Superconductivity Without Phonons: An Update

Gil Lonzarich, University of Cambridge

Early Proposals:

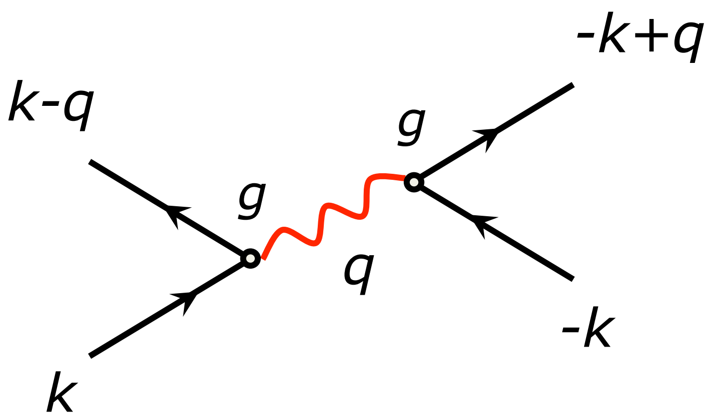
W Heisenberg, *Z. Naturforsch* (1947);
F London, *Phys. Rev.* (1948); …

Recent Discussions:

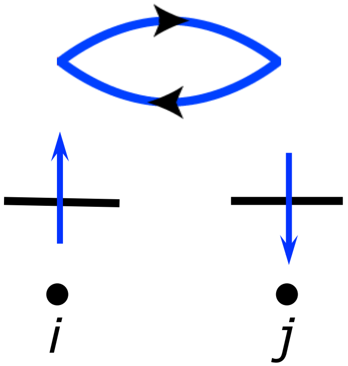
e.g., Strong Correlations and Unconventional Superconductivity:
Towards a Conceptual Framework, KITP 2014

Philippe Monthoux and David Pines,
with thanks also to many colleagues for their insights
and contributions (to be cited in relevant slides).

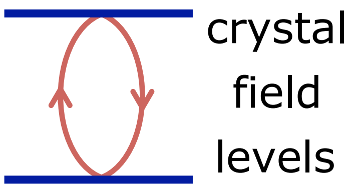
Induced Interactions Between Charge Carriers

