The Physics of Surface States with Interactions Mediated by Bulk Properties, Defects and Surface Chemistry

A MURI at Princeton University, Pennsylvania State University and UC Berkeley.
With collaborations at Brookhaven National Laboratory

ARO POC
Marc Ulrich
919 549 4319
Marc.d.ulrich.civ@mail,mil

Official start date September 2012
funding $1.2 million/year for 3 years

Option period to begin September 2015
for 2 more years, proposed $1.2 million per year

Supports 7 PIs
10 graduate students 6 postdocs 1 undergrad summer

Robert Cava, PI, Department of Chemistry,
Princeton University Princeton NJ 08540
609 258 0016 rcava@princeton.edu

The objective of our MURI is
to be the international leaders in the basic science of
Topological surface states
a new electronic state of matter

Predicted by theorists in 2006
First actually observed in 2007.

It wasn't the first publication,
but our observation of these states
on the surface of a Bi-Sb crystal
in 2008 seeded the explosion of the field.

It is now a very active, highly competitive field world-wide.
Important because its subject is a completely new electronic phenomenon.
Little is known, and new effects are predicted almost daily.

MURI PIs -

Technical approach is to vertically integrate specialties

<u>Materials Makers</u>

Robert Cava (Chemistry, Princeton)

New Materials and crystal growth

Nitin Samarth (Experimental Physics, Penn State)

MBE synthesis of thin films and transport

Jeffrey Schwartz (Chemistry, Princeton)

Molecular modification of surfaces

<u>Materials Measurers</u>

Phuan Ong (Experimental Physics, Princeton)

Charge transport of surface states

Ali Yazdani (Experimental Physics, Princeton)

Scanning Tunneling Microsc. of surface states

<u>Theorists</u>

Andrei Bernevig
(Theoretical Physics, Princeton)

Topological Physics Theory

Ashvin Vishwanath (Theoretical Physics, Berkeley)

Topological Physics Theory

Collaborators in Physics at Brookhaven National Laboratory (not funded by MURI) bring additional specialties

Tonica Valla

Angle Resolved Photoemission Spectroscopy

Jing Tao

Transmission Electron Microscopy of defects and heterostructures, ultrahigh resolution surface Scanning Electron Microscopy

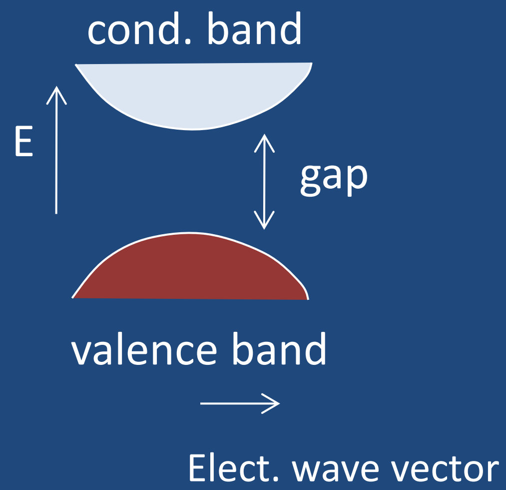
John Hill

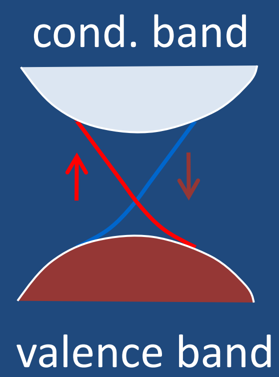
Elastic and inelastic X-ray scattering

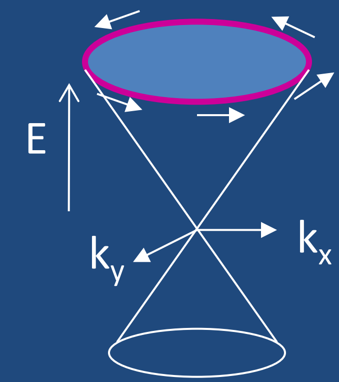
Genda Gu

Crystal Growth

First, what is a Topological Insulator? ("TI")







Conventional Insulator

An energy gap separates conduction band from valence band states.

Topological Insulator

Surface states cross the band gap due to inversion of the normal energy order of the bulk states and strong spin-orbit coupling.

