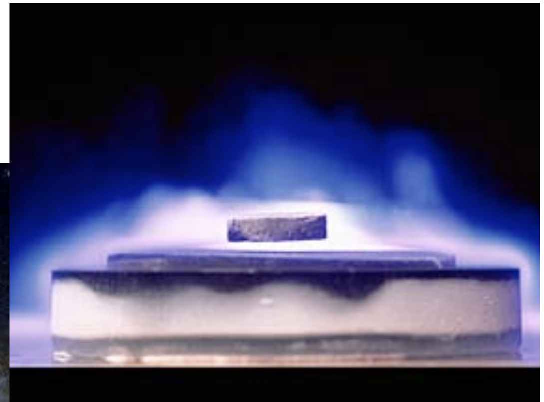
Qu-Transitions:



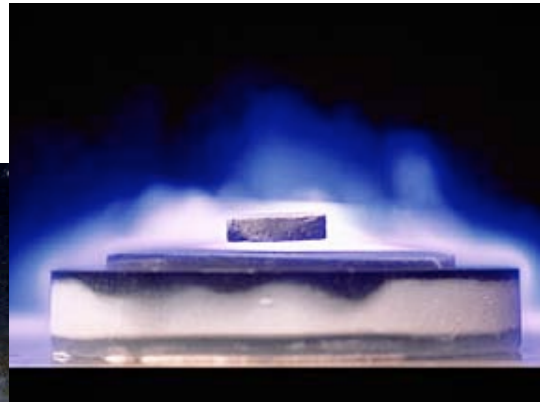
P. Coleman
(CMT, Rutgers)

Toronto QCP
"Statics and Dynamics"
Sept 25th 2008.

Rutgers
Center for Materials Theory

Qu-Transitions:

"Frontier Challenge in C.M.P. "



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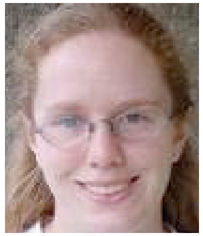
Collaborators


Flint


Nev.


Dzero


Rech

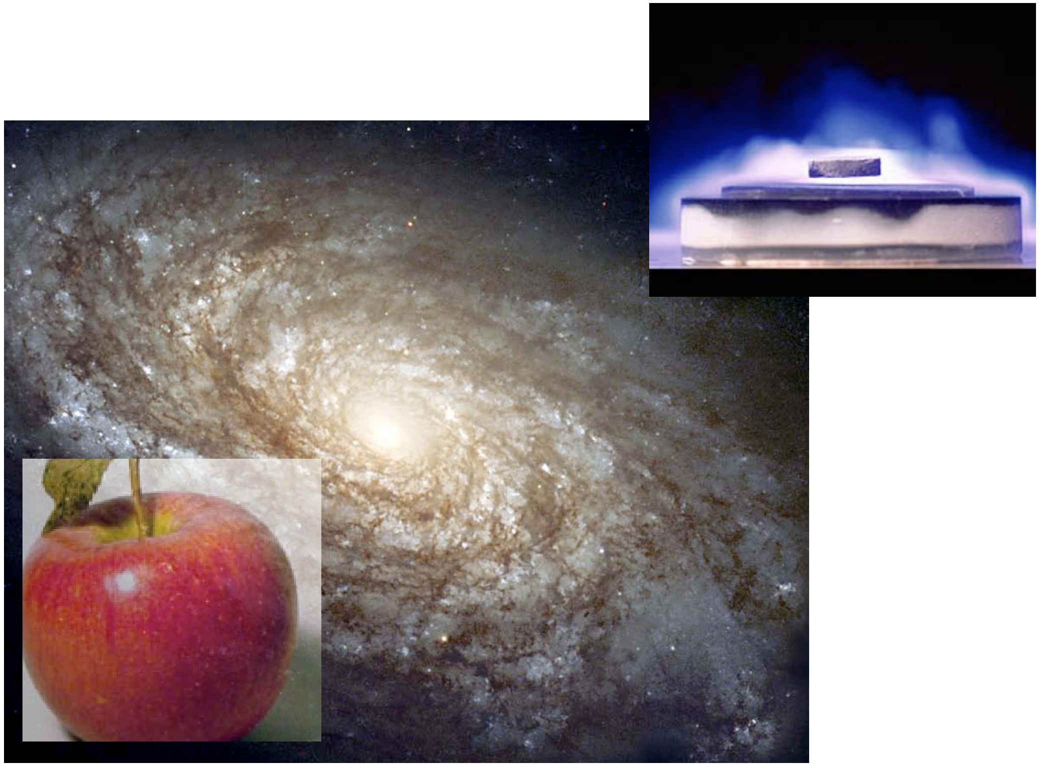

Lebanon

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

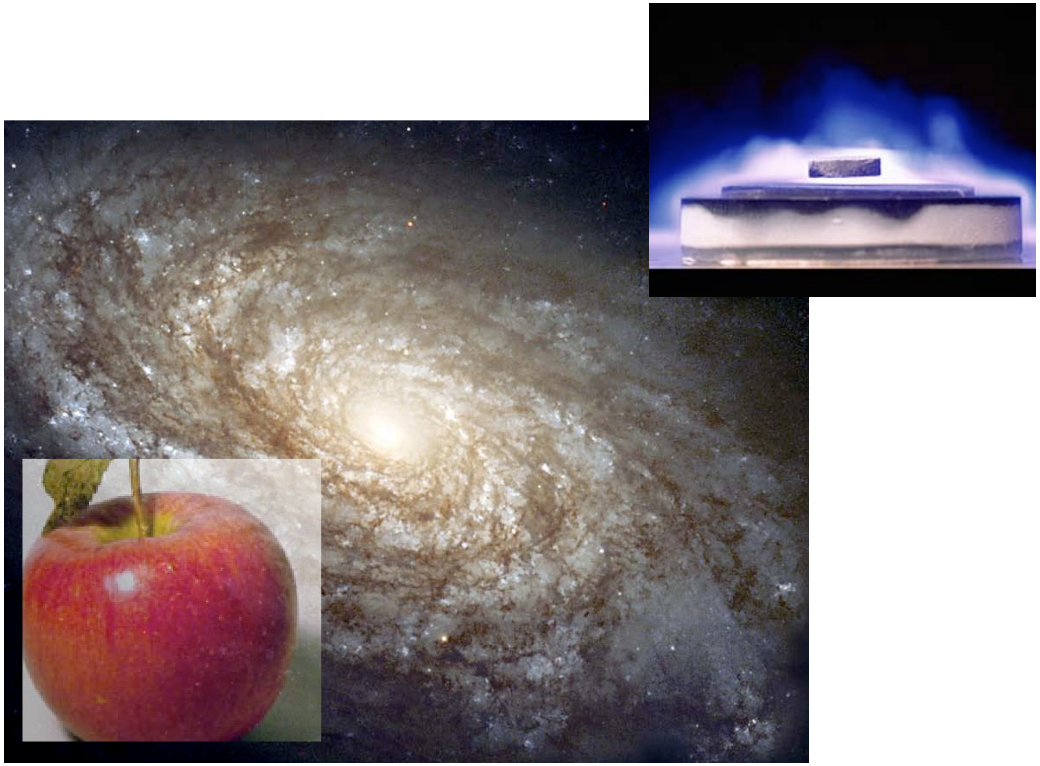
P. Coleman and A. J. Schofield, Nature (London) 433, 226 (2005).
P. Gegenwart, Q. M. Si, F. Steglich, Nature Physics 4, 157 (2008).

- Quantum Criticality: critical zero point motion
- Heavy electron quantum criticality
- Breakdown of the standard model.
- New ideas and approaches.

Quantum zero point fluctuations:



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



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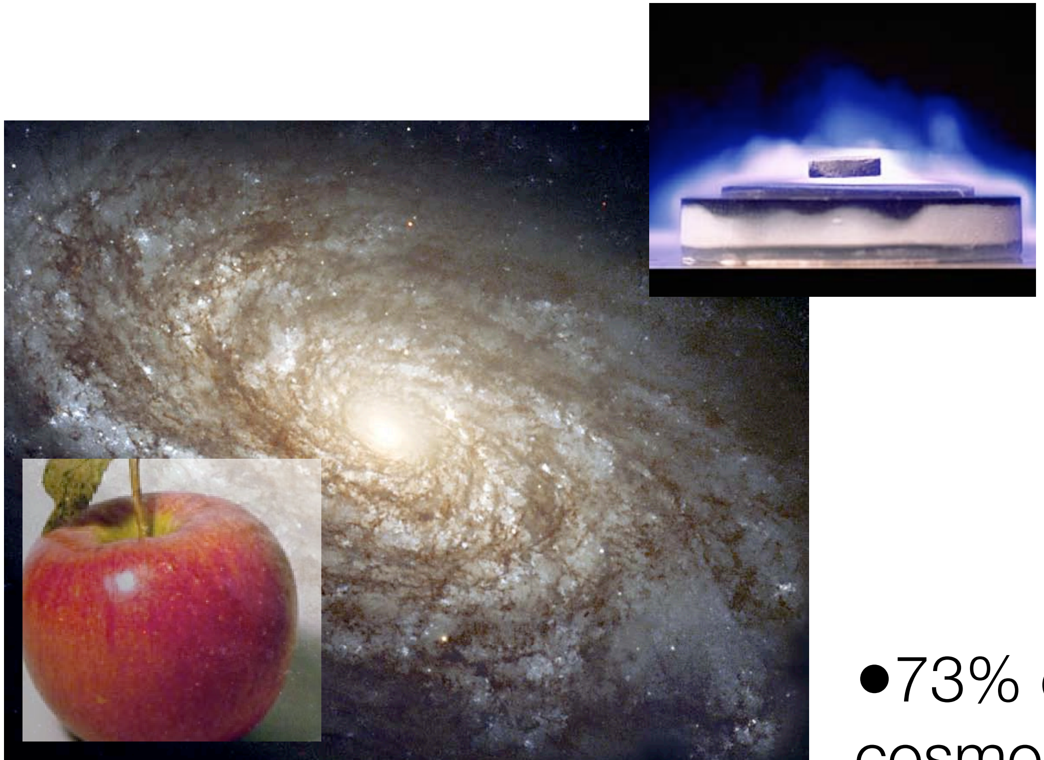
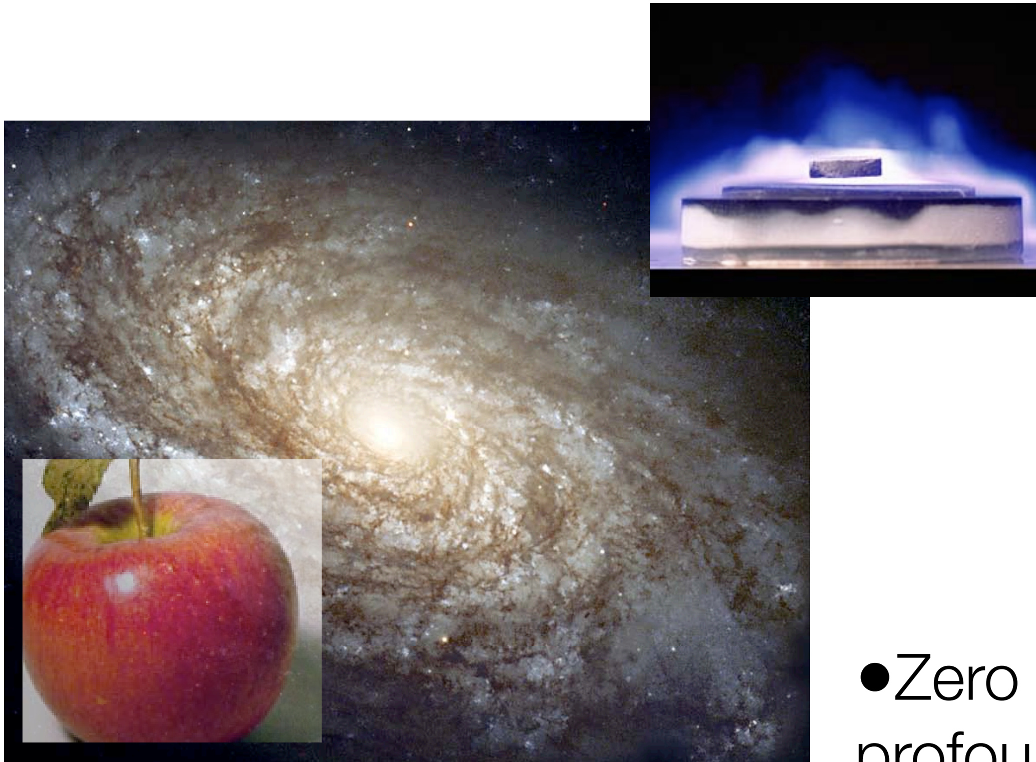


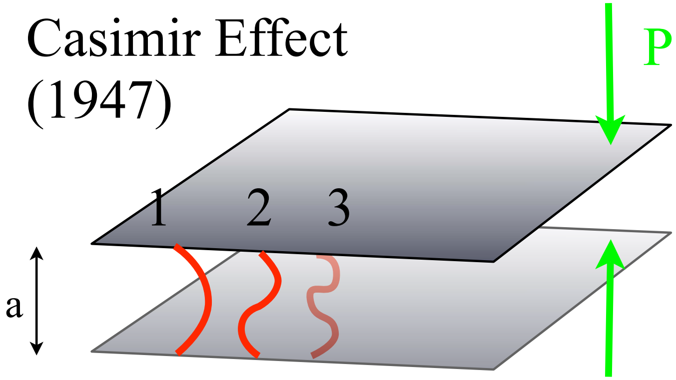
- 73% of the mass of the cosmos is “Dark Energy”: an unidentified form of zero point energy, causing the expansion to accelerate.

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.

Casimir Effect
(1947)



$$\frac{E_{ZP}}{A} = 2 \times \sum_{q_\perp, n} \frac{\hbar \omega_{qn}}{2}$$

$$= \sum_{n>0} \int \frac{q dq}{\pi} \hbar \omega_{qn}$$

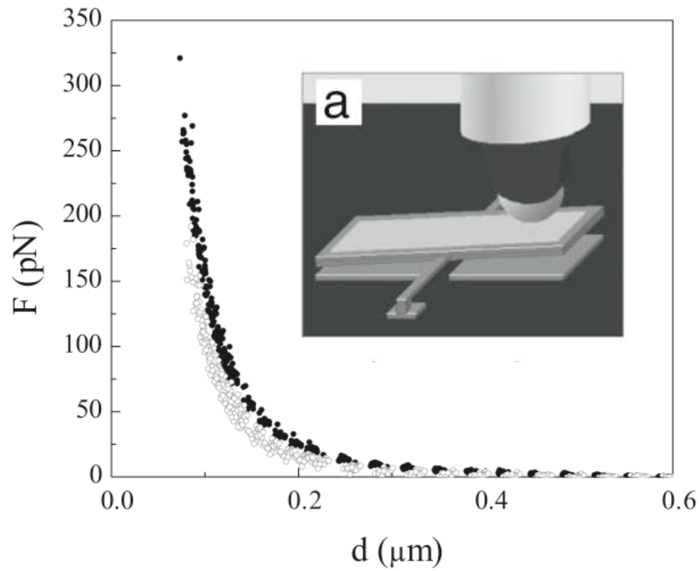
$$\frac{\Delta E_{ZP}}{A} = -\frac{\pi^2 \hbar c}{720 a^3}$$

$$P = -\frac{1}{A}\frac{\partial E_{ZP}}{\partial a} = \frac{\pi^2 \hbar c}{240 a^4}$$

$$q_n = \left(\frac{\pi}{a}\right) n$$

$$\omega_{qn} = c\sqrt{q_\perp^2 + n^2 \left(\frac{\pi}{a}\right)^2}$$

Discrete modes

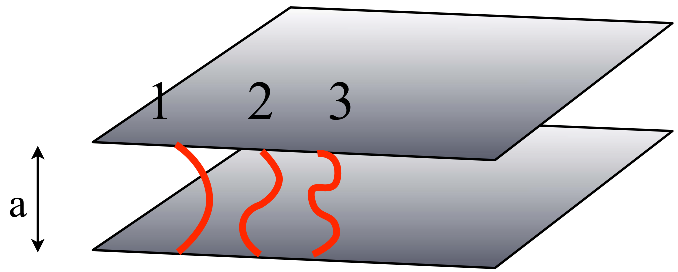


Lisanti,Iannuzi and Capasso
(PNAS, 2005)

4

Casimir Effect : alternative interpretation

Palova, Chandra, Coleman (08)



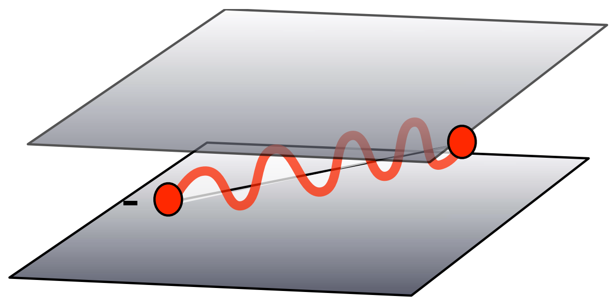
Manifestation of the quantum criticality of the vacuum

$$V(r) \sim \frac{1}{4\pi\epsilon_0 r}, \qquad V(q) \sim \frac{1}{\epsilon_0 q^2}$$

$$V(q) \sim \langle \delta\phi_q \delta\phi_{-q} \rangle = \frac{1}{q^2} \rightarrow \frac{1}{q_\perp^2 + \left(\frac{\pi}{a}\right)^2}$$

Plates remove zero modes
Inducing finite correlation length

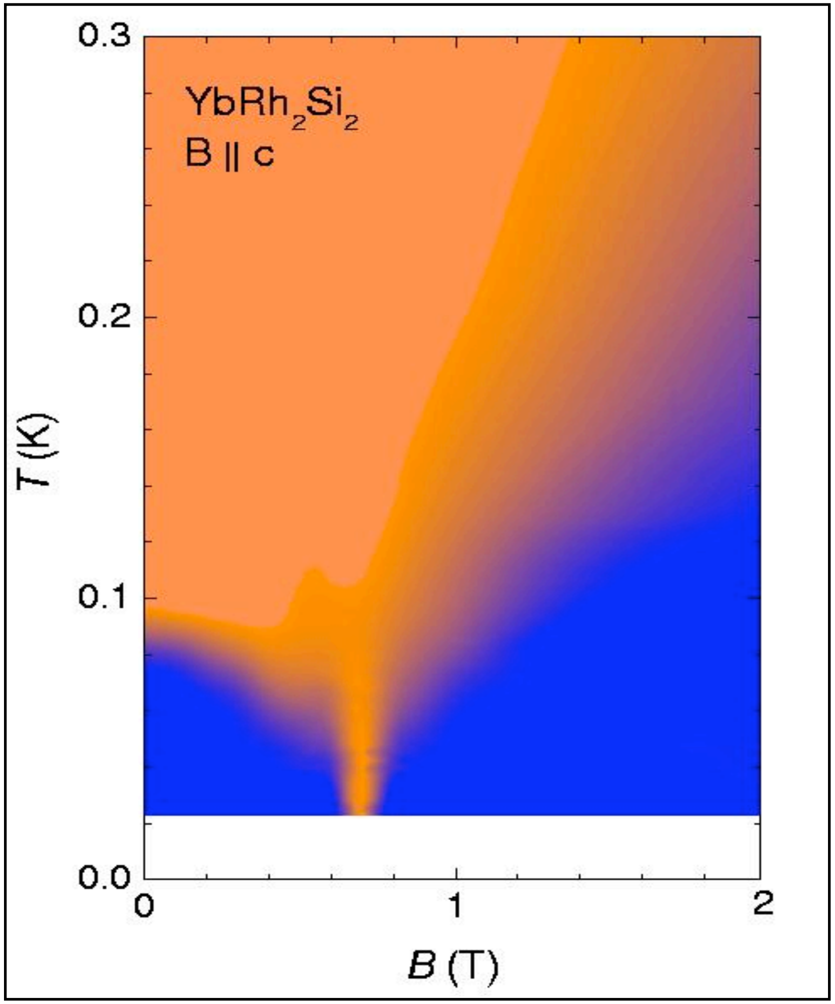
$$\xi = \frac{a}{\pi}$$



$$V(r) \sim \ln r \times e^{-r/\xi}$$

Quantum Phase-Transition

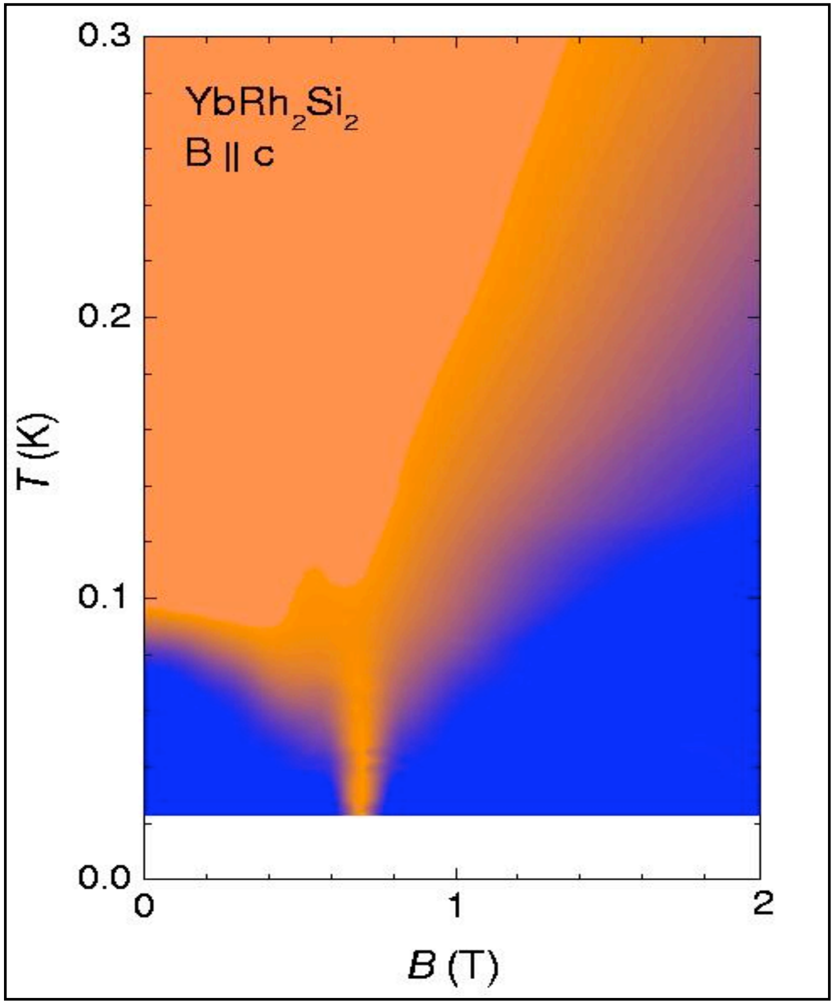
Custers et al (2002)



Quantum Phase-Transition

Custers et al (2002)

Phase transition
driven by zero point energy.



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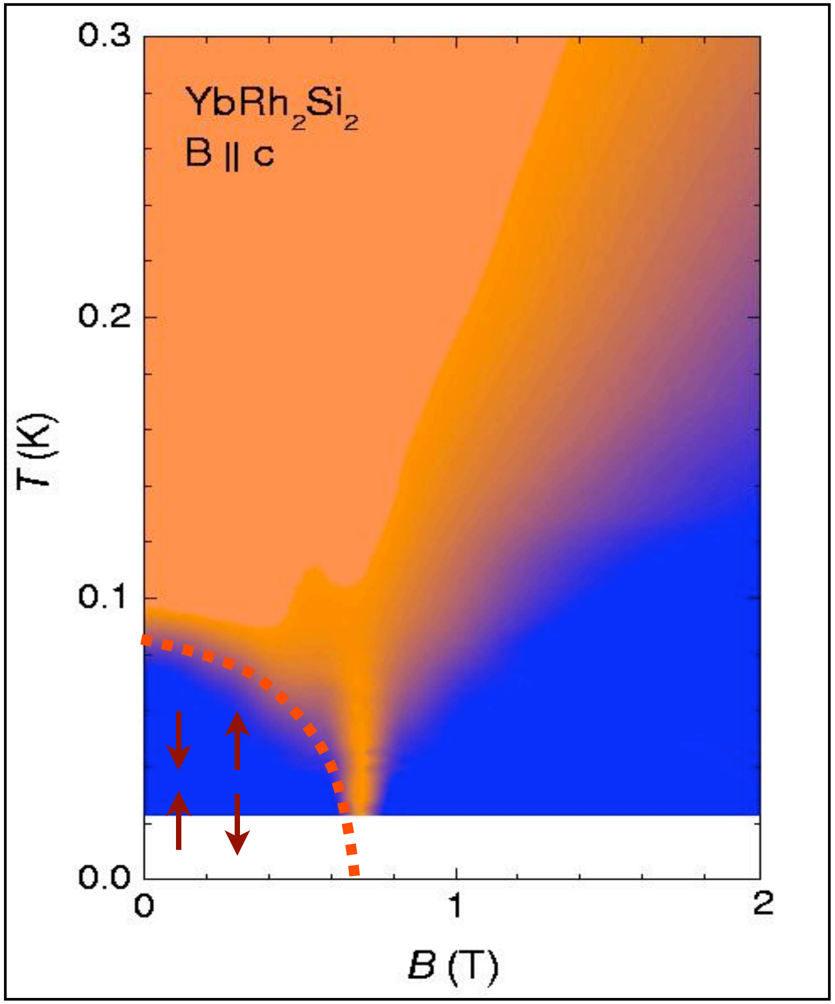

Quantum Phase-Transition

Phase transition
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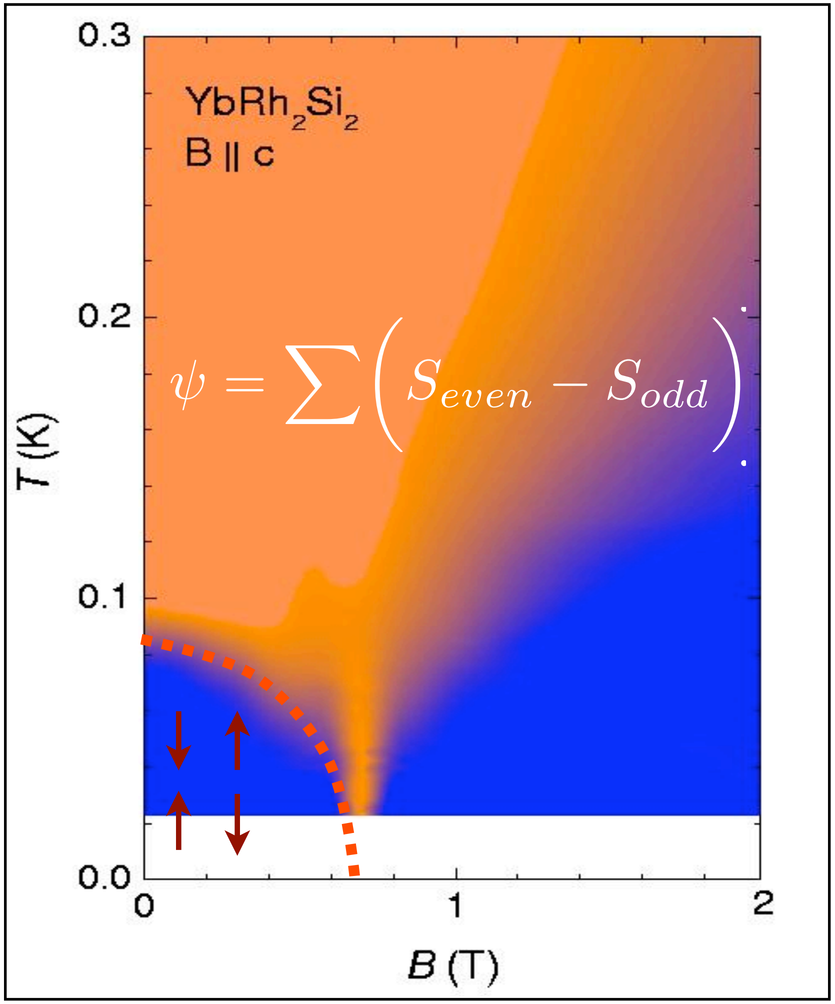
$$[H, \psi] \neq 0$$

Custers et al (2002)



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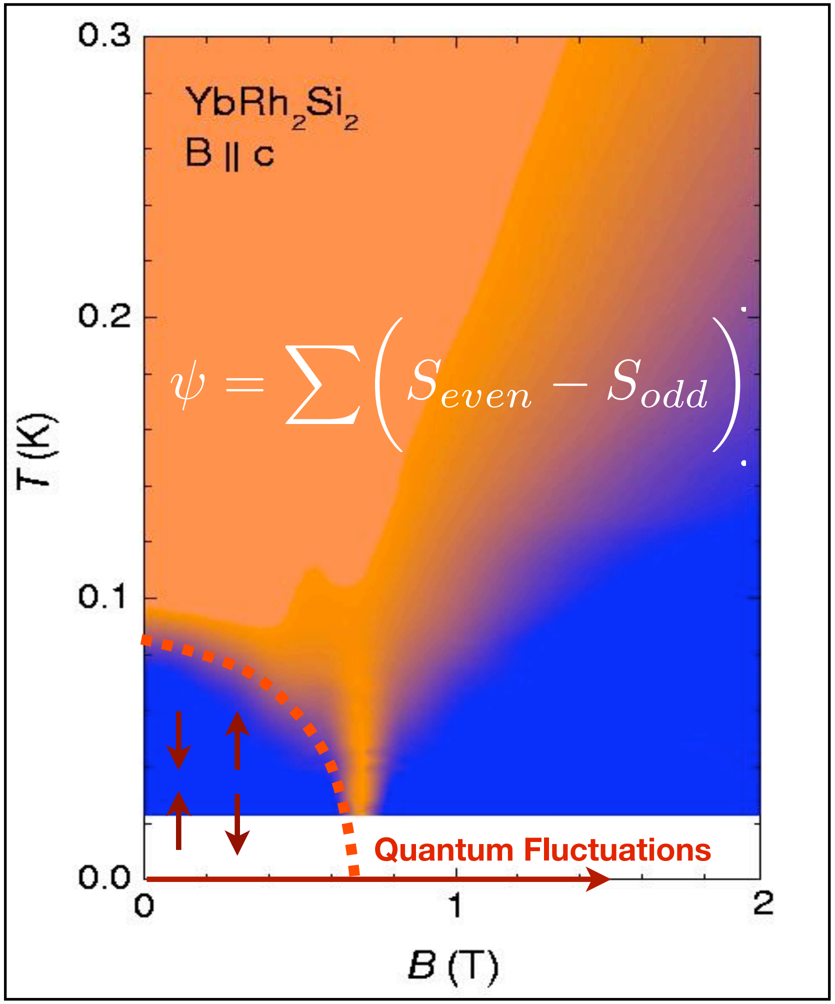

What happens when the time and length scale of coherent fluctuations expands to fill the entire material?

Quantum Phase-Transition

Custers et al (2002)

Phase transition
driven by zero point energy.

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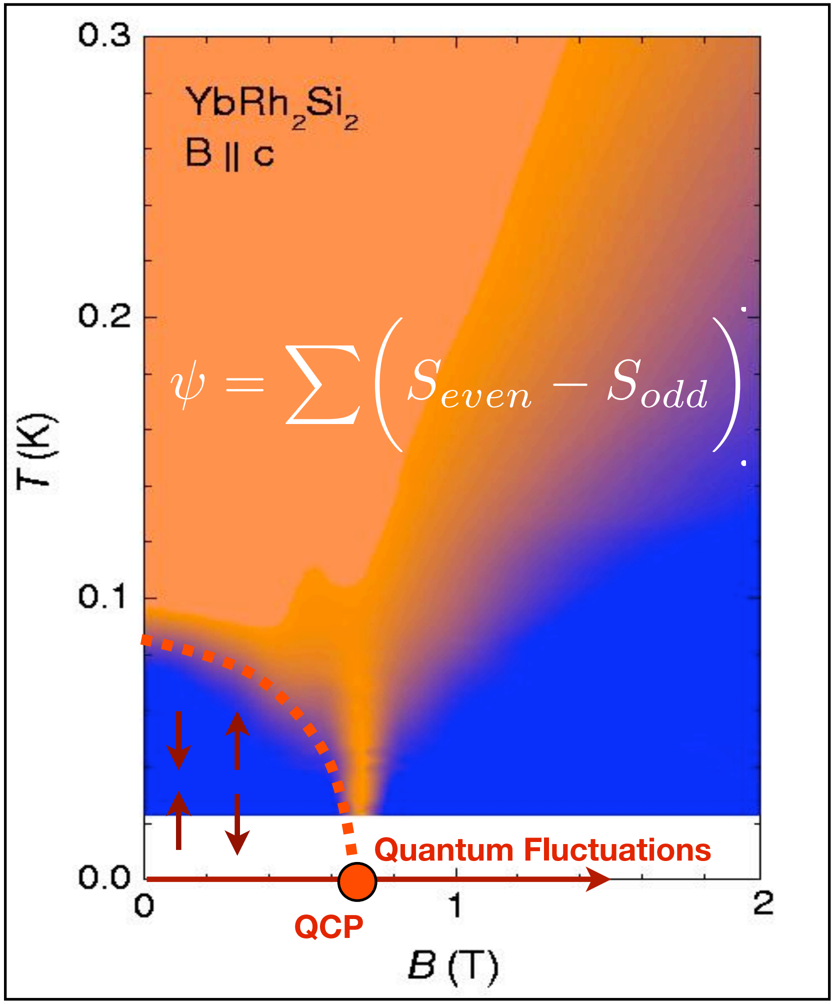


What happens when the time and length scale of coherent fluctuations expands to fill the entire material?

Many quantum critical points:

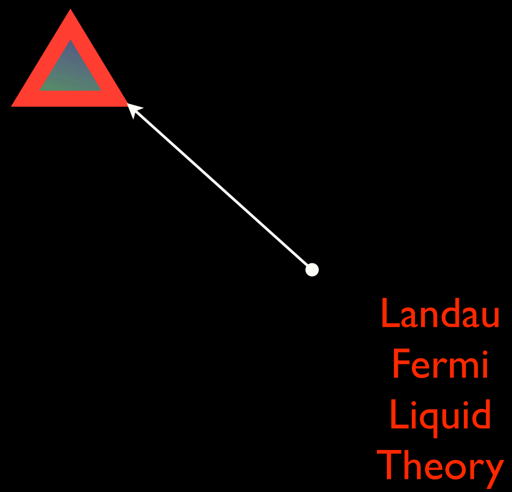
- SC/Insulating
- Ferro-electric; multiferroic
- Quantum Hall.
- Quantum Critical End points
- Mott-Hubbard
- (Antiferro) magnetic *

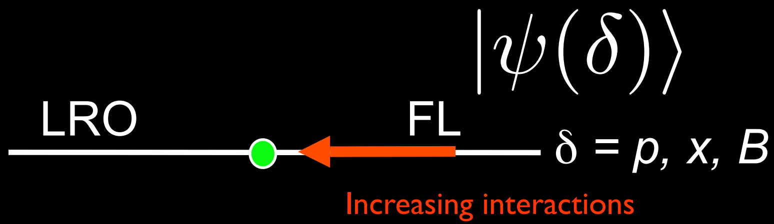
Collision of ideas.

$$|\psi(\delta)\rangle$$

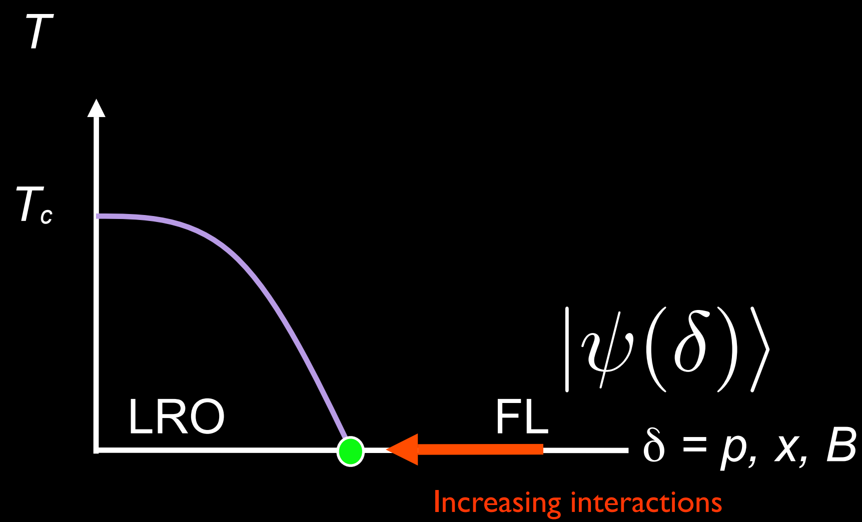
FL

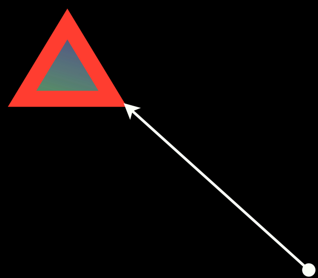
Collision of ideas.





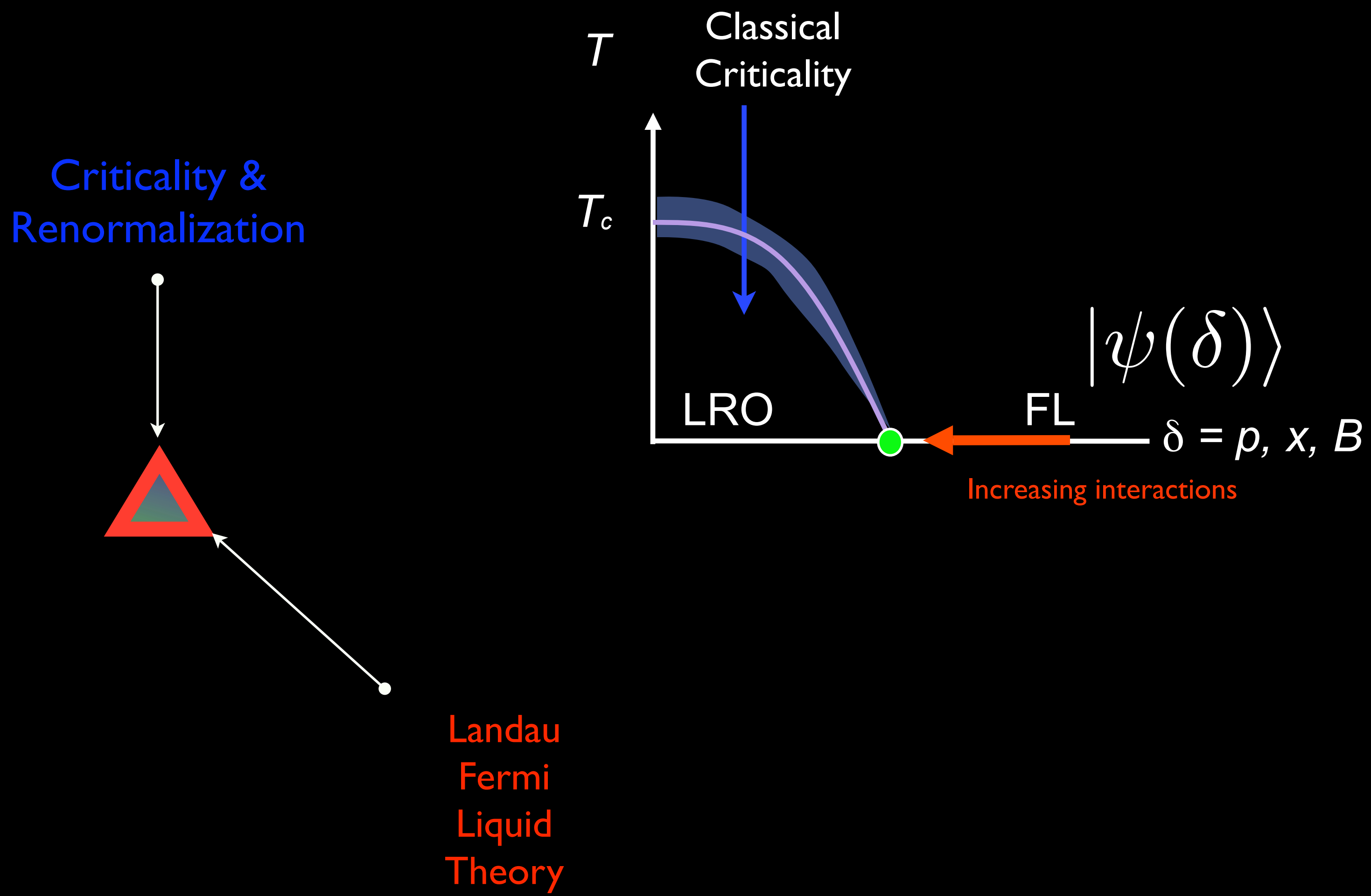
Collision of ideas.