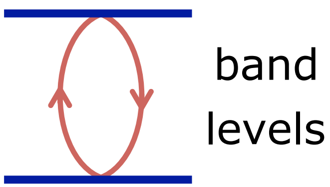


Polarizer-Analyzer Model



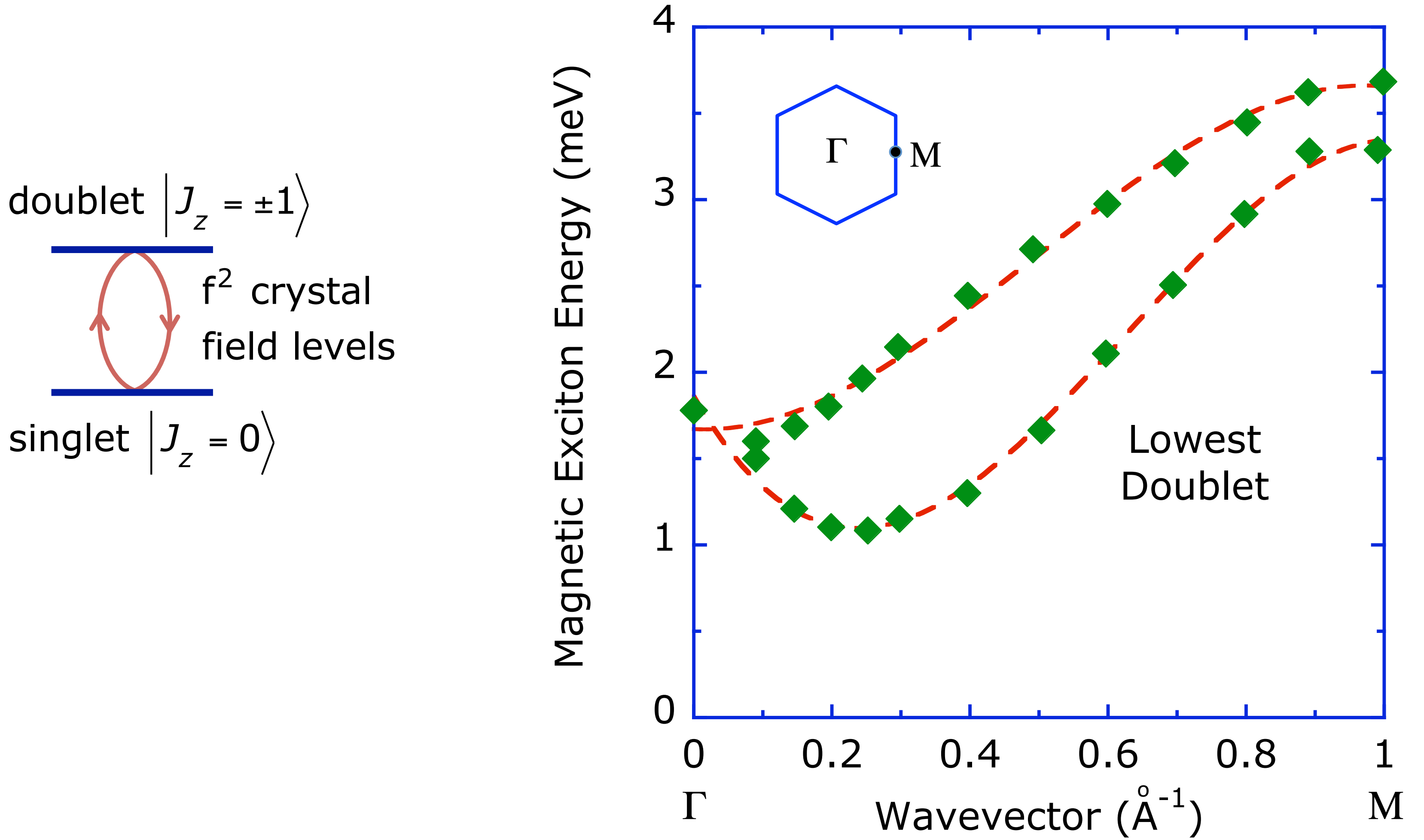
Kinetic Superexchange Model





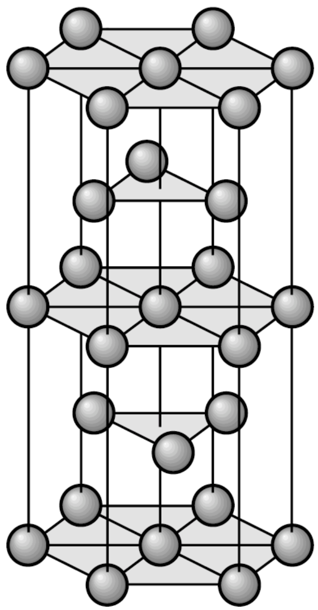
