

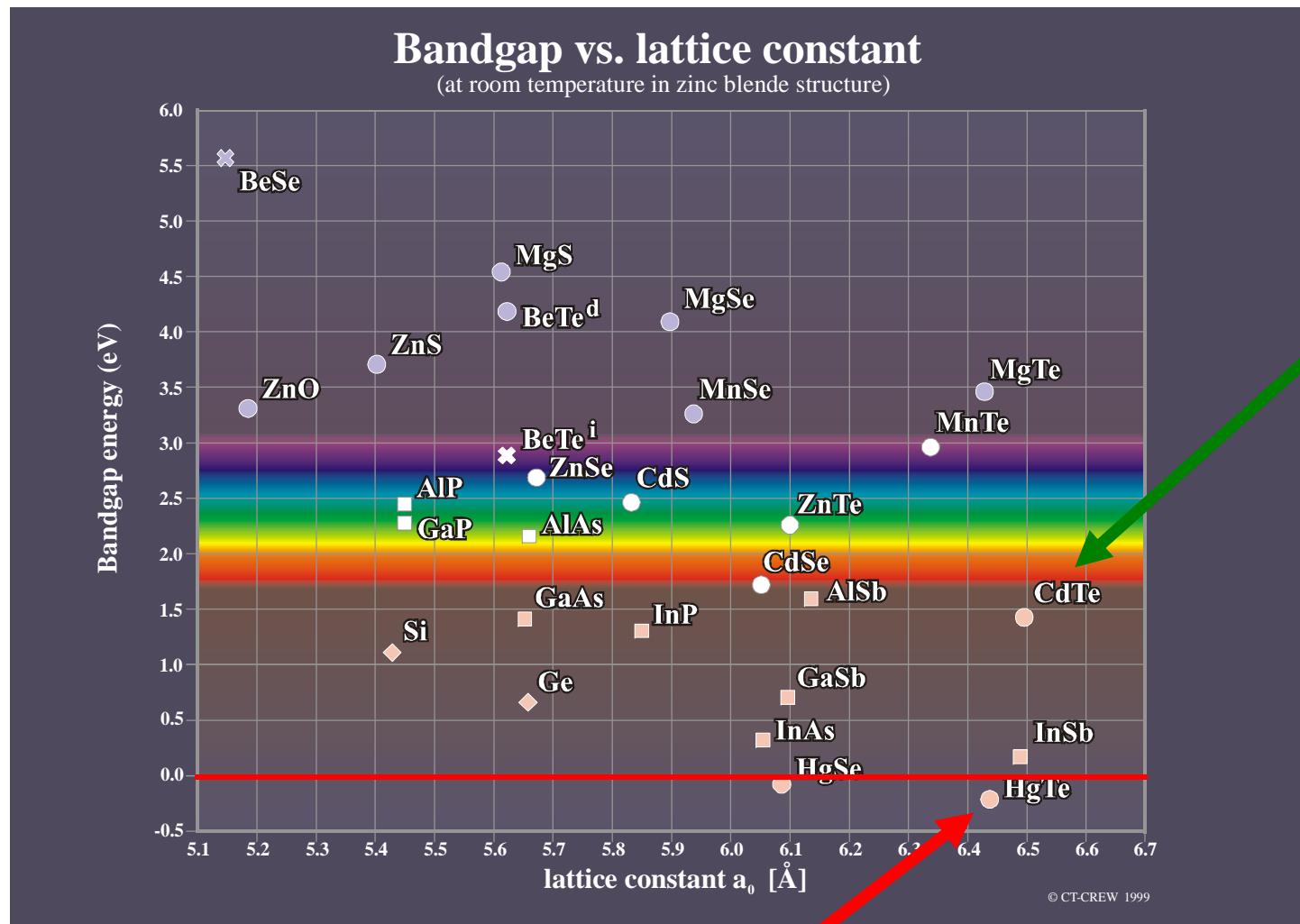
Dirac Fermions in HgTe

Laurens W. Molenkamp

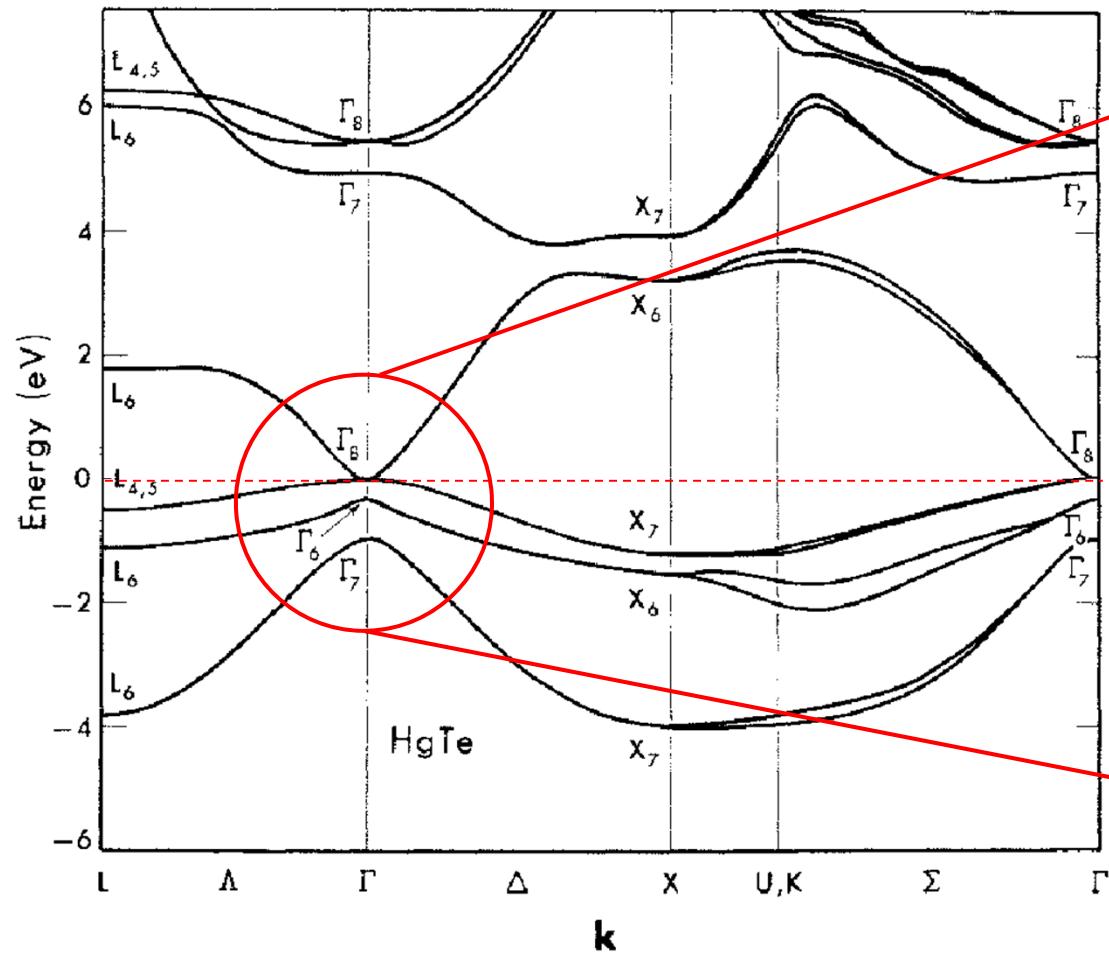
Physikalisches Institut, EP3
Universität Würzburg

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

MBE-Growth

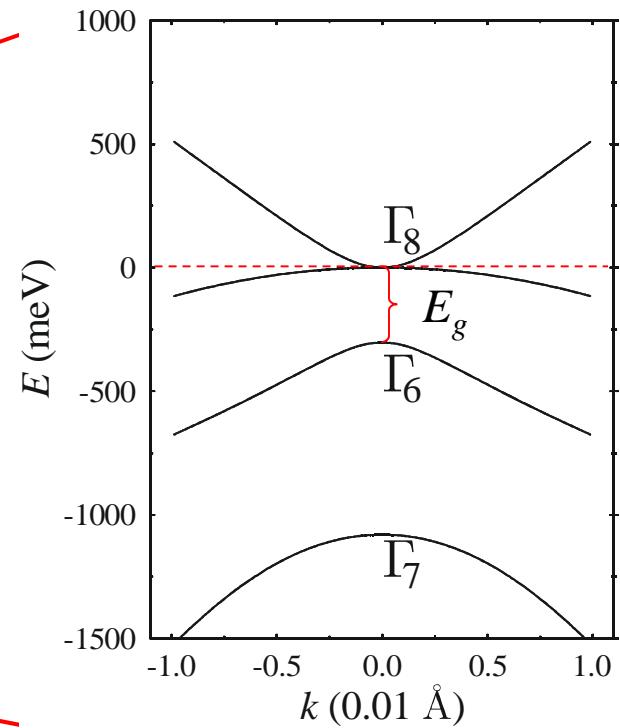


band structure



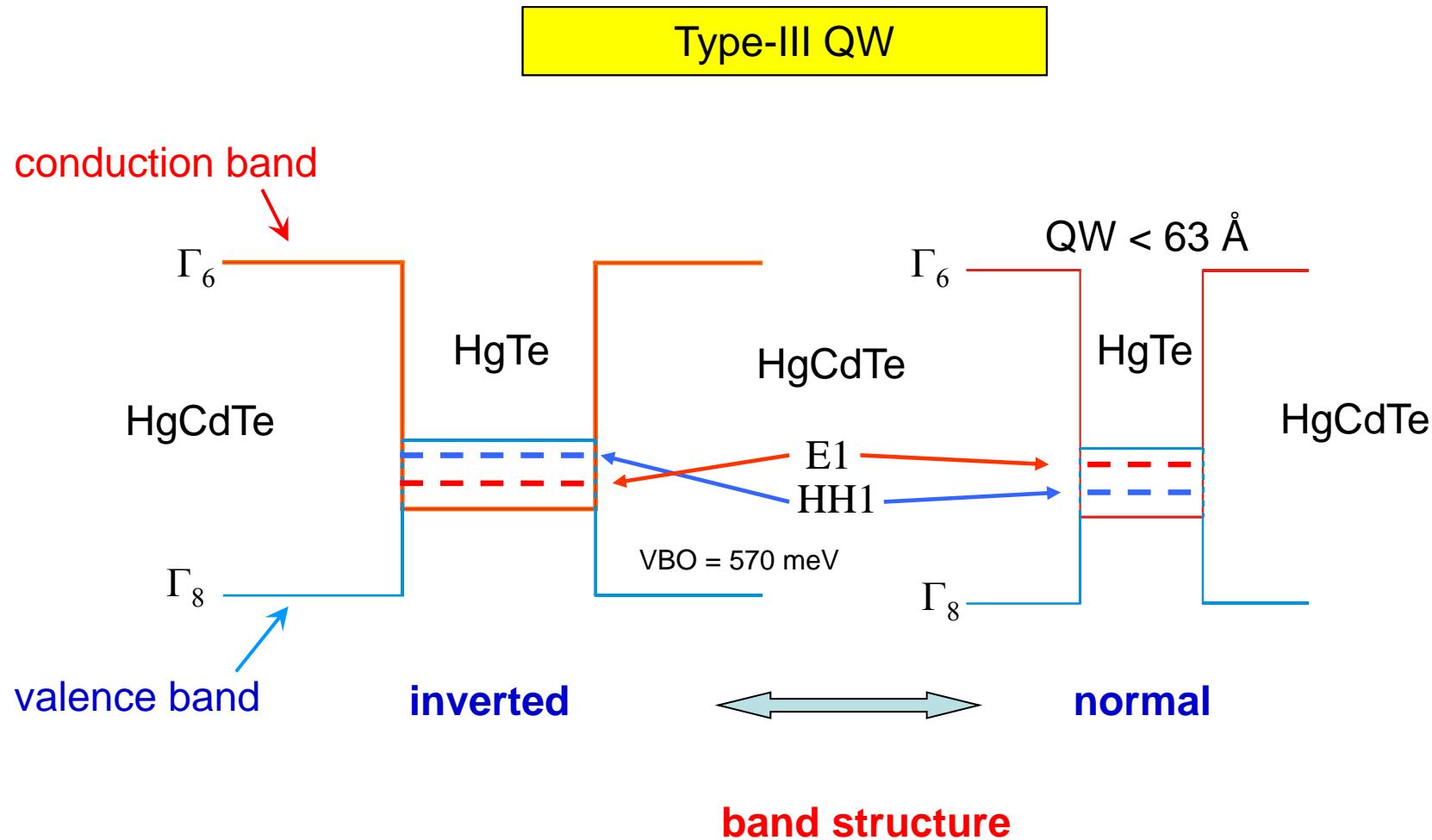
D.J. Chadi et al. PRB, 3058 (1972)

semi-metal or semiconductor



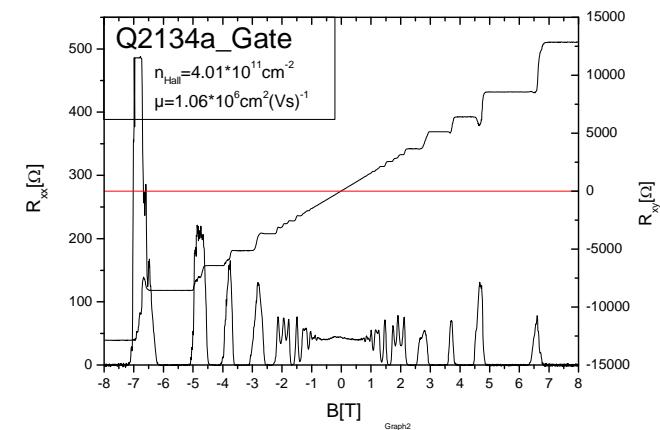
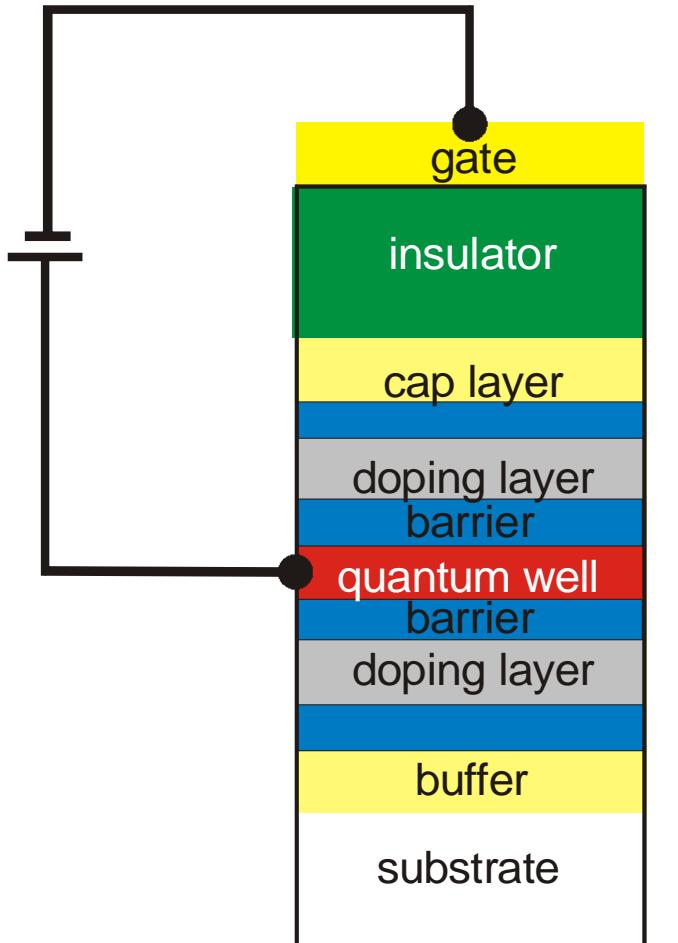
fundamental energy gap

