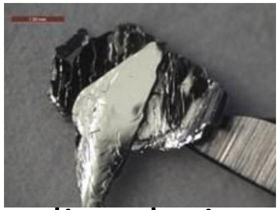
Emergent Frontiers in Quantum Materials:

High Temperature superconductivity and Topological Phases

Jiun-Haw Chu

University of Washington

The nature of the problem in Condensed Matter Physics



Consider a small piece (mm size) of metal.

- ~10^{20} valence electrons and atoms
- They are all mutually interacting via electromagnetic forces and Pauli exclusion principles
- The goal of condensed matter physics is to understand and ultimately control the emergent collective behavior

Problem: How do we solve a Schrodinger Equation with ~ 10^{20} degrees of freedom?

$$\mathcal{H} = -\sum_{j}^{N_e} \frac{\hbar^2}{2m} \nabla_j^2 - \sum_{\alpha}^{N_i} \frac{\hbar^2}{2M_\alpha} \nabla_\alpha^2 - \sum_{j}^{N_e} \sum_{\alpha}^{N_i} \frac{Z_\alpha e^2}{|\vec{r}_j - \vec{R}_\alpha|} + \sum_{j \ll k}^{N_e} \frac{e^2}{|\vec{r}_j - \vec{r}_k|} + \sum_{\alpha \ll \beta}^{N_j} \frac{Z_\alpha Z_\beta e^2}{|\vec{R}_\alpha - \vec{r}_\beta|}$$

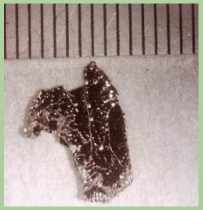
Diverse behavior emerging from a simple equation

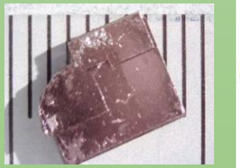
Diverse intriguing physical phenomena arising from the collective behaviors of electrons and atoms in REAL MATERIALS.

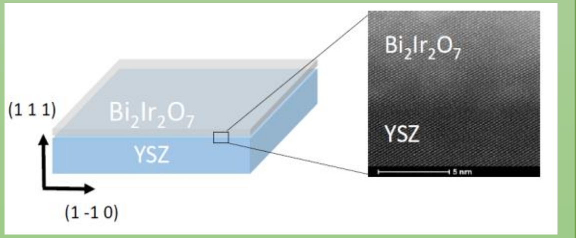
Intriguing physical phenomena:

Superconductivity, Charge/Spin density wave,
Ferromagnetism, Anti-ferromagnetism,
Ferroelectricity, Antiferroelectricity,
Band Insulator Mott Insulator, Anderson Insulator,
Heavy Fermion, High temperature superconductor
Frustrated magnet, Spin ice, Spin liquid,
Integer/Fractional Quantum Hall Effect
Quantum Spin Hall effect, Topological Insulator,
Topological superconductor, Topological semimetal,
Dirac Fermion, Weyl Fermion, Majorana Fermion, ….

REAL MATERIALS.







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- The task seems obvious – we just need to solve the equation and make the prediction.
- Problem – there is almost no exact solution beyond two particles. Even with powerful computer it's hard to solve numerically.
- Just to give you an idea, you need to diagonalize a 10^{18} x 10^{18} matrix if you just simply consider 32 electrons occupying 8x8 lattice sites with a single quantum state.

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Physicist built powerful phenomenological models to describe the emergent behaviors observed in experiment

Landau Fermi Liquid theory

BCS Theory of superconductivity

Landau theory of symmetry breaking phase transition

……

Quantum Materials: beyond the standard model

New materials and phenomenon challenge the old paradigm, they also bring in new concept, such as quantum critical point, topology,

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A quick comparison to the situations in high energy physics

- There are good “Standard Models”
    - Landau Fermi Liquid theory
    - BCS Theory of superconductivity
    - Landau theory for symmetry breaking
    - Wilson-Fisher theory of criticality
    - …
- The Theory of Everything is known

$$\mathcal{H} = -\sum_{j}^{N_e} \frac{\hbar^2}{2m} \nabla_j^2 - \sum_{\alpha}^{N_i} \frac{\hbar^2}{2M_\alpha} \nabla_\alpha^2 - \sum_{j}^{N_e} \sum_{\alpha}^{N_i} \frac{Z_\alpha e^2}{|\vec{r}_j - \vec{R}_\alpha|} + \sum_{j \ll k}^{N_e} \frac{e^2}{|\vec{r}_j - \vec{r}_k|} + \sum_{\alpha \ll \beta}^{N_j} \frac{Z_\alpha Z_\beta e^2}{|\vec{R}_\alpha - \vec{r}_\beta|}$$

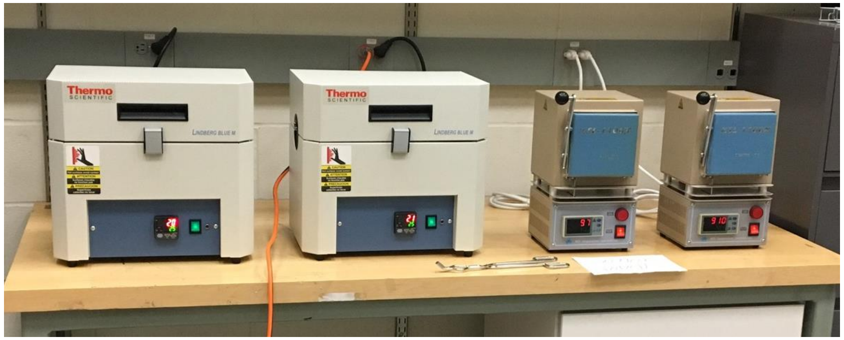
- Experiments for physics beyond standard model are abundant

Non-Fermi liquid behavior in high temperature superconductors

Topological phases that cannot be classified by broken symmetry

How do we make this happen?

