Title: Qu-transitions. Phase transitions in the quantum era.

Date: Apr 22, 2009 02:00 PM

URL: http://pirsa.org/09040013

Abstract: Physicists are often so awestruck by the lofty achievements of the past, we end up thinking all the big stuff is done, which blinds us to the revolutions ahead. We are still firmly in the throes of the quantum revolution that began a hundred years ago. Quantum gravity, quantum computers, qu-bits and quantum phase transitions, are manifestations of this ongoing revolution. Nowhere is this more so, than in the evolution of our understanding of the collective properties of quantum matter. Fifty years ago, physicists were profoundly shaken by the discovery of universal power-law correlations at classical second-order phase transitions. Today, interest has shifted to Quantum Phase Transitions: phase transitions at absolute zero driven by the violent jigglings of quantum zero-point motion. Quantum, or Qu-transitions have been observed in ferromagnets, helium-3, ferro-electrics, heavy electron and high temperature superconductors. Unlike its classical counterpart, a quantum critical point is a kind of 'black hole' in the materials phase diagram: a singularity at absolute zero that profoundly influences wide swaths of the material phase diagram at finite temperature. I'll talk about some of the novel ideas in this field including 'avoided criticality' - the idea that high temperature superconductivity nucleates about quantum critical points - and the growing indications that electron quasiparticles break up at a quantum critical point.

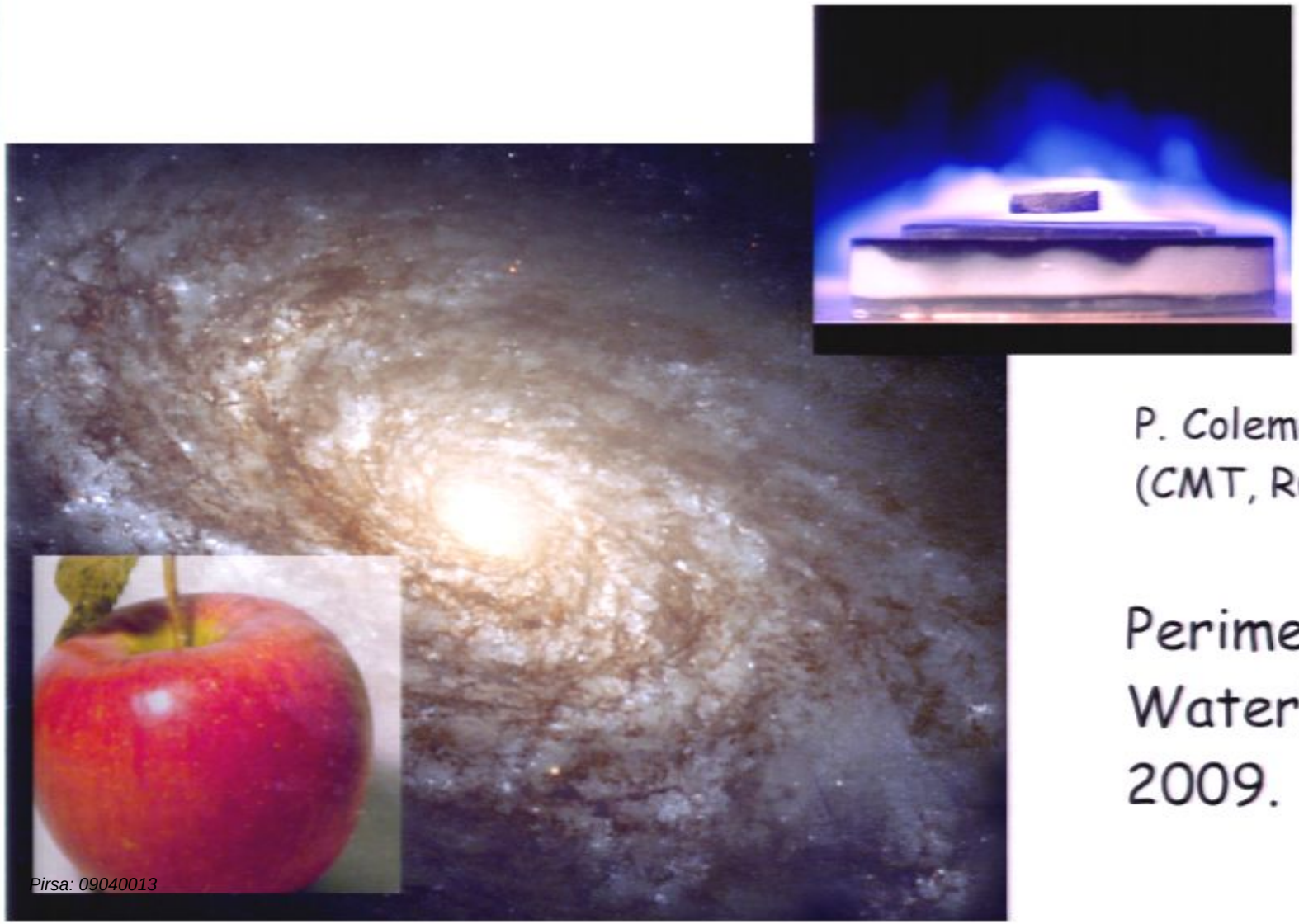
Qu-Transitions

P. Coleman
(CMT, Rutgers)

Perimeter Inst.
Waterloo, Apr 21
2009.

Rutgers
Center for Materials Theory

Qu-Transitions



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Phase transitions in the quantum era"

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

1758 in Paris: 72 years after “Principia”

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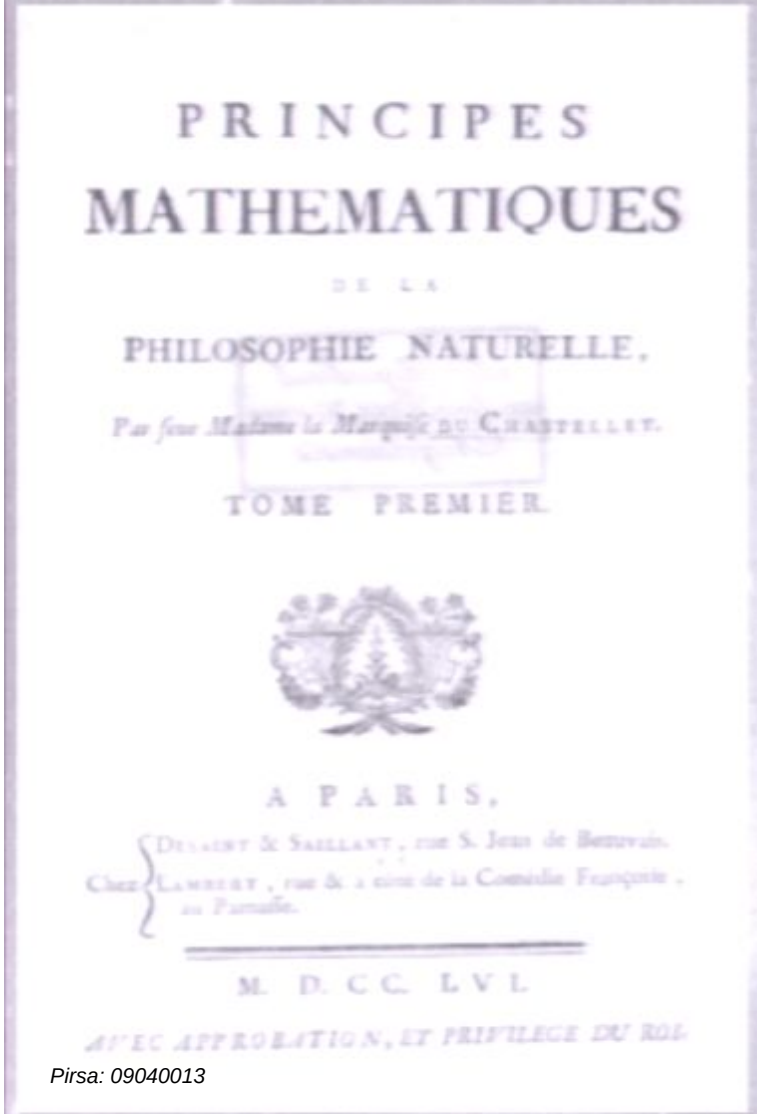

PRINCIPES
MATHEMATIQUES
DE LA
PHILOSOPHIE NATURELLE,
Par feue Madame la Marquise DU CHASTELLET.
TOME PREMIER.

A PARIS,
Chez DESAINT & SAILLANT, rue S. Jean de Beauvais.
LAMBERT, rue & à côté de la Comédie Françoise, au Parnasse.
M. D. CC. LVI.
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$$\sum_i m_i \vec{v}_i$$

Leibniz' *"vis vivre"*

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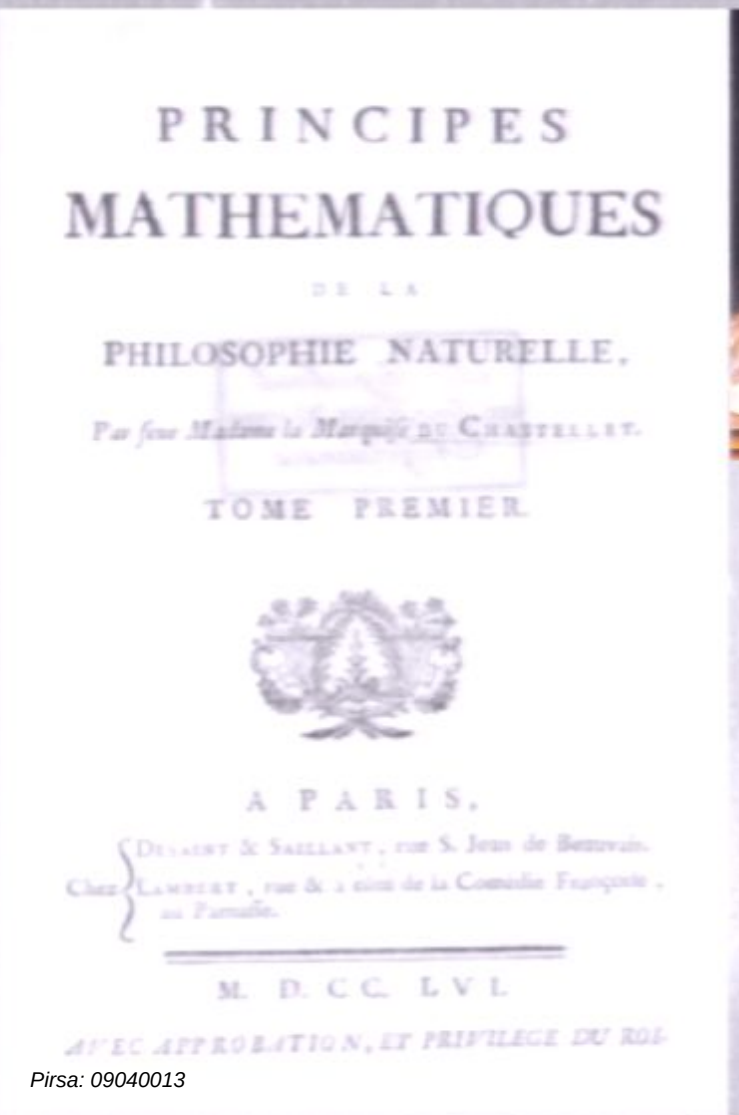

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Resolution of the controversy (and the missing factor of a half) required a further 60-80 years.

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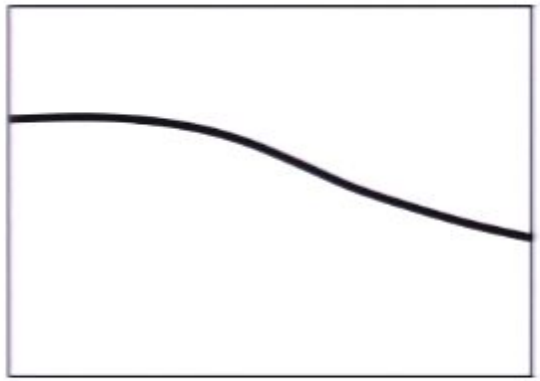

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"With a heavy heart, I have been converted to the idea that Fermi -Dirac, not Einstein-Bose is the correct statistics. I wish to write a short note on its application to paramagnetism."

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

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David Pines in
musicofthequantum.rutgers.edu

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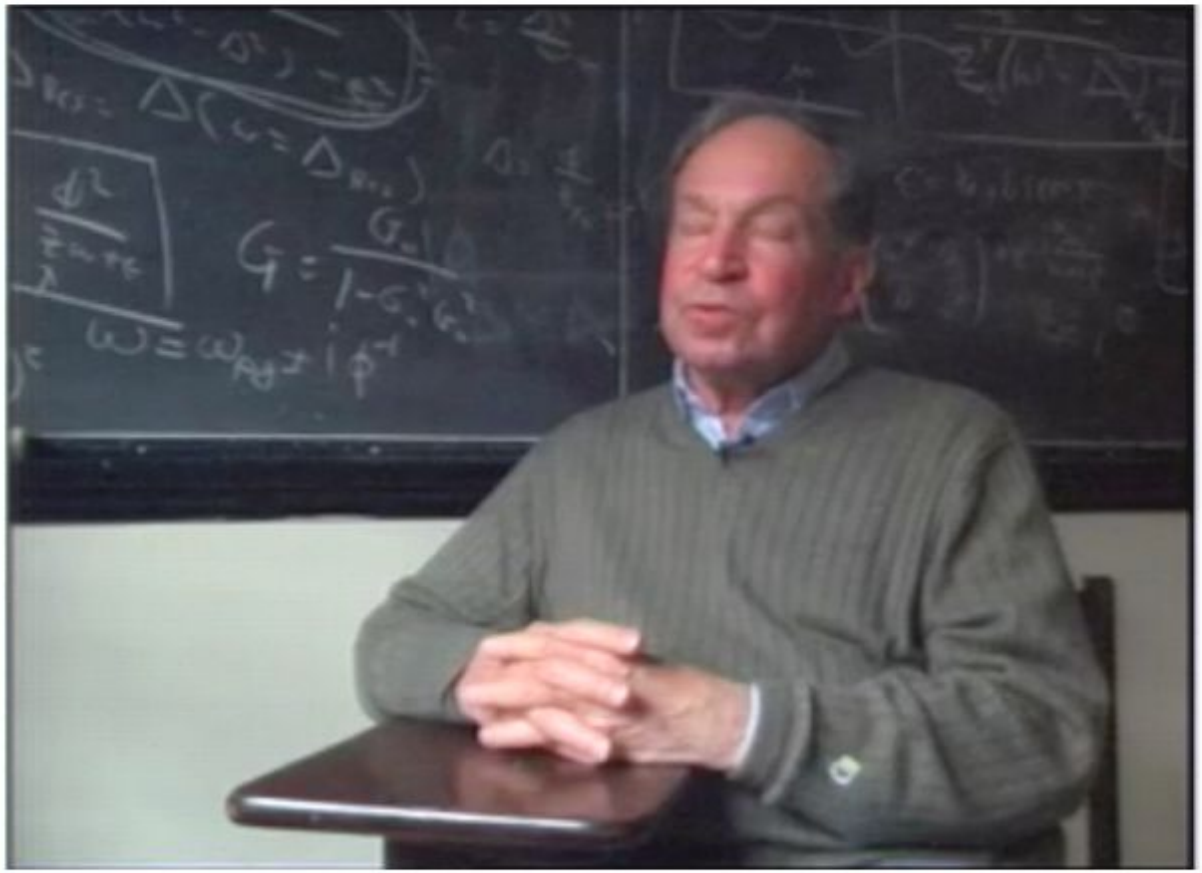

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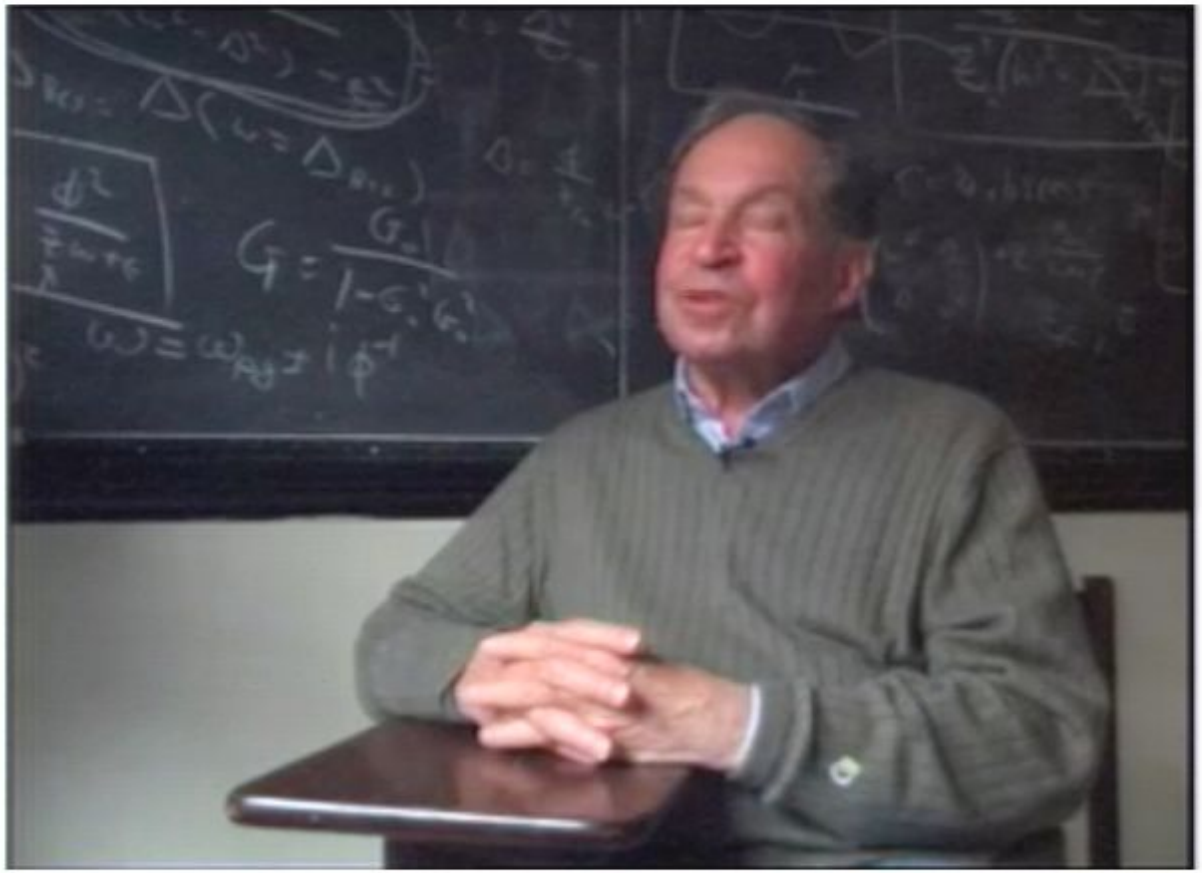

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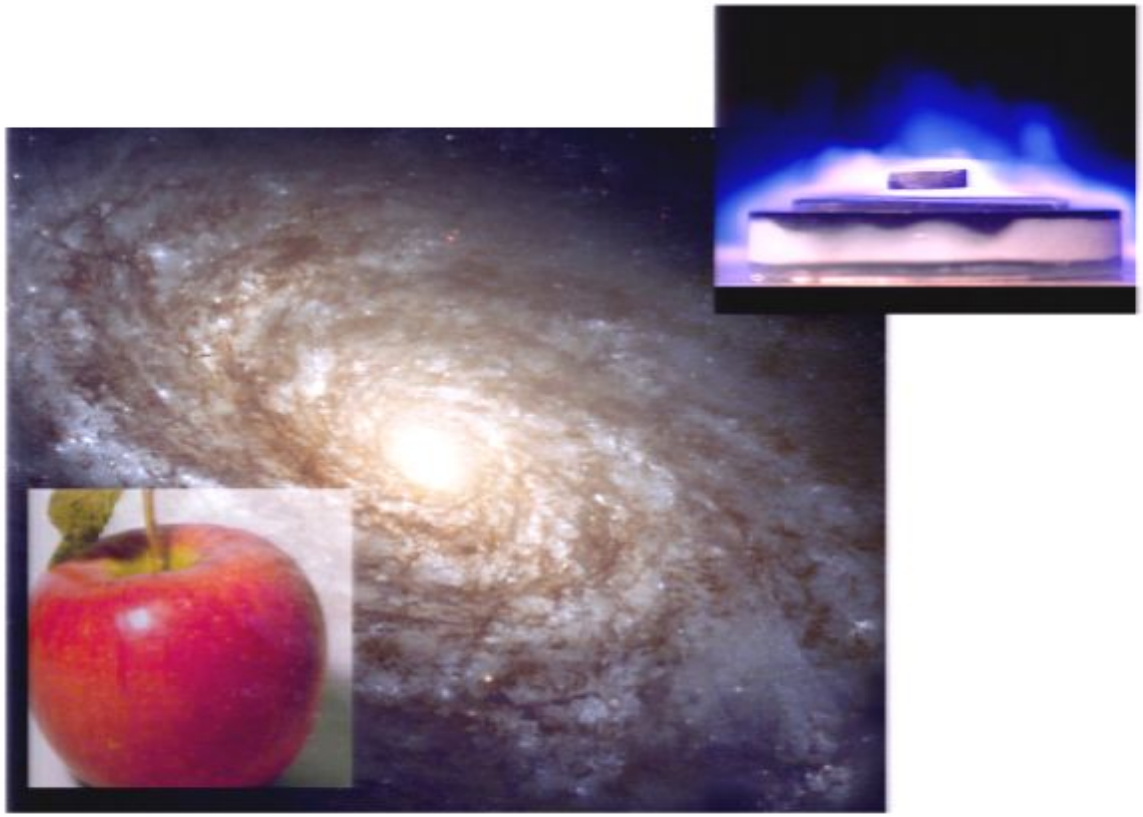
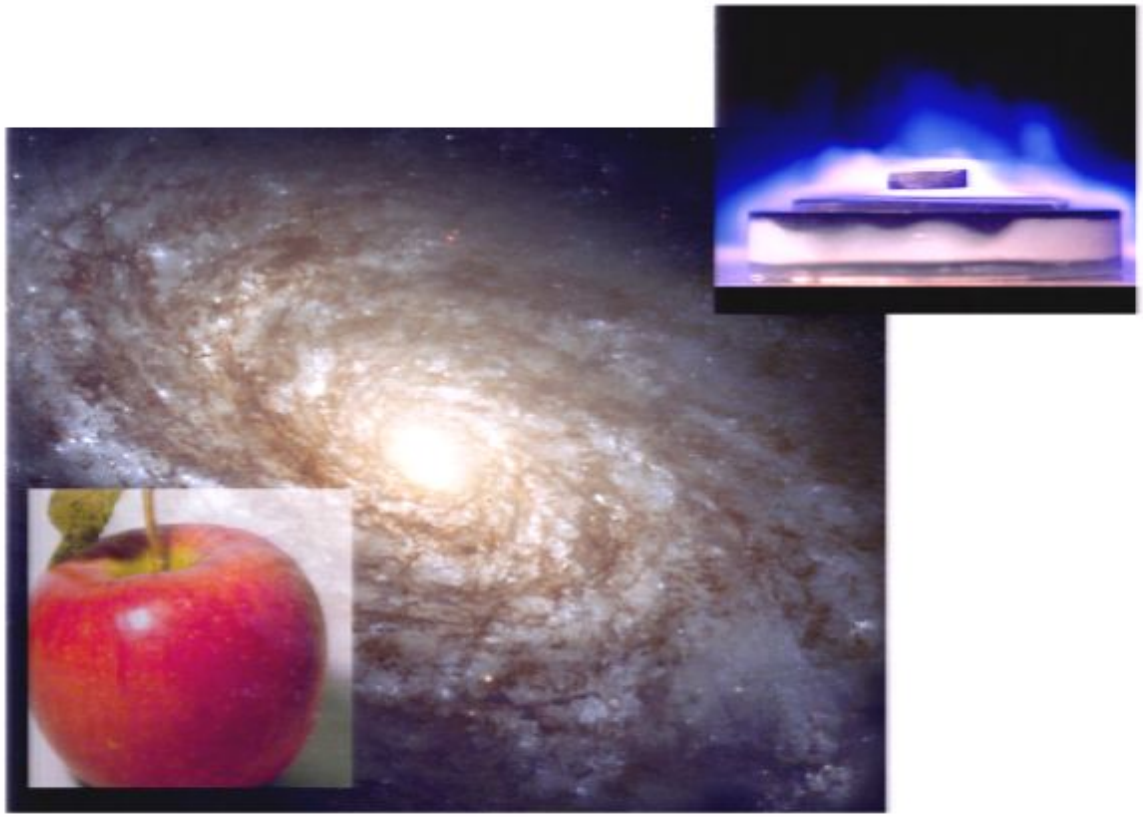
Quantum zero point fluctuations:



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



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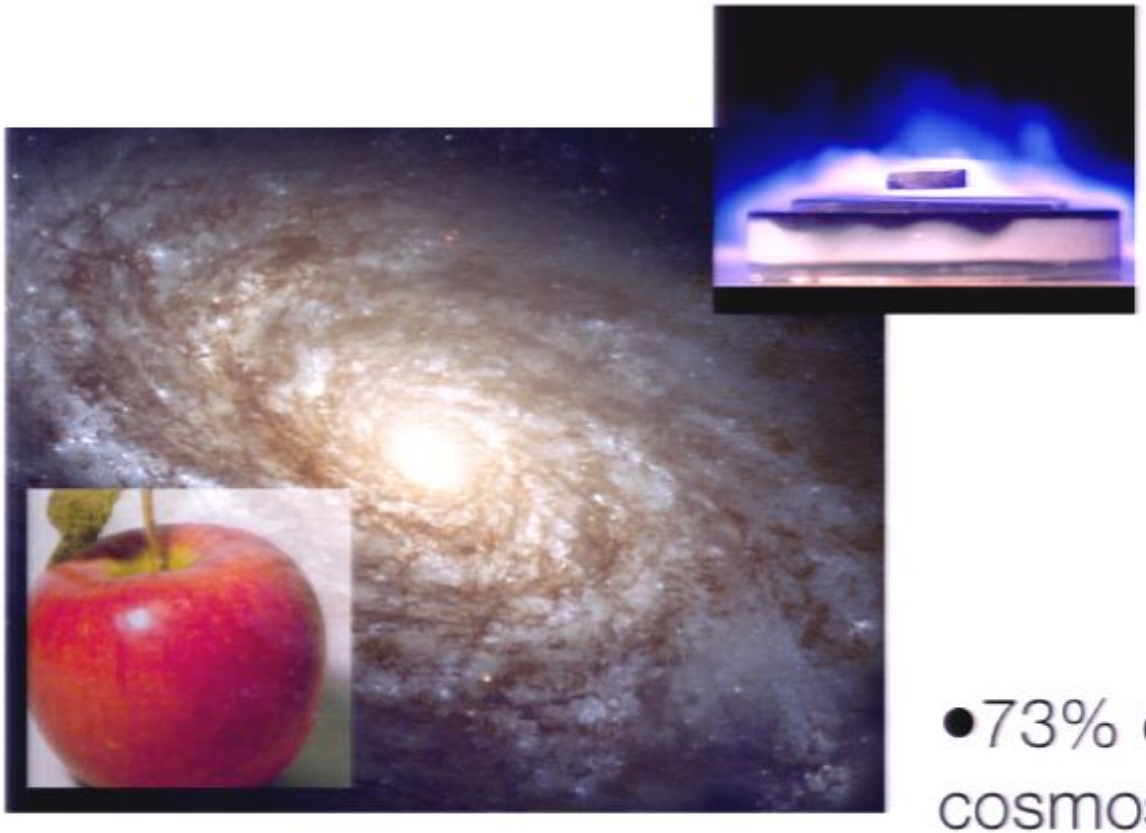
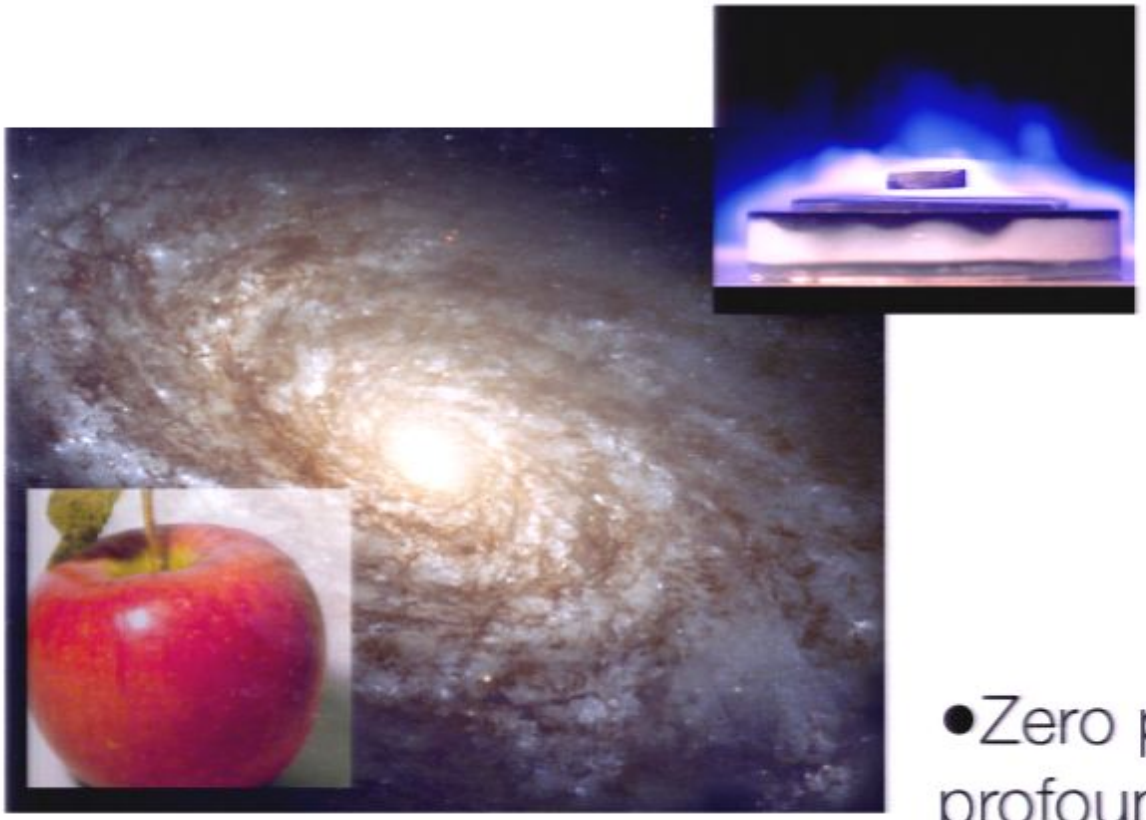


- 73% of the mass of the cosmos is “Dark Energy”: an unidentified form of zero point energy, causing the expansion to accelerate.

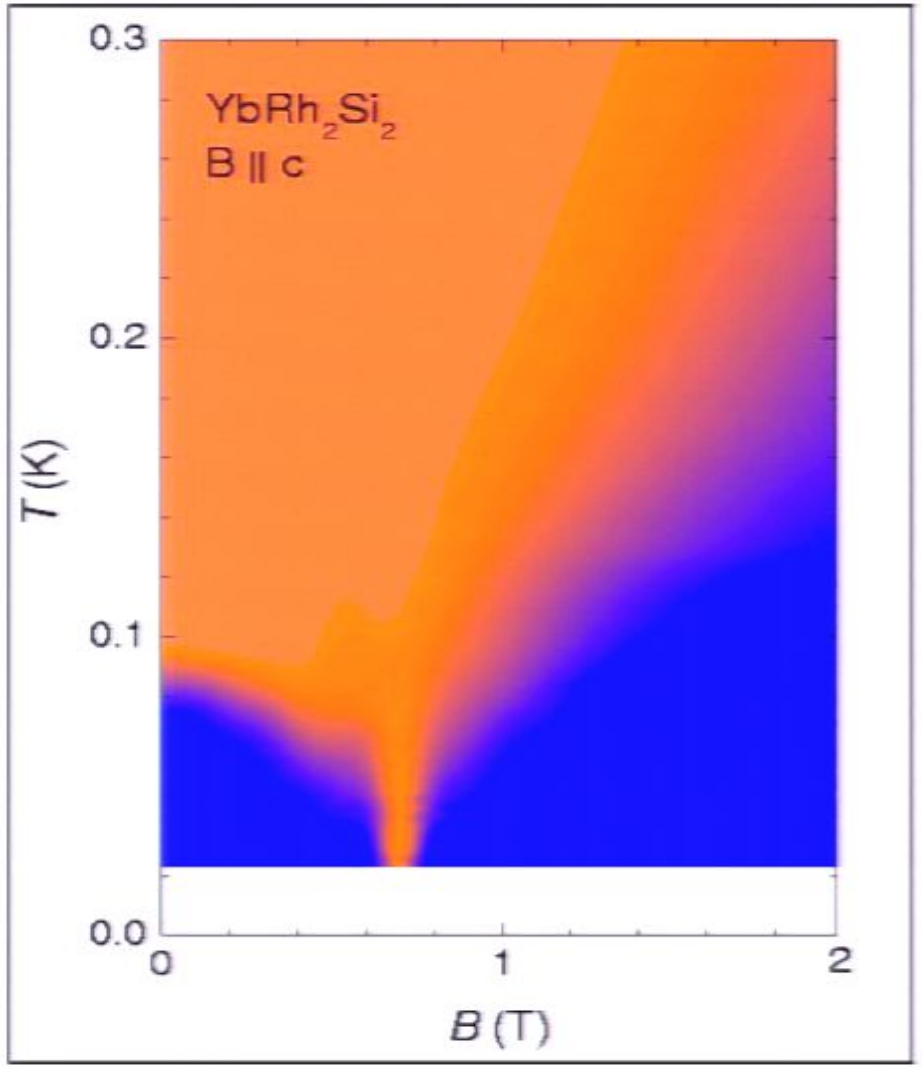
Quantum zero point fluctuations: major unsolved problem of the quantum era.



- 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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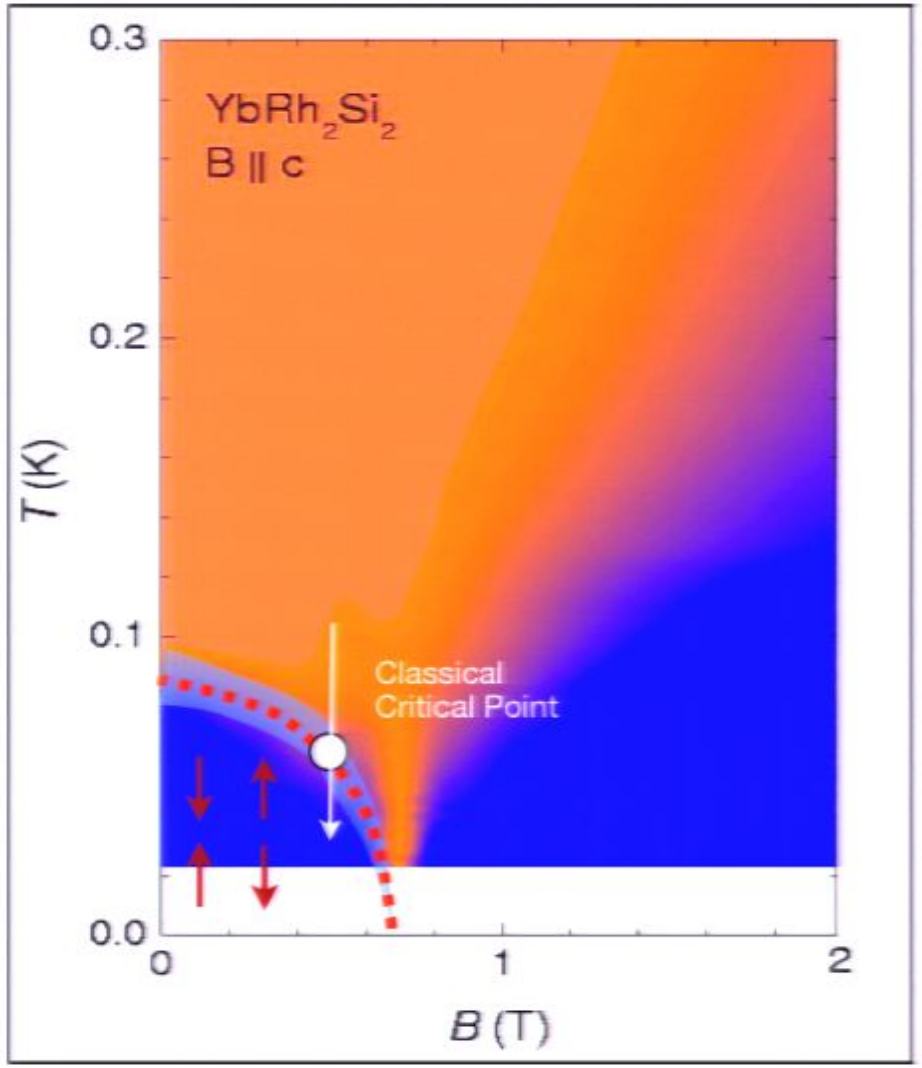

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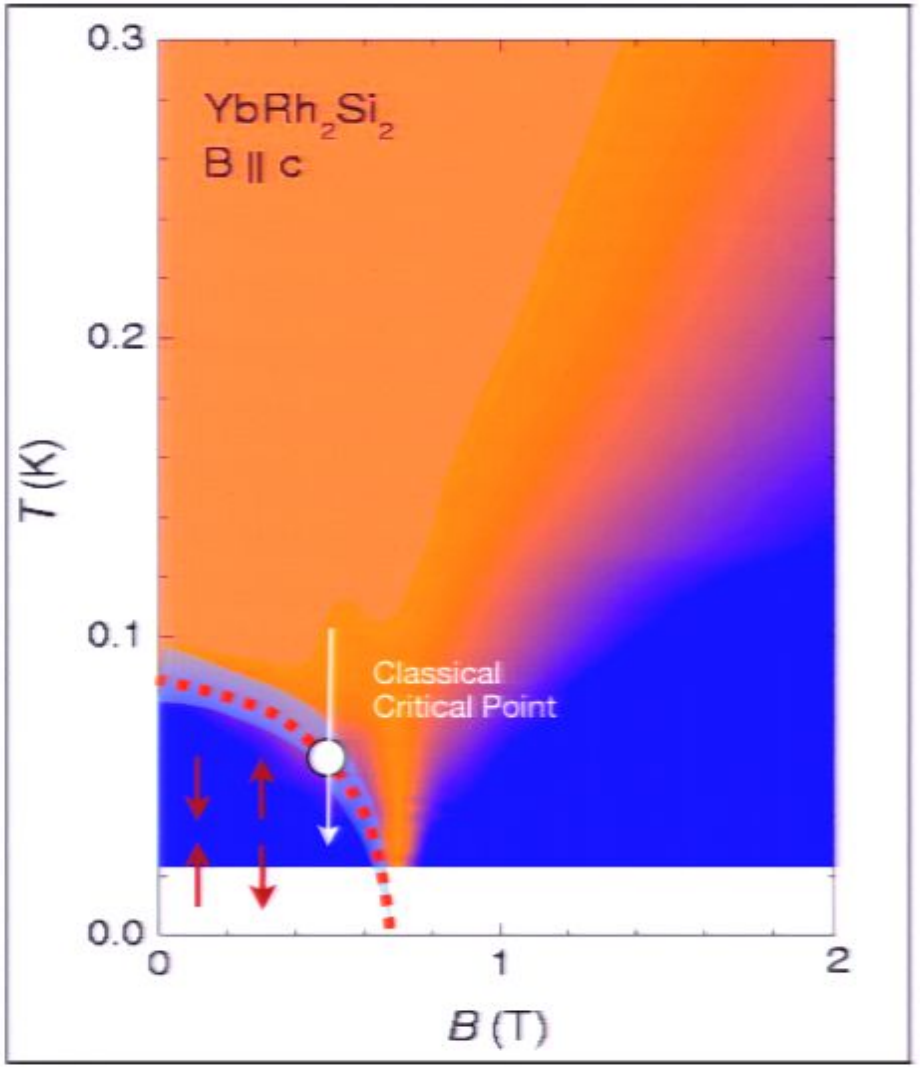

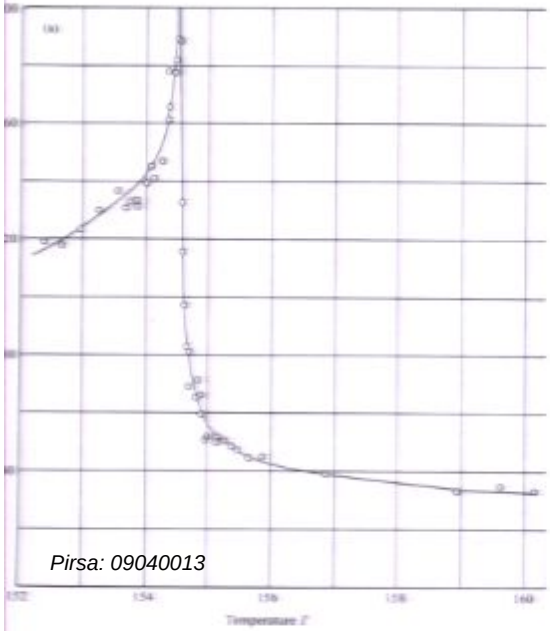

Oxygen. (Voronel et al 1963).

