IEEE/CSC & ESAS EUROPEAN SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2016.
Plenary presentation 4PL-03 given at ASC 2016; Denver,Colorado,USA, September 4 – 9, 2016.

High-Temperature Superconductivity: From History to Mystery

Laura H. Greene

National MagLab (FSU-UF-LANL) and FSU
Center for Emergent Superconductivity (CES)

NATIONAL HIGH MAGNETIC FIELD LABORATORY

CES center for emergent superconductivity

ASC 2016 Sept. 8, 2016 Denver, CO

Outline

I. Lessons Learned
   But, We Still Care About Fundamentals
II. Some History to Define:
   Conventional *vs. Unconventional* SCs
III. Ubiquitous Phase Diagram and
   "***Electron Matter***" in Unconventional
IV. Point-Contact Spectroscopy (PCS)
V. Towards Predictive Design…
VI. Conclusion: Experiment / theory progress!

And we are having fun!

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Lessons Learned: Kamerlingh Onnes & ASC

1909 Liquefied Helium

1911 Discovered Superconductivity: *Tc* and later ***Ic***

1913 Received Nobel Prize

1913 ***Press Releases on possible applications***

1926 Paper on Critical Field (*Hc*)

Journal
of
The Franklin Institute
Devoted to Science and the Mechanic Arts

Vol. 201 APRIL, 1926 No. 4

THE DISTURBANCE OF SUPRA-CONDUCTIVITY BY MAGNETIC FIELDS AND CURRENTS. THE HYPOTHESIS OF SILSBEE.*

BY

W. TUYN, Ph.D., and H. KAMERLINGH ONNES, Ph.D., Sc.D.

Emeritus Director, Physical Laboratory, University of Leiden;
Honorary Member of the Institute, Franklin Medalist.

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Lessons Learned, Continued

1930s and following: Much ASC Research & Applications

1957 BCS THEORY (after applications realized)

1979 First Unconventional SC Identified

1986 HTS Discovered (Bednorz and Müller)

1987 HTS Nobel Prize for Discovery

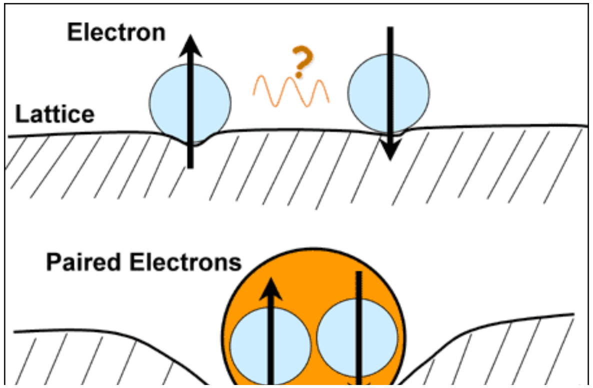
1989 R&D in HTS Cables

1991 Successful HTS Cables Demoed

2016 ASC 2016: Plethora of amazing applications rept.

2016 Mechanisms & Predictive Design: A Mystery!

So why give a CARE about fundamentals?



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Lessons Learned: So Why Care?

Reason we put on proposals, some consider a "belief" but really making progress towards this goal:

"Understanding the mechanisms of unconventional SC will lead to predictive design of new SCs that may have transformative applications."

Another reason; just as important:

The physics is absolutely gorgeous!

…and, it's nice to know what your siblings are up to…

Few motivational slides follow…

Warning: Extreme analogies!

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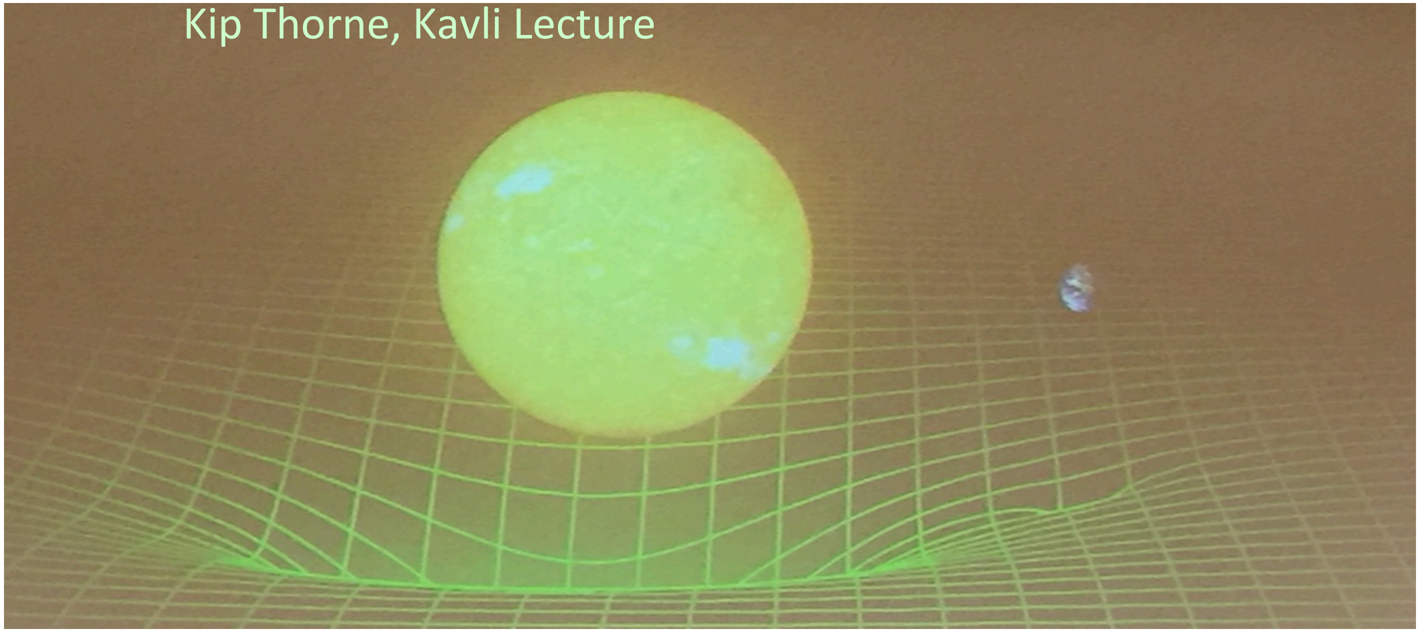
Recent Inspiration: Gravity



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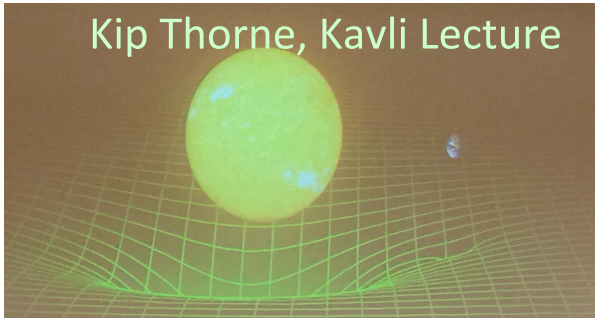
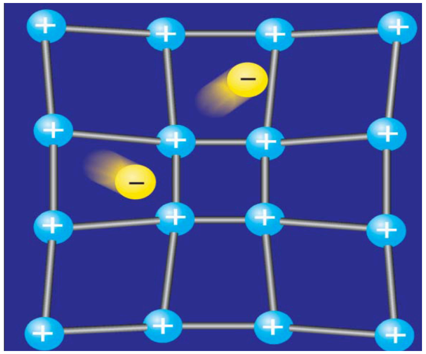
Gravity   Condensed Matter

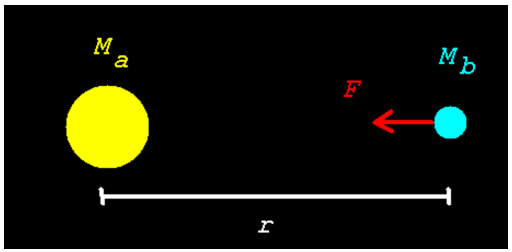


Einstein   BCS



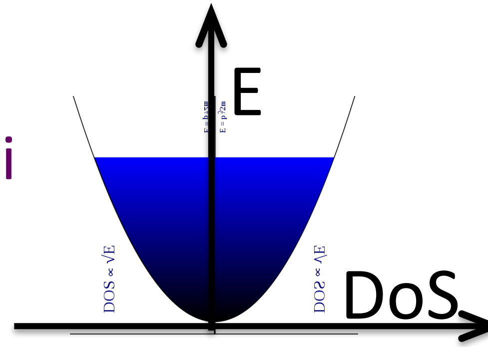
Gravity

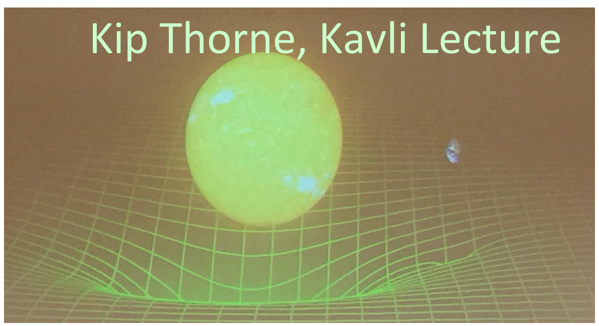
Condensed Matter



Newton

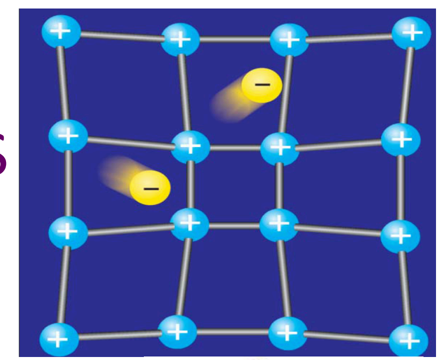
Fermi

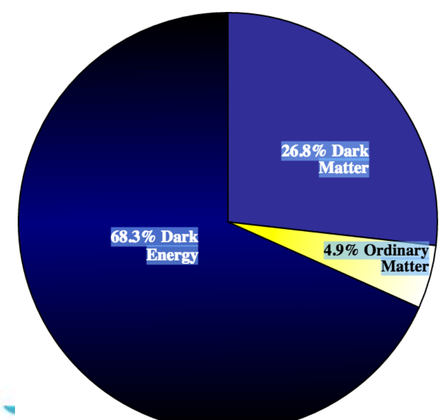




Einstein

BCS





Dark Energy

Electron Matter

superconductivity

What is Electron Matter?

