Two-fluid Model for Heavy Fermions and Cuprates

Yi-feng Yang

Institute of Physics
Chinese Academy of Sciences

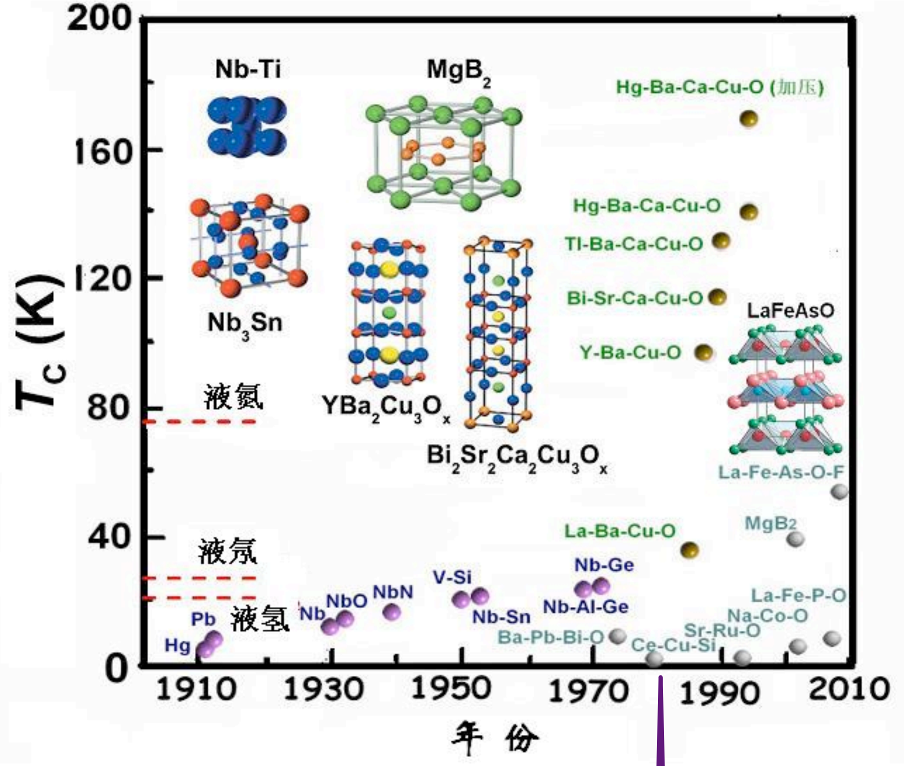
Collaborators
David Pines, Nick Curro (UC Davis), Zach Fisk (UC Irvine)
Joe D Thompson, Han-Oh Lee, Ricardo Urbano (LANL)

Nov 10, 2012 — Workshop on "Heavy Fermions and Quantum Phase Transitions"

Outline

- Theoretical and experimental motivations
- A hybridized spin liquid -- reduced exchange couplings
- An itinerant Kondo liquid -- emergent heavy electrons
- A phenomenological two-fluid framework

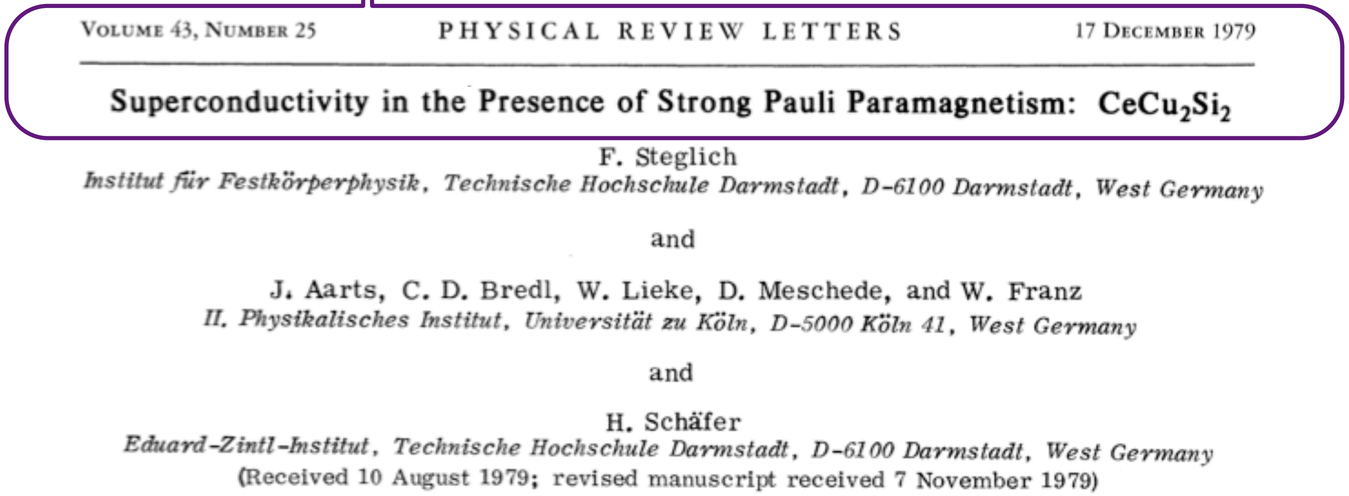
Heavy Fermion Superconductors



	T_c(K)	
	Ce-based	
$CeCu_2Si_2$	0.7	('79 DA/K)
[p = 2.9 GPa:	2.3	('84 GE/GR)]
$CeNi_2Ge_2$	0.2	('97 DA, '98 CA/GR)
$CeIrIn_5$	0.4	('00 LANL)
$CeCoIn_5$	2.3	('00 LANL)
Ce_2CoIn_8	0.4	('02 NA)
Ce_2PdIn_8	0.7	('09 WR)
$CePt_3Si$	0.7	('03 VI)
p > 0		
$CeCu_2Ge_2$	0.6	('92 GE)
$CePd_2Si_2$	0.4	('94 CA)
$CeRh_2Si_2$	0.4	('95 LANL)
$CeCu_2$	0.15	('97 GE/KA)
$CeIn_3$	0.2	('98 CA)
$CeRhIn_5$	2.1	('00 LANL)
Ce_2RhIn_8	1.1	('03 LANL)
$CeRhSi_3$	0.8	('05 SE)
$CeIrSi_3$	1.6	('06 OS)
$CeCoGe_3$	0.7	('06 OS)
$Ce_2Ni_3Ge_5$	0.26	('06 OS)
$CeNiGe_3$	0.4	('06 OS)
$CeRhGe_2$	0.4	('09 OS)
$CePt_2In_7$	1.5	('09 LANL)

	T_c(K)	
	Pr-based	
$PrOs_4Sb_{12}$	1.85	('01 UCSD)
	Yb-based	
β-$YbAlB_4$	0.08	('08 TO/IR)
	U-based	
UBe_{13}	0.9	('83 Z/LANL)
UPt_3	0.5	('84 LANL)
URu_2Si_2	1.4	('84 K/DA)
UNi_2Al_3	1.2	('91 DA)
UPd_2Al_3	2.0	('91 DA)
URhGe	0.3	('01 GR)
UCoGe	3.0	('07 AM/KA)
p > 0		
UGe_2	0.7	('00 CA/GR)
UIr	0.14	('04 OS)
	Np-based	
$NpPd_5Al_2$	5.0	('07 OS)
	Pu-based	
$PuCoGa_5$	18.5	('02 LANL)
PuRhGa5	8.7	('03 KA)
	Am-based	
p > 0		
Am metal	2.2	('05 KA)

(source: F. Steglich)



VOLUME 43, NUMBER 25 PHYSICAL REVIEW LETTERS 17 DECEMBER 1979

Superconductivity in the Presence of Strong Pauli Paramagnetism: $CeCu_2Si_2$

F. Steglich
Institut für Festkörperphysik, Technische Hochschule Darmstadt, D-6100 Darmstadt, West Germany

and

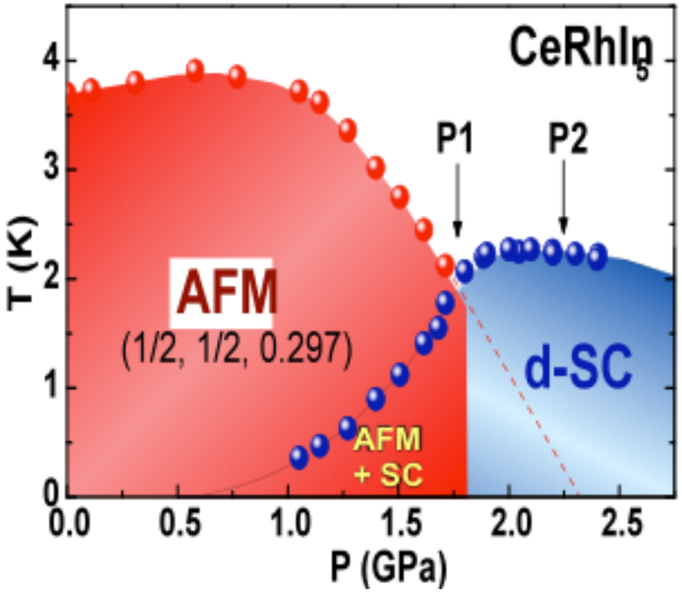
J. Aarts, C. D. Bredl, W. Lieke, D. Meschede, and W. Franz
II. Physikalisches Institut, Universität zu Köln, D-5000 Köln 41, West Germany

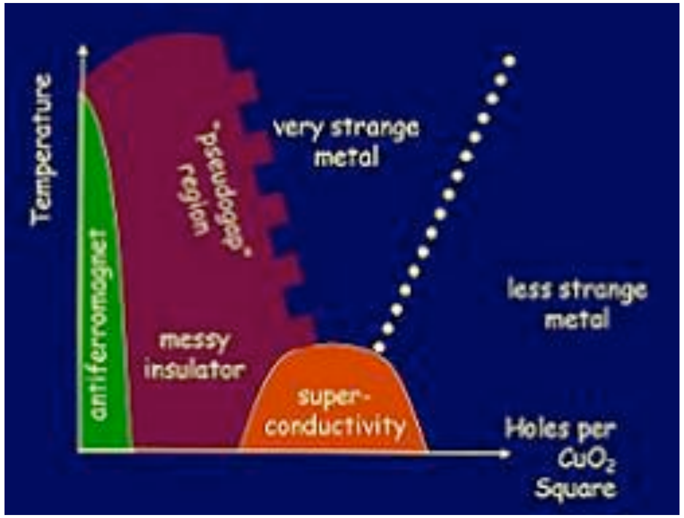
and

H. Schäfer
Eduard-Zintl-Institut, Technische Hochschule Darmstadt, D-6100 Darmstadt, West Germany

(Received 10 August 1979; revised manuscript received 7 November 1979)

Heavy Fermions vs Cuprates





Similarity

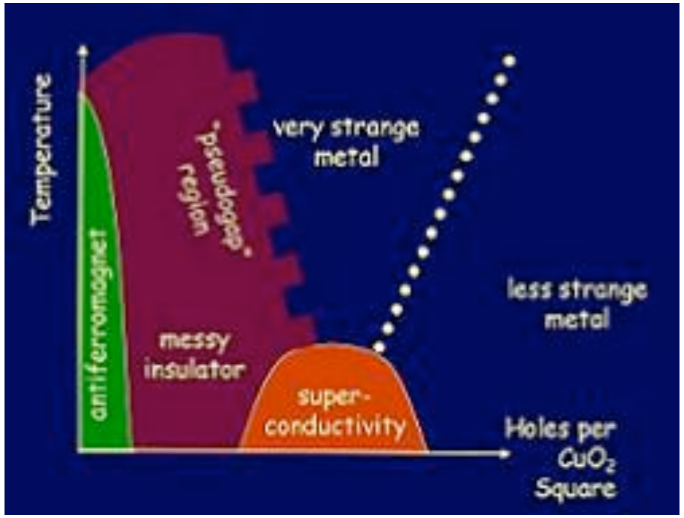
- An antiferromagnetic parent state, AFM&SC closely related
- A quantum critical point beneath the superconducting dome?
- Non-Fermi liquid behavior in the normal state
- Change of Fermi surface with pressure (doping)

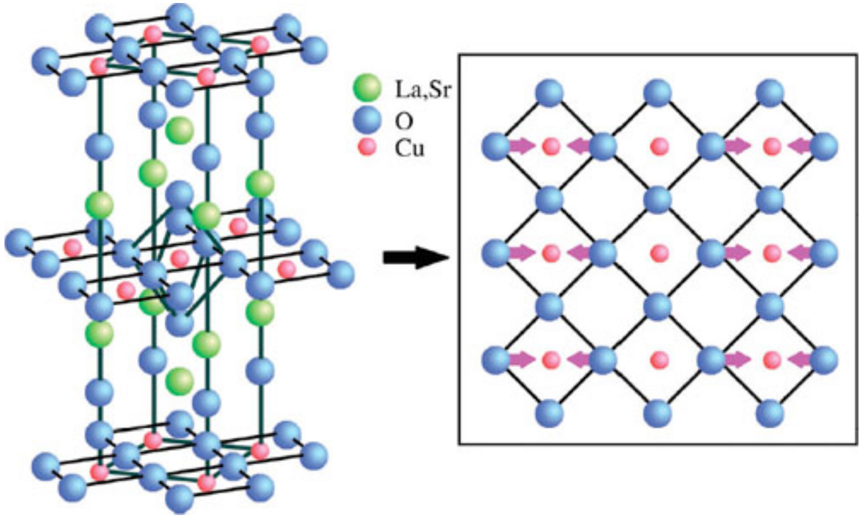
Difference

- Inhomogeneity (cuprates)
- Pseudo gap (cuprates)
- Rich variety in critical behaviors
- Microscopic coexistence of AFM&SC

Superconductivities are both mediated by spin fluctuations !

Basic Models for Cuprates





One band Hubbard model

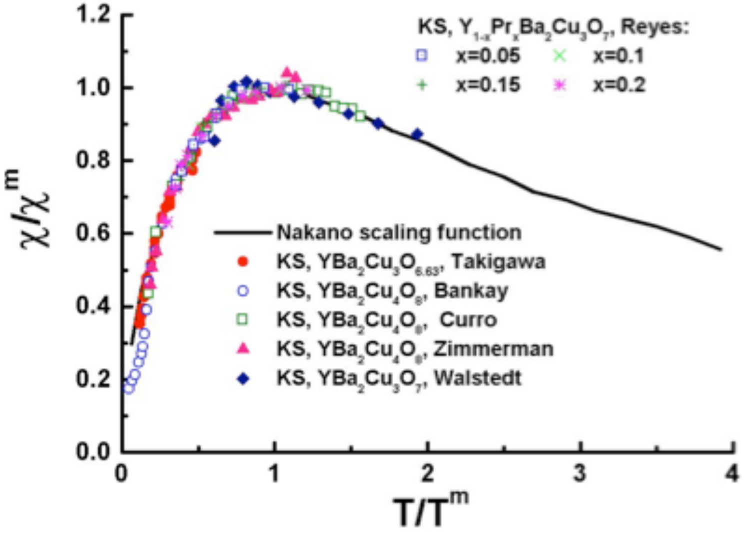
t-J model

$$H = -t \sum_{\langle i,j\rangle,\sigma} \left(c^{\dagger}_{i\sigma} c_{j\sigma} + h.c. \right) + U \sum_{i} n_{i\uparrow} n_{i\downarrow} \quad \Longrightarrow \quad H = -t \sum_{\langle i,j\rangle,\sigma} \left(\tilde{c}^{\dagger}_{i\sigma} \tilde{c}_{j\sigma} + h.c. \right) + J \sum_{\langle i,j\rangle} \mathbf{S}_i \cdot \mathbf{S}_j$$

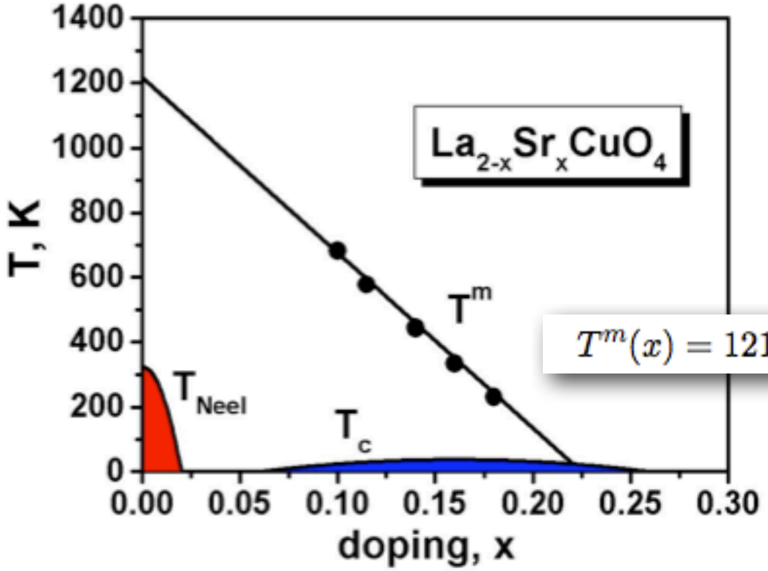
It may therefore be possible to approximate the physics of doped system as an effective spin system plus some additional hole excitations.

Nakano Scaling and the Reduced Exchange Coupling

Nakano scaling

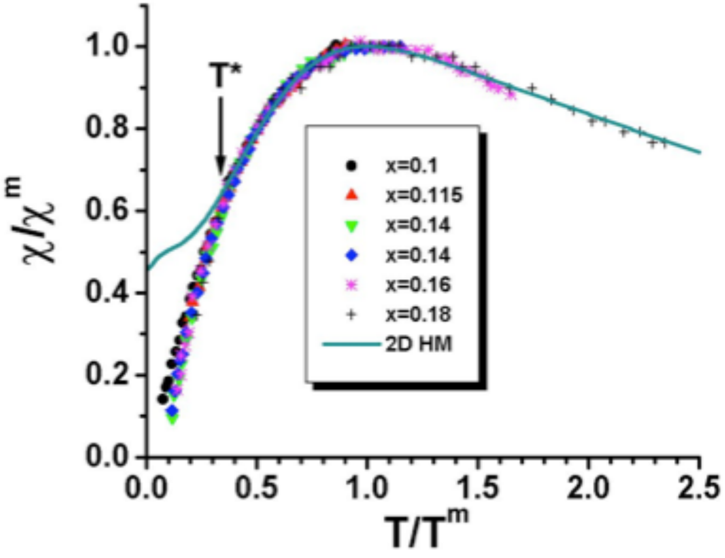


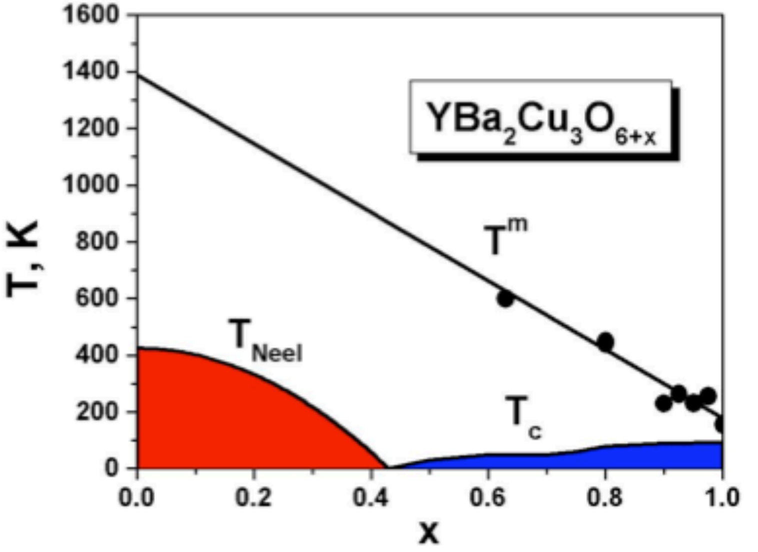
A reduced effective coupling



$$T^m(x) = 1218K(1 - 4.45x).$$

2D Heisenberg model



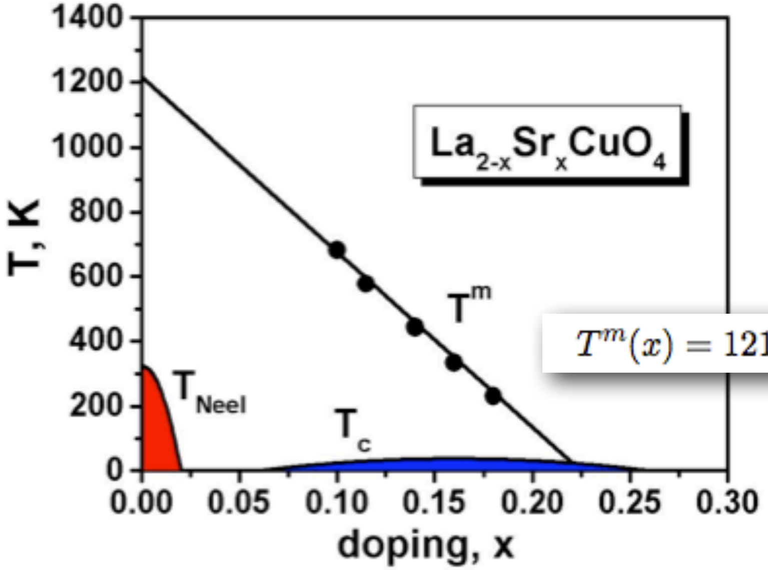


Nakano's formula may be understood from a 2D Heisenberg lattice with a reduced exchange coupling.

