Qu-Transitions

P. Coleman
(CMT, Rutgers)

IIT Kanpur
Feb 7, 2010.

Rutgers
Center for Materials Theory

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"Phase transitions in the quantum era"

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Classical vs quantum criticality.

Peierls' question.

Heavy electron Quantum Criticality

New Ideas: breakup of the electron.

Qu-frustration.

http://physics.rutgers.edu/talks/kanpurcolloq09.pdf

RUTGERS
UNIVERSITY

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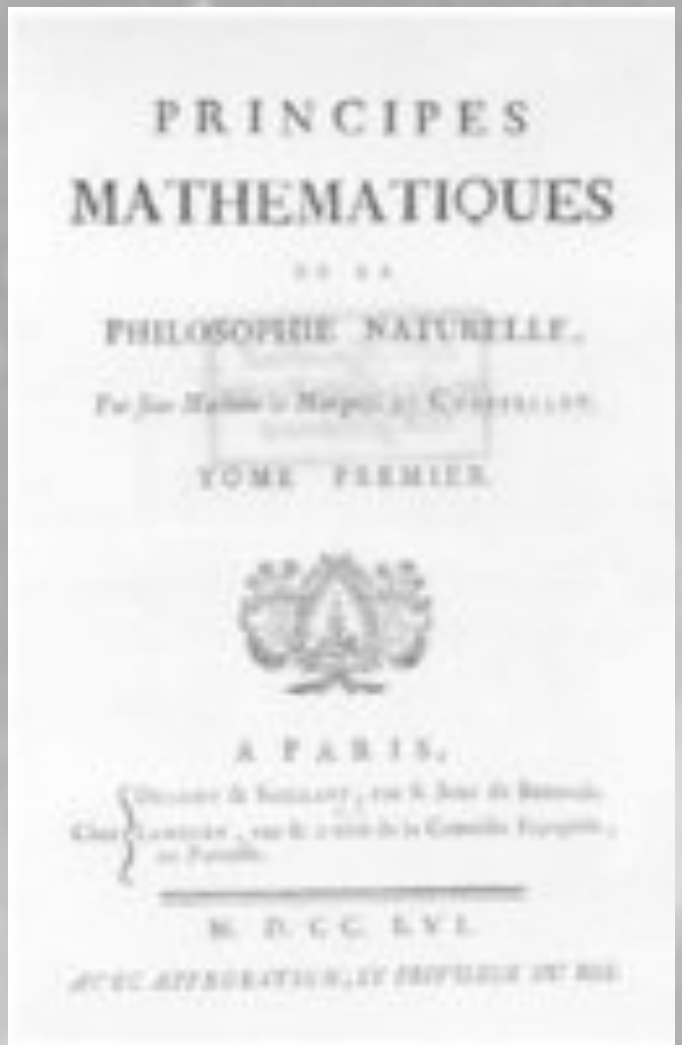
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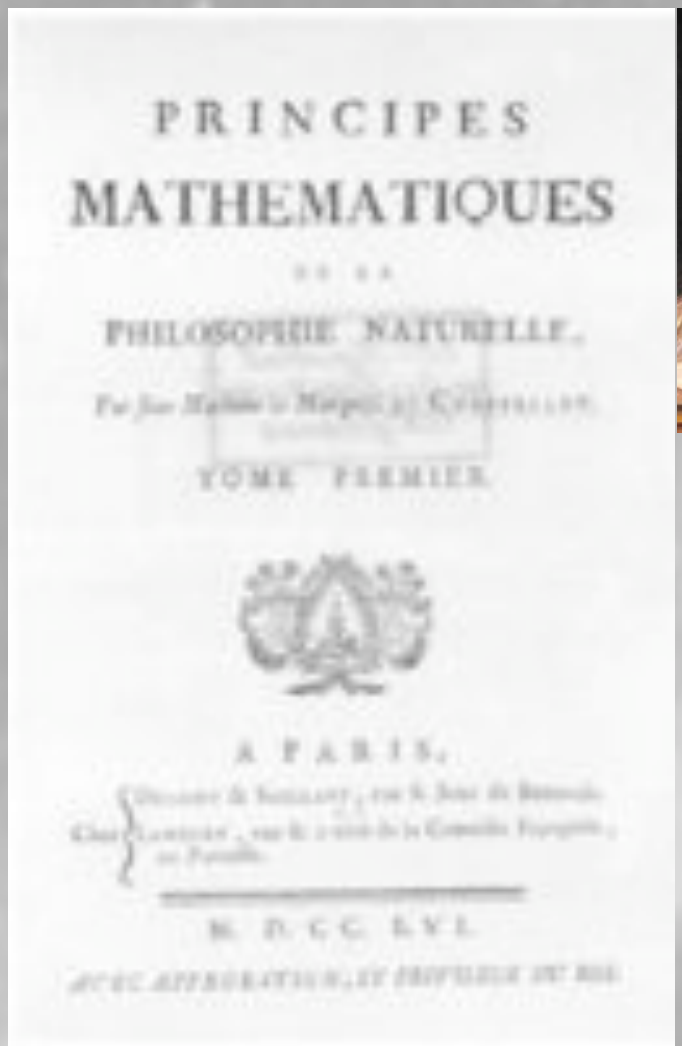
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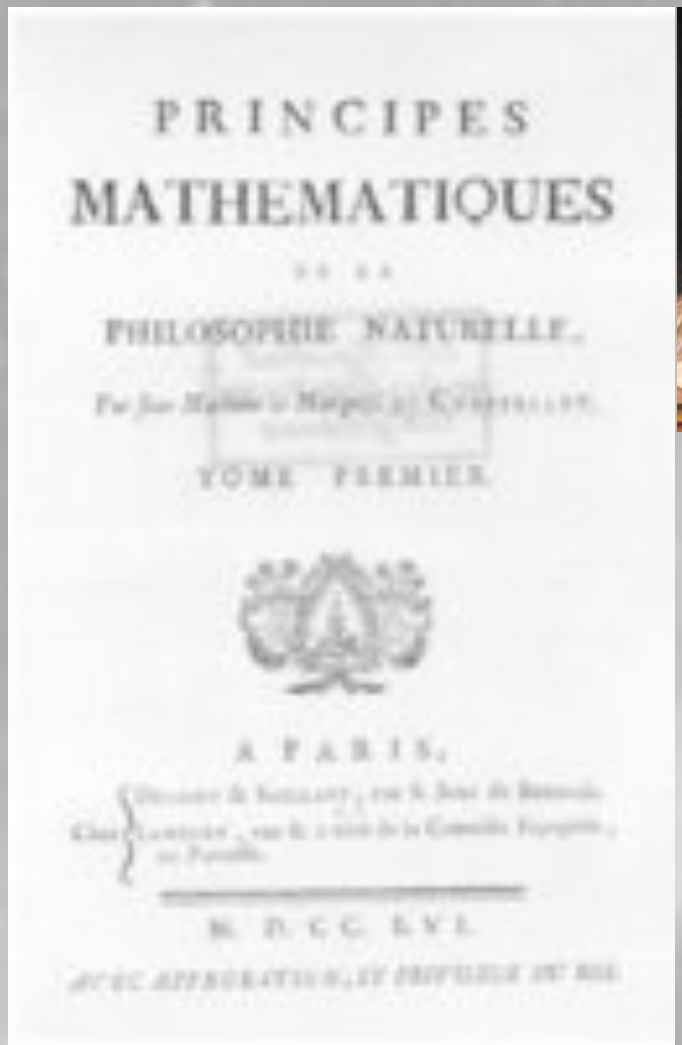
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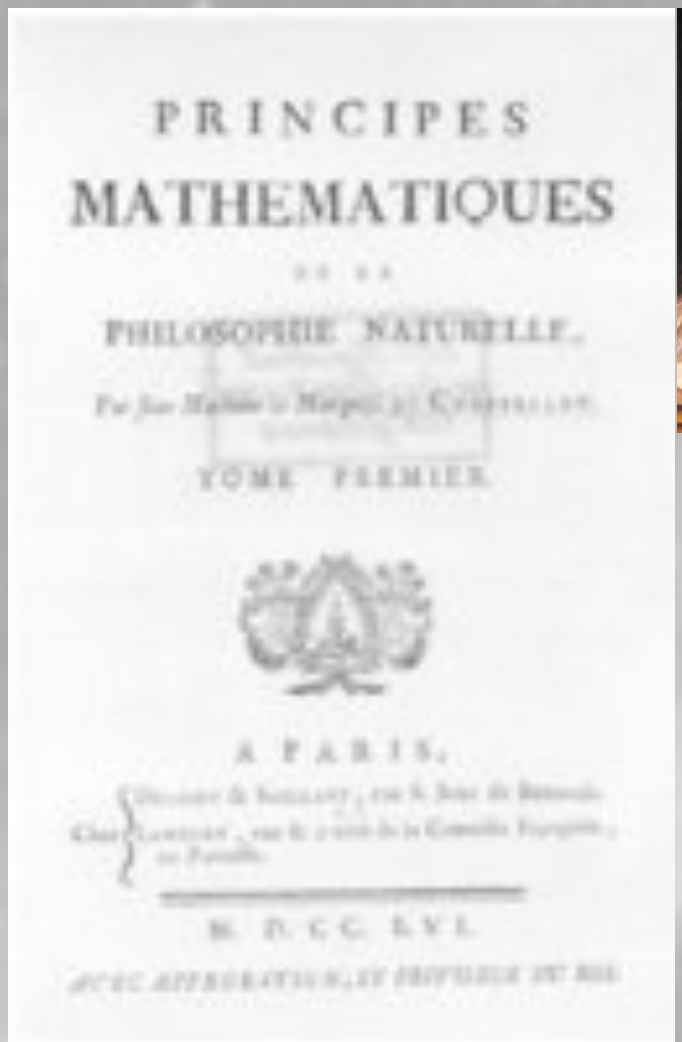
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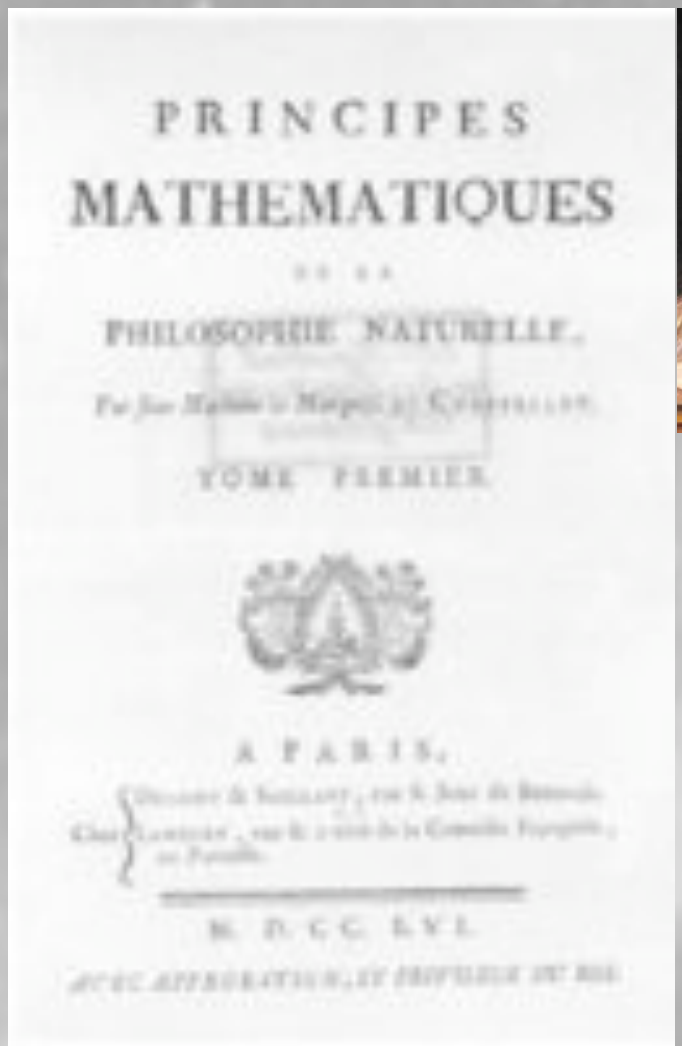
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Resolution of the controversy (and the missing factor of a half) required a further 60-80 years.

108 years after Planck, many
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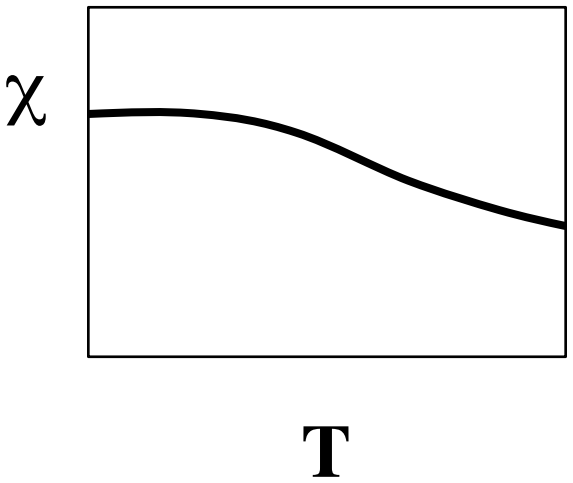

"With a heavy heart, I have been converted to the idea that Fermi -Dirac, not Einstein-Bose is the correct statistics. I wish to write a short note on its application to paramagnetism."

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

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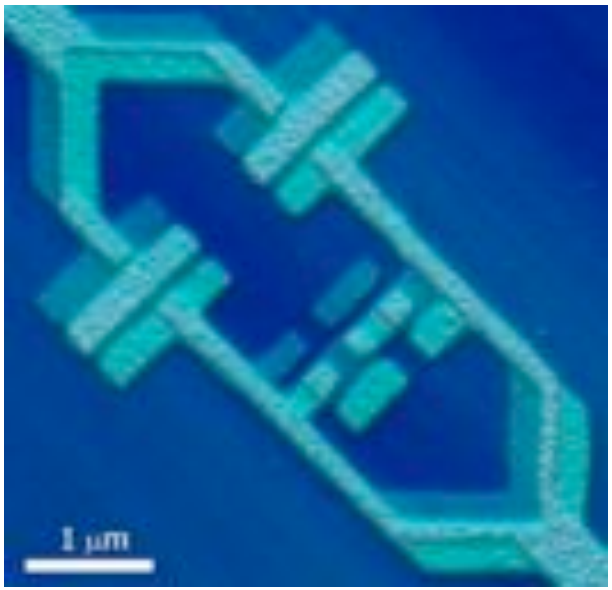

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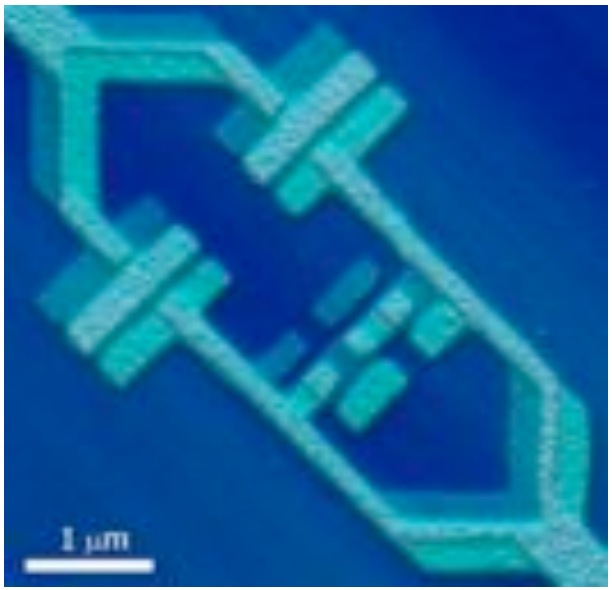

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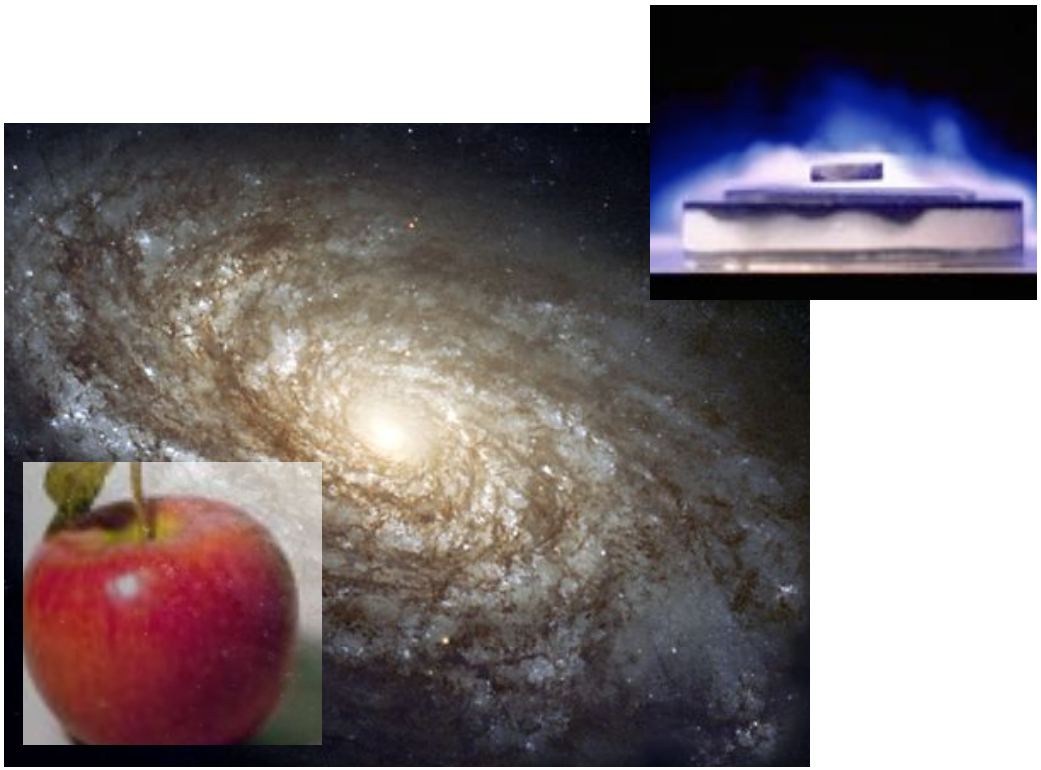
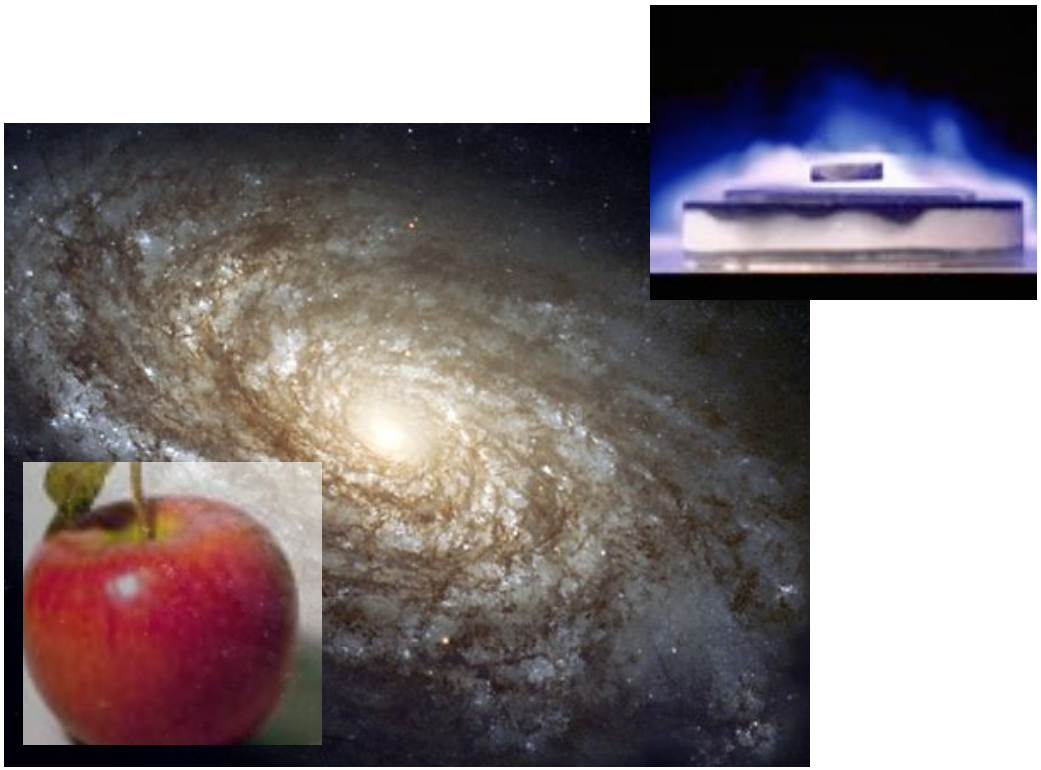
David Pines in
musicofthequantum.rutgers.edu

Quantum zero point fluctuations:



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



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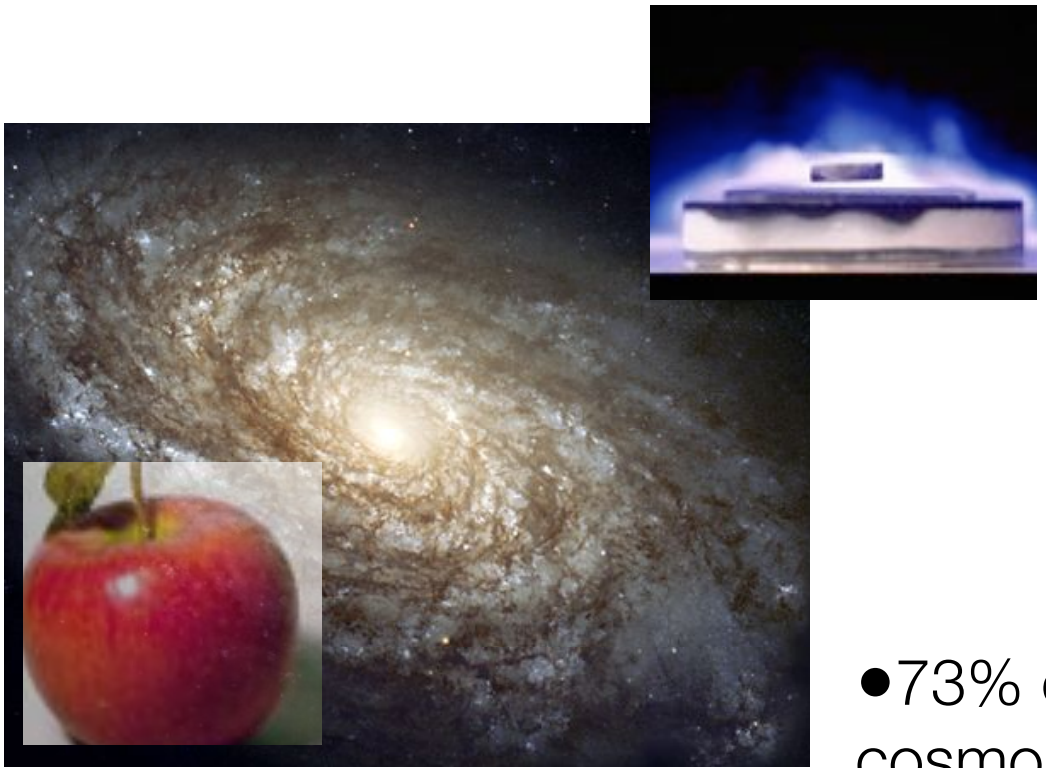

- 73% of the mass of the cosmos is “Dark Energy”: an unidentified form of zero point energy, causing the expansion to accelerate.

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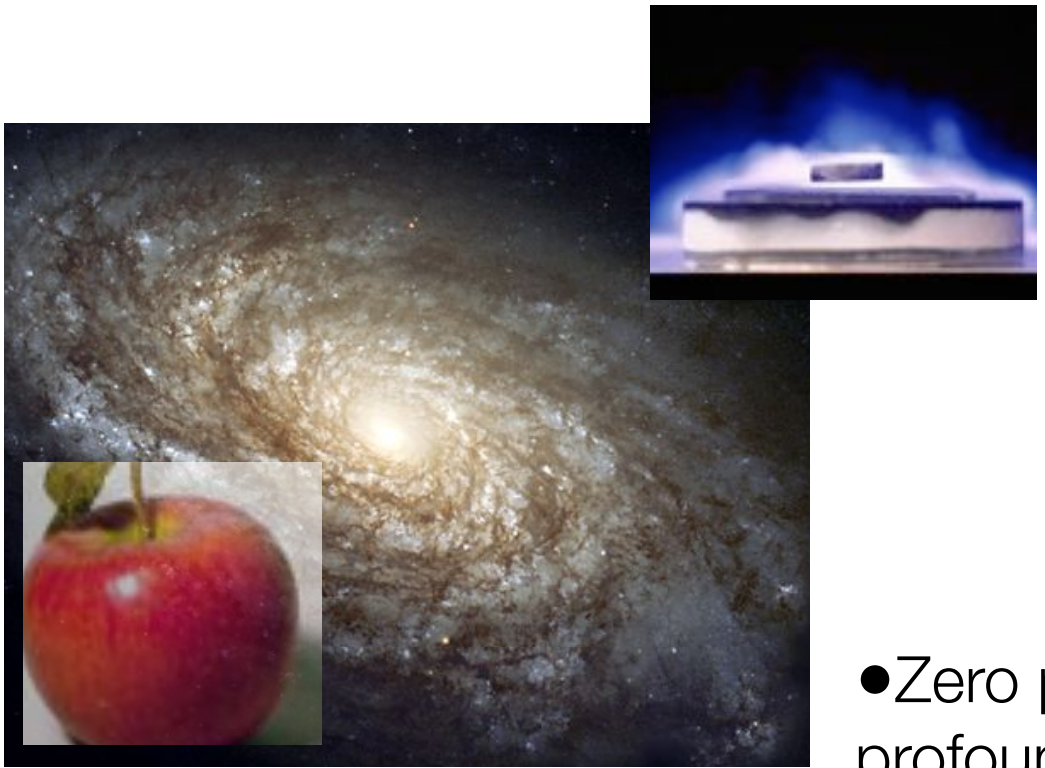

- Zero point fluctuations profoundly transform matter, endowing it with marked tendency to develop new forms of order.

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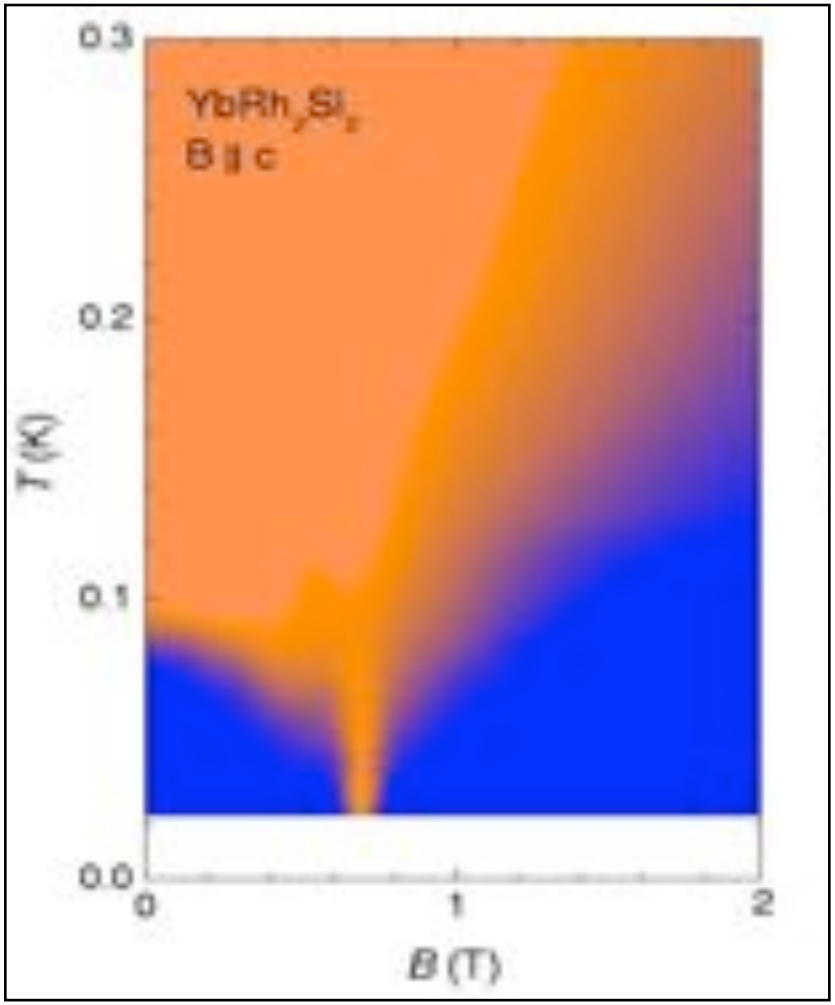

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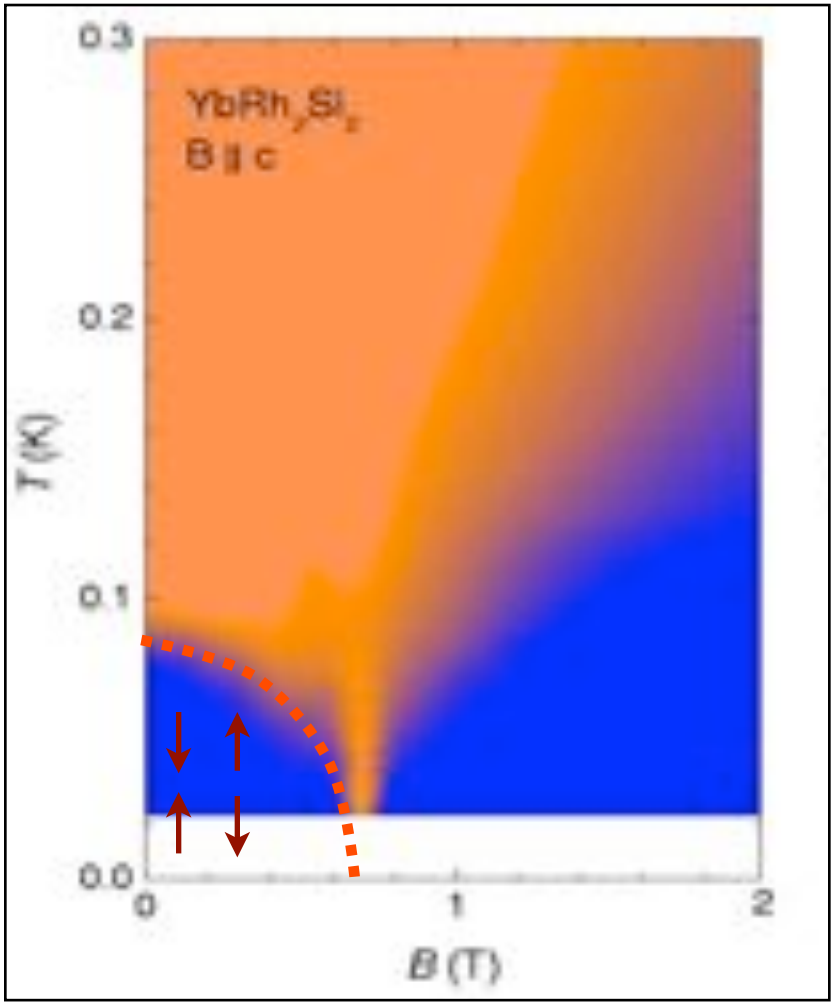

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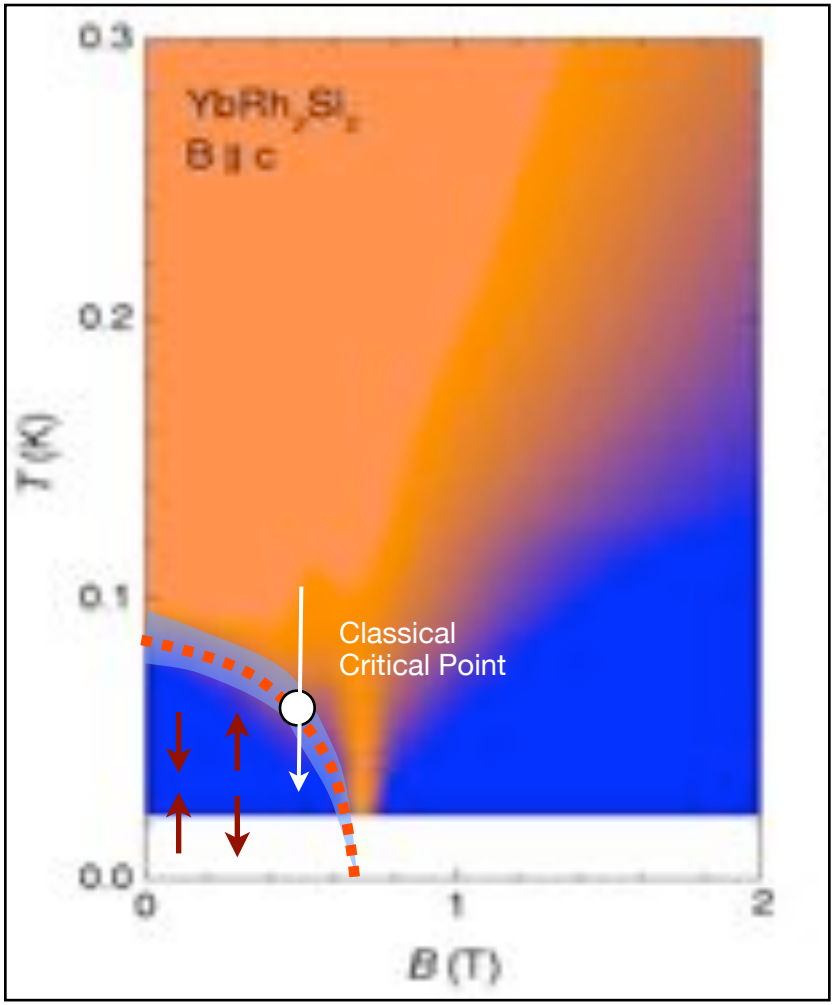

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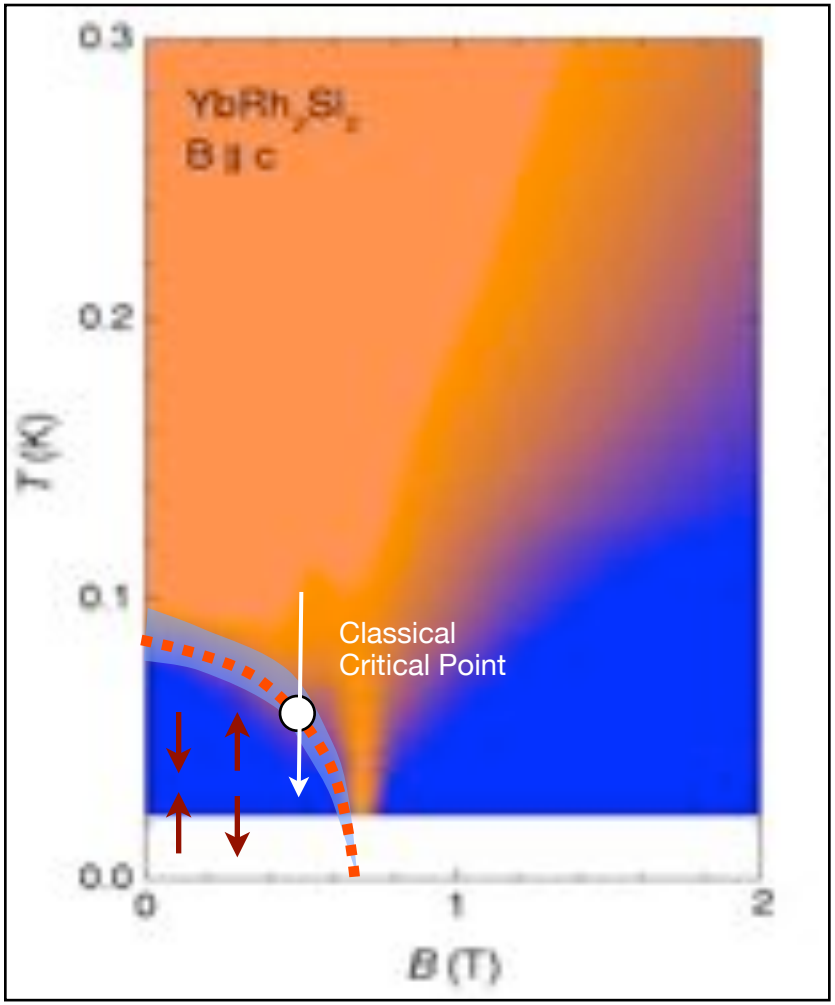

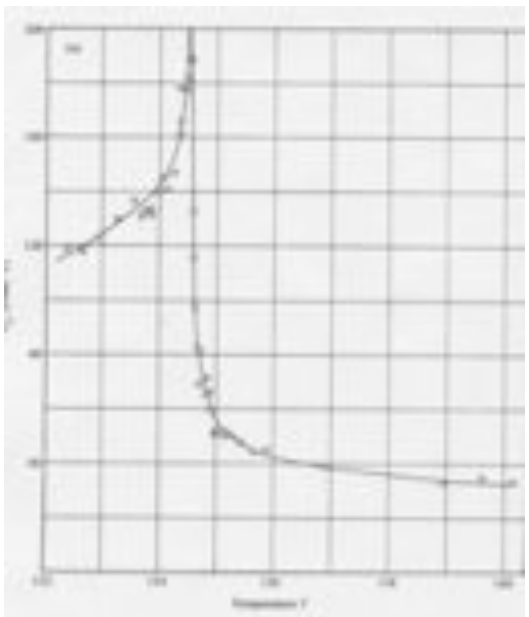

Oxygen. (Voronel et al 1963).

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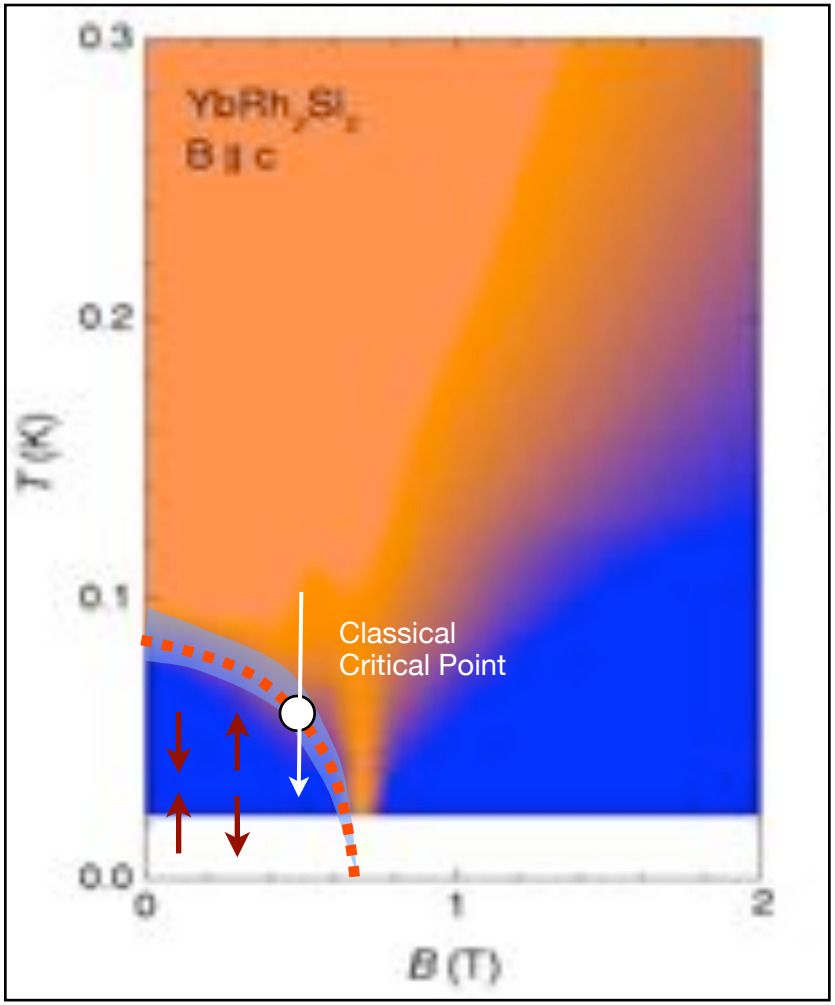

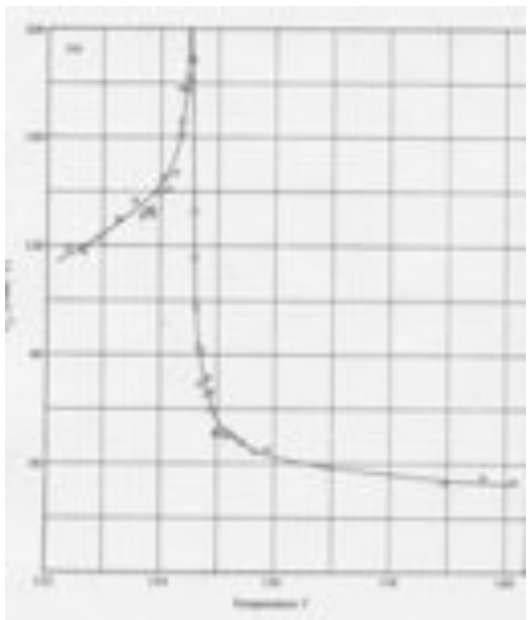

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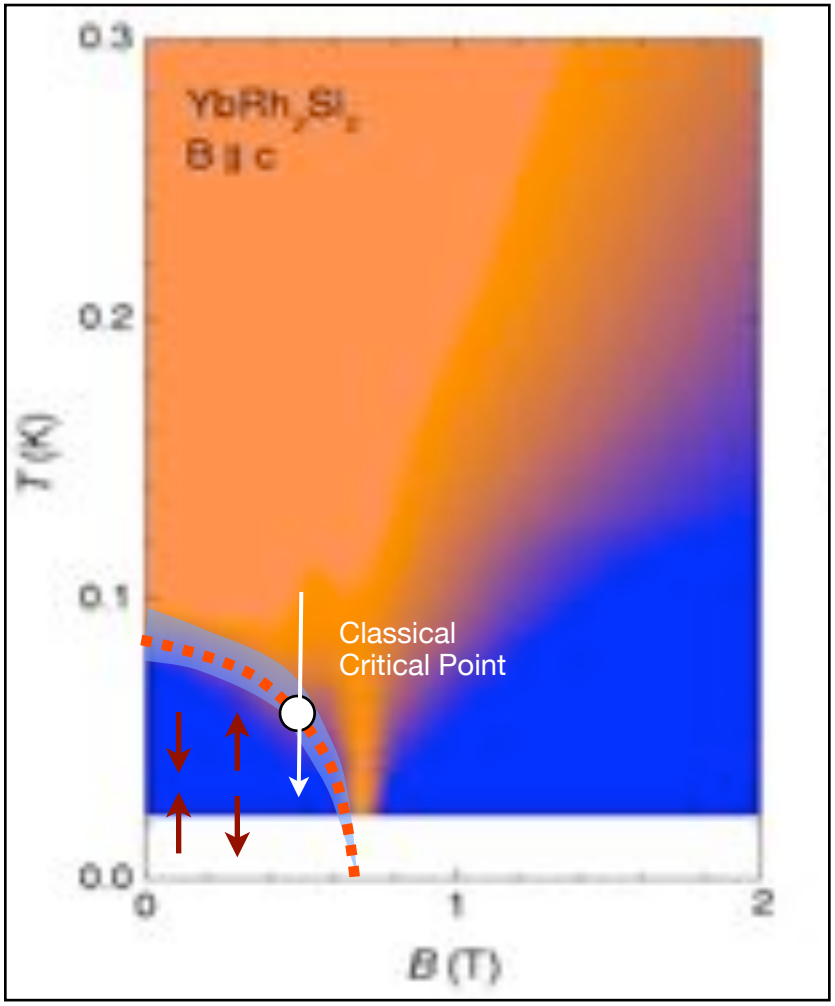

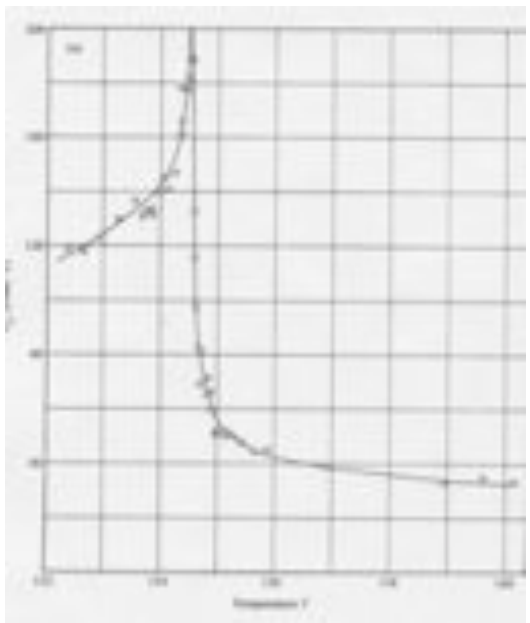

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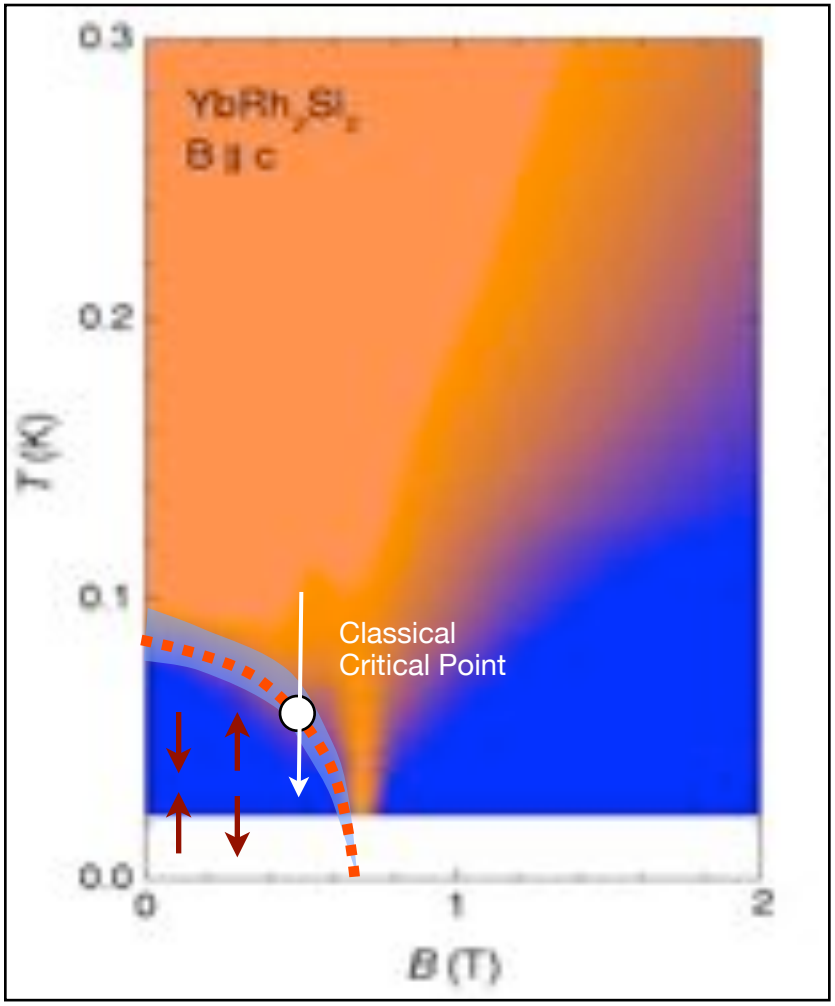