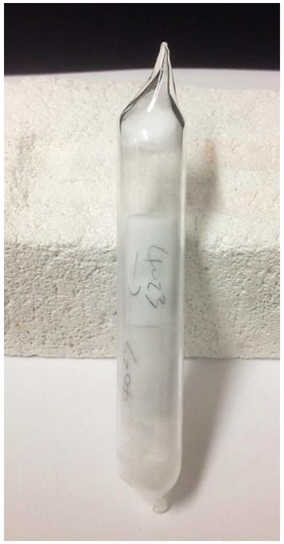
Hydrogen torch station T ~ 3000K



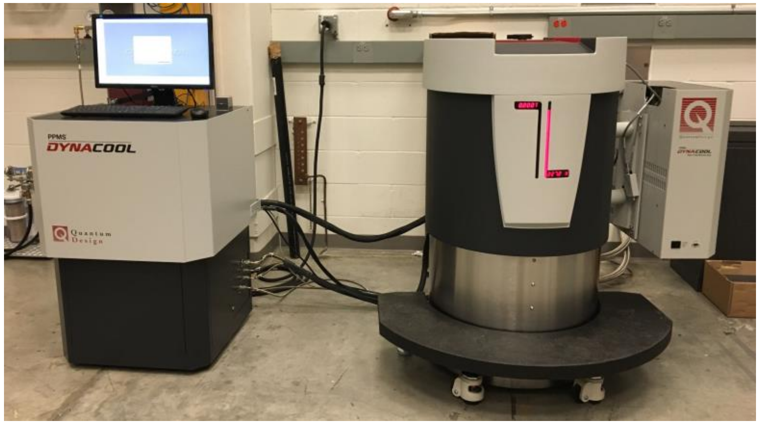
Tube and box furnaces T ~ 1500K

The art of crystal growth:

Learn to become an alchemist



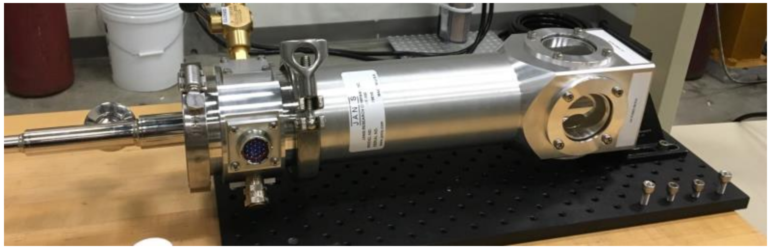
How do we make this happen?



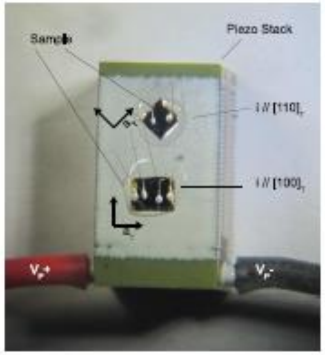
PPMS Dynacool T ~ 2K   B ~ 14T

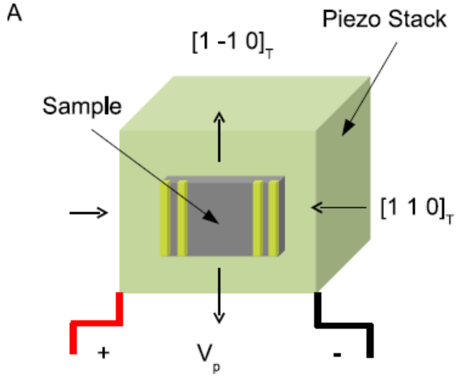
And then we take it down to low temperatures and high magnetic field

Applying elastic strain field



Janis flow cryo system 500K ~ 80K (LN_2) or 10K (LHe)

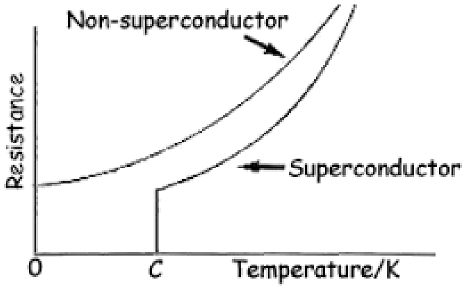




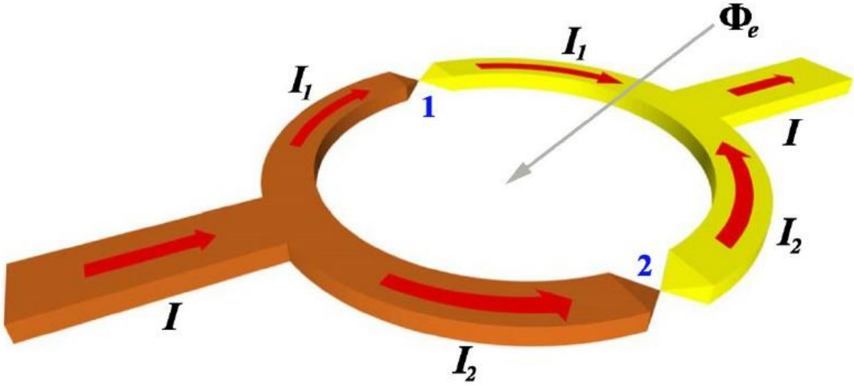
- High temperature superconductivity

- Topological phases

A short introduction of superconductivity



C = critical temperature

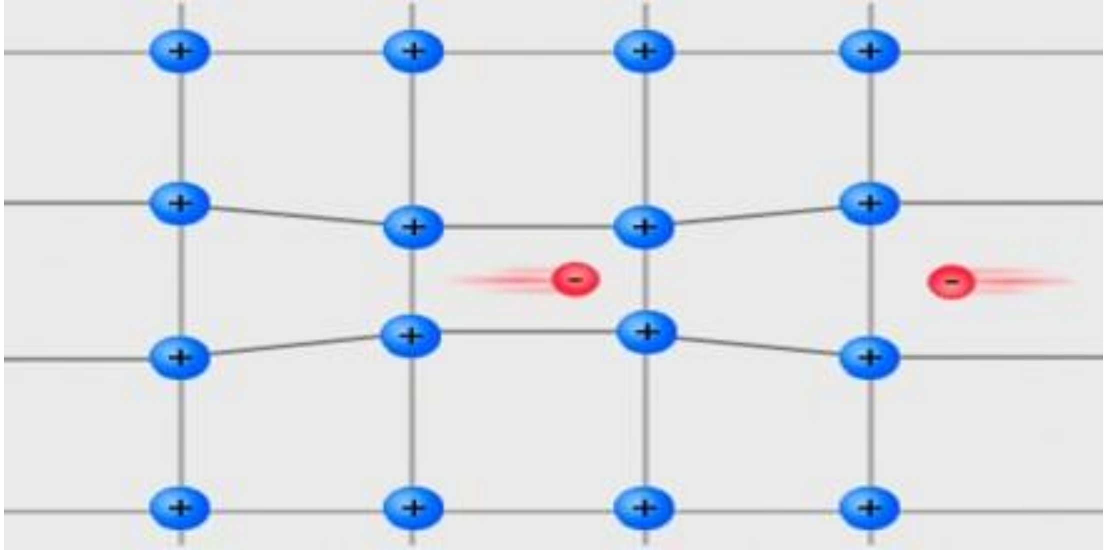


Bardeen-Cooper-Schrieffer theory of superconductivity

Electrons bind into Cooper pairs by phonon interactions.

Cooper pairs condensate into macroscopic wave function.

The phonon set the energy scale of this phenomenon, therefore set the critical temperature.



