Dirac Fermions in HgTe Quantum Wells

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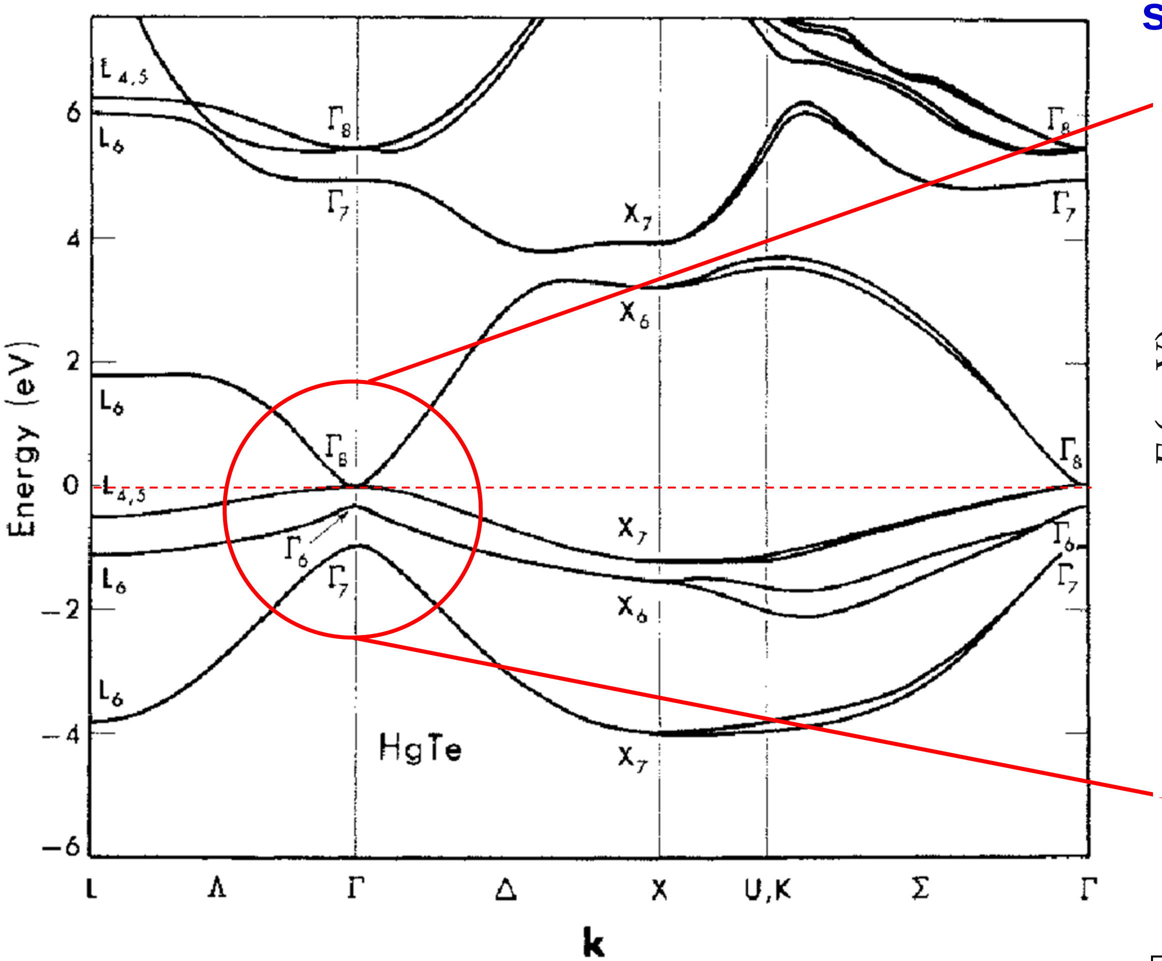
Overview

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

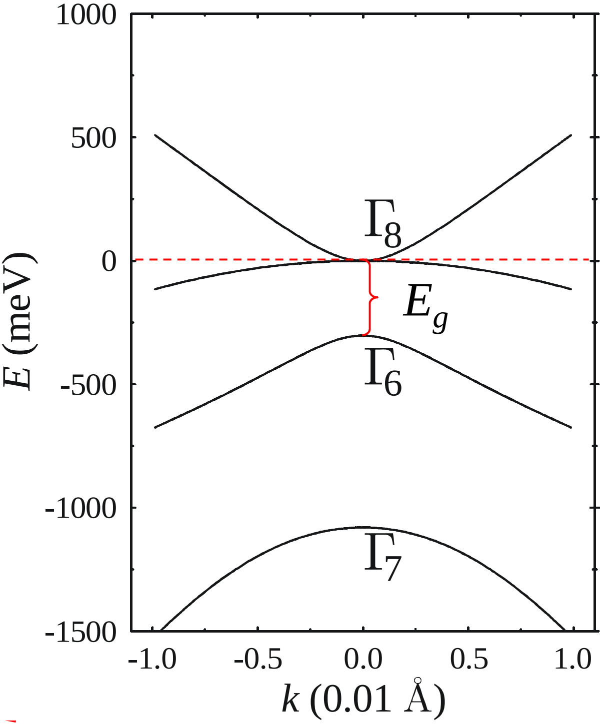
HgTe

band structure



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

semi-metal or semiconductor

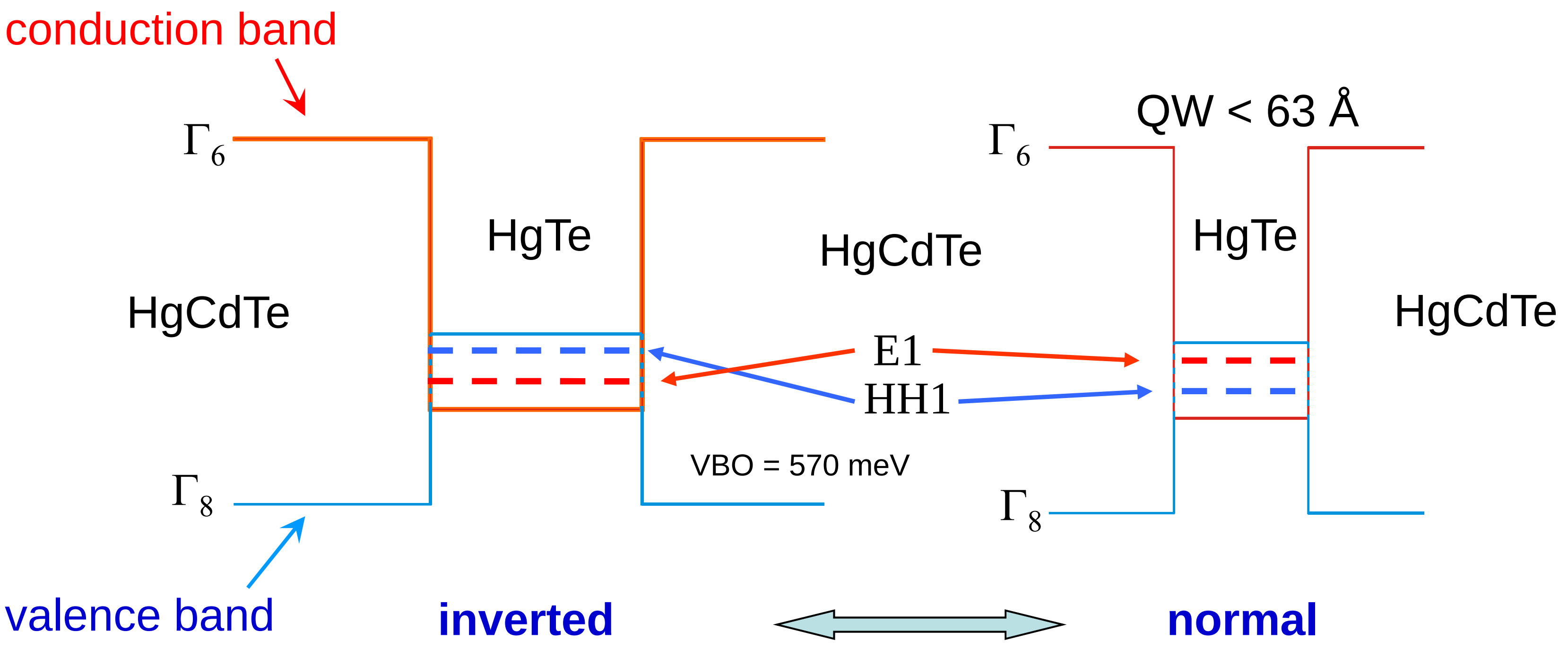


fundamental energy gap

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

HgTe-Quantum Wells

Type-III QW



conduction band

Γ_6

HgTe

HgCdTe

HgCdTe

Γ_8

valence band

QW < 63 Å

Γ_6

HgTe

HgCdTe

E1

HH1

VBO = 570 meV

Γ_8

inverted

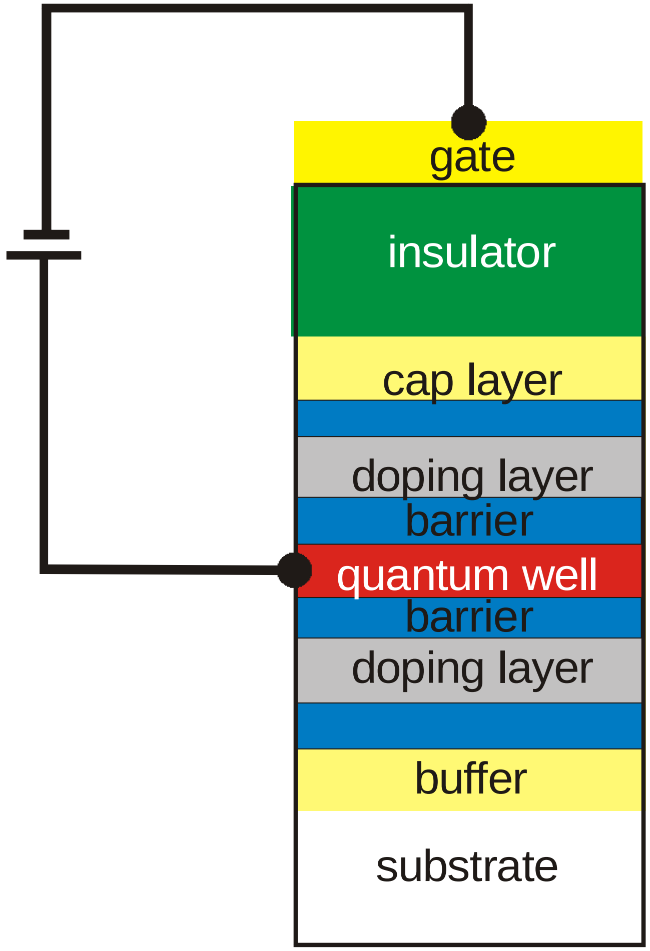
normal

band structure

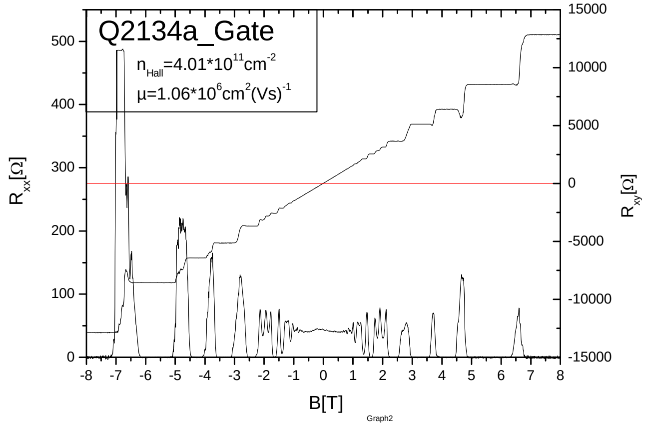
Layer Structure

Carrier densities: $n_s = 1\text{x}10^{11} \ldots 2\text{x}10^{12}\ \text{cm}^{-2}$

Carrier mobilities: $\mu = 1\text{x}10^{5} \ldots 1.5\text{x}10^{6}\ \text{cm}^2/\text{Vs}$

