Title: When topology meets strong interactions in quantum matter

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Series: Colloquium

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Abstract: The study of strongly interacting quantum matter has been at the forefront of condensed matter research in the last several decades. An independent development is the discovery of topological band insulators. In this talk I will describe phenomena that occur at the confluence of topology and strong interactions. I will first discuss how insights from the study of the relatively simple topological insulators are revolutionizing our theoretical understanding of more complex quantum many body systems. Next I will describe some experimental situations in which both band topology and strong correlations are present, the resulting novel phenomena, and the theoretical challenges they present.

When topology meets strong interactions in quantum matter

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(MIT)

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When topology meets strong interactions
in ***quantum matter***

Macroscopic quantum matter

Ordinary macroscopic matter: Large number (10^{23}) of interacting degrees of freedom which must be treated quantum mechanically.

Example: electrons inside a macroscopic piece of solid.

Room temperature is cold: electron motion is quantum rather than thermal.

Phases of matter

Macroscopic matter in equilibrium organizes itself into phases.

Solids, liquids, gases.......

Magnets........

Superconductors.............

Some questions:

What are the possible phases?

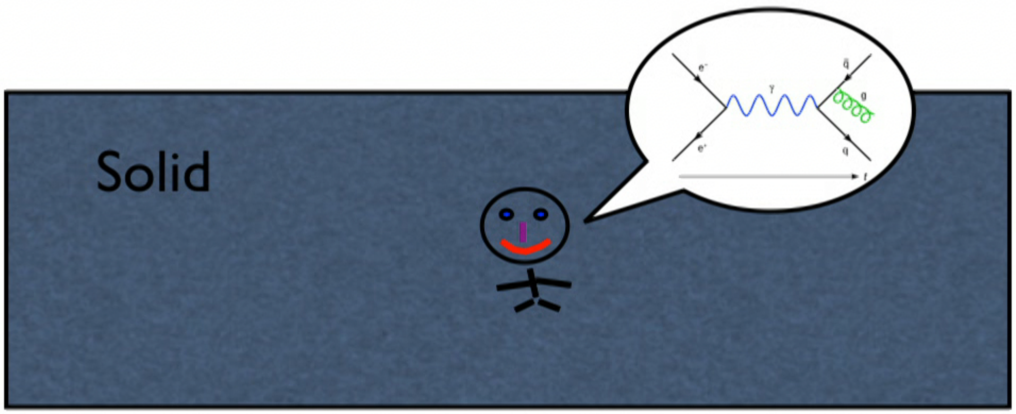
How to describe them theoretically and distinguish them in experiments?

How do phases evolve into one another?

A solid as a universe

Different phases of quantum matter define different kinds of `universes'
as seen by a microbe living inside.

Microbe is a ``particle" physicist with a limited budget for experiments - cannot go to very high energies.



A solid as a universe

What is the `standard model' of the universe perceived by such a physicist?

1. What are the `elementary particles'?

2. What are their interactions?

Answer depends on which phase of matter the solid is in (metal/insulator/magnet/superconductor/.....).

A solid as a universe

Key insight in quantum condensed matter physics (1930s - 1950s):

Such `elementary' particles exist!

Terminology: ``Quasiparticles"

May differ substantially from the particles (nuclei, electrons) that form the solid in the first place.

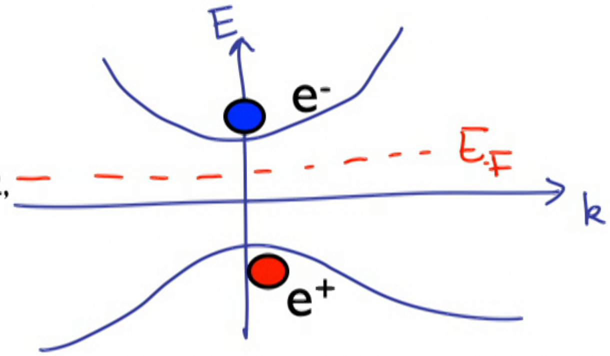
The universe inside solids:
Example 1

Conventional insulator (completely fill energy bands):

``Elementary particles''

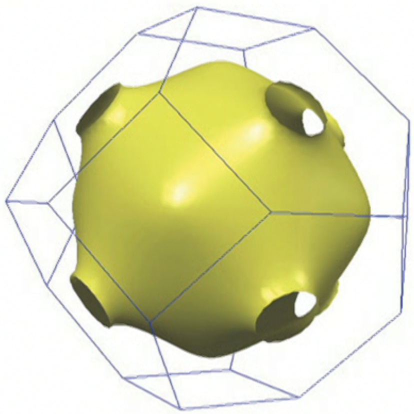
1. Electron (spin-1/2, charge - e fermion) or a hole (spin-1/2, charge +e fermion)

2. Phonons (quantized lattice vibrations)



The universe inside solids:
Example II

An ordinary metal, eg, Copper.



``Elementary particles"(a.k.a ``quasiparticles")

Fermions with electric charge e, spin-1/2 that fill up a Fermi sea in momentum space.

Highest occupied momenta form a Fermi surface.

Quasiparticles long lived near Fermi surface, and have well-defined energy-momentum relation.

``Landau Fermi Liquid Theory"

When topology meets ***strong interactions*** in quantum matter

Strongly interacting electrons in solids

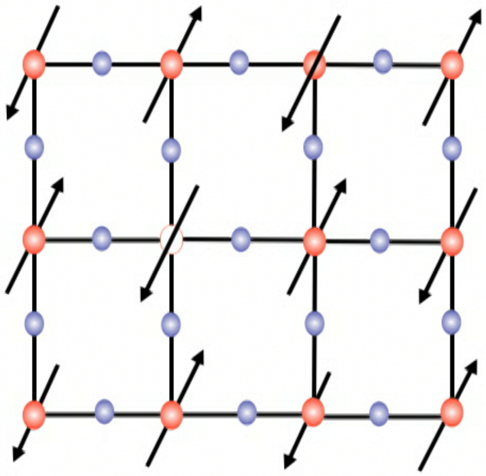
In a class of solids, the weak coupling perturbative treatment of Coulomb interaction (beyond Hartree-Fock) fails.

``Strongly correlated electrons"

Many interesting phenomena result.

A simple example: a Mott insulator

What is a Mott insulator?



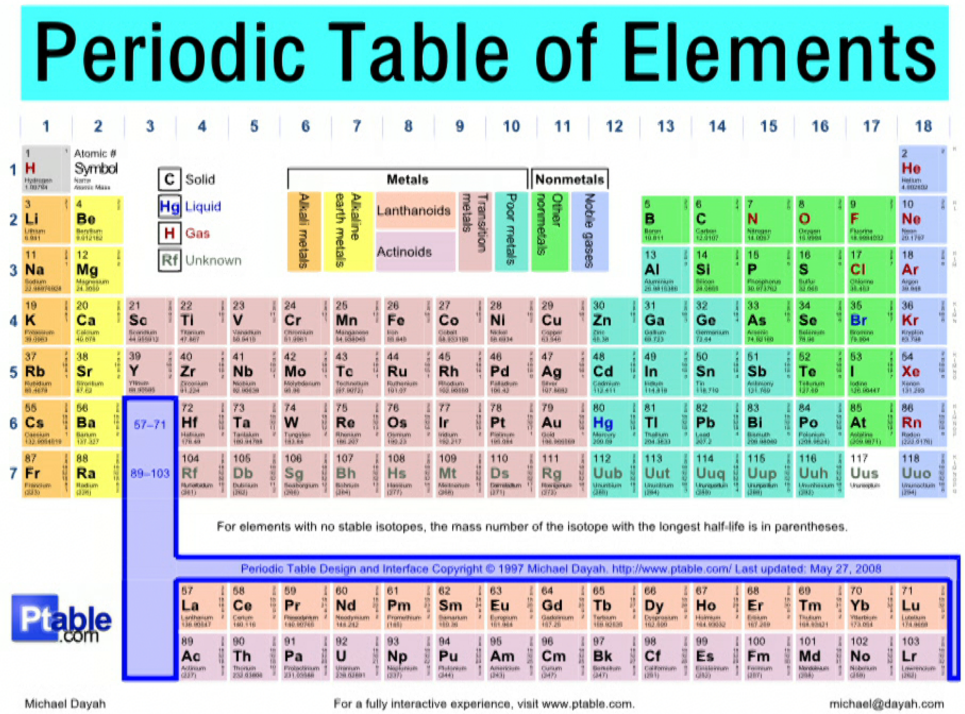
Insulation due to jamming effect of Coulomb repulsion

Coulomb cost of two electrons
occupying same atomic orbital dominant

⇒Electrons can't move if every possible atomic orbital site is already occupied by another electron.

