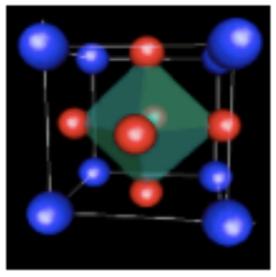
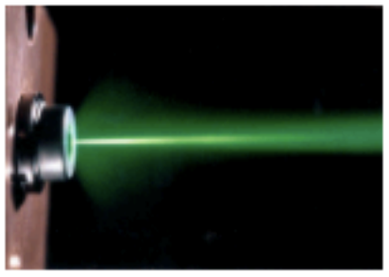
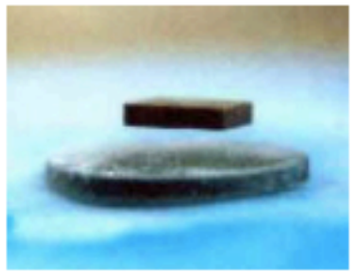
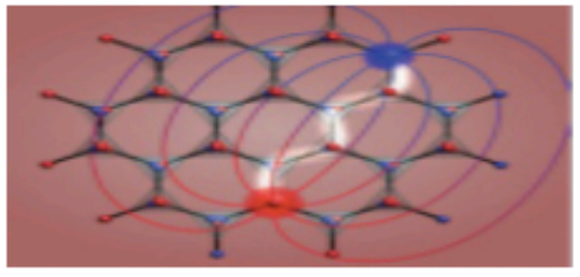
Physics 602: Graduate Solid State Physics II

Adventures in Quantum Materials:
A Selected Survey of Great Papers from Last Year and Last Century (and maybe even Last Week!)

Spring 2021

Welcome !!

Today's Plan

Intro/Topics/Tentative Syllabus

Course Specifics

"Meet and Greet"

Sighting of Wigner Crystals ??

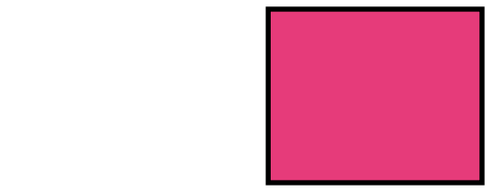
Something about My Story

My Multicultural Background

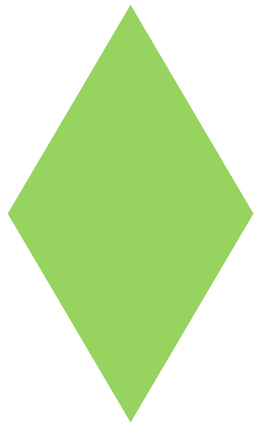
U.S.A.

