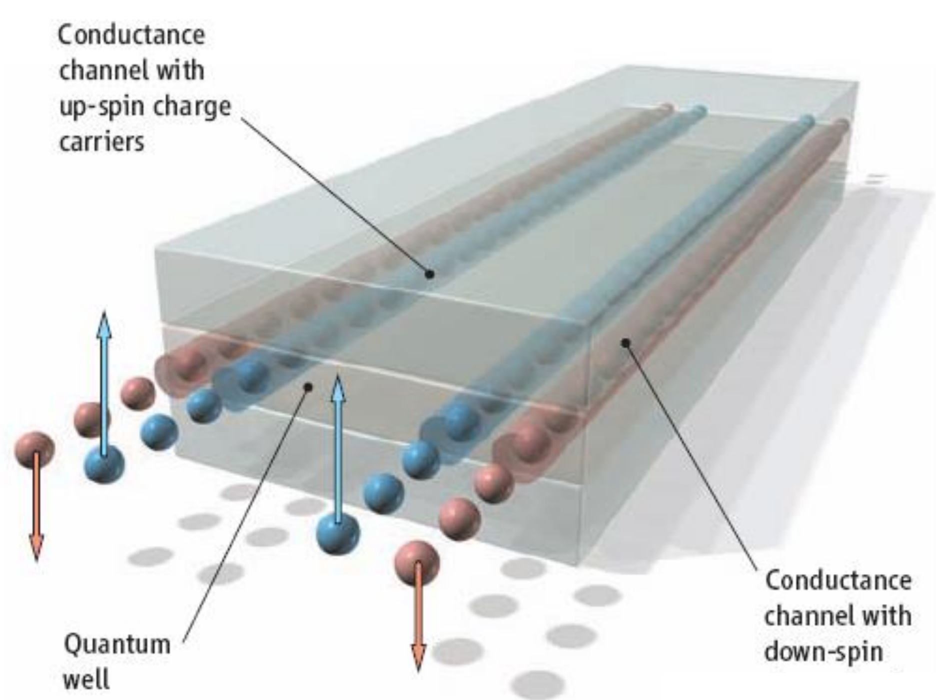
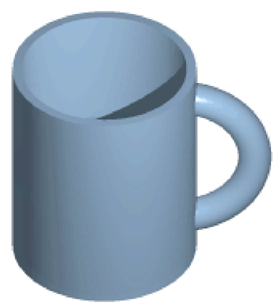
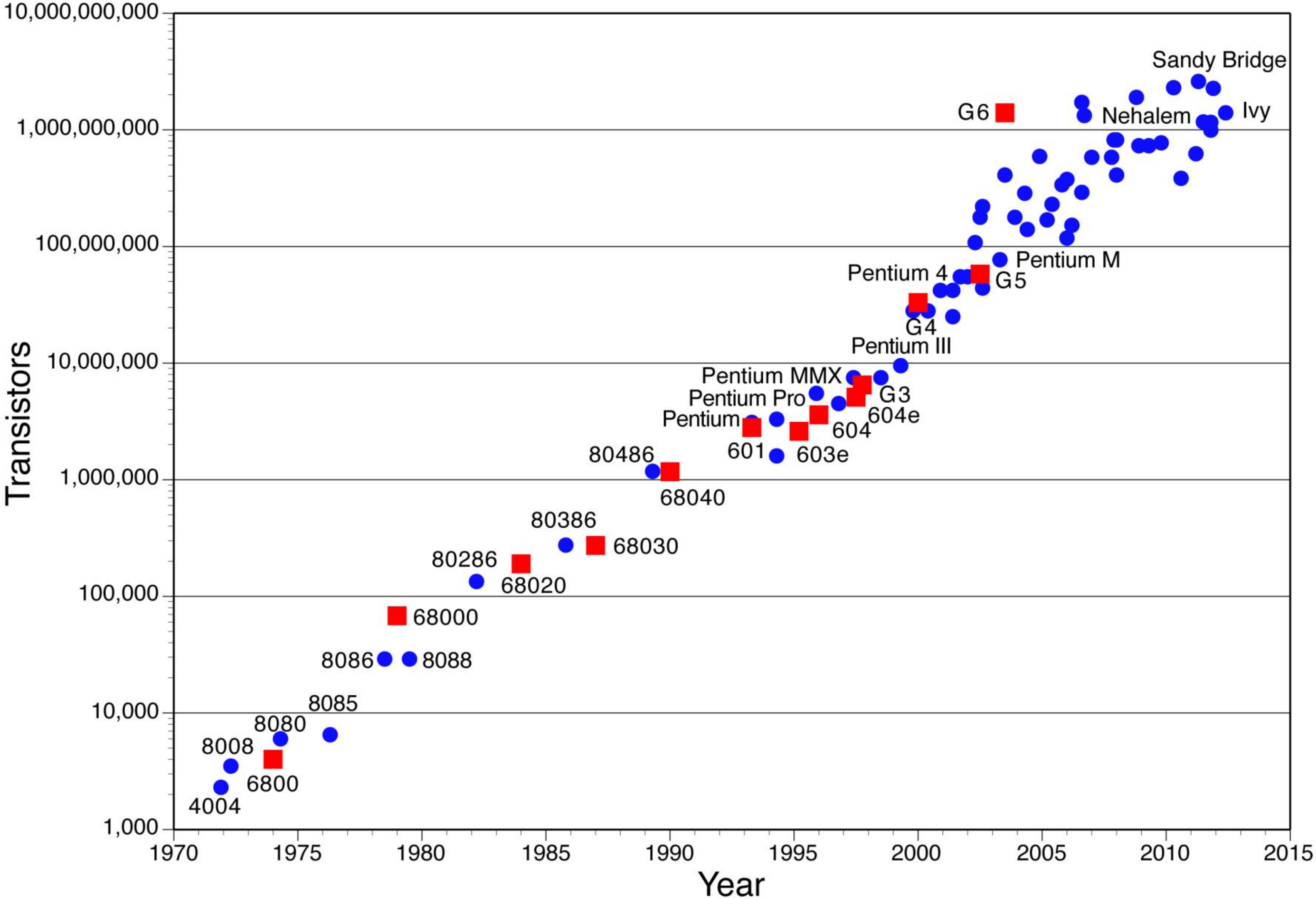
Science and applications of topological insulators



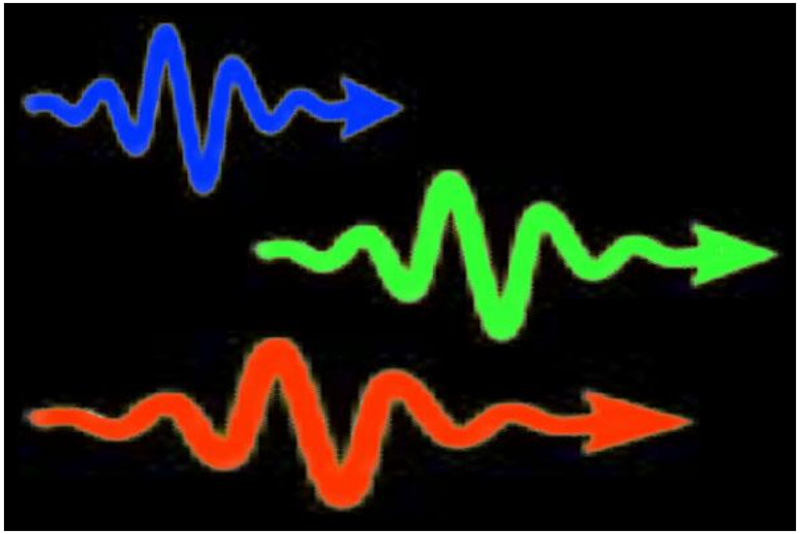


CAS 2014
Shoucheng Zhang, Tsinghua and Stanford University

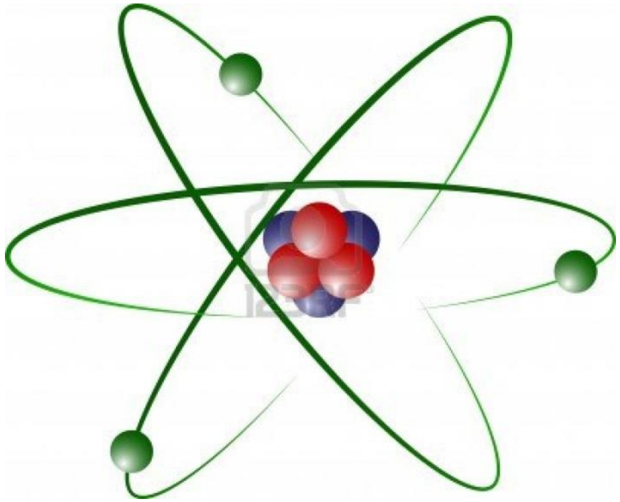
Moore's law of the information age



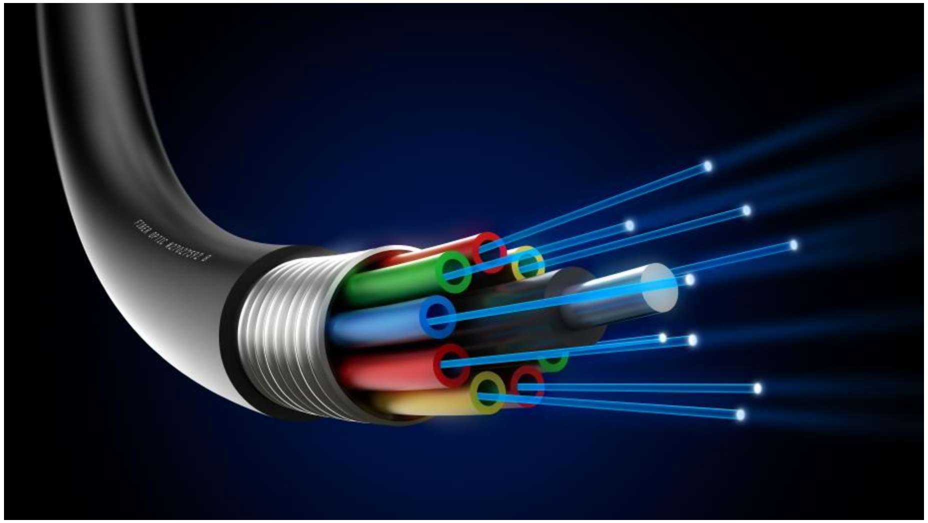
Two elementary particles of the information age



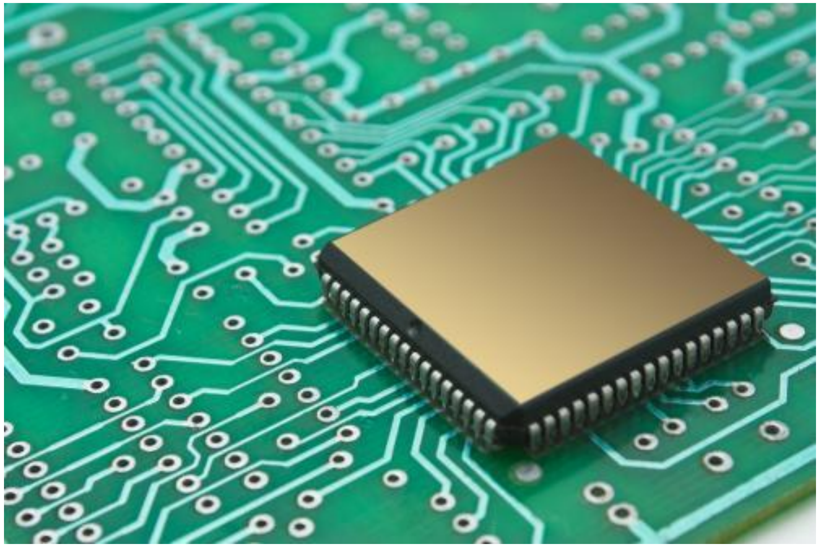
Photon



Electron

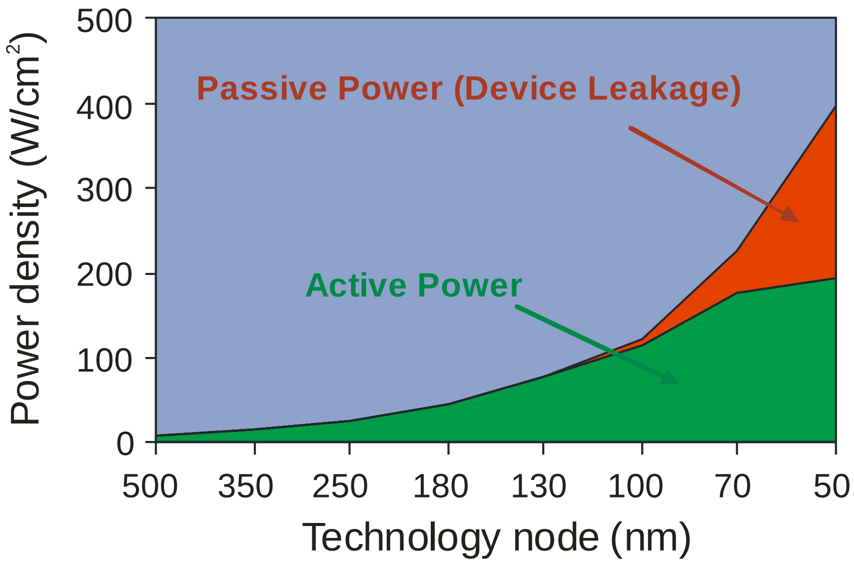


Fiber optical communication



Computing chips

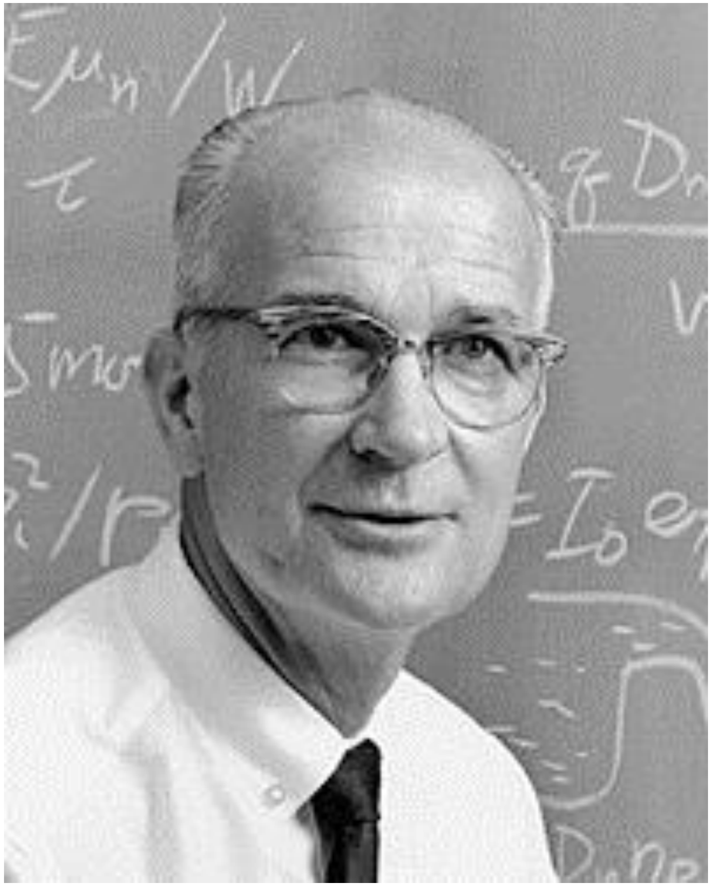
From traffic jam to info-superhighway



Traffic jam inside chips today

Info highways for the chips in the future

Crisis and opportunity for basic science and the silicon valley



危机

Search for a new electronic states of matter

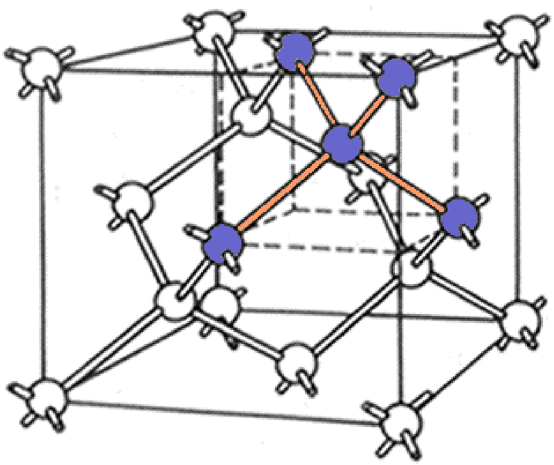
The search for new elements led to a golden age of chemistry.

The search for new particles led to the golden age of particle physics.

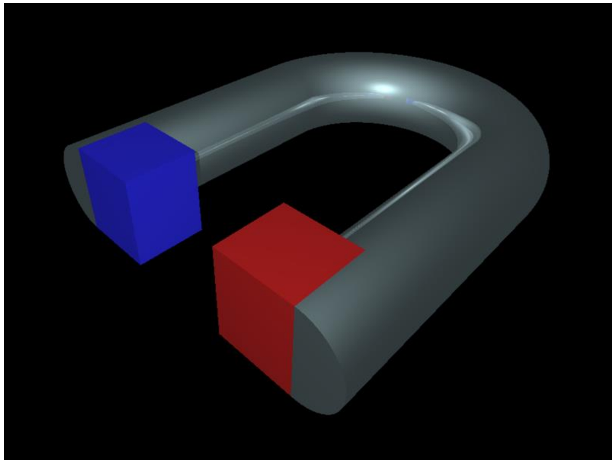
Complex states of matter from the simplicity of the building blocks!

In the classical world we have solid, liquid and gas. The same H_2O molecules can condense into ice, water or vapor.

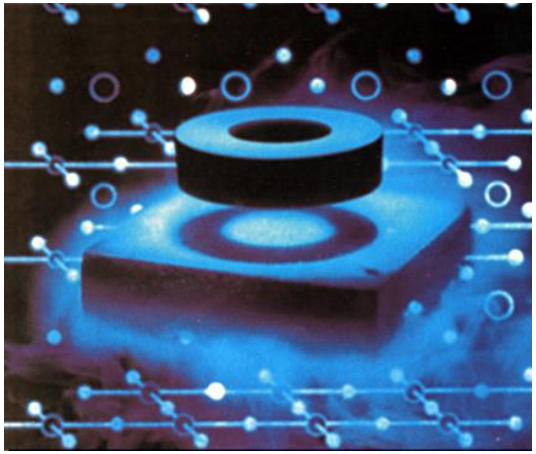
In the quantum world we have metals, insulators, superconductors, magnets etc.



