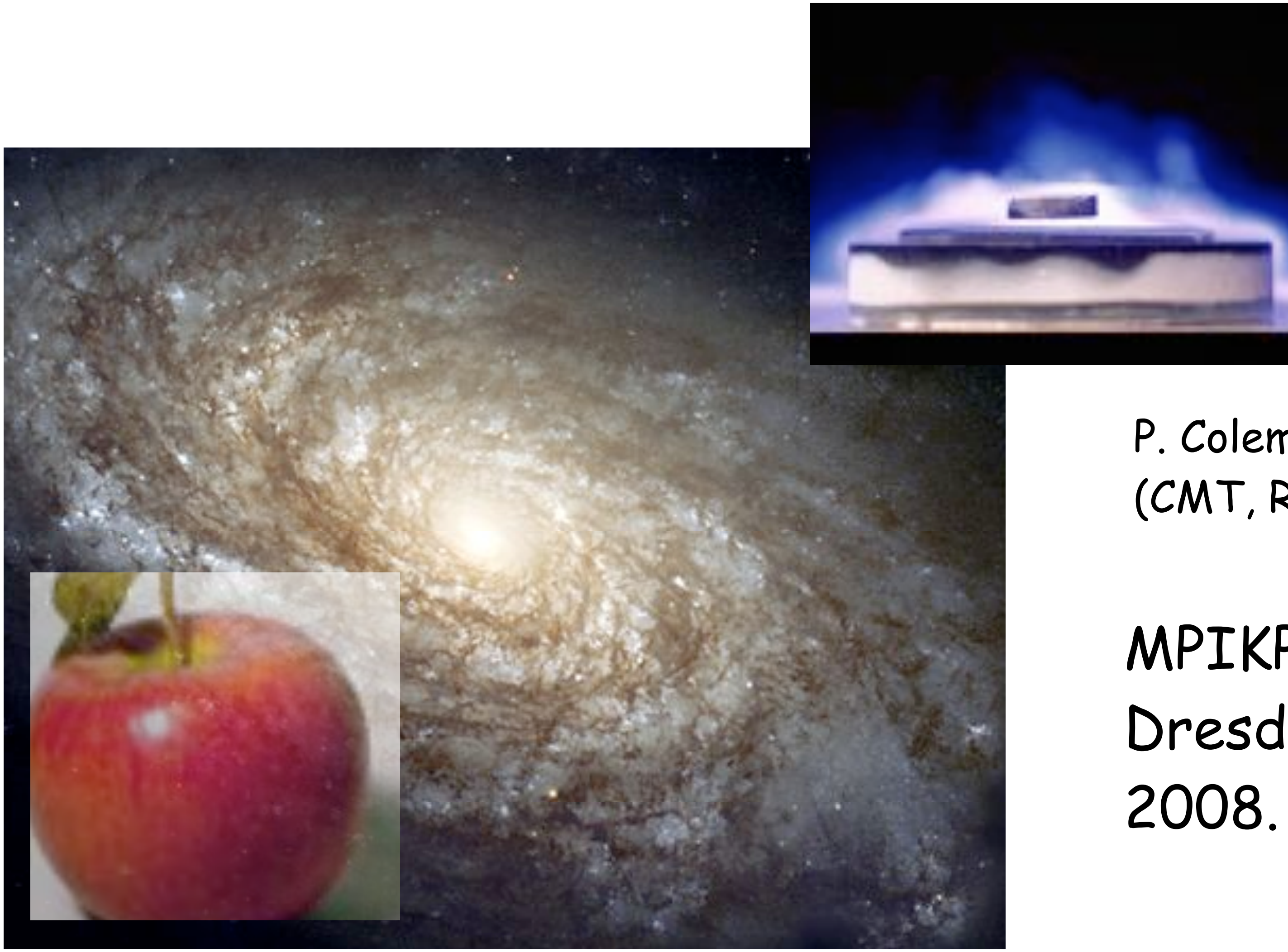
Qu-Transitions



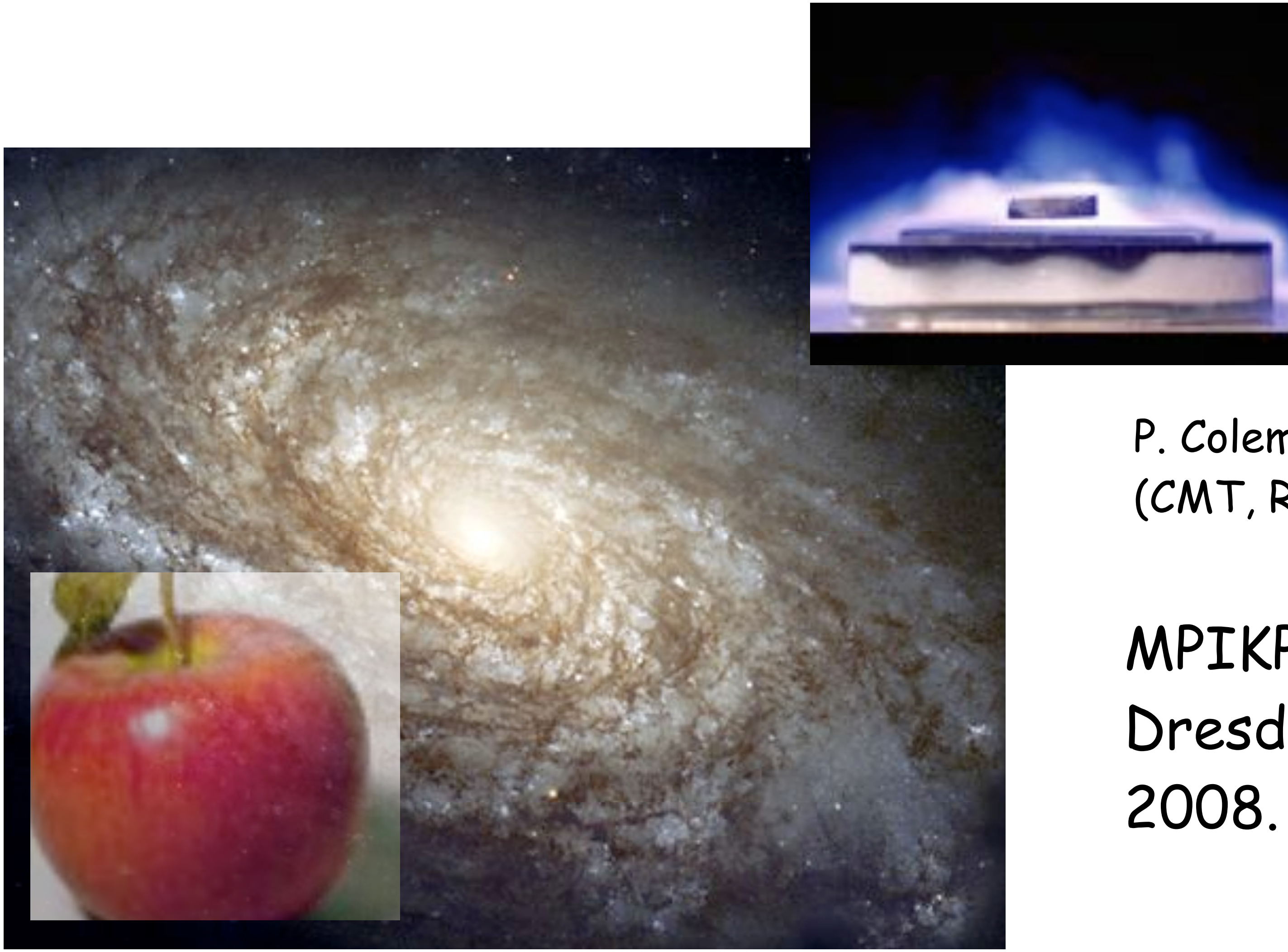
P. Coleman
(CMT, Rutgers)

MPIKPS: COFUS08
Dresden, Jun 30th 2008.

Rutgers
Center for Materials Theory

Qu-Transitions

"Phase transitions in the quantum era"



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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

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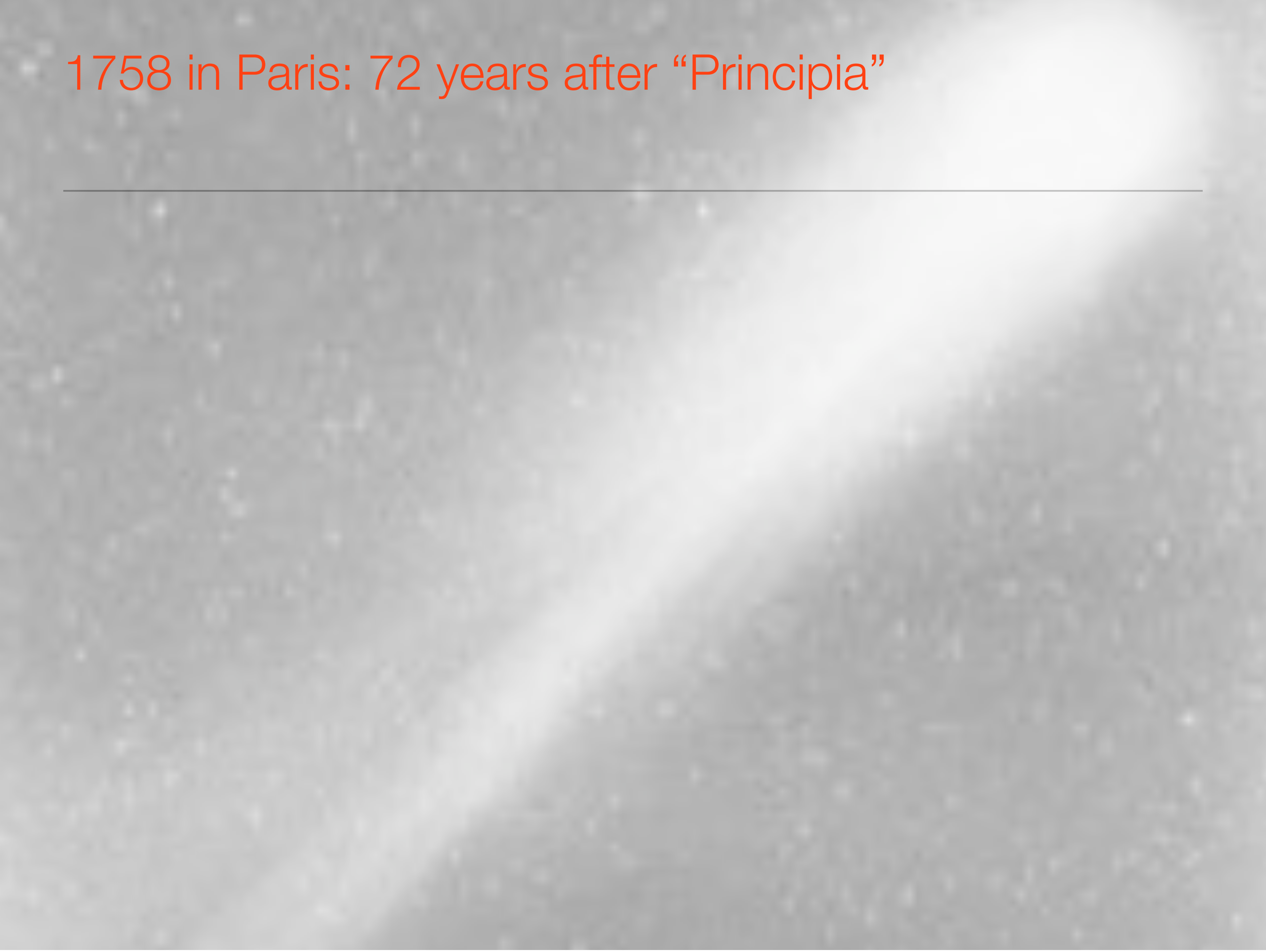
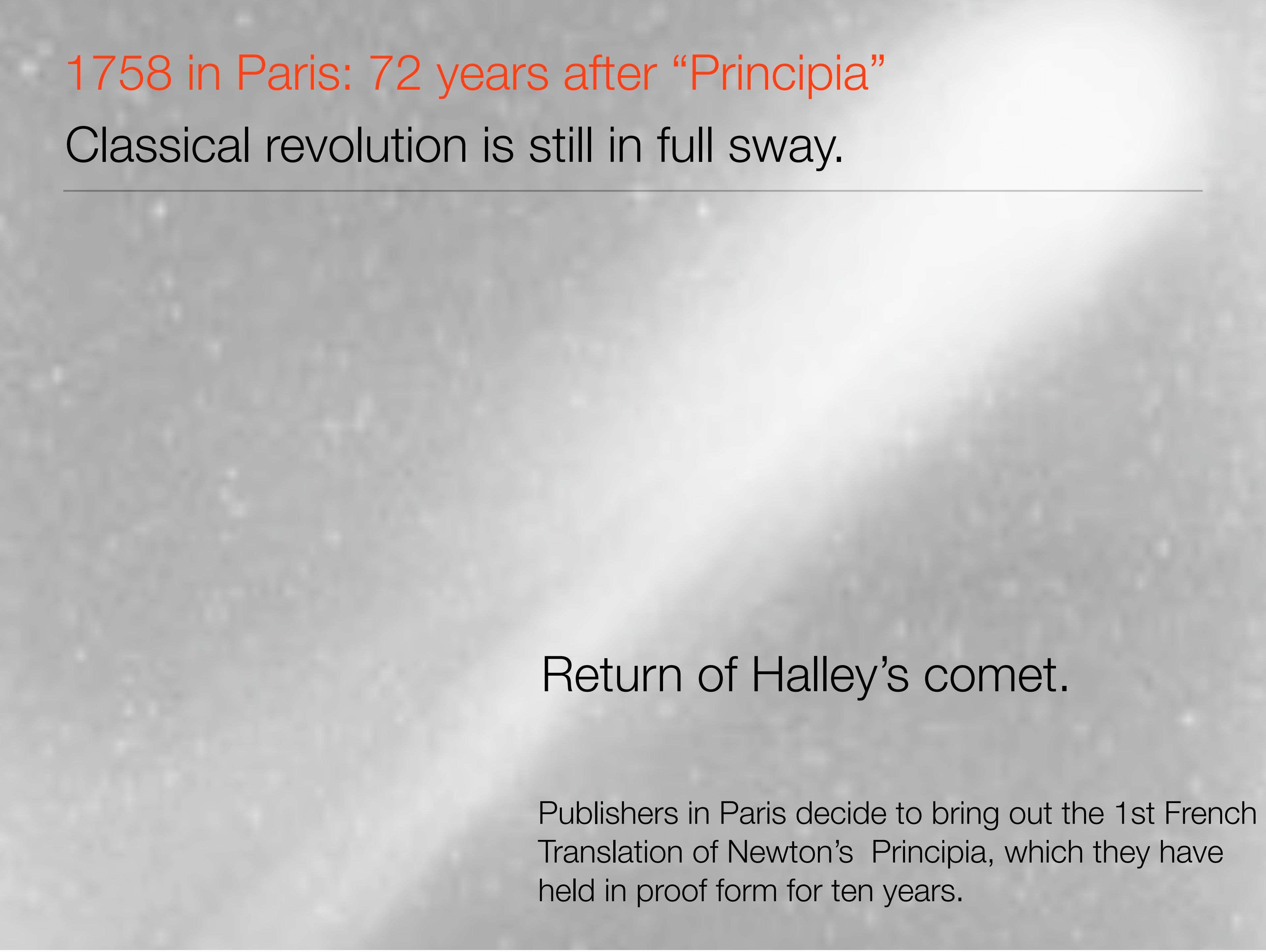
1758 in Paris: 72 years after “Principia”



1758 in Paris: 72 years after “Principia”

Classical revolution is still in full sway.



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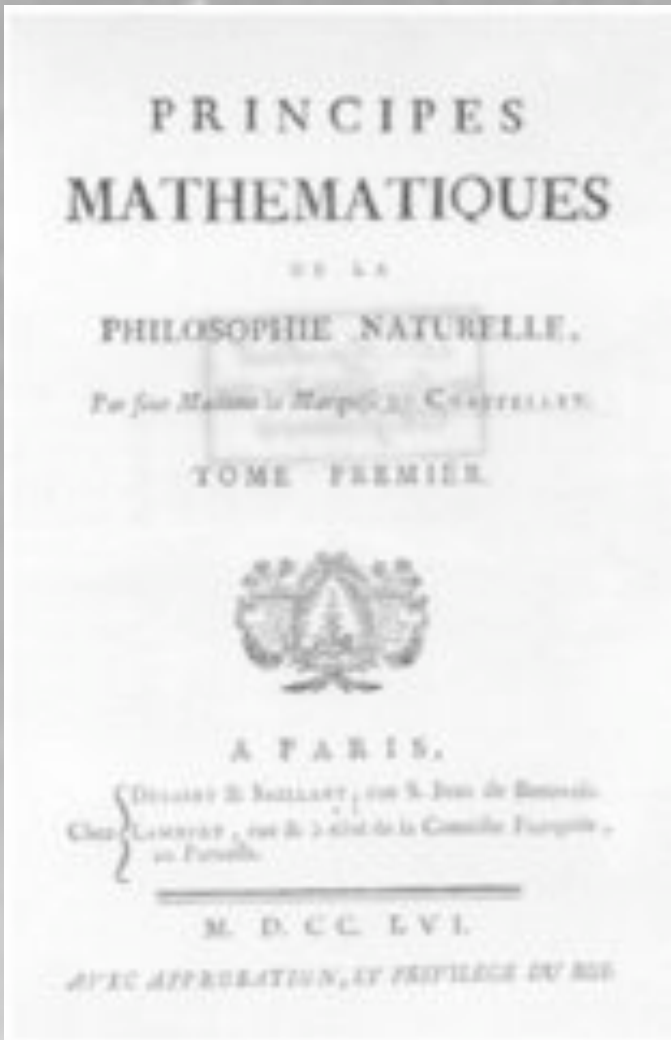

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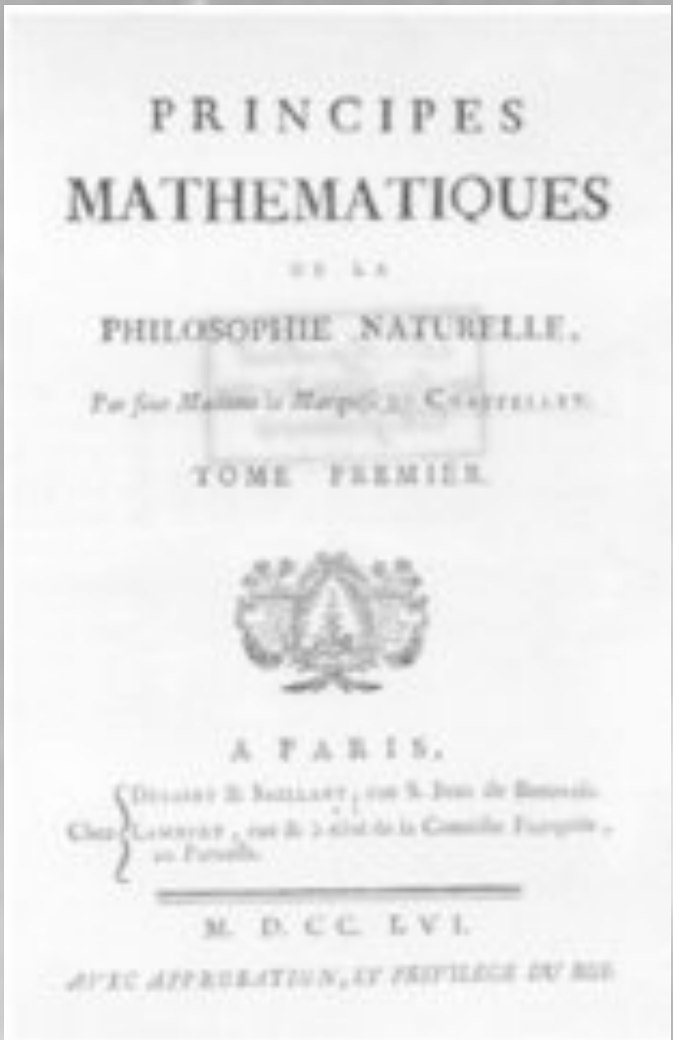
PRINCIPES

MATHEMATIQUES

PHILOSOPHIE NATURELLE.

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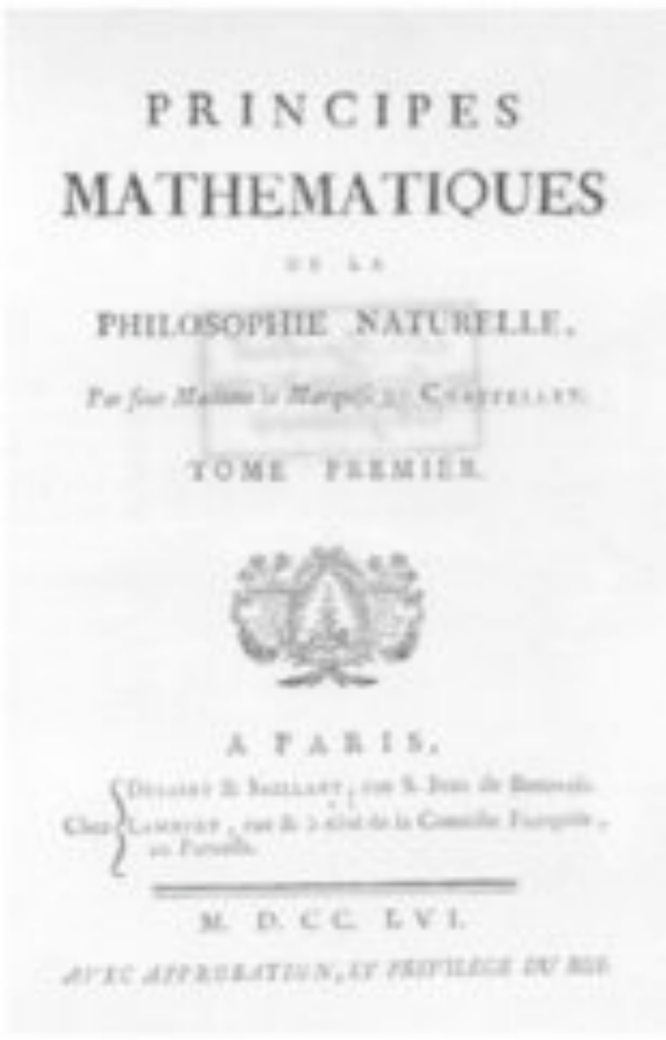

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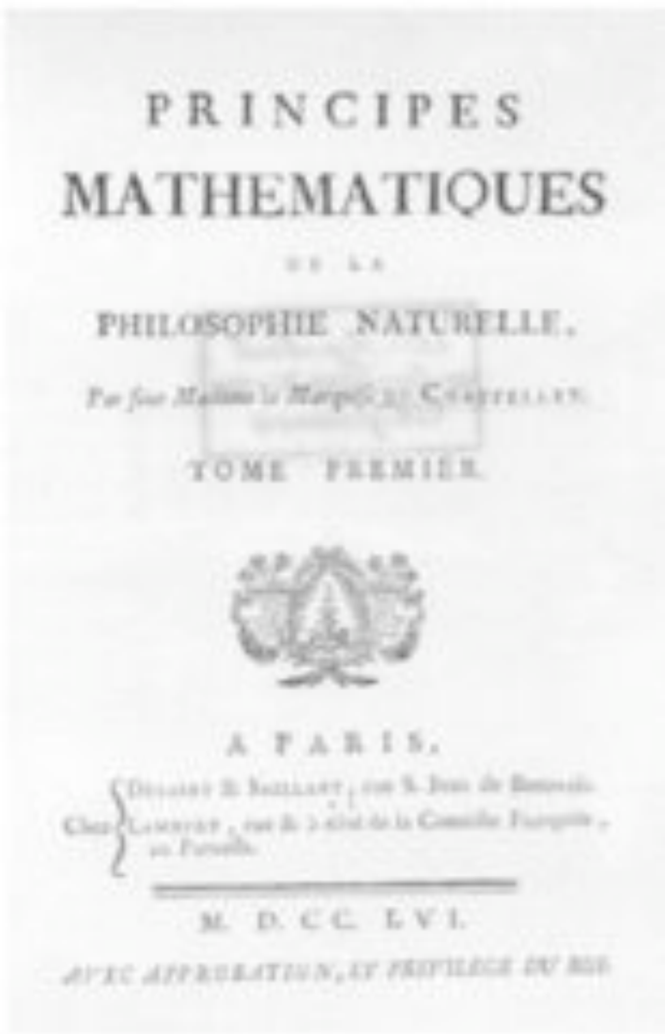
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Newtons Momentum

$$\sum_i m_i \vec{v}_i$$

Leibniz’ *“vis vivre”*

$$\sum_i m_i (v_i)^2$$

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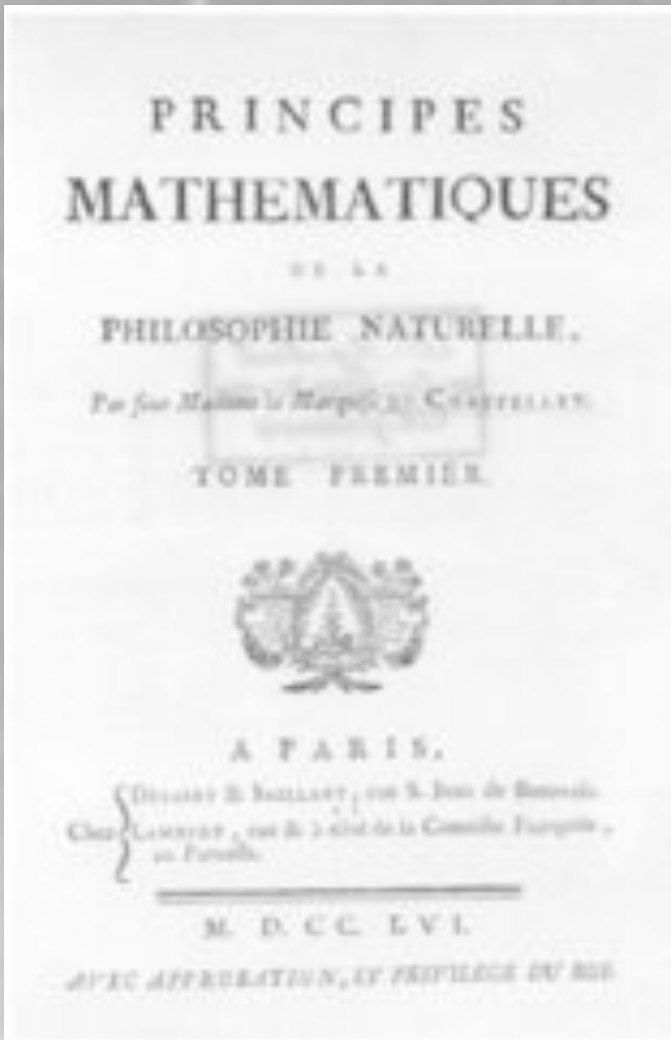

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Newtons Momentum	Leibniz' *"vis vivre"*
$\sum_i m_i \vec{v}_i$	$\sum_i m_i (v_i)^2$

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

Dresden, 2008. 107 years after Planck, many surprises later, the quantum era is in full sway.

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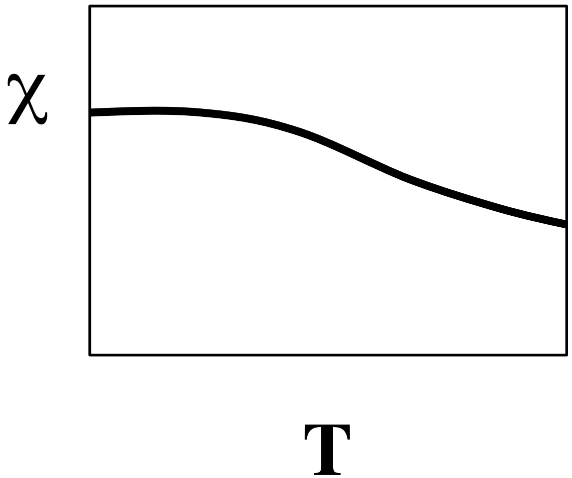


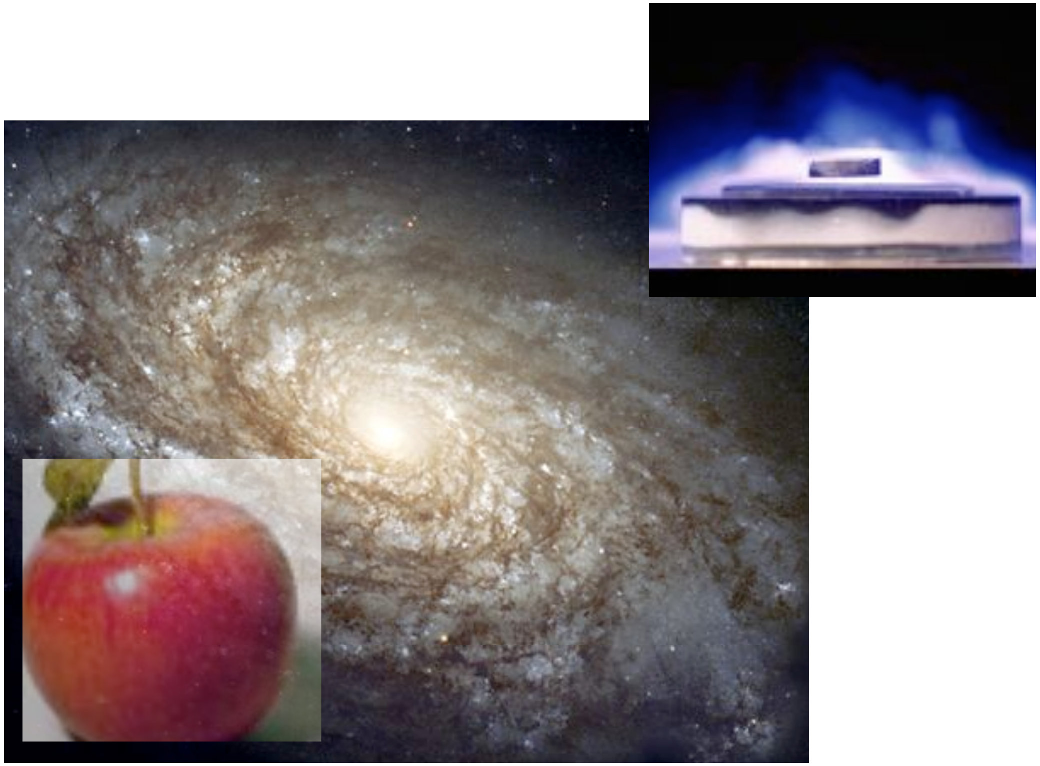
"With a heavy heart, I have been converted to the idea that Fermi -Dirac, not Einstein-Bose is the correct statistics. I wish to write a short note on its application to paramagnetism."

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

Dresden, 2008. 107 years after Planck, many surprises later, the quantum era is in full sway.

David Pines in
musicofthequantum.rutgers.edu

Quantum zero point fluctuations:



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

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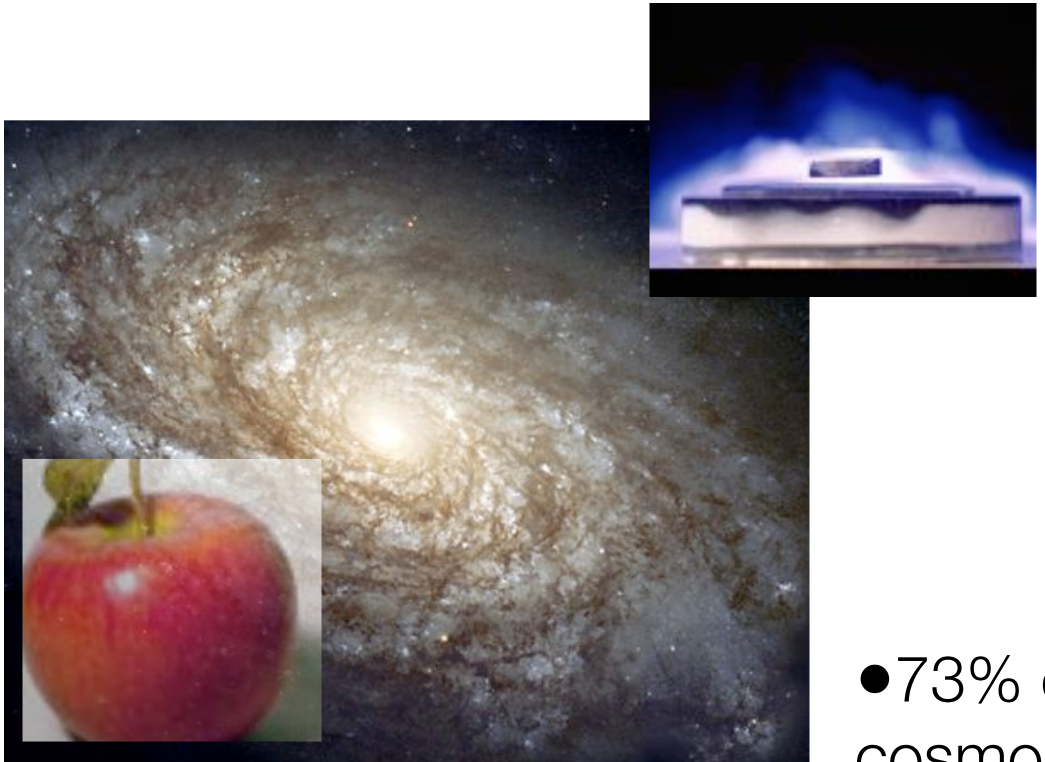
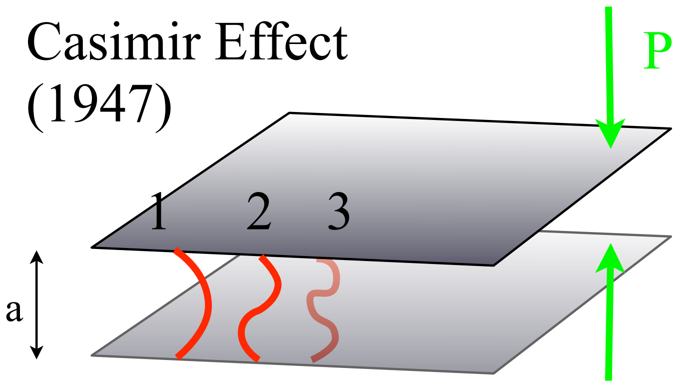


- 73% of the mass of the cosmos is “Dark Energy”: an unidentified form of zero point energy, causing the expansion to accelerate.

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)



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

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

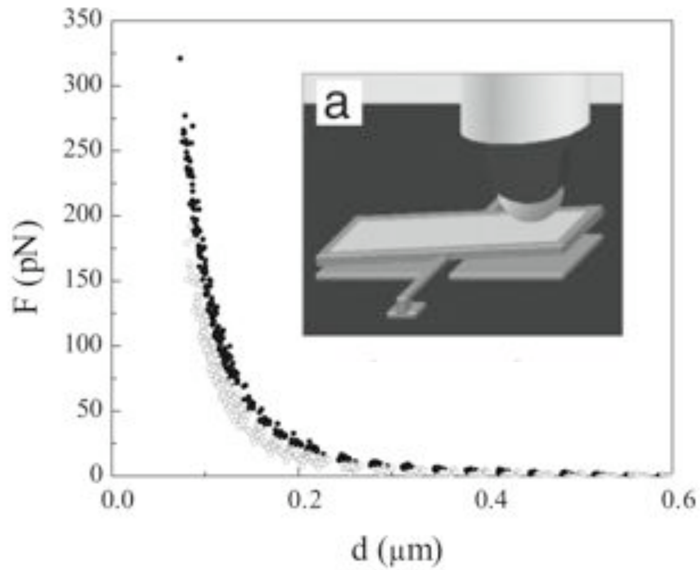
$$\frac{\Delta E_{ZP}}{A} = -\frac{\pi^2 \hbar c}{720 a^3}$$

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

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

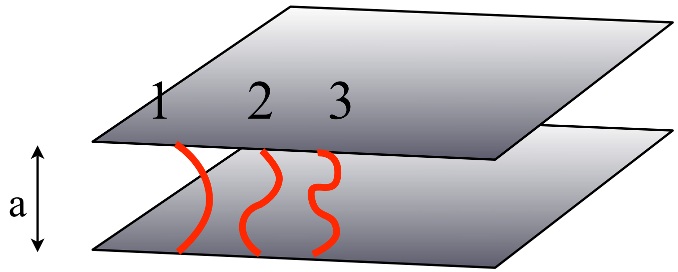
$$\omega_{qn} = c\sqrt{q_\perp^2 + n^2 \left(\frac{\pi}{a}\right)^2}$$

Discrete modes



Lisanti,Iannuzi and Capasso
(PNAS, 2005)

Casimir Effect : alternative interpretation



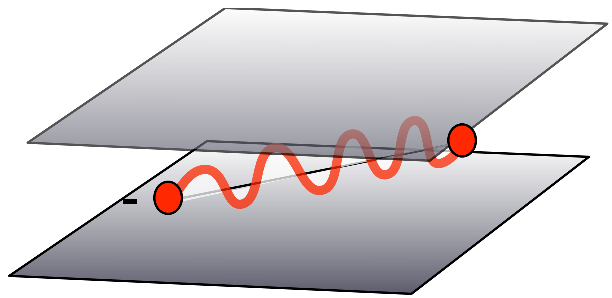
Manifestation of the quantum criticality of the vacuum

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

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

Plates remove zero modes
Inducing finite correlation length

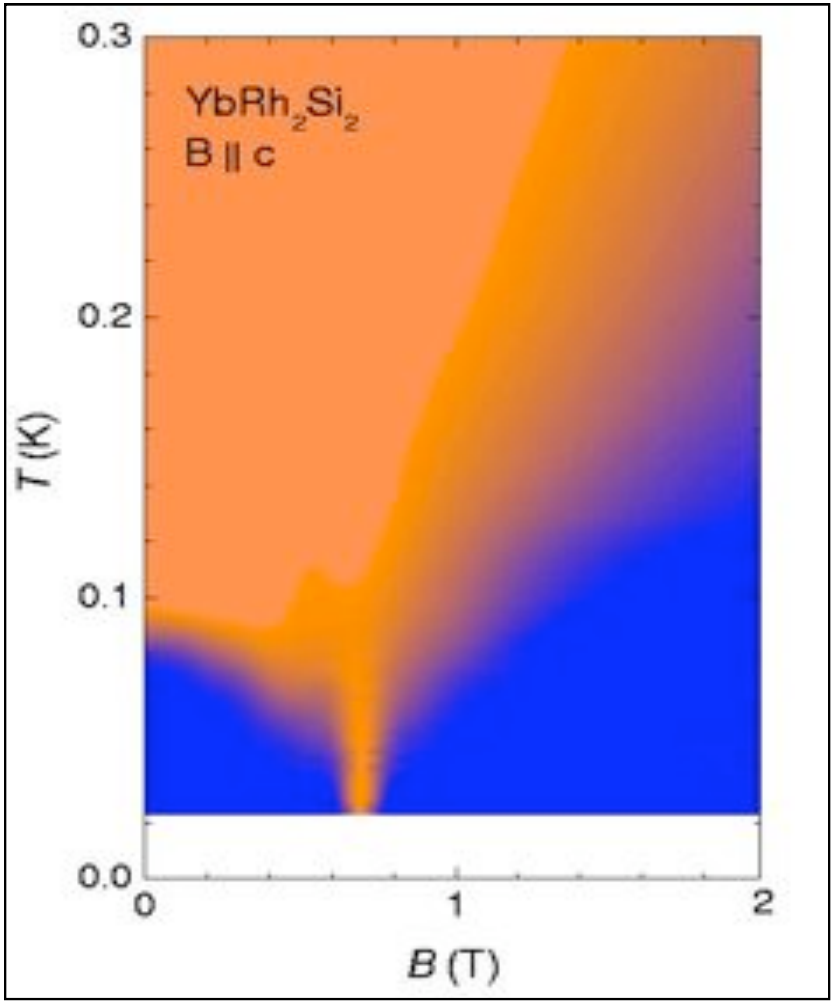
$$\xi = \frac{a}{\pi}$$



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

Qu-Transition

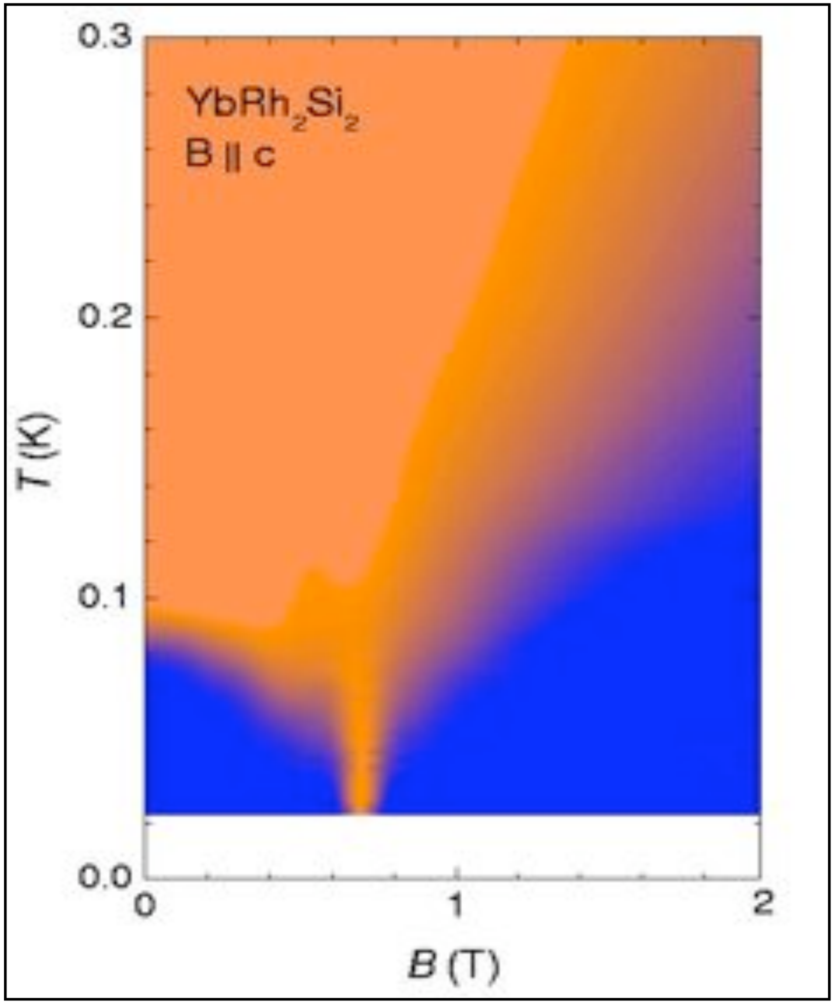
Custers et al (2002)



Qu-Transition

Phase transition
driven by zero point energy.

