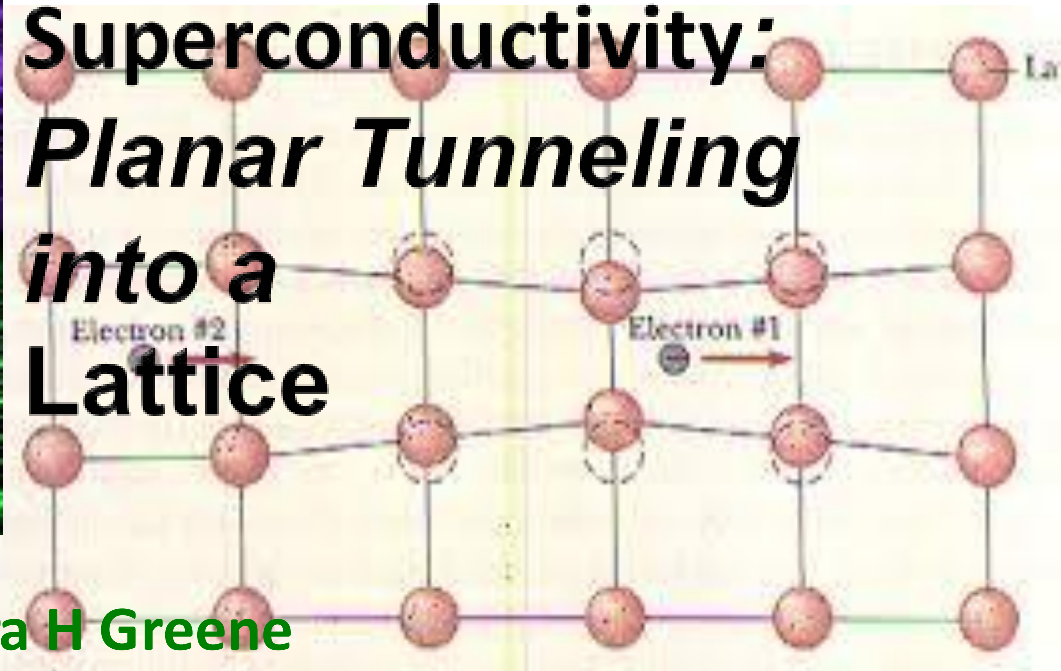
Unconventional Superconductivity:
Overview and Planar Tunneling
Planar Tunneling into a
Kondo Lattice



Laura H Greene

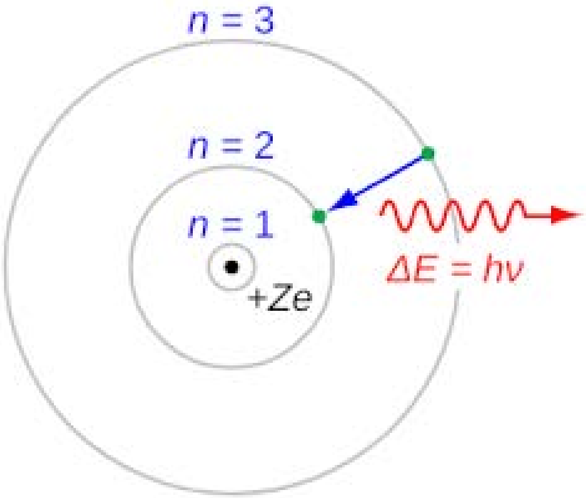
- *National MagLab (FSU-UF-LANL) & Florida State University*
- *IUPAP Vice President for Ethics and Outreach*
- *President’s Council of Advisors on Science & Technology (PCAST)*

lhgreene@magnet.fsu.edu

School on Correlated Electrons Julich 16 Sep 2024

Outline

- PCAST: President’s Council of Advisors for Science and technology
- The National **MagLab** (NHMFL)
- Overview of ***Unconventional*** Superconductivity
- Dark Energy of Quantum Materials: A Fun Analogy
- Planar Tunneling Spectroscopy
- Harrison’s theorem: Planar tunneling detects NFLs
- f-level paring in a heavy fermion superconductor
- Conclusion: I’m around all week – let’s chat!



PCAST: Appointed by Joe Biden, 2022

They only pay us in pictures and bragging rights

State Dining room, WH West Wing

When I presented to POTUS on AI for Materials Discovery

WH East Wing: Signing of the EO on AI

Recently in the West Wing

March 24, 2022

Yes, I have met Kamala!

PCAST Consensus REPORTS (19 in total)

https://www.whitehouse.gov/pcast/documents-reports/

In Progress:

- **Social and Behavioral Sciences**
- **Groundwater**
- Nutrition
- Vibrancy of Basic Research
- Federal STEM Workforce

Published in 2024

- Report on Recommendations for Supercharging Research: **Harnessing Artificial Intelligence to Meet Global Challenges. Co-Chair with Terrence Tao**.
- Joint Statement to Leaders from PCAST and the United Kingdom’s Prime Minister’s Council for Science and Technology
- Report on Recommendations for Strategy for Cyber-Physical Resilience
- Report on Recommendations for Accelerating Effective Reduction of Greenhouse Gas Emissions

PCAST REPORTS

Published in 2023

- Report on Recommendations for A Transformational Effort on Patient Safety
- Letter on Recommendations for Advancing Public Engagement with the Sciences
- Report on Recommendations for the National Nanotechnology Initiative
- Report on Recommendations for Supporting the U.S. Public Health Workforce
- Report on Recommendations for Enhancing Prediction and Protecting Communities Against Extreme Weather Risk
- Report on Recommendations for Modernizing Wildland Firefighting

Published in 2024

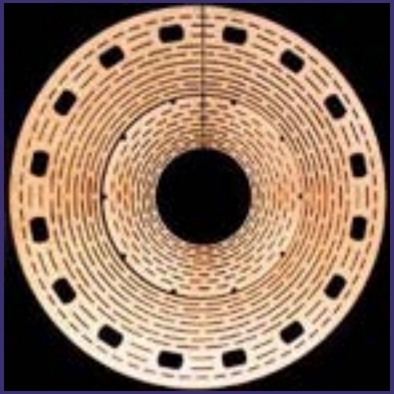
- Report on Recommendations for Strengthening U.S. Biomanufacturing
- Report on Recommendations for Semiconductors R&D
- Letter on Recommendations for Semiconductors R&D
- **Exploratory Group on Innovation, Competitiveness, and Hubs. Co-Chair (With Andrea Goldsmith) (Internal Report: unpublished)**

My course this semester:

Science Literacy: Mis vs Dis - Information

This survey course addresses aspects of scientific literacy including the importance of **scientific method** and defining traditional scientific misconduct in the US. We will discuss how to identify **pathological science, premeditated fraud**, and cases that fall between those extremes. These extremes **map onto what we more recently, and more generally, identify as misinformation and disinformation**. In enhancing science literacy, we will discuss how to read and write a scientific paper and tour scientific facilities such as the MagLab and the John D Fox Nuclear Laboratory at FSU. We will also discuss how responsible use of AI can enhance our science literacy and supercharge scientific research.

Mission (1990-present)



- Operate a world-leading high-magnetic-field user program
- Carry out in-house research in support of the user program
- Maintain facility and develop new magnets/instrumentation
- Conduct education and outreach activities

21.1 T / 105 mm NMR

21 T / 123 mm ICR

45 T hybrid magnet

101 T pulsed fields

11 T / 400 mm MRI

<1 mK High B/T

National High Magnetic Field Laboratory

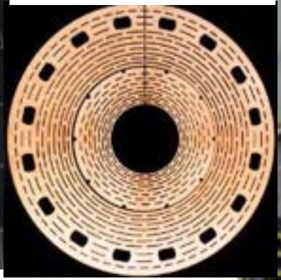
1.4 GW Generator

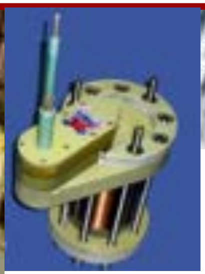
Florida State University

Los Alamos National Laboratory

University of Florida

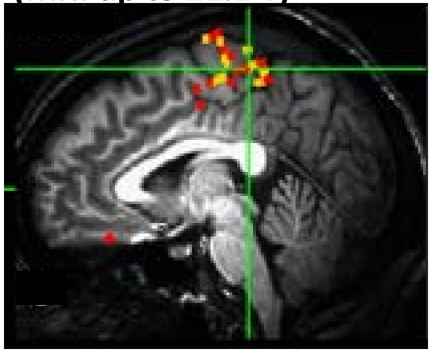
45T Hybrid
DC Magnet





101T Pulse Magnet
10mm bore

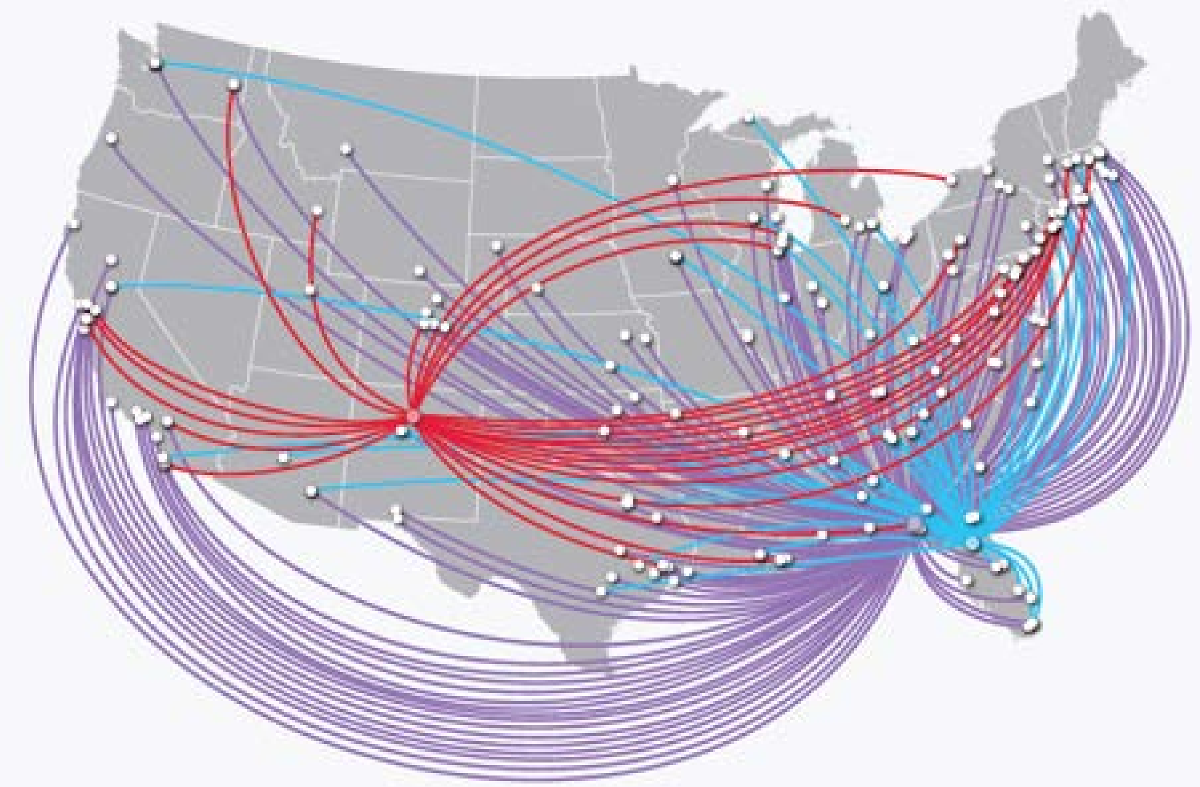
Advanced Magnetic
Resonance Imaging
and Spectroscopy Facility
(MRI up to 21.1 T)



High B/T Facility
17T at 0.5mK

900MHz, 105mm bore
21T NMR/MRI Magnet

The MagLab attracts High Magnetic Field Research from Around The World



Yearly, we host:

~ 2000 users from

~ 200 institutions

across the United States…

…and ~300 institutions internationally.

Helped train 250 postdocs

550 graduate students

> 400 refereed publications.

Newcomers are welcome:

25% Principal Investigators are first-time MagLab users!

Unique Infrastructure and World-Record Magnets Enable the Scientific Productivity

Some Hits:

2017

36 T Series Connected Hybrid (1.5 GHz NMR and 1.0THz EMR)

2017

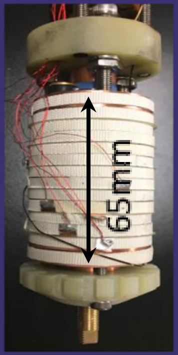
41.5 T / 34 MW resistive magnet

2017

32 T HTS / LTS ALL superconducting magnet

2018

45.5 T HTS test coil



2020

77 T duplex pulsed magnet (capacitor-bank-driven)

Three World-Record User Magnets Commissioned in One Year

Proof-of-Principle that HTS/LTS Magnets can go beyond 32T.

2021: *NSF funded 40T superconducting magnet design*

Complex decade-long basic research and design

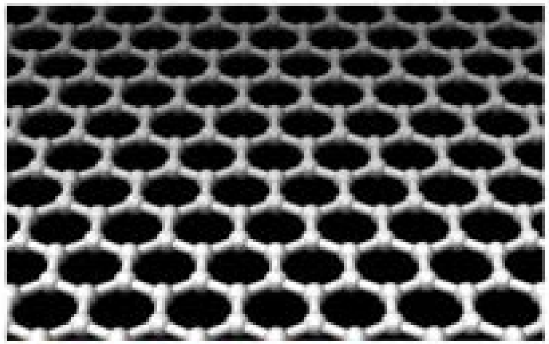
National MagLab magnet recognized with R&D 100 award

32 T all-superconducting magnet user facility

32 tesla superconducting magnet recognized with R&D 100 award

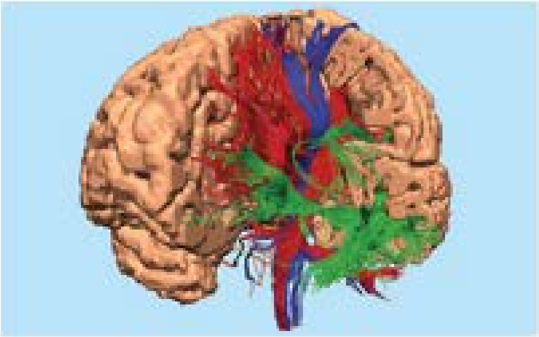
World's strongest superconducting magnet celebrated as a top 100 revolutionary technology.

Some Science Highlights

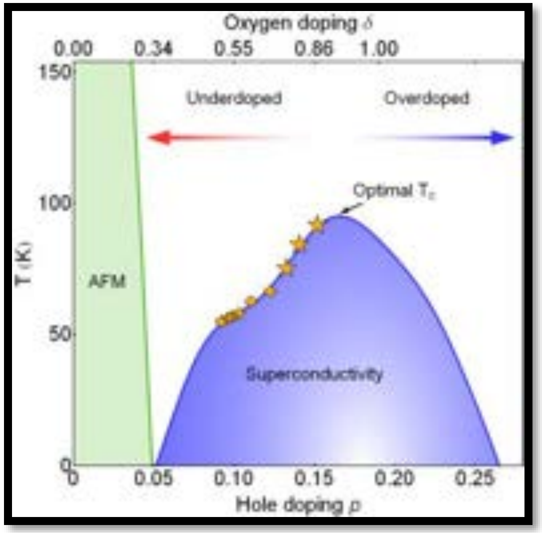


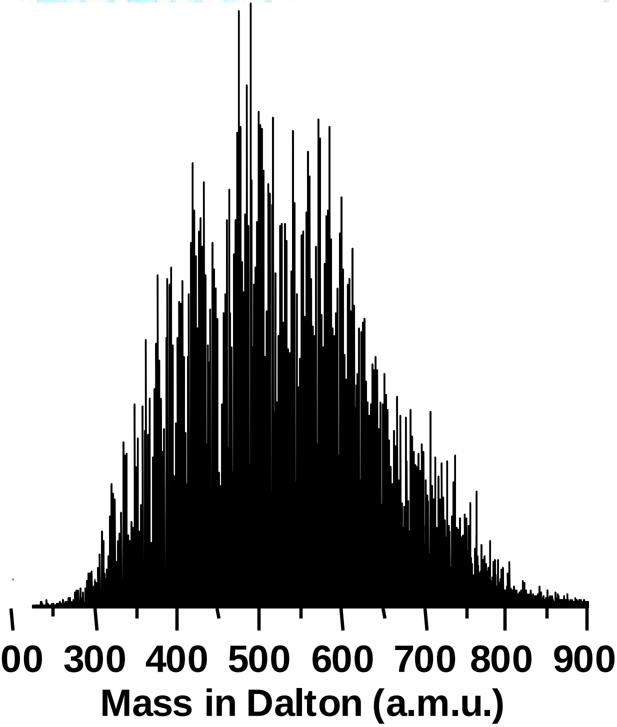
MATERIALS

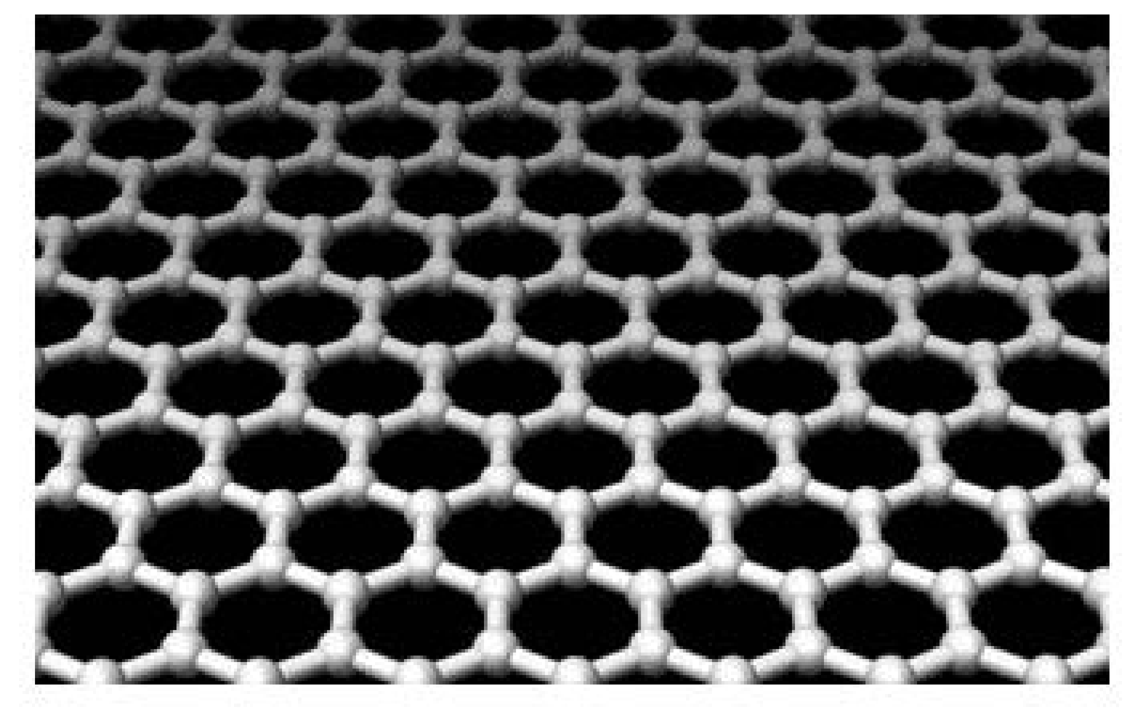
ENERGY



LIFE



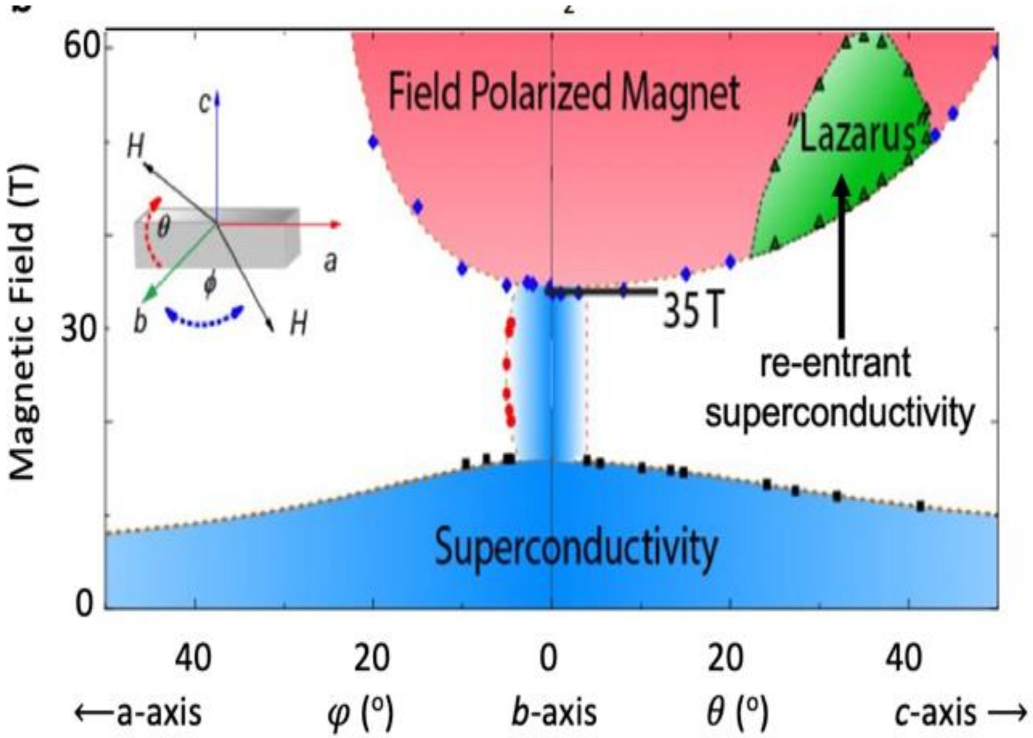




MATERIALS EXAMPLES

Materials Example: Complex Superconducting Phase Diagrams

Phase diagram of the heavy-fermion superconductor UTe_2 : Three superconducting phases: one ***Completely new and intriguing superconducting state***:



