Heavy fermions : condensed matter theory perspective

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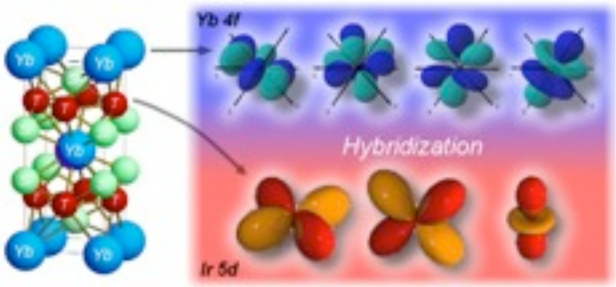
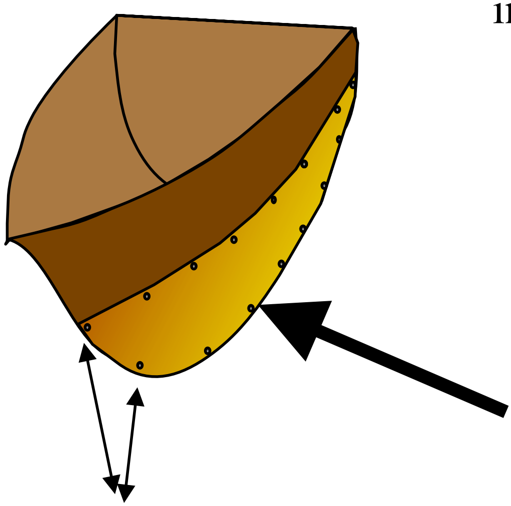
KITP, Oct. 13th 2011



Materials in the Revolutionary Wars.

1779: end of war of independence.

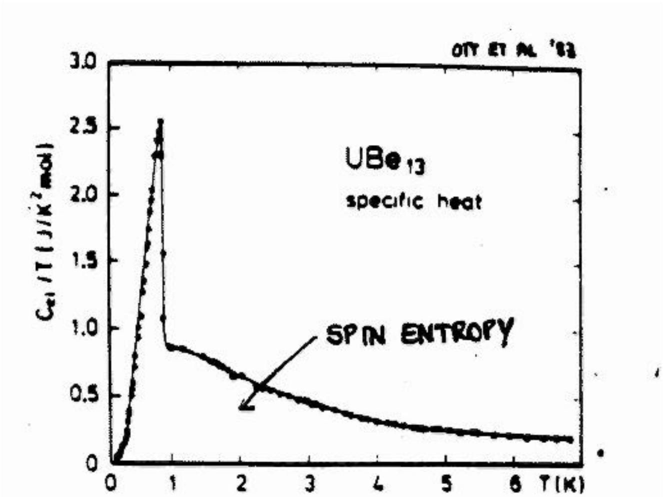


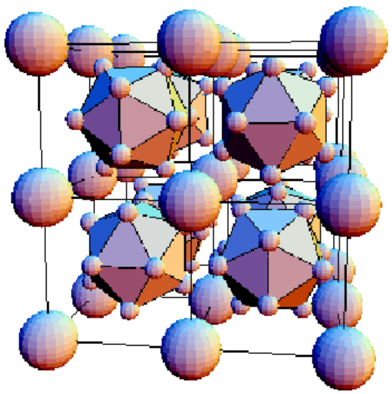
"For God's sake and our countries- send copper bottomed ships to relieve the foul and crippled ones."

Copper plated Hull

IRON BOLTS : RAPIDLY CORRODED

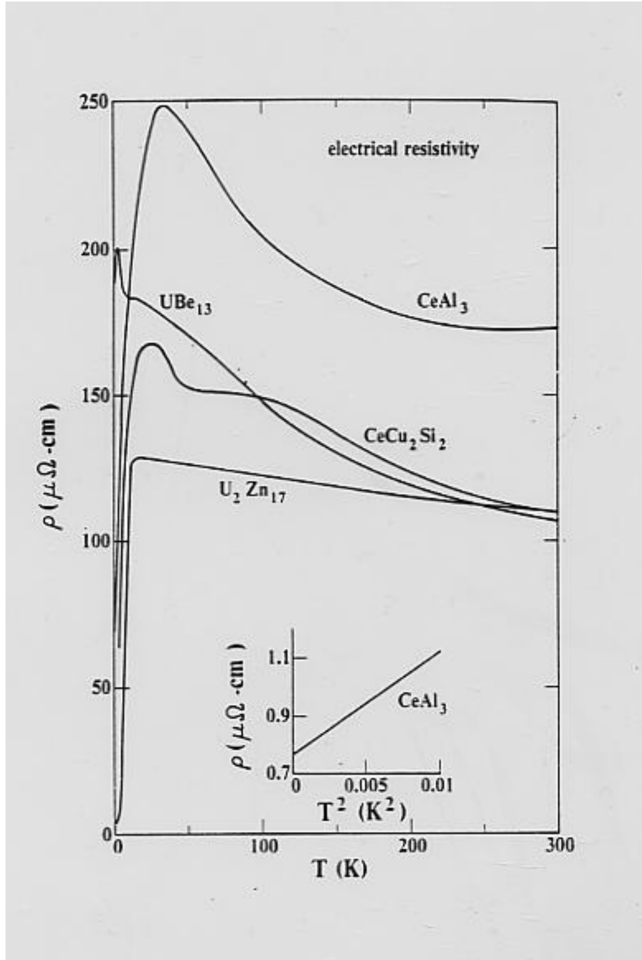
Heavy Fermion Metals: Extreme Limit of Mass Renormalization.





UBe_{13}

$$\frac{m^*}{m} \sim 1000$$



3

Ce : $4f^1$ | Yb : $4f^{13}$ | U : $5f^2$

S=1/2 L=3
Spin Orbit : J= |L-S|= 5/2

S=1/2 L=3
S O : J= |L+S|= 7/2

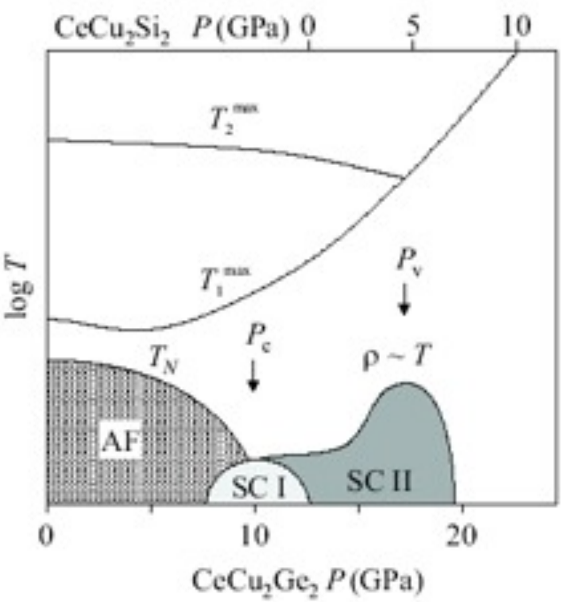
S=1 L=3+2
S O : J= |L-S|= 4

Crystal Electric Field effects split the big moments and compete with Hunds rules

→ Ferromagnetic fluctuations
→ valence fluctuations
→ multiple stage screening ?

