A phenomenological framework for heavy electron materials

Yi-feng Yang

Institute of Physics
Chinese Academy of Sciences

Collaborators

David Pines, Zach Fisk, Joe Thompson,
Nick Curro, Han-Oh Lee, Ricardo Urbano

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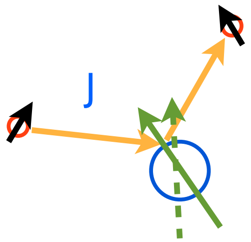
Outline

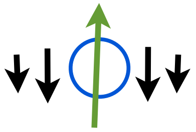
- Kondo physics versus Kondo lattice physics
- Empirical laws: RKKY energy scale and universal behavior
- Hybridization effectiveness and a generalized two-fluid model
- Application to $CeRhIn_5$ and others and a new phase diagram

Kondo physics vs. Kondo lattice physics

$T >> T_K$:



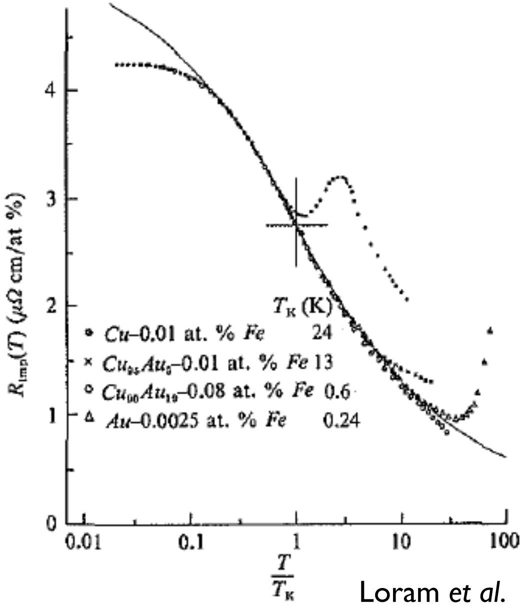
$T < T_K$:



Crossover to the low temperature singlet defines

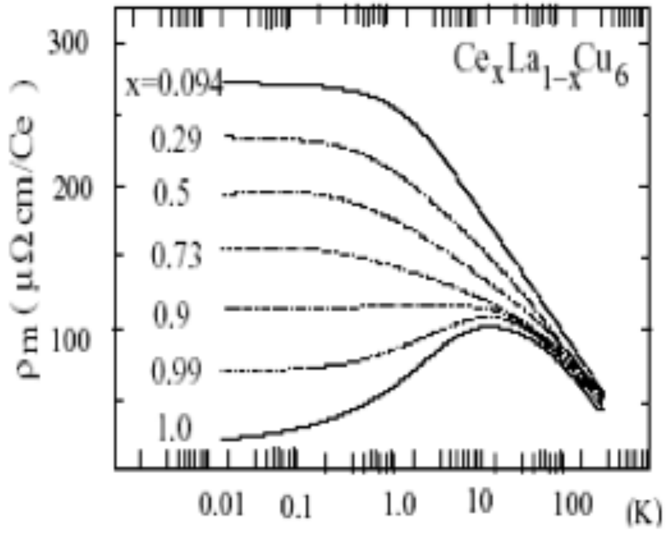
- ➡ Kondo temperature T_K and universal scaling
- ➡ Kondo screening and collective Kondo clouds
- ➡ Large Fermi surface containing local spin

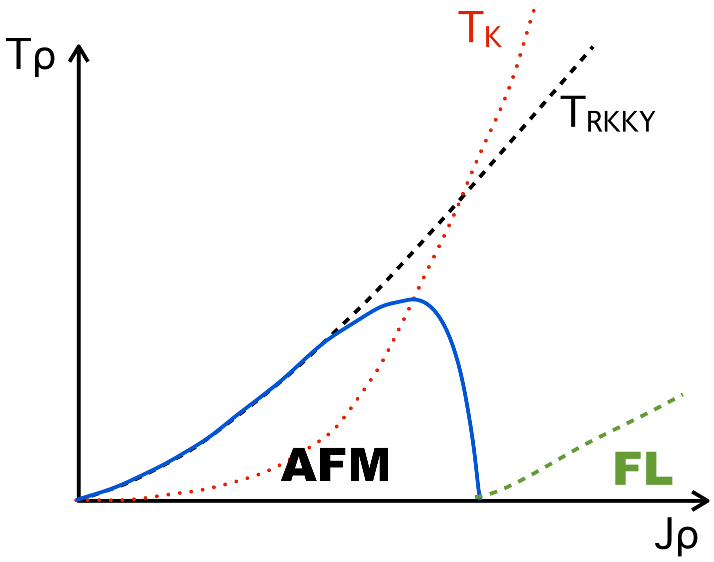
$$T_K = \rho^{-1} e^{-1/J\rho}$$



Loram *et al.*

- ➡ Is there a characteristic temperature T^*?
- ➡ Is there universality related to T^*?





- Extensively used in the literature
- No temperature evolution
- No experimental determination

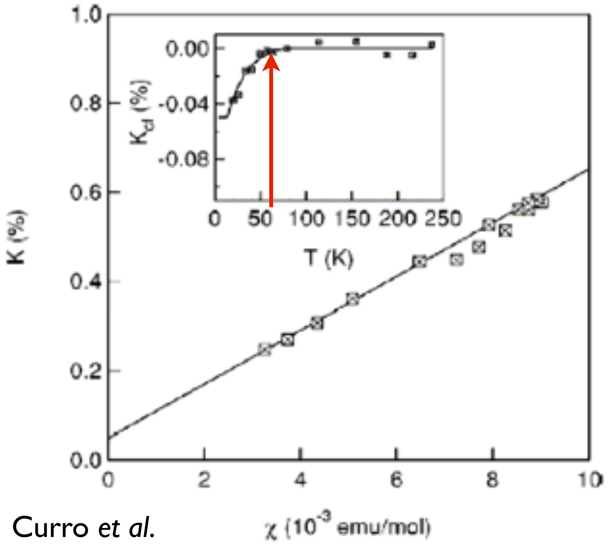
- Determine temperature scales
- Describe temperature evolution
- Connect high and low-T states

Determination of T^*

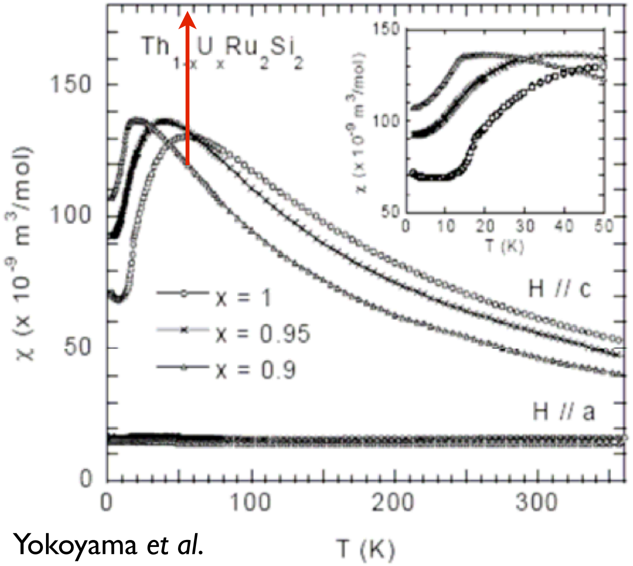
Crystal field effect may play a role, but not essential.