Custers et al (2002)



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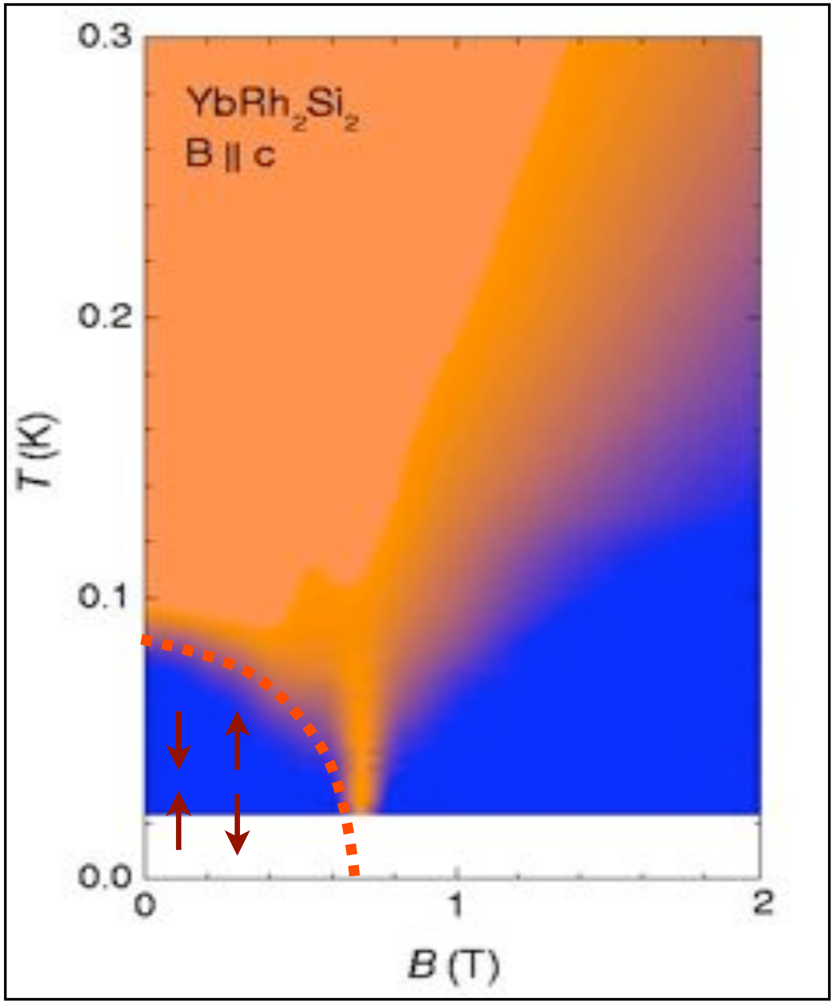

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$$[H, \psi] \neq 0$$

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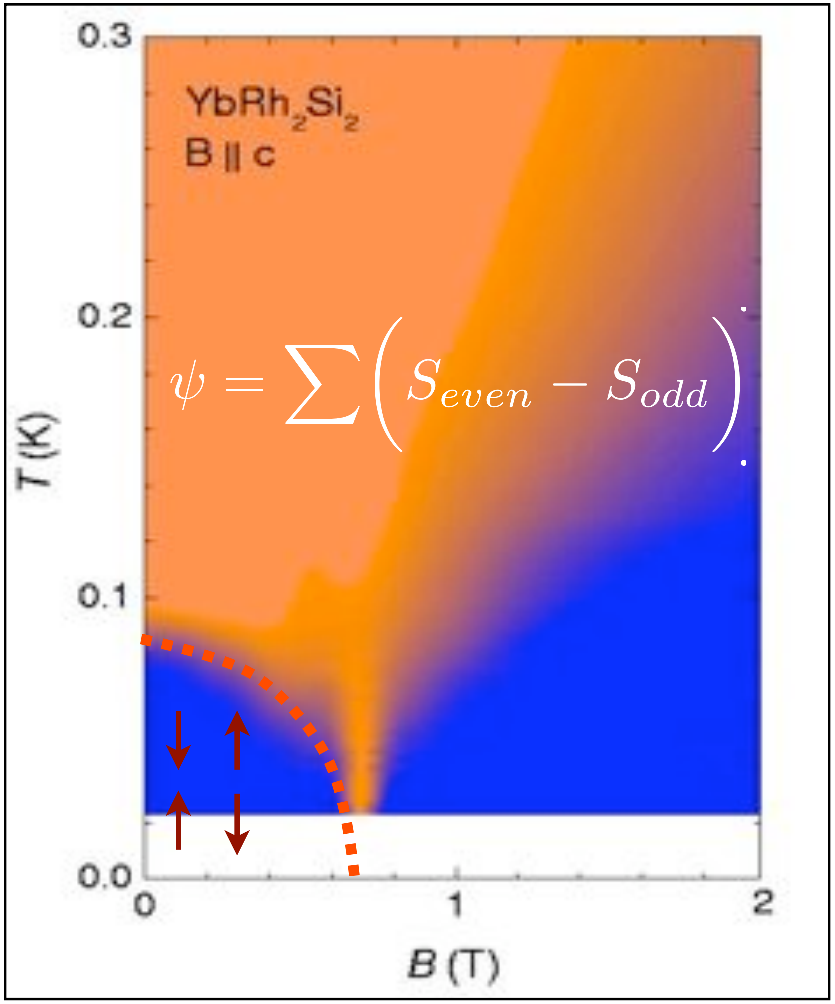

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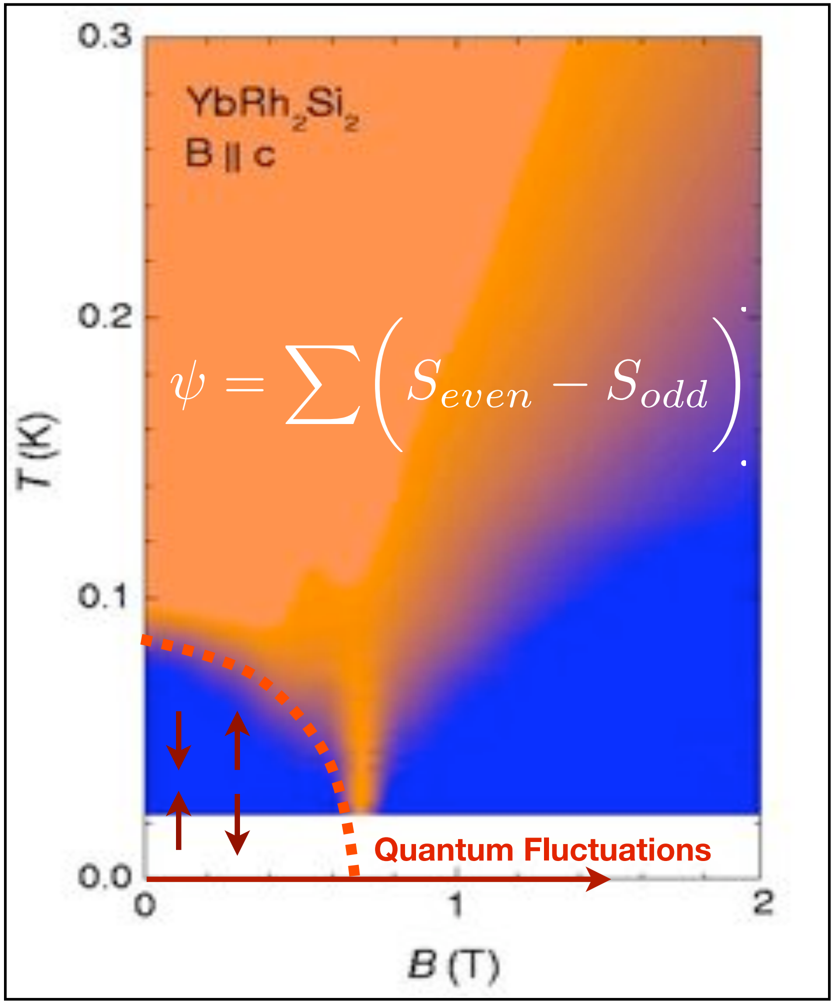

$$[H, \psi] \neq 0$$

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

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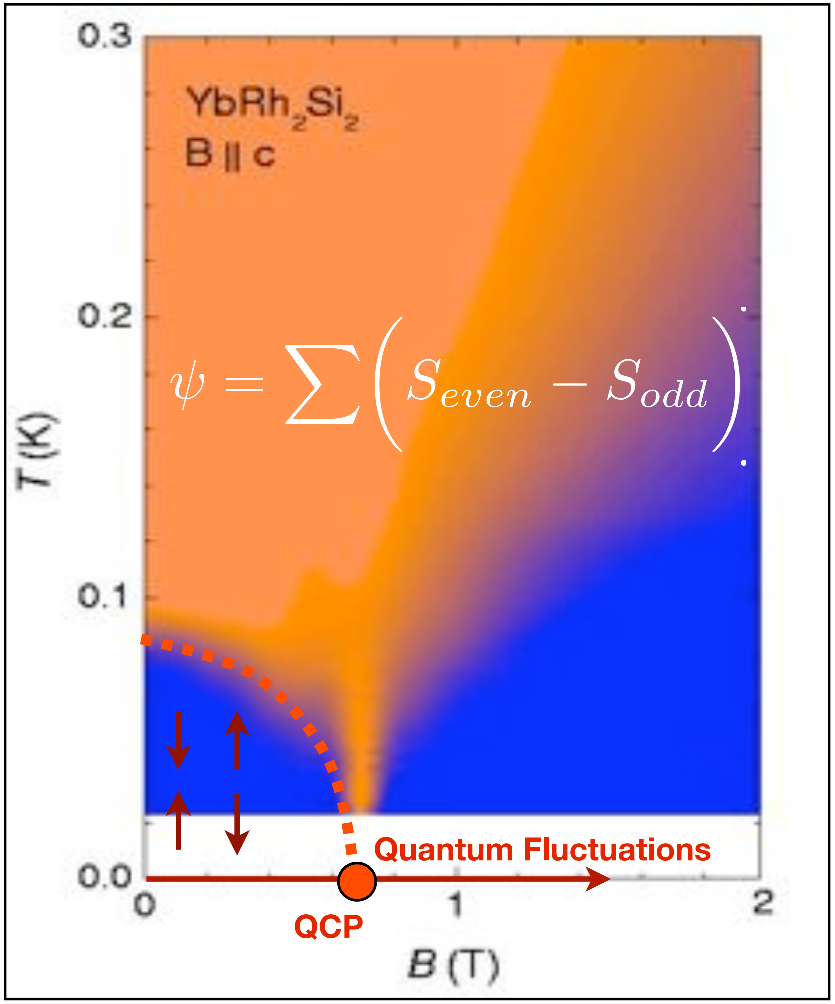
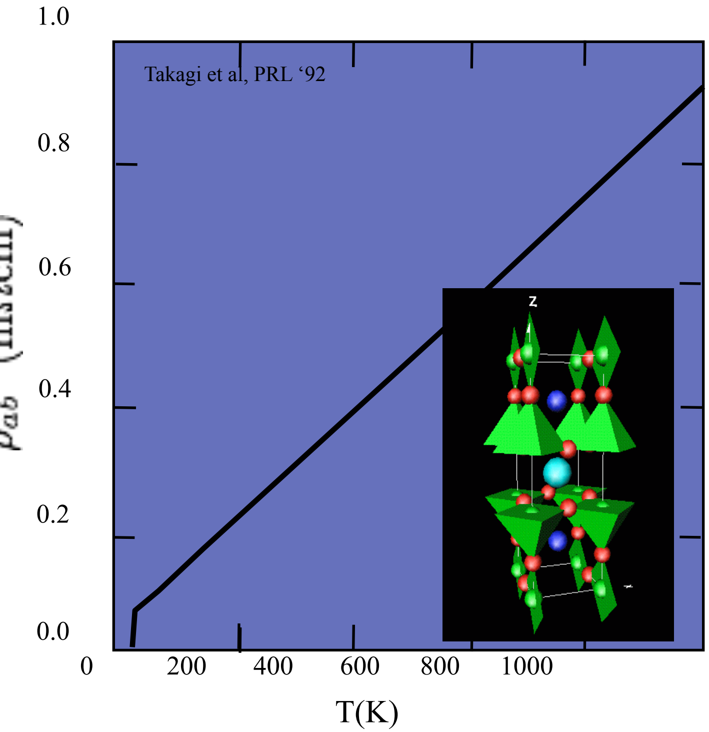
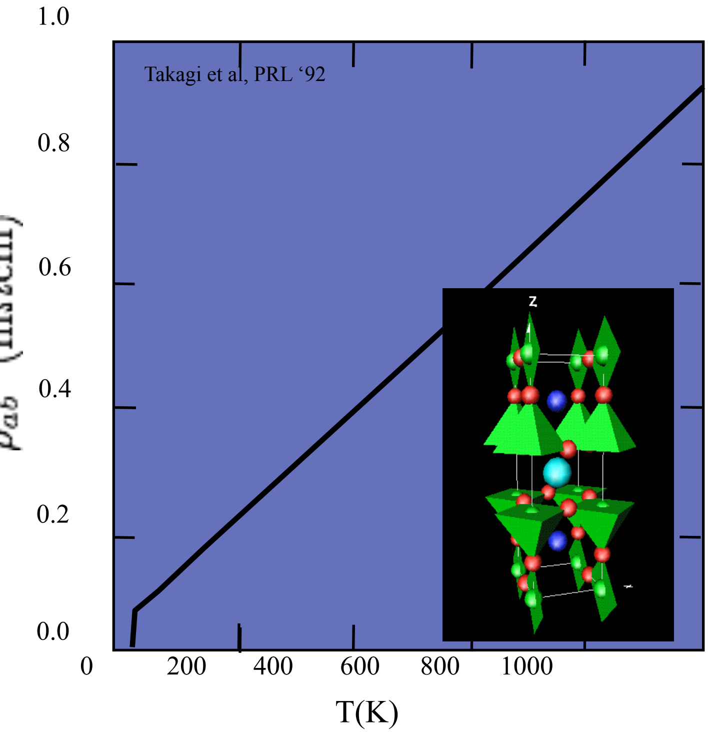
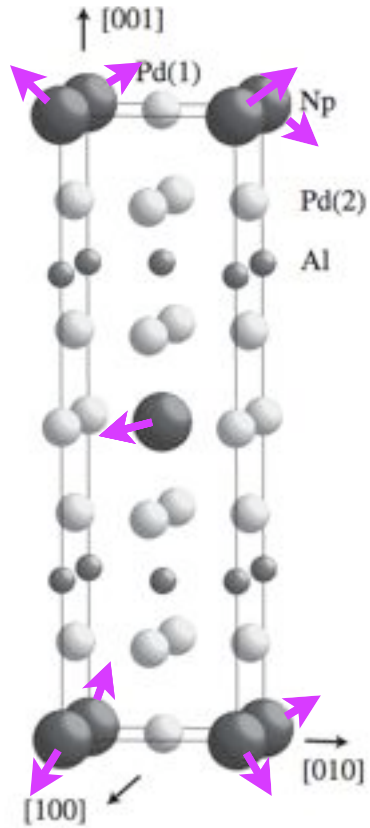


- Motivation
- Heavy Fermion Quantum Criticality.
- New Approaches and Ideas
- Avoided Criticality



Cuprates
Tc=11-92K

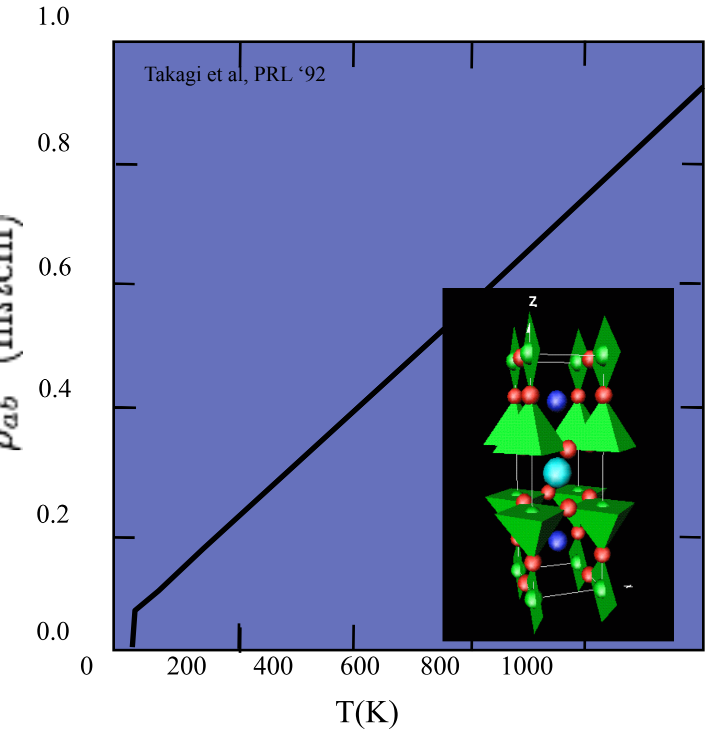


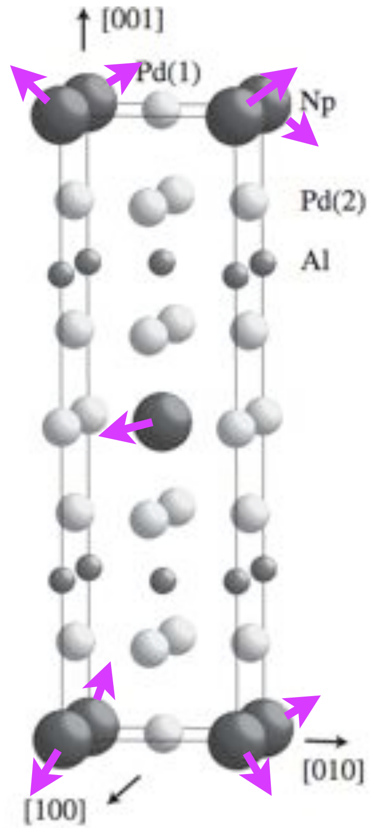


NpAl₂Pd₅

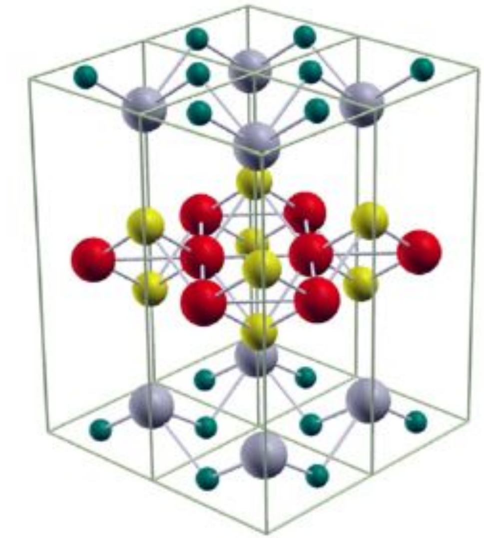
Cuprates
Tc=11-92K

HF 115s
Tc=0.2 -18.5 K





$NpAl_2Pd_5$



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

Cuprates
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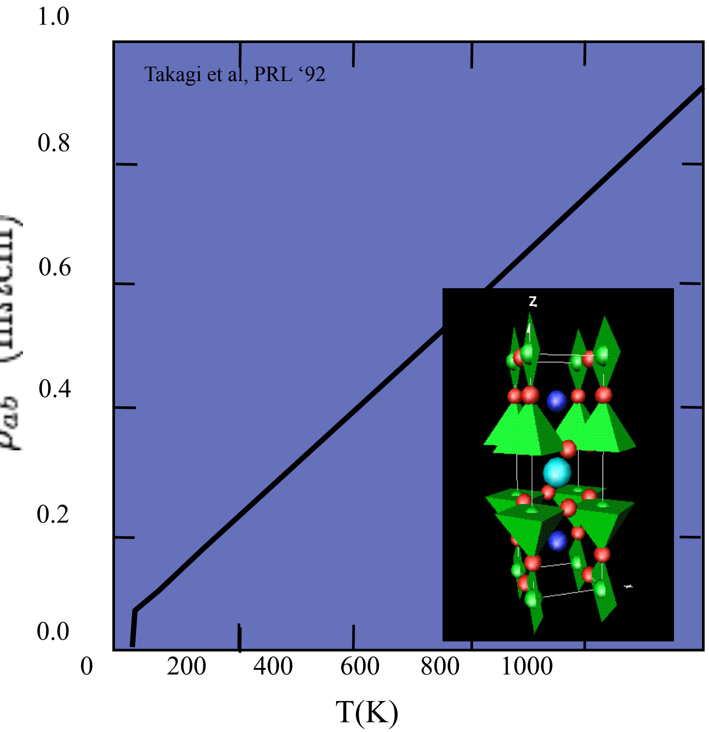
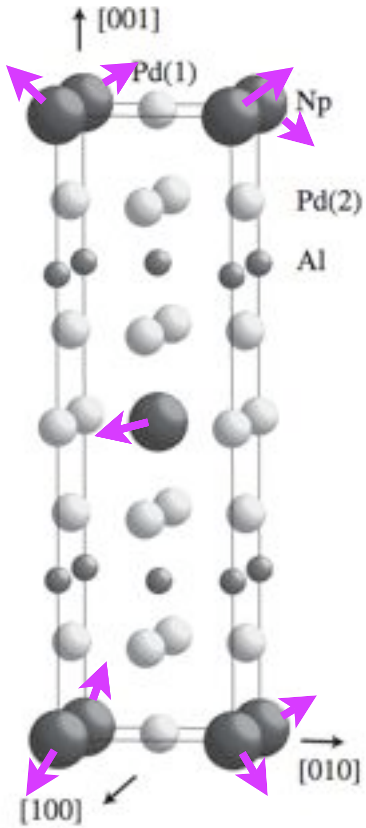
HF 115s
Tc=0.2 -18.5 K

Iron oxypnictides
Tc= 6 - 53 ++ ? K





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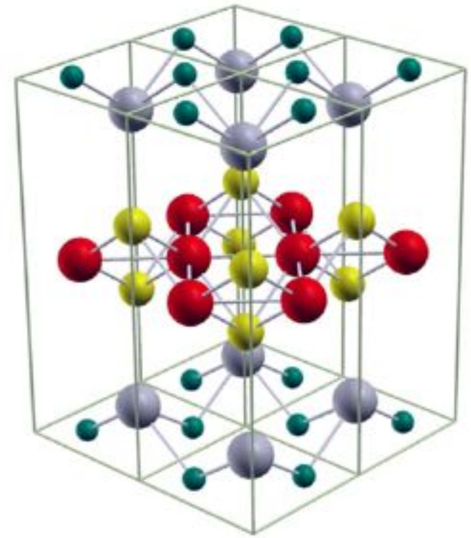

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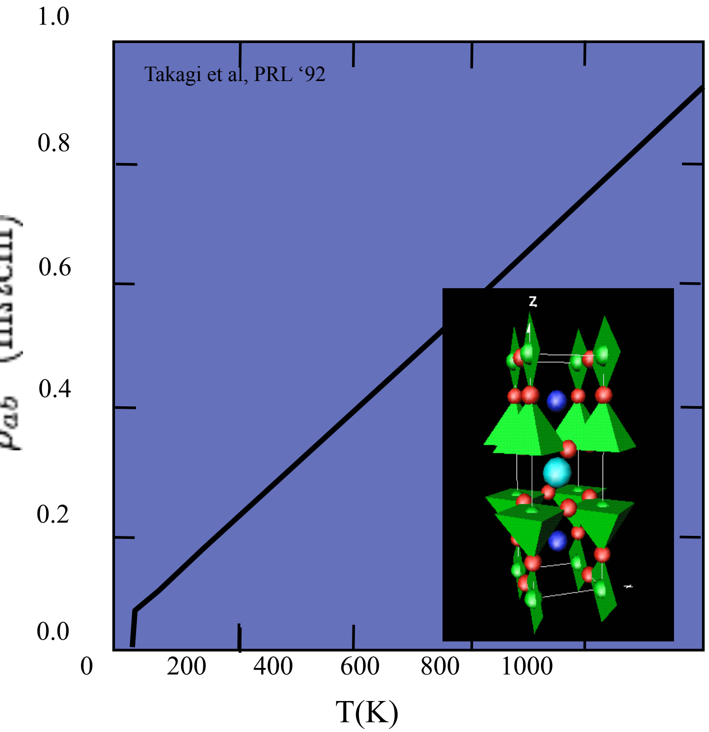
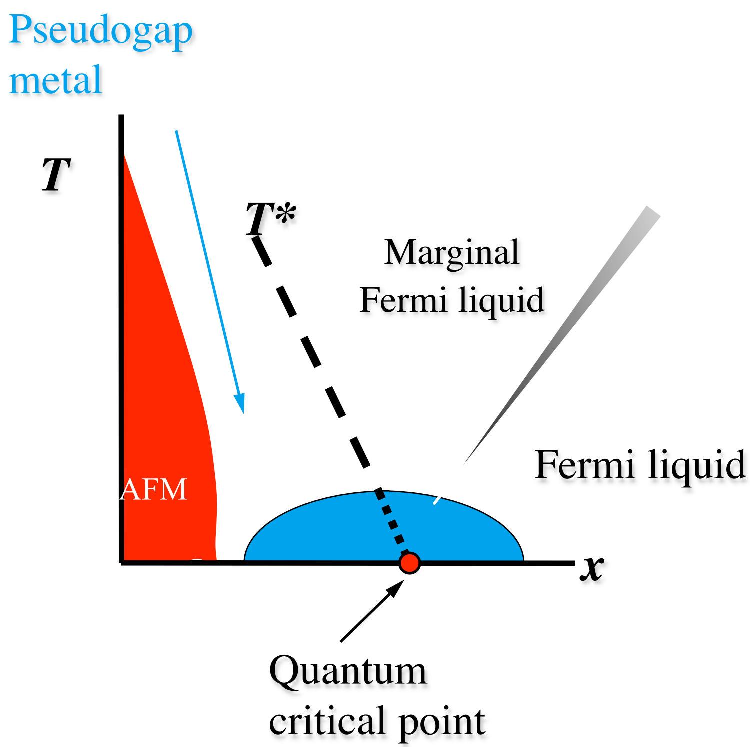
What kind of electronic fluid yields high Tc superconductivity?





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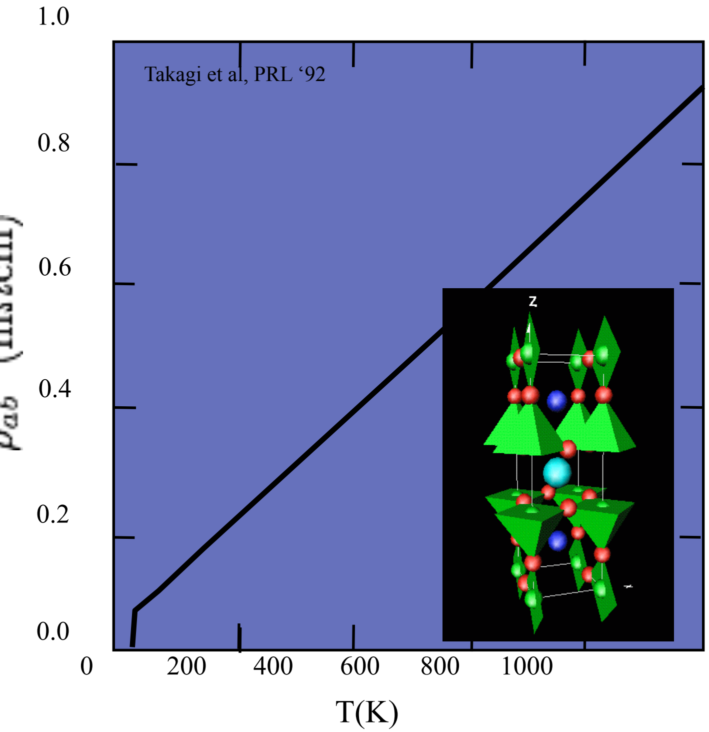
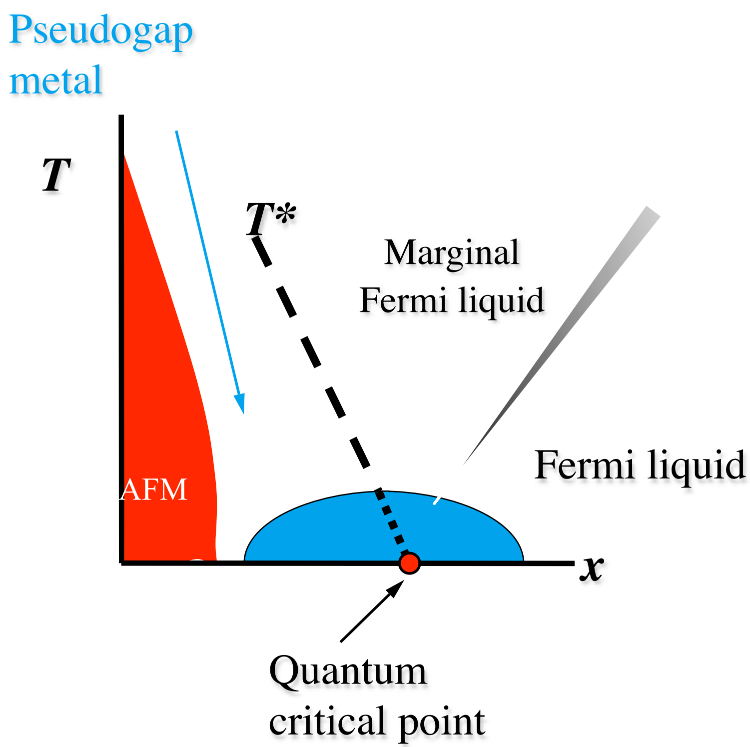
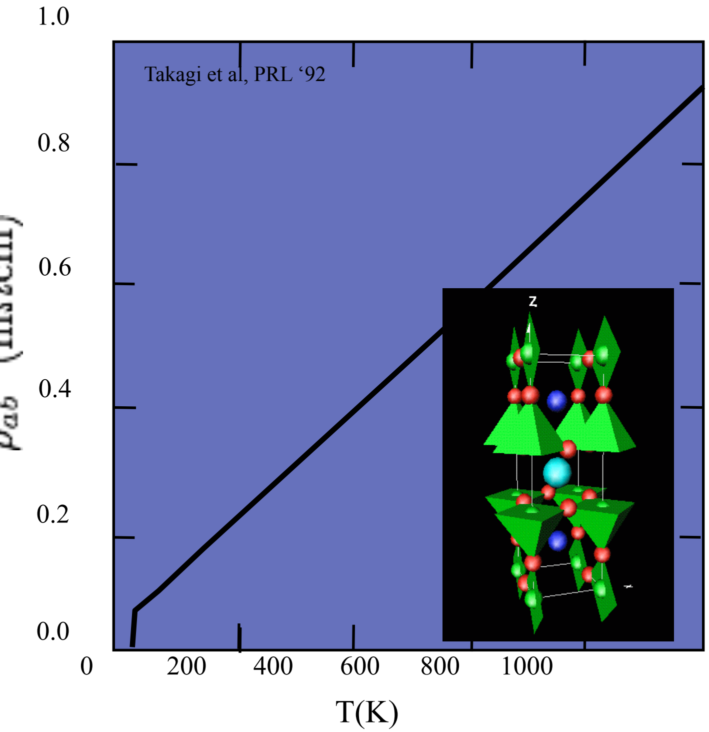




Cuprates
Tc=11-92K

“Avoided criticality”



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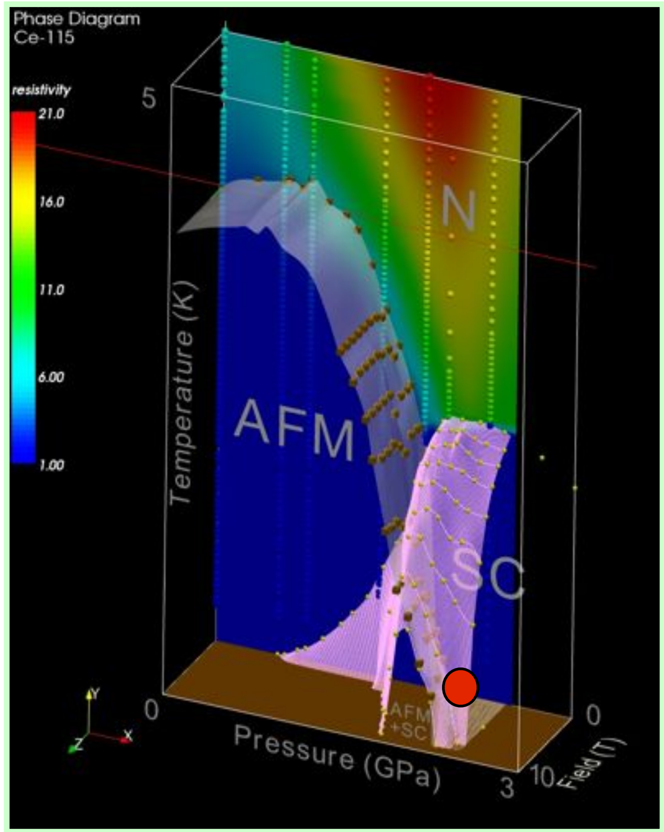

Tuson Park, (2007).

Landau's Question.

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

Landau's Question.

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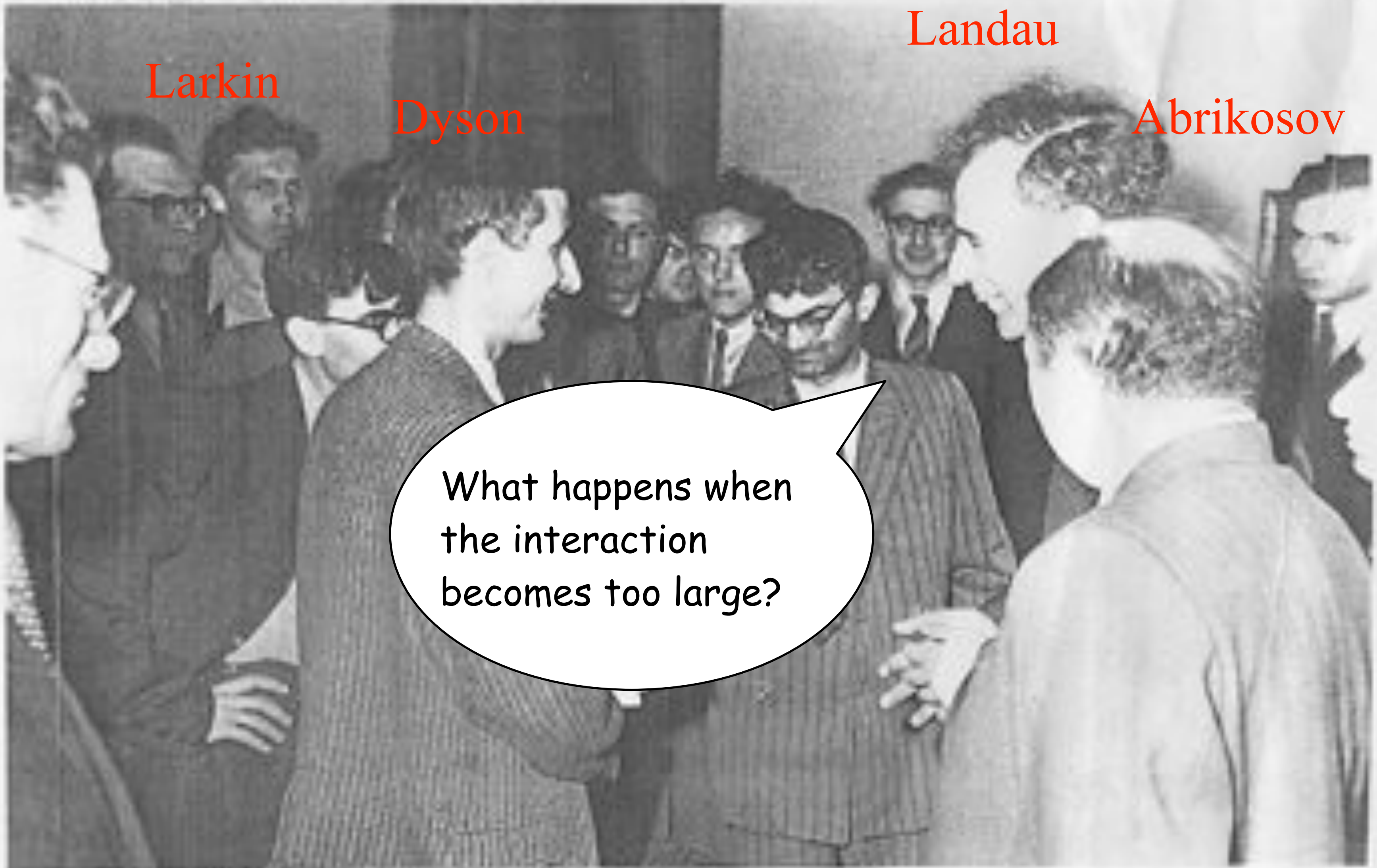
Landau's Question.



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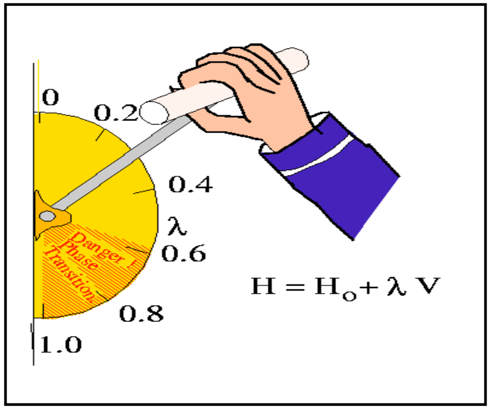

Landau: interactions can be turned on adiabatically, preserving the excitation spectrum.