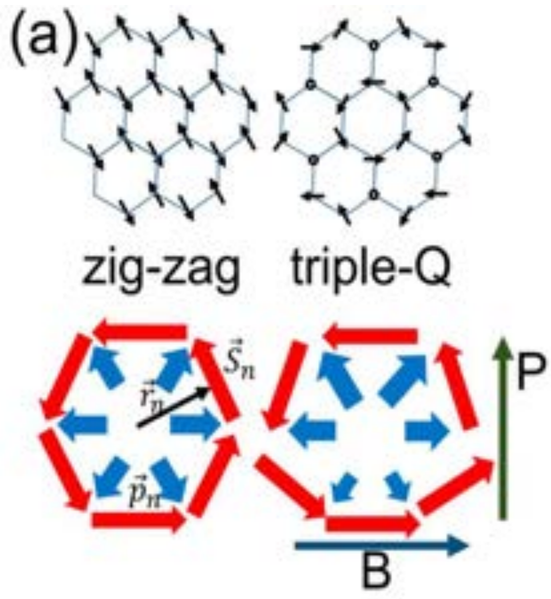
*The **re-entrant ("Lazarus") superconducting phase (green) appears in a polarized state, suggesting spin-triplet SC** desirable for topological quantum computing (Sheng et al 2019)*

DC** and **Pulsed User Facilities

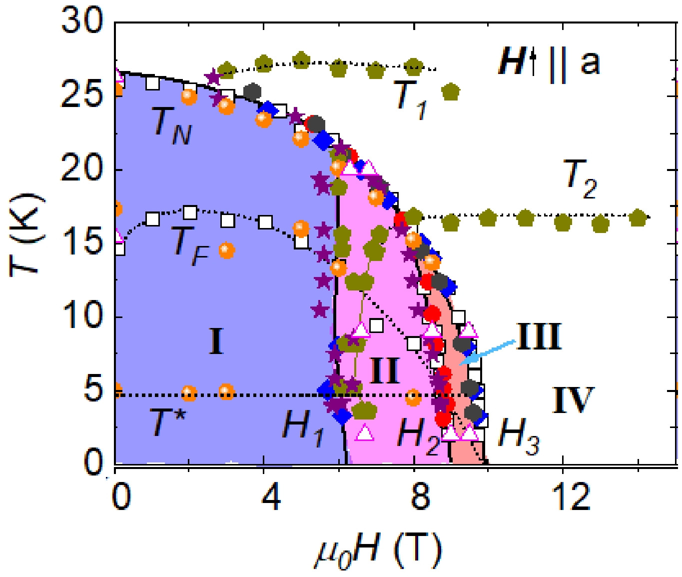
Materials Example: Possible Quantum Spin Liquid

Honeycomb lattice $Na_2Co_2TeO_6$ Coupling *via* cobalt spins

To look for evidence of the sought-after spin liquid state, investigate the magnetic excitations and elucidate the spin-structure of the $Na_2Co_2TeO_6$ a large suite of measurement techniques are needed.



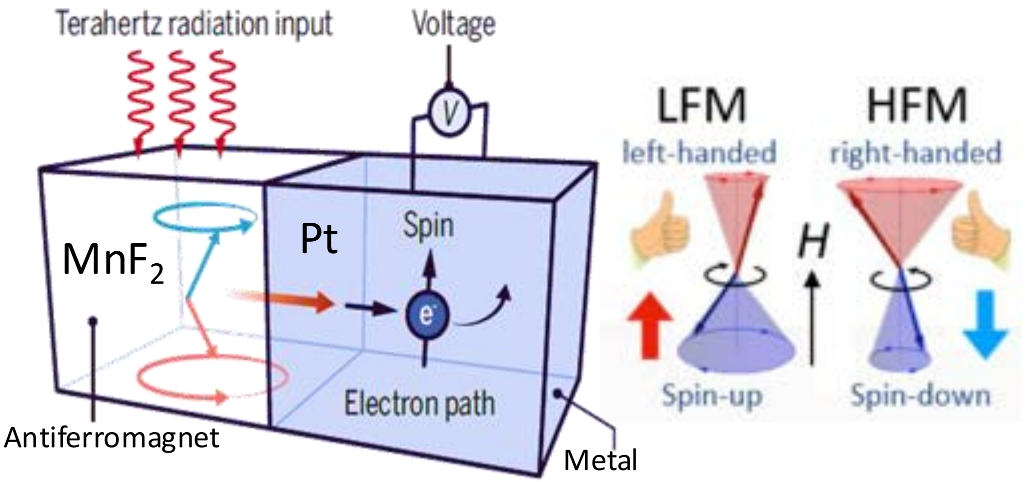
T- H phase diagram: Region III remains candidate for spin liquid behavior



Zhang, S.; Lee, S.; Woods, A.J.; Peria, W.K.; Thomas, S.M.; Movshovich, R.; Brosha, E.; Huang, Q.; Zhou, H.; Zapf, V.; Lee, M., *Electronic and magnetic phase diagrams of the Kitaev quantum spin liquid candidate* $Na_2Co_2TeO_6$, Phys Rev B **108**, 064421 (2023).

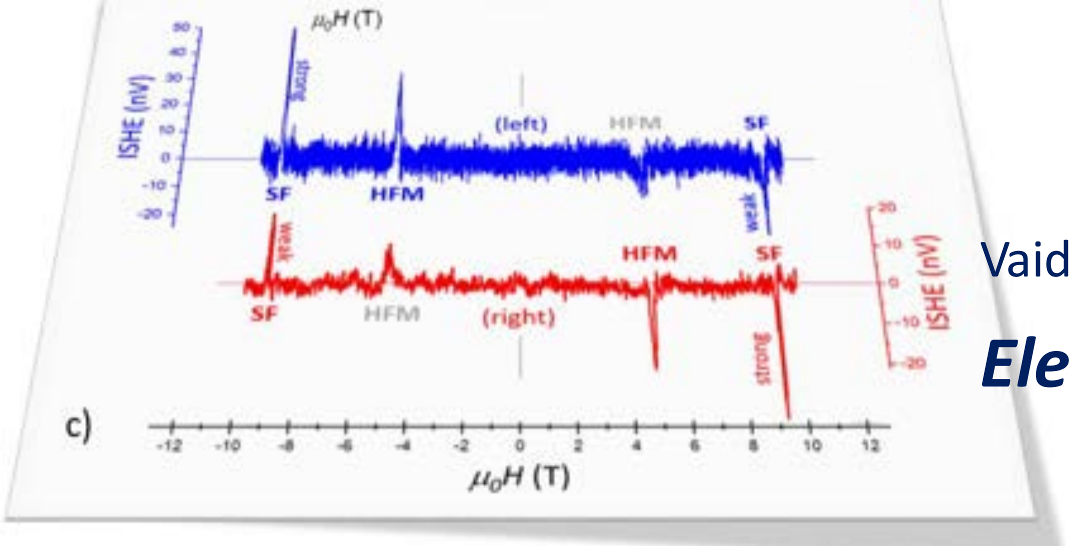
L. Xiang, R. Dhakal, M. Ozerov, Y. Jiang, B S. Mou, A. Ozarowski, Q. Huang, H. Zhou, J. Fang, S. M. Winter, Z. Jiang, and D. Smirnov, *Disordered-enriched magnetic excitations in a Heisenberg-Kitaev Quantum Magnet* $Na_2Co_2TeO_6$*, PRL* **131**, 076701 (2023).

Materials Example: THz Spin Pumping into Antiferromagnet: Spin-Charge Interconversion



- First observation of **THz radiation pumping spin-polarized current from an <u>antiferromagnet</u> into an adjacent non-magnetic metal.**
- Then **conversion into ultra-fast electrical signals, 2-3 orders of magnitude faster than ferromagnetic devices**.
- Important for development of **<u>high-efficiency spintronics devices</u>** operating at high speeds/frequencies.

Comparison of electrical signals for different circular polarizations



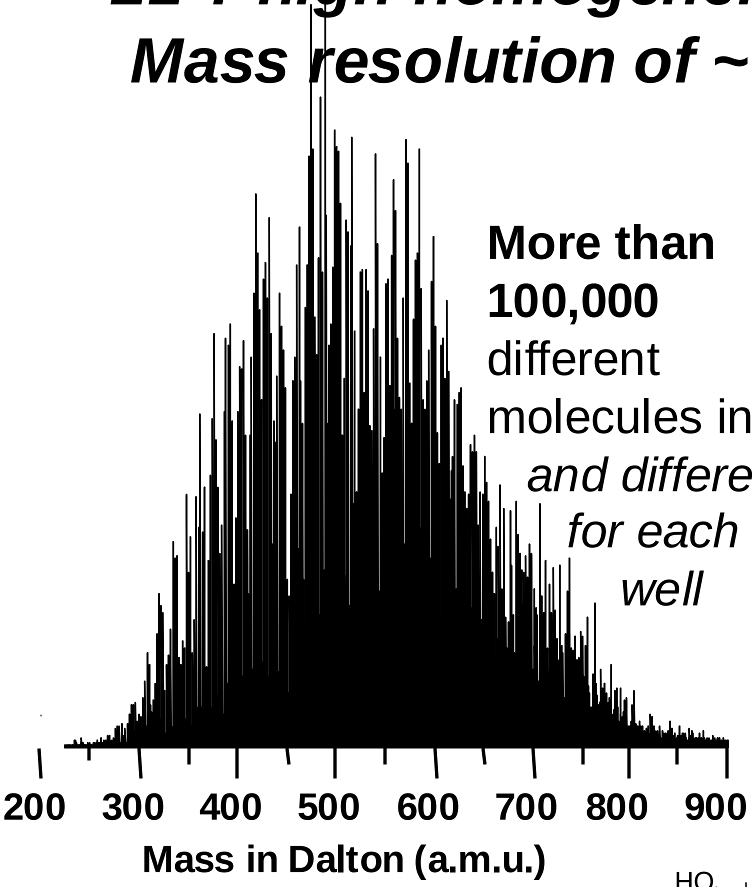
Vaidya *et al*., Science **368**, 160 (2020)

Electron Magnetic Resonance (EMF) User Facility

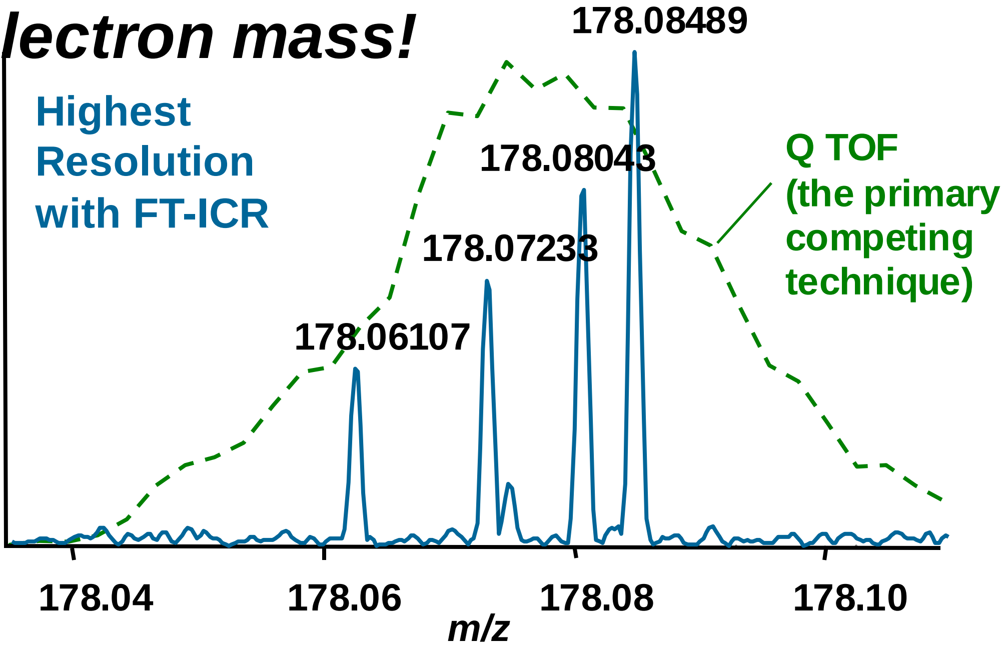
ENERGY EXAMPLES

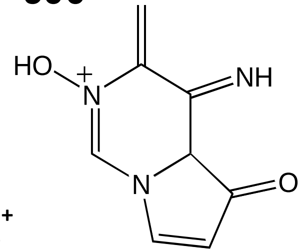
Energy: Ion Cyclotron Resonance (ICR) is Extremely High Resolution Mass Spectrometry

21 T high-homogeneity magnet gives a Mass resolution of ~ 1 electron mass!

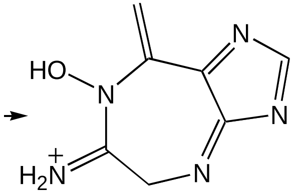


More than 100,000 different molecules in oil *and different for each oil well*



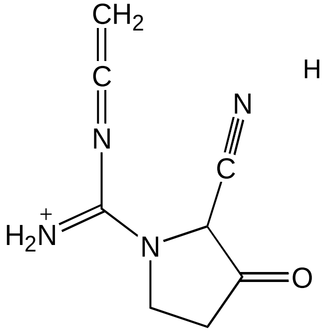


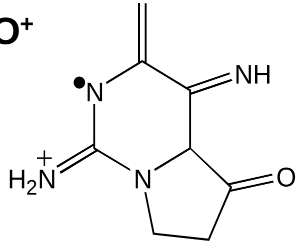
$C_8H_8N_3O_2^+$
***m/z* 178.06110**



$C7H8N5O^+$
***m/z* 178.07234**

$^{12}C7^{13}C1H9N4O^+$
***m/z* 178.08044**





$C_8H_{10}N_4O^{+\bullet}$
***m/z* 178.08491**

Energy : Ion Cyclotron Resonance (ICR)

21 T high-homogeneity wide-bore magnet,
1 part-per-ten billion mass resolution
Petroleum, metabolic, and organic compounds

Petroleomics:

- Did BP and Exxon strike the same well in the Gulf (drill cost ~ $1B/ea)
- Where did a spill originate? (Forensics)

Proteomics:

- Identify PROTEIN FOLDING through H-D exchange: Identified p53 registrations to classify malignant/non-malignant
- Protein makeups

Climate Change & Sustainability:

- Identify soluble vs insoluble carbon compounds; and other structures.
- Classifying carbon in the arctic permafrost
- Plastics & PFAS breakdown

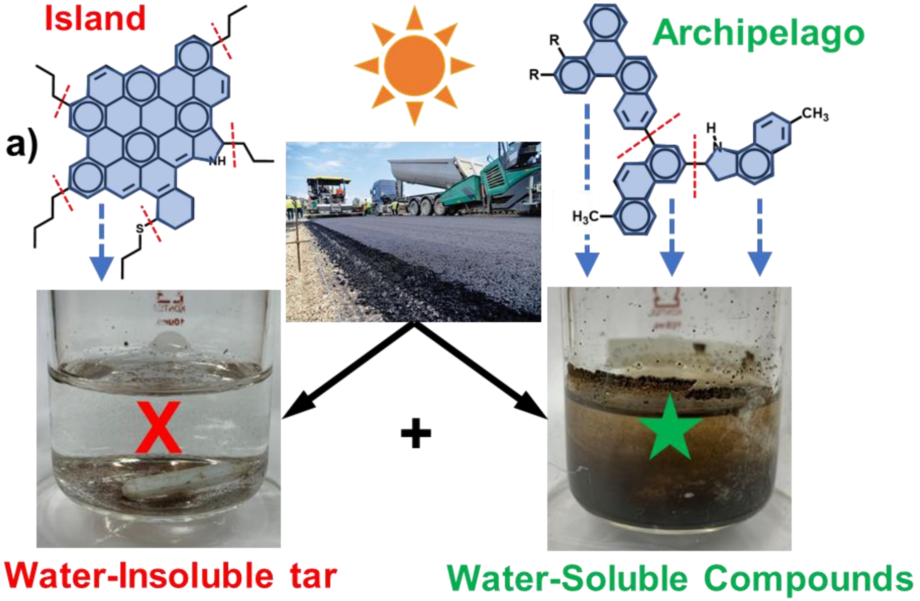
Sustainability: ICR to Study Dissolved Organic Matter (DOM):

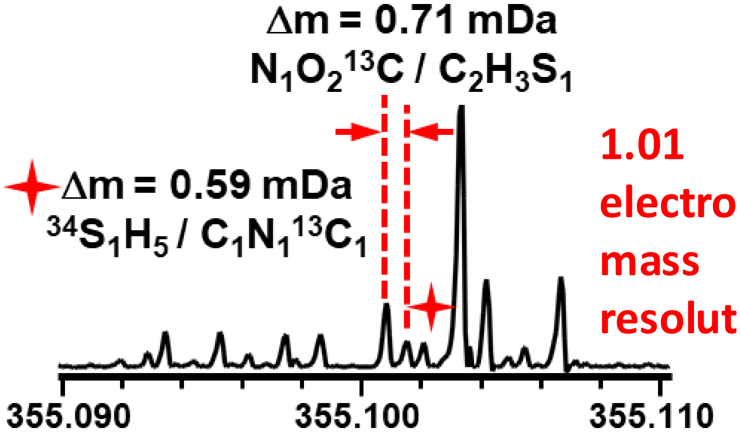
Molecular-Level Signatures of the Changing Arctic and the Built Planet

What controls DOM composition in space and time in the Arctic?

- Arctic Great Rivers Observatory
- 6 rivers, 6 years, 6 samples/year – captures seasonality (across the highly dynamic hydrograph)
- Insights from FT-ICR MS and carbon isotopes (stable and radiocarbon)

PFAS in Groundwater: EPA test for a few of them where there are hundreds of thousands of distinct PFAS species that ICR can identify





1.01 electron mass resolution!