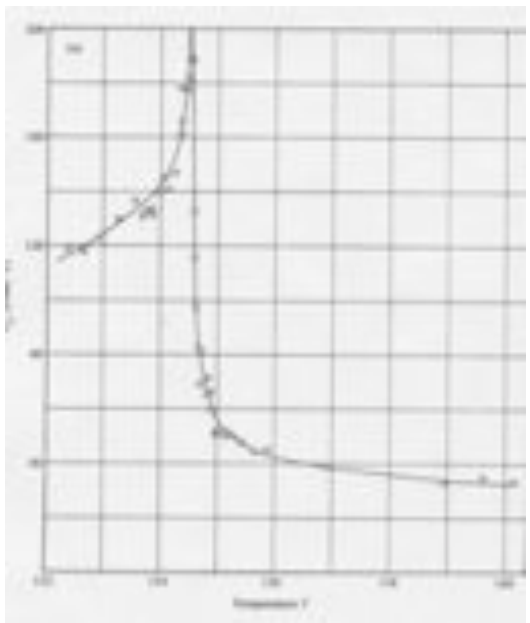

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"20th Century Revolution"

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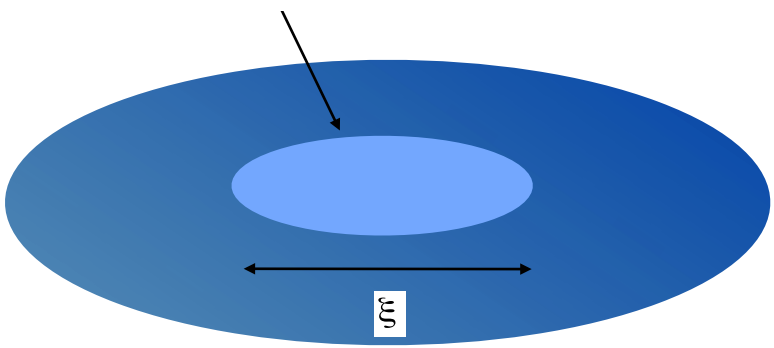
Critical matter



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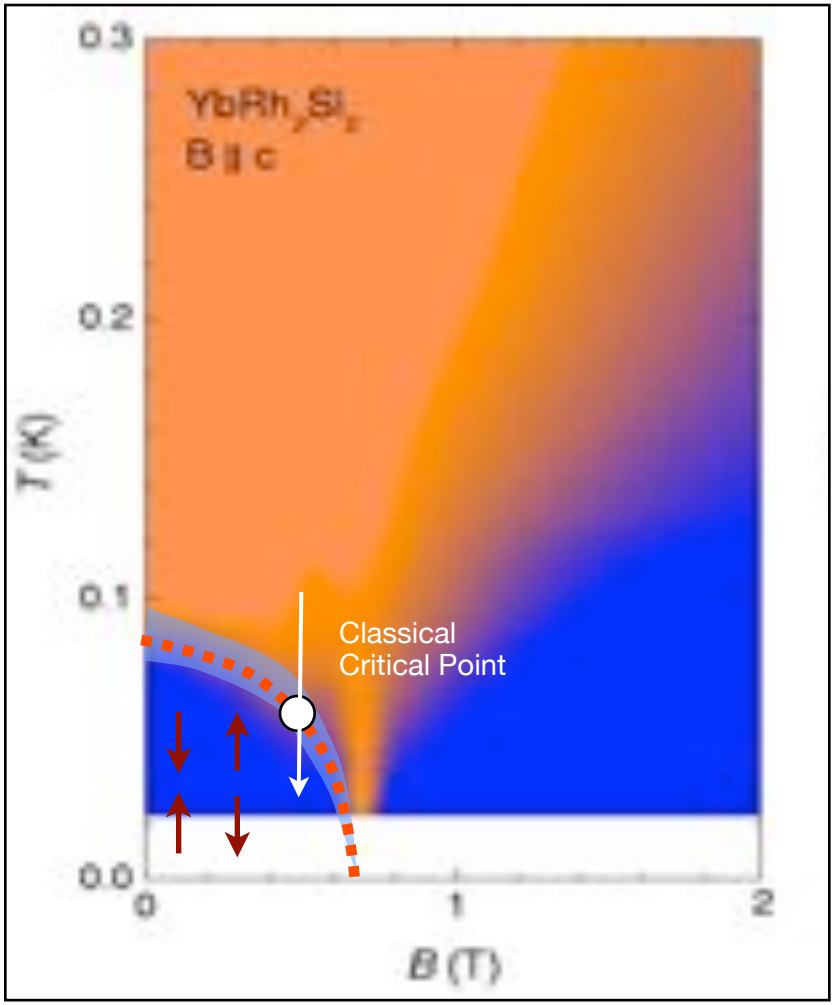

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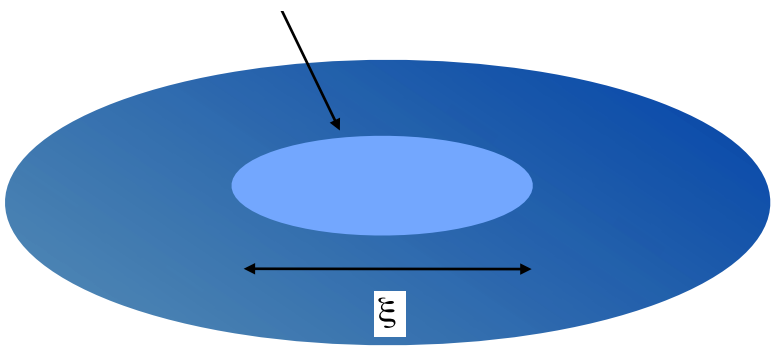

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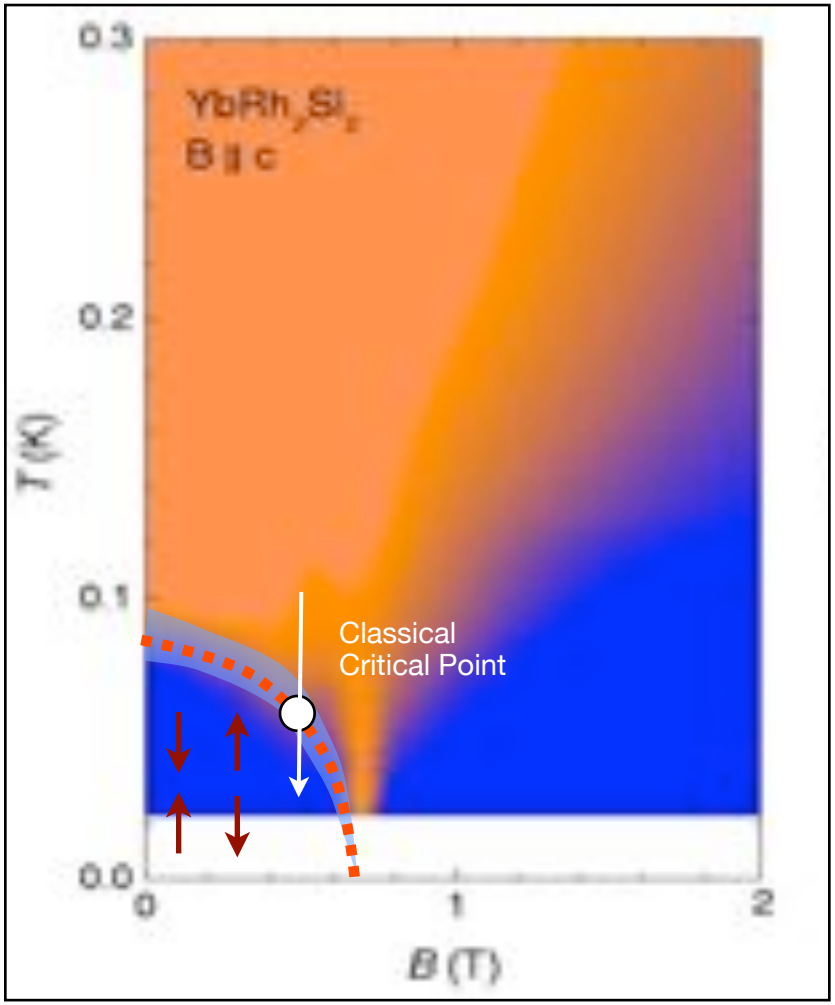

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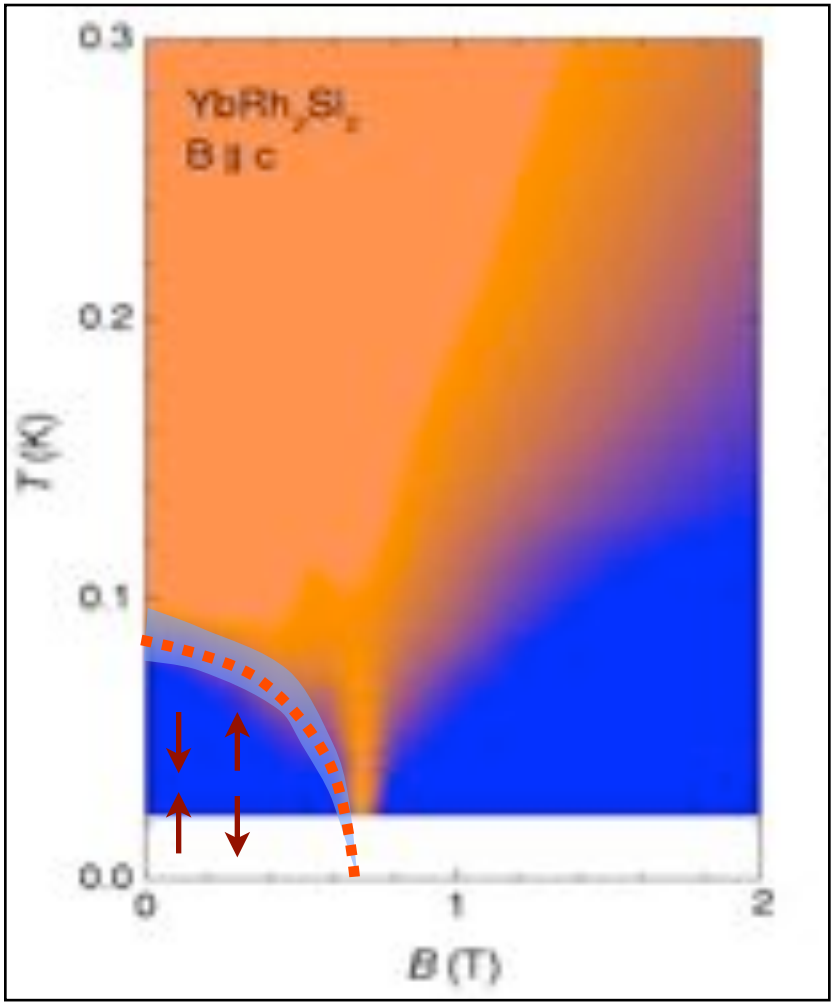

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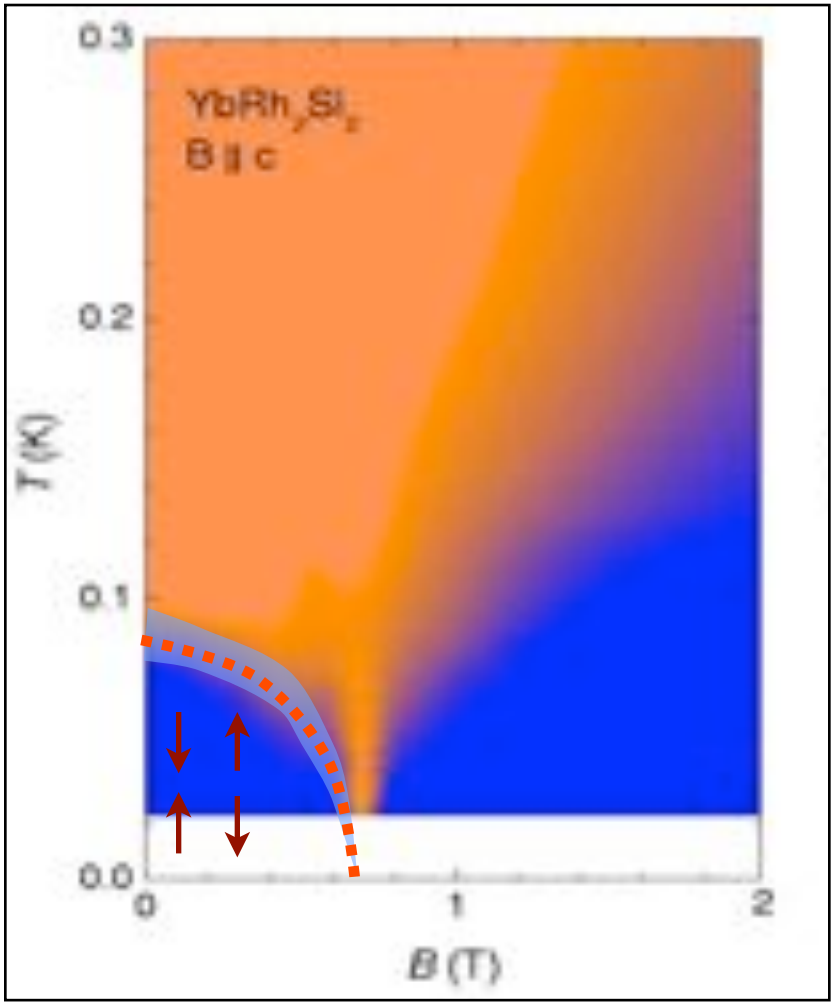

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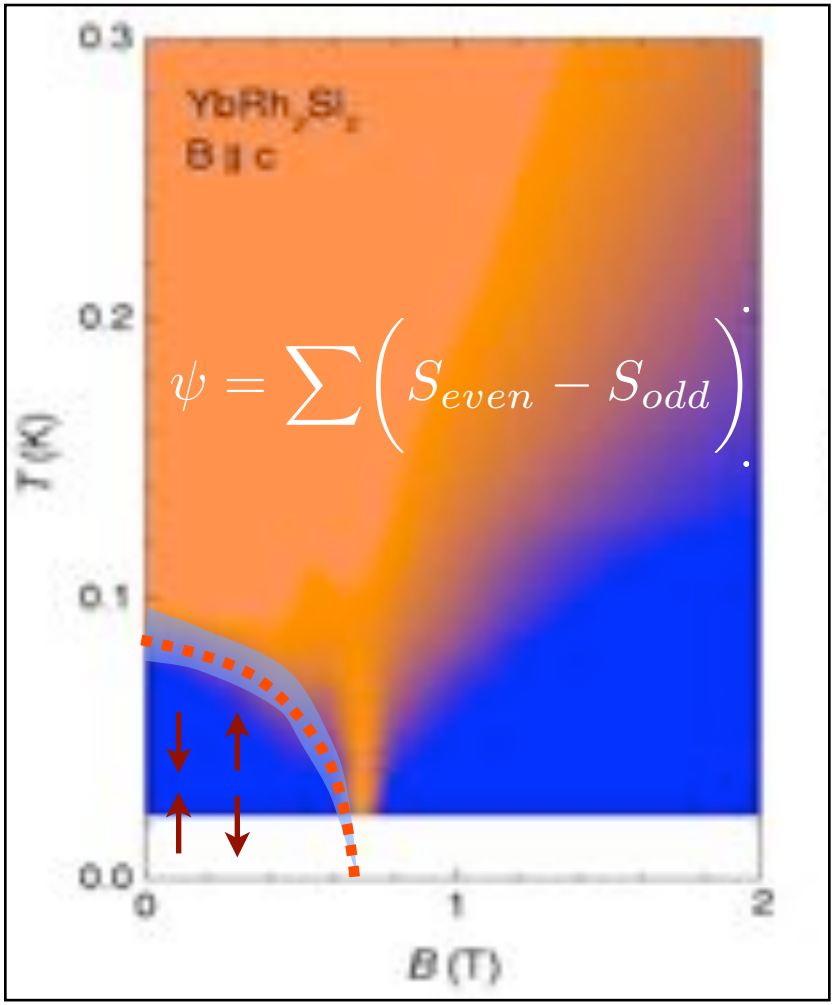

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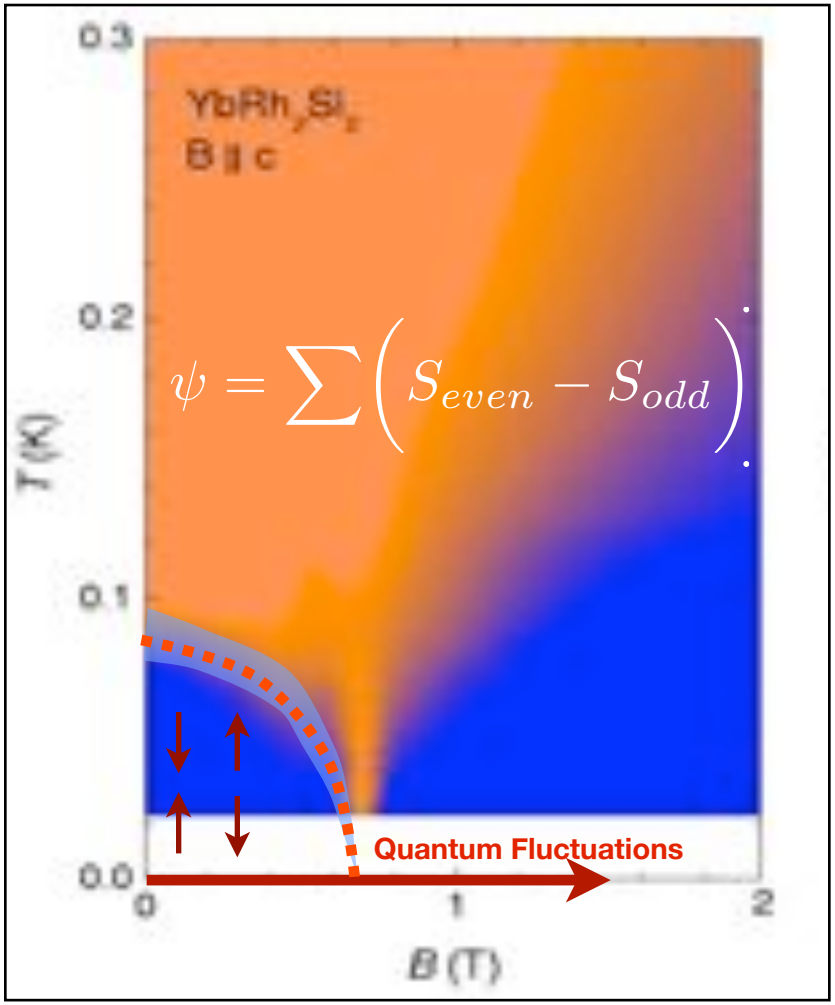

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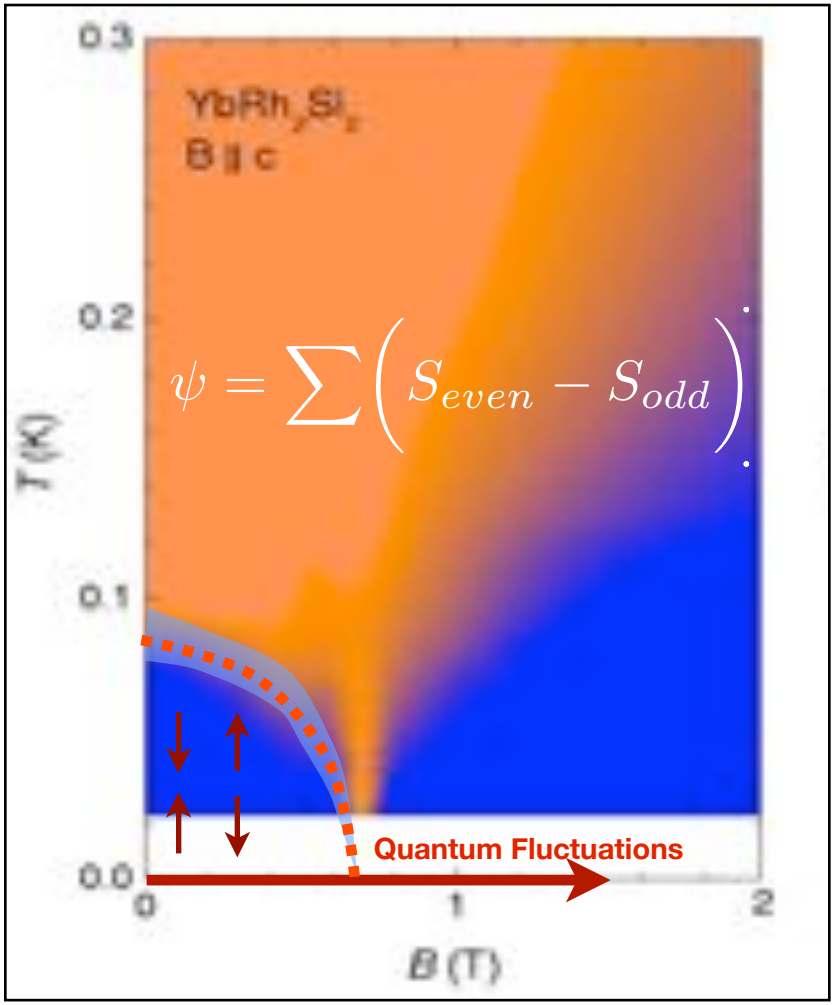

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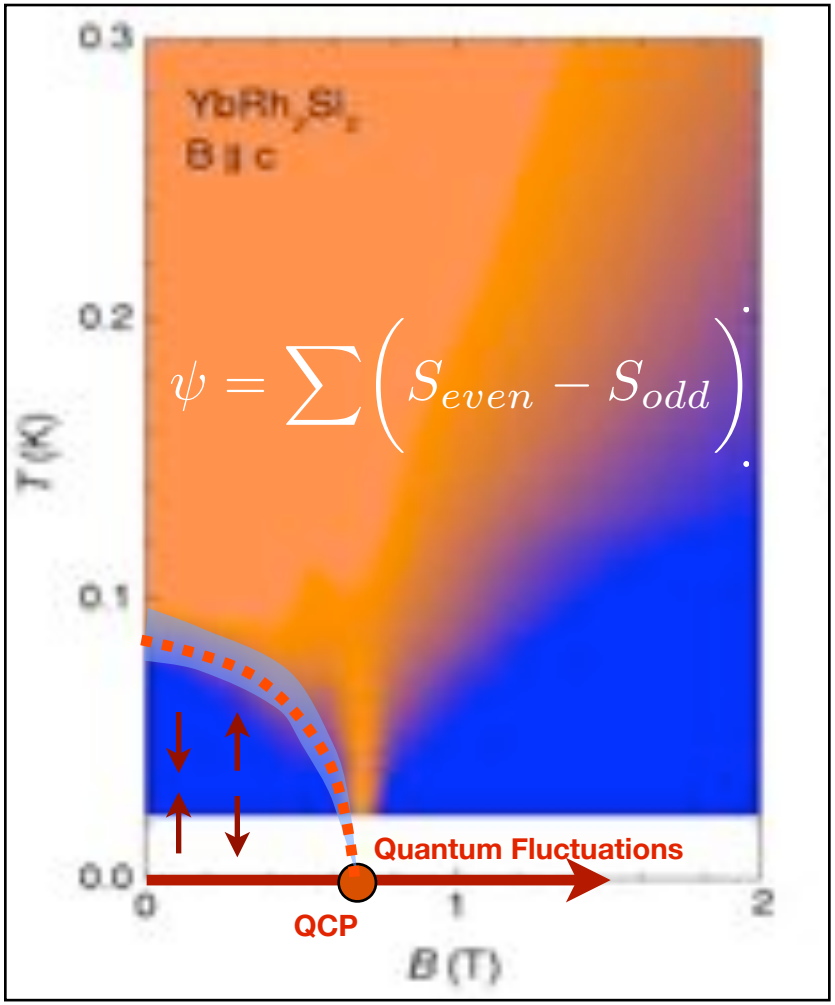

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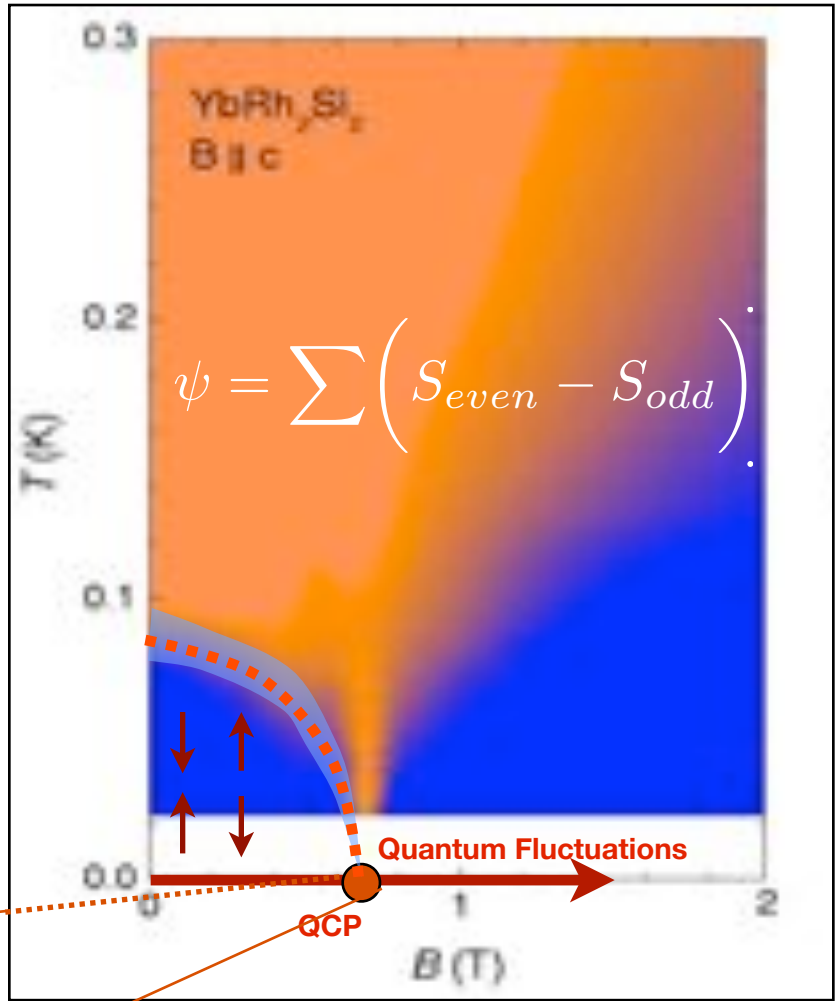

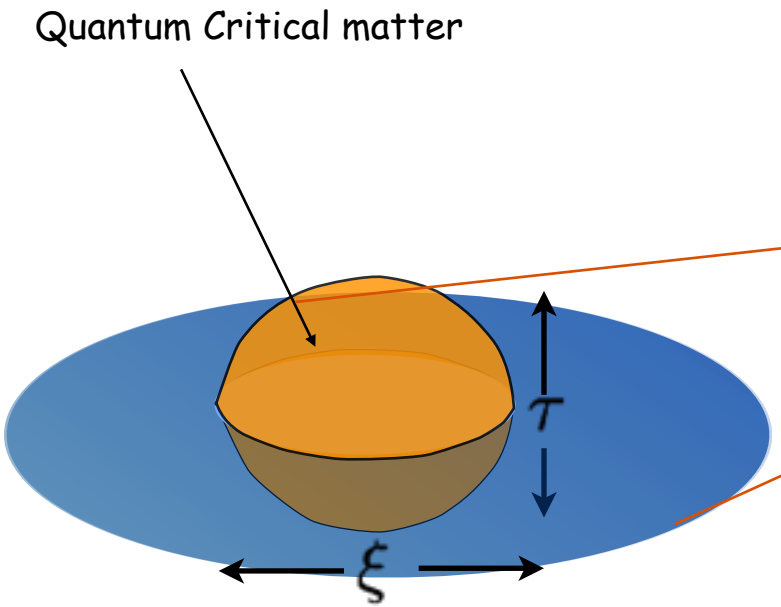

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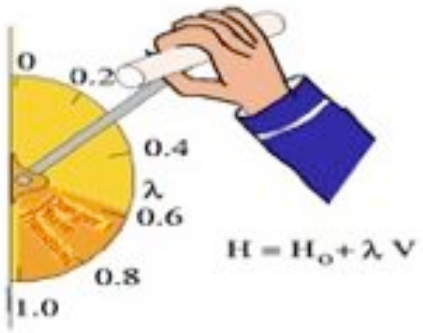
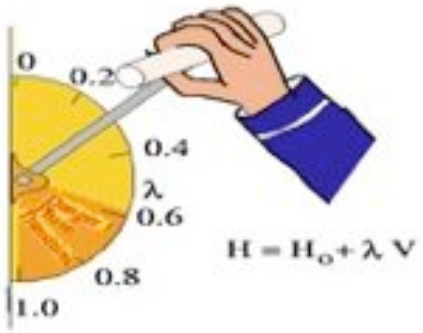


Landau: interactions can be turned on adiabatically, preserving the excitation spectrum.



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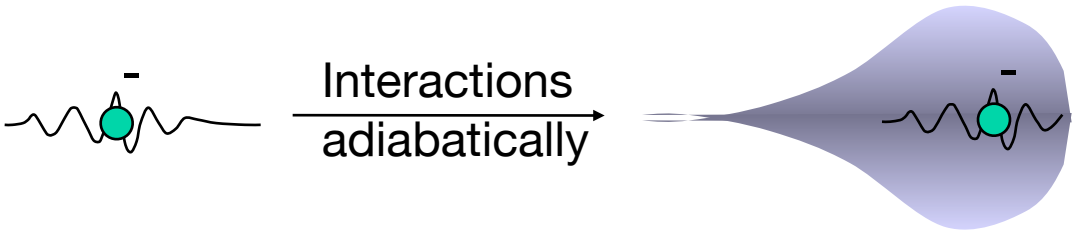

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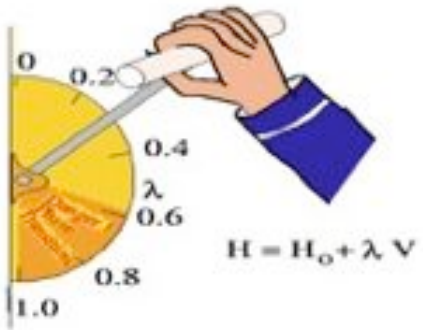

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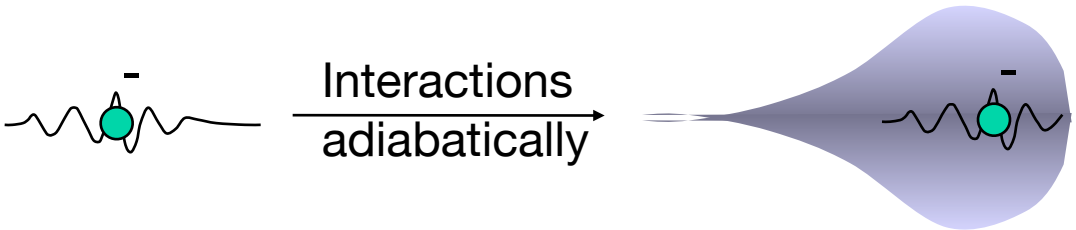

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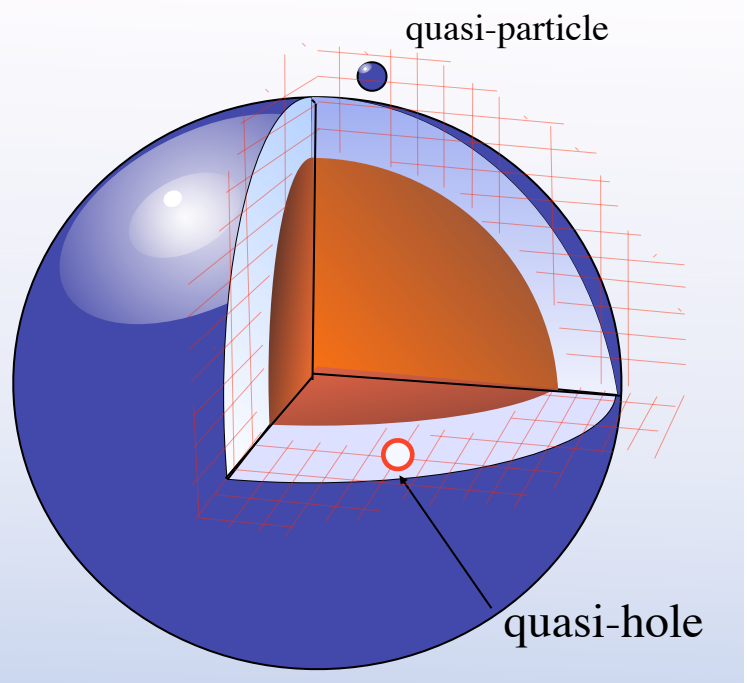

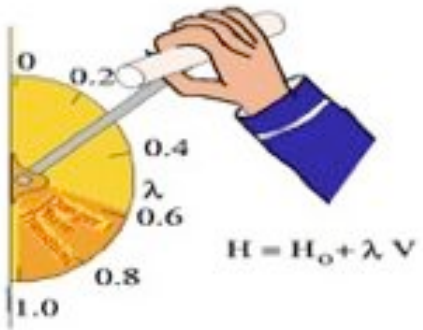

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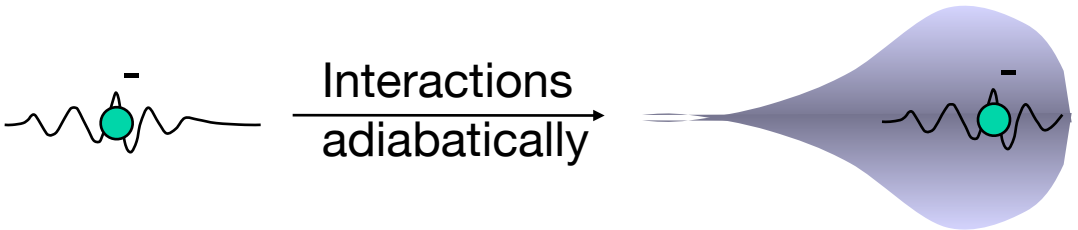

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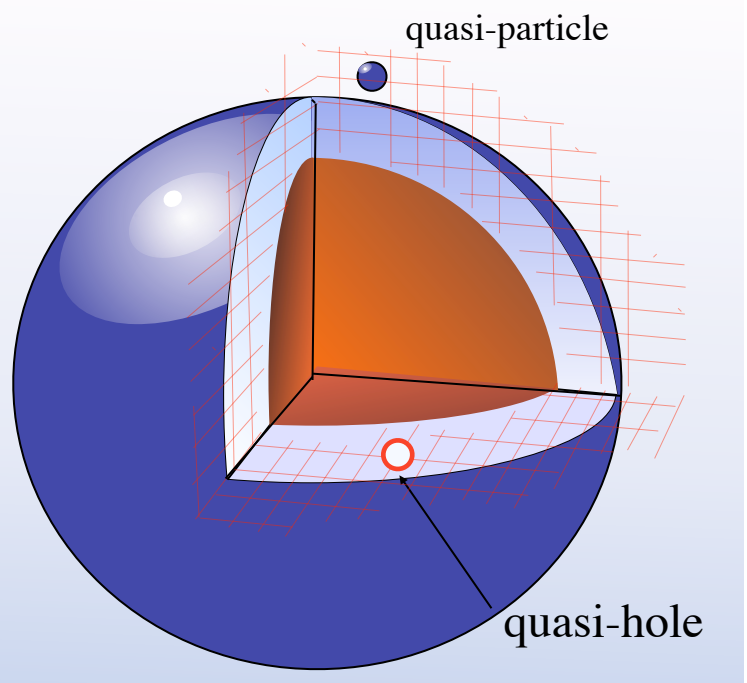
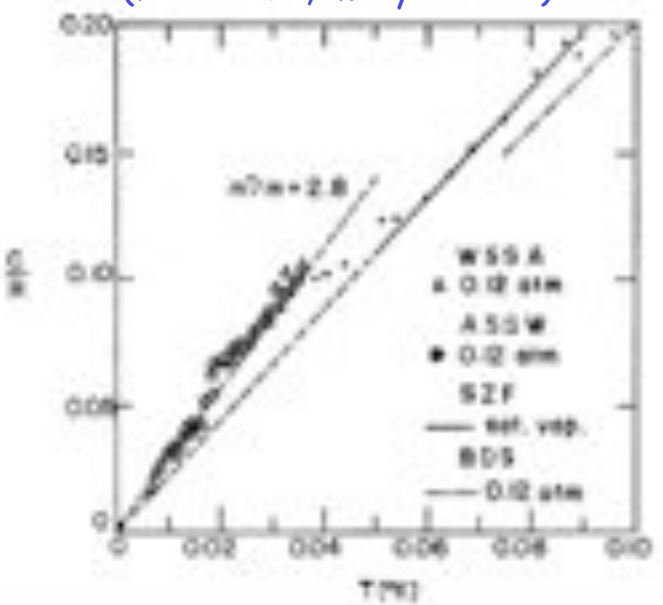


$$\frac{m^*}{m} = \frac{N(0)^*}{N(0)} = 1 + \frac{F_1^s}{3}$$

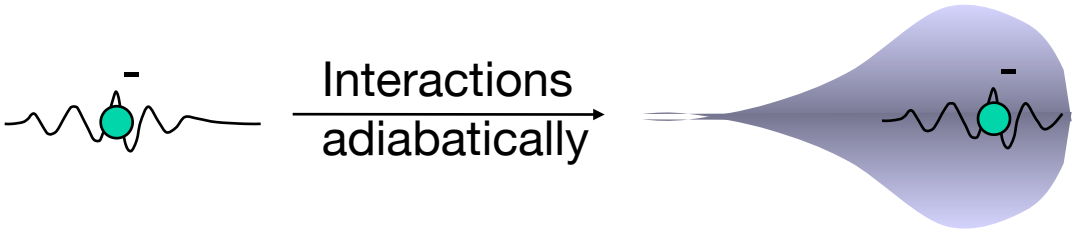
Landau, JETP 3, 920 (1957)

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



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

"Quasiparticle"



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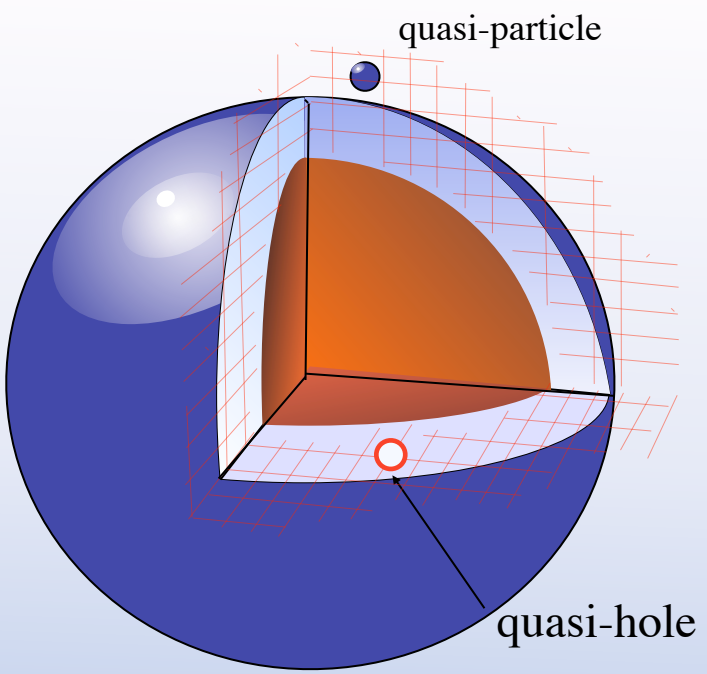

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Landau's Question.