Atlantic Ocean

Poland

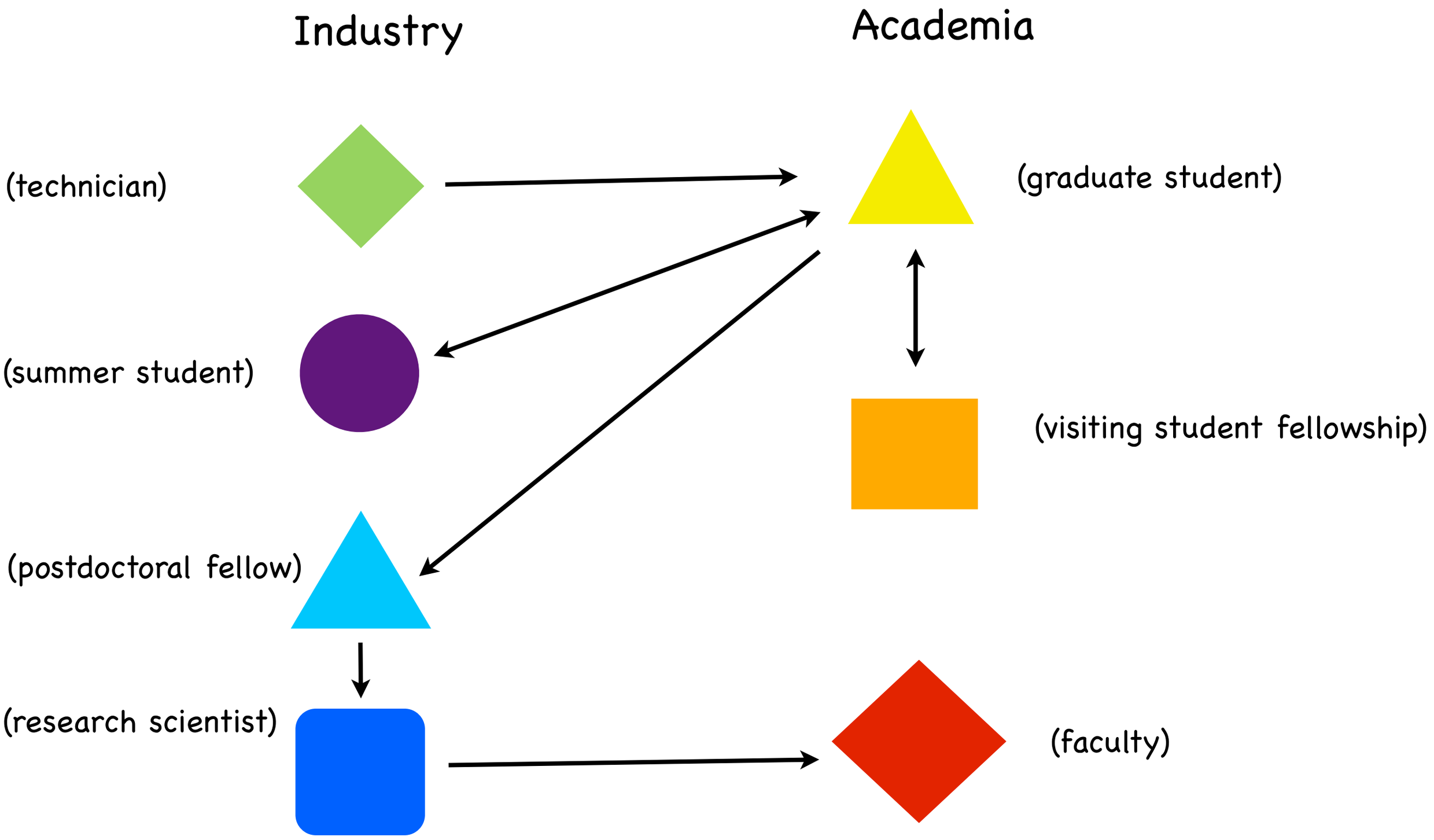


France



India

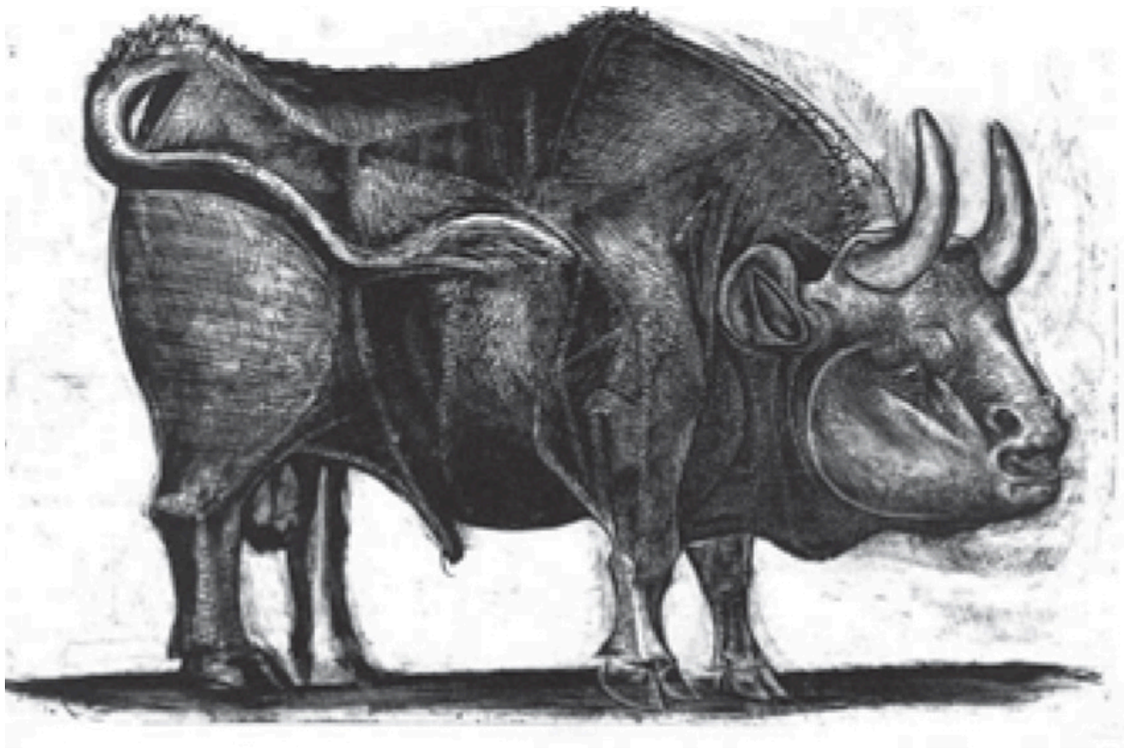
A Schematic History of my Professional Life after College