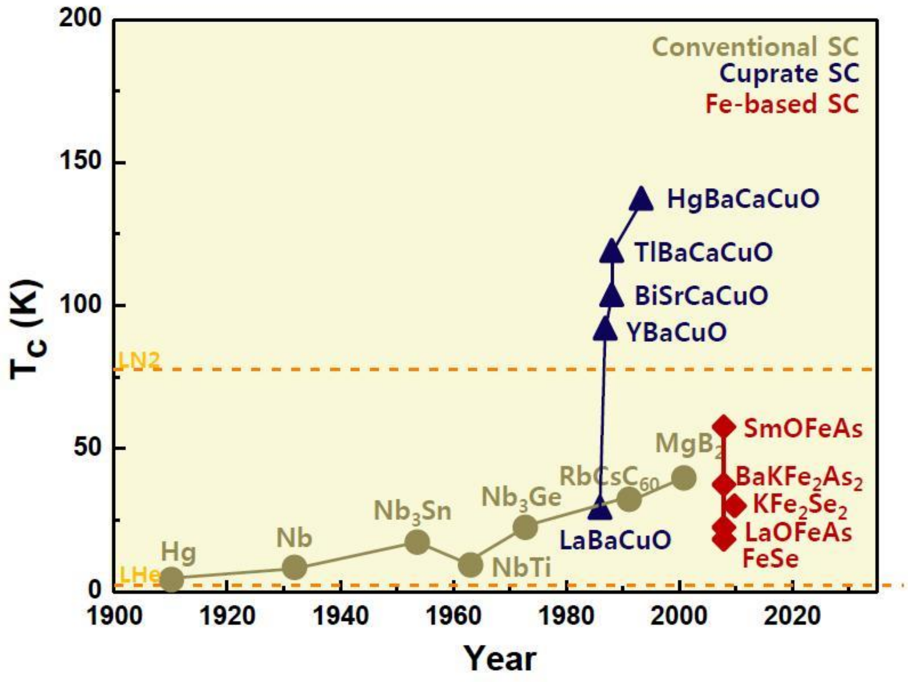
A short history of superconductivity

- 1911 Kamerlingh Onnes discovered the first superconductor

  Hg ~ 4K

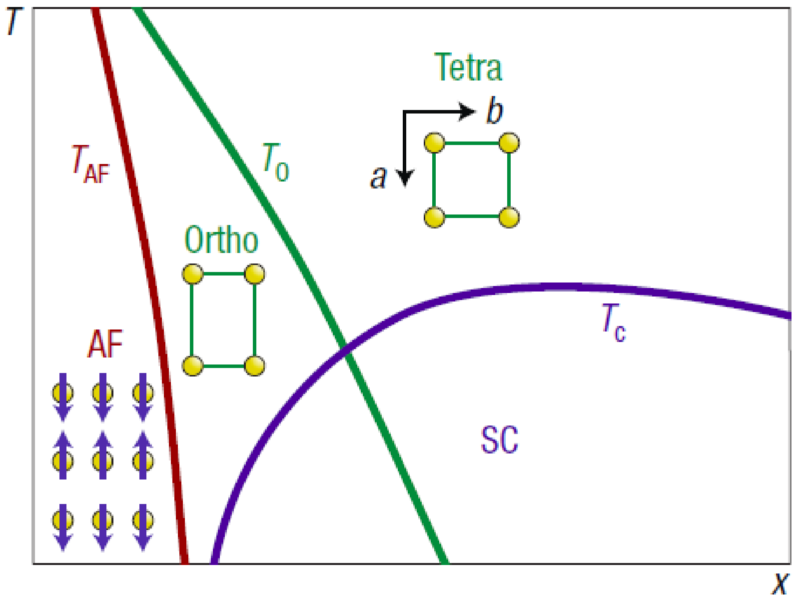
- 1957 Bardeen – Cooper – Schrieffer theory of superconductivity

- 1986 Cuprates (Tc ~ 100K)
- 2008 Iron based (Tc ~ 50K)

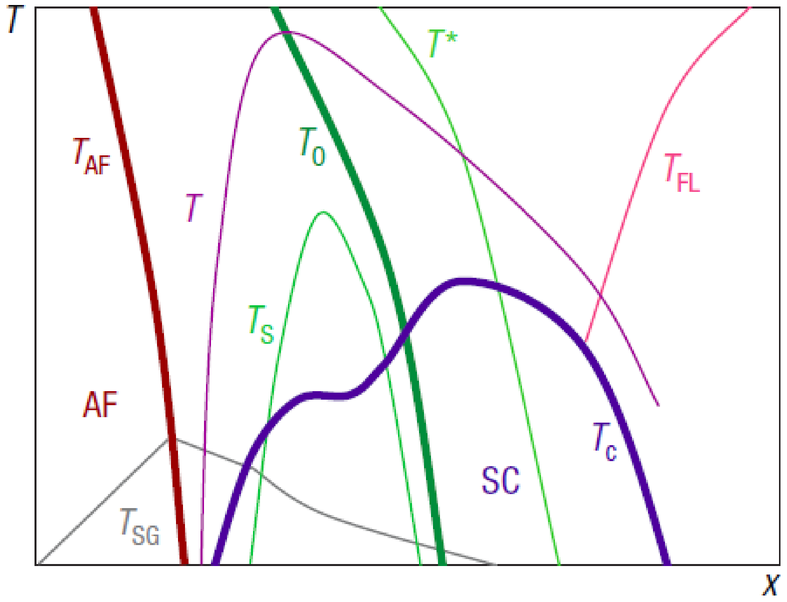


High temperature superconductors: the big question

Fe pnictides:



Cuprates:



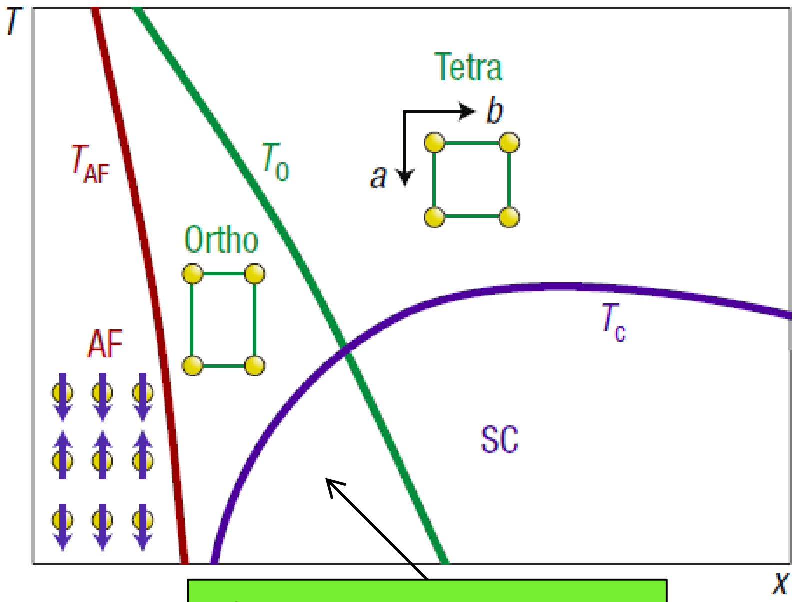
Kivelson & Yao,
Nature Materials **7**, 927 (2010).