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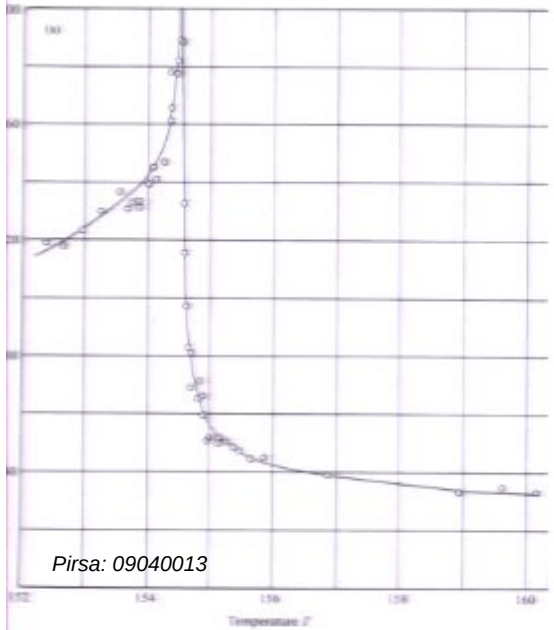

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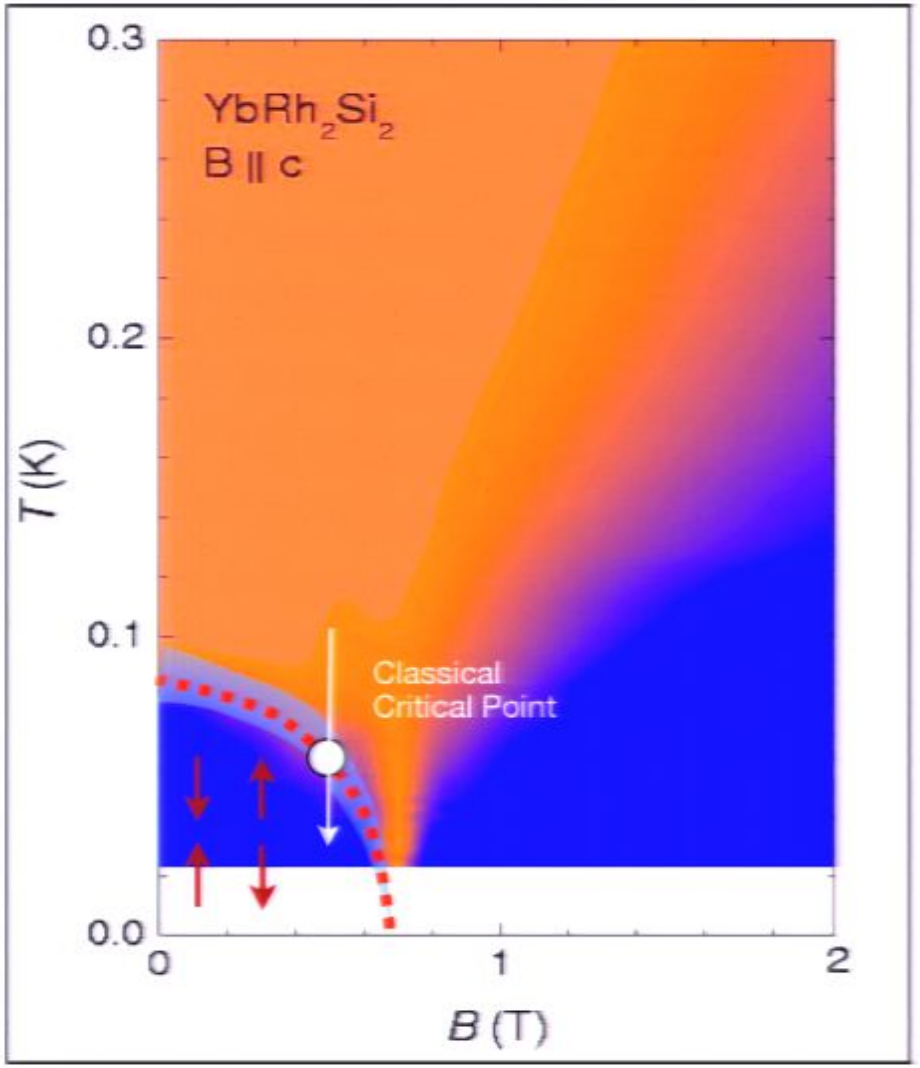

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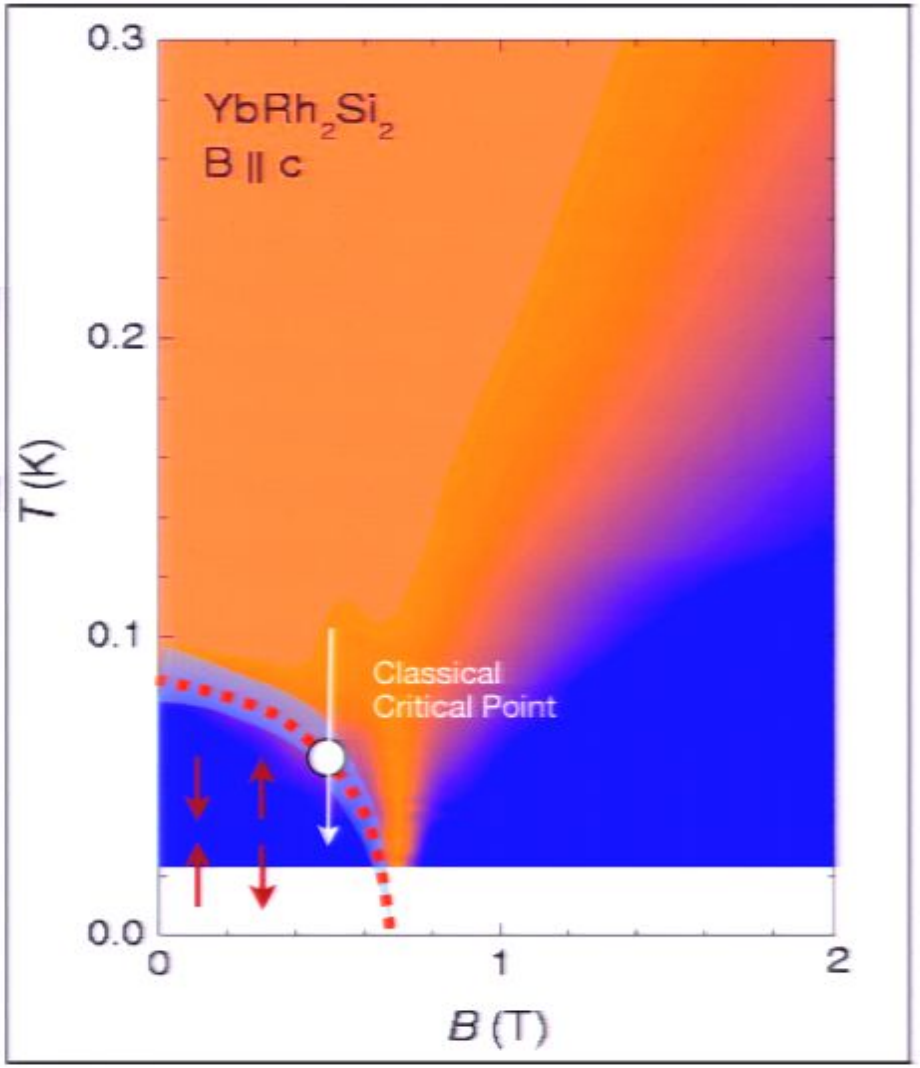

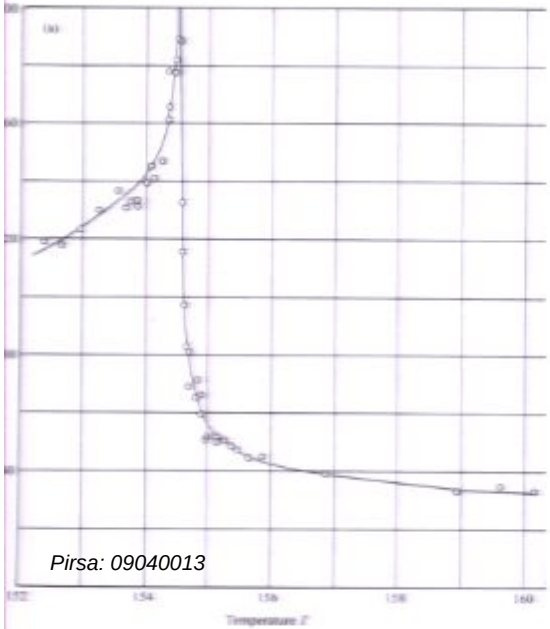

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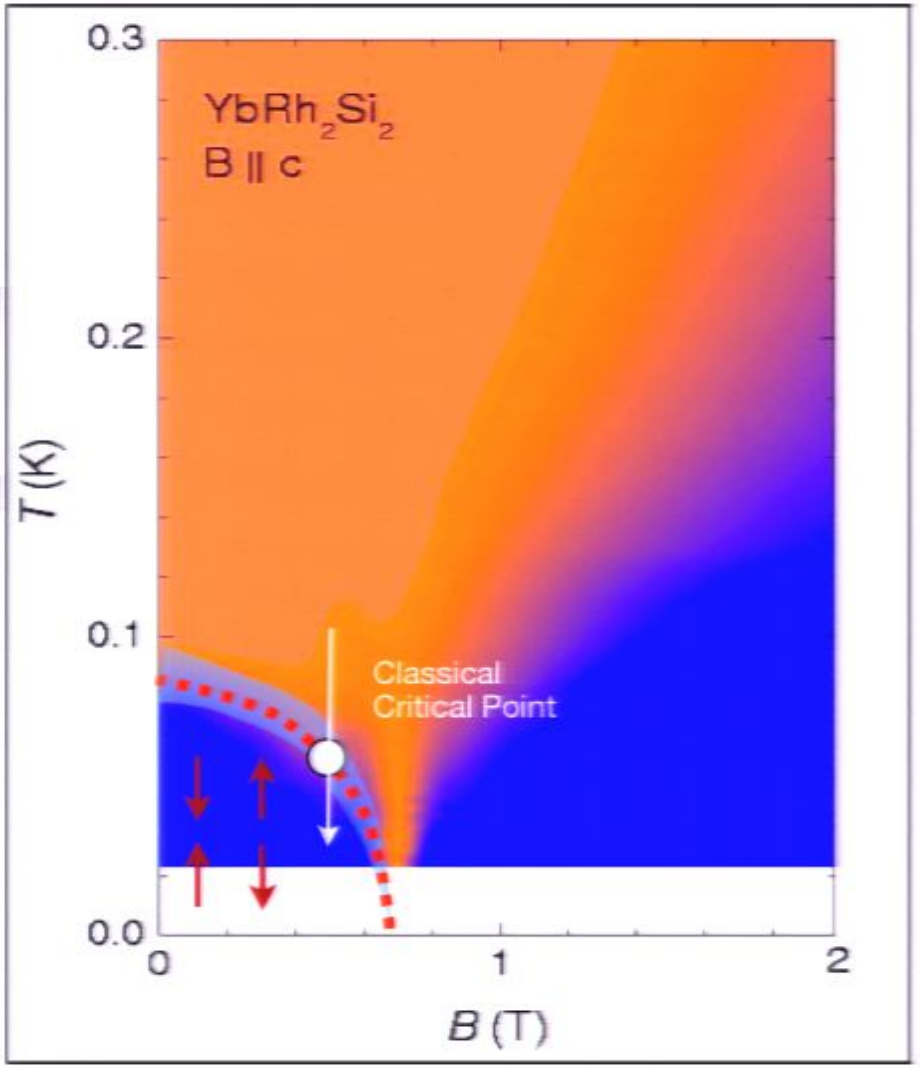

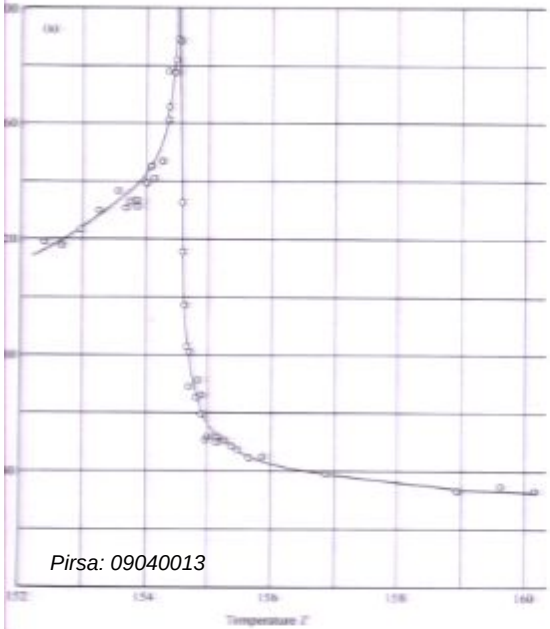

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"20th Century Revolution"

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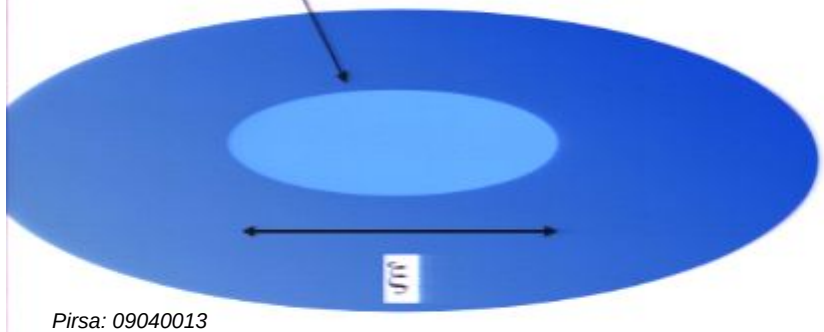
$$\langle \psi(x)\psi(0)\rangle \sim \frac{1}{x^{d-2+\eta}}$$

Critical matter



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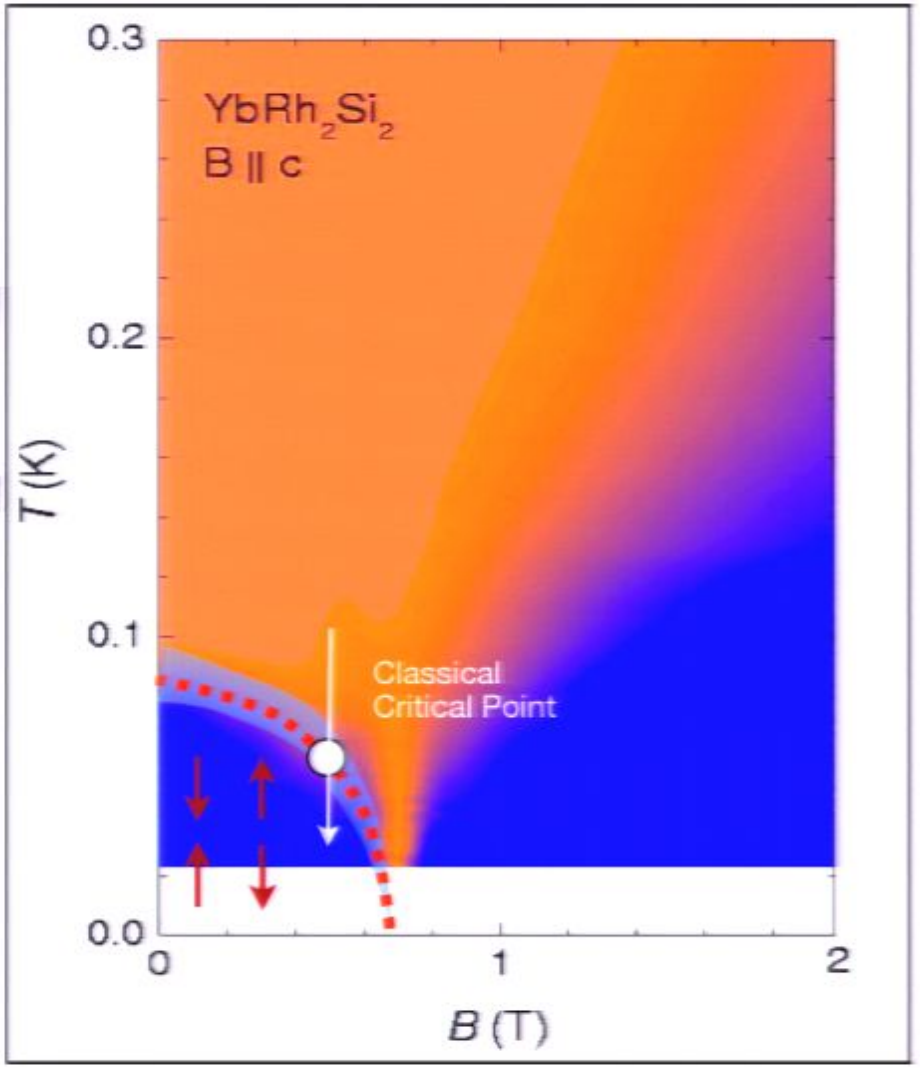

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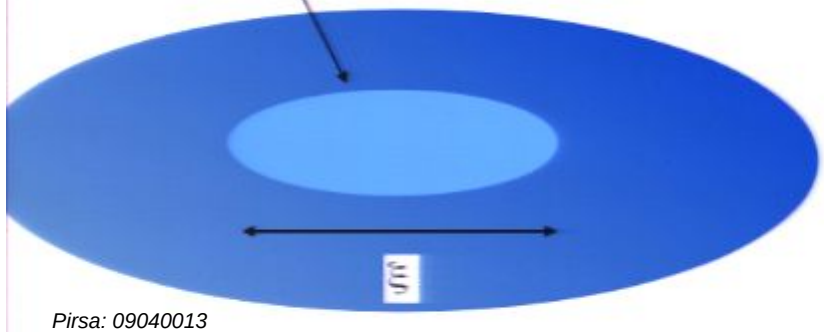
Critical matter - universal



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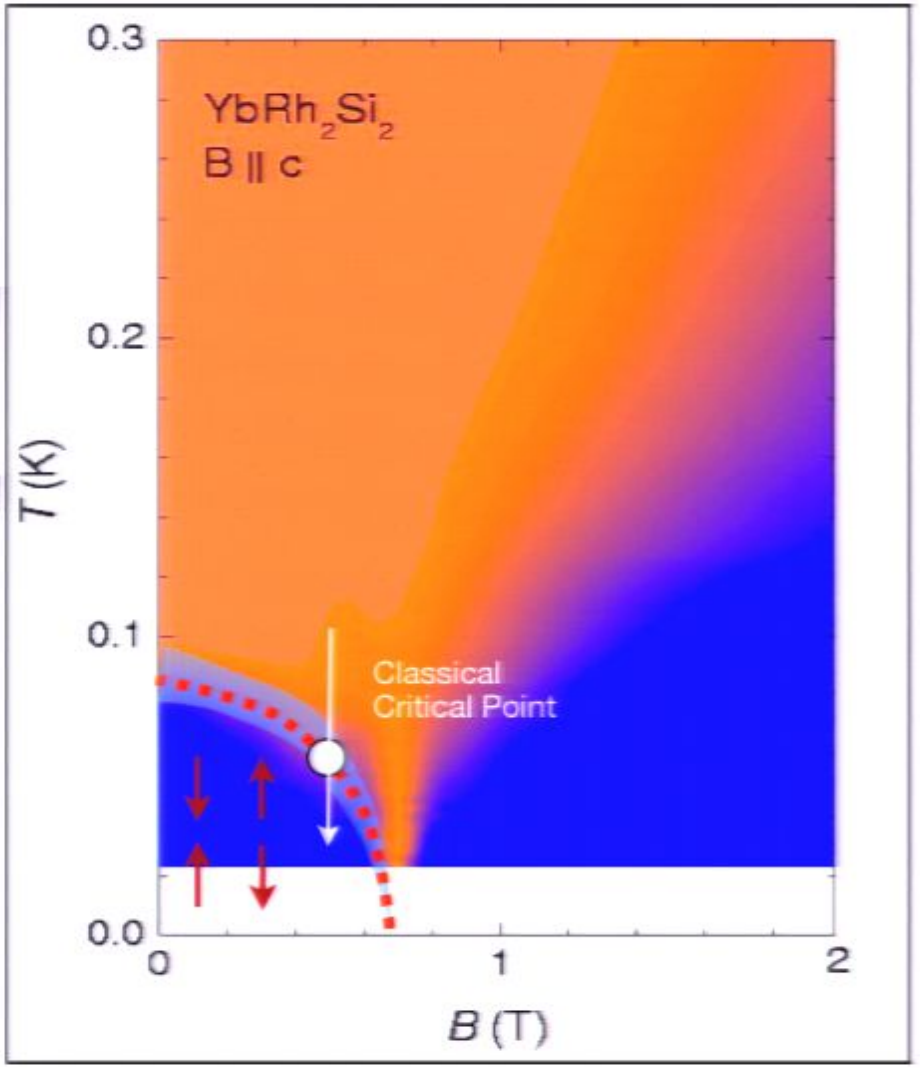

"20th Century Revolution"

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driven by zero point energy.

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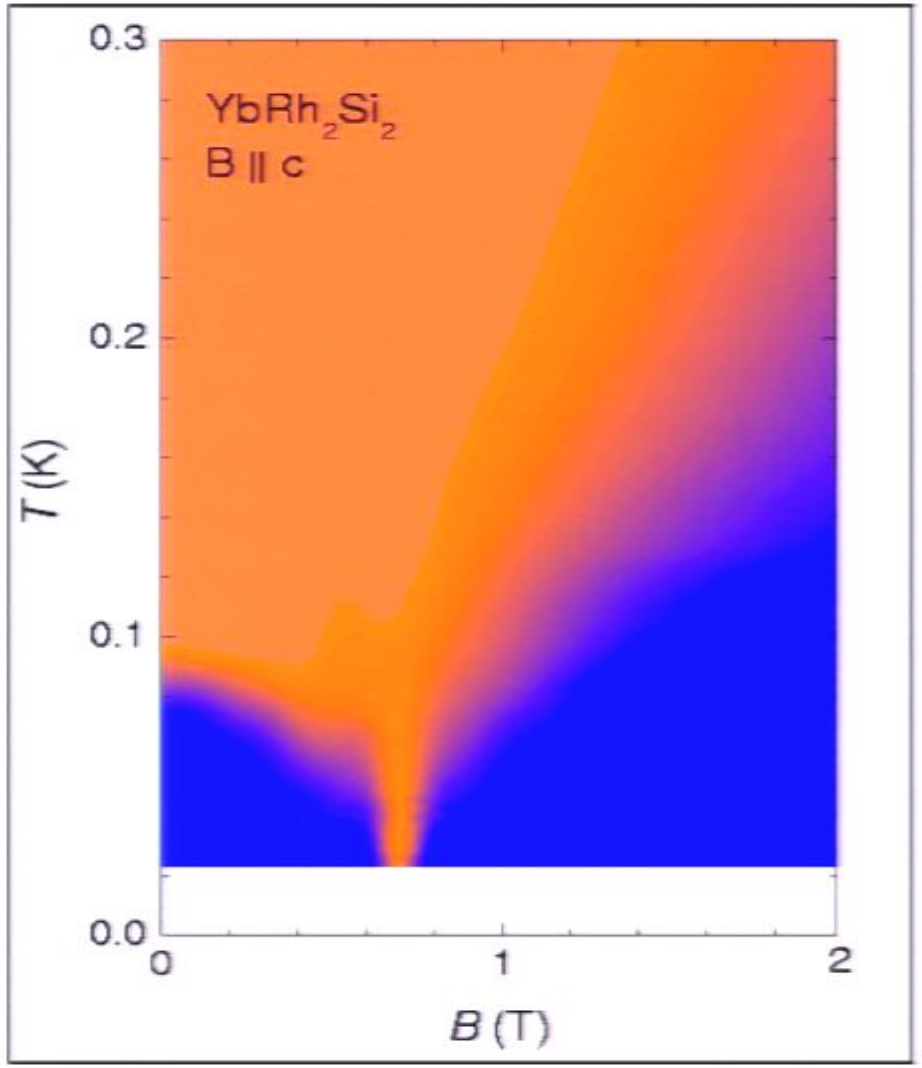

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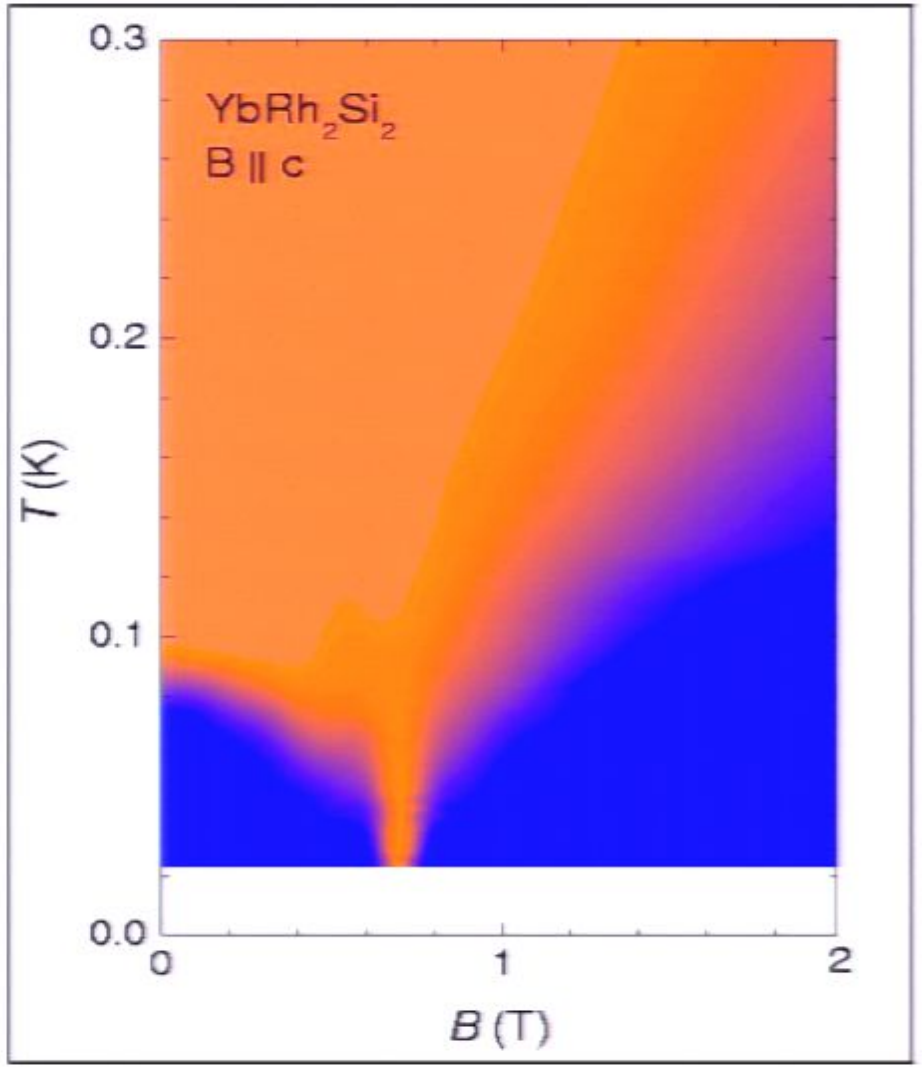

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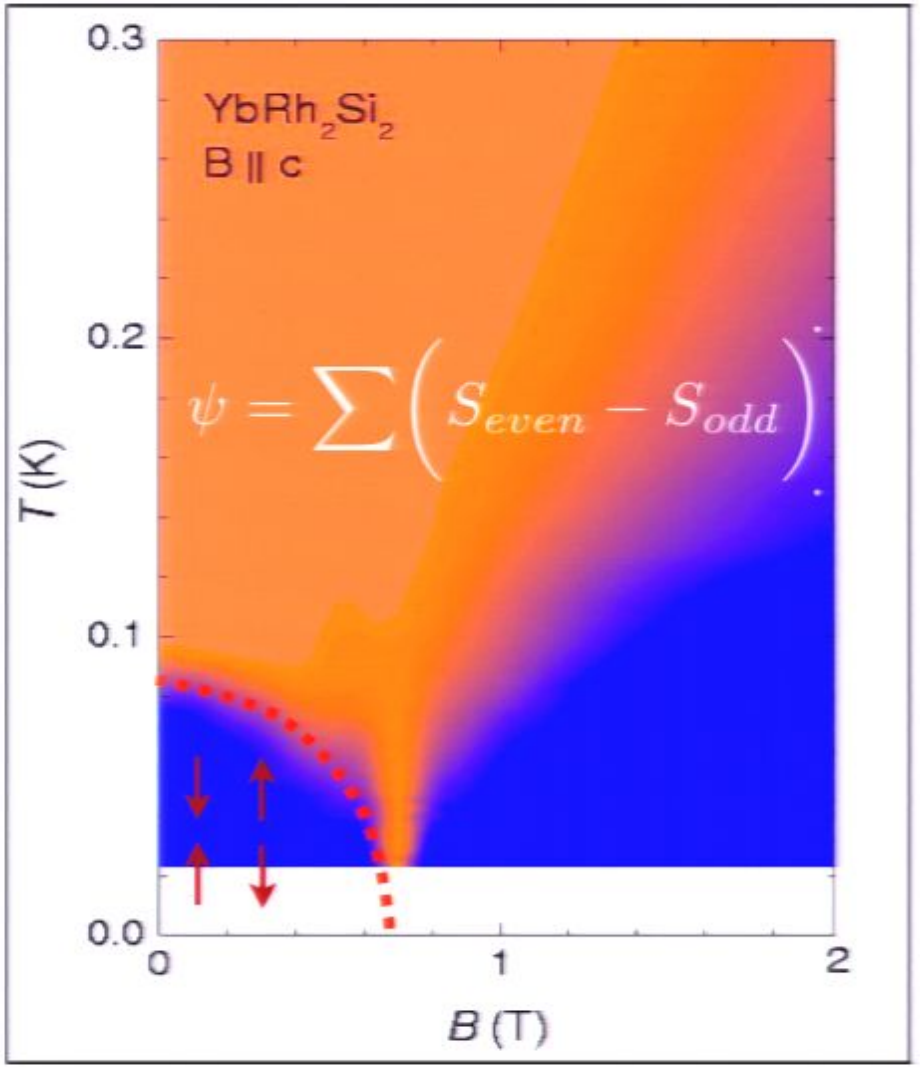

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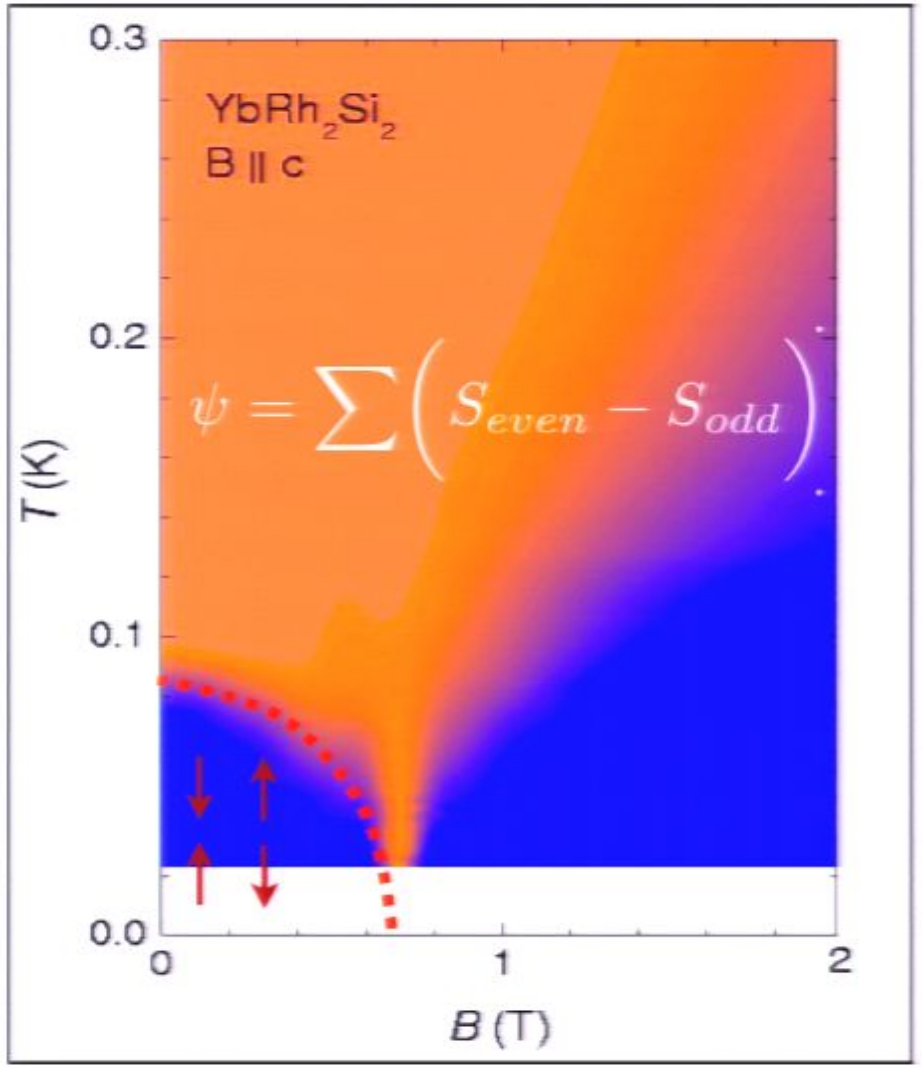

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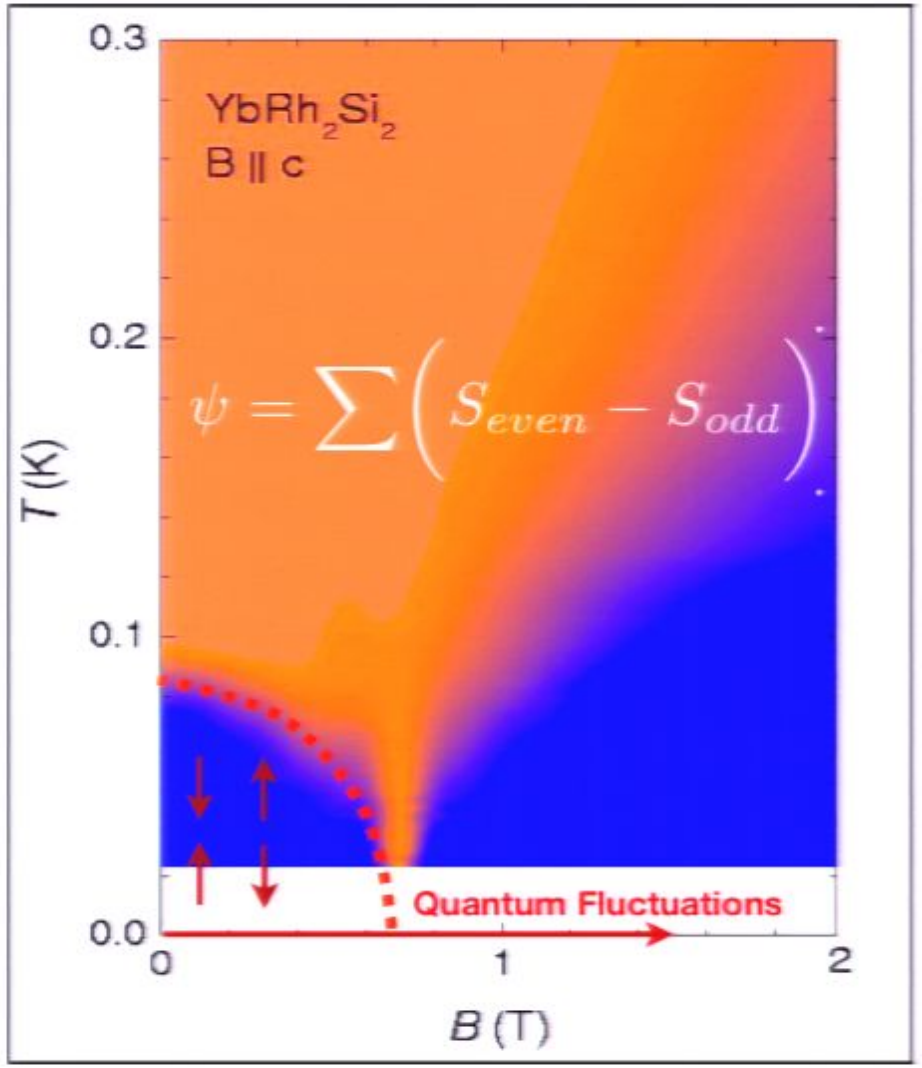

What happens when the time and length scale of coherent fluctuations expands to fill the entire material?

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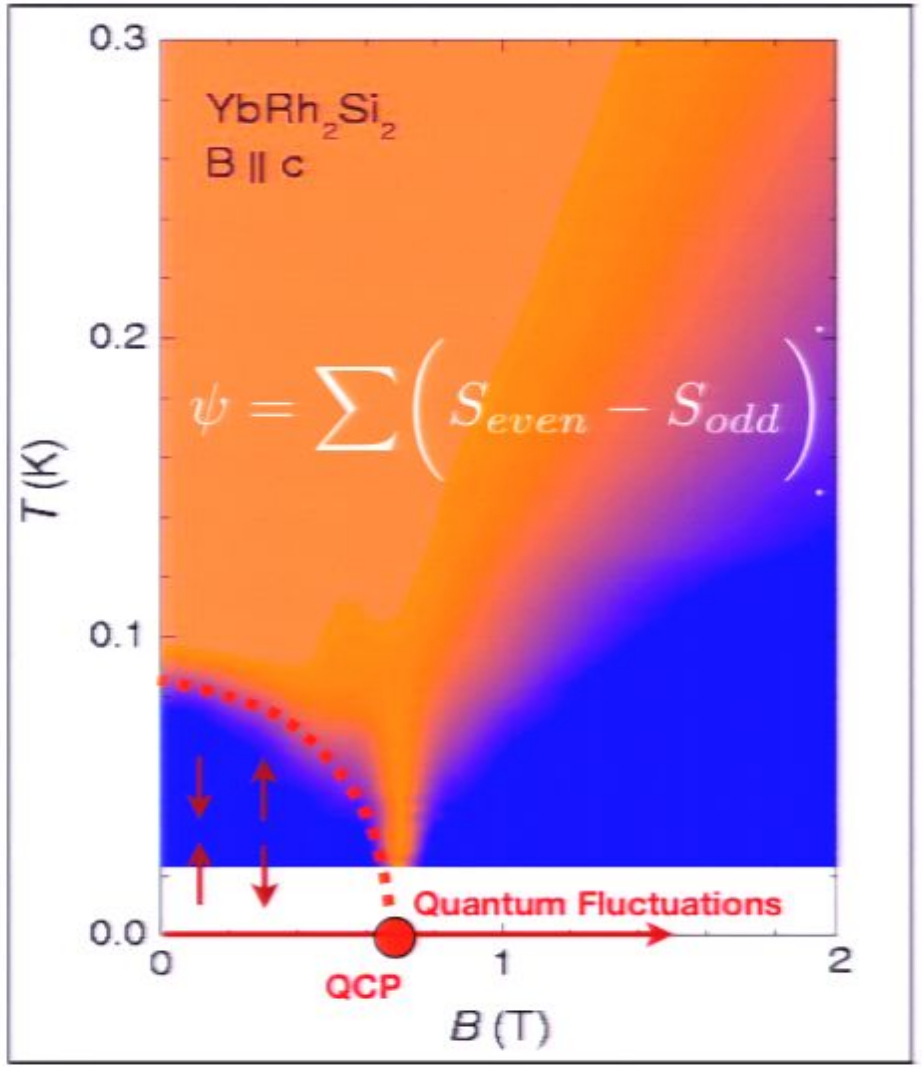

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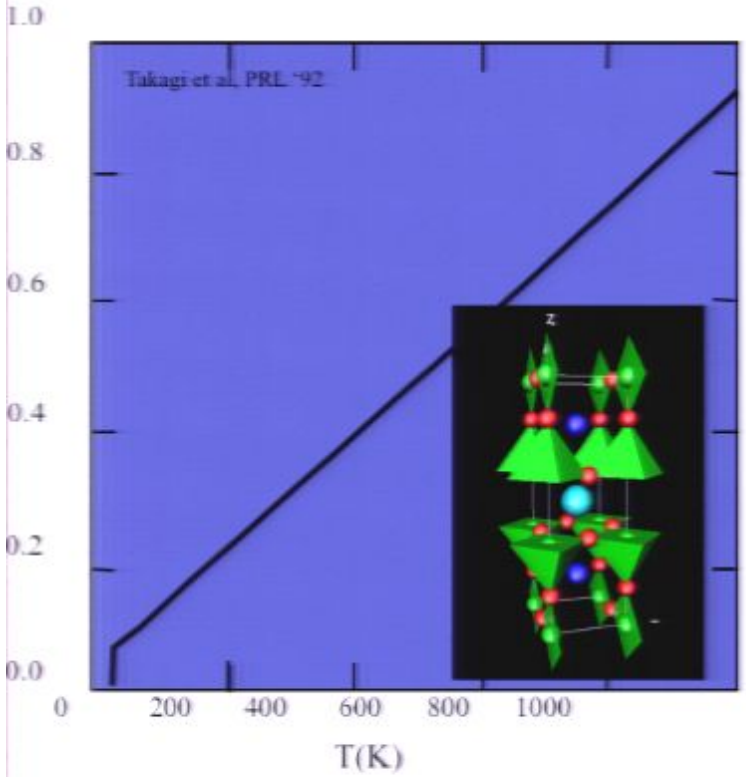

Cuprates
Tc=11-92K

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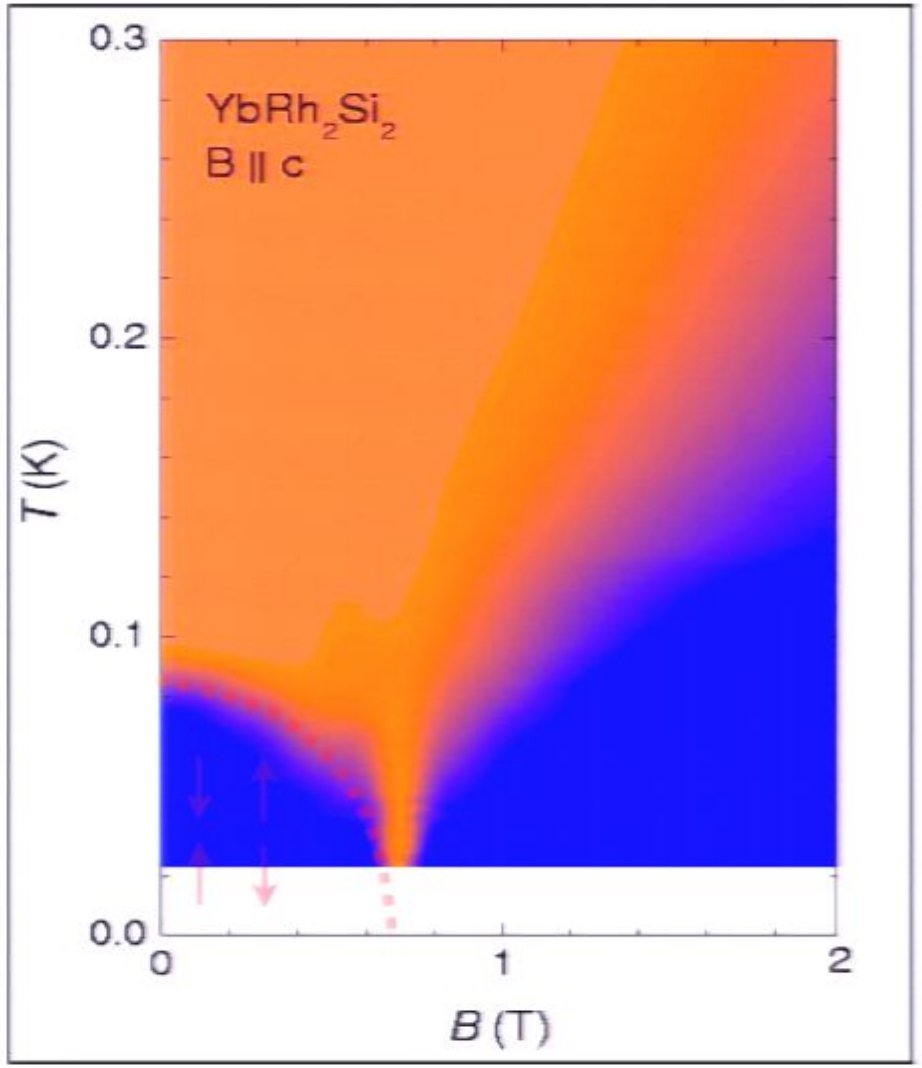

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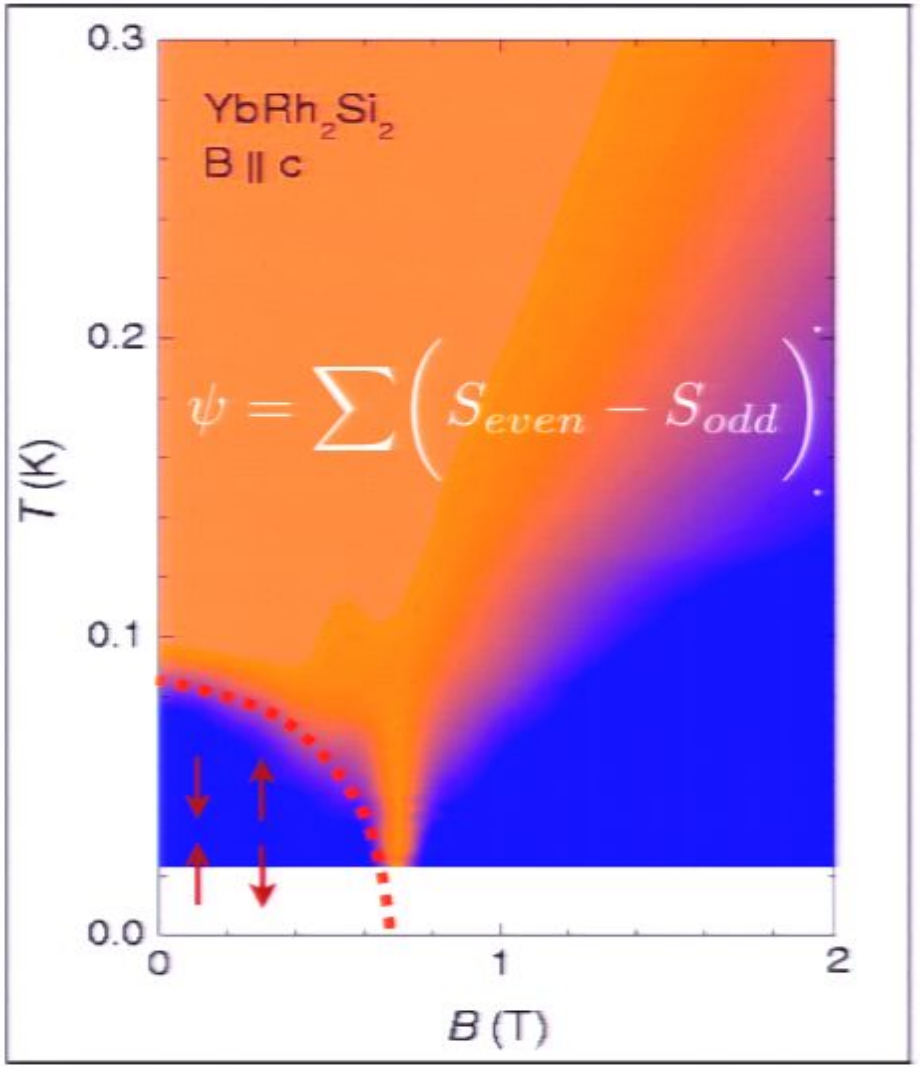

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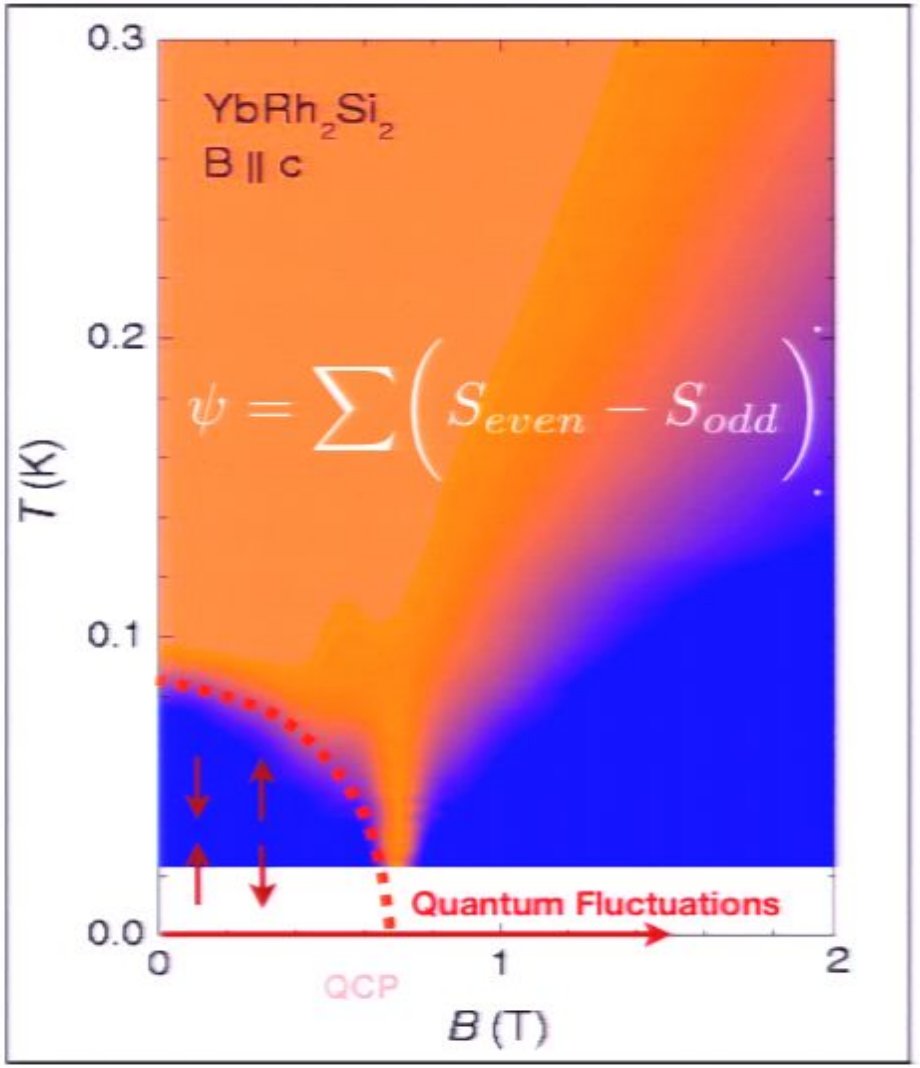