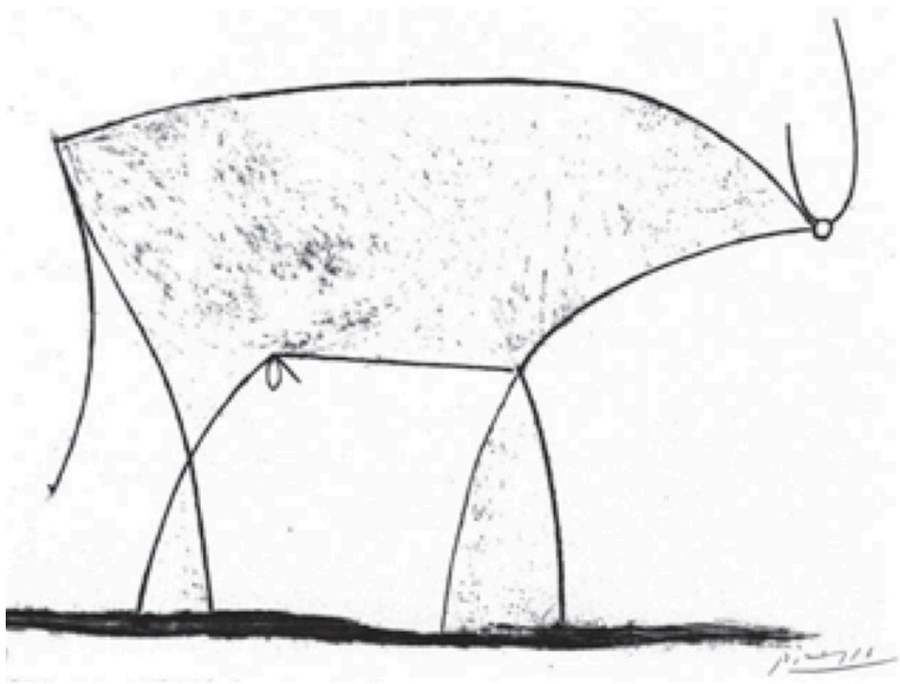


Let me introduce myself.....I'm a materials-inspired theorist

What's That??

A Visual Analogy from a (Great) Artist

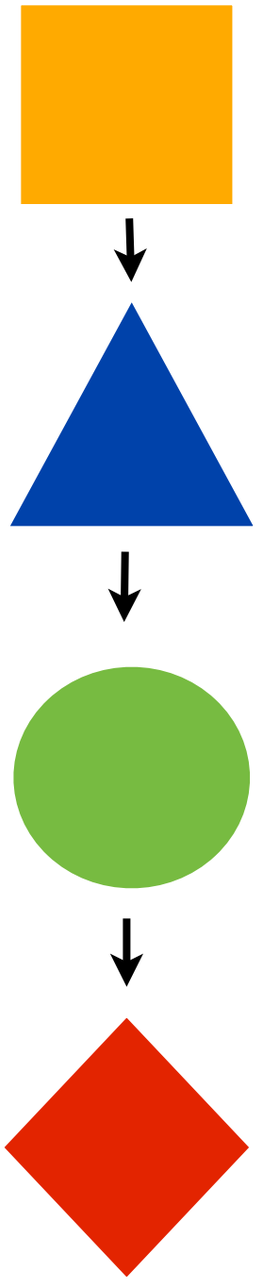




Development of minimalist models for complex materials.....with predictions for experiment!

Let me introduce myself.....I'm a materials-inspired theorist

What's That??