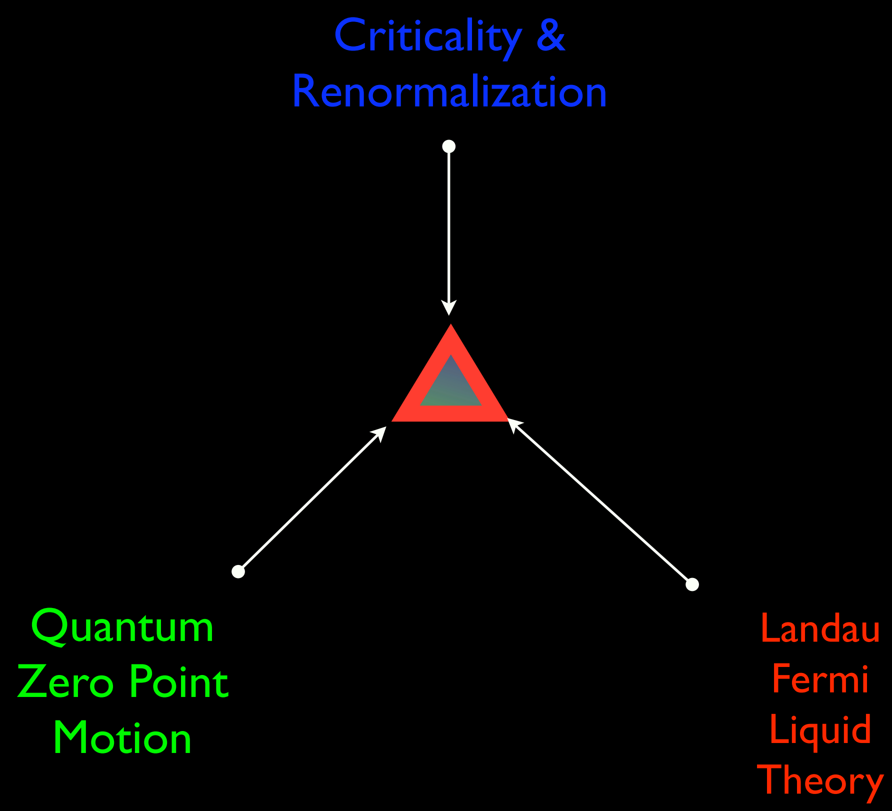


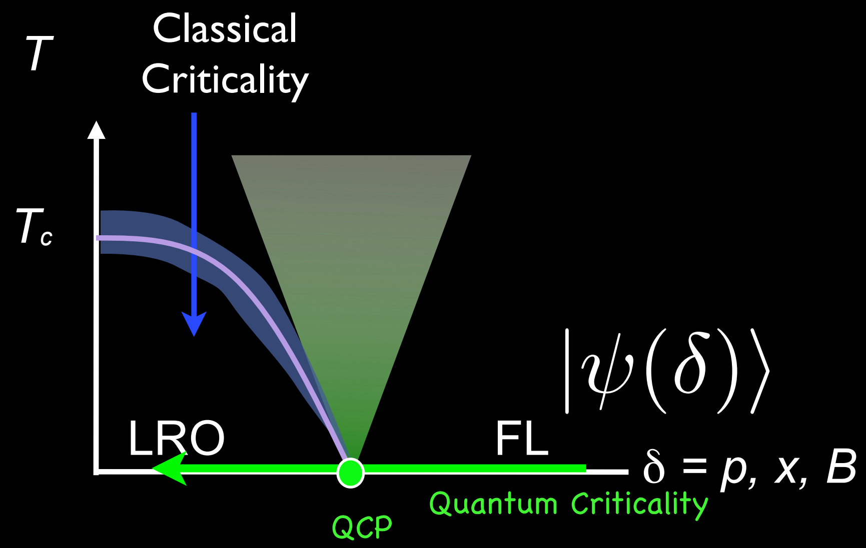
Landau
Fermi
Liquid
Theory

Collision of ideas.

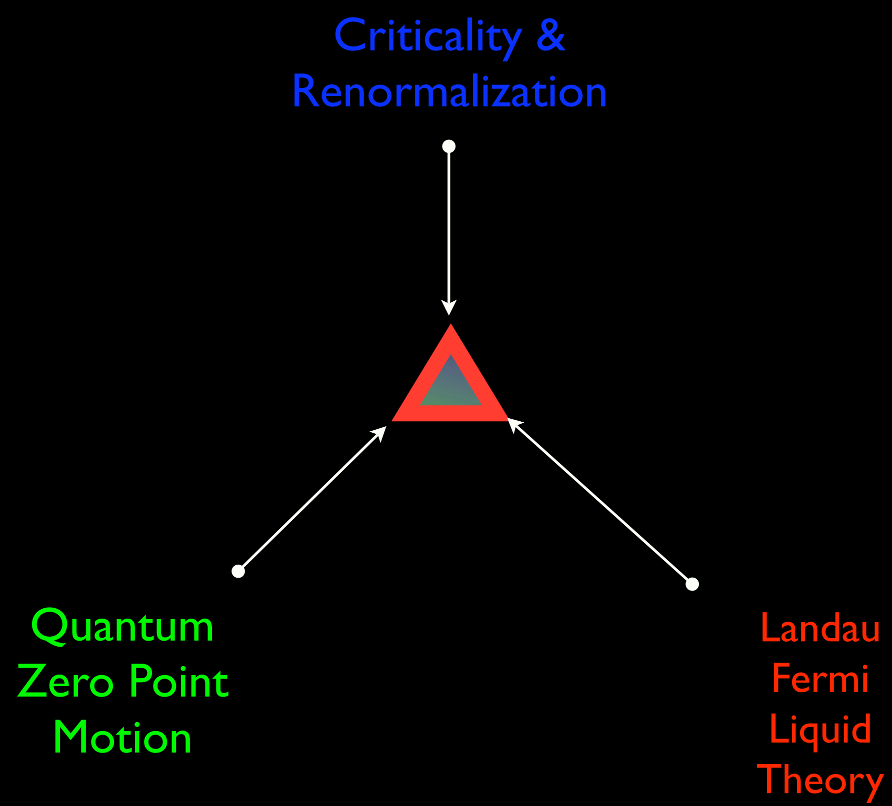


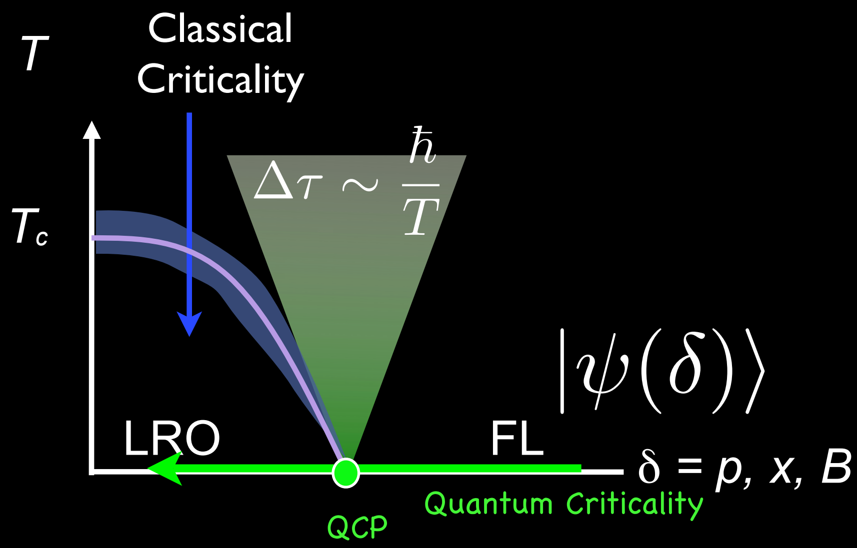
Collision of ideas.





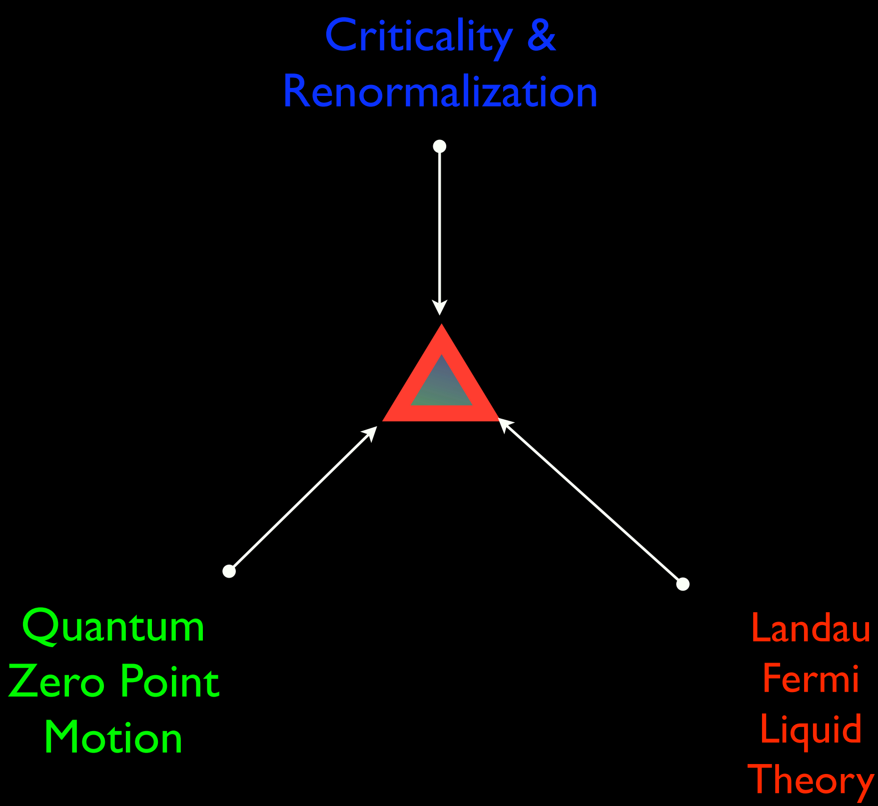
Collision of ideas.

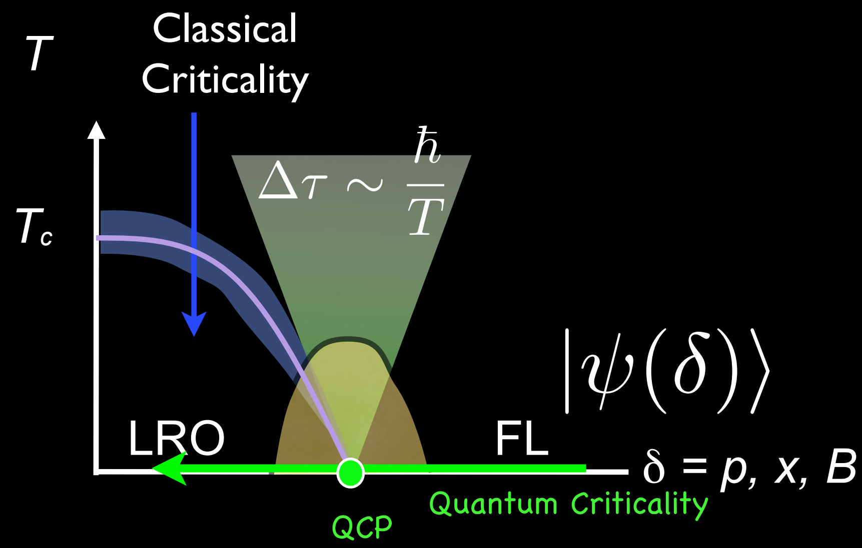




•Temperature NOT a tuning parameter, but a boundary condition in time.

Collision of ideas.





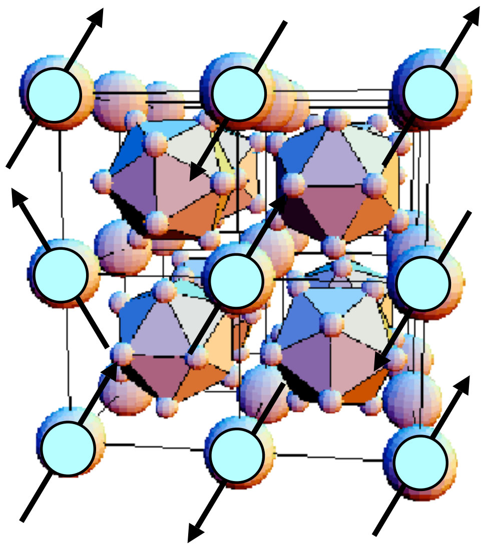
- Temperature NOT a tuning parameter, but a boundary condition in time.

- New phases tend to nucleate around unstable fixed point.

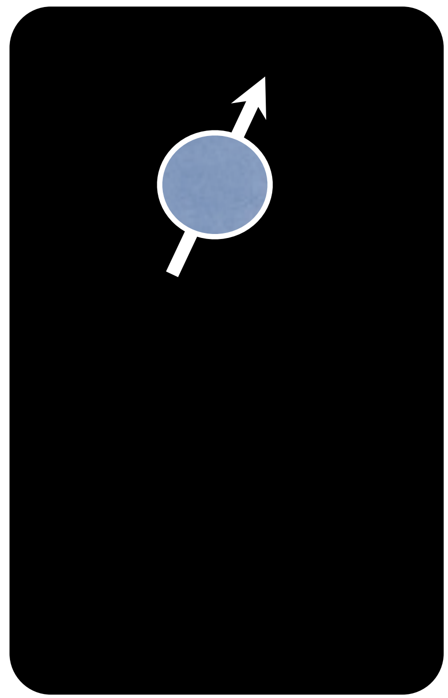
Heavy Electron Quantum Criticality.

Heavy Fermion Metals

Review: cond-mat/0612006



UBe_{13}



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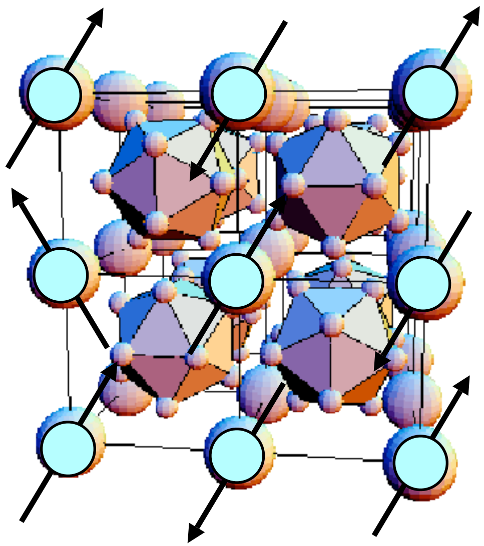

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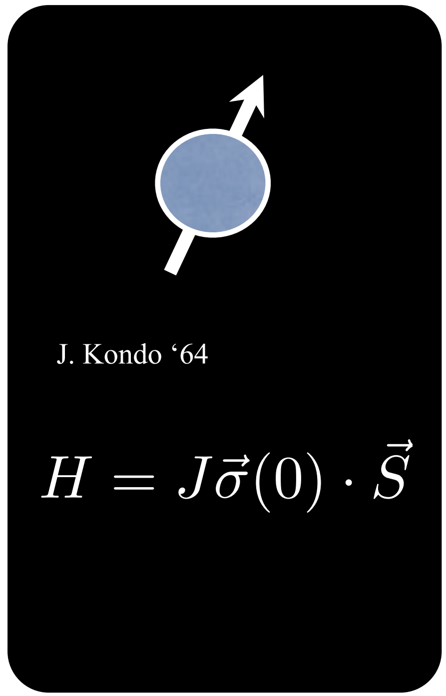

Heavy Fermion Metals

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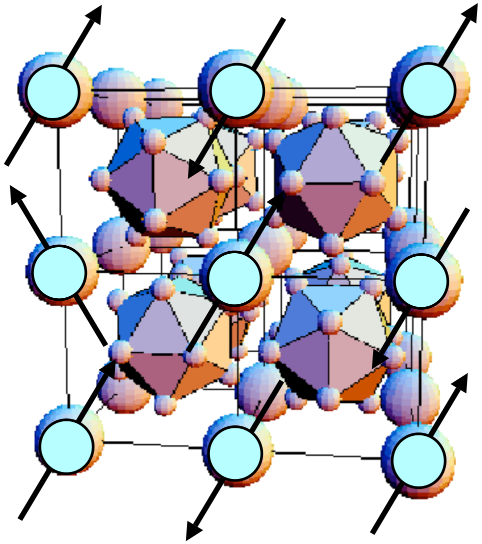

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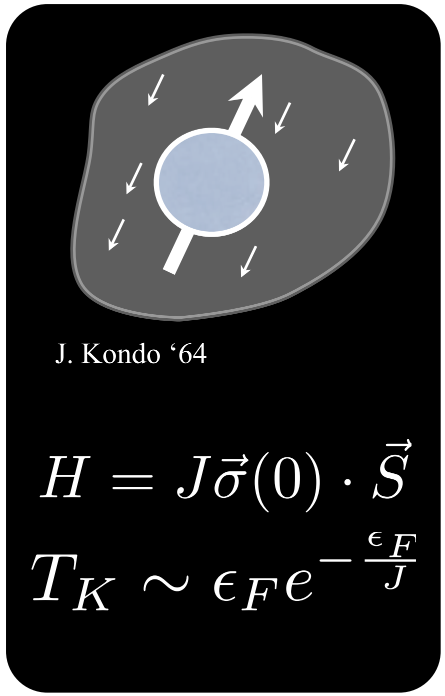
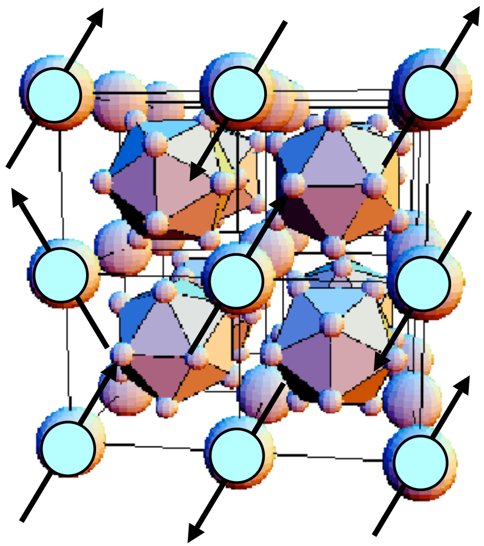


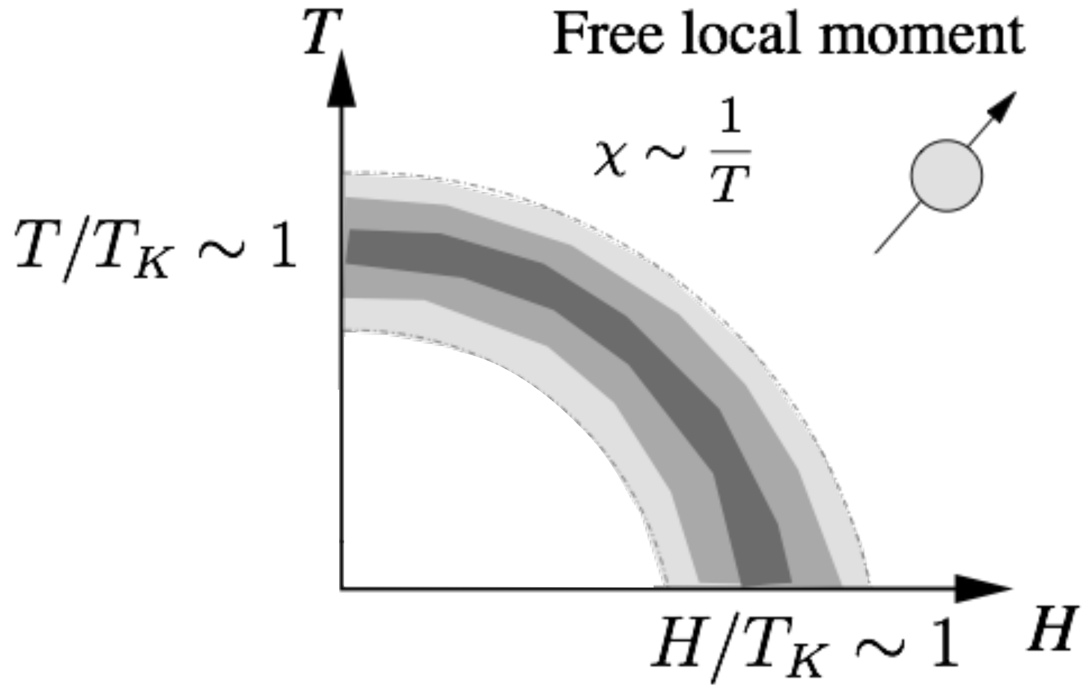
"Kondo Effect"

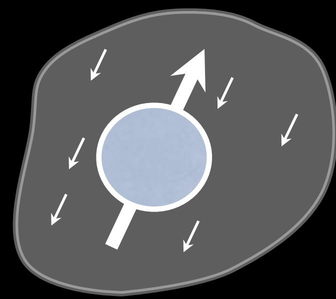
Heavy Fermion Metals

[Review: cond-mat/0612006](cond-mat/0612006)



UBe_{13}





J. Kondo '64

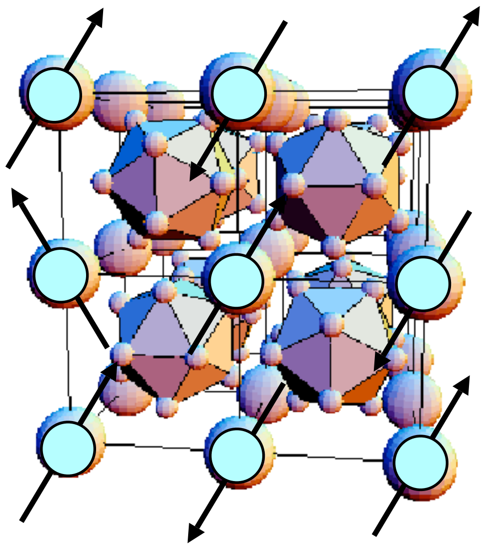
$$H = J\vec{\sigma}(0) \cdot \vec{S}$$

$$T_K \sim \epsilon_F e^{-\frac{\epsilon_F}{J}}$$

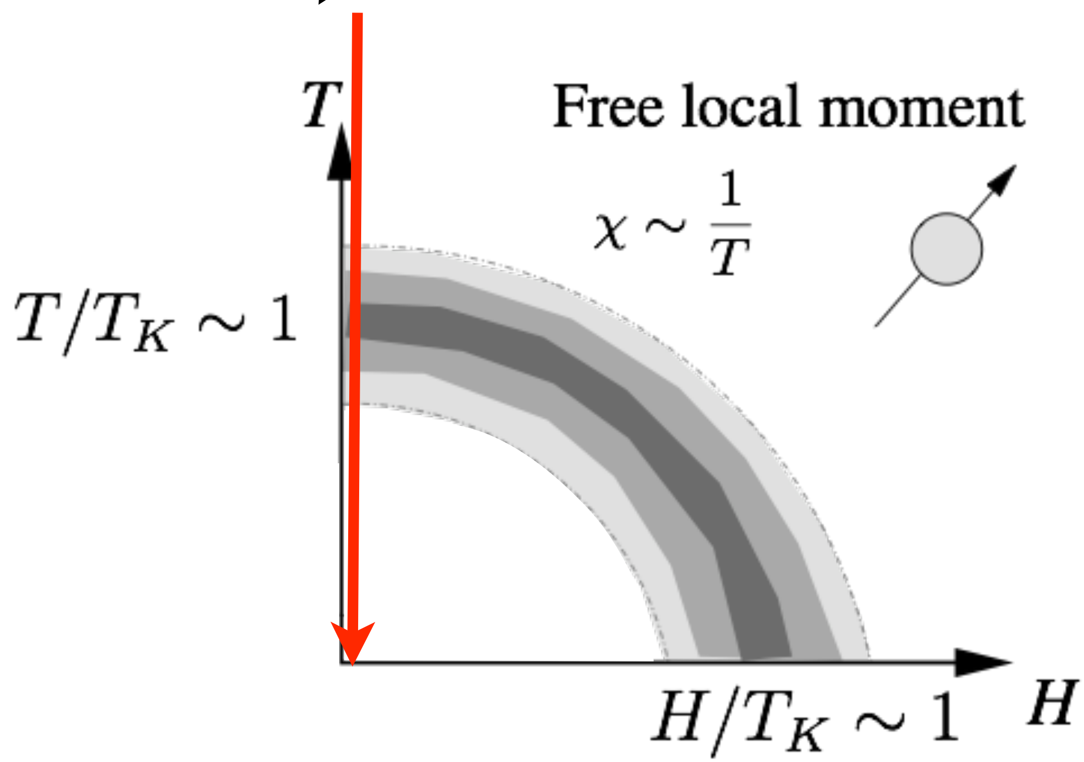
"Kondo Effect"

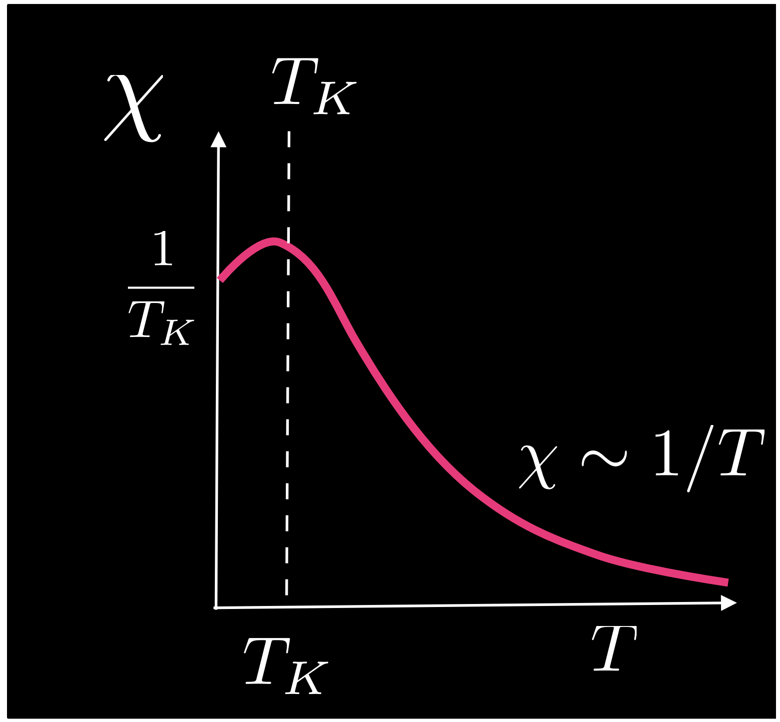
Heavy Fermion Metals

[Review: cond-mat/0612006](cond-mat/0612006)



UBe_{13}





"Kondo Effect"

Heavy Fermion Metals

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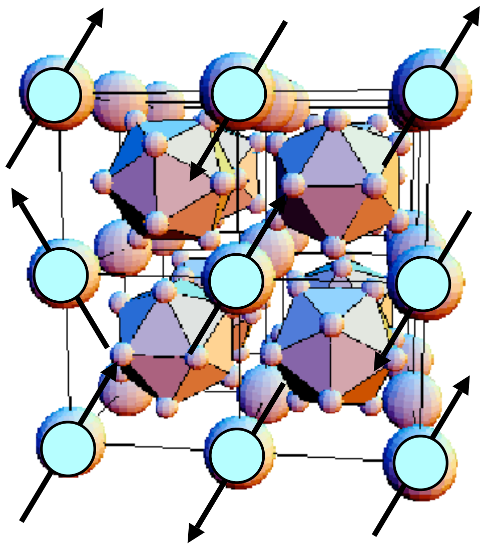
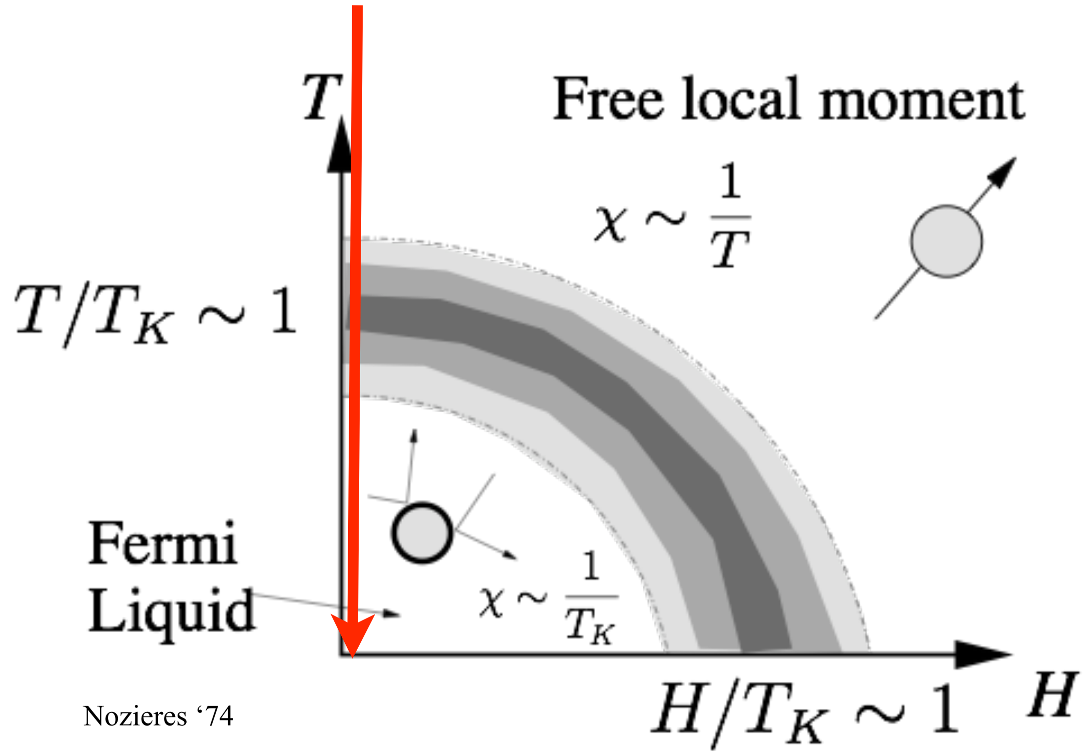
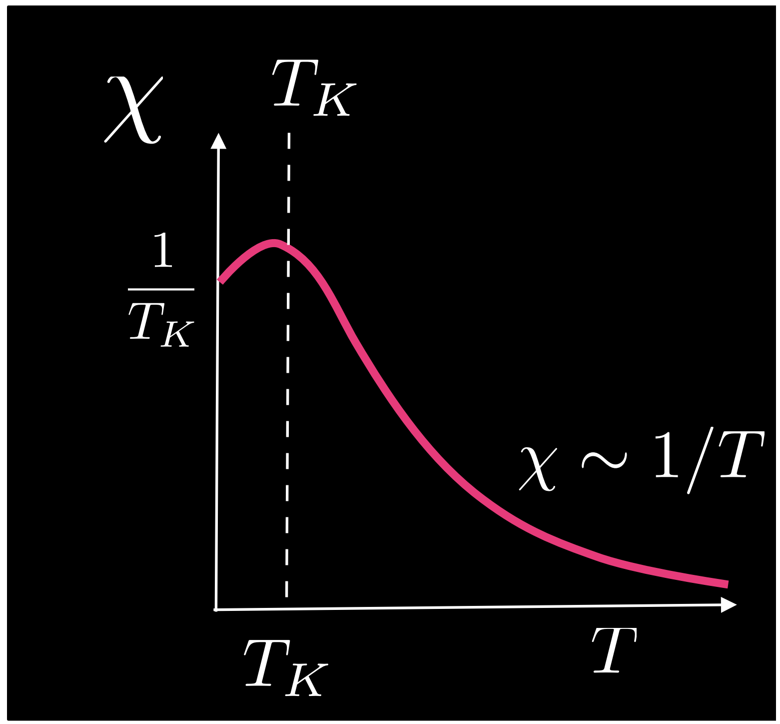


UBe_{13}



Nozieres '74



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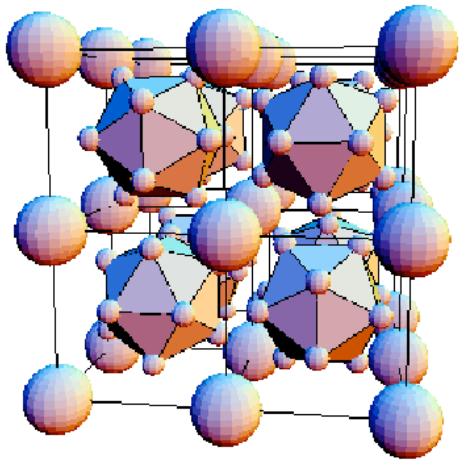
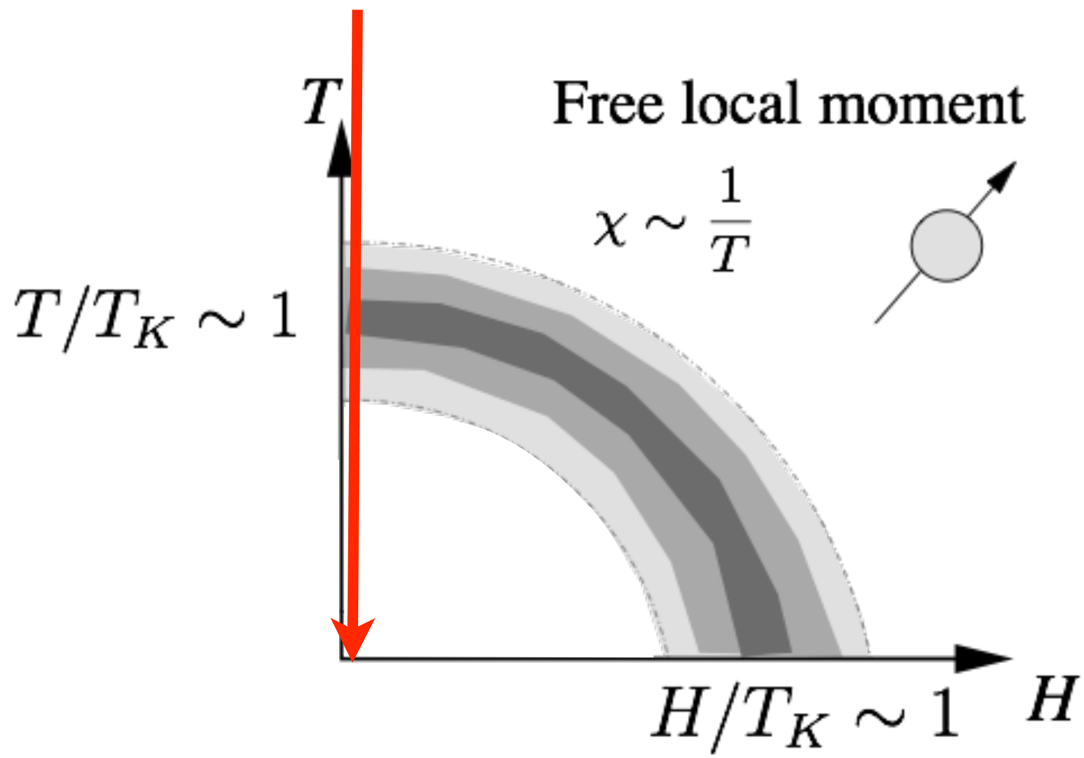
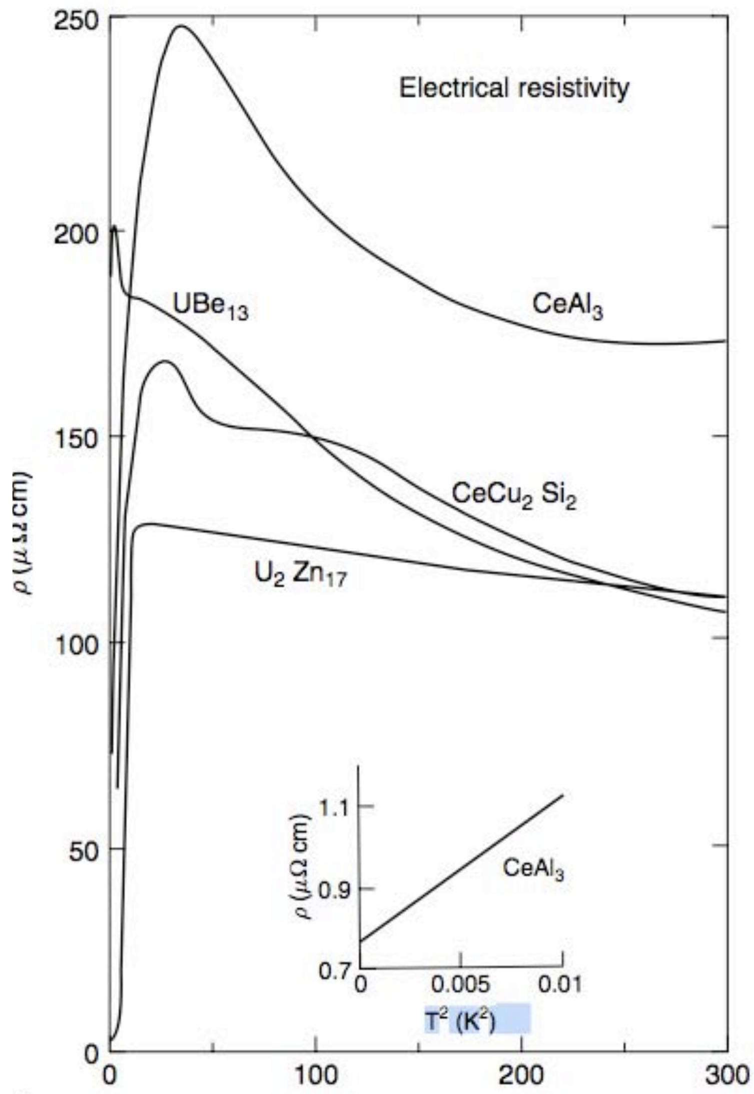


UBe_{13}

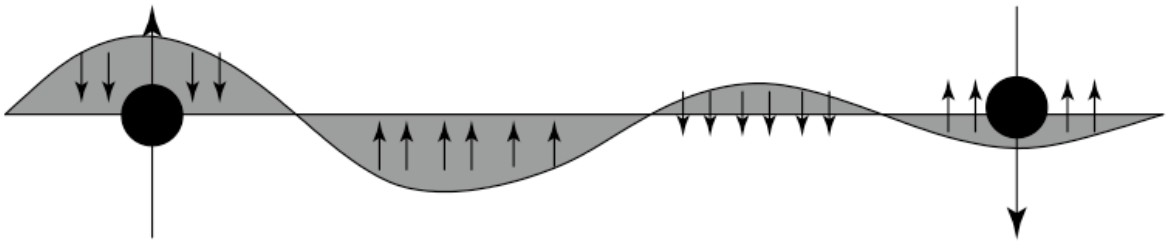




DONIACH'S Hypothesis.