Odd number of electrons per unit cell: band theory predicts metal.

When Mott insulator?



Some classic Mott insulating materials: transition metal oxides (eg: NiO, MnO, V_2O_3, La2CuO4, LaTiO3,.......) of 3d series, halides, sulfides, many f-electron insulators,…..

3d or 4f orbitals close to nucleus: large on-site repulsion compared to inter-site hopping.

The Mott insulator: simply understood from a real space point of view - ***electrons as particles.***

In contrast with

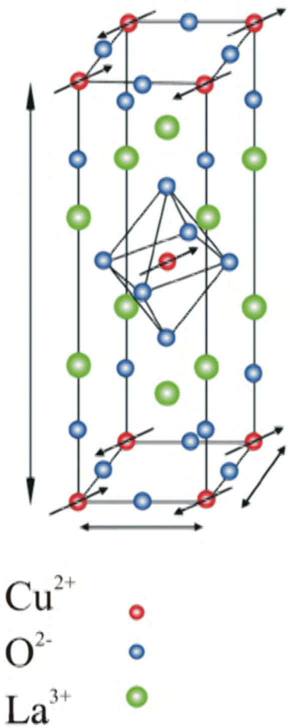
A metal: simply understood from a momentum space point of view (filling a Fermi surface)

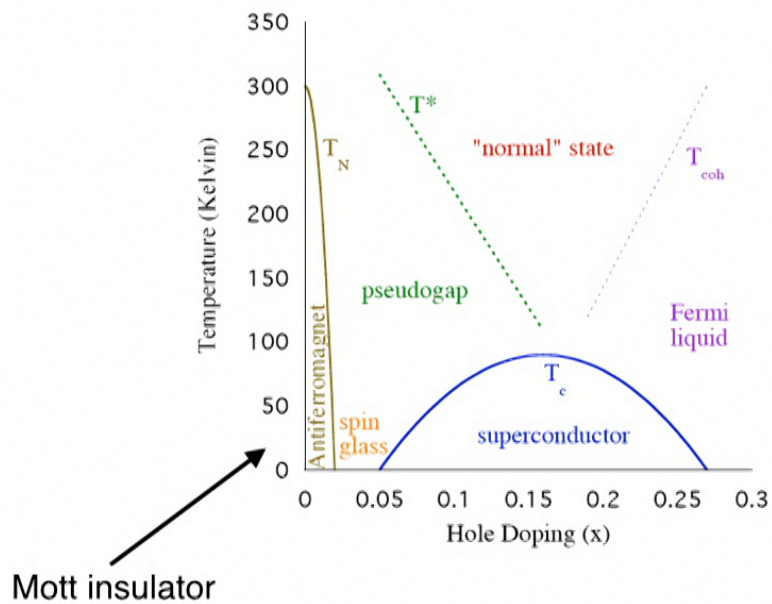
- ***electrons as waves***

Many fascinating phenomena in vicinity of a transition from metal to Mott insulator: neither particle nor wave point of view necessarily superior.

Striking example - high temperature superconductivity

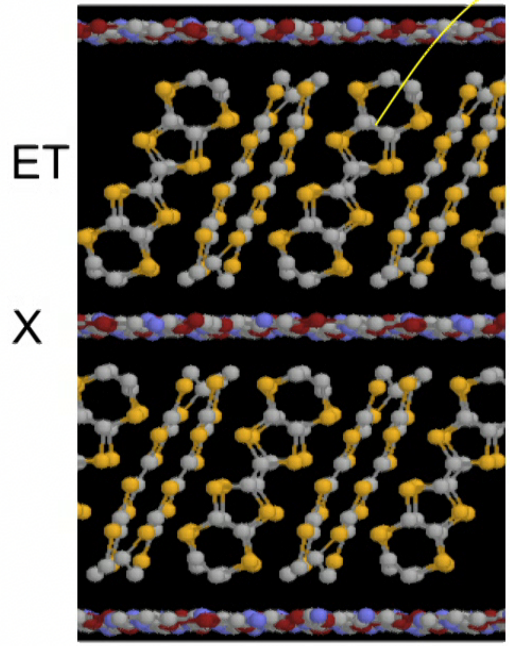
High temperature superconductivity in Copper-oxide materials



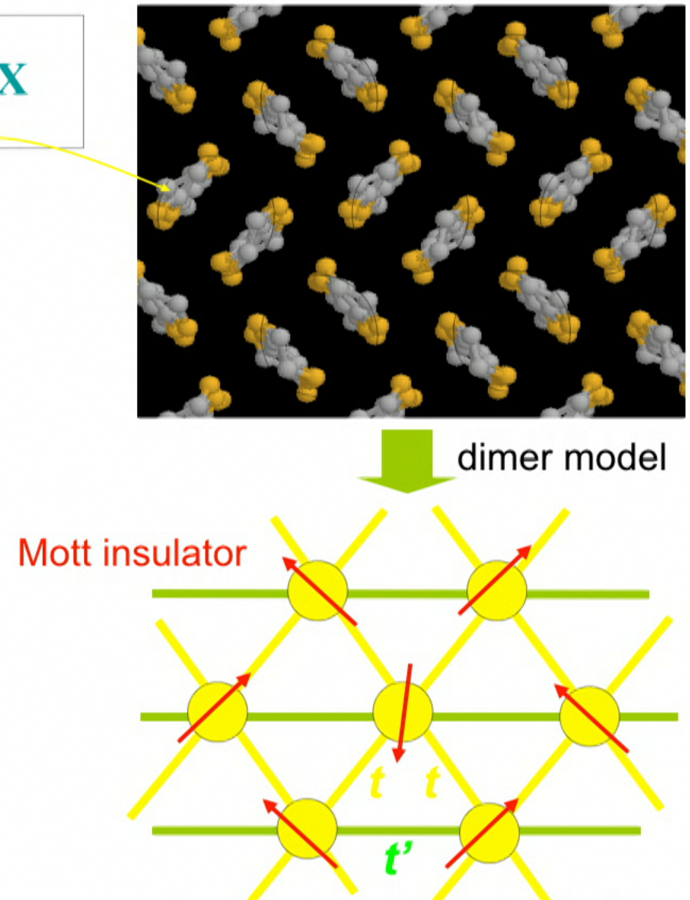


Eg: $La_{2-x}Sr_xCu_2O_4$

Quasi-2D organics κ-$(ET)_2X$

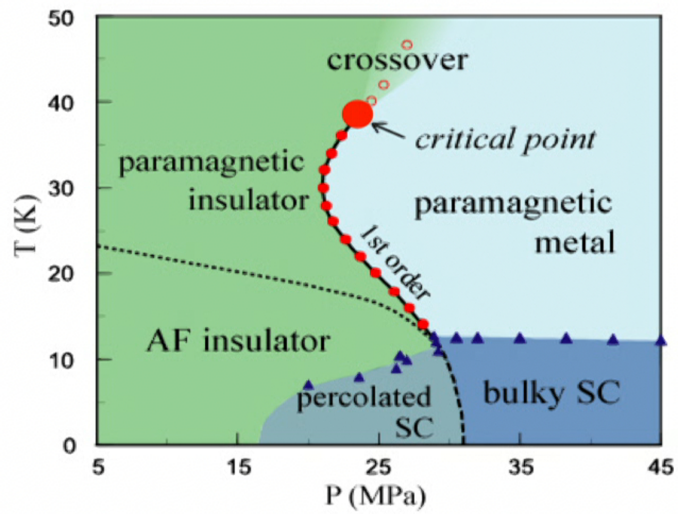


X = $Cu(NCS)_2$, $Cu[N(CN)_2]Br$, $Cu_2(CN)_3$…..