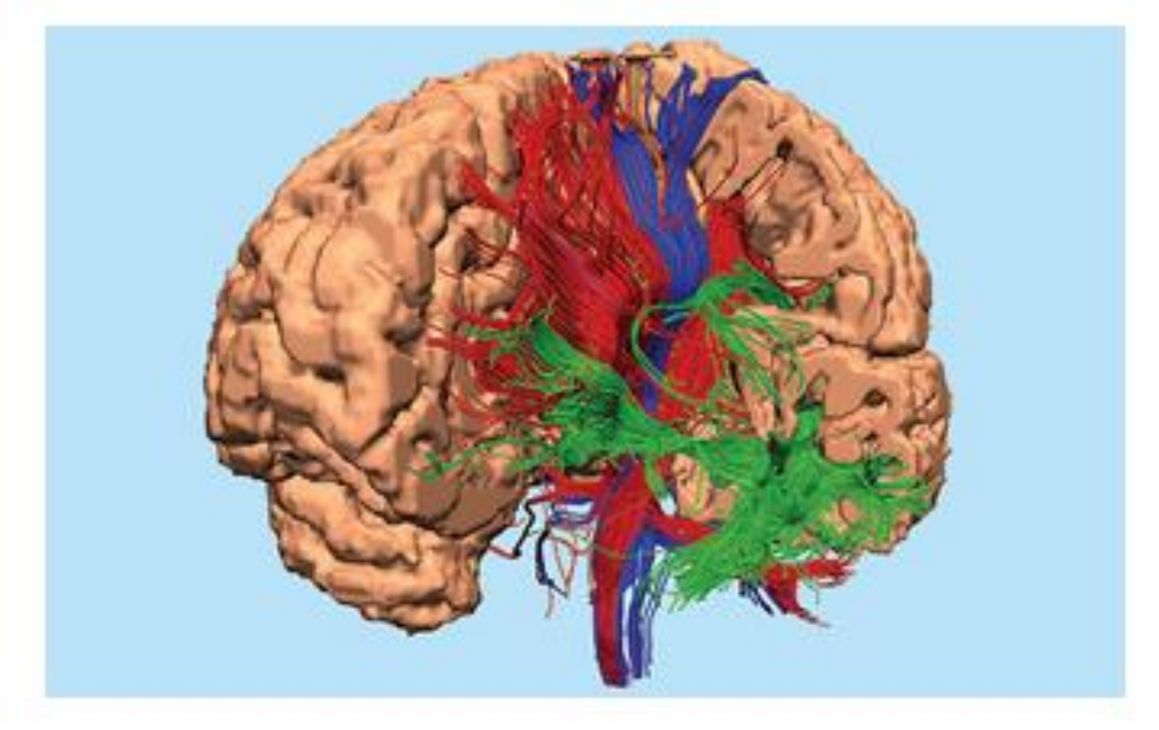
Ion Cyclotron Resonance User Facility

Sustainability: ICR finds
Sunlight converts plastics into complex chemical mixtures: Emerging control of Plastic Photochemical Fate in Oceans

- Studied photochemical breakdown of shopping bags from Target, Walmart, CVS, and pure polyethylene.
- Found ***plastics are NOT inert*** in the environment and sunlight can chemically transform plastics into a diverse suite of ***new compounds with unknown fates and impacts***.

Walsh *et al.*, Envi Sci & Tech (2021)

Ion Cyclotron Resonance User Facility



LIFE EXAMPLES

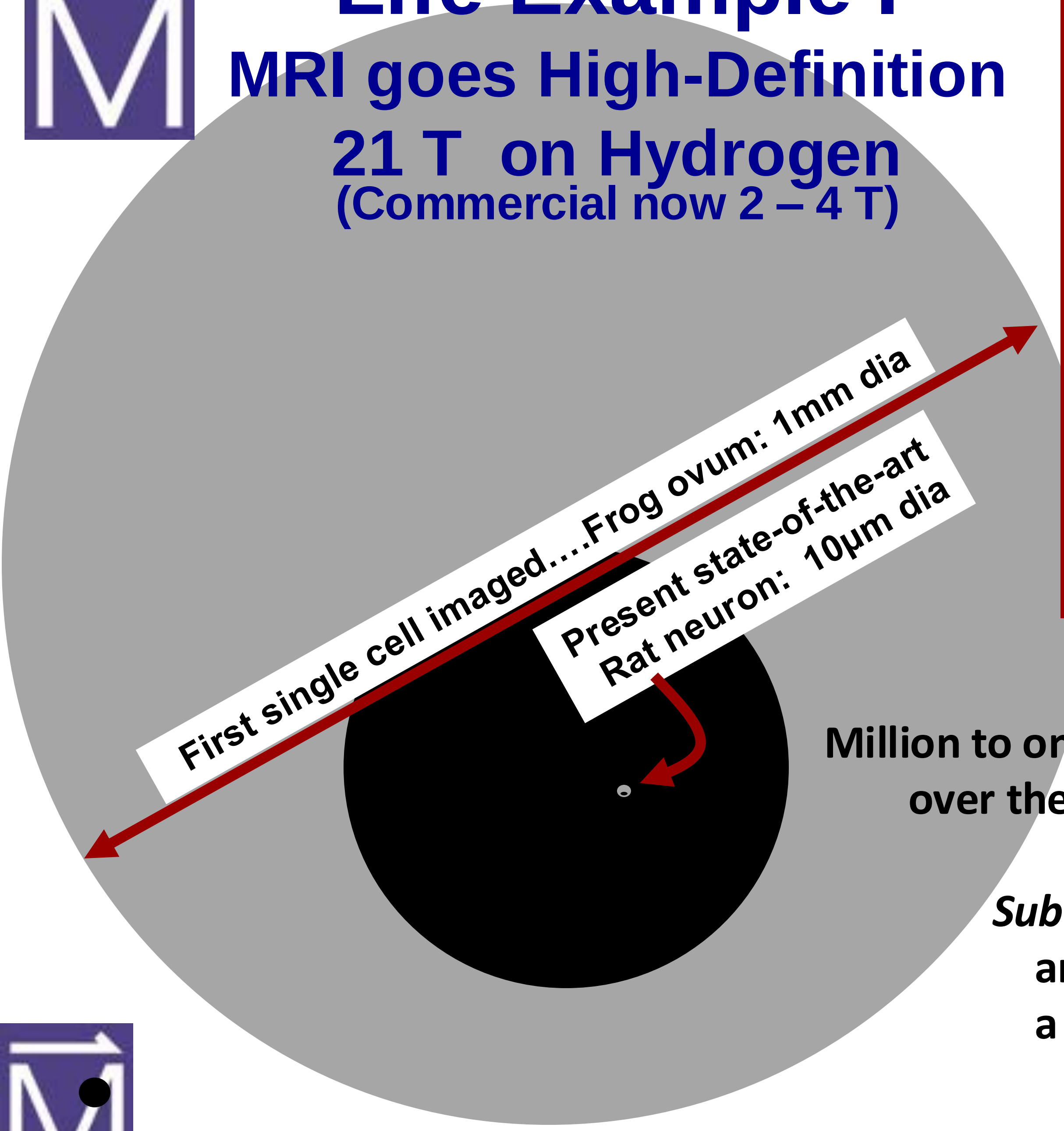
*Advanced Magnetic Resonance Imaging & Spectroscopy (**AMRIS**) UF, Gainesville, and **NMR*** FSU. Tallahassee

Life Example I

MRI goes High-Definition

21 T on Hydrogen

(Commercial now 2 – 4 T)



First single cell imaged….Frog ovum: 1mm dia

Present state-of-the-art
Rat neuron: 10μm dia

Million to one decrease in voxel size over the past 20 years

Sub-cellular **structures are now able to be imaged: a few *microns* on a side!**

Mag Lab Life Example II: High-Definition MRI

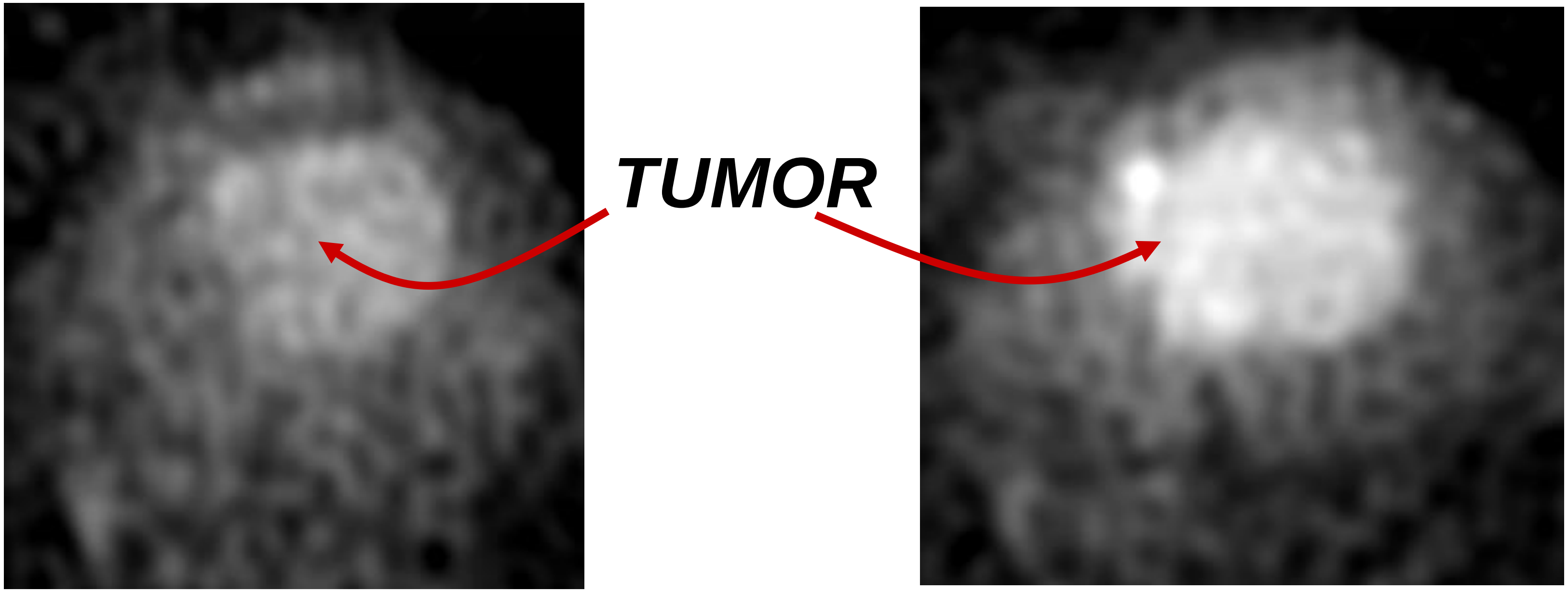
At 21 Tesla: the earliest detection of plaque amyloids, for Alzheimer's on the planet

50 µm isotropic resolution images from wildtype and diseased brains on our 900

Detecting microhemorrhages

Mag Lab Life Example III: MRI Across the Periodic Table

Imaging Sodium in Living Mouse Brain at *21 T*



Before Chemotherapy

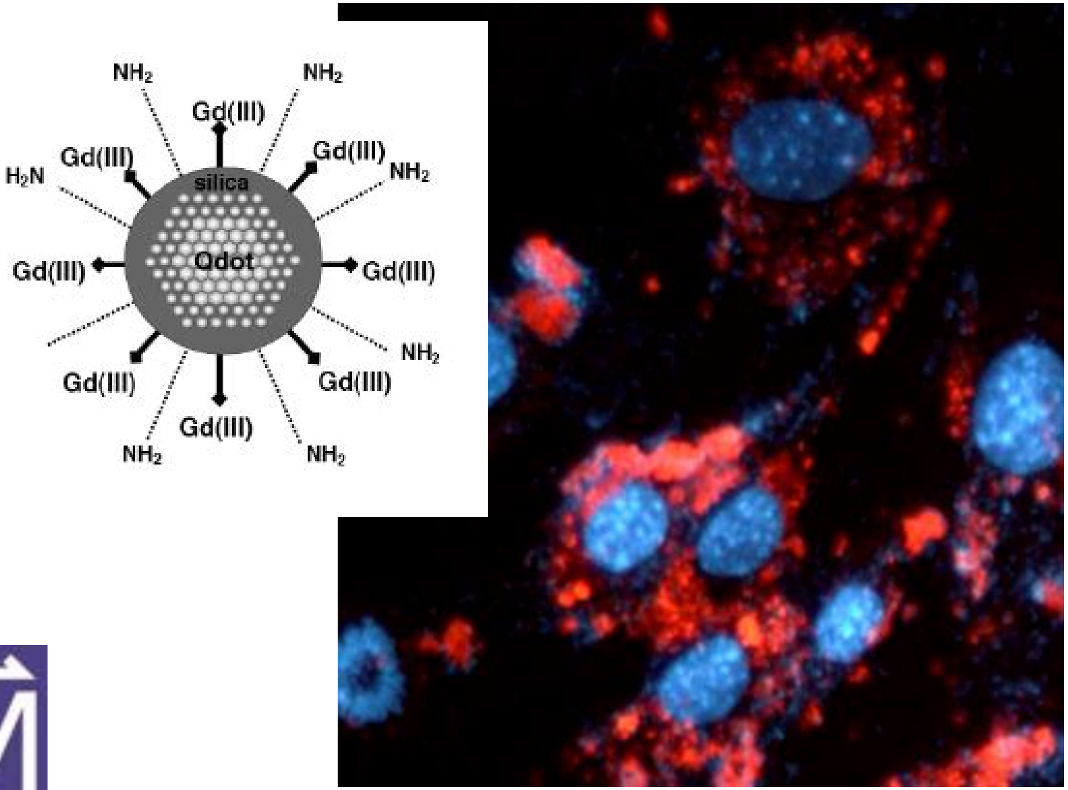
4 Days After

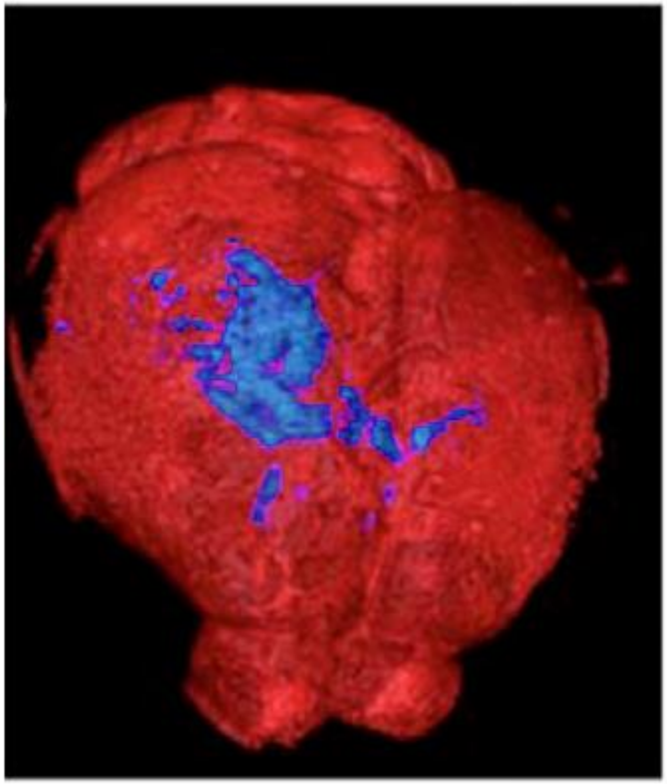
The ‘lighting up’ of the tumor indicates the chemotherapy may be working

Mag Lab Life Example IV:

Magnetic Quantum Dots for Live Stem Cell Tracking: ***In-vivo* at 17.6 T**

Living stem cells labeled with Gd nanoparticles tracked *in vivo* using MRI in a living mouse brain as they respond to brain damage resulting from a stroke.

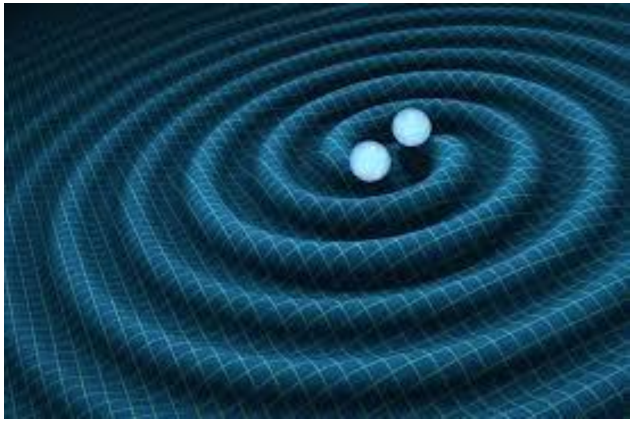




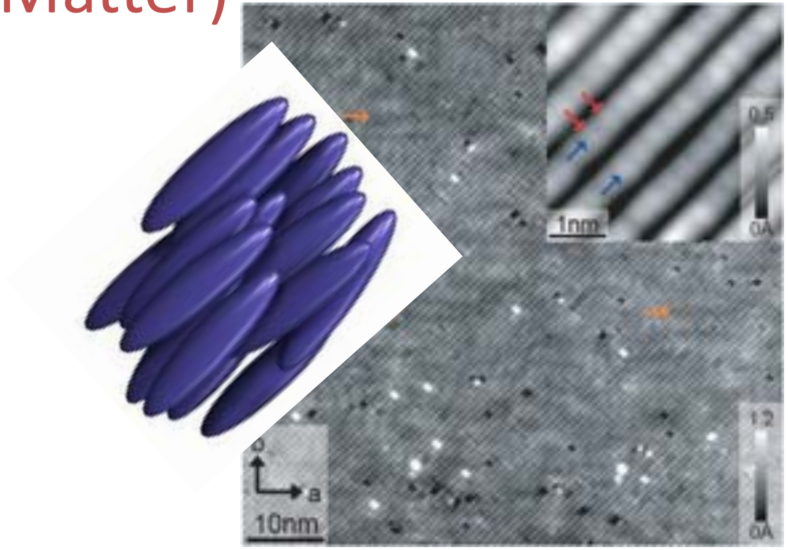
The Dark Energy of Quantum Materials

Why this title? *(public engagement and my view from 35k)*

Quantum Materials: *Many* unsolved questions that are no less fundamental than those in **Cosmology** (Gravity Waves to Dark Energy & Dark Matter)



Colliding Black Holes create:
Gravity waves across the universe.
10^{26} meters - (10^{49} Watts)



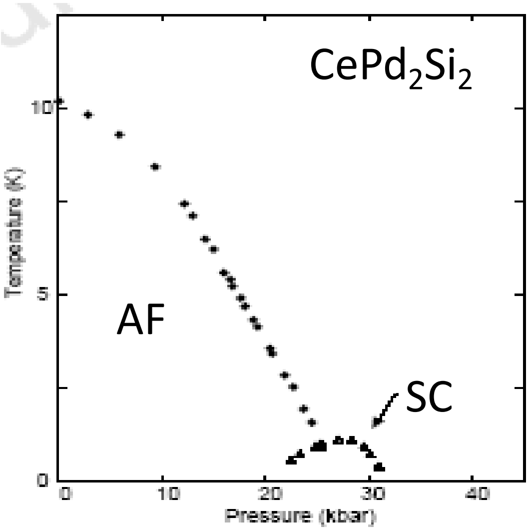
Quantum Materials -
Electrons form “clumps.”
10^{-10} meters - (10^{-21} Watts)

Difference: 10^{36} in length and (10^{70} in power)!

Discovery of *Unconventional* Superconductivity: 1979

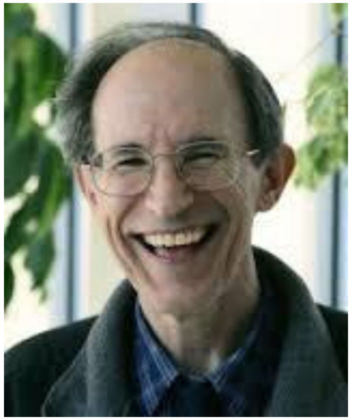
Frank Steglich in Heavy-fermions.

In Köln – nearby here!