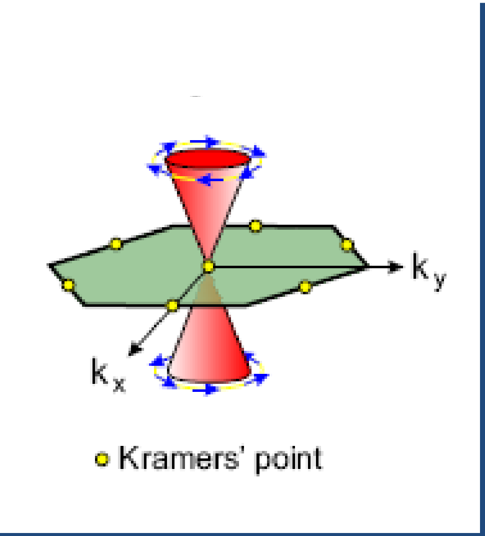
Surface states are **helical**

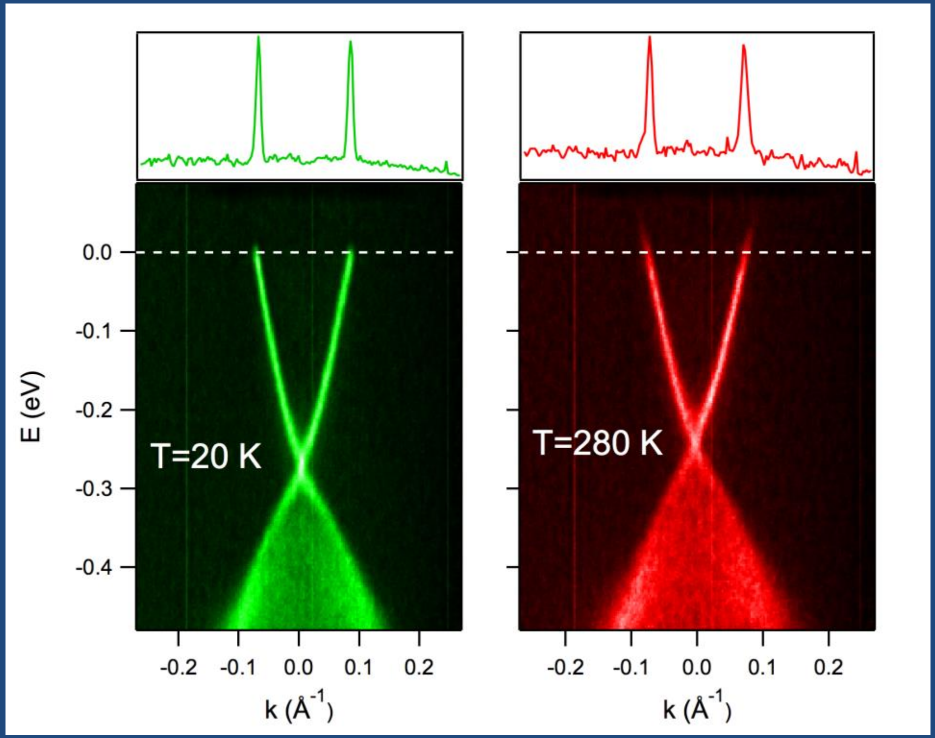
Electron spin direction is locked to momentum direction (**k**)

Electrons usually come in pairs with opposing spins. But these states are occupied by a single spin type.

Observation of the Topological states on a Bi_2Se_3 crystal surface

Need surface sensitive techniques
Bi_2Se_3 (001) plane surface
Angle Resolved
PhotoEmission Spectroscopy





Very fast, chiral electron states are expected.
What are their transport properties?