What it is not:

- Fermi Liquid or Superconductor

General definitions:

- **Theory**: The normal-state electronic properties cannot be explained by the crystal structure
- **Experiment:** The electrons assemble into astounding states: Like form clumps, line up, or get really heavy.

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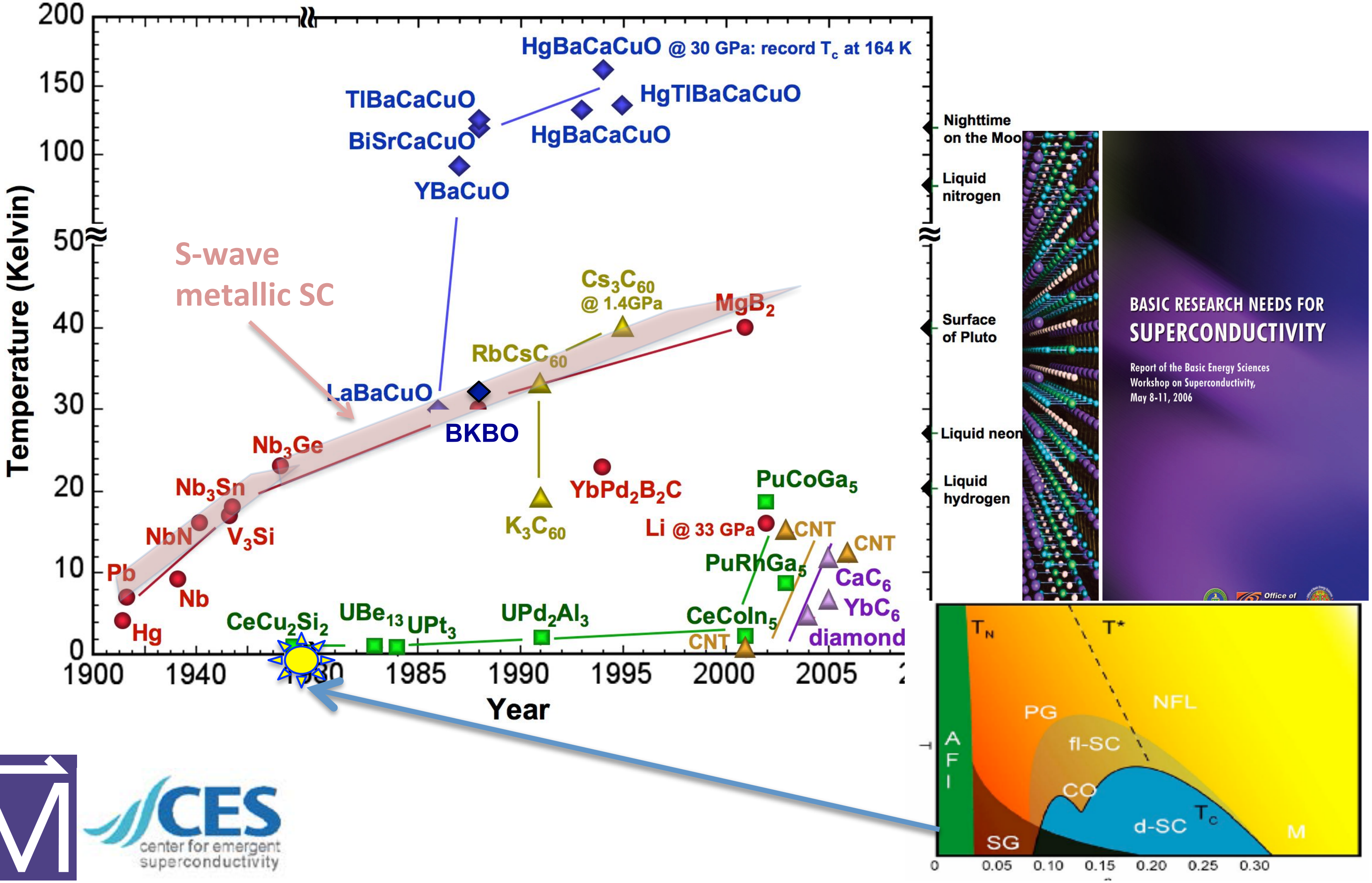
Lessons Learned: Why We Care

Two Great Unsolved Problems Today in Physics

PROGRESS	Gravity	Condensed Matter	PROGRESS
Forces between objects derived from mass and positions	Newtonian -Classical	Fermi Liquid -simple metals	Properties derived from crystal atoms and positions
Distortions in background (space-time continuum)	Einsteinian -General Relativity)	BCS SC -One Electron Matter solved!	Distortions in background (lattice via el-phonon int.)
UNSOLVED: May show how stars form…etc.	Dark Energy and Dark Matter	Electron Matter (correlations)	UNSOLVED: All unconv SCs have them

History: 2006 DoE-BES Report: "T_c vs. Time" & Phase Diagram



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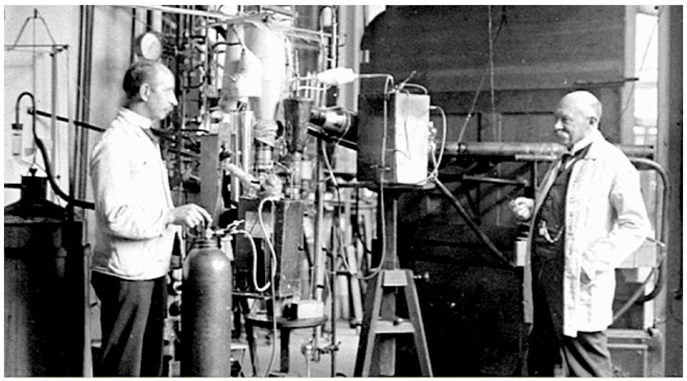
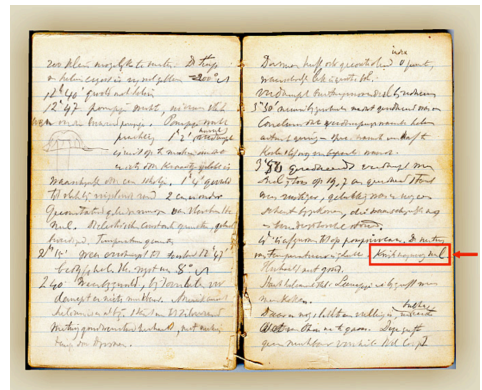
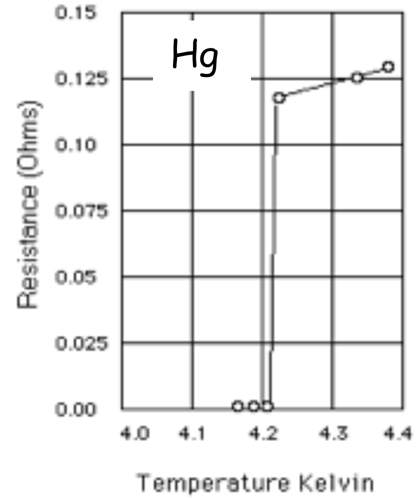
History – Discovery

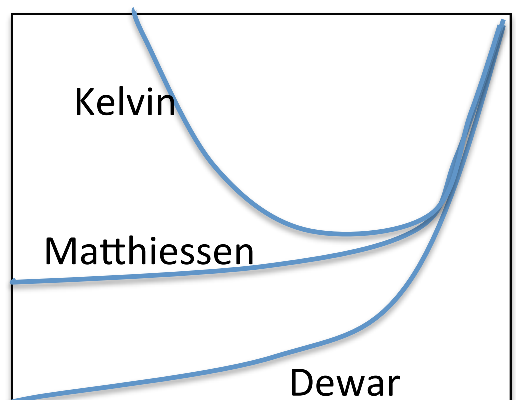
1911 Heike Kamerlingh Onnes







1908: Liquefied He
1911: Curiosity led to measuring the resistance of Hg mercury, *expecting*:



1913: Nobel Prize!
And stated *"superconductors world impact the world energy crisis!"*

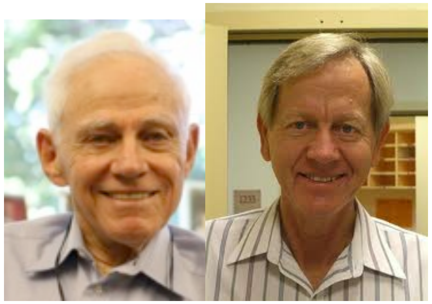
History – Matthias Era

Next few decades, Tc slowly increased through systematic tests of elements, alloys, and compounds.

1952: Bernd Matthias discovered first "new class" of superconductors, combining ferromagnetic and semiconducting elements: **$CoSi_2$**

Matthias' Rules:

1. Transition metals are better than simple metals
2. Peaks of density of states at Fermi level good
3. High symmetry is good: Cubic best
4. Stay away from oxygen, magnetism, insulating phases, and theorists.



- Geballe and Hulm, "*Bernd Theodore Matthias*" – NAS '96
- W. E. Pickett, "*The other HTS*" '01

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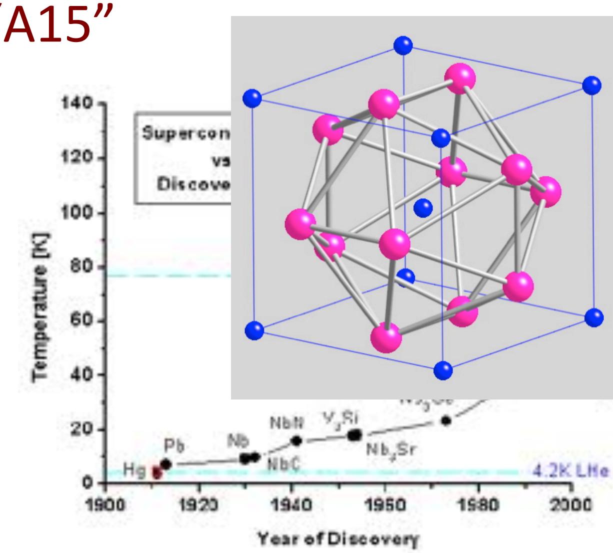
History – High Critical Current, Jc

Also in 1952, John Hulm & George Hardy discovered the first of the "A15" superconductors.