Doniach (1977)

Friedel Oscillations



$$\langle \vec{\sigma}(r) \rangle \sim -J\rho \frac{\cos 2k_F r}{|k_F r|^3}$$

DONIACH'S Hypothesis.

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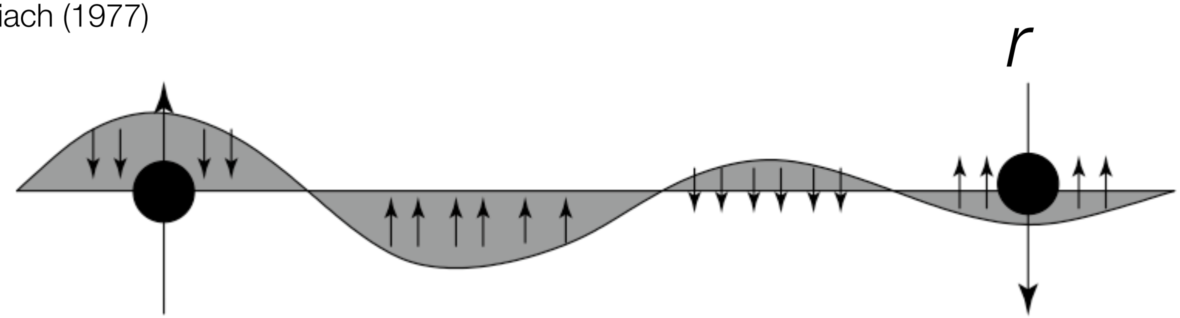
Friedel Oscillations



$$\langle \vec{\sigma}(r) \rangle \sim -J\rho \frac{\cos 2k_F r}{|k_F r|^3}$$

$$\langle \vec{\sigma}(\mathbf{x}) \rangle = -J\chi(\mathbf{x}-\mathbf{x}_0)\langle \vec{S}(\mathbf{x}_0) \rangle$$

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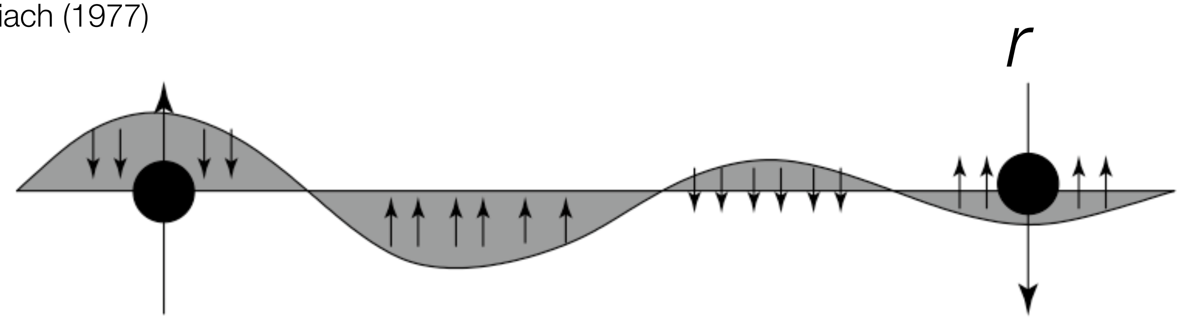

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$$\chi(x) = 2\sum_{\mathbf{k},\mathbf{k}'} \left(\frac{f(\epsilon_{\mathbf{k}}) - f(\epsilon_{\mathbf{k}'})}{\epsilon_{\mathbf{k}'} - \epsilon_{\mathbf{k}}} \right) e^{i(\mathbf{k}-\mathbf{k}')\cdot\mathbf{x}} \sim \rho \frac{\cos 2k_F r}{|k_F r|^3}$$

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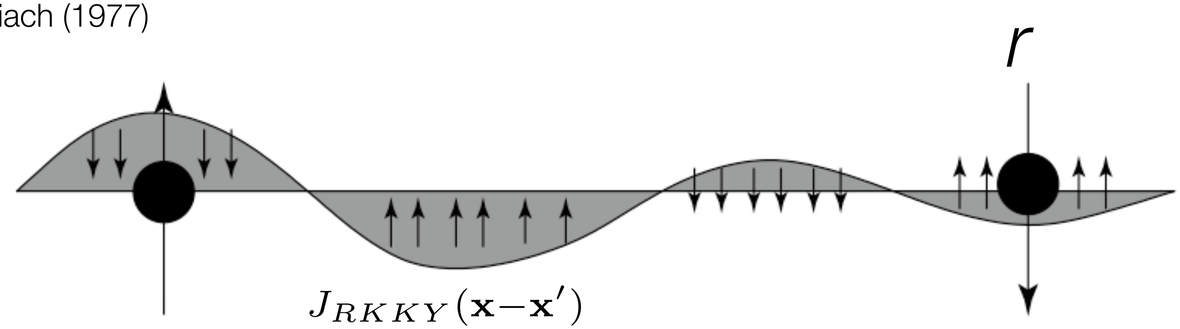

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$$H_{RKKY} = \overbrace{-J^2 \chi(\mathbf{x} - \mathbf{x}')}^{J_{RKKY}(\mathbf{x}-\mathbf{x}')} \vec{S}(\mathbf{x}) \cdot \vec{S}(\mathbf{x}').$$

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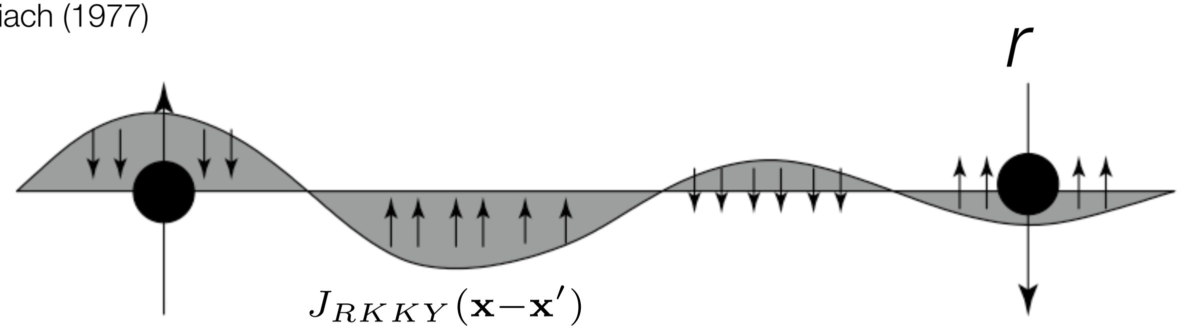

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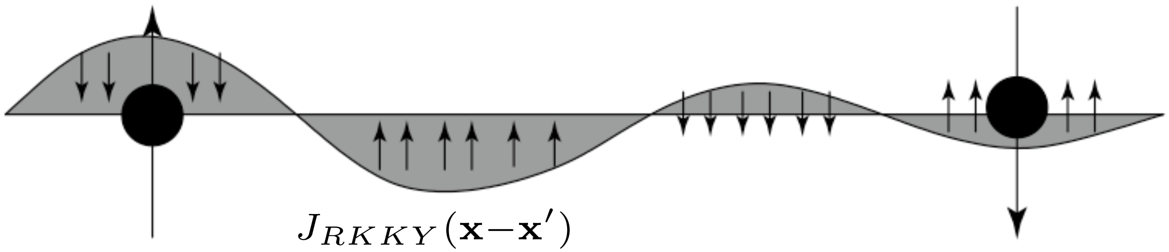
$$\begin{aligned} T_K &= De^{-1/(2J\rho)} \\ T_{RKKY} &= J^2 \rho \end{aligned}$$

DONIACH'S Hypothesis.

Doniach (1977)

Friedel Oscillations



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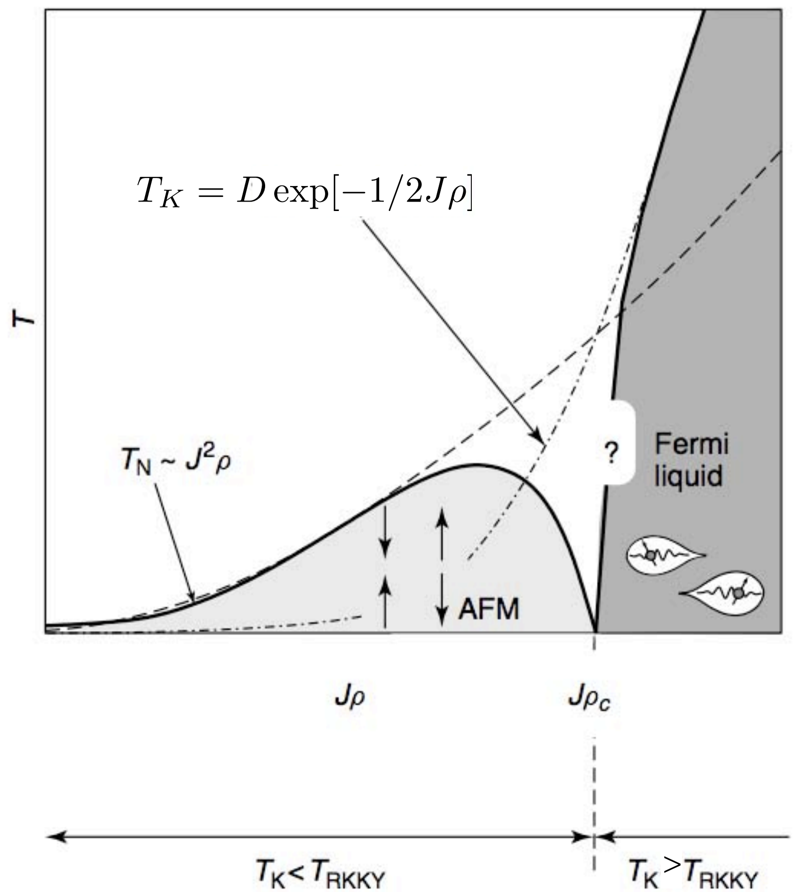
$$H_{RKKY} = \overbrace{-J^2\chi(\mathbf{x}-\mathbf{x}')}^{J_{RKKY}(\mathbf{x}-\mathbf{x}')} \vec{S}(\mathbf{x}) \cdot \vec{S}(\mathbf{x}').$$

$$\chi(x) = 2\sum_{\mathbf{k},\mathbf{k}'} \left(\frac{f(\epsilon_{\mathbf{k}}) - f(\epsilon_{\mathbf{k}'})}{\epsilon_{\mathbf{k}'} - \epsilon_{\mathbf{k}}} \right) e^{i(\mathbf{k}-\mathbf{k}')\cdot\mathbf{x}} \sim \rho \frac{\cos 2k_F r}{|k_F r|^3}$$

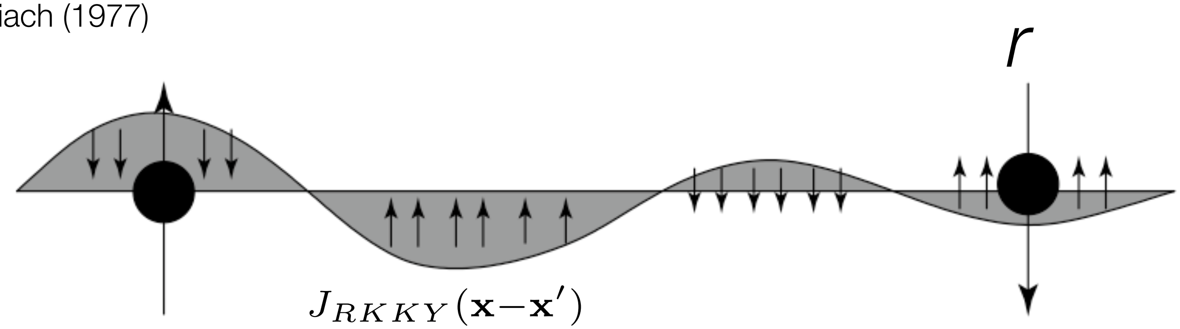
$$\begin{aligned} T_K &= De^{-1/(2J\rho)} \\ T_{RKKY} &= J^2\rho \end{aligned}$$



DONIACH'S Hypothesis.

Doniach (1977)

Friedel Oscillations



$$\langle \vec{\sigma}(r) \rangle \sim -J\rho \frac{\cos 2k_F r}{|k_F r|^3}$$

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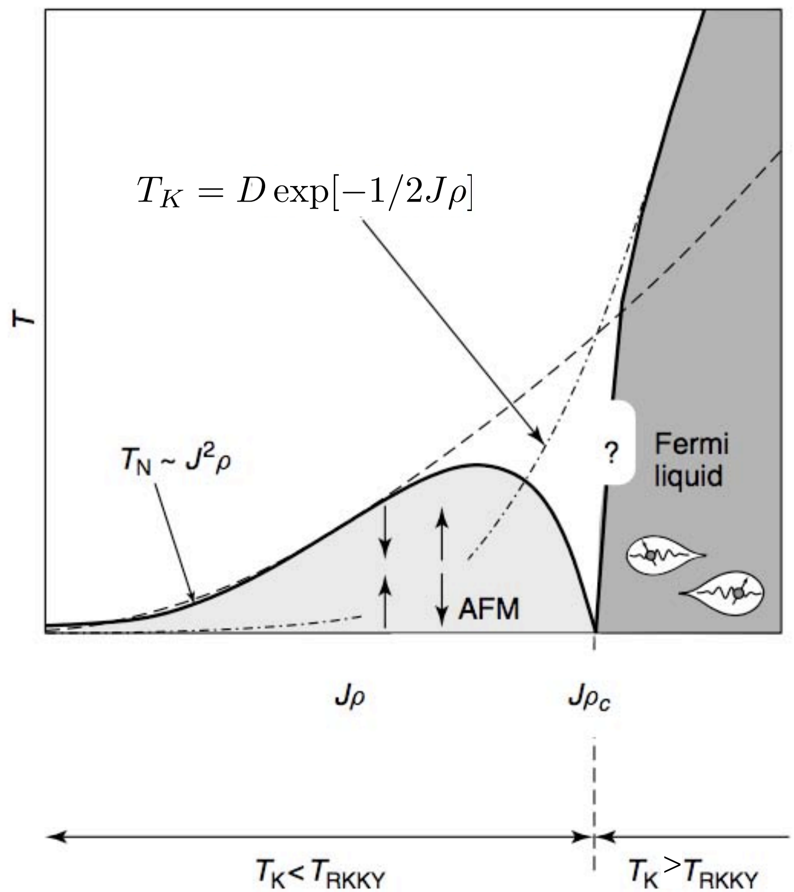
Increasing U: J ~ V^2/U



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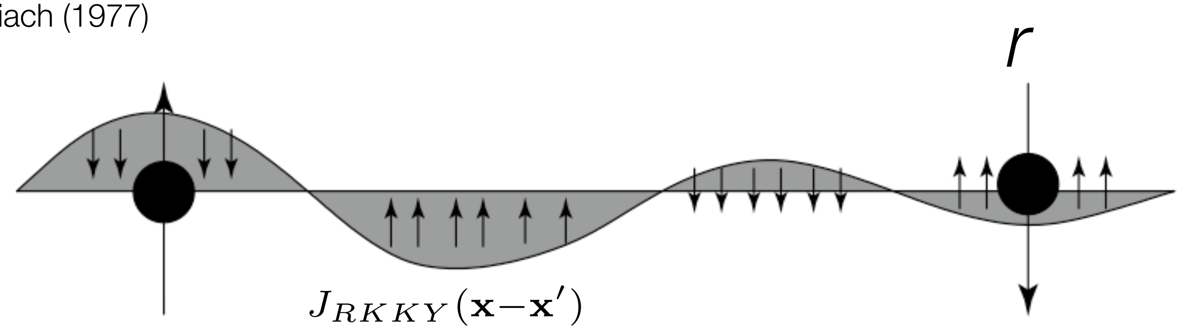

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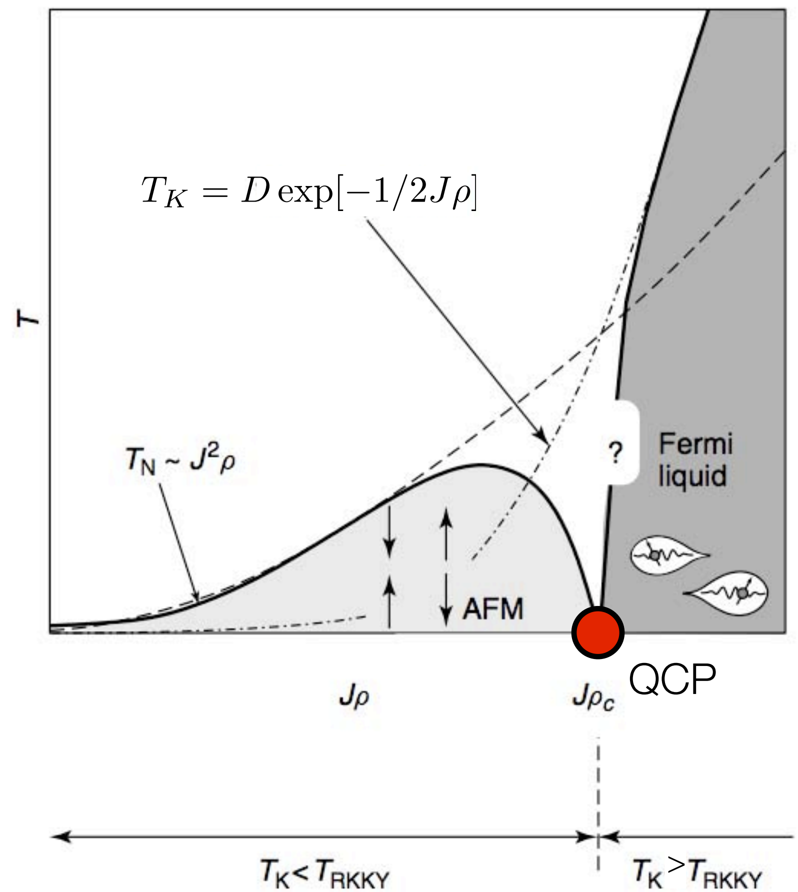
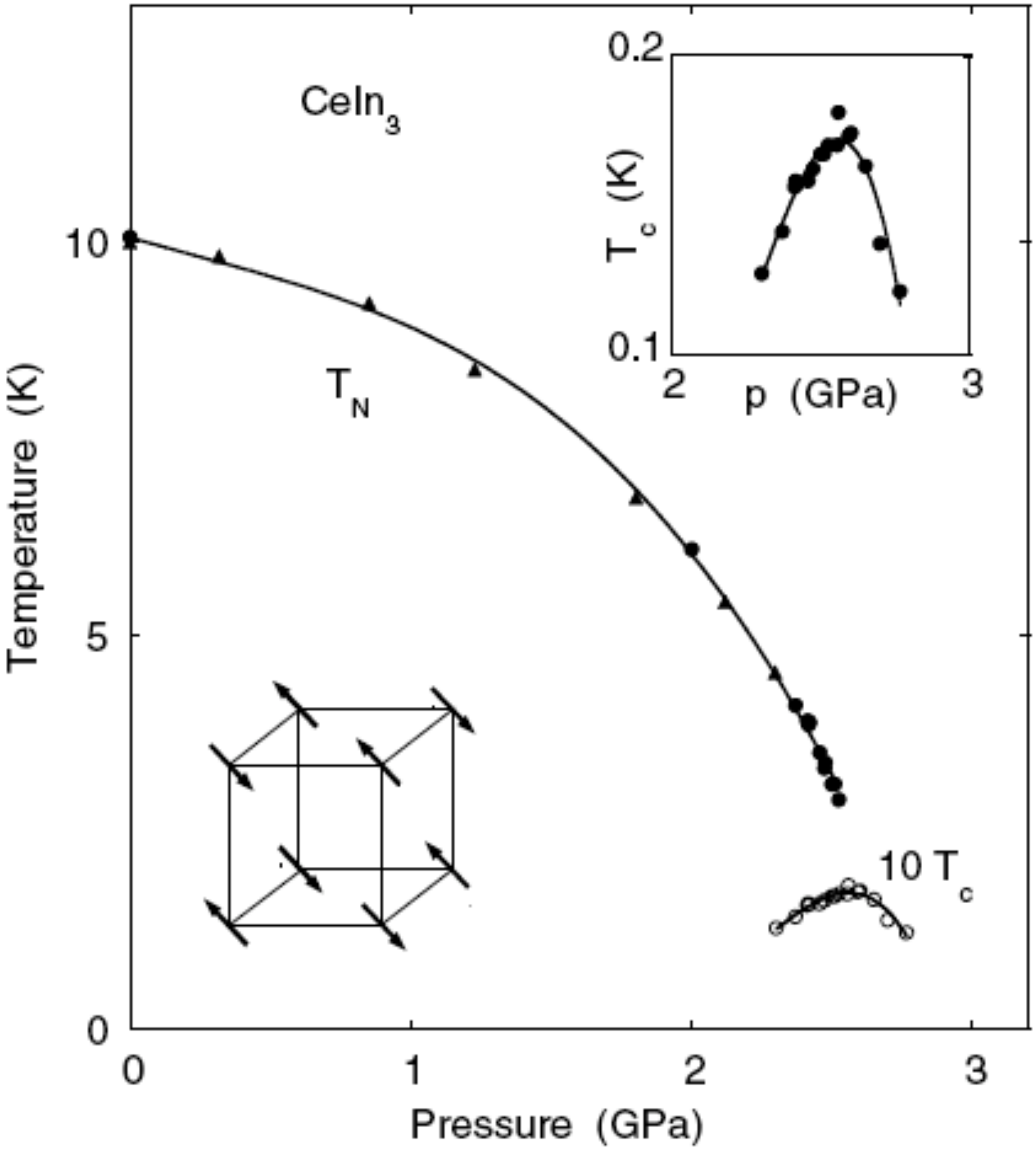
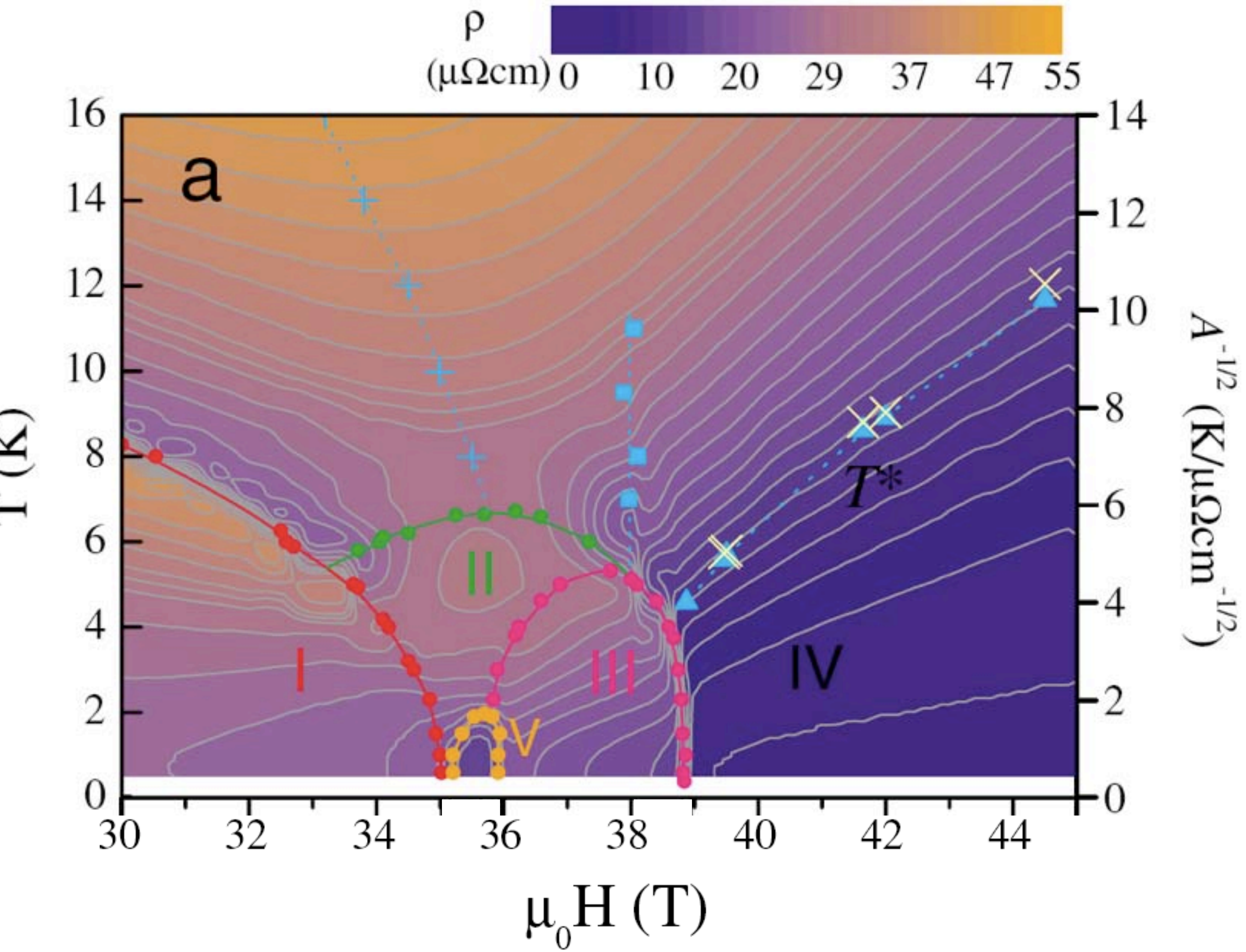
Increasing U: $J \sim V^2/U$



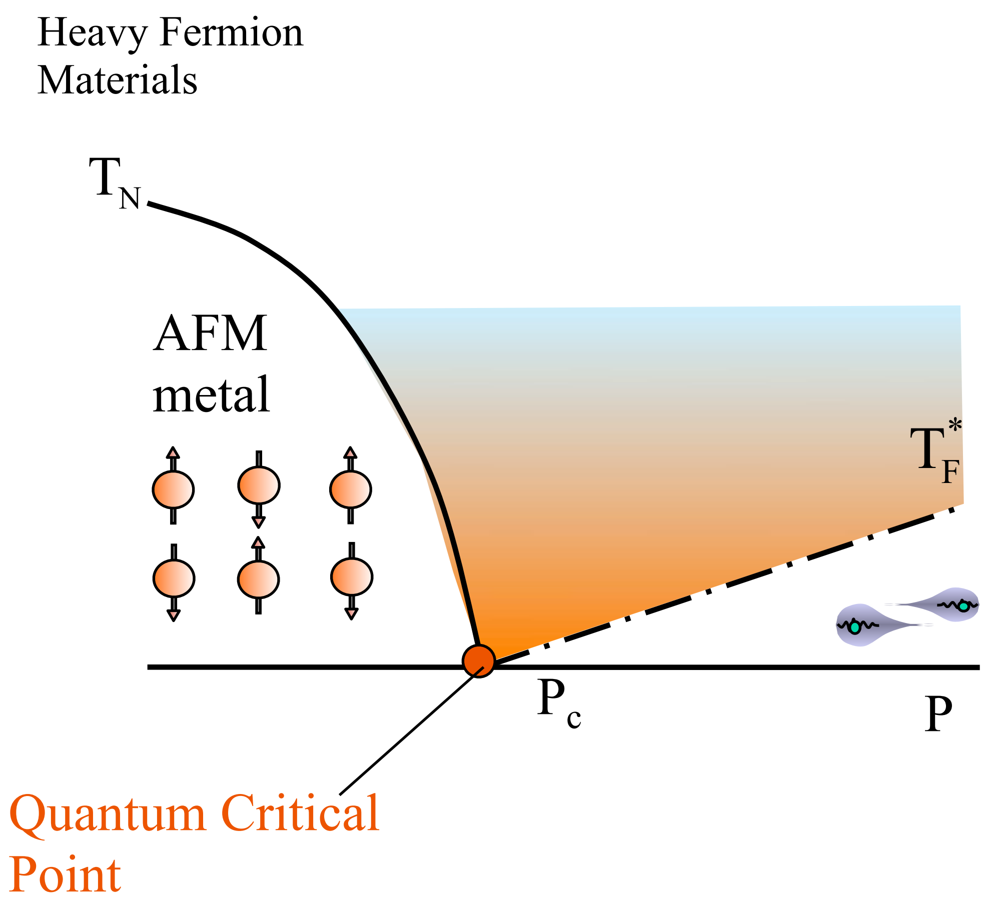


Mathur et al, Nature 394, 39 (1998)

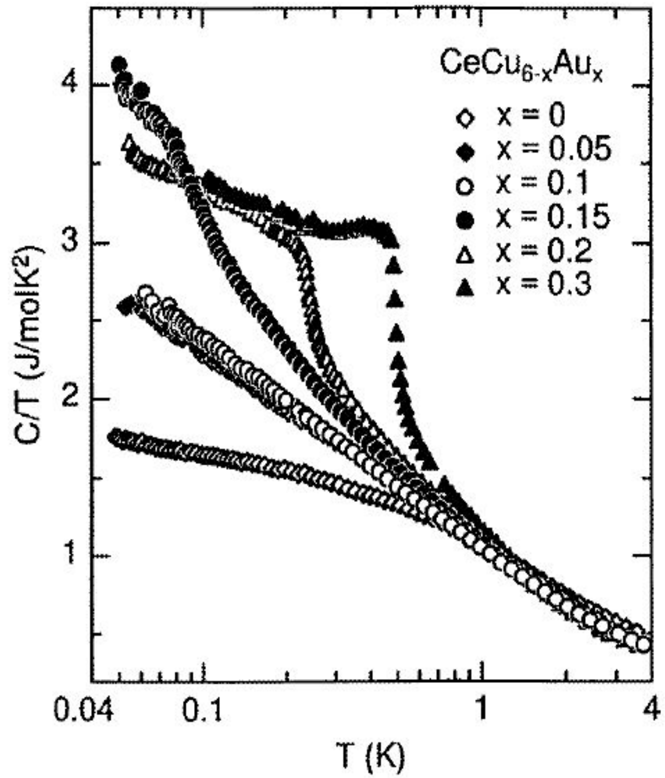
Kim et al, PRL, 91, 256401 (2003)



Quantum Criticality: divergent specific heat capacity



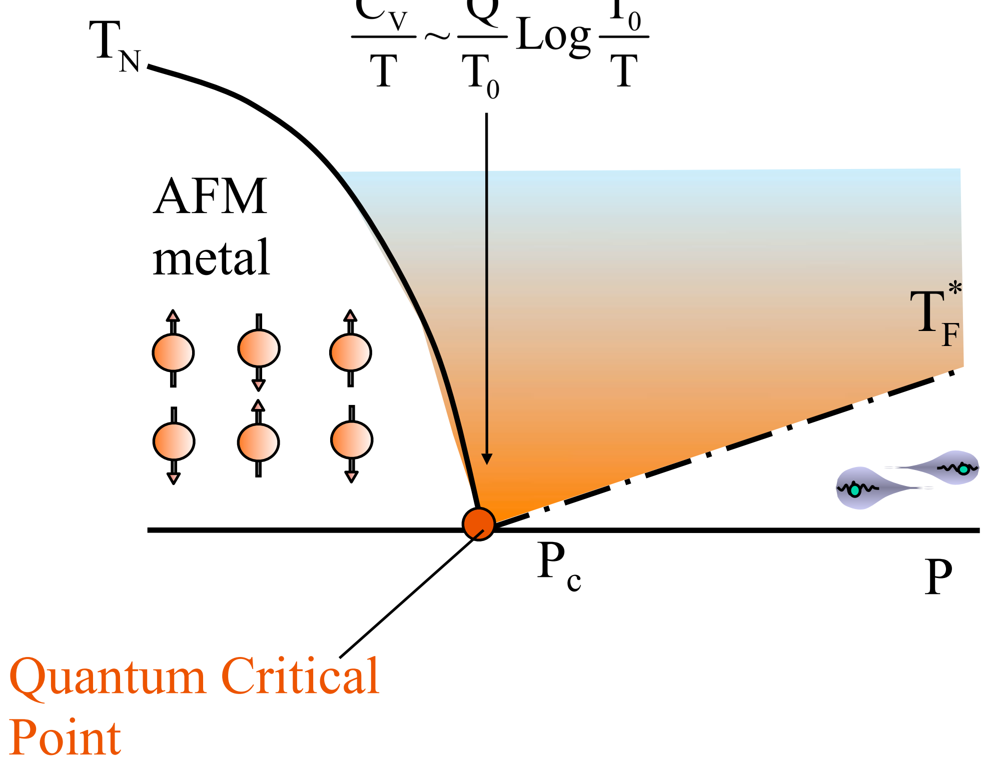
H. Von Lohneyson (1996)



Quantum Criticality: divergent specific heat capacity

Heavy Fermion Materials

$$\frac{C_V}{T} \sim \frac{Q}{T_0} \mathrm{Log} \frac{T_0}{T}$$



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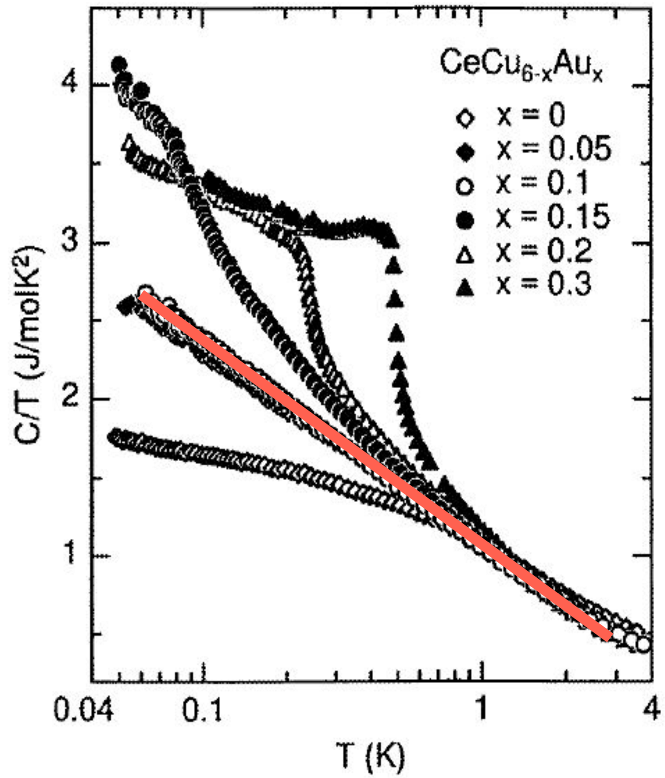

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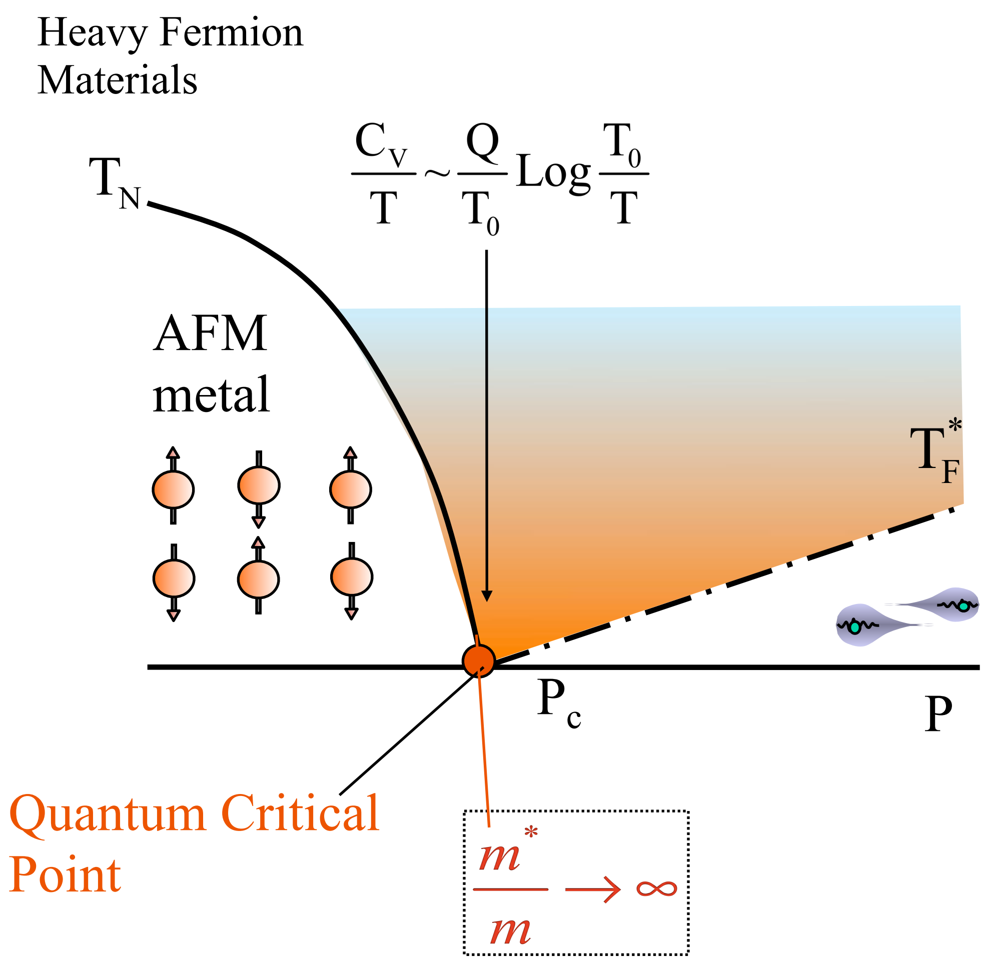

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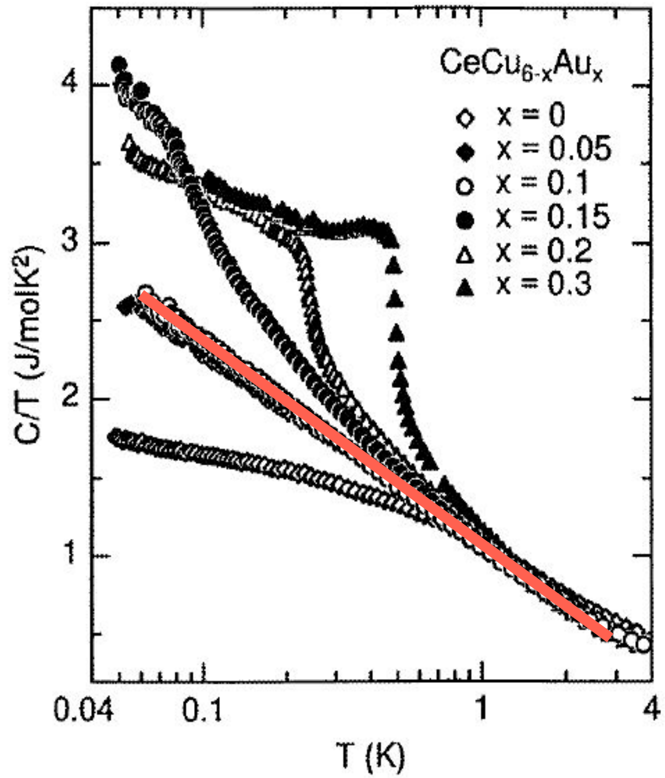

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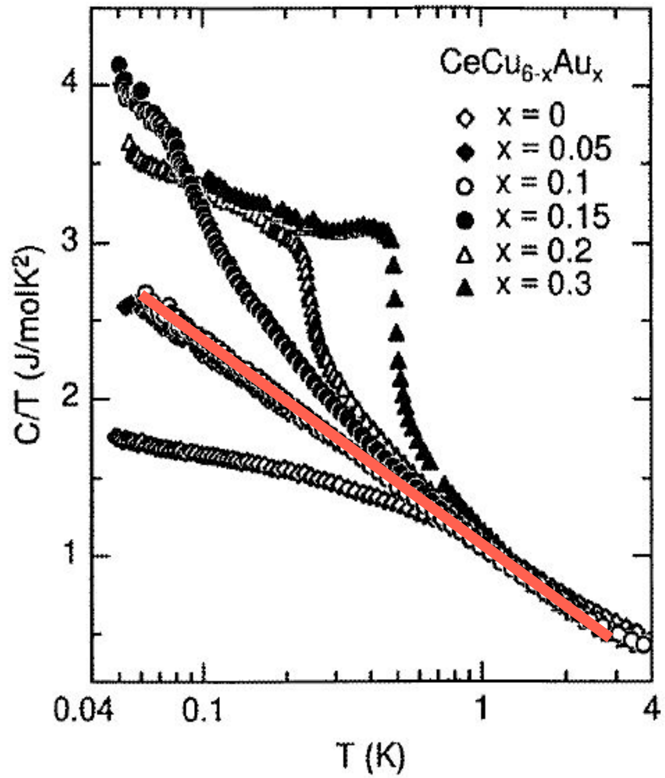