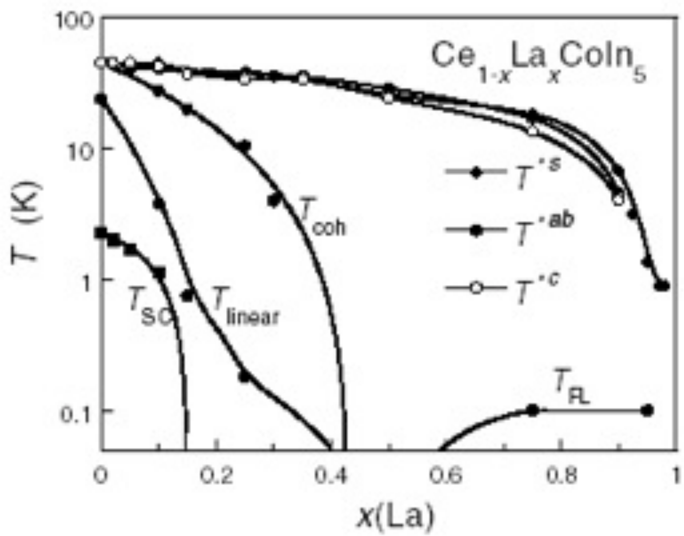
Miyake 99-04

Valence fluctuations at pc



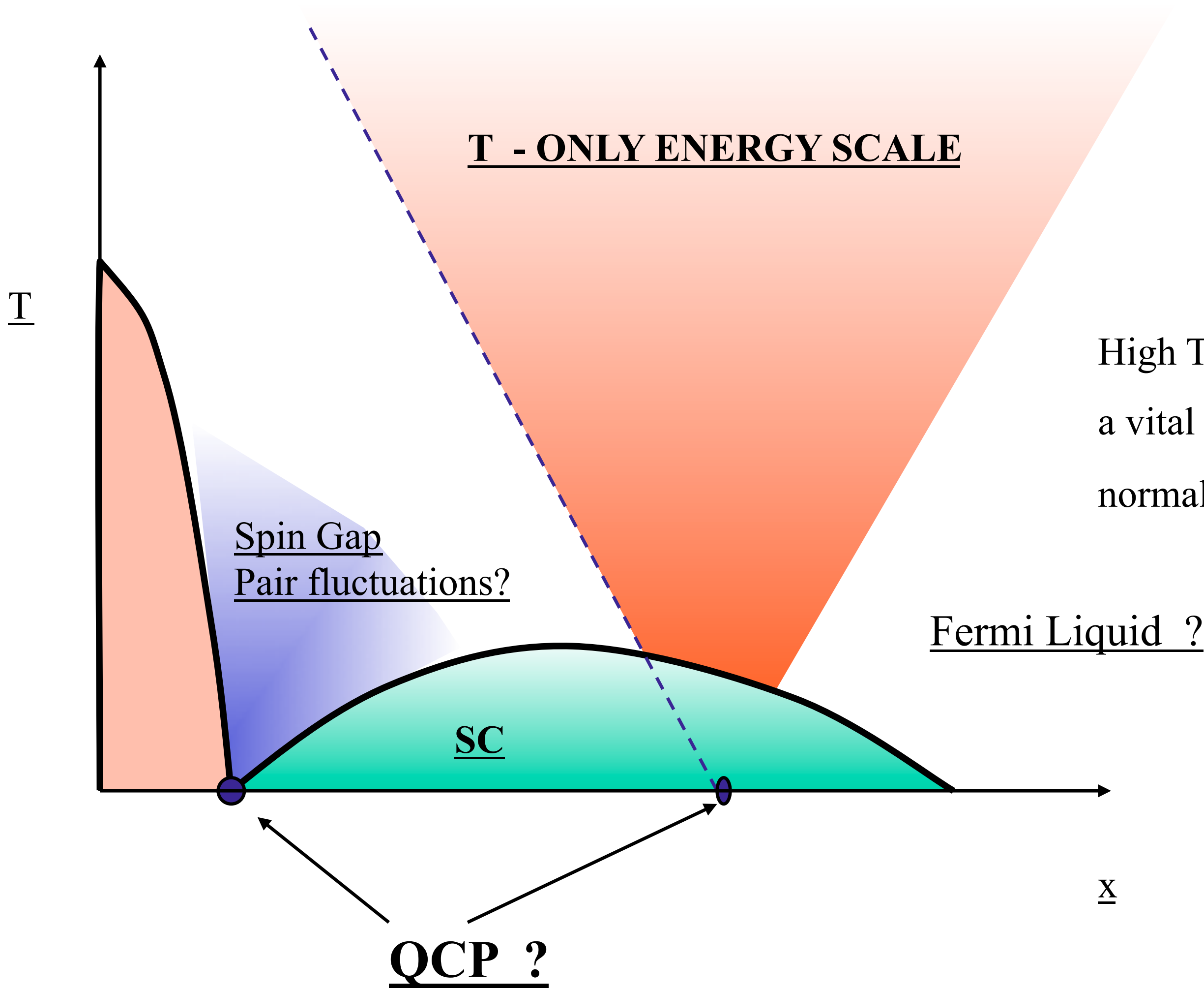
Jaccard 03

Multiple Kondo screening



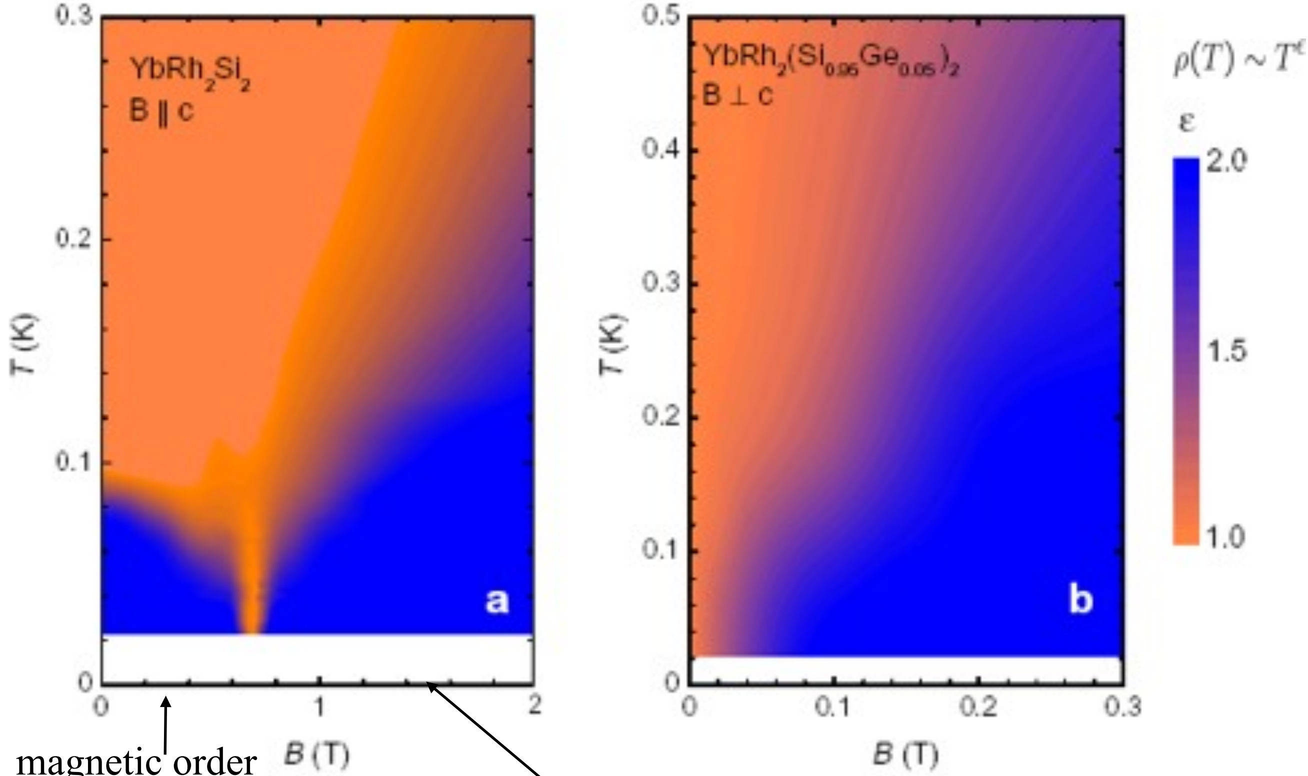
Nakatsuji 03

Quantum criticality



High Tc: QCP may play a vital role in setting the normal state properties.

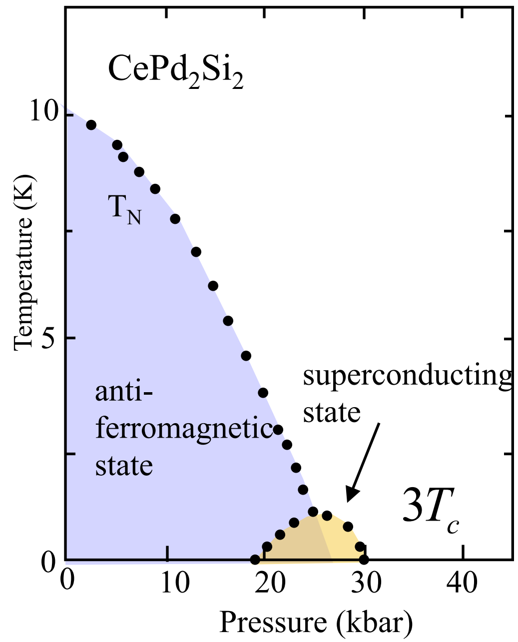
Do we understand QCPs
where the order parameter is uncontraversial?

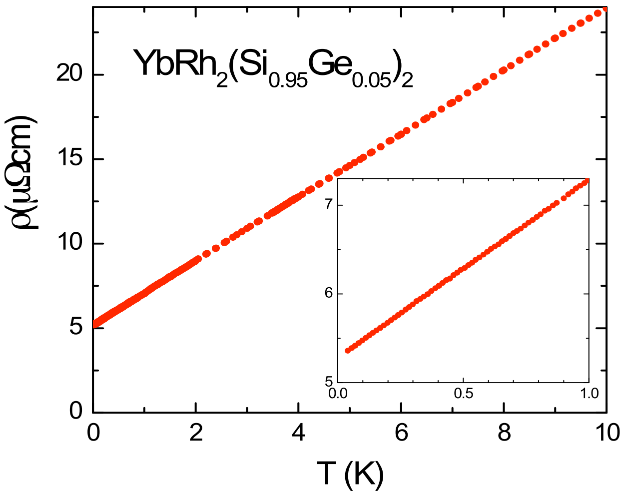


magnetic order

heavy Fermi liquid

Lhoneysen, (1999)





Custers et al (CP), Nature 2003

Resistivity linear !