Polarizer-Analyzer Model: Virtual Transitions in Electron System

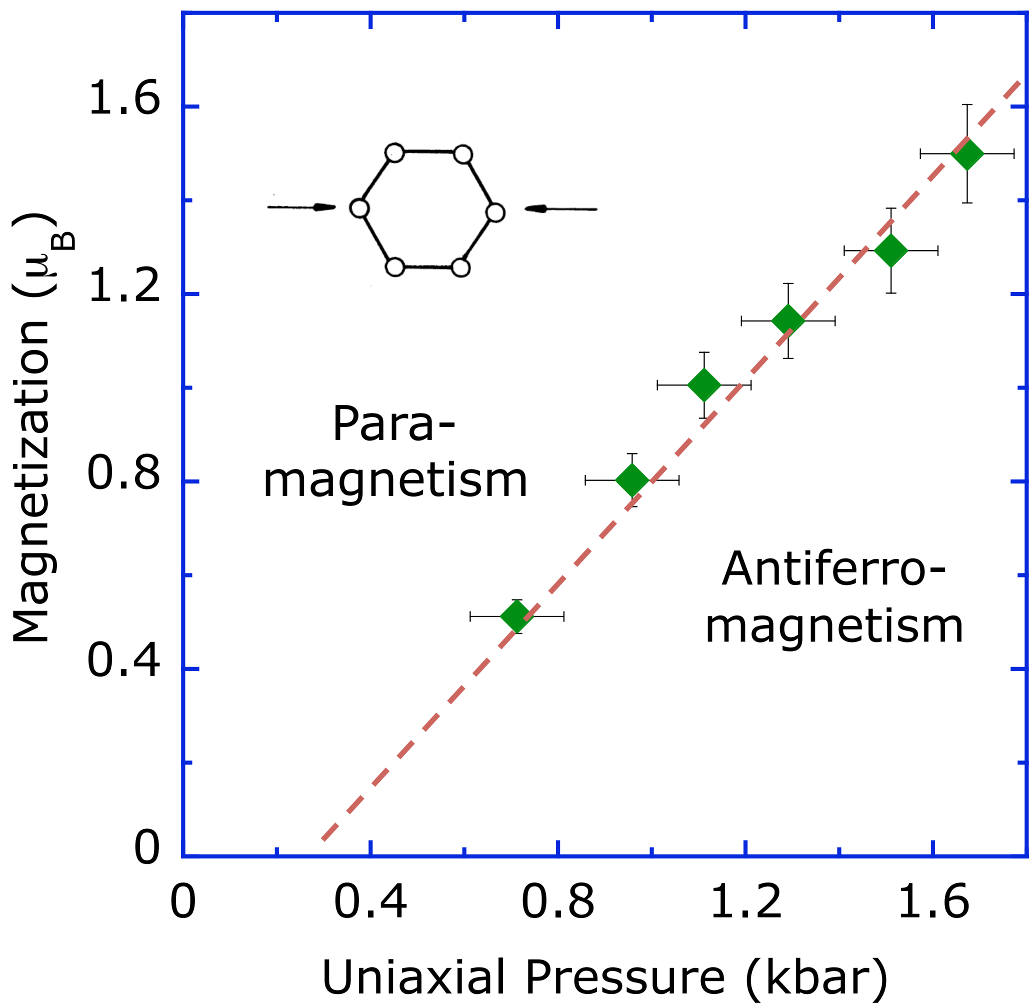
Pr: Lowest Crystal Field Excitations of 4f Electron States
Two f Electrons with L=5, S=1 and J=L-S=4