A_3B structure, with
A = transition metal



Bernd Matthias then discovered over 30 A15s with values of T_c ranging up to **23 K for Nb_3Ge**.

These were the first superconductors to show a *high critical current* in a *strong magnetic field*: **Crucial for applications**!

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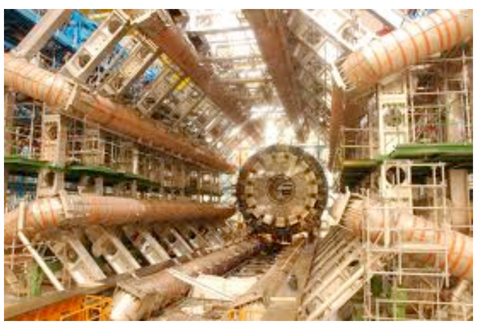
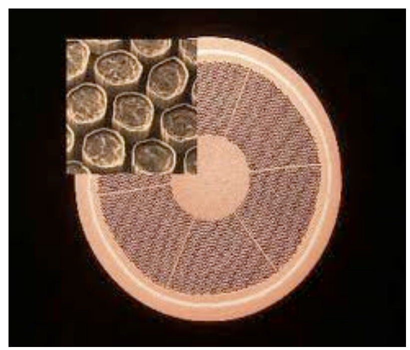
History – Practical Wires

1963 – Hulm (Westinghouse) made the first practical wires of **Nb:Ti** (mat'l discovered at Rutherford-Appleton Labs, UK)

- Random alloy with a high-T_c and high J_c
- Not as high as A15s – but malleable and reliable
- Industry standard for applications (unless NEED high J_c)





"High T_c gets Nobel prizes, High J_c saves lives"
-- John Rowell

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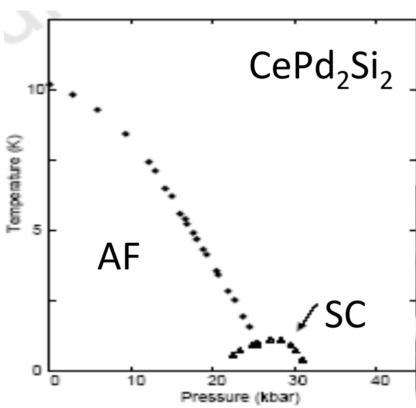
History – Tunable and Novel

1979: Frank Steglich: superconductivity in **heavy fermion materials** *that have*

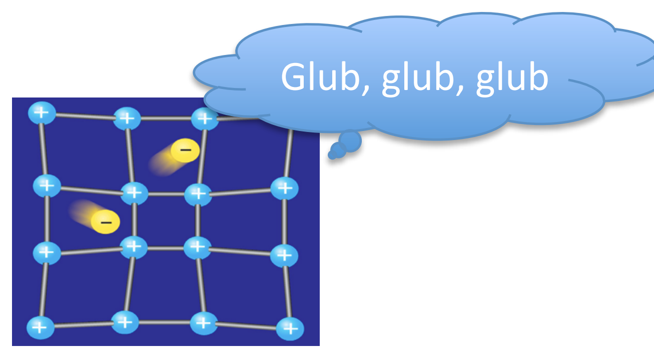
- *A magnetic ground state*
- *Electron masses: up to 1000 x m_e*

Led to discovery of the "domed" phase diagram



David Pines

1[st] "unconventional" SC:
Magnetism ***good*** for SC
(BCS el-ph mech. breaking down)

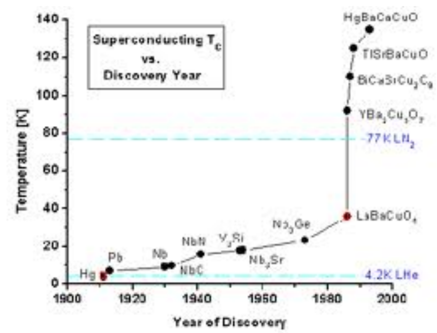


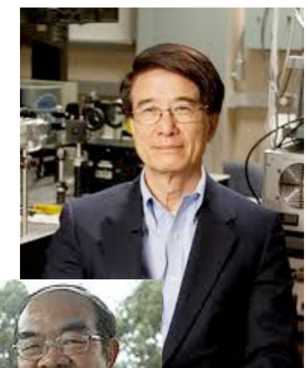
History – Oxides to Cuprates

1964: Marvin Cohen ***predicts*** **$SrTiO_3$**

1983: Mattheiss and Hamann ***predict*** **$BaK_xBi_{1-x}O$**

1986: Bednorz and Muller: **$La_{1-x}Ba_xCuO_4$**





1987: Wu … Chu:

$YBa_2Cu_3O_7$; Tc = 90 K

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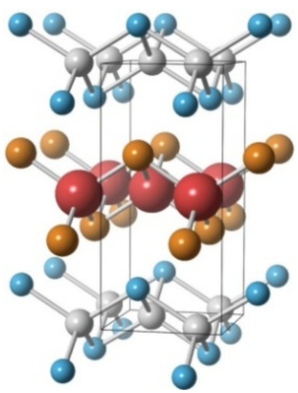
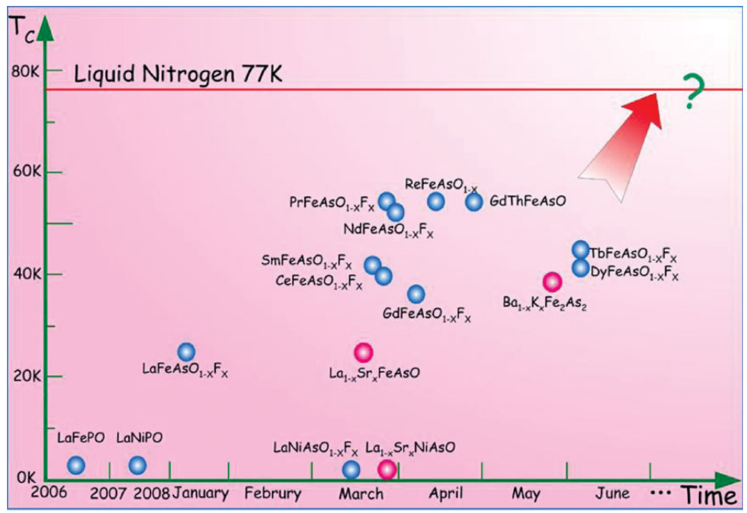
History – From the Copper to the Iron Age of HTS (2008)

Hosono (Japan): **$LaFeAsO_{1-x}F_x$** $T_c = 26$ K

Zhao (China): $T_c = 58$ K



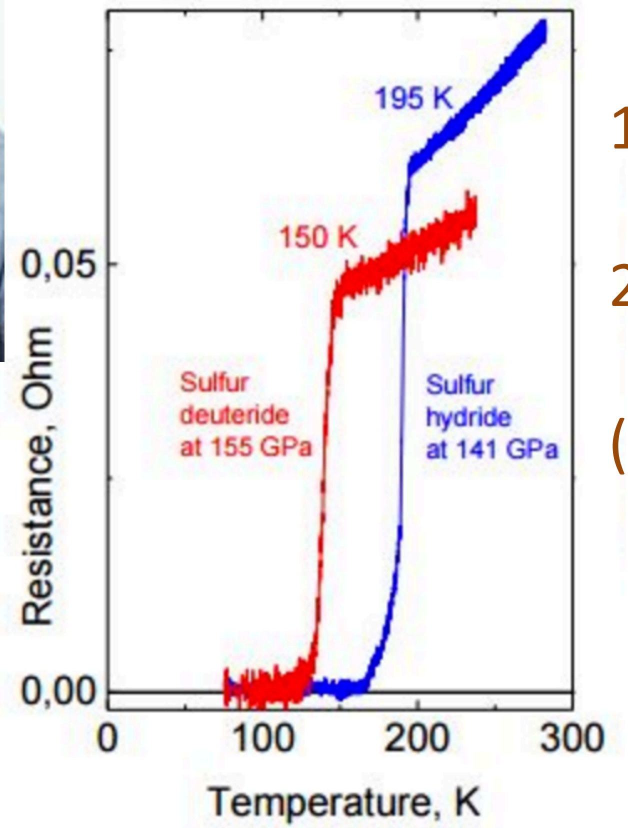


A second class of high-temperature superconductors had finally been found: ***Is there a third?***

