Qu-Transitions

P. Coleman
(CMT, Rutgers)

University Toronto
Toronto, Sept 17
2009.

Rutgers
Center for Materials Theory

Qu-Transitions

"Phase transitions in the quantum era"

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Center for Materials Theory

- The Qu-era: from classical to quantum.
- Classical criticality
- Heavy Fermion Quantum Criticality.
- New Approaches and Ideas
- Avoided Criticality

RUTGERS
UNIVERSITY

1758 in Paris: 72 years after “Principia”

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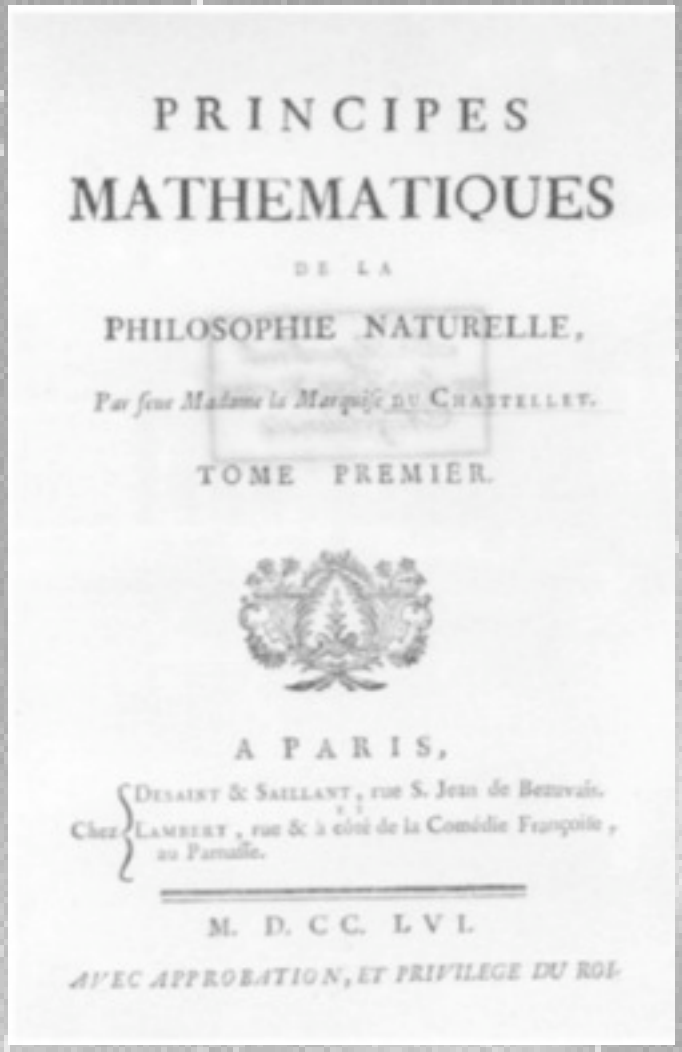

PRINCIPES

MATHEMATIQUES

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PHILOSOPHIE NATURELLE,

Par feue Madame la Marquise DU CHASTELLET.

TOME PREMIER.

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M. D. CC. LVI.

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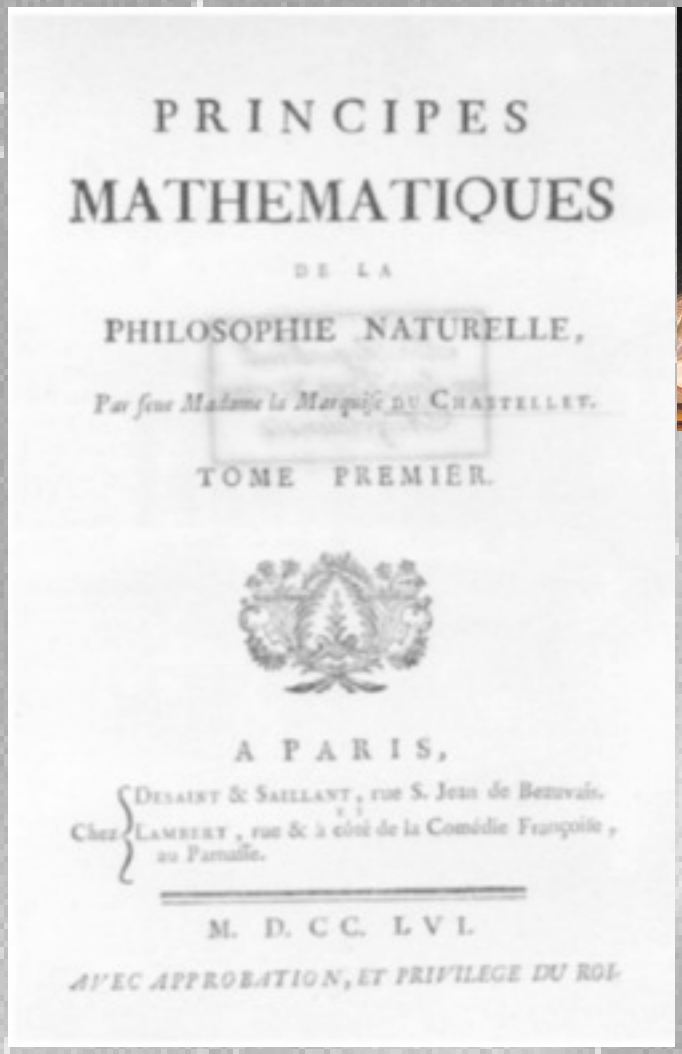

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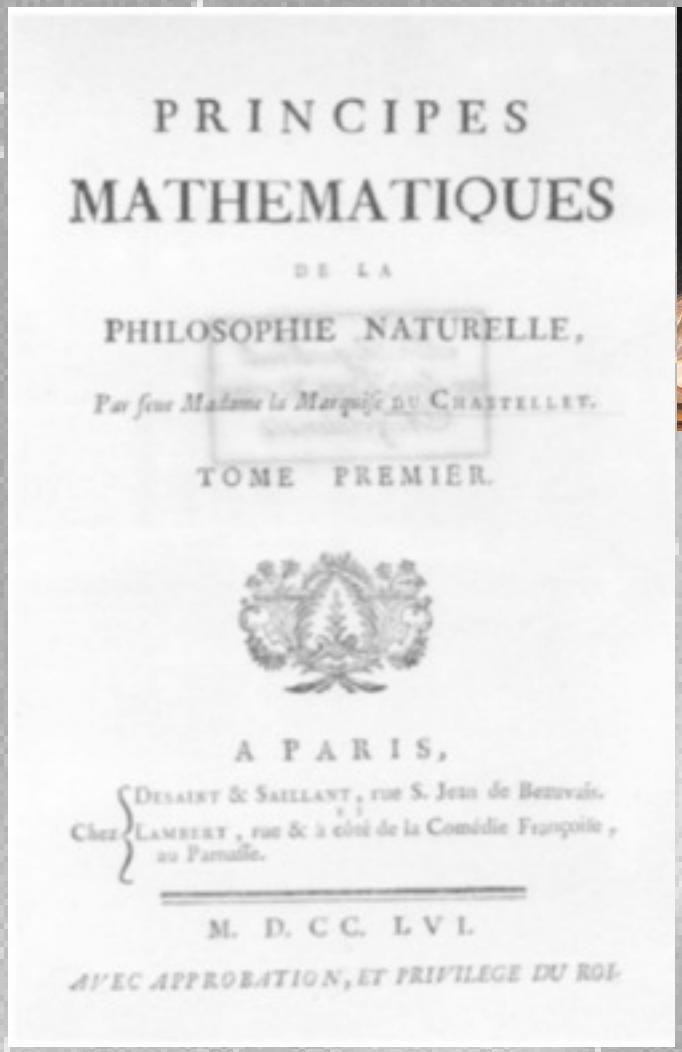

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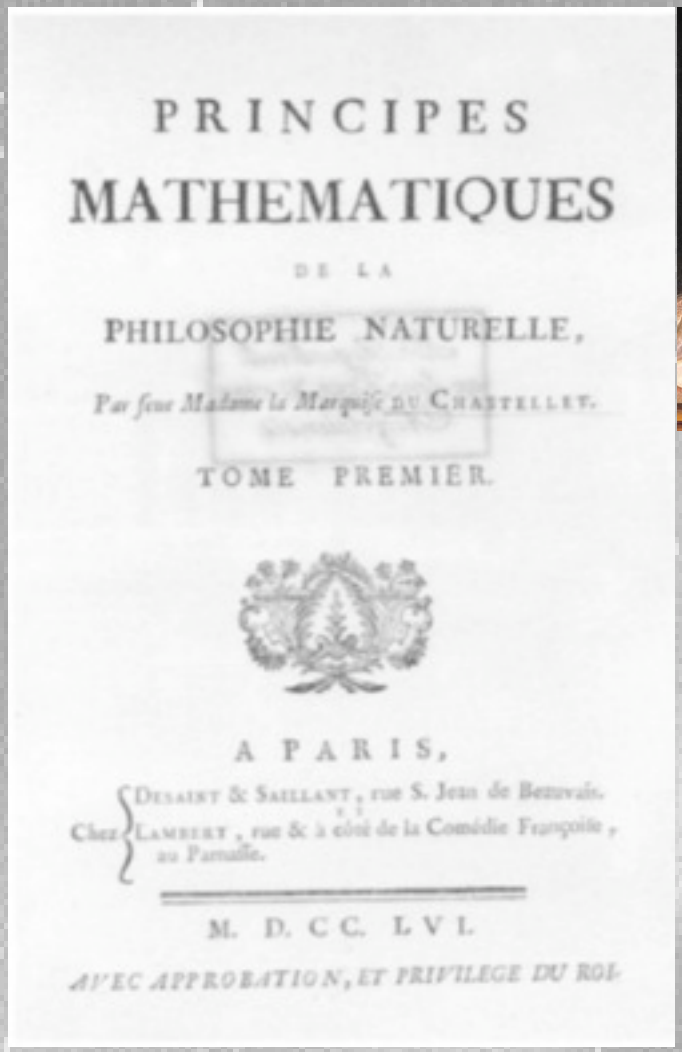

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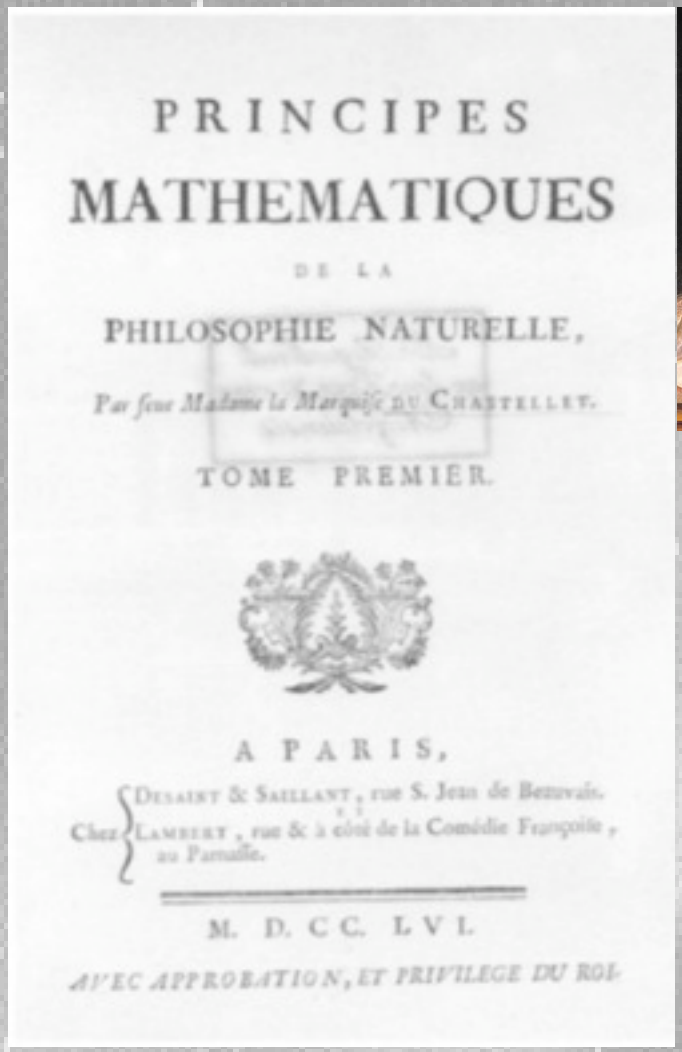

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Resolution of the controversy (and the missing factor of a half) required a further 60-80 years.

108 years after Planck, many
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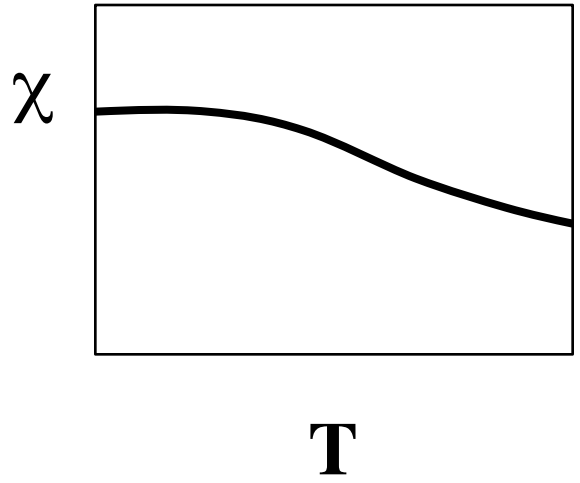


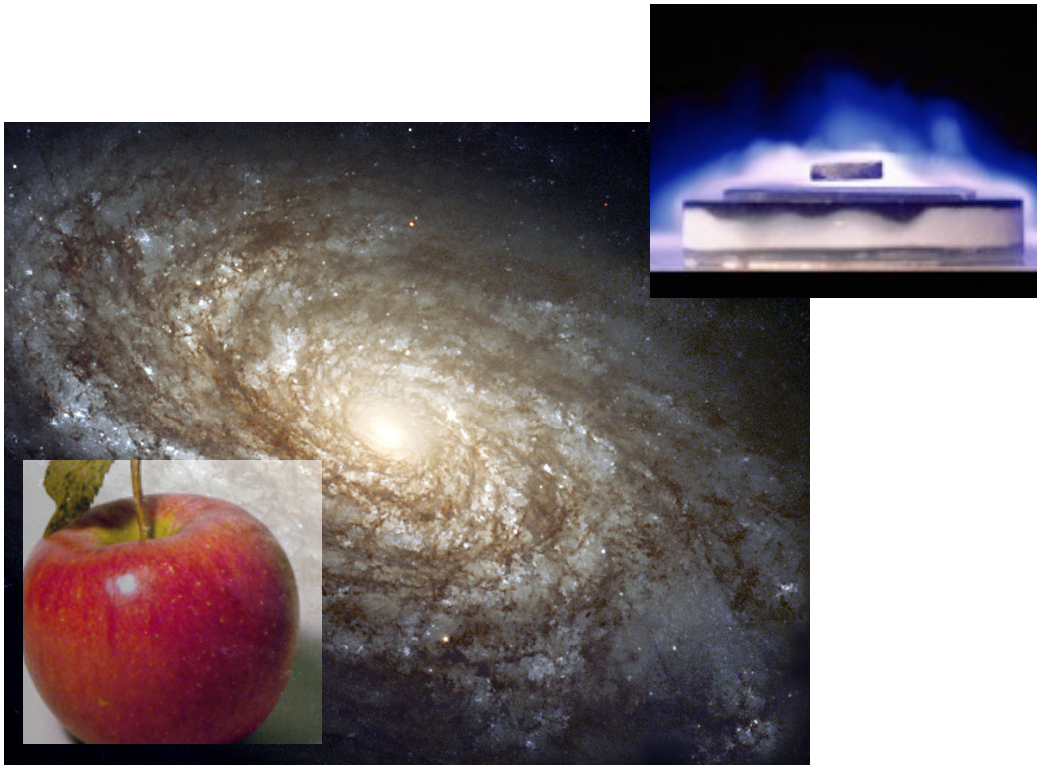
"With a heavy heart, I have been converted to the idea that Fermi -Dirac, not Einstein-Bose is the correct statistics. I wish to write a short note on its application to paramagnetism."

W. Pauli, in letter to Schrödinger, Dec 1926.

108 years after Planck, many surprises later, the quantum era is in full sway.

David Pines in
musicofthequantum.rutgers.edu

Quantum zero point fluctuations:



Quantum zero point fluctuations:
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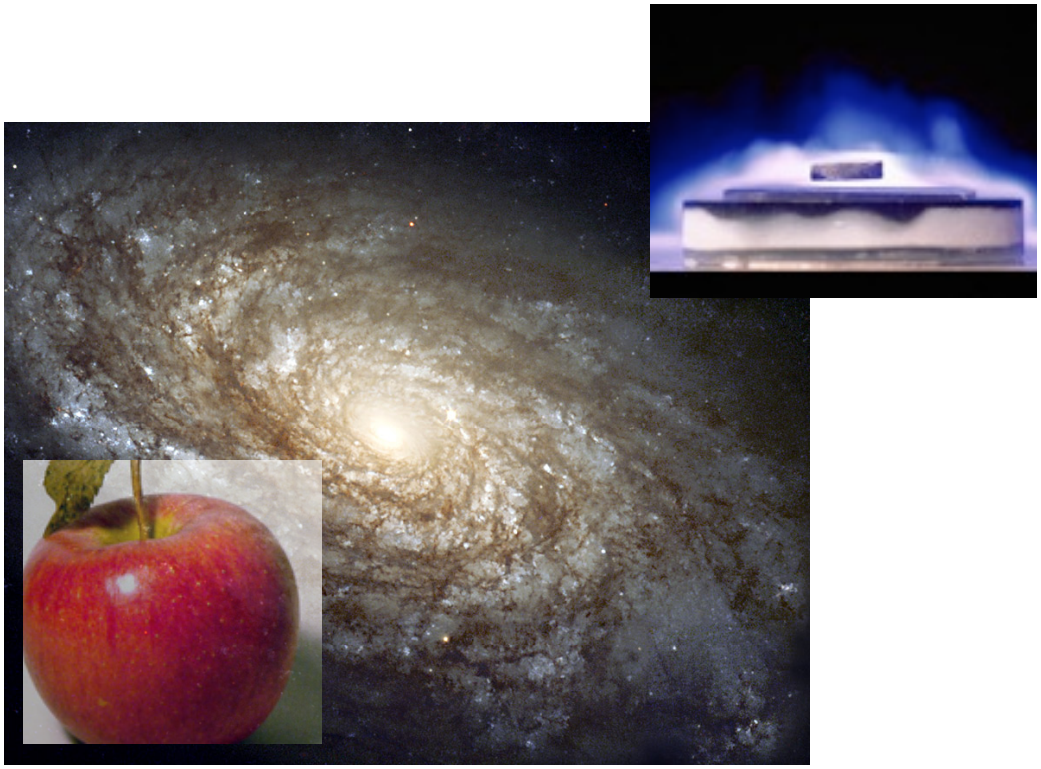

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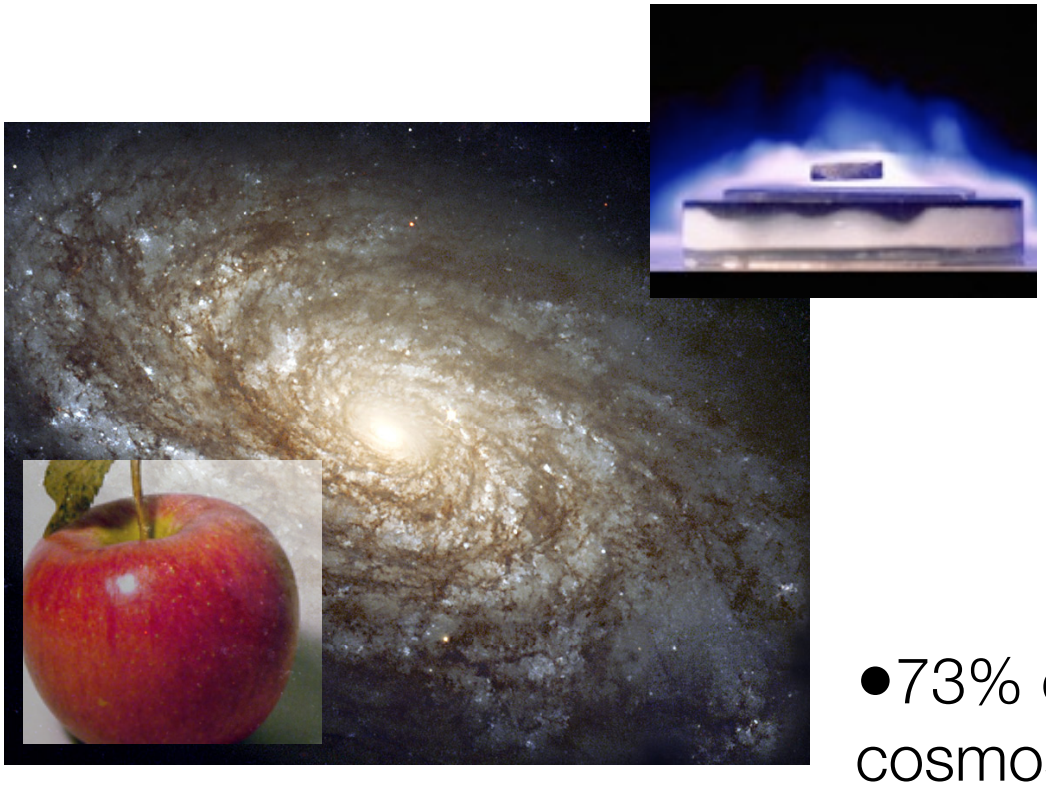
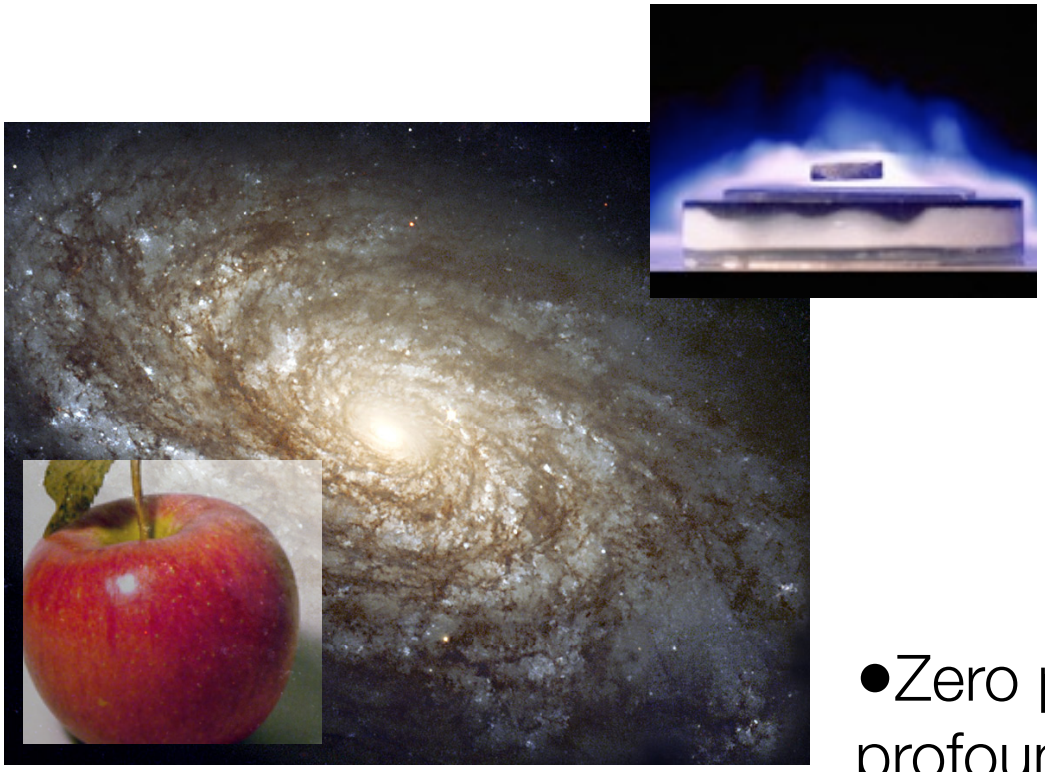


- 73% of the mass of the cosmos is “Dark Energy”: an unidentified form of zero point energy, causing the expansion to accelerate.

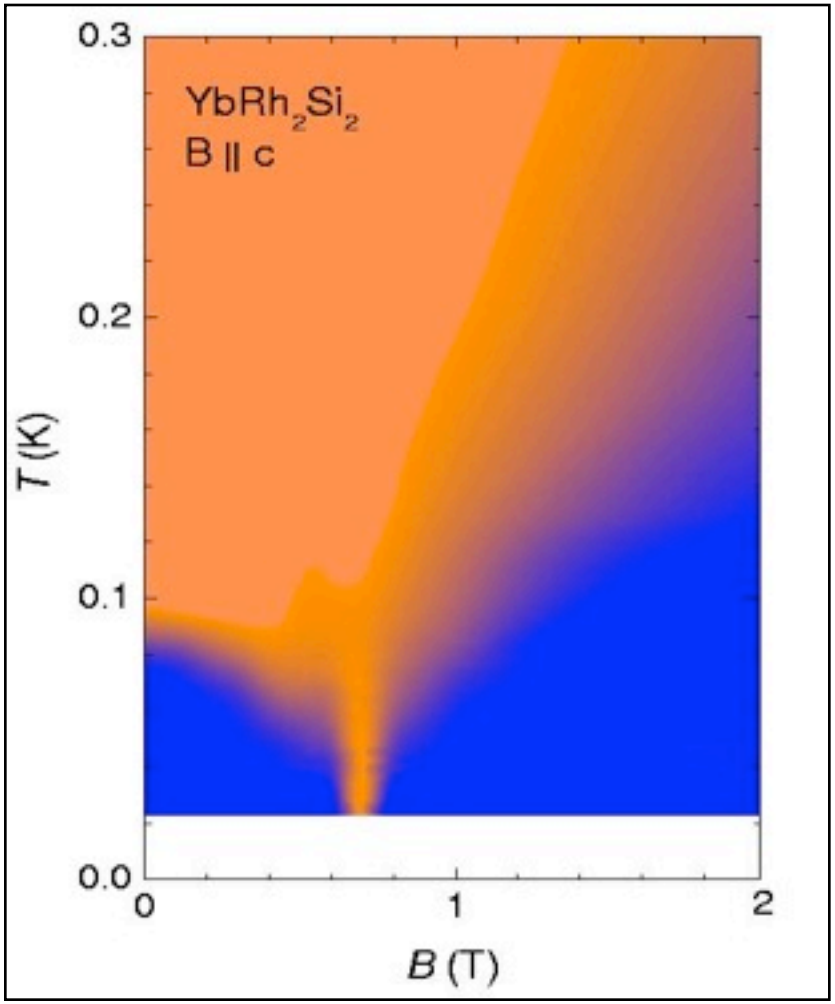
Quantum zero point fluctuations: major unsolved problem of the quantum era.



- Zero point fluctuations profoundly transform matter, endowing it with marked tendency to develop new forms of order.

Classical Criticality

Custers et al (2002)



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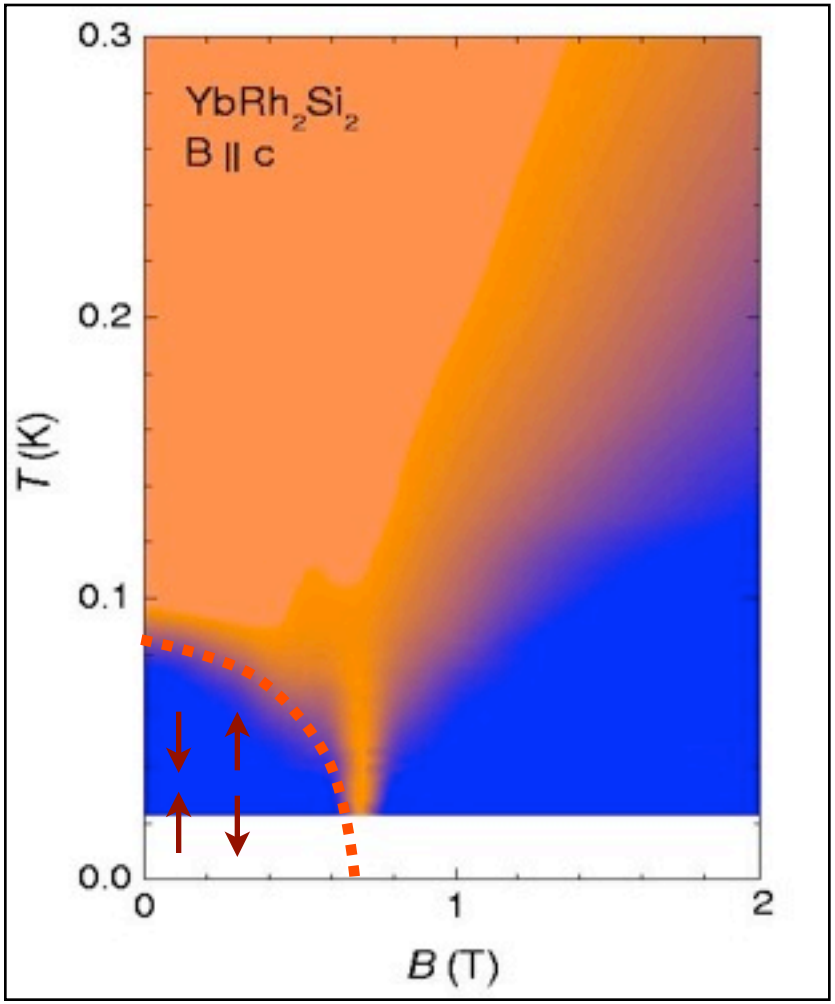

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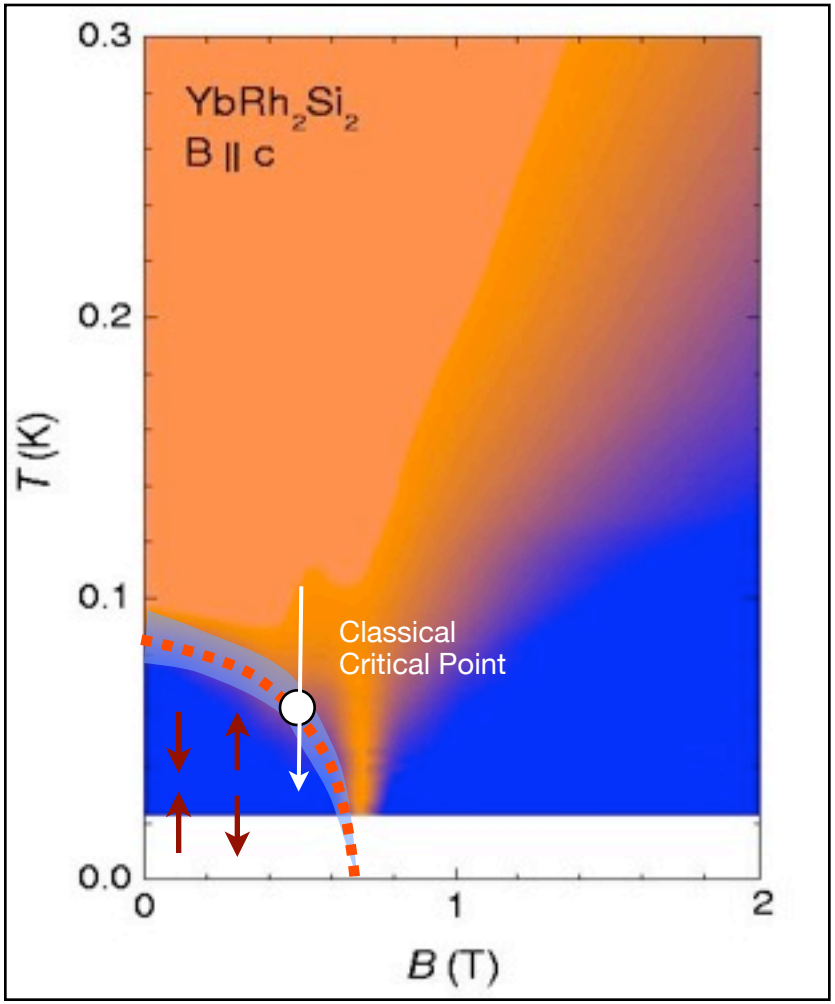

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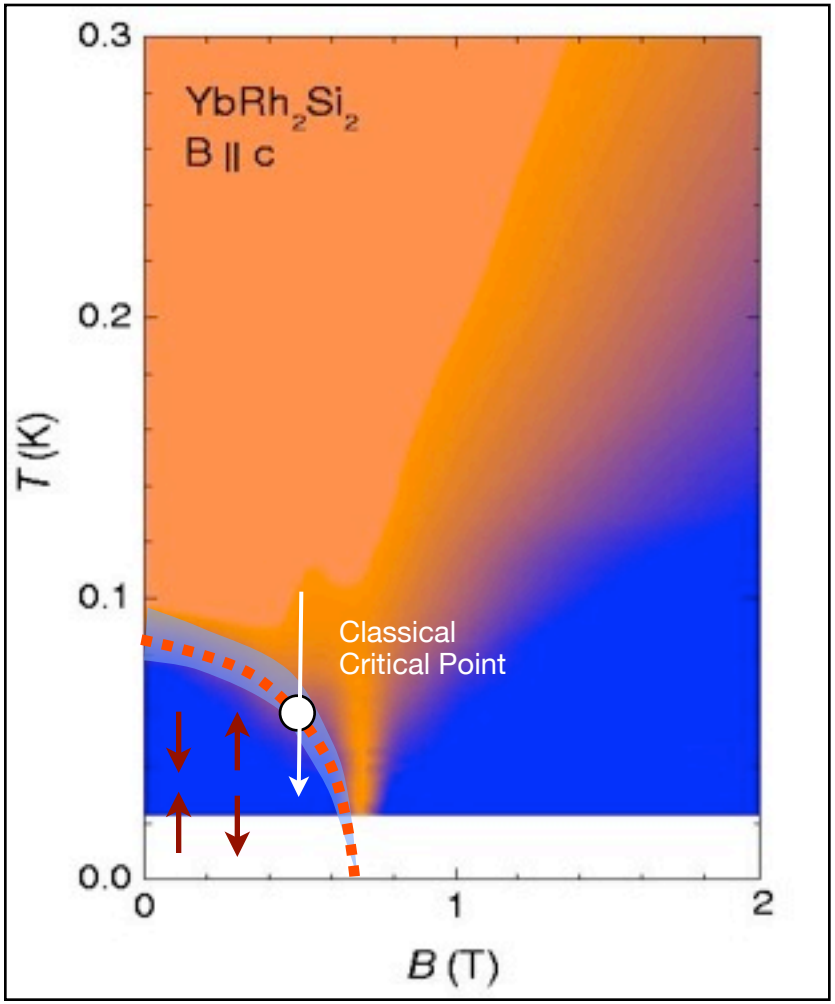

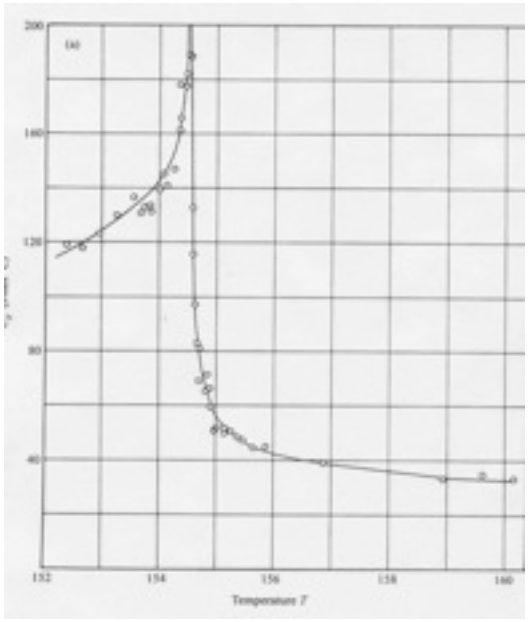

Oxygen. (Voronel et al 1963).

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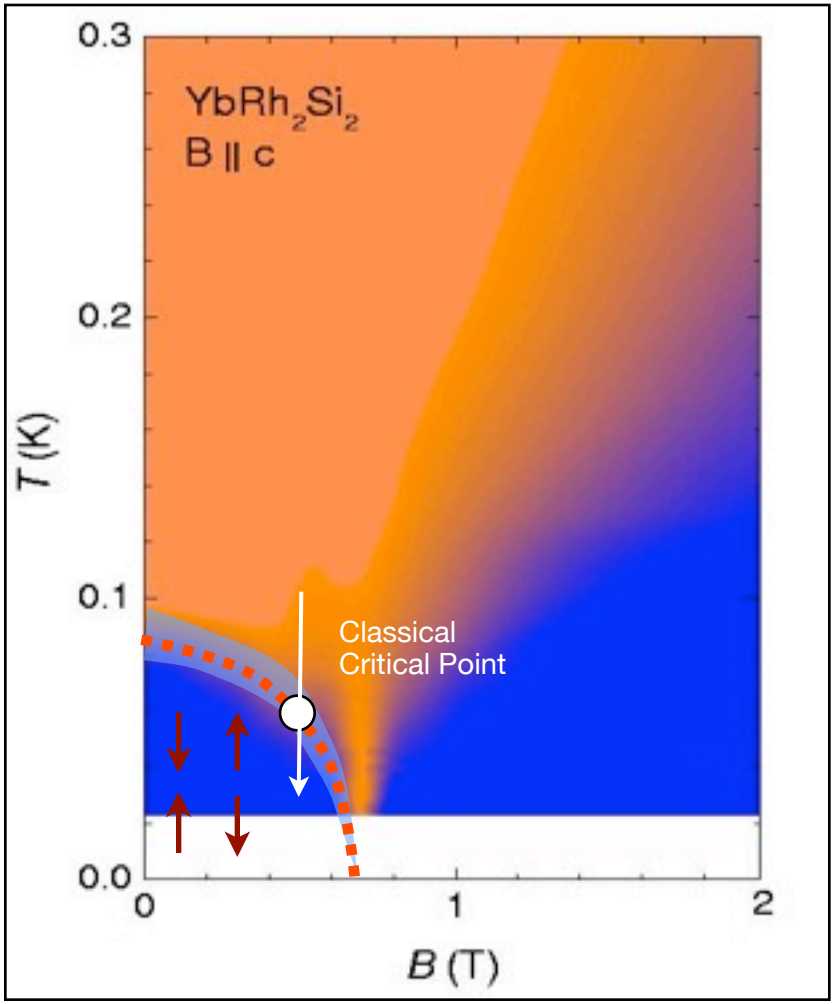

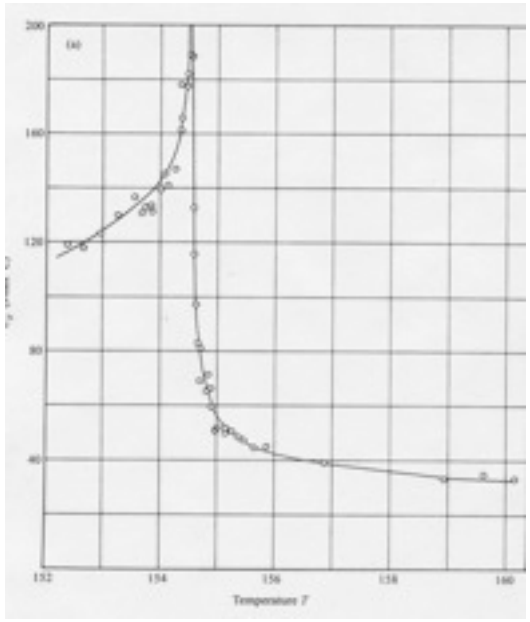

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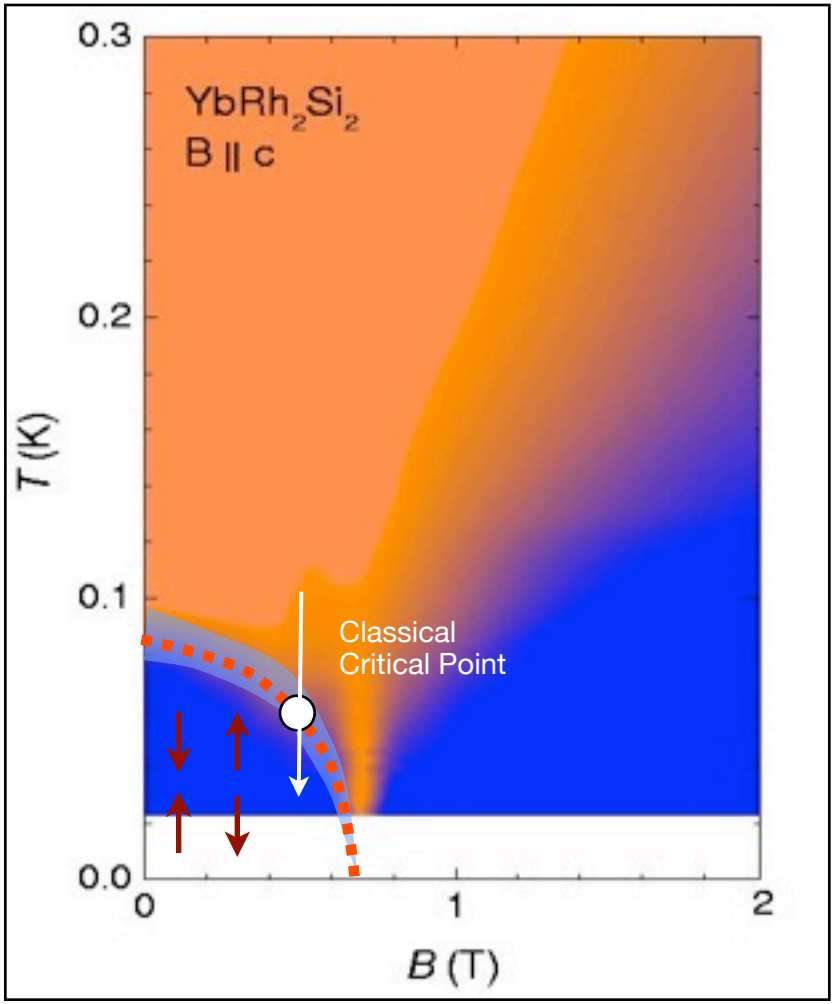

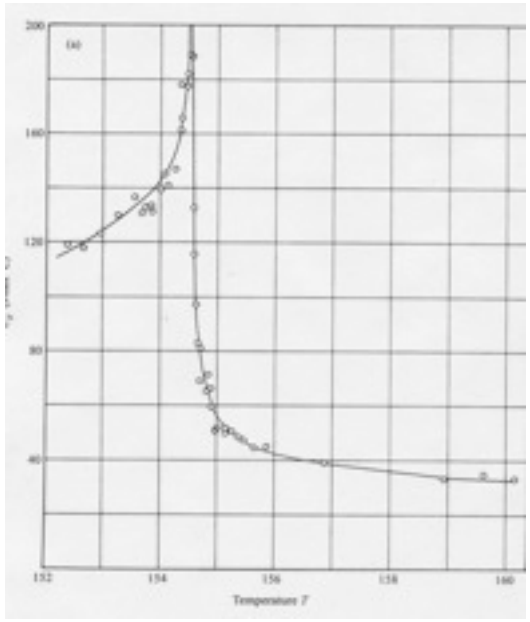

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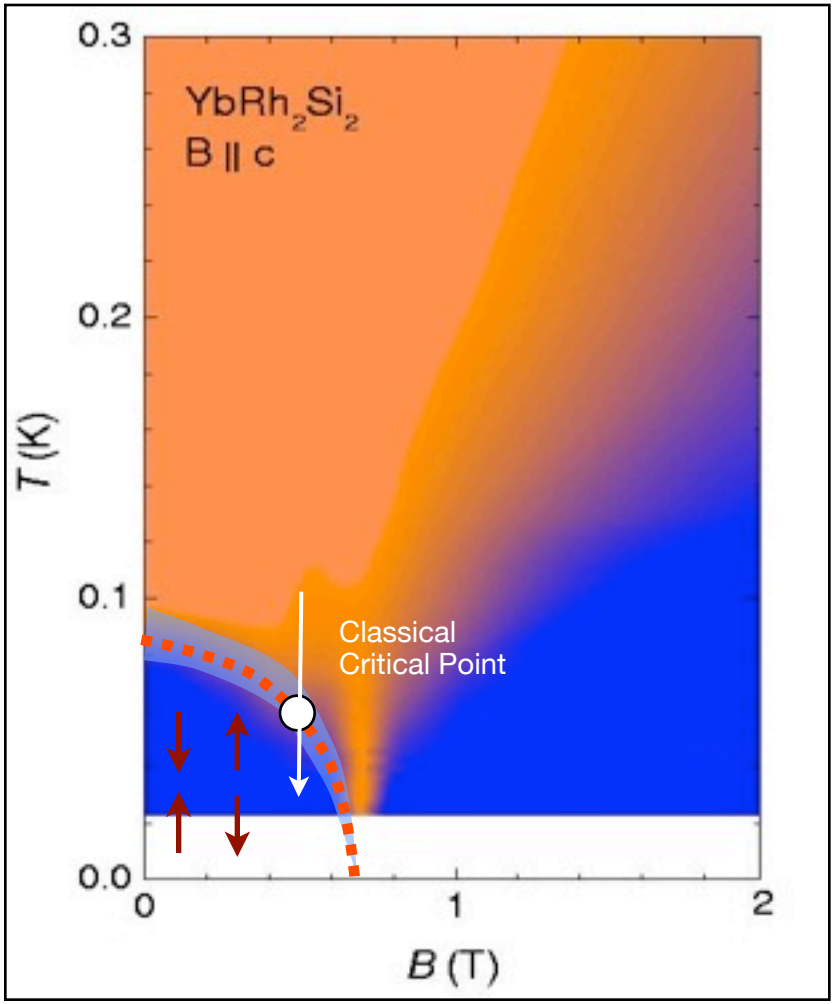

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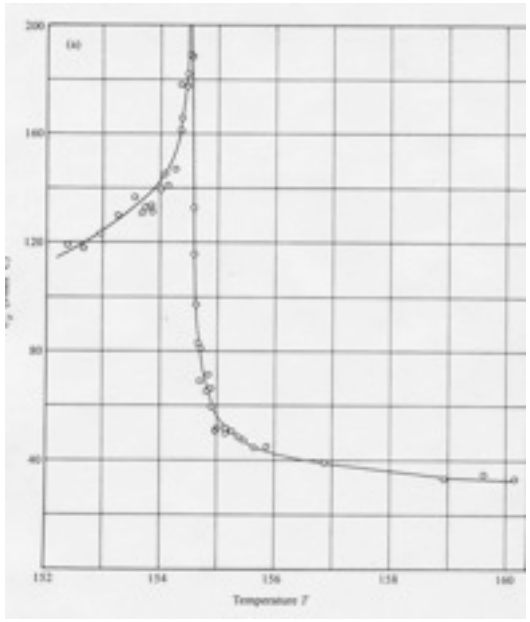