JG Houmann, BD Rainford, J Jensen & AR Mackintosh, *Phys. Rev. B* (1979)

Pr: Two Localized 4f Electrons Coupled to Three Conduction Electrons per Pr on the Border of Antiferromagnetism





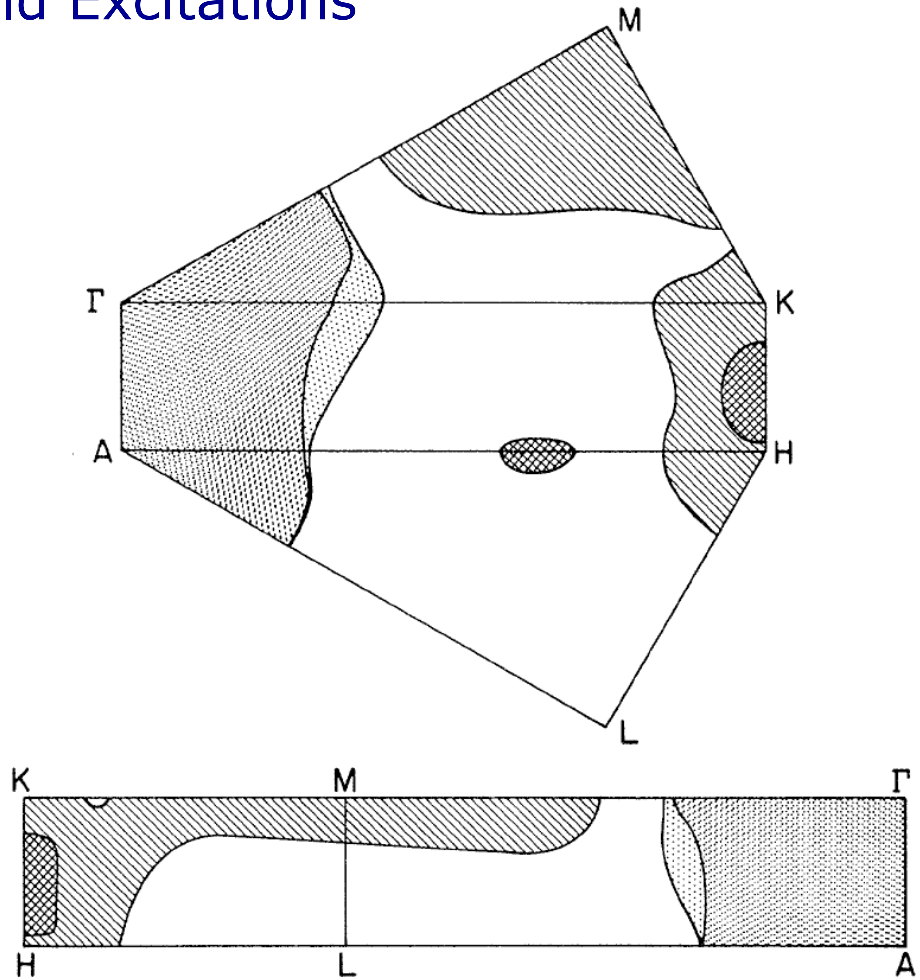
KA McEwen, WG Stirling & C Vettier, *Physica B* (1983)