Barzykin & Pines, 2009.

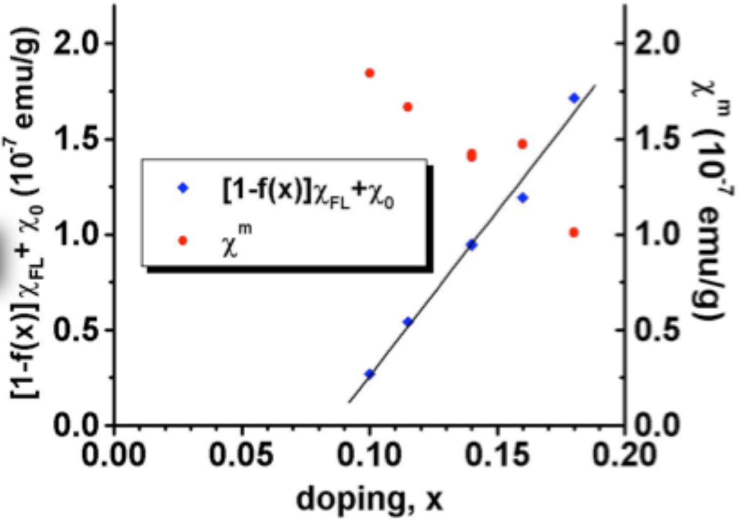
Two-Fluid Scenario for Cuprates

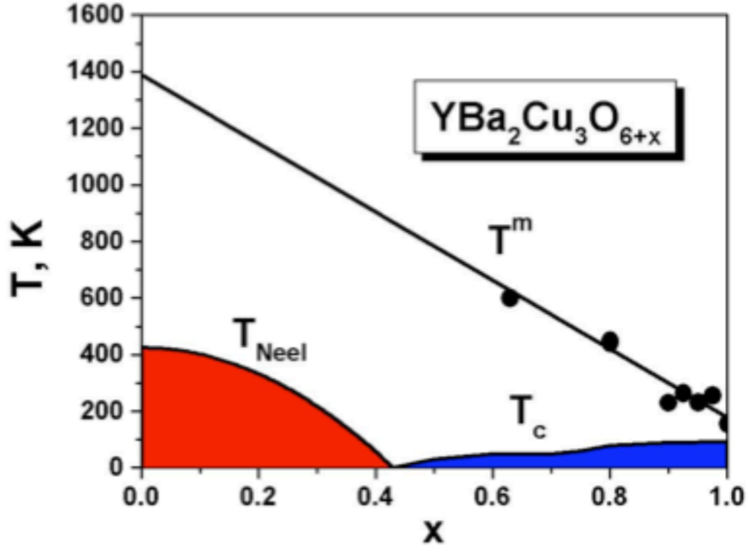
A reduced effective coupling

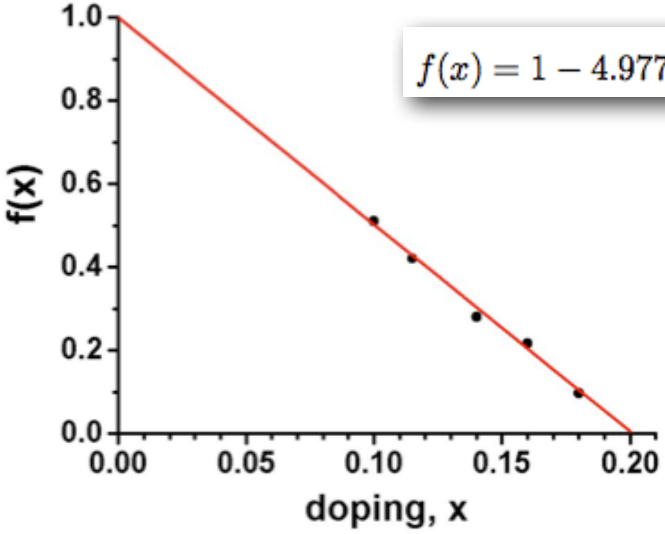


$$T^m(x) = 1218K(1-4.45x)$$

$$\chi(T) = f(x)\chi_{SL}(T/T^m(x)) + (1-f(x))\chi_{FL} + \chi_0$$





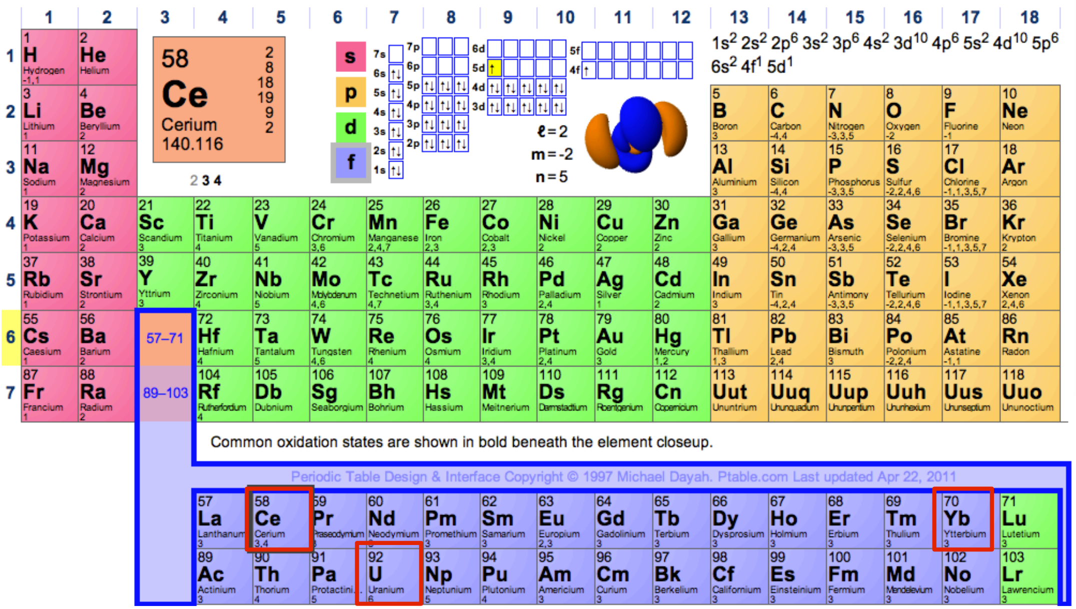


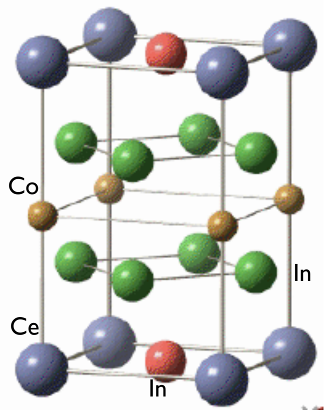
$$f(x) = 1 - 4.977x$$

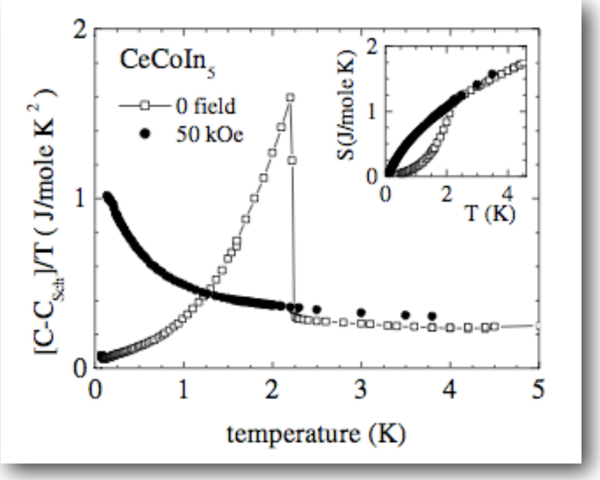
More Knight shift experiments argue against a single fluid picture.
In a two-fluid picture, the second component increases with increasing doping.

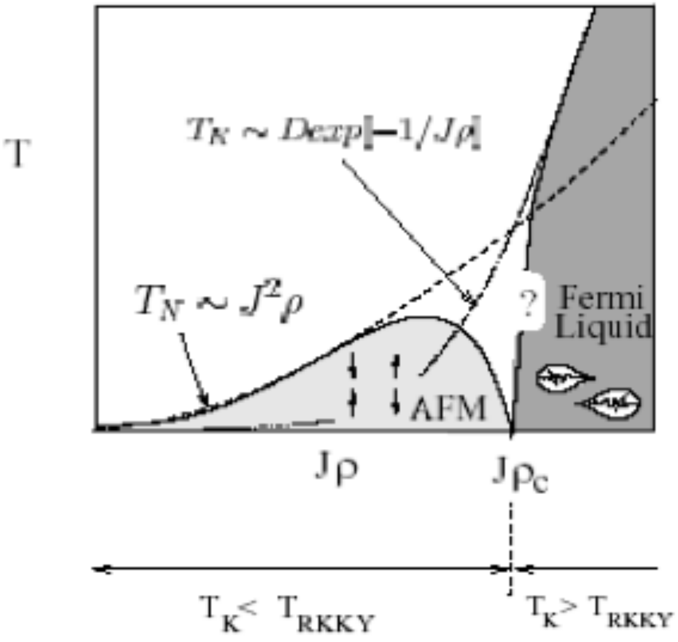
Barzykin & Pines, 2009.

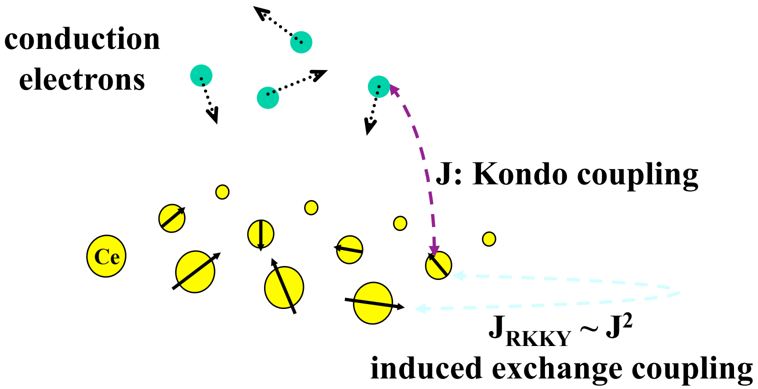
Theoretical Studies on Heavy Fermions











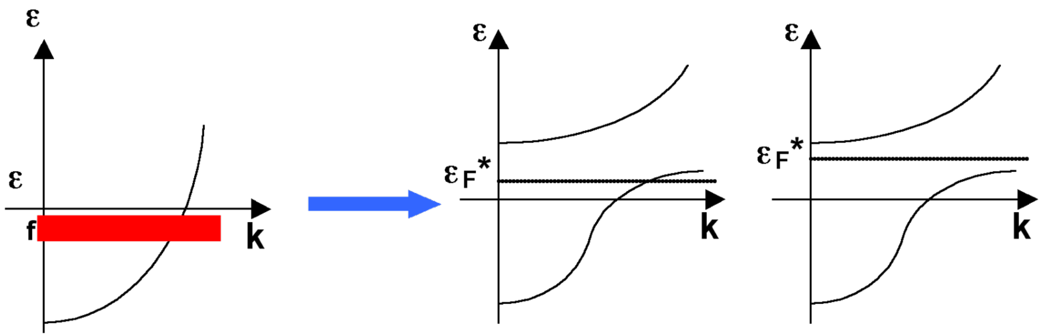
Kondo lattice model

$$H_{KLM} = \sum_{k\sigma} c^{\dagger}_{k\sigma} c_{k\sigma} + J \sum_{i} \mathbf{S}_i \cdot \mathbf{s}_i + J_{RKKY} \sum_{\langle ij \rangle} \mathbf{S}_i \cdot \mathbf{S}_j$$

Competition between Kondo and RKKY

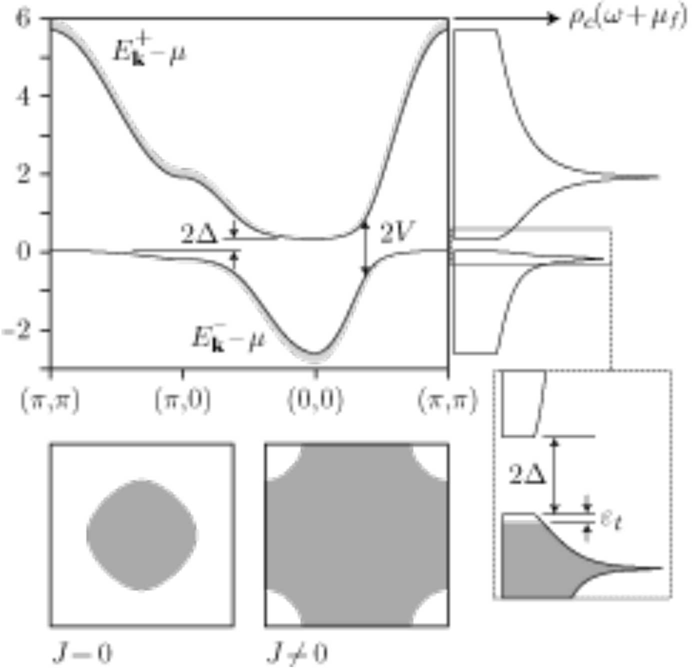
Start from the Kondo Regime

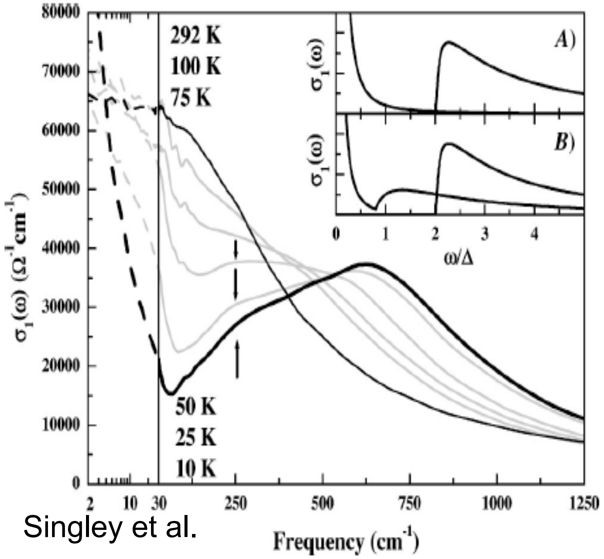
Hybridization gap



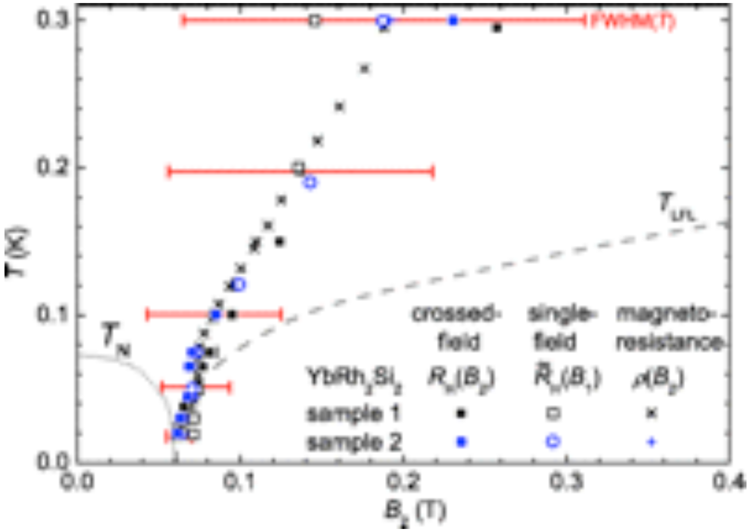
Unhybridized f-electrons **Heavy fermion** **Kondo insulator**

f-electrons become part of the Fermi Surface via the Kondo coupling.





Singley et al.



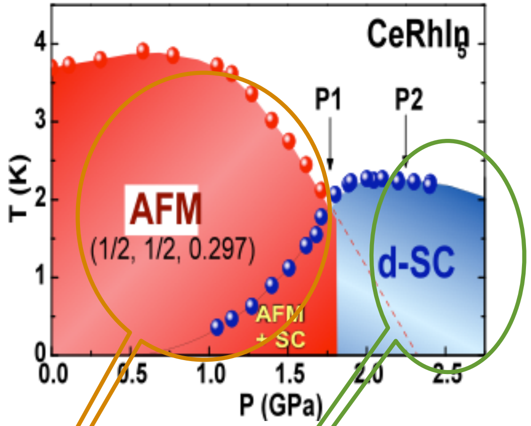
Numerical Methods: EDMFT, DMFT(OCA), DMFT(CTQMC), etc

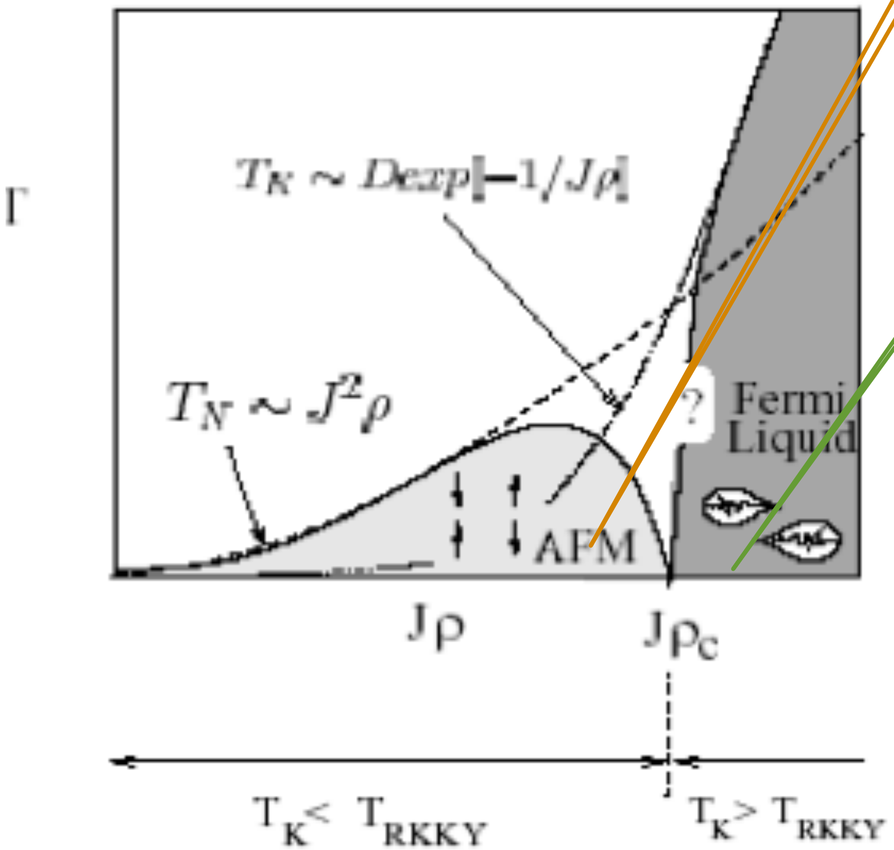
Fermi surface reconstruction

Start from the Magnetic Regime

$$H_{KLM} = \sum_{k\sigma} c^{\dagger}_{k\sigma} c_{k\sigma} + J \sum_{i} \mathbf{S}_i \cdot \mathbf{s}_i + J_{RKKY} \sum_{\langle ij \rangle} \mathbf{S}_i \cdot \mathbf{S}_j$$

No good solution to this model with nonlocal RKKY correlations.