History – Hydrogen Sulfide at 203 K

2015: Mikhail Eremets

Looks like a conv. SC at ~ 150 GPa

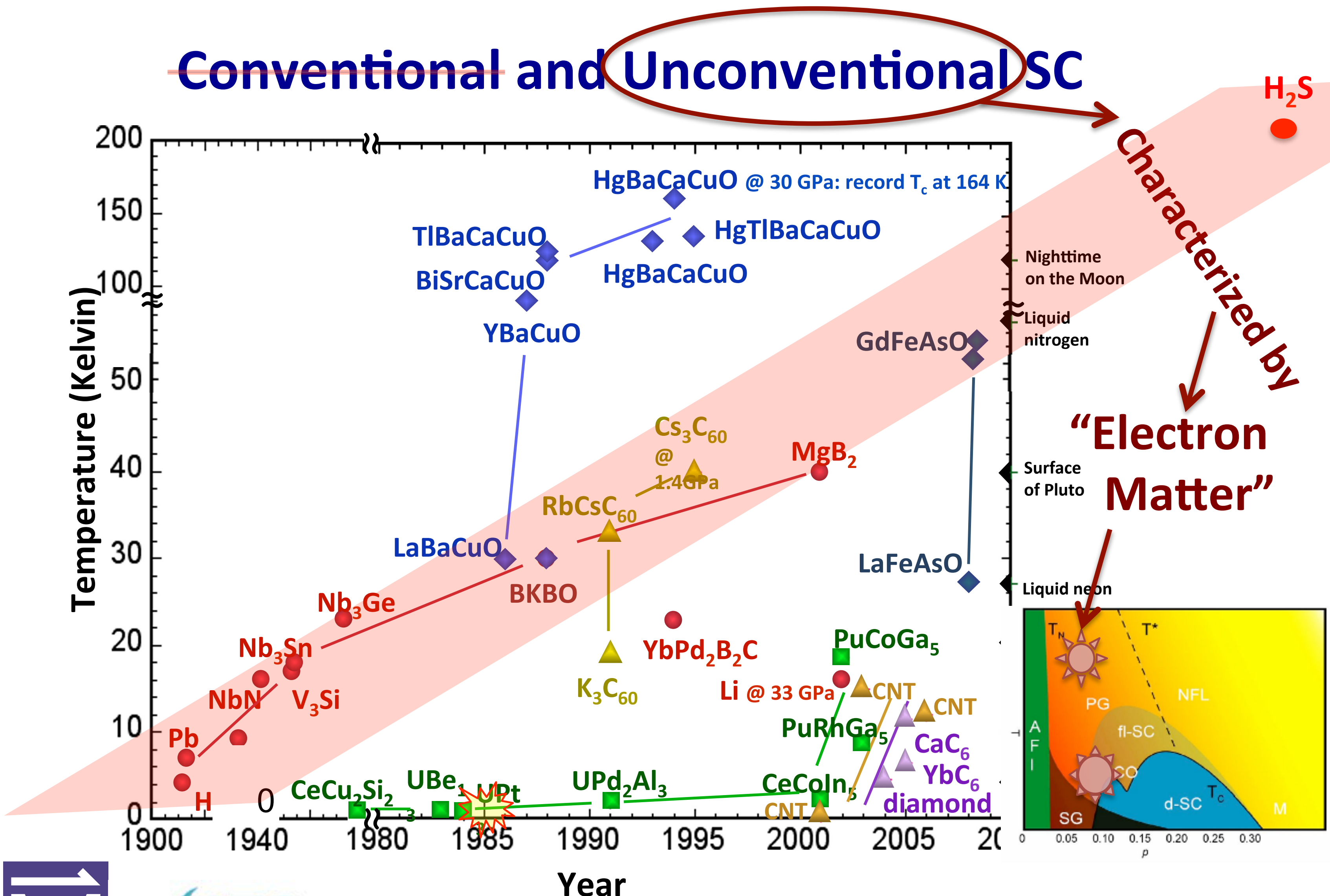


1. Doesn't look too practical
2. Conventional: BCS el-phonon

(No electron matter)

Just too cool not to mention here!

~~Conventional~~ and Unconventional SC



Recap: What is Electron Matter?

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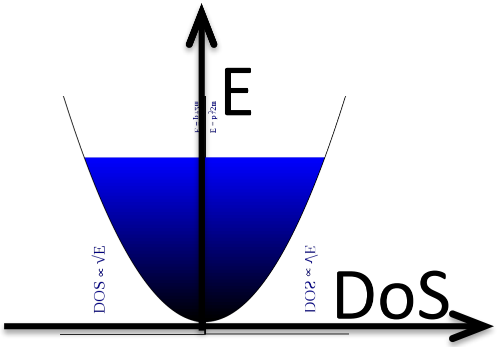
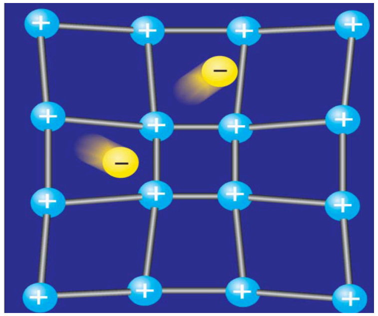
Conventional Superconductors

Tc ≤ 40 K (except H_2S; Tc ~ 202 K)

Above Tc: Simple metal (*Fermi Liquid*)



Below Tc: Cooper pairs: (*Electron-Phonon Mediated BCS; BdG eqns.*)



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Conventional Superconductors

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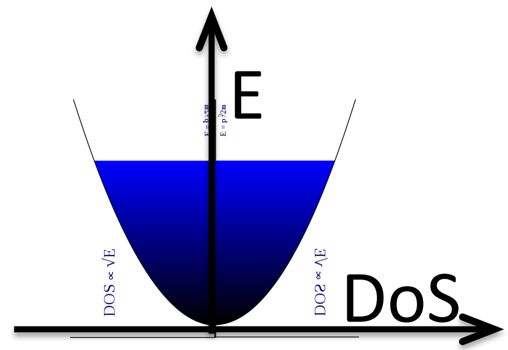
SOLVED !!!



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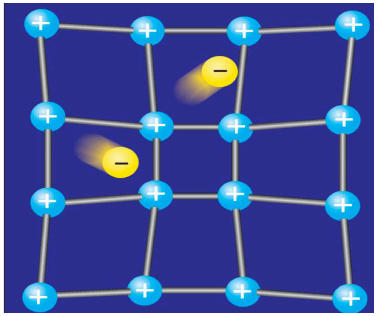

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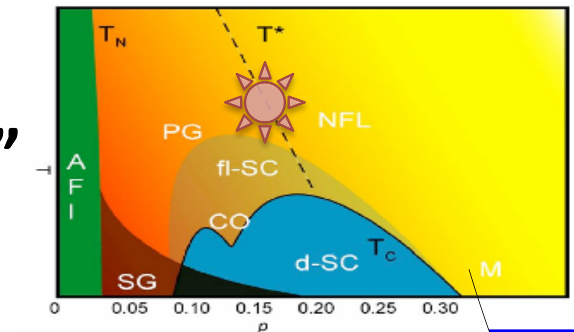
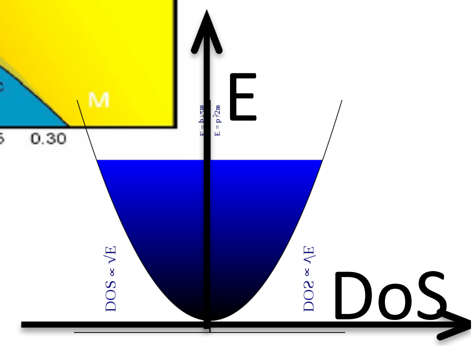
Unconventional Superconductors

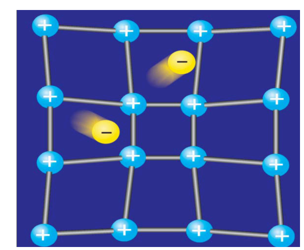
Tc ≤ 165 K
Ubiquitous "Domed" phase diagram



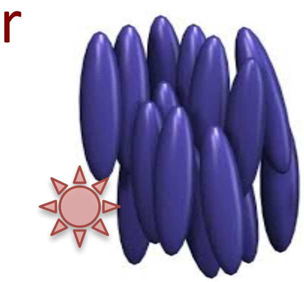


Above Tc: FAR RIGHT side of phase diag: Simple metal (*Fermi Liquid*)

Below Tc: Cooper pairs: (*Electron-Phonon Mediated BCS; BdG eqns.*)



Above Tc: Rest of phase diag: Electron Matter (*Non-Fermi Liquid; correlated*)



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Unconventional Superconductors

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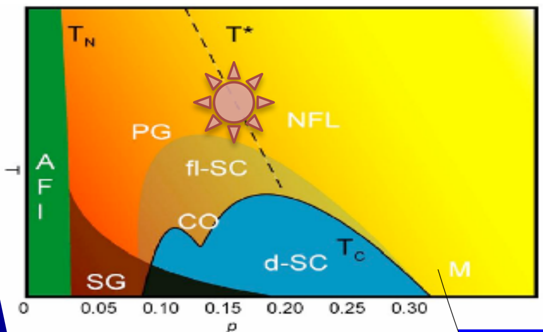

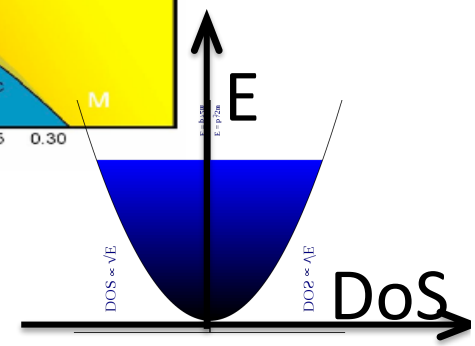

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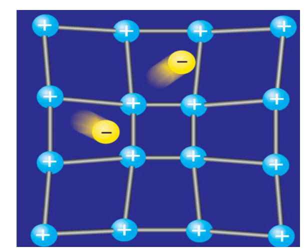
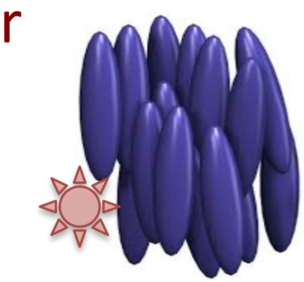


Below Tc: Cooper pairs: (*Electron-Phonon Mediated BCS; BdG eqns.*)

SOLVED !!!

Above Tc: Rest of phase diag: Electron Matter (*Non-Fermi Liquid; correlated*)

UNSOLVED !!!



