Heavy fermions: Interplay between Kondo entanglement, quantum criticality and unconventional superconductivity

F. Steglich

MPI for Chemical Physics of Solids, 01187 Dresden, Germany

Collaboration

J. Arndt, O. Stockert, S. Wirth (MPI CPS)
G. M. Pang, M. Smidman, H. Q. Yuan (CCM, ZJU)
E. Schuberth, M. Tippmann, L. Steinke (WMI)
E. M. Nica, R. Yu, Q. Si (RCQM, Rice U.)

Outline

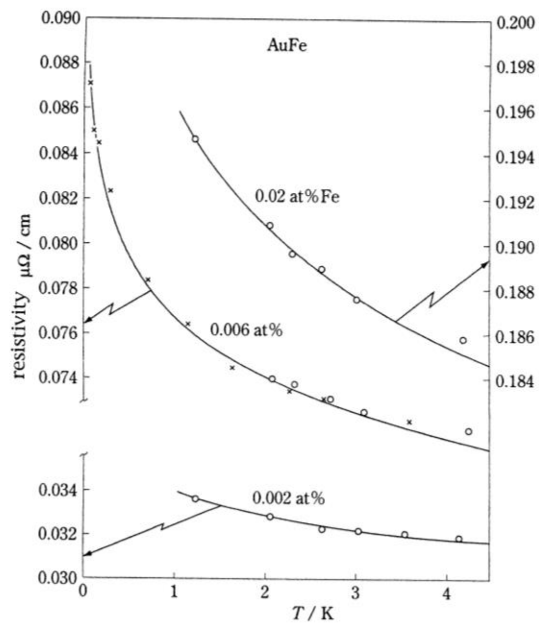
Kondo effect
Heavy-fermion (HF) superconductivity (SC)
Quantum critical point (QCP) in HF metals
SC near an itinerant AF (SDW) QCP in $CeCu_2Si_2$
SC due to nuclear AF order in $YbRh_2Si_2$


SPEED
カラオケ

~ 1930: $\rho(T)$ anomaly in pure Cu [Meissner & Voigt (1930),
van den Berg et al. (1934)]

~ 1950: $\rho(T)$ anomaly due to transition-metal impurities

AuFe



Mac Donald et al. (1962)

J. Kondo (1964)

K. Wilson (1975)

$H_{int} = 2\, J_K\, \boldsymbol{S}\, \boldsymbol{s}$

$J_K > 0$

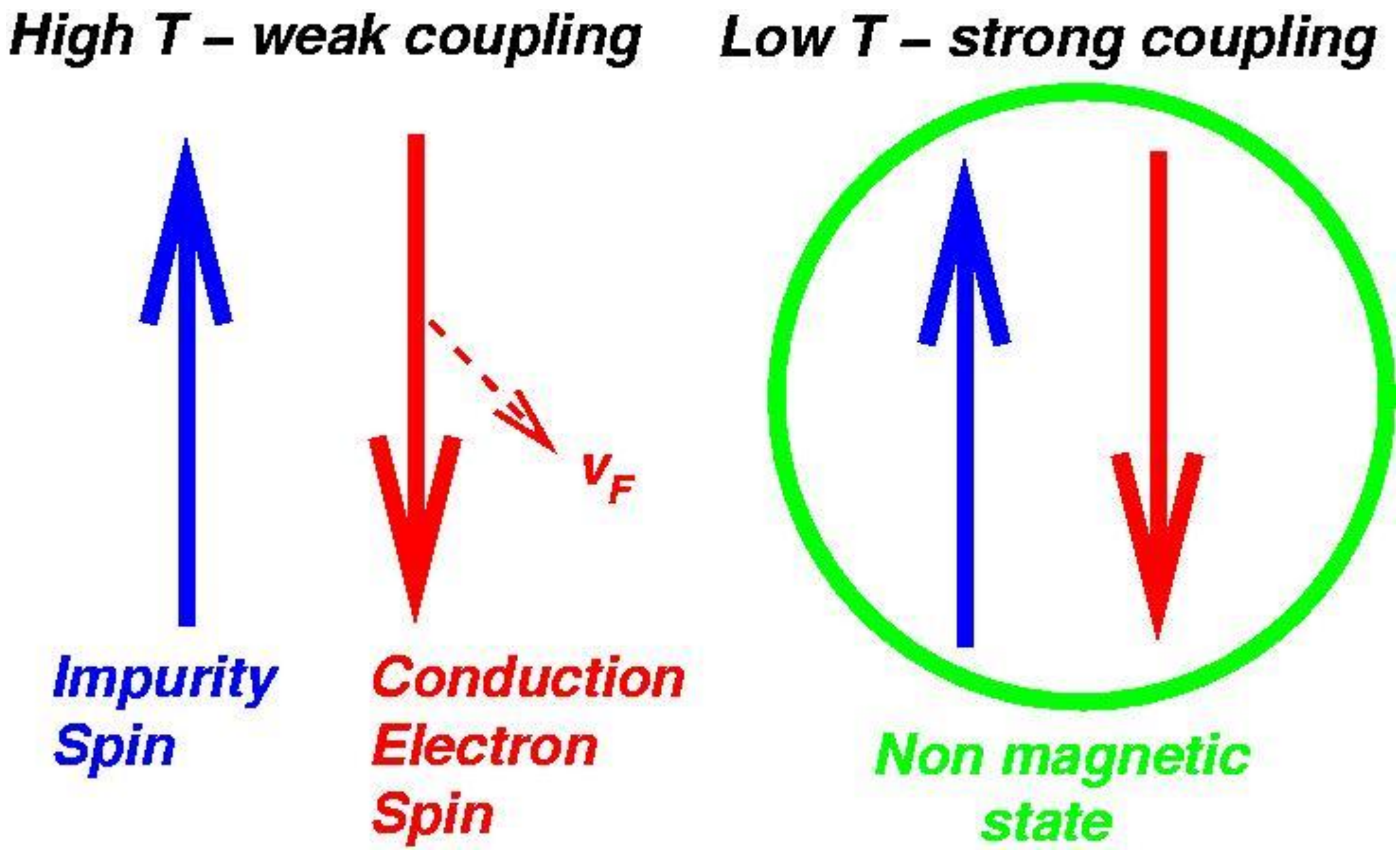
$T_K \sim T_F \exp(-1/N_F J_K)$

$-\,dJ_K/dl = \beta(J_K) = J_K^2$

$\rho(T)$ minimum

asymptotic freedom

Kondo effect



magnetic susceptibility

Curie Weiss law: $\chi \sim (T+\theta)^{-1}$, $\theta = \mathrm{f}(T_K) > 0$

effective moment $\mu_{eff}(T)$: $= \chi \cdot T \rightarrow 0 \ (T \rightarrow 0)$

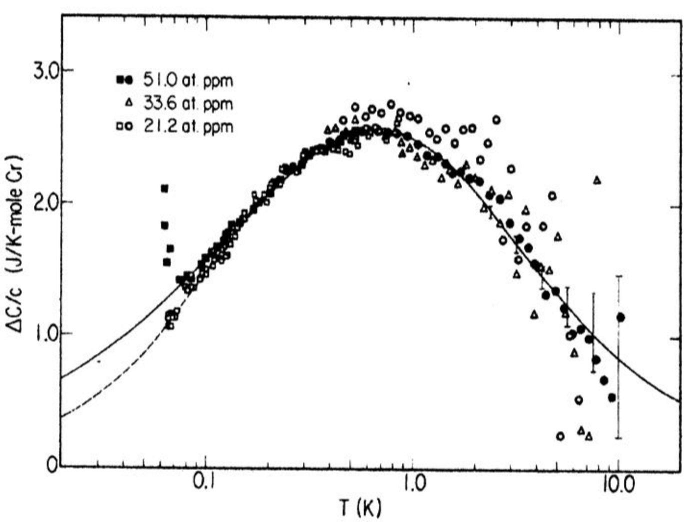
specific heat

Triplett & Philipps (1971): $Cu_{1-x}M_x$ (M: Cr, Fe)

incremental specific heat: $\Delta C = C - C_{Cu}$

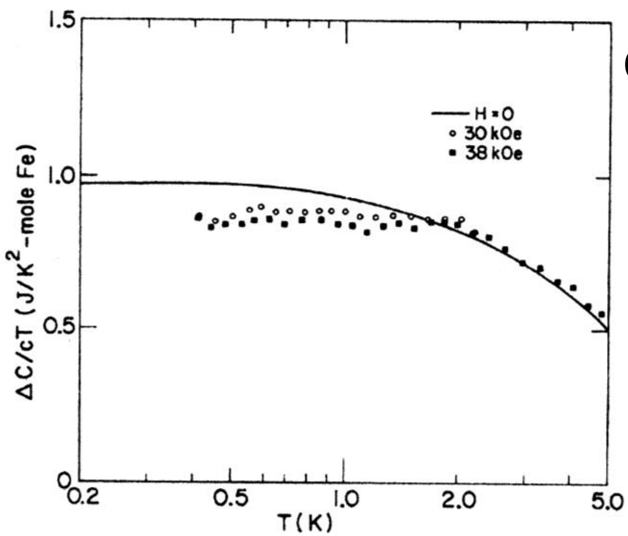
per mole *M*: $\Delta C/x = \gamma T$ ($T \ll T_K$): „Kondo resonance“

CuCr



γ $(J/K^2\text{-mole}^{Cr}_{Fe})$

16 1.0



CuFe

P. Nozières (1974) $T \ll T_K$: local Fermi liquid

outline

Kondo effect

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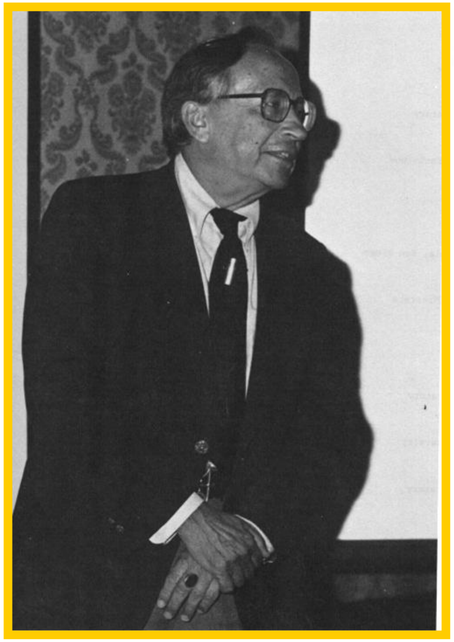
SC due to nuclear AF order in $YbRh_2Si_2$

T_c of $La_{0.99}RE_{0.01}$



VOLUME 1, NUMBER 3 PHYSICAL REVIEW LETTERS AUGUST 1, 1958

SPIN EXCHANGE IN SUPERCONDUCTORS

B. T. Matthias, H. Suhl, and E. Corenzwit
Bell Telephone Laboratories,
Murray Hill, New Jersey
(Received July 15, 1958)

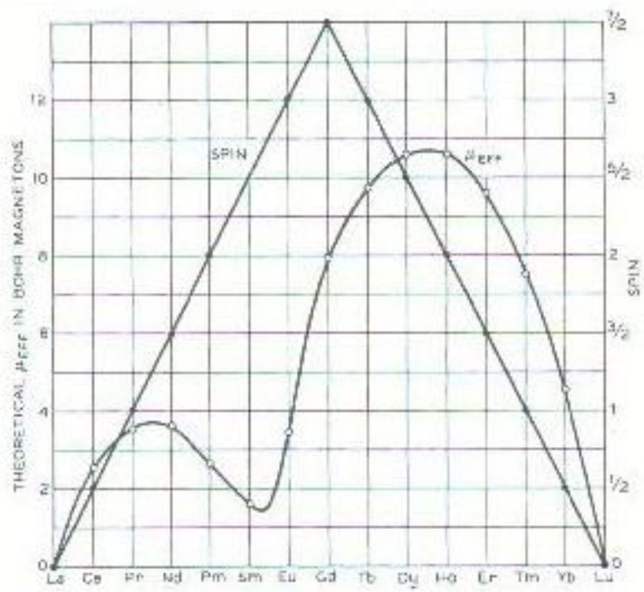


FIG. 1. Effective magnetic moments and spins of the rare earth elements (see reference 2).