Landau, JETP 3, 920 (1957)

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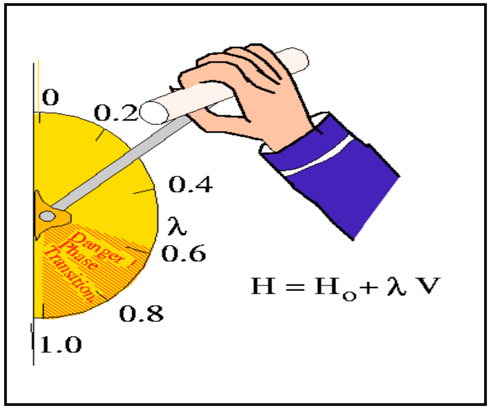

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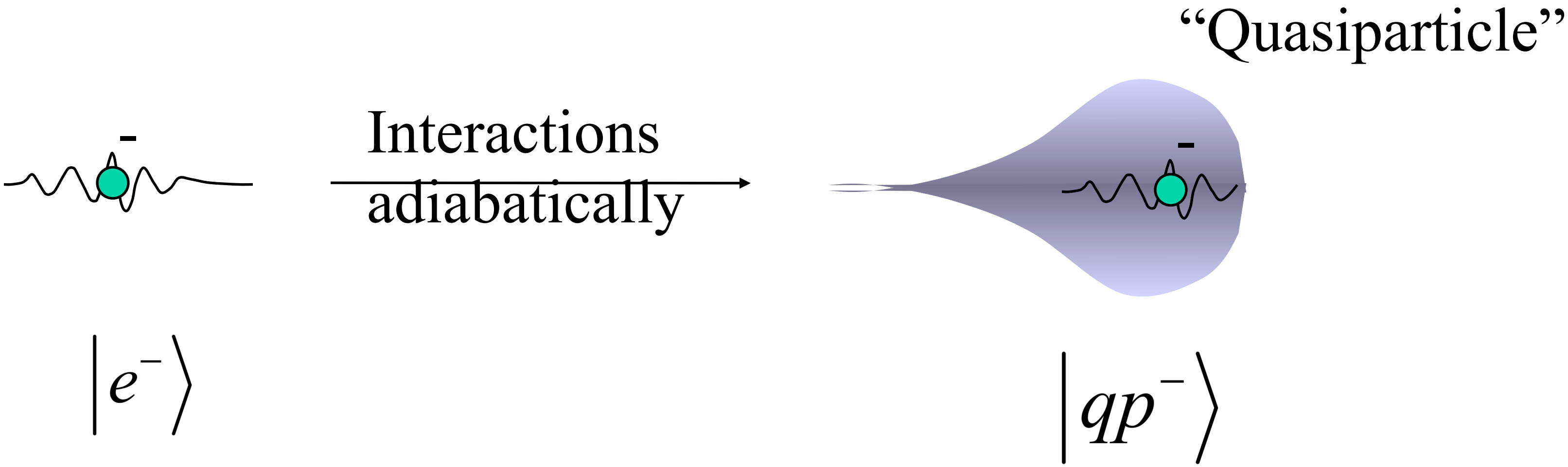

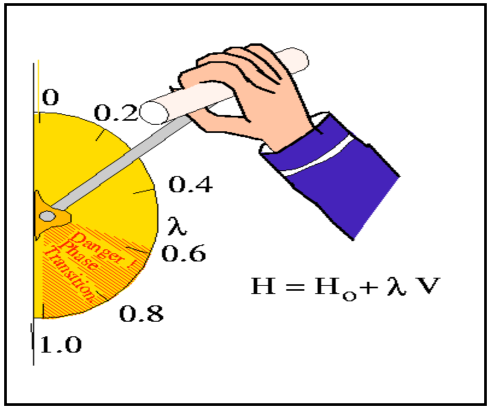

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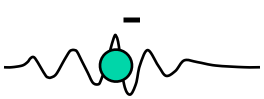
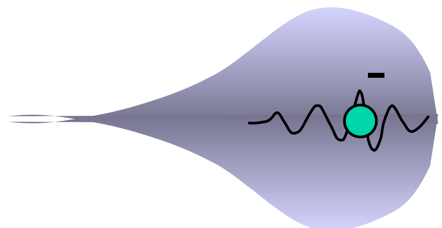
Landau, JETP 3, 920 (1957)

“Quasiparticle”



Interactions adiabatically



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

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

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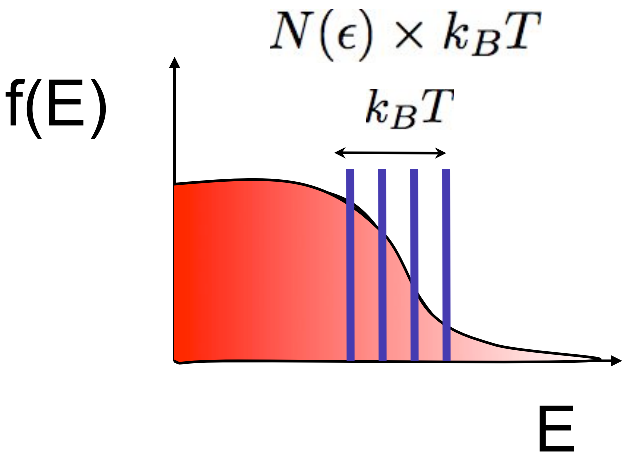
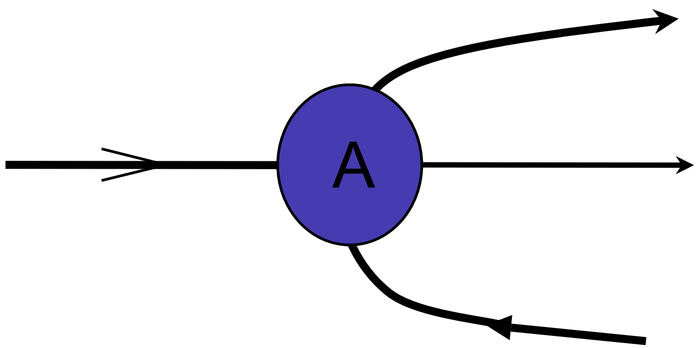


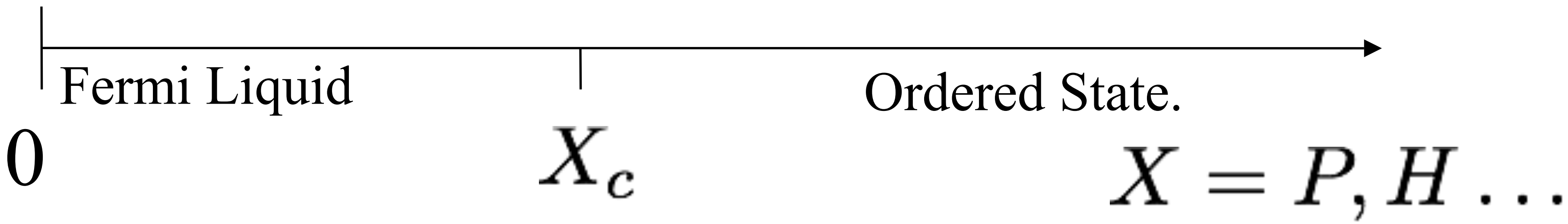
$$\frac{dE}{dT} = C_V = \gamma T$$

$$\gamma \propto N(\epsilon_F) \propto m^*$$



$$\rho \propto \Gamma(T) \sim E^2 + T^2$$

What happens when the interaction becomes too large ?



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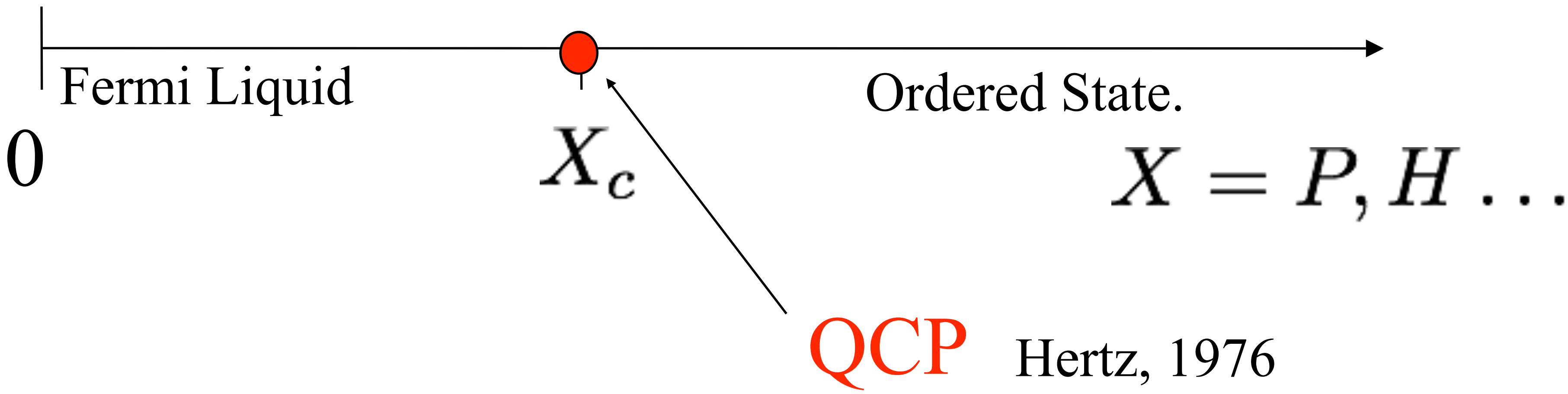

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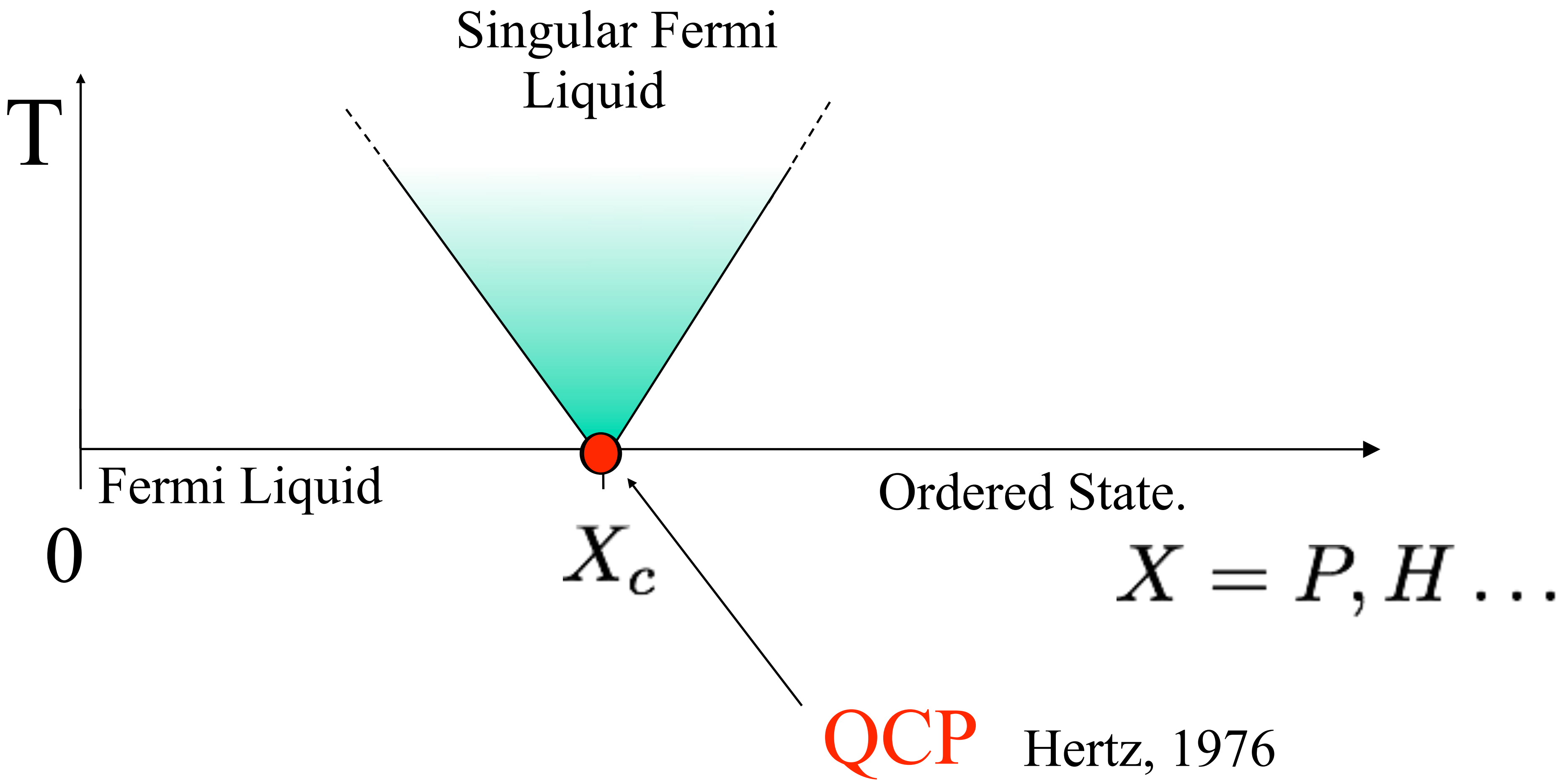

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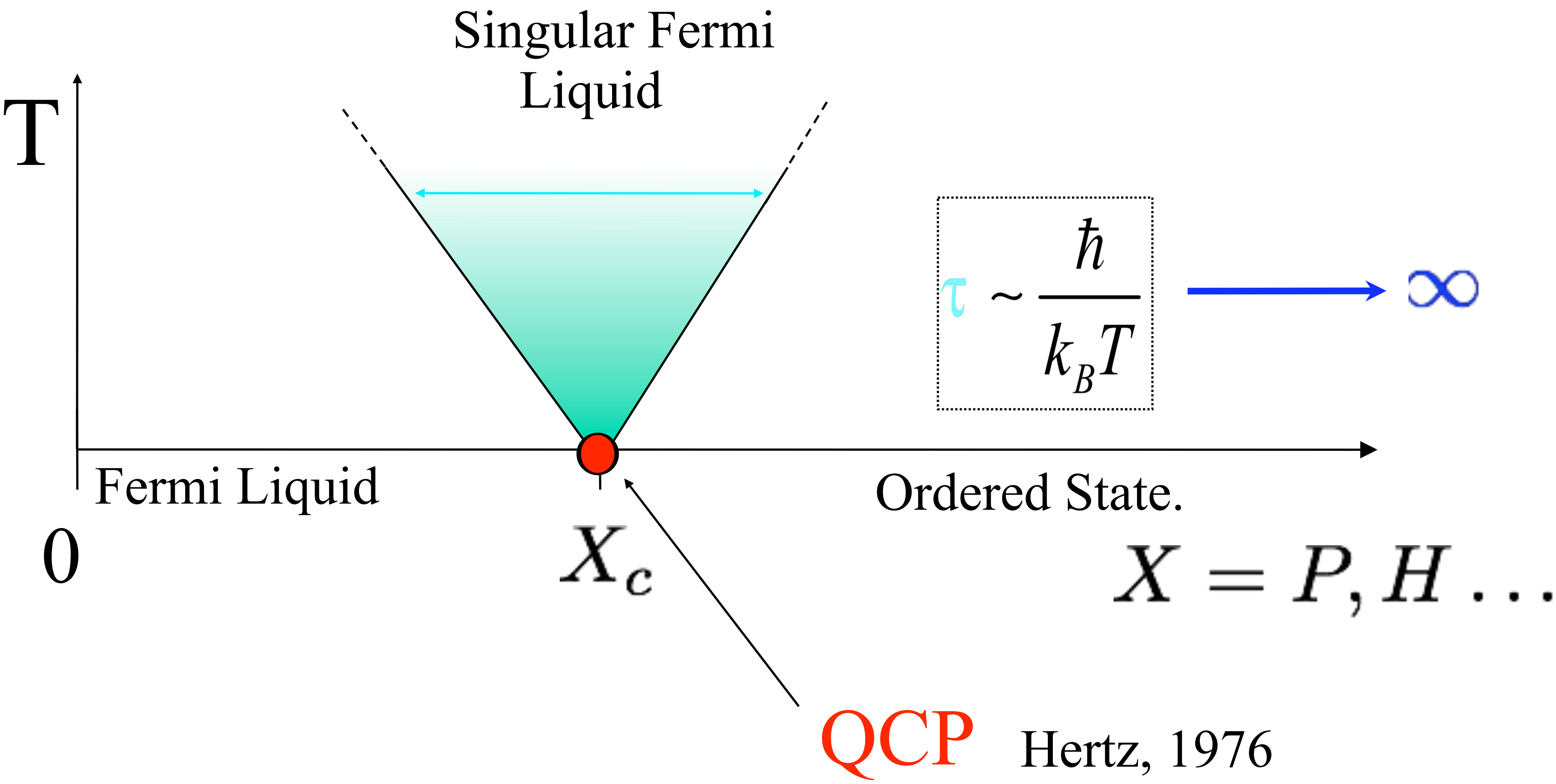

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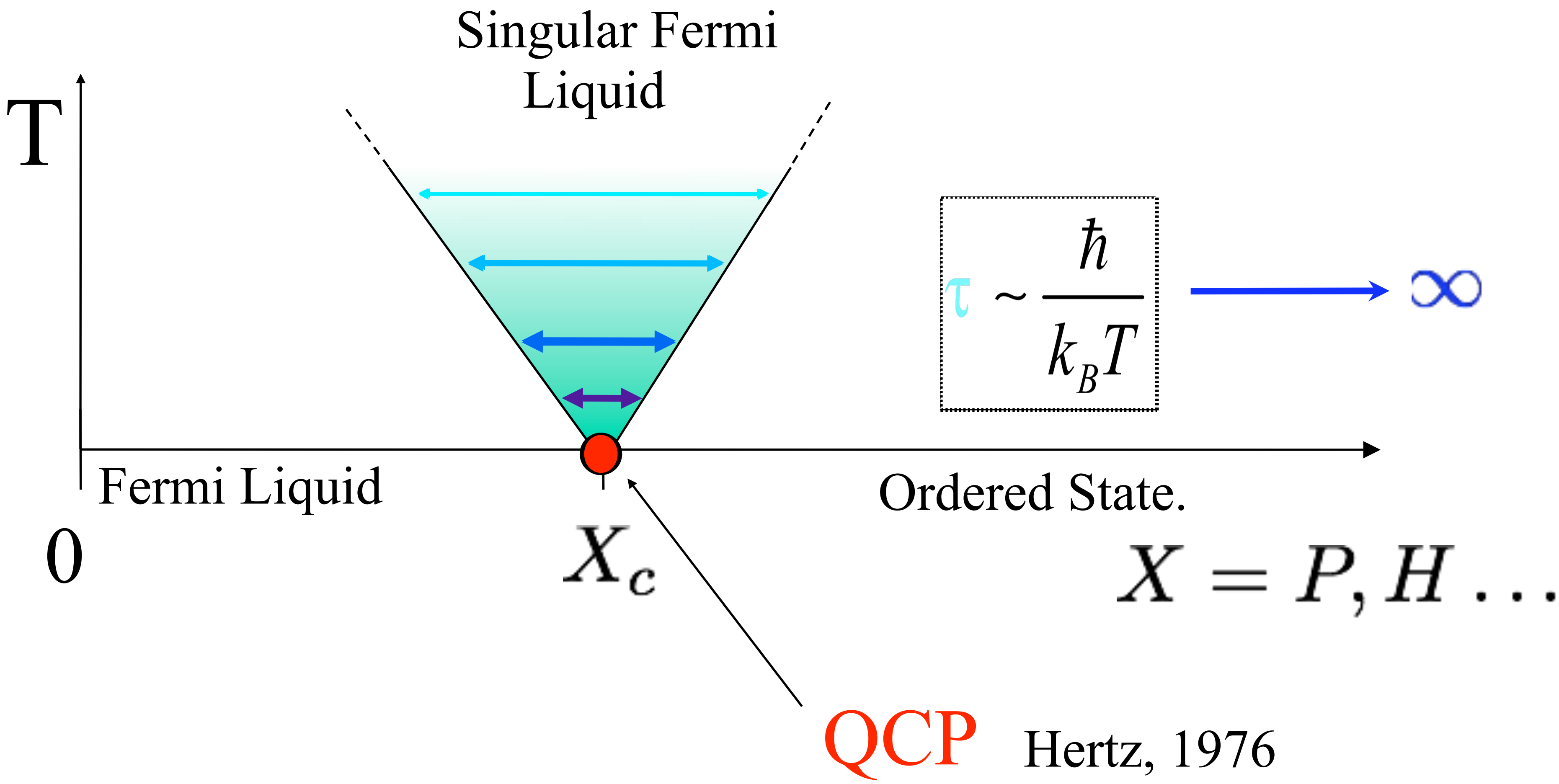
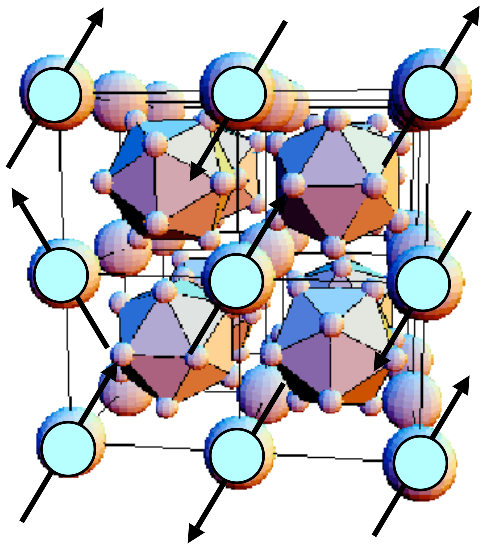


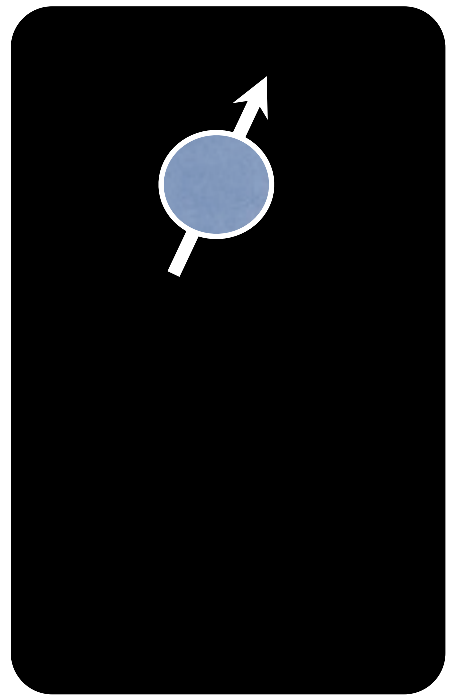
Heavy Electron Quantum Criticality.

Heavy Fermion Metals

Review: cond-mat/0612006



UBe_{13}



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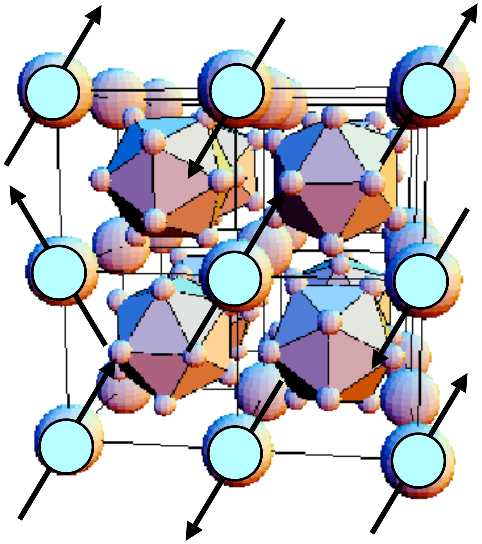

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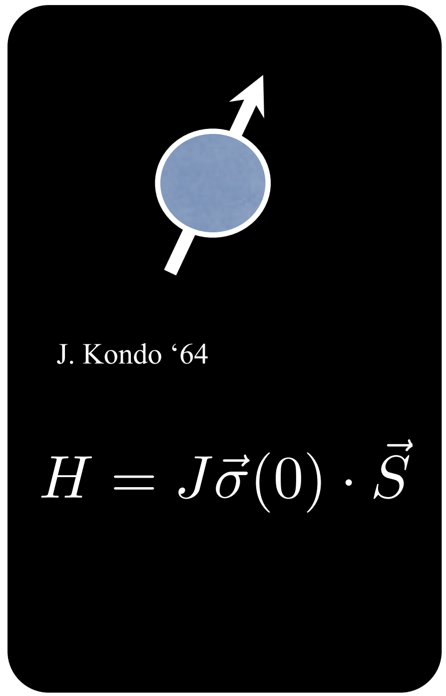

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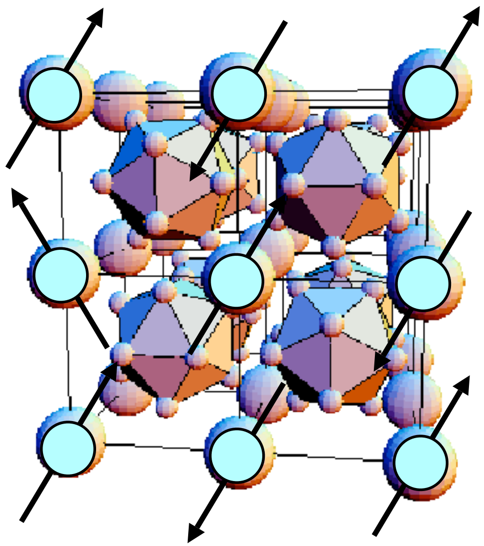
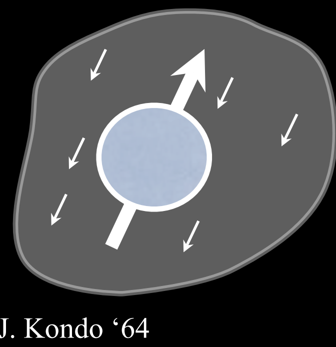


UBe$_{13}$



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

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

"Kondo Effect"

Heavy Fermion Metals

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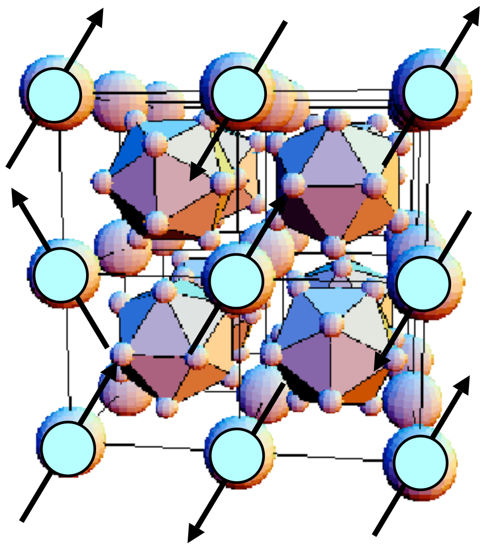

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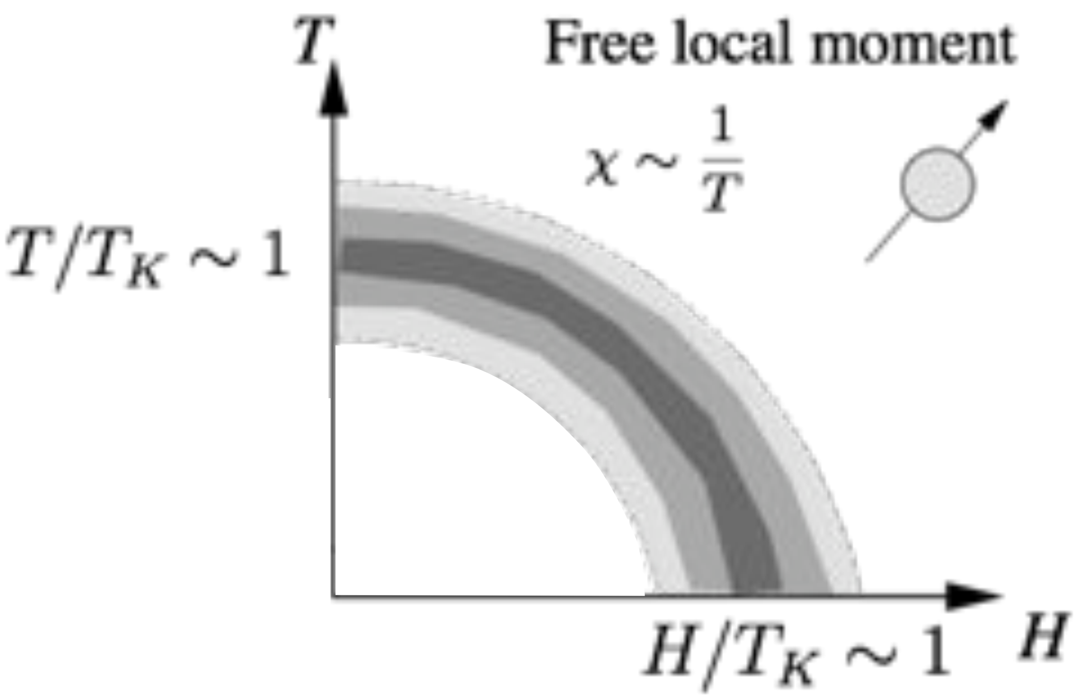

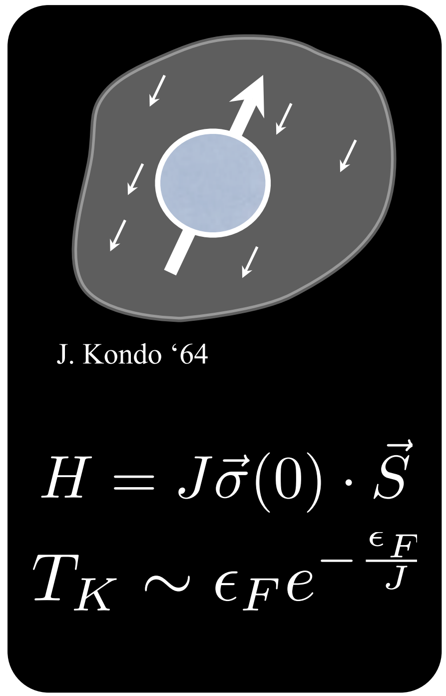

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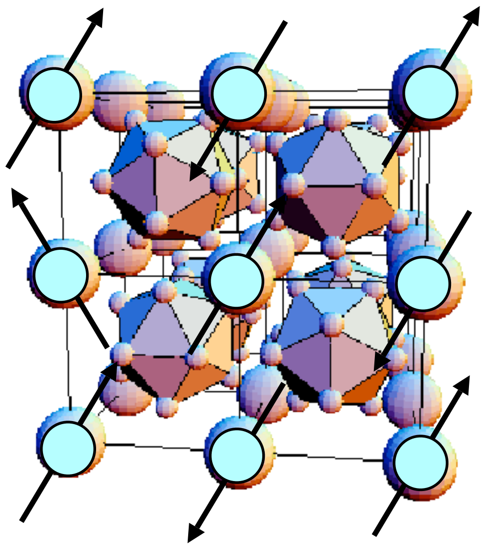

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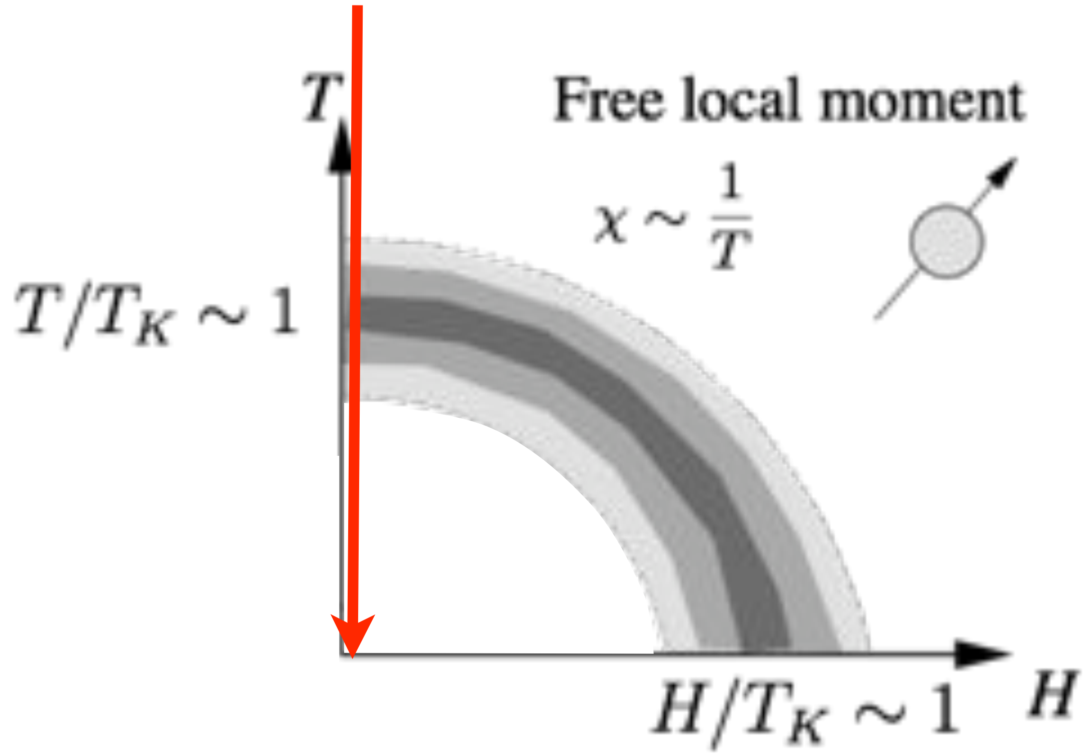

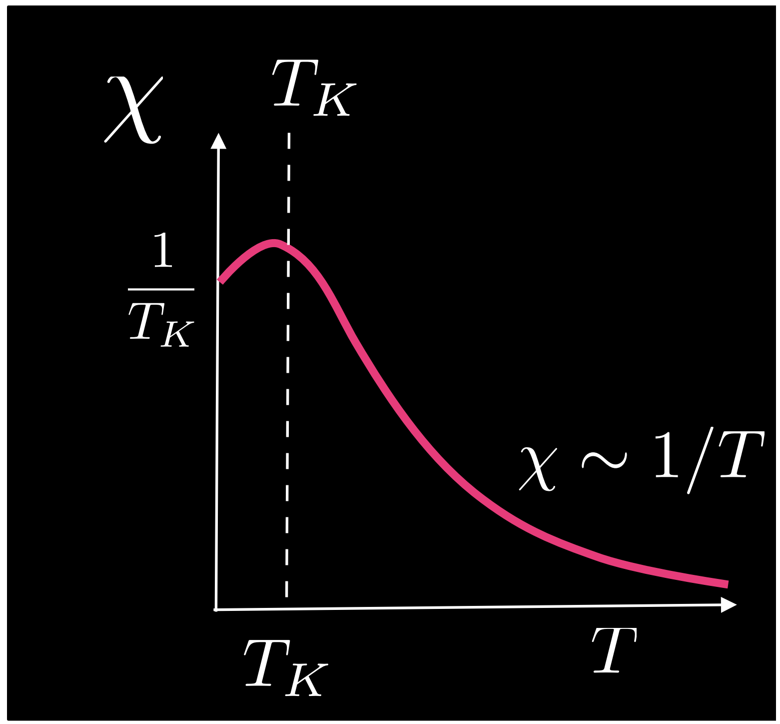

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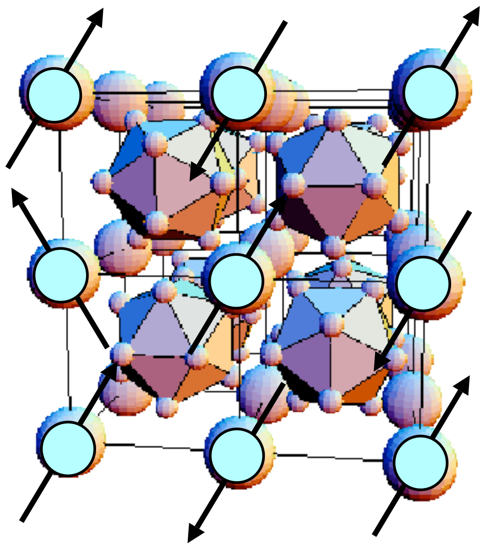

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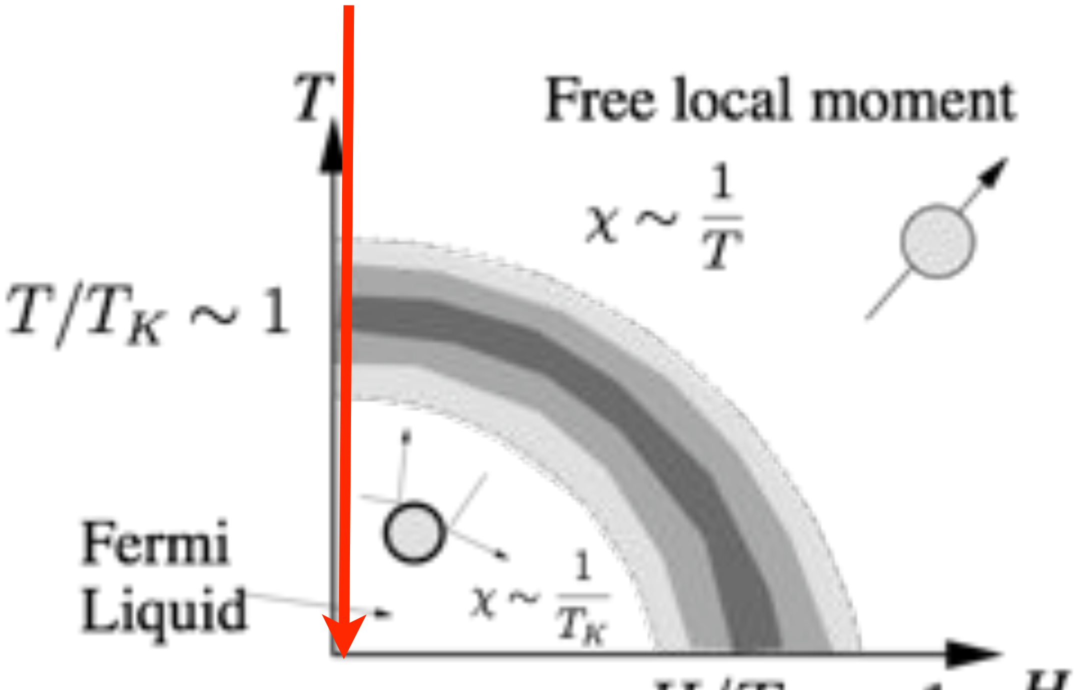
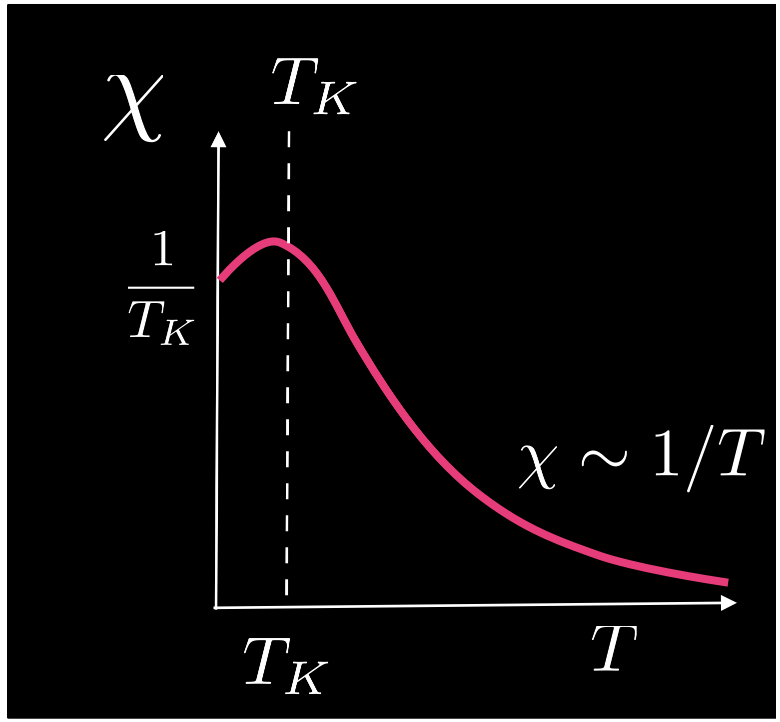


Nozieres ‘74



“Kondo Effect”

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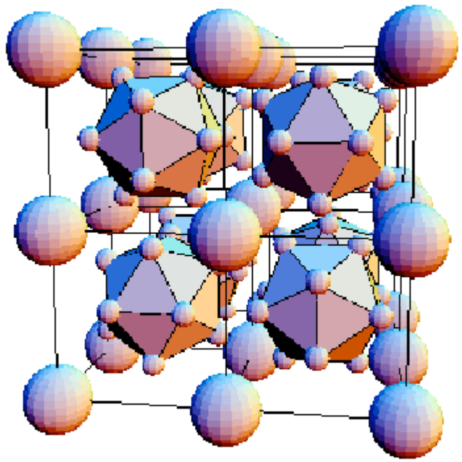