Pr: Renormalization of Conduction Electrons by Crystal Field Excitations

$$V_{ex} = -I(g-1)\sum_i \sigma_i \cdot J_i$$

$I(F) = 0.11$ eV $\quad I(m^*) = 0.13$ eV

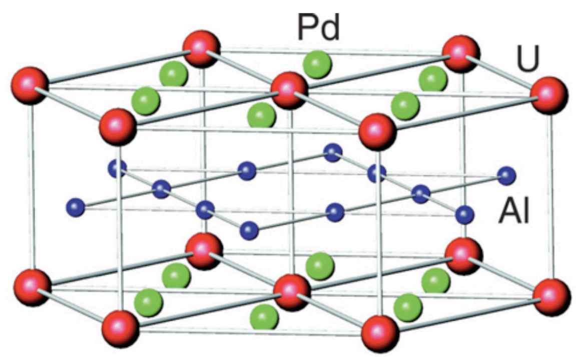
$$m^*/m_{band} = 2.9 \text{ to } 7.8$$

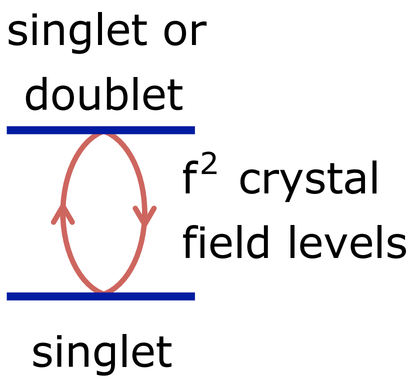


Fermi Surface Cross-Sections

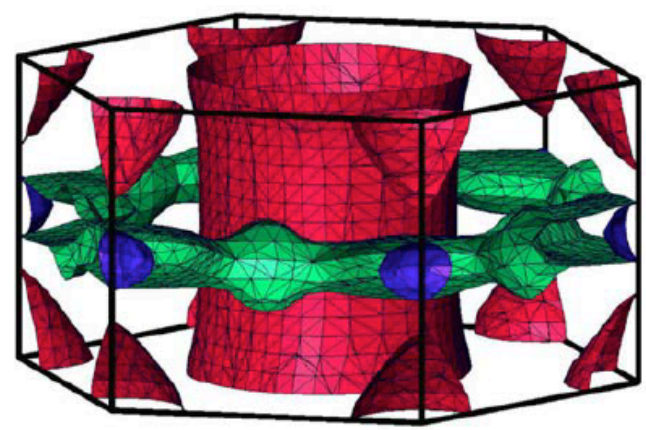
GS Fleming, SH Liu & TL Loucks, *Phys. Rev. Lett.* (1968); RM White & P Fulde, *Phys. Rev. Lett* (1981); M Wulff, GGL, D Fort & HL Skriver, *Europhys. Lett.* (1988)
Cf. UPt_3: m^*/m_{band} ~ 20, L Taillefer & GGL , *Phys. Rev. Lett.* (1988)

UPd_2Al_3: Two Localized 5f Electrons & One Itinerant 5f Electron per U on Border of Antiferromagnetism