URu_2Si_2

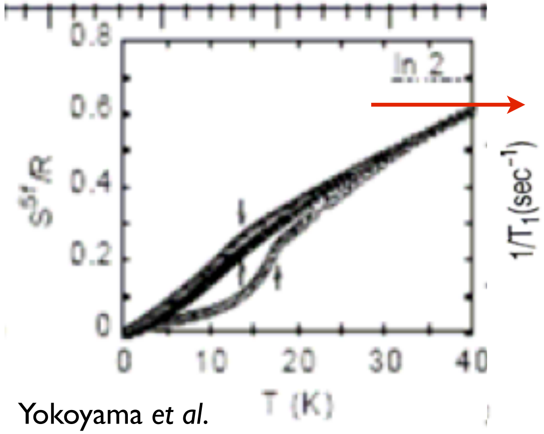
- Resistivity
- Susceptibility
- Knight shift anomaly
- Hall anomaly
- Optical conductivity
- Magnetic entropy
- Point contact spectroscopy
- Neutron/Raman scattering
- NMR spin-lattice relaxation



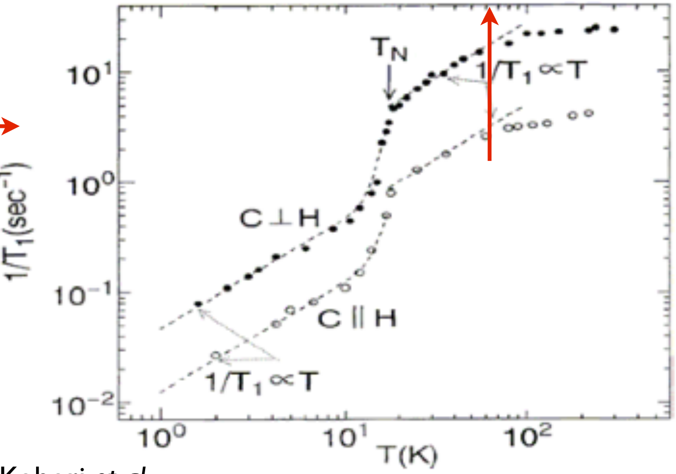
Curro *et al.*



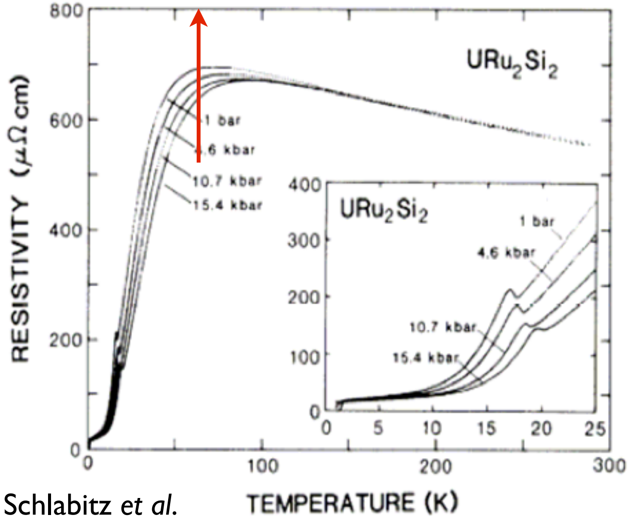
Yokoyama *et al.*



Yokoyama *et al.*

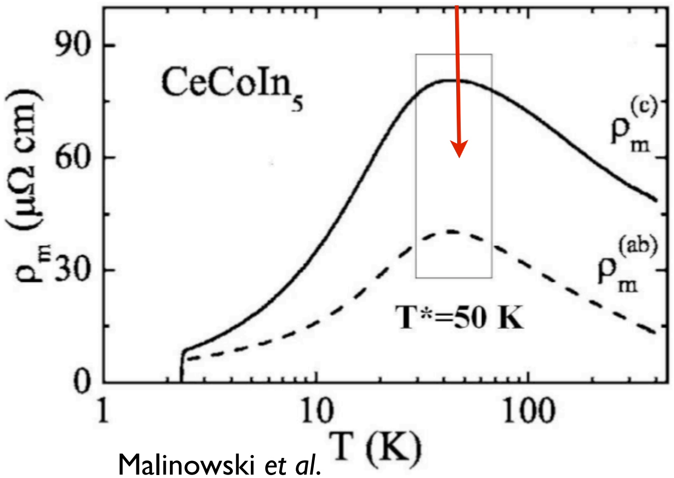


Kohori *et al.*

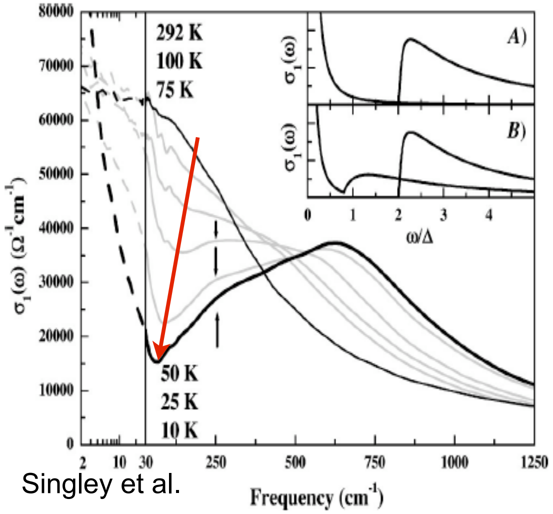


Schlabitz *et al.*

Coherence Temperature



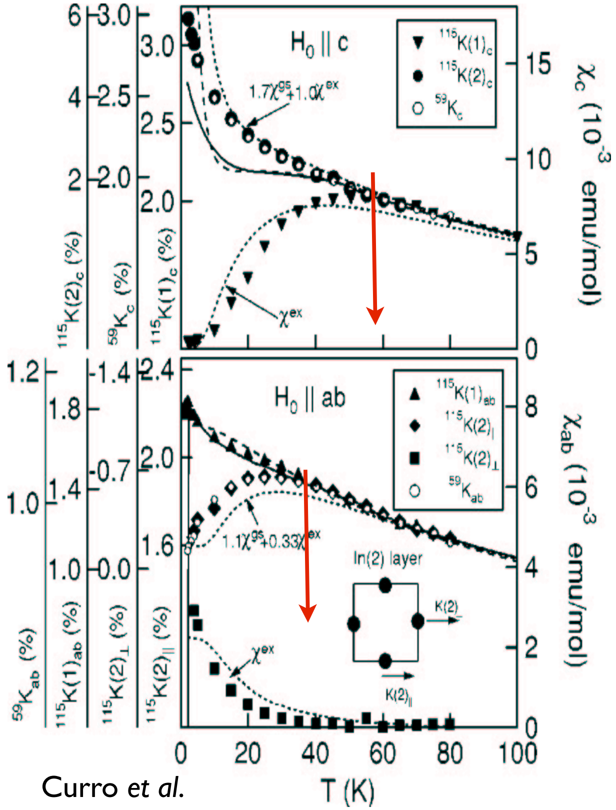
Malinowski *et al.*



Singley et al.

The coherence temperature marks the onset of f-electron band. However, its value was not taken seriously and was often regarded as the Kondo temperature based on the Doniach picture. In many literatures, the coherence temperature also refers to the Fermi liquid temperature.