Semiconductors

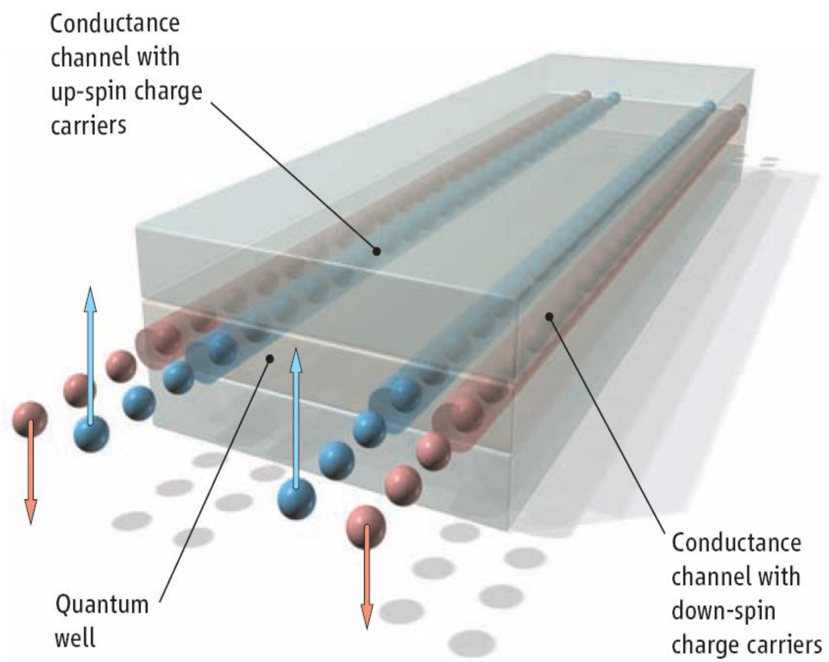


Magnets

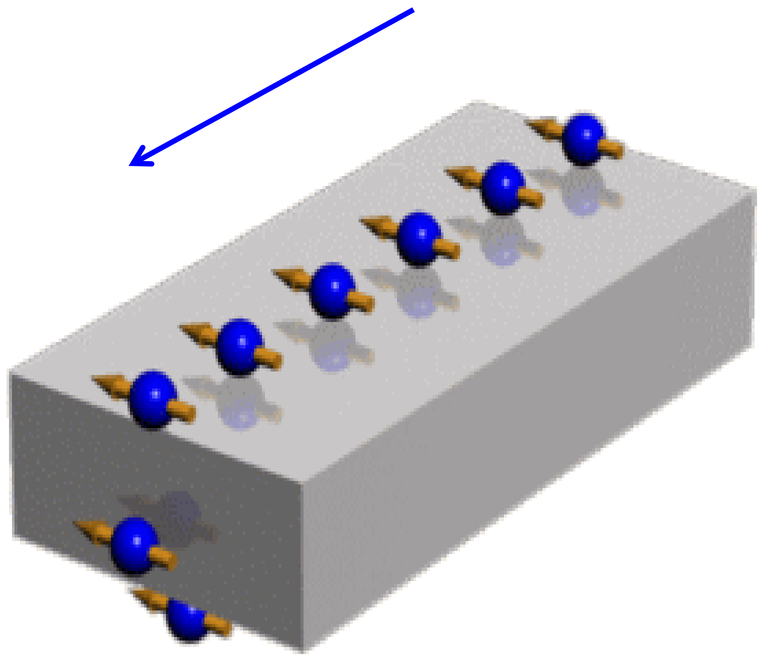


Superconductor

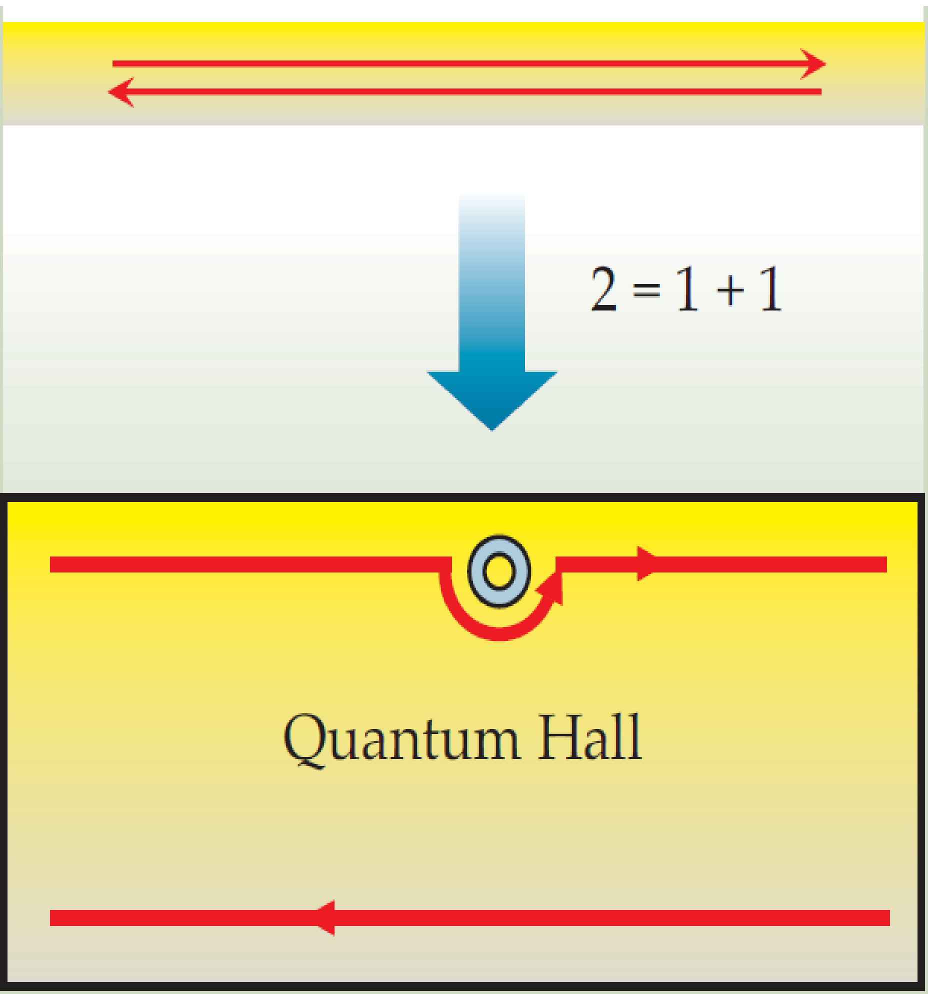
Discovery of topological insulator materials

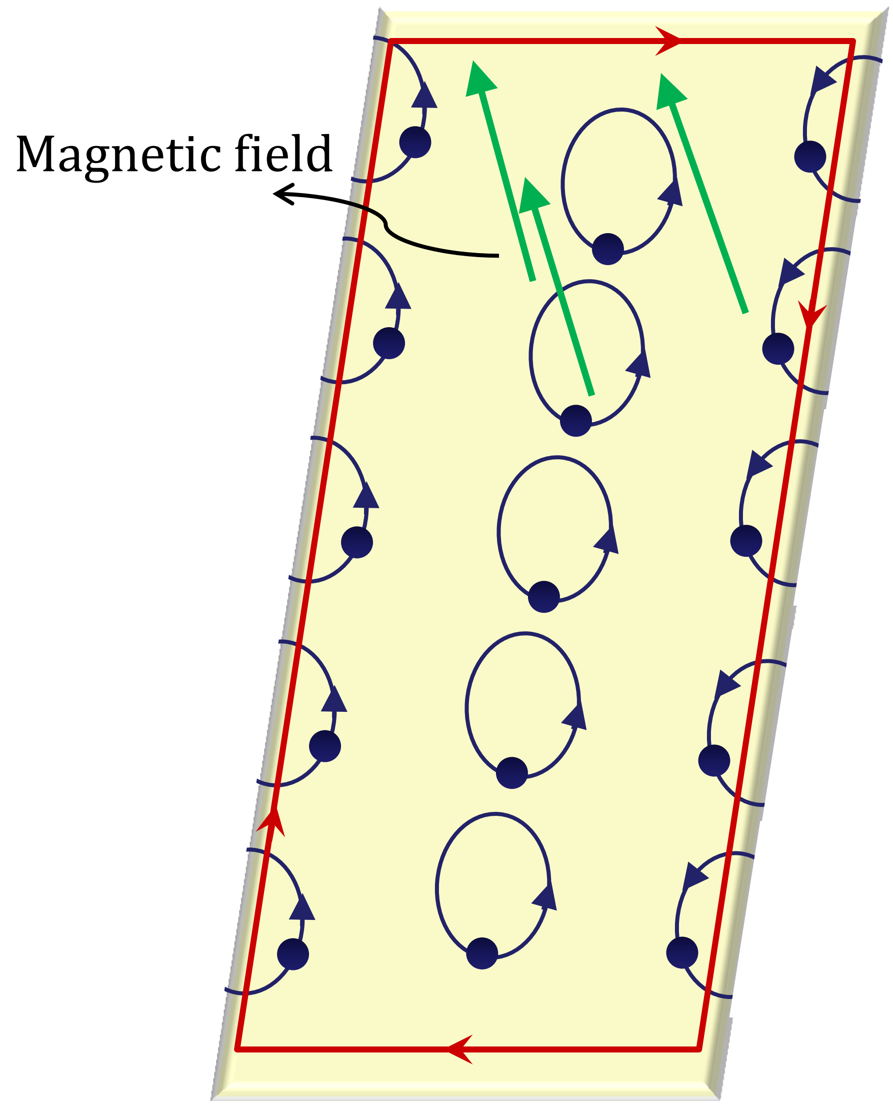


Schematic of the spin-polarized edge channels in a quantum spin Hall insulator.

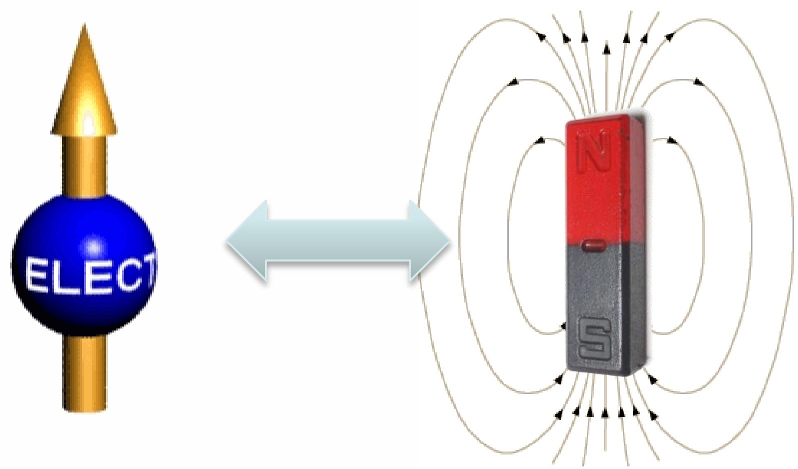


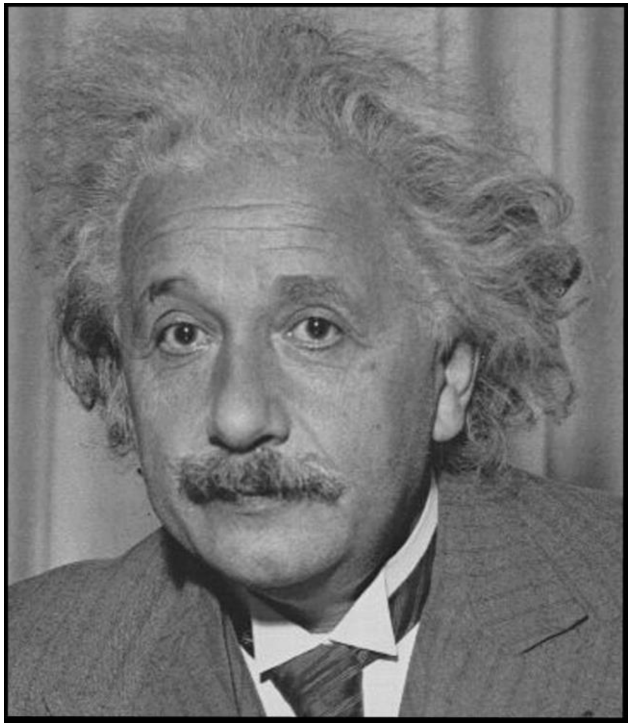
How to build a highway for the electrons?

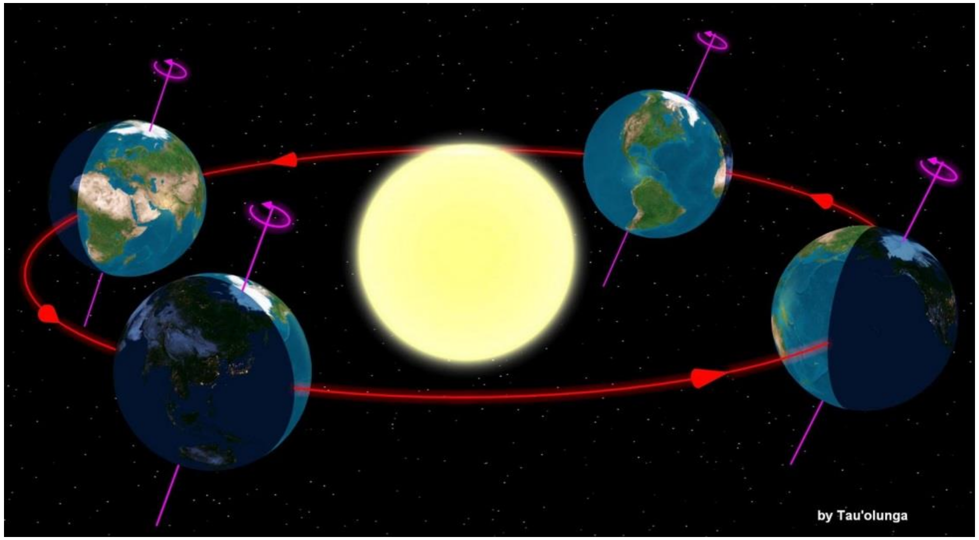


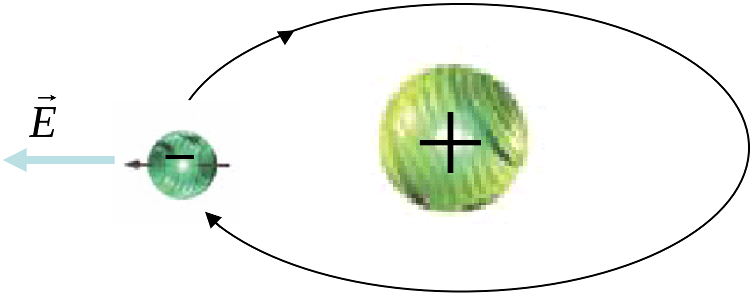


Electrons have spin, and spin-orbit coupling!