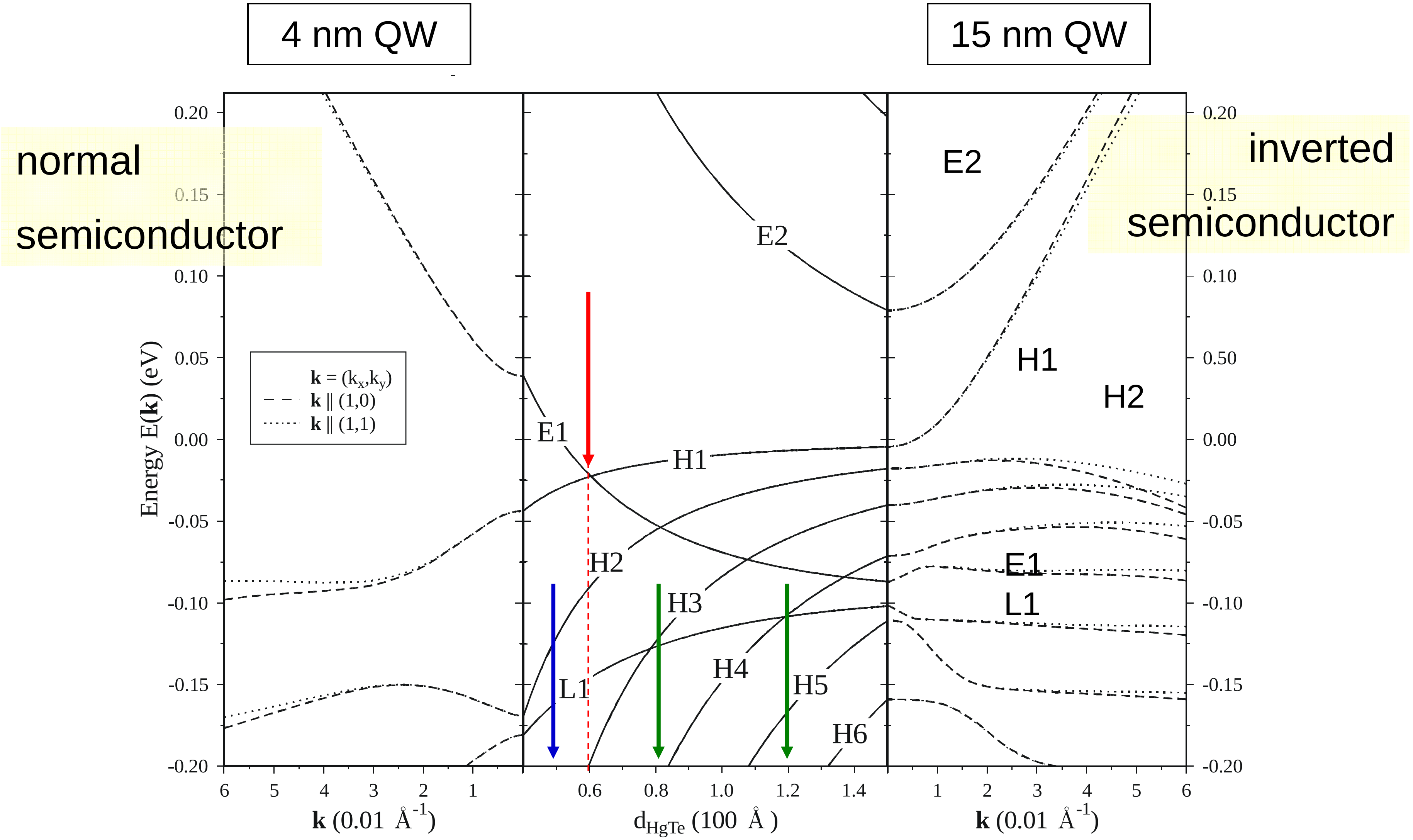


gate	Au
insulator	100 nm Si_3N_4/SiO_2
cap layer	25 nm CdTe
	10 nm HgCdTe x = 0.7
doping layer	9 nm HgCdTe with I
barrier	10 nm HgCdTe x = 0.7
quantum well	4 - 12 nm HgTe
barrier	10 nm HgCdTe x = 0.7
doping layer	9 nm HgCdTe with I
	10 nm HgCdTe x = 0.7
buffer	25 nm CdTe
substrate	CdZnTe(001)



symmetric or asymmetric doping

Band Gap Engineering



4 nm QW

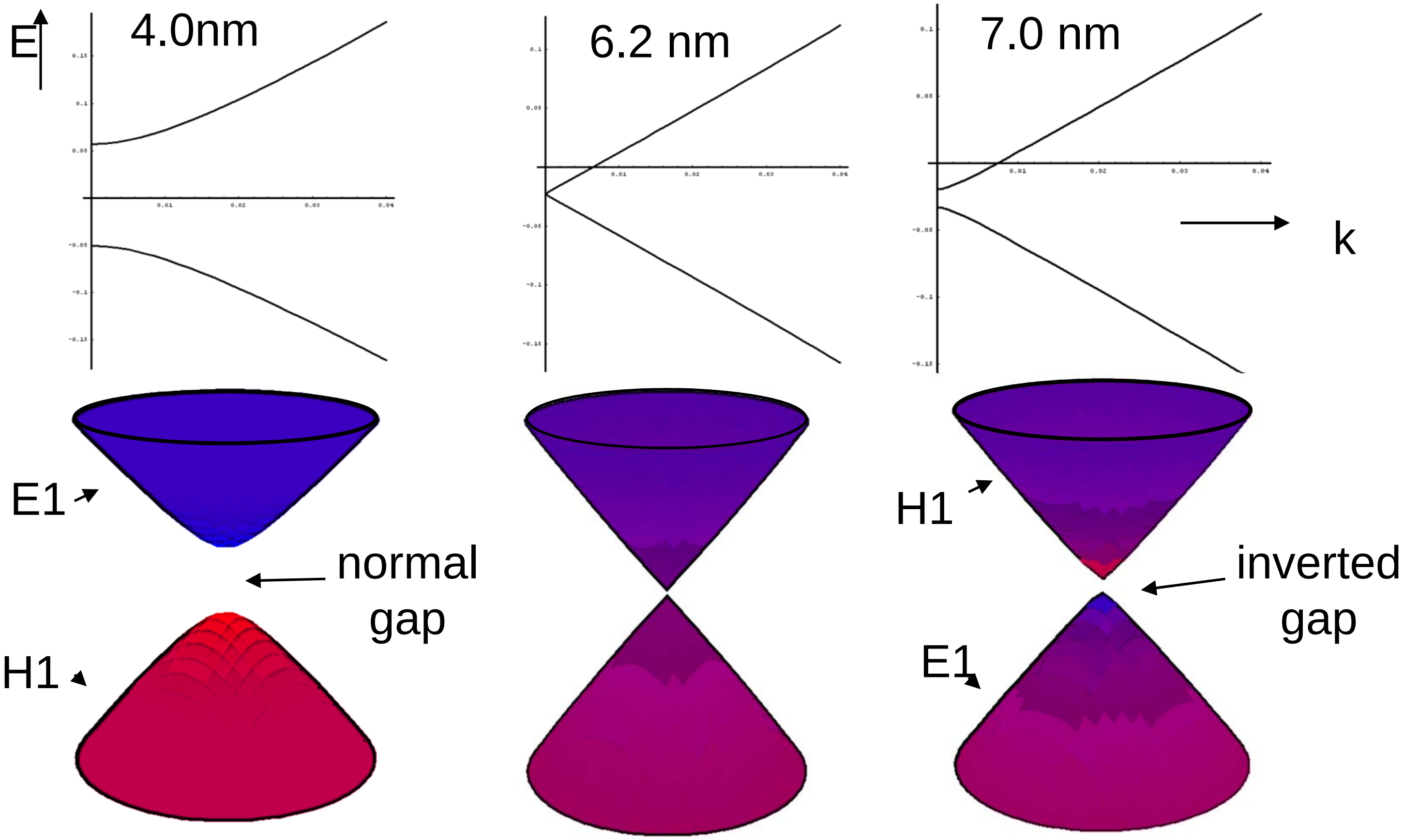
15 nm QW

normal semiconductor

inverted semiconductor

Bandstructure HgTe

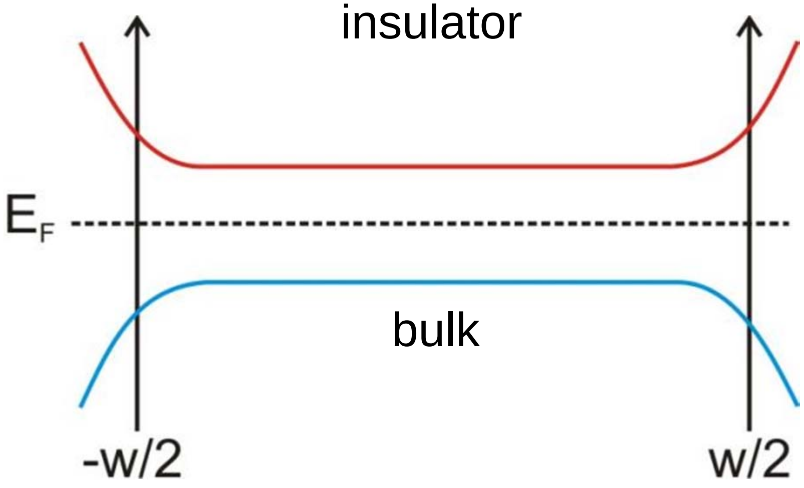
B.A Bernevig, T.L. Hughes, S.C. Zhang, Science **314**, 1757 (2006)