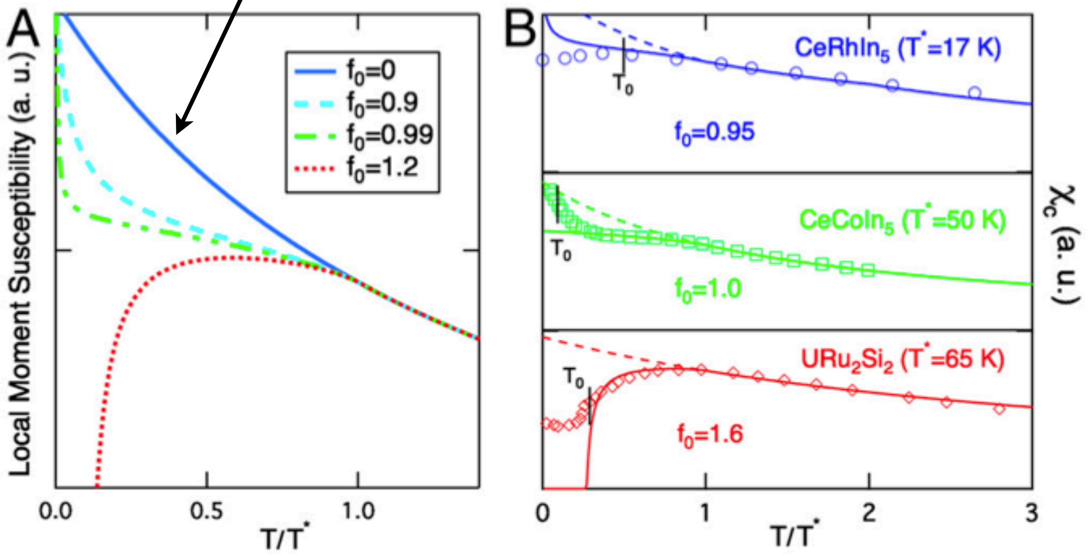


1. Is the Fermi liquid really described by Kondo singlets?
2. What is the role of the RKKY interaction?
3. How can we determine these scales experimentally?

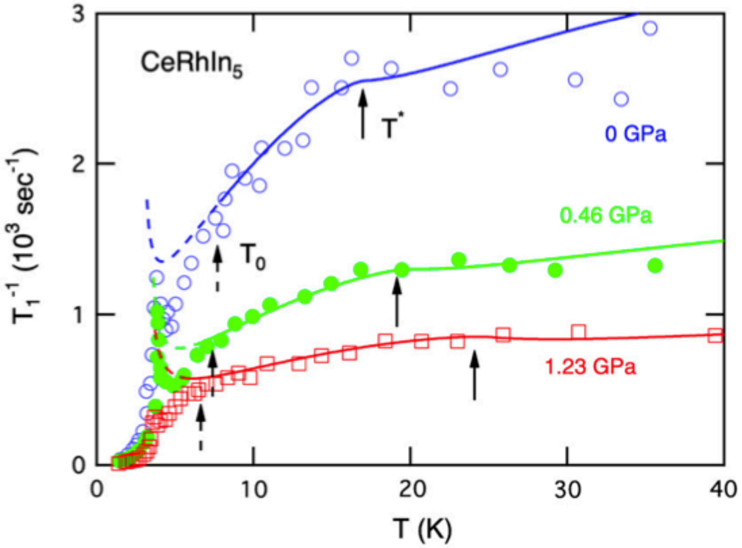
We may also start from the magnetic regime where the system can be well described by a spin lattice and see what may happen if we introduce the hybridization.

$$J \rightarrow \tilde{J} = J f_l(T)$$

A Hybridized Spin Liquid



Curie-Weiss law



$$\chi_l(q,\omega) = \frac{f_l \chi_0}{1 - zJ_q f_l \chi_0 - i\omega/\gamma_l}$$

$$\frac{1}{T_1} = \gamma^2 T \lim_{\omega\to 0} \sum_q F(q)^2 \frac{\mathrm{Im}\chi_l(q,\omega)}{\omega}$$

$$f_h(T) = f_0\left(1 - \frac{T}{T^*}\right)^{3/2}$$

We may also start from the magnetic regime where the system can be well described by a spin lattice and see what may happen if we introduce the hybridization.

$$J \to \tilde{J} = J f_l(T)$$

Yang and Pines, PNAS 109, 18241 (2012)

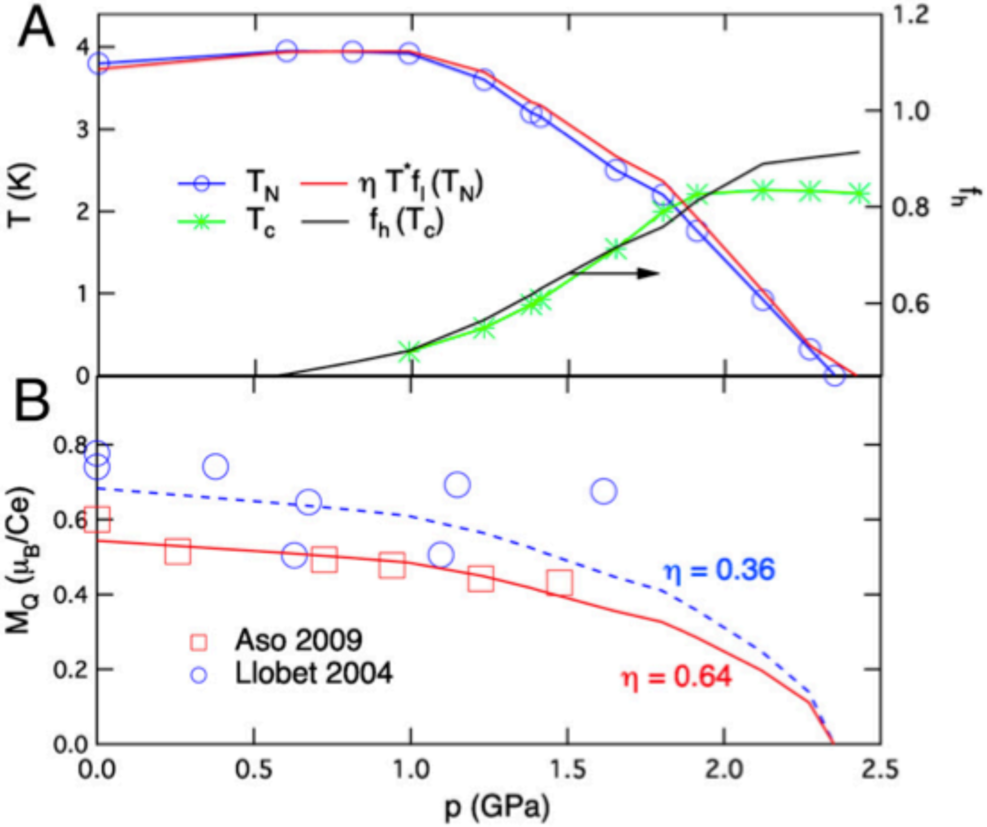
Antiferromagnetism: Suppression of T_N

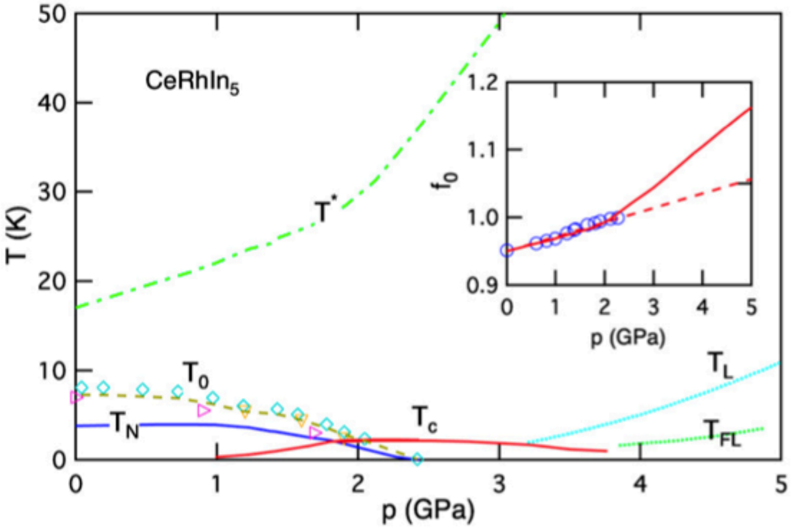
$$\chi_l(q,\omega) = \frac{f_l\chi_0}{1 - zJ_q f_l \chi_0 - i\omega/\gamma_l}$$

$$zJ_Q f_l(T_N)\chi_0(T_N) = 1.$$

$$\frac{T_N}{T^*} = \eta f_l(T_N),$$

$$\frac{\mu^2}{\mu_0^2} = f_l(T_N)$$

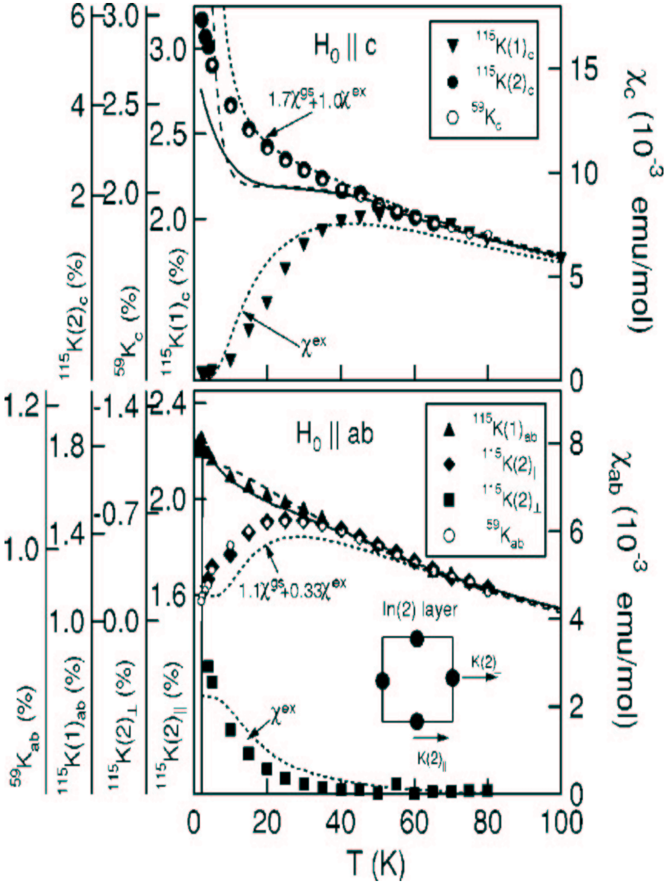




Yang and Pines, PNAS 109, 18241 (2012)

Emergent Heavy Electrons: Knight Shift Anomaly

CeCoIn$_5$

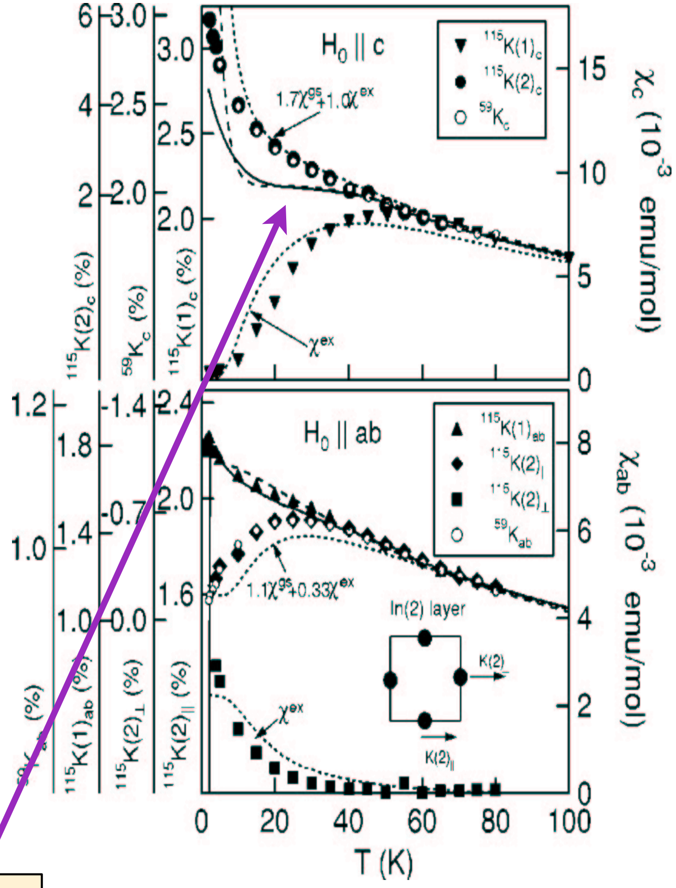


Curro et al, PRL 90, 227202 (2003)

Yang & Pines, PRL 100, 096404 (2008)

Emergent Heavy Electrons: Knight Shift Anomaly

CeCoIn$_5$



Curro et al, PRL 90, 227202 (2003)

$T > T^* :$ $\chi = \chi_{sl}$

$K = K_0 + A\chi_{sl}$

$T < T^* :$ $\chi = \chi_{sl} + \chi_{kl}$

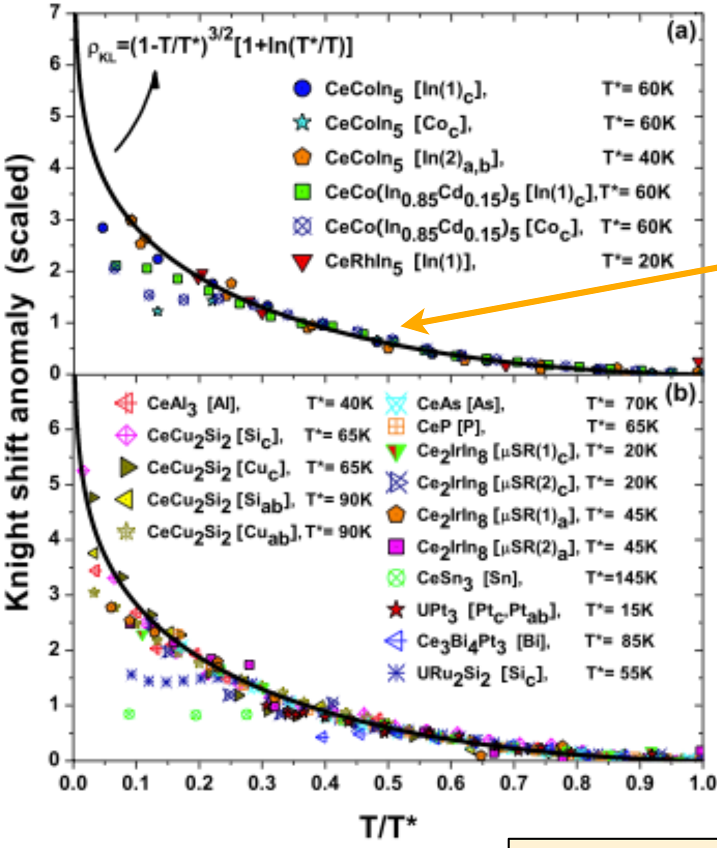
$K = K_0 + A\chi_{sl} + B\chi_{kl}$

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

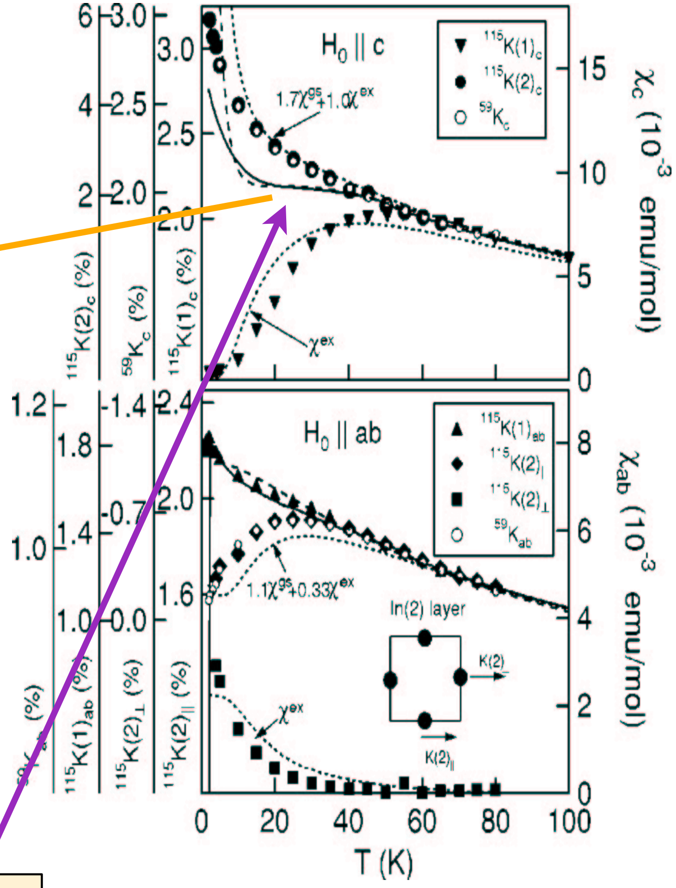
Yang & Pines, PRL 100, 096404 (2008)

Emergent Heavy Electrons: Knight Shift Anomaly

Knight shift anomaly



CeCoIn$_5$



Curro et al, PRL 90, 227202 (2003)

$T > T^*$: $\chi = \chi_{sl}$

$K = K_0 + A\chi_{sl}$

$T < T^*$: $\chi = \chi_{sl} + \chi_{kl}$

$K = K_0 + A\chi_{sl} + B\chi_{kl}$

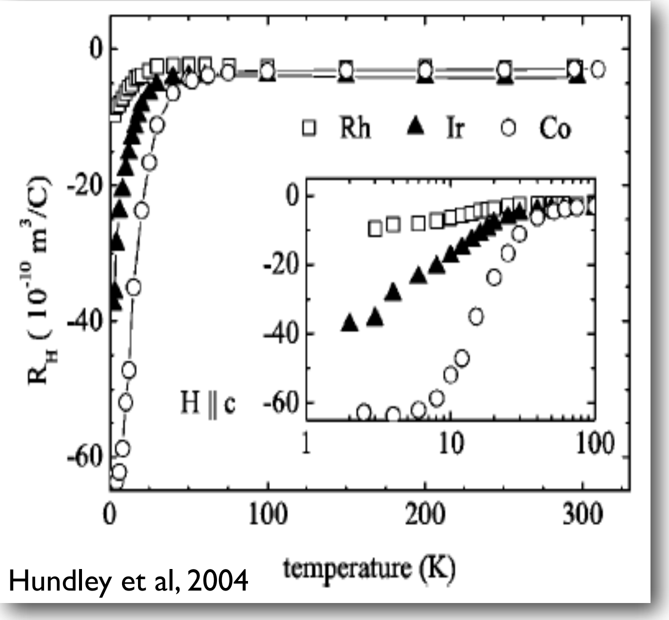
$K_a = K - K_0 - A\chi = (B - A)\chi_{kl}$

The Knight shift anomaly is therefore a strong evidence for the universality of an emergent state in heavy electron materials. It shouldn't be ascribed to crystal field effect.