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"20th Century Revolution"

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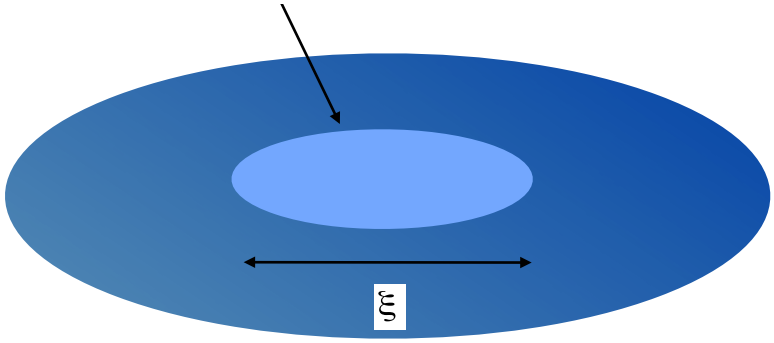
Critical matter



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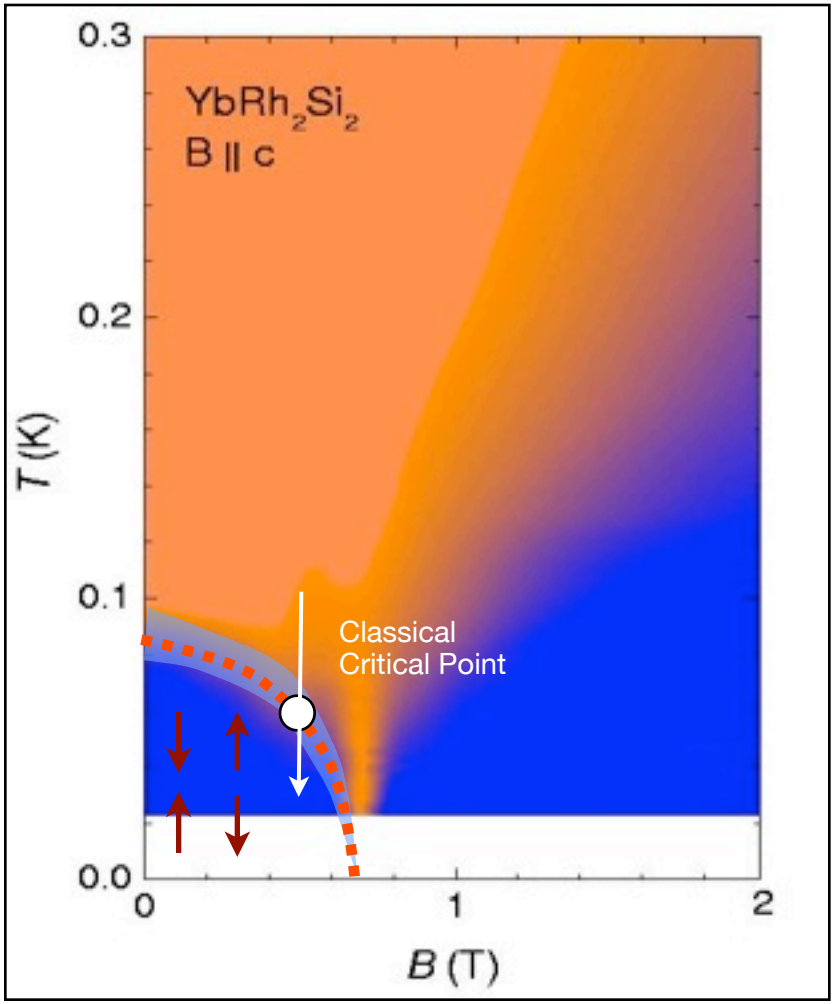

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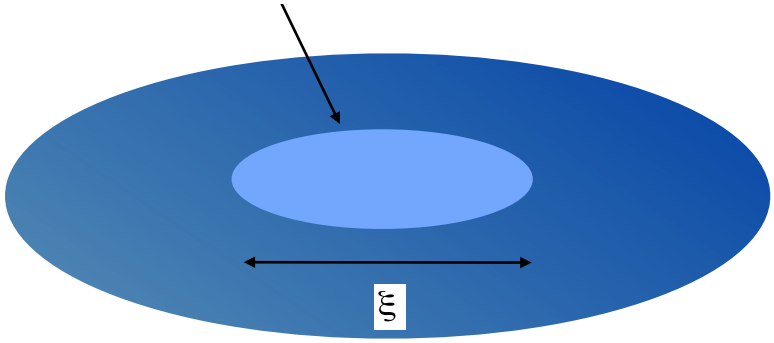
Critical matter - universal



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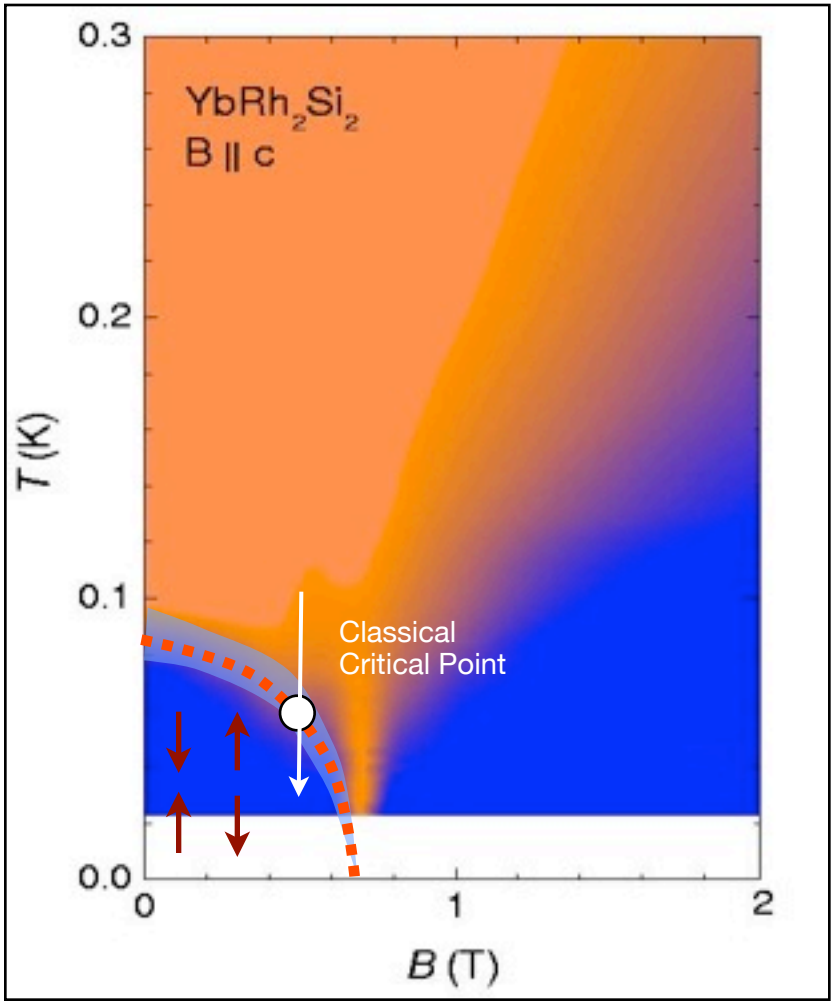

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Quantum Phase-Transition

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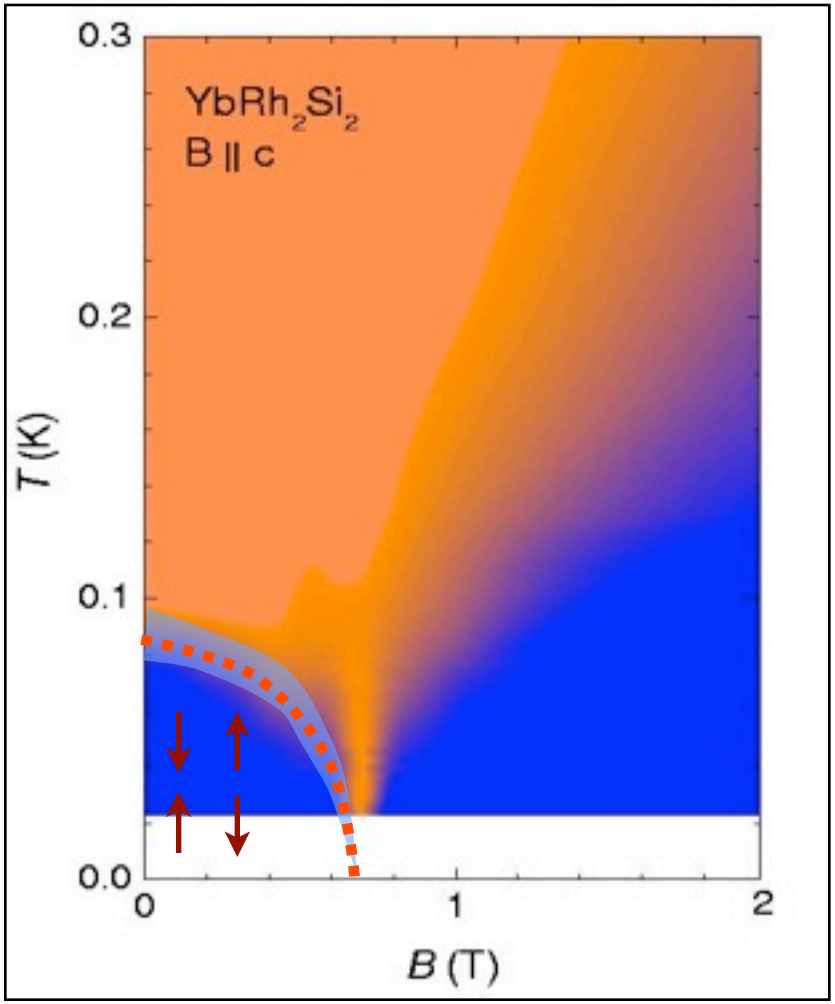

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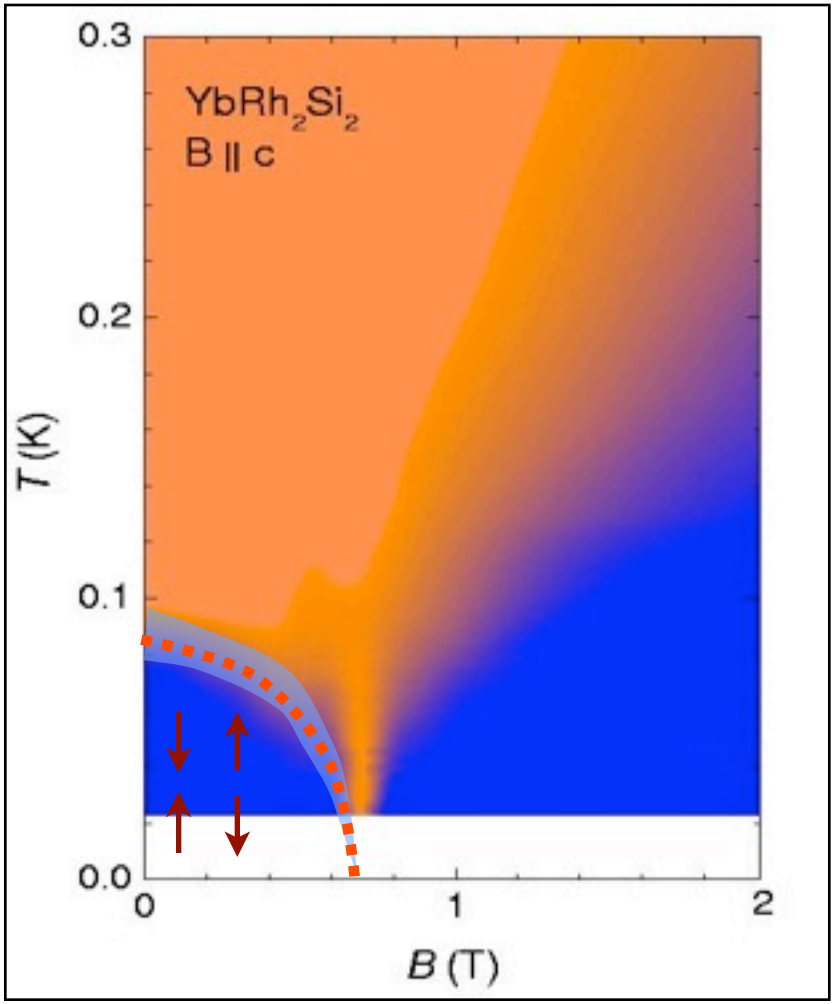
Phase transition
driven by zero point motion.



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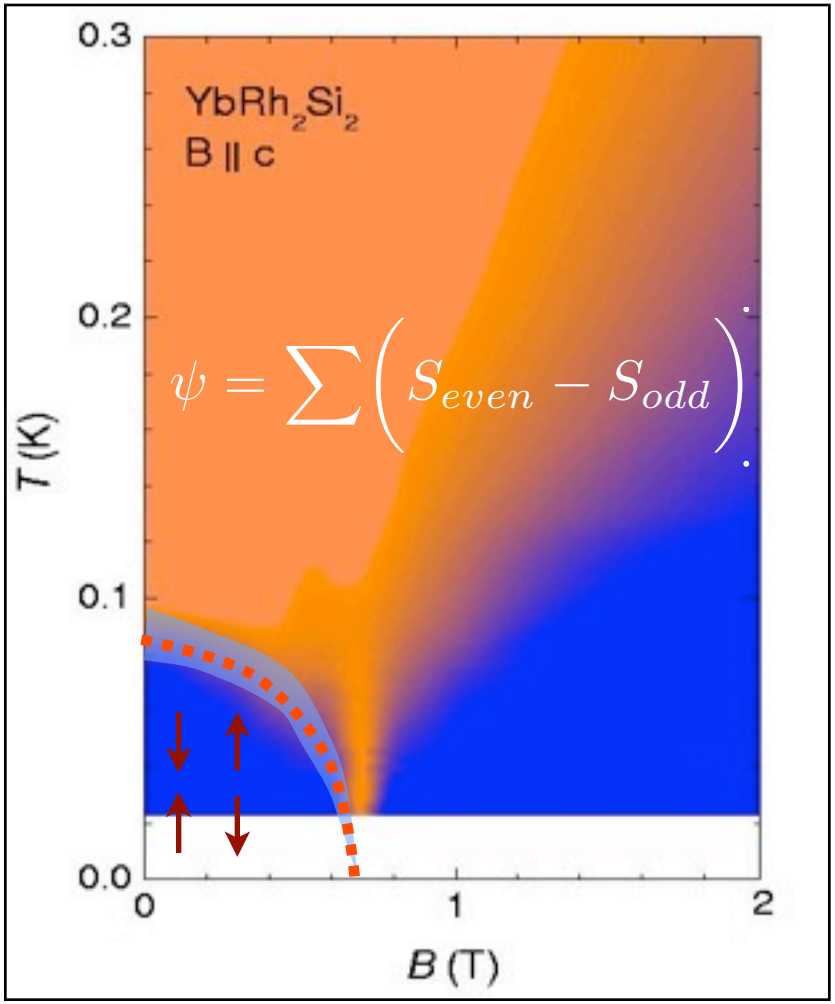

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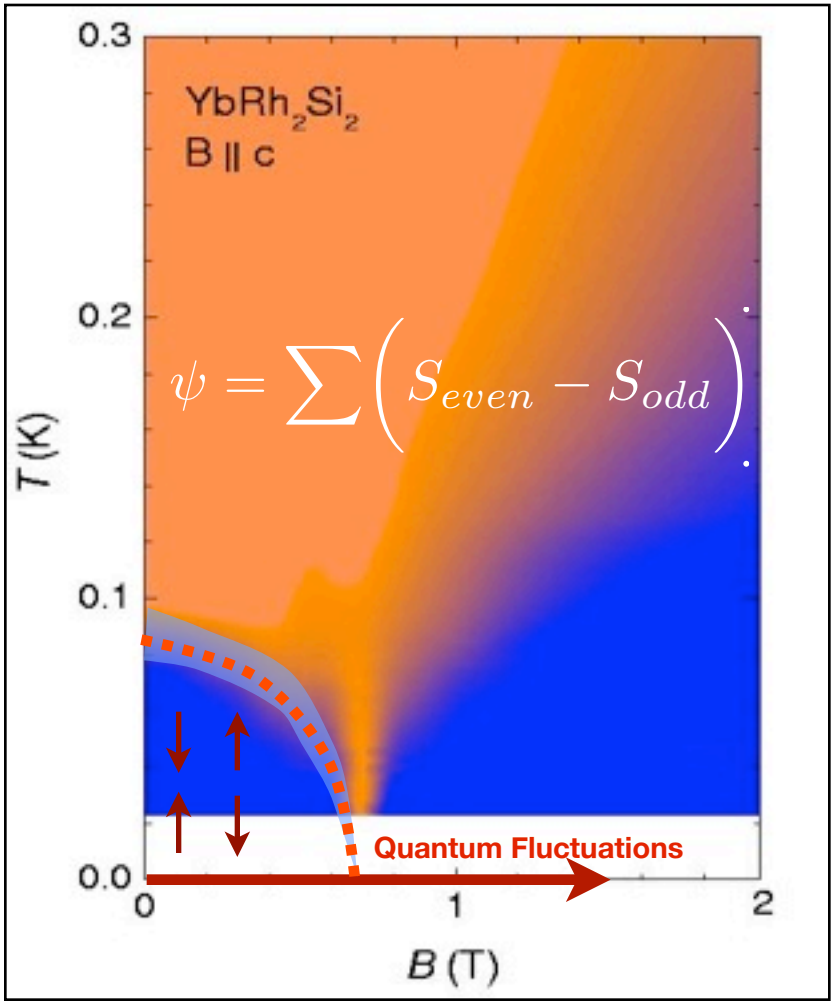

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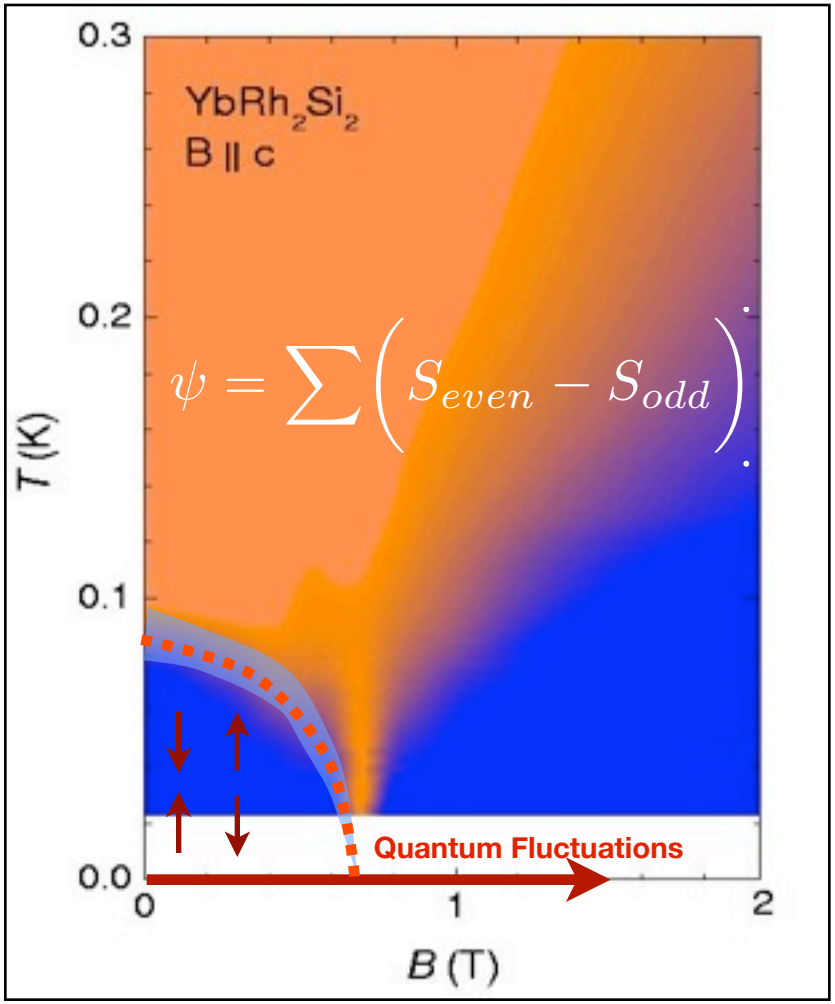

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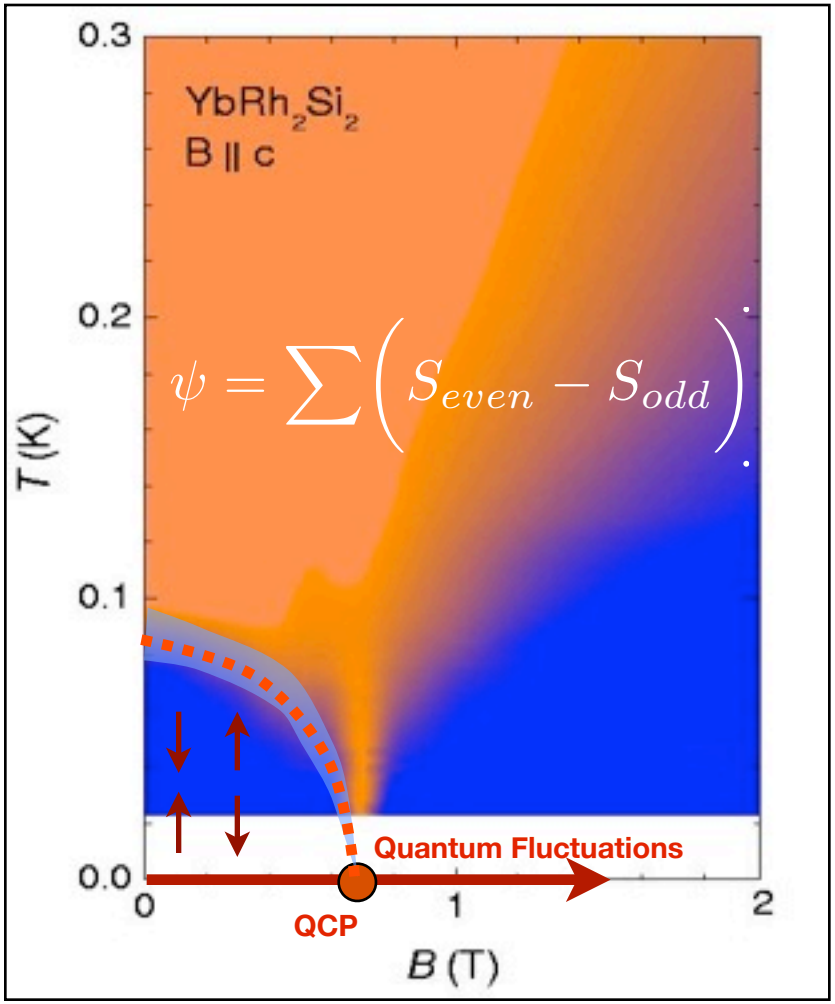

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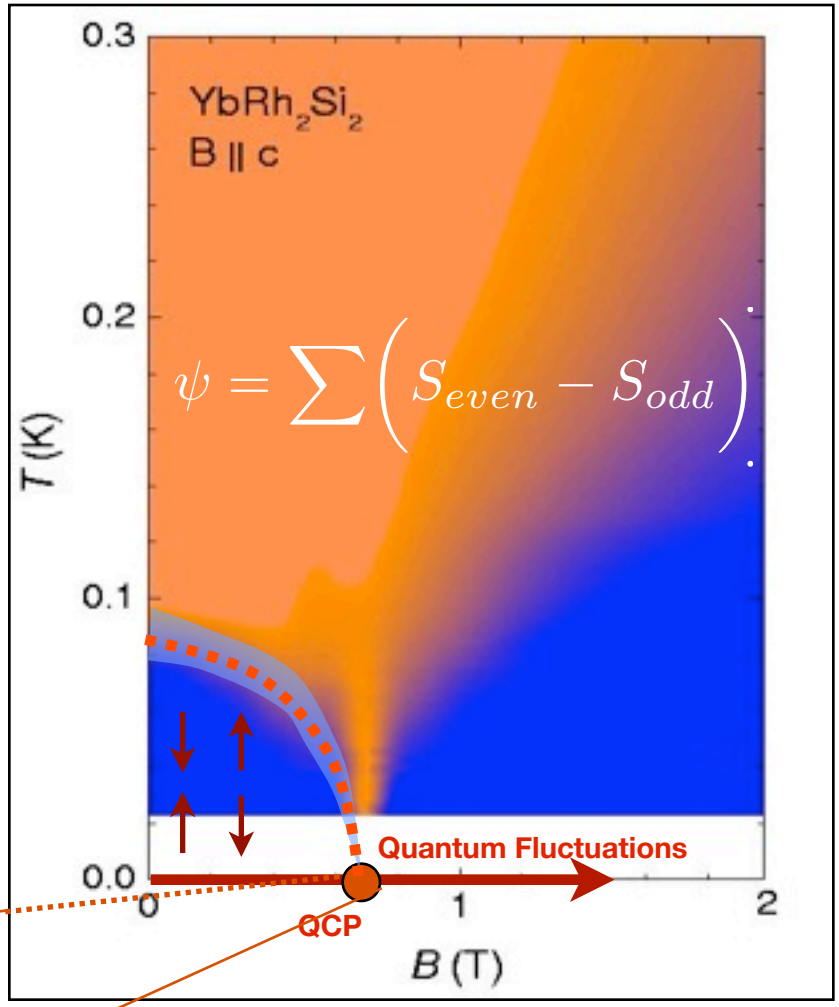

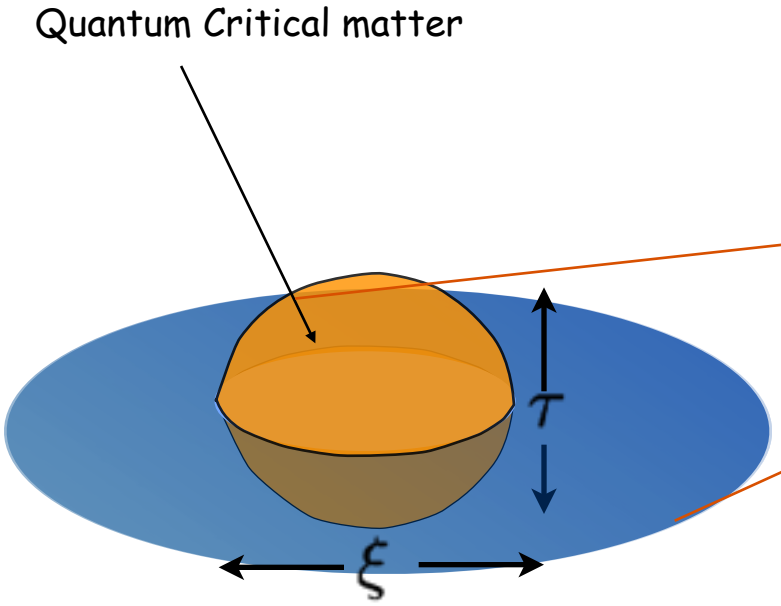

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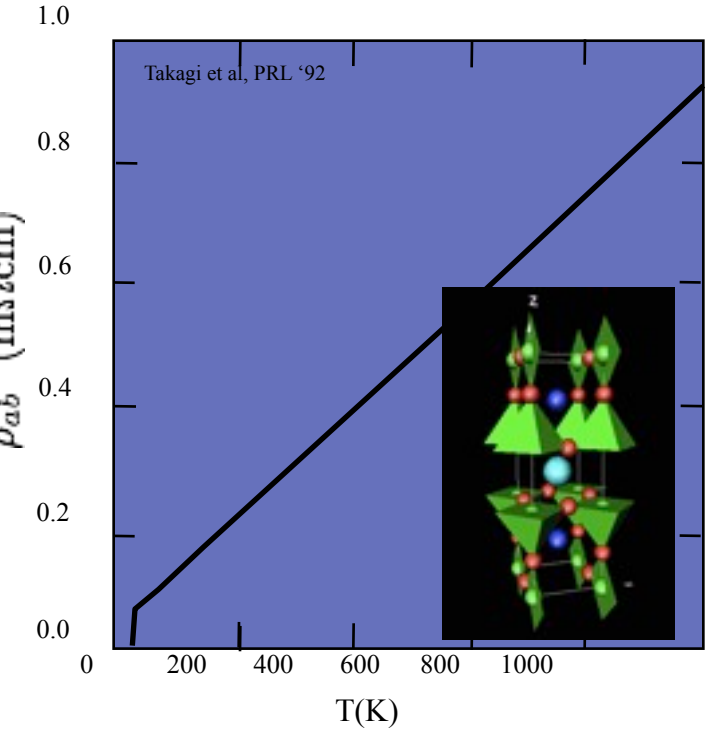
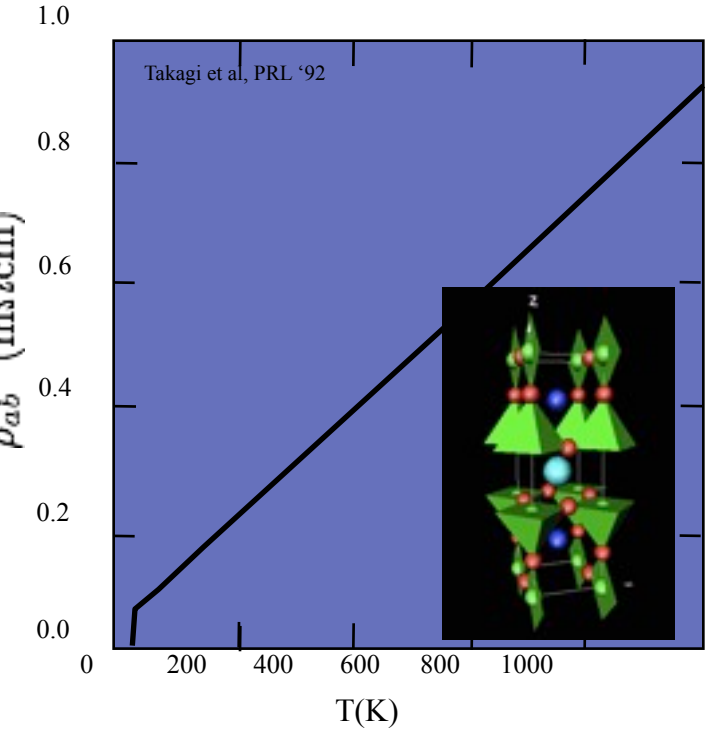
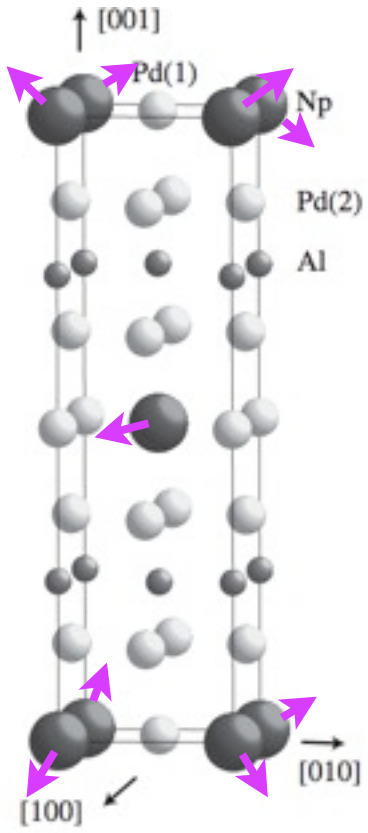


Cuprates
Tc=11-92K





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Cuprates
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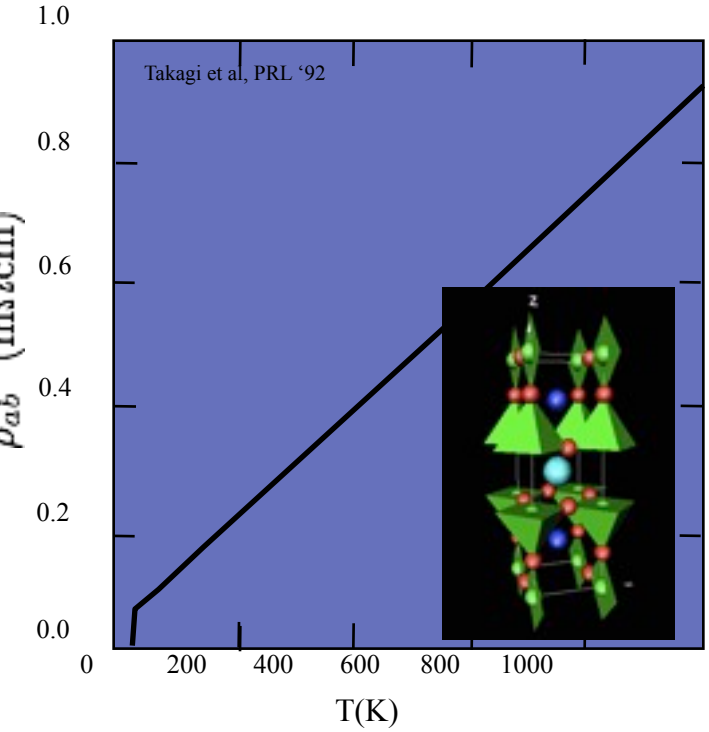
HF 115s
Tc=0.2 -18.5 K



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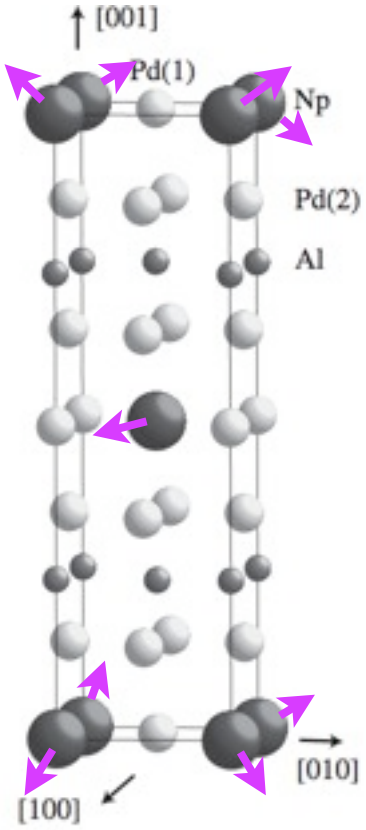

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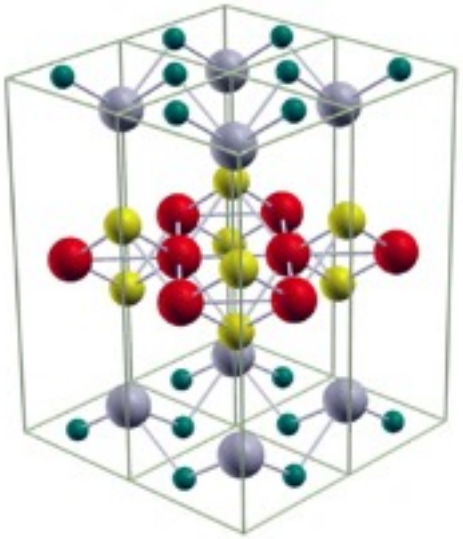
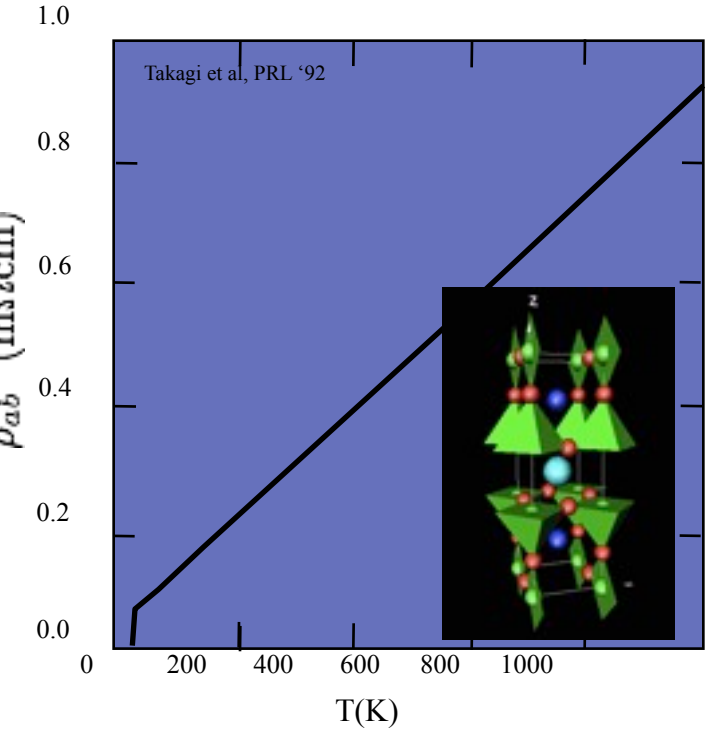


$PrF_xO_{1-x}FeAs$
Z.A. Ren et.al, Beijing, (08)

Iron based SC
Tc= 6 - 53 ++ ? K



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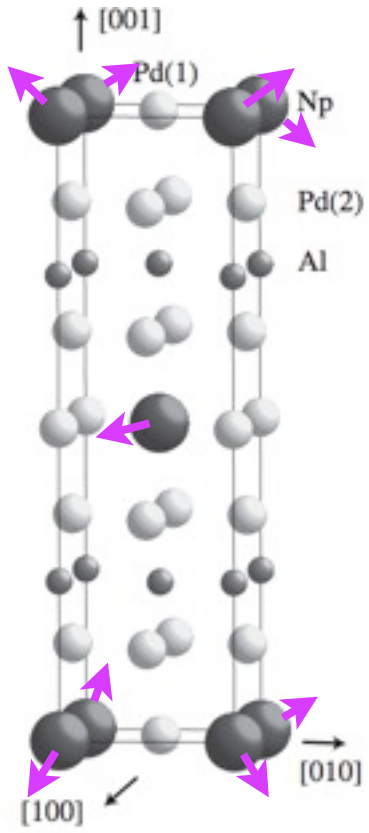

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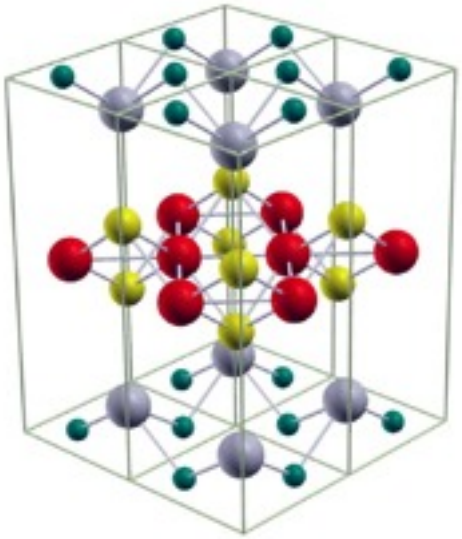

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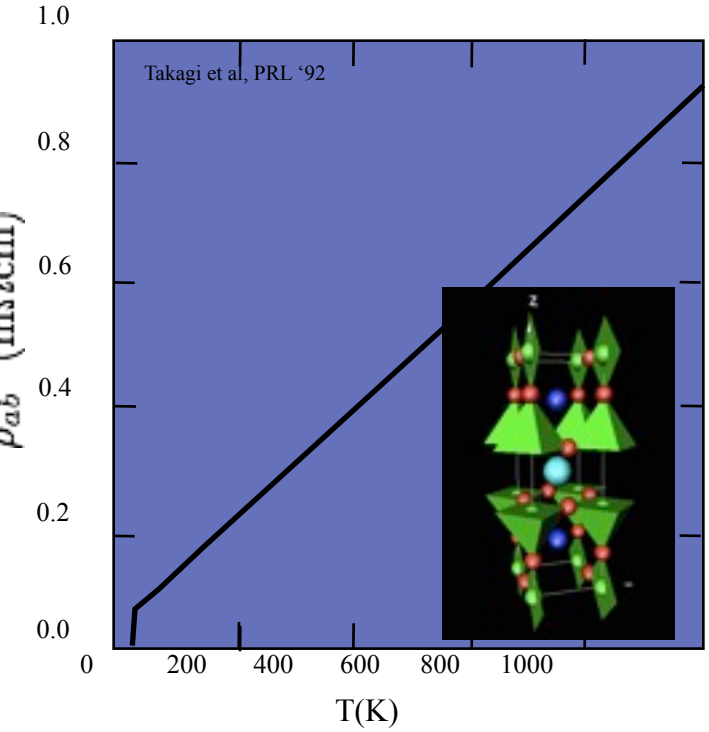
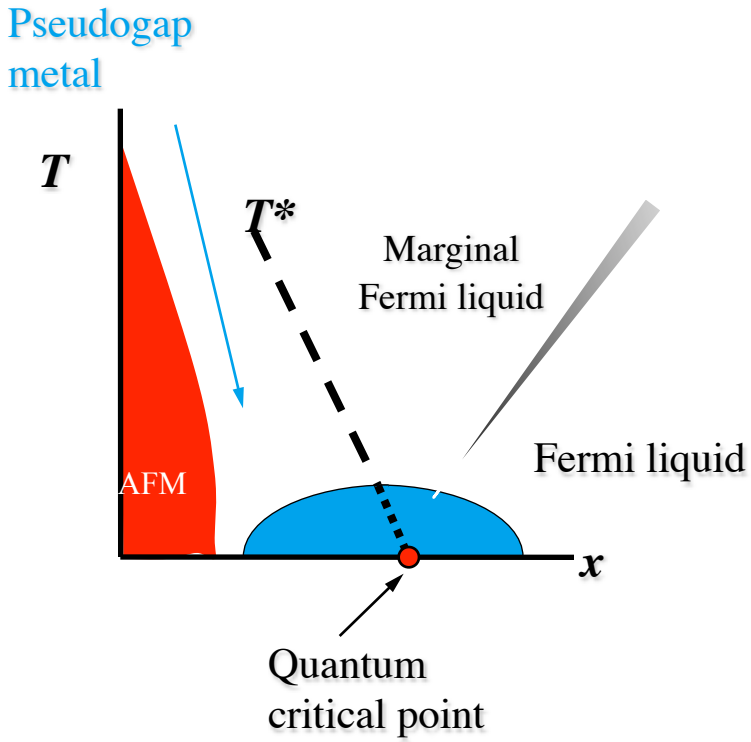
Z.A. Ren et.al, Beijing, (08)

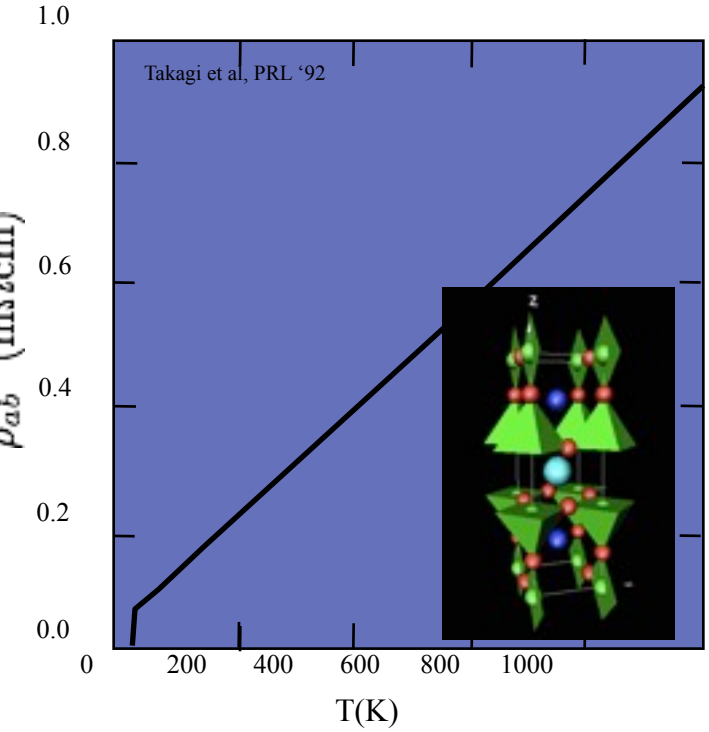
Iron based SC
Tc= 6 - 53 ++ ? K

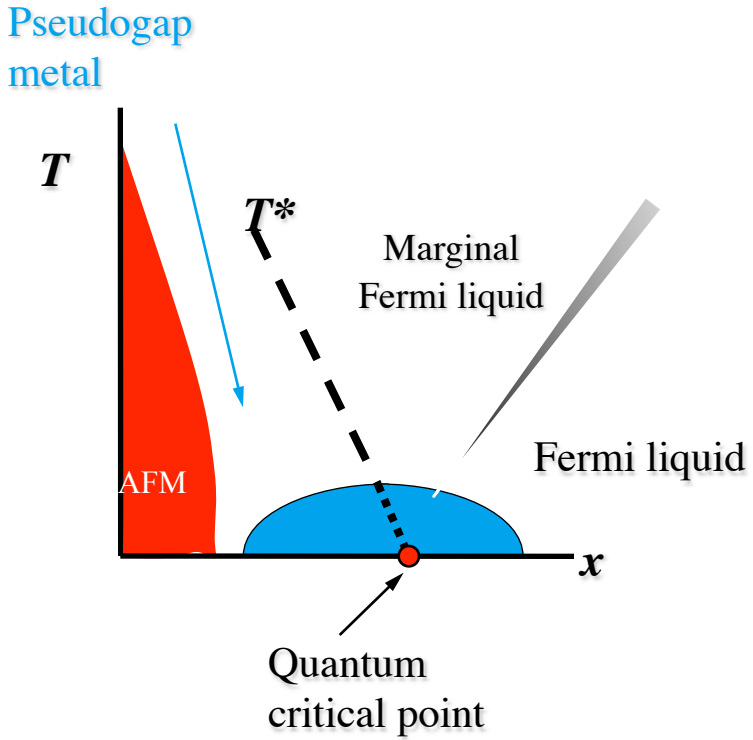
What kind of electronic fluid yields high Tc superconductivity?