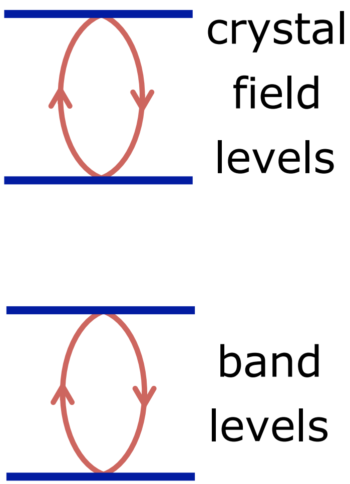
$$m^*/m_{band} \approx 10$$

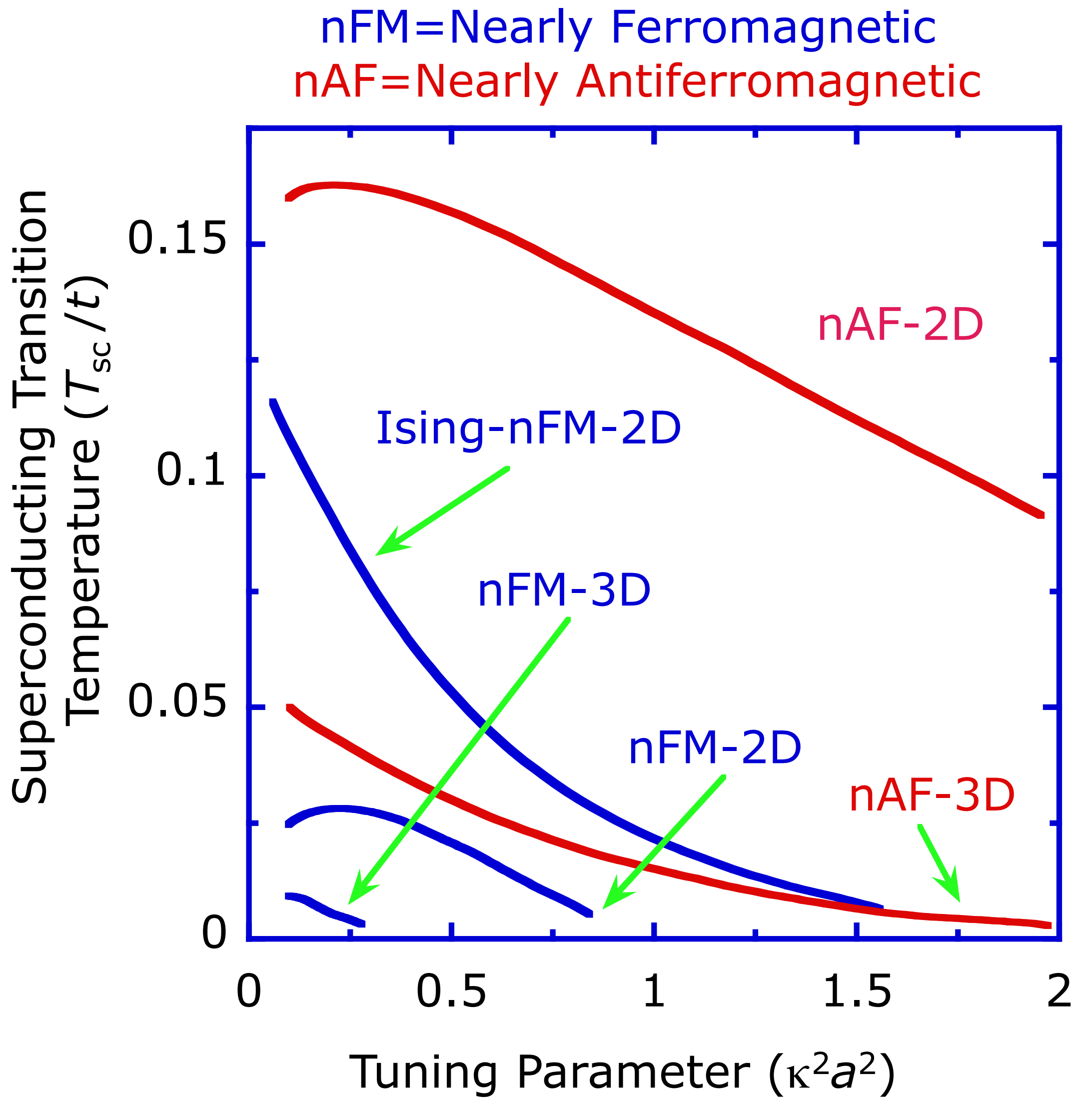


Model consistent with observed superconducting transition at $T_{sc} \approx 1.8$ K in opposite spin pairing state

G Zwicknagl, A Yaresko & P Fulde, *Phys. Rev. B* (2003); P Thalmeier, *Euro. Phys. J. B* (2002);
P McHale, P Fulde & P Thalmeier, *Phys. Rev. B* (2004);
Cf. itinerant f–electrons in UPt_3: GJ McMullan, SR Julian *et al.*, *New J. Phys.* (2008)

Magnetically Mediated Superconductivity in Spin-Fermion Model

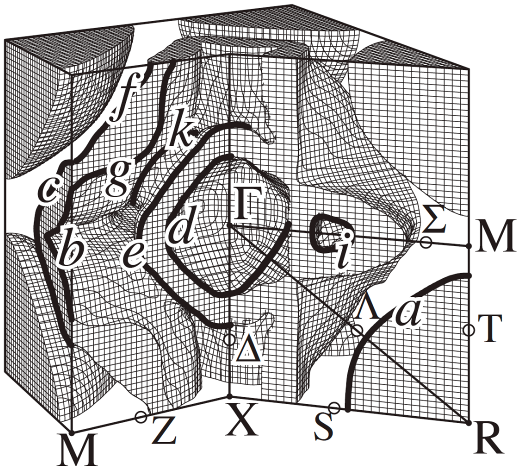




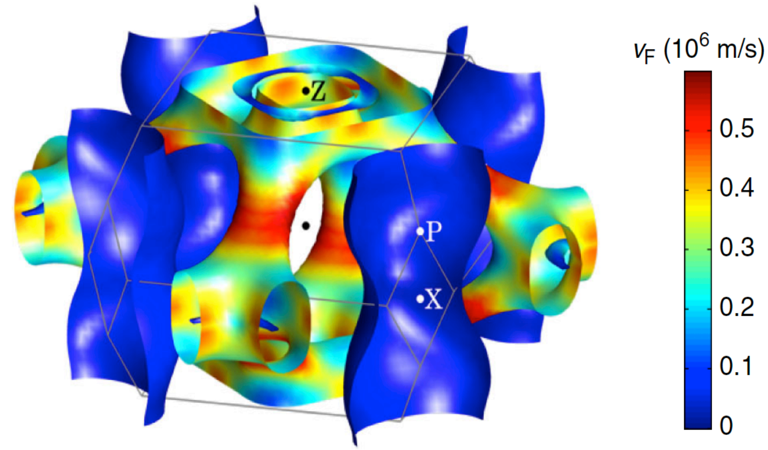
κ= correlation wavevector, t = hopping parameter
Band Parameters: $t'/t = 0.45$, $n = 1.1$
Interaction Parameters: $\kappa_0^2 a^2 = 12$, $g^2\chi_0/t = 5$