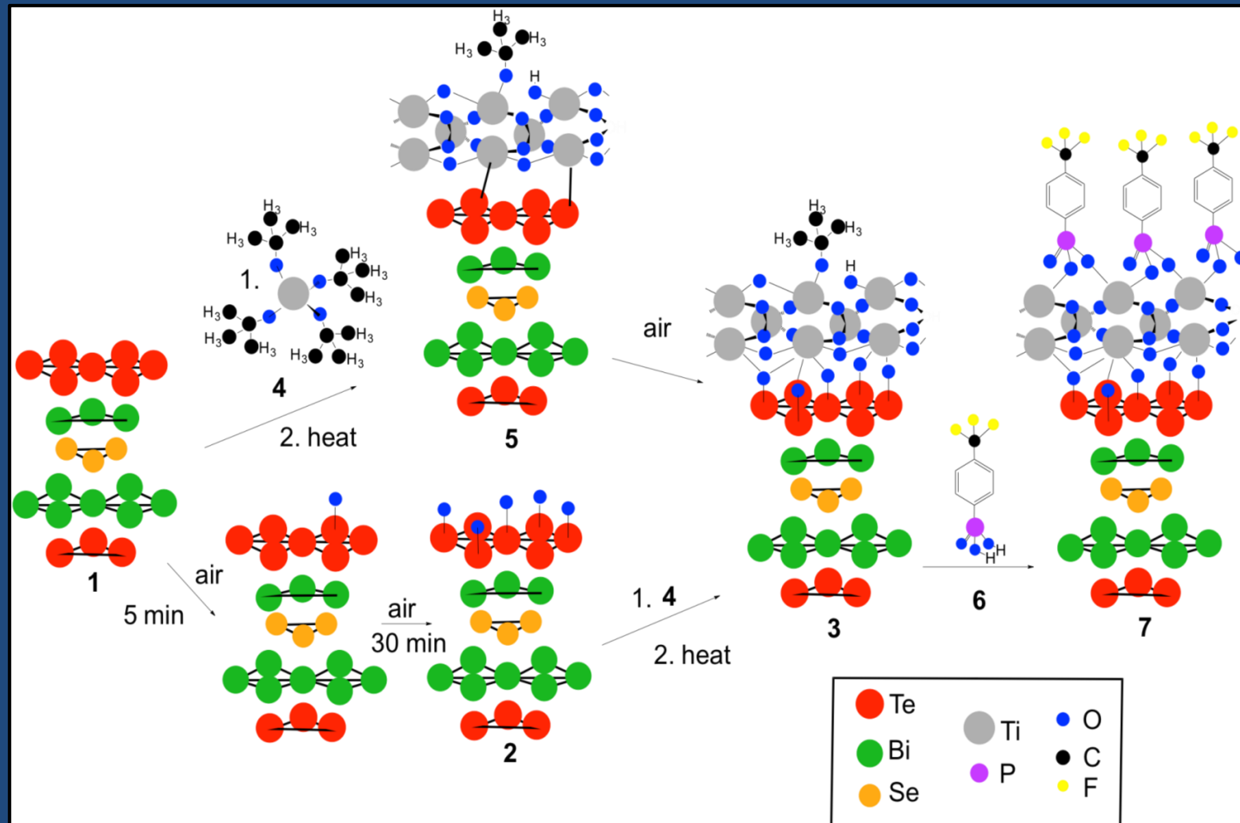
To see the surface electron transport,
the bulk electron conductivity has to be
very strongly suppressed.

How do you make the bulk materials
in the TI family truly insulating?

We have increased the resistivity of bulk crystals
By 6 orders of magnitude in 6 years.

Bridgman growth of single crystals

Can the topological surface states be manipulated by chemical modification of the surfaces?



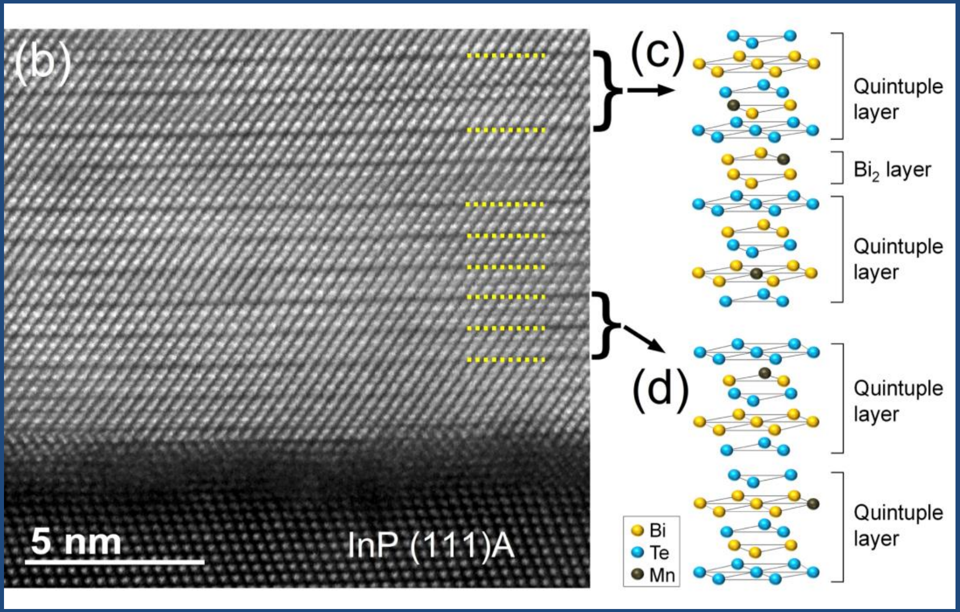
The Challenges are to get molecules with dipoles to stick to the surface and then measure the transport properties of the surface states.

(It is working)

How do the TI surface states interact with ferromagnetism?