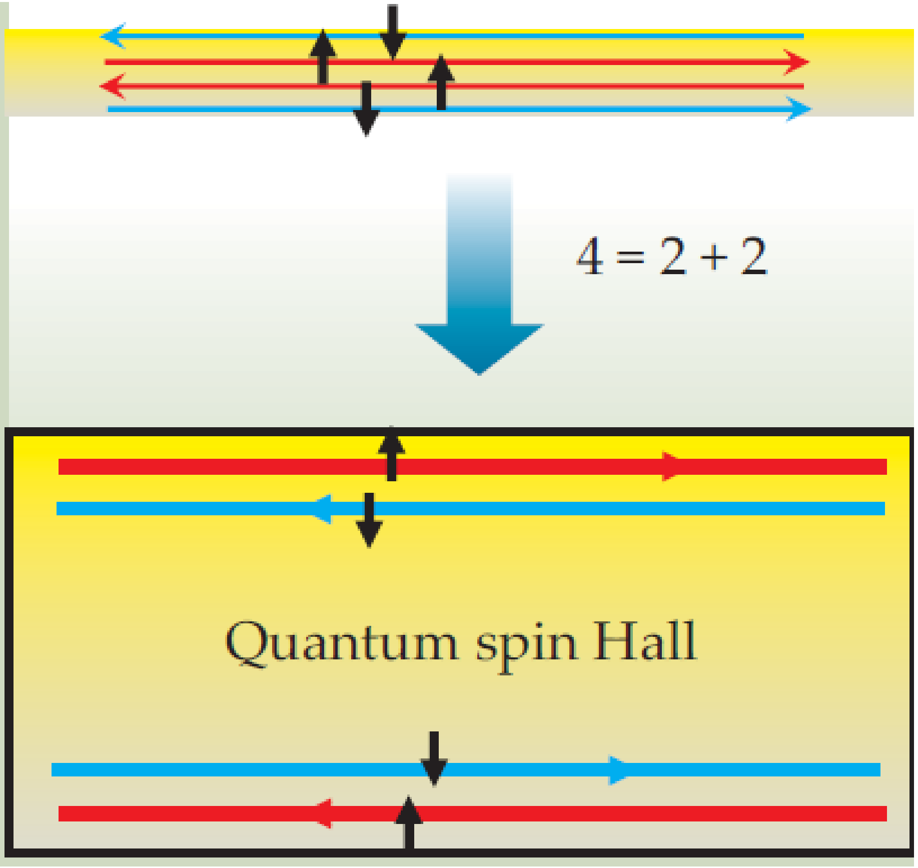


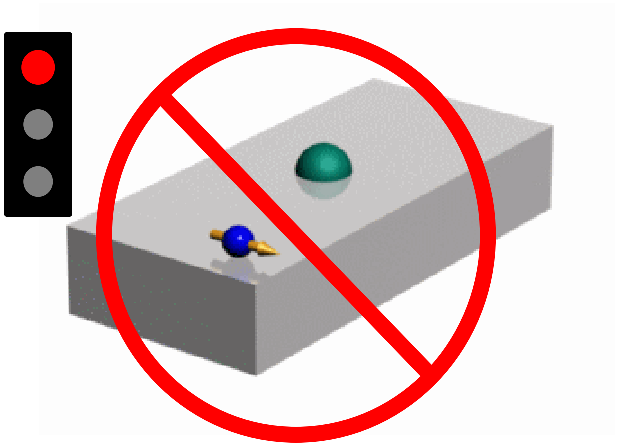


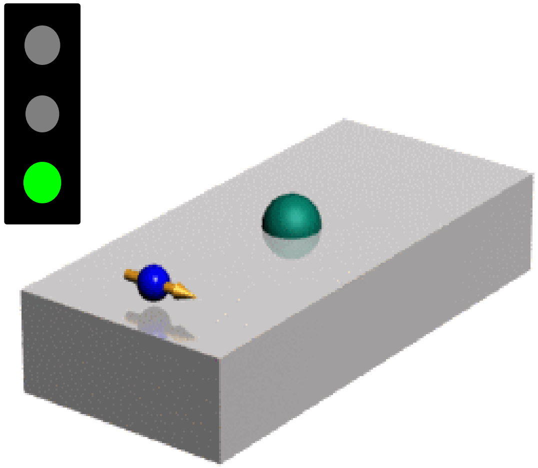


Relativity predicts spin-orbit coupling

Replace the magnetic field by the spin of electron

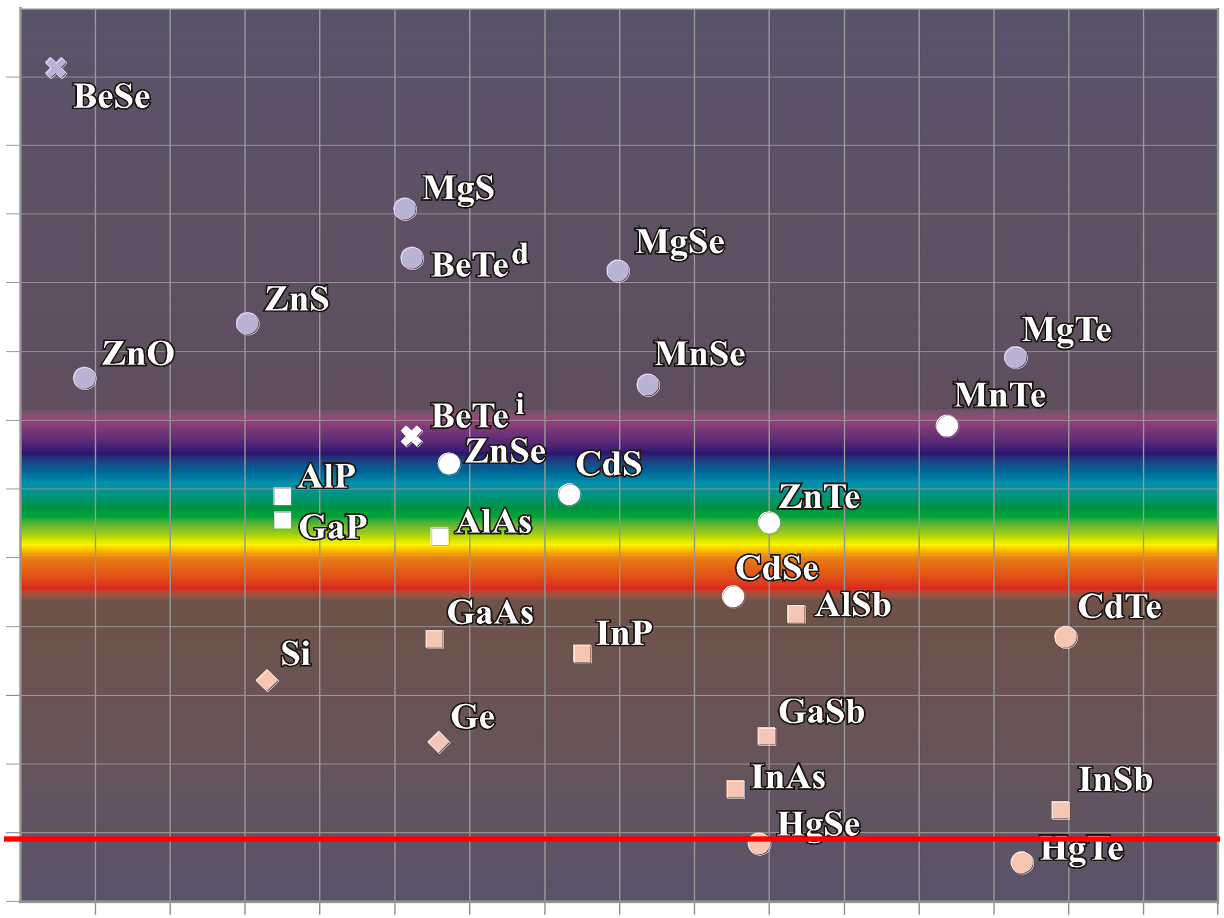






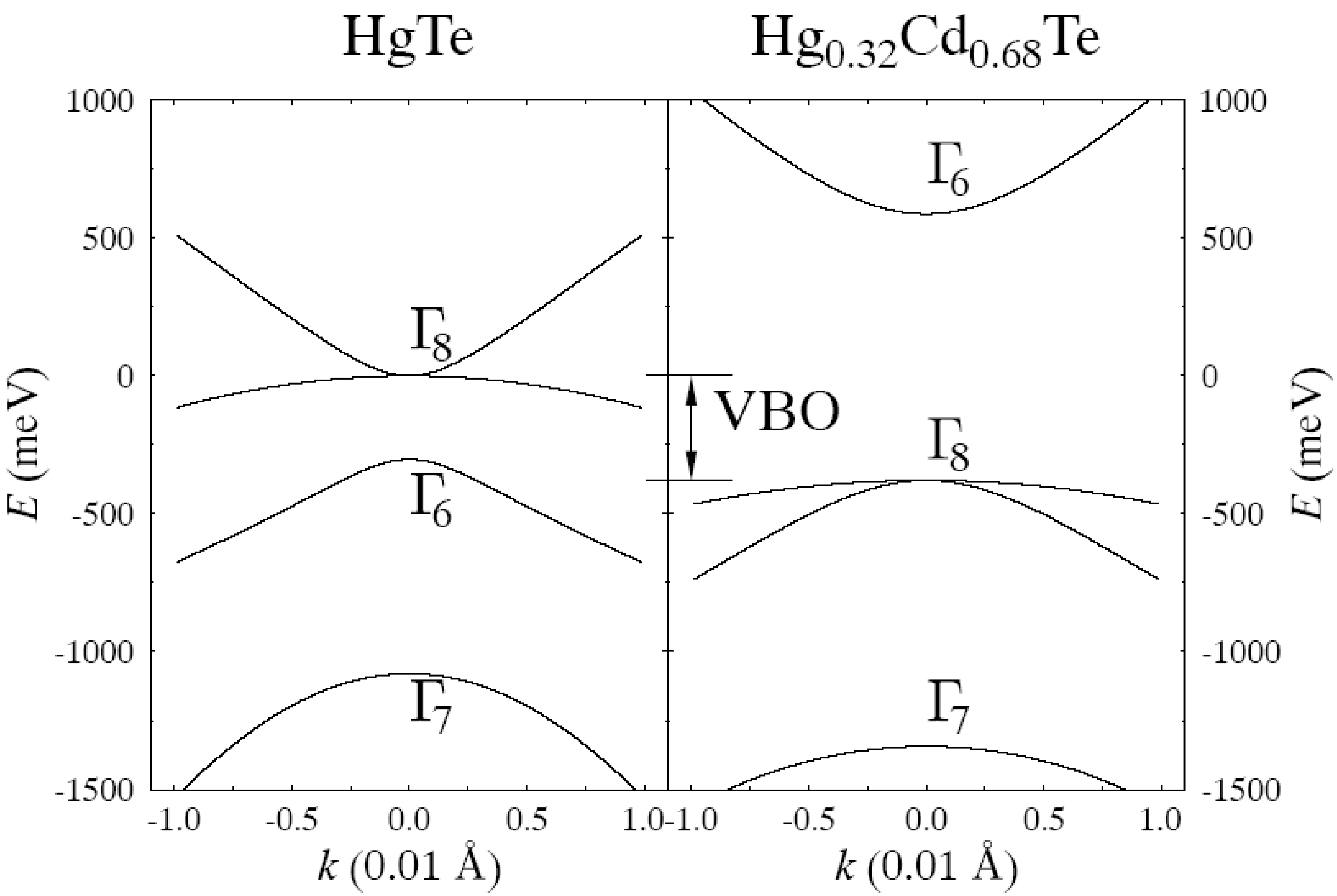
Quantum Spin Hall Effect and Topological Phase Transition in HgTe Quantum Wells

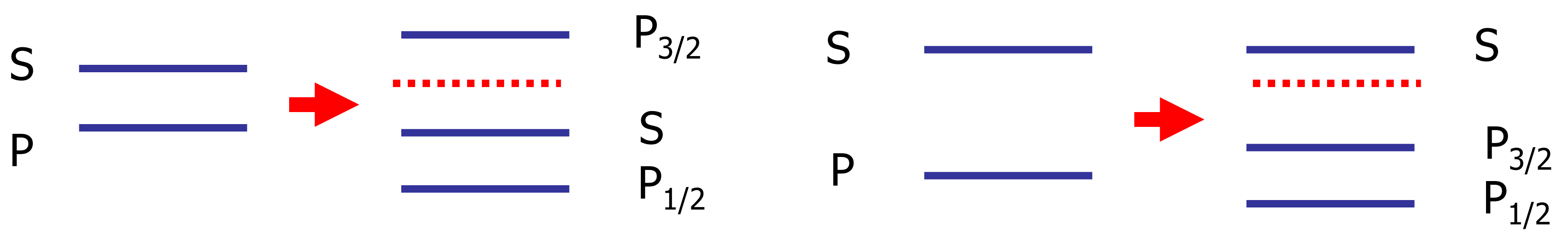
B. Andrei Bernevig,[1,2] Taylor L. Hughes,[1] Shou-Cheng Zhang[1]*



Thanks to many discussions with Wurzburg group.

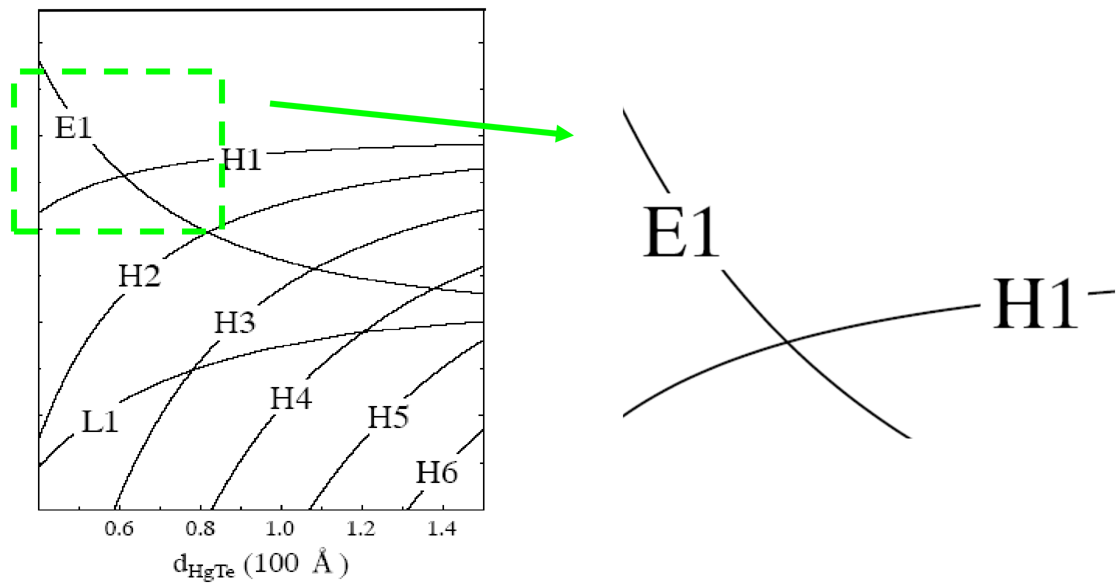
Band Structure of HgTe

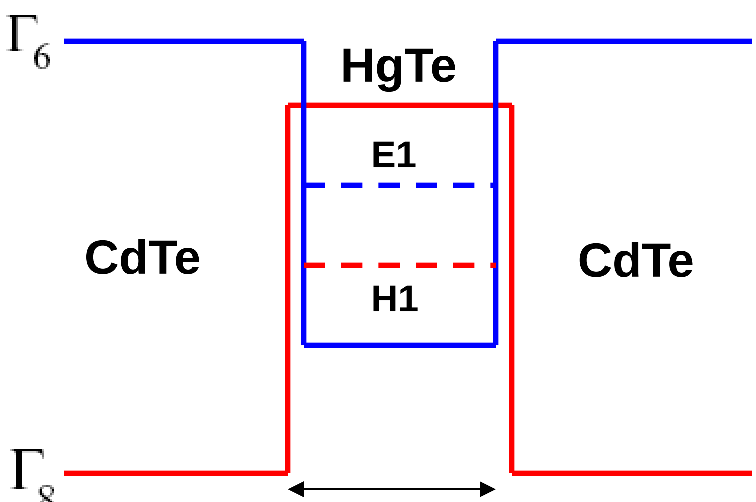




Band inversion in HgTe leads to a topological quantum phase transition

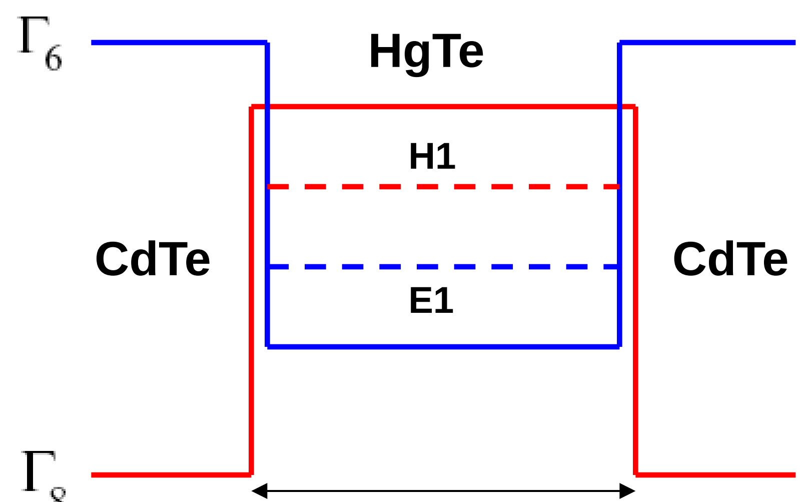
Let us focus on E1, H1 bands close to crossing point





$d < d_c$

normal



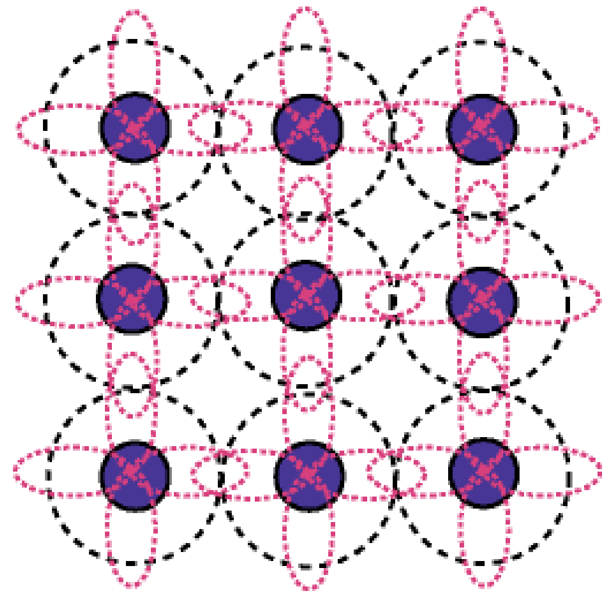
$d > d_c$

inverted

The model of the 2D topological insulator (BHZ, Science 2006)

Square lattice with 4-orbitals per site:

$$|s,\uparrow\rangle, |s,\downarrow\rangle, |(p_x+ip_y,\uparrow\rangle, |-(p_x-ip_y),\downarrow\rangle$$



Nearest neighbor hopping integrals. Mixing matrix elements between the s and the p states must be odd in k.

$$H_{eff}(k_x,k_y)=\begin{pmatrix} h(k) & 0 \\ 0 & h^*(-k) \end{pmatrix}$$

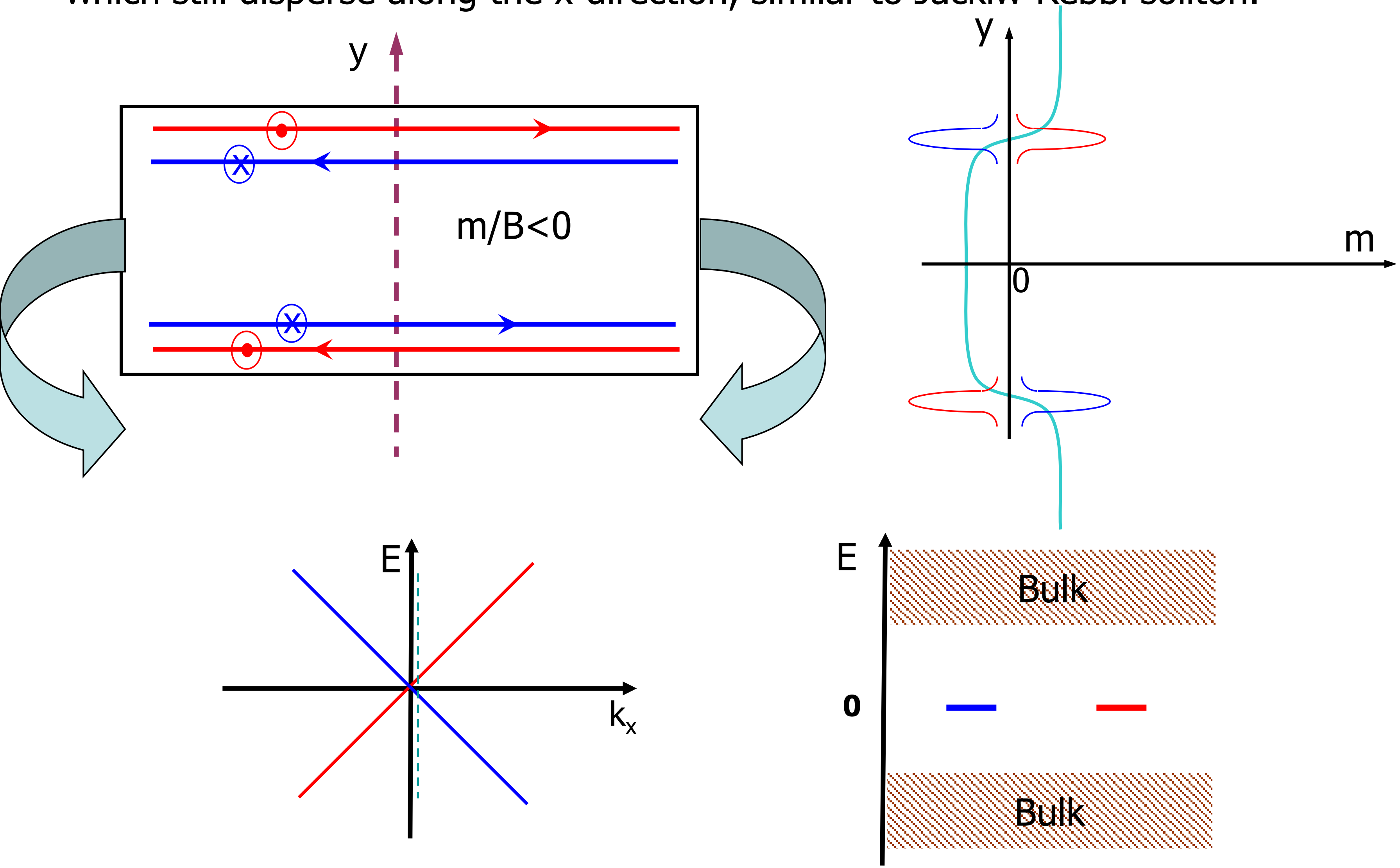
$$h(k)=\begin{pmatrix} m(k) & A(\sin k_x - i\sin k_y) \\ A(\sin k_x + i\sin k_y) & -m(k) \end{pmatrix} \equiv d_a(k)\tau^a$$

$$\Rightarrow \begin{pmatrix} m+Bk^2 & A(k_x-ik_y) \\ A(k_x+ik_y) & -m-Bk^2 \end{pmatrix}$$

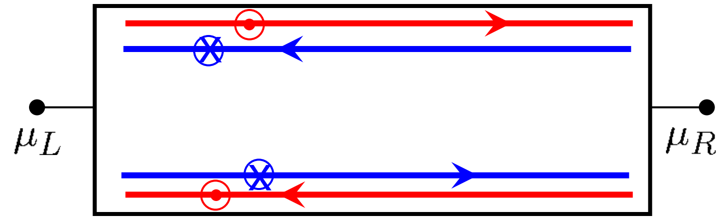
Similar to relativistic Dirac equation in 2+1 dimensions, with a mass term tunable by the sample thickness d! m/B<0 for d>d$_c$.

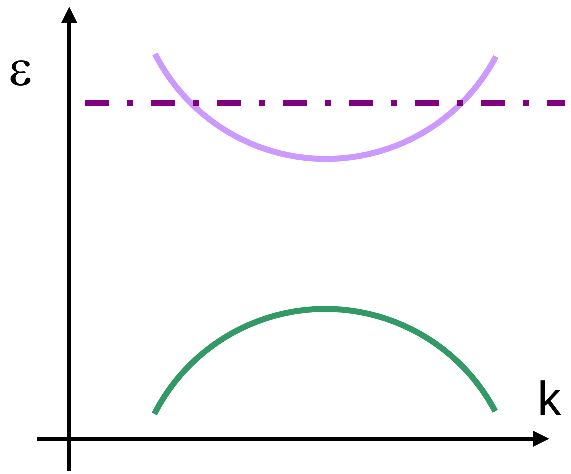
Mass domain wall

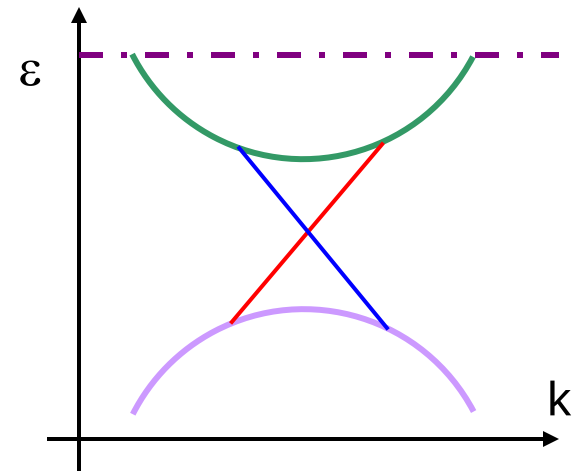
Cutting the Hall bar along the y-direction we see a domain-wall structure in the band structure mass term. This leads to states localized on the domain wall which still disperse along the x-direction, similar to Jackiw-Rebbi soliton.