What is critical and what is not ?

Clear NFL in transport and specific heat

Explained by the standard theory of itinerant magnetism ?

Is the anomaly due to Quantum Criticality ?

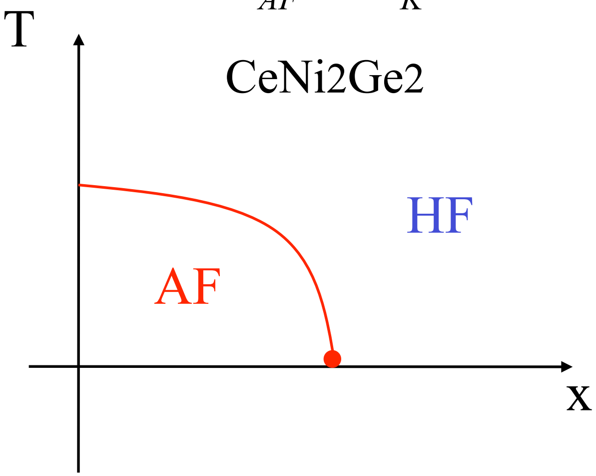
Compound	$H_c/P_c/x_c$	$\frac{C_v}{T} \to \infty$?	$\rho \sim T^a$	Reference
$YbRh_2(Si_{1-x}Ge_x)_2$	$x_c = 0.05$ $H_c^{\parallel c} = 0.66T$ $H_c^{\perp c} = 0.06T$	$T^{-0.34}$	T	Dresden, Grenoble
$CeCoIn_5$	$H_c = 5T$	$T^{-\alpha}$	T	Los Alamos, Grenoble
$Ce(Cu_{1-x}Au_x)_6$	$x_c = 0.016$	$Log\left(\frac{T_o}{T}\right)$	T	Karlsruhe
$CeCu_{6-x}Ag_x$	$x_c = 0.2$	$Log\left(\frac{T_o}{T}\right)$	$T^{1.1}$	Gainesville
$CeNi_2Ge_2$	$P_c = 0$	$Log\left(\frac{T_o}{T}\right)$	$T^{1.4}$	Karlsruhe, Cambridge
U_2Pt_2In	$P_c = 0$	$Log\left(\frac{T_o}{T}\right)$	T	Leiden
$CeCu_2Si_2$	$Pc = 0$	$Log\left(\frac{T_o}{T}\right)$	$T^{1.5}$	Dresden, Grenoble
$Ce(Ni_{1-x}Pd_x)Ge_2$	$x = 0.065$	$\gamma_0 - T^{1/2}$	$\rho_0 + T^{3/2}$	Los Alamos
$YbAgGe$	$H = 4T$	$Log\left(\frac{T_o}{T}\right)$	T	Ames, Grenoble
$CeIn_{3-x}Sn_x$	$p_c = 26kbar$	?	$T^{1.6}$	Dresden
U_2Pd_2In	$P_c < 0$	?	T	Leiden
$CePd_2Si_2$	$P_c > 0$	?	$T^{1.2}$	Karlsruhe, Dresden
$CeRhIn_5$	$P_c \sim 1.6GPa$	?	T	Los Alamos, Grenoble
$CeIn_3$	$P_c > 0$	?	$T^{1.5}$	Dresden
$Ce_{1-x}La_xRu_2Si_2$	$x_c = 0.1$	no	?	Grenoble
$U_3Ni_3Sn_4$	$P_c > 0$	no	?	Leiden

Two scenarios

Spin Density Wave

$$E_{AF} \leq J_K$$

CeNi2Ge2



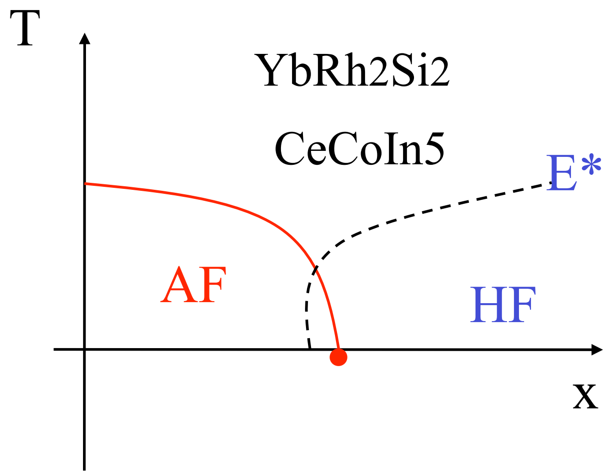
SDW scenario:
big Fermi surface at the QCP

Kondo Breakdown

$$E_{AF} \geq J_K$$

YbRh2Si2

CeCoIn5



QCP with fractionalization

Theoretical approaches

Low energy properties ⟷ Universality

UV

High energy physics – microscopic hamiltonian

Integrate out the “fast”
degrees of freedom

IR

Low energy, slow, universal part

Universality

Low energy properties $\longleftrightarrow$ Universality

UV

High energy physics – microscopic hamiltonian

Integrate out the "fast" degrees of freedom

IR

Low energy, slow, universal part

Universality

What is observed around some QCP in heavy fermions

$\rho(T) \sim T$,

$\chi(T) \sim T^{-\alpha}$, with $\alpha \leq 1$

$\gamma_P(T) = \frac{C_P}{T} \sim T^{-\beta}$, with $\beta \leq 1$.

Universal Too!

Landau Fermi liquid theory verified by ``all '' conductors above 1D

$\rho(T) \sim T^2$,

$\chi(T) \sim \mu_0^2 \rho(\epsilon_F)$,

$\gamma_P(T) = \frac{C_P}{T} \sim \frac{k_B^2 \pi^2}{3} \rho(\epsilon_F)$.

Universal exponents

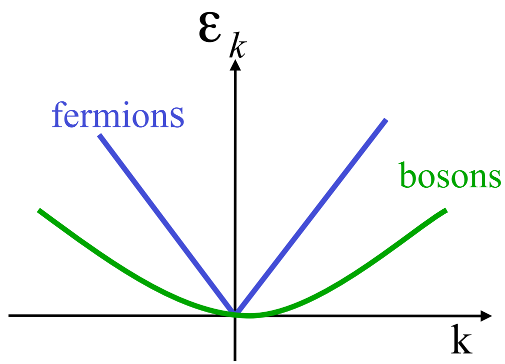
Can we integrate the fermions out of the partition function?

φ^4 effective bosonic theory

For example z=2

$$D^{-1}(q,\Omega) = \frac{|\Omega|}{E_F} + \frac{q^2}{k_F^2}$$

fermions are mass-less but fast compared to bosons?



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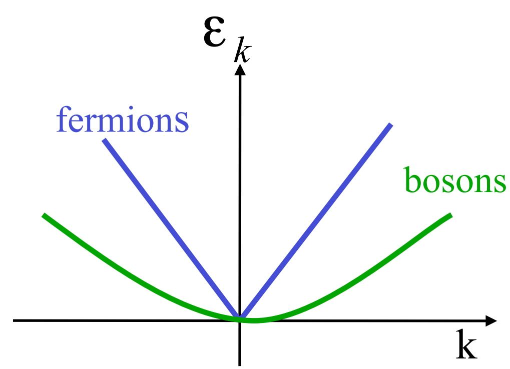
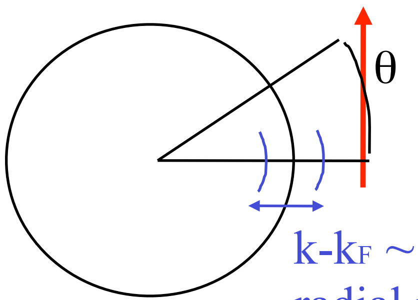


Two types of modes cannot be separated at the level of the action

transverse modes are slow!
(controlled by boson fluctuations)

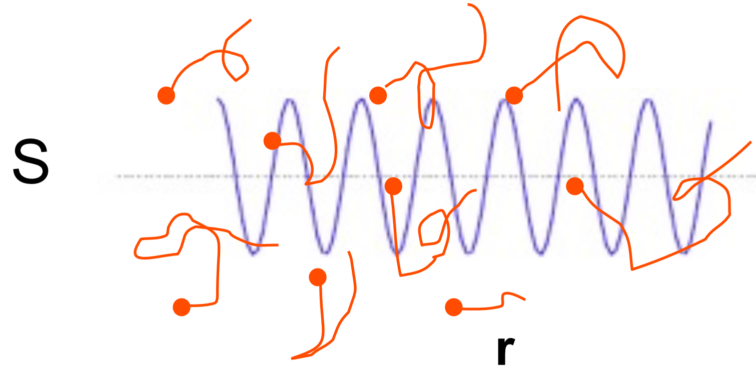


k-k$_F$ ~ T
radial modes are fast

$$q_{radial} \sim T$$
$$q_{transverse} \sim \sqrt{T}$$

John A. Hertz.

The Spin Density Wave Scenario

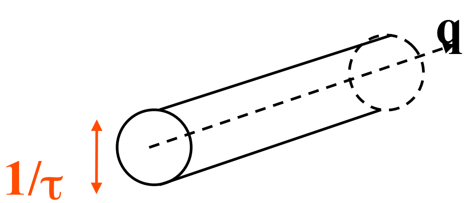


Hertz-Millis-Moryia-Beal-Monod

$$F = M\left(i\alpha\omega + \xi^2 q^2 + \delta\right) M + bM^4 \ .$$

$\delta = a(T - T_c)$ and the QCP occurs at $T_c = 0$.

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



$z = 3$ for the ferromagnet ($\alpha = c/q$)

$z = 2$ for the anti-ferromagnet ($\alpha = c$)

The spin-fermion model

A Abanov, A. Chubukov, RMP 2003
Belitz, Kirkpatrick, Vojta, RMP 05
J Rech, CP, A Chubukov.

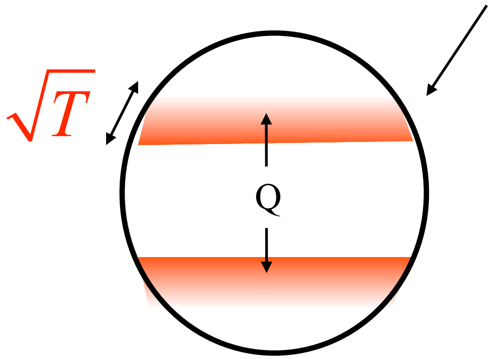
$$\frac{m^*}{m} \sim 1 - \frac{\partial \Sigma}{\partial \omega} \sim Log\left(\frac{T_0}{T}\right)$$

- 3D Spin Density Wave

Rosch, '98

Ex: CeNi2Ge2 ...

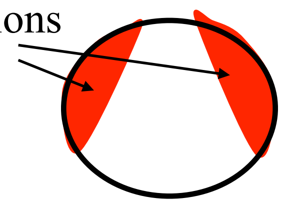
$$\Delta\rho(T) \sim T^{3/2}$$
$$\gamma_p(T) \sim Cst - \sqrt{T}$$



- 2D Spin Density Wave into 3D metal

Rosch ('98), Georges, Kotliar, Paul ('03)

hot regions



Ex: CeCu6Au, or CeCu6Ag ...

No anomalous exponent in spin susceptibility

$$\Delta\rho(T) \sim T$$
$$\gamma_p(T) \sim Log\left(\frac{T_0}{T}\right)$$

Eliashberg theory around itinerant ferromagnetism, or U(1) gauge theory coupled to matter

$$H_{sf} = \sum_{k,\alpha} \epsilon_k c^\dagger_{k,\alpha} c_{k,\alpha} + \sum_q \chi^{-1}_{s,0}(q) \mathbf{S}_q \mathbf{S}_{-q}$$

$$+ g \sum_{k,q,\alpha,\beta} c^\dagger_{k,\alpha} \boldsymbol{\sigma}_{\alpha\beta} c_{k+q,\beta} \cdot \mathbf{S}_q,$$

$$\chi_{s,0}(q,\Omega) = \frac{\chi_0}{\xi^{-2} + q^2 + A\Omega^2 + O(q^4,\Omega^4)}.$$

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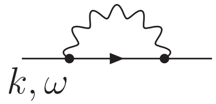
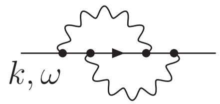
d=2



$\omega_0^{1/3} \; \omega^{2/3}$

$\left(\frac{\omega_0}{\omega}\right)^{1/3}$



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Rech, CP, Chubukov (06)

The bare power counting diverges in $d \leq 3$

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- neglect vertex corrections
- dressed propagators (self-energy)

$$\alpha \sim \frac{\bar{g}^2}{\gamma v_F^3} \sim \frac{\bar{g}}{N E_F} \ll 1 \qquad \beta \sim \frac{m\bar{g}}{\gamma v_F} \sim \frac{m_B}{Nm} \ll 1.$$

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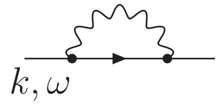

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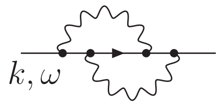
$\downarrow \quad \left(\frac{\omega_0}{\omega}\right)^{1/3}$



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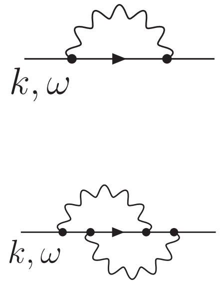

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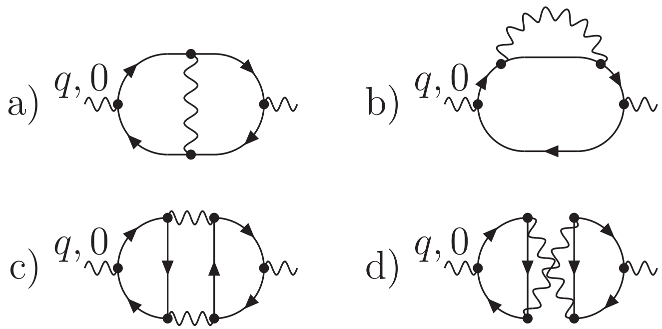

BKV type singularity

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Belitz, Vojta, Kirkpatrick(03),
Chubukov, Maslov (07)
Green, ben Simon(11)

And the culprit is ...

$2k_F$- scattering processes

the back -scattering

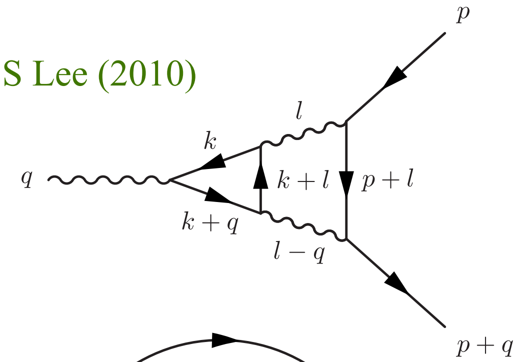
affecting AFM, nematic, and Ferro

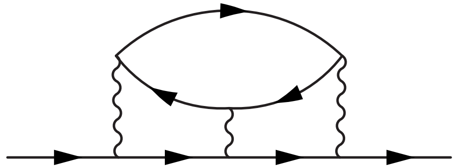
- FS deformed at the hot spots
- anomalous exponents

$2k_F$- scattering processes

the back -scattering

SS Lee (2010)





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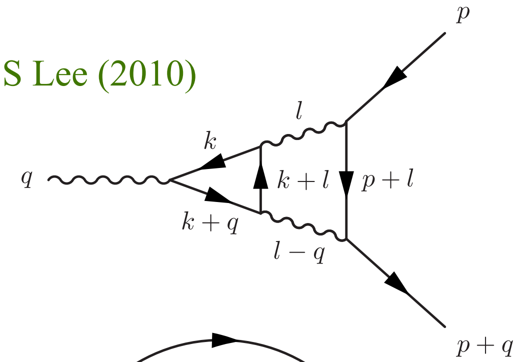

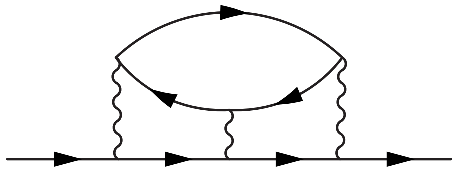

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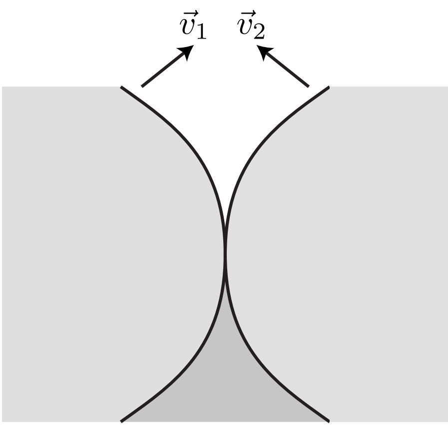
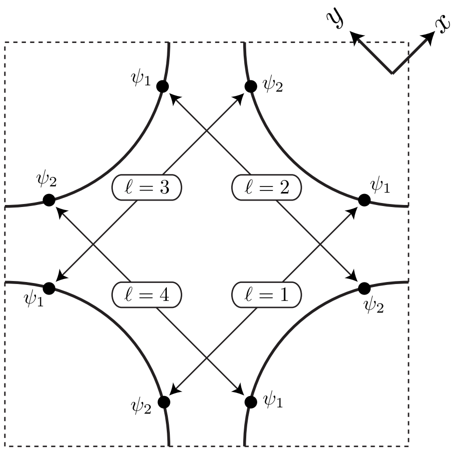
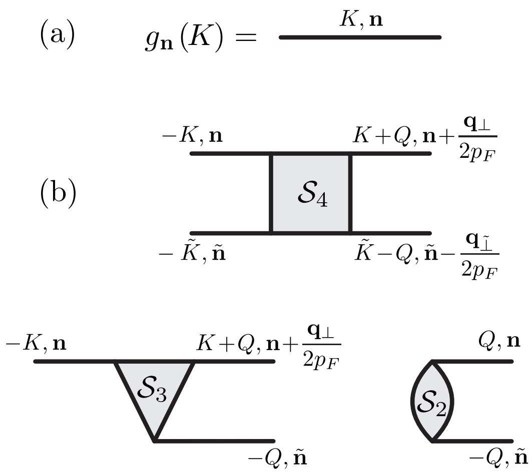