Predictions are that the TI states will break up in the magnetic field

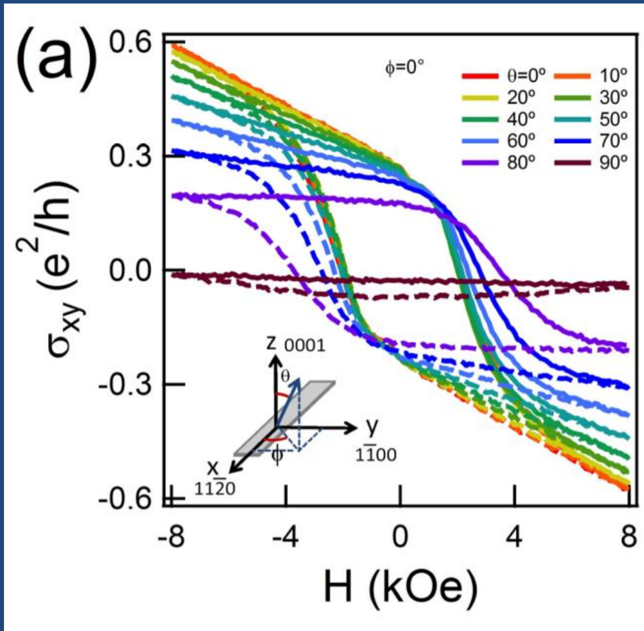
We work on ferromagnetism in the Mn-doped TI Bi_2Te_3



The challenge is to first make and then characterize TI materials that are also ferromagnetic.

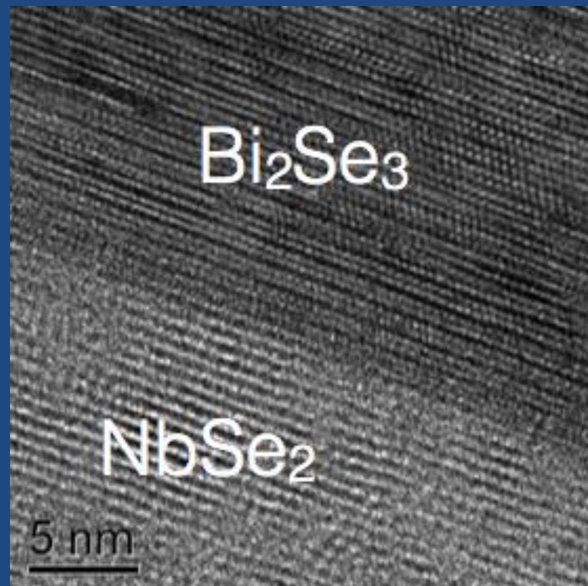
Mn dissolves into Bi_2Te_3. TEM study of a Molecular Beam Epitaxy grown Mn-doped bismuth telluride shows how it is accommodated.

Robust ferromagnetism is present on the surface. (seen here in the Hall Effect) Experiments are in progress



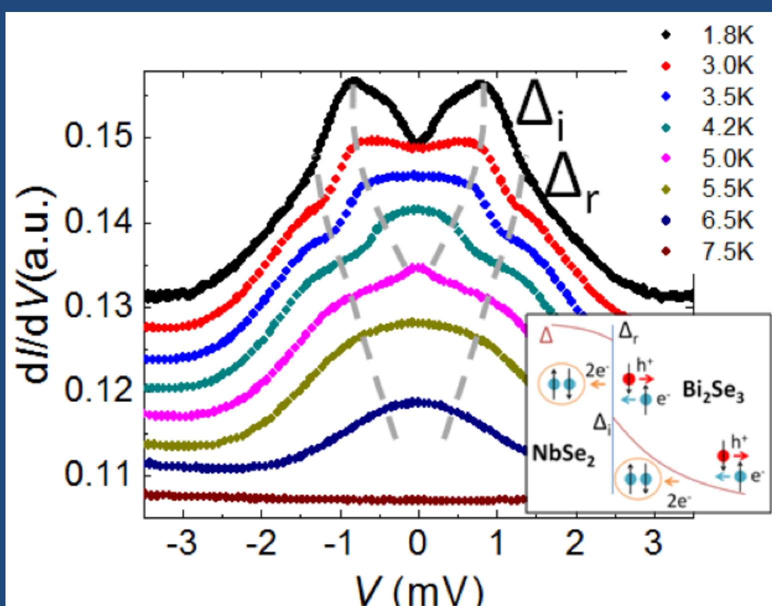
How do TI surface states interact with superconductivity?

The superconductor (SC) $NbSe_2$ induces superconductivity in the TI Bi_2Se_3



First - Synthesis of epitaxial Bi_2Se_3 on $NbSe_2$ substrates.