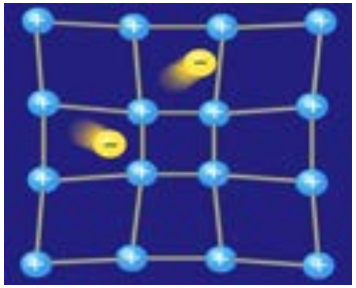


Gil Lonzarich discovers "Domed" phase diagram with a possible magnetic quantum critical point:

a signature of unconventional SC

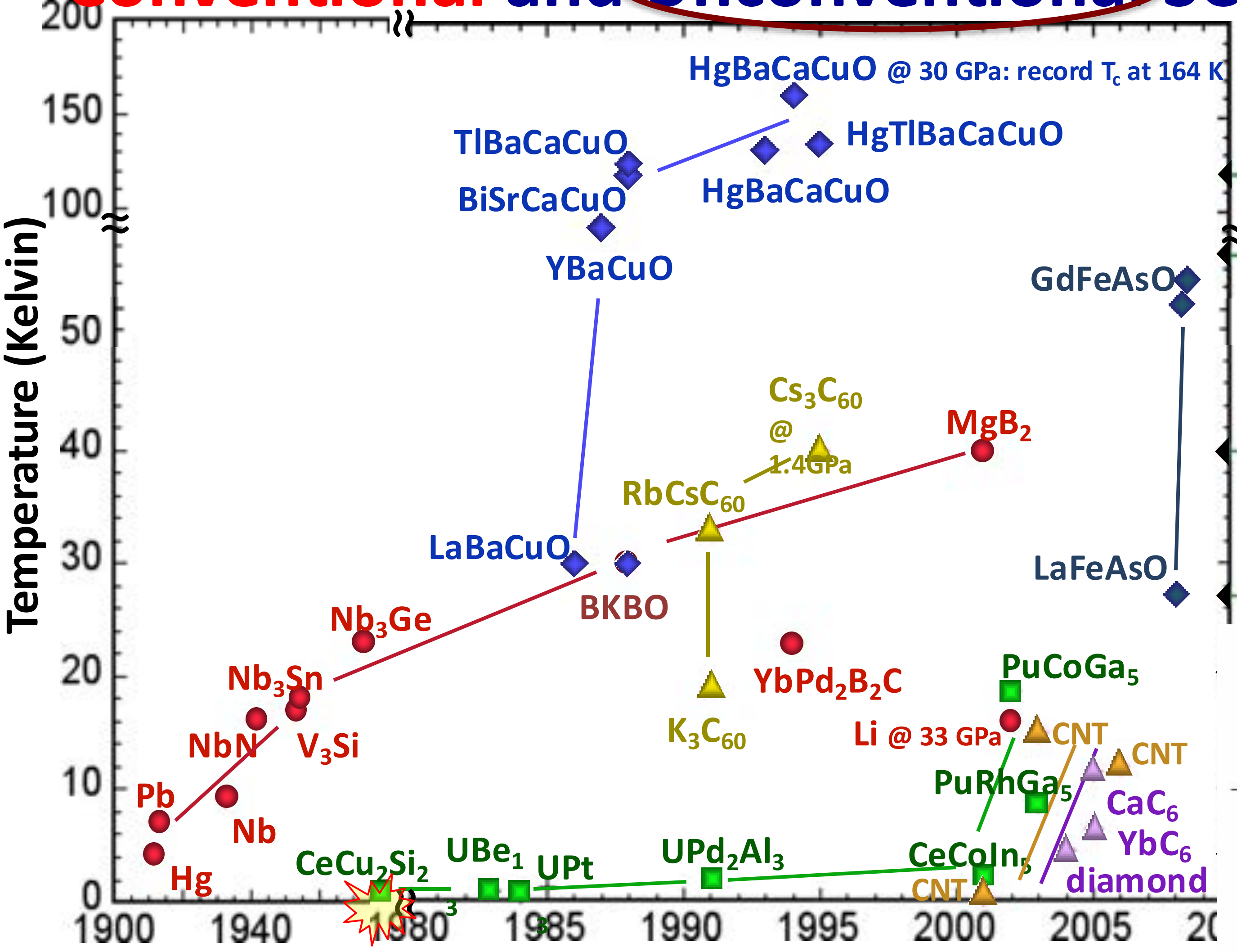


=> BCS Electron-phonon pairing cannot be entire mechanism



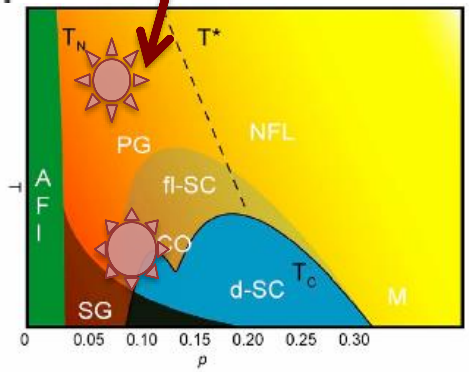
Superconducting Tc vs. Year of Discovery

Conventional and Unconventional SC



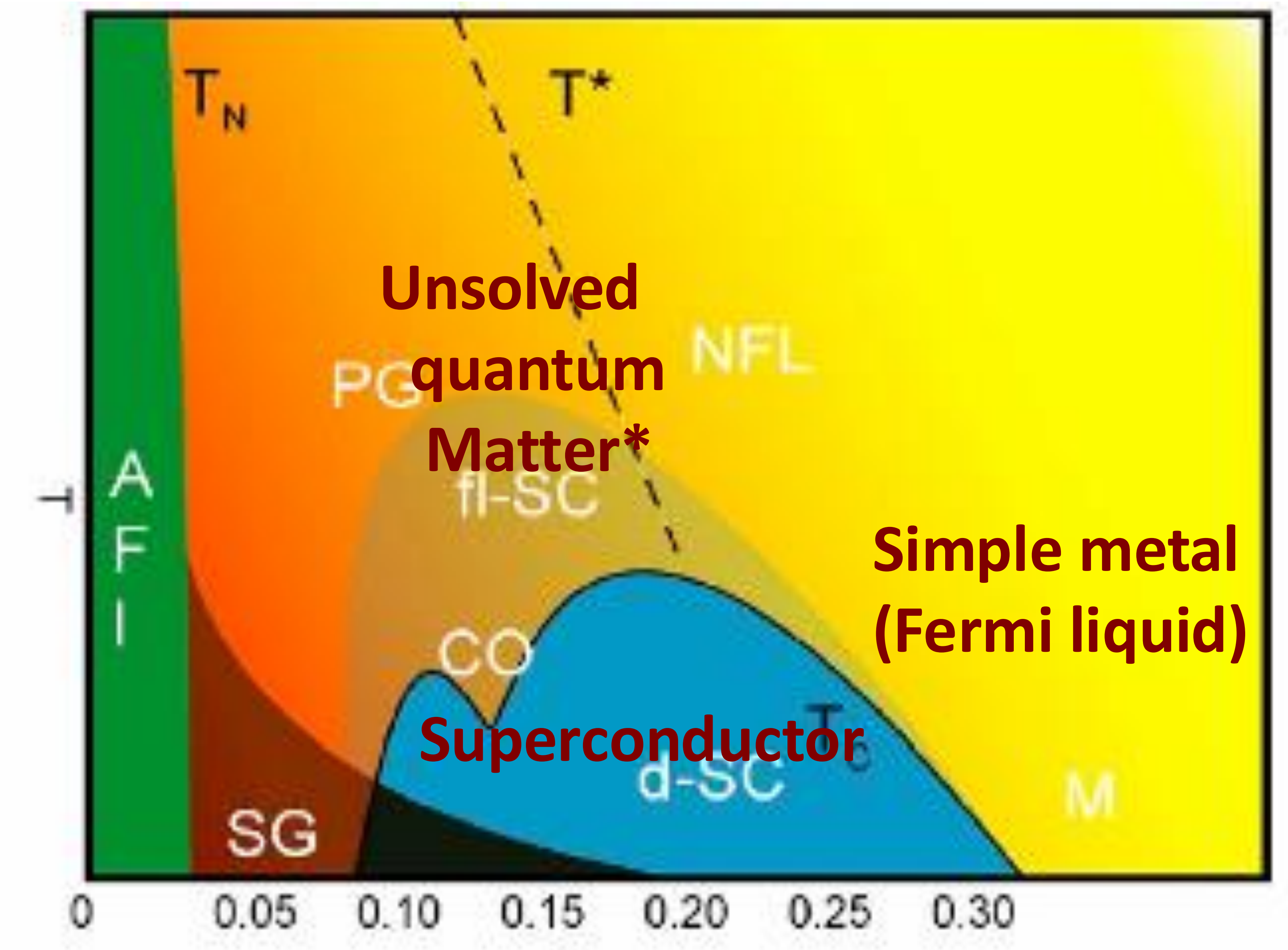
Characterized by

Non Fermi-liquid behavior



*Non-Fermi Liquid / not a simple metal

Canonical Domed Phase Diagram



Unsolved quantum Matter*

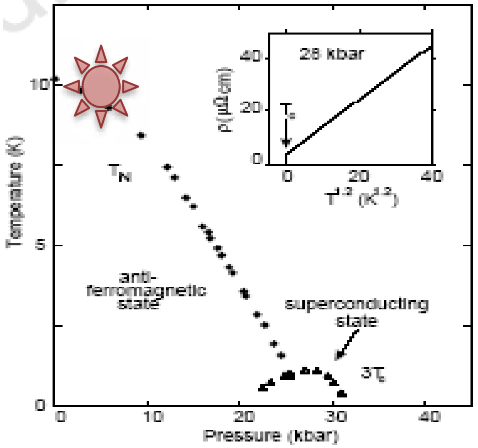
Simple metal (Fermi liquid)

Superconductor

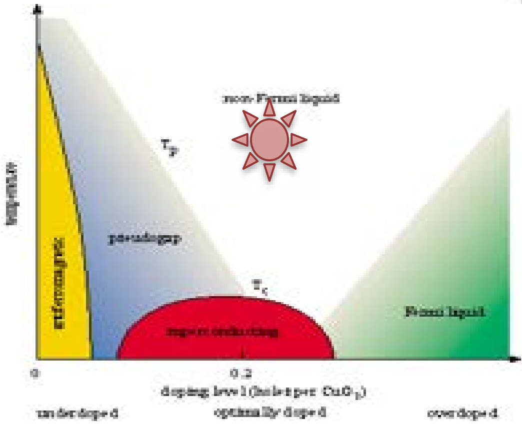
***Correlated Electrons / Non-Fermi Liquid / not a simple metal**

Ubiquitous Phase diagram:
At least 50 families of Unconventional SCs

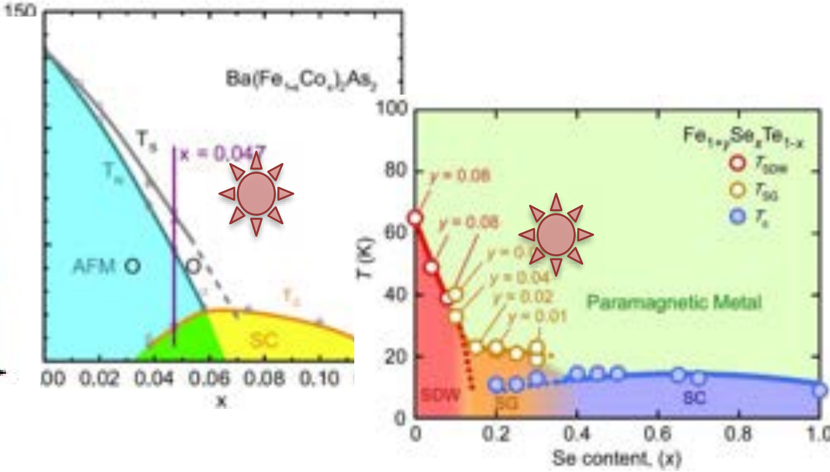
Heavy Fermions



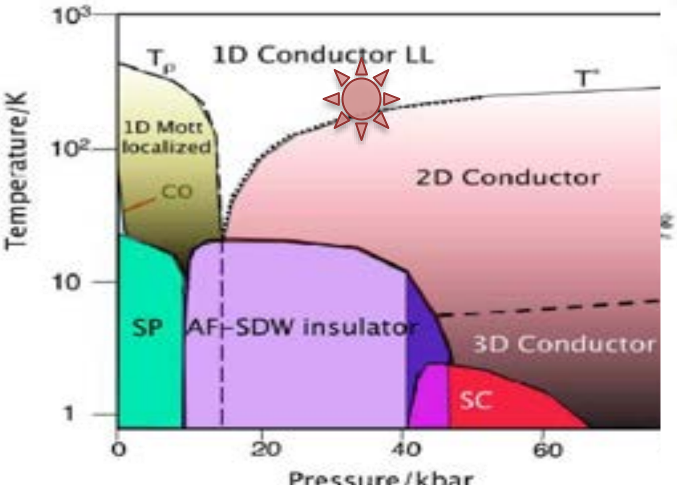
Cuprates



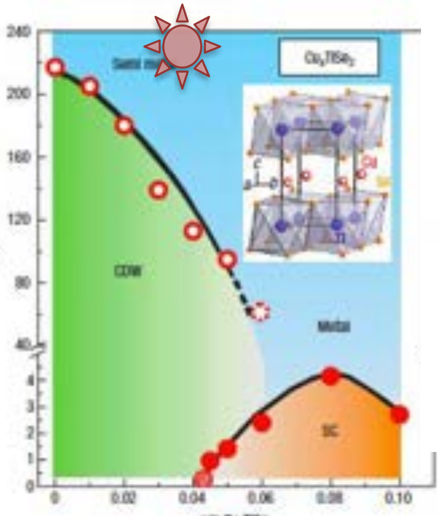
Fe-Based



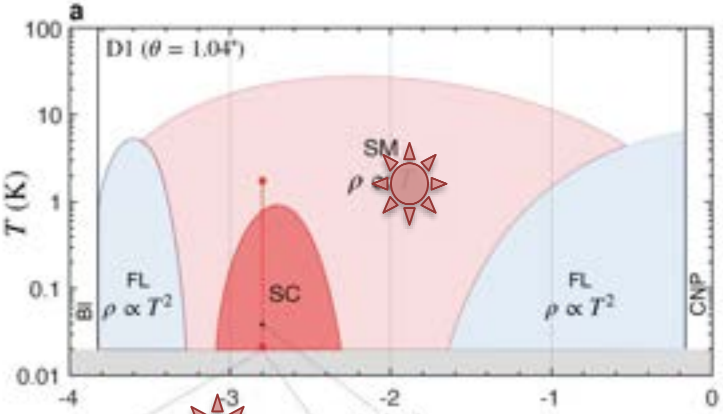
Organics



Di-chalcogenides



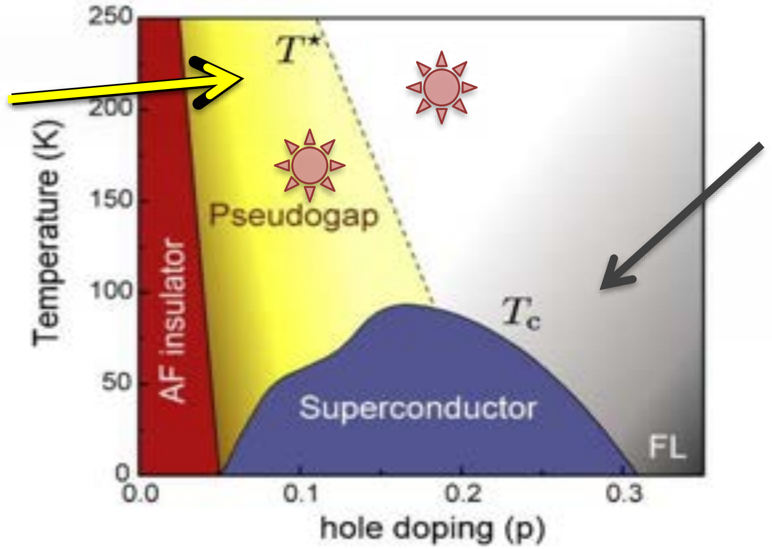
Twisted bilayer graphene



Electron Matter

Intriguing Point About The Dome

Quantum
Matter
(highly
correlated)



Simple Metal
(Fermi liquid)

1. ~ All High-Tc SCs are Unconventional
2. ~ All Unconventional SCs have Quantum Matter
3. Quantum Matter Suppresses Tc
4. But you don’t get HTS without it

=> Some kind of delicate balance!

So I study quantum matter…

Some Examples of Electron Matter: Non-Fermi Liquid (NFL) Behavior

C4 symmetry breaking; static or fluctuating:

Electronic Nematicity

Heavy Electrons →

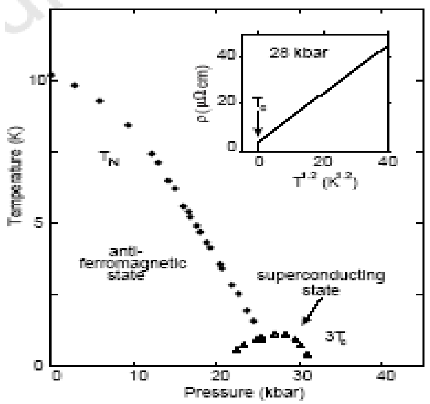
Stripes

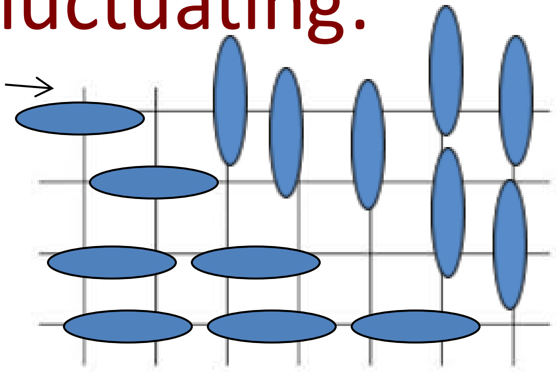
CDWs in Cuprates

Pseudogap in Cuprates

T-dep CDW's in TM-oxides

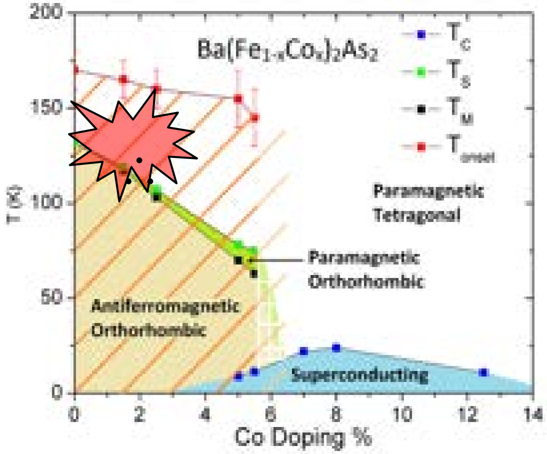
Quantum critical fluctuations

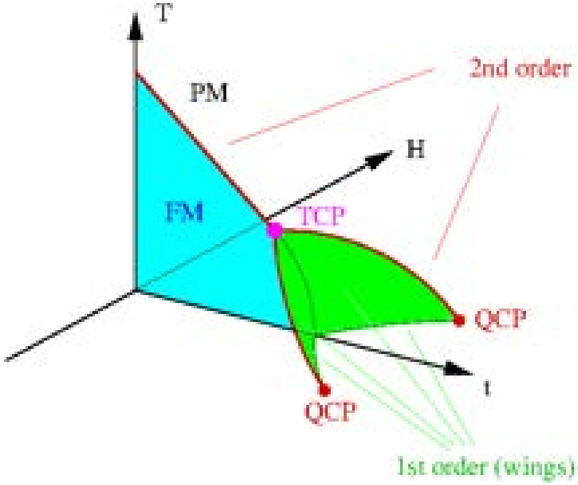




C2 el's

C4 lattice



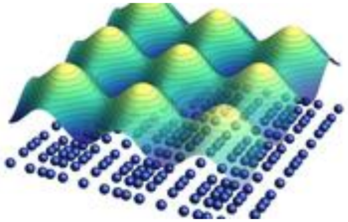


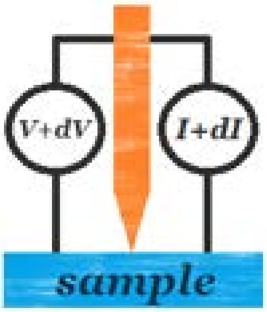
Ubiquitous Phase Diagram

MANY techniques have been developed to study quantum matter, including:

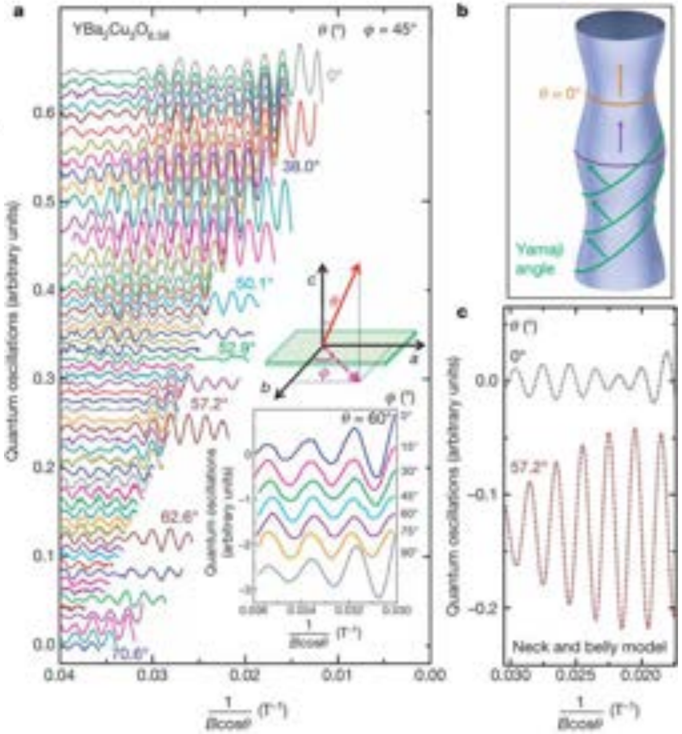
STM
ARPES (+spin, THz...)
RIXS
Quantum Oscillations
Terahertz
New ultra-sensitive
  transport, optical...
In High Mag Fields
Point Contact
Planar Tunneling
And a lot more...