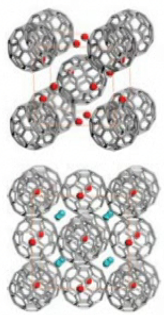
anisotropic triangular lattice

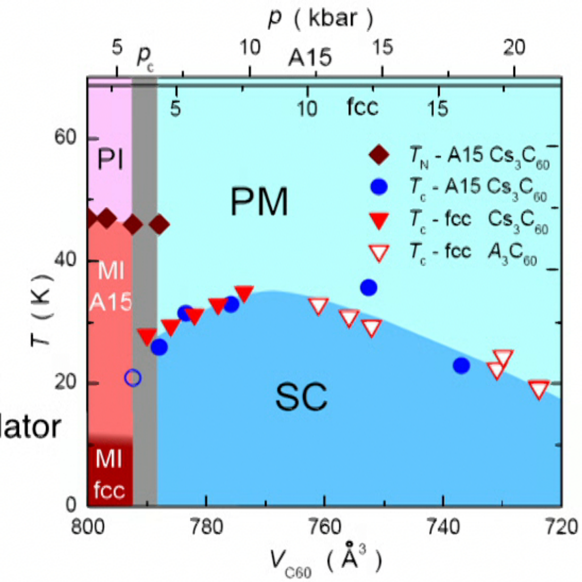
Pressure tuned superconductivity near a Mott insulator in the organics



κ-$Cu[N(CN)_2]Cl$
t'/t = 0.75

Pressure tuned SC in fcc Cs3C60





Ganin et al, Nature Materials, 2008, and Nature, 2010.

Ihara, Alloul, et al, PRL 2010.

Moire patterns in twisted bilayer graphene

Two layers of graphene that are twisted relative to each other form a triangular moire pattern.

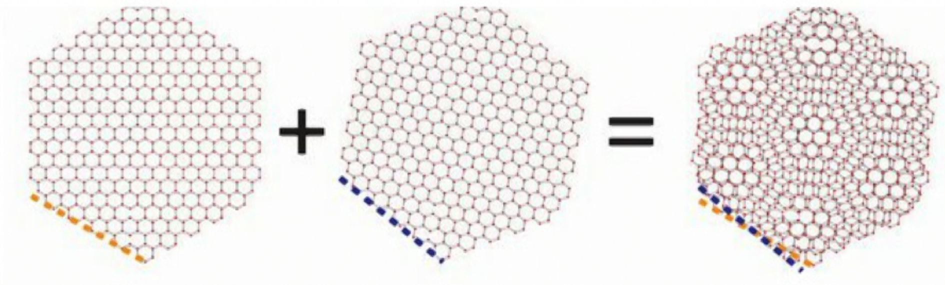
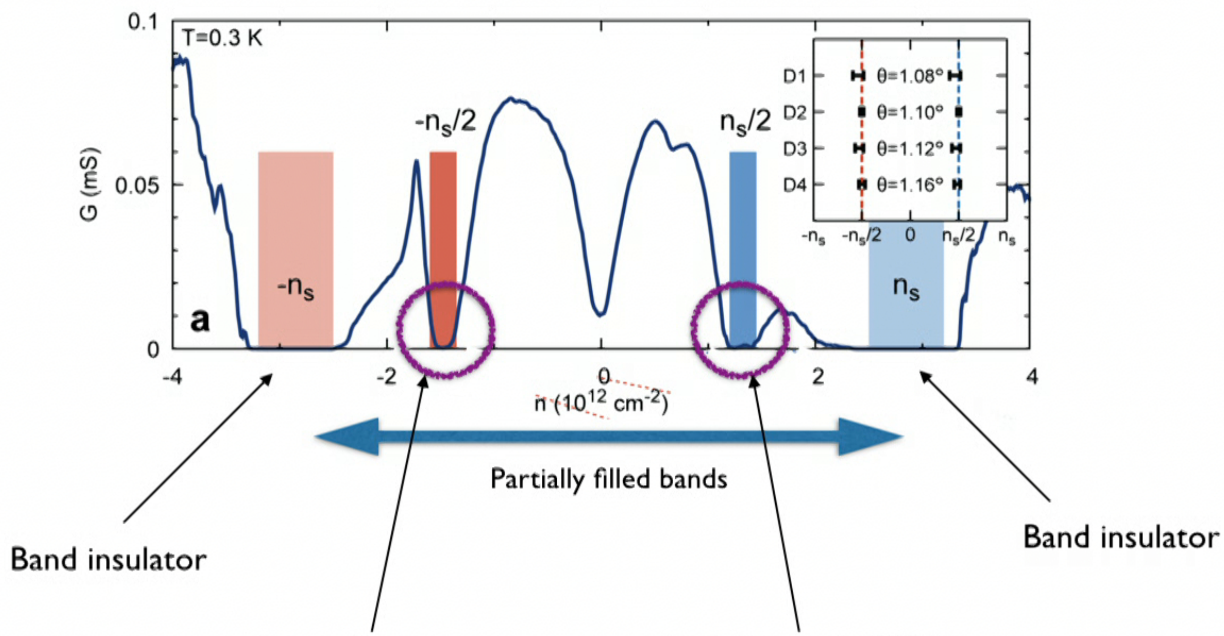


Fig Credit: Kim et al, PNAS 2017

Moire ``superlattice'' reconstructs electronic bands.
Small twist angles: Dirac cones of 2 layers strongly couple to each other.

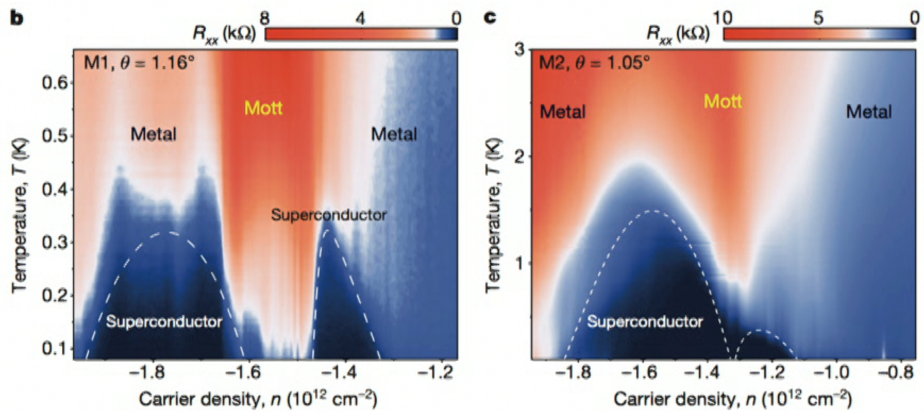
Recent excitement: Correlated electron physics near a ``magic'' twist angle

Cao, Jarillo-Herrero et al, Nature **556**, 80 (2018)
Cao, Jarillo-Herrero et al, Nature **556**, 43 (2018)