Cuprates
Tc=11-92K

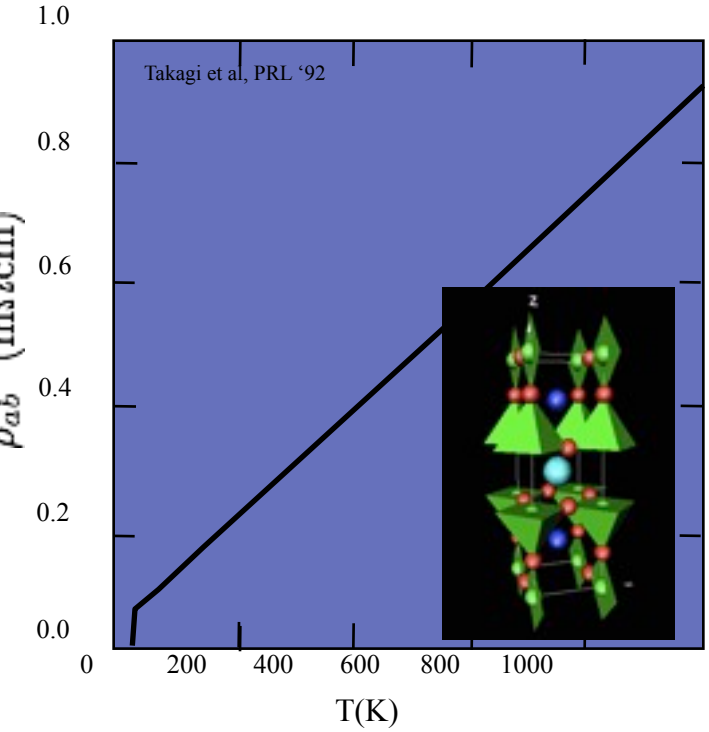






Cuprates
Tc=11-92K

"Avoided criticality"



Cuprates
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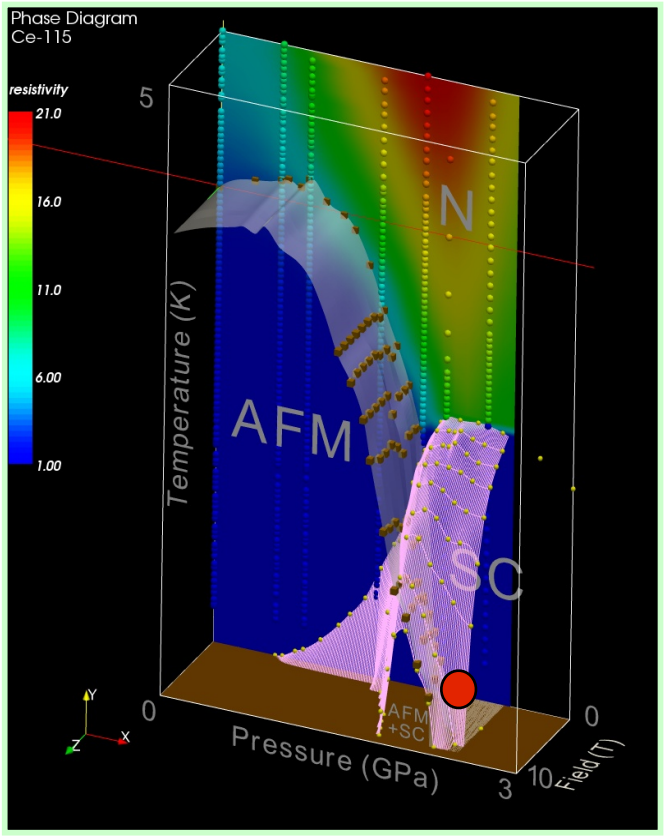
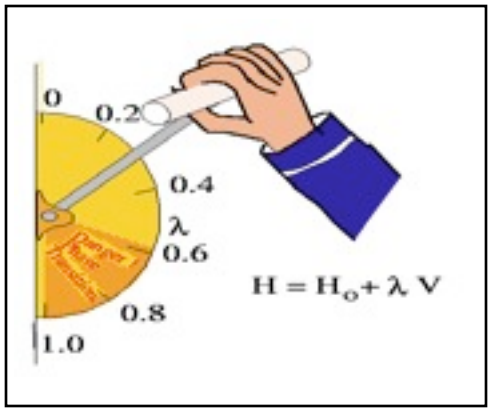
$CeRhIn_5$

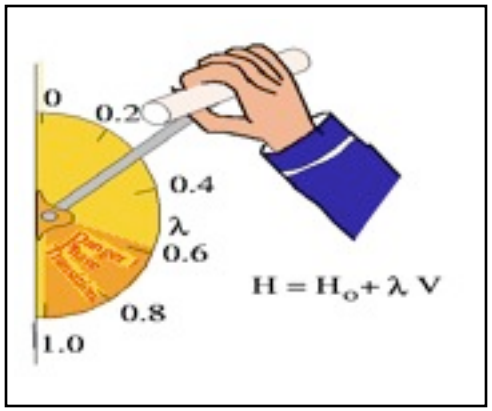


Tuson Park, (2007).



Landau: interactions can be turned on adiabatically, preserving the excitation spectrum.

Landau, JETP 3, 920 (1957)



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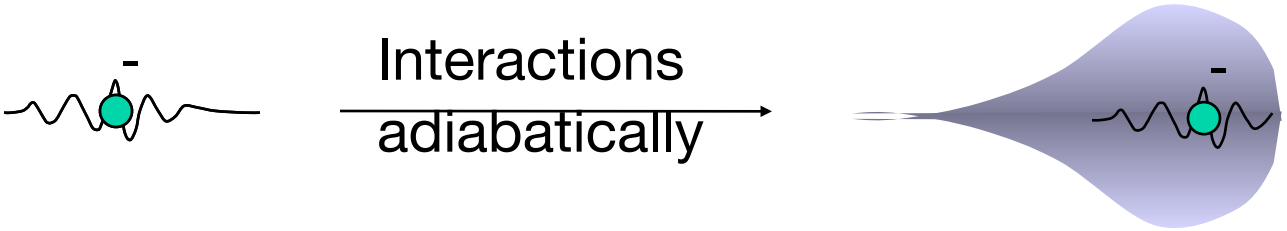
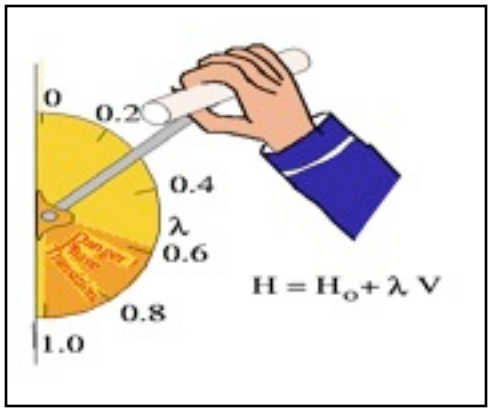
"Quasiparticle"



$|e^-\rangle$ $\quad$ $|qp^-\rangle$



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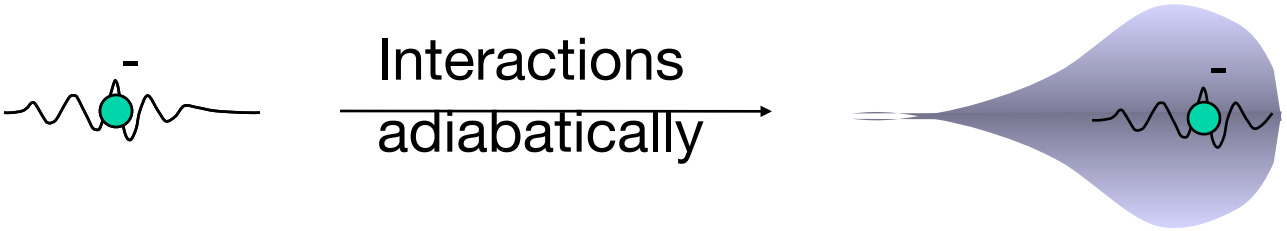
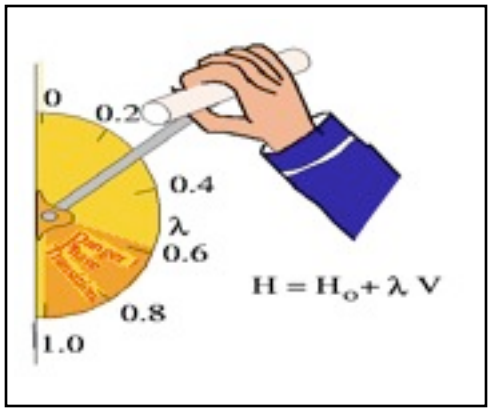


$$|e^-\rangle$$

$$|qp^-\rangle$$

$$\frac{m^*}{m} = \frac{N(0)^*}{N(0)} = 1 + \frac{F_1^s}{3}$$



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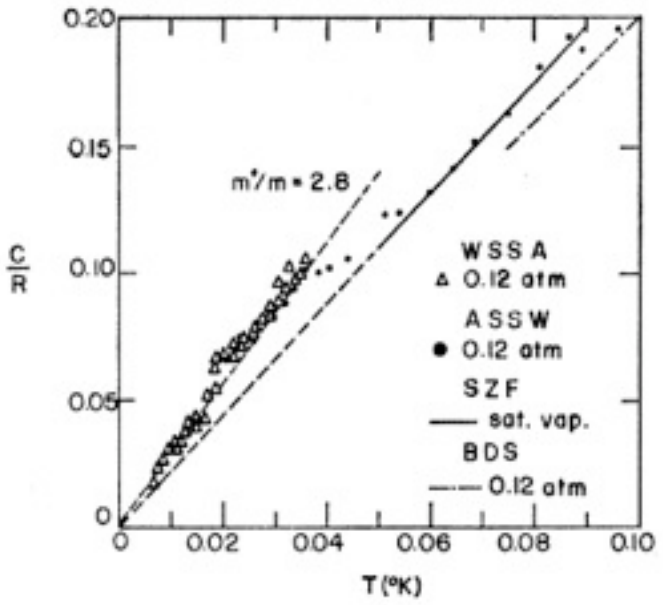
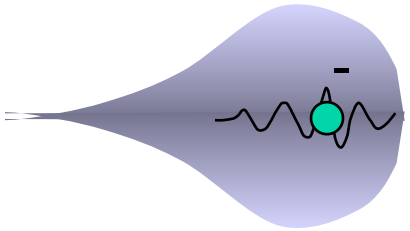
Landau, JETP 3, 920 (1957)

He-3 (1950/60s)
(Fairbanks, many others)



"Quasiparticle"



$$\left| qp^{-} \right\rangle$$

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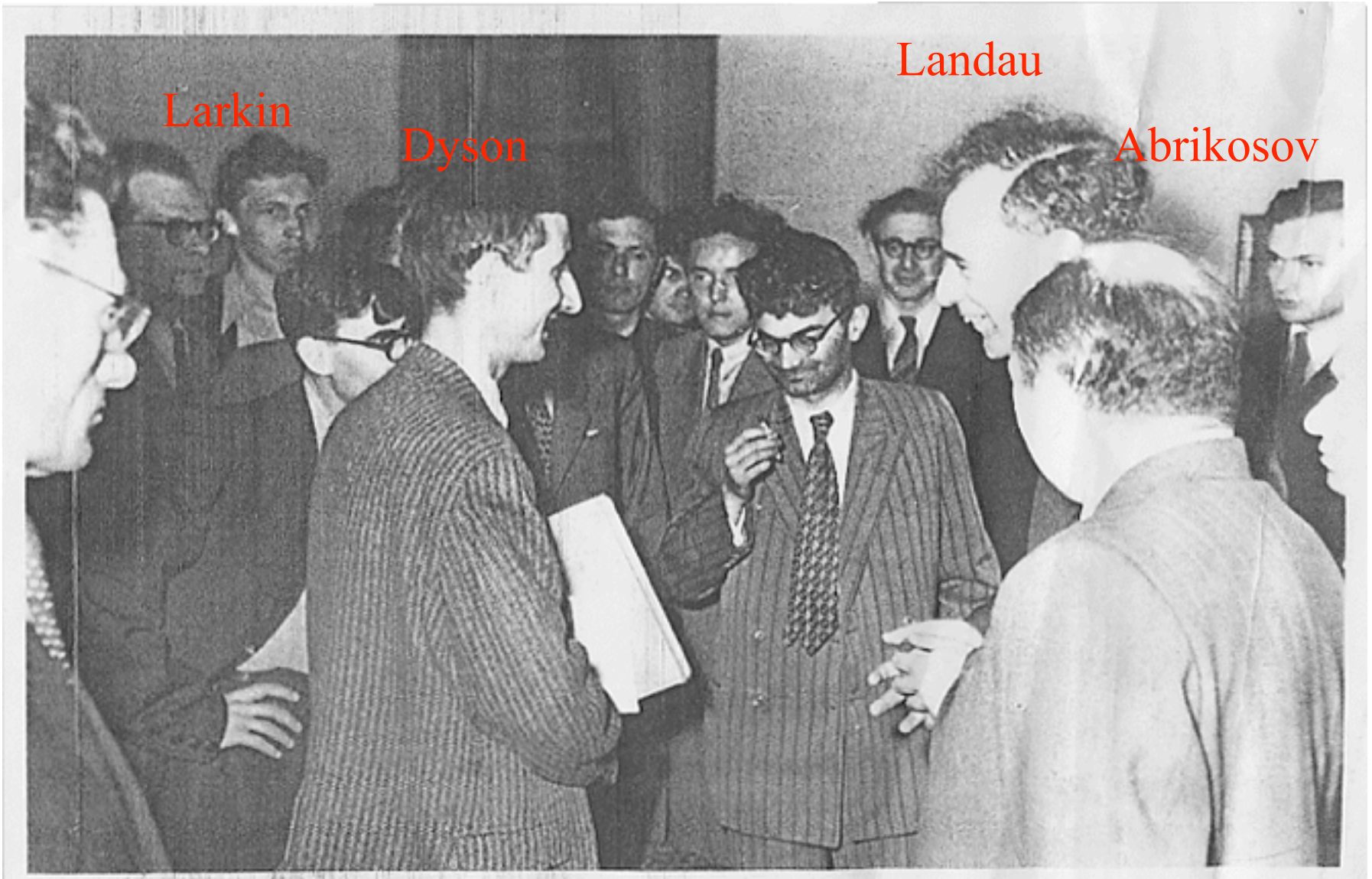
Landau's Question.

20. Moscow, 1956. Freeman Dyson (front, left), talking with I. Pomeranchuk and Lev Landau.

Landau's Question.



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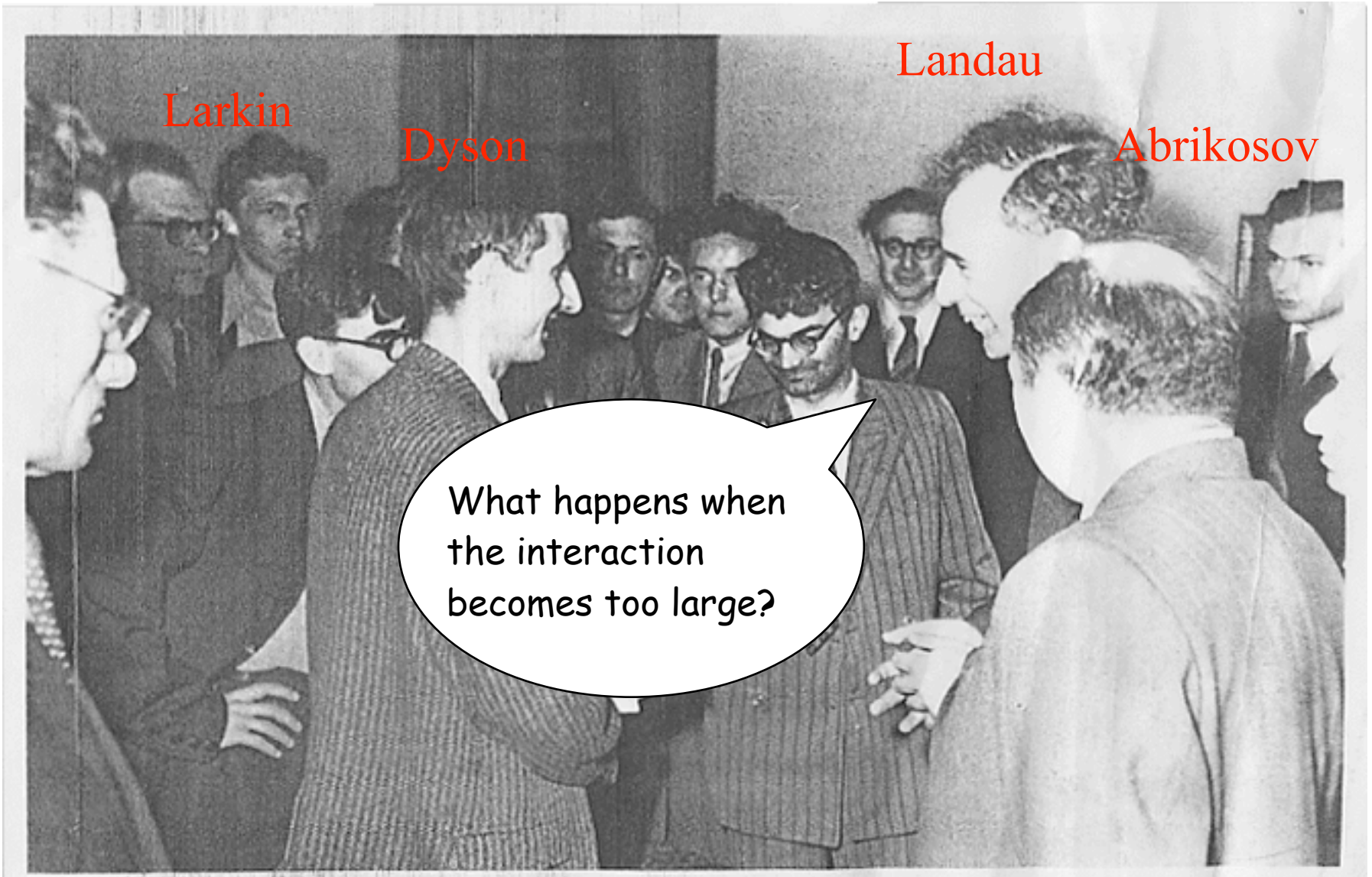

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What happens when the interaction becomes too large?

Landau 1936

"Electrons order"

What happens when the interaction becomes too large?

Landau 1936

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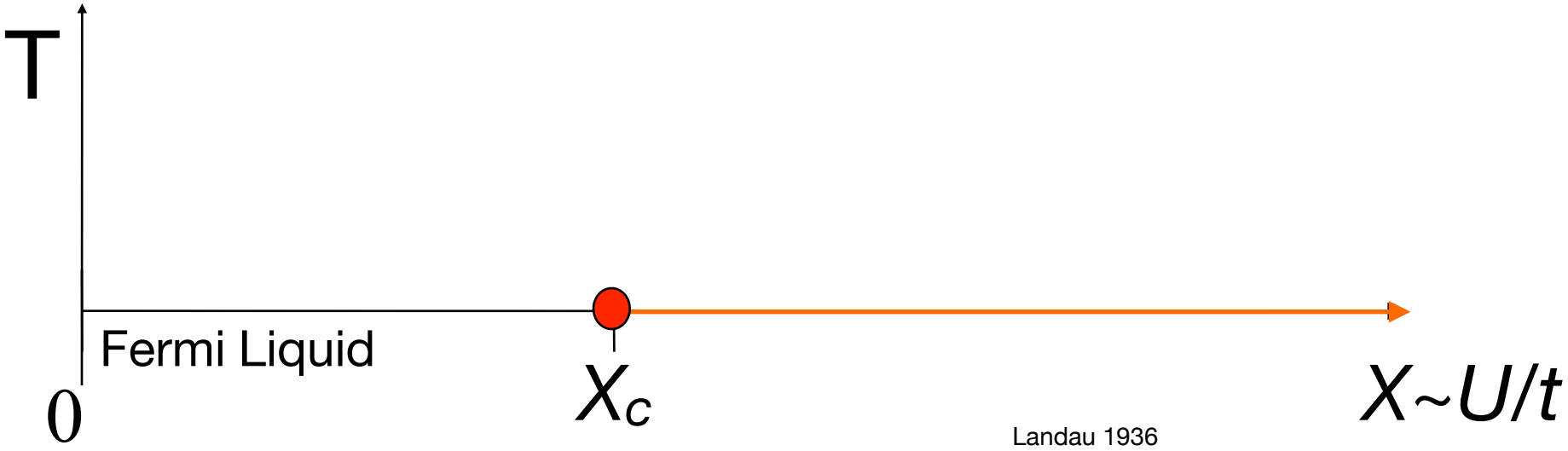
What happens when the interaction becomes too large?

Mott 1947

"Electrons localize"



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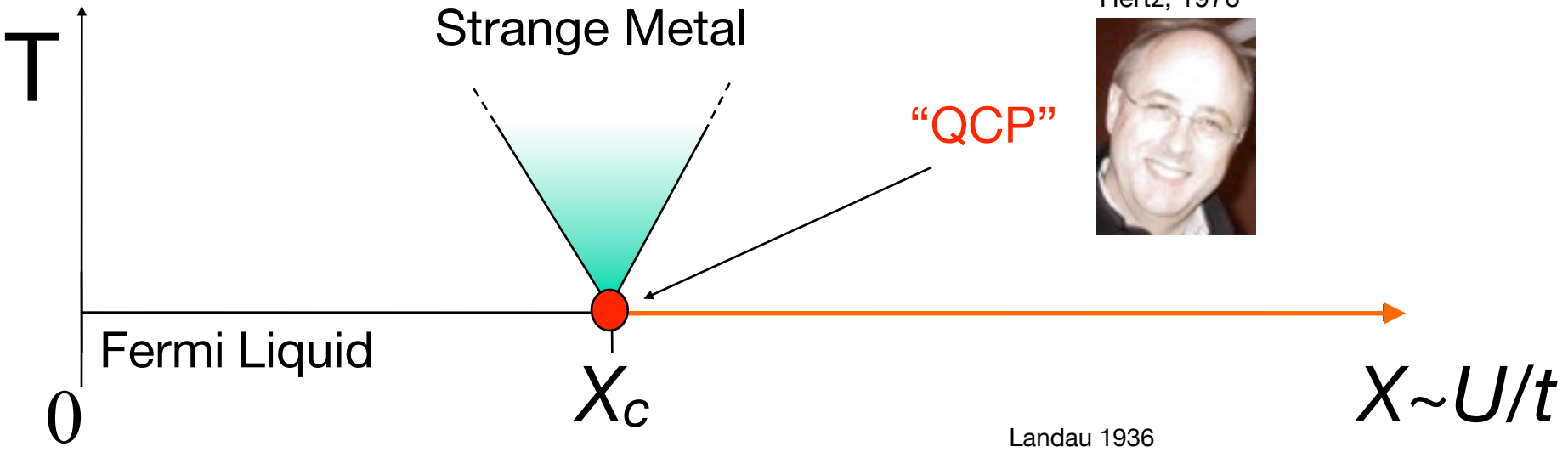
Anderson 1961

"Local moments form"



Hertz, 1976

Landau 1936

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Kondo effect

Kondo effect (a digression)

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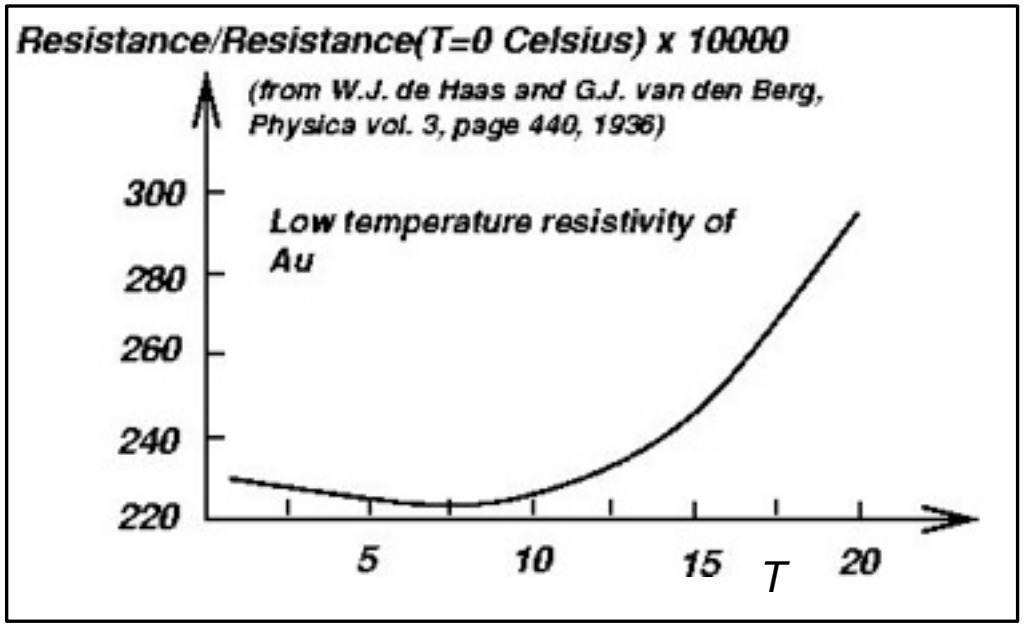
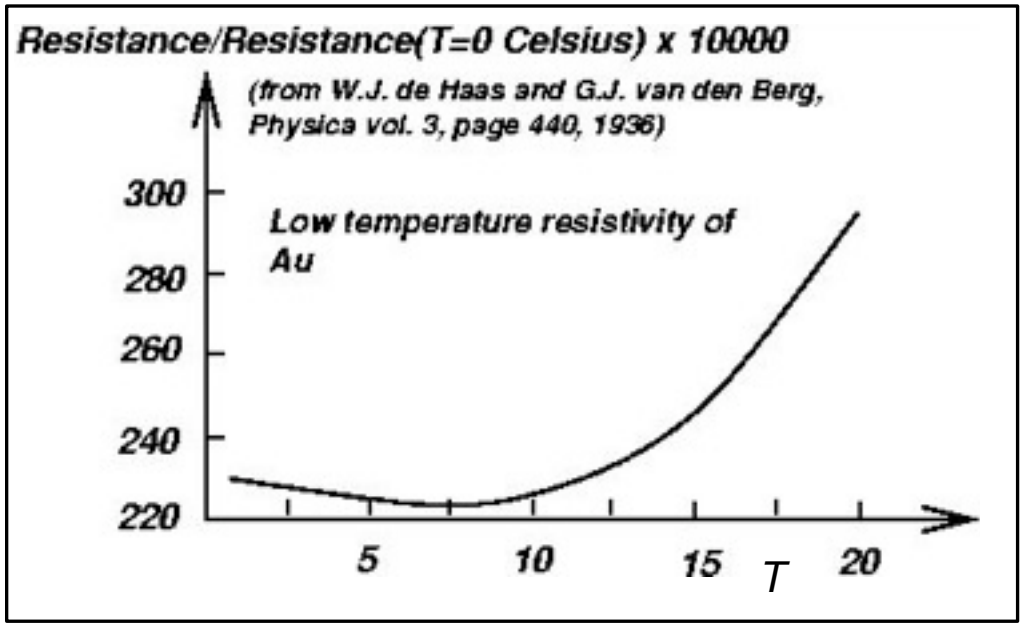
"Kondo"

Kondo KHR-2 HV, the robot that plays soccer, fights with other bots and dances salsa

Kondo effect (a digression)



Kondo effect (a digression)



"A 75 year odyssey"

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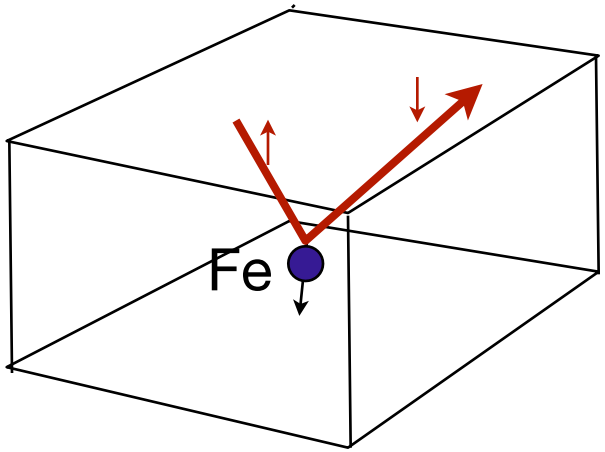
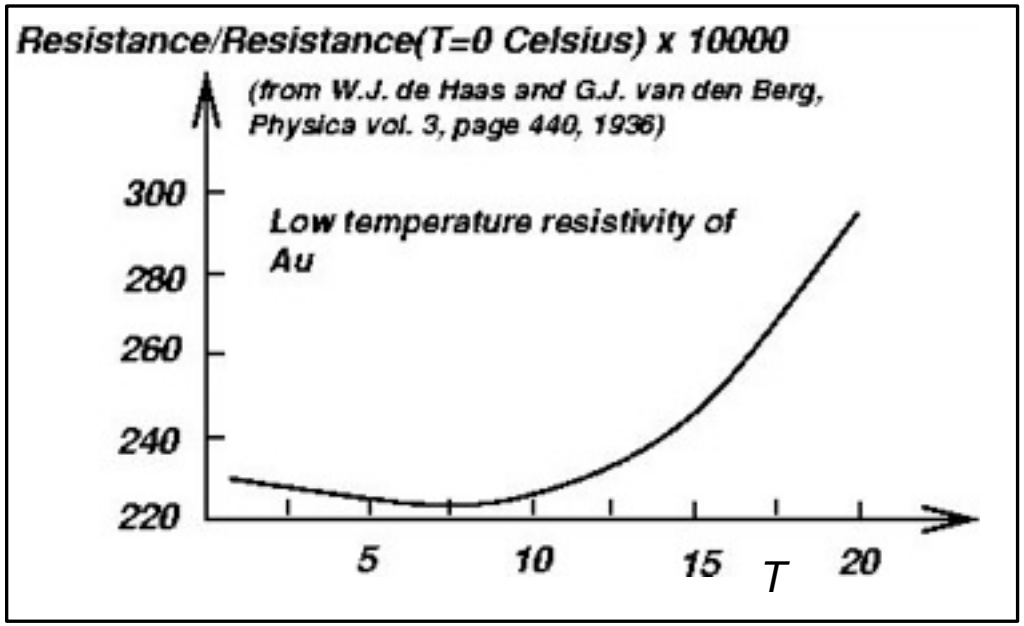


$$H = \sum \epsilon_k c^\dagger_{k\sigma} c_{k\sigma} + J(\psi^\dagger \vec{\sigma} \psi) \cdot \vec{S}$$

Kondo (1962)

$$T_K = D\sqrt{J\rho}\exp\left[-\frac{1}{2J\rho}\right]$$

"Kondo Temperature"



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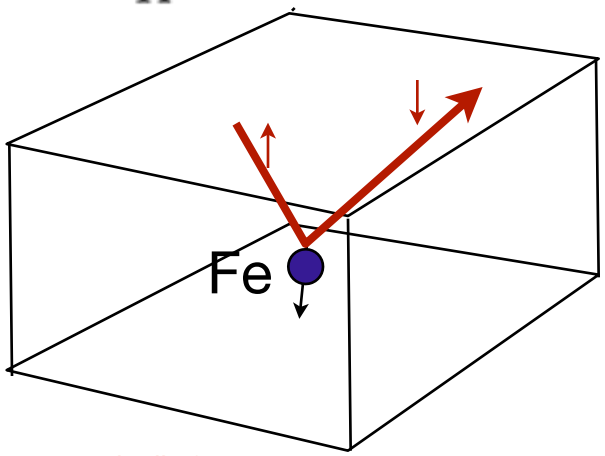
$T >> T_K$



Spins asymptotically free

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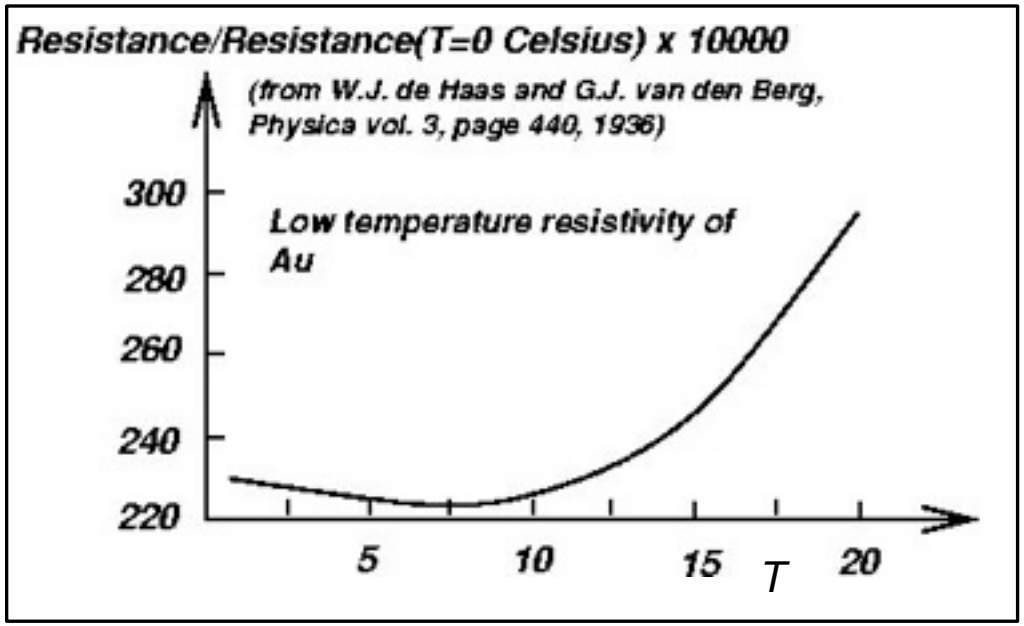

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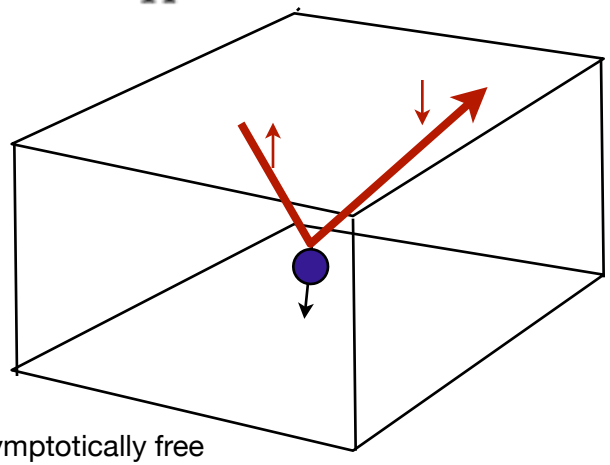

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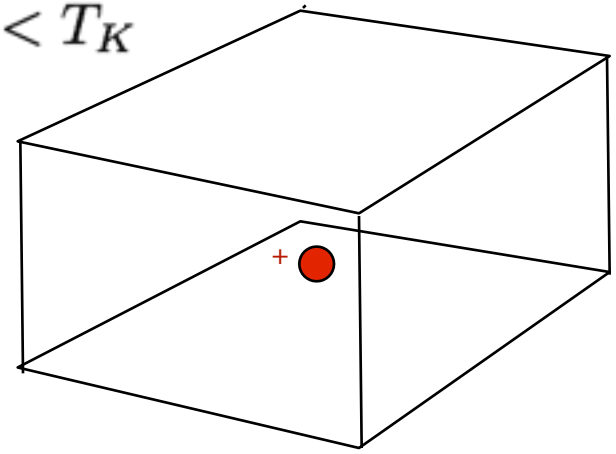

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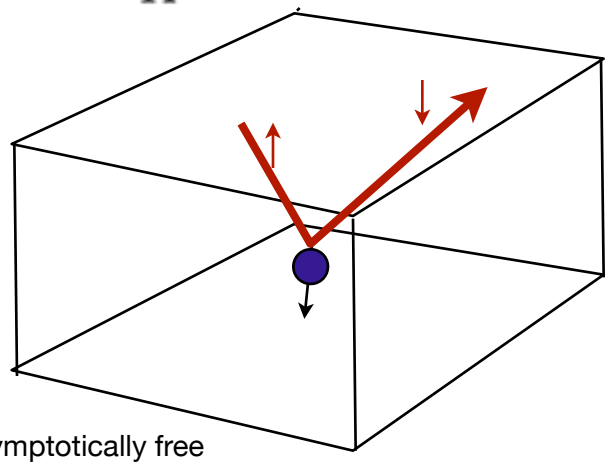

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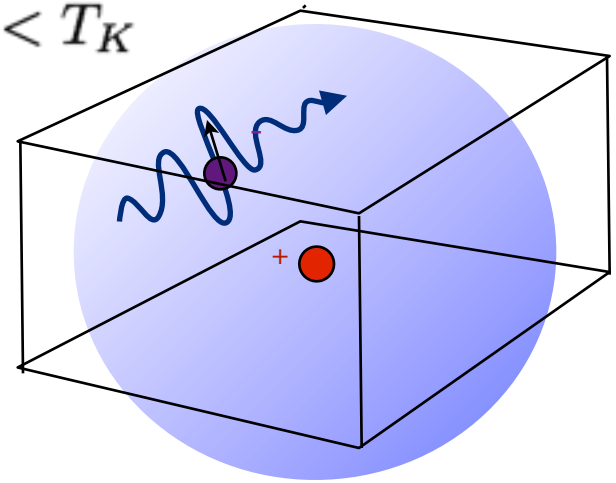

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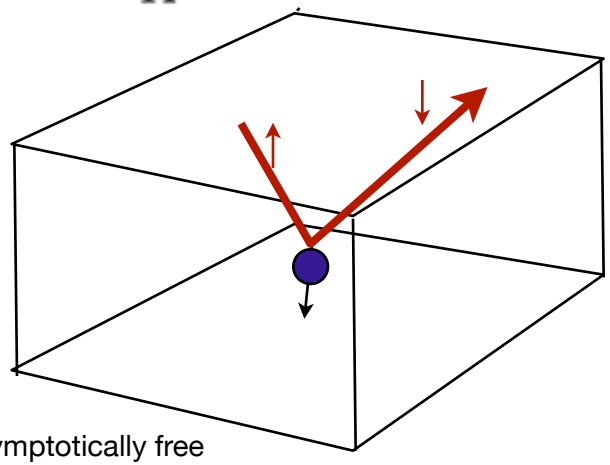

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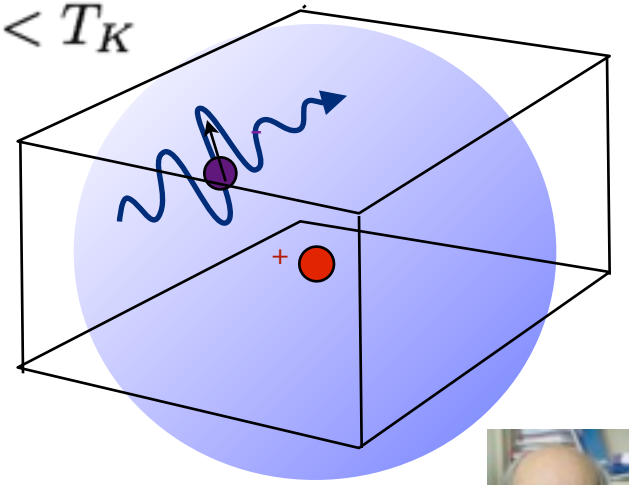
"Kondo Temperature"

Spins absorbed into singlet ground-state

$T << T_K$



"Nozieres Local Fermi liquid"
(Nozieres 76)

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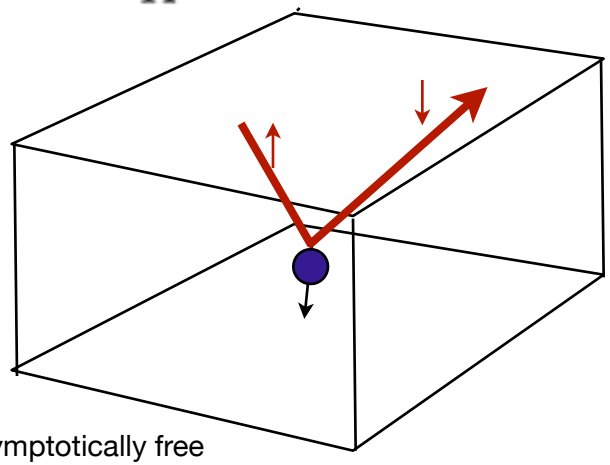

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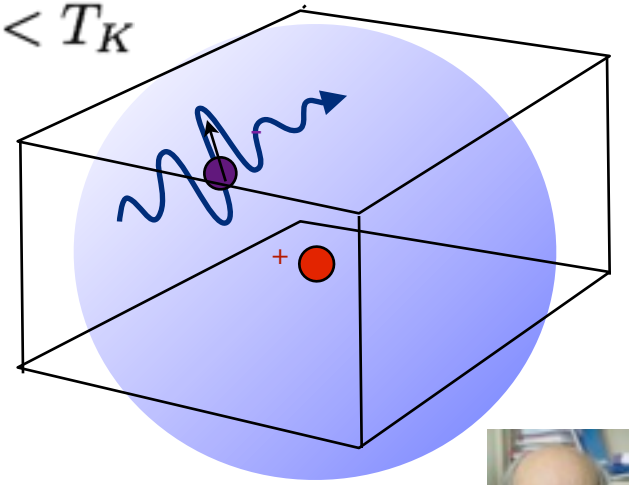

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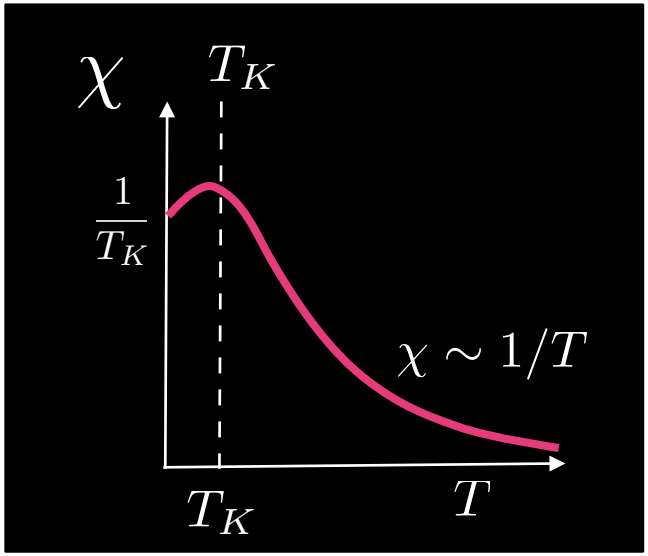
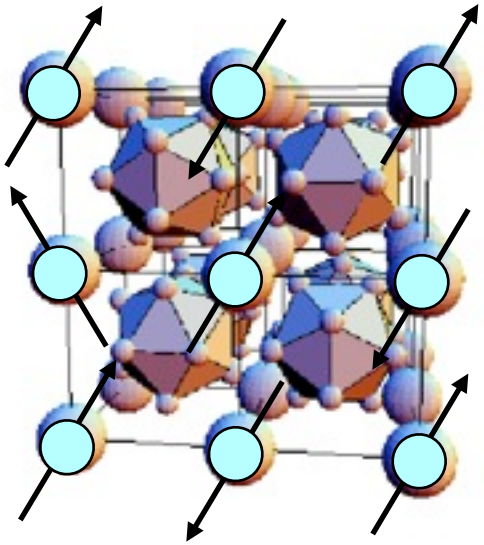


Heavy Fermion Metals

Review: cond-mat/0612006



UBe_{13}

Heavy Fermion Metals

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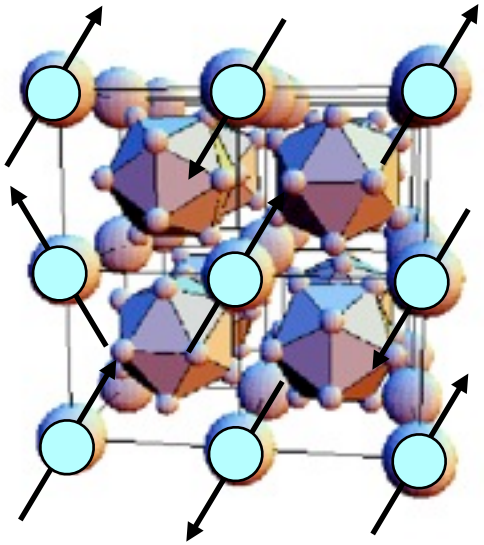

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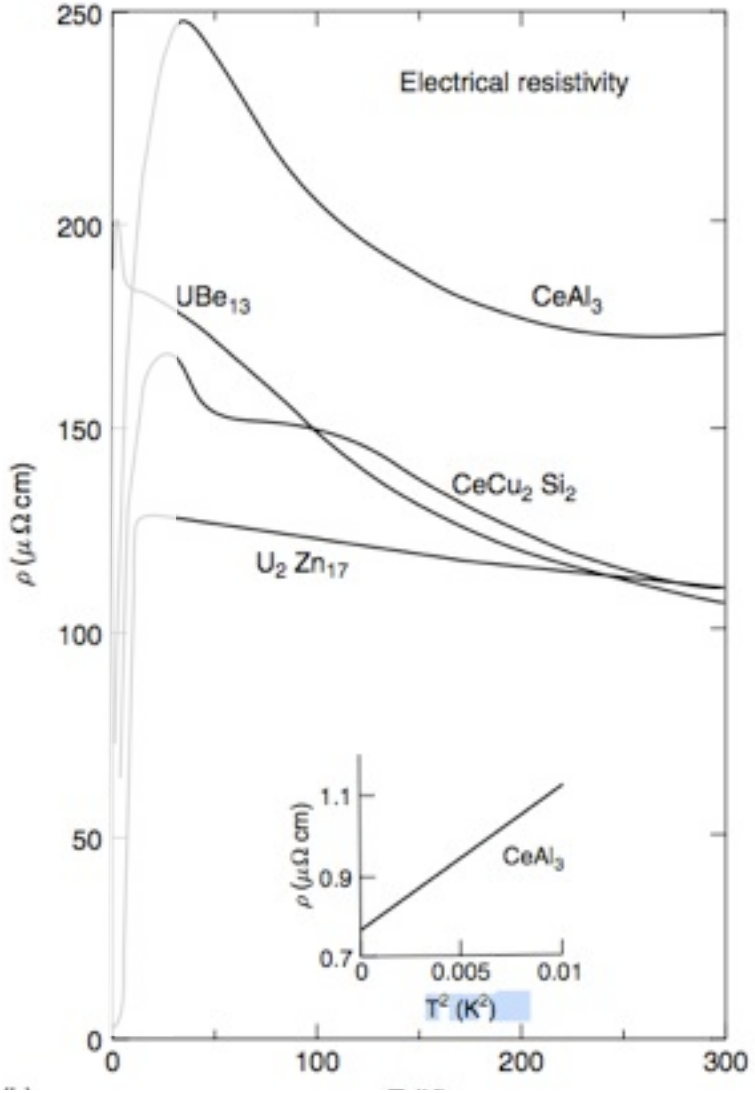

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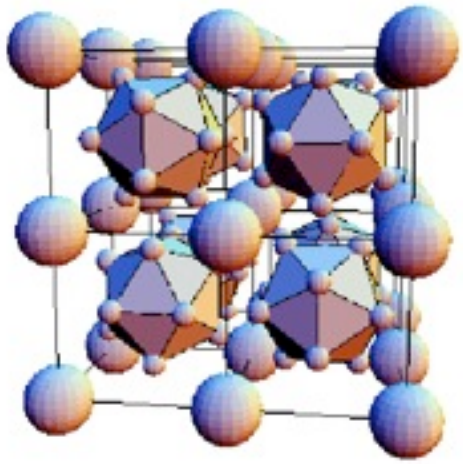

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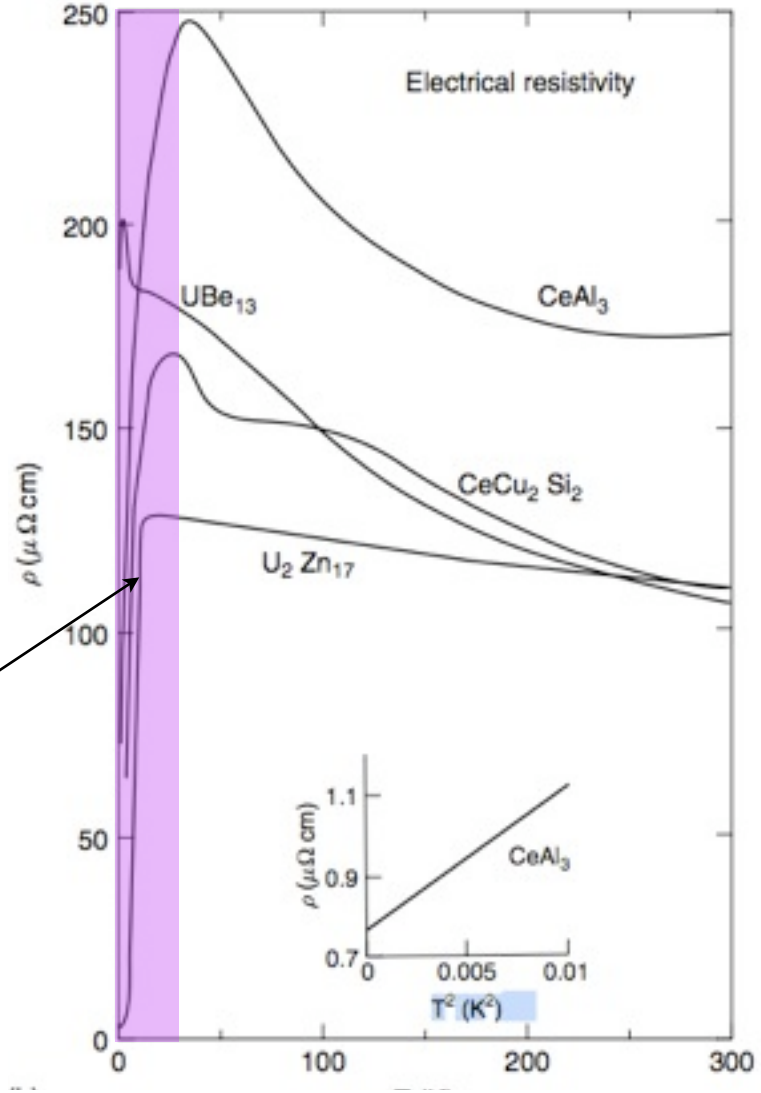
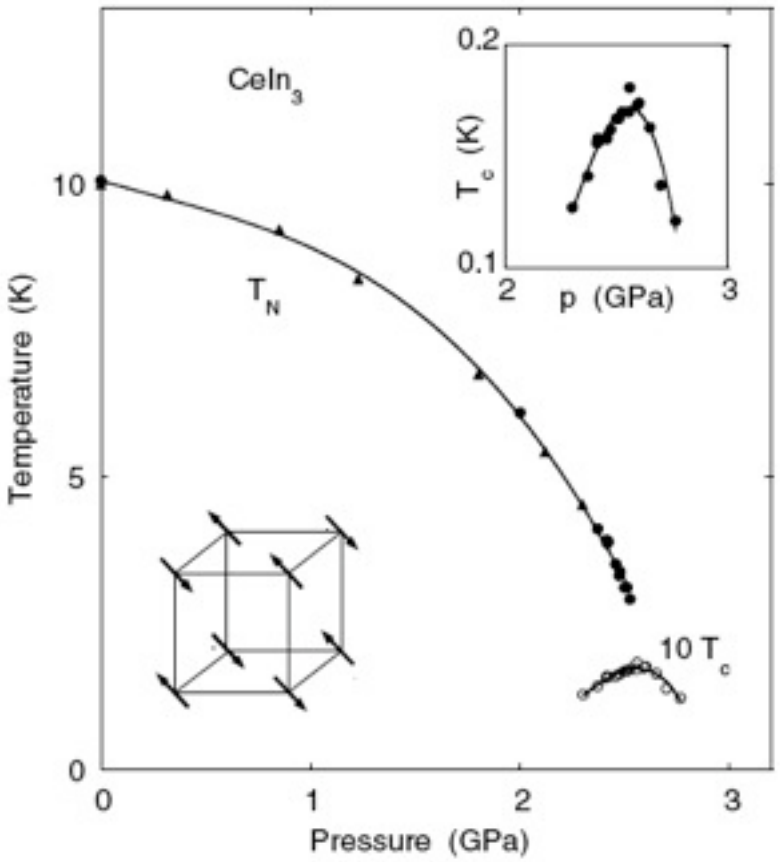


Coherent
Heavy Fermi Liquid

Heavy Electron Quantum Criticality.