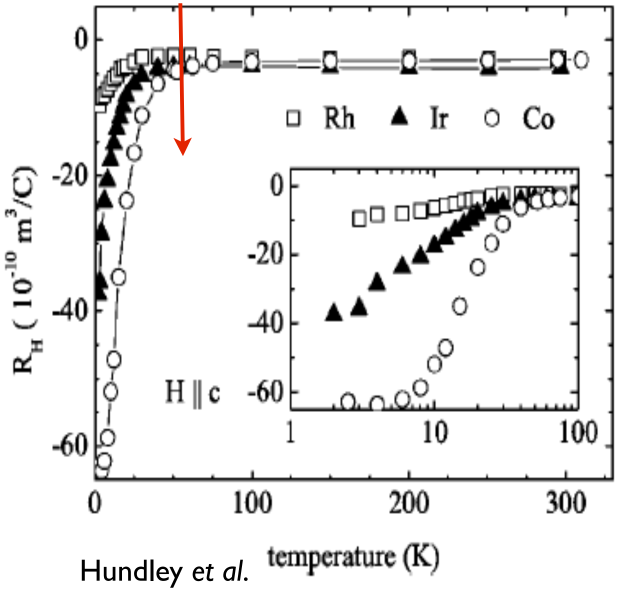
Knight Shift and Hall Anomalies



Curro *et al.*

Often explained as due to crystal field effect.

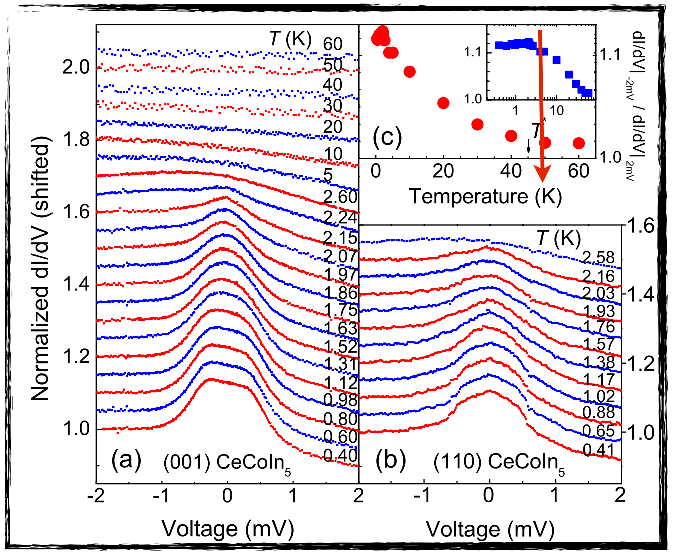
However, the anomaly takes place also at T*.



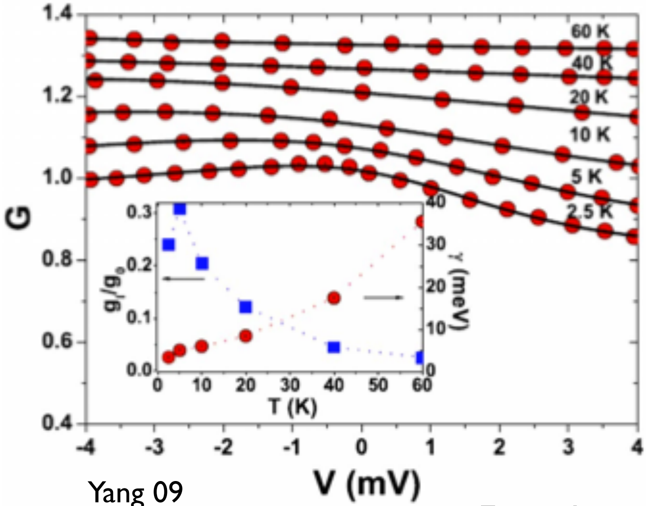
Hundley *et al.*

Hall measurements point to an emergent component.

Fano Line-shape in the Point Contact Spectroscopy



Park *et al.*



Yang 09

Yi-feng Yang, PRB 79, 241107 (2009).

$$H=\sum_{k,m}[\epsilon_k c^\dagger_{km}c_{km}+\epsilon_0 f^\dagger_{km}f_{km}+\tilde{V}(c^\dagger_{km}f_{km}+\mathrm{H.c.})],$$

$$H_t=\sum_{km}(M_{fkm}f^\dagger_{km}t+M_{ckm}c^\dagger_{km}t+\mathrm{H.c.}),$$

$$d_{1km}=u_k f_{km}+v_k c_{km},$$

$$d_{2km}=-v_k f_{km}+u_k c_{km},$$

$$|(d_{1km}|H_t|t)|^2=|u_k(f_{km}|H_t|t)+v_k(c_{km}|H_t|t)|^2$$

$$=\left|q+\frac{v_k}{u_k}\right|^2|u_k|^2|M_{ckm}|^2=\frac{|q-\tilde{E}_{1k}|^2}{1+\tilde{E}^2_{1k}}|M_{ckm}|^2,$$

$$|(d_{2km}|H_t|t)|^2=|-v_k(f_{km}|H_t|t)+u_k(c_{km}|H_t|t)|^2$$

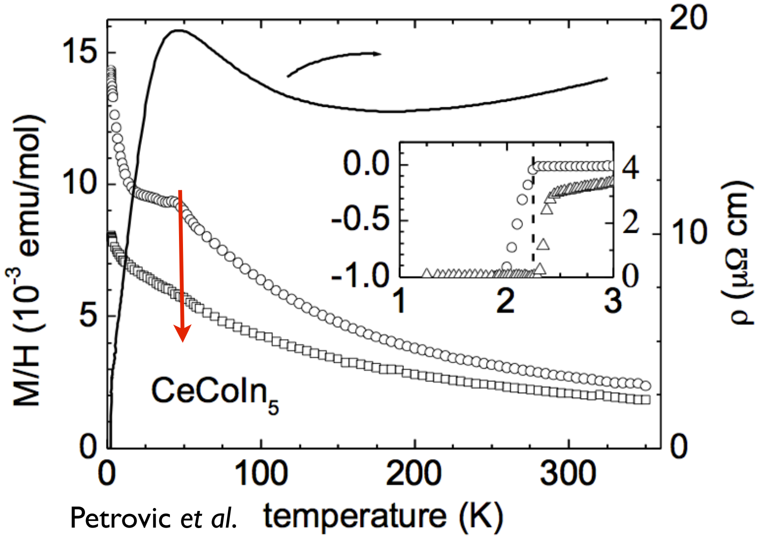
$$=\left|q-\frac{u_k}{v_k}\right|^2|v_k|^2|M_{ckm}|^2=\frac{|q-\tilde{E}_{2k}|^2}{1+\tilde{E}^2_{2k}}|M_{ckm}|^2,$$

$$G(V,T)=g_0+\int g_I(E)T(E)\frac{df(E-V)}{dV}dE\approx g_0+g_I T(V)$$

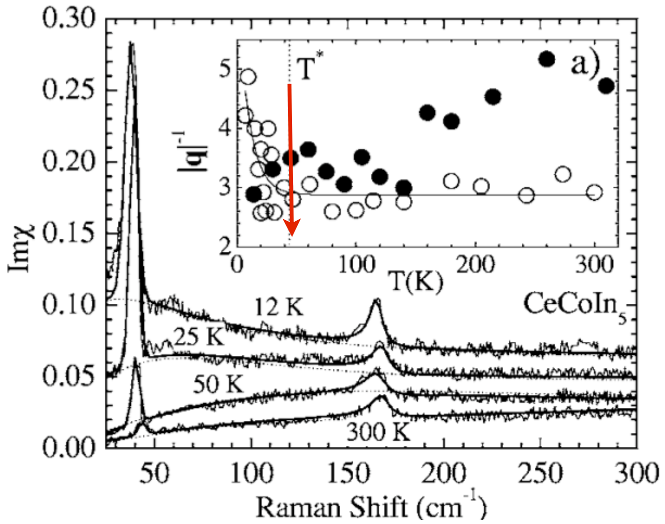
$$\boxed{T(E)=\frac{|q-\tilde{E}|^2}{1+\tilde{E}^2}}$$

First theoretical explanation of the Fano line-shape in a Kondo lattice material observed in PCS and later also in STM/STS measurements.

Susceptibility and Raman Shift



Petrovic *et al.*



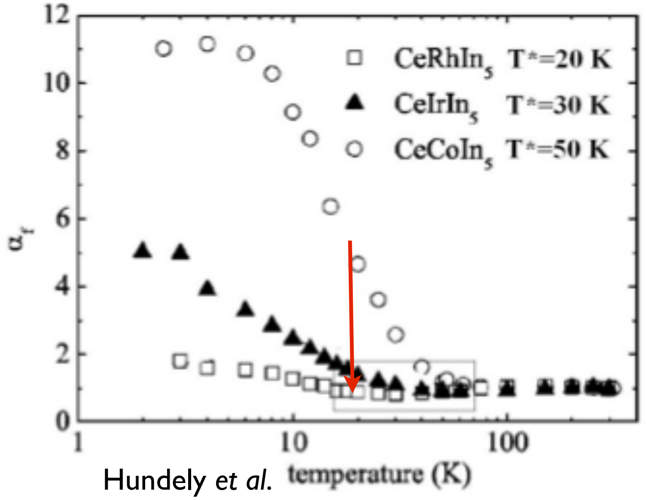
Plateau in the magnetic susceptibility
and deviation from Curie-Weiss law

Raman suggests emergent heavy electrons

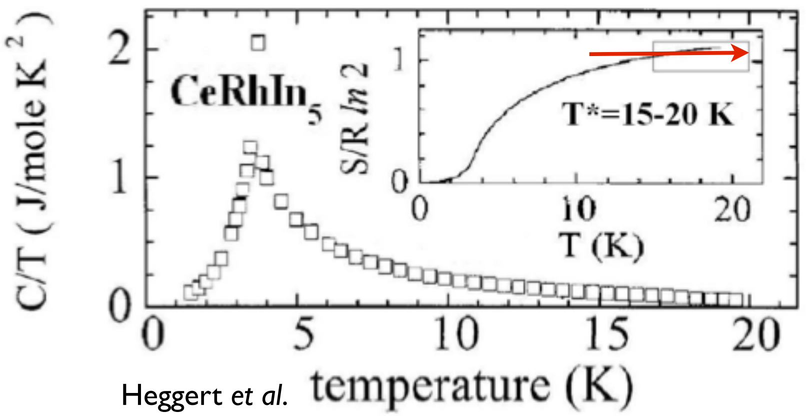
These phenomena were often attributed to different origins.
However, the fact that they all take place at ~T* suggests a common origin.

This is in contrast to single impurity Kondo physics, where even though we can define a temperature scale T$_K$, it starts to take effect at very different temperature ranges in different physical quantities.

Entropy Quench Below T^*



Hundely *et al.*



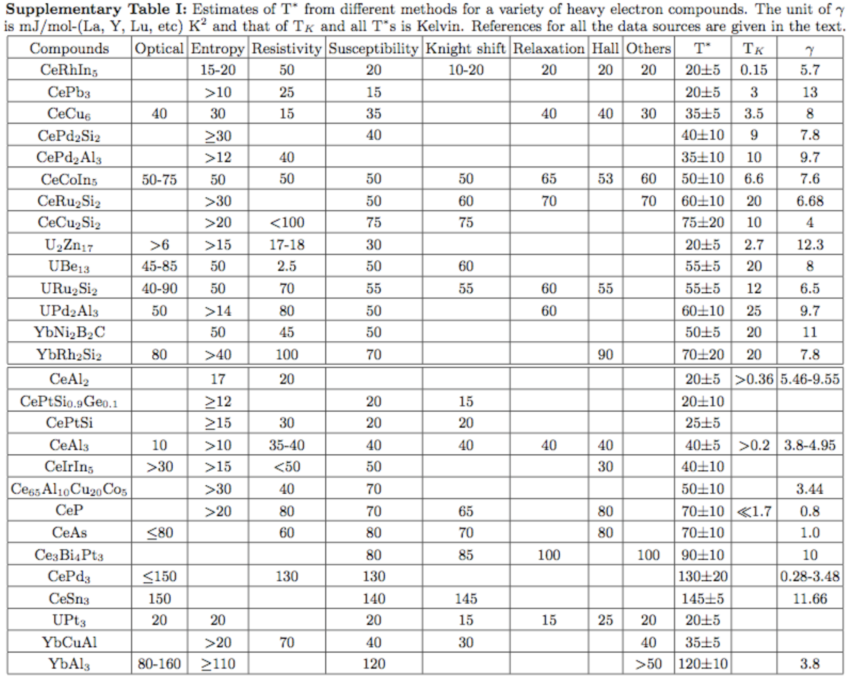
Heggert *et al.*

Entropy also starts to be quenched at T^*, different from conventional idea of f-electron band formation from local Kondo resonances.

For single impurity, Kondo screening occurs above T_K with $S(T_K)=R\ln 2/2$.

T^* sets the temperature scale for coherence, magnetic correlations and various anomalies.

RKKY origin of T^*



Supplementary Table I: Estimates of T^* from different methods for a variety of heavy electron compounds. The unit of γ is mJ/mol-(La, Y, Lu, etc) K^2 and that of T_K and all T^*s is Kelvin. References for all the data sources are given in the text.

Compounds	Optical	Entropy	Resistivity	Susceptibility	Knight shift	Relaxation	Hall	Others	T^*	T_K	γ
$CeRhIn_5$		15-20	50	20	10-20	20	20	20	20±5	0.15	5.7
$CePb_3$		>10	25	15					20±5	3	13
$CeCu_6$	40	30	15	35		40	40	30	35±5	3.5	8
$CePd_2Si_2$		≥30		40					40±10	9	7.8
$CePd_2Al_3$		>12	40						35±10	10	9.7
$CeCoIn_5$	50-75	50	50	50	50	65	53	60	50±10	6.6	7.6
$CeRu_2Si_2$		>30		50	60	70		70	60±10	20	6.68
$CeCu_2Si_2$		>20	<100	75	75				75±20	10	4
U_2Zn_{17}	>6	>15	17-18	30					20±5	2.7	12.3
UBe_{13}	45-85	50	2.5	50	60				55±5	20	8
URu_2Si_2	40-90	50	70	55	55	60	55		55±5	12	6.5
UPd_2Al_3	50	>14	80	50		60			60±10	25	9.7
$YbNi_2B_2C$		50	45	50					50±5	20	11
$YbRh_2Si_2$	80	>40	100	70			90		70±20	20	7.8
$CeAl_2$		17	20						20±5	>0.36	5.46-9.55
$CePtSi_{0.9}Ge_{0.1}$		≥12		20	15				20±10		
$CePtSi$		≥15	30	20	20				25±5		
$CeAl_3$	10	>10	35-40	40	40	40	40		40±5	>0.2	3.8-4.95
$CeIrIn_5$	>30	>15	<50	50			30		40±10		
$Ce_{65}Al_{10}Cu_{20}Co_5$		>30	40	70					50±10		3.44
CeP		>20	80	70	65		80		70±10	≪1.7	0.8
$CeAs$	≤80		60	80	70		80		70±10		1.0
$Ce_3Bi_4Pt_3$				80	85	100		100	90±10		10
$CePd_3$	≤150		130	130					130±20		0.28-3.48
$CeSn_3$	150			140	145				145±5		11.66
UPt_3	20	20		20	15	15	25	20	20±5		
$YbCuAl$		>20	70	40	30			40	35±5		
$YbAl_3$	80-160	≥110		120				>50	120±10		3.8