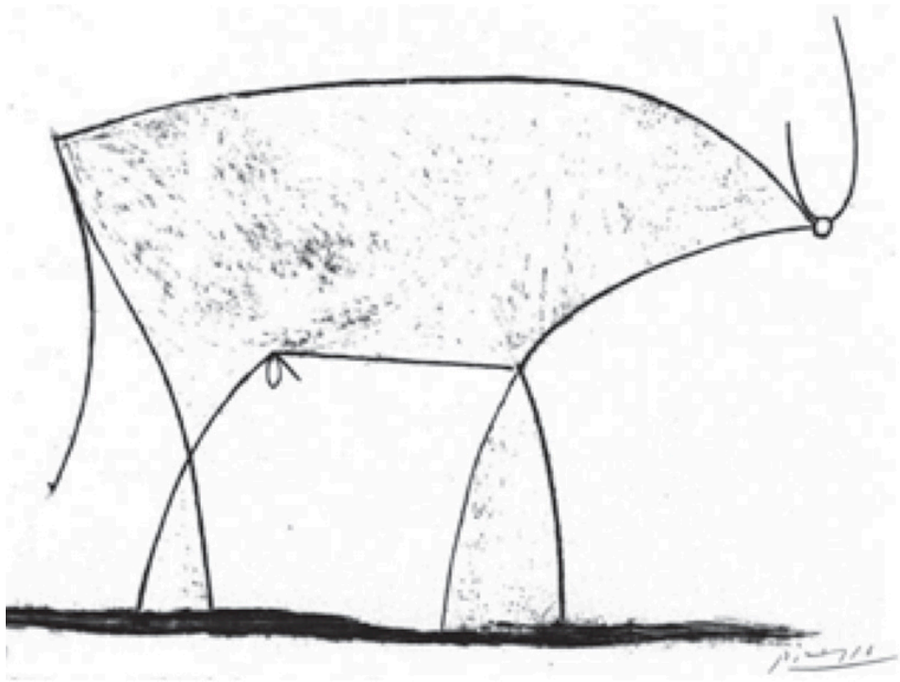


Experiment

Phenomenology

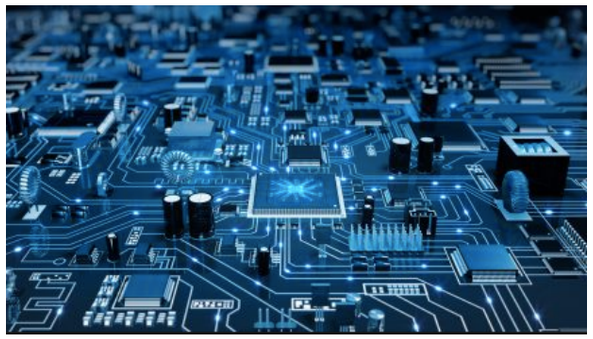
Microscopic Model

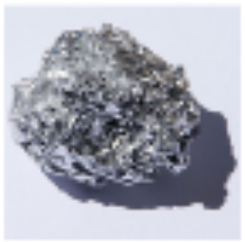
Predictions for
Future Experiment

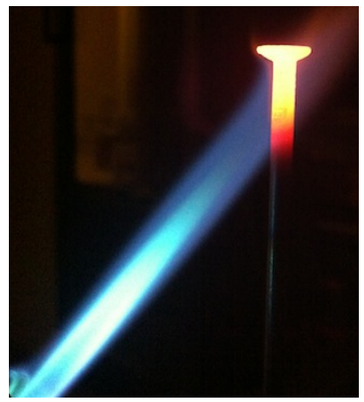


What's a Quantum Material?

"Weird and "Wonderful" Electrons + Crystal Lattice



Conductors	Insulators
 Aluminum	 Wood
 Steel	 Plastic
 Gold	 Rubber



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 !!

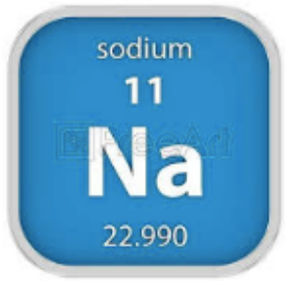
Quantum Mechanics + Complexity

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 ??

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

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

How Many Stars in Our Observable Universe ??

$$100 \text{ billion galaxies} \times 100 \text{ billion stars/galaxy}$$

$$\downarrow$$

$$10^{22} \text{ stars}$$

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

Majorana

Majorana Fermion

Still Looking…..

Different Situation in Quantum Materials

Physics

Viewpoint: Where the Weyl Things Are

Ashvin Vishwanath

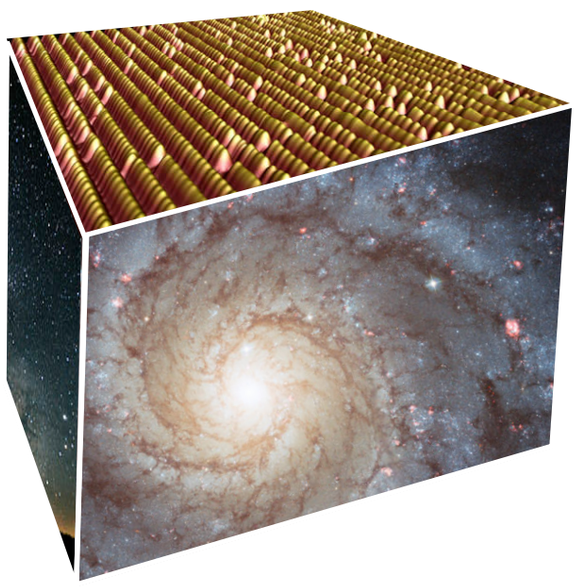
Analogs to massless fermions predicted by particle physicists 80 years ago have been found in a crystalline metal and in a photonic crystal.