Insulators at partial band filling

Superconductivity near the correlated insulator



Cao, Jarillo-Herrero et al, Nature **556**, 80 (2018)
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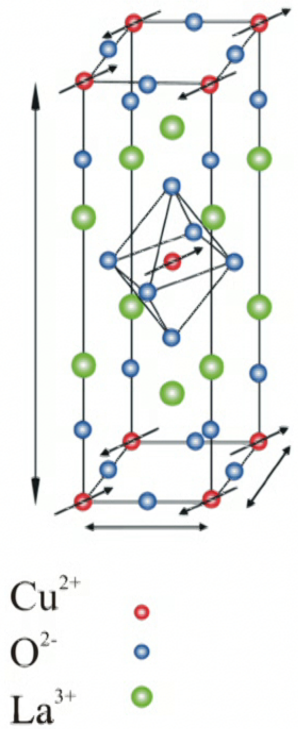
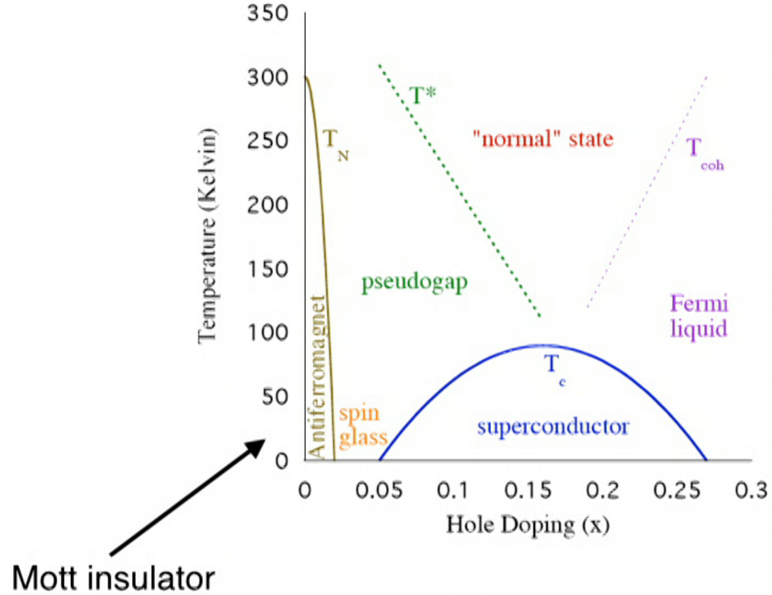
Highly tunable platform - can change from insulator to superconductor by dialing a voltage!

High temperature superconductivity in Copper-oxide materials





Eg: $La_{2-x} Sr_x Cu_2O_4$

Comments

There are many other amazing phenomena in strongly interacting many body quantum systems

- phases with quasiparticles with fractional statistics, fractional quantum numbers

- phases with no quasiparticles at all

Traditional Hartree-Fock + perturbation theory framework for dealing with Coulomb interaction fundamentally inadequate.

Many surprises and fun with correlated electrons!

When ***topology*** meets strong interactions in quantum matter

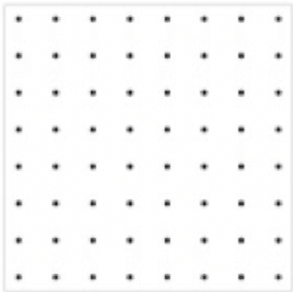
Fun even within band theory

In last 15 years we have learnt that even within free fermion band theory there is a lot of beautiful physics and surprises that went unnoticed for decades:

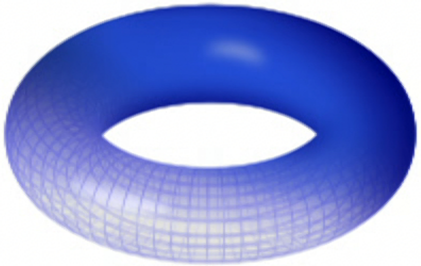
Topological aspects of band theory

Basics of band theory

Electrons in a d-dimensional periodic crystal:
Momentum space is a torus T^d.



Real space



Momentum space

Quantum mechanical states $|n\vec{k}\rangle$ for each band n, and momentum $\vec{k}\rangle$

Chern bands in 2d

Thouless et al 1983;
Haldane 1988
(2016 Nobel)

For an isolated band, there is a Berry gauge field

$$\vec{a}_n(\vec{k}) = i\langle n\vec{k}|\frac{d}{d\vec{k}}|n\vec{k}\rangle$$

Chern number $C_n = \frac{1}{2\pi}\int \vec{\nabla}_k \times \vec{a}_n(\vec{k}) \in Z$.

C_n counts the number of Berry magnetic monopoles inside the k-space torus, and is a topological invariant.

Bands with different C_n are topologically distinct.

Physical consequences of Chern number: one way edge states at spatial boundary to vacuum

Breaks time reversal symmetry

Generalization:
Time Reversal Symmetric Topological insulators

Free electron band theory:

two distinct insulating phases of electrons in the presence of time reversal symmetry.

(i) Conventional Band Insulator

(ii) Topological Band Insulator (TBI)

TBI occurs in materials with strong spin-orbit coupling.

A triumph for theory

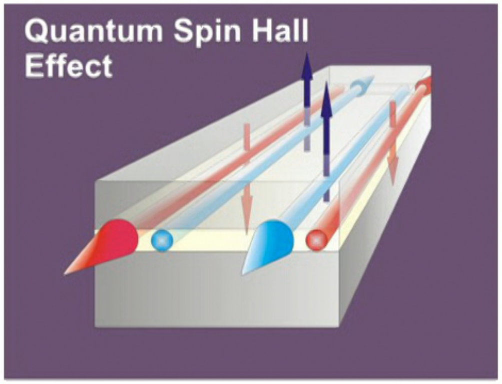
Theoretical possibility of (time reversal symmetric) topological band insulators:
2005-2007 (Kane, Mele, Fu, Moore, Balents, Roy)

Prediction of materials: 2006 -
(Bernevig, Hughes, Zhang; Fu, Kane, ...)

Experiments: 2007-.....
Molencamp et al, Hassan et al,.....

Properties of topological band insulators

Usual characterization: `Unusual' conductor at surface of bulk insulator.



2d: `edge modes' with spin tied to momentum.

3d: odd number of Dirac cones

Why is surface interesting?

Within band theory:

Metallic surface in a bulk insulator.

Surface cannot be made insulating with any amount of impurities (so long as time reversal symmetry is preserved).

d-dimensional solid:
Surface theory is `impossible" in a strictly d-1 dimensional solid with same symmetries.

Eg: Single massless Dirac cone not allowed band structure of 2d time reversal symmetric metal (old theorem by Nielssen and Ninomiya, 1983)

Topological insulating materials

In 3d the TBI requires spin-orbit coupling which destroys conservation of all components of spin (but preserves time reversal).

Early: $Bi_{1-x}Sb_x$, Bi_2Se_3, Bi_2Te_3, ...

Many materials by now.

Topology meets strong correlations

Many reasons to study situations where both band topology and strong correlations play an important role.

1. Materials where both are relevant

- some modern candidate topological insulators

SmB_6 (**Samarium** hexaboride), other rare-earth alloys, **Iridium** oxides, ...

(Involve electrons from atomic d or f orbitals: ``strong'' electron interactions).

- Moire graphene materials (see later)

(strong correlations in a partially filled topological band)

2. Foundational reasons

- many deep insights from topological perspective on strong coupling phenomena

Topological insulators 2.0

Beyond band theory

Band theory: Independent electron approximation

How does physics change when electron-electron interactions are included?

Important in context of ongoing search for topological insulation in correlated materials, and for conceptual/foundational theoretical reasons.

Some fundamental questions

0. Are topological band insulators distinct from ordinary insulators in the presence of interactions?

1. Are there new phases that have no non-interacting counterpart?

    - Physical properties ?

    - Which materials ?

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Need to think about phenomenon of topological insulation without crutch of free fermion models/band theory.

Some fundamental questions

0. ***Are topological band insulators distinct from ordinary insulators in the presence of interactions?***

1. Are there new phases that have no non-interacting counterpart?

   - Physical properties ?
   - Which materials ?

Need to think about phenomenon of topological insulation without crutch of free fermion models/band theory.

Some trivial observations about electronic insulators

Insulator with no exotic elementary excitations:

All excitations carry integer charge ne (e = electron charge).

n odd: fermion (eg: n = 1 is electron)
n even: boson. (eg: n= 2 is Cooper pair)

A powerful ***conceptual*** tool

A `gedanken' experiment:

Probe the fate of a magnetic monopole inside the material.