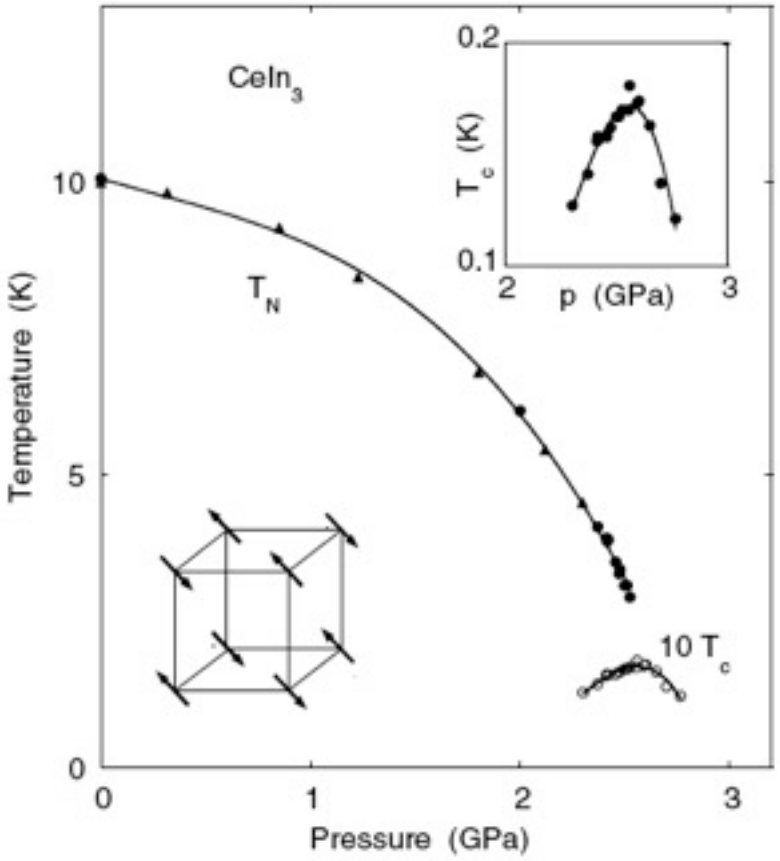
Experiments

“Avoided Criticality”



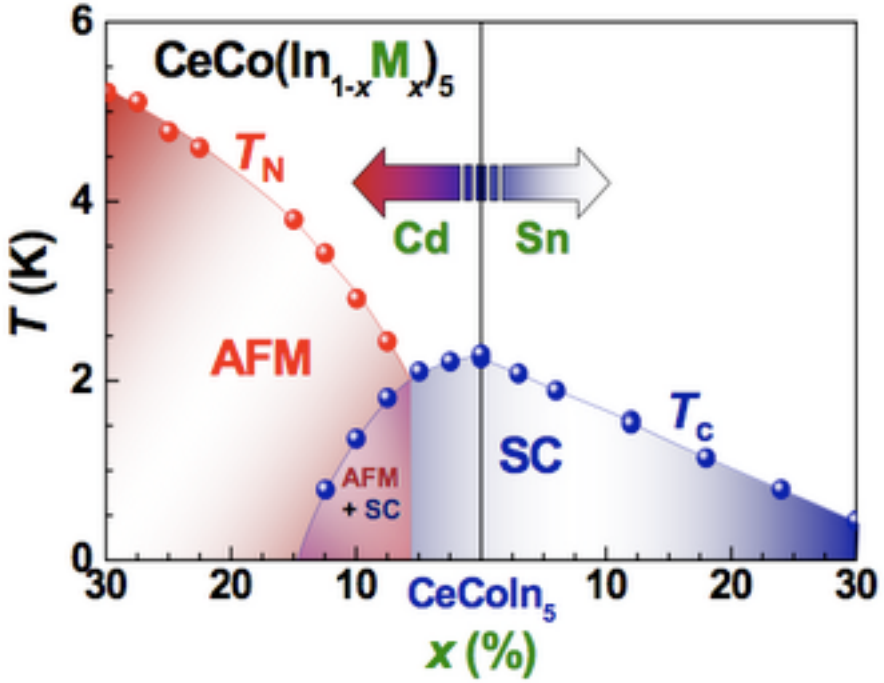
Mathur et al, Nature 394, 39 (1998)

“Avoided Criticality”



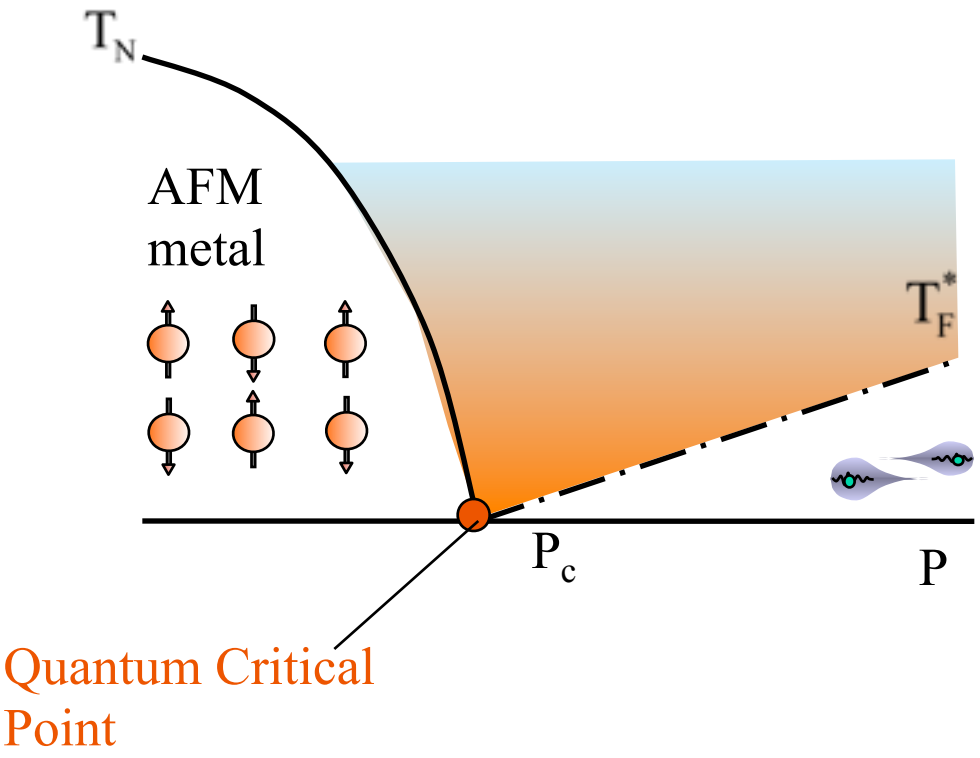
Mathur et al, Nature 394, 39 (1998)

N. Curro, PRL 99, 146402 (2007)

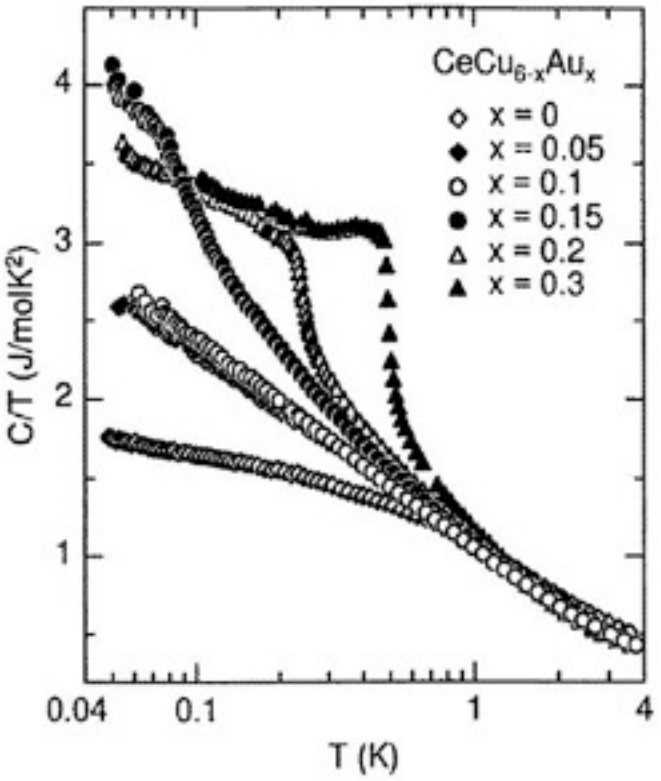


Quantum Criticality: divergent specific heat capacity

Heavy Fermion Materials



H. Von Lohneyson (1996)



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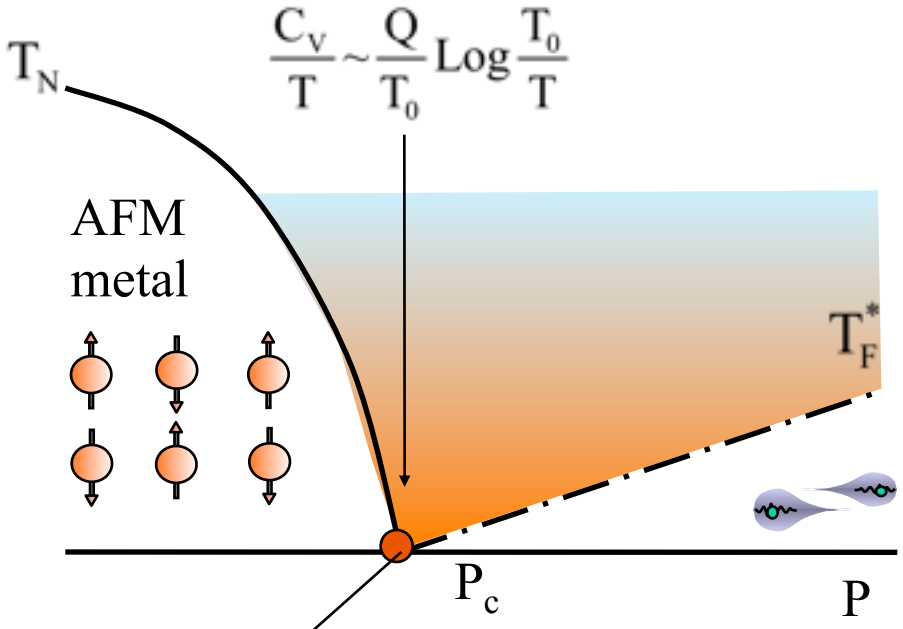
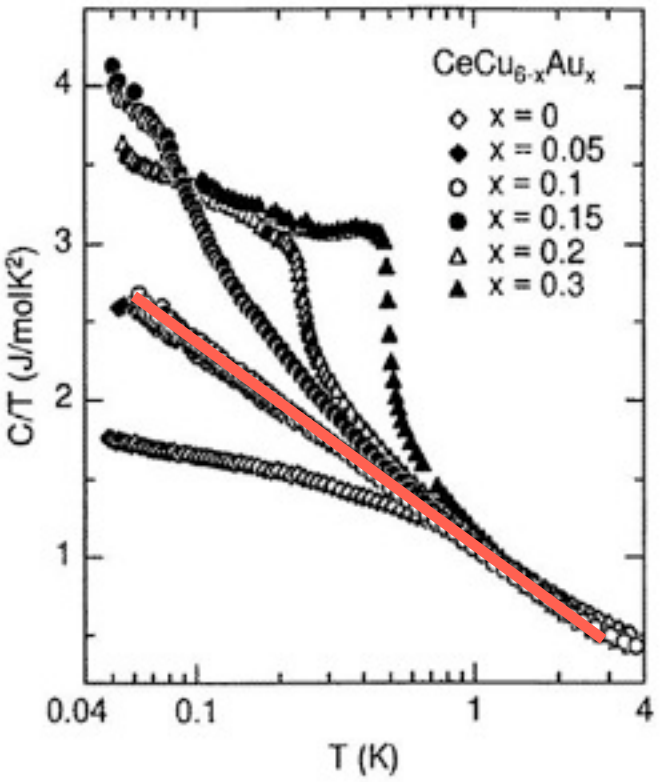


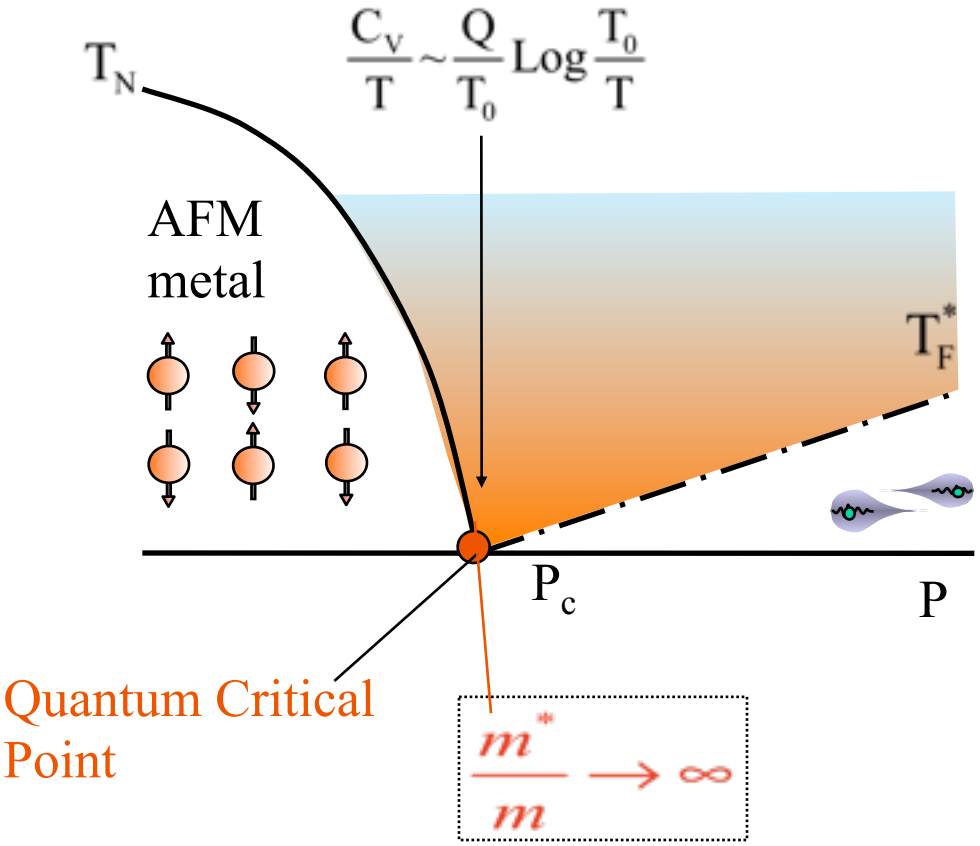
Quantum Critical Point

H. Von Lohneyson (1996)



Quantum Criticality: divergent specific heat capacity

Heavy Fermion Materials



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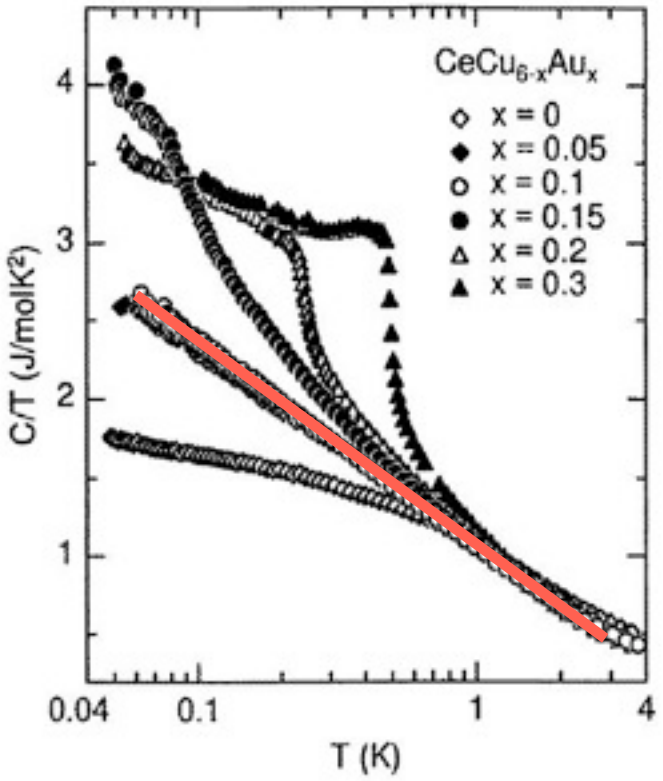
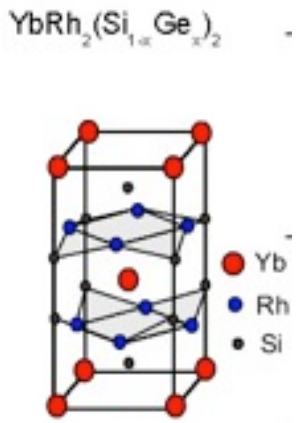
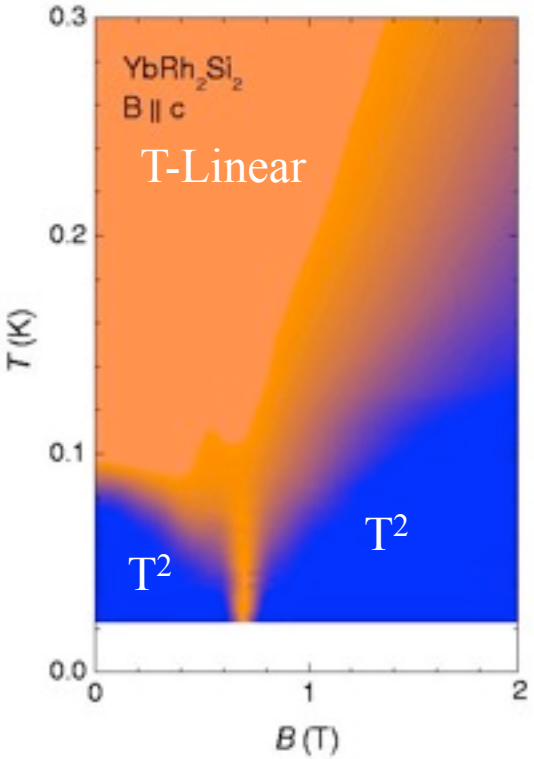
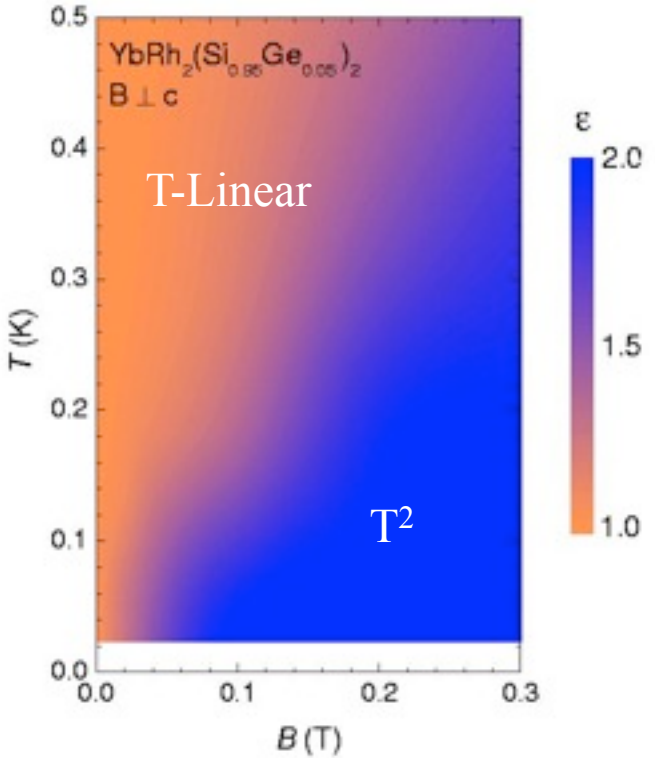


Divergence of Interaction and Effective Mass

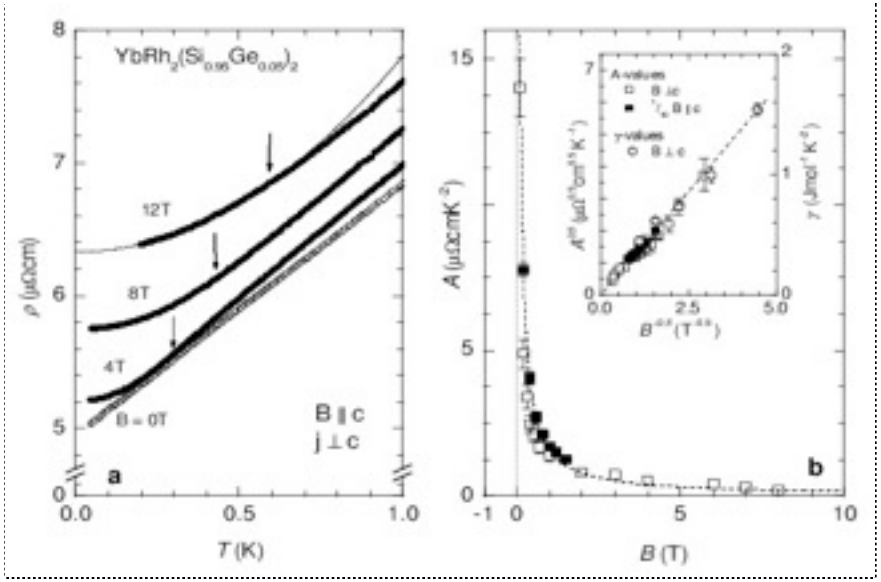
Gegenwart et al (2002)







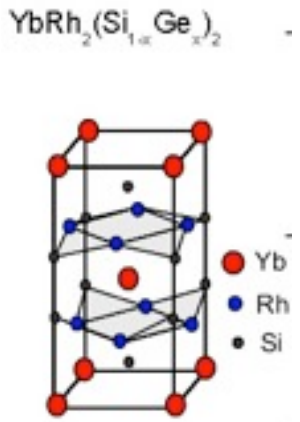
Divergence of Interaction and Effective Mass

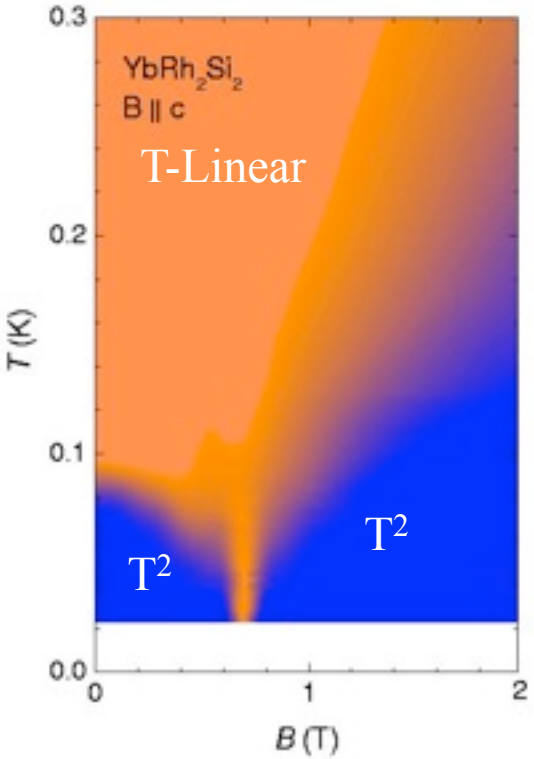


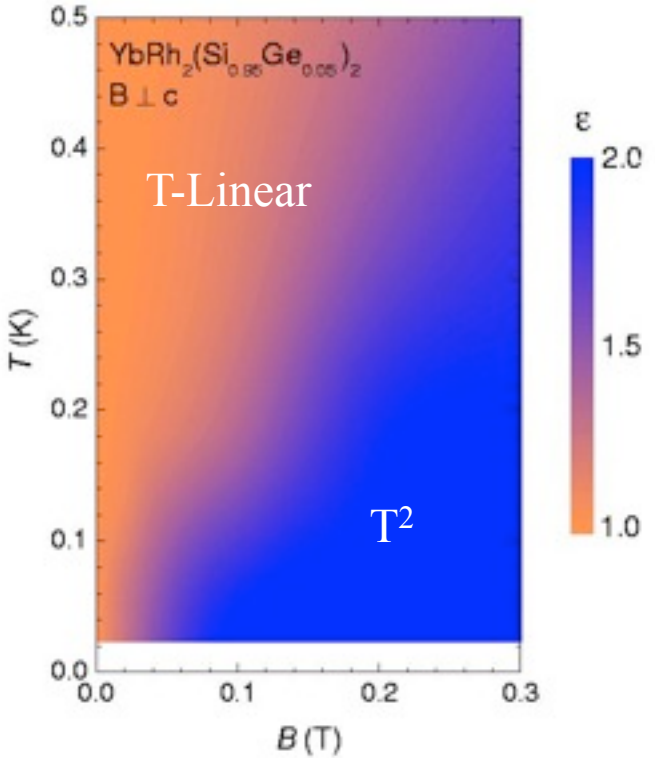
$$\rho = AT^2 + \rho_0$$

$$A \propto \frac{1}{T_F^{\,2}} \propto \frac{1}{B - B_c}$$

Gegenwart et al (2002)

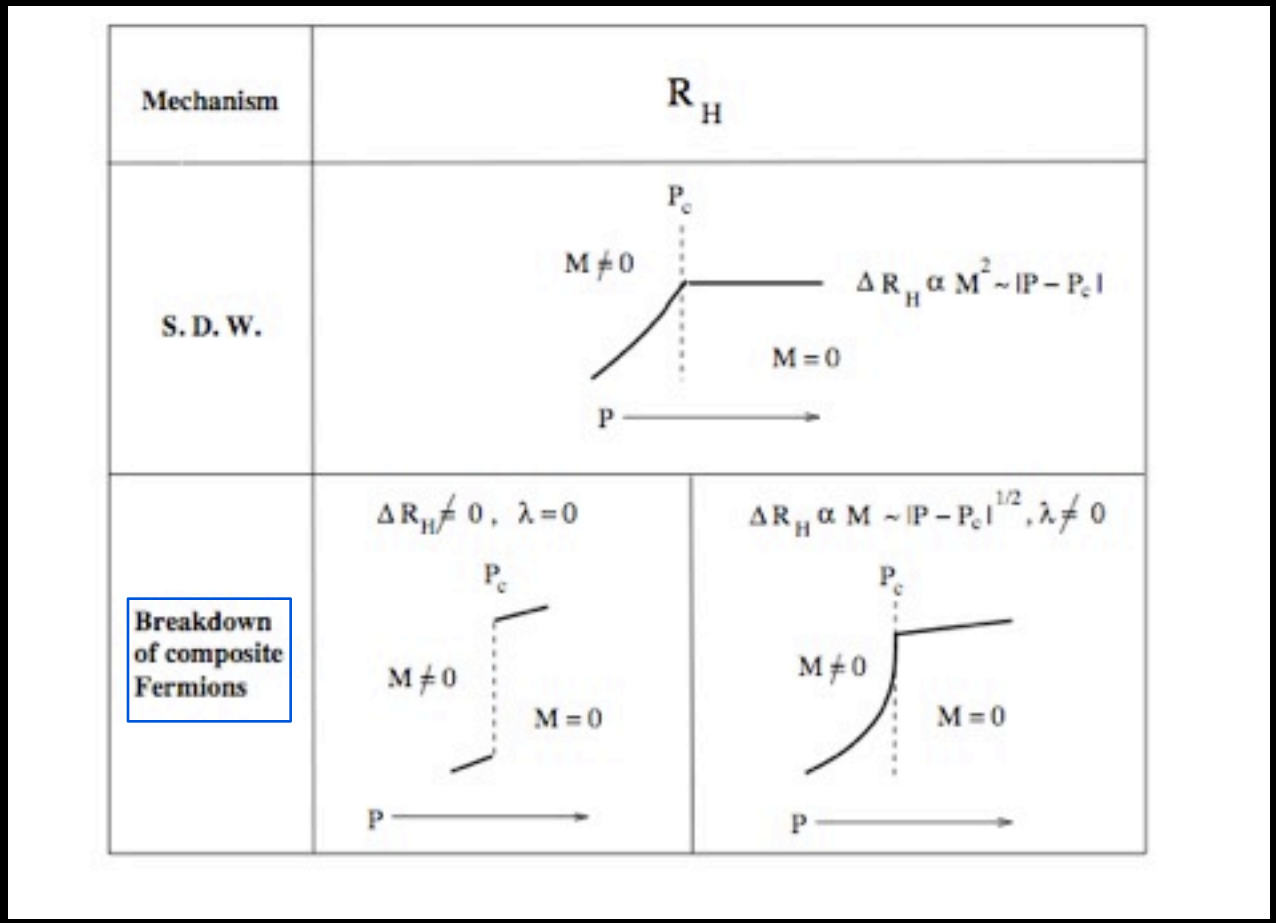




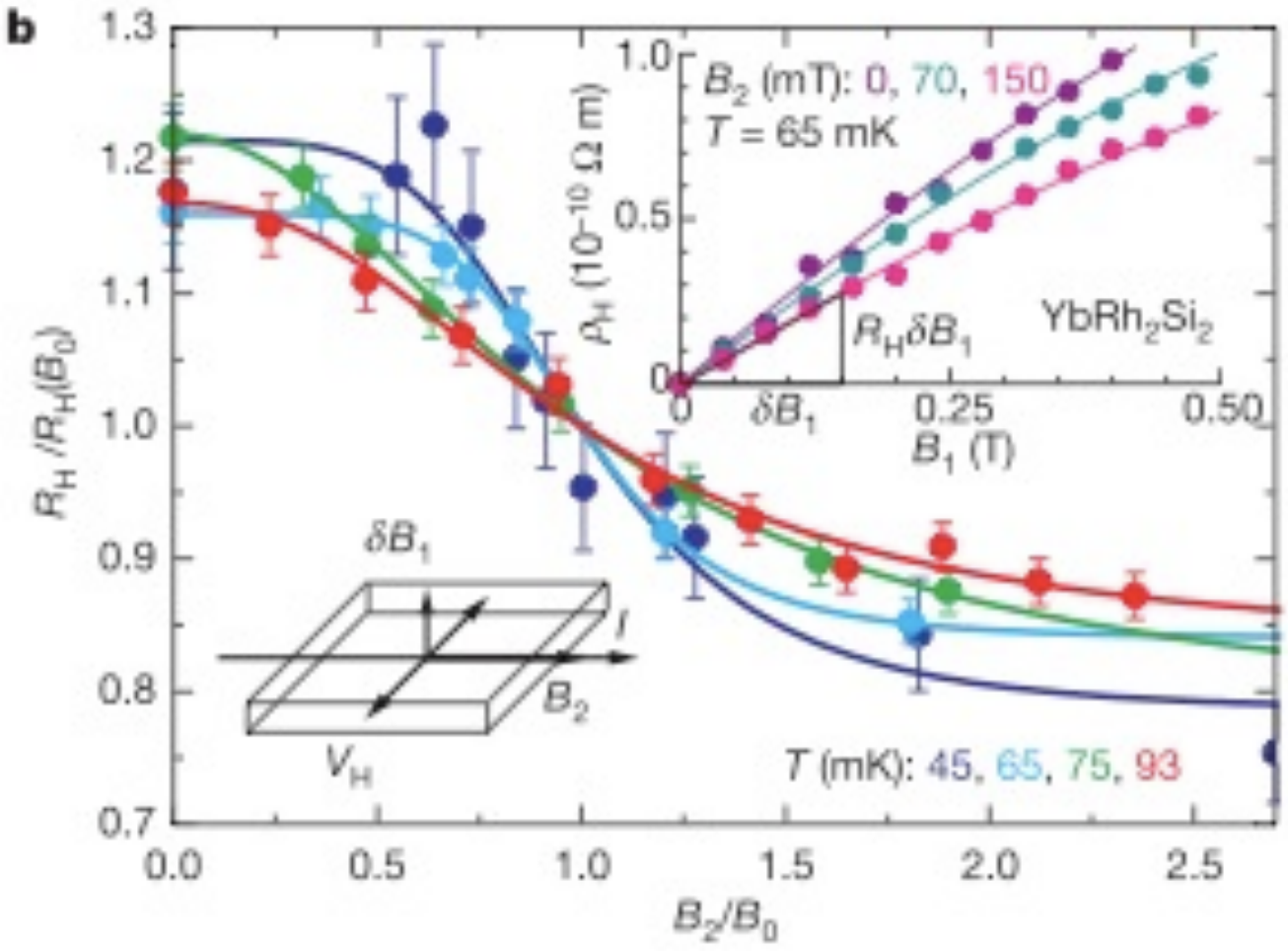


"How do fermions get heavy and die?" PC, Pepin, Si and Ramazashvili, J. Cond Matt. ,13}, R723 (2001).

anticipated an abrupt change in FS when a composite heavy electron undergoes a Kondo "breakdown".



S. Paschen et al, Nature 432, 881 (2004)



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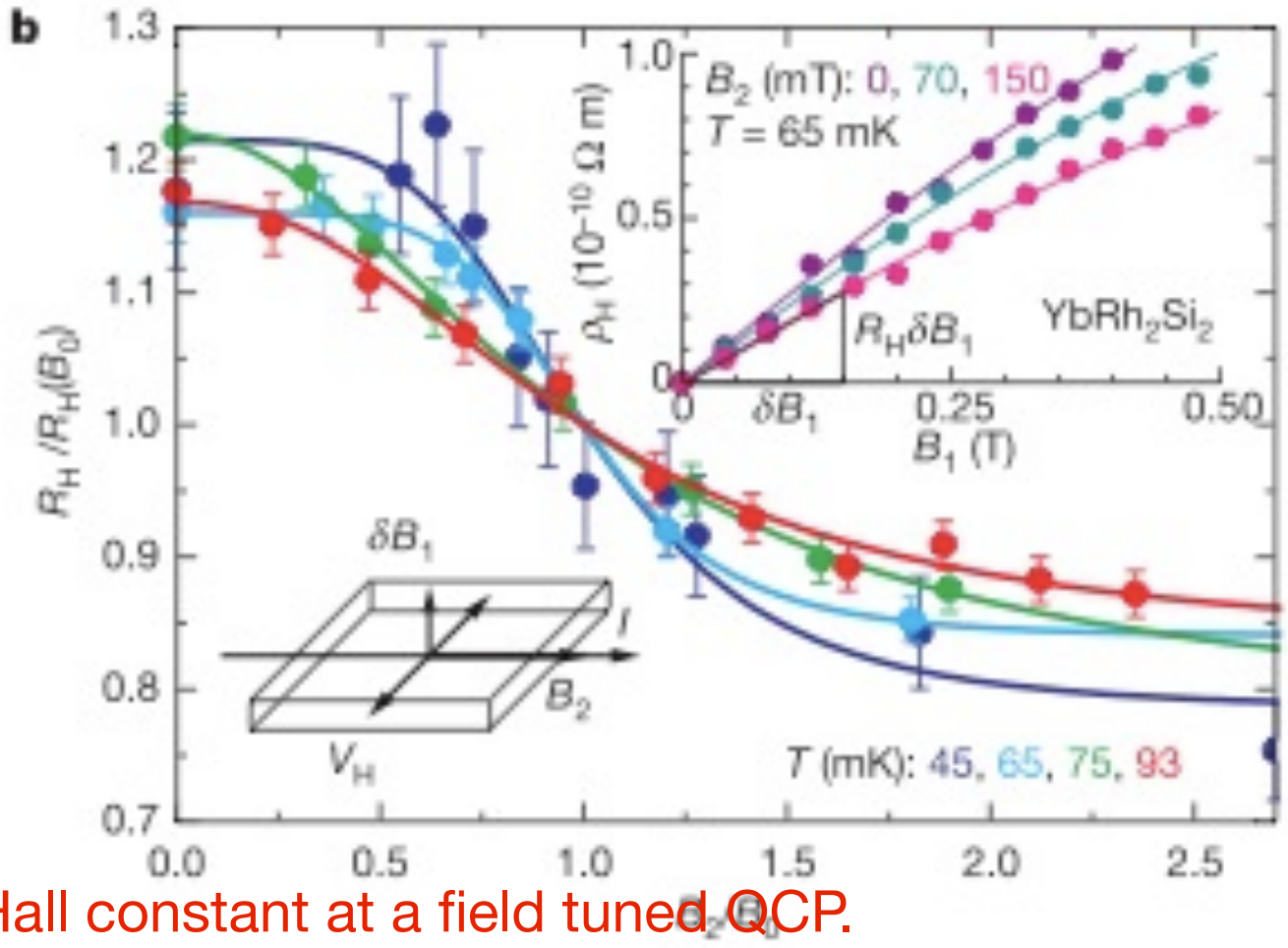
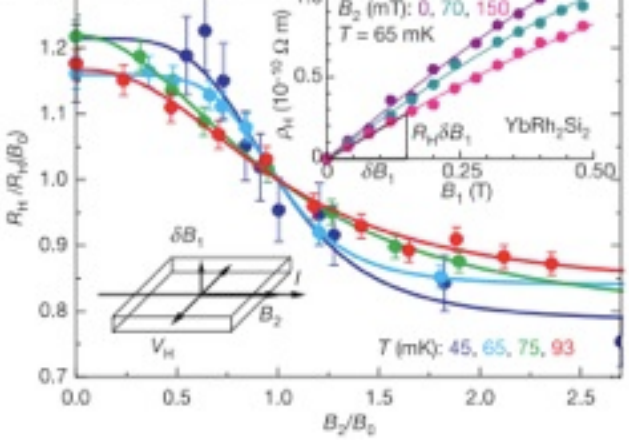
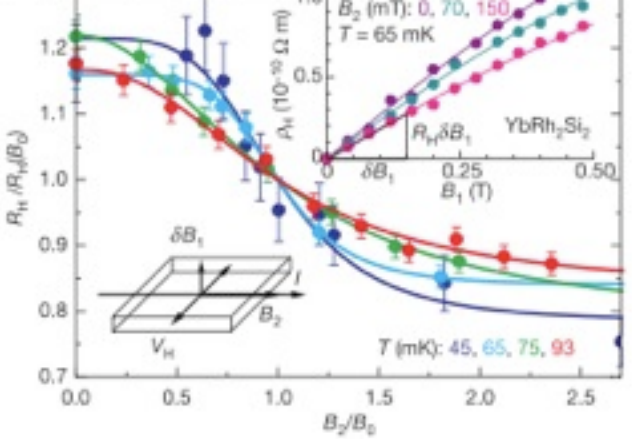


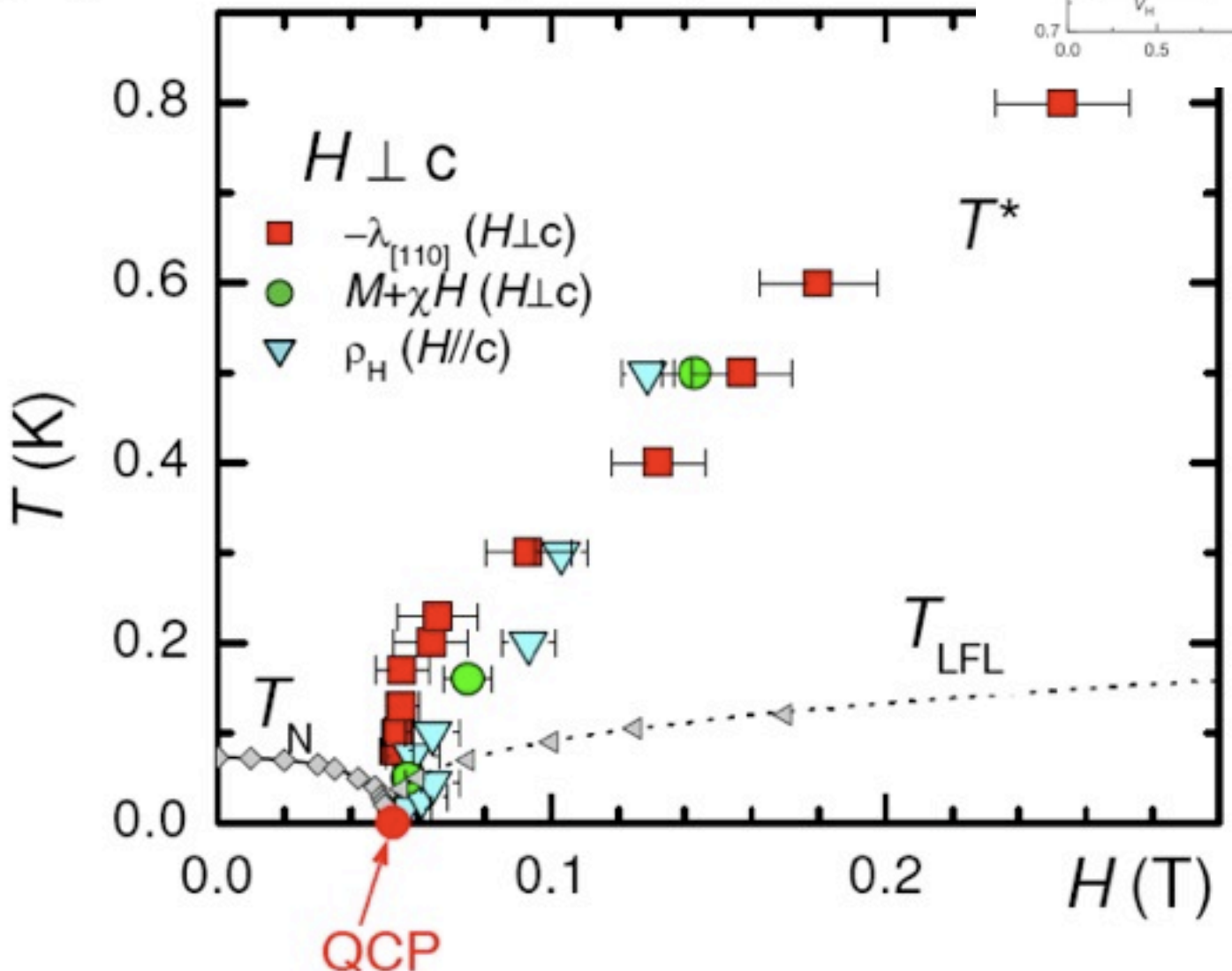
Jump in the Hall constant at a field tuned QCP.