A critical step

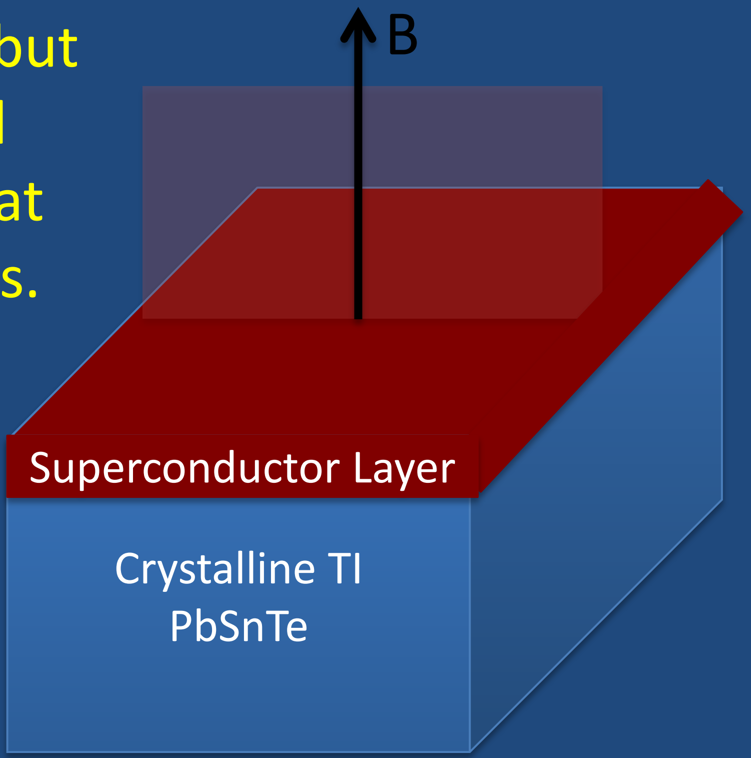


Then ARPES spectra reveal clear signature of induced superconducting gap in the surface state (data not shown).

And point contact spectroscopy shows possible evidence for two SC gaps: *bulk and surface*?

Can Majorana Fermions be observed in solids?
If so, then how do they interact?

Majoranas are predicted but so far unobserved neutral spin 1/2 quasiparticles that are their own antiparticles.



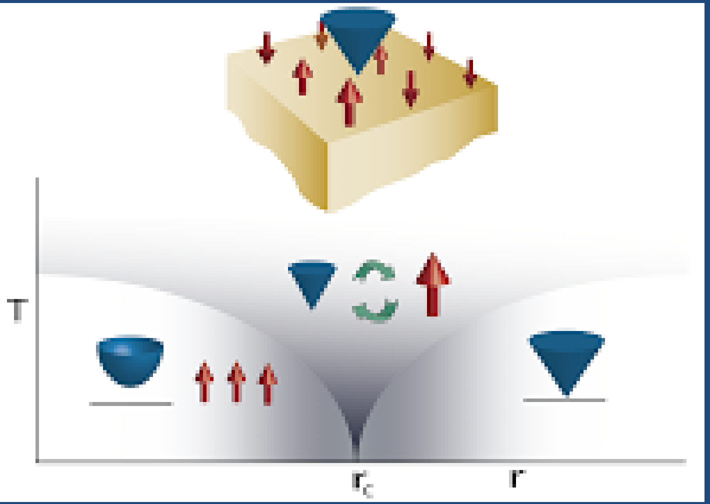
Theorists propose: Majoranas and their interactions can be observed in superconductor-TI heterostructures.

Our theorists propose a specific materials combination.
The magnetic field of the vortex in a superconductor in combination with a mirror-symmetry protected surface state ("Crystalline TI") should result in Majoranas at the TI surface

How does this new electronic state of matter connect to broader concepts in physics?

Our theorists ask: Is there Emergent Supersymmetry at the surface of a Topological Phase?