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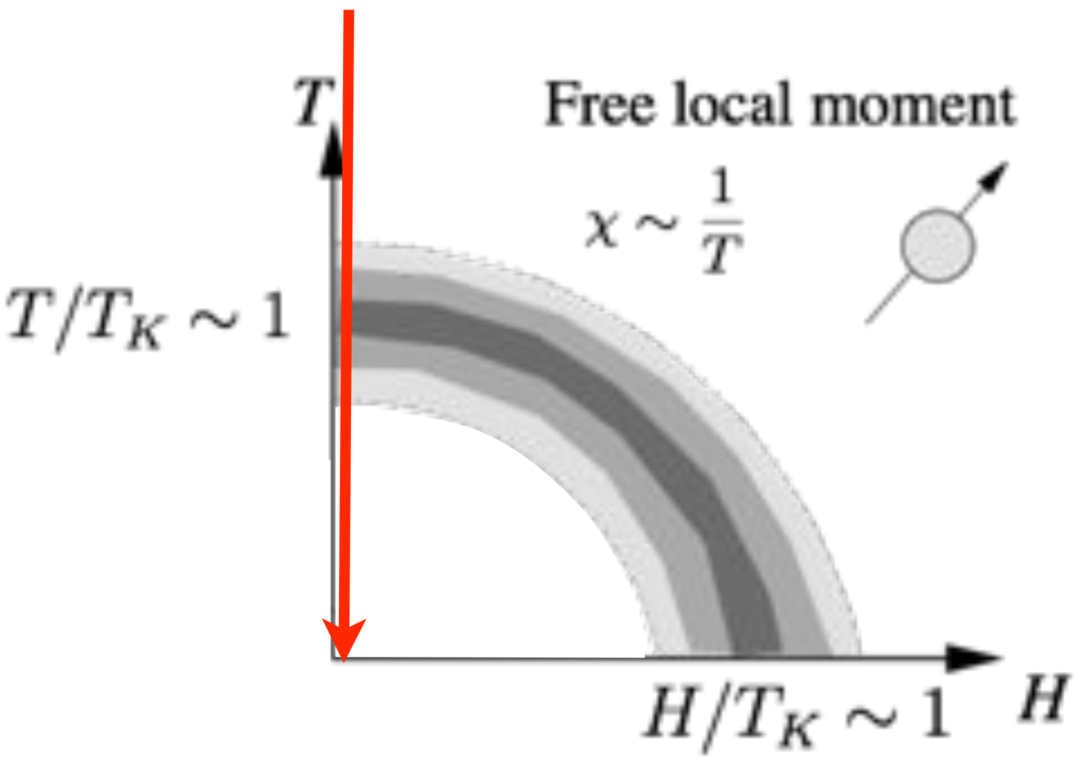
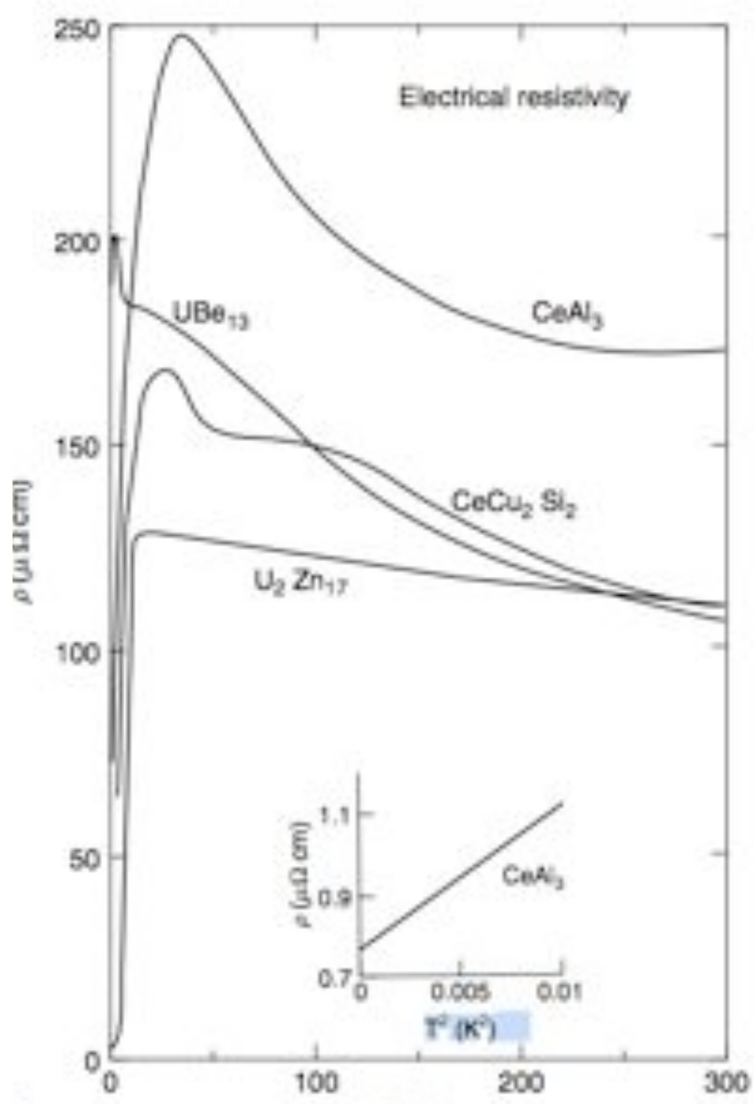
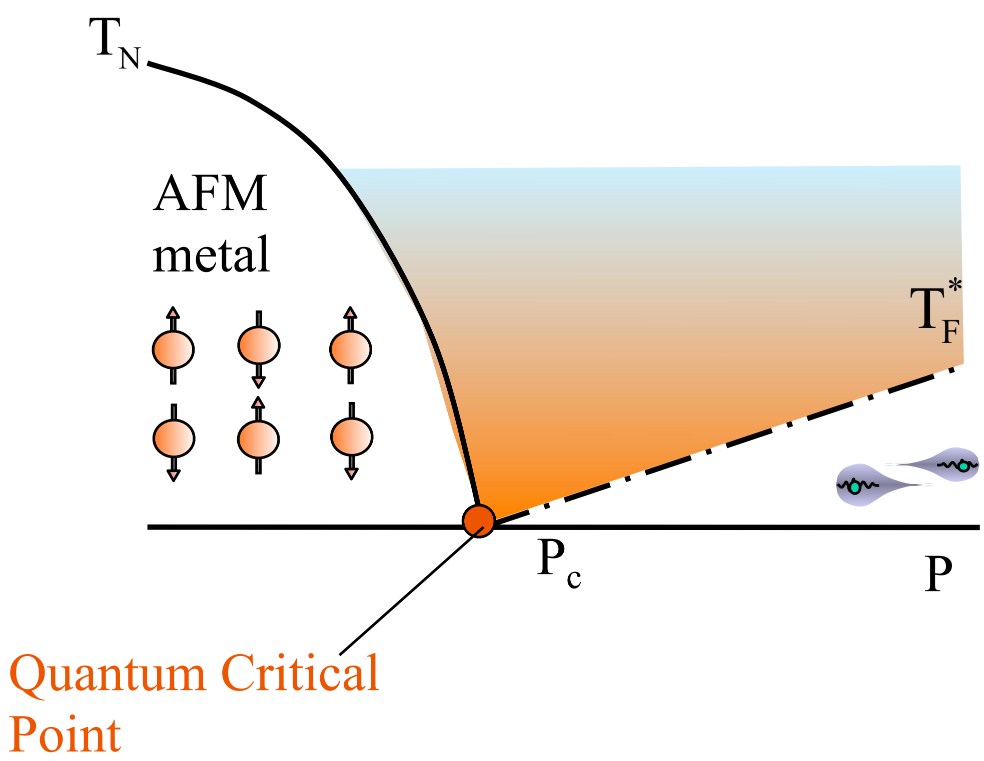




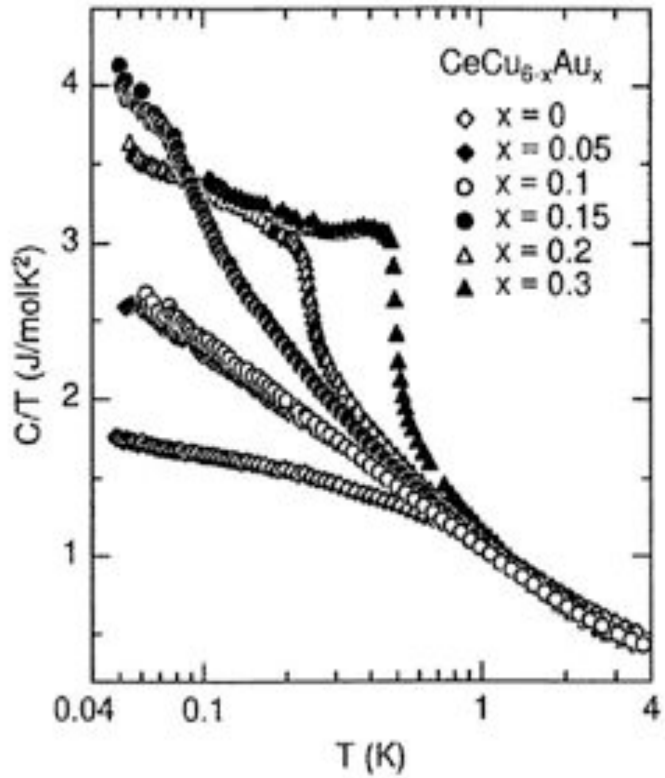
Some Key Observations

Quantum Criticality: divergent specific heat capacity

Heavy Fermion Materials



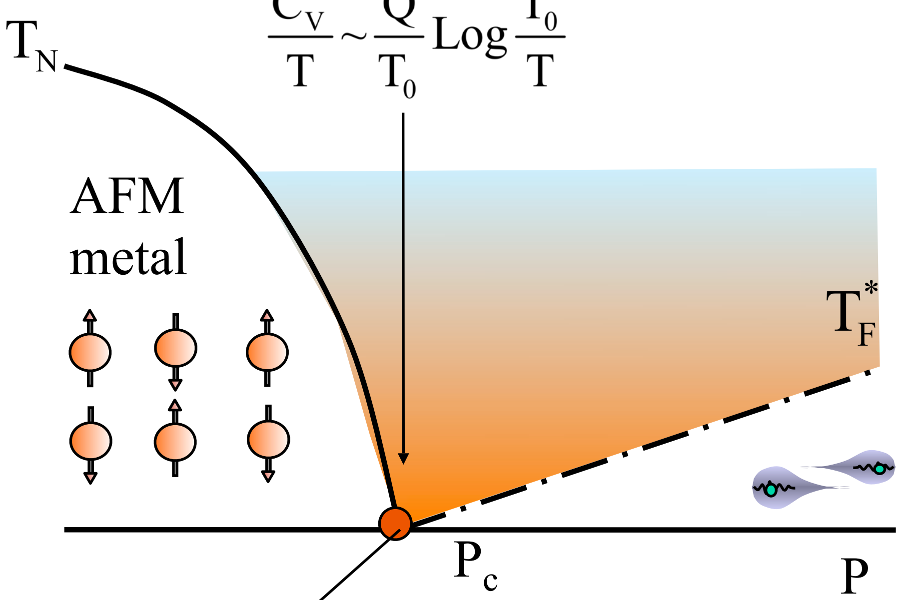
H. Von Lohneyson (1996)



Quantum Criticality: divergent specific heat capacity

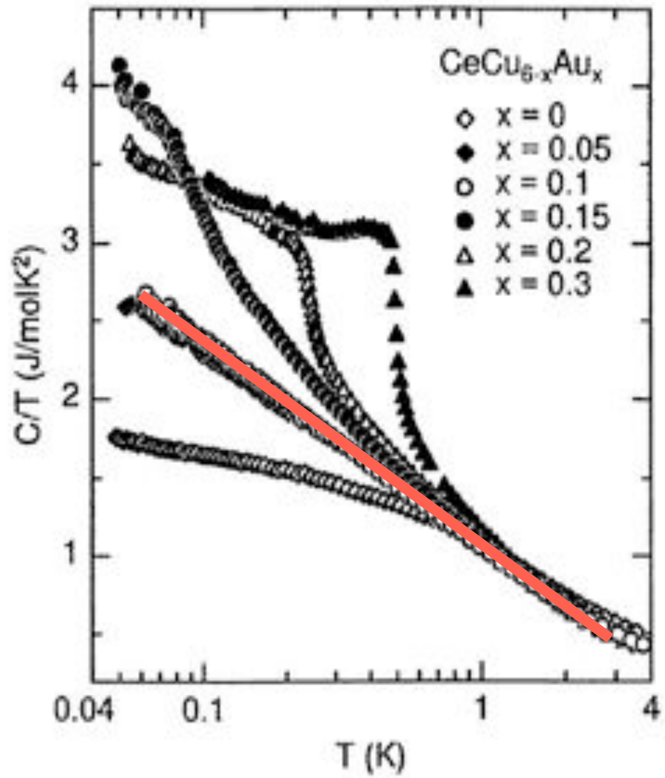
Heavy Fermion Materials

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

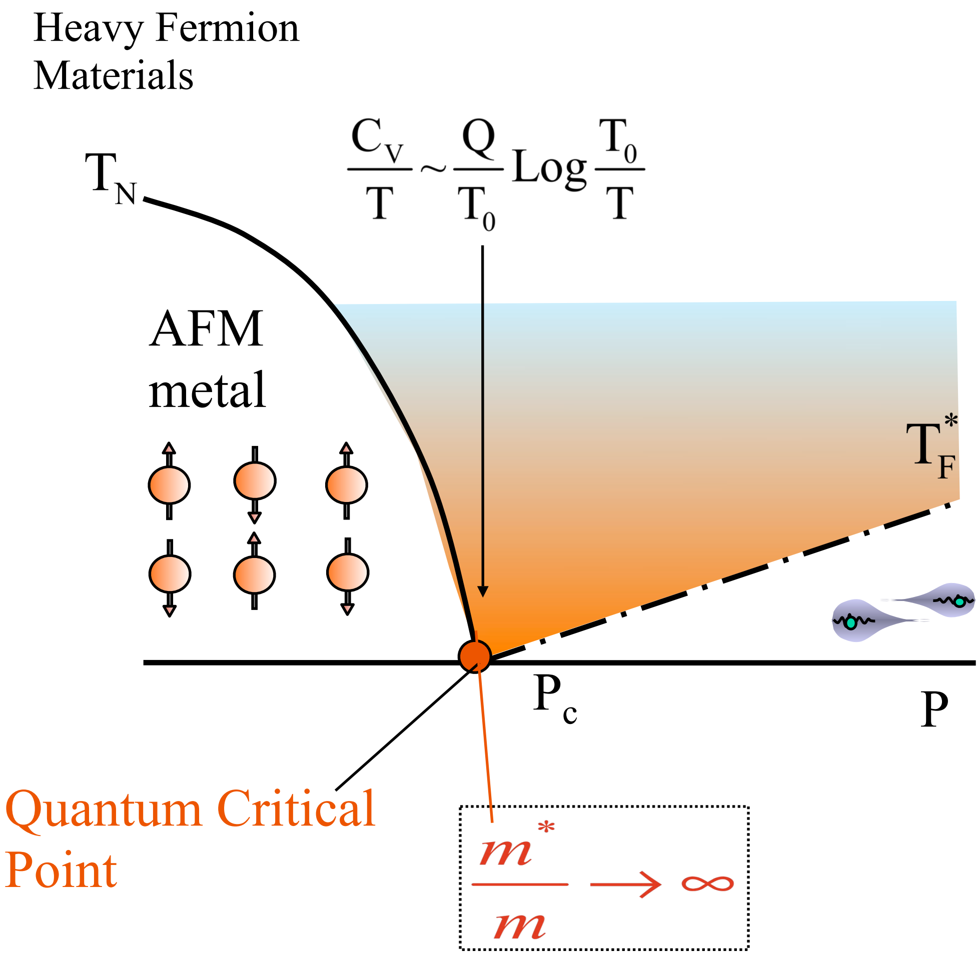


Quantum Critical Point

H. Von Lohneyson (1996)



Quantum Criticality: divergent specific heat capacity



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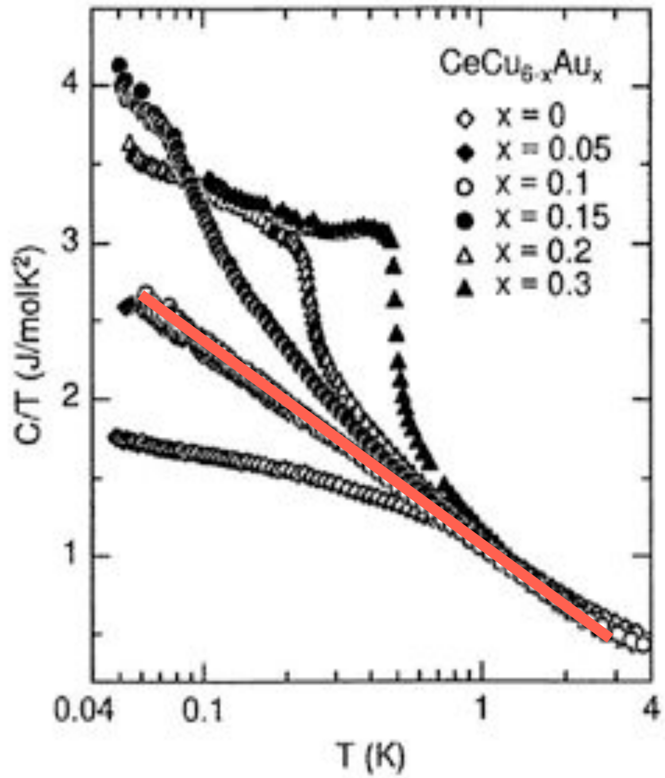
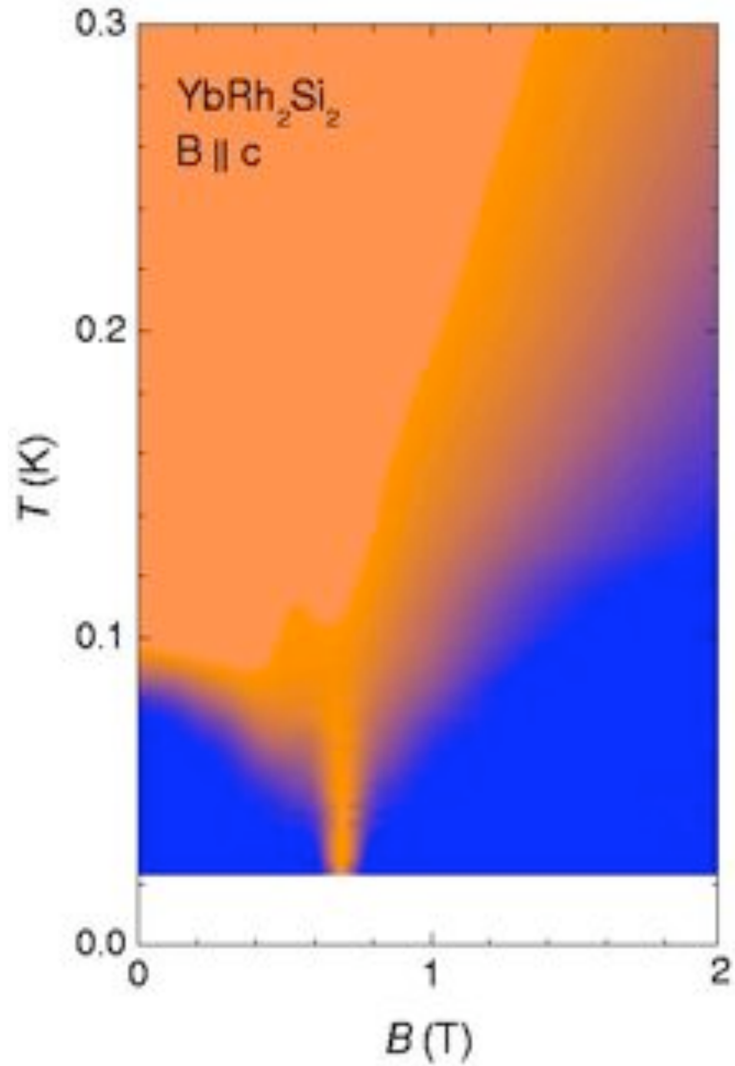


Field Tuned Criticality in YbRh2Si2.



$YbRh_2Si_2$

Trovarelli et al (2000).

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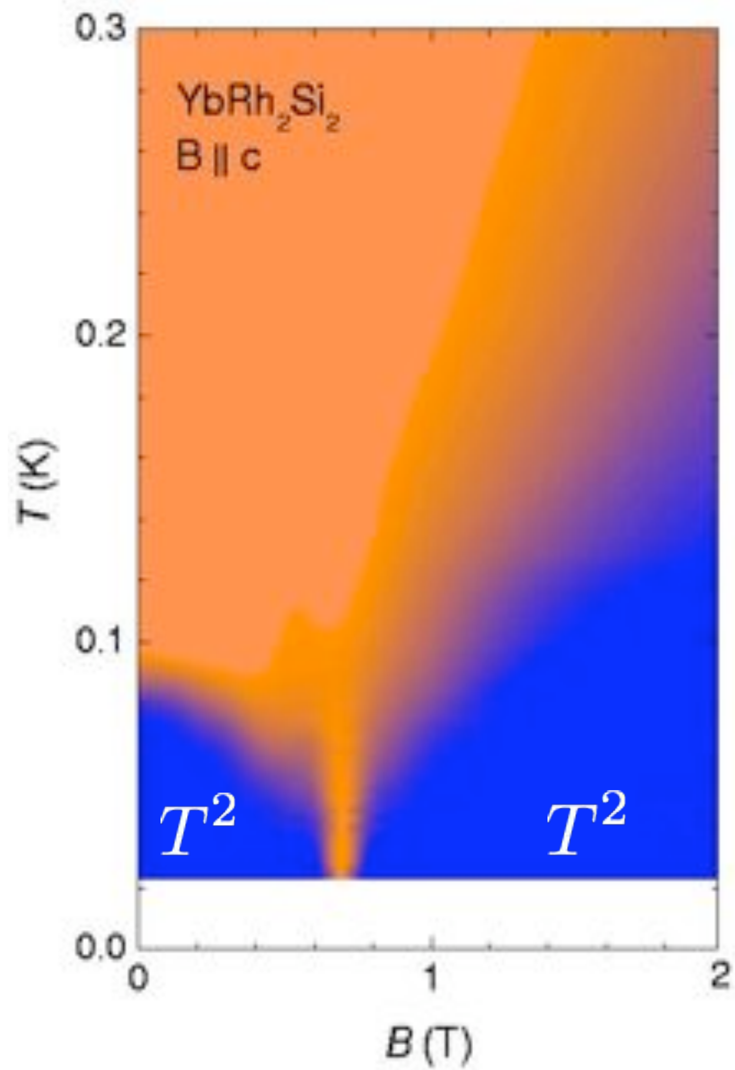

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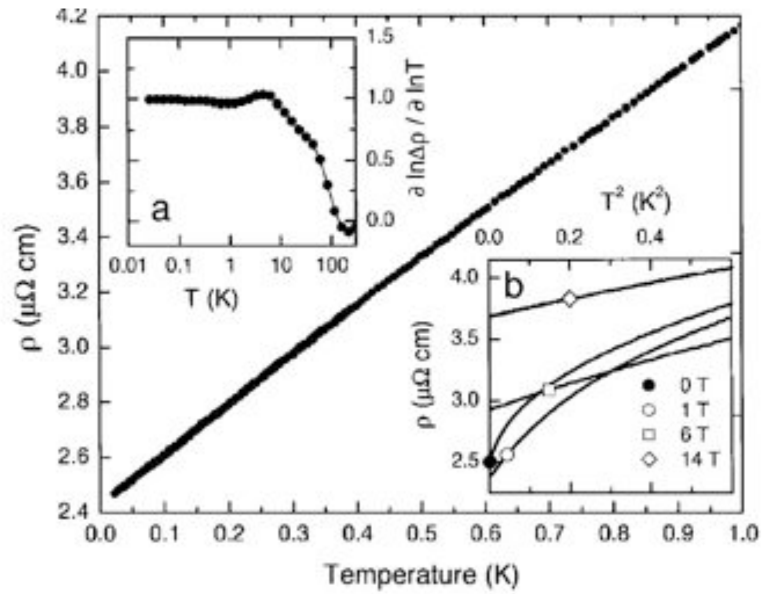

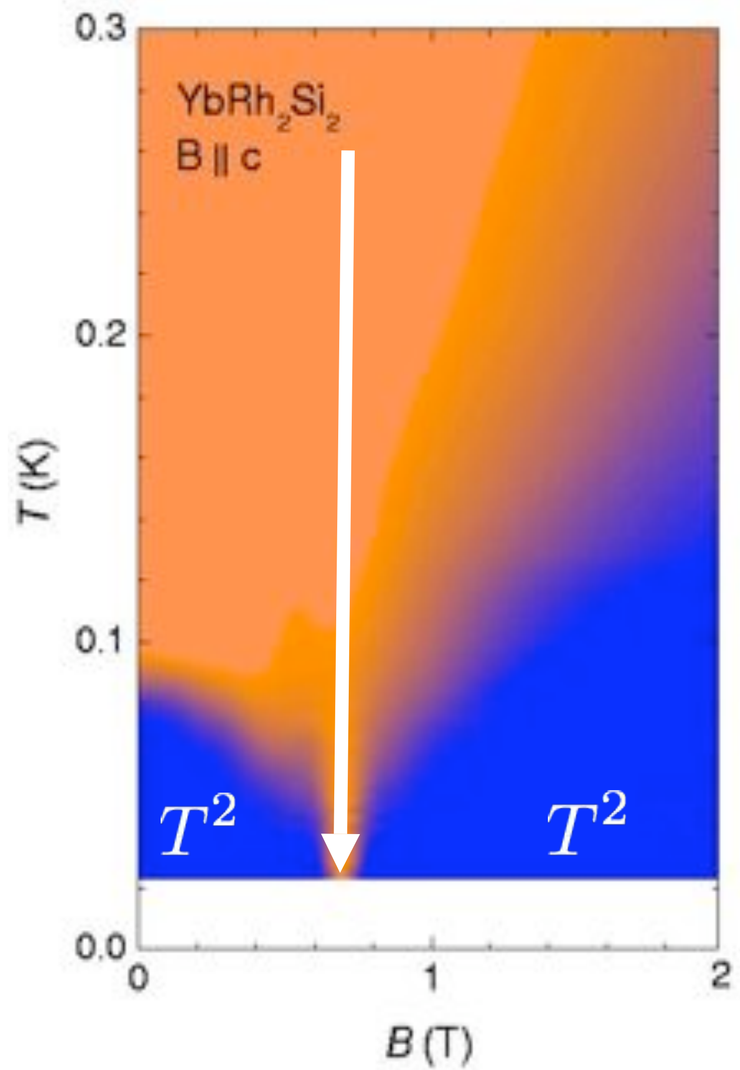

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Breakdown of Landau Fermi liquid.

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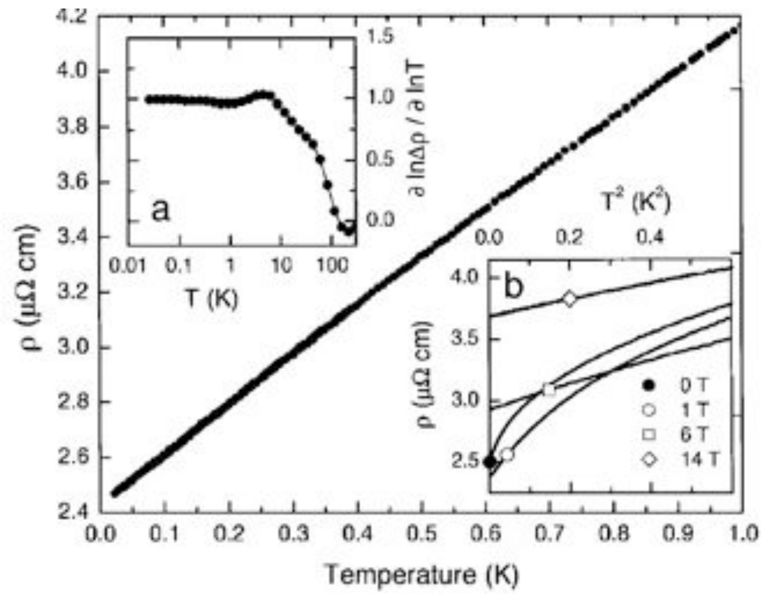

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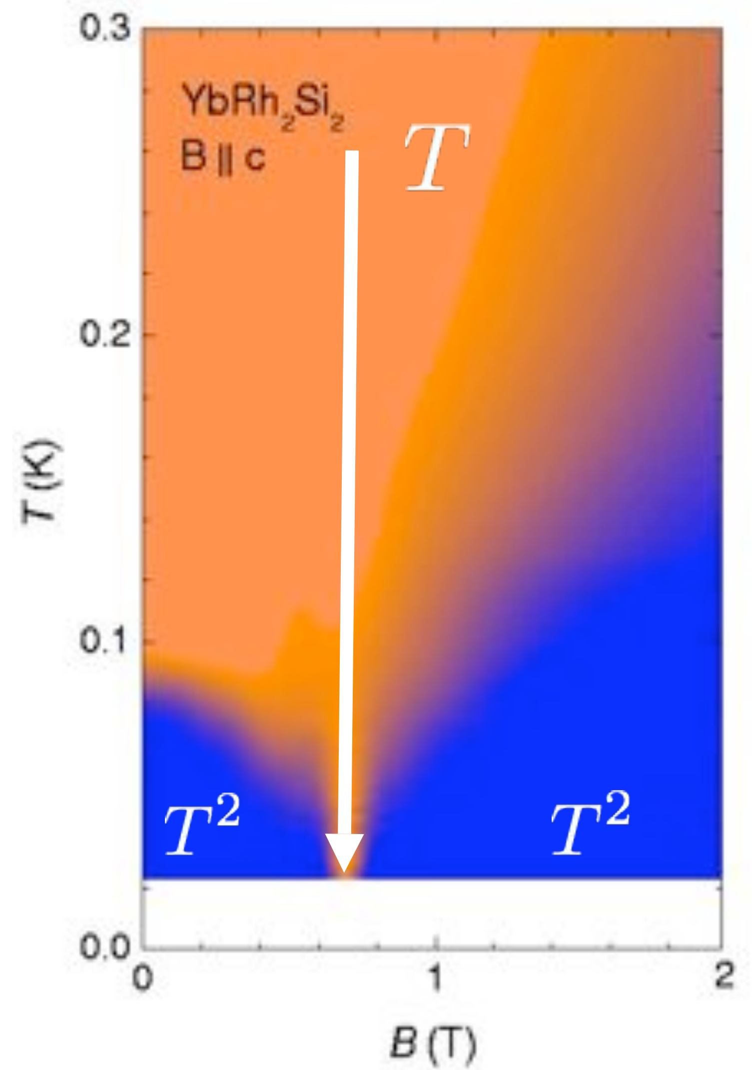
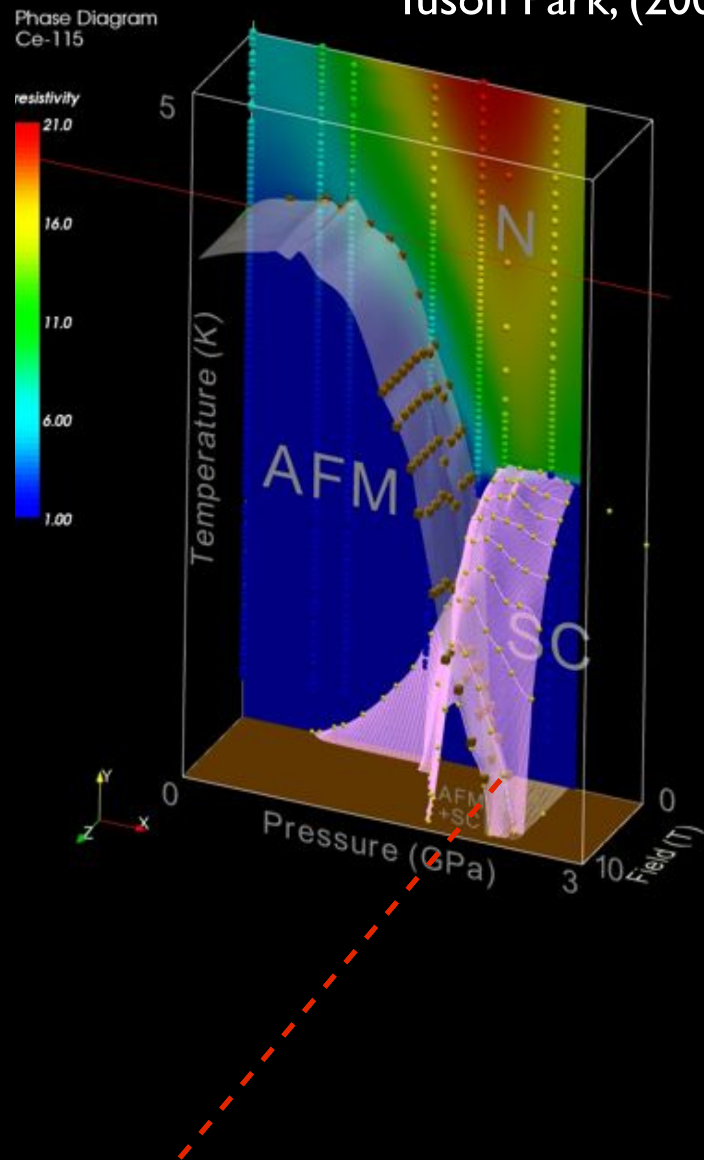


Breakdown of Landau Fermi liquid.

Reconstruction of the Fermi Surface and mass divergence

Tuson Park, (2007).



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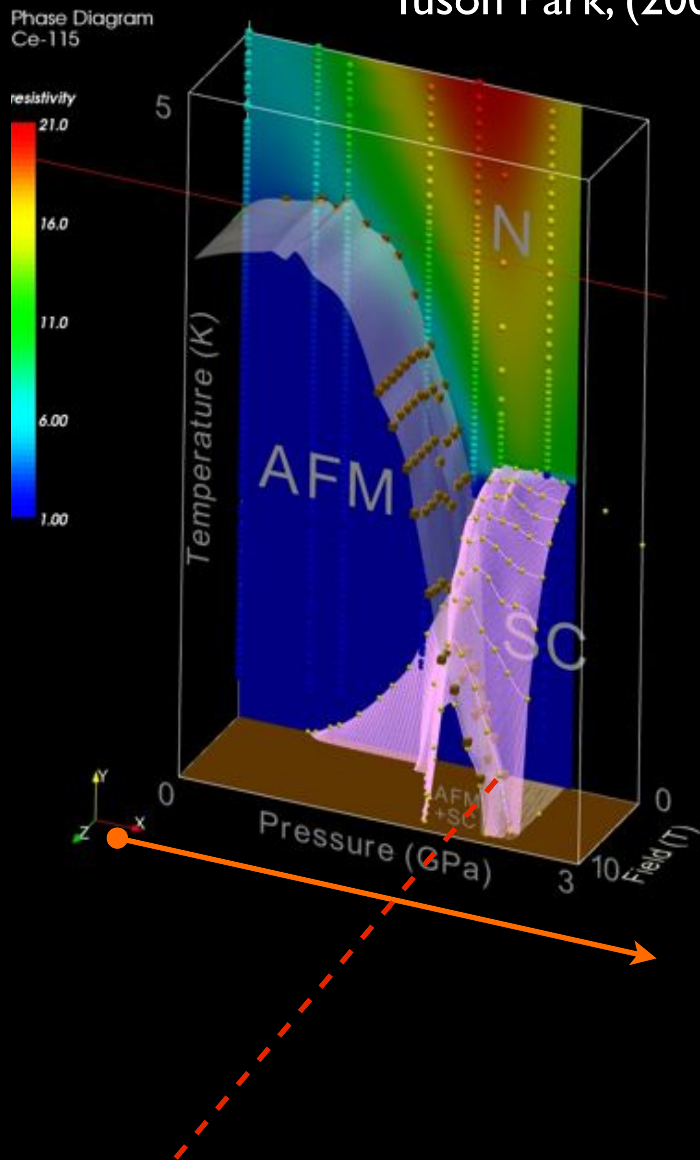

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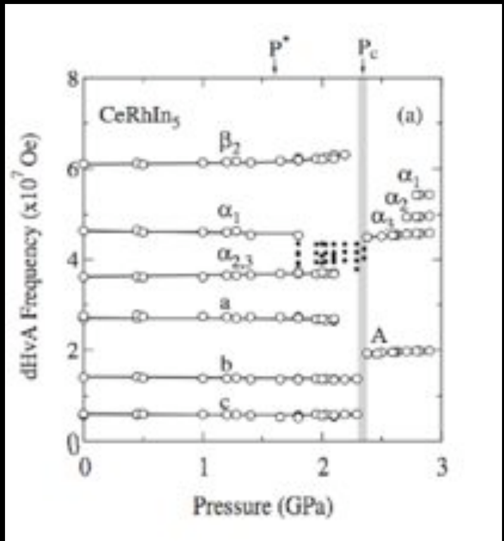

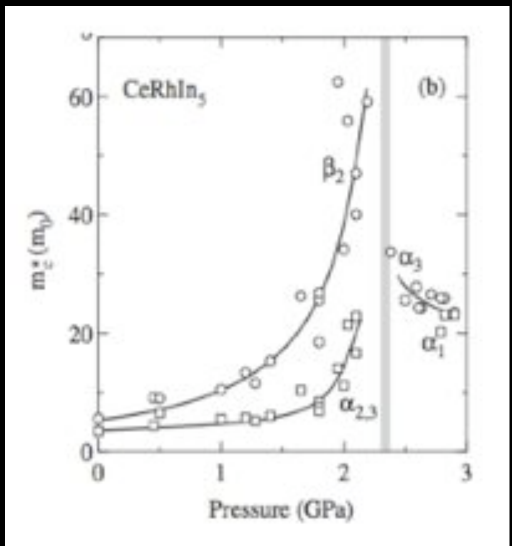

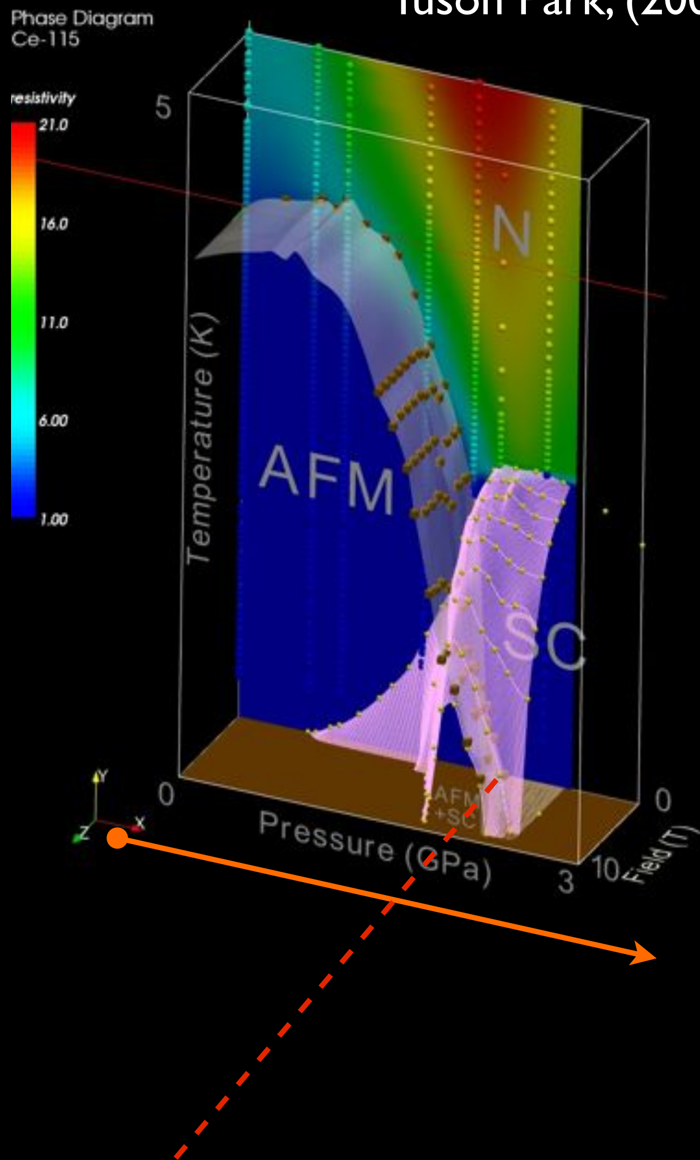

Shimuzu et al (2006)

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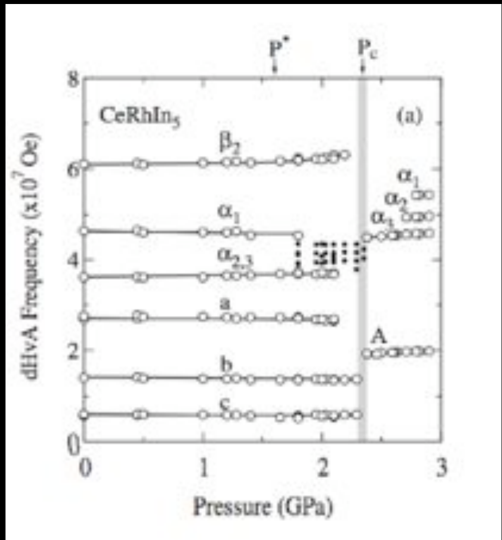

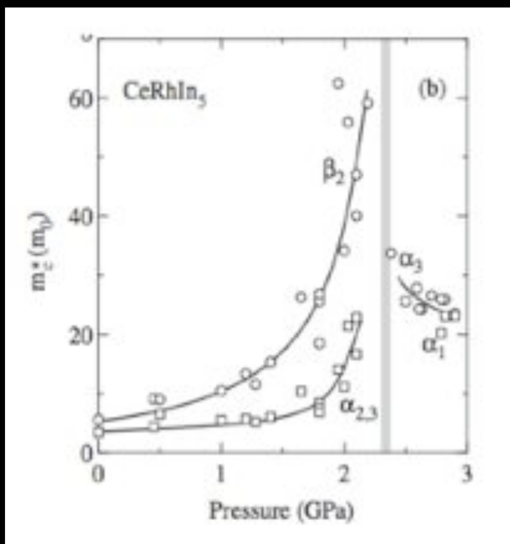

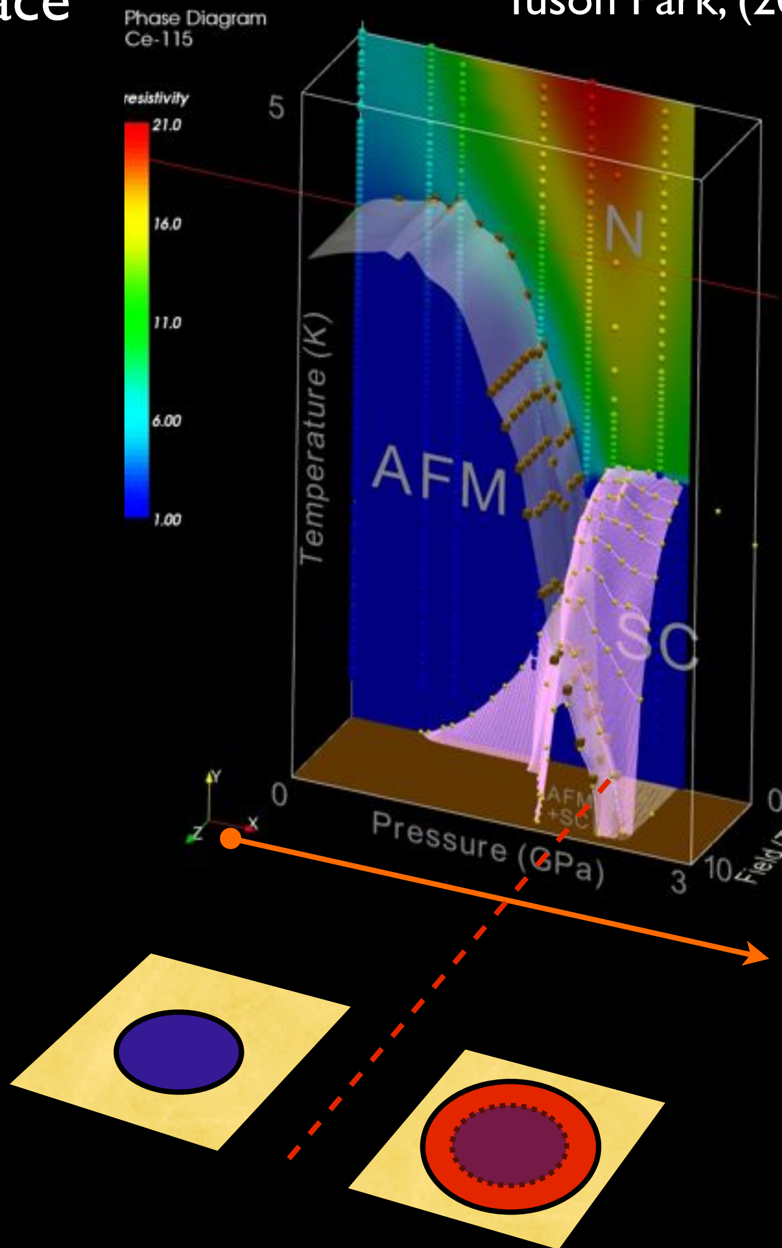

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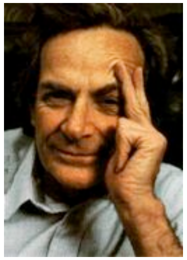
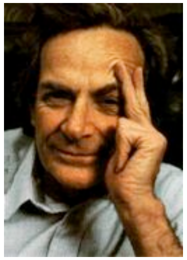

Feynman


Hertz

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



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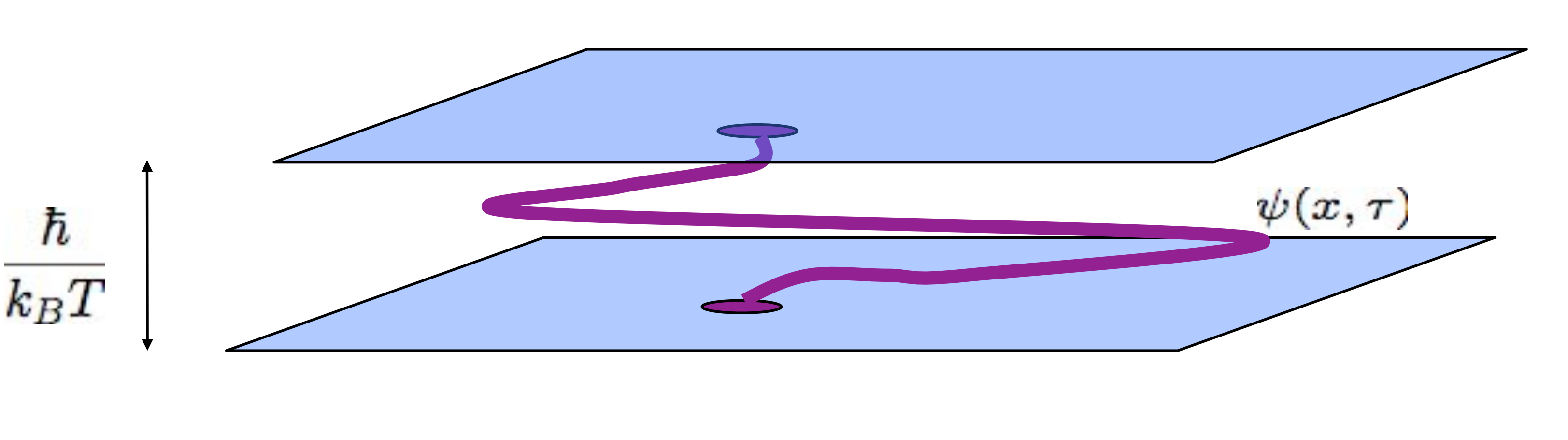

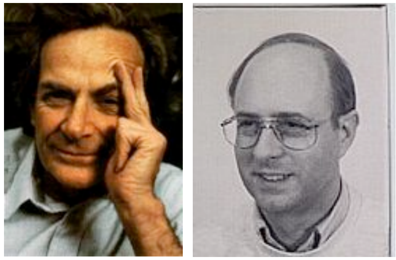

Feynman Hertz

Temperature: "Casimir effect" in time.