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

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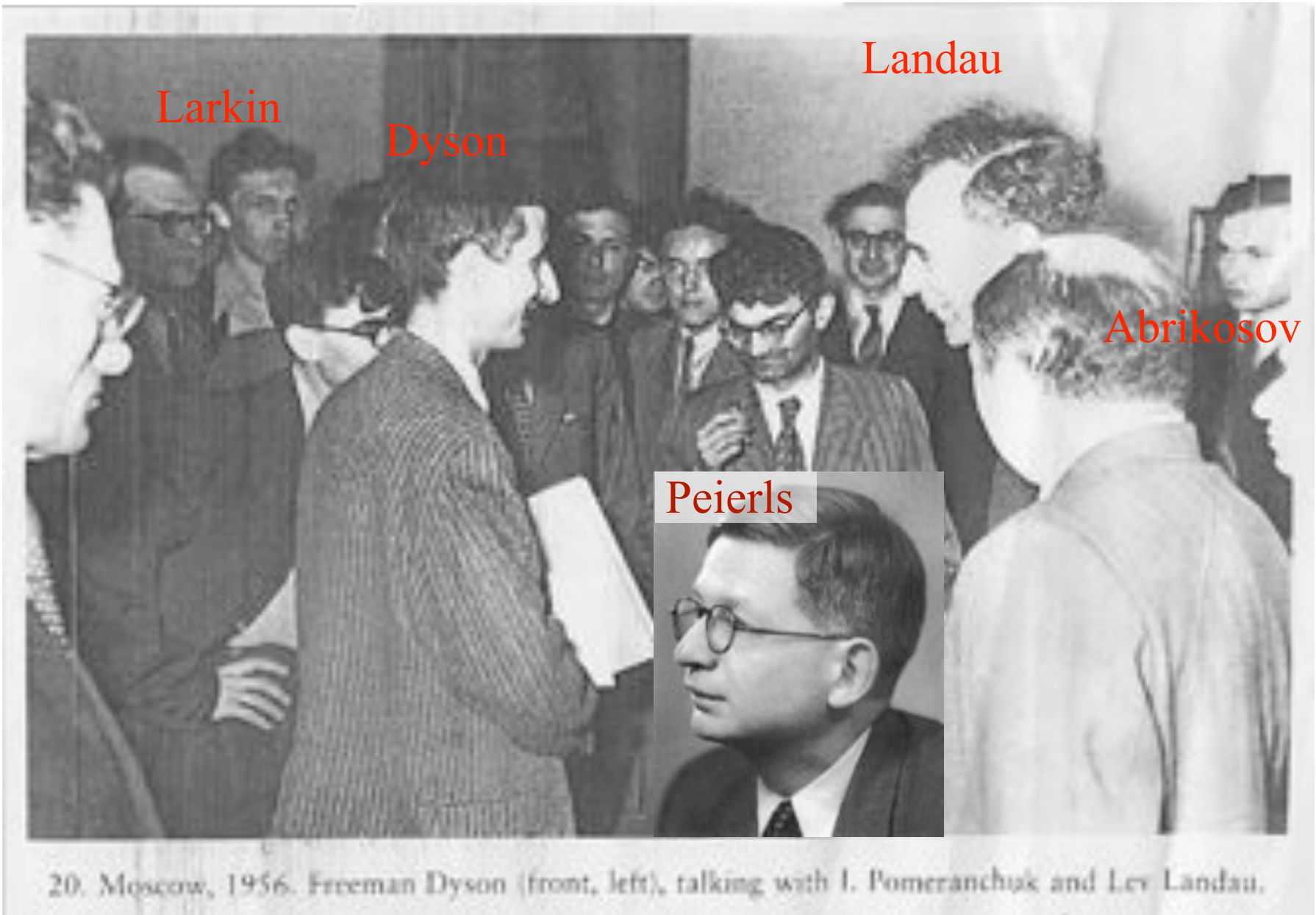

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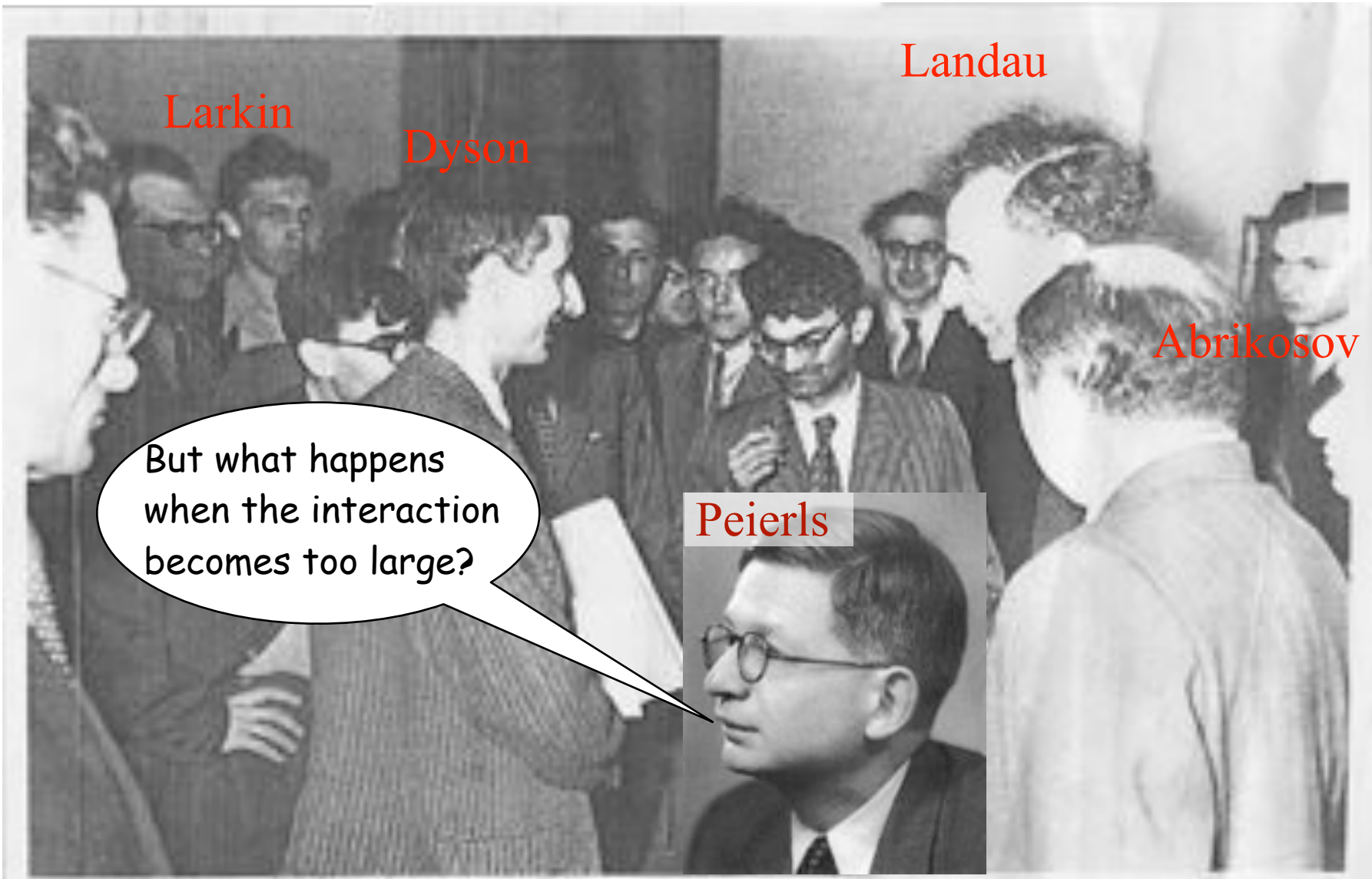

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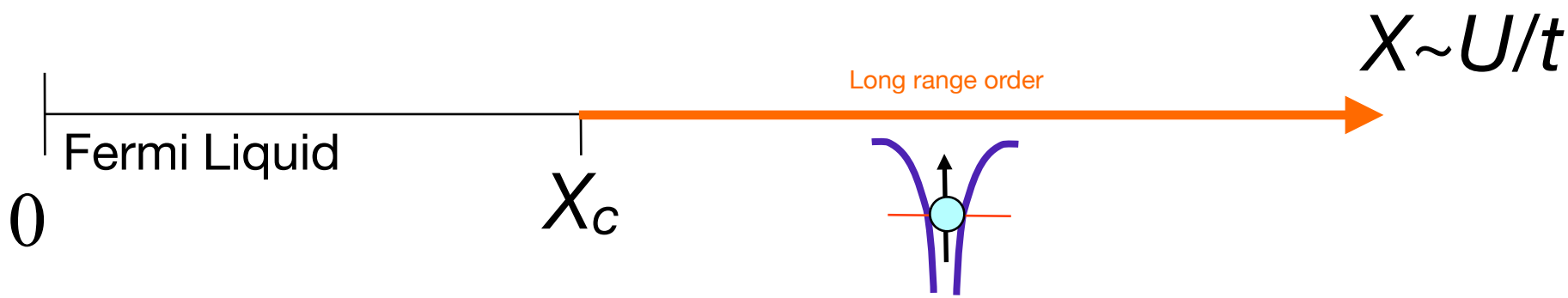

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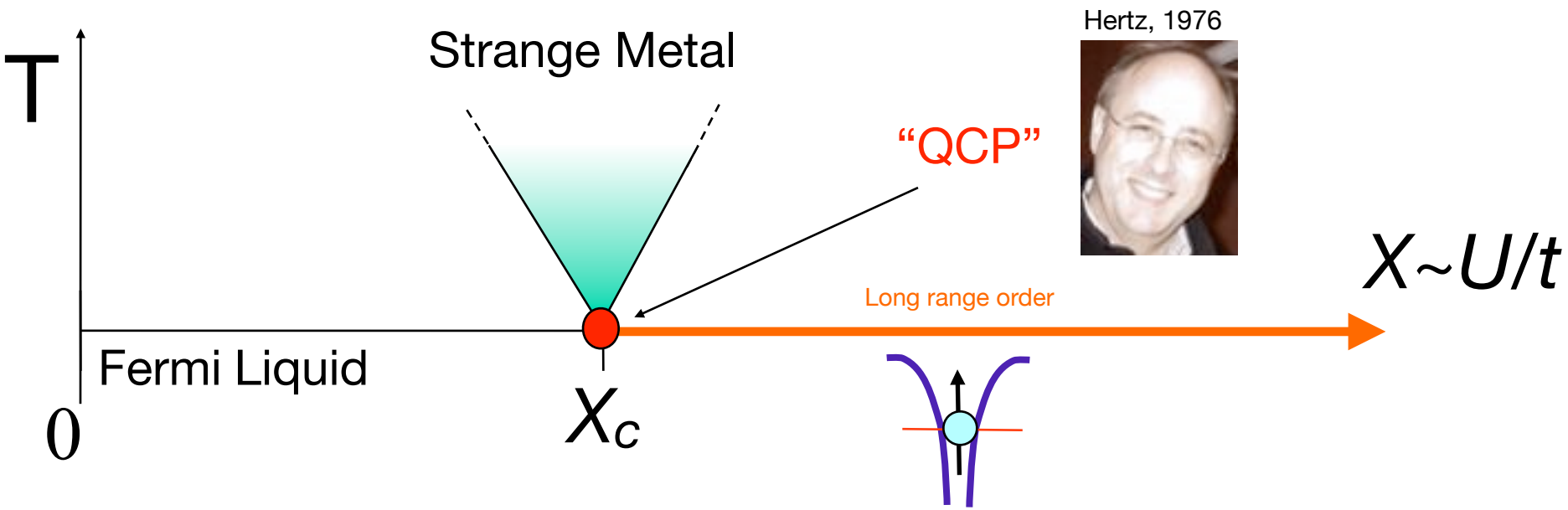

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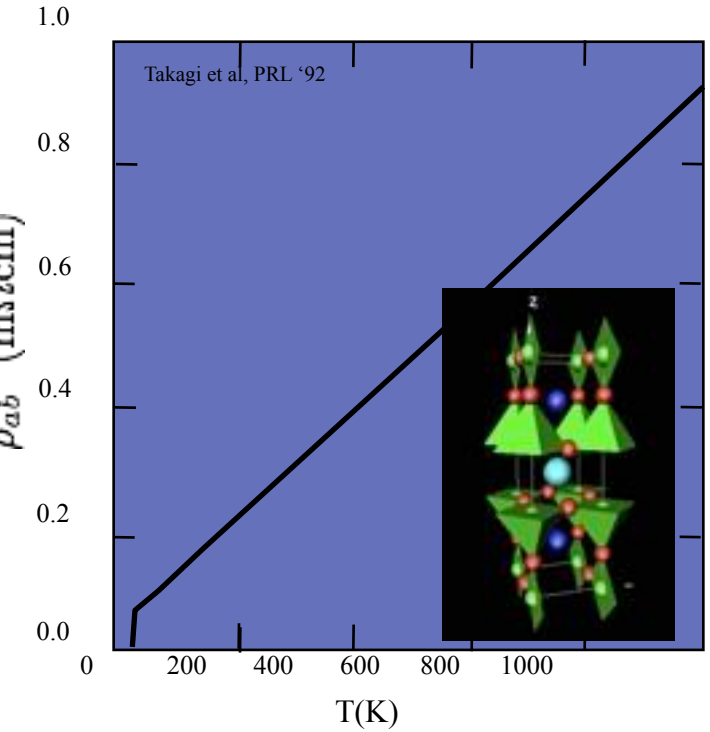
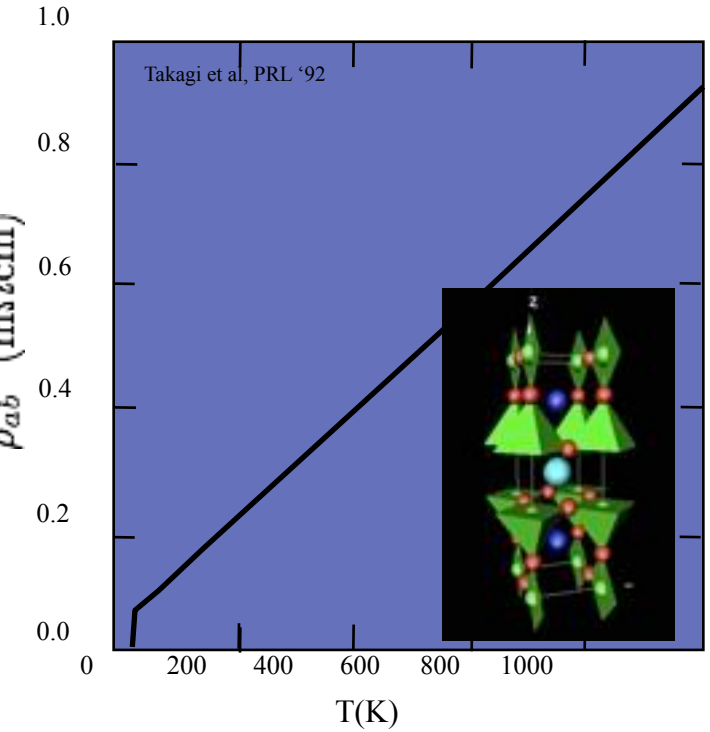


"Avoided Criticality"

Cuprates
Tc=11-92K



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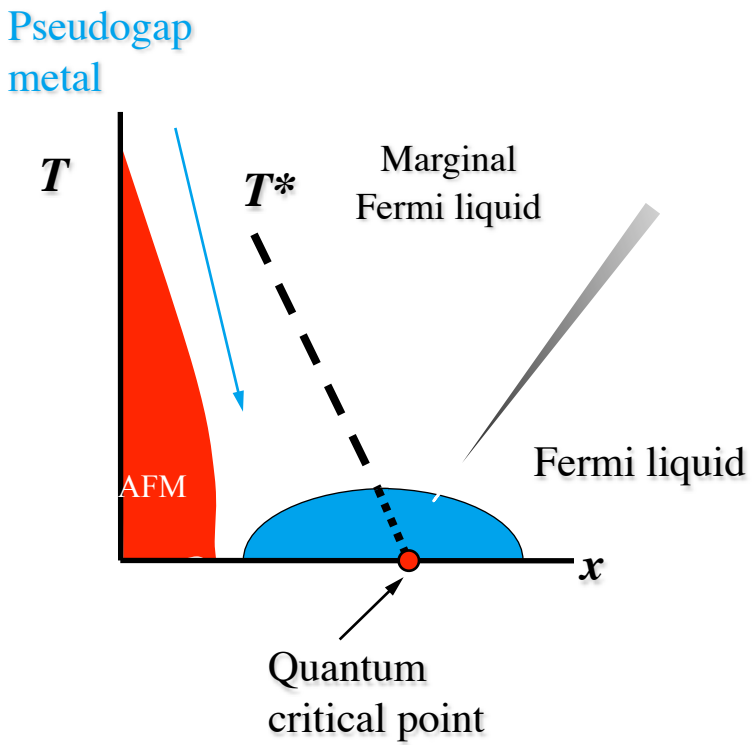

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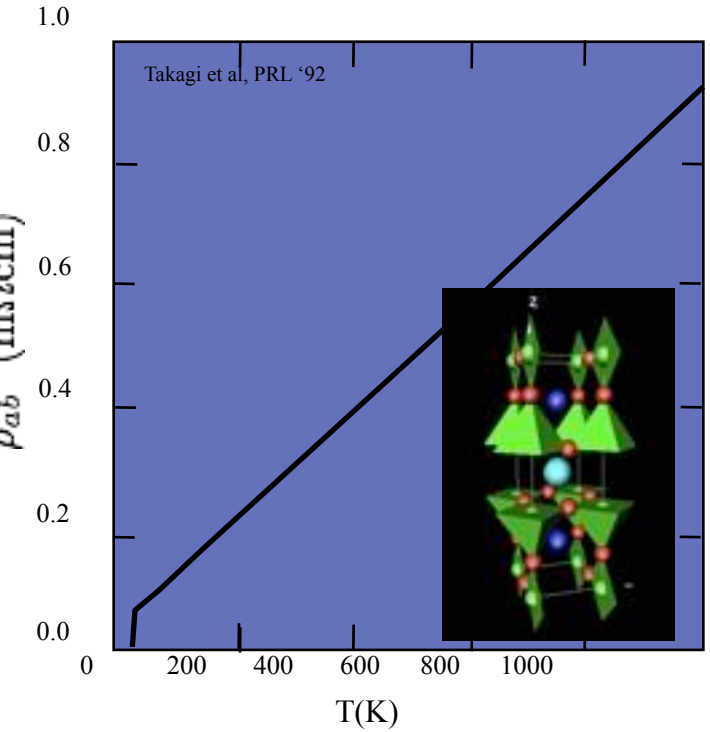

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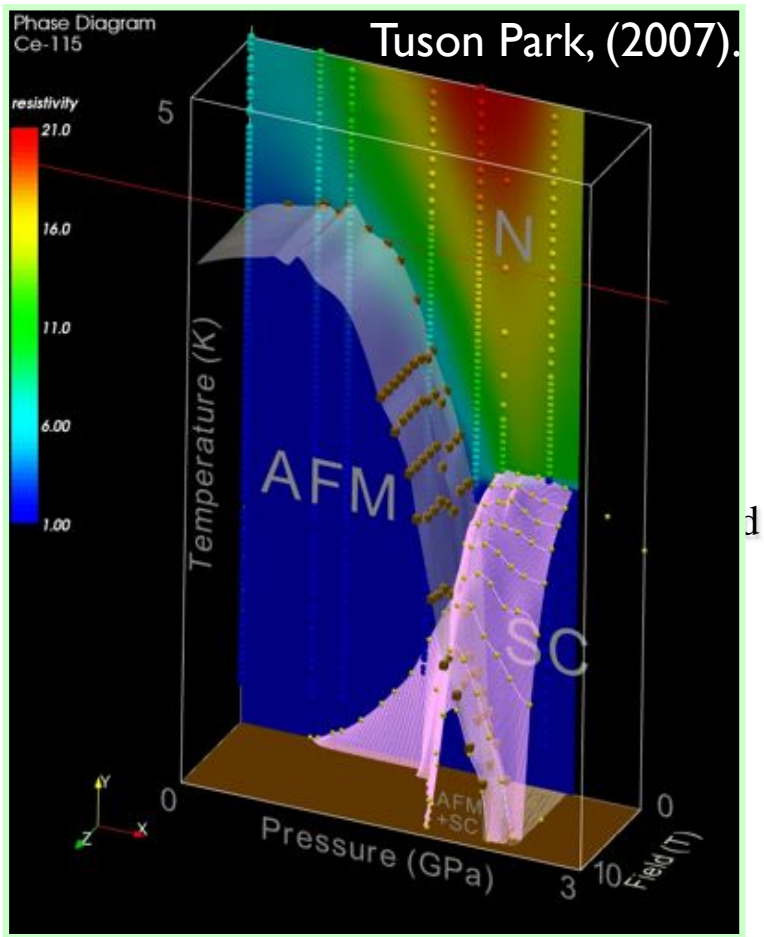

Cuprates
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Qu-era: revolutions always have a second part.

Classical vs quantum criticality.

Peierls' question.

Heavy electron Quantum Criticality

New Ideas: breakup of the electron.

Qu-frustration.

Kondo effect

Kondo effect (a digression)

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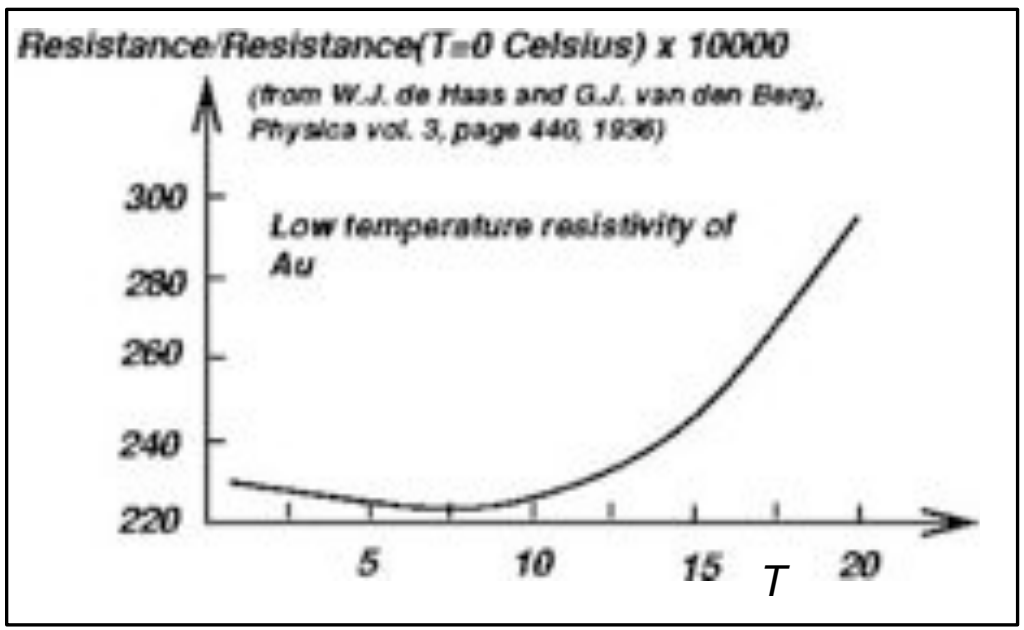
"Kondo"

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

Kondo effect (a digression)



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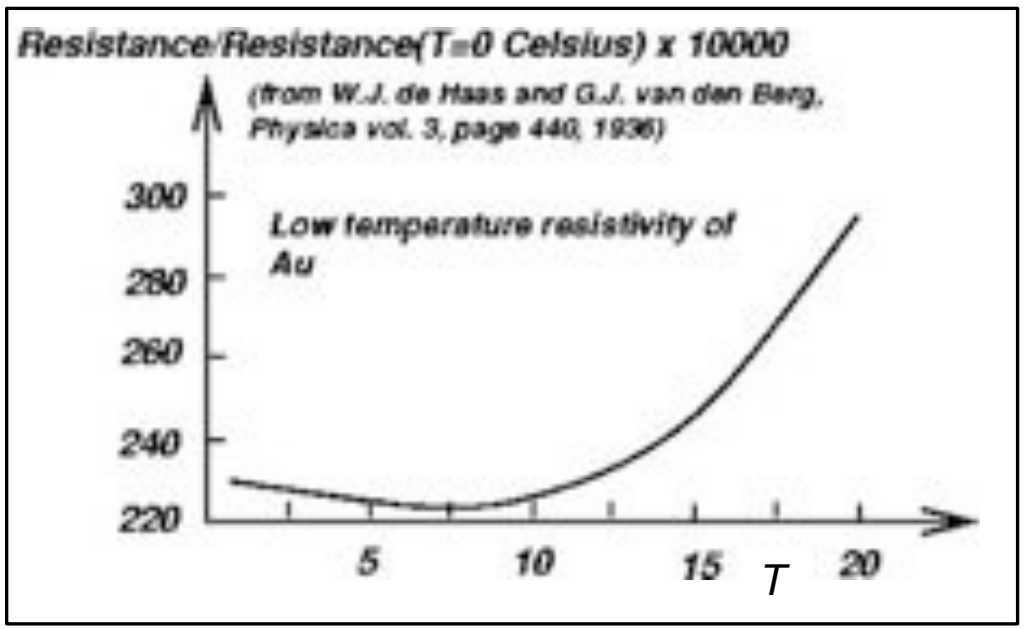

"A 75 year odyssey"

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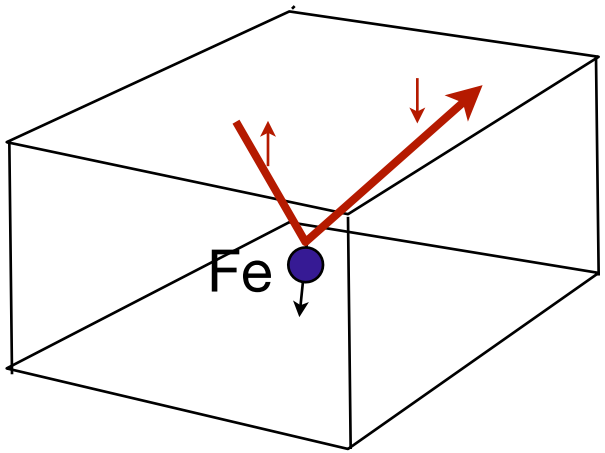

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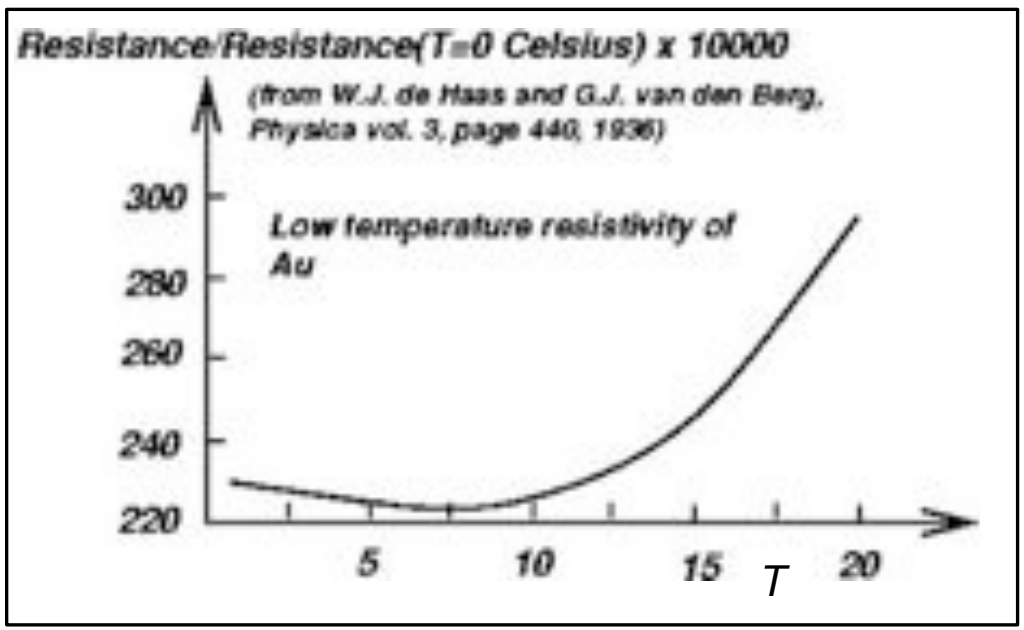
Kondo (1962)

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

"Kondo Temperature"



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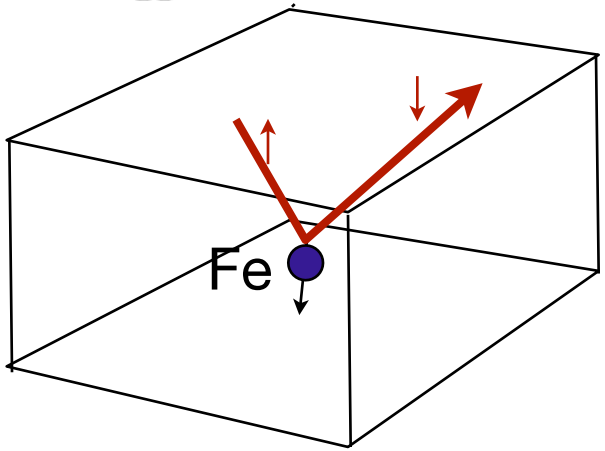

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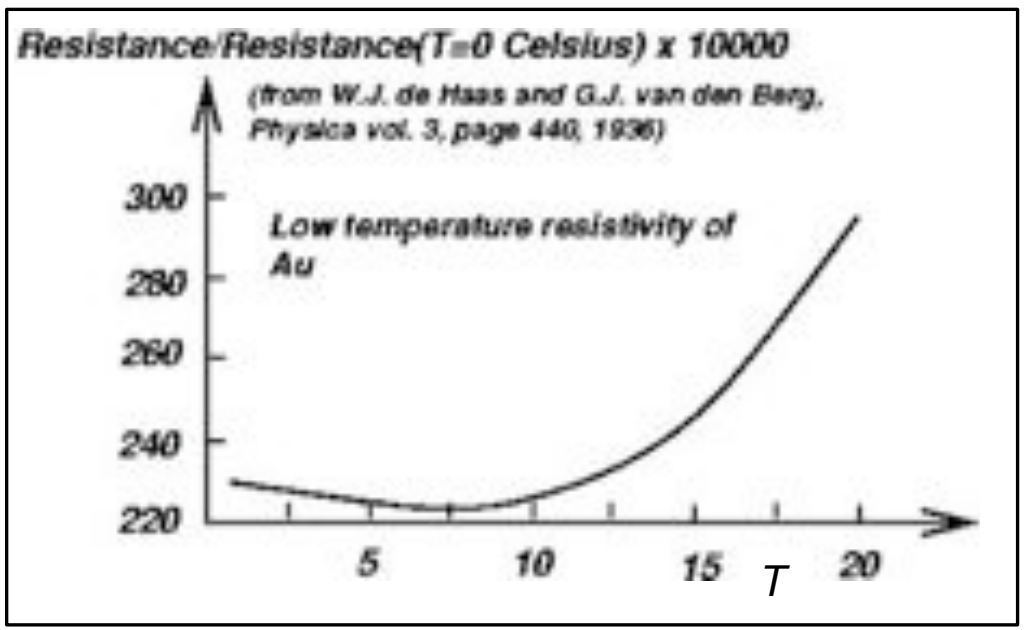

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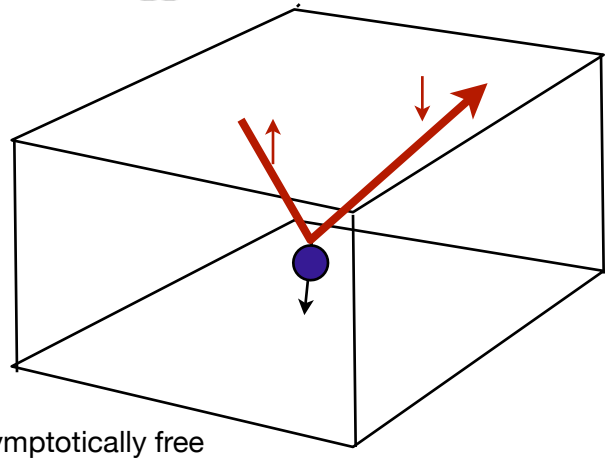

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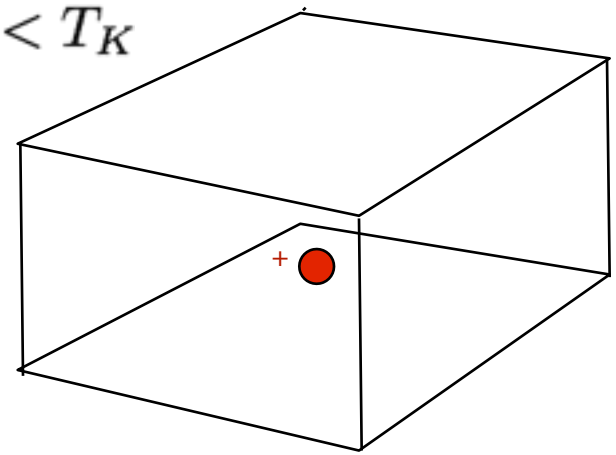

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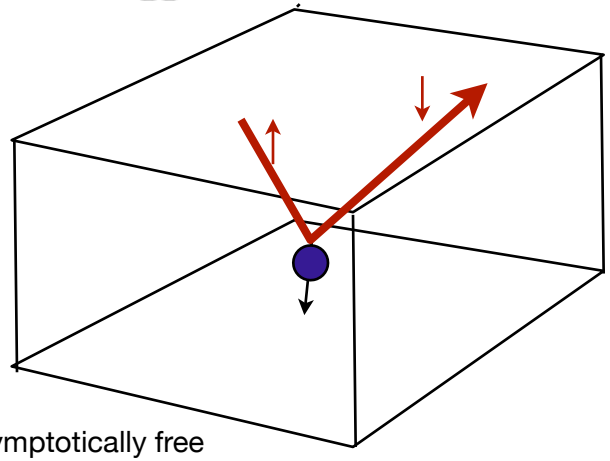

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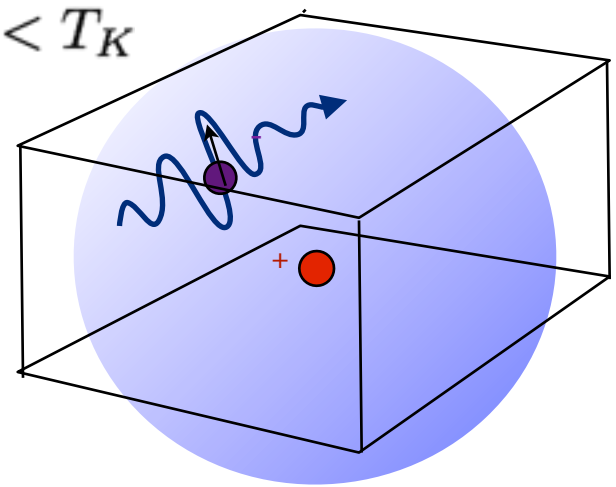

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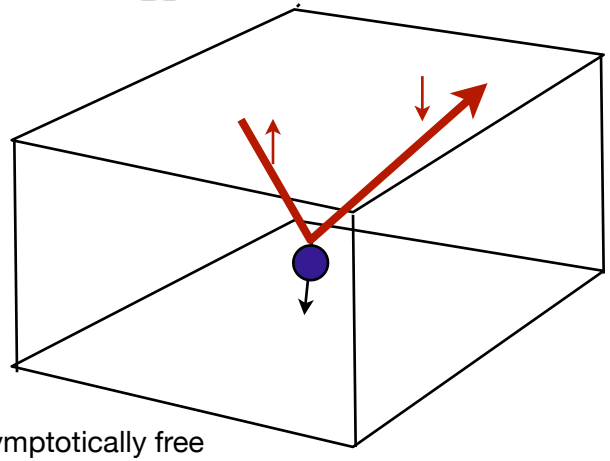

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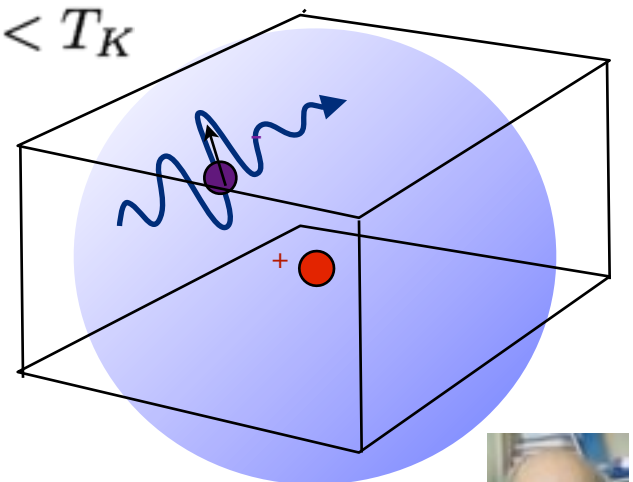

"Nozieres Local Fermi liquid"
(Nozieres 76)

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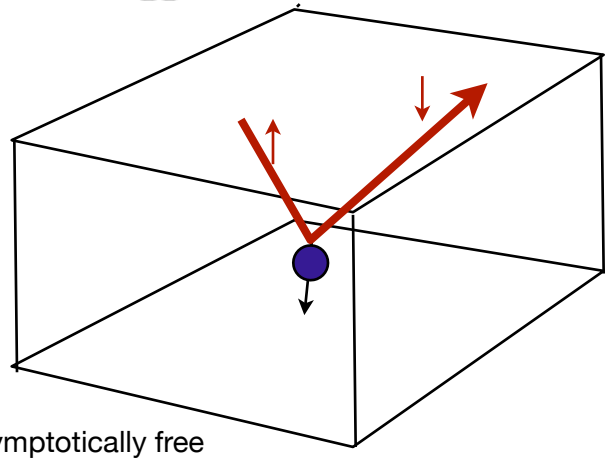

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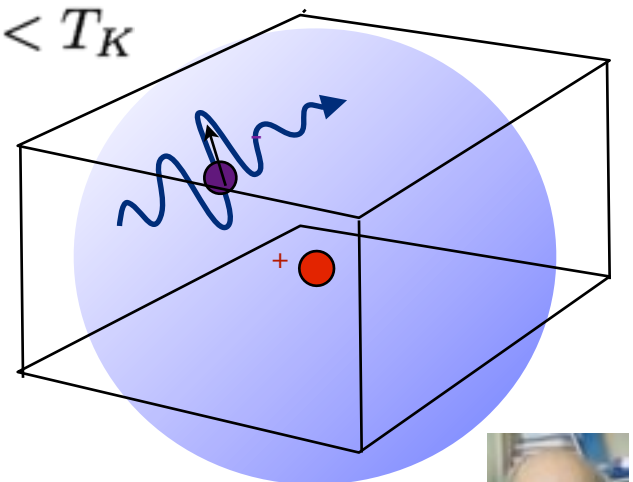

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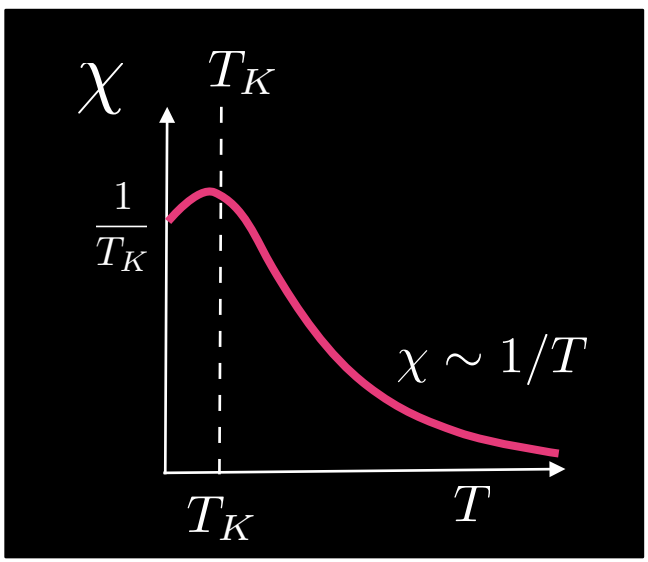

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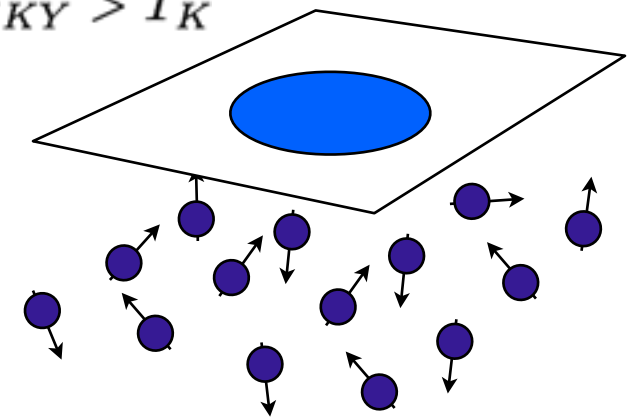

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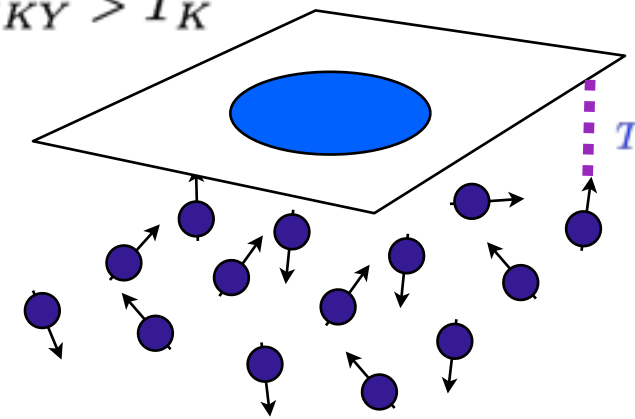

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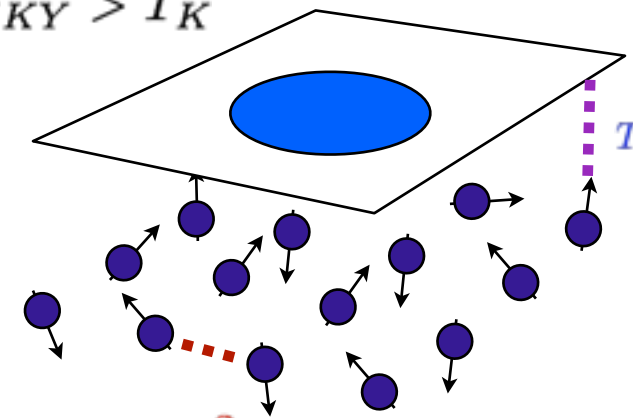

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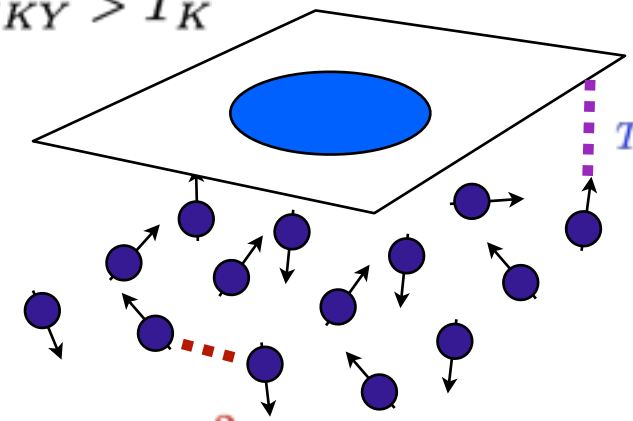

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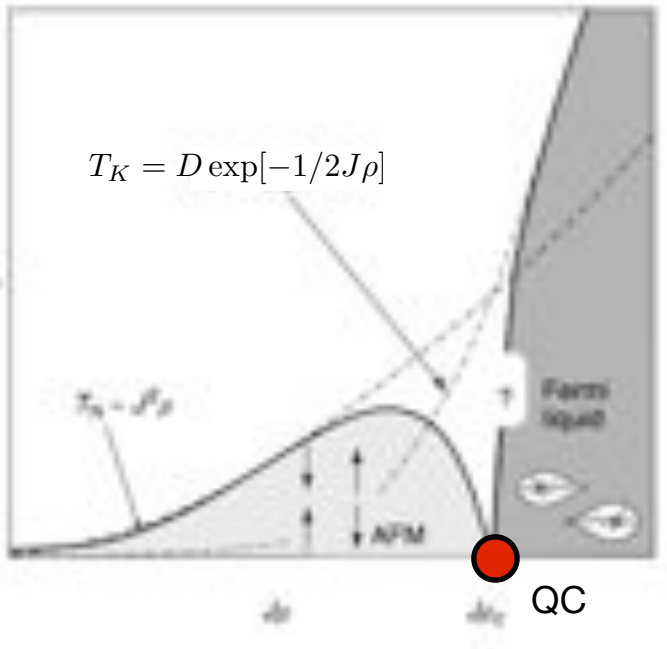

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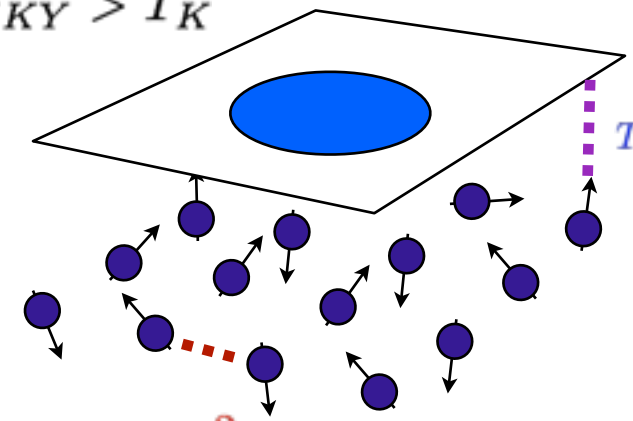

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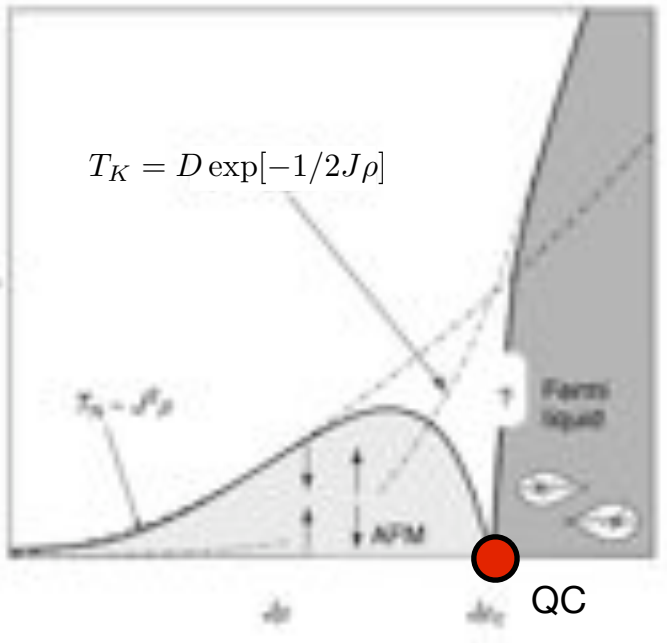

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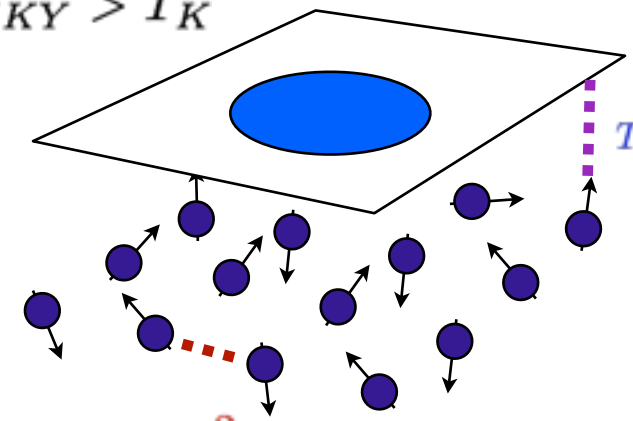

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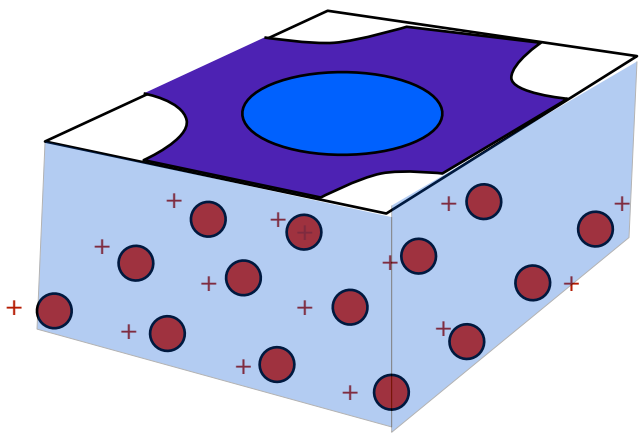
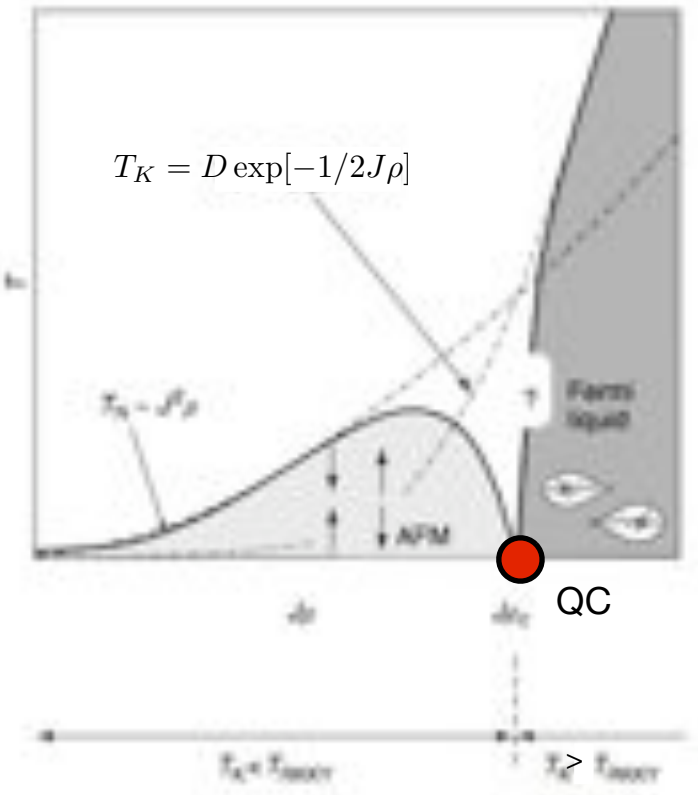
Large Fermi surface of composite Fermions