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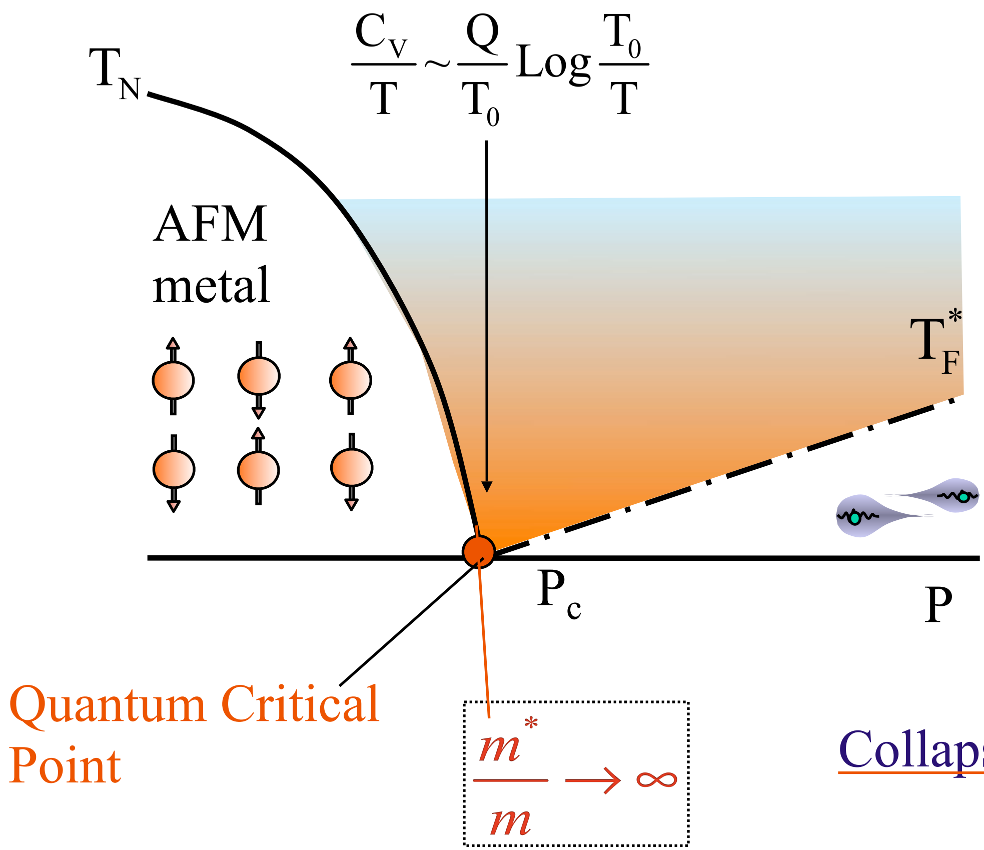
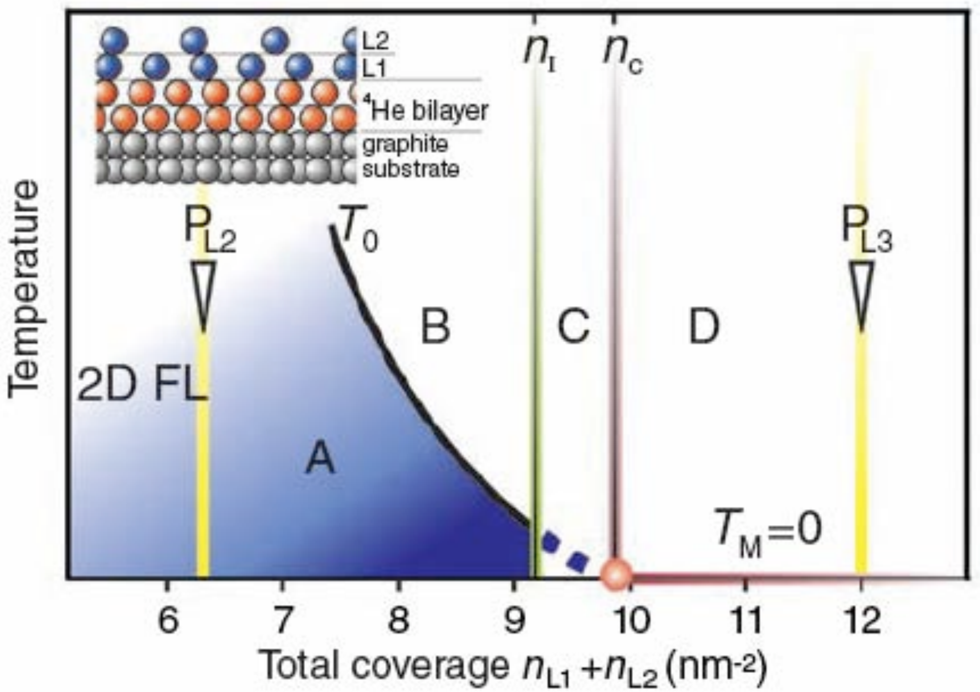
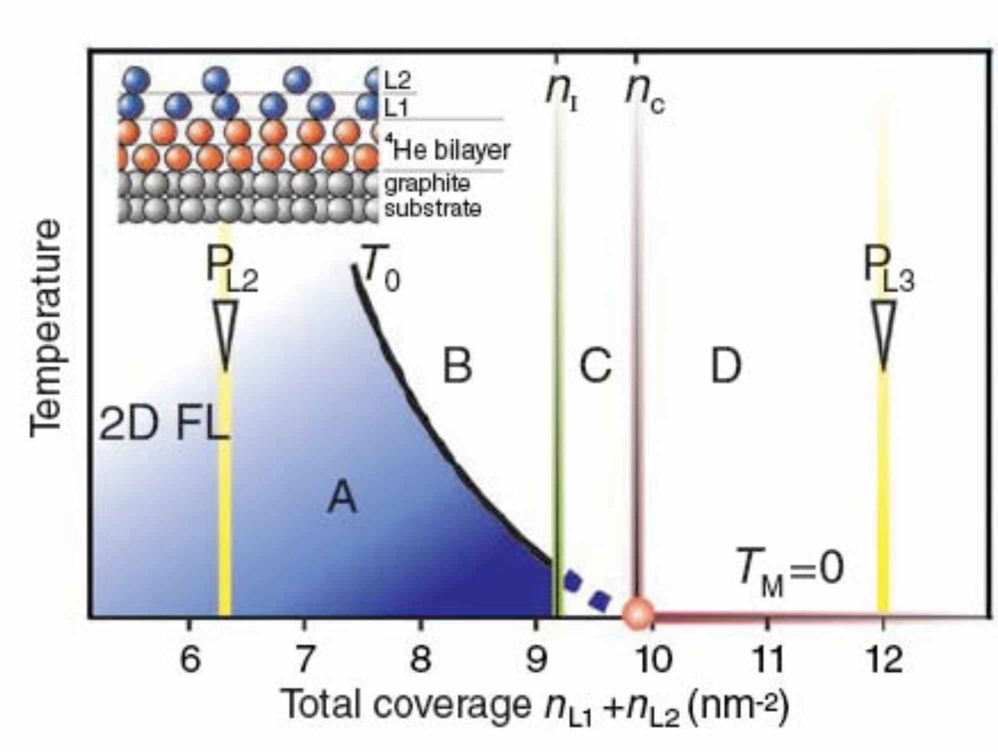


Collapse of energy scales



Neumann, Nyeki,Cowan and Saunders, Science 317, 1356 (2007).



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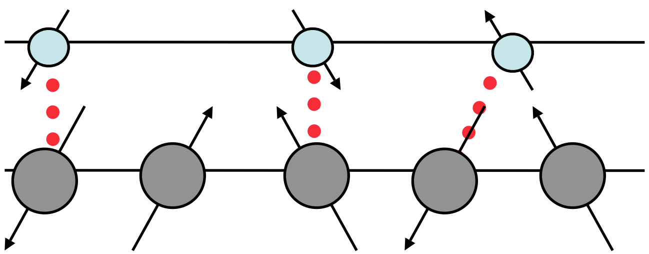
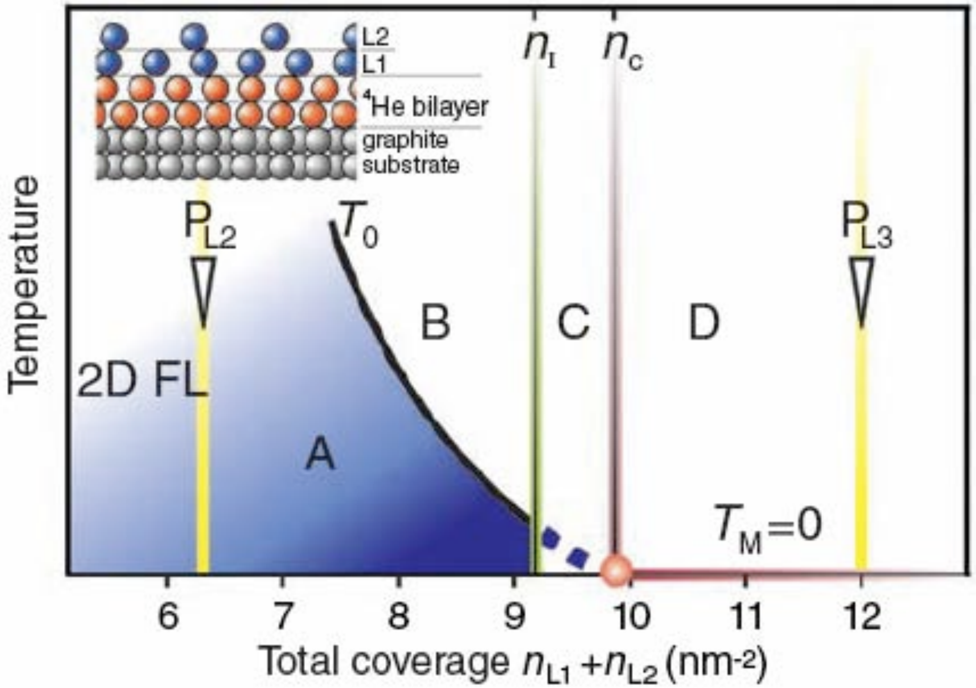


Lowest layer – almost localized ~ "heavy –fermions"
Upper layer – lighter "conduction fermions"



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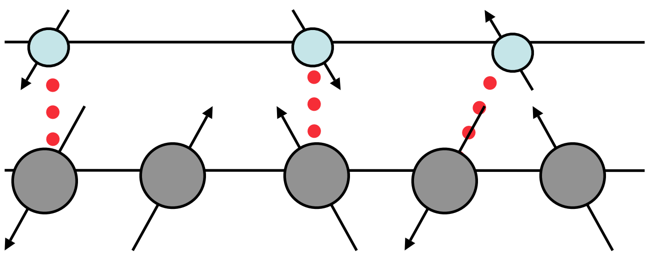

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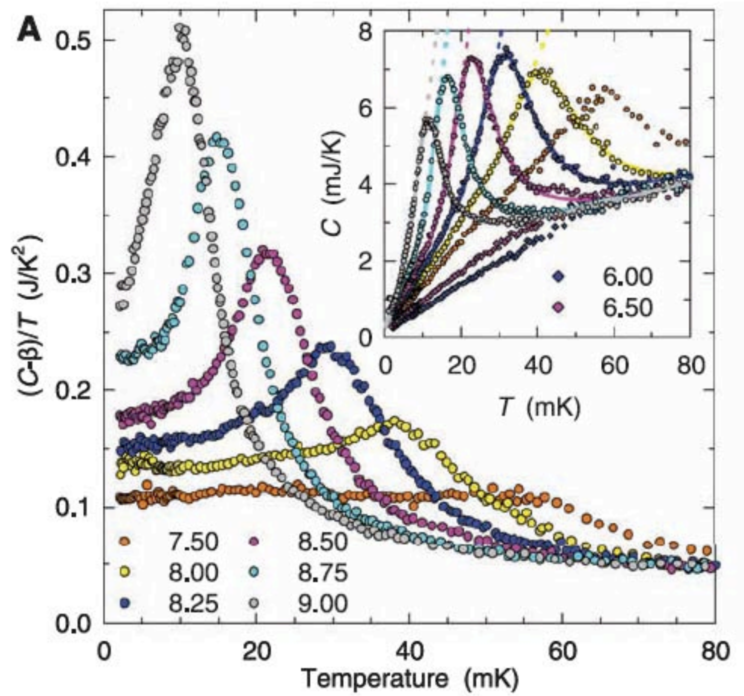

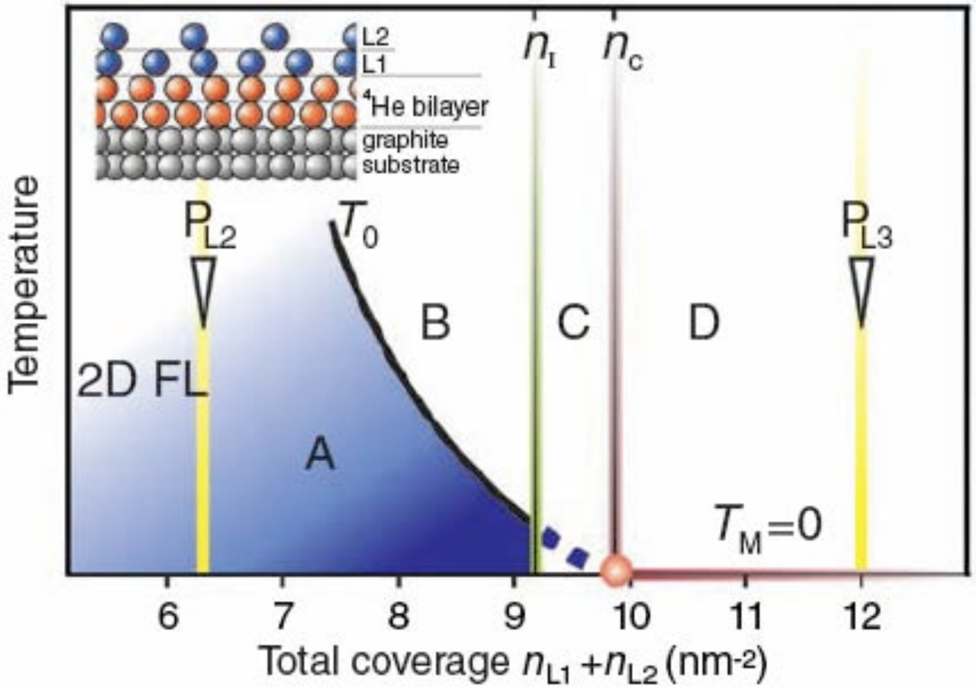

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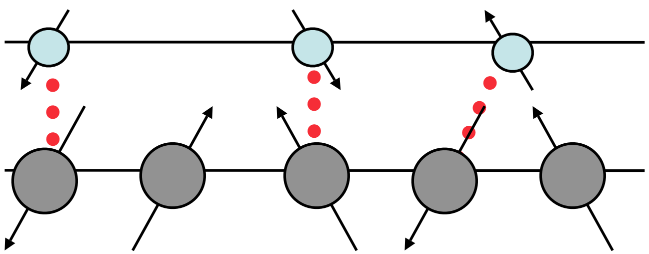

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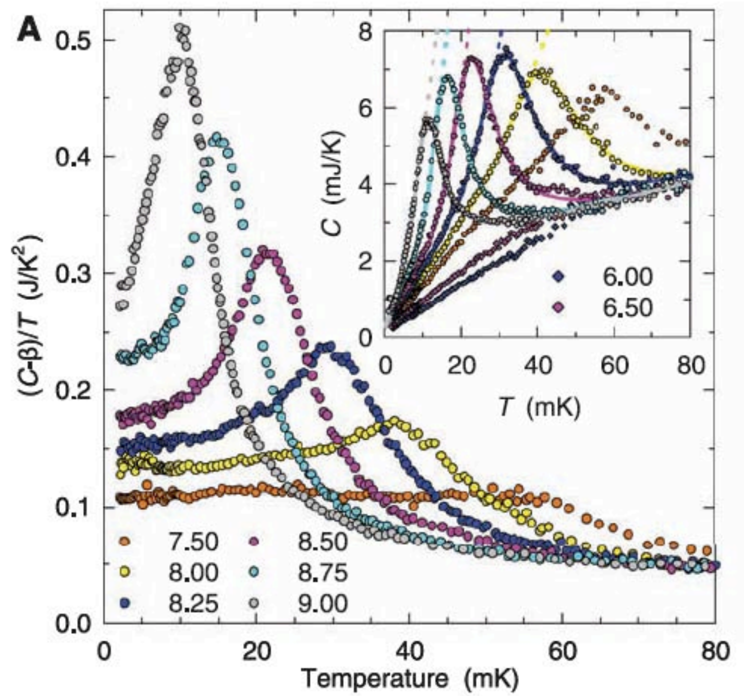
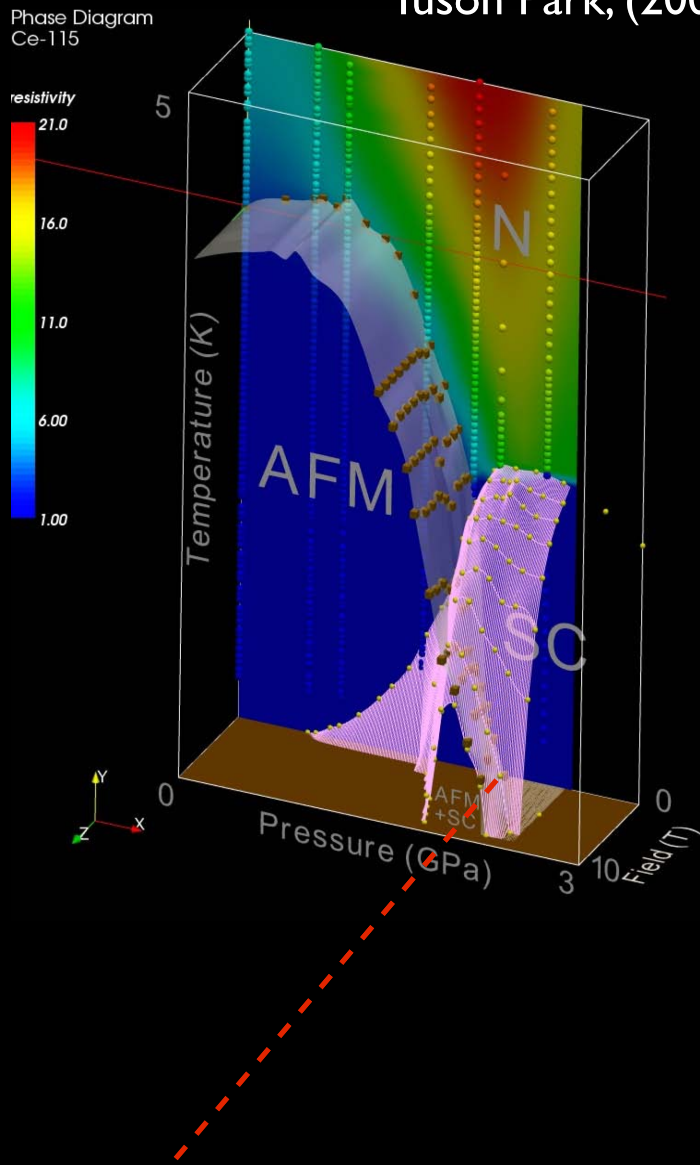


Reconstruction of the Fermi Surface and mass divergence

Tuson Park, (2007).

CeRhIn$_5$



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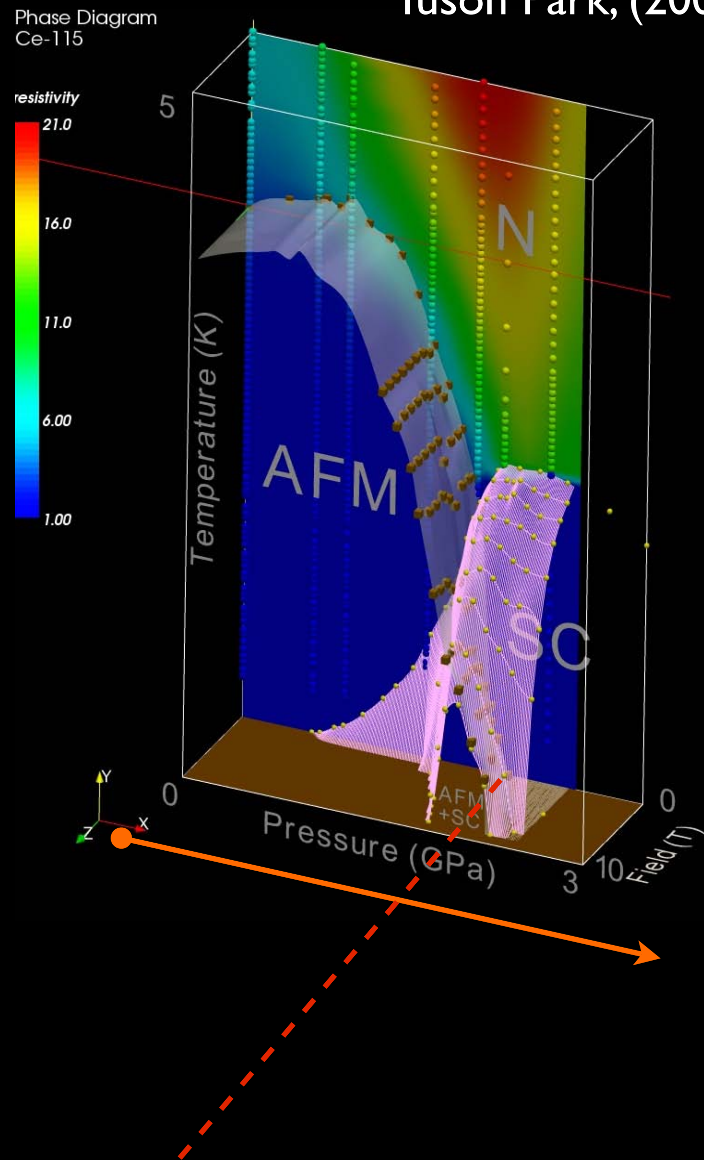

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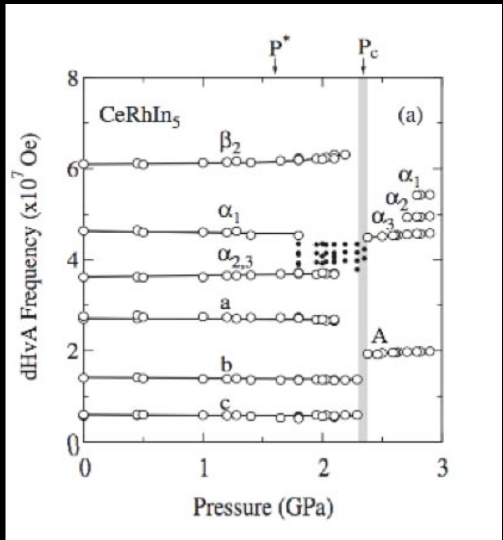

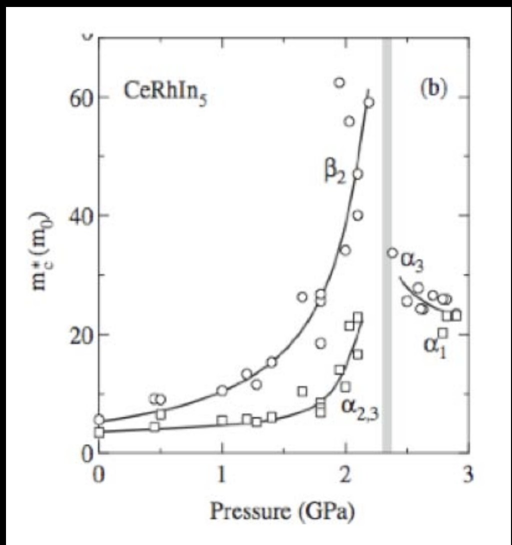

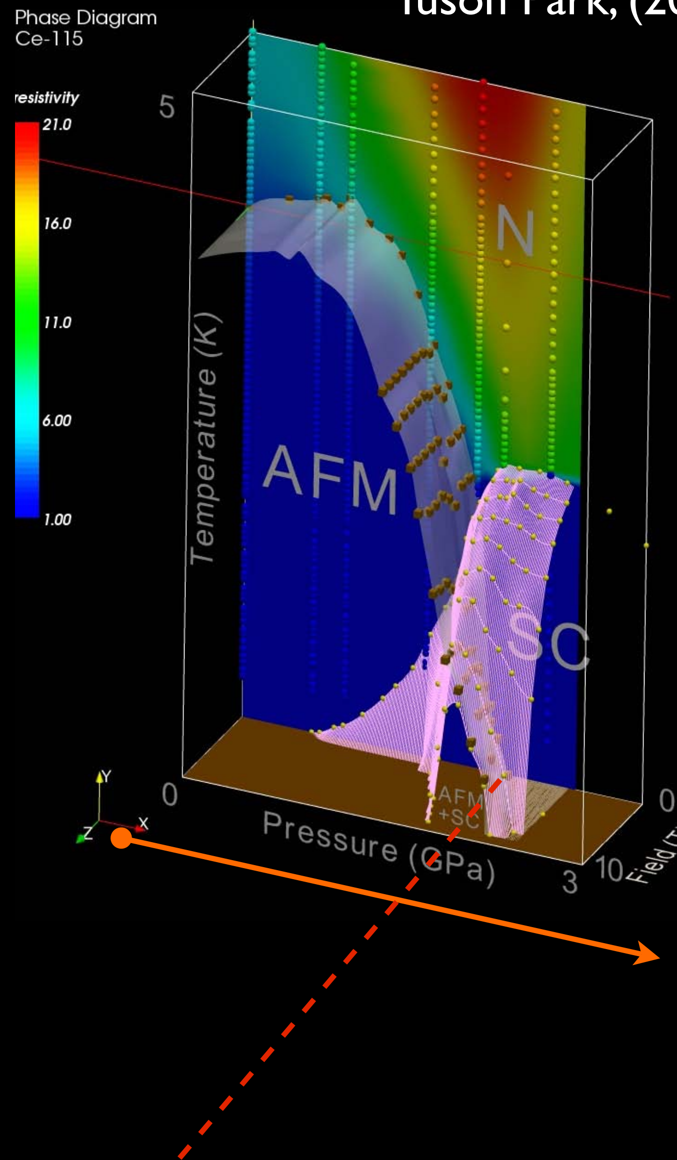

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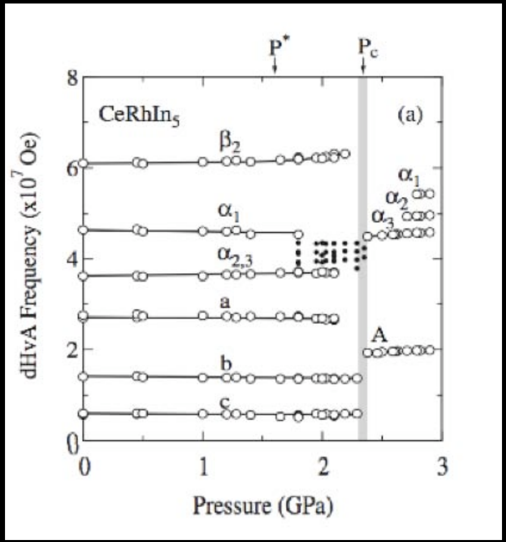

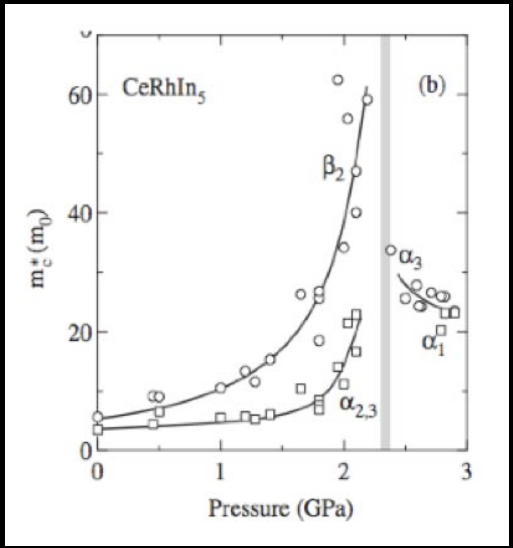

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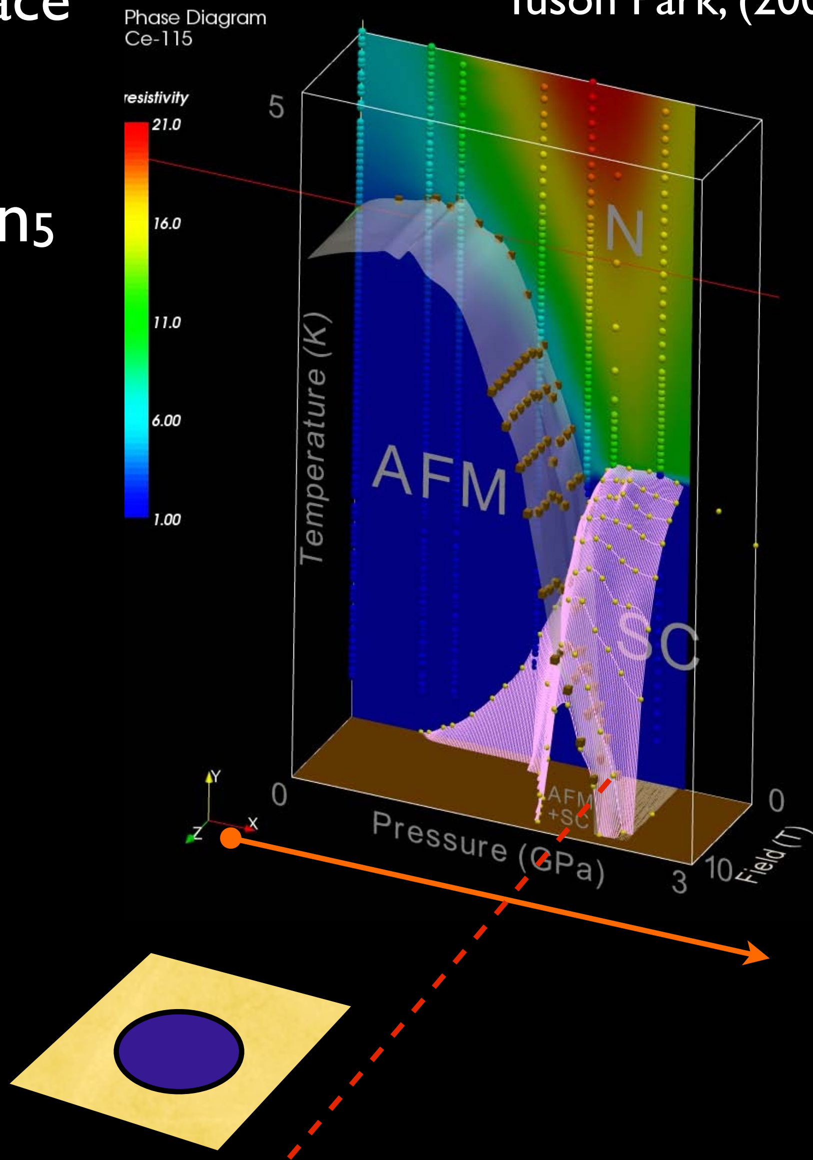

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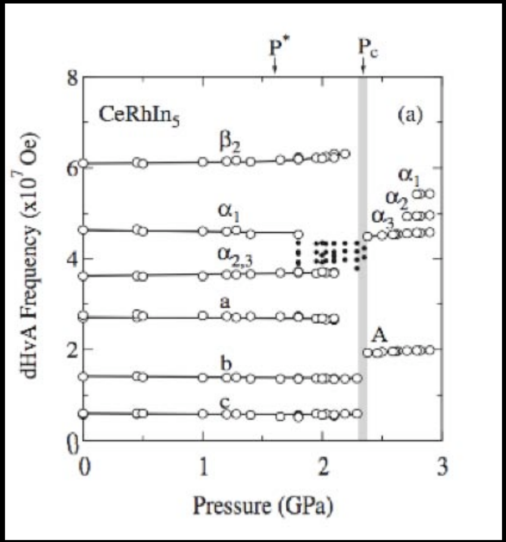

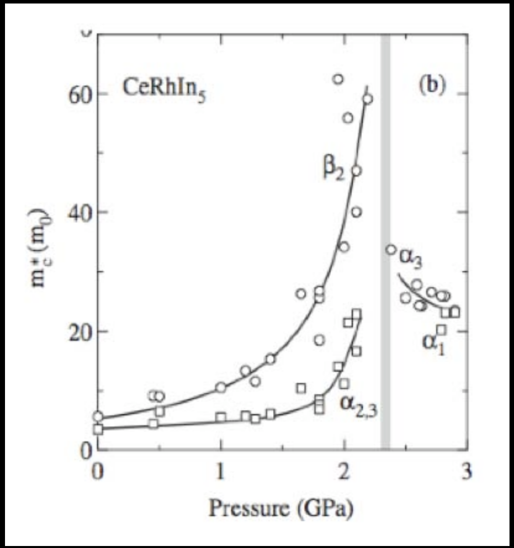

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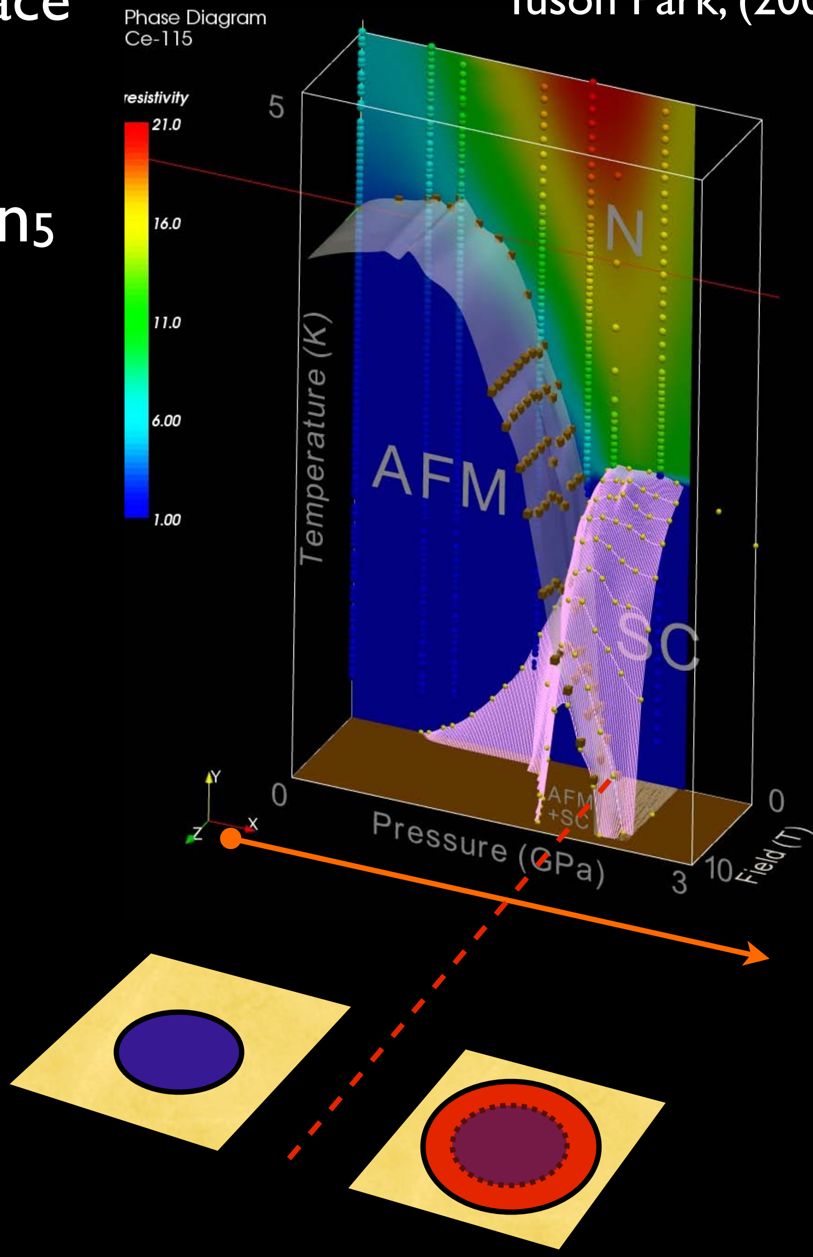

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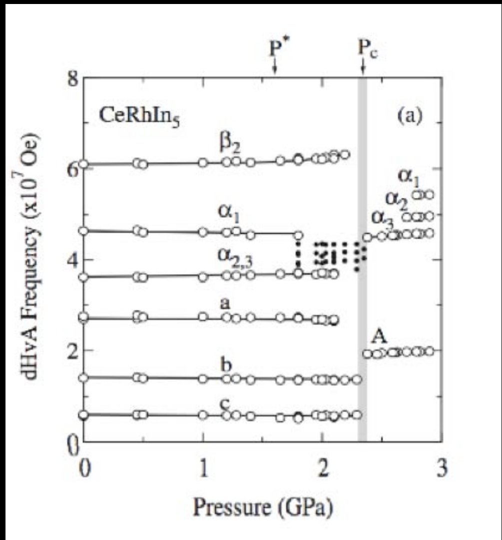

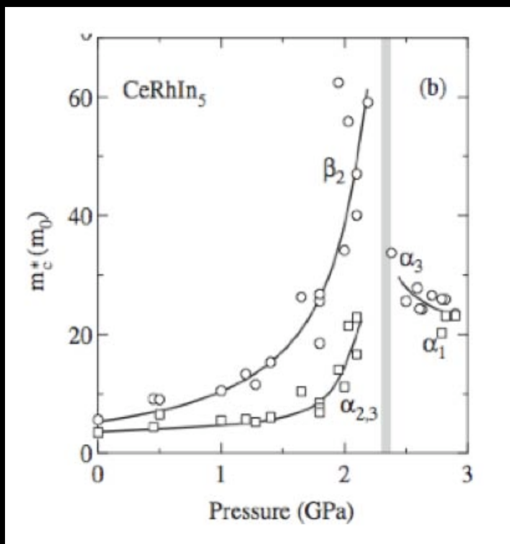

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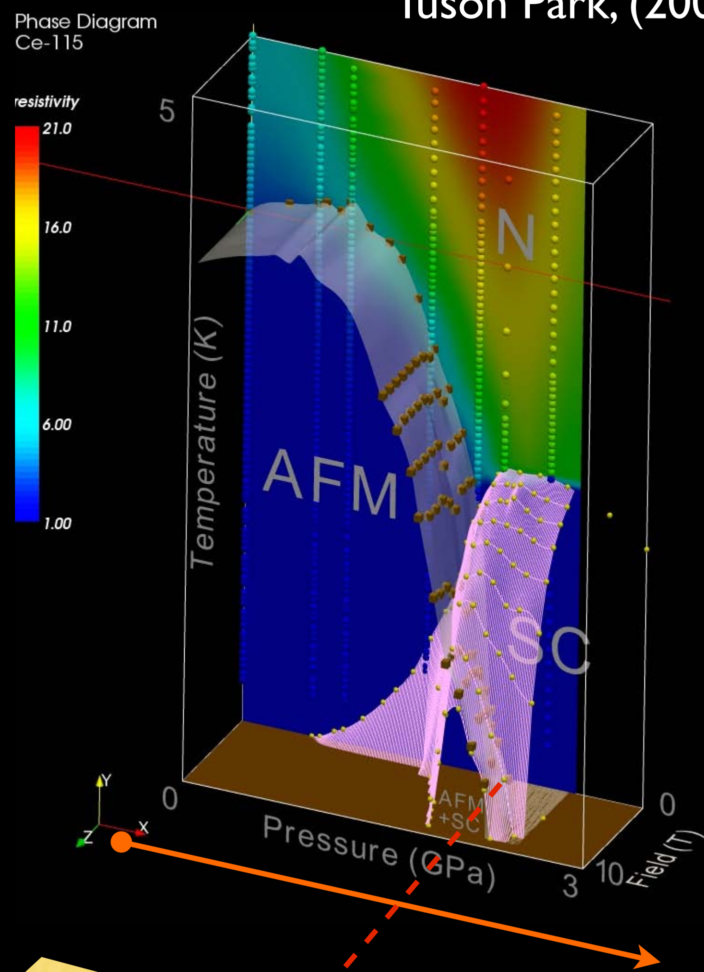

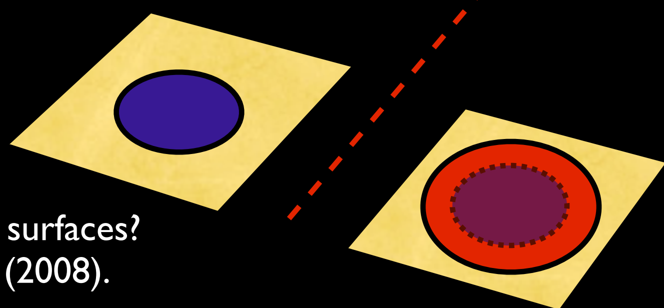

Critical Fermi surfaces?
Senthil PRB (2008).