(PC, L. Palova, P. Chandra (08)

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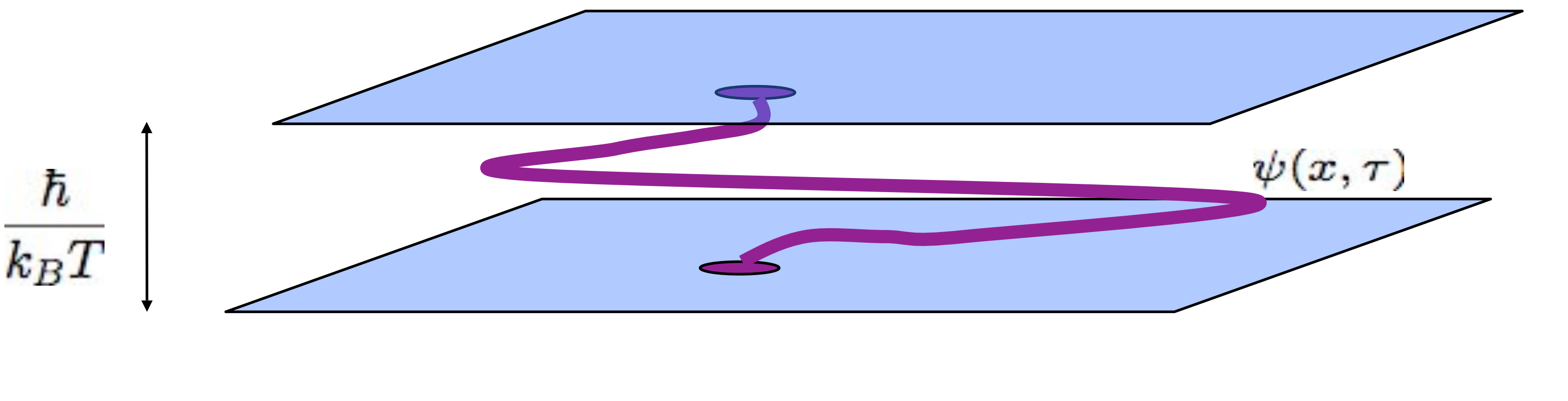

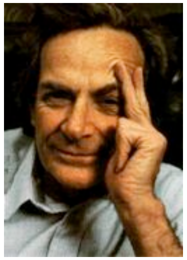

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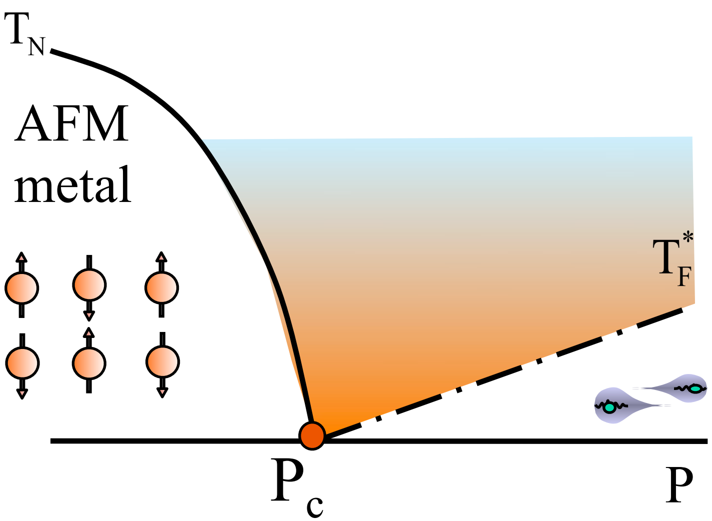

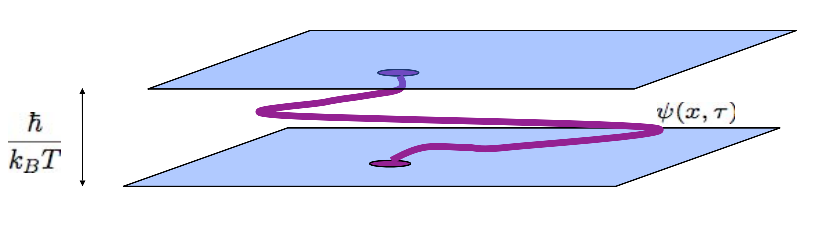

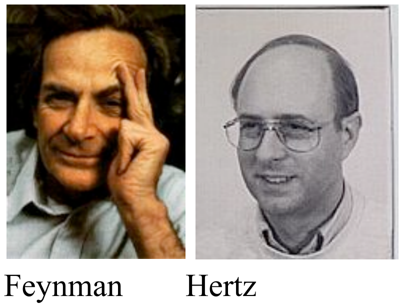

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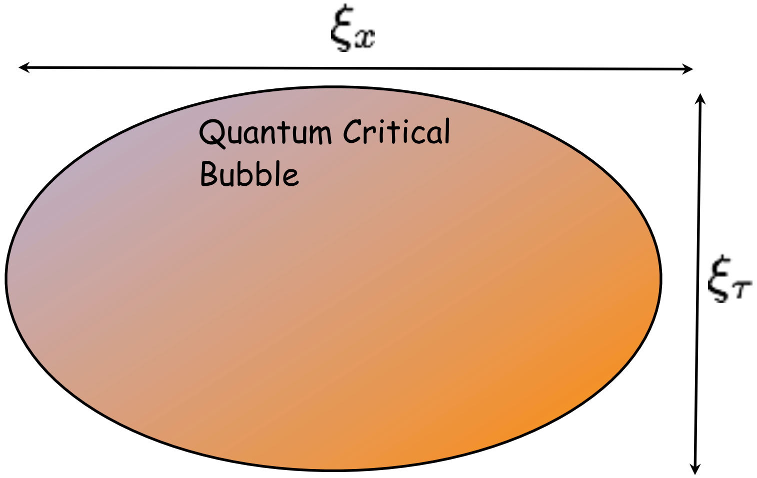

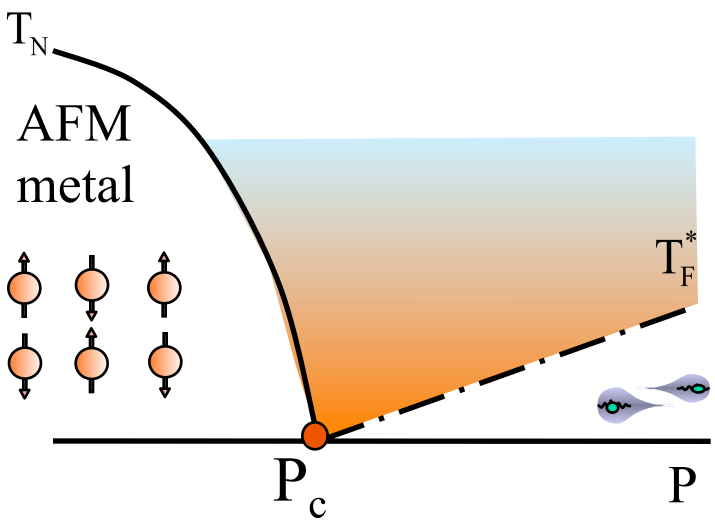

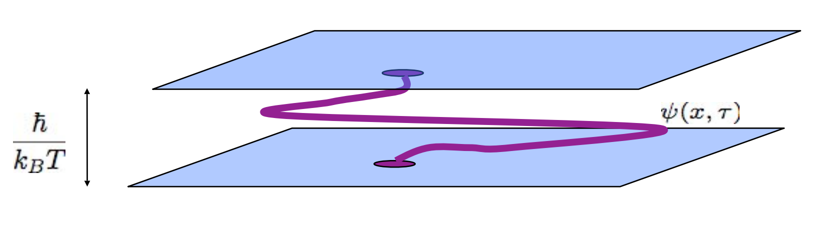

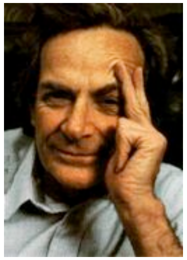

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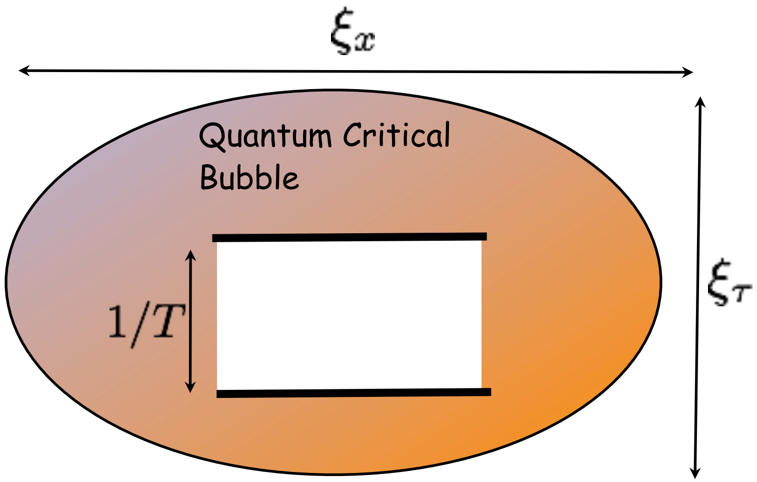

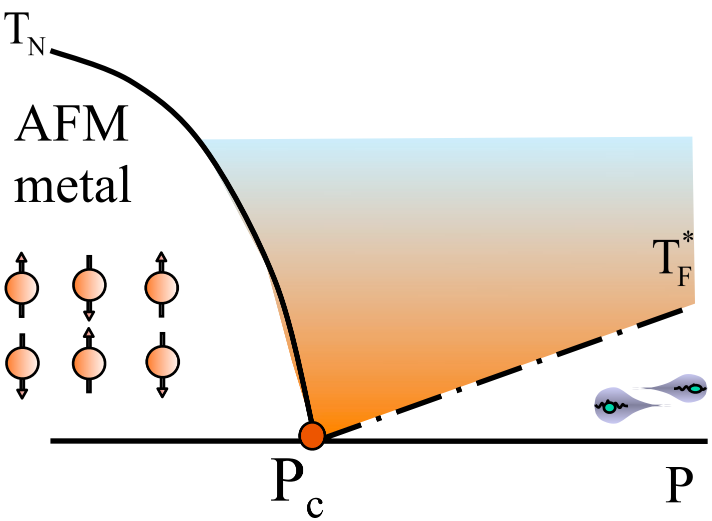

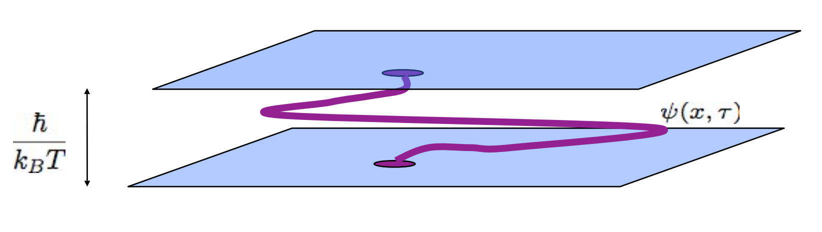

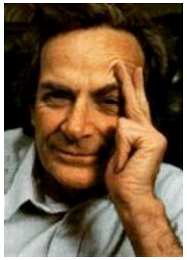

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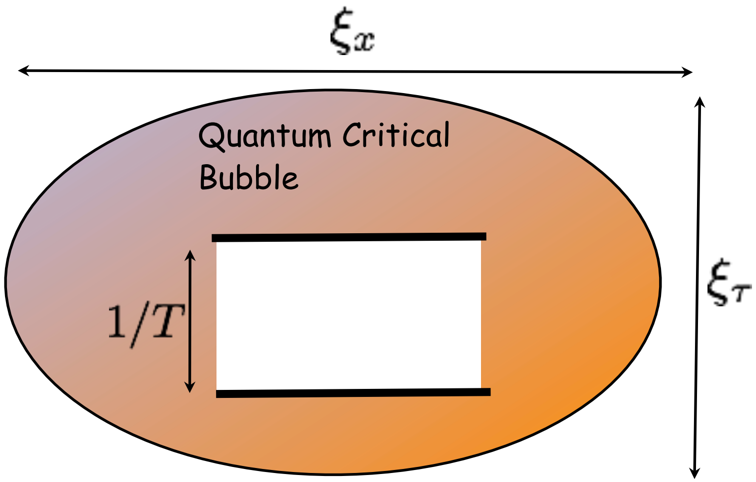
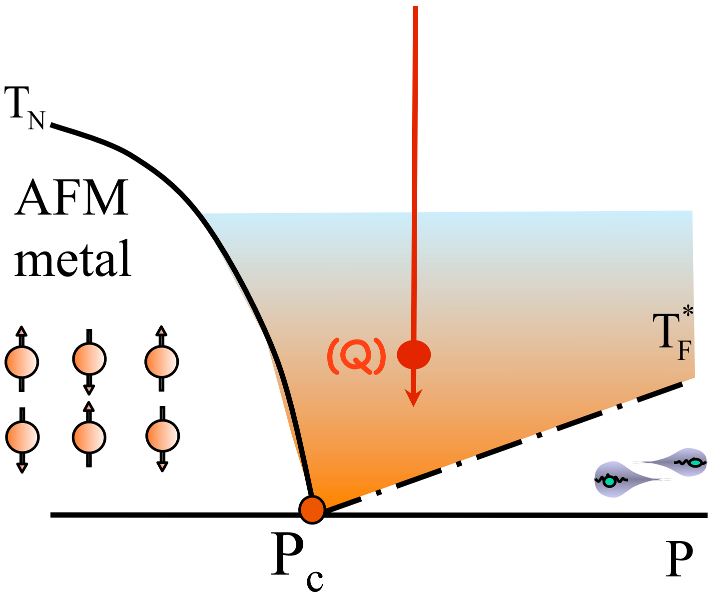
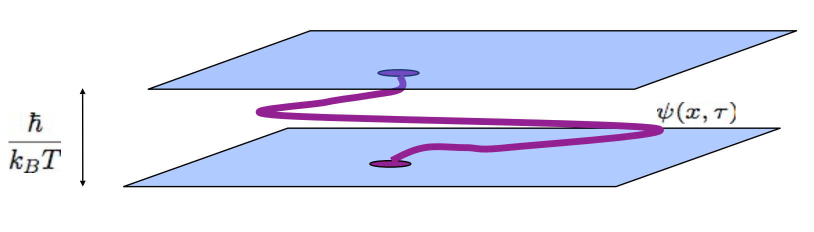
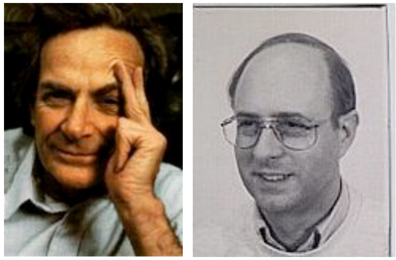


(Q) Quantum critical region: interior of correlation bubble.







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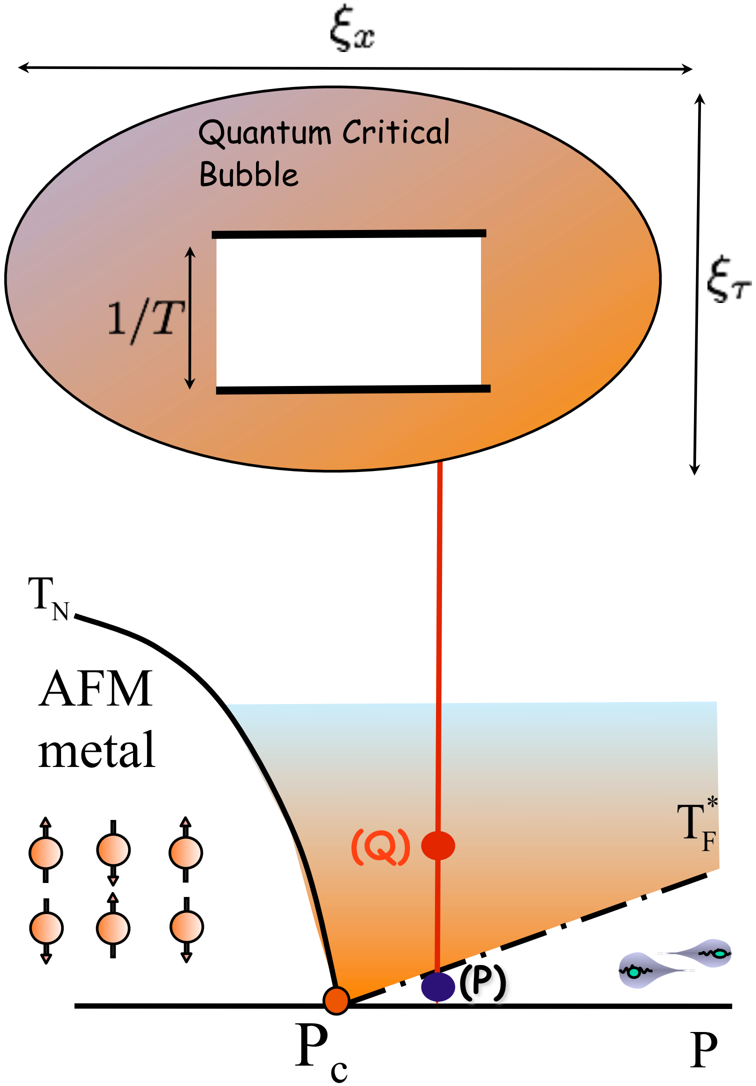
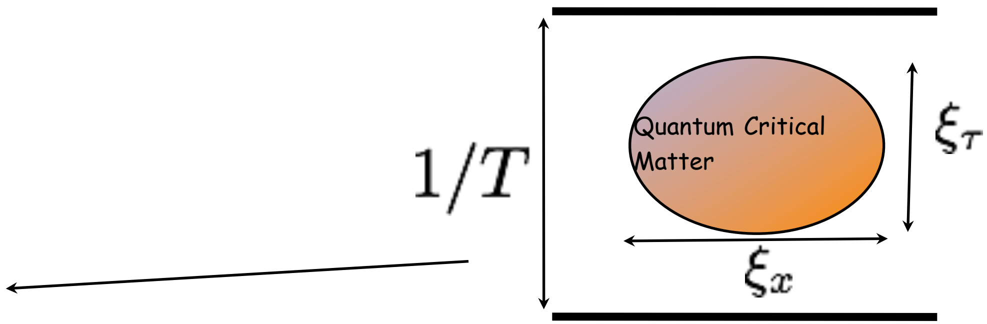
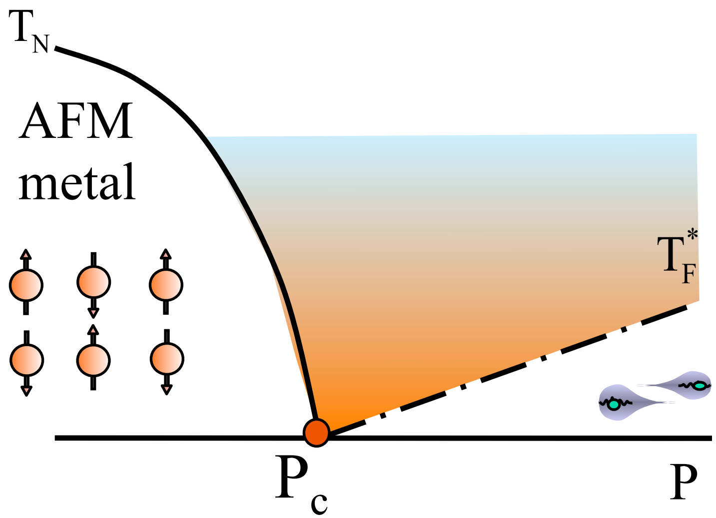


(Q) Quantum critical region: interior of correlation bubble.

(P) Paramagnet: probes exterior of correlation bubble



"Black Hole in the Phase Diagram".



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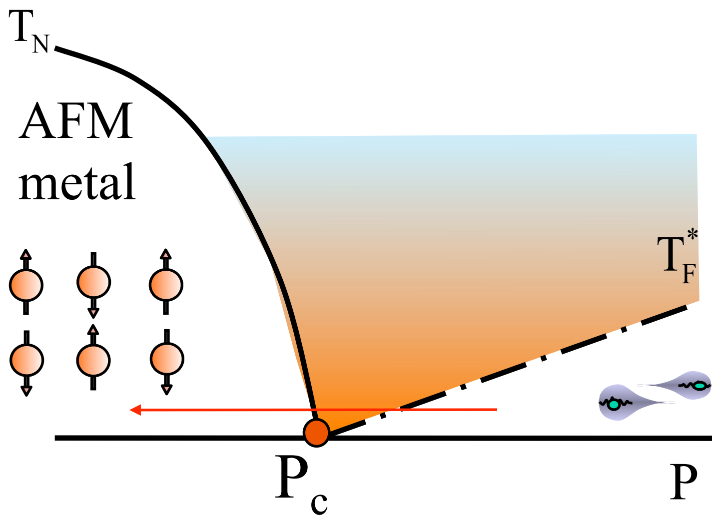

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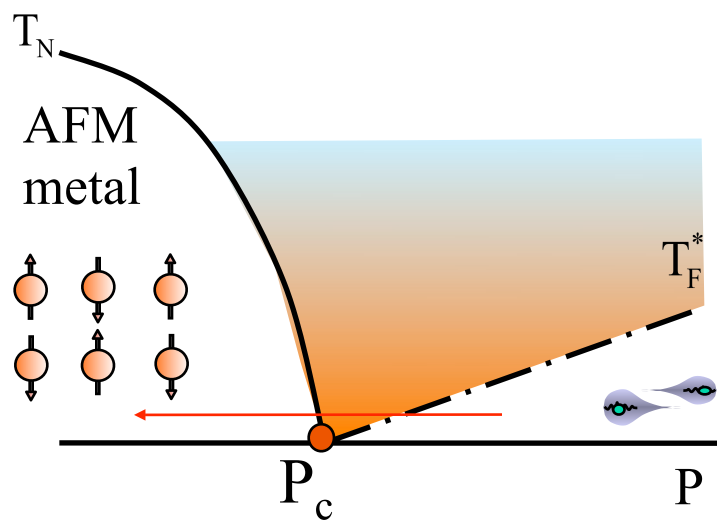
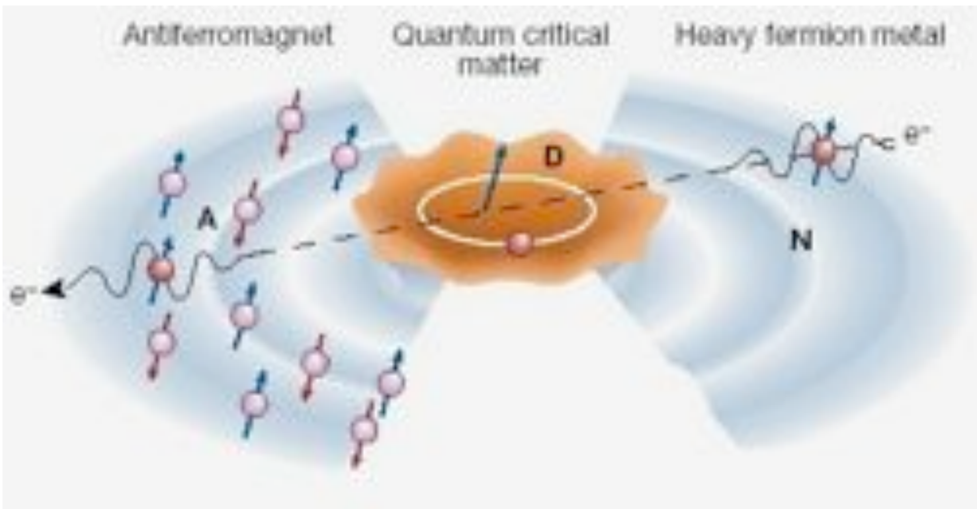
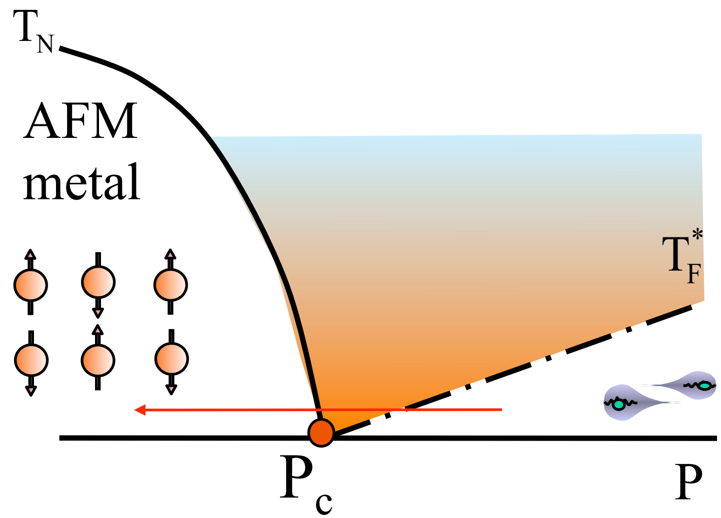
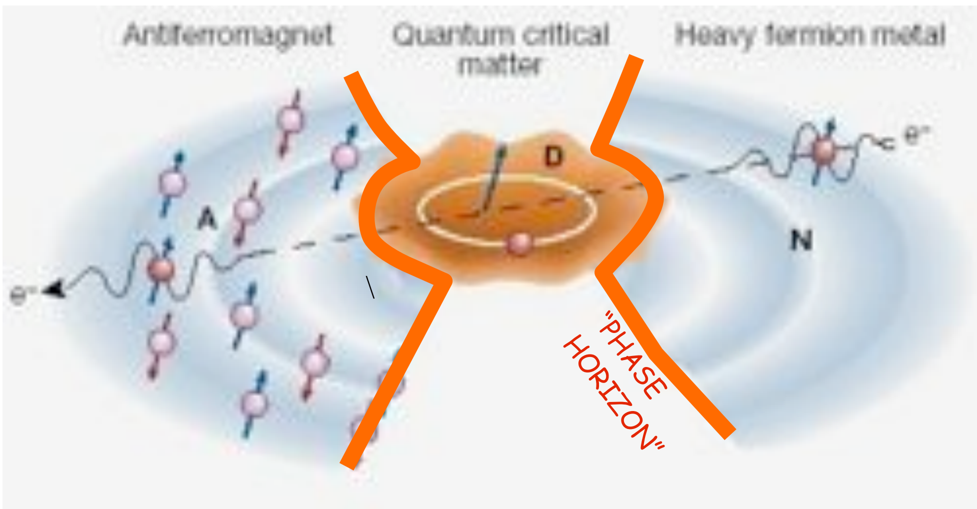




P.C and A. Schofield, Nature (2005)

“Black Hole in the Phase Diagram”.





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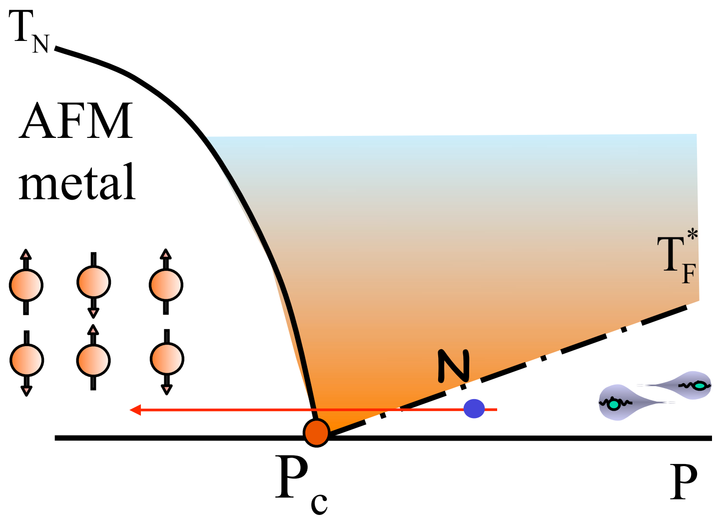

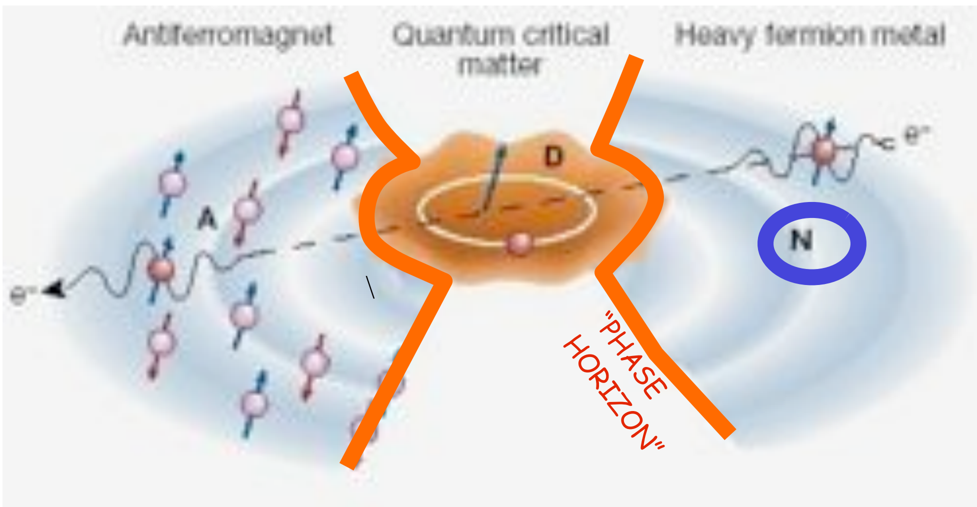

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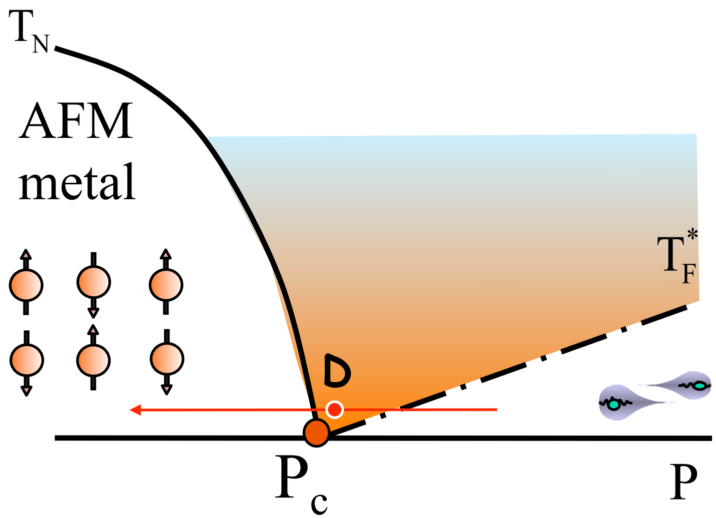

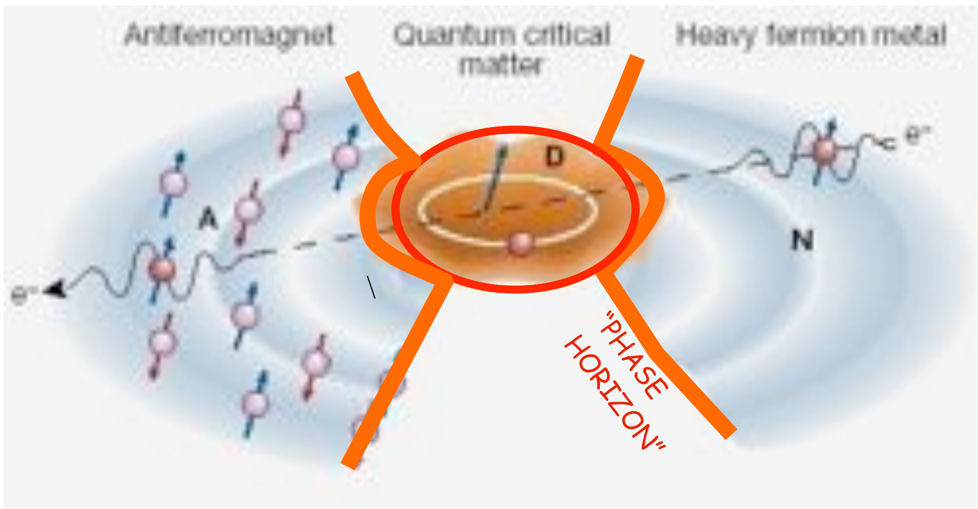

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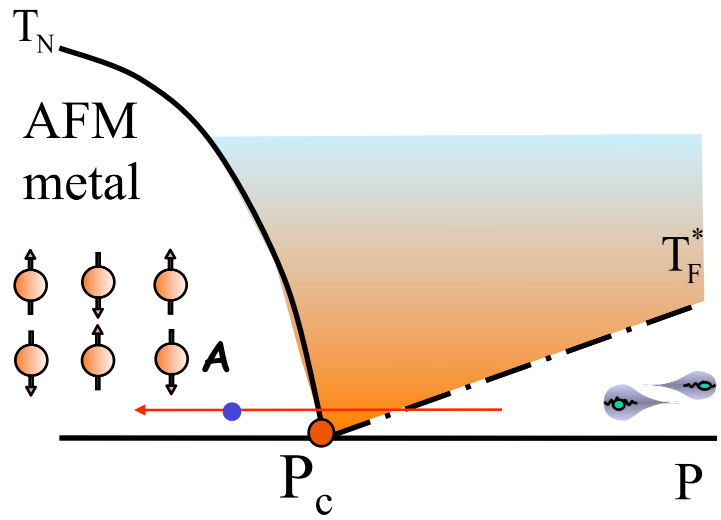

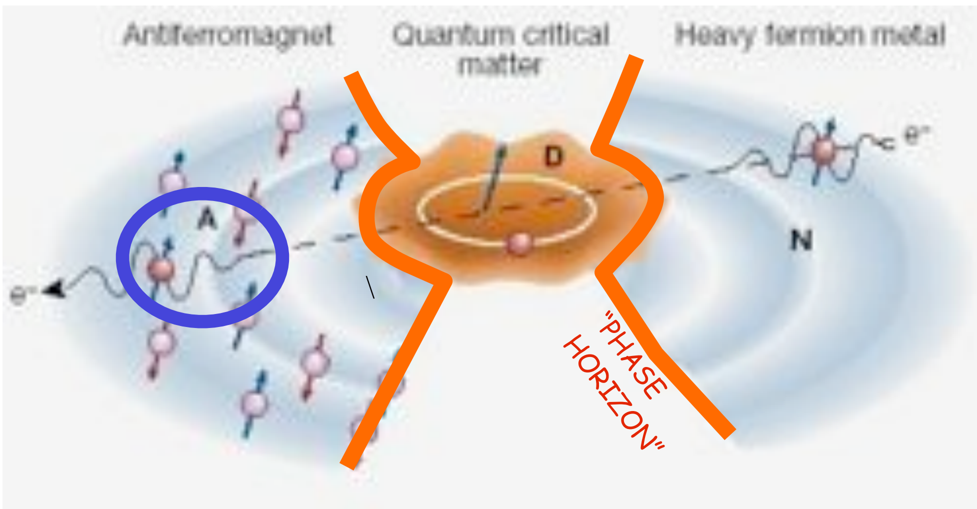

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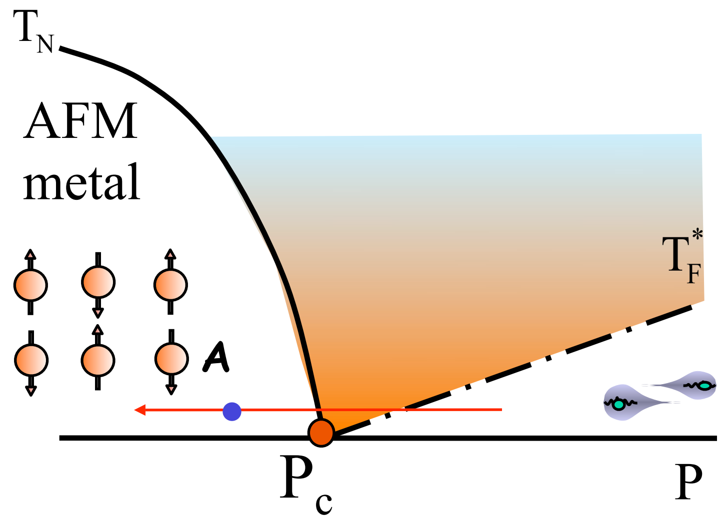
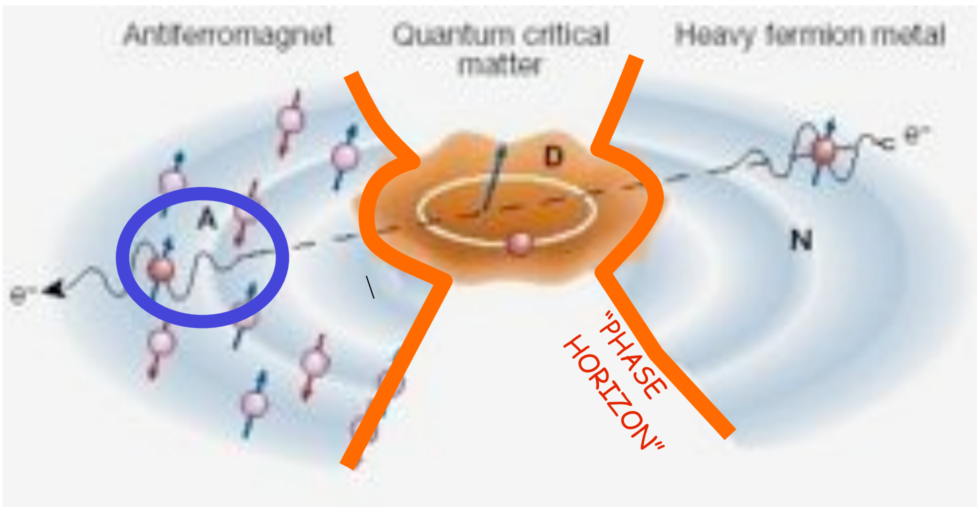




P.C and A. Schofield, Nature (2005)

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

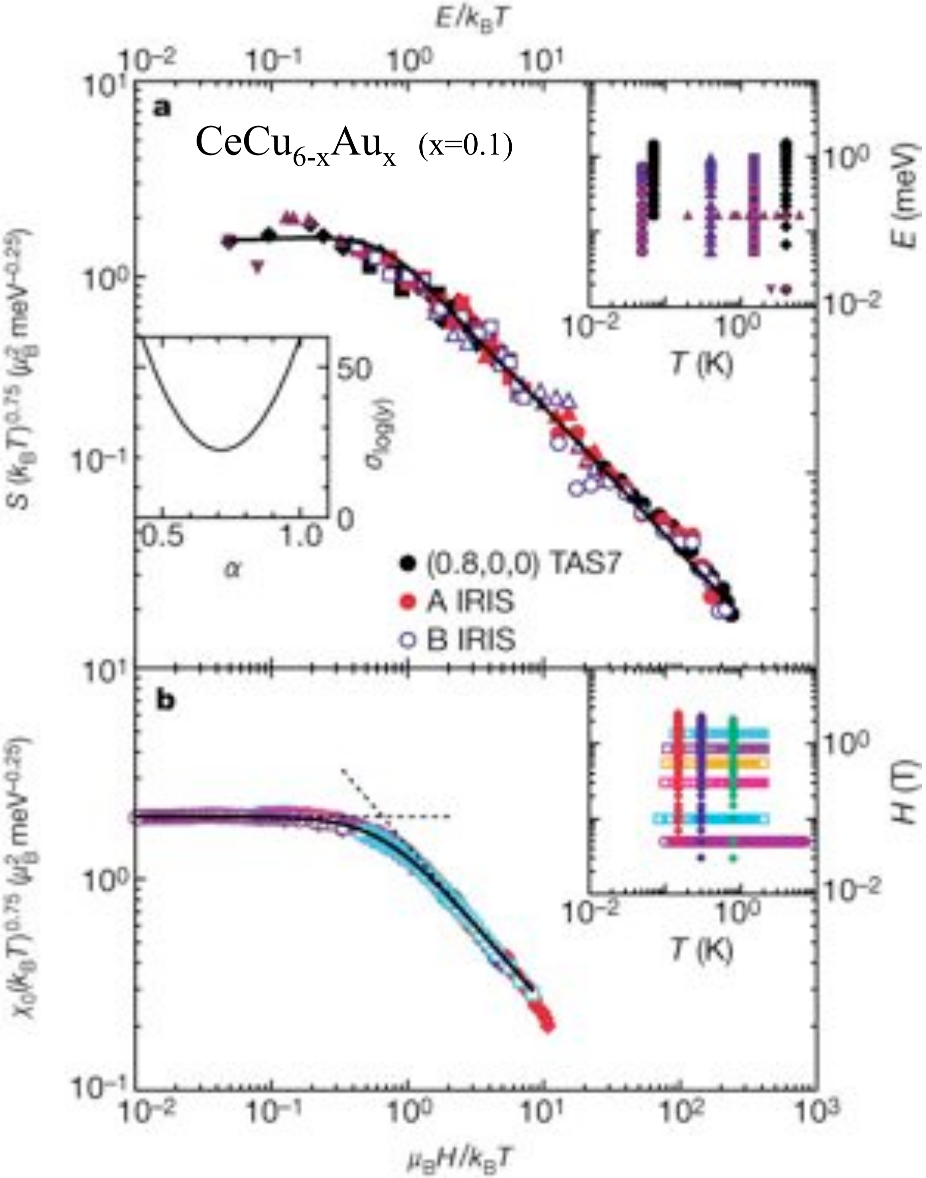
E/T Scaling:

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

Almut Schroeder

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

Physics Below the upper Critical Dimension.