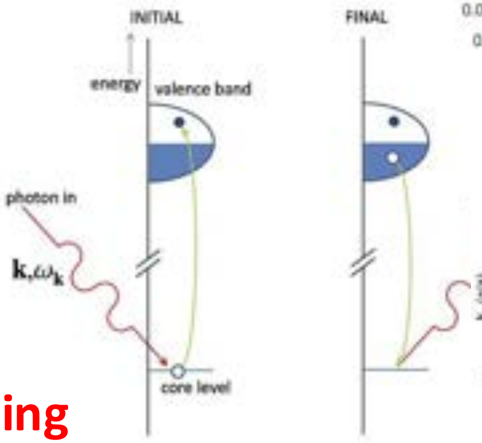
Combinng all these new
Mesurement techniques
  + Growth
    + Computation
= Knowledge & understanding

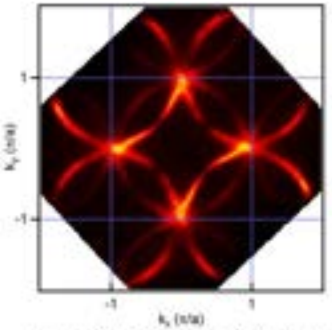




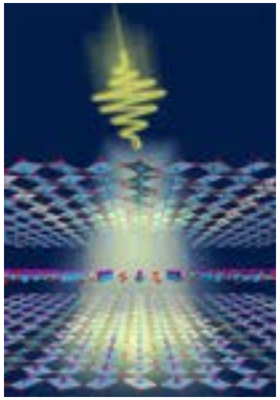
Needle-anvil PCS







Fermi surface of a lead-doped sample of the cuprate superconductor Bi2201, measured by ARPES at the Advanced Light Source, Merlin Beamline (Beamline 4.0.3).



Unsolved Quantum Matter

Solved:

- **Fermi Liquids (i.e., simple metal) :** General electronic structure calculations work well (from crystal components and structure)
- **Superconductors** (one of 3 solved quantum materials): All have Cooper pairs, so Bogolioubov-de Gennes equations (BdG) work well.

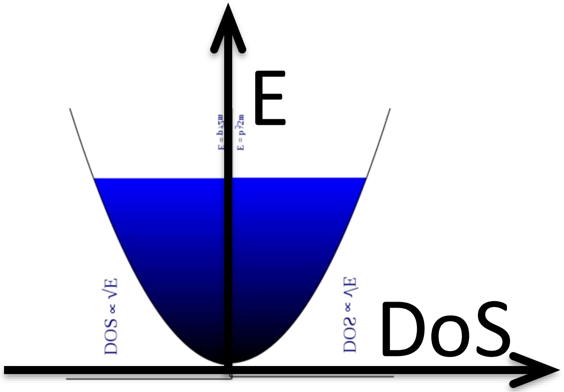
General definitions for Unsolved QM:

- **Theory**: The electronic properties can**not** be explained by the crystal structure and atoms
- **Experiment:** The electron-electron interaction is stronger than the electron-lattice interaction: Electron fluid has a lower symmetry than underlying lattice.

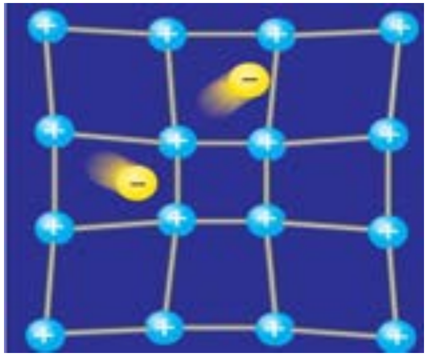
Conventional Superconductors

Tc typically ≤ 40 K (at easily attainable pressures)

High Temp: Fermi Liquid



Low Temp: Superconducting
Cooper pairs

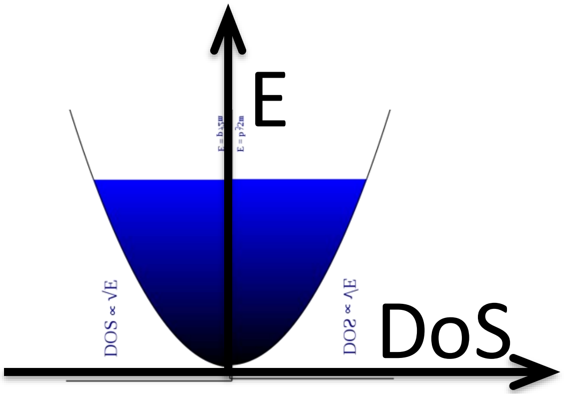


Conventional Superconductors

Tc typically ≤ 40 K (at easily attainable pressures)

High Temp: Fermi Liquid

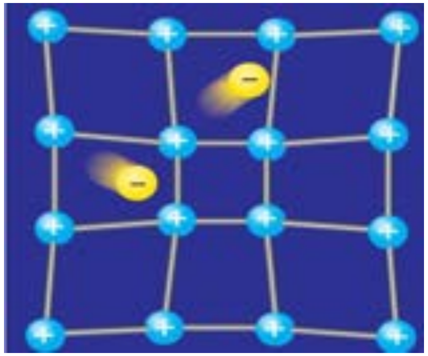
SOLVED !!!



Low Temp: Superconducting

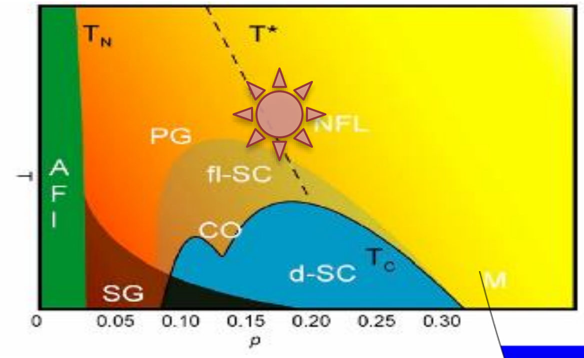
Cooper pairs

SOLVED !!!

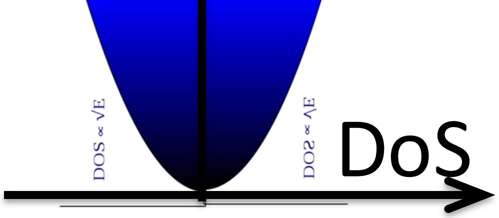


Unconventional Superconductors

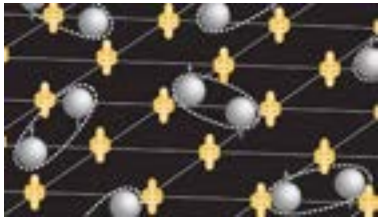
Tc ≤ 165 K
“Domed”
phase diagram



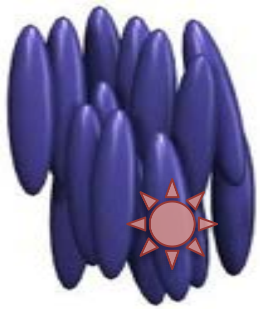
Above Tc: FAR RIGHT side of phase diag: Simple metal



Below Tc: Cooper pairs

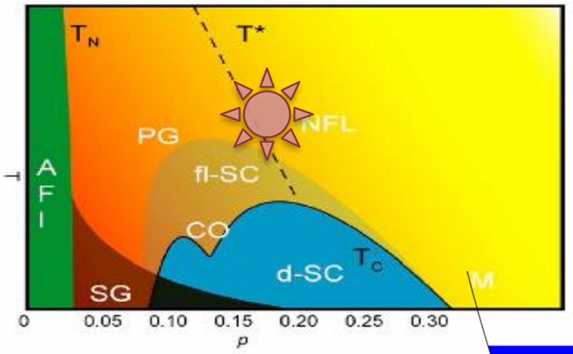


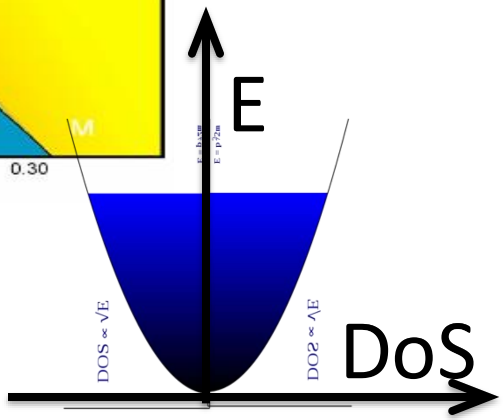
Above Tc: Quantum Matter



Unconventional Superconductors

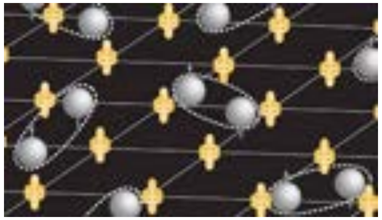
Tc ≤ 165 K
“Domed”
phase diagram





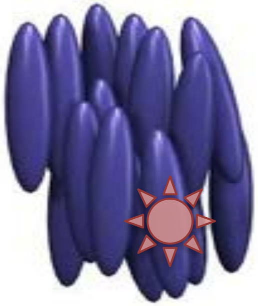
Above Tc: FAR RIGHT side of phase diag: Simple metal

SOLVED !!!



Below Tc: Cooper pairs

CAN MODEL !!!

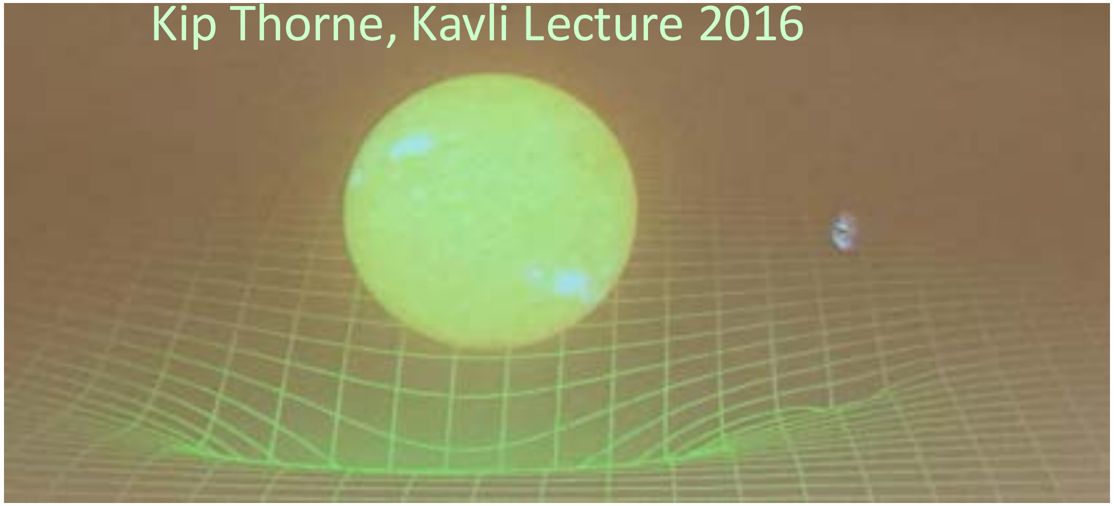


Above Tc: Most of rest of phase diag: Quantum Matter

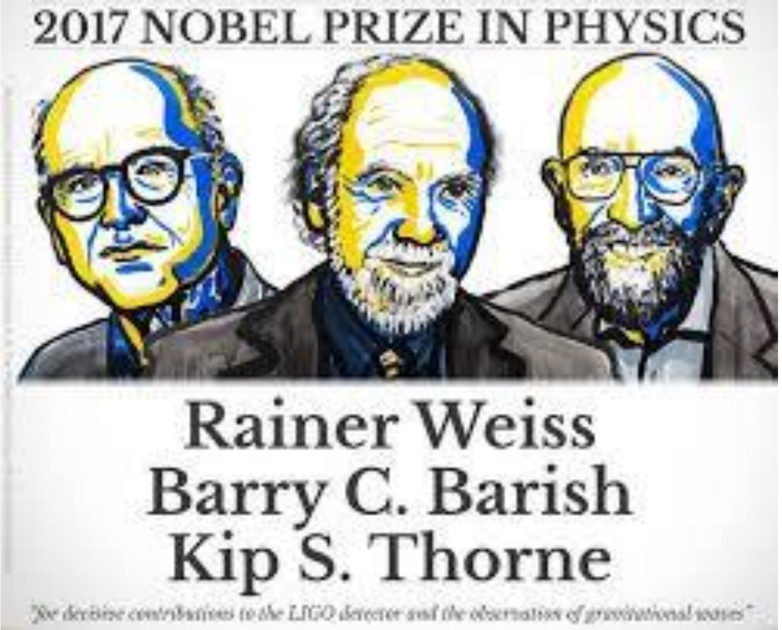
UNSOLVED !!!


CAUTION
ANALOGIES AHEAD
PROTECTIVE HEADGEAR MUST BE WORN IN THIS AREA

Recent Inspiration: Gravity



Kip Thorne, Kavli Lecture 2016



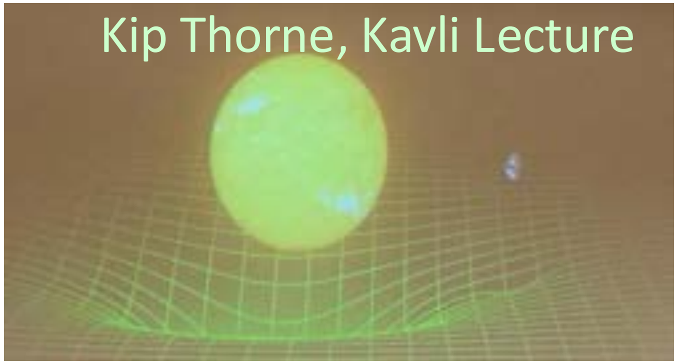
2017 NOBEL PRIZE IN PHYSICS

Rainer Weiss
Barry C. Barish
Kip S. Thorne

"for decisive contributions to the LIGO detector and the observation of gravitational waves"

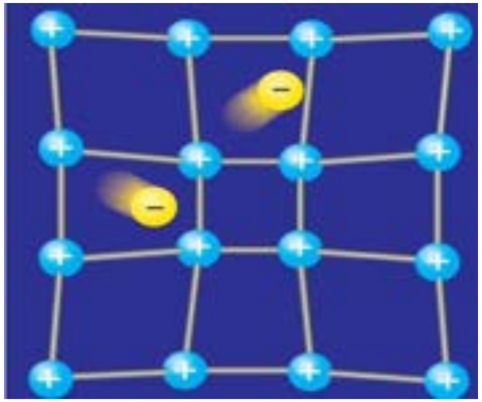
Gravity

Quantum Matter


Kip Thorne, Kavli Lecture

Einstein

BCS



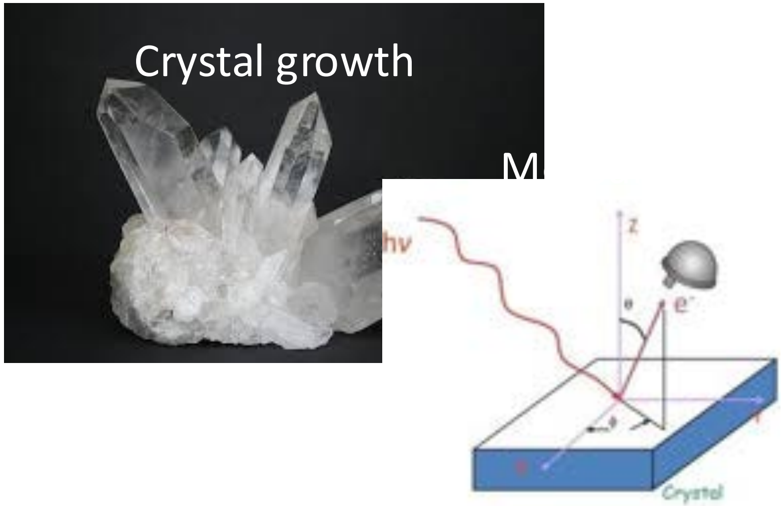
The Gravity Wave Detector: LIGO

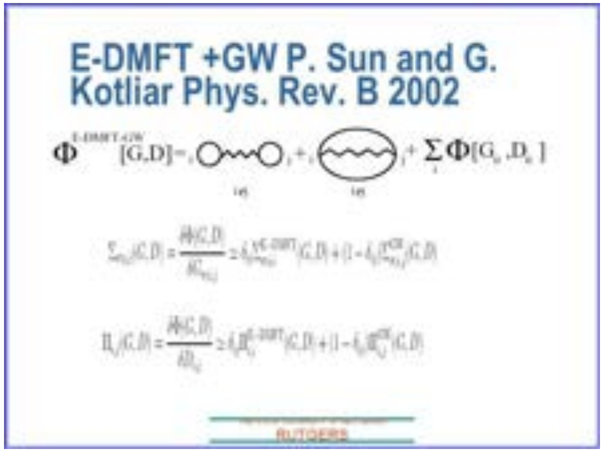

Two black holes colliding.


Detector moved less than the width of a proton

Energy was more than the combined power of all light radiated by all the stars in the observable universe!

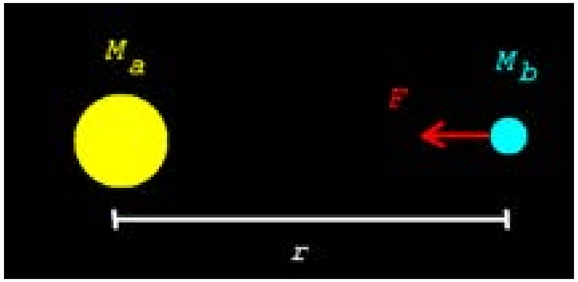
Many Quantum Matter Detectors


Crystal growth


E-DMFT +GW P. Sun and G. Kotliar Phys. Rev. B 2002

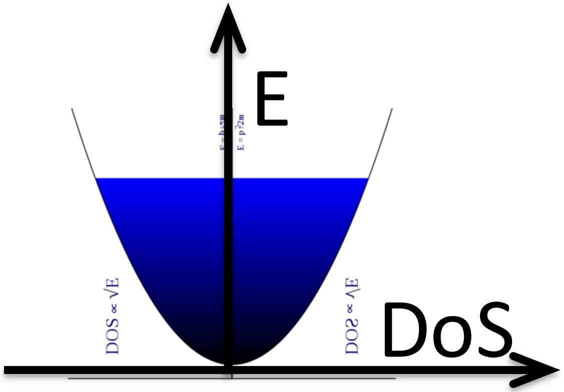
Gravity

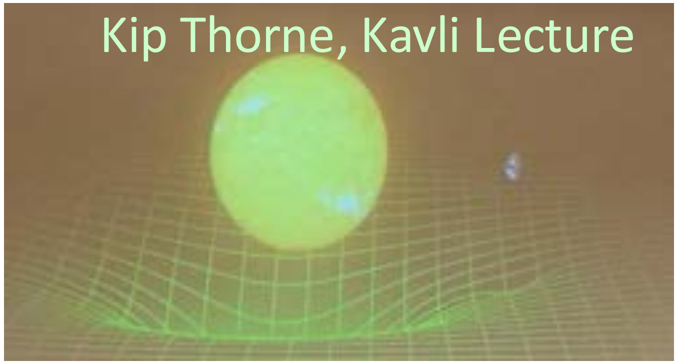
Quantum Matter



Newton

Fermi

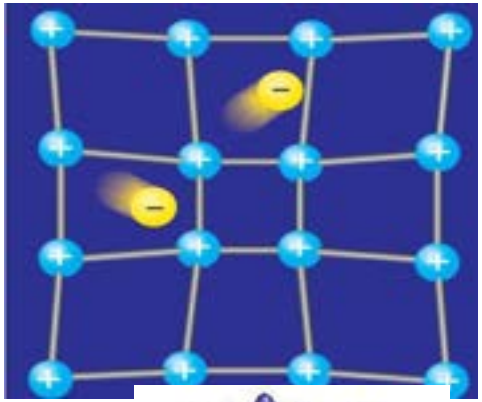


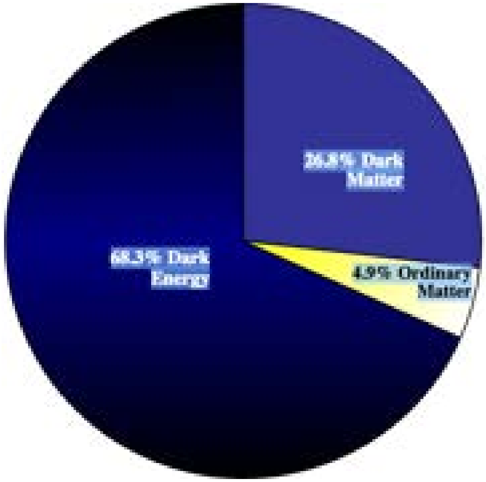


Kip Thorne, Kavli Lecture

Einstein

BCS





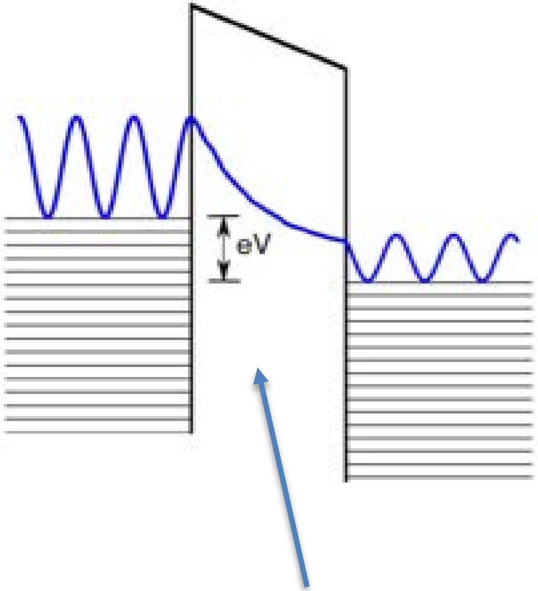
Dark Energy

Quantum Matter

Two Great Unsolved Problems in Physics

PROGRESS	**Gravity**	**Quantum Matter**	**PROGRESS**
Forces between objects derived from mass and positions	**Newtonian -Classical**	**Simple metals**	Properties derived from crystal atoms and positions
Masses create distortions in background (space-time continuum)	**Einsteinian -General Relativity**	**BCS SC -One Electron Matter solved!**	Electrons create distortions in background (crystal lattice)
UNSOLVED: May show how stars form…etc.	**Dark Energy and Dark Matter**	**Electron Matter (correlations)**	**UNSOLVED: All unconv SCs have them**

Electron Tunneling



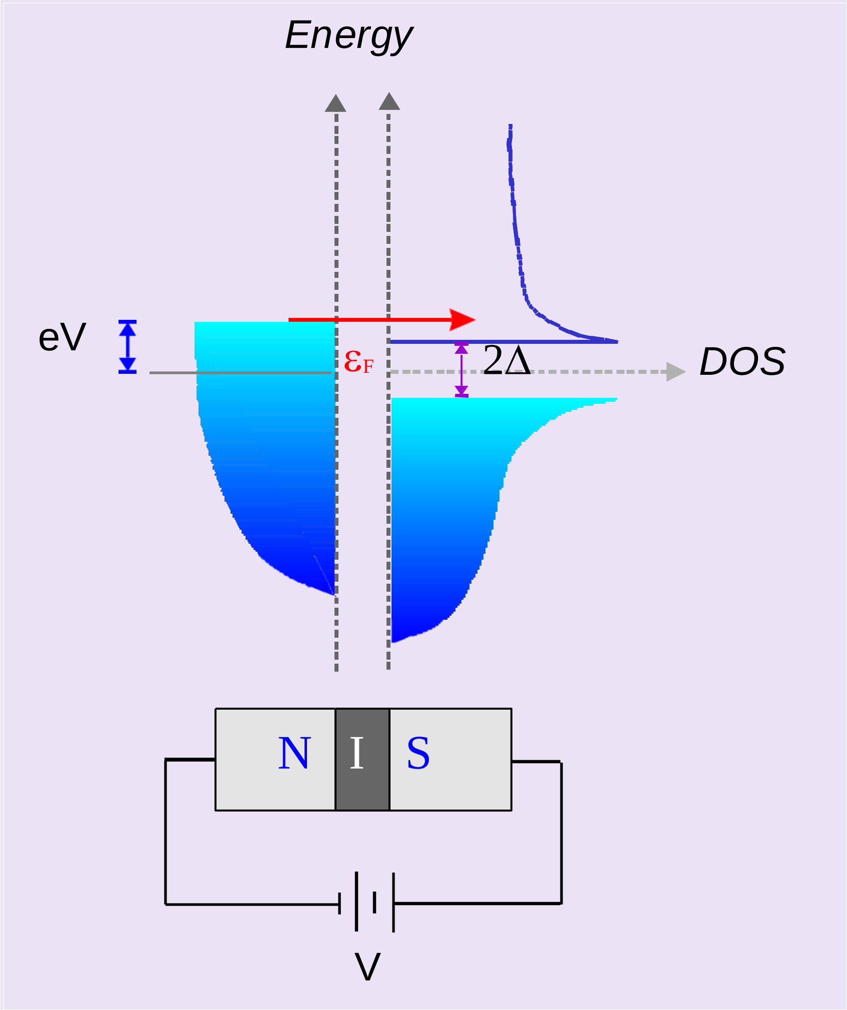
Classically Forbidden Region

Fermi's Golden Rule

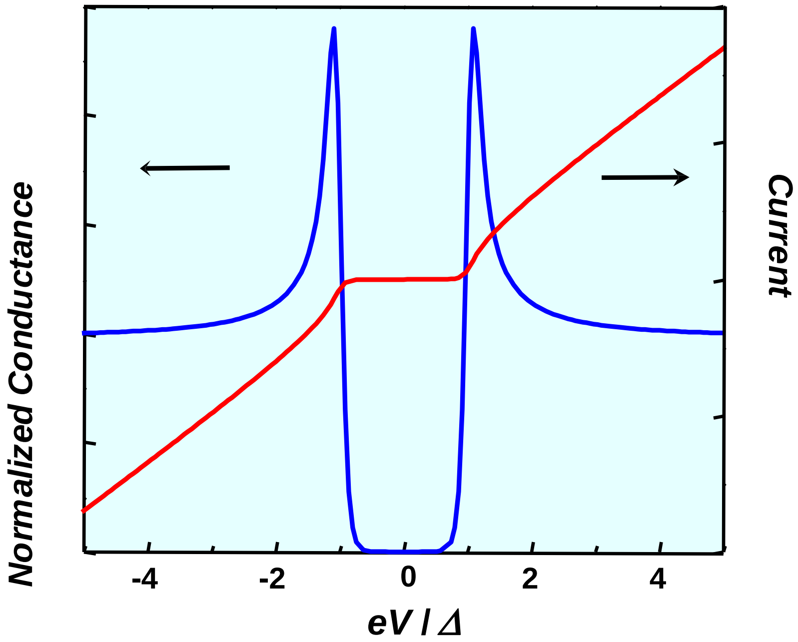
$$\Gamma_{i\to f} = \frac{2\pi}{\hbar}\left|\left\langle f\left|H'\right|i\right\rangle\right|^2 \rho$$

DoS or N(E)

Electron Tunneling Spectroscopy: DoS



Conductance Reveals the "*Tunneling* Density of States"

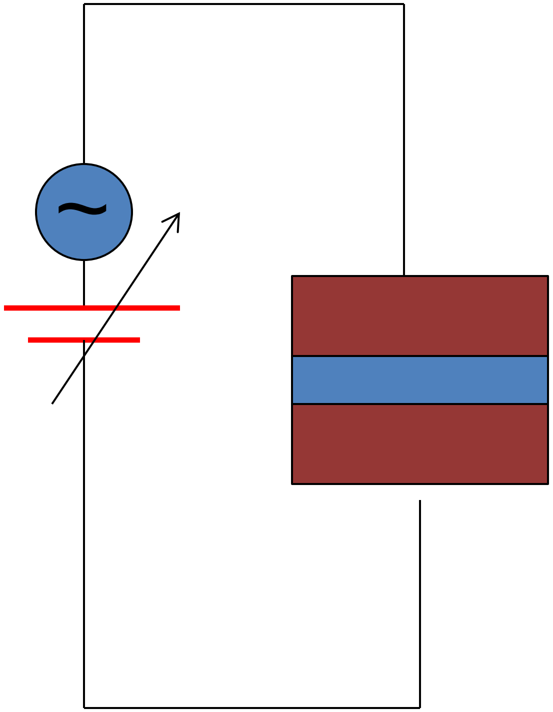


$$\frac{N_n(E)}{N_n(E_F)} = \left(\frac{E}{E_F}\right)^{1/2}$$

$$\frac{N_s(E)}{N_n(E_F)} = \begin{cases} \dfrac{E}{\left(E^2-\Delta^2\right)^{1/2}} & (E>\Delta) \\ 0 & (E<\Delta) \end{cases}$$

Harrison's theorem (1961)

Let's discuss during the week!



Planar tunneling conductance for small bias:

$$\frac{dI}{dV} \propto \int dk\, v_k\, \mathrm{Im}\, G(k, eV)$$

For simple metals (weak correlations)

$$v_k = \frac{d\varepsilon_k}{dk} \quad , \quad \mathrm{Im}\, G(k, eV) = \delta(\varepsilon_k - eV)$$

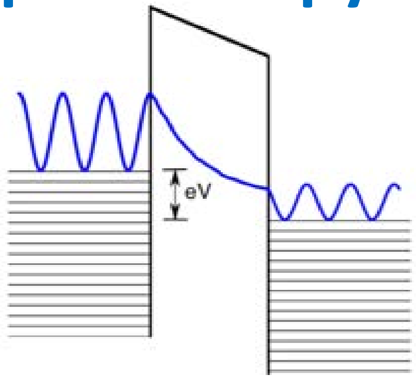
$$\frac{dI}{dV} = const.$$

ImG(k, eV) = the imaginary part of the Green's function: The ***Spectral function***

Therefore, above T_c, planar tunneling gives ohm's law: flat, featureless conductance.

Why do we see the superconducting tunneling detect the DoS?

These two slides are on how Planar Tunneling Spectroscopy reveals non-Fermi liquid behavior



Fermi's Golden Rule

$$\Gamma_{i \to f} = \frac{2\pi}{\hbar} \left| \langle f | H' | i \rangle \right|^2 \rho$$

Tunneling current can be derived as:

$$\mathbf{J} = -\frac{2\pi e \tau}{\hbar} \sum_{i,f} \int_{\mathrm{BZ}} \frac{d\mathbf{k}}{(2\pi)^D} |\mathbf{v}_i - \mathbf{v}_f| (f_i(\mathbf{k}) - f_f(\mathbf{k})) |H'_{if}|^2 \delta(E_f(\mathbf{k}) - E_i(\mathbf{k}) - \hbar\omega),$$

Fermi velocity

Density of states

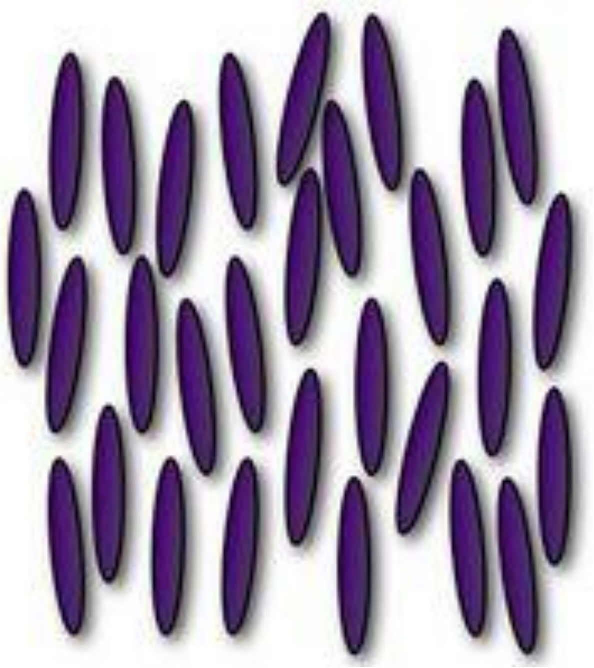
v_F ~dE/dk* and *N(E) ~ dk/dE: they divide out for a FL!

Q: Why do we see the SC gap, electronic nematicity, Kondo effects….?

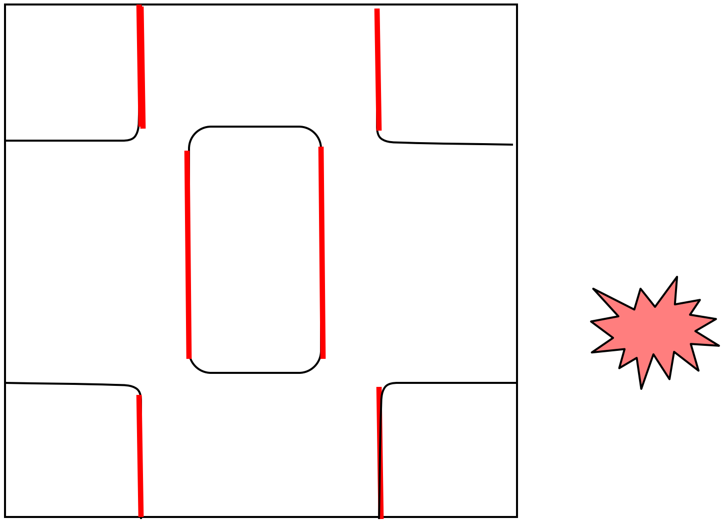
A: They are not Fermi Liquids!

Let's discuss during the week!

Electronic Nematic Phase (NFL)