- The parent stoichiometric compound is almost always non-superconducting. Optimal superconductivity needs to be induced by chemical substitutions.

- In the T-x phase diagram, superconductivity is always interweaved by various lines: phase boundary, cross-over….

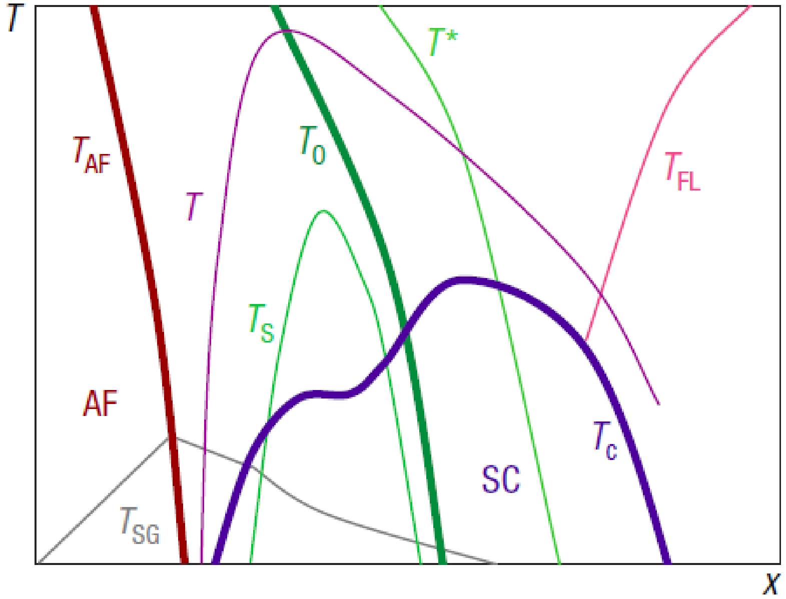
High temperature superconductors: the big question

Fe pnictides:



Electronic nematic

Cuprates:



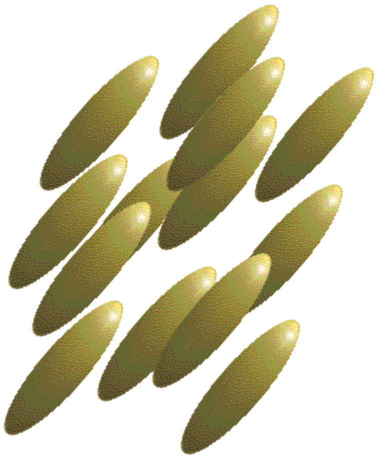
Kivelson & Yao, Nature Materials **7**, 927 (2010).

- The big question in high Tc: what are these lines? Are they phase boundaries? Symmetry breaking phase transitions? What symmetry is broken? .
- Some of these phases are well studied but some others are poorly understood, eg. Electronic nematic phase

Broken rotational symmetry in solid crystals:
Electronic nematic phase

Soft condensed matter

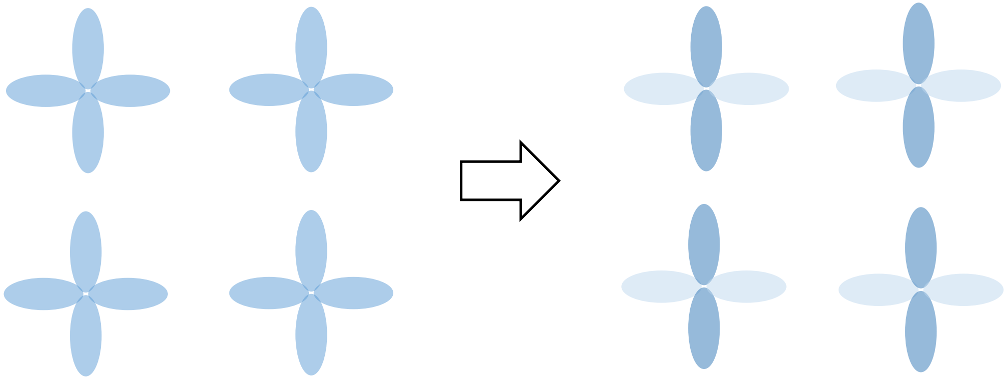
Nematic liquid crystal phase, long molecules spontaneously breaks full rotational symmetry.



Strongly correlated electronic system

Electronic nematic phase, spontaneous electronic order breaks discrete rotational symmetry

Electrical ferro-quadrupole order



Example of electron nematic phase in real space

Broken rotational symmetry in solid crystals:
Electronic nematic phase

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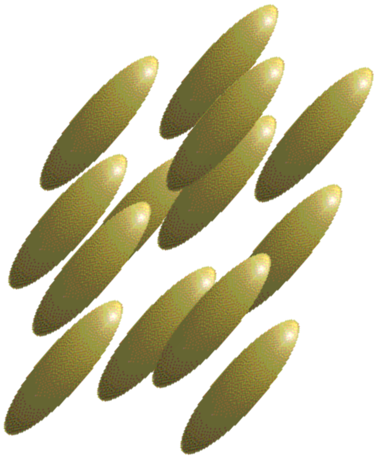