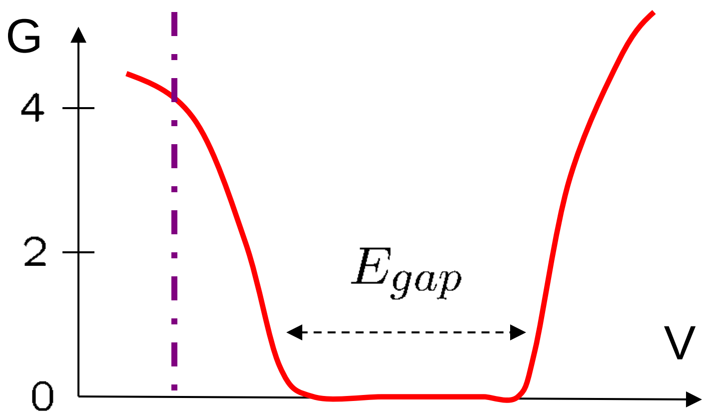


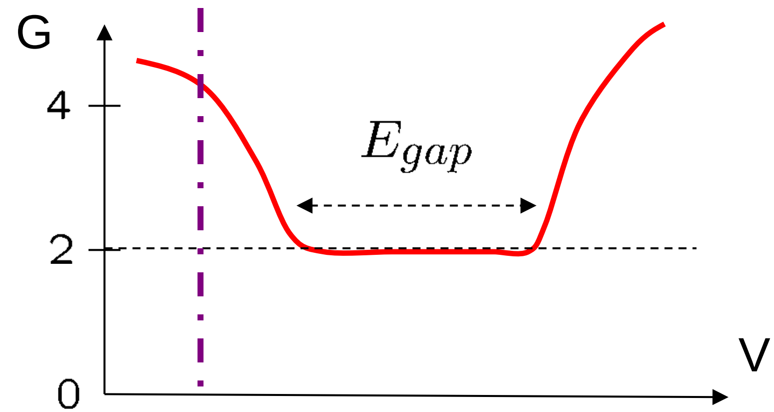
Metal, insulator, semiconductor and topological insulators



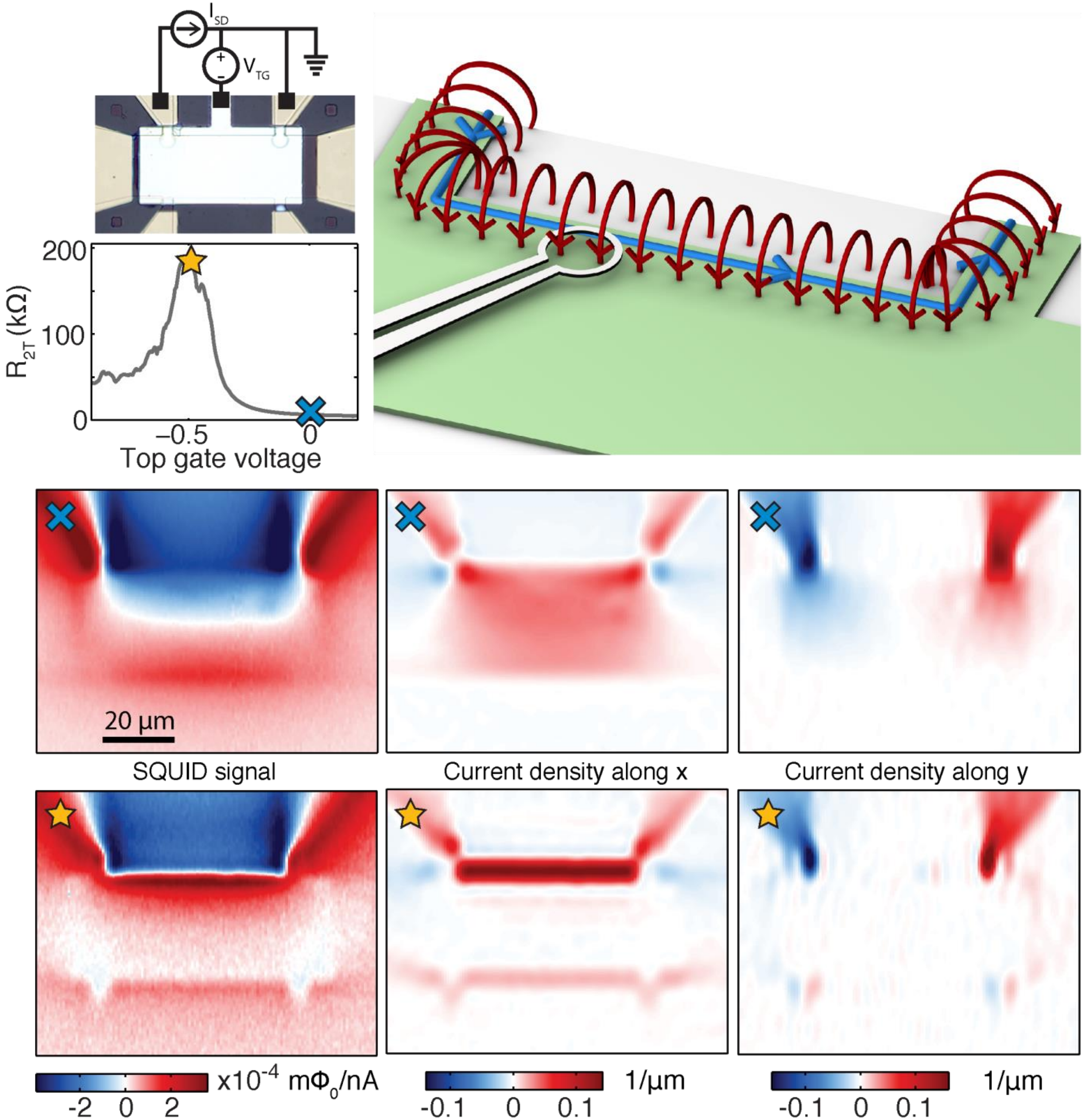






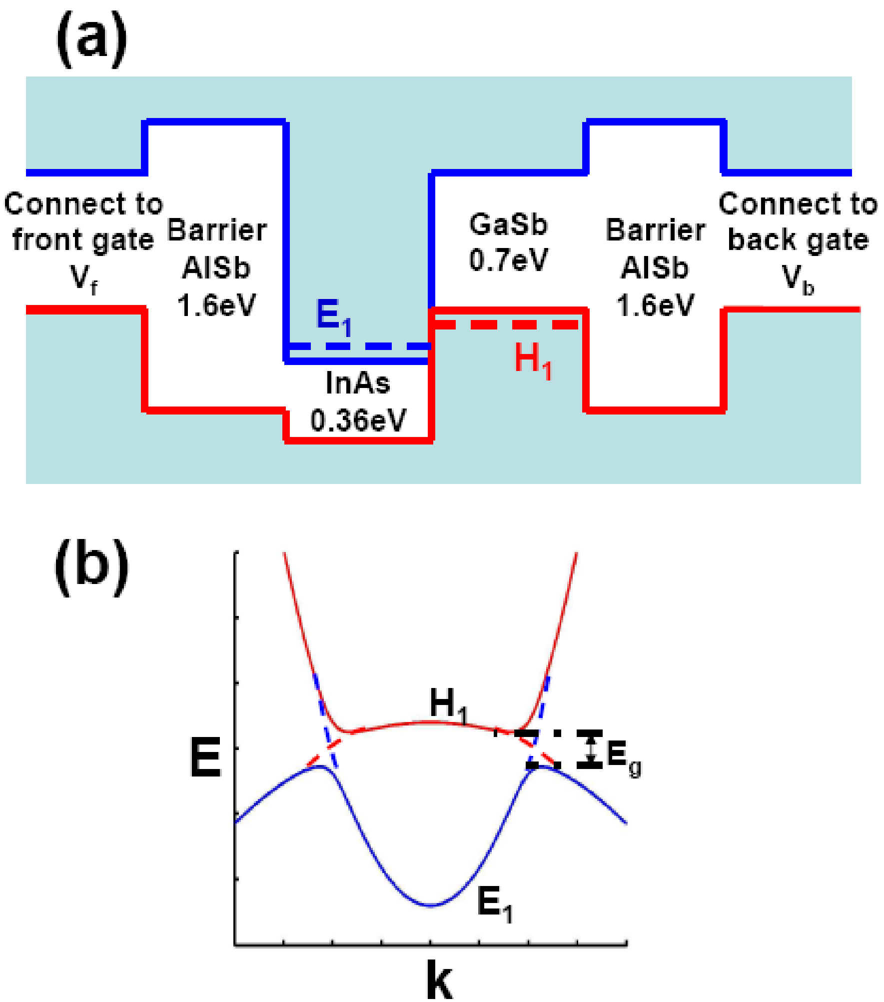


Measuring the edge current from its magnetic field

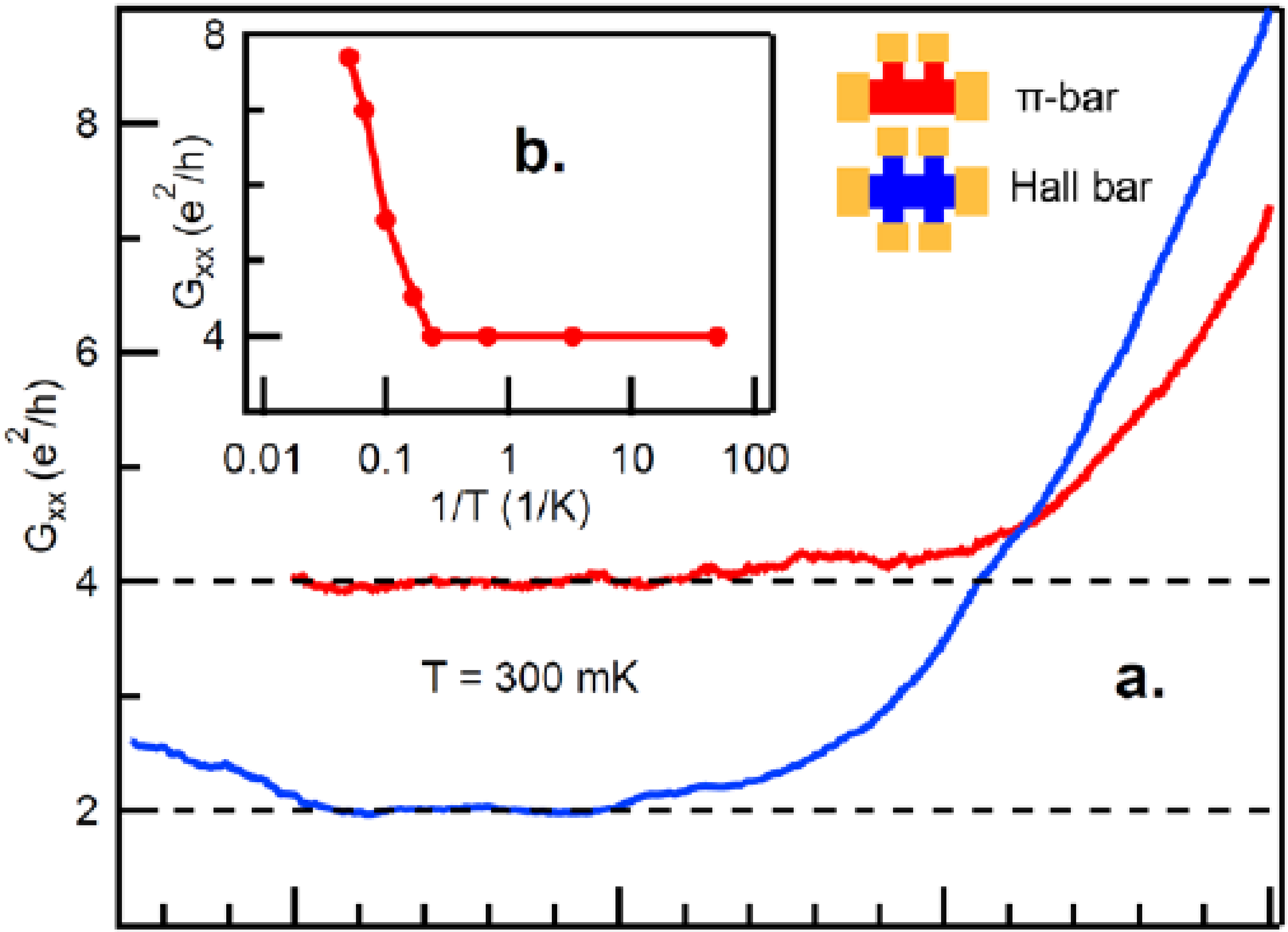


QSH state in InAs/GaSb type II quantum wells
(theoretically predicted by Liu et al PRL 100, 236601 (2008), Zhang group)

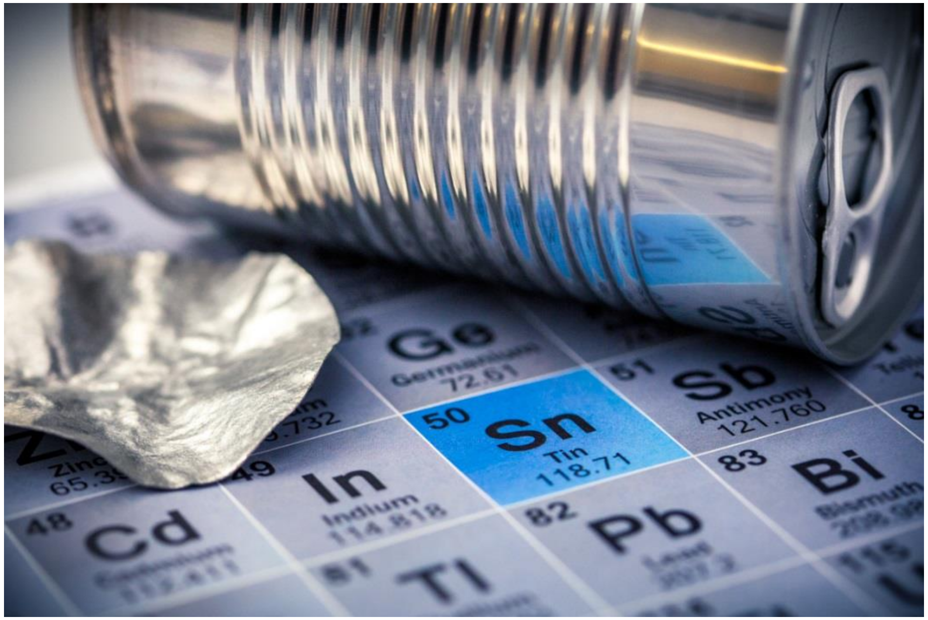
• In HgTe, the band inversion occurs intrinsically in the material. However, in InAs/GaSb quantum wells, a similar inversion can occur, since the valance band edge of GaSb lies above the conduction band edge of InAs.
• A small hybridazation gap opens up due to tunneling at the interface.
• Theoretical work show that the QSH can occur in InAs/Gab quantum wells. This material can be fabricated commercially in many places around the world.
• InAs can also be used for superconducting proximity effect.

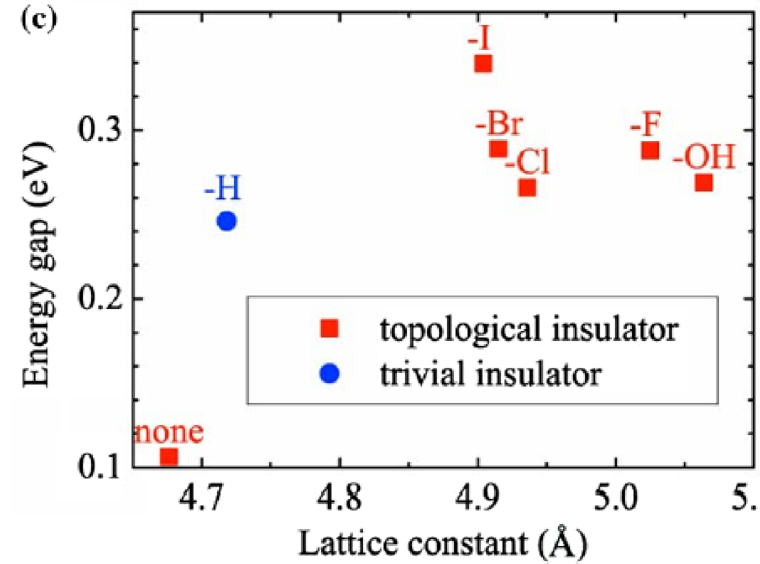


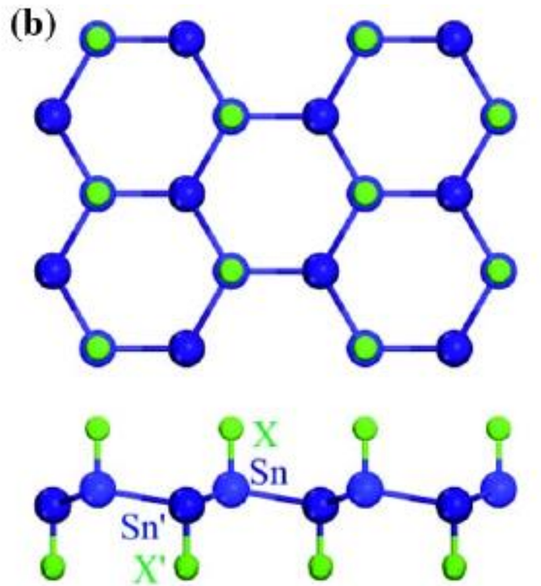
QSH state in InAs/GaSb type II quantum wells
(experimentally observed in Ruirui Du group)



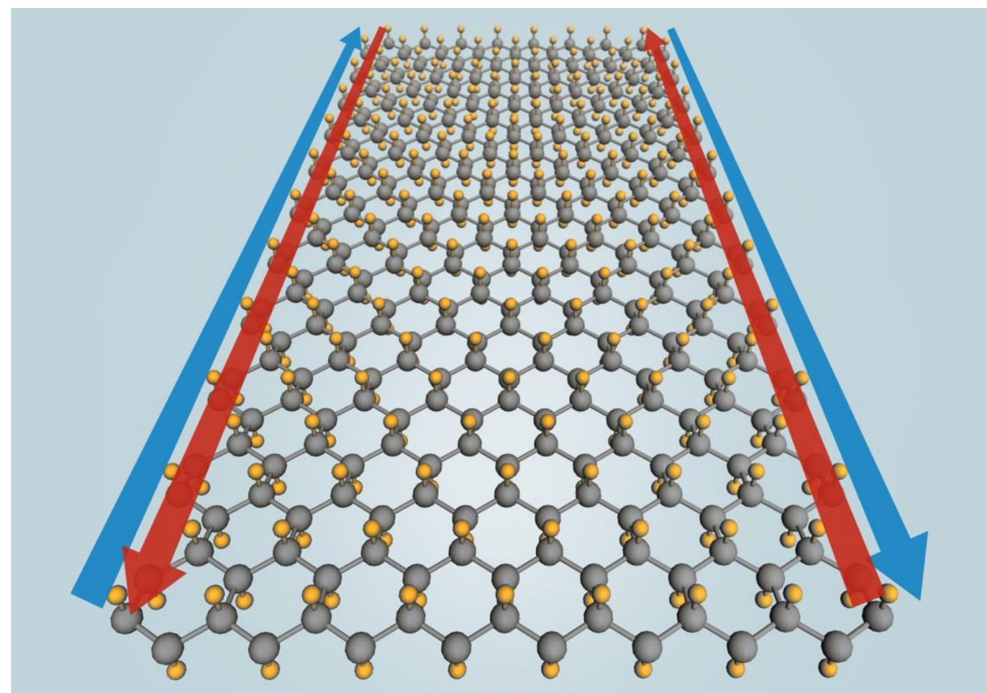
Stanene: new materials for 2D topological insulators