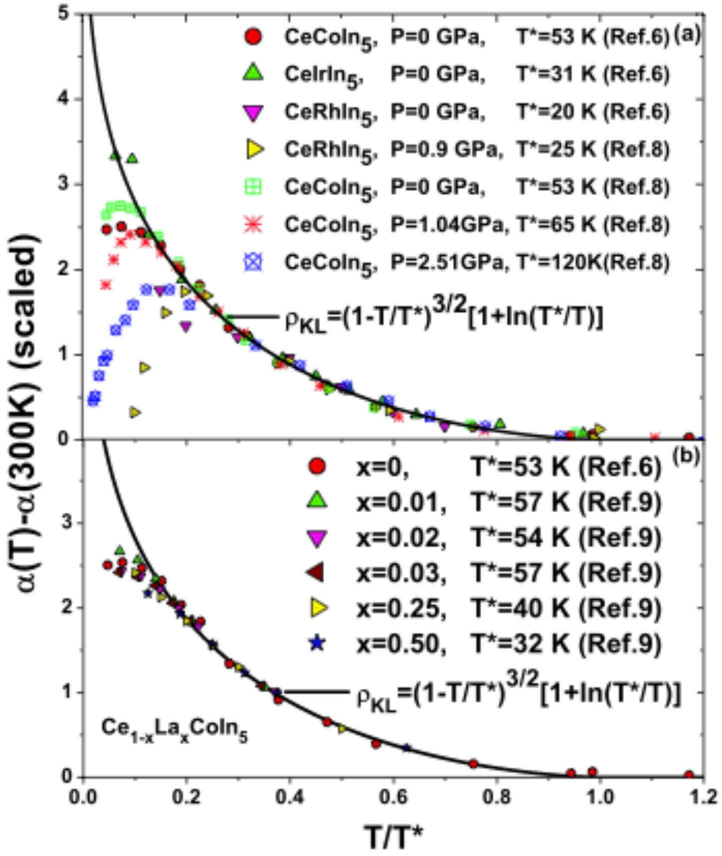
Yang & Pines, PRL 100, 096404 (2008)

Emergent Heavy Electrons: Hall Anomaly

Hall coefficient



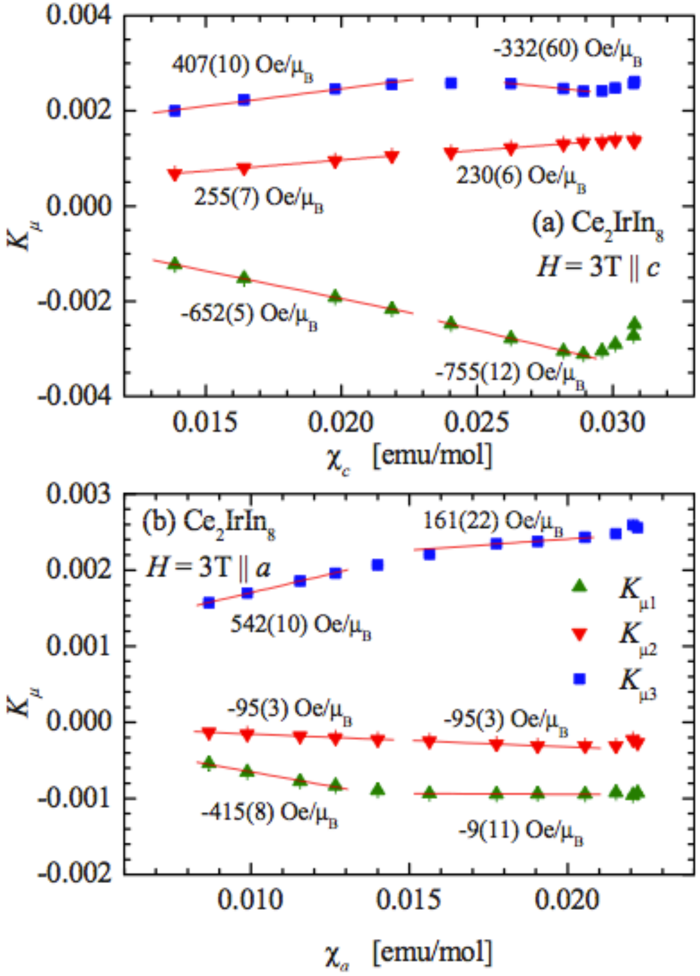
Hundley et al, 2004

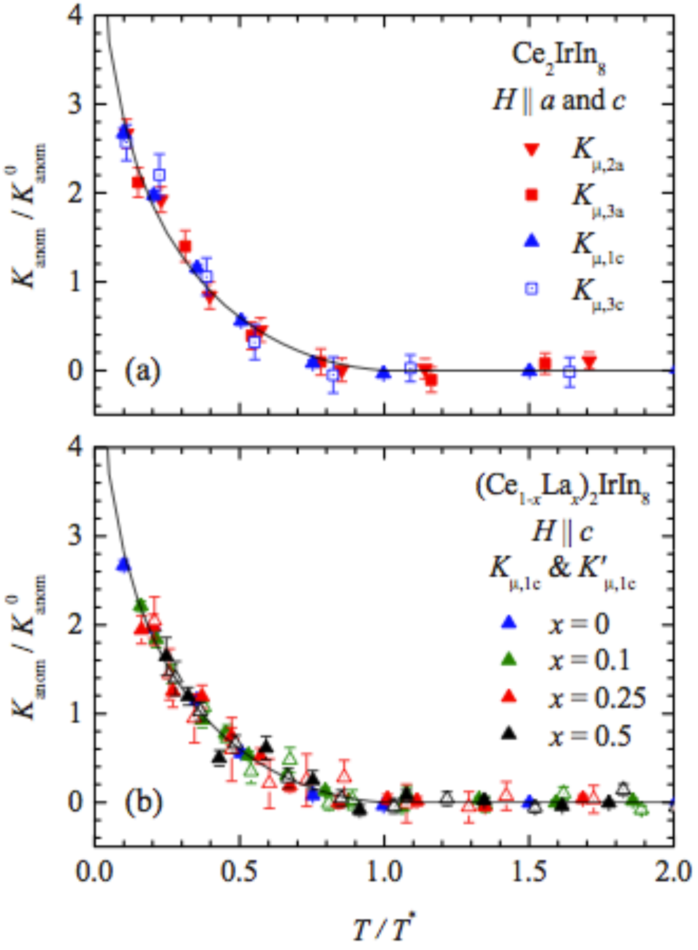


Hundley et al, PRB 70, 035113 (2004)
Nakajima et al, JPSJ 76, 024703 (2007)

Yang & Pines, PRL 100, 096404 (2008)

Further Experiment: μSR on $(Ce_{1-x}La_x)_2IrIn_8$



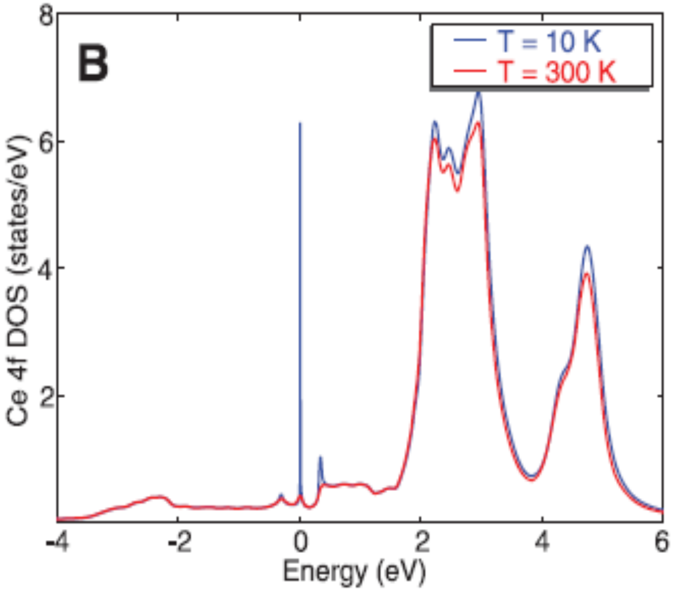


If the emergent state is real, what does it tell us about the physics of heavy electron materials.

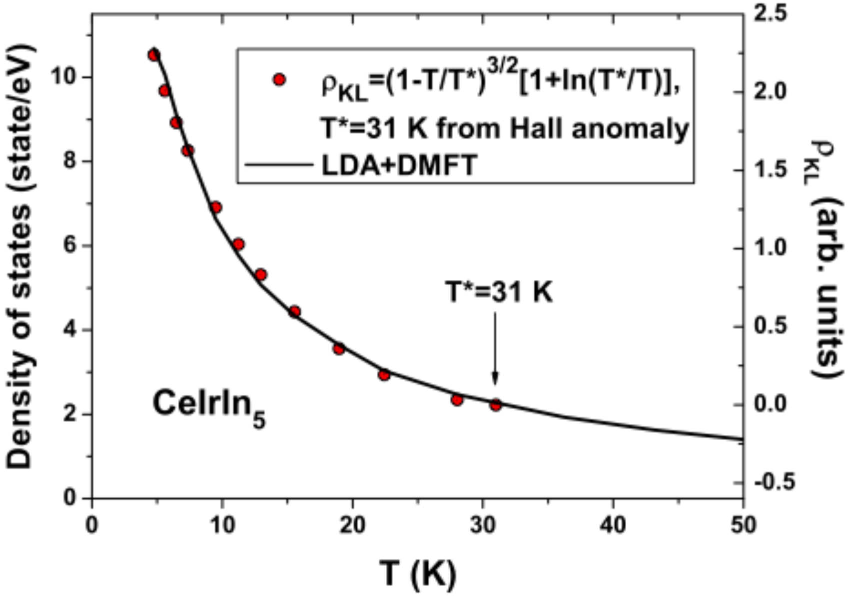
Ohishi et al, PRB 80, 25104 (2009)

Agreement with LDA+DMFT calculation

LDA+DMFT for CeIrIn$_5$



Shim et al, Science 318, 1615 (2007)



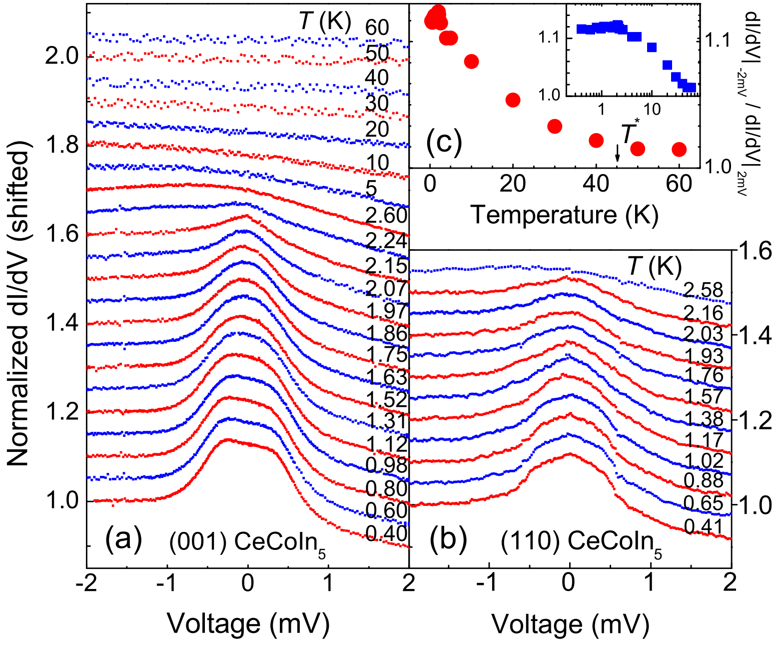
The two-fluid scenario reflects the gradual screening of the local f-moments, by their surrounding conduction electrons and neighboring f-electrons.

How can it be?

Yang & Pines, PRL 100, 096404 (2008)

Tunneling into Heavy Electrons: The Fano Interference

A composite state of conduction and f-electrons



Park et al, PRL 100, 177001 (2008)

A theoretical explanation for the Fano line-shape in Yang, PRB 79, 241107(R) (2009)

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

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

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

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

$$|(d_{1km}|H_t|t)|^2=|u_k(f_{km}|H_t|t)+v_k(c_{km}|H_t|t)|^2$$
$$=\left|q+\frac{v_k}{u_k}\right|^2|u_k|^2|M_{ckm}|^2=\frac{|q-\tilde{E}_{1k}|^2}{1+\tilde{E}^2_{1k}}|M_{ckm}|^2,$$

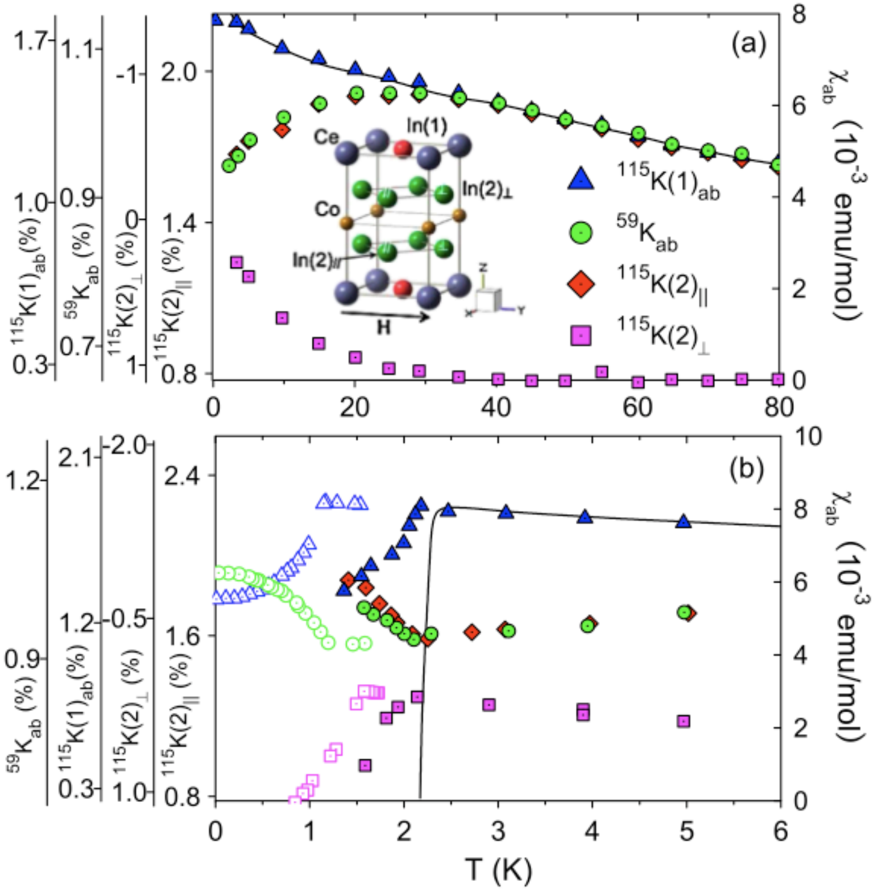
$$|(d_{2km}|H_t|t)|^2=|-v_k(f_{km}|H_t|t)+u_k(c_{km}|H_t|t)|^2$$
$$=\left|q-\frac{u_k}{v_k}\right|^2|v_k|^2|M_{ckm}|^2=\frac{|q-\tilde{E}_{2k}|^2}{1+\tilde{E}^2_{2k}}|M_{ckm}|^2,$$

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

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

Heavy Electron Condensation: Superconductivity

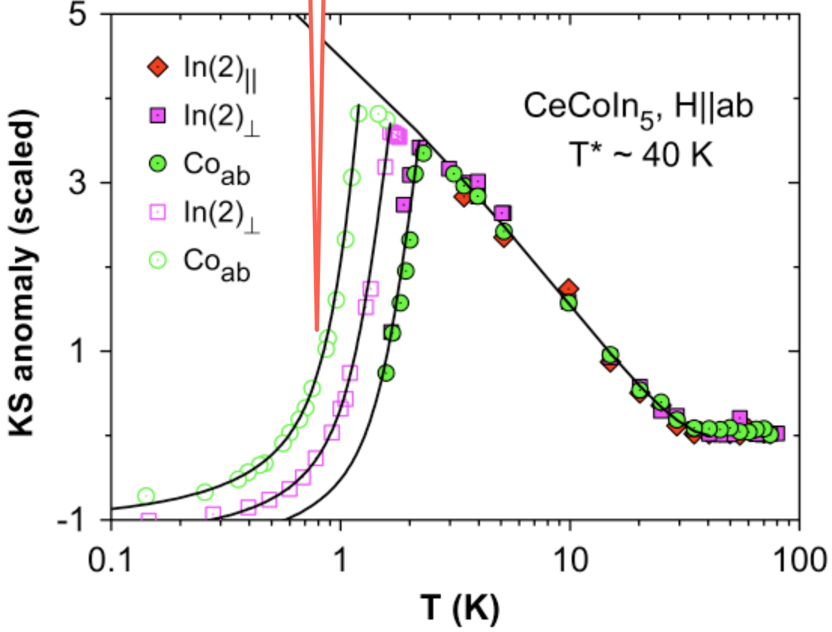
Knight shift anomaly



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

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

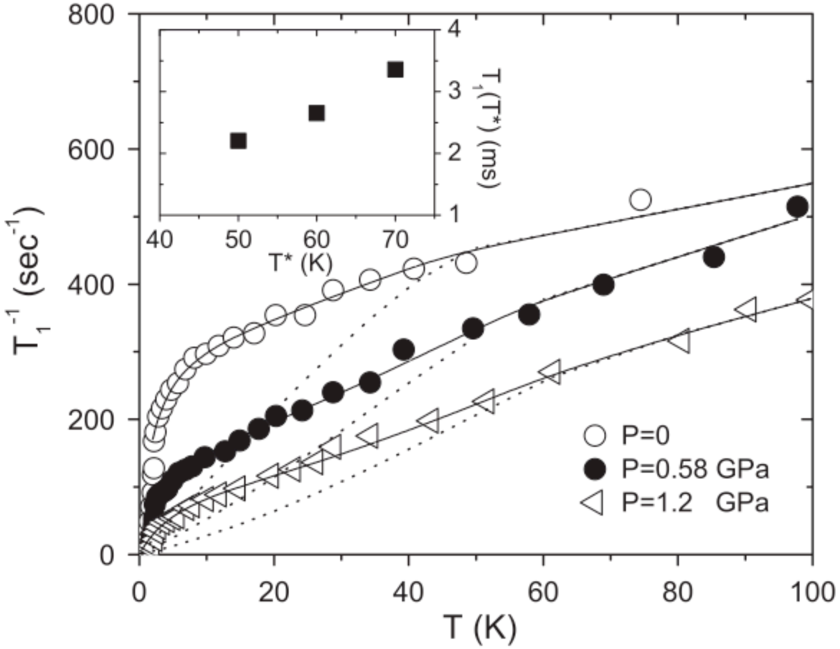
$$\Delta_k(T) = g_k \Delta(0) \tanh\left[\sqrt{\left|\frac{\partial \Delta^2}{\partial T}\right|_{T_c} \frac{T_c}{\Delta(0)^2}\left(\frac{T_c}{T} - 1\right)}\right],$$

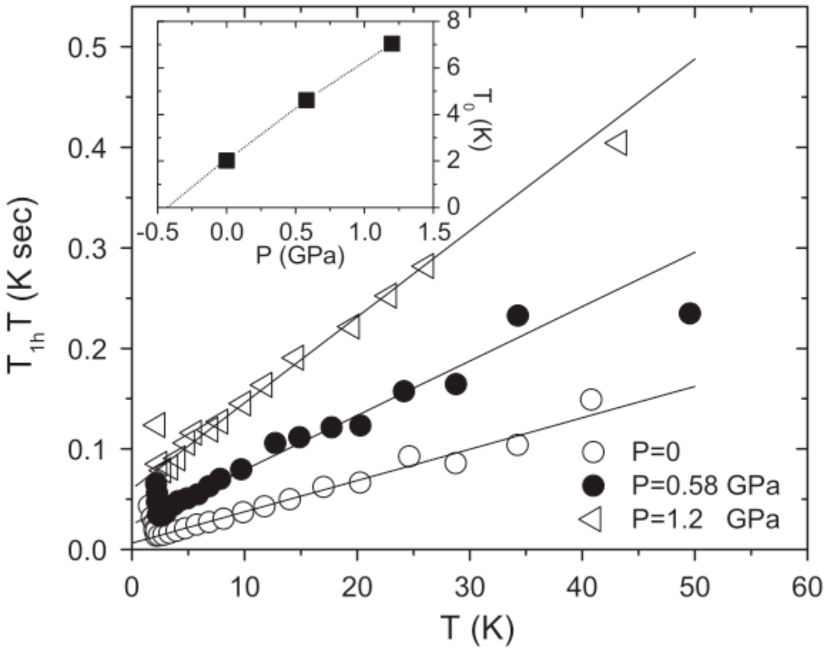


Kondo liquid is responsible for superconductivity.

Yang et al, PRL 103, 197004 (2009)

Heavy Electron Condensation: Critical Fluctuations





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

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

Kondo liquid exhibits critical fluctuations

Yang et al, PRL 103, 197004 (2009)

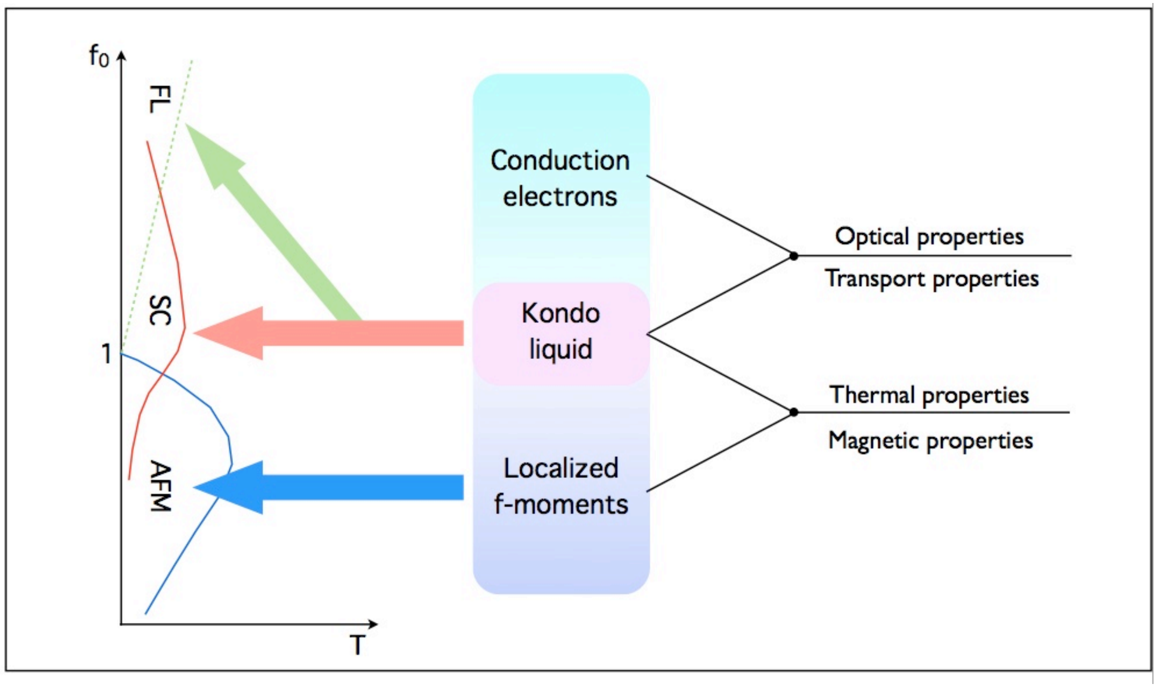
A Two-fluid Scenario

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

A hybridization effectiveness that varies with temperature and pressure determines the properties of both normal and ground states

$f_0 > 1$, no f-moments

$f_0 < 1$, f-moments exist



This illustrates the whole idea of the two fluid model. Each physical property is determined by a background contribution from the localized f-moments and a universal contribution from the Kondo liquid.