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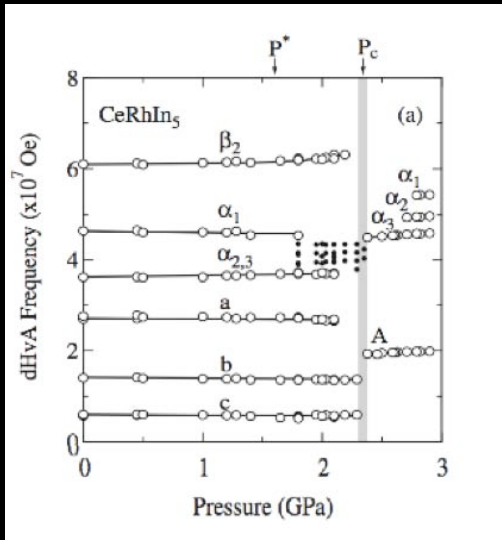

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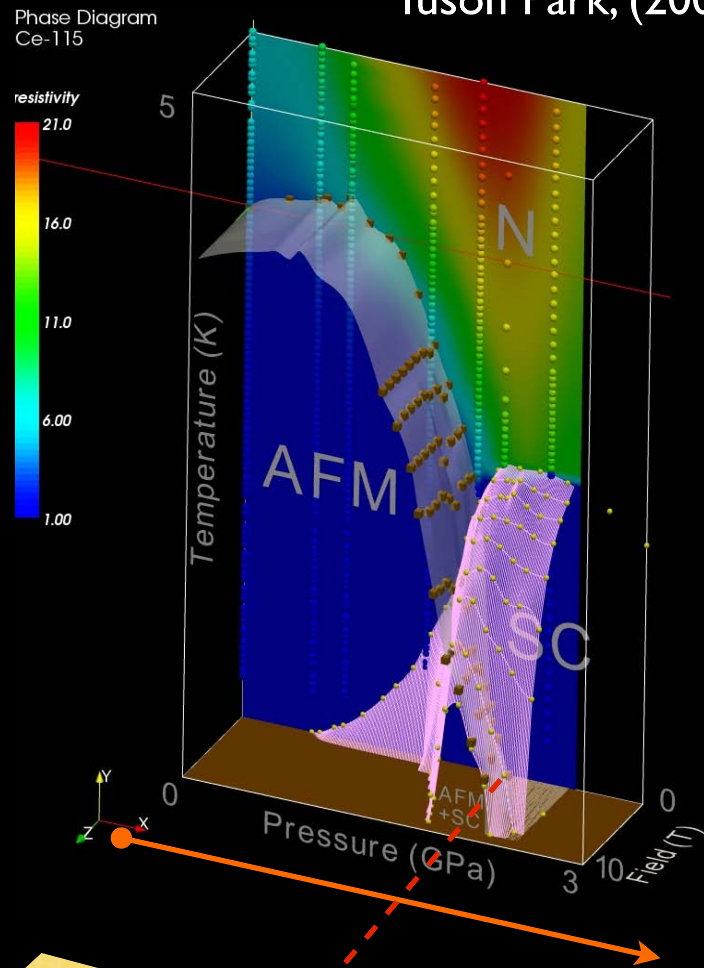

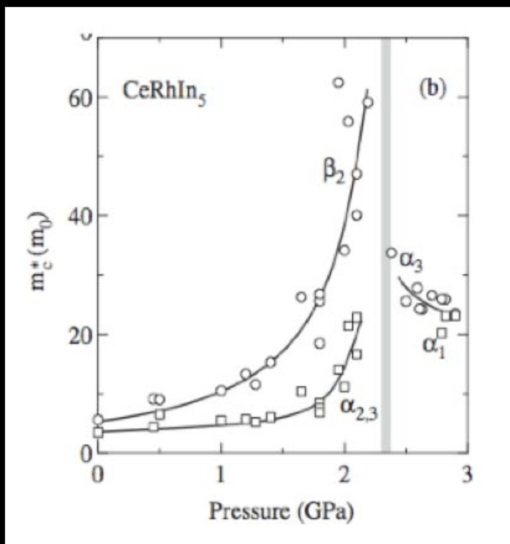

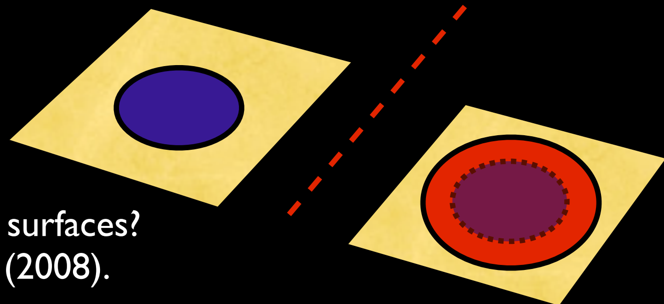

Critical Fermi surfaces?
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Shimuzu et al (2006)

What charged excitation causes the change in FS volume?

Tuson Park et al.
Nature (2008).

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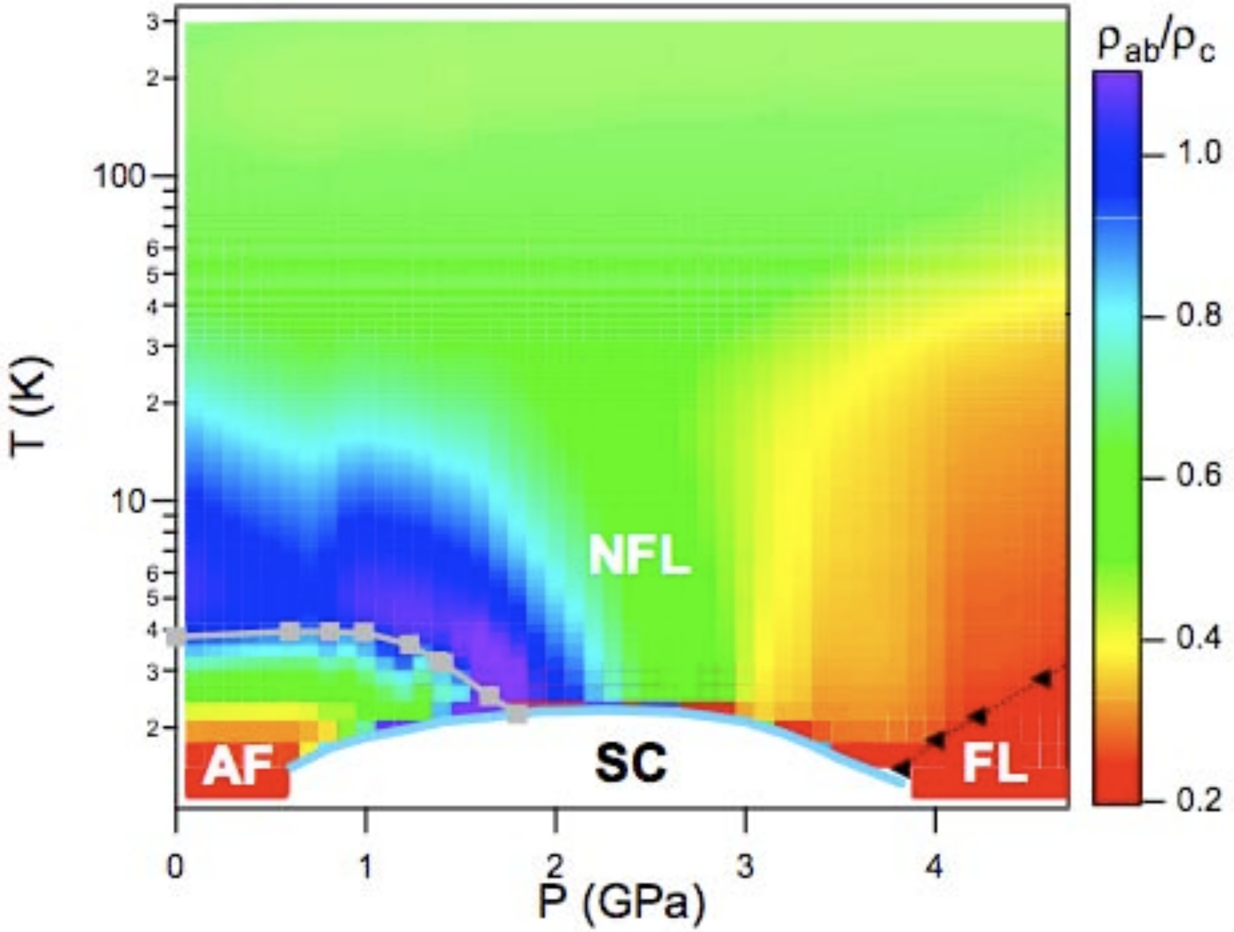

Tuson Park et al.
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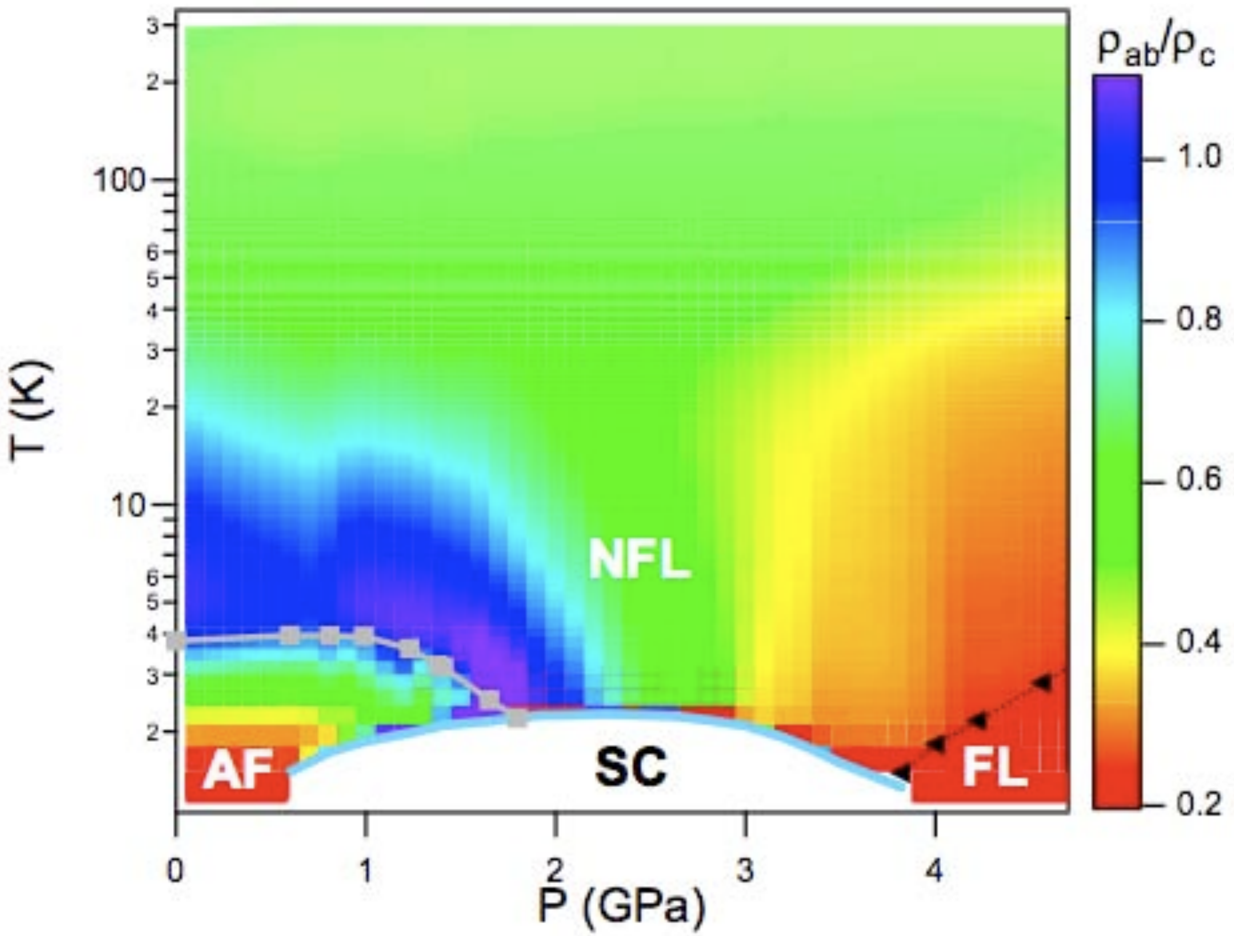

High temperature isotropy extends to the QCP.

Tuson Park et al.
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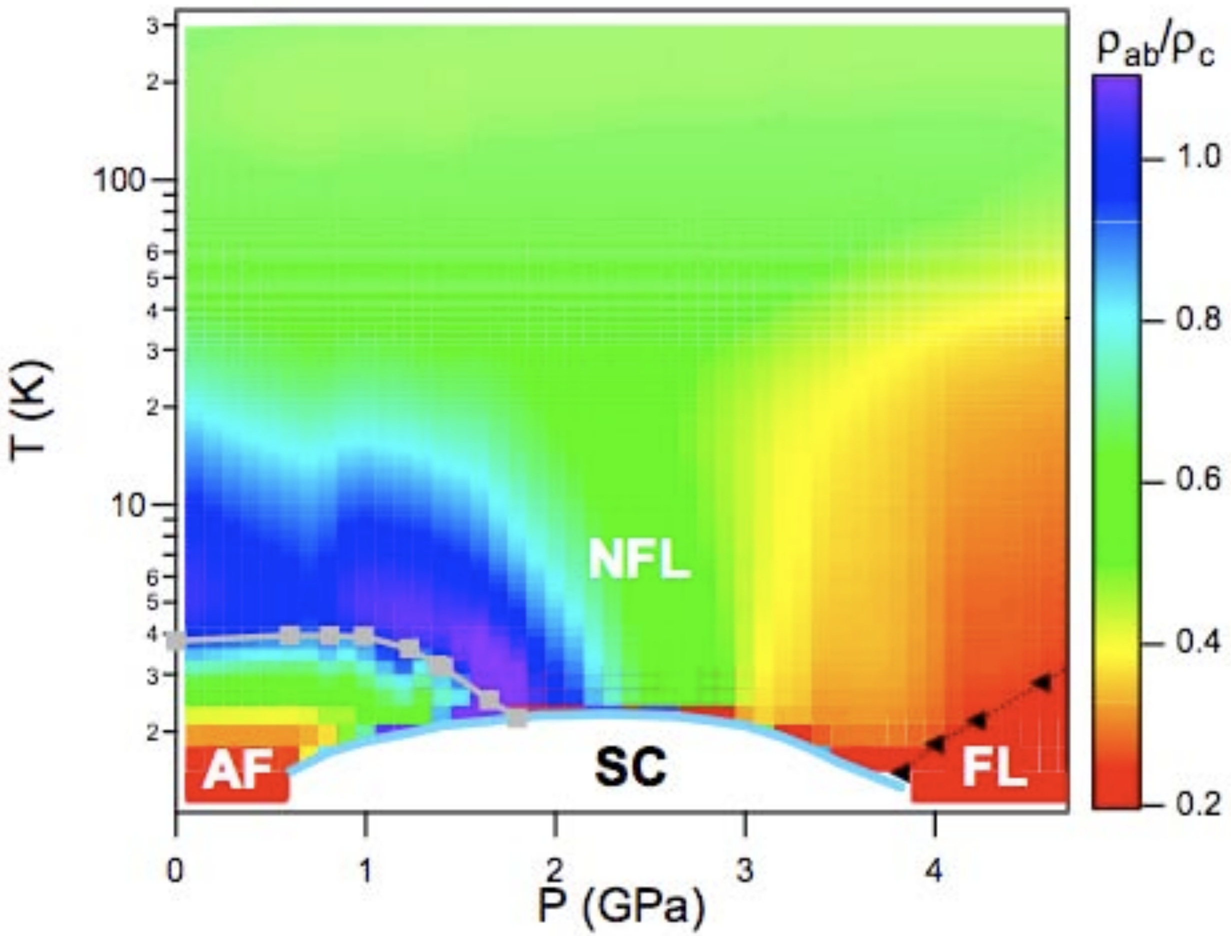
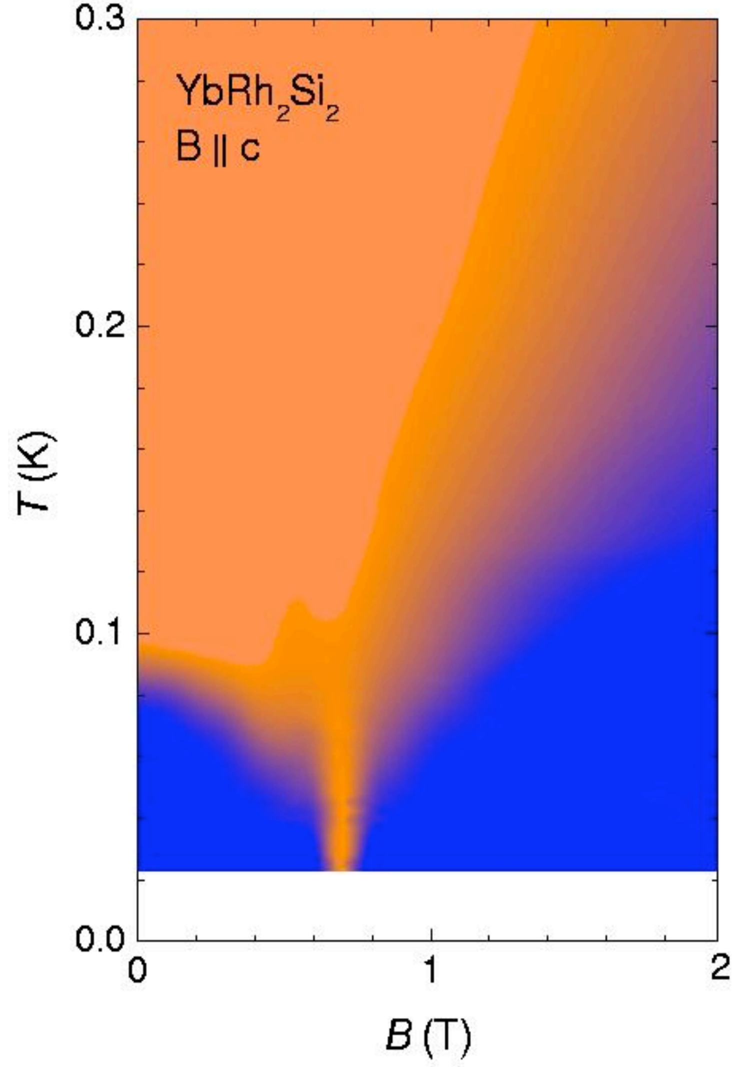


High temperature isotropy extends to the QCP.

Local?

Field Tuned Criticality in YbRh2Si2.



$YbRh_2Si_2$

Trovarelli et al (2000).

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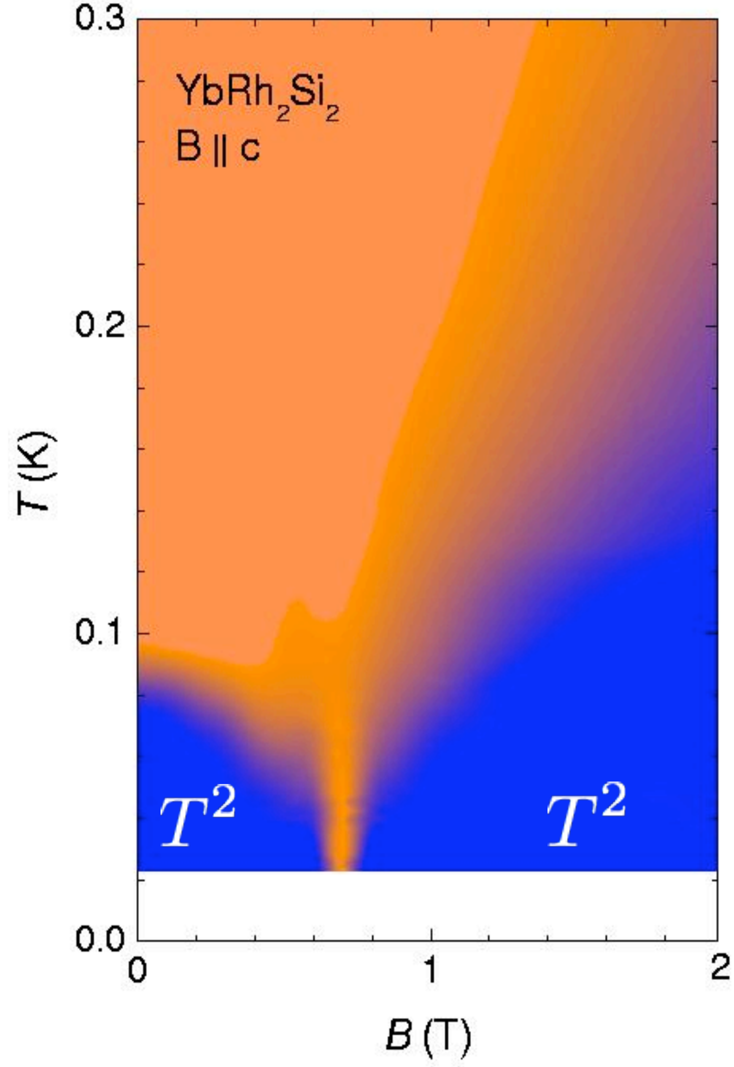

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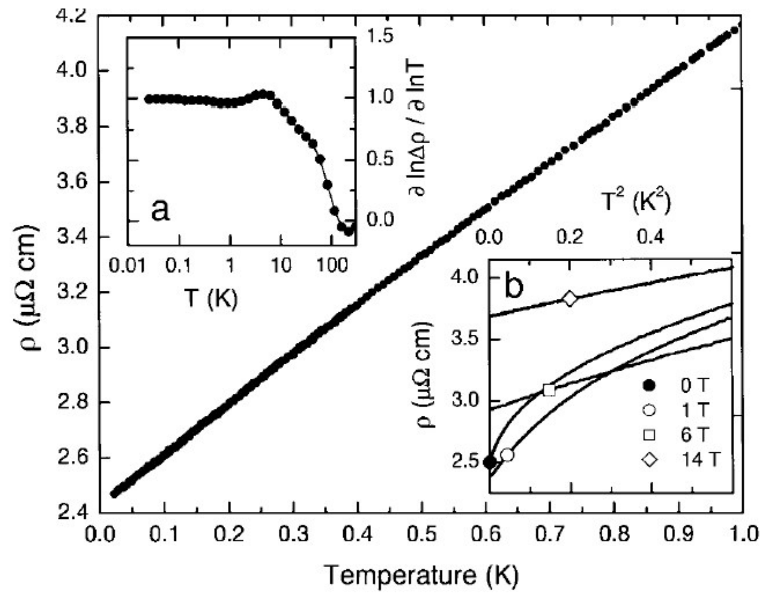

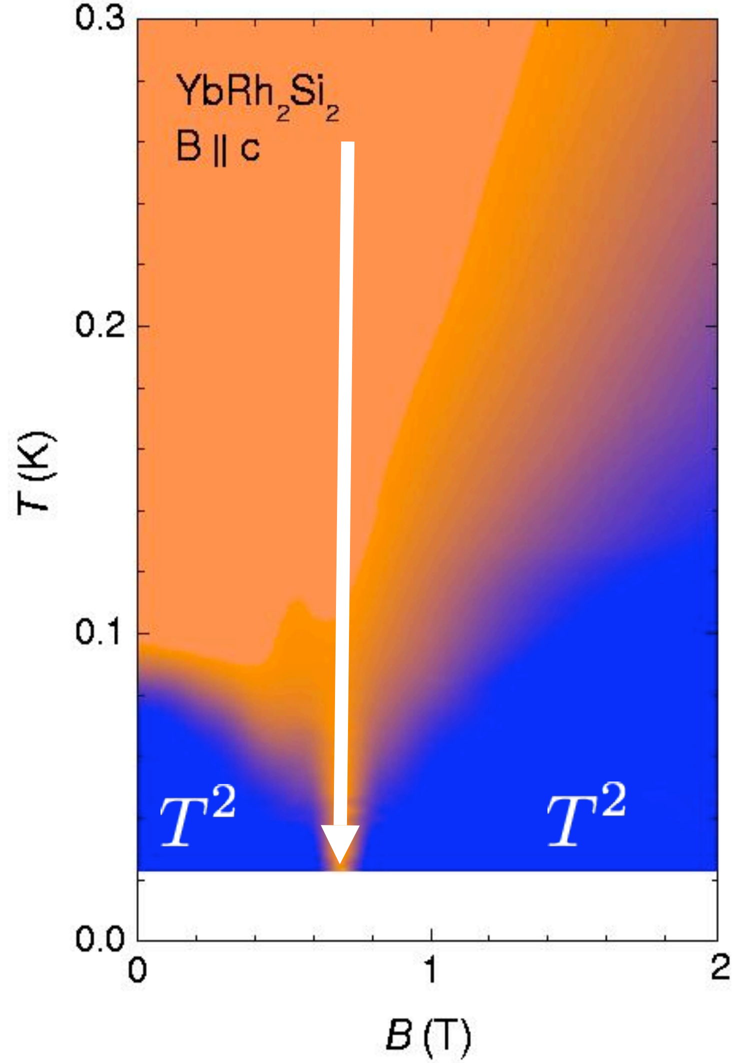

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Breakdown of Landau Fermi liquid.

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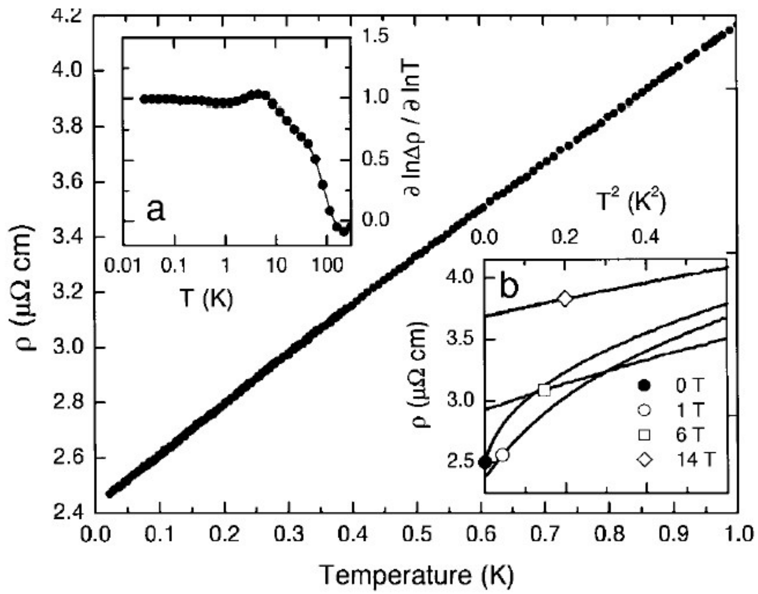

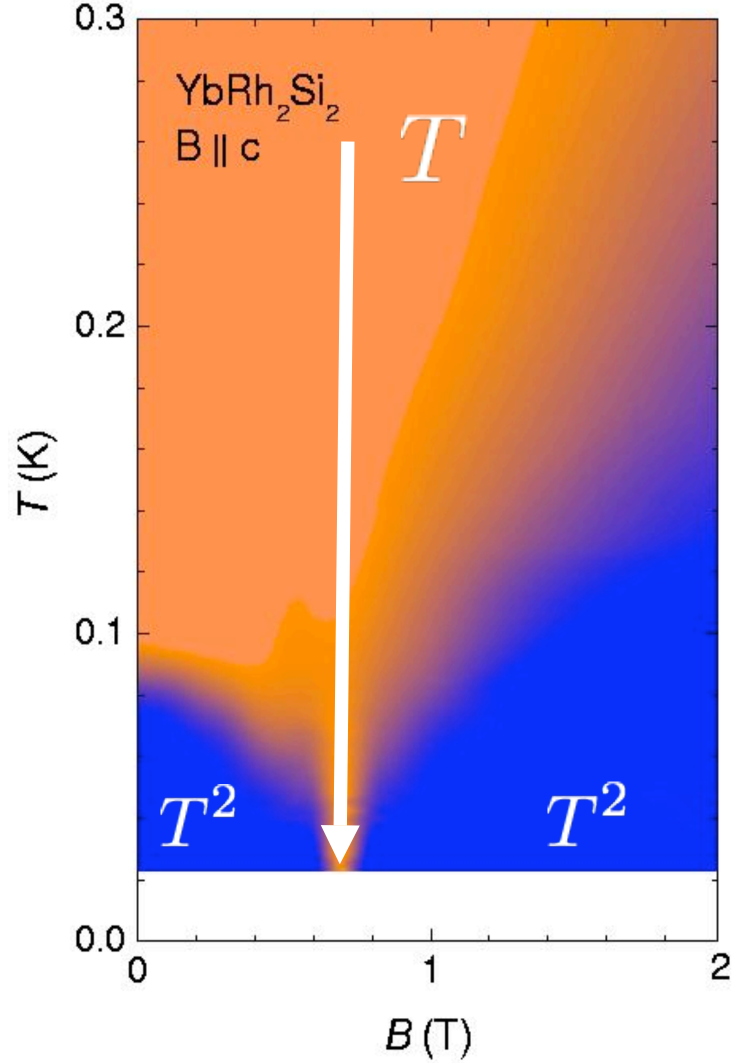

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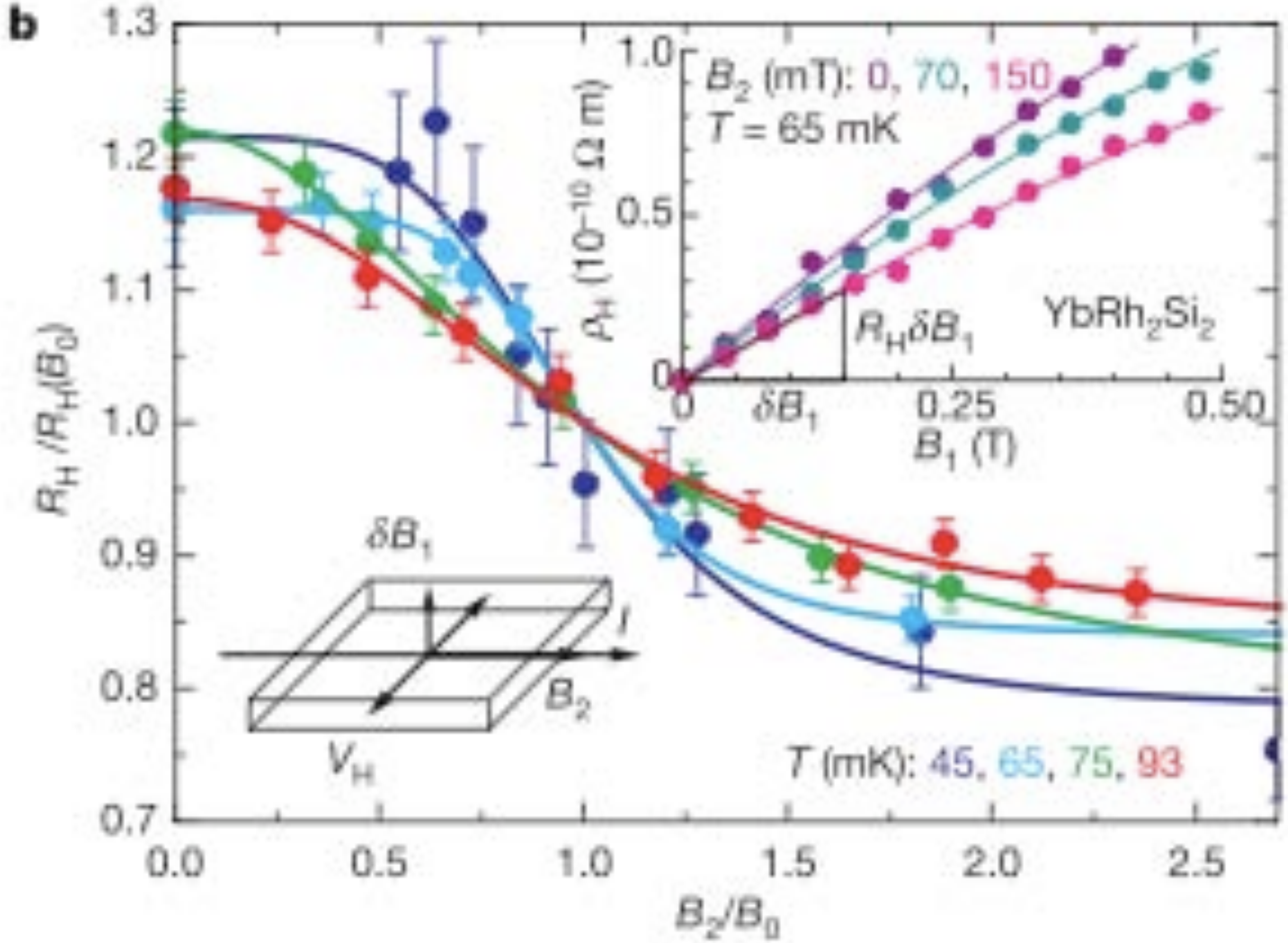
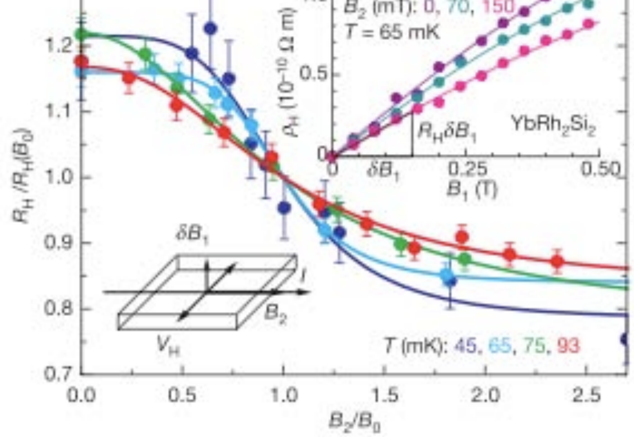
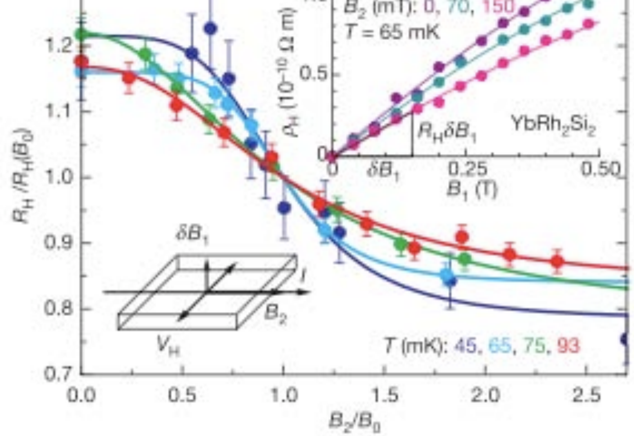
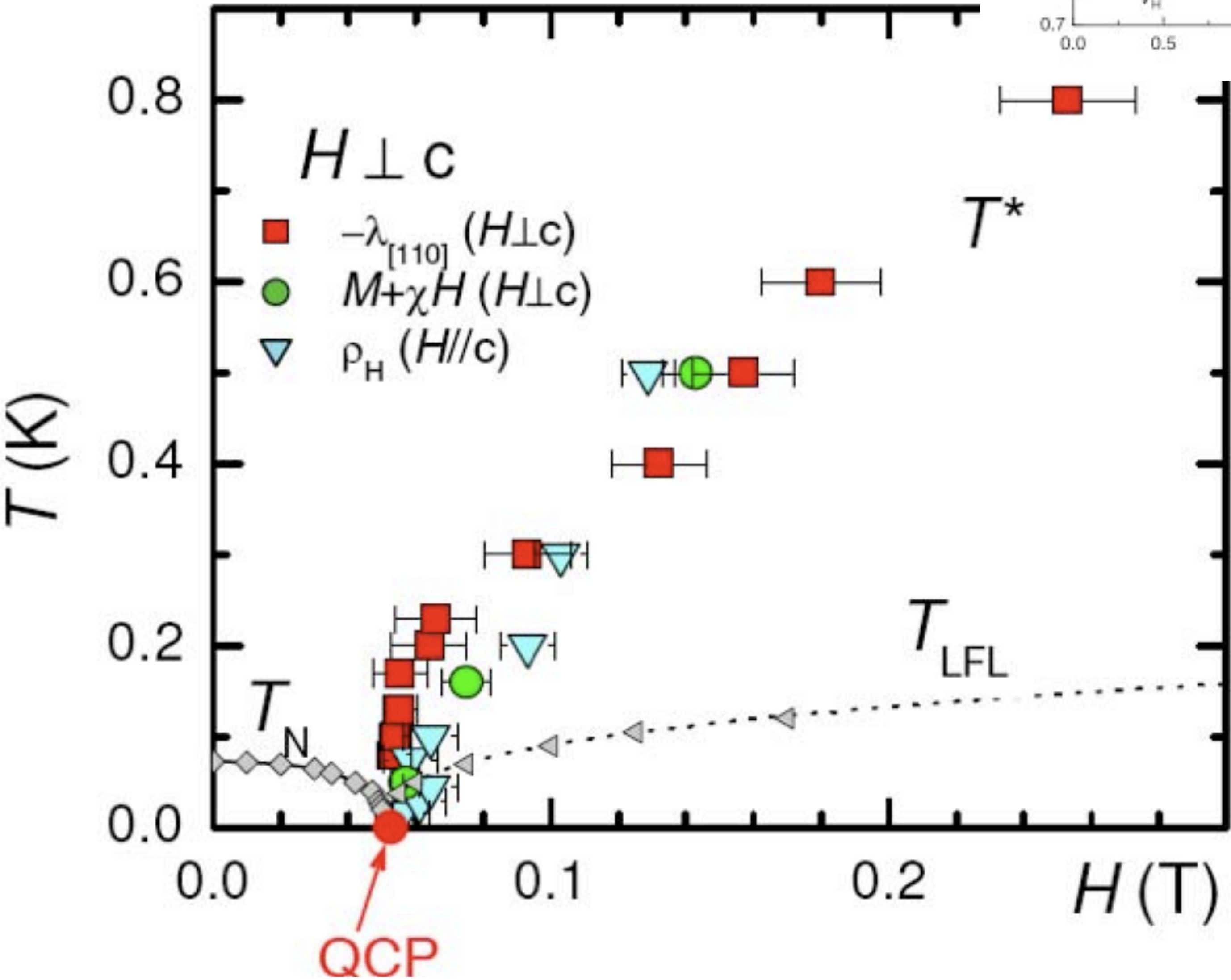
S. Paschen et al, Nature 432, 881 (2004)