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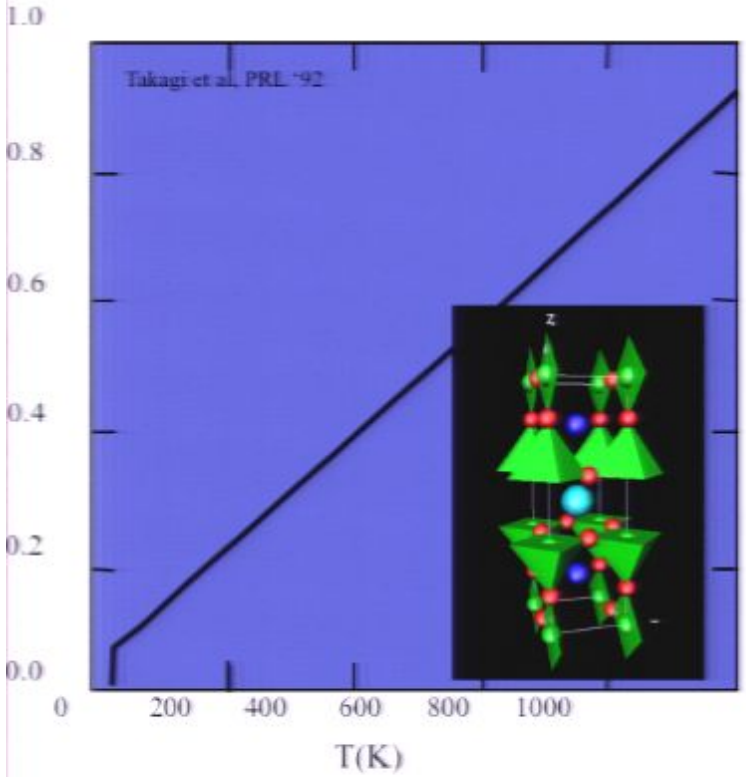

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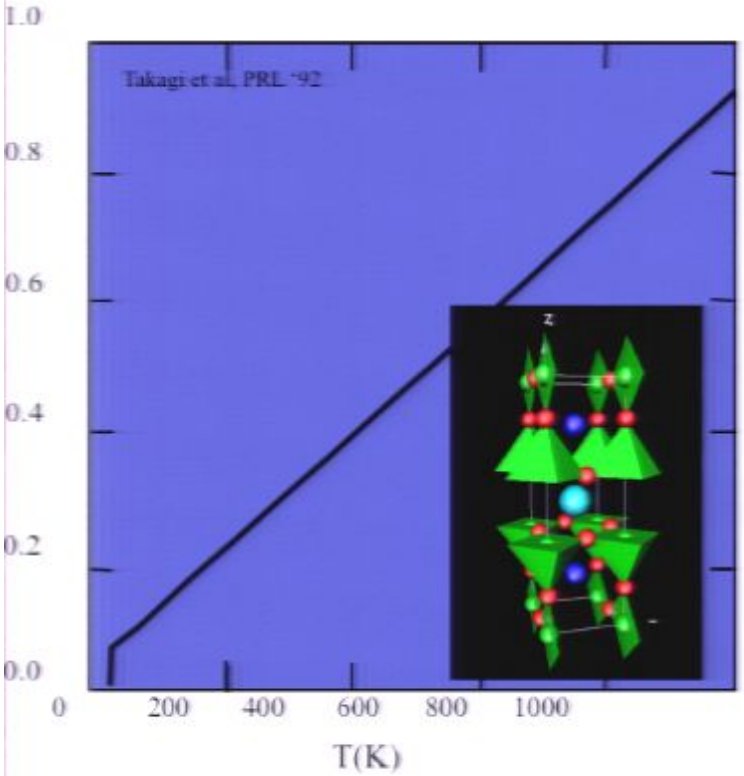

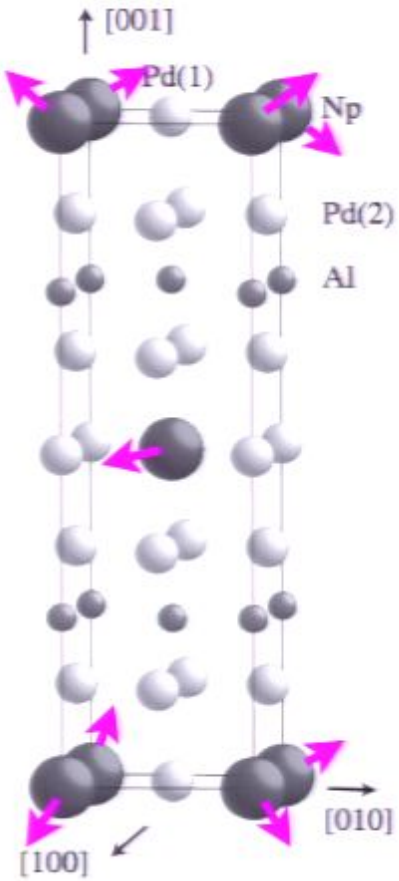

$NpAl_2Pd_5$

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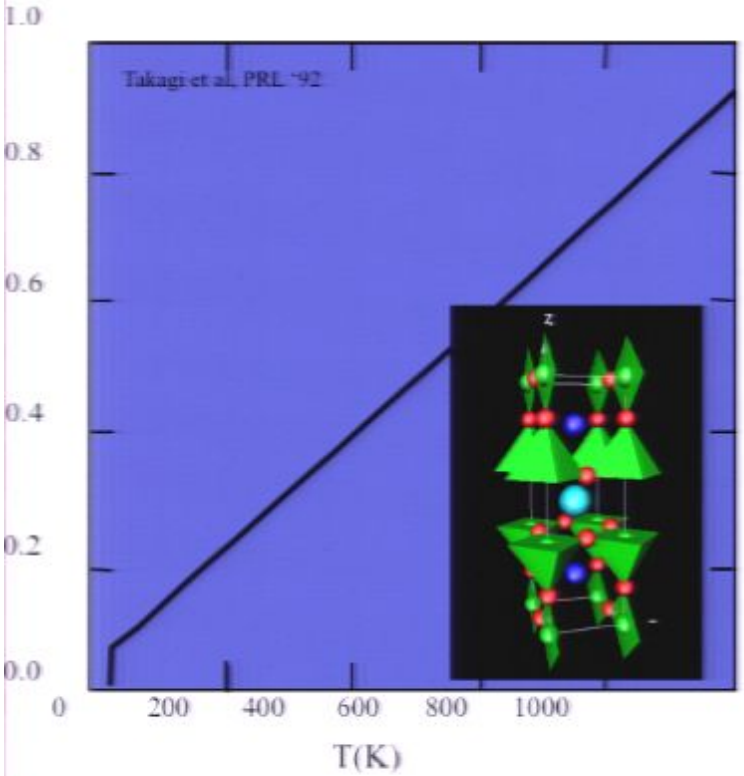

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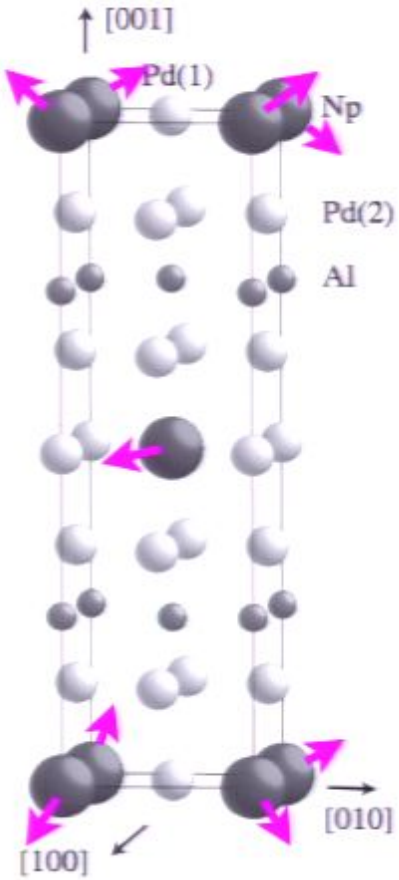

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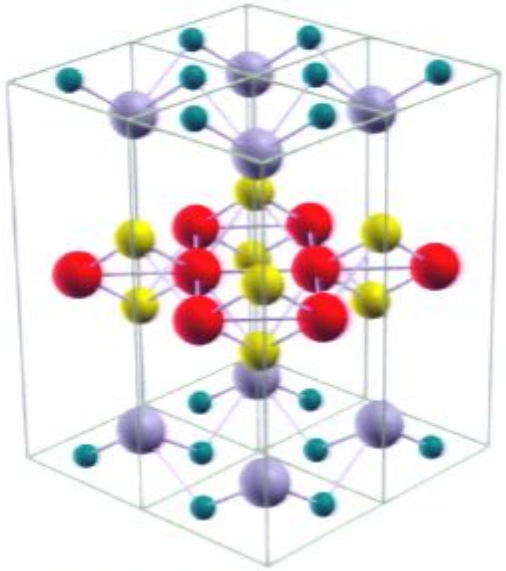
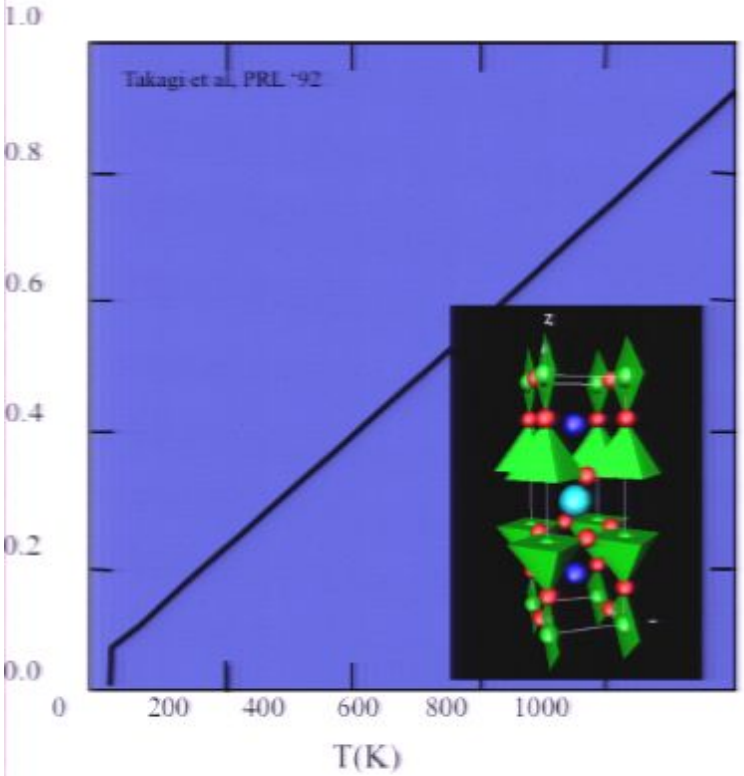
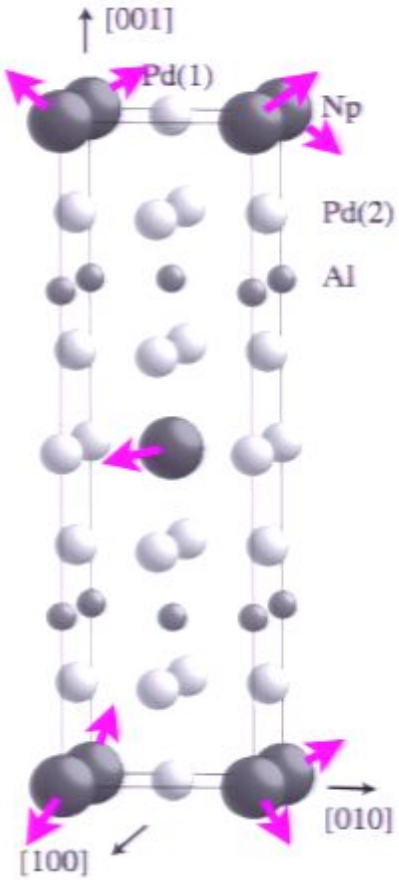


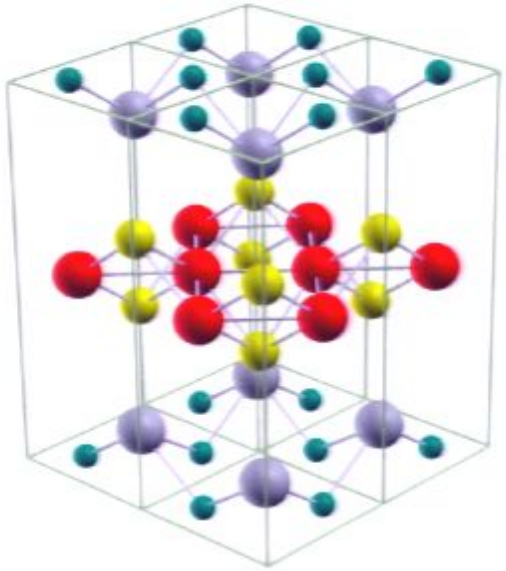
$PrF_xO_{1-x}FeAs$
Z.A. Ren et.al. Beijing. (08)

Iron oxypnictides
Tc= 6 - 53 ++ ? K





$NpAl_2Pd_5$



$PrF_xO_{1-x}FeAs$

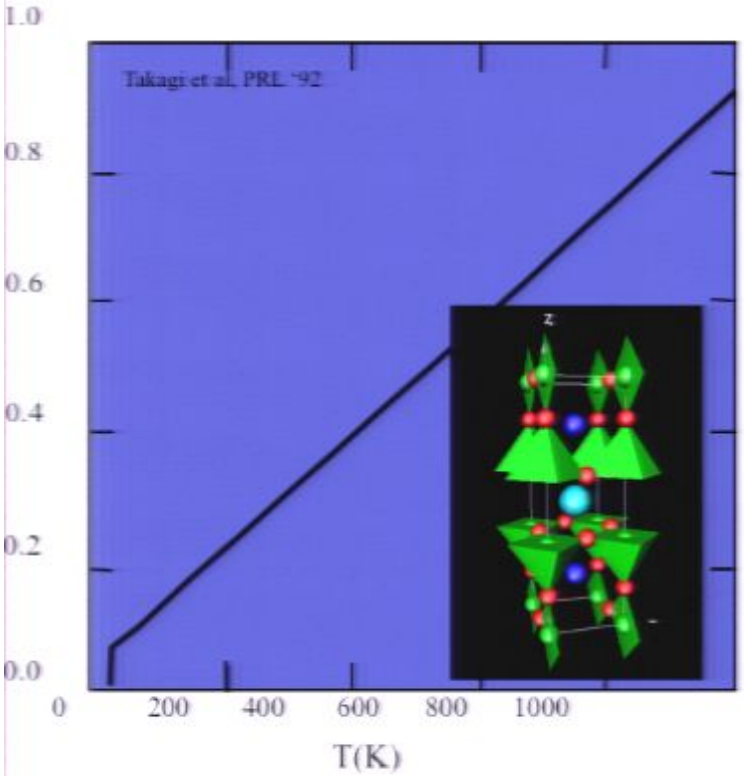
Z.A. Ren et.al. Beijing. (08)

Cuprates
Tc=11-92K

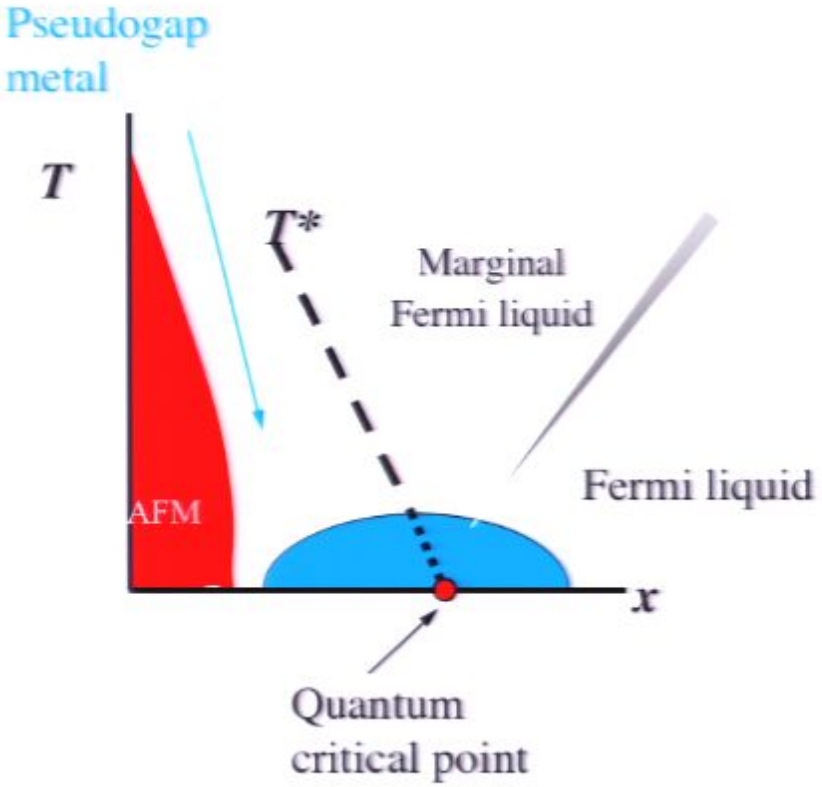
HF 115s
Tc=0.2 -18.5 K

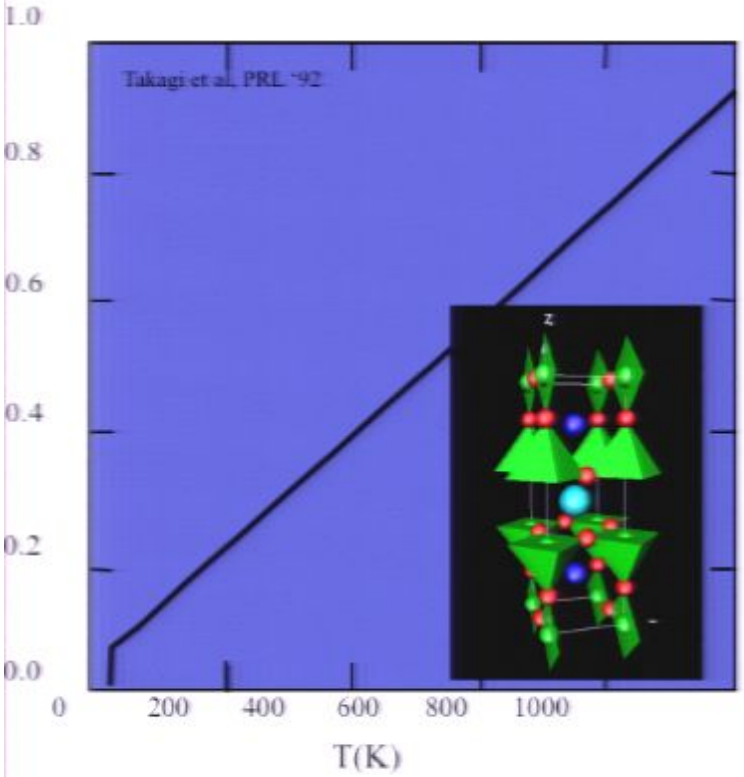
Iron oxypnictides
Tc= 6 - 53 ++ ? K

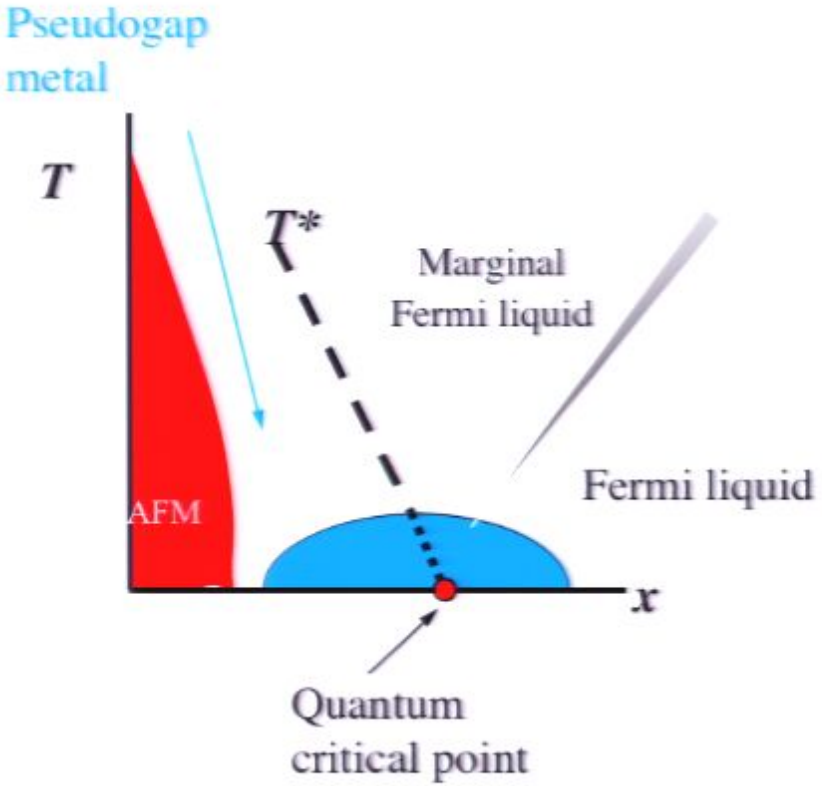
What kind of electronic fluid yields high Tc superconductivity?



Cuprates
Tc=11-92K

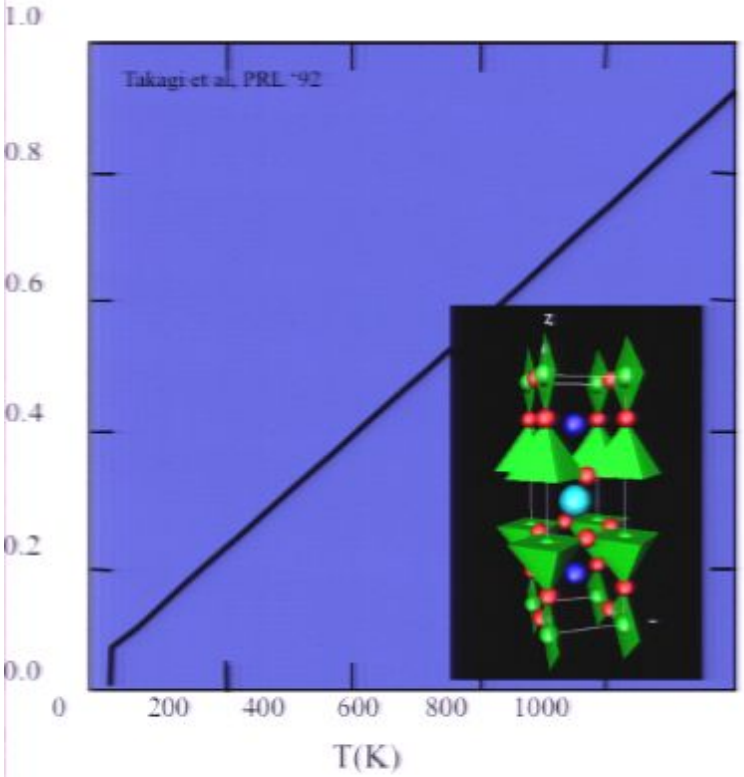


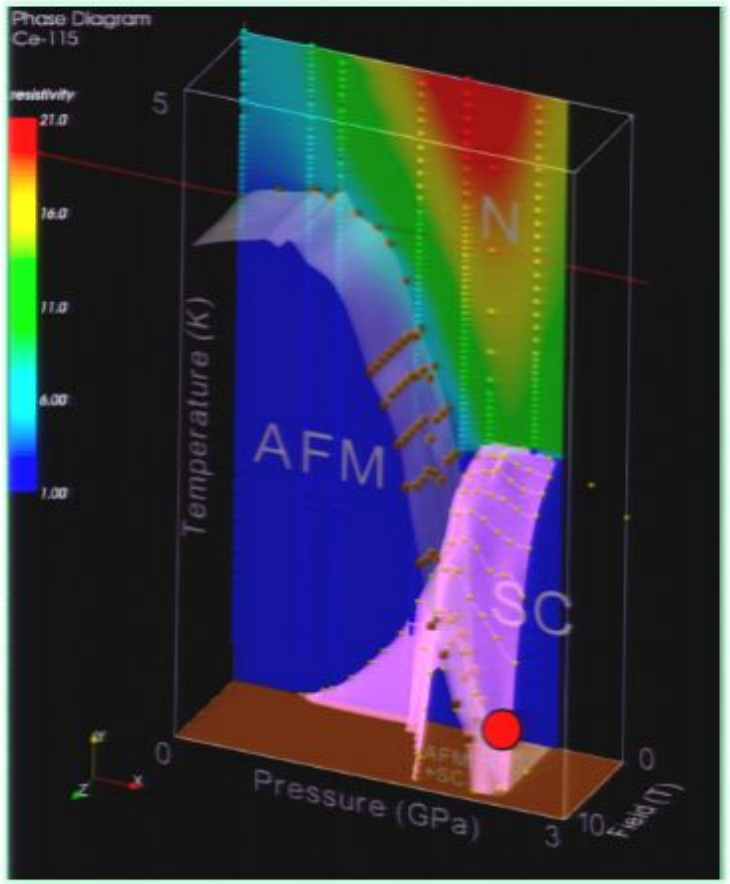




Cuprates
Tc=11-92K

"Avoided criticality"

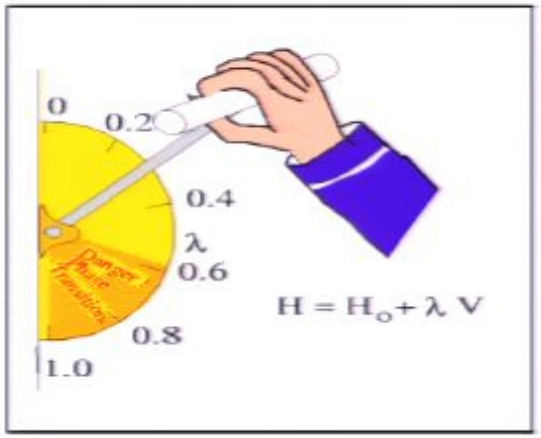




Cuprates
Tc=11-92K

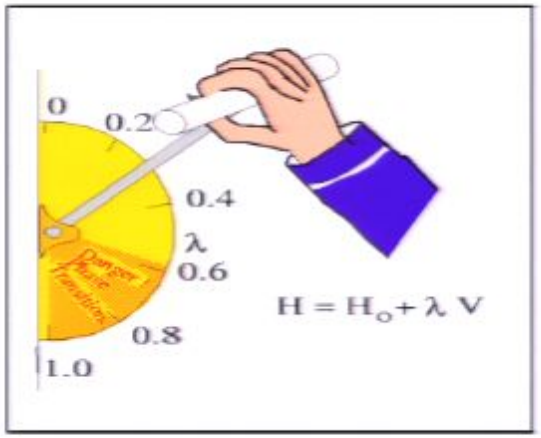
"Avoided criticality"

Tuson Park, (2007).



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

Landau, JETP 3, 920 (1957)



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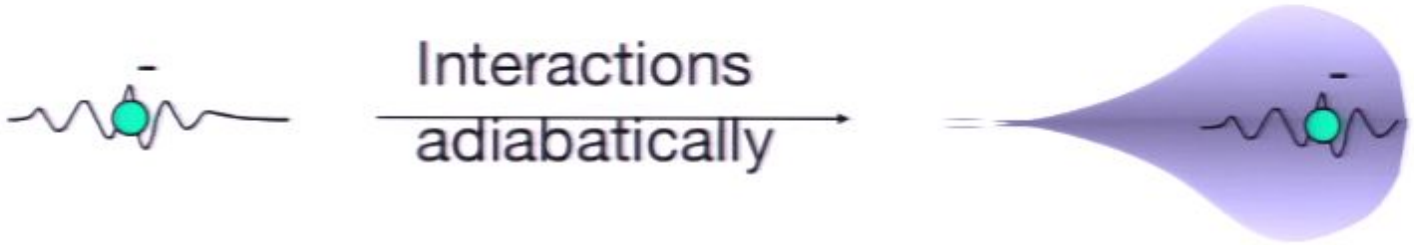
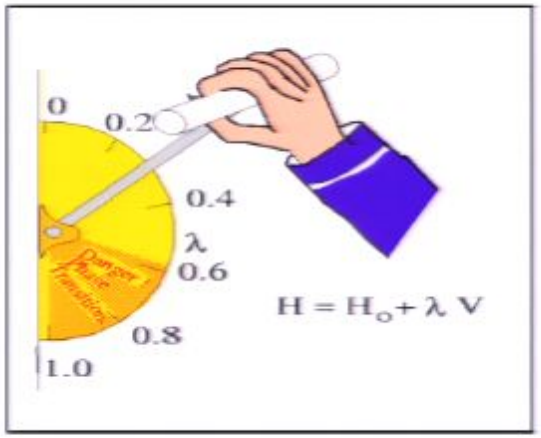
"Quasiparticle"



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



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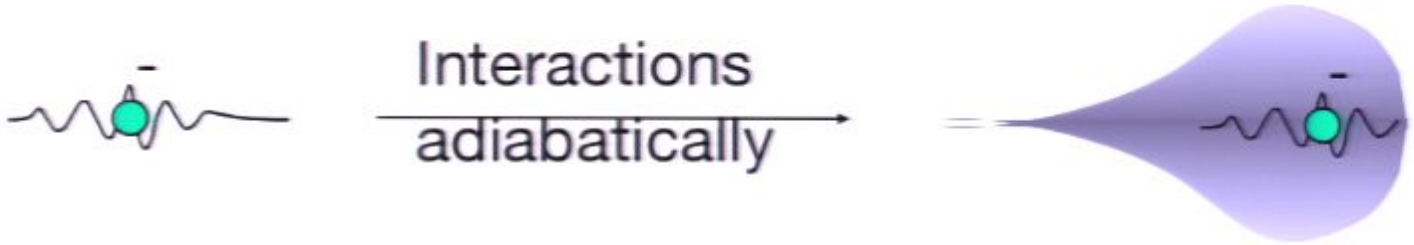
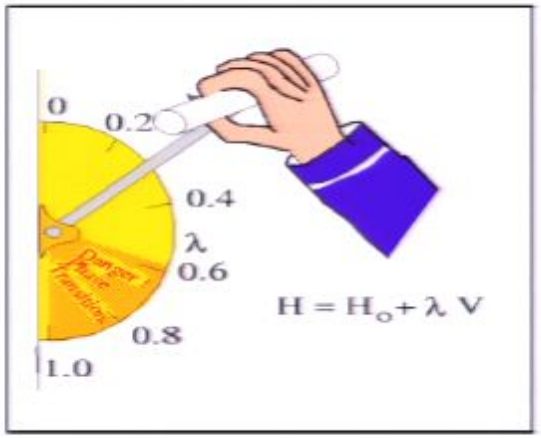


$|e^-\rangle$ $\qquad$ $|qp^-\rangle$

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



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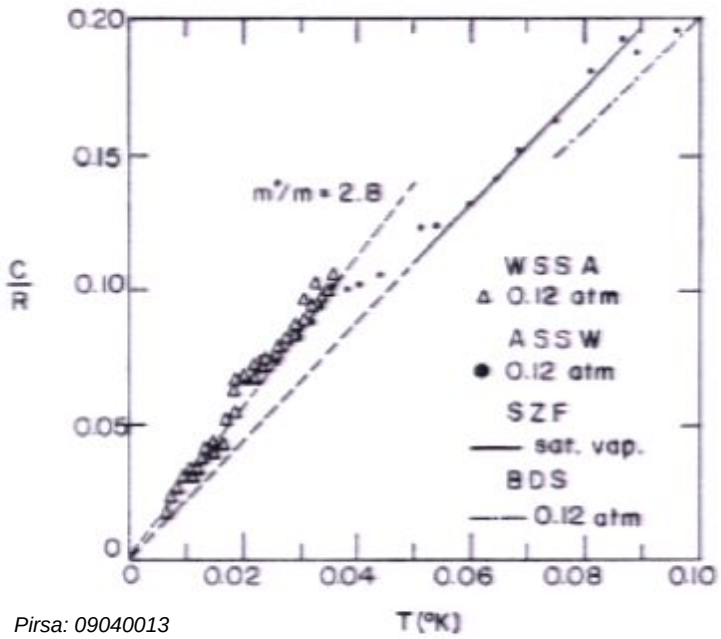
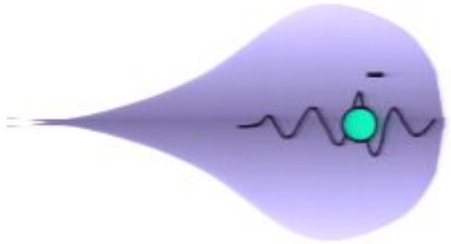
Landau, JETP 3, 920 (1957)

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



"Quasiparticle"



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

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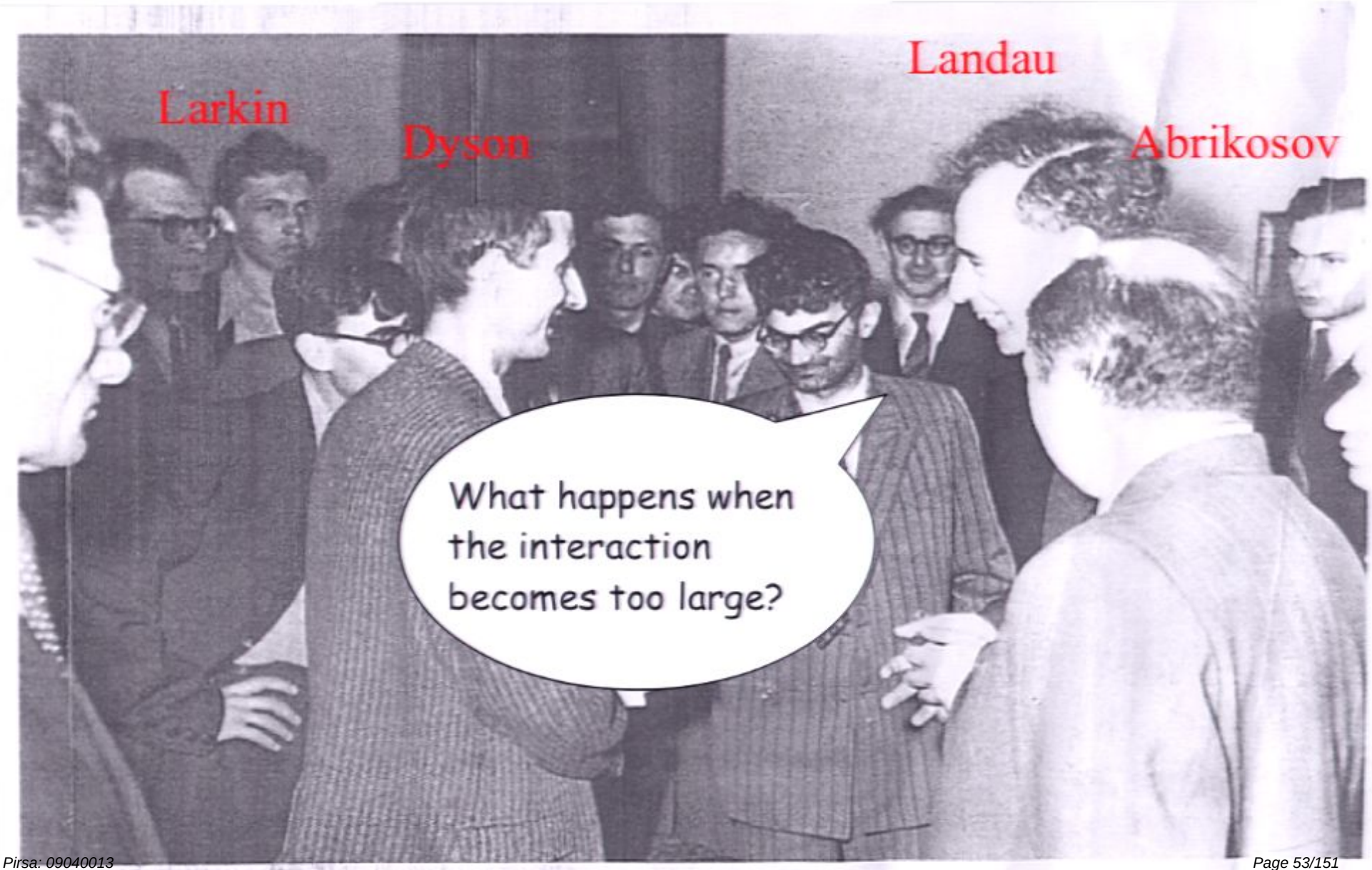
Landau's Question.

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

Landau's Question.



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What happens when the interaction becomes too large?

Landau 1936

"Electrons order"

What happens when the interaction becomes too large?

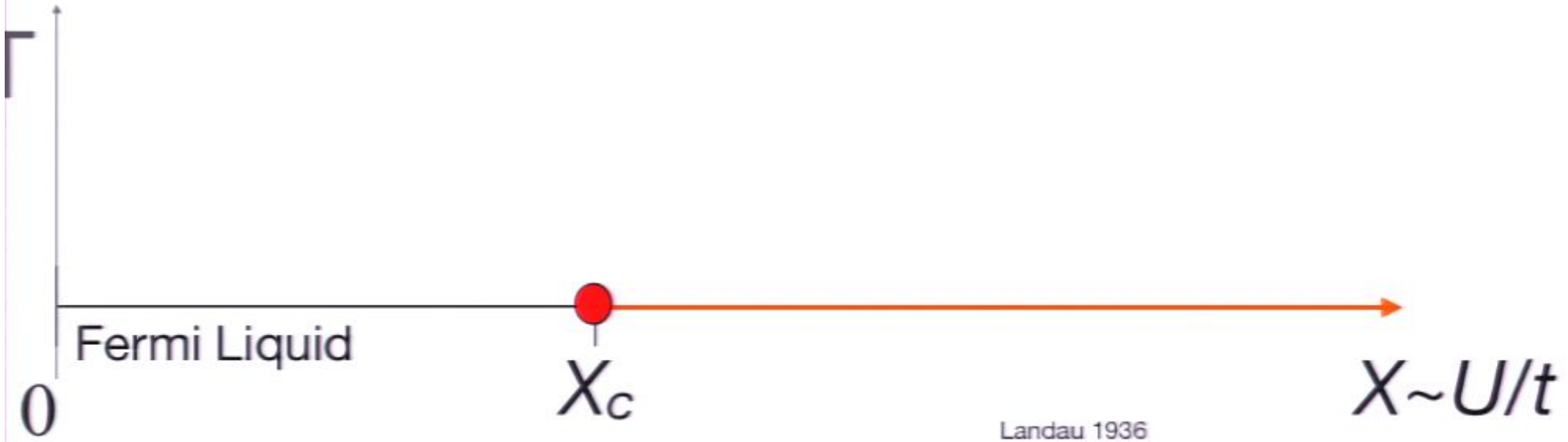
Landau 1936

"Electrons order"

What happens when the interaction becomes too large?

Mott 1947

"Electrons localize"



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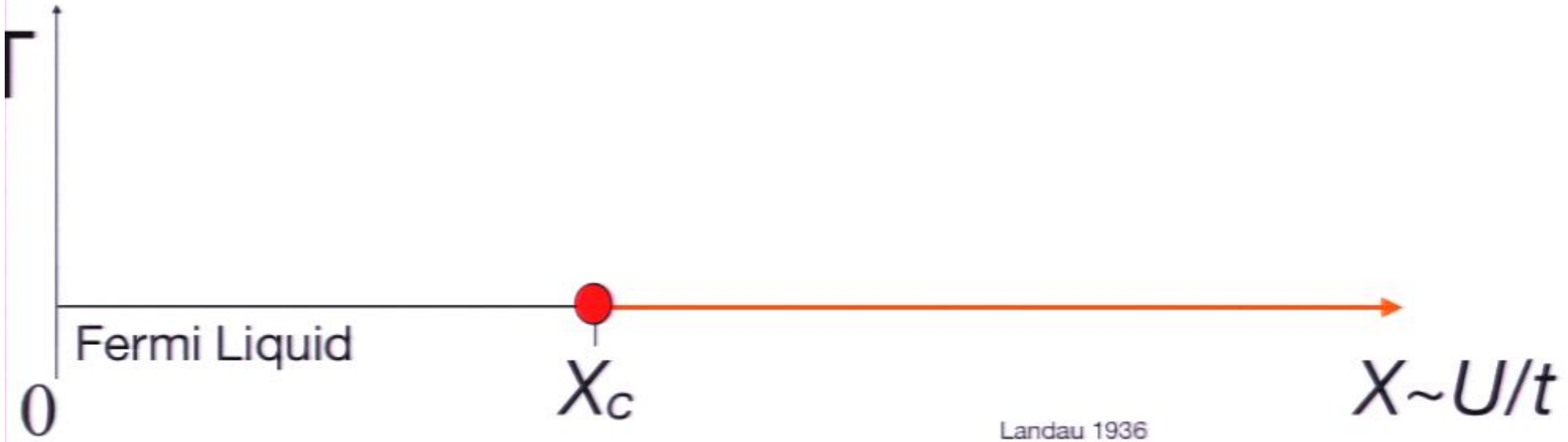
"Local moments form"



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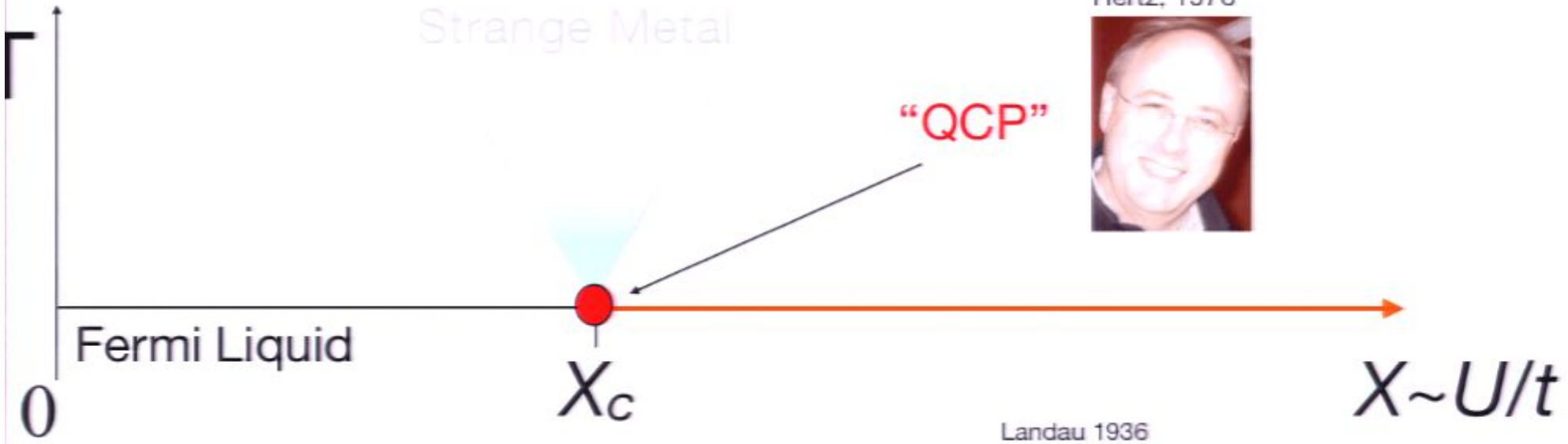

Hertz, 1976

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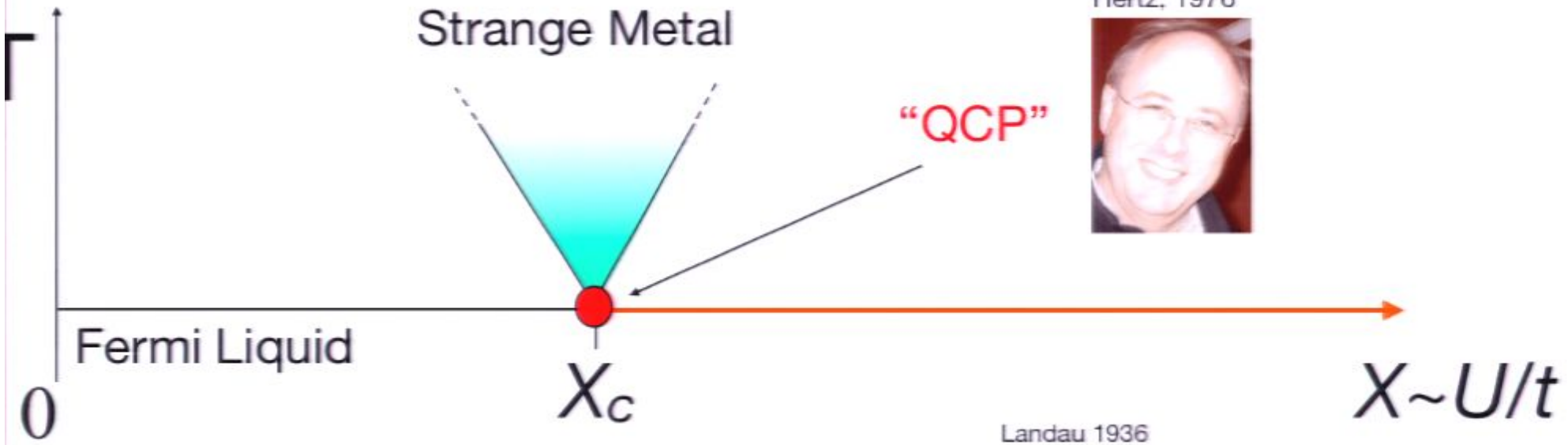

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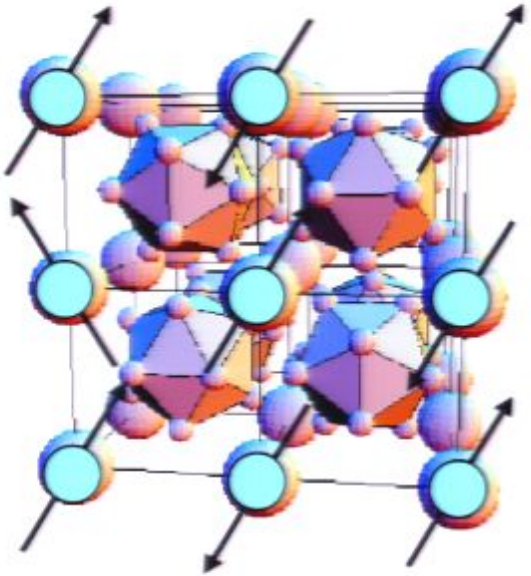
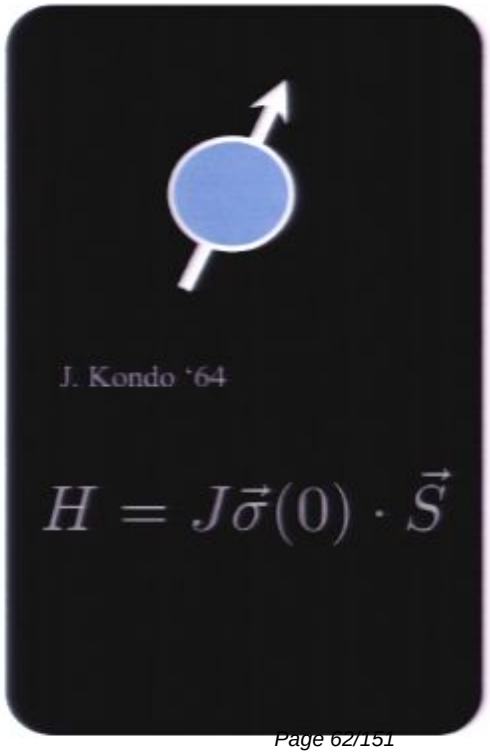
Heavy Electron Quantum Criticality.