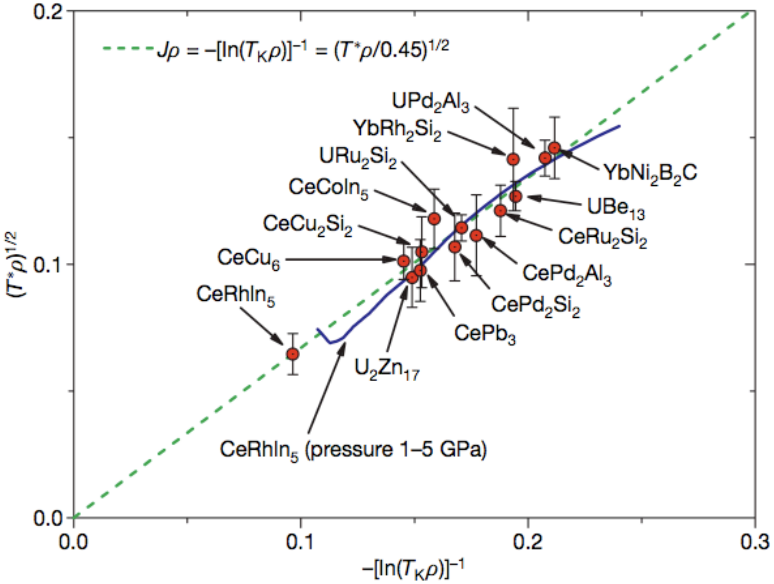


Figure 1 | Confirmation of T^* given by the intersite RKKY interaction for a variety of Kondo lattice materials. The solid line shows T^* (resistivity peak) of $CeRhIn_5$ under pressure from 1 GPa (lower left) to 5 GPa (upper right).

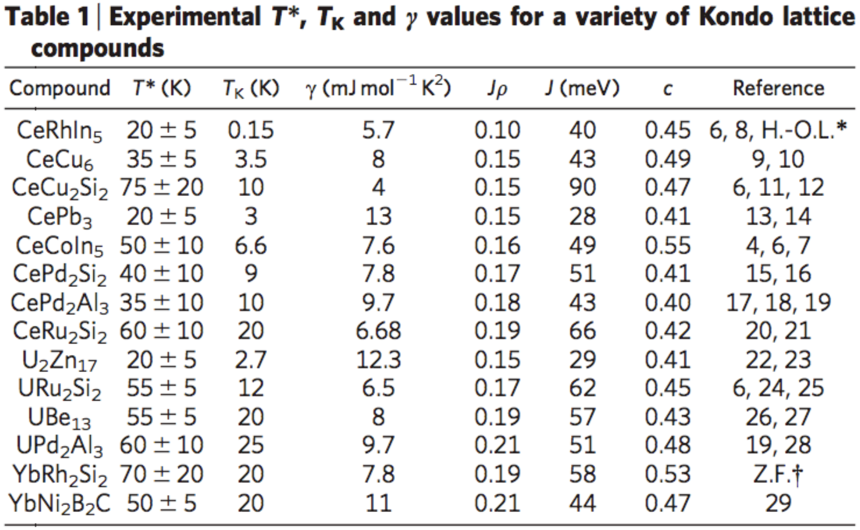


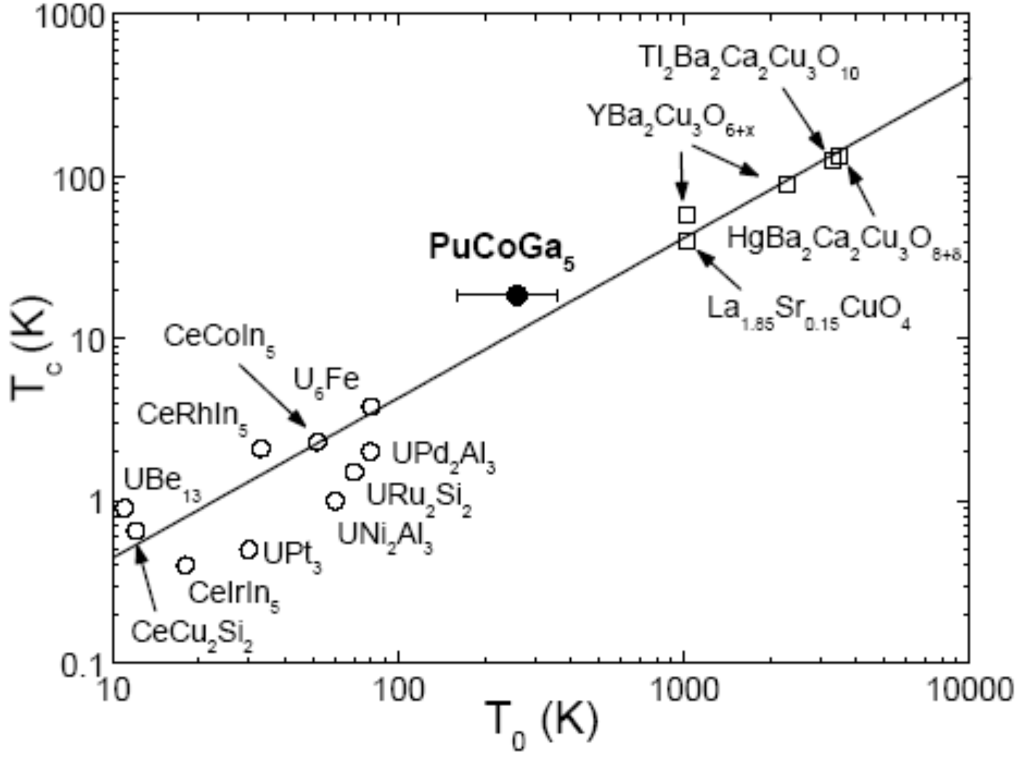
Table 1 | Experimental T^*, T_K and γ values for a variety of Kondo lattice compounds