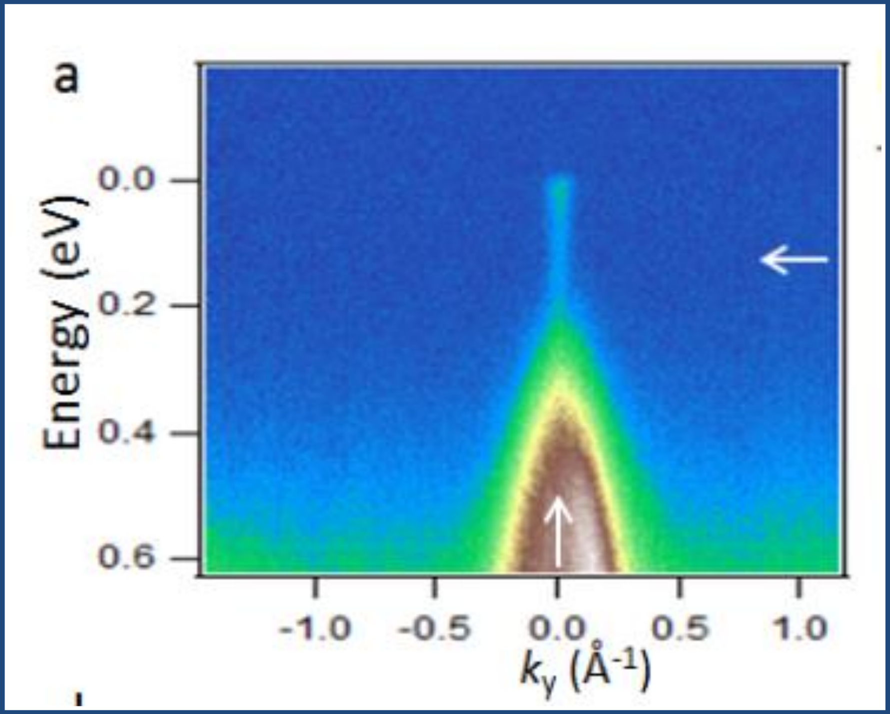
- Supersymmetry (SUSY) in a condensed matter system?
- Possible at certain quantum phase transitions on the surface of topological superconductor/insulators.
- Deep connection between TI surfaces and SUSY?



When a new phenomenon is discovered in materials physics
New materials have a big impact on the direction of the field

How can new materials drive this field in new directions?

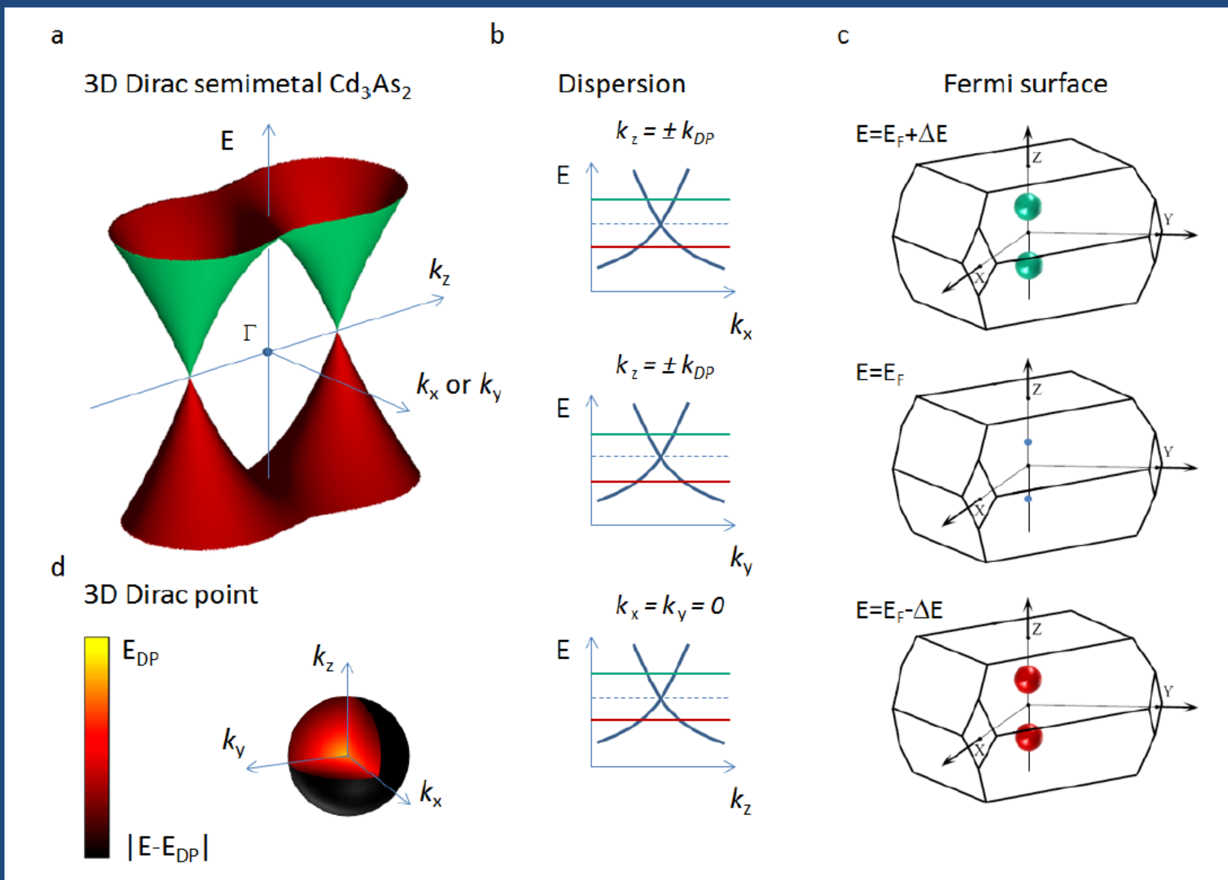
One of those new directions is "Dirac Semimetals "
Bulk materials with Dirac electrons



Found in our material
Cd_3As_2

ARPES shows an extremely sharp feature in the bulk band structure

The deduced bulk E vs. *k* relations at the Fermi level of *bulk* Cd_3As_2



Two Dirac cones
At E_F in the bulk electronic system.