Heavy Fermion Metals

Review: cond-mat/0612006



UBe_{13}



Heavy Fermion Metals

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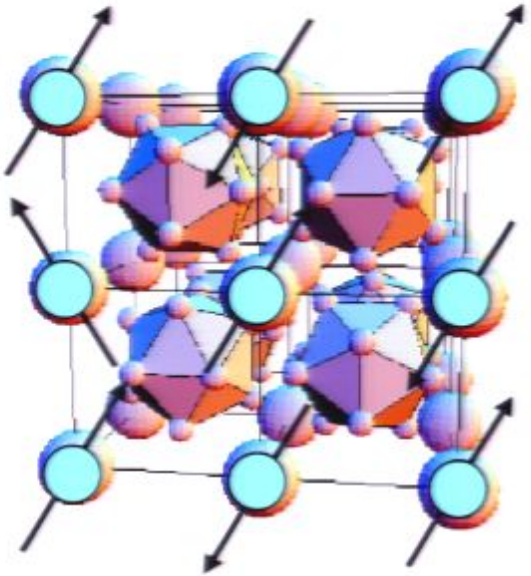

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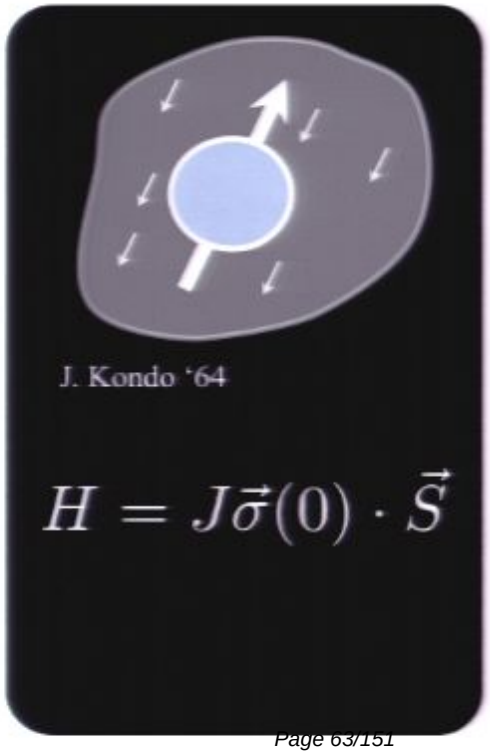

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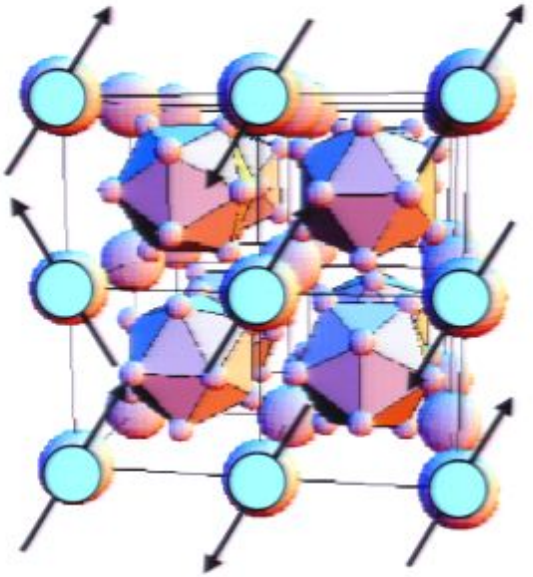

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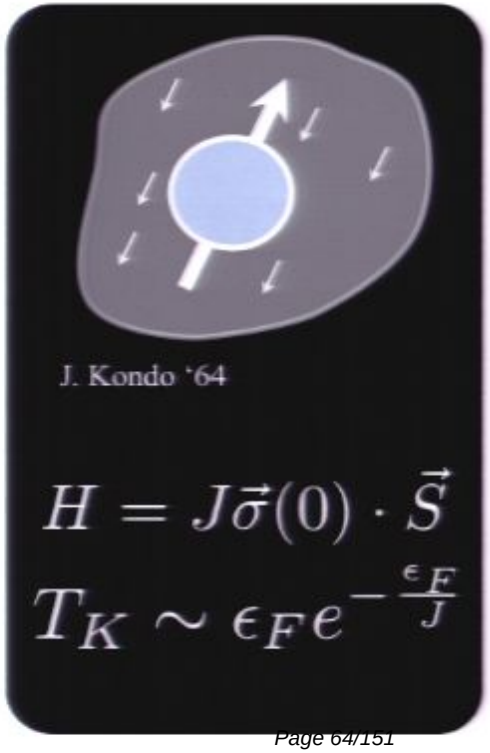

"Kondo Effect"

Heavy Fermion Metals

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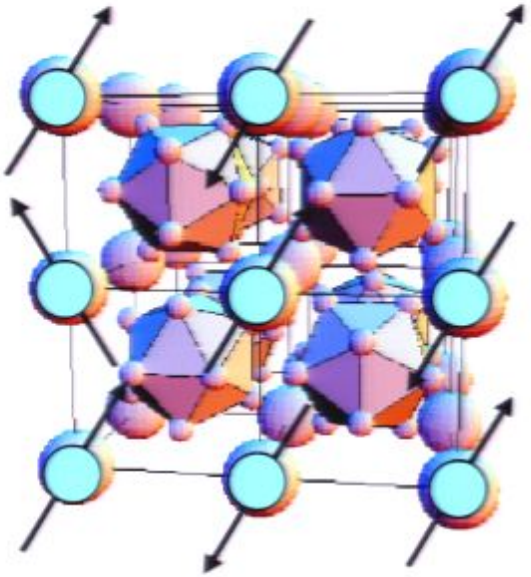

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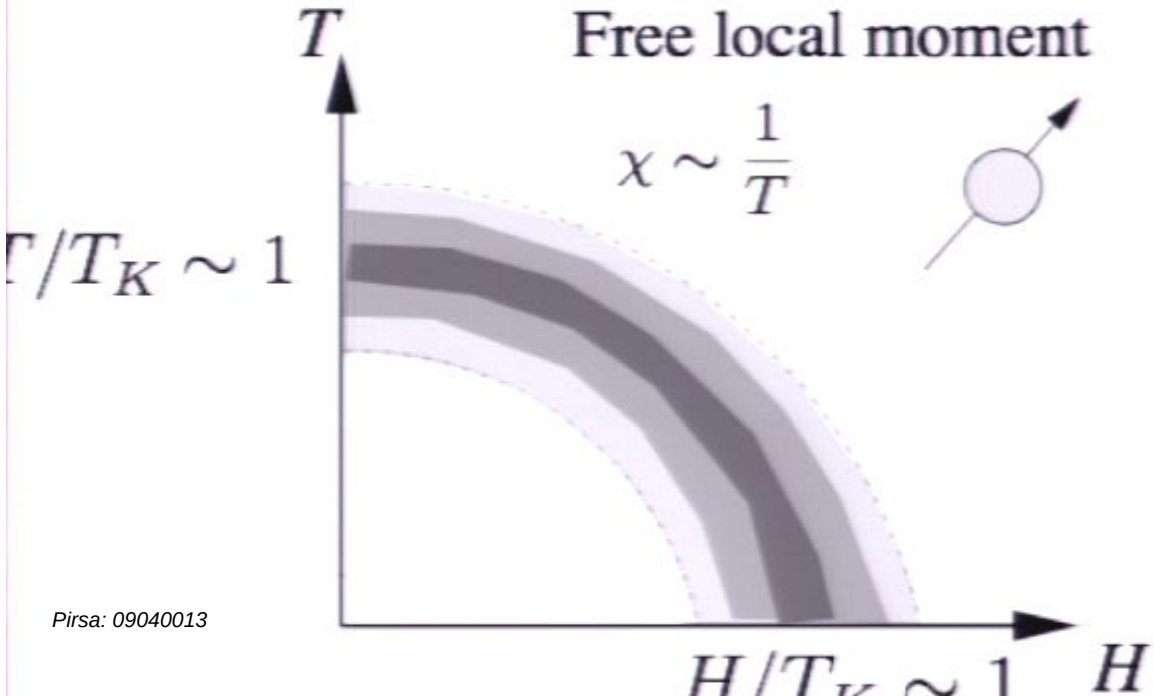

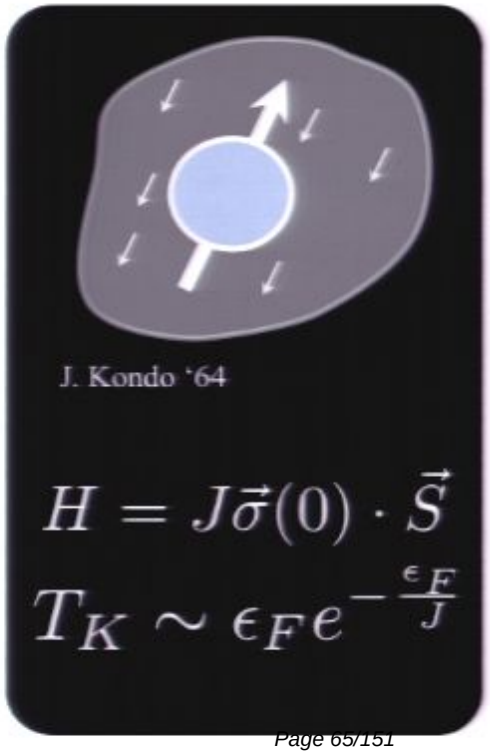

"Kondo Effect"

Heavy Fermion Metals

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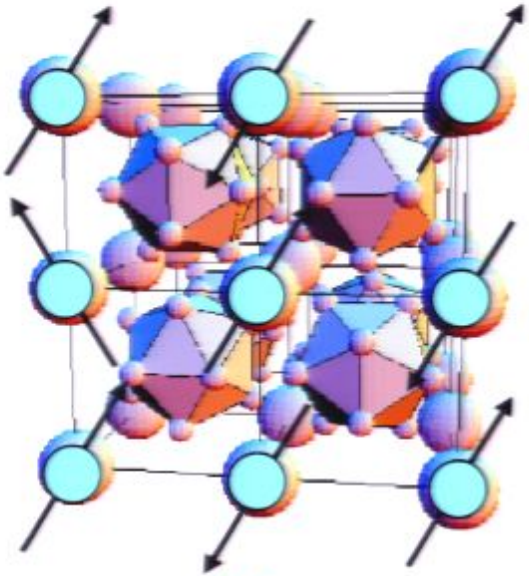

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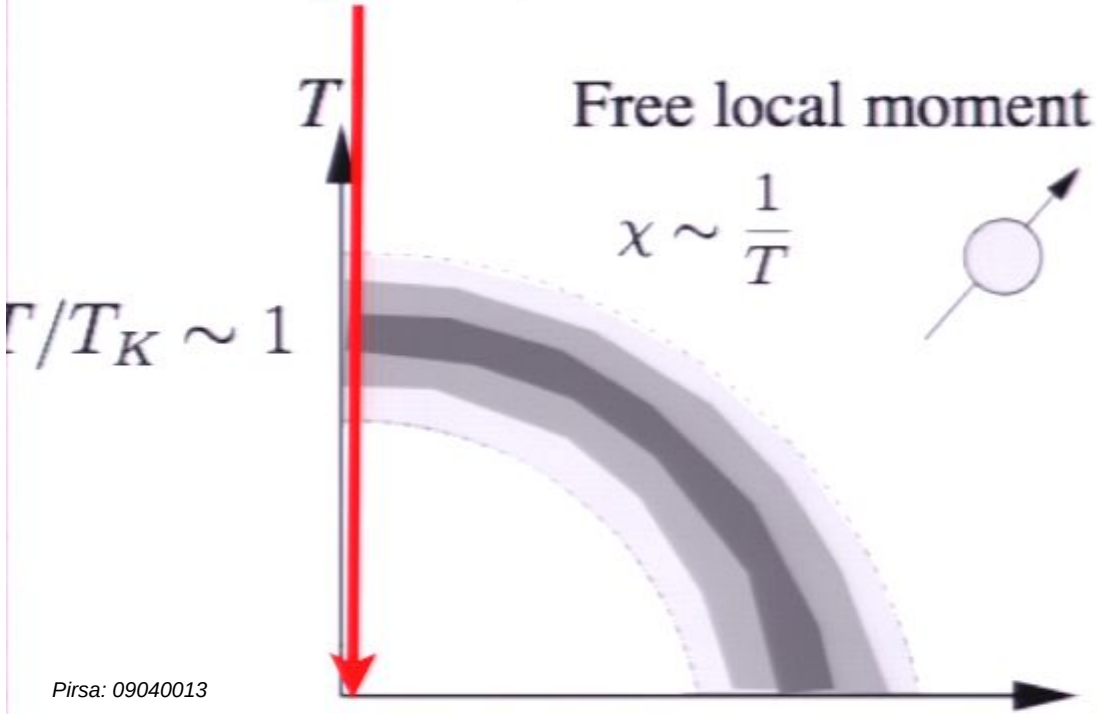

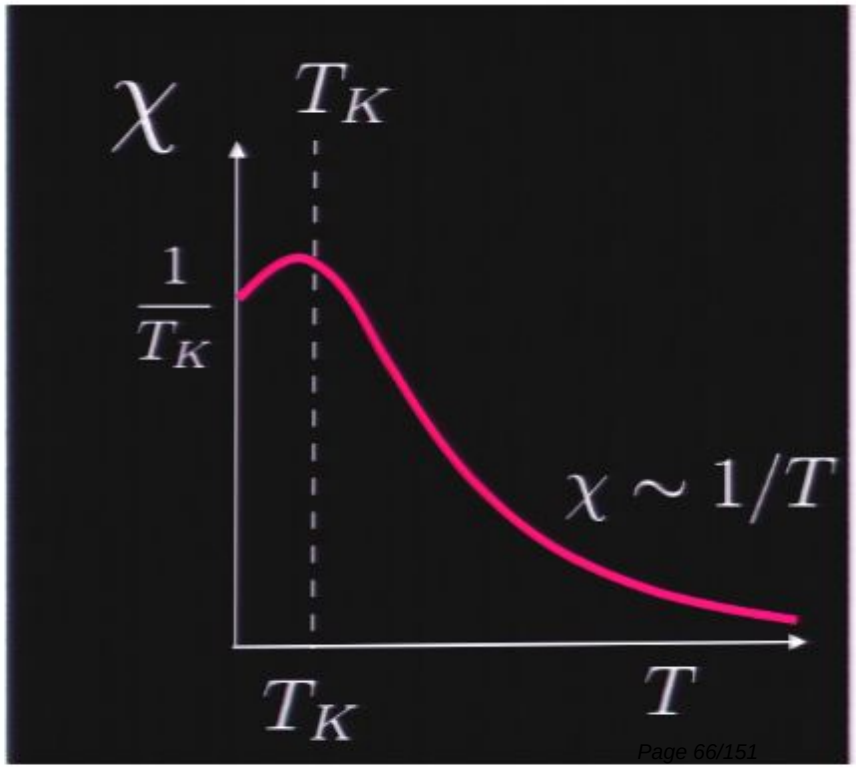

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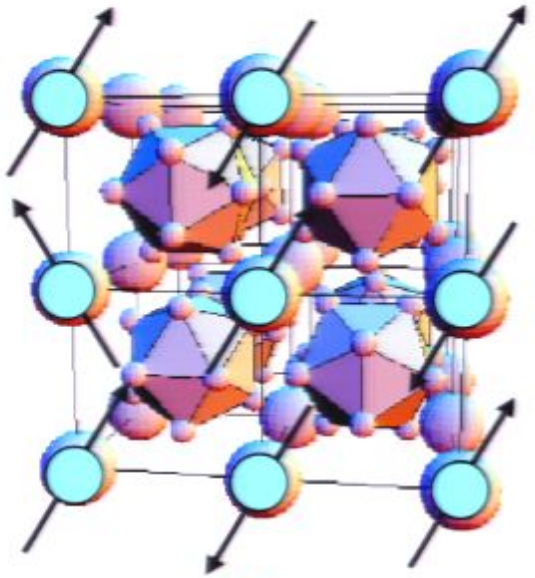

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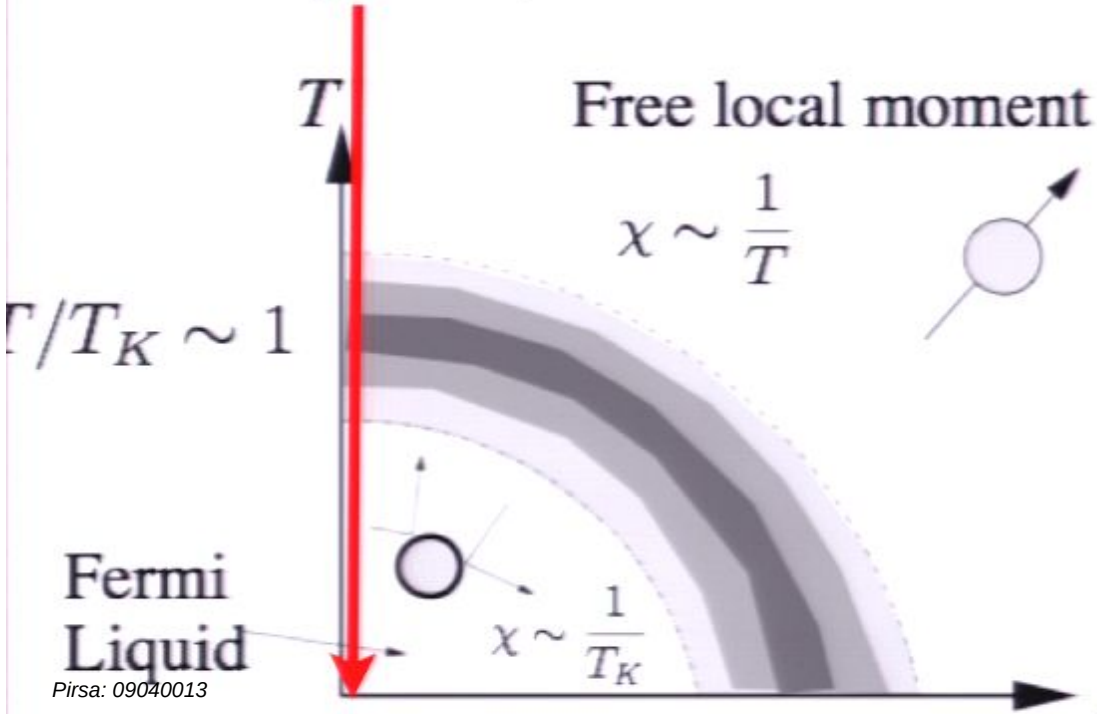

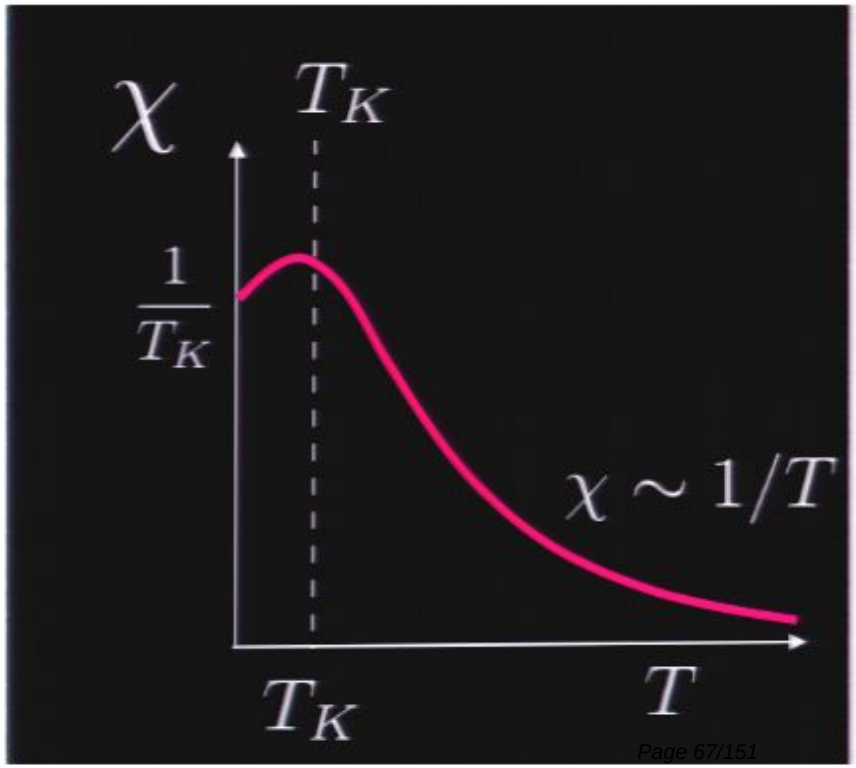

"Kondo Effect"

Nozieres '74

Heavy Fermion Metals

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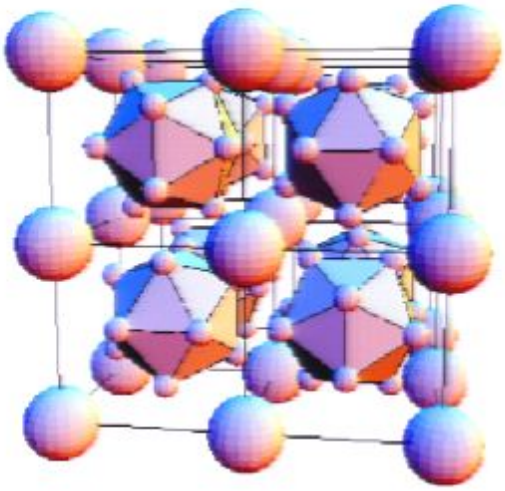

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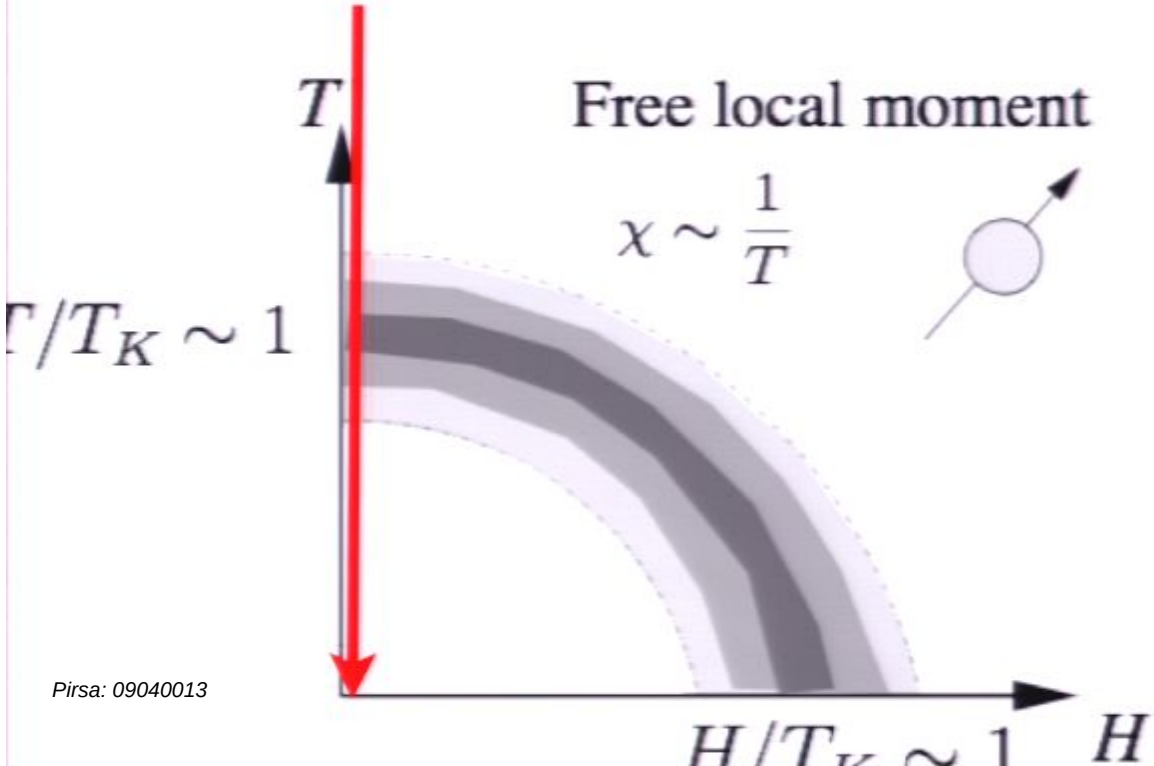
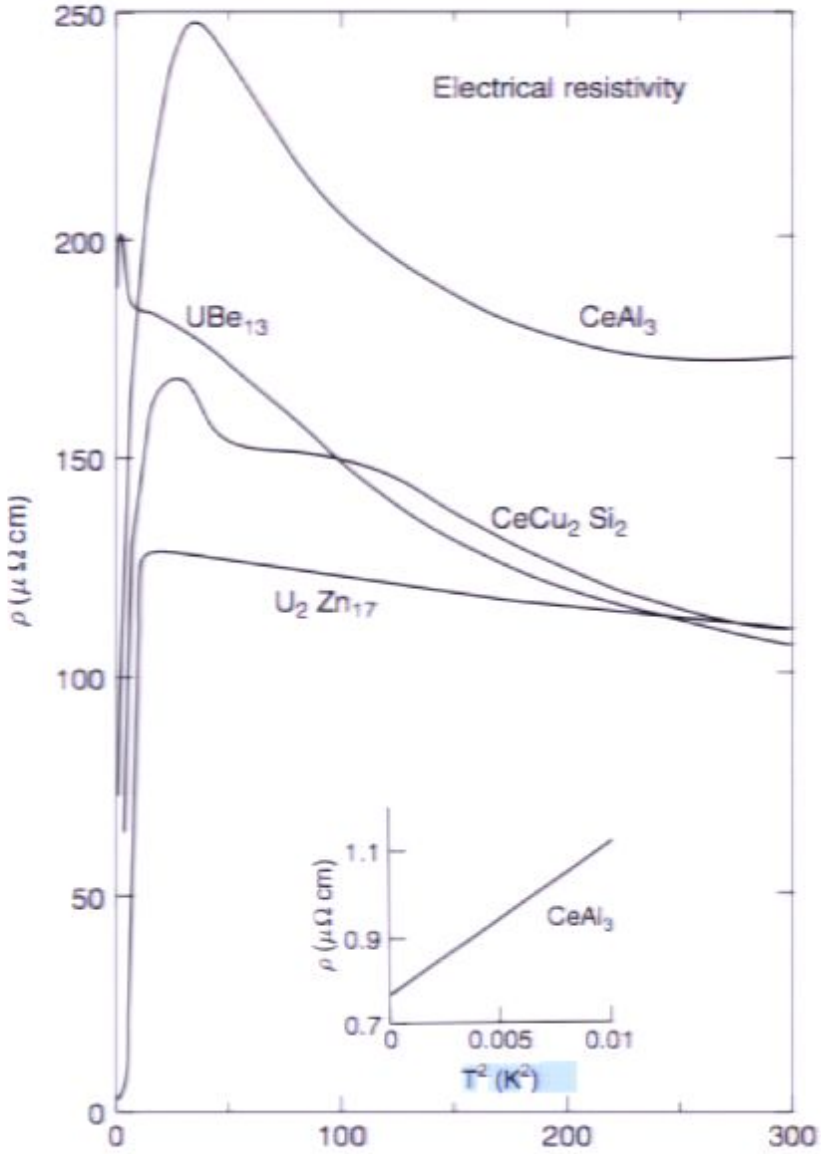
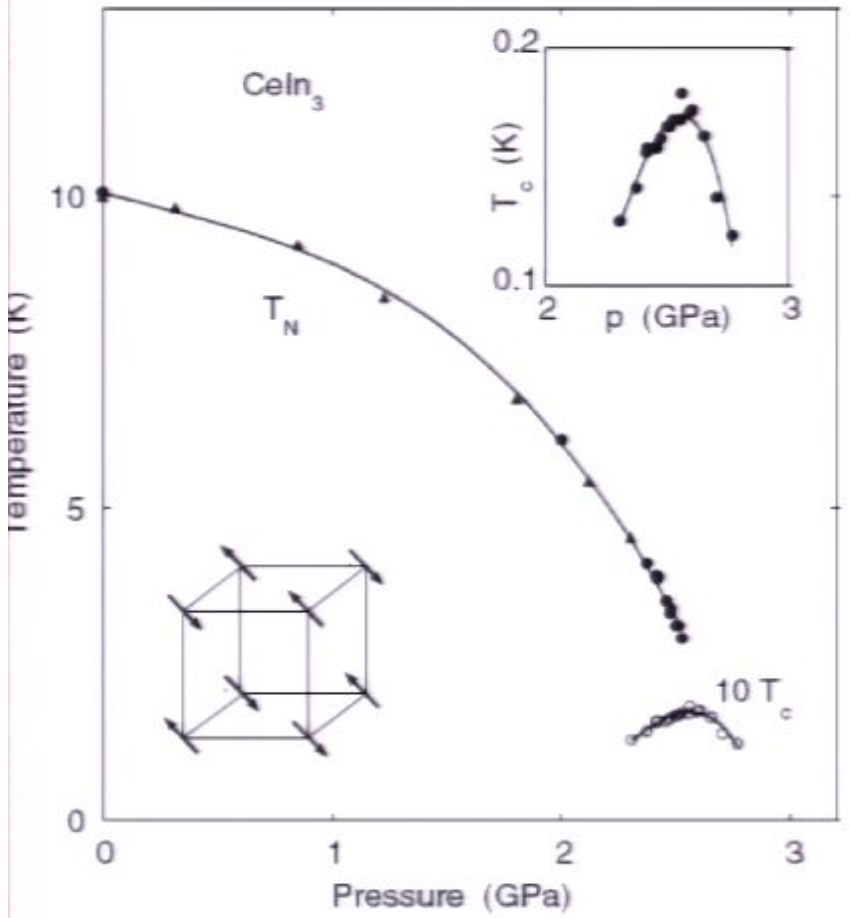




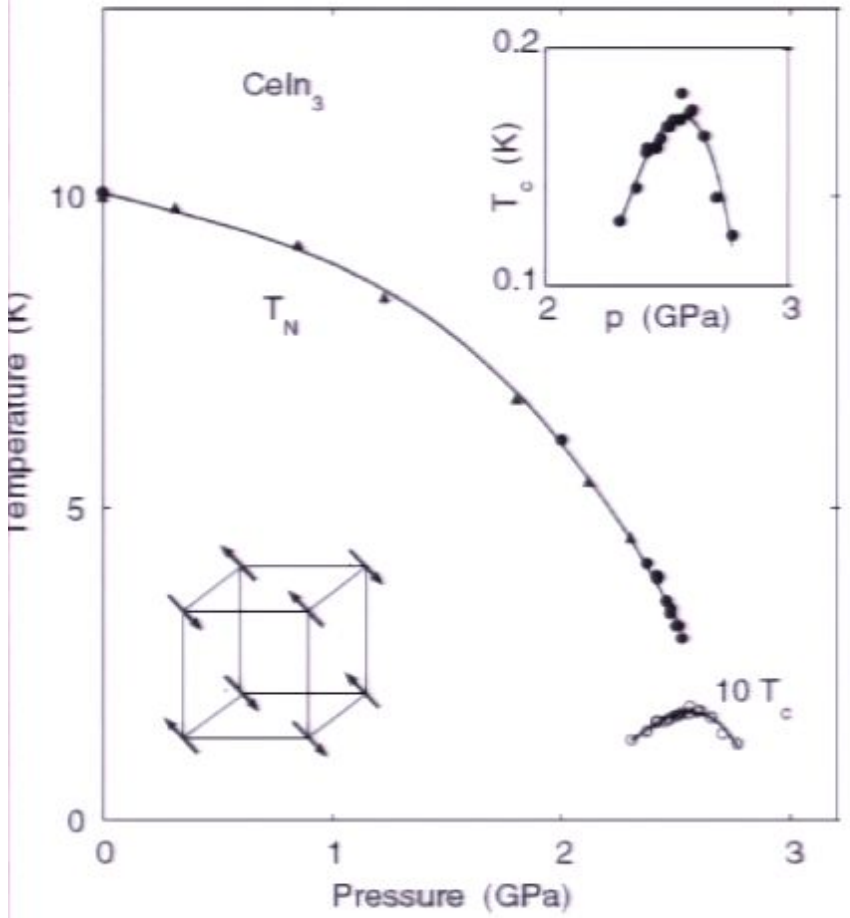
Experiments

“Avoided Criticality”



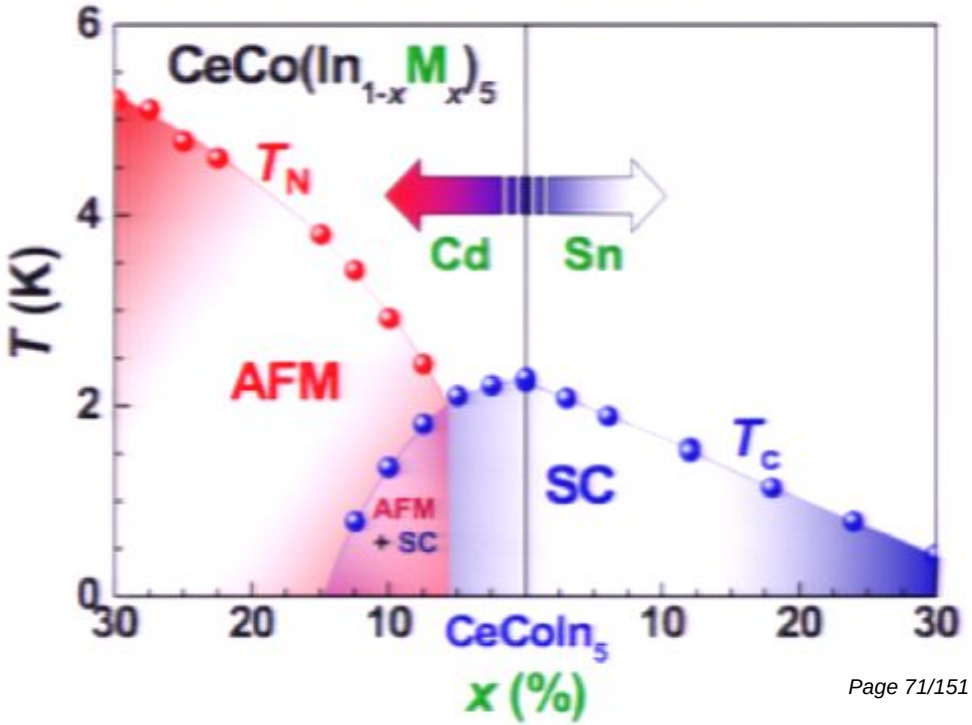
Mathur et al, Nature 394, 39 (1998)

"Avoided Criticality"



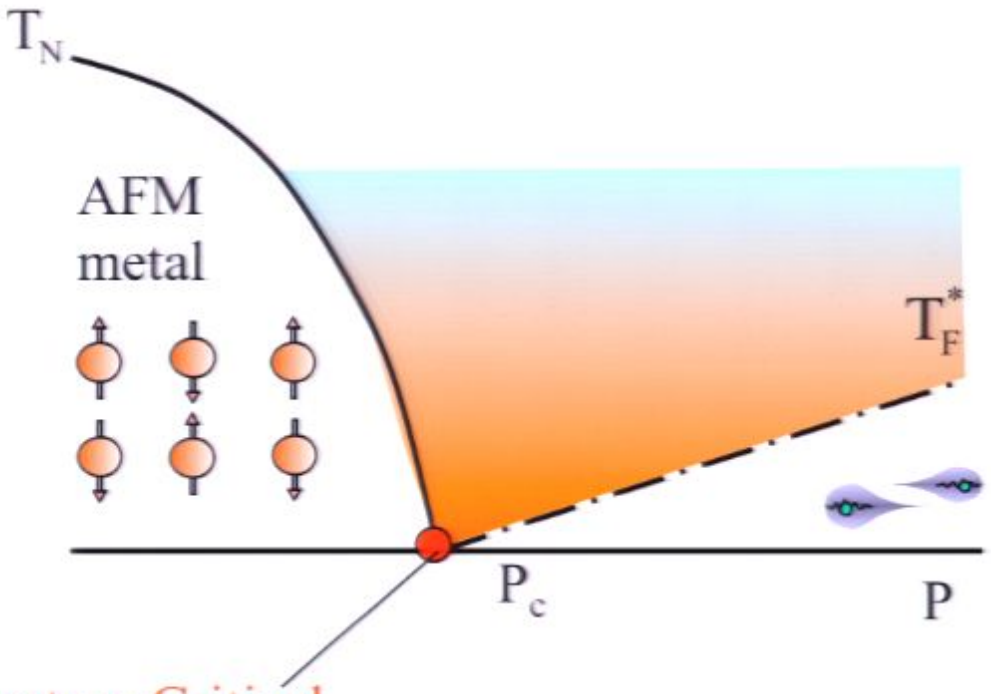
Mathur et al, Nature 394, 39 (1998)

N. Curro, PRL 99, 146402 (2007)



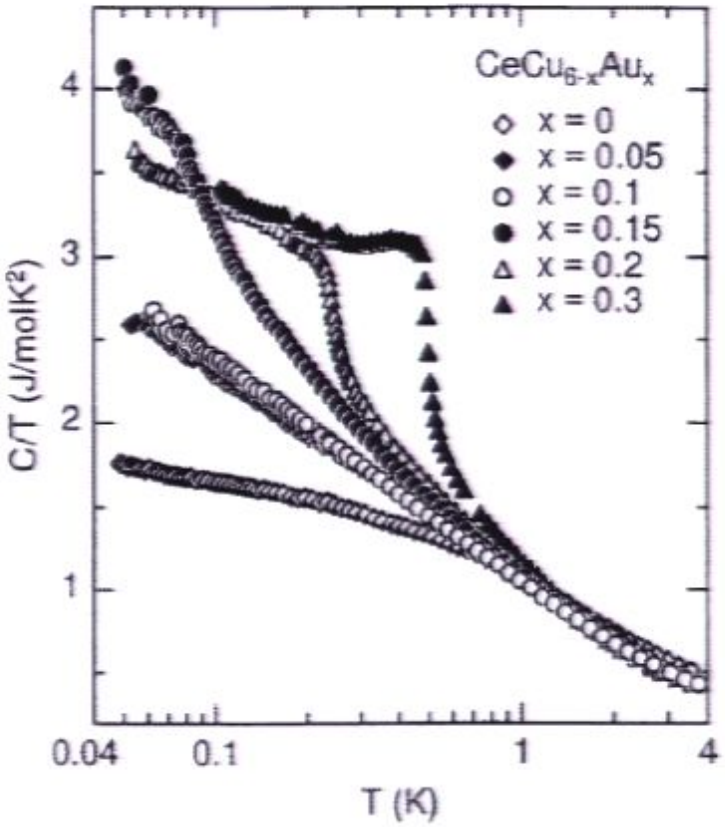
Quantum Criticality: divergent specific heat capacity

Heavy Fermion Materials



Quantum Critical Point

H. Von Lohneyson (1996)



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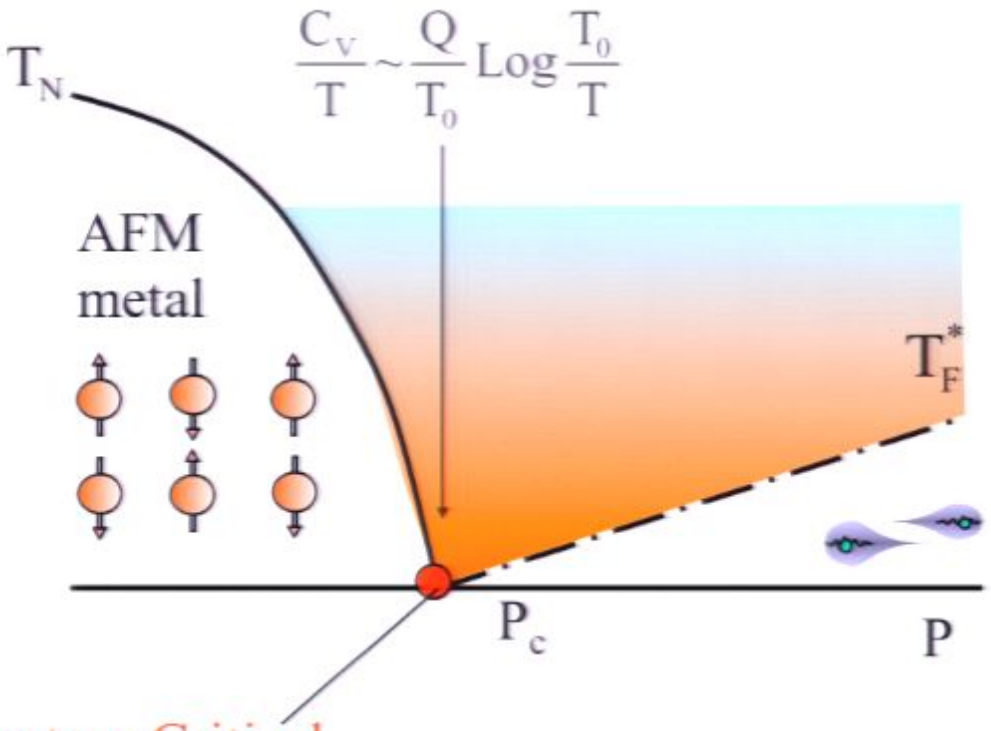