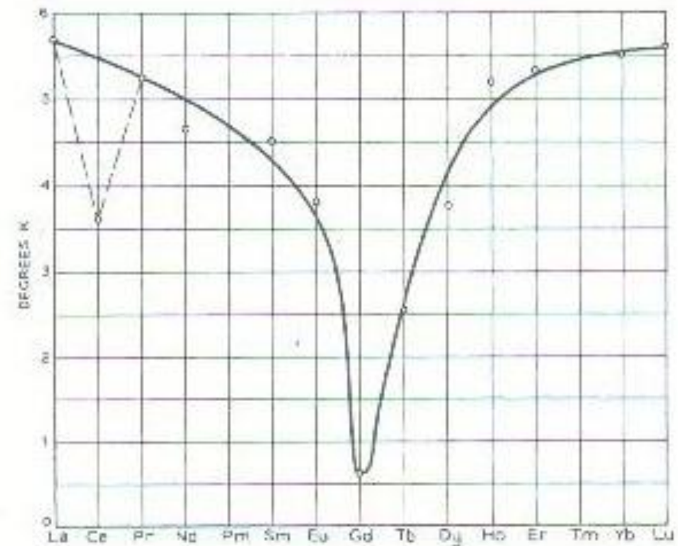


FIG. 2. Superconducting transition temperatures of 1 at % rare earth solid solutions in lanthanum.

4f-Virtual-Bound-State Formation in $CeAl_3$ at Low Temperatures

K. Andres and J. E. Graebner
Bell Laboratories, Murray Hill, New Jersey 07974

and

H. R. Ott
Laboratorium für Festkörperphysik, Eidgenössische Technische Hochschule, Hönggerberg, Zürich, Switzerland

(Received 25 August 1975)

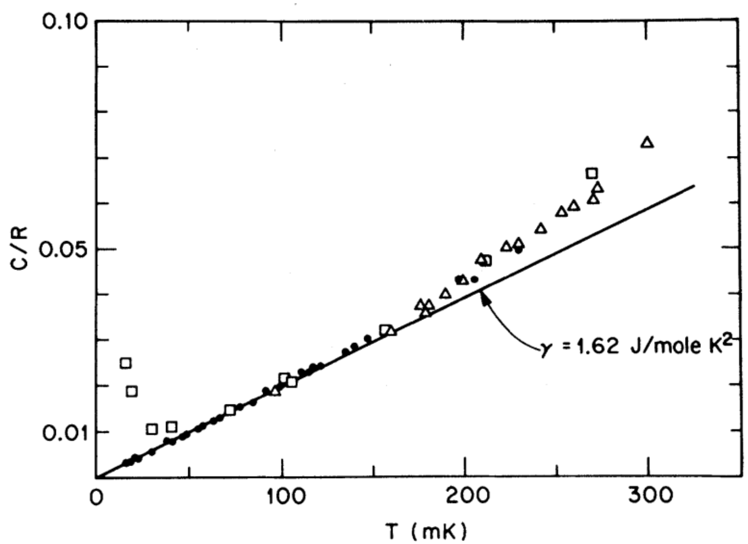


FIG. 1. Specific heat of $CeAl_3$ at very low temperatures in zero field (●, △) and in 10 kOe (□).

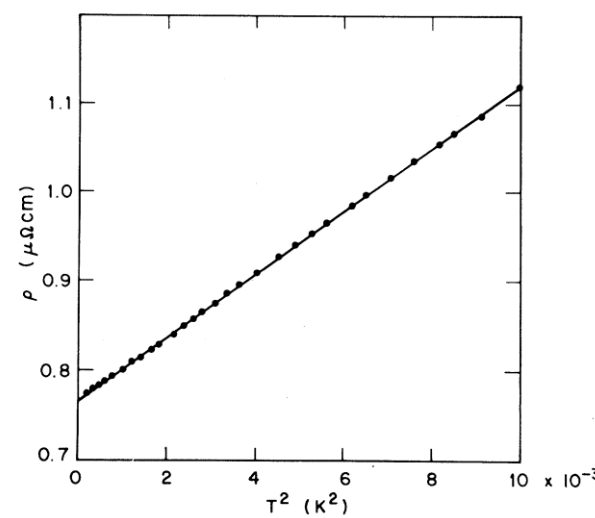


FIG. 3. Electrical resistivity of $CeAl_3$ below 100 mK, plotted against T^2.

$\gamma = 1.62$ J/K^{2}mole

$A = 35$ μΩcm/K^2

Superconductivity in $CeCu_2Si_2$

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

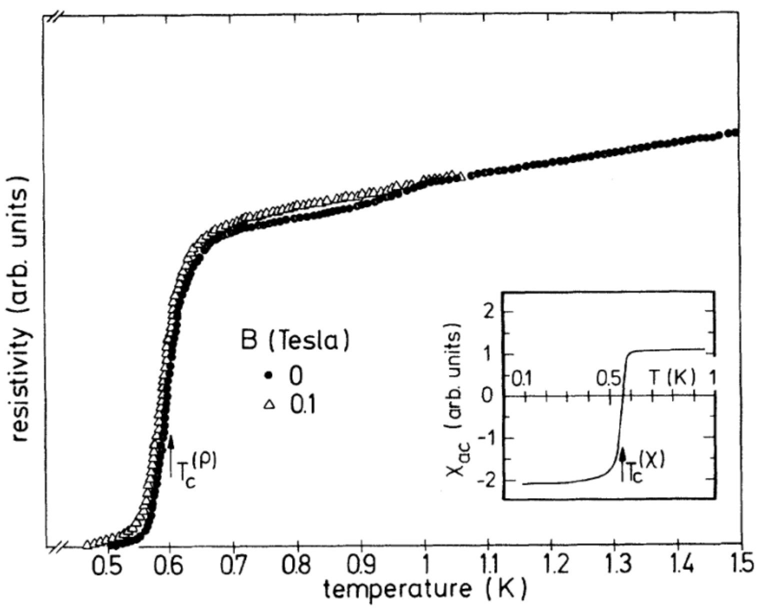
and

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

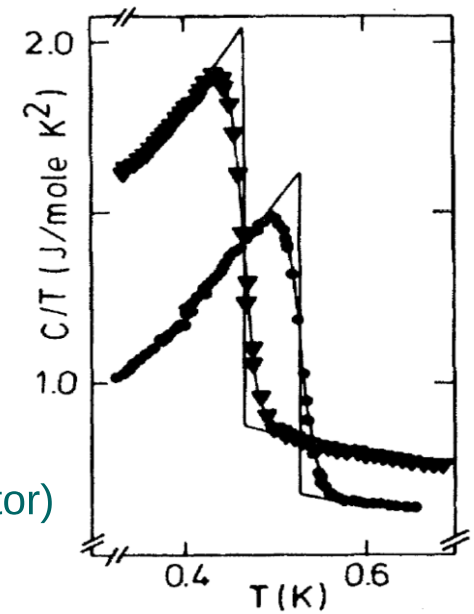
H. Schäfer
Eduard-Zintl-Institut, Technische Hochschule Darmstadt, D-6100 Darmstadt, West Germany

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



100 at% Ce^{3+} ions **necessary** for superconductivity

($LaCu_2Si_2$ is not a superconductor)



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… Since the Debye temperature Θ is of order of 200 K, we find $T_c < T_F^* < \Theta$ with $T_c/T_F^* \approx T_F^*/\Theta \approx 0.05$. This suggests that $CeCu_2Si_2$

(i) behaves as a „high – T_c superconductor“ and

(ii) cannot be described by conventional theory of superconductivity which assumes a typical phonon frequency $k_B\Theta/h \ll k_B T_F^*/h$, the characteristic frequency of the fermions.

Heavy-fermion superconductivity in $CeCu_2Si_2$

VOLUME 52, NUMBER 6 PHYSICAL REVIEW LETTERS 6 FEBRUARY 1984

Superconductivity in $CeCu_2Si_2$ Single Crystals

W. Assmus and M. Herrmann
Physikalisches Institut, Universität Frankfurt, D-6000 Frankfurt am Main, West Germany

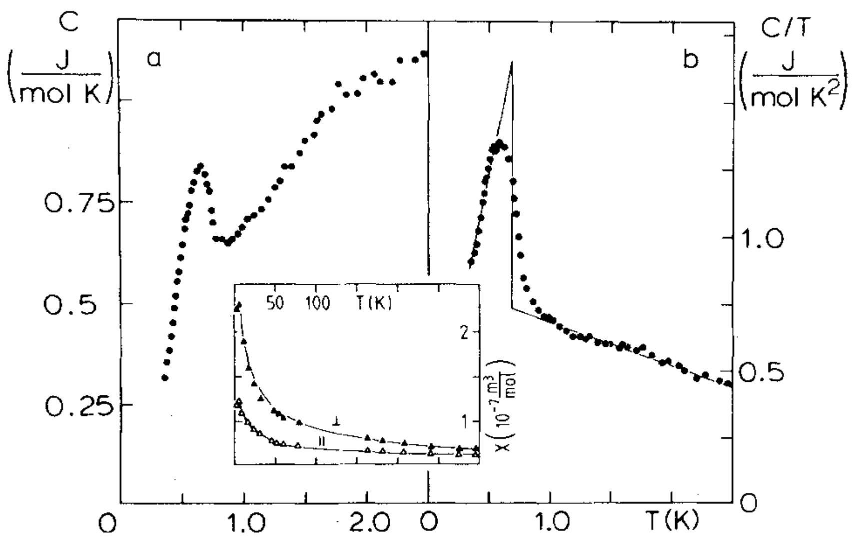
and

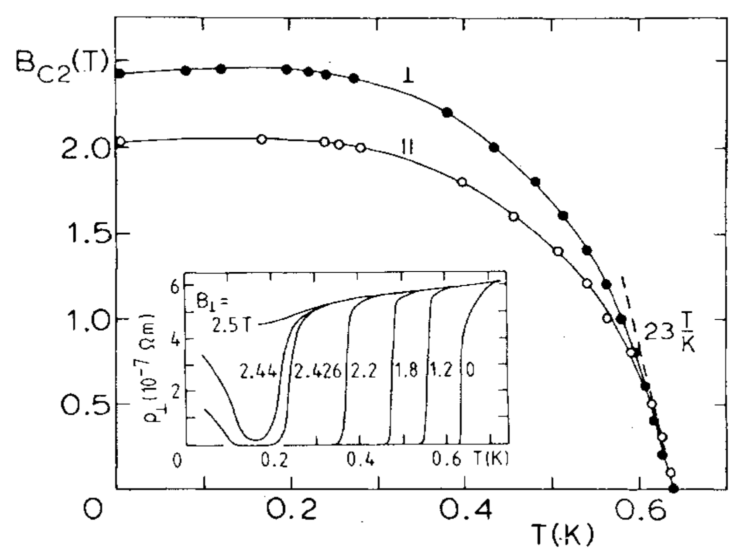
U. Rauchschwalbe, S. Riegel, W. Lieke, H. Spille, S. Horn, G. Weber, and F. Steglich
Institut für Festkörperphysik, Technische Hochschule Darmstadt, D-6100 Darmstadt, West Germany

and

G. Cordier
E. Zintl Institut, Technische Hochschule Darmstadt, D-6100 Darmstadt, West Germany

(Received 19 August 1983)





Heavy-fermion superconductivity in UBe_{13}

VOLUME 50, NUMBER 20 PHYSICAL REVIEW LETTERS 16 MAY 1983

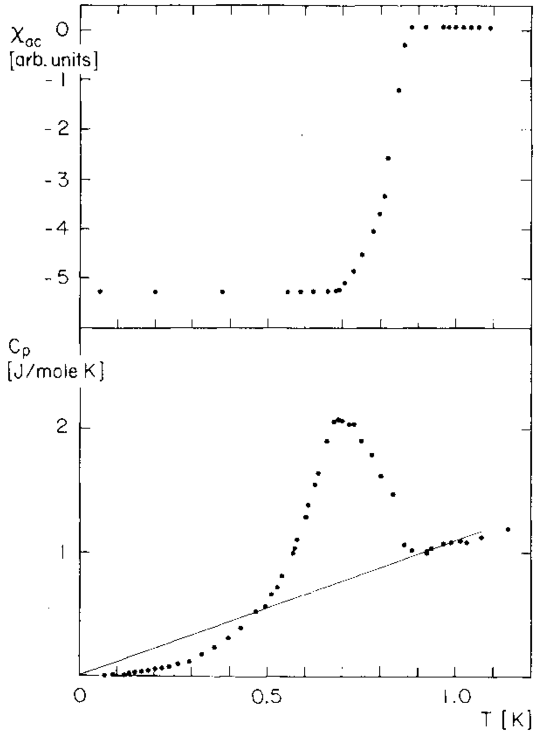
UBe_{13}: An Unconventional Actinide Superconductor

H. R. Ott and H. Rudigier
Laboratorium für Festkörperphysik, Eidgenössische Technische Hochschule–Hönggerberg, CH-8093 Zürich, Switzerland

and

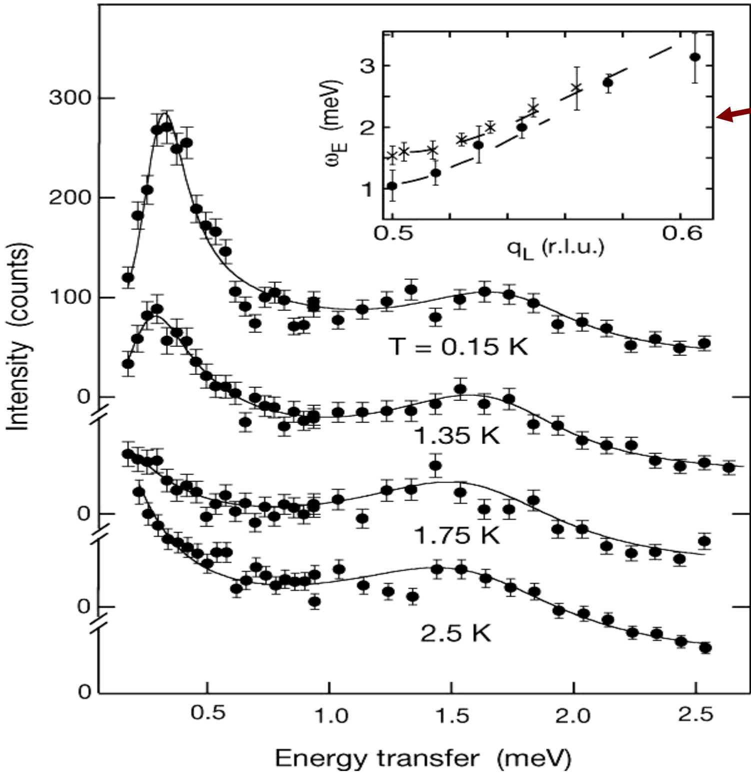
Z. Fisk and J. L. Smith
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

(Received 14 March 1983)



UPd_2Al_3: Inelastic neutron scattering

[N. K. Sato et al., Nature **410**, 340 (2001)]



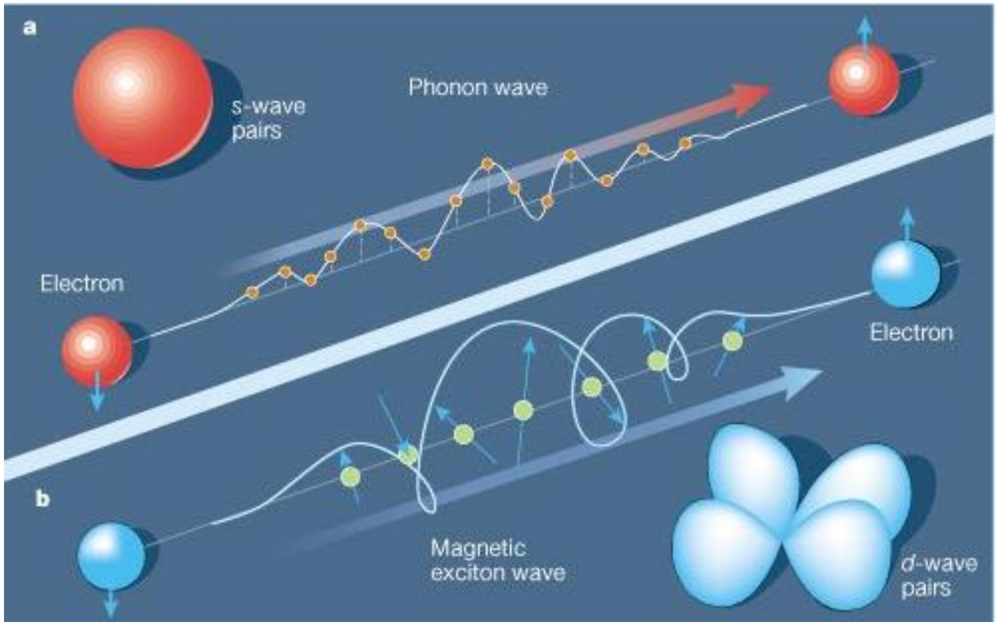
acoustic magnon ("magnetic exciton")

cf. M. Jourdan et al. '99: anomaly in d*I*/d*V* vs *V* at $V \approx 1$ mV ($T \ll T_c$)

$\boldsymbol{Q} = \boldsymbol{Q}_{AF} = (0, 0, 1/2)$

$T_c = 1.8$ K

Magnetically driven SC



Cooper pairs formed by heavy electrons ("itinerant" 5*f* electrons)

superconducting glue provided by magnetic excitons in the system of "localized" 5*f* electrons

Heavy-Fermion Superconductors

		T_c(K)	
$CeCu_2Si_2$		0.6	('79 K)
[*p* = 2.9 GPa:		2.3	('84 GE/GR)]
$CeNi_2Ge_2$		0.2	('97 DA, '98 CA/GR)
$CeIrIn_5$		0.4	('01 LANL)
$CeCoIn_5$		2.3	('01 LANL)
Ce_2CoIn_8		0.4	('02 NA)
Ce_2PdIn_8		0.7	('09 WR)
$CePt_3Si$		0.7	('04 VI)
$CeCu_2Ge_2$	***p* > 0**	0.6	('92 GE)
$CePd_2Si_2$	"	0.4	('98 CA)
$CeRh_2Si_2$	"	0.35	('96 LANL)
$CeCu_2$	"	0.15	('97 GE)
$CeIn_3$	"	0.2	('98 CA)
$CeRhIn_5$	"	2.1	('00 LANL)
Ce_2RhIn_8	"	2.0	('03 LANL)
$CeRhSi_3$	"	1.0	('05 SE)
$CeIrSi_3$	"	1.6	('06 OS)
$CeCoGe_3$	"	0.7	('07 OS)
$Ce_2Ni_3Ge_5$	"	0.26	('06 OS)
$CeNiGe_3$	"	0.4	('06 OS)
$CePd_5Al_2$	"	0.57	('08 OS)
$CeRhGe_2$	"	0.45	('09 OS)
$CePt_2In_7$	"	2.1	('10 LANL)
$CeIrGe_3$	"	1.5	('10 OS)
$CeAu_2Si_2$	"	2.5	('14 GE)