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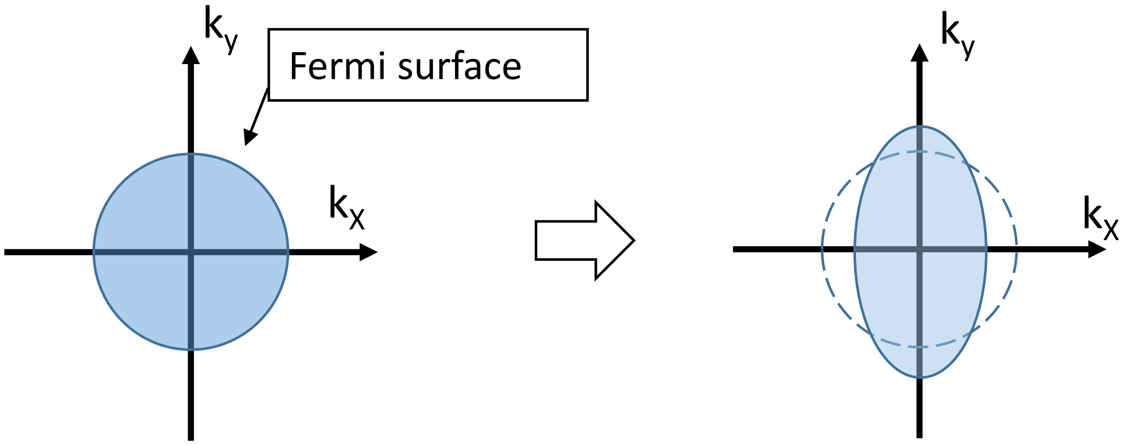
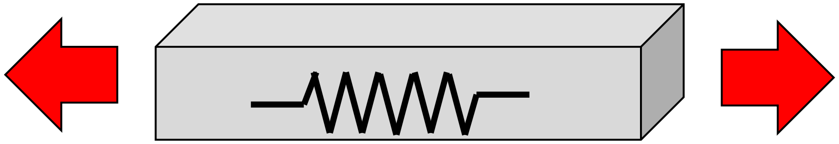
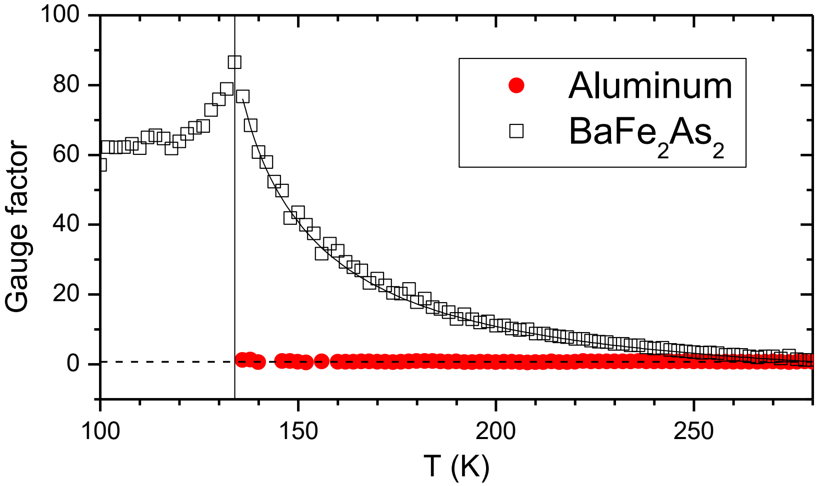


Example of electron nematic phase in momentum space

The signature of an electronic nematic phase: Divergent elastoresistance



$$R = \frac{\rho L}{A} \Rightarrow \frac{\Delta R}{R} = \frac{\Delta \rho}{\rho} + \frac{\Delta L}{L} - \frac{\Delta A}{A}$$



However, not all materials behave the same way, and it’s related to the idea of **Broken symmetries**

High temperature superconductors: big question

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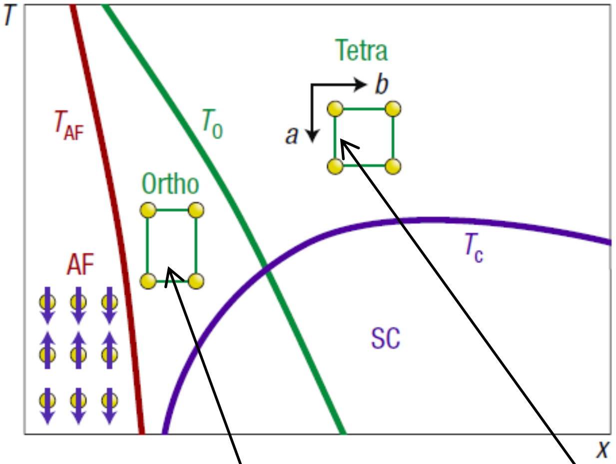
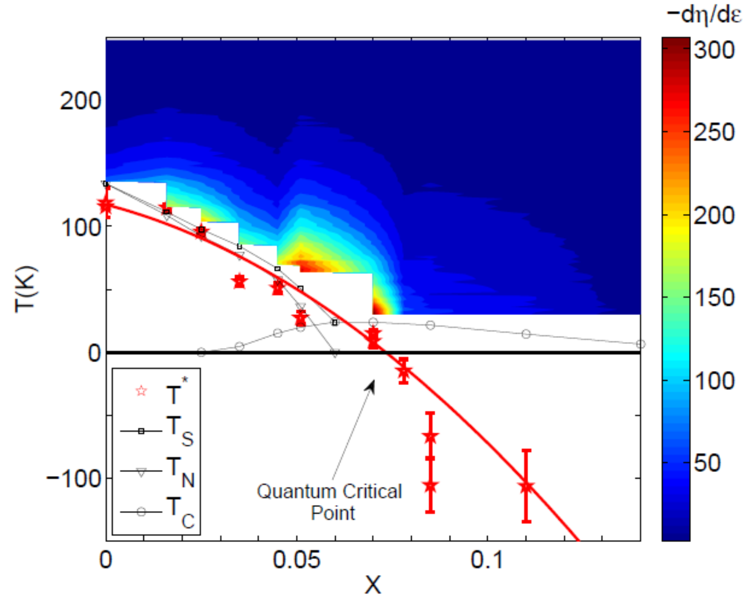


Electronic nematic

Nematic fluctuations



- If nematic fluctuations are responsible for superconducting pairing, can we design new superconductors by deliberately create a nematic quantum critical point?

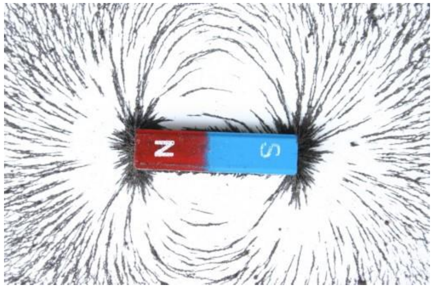
- High temperature superconductivity

- Topological phases

What is a topological phase

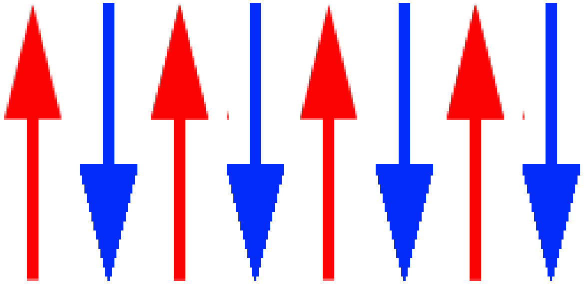
- A major goal of condensed matter physics is to discover and understand new state of matter.
- New states of matter often can be characterized by the symmetries they break.