QSHE, Simplified Picture

m > 0

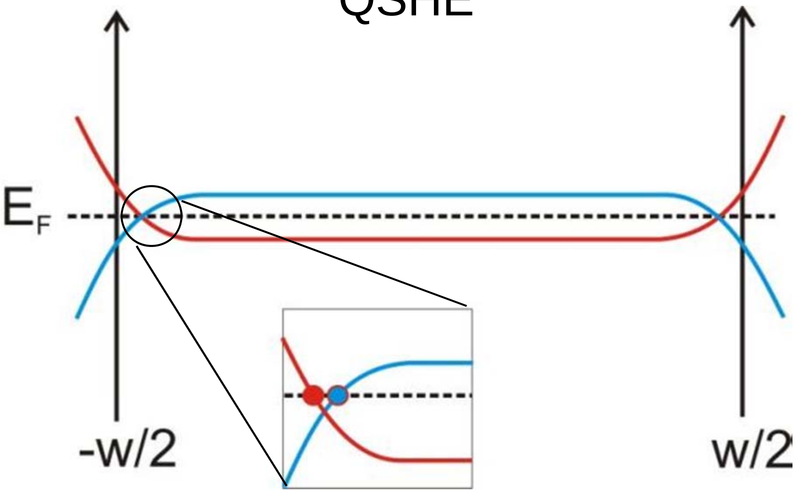
normal insulator

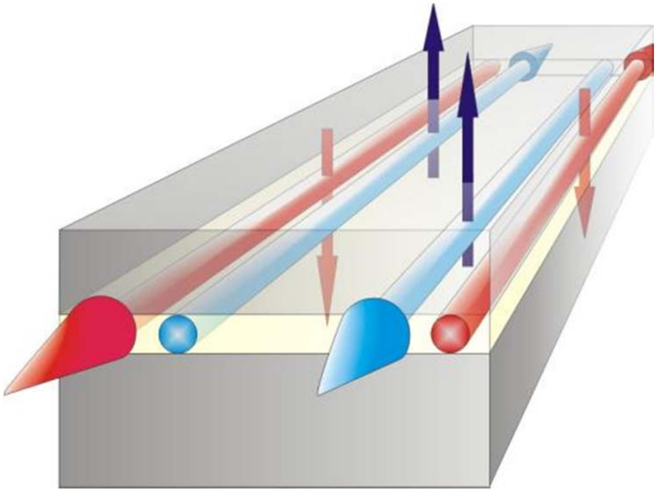



entire sample insulating

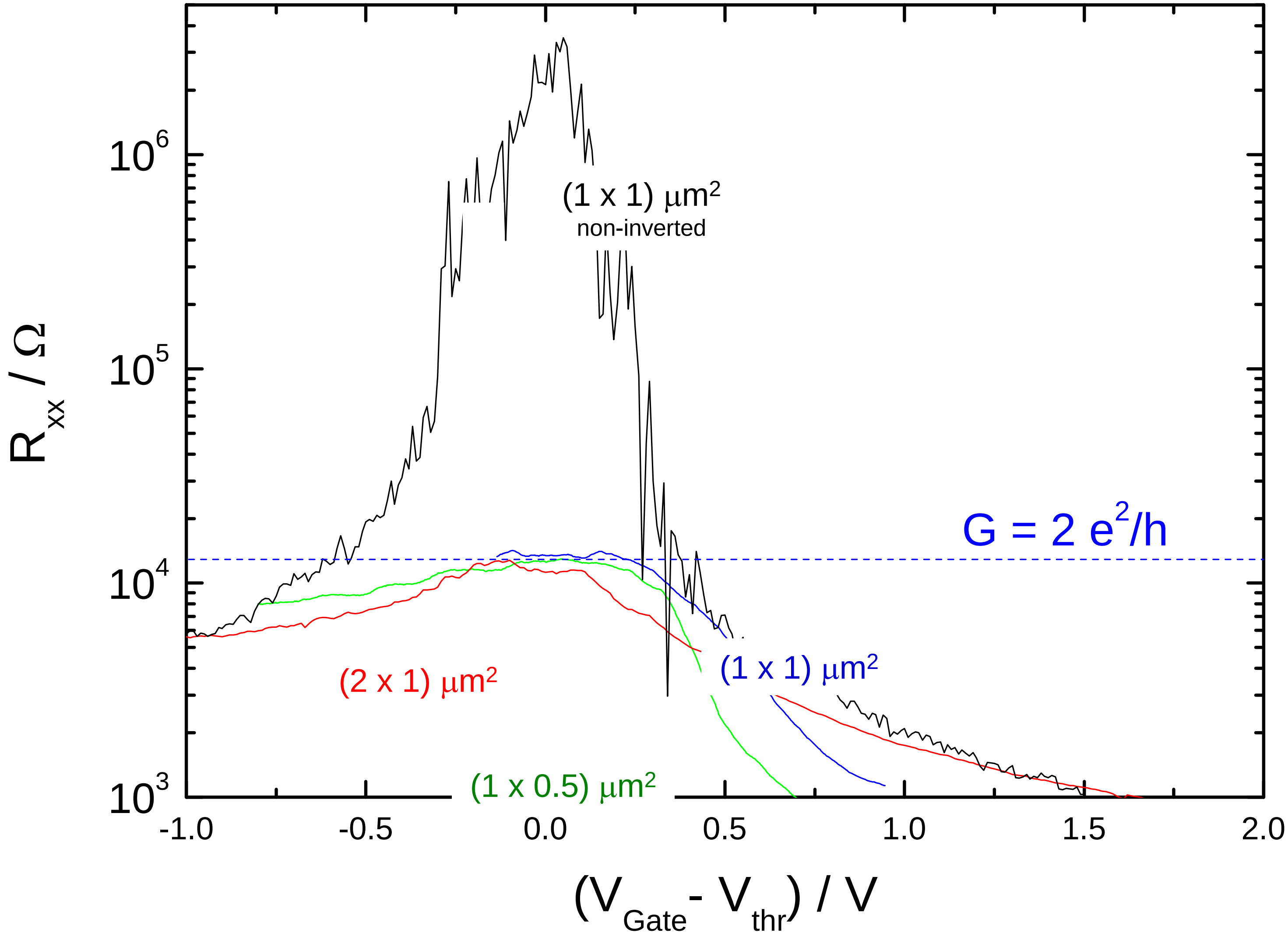
m < 0

QSHE



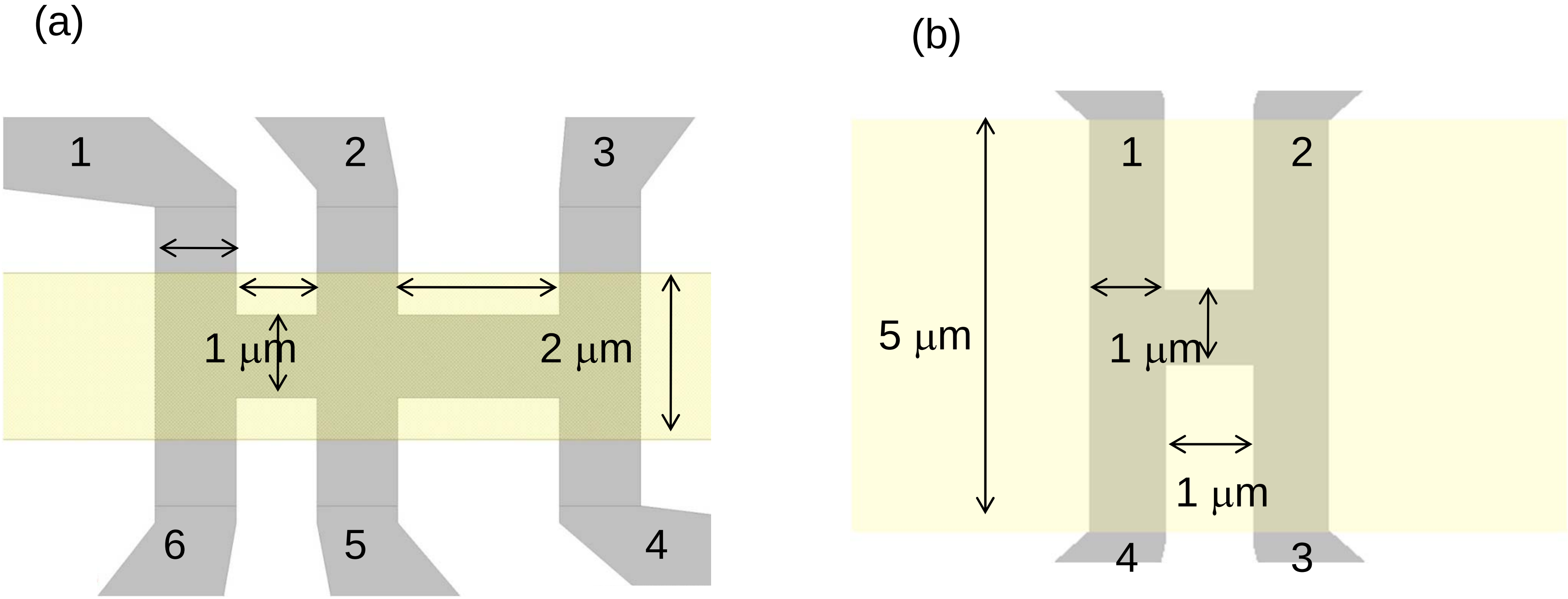


Observation of QSH Effect



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

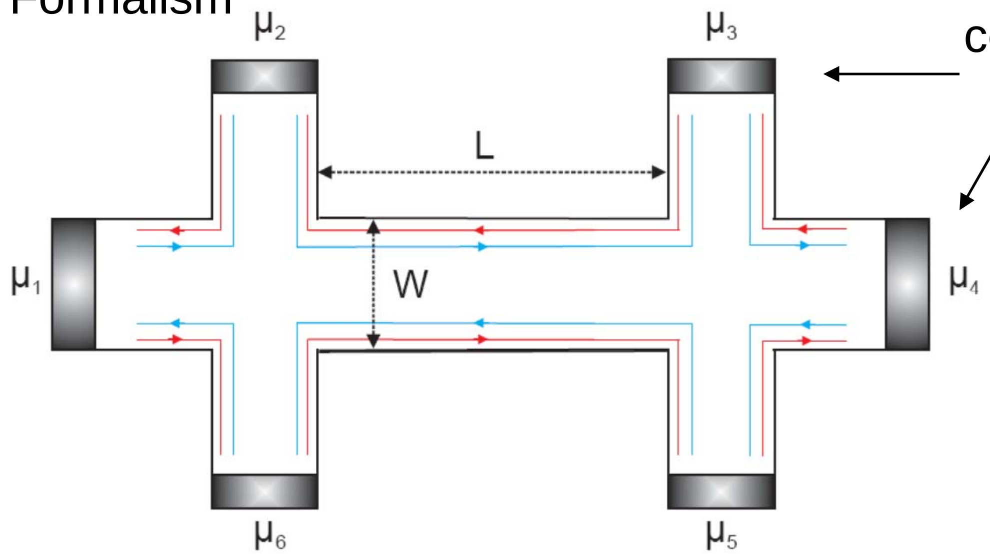
Verify helical edge state transport



Multiterminal /Non-local transport samples

Multi-Terminal Probe

Landauer-Büttiker Formalism



normal
conducting contacts
➔ **no QSHE**

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

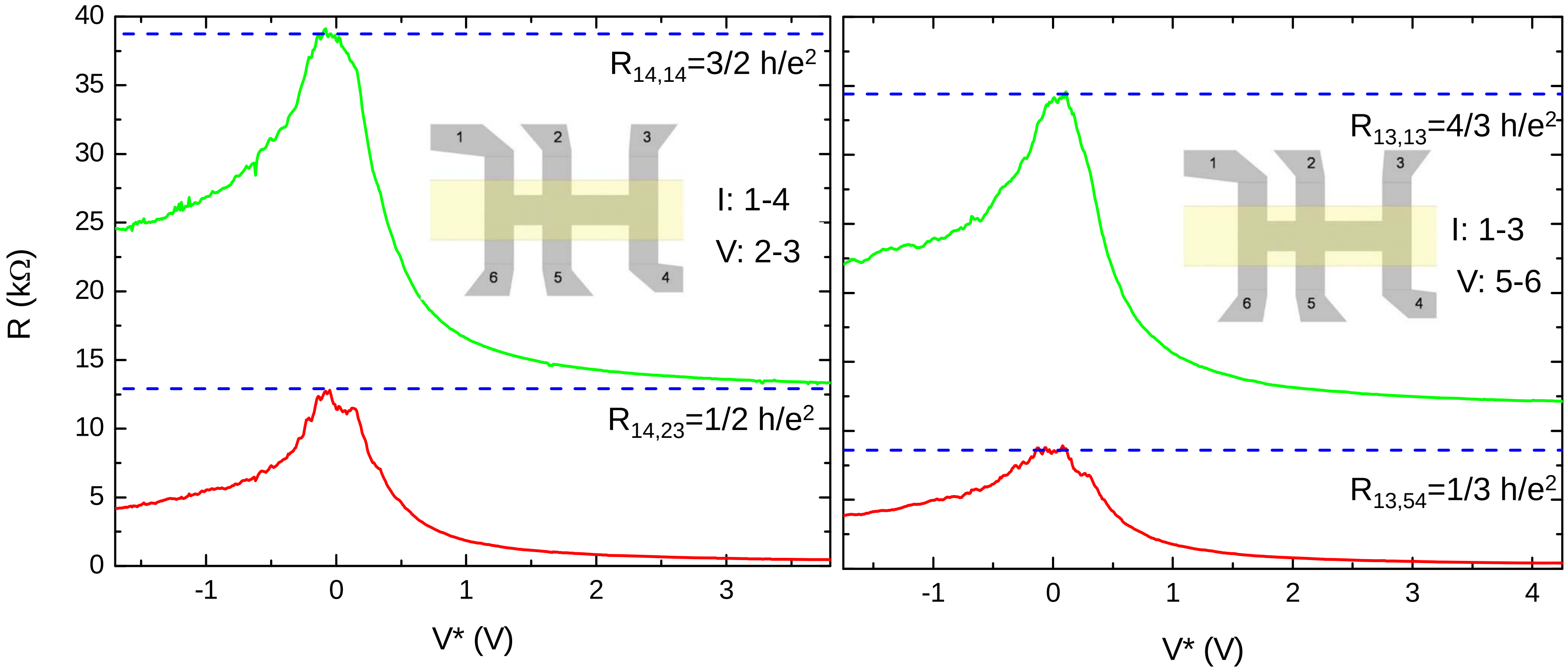
generally

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

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

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

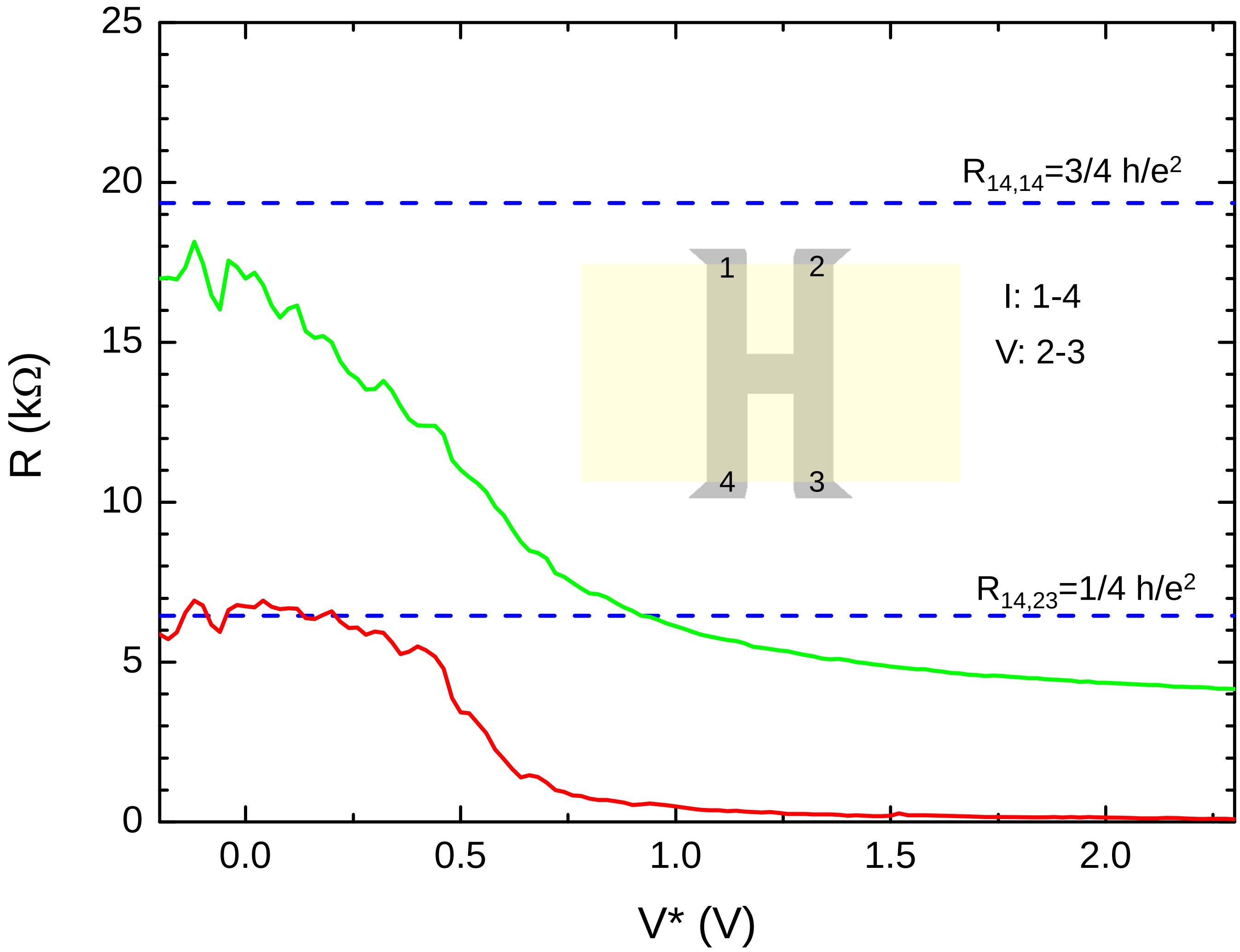
Multi-Terminal Measurements