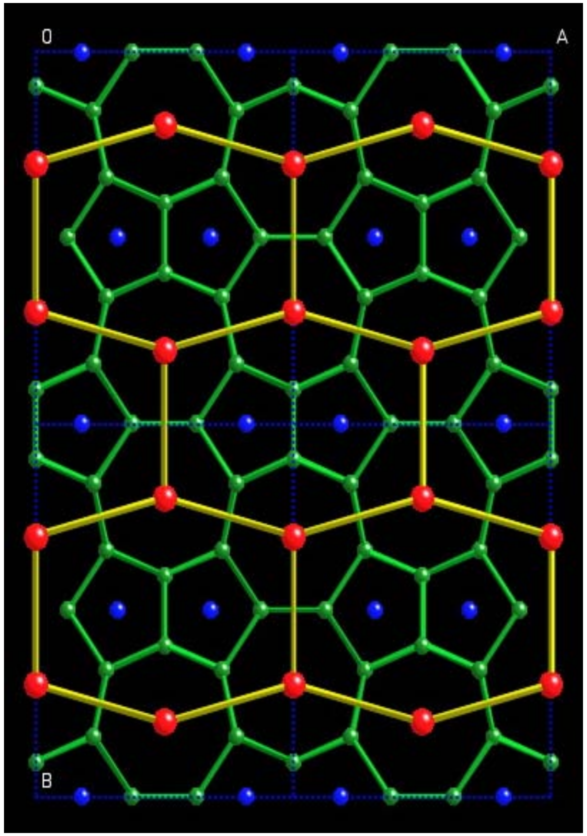


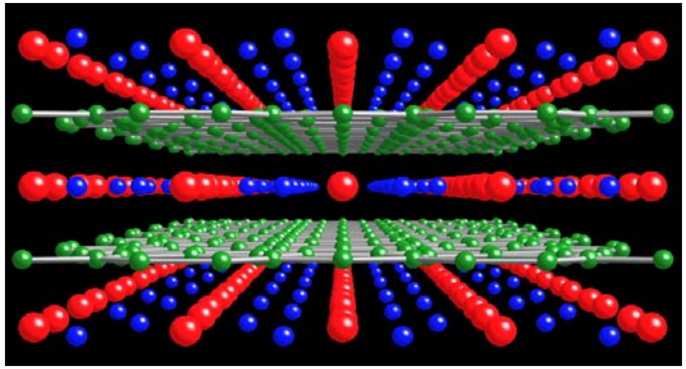

B_2 (mT): 0, 70, 150
T = 65 mK
ρ_H (10^{-10} Ω m)
$R_H\delta B_1$
$YbRh_2Si_2$
δB_1
B_1 (T)
$R_H / R_H(B_0)$
δB_1
I
B_2
V_H
T (mK): 45, 65, 75, 93
B_2/B_0



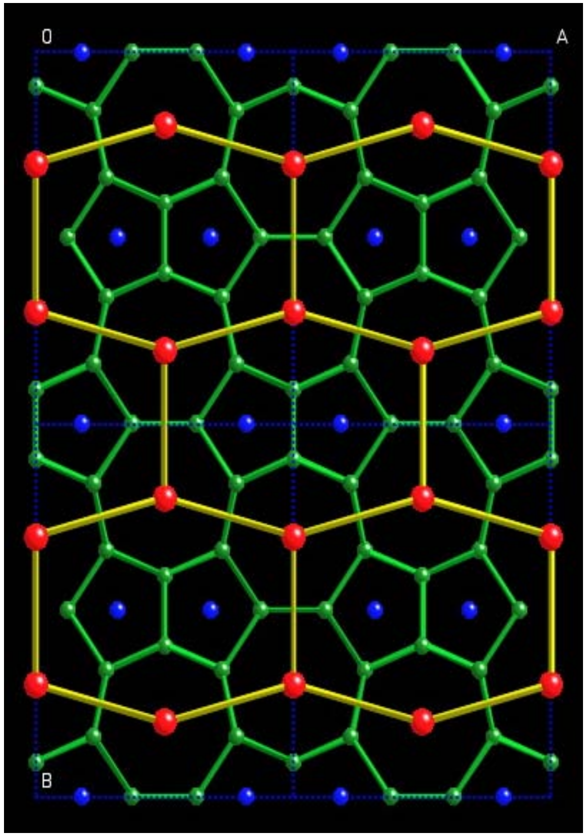
T_{Hall} represents a new energy scale (T^*)

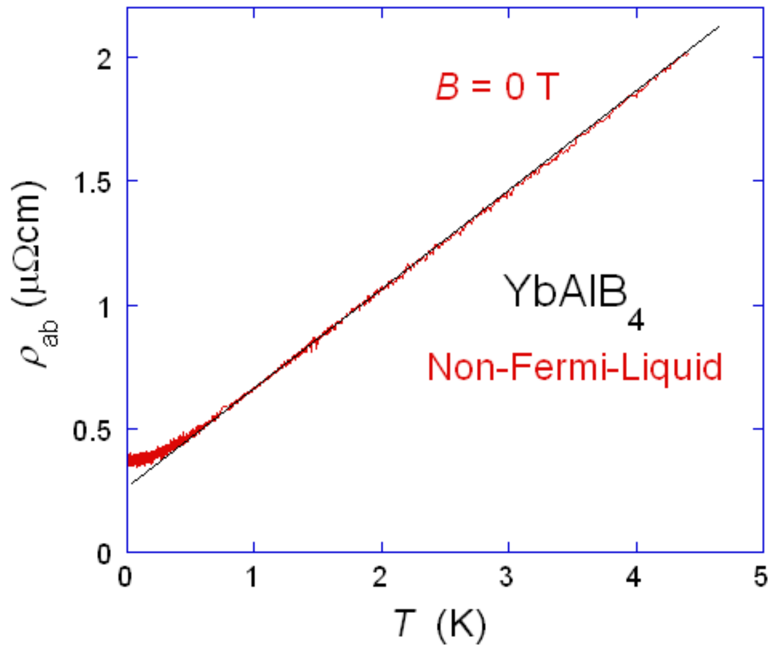






$YbAlB_4$ S. Nakatsuji et al, Nature Physics (2008).





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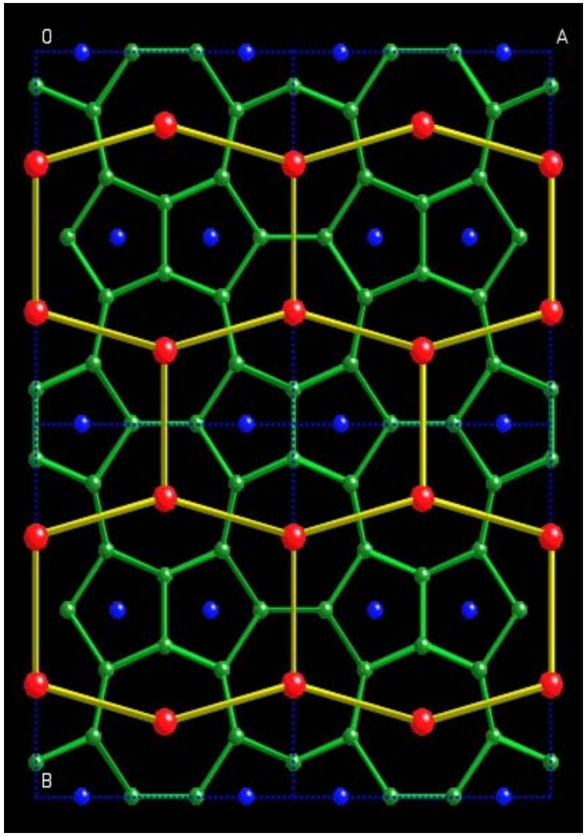

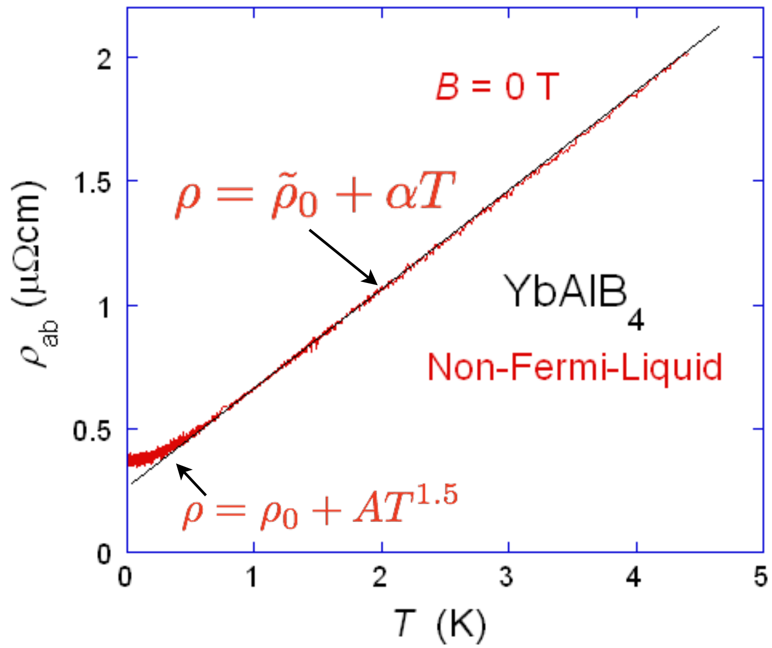

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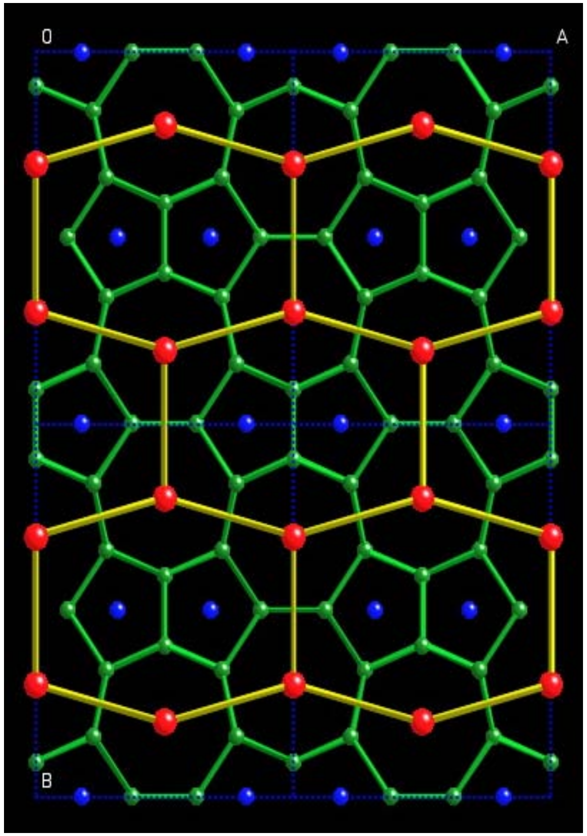

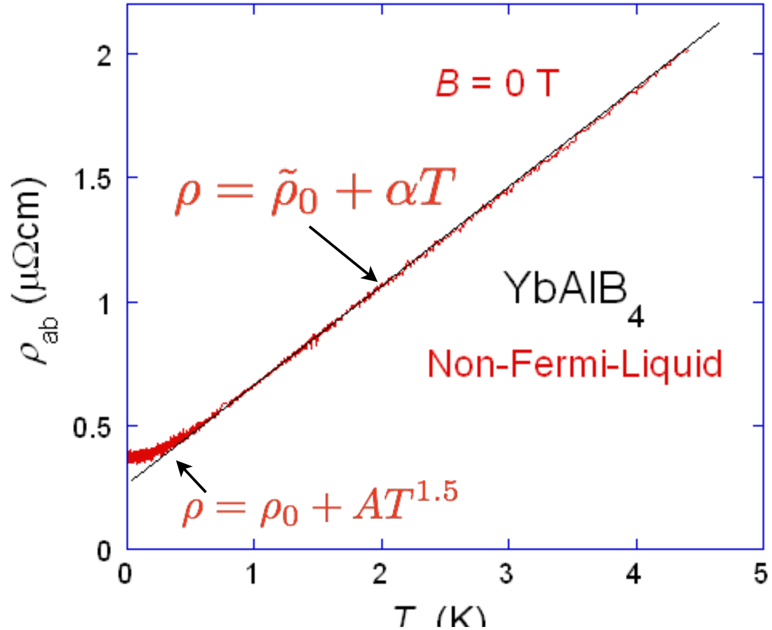

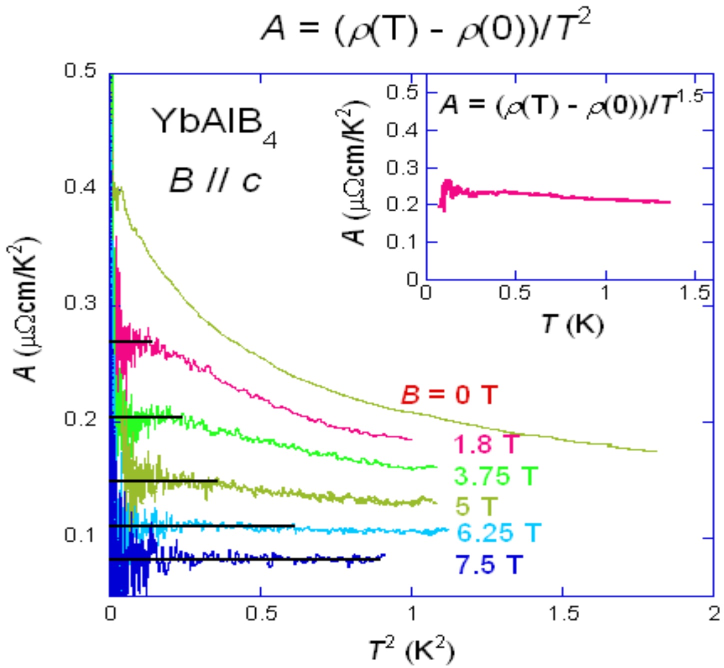

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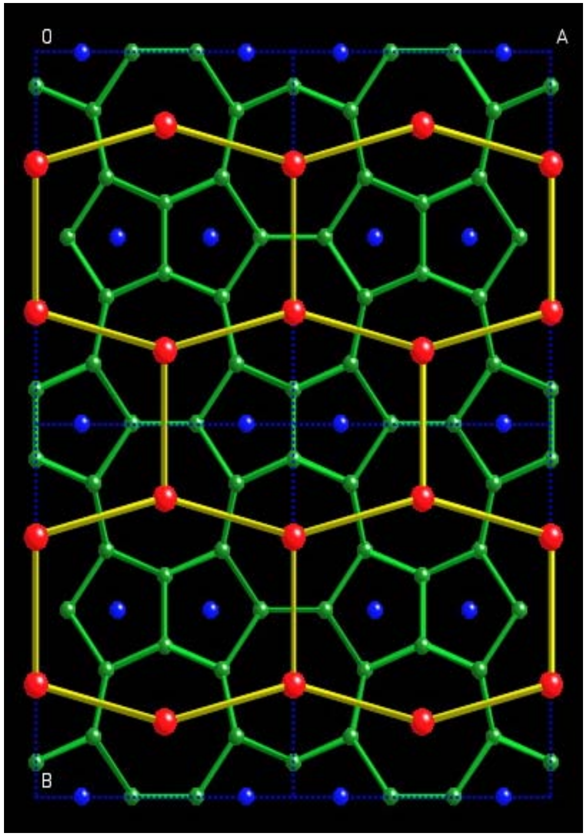

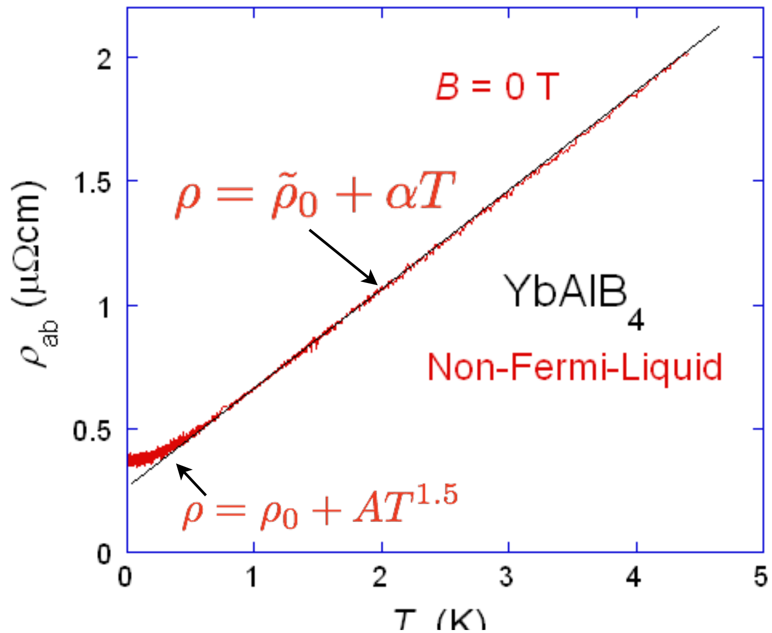

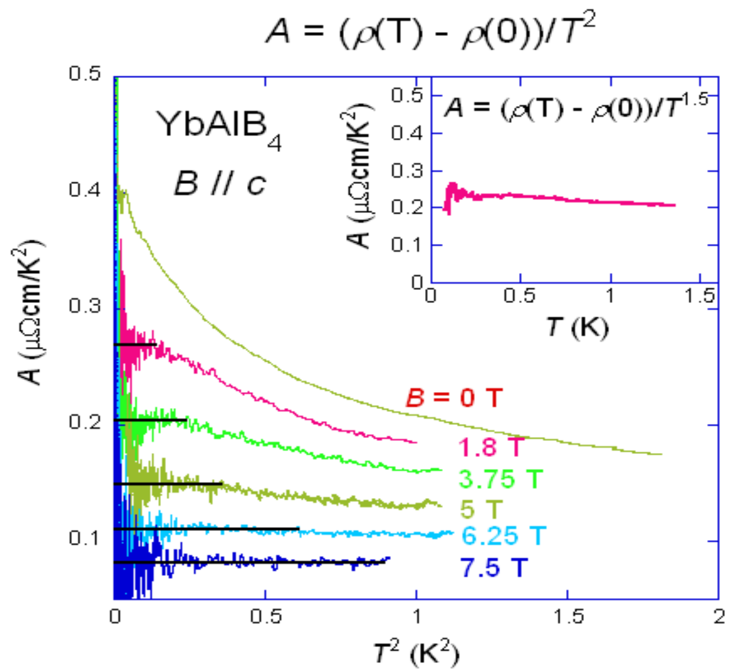

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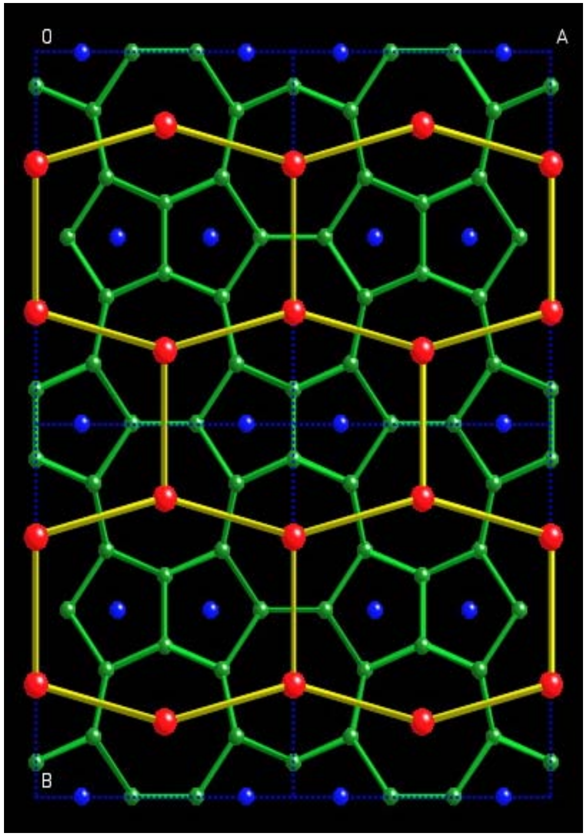
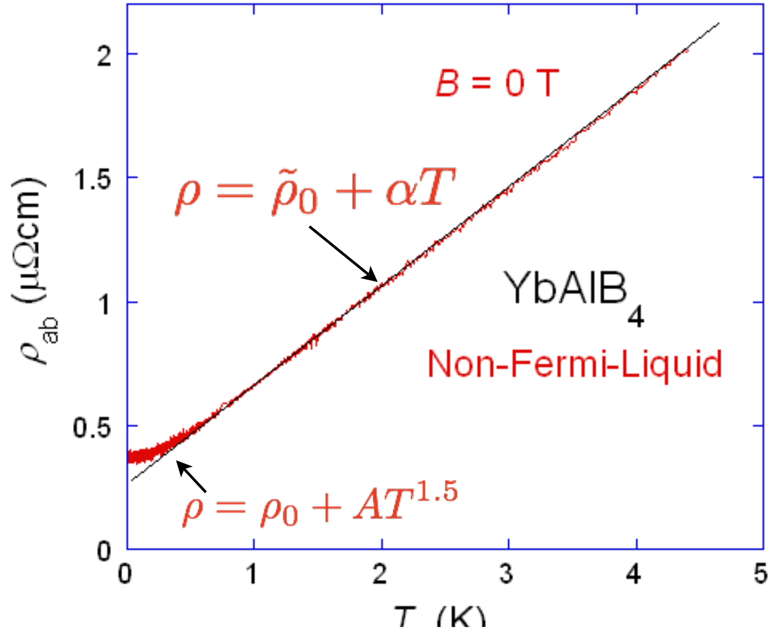
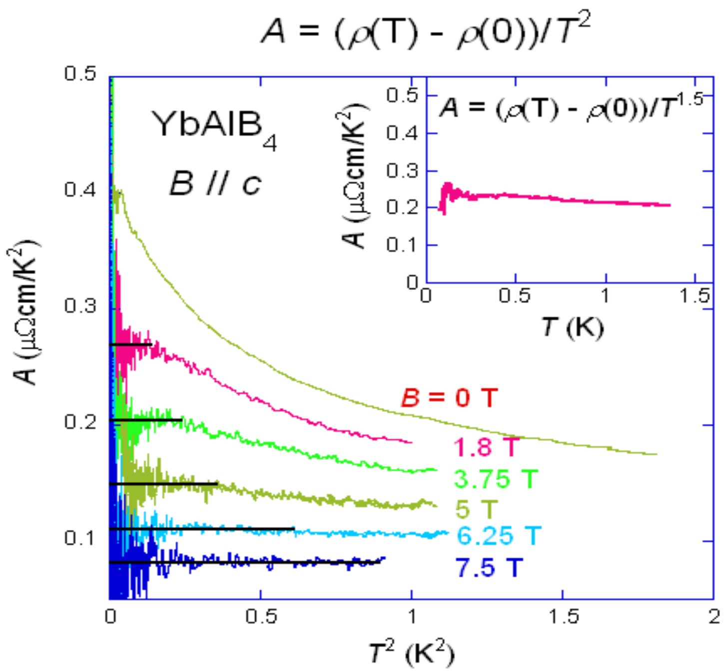
Stoichiometrially quantum critical and superconducting (Tc = 0.08K) with no interlayer frustration.







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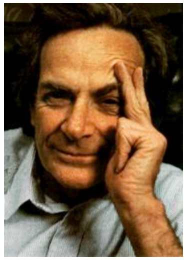
Stoichiometrially quantum critical and superconducting (Tc = 0.08K) with no interlayer frustration.

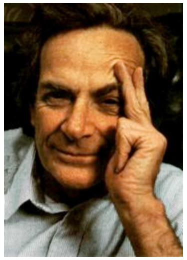
Critical phase or point?
(c.f Ir, Ge doped YRS, Cuprates)

A new role for Temperature.

Feynman Hertz

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



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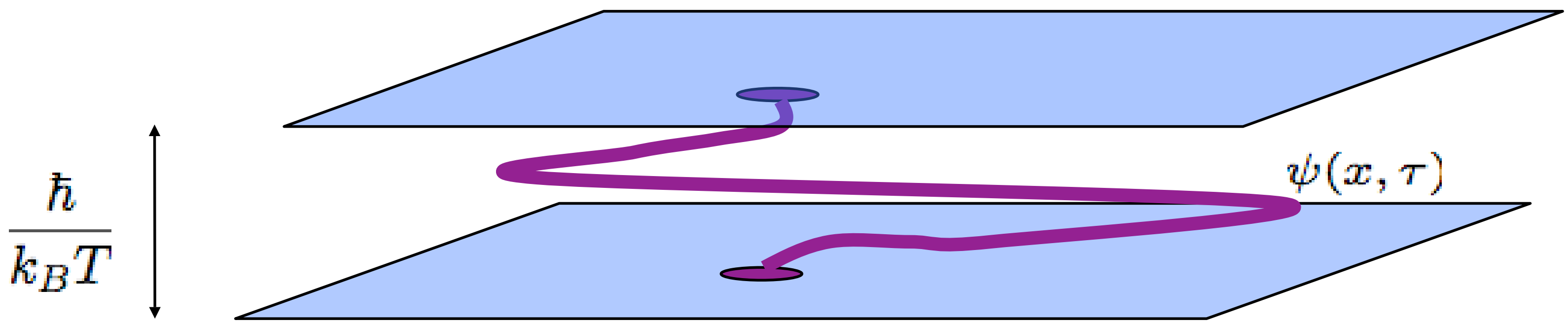
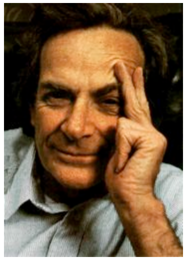
$$Z = \sum_{\text{Histories}} \exp\left[- \int_0^{1/T} L[\psi(x,\tau)] d\tau \right]$$





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Temperature: "Casimir effect" in time.

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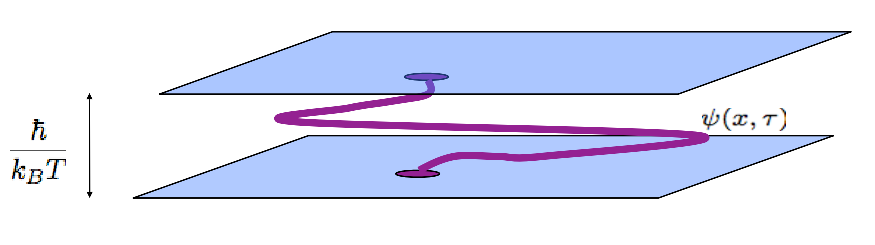

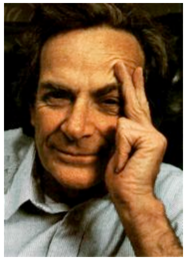
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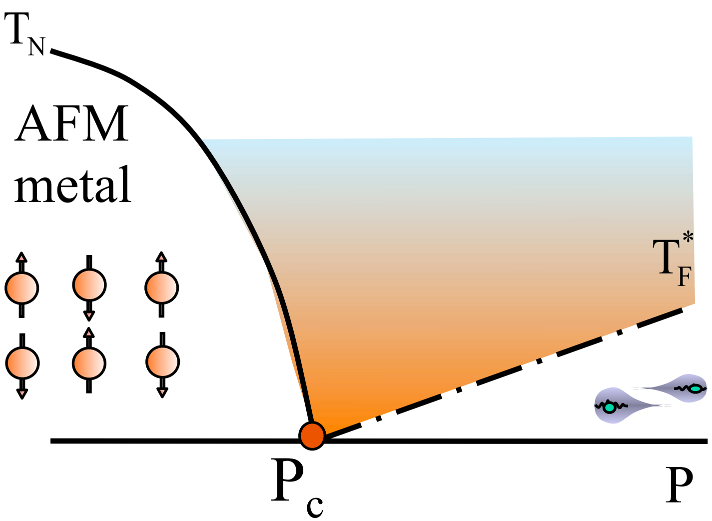

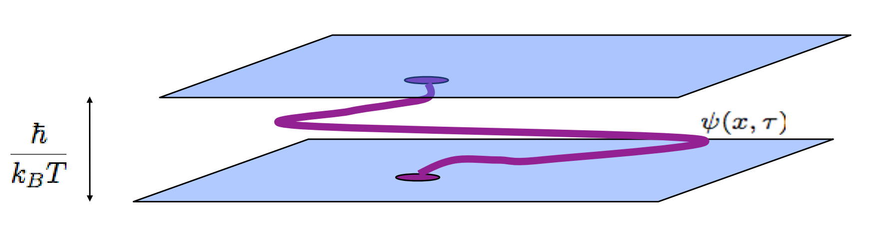

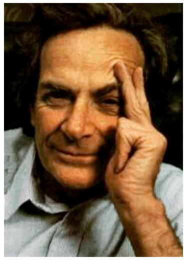

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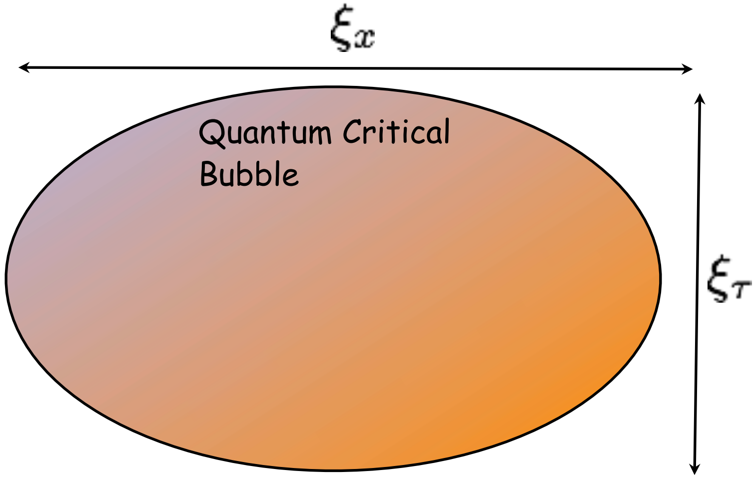

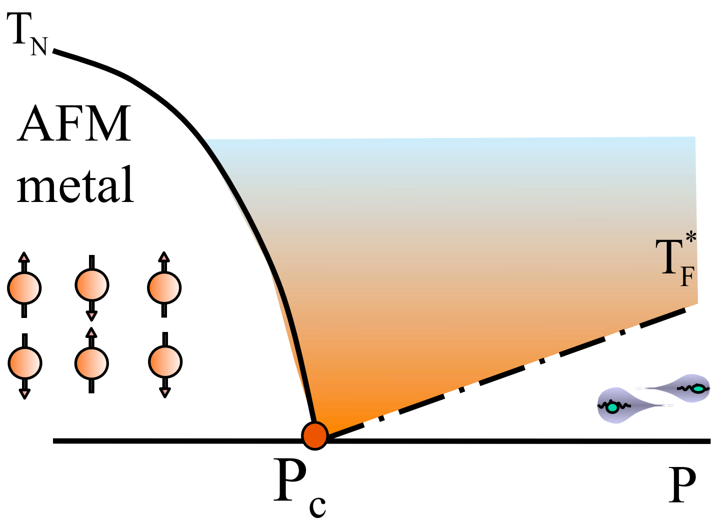

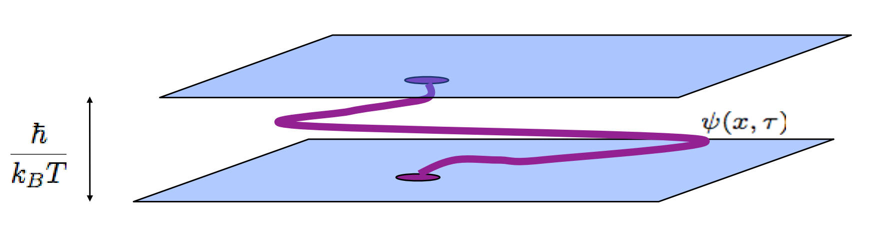

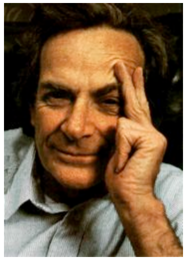

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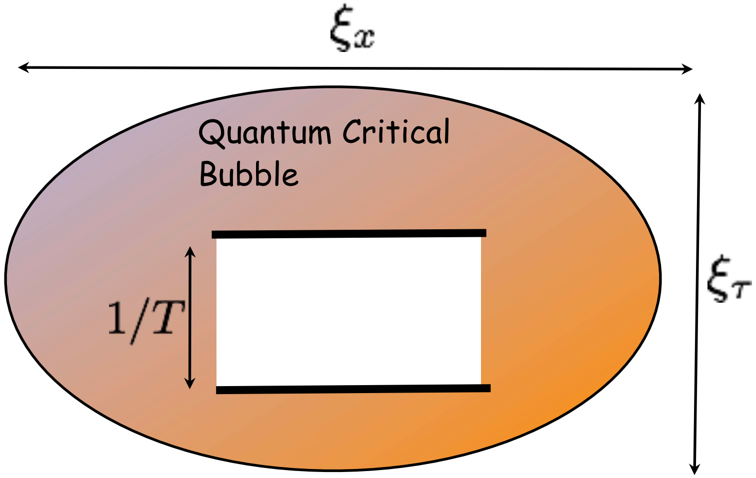

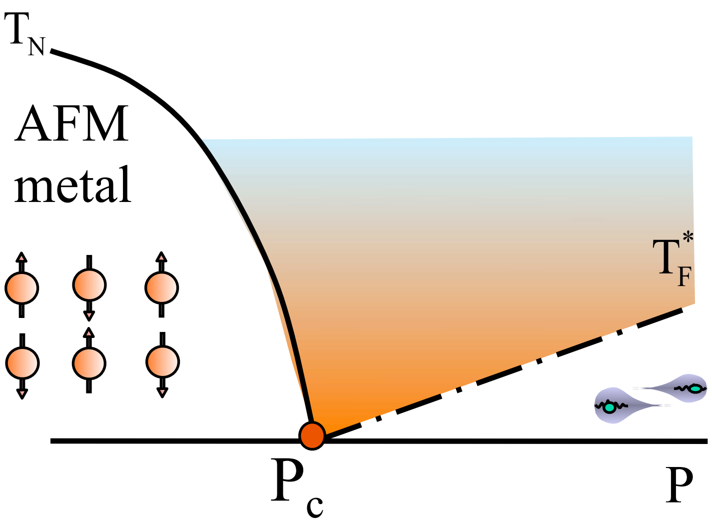

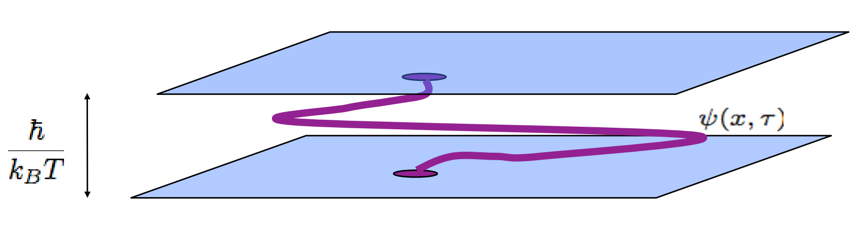

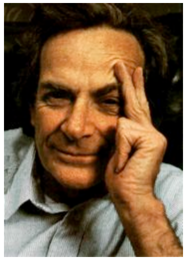

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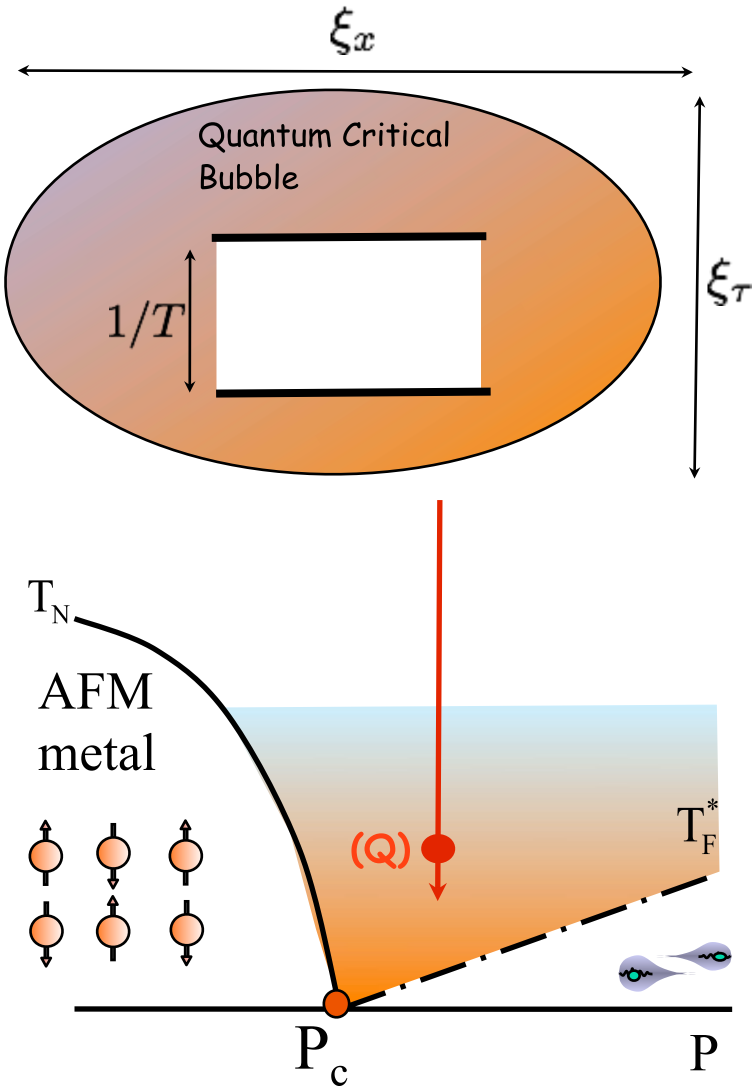
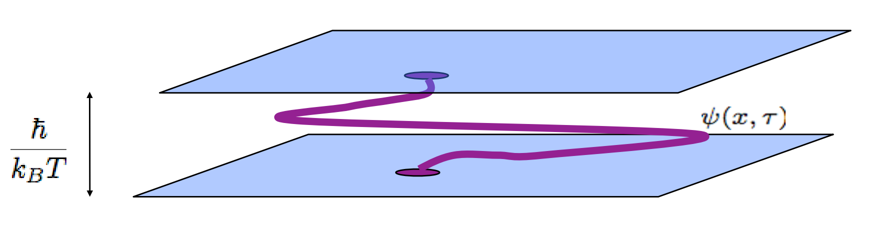
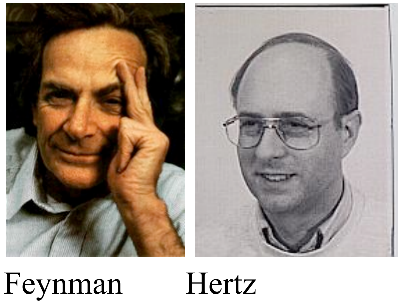


(Q) Quantum critical region: interior of correlation bubble.