Rutgers Center for Materials Theory

The Standard Model

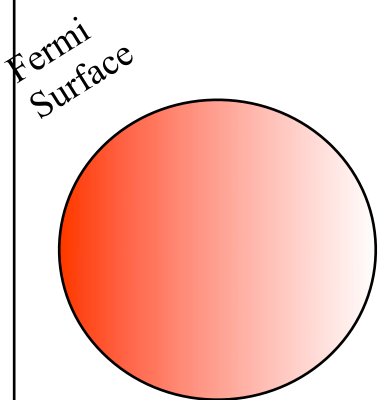
Standard Model: Quantum SDW?




Doniach Schrieffer Hertz Millis

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

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



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

F.S. instability

Rutgers
Center for Materials Theory

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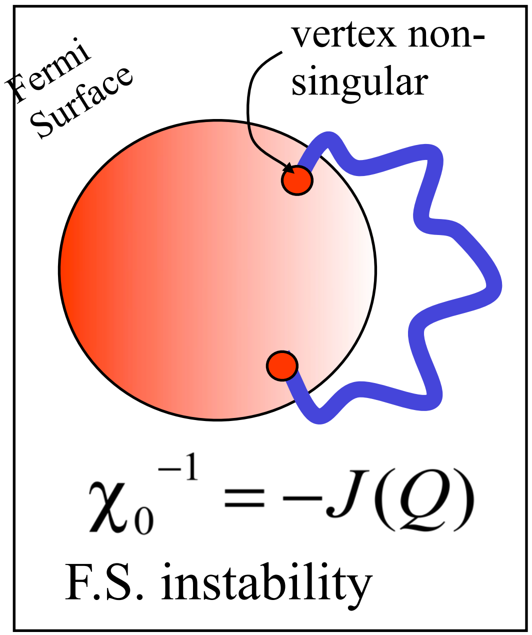

$$\chi^{-1}(q,\omega) \propto (\xi^{-2} + (q-Q)^2 - i\omega / \Gamma)$$

Rutgers
Center for Materials Theory

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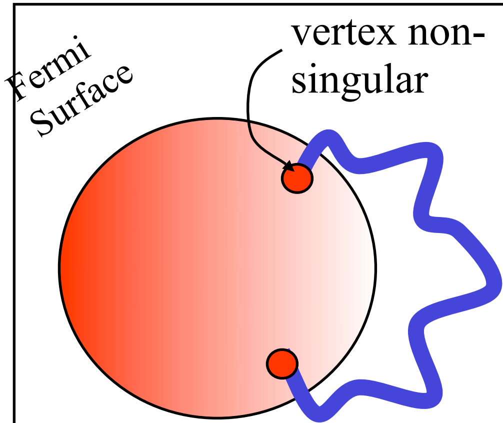

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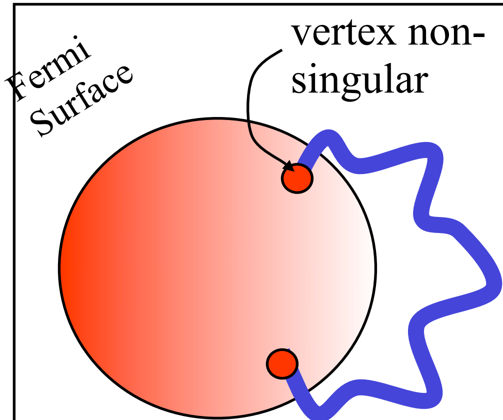

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Time counts as z =2 scaling dimensions

Rutgers
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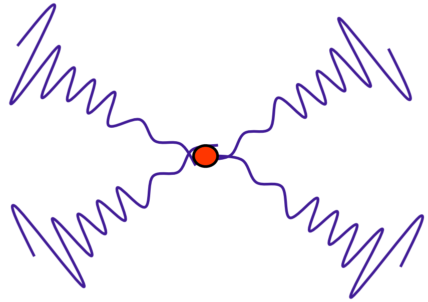

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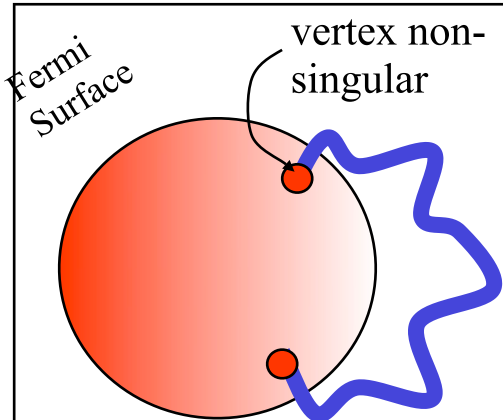
$$d_{eff} = d + z$$

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



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Rutgers Center for Materials Theory

$$V_{eff}(\vec{q},\omega) = g^2 \frac{\chi_o}{(\vec{q}-\vec{Q})^2 - i\omega/\Gamma_Q}$$

$$V_{eff}(\vec{r},\omega=0) \propto \frac{1}{r} e^{i\vec{Q}.\vec{r}}$$

Singular potential is rapidly modulated:
only affects electrons along hot-lines.

$$\varepsilon_{k_F} = \varepsilon_{k_F+Q}$$

Predicts:

Landau's Fermi Liquid Should
Survive at a Quantum Critical Point.

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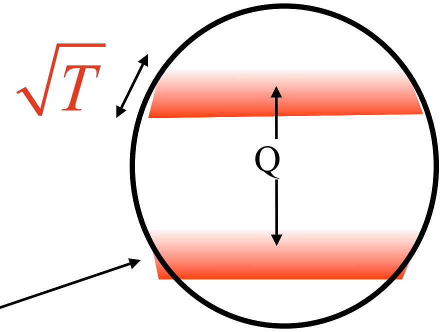

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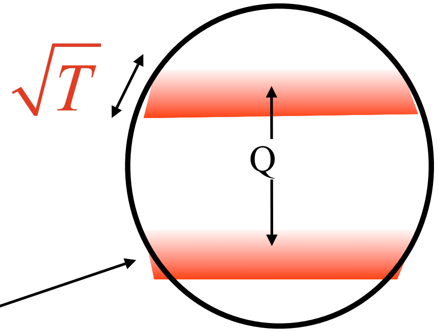
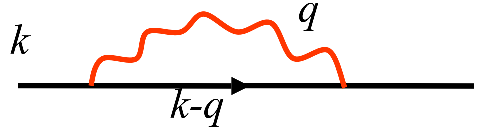


$$\Sigma(k,\omega) = -T\sum_{q,\nu} g^2 \chi_o(q,\nu) G(k-q,\omega-\nu)$$



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Landau's Fermi Liquid Should Survive at a Quantum Critical Point.

Rutgers Center for Materials Theory

$$\frac{m^*}{m} \sim 1 - \frac{\partial \Sigma}{\partial \omega} \sim \ln(\Gamma / T)$$

divergent

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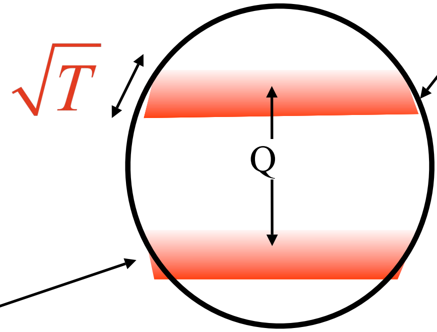

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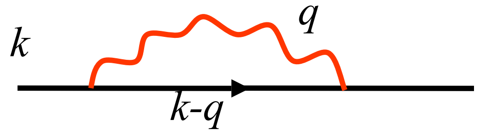

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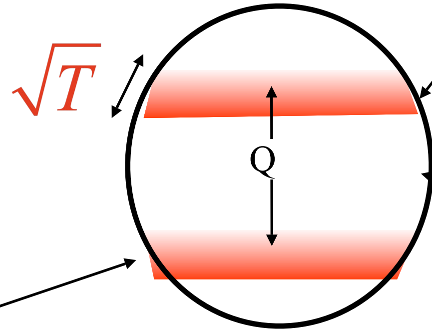

$$\frac{m^*}{m}$$ finite

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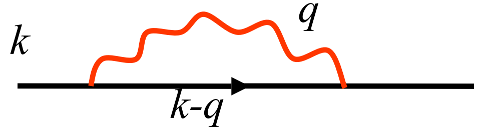

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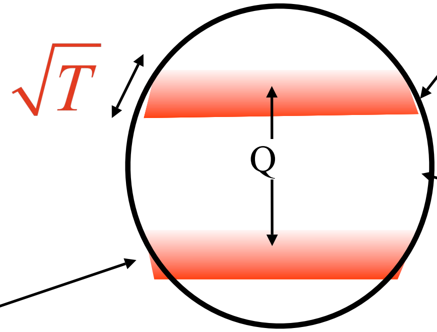

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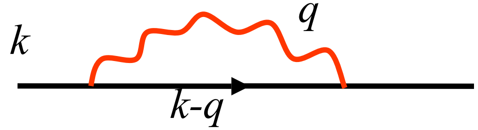

$$F_{Singular} \sim T\sum\int d^3q \log[\chi^{-1}(q,\omega)]$$
$$\sim T(T^{3/z}) \sim T^{5/2}$$

$$\frac{C_V}{T} \sim \gamma_o - A\sqrt{T}$$

Predicts:

Landau's Fermi Liquid Should
Survive at a Quantum Critical Point.

Rutgers
Center for Materials Theory

New Ideas:

Break up of the electron.

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

"THE BATTLEGROUND"

Kondo Lattice Model

(Kasuya, 1951)

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"THE BATTLEGROUND"

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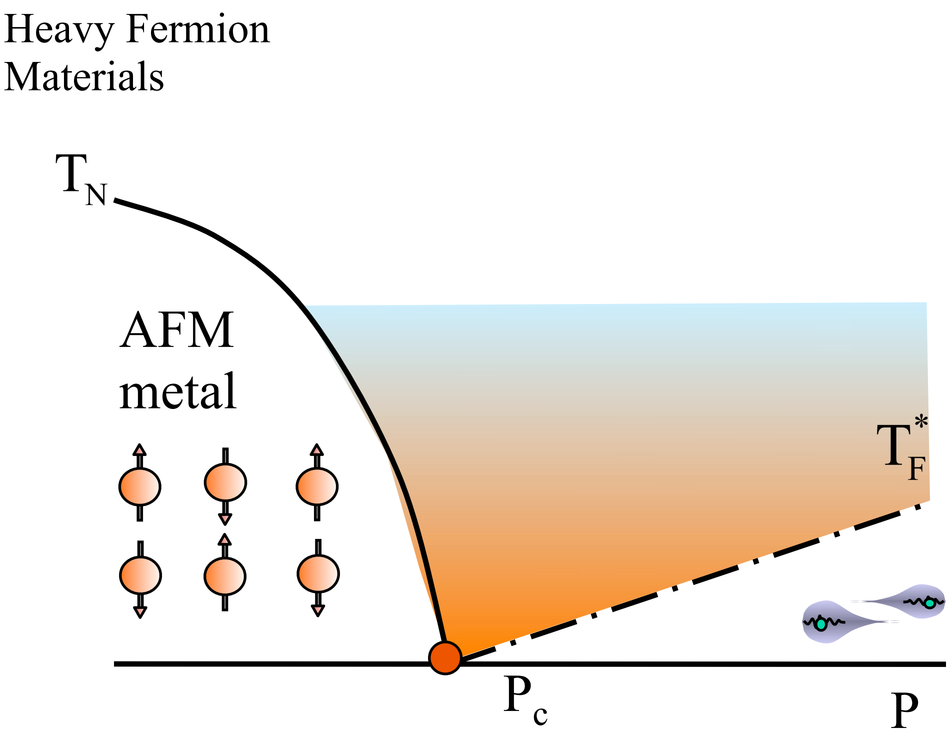

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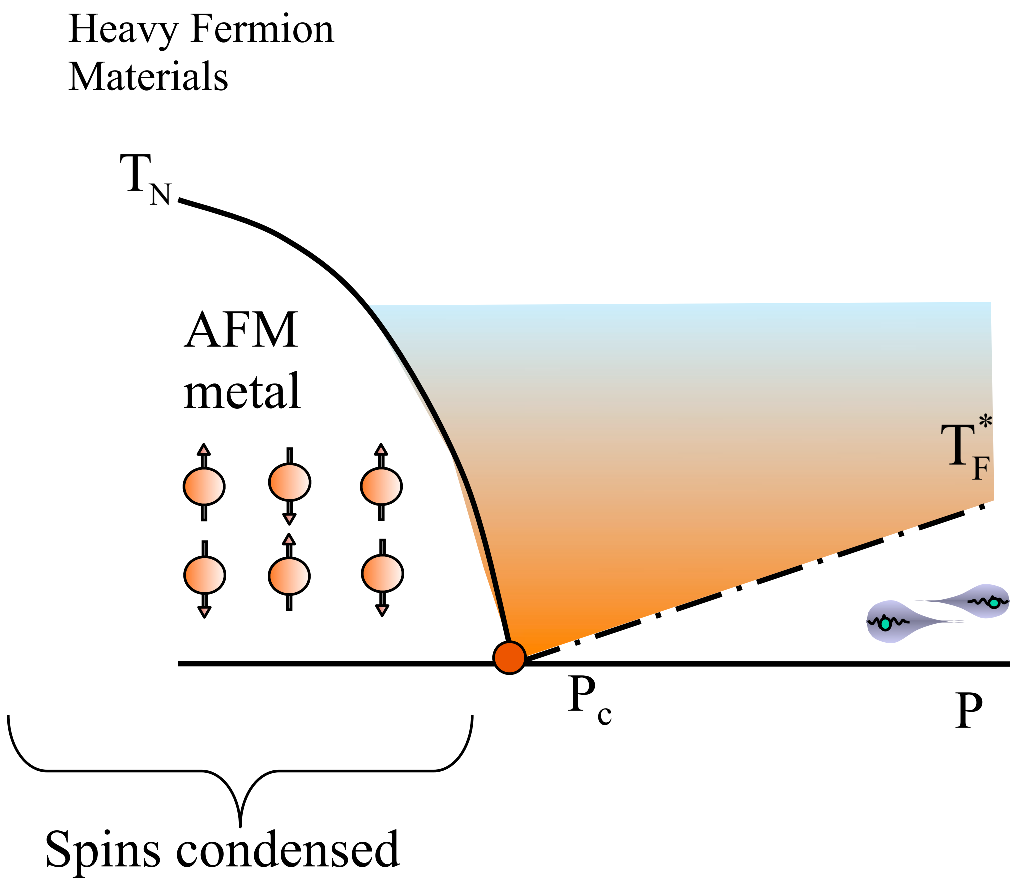

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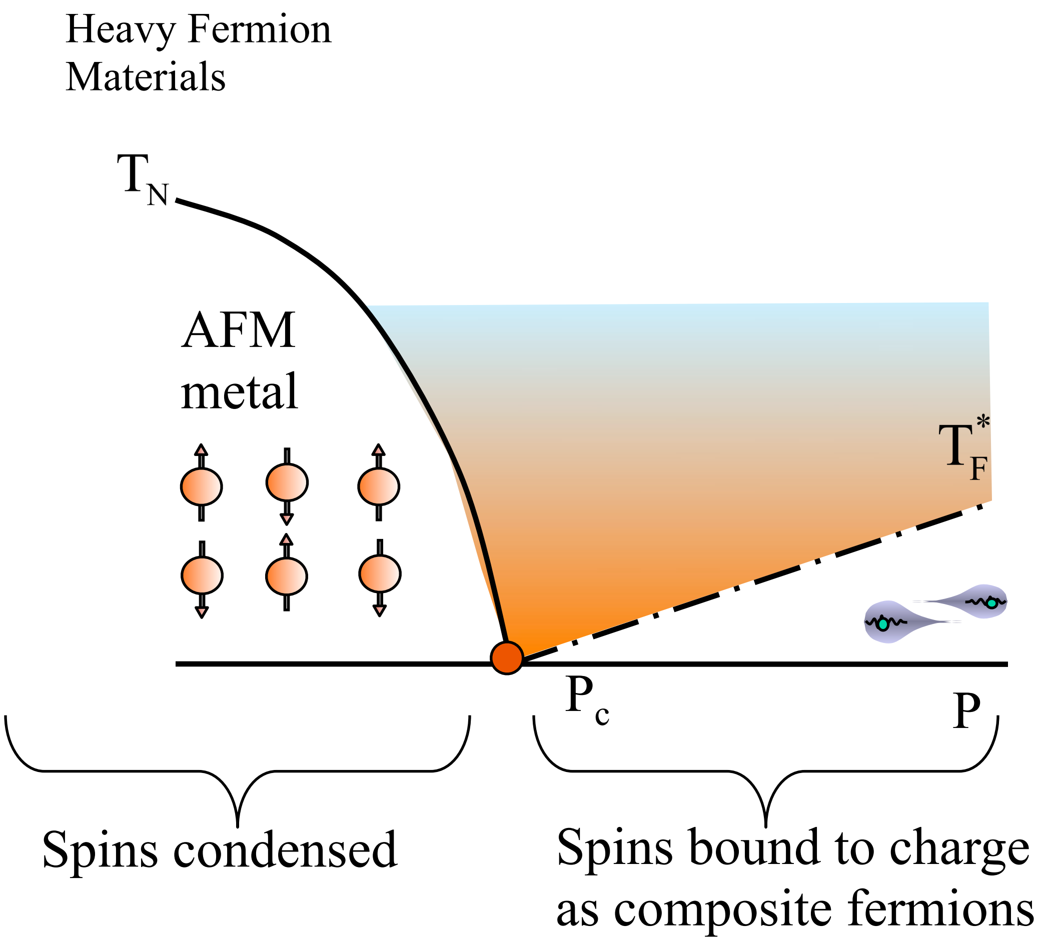

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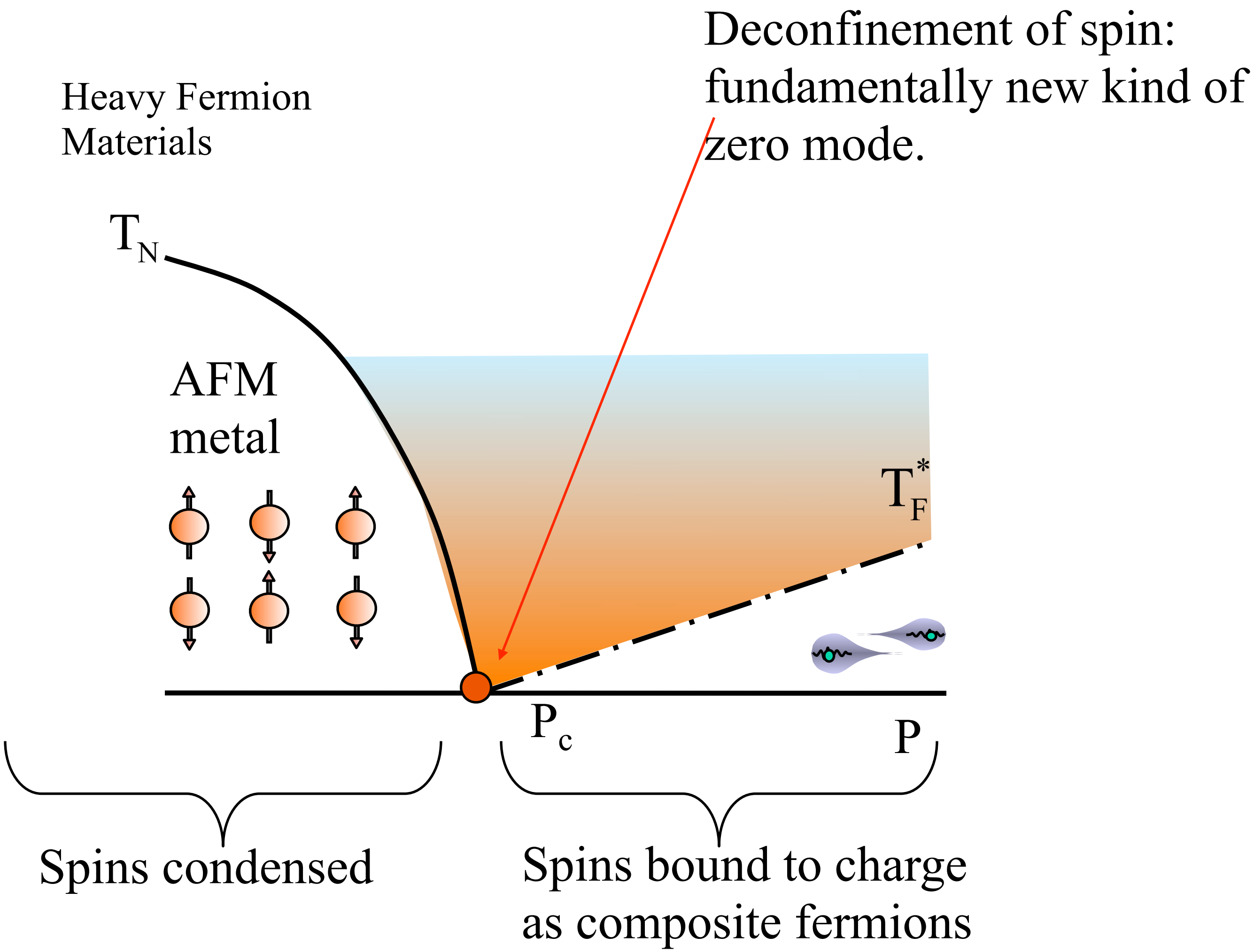


New Ideas

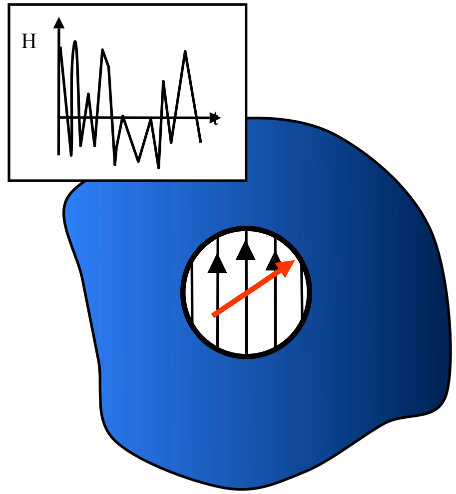
New Ideas

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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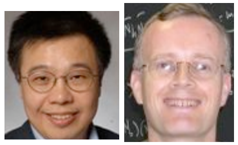

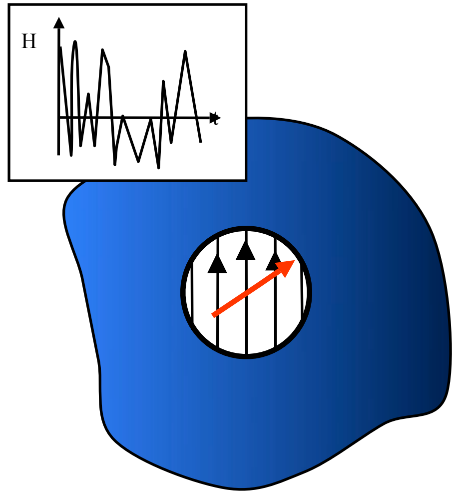

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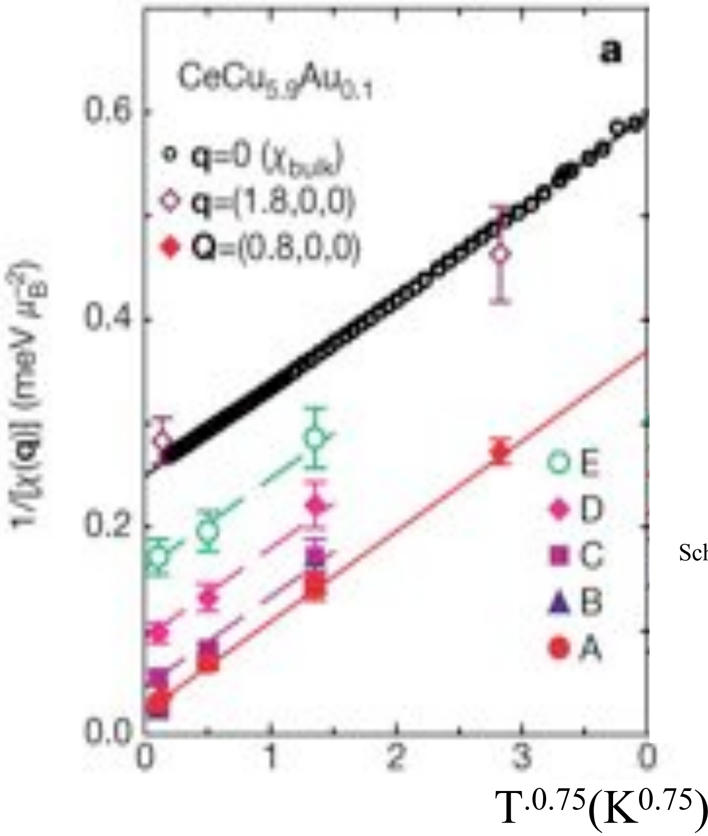
Locality of critical fluctuations

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



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

New Ideas

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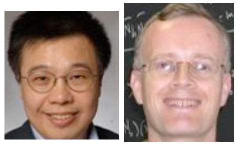

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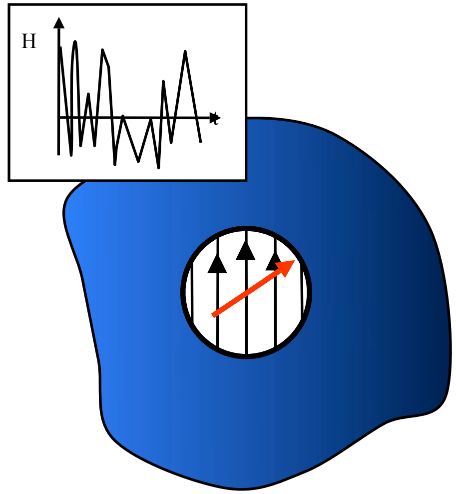

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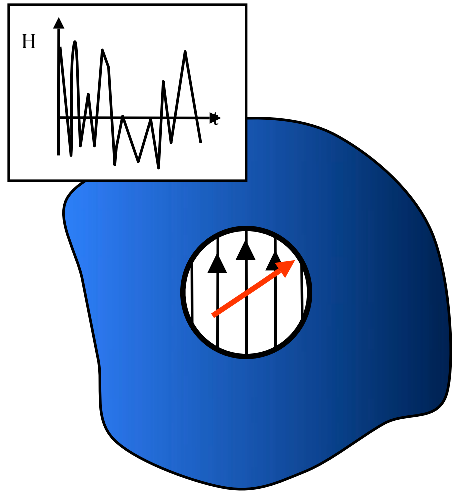

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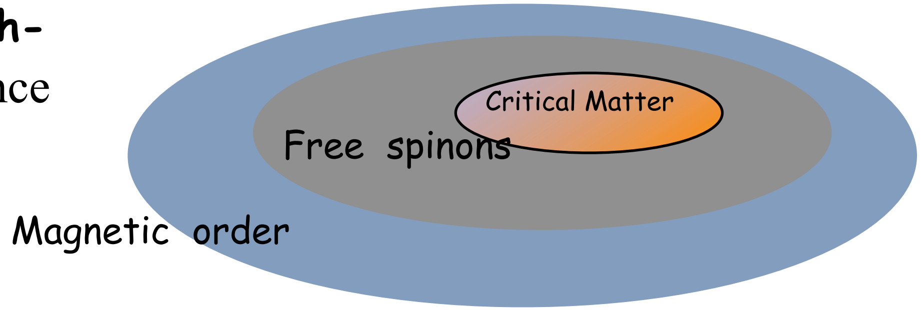
- **Deconfined Criticality: Two diverging length-scales.** (Hermele et al 2004; Senthil et al, Science 2004).



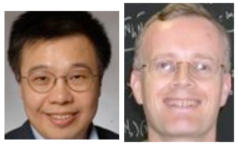
Senthil

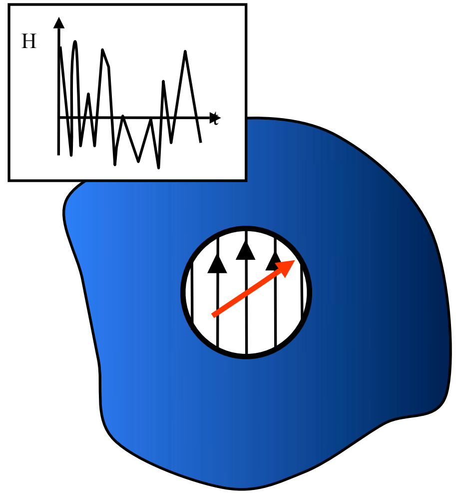
Sachdev

Vishwanath

New Ideas

Si, Ingersent





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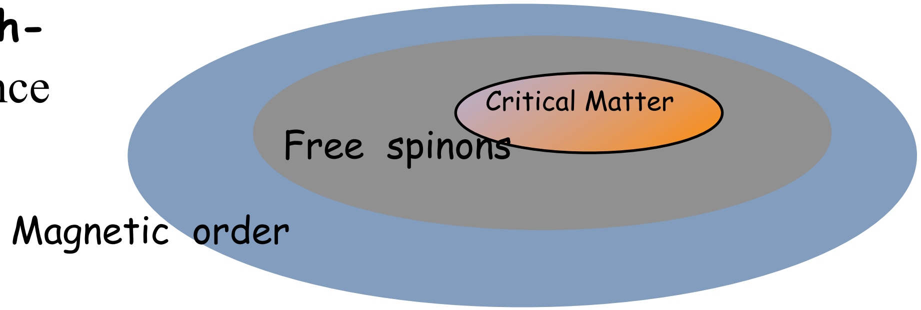
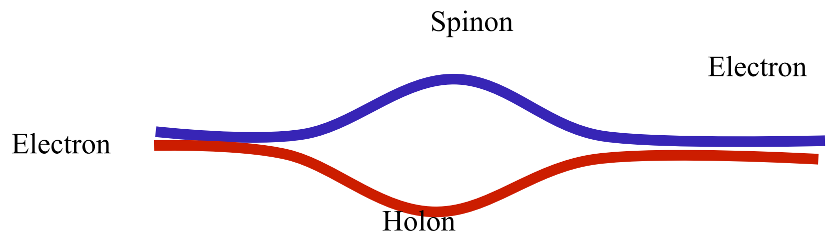


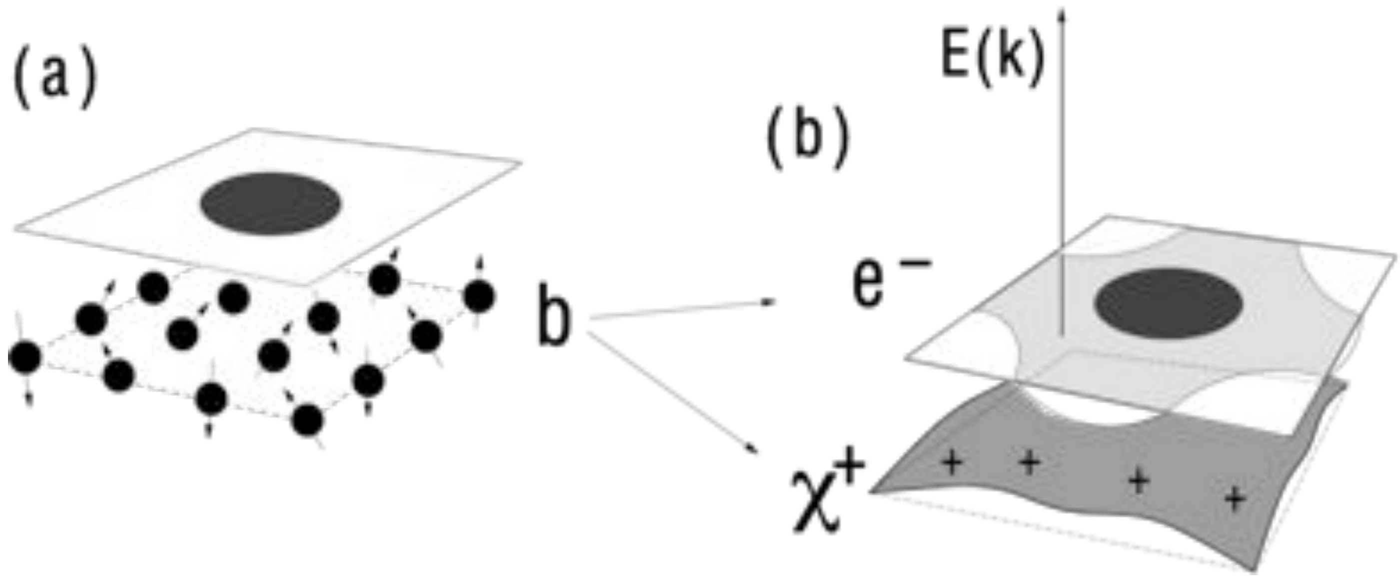
Senthil Sachdev Vishwanath

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



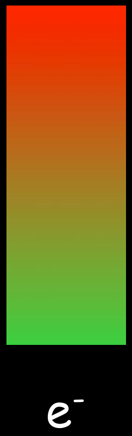
Pepin

“Spins dissolved in a polar fluid”

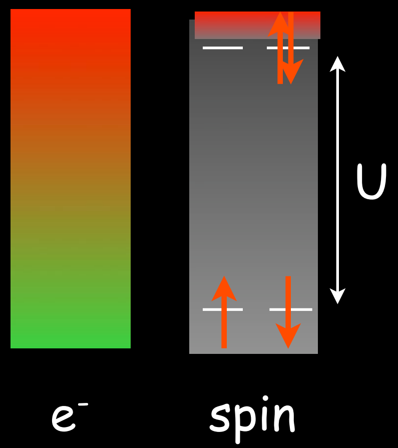


QCP: liberation of spinless charged fermions.

New Methods



New Methods



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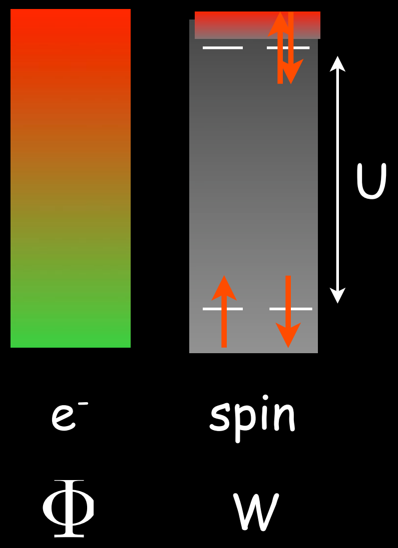
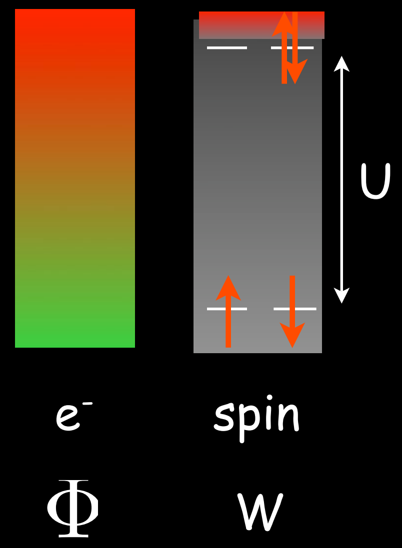


Elimination of States implies Gauge Fields.

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

New Methods



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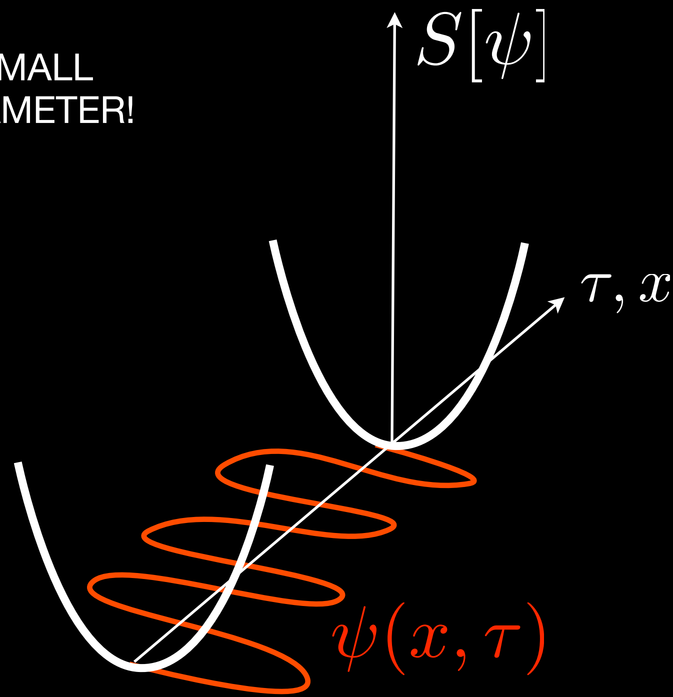
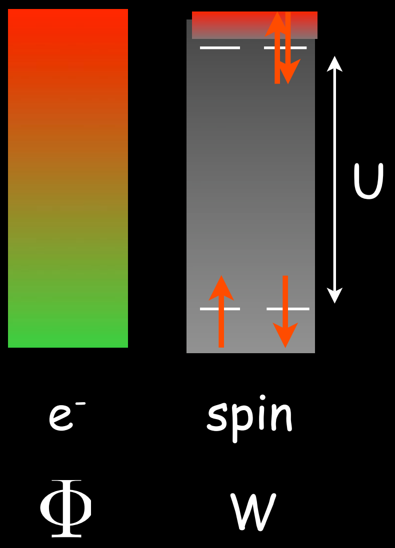
NO SMALL PARAMETER!



New Methods



Elimination of States implies Gauge Fields.