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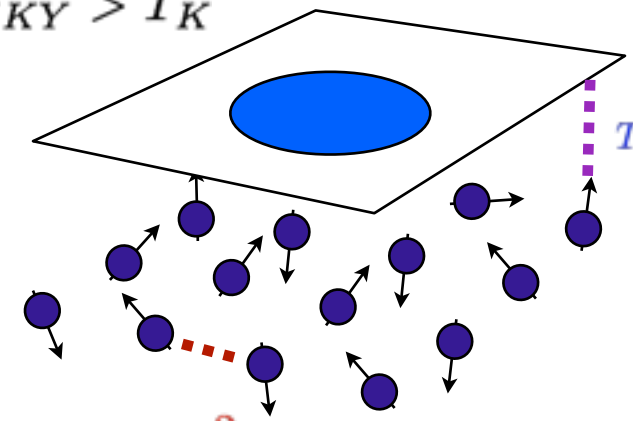

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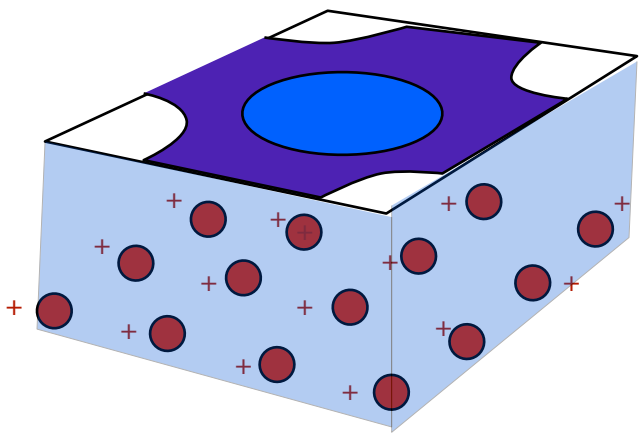
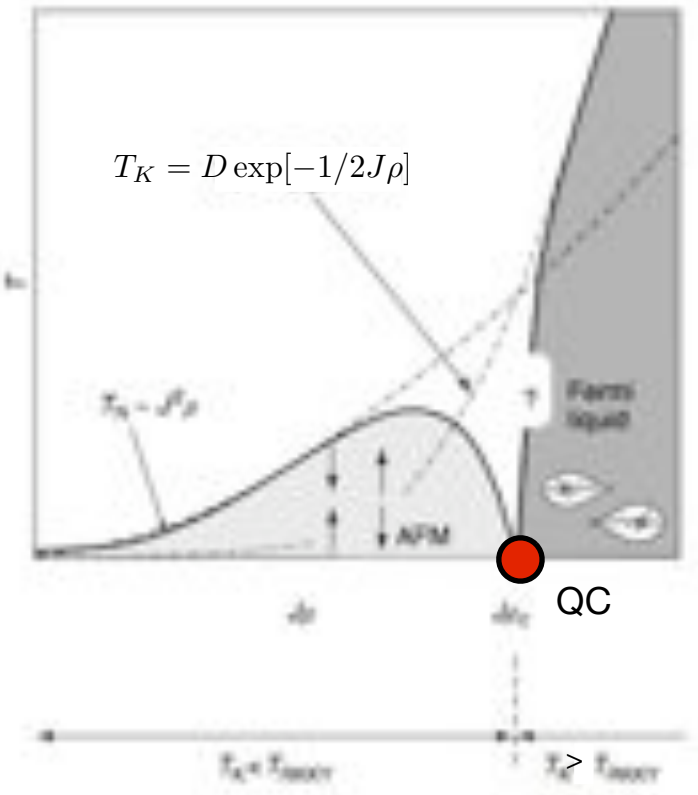
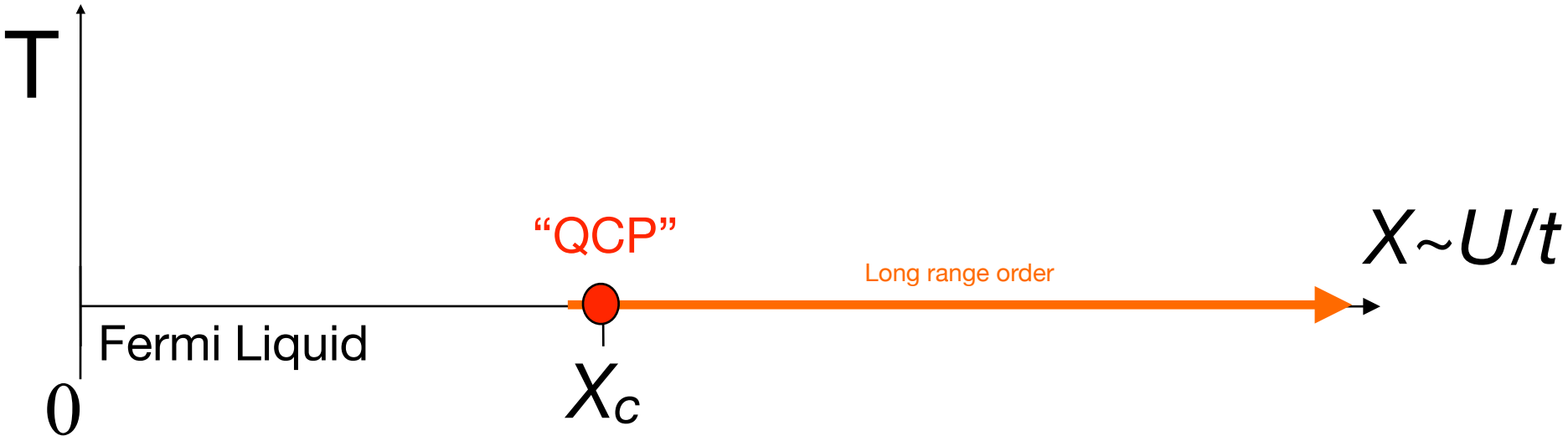
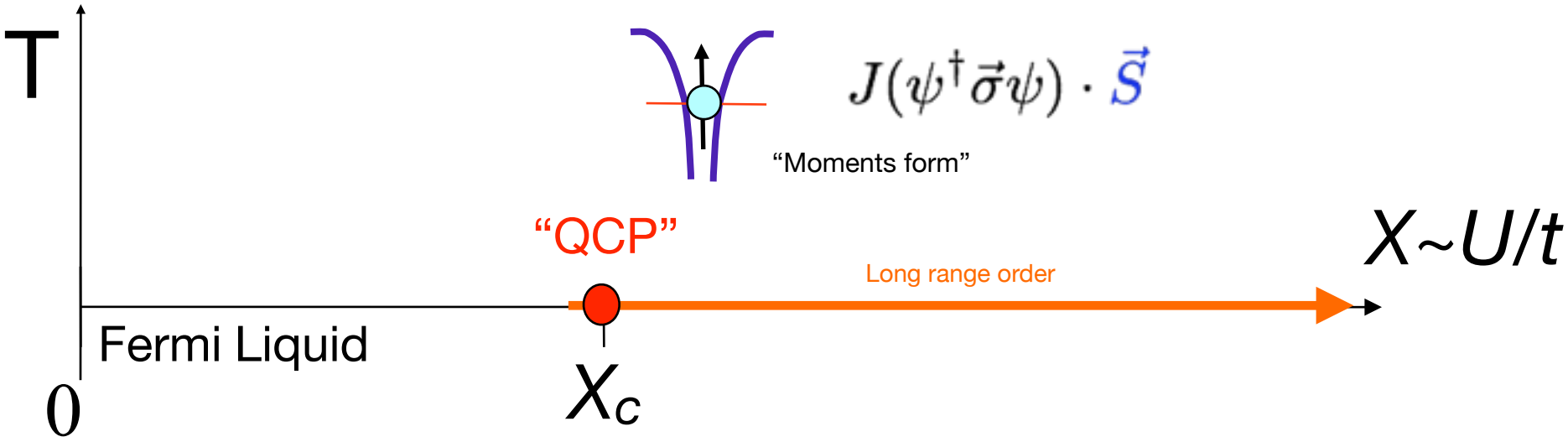
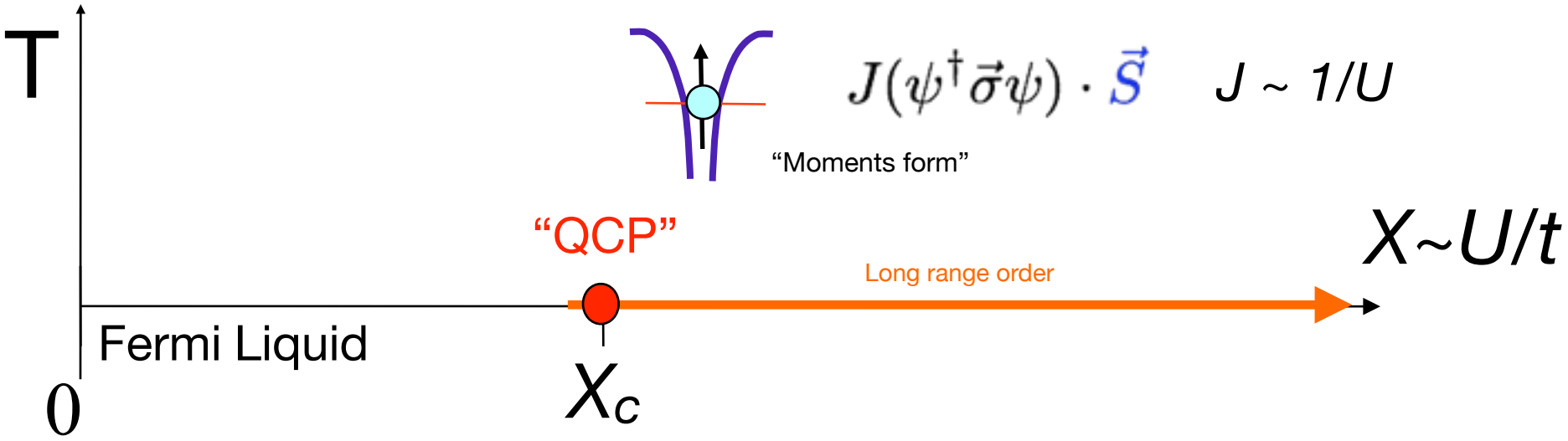


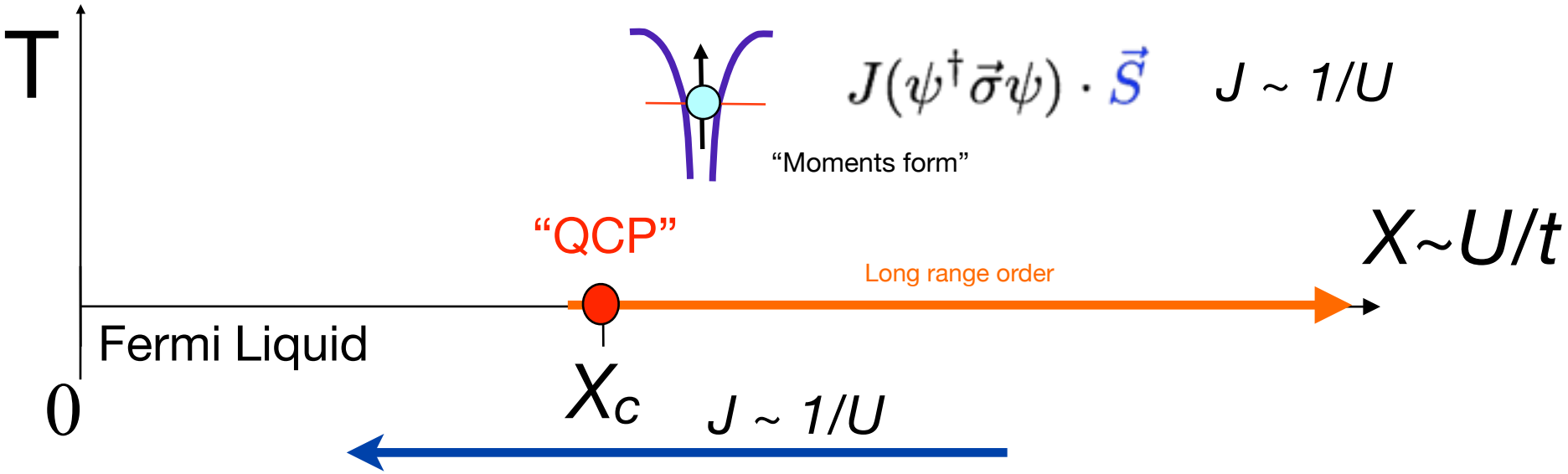


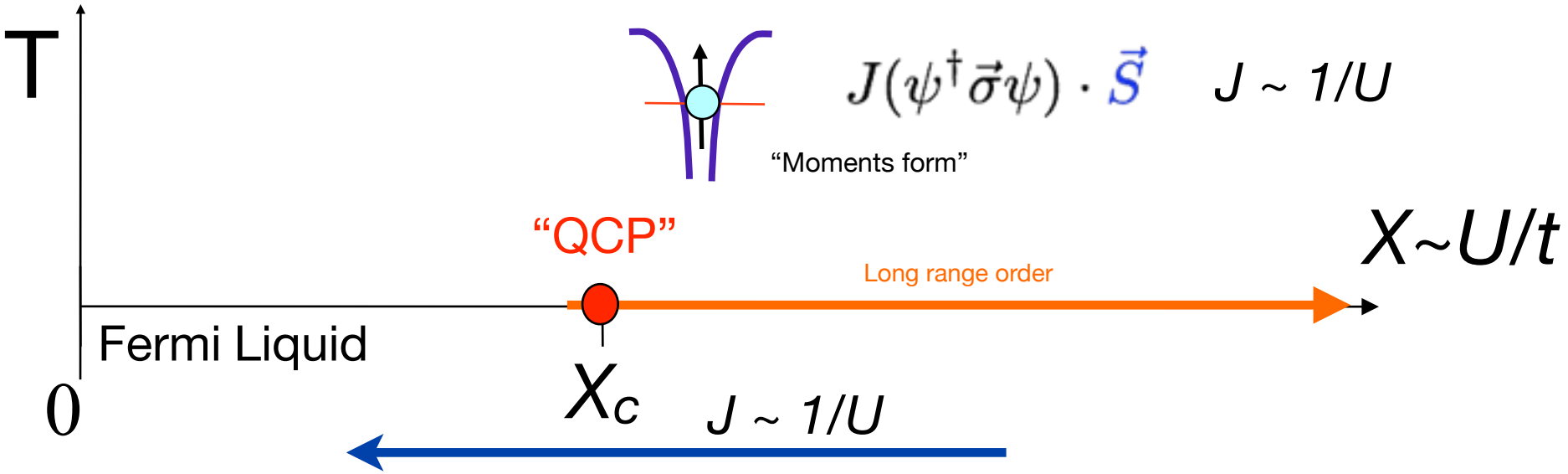
?

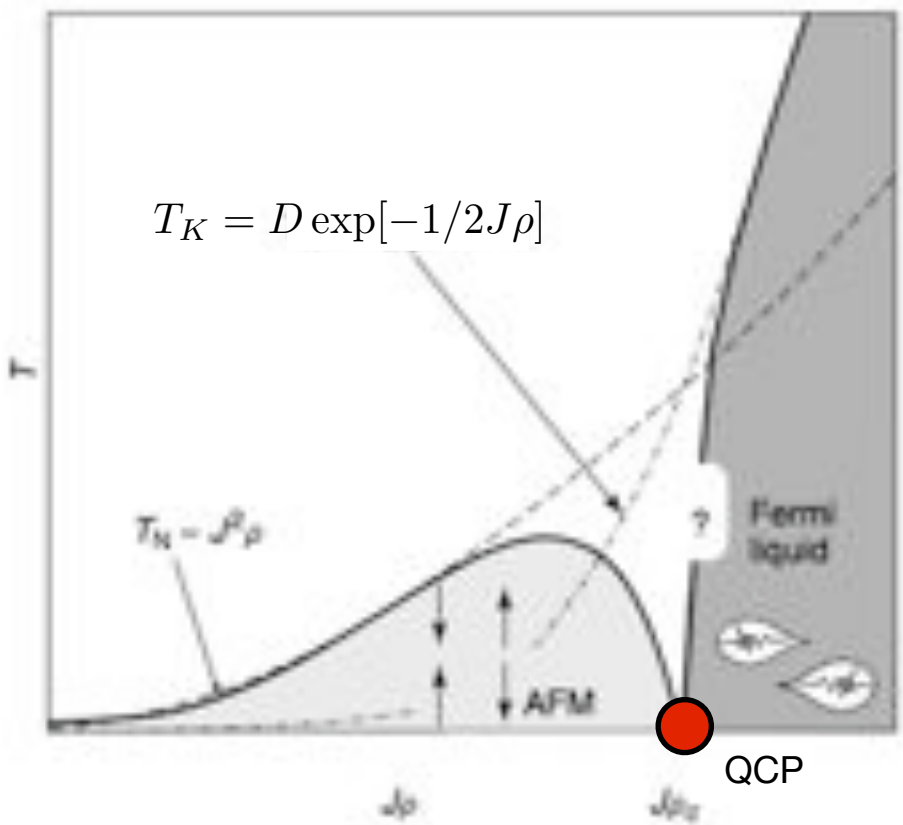

T
"QCP"
X~U/t
Long range order
Fermi Liquid
0
X_c

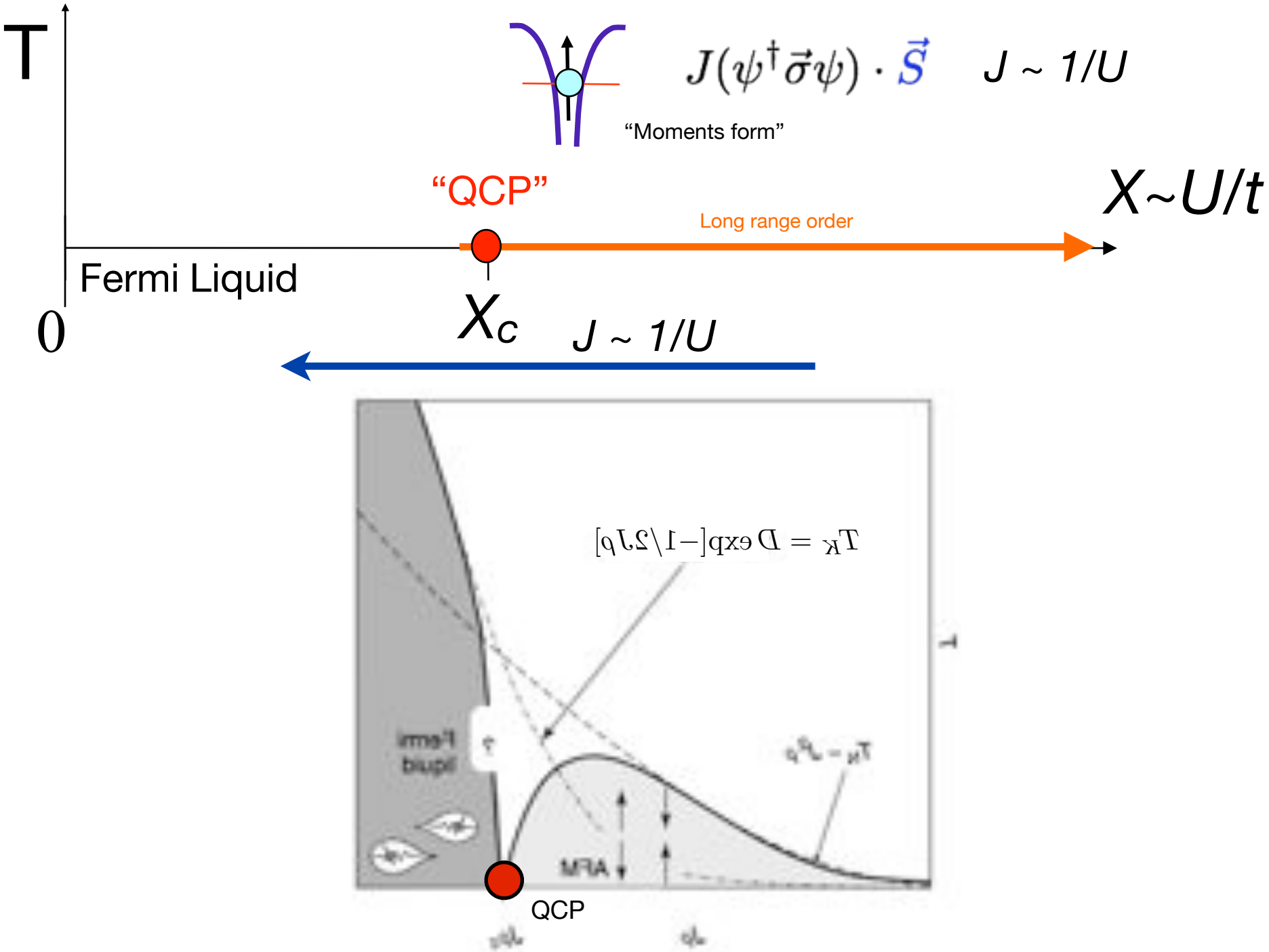

T
$J(\psi^\dagger \vec{\sigma} \psi) \cdot \vec{S}$
"Moments form"
"QCP"
X~U/t
Long range order
Fermi Liquid
0
X_c


T
$J(\psi^\dagger \vec{\sigma} \psi) \cdot \vec{S}$
J ~ 1/U
"Moments form"
"QCP"
X~U/t
Long range order
Fermi Liquid
0
X_c


T
$J(\psi^\dagger \vec{\sigma} \psi) \cdot \vec{S}$
J ~ 1/U
"Moments form"
"QCP"
X~U/t
Long range order
Fermi Liquid
0
X_c
J ~ 1/U

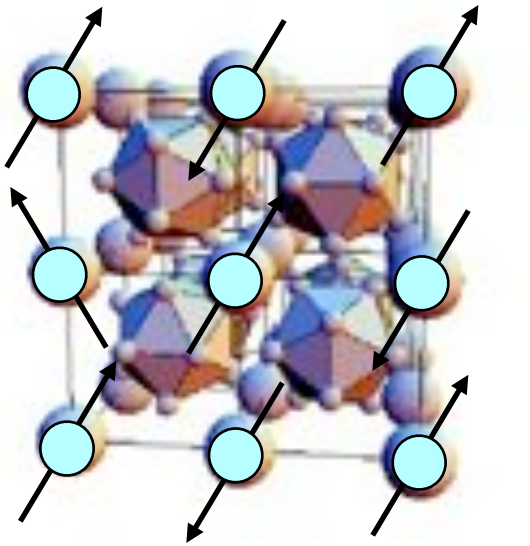

T
$J(\psi^\dagger \vec{\sigma} \psi) \cdot \vec{S}$
J ~ 1/U
"Moments form"
"QCP"
X~U/t
Long range order
Fermi Liquid
0
X_c
J ~ 1/U


$T_K = D \exp[-1/2J\rho]$
T
$T_N \sim J^2\rho$
?
Fermi liquid
AFM
QCP


T
$J(\psi^\dagger \vec{\sigma} \psi) \cdot \vec{S}$
J ~ 1/U
"Moments form"
"QCP"
X~U/t
Long range order
Fermi Liquid
0
X_c
J ~ 1/U
QCP

Heavy Fermion Metals

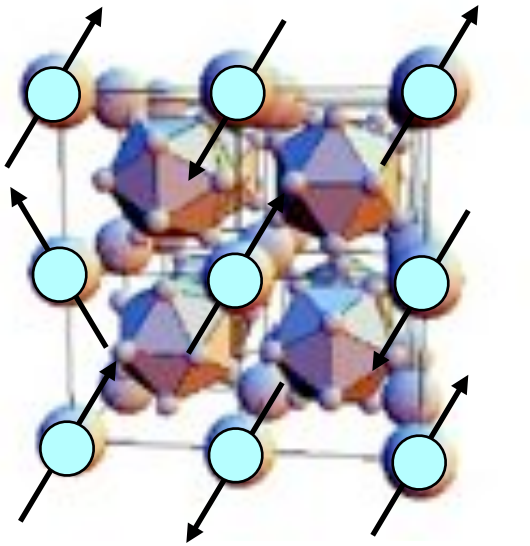
Review: cond-mat/0612006



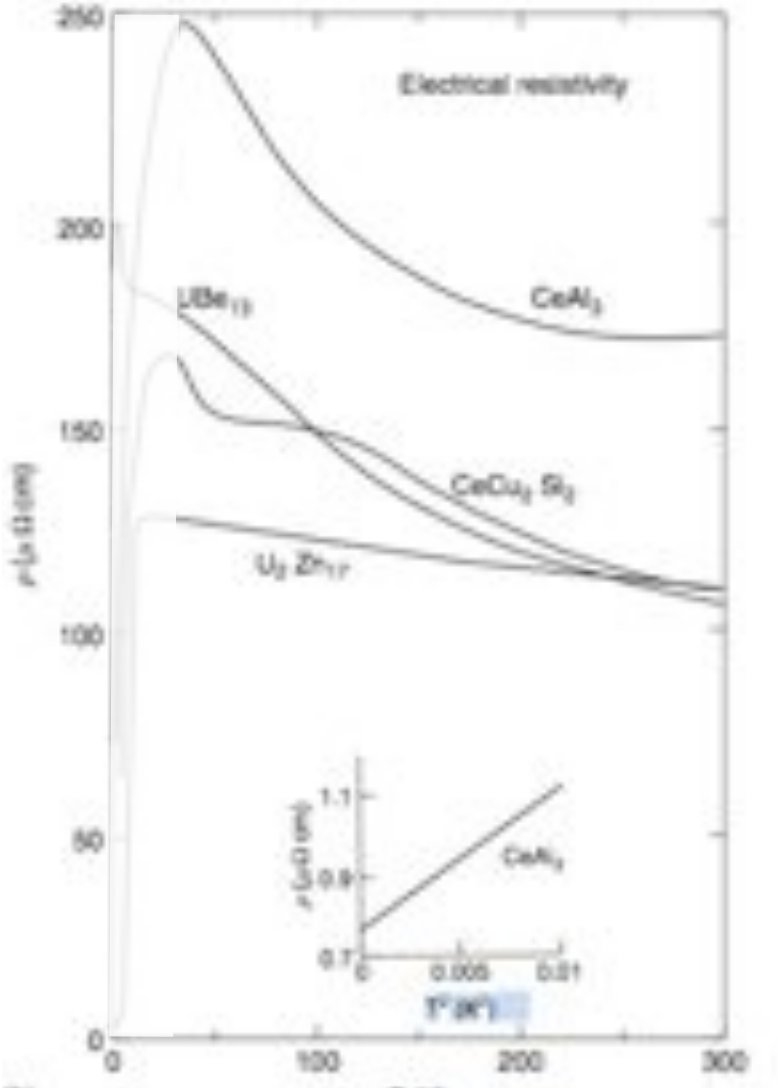
UBe_{13}

Heavy Fermion Metals

Review: cond-mat/0612006

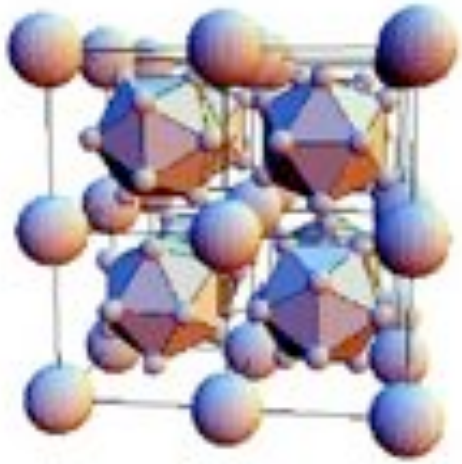


UBe_{13}

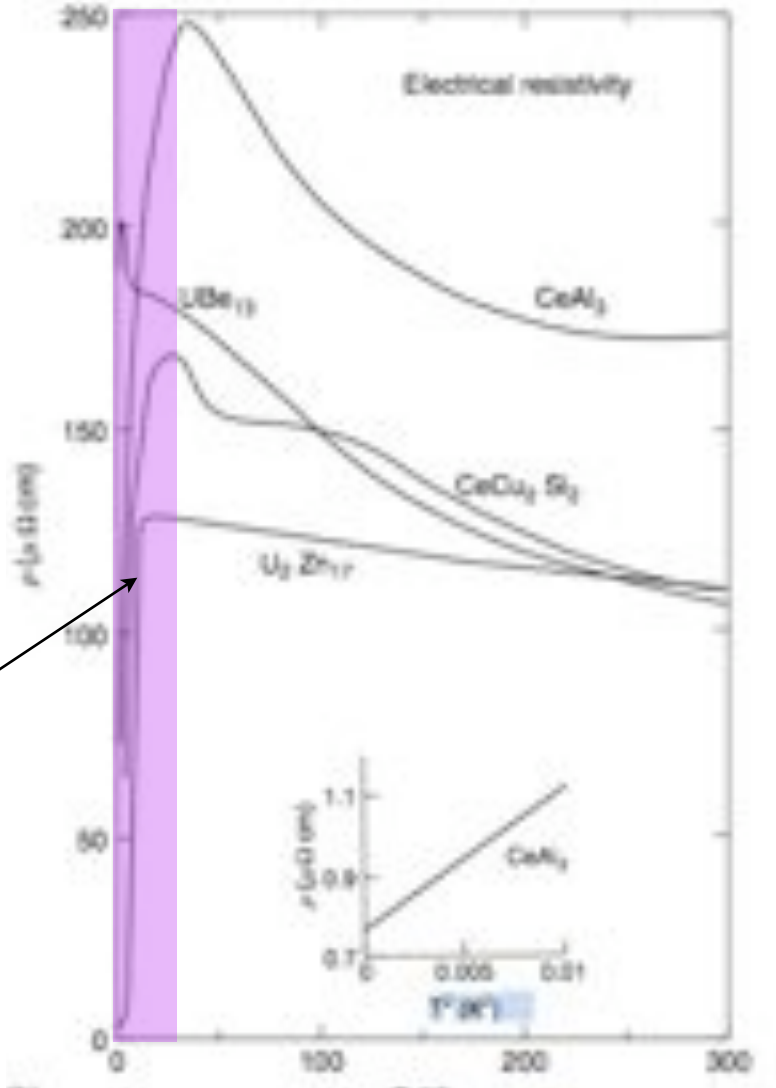


Heavy Fermion Metals

Review: cond-mat/0612006



UBe_{13}



Coherent
Heavy Fermi Liquid

Qu-era: revolutions always have a second part.

Classical vs quantum criticality.

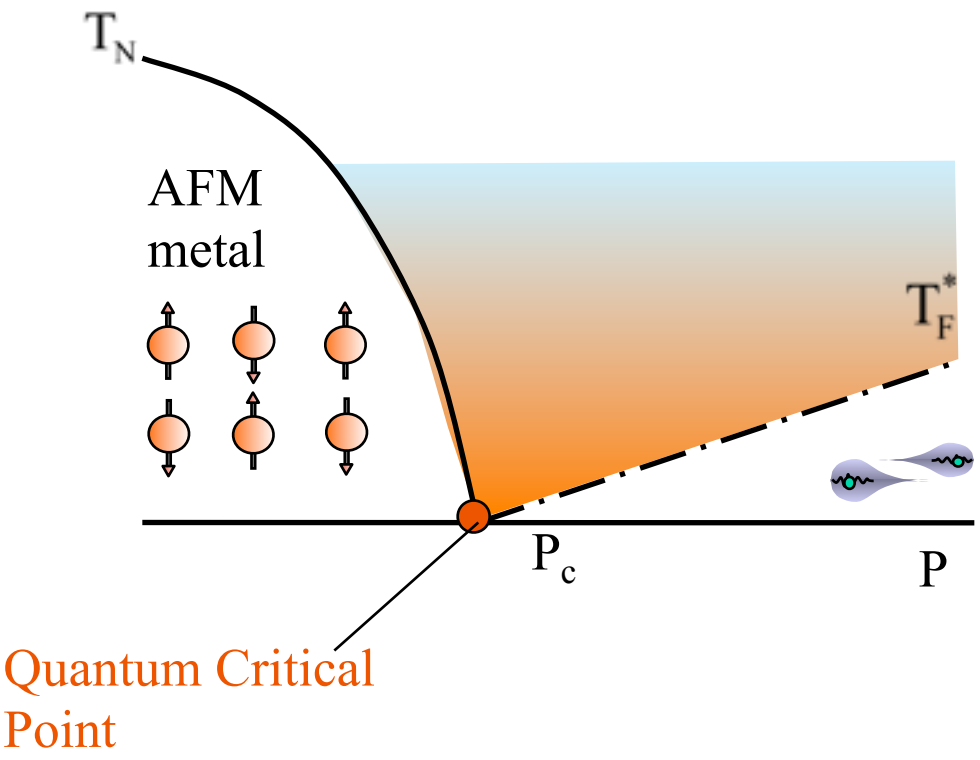
Peierls' question.

Heavy electron Quantum Criticality:

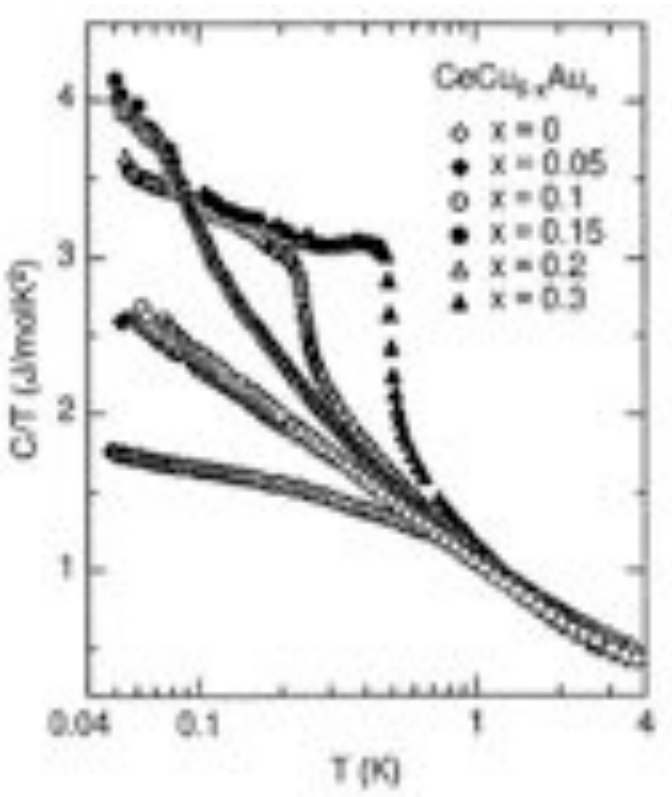
Experiments

Quantum Criticality: divergent specific heat capacity

Heavy Fermion Materials

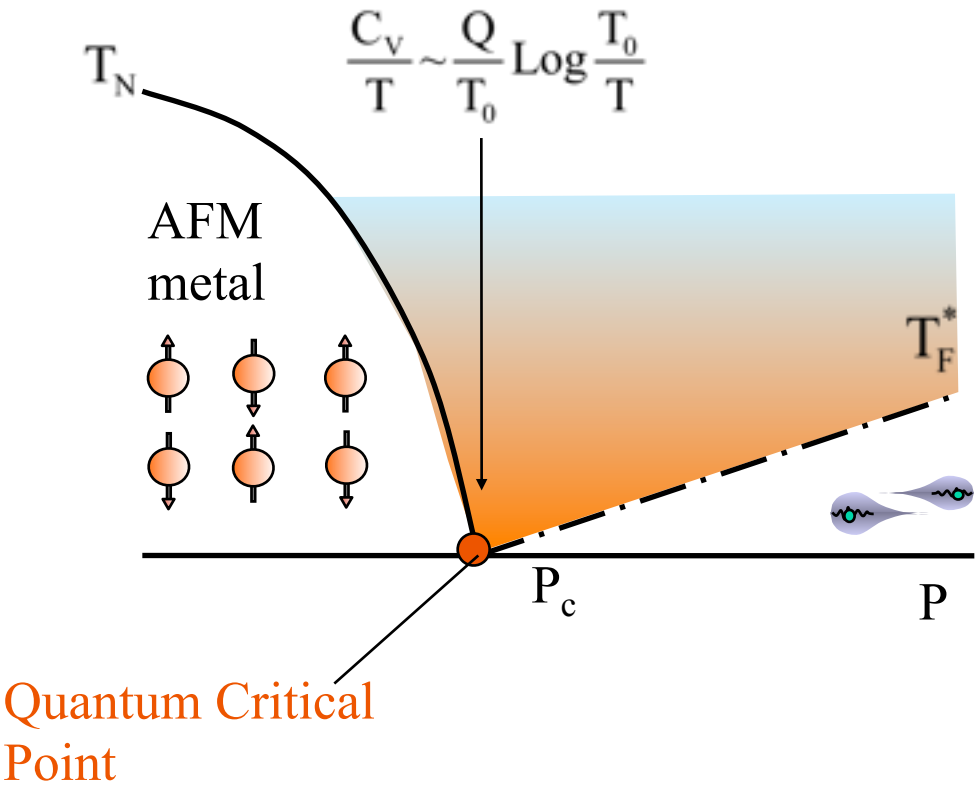


H. Von Lohneyson (1996)



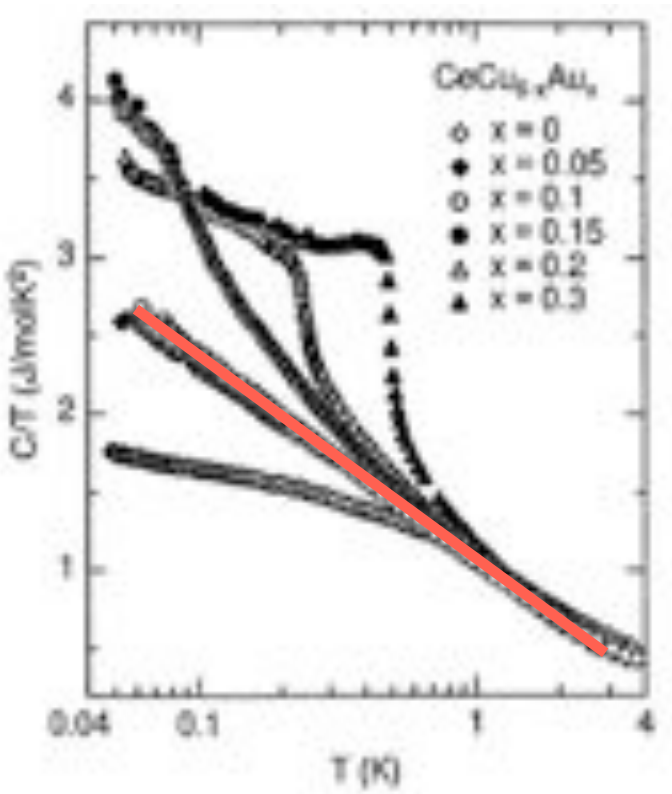
Quantum Criticality: divergent specific heat capacity

Heavy Fermion Materials



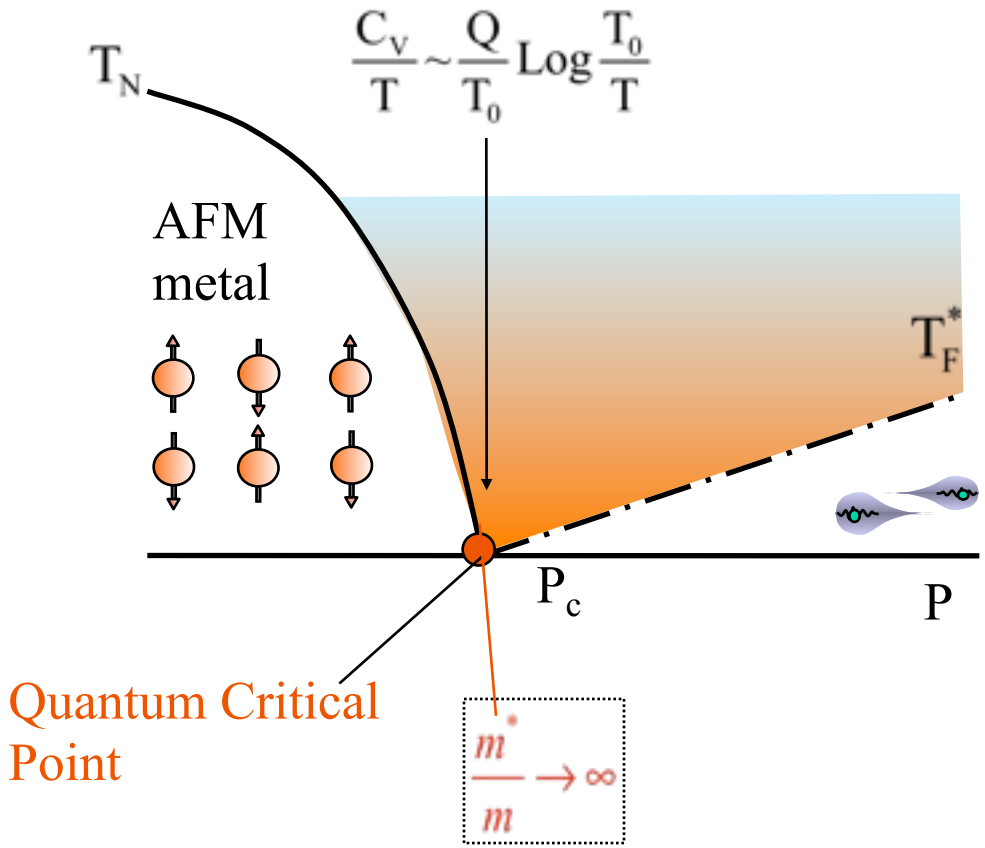
Quantum Critical Point

H. Von Lohneyson (1996)



Quantum Criticality: divergent specific heat capacity

Heavy Fermion Materials



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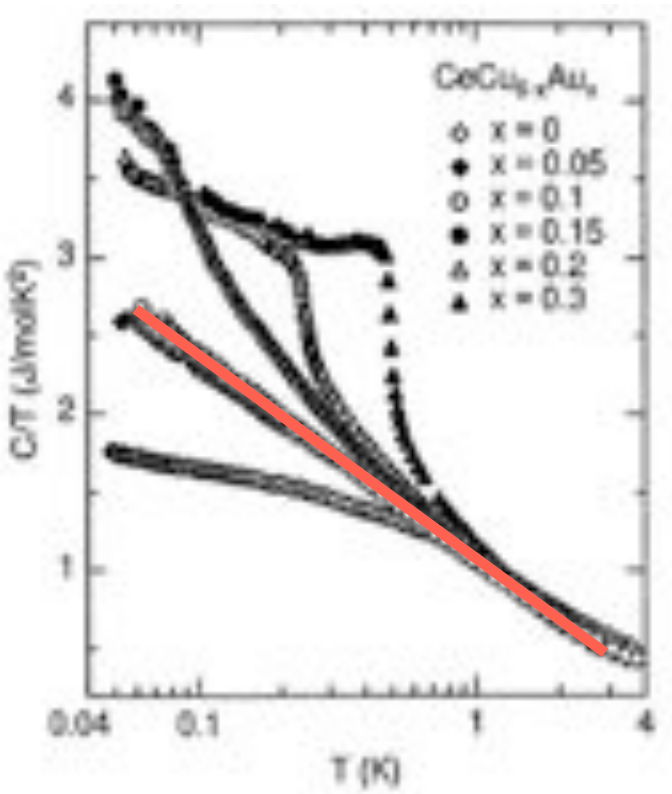
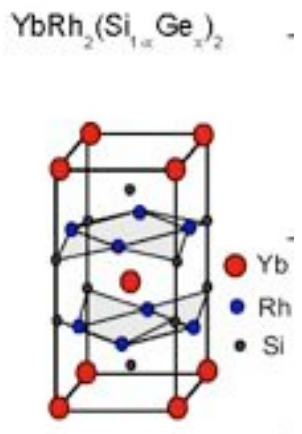
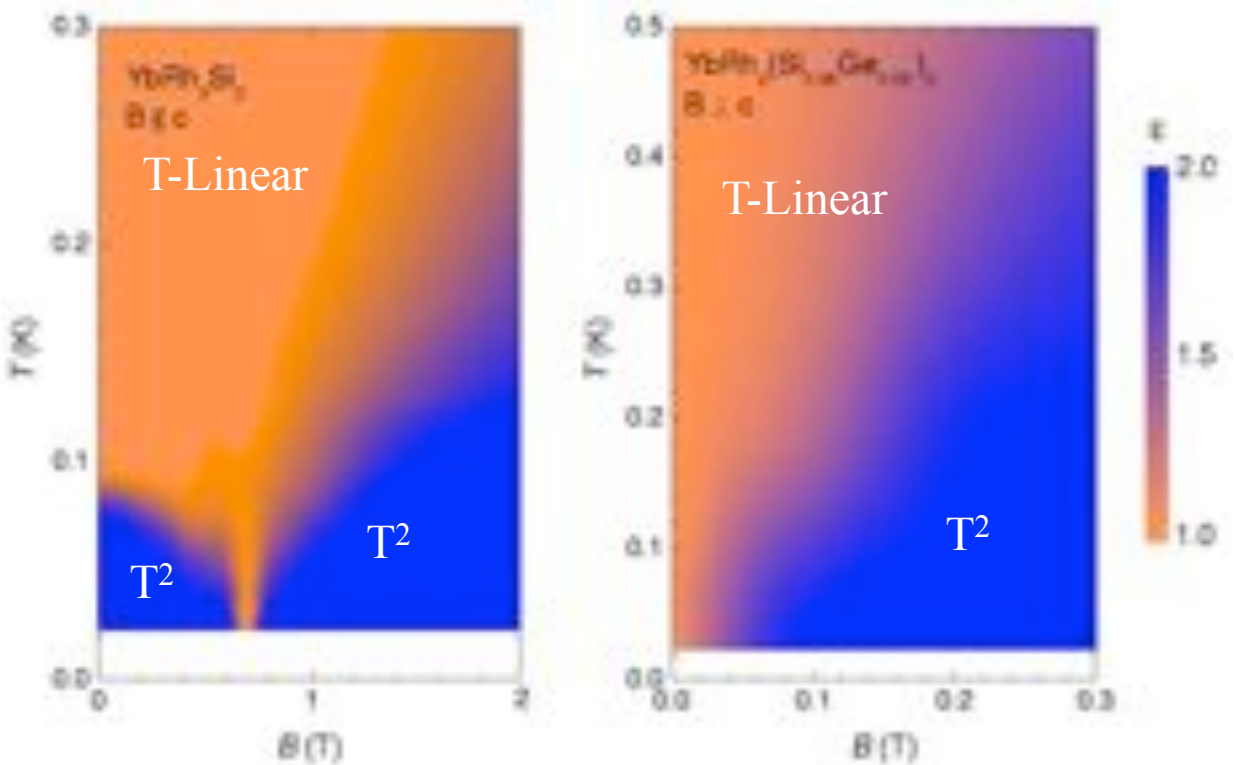