		T_c(K)	
Ce_3PdIn_{11}		0.42	(`15 PR)
Ce_3PtIn_{11}		0.32	(`15 PR)
$PrOs_4Sb_{12}$		1.85	('01 UCSD)
$PrIr_2Zn_{20}$		0.05	('10 HI)
$PrTi_2Al_{20}$		0.2	('12 TO)
β-$YbAlB_4$		0.08	('08 TO/IR)
$YbRh_2Si_2$		0.002	('16 M/DD)
Eu metal	***p* > 0**	1.8-2.8	('09 SL/OS)
UBe_{13}		0.9	('83 Z/LANL)
UPt_3		0.5	('84 LANL)
URu_2Si_2		1.5	('84 K/DA)
U_2PtC_2		1.5	('84 LANL)
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)
UGe_2	***p* > 0**	0.7	('00 CA/GR)
UIr	"	0.14	('04 OS)
$NpPd_5Al_2$		5.0	('07 OS)
$PuCoGa_5$		18.5	('02 LANL)
$PuRhGa_5$		8.7	('03 KA)
$PuCoIn_5$		2.5	('12 LANL)
$PuRhIn_5$		1.7	('12 LANL)
Am metal	***p* > 0**	2.4;1.7	('05 KA)
YFe_2Ge_2		1.8	(`14 CA)
CrAs	***p* > 0**	1.7	(`14 BEI/TO)

outline

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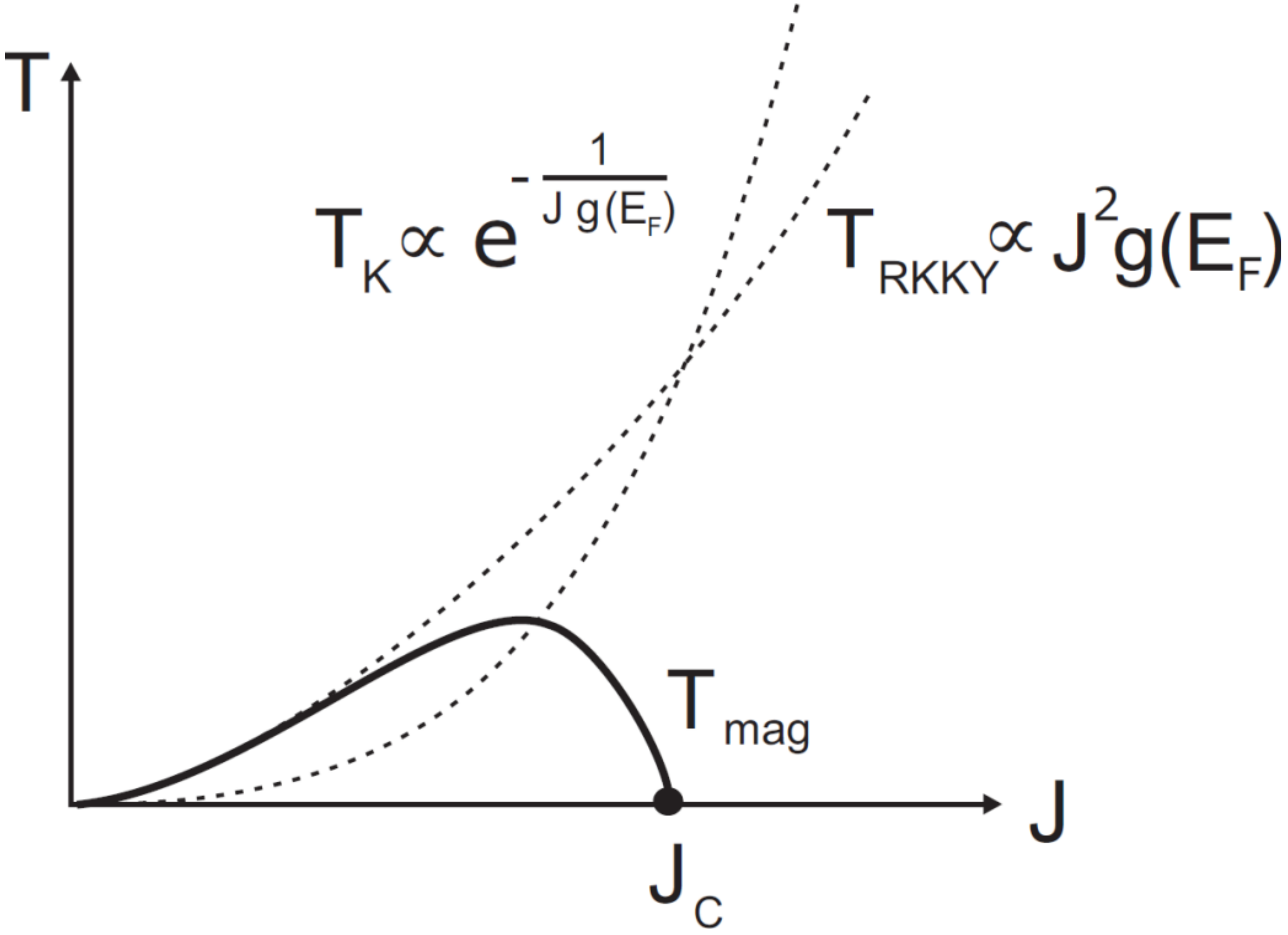
SC near an itinerant AF (SDW) QCP in $CeCu_2Si_2$

SC due to nuclear AF order in $YbRh_2Si_2$

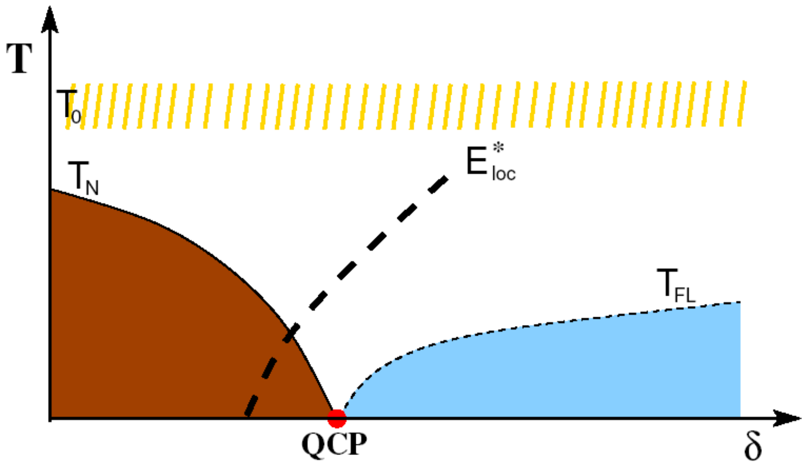
Doniach phase diagram

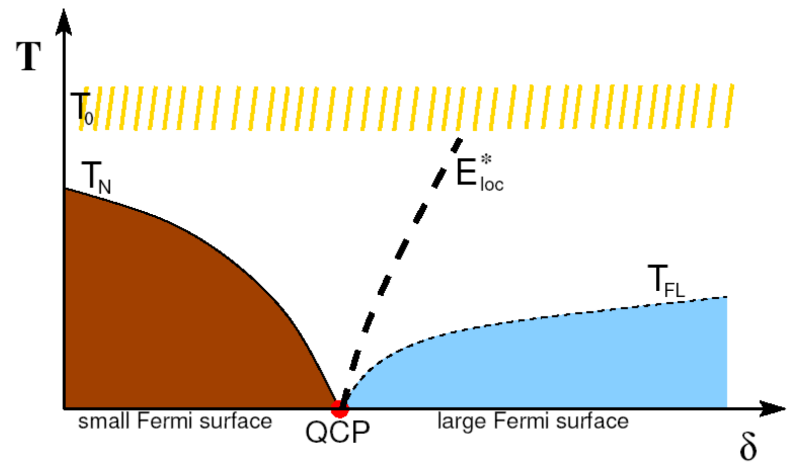
[S. Doniach, Physica B+C **91**, 231 (1977)]



Two types of QCPs

[P. Gegenwart, Q. Si & F.S., Nature Phys. **4**, 186 (2008)]



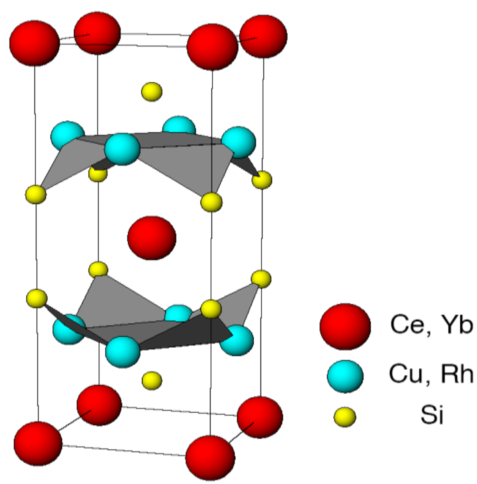


- SDW QCP
  (Hertz, Moriya, Millis…)
  HFs intact
  FS large

exemplary material:

$CeCu_2Si_2$

$T_K \approx 15$ K



- Kondo breakdown QCP
  (Si et al., Coleman et al., 2001)
  HFs disintegrate
  abrupt FS reconstruction

$YbRh_2Si_2$

$T_K \approx 30$ K

Quantum critical paradigm: AF QCP in pure HF metal ↷ unconventional SC!

BCS – type SC?

No SC? $T_c < 10$ mK

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$\mathrm{CeCu_2Si_2}$

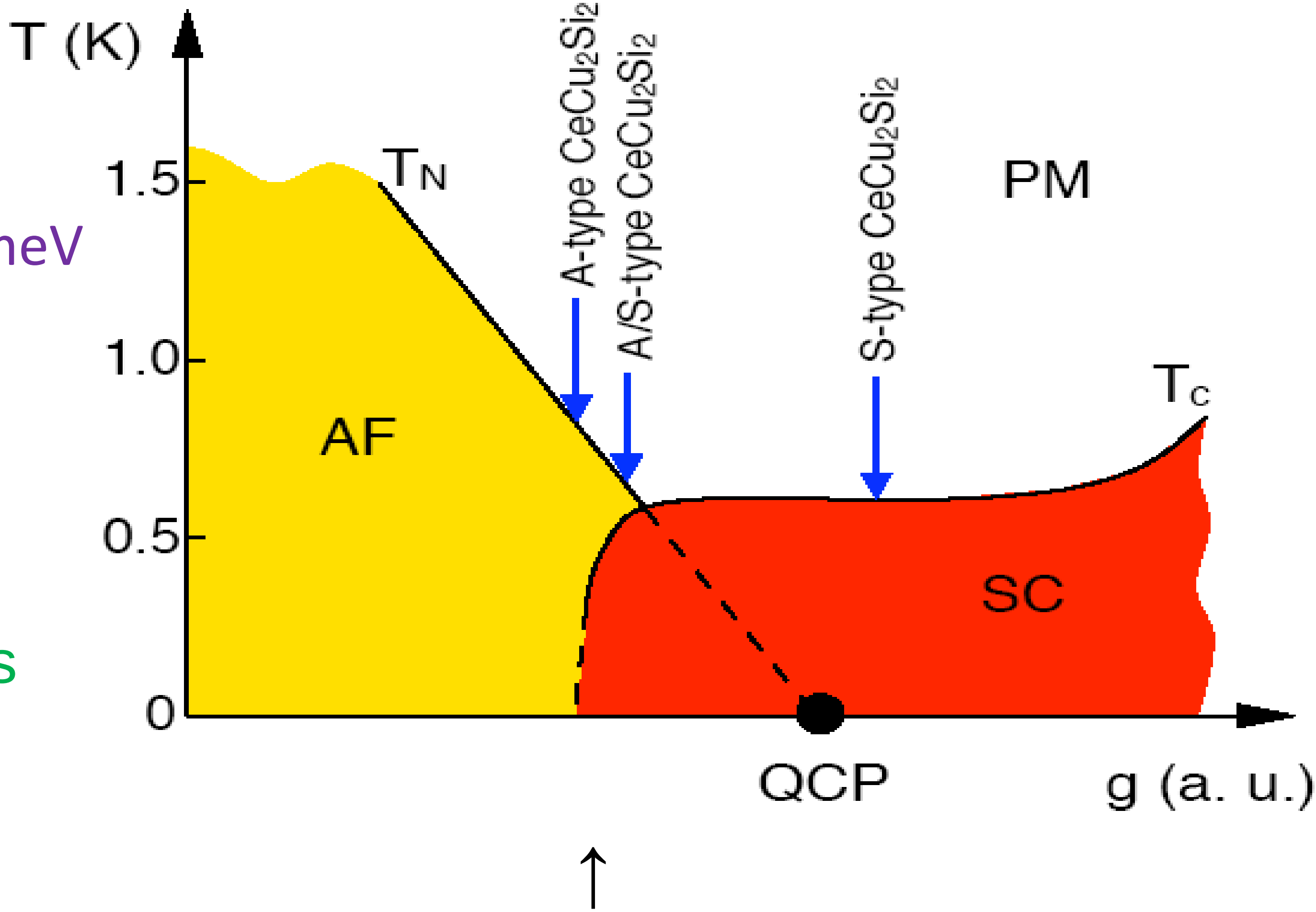
Homogeneity range: ~ 1% Cu/Si site exchange

$\Delta_{CF} \gg k_B T_K \backsim J_K \simeq 2$ meV

$S_{eff} = 1/2$

Pairing interactions

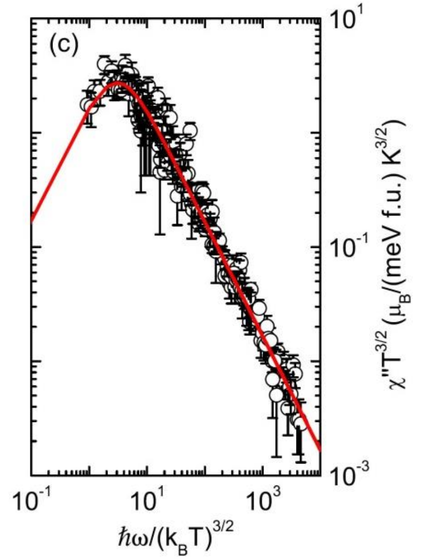
$\leq I_{RKKY} \simeq J_K$



← Cu deficit true stoichiometry Cu excess →

Quantum criticality in $CeCu_2Si_2$

$\Delta\rho \sim T^{3/2}$, $\gamma = \gamma_0 - bT^{1/2}$ P. Gegenwart et al. , Phys. Rev. Lett. **81**, 1501 (‘98)



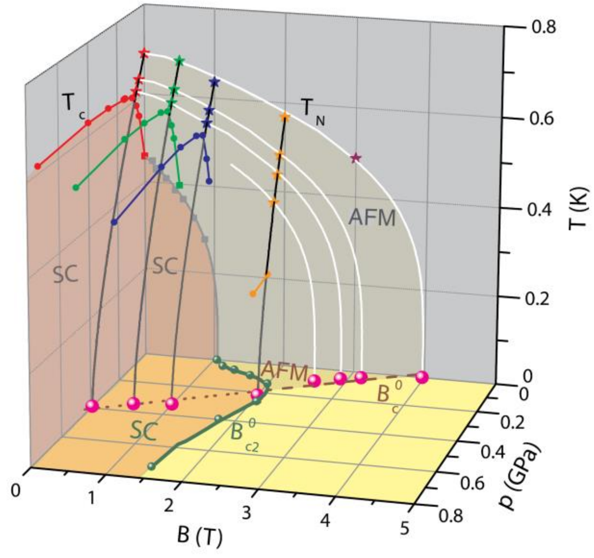
3D-SDW QCP

$\chi'' T^{3/2} = f(\hbar\omega/(k_B T)^{3/2})$

J. Arndt et al., Phys. Rev. Lett. **106**, 246401 (’11)

***B* - *p* phase diagram**

E. Lengyel et al.,
Phys. Rev. Lett. **107**, 057001 (‘11)



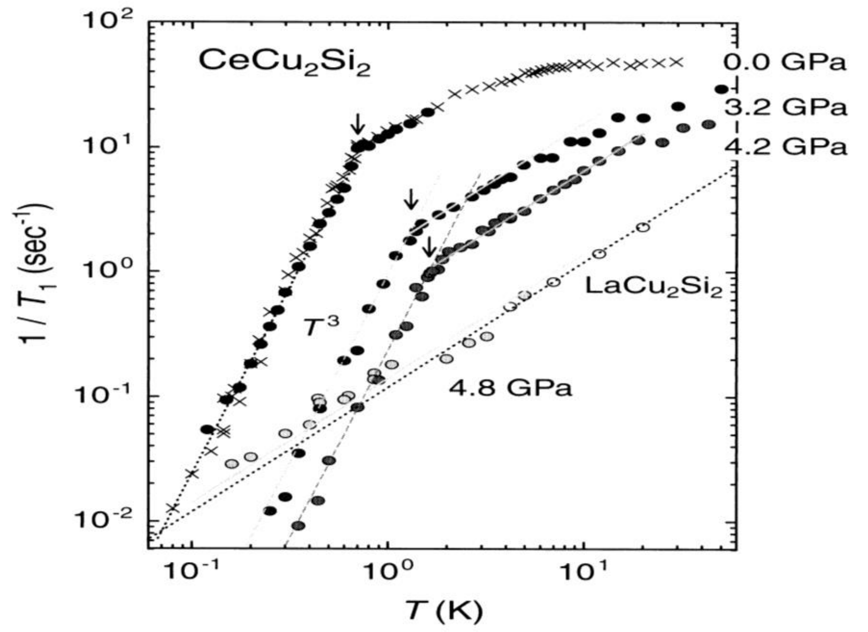
(1-band) *d* - wave superconductivity in $CeCu_2Si_2$

Cu NQR

K. Fujiwara et al., *JPSJ* **77,** 123711 (‘08)

cf. also

K. Ishida et al., *PRL* **82**, 5353 (‘99)



$T = T_c$: no Hebel-Slichter peak

$T < T_c$: $1/T_1 \sim T^3$

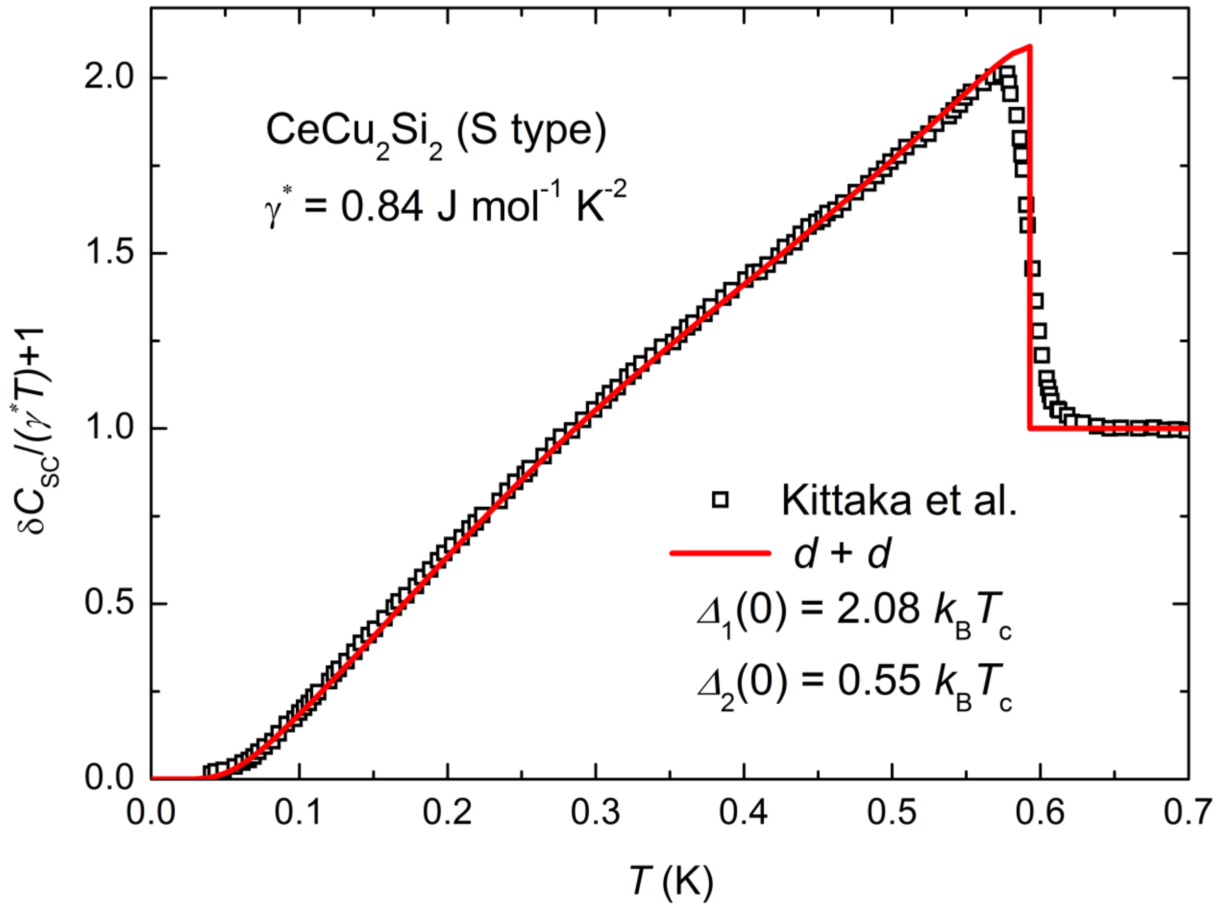
d - wave SC, nodes of $\Delta(k)$

strong coupling
d – wave SC: $2\Delta_0/k_B T_c = 5$

[weak coupling
d - wave SC: $2\Delta_0/k_B T_c = 4.3$]

T - dependence of specific heat for $CeCu_2Si_2$

[S. Kittaka et al., *PRL* **112**, 067002 (2014)]



Fully gapped as $T \to 0$

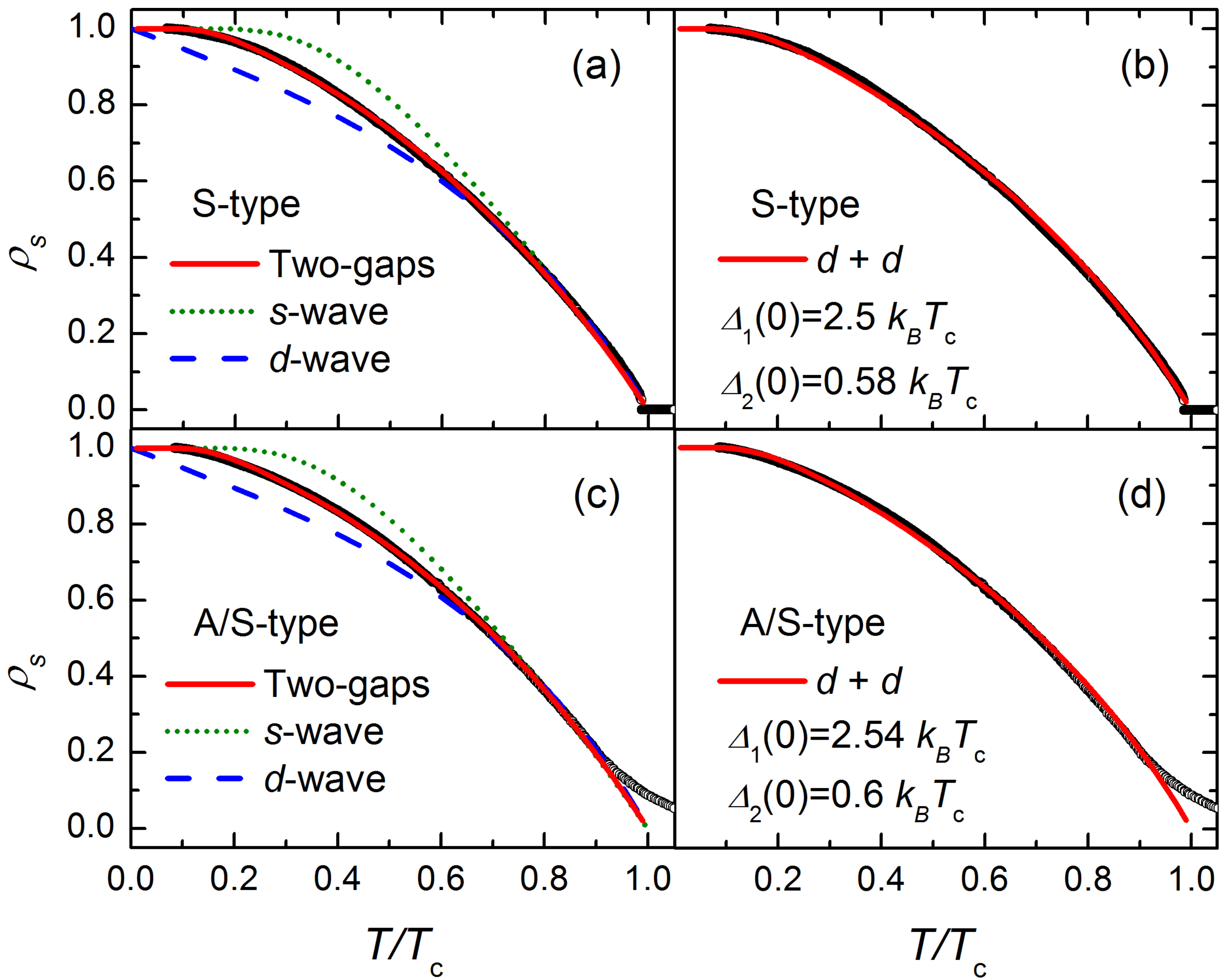
T. Takenaka et al., *PRL* **119**, 077001 (2017): T_c insensitive against el-irradiation

↷

$CeCu_2Si_2$: Two-band *s*-wave superconductor without sign-changing $\Delta(\boldsymbol{k})$ [BCS SC]

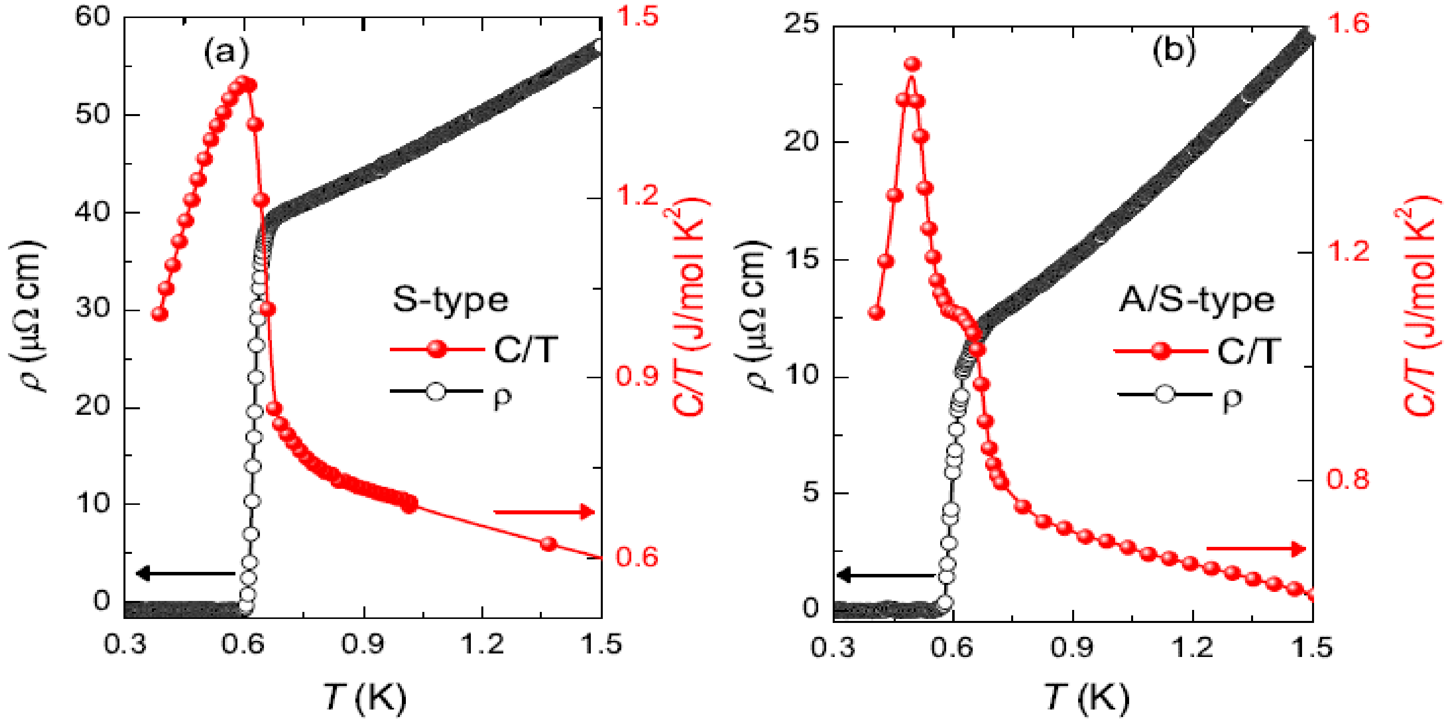
T - dependence of superfluid density $\varrho_s(T)$ in $CeCu_2Si_2$

[G. M. Pang et al., *PNAS* **115**, 5343 (2018)]



Harmless disorder in $CeCu_2Si_2$

G. M. Pang et al., *PNAS* **115**, 5343 (2018)



$T_c \simeq 0.6$ K **insensitive** against variations of ϱ_0 : $\varrho_0(\text{"}S\text{"}) \simeq \mathbf{4}\ \varrho_0(\text{"}A/S\text{"})$

- Cu/Si interchange < 1 % (change of ϱ_0)

harmless

- shift from lattice sites into interstitials (el. irradiation)

Atomic substitution in $CeCu_2Si_2$

[H. Spille, U. Rauchschwalbe, FS, *Helv. Phys. Acta* **56**, 165 (1983);
H. Q. Yuan, F. M. Grosche, M. Deppe et al., *Science* **302**, 2104 (2003)]

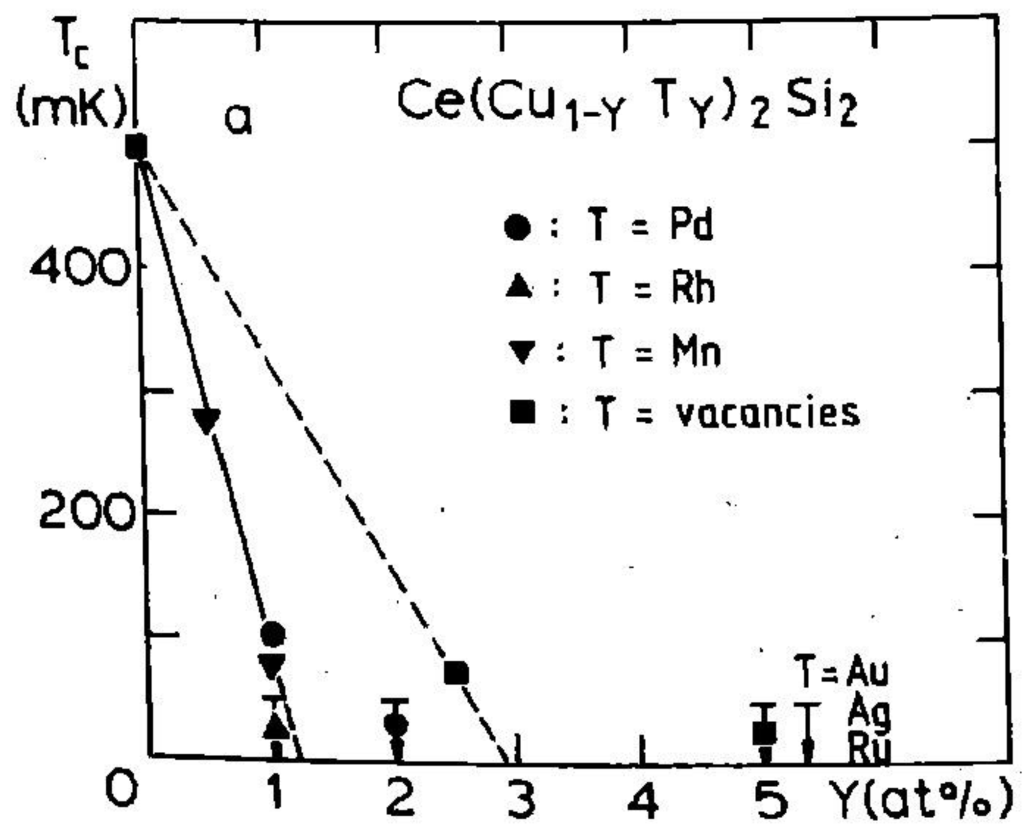
site dependence

Si-site:
x_c: (15 – 20) at% for Ge
x = 0.1: $l_{mfp} > \xi$; 0.25: $l_{mfp} < \xi$

Cu-site:
$x_c \simeq$ 1 at%
for Mn, Pd, Rh ($\Delta T_K \simeq$ + 7 mK)

Ce-site
(**size**-dependence):

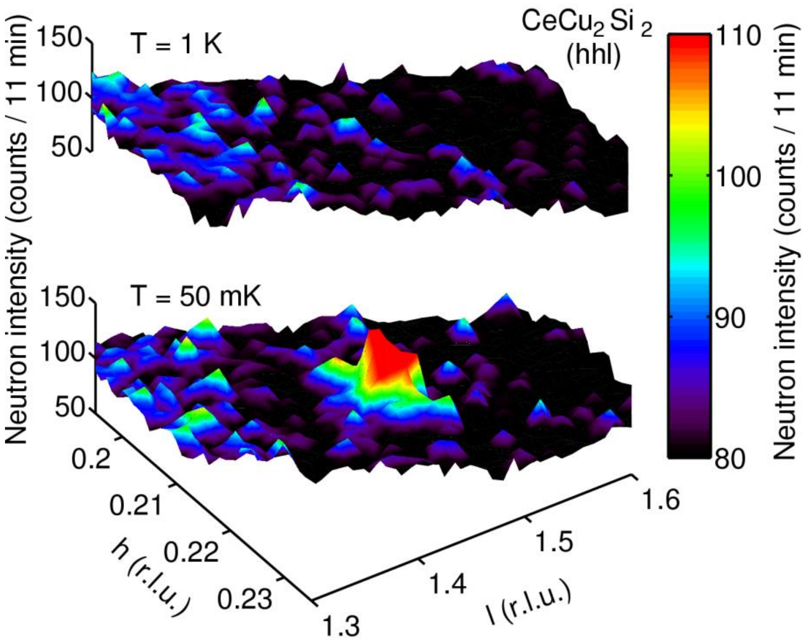
	$\Delta r_{Ce\text{-}M}$ [Å]	x_c[at%]
Sc	+ 0.28	1
Y	+ 0.13	6
Th	+ 0.06	20
La	- 0.03	10