The two components are also responsible for the low temperature emergent ordered states.

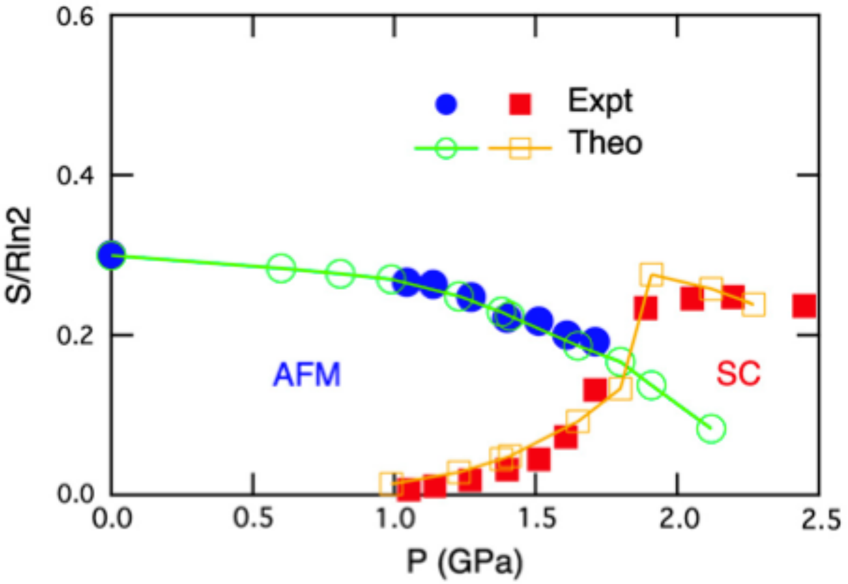
Thermodynamics: Entropy and Specific Heat

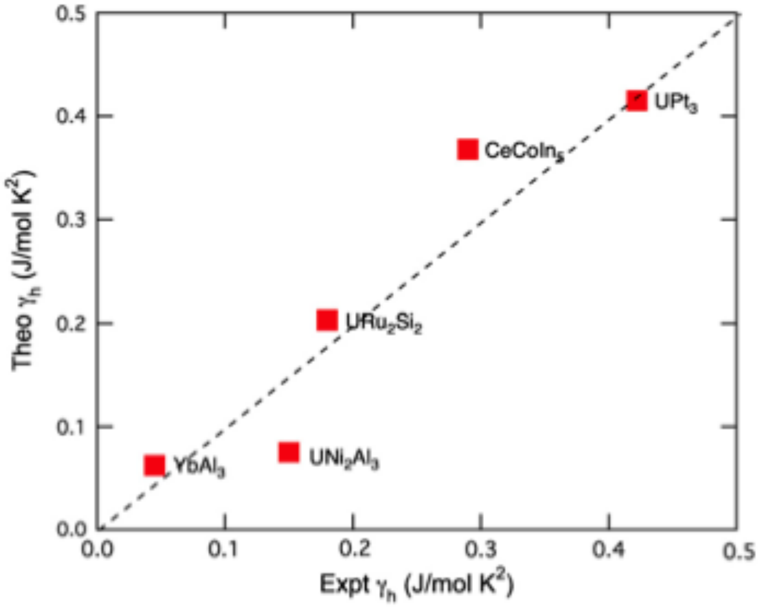
$$S(T) = R\ln 2\left[f_l(T) + f_h(T)\frac{T}{2T^*}\left(2+\ln\frac{T^*}{T}\right)\right].$$

$$S(T_c) = r_N f_l(T_N)[1-a(T_c)]R\ln 2 + r_N f_h(T_N)S_h(T_N)\frac{T_c}{T_N}$$

$$S_h(T_x) = R\ln 2\,\frac{T_x}{2T^*}\left[2+\ln\left(\frac{T^*}{T_x}\right)\right].$$

$$\gamma_h \sim \frac{S_h(T_L)}{T_L} = \frac{R\ln 2}{2T^*}\left[2-\ln\left(1-f_0^{-2/3}\right)\right].$$





Yang and Pines, PNAS 109, 18241 (2012)

Transport: Anomalous Hall Effect

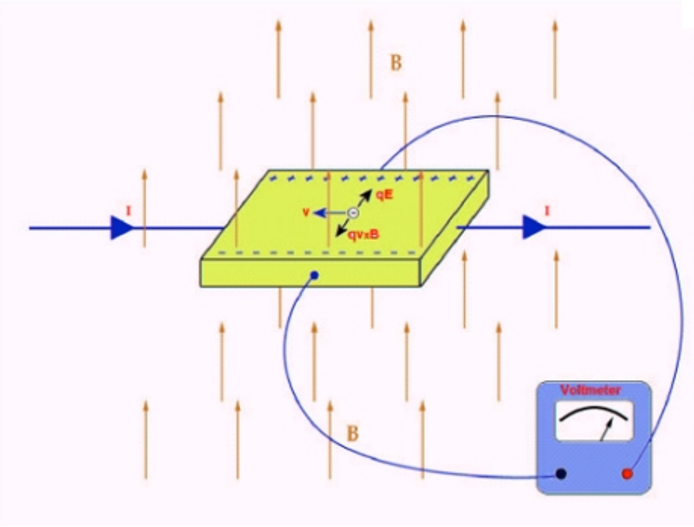
$$R_H = R_0 + R_s$$

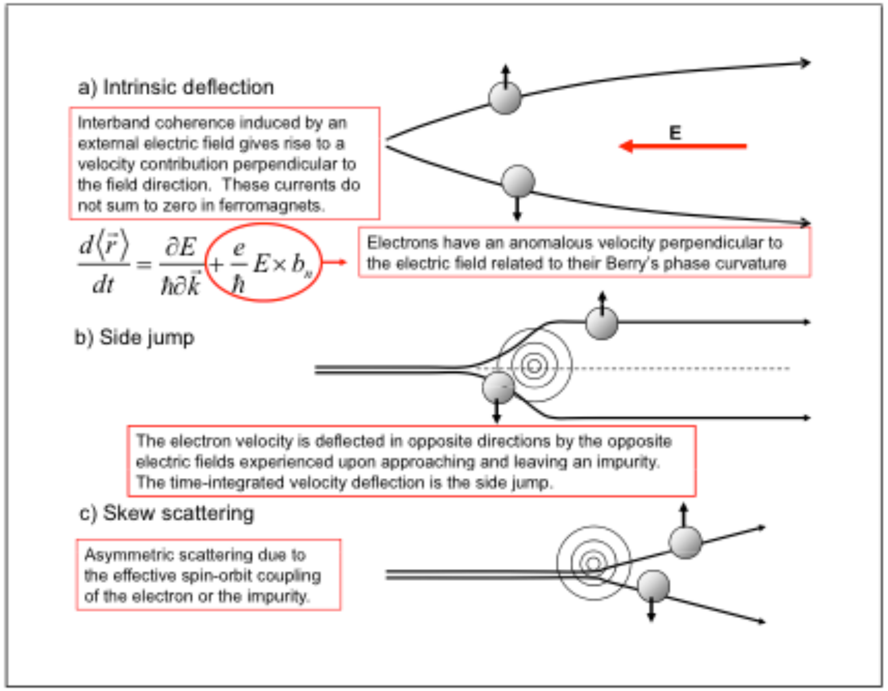
Ordinary Hall coefficient

Anomalous Hall coefficient

intrinsic
skew scattering
side-jump

$$\sigma_{xy}^{AH} = \sigma_{xy}^{AH-int} + \sigma_{xy}^{AH-skew} + \sigma_{xy}^{AH-sj}$$





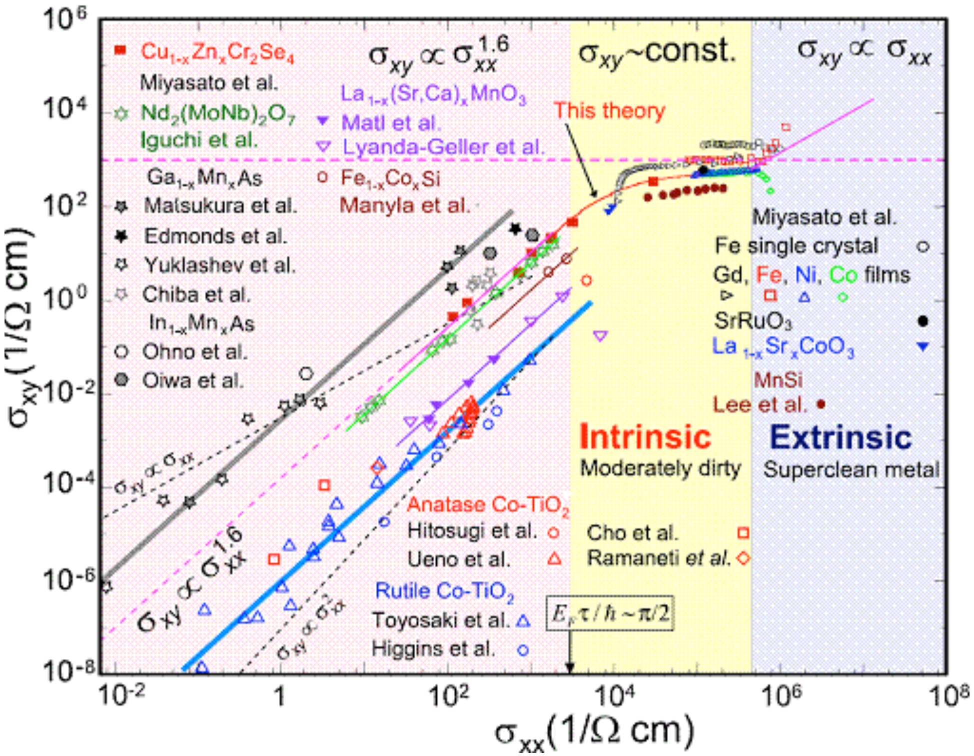
Interband coherence induced by an external electric field gives rise to a velocity contribution perpendicular to the field direction. These currents do not sum to zero in ferromagnets.

$$\frac{d\langle\vec{r}\rangle}{dt} = \frac{\partial E}{\hbar\partial\vec{k}} + \frac{e}{\hbar}E\times b_n$$

Electrons have an anomalous velocity perpendicular to the electric field related to their Berry's phase curvature

The electron velocity is deflected in opposite directions by the opposite electric fields experienced upon approaching and leaving an impurity. The time-integrated velocity deflection is the side jump.

Asymmetric scattering due to the effective spin-orbit coupling of the electron or the impurity.



Nagaosa et al., RMP 82, 1539 (2010)

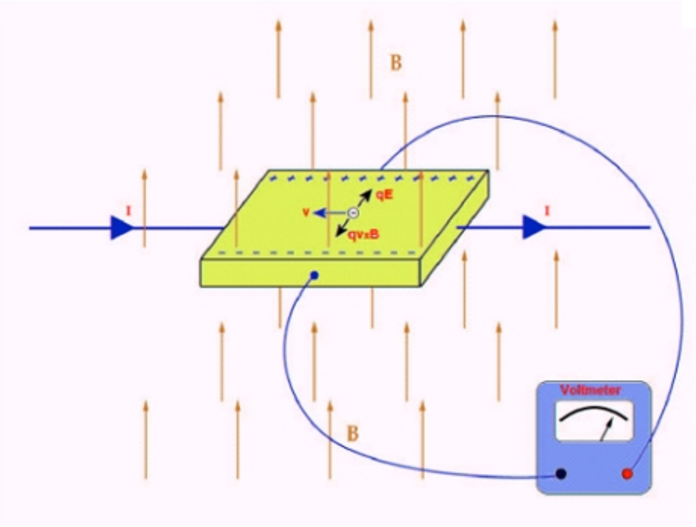
Anomalous Hall Effect: Skew Scattering

$$R_H = R_0 + R_s$$

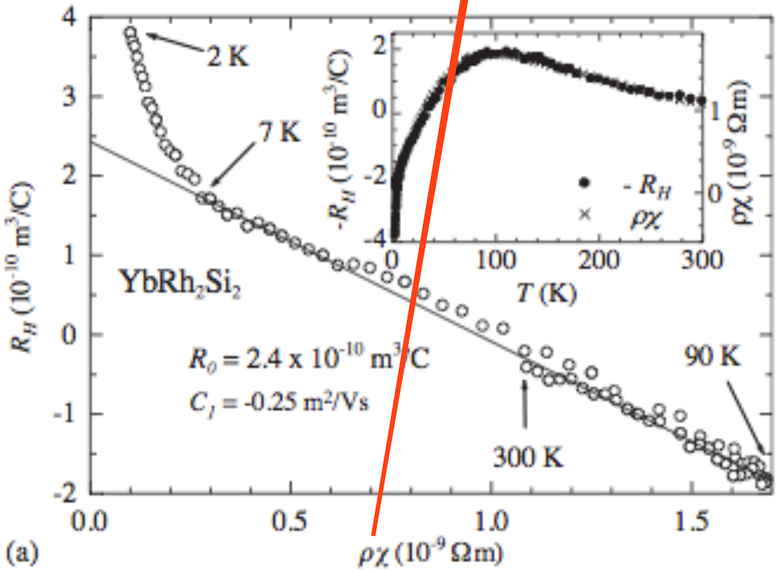
Ordinary Hall coefficient

Anomalous Hall coefficient

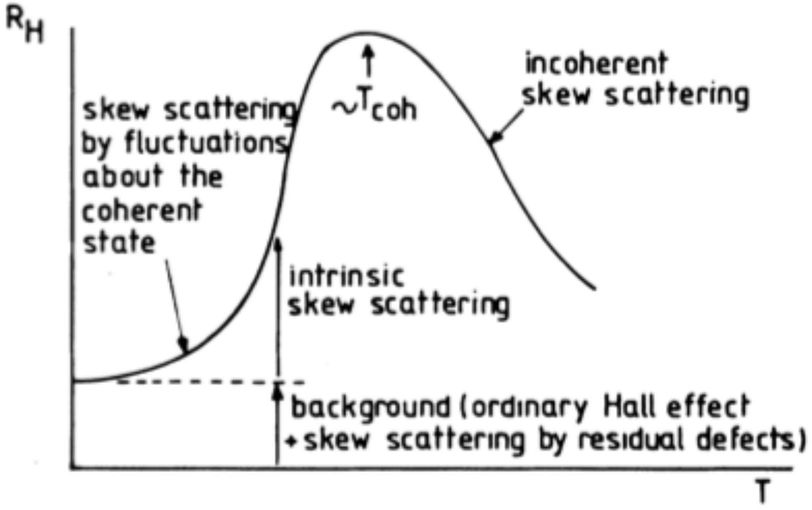
- intrinsic
- skew scattering
- side-jump



independent local f-moments



Paschen et al, Physica B 359-361, 44 (2005)



Fert & Levy, PRB 36, 1907 (1987)

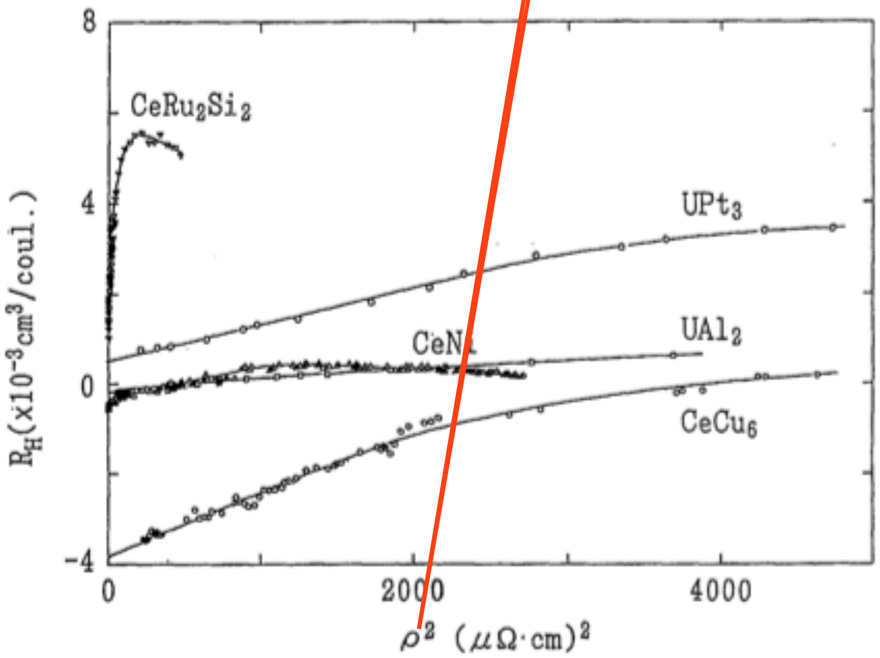
Anomalous Hall Effect: Coherent Contribution

$$R_H = R_0 + R_s$$

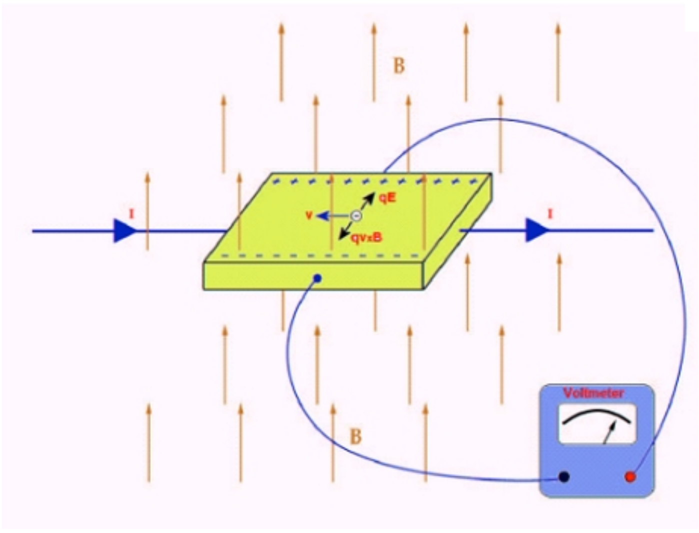
Ordinary Hall coefficient

Anomalous Hall coefficient

- intrinsic
- skew scattering
- side-jump



Yamada et al, Prog Theor Phys, 89, 1155 (1993)