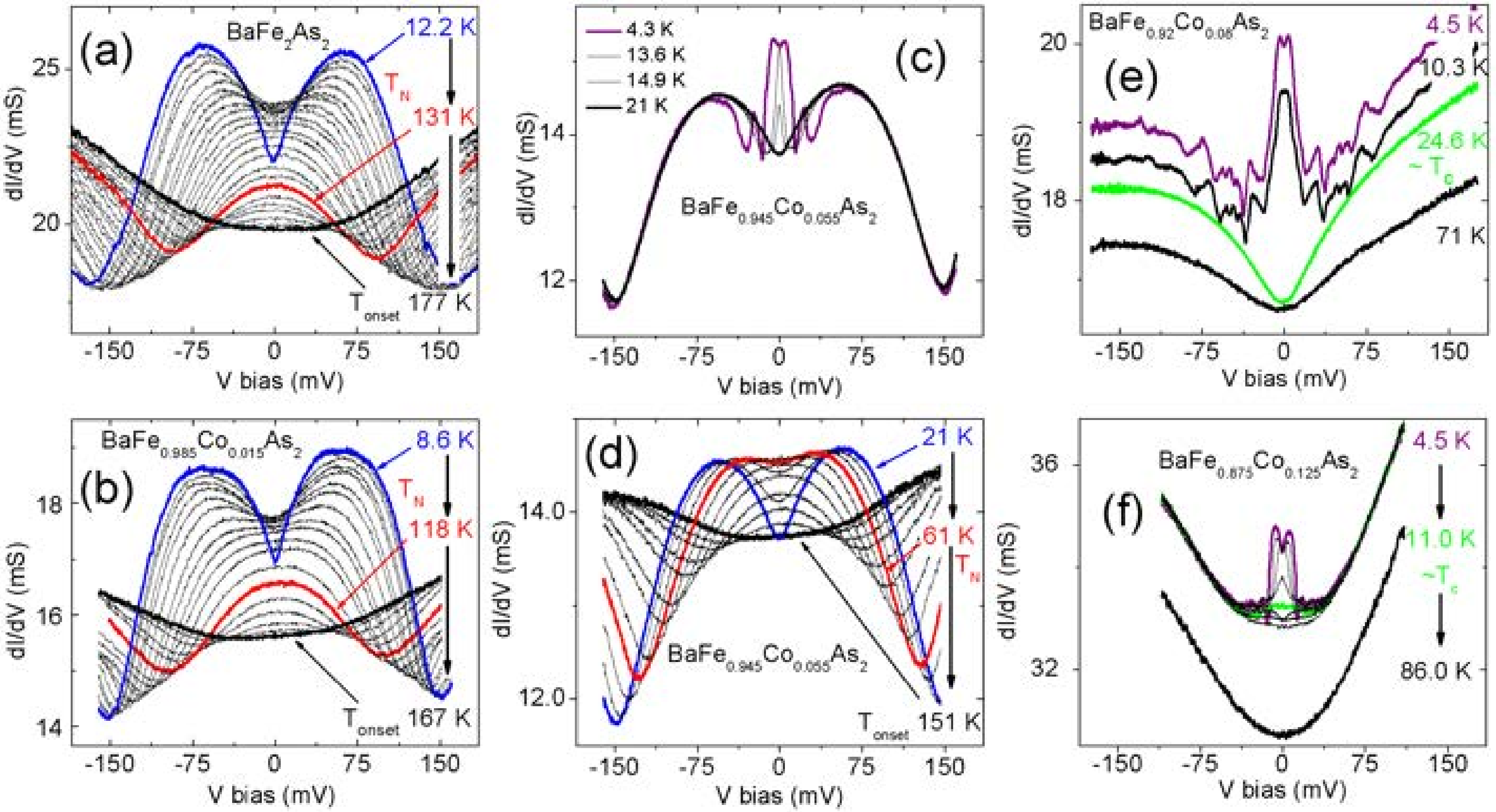


Nematic phase in liquid crystal



Electronic nematic phase: Fermi Surface distortion by orbital ordering

Summary PCS raw data $Ba(Fe_{1-x}Co_x)_2As_2$



AF

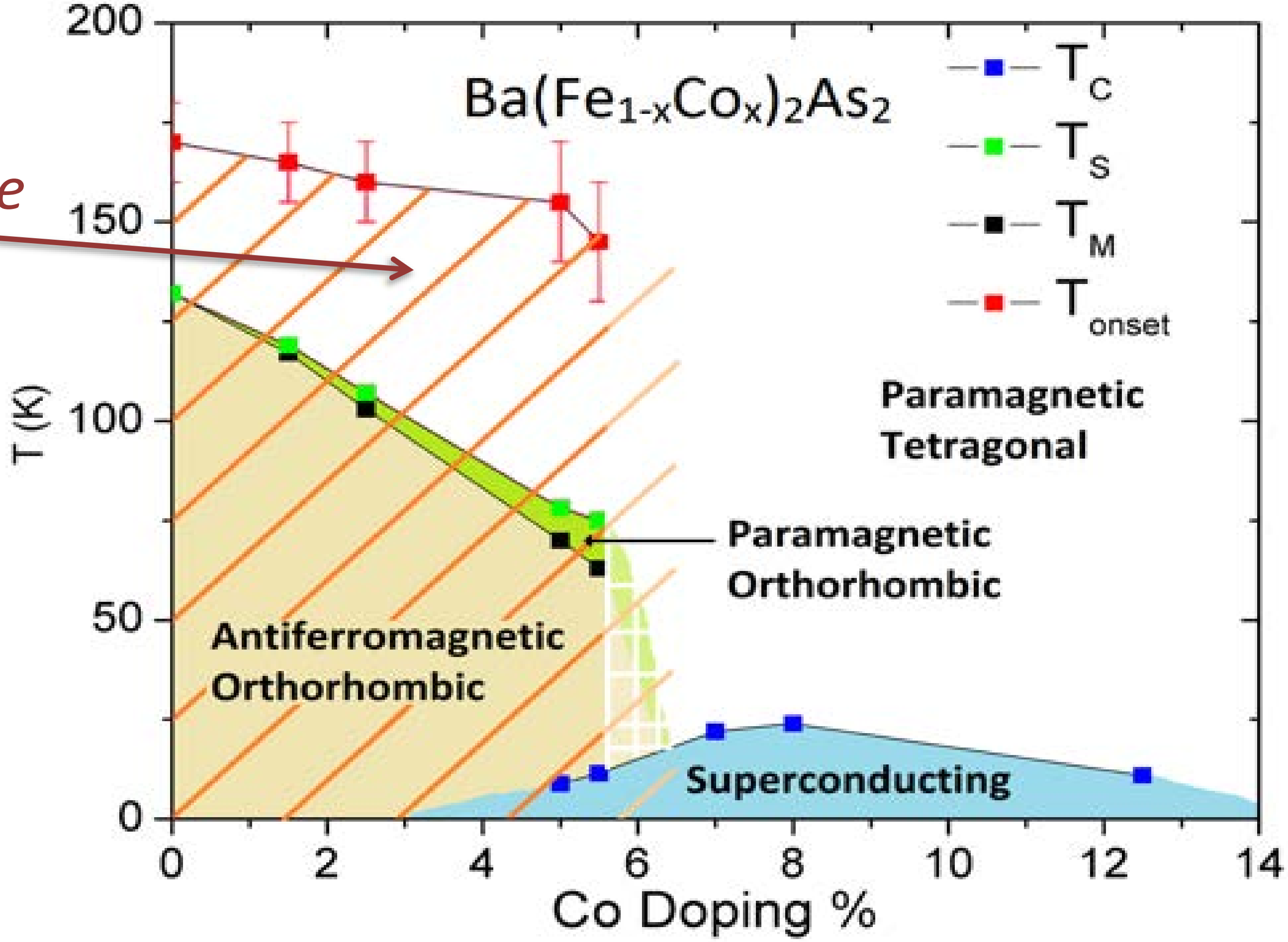
SC+AF

SC

Another example of NFL being detected

Electronic Nematic Phase

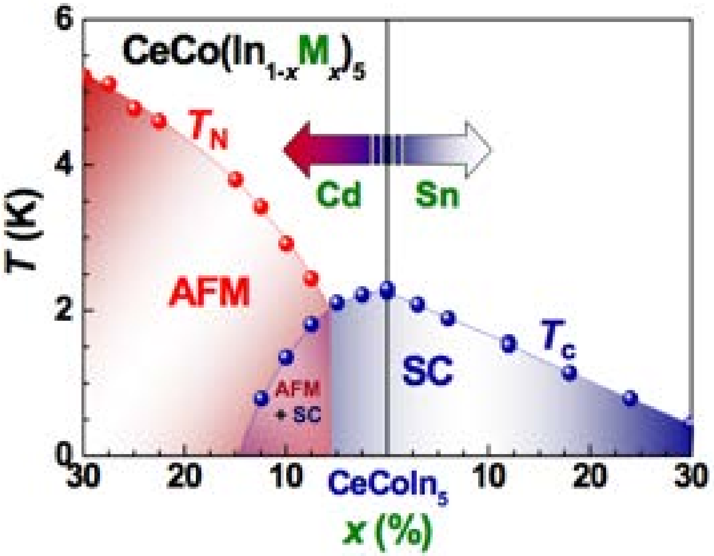
H. Z. Arham et al.



$CeCoIn_5$ Introduction and Motivation

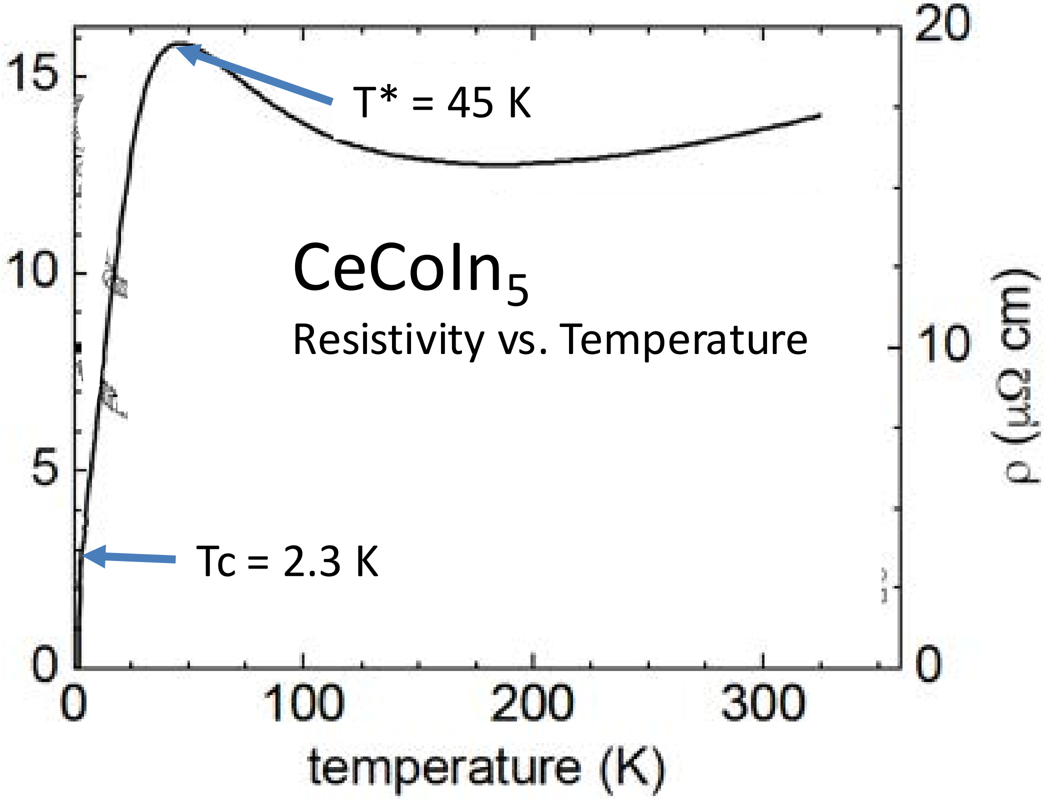
Heavy Fermion Superconductivity and Non-Fermi Liquid behavior

High T_c = 2.3 K (for a heavy fermion superconductor)



Domed Phase Diagram
Looks like
unconventional
superconductivity

C. Petrovic et al., (2001)



T* = 45 K

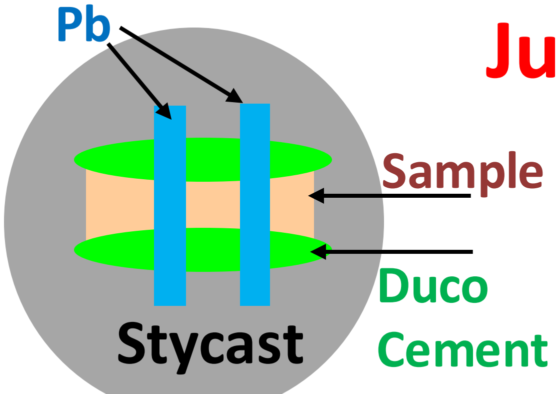
$CeCoIn_5$
Resistivity vs. Temperature

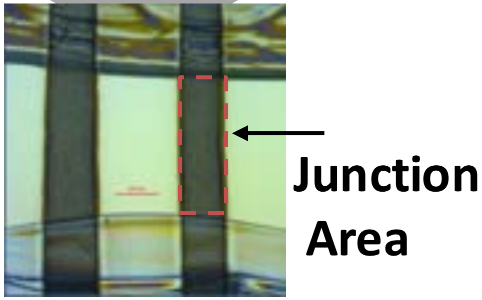
Tc = 2.3 K

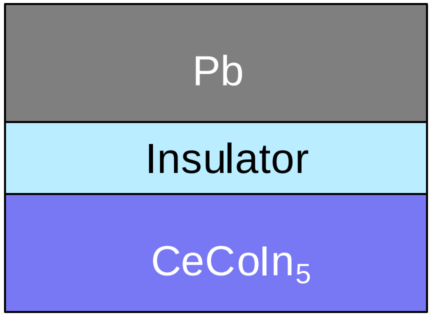
Non-Fermi liquid resistivity
Phase diagram: Unconventional SC

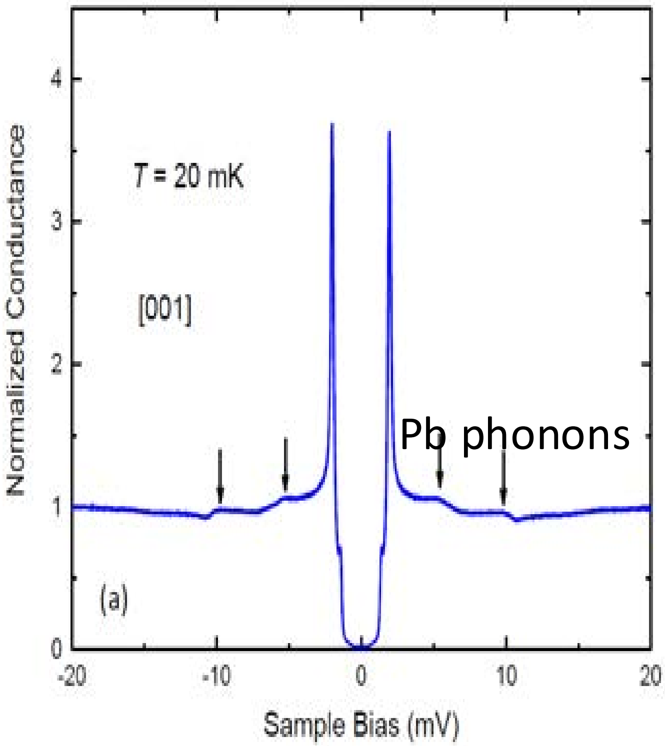
Junction Fabrication and Diagnostics

$CeCoIn_5$ / AlO_x / Pb (SIS Junctions)









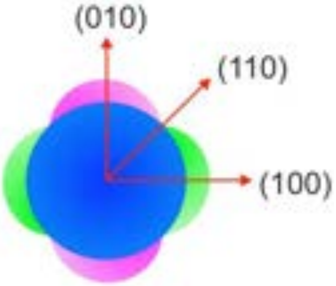
- Polish sample surface
- Deposit ~ 20 Å Al
- Plasma Oxidize (5 W)
- Insulate edges w/ Duco
- Deposit 2500 Å Pb

$R_{J.}$ = 20 - 100 Ω
R_J.A ≈ 10 - 20 Ω mm^2
Area = ~200 x 400 µm
Roughness: 1 – 1.5 nm (AFM)

Junction quality determined by

- **Pb tunneling density of states**
- **Junction reproducibility**

CeCoIn$_5$ DoS along major crystallographic directions



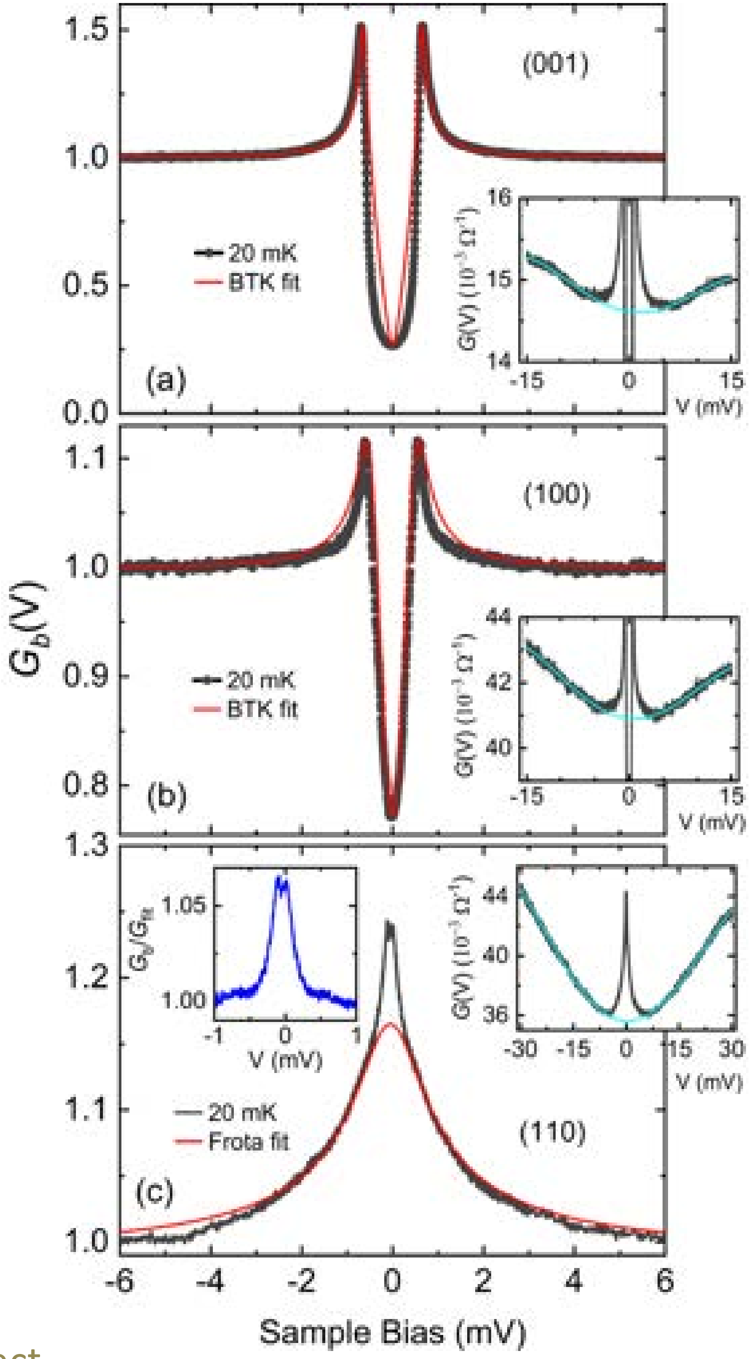
H = 0.2 T applied field => Pb normal
T = 20 mK

(001) and (100): Sharp coherence peaks
Δ = 0.6 meV at *T* = 0.4 K.

(110) Split ZBCP: Andreev Bound States???
Masked due to broad peak from Kondo resonance.

=> **More spectroscopic proof of d_{x2-y2} symmetry**

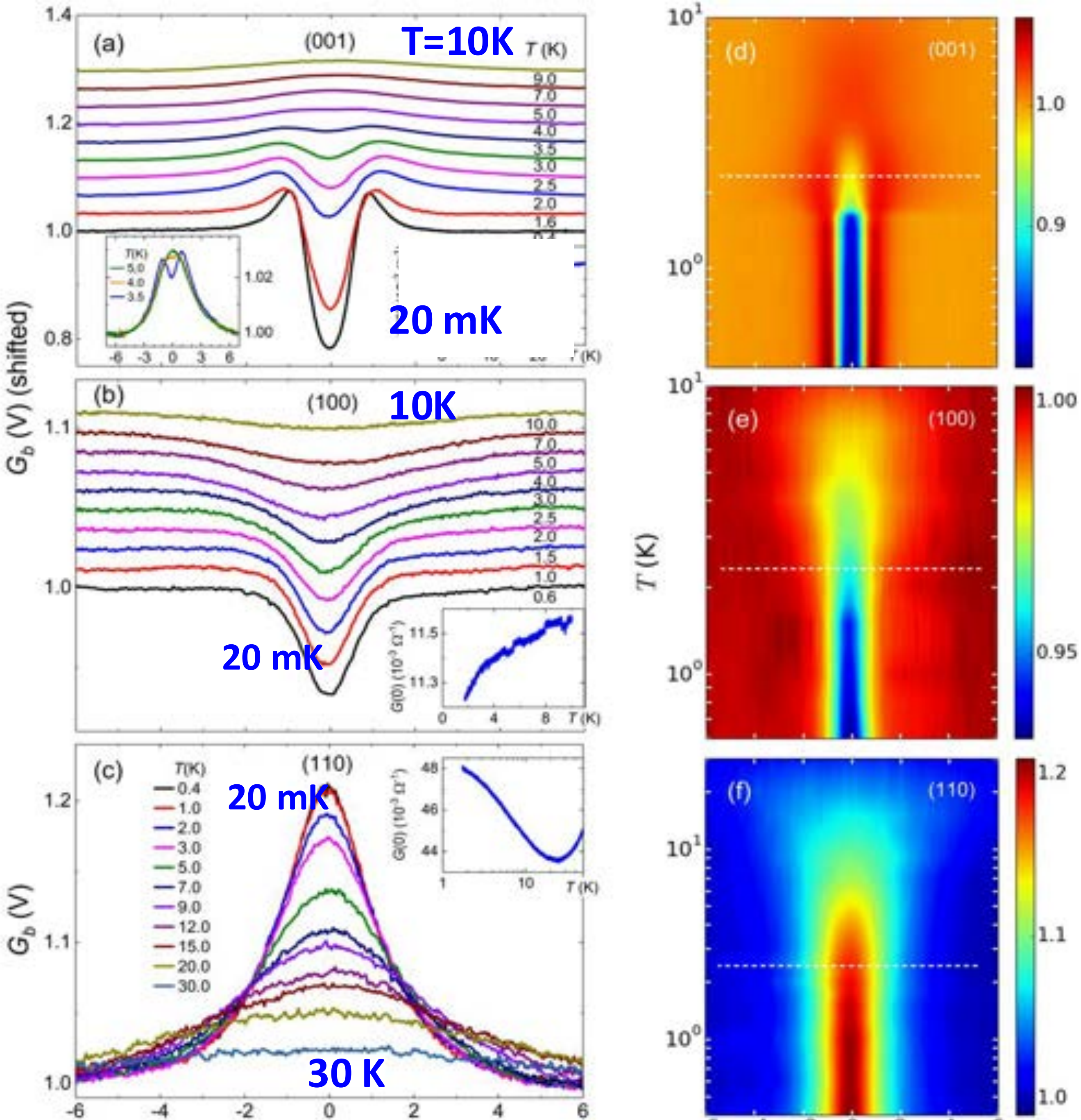
d-wave BTK fit:
Delta - Gamma - Z
(001): 0.66 meV - 042 meV - 2.28
(100): 0.54 meV - 0.198 meV 1.21
Roundness in (001) explained by tunneling cone effect.