Configurations would be equivalent in quantum adiabatic regime

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

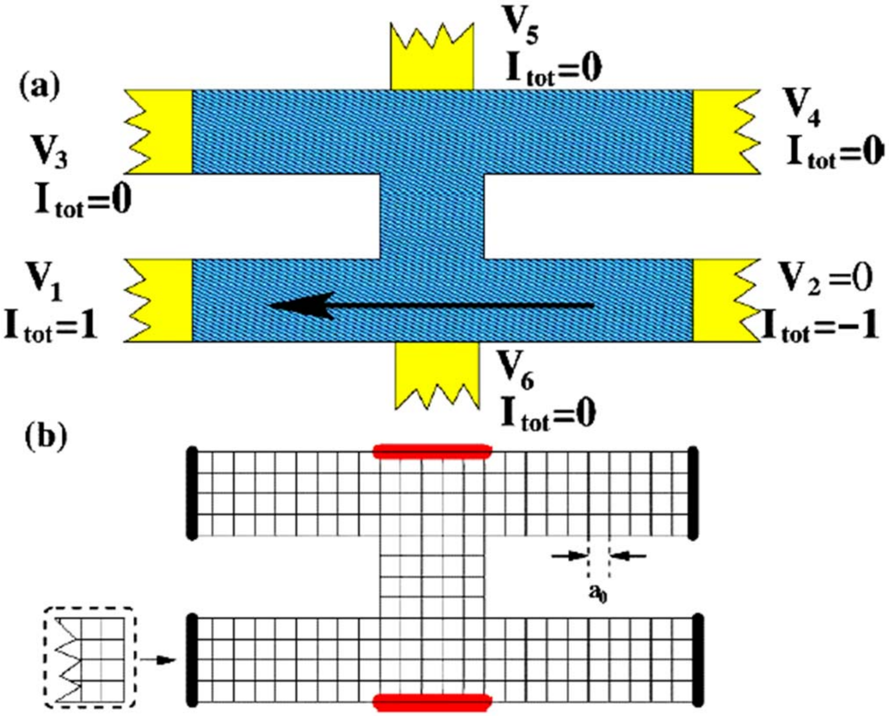
Non-Local data on H-bar

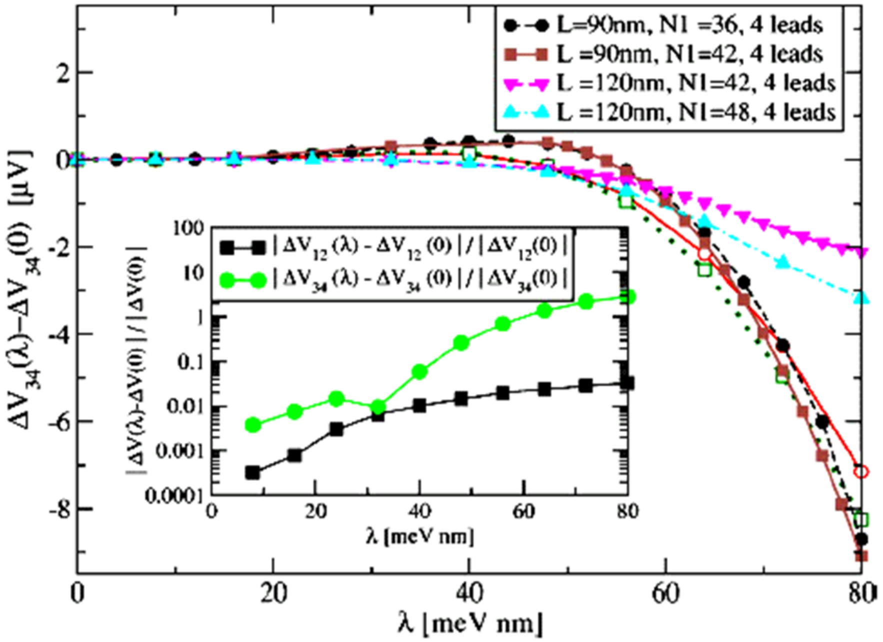


A. Roth et al., Science **325**, 294 (2009).

H-bar for detection of Spin-Hall-Effect

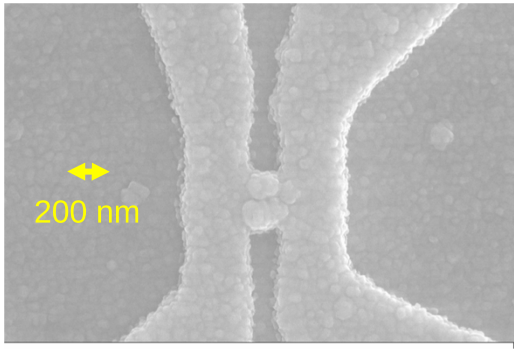
(electrical detection through inverse SHE)

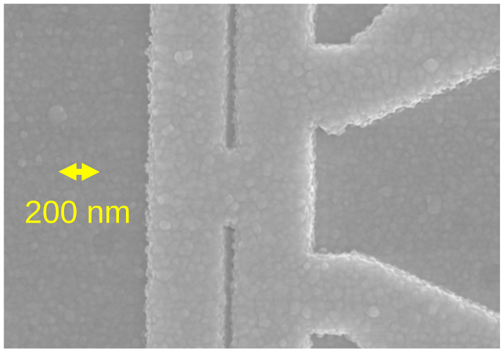


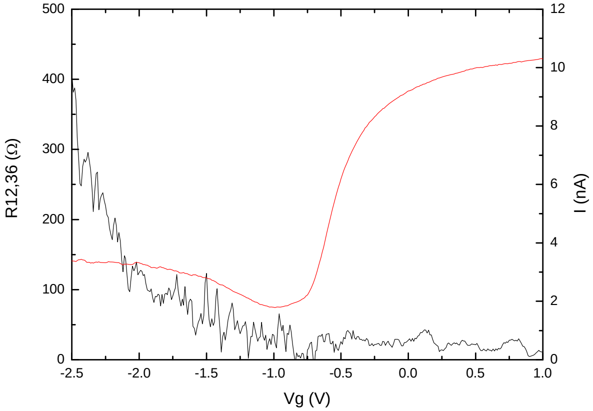


E.M. Hankiewicz et al ., PRB **70**, R241301 (2004)

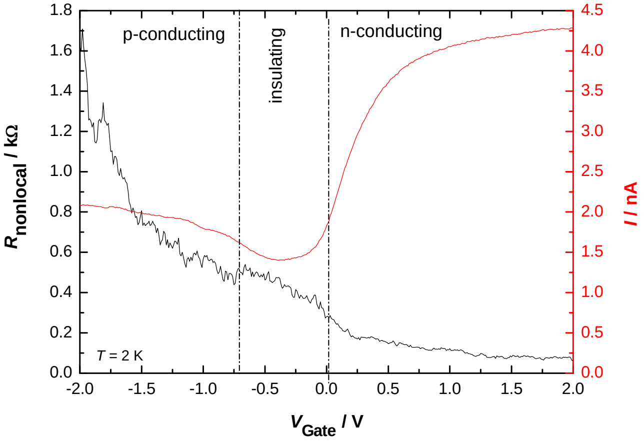
H-bar experiments



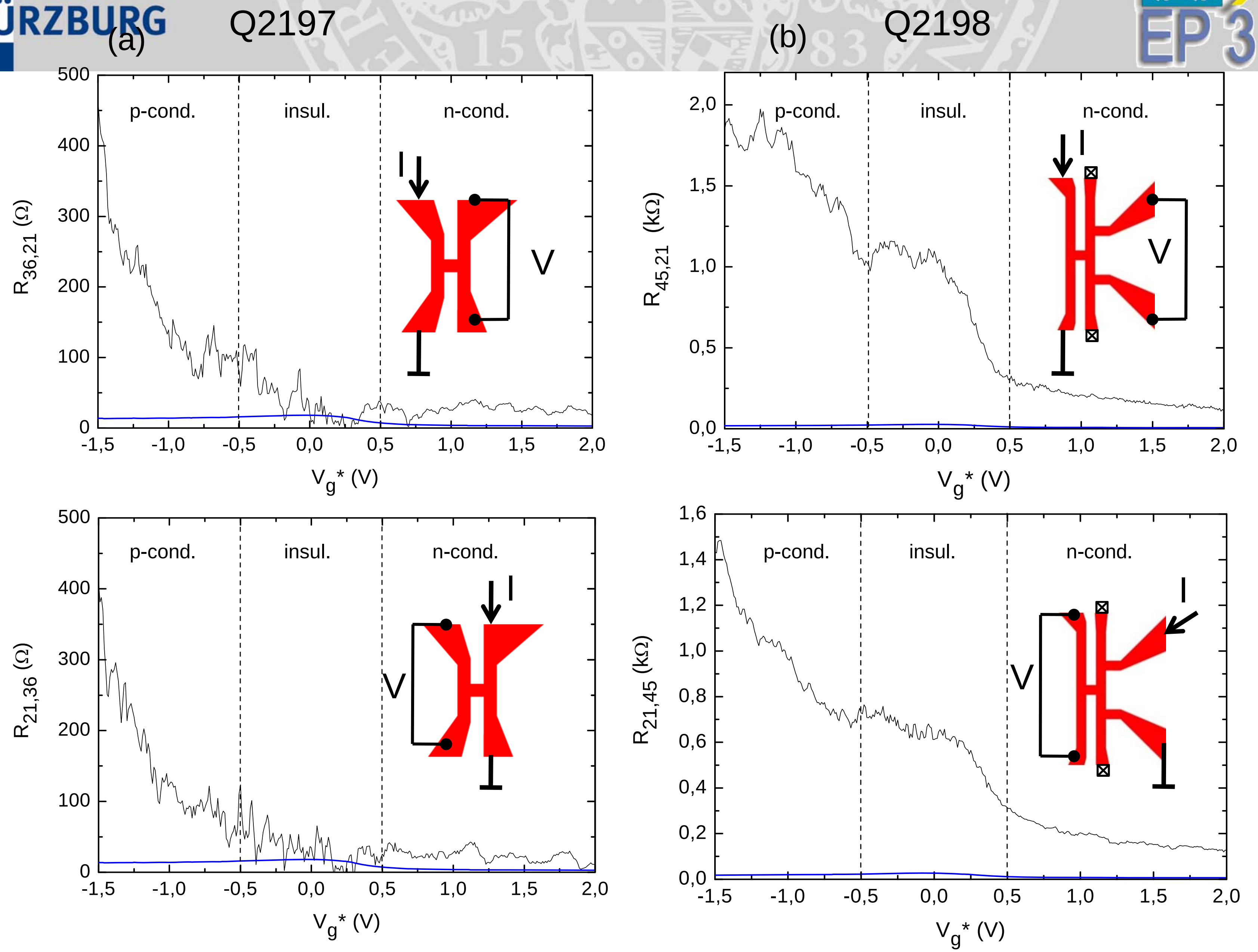




C. Brüne et al., Nature Physics **6**, 448 (2010).



- Suppress non-local QSHE using long leads or narrow wires
- Intrinsic metallic SHE only shows up for holes: larger spin-orbit
- Amplitude in agreement with modeling (E. Hankiewicz, J. Sinova)