Reports on Progress in Physics

REVIEW ARTICLE

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

Jason Alicea



Quantum Mechanics + Complexity

↓

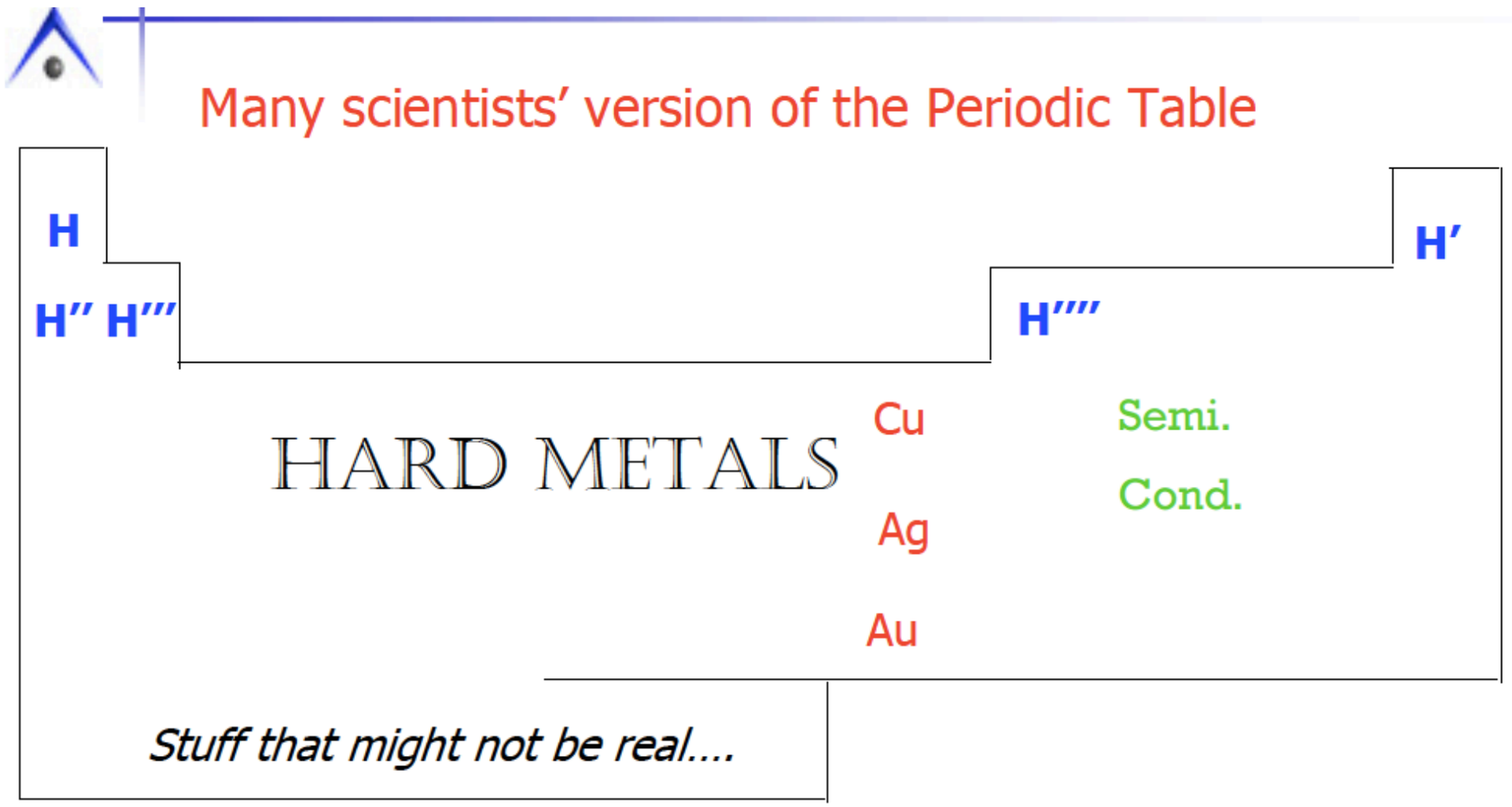
Quantum Materials

=

Tunable Universes

Explore, Model and Apply

Our “multiverse” playground : The Periodic Table

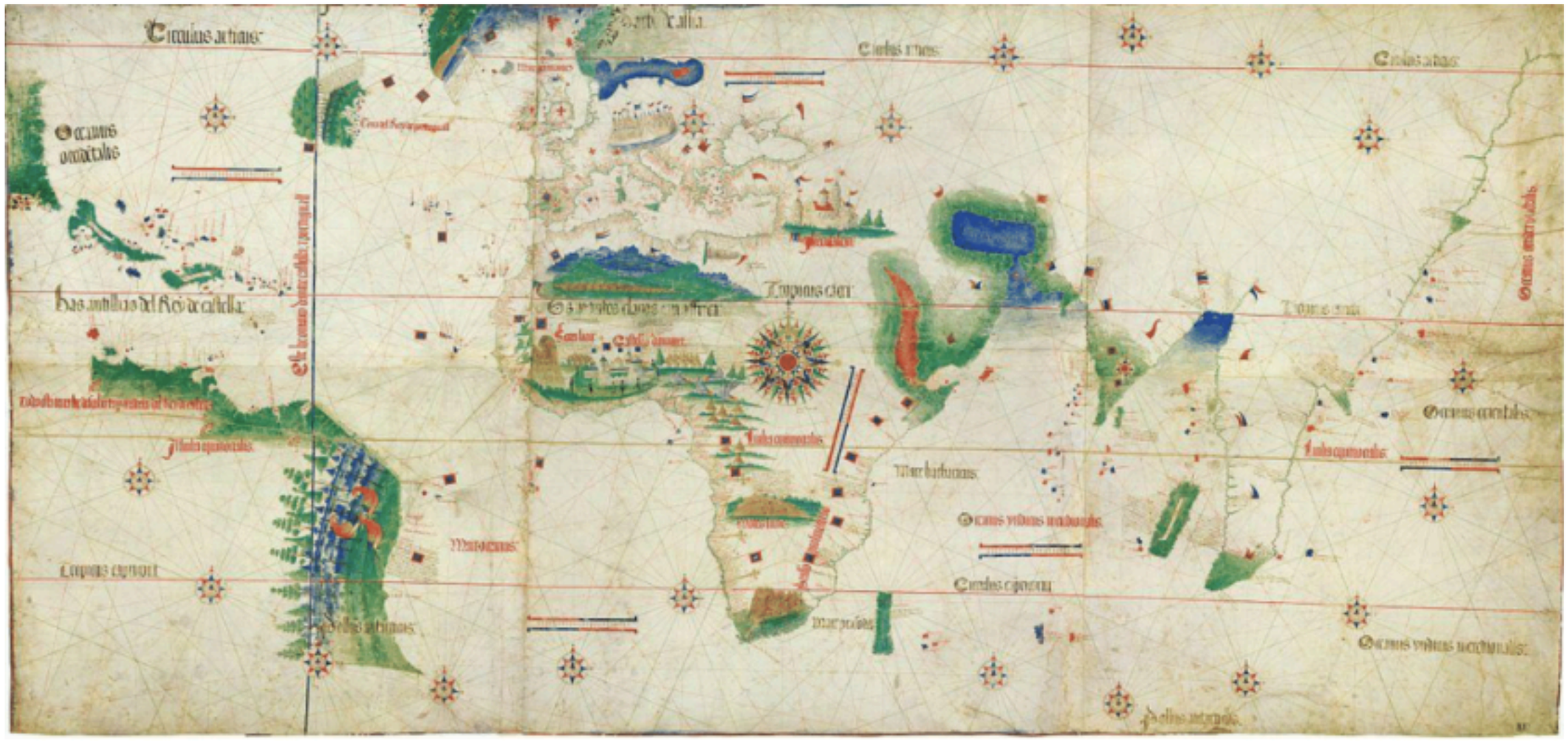


← Won’t Be On the Final Exam →

← BOMBS AND OTHER NASTY STUFF →

(courtesy: P.C. Canfield)