Ferromagnet



Time reversal
Rotational

Antiferromagnet



Time reversal
Rotational
Translational

Superconductor

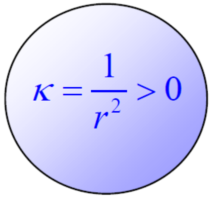
Gauge symmetry

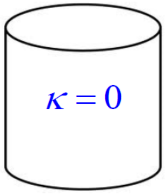
What is a topological phase

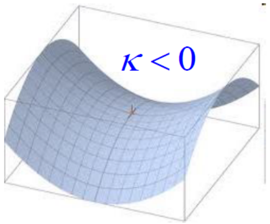
> More precisely, topology studies properties that are preserved under continuous deformations, including stretching and bending, but not tearing or gluing. -- Wikipeida

g is an integer topological invariant that can be expressed in terms of the gaussian curvature κ that characterizes the local radii of curvature

$$\kappa = \frac{1}{r_1 r_2}$$







Gauss Bonnet Theorem : $\int_S \kappa dA = 4\pi(1-g)$

First Topological phase – Quantum Hall Effect

"For the greatest benefit to mankind"

Alfred Nobel

2016 NOBEL PRIZE IN PHYSICS

David J. Thouless

F. Duncan M. Haldane

J. Michael Kosterlitz

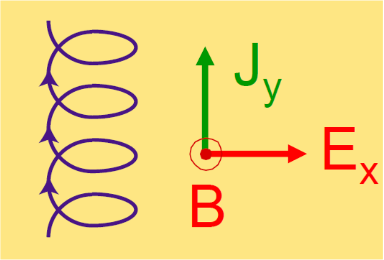
For theoretical discoveries of topological phase transitions and topological phases of matter

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

$$n = \frac{1}{2\pi}\int_{BZ} d^2k\,\mathbf{F}(\mathbf{k}) = \frac{1}{2\pi}\oint_C \mathbf{A}\cdot d\mathbf{k}$$

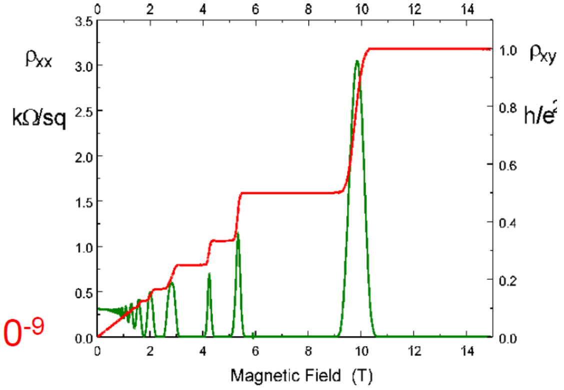
Thouless, Kohmoto, Nightingale and den Nijs 82

Quantized Hall conductivity : $J_y = \sigma_{xy}E_x$



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

Integer accurate to 10^{-9}



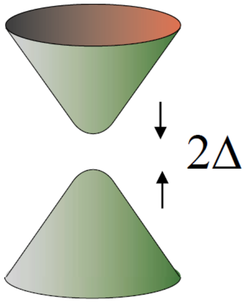
Quantum Hall effect without time reversal symmetry breaking: Quantum Spin Hall Effect

Energy gaps in graphene:

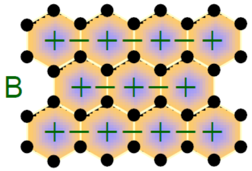
$\sigma_z \sim$ sublattice
$\tau_z \sim$ valley
$s_z \sim$ spin

$$H = \mathrm{v}_F \sigma \cdot p + V$$

$$E(p) = \pm\sqrt{\mathrm{v}_F^2 p^2 + \Delta^2}$$



. Periodic Magnetic Field with no net flux (Haldane PRL '88)



$$V = \Delta_{\mathrm{Haldane}} \sigma^z \tau^z$$

Broken Time Reversal Symmetry

Quantized Hall Effect $\sigma_{xy} = \operatorname{sgn}\Delta \frac{e^2}{h}$

Intrinsic Spin Orbit Potential

$$V = \Delta_{SO} \sigma^z \tau^z s^z$$

Respects ALL symmetries

Quantum Spin-Hall Effect

What is the Topological invariant

Inversion (P) Symmetry : determined by Parity of occupied 2D Bloch states

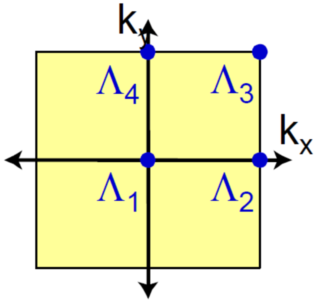
$$P|\psi_n(\Lambda_a)\rangle = \xi_n(\Lambda_a)|\psi_n(\Lambda_a)\rangle$$

$$\xi_n(\Lambda_a) = \pm 1$$

In a special gauge: $\delta(\Lambda_a) = \prod_n \xi_n(\Lambda_a)$

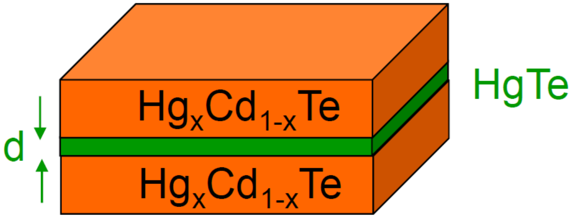
$$\boxed{(-1)^\upsilon = \prod_{a=1}^{4}\prod_n \xi_{2n}(\Lambda_a)}$$

T - invariant momenta



Bulk 2D Brillouin Zone

2D topological insulator with larger gap



Theory: Bernevig, Hughes and Zhang, Science '06

Expt: Konig, Wiedmann, Brune, Roth, Buhmann, Molenkamp, Qi, Zhang Science 2007

WTe2 :David Cobden et. al.

3D Topological Insulator

Each of the time reversal invariant planes in the 3D Brillouin zone is characterized by a 2D invariant.

Weak Topological Invariants (vector):

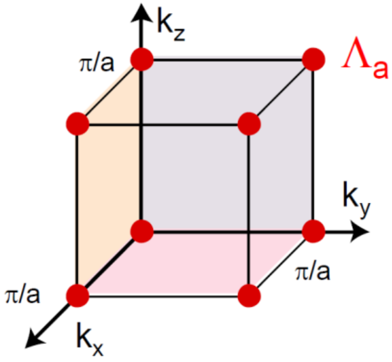
$$(-1)^{\nu_i} = \prod_{a=1}^{4} \delta(\Lambda_a) \Big|_{\substack{k_i=0 \\ \text{plane}}} \qquad \mathbf{G}_\nu = \frac{2\pi}{a}(\nu_1, \nu_2, \nu_3)$$

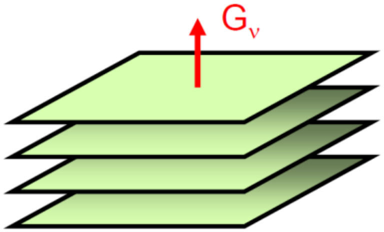
"mod 2" reciprocal lattice vector indexes lattice planes for layered 2D QSHI