Metlitski, Sachdev (2010)

Recent susy-bosonization in high dimensions

Hendrik Meier,CP, Efetov



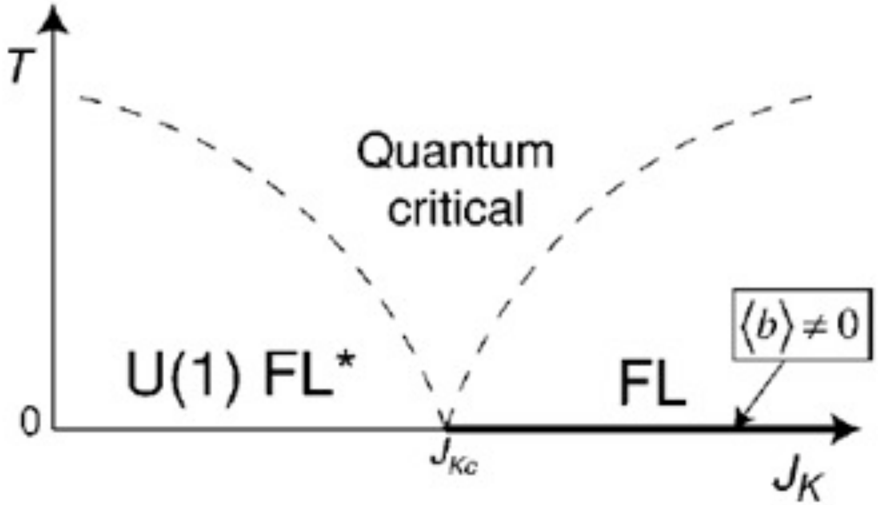
- Re-summation of the BS processes
- Curvature effects : charge and spin channels are coupled
- Re-summation of all non analyticities for the FL theory

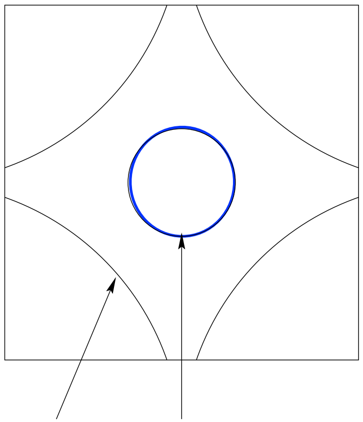
$$\delta\Omega = \frac{\zeta(3)T^3}{\pi v_F^2}\left\{\frac{\ln^2(1+\gamma_\pi^{\mathrm{I}} L)}{L^2} + 3\,\frac{\ln^2(1+\gamma_\pi^{\mathrm{II}} L)}{L^2}\right\}$$

$$\gamma_I = \gamma_c - 3\gamma_s$$
$$\gamma_{II} = \gamma_c + \gamma_s$$

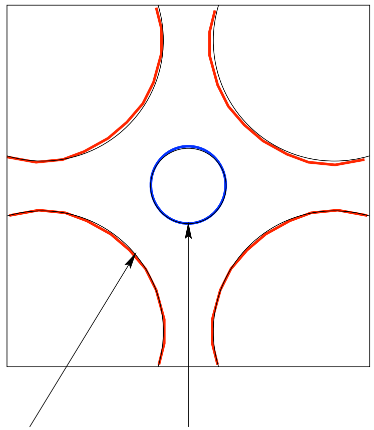
* K.B. Efetov, C. Pepin, H. Meier,
Exact bosonization for an interacting Fermi gas in arbitrary dimensions
Phys. Rev. Lett. 103,186403 (2009); PRB 82,235120 (2010), preprint 2011

Strong(er) coupling

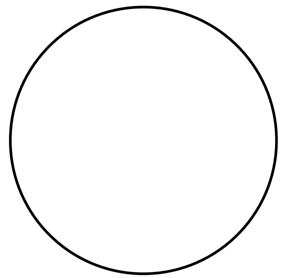




Spin liquid



Quantum Critical



Heavy fermi liquid

Senthil, Sachdev, Vojta -PRL2003 PRB 2004

Entropic considerations

Ce : $4f^1$

S=1/2 L=3

Spin Orbit : J= |L-S|= 5/2

Yb : $4f^{13}$

S=1/2 L=3

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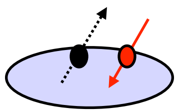

Kondo screening

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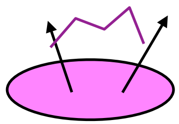
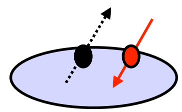
S=1 L=3+2

S O : J= |L-S|= 4



Spin Liquid



Kondo screening

Entropic considerations

Ce : $4f^1$

S=1/2 L=3

Spin Orbit : J= |L-S|= 5/2

Yb : $4f^{13}$

S=1/2 L=3

S O : J= |L+S|= 7/2

U : $5f^2$

S=1 L=3+2

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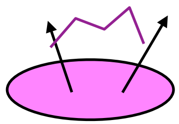
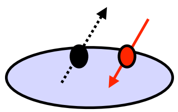
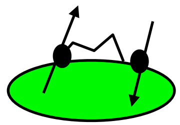


Spin Liquid



Kondo screening



Cooper pairs

Entropic considerations

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Spin Orbit : J= |L-S|= 5/2

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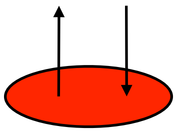
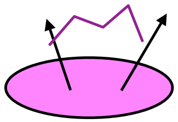
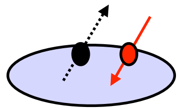


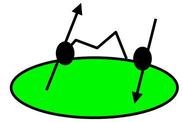
AF singlets



Spin Liquid



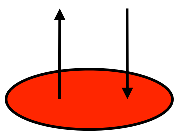
Kondo screening



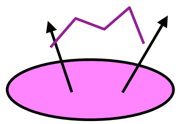
Cooper pairs

Entropic considerations

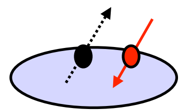
Ce : $4f^1$	Yb : $4f^{13}$	U : $5f^2$
S=1/2 L=3	S=1/2 L=3	S=1 L=3+2
Spin Orbit : J= |L-S|= 5/2	S O : J= |L+S|= 7/2	S O : J= |L-S|= 4