Compound	T^* (K)	T_K (K)	γ (mJ mol^{-1} K^2)	$J\rho$	J (meV)	c	Reference
$CeRhIn_5$	20 ± 5	0.15	5.7	0.10	40	0.45	6, 8, H.-O.L.*
$CeCu_6$	35 ± 5	3.5	8	0.15	43	0.49	9, 10
$CeCu_2Si_2$	75 ± 20	10	4	0.15	90	0.47	6, 11, 12
$CePb_3$	20 ± 5	3	13	0.15	28	0.41	13, 14
$CeCoIn_5$	50 ± 10	6.6	7.6	0.16	49	0.55	4, 6, 7
$CePd_2Si_2$	40 ± 10	9	7.8	0.17	51	0.41	15, 16
$CePd_2Al_3$	35 ± 10	10	9.7	0.18	43	0.40	17, 18, 19
$CeRu_2Si_2$	60 ± 10	20	6.68	0.19	66	0.42	20, 21
U_2Zn_{17}	20 ± 5	2.7	12.3	0.15	29	0.41	22, 23
URu_2Si_2	55 ± 5	12	6.5	0.17	62	0.45	6, 24, 25
UBe_{13}	55 ± 5	20	8	0.19	57	0.43	26, 27
UPd_2Al_3	60 ± 10	25	9.7	0.21	51	0.48	19, 28
$YbRh_2Si_2$	70 ± 20	20	7.8	0.19	58	0.53	Z.F.†
$YbNi_2B_2C$	50 ± 5	20	11	0.21	44	0.47	29

T^* has a form of RKKY coupling for all heavy electron materials with AFM/SC ground state or near QCP.

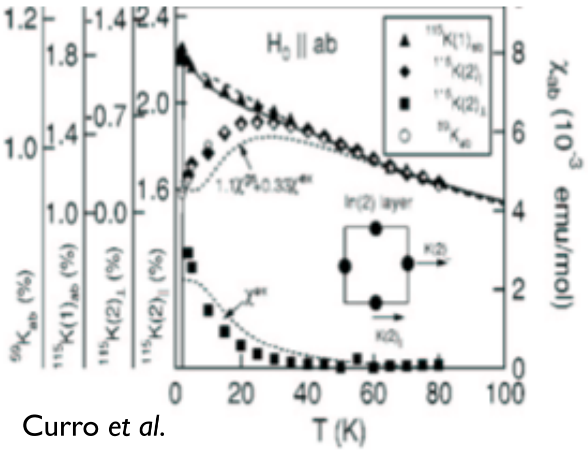
Contradiction with conventional scenario suggesting competition with Kondo screening.

Yi-feng Yang et al, Nature 454, 611 (2008).

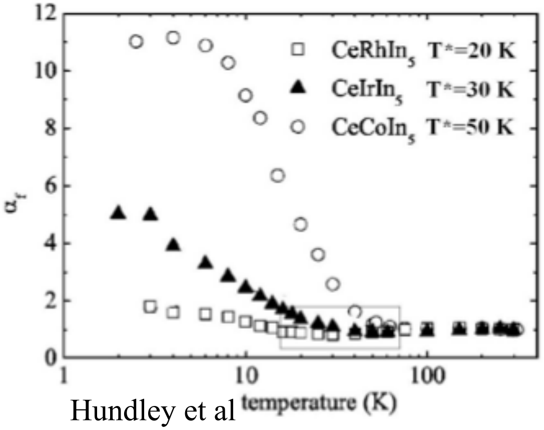


Supplementary Figure 1. The superconducting transition temperature, T_c, versus the characteristic spin fluctuation temperature, T_0. Data are shown for the heavy-fermion compounds (open circles), high- T_c cuprates (open squares), and $PuCoGa_5$ (solid circle). The line is a guide to the eye with $T_c \sim T_0$. Such a proportionality over three orders of magnitude implies that a single energy scale governs both the superconducting transition temperature and the spin-lattice relaxation in the normal state, leading to the scaling relation of $1/T_1$ shown in Figure 3(b). The data are taken from Refs.[18,28], except that for $CeMIn_5$ (M=Co, Rh, Ir)[29] and $PuCoGa_5$[17].

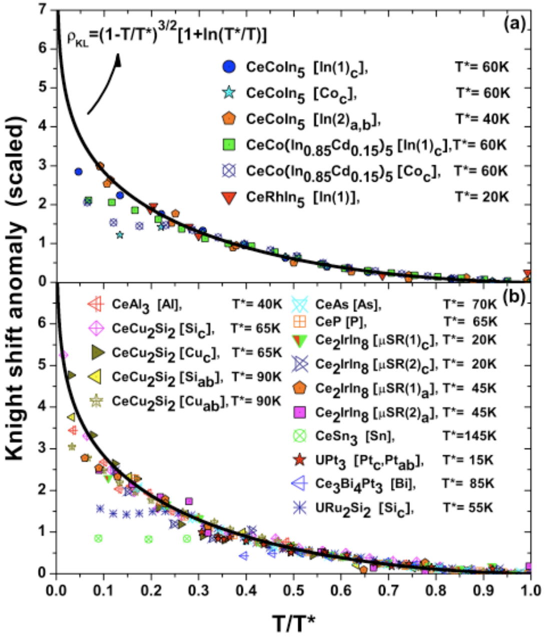
Scaling behavior below T*

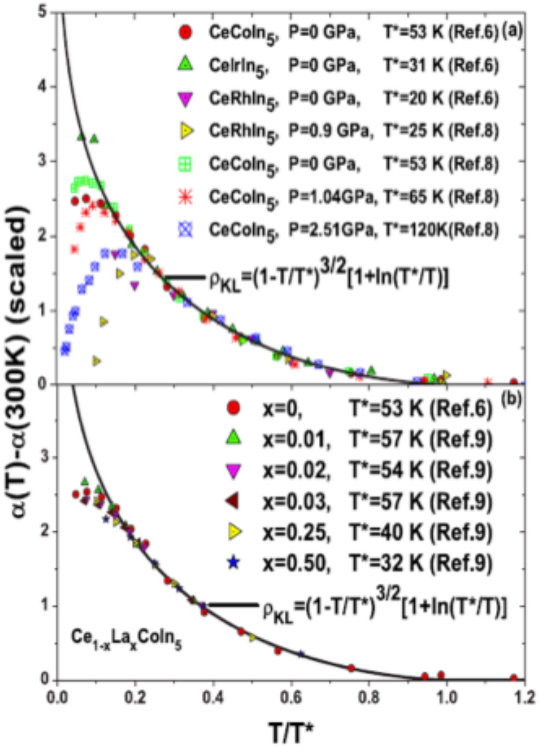


Curro *et al.*



Hundley et al





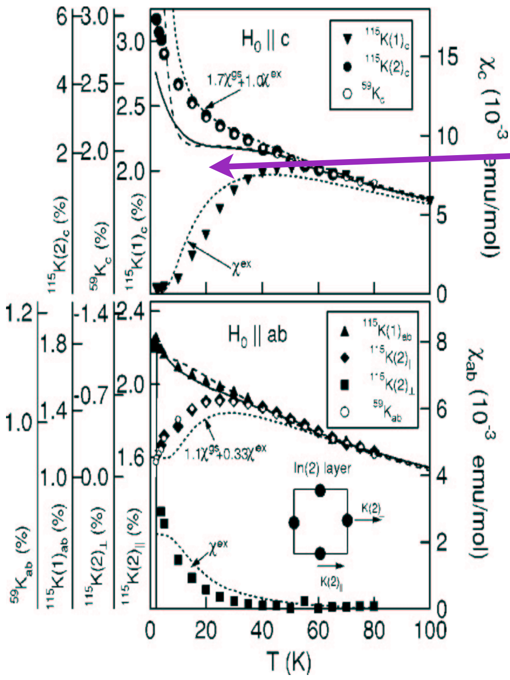
N.J. Curro *et al.*, PRB 70, 235117 (2004)
Yi-feng Yang and David Pines, PRL 100, 096404 (2008)

- A characteristic temperature T^* given by RKKY coupling
- A novel scaling law below T^* in various anomalous properties

Just like in Kondo physics, this empirical laws should also guide our research in understanding heavy electron physics.

A two-fluid model

- A phenomenological two-fluid description below T^*
- Gradual emergence of heavy electrons quantified by $f_h(T)$
- An emergent Kondo liquid exhibiting universal scaling behavior
- A residual localized component with a reduced strength $f_l(T)=1-f_h(T)$



$$T > T^* : \quad \chi = \chi_{sl}$$
$$K = K_0 + A\chi_{sl}$$

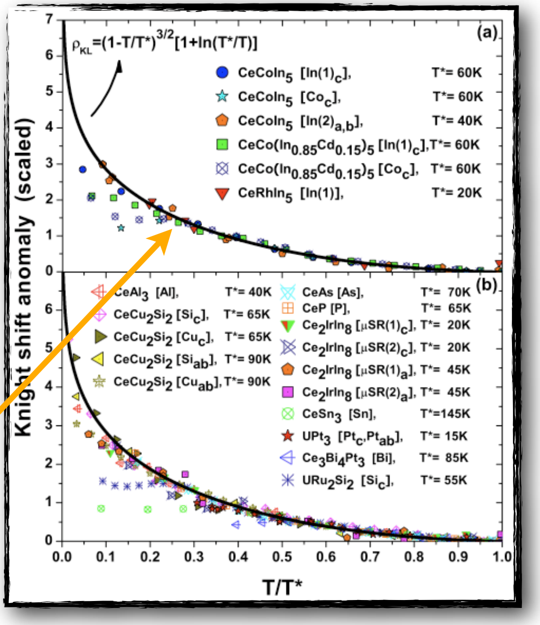
$$T < T^* : \quad \chi = \chi_{sl} + \chi_{kl}$$
$$K = K_0 + A\chi_{sl} + B\chi_{kl}$$

$$K_a = K - K_0 - A\chi = (B - A)\chi_{kl}$$

$$\chi_h = f_h \chi_{KL}$$

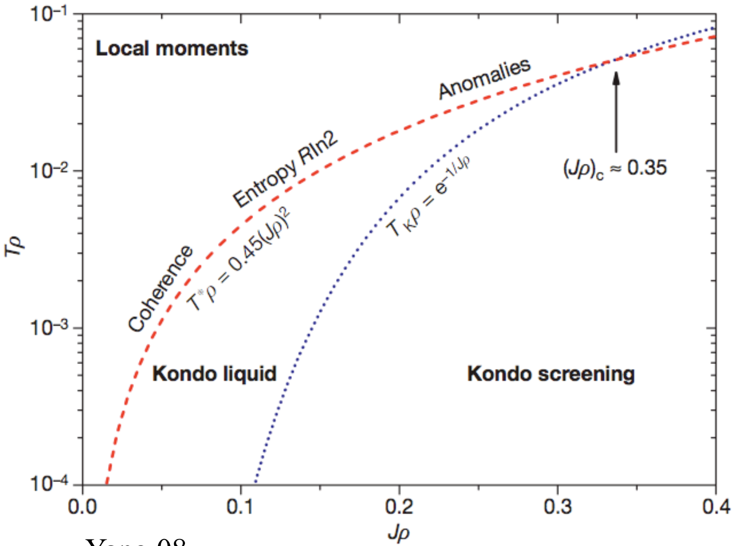
$$f_h(T) = f_0\left(1 - \frac{T}{T^*}\right)^{1.5}$$

$$\chi_{KL}(T) \propto 1 + \ln\frac{T^*}{T}$$

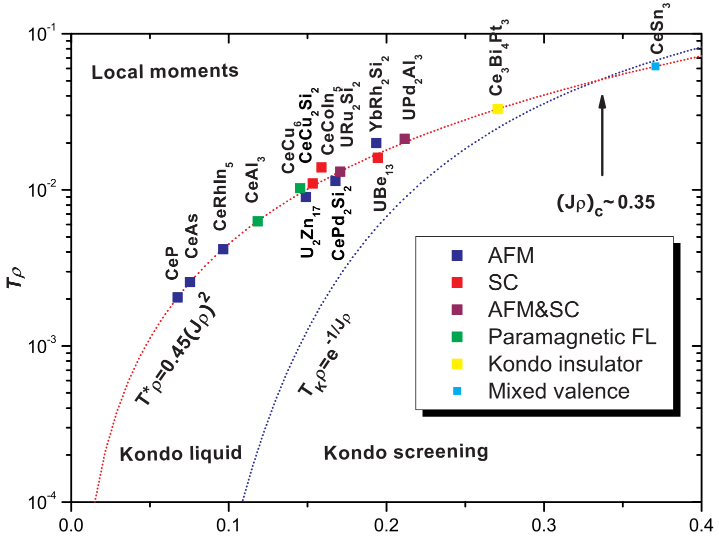


S. Nakatsuji *et al.*, PRL 92, 016401 (2004)
N. J. Curro *et al.*, PRB 70, 235117 (2004)
Yi-feng Yang and David Pines, PRL 100, 096404 (2008)

A new phase diagram: high temperature part



Yang 08



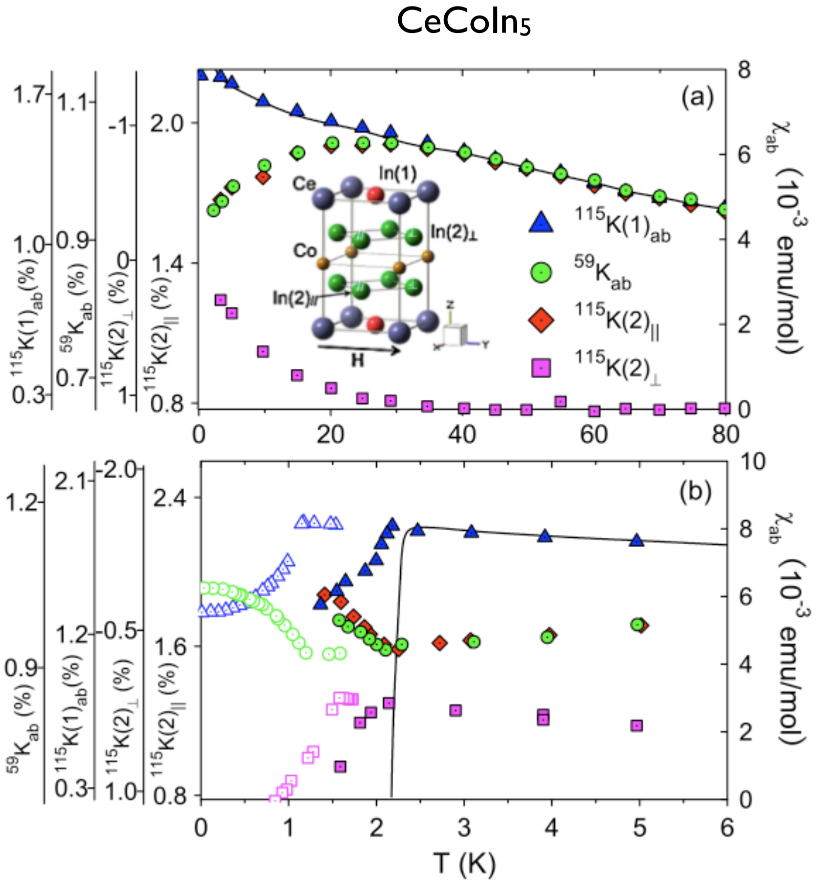
Yang 11

A temperature scale unifies emergence of coherence, magnetic correlations and all anomalies.