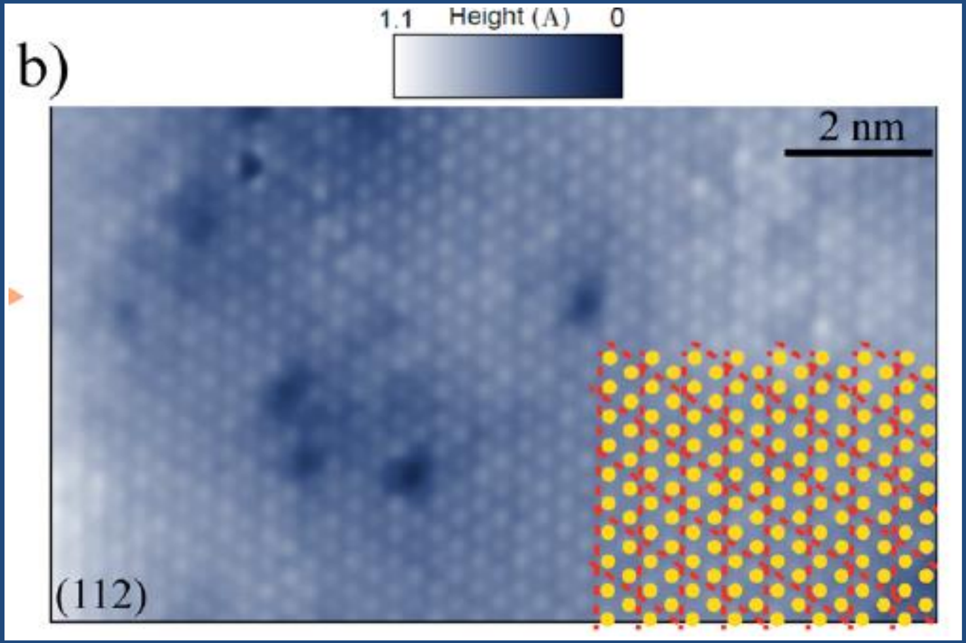
Two pockets displaced along z (tetragonal symmetry).

Nothing else at the Fermi energy.

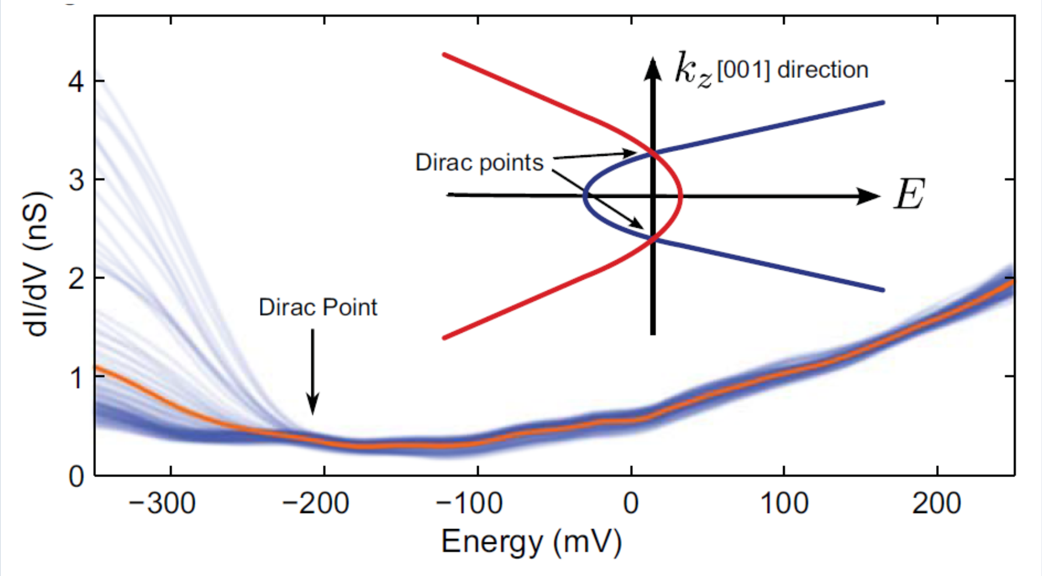
A Dirac Semimetal!