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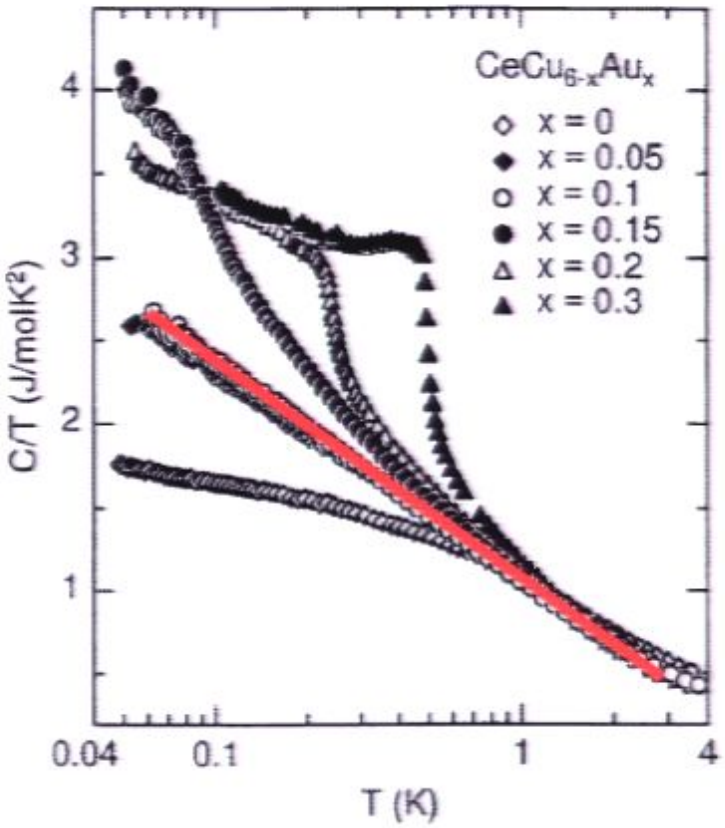

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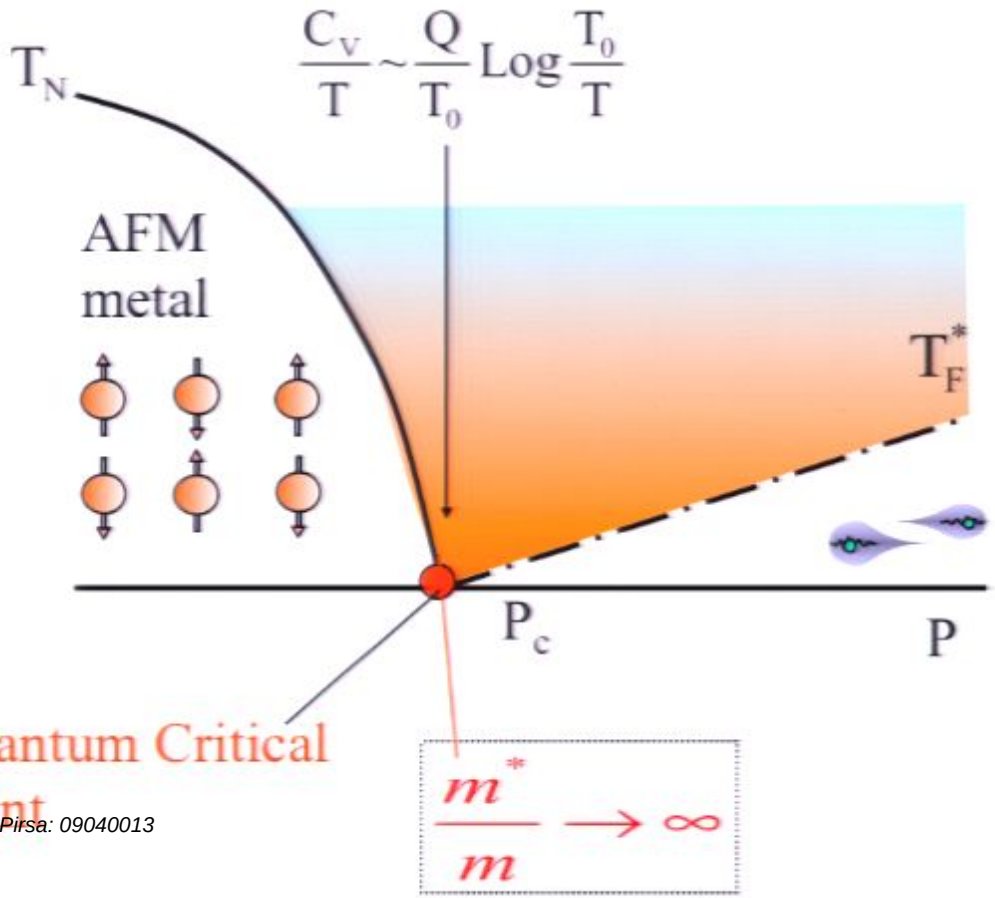

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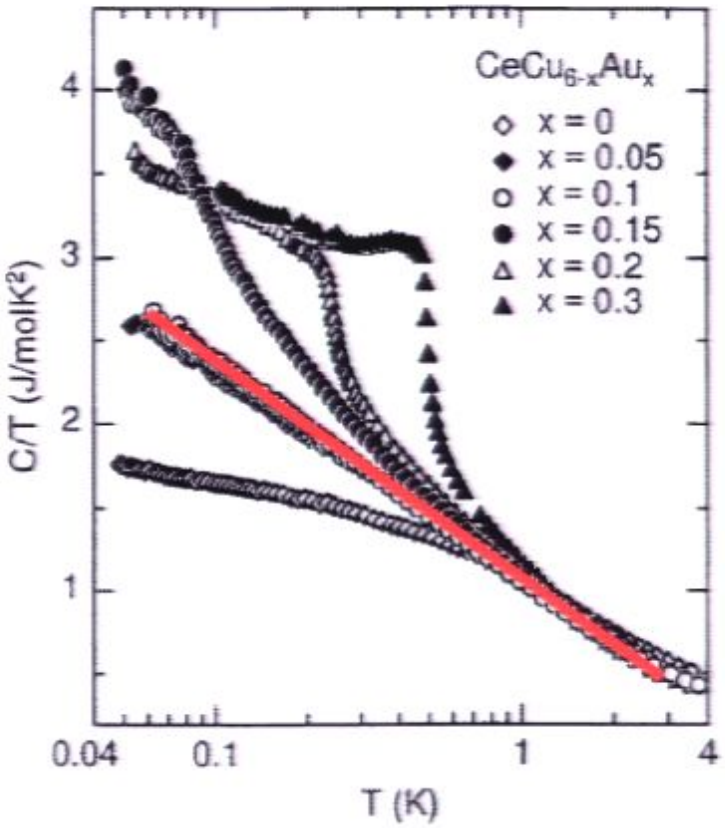
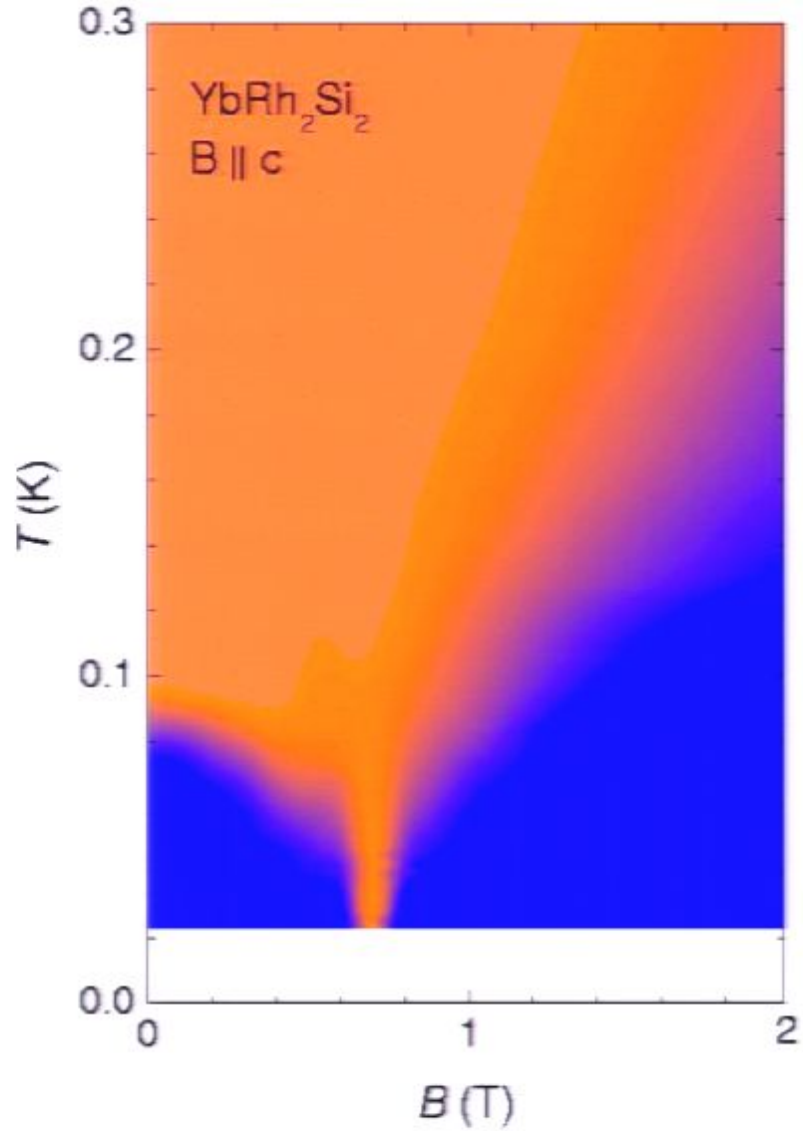


Field Tuned Criticality in YbRh2Si2.



$YbRh_2Si_2$

Trovarelli et al (2000).

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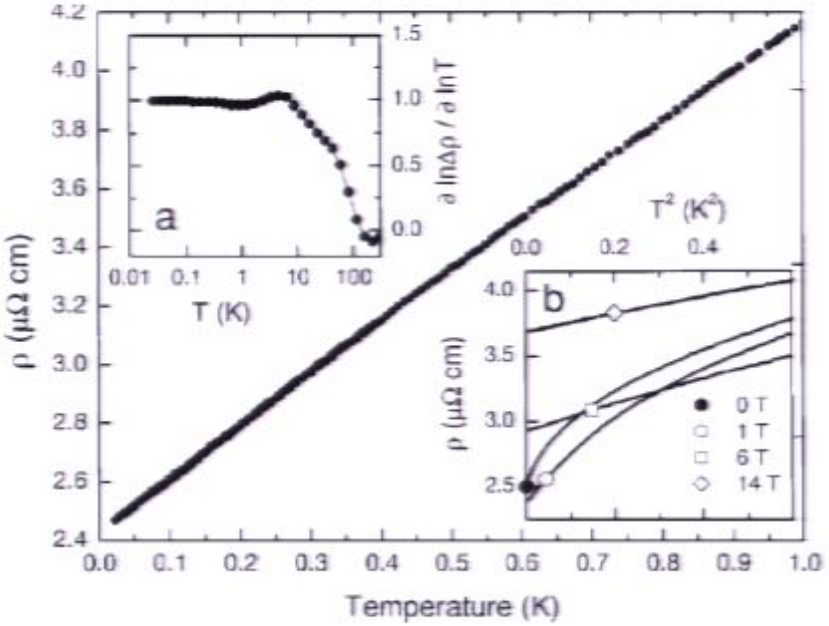

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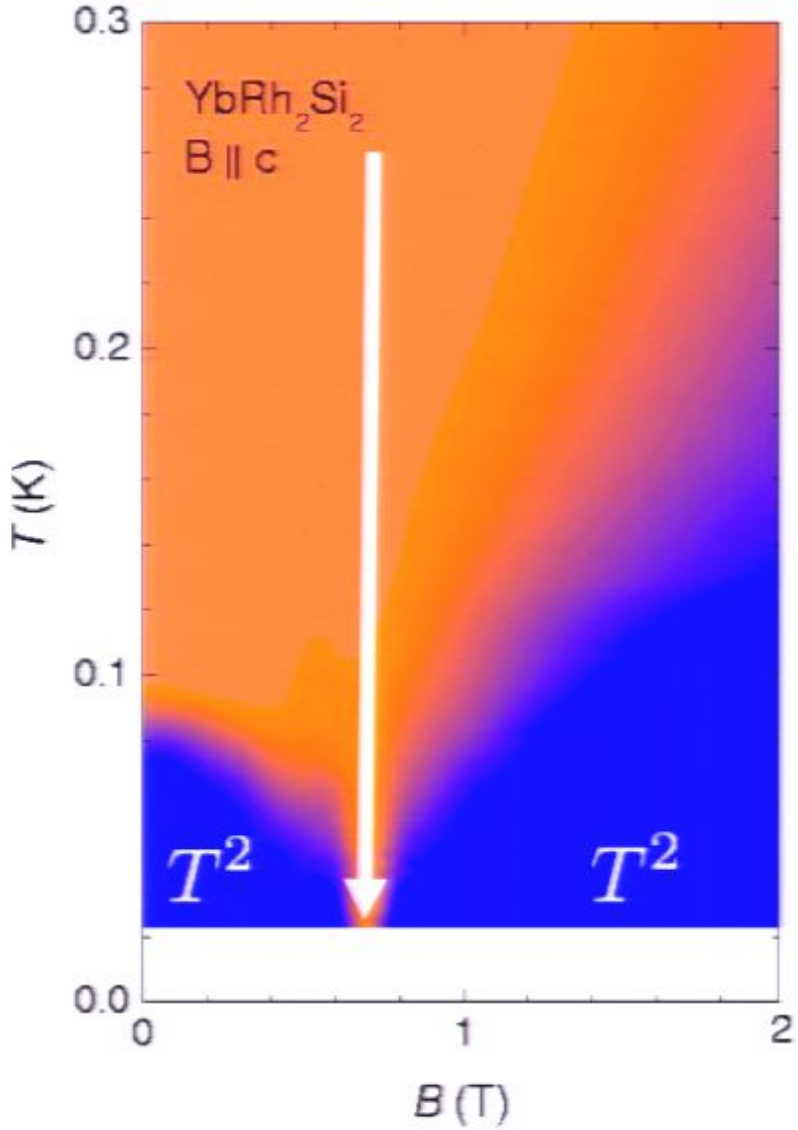
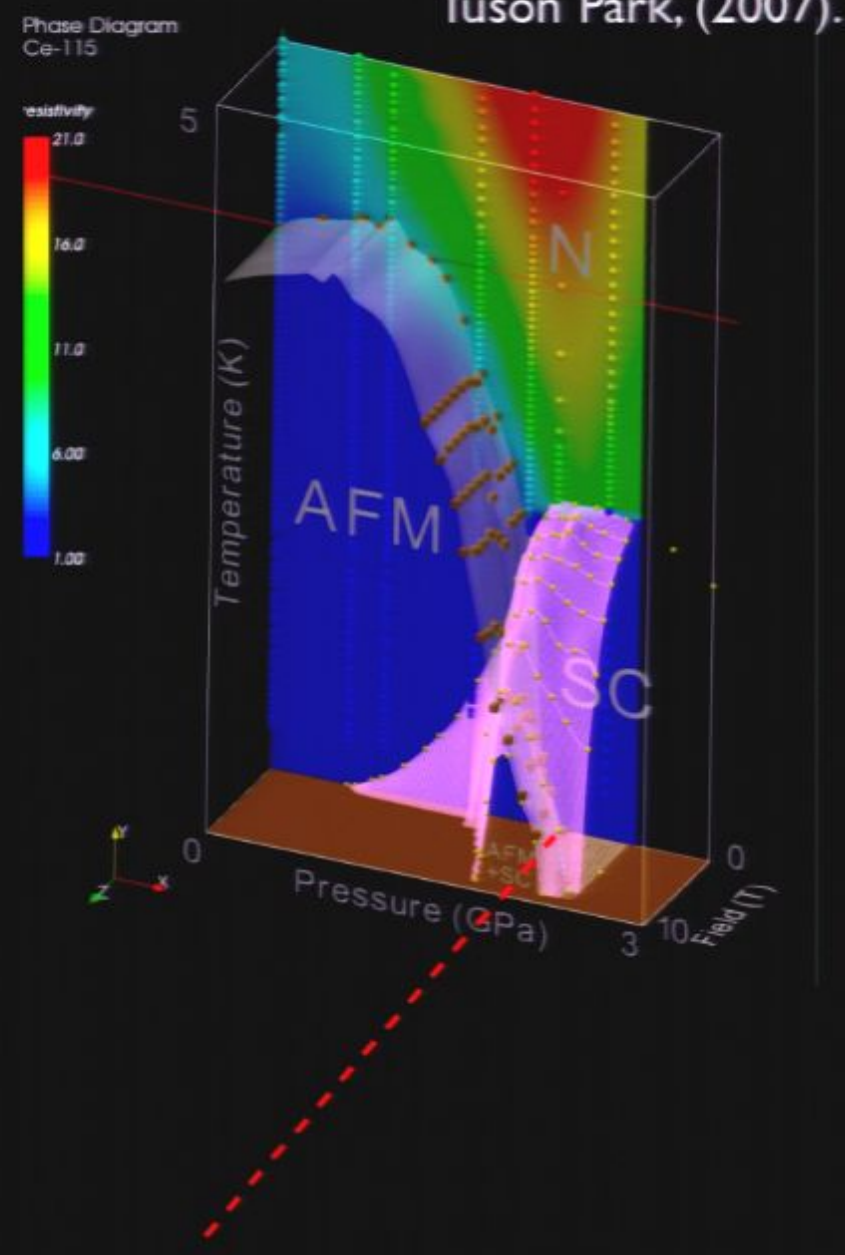


Breakdown of Landau Fermi liquid.

Reconstruction of the Fermi Surface and mass divergence

Tuson Park, (2007).



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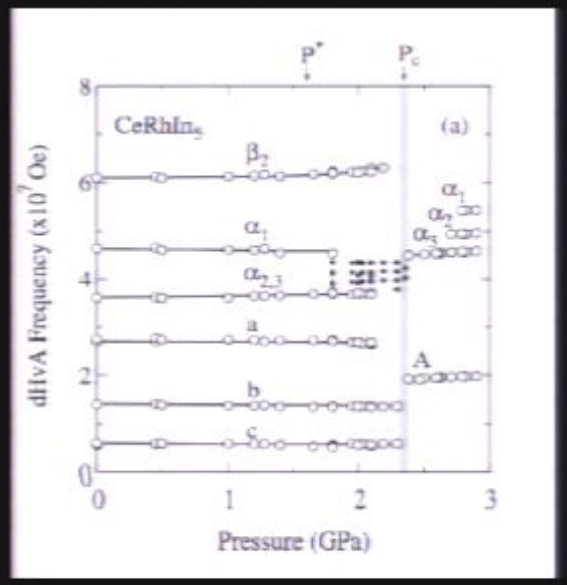
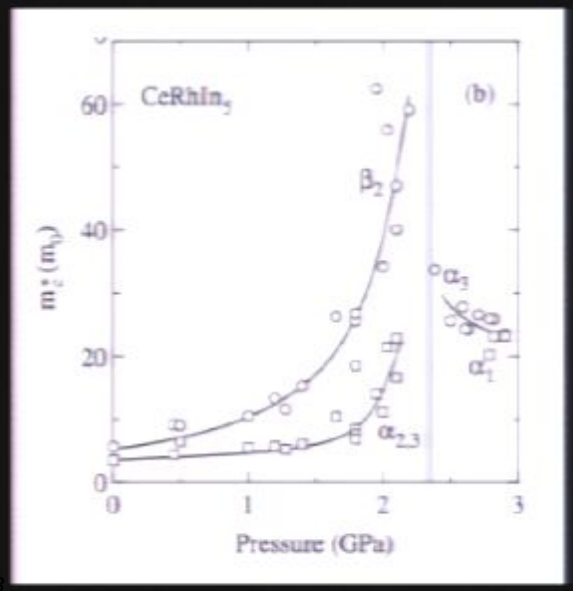
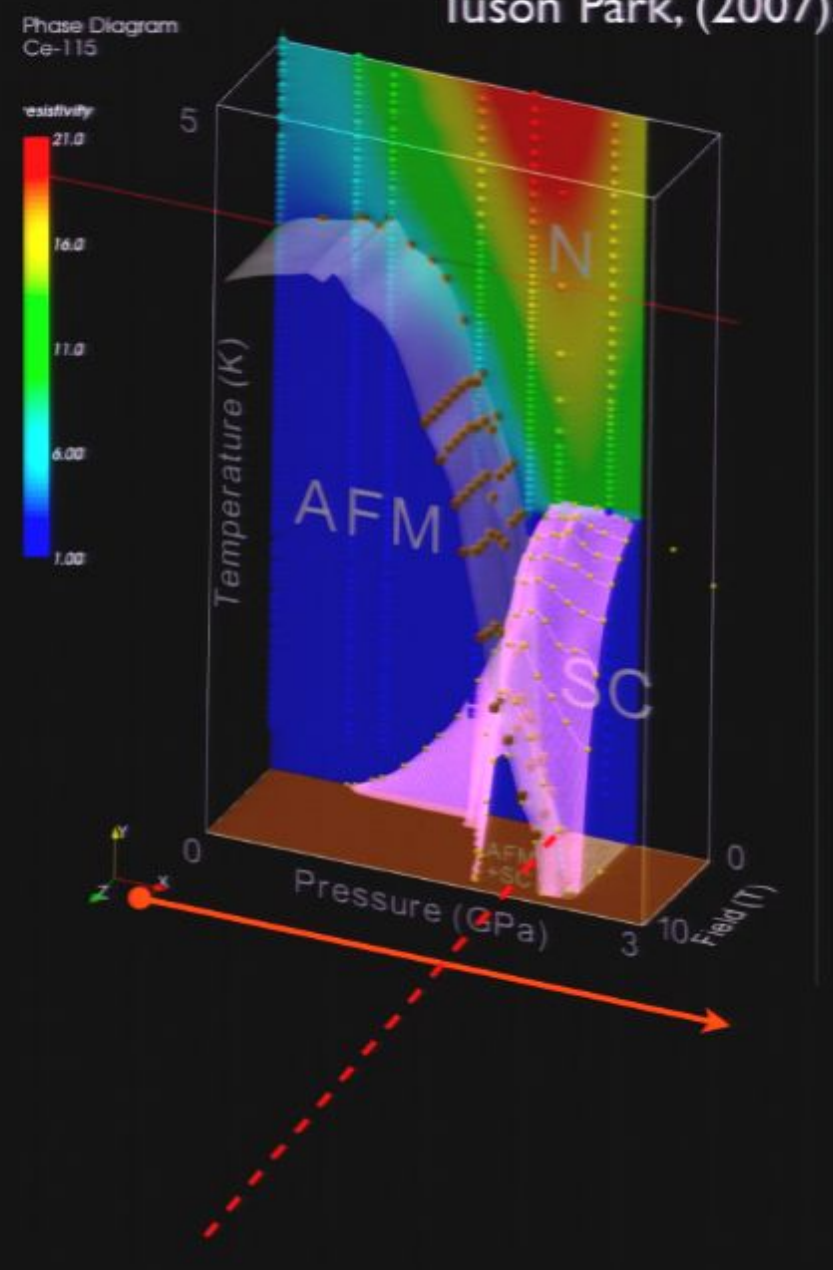


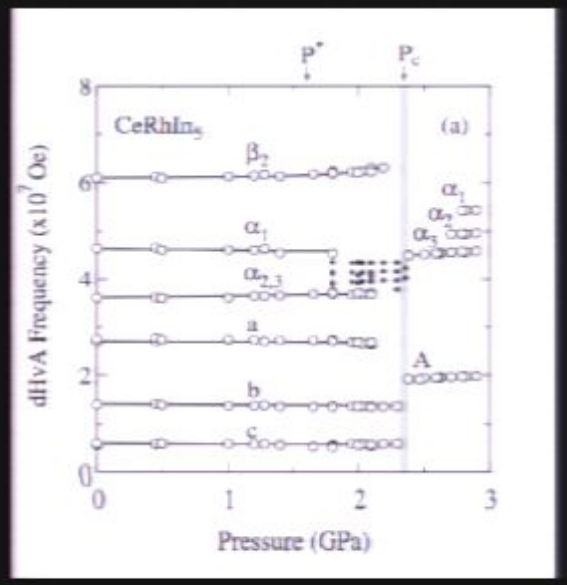


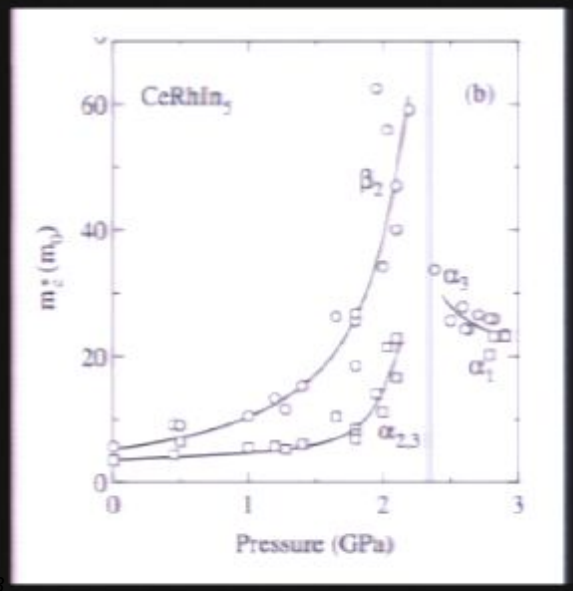
Shimuzu et al (2006)

Tuson Park, (2007).



Reconstruction of the Fermi Surface and mass divergence





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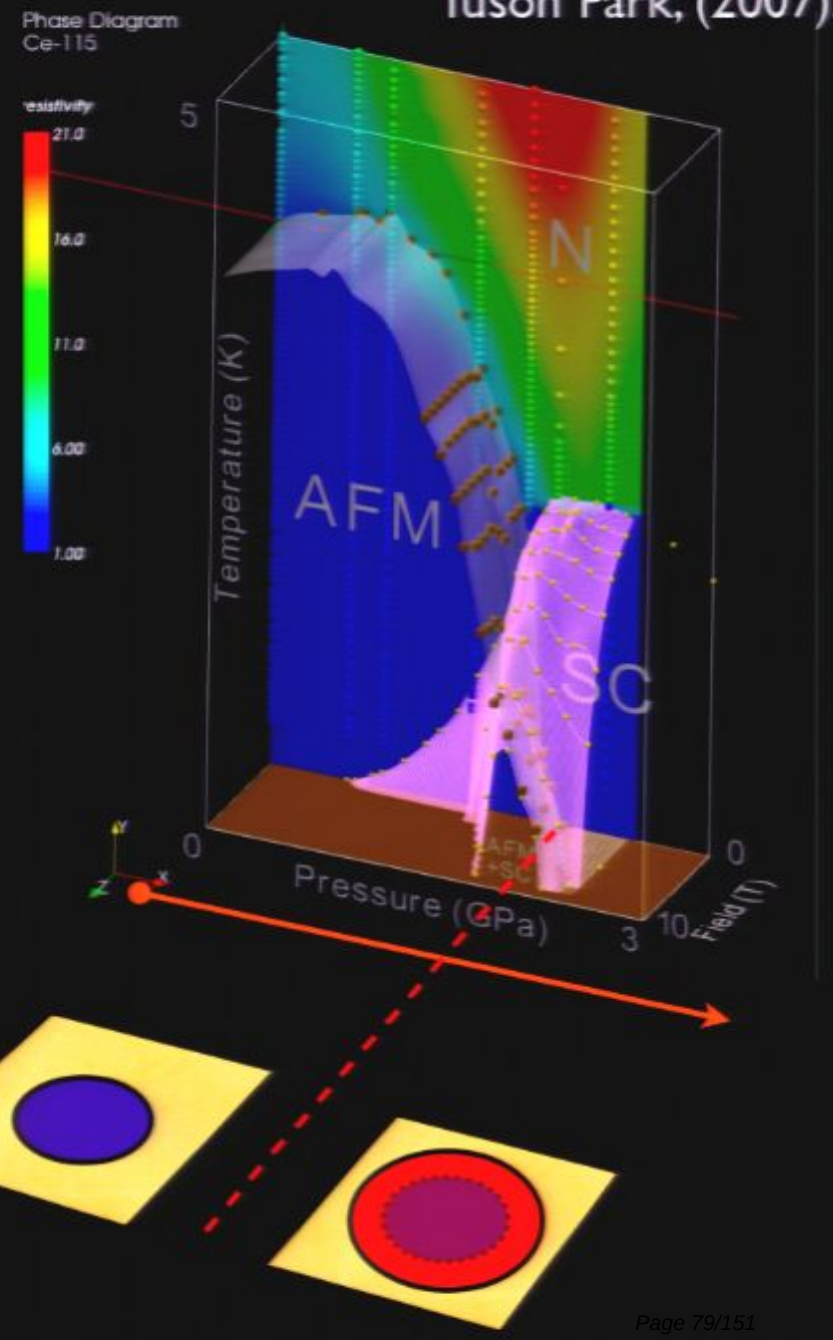
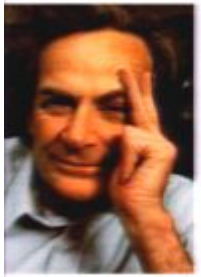


Black Hole in the Phase Diagram.



Feynman Hertz

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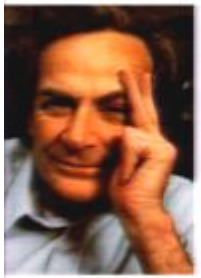

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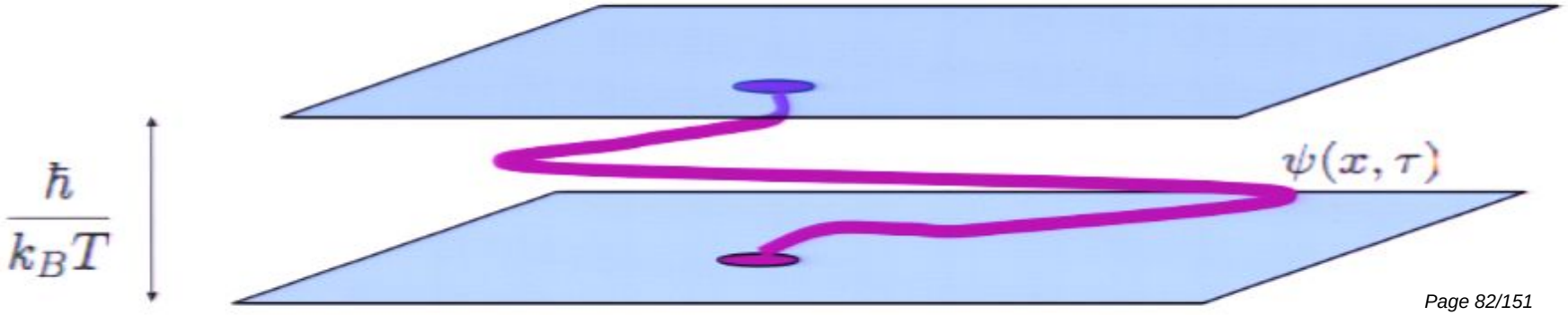

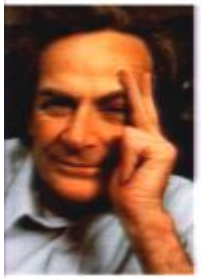

Feynman

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Temperature: "Casimir effect" in time.

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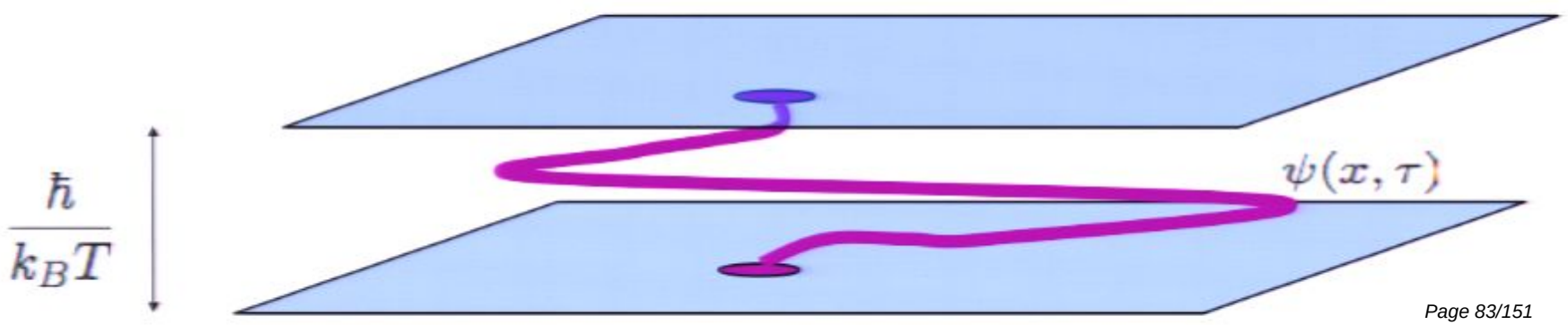

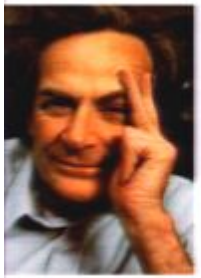

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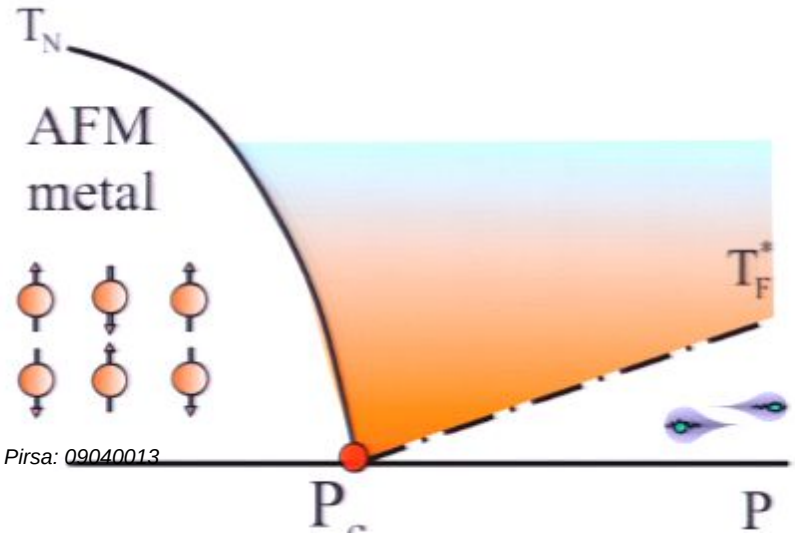

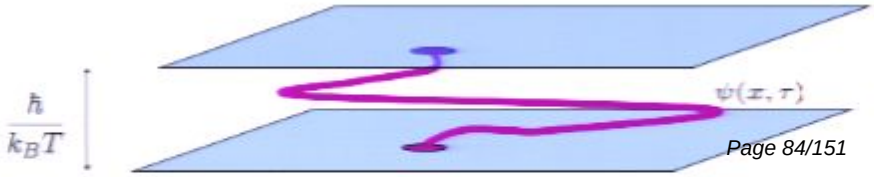

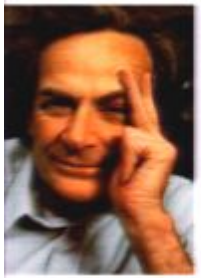

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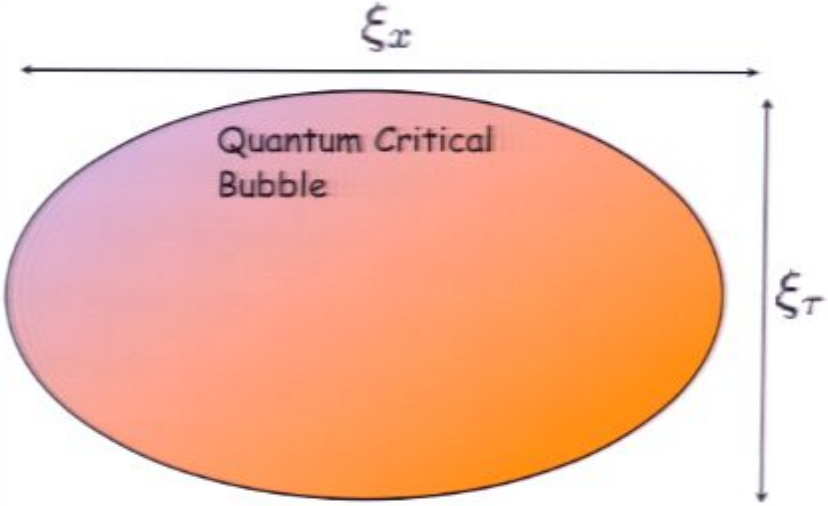

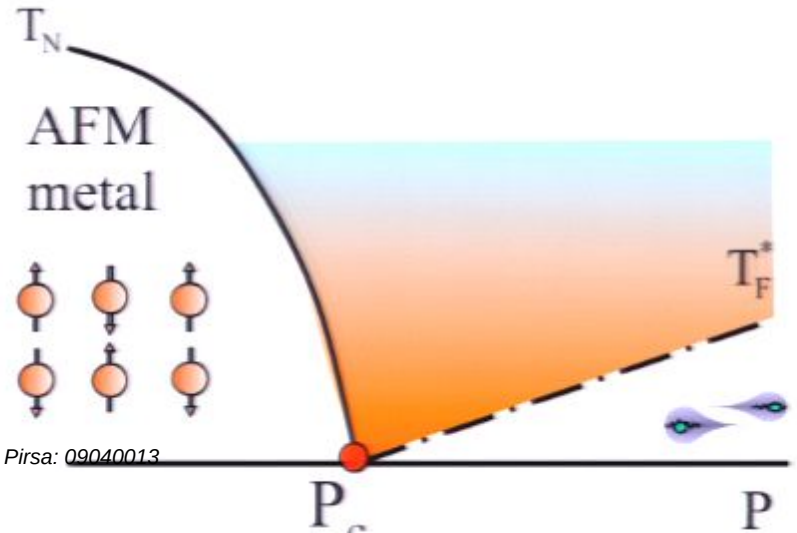

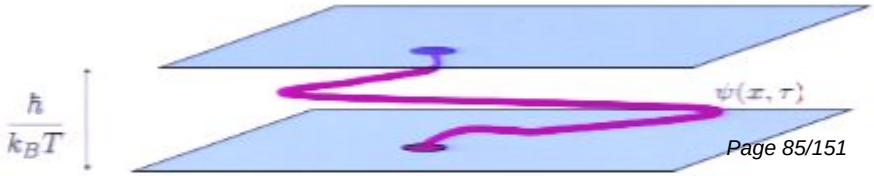

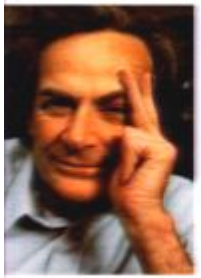

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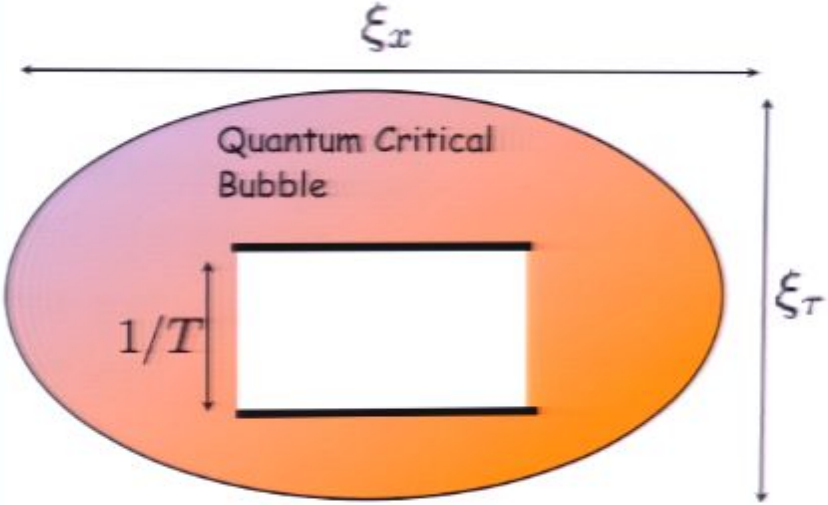

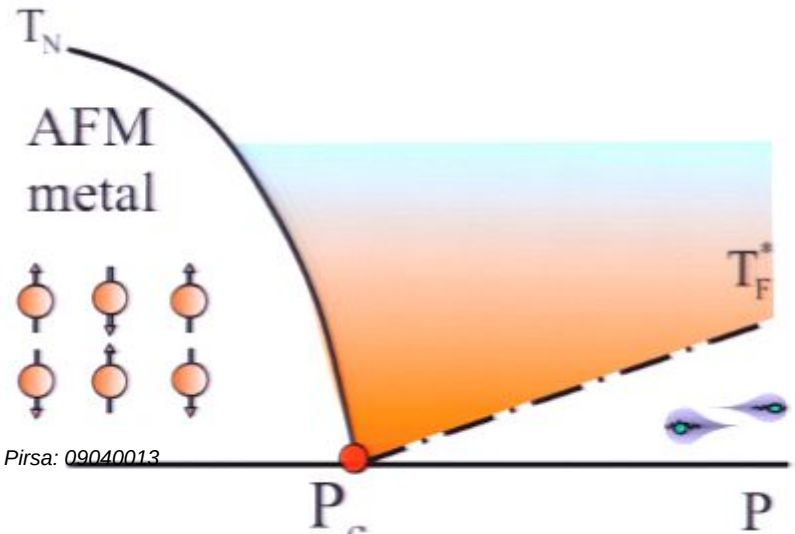

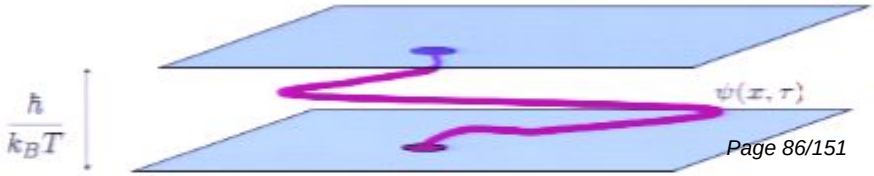

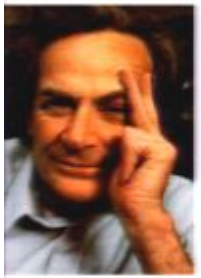

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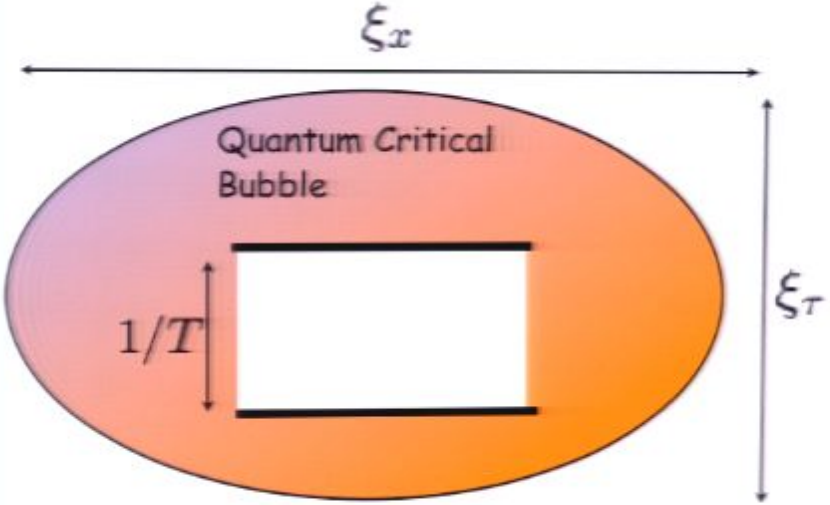
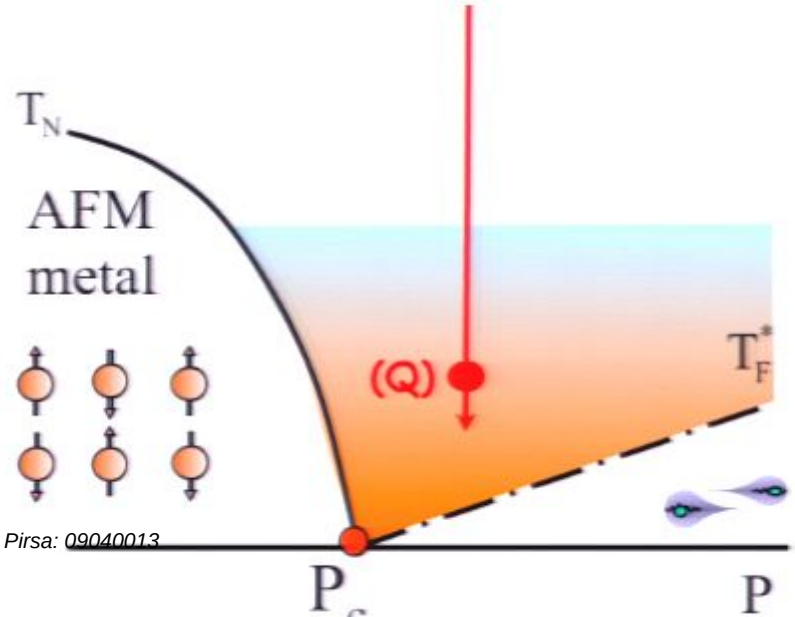
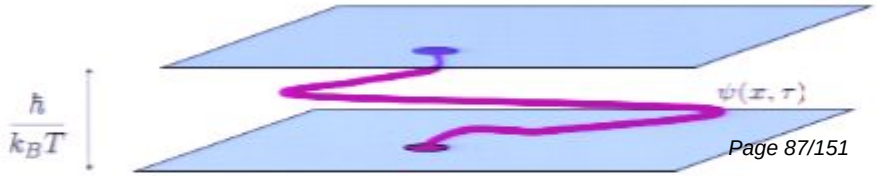
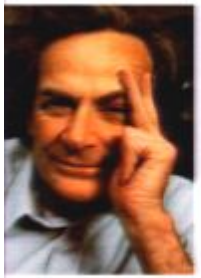


(Q) Quantum critical region: interior of correlation bubble.