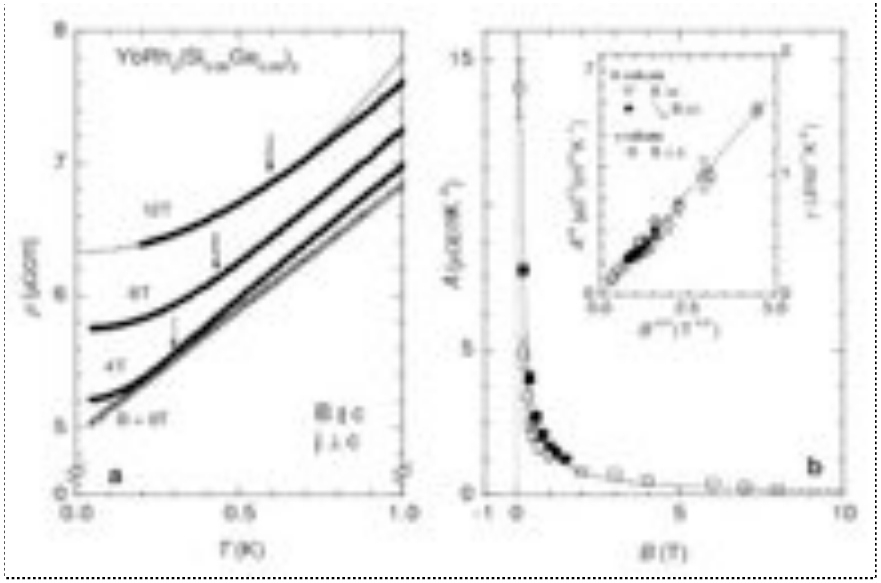
Divergence of Interaction and Effective Mass

Gegenwart et al (2002)





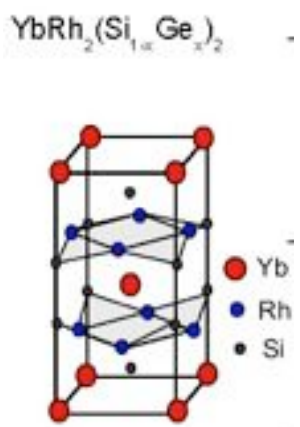
Divergence of Interaction and Effective Mass

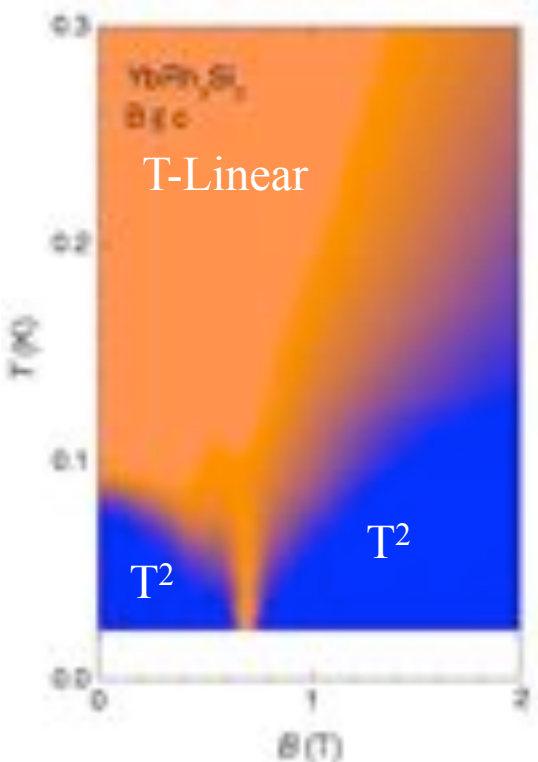


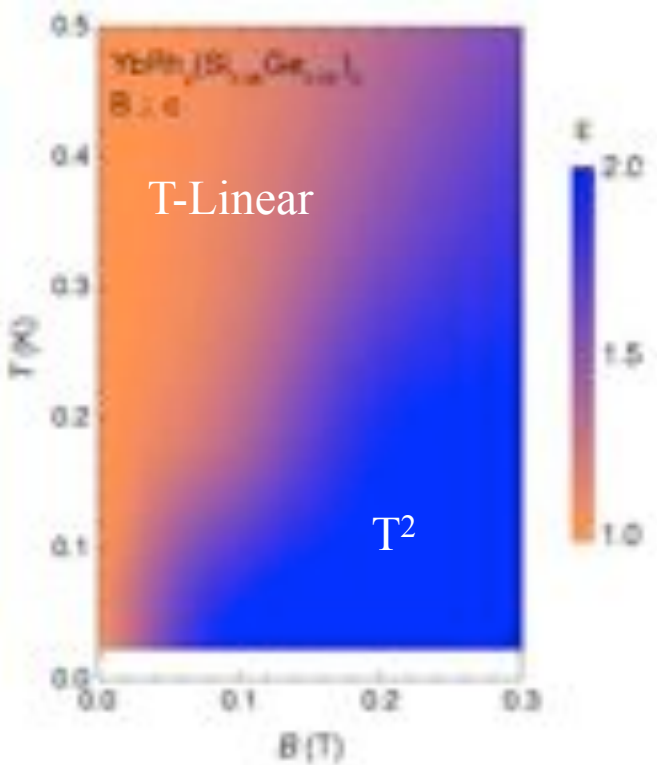
$$\rho = AT^2 + \rho_0$$

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

Gegenwart et al (2002)

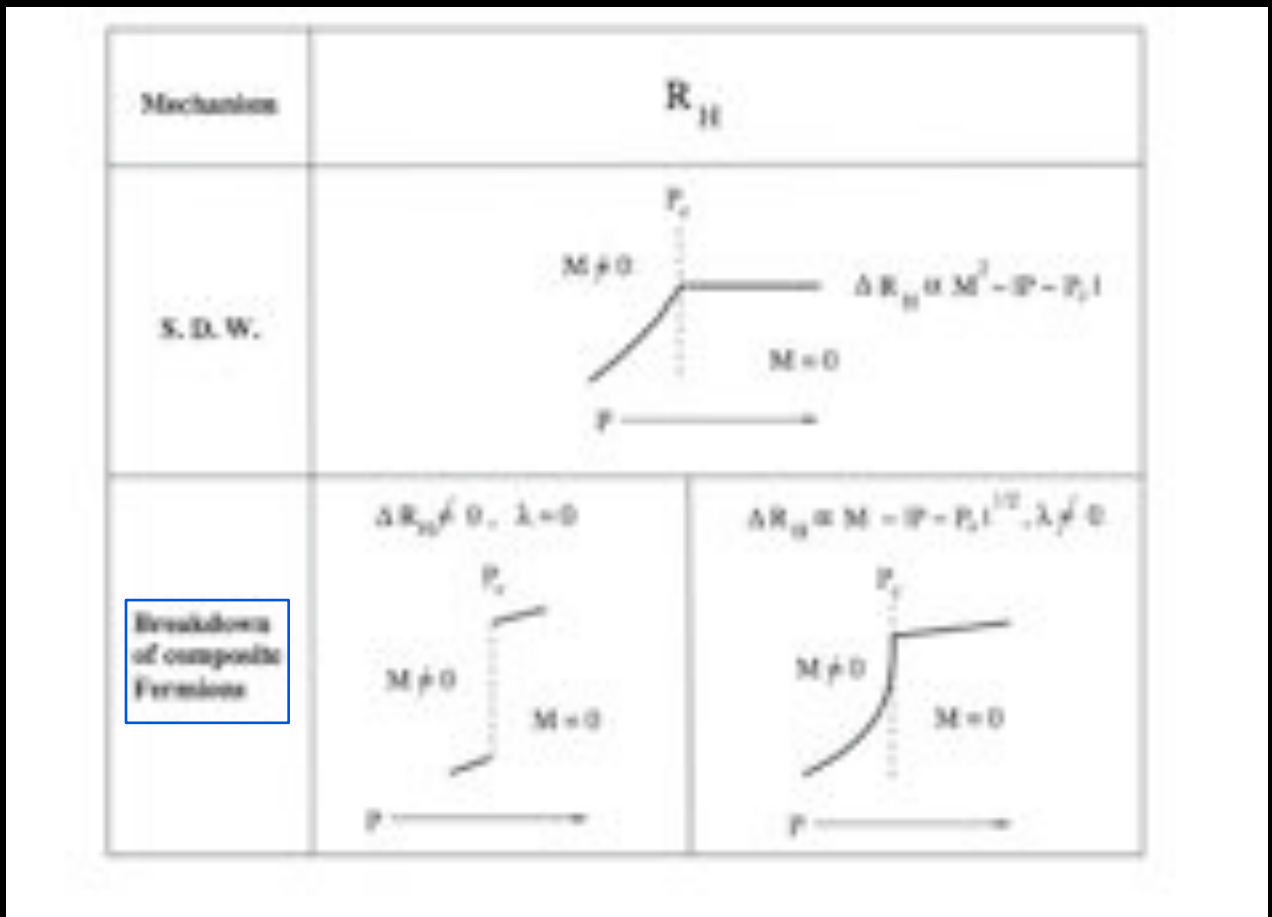




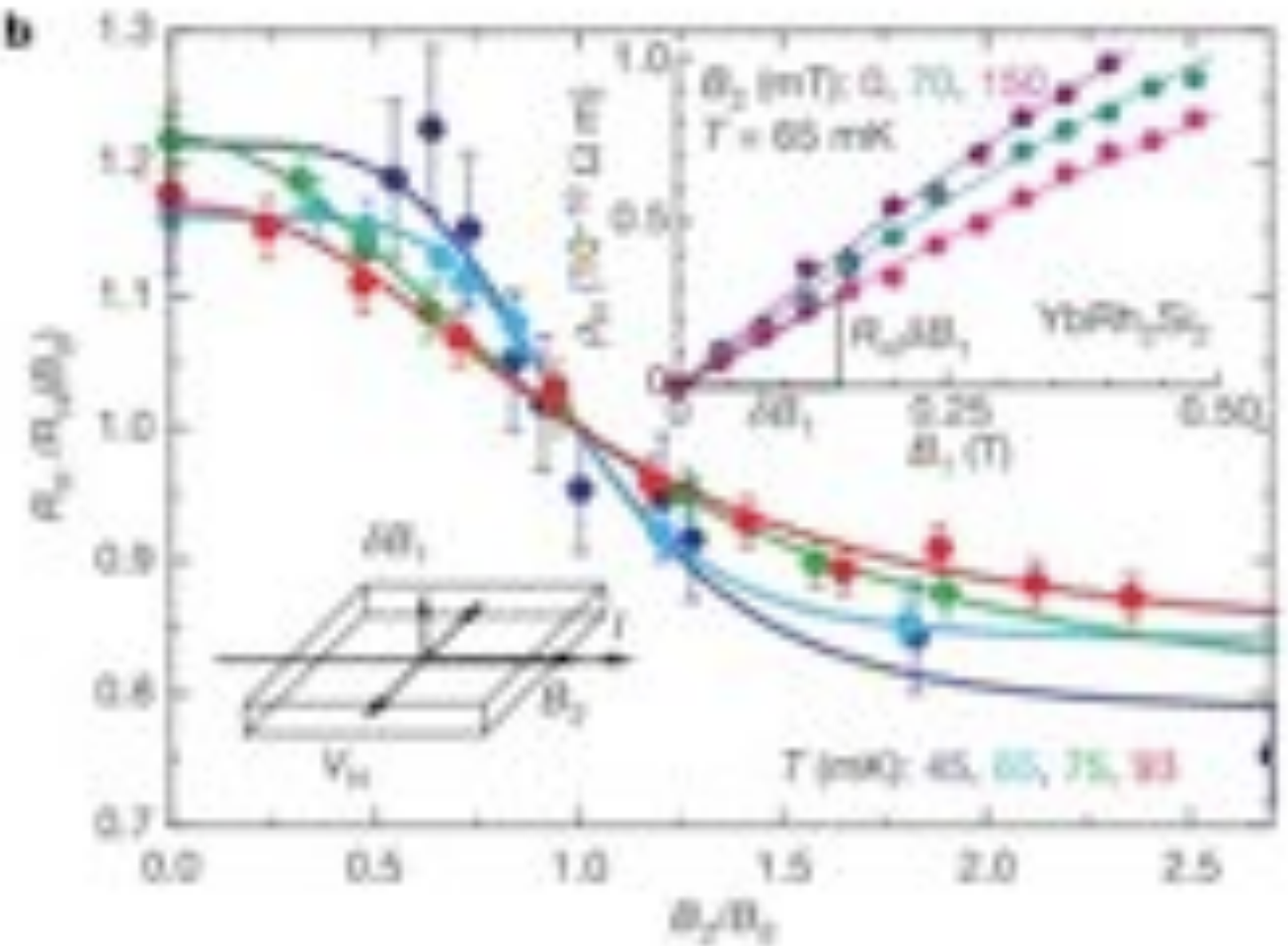


"How do fermions get heavy and die?" PC, Pepin, Si and Ramazashvili, J. Cond Matt. ,13}, R723 (2001).

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



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



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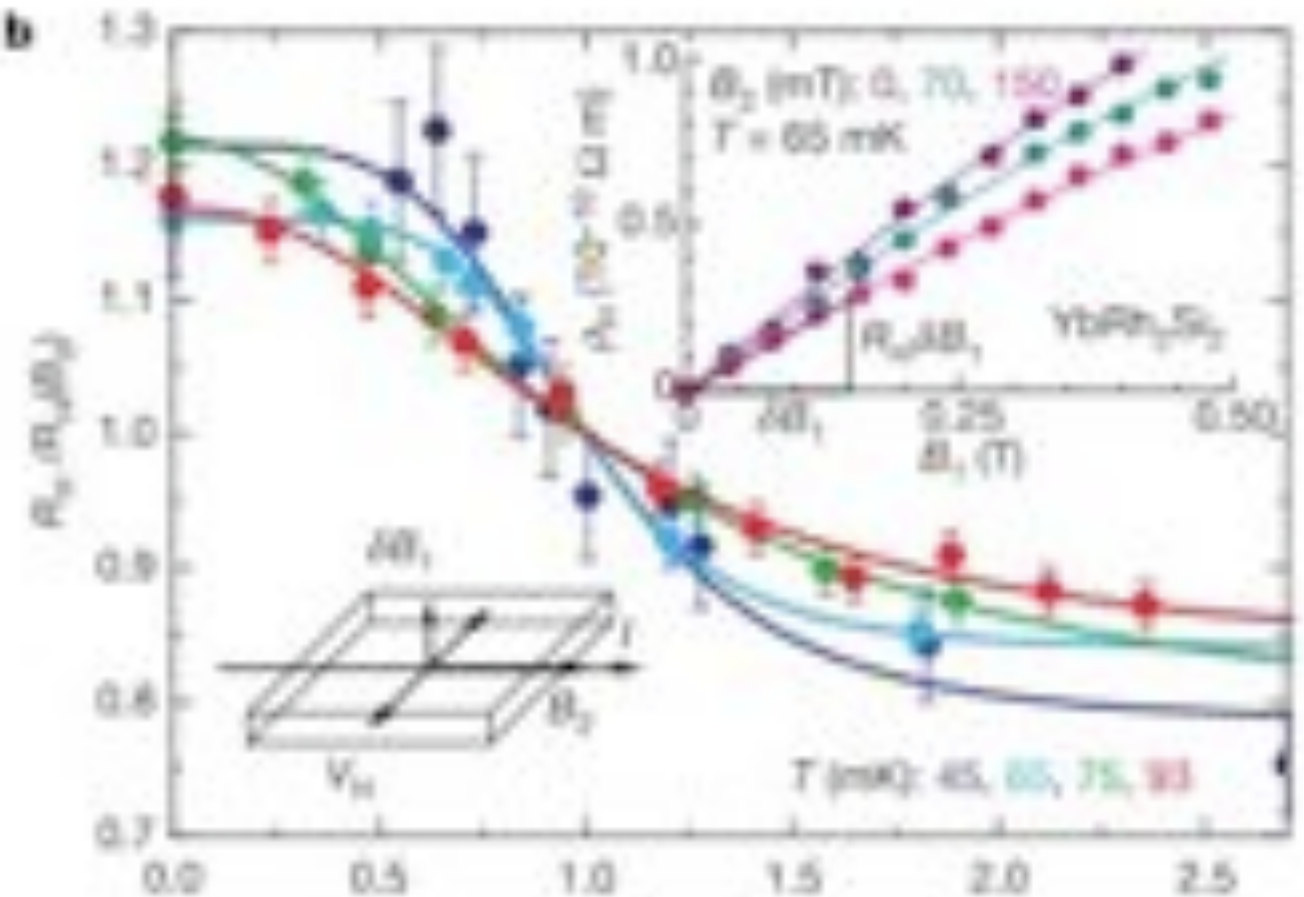
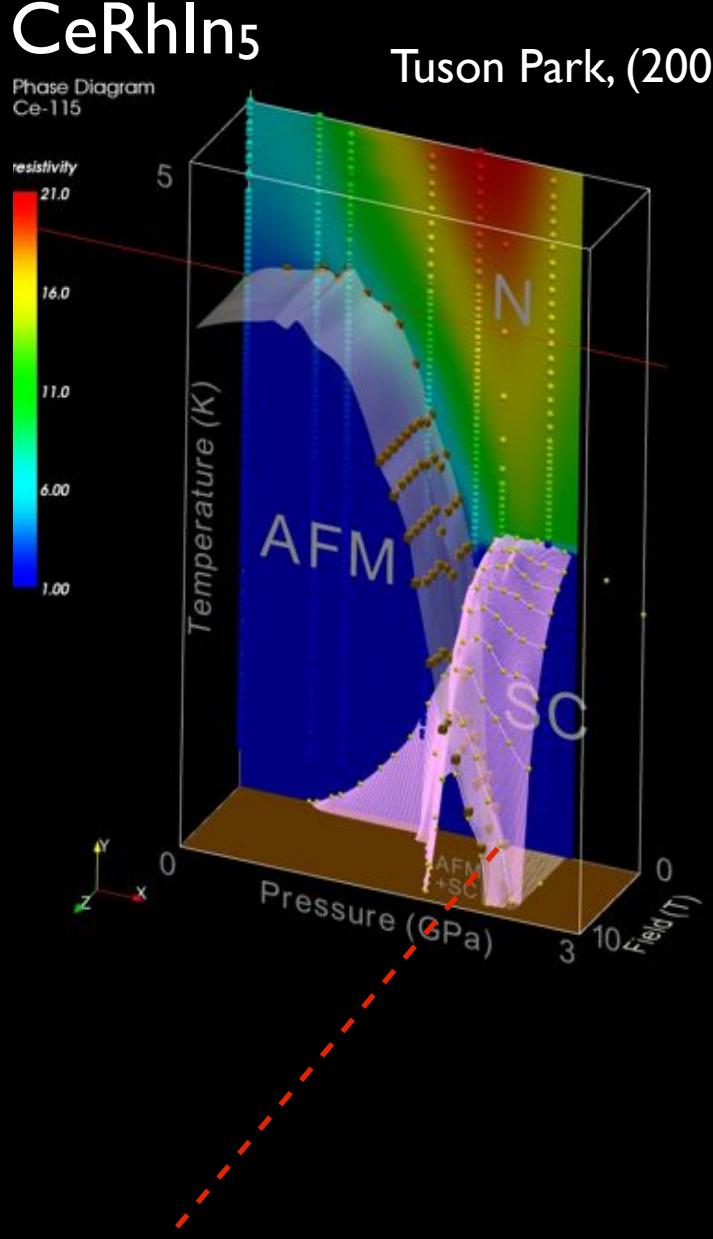
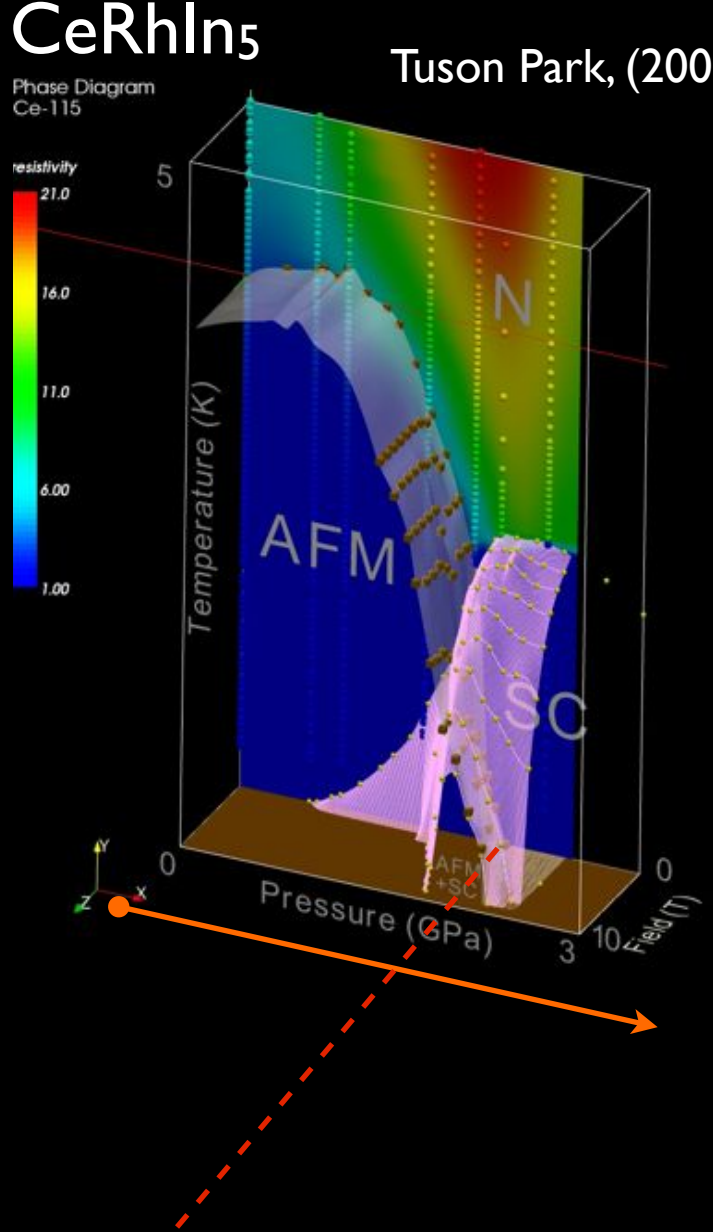


Jump in the Hall constant at a field tuned QCP.

Reconstruction of the Fermi Surface and mass divergence



Reconstruction of the Fermi Surface and mass divergence



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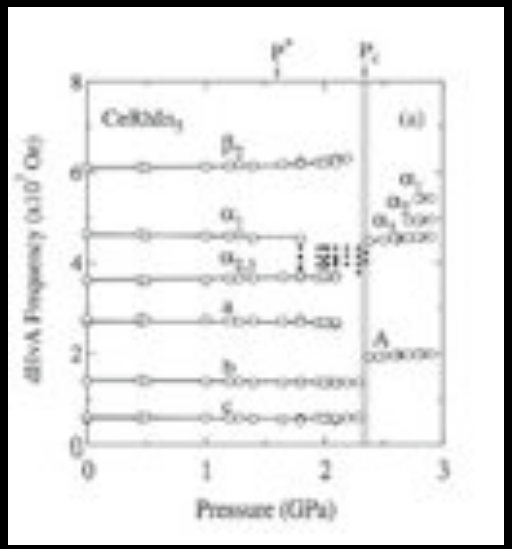
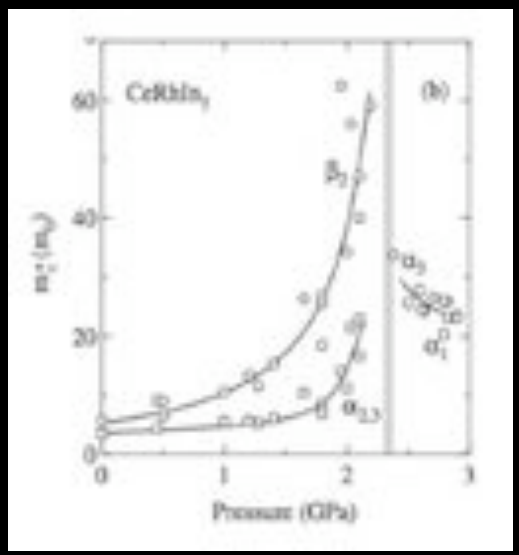
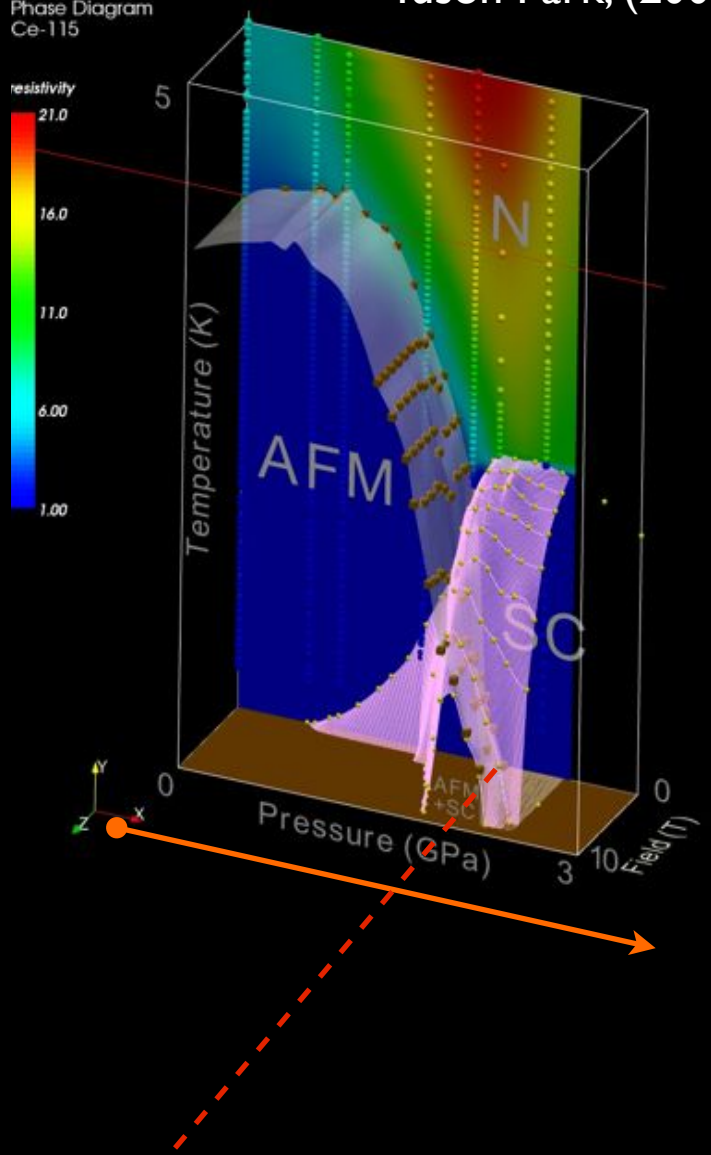




Shishido et al (2006)

CeRhIn5

Tuson Park, (2007).



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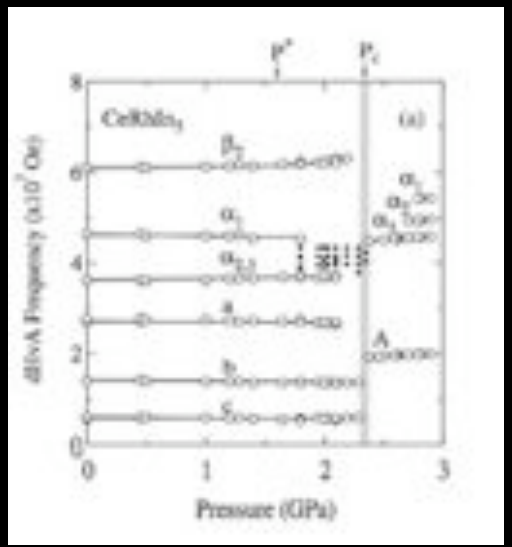

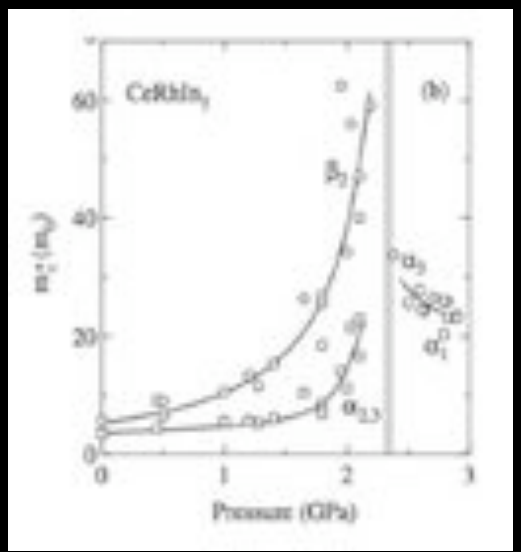

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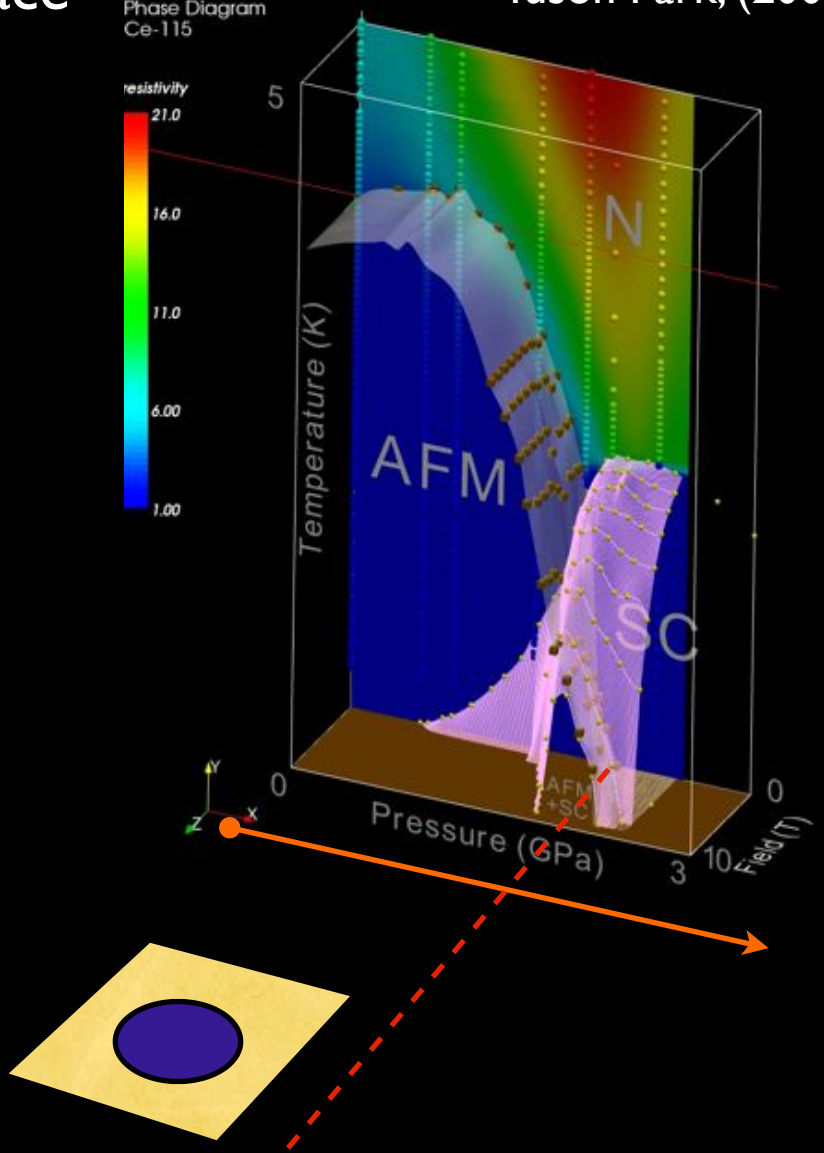

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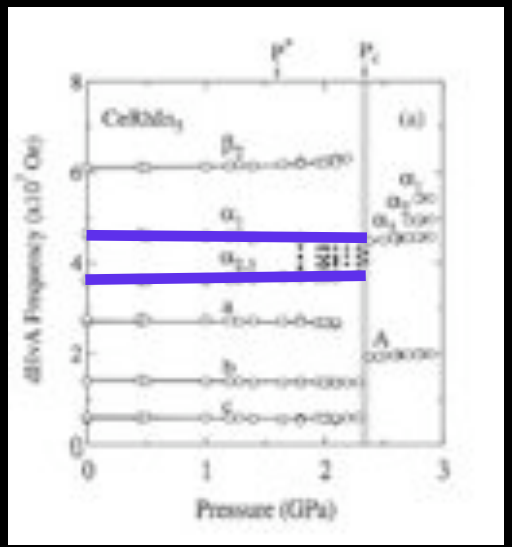

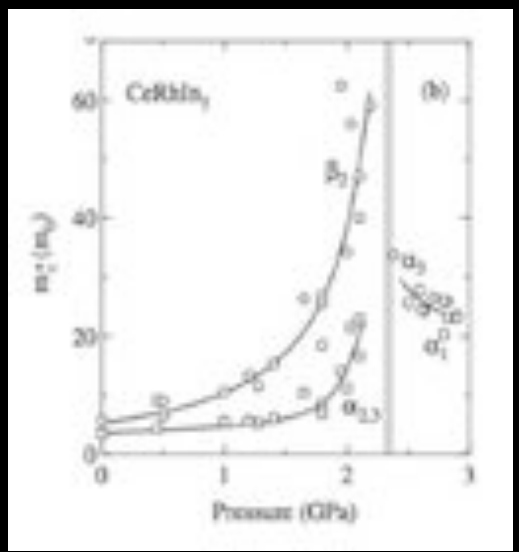

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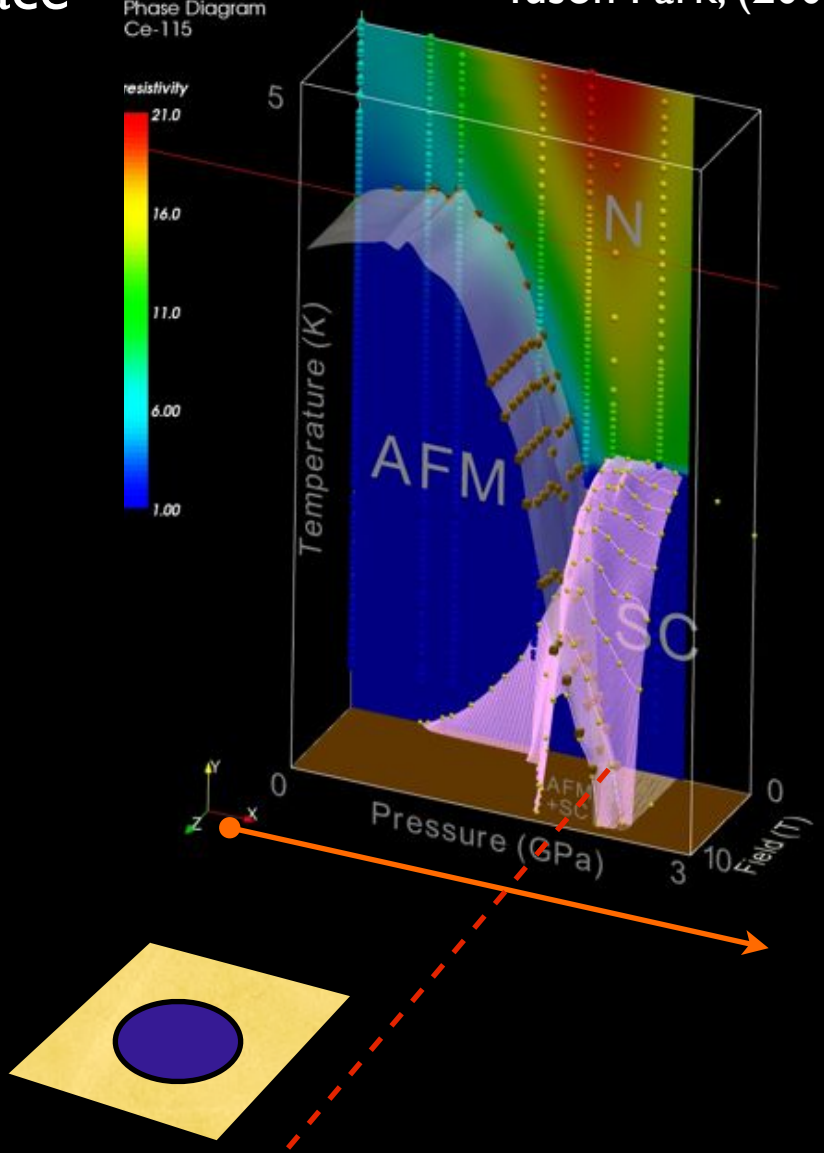

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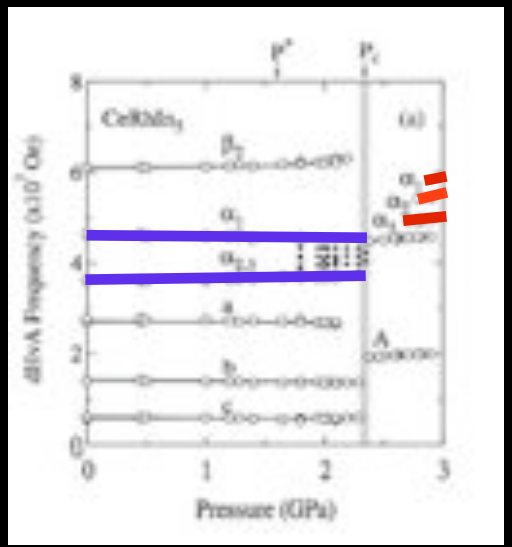

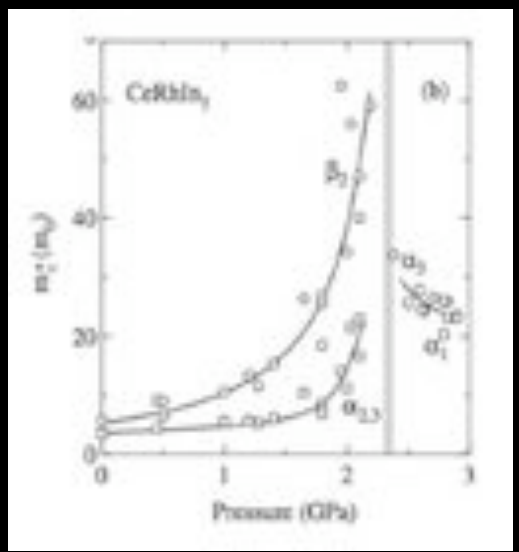

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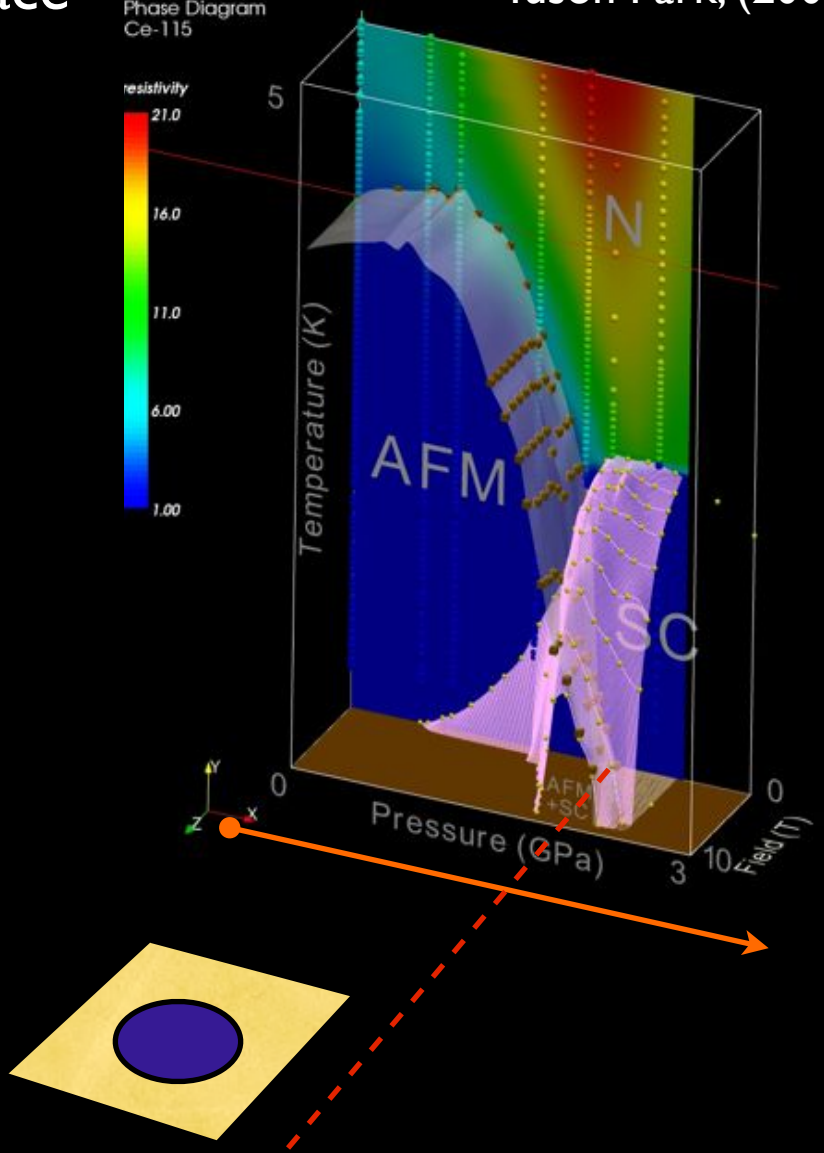

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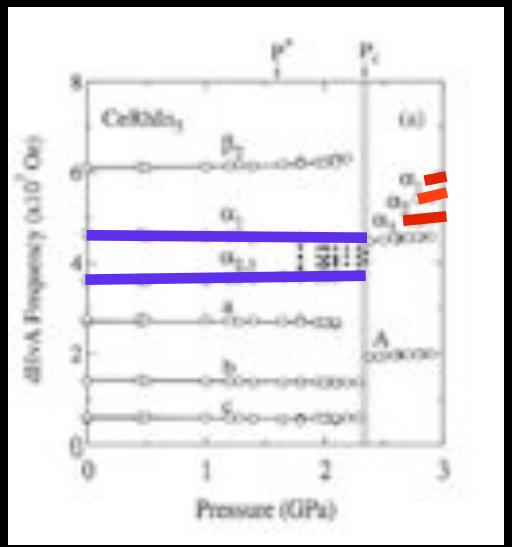

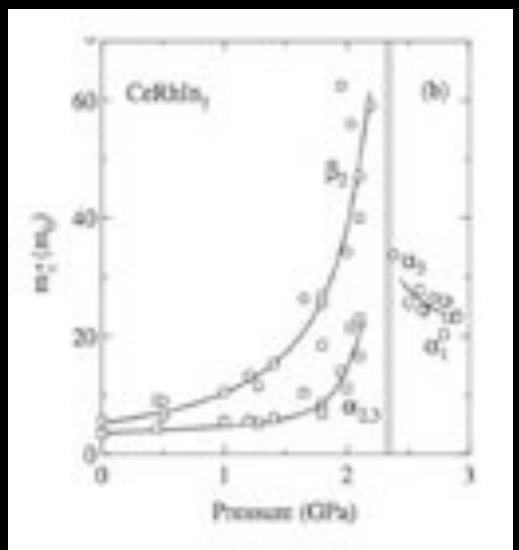

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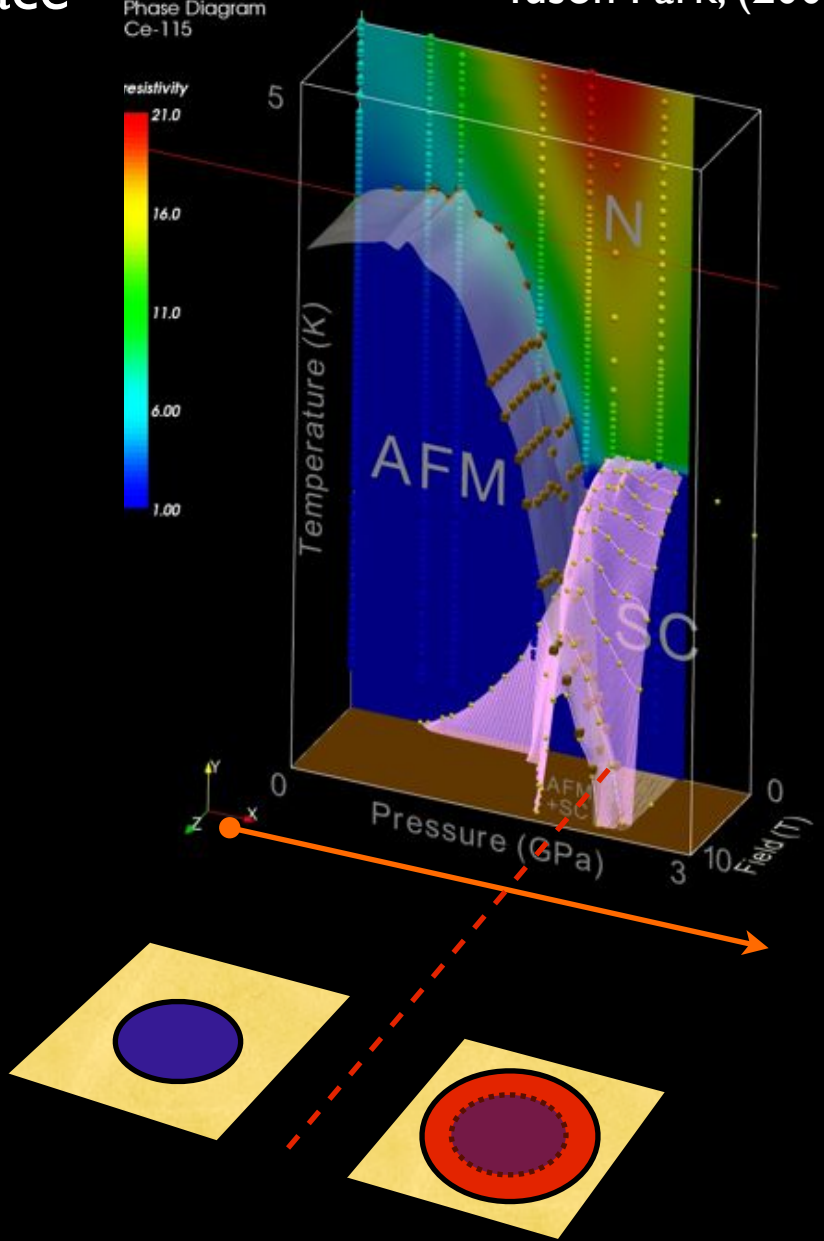

Qu-era: revolutions always have a second part.