$R_H/R_H(B_0)$
B_2/B_0
T (mK): 45, 65, 75, 93
δB_1
I
B_2
V_H
P_H (10^{-10} Ω m)
B_2 (mT): 0, 70, 150
T = 65 mK
$R_H\delta B_1$
YbRh$_2$Si$_2$
B_1 (T)

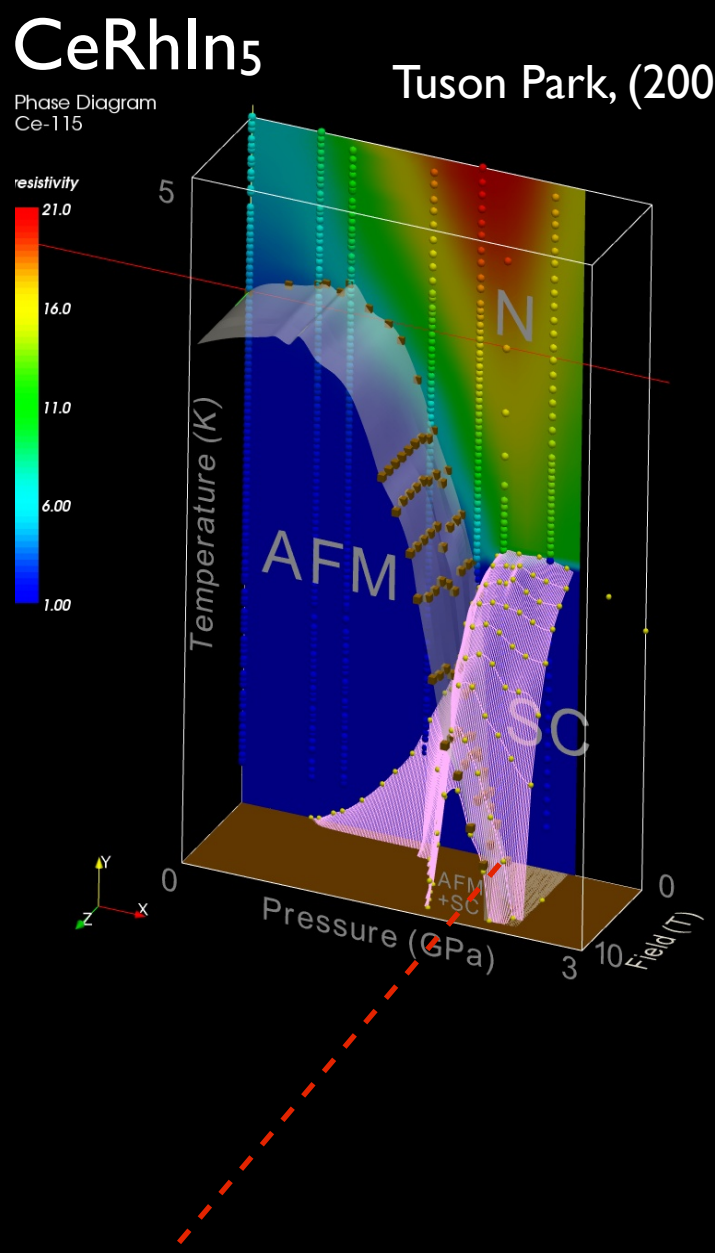
P. Gegenwart, T. Westerkamp et al., Science 315, 5814 (2007)



T_{Hall} represents a new energy scale (T^*)



Reconstruction of the Fermi Surface and mass divergence



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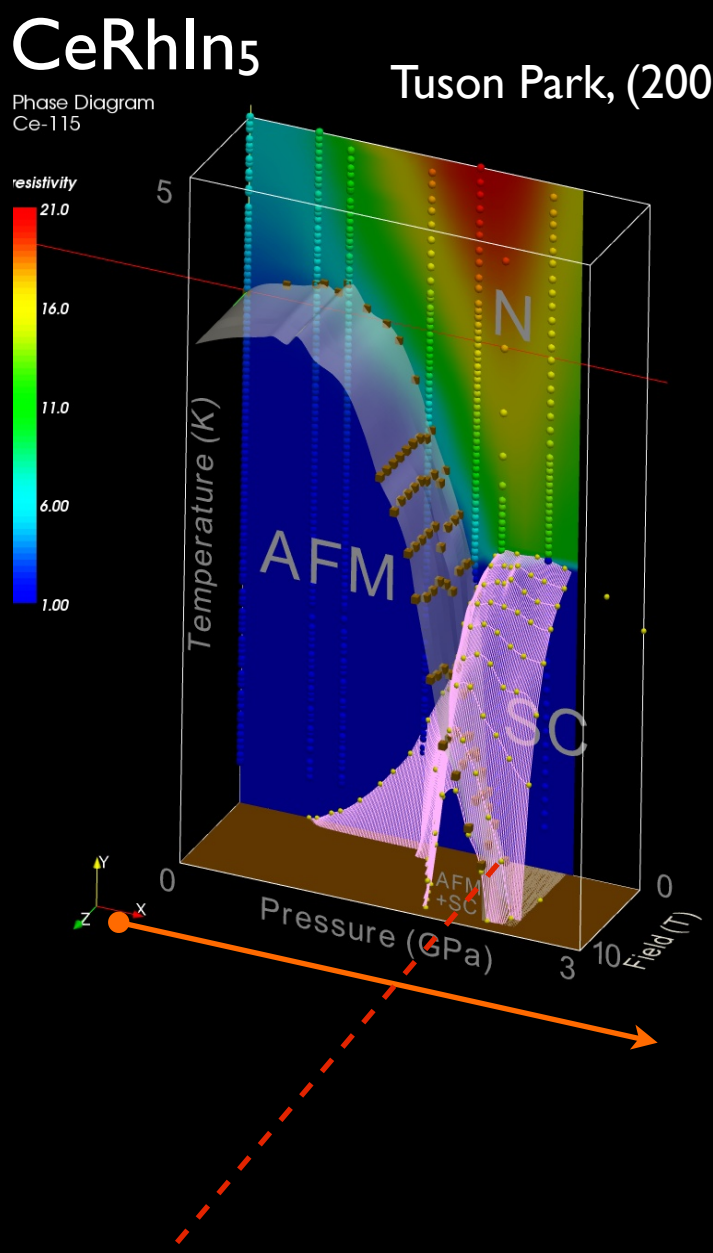

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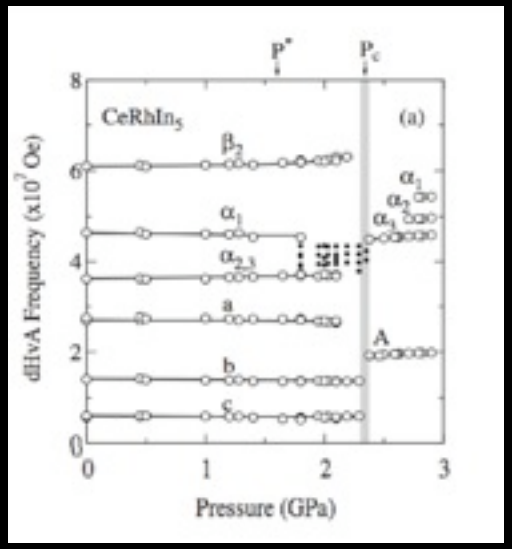
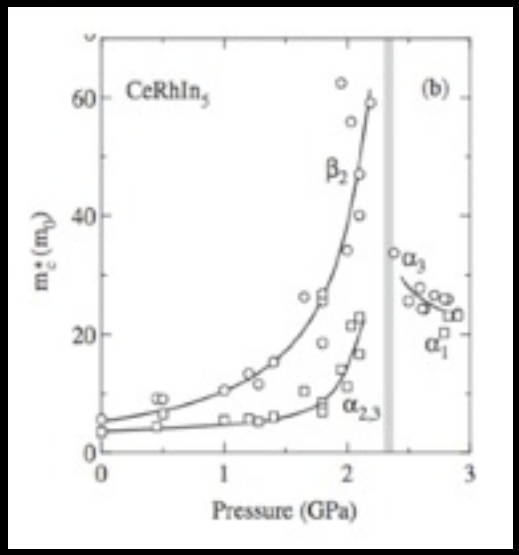
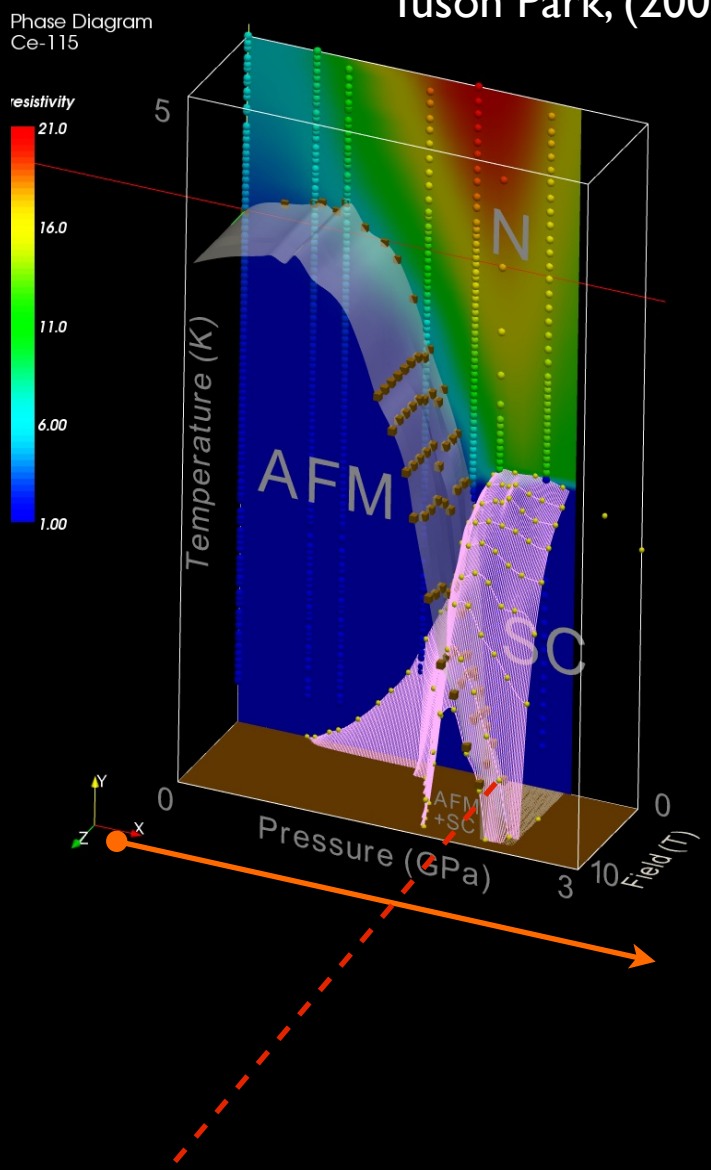




Shimuzu et al (2006)

$CeRhIn_5$

Tuson Park, (2007).



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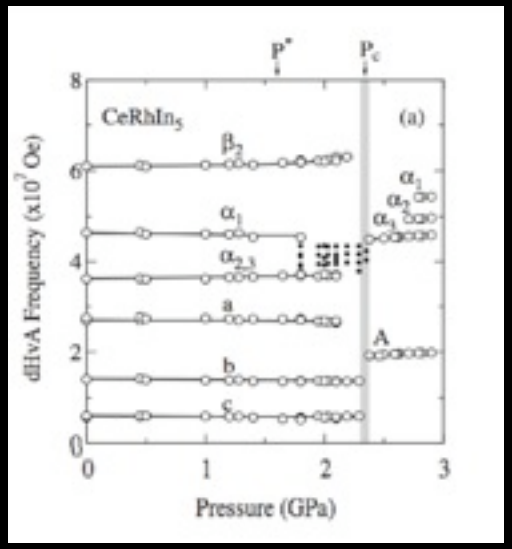

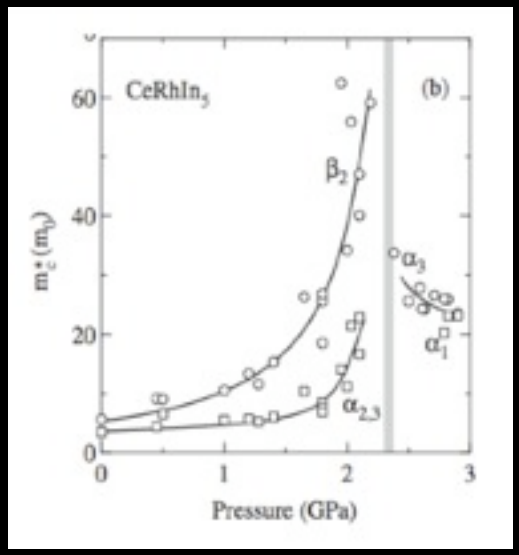

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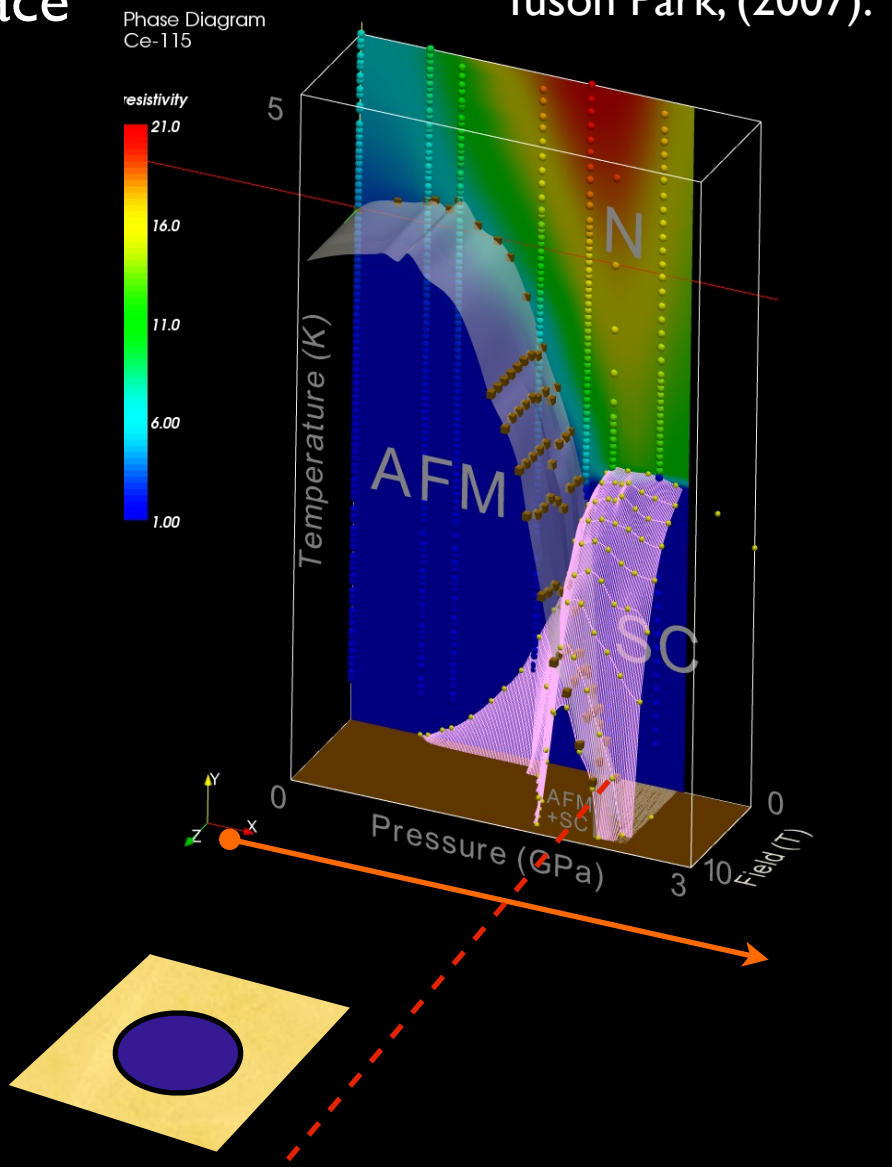

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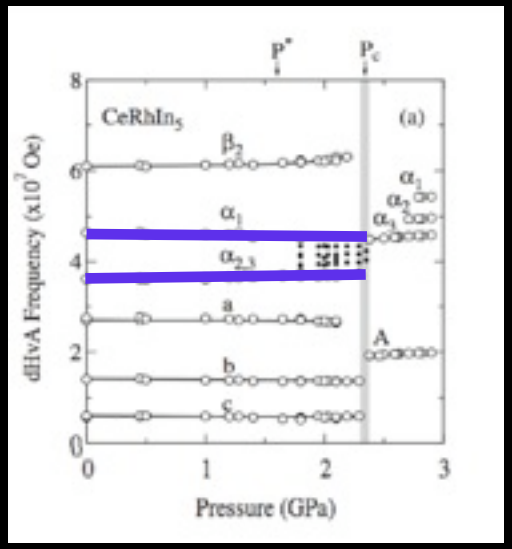

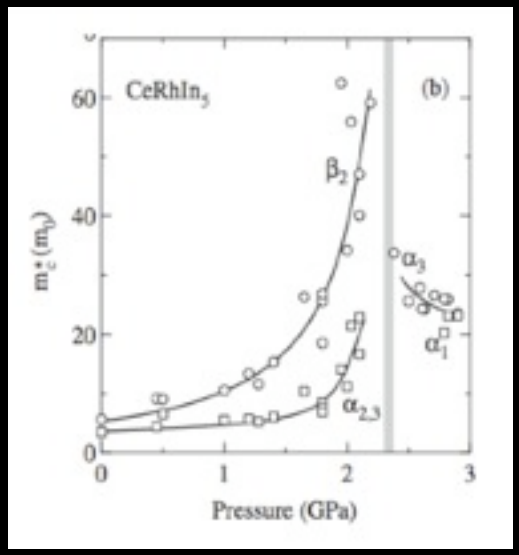

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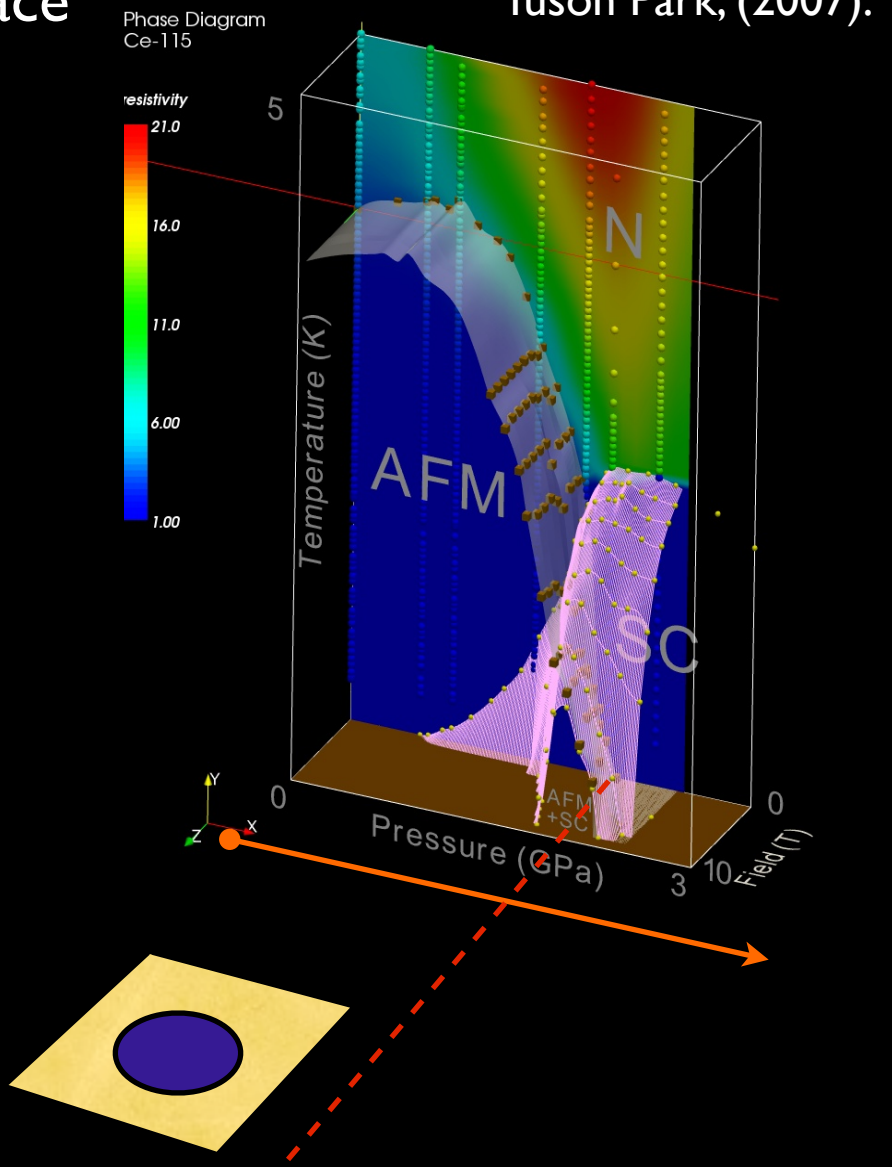

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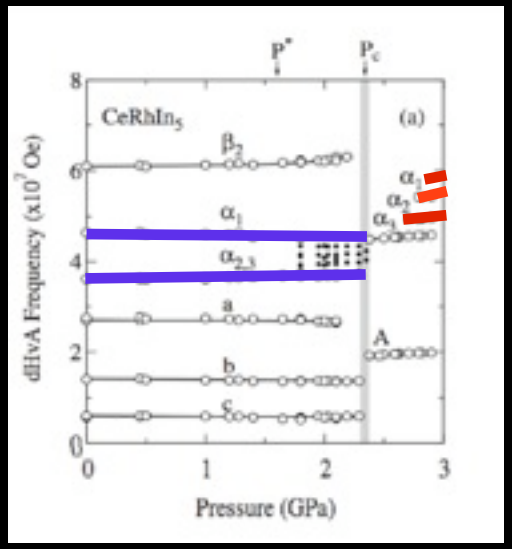

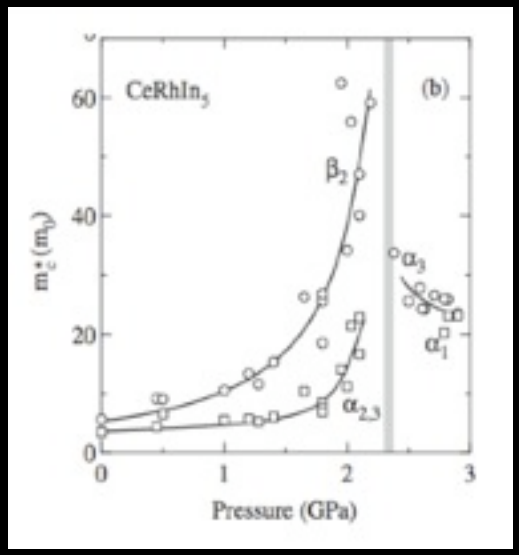

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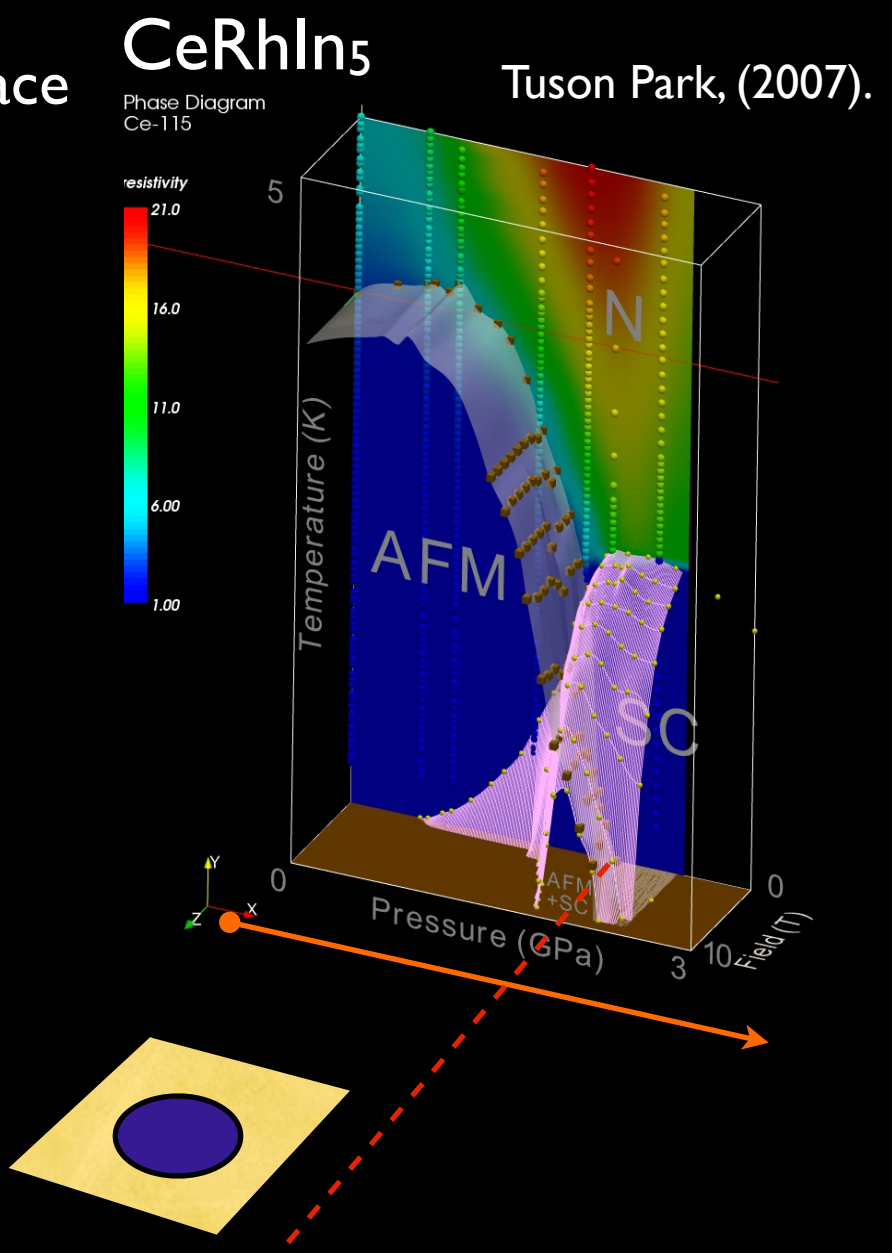

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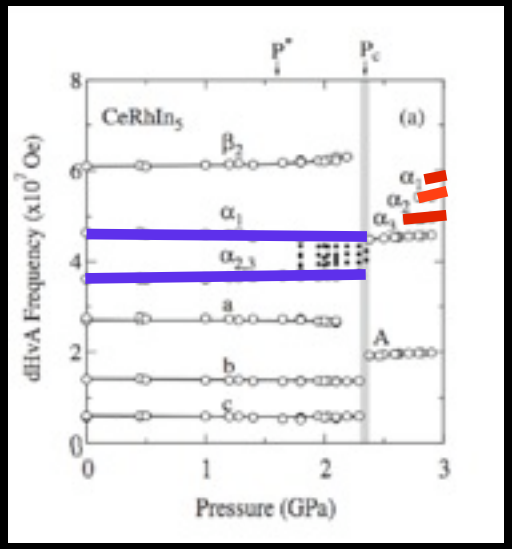

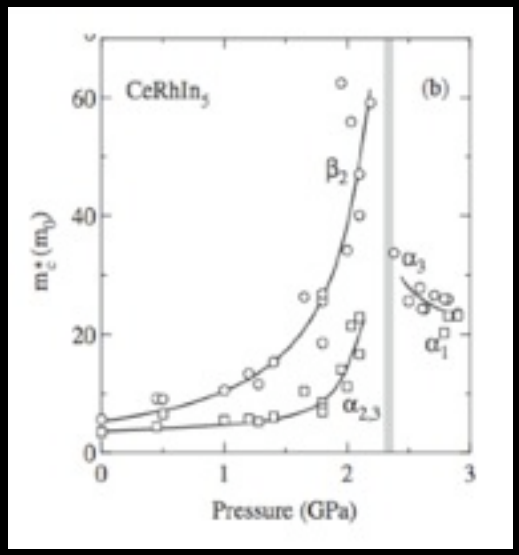

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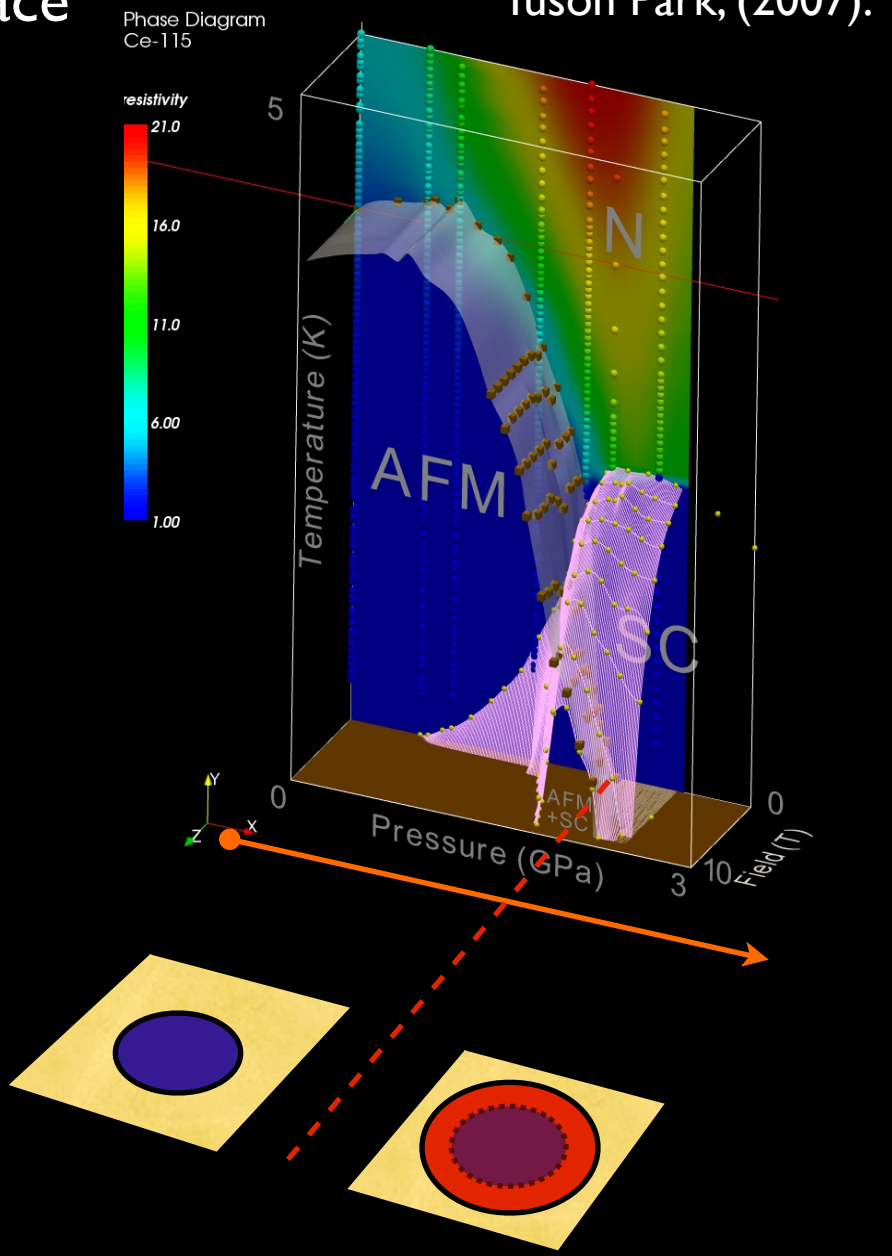
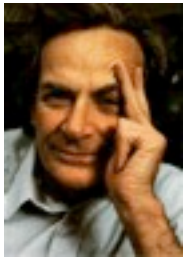
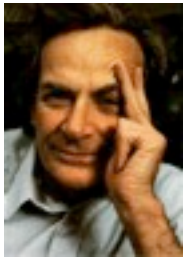


Black Hole in the Phase Diagram.




Feynman Hertz

$$Z = \sum_{\text{Histories}} \exp\left[-\int_0^{1/T} L[\psi(x,\tau)]d\tau\right]$$



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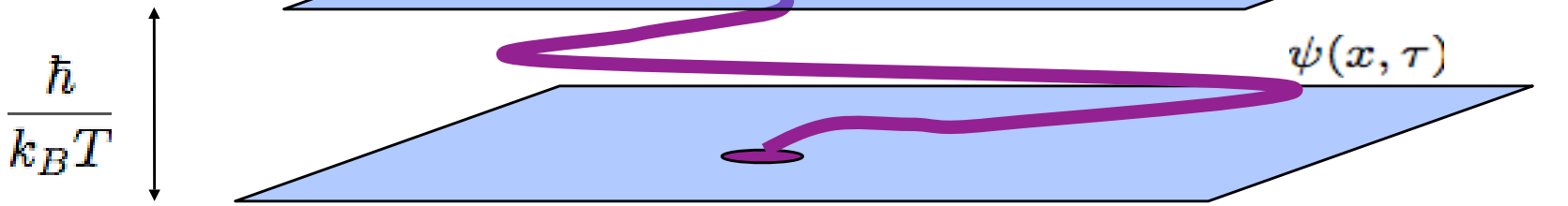

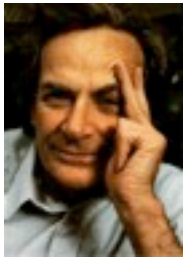

Feynman

Hertz

Temperature: Boundary condition in time.

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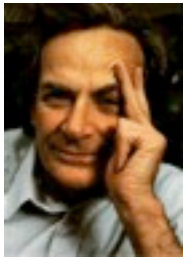
Sachdev (1999), Continentino (2001), Palova (2009).



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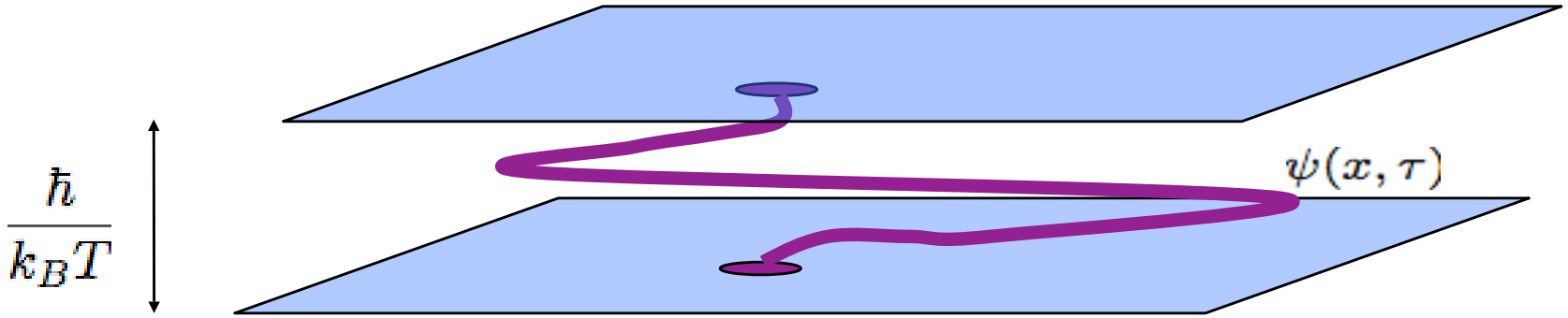

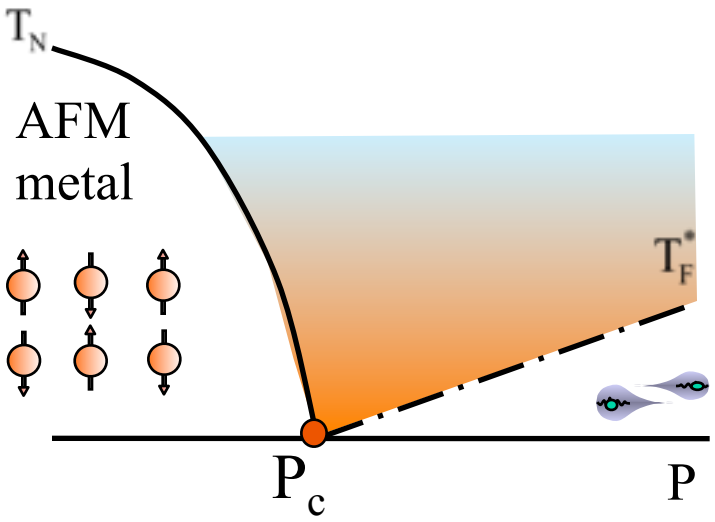

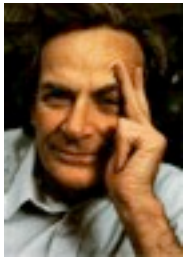

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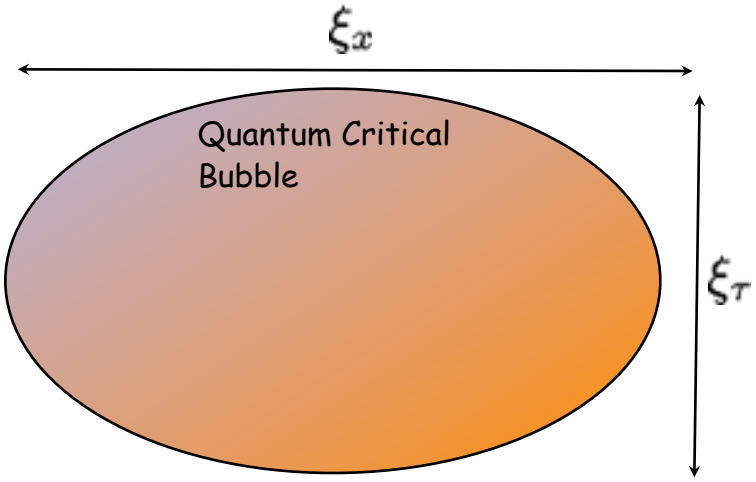

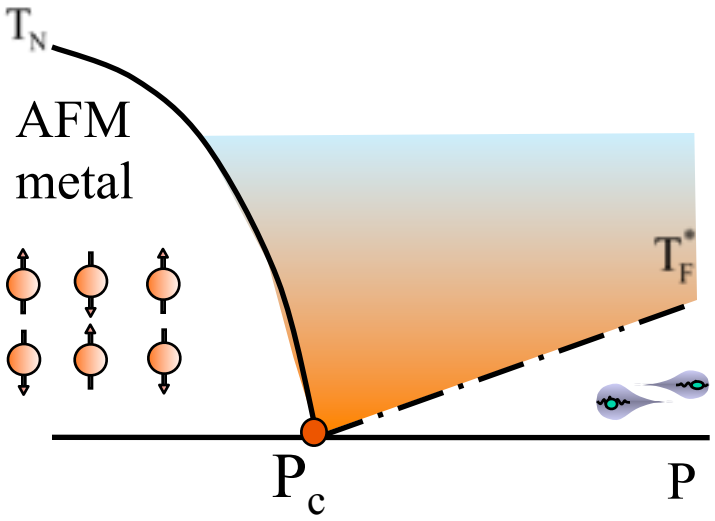

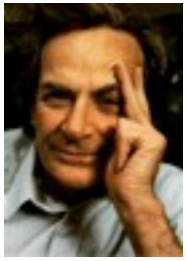
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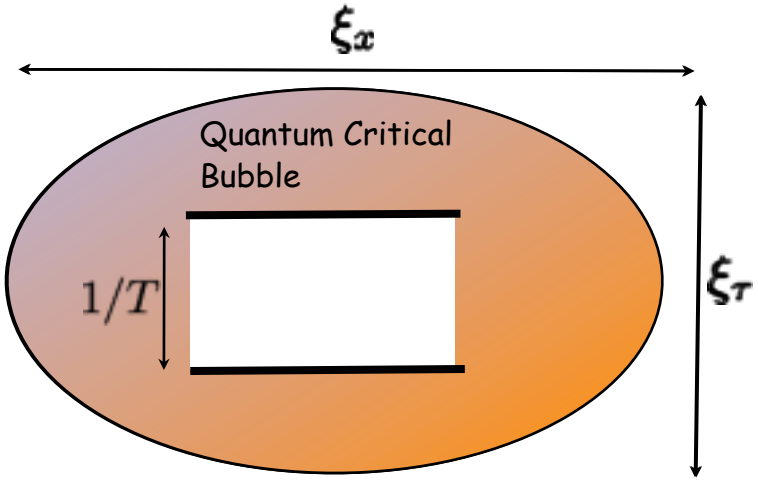

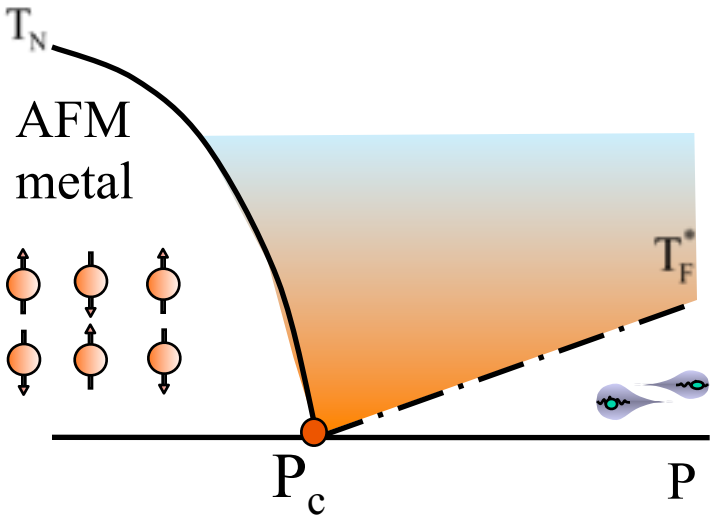

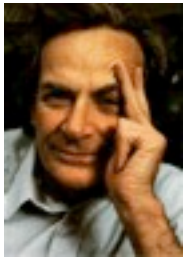

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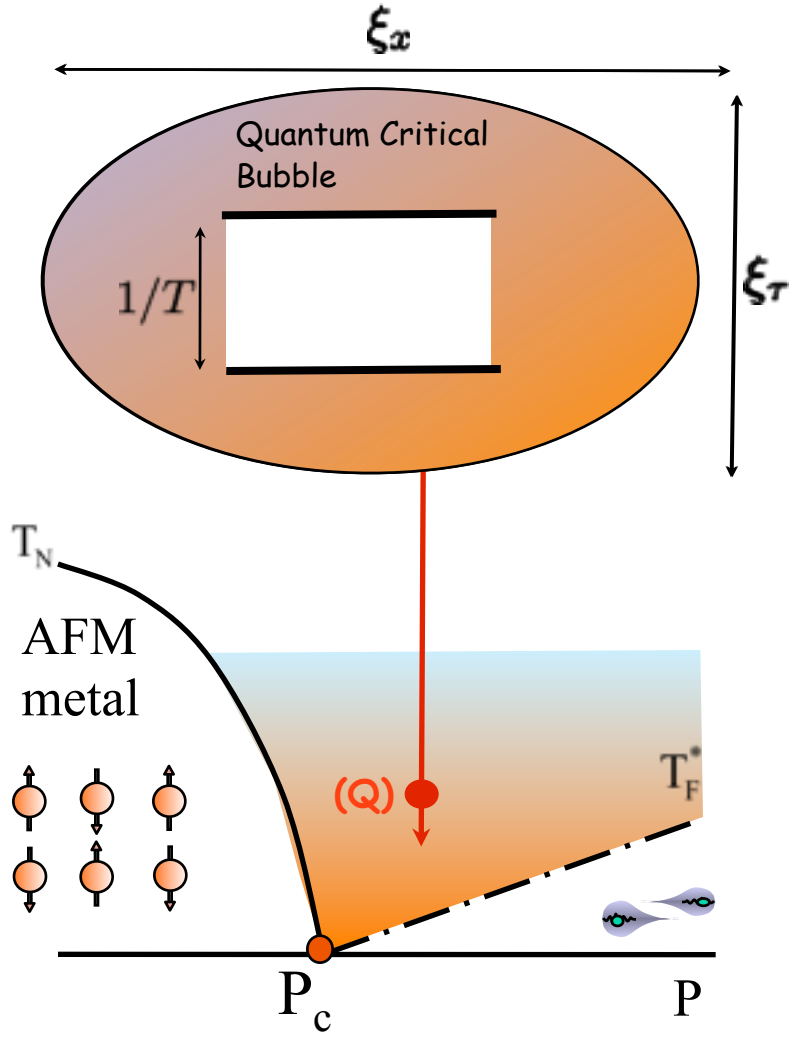
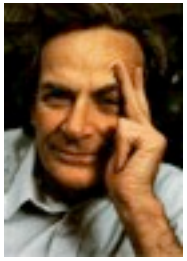


(Q) Quantum critical region: interior of correlation bubble.