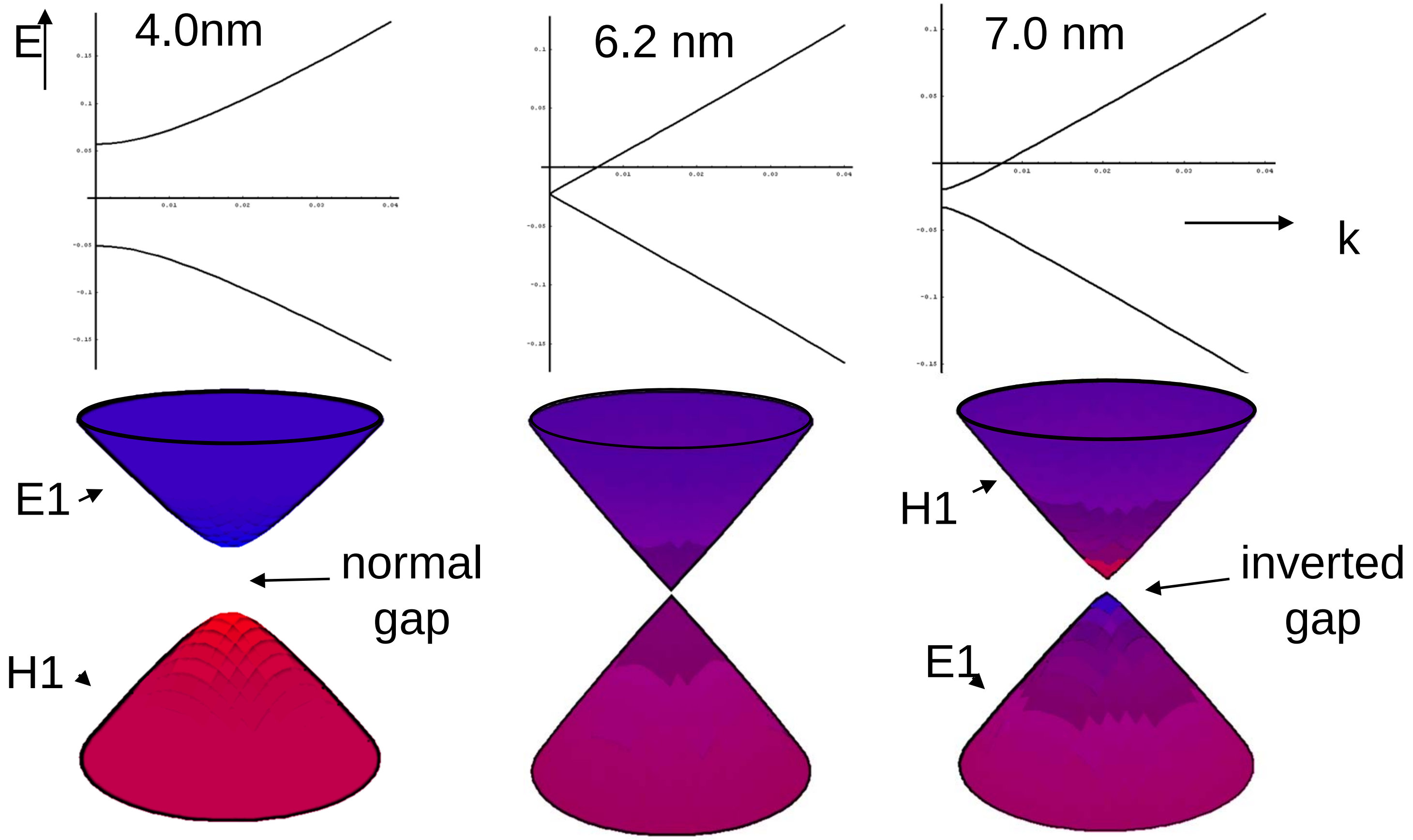


C. Brüne et al., Nature Physics **6**, 448 (2010).

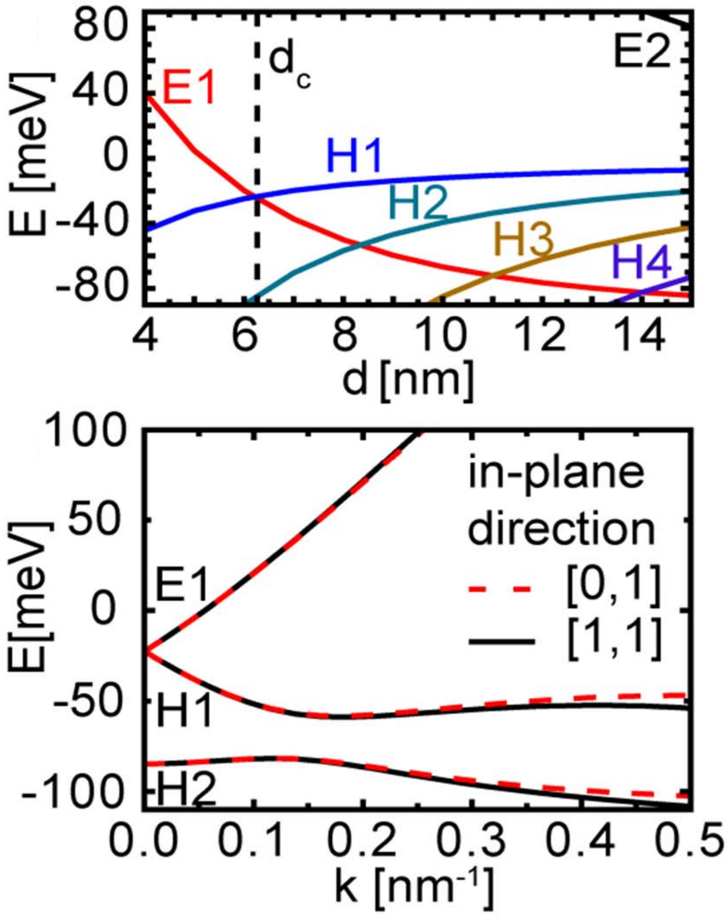
Zero gap HgTe well as a Dirac system

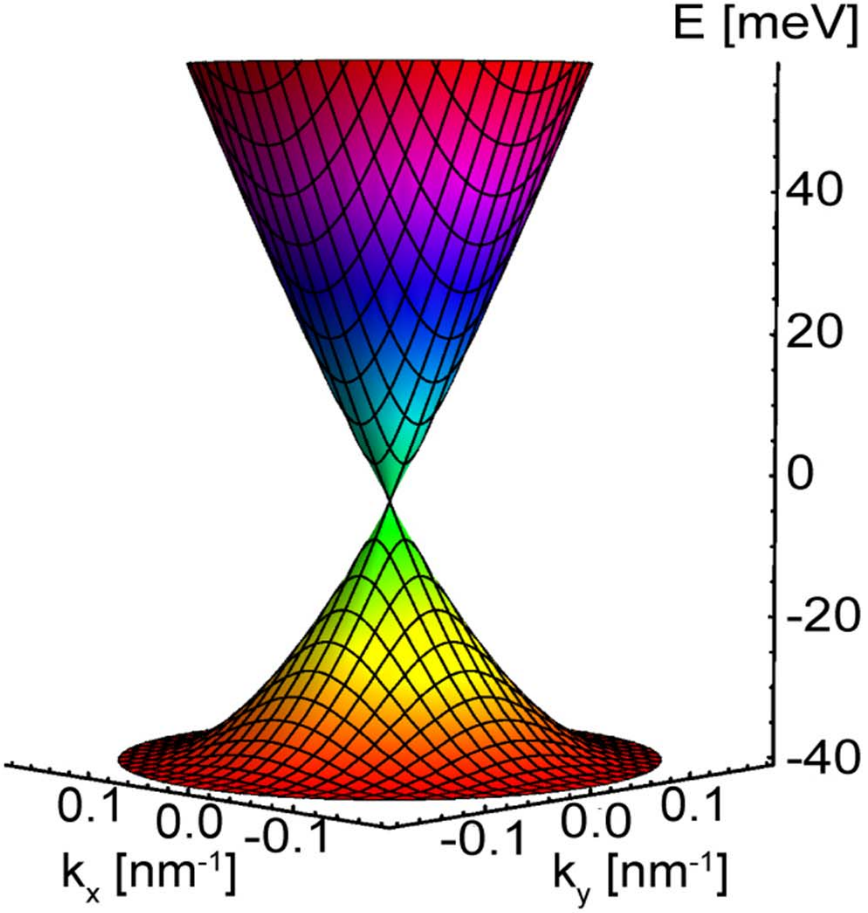
Bandstructure HgTe

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



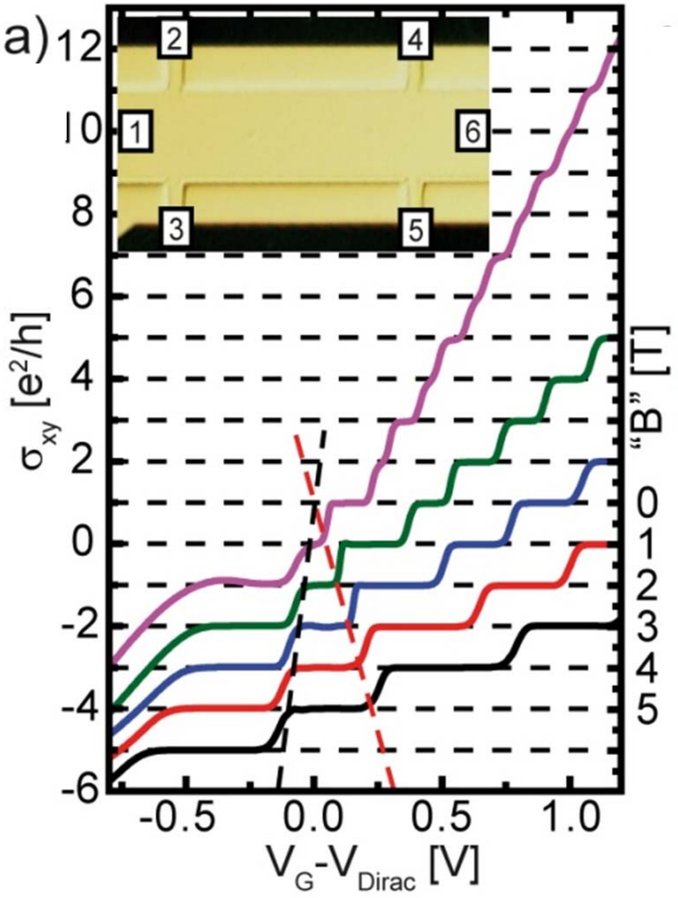
Dispersion at d=d_c is Dirac-like

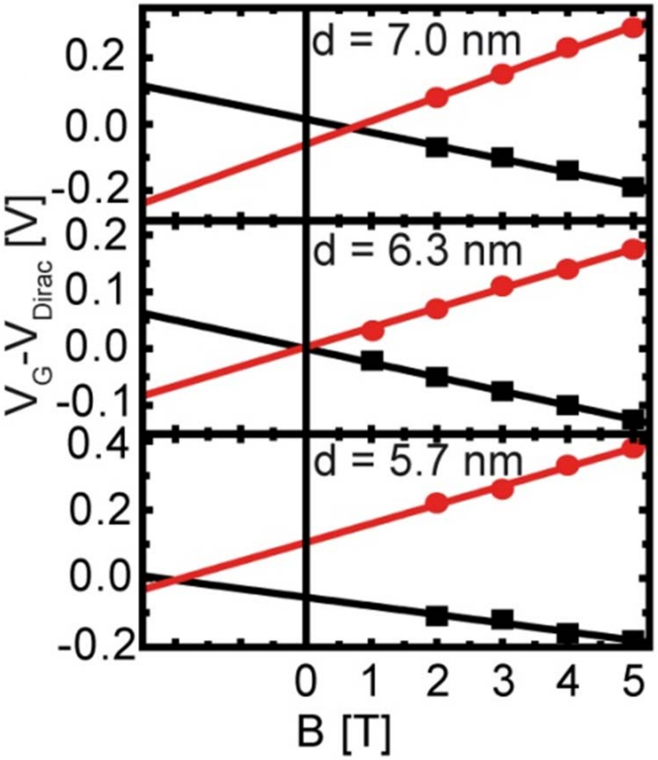




For well thickness d=6.3 nm, the gap closes,
especially the conductionband shows a linear dispersion: **single** Dirac cone

Zero mode dispersion

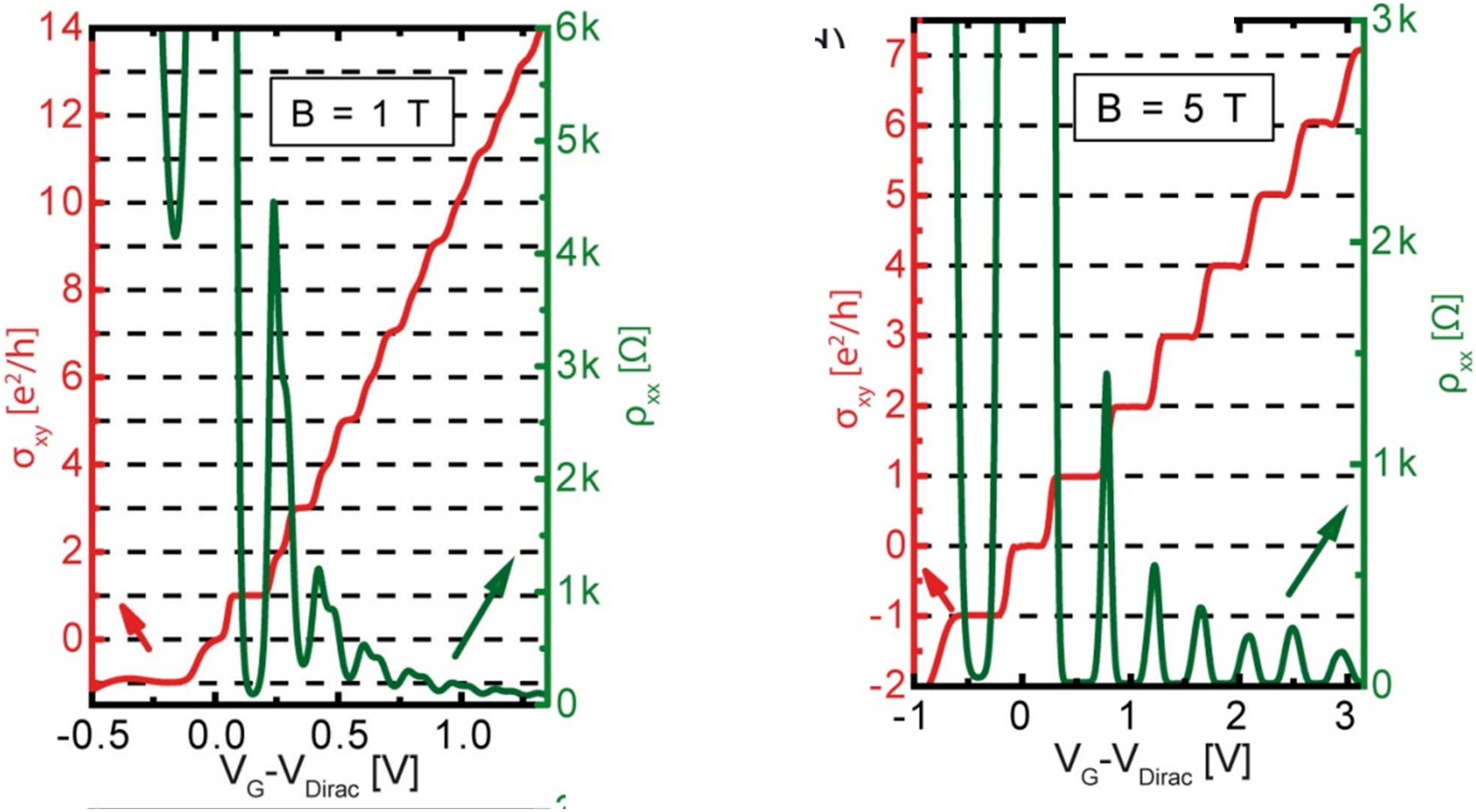




B. Büttner et al., Nature Physics doi:10.1038/nphys1914

Zero mode spin splitting allows to select sample at d_c.