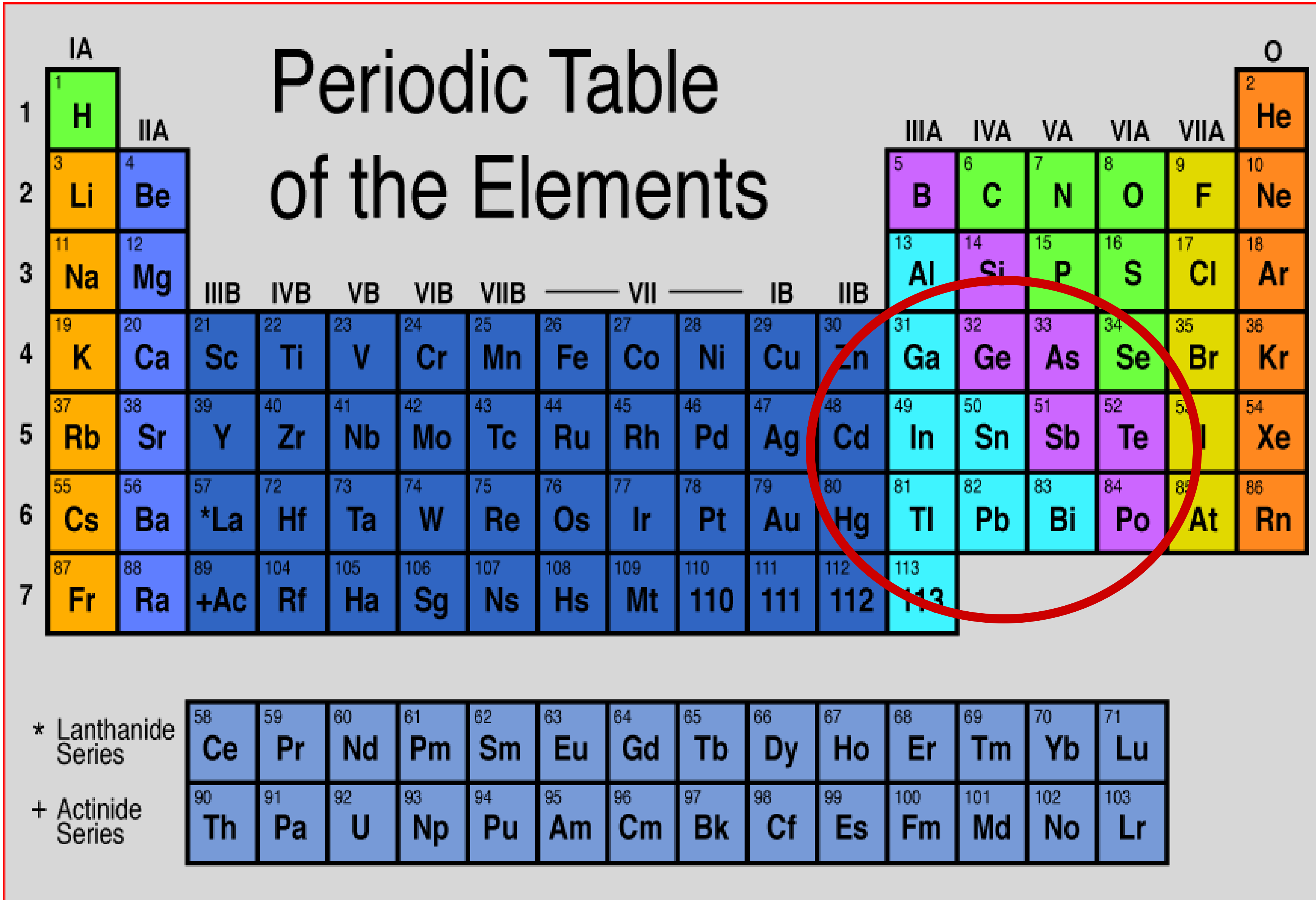




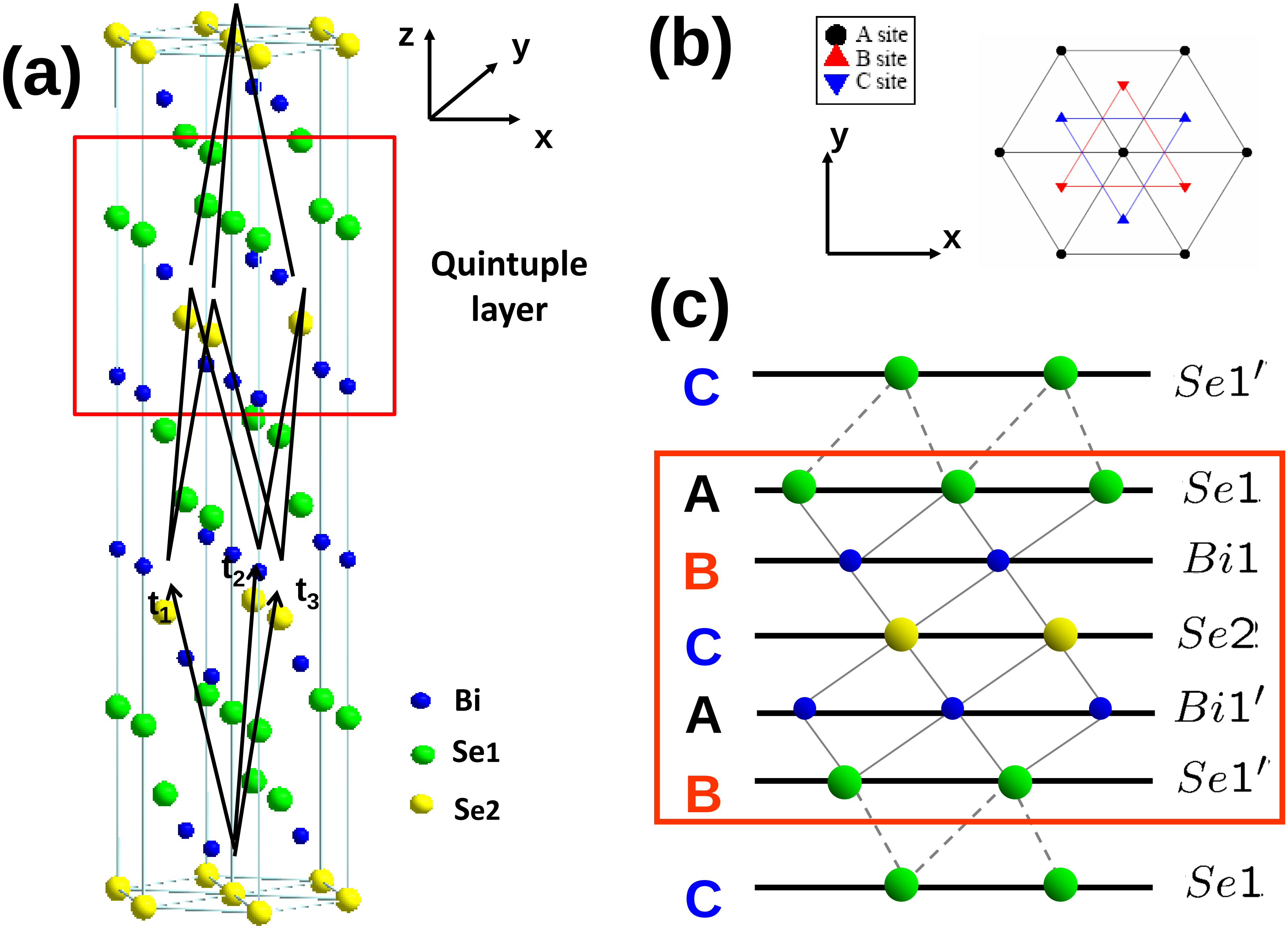
decorated stanene (2D SnX)



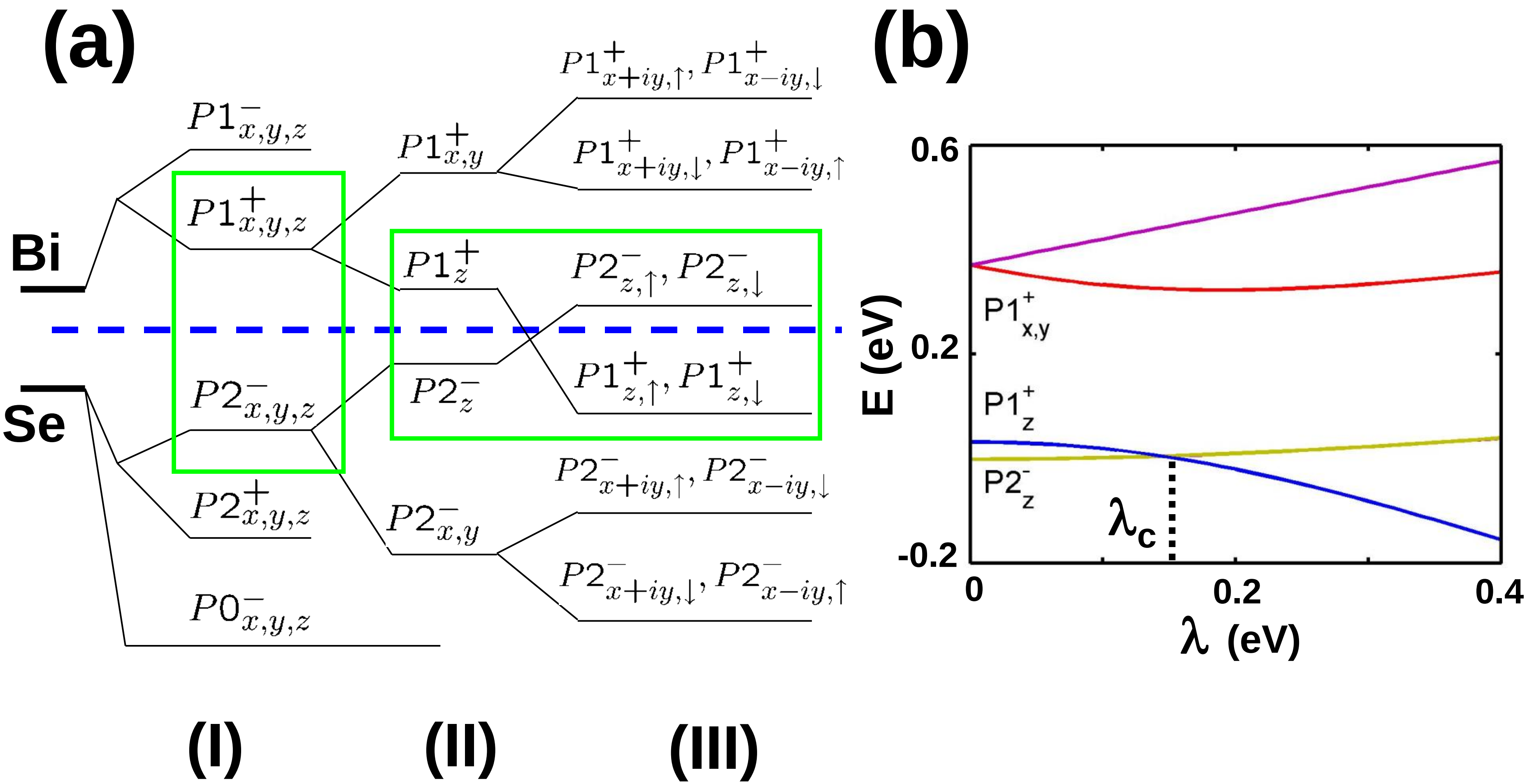
3D topological insulators



3D insulators with a single Dirac cone on the surface

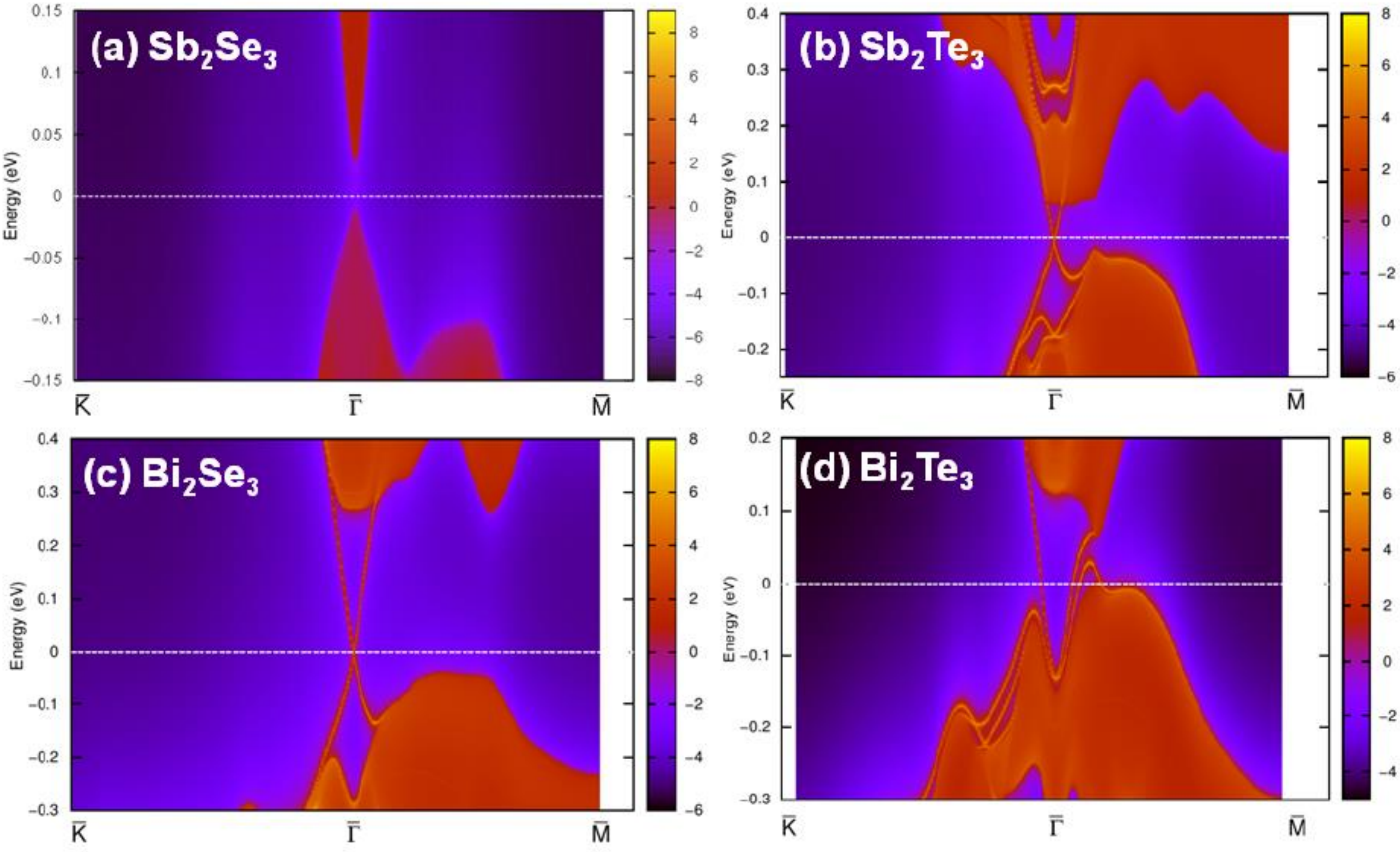


Relevant orbitals of Bi2Se3 and the band inversion



Topological insulators in Bi_2Se_3, Bi_2Te_3 and Sb_2Te_3 with a single Dirac cone on the surface

Haijun Zhang[1], Chao-Xing Liu[2], Xiao-Liang Qi[3], Xi Dai[1], Zhong Fang[1] and Shou-Cheng Zhang[3]*



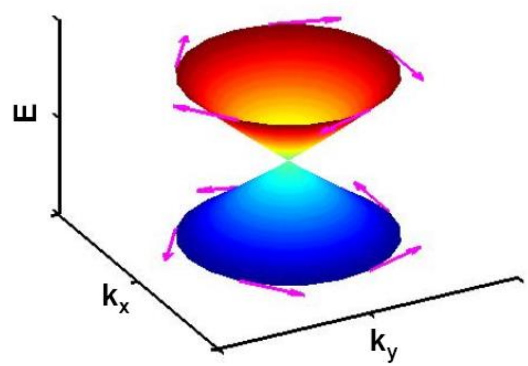
Model for topological insulator Bi2Te3, (Zhang et al, 2009)

$$H(\mathbf{k}) = \epsilon_0(\mathbf{k})\mathrm{I}_{4\times 4} + \begin{pmatrix} \mathcal{M}(\mathbf{k}) & A_1 k_z & 0 & A_2 k_- \\ A_1 k_z & -\mathcal{M}(\mathbf{k}) & A_2 k_- & 0 \\ 0 & A_2 k_+ & \mathcal{M}(\mathbf{k}) & -A_1 k_z \\ A_2 k_+ & 0 & -A_1 k_z & -\mathcal{M}(\mathbf{k}) \end{pmatrix} + o(\mathbf{k}^2)$$

Pz+, up, Pz-, up, Pz+, down, Pz-, down

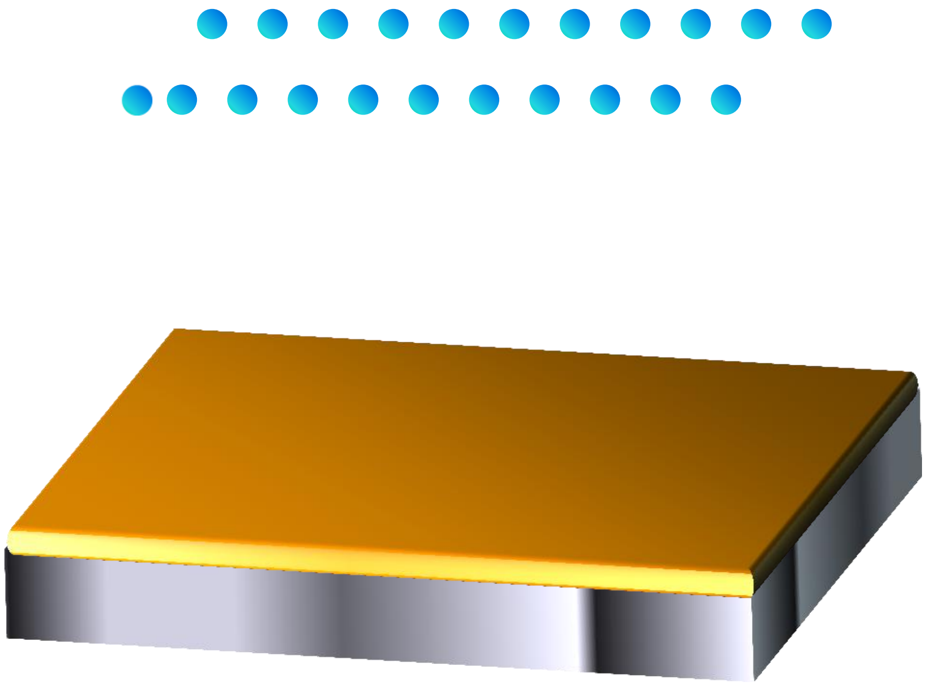
Single Dirac cone on the surface of Bi2Te3

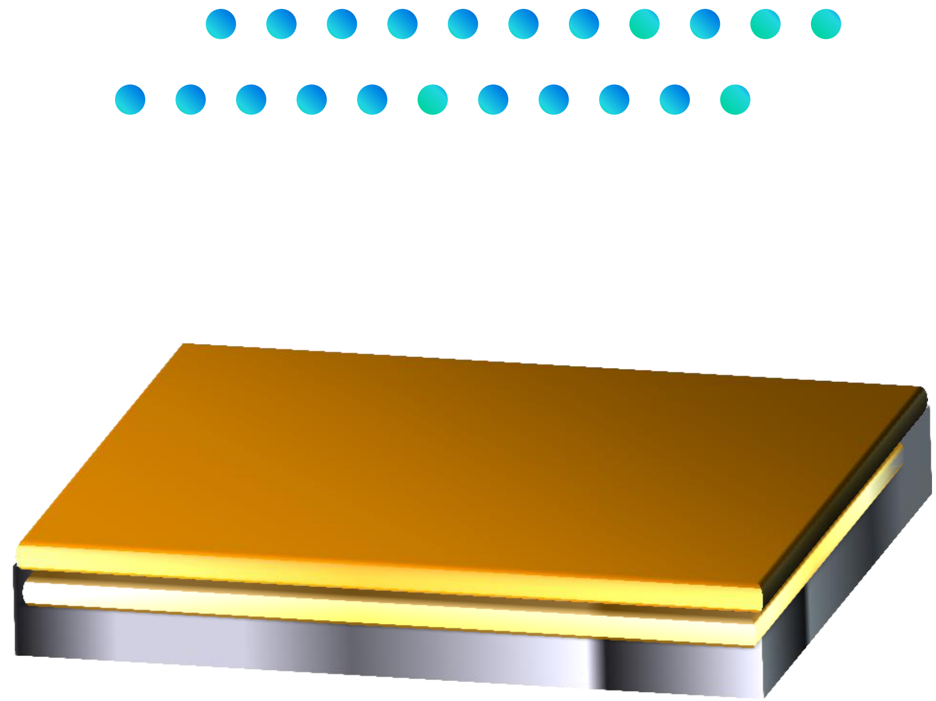
$$H = \int d^2\mathbf{x}\psi^\dagger(\mathbf{x})\left[\hbar v_f(\hat{\mathbf{z}} \times (-i\nabla)) \cdot \boldsymbol{\sigma} - \mu\right]\psi(\mathbf{x}),$$



Surface of Bi2Te3 = ¼ Graphene !