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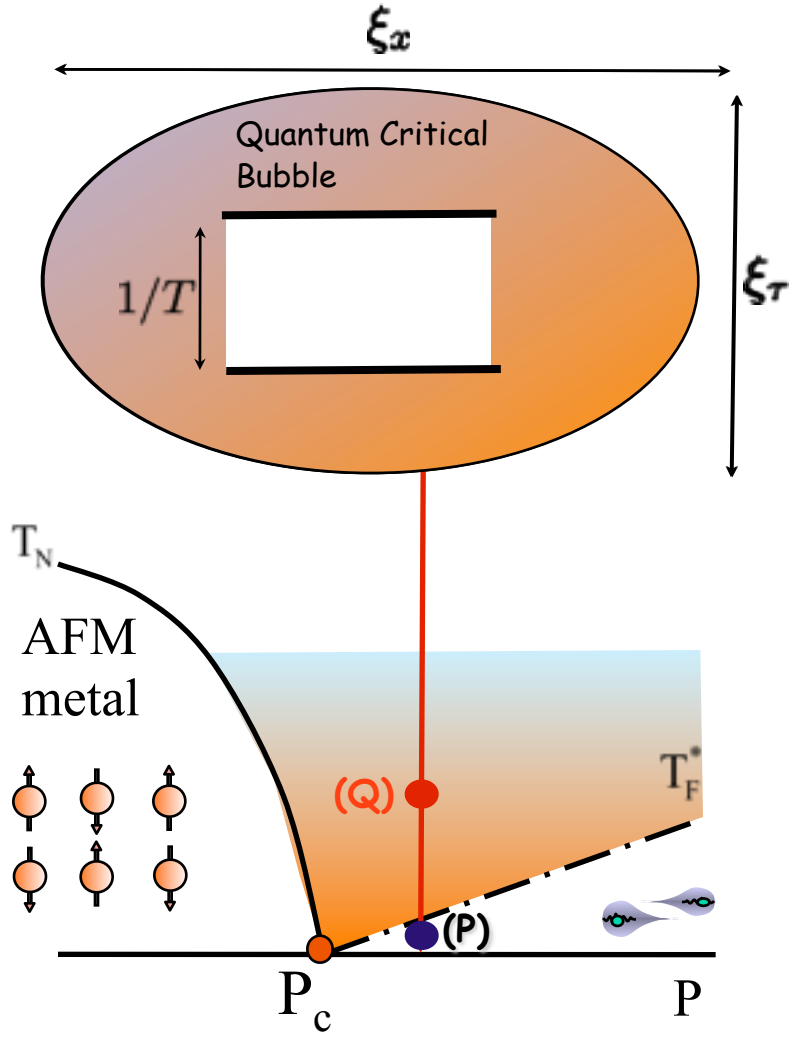
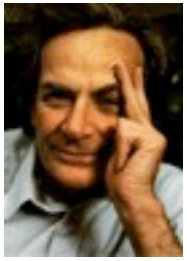


(Q) Quantum critical region: interior of correlation bubble.

(P) Paramagnet: probes exterior of correlation bubble



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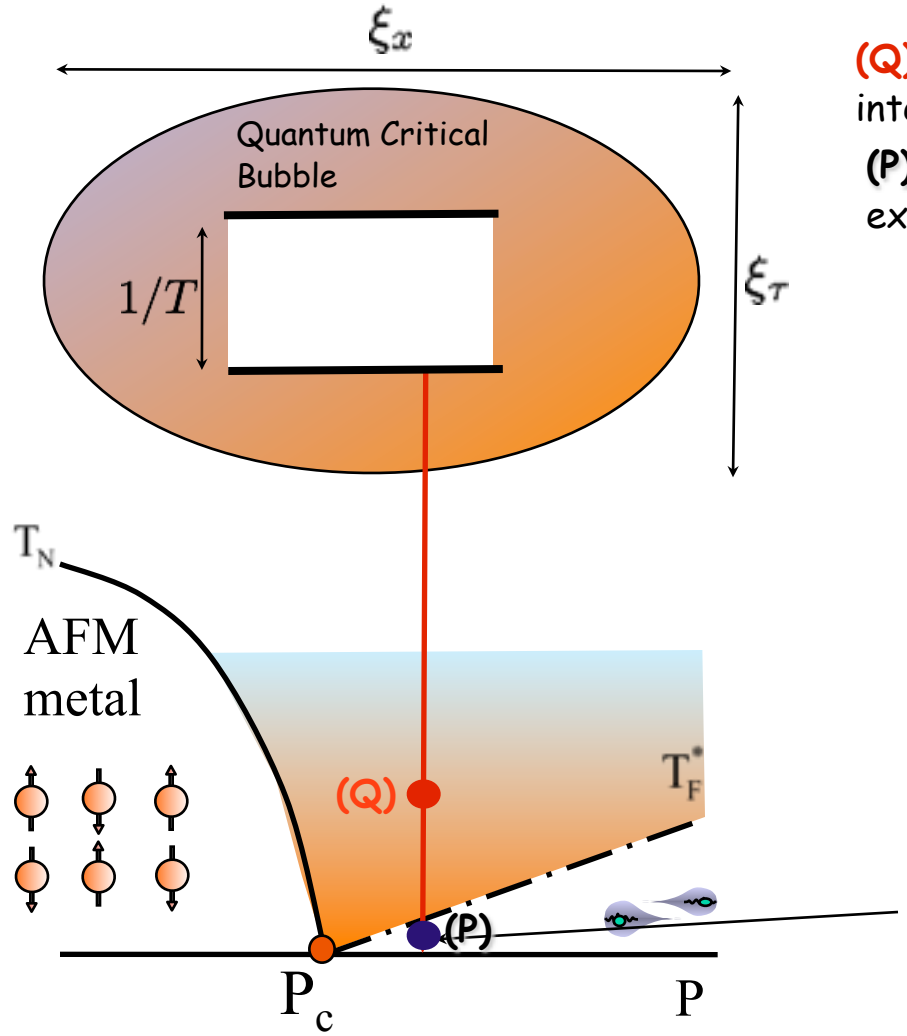

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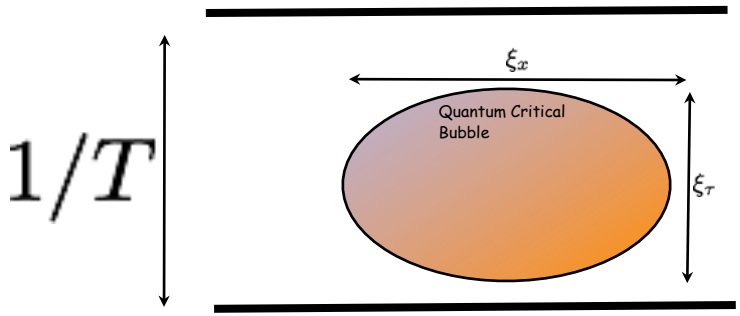
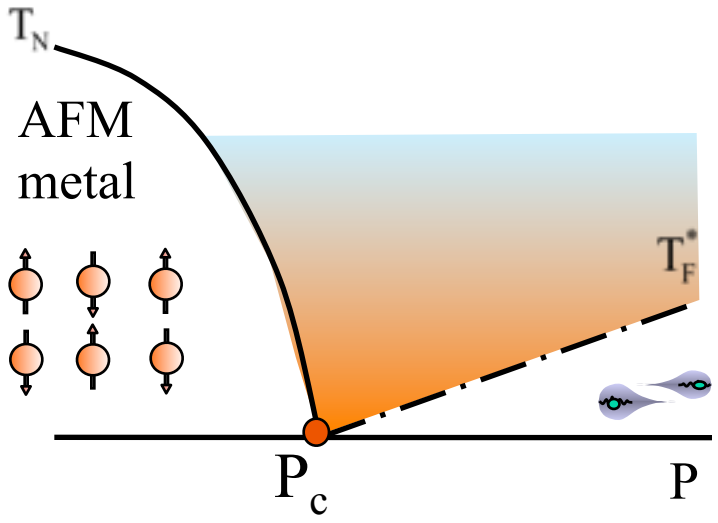


"Black Hole in the Phase Diagram".



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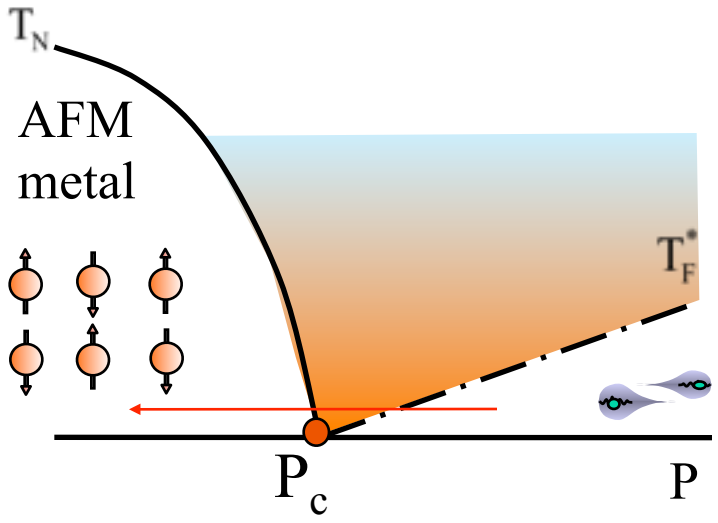
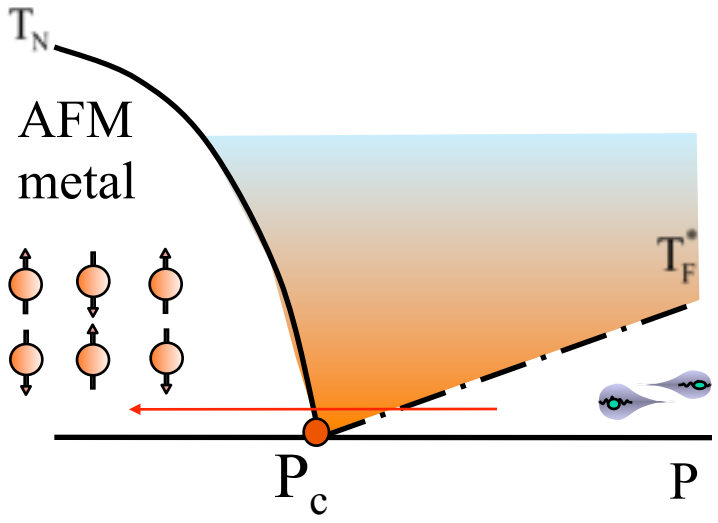
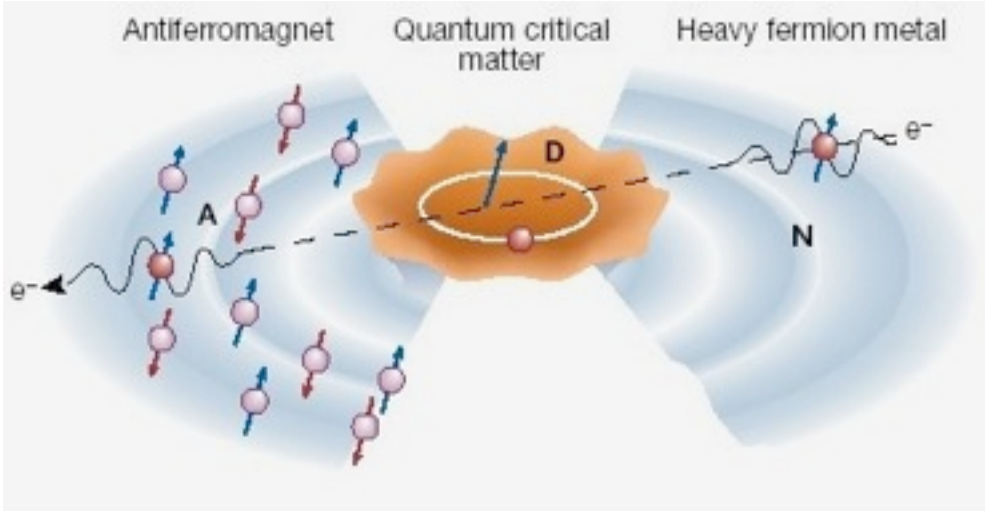


"Black Hole in the Phase Diagram".





P.C and A. Schofield, Nature (2005)

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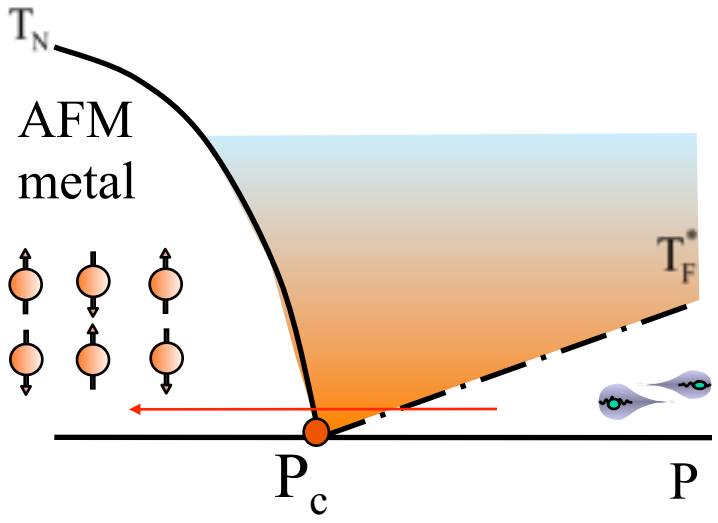

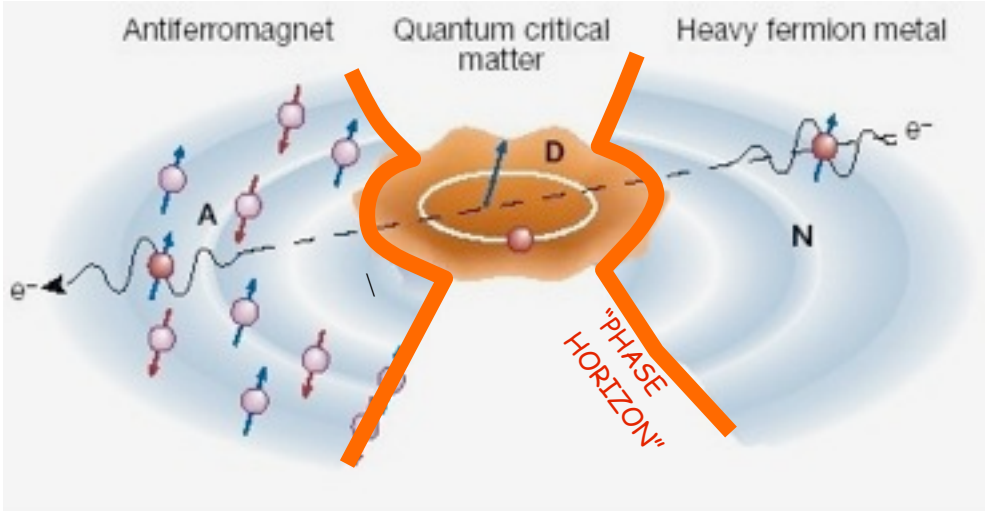

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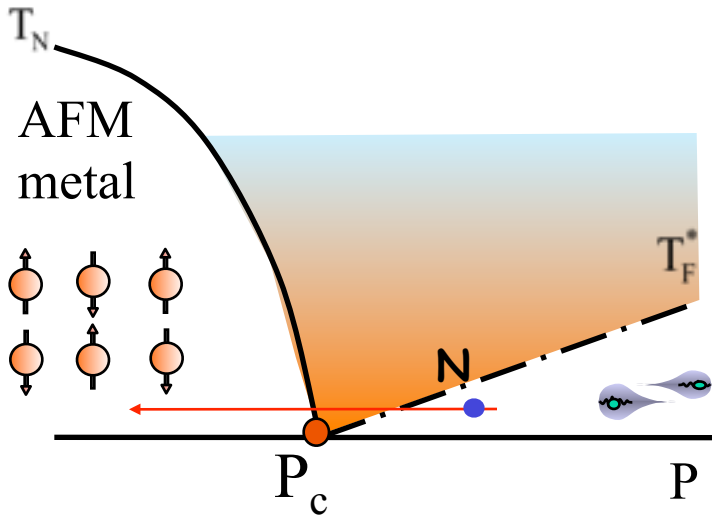

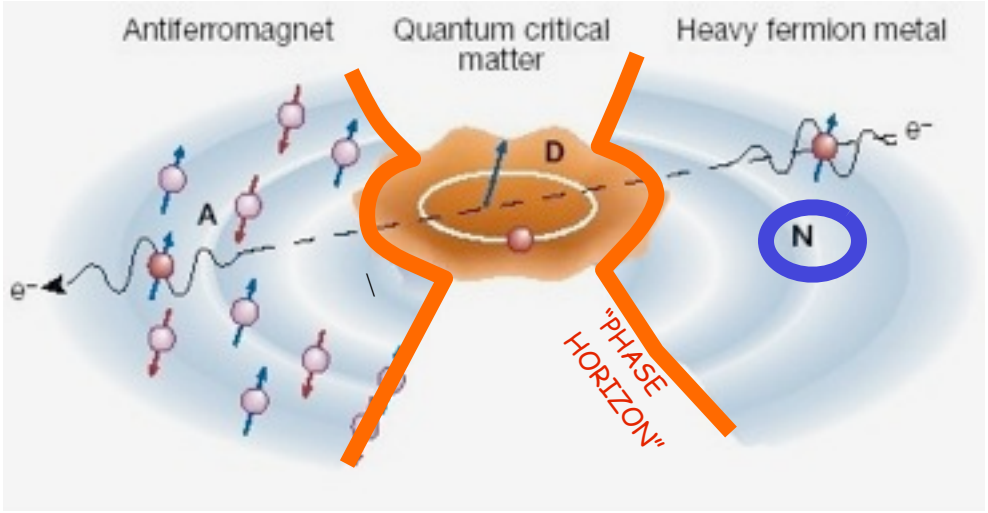

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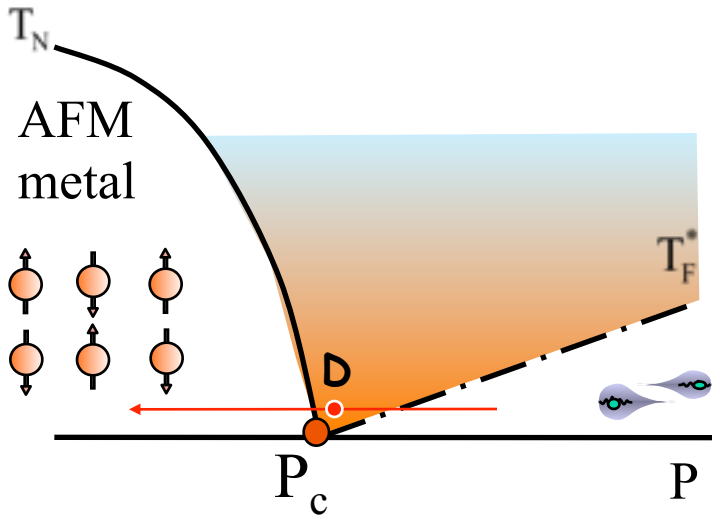

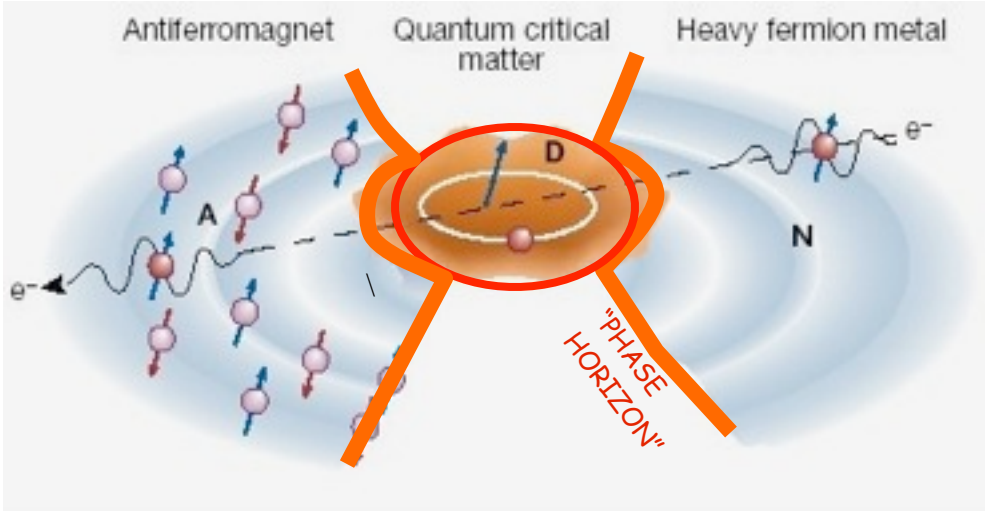

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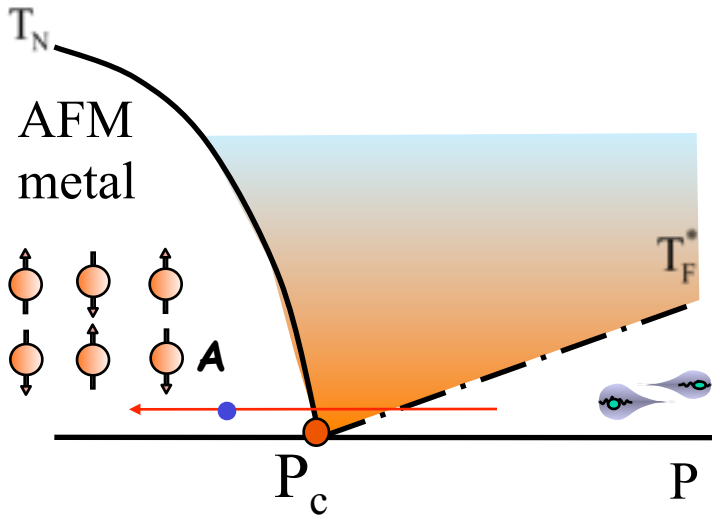

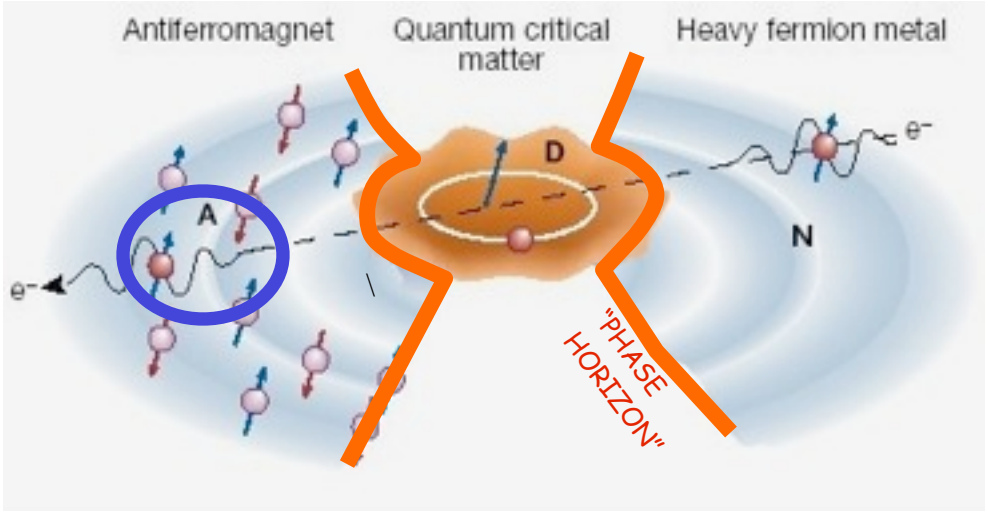

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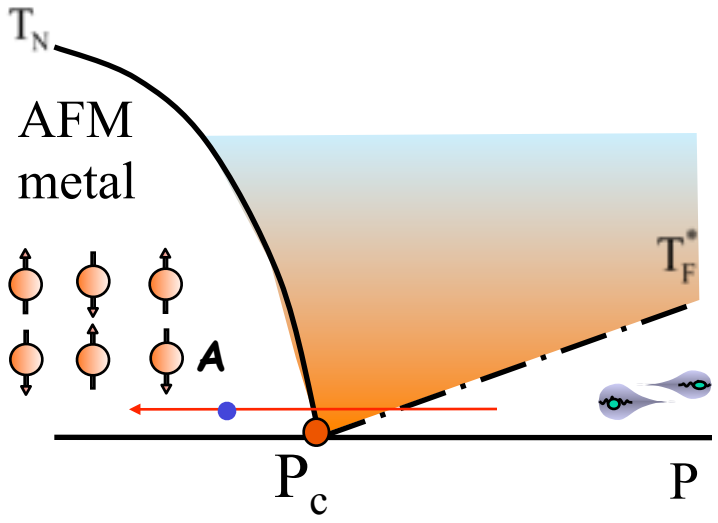
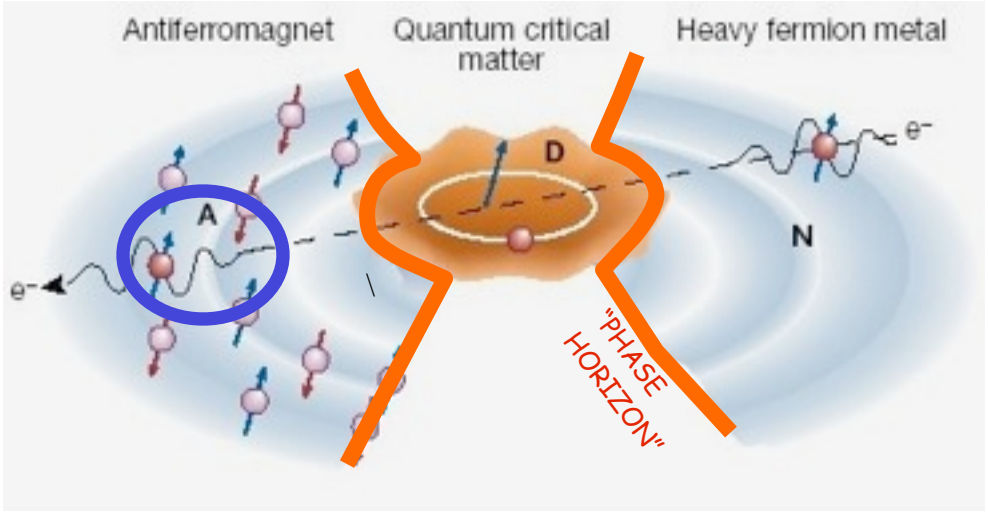




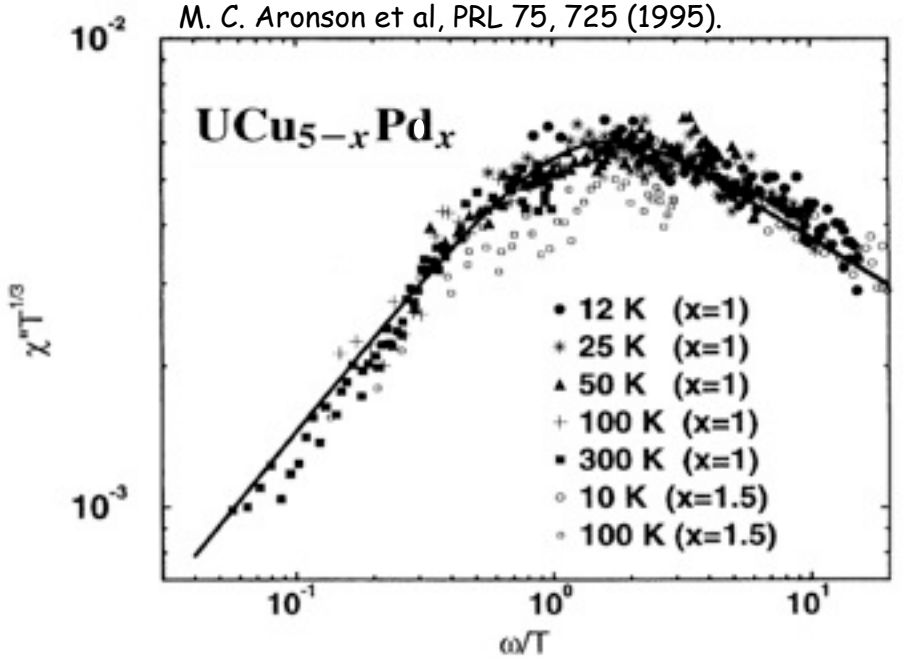
P.C and A. Schofield, Nature (2005)

John Hertz: Critical droplet is **Quantum** if $\hbar\omega(q)\big|_{q=\xi^{-1}} >> k_B T$

E/T Scaling:

Meigan Aronson

M. C. Aronson et al, PRL 75, 725 (1995).



Rutgers
Center for Materials Theory

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$$\chi''(E) = \frac{1}{E^{1-\alpha}} G\left(\frac{E}{T}\right)$$

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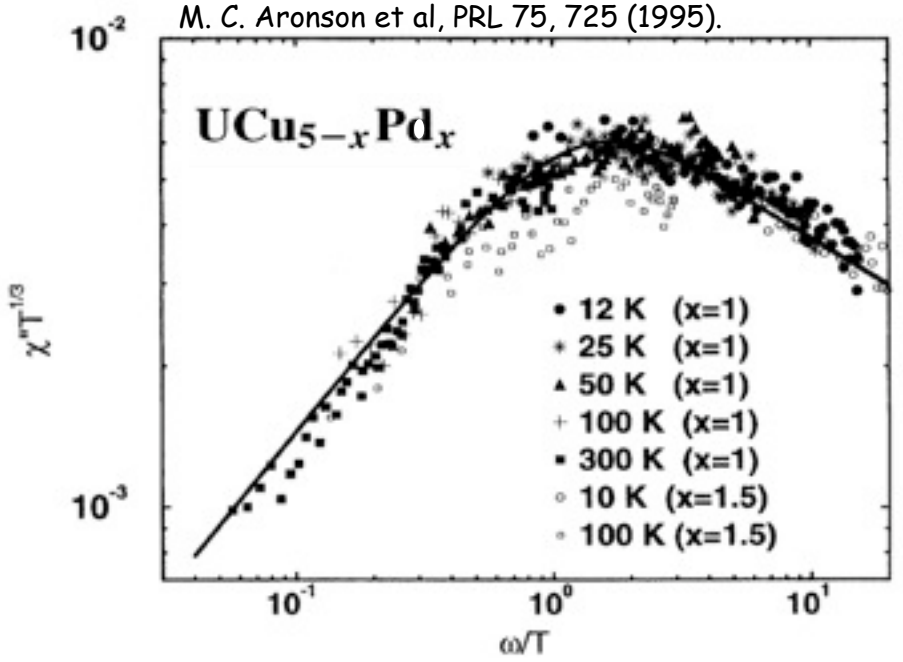

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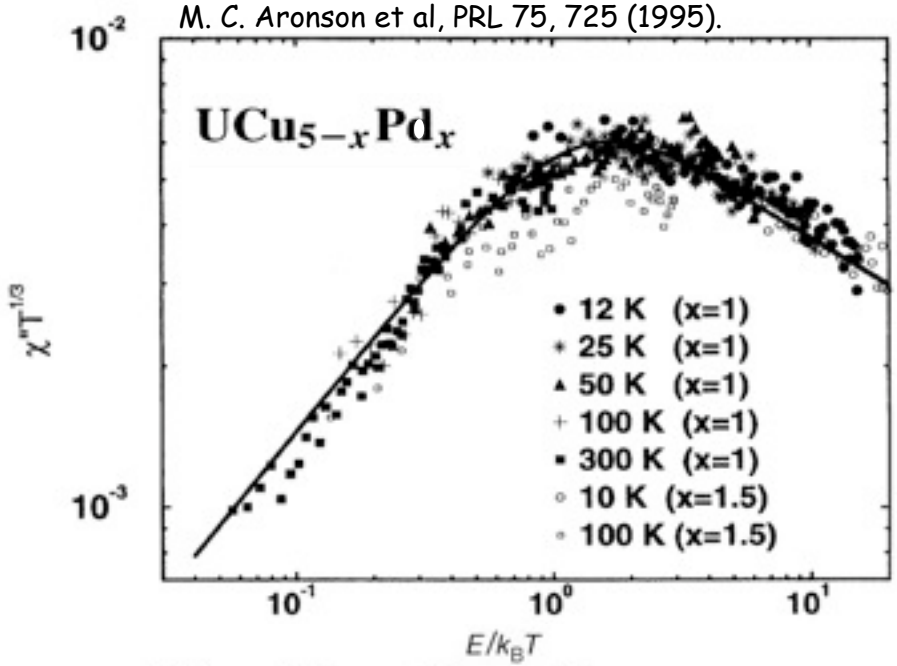

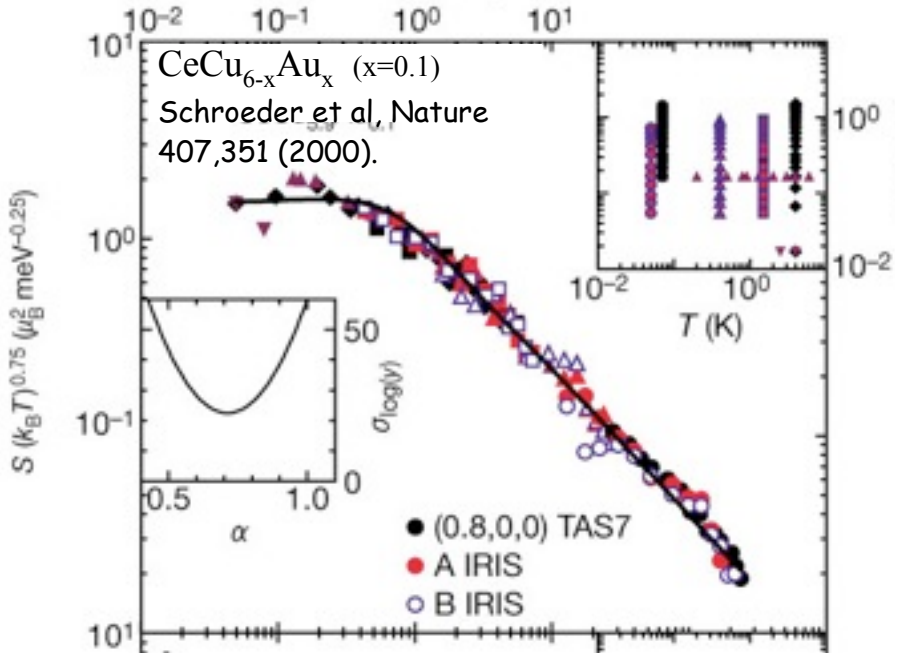

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Physics Below the upper Critical Dimension.

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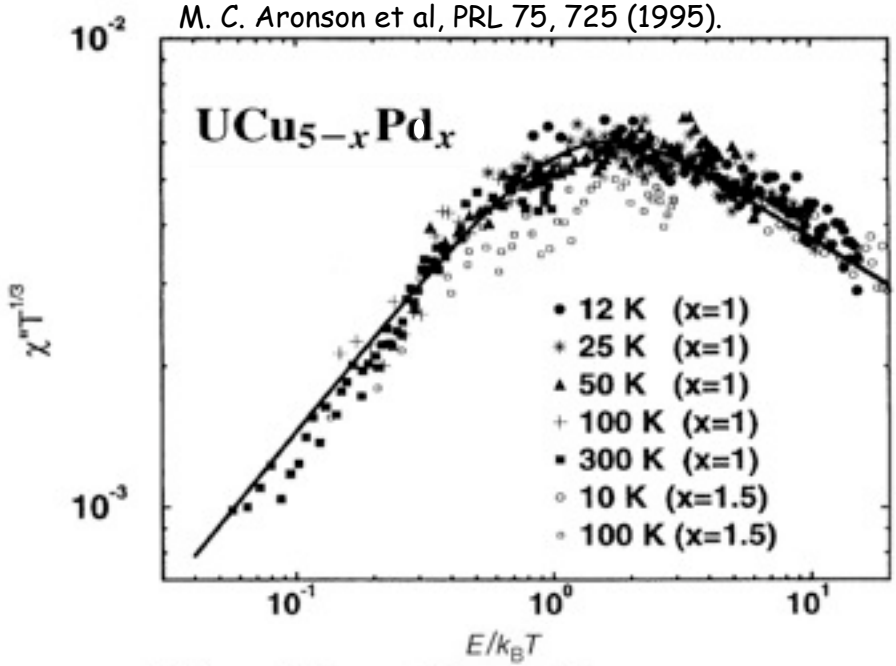

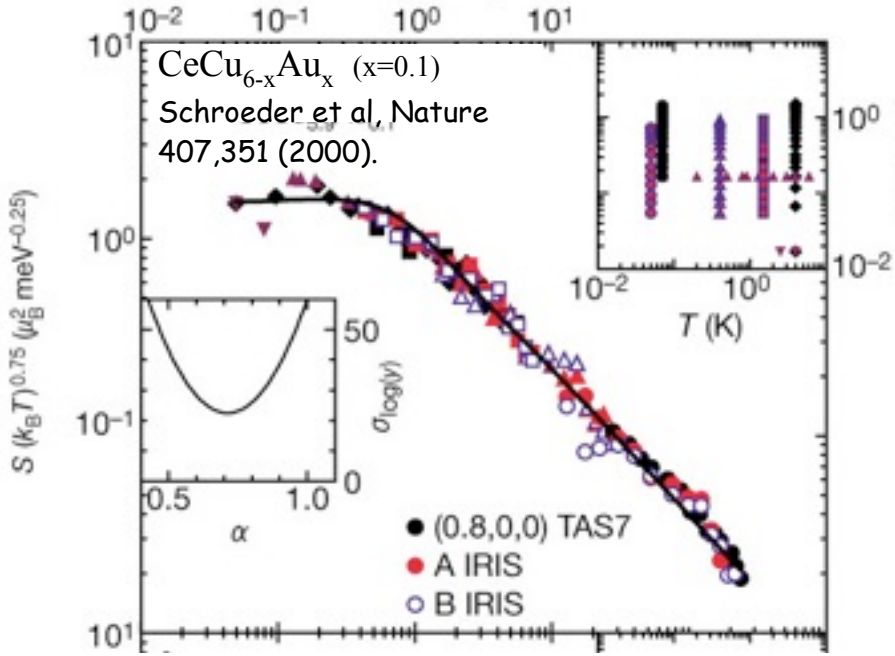

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The Standard Model

Standard Model: Quantum SDW?


Doniach

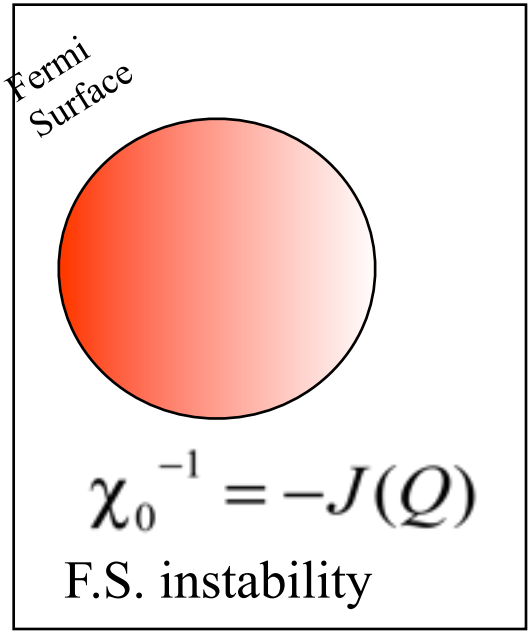

Schrieffer


Hertz


Millis

- Moriya, Doniach, Schrieffer (60s)
- Hertz (76)
- Millis (93)

$$d_{eff} = d + z$$



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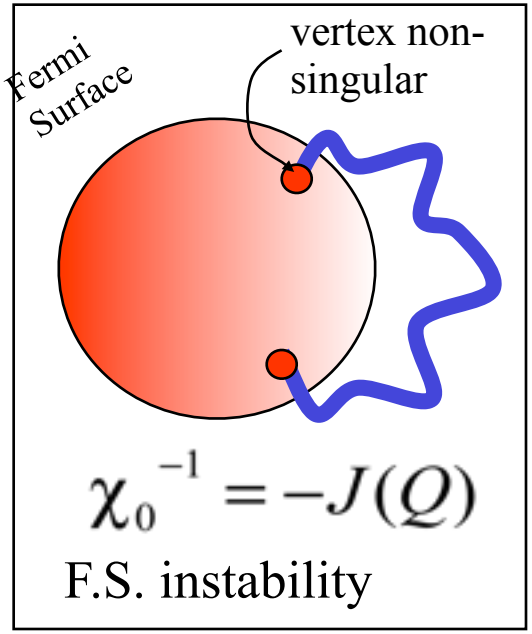

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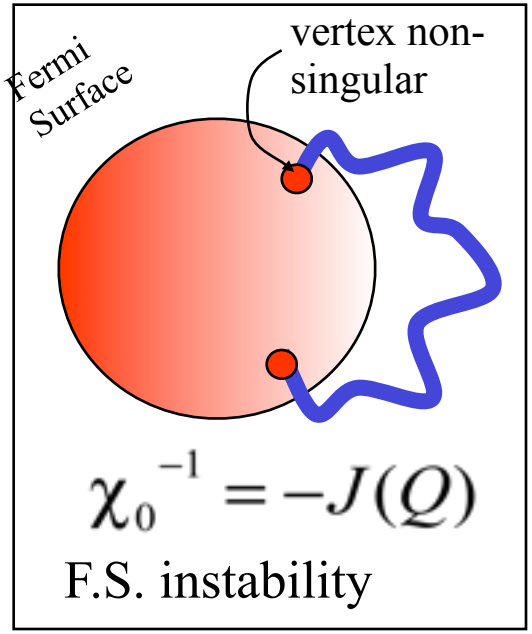

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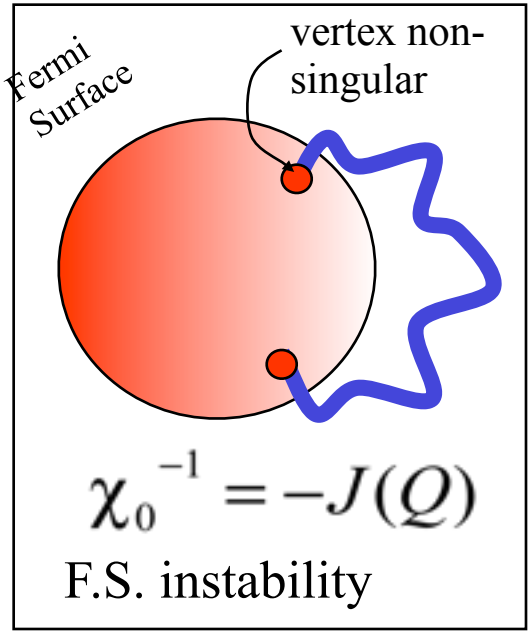

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Time counts as z =2 scaling dimensions

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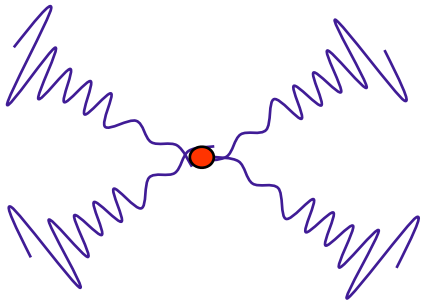

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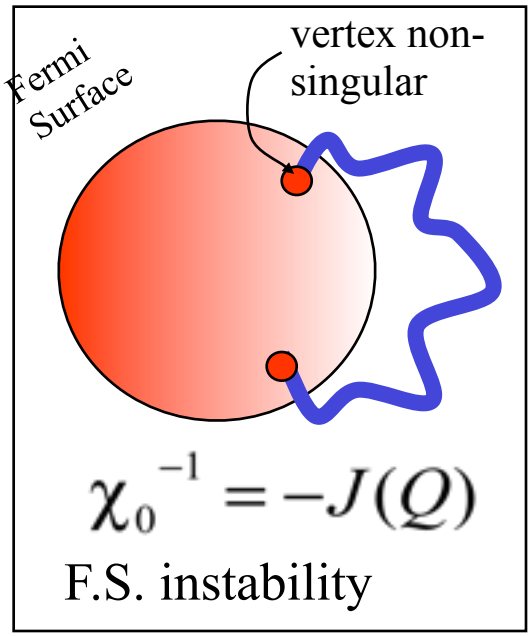
$$d_{eff} = d + z$$

If $d + z = d + 2 > 4$:
ϕ^4 terms "irrelevent"
Critical modes are Gaussian.
T is not the only energy scale.