Classical vs quantum criticality.

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Heavy electron Quantum Criticality:

"Black hole in the phase diagram"

“Black Hole in the Phase Diagram”.

Zachary Fisk

"Black Hole in the Phase Diagram".

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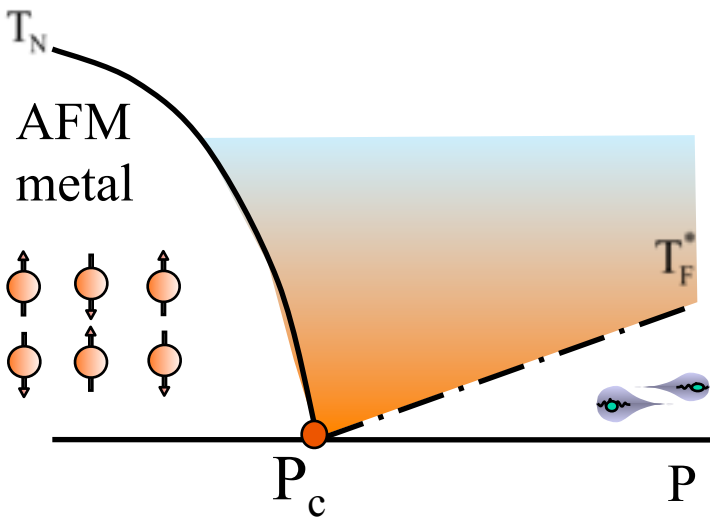
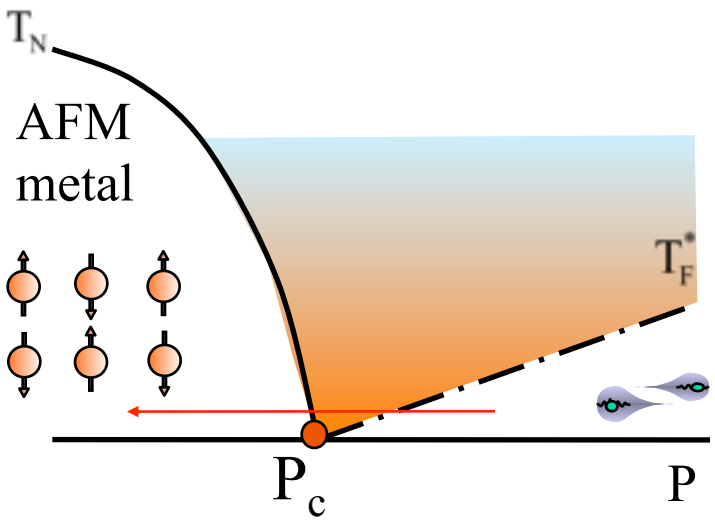


"Black Hole in the Phase Diagram".


Zachary Fisk



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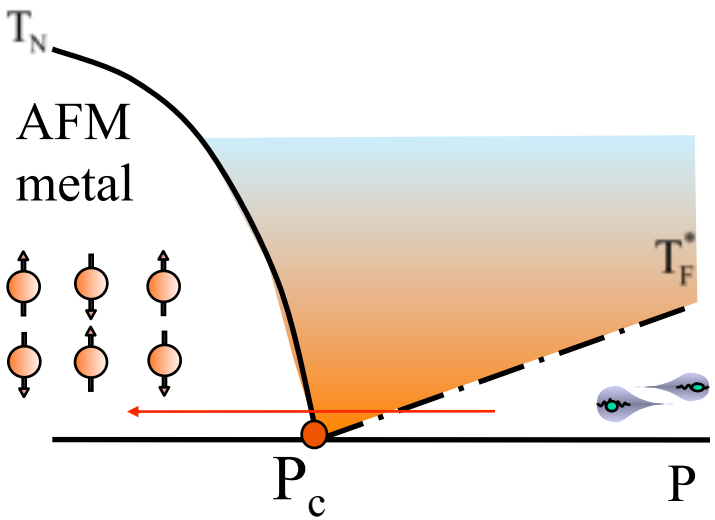

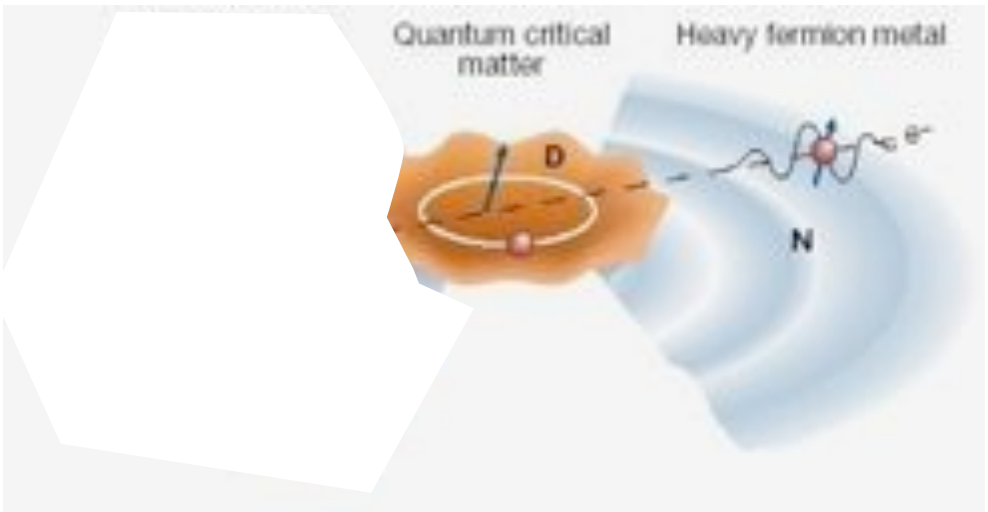

P.C and A. Schofield, Nature (2005)

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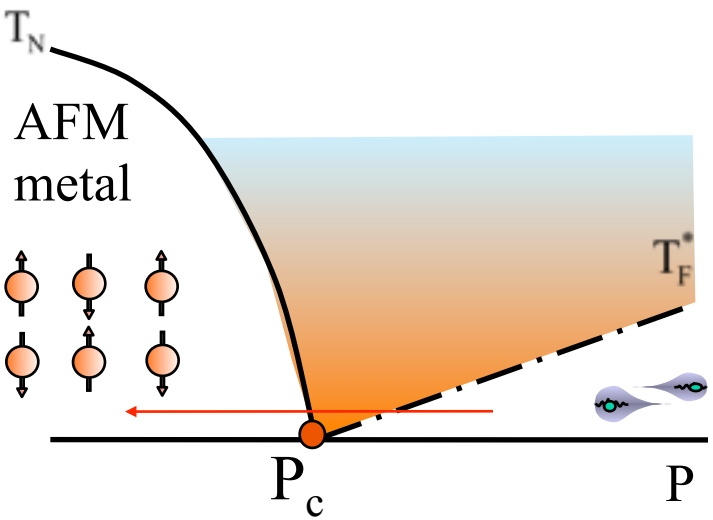

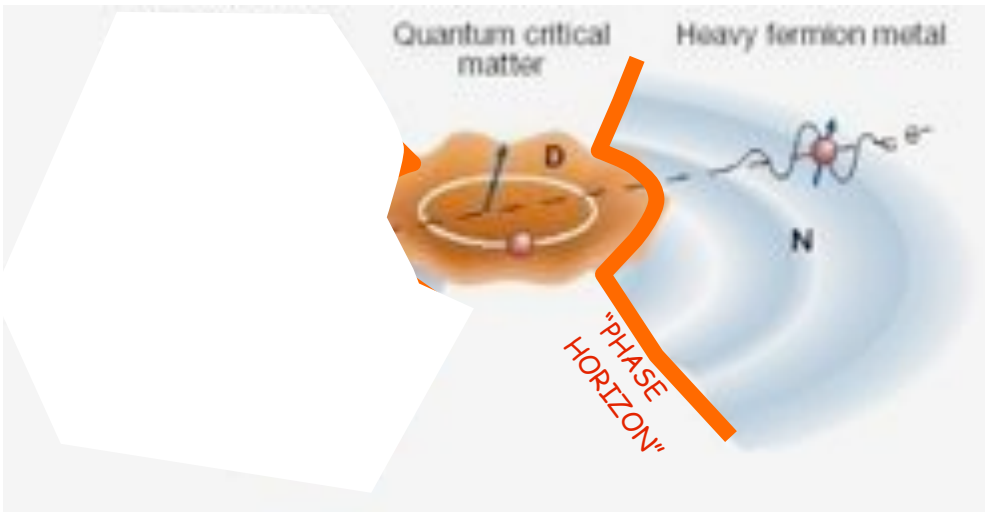

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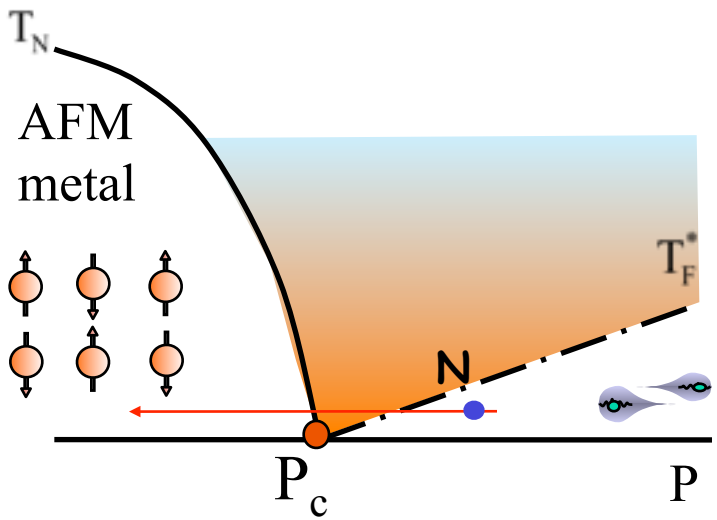

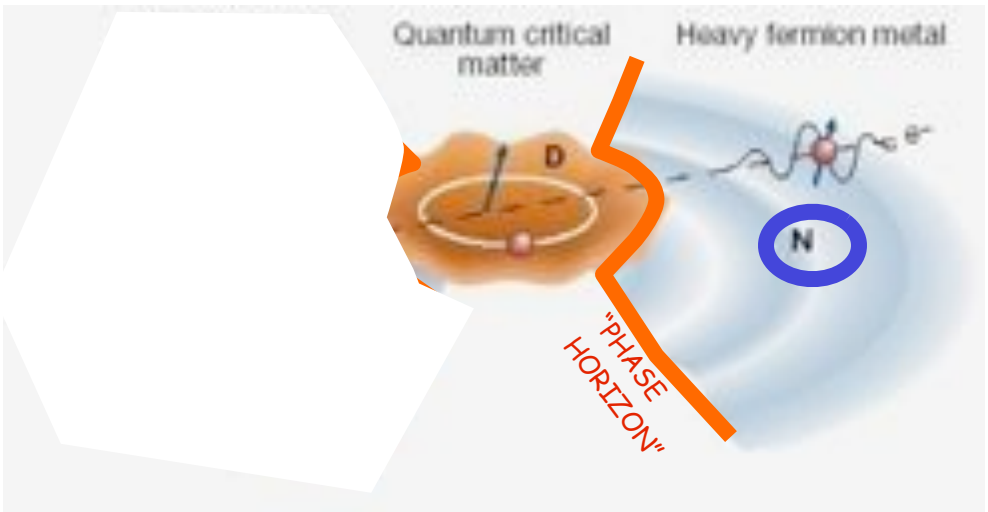

P.C and A. Schofield, Nature (2005)

"Black Hole in the Phase Diagram".


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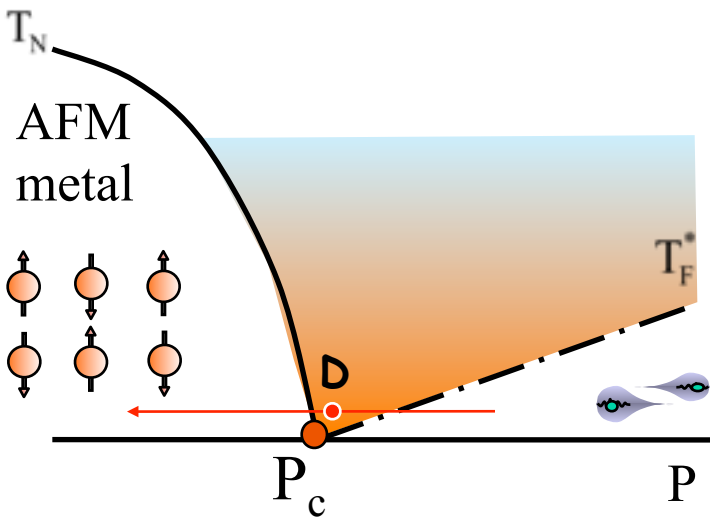

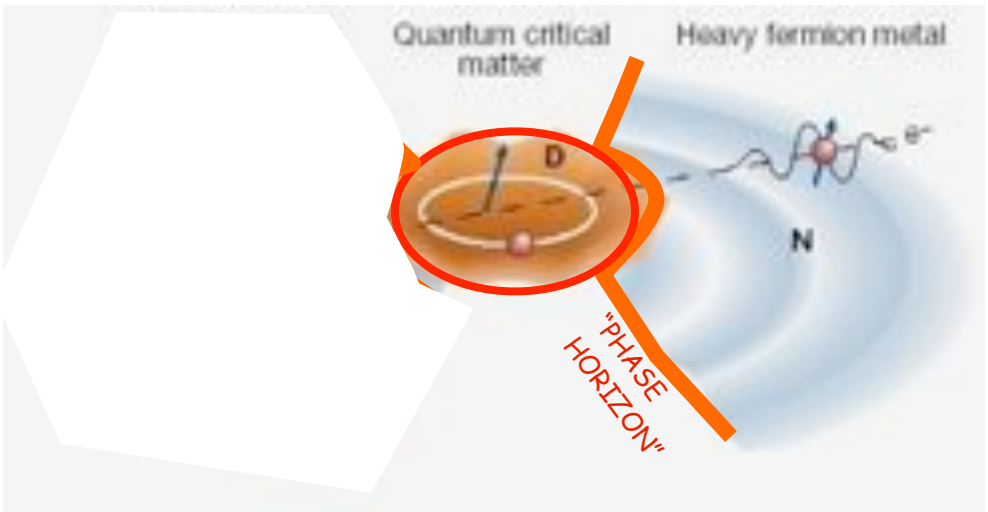

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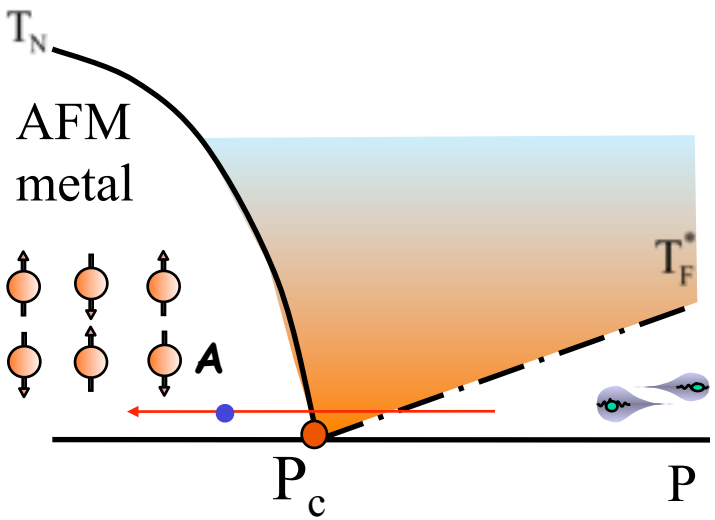

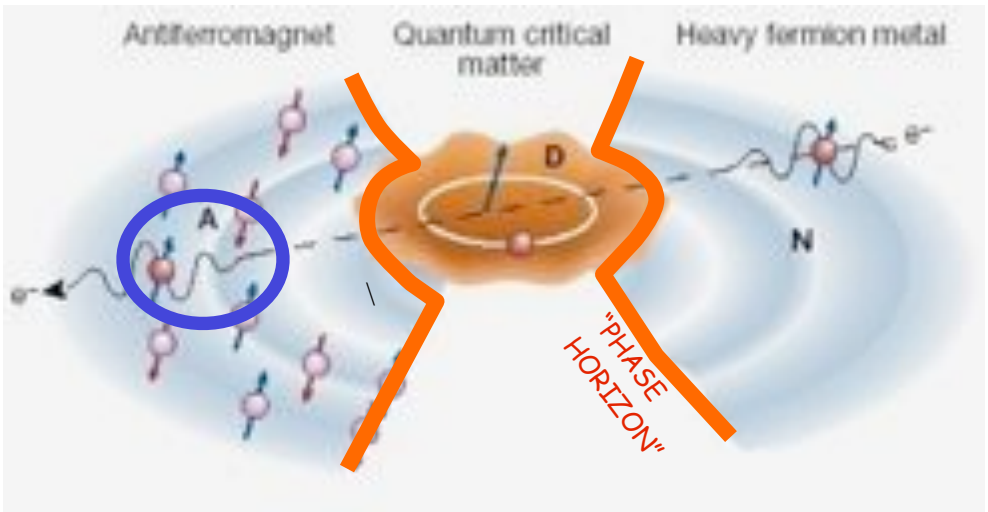

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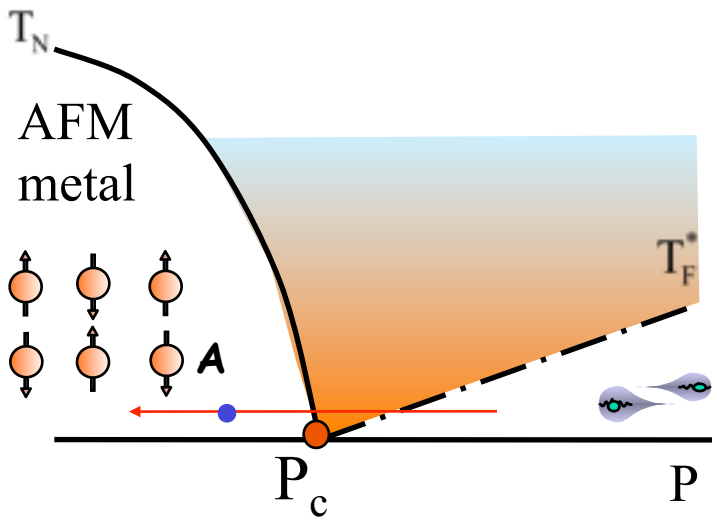

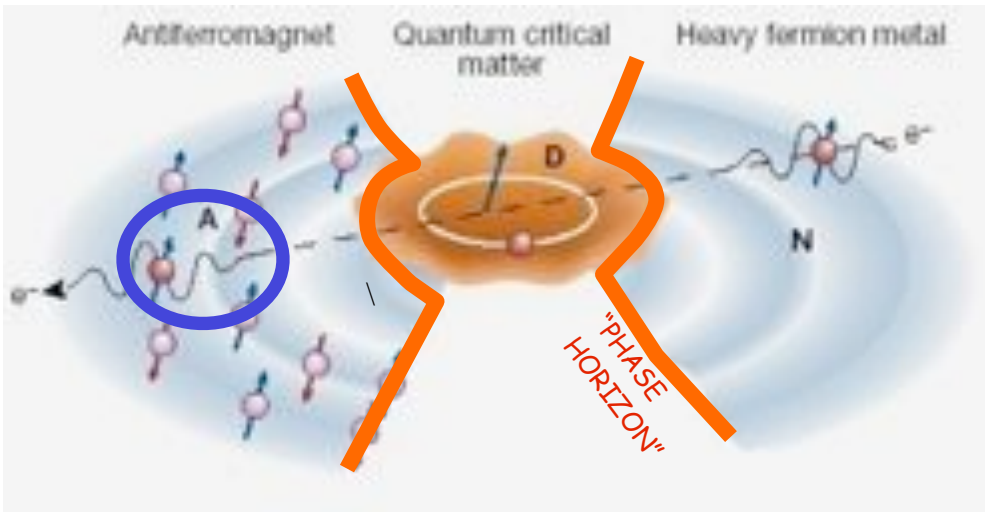

P.C and A. Schofield, Nature (2005)

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


Feynman Hertz

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

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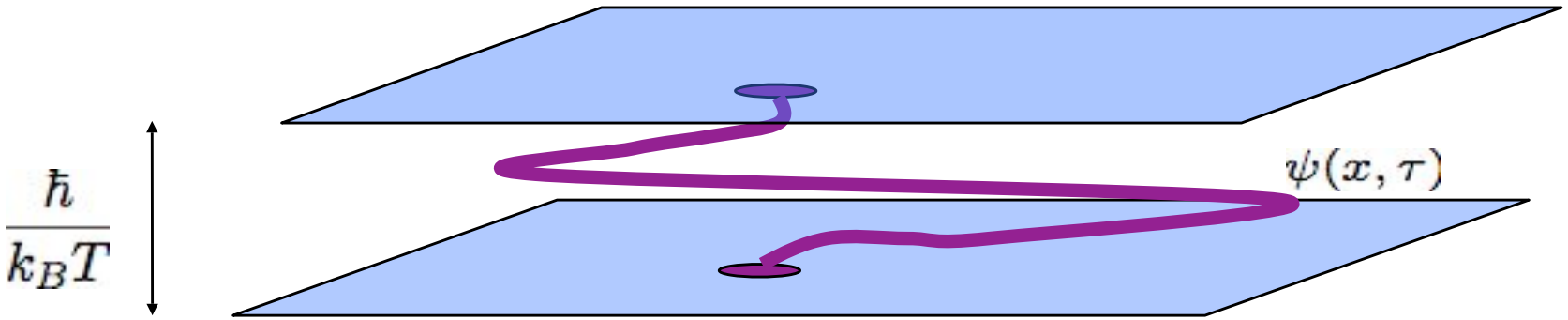

Feynman

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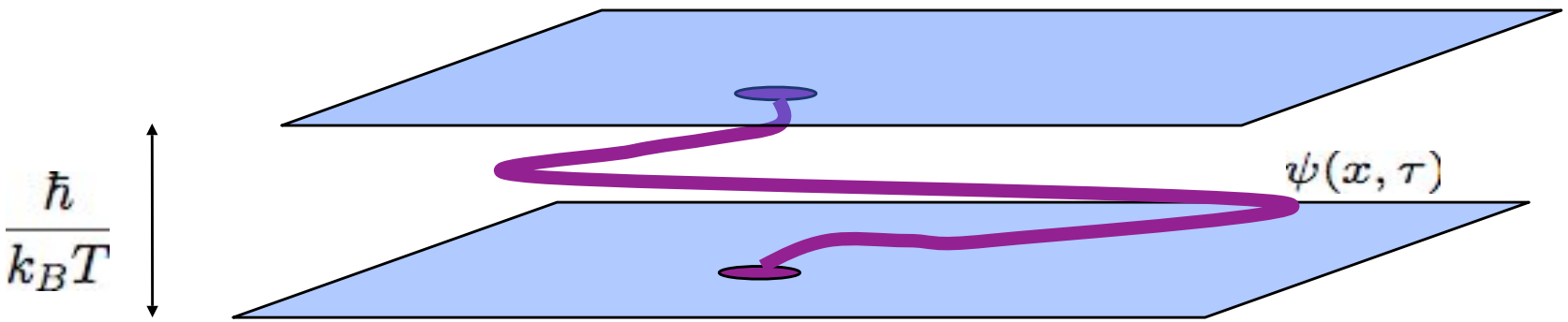

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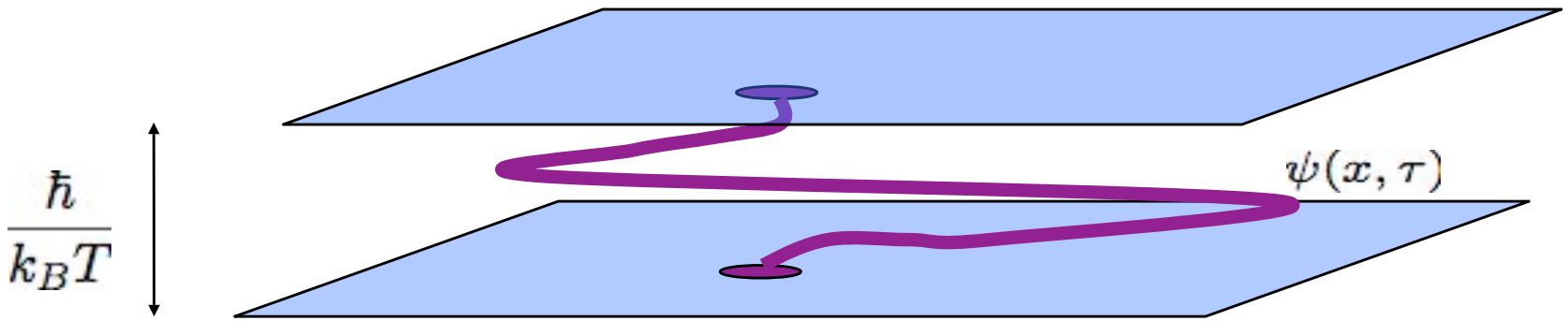

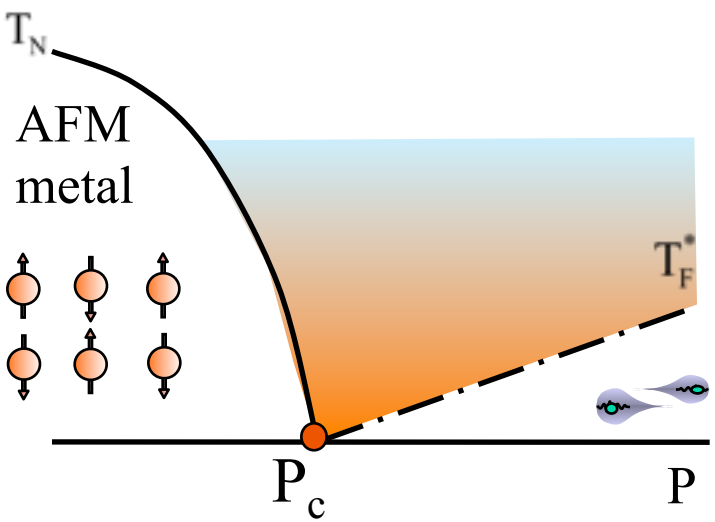

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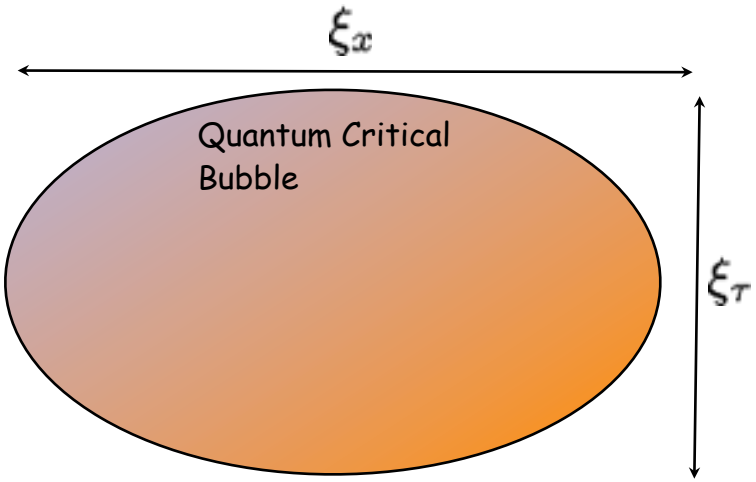

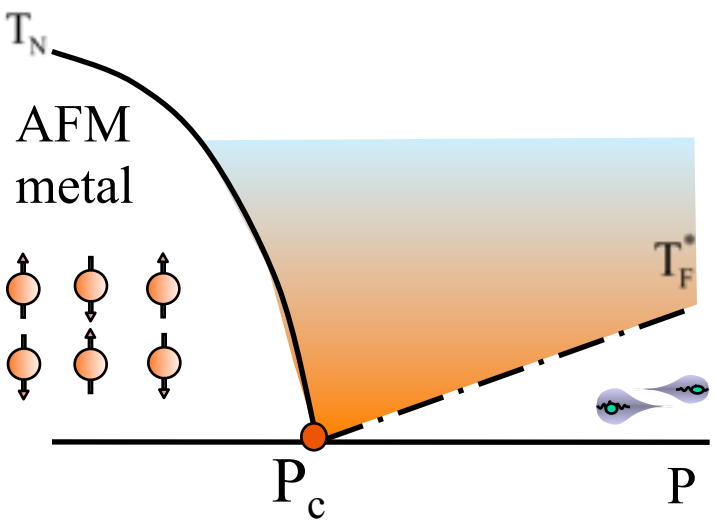

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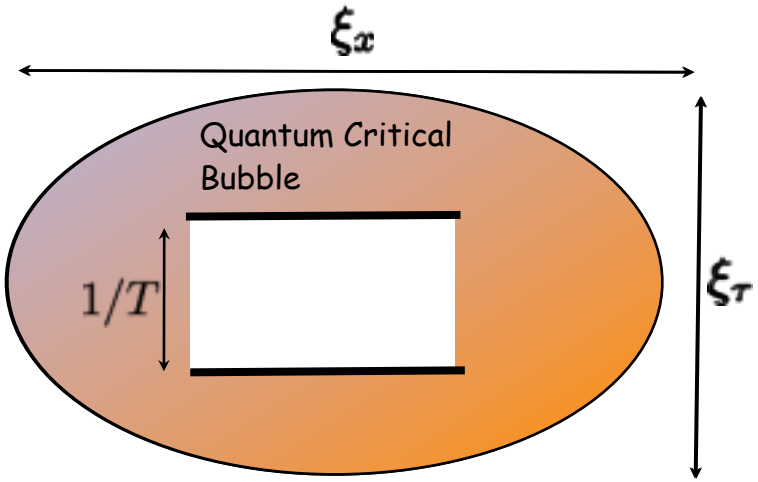

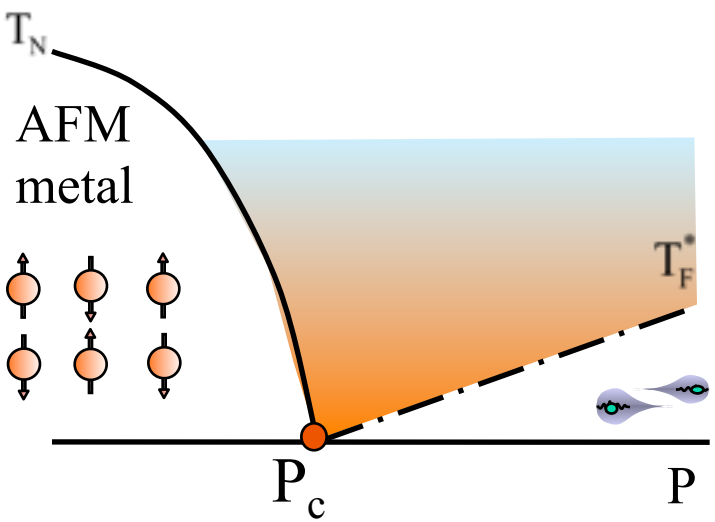

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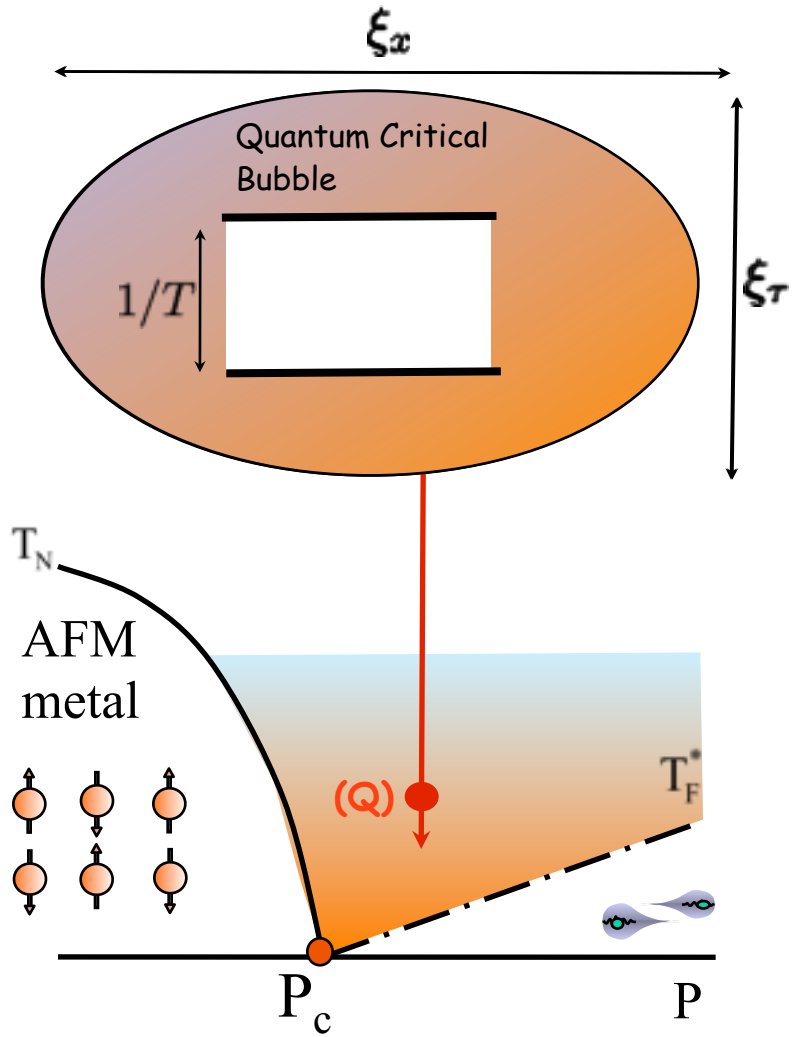

(Q) Quantum critical region: interior of correlation bubble.

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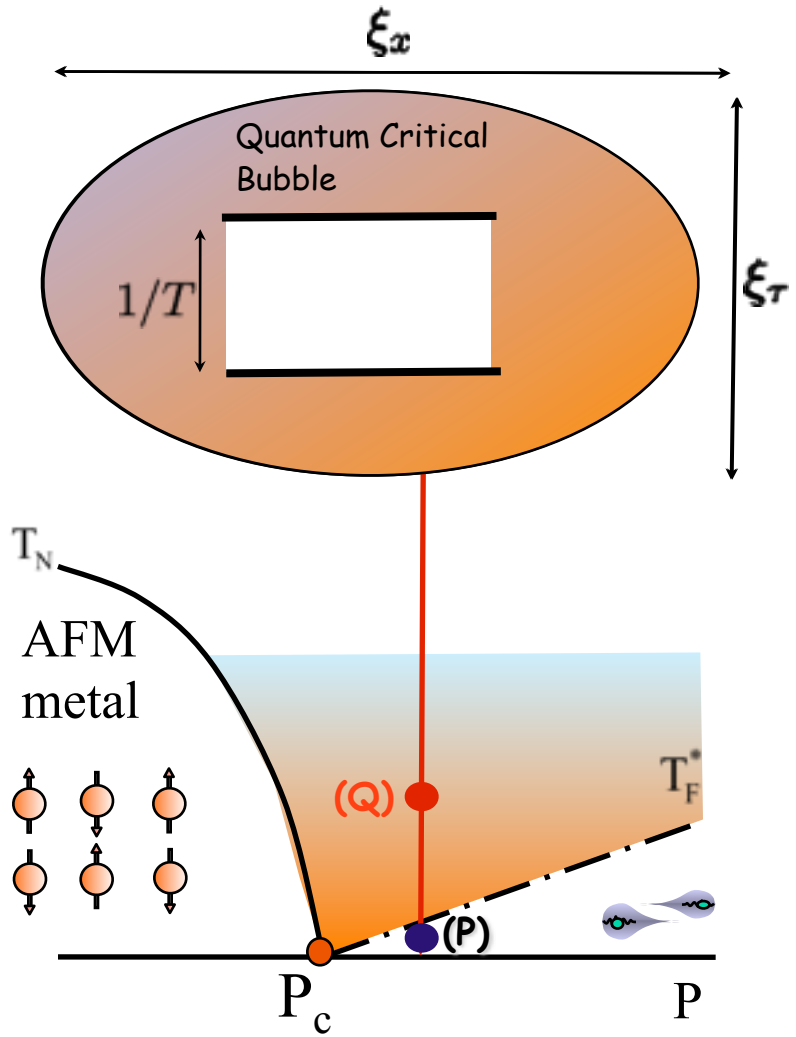

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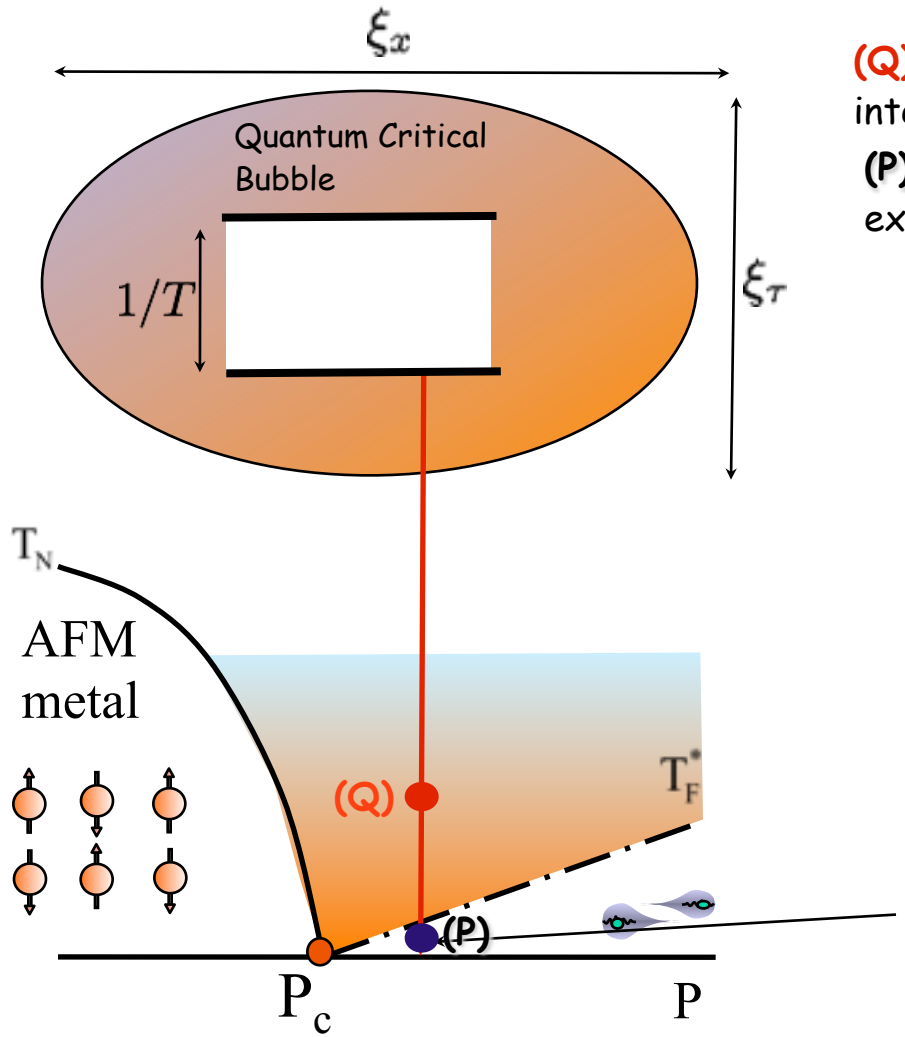

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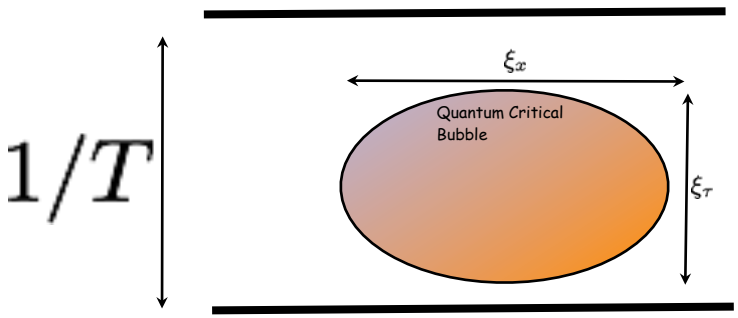

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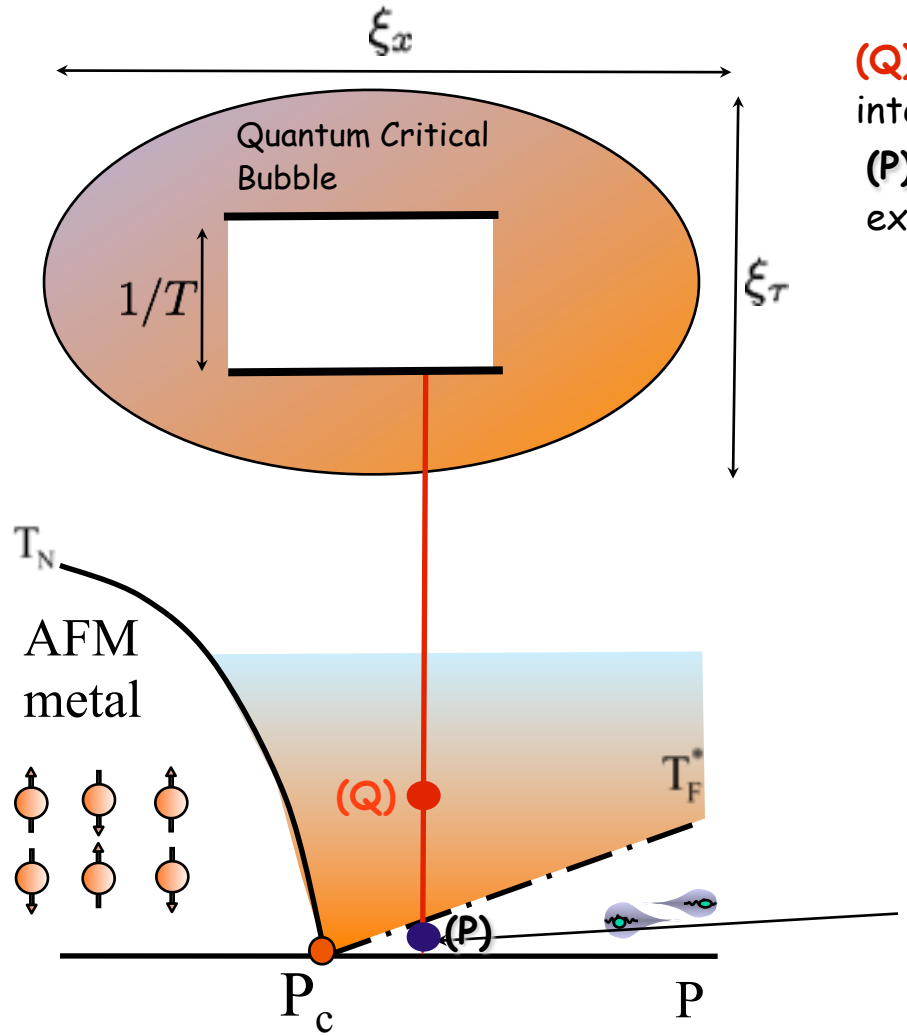

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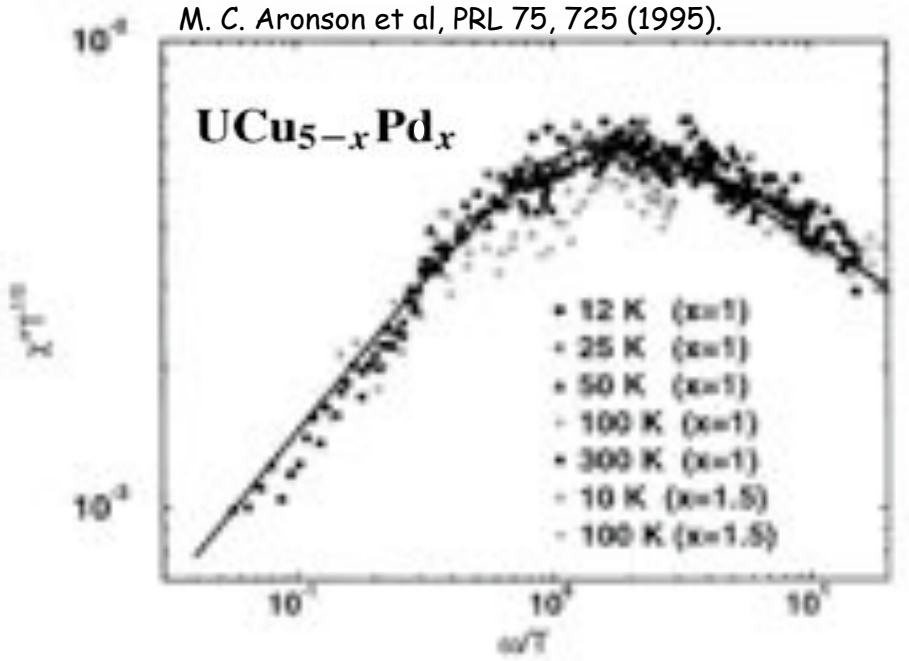
Meigan Aronson

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



Rutgers
Center for Materials Theory

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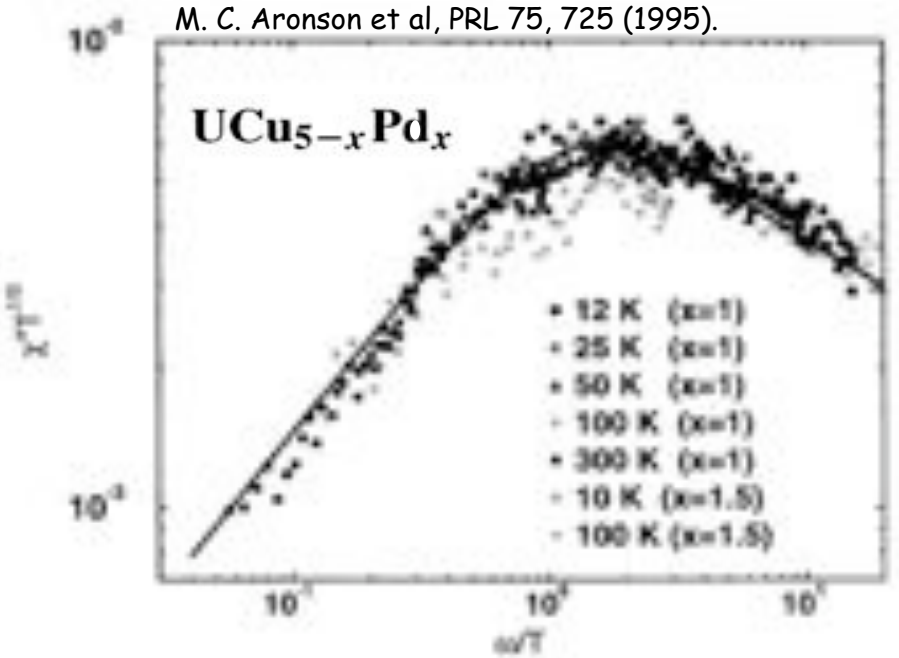

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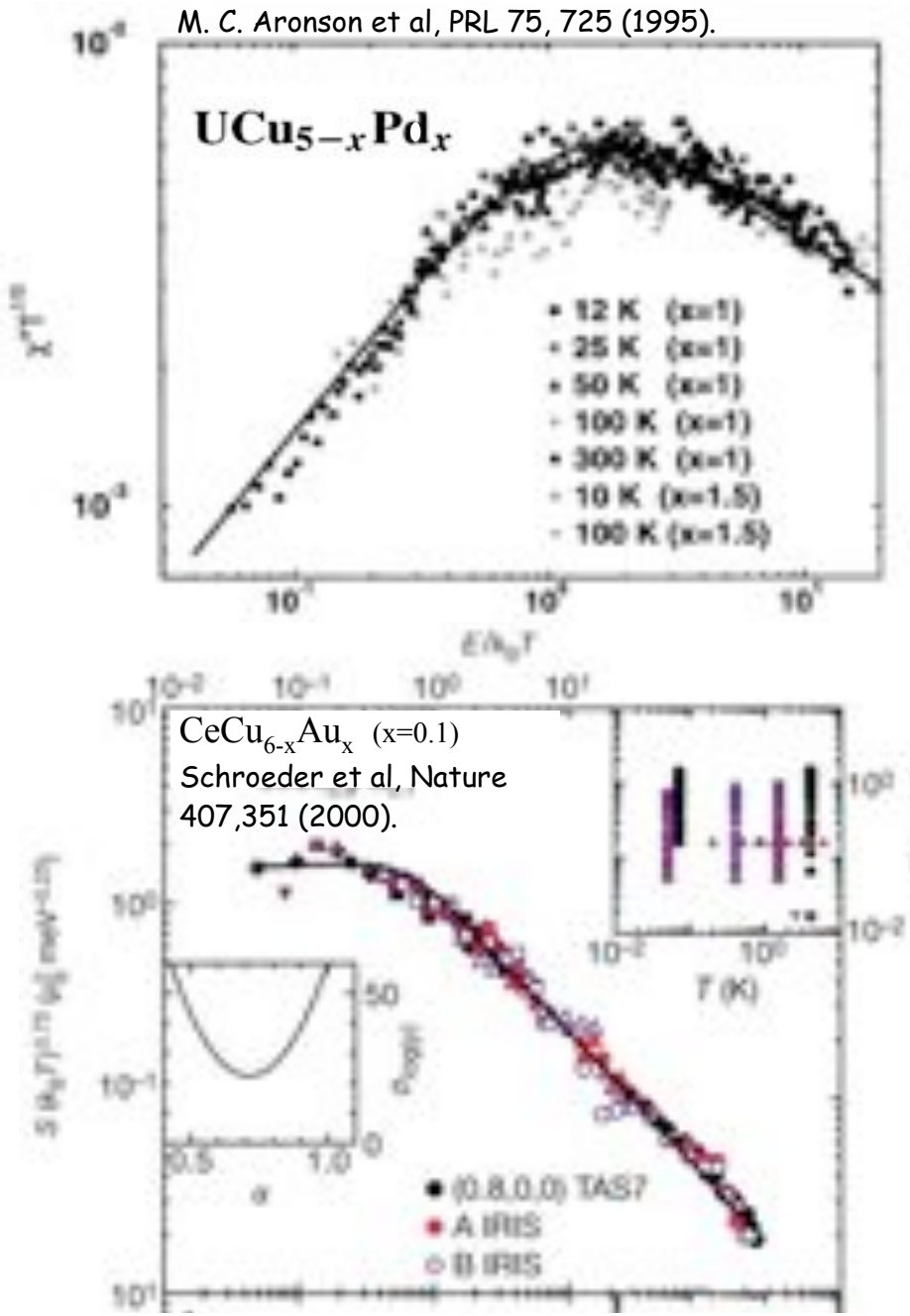

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Physics Below the upper Critical Dimension.