Strong Topological Invariant (scalar)

$$(-1)^{\nu_o} = \prod_{a=1}^{8} \delta(\Lambda_a)$$

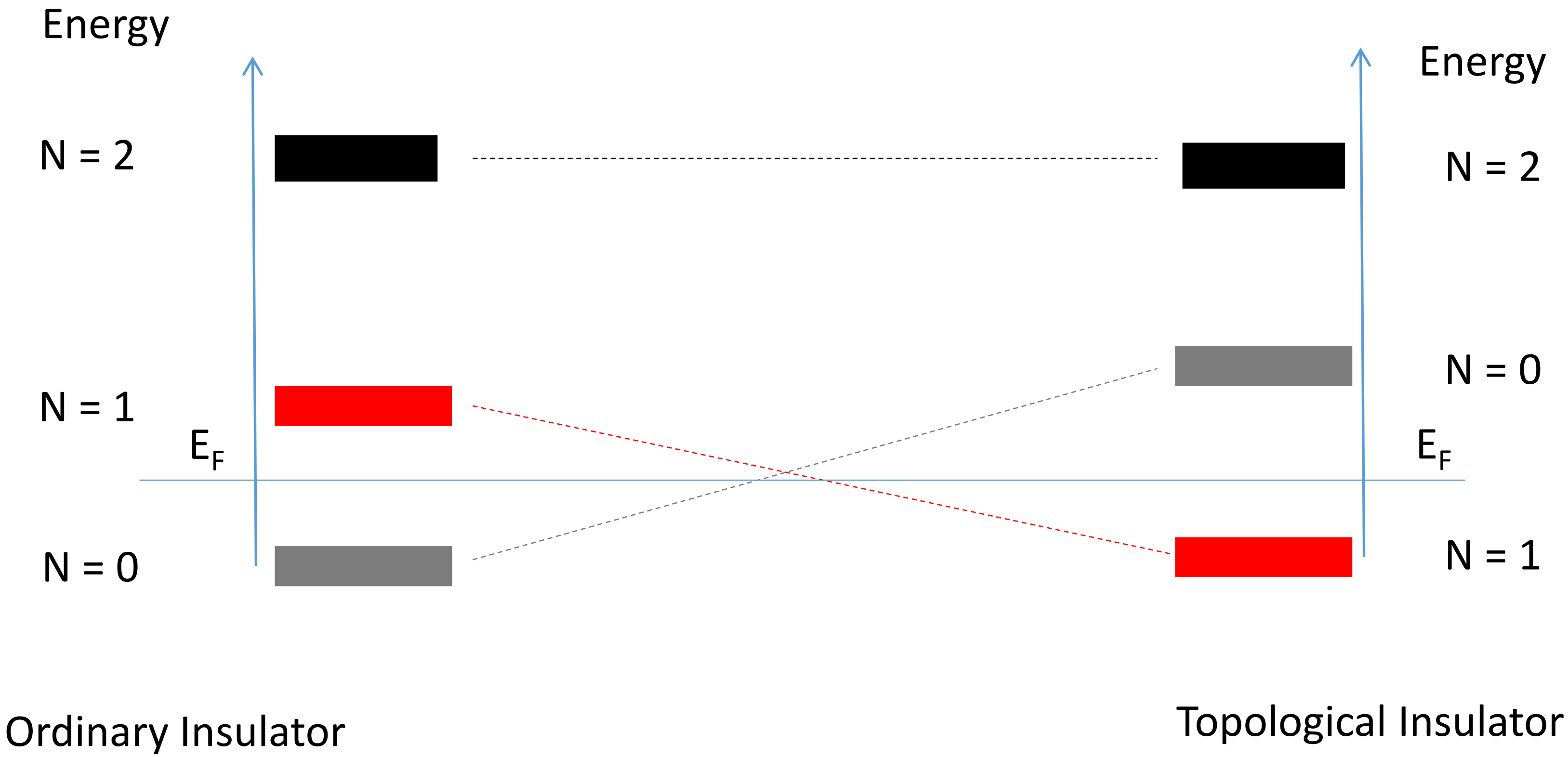
Example: $Bi_{1-x}Sb_x$, Bi_2Se_3





Surface states of TI

In the interface between a topological insulator and an ordinary insulator(or vacuum), there are energy states connecting between the conduction/valence bands of the two insulators



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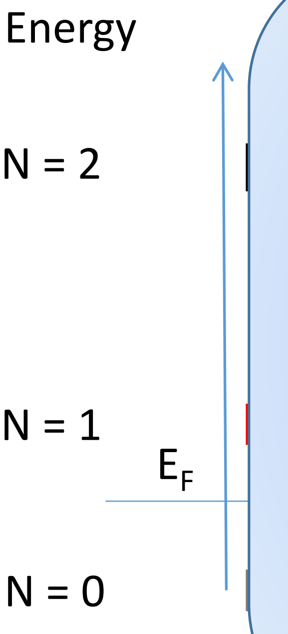
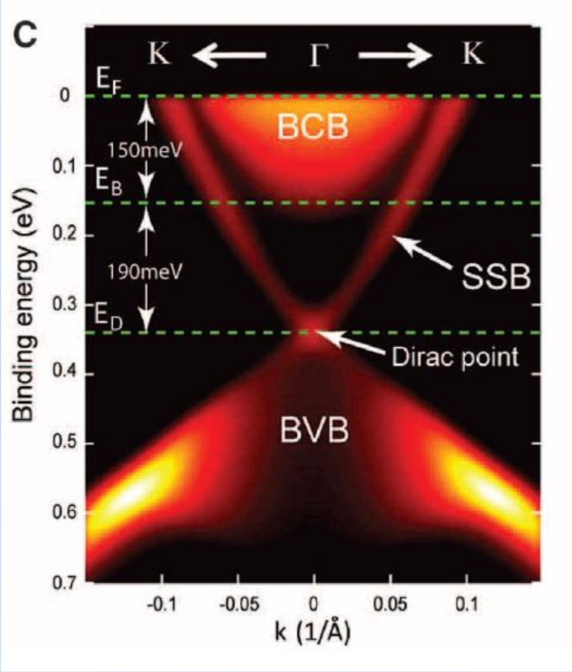
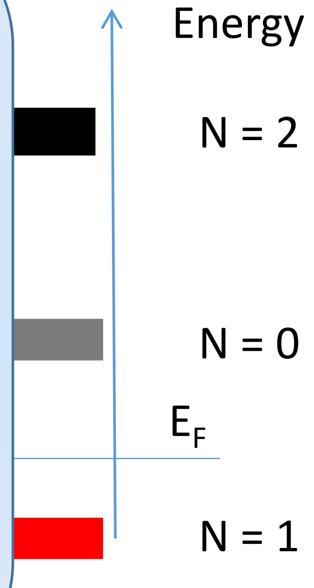




YL Chen, JH Chu, et al. Science, 329, 659



Ordinary Insulator

Topological Insulator

Surface states of Hong Kong

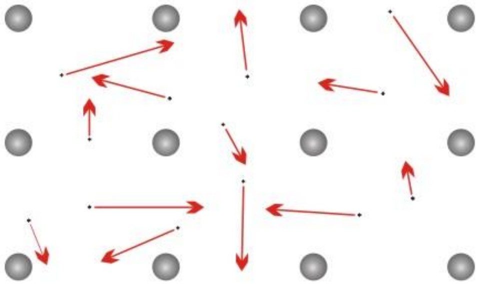
Design by nl architects (www.nlarchitects.nl).

