Welcome!!

Today’s Plan

Intro/Topics/Tentative Syllabus

Course Specifics

“Meet and Greet”

Sighting of Wigner Crystals ??
Something about My Story

My Multicultural Background

U.S.A., Atlantic Ocean, France, Poland, India
A Schematic History of my Professional Life after College

Industry

(technician)

(summer student)

(postdoctoral fellow)

(research scientist)

Academia

(graduate student)

(visiting student fellowship)

(faculty)
Let me introduce myself.....I’m a materials-inspired theorist

What’s That??

A Visual Analogy from a (Great) Artist

Development of minimalist models for complex materials........with predictions for experiment!
Let me introduce myself.....I’m a materials-inspired theorist

What’s That??

Experiment

Phenomenology

Microscopic Model

Predictions for Future Experiment
What’s a Quantum Material?

“Weird and “Wonderful” Electrons + Crystal Lattice

<table>
<thead>
<tr>
<th>Conductor</th>
<th>Insulator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>Wood</td>
</tr>
<tr>
<td>Steel</td>
<td>Plastic</td>
</tr>
<tr>
<td>Gold</td>
<td>Rubber</td>
</tr>
</tbody>
</table>

Are all materials then quantum??
What’s meant here by a Quantum Material?

What if these “weird and “wonderful” electrons interact (or even “know” about one another) ???

Many possible ways to do so………complexity !!

Quantum Mechanics  +  Complexity

Emergent Properties

(Whole greater or different than sum of parts)
Examples of Emergence

More constituents lead to more complexity !!

Just How Many Electrons are Involved  ??
How Many Electrons in One Gram of Iron??

1 gram H $\rightarrow$ $6 \times 10^{23}$ electrons

1 gram Fe $\rightarrow$ $3 \times 10^{23}$ electrons

How Many Stars in Our Observable Universe??

100 billion galaxies $\times$ 100 billion stars/galaxy

$\Downarrow$

$10^{22}$ stars

Emergence not only in external universe but also in the inner universe of quantum materials too!!
Quantum Materials = Tunable Universes

Tunable ??

Musical Instrument

Our Tuning Knobs: Pressure, Magnetic Field

We can change the properties of quantum materials in the laboratory by tuning the electron interactions
Predicted Particles in Our Universe

Dirac

Antimatter (Positron)

Detected in Cosmic Rays

Weyl

Weyl Fermion

Still Looking.....

Majorana

Majorana Fermion
Different Situation in Quantum Materials

Viewpoint: Where the Weyl Things Are

Analogs to massless fermions predicted by particle physicists 80 years ago have been found in a crystalline metal and in a photonic crystal.

Reports on Progress in Physics

New directions in the pursuit of Majorana fermions in solid state systems

Jason Alicea

Quantum Mechanics + Complexity

Quantum Materials

Tunable Universes
Explore, Model and Apply

Our “multiverse” playground: The Periodic Table

Many scientists’ version of the Periodic Table

H
H’
H’’
H’’’

HARD METALS

Cu
Semi.
Ag
Cond.
Au

Stuff that might not be real....

Won’t Be On the Final Exam

Bombs and other Nasty Stuff

(courtesy: P.C. Canfield)
Explore, Model and Apply

Cantino planisphere (1502) anonymous Portuguese
Biblioteca Estense Universitaria, Modena, Italy

Characterize Known Territories and Search for New Ones
Signatures of bilayer Wigner crystals in a transition metal dichalcogenide heterostructure

You Zhou¹,², Jiho Sung¹,², Elise Brutschea¹, Ilya Esterlis², Yao Wang²,³, Giovanni Scuri², Ryan J. Gelly², Hoseok Heo¹,², Takashi Taniguchi⁴, Kenji Watanabe⁴, Gergely Zaránd⁵, Mikhail D. Lukin², Philip Kim²,⁶, Eugene Demler²† & Hongkun Park¹,²†

What are Wigner Crystals (WCs)?

Why are WCs so difficult to observe?

What’s New Here?

What’s Next?
Fig. 2. – (bottom) Soundwave absorption by a two dimensional electron gas (2DEG) under strong magnetic field. The frequencies at which the sound is absorbed correspond to the eigenmodes of the crystal (see Sec. 2’2), and are interpreted as evidence of a Wigner crystal in this system (from [13]); (top Right) Transport properties of a 2DEG. At strong magnetic field an insulating phase appears, again suggestive of the formation of a pinned Wigner crystal (from [14]). (top left) Current vs. voltage characteristics. One clearly sees a threshold field needed to have conduction. This is again reminiscent of what one expects of a pinned crystal (From [15]).
Challenge: WC without Magnetic Field  
(lower densities then needed)

New Results

New Player in Town: TMDs that give access to different range of temperatures and densities (and even observational techniques) mainly due to larger mass of particles
Signatures of bilayer Wigner crystals in a transition metal dichalcogenide heterostructure

You Zhou\textsuperscript{1,2}, Jiho Sung\textsuperscript{1,2}, Elise Brutschea\textsuperscript{1}, Ilya Esterlis\textsuperscript{2}, Yao Wang\textsuperscript{2,3}, Giovanni Scuri\textsuperscript{2}, Ryan J. Gelly\textsuperscript{2}, Hoseok Heo\textsuperscript{1,2}, Takashi Taniguchi\textsuperscript{4}, Kenji Watanabe\textsuperscript{4}, Gergely Zaránd\textsuperscript{5}, Mikhail D. Lukin\textsuperscript{2}, Philip Kim\textsuperscript{2,6}, Eugene Demler\textsuperscript{2}\textdagger& Hongkun Park\textsuperscript{1,2}\textdagger

Probed with optical signatures

What’s Next??

Direct Imaging of Wigner Crystal??

“Old” Transport Probes??

Extra “Knob”: Magnetic Field??