D Fay & J Appel, *Phys. Rev. B* (1980); …
P Monthoux & GGL, *Phys. Rev. B* (1999); P Monthoux, D Pines & GGL, *Nature* (2007) …

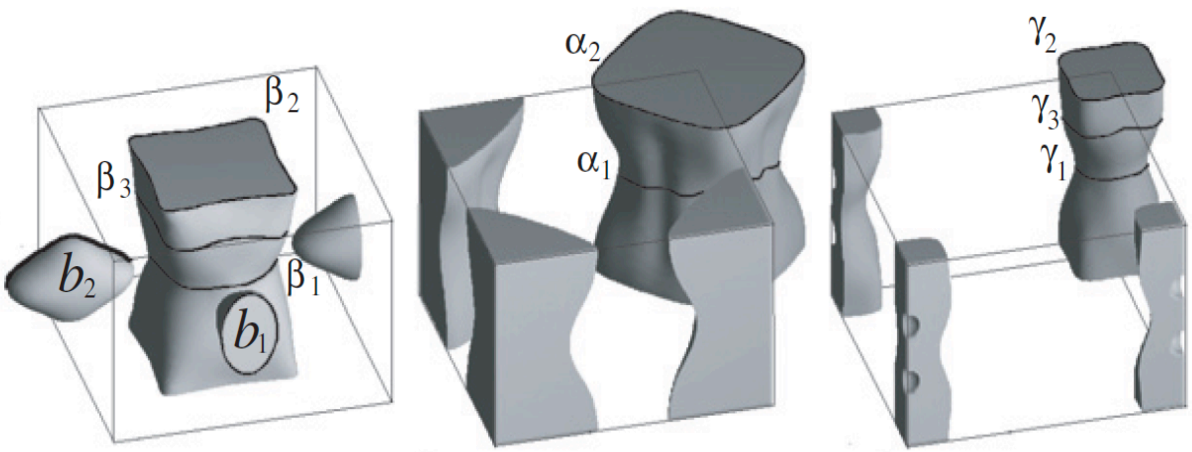
$CeIn_3$: $T_{sc} \leq 0.2$ K



CeM_2X_2: $T_{sc} \leq 2$ K

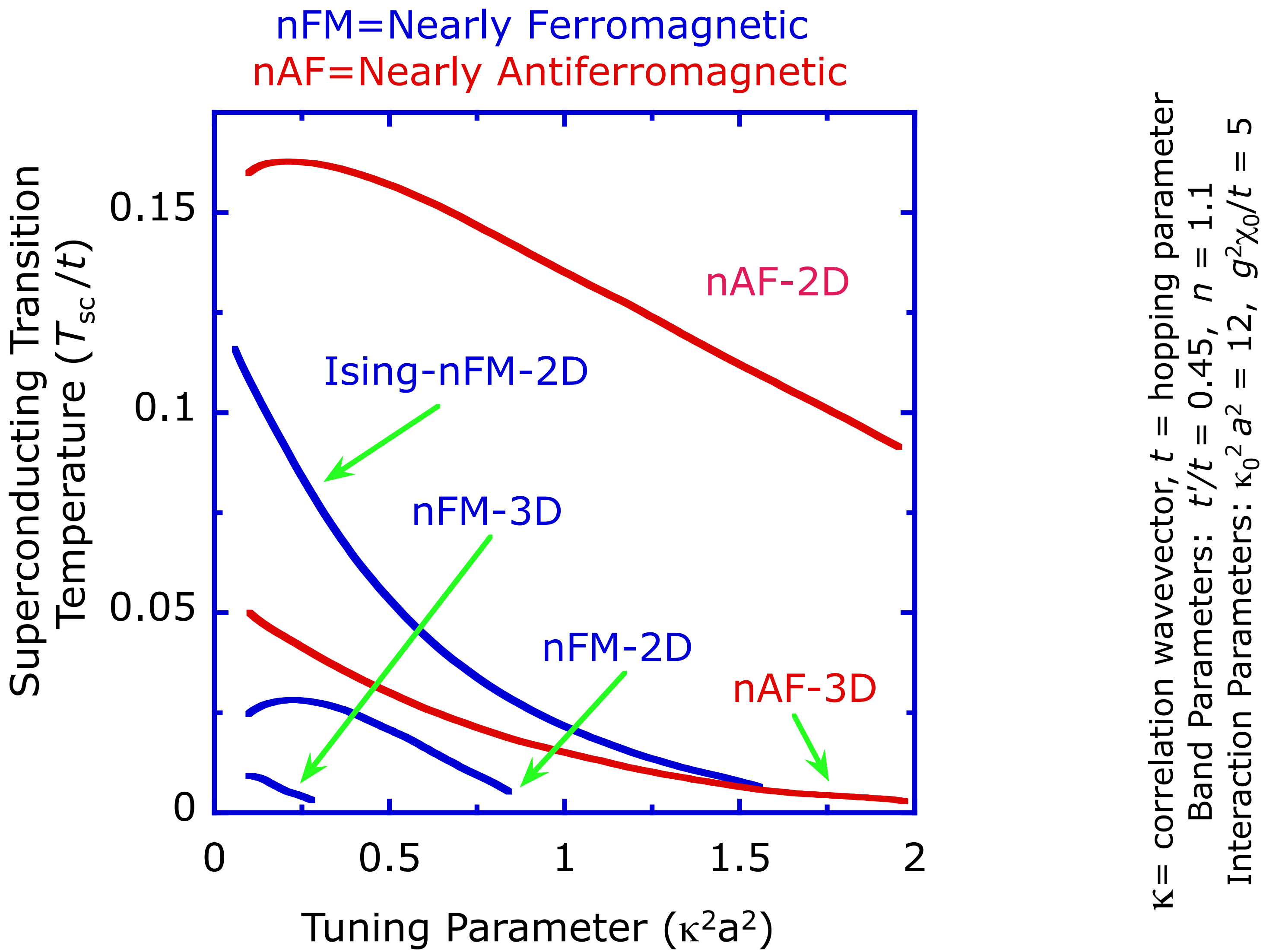


$CeMX_5$ & $PuMX_5$: $T_{sc} \leq 20$ K



$CeIn_3$: IR Walker, FM Grosche, D Freye & GGL, *Physica C* (1997); N Mathur *et al., Nature* (1998); K Betsuyaku & H Harima, *JMMM*(2004); …
$CeCu_2Si_2$: F Steglich *et al., Phys. Rev. Lett.* (1979); S Kittaka *et al.* (2014);
CeRhIn5: H Hegger *et al., Phys. Rev. Lett.* (2000);
$PuCoGa_5$: JD Sarrao *et al.*, *Nature* (2002); T Maehira, T Hotta, K Ueda & A Hasegawa, *New J. Phys.* (2006); …

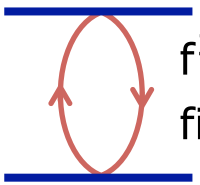
Magnetically Mediated Superconductivity in Spin-Fermion Model



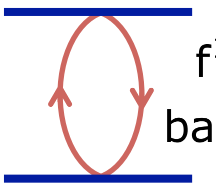
D Fay & J Appel, *Phys. Rev. B* (1980); …; P Monthoux & GGL, *Phys. Rev. B* (1999); …
R Roussev & AJ Millis, , *Phys. Rev. B* (2001); …
Cf. T Nomura & K Yamada, *J. Phys. Soc. Jpn.* (2000); J Kondo, *J. Phys. Soc. Jpn.* (2001);

