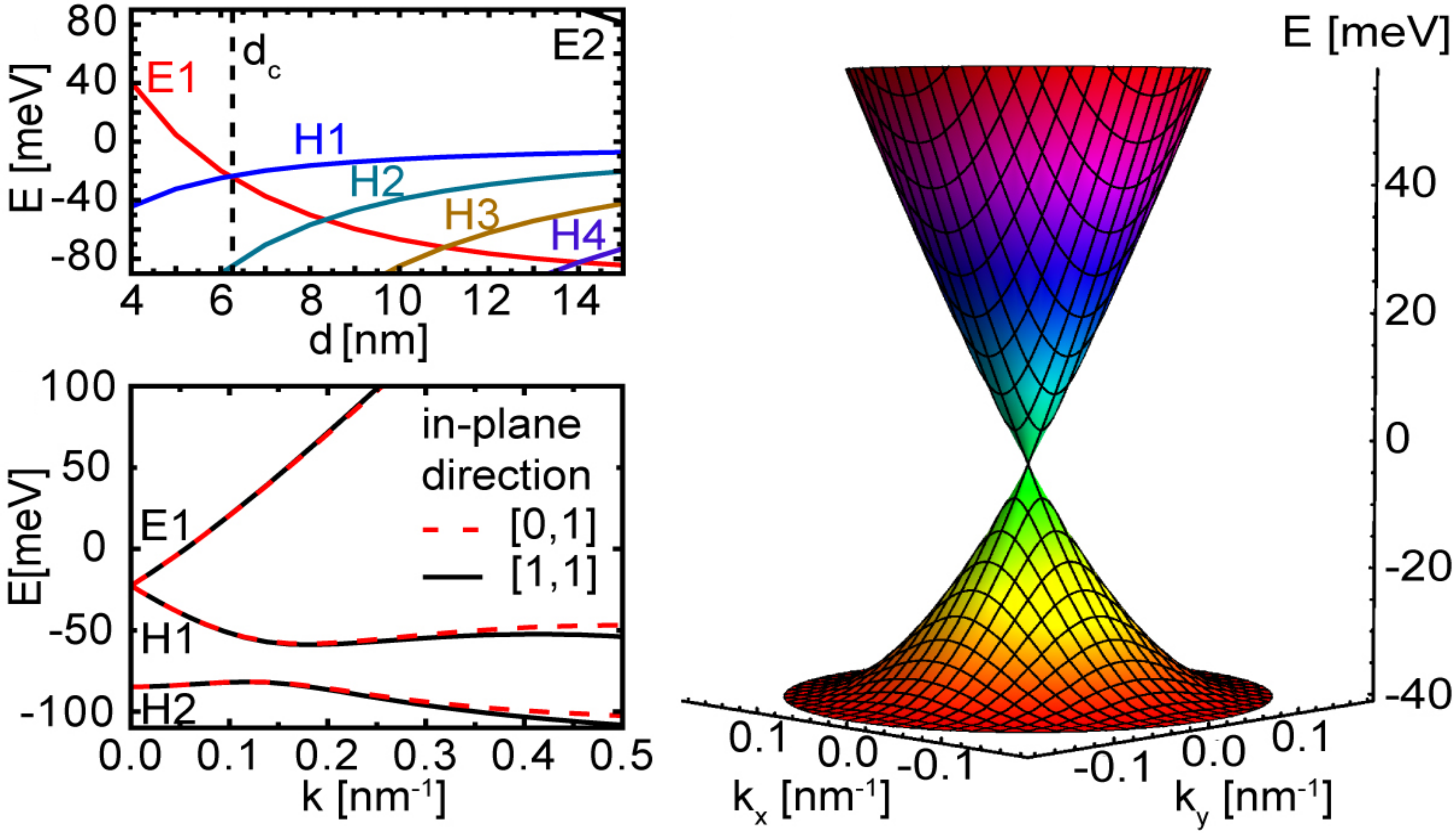
# Bandstructure HgTe



B.A Bernevig, T.L. Hughes, S.C. Zhang, Science **314**, 1757 (2006)