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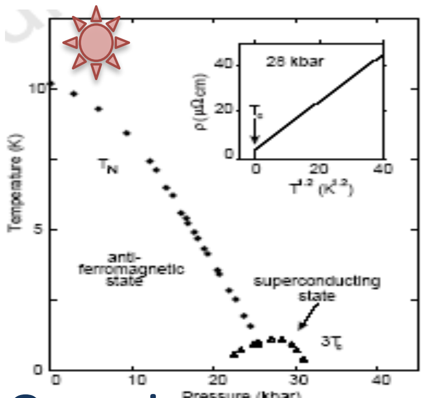
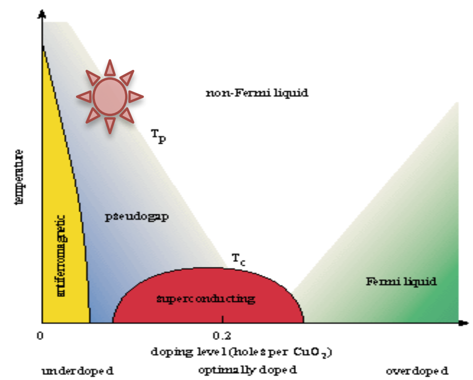
Ubiquitous Phase diagram: T vs. pressure, doping (more than 50 families)

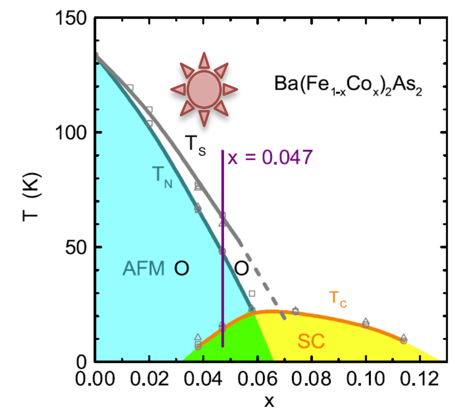
Heavy Fermions



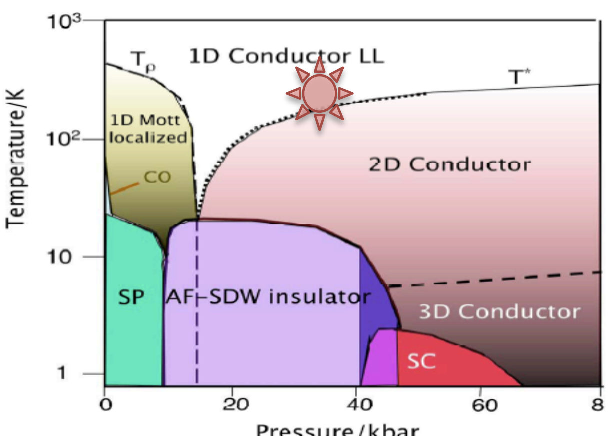
Cuprates



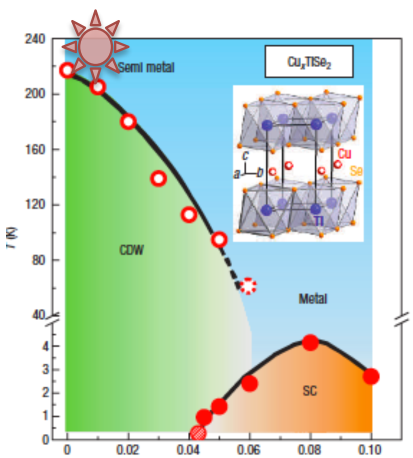
Fe-Based

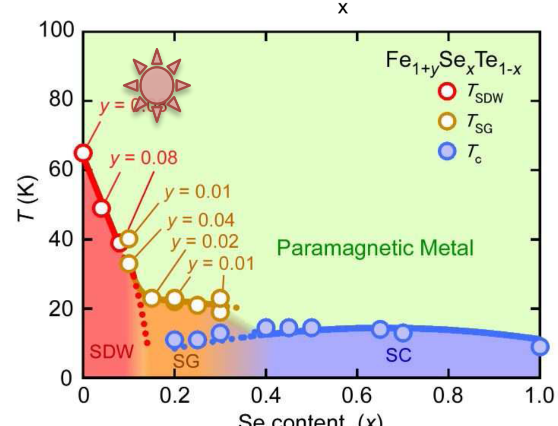


Organics



Di-chalcogenides

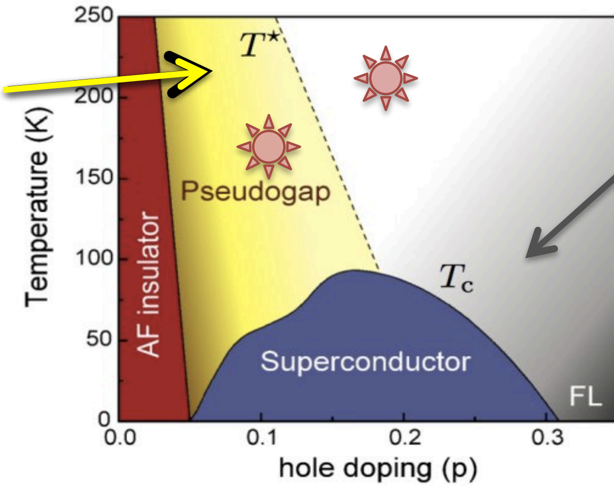




Electron Matter

Intriguing Point About HTS Dome

Electron Matter (highly correlated)



Fermi Liquid (weakly correlated)

1. All Practical High-Tc SCs are Unconventional
2. All Unconventional SCs have Electron Matter
3. Electron Matter Suppresses Tc
4. But you don't get HTS without it

Must be some kind of delicate balance!

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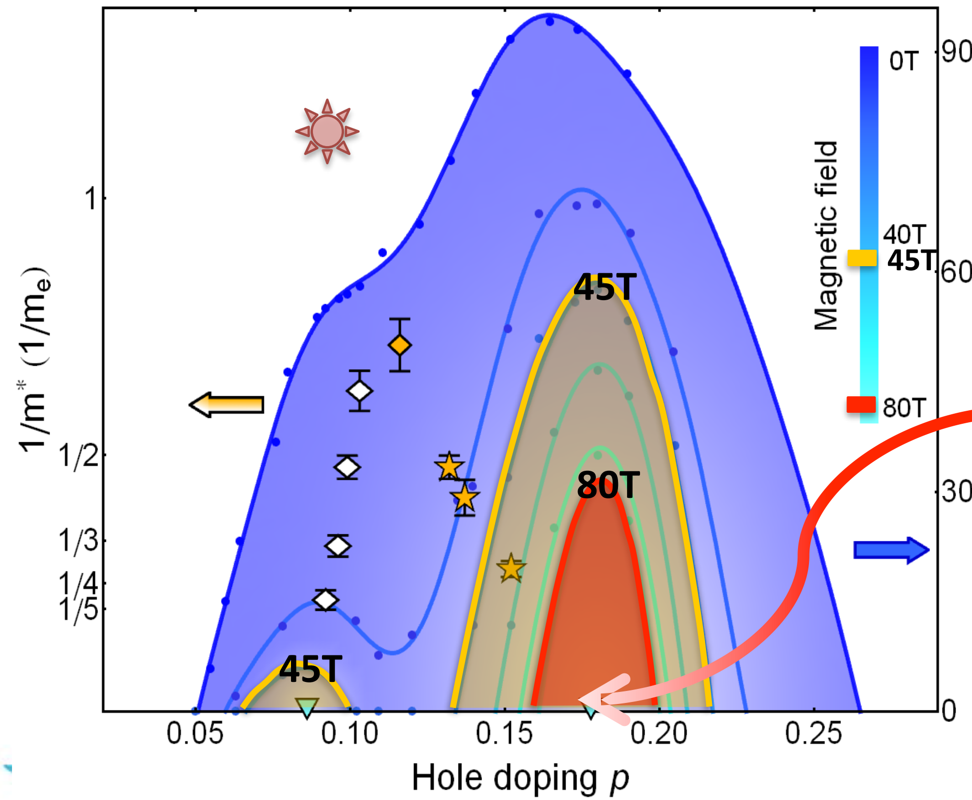
So I study electron matter...

Electron Matter Exists UNDER THE DOME

MagLab fields (45T) suppress the SC to see this.
Higher B needed to find nature of N-state under dome*

S.E. Sebastian *et al.*, PNAS (2010);
B.J. Ramshaw, *et al.*, Science (2015)

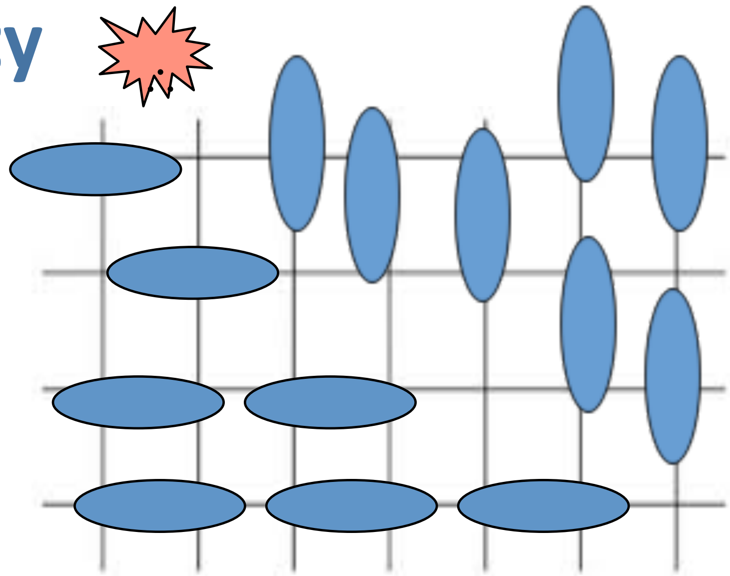


*You **need** the HTS cuprates

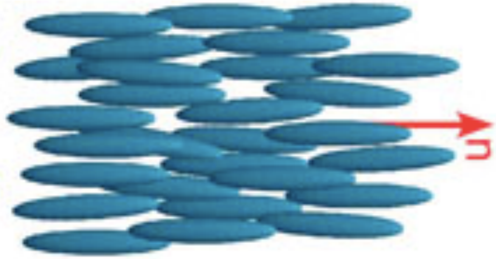
Why does HTS emerge out of these competing phases?