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New Ideas:

Break up of the electron.

$$H = \sum \varepsilon_k c_{k\sigma}{}^{\dagger} c_{k\sigma} + J \sum_j (\psi^{\dagger}{}_j \vec{\sigma} \psi_j) \bullet \vec{S}_j$$

"THE BATTLEGROUND"

Kondo Lattice Model

(Kasuya, 1951)

$$H = \sum \varepsilon_k c_{k\sigma}^{\dagger} c_{k\sigma} + J \sum_j (\psi^{\dagger}{}_j \vec{\sigma} \psi_j) \cdot \vec{S}_j$$

"THE BATTLEGROUND"

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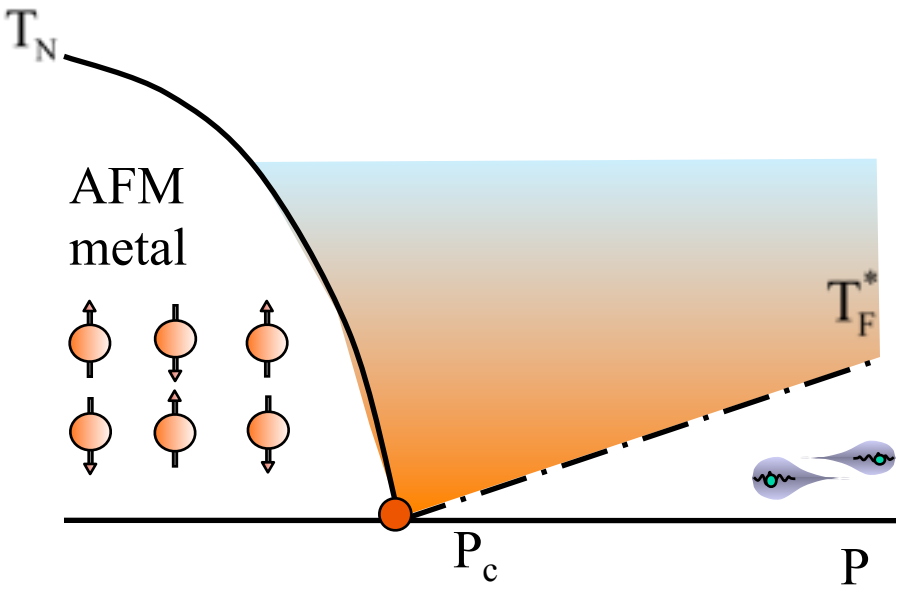
Heavy Fermion Materials



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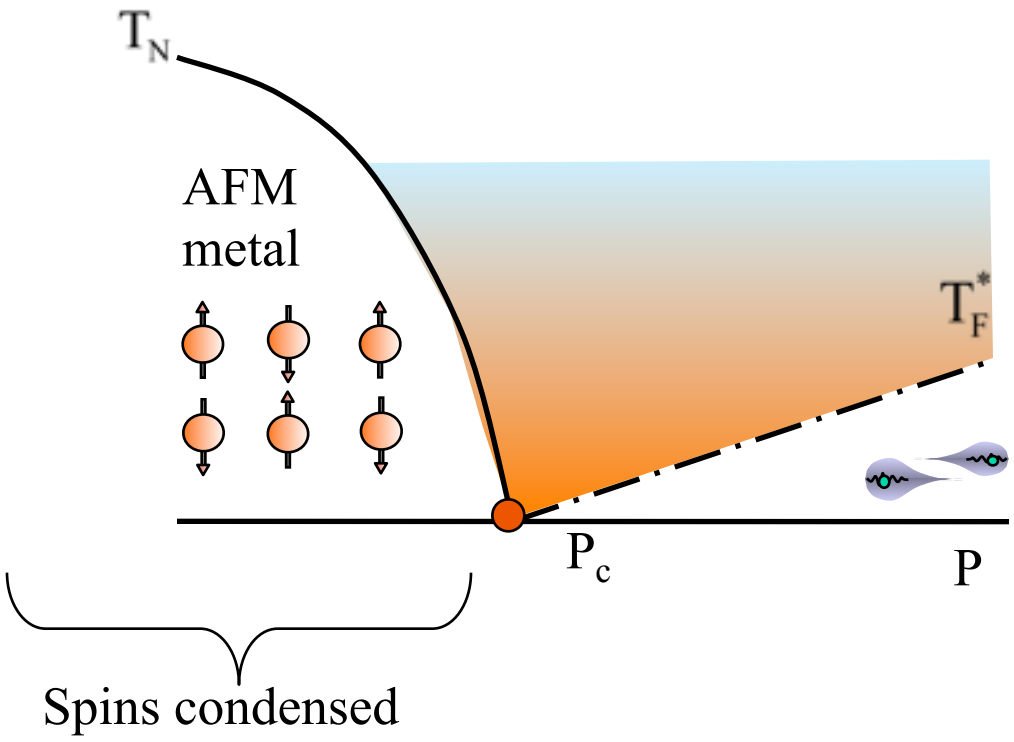

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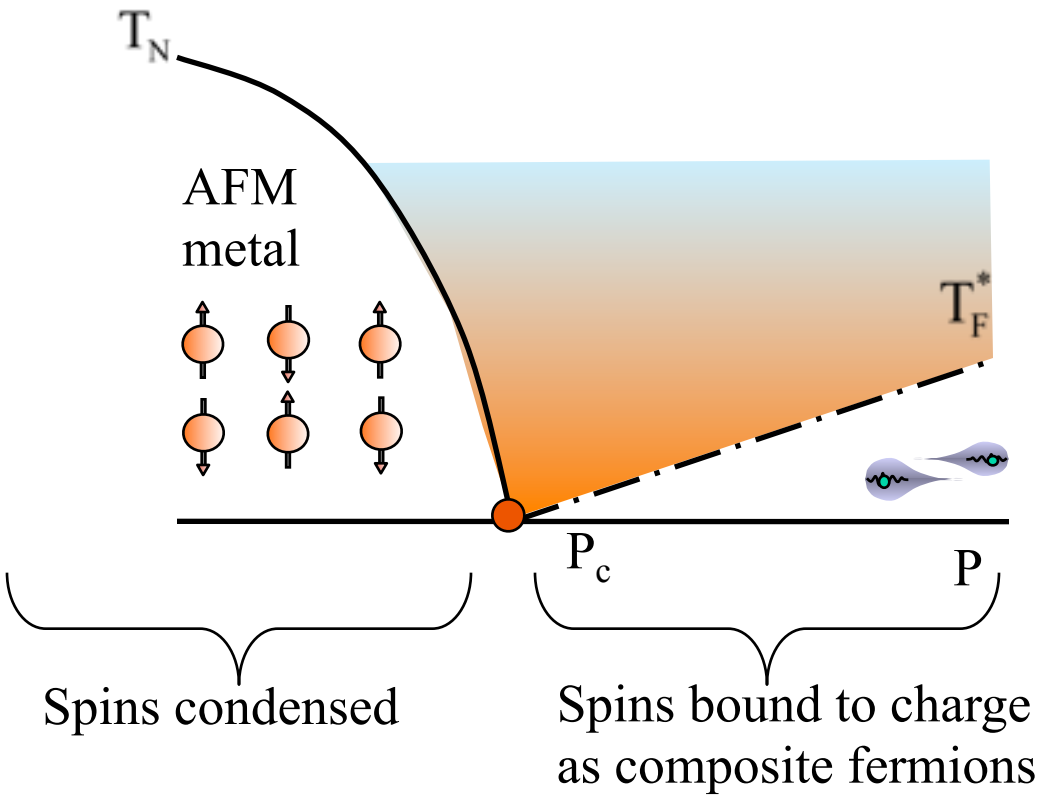

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"THE BATTLEGROUND"

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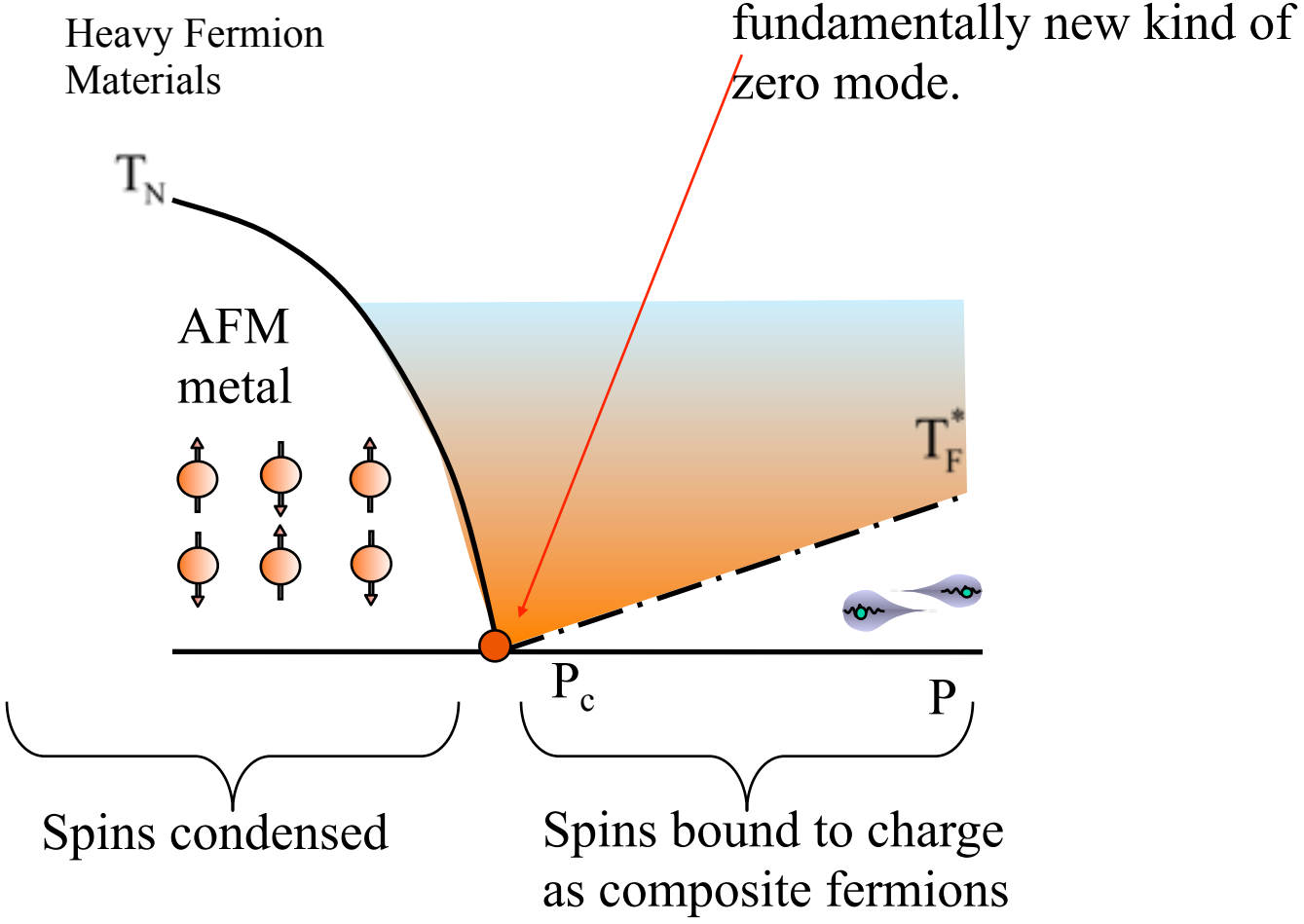
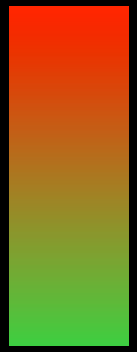
Deconfinement of spin: fundamentally new kind of zero mode.

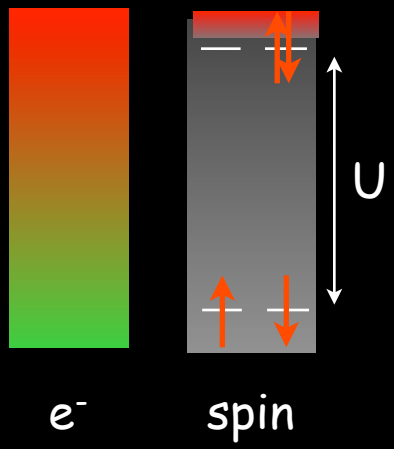


New Methods



e^-

New Methods



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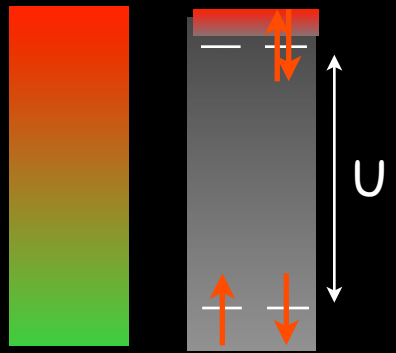


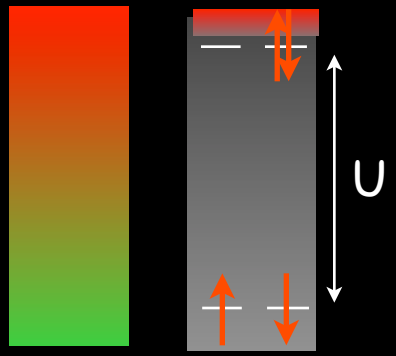
e^- spin

Φ W

Elimination of States
implies Gauge Fields.

(Read Newns, PC, Millis Lee... 80's)

New Methods



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$$\vec{S} = b^\dagger{}_\alpha \left(\frac{\vec{\sigma}}{2}\right)_{\alpha\beta} b_\beta$$

J. Schwinger '55

$$U(1): \qquad b_j \rightarrow e^{i\theta_j} b_j$$

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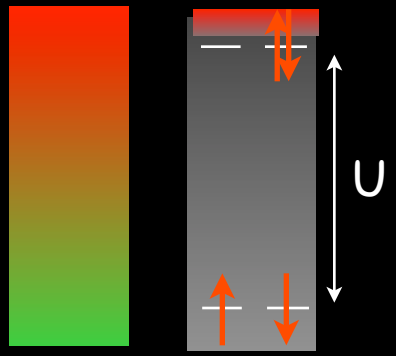

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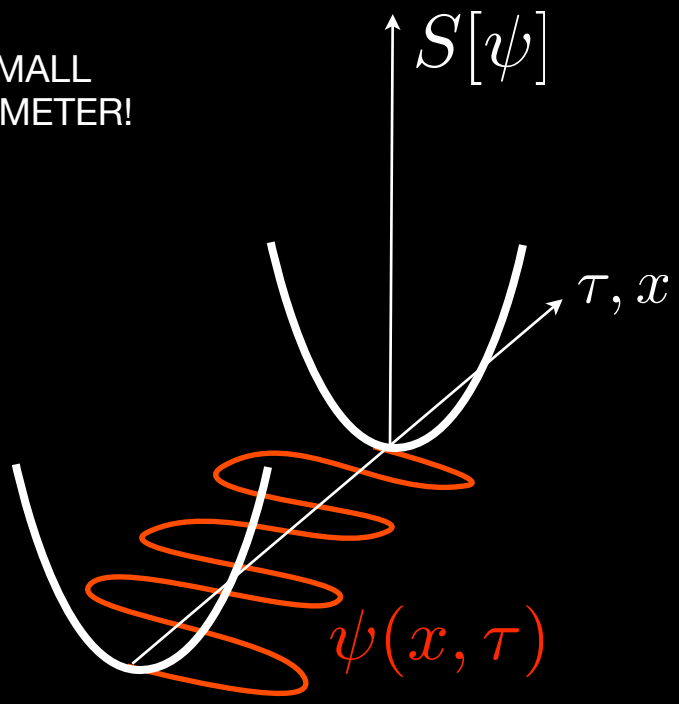

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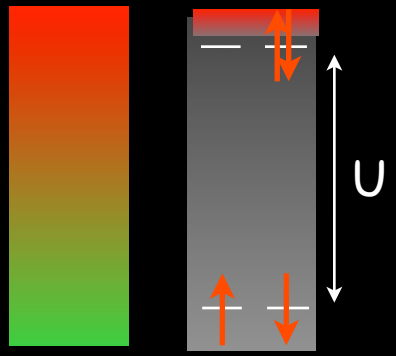

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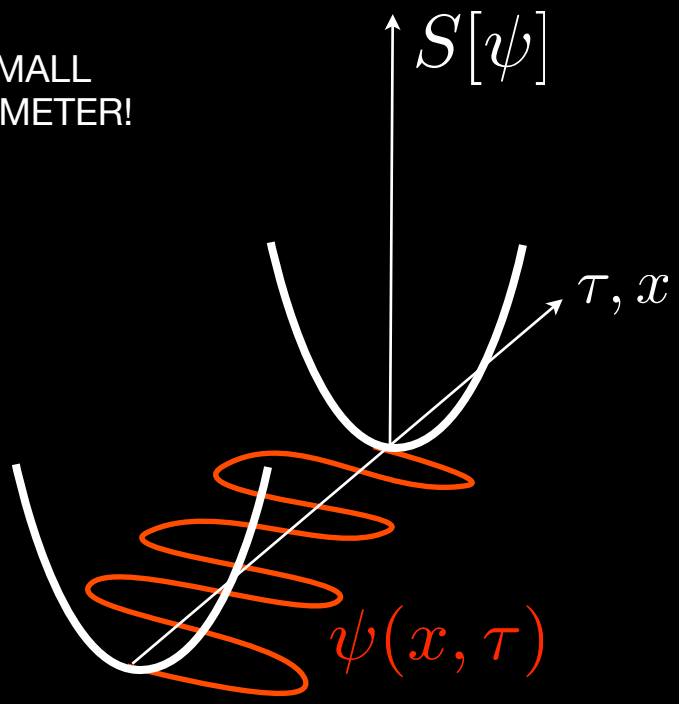
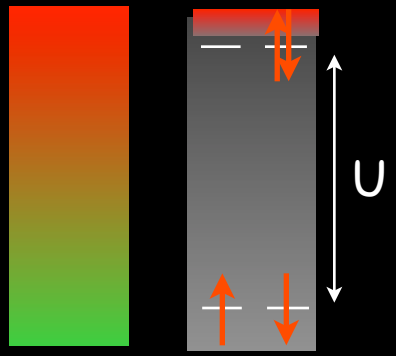


Large N : family of models with "N" spin components, which retain the key physics and can be solved in the large N limit.

New Methods



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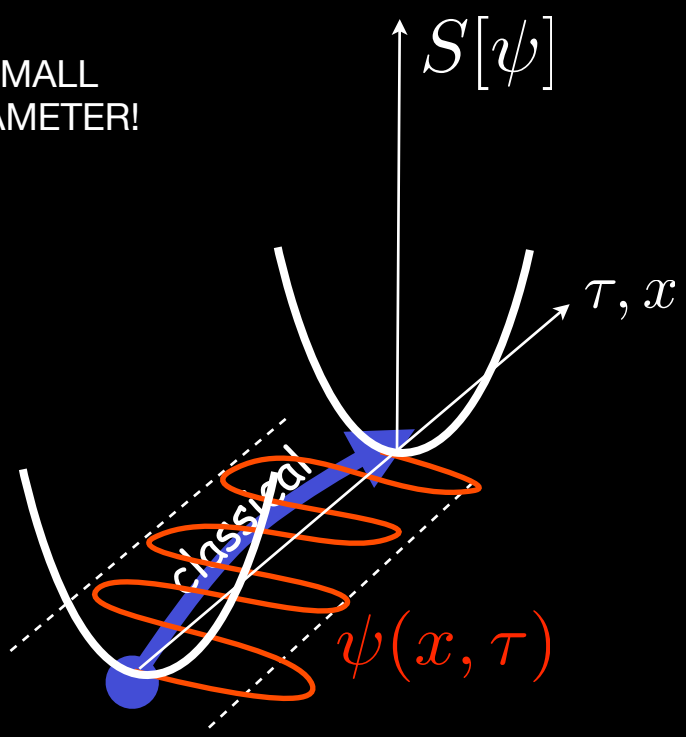


$$\frac{1}{N} \sim \hbar_{eff}$$

Large N : family of models with "N" spin components, which retain the key physics and can be solved in the large N limit.

New Ideas

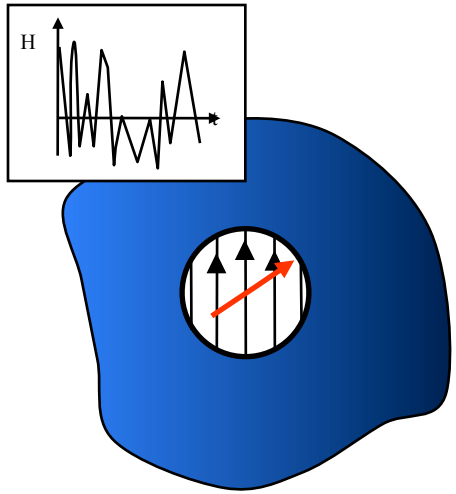
New Ideas

Si, Ingersent


- **Local quantum criticality**

(Si, Ingersent, Smith, Rabello, Nature 2001):
Spin is the critical mode,
Fluctuations critical in time.

Requires a two dimensional spin fluid



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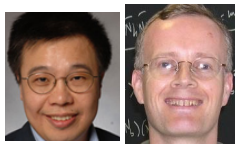

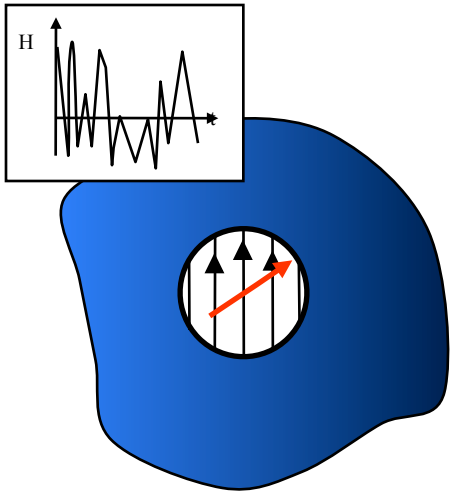

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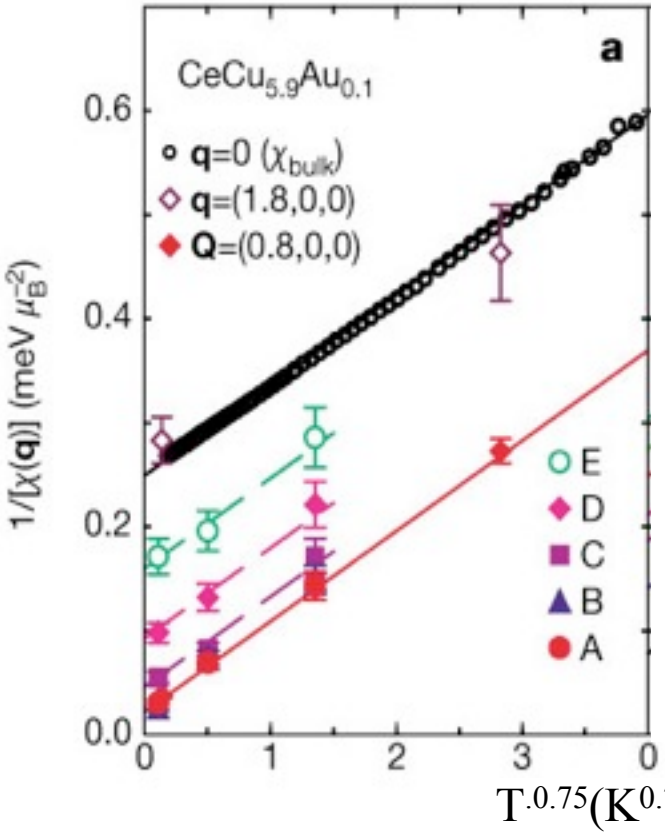
Locality of critical fluctuations

$$\chi^{-1} = \chi_0^{-1} + AT^{\alpha}$$



Schroeder et al, Nature 407,351(2000).

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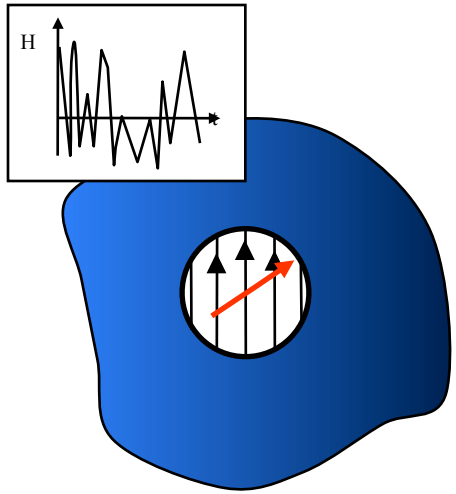

New Ideas

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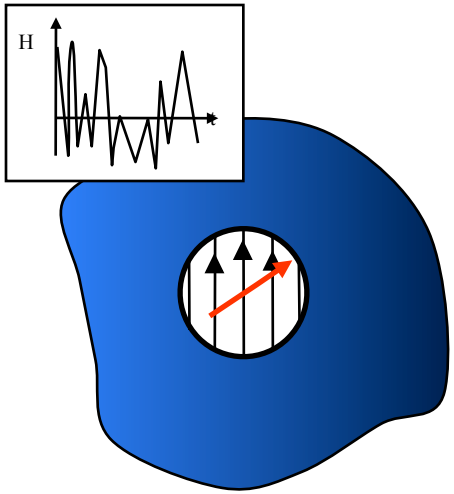

• **Local quantum criticality** (Si, Ingersent, Smith, Rabello, Nature 2001):
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Fluctuations critical in time.

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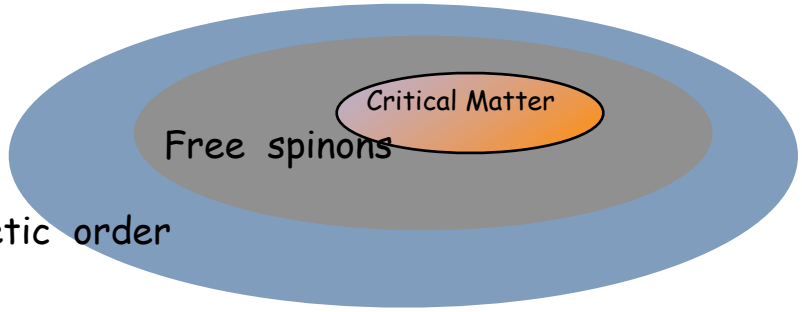
Sachdev


Vishwanath



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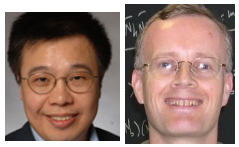

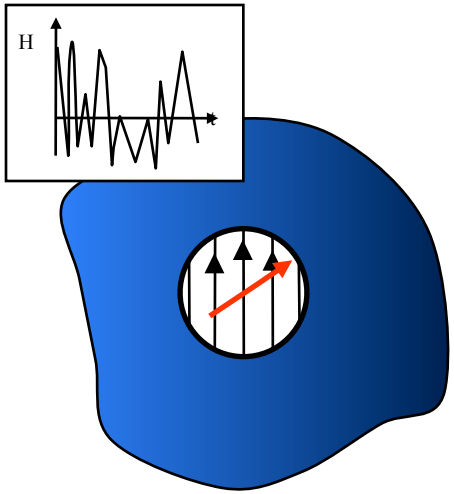

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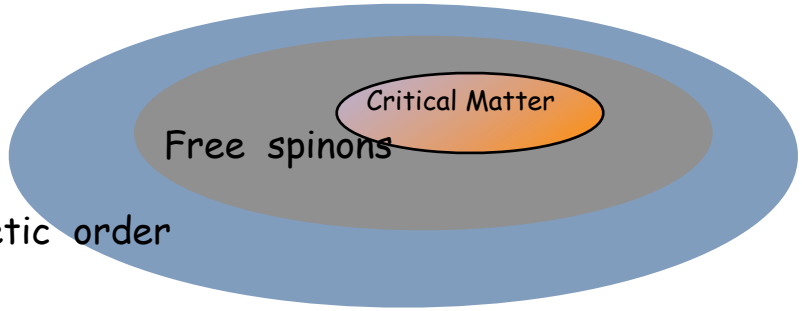

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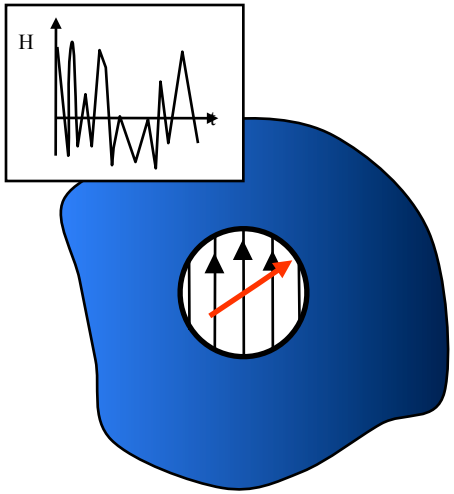

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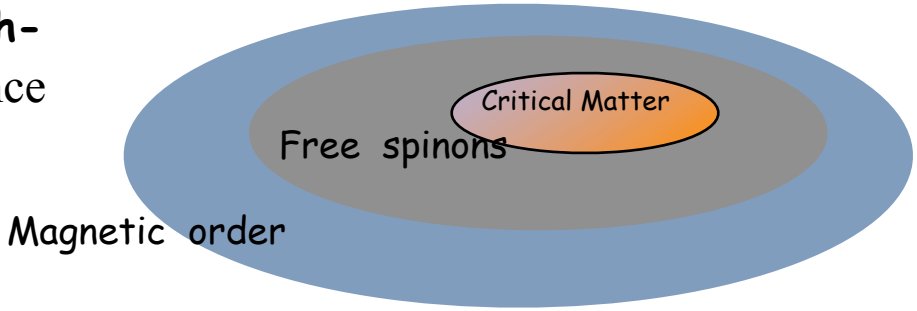
Senthil Sachdev Vishwanath



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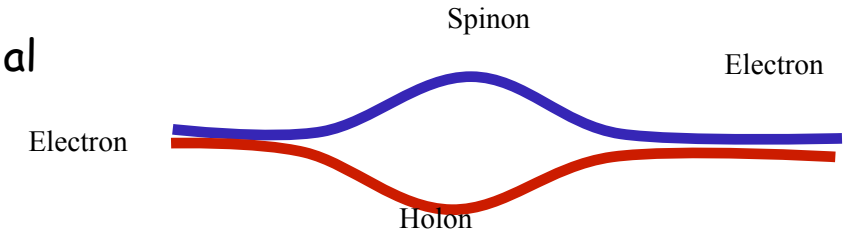

Q-Frustration

Kondo meets frustration

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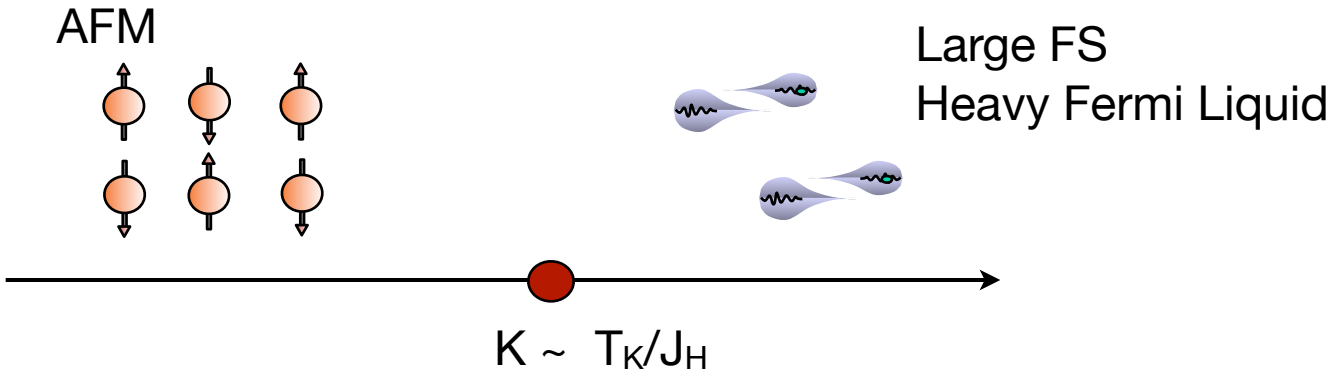

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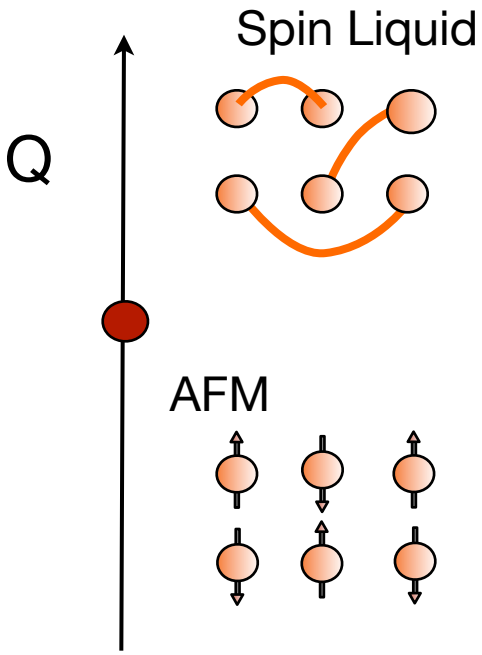

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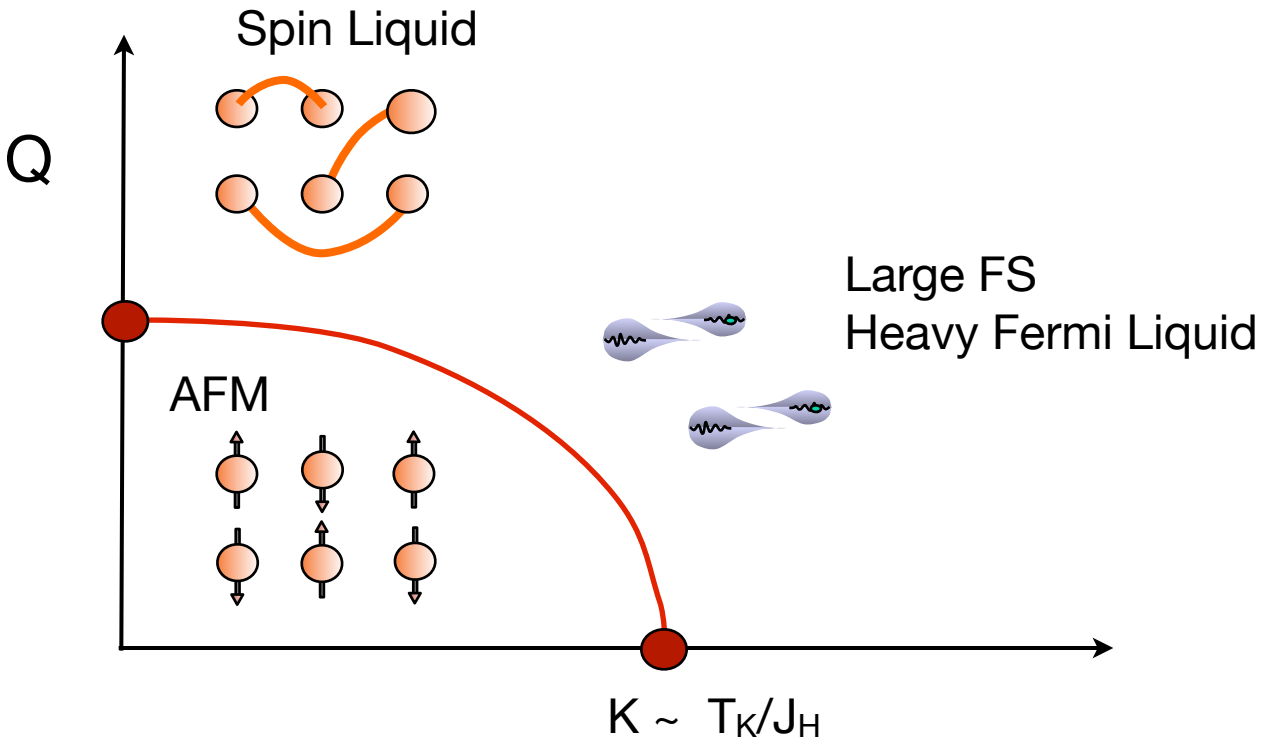

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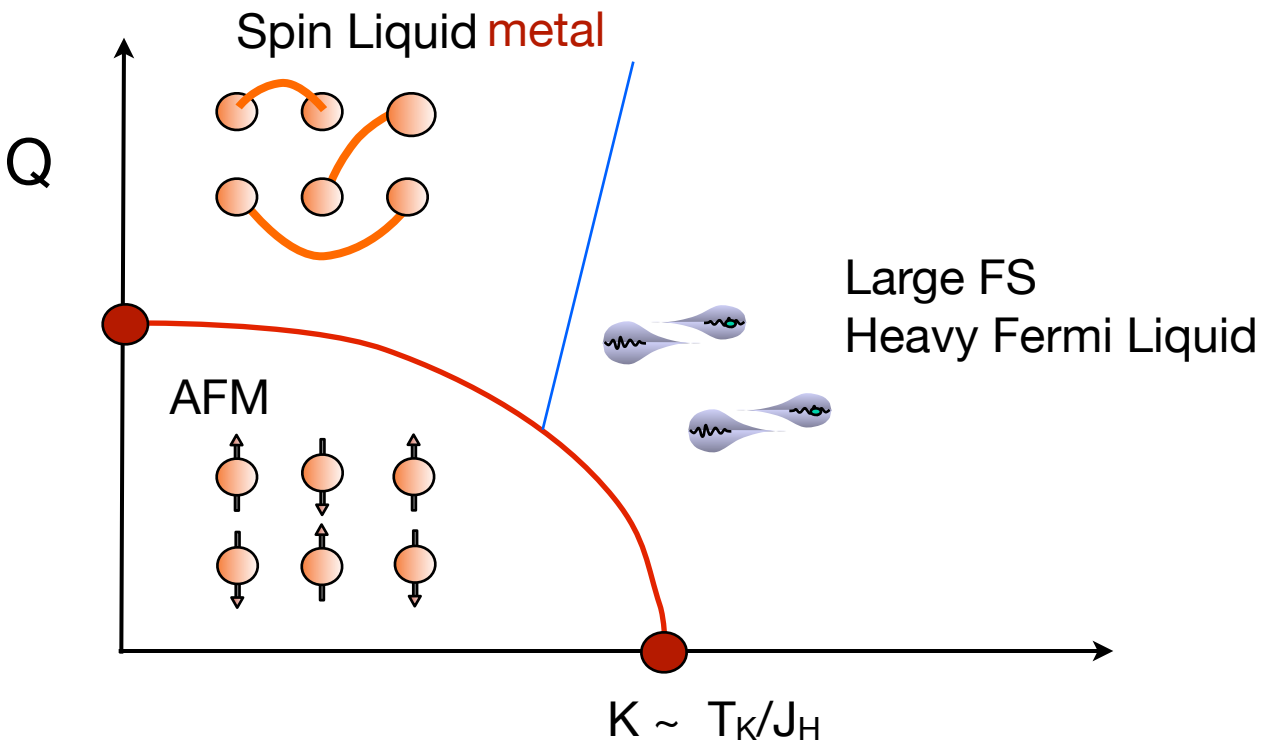

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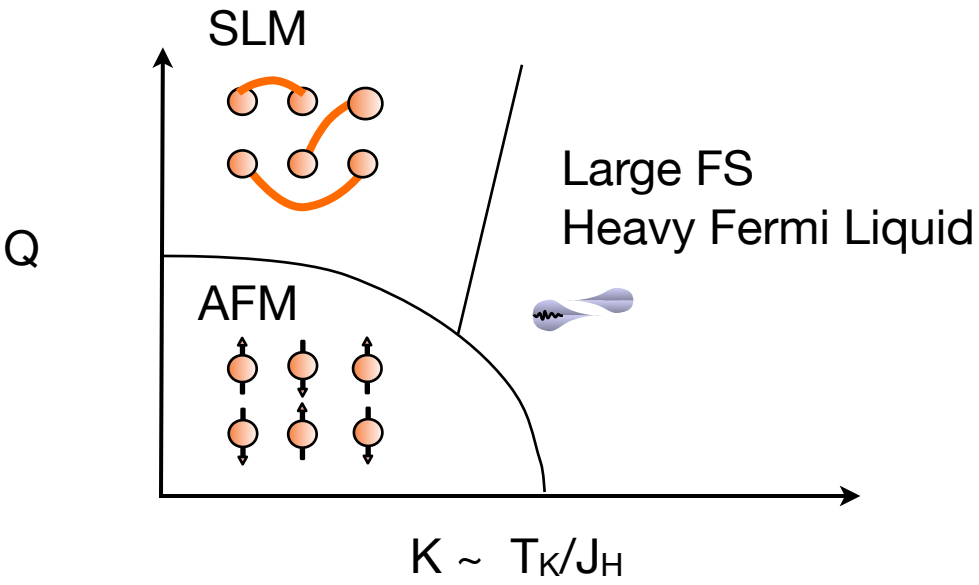

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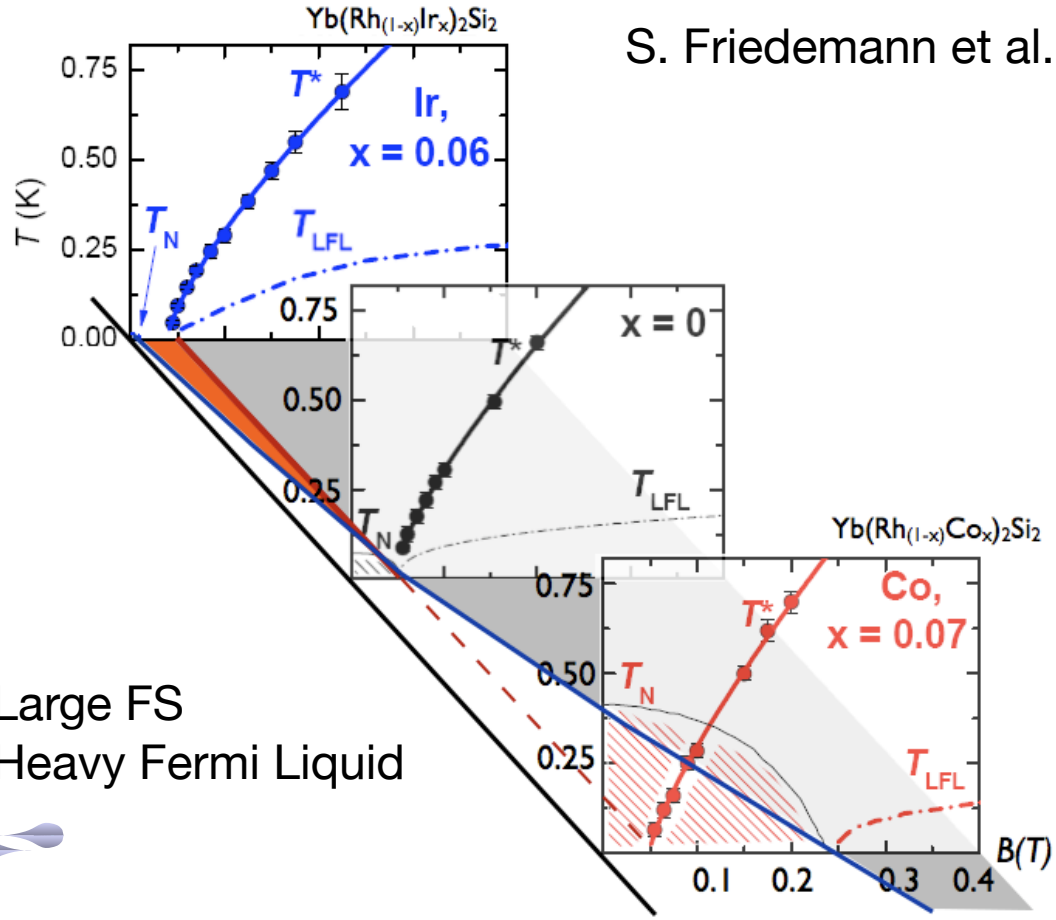

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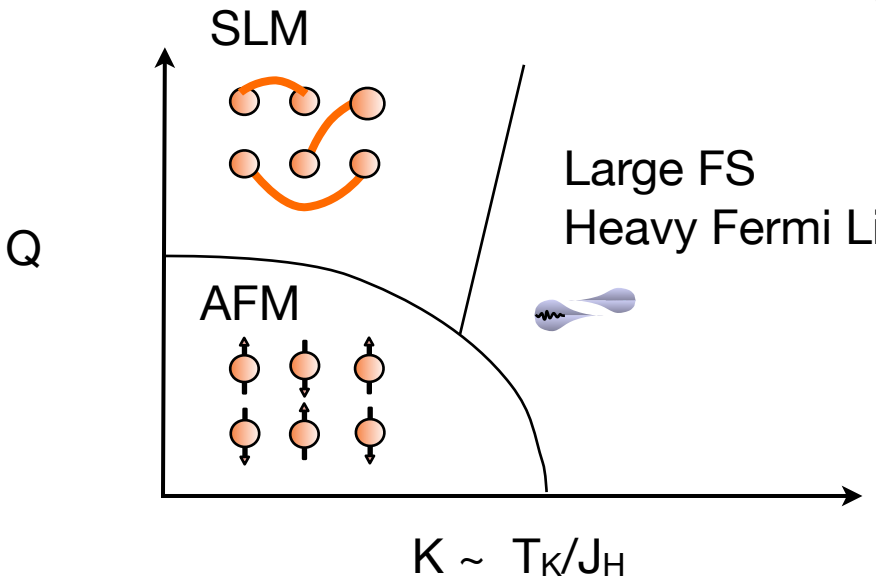

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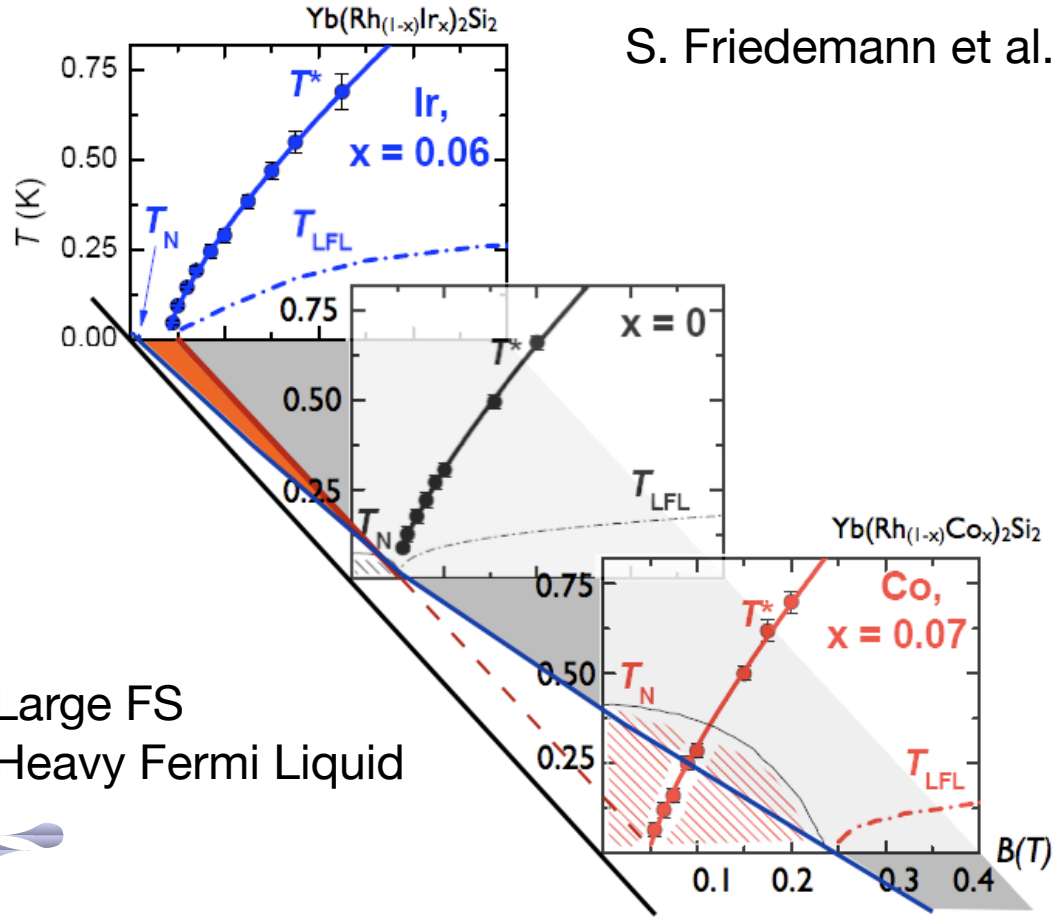