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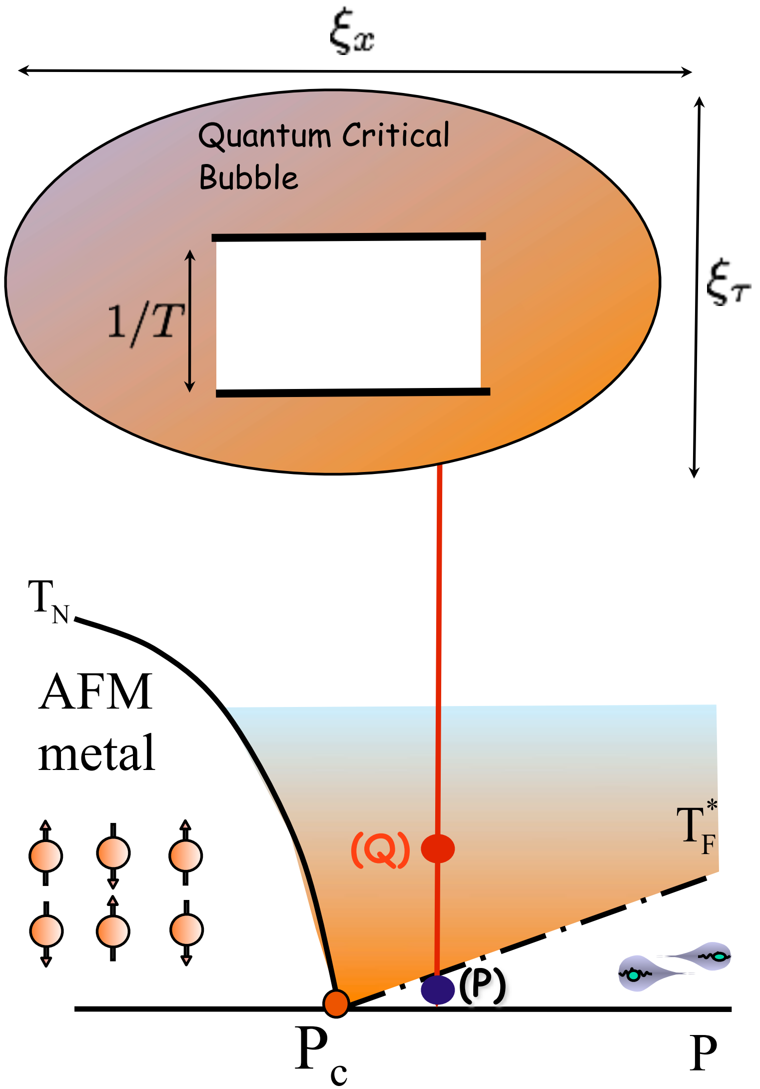
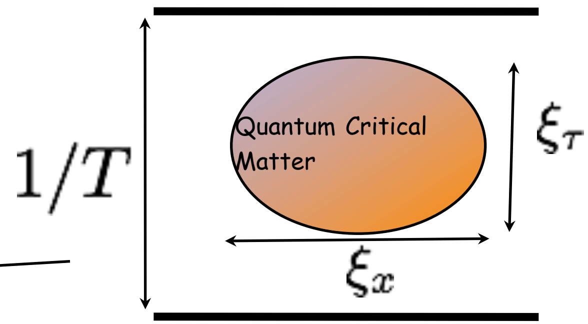


(Q) Quantum critical region: interior of correlation bubble.

(P) Paramagnet: probes exterior of correlation bubble



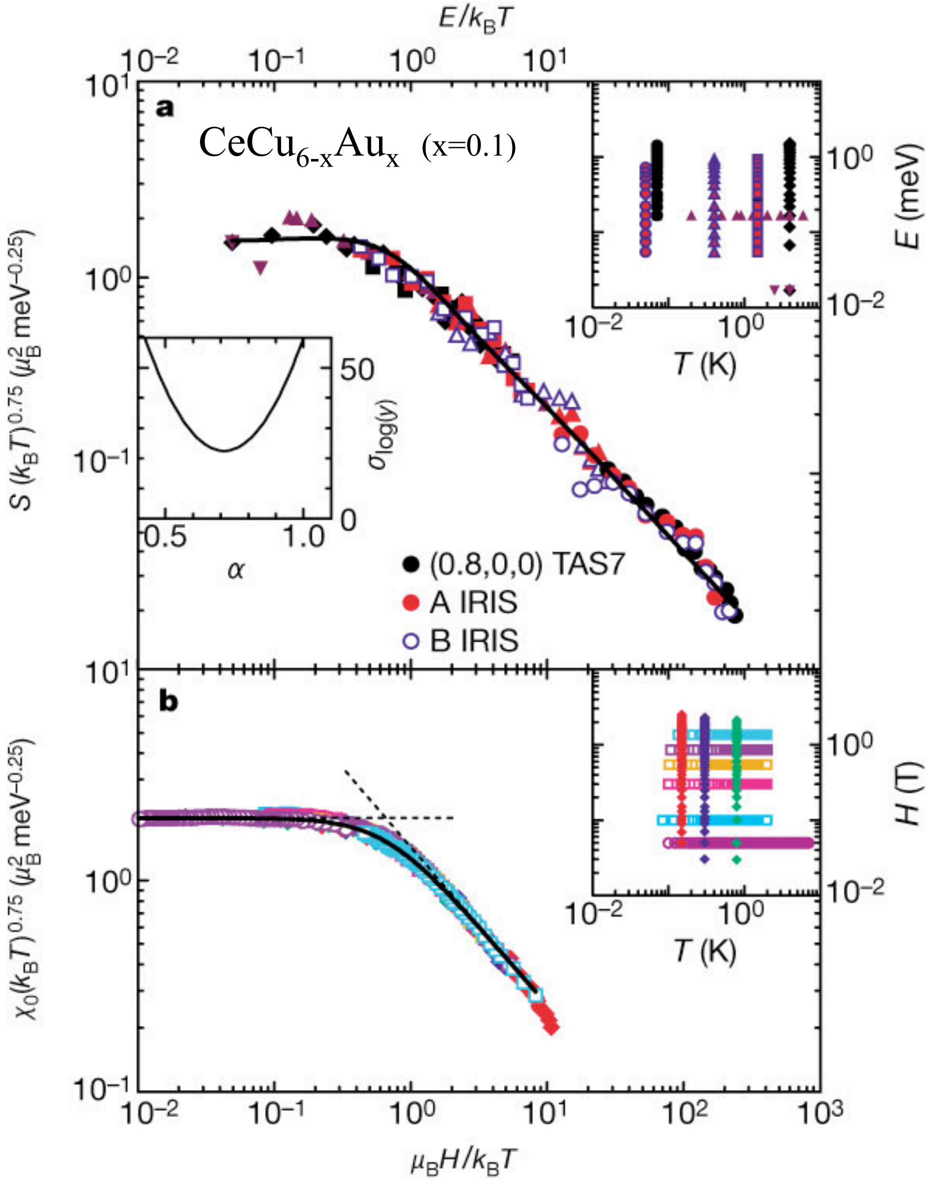
E/T Scaling:

Almut Schroeder

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

Physics Below the upper Critical Dimension.

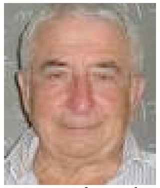
Schroeder et al, Nature 407,351 (2000).



Rutgers Center for Materials Theory

The Standard Model

Standard Model: Quantum SDW?



Doniach

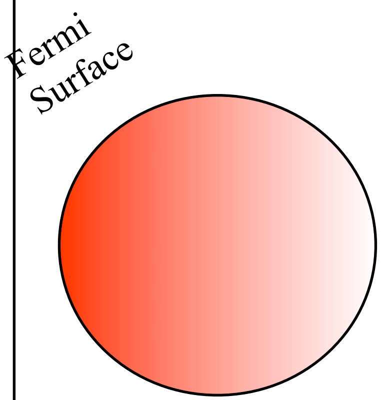
Schrieffer

Hertz

Millis

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

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



$$\chi_0^{-1} = -J(Q)$$

F.S. instability

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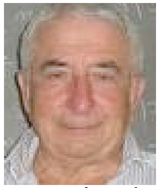
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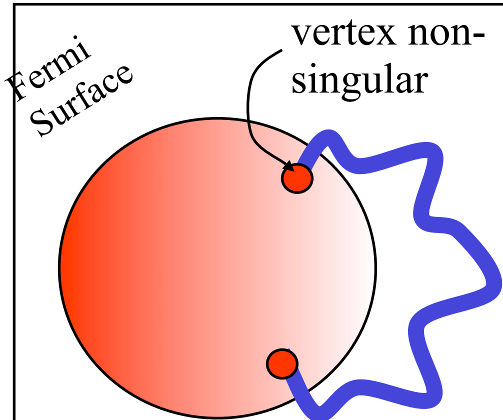

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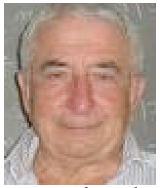
$$\chi^{-1}(q,\omega) \propto (\xi^{-2} + (q-Q)^2 - i\omega / \Gamma)$$

Rutgers
Center for Materials Theory

Standard Model: Quantum SDW?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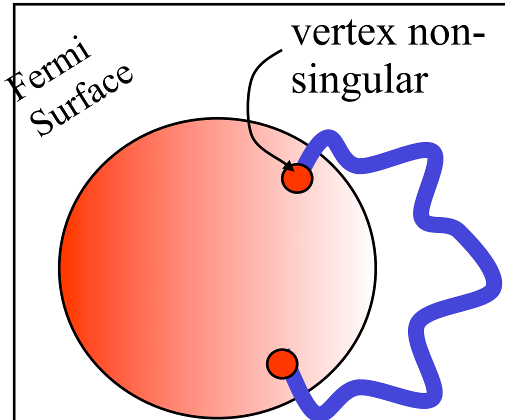

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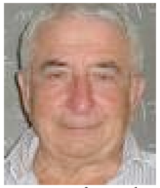

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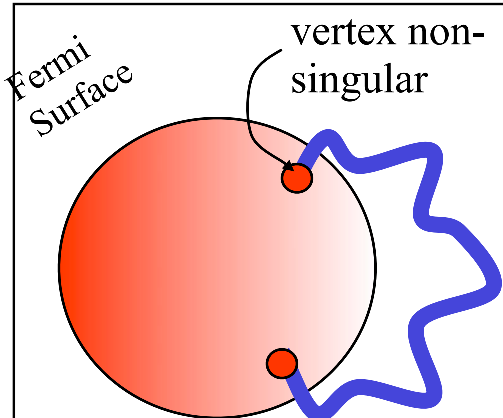

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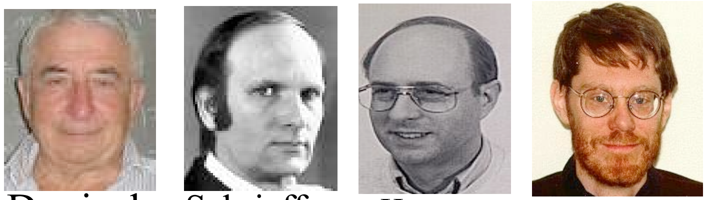
Time counts as z =2 scaling dimensions

Rutgers Center for Materials Theory

Standard Model: Quantum SDW?



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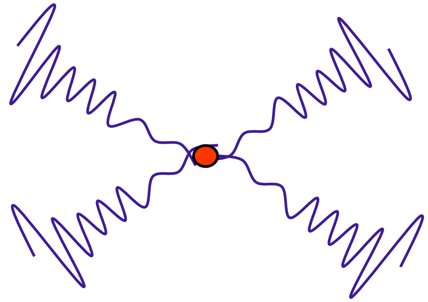
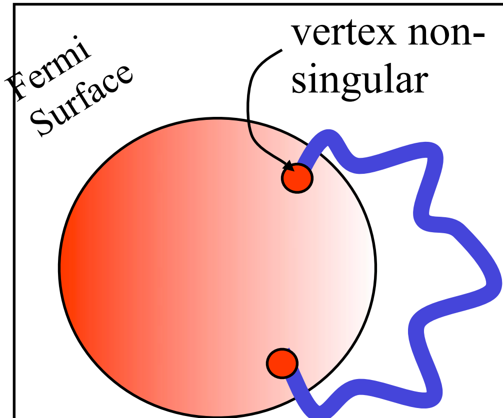


If $d + z = d + 2 > 4$:
ϕ^4 terms "irrelevent"
Critical modes are Gaussian.
T is not the only energy scale.



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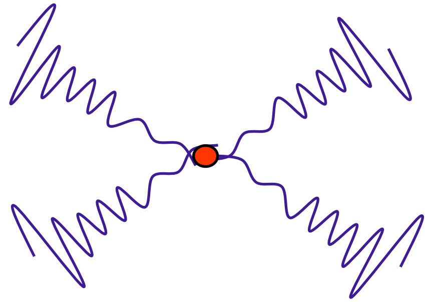

•Moriya, Doniach, Schrieffer (60s)
•Hertz (76)
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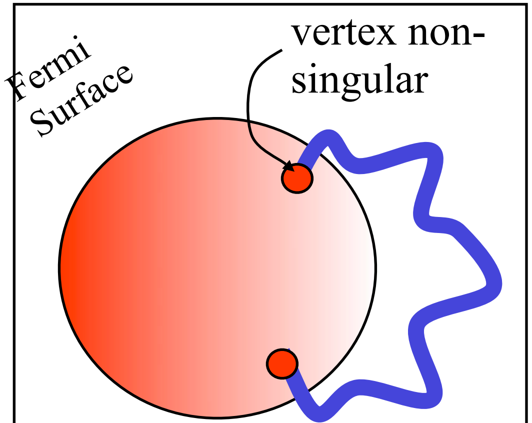
$$d_{eff} = d + z$$

Can not account for:

- the mass divergence
- the E/T scaling
- the abrupt change in Fermi surface
- the quasi-linear resistivity.



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F.S. instability

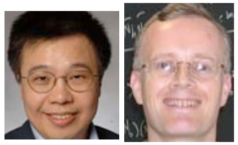
New Ideas:

Break up of the electron.

New Ideas

New Ideas

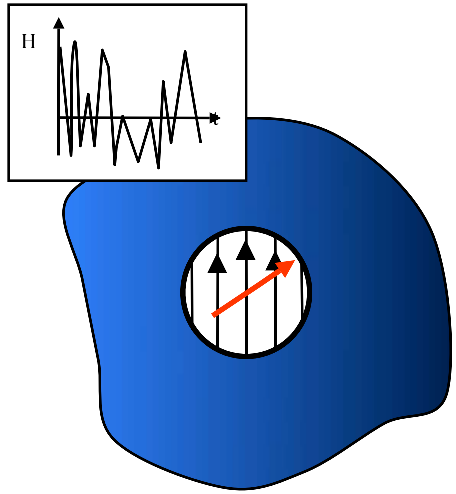
Si, Ingersent



- **Local quantum criticality**

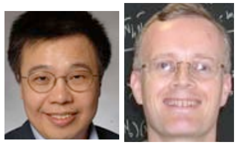
(Si, Ingersent, Smith, Rabello, Nature 2001):
Spin is the critical mode,
Fluctuations critical in time.

Requires a two dimensional spin fluid



New Ideas

Si, Ingersent



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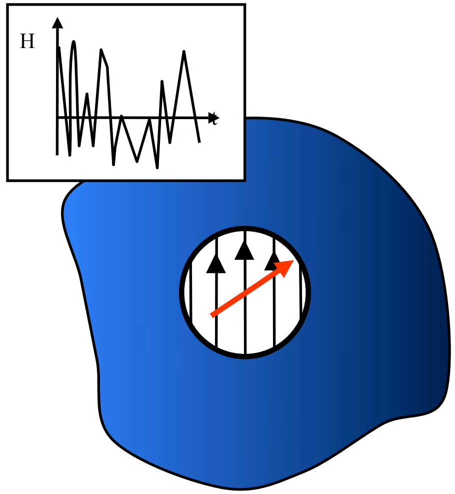
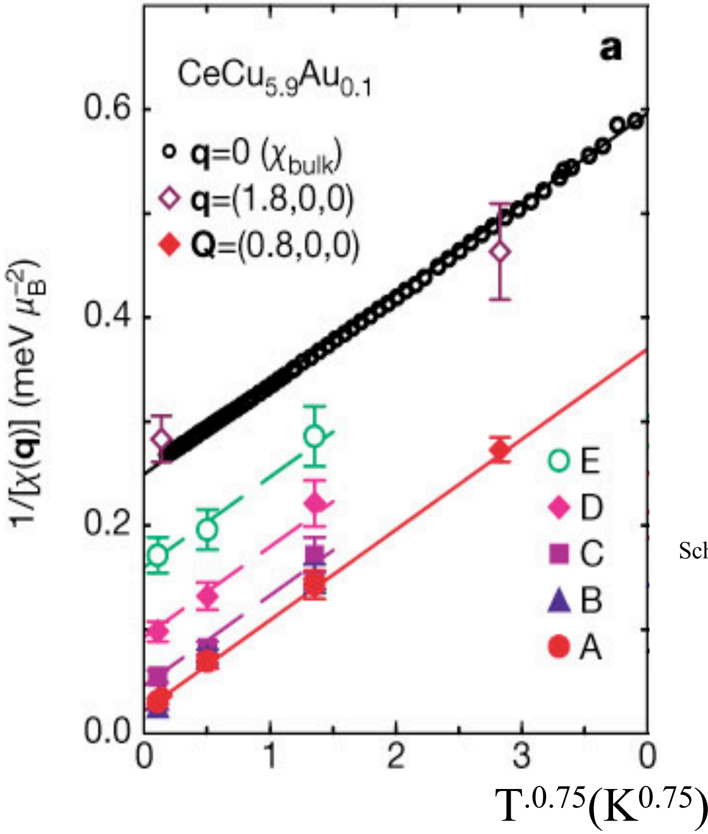


Requires a two dimensional spin fluid

Locality of critical fluctuations

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



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

New Ideas

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


Senthil


Sachdev


Vishwanath

New Ideas

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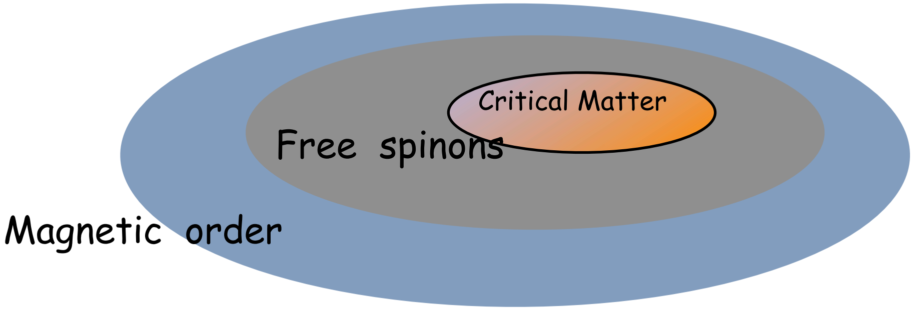
Senthil Sachdev Vishwanath



New Ideas

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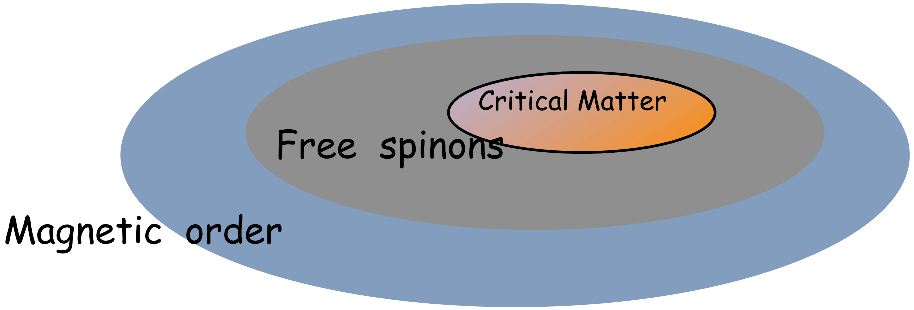
Senthil

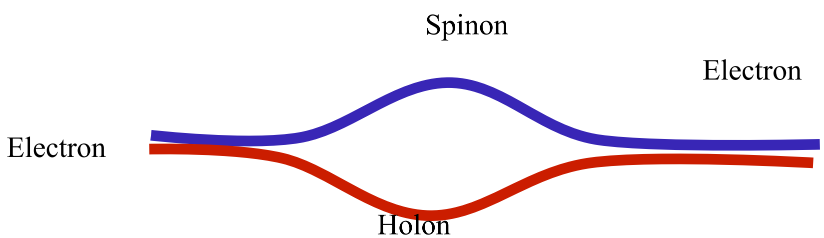

Sachdev


Vishwanath

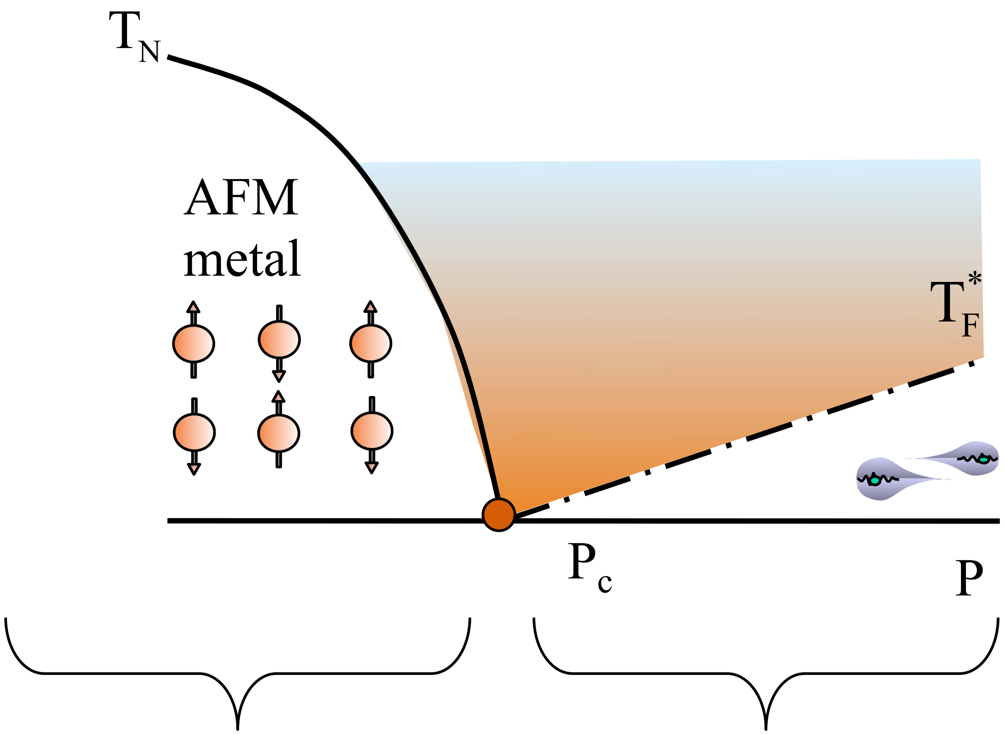


- **Search for a new mean-field theory.** (PC, Pepin et al JCM, 2001, Rech et al 2005, Lebanon et al 2006.).

Pepin

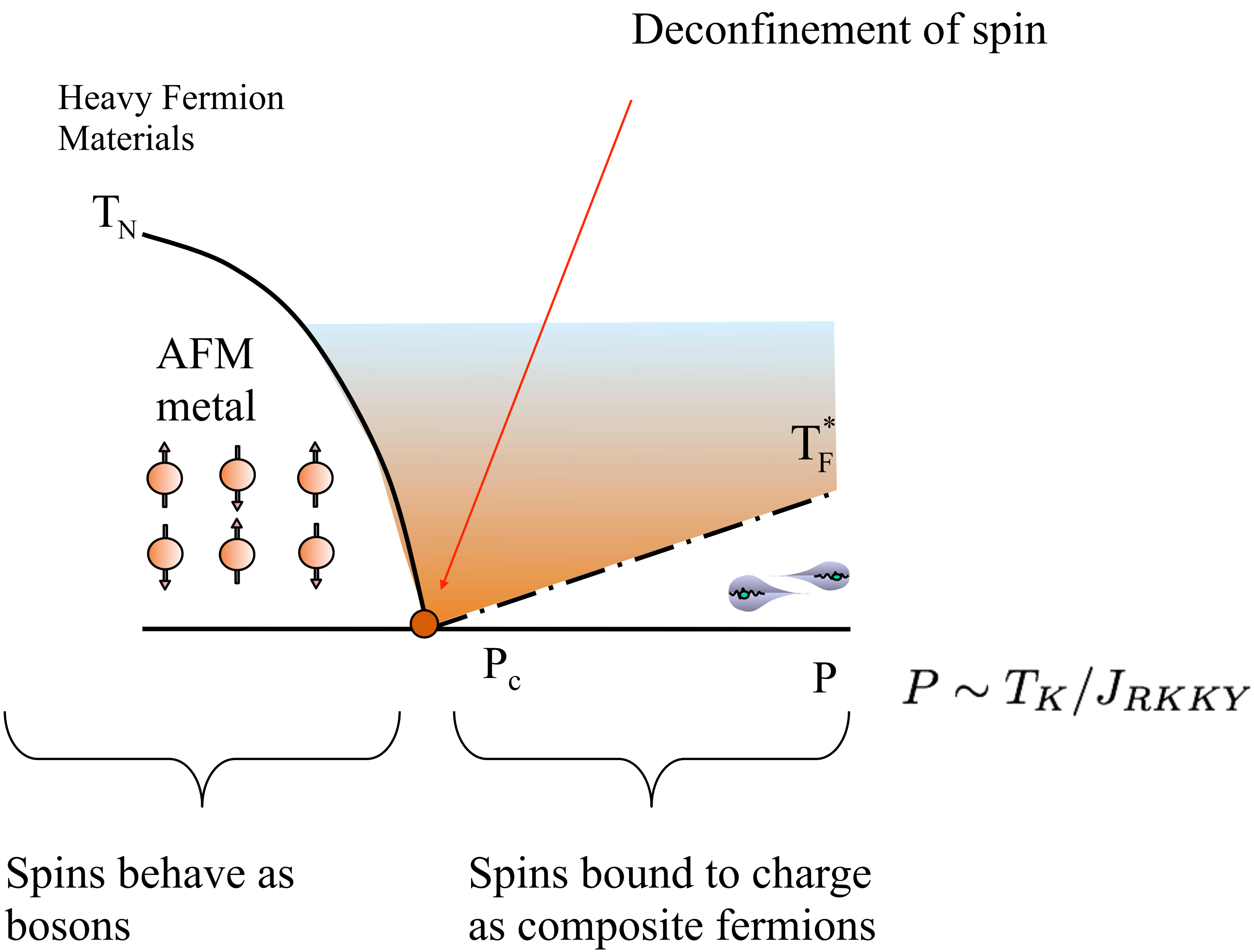
Heavy Fermion
Materials



$P \sim T_K / J_{RKKY}$

Spins behave as
bosons

Spins bound to charge
as composite fermions

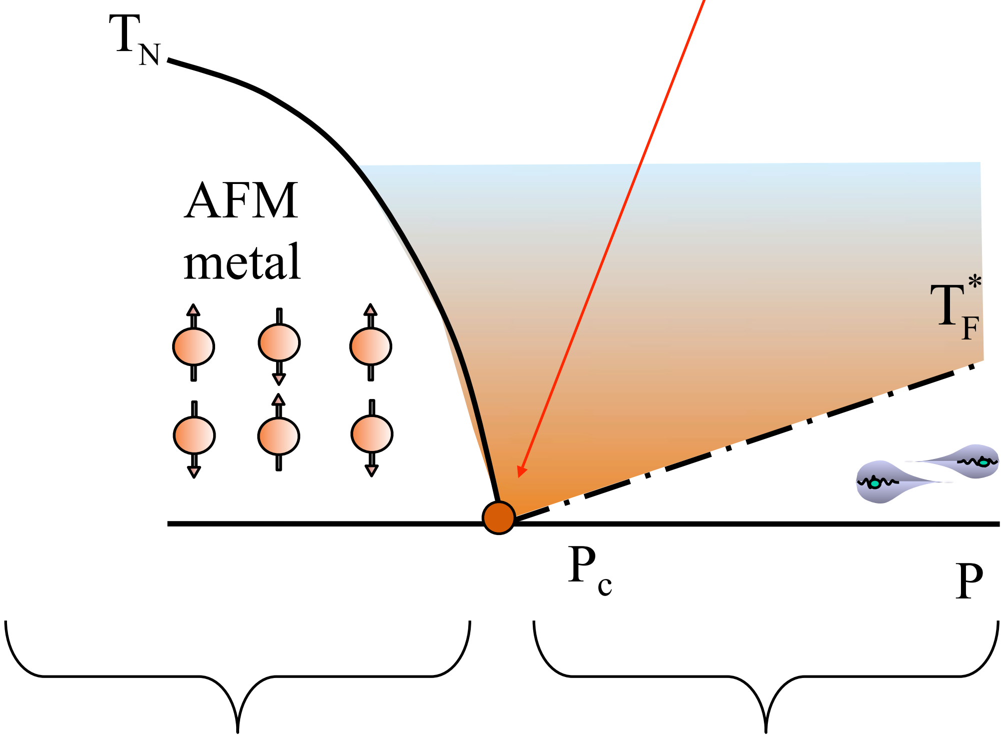

Deconfinement of spin
Heavy Fermion
Materials
T_N
AFM
metal
T_F^*
P_c
P
$P \sim T_K/J_{RKKY}$
Spins behave as
bosons
Spins bound to charge
as composite fermions

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

Kondo Lattice Model
(Kasuya, 1951)

Deconfinement of spin

Heavy Fermion Materials



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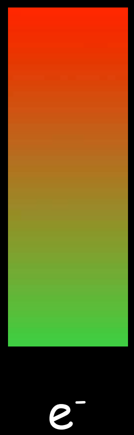
New Methods



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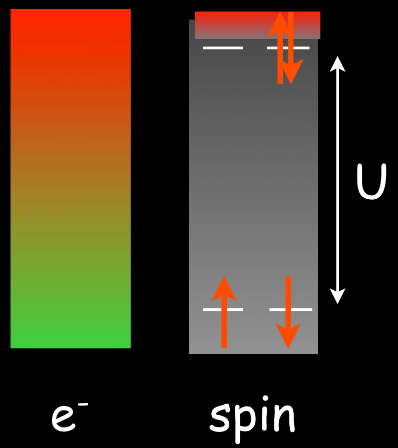

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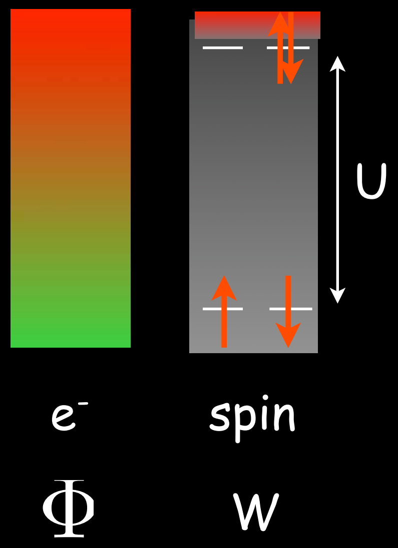

Elimination of States
implies Gauge Fields.

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

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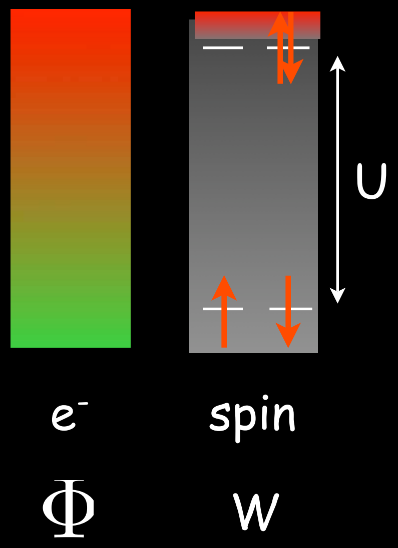

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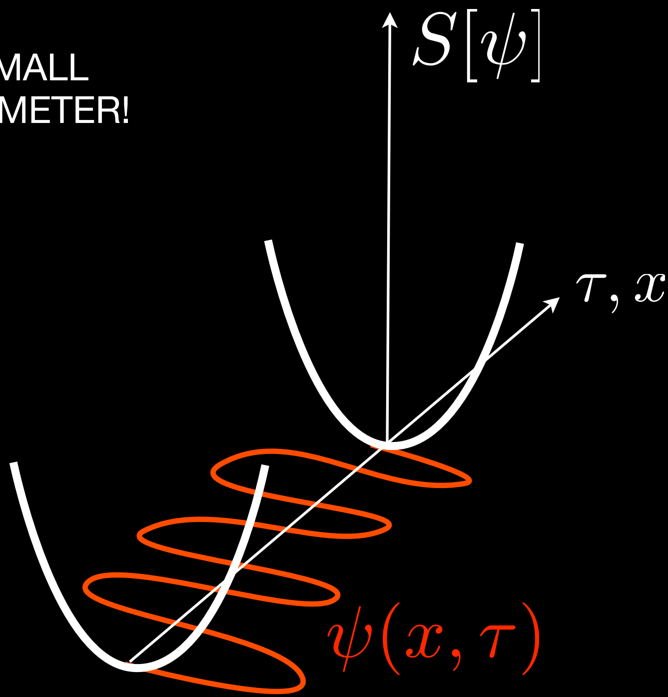

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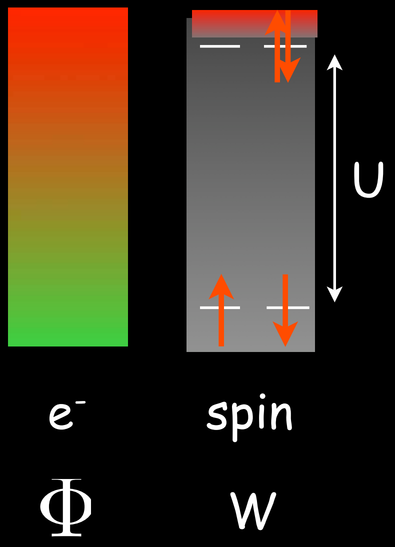

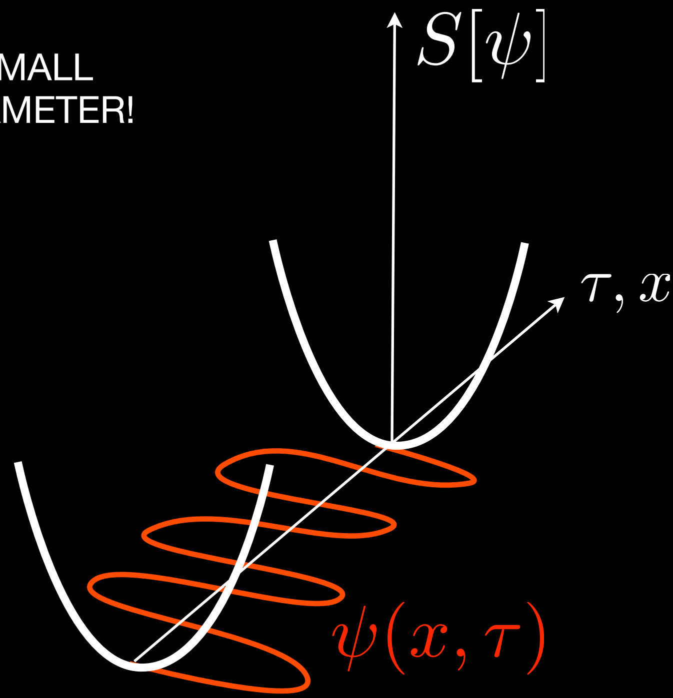

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Large N : family of models with "N" spin components, which retain the key physics and can be solved in the large N limit.