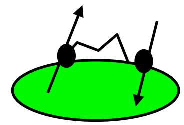
AF singlets



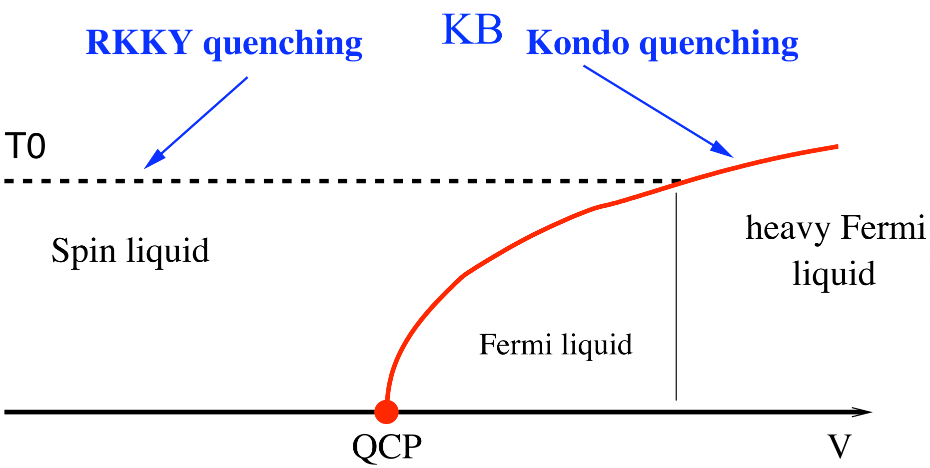
Spin Liquid



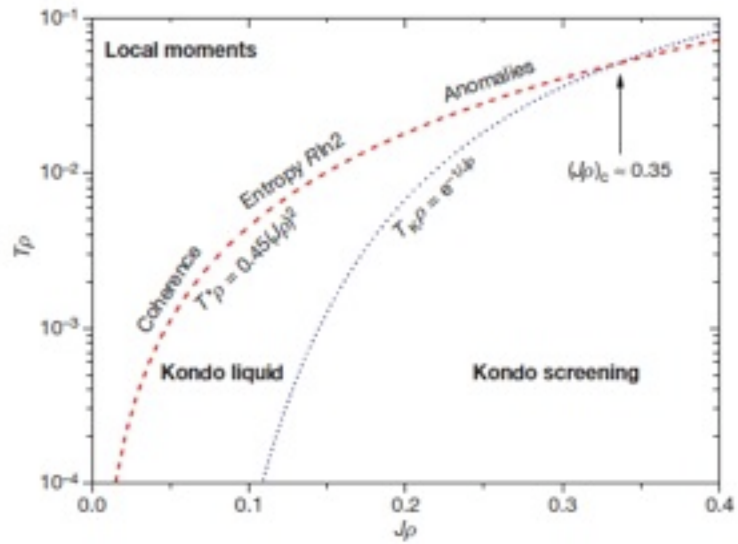
Kondo screening



Cooper pairs



Yang, Pines, Fisk, Thompson, 2008



Competition between Coulomb and Kinetic energy

$$H_{Coulomb} = U \sum_i n_{f\uparrow} n_{f\downarrow}$$

$$H_{Kinetic} = -\sum_{\langle ij \rangle} f_i^\dagger t_{ij} f_j$$

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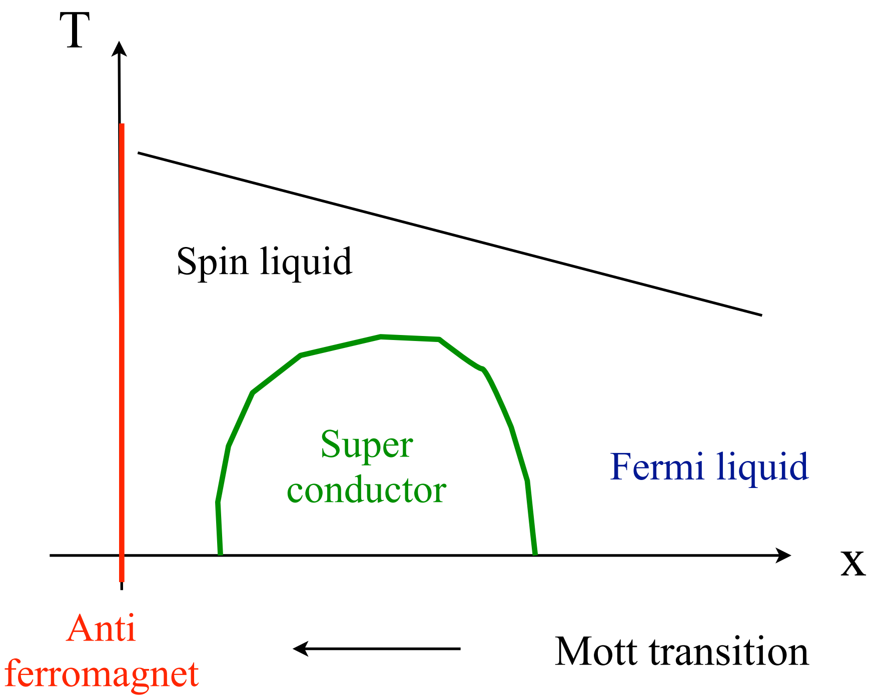
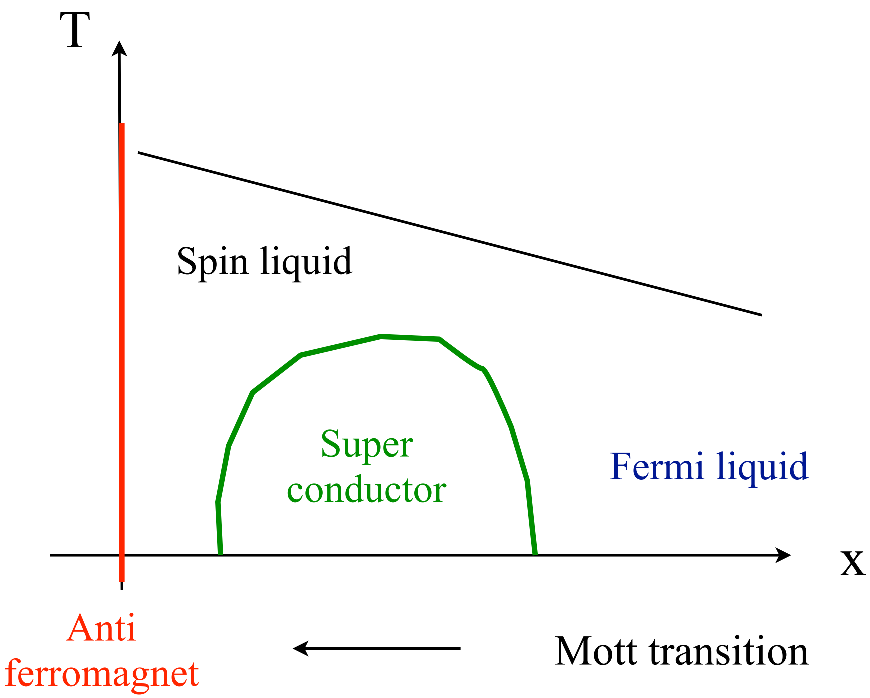


High Tc

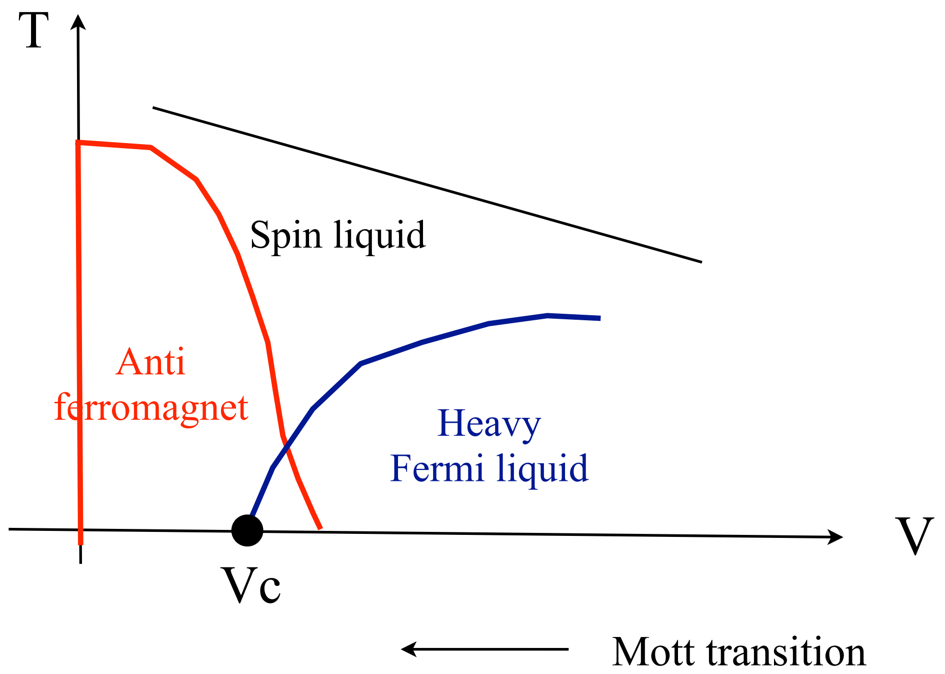
Competition between Coulomb and Kinetic energy

$$H_{Coulomb} = U \sum_i n_{f\uparrow} n_{f\downarrow}$$

$$H_{Kinetic} = -\sum_{\langle ij \rangle} f_i^\dagger t_{ij} f_j$$



High Tc



Anderson lattice

Breakdown of the Kondo effect associated with a Mott transition on the f-electrons

Zhu, Martin, PNP (09)
modulations in Kondo breakdown

P. Coleman (Schroder 2000)
deconfinement, fractionalization

Q. Si, Nature (02-)
S. Kirchner (06,08)
locally quantum critical

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breakdown by exhaustion

Pines, Zhang, Fisk (08)
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two fluids model

B. Jones (2010)
RG on Kondo Breakdown

Continentino (09) Vekhter + Seo+ CP (10) Paul ,Norman (10)
SC quantum critical point