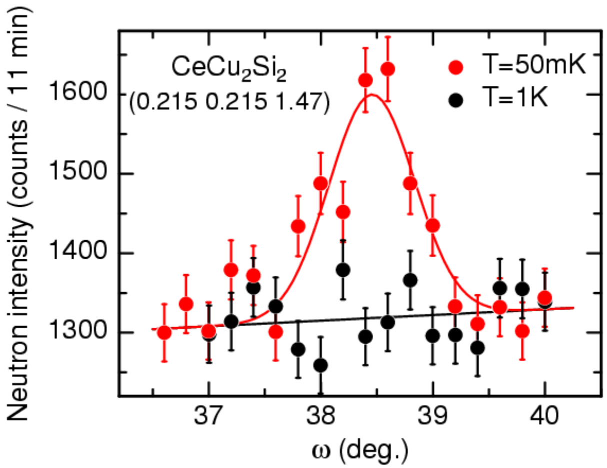


Incompatible with s_{++} pairing
[P. W. Anderson, *Phys. Rev. Lett.* **3**, 325

Nature of the AFM (*A*) phase in $CeCu_2Si_2$

[O. Stockert, G. Zwicknagl et al., Phys. Rev. Lett. **92**, 136401 (2004)]





Observation of AF satellite peaks in (*hhl*) scattering plane

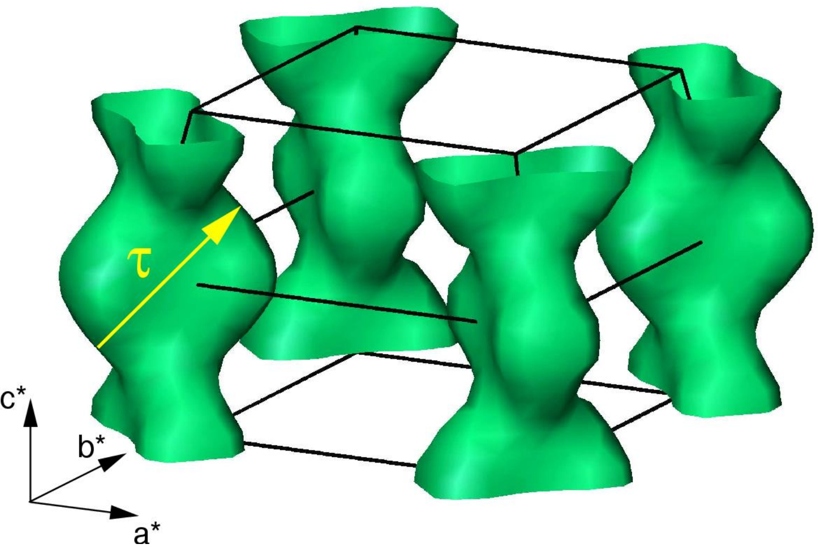
Long-range AF order with propagation vector τ = (0.215 0.215 0.530) at T = 50 mK

$T_N \approx 0.8$ K

$m_0 \sim 0.1\ \mu_B$

Nesting properties of Fermi surface in $CeCu_2Si_2$

[O. Stockert, G. Zwicknagl et al., PRL **92,** 136401 (2004)]

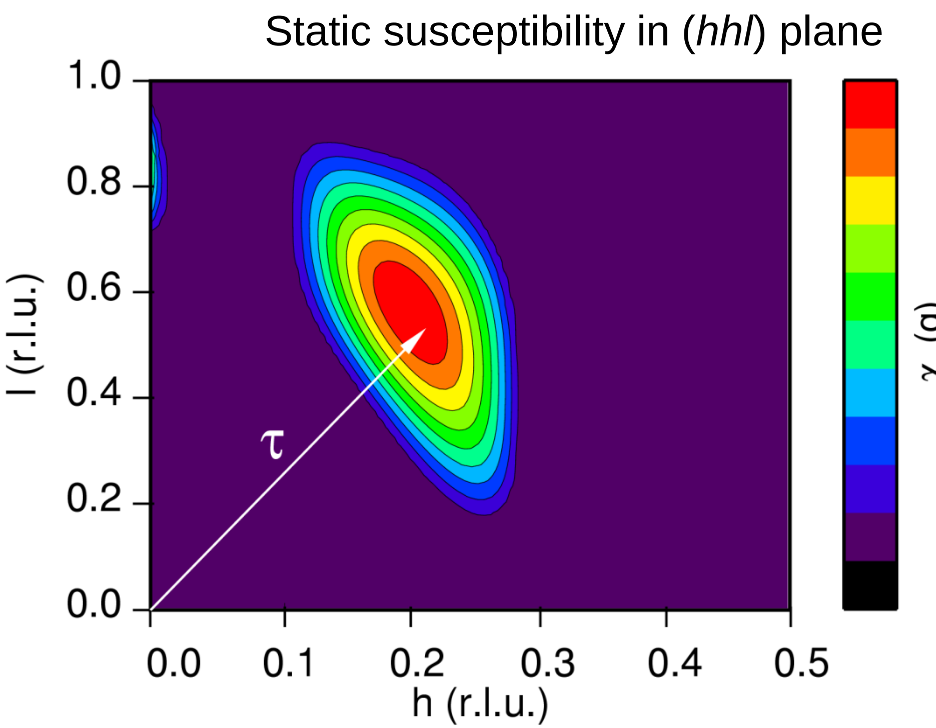


Fermi surface of heavy quasiparticles calculated with renormalized band method,
$m^* \approx 500\ m_e$

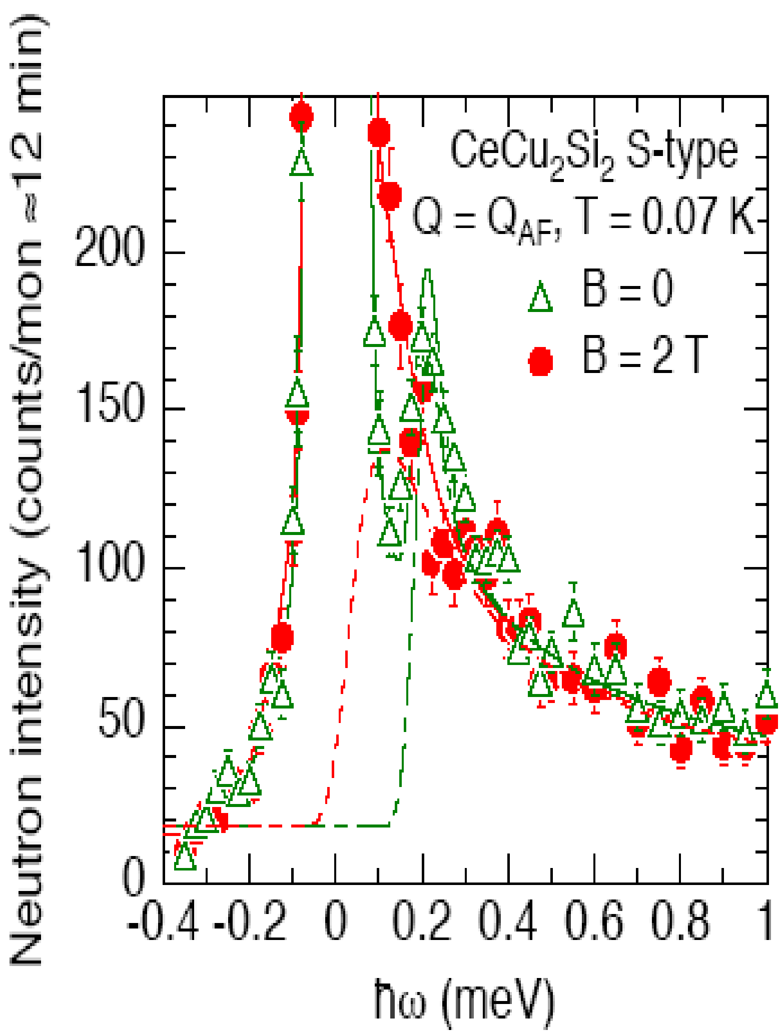
warped columns along tetragonal axis

Nesting for incommensurate wave vector
$\tau \approx (0.21\ 0.21\ 0.55)$

Fermi surface unstable with respect to formation of spin-density wave



Inelastic n-scattering reveals sign change of $\Delta(k)$
[O. Stockert et al., *Nature Phys.* **7**, 119 (2011)]



Large INS intensity in sc state at $\boldsymbol{k} = \boldsymbol{Q}_{AF}$ and **low** $\hbar\omega$, i.e.,
coherence factor $\{1-\cos[\Phi(\boldsymbol{k})]\} \simeq 2$,
where $\Phi(\boldsymbol{k})$ is the phase difference in $\Delta(\boldsymbol{k})$ between $\boldsymbol{k}$ & $\boldsymbol{k} + \boldsymbol{Q}_{AF}$,
↷ $\Phi(\boldsymbol{k}) \simeq \pi$
↷ sign change of $\Delta(\boldsymbol{k})$ along $\boldsymbol{Q}_{AF}$ inside dominating HF band

↷

No *s* - wave superconductor

s_{++} : doesn‘t show sign change in $\Delta(k)$!
no onsite pairing of HFs: $U_{eff} \simeq k_B T_K$!

s_{+-} : nesting wavevector *different* from $\boldsymbol{Q}_{AF}$
can‘t explain spin resonance!