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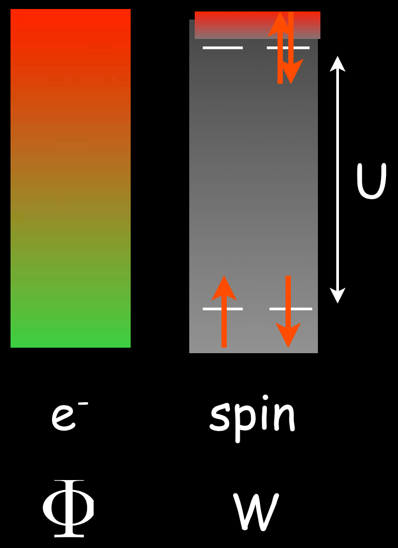

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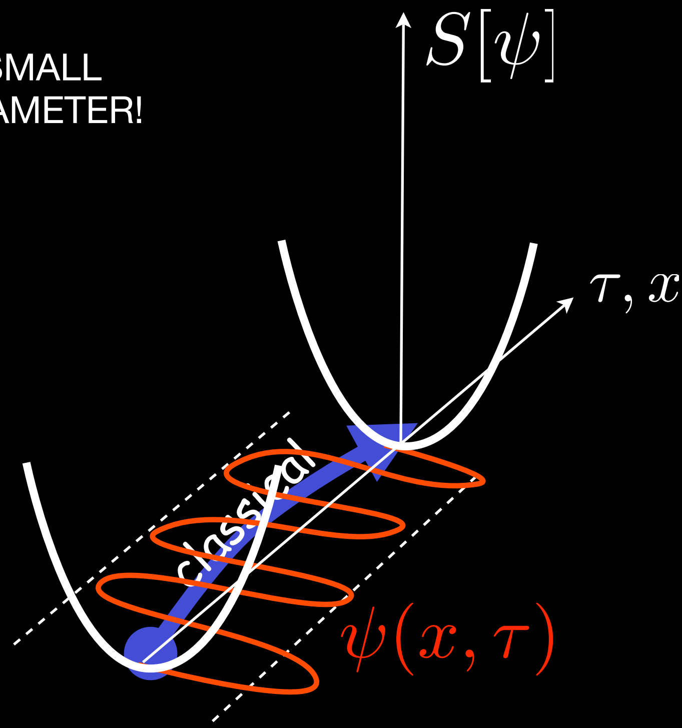
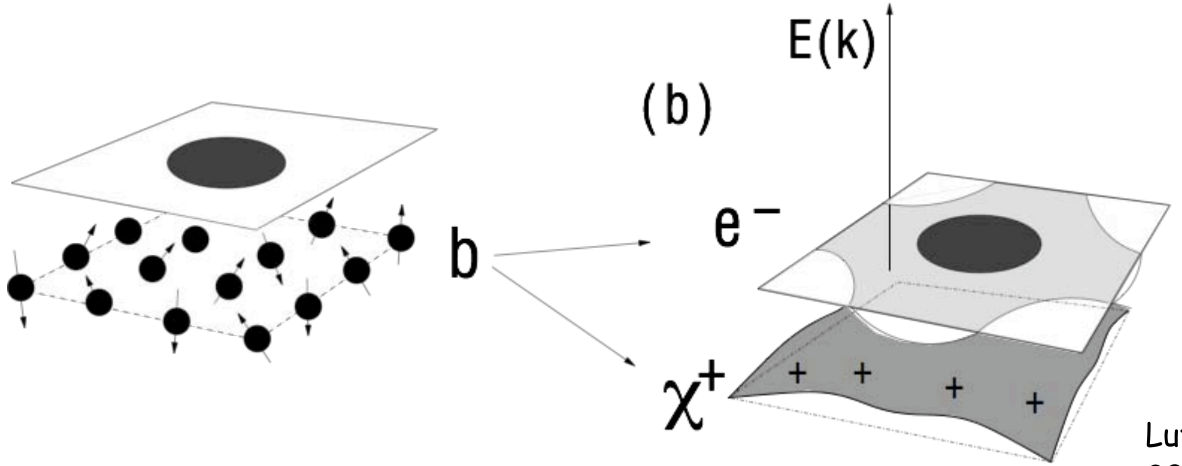


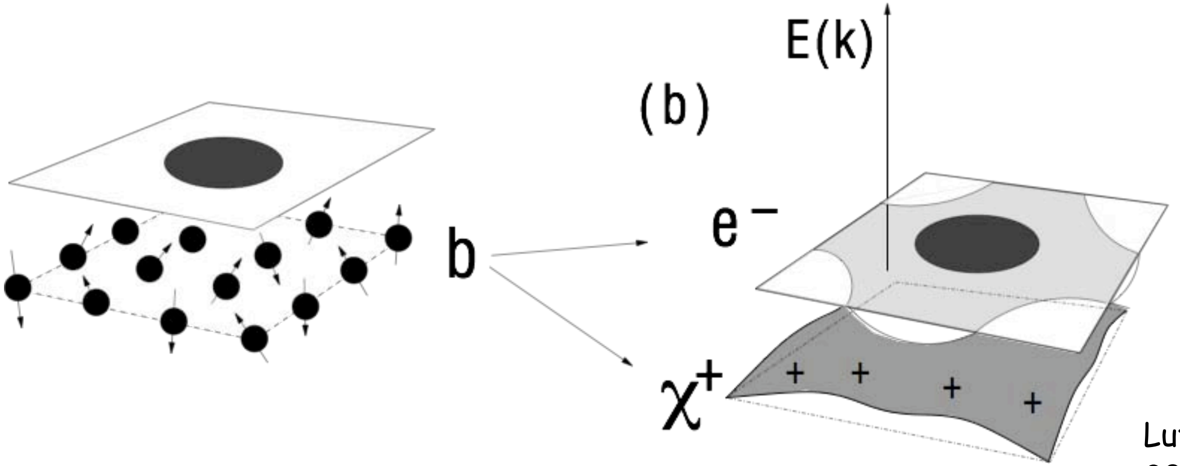
$$\frac{1}{N} \sim \hbar_{eff}$$

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



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

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



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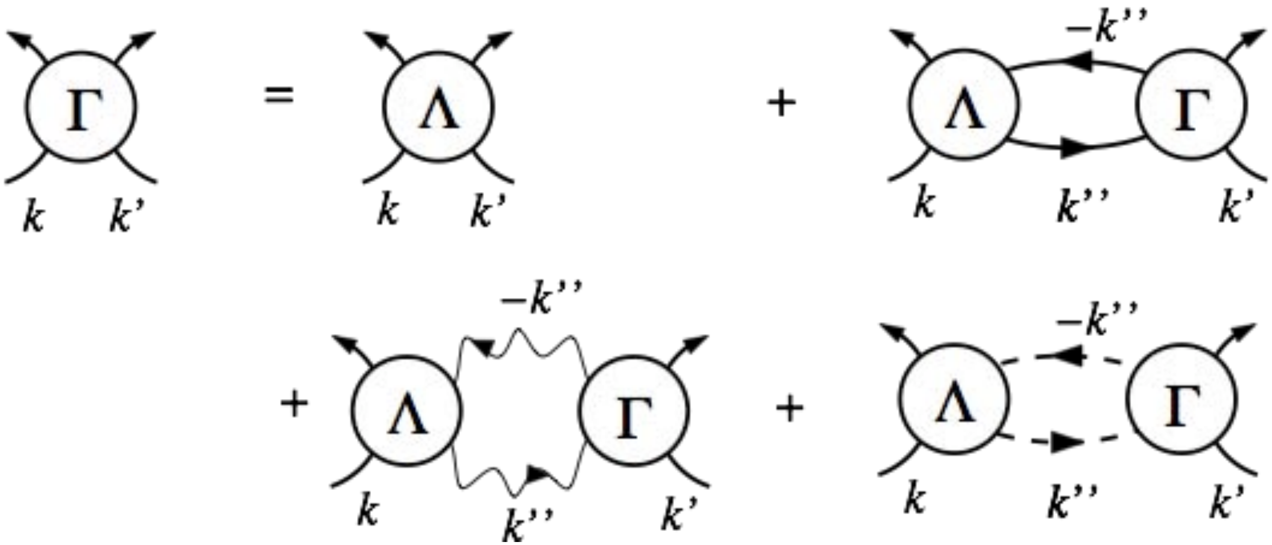

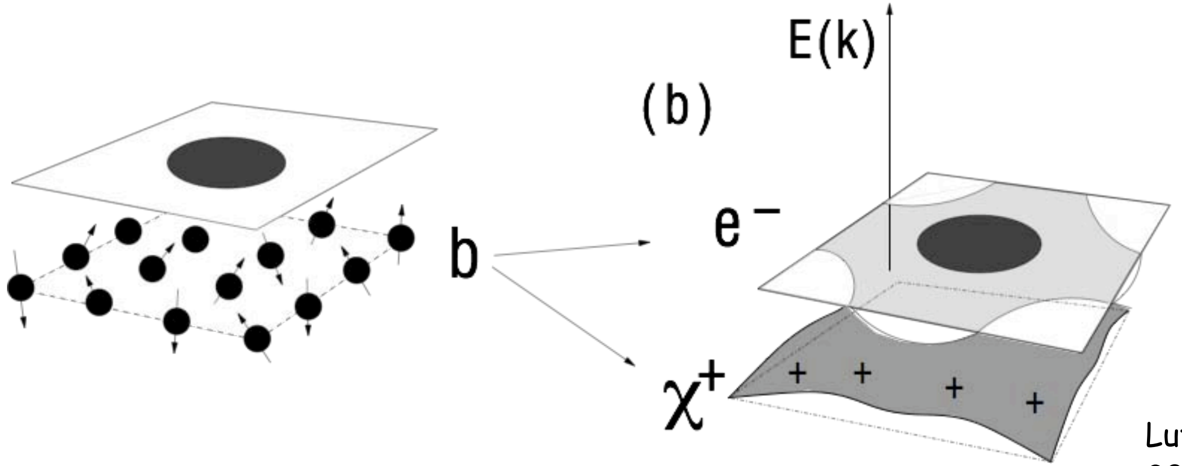

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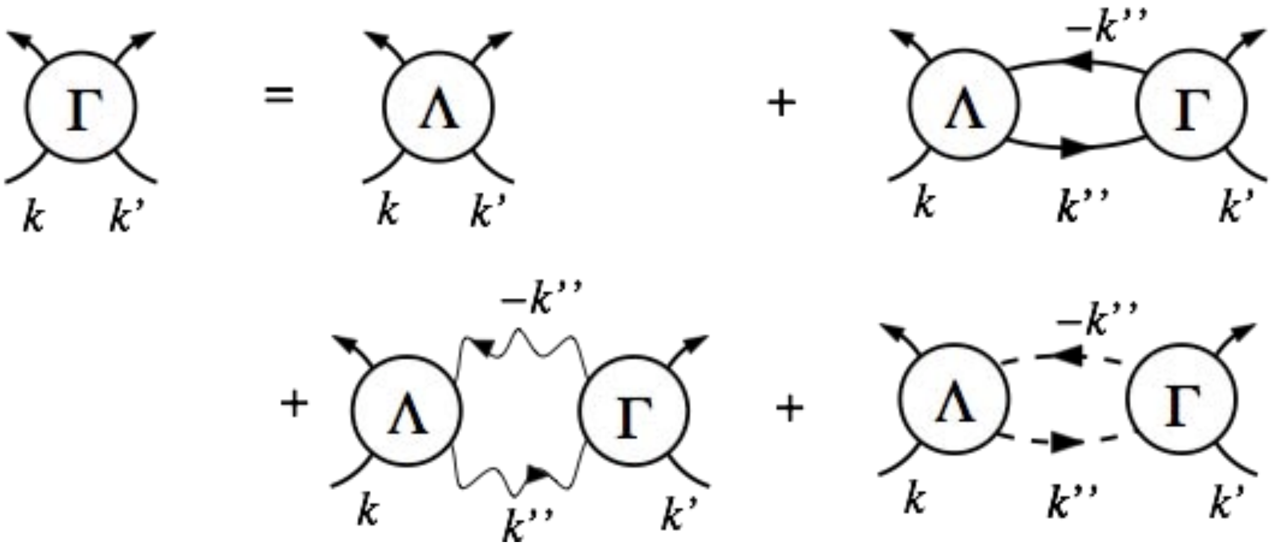
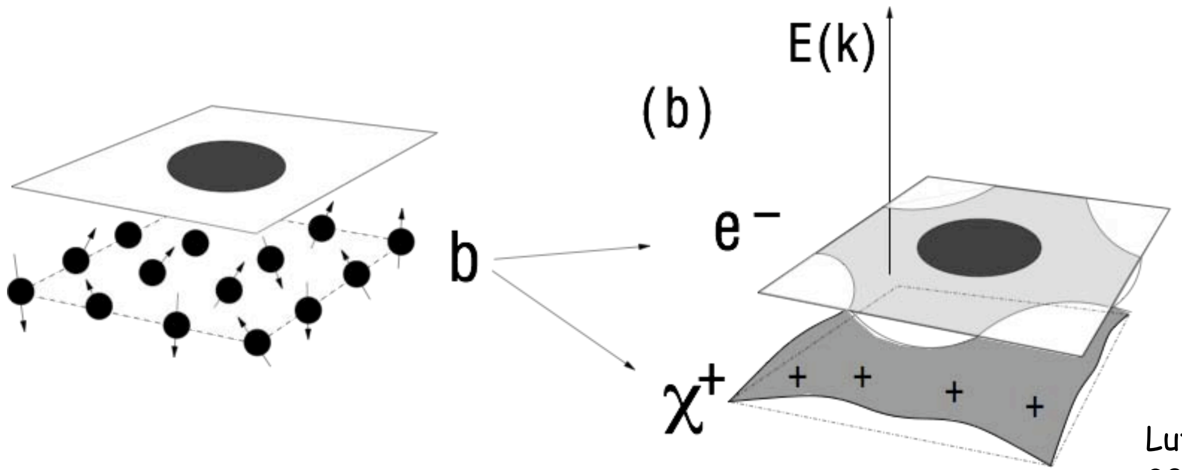


Virtual spinons.



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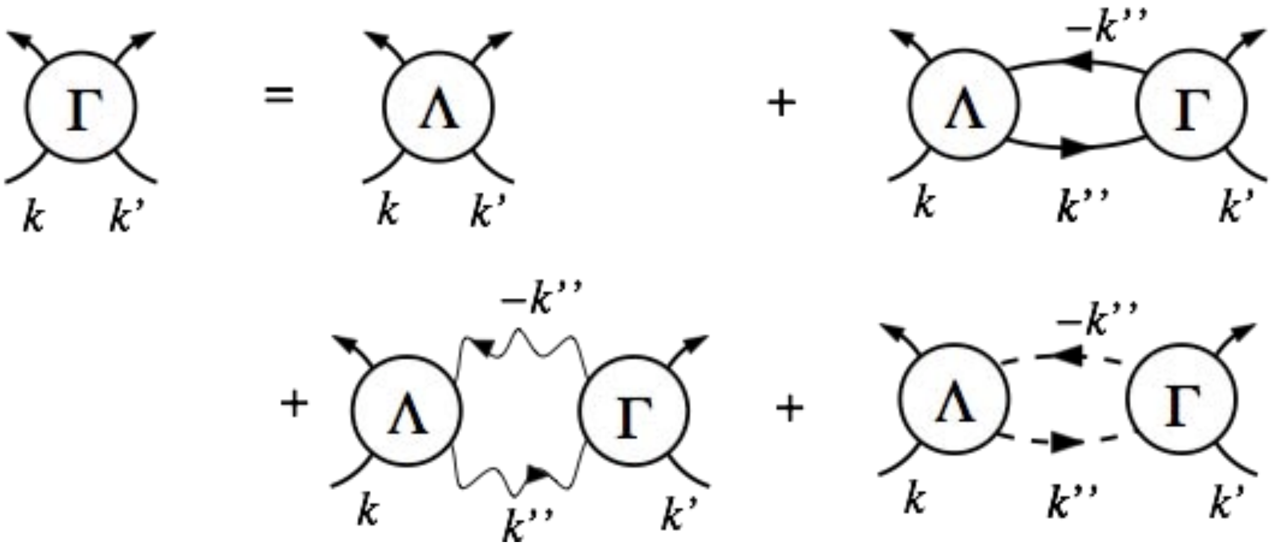

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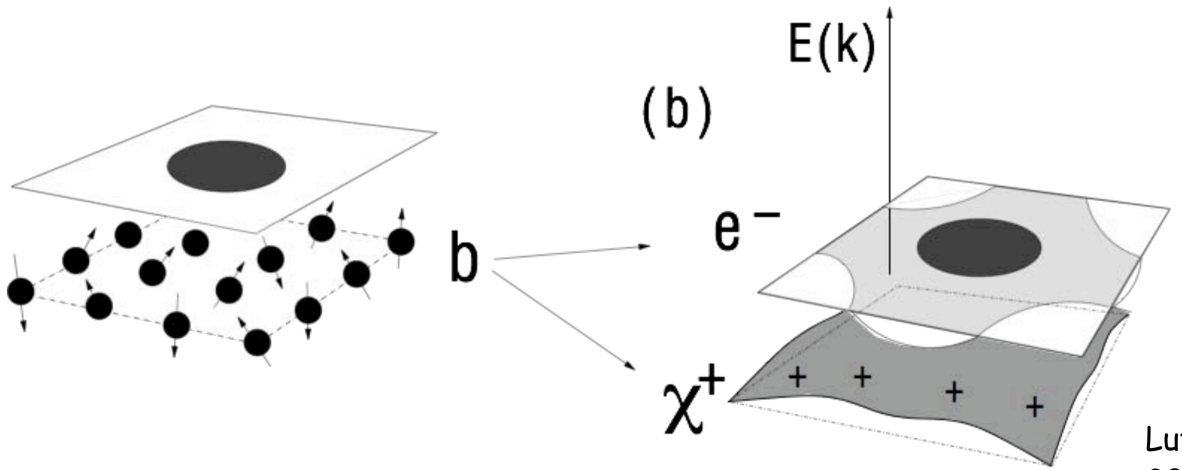

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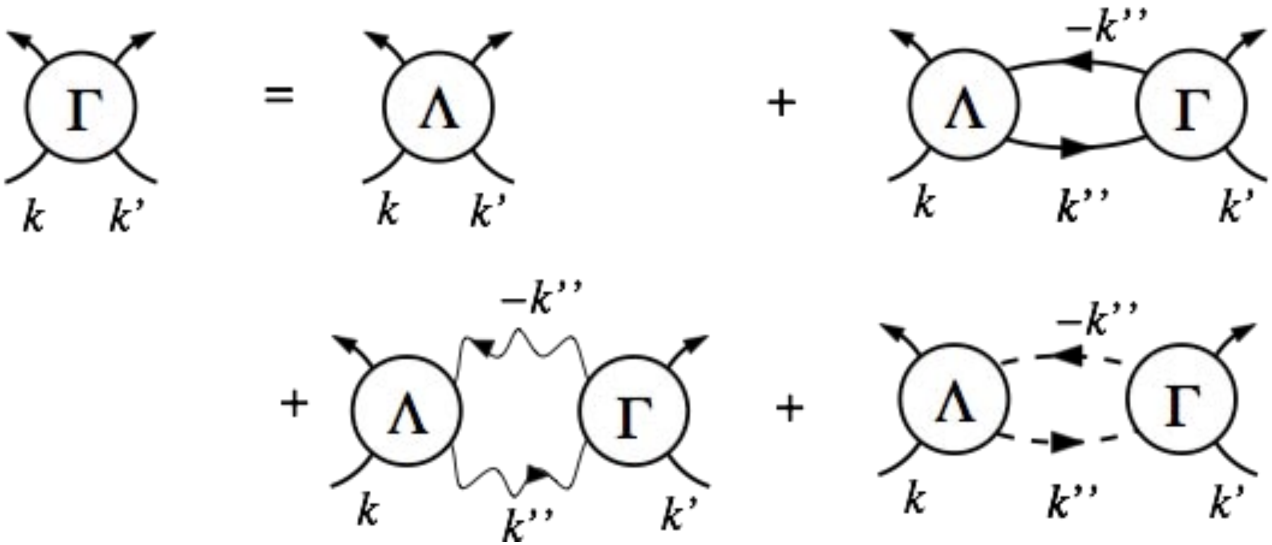

Fermi Liquid scattering parameters determined primarily by excitation of low-lying spinon and holon states..

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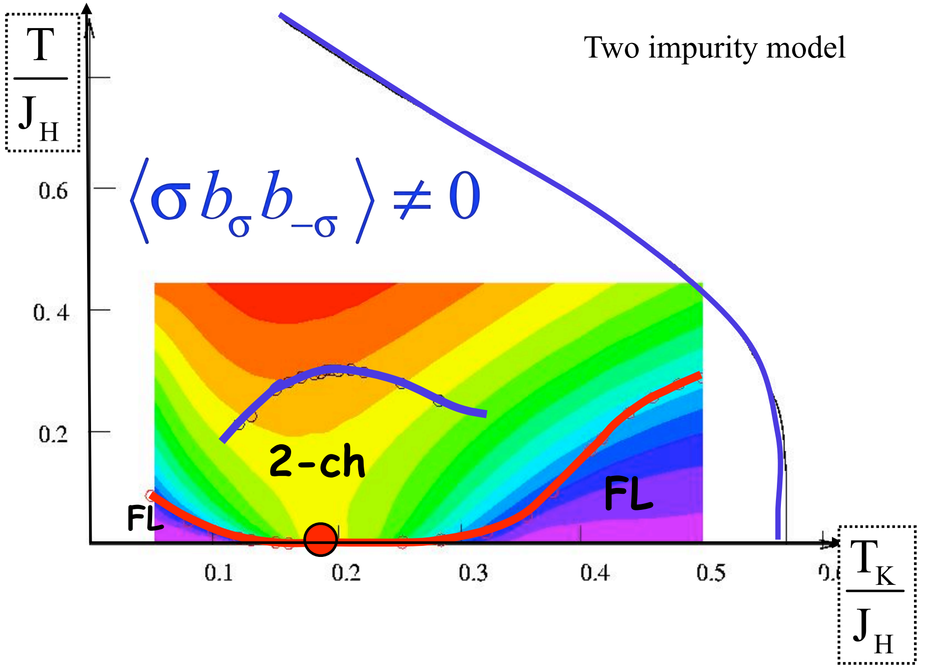
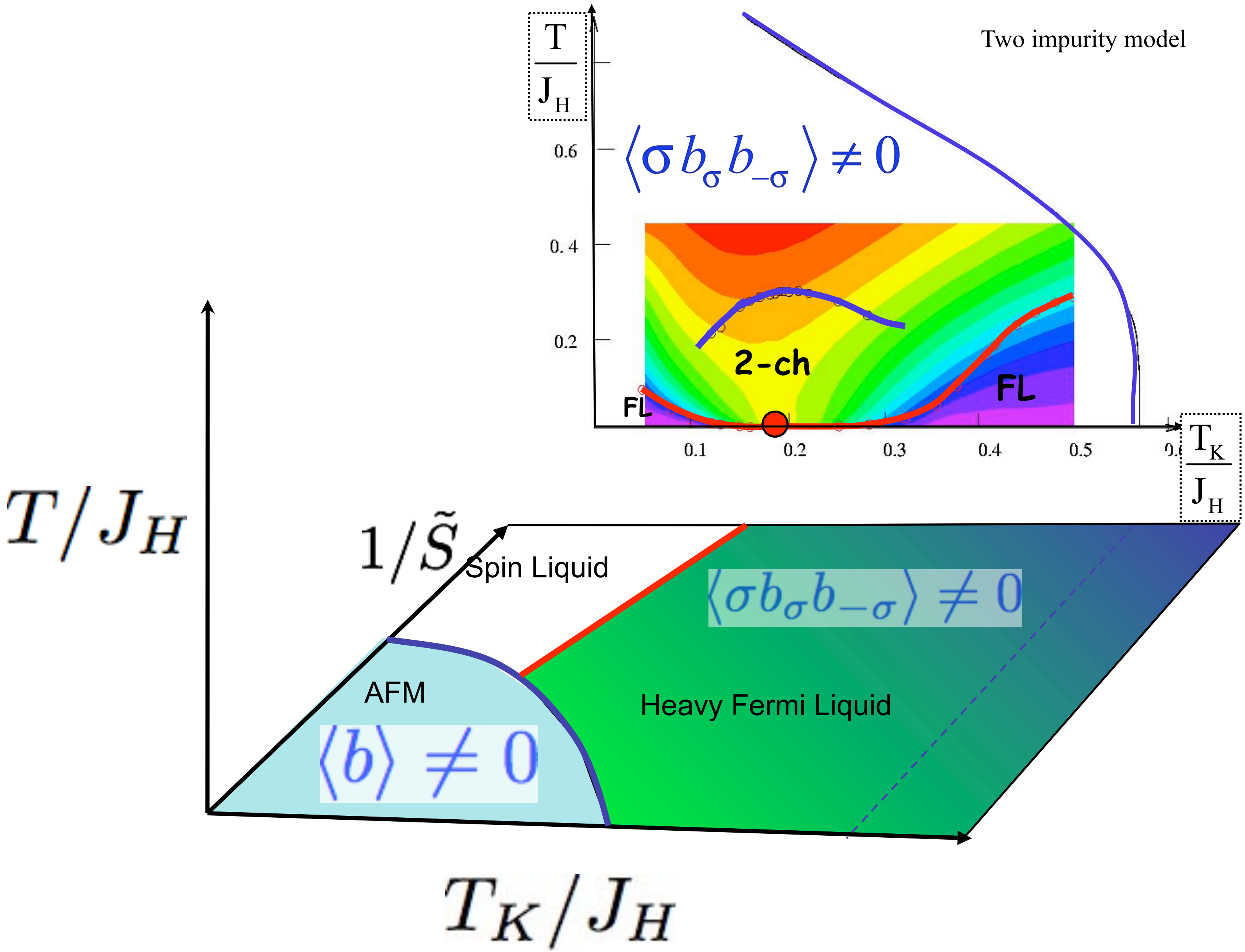


Two impurity model
$\frac{T}{J_H}$
0.6
0. 4
0.2
$\langle \sigma b_\sigma b_{-\sigma} \rangle \neq 0$
2-ch
FL
FL
0.1
0.2
0.3
0.4
0.5
$\frac{T_K}{J_H}$



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T_K / J_H
T/J_H
$1/\tilde{S}$
Spin Liquid
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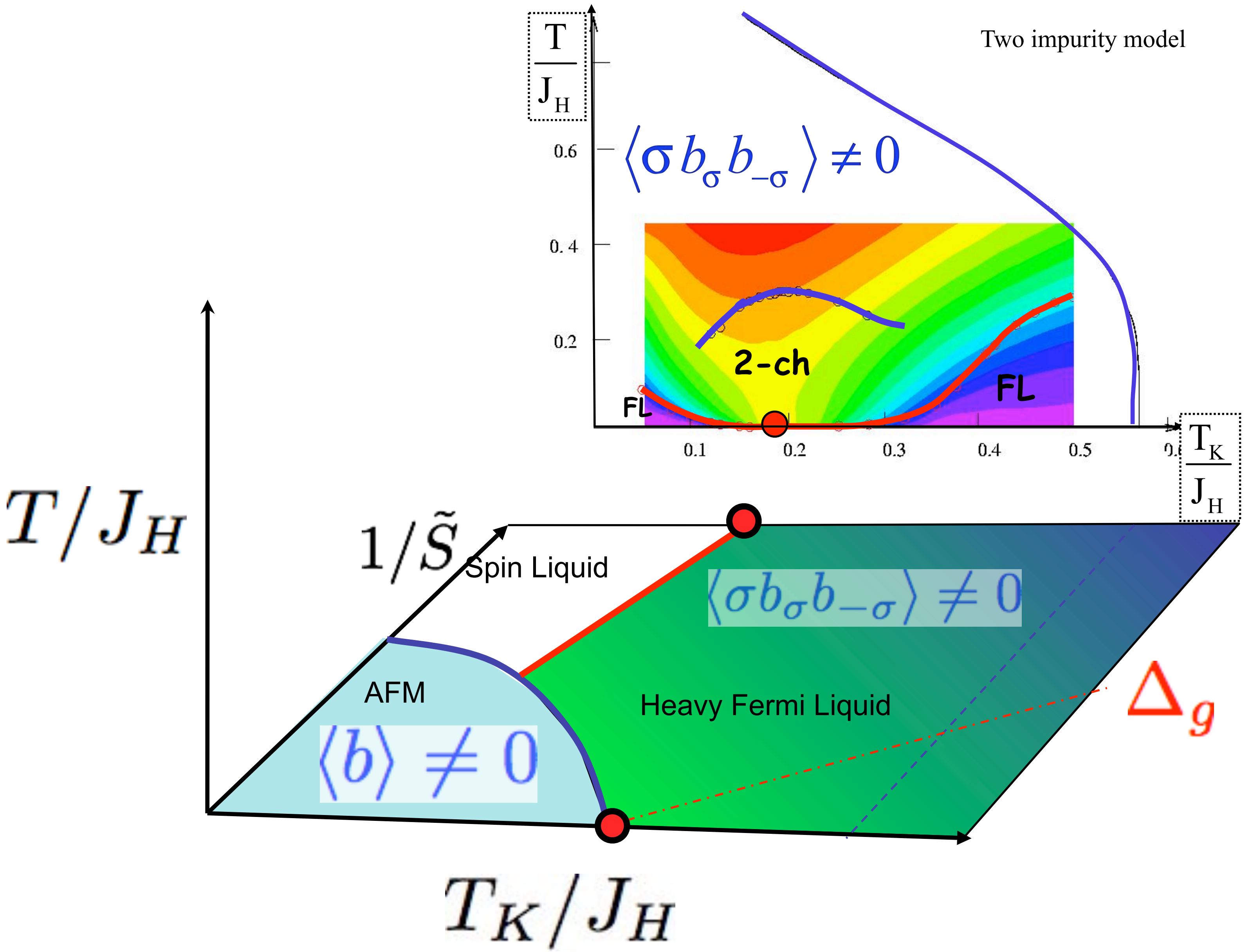
Heavy Fermi Liquid
T_K/J_H



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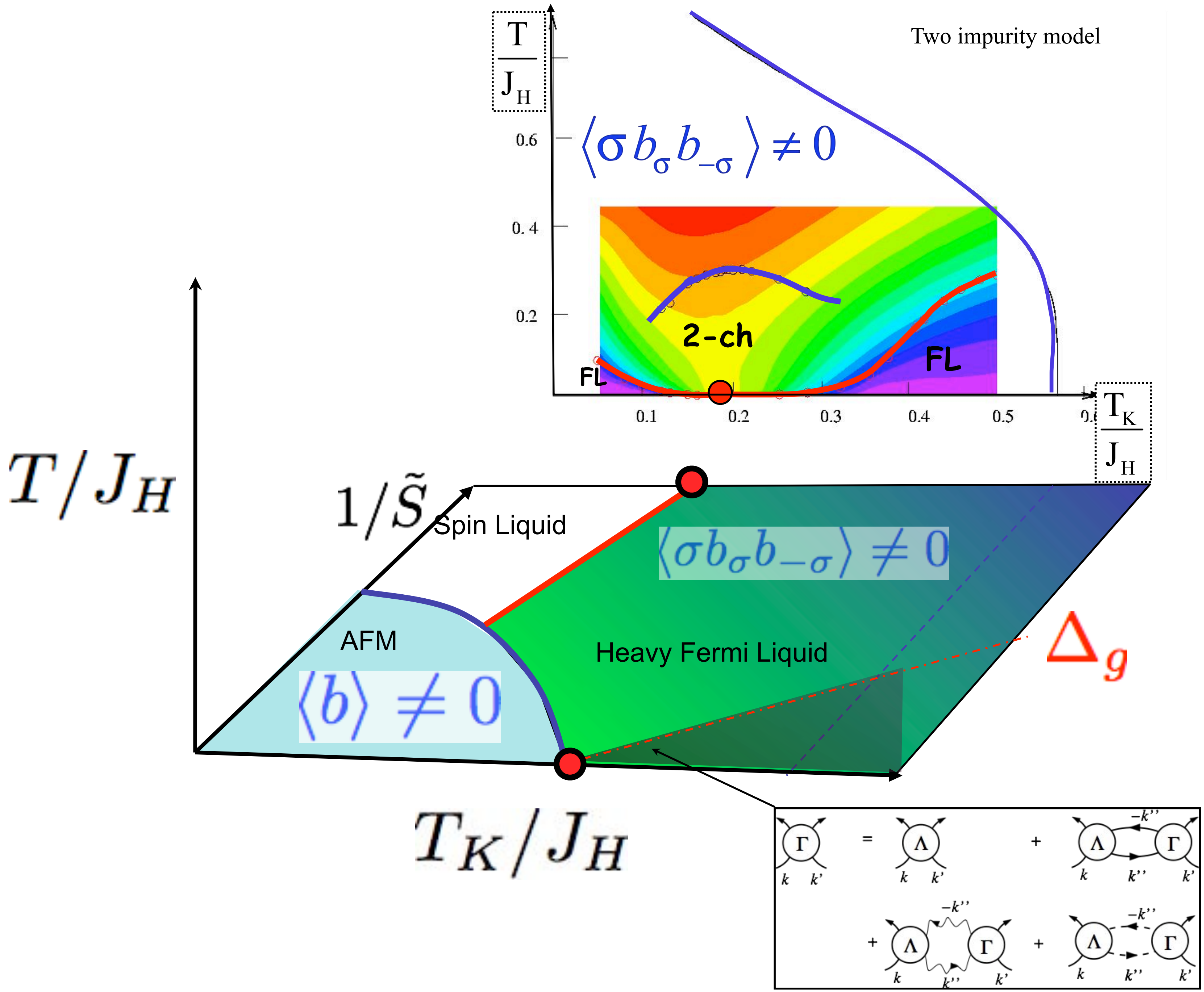
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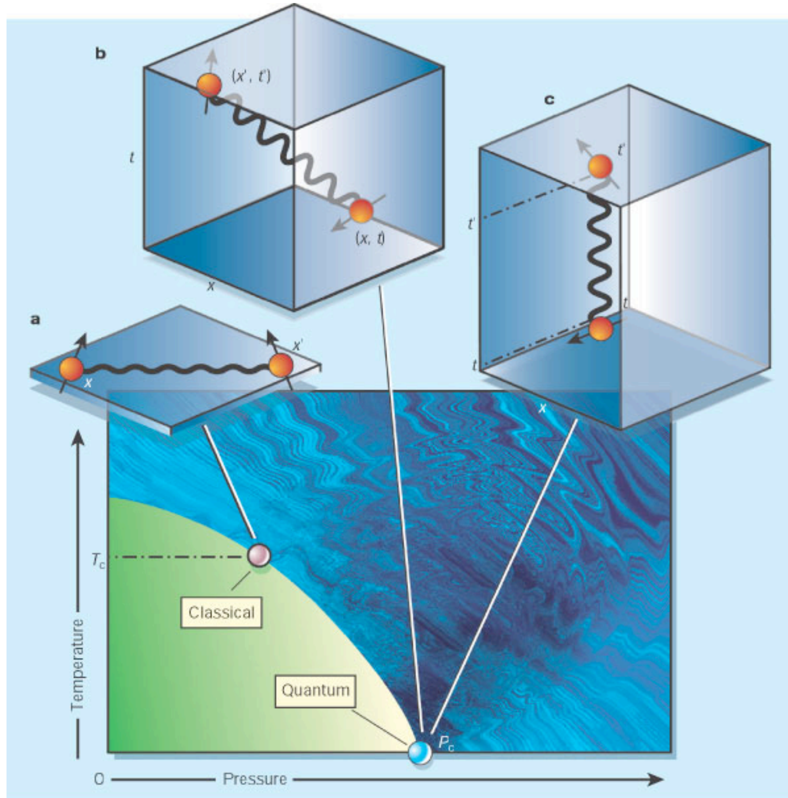
Δ_g
T_K/J_H
Γ
Λ
k
k'
k''
-k''

Conclusions



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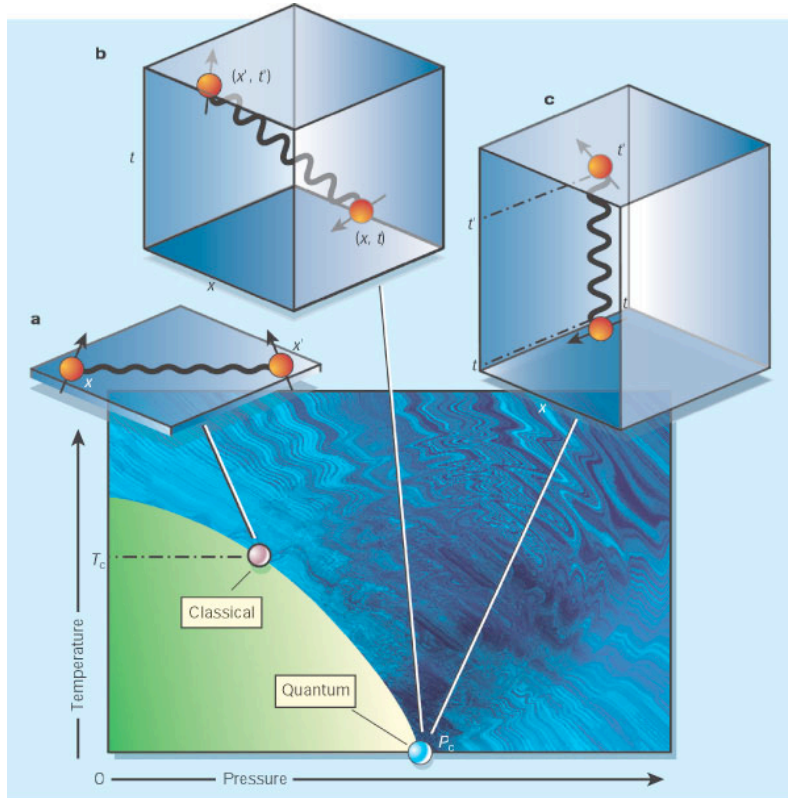
Qu-transitions: phase transition driven by zero point fluctuations of radically new type.



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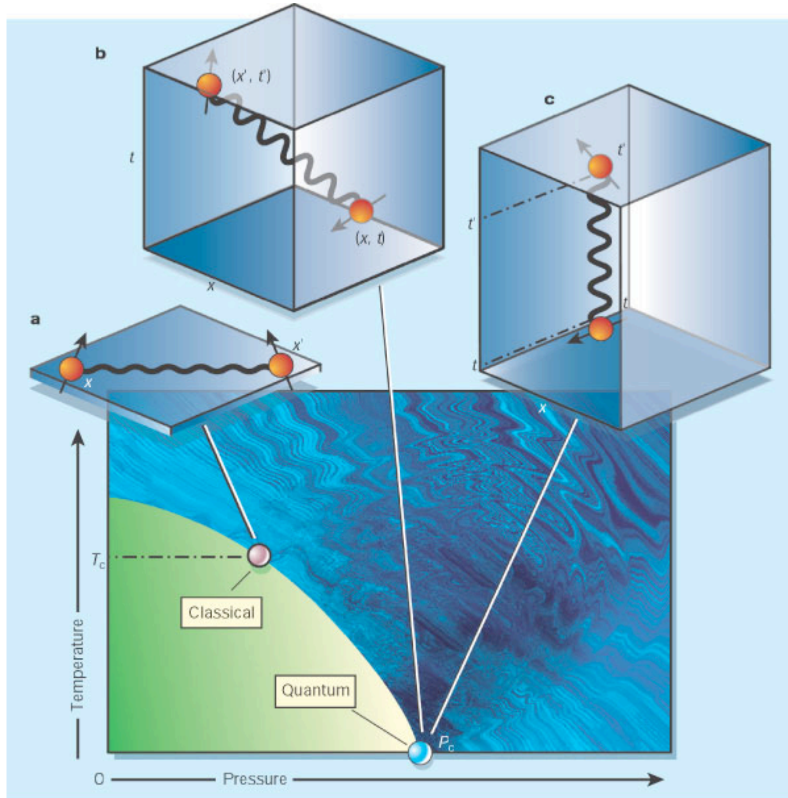

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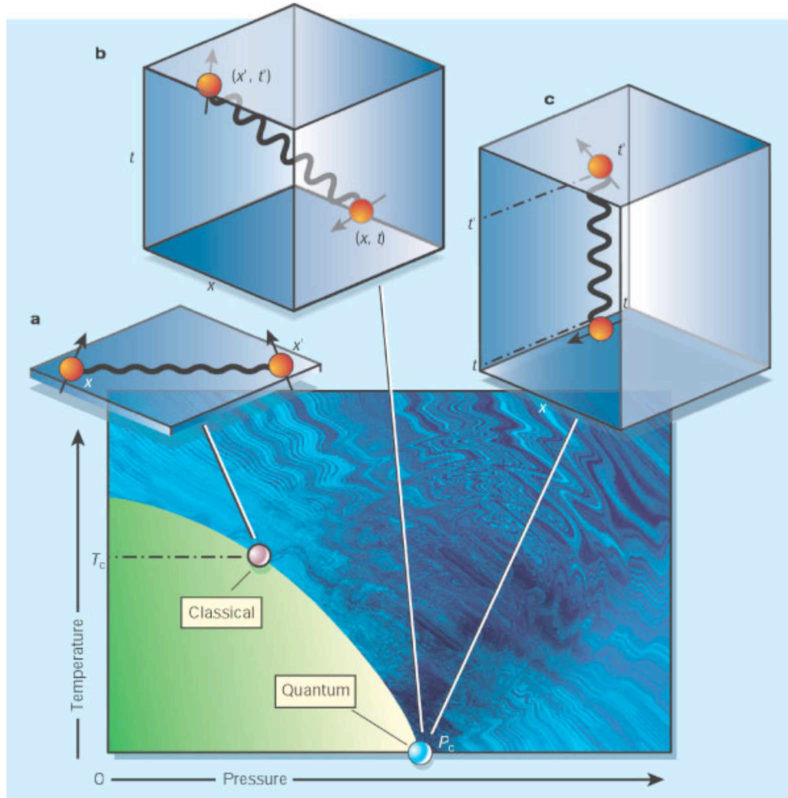

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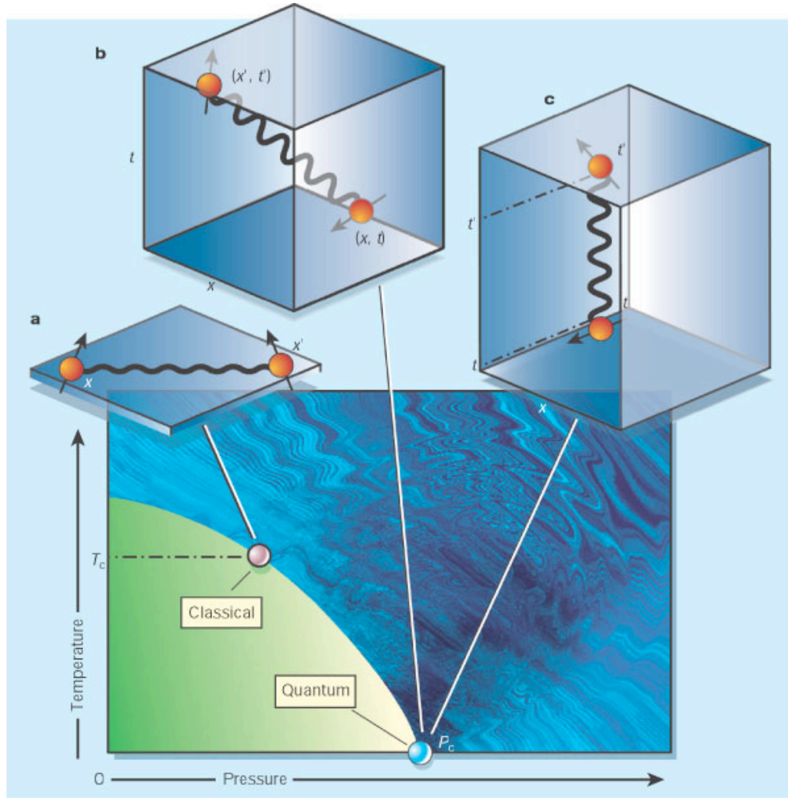

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New rule in material physics: avoided criticality.
New phases develop in order to avoid the singular quantum critical point.