Thinking about the monopole is a profoundly simple way to non-perturbatively constrain the physics of the material.

Monopoles and symmetries

Time-reversal: Magnetic charge is odd
Electric charge is even

Suppose the monopole M has electric charge q.

Time reversed partner TM also has electric charge q but opposite magnetic charge.

Monopoles and symmetries

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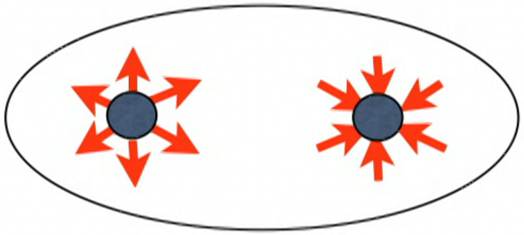
Electric charge is even



Suppose the monopole M has electric charge q.

Time-reversed partner TM also has electric charge q but opposite magnetic charge.

Bring M and TM together: result must be an excitation of the underlying material.

=> $2q = ne$ (n = integer)

Only two distinct possibilities consistent with time reversal
$q = 0, e, 2e, \ldots\ldots$ or $q = e/2, 3e/2, \ldots\ldots\ldots$

Fundamental distinction: $q = 0$ or $q = e/2$ (obtain rest by binding electrons)

Monopoles and topological insulators

Ordinary insulator: Monopoles have q = 0.

Topological band insulator: Monopoles have q = e/2.
(Qi, Hughes, Zhang 09)(*)

Fractional charge on probe monopole cannot be shifted by any perturbations (which preserve symmetry).

Topological band insulator stable to interactions.

(*) Proof : Solve surface Dirac equation on sphere in presence of monopole in the bulk, or alternately use $\theta = \pi$ electromagnetic response and it's ``Witten effect''

A converse question

Is fractional electric charge q = e/2 on a probe monopole in an **electronic** insulator only possible for the standard topological band insulator?

No!

q = e/2 on a probe monopole is a property of 4 distinct time reversal symmetric topological insulators (with spin-orbit coupling) of electrons in 3d (Wang, Potter, TS, 2014; Freed, Hopkins, 2016).

Only one of them is standard topological band insulator; others require interactions.

Rather than just an isolated curiosity, symmetry protected interacting topological insulators are centrally connected to other frontiers of modern condensed matter physics and quantum field theory.

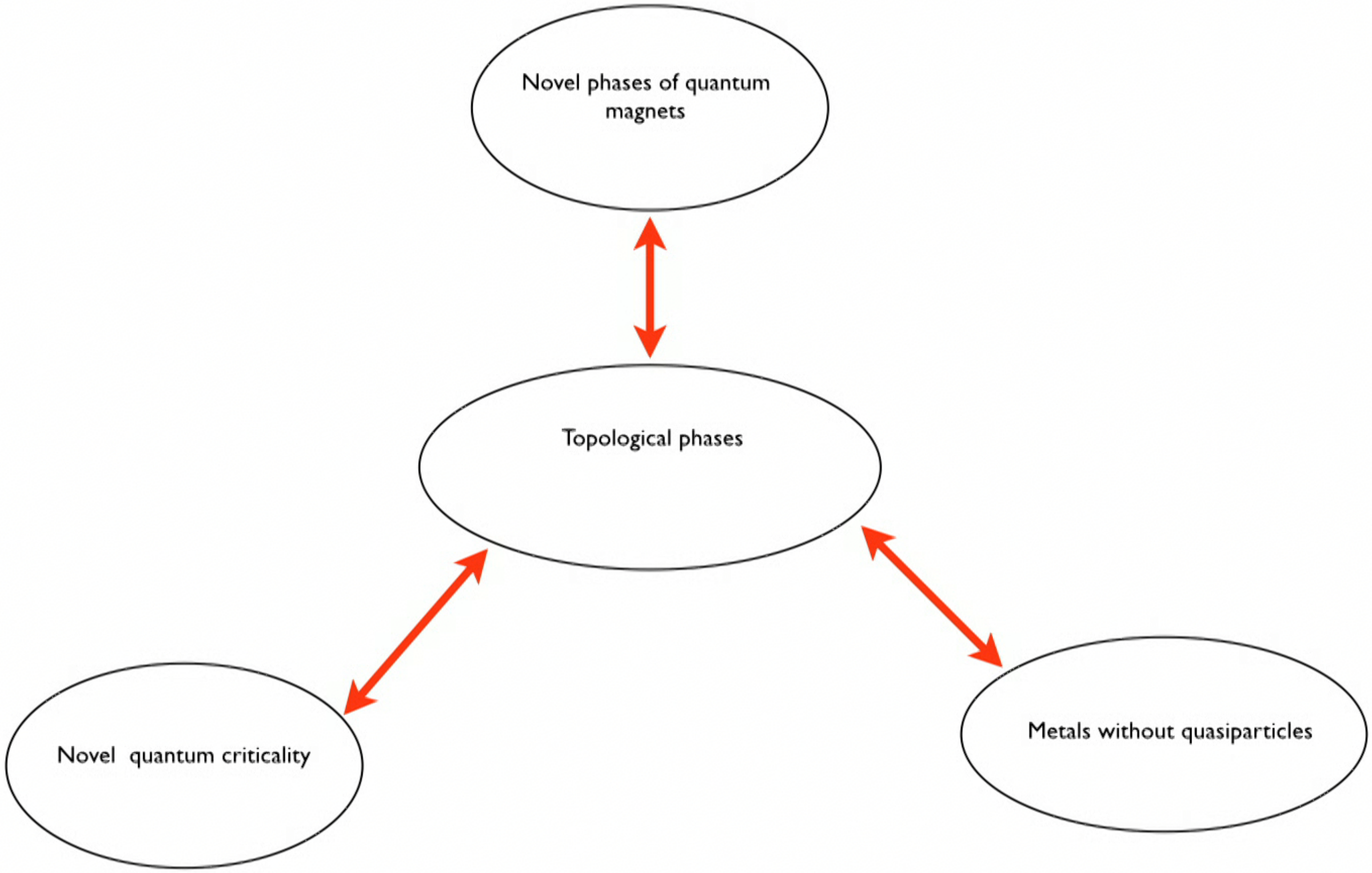
Possibly simplest context to study interplay of symmetry, topology, and strong interactions.