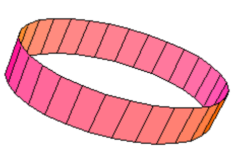
Magic of the topological surface state

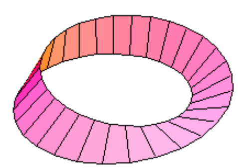




Coating insulator with a metallic surface

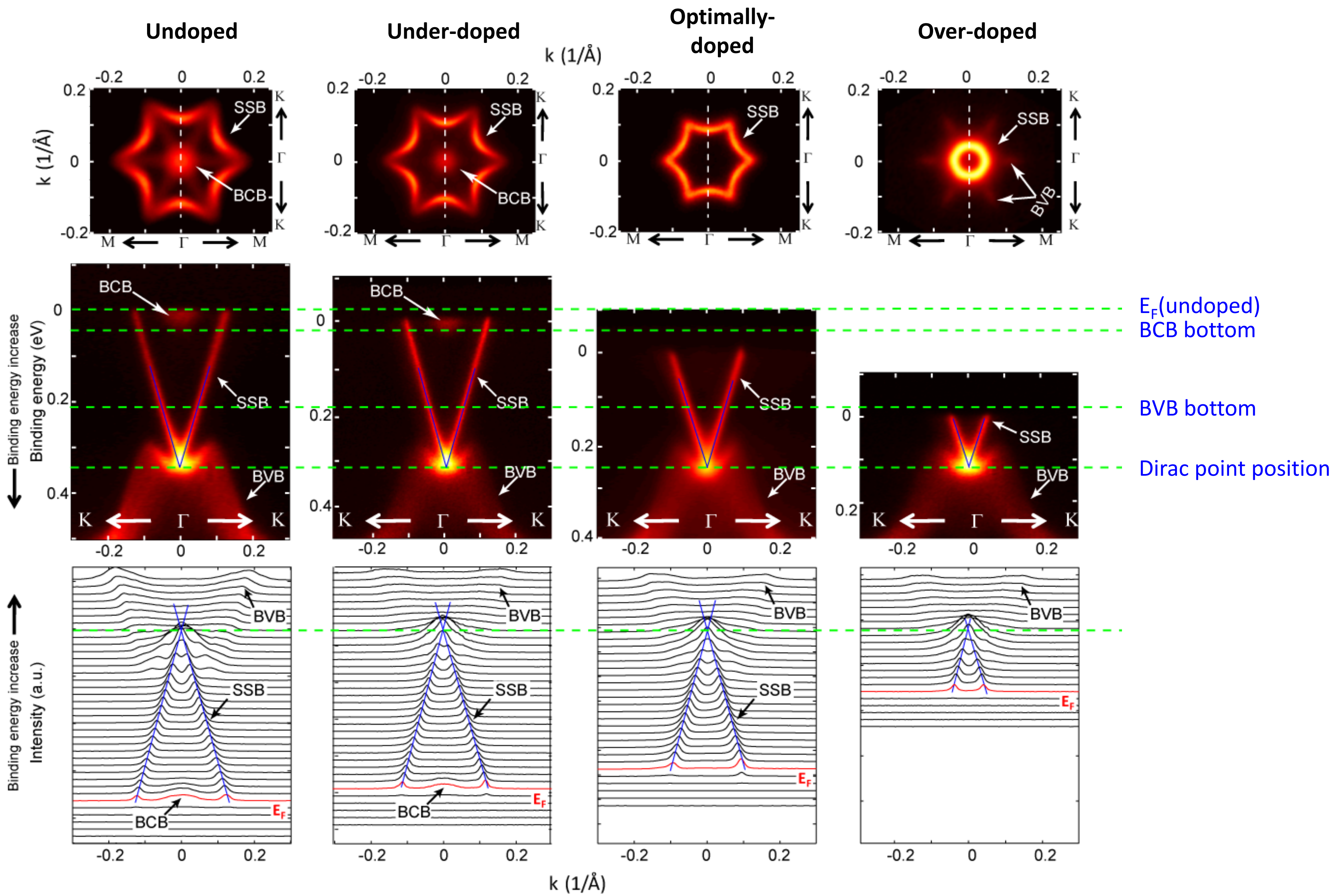
Topological surface state



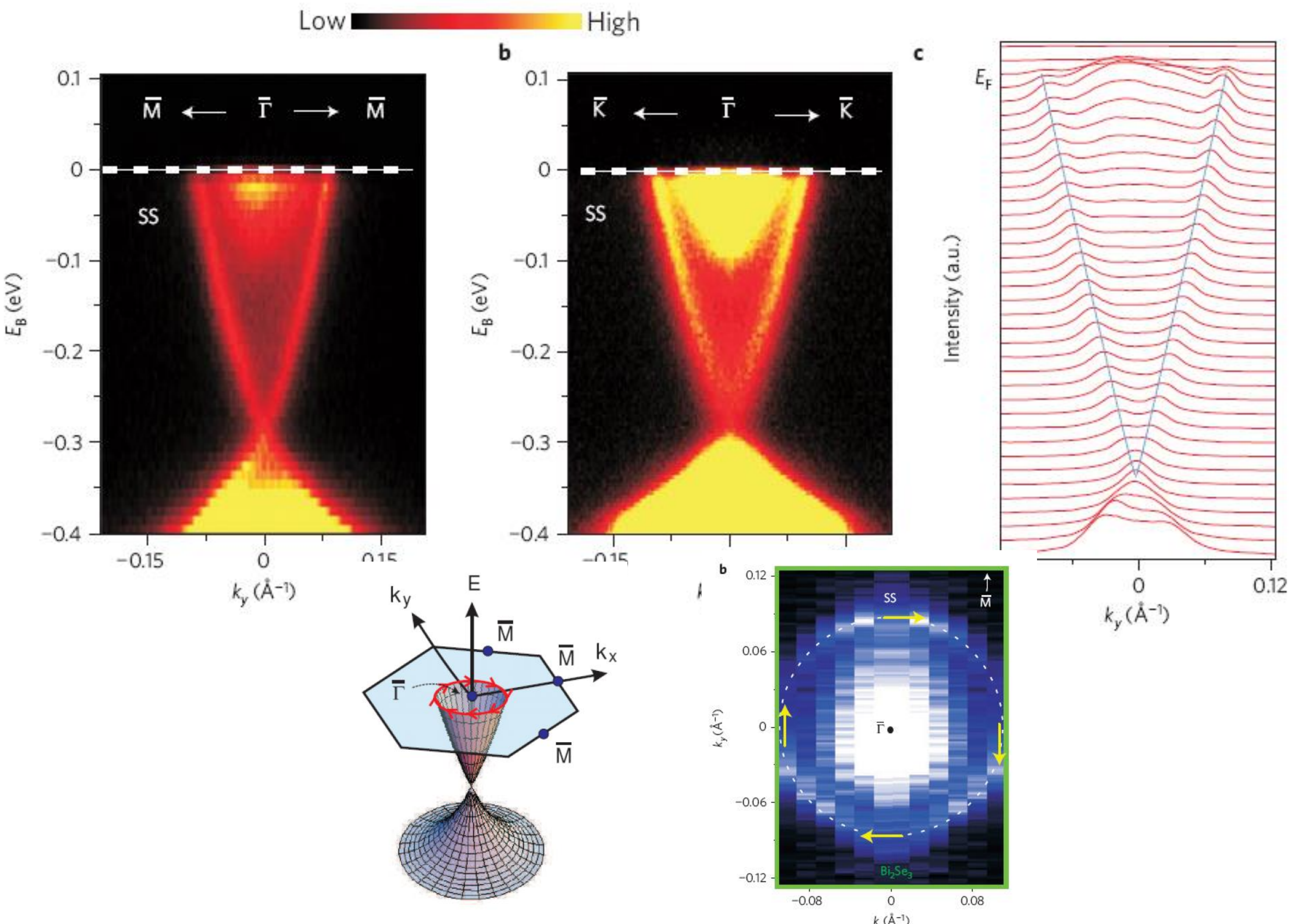


Arpes experiment on Bi2Te3 surface states, Shen group

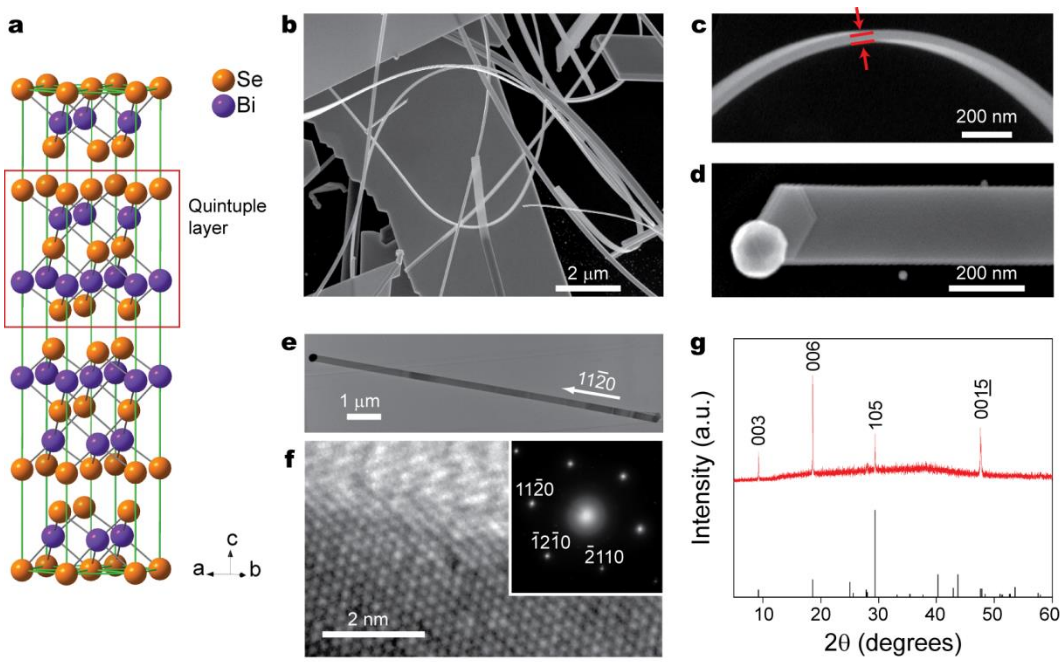
Doping evolution of the FS and band structure

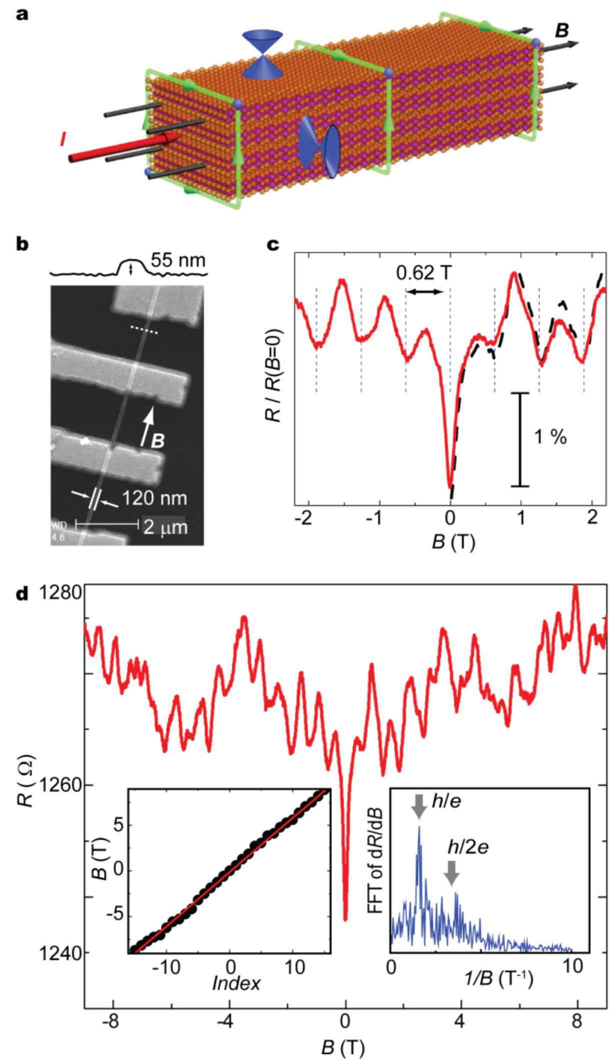


Arpes experiment&theory on Bi2Se3 surface states,
Hasan+Cava group

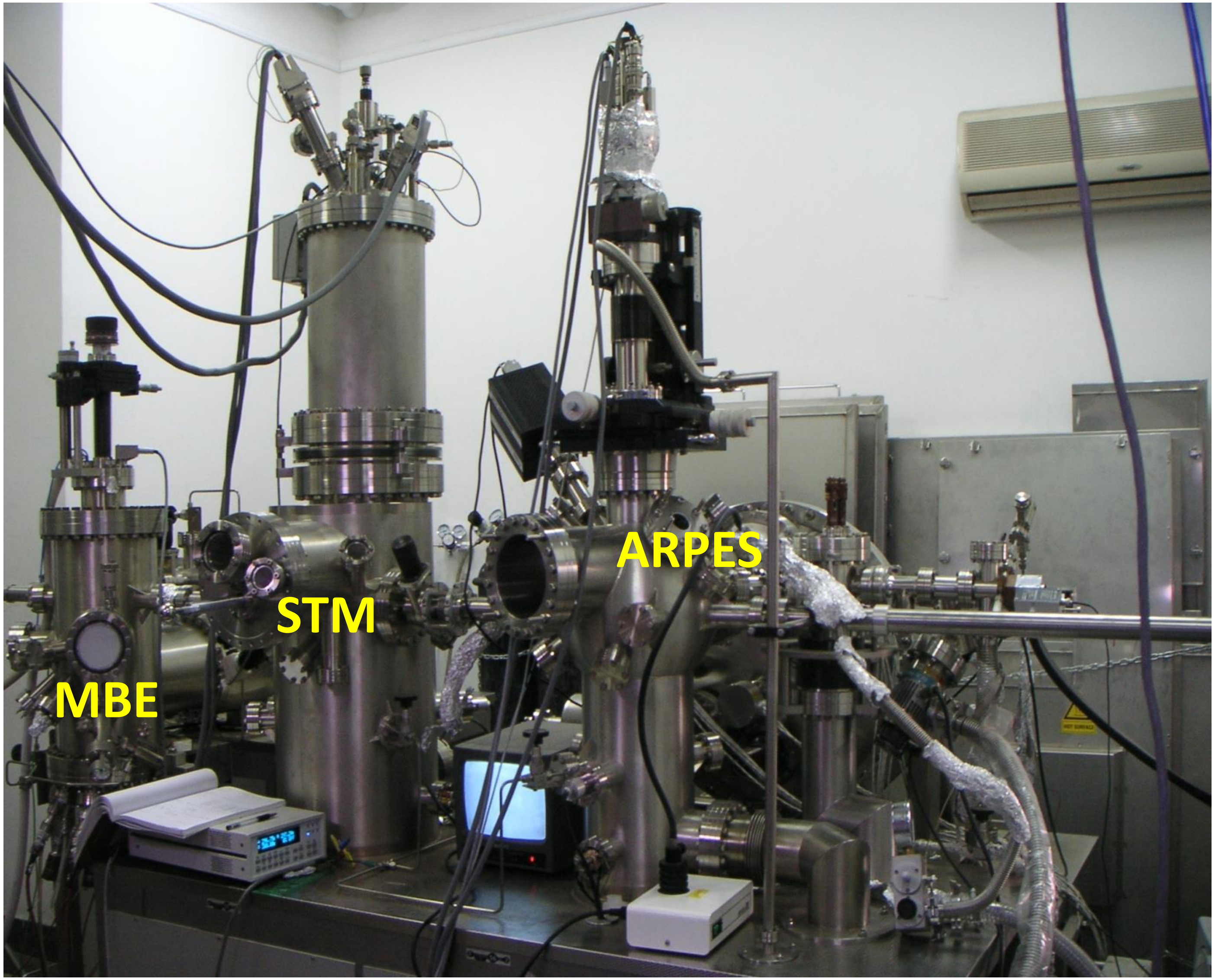


AB oscillations in nano-ribbon of Bi2Se3, Cui group





MBE-STM-ARPES System at Tsinghua University



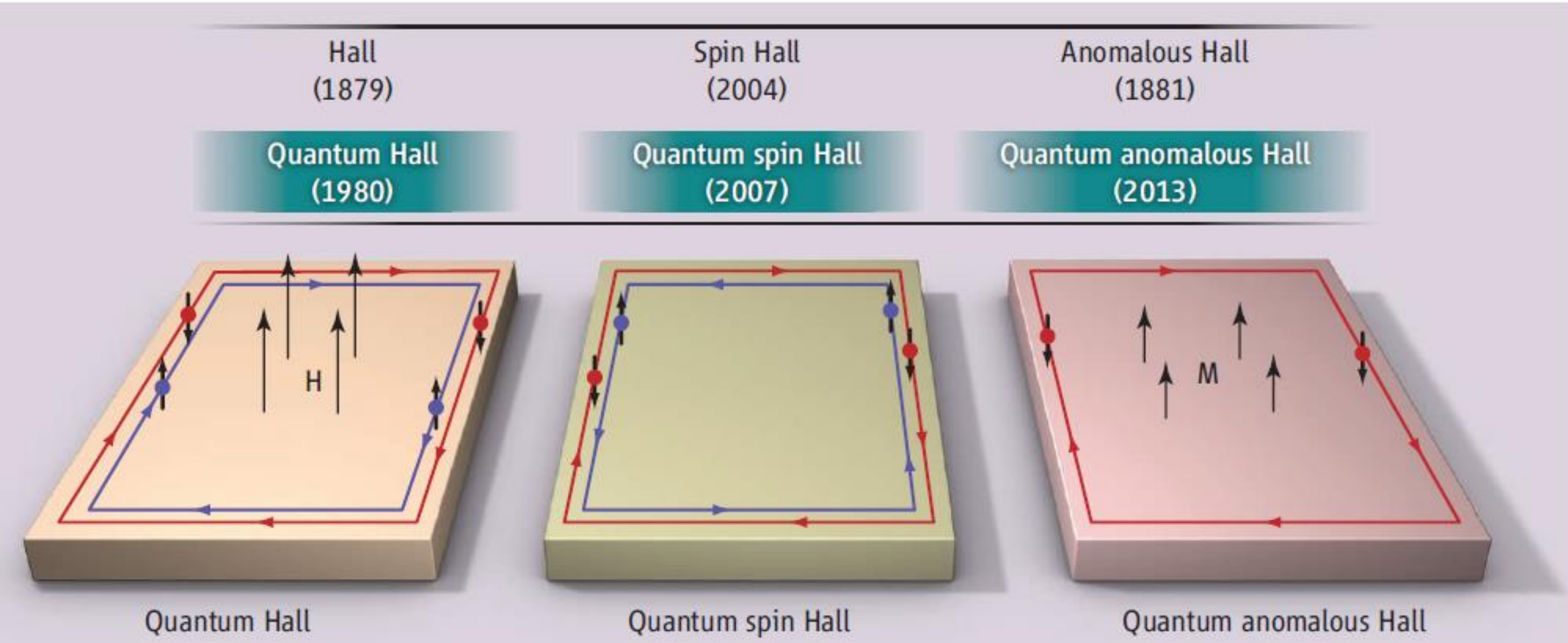
Results in the TI field:

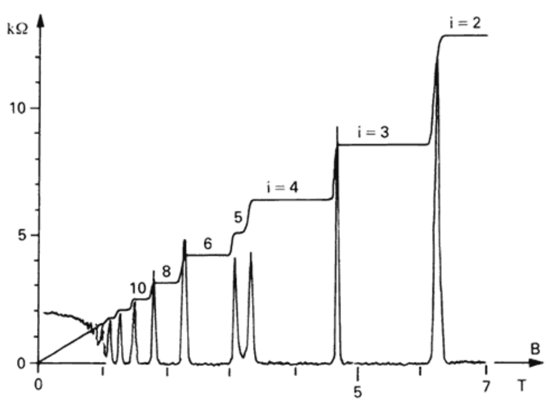
First MBE growth.