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

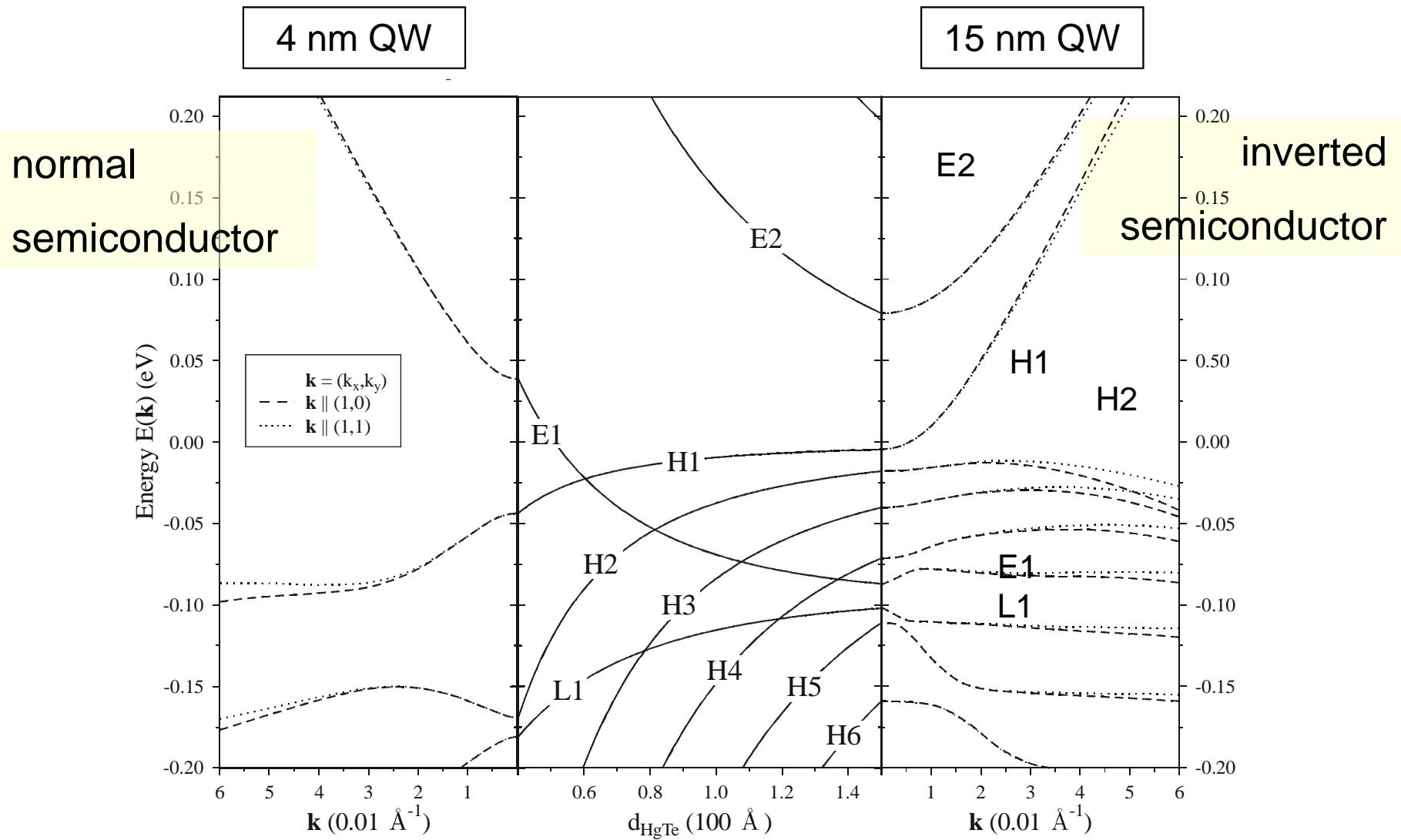


Carrier densities: $n_s = 1 \times 10^{11} \dots 2 \times 10^{12} \text{ cm}^{-2}$

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

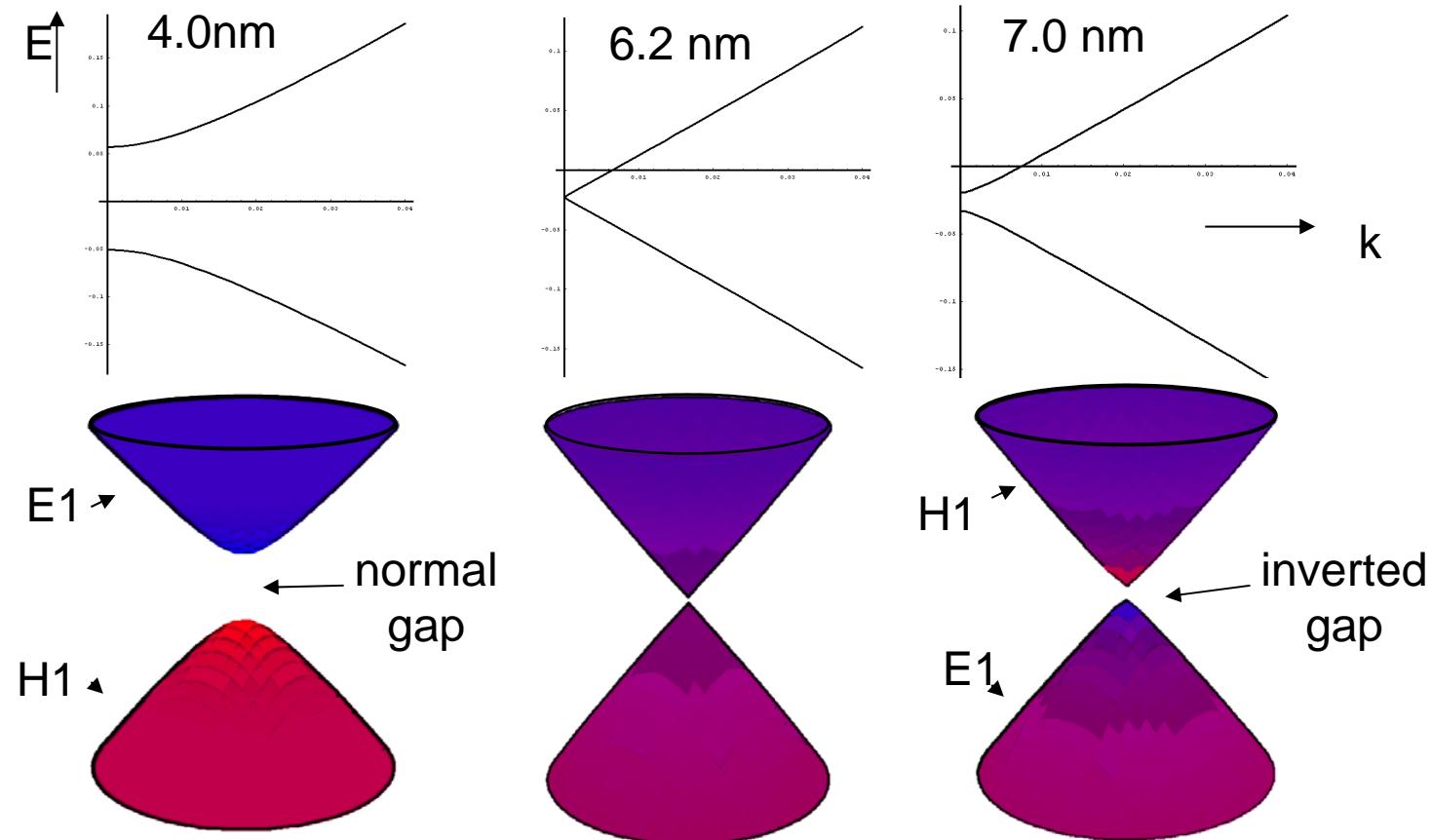


symmetric or asymmetric
doping



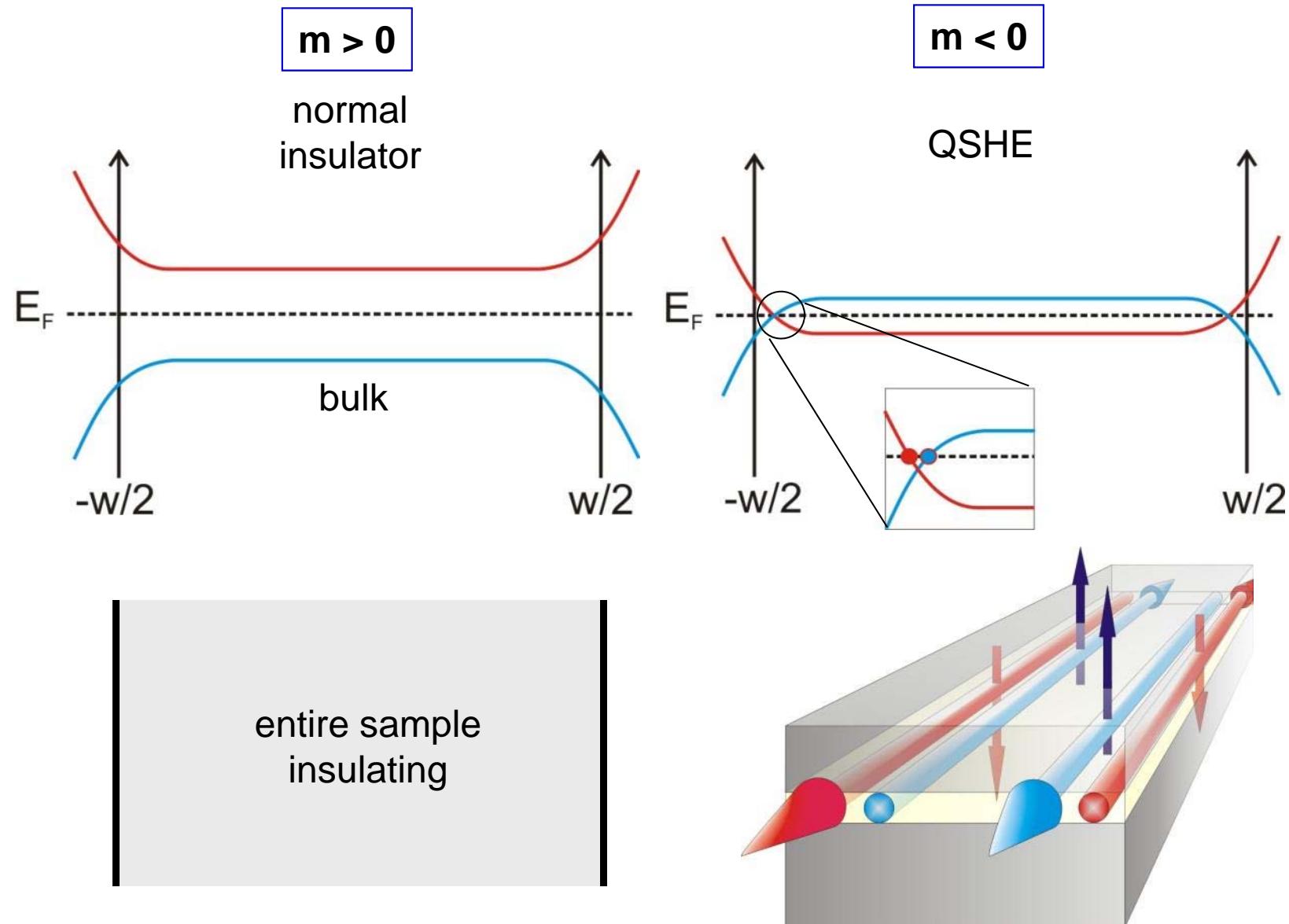
Bandstructure HgTe

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

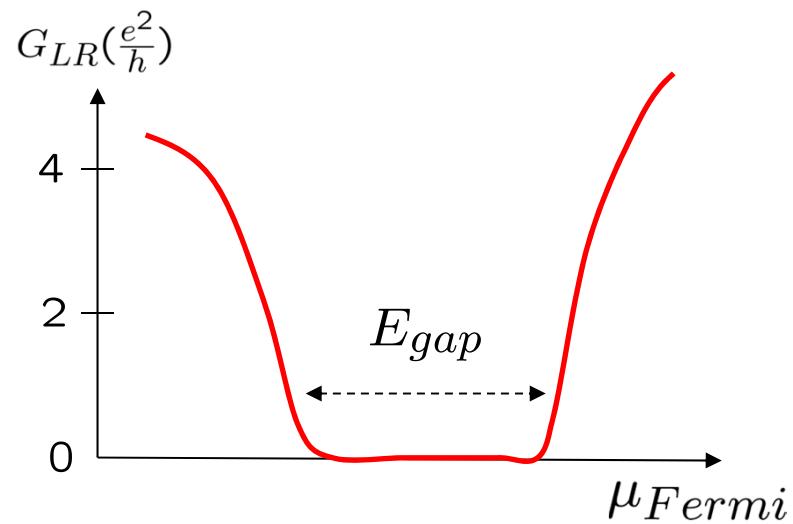




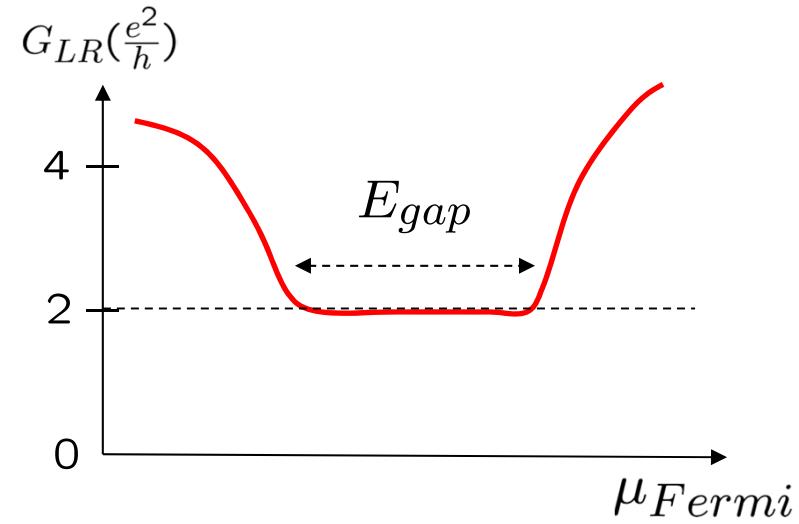
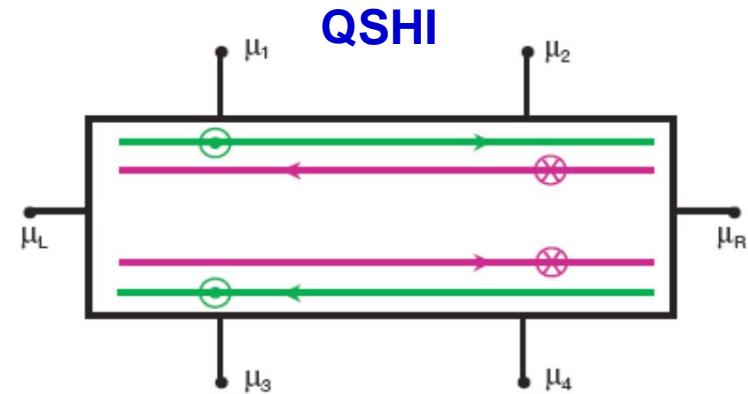
Quantum Spin Hall Effect



normal insulator state

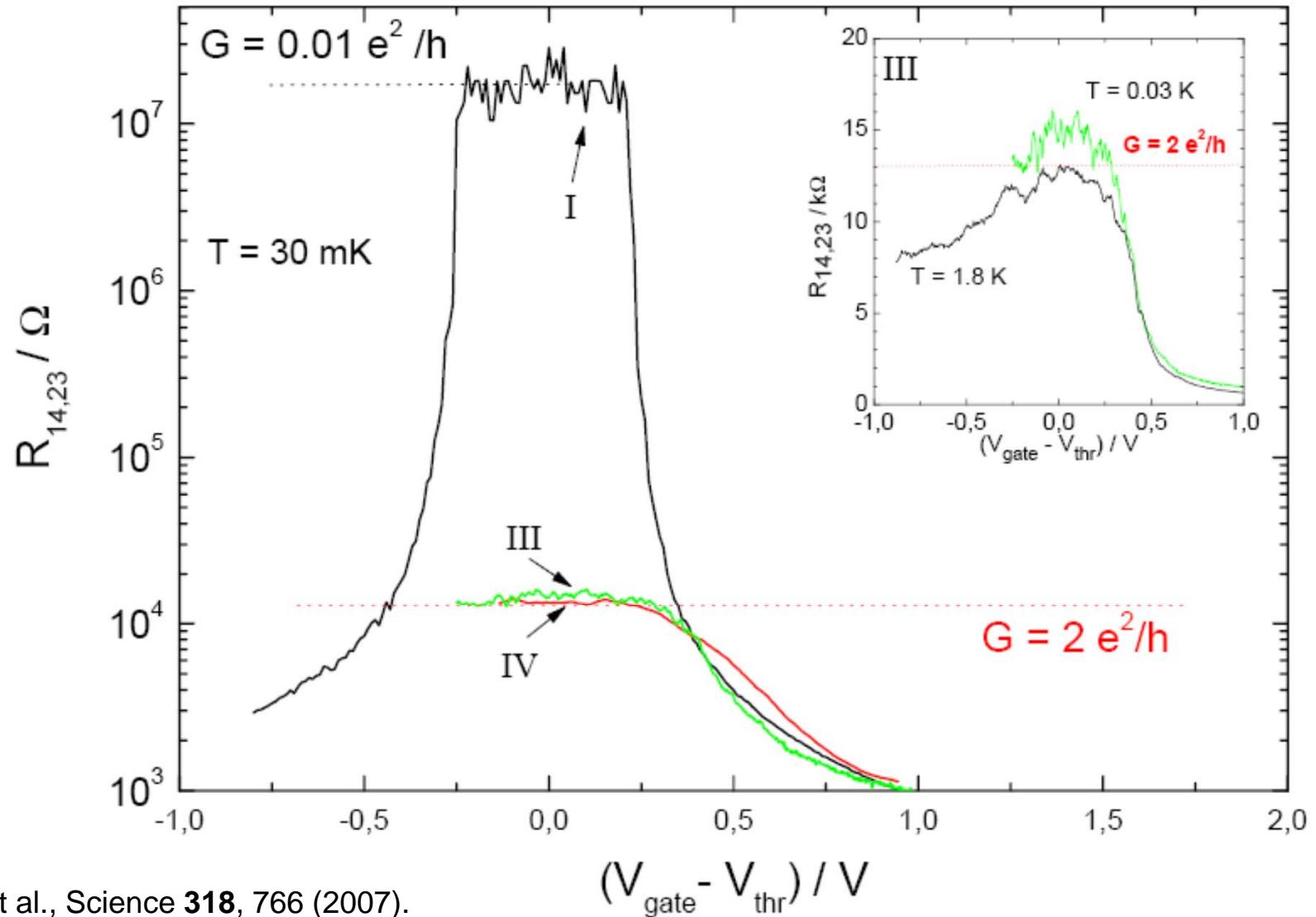


$d < d_c$, normal regime

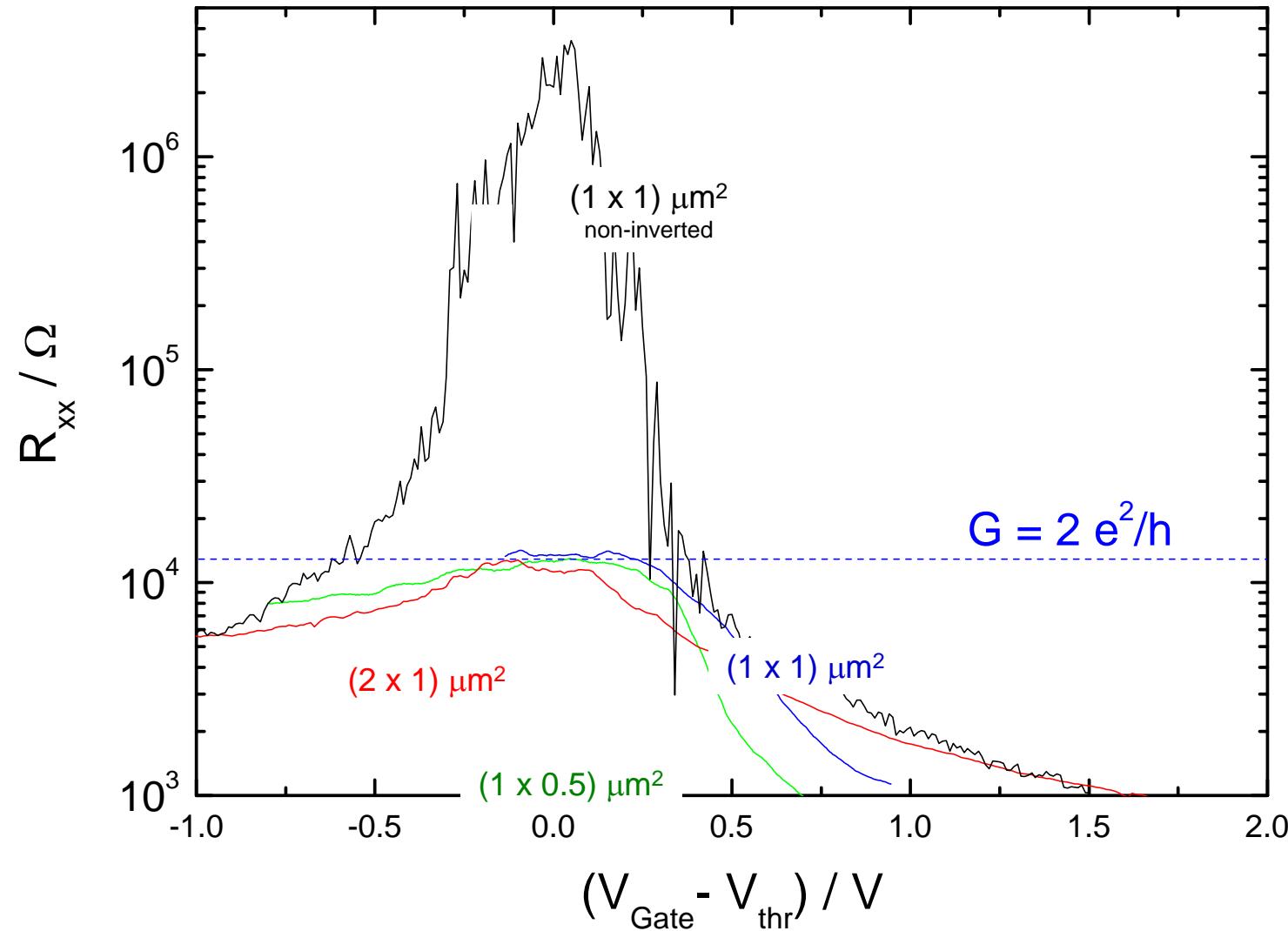


$d > d_c$, inverted regime

Observation of QSHI state

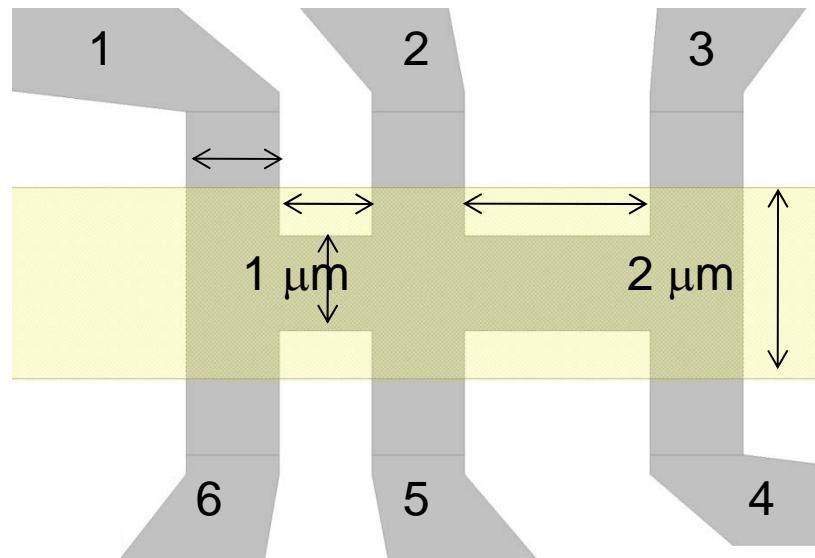


Observation of QSH Effect

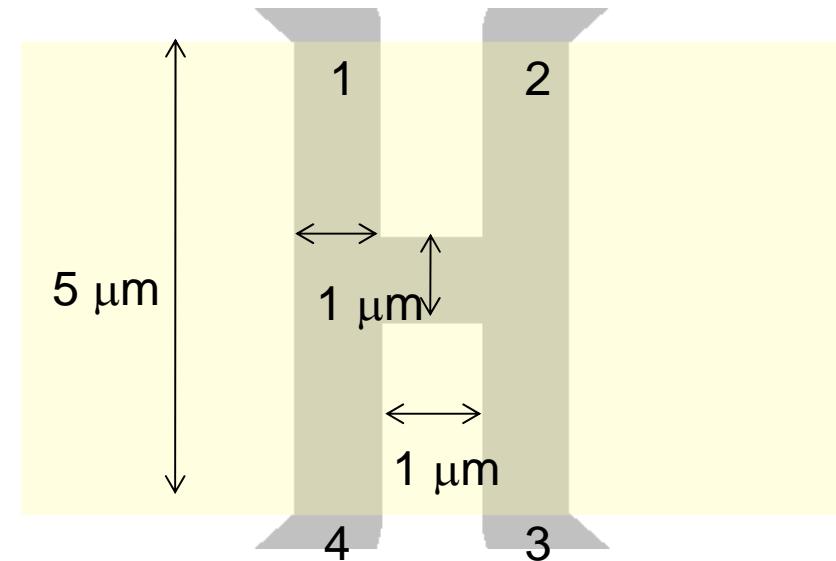


Verify helical edge state transport

(a)

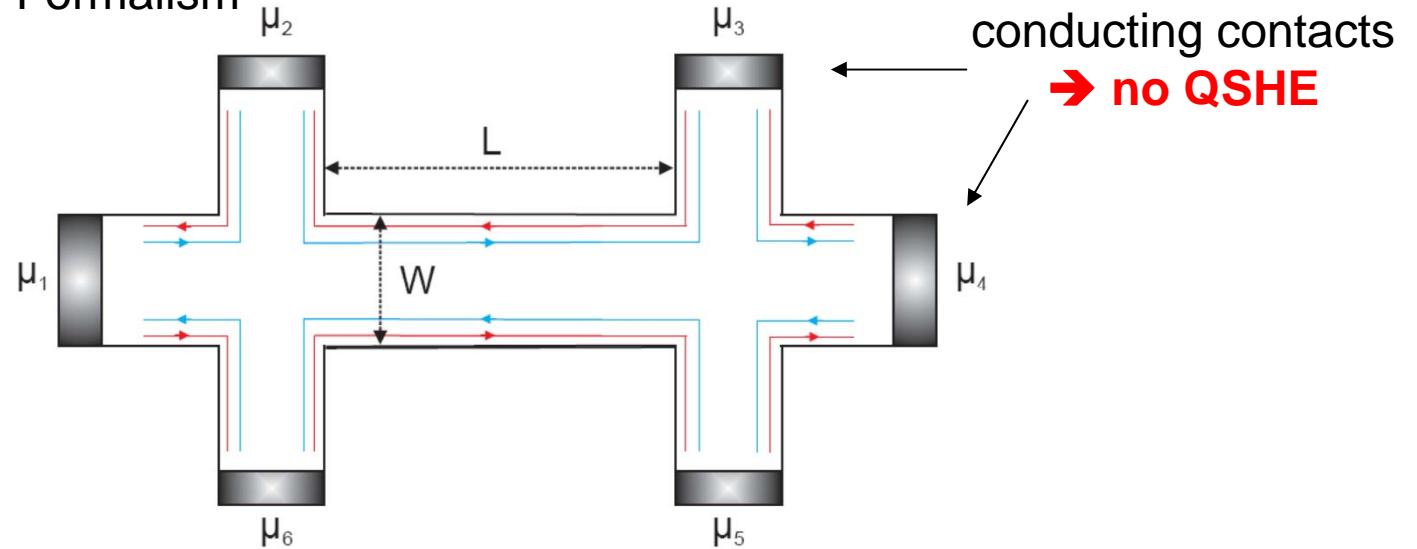


(b)



Multiterminal /Non-local transport samples

Landauer-Büttiker Formalism



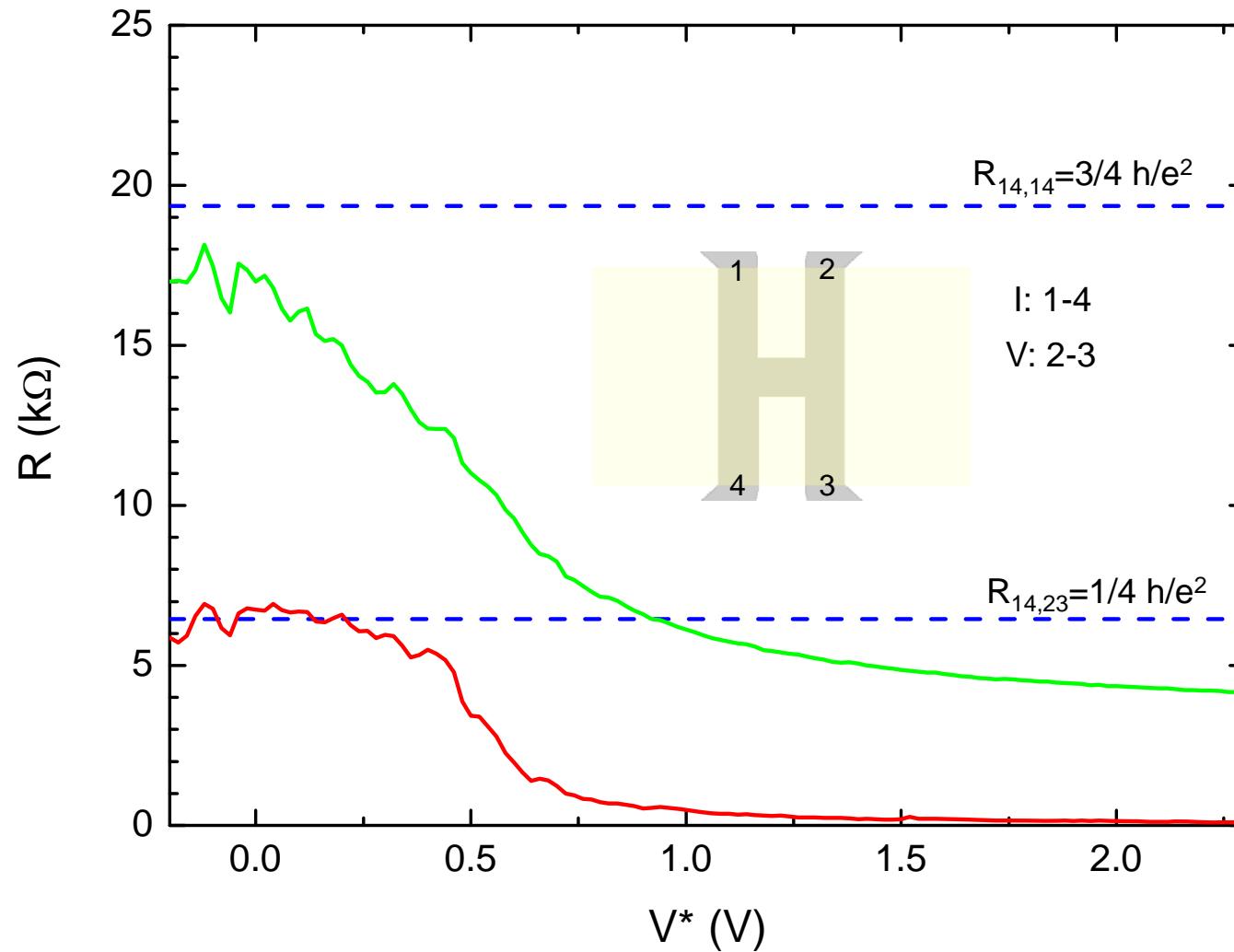
$$T = \begin{pmatrix} -2 & 1 & 0 & 0 & 0 & 1 \\ 1 & -2 & 1 & 0 & 0 & 0 \\ 0 & 1 & -2 & 1 & 0 & 0 \\ 0 & 0 & 1 & -2 & 1 & 0 \\ 0 & 0 & 0 & 1 & -2 & 1 \\ 1 & 0 & 0 & 0 & 1 & -2 \end{pmatrix} \Rightarrow \begin{cases} G_{2t} = \frac{I_{14}}{\mu_4 - \mu_1} = \frac{2}{3} \frac{e^2}{h} \\ G_{4t} = \frac{I_{14}}{\mu_3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

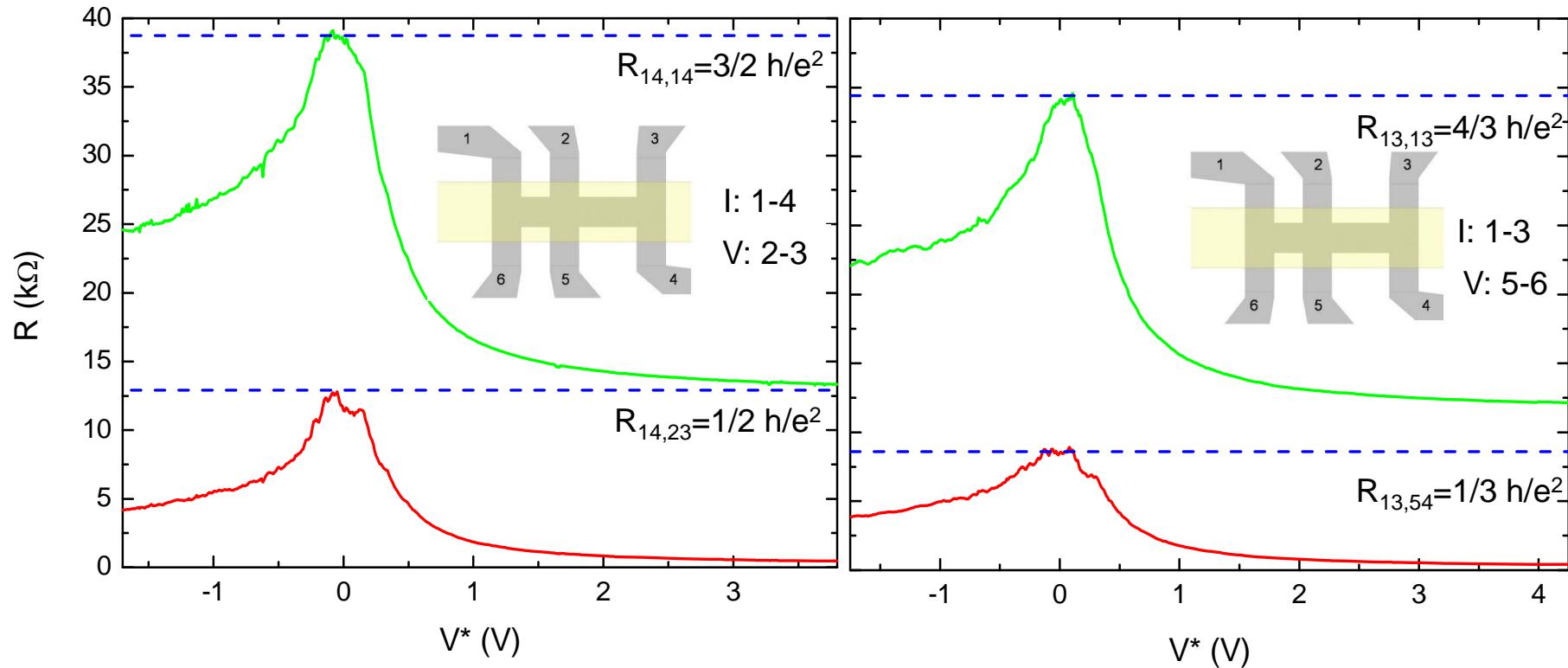
generally

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

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

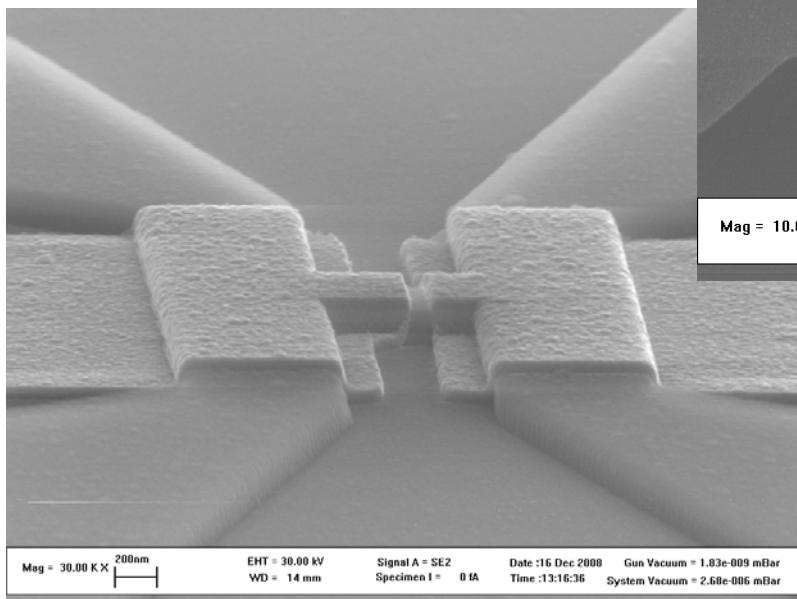
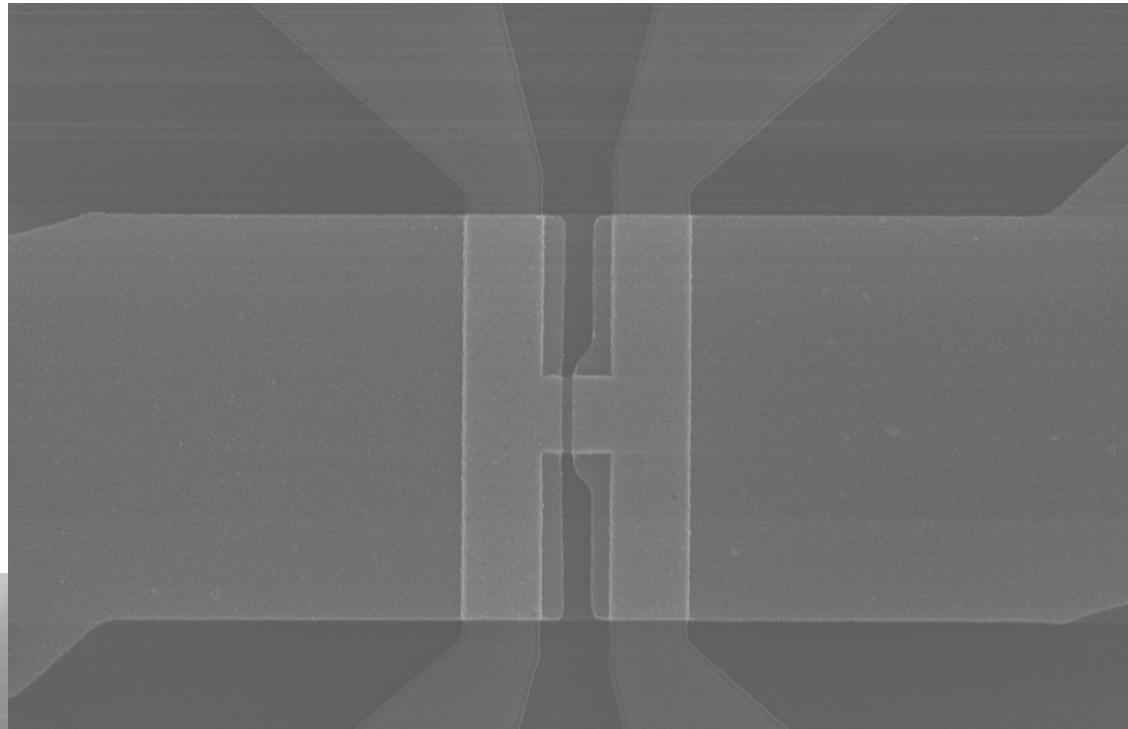
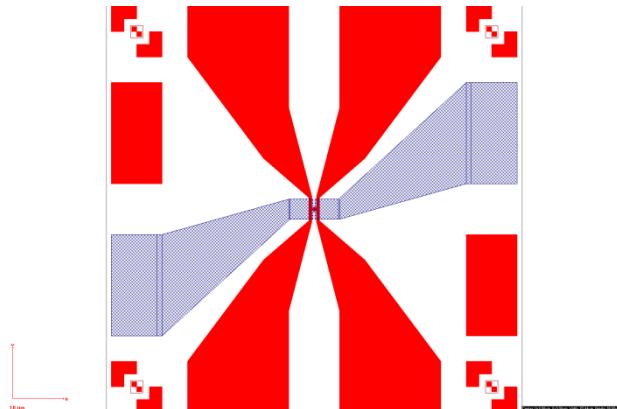
$\left. \frac{R_{2t}}{R_{4t}} \right|_{\exp} \approx 3$





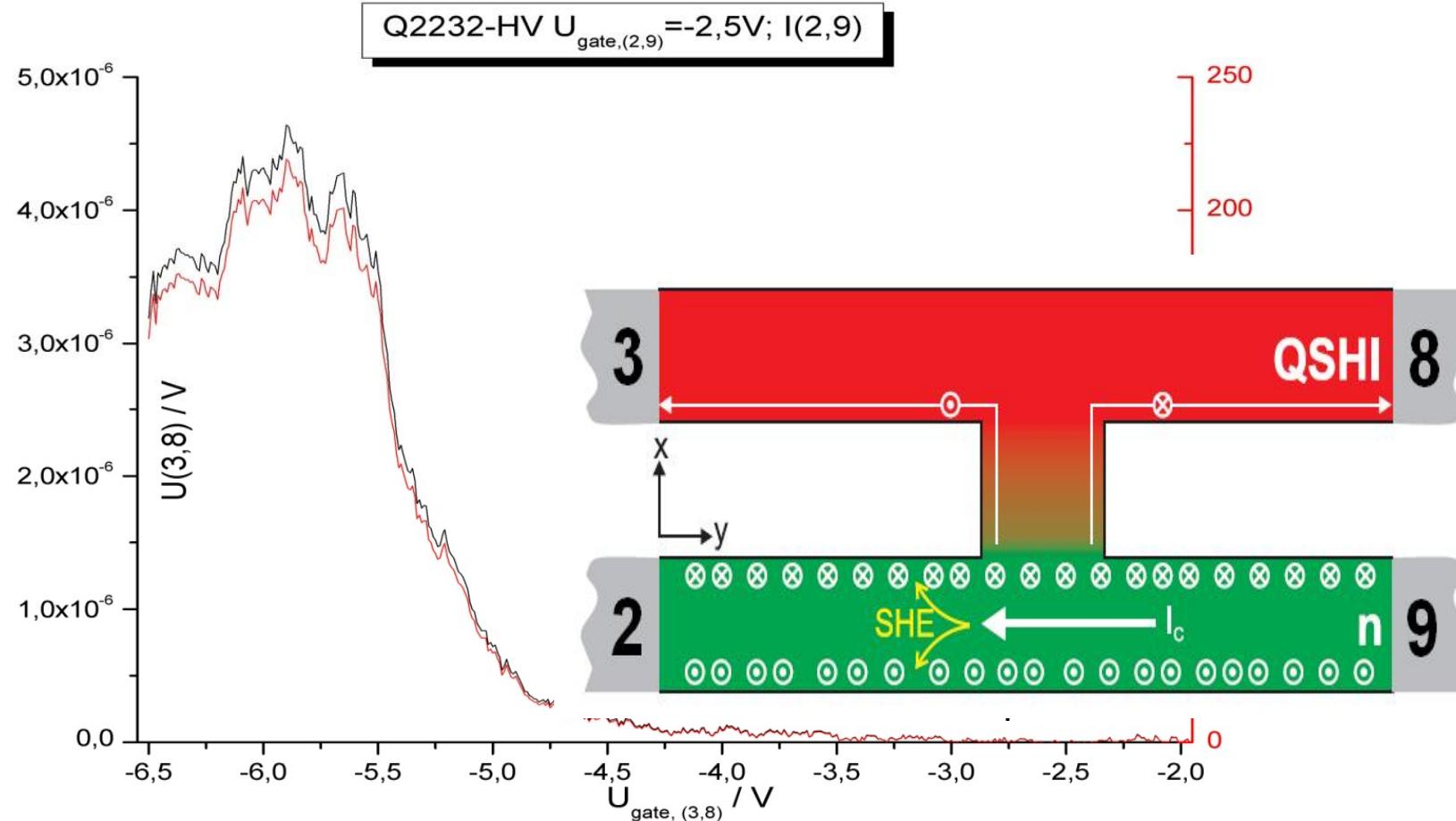
Configurations would be equivalent in quantum adiabatic regime

QSHE and iSHE as spin injector and detector



Split-gated H-bar

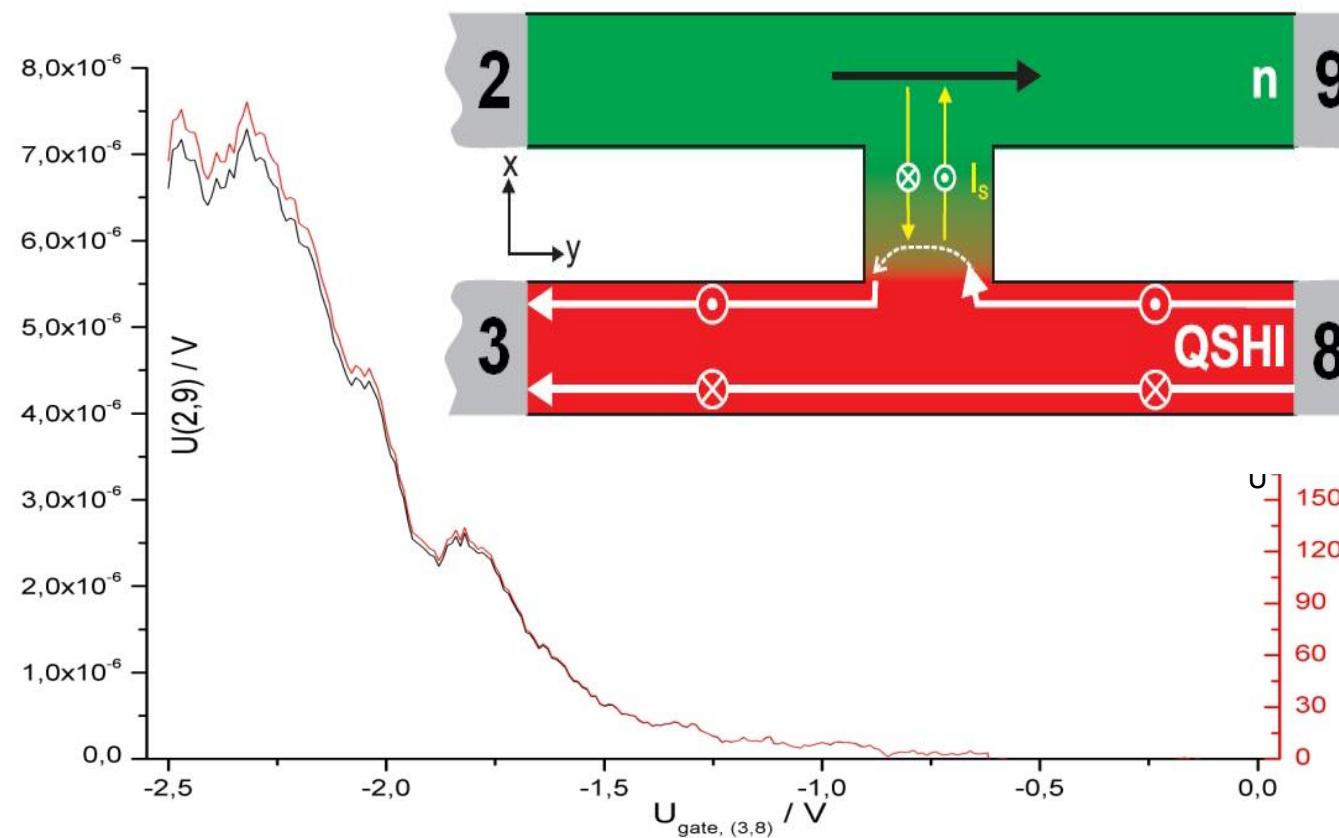
Detect iSHE through QSHI edge channels



Gate in 3-8 leg is scanned, 2-9 leg is n-type metallic,
current passed between contacts 2 and 9.

C. Brüne et al.,
Nature Physics 8, 486–491 (2012)

Detect QSHI through inverse iSHE



Gate in 3-8 leg is scanned, 2-9 leg is n-type metallic,
current passed between contacts 3 and 8

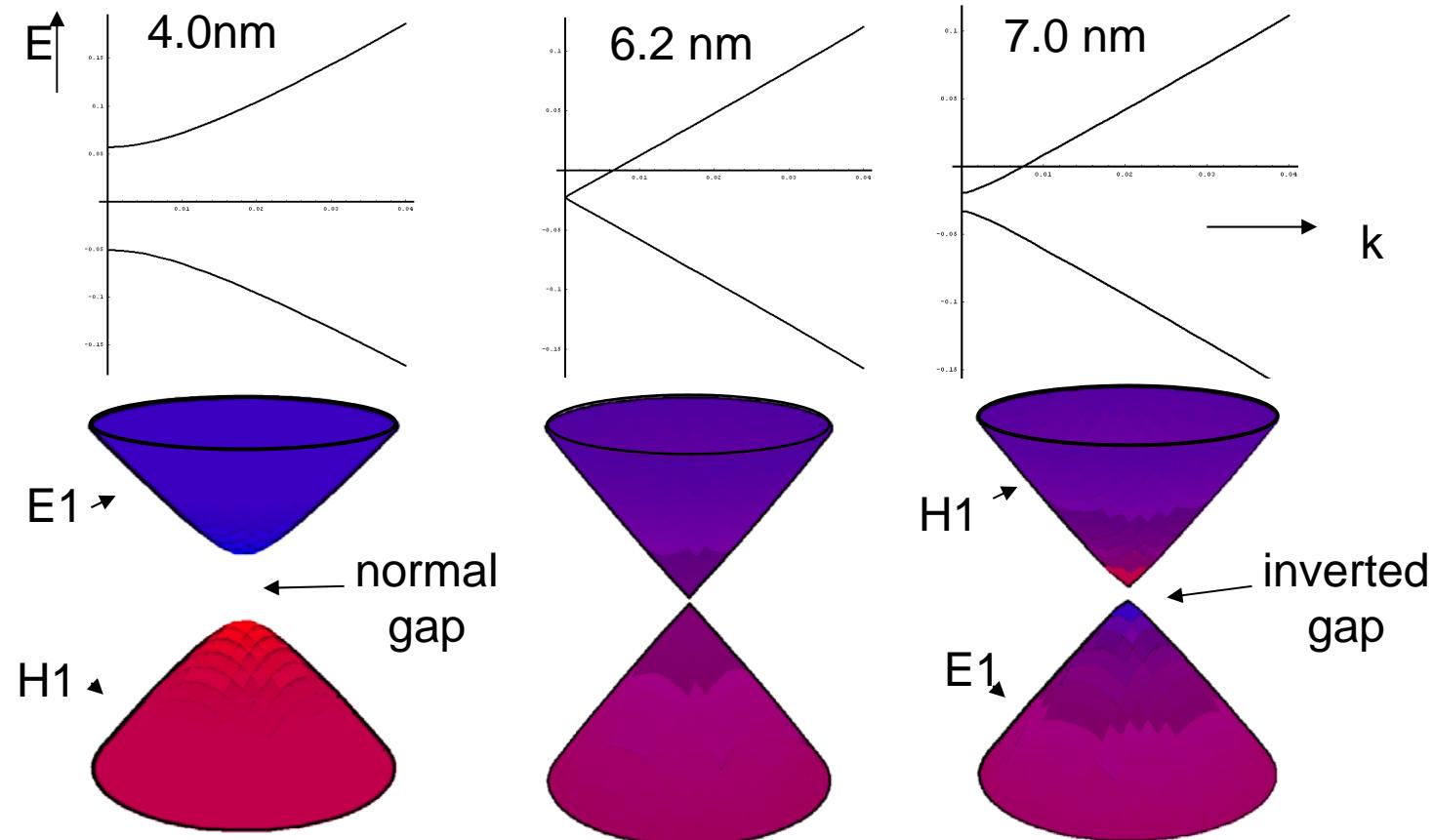
C. Brüne et al.,
Nature Physics **8**, 486–491 (2012).

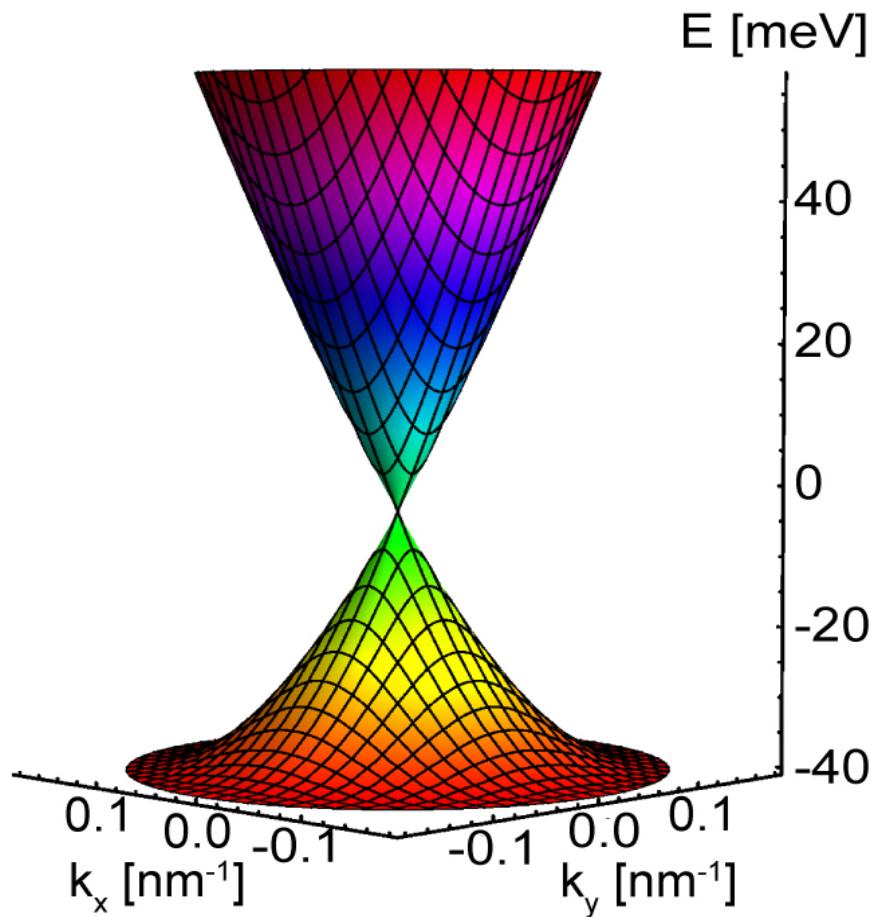
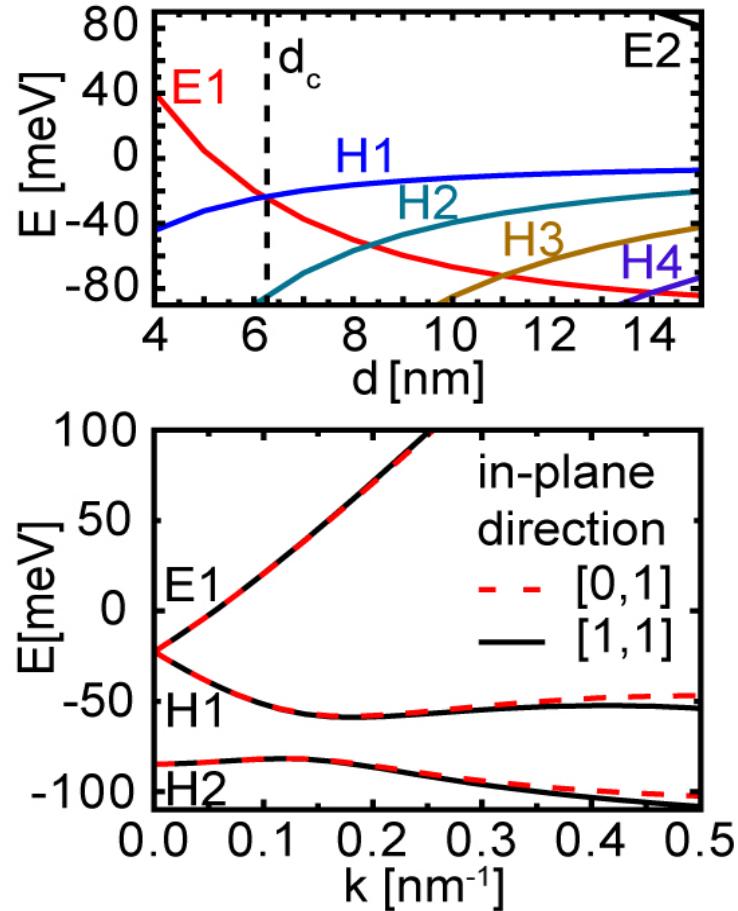


zero gap HgTe well as a Dirac system

Bandstructure HgTe

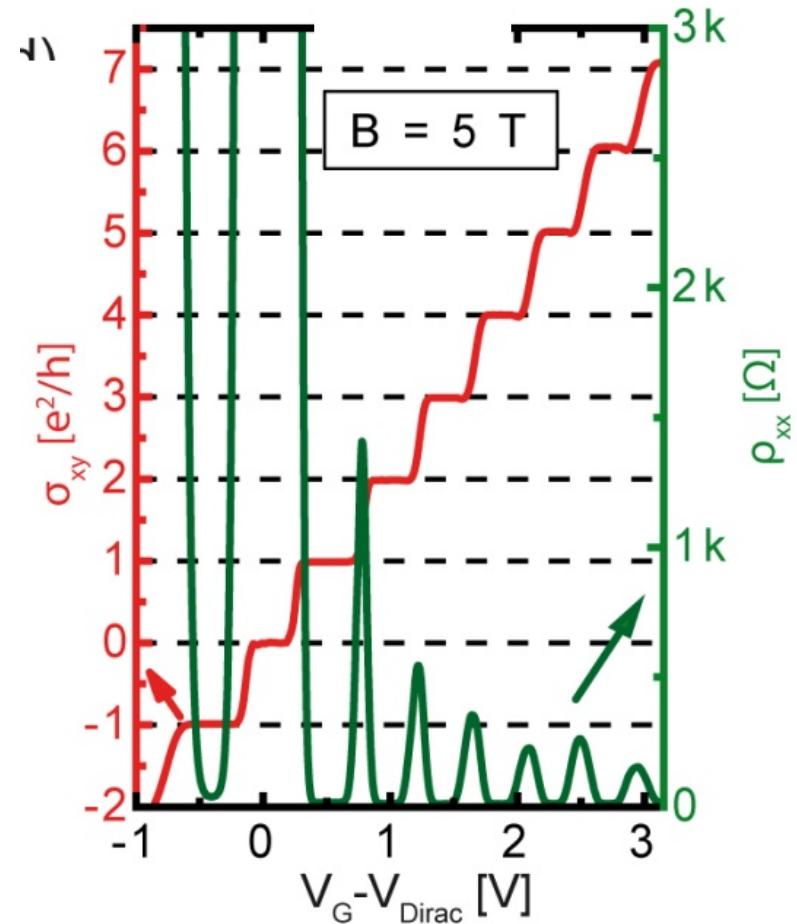
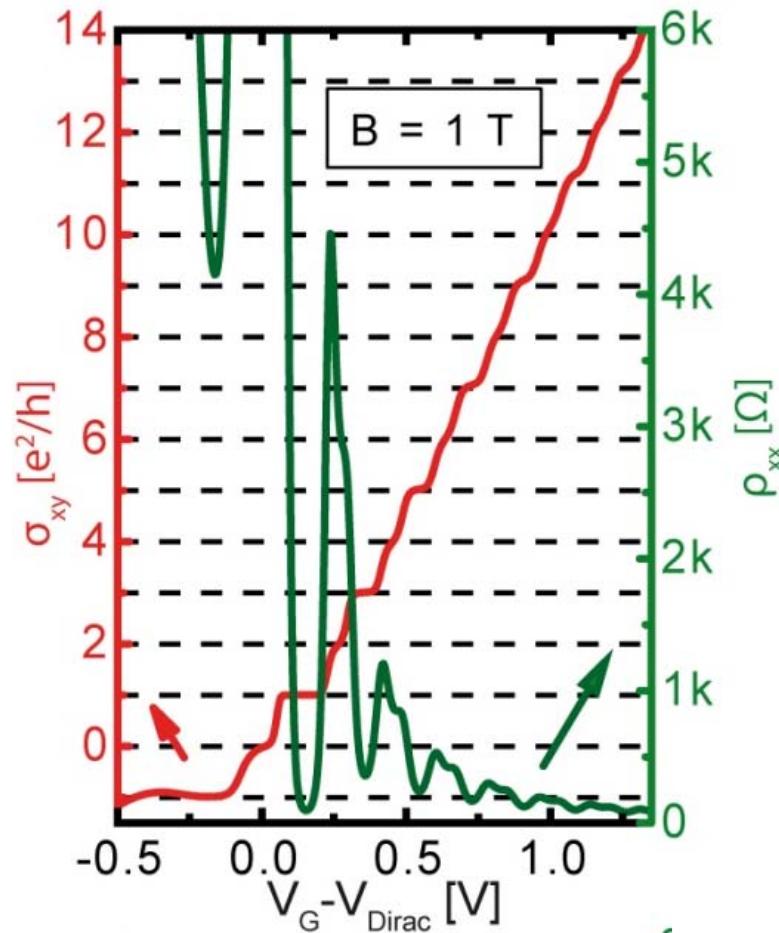
B.A Bernevig, T.L. Hughes, S.C. Zhang, Science **314**, 1757 (2006)





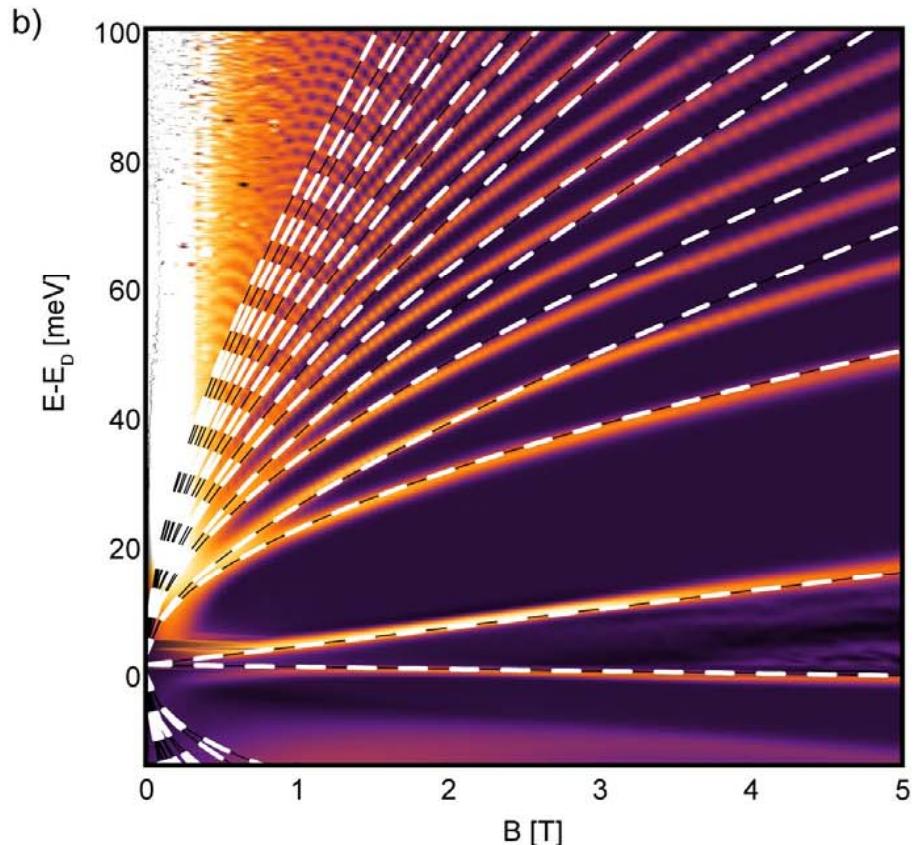
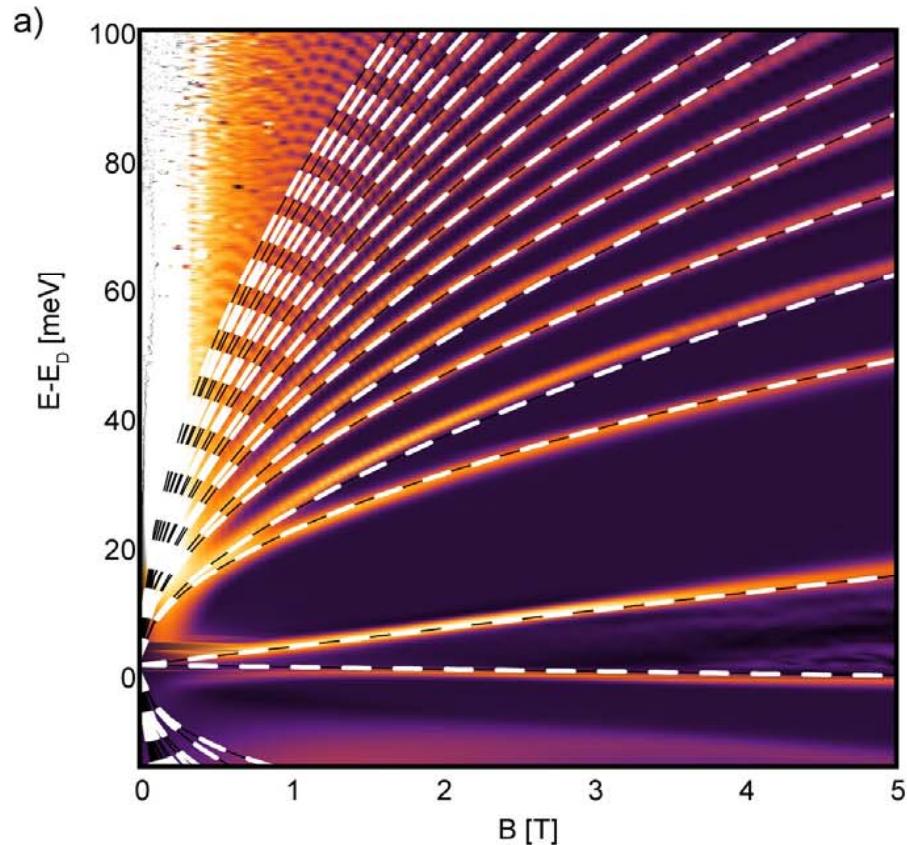
For well thickness $d=6.3$ nm, the gap closes,
especially the conduction band shows a linear dispersion: **single** Dirac cone

Quantum Hall effect shows Berry phase



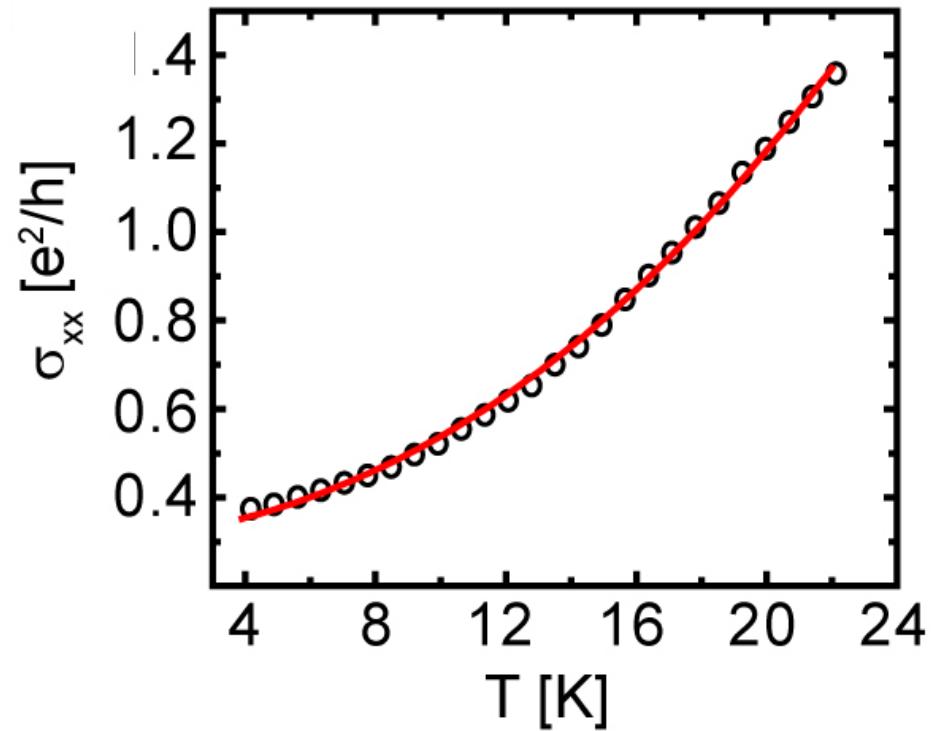
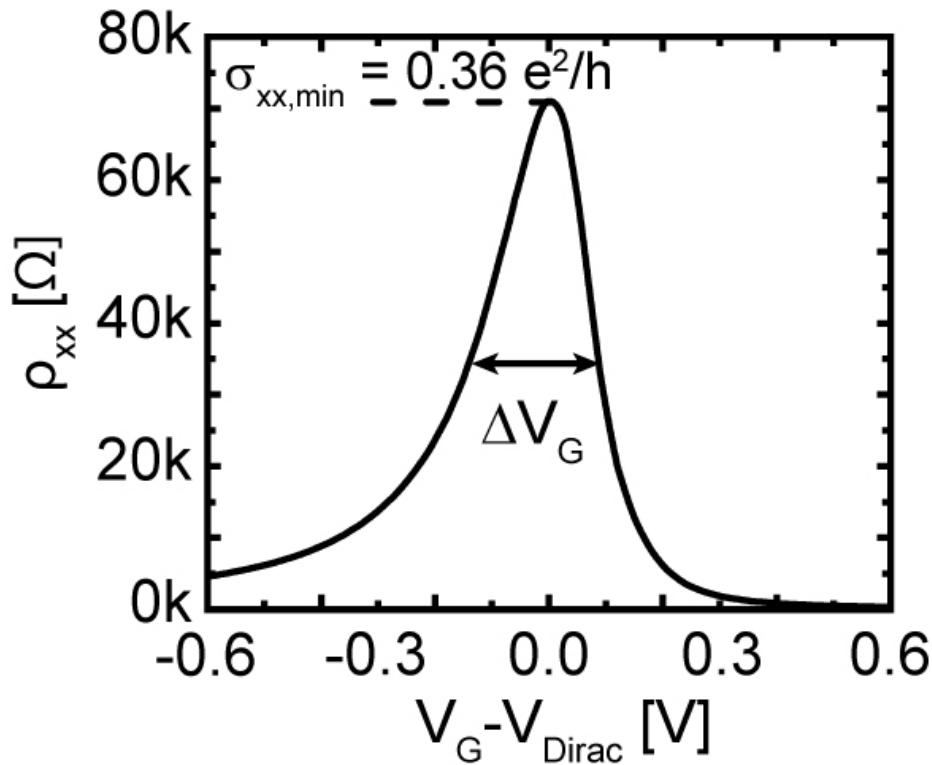
B. Büttner et al., Nature Physics 7, 418 (2011).

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.