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

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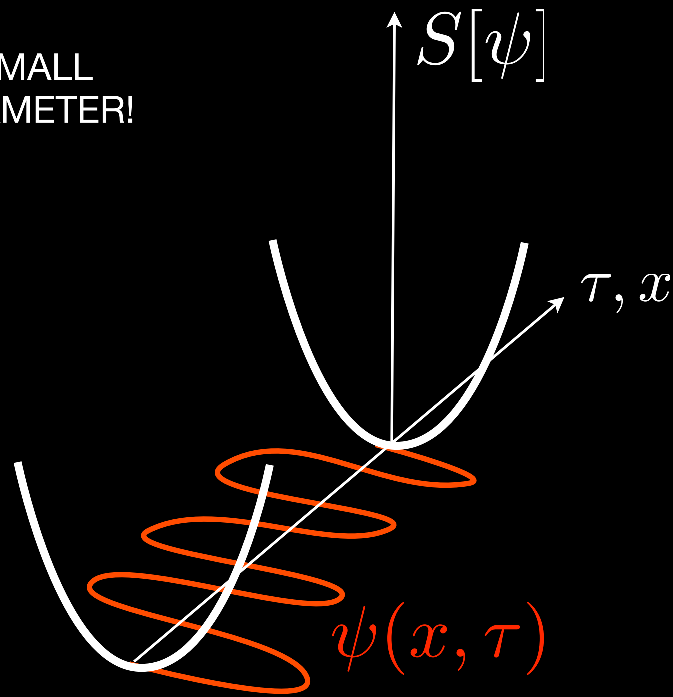
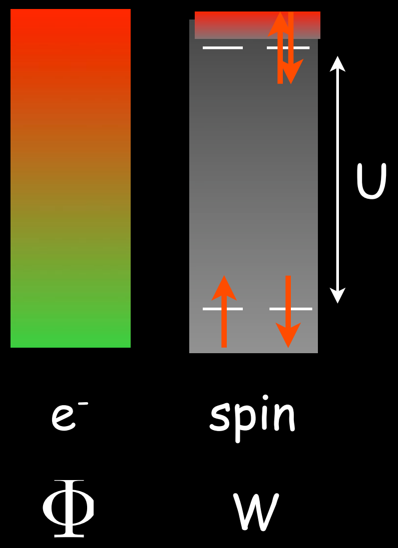


Large N : family of models with "N" spin components, which retain the key physics and can be solved in the large N limit.

New Methods



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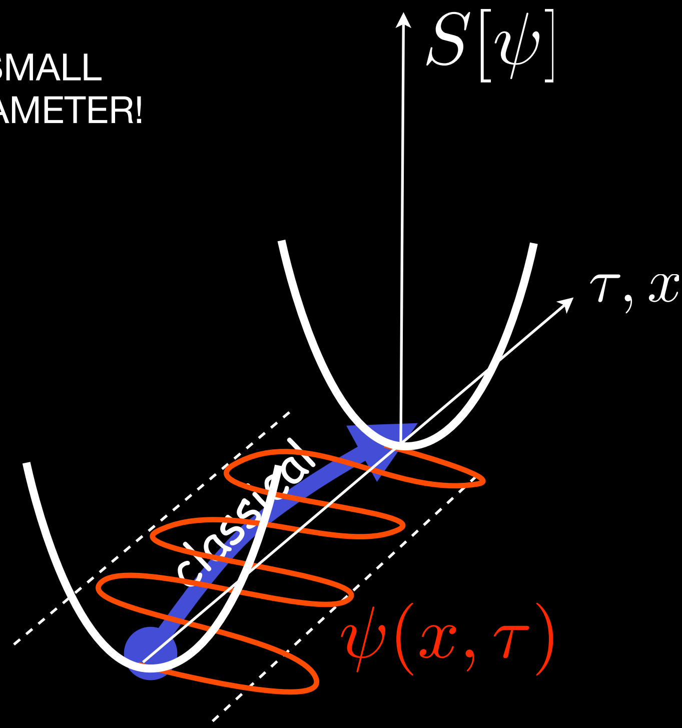
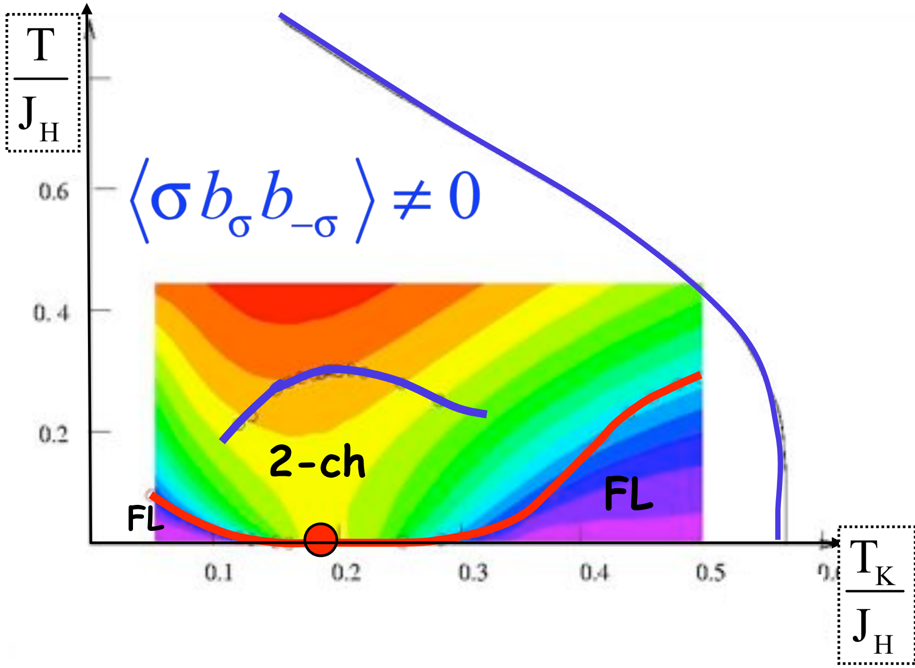
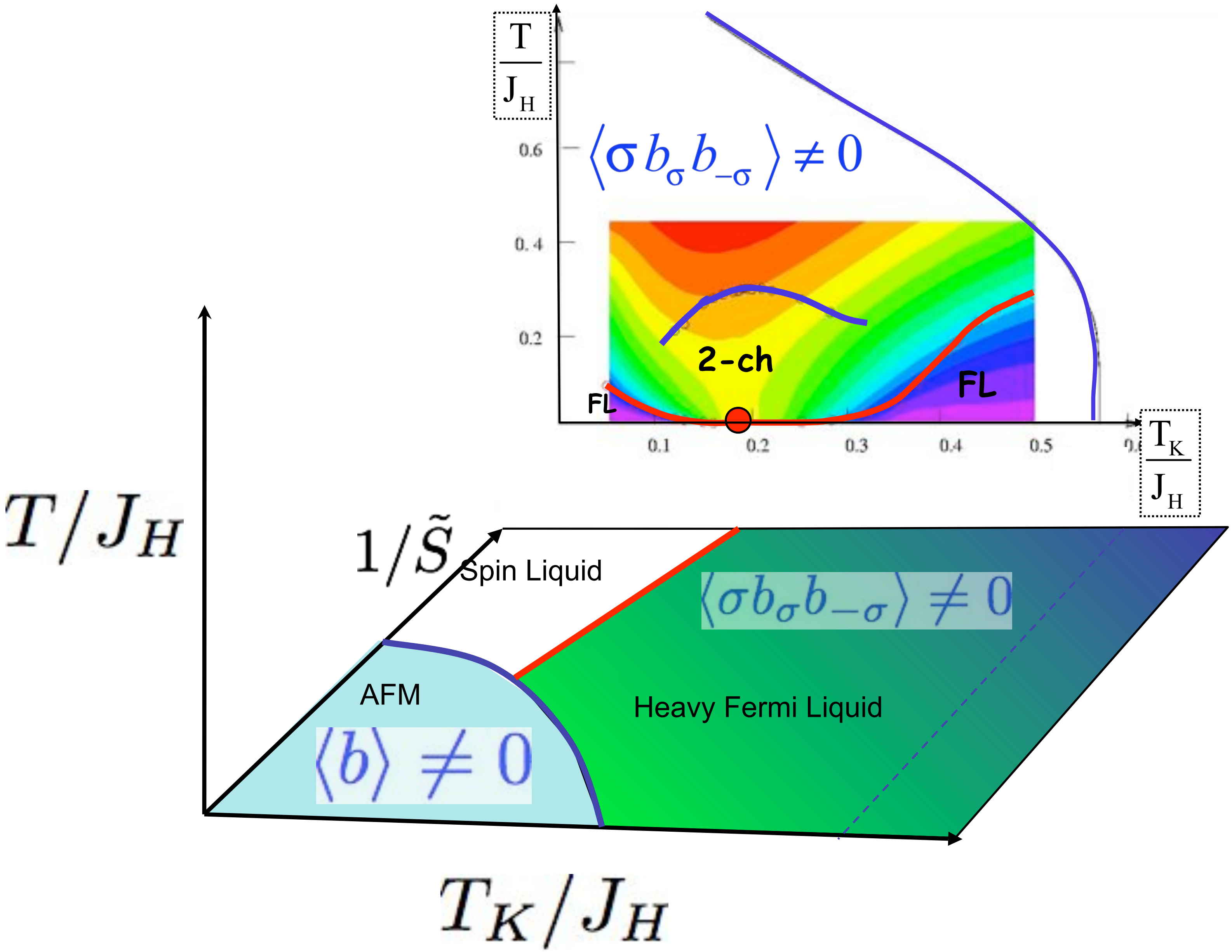


$$\frac{1}{N} \sim \hbar_{eff}$$

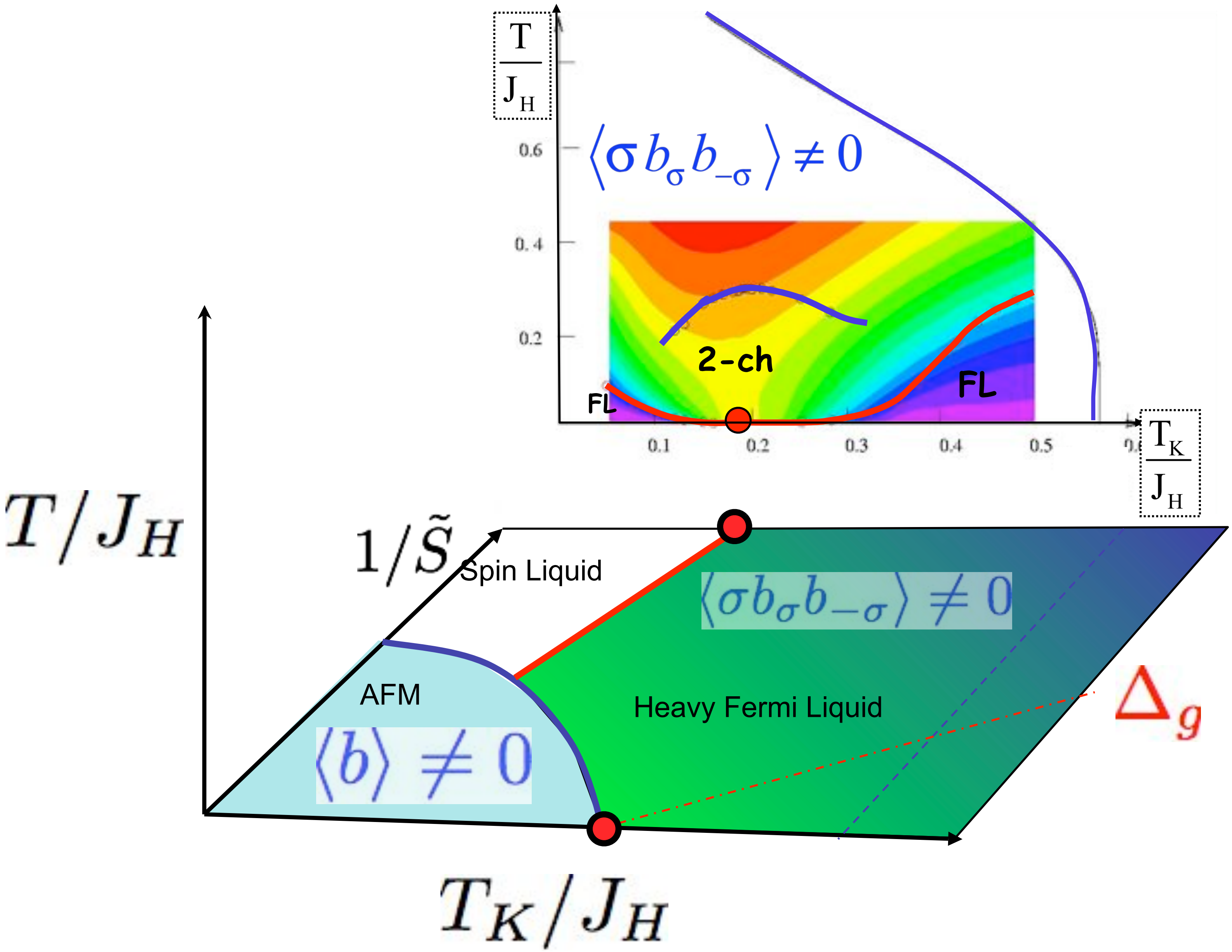
Large N : family of models with "N" spin components, which retain the key physics and can be solved in the large N limit.



$\frac{T}{J_H}$
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
$\frac{T_K}{J_H}$



T / J_H
0.6
0.4
0.2
⟨σ b_σ b_−σ ⟩ ≠ 0
2-ch
FL
FL
0.1
0.2
0.3
0.4
0.5
T_K / J_H
T/J_H
1/S̃
Spin Liquid
⟨σb_σb_−σ⟩ ≠ 0
AFM
⟨b⟩ ≠ 0
Heavy Fermi Liquid
T_K/J_H


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
T_K / J_H
T/J_H
$1/\tilde{S}$
Spin Liquid
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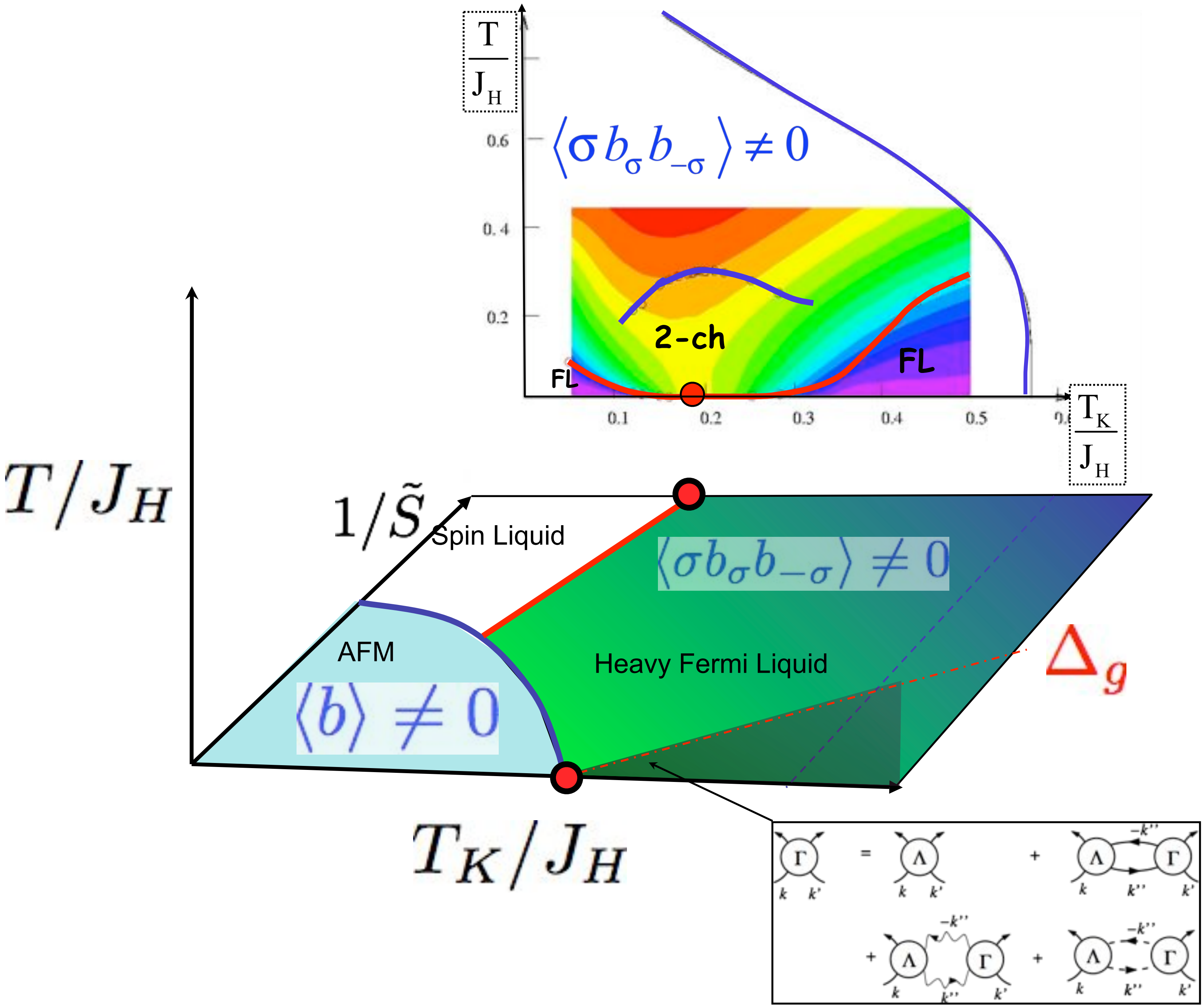
$\langle b \rangle \neq 0$
Heavy Fermi Liquid
Δ_g
T_K/J_H



T / J_H
0.6
0.4
0.2
⟨σ b_σ b_−σ⟩ ≠ 0
2-ch
FL
FL
0.1
0.2
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T_K / J_H
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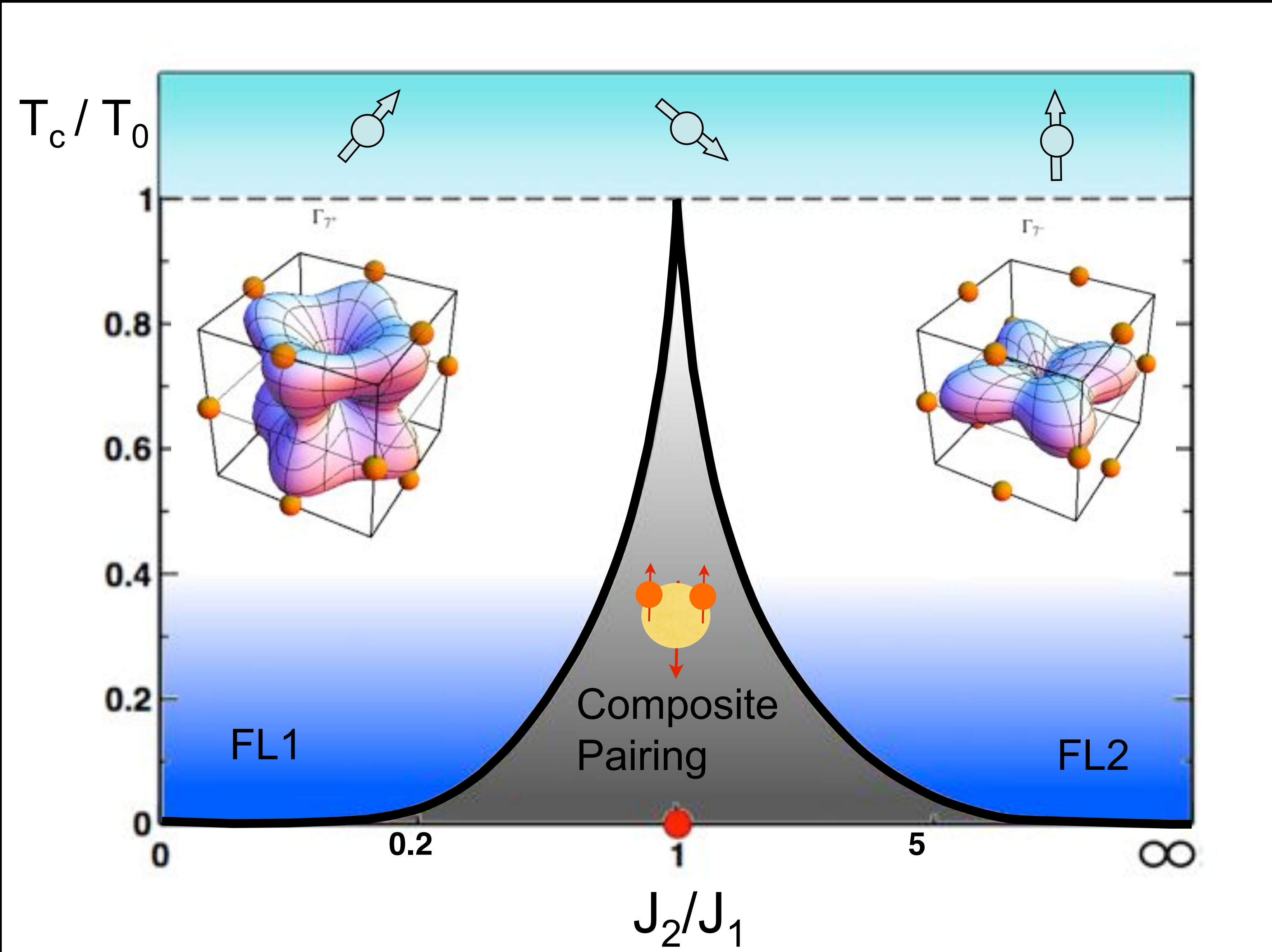
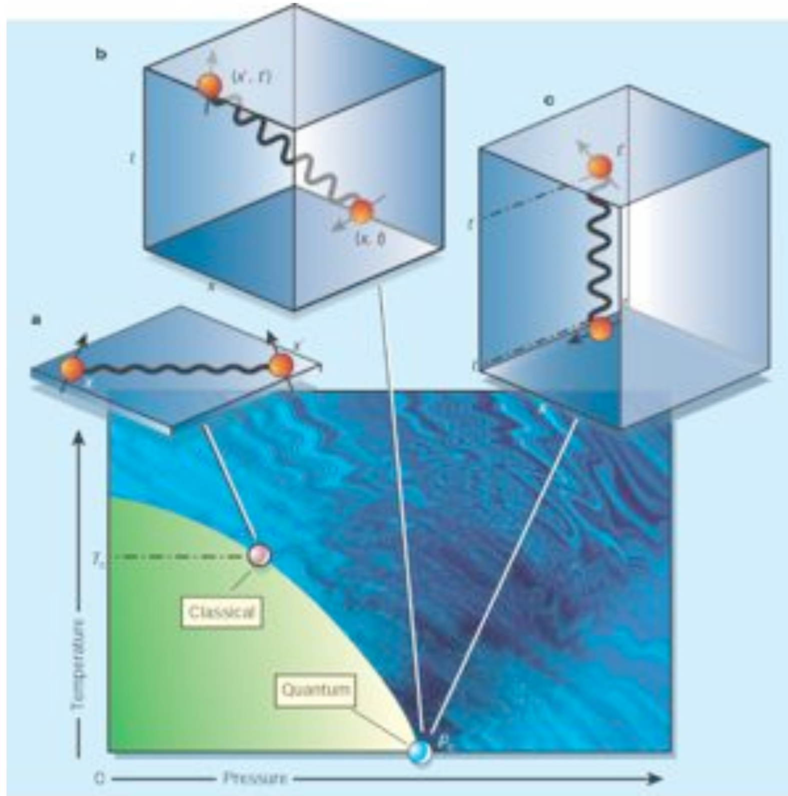
Δ_g
T_K/J_H
Γ
=
Λ
+
Λ
Γ
+
Λ
Γ
+
Λ
Γ
k
k'
k''
−k''



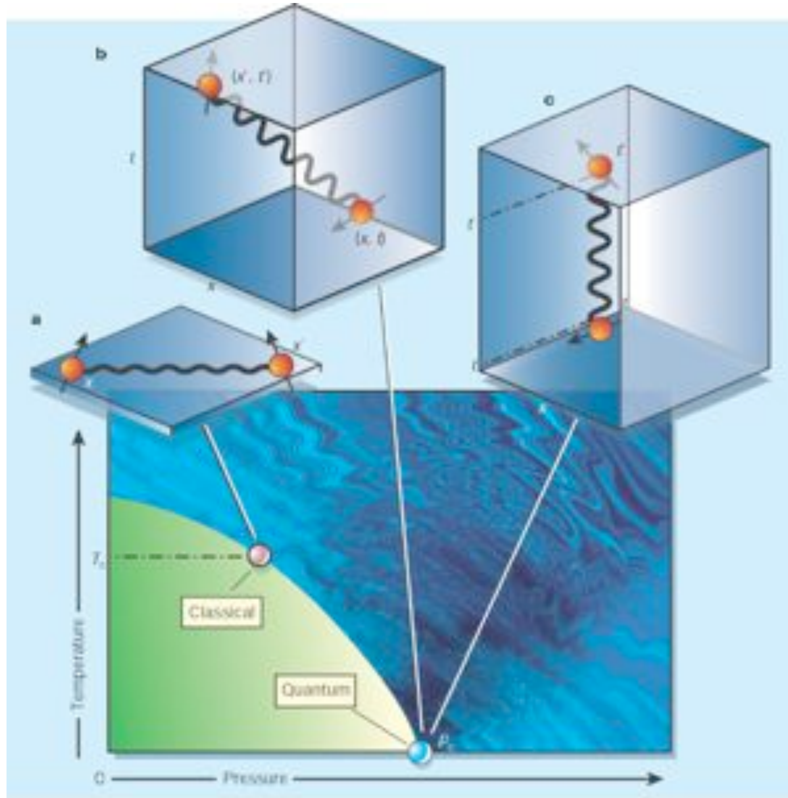
Tc / T0
1
0.8
0.6
0.4
0.2
0
Γ7-
Γ7-
FL1
Composite
Pairing
FL2
0
0.2
1
5
∞
J2/J1

Conclusions



Conclusions

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



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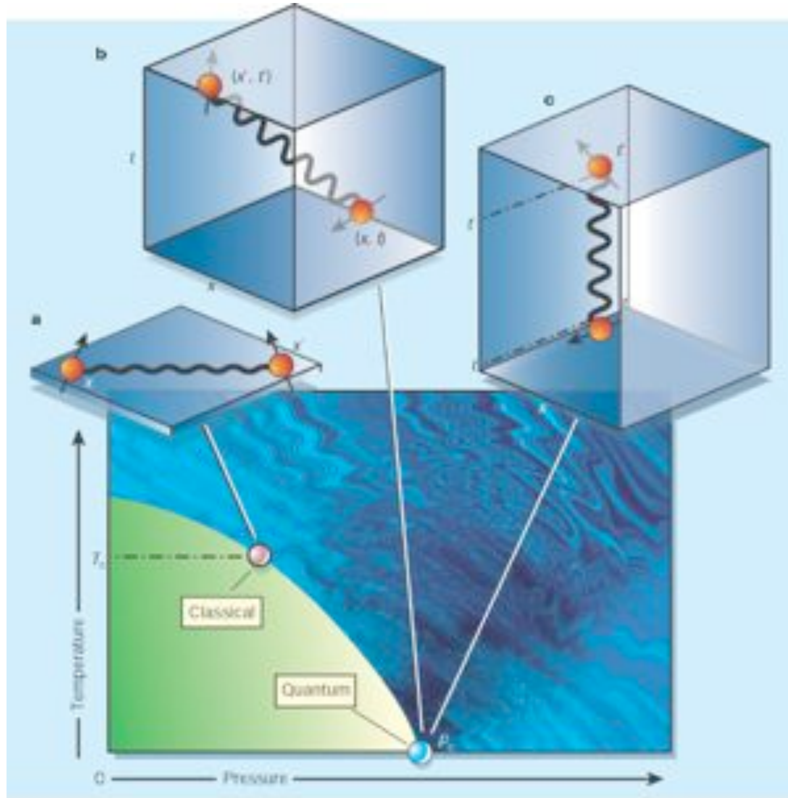
Qu-transitions: phase transition driven by zero point fluctuations.



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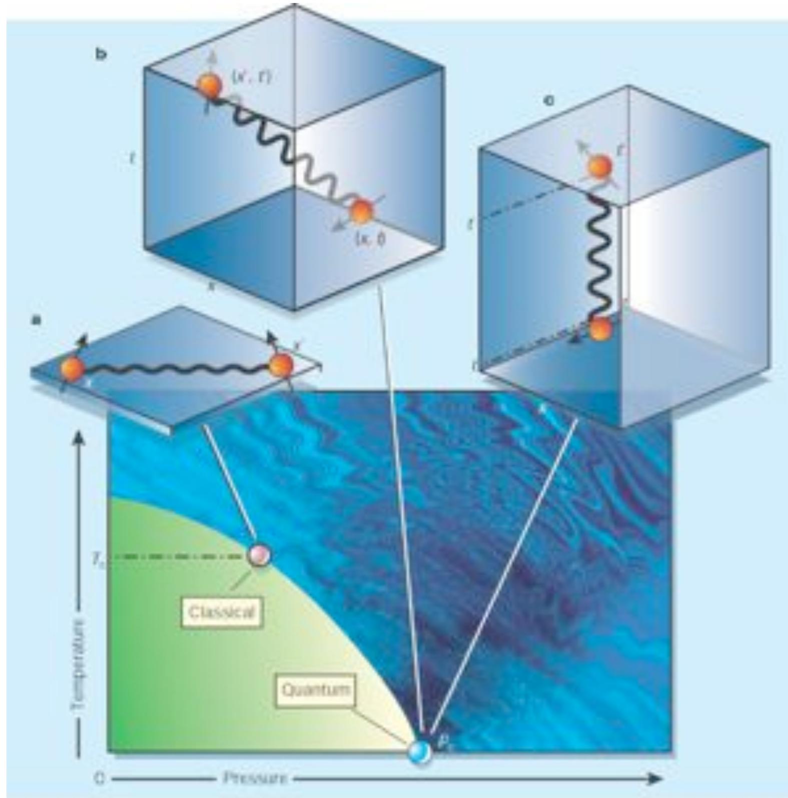

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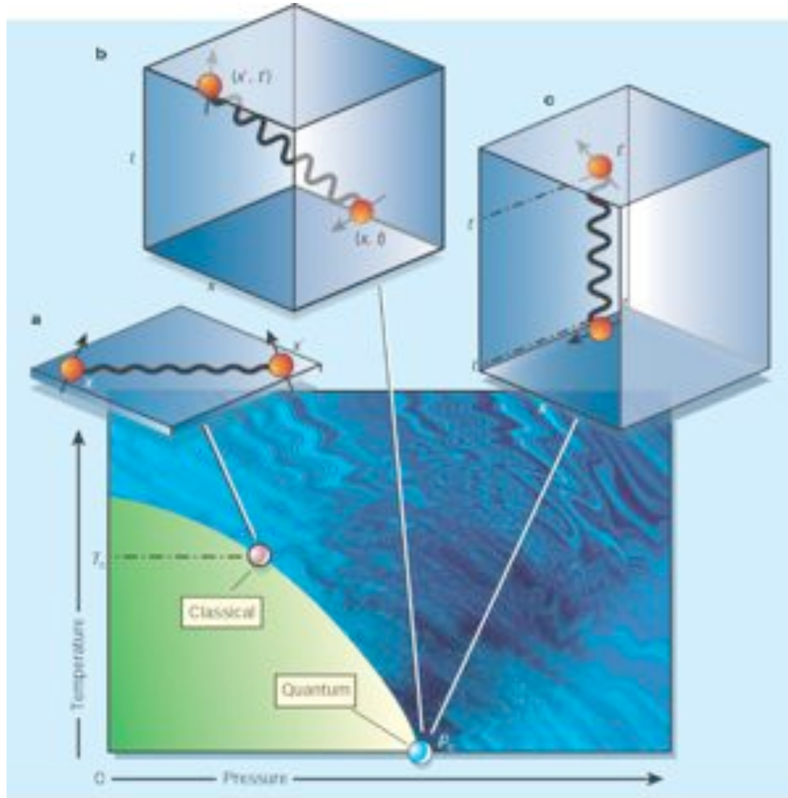

Landau Quasiparticle “breaks up” at certain QT.
Need for a radically new type of theory: ideas of confinement, gauge theories and large N.

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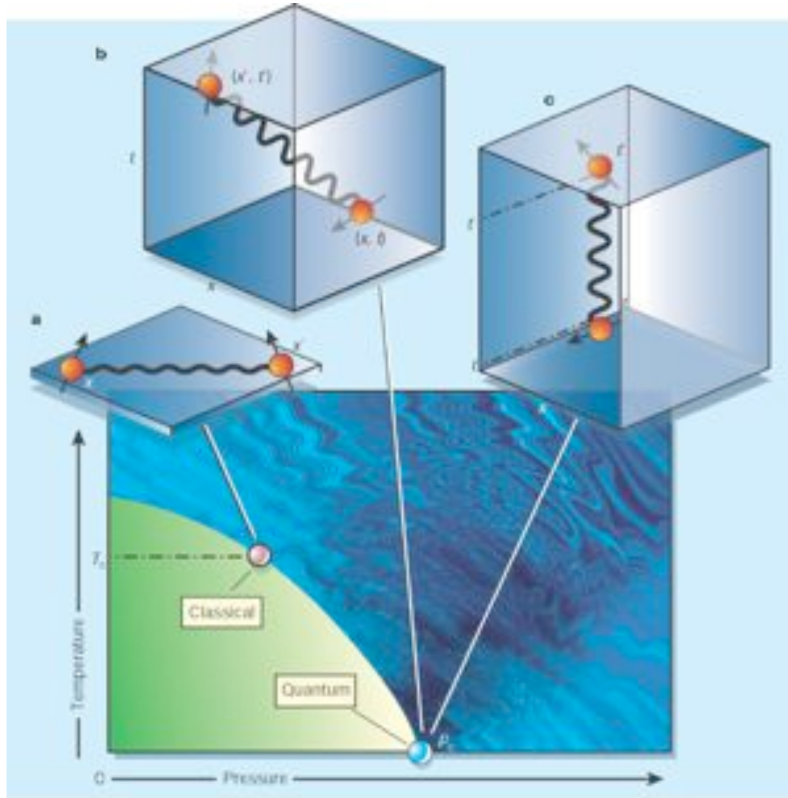


Landau Quasiparticle “breaks up” at certain QT. Need for a radically new type of theory: ideas of confinement, gauge theories and large N.

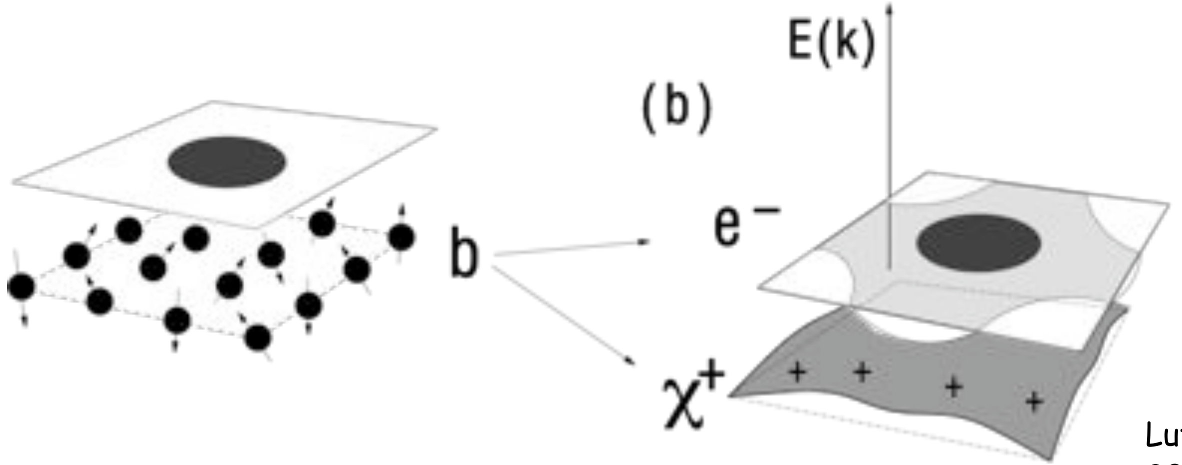
New rule in material physics: avoided criticality. New phases develop in order to avoid the singular quantum critical point.

Avoided Criticality.

Many open quantum problems of a general nature

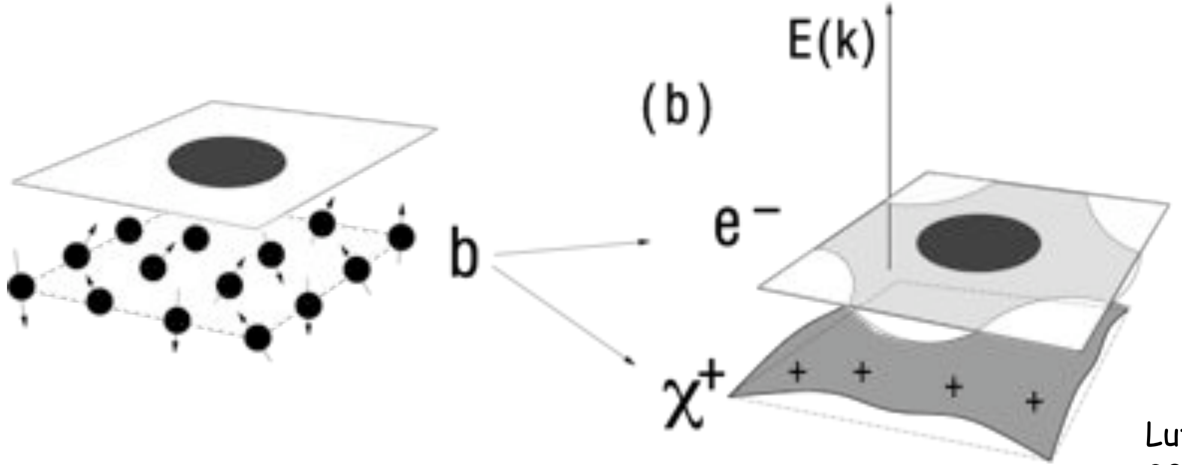
Quantum:

- zero point, criticality, “dark energy”
- emergence: principles/mechanisms
- protection: room temperature SC/qubits
- non equilibrium
- gravity/unsolved problem of torqued tops.