- in contradiction with Fert & Levy
- seldom observed

$R_H^a \propto \rho^2$ $\qquad$ $R_H^a \propto \chi_k \cdot \rho^0$

T~T$_M$ $\qquad$ T

$|\mu - E_M^f| \gg \Delta_{kM},$ $\qquad$ $|\mu - E_M^f| \lesssim \Delta_{kM}$

resonant level

broadening, the imaginary part of the self-energy

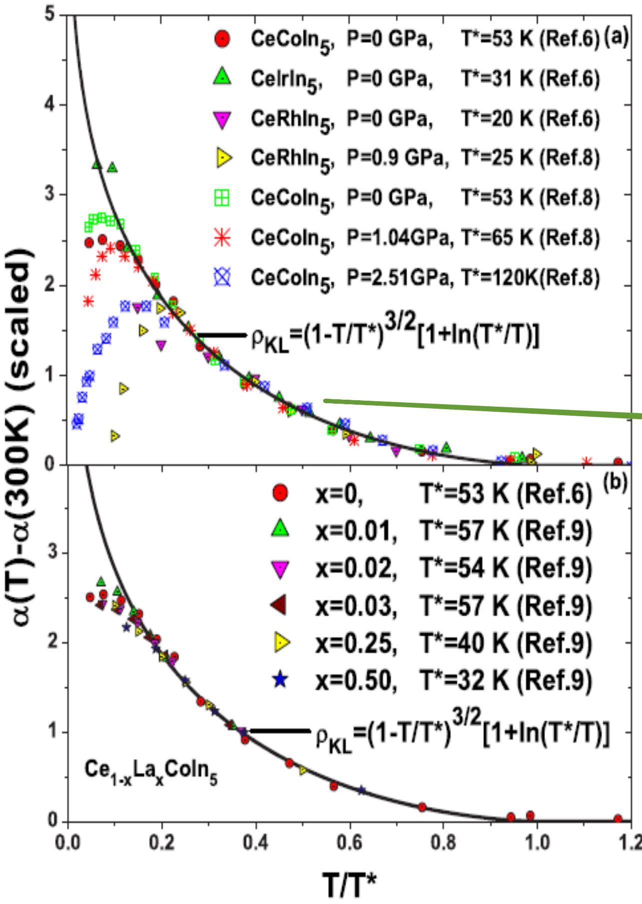
Kontani & Yamada, JPSJ 63, 2627 (1994)

Anomalous Hall Effect: Coherent Contribution

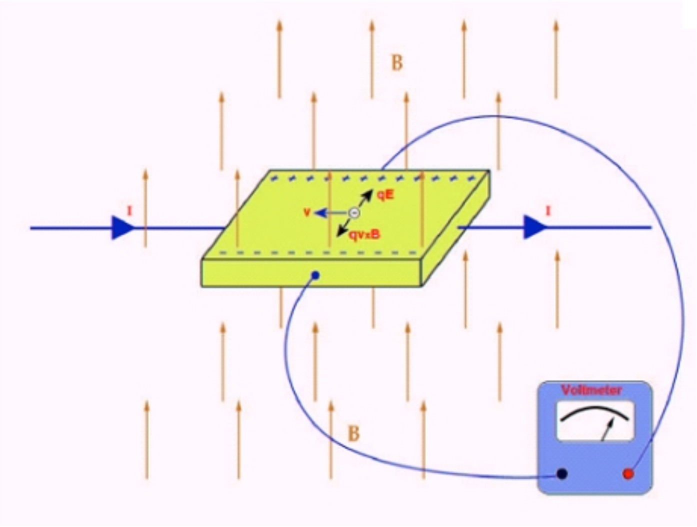
$$R_H = R_0 + R_s$$

Ordinary Hall coefficient

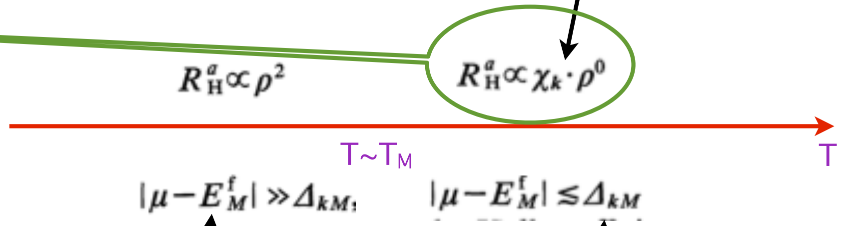
Anomalous Hall coefficient



Yang & Pines, PRL 100, 096404 (2008)



- in contradiction with Fert & Levy
- seldom observed



$R^a_H \propto \rho^2$

$R^a_H \propto \chi_k \cdot \rho^0$

T~T$_M$

T

$|\mu - E^f_M| \gg \Delta_{kM}$,

$|\mu - E^f_M| \lesssim \Delta_{kM}$

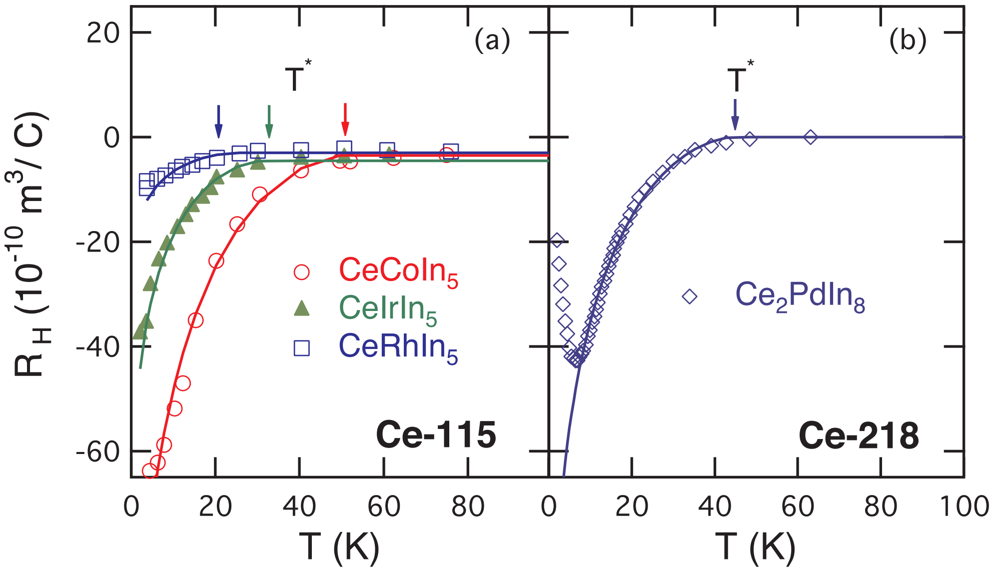
resonant level

broadening, the imaginary part of the self-energy

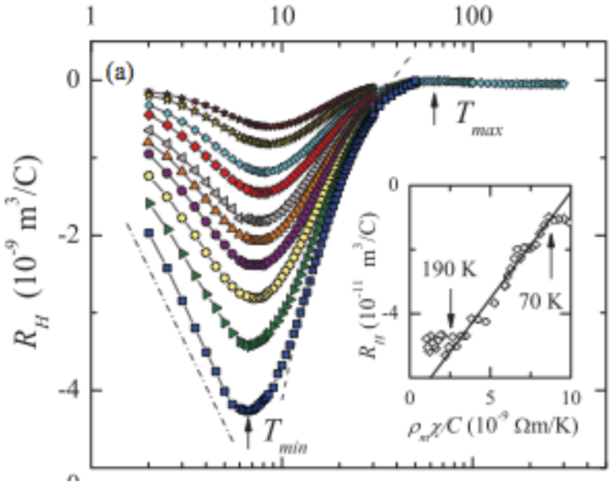
Kontani & Yamada, JPSJ 63, 2627 (1994)

Anomalous Hall Effect: Scaling

$$\chi_h = \min\left\{\chi, \chi_0\left(1-\frac{T}{T^*}\right)^{3/2}\left(1+\ln\frac{T^*}{T}\right)\right\}$$



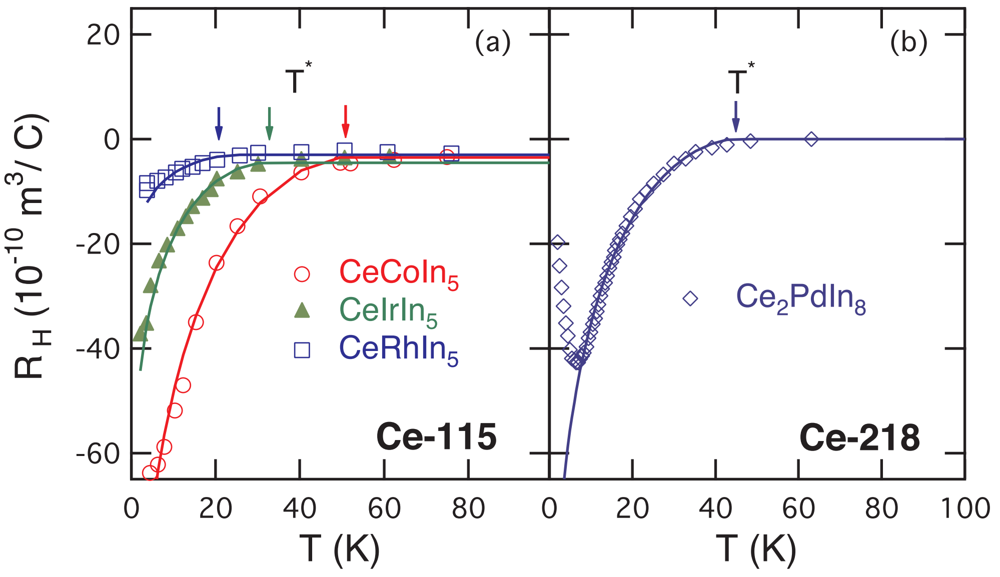
Yang, arXiv:1207.0646 (2012).

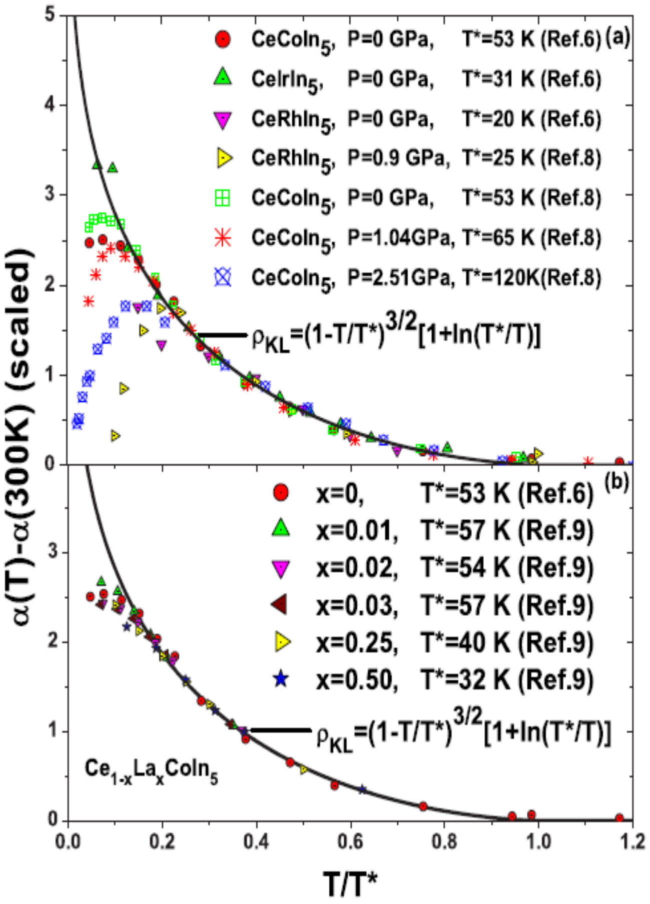


Gnida et al, PRB 85, 060508 (2012).

Anomalous Hall Effect: Scaling

$$\chi_h = \min\left\{\chi, \chi_0\left(1-\frac{T}{T^*}\right)^{3/2}\left(1+\ln\frac{T^*}{T}\right)\right\}$$





$$R_H = R_0 + r_l \rho \chi_l + r_h \chi_h$$

incoherent skew scattering from f-moments

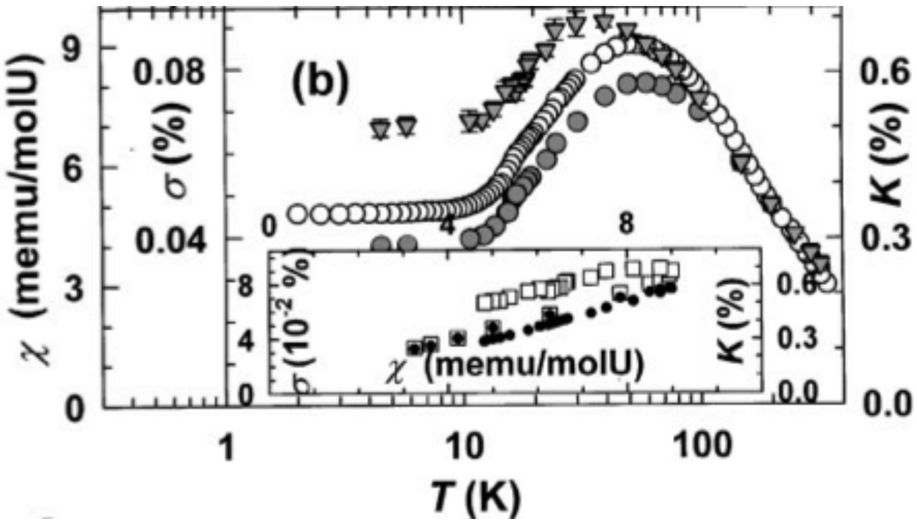
coherent skew scattering from itinerant heavy f-electrons

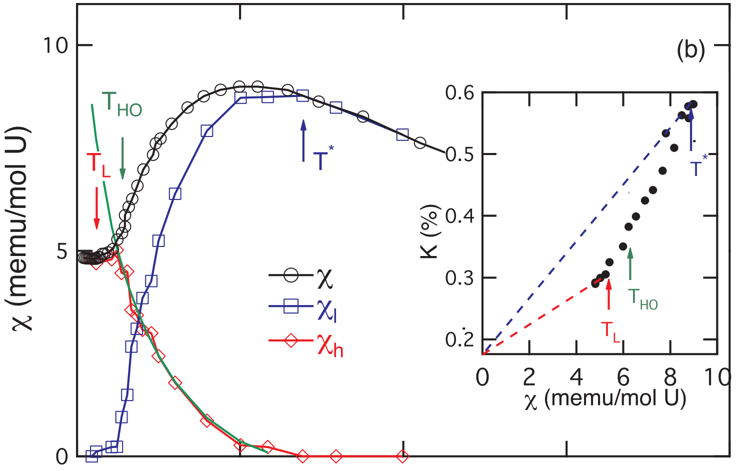
Yang, arXiv:1207.0646 (2012).

To prove this formula, we need to separate the two components.

URu_2Si_2: Separation of Two Components

Bernal et al, Physica B, 281&282, 236 (2000)





$T > T^* :$ $\chi = \chi_{sl}$

$K = K_0 + A\chi_{sl}$

$T < T^* :$ $\chi = \chi_{sl} + \chi_{kl}$

$K = K_0 + A\chi_{sl} + B\chi_{kl}$

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

$T < T_L :$ $\chi = \chi_{kl}$

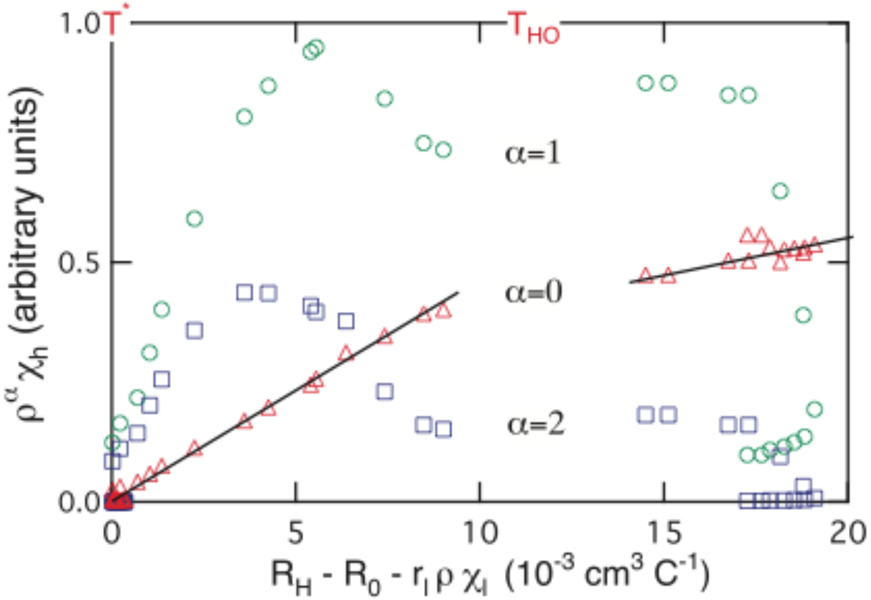
$K = K_0 + B\chi_{kl}$

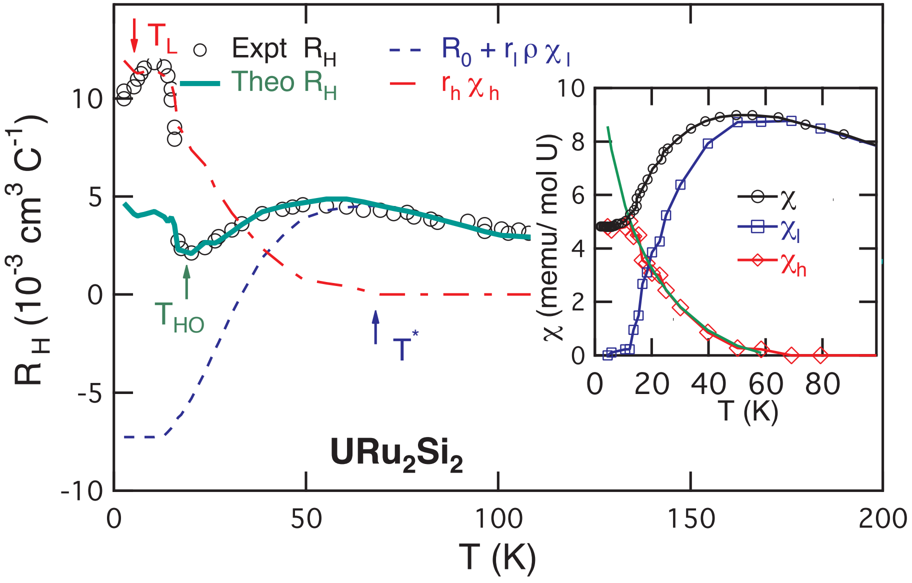
$K_b = K - K_0 - B\chi = (A - B)\chi_{sl}$

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

Yang, arXiv:1207.0646 (2012).
Shirer et al, PNAS 109, 18249 (2012).

Anomalous Hall Effect: URu_2Si_2





$$R_H = R_0 + r_l \rho \chi_l + r_h \chi_h$$

incoherent skew scattering from f-moments

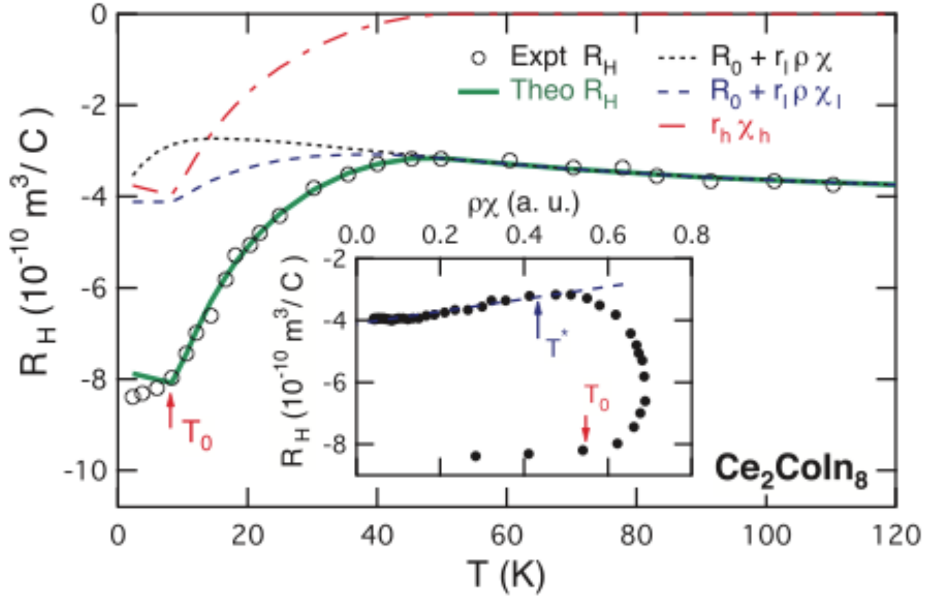
coherent skew scattering from itinerant heavy f-electrons

Yang, arXiv:1207.0646 (2012).