↷

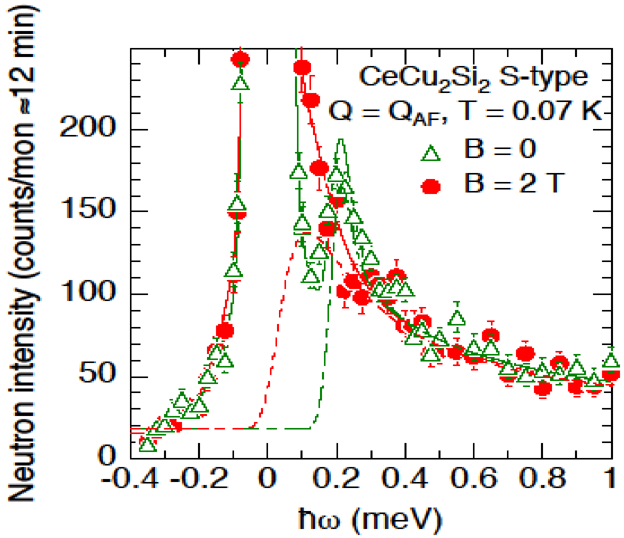
“*d*+*d* band - mixing“ Cooper pairing
[E. Nica et al. ‘16]

2 - band *d* - wave SC without nodes,
cf. ^{3}He - *B* phase (*p* - wave pairing)

Superconductivity in $CeCu_2Si_2$ near a (3D) SDW QCP

[O. Stockert et al., *Nature Phys.* **7**, 119 (2011)]

k = Q_{AF}

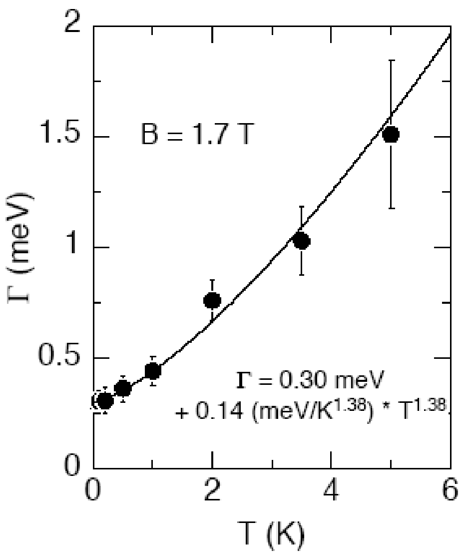


B = 2 T: quasielastic line, HWHM ~ T_K

B = 0: spin gap below peak at 0.2 meV

Propagating ‘paramagnon‘ mode (not a ‘spin resonance‘) at 3.9 $k_B T_c$ [< $2\Delta_1(T=0) \simeq 5\, k_B T_c$]

[J. Arndt et al., *PRL* **106**, 246401 (2011)]

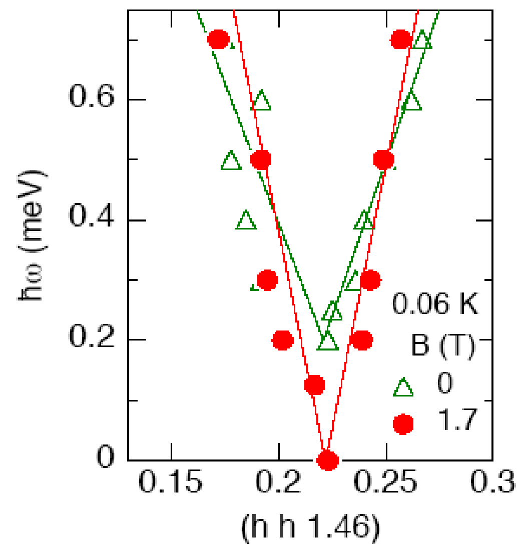


“slowing down“

$\Delta\Gamma \sim T^{\alpha}$

$\alpha = 1.38 \mp 0.16$

(3D SDW) $\alpha = 1.5$



outline

Kondo effect

Heavy-fermion (HF) superconductivity (SC)

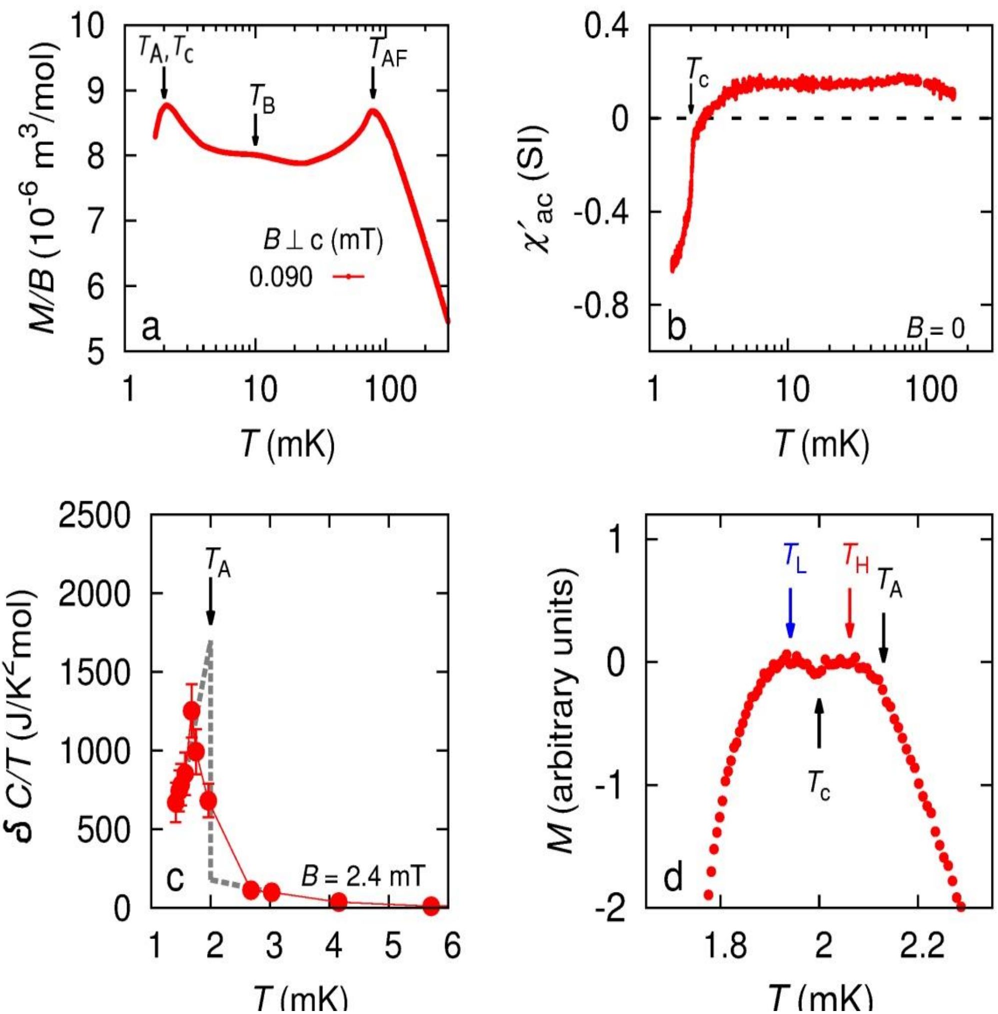
Quantum critical point (QCP) in HF metals

SC near an itinerant AF (SDW) QCP in $CeCu_2Si_2$

SC due to nuclear AF order in $YbRh_2Si_2$

$YbRh_2Si_2$: Emergence of SC by nuclear AF order

[E. Schuberth et al., *Science* **351**, 485 (2016)]



a. $T_N \simeq 70$ mK: 4*f* - electr. AF order

$T_B \simeq 10$ mK: increase of $M(T)$

$T_A \simeq 2$ mK: new phase transition

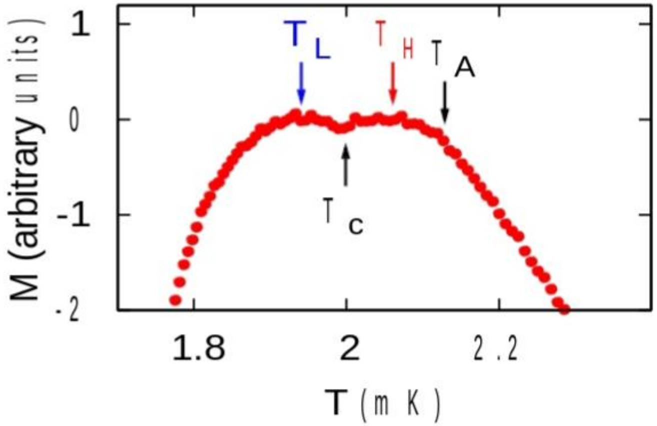
b. $T_c \simeq 2$ mK: SC [$\chi'(T)$: 1st order!)]

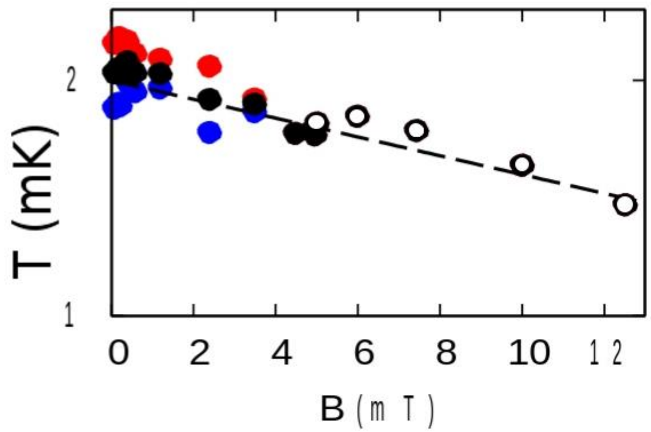
c. $T_A \simeq 2$ mK: "*A* - phase"

d. $B < 4$ mT: $T_A > T_c$

Summary $\color{red}{Yb}Rh_2Si_2$

E. Schubert et al. (2016)





$B_{c2}' \simeq 25$ T/K from Meissner measurements (same from shielding measurements)

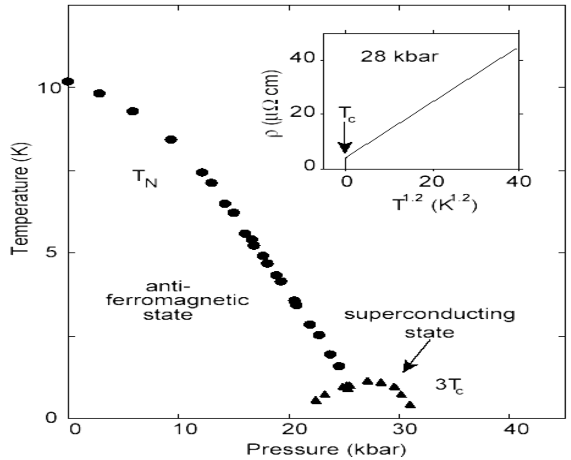
- M_{DC}(T), $\chi_{AC}(T)$ **prove** : (bulk) heavy-fermion SC at $B < 4$ mT

- YbRh_2Si_2:
  - SC near (4*f* – "Mott – type") transition ($T = 0$), like Ce$RhIn_5$ at $p > 0$
  - both systems form **link** between (≃ 50) **HFSCs** and **cuprates, organics, …** near true Mott transition

Quantum Critical Paradigm:
Unconventional SC at HF AF QCPs

$CePd_2Si_2$

N. D. Mathur et al.,
Nature **394**, 39 (1998)



- $YbRh_2Si_2$:
  HF SC, T_c = 2 mK

- $CeCu_2Si_2$:
  fully gapped 2 - band *d* - wave superconductor

- **Unconventional SC near AF QCPs: robust phenomenon**

Further reading:
M. Smidman et al., *Phil. Mag.* **98**, 2930 (2018)