T-Dependence of Junctions

H = 0.2 T applied field to drive the Pb normal

Note excess conductance above T_c



T=10K

20 mK

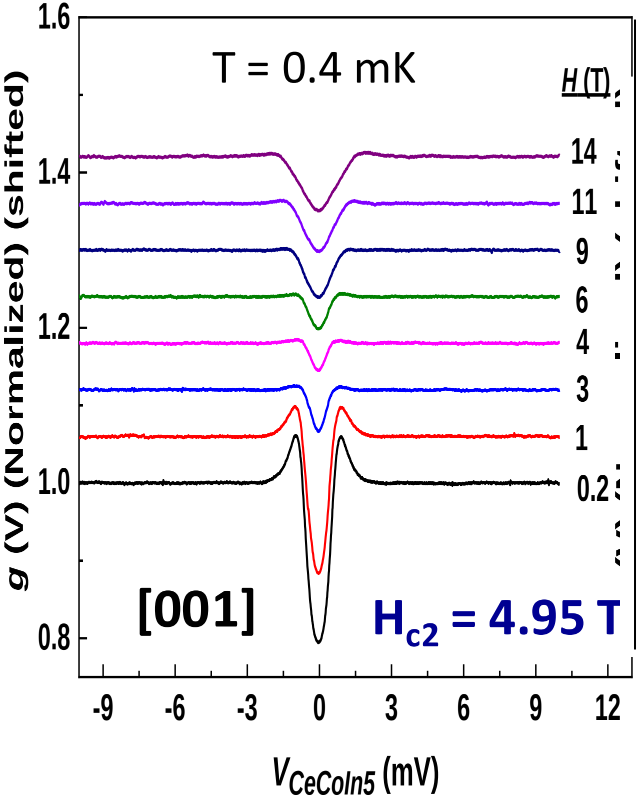
10K

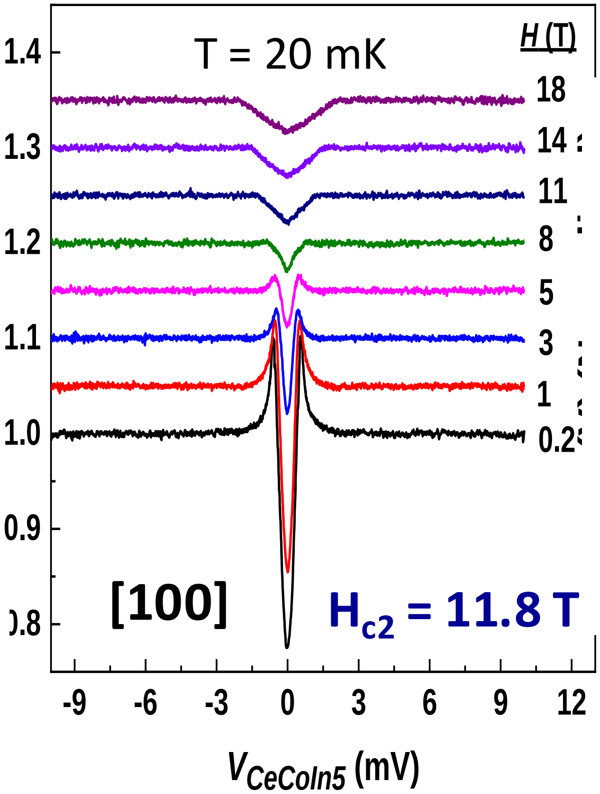
20 mK

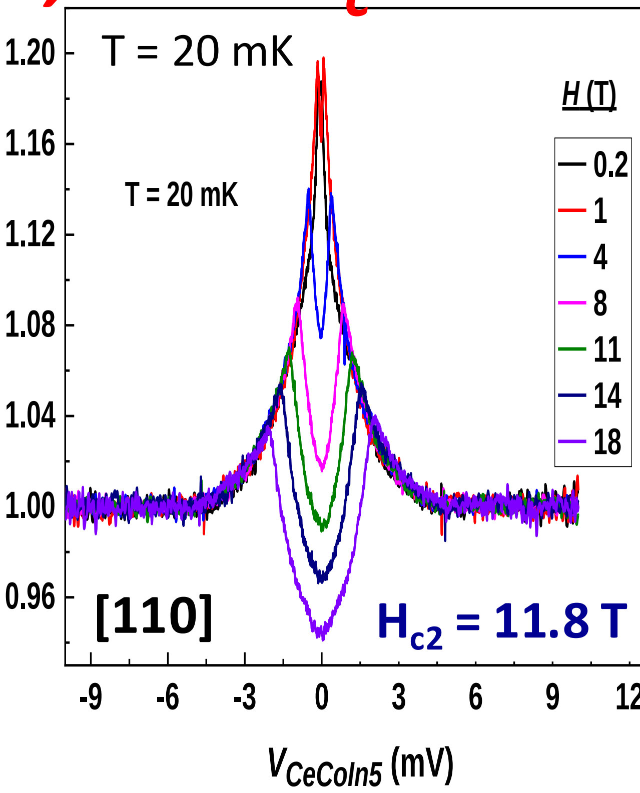
20 mK

30 K

Magnetic Evolution: *T = 20mK; T << T_c*







[001] & [100]: Coherence peaks move inward, **evolving** into **another** gap-like feature splitting

All splitting persist to highest measured field of 18 T; well above H_{c2}

[110]: ZBCP decreases, then splits w/ increasing field (Effects start at lower field due to intrinsic pair breaking in this direction.)

Magnetic Evolution: T = 4K; T > Tc

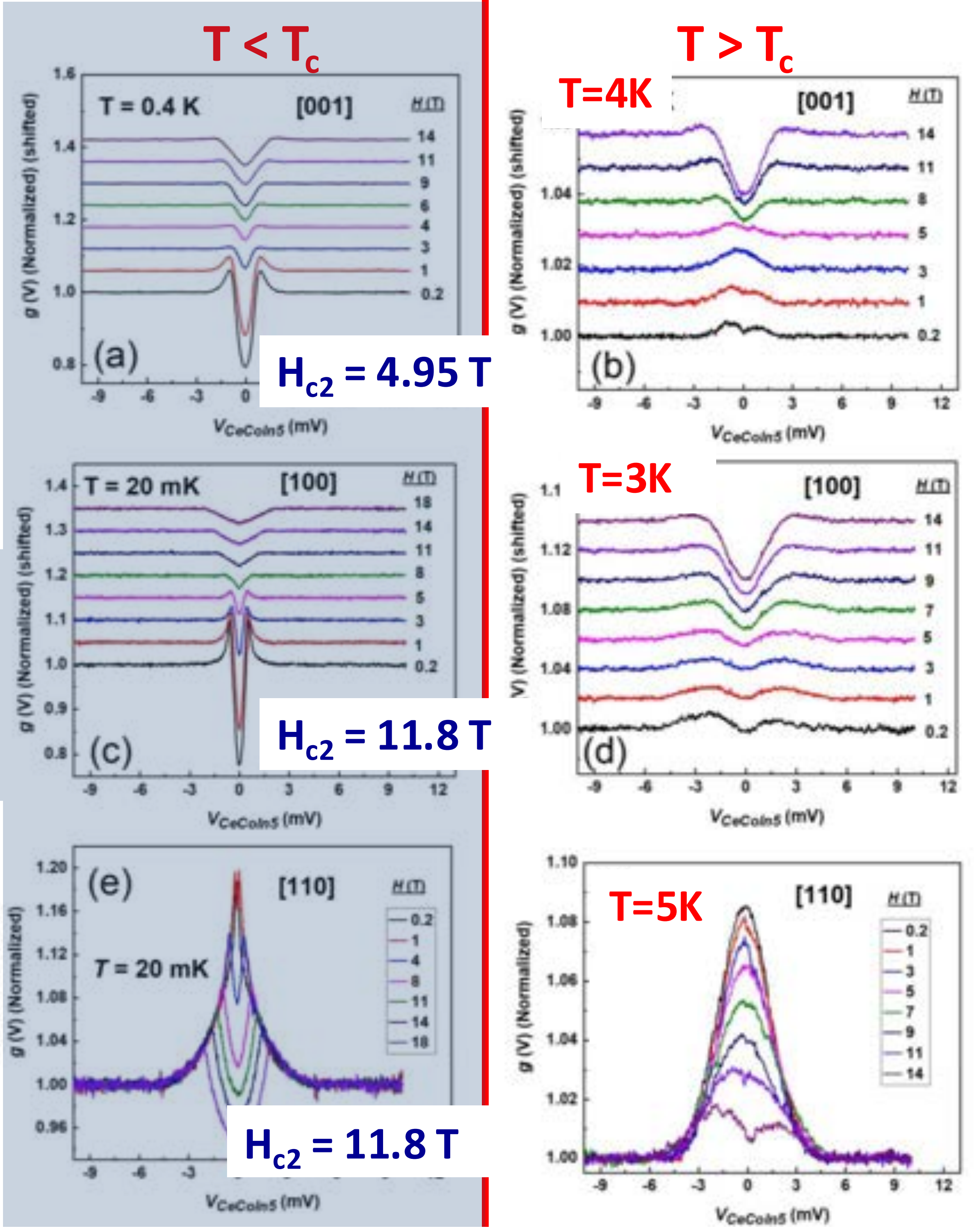
Splittings grow even with T > T_c

LH Column (T < T_c)

(from last slide)

RH Column (T > T_c)

(T_c = 2.3 K)



T < T_c

T > T_c

H_{c2} = 4.95 T

H_{c2} = 11.8 T

H_{c2} = 11.8 T

T=4K

T=3K

T=5K

Magnetic Evolution:
T = 10 K and 15 K
(T >> Tc)

No Field-Induced Gap "FIG"

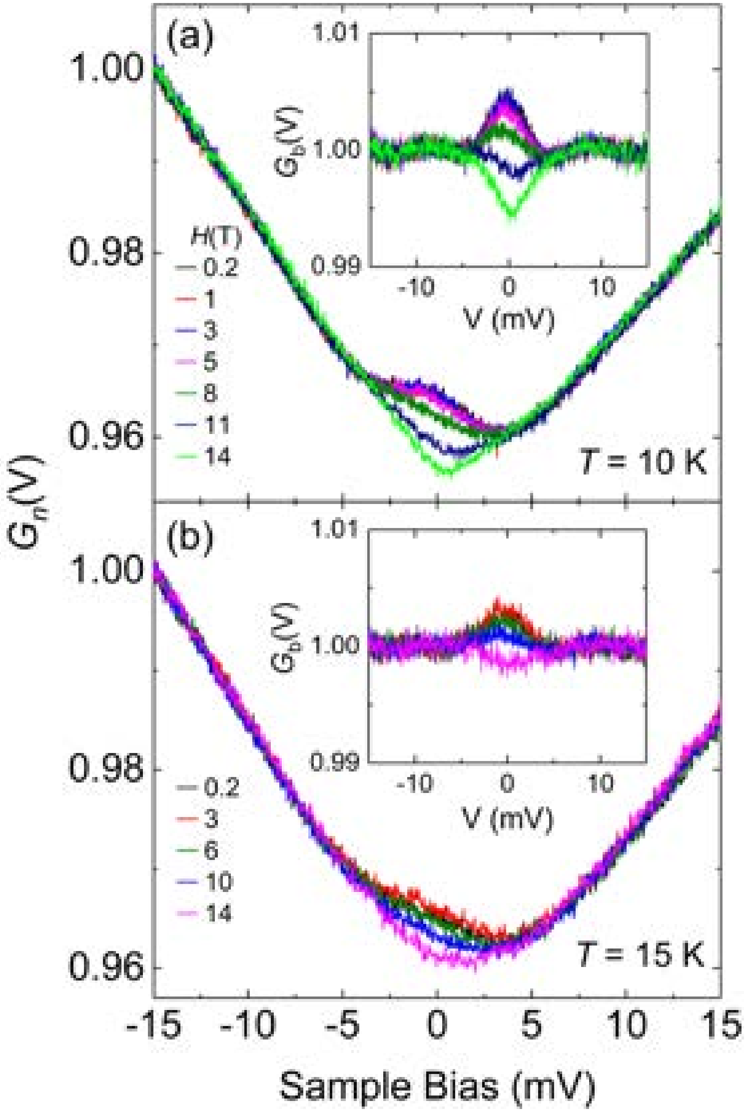
(high-field splitting)

Above T = 5 K ~ T_p

(preformed pairs)

Broad peak is only gradually suppressed with field:

Insets show a small change up to 14 T (< 0.5%)



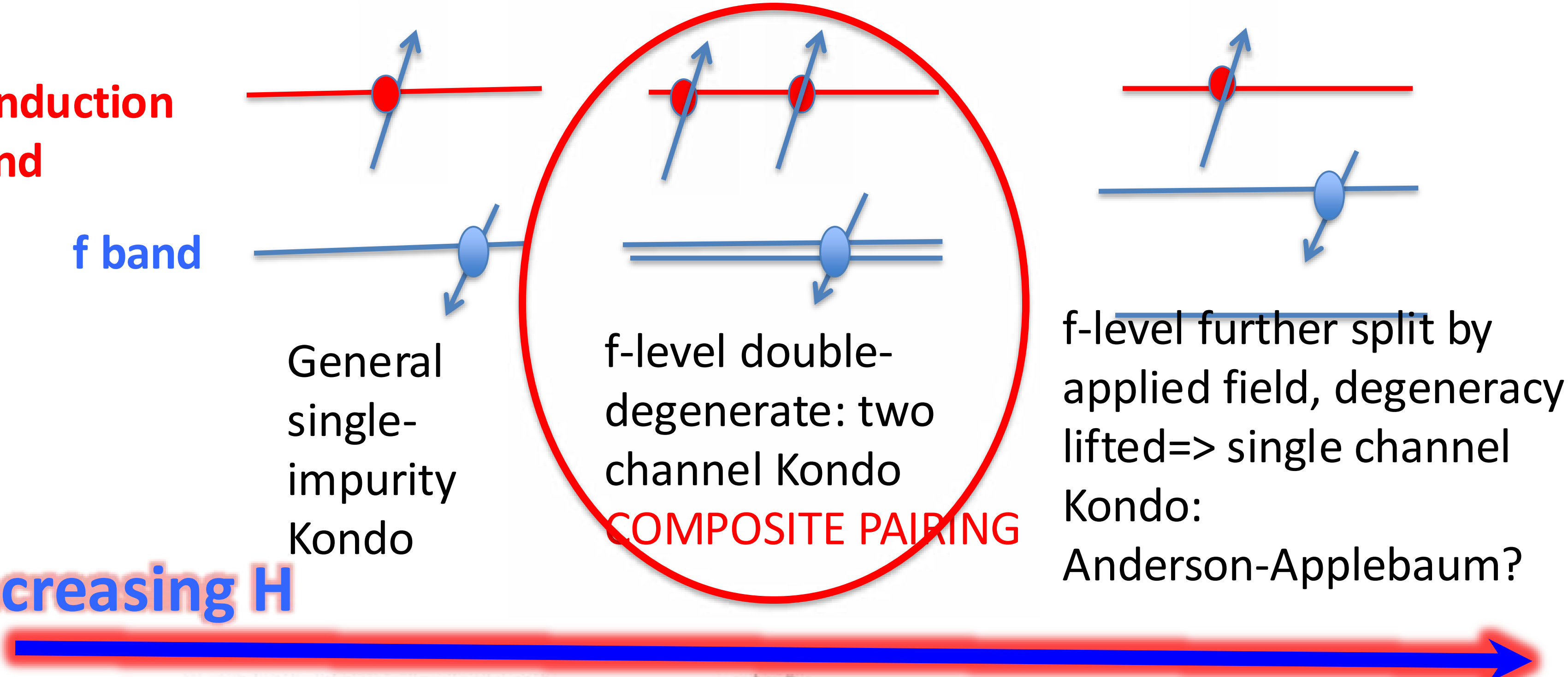
High-field splitting only appears when there are:

preformed (T < Tp ~5 K) or

coherent (T < Tc = 2.3K) Cooper pairs

Model of Composite Cooper Pairing

Cooperative Kondo screening via two channels in the same f-center, so spin direction of Kondo scattering is correlated.



Conduction band

f band

General single-impurity Kondo

f-level double-degenerate: two channel Kondo COMPOSITE PAIRING

f-level further split by applied field, degeneracy lifted=> single channel Kondo: Anderson-Applebaum?

Increasing H

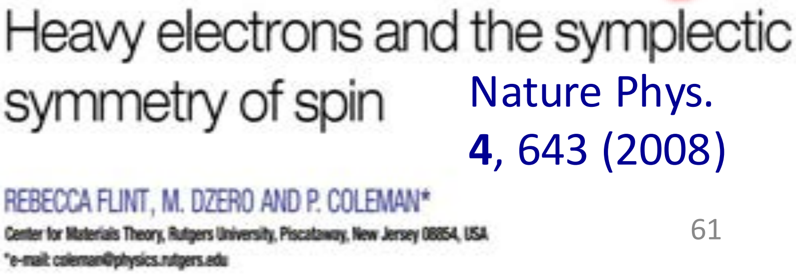
PRL 105, 246404 (2010) PHYSICAL REVIEW LETTERS week ending 10 DECEMBER 2010

Tandem Pairing in Heavy-Fermion Superconductors

Rebecca Flint and Piers Coleman

Center for Materials Theory, Rutgers University, Piscataway, New Jersey 08854, USA

(Received 10 May 2010; published 8 December 2010)



Heavy electrons and the symplectic symmetry of spin

REBECCA FLINT, M. DZERO AND P. COLEMAN*

Center for Materials Theory, Rutgers University, Piscataway, New Jersey 08854, USA

*e-mail: coleman@physics.rutgers.edu

Nature Phys. **4**, 643 (2008)

I. Summary Notes: Our $CeCoIn_5$ PTS data show

1. d_{x2-y2} pairing symmetry.
2. Preformed pairs exist at least to ~ 5 K (T_c = 2.3 K).
3. Increasing magnetic field suppresses the SC gap and induces a new gap persisting up to 18 T, the highest field measured (well above H_{c2}).
4. Smooth conductance field evolution from SC to field-induced gap.
5. There is no field-induced gap above preformed pair T ~ 5K
6. The field-induced gap grows linearly with field: Zeeman-like, just like the single-impurity Kondo effect (Anderson-Applebaum).
7. The neutron spin-resonance seen in the tunneling in the cuprate and Fe-based SCs is ***NOT SEEN*** in any of the tunneling into $CeCoIn_5$.

   (see next slide…)

Summary II: Planar Tunneling Spectroscopy of $CeCoIn_5$

The neutron spin-resonance seen in the tunneling in the cuprate and Fe-based SCs is ***NOT SEEN*** in any of the tunneling into $CeCoIn_5$.

In the **cuprates and Fe-based SCs**, the INS resonance at ~ 40 meV is spin-exciton-like and is observed in STM. This is taken not only as a signature of the sign change of the order parameter, but since this spin-spin correlation peak is observed in the tunneling spectra, this exciton plays a major role in the Cooper pairing.

Yu Song et al measure the inelastic neutron scattering in **Ce_{1-x} Yb $_x$CoIn$_5$** and find the resonance at 0.6 meV:

a) This peak is robust against Yb doping (not Tc-dep);
b) It is magnon-like, not spin-exciton-like in character

Robust upward dispersion of the neutron spin resonance in the heavy fermion superconductor $Ce_{1-x}Yb_xCoIn_5$

Yu Song, John Van Dyke, I. K. Lum, B. D. White, Sooyoung Jang, Duygu Yazici, L. Shu, A. Schneidewind, Petr Čermák, Y. Qiu, M. B. Maple, Dirk K. Morr & Pengcheng Dai

Nature Communications **7**, Article number: 12774 (2016) | Download Citation

That this neutron resonance is not seen in any of the tunneling into $CeCoIn_5$ indicates it does mot play a major role in the Cooper pairing.

Conclusions: Our $\mathrm{CeCoIn_5}$ PTS data show

Our temperature, magnetic field, and orientational - dependent planar tunneling data (high-quality and reproducible), and considering other published data, our results are consistent with Cooper paring due to:

- **Two Channel Kondo Scattering; and**
- **Composite d-wave pairing as <u>candidate</u> for the mechanism**

Some Grand Challenges

- What are the different ways quantum matter* can order?
  *Largely unsolved; ~50 classes of non-Fermi liquids
- What are the potential uses of **correlated and topological states of matter**?
- Can quasiparticles be "engineered?"
- **Overarching Theme:** The **1st quantum revolution** led to the notion of electrons and holes in semiconductors that fueled much of modern information technology. What new powerful ideas will come out of the **2nd quantum revolution** that will help us create the next generation of quantum devices? Or:
  "The 1st quantum revolution: understanding and controlling the magnitude of the quantum
  The 2nd quantum revolution is about controlling its phase"

Materials are the Future

All advances in the human condition are all based on advances in materials research. **We use materials to describe human progress – the bronze age, the iron age, and today silicon - have each ushered in new eras of expansion.** Today, advances in semiconductors power the digital world, novel materials are advancing batteries and energy storage, making carbon capture possible, new biologics improve health outcomes, and superconductors make MRI possible have promise to revolutionize our energy needs.

Many of the most important breakthrough discoveries in material science have been serendipitous – based on hunches from people who have had decades of experience, trying out new things, who seem to know “where to go” to find the next novel material. The breakthrough is followed by further incremental innovations to bring the discovery to reality.

It’s worth adding, that for quantum detection and computation, we have not found the qubits that are both usable and scalable (cold atoms, superconductors):

We need fundamental materials research.