Superconductivity on Border of 5f-Electron Ferromagnetism

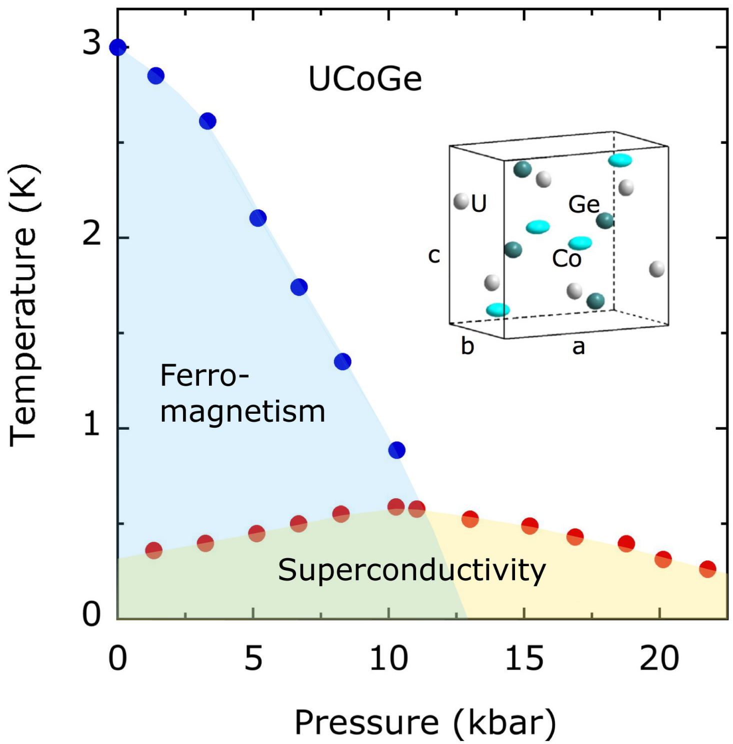
Uniaxial Ferromagnet



f^2 crystal field levels



f^1 & spd band levels



Two Localized Plus One Itinerant U f Electrons

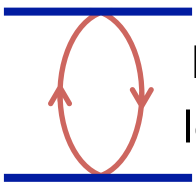
Mineev (2013); Hattori & Tsunetsugu, *Phys. Rev. B* 2013; …

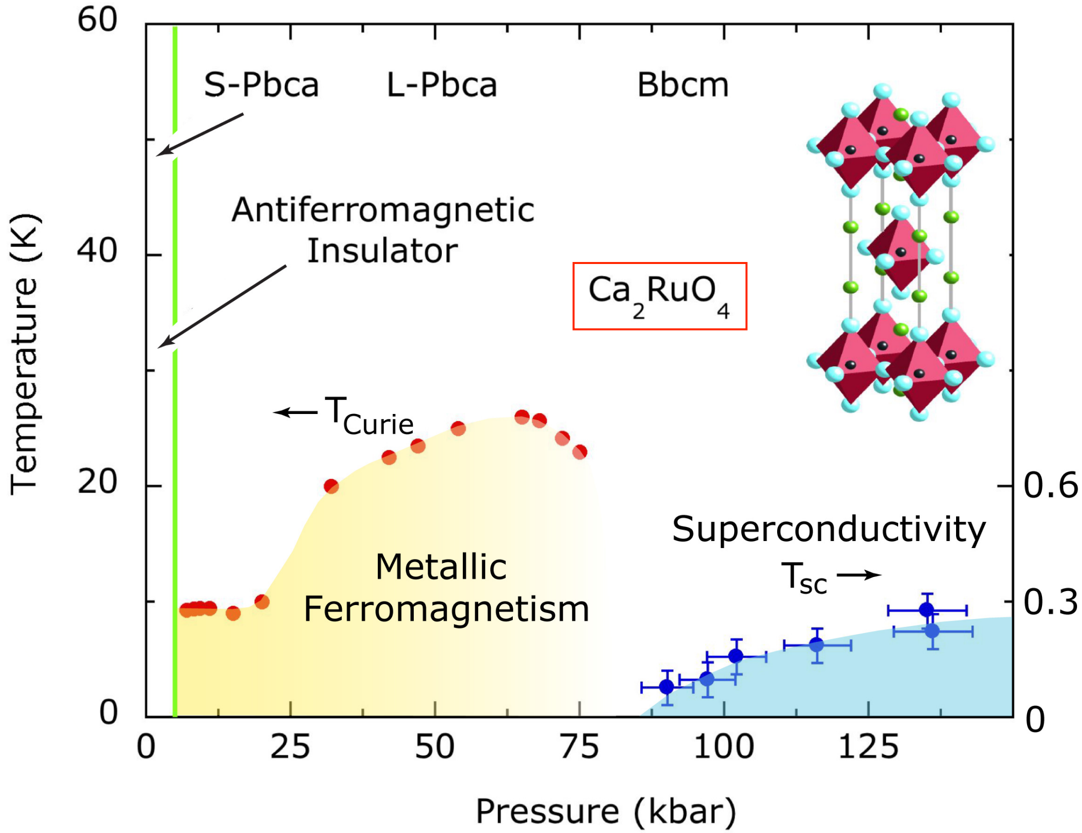
UCoGe: A Gasparini *et al.*, *J Low Temp Phys* (2010); U_2PtC_2: JD Thompson *et al.*, this meeting;
UIr: T Akazawa *et al.*, *JPSJ* (2006);
URhGe: AD Huxley, *et al.*, *JPSJ* (2007); D Aoki *et al.*, *Nature* (2001);
AD Huxley, *et al.*, *J Phys: Condens. Matter* (2003); …
UGe_2: SS Saxena *et al.*, *Nature* (2000); …

NQR Studies: T Ohta, *et al.*, *JPSJ* (2010); T Hatton *et al.*, *Physica C* (2010); