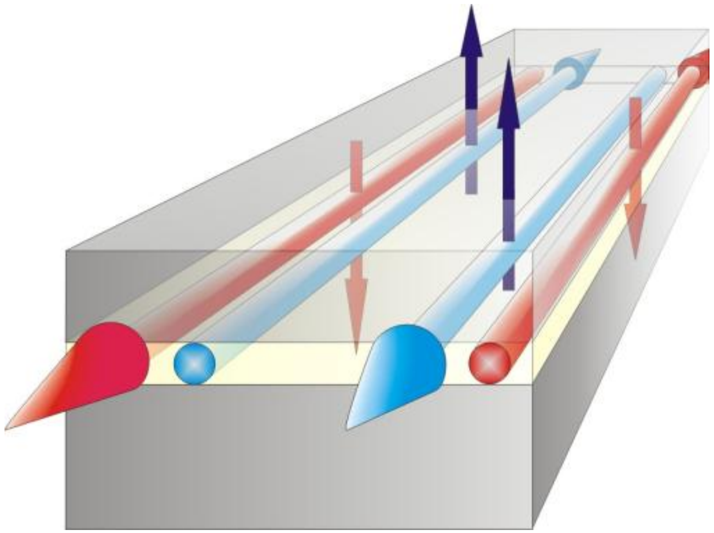
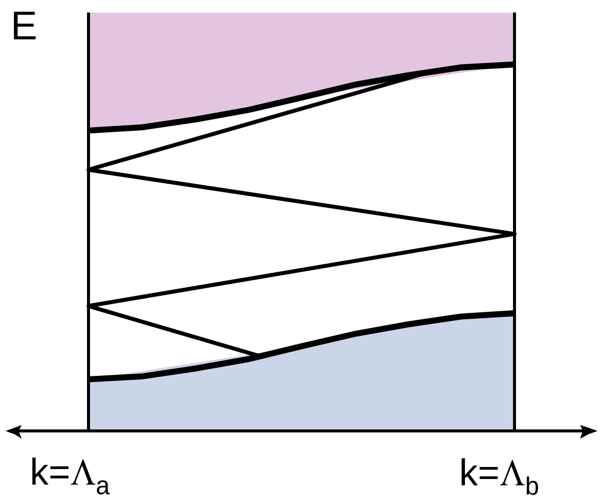
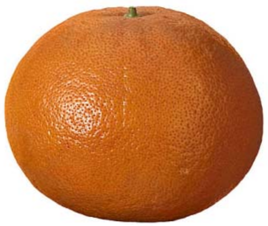
Quantum Spin Hall Effect and Topological Insulators







Laurens W. Molenkamp
Physikalisches Institut (EP3), Universität Würzburg

Quantum Spin Hall Effect and Topological Insulators

I. Introduction

- Topological Classification of Insulators
- Edge States with and w/o Time Reversal Symmetry

II. Two Dimensional TI : Quantum Spin Hall Effect

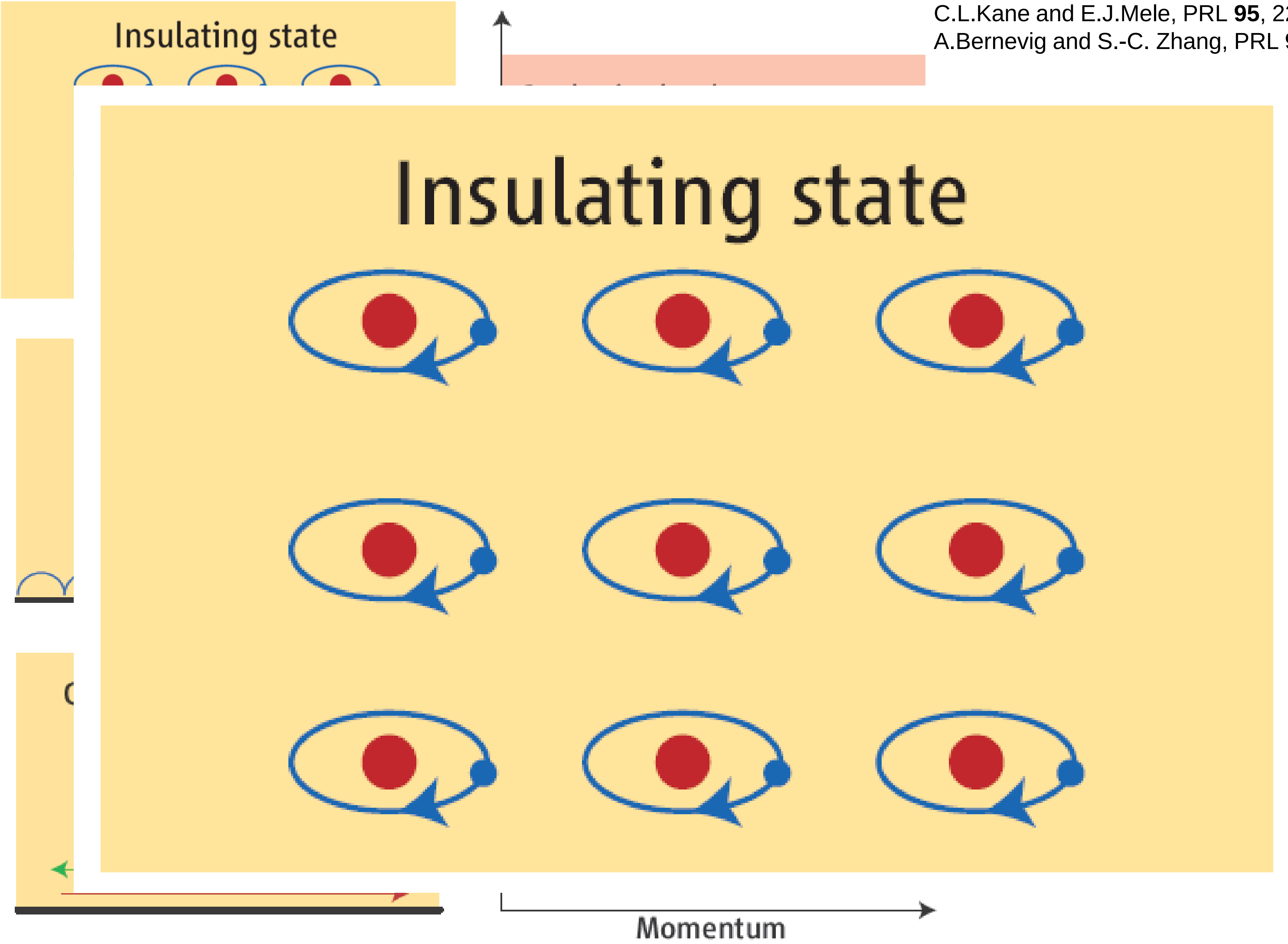
- Transport in HgTe quantum wells

III. Three Dimensional TI :

- Topological Insulator & Surface States
- Photoemission on Bi_xSb_{1-x} and Bi_2Se_3
- Transport in strained bulk HgTe

The Insulating State – Topologically Generalized

C.L.Kane and E.J.Mele, PRL **95**, 146802 (2005)
C.L.Kane and E.J.Mele, PRL **95**, 226801 (2005)
A.Bernevig and S.-C. Zhang, PRL **96**, 106802 (2006)



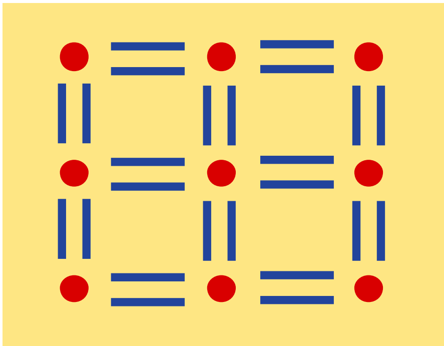
C.L.Kane and E.J. Mele, Science **314,** 1692 (2006)

The Usual Boring Insulating State

Characterized by energy gap: absence of low energy electronic excitations

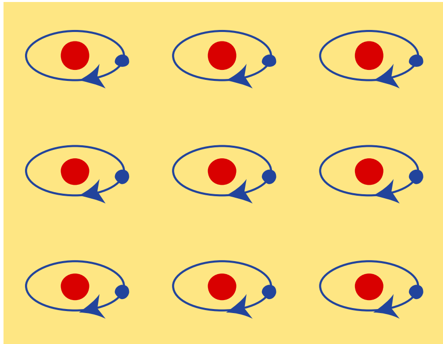
Covalent Insulator

e.g. intrinsic semiconductor

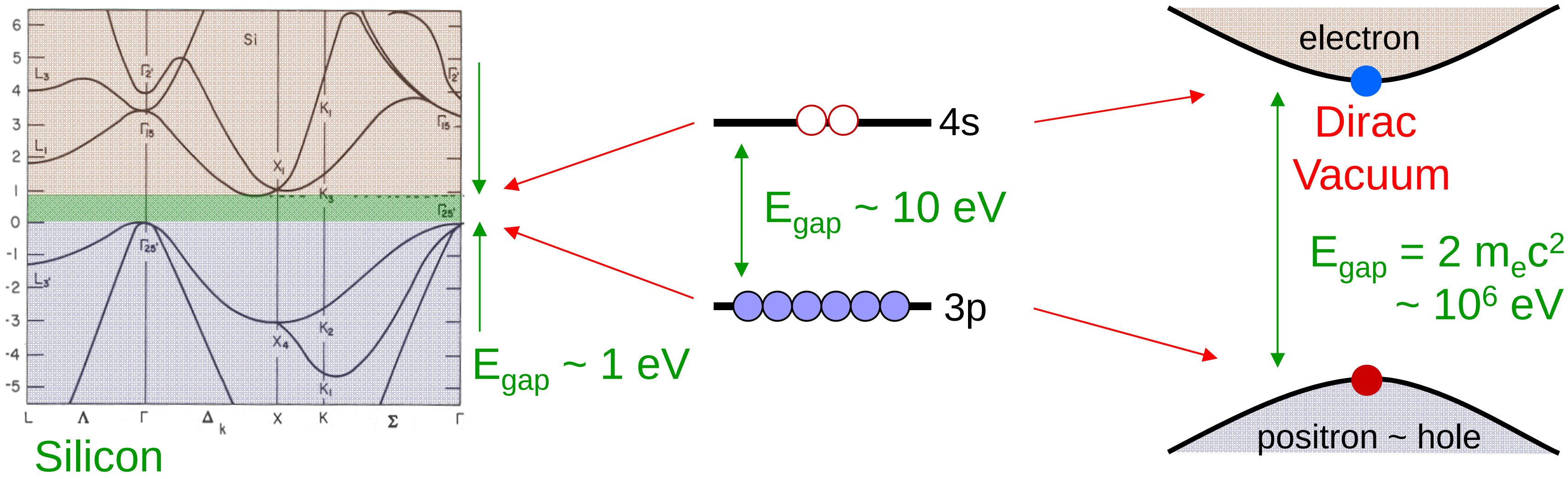


Atomic Insulator

e.g. solid Ar



The vacuum



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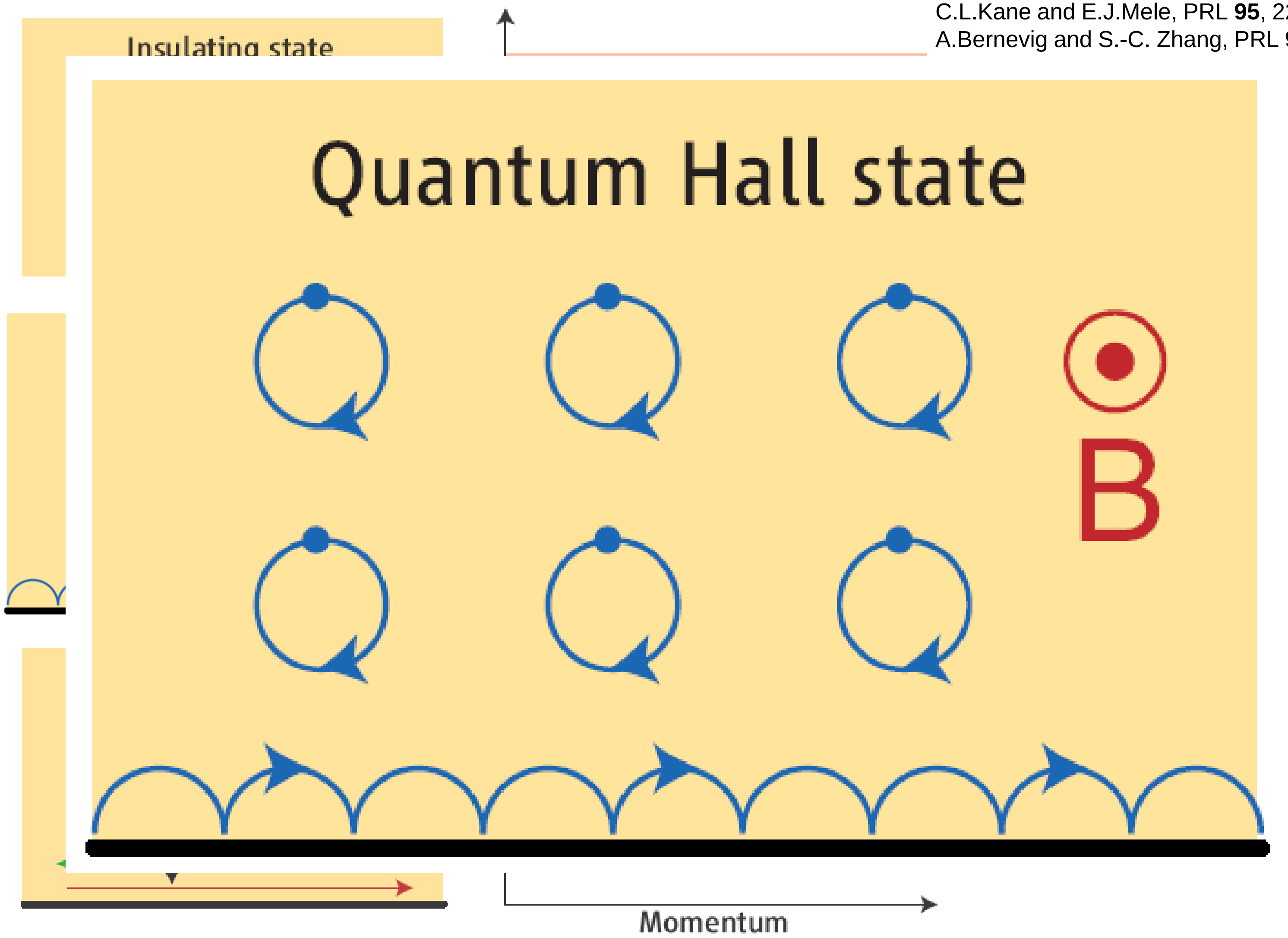
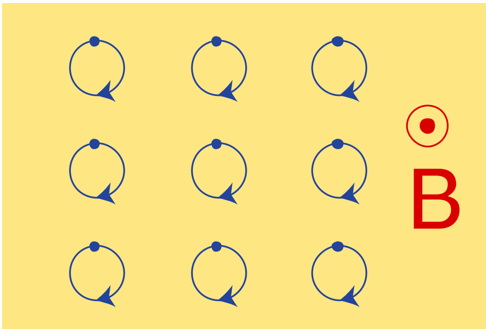
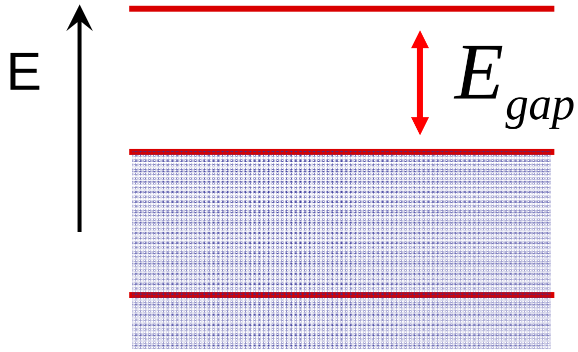


C.L.Kane and E.J. Mele, Science **314,** 1692 (2006)

The Integer Quantum Hall State

2D Cyclotron Motion, Landau Levels

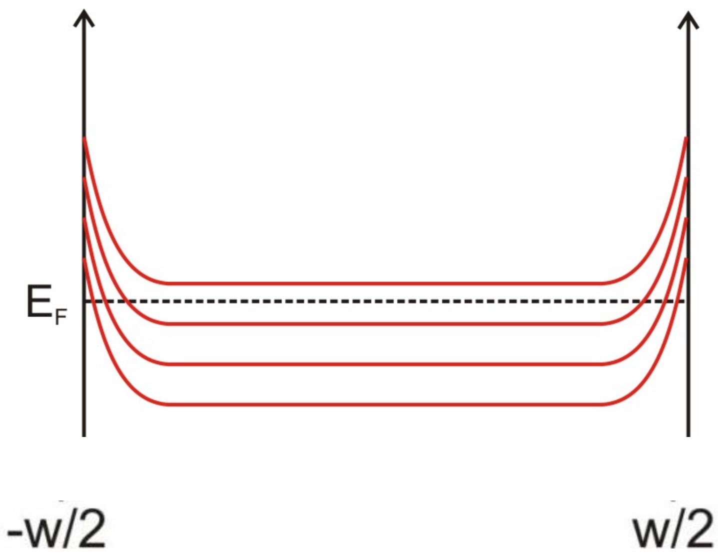


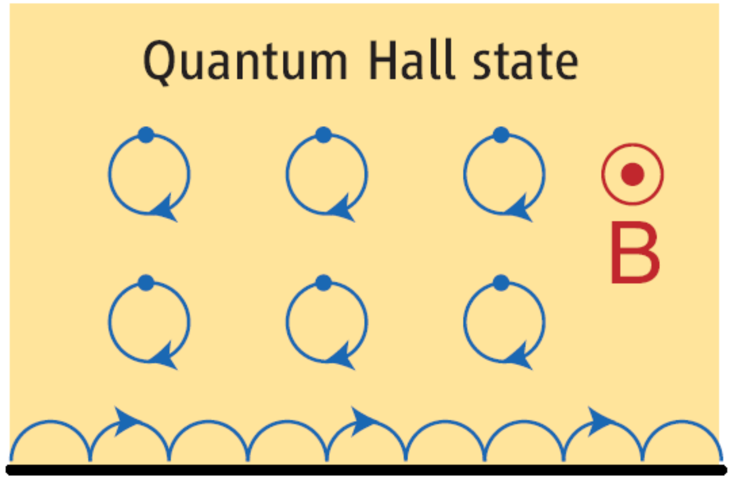


$$E_{gap} = \hbar\omega_c$$

Energy gap, but NOT an insulator

Edge States (as experimentalists see them)





Quantized Hall conductivity :

$$J_y = \sigma_{xy} E_x$$

$$\sigma_{xy} = n \frac{e^2}{h}$$

Integer accurate to 10^{-9}

Topological Band Theory

The distinction between a conventional insulator and the quantum Hall state
is a topological property of the manifold of occupied states

$H(\mathbf{k})$: Brillouin zone (torus) $\mapsto$ Bloch Hamiltonians
with energy gap

Classified by Chern (or TKNN) integer topological invariant (Thouless et al, 1982)

$$n = \frac{1}{2\pi i}\int_{BZ} d^2\mathbf{k} \cdot \langle \nabla_{\mathbf{k}} u(\mathbf{k}) | \times | \nabla_{\mathbf{k}} u(\mathbf{k}) \rangle$$

$u(\mathbf{k})$ = Bloch wavefunction

Insulator : $n = 0$
IQHE state : $\sigma_{xy} = n\, e^2/h$

The TKNN invariant can only change at a phase transition where the energy gap goes to zero

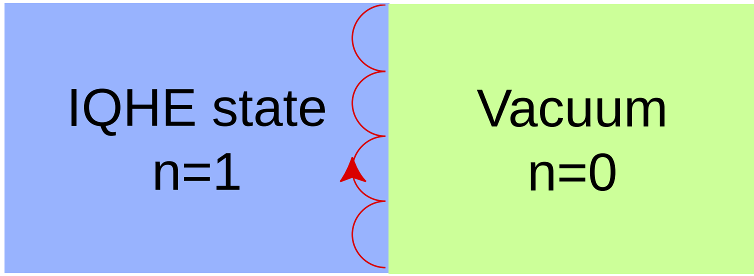
Analogy: Genus of a surface : g = # holes

g=0

g=1

Edge States

Gapless states must exist at the interface between different topological phases



Edge states ~ skipping orbits

Bulk – Boundary Correspondence : Δn = # Chiral Edge Modes

This approach can actually be generalized to a spinfull QHE at zero magnetic field:
the Quantum Spin Hall Effect

The Insulating State – Topologically Generalized

C.L.Kane and E.J.Mele, PRL **95**, 146802 (2005)
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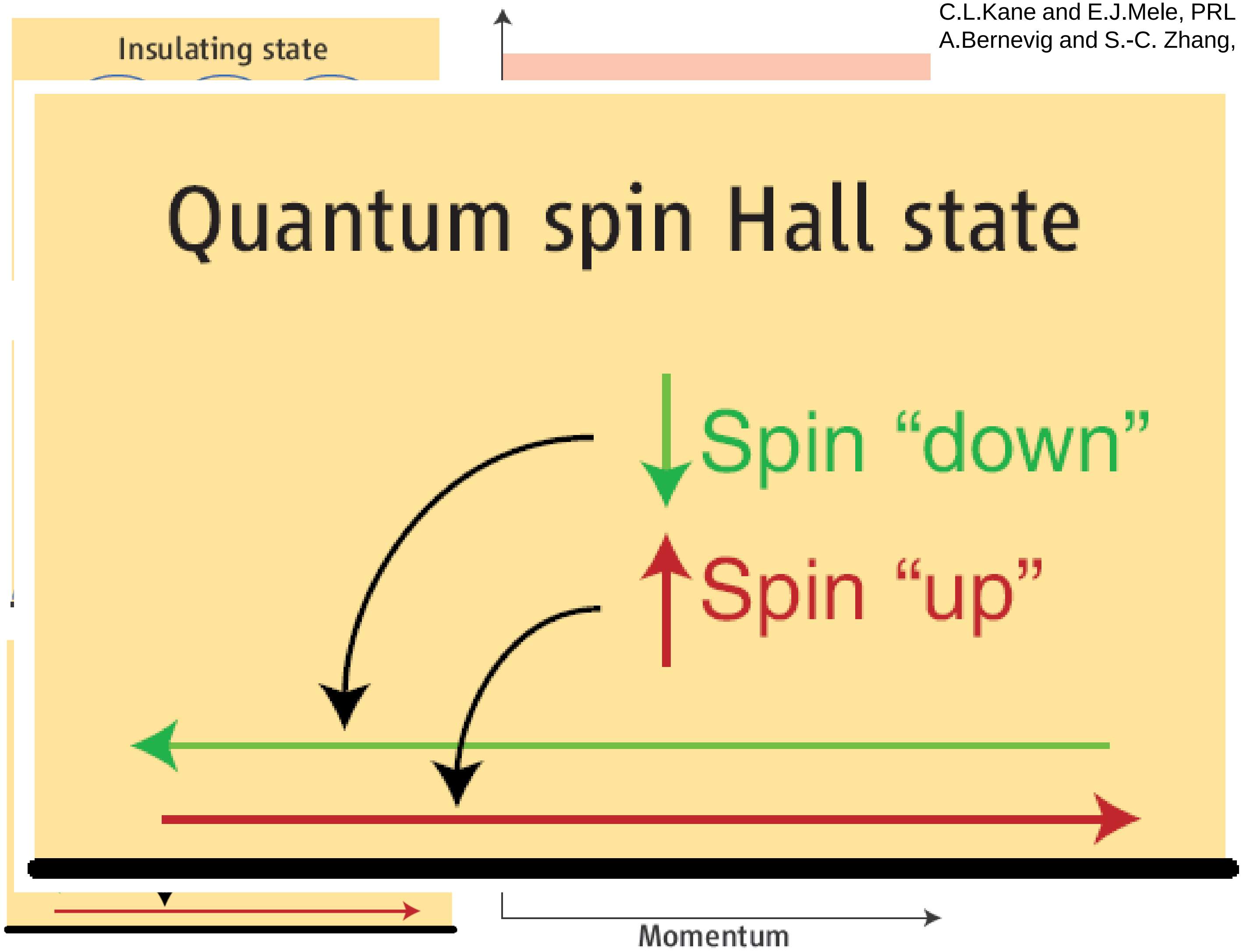


C.L.Kane and E.J. Mele, Science **314,** 1692 (2006)

Topological Insulator : A New B=0 Phase

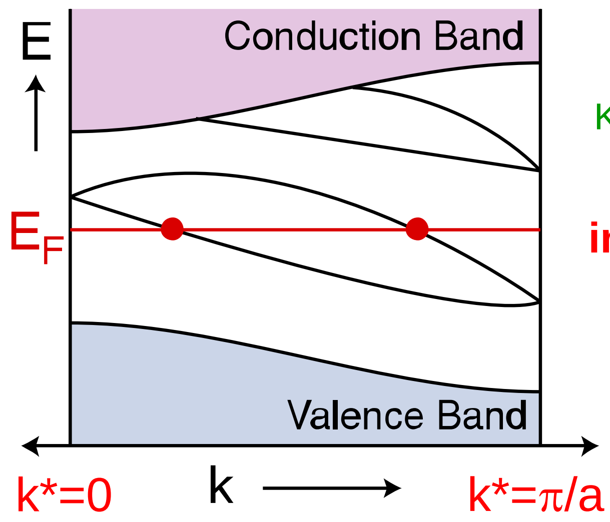
There are 2 classes of 2D time reversal invariant band structures

Z_2 topological invariant: ν = 0,1

ν is a property of bulk bandstructure, but can be understood by from the bulk - boundary correspondence

Edge States for 0<k<π/a

ν=0 : Conventional Insulator



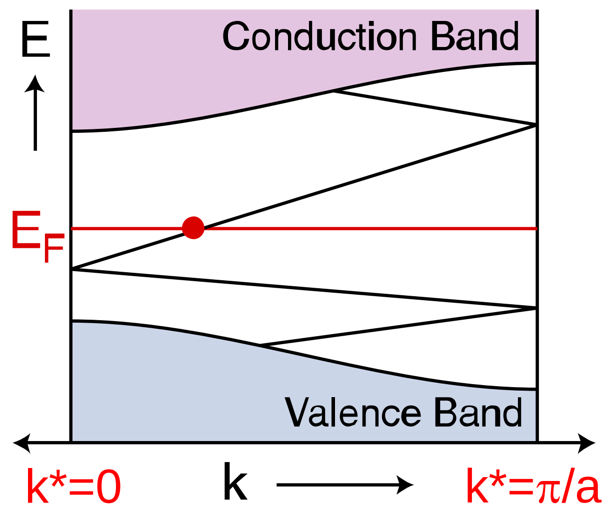
Even number of bands crossing Fermi energy

Kramers degenerate at

time reversal invariant momenta

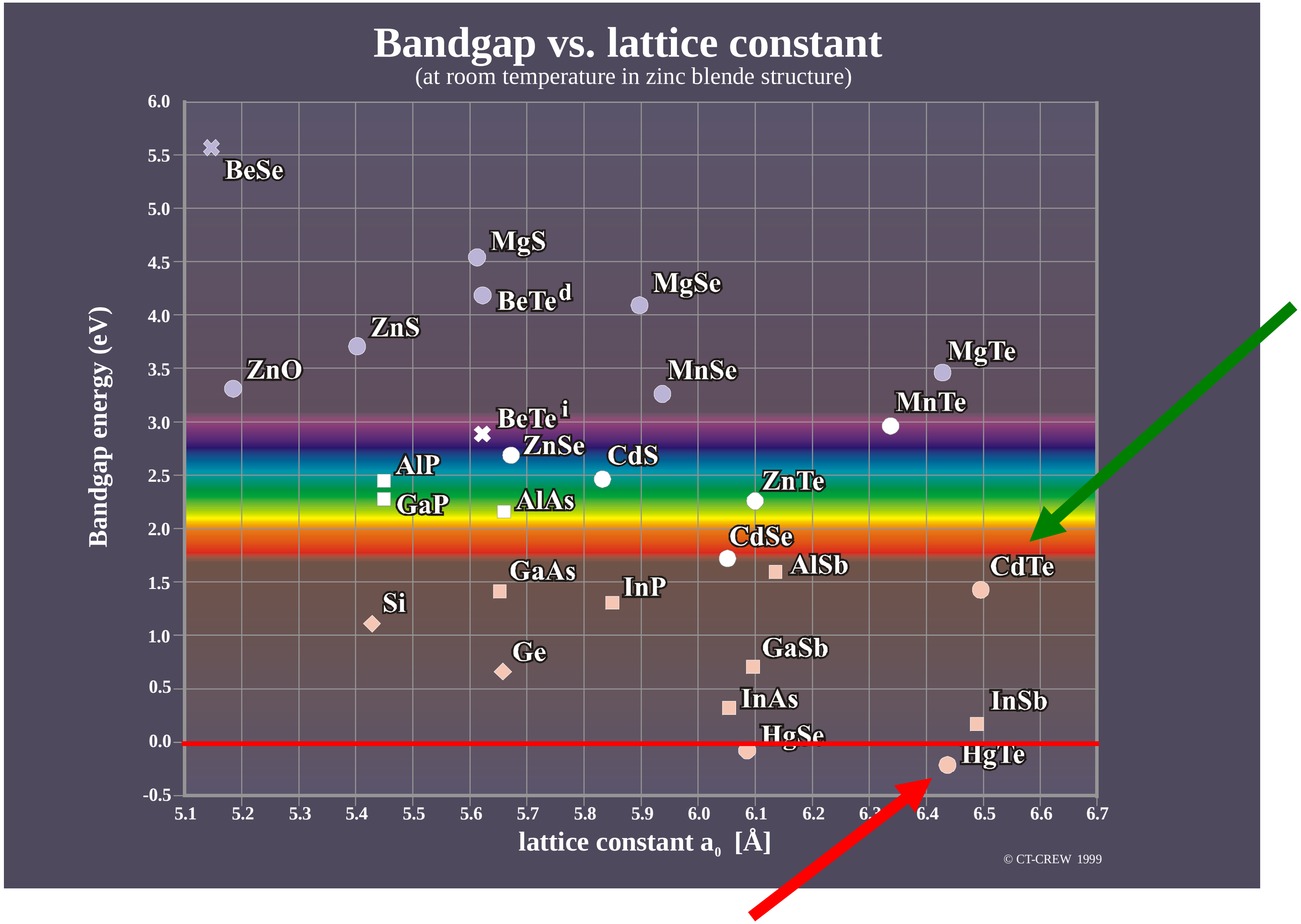
k* = –k* + G

ν=1 : Topological Insulator



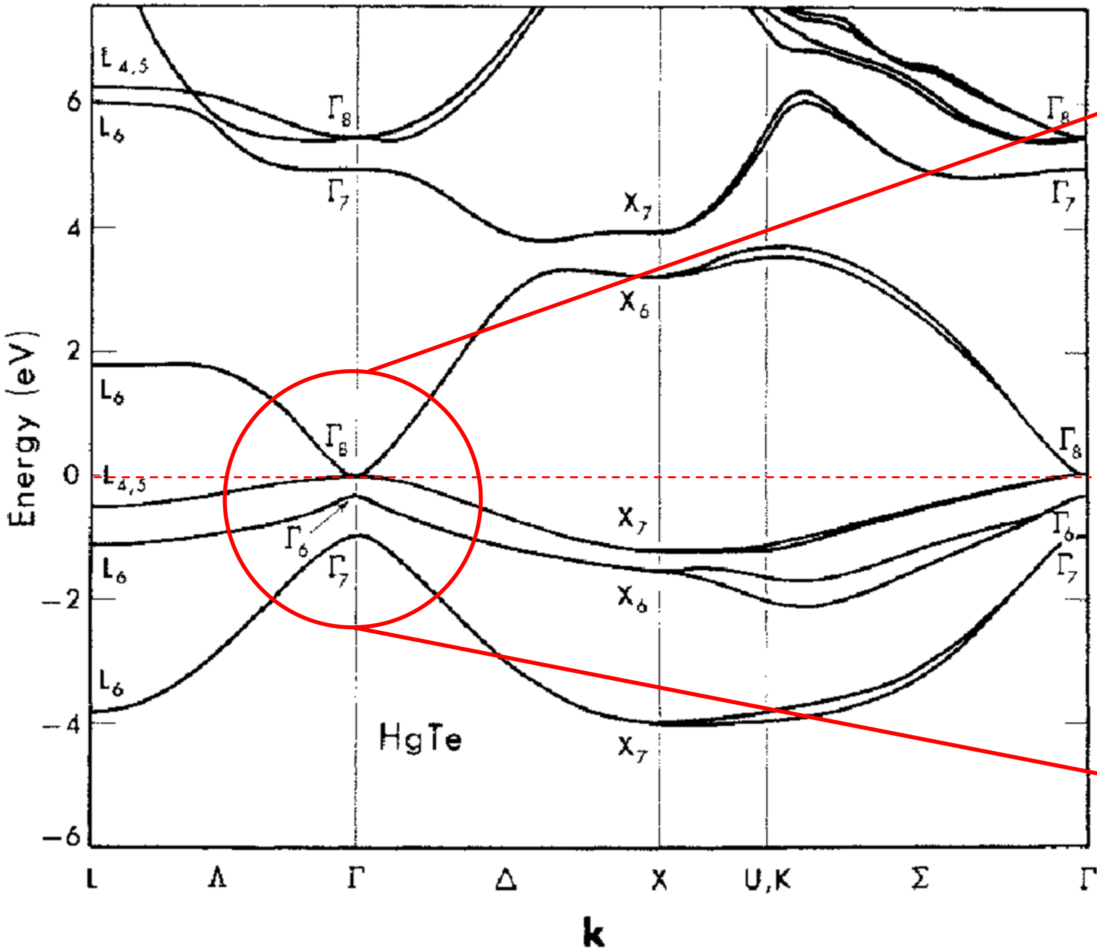
Odd number of bands crossing Fermi energy

(Hg,Cd)Te compound semiconductors



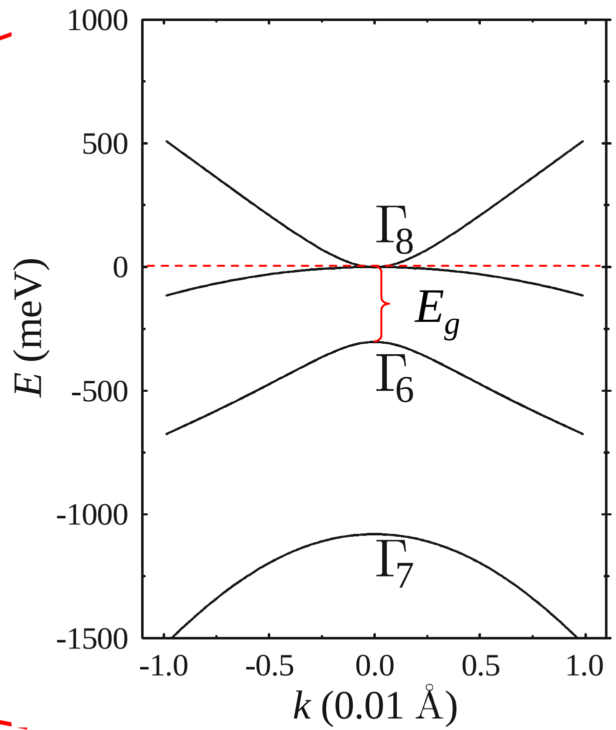
HgTe bulk band structure

band structure



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

semi-metal or semiconductor



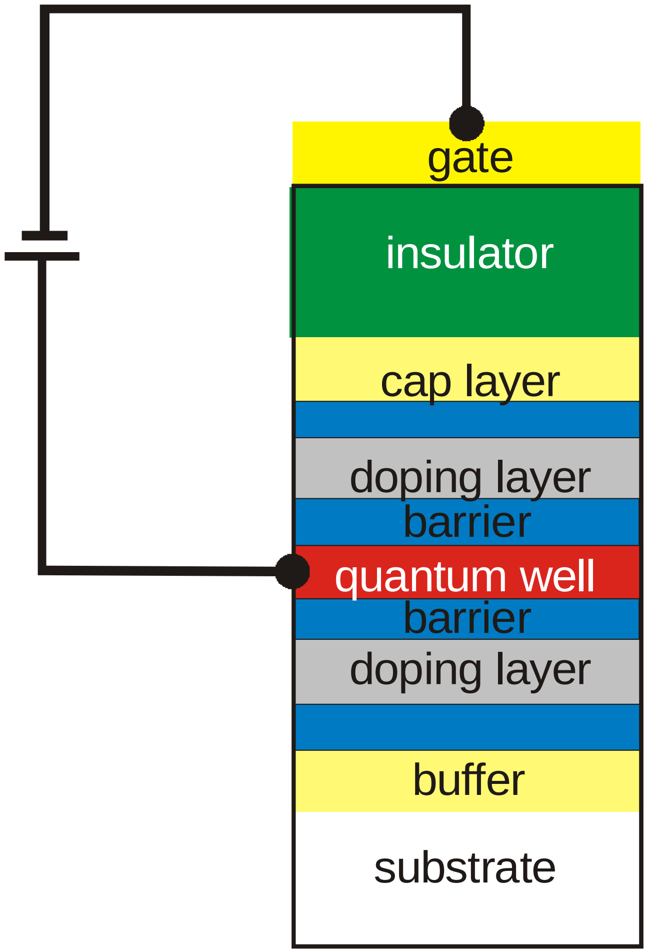
fundamental energy gap

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

Layer Structure

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

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



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

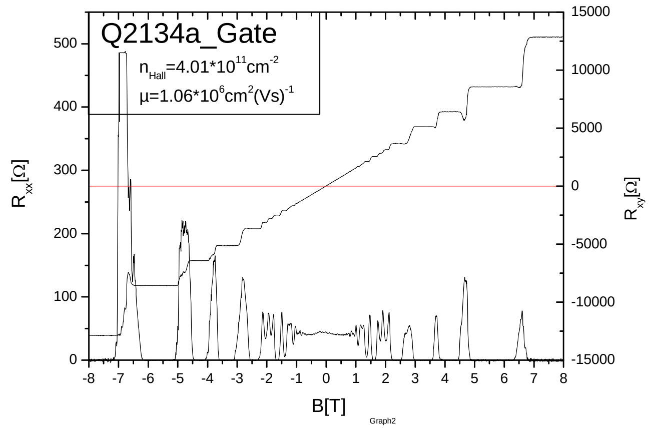
10 nm HgCdTe x = 0.7

9 nm HgCdTe with I

10 nm HgCdTe x = 0.7

25 nm CdTe

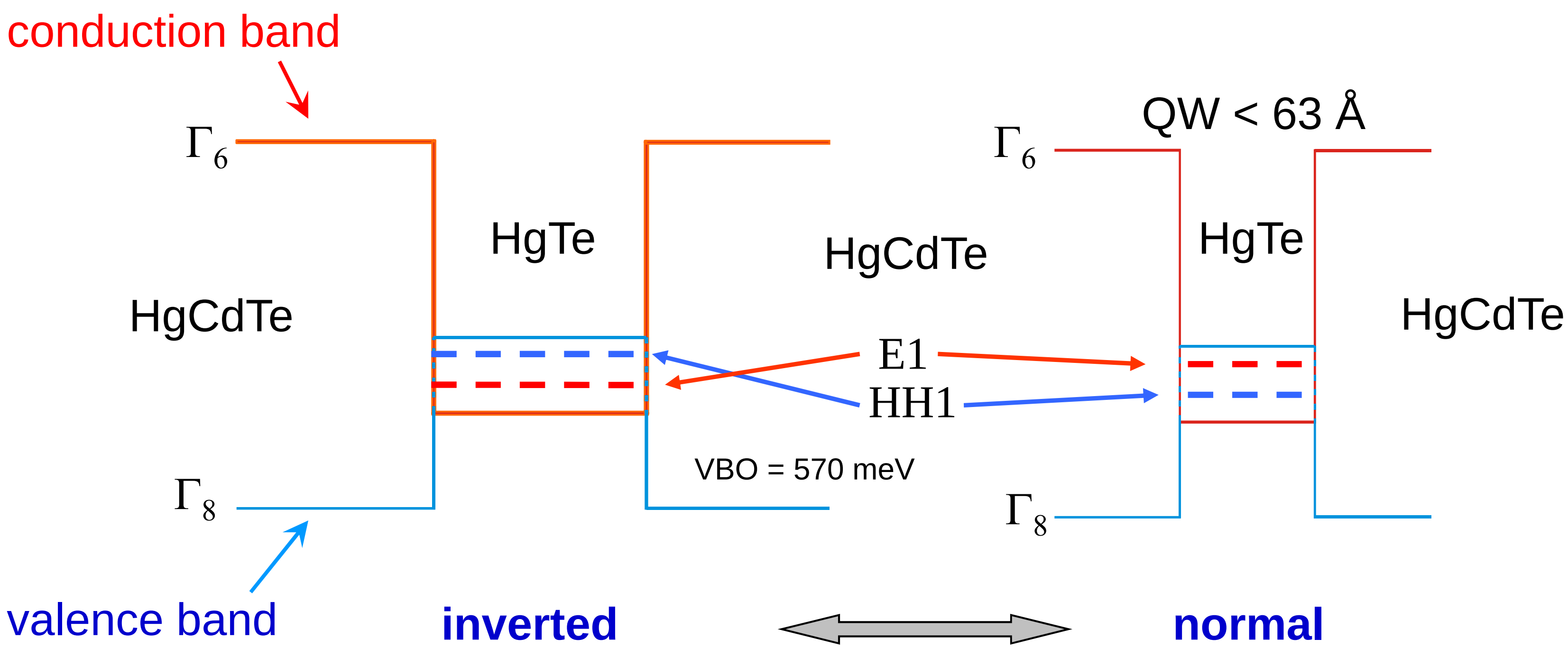
CdZnTe(001)



symmetric or asymmetric doping

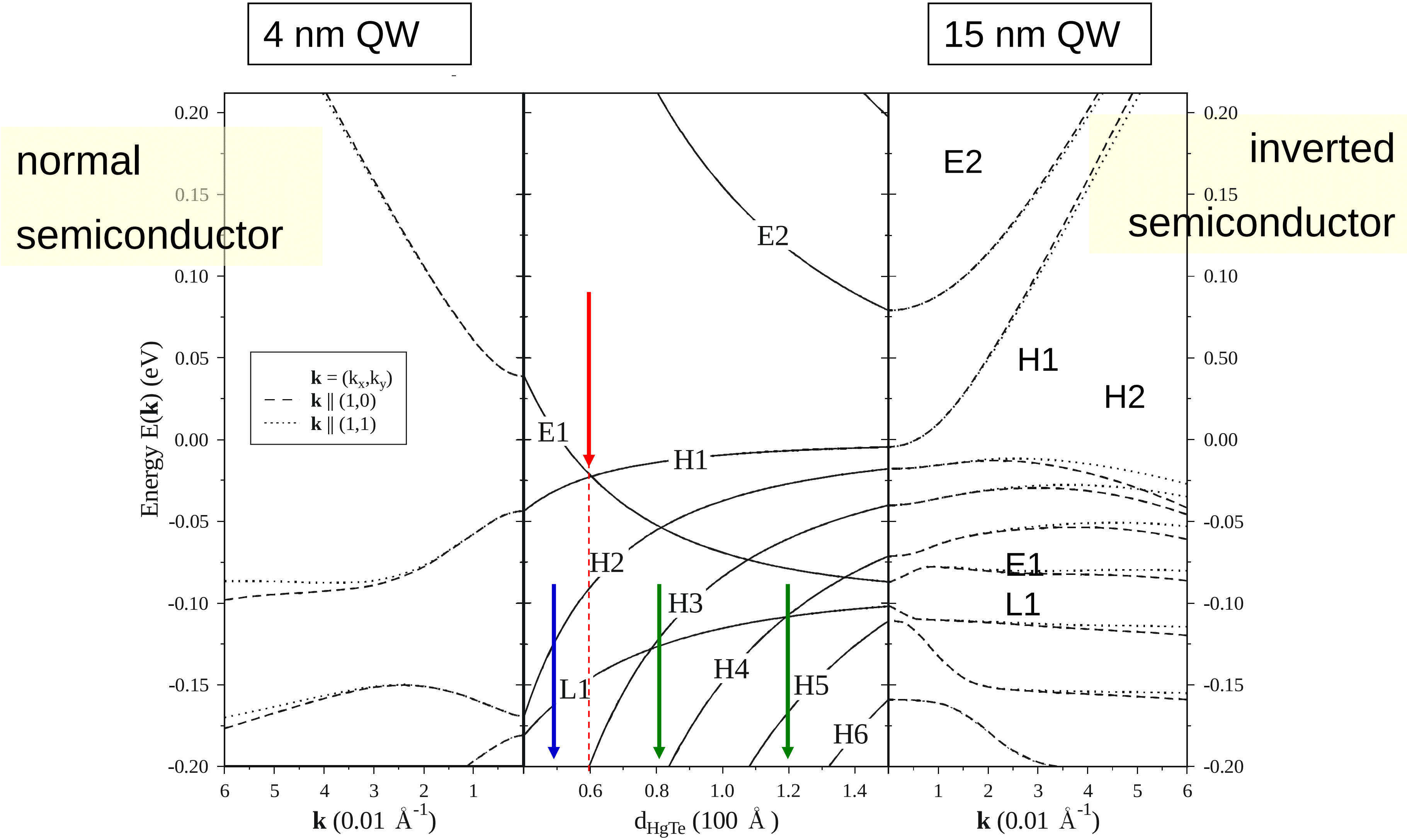
HgTe-Quantum Wells

Type-III QW



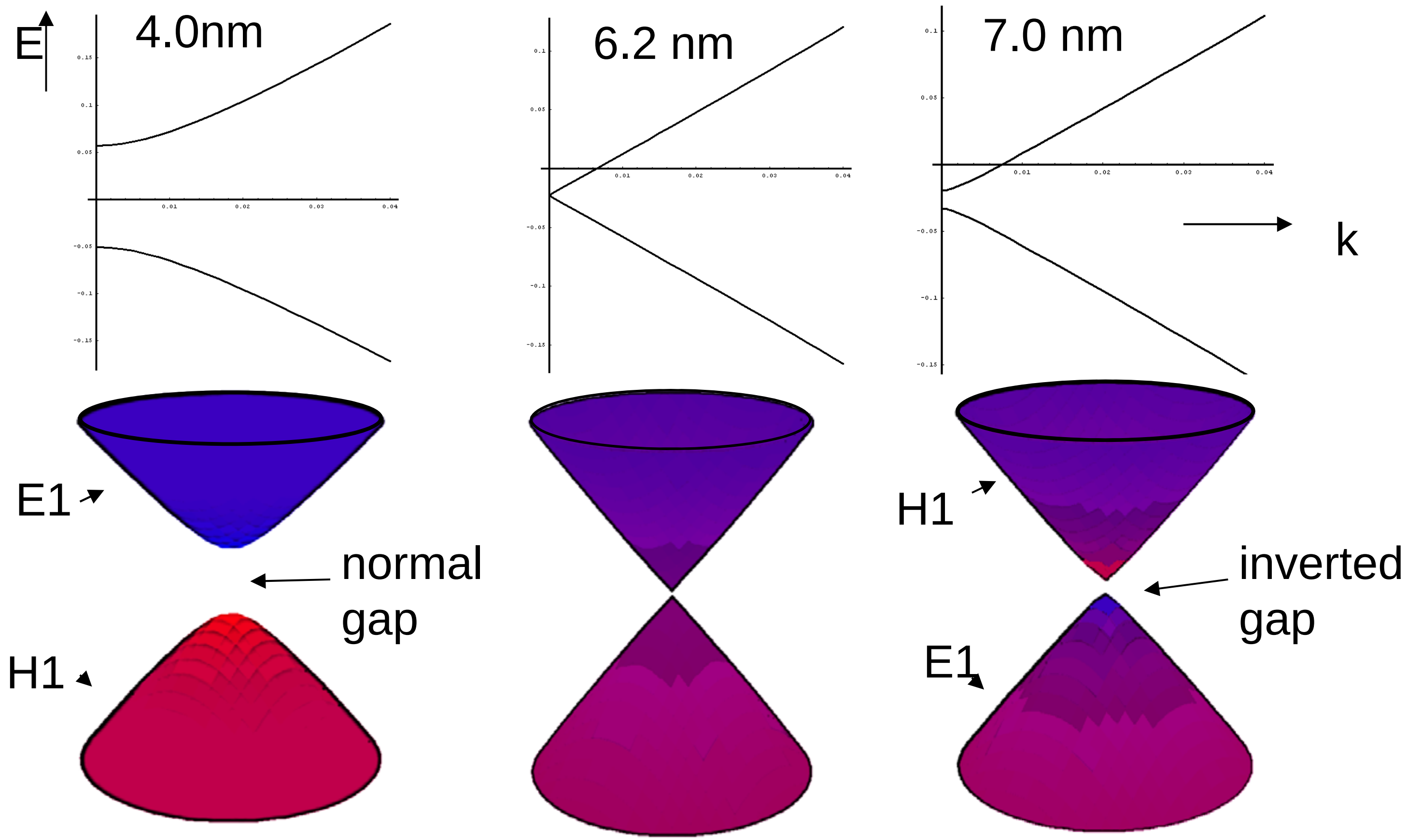
band structure

QW Band Structure from k.p Model



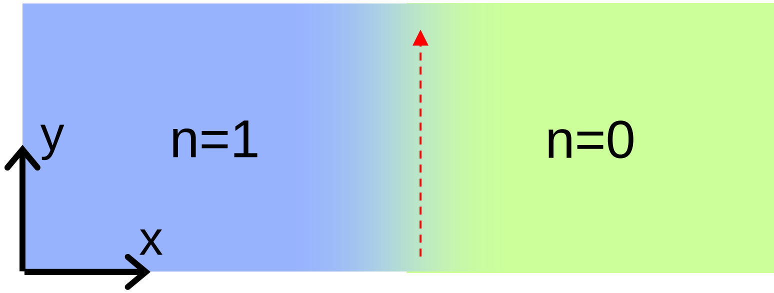
Dirac Bandstructure near d_c

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



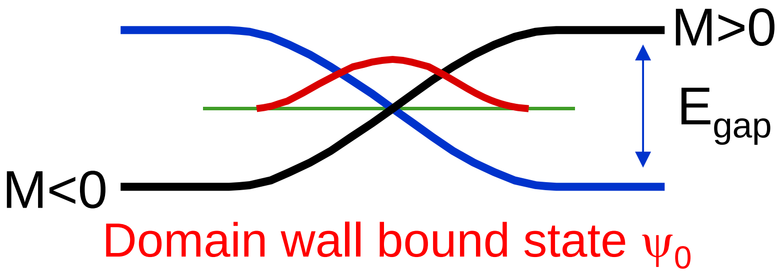
Edge States

Gapless states must exist at the interface between different topological phases



Smooth transition : gap must pass through zero

Band inversion – Dirac Equation



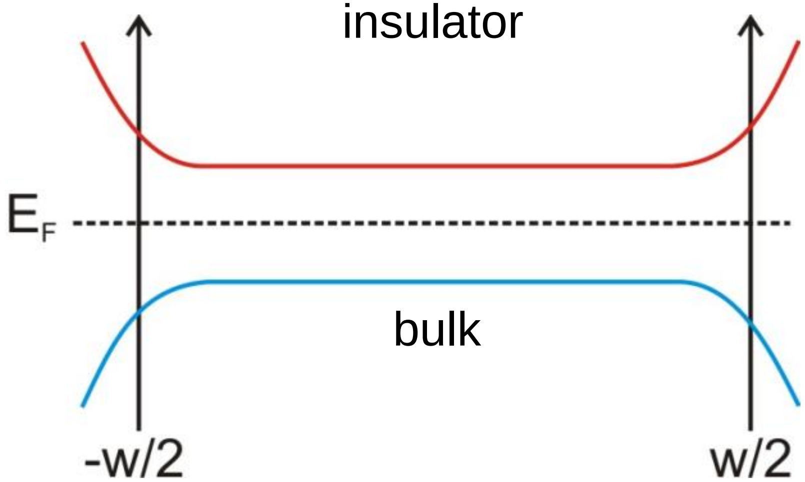
Jackiw, Rebbi (1976)
Su, Schrieffer, Heeger (1980)

This is the zero B-field generalization of the Quantum Hall effect:
the Quantum Spin Hall Effect

QSHE, Simplified Picture

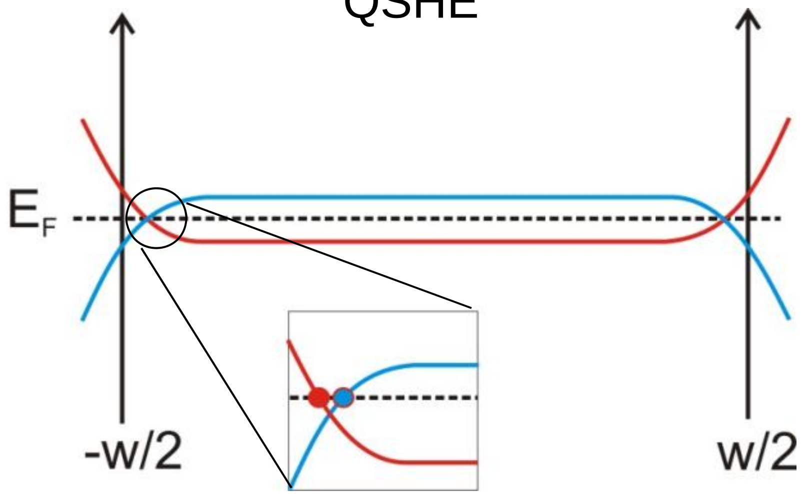
m > 0

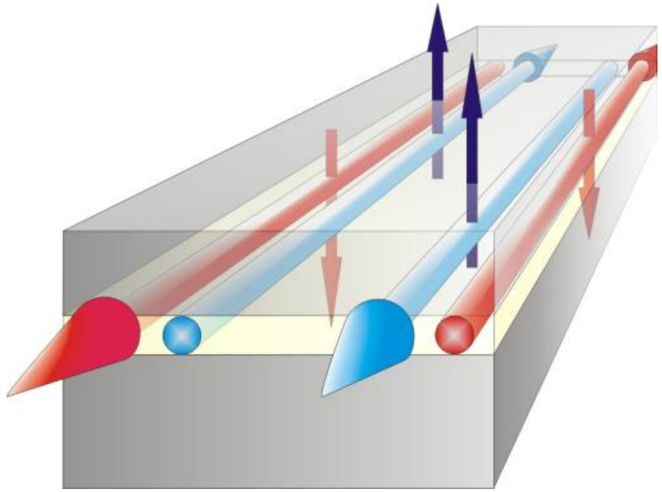
normal insulator



m < 0

QSHE

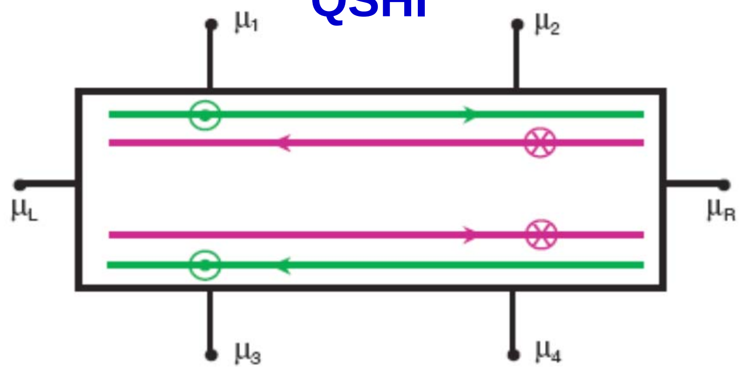


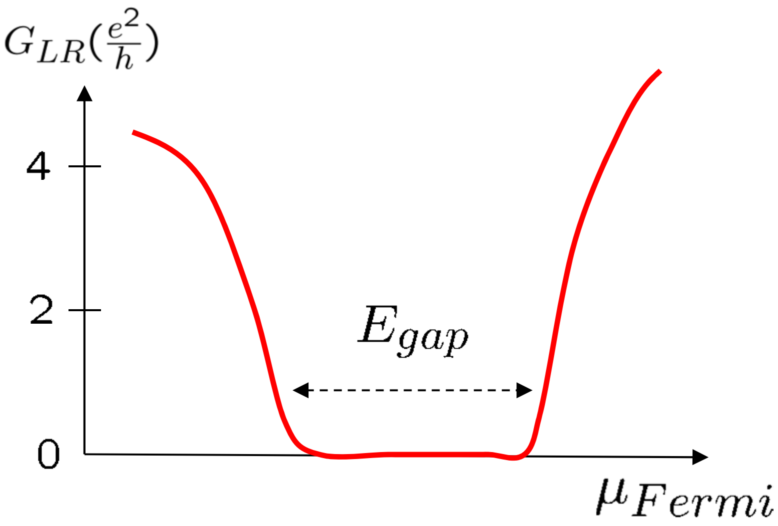


Experimental Signature

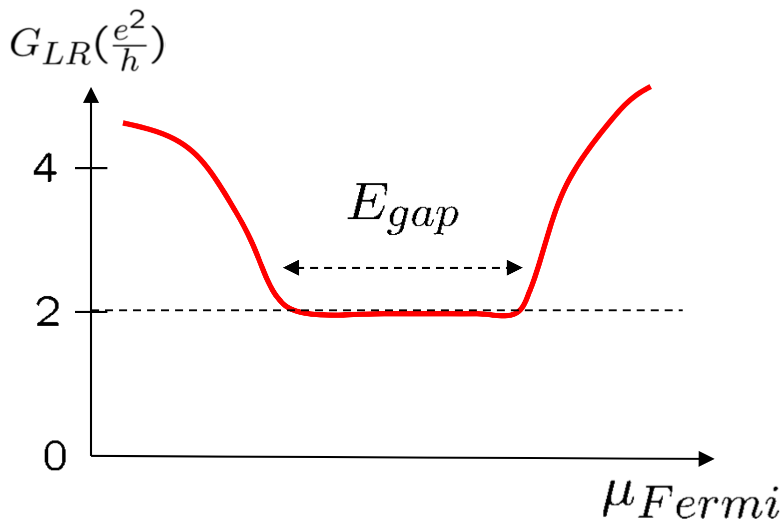
normal insulator state

QSHI



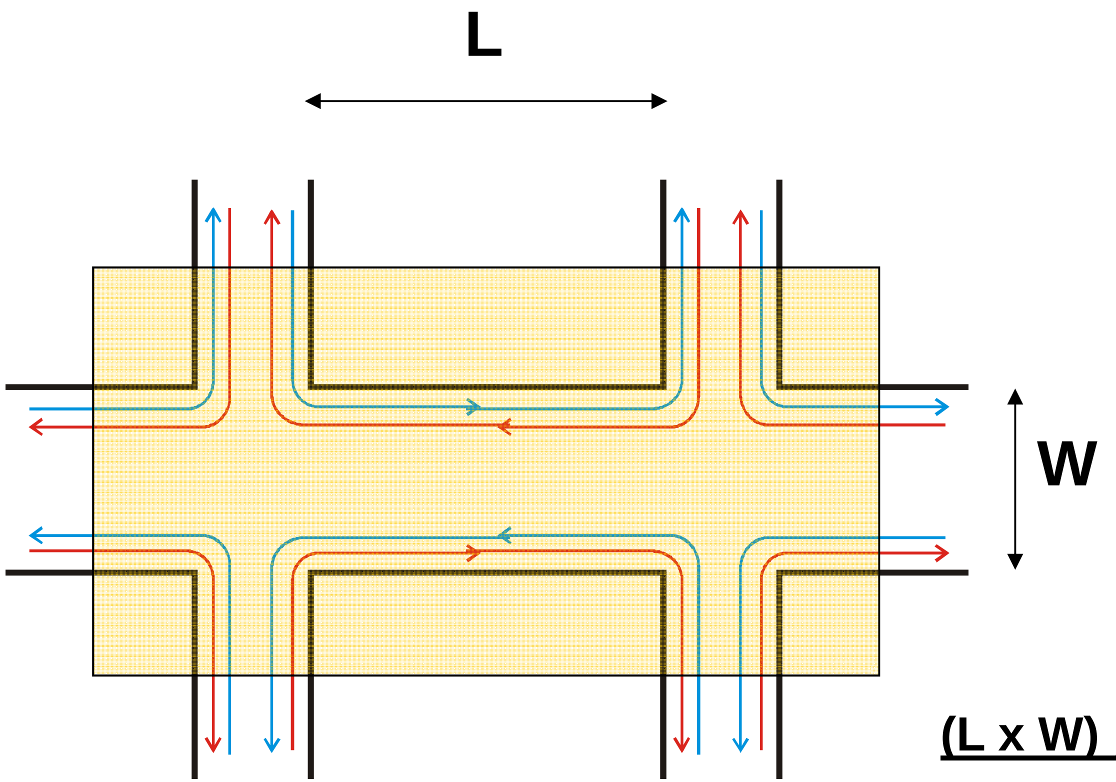


$d < d_c$, normal regime



$d > d_c$, inverted regime

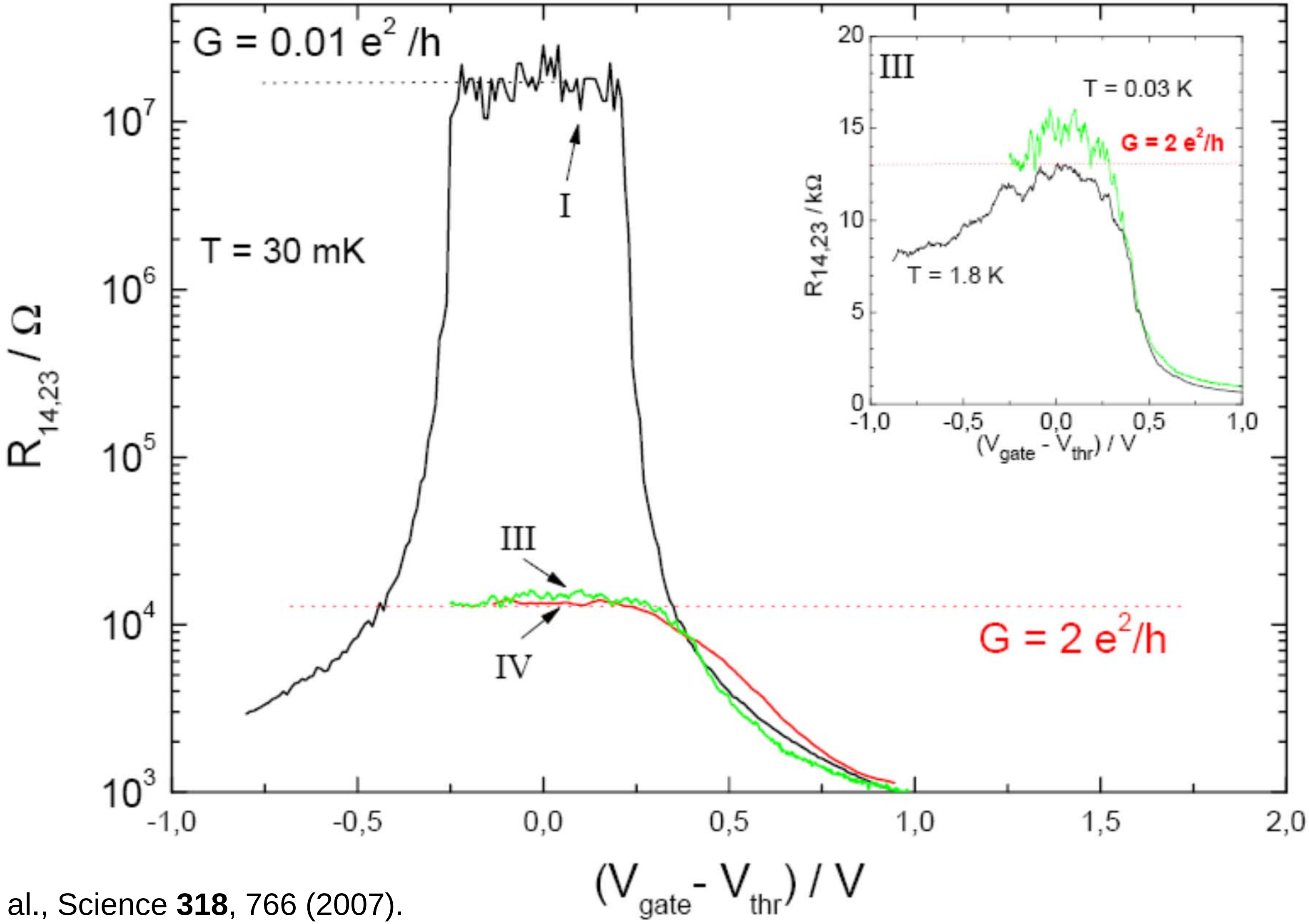
Need small Samples



(L x W) μm

2.0 x 1.0 μm
1.0 x 1.0 μm
1.0 x 0.5 μm

First Observation of QSHI state

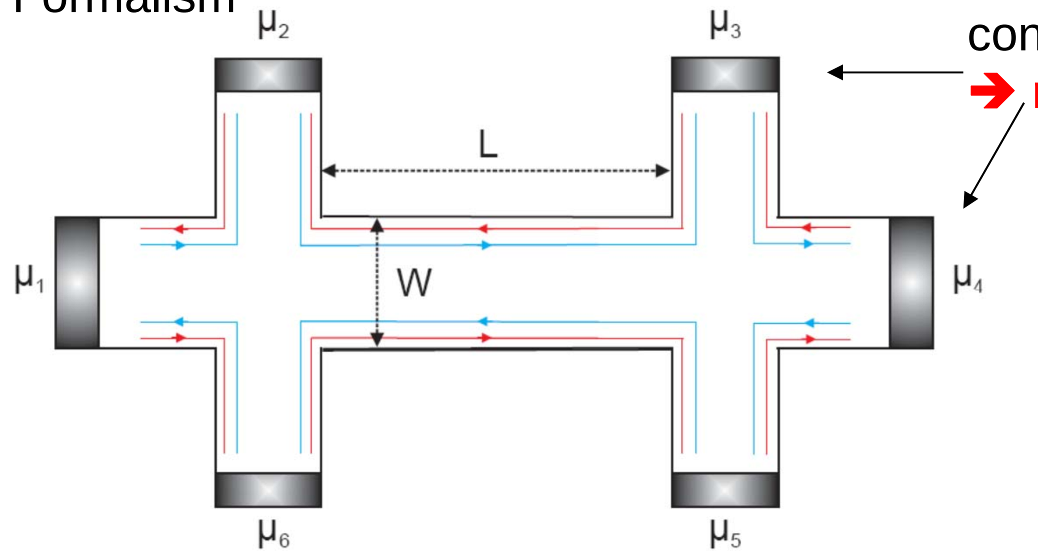


M. König et al., Science **318**, 766 (2007).

Multi-Terminal Probe

Landauer-Büttiker Formalism

normal
conducting contacts
➔ **no QSHE**



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

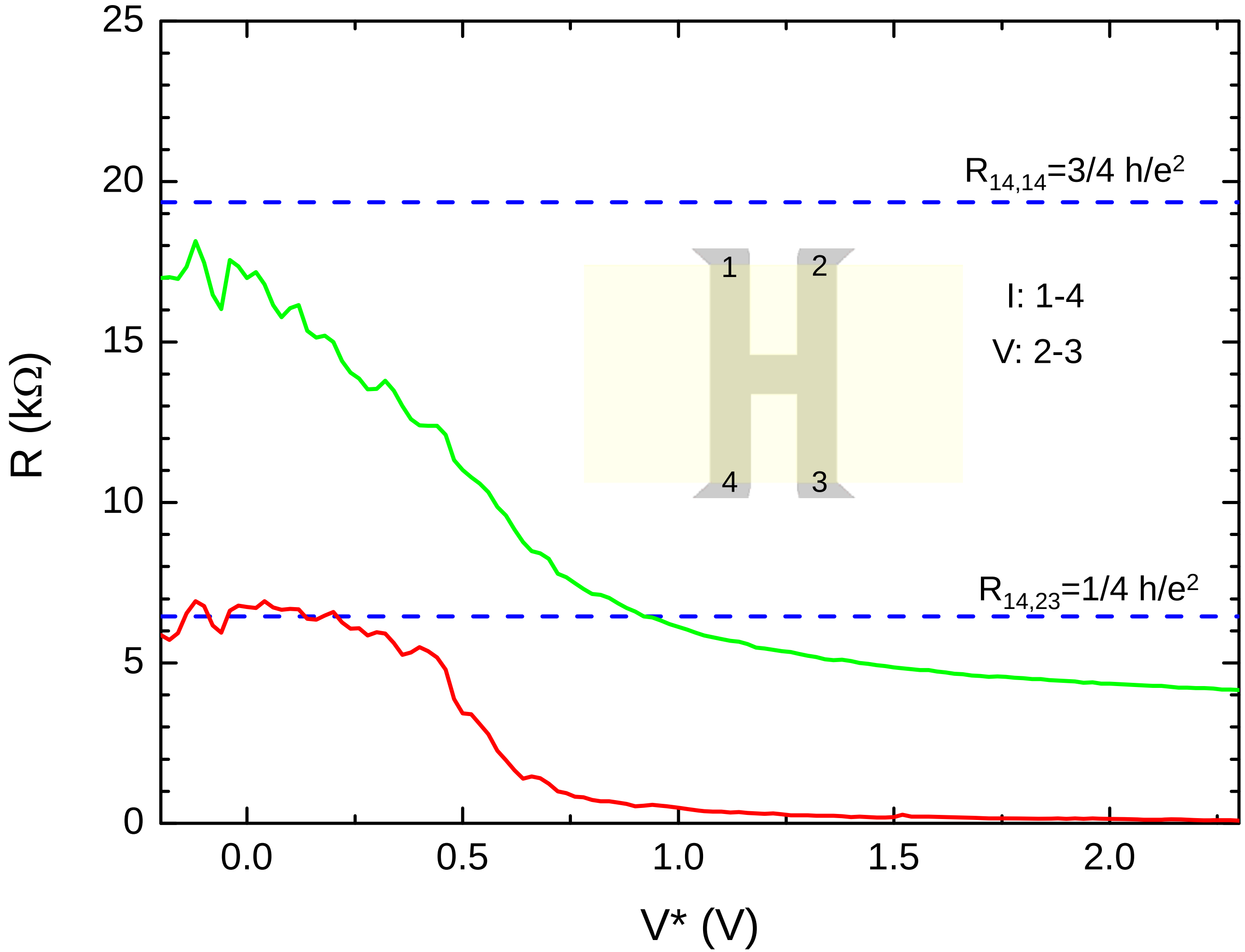
generally

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

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

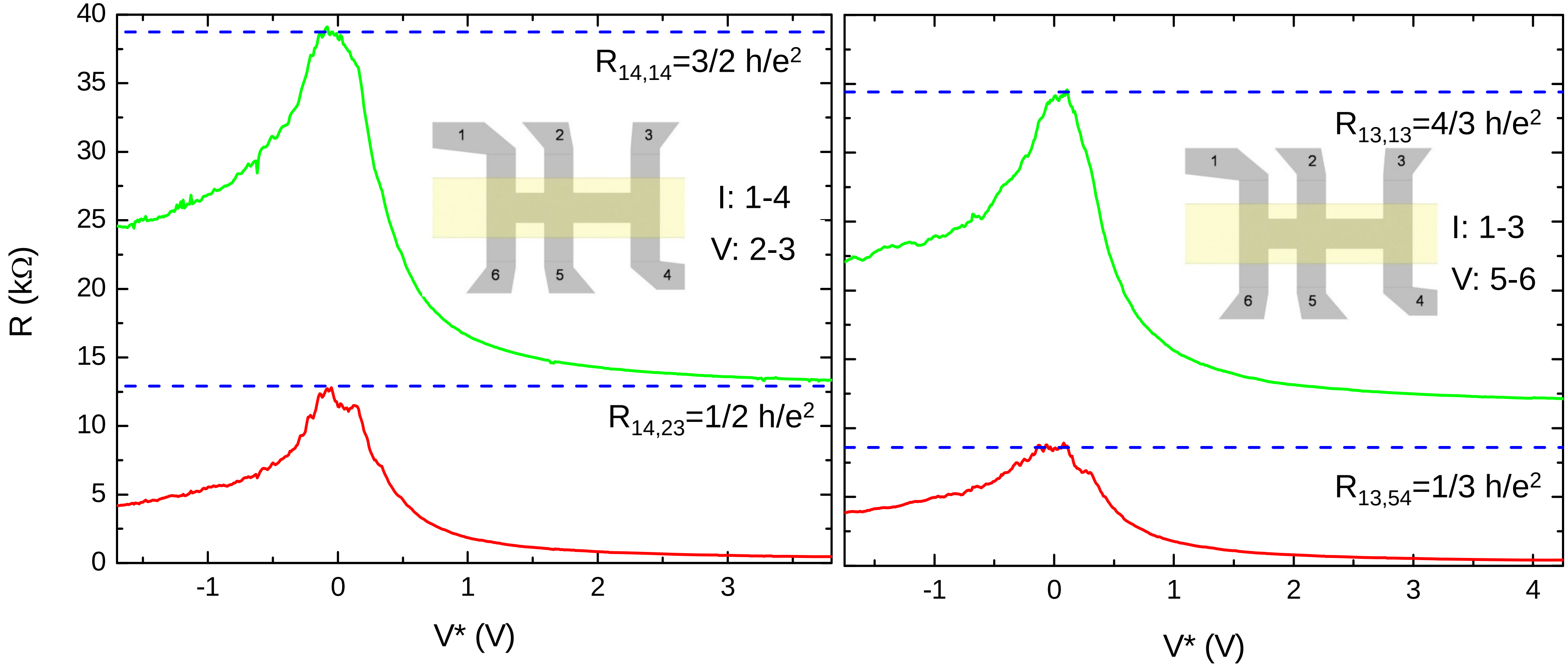
$$\left.\frac{R_{2t}}{R_{4t}}\right|_{\exp} \approx 3$$

Non-Local data on H-bar



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

Multi-Terminal Measurements



Configurations would be equivalent in quantum adiabatic regime

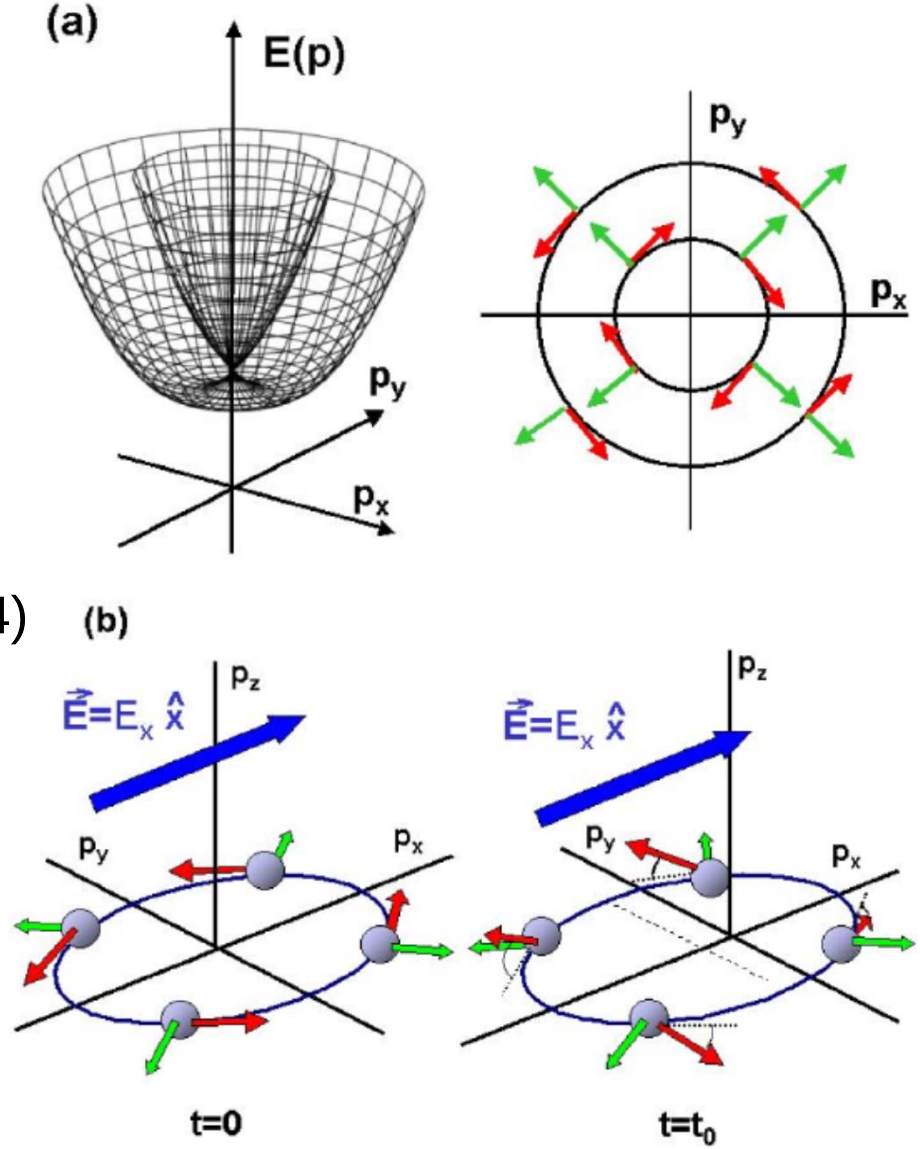
A. Roth et al., Science **325**, 294 (2009).

Metallic Spin-Hall Effect

Intrinsic SHE

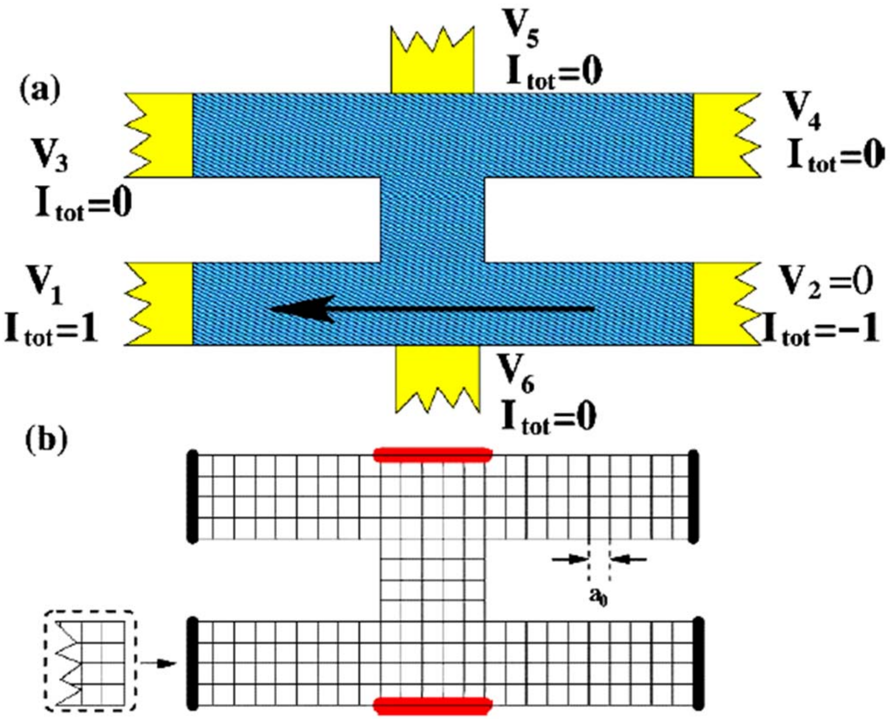
Rashba effect

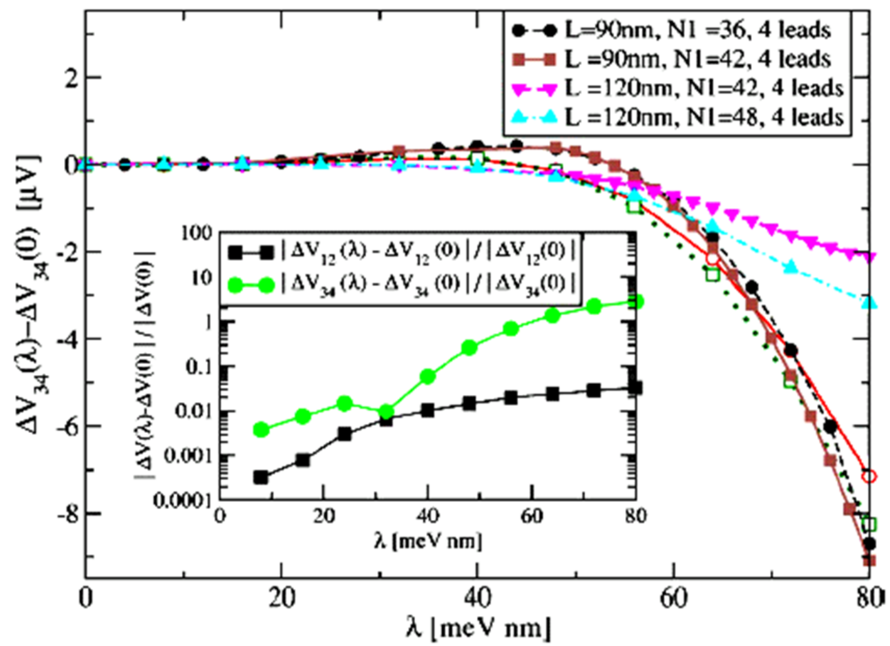
J.Sinova et al.,
Phys. Rev. Lett. **92**, 126603 (2004)



H-bar for detection of Spin-Hall-Effect

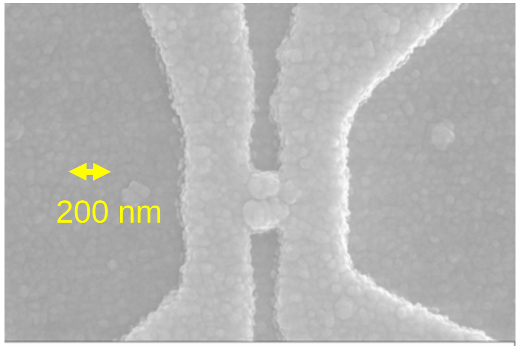
(electrical detection through inverse SHE)

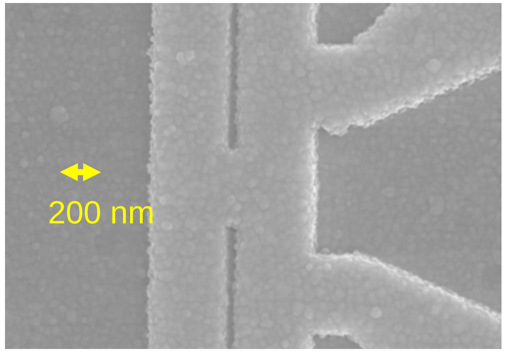


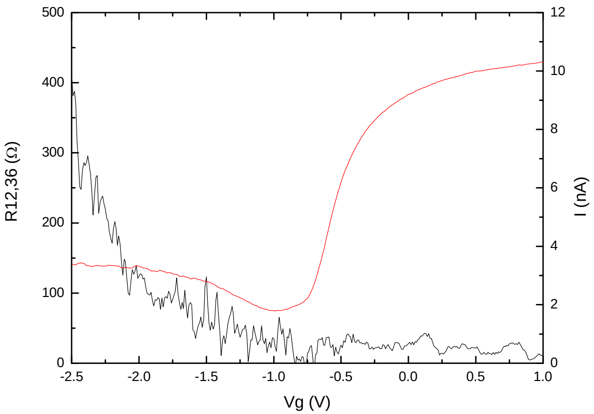


E.M. Hankiewicz et al ., PRB **70**, R241301 (2004)

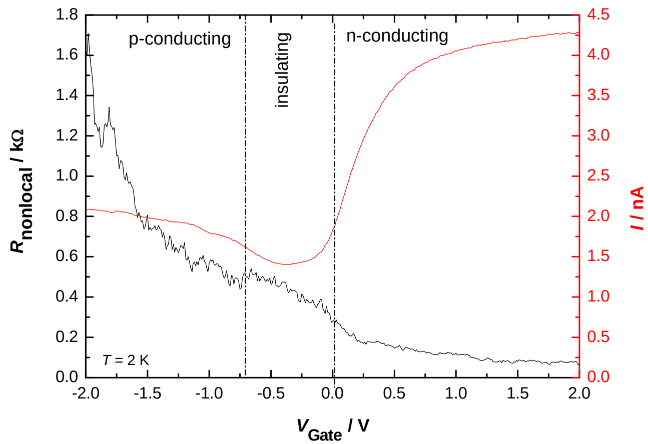
H-bar experiments







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

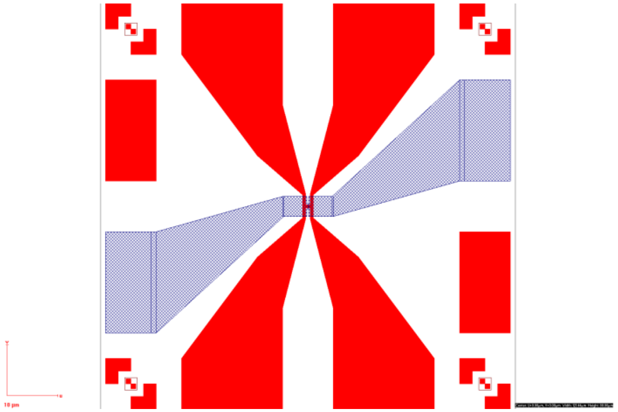


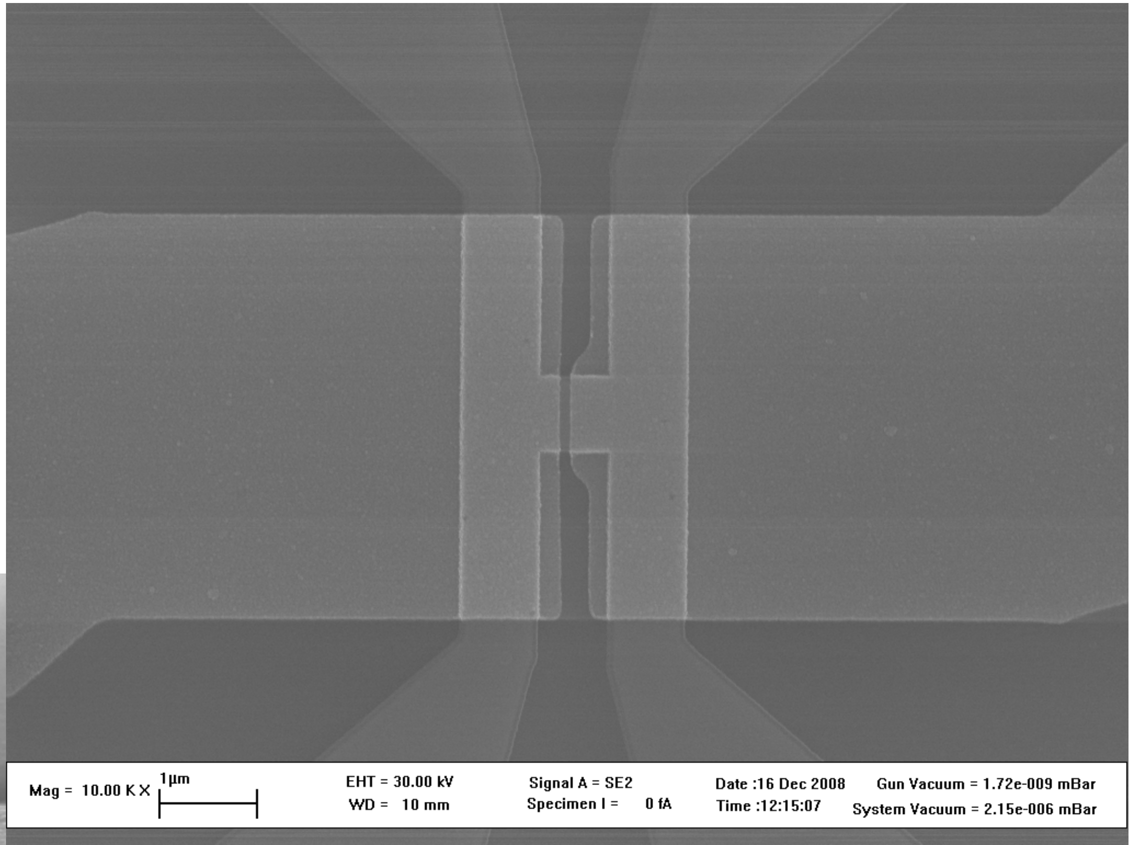
– Suppress non-local QSHE using long leads or narrow wires

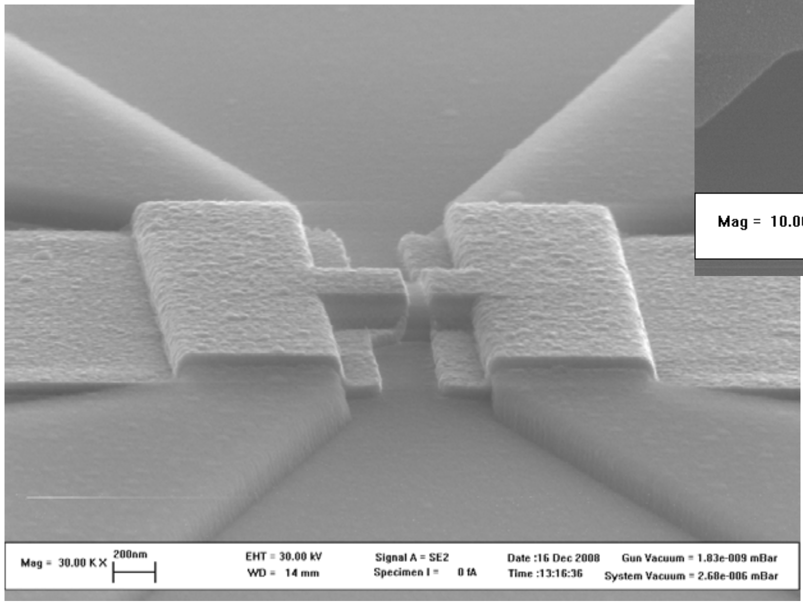
– Intrinsic metallic SHE only shows up for holes: larger spin-orbit

– Amplitude in agreement with modeling (E. Hankiewicz, J. Sinova)

QSHE and iSHE as spin injector and detector

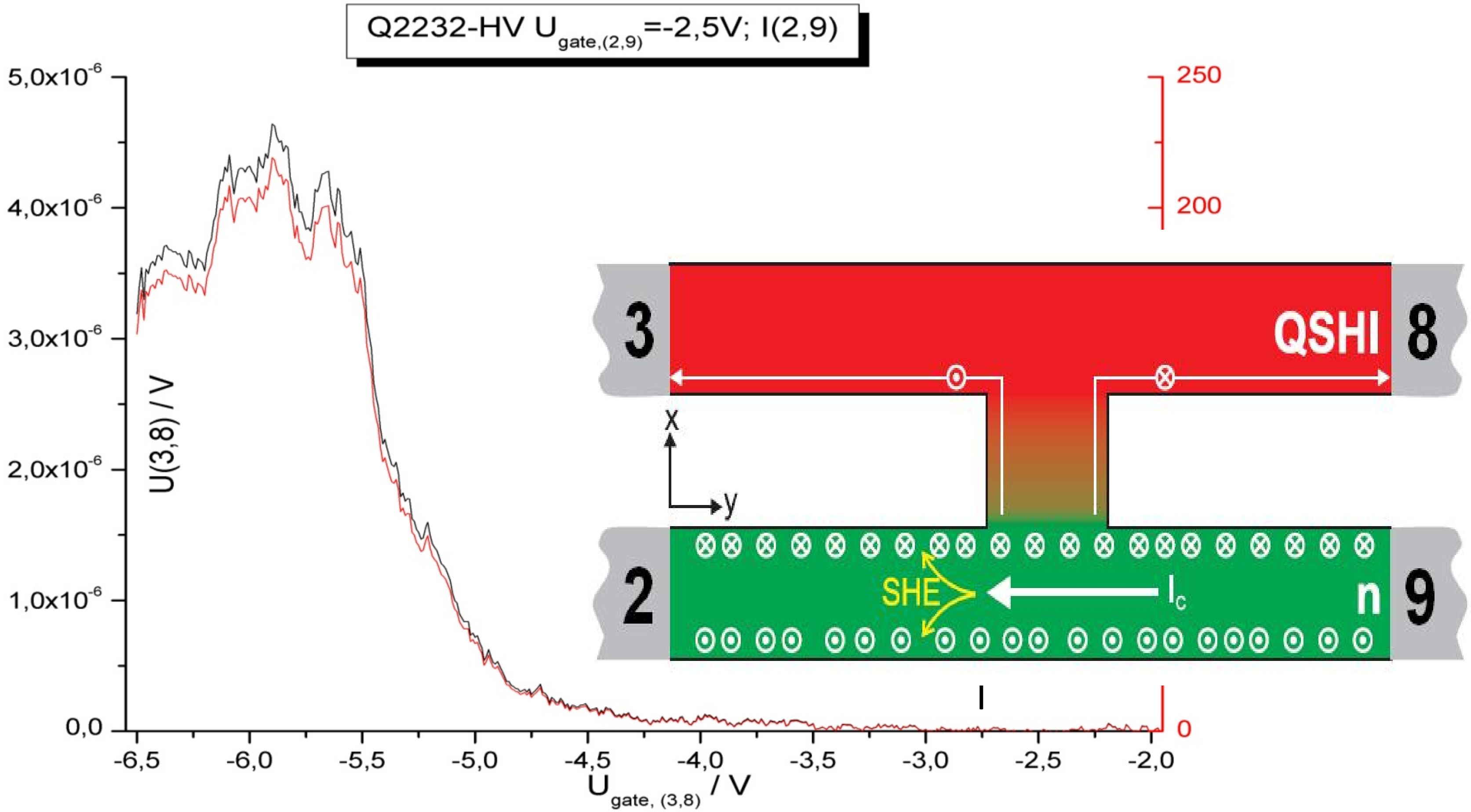






Split-gated H-bar

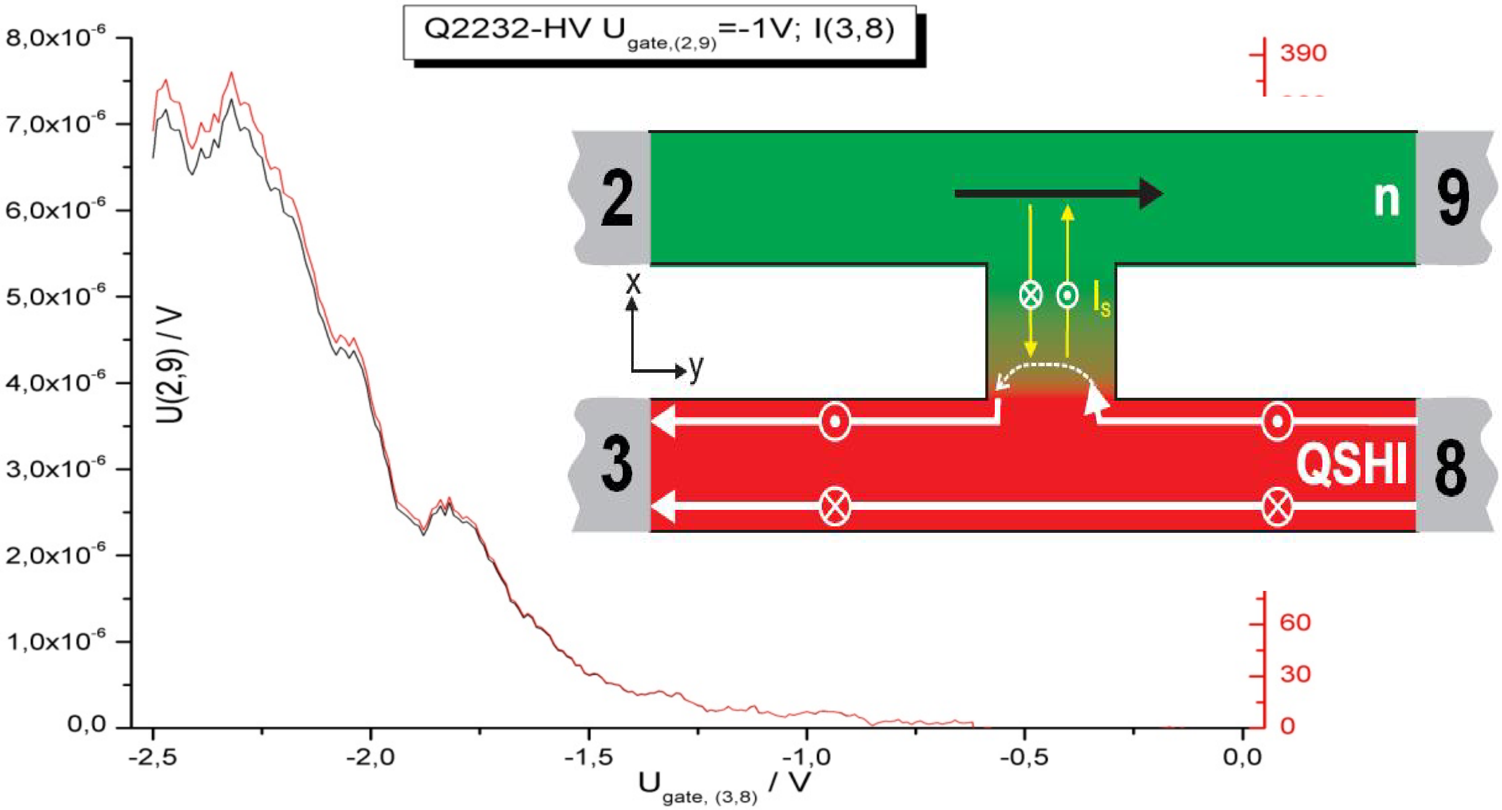
Detect iSHE through QSHI edge channels



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

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

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)

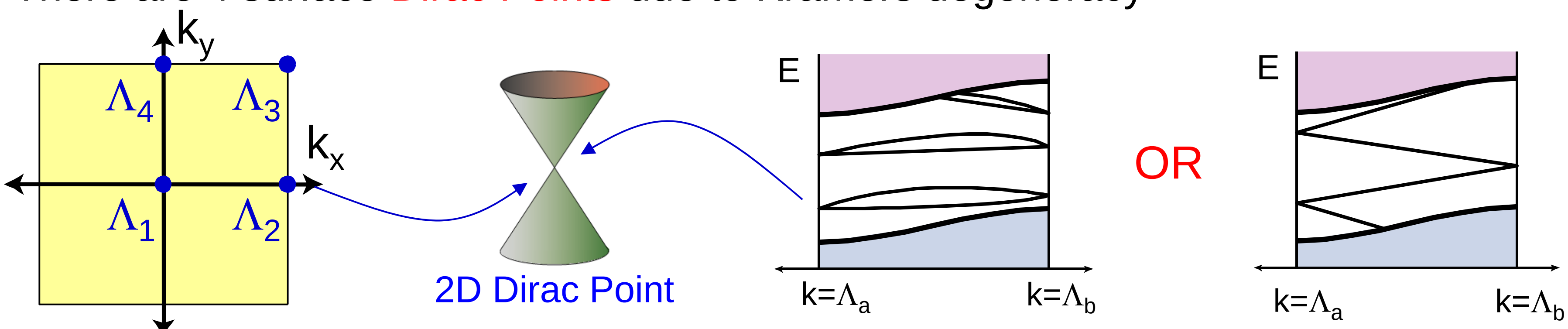
From traffic jam to info-superhighway on chip

Traffic jam inside chips today

Info highways for the chips in the future

3D Topological Insulators

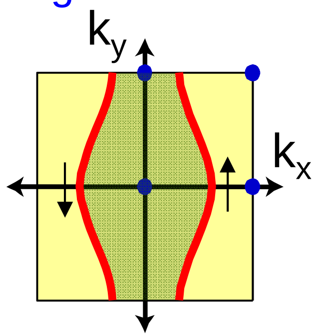
There are 4 surface Dirac Points due to Kramers degeneracy



Surface Brillouin Zone

How do the Dirac points connect? Determined by 4 bulk Z_2 topological invariants ν_0 ; $(\nu_1\nu_2\nu_3)$

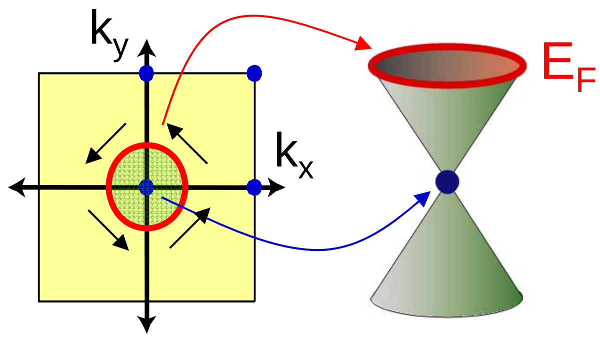
$\nu_0 = 0$: Weak Topological Insulator



Related to layered 2D QSHI ; $(\nu_1\nu_2\nu_3)$ ~ Miller indices

Fermi surface encloses even number of Dirac points

$\nu_0 = 1$: Strong Topological Insulator



Fermi circle encloses odd number of Dirac points

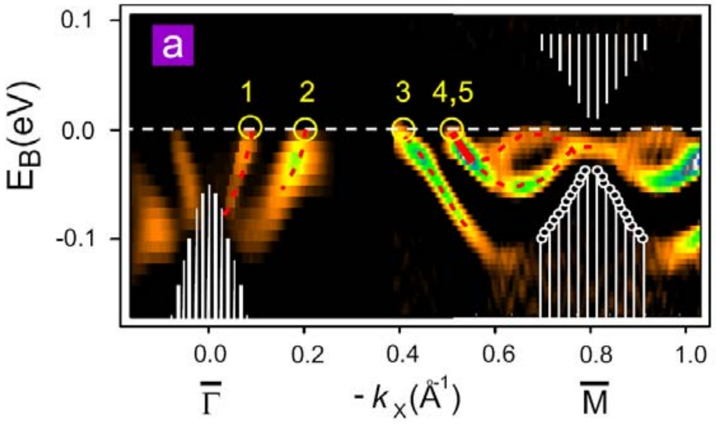
Topological Metal :

- 1/4 graphene
- Berry's phase π
- Robust to disorder: impossible to localize

$Bi_{1-x}Sb_x$

Theory: Predict $Bi_{1-x}Sb_x$ is a topological insulator by exploiting inversion symmetry of pure Bi, Sb (Fu,Kane PRL'07)

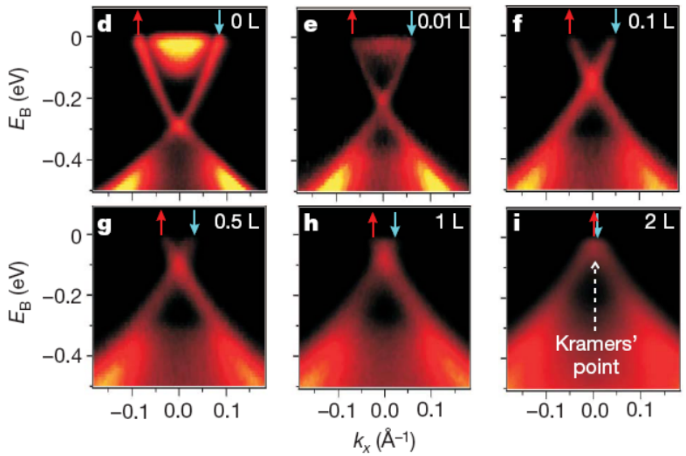
Experiment: ARPES (Hsieh et al. Nature '08)



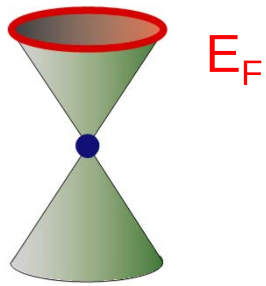
- $Bi_{1-x}Sb_x$ is a Strong Topological Insulator $\nu_0;(\nu_1,\nu_2,\nu_3) = 1;(111)$
- 5 surface state bands cross E_F between Γ and M

Bi_2Se_3

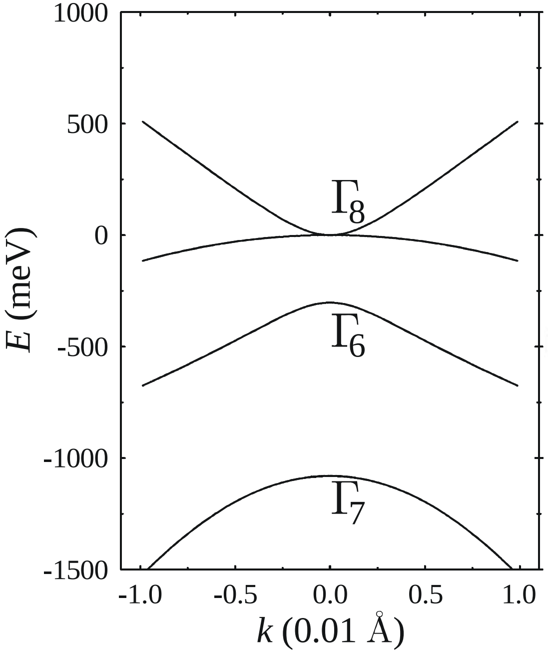
ARPES Experiment : Y. Xia et al., Nature Phys. (2009).
Band Theory : H. Zhang et. al, Nature Phys. (2009).

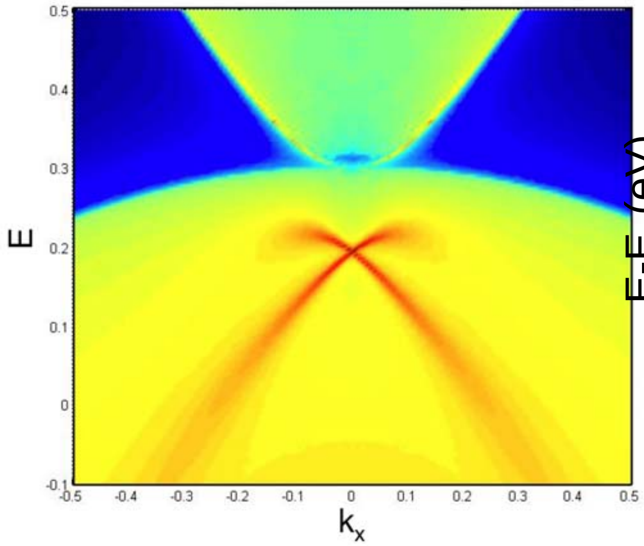


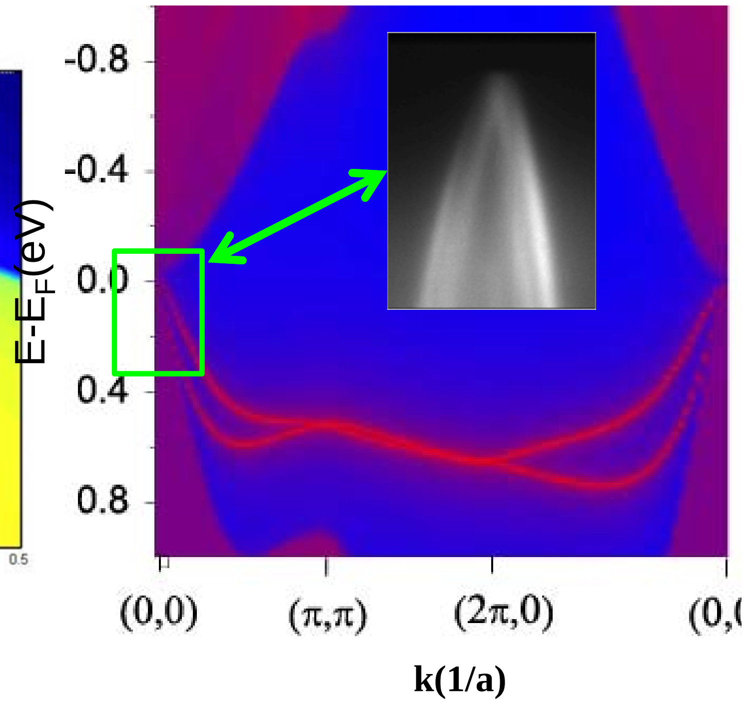
- $\nu_0;(\nu_1,\nu_2,\nu_3) = 1;(000)$: Band inversion at Γ
- Energy gap: $\Delta \sim .3$ eV : A room temperature topological insulator
- Simple surface state structure : Similar to graphene, except only a single Dirac point



Bulk HgTe as a 3-D Topological ‚Insulator'







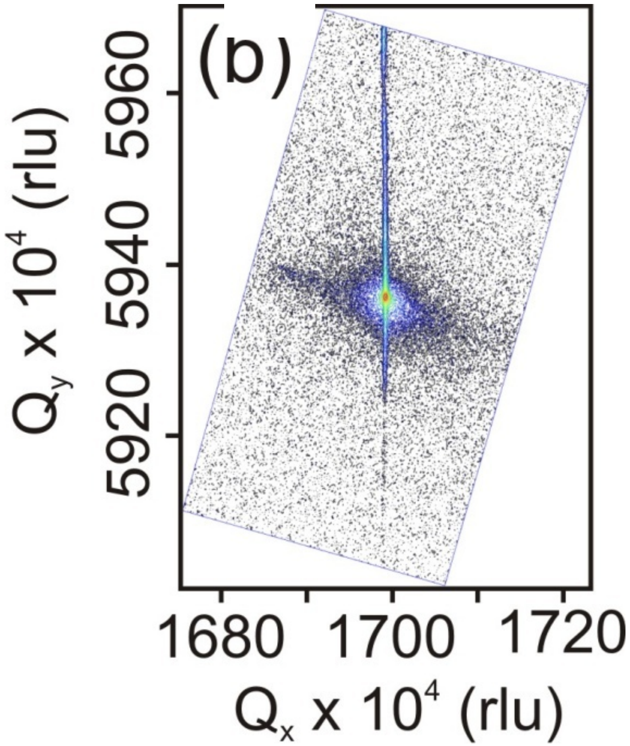
Bulk HgTe is semimetal,

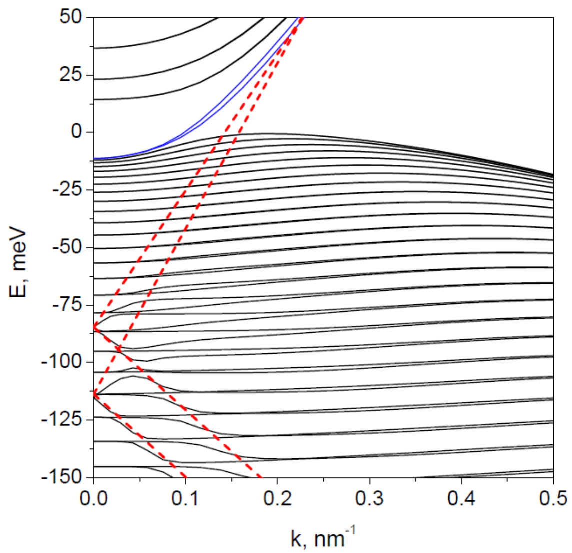
topological surface state overlaps w/ valenceband.

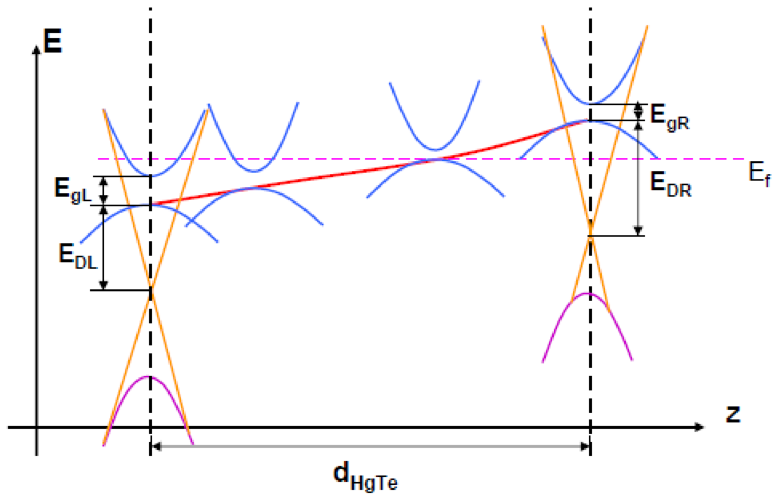
C. Brüne et al., Phys. Rev. Lett. **106**, 126803 (2011).

ARPES:
Yulin Chen, ZX Shen,
Stanford

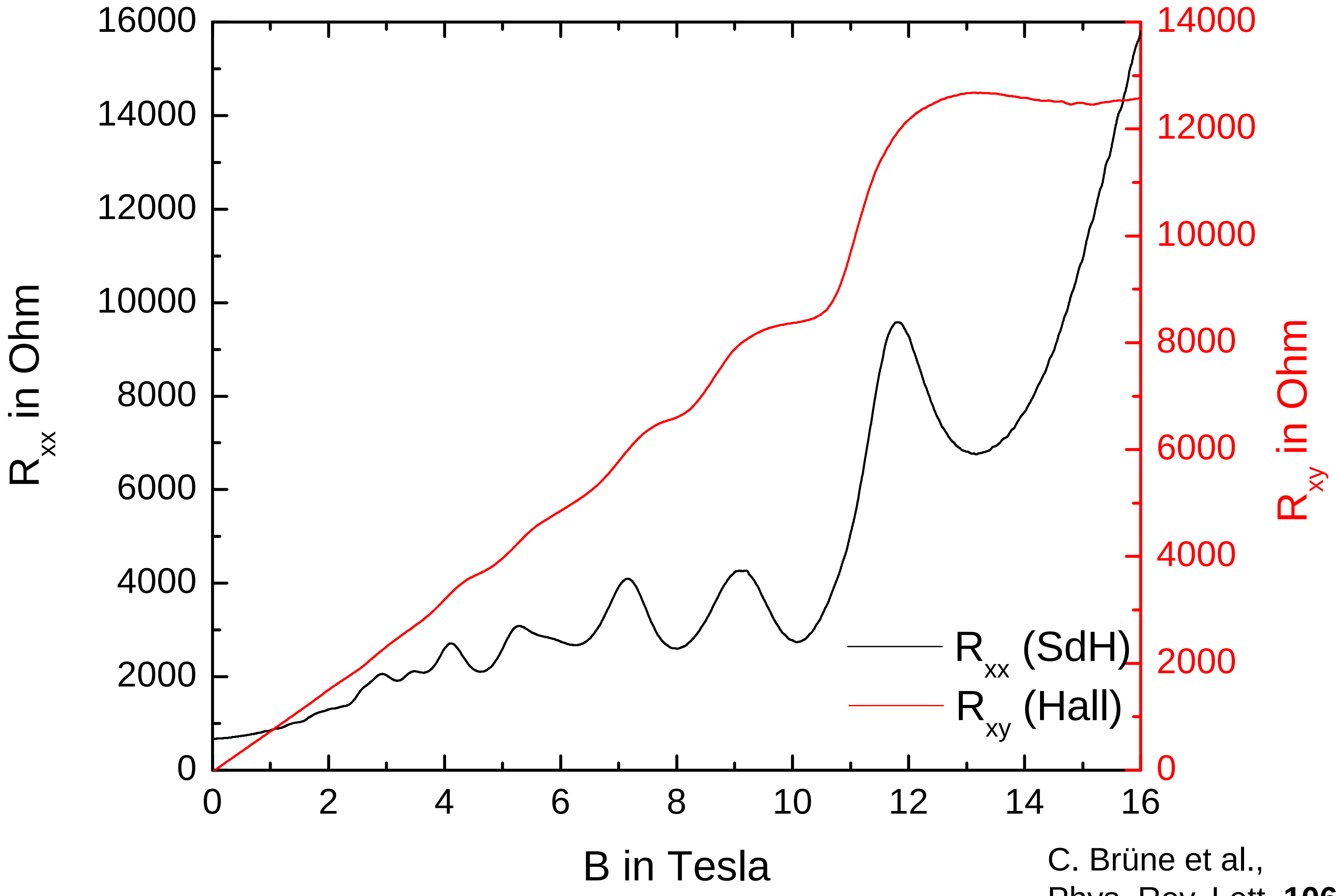
70 nm layer on CdTe substrate:
coherent strain opens gap







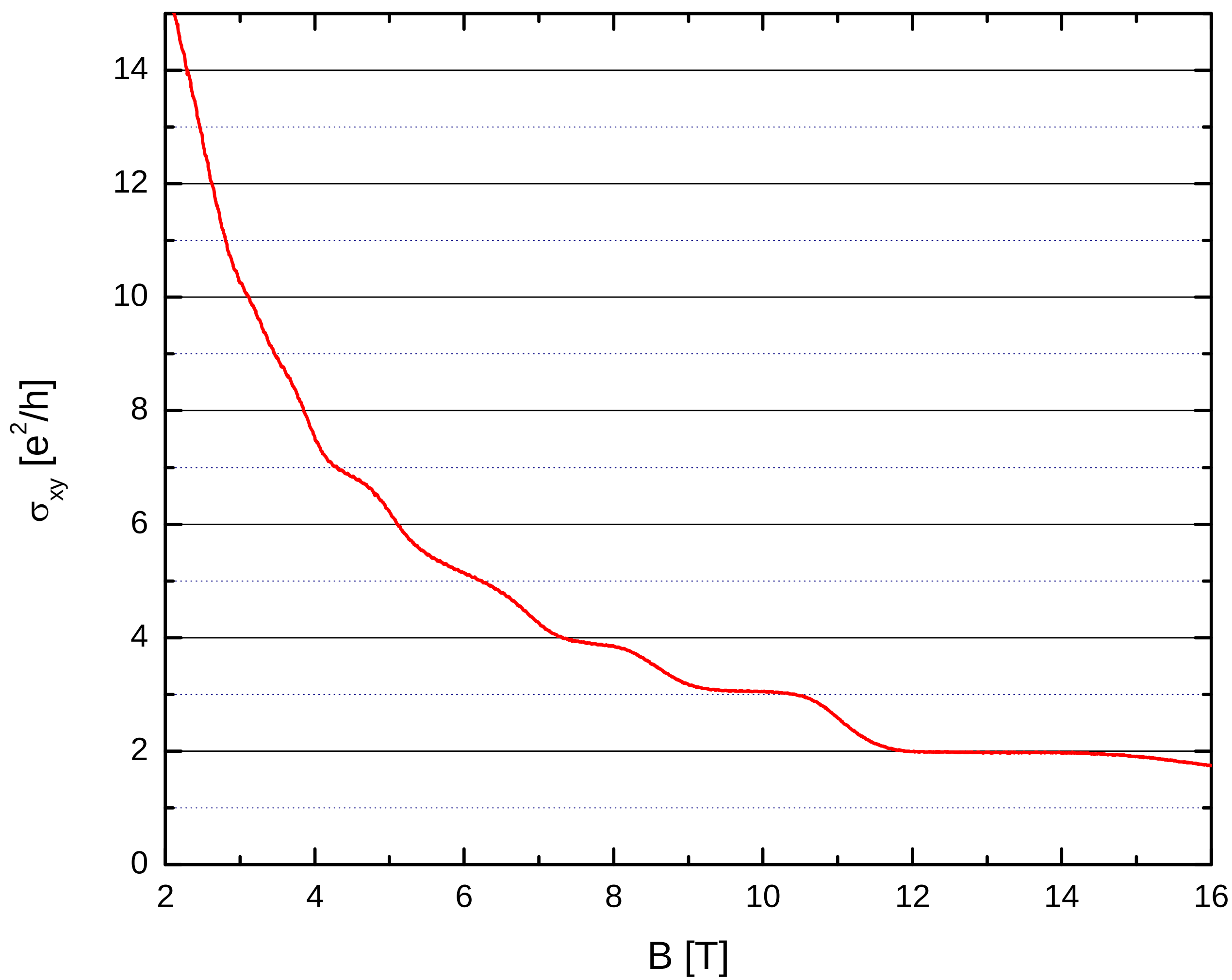
Bulk HgTe as a 3-D Topological 'Insulator'



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

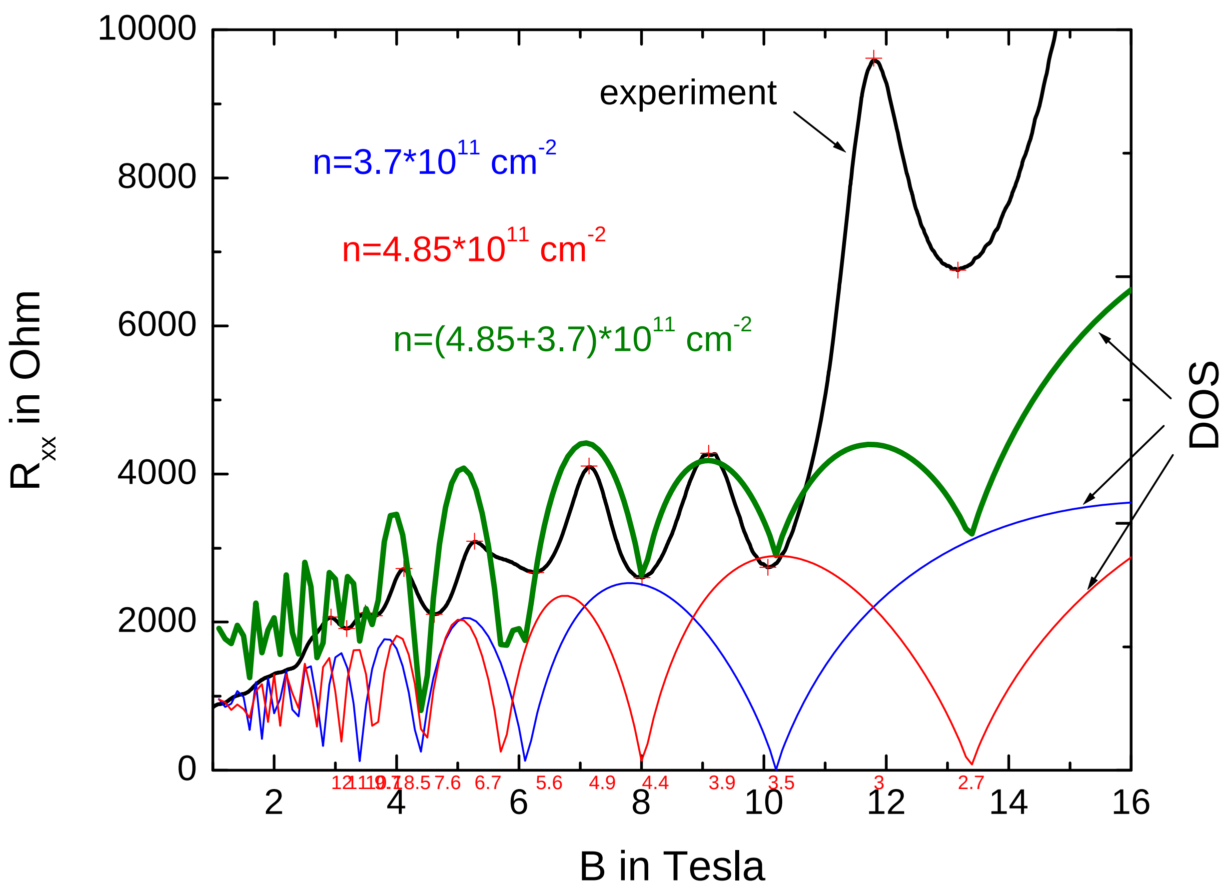
@ 20 mK: bulk conductivity almost frozen out - Surface state mobility ca. 35000 cm^2/Vs

Bulk HgTe as a 3-D Topological ‚Insulator'



@ 20 mK: same data, plotted as conductivity

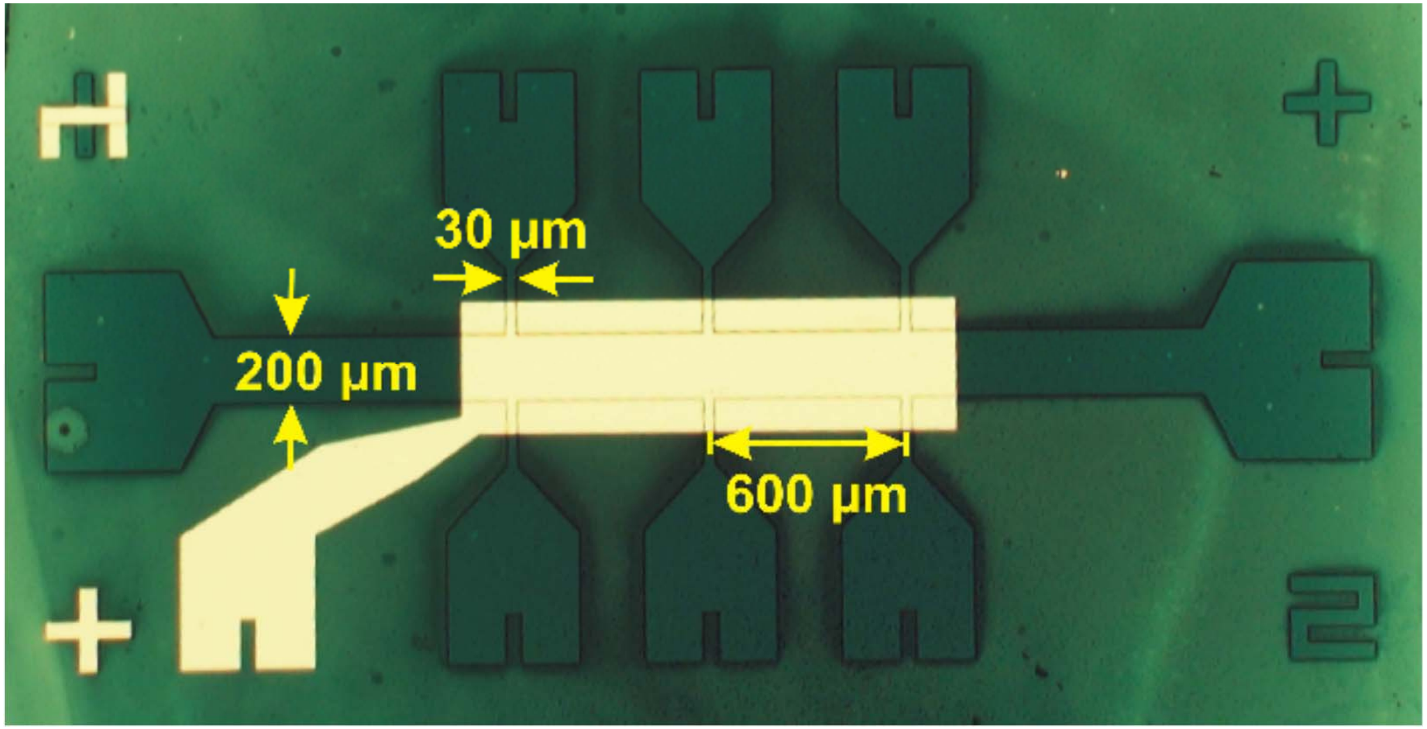
3D HgTe-calculations



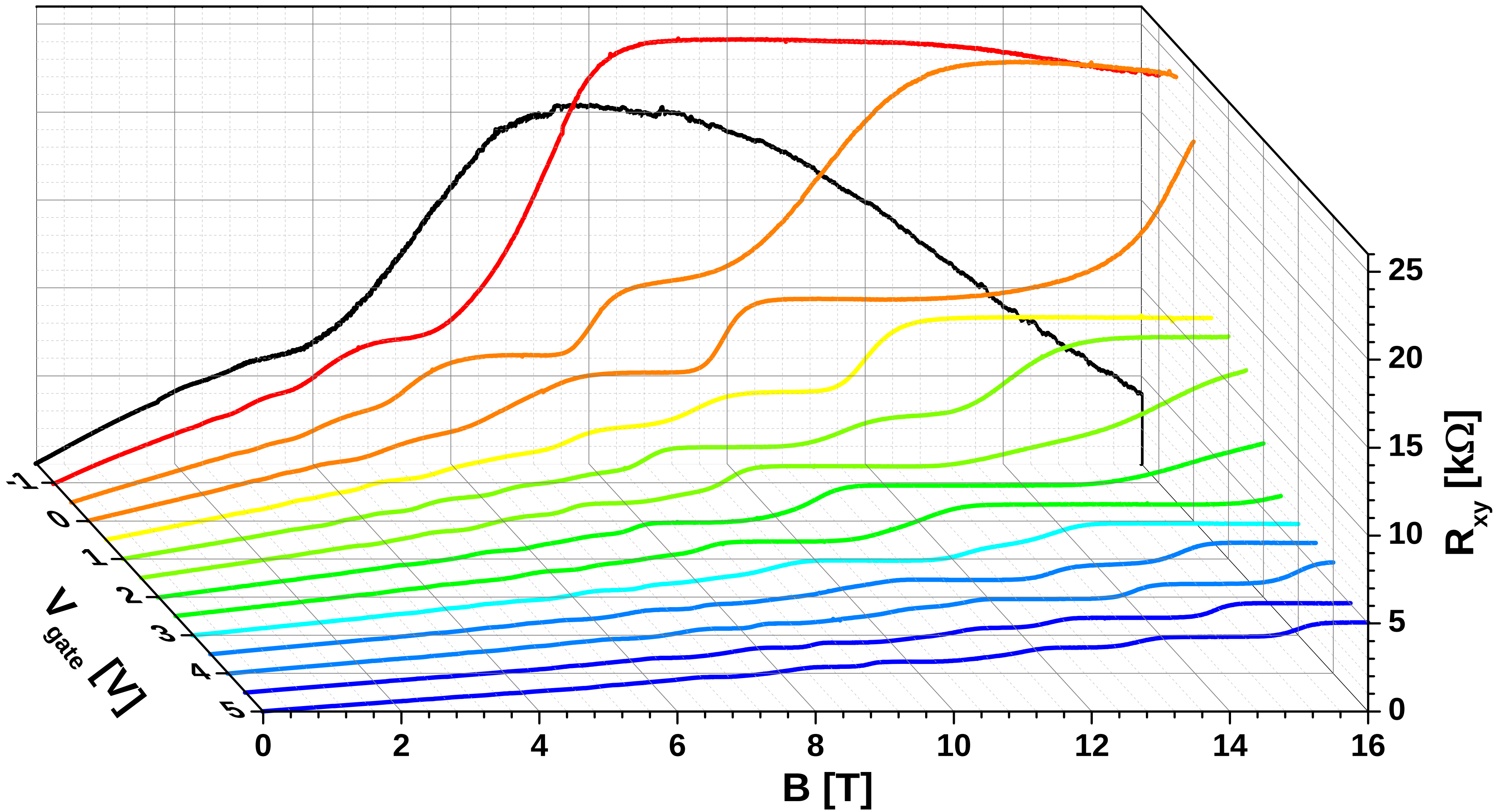
C. Brüne et al., Phys. Rev. Lett. **106**, 126803 (2011).

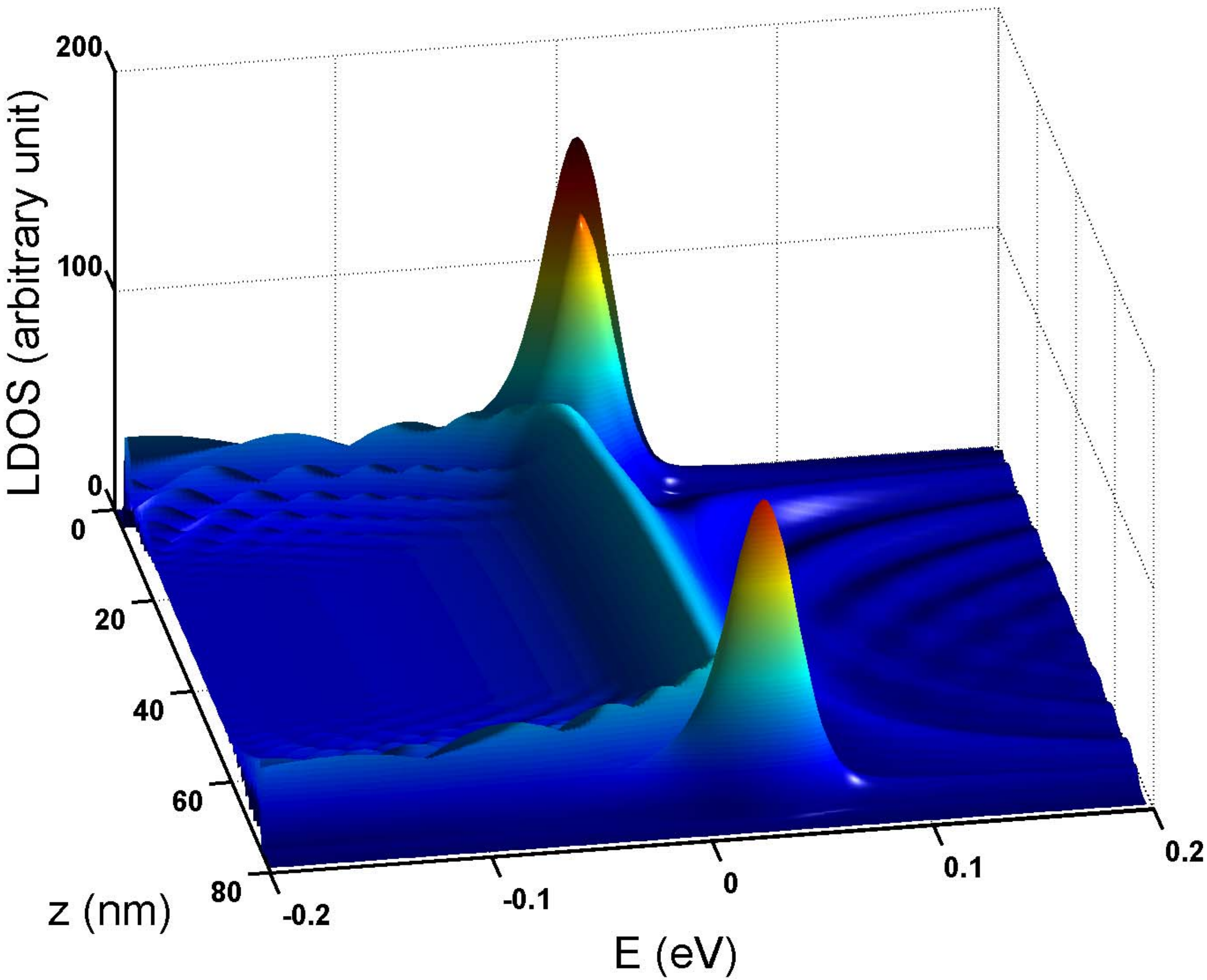
Red and blue lines : DOS for each of the Dirac-cones with the corresponding fixed 2D-density,
Green line: the sum of the blue and red lines

Experiments on a gated Hallbar



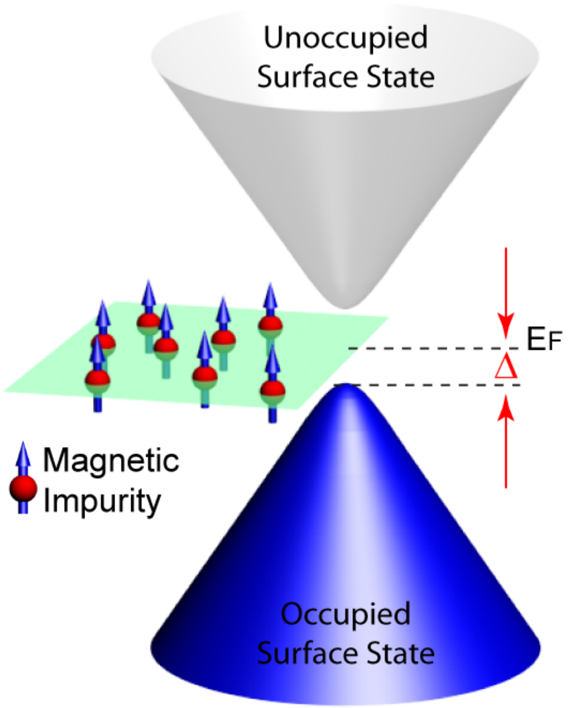
Rxy from -1.5V to 5V

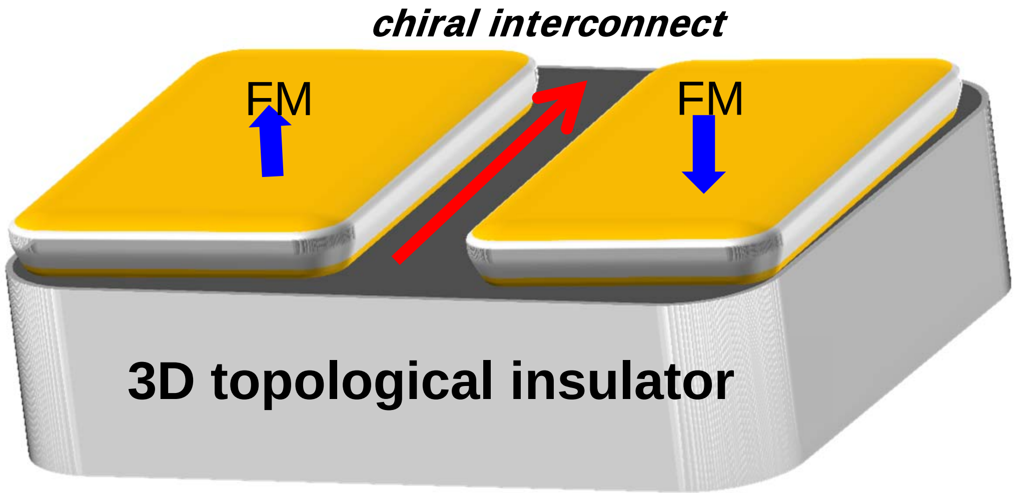




LDOS (arbitrary unit)
200
100
0
0
20
40
60
80
z (nm)
-0.2
-0.1
0
0.1
0.2
E (eV)

Applications of TI in IT



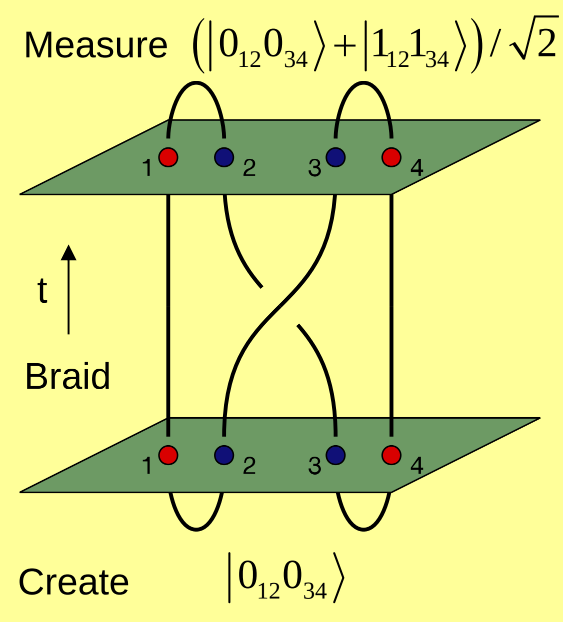


Topological chiral interconnects

Majorana Fermions

Topological Quantum Computing Kitaev, 2003

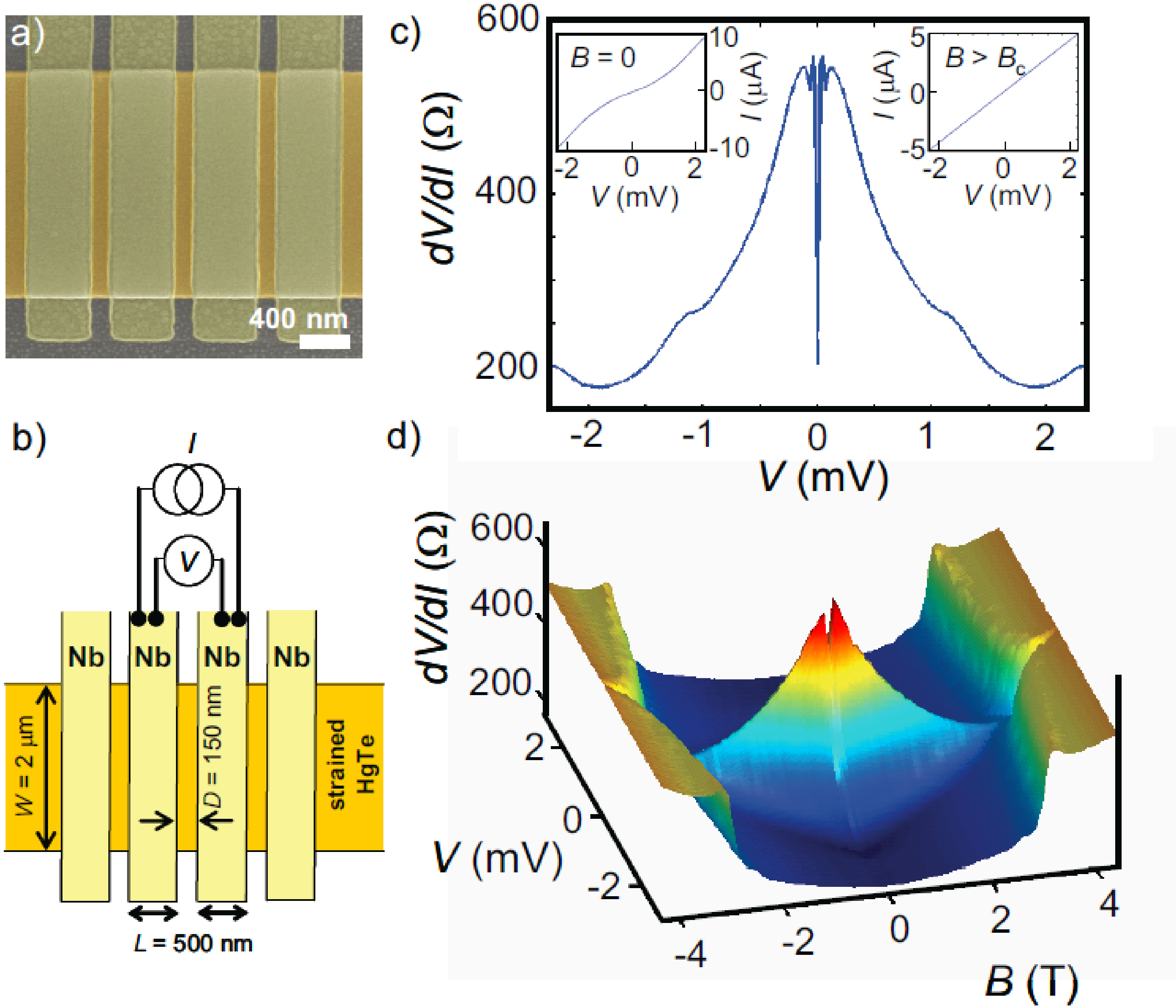
- 2 Majorana bound states = 1 fermion $\Psi = \gamma_1 + i\gamma_2$
  - 2 degenerate states (full/empty) = 1 qubit
- 2N separated Majoranas = N qubits
- Quantum Information is stored non locally
  - Immune from local decoherence
- Adiabatic Braiding performs unitary operations
  - Non Abelian Statistics



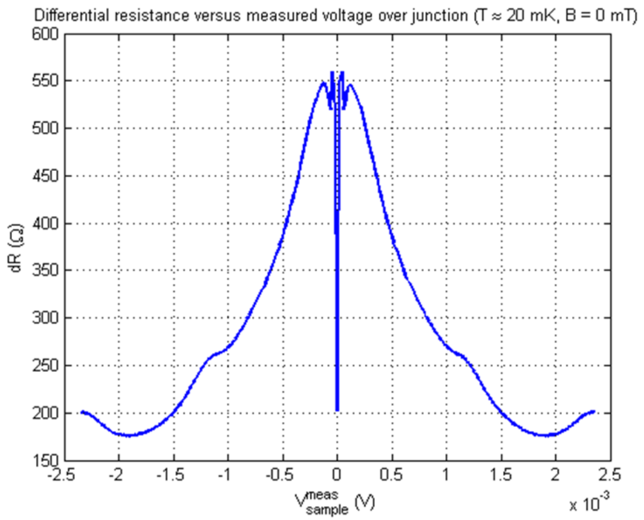
Potential Condensed Matter Hosts :

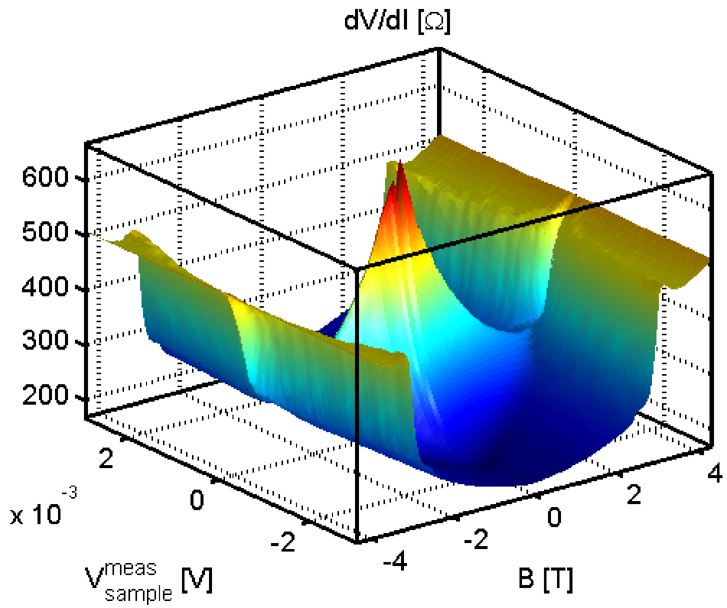
- Quasiparticles in fractional Quantum Hall effect at ν=5/2
  Moore, Read '91
- s-wave superconductor / Topological Insulator structure
  Fu, Kane '08
- semiconductor - magnet - superconductor structures
  Sau, Lutchyn, Tewari, Das Sarma '09
- .... among others

Superconducting contacts on strained HgTe

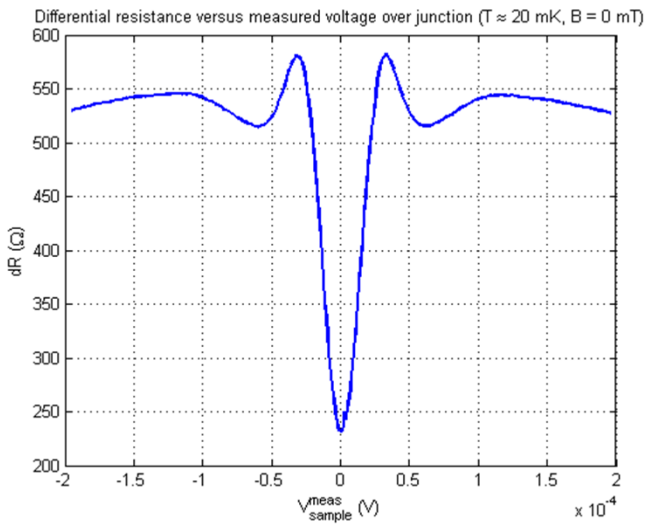


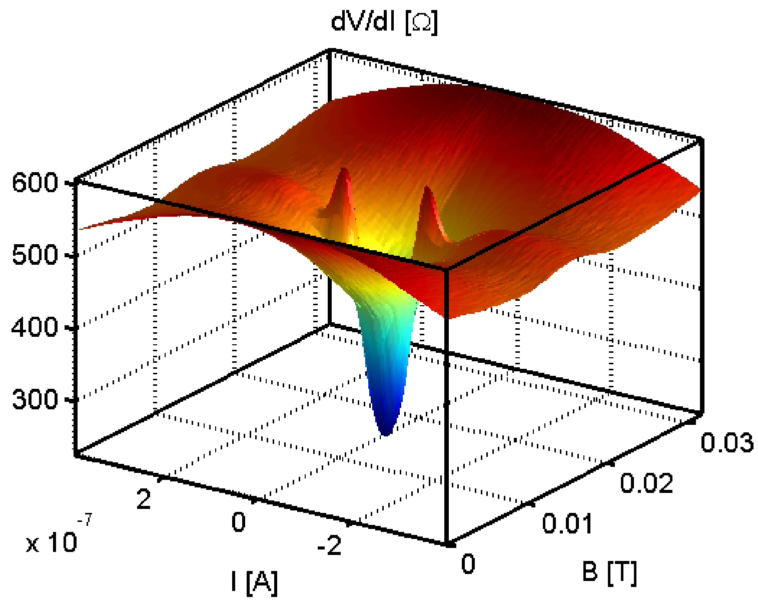
dV/dI (V_{bias}, B) at 20 mK

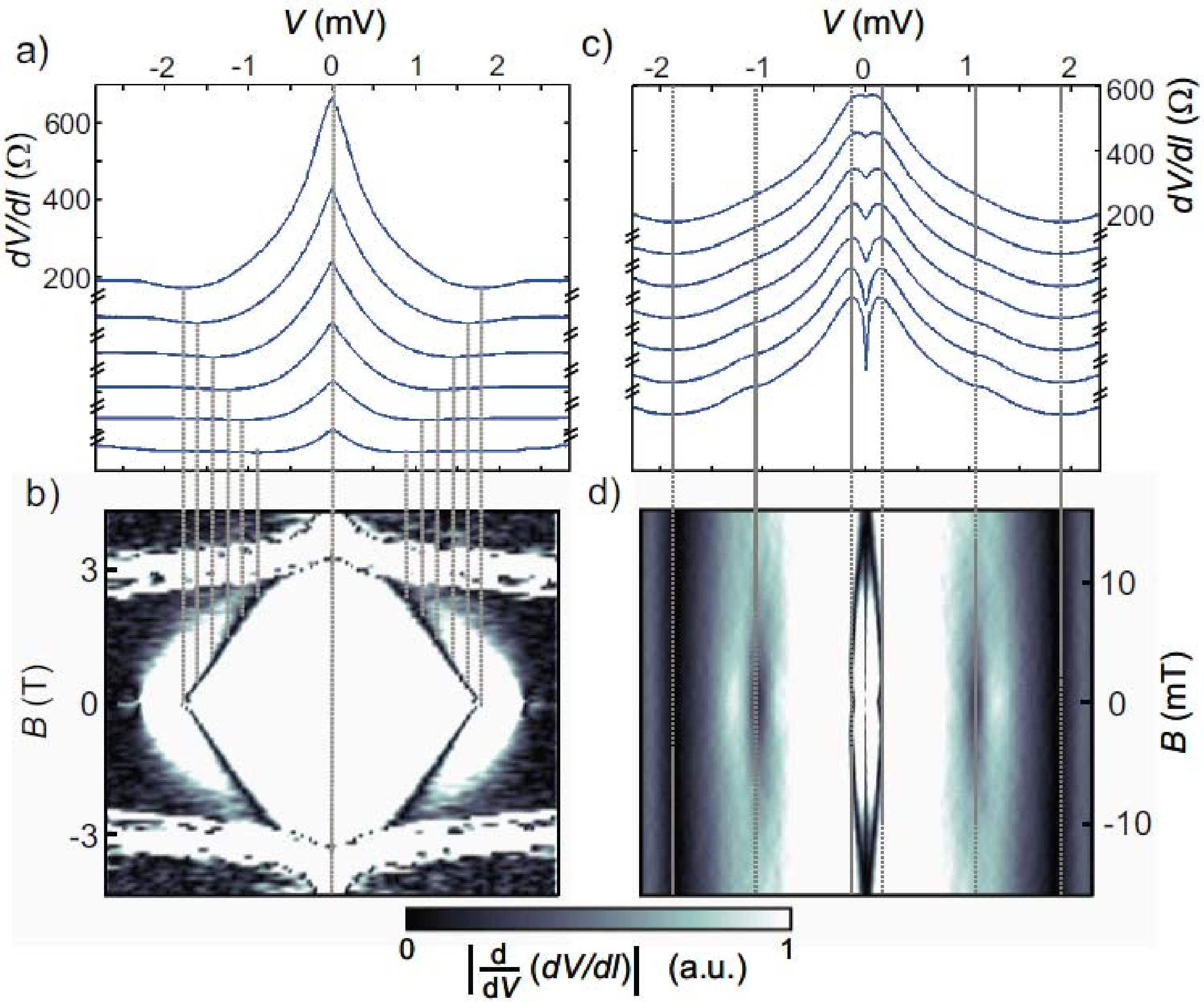




dV/dI (I_{bias}, B) at 20 mK







a)
V (mV)
-2
-1
0
1
2
dV/dI (Ω)
600
400
200
b)
B (T)
3
0
-3
c)
V (mV)
-2
-1
0
1
2
600
400
200
dV/dI (Ω)
d)
B (mT)
10
0
-10
0
1
|d/dV (dV/dI)| (a.u.)

Outlook

- A new electronic phase of matter has been predicted and observed
  - 2D : Quantum spin Hall insulator in (Hg,Cd)Te QW's
  - 3D : Strong topological insulator in Bi_2Se_3, Bi_2Te_3 and strained HgTe
- Dissipationless transport in spin-polarized 1D channels
- Strong Magnetoelectric Effect; Possibilities for domain wall transport?
- Superconductor/Topological Insulator structures host Majorana Fermions
  - A Platform for Topological Quantum Computation
- Some Challenges in the near future:
  - Transport Measurements on topological insulators
  - Superconducting structures :
    - Create, Detect Majorana bound states
  - Magnetic structures :
    - Create chiral edge states, chiral Majorana edge states

Acknowledgements

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