Superconductors cluster around Jρ~0.15, much smaller than the "critical" coupling.

Yi-feng Yang *et al.*, JPCS 273, 012066 (2011)

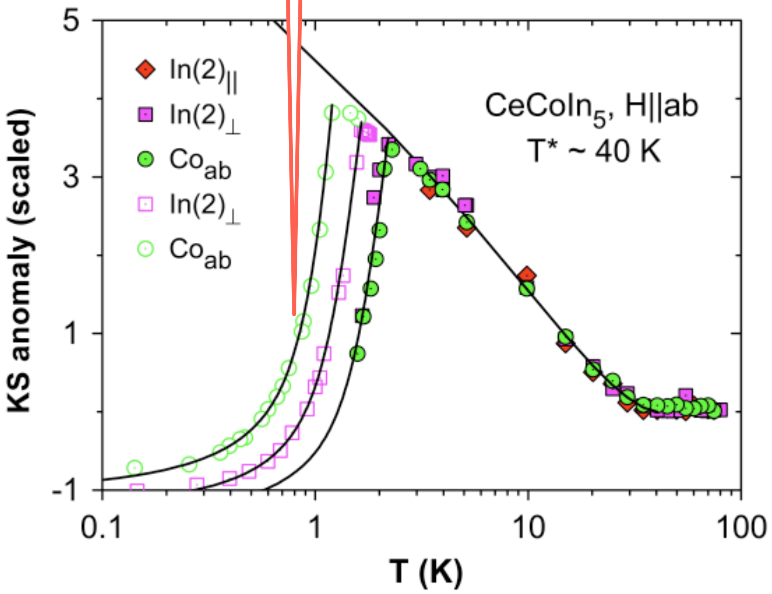
CeCoIn$_5$: superconductivity



$$K_{\text{anom}}(T) - K_{\text{anom}}(0) \propto \int dE\left(-\frac{\partial f(E)}{\partial E}\right)N(E),$$

$$N(E) \propto \langle |E|/\sqrt{E^2 - \Delta_k(T)^2}\rangle_{\text{FS}}$$

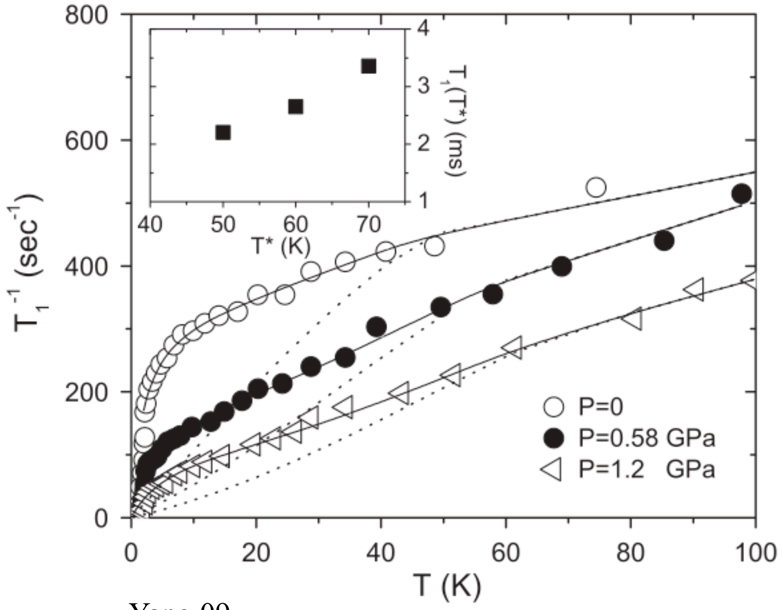
$$\Delta_k(T) = g_k\Delta(0)\tanh\left[\sqrt{\left|\frac{\partial\Delta^2}{\partial T}\right|_{T_c}\frac{T_c}{\Delta(0)^2}\left(\frac{T_c}{T} - 1\right)}\right],$$



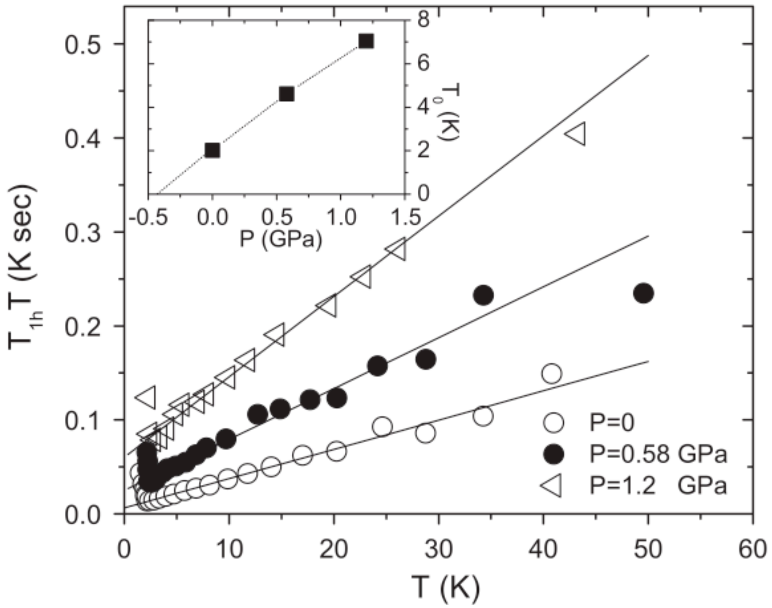
Kondo liquid is responsible for superconductivity.

Yi-feng Yang *et al.*, PRL 103, 197004 (2009)

CeCoIn$_5$: superconductivity



Yang 09



$$\boxed{\frac{1}{T_1} = \frac{1-f(T)}{T_{1l}} + \frac{f(T)}{T_{1h}}}$$

$$\boxed{T_{1h}T \propto (T + T_0)}$$

Kondo liquid exhibits critical fluctuations.

A New Framework

- Empirical laws:
  - A characteristic temperature T^* given by RKKY
  - A unified explanation of many anomalies at T^*
  - A novel scaling law and a two-fluid description
- Hybridization effectiveness and a new phase diagram
- Understanding AFM and SC
  - Antiferromagnetism from a hybridized quantum spin liquid
  - Superconductivity from the Kondo liquid

Yi-feng Yang and David Pines, PRL 100, 096404 (2008).
Yi-feng Yang et al, Nature 454, 611 (2008).
Yi-feng Yang, PRB 79, 241107(R) (2009).
Yi-feng Yang et al., PRL 103, 197004 (2009).
Yi-feng Yang et al., JPCS 273, 012066 (2011).
apRoberts-Warren et al., PRB 83, 060408(R) (2011).
Yi-feng Yang and David Pines, in preparation.