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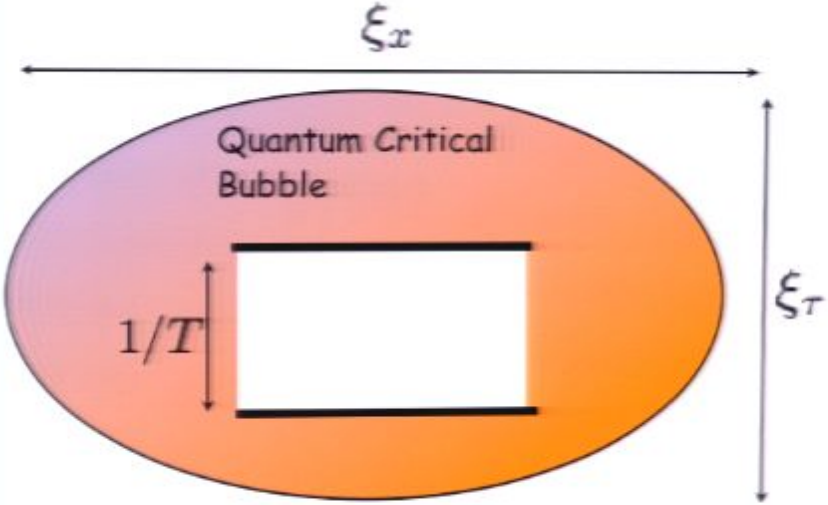

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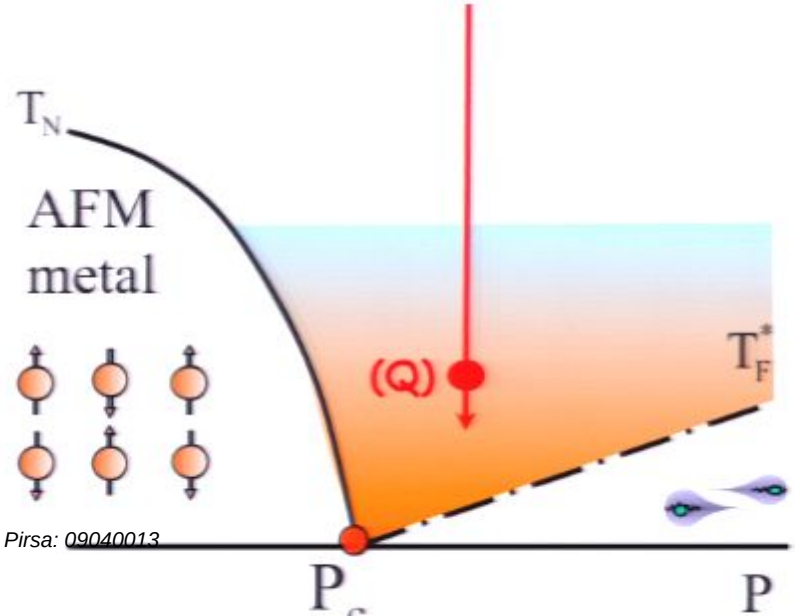

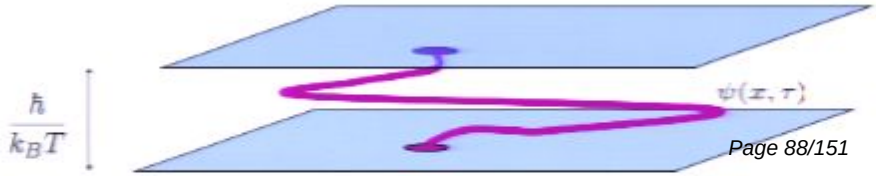

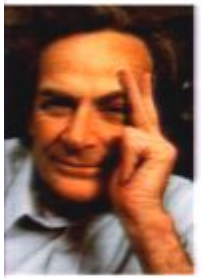
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Hertz

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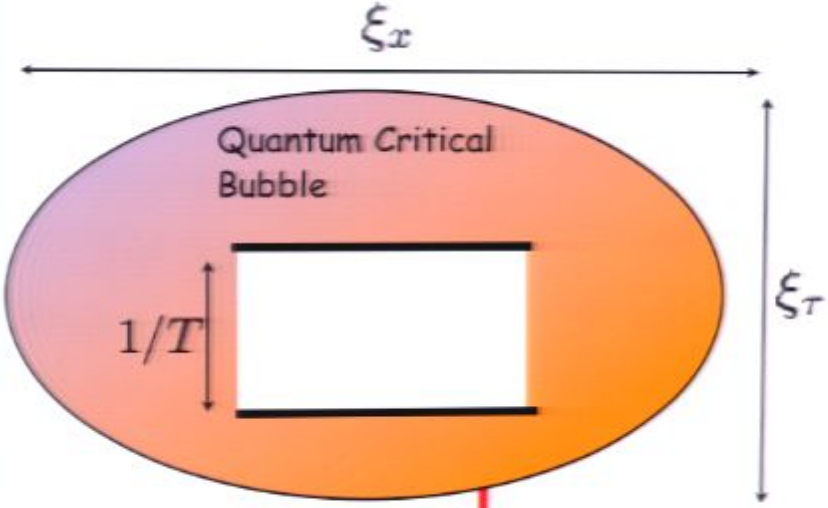
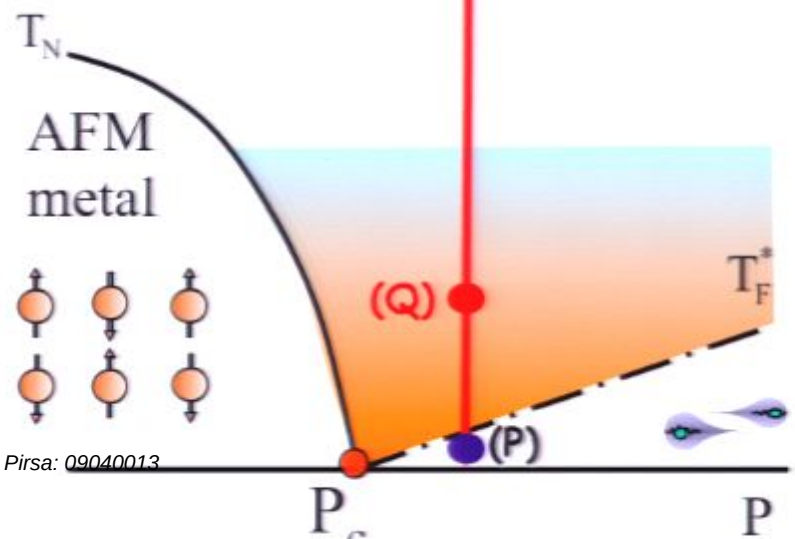
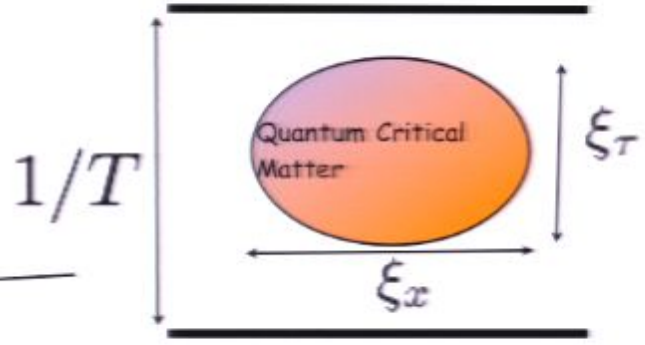


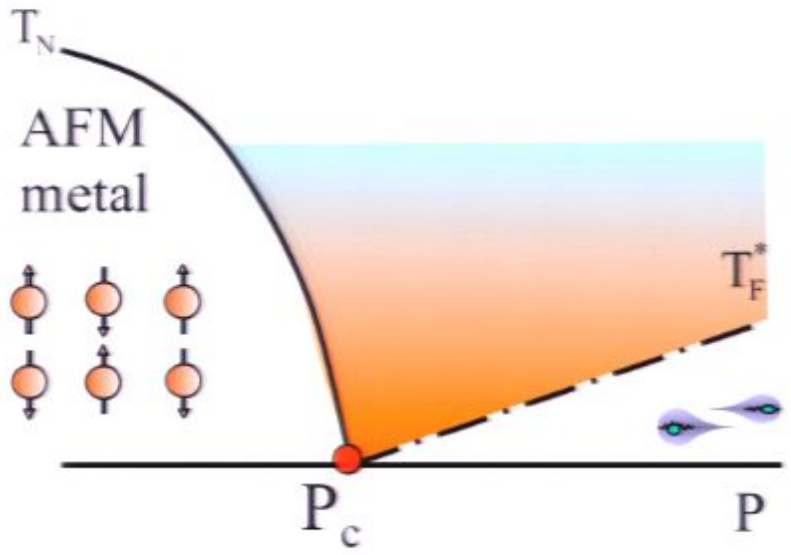
(Q) Quantum critical region: interior of correlation bubble.

(P) Paramagnet: probes exterior of correlation bubble





"Black Hole in the Phase Diagram".



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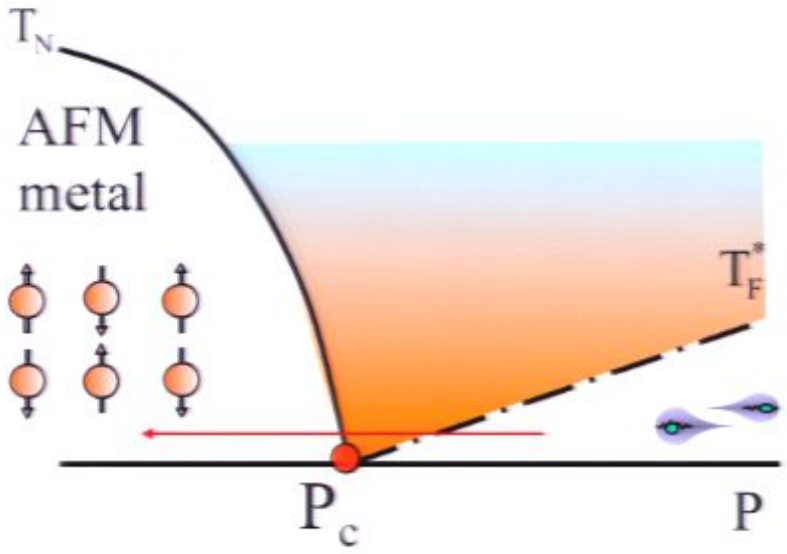

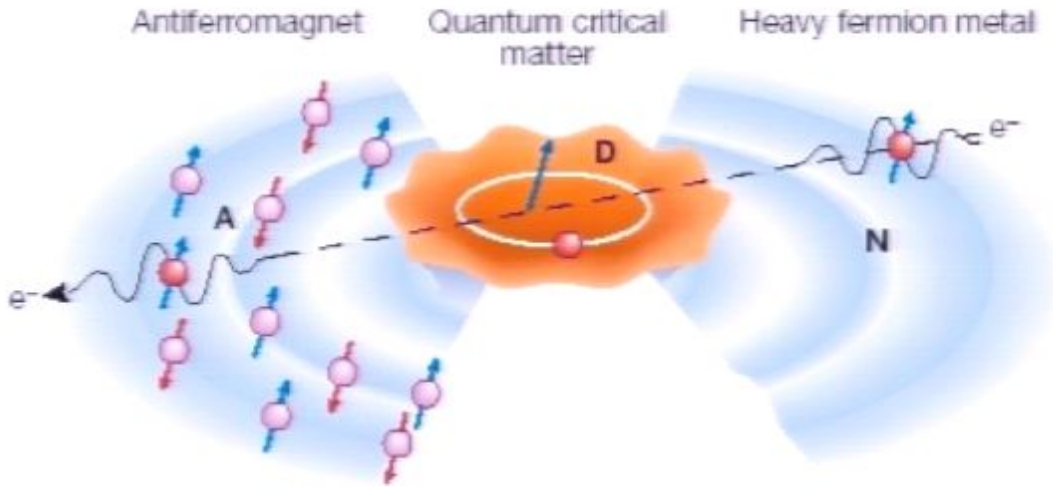

P.C and A. Schofield, Nature (2005)

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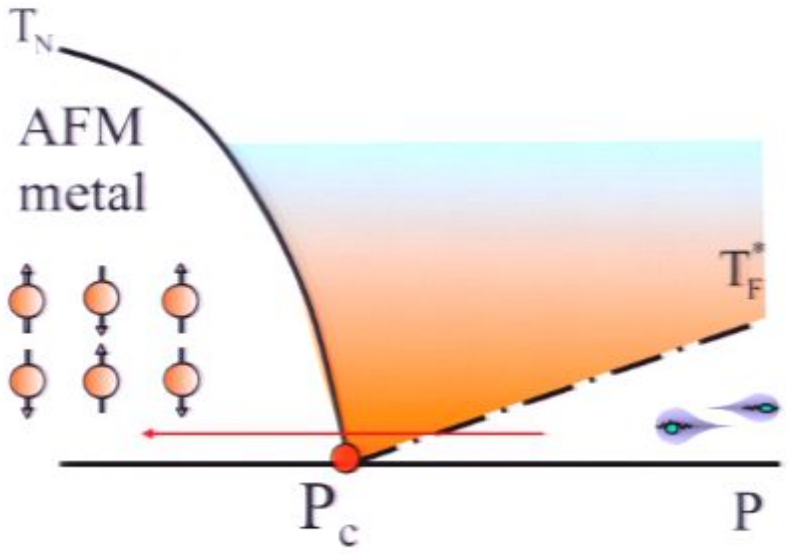

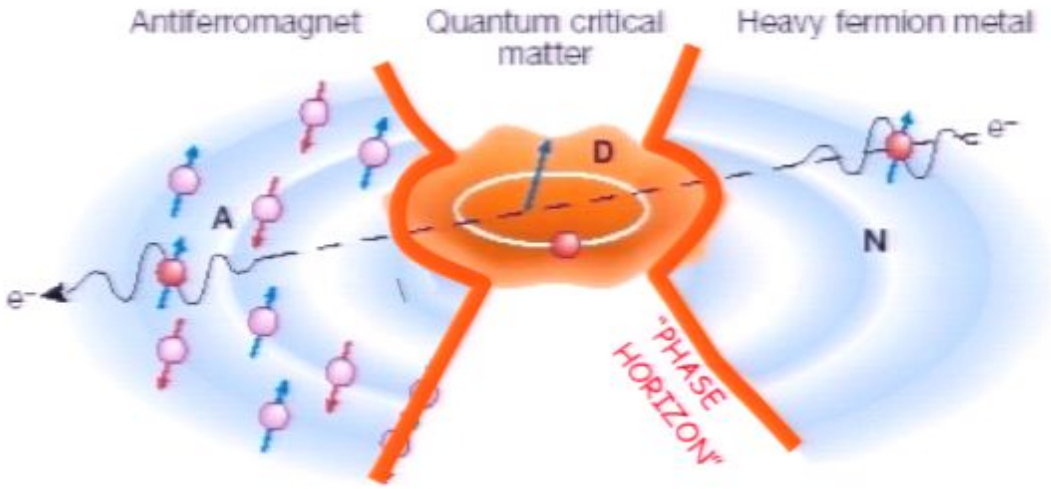

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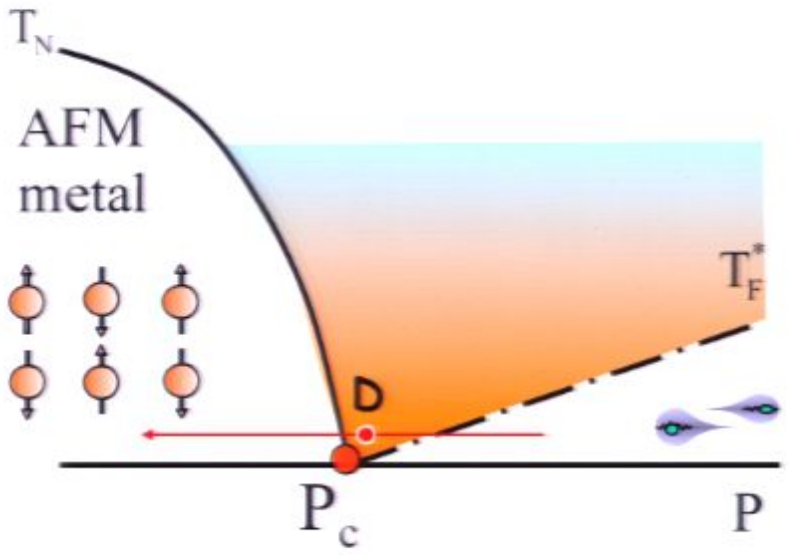

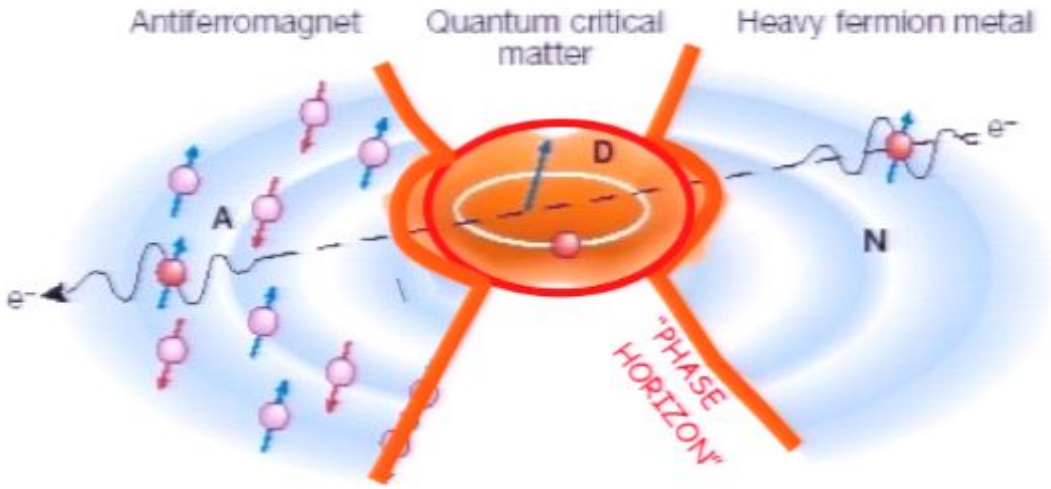

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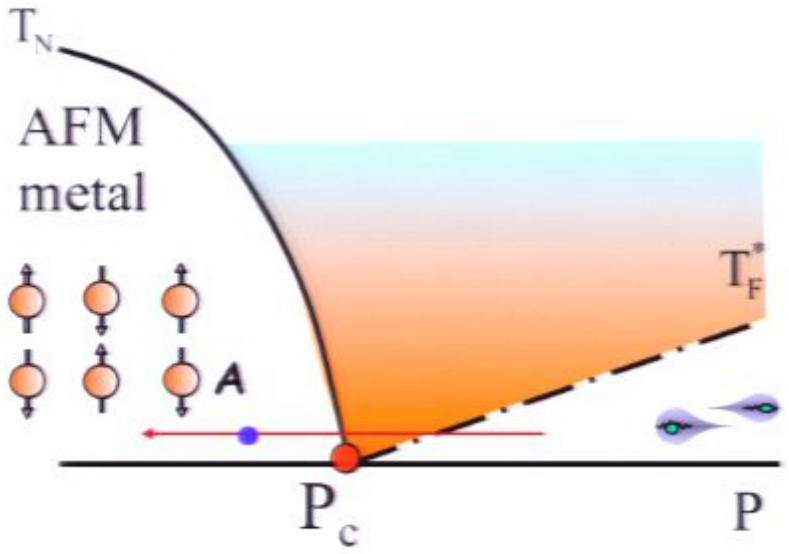

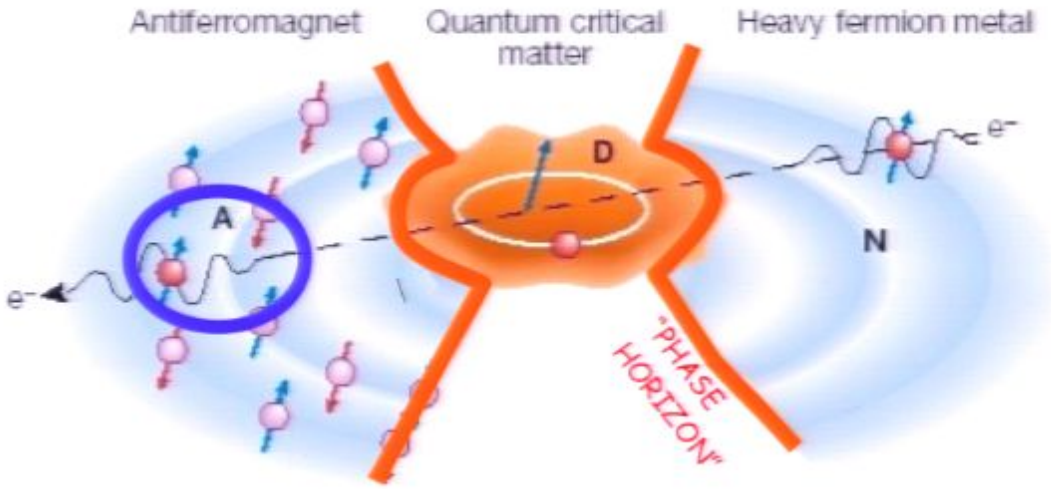

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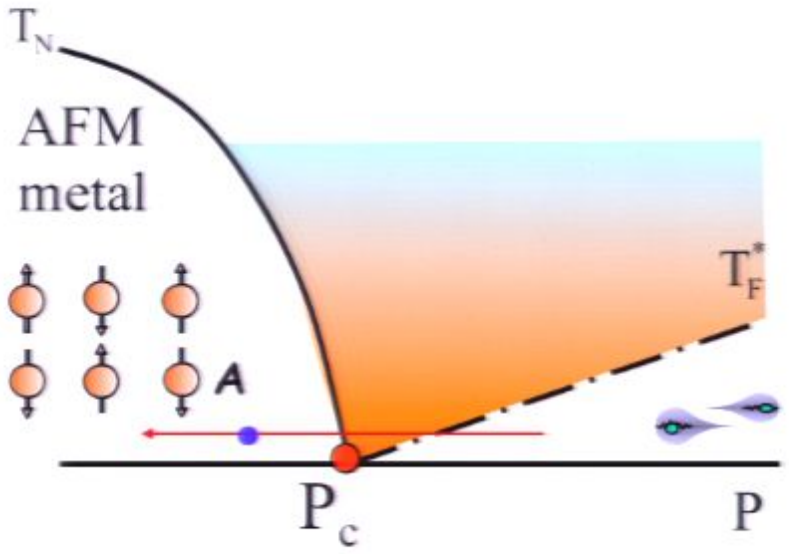
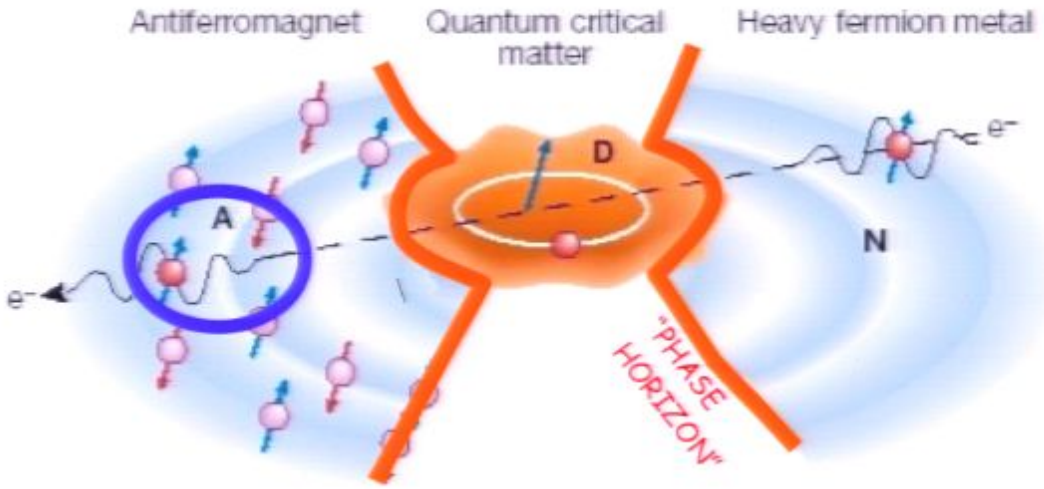




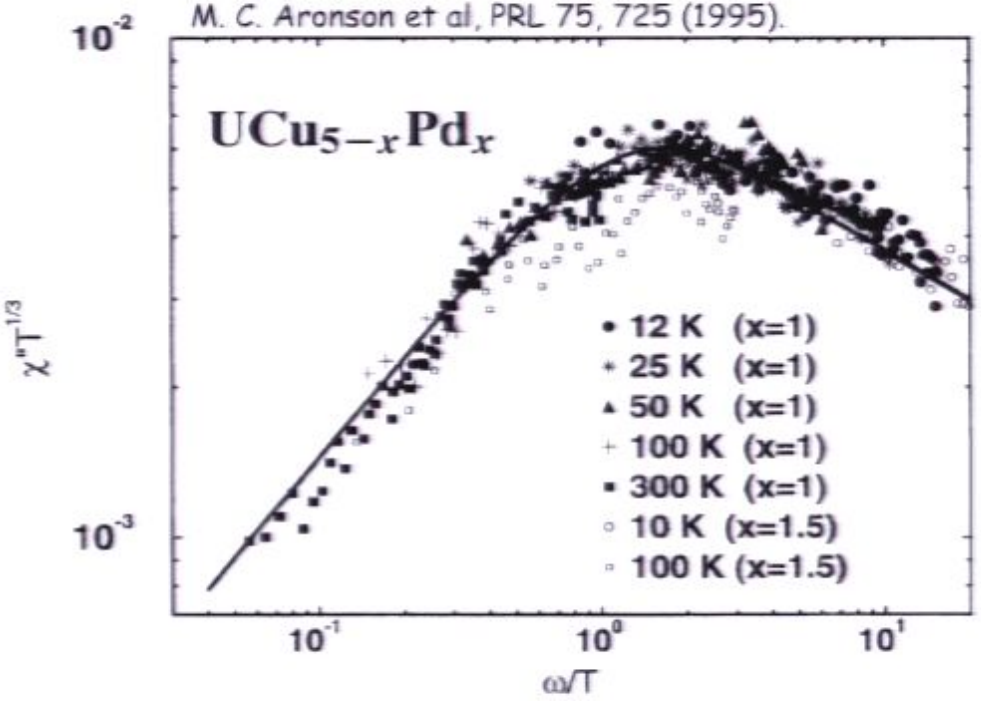
P.C and A. Schofield, Nature (2005)

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

E/T Scaling:

Meigan Aronson

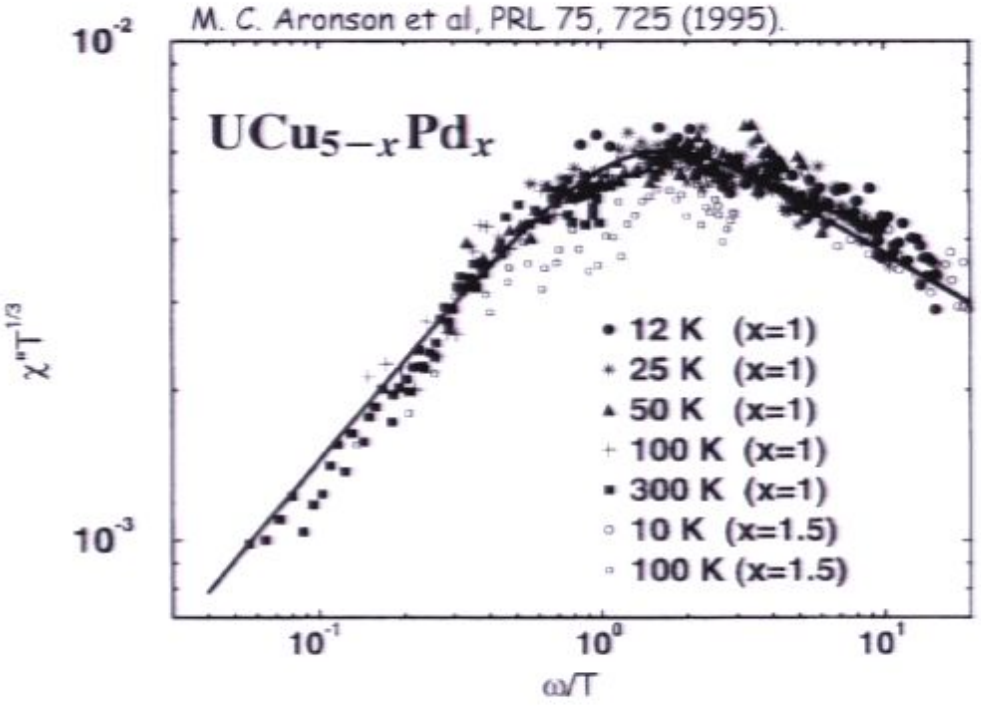
M. C. Aronson et al, PRL 75, 725 (1995).



E/T Scaling:

Meigan Aronson

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



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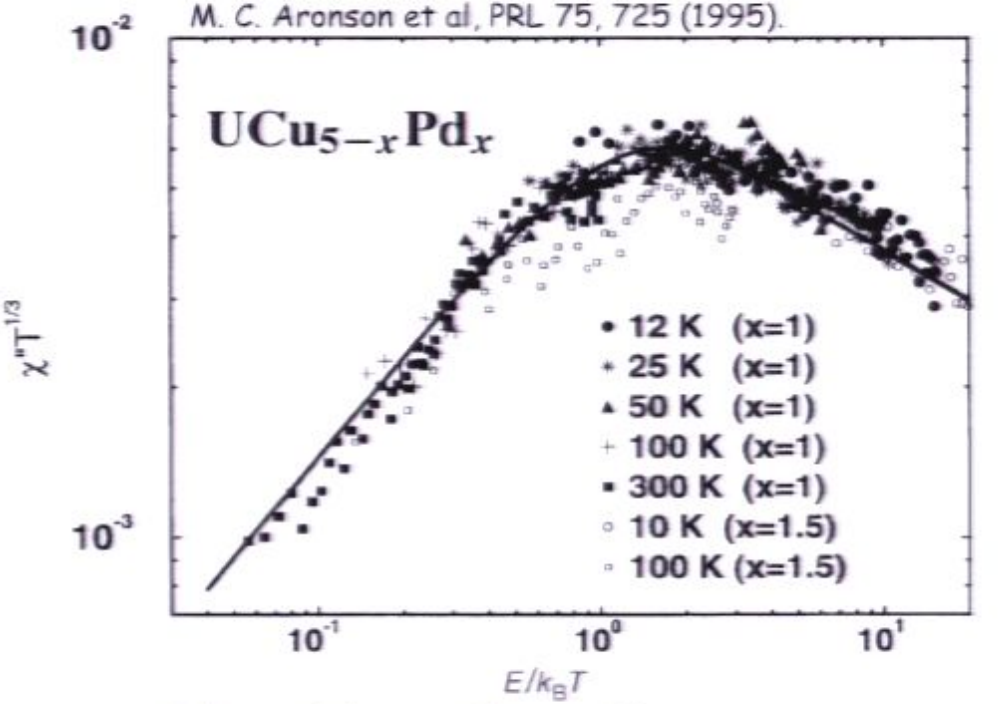

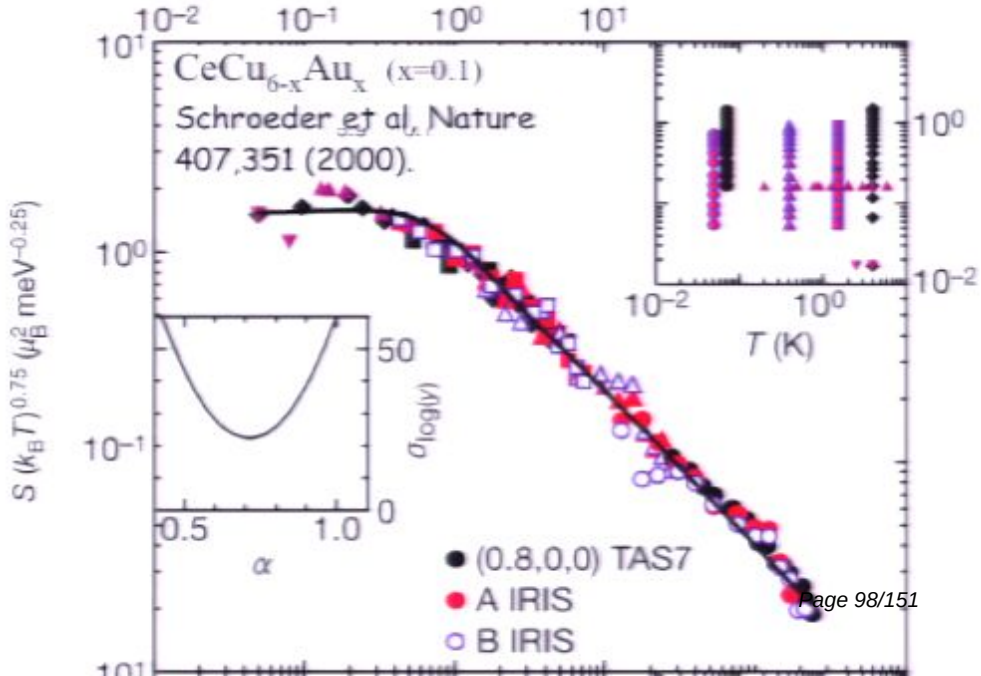

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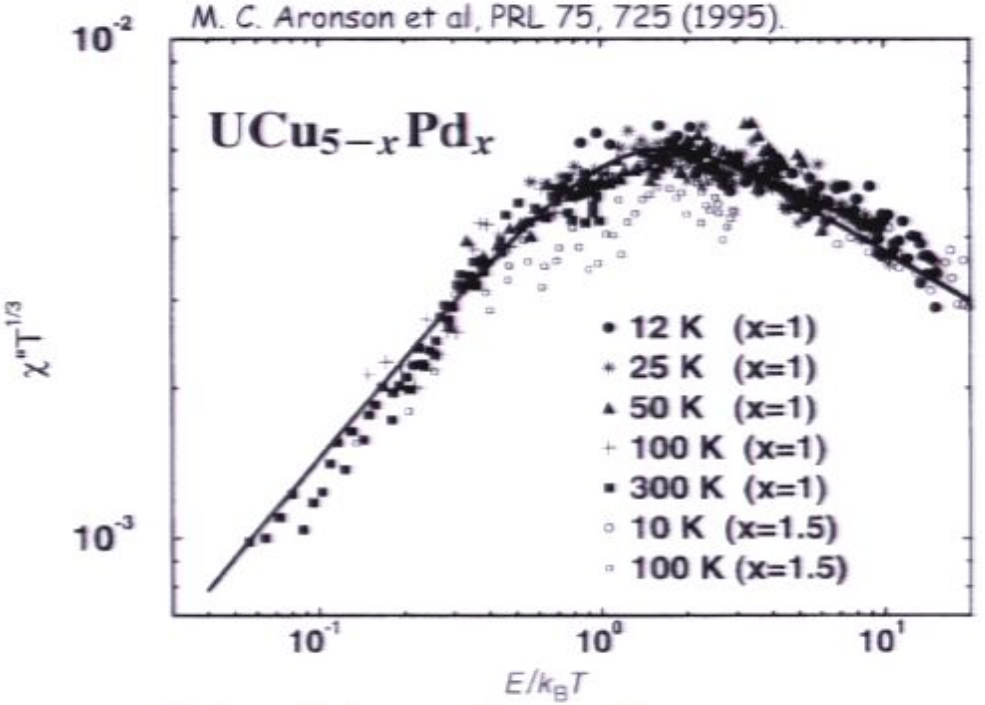
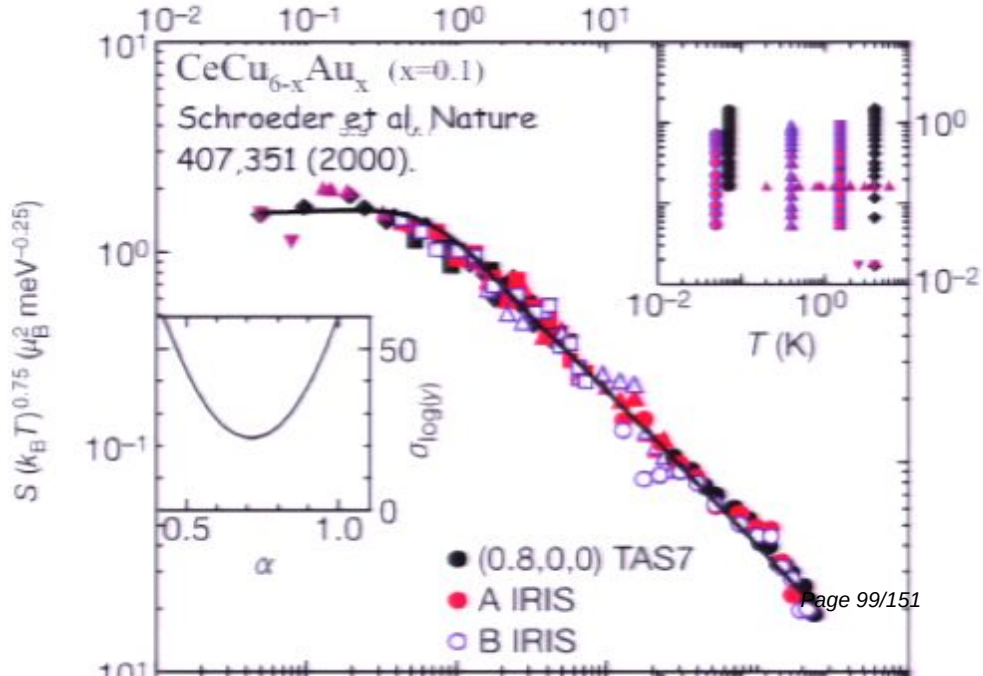
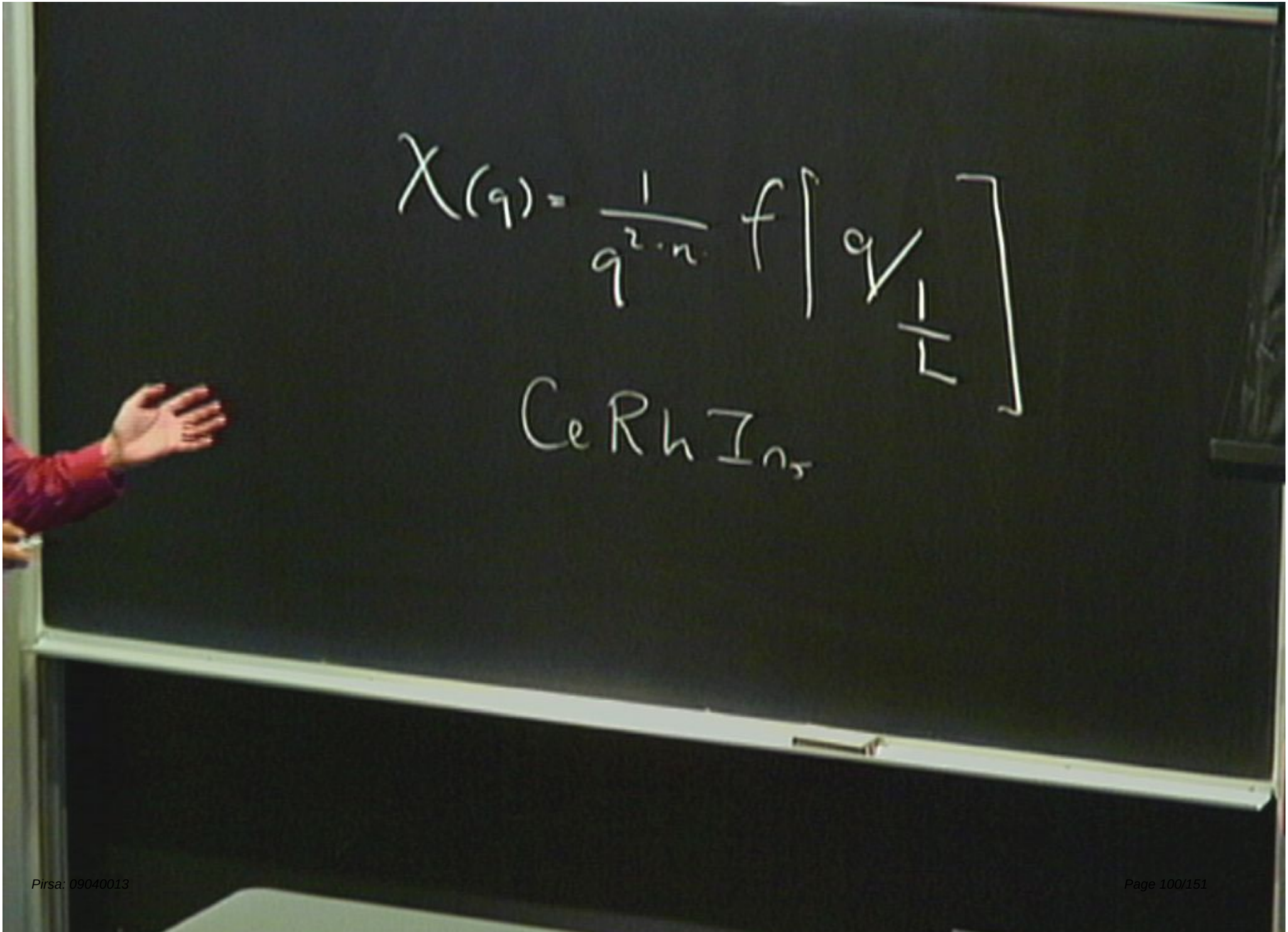
Physics Below the upper Critical Dimension.






$\chi(q) = \frac{1}{q^{2-n}} f\left[q^{\frac{1}{L}}\right]$
CeRhIn$_5$

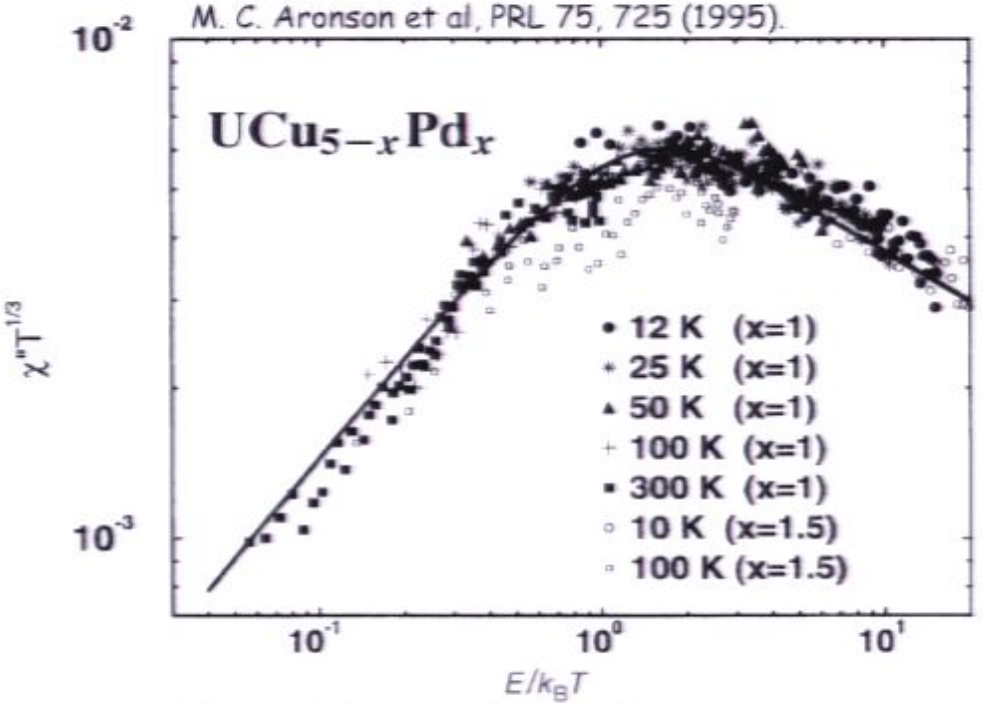
E/T Scaling:

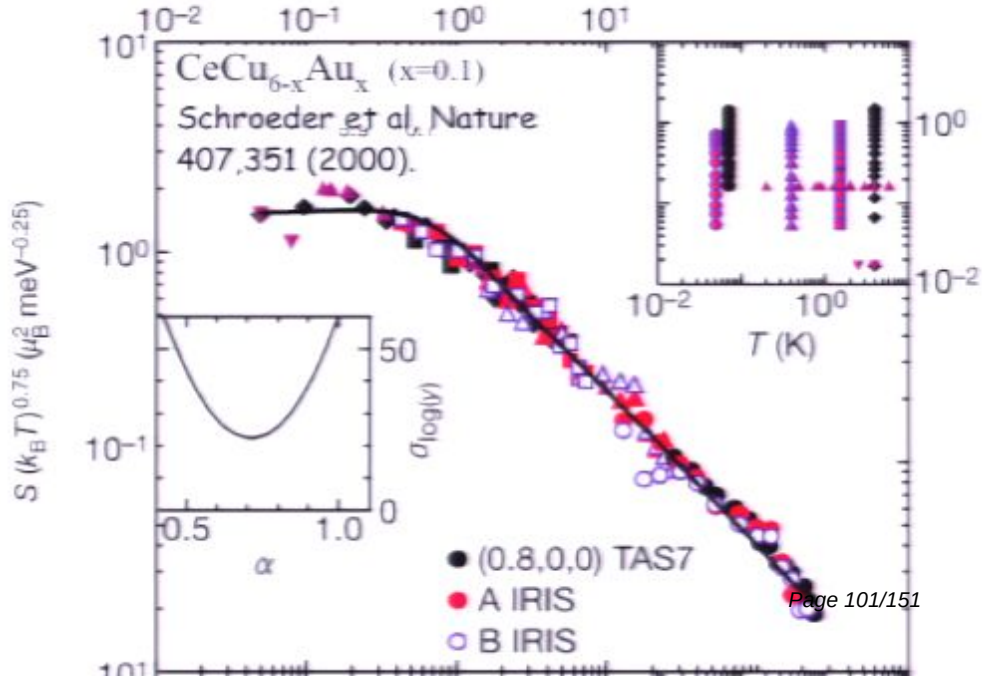
Meigan Aronson

Almut Schroeder

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

Physics Below the upper Critical Dimension.