Ordinary Insulator

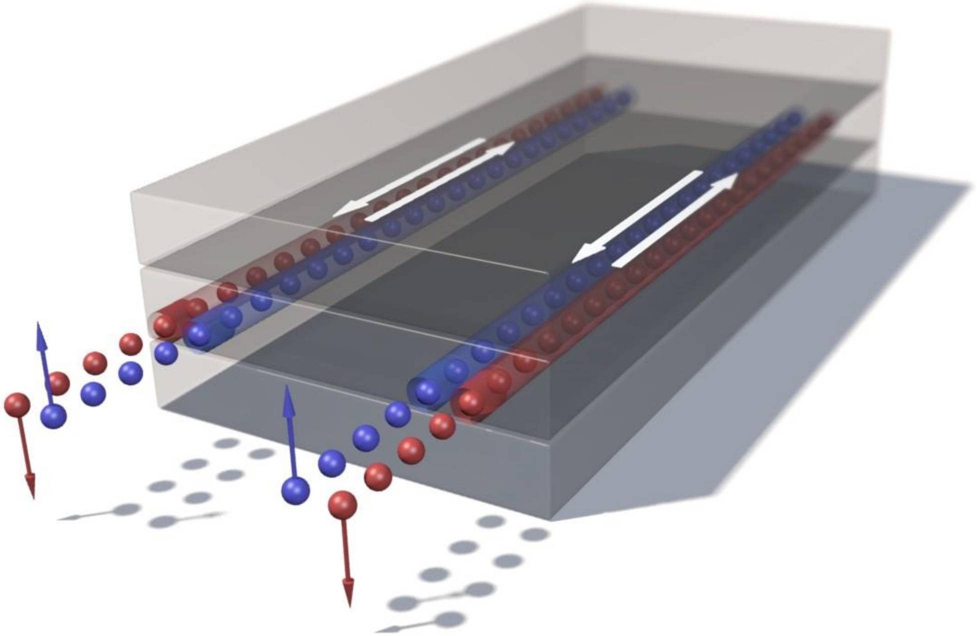
Topological Insulator

2D topological insulator:
Quantum spin Hall effect

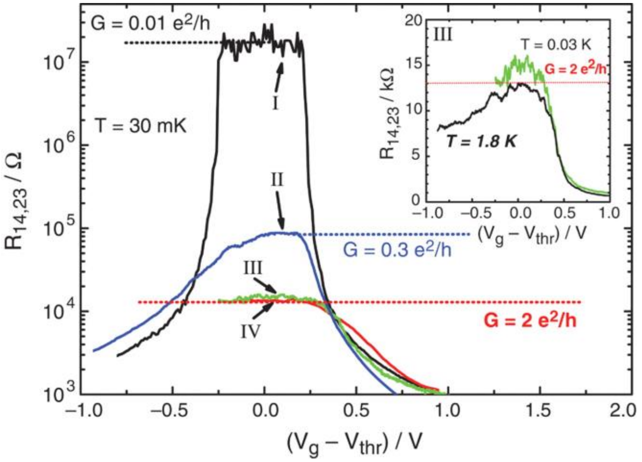
Electrons in conventional materials



Electron transport in 2D topological insulator



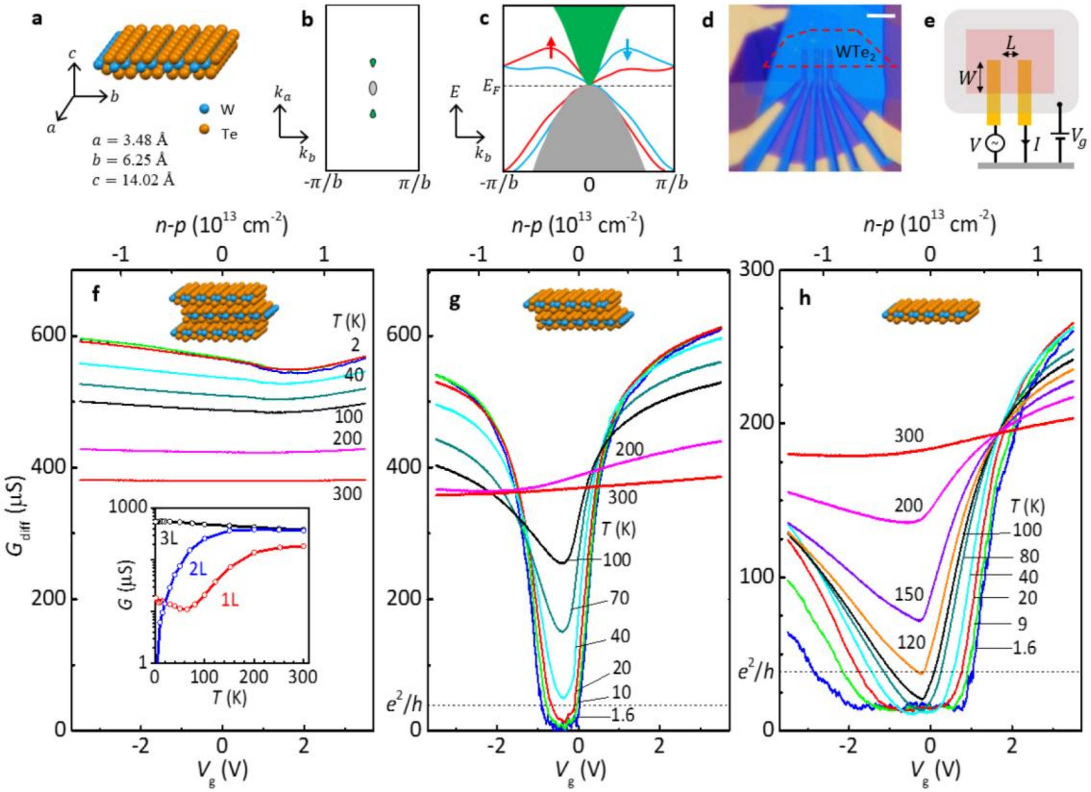
2D topological insulator:
Quantum spin Hall effect



HgTe quantum well theoretically proposed by Bernevig, Hughes and Zhang

Realized by Molenkamp

Science 02 Nov 2007:
Vol. 318, Issue 5851, pp. 766-770



Monolayer WTe$_2$ discovered by David Cobden@UW

Nature Physics **volume13**, pages677–682 (2017)

Controlling Topological Materials Using Elastic Strain

Q: How do we control topological phase of matter?

Topological properties by definition is robust against deformation?

A: By proper choice of material, one can control the electronic topology by small mechanical deformation of the crystal lattice.