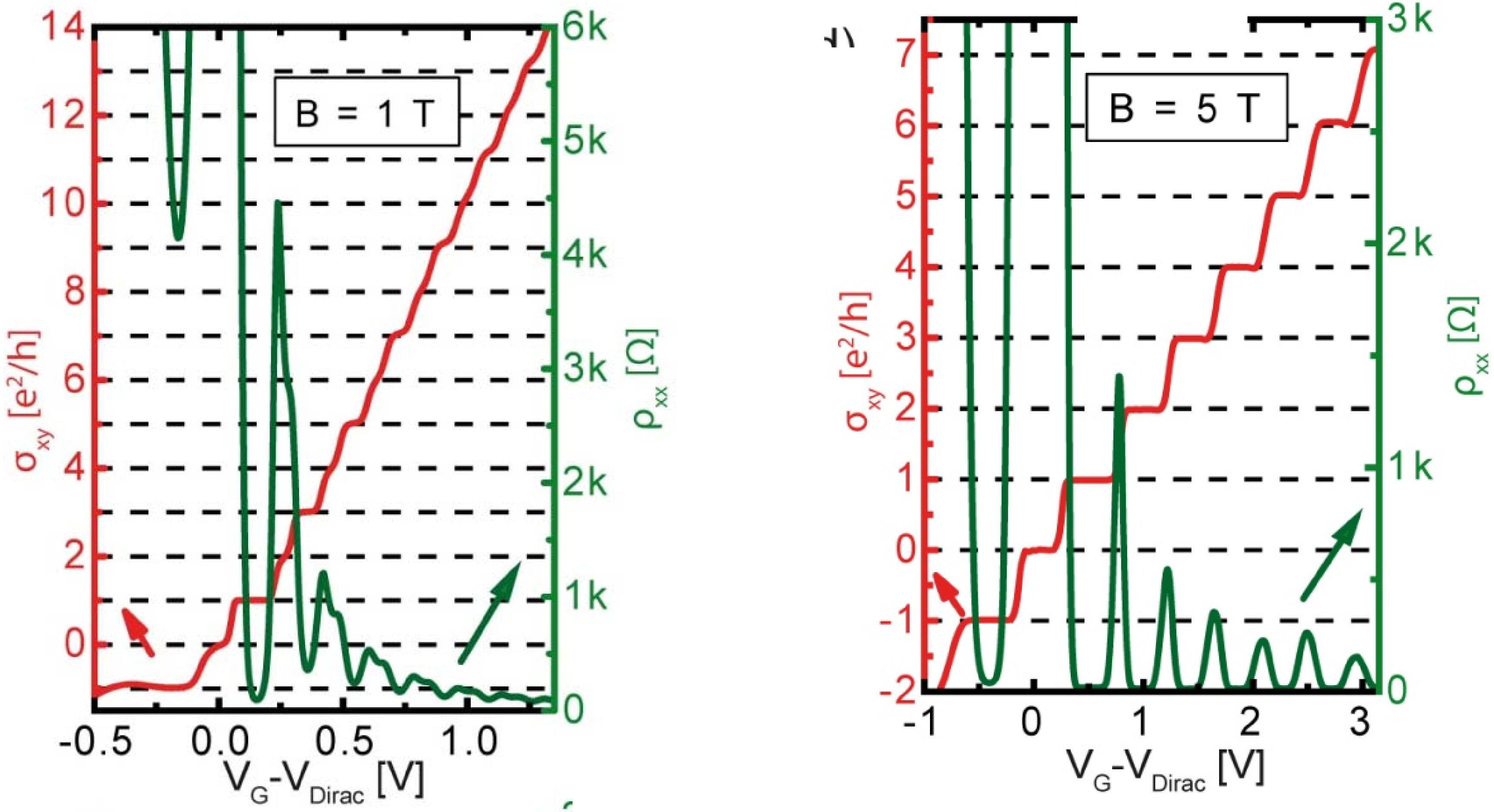


# Dispersion at $d=d_c$ is Dirac-like




For well thickness d=6.3 nm, the gap closes,
especially the conductionband shows a linear dispersion: **single** Dirac cone

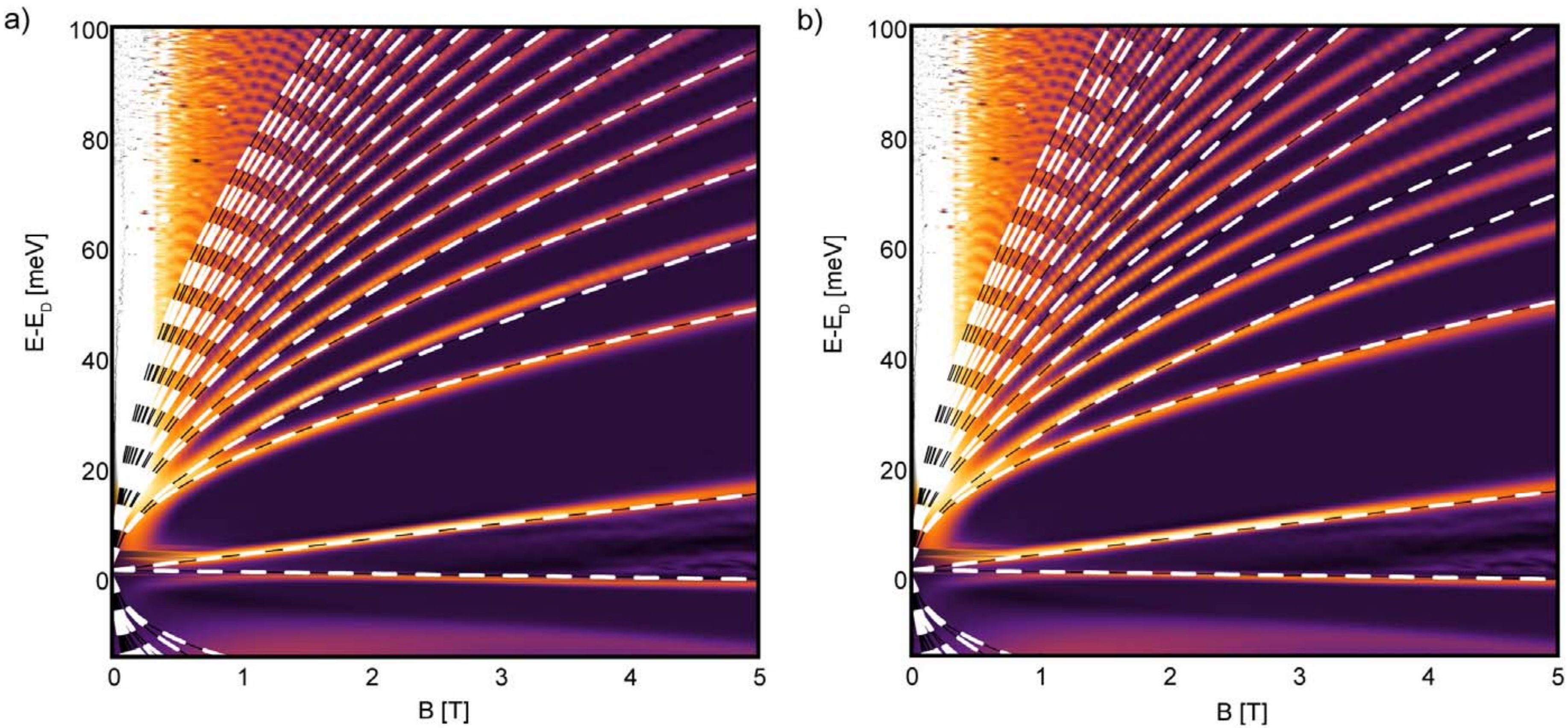
# Quantum Hall effect shows Berry phase




B. Büttner et al., Nature Physics **7**, 418 (2011).

Large g-factor (g=55) responsible for spin slitting already at low fields.
Hall quantization reflects single valley character of the band structure:
a HgTe quantum well at d=6.3 nm is half-graphene.