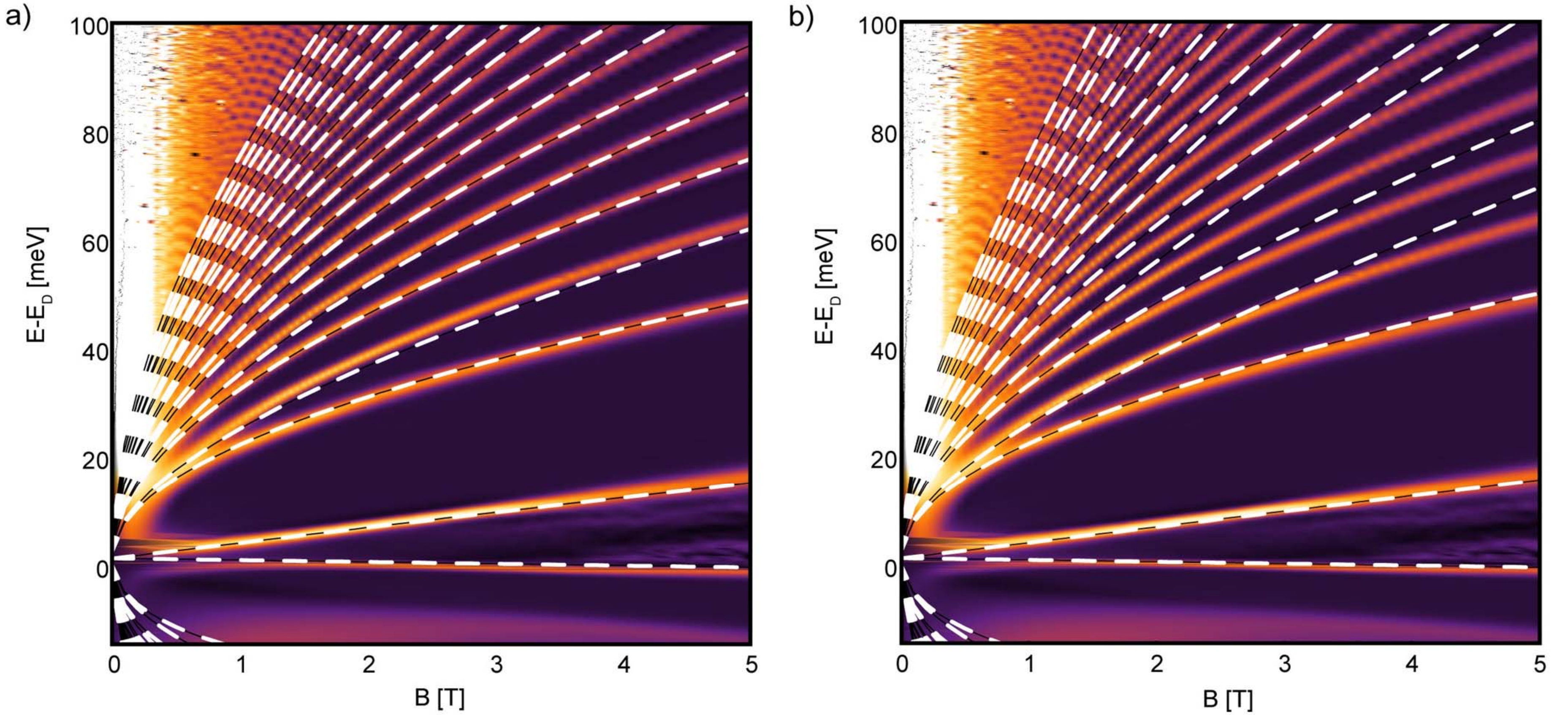
Quantum Hall effect shows Berry phase



B. Büttner et al., Nature Physics doi:10.1038/nphys1914

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.