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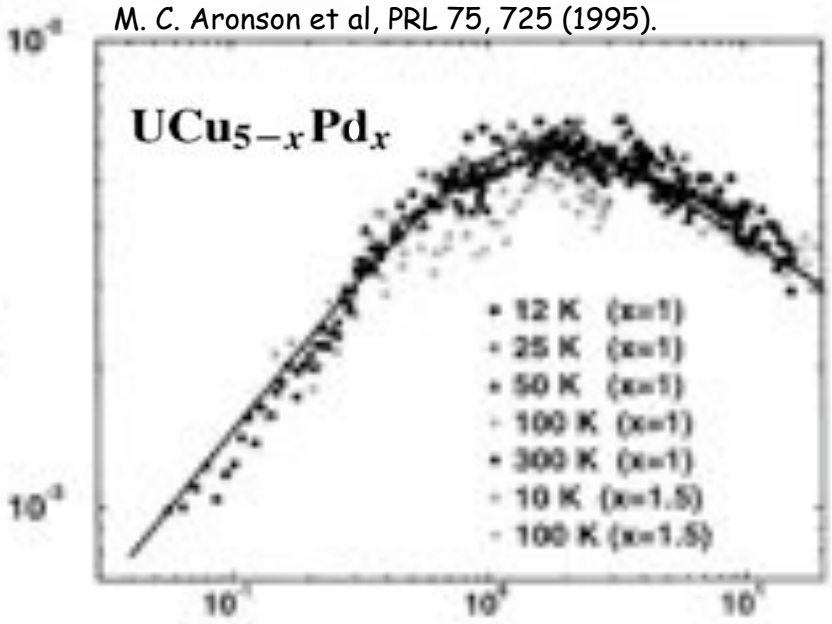

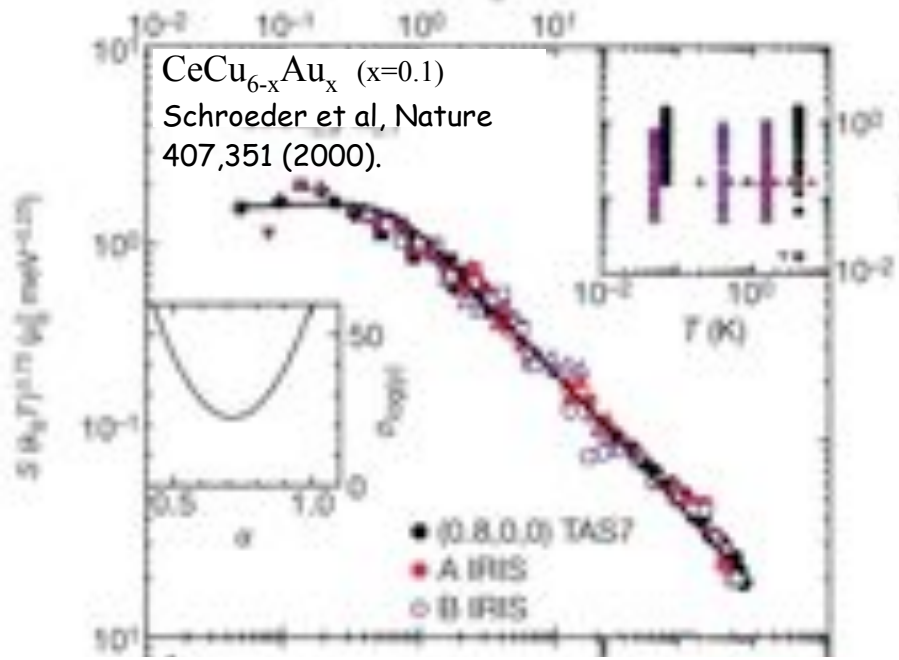

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Center for Materials Theory

Qu-era: revolutions always have a second part.

Classical vs quantum criticality.

Peierls' question.

Heavy electron Quantum Criticality:

Failure of the
Standard model

Standard Model: Quantum SDW?


Moriya


Doniach

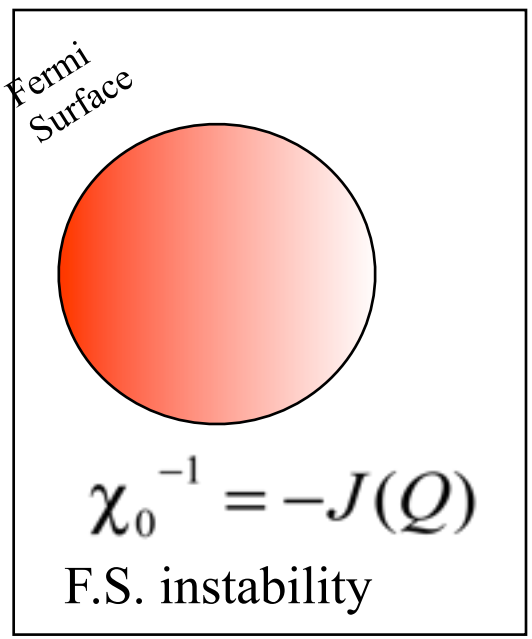

Schrieffer


Hertz


Millis

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

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



Rutgers
Center for Materials Theory

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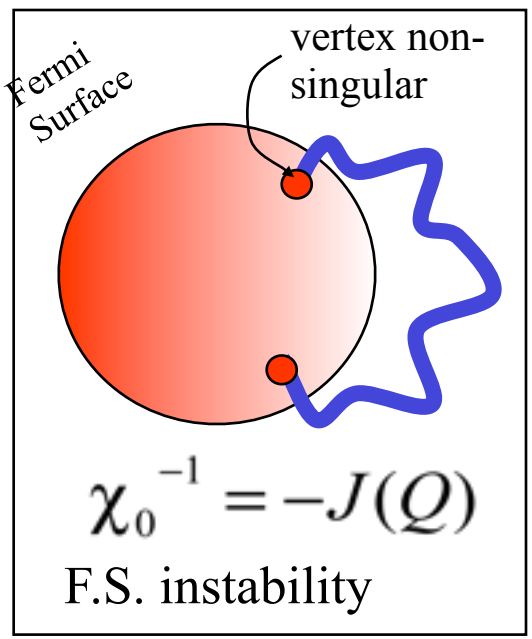

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Rutgers
Center for Materials Theory

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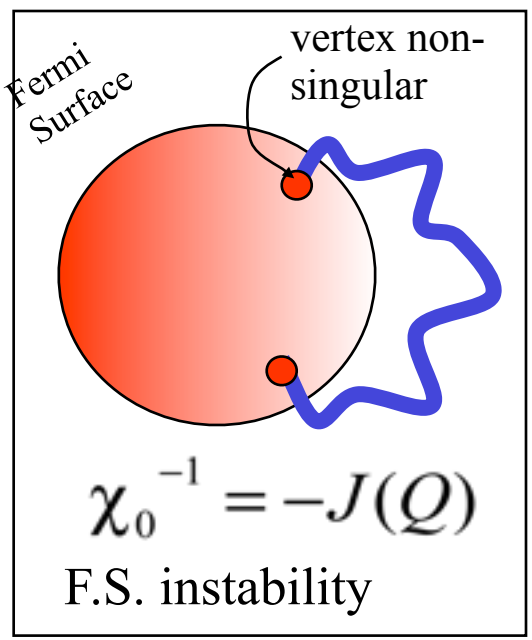

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Rutgers
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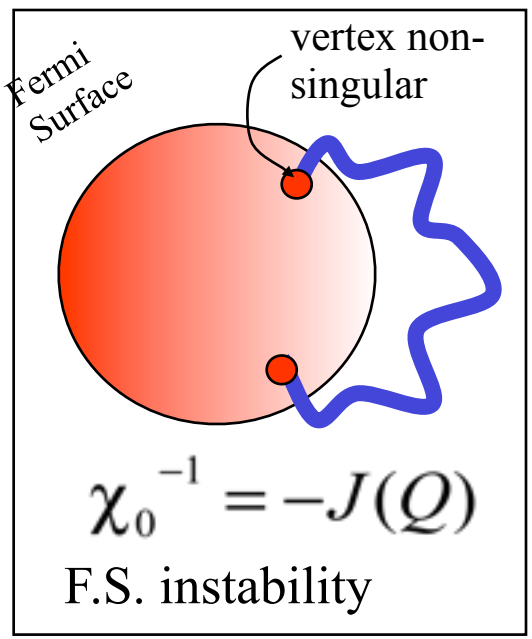

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Time counts as z =2 scaling dimensions

Rutgers
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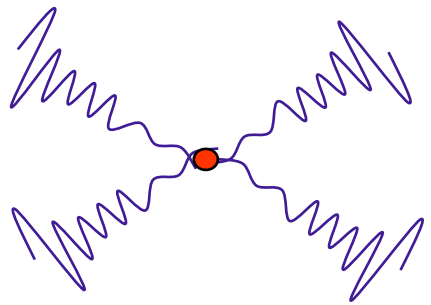

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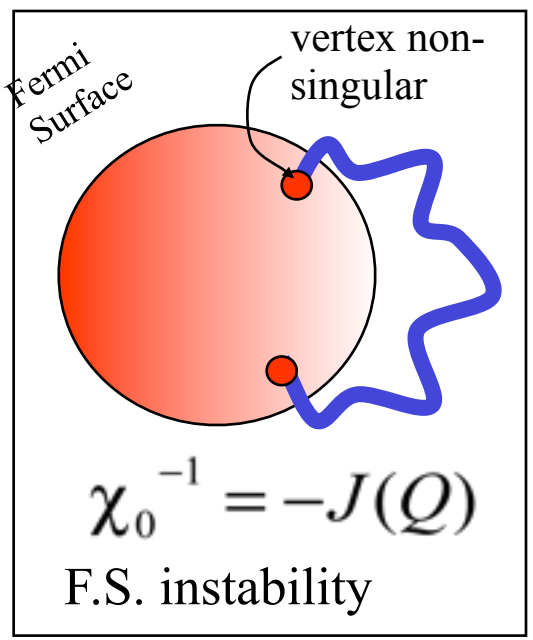
$$d_{eff} = d + z$$

If $d + z = d + 2 > 4$:
ϕ^4 terms "irrelevent"
Critical modes are Gaussian.
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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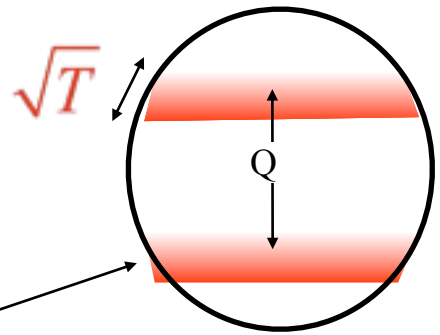

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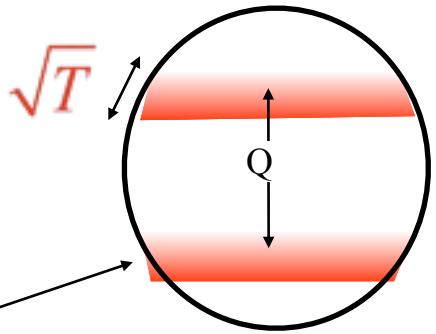

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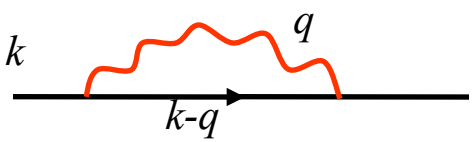

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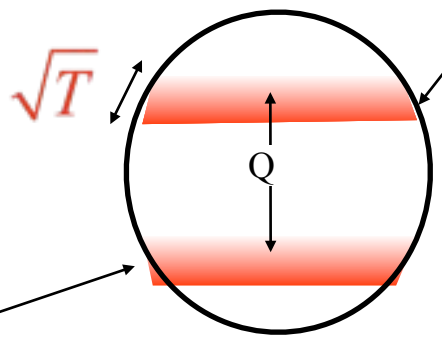
divergent



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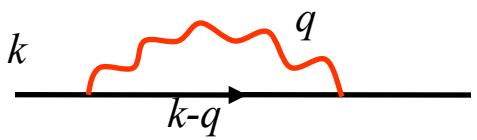

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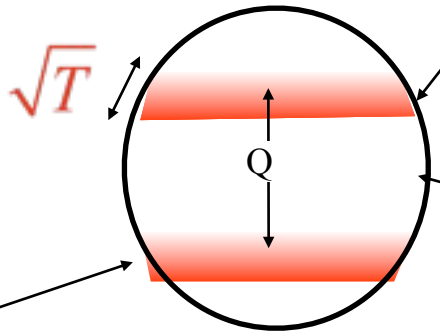

$\frac{m^*}{m}$ finite

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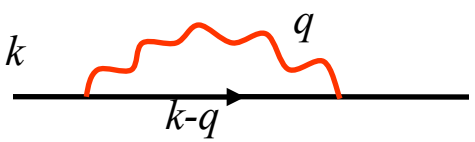

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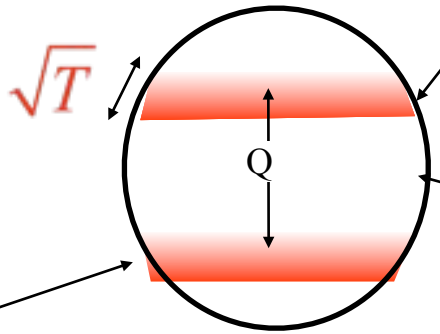
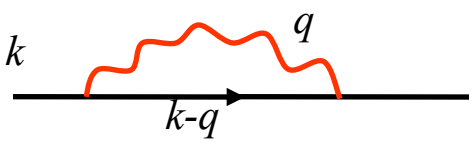


$\frac{m^*}{m}$ finite

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



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

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

Predicts:

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

Rutgers
Center for Materials Theory

Qu-era: revolutions always have a second part.

Classical vs quantum criticality.

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New Ideas

Si, Ingersent


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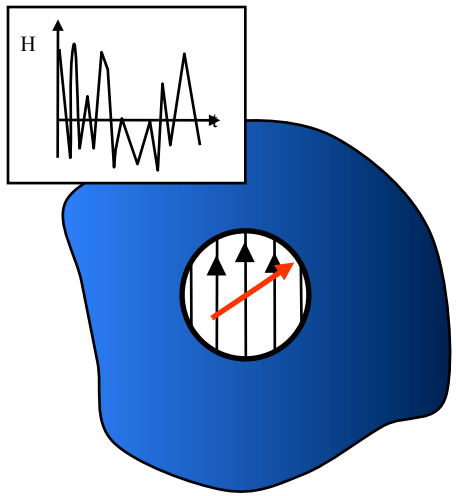
(Si, Ingersent, Smith, Rabello, Nature 2001):
Spin is the critical mode,
Fluctuations critical in time.

Requires a two dimensional spin fluid



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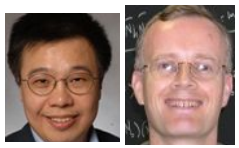

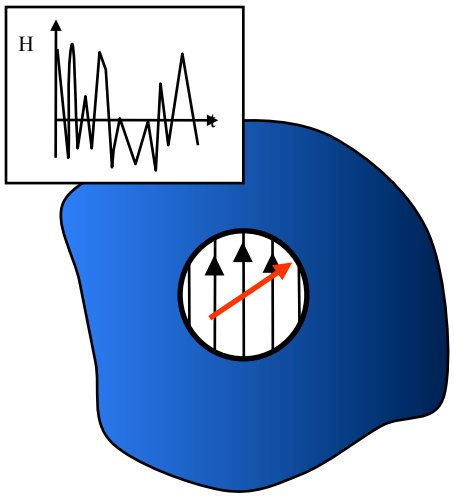

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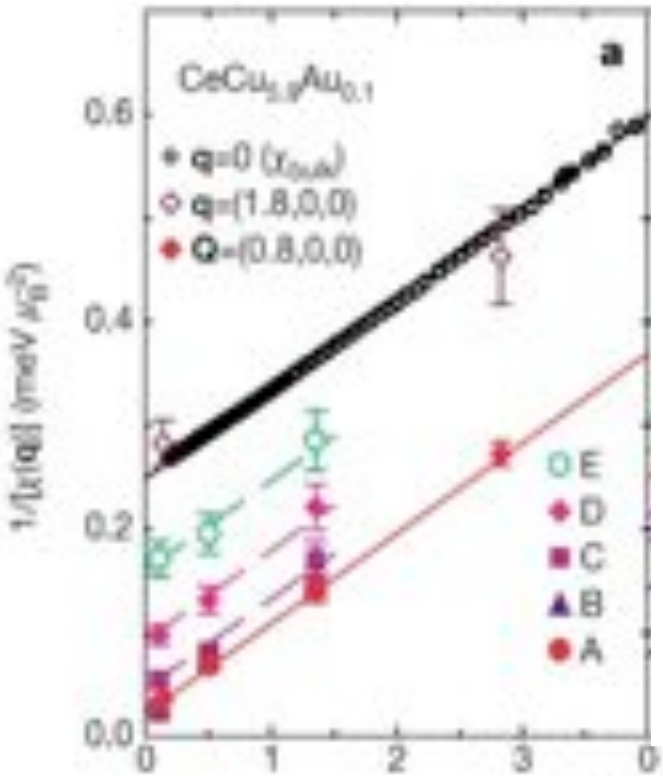
Locality of critical fluctuations

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



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

$T^{.0.75}(K^{0.75})$

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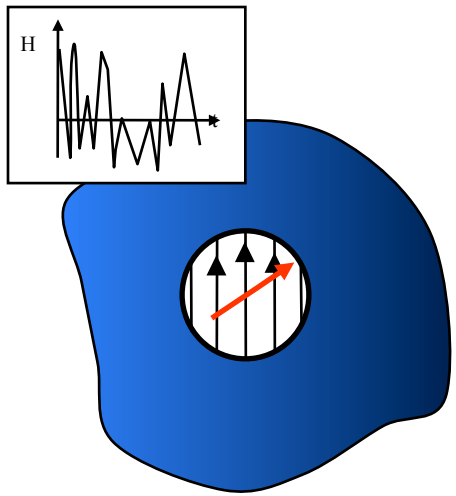

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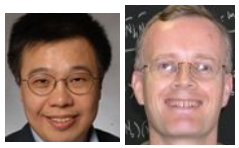

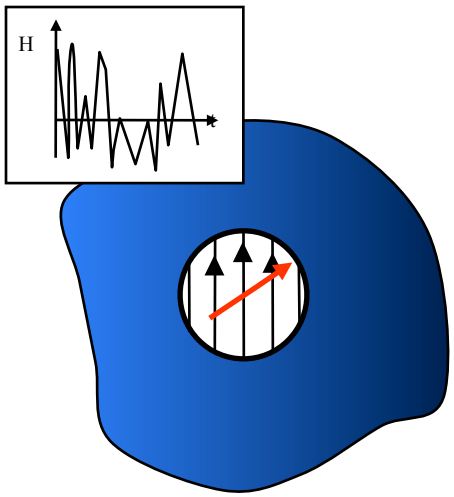

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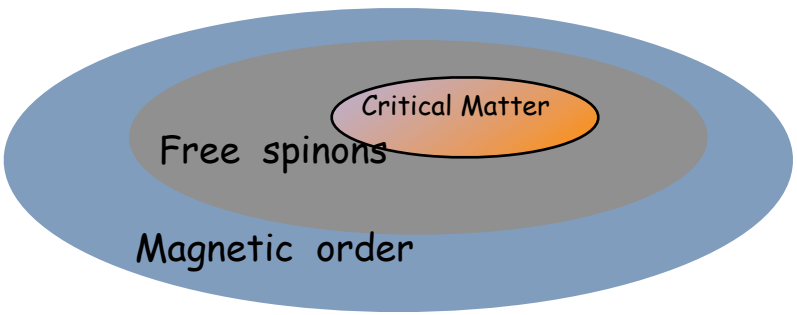
Senthil Sachdev Vishwanath



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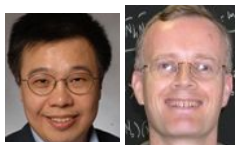

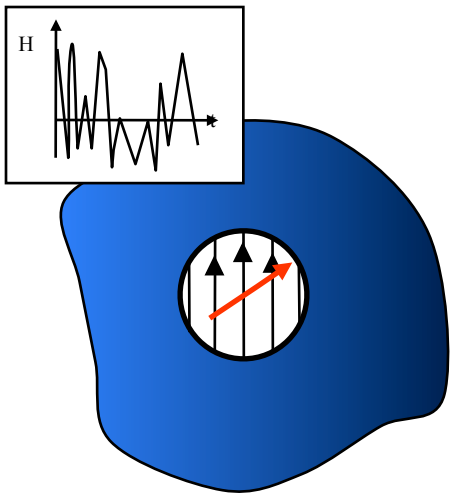

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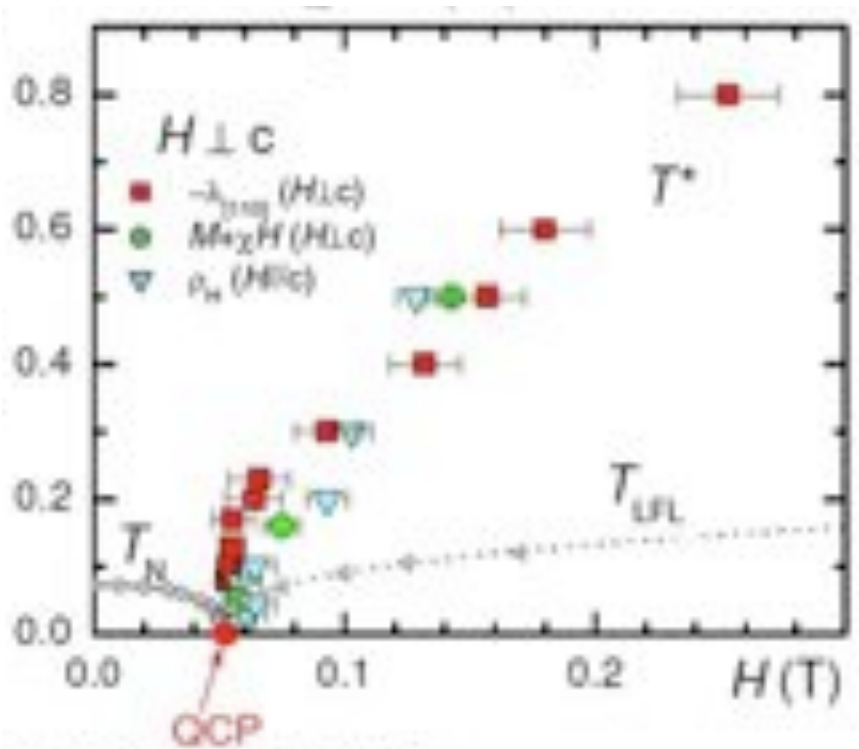
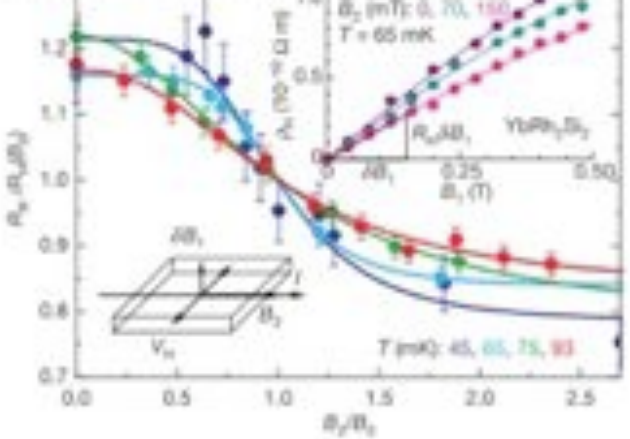
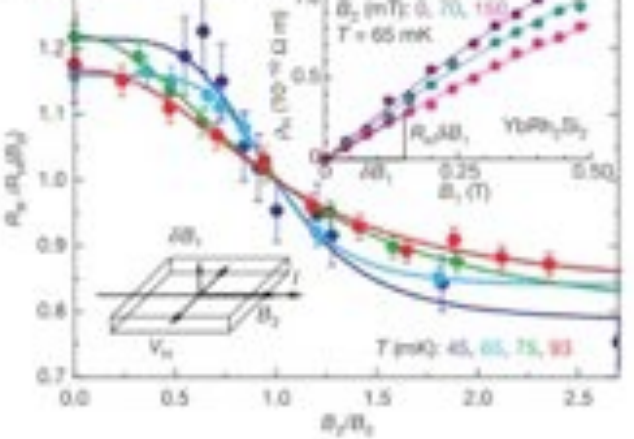
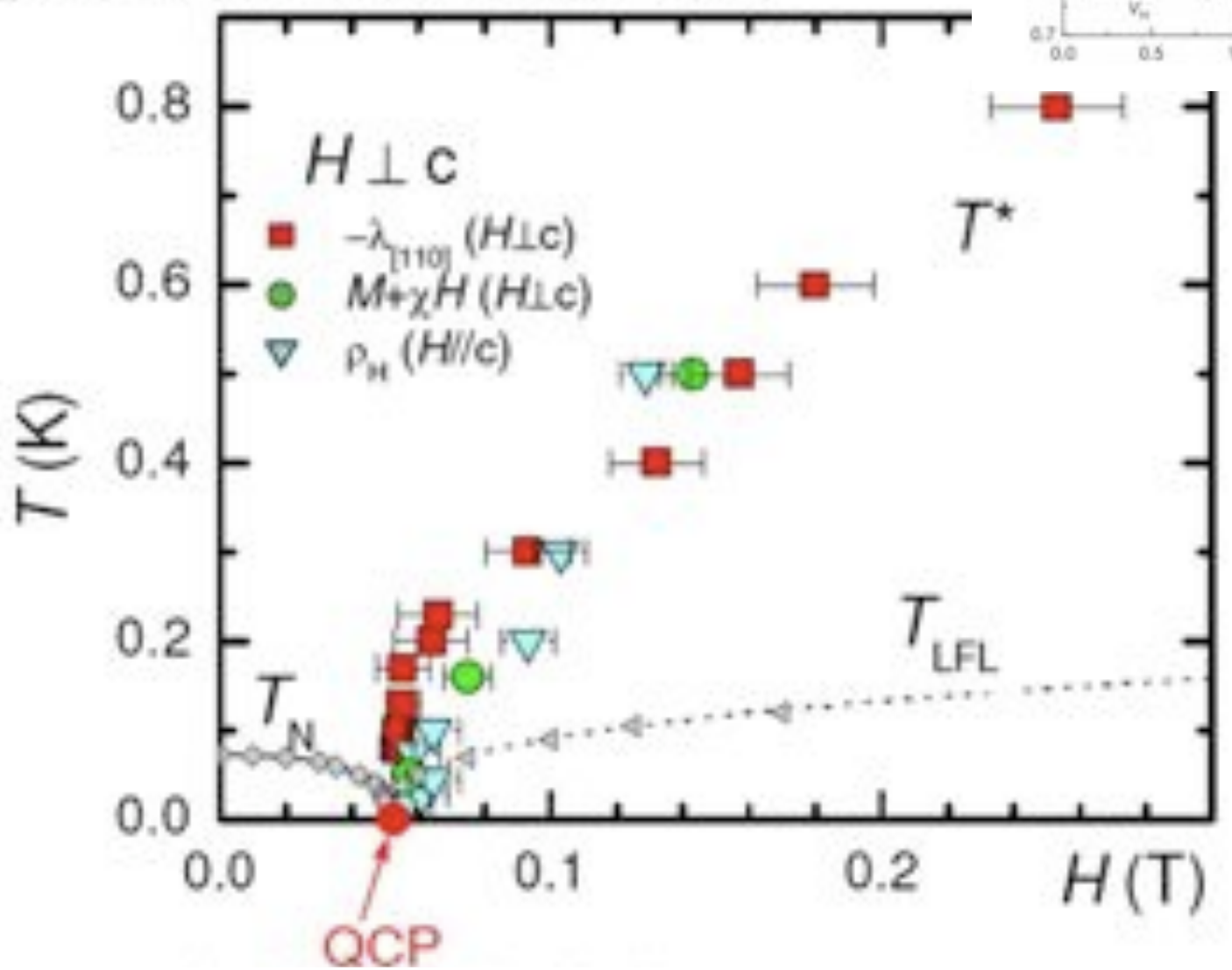



T (mK): 45, 65, 75, 93
T = 65 mK
YbRh2Si2
B2/B0

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



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



New Ideas

Large N Approaches.
(PC et al JCM, 2001, Rech et al 2005,
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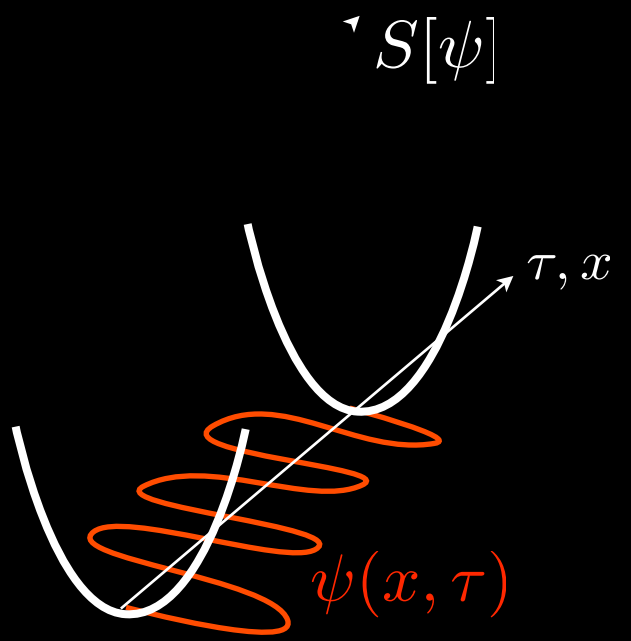
Pepin 

New Ideas



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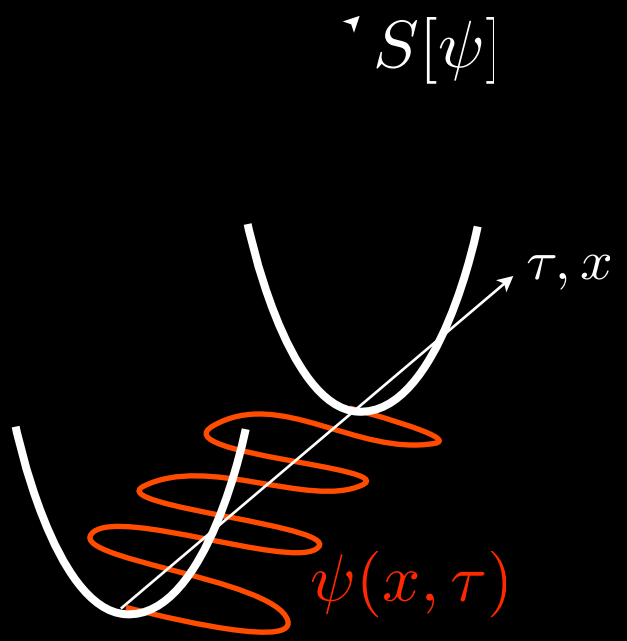

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$\sigma \in (-\frac{1}{2}, \frac{1}{2})$

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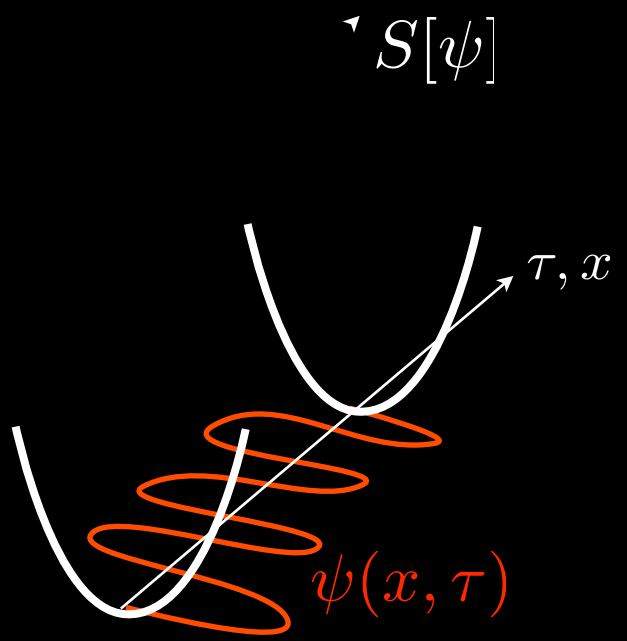

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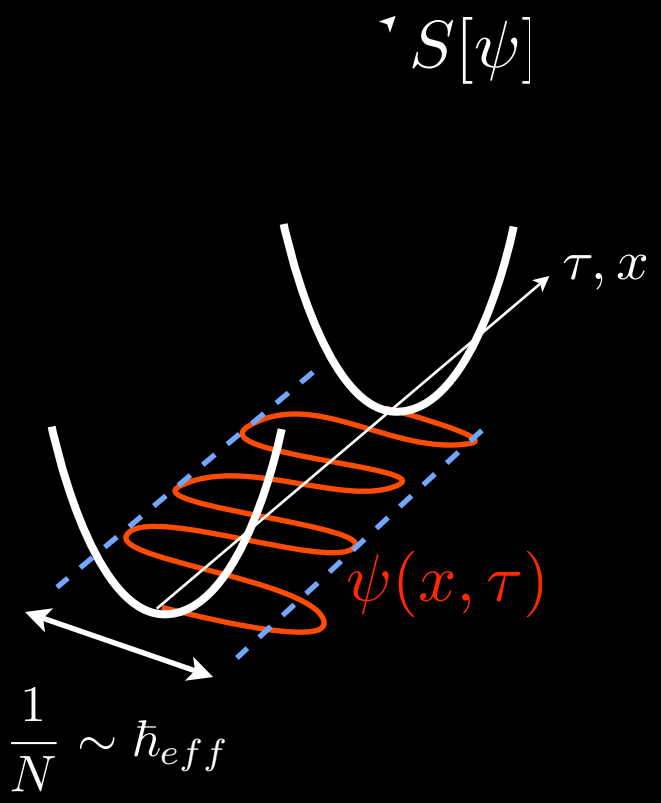
New Ideas



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New Ideas

$N \rightarrow \infty$

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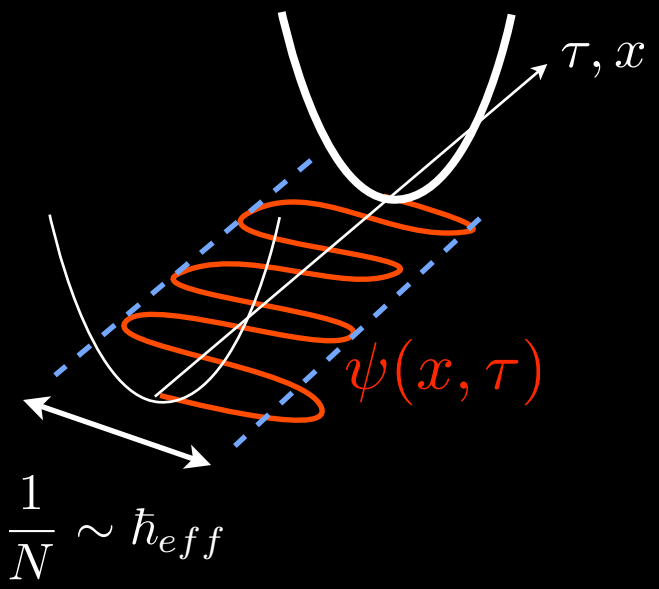

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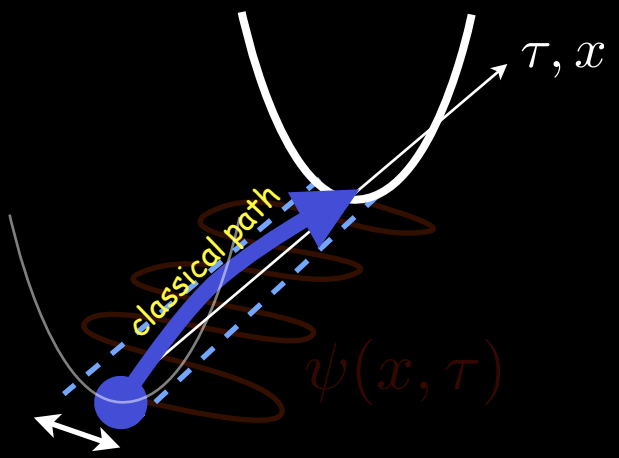

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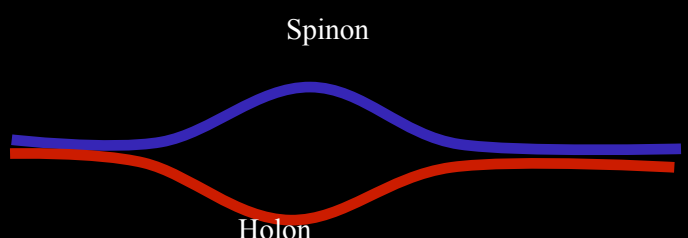

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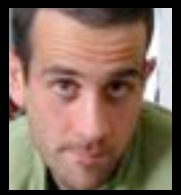
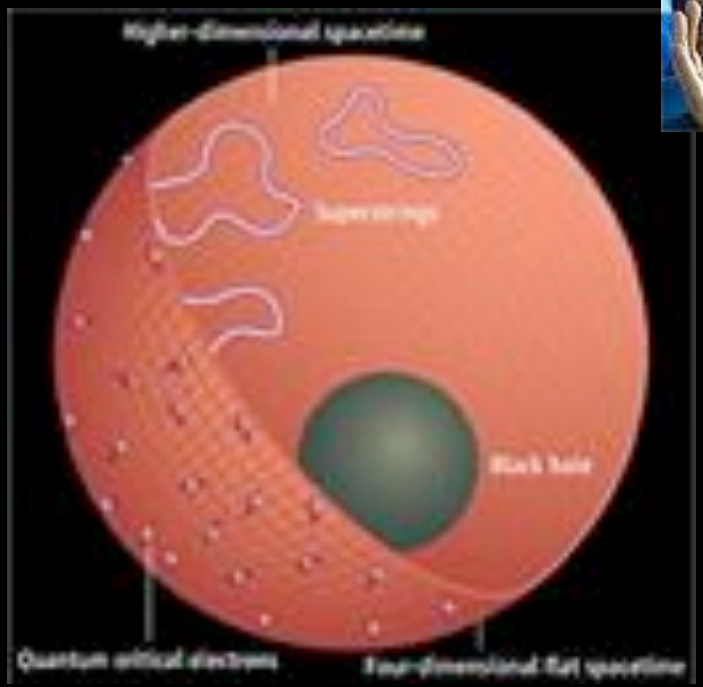
Zaanen

Liu

McGreevy



M Cubrovic, J **Zaanen**, K Schalm - **Science**, **2009**



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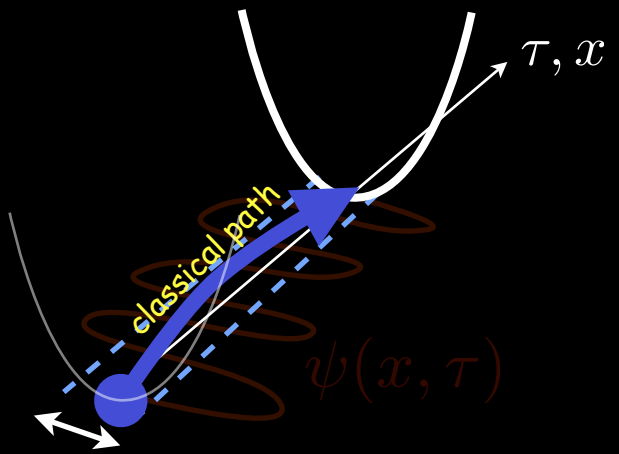

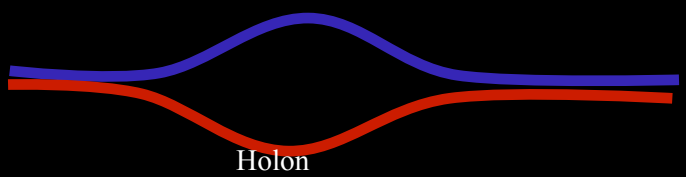

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New Ideas: breakup of the electron.