# Landau-fan

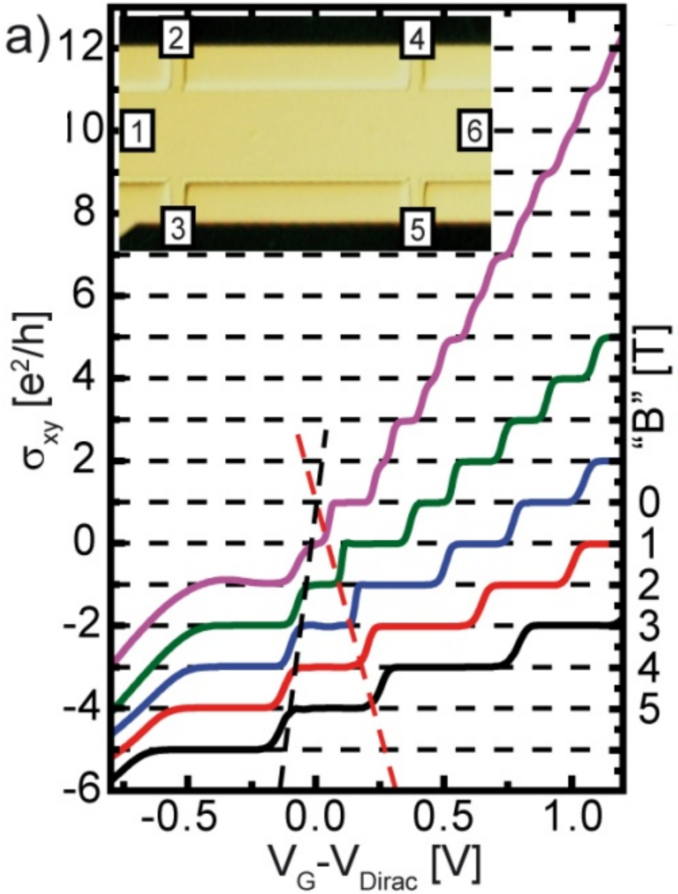


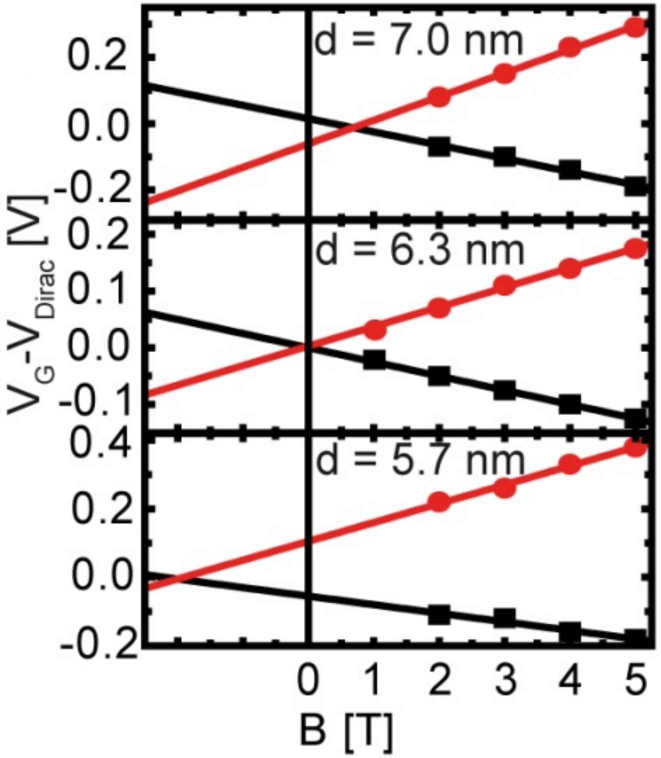

B. Büttner et al., Nature Physics **7**, 418 (2011).

Color coded: gate voltage derivative of longitudinal resistivity.
Fits: left – 8-band Kane model, right – Dirac Hamiltonian

# Zero mode dispersion





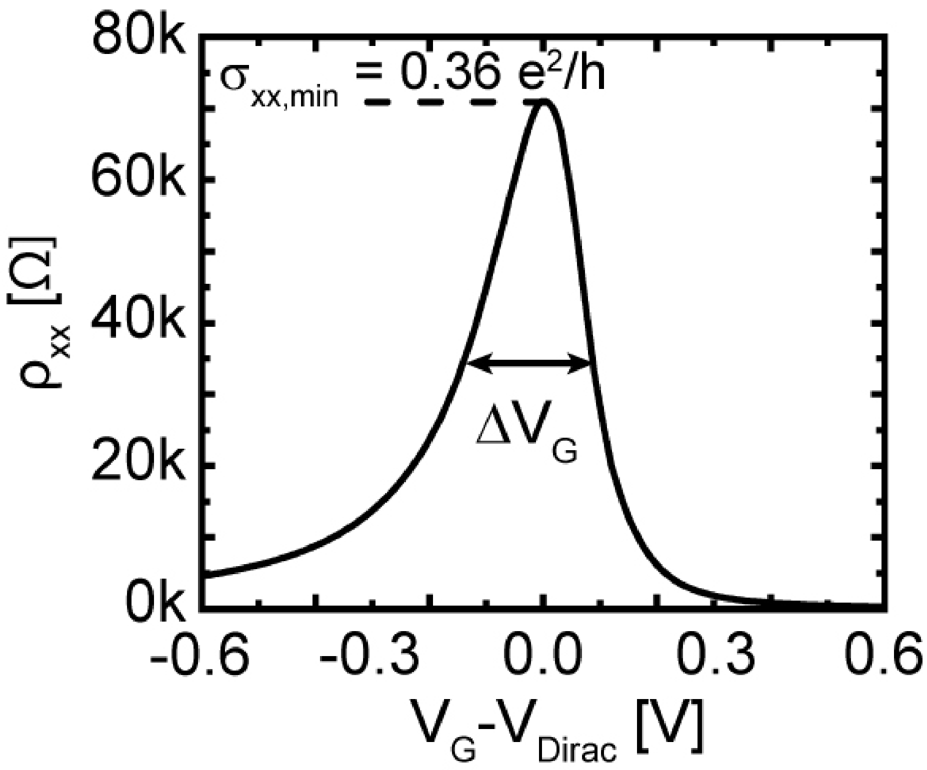



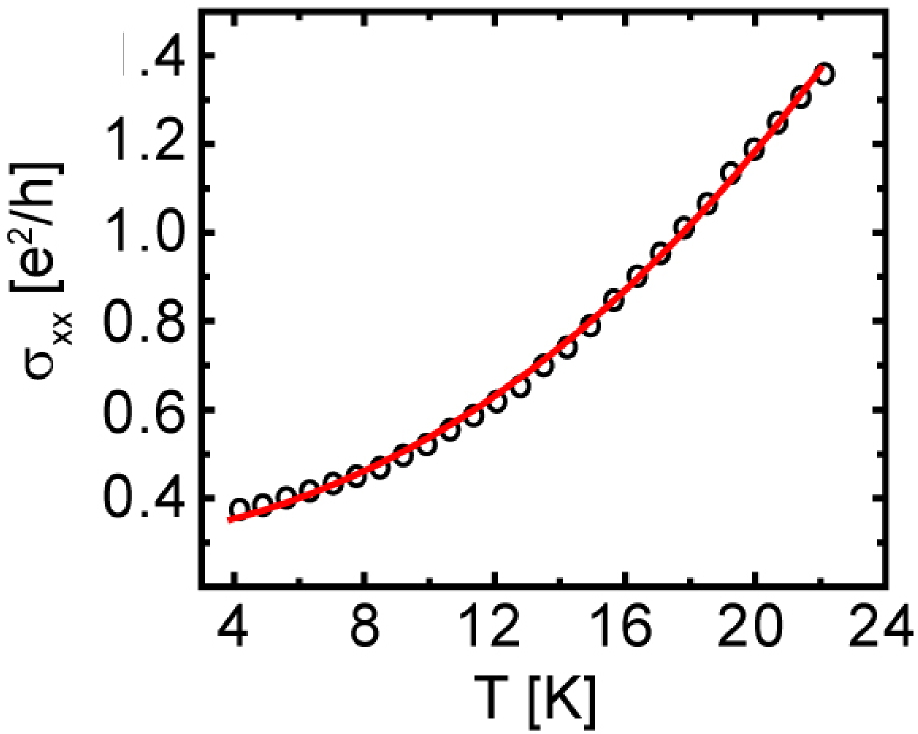

B. Büttner et al., Nature Physics **7**, 418 (2011).

Zero mode spin splitting allows to select sample at $d_c$.

# Dirac peak at B=0






Peak width and mobilities comparable with/better than free standing graphene
Scattering mechanisms: probably mass fluctuations + Coulomb (fit is Kubo model)

# Adding a Dirac mass

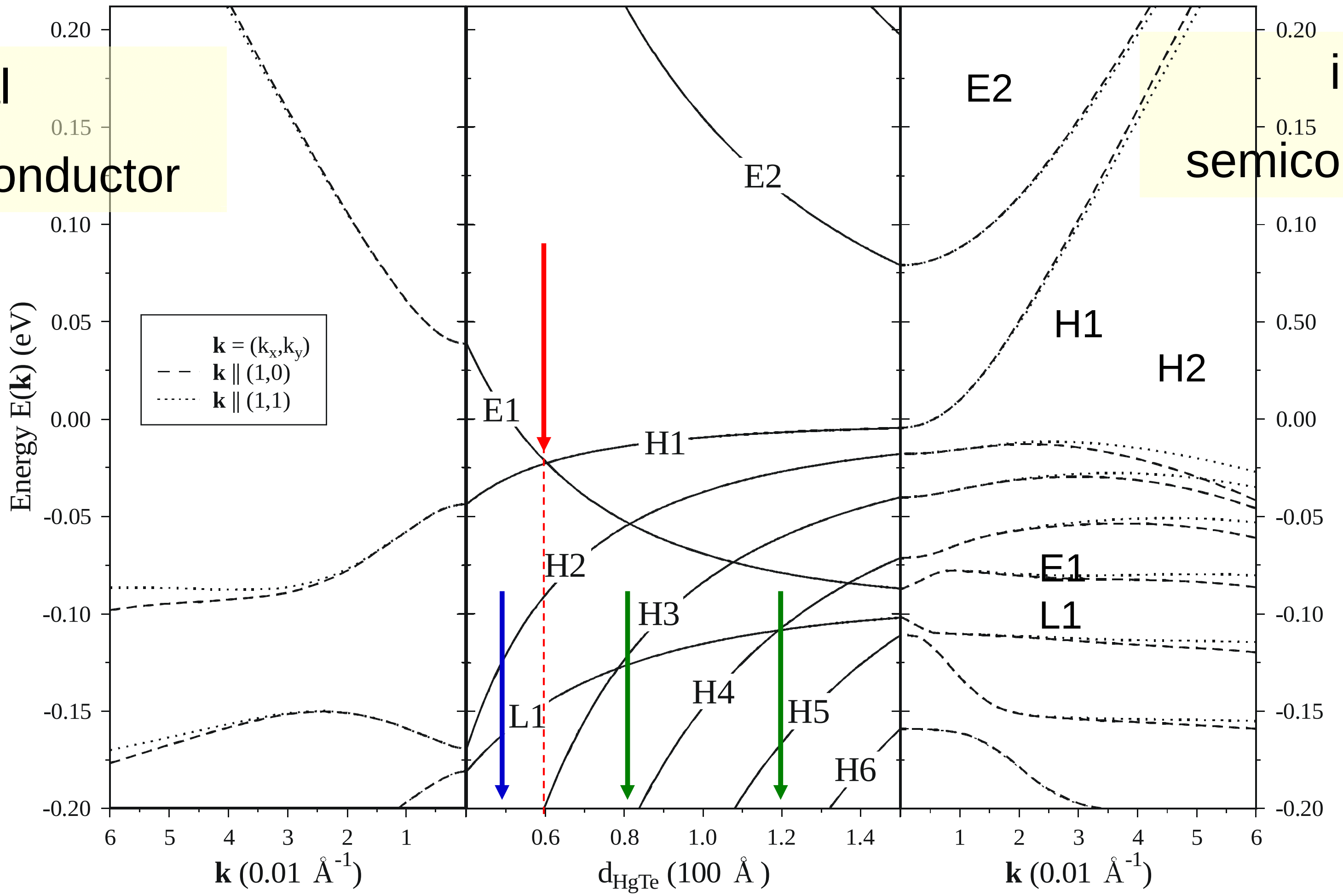
# Changing well width changes Dirac mass

4 nm QW

15 nm QW

normal semiconductor

inverted semiconductor



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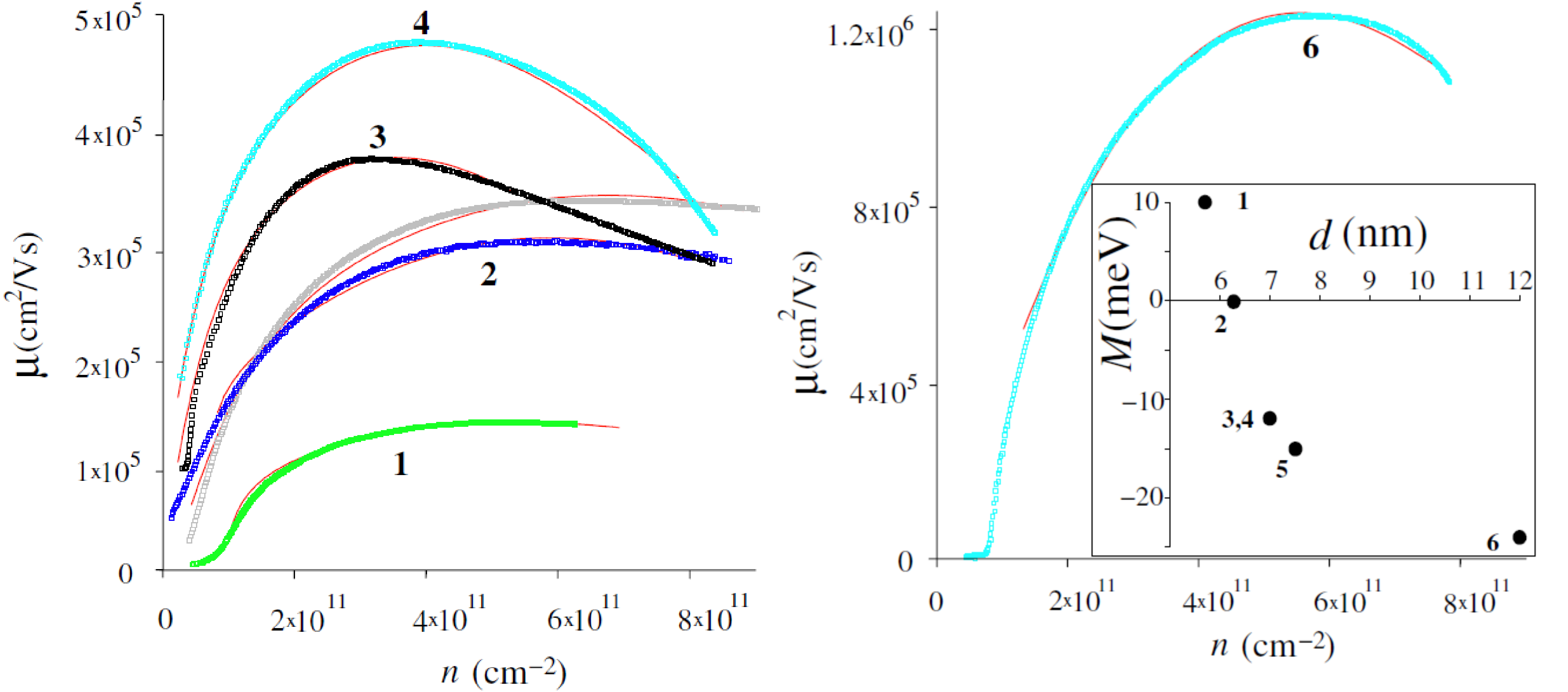
# Mobility for finite Dirac mass

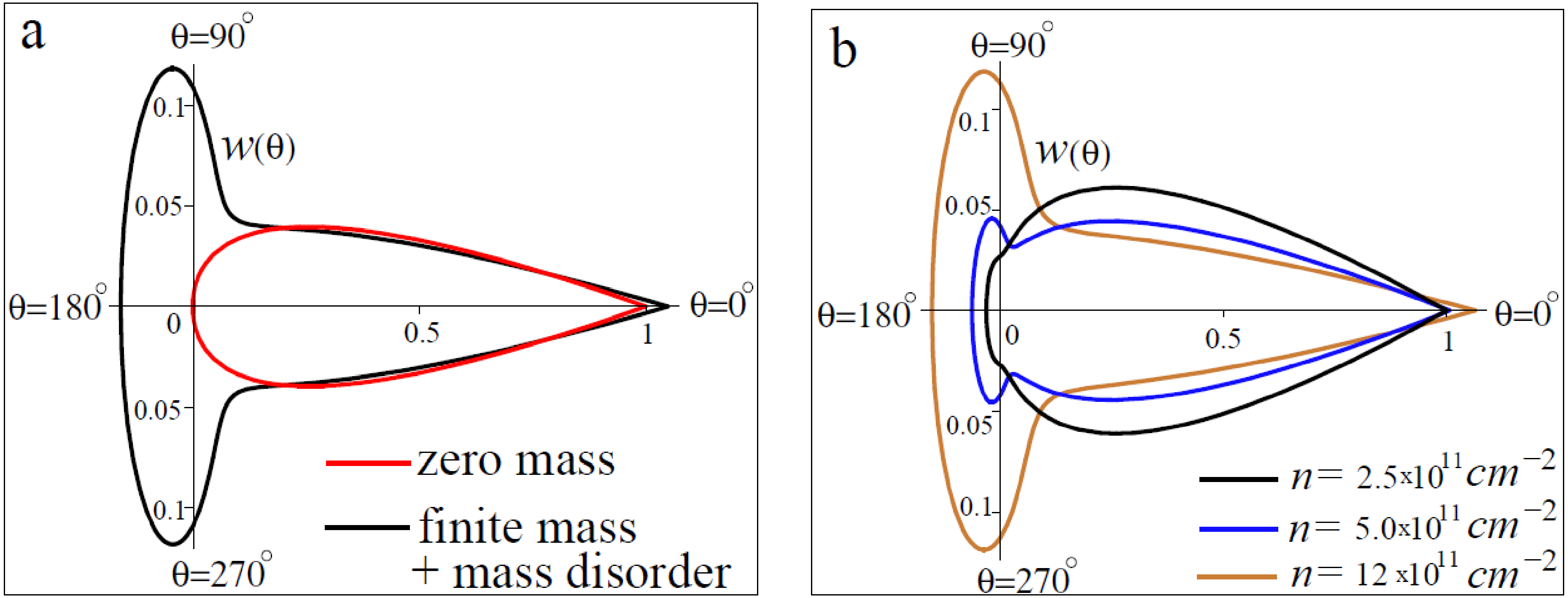
EP 3




B. Büttner et al., Phys. Rev. Lett. **106**, 076802 (2011).

Originally increase in mobility from reduced impurity scattering,
then changeover to behavior due to well width (Dirac mass) fluctuations.

# Mobility for finite Dirac mass

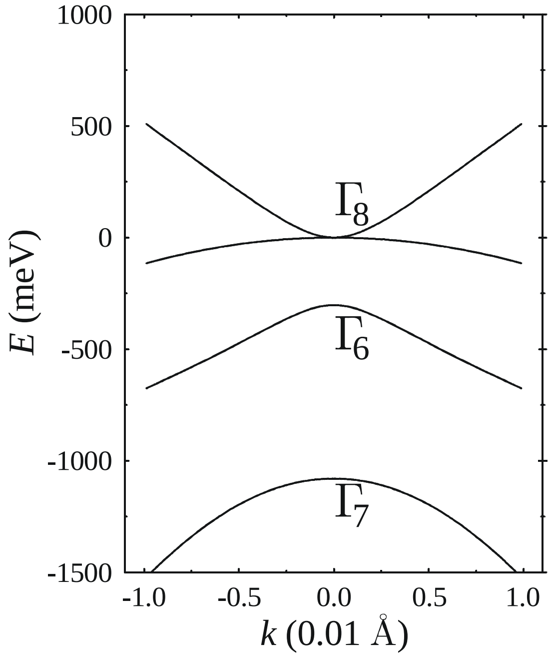


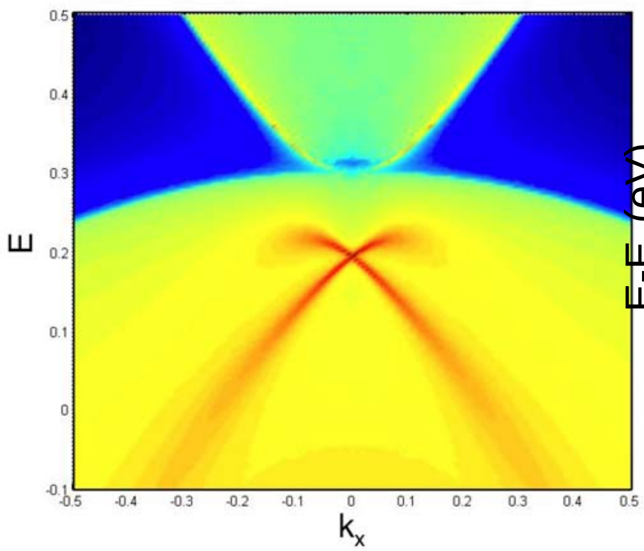

B. Büttner et al., Phys. Rev. Lett. **106**, 076802 (2011).

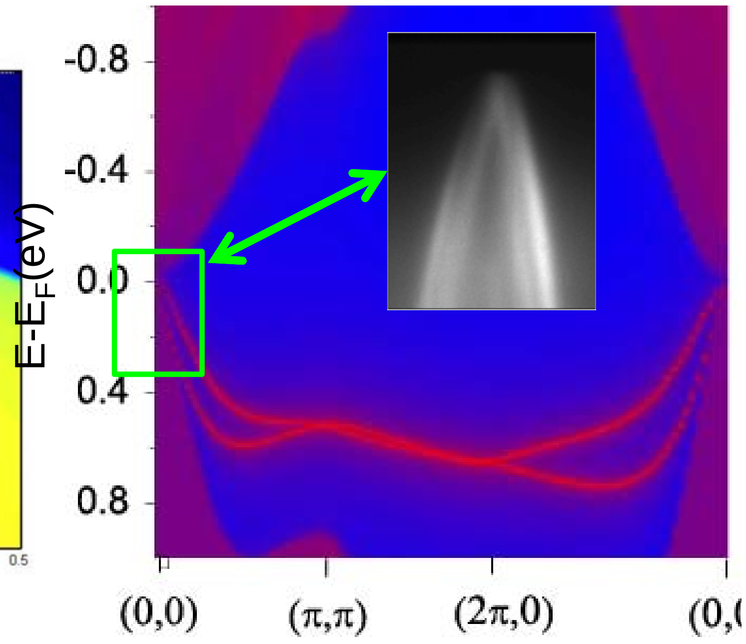
Modeling by Grigory Tkachov and Ewelina Hankiewicz:
Mass and disorder induce backscattering of Dirac fermions.

# Dirac Surface States
# on
# strained bulk HgTe

# Bulk HgTe as a 3-D Topological ‚Insulator'



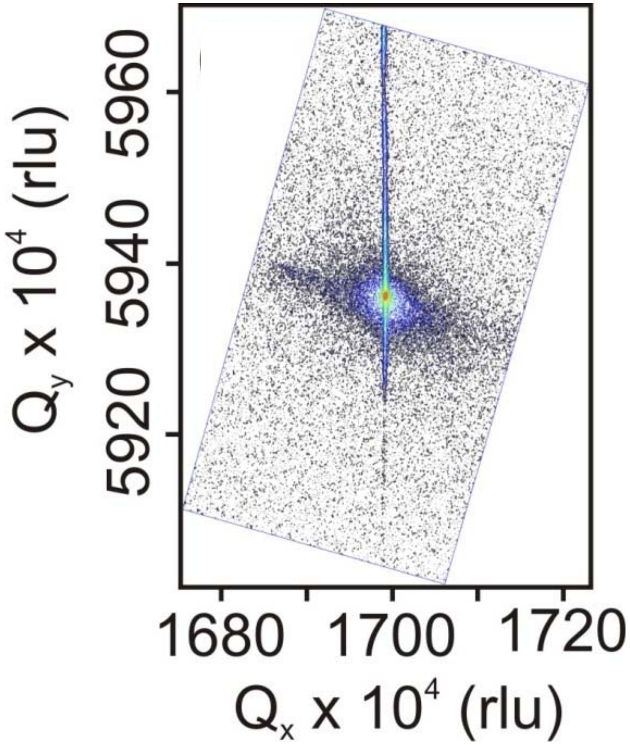

Bulk HgTe is semimetal,

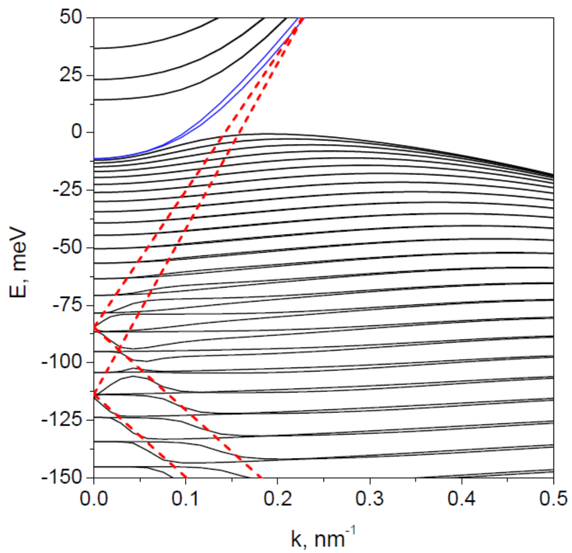
topological surface state overlaps w/ valenceband.

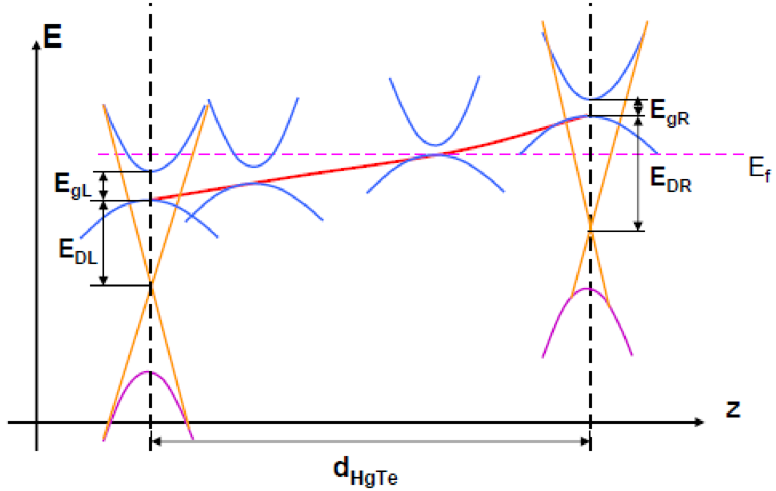
C. Brüne et al., Phys. Rev. Lett. **106**, 126803 (2011).