Explore, Model and Apply



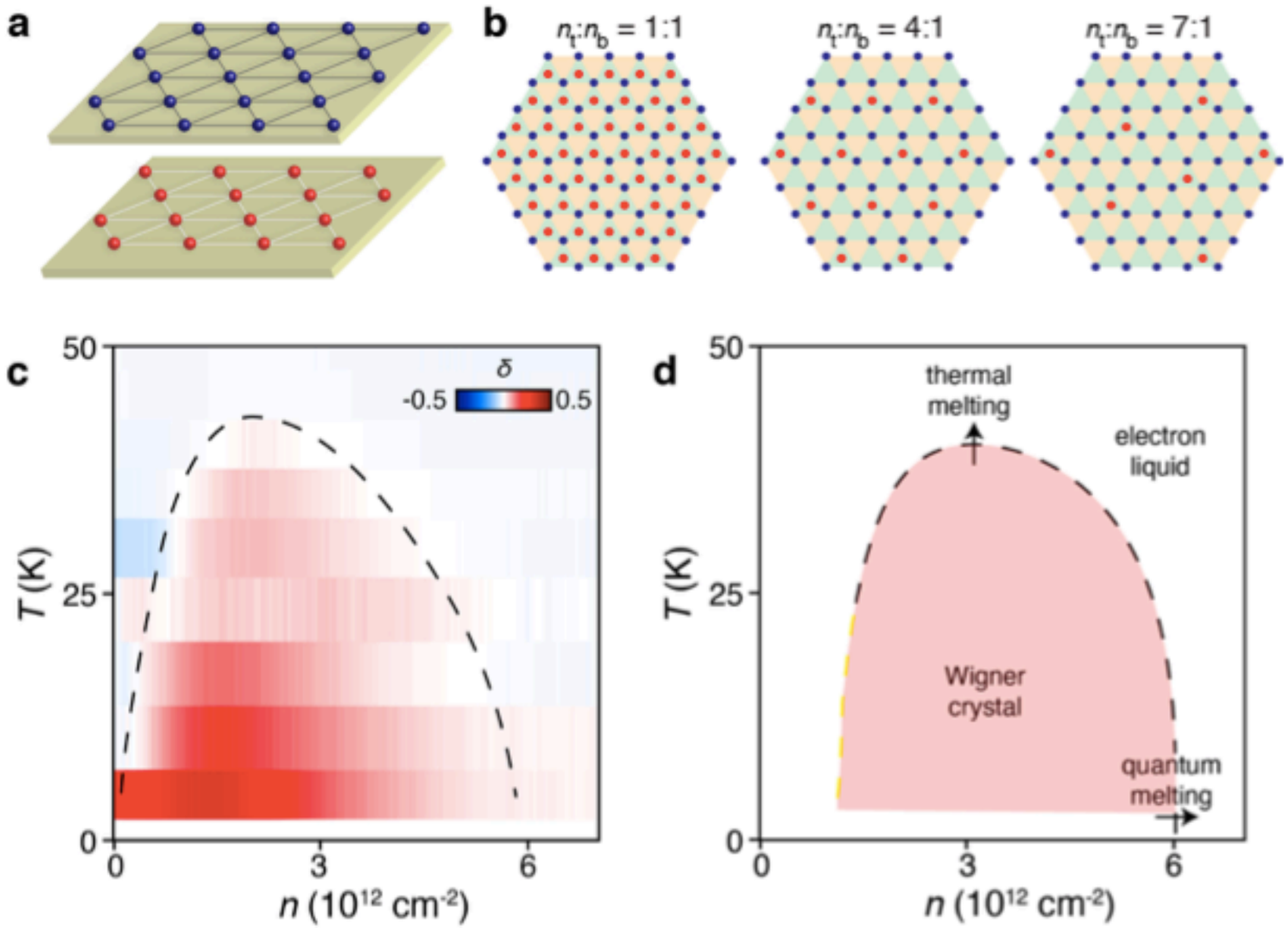
Cantino planisphere (1502) anonymous Portuguese
Biblioteca Estense Universitaria, Modena, Italy

Characterize Known Territories and Search for New Ones

Signatures of bilayer Wigner crystals in a transition metal dichalcogenide heterostructure