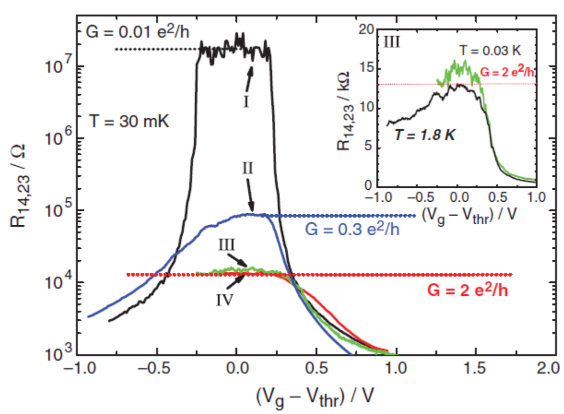
QAH effect.

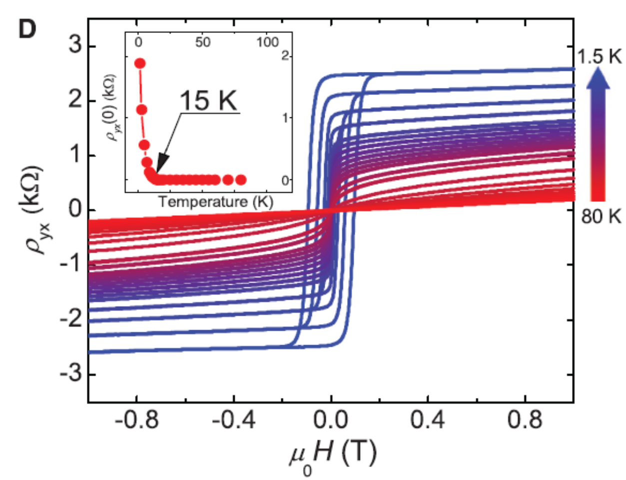
Landau levels for the Dirac surface state.

The quantum Hall trio

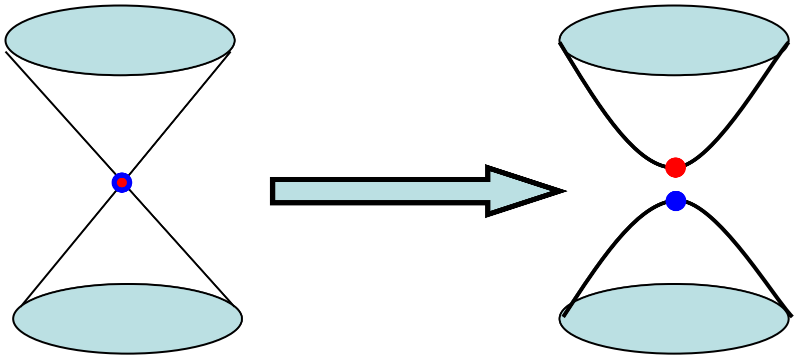


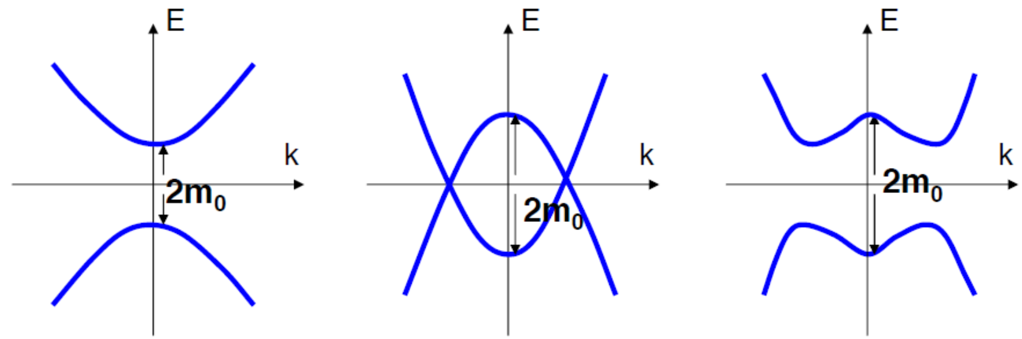


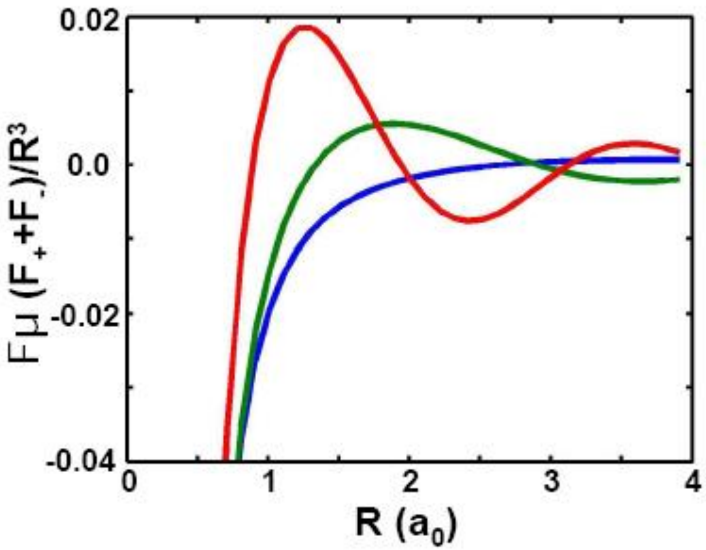


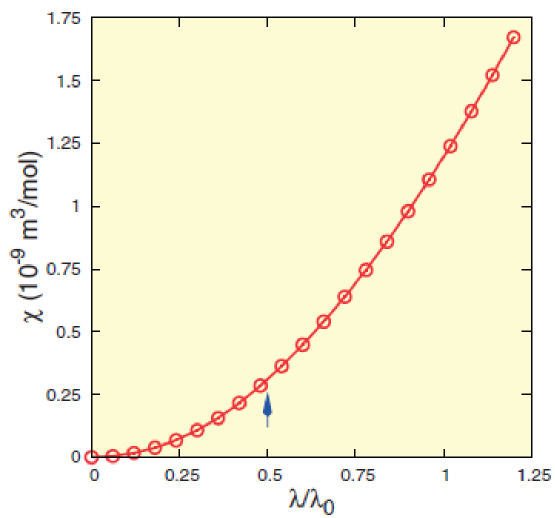


Mechanism of magnetic TI









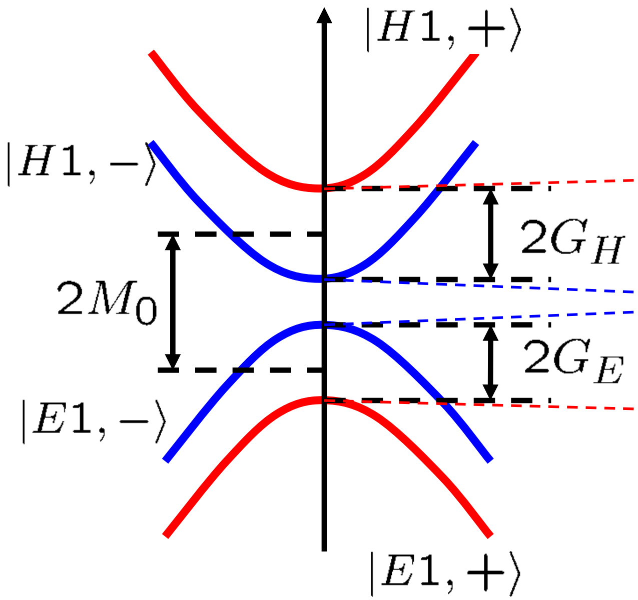
Ferromagnetic coupling through the RKKY interaction on the TI surface. (Zhang group, PRL2009).

Spin-orbit coupling and band inversion increases magnetic susceptibility, leading to magnetic order in the TI state. (IOP+Zhang group, Science 2010).

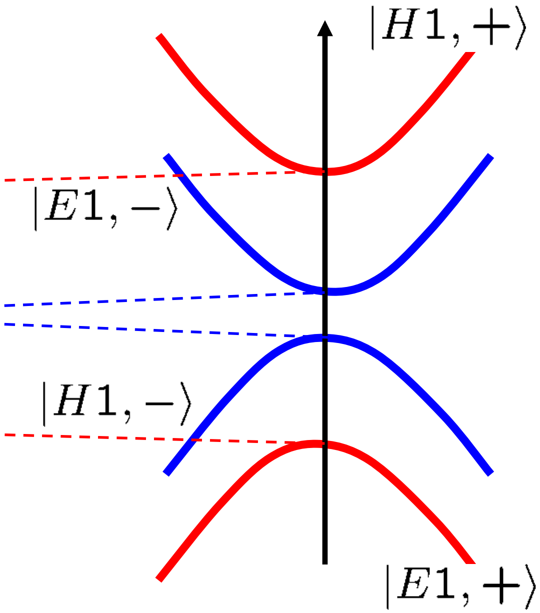
Understanding from edge states: QAH

Small spin splitting, σ_H=0

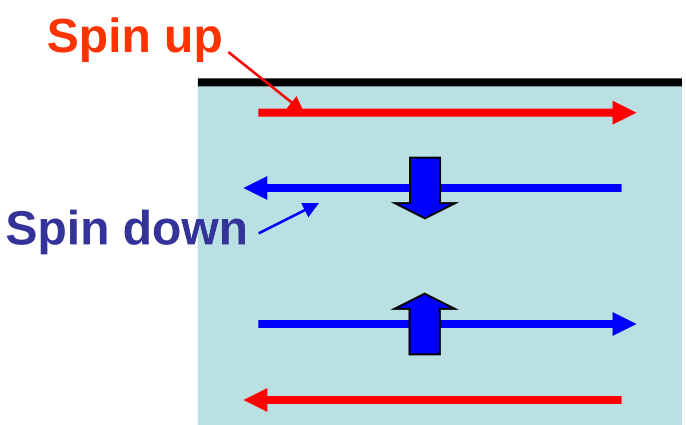
Large splitting, σ_H=e^2/h

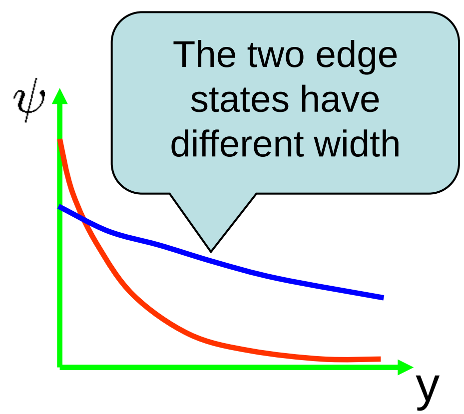


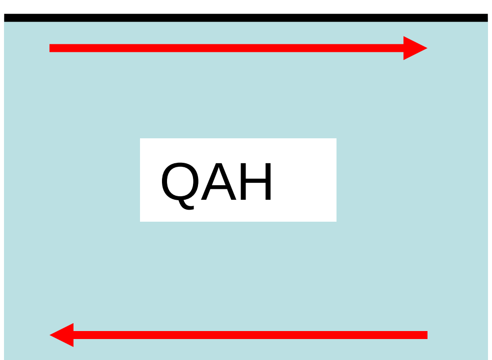
Further increase $|G_H|$ and $|G_E|$



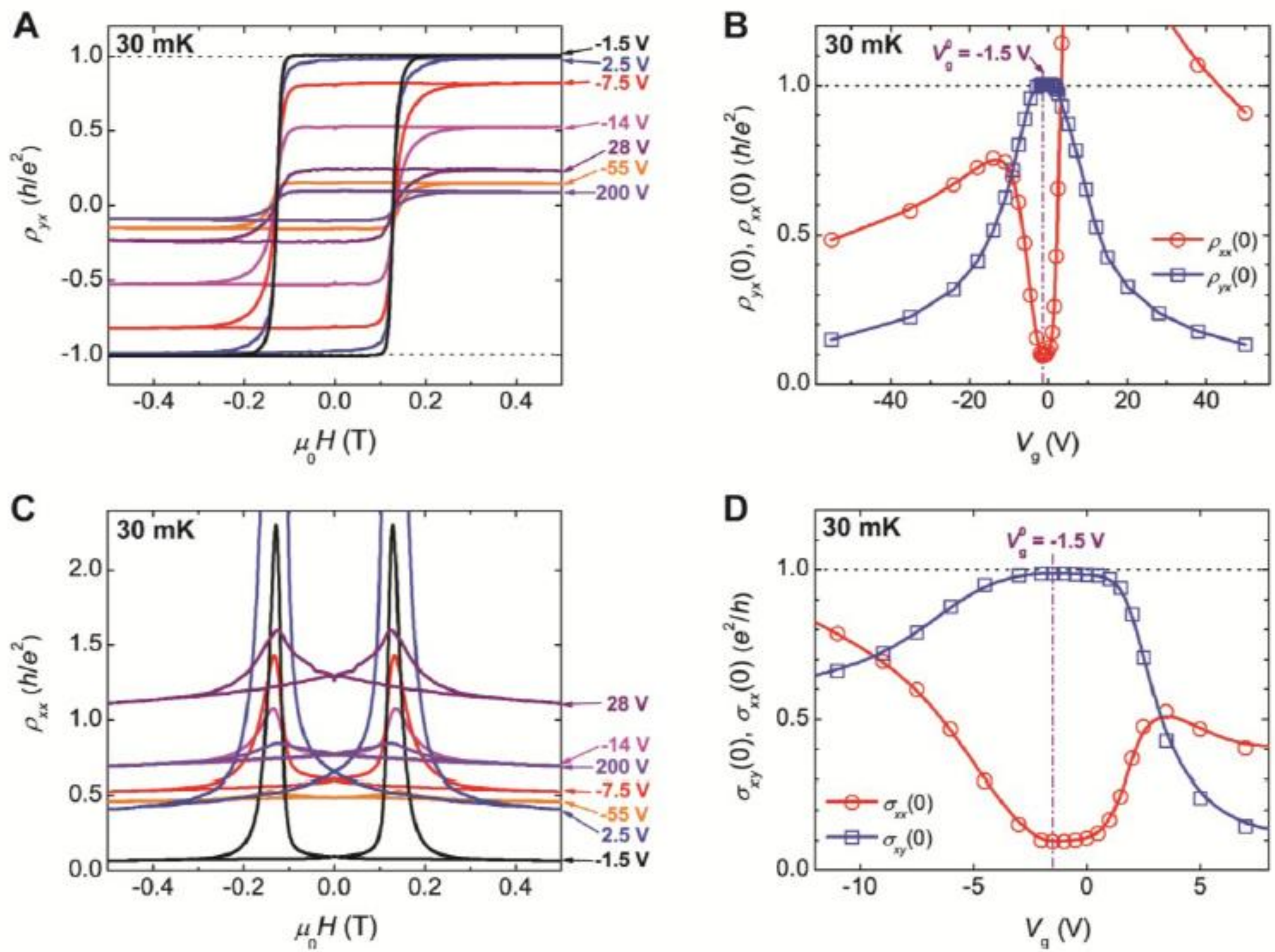
Note that G_E and G_H have opposite sign





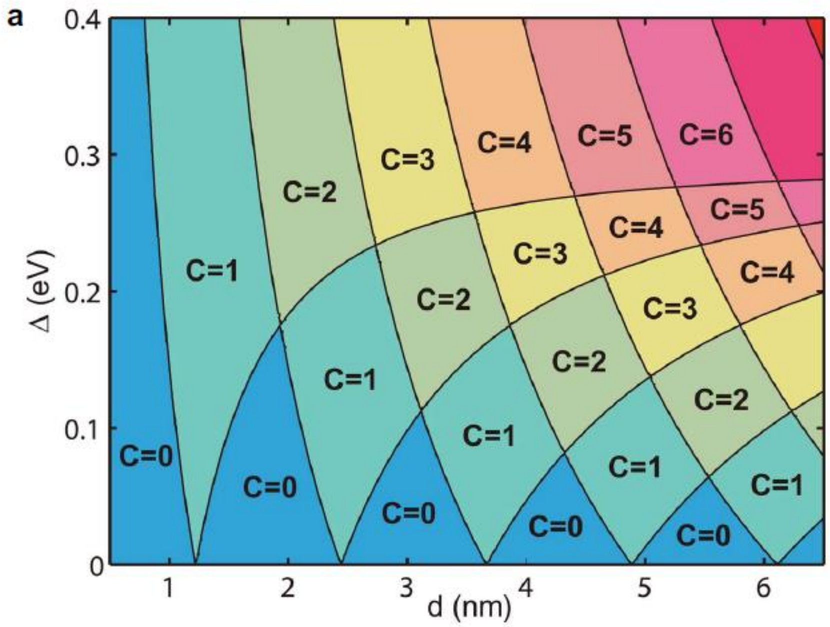


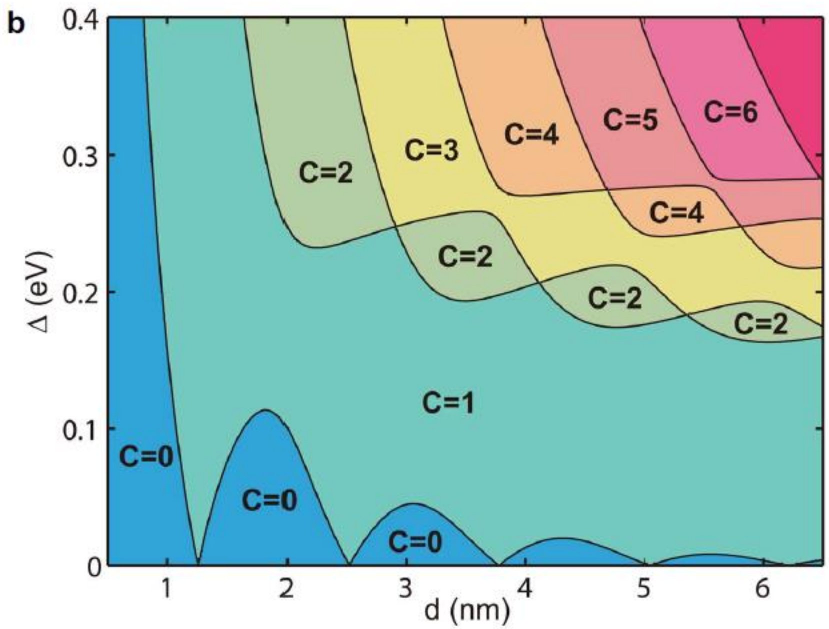
Discovery of the QAH (Tsinghua University, China)



Quantum Anomalous Hall with Higher plateaus

Theoretical phase diagram of QAH (thickness d , exchange field Δ)