ARPES:
Yulin Chen, ZX Shen,
Stanford

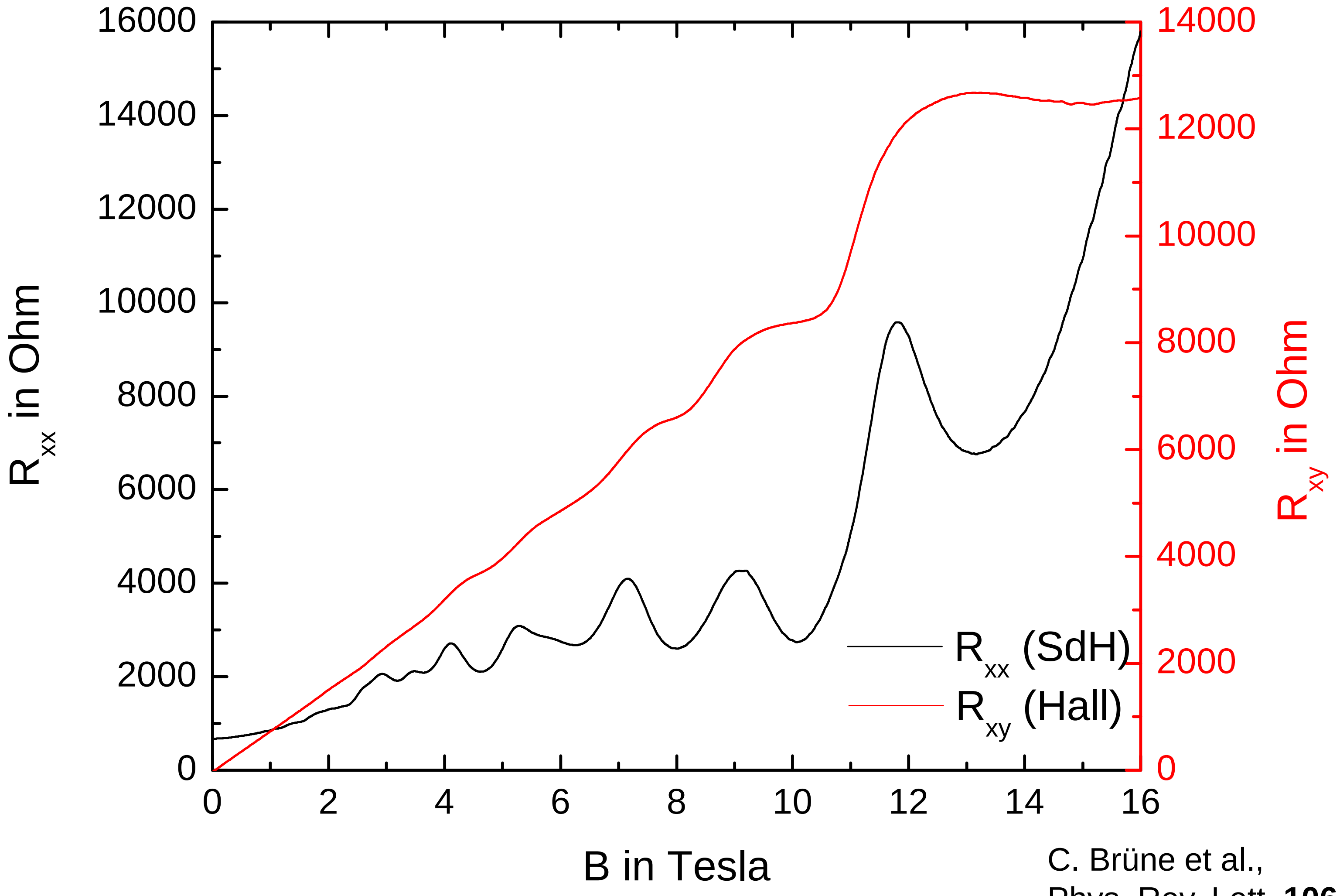
# 70 nm layer on CdTe substrate: coherent strain opens gap



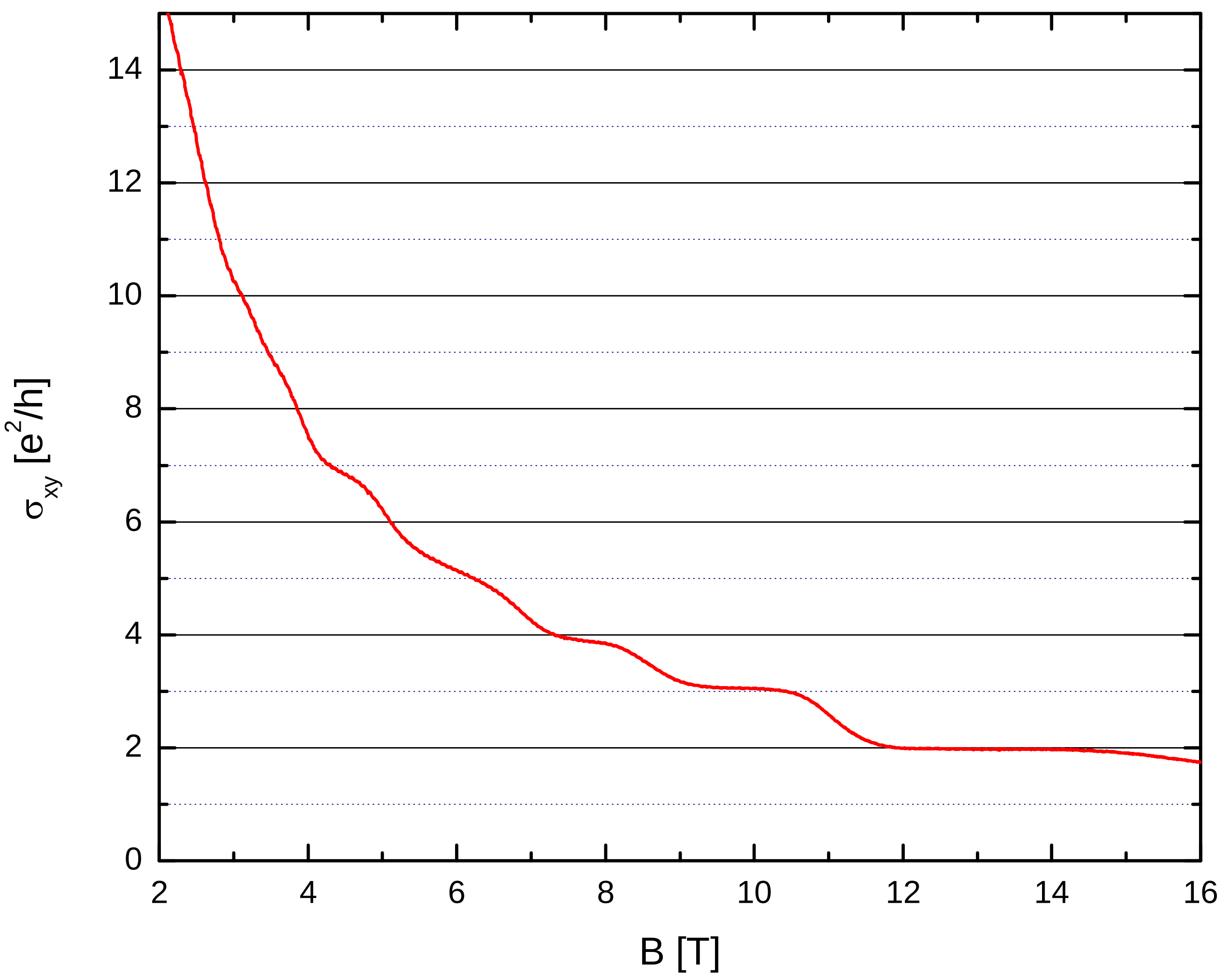
# Bulk HgTe as a 3-D Topological ‚Insulator‘