Anomalous Hall Effect: Ce_2CoIn_8

If a separation is not available from other experiment,

$$\chi_h = \min\left\{\chi, \chi_0 \left(1 - \frac{T}{T^*}\right)^{3/2} \left(1 + \ln\frac{T^*}{T}\right)\right\}$$



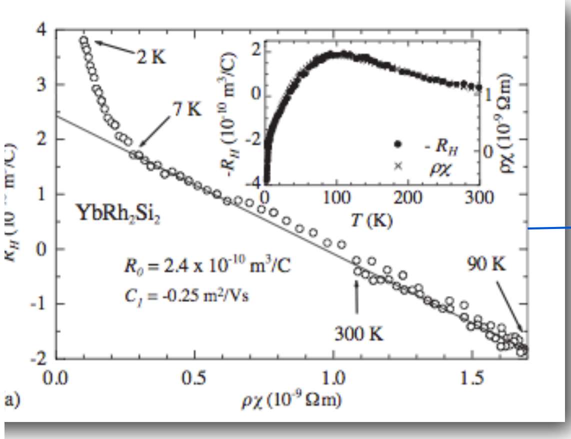
$$R_H = R_0 + r_l \rho \chi_l + r_h \chi_h$$

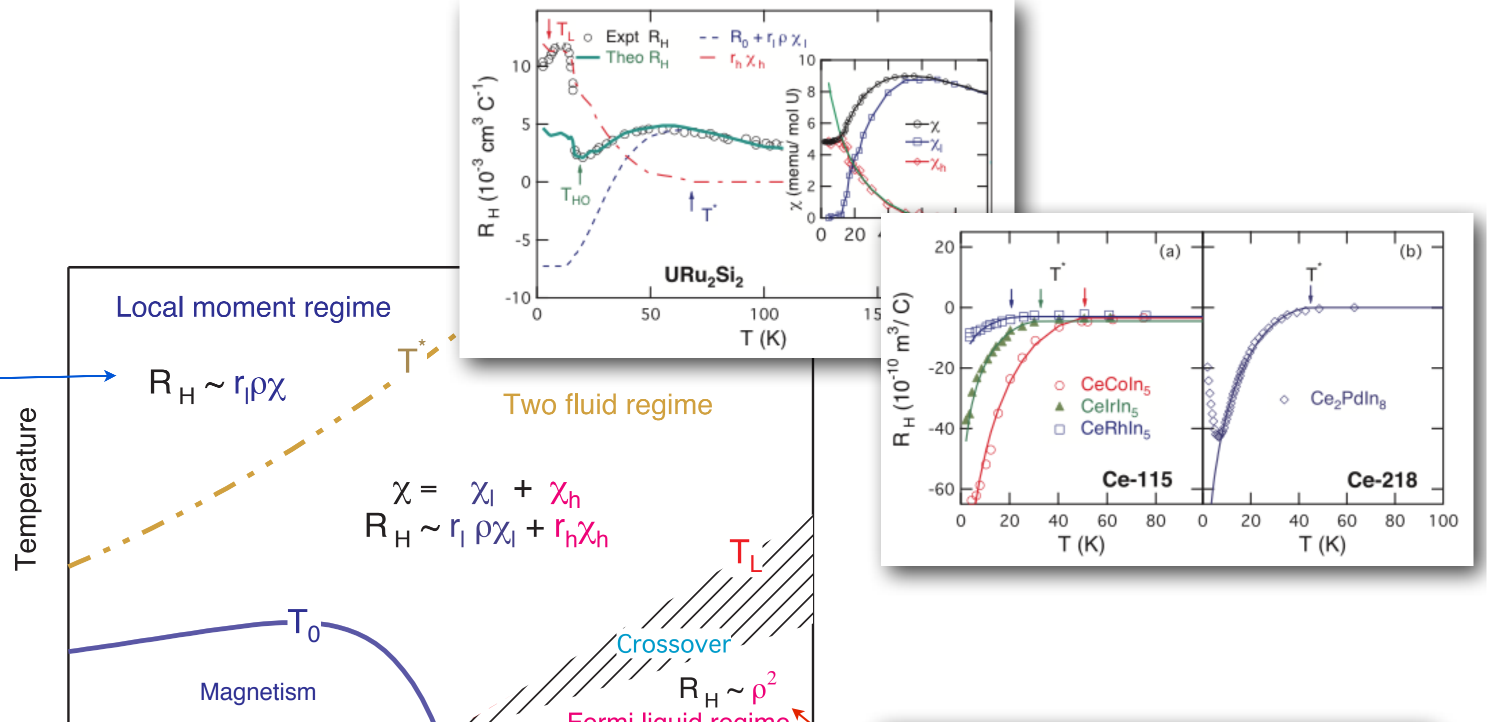
incoherent skew scattering from f-moments

coherent skew scattering from itinerant heavy f-electrons

Yang, arXiv:1207.0646 (2012).

Anomalous Hall Effect: A New Scenario




Local moment regime

$R_H \sim r_l \rho\chi$

T^*

Two fluid regime

$\chi = \chi_l + \chi_h$

$R_H \sim r_l \rho\chi_l + r_h\chi_h$

T_L

T_0

Magnetism

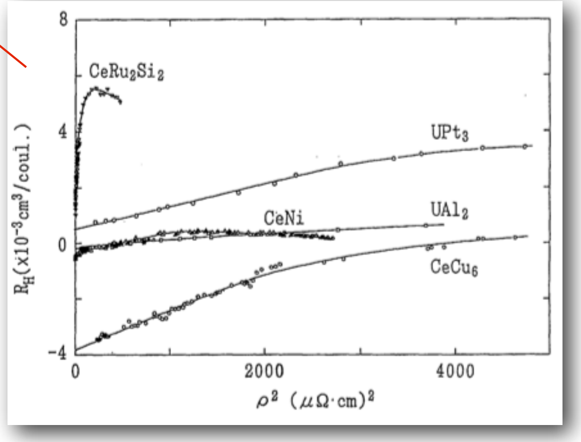
Crossover

$R_H \sim \rho^2$

Fermi liquid regime

Temperature

Pressure



$$R_H = R_0 + r_l \rho \chi_l + r_h \chi_h$$

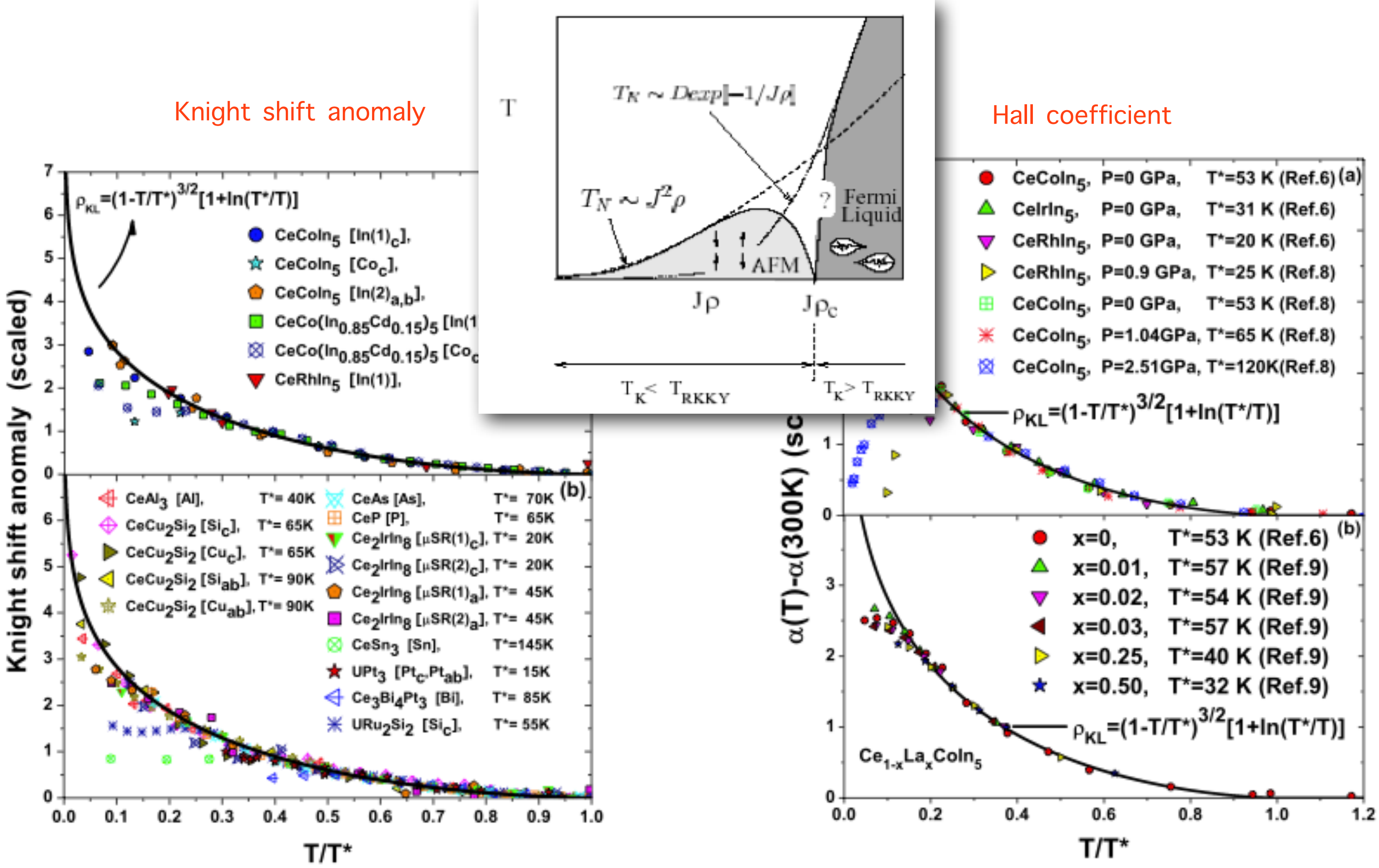
incoherent skew scattering from f-moments

coherent skew scattering from itinerant heavy f-electrons

Yang, arXiv:1207.0646 (2012).

The Hall effect is therefore another evidence for the emergent state.

Universal Scaling vs Competing Scales



Hundley et al, PRB 70, 035113 (2004)
Nakajima et al, JPSJ 76, 024703 (2007)

This universal scaling behavior seems to argue against the scenario based on competing scales. It could be that Kondo coupling shows up in a different way in lattice system.

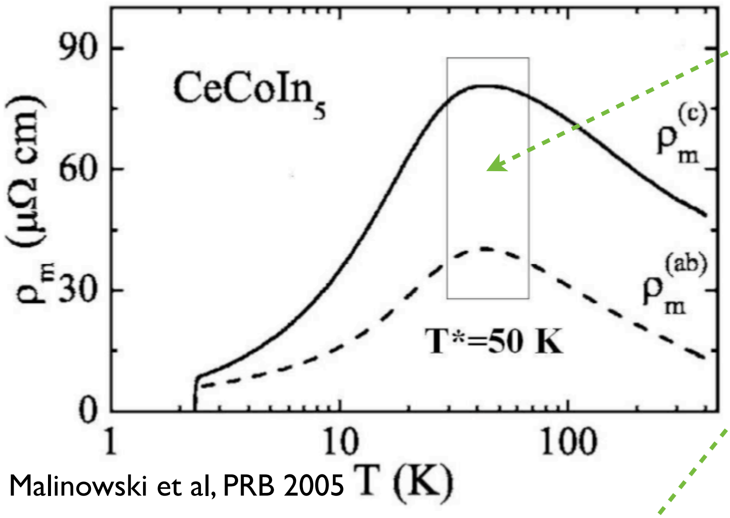
Yang & Pines, PRL 100, 096404 (2008)

Unification of Scales

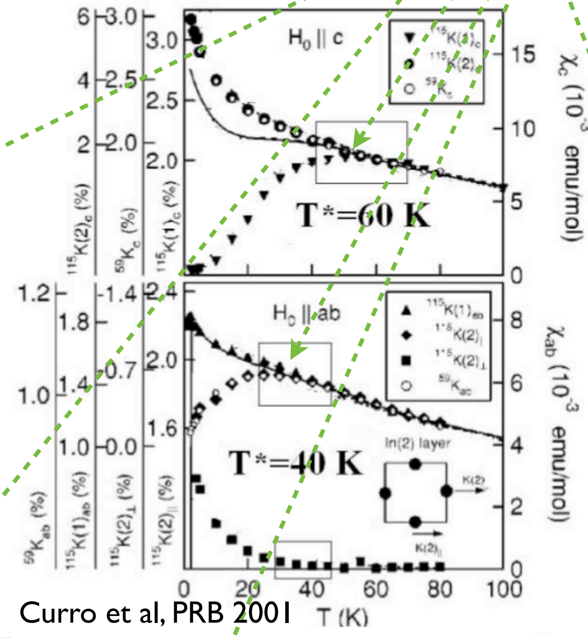
CeCoIn$_5$

A common T*~50K!

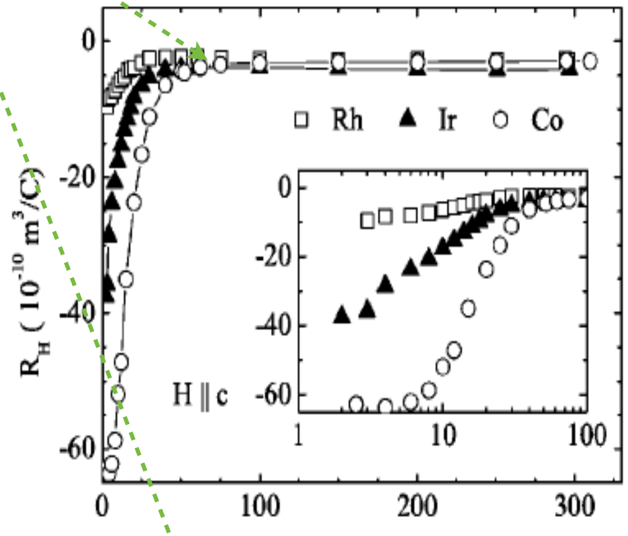
Yi-feng Yang et al, Nature 454, 611 (2008).



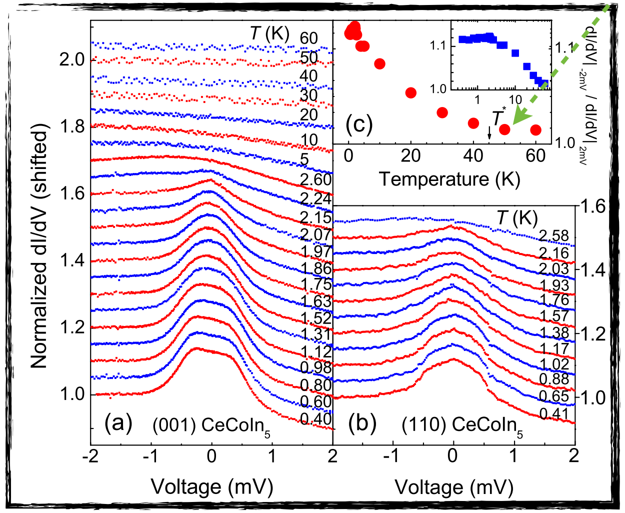
Malinowski et al, PRB 2005



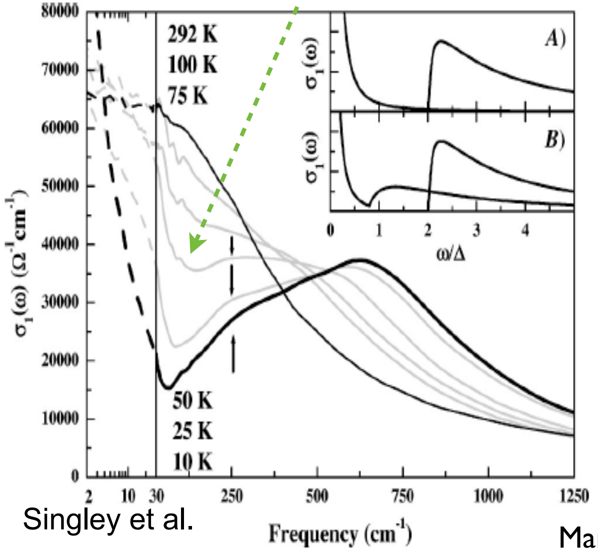
Curro et al, PRB 2001



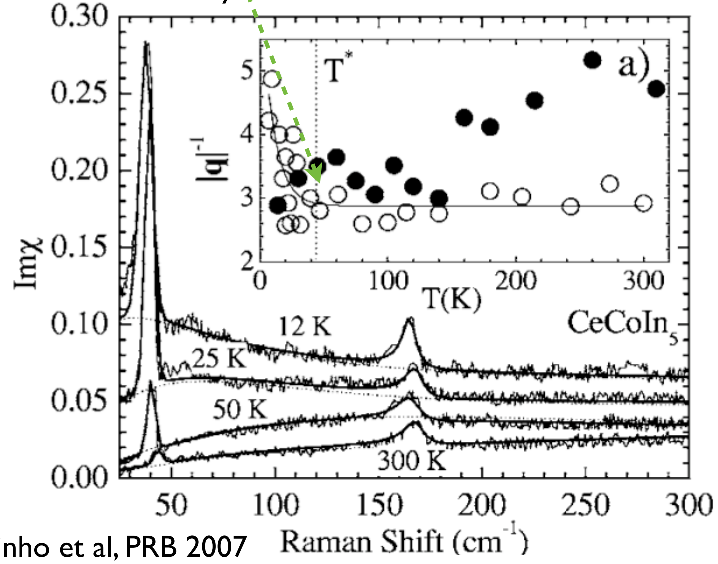
Hundley et al, PRB 2004



Park et al, PRL 2008



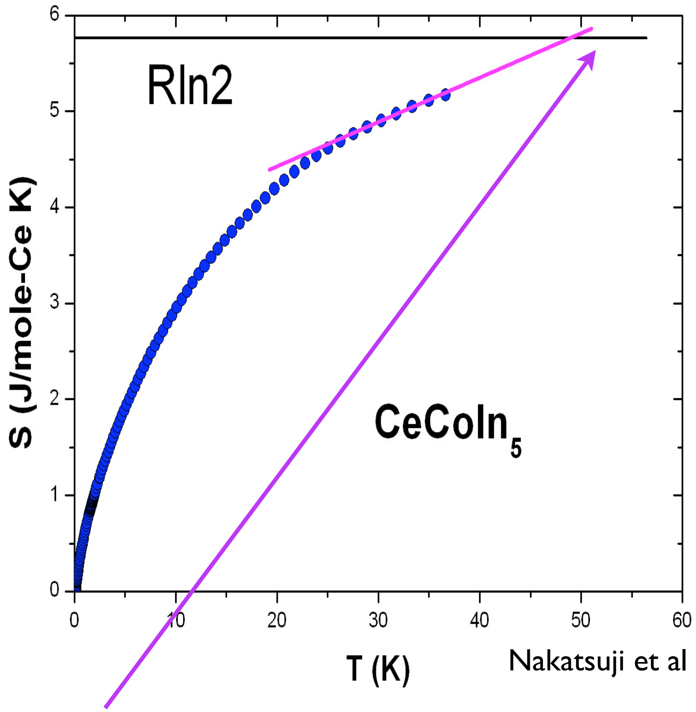
Singley et al.



Martinho et al, PRB 2007

Onset of magnetic correlation at T^*

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



Nakatsuji et al

- T^* cannot be ascribed to the crystal field effect.
- T^* cannot be the Kondo temperature since the entropy is Rln2/2 at T_K.
- At $T=T^*$, the magnetic entropy starts to be quenched. T^* marks the onset of magnetic correlation.
- Another possibility: T^* originates from the spin-correlation between f-ions

Yang et al, Nature 454, 611 (2008).

Inter-site coupling origin of T^*

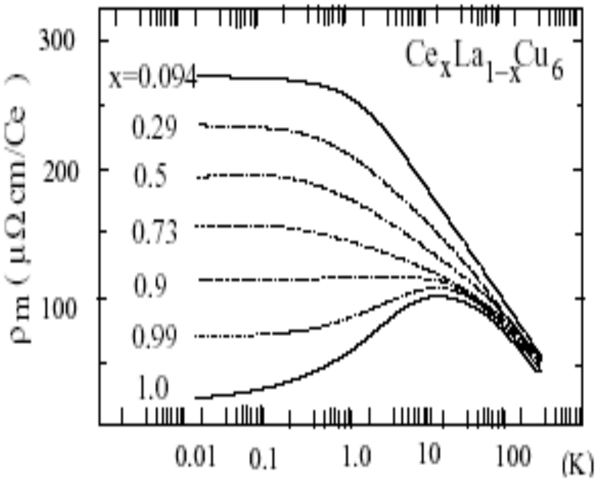
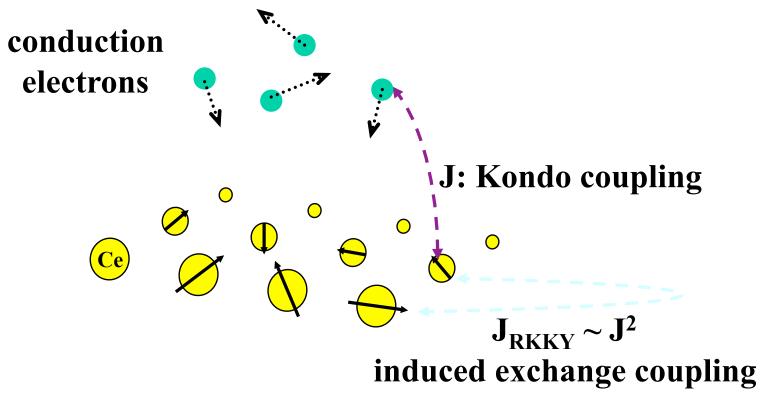


FIGURE 15. Development of coherence in heavy fermion systems. Resistance in $Ce_{1-x}La_xCu_6$ after Onuki and Komatsubara[35]



conduction electrons

J: Kondo coupling

$J_{RKKY} \sim J^2$
induced exchange coupling

Kondo lattice model

Yang et al, Nature 454, 611 (2008).