Qu-frustration.

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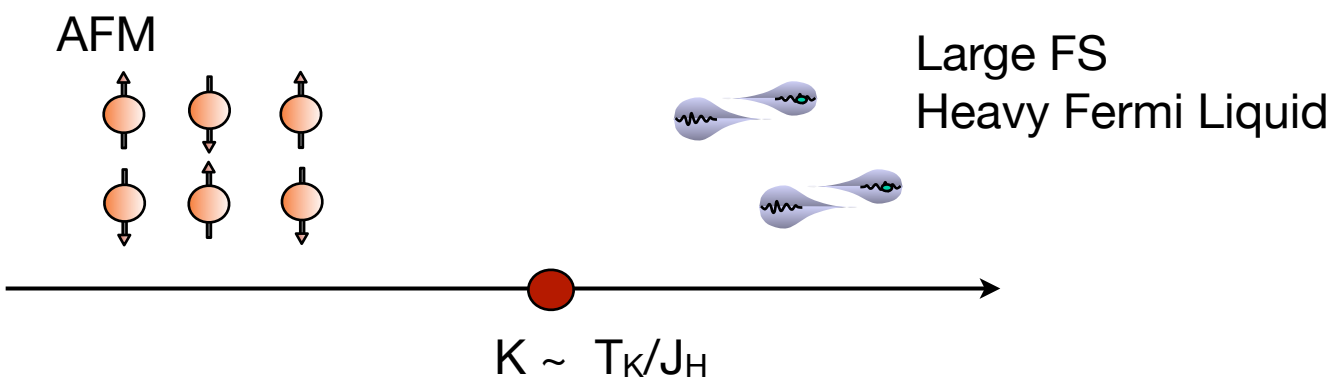

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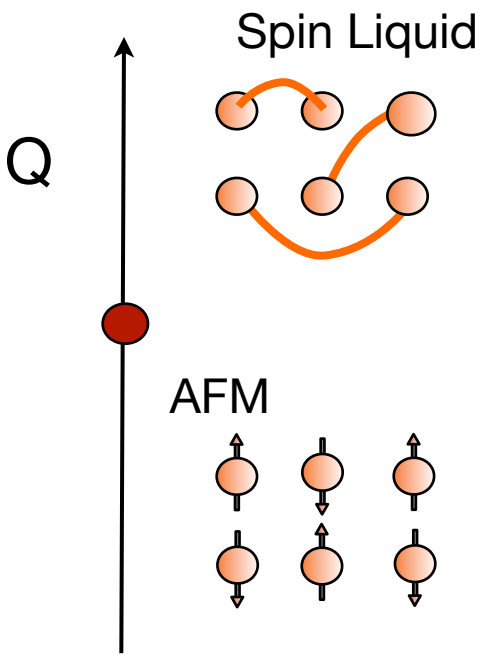

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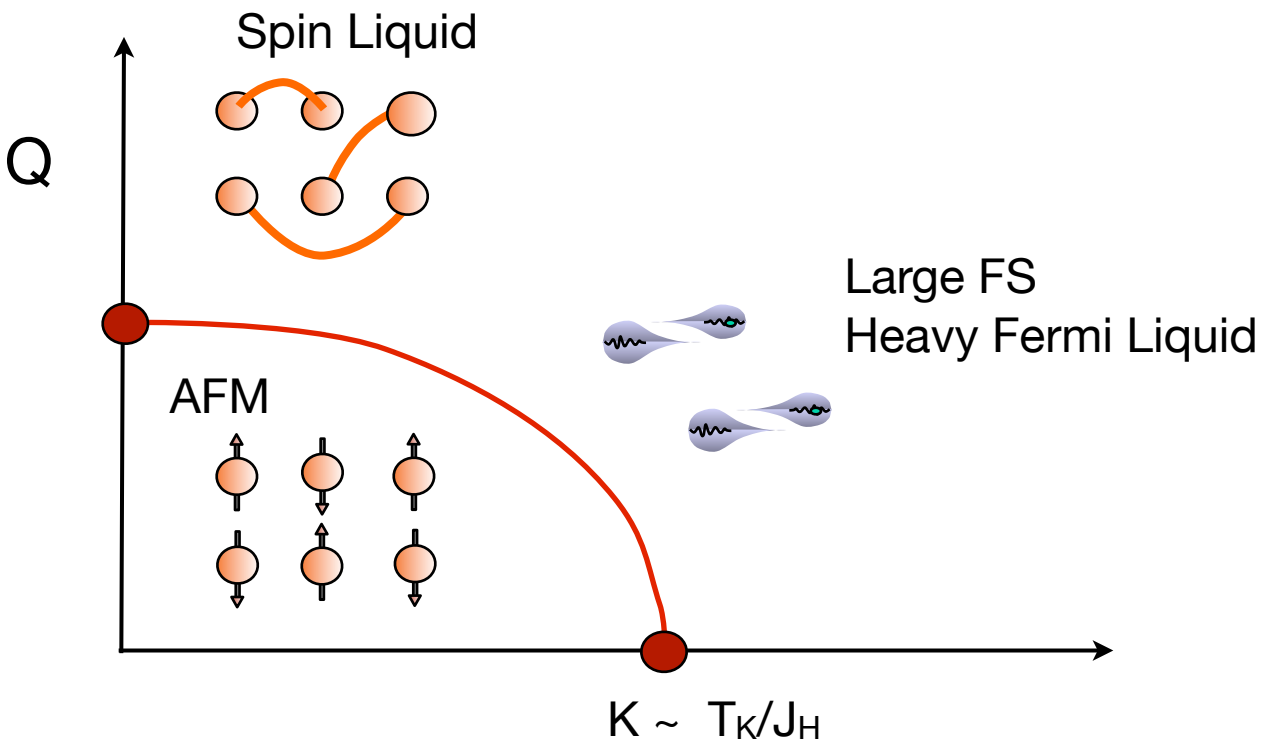

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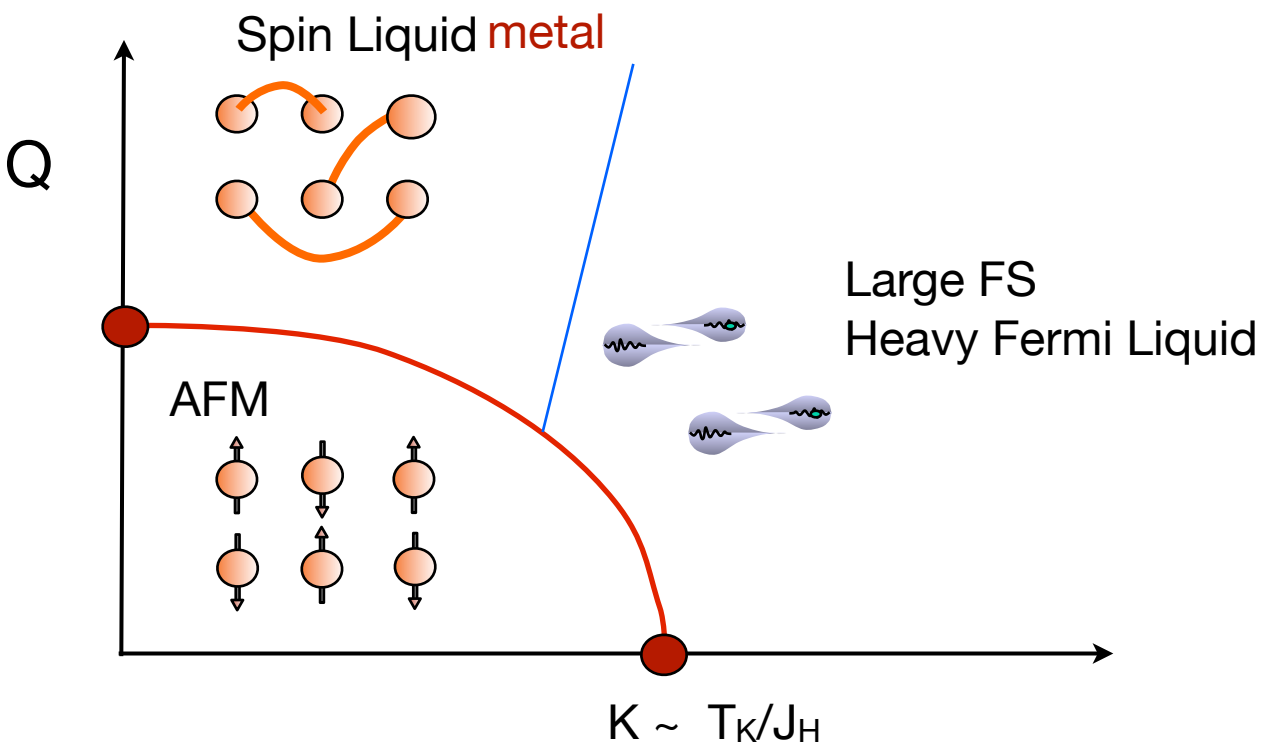
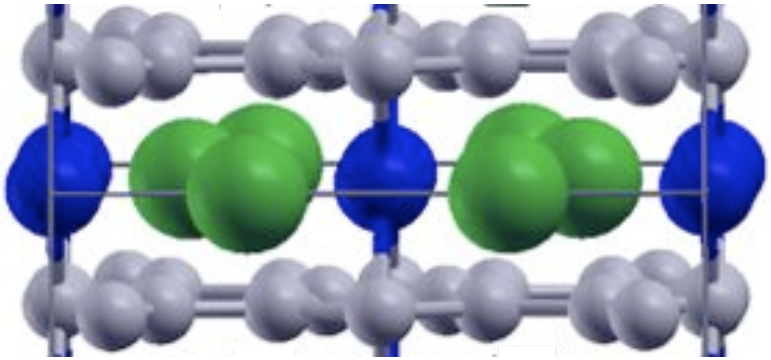
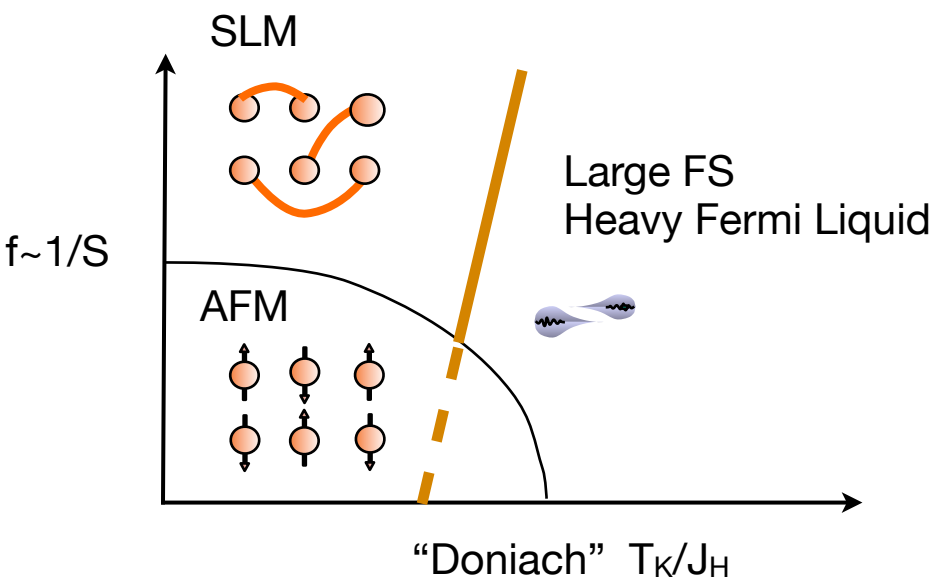


Experimental Support



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

β-YbAlB$_4$



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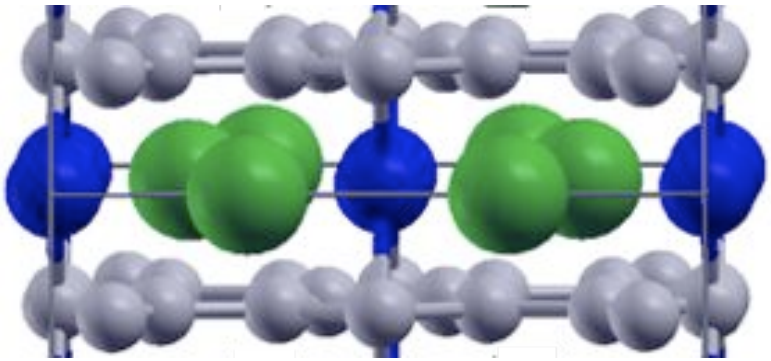

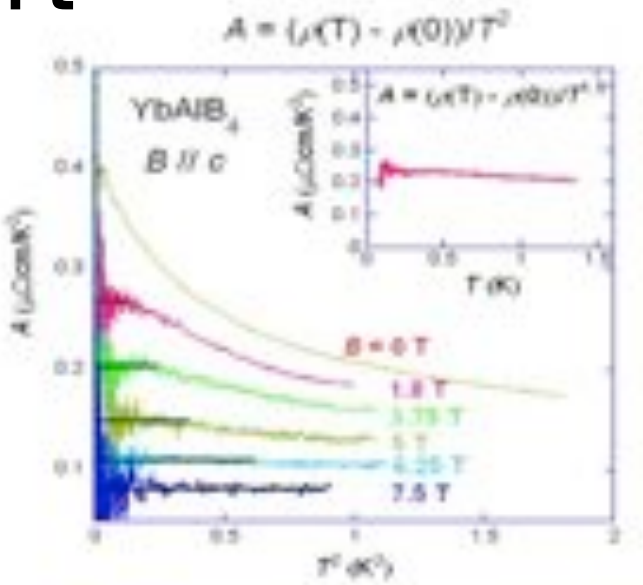

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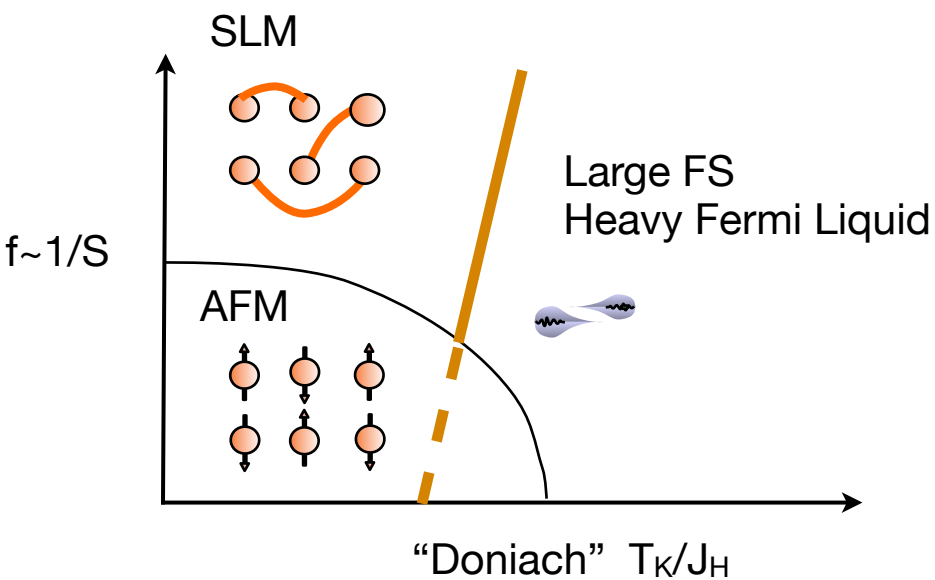

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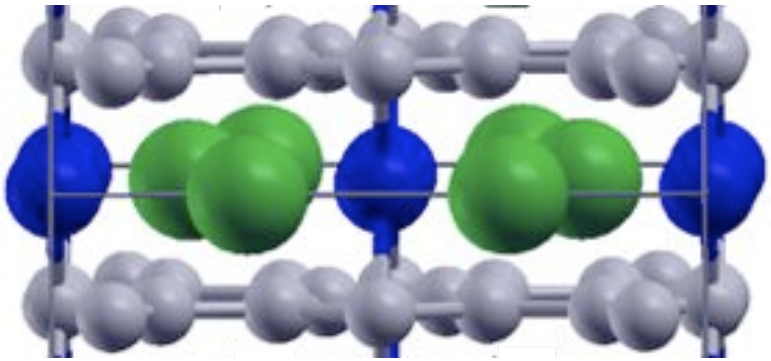

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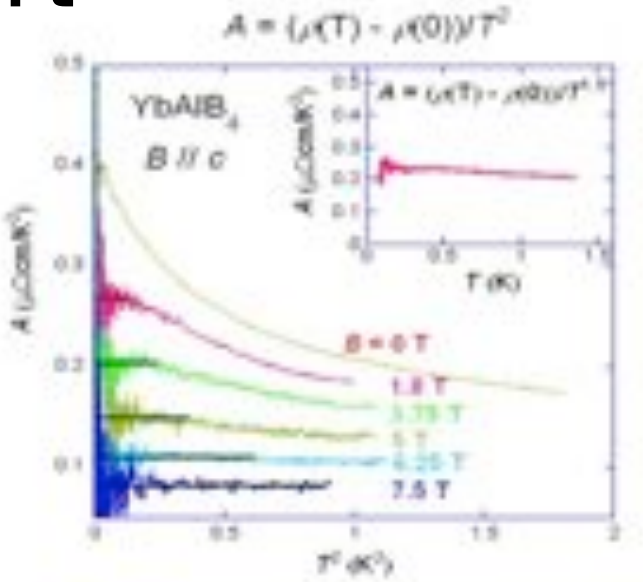
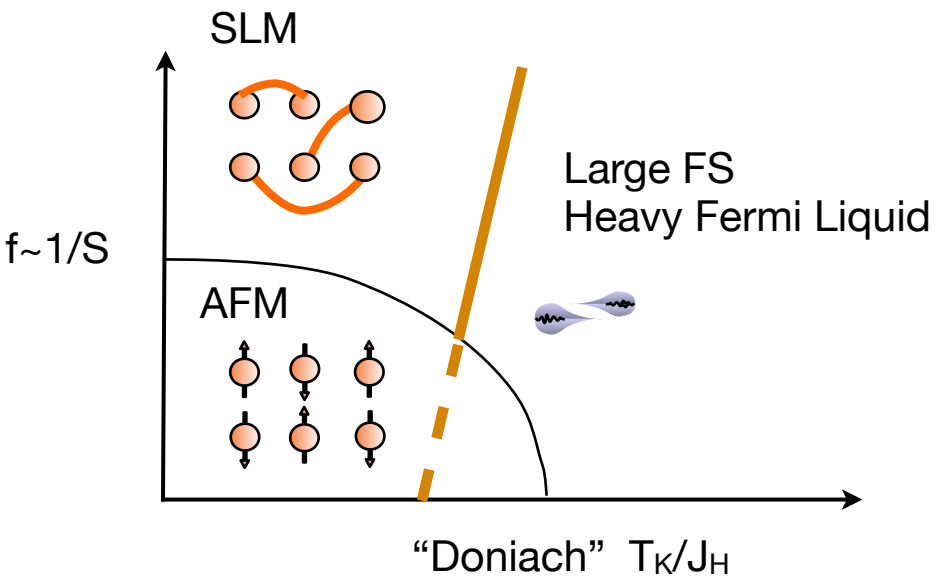


Non-Fermi liquid at B=0.
Small field restores Fermi liquid behavior.

$$m^*/m_e = (B - B_c)^{-1/4}, \qquad B_c \sim 0.$$



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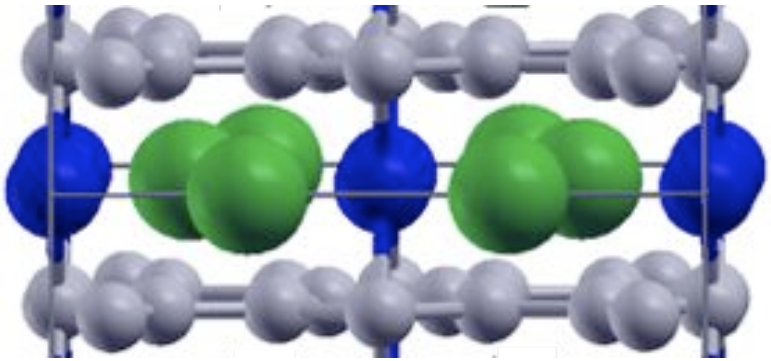

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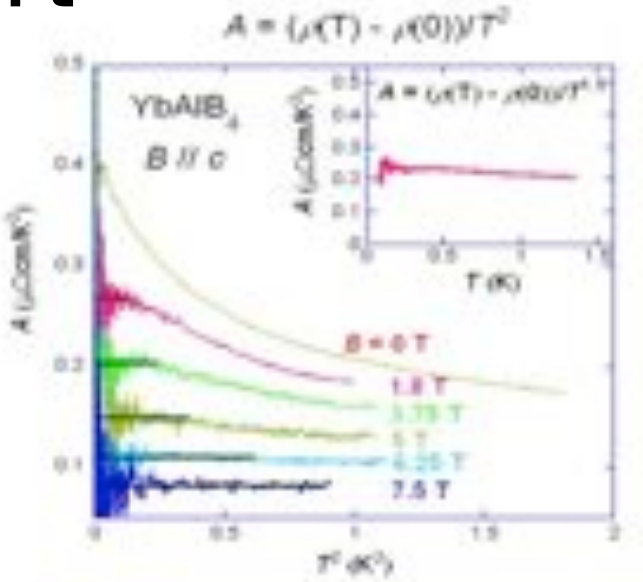

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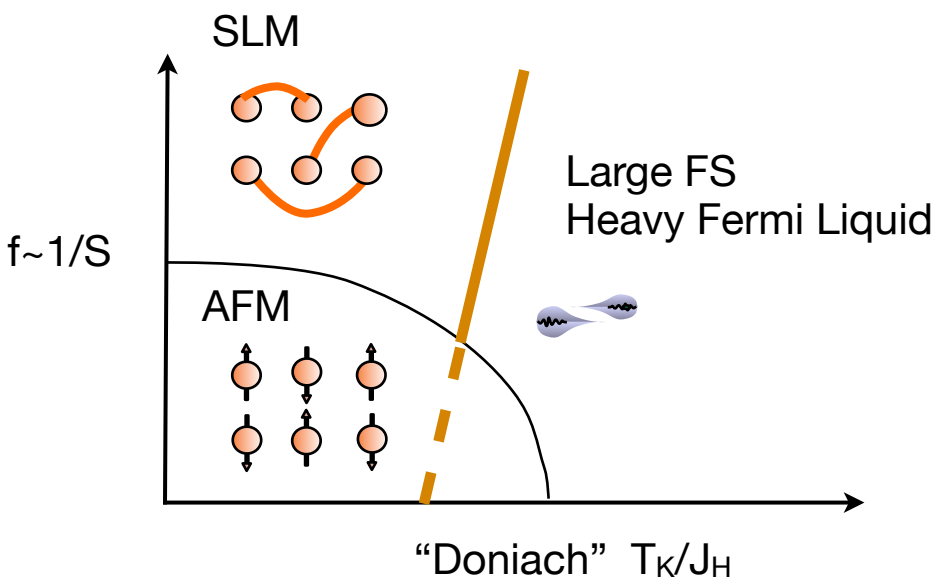

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Critical Phase?

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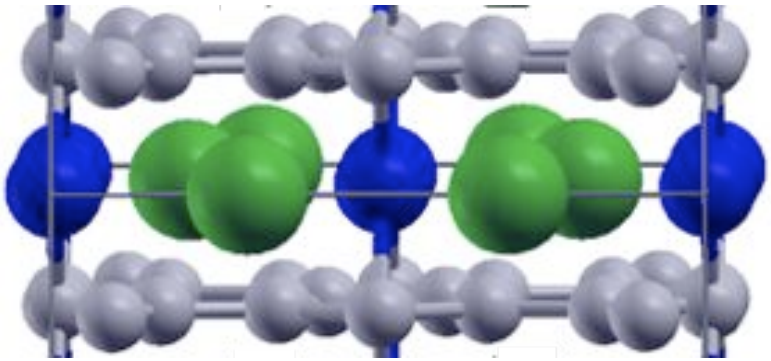

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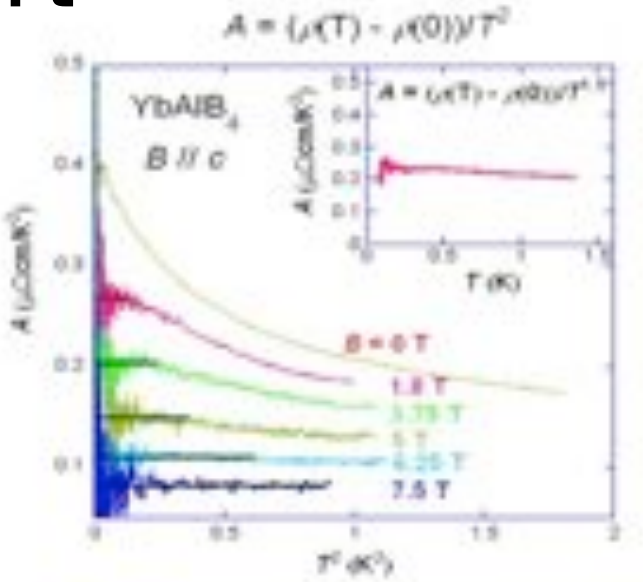

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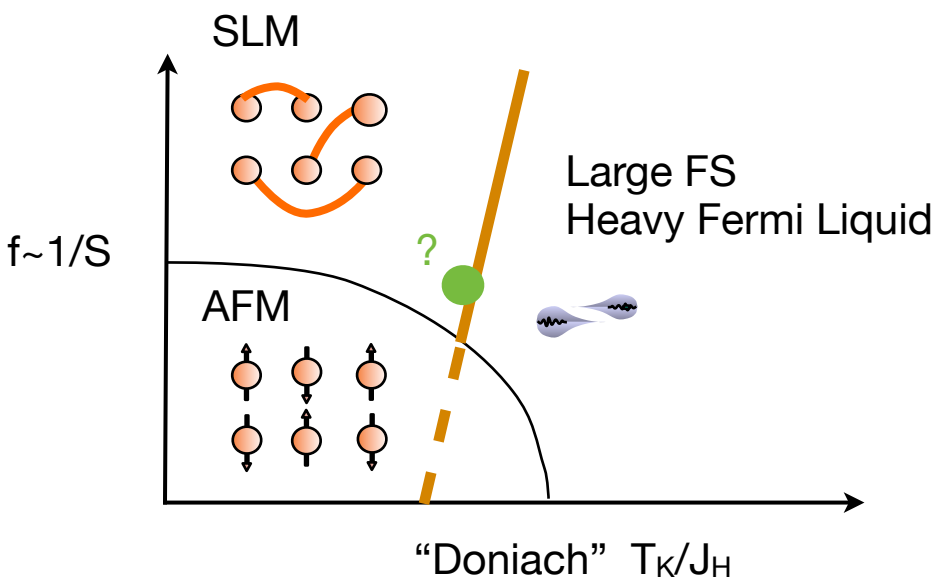

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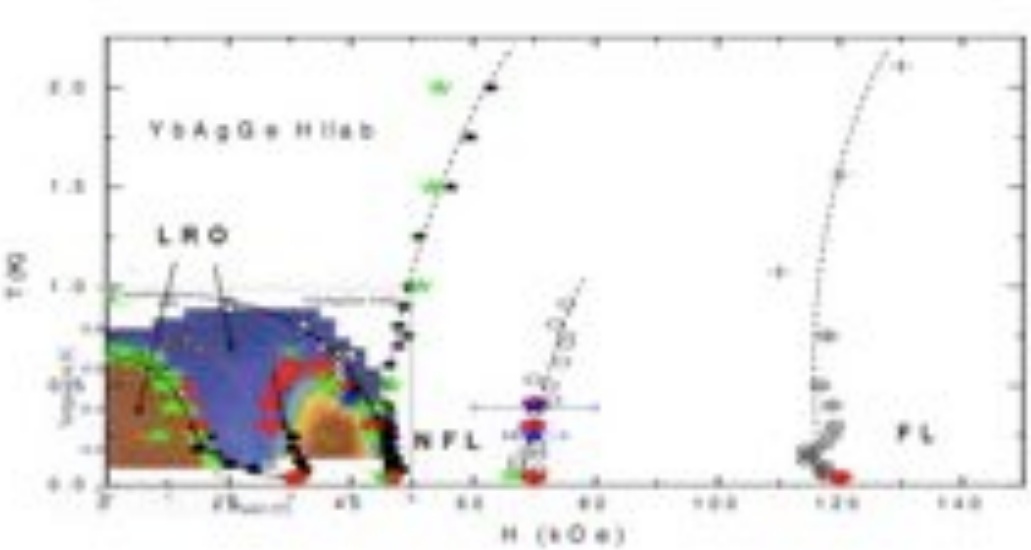
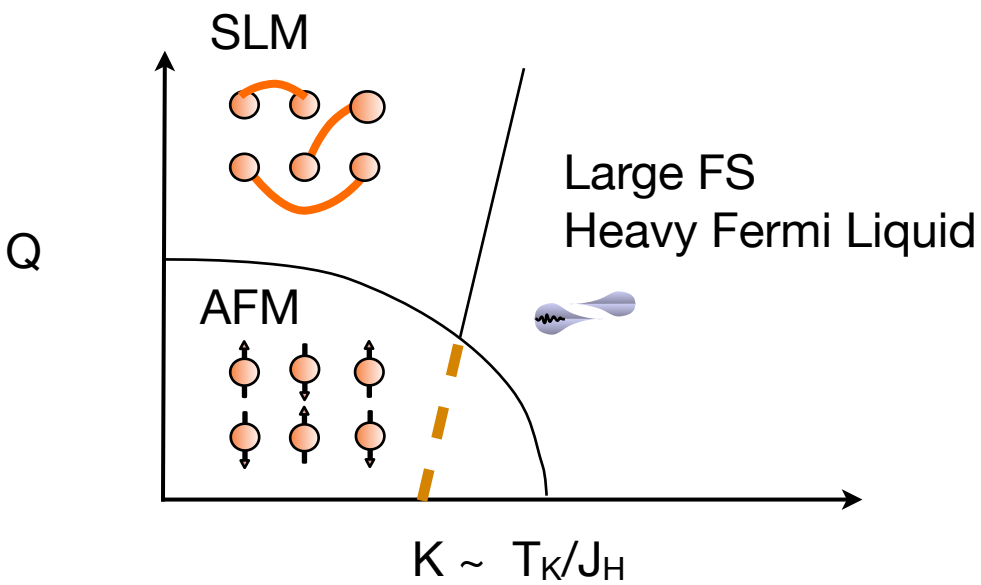
See:
A. Nevidomskyy & PC PRL (2009).
T. Senthil, S.Sachdev, M.Vojta,PRL **90**, 216403; PRB **69**, 035111 (2004);
P. W.Anderson, arXiv:0810.0279 (2008)

Experimental Support II



Canfield et al (unpublished)



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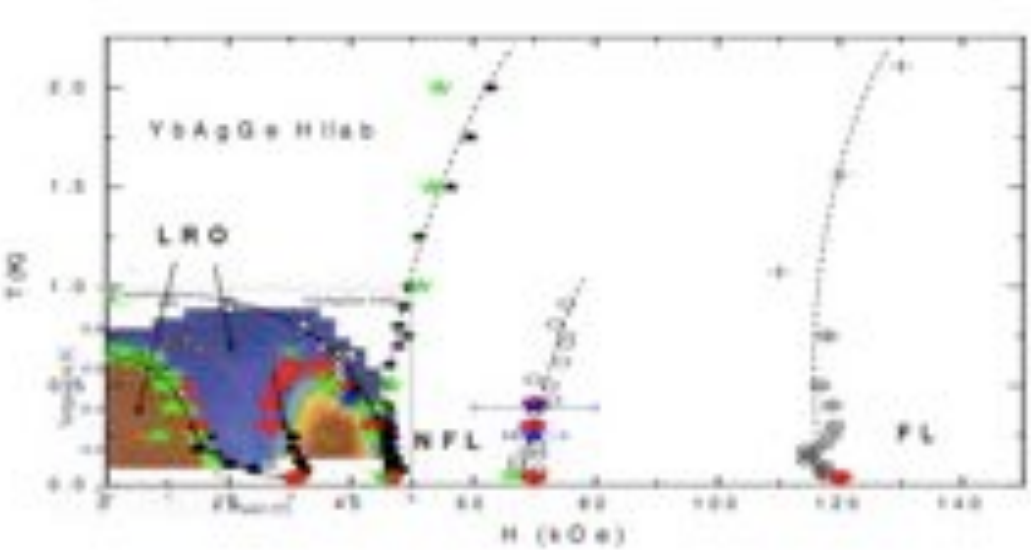

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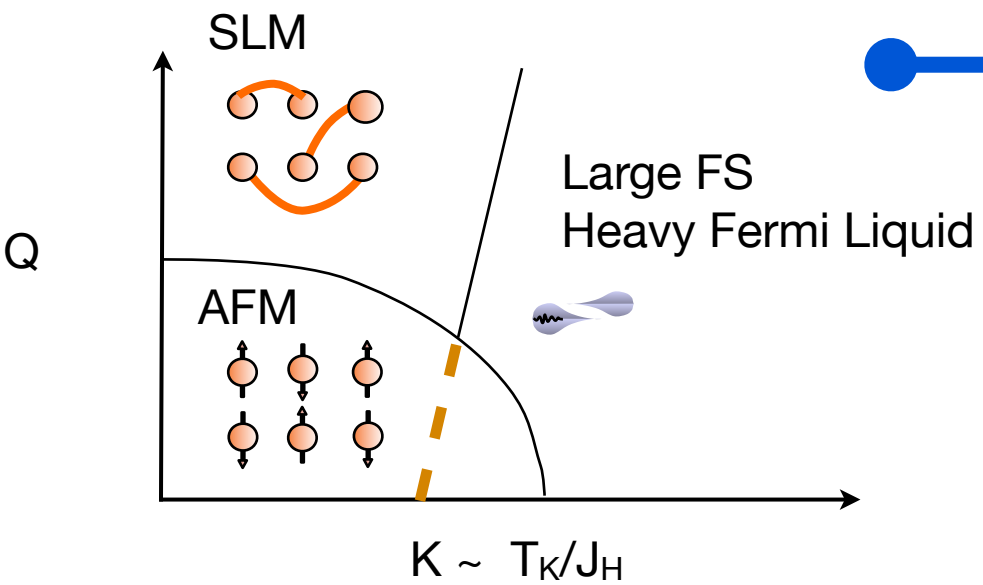

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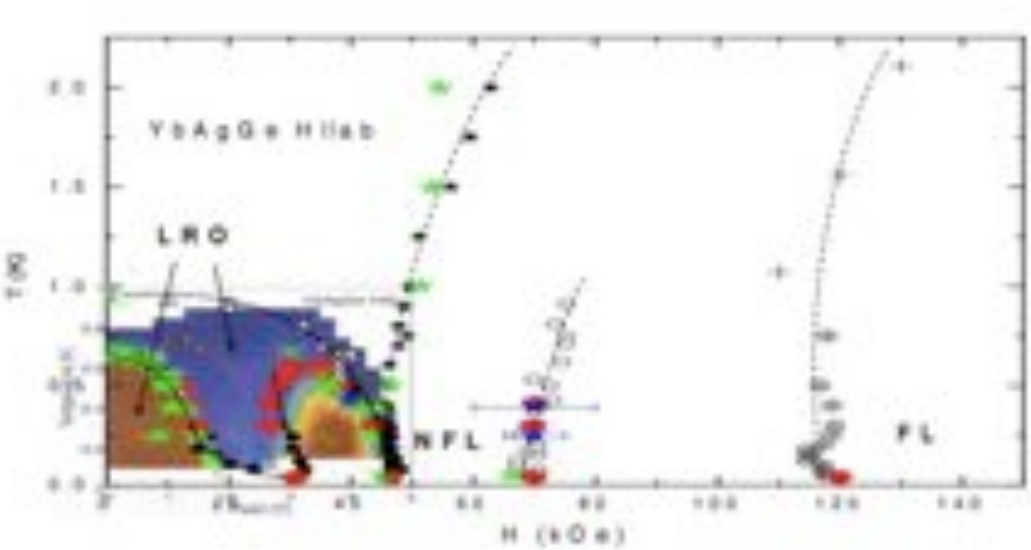

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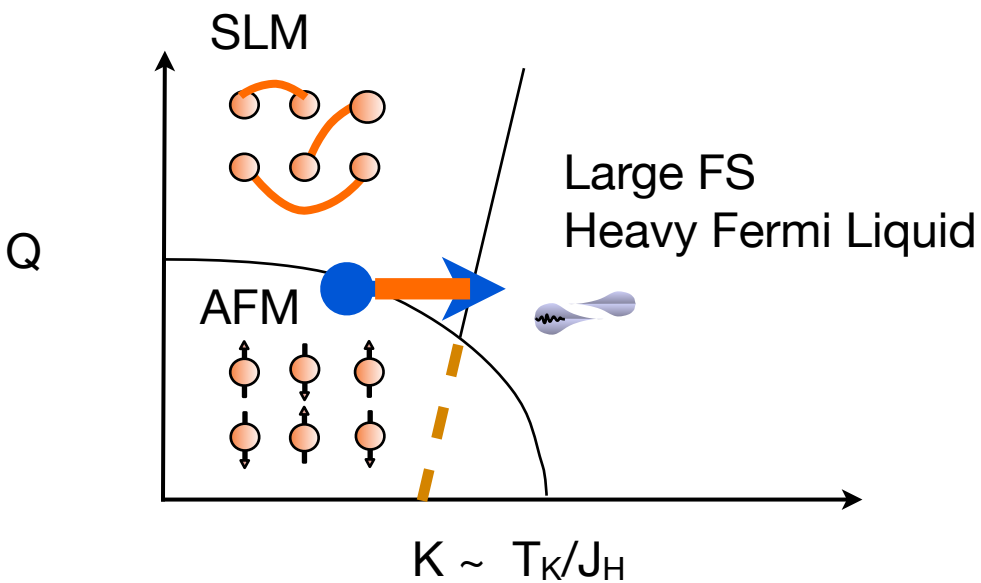

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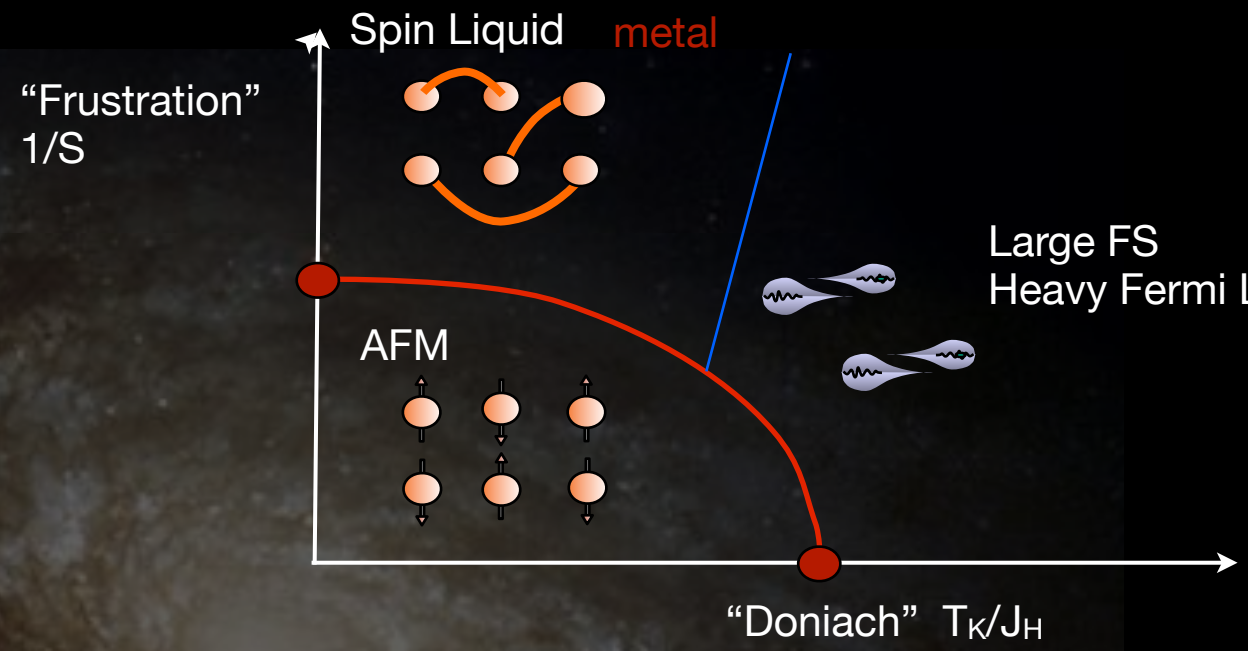

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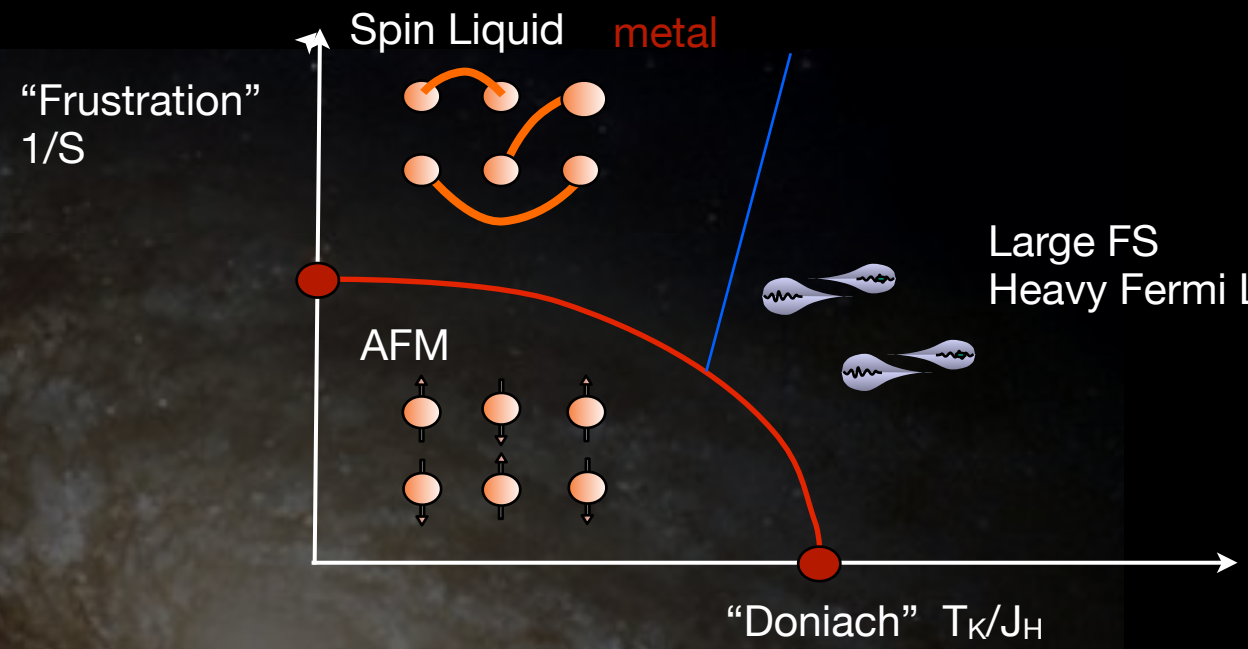

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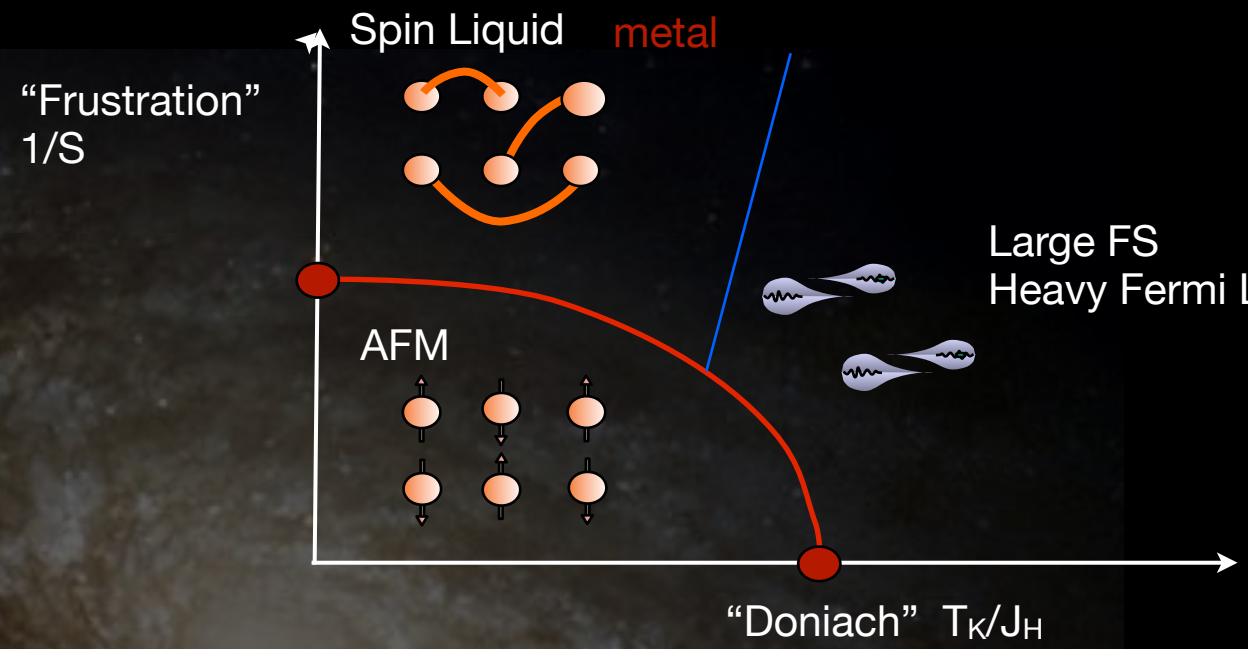

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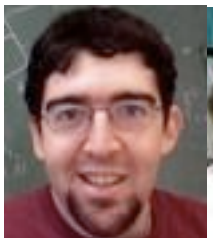
Collaborators


Flint


Nev.


Dzero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