Some Examples of Electron Matter

- **Electronic Nematicity**
- Stripes and other "charge clumping"
- Pseudogap
- Heavy electrons
- Quantum criticality
- And more…



Electron sausage clouds in a square lattice



Nematic liquid crystal

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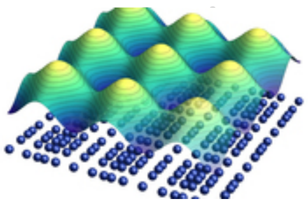
Some Examples of Electron Matter

- Electronic Nematicity



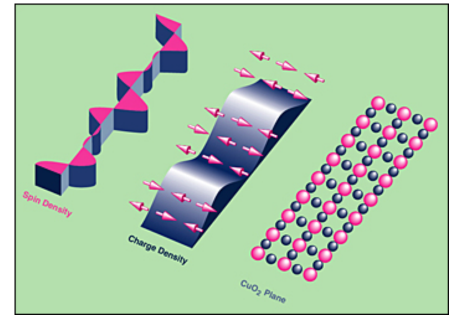
and other
...rge clumping'

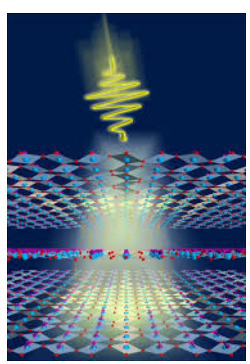
...ap

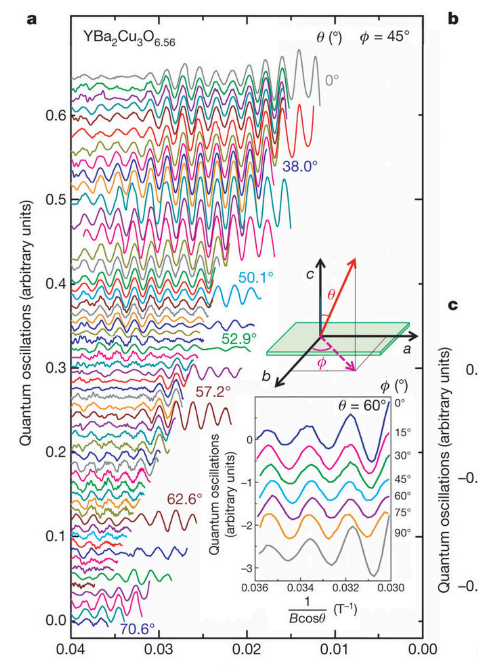
- Heavy electrons
- Quantum criticality
- And more...

MANY new techniques have been developed to elucidate electron matter, including:

STM
ARPES
RIXS
Quantum Oscillations
Ultra-sensitive transport, thermo, and optical meas.
Terahertz
DNP
ICR
....







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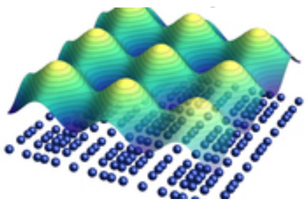
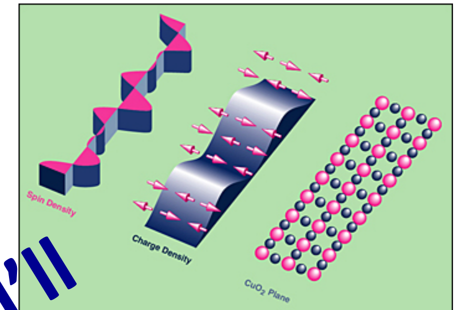
Some Examples of Electron Matter

- Electronic Nematicity



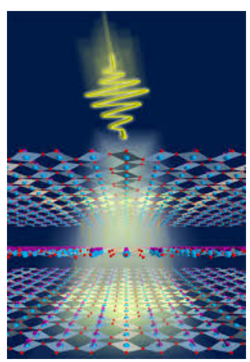
- ... and other "...rge clumping"
- ...ogap
- Heavy electrons
- Quantum criticality
- And more...

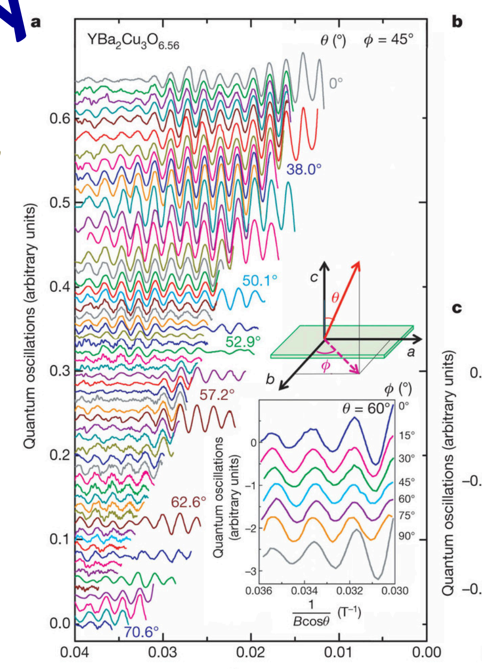


STM
ARPES
RIXS
Quantum Oscillations
Ultra-sensitive transport, thermo, and optical meas.
Terahertz
DNP
ICR
....

MANY new techniques have been developed to elucidate electron matter, including:

Wish I could discuss them all, but now I'll outline one of my techniques...





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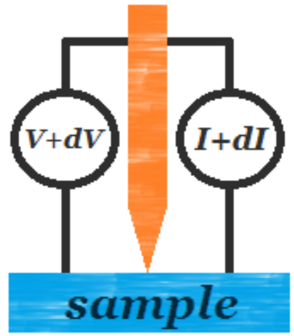
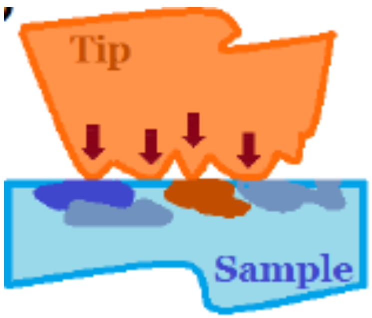
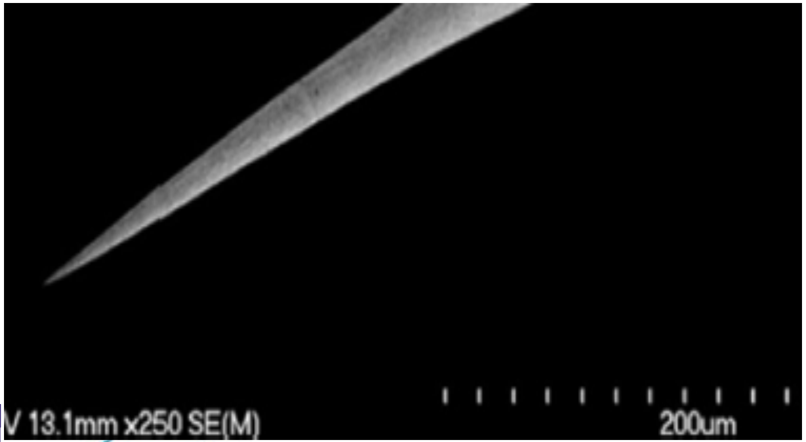
Point Contact Spectroscopy