C. Brüne et al.,
Phys. Rev. Lett. **106**, 126803 (2011).

@ 20 mK: bulk conductivity almost frozen out - Surface state mobility ca. 35000 $cm^2/Vs$

# Bulk HgTe as a 3-D Topological ‚Insulator‘




@ 20 mK: same data, plotted as conductivity

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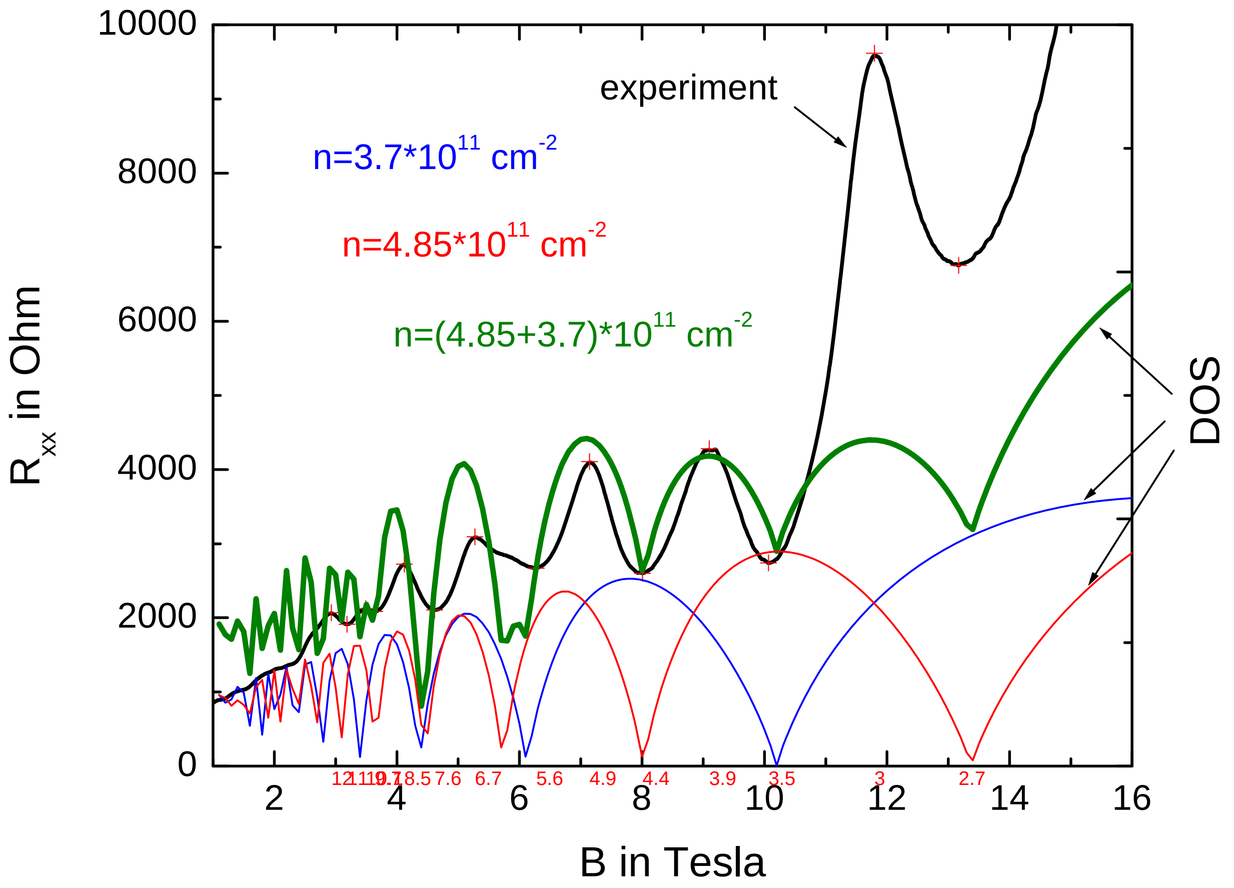
# 3D HgTe-calculations




C. Brüne et al., Phys. Rev. Lett. **106**, 126803 (2011).

Red and blue lines : DOS for each of the Dirac-cones with the corresponding fixed 2D-density,
Green line: the sum of the blue and red lines

# Conclusions

- HgTe quantum wells: normal and inverted gap, linear (Dirac) dispersion
- First observation of Quantum Spin Hall Effect
- At d=dc, a HgTe QW is ideal model system for zero mass Dirac fermion physics
- Can conveniently study Dirac fermions w/ finite Dirac mass
- Strained 3D layers show QHE of topological surface states

Collaborators:
Bastian Büttner, Christoph Brüne, Hartmut Buhmann, Markus König, Matthias Mühlbauer, Andreas Roth, Volkmar Hock

Theory: Alena Novik, Chaoxing Liu, Ewelina Hankiewicz , Grigory Tkachov, Patrick Recher, Björn Trauzettel (all @ Würzburg), Jairo Sinova (TAMU), Shoucheng Zhang, Xiaoliang Qi (Stanford)

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