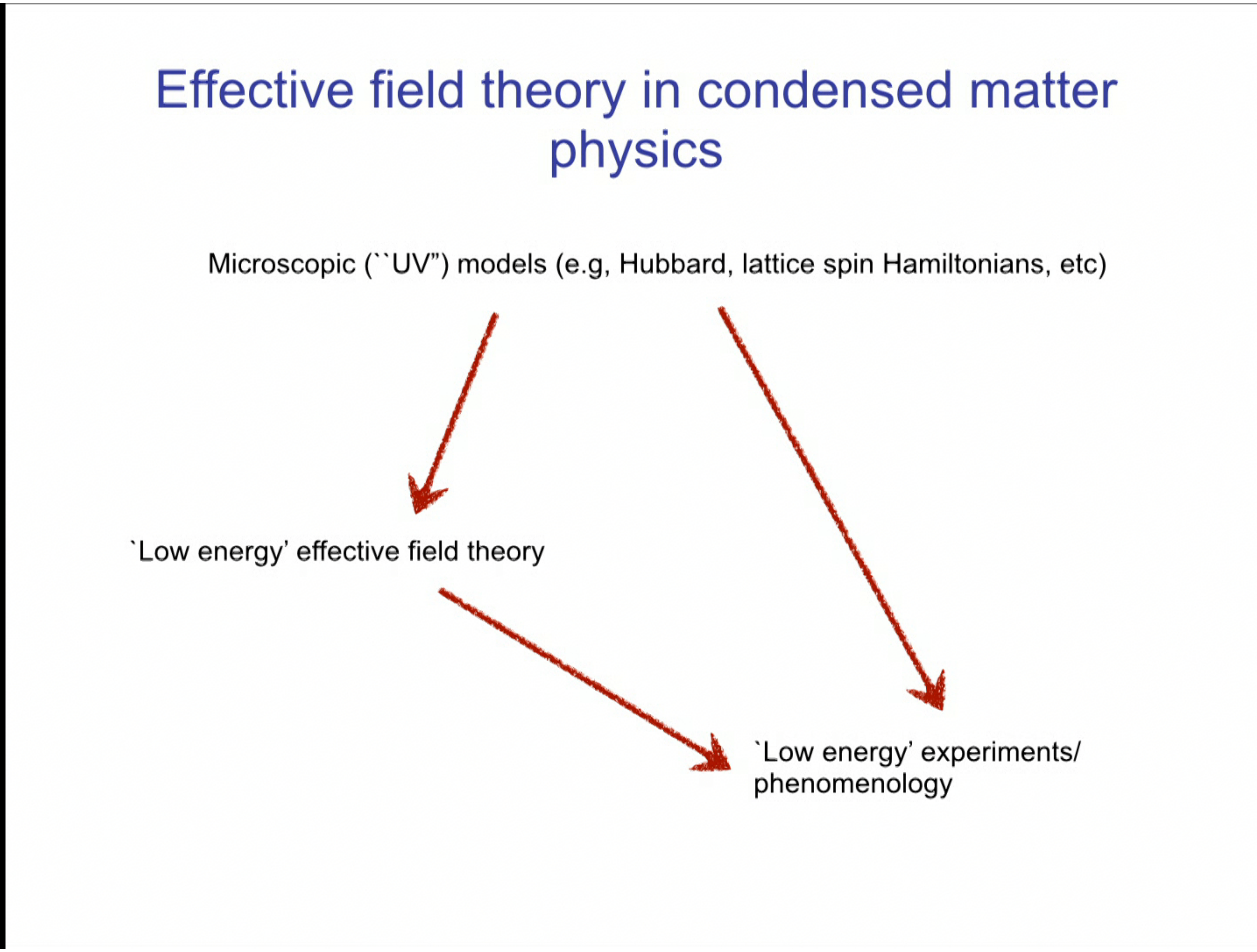
Many profound and surprising insights into more complex systems.

- many interesting connections to recent developments in field theory/math literature.

Many interesting/fruitful interactions of condensed matter with field (string) theory/math.

Deep connections between many apparently different problems




Effective field theory in condensed matter physics
Microscopic (``UV”) models (e.g, Hubbard, lattice spin Hamiltonians, etc)
`Low energy’ effective field theory
`Low energy’ experiments/ phenomenology

Effective field theory:*minimal* requirements/ challenges

1. **`Tractable':** Must be simpler to understand than original microscopic models and relate to experiments

- continuum field theory often useful but not necessarily of the kind familiar from high energy physics.

Effective field theory: *minimal* requirements/ challenges

1. **`Tractable':** Must be simpler to understand than original microscopic models and to relate to experiments

- continuum field theory often useful but not necessarily of the kind familiar from high energy physics.

2. **`Emergeable':** A proposed low energy field theory must (at the very least) be *capable of emerging* from microscopic lattice models in the *`right' physical Hilbert space* with the *right symmetries*.

- demonstrate by calculations on `designer' lattice Hamiltonians.

Designer Hamiltonians do not need to be realistic to serve their purpose.

Conventional condensed matter physics:

Hartee-Fock + fluctuations

Structure of effective field theory:
Landau quasiparticles + broken symmetry order parameters (if any).

Modern condensed matter physics:

Many examples of phases of quantum matter where low energy field theory involves `exotic' ingredients (no simple or even local connection to UV degrees of freedom)

Fractional quantum Hall effect - Chern-Simons gauge theory.

Symmetry and effective field theory

Effective field theory often has extra global symmetry which is emergent at low energy.

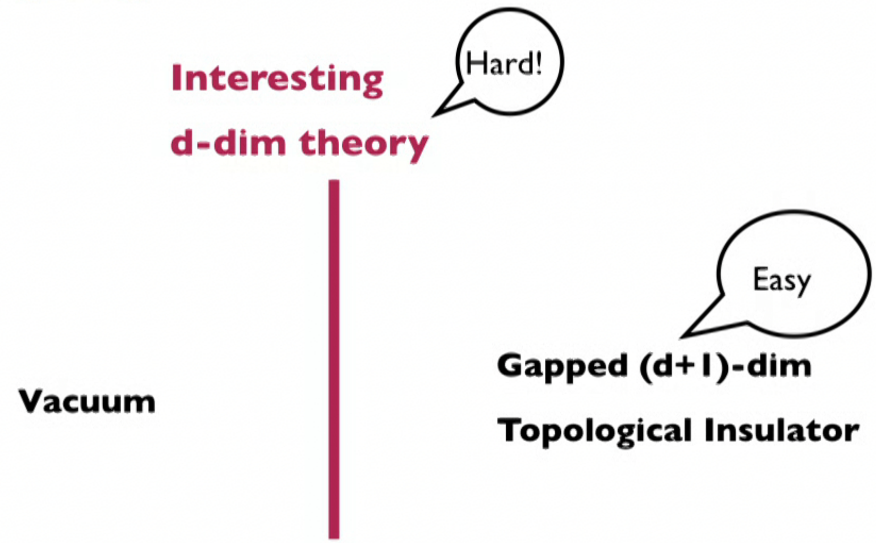
These emergent symmetries may have ``anomalies" ('t Hooft anomalies) similar to those familiar in quantum field theory.

Example of role of topology

Q: How should we UV complete the effective field theory in a way that preserves the anomalous emergent symmetry?

A: Regard the theory as living at the boundary of a higher dimensional gapped topological phase of matter

Study relatively simple gapped topological phase to learn about the more complex boundary theory.



Remarkably intimate connections between theories of many different kinds of phases/ phase transitions

- spectacular new progress in various directions in last few years.

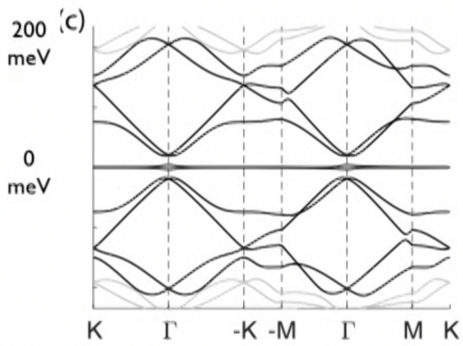
However in the rest of the talk I want to highlight a different fascinating meeting of topology and strong interactions in quantum matter.

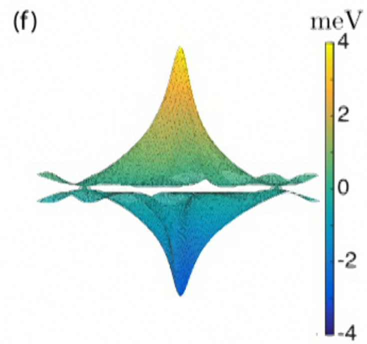
Flattening the bands: ``magic angles"

Theory: Can get nearly flat bands by tuning the twist angle close to ``magic" values.
(Suarez Morell et al, '10; Biztritzer, MacDonald '11, …..)

First magic angle is ≈ 1.1 deg.

Modern calculations (eg Koshino et al, 2018, Po et al 2018, Carr,…..Kaxiras, 2019)





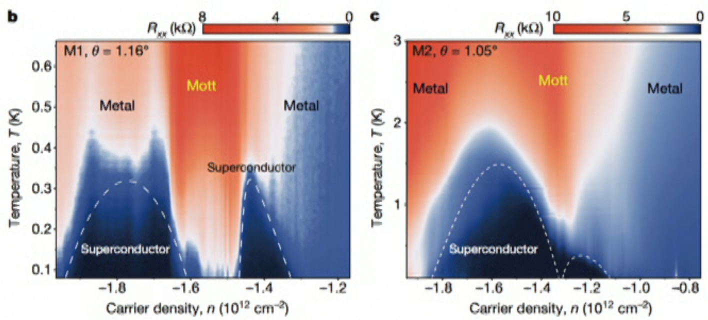
Physics in the nearly flat bands

Bandwidth $W \approx 10meV$

Coulomb interaction U comparable to W.