Metallic contact: Junction size < el mean free path



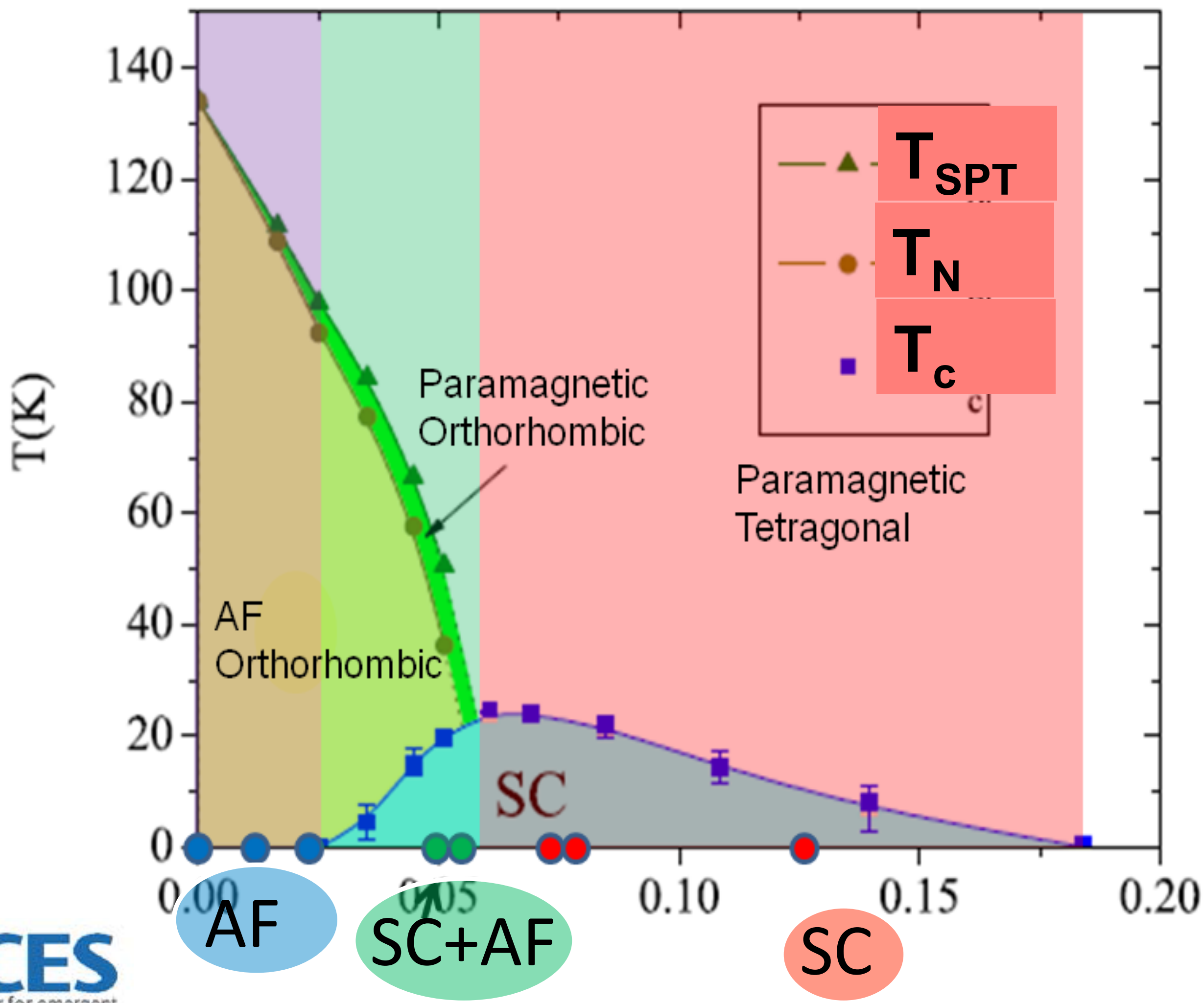
Needle-anvil PCS



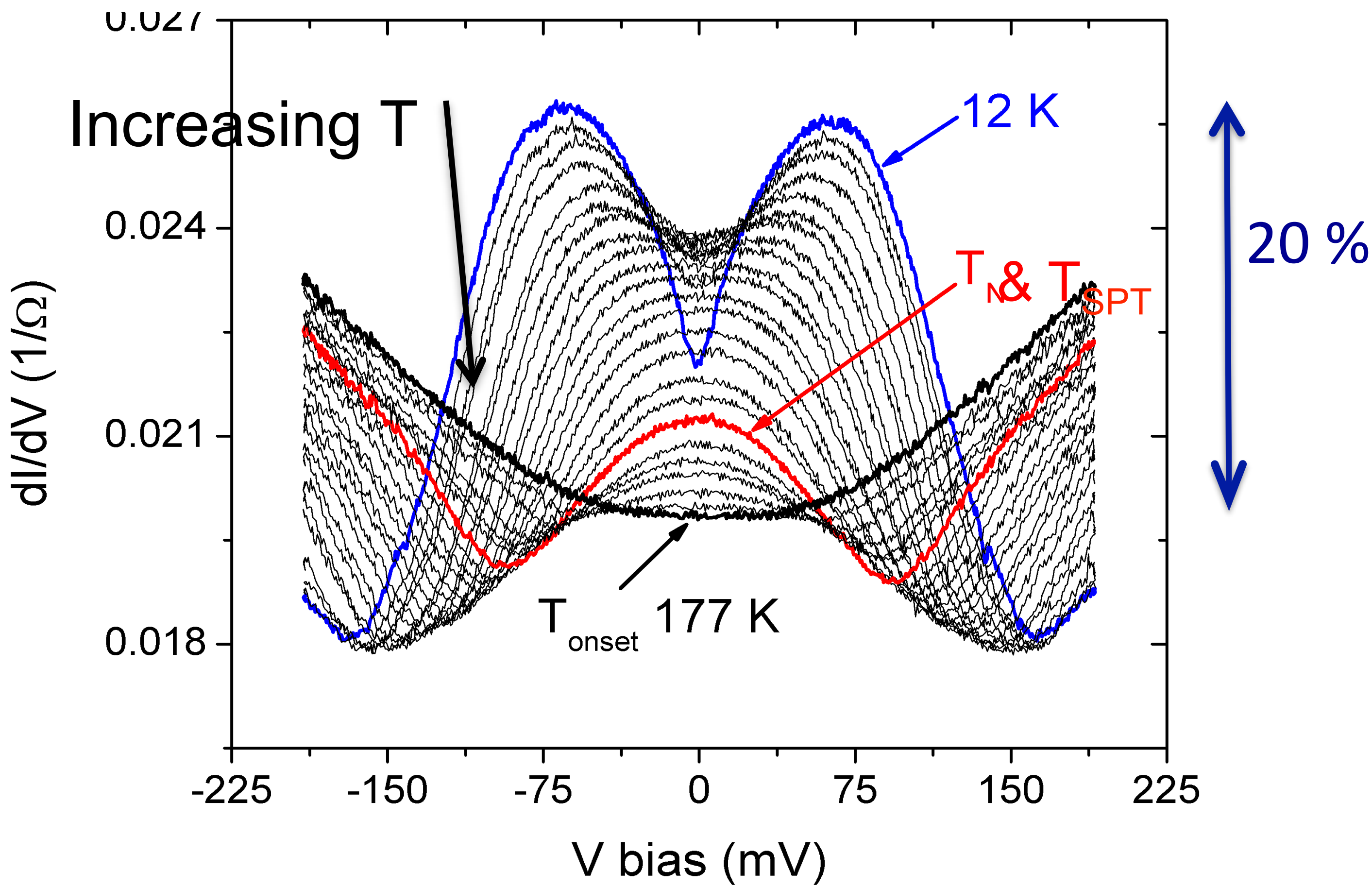


WK Park *et al,*. RSI '06
Narasiwodeyar *et al,*. RSI '15
Tortello *et al.,* RSI '16