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

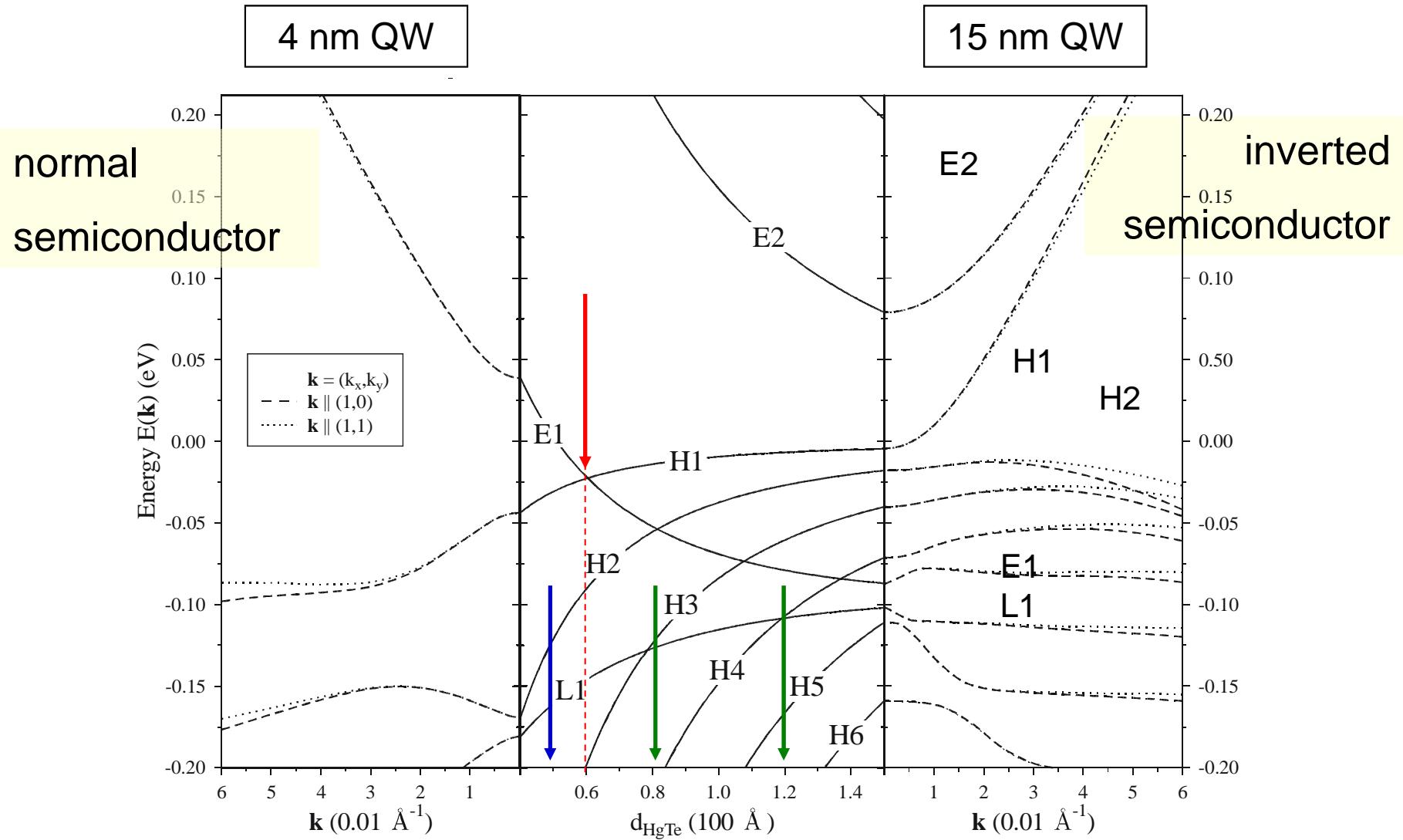


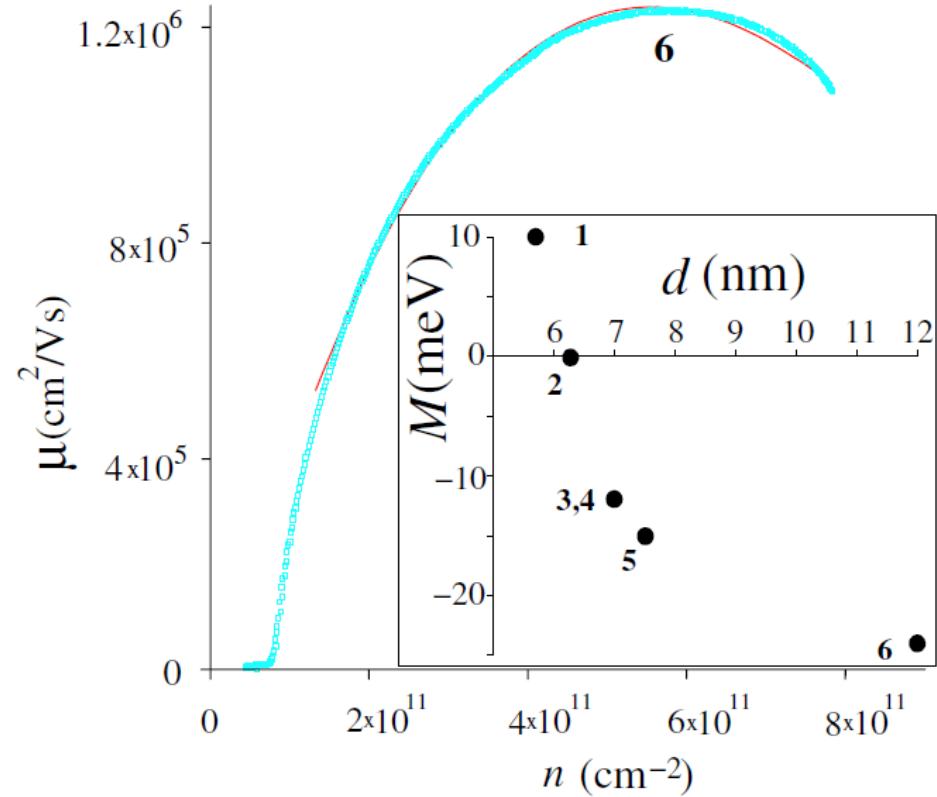
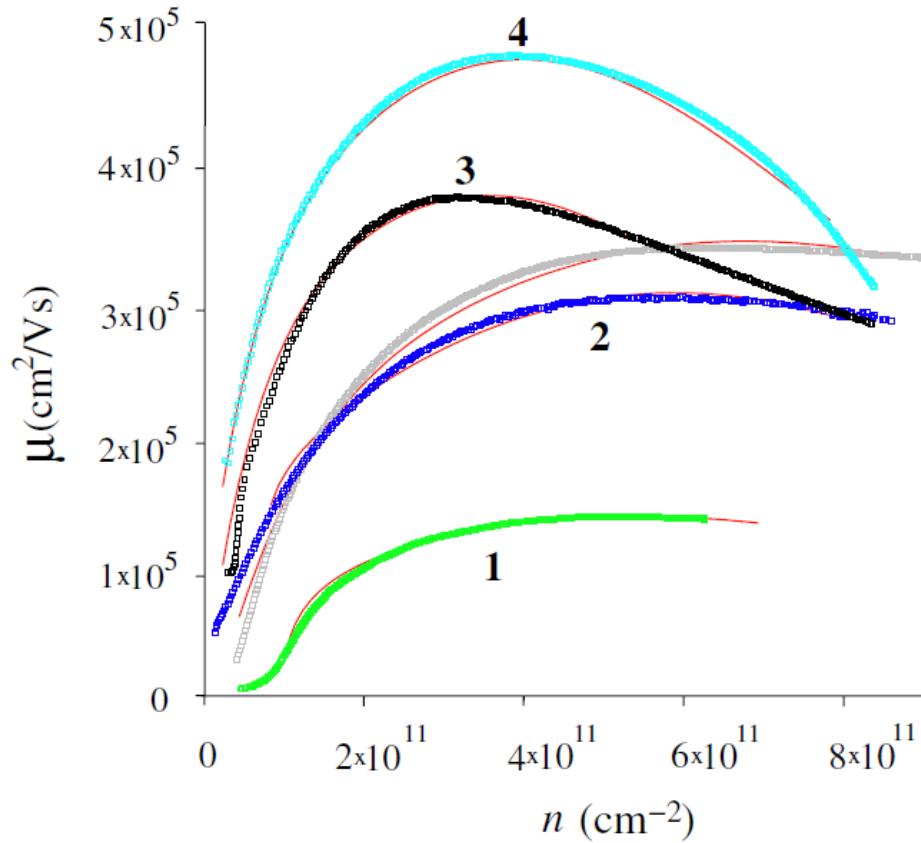
Peak width and mobilities comparable with/better than free standing graphene
Scattering mechanisms: probably mass fluctuations + Coulomb (fit is Kubo model)



Adding a Dirac mass

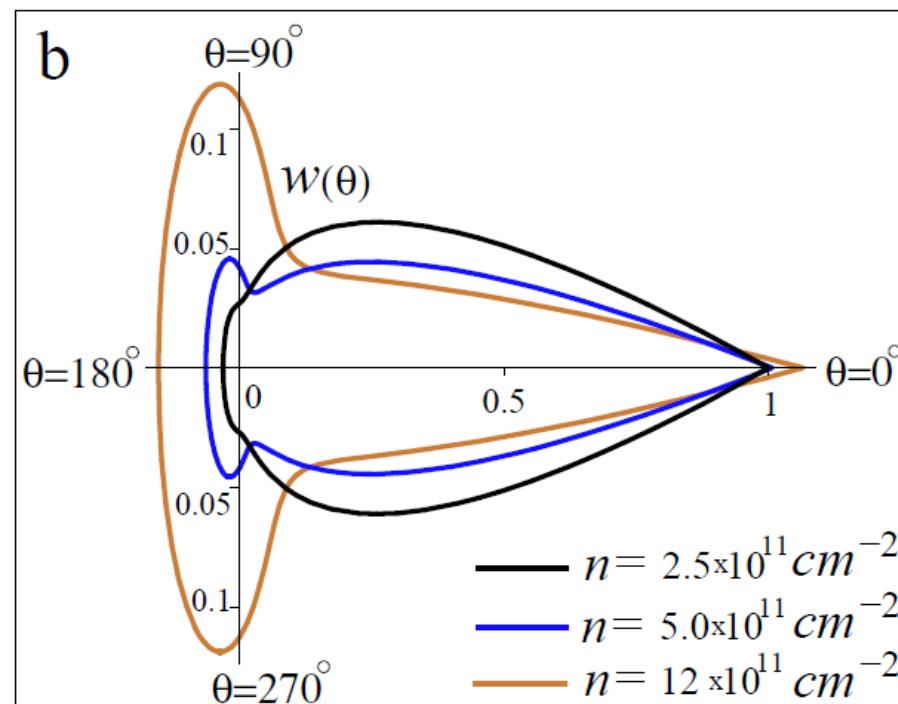
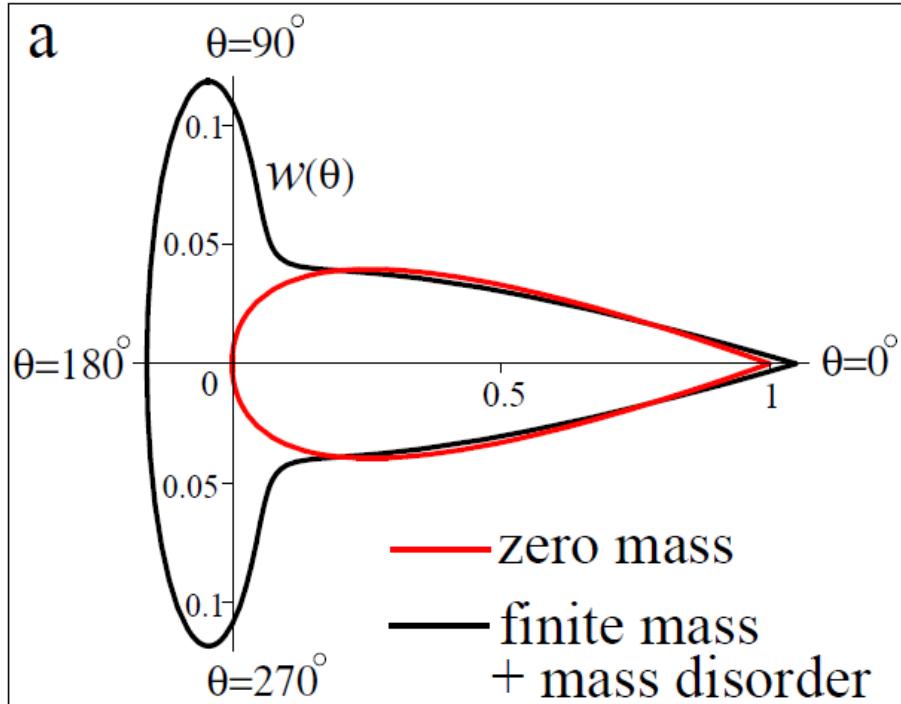
Changing well width changes Dirac mass





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.

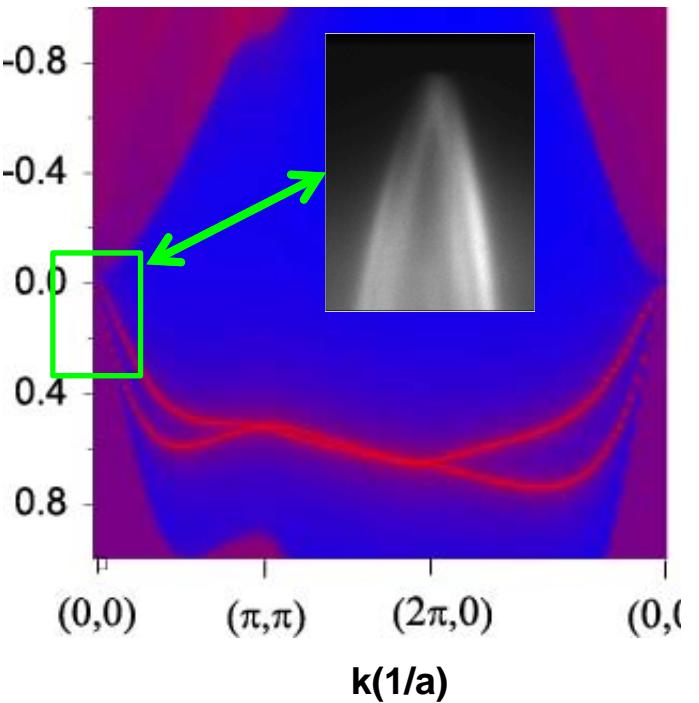
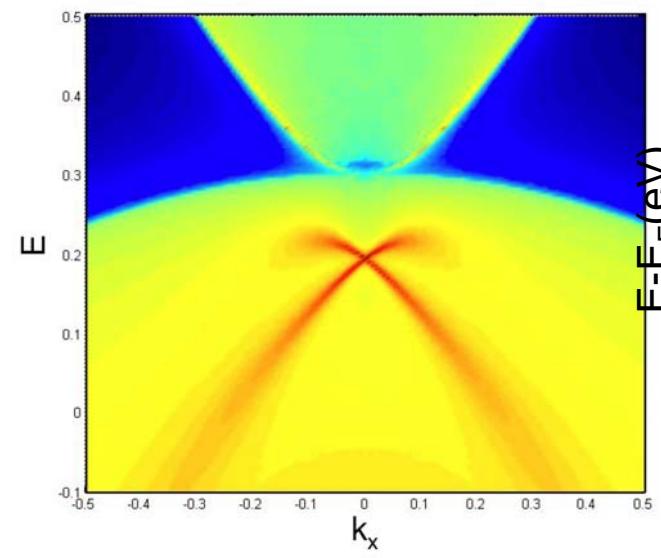
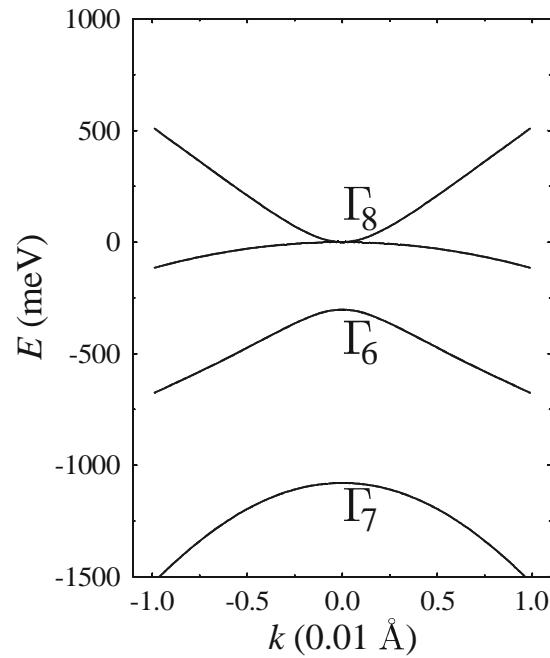