Interesting correlation effects ?? Biztritzer, MacDonald '11,

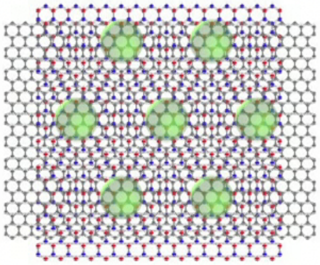
Correlated insulator/superconductor found in 2018!



Cao, Jarillo-Herrero et al, Nature **556**, 80 (2018)
Cao, Jarillo-Herrero et al, Nature **556**, 43 (2018)

Other routes to moire bands in graphene

Eg: n-layer graphene aligned with a hexagonal Boron Nitride (h-BN) substrate



Slight lattice mismatch between graphene and h-BN leads to a moire pattern.

Moire lattice spacing >> microscopic graphene lattice spacing

Eg: ABC trilayer graphene/h-BN: nearly flat moire bands (Feng Wang 2018)

Many amazing discoveries in variety of moire materials

``Classic'' twisted bilayer graphene (Jarillo-Herrero, Dean, Young, Efetov):
correlated insulator, superconductivity, strange metallic transport

Further align with h-BN (Kastner, Goldhaber-Gordon):
Ferromagnetism, spontaneous (quantum?) Hall effect

ABC trilayer/h-BN (Feng Wang):
Electrically tunable Mott insulator, superconductivity (?)

Twisted double bilayer graphene (P. Kim, Jarillo-Herrero, G. Zhang) :
Spin polarized correlated insulators, superconductivity

What about theory?

Amazingly many of these moire systems the active bands important for low energy physics are topological.

Thus we are forced to confront the effects of strong correlations in a partially filled topological band.

Band topology in moire graphene systems

Many moire systems have a **familiar** form of band topology:
Zhang, Mao, Cao, Jarillo-Herrero, TS, PR B, 19 (arXiv,1805: 08232)

A pair of degenerate bands with equal and opposite Chern number

ABC-trilayer graphene/h-BN: $C = \pm 3$

Twisted double bilayer: $C = \pm 2$.

Twisted bilayer aligned with h-BN: $C = \pm 1$
(Bultinck, Chatterjee, Zaletel, arXiv 2019; Zhang, Mao, TS, arXiv 2019)

Classic twisted bilayer graphene has a much more subtle form of band topology
Po, Zou, Vishwanath, TS, PR X, 2018; Zou, Po, Vishwanath, TS, PR B 2018;
Song,……,Bernevig, arXiv:1807.10676; Po, Zou, TS, Vishwanath, arXiv:1808.02482

Comment: Moire is different(*)

For many (though not all) flat band moire systems, need to understand

Topological band structure + strong correlations.

Can write down lattice models only at the cost of introducing auxiliary bands that ``cancel" the band topology

(*) Slogan from Baskaran

Key collaborators on these topics

Former/current students:

Chong Wang (Perimeter)

Andrew Potter (Honeywell)

Liujun Zou (MIT)

Ya-Hui Zhang (MIT)

Dan Mao (MIT)

Former/current postdocs:

Adam Nahum (Oxford)

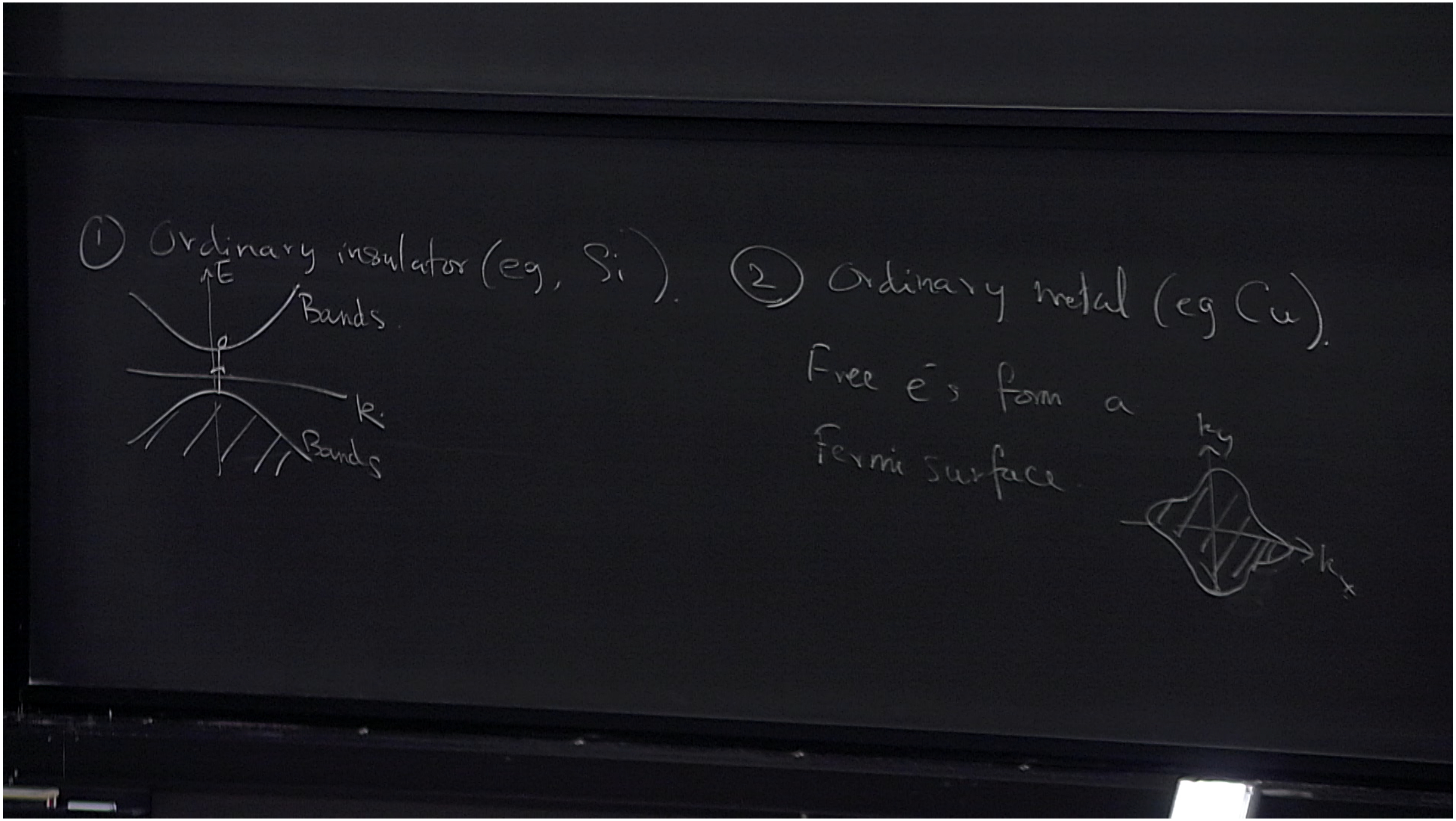
Inti Sodemann (Dresden)