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

arXiv:2010:03037



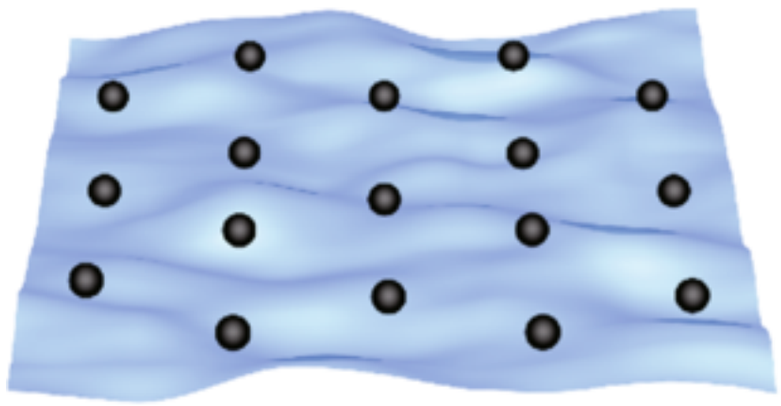
Wigner crystals in transition metal dichalcogenides

What are Wigner Crystals (WCs)?

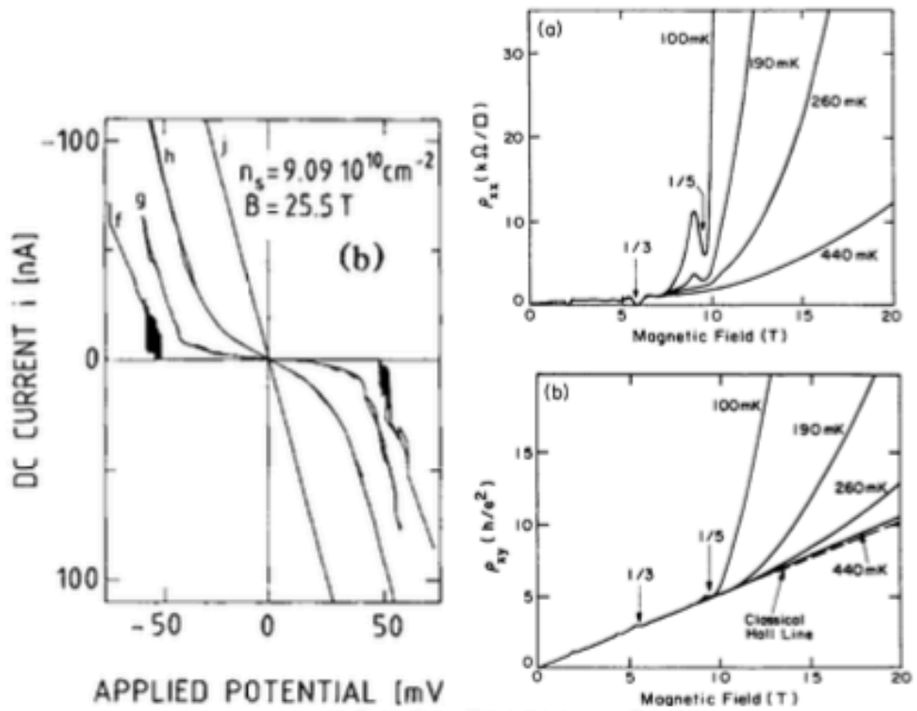
Why are WCs so difficult to observe ?

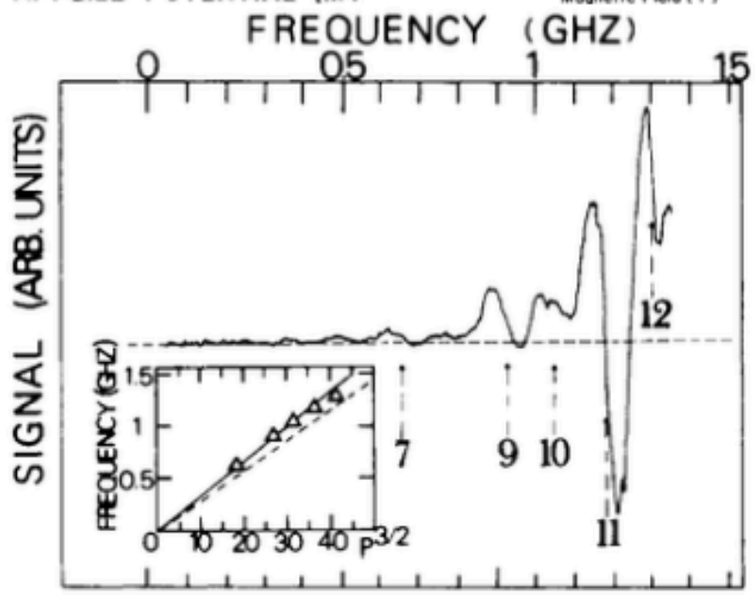
What's New Here ?

What's Next ?