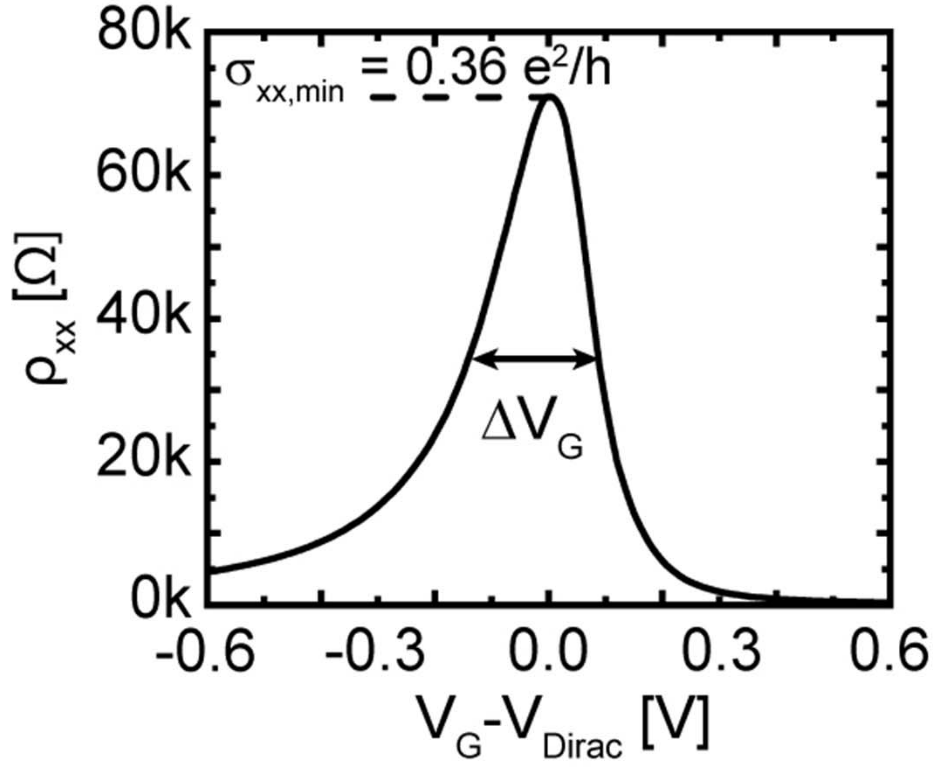
Landau-fan

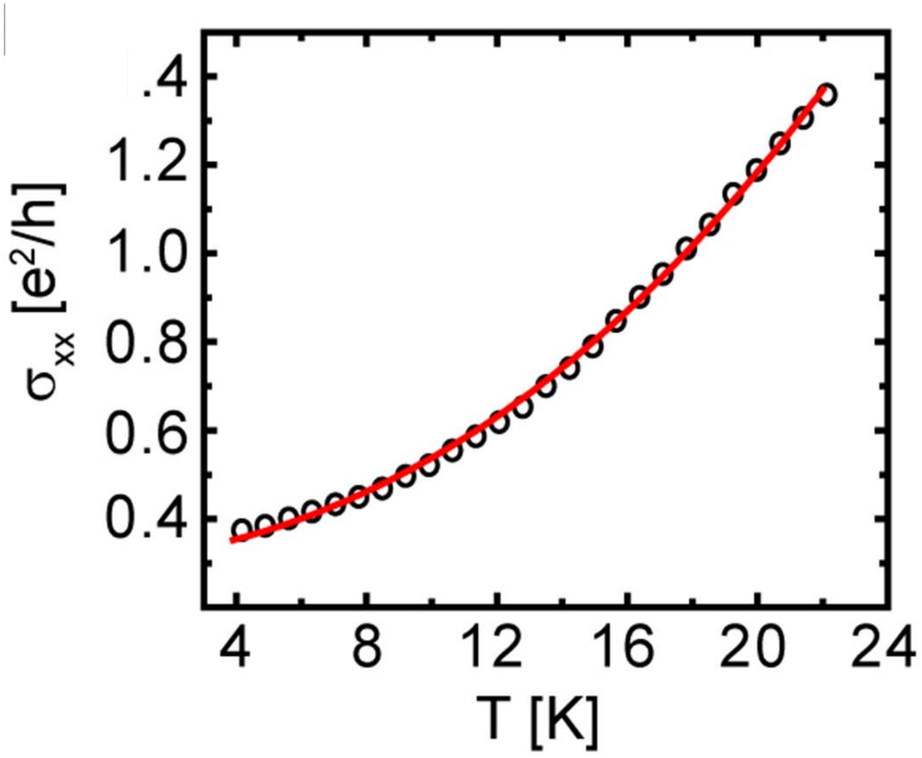


B. Büttner et al., Nature Physics doi:10.1038/nphys1914

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

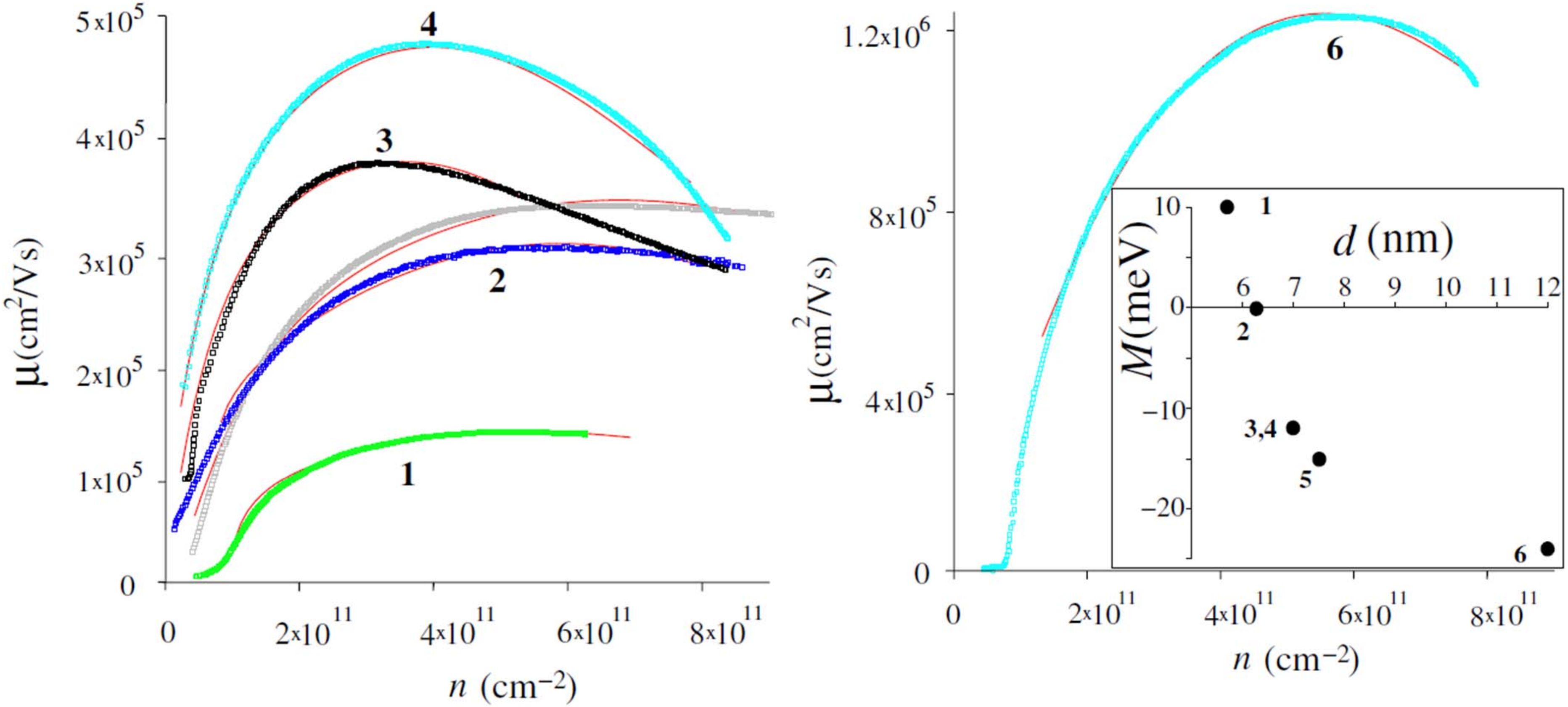
Dirac peak at B=0





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

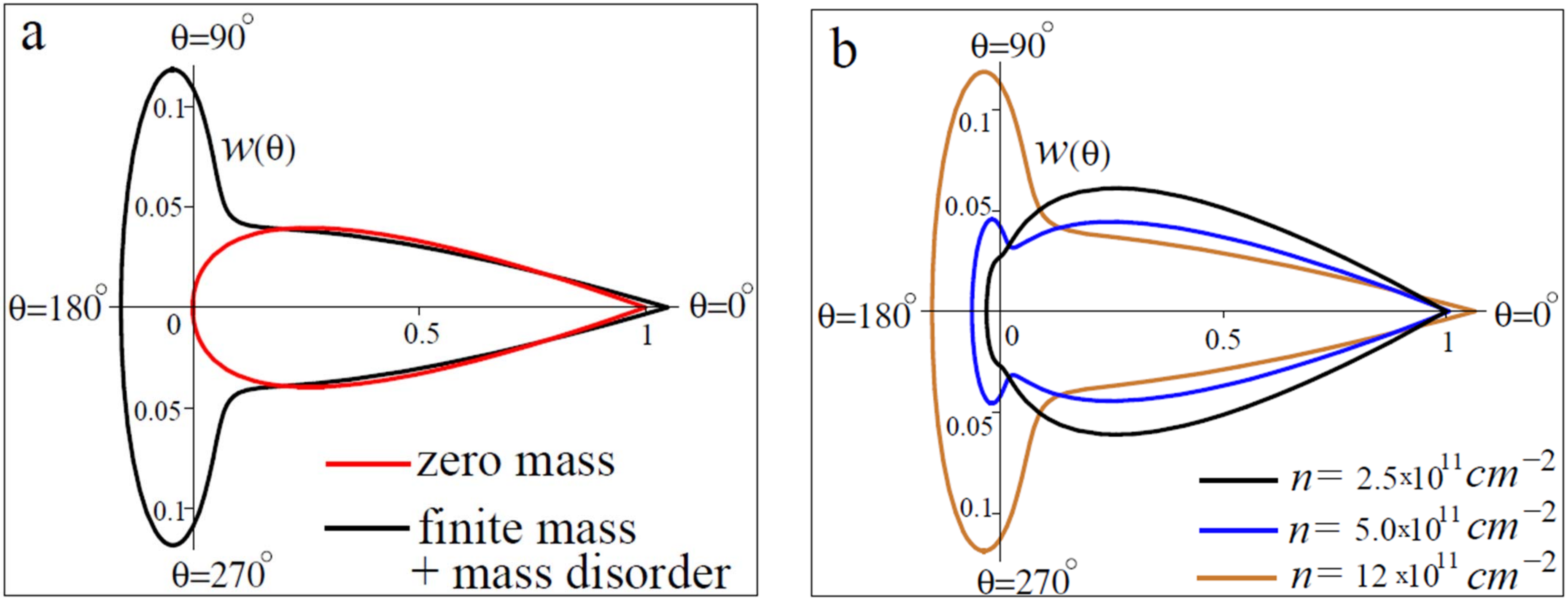
Mobility for finite Dirac mass



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

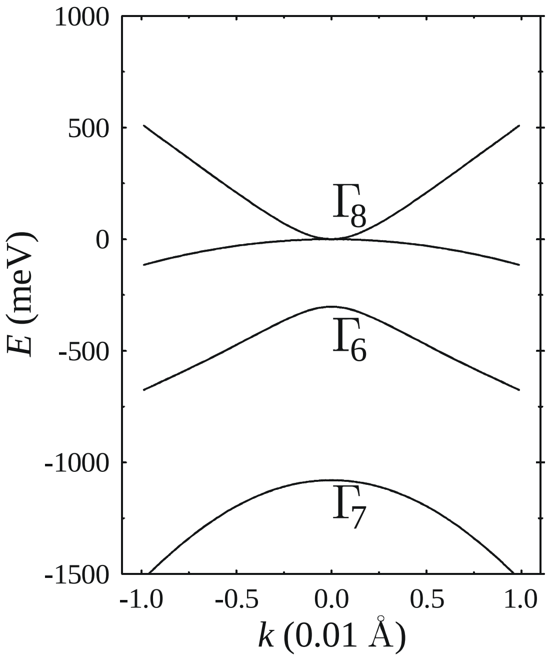


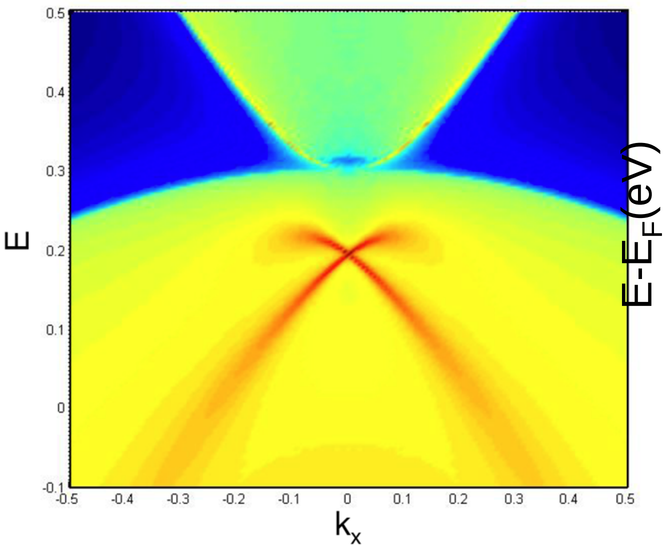
B. Büttner et al., Phys. Rev. Lett. **106**, 076802 (2011).

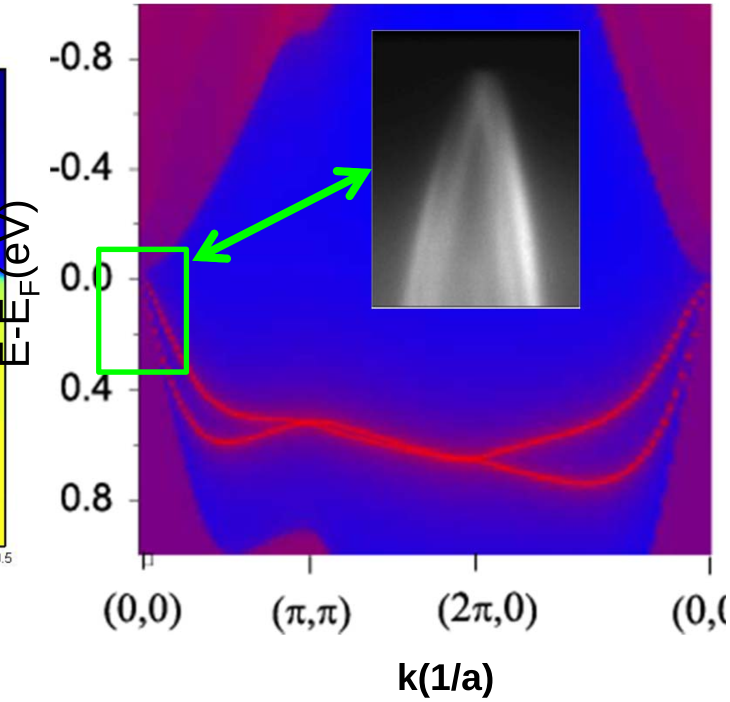
Modeling by Grigory Tkachov and Ewelina Hankiewicz:
Mass and disorder induce backscattering of Dirac fermions.

Dirac Surface States
on
strained bulk HgTe

Bulk HgTe as a 3-D Topological ‚Insulator‘







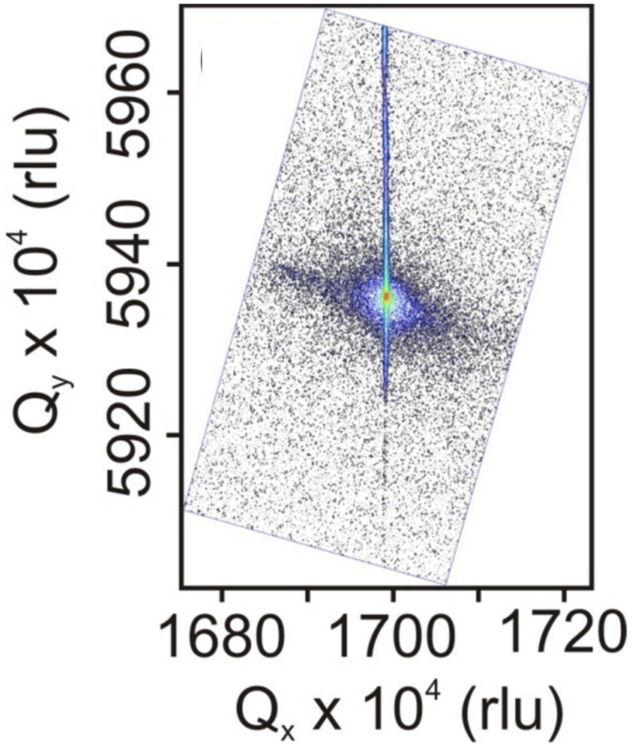
Bulk HgTe is semimetal,

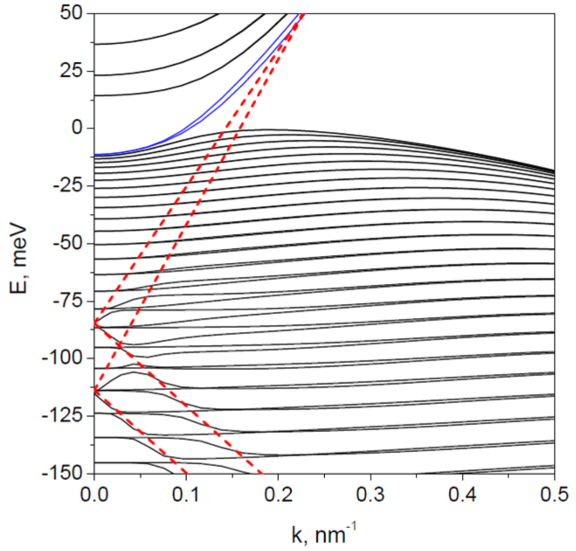
topological surface state overlaps w/ valenceband.

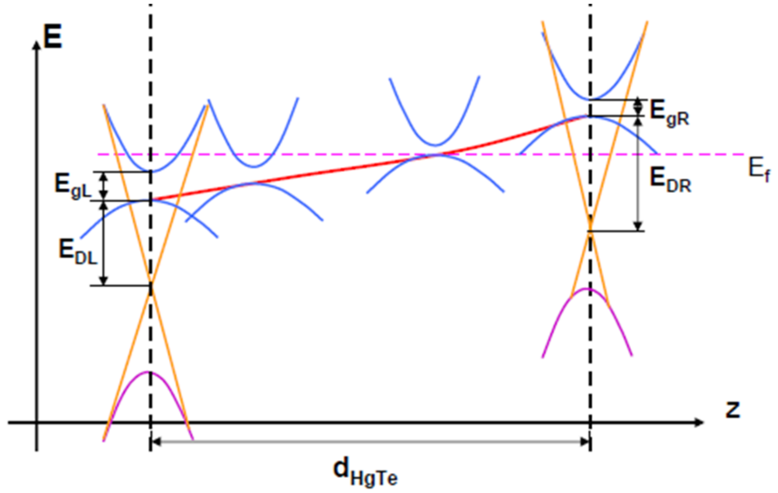
C. Brüne et al., Phys. Rev. Lett. **106**, 126803 (2011).

ARPES:
Yulin Chen, ZX Shen,
Stanford

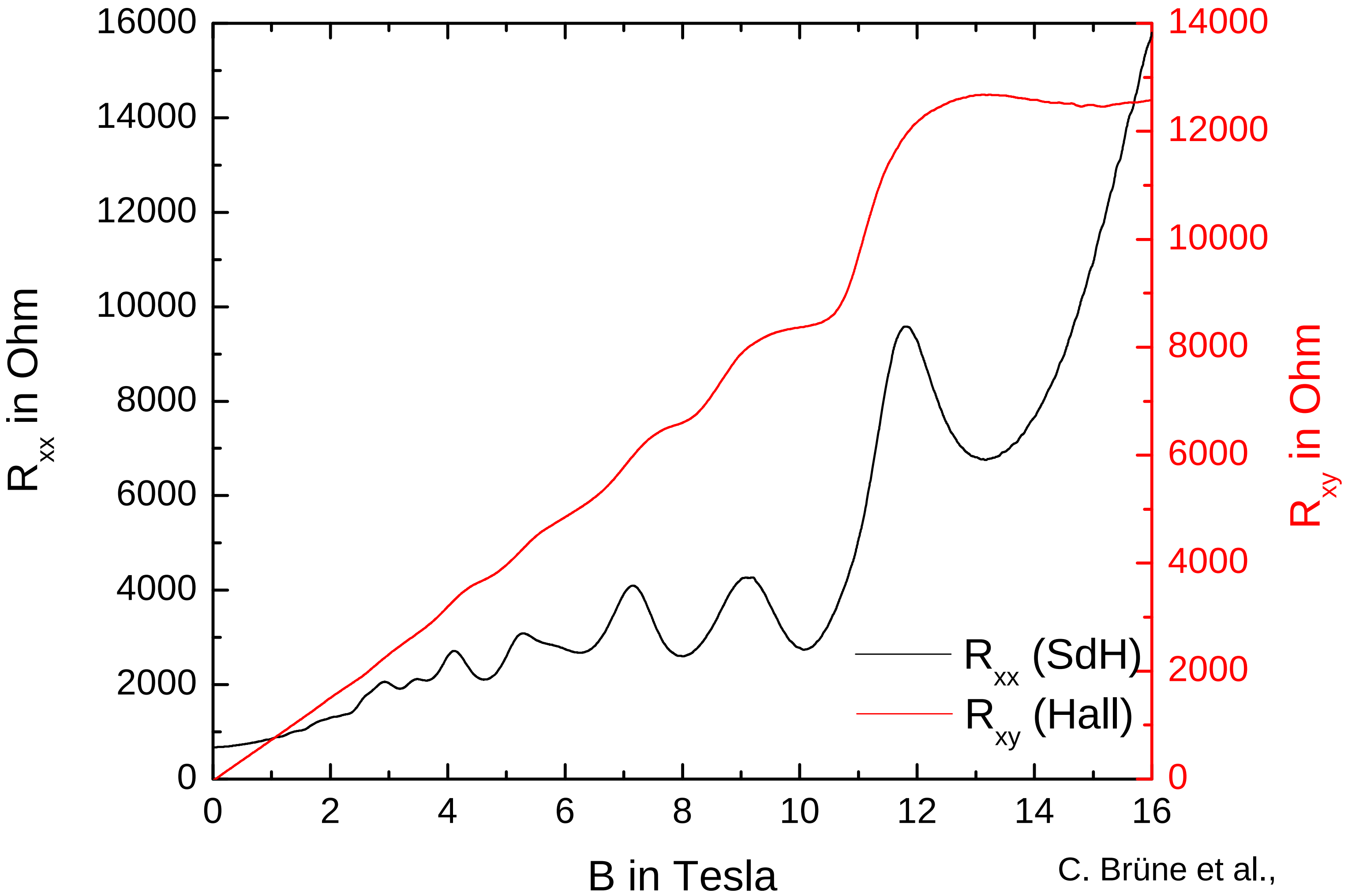
70 nm layer on CdTe substrate: coherent strain opens gap