The Standard Model

Standard Model: Quantum SDW?


Doniach

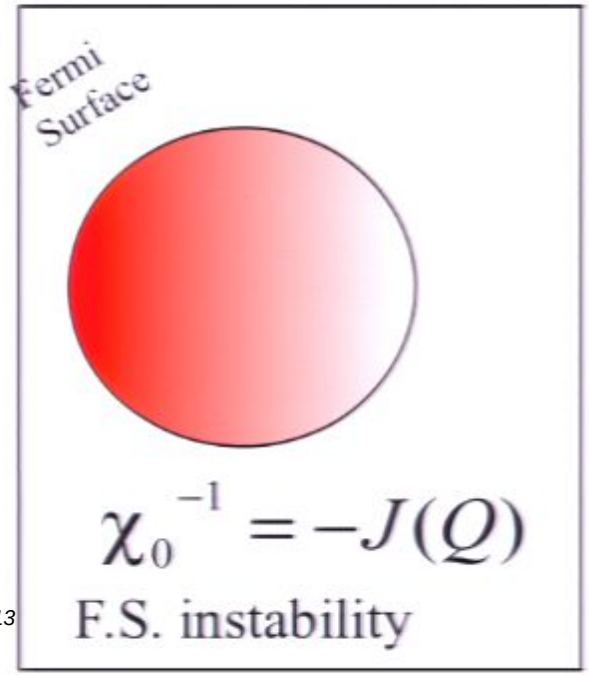

Schrieffer


Hertz


Millis

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

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



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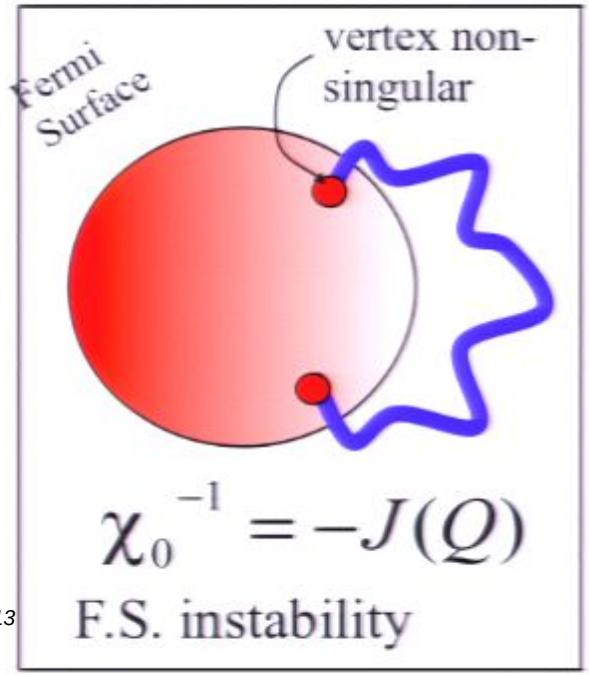

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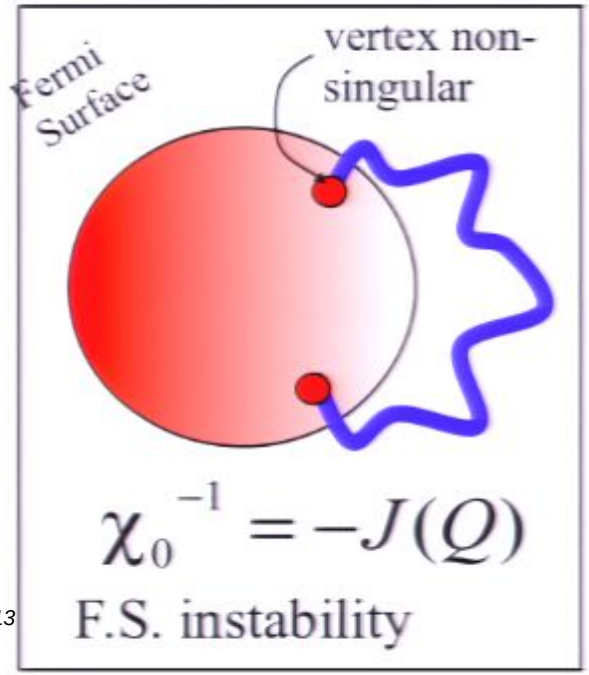

$$\chi^{-1}(q,\omega) \propto (\xi^{-2} + (q-Q)^2 - i\omega/\Gamma)$$

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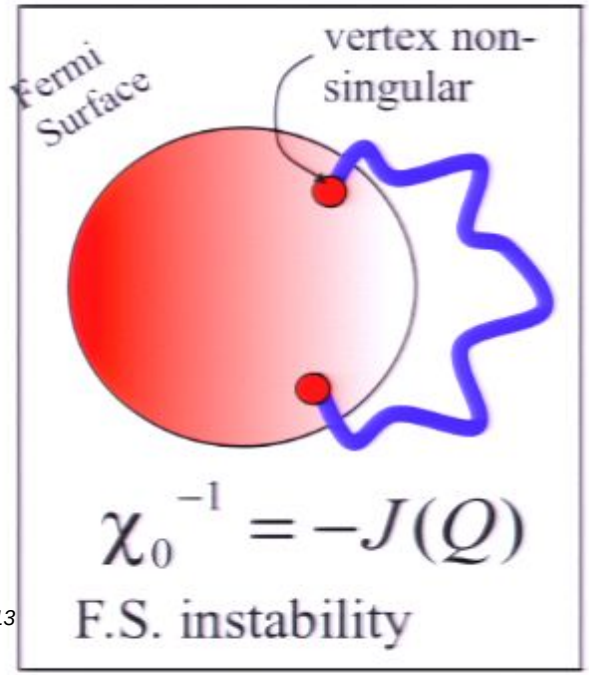

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Time counts as z =2 scaling dimensions

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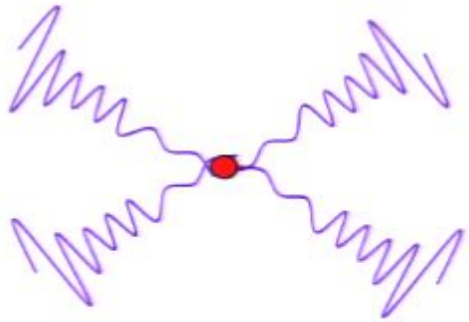

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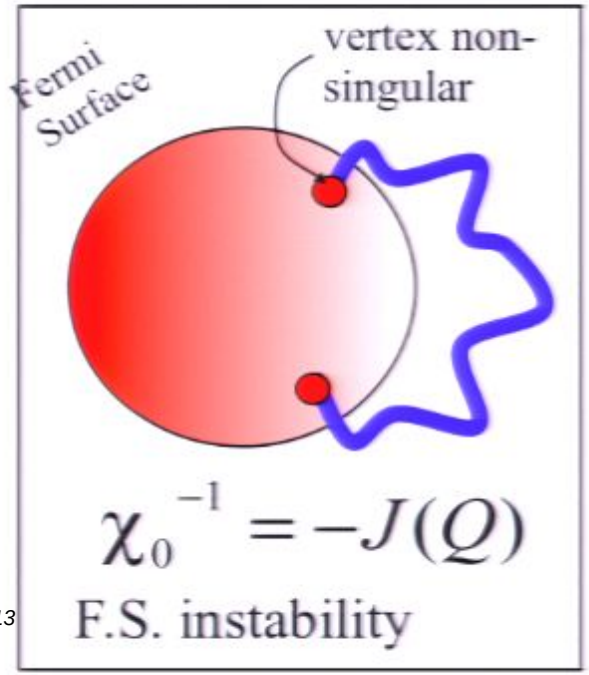
$$d_{eff} = d + z$$

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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Time counts as z =2 scaling dimensions

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)

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

"THE BATTLEGROUND"

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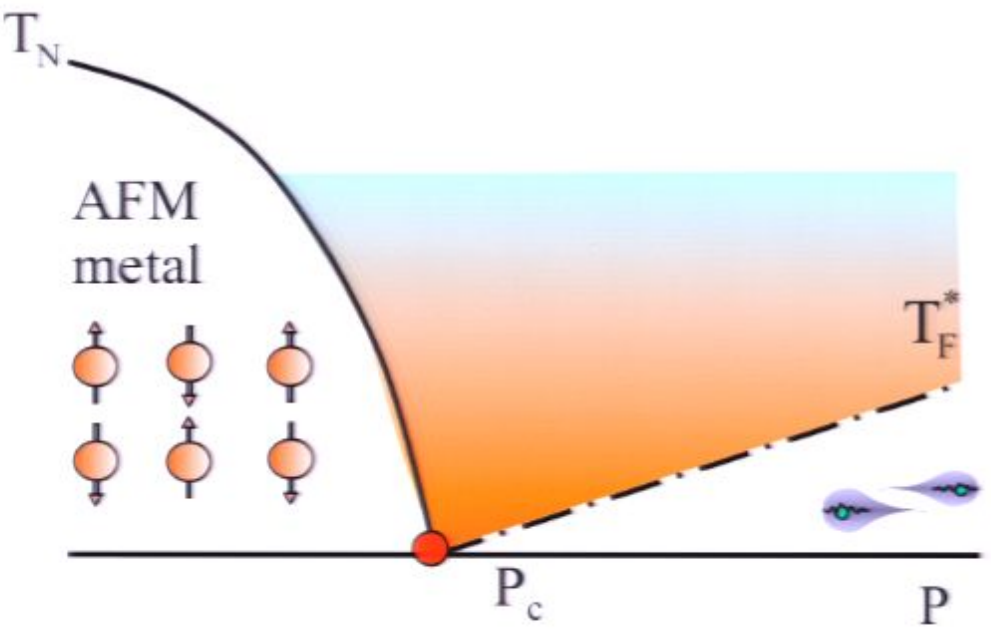
Heavy Fermion Materials



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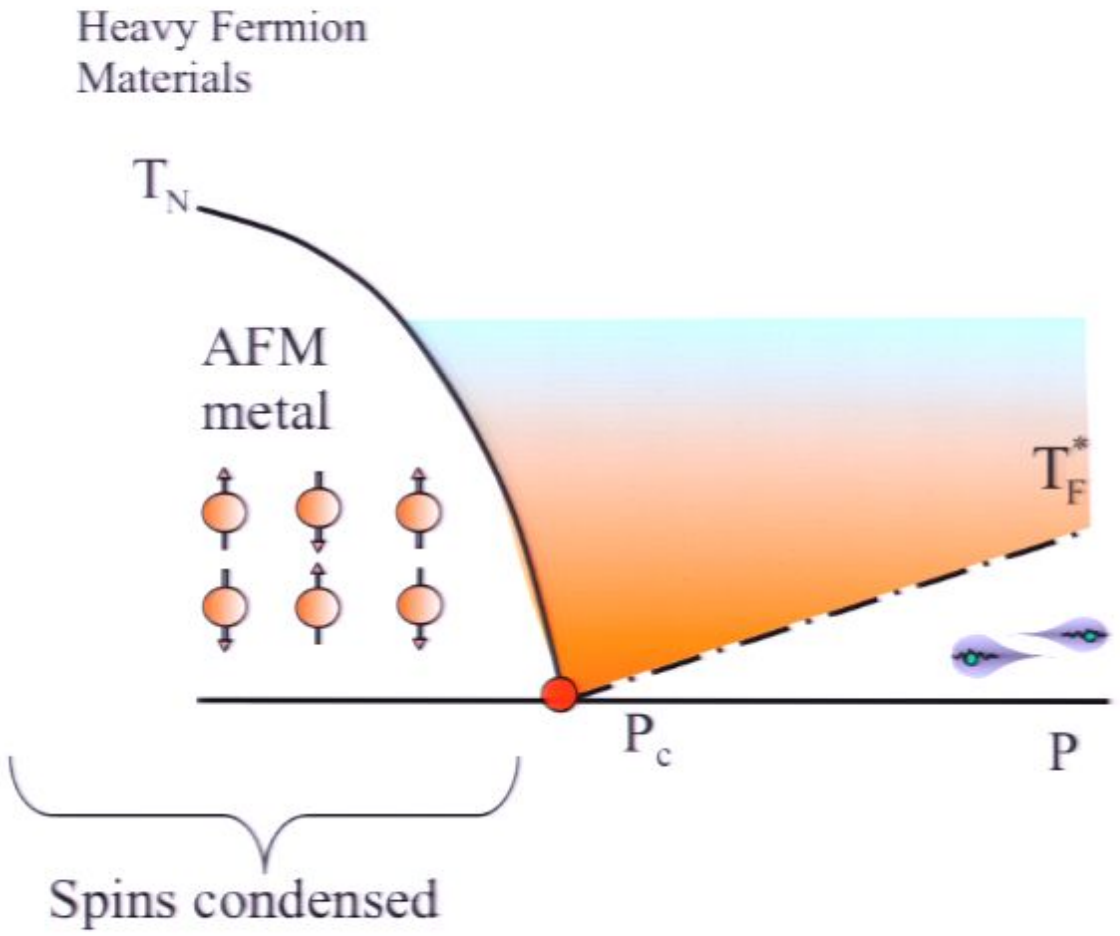

$$H = \sum \varepsilon_k c_{k\sigma}^{\dagger} c_{k\sigma} + J \sum_j (\psi^{\dagger}{}_j \vec{\sigma} \psi_j) \cdot \vec{S}_j$$

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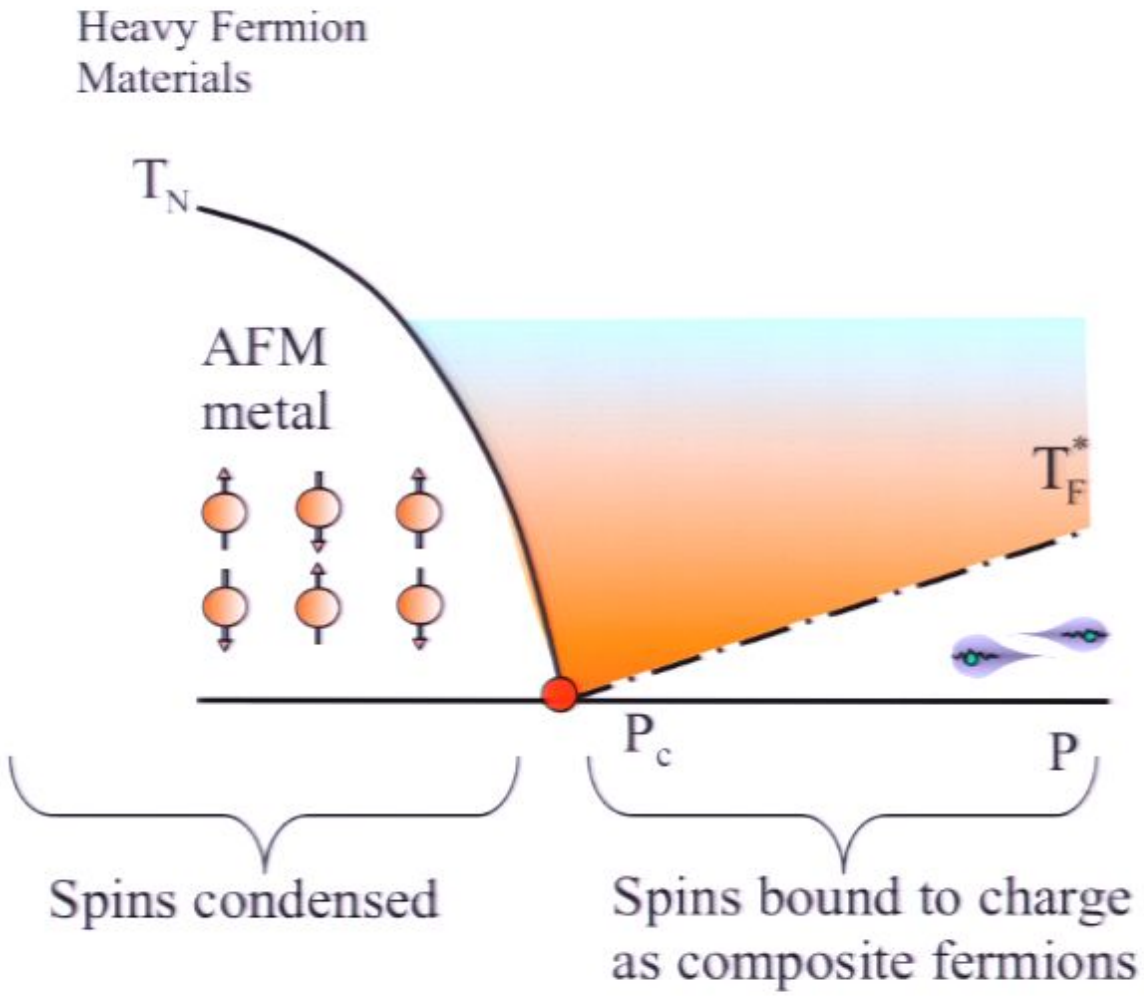

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"THE BATTLEGROUND"

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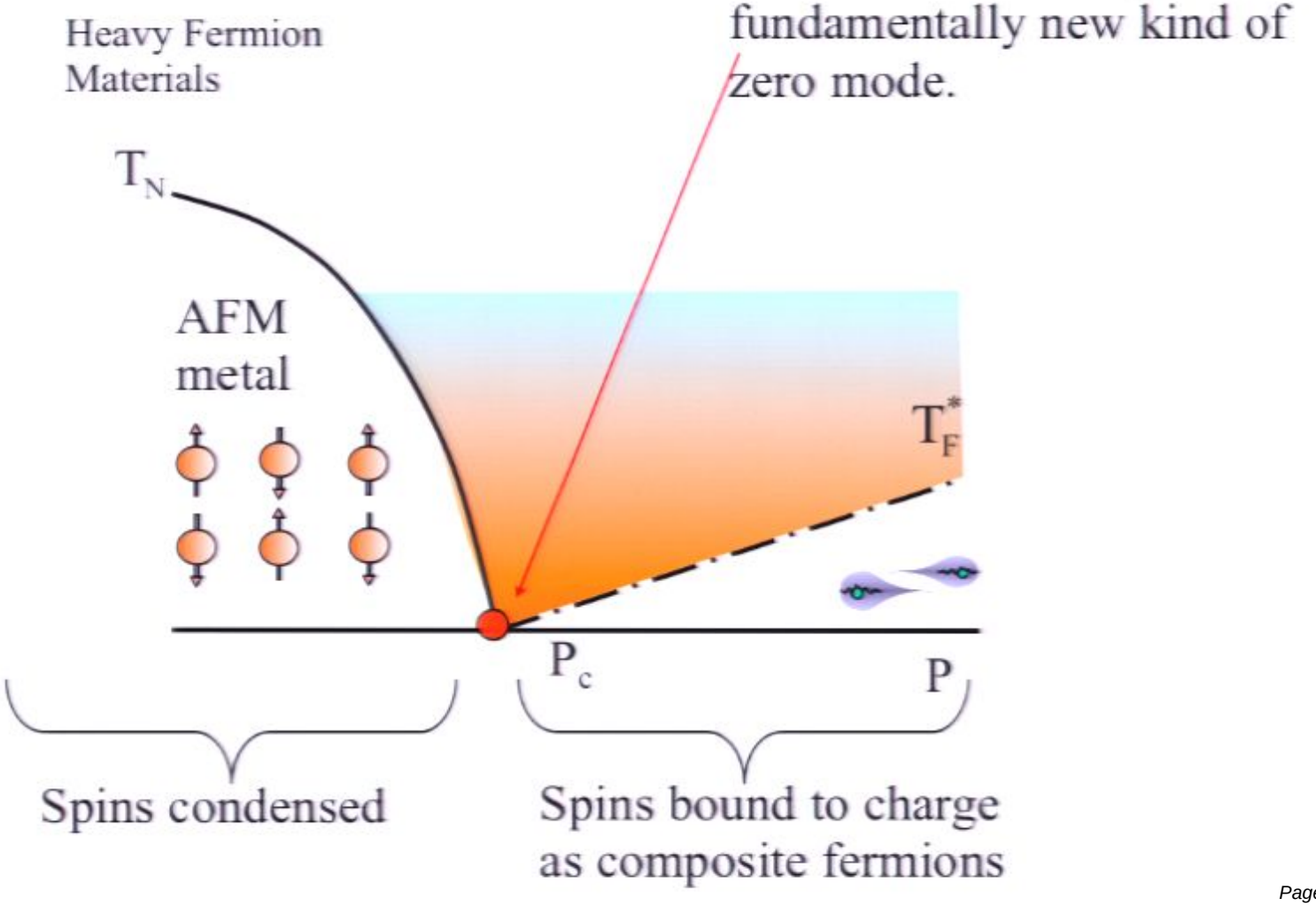
Deconfinement of spin: fundamentally new kind of zero mode.

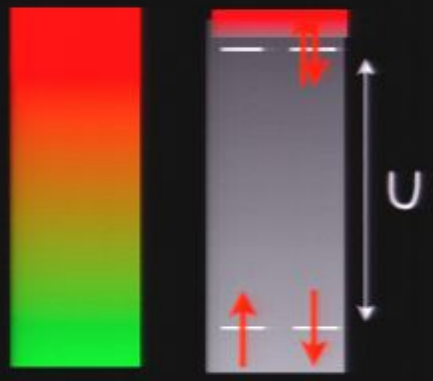


New Methods

e^-

New Methods

New Methods



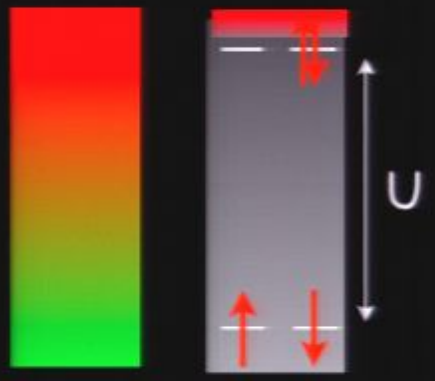
e^- spin

Φ W

Elimination of States
implies Gauge Fields.

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

New Methods



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

J. Schwinger '55

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

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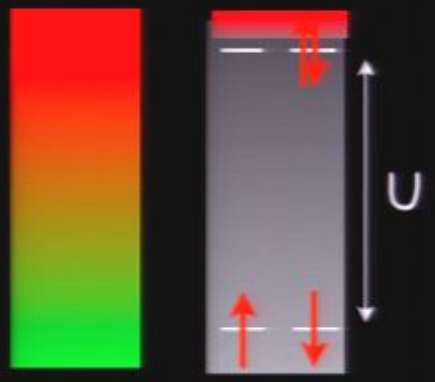

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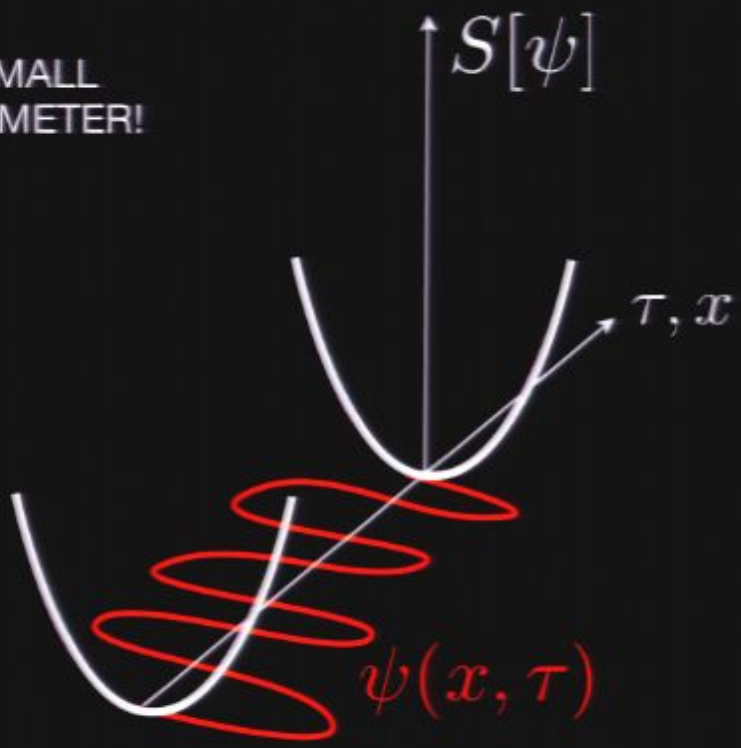
NO SMALL PARAMETER!



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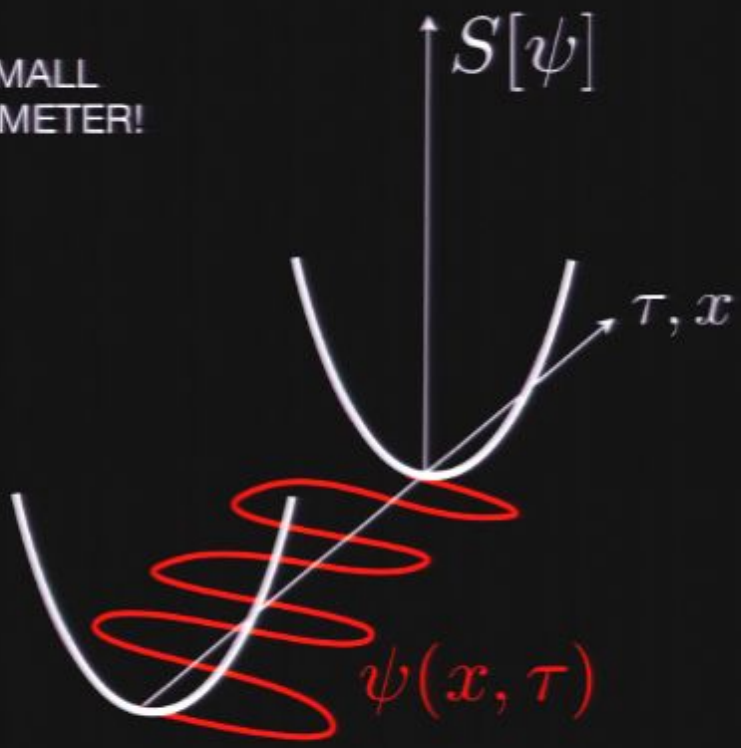

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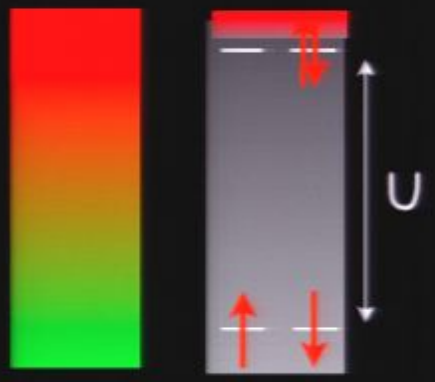
Large N : family of models with "N" spin components, which retain the key physics and can be solved in the large N limit.

New Methods



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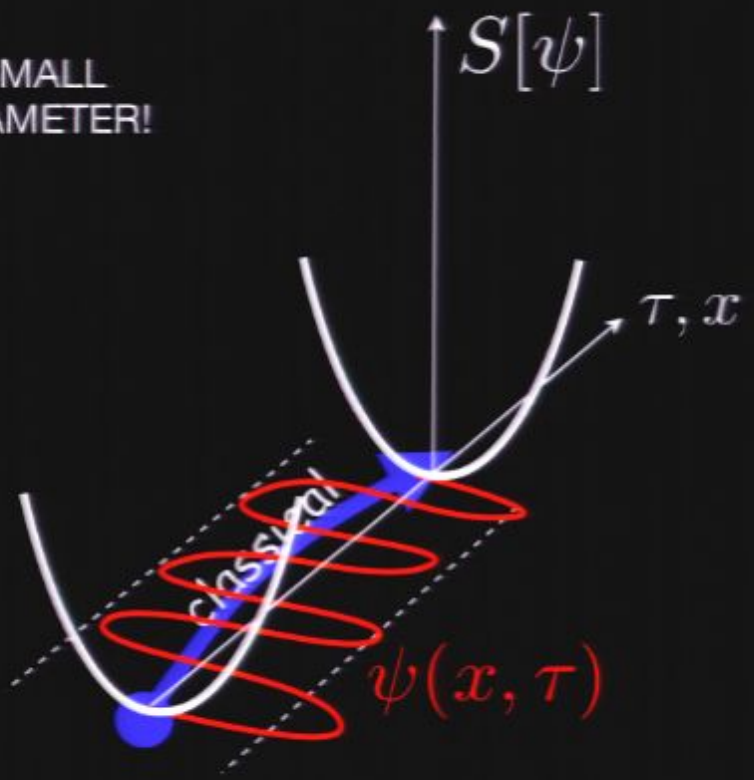


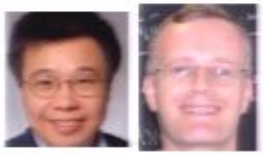
$$\frac{1}{N} \sim \hbar_{eff}$$

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

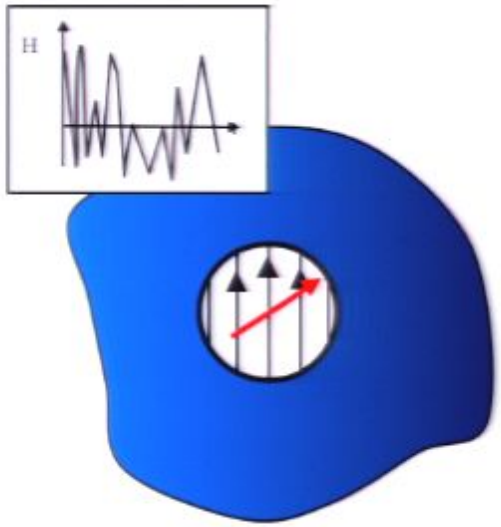
Si, Ingersent



- **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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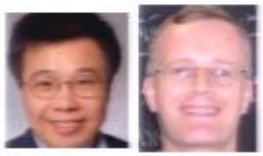

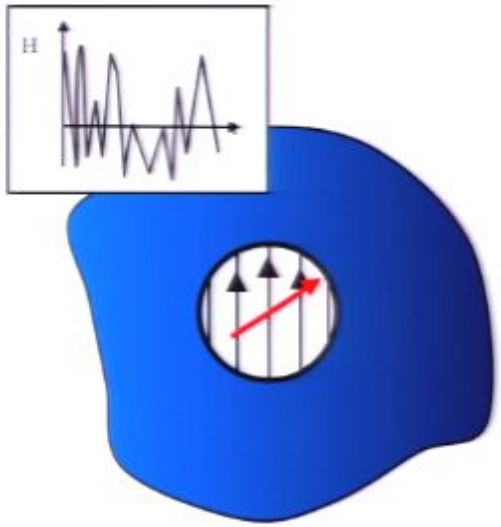

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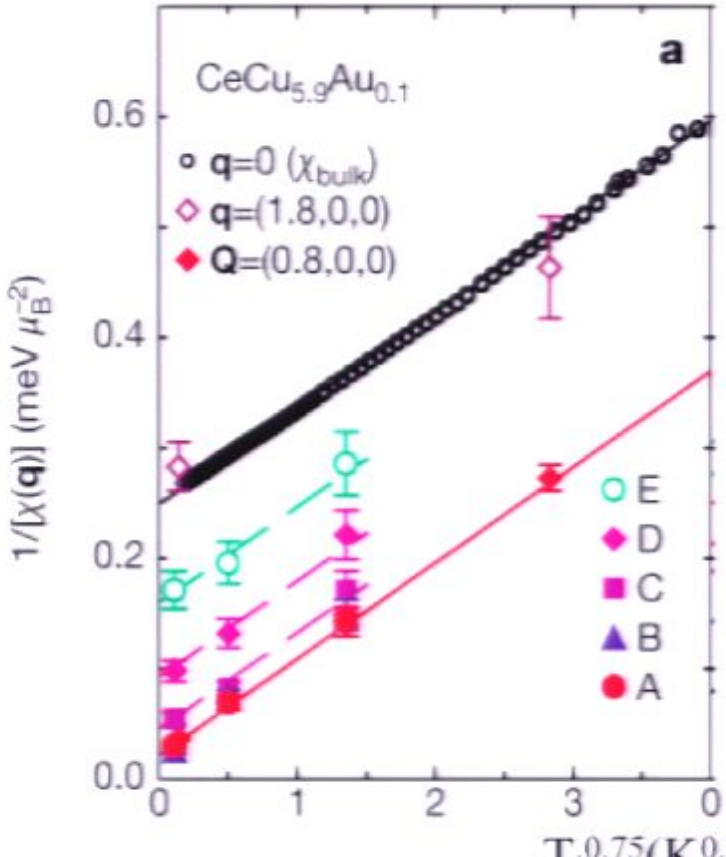
Locality of critical fluctuations

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



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

New Ideas

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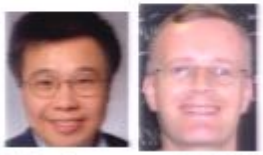

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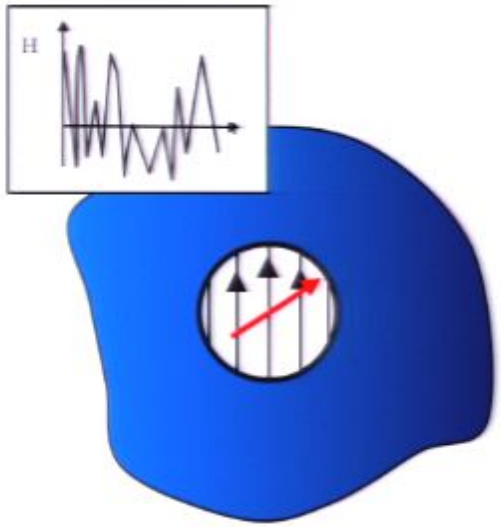

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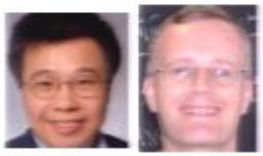

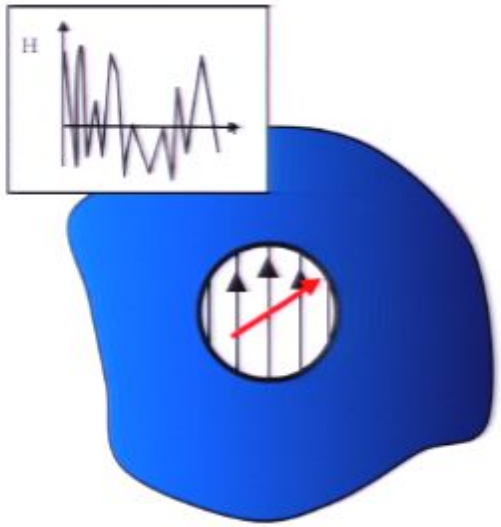

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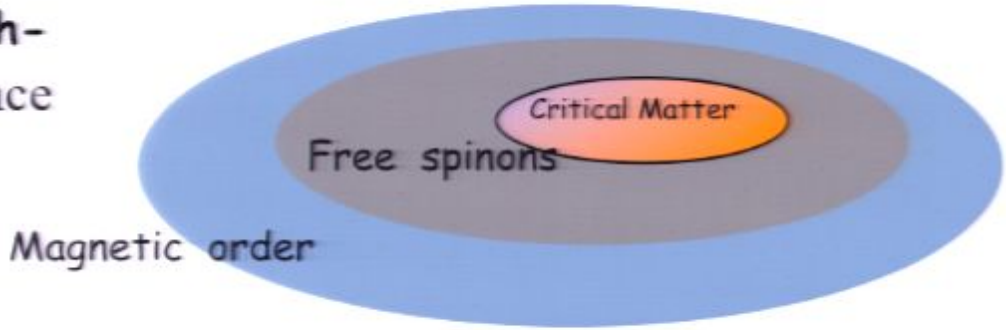
· **Deconfined Criticality: Two diverging length-scales.** (Hermele et al 2004; Senthil et al, Science 2004).

Senthil Sachdev Vishwanath



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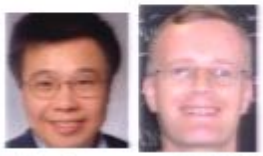

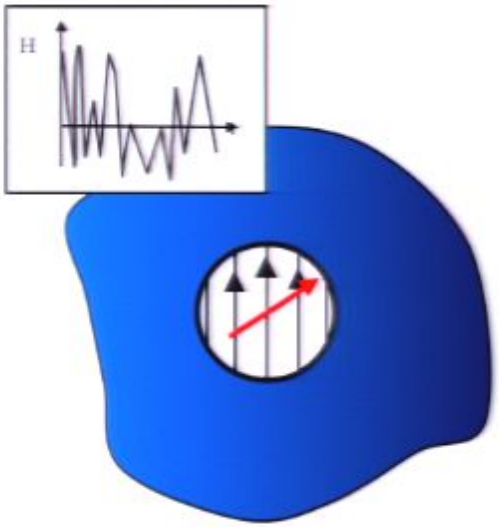

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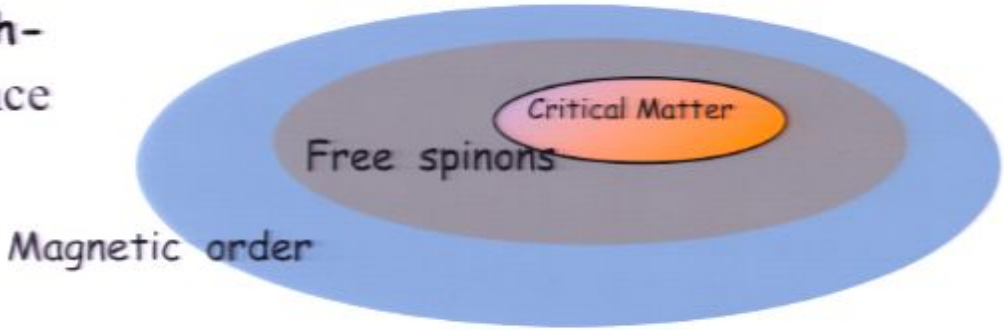
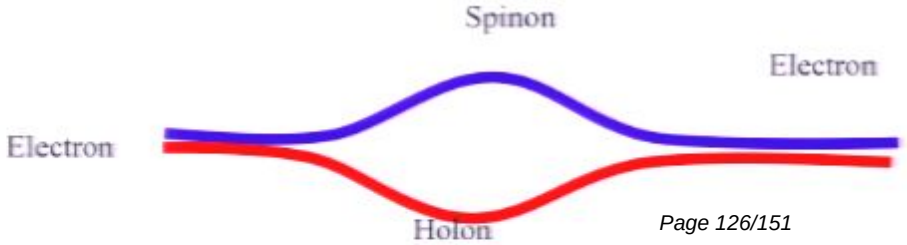


· **Search for a new mean-field theory.**
(PC, Pepin et al JCM, 2001, Rech et al 2005, Lebanon et al 2006.).

Pepin



Q-Frustration

Kondo meets frustration

- Frustration and Kondo have different effects.