The STM image of the Cd_3As_2 cleavage plane

The structure at the atomic scale.

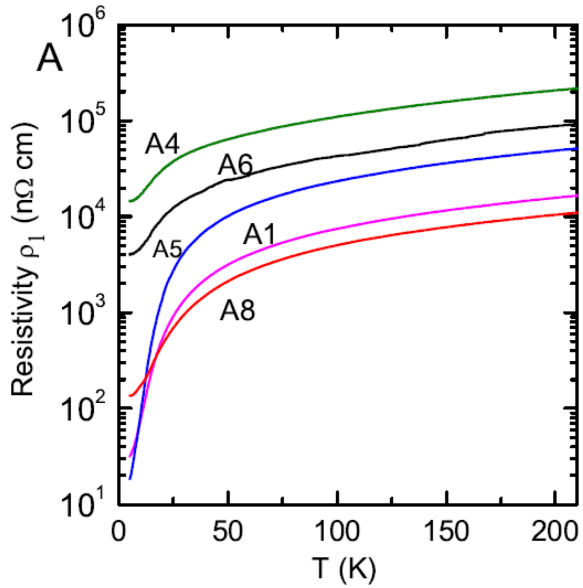


Electronic characterization at the atomic scale:
STM tunneling
at many points on the surface.

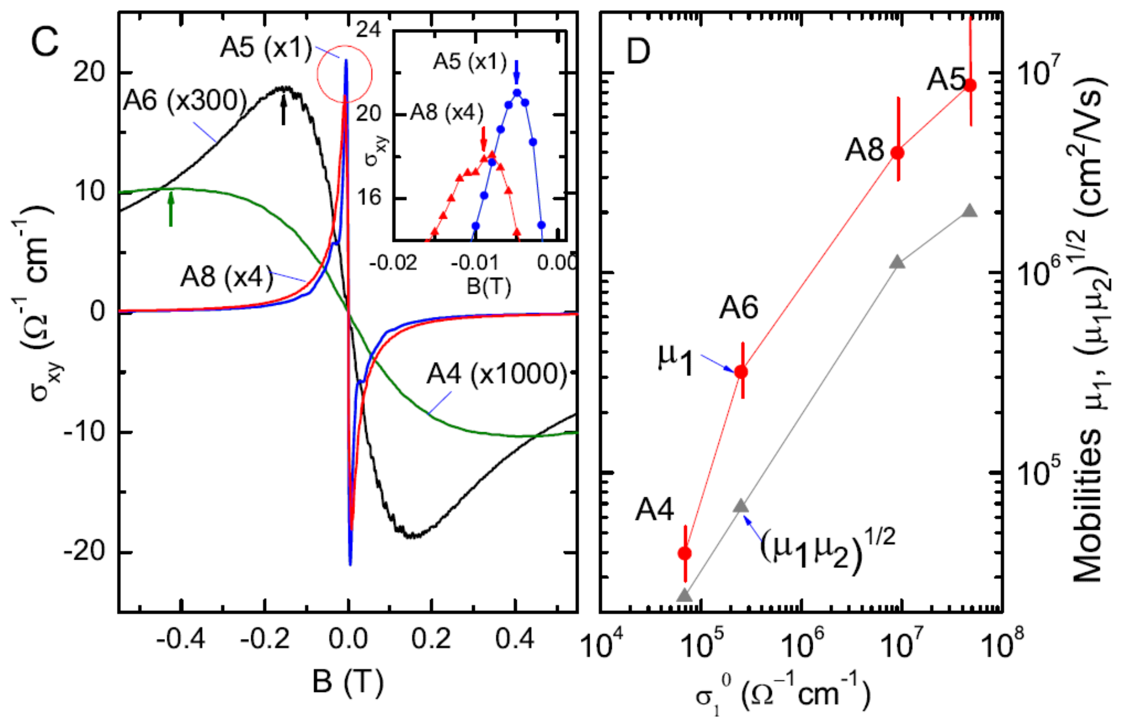


The usual distribution of states below the Dirac Point

due atomic defects, but above the Dirac Point? Why is it like this?



σ= neμ
conductivity = number of carriers times electron charge times electron mobility



A major surprise – some crystals of Cd_3As_2 have ultra high electron mobility

"ordinary Cd_3As_2" mobilities = 10^4 cm^2/Vs
Very large

Some crystals have mobility = 10^7 cm^2/Vs

10^7? Made in my lab?

An *extremely* large value
Like super-pure GaAs multilayers.
How can this be?

This is a very exciting field and challenging project because there is so much new science to discover

and the international competition is fierce.

We are thankful to have the opportunity to work on it.