B. Büttner et al., Phys. Rev. Lett. **106**, 076802 (2011).

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

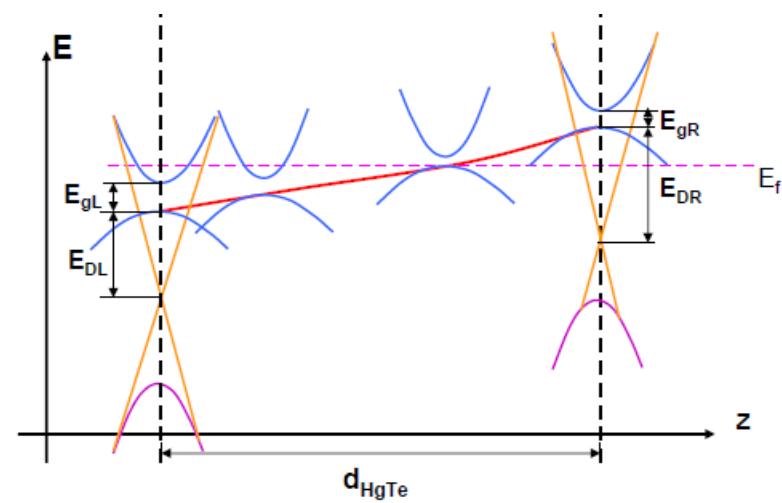
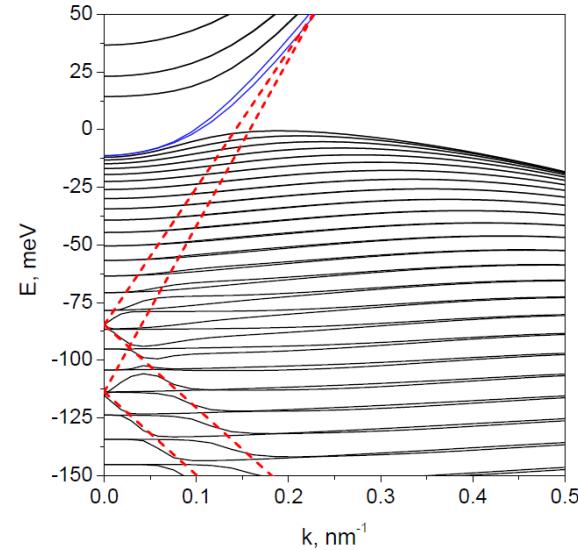
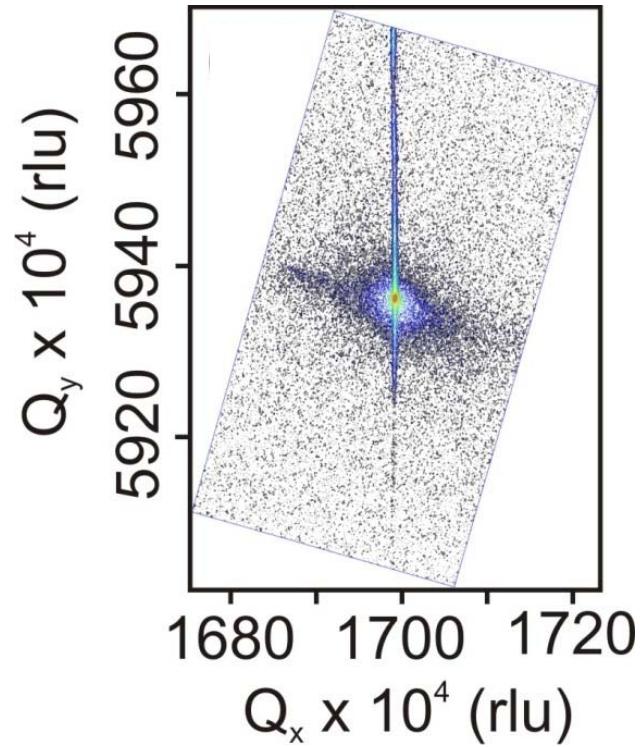


Bulk HgTe is semimetal,
topological surface state overlaps w/ valenceband.

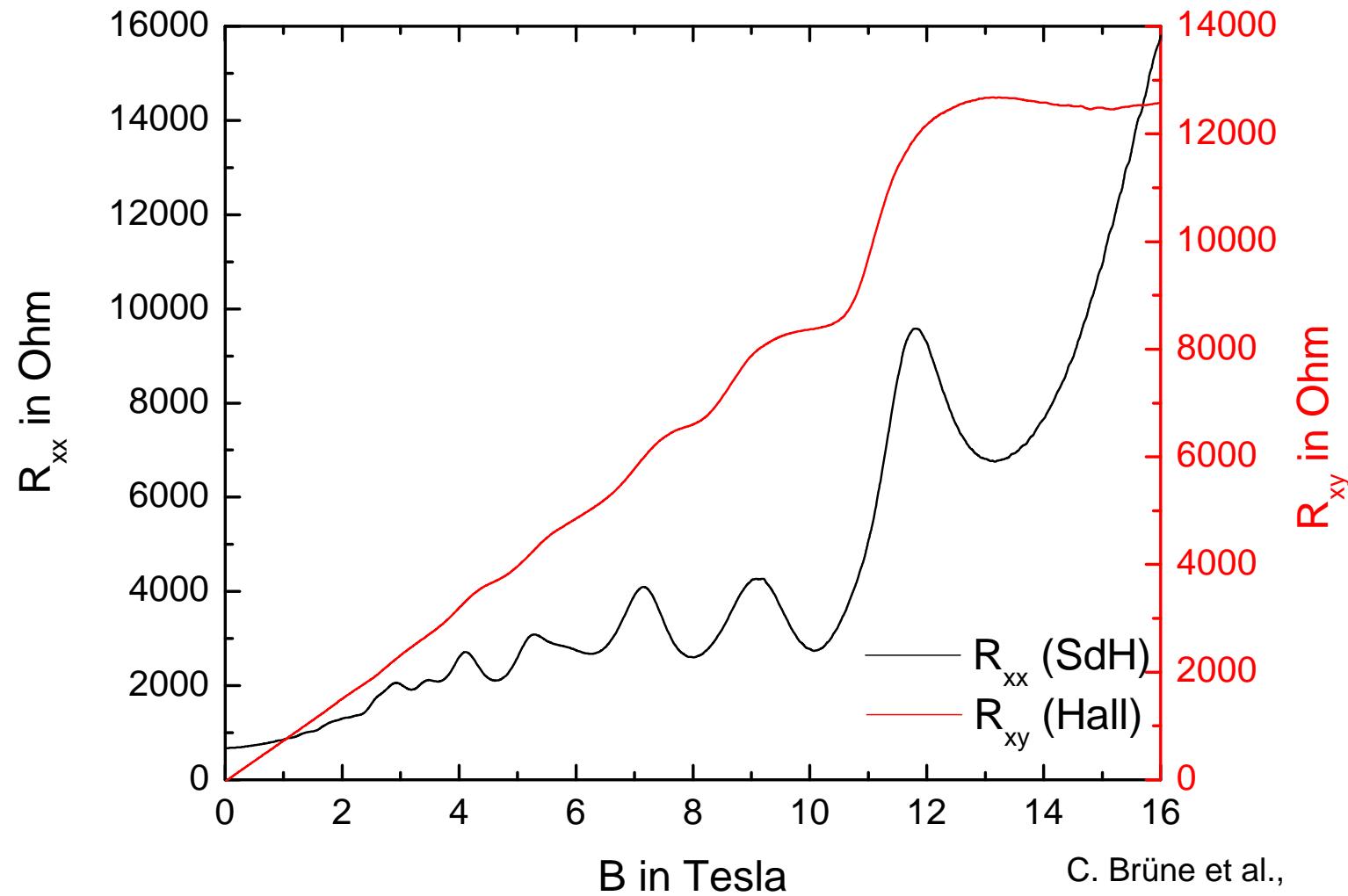
C. Brüne et al., Phys. Rev. Lett. **106**, 126803 (2011).

ARPES:
Yulin Chen, ZX Shen,
Stanford

70 nm layer on CdTe substrate: coherent strain opens gap



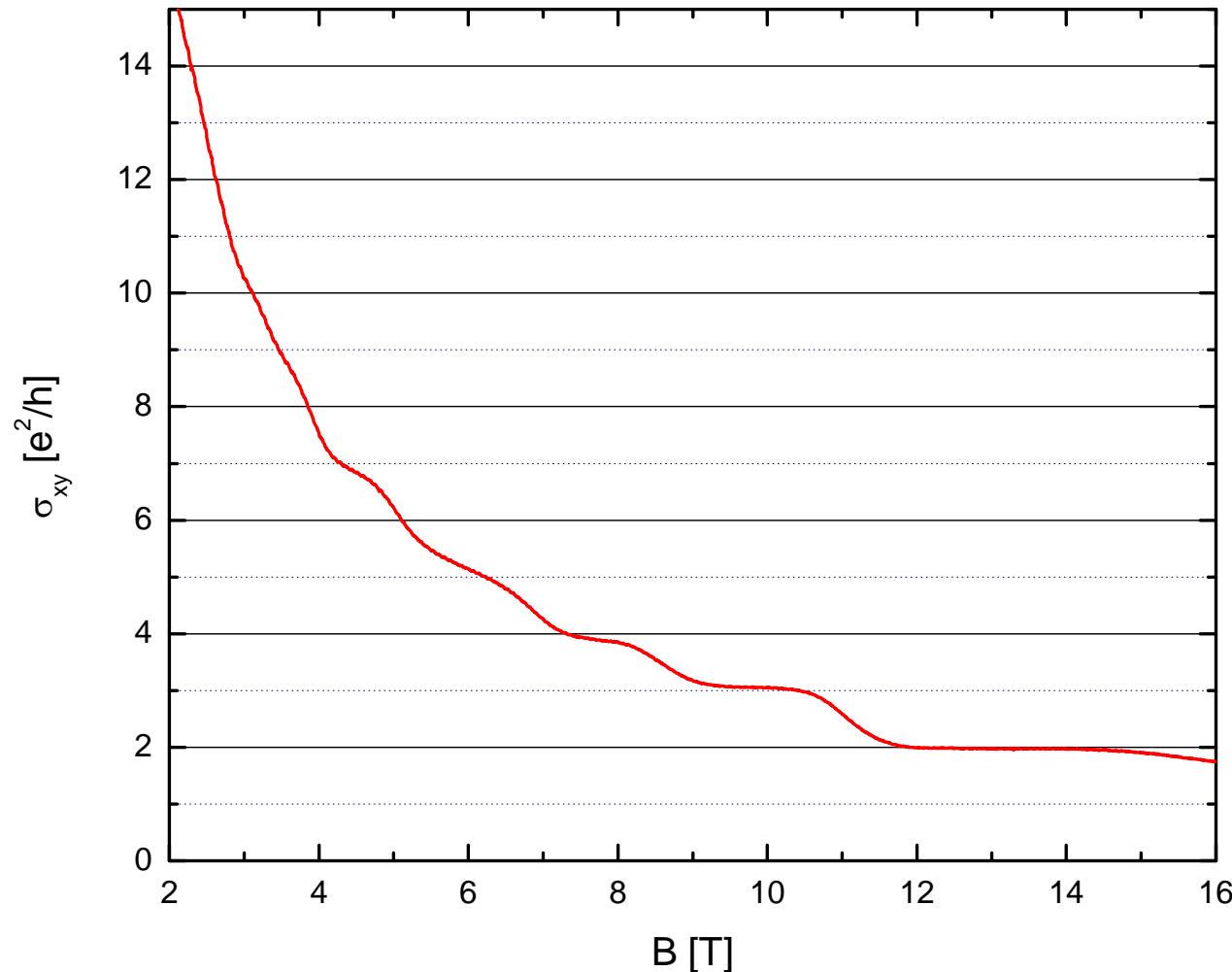
Bulk HgTe as a 3-D Topological Insulator'



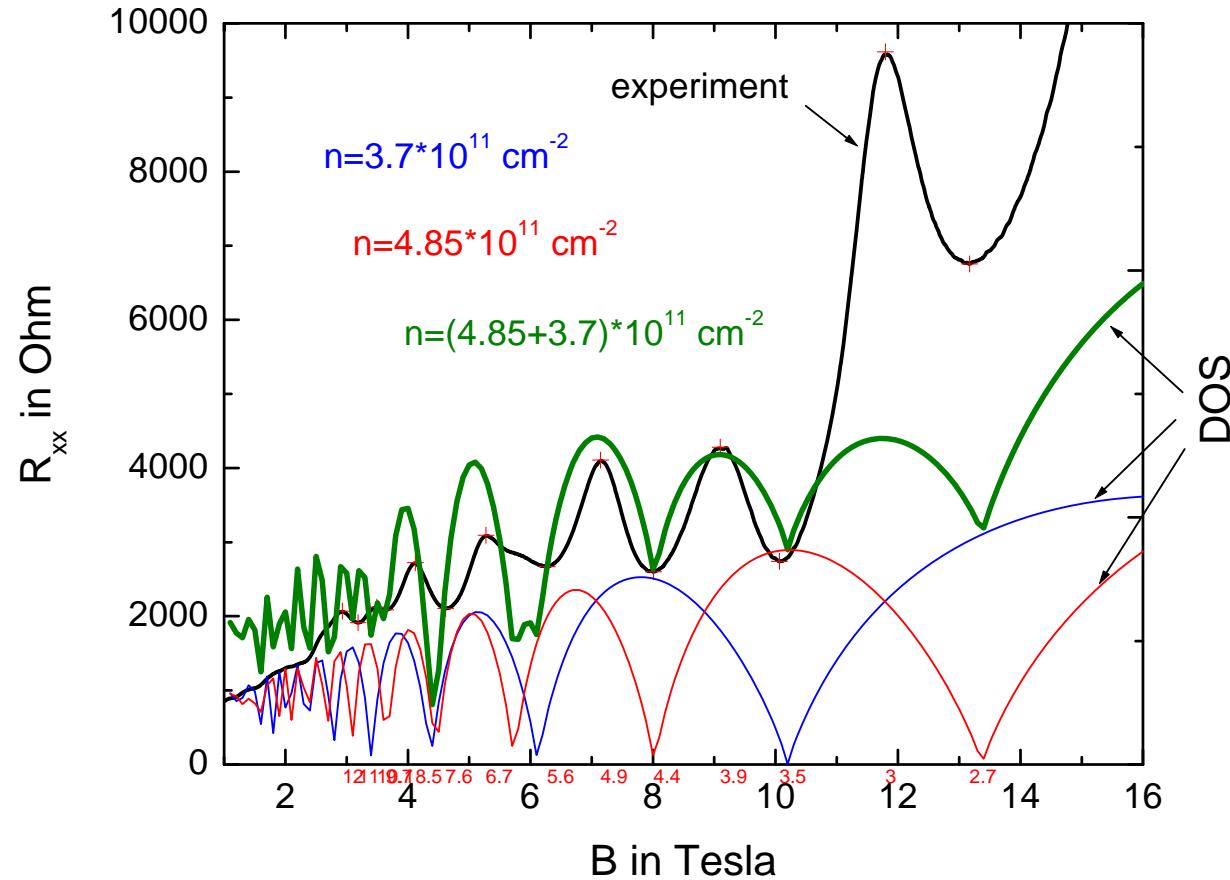
C. Brüne et al.,
Phys. Rev. Lett. **106**, 126803 (2011).

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

Bulk HgTe as a 3-D Topological Insulator'



@ 20 mK: same data, plotted as conductivity



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
- show Quantum Spin Hall Effect and Quantum Anomalous Hall Effect
- At $d=d_c$, a HgTe QW is ideal model system for zero mass Dirac fermion physics
- strained 3D layers show QHE of topological surface states
- In which a supercurrent can be induced

Collaborators:

Bastian Büttner, Christoph Brüne, Hartmut Buhmann, Markus König, Luis Maier, Matthias Mühlbauer, Jeroen Oostinga, 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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