CP, Norman ,Paul (07)
selective Mott transition, z=3 regime of fluctuations

Senthil, Sachdev ,Vojta (04)
model for fractionalization, spin liquid

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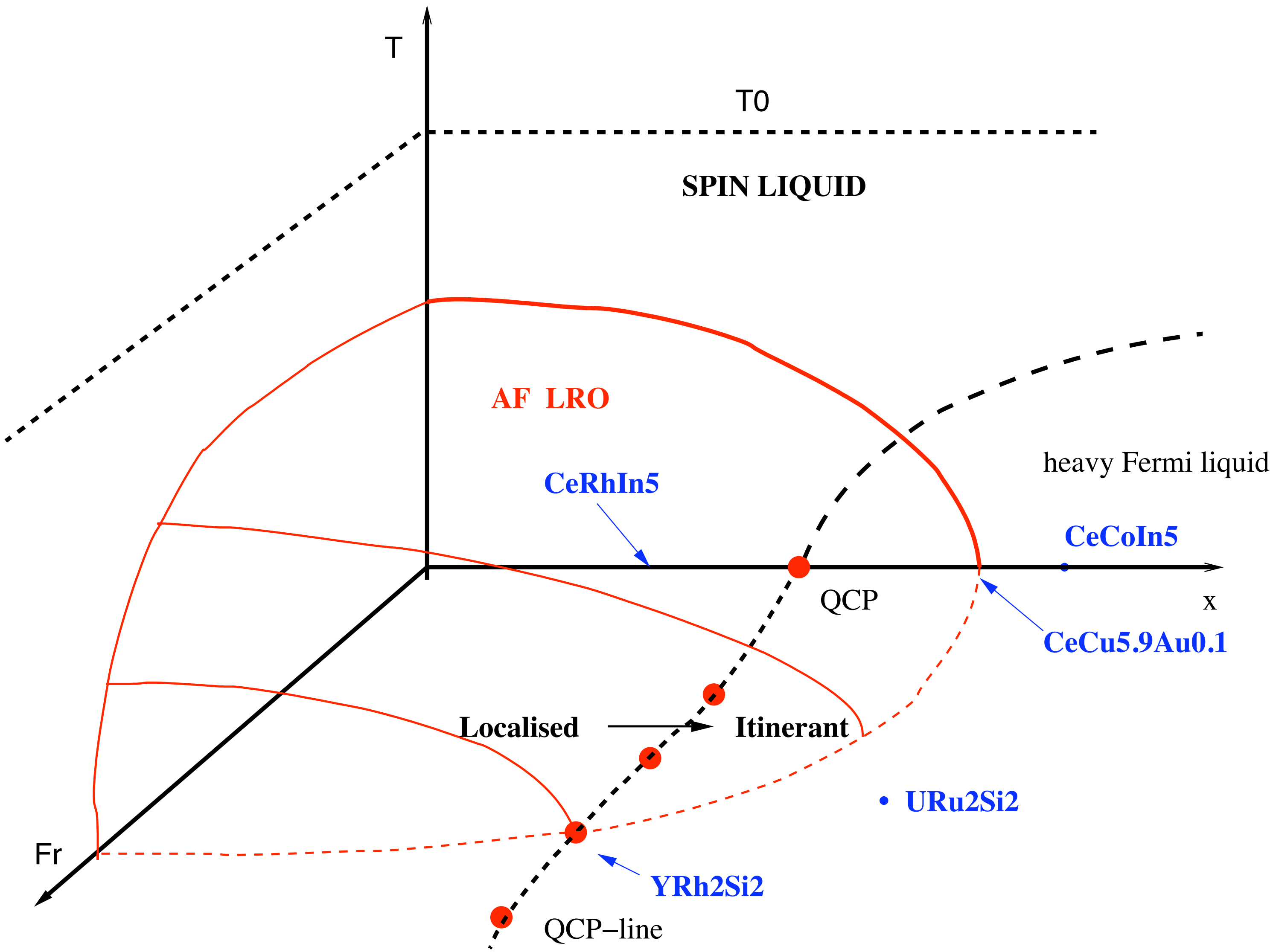
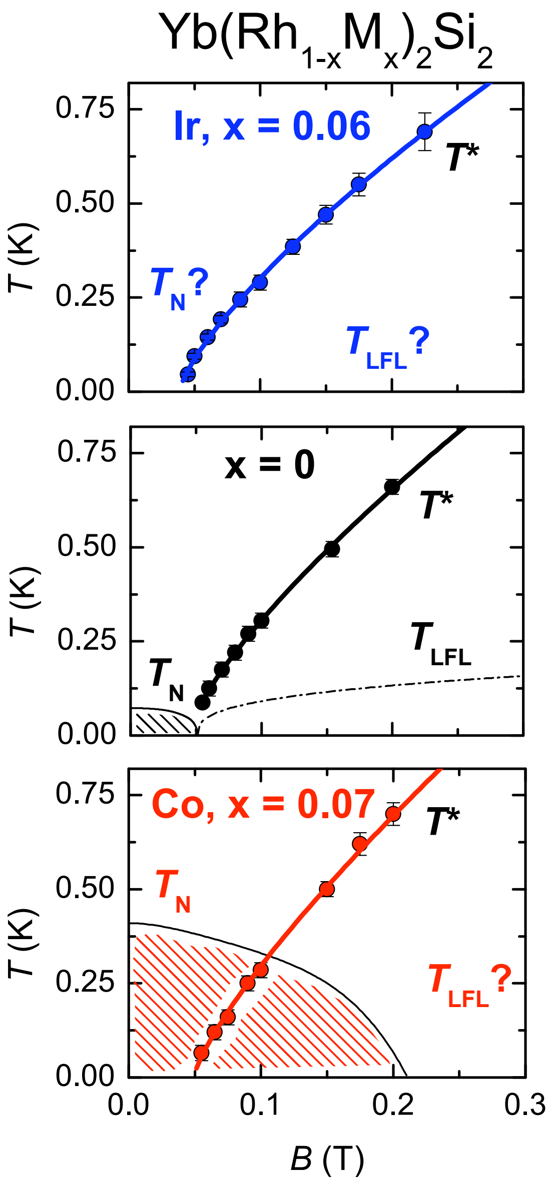

T
T0
SPIN LIQUID
AF LRO
heavy Fermi liquid
CeRhIn5
CeCoIn5
QCP
x
CeCu5.9Au0.1
Localised
Itinerant
URu2Si2
Fr
YRh2Si2
QCP–line

Doping plays the role of pressure

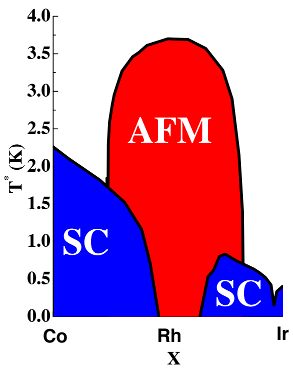


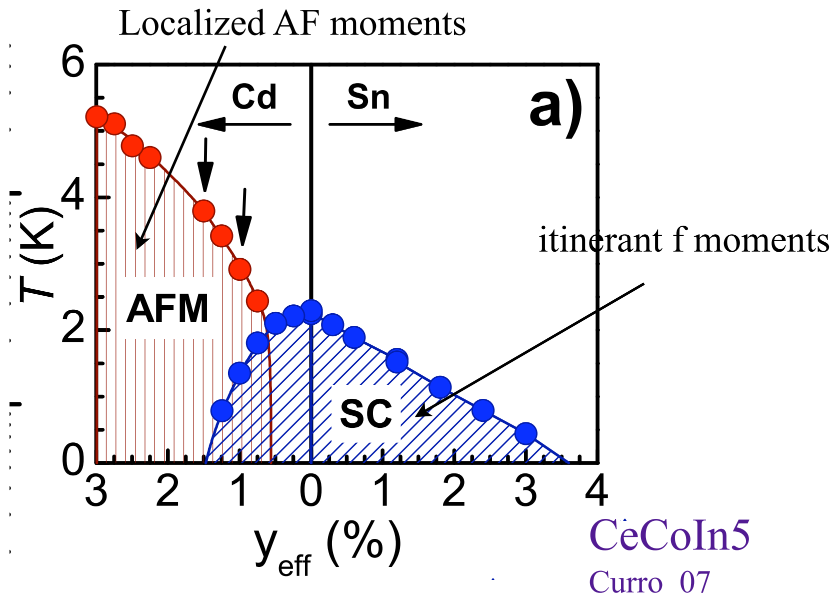
Dresden group (10)

Is there a spin liquid on the left of T* ?

Differentiate the scenarios where the KB is tight to AFM transition (Si et al.) from the ones where the KB is alone

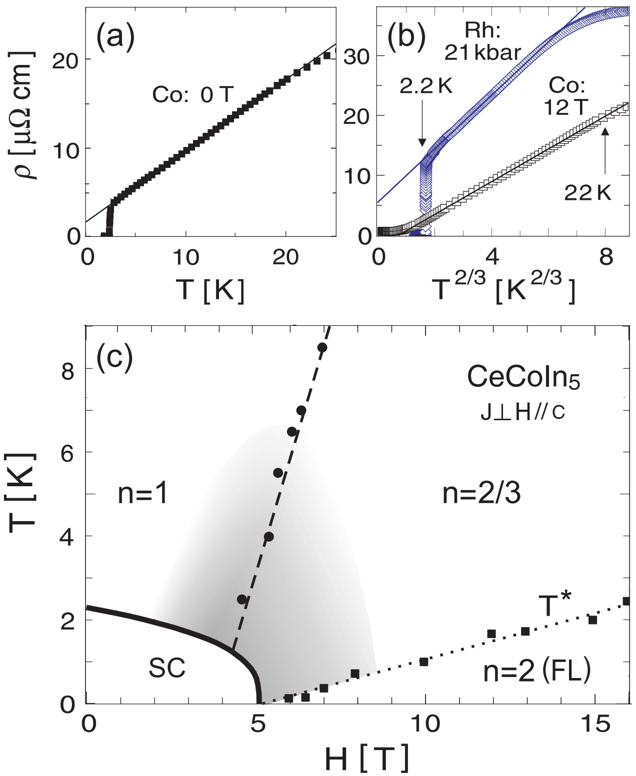
Evidence for localization in 115 .