The Iron Based HTS: $Ba(Fe_{1-x}Co_x)_2As_2$

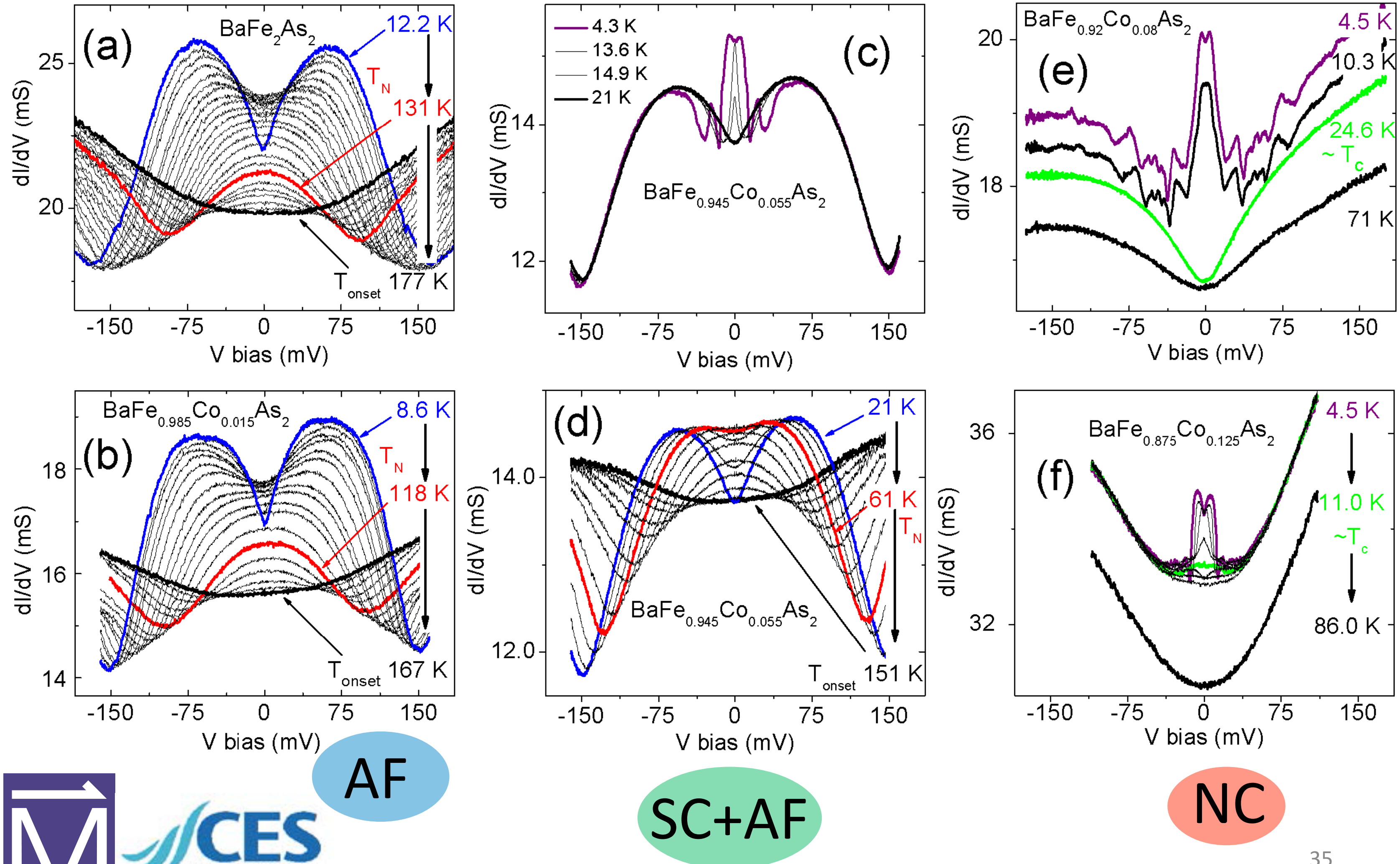


PCS on Parent Compound: $BaFe_2As_2$

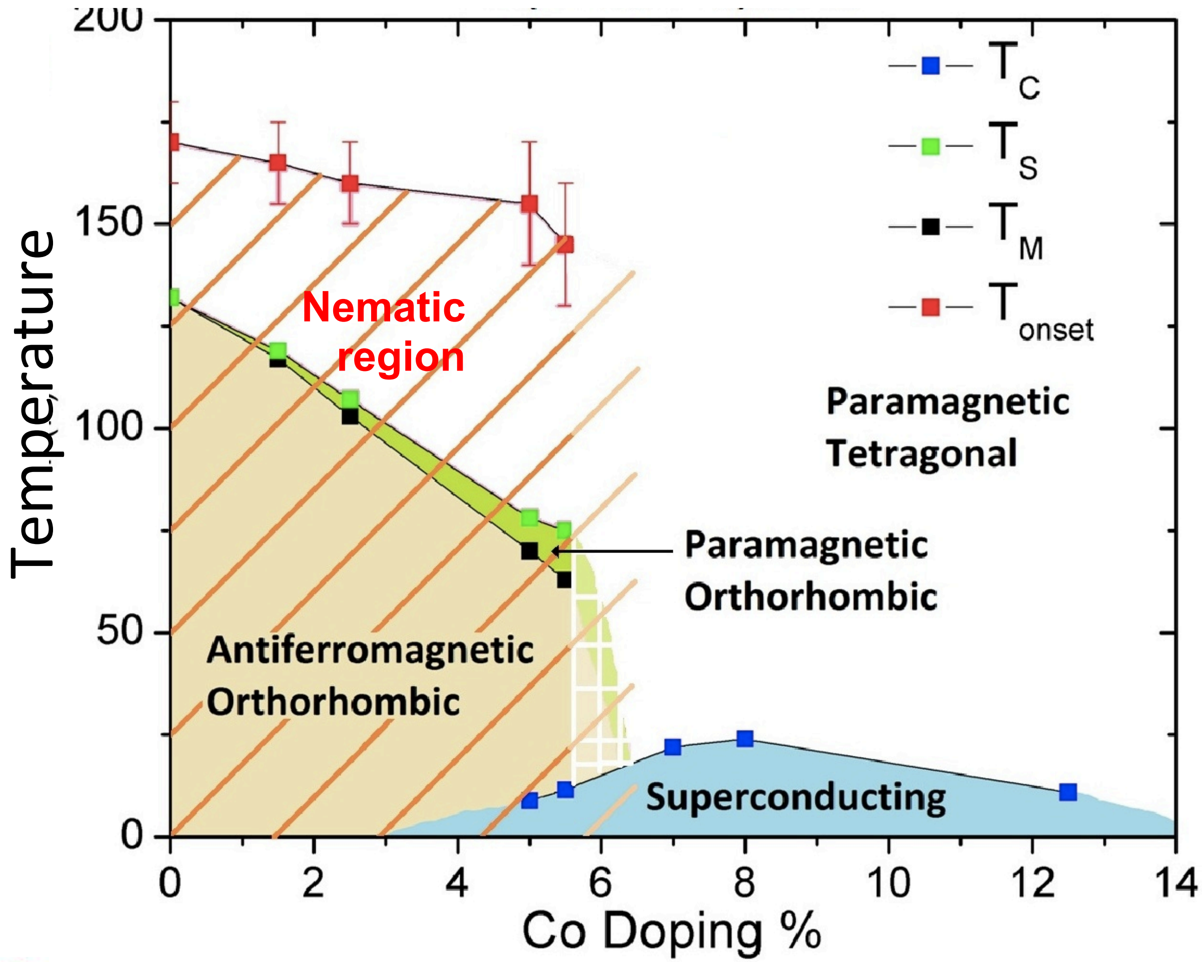


Raw Data

Summary of PCS on $Ba(Fe_{1-x}Co_x)_2As_2$



Nematic region in $Ba(Fe_{1-x}Co_x)_2As_2$ Phase Diagram

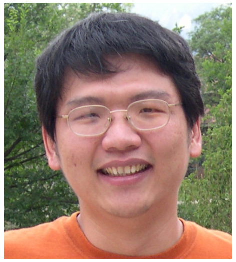


Arham *et al.*, PRB '12

Theory of Point Contact Spectroscopy in Correlated Materials

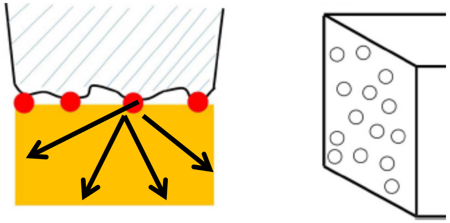
PNAS (2015)

Wei-Cheng Lee *, Wan Kyu Park * , Hamood Z. Arham * , Laura H. Greene * , and Philip W. Phillips



Wei-Cheng Lee

Shows how PCS specifically filters for Electron Matter!



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Notes on Predictive Design of SCs

Matthias' rules for conventional SC.

1. Transition metals are better than simple metals
2. Peaks of density of states at Fermi level good
3. High symmetry is good: Cubic best
4. Stay away from Oxygen, magnetism, and insulating phases (and theorists!)

Our rules for unconventional SCs

1. Reduced Dimensionality
2. Transition metal & other large U ions
3. Light atoms
4. Charged and multivalent ions
5. Low dielectric constant
6. SC borders antiferromagnetism

Only give materials properties that correlate with increased Tc within a class, but **do *not* help to design new superconductors**; and ***fail to predict new classes***

PCS finds electron matter!

No one can predictively design Superconductors: (*we are trying…*)

physicsworld.com

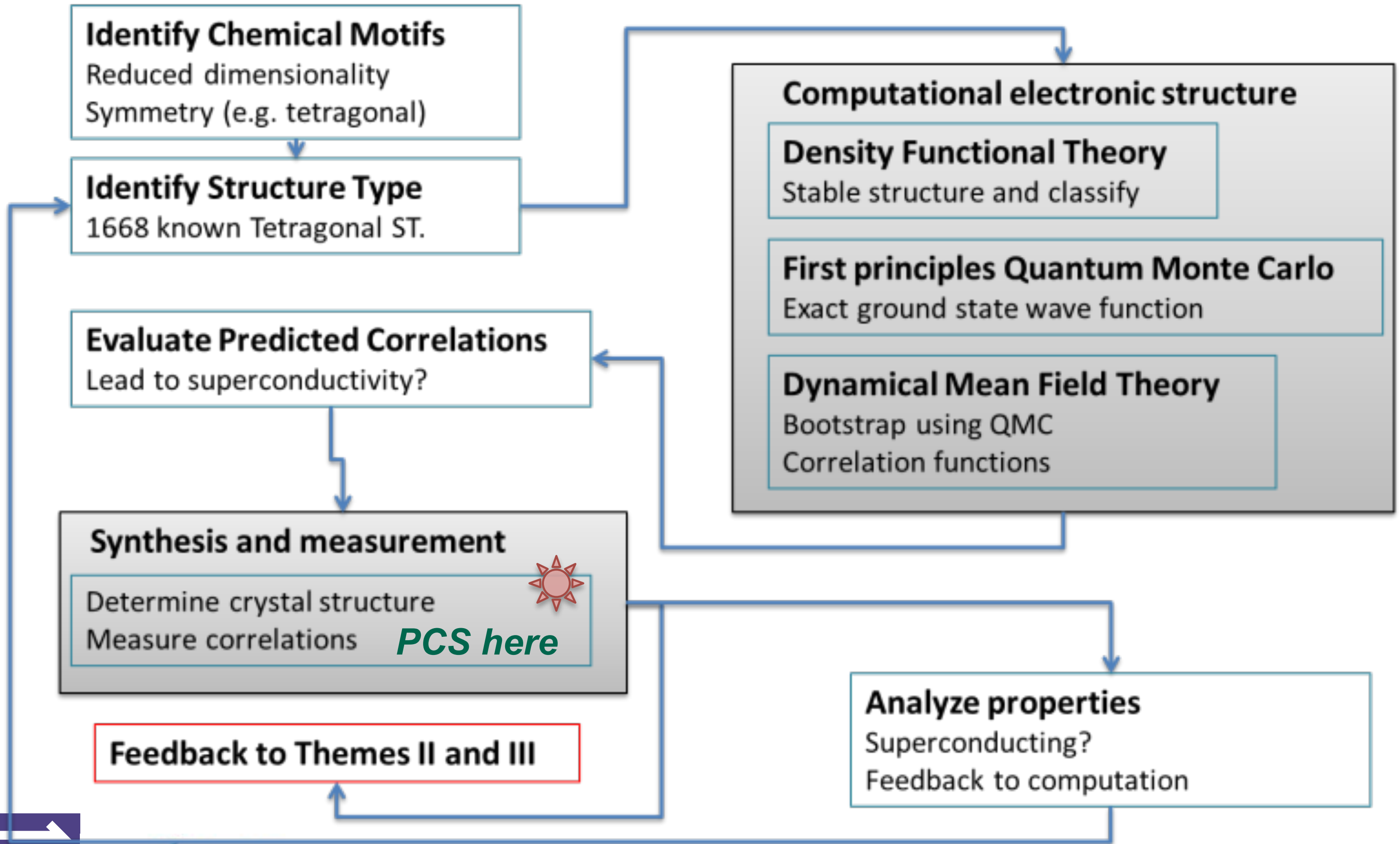
Superconductivity: Another class

Taming serendipity

The discovery of high-temperature iron-based superconductors in 2008 thrilled researchers because it indicated that there could be another – more useful – class of superconductors just waiting to be found. **Laura H Greene** shares that enthusiasm and calls for global collaboration to reveal these new materials

iStockphoto.com

Our Center for Emergent Superconductivity Plans for New Superconductor Design (MGI):



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Conclusions - Future Directions

- Lessons Learned: Great strides in SC accomplished w/o needing microscopic mechanisms
- We still continue to search for fundamentals as the questions themselves are inspiring and beautiful , and it is becoming clear that deciphering the electron matter will help us work out the mechanisms of HTS and lead to predictive design new superconductors.
- New experimental and theoretical techniques offer innovative probes – and great strides have been made!

Are these techniques condensed matter's LIGO for gravity waves?

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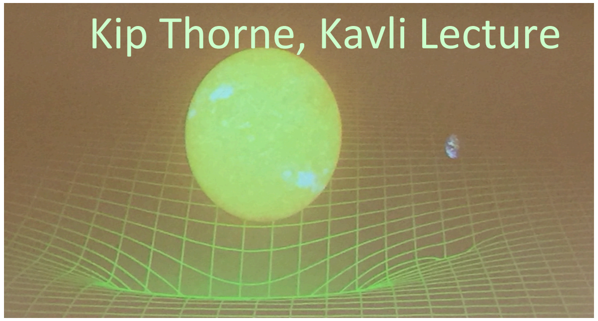
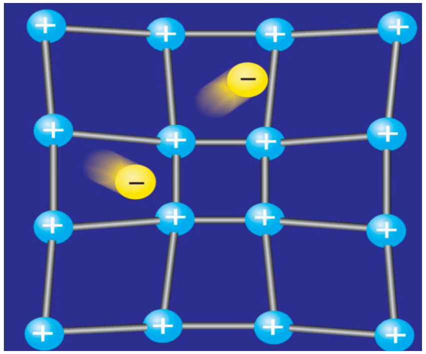
Conclusions - Future Directions

- Applications will keep on making progress
- The fundamental questions drive and progress our understanding of these fascinating, materials.
- I see us all working together in the near future

And having fun!





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