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

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



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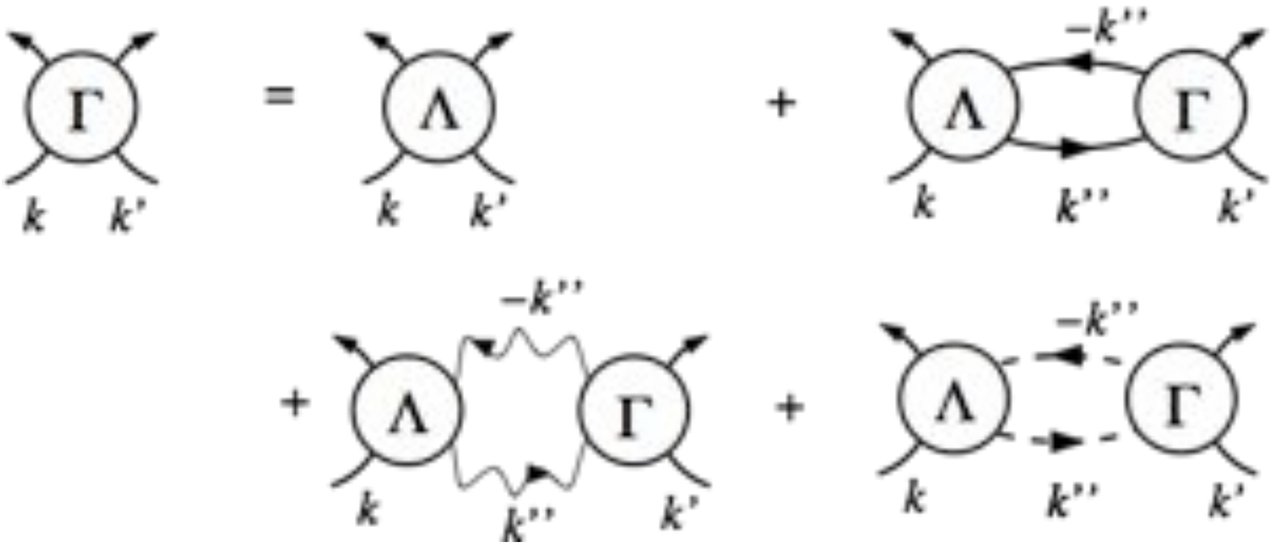

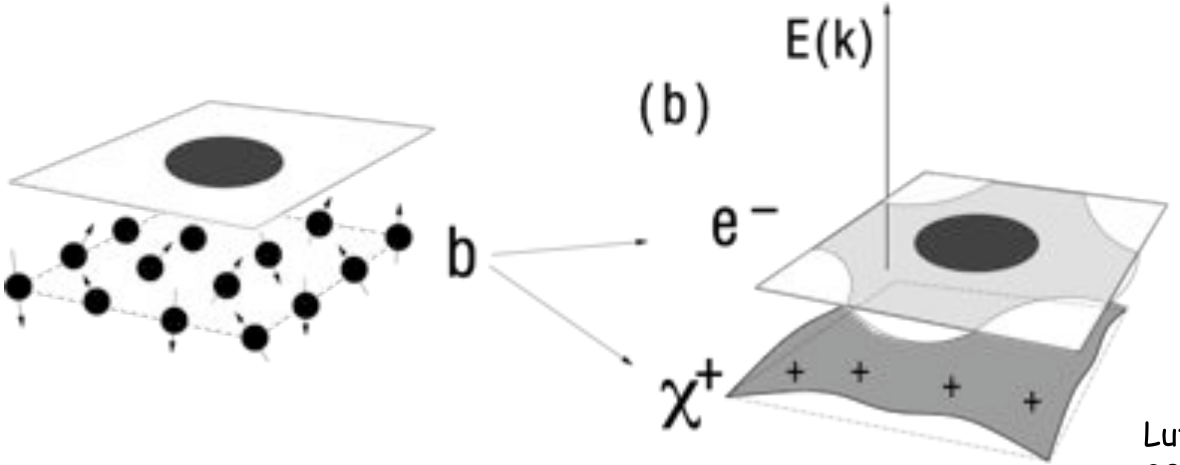

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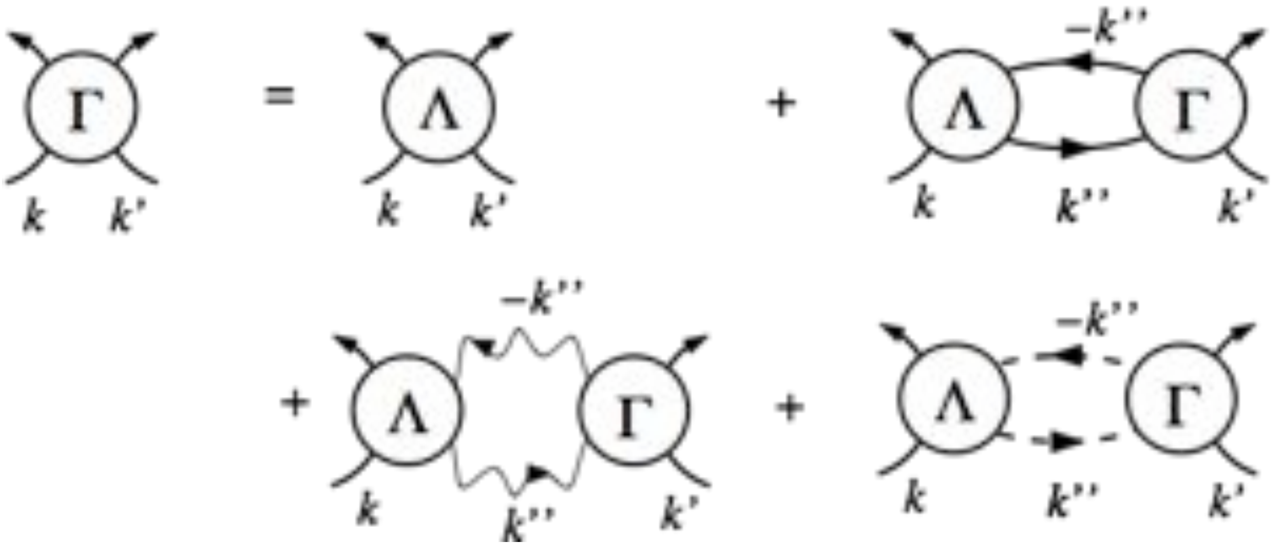
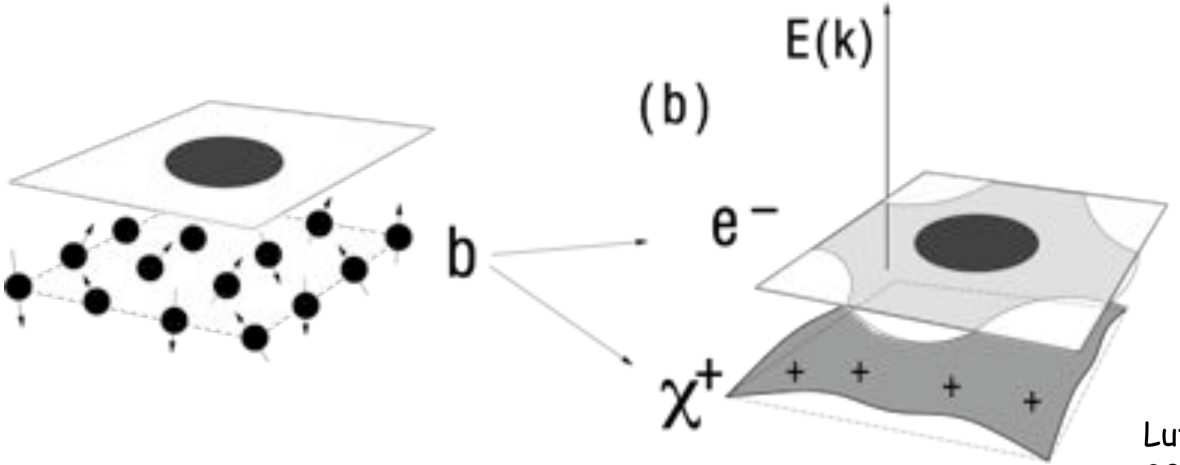


Virtual spinons.



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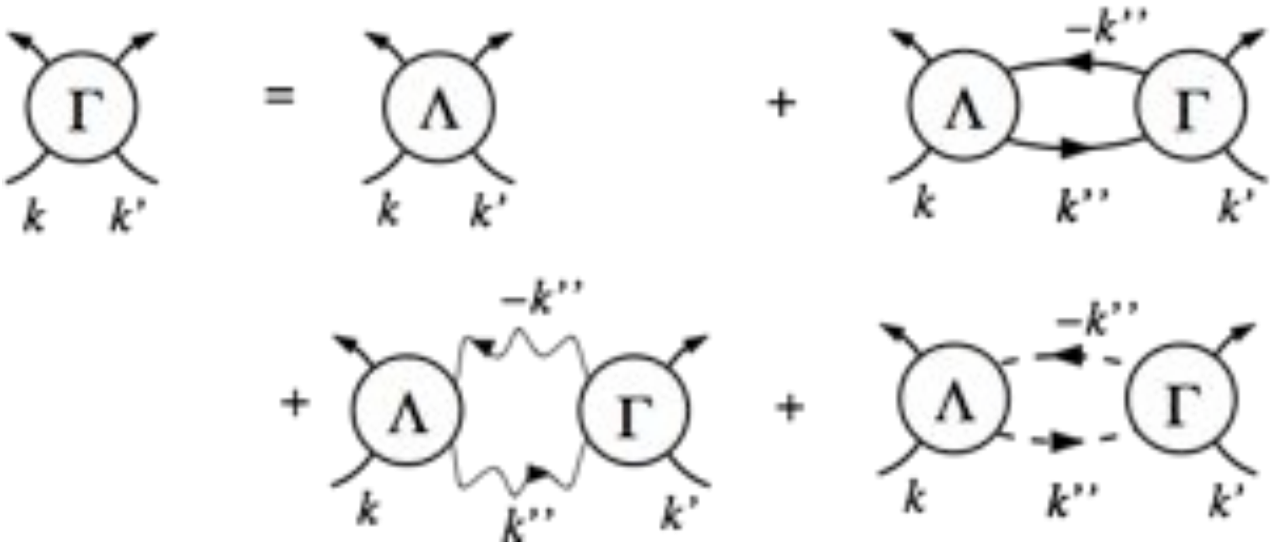

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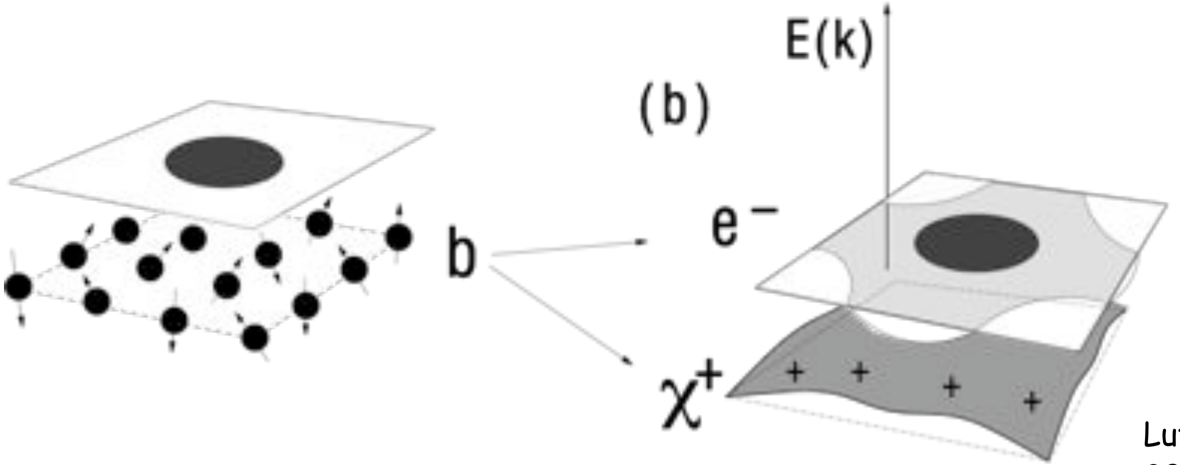
Virtual holons.



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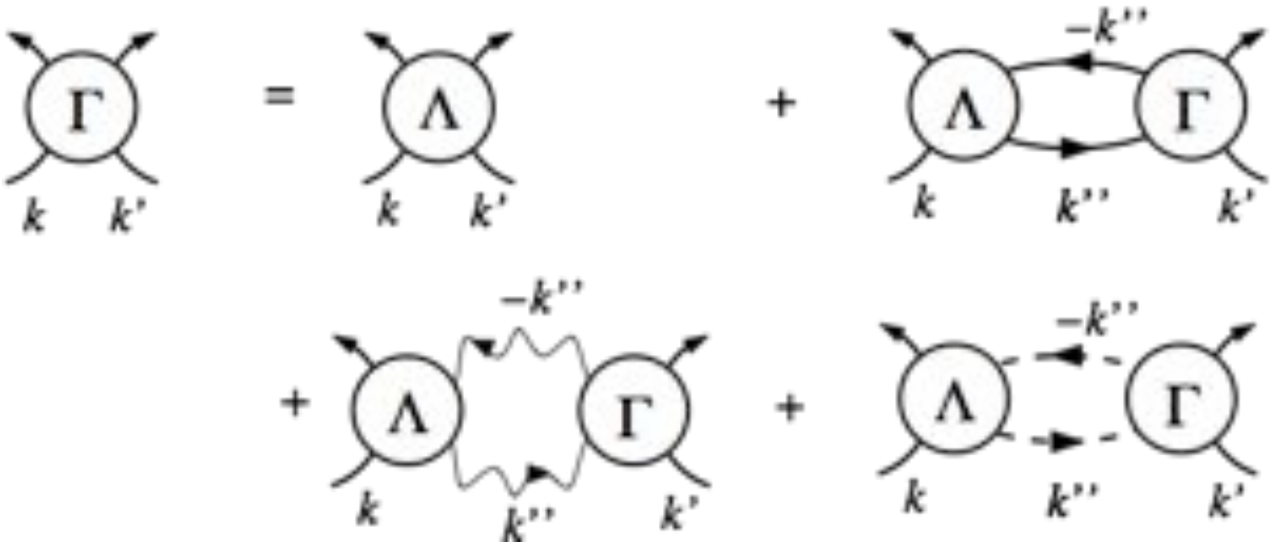


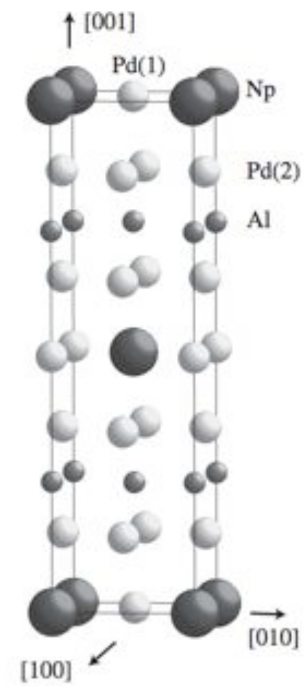
Fermi Liquid scattering parameters determined primarily by excitation of low-lying spinon and holon states..

Virtual spinons.

Virtual holons.

New HF Superconductors: $PuCoGa_5$ & $NpAl_2Pd_5$

D. Aoki et al., JPSJ 76 (2007)



4.5K Heavy Fermion S.C
$NpAl_2Pd_5$

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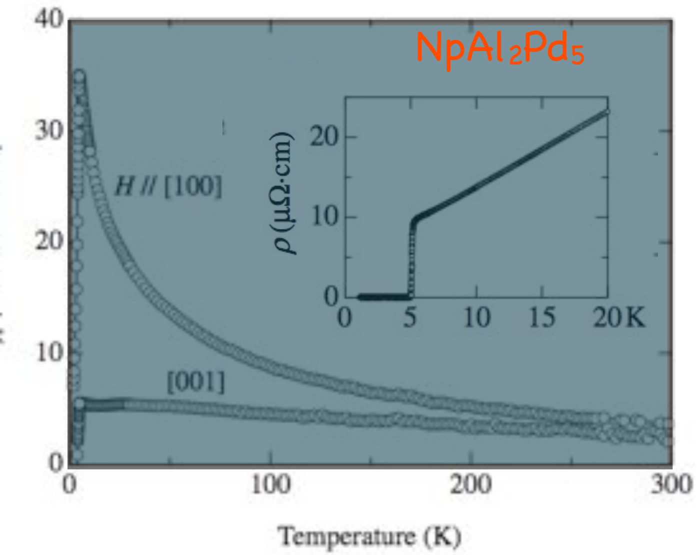
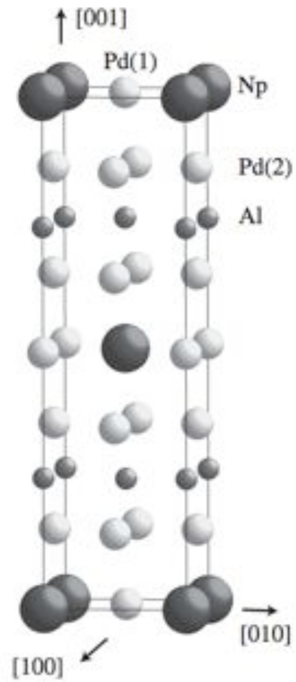


Directly Curie PM to SC

D. Aoki et al., JPSJ 76 (2007)



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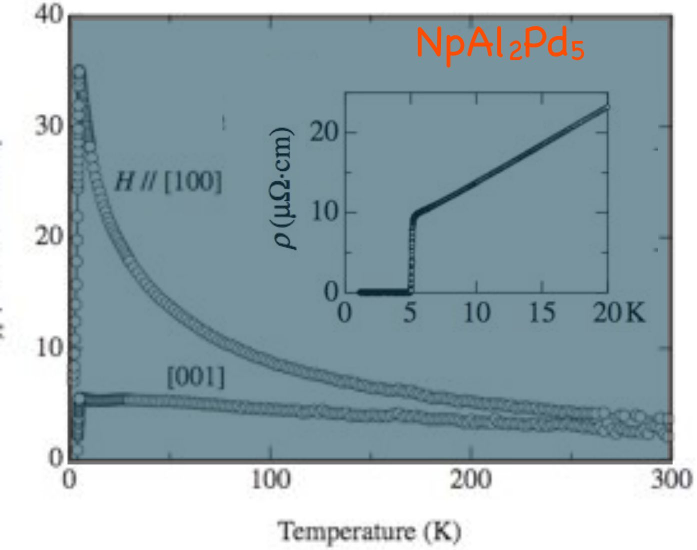

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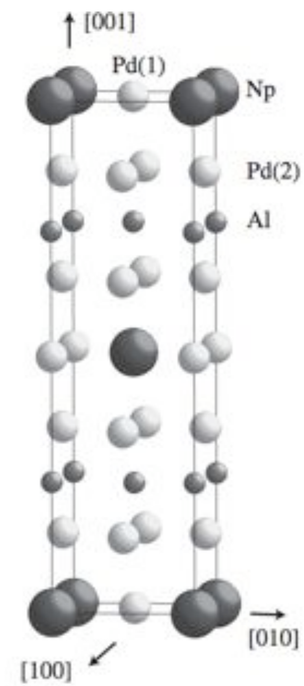

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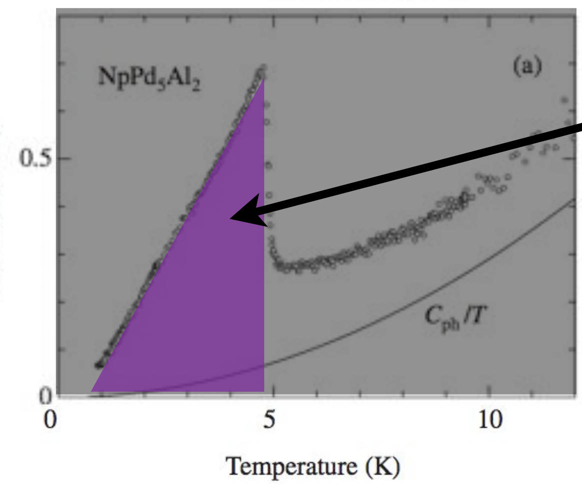

Substantial fraction of spin entropy.
1/3 R ln 2

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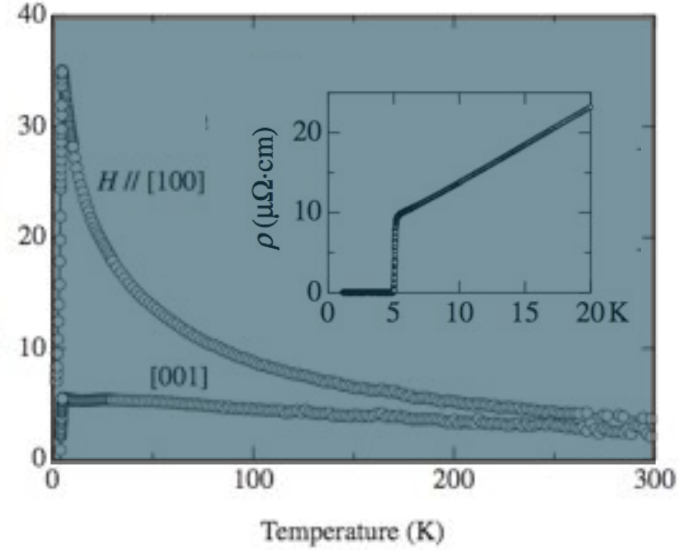

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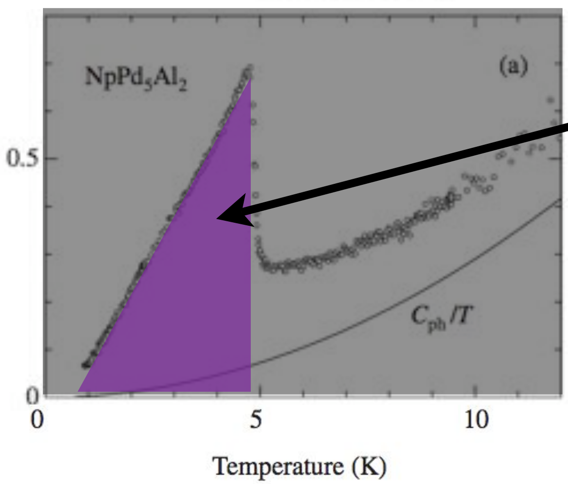

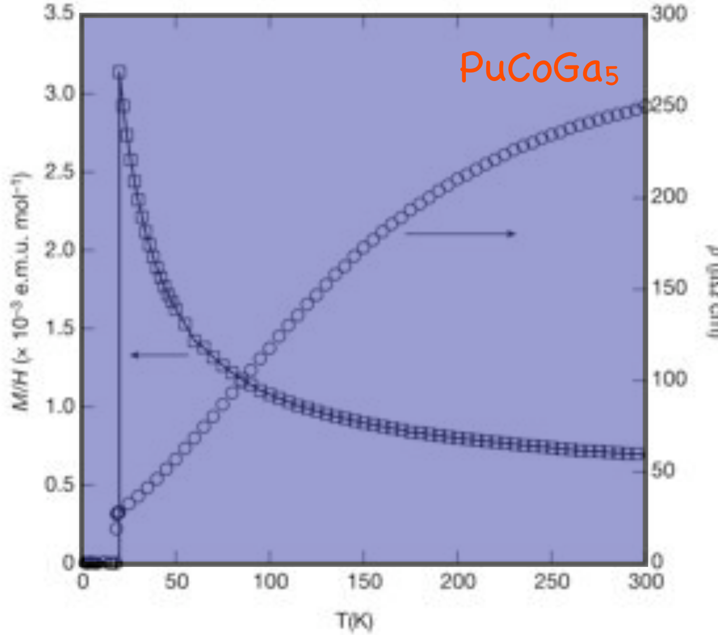

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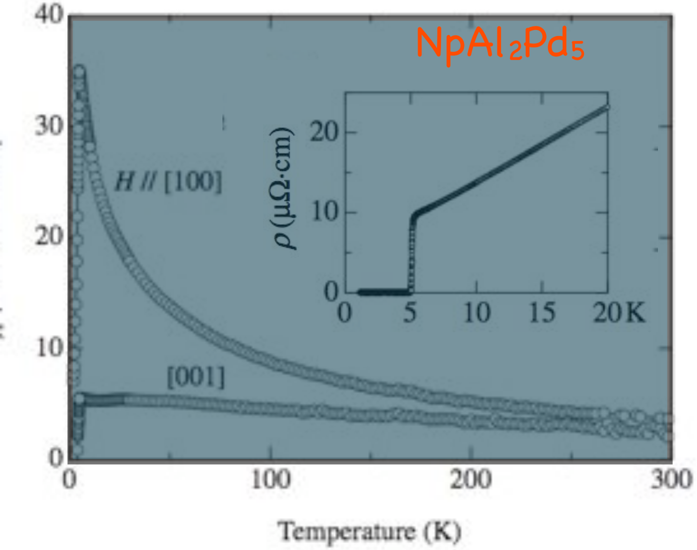

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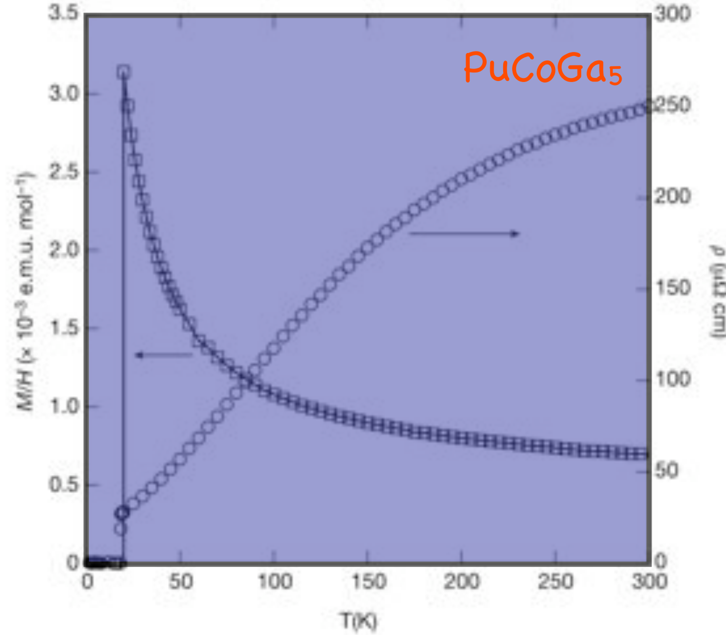
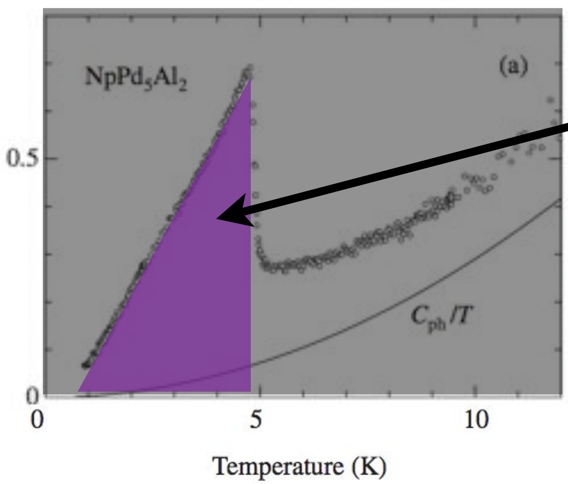


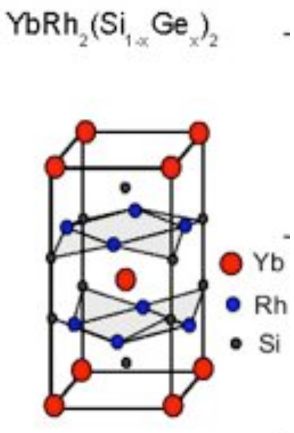


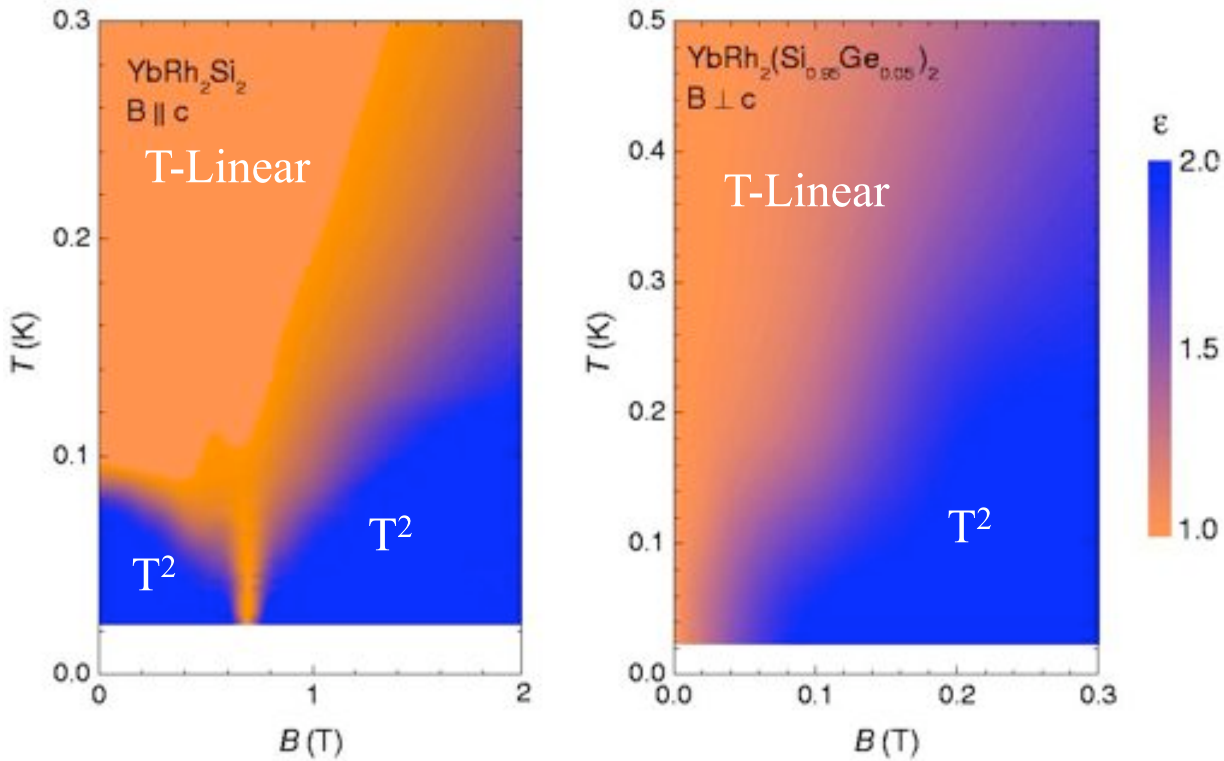
•Suggests Kondo spin quenching and superconductivity develop <u>simultaneously.</u>

•Spin is not the glue, but the *fabric*

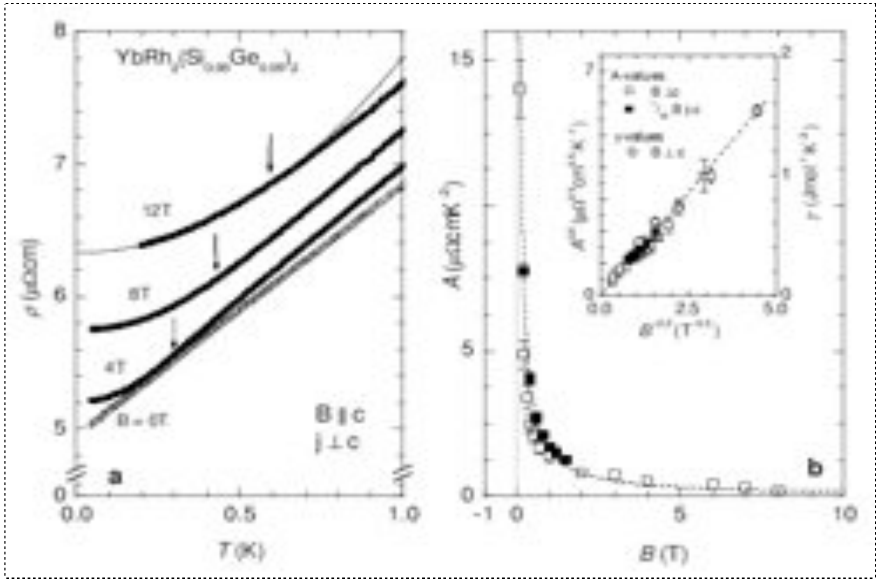
Divergence of Interaction and Effective Mass

Gegenwart et al (2002)





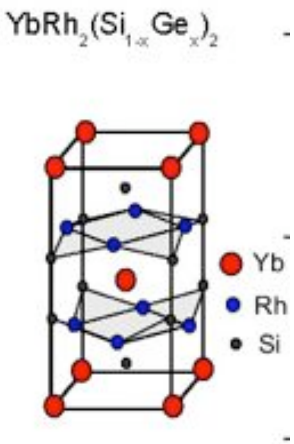
Divergence of Interaction and Effective Mass

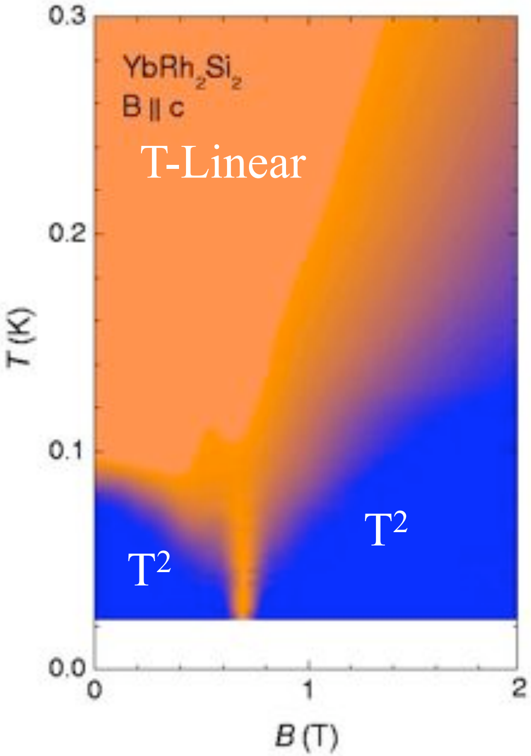


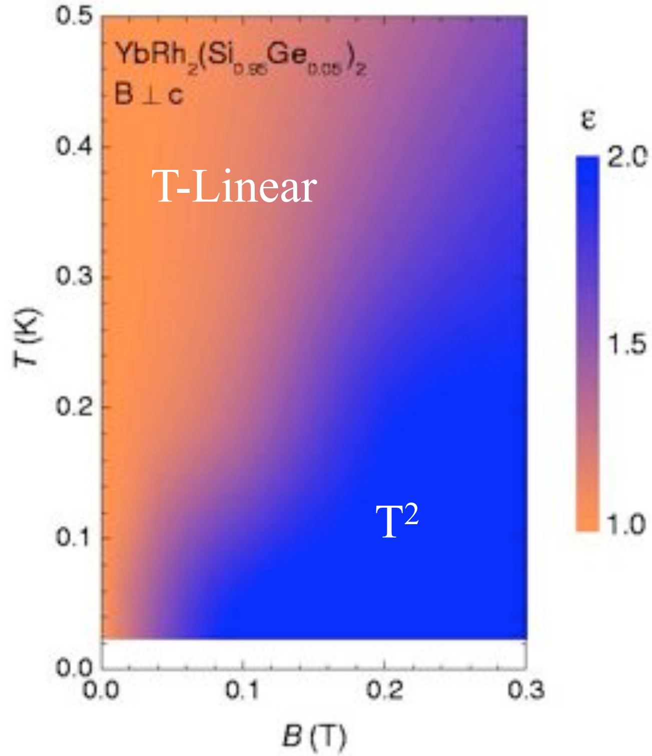
$$\rho = AT^2 + \rho_0$$

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

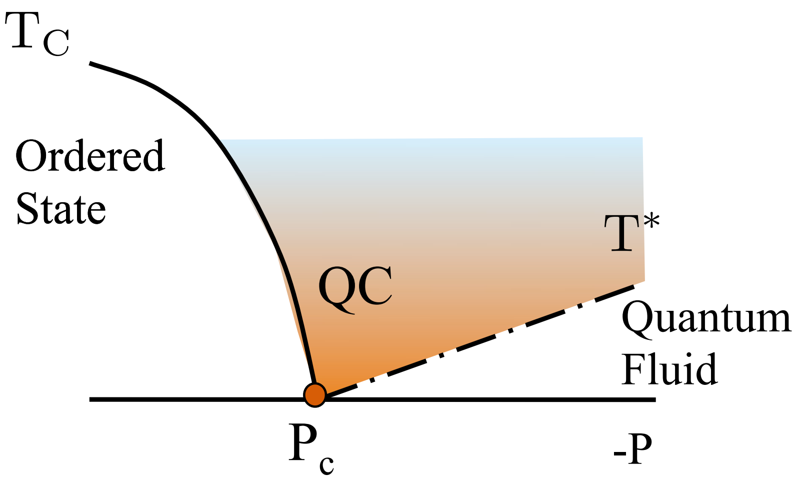
Gegenwart et al (2002)



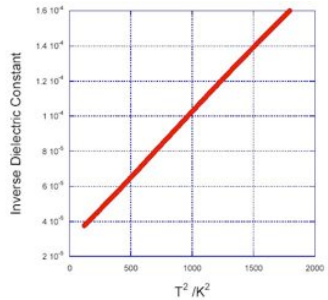




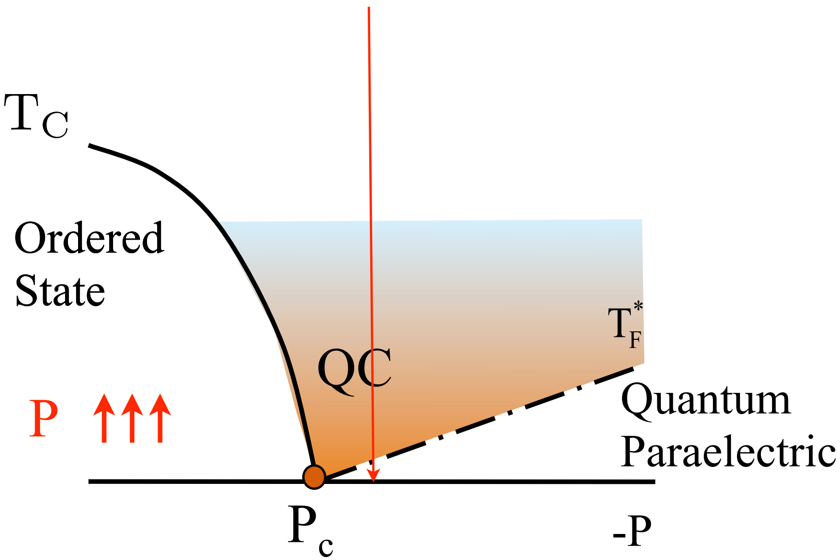
Quantum Criticality

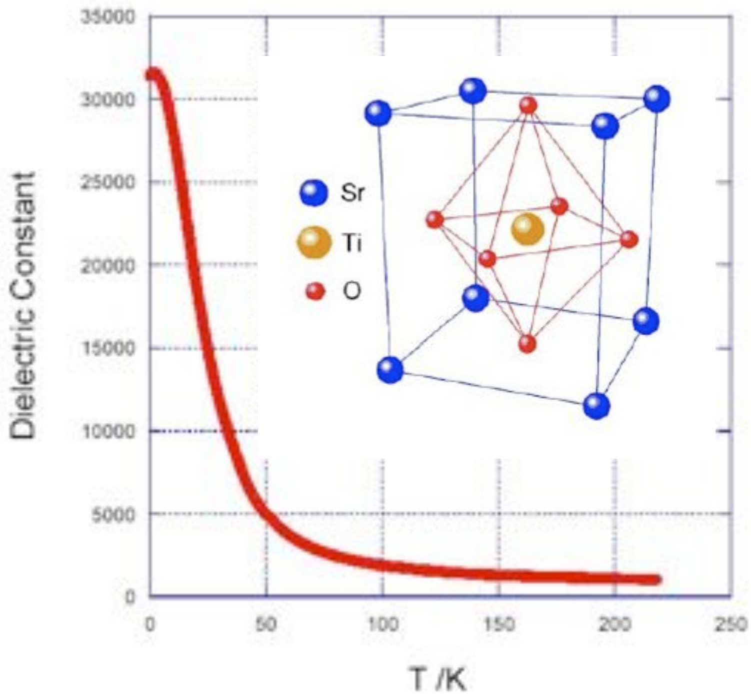


Quantum
Criticality: Ferro-electric



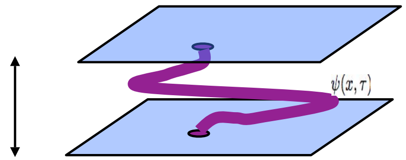
$$\chi_E \sim \frac{1}{T^2}$$

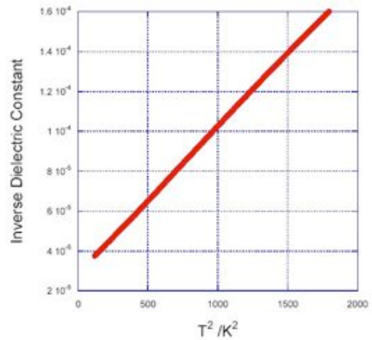




Rowley et al (to be published)

Finite size $\dfrac{\hbar}{k_B T}$



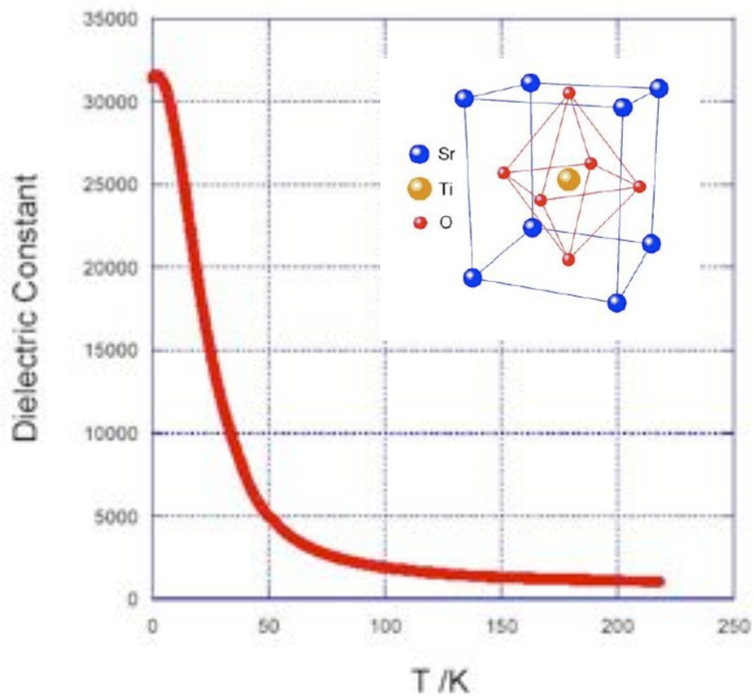


$$\chi_E \sim \frac{1}{T^2}$$

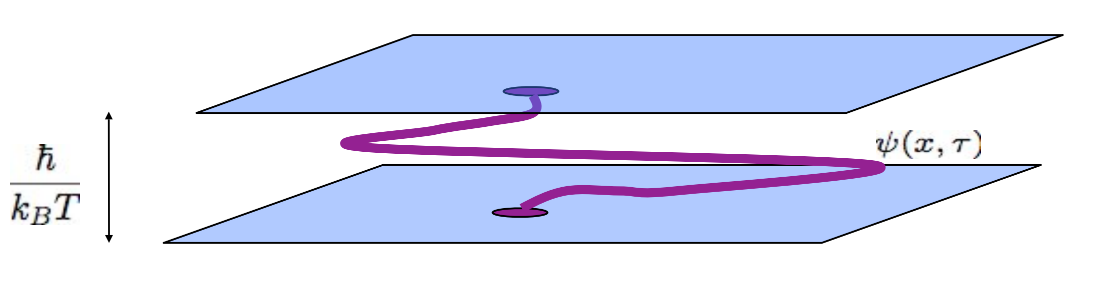
$$\langle P_{q,\omega} P_{-q,-\omega} \rangle \sim \frac{1}{\omega^2 + c_s^2 q^2}$$

$$\longrightarrow \frac{1}{\omega^2 + c_s^2 q^2 + (\alpha T)^2}$$

$$\chi_E = \langle P_{q,\omega} P_{-q,-\omega} \rangle_{\omega=q=0} \propto \frac{1}{T^2}$$



Rowley et al (unpublished)



$\frac{\hbar}{k_B T}$
$\psi(x, \tau)$