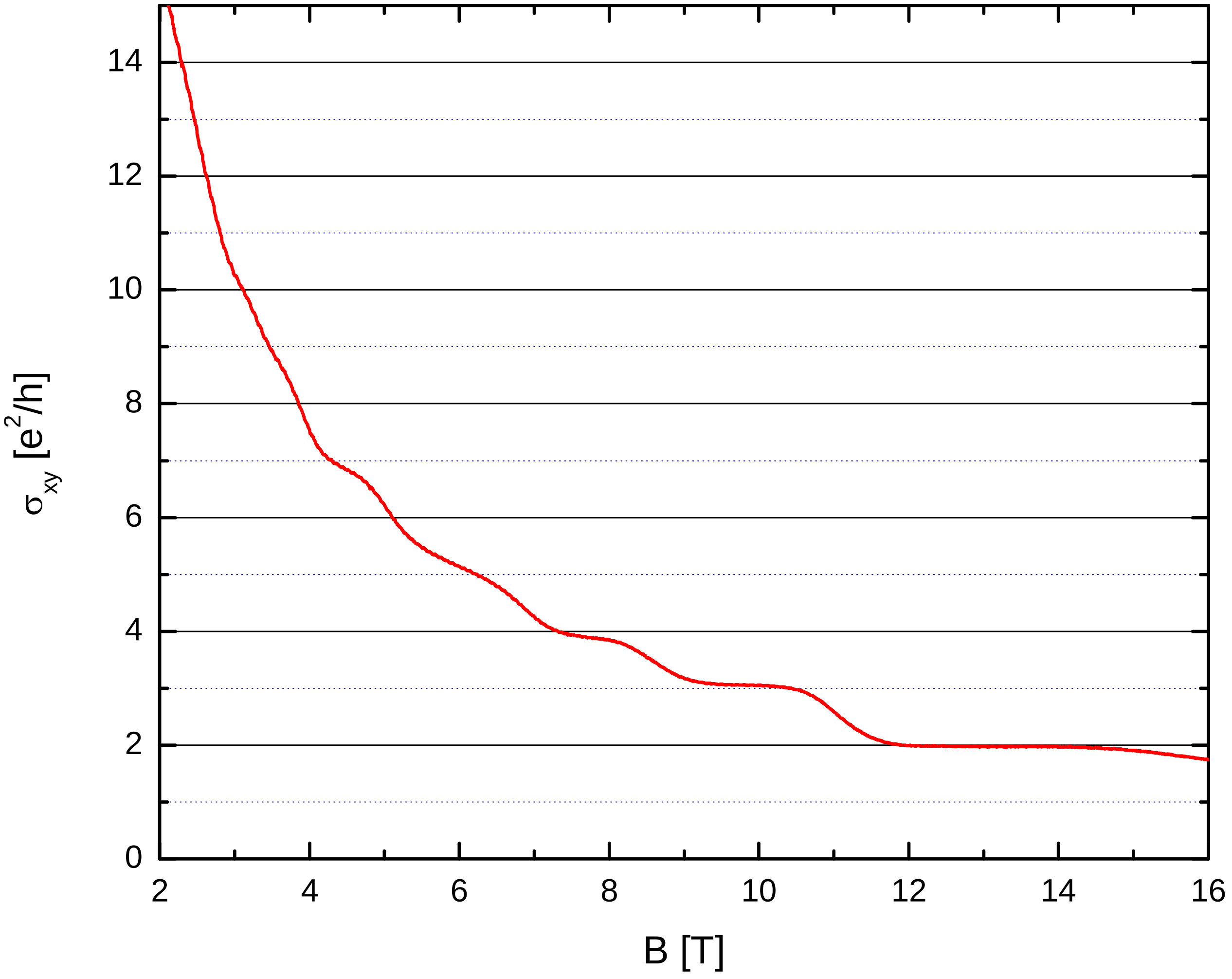
Bulk HgTe as a 3-D Topological ‚Insulator‘



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

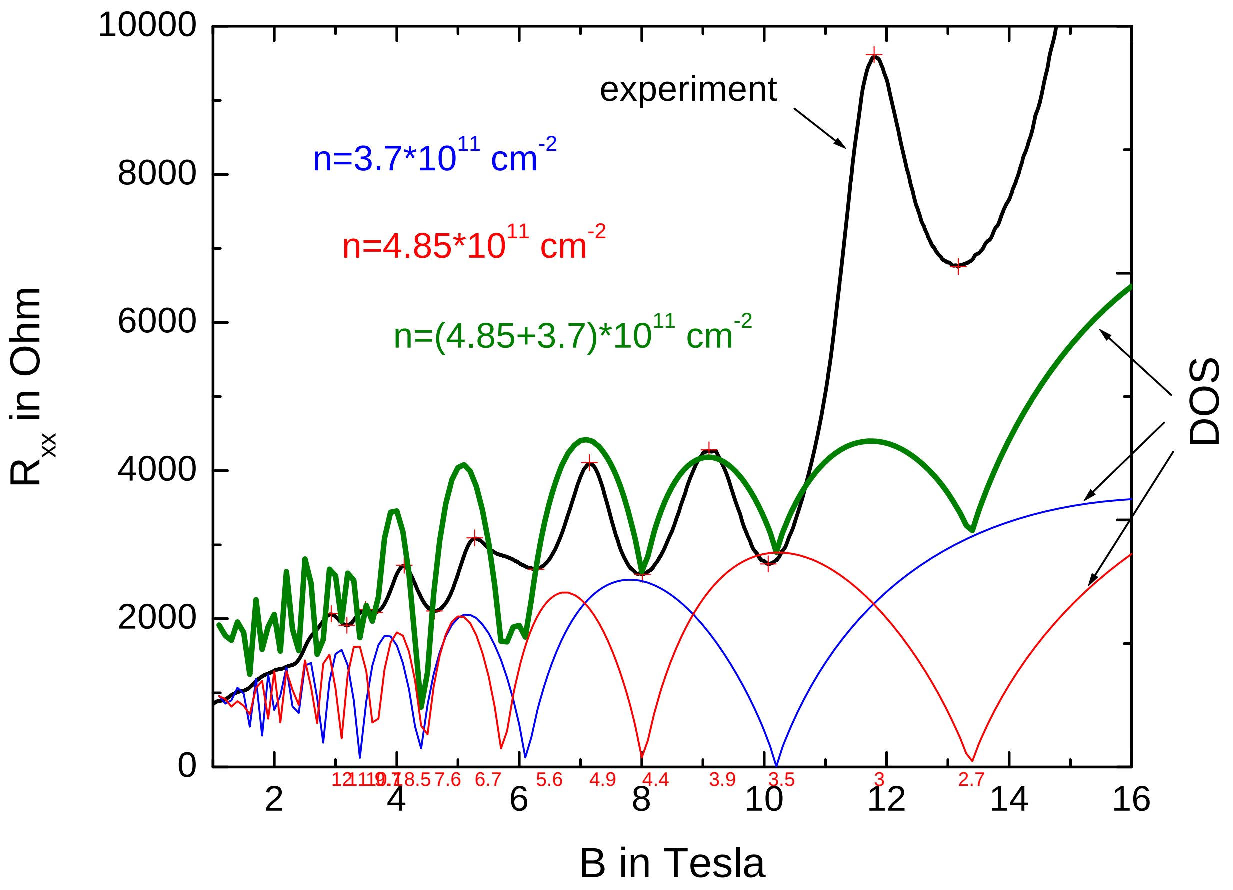
@ 20 mK: bulk conductivity almost frozen out - Surface state mobility ca. 35000 cm^2/Vs

Bulk HgTe as a 3-D Topological ‚Insulator'



@ 20 mK: same data, plotted as conductivity

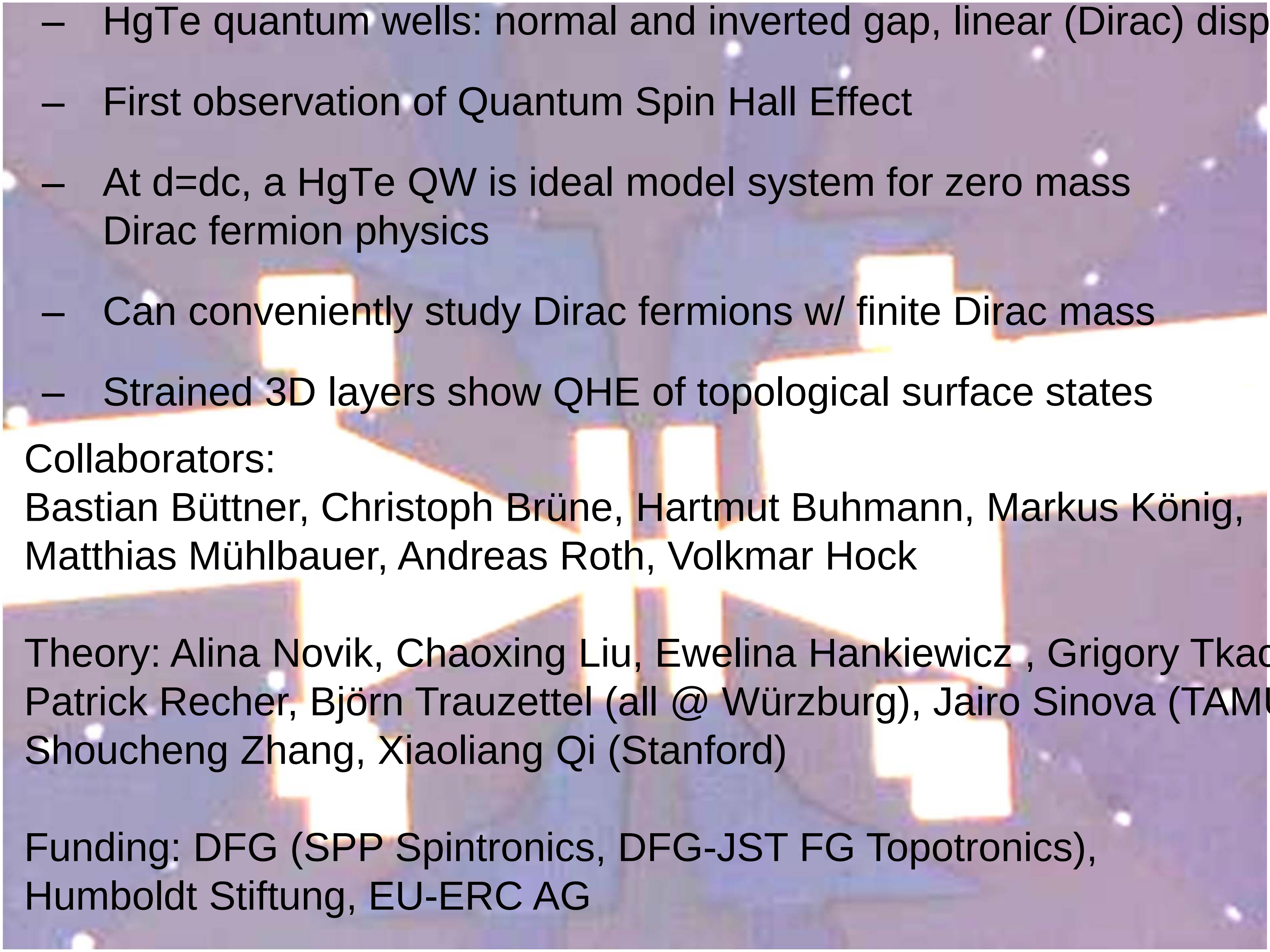
3D HgTe-calculations



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: Alina 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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