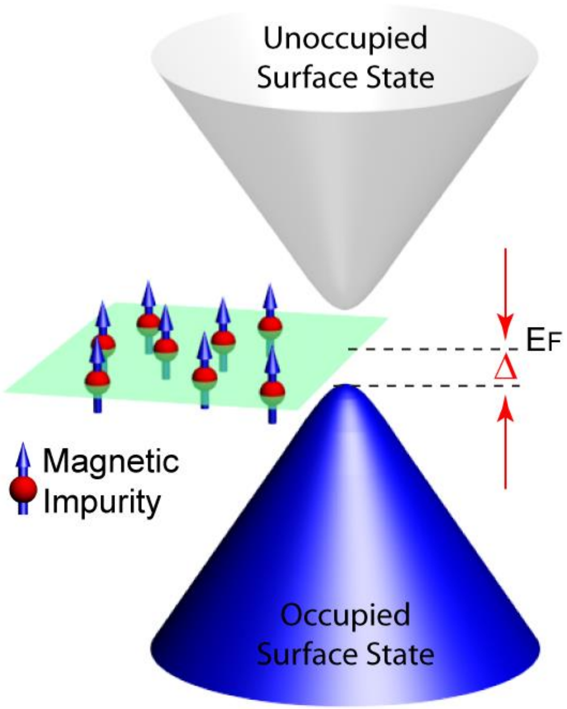


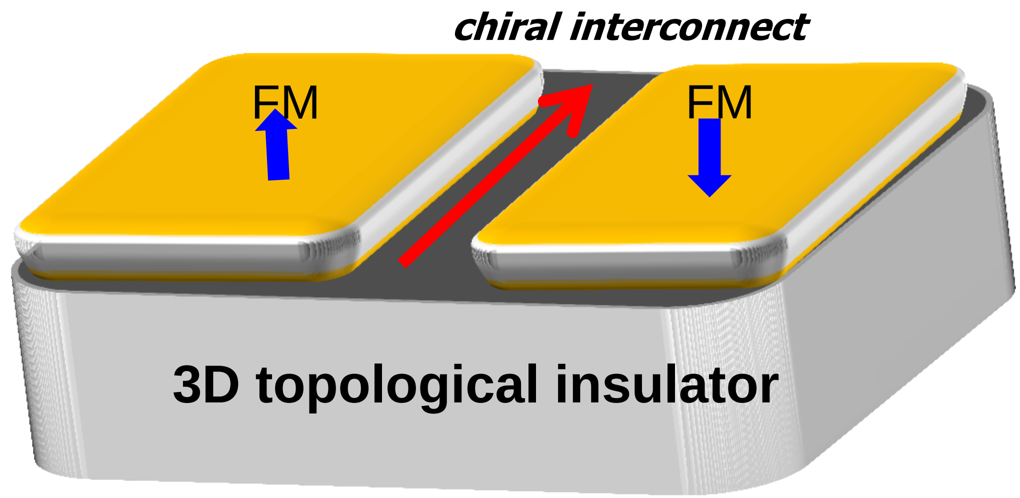
Without z direction SOC

With z direction SOC

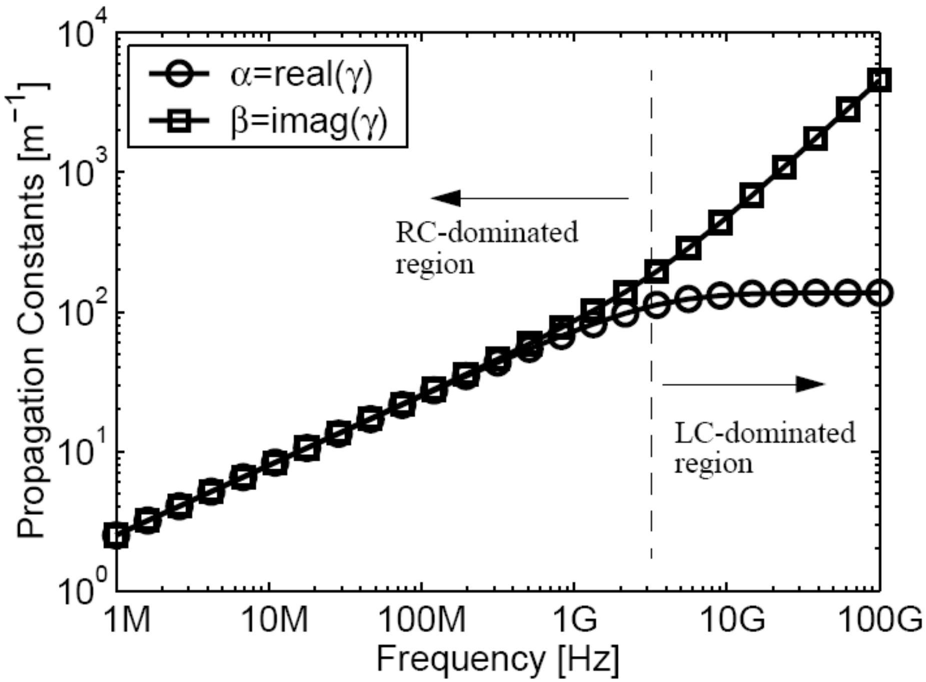
Zhang group, arXiv:1305.7500, submitted to PRL

Applications: chiral interconnects





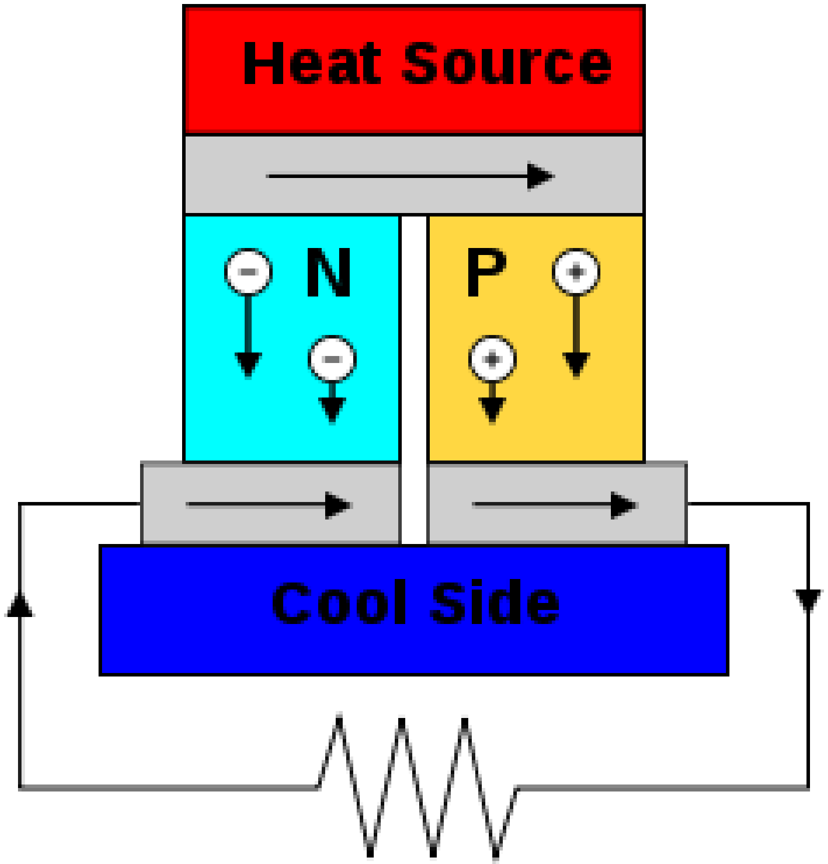
Bottleneck of the current copper interconnect: high dissipation



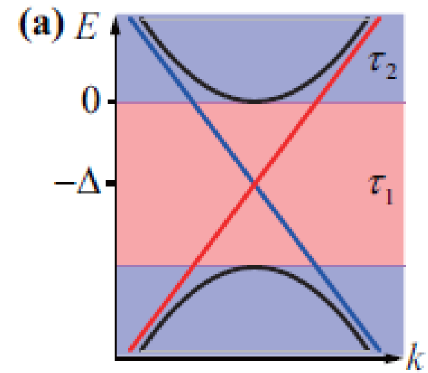
Around 3GHz, the current interconnect works in the RC dominated region; delay time 158 ns/mm; signal distortion due to $\omega = iD\,k^2$ dispersion law.

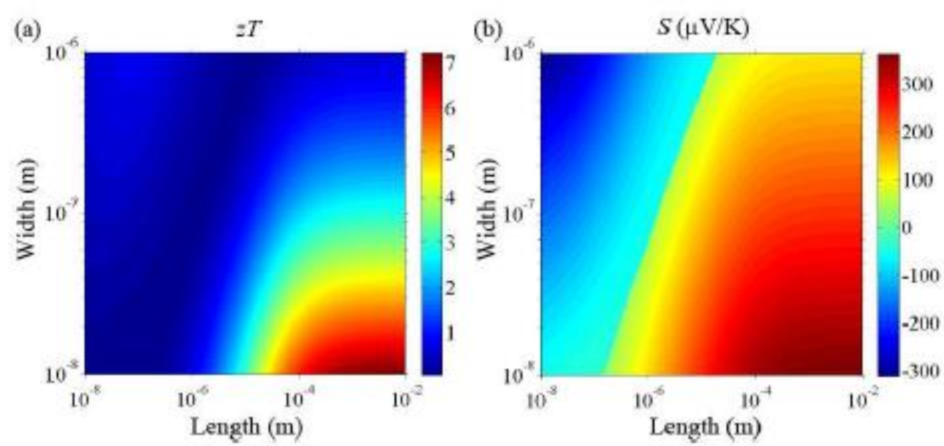
Currently the industry is considering optical interconnect solution inside the chip!

Energy applications: thermal electrics



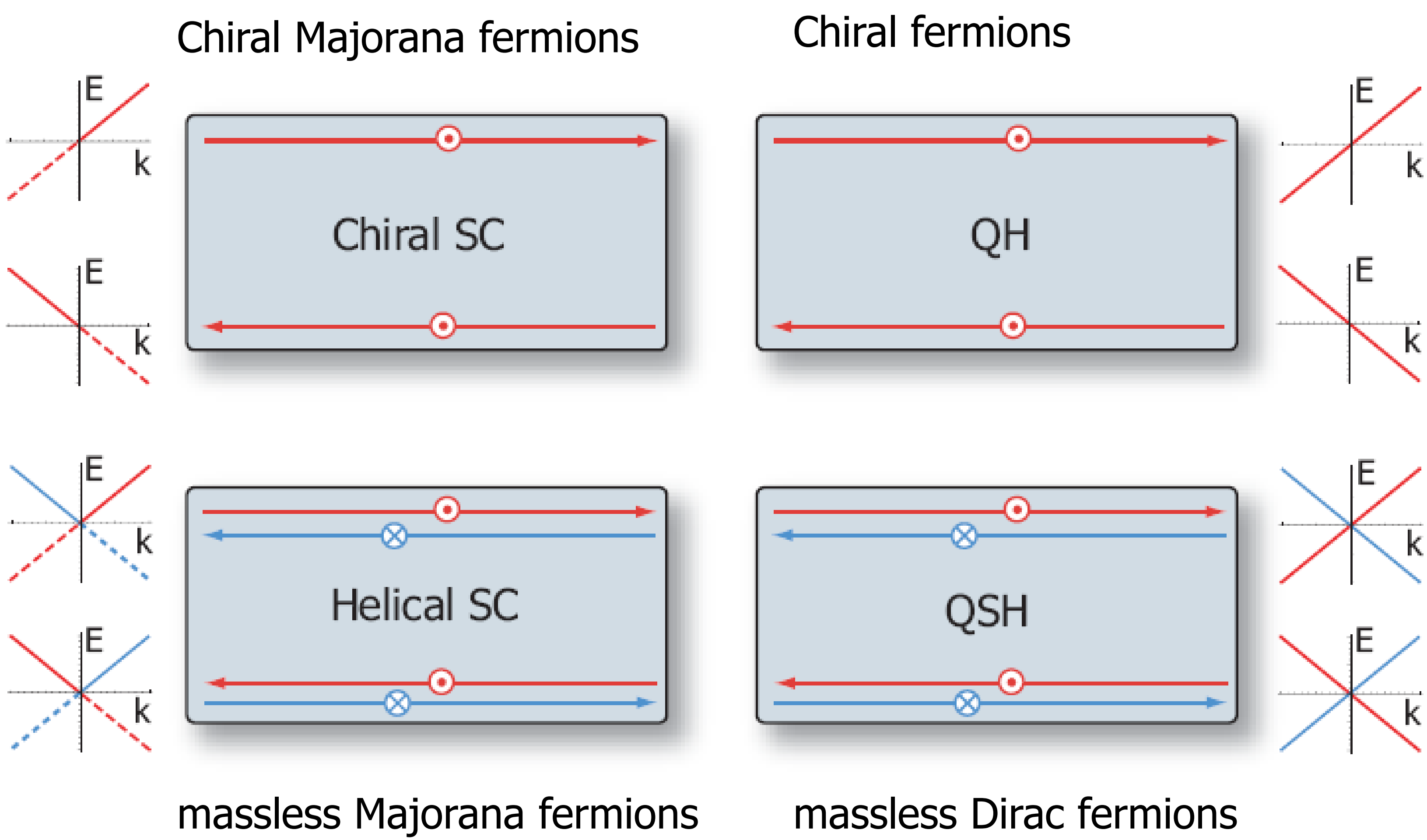
$$zT = \frac{\sigma S^2 T}{\kappa} \qquad zT = \frac{G S^2 T}{K}$$





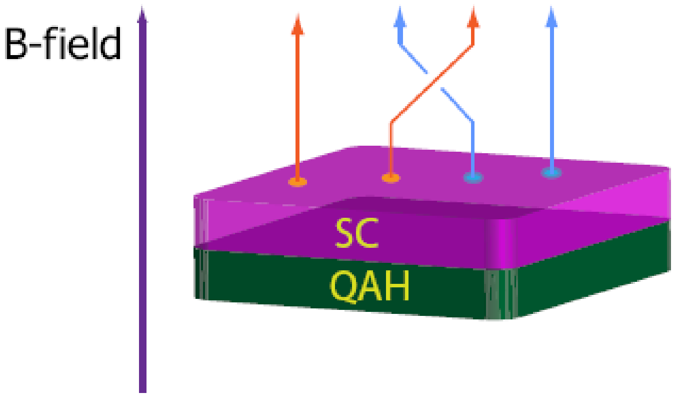
Topological insulators and superconductors

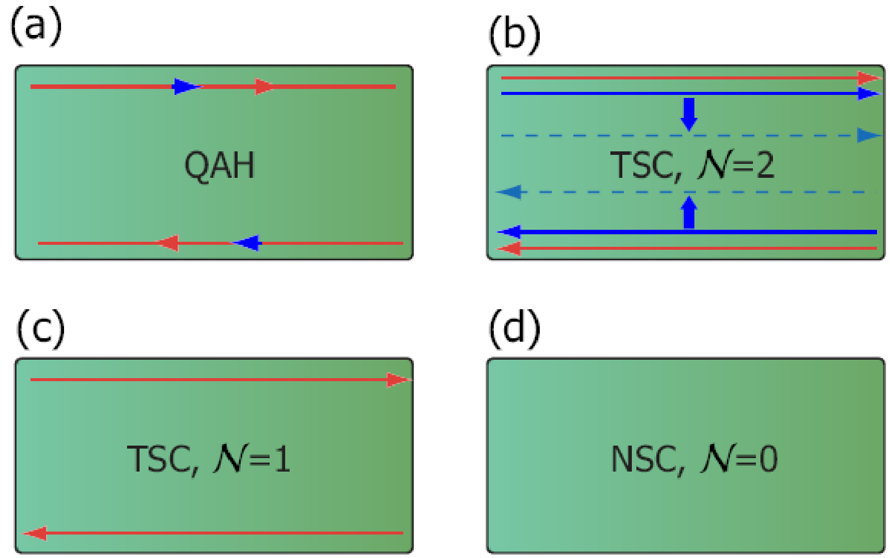
Full pairing gap in the bulk, gapless Majorana edge and surface states

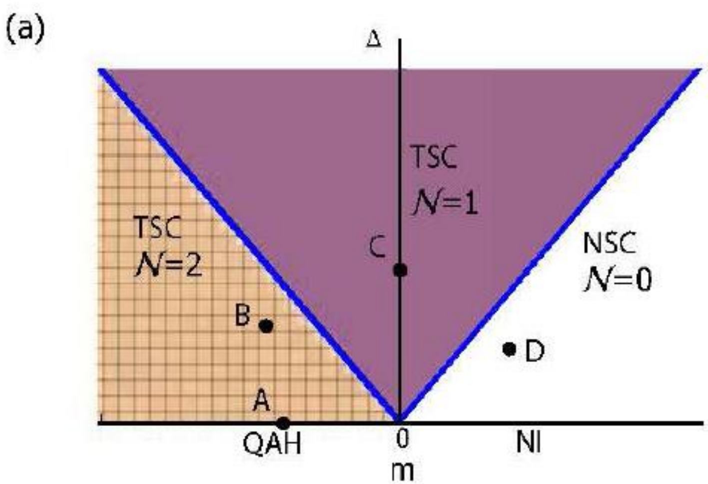


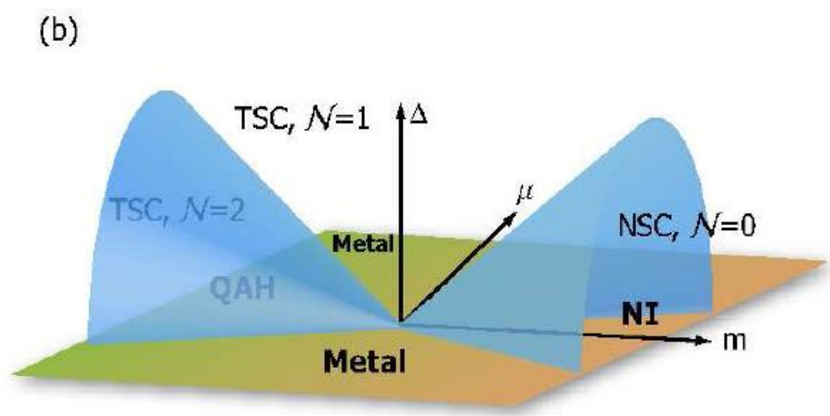
Qi, Hughes, Raghu and Zhang, PRL, 2009

Chiral superconductor obtained from QAH+SC (Qi, Hughes and SCZ, 2010)

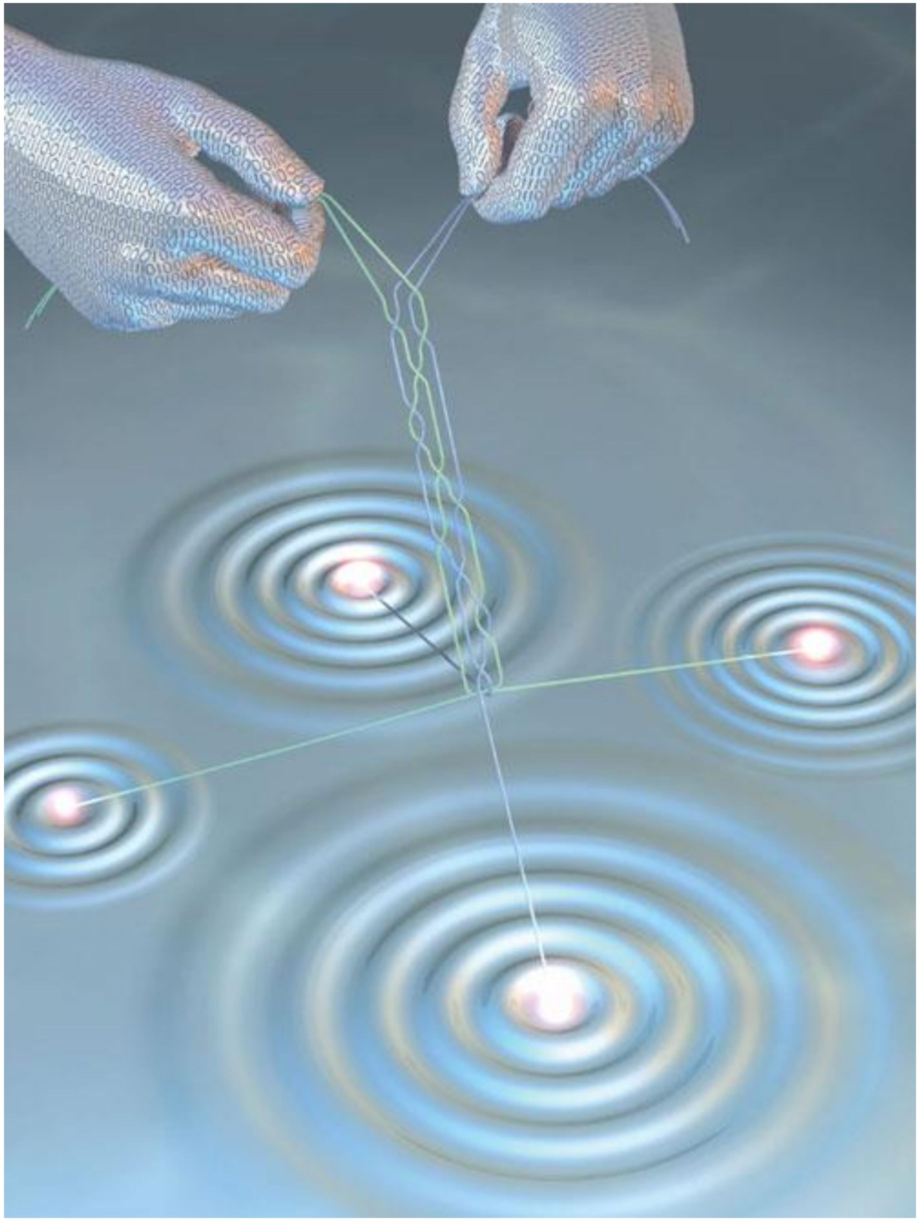








Topological quantum computers



15 = 3 x 5

1547502747204726405729303484737456393847239373922736464836293743932729327292723632927292820282739374
= ?

Topological insulators

New material for the future

Novel applications in electronics and energy

Using Moore's law to save Moore's law!