Inter-site coupling origin of T^*

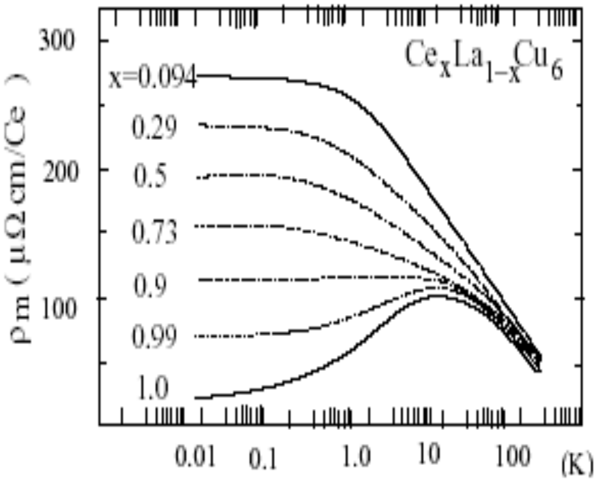
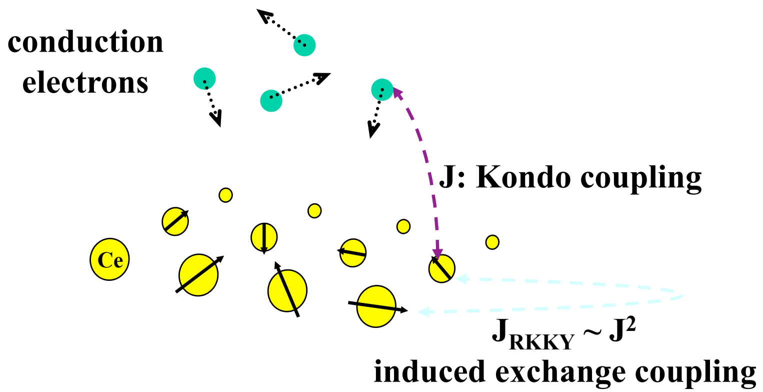


FIGURE 15. Development of coherence in heavy fermion systems. Resistance in $Ce_{1-x}La_xCu_6$ after Onuki and Komatsubara[35]



Kondo lattice model

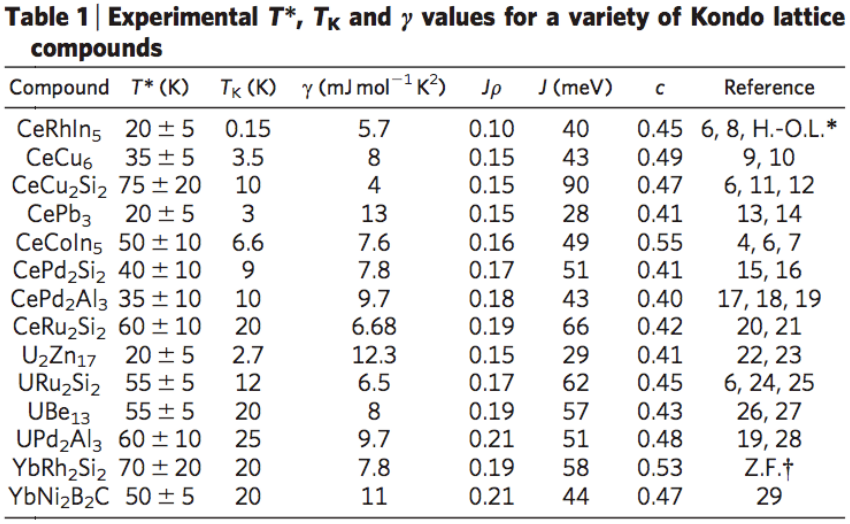


Table 1 | Experimental T^*, T_K and γ values for a variety of Kondo lattice compounds

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

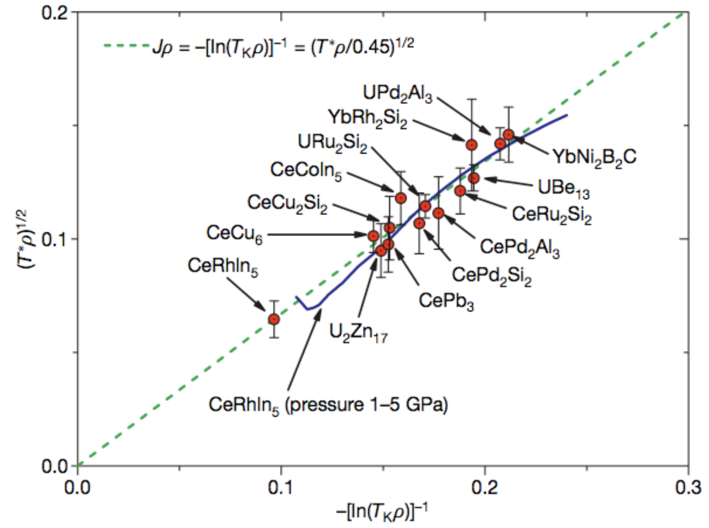
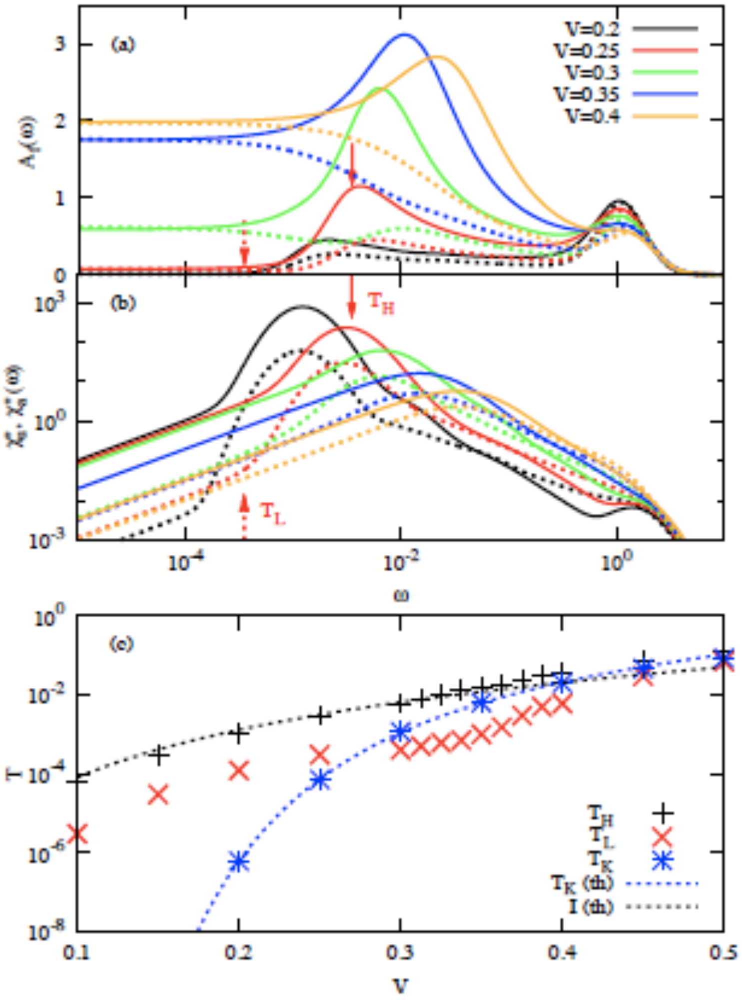


Figure 1 | Confirmation of T^* given by the intersite RKKY interaction for a variety of Kondo lattice materials. The solid line shows T^* (resistivity peak) of $CeRhIn_5$ under pressure from 1 GPa (lower left) to 5 GPa (upper right).

A systematic analysis suggests that T* originates from the inter-ion RKKY coupling instead of the Kondo temperature.

Yang et al, Nature 454, 611 (2008).

NRG calculation for two impurities



Zhu & Zhu, PRB 83, 195103 (2011)

A New Framework

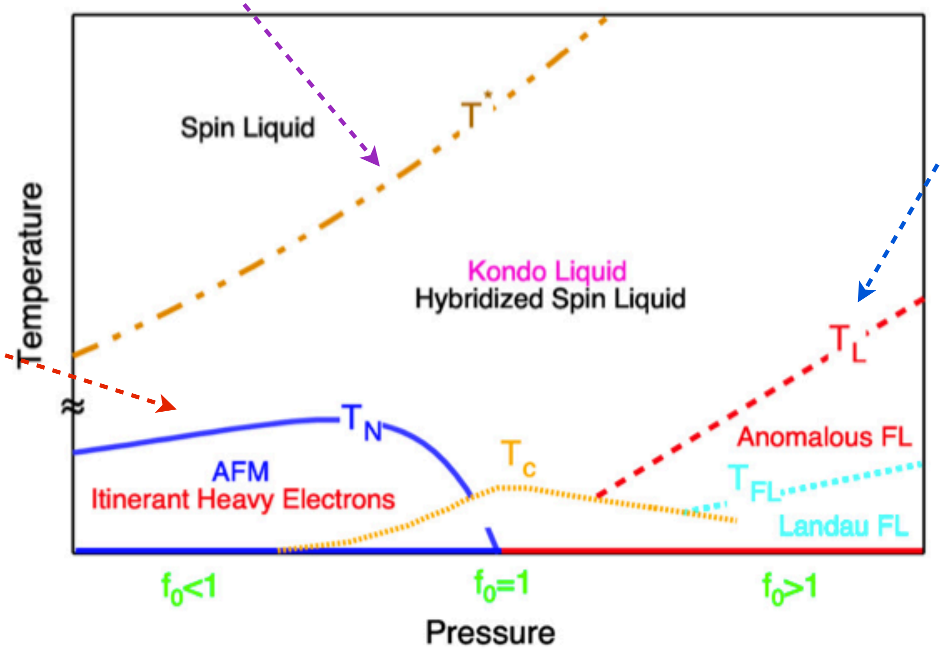
transfer of spectral weight from localized f-moments to itinerant f-electrons due to collective hybridization

$$\chi_l(\mathbf{q},\omega) = \frac{f_l \chi_l}{1 - J_{\mathbf{q}} f_l \chi_l - i\omega/\gamma_l}$$

$$\boxed{J_{\mathbf{Q}} f_l(T_N)\chi_l(T_N) = 1}$$

$$\boxed{1 - \frac{T_N}{\eta T^*} = f_0\left(1 - \frac{T_N}{T^*}\right)^{3/2}}$$

Coherence, magnetic correlations, anomalies



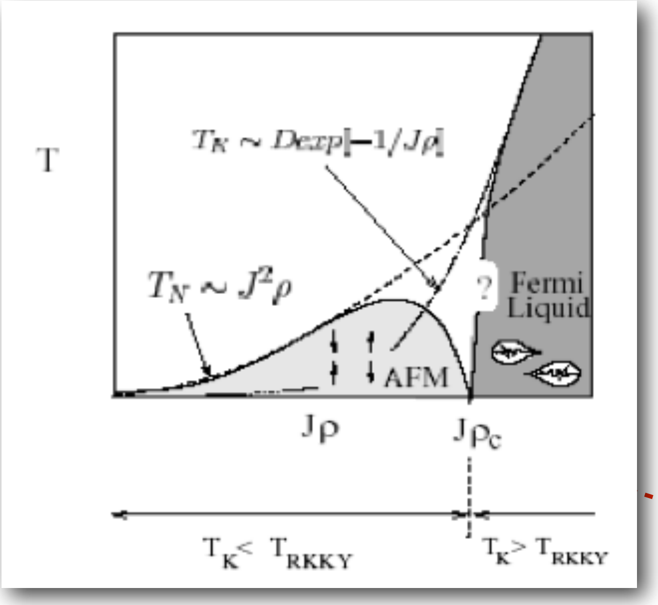
$$\boxed{f_0\left(1 - \frac{T_L}{T_*}\right)^{1.5} = 1}$$

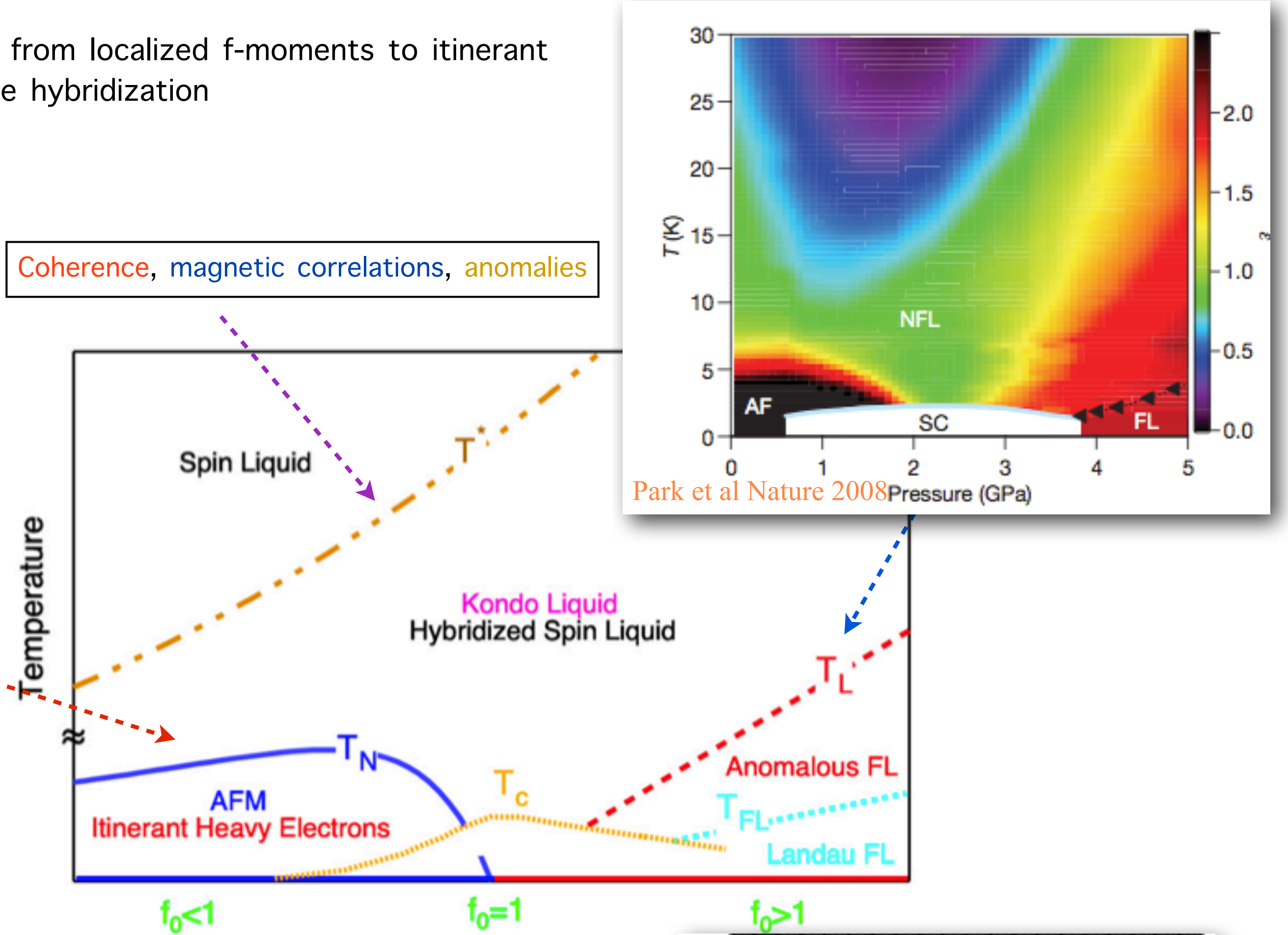
There may also exist AFM from the Kondo liquid (UNi$_2$Al$_3$ compared to UPd$_2$Al$_3$)

Yang and Pines, PNAS 109, 18241 (2012)

A New Framework

transfer of spectral weight from localized f-moments to itinerant f-electrons due to collective hybridization

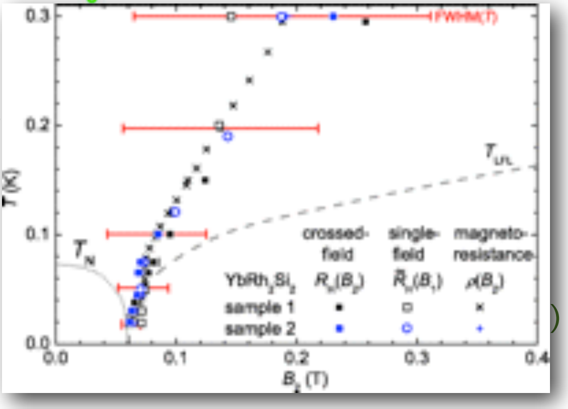




Park et al Nature 2008

Pressure

There may also exist AFM from the Kondo liquid (UNi2



Yang

More Experiments to be Done

- Further examination of the emergent state in NMR, Hall etc
- Comparing T^* and T_K with pressure experiment like in La-doped CeRhIn$_5$
- Detecting two coexisting fluids. How? (Neutron, ESR ...)
- Measurement of Fermi surface evolution at T_L
- Relation between Kondo liquid scaling and quantum critical scaling

References

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, arXiv:1207.0646 (2012)

Yi-feng Yang and David Pines, PNAS 109, E3060 (2012)
K. R. Shirer et al., PNAS 109, E3067 (2012)

Work supported by IOP, CAS, NSF-China!

More Experiments to be Done

- Further examination of the emergent state in NMR, Hall etc
- Comparing T^* and T_K with pressure experiment like in La-doped $CeRhIn_5$
- Detecting two coexisting fluids. How? (Neutron, ESR ...)
- Measurement of Fermi surface evolution at T_L
- Relation between Kondo liquid scaling and quantum critical scaling

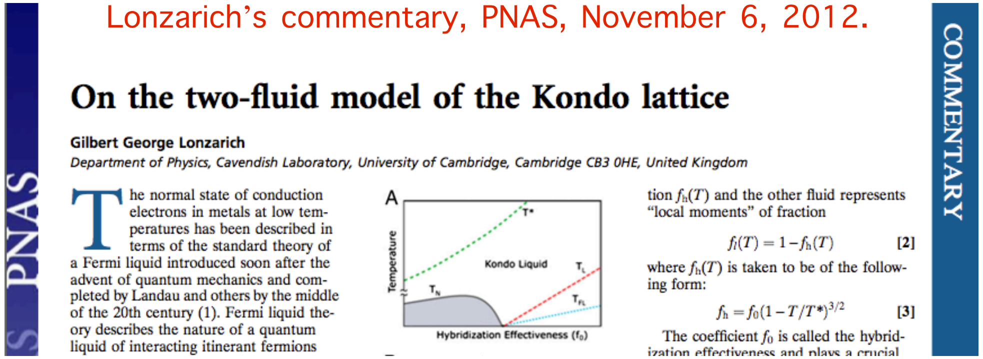
References

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, arXiv:1207.0646 (2012)

Yi-feng Yang and David Pines, PNAS 109, E3060 (2012)
K. R. Shirer et al., PNAS 109, E3067 (2012)

Strongly recommended!

Lonzarich's commentary, PNAS, November 6, 2012.



On the two-fluid model of the Kondo lattice

Gilbert George Lonzarich
Department of Physics, Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, United Kingdom

The normal state of conduction electrons in metals at low temperatures has been described in terms of the standard theory of a Fermi liquid introduced soon after the advent of quantum mechanics and completed by Landau and others by the middle of the 20th century (1). Fermi liquid theory describes the nature of a quantum liquid of interacting itinerant fermions

tion $f_h(T)$ and the other fluid represents "local moments" of fraction

$$f_l(T) = 1 - f_h(T) \quad [2]$$

where $f_h(T)$ is taken to be of the following form:

$$f_h = f_0(1 - T/T^*)^{3/2} \quad [3]$$

The coefficient f_0 is called the hybridization effectiveness and plays a crucial

Work supported by IOP, CAS, NSF-China!