Kondo meets frustration

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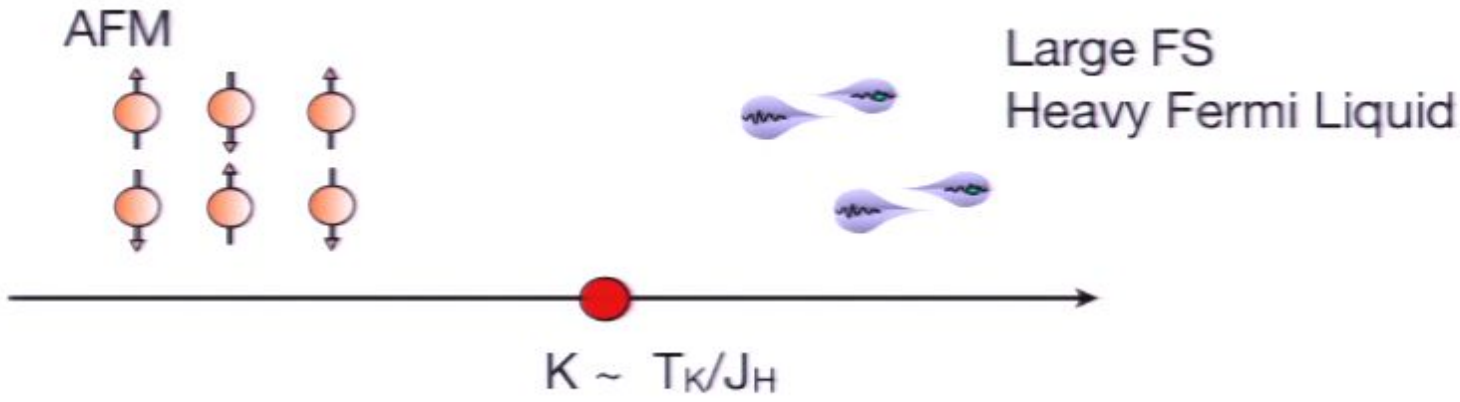

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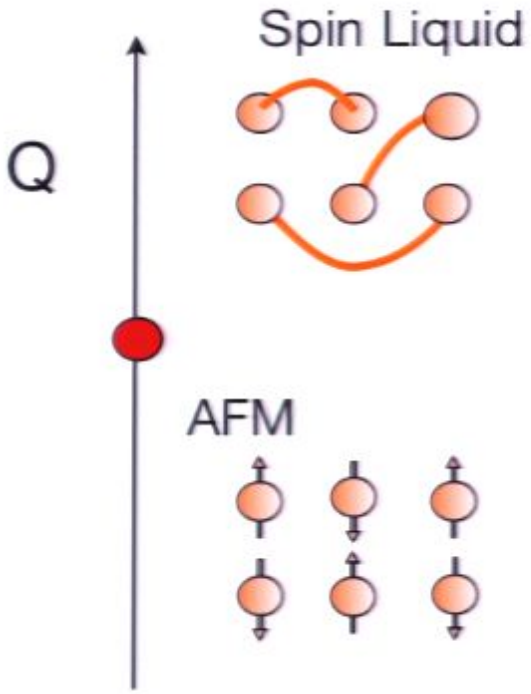

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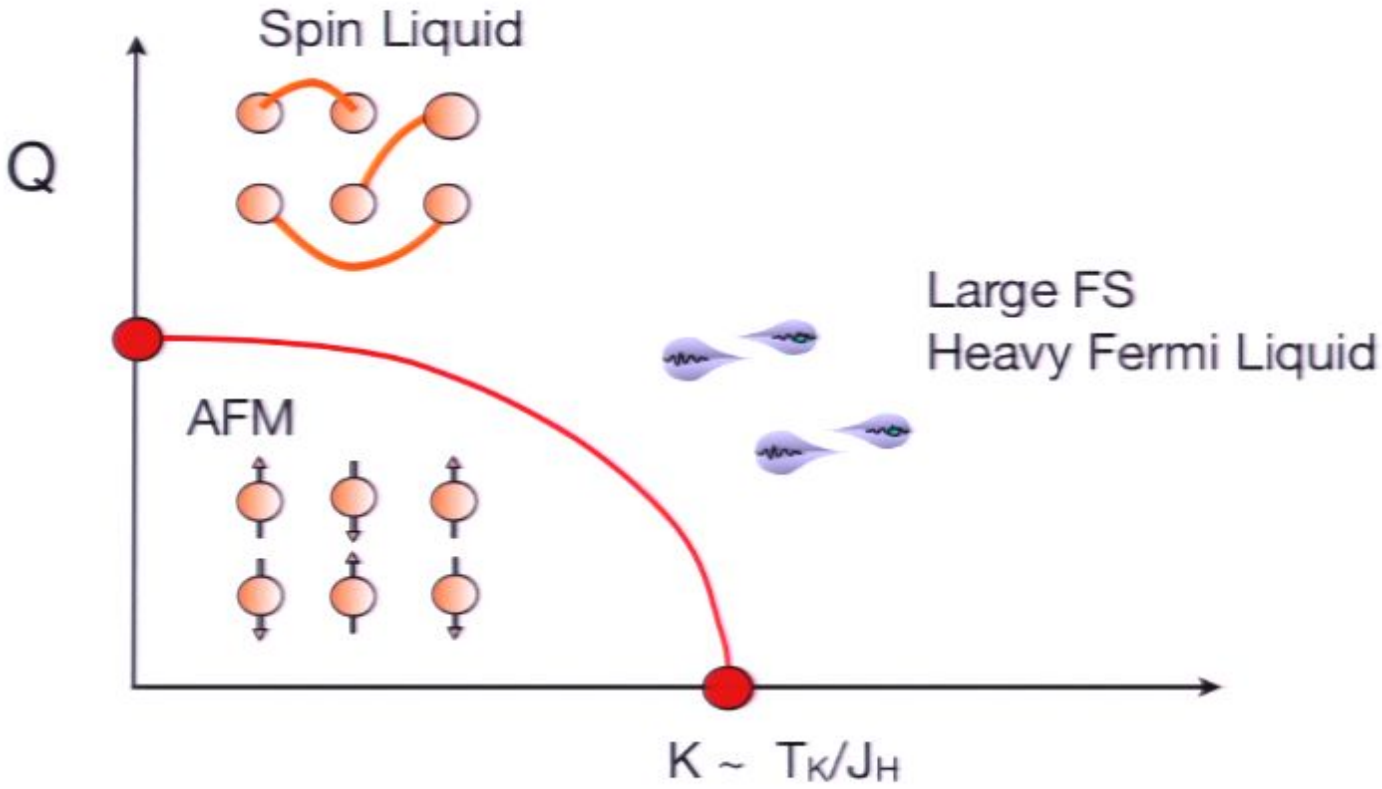
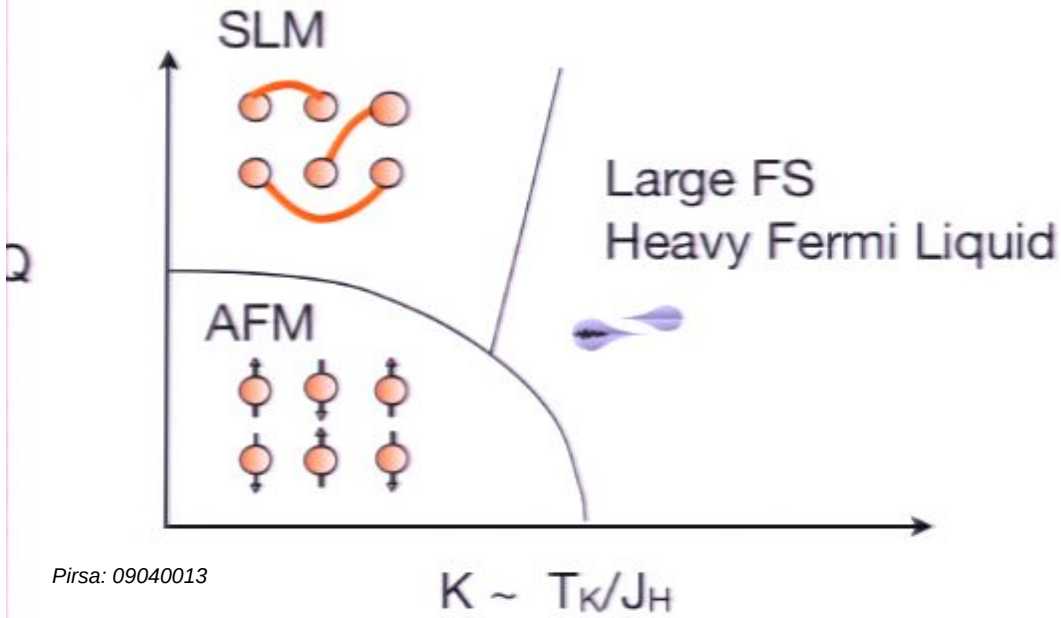
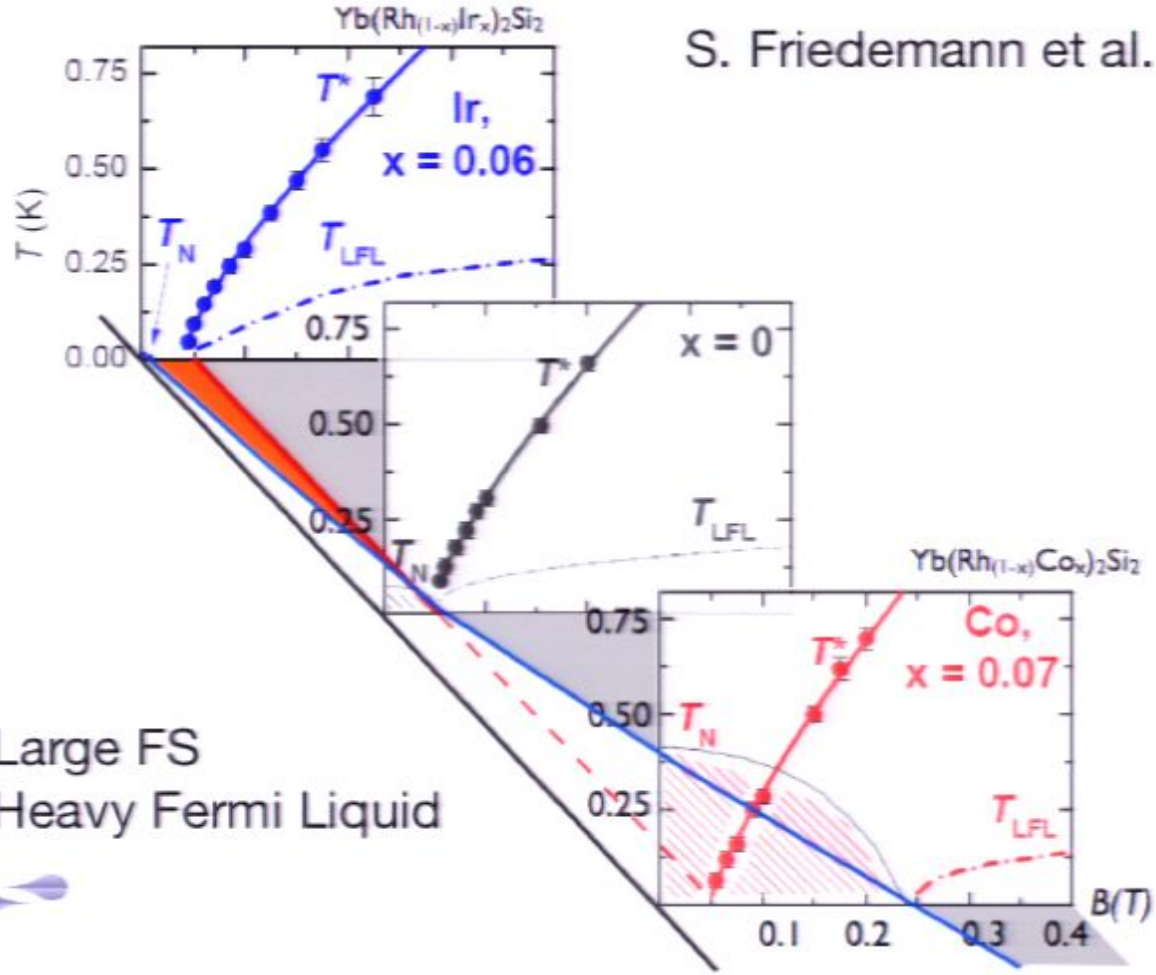


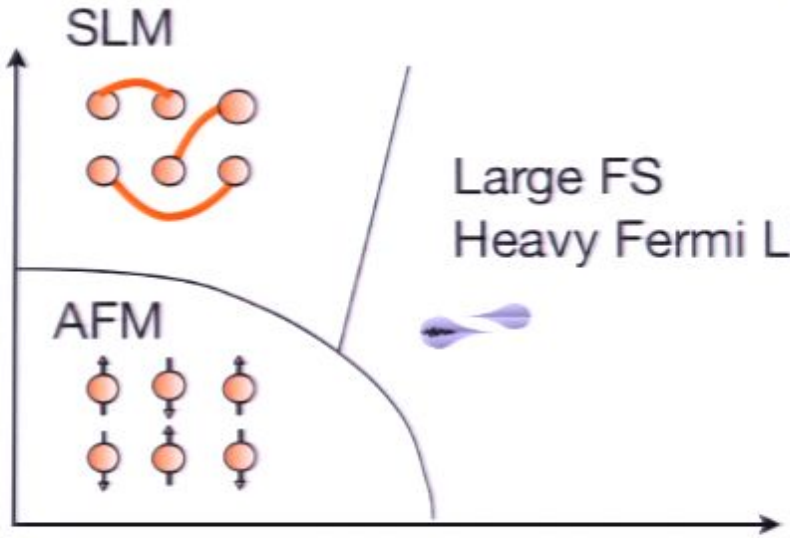
Experimental Support I



Experimental Support I

S. Friedemann et al. (2009).





Large FS
Heavy Fermi Liquid

Experimental Support I

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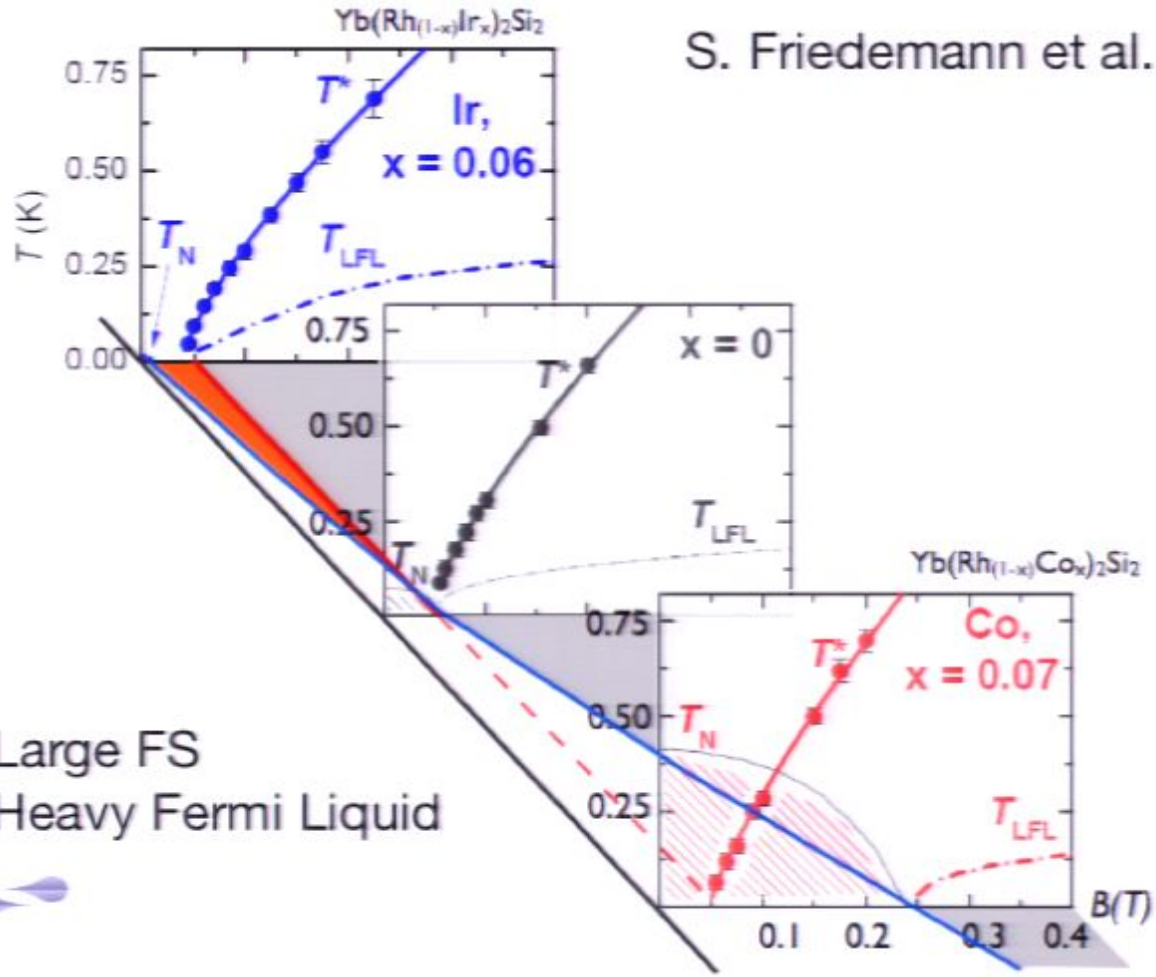
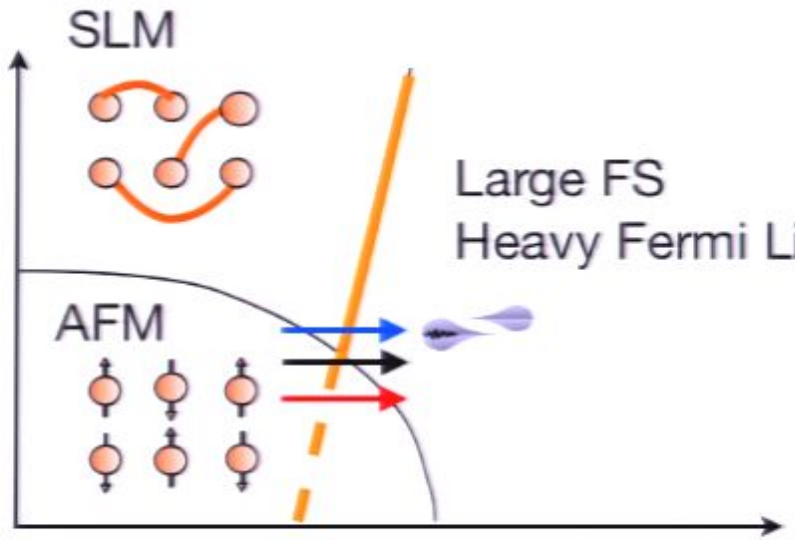
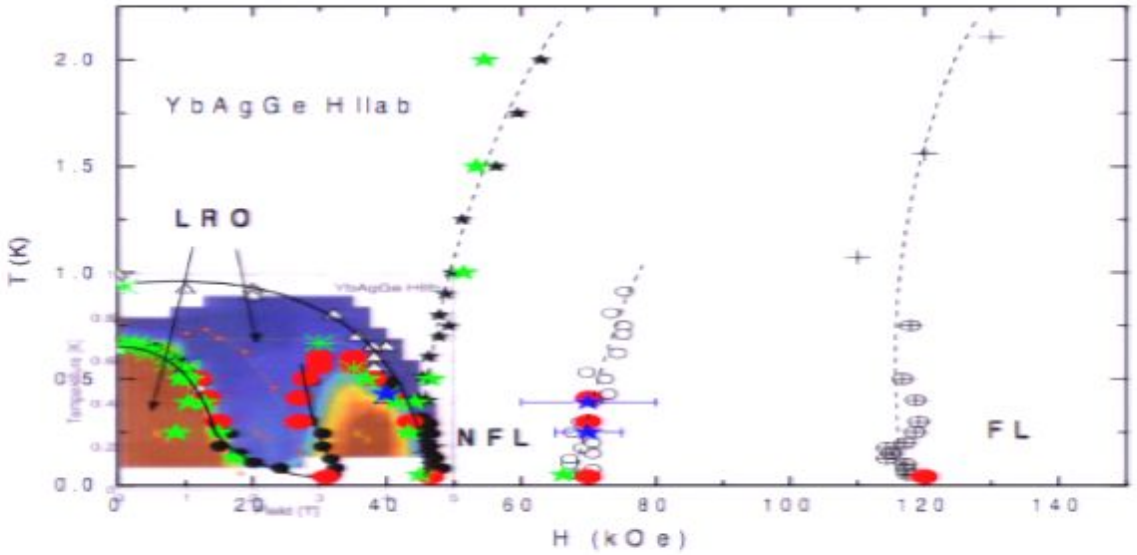
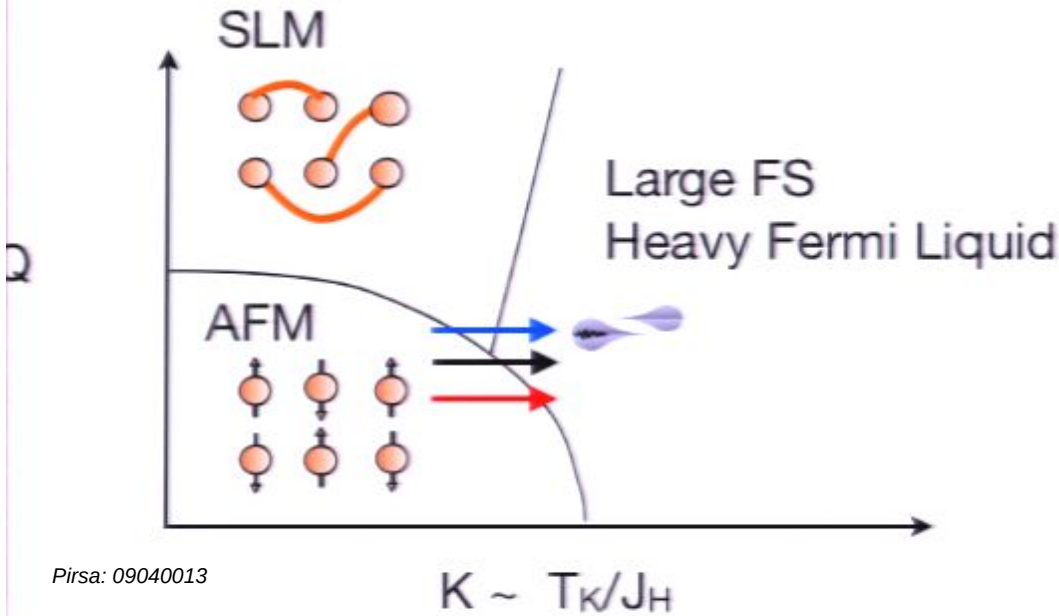


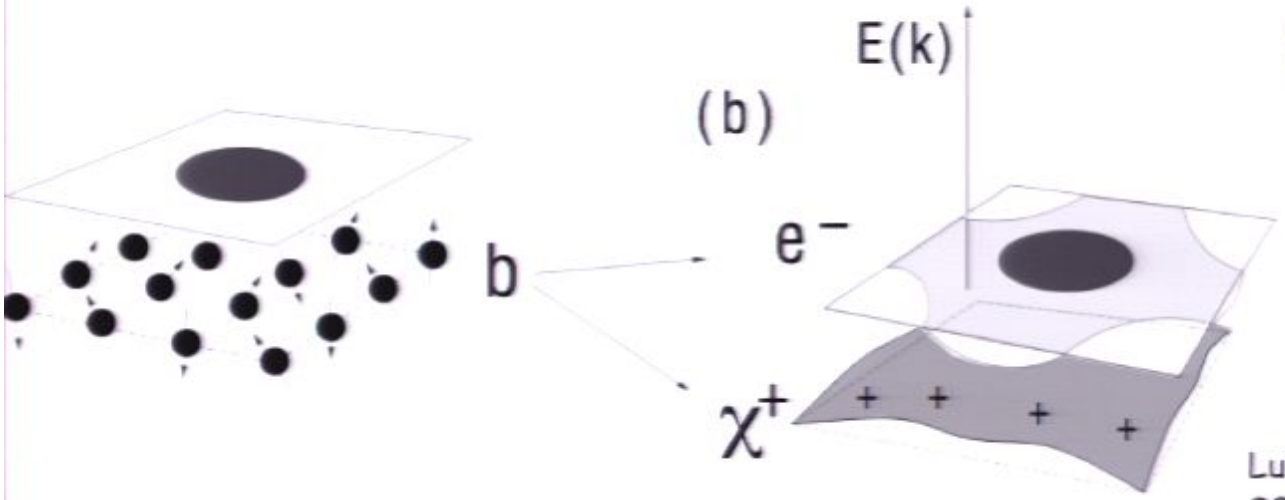


Experimental Support II



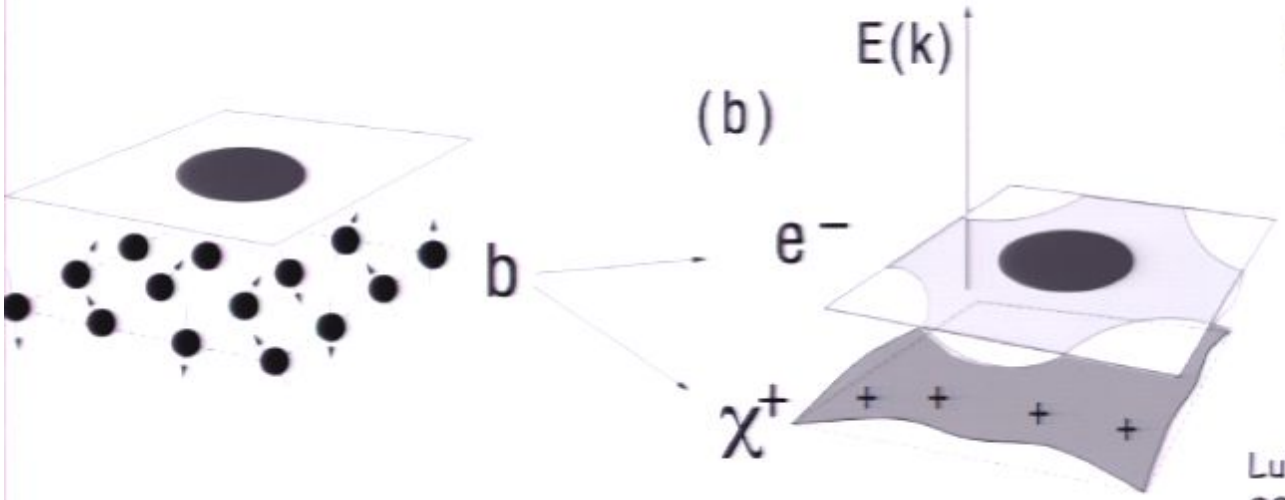
Canfield et al (unpublished)





$$\frac{n_e}{K} = N\frac{v_{FS}}{(2\pi)^D} - \underbrace{\frac{v_\chi}{(2\pi)^D}}_{=1}$$

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



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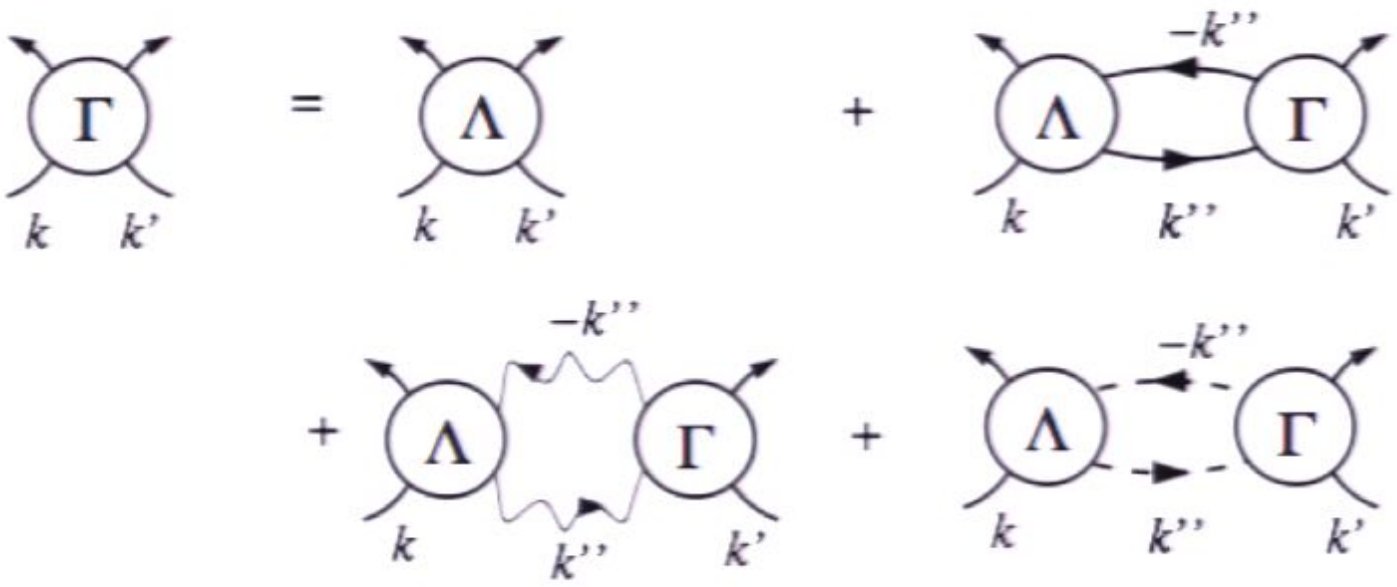

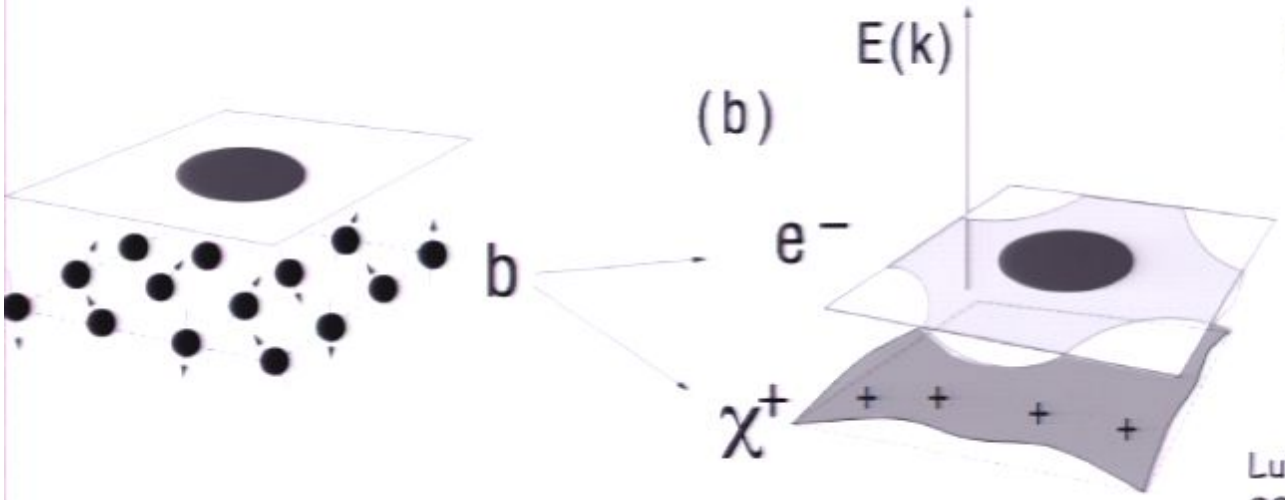

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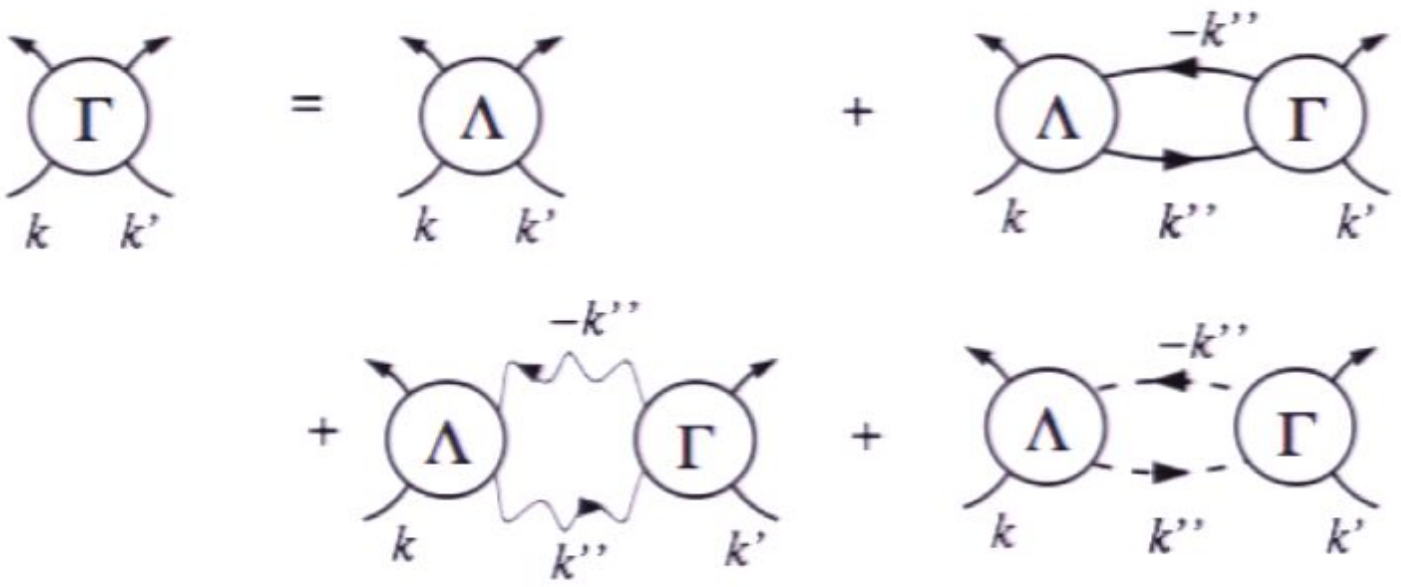

Fermi Liquid scattering parameters determined primarily by excitation of low-lying spinon and holon states..

Virtual spinons.

Virtual holons.

Towards a new Conjunction of ideas.

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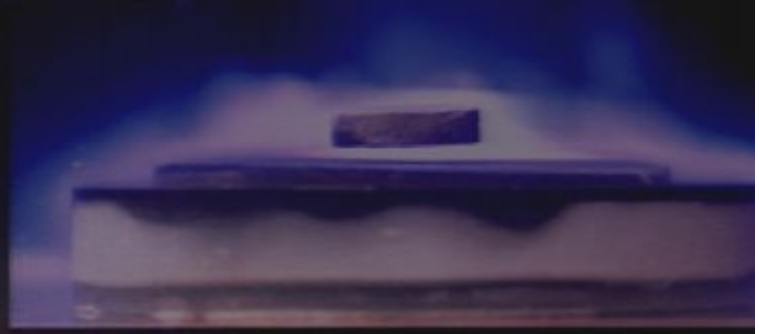

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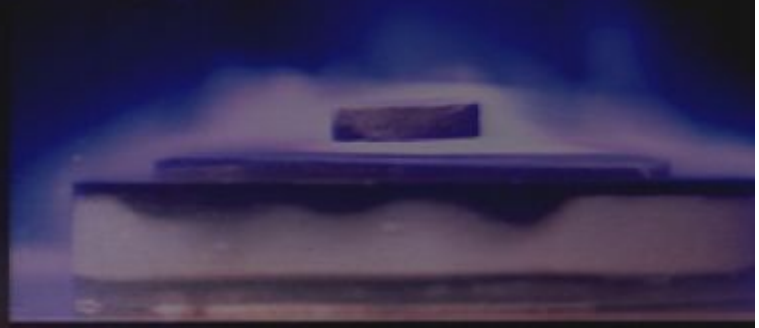

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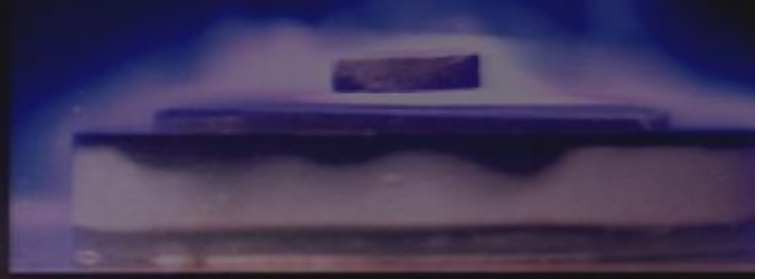

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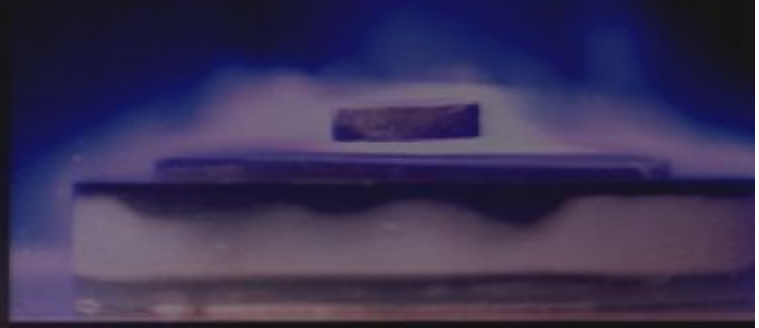

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All have in common the idea of a critical Fermi surface with branch-cuts replacing poles.

Collaborators


Flint


Nev.


Dzero

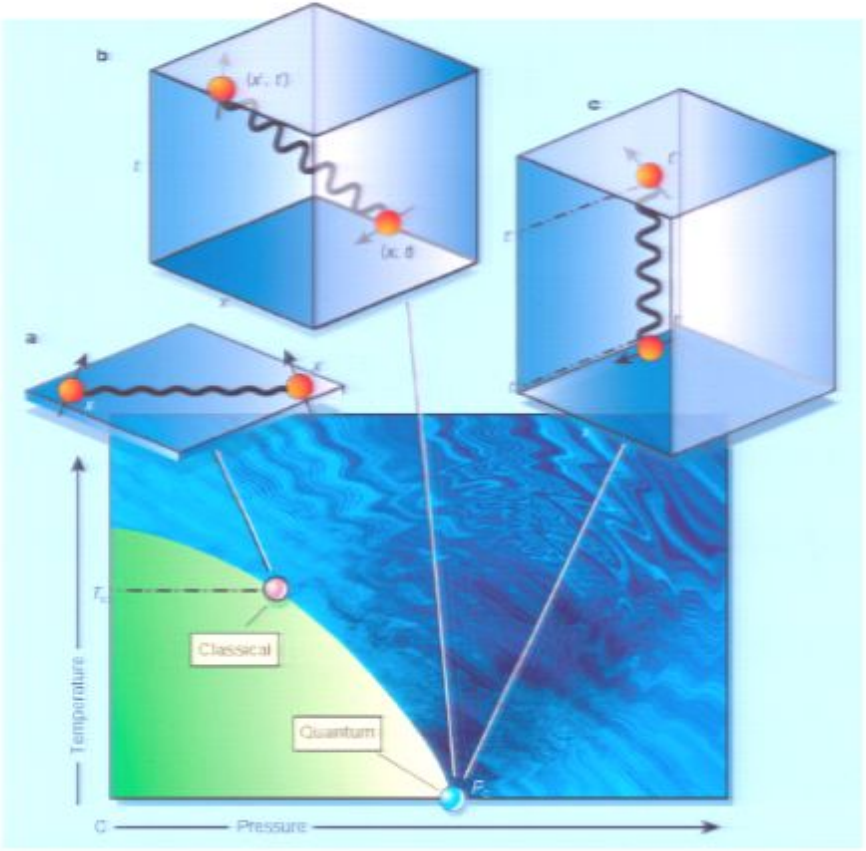

Rech


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. Löhneysen	Karlsruhe

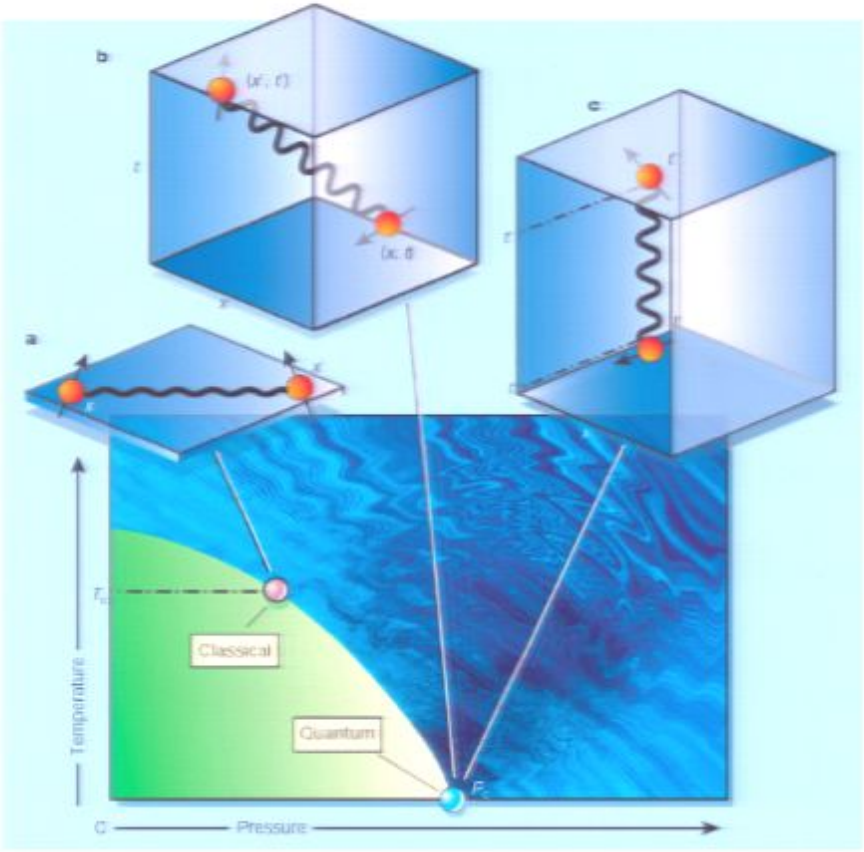
Rutgers
Center for Materials Theory

Conclusions



Conclusions

Revolutions take a long time: we are just at the beginning of the quantum era.



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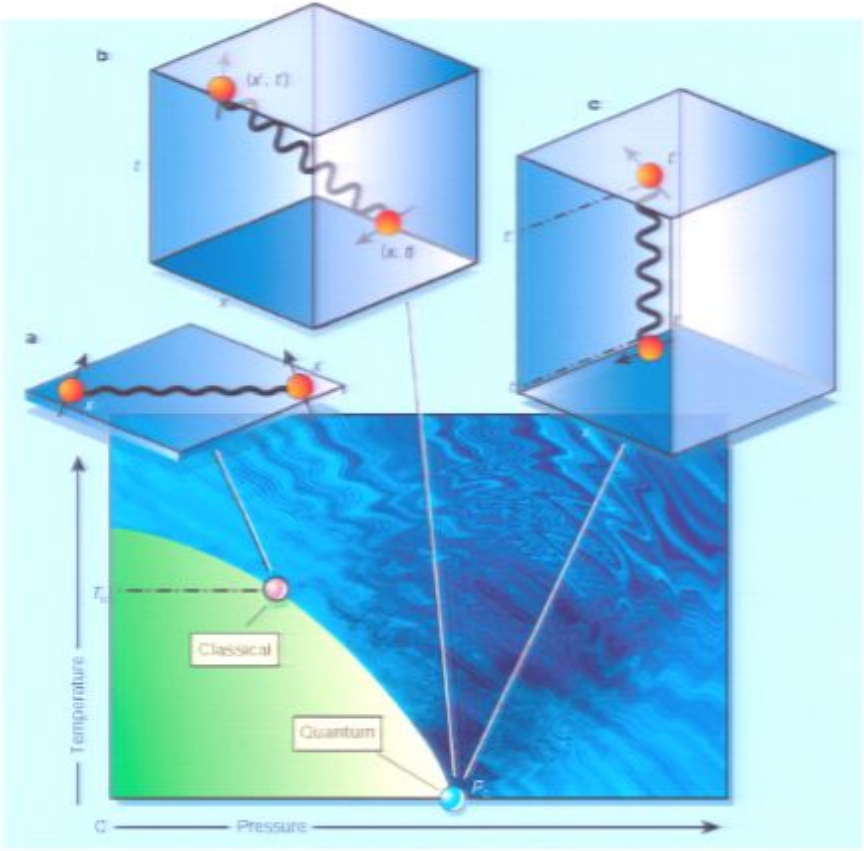

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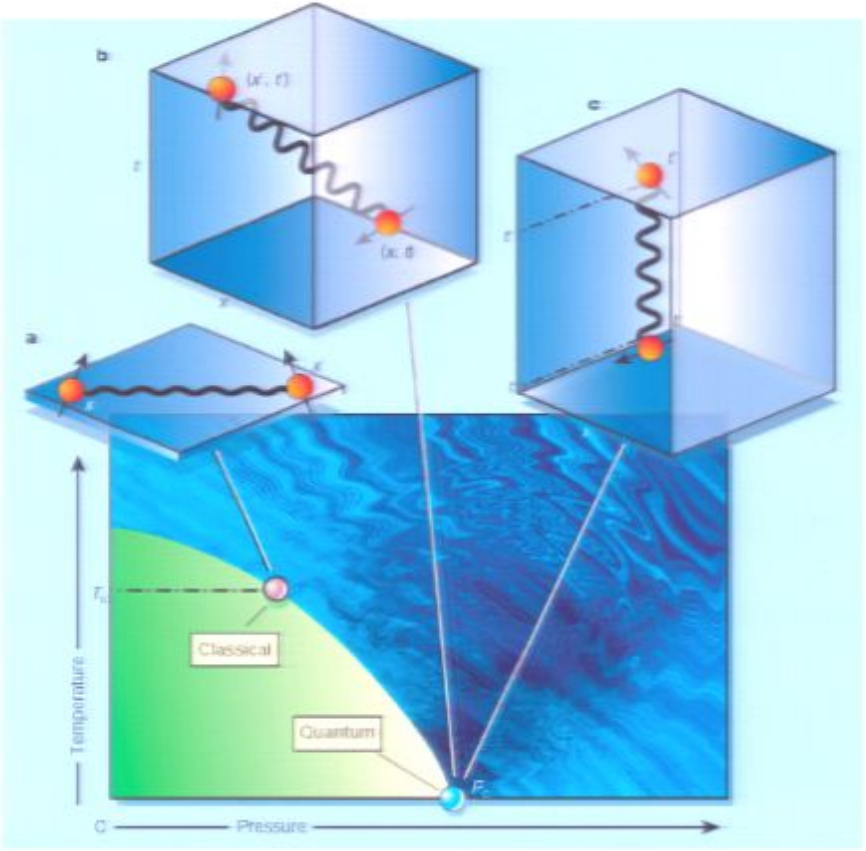

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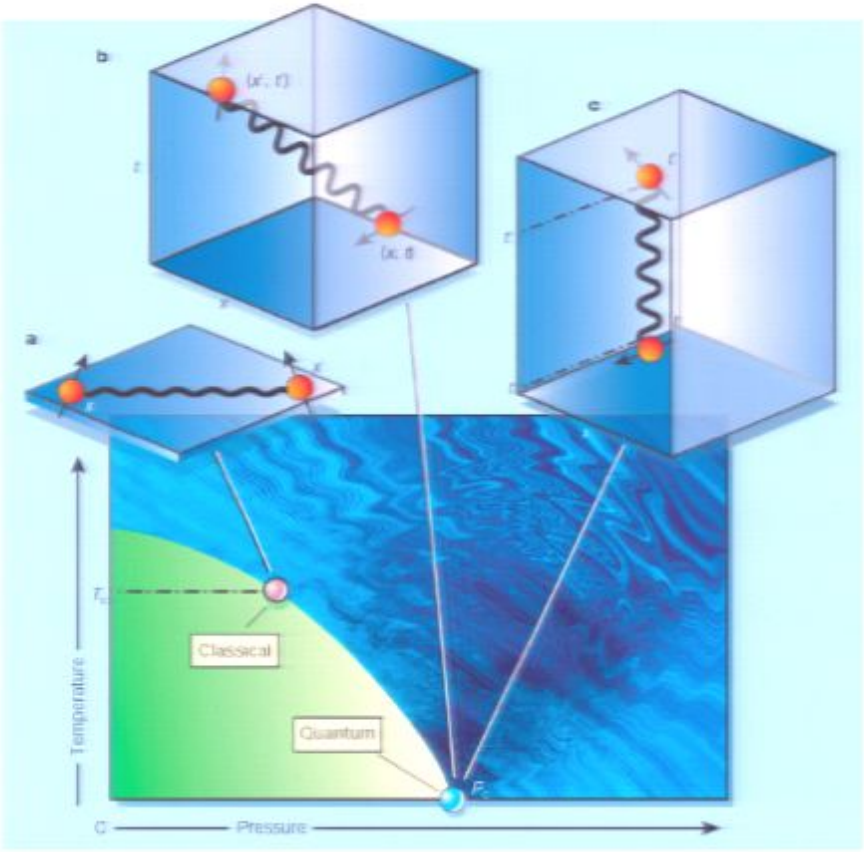

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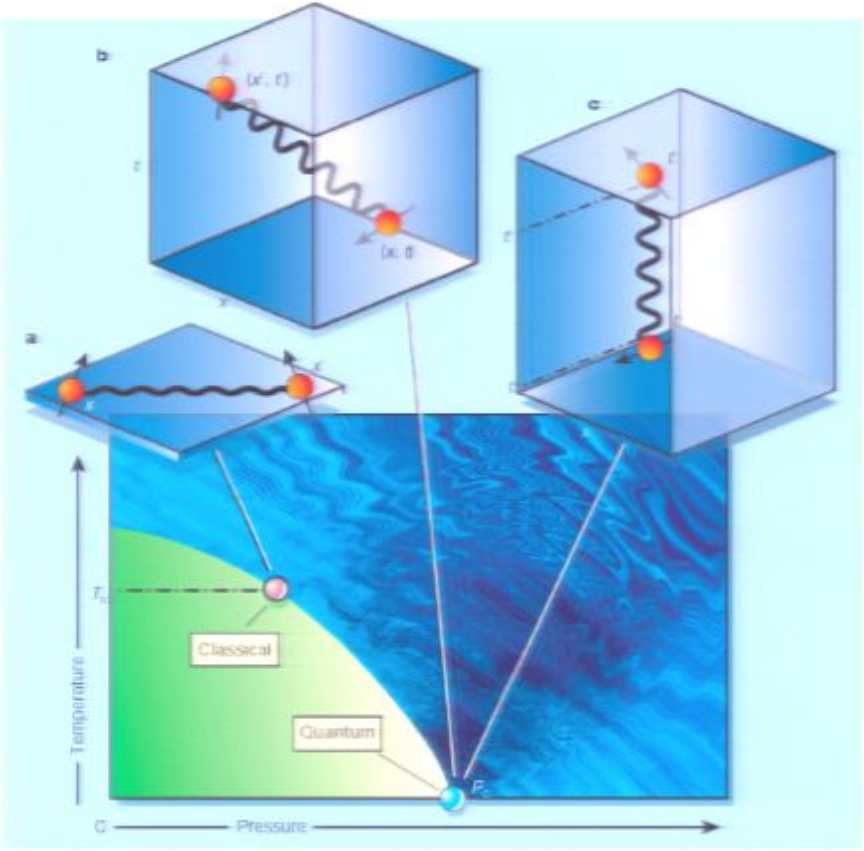

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Need for a radically new type of theory: ideas of confinement, gauge theories and large N.

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