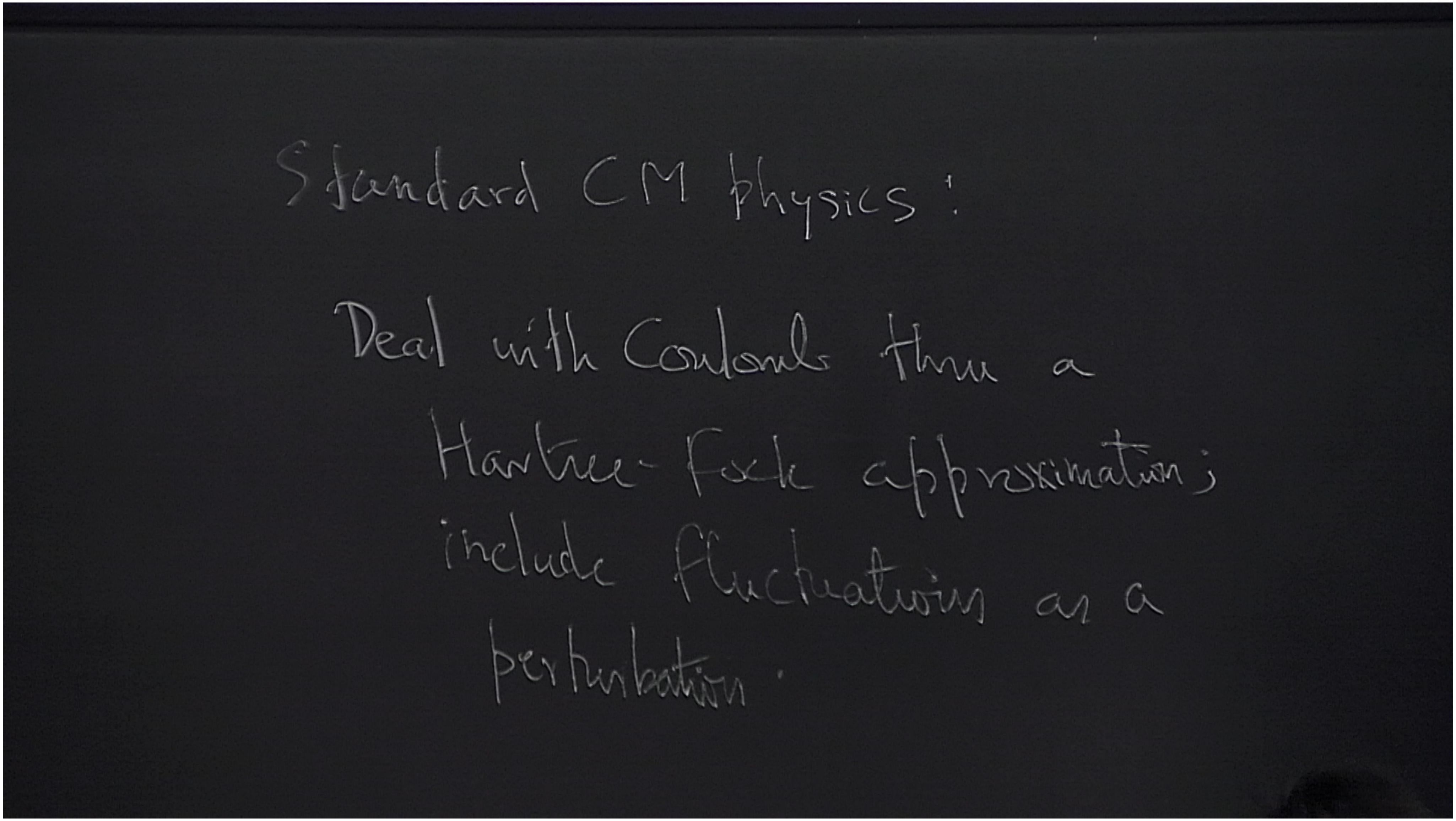
Debanjan Chowdhury (MIT)

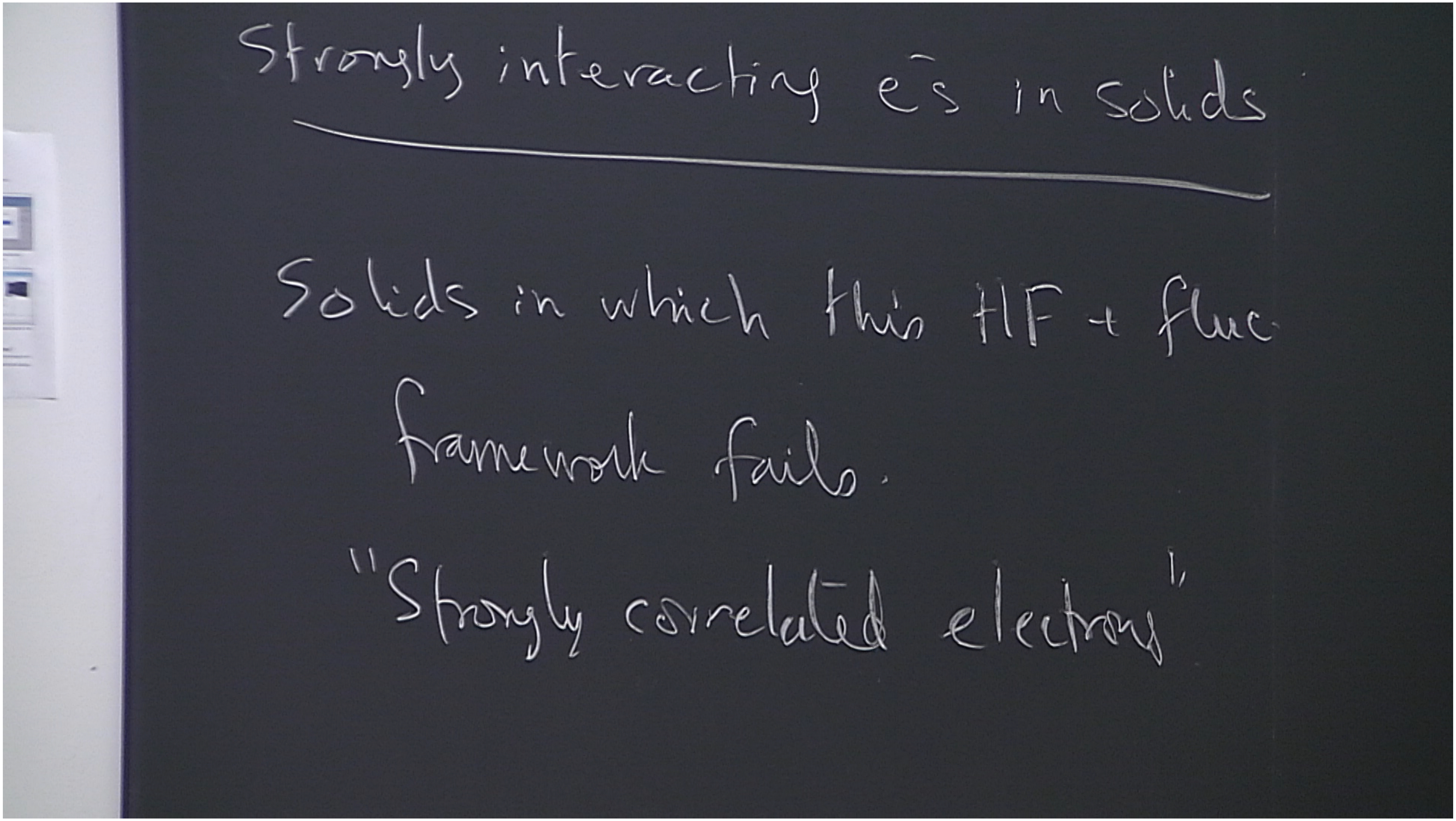
Zhen Bi (MIT)

Hoi-Chun (Adrian) Po (MIT)

Faculty: Ashvin Vishwanath (Harvard), Max Metlitski (MIT), Nati Seiberg (IAS). Edward Witten (IAS)


① Ordinary insulator (eg, Si).
E
Bands
k
Bands
② Ordinary metal (eg Cu).
Free e⁻'s form a
fermi surface.
ky
kx


Standard CM physics:
Deal with Coulomb thru a
Hartree-Fock approximation;
include fluctuations as a
perturbation.


Strongly interacting e^-'s in solids
Solids in which this HF + fluc framework fails.
"Strongly correlated electrons"