CeCoIn5

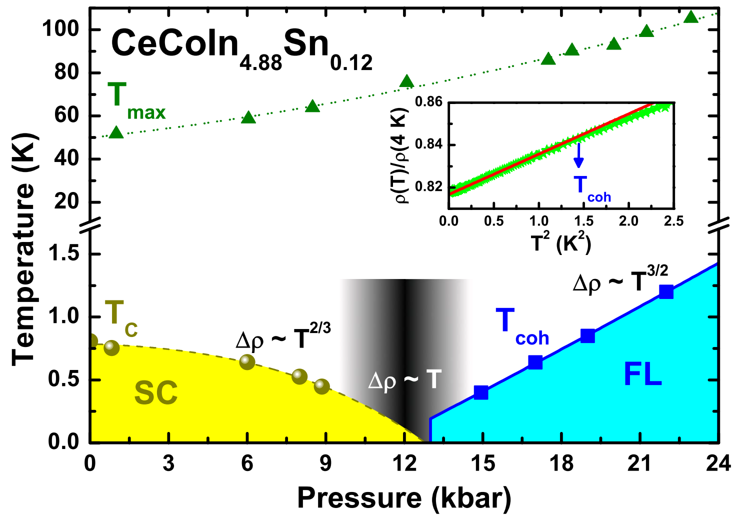
Curro 07



Paglione 04

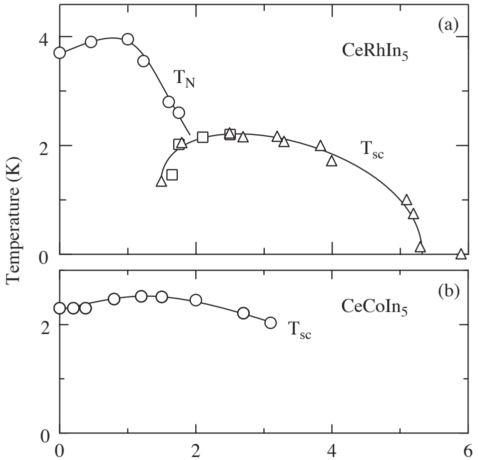
KB + Cross-over 3D → 2 D

sub-linear exponents

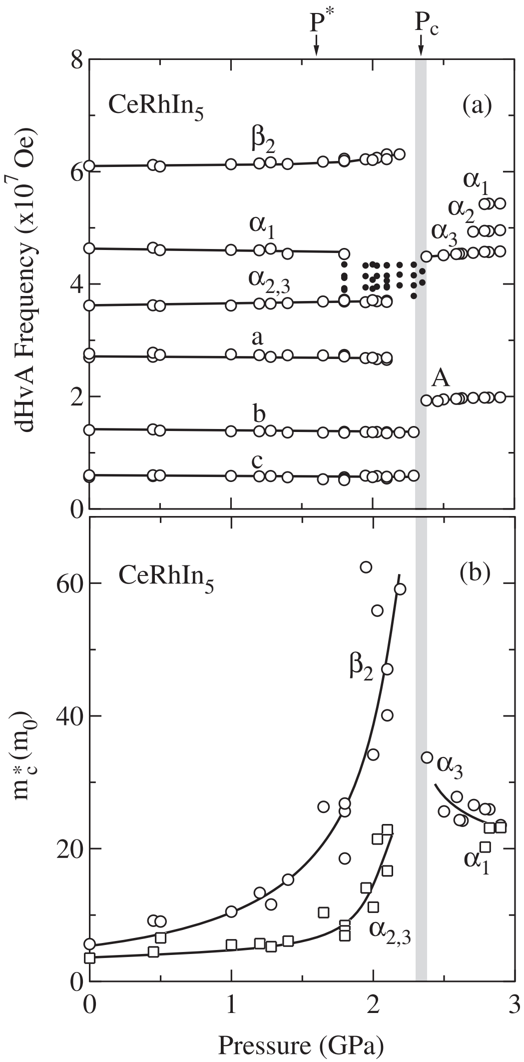


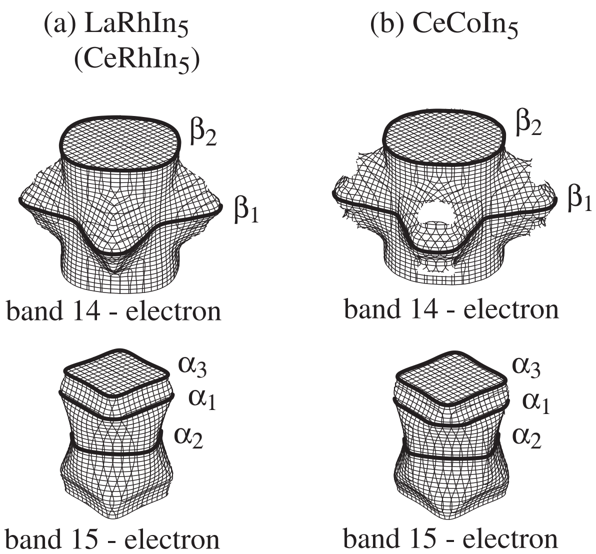
Pagliuso
Saitovich
Contientino
(10)

Pressure induced superconductivity in 115 series



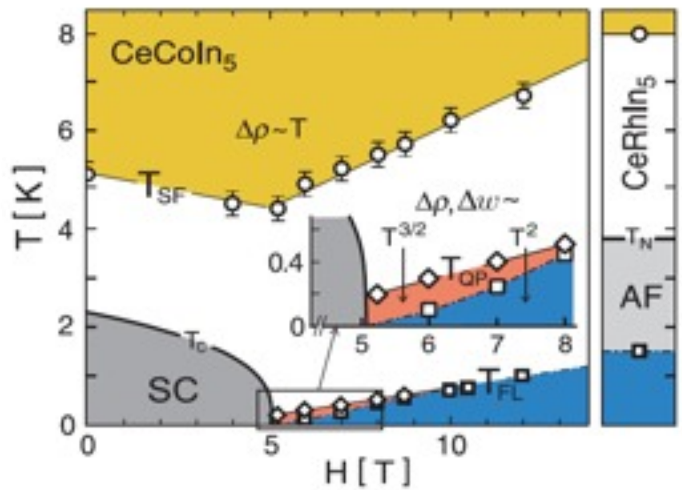
similar to UGe2
(Lonzarich'stalk)
but AFM vs FM





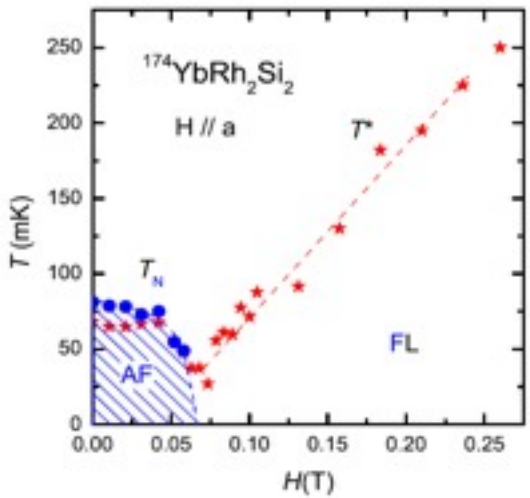
Onuki's group (05)

Multiple Energy Scales in Quantum Critical Regime



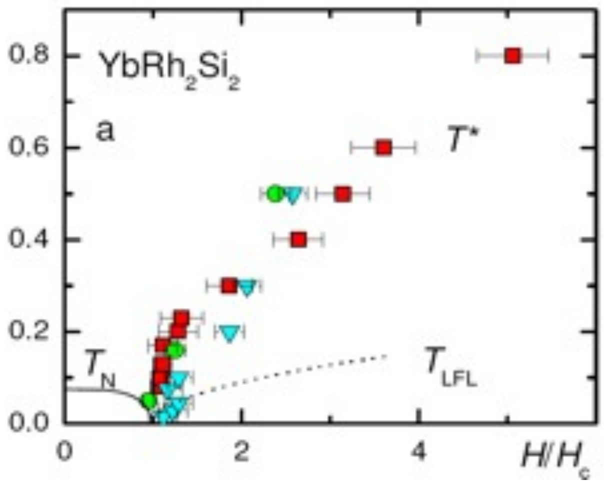
Finite energy scales T_{SF}, T_{QP} in QC regime.

J. Paglione *et al*, cond-mat/0605124



Finite T_{FL} at QCP from resistivity.

Courtesy J. Flouquet (unpublished)



Gegenwart *et al*, cond-mat/0604571

Finite low-energy scale near Kondo breakdown QCP

Conclusions

- Strong experimental evidence for anomalous quantum criticality in HF compounds

- Breakdown of the conventional techniques which integrate out the fermions for (almost all?) models below d=3.

- Fractionalization-deconfinement and emerging spin liquid represent the state of the art to explain the data

- Better theories (and methods) needed ... for example

  Ads/CMT or ... a new bosonization technique ?