Selected Previous (Indirect) Measurements





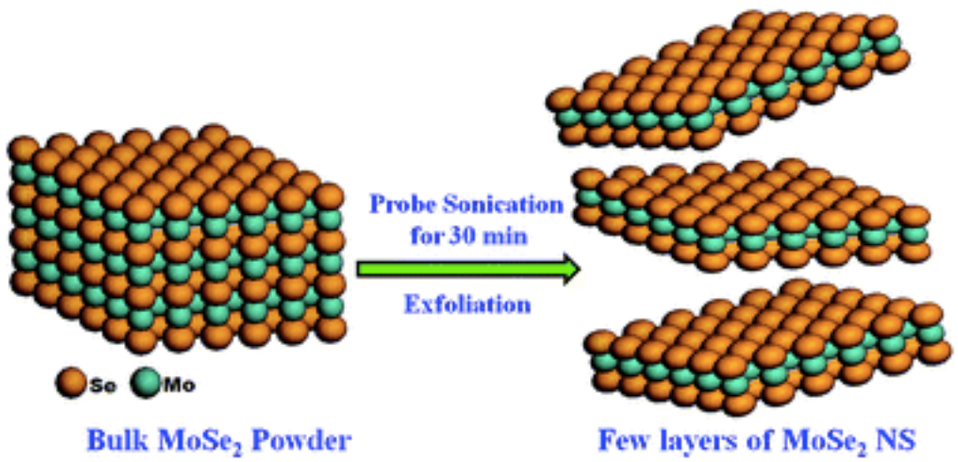
Serious tuning of
Field,
Density and
Temperature Required !!

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



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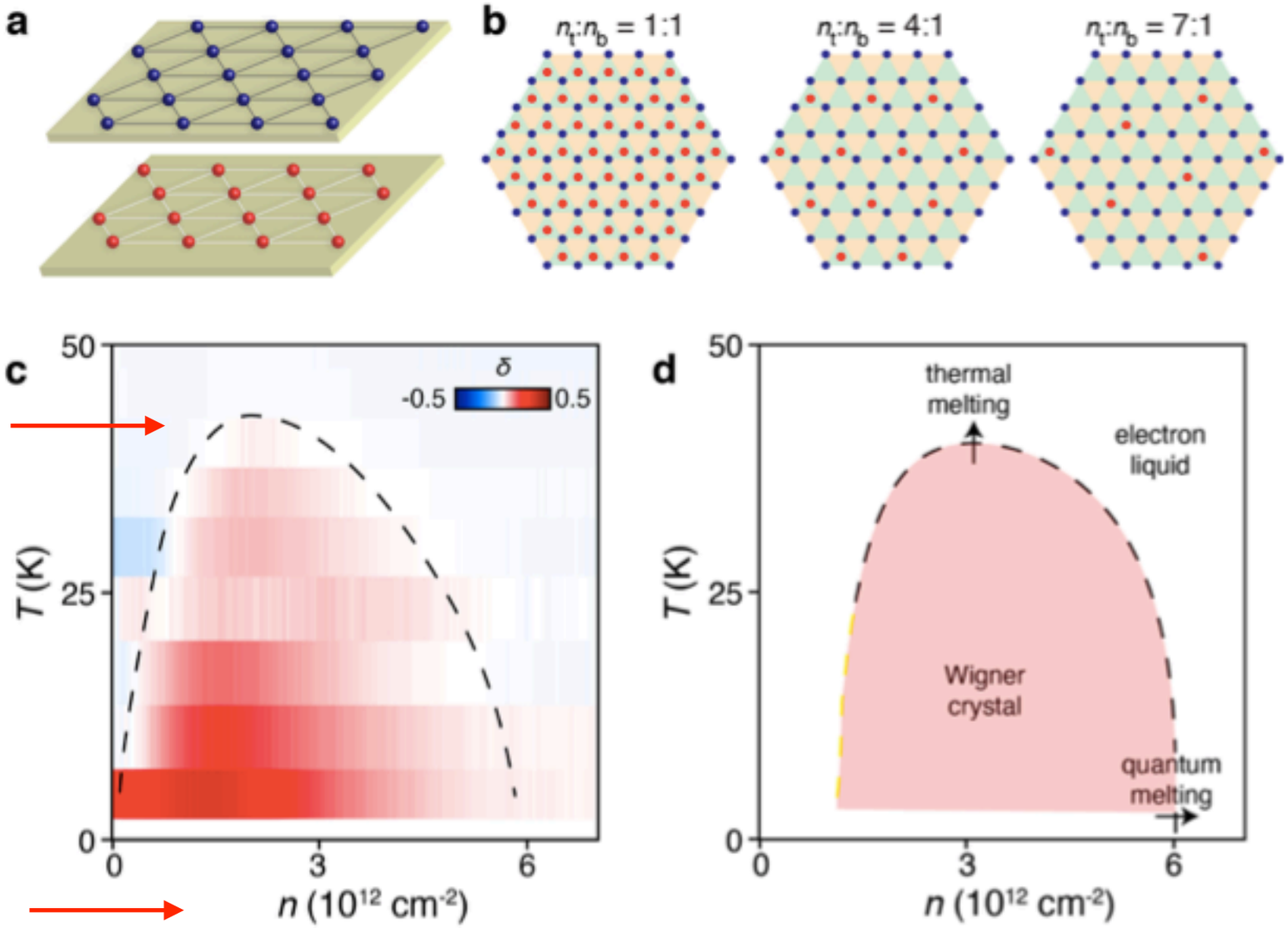
Probed with optical signatures

arXiv:2010:03037



What's Next ??

Direct Imaging of Wigner Crystal ??

"Old" Transport Probes ??

Extra "Knob": Magnetic Field ??