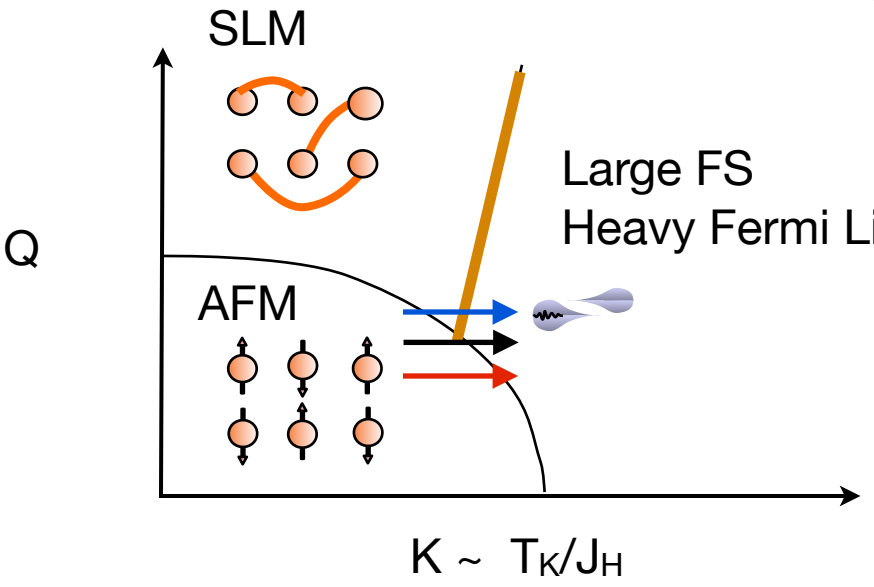

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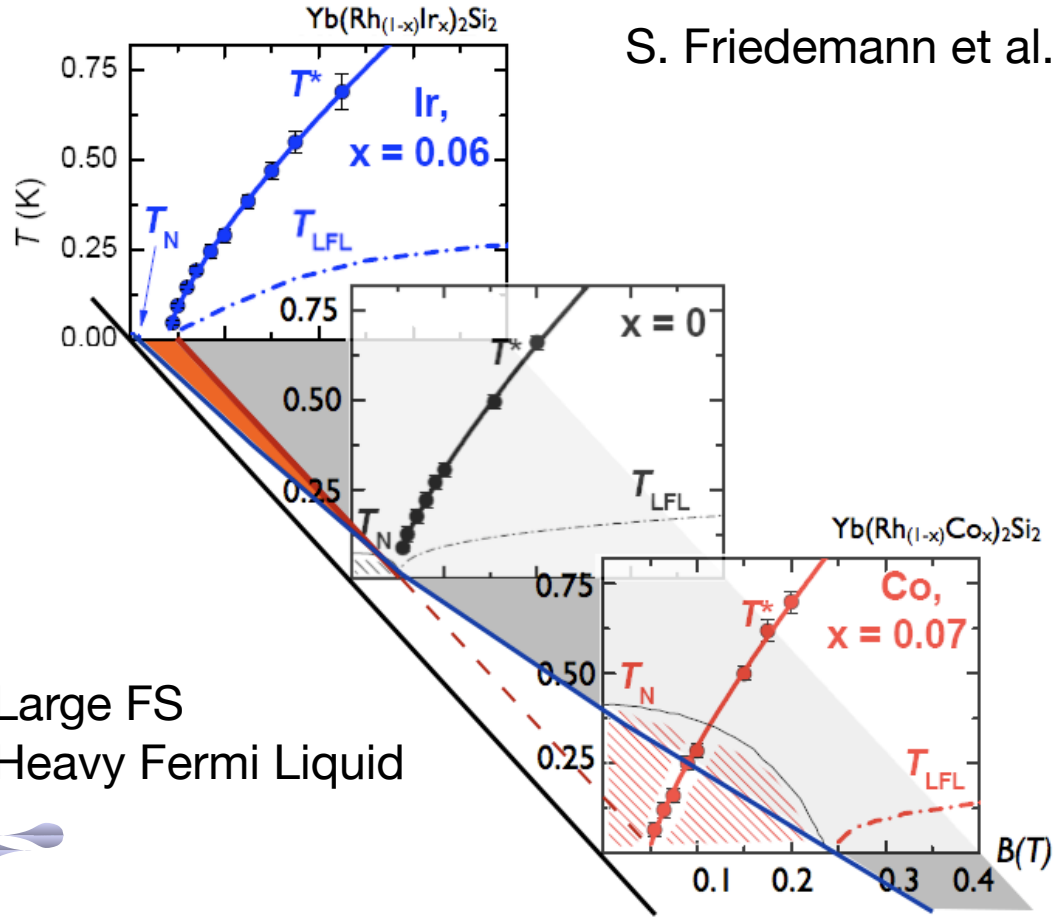

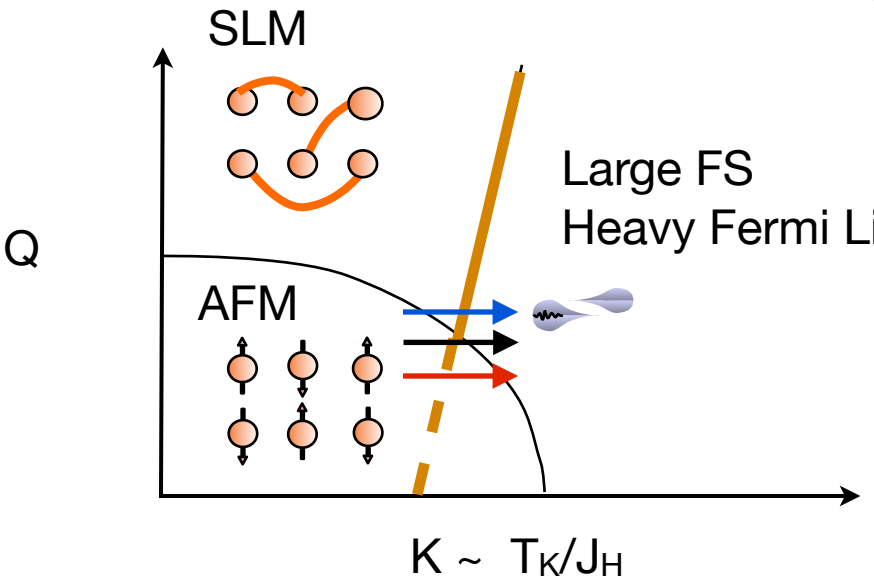

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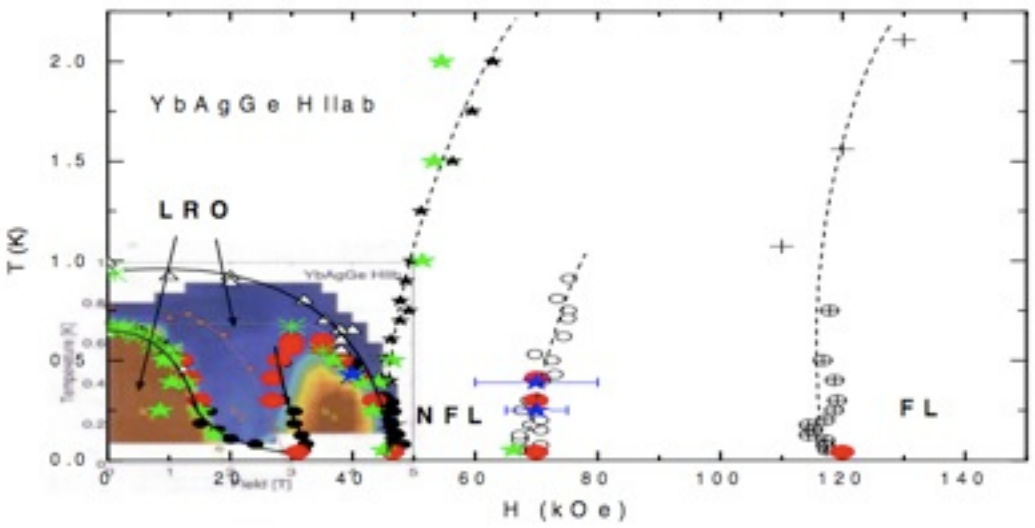
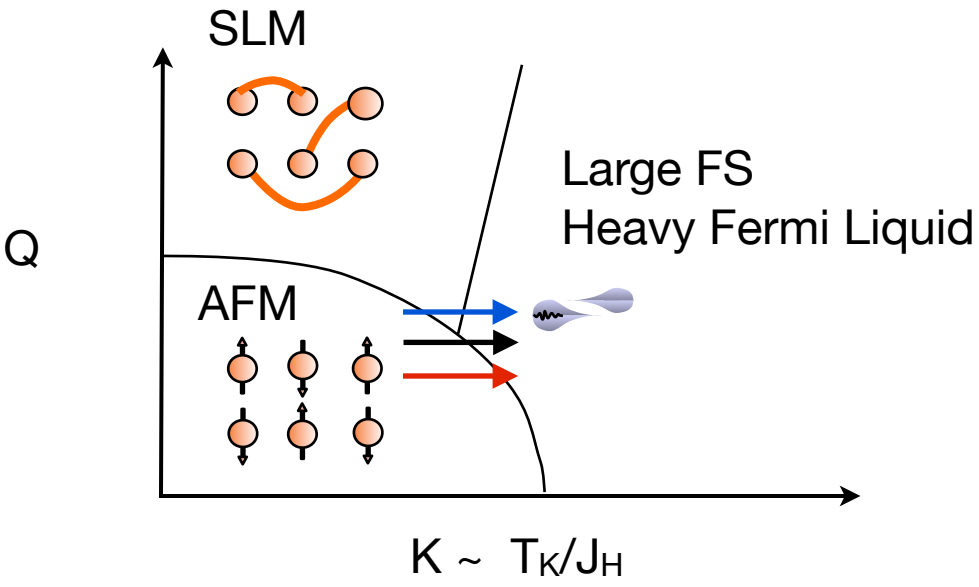
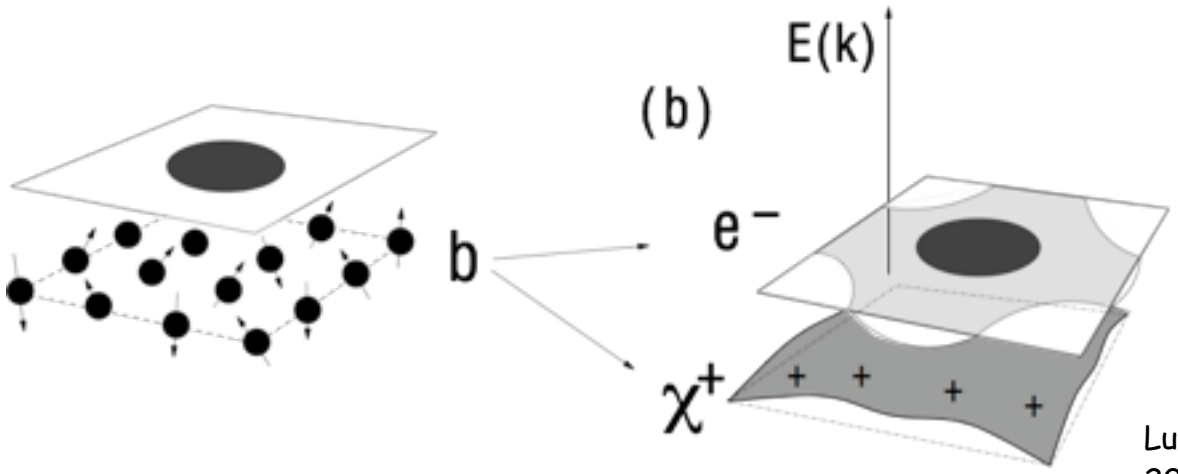


Canfield et al (unpublished)





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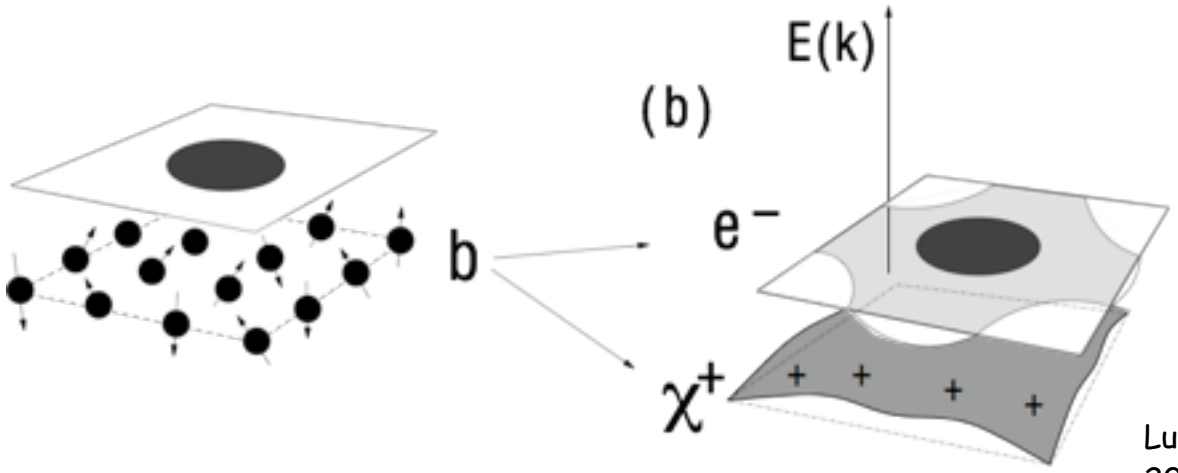
Luttinger sum rule for Kondo Lattice (Oshikawa, 2000) P.C, I.Paul, J. Rech (05)



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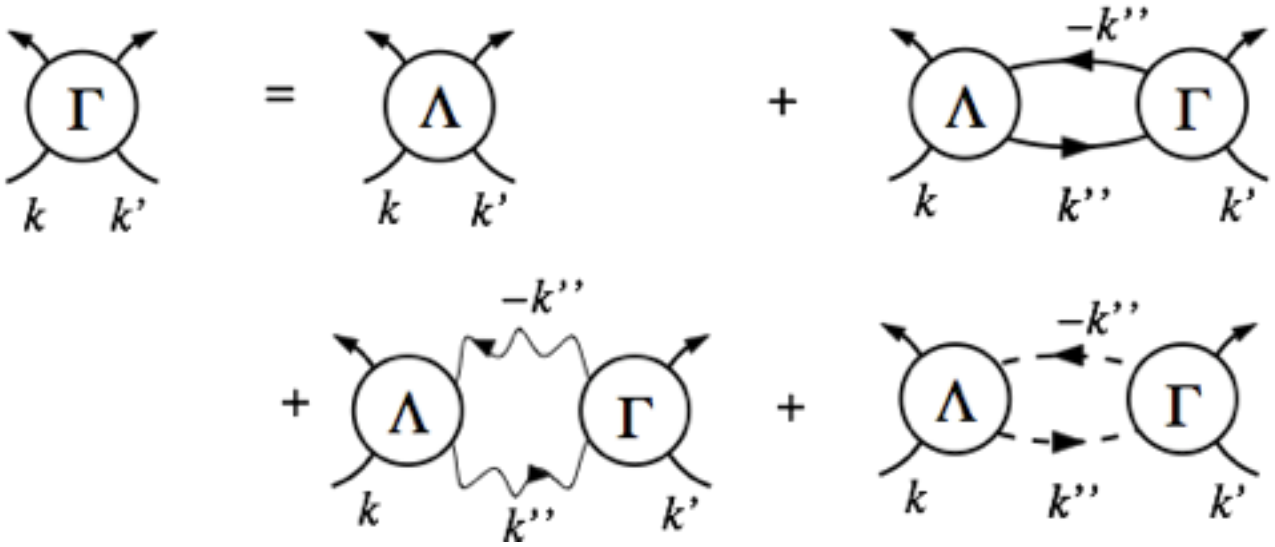

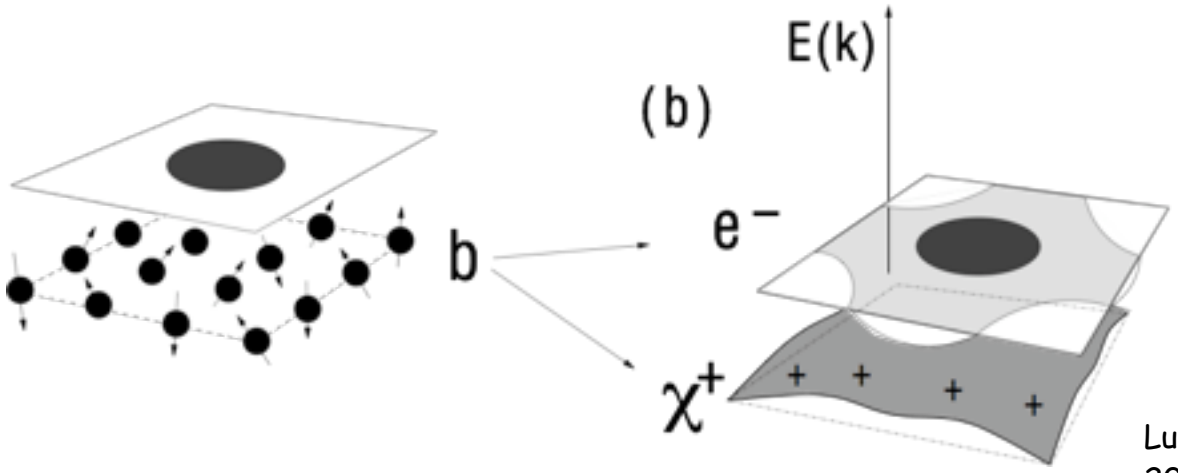

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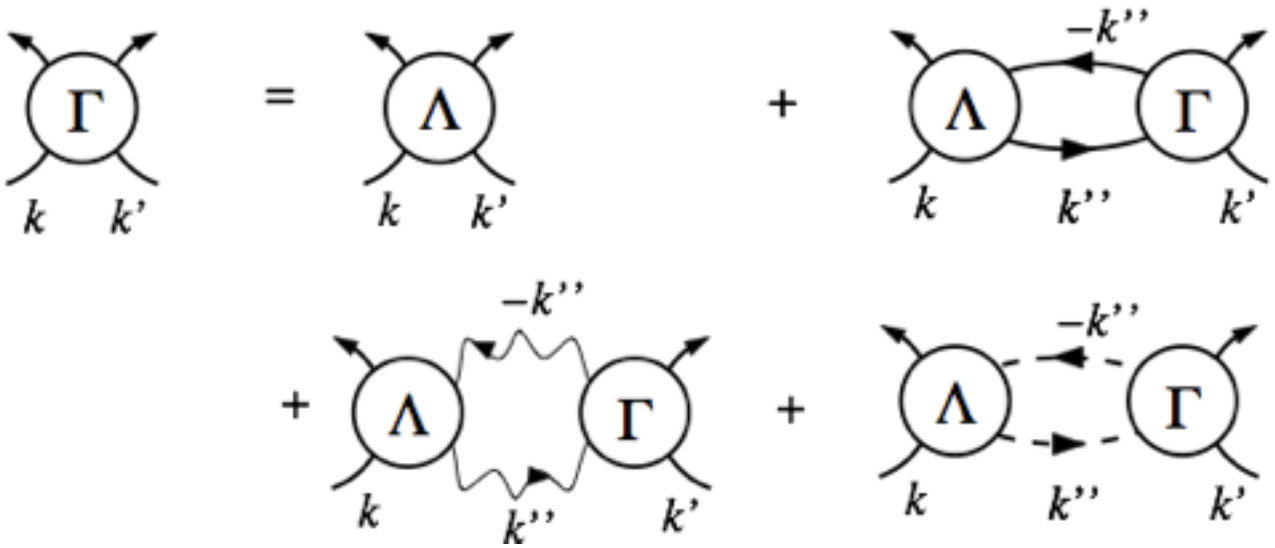
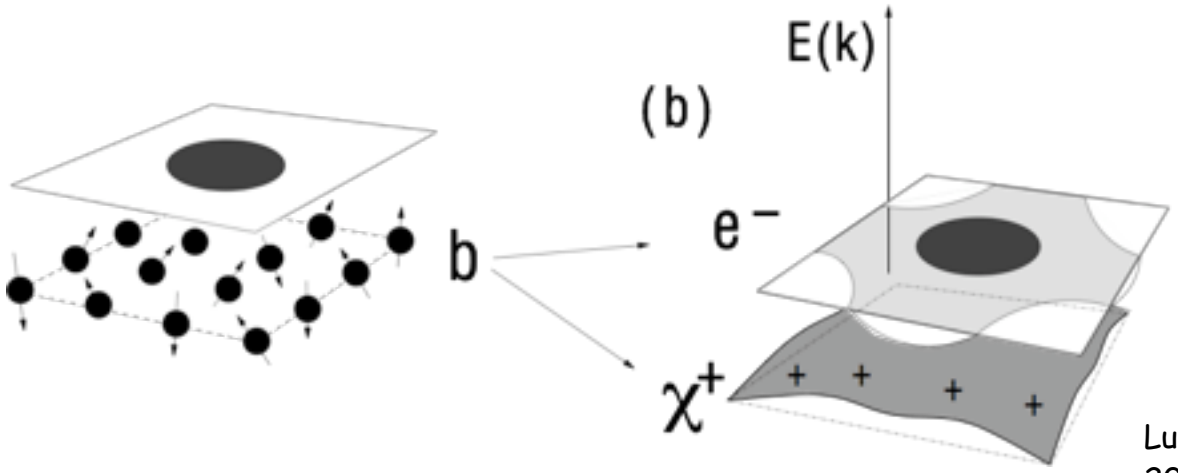


Virtual spinons.



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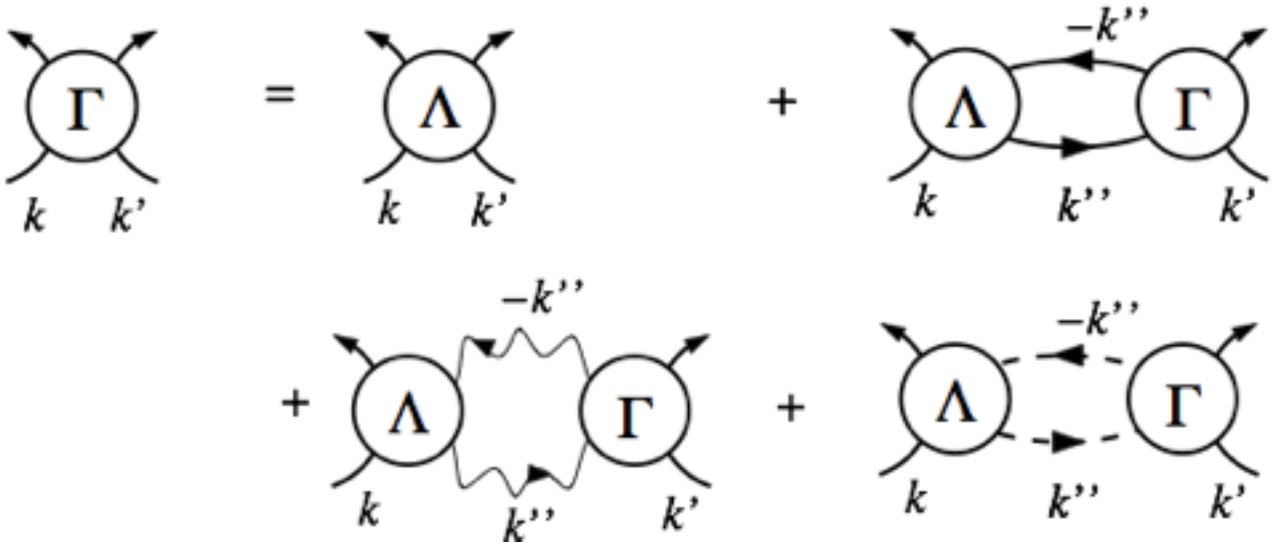

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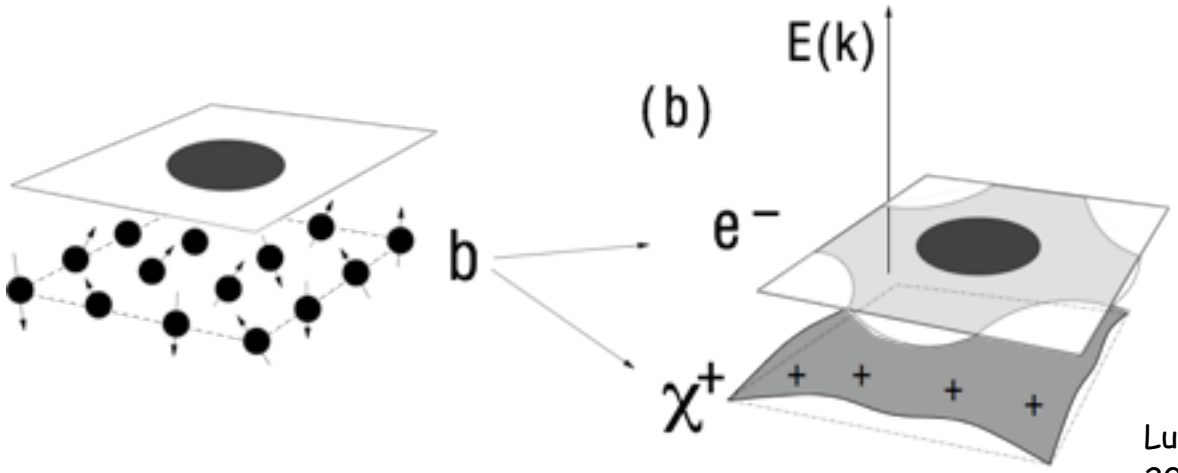

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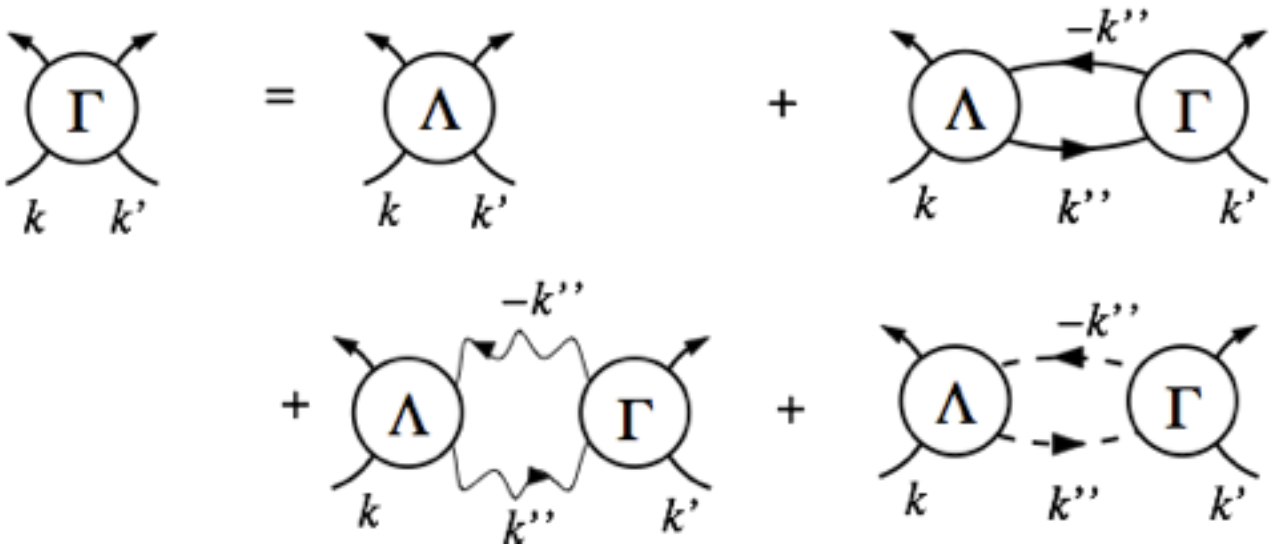

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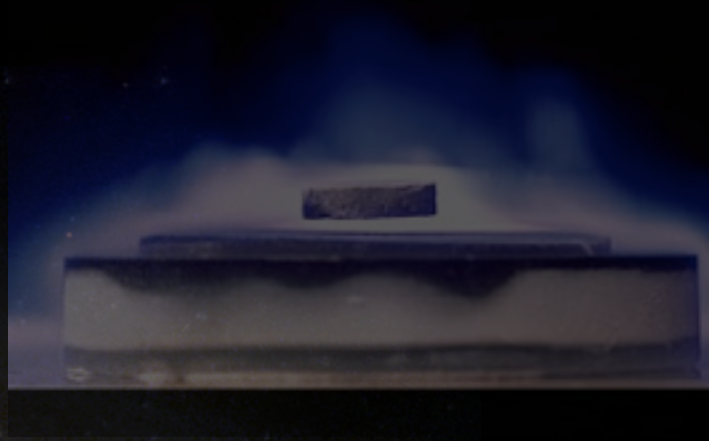
Towards a new Conjunction of ideas.



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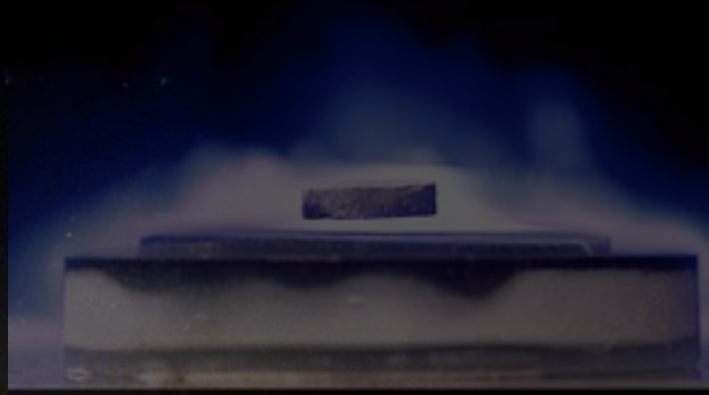

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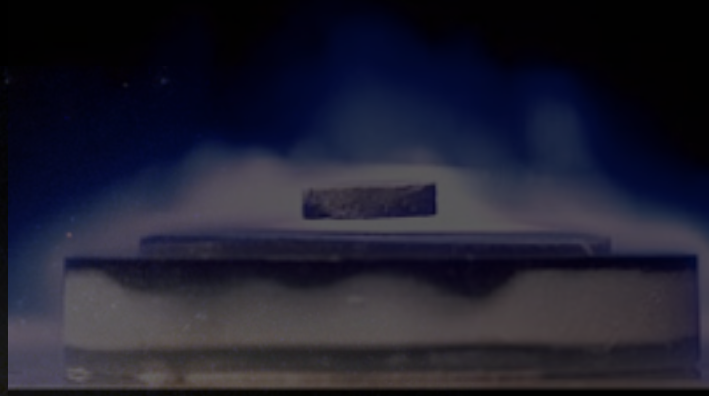

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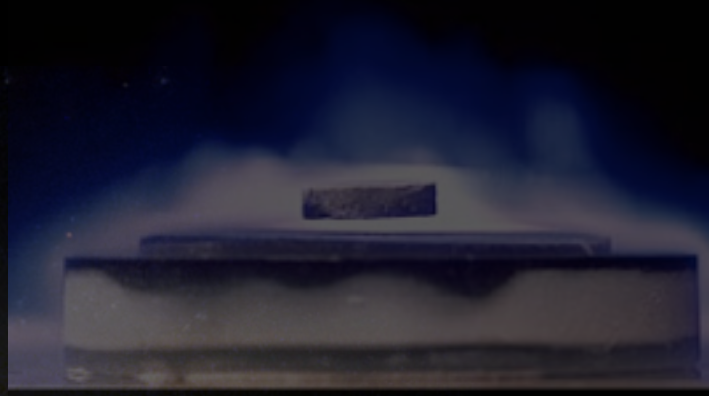

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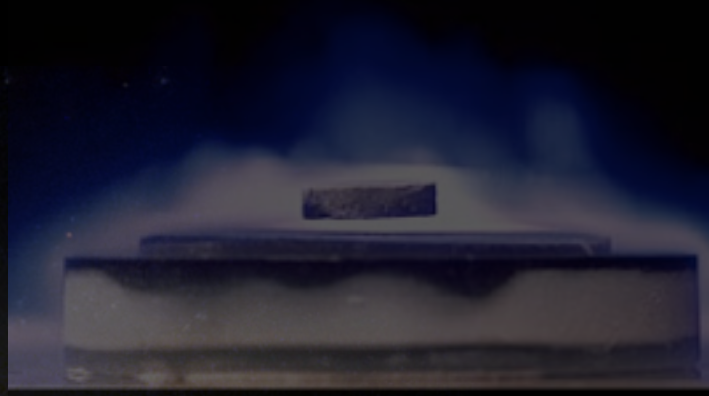

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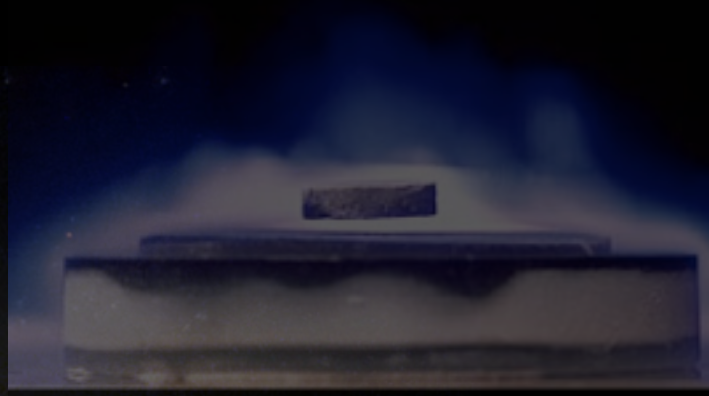

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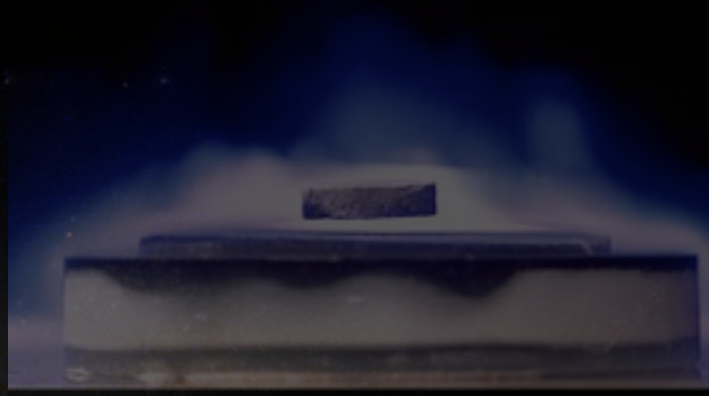

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Collaborators


Flint


Nev.


Dzero

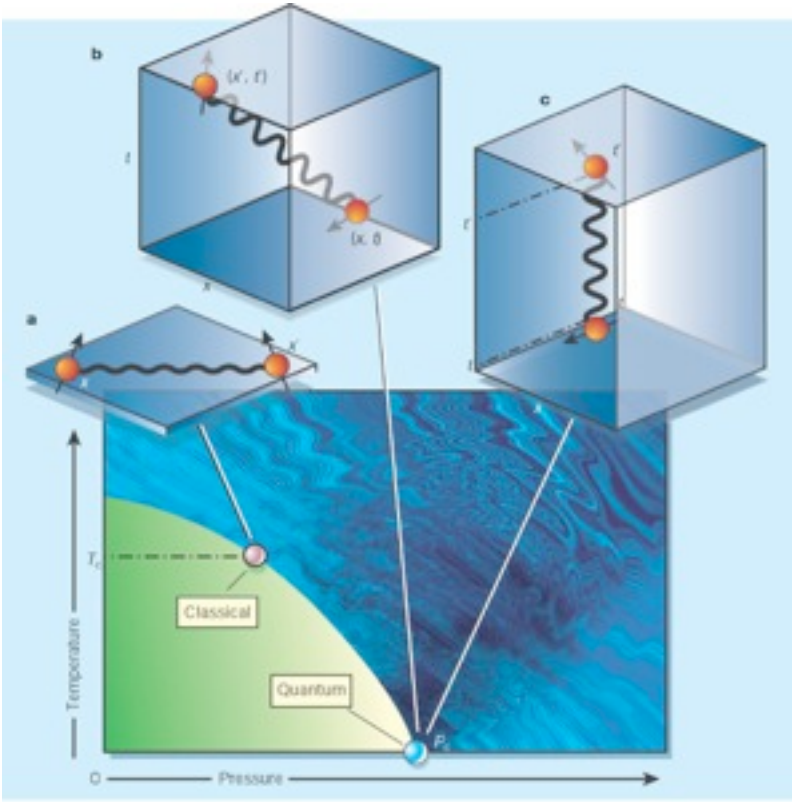

Rech


Lebanon

Rebecca Flint	Rutgers
Andriy Nevidomskyy	Rutgers
Maxim Dzero	Columbia/Rutgers
Jerome Rech,	ANL/Munich.
Eran Lebanon,	Israel.
Indranil Paul,	CNRS, Grenoble
Lucia Palova	Rutgers
Premi Chandra	Rutgers
Gergely Zarand	Budapest
Olivier Parcollet	SpHT Paris.
Andy Schofield	Birmingham
Qimiao Si	Rice, Houston
Catherine Pepin	SpHT Paris.
Almut Schroeder	Kent State
Gabriel Aeppli	LCN
Hilbert v. Lohneysen	Karlsruhe

Rutgers
Center for Materials Theory

Conclusions



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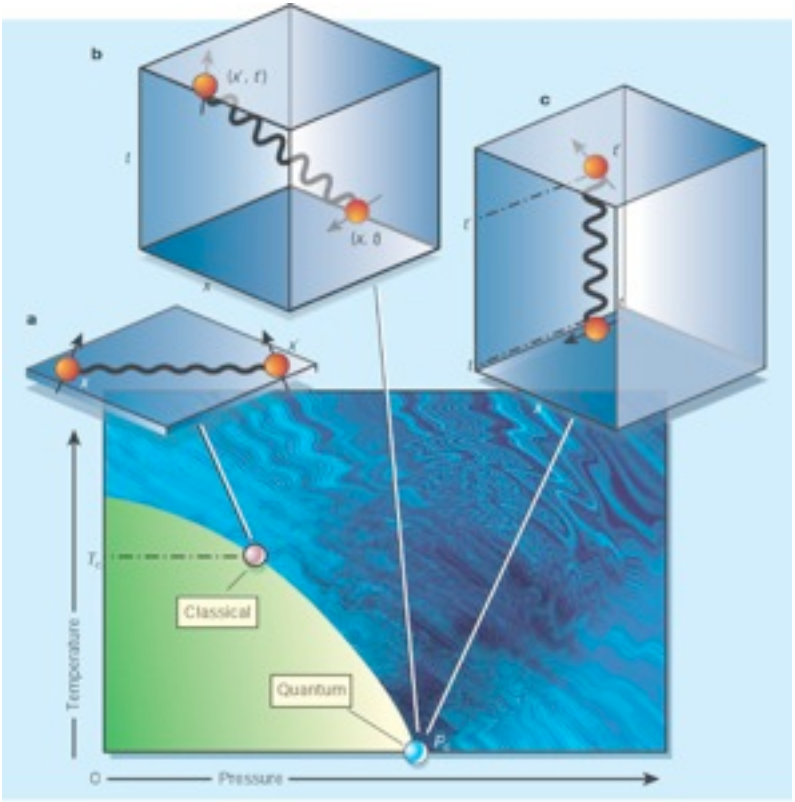

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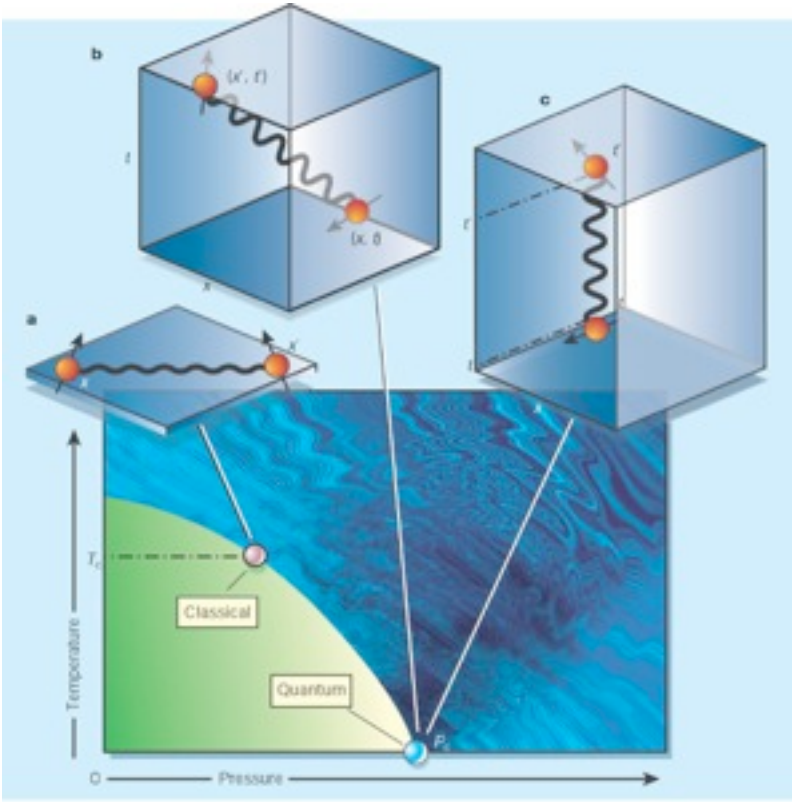

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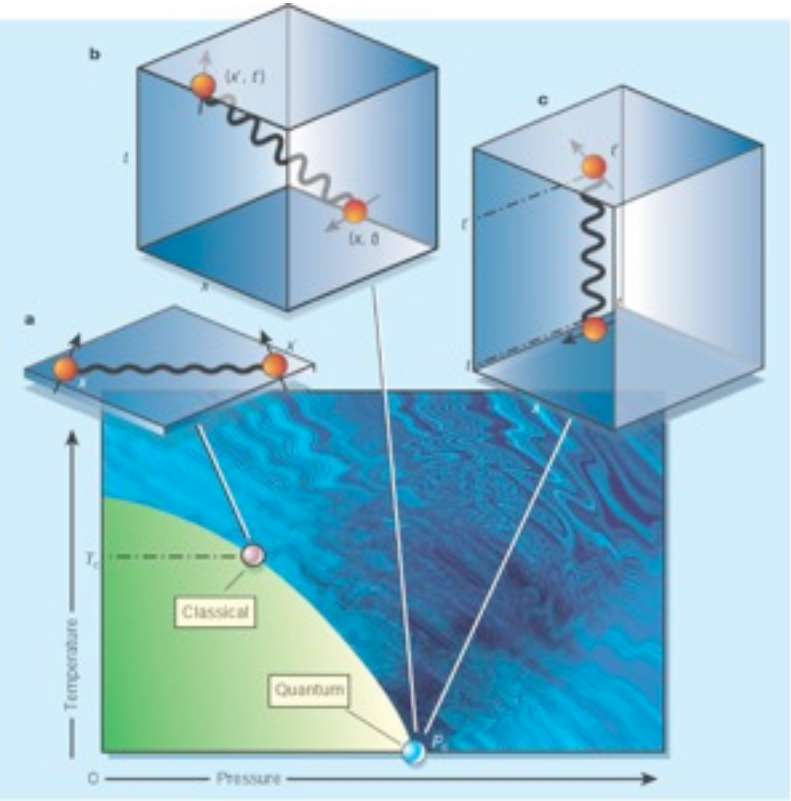

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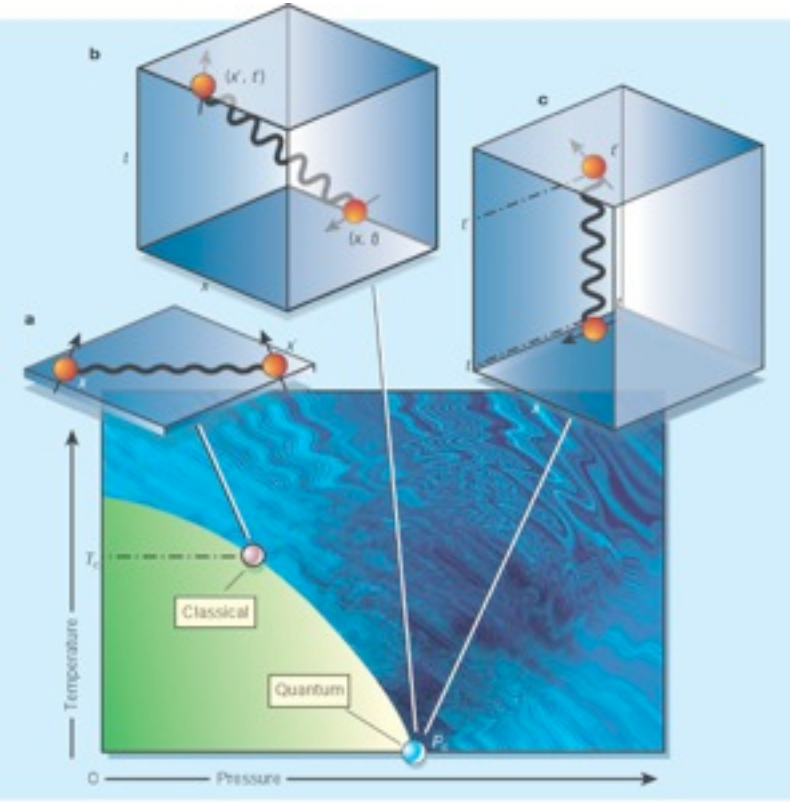

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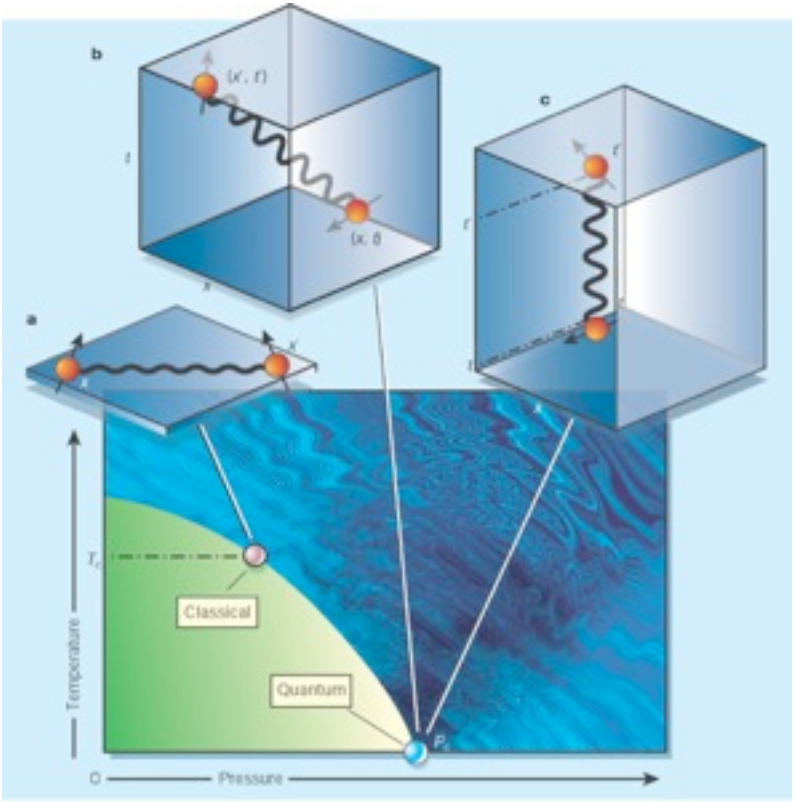

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New rule in material physics: avoided criticality. New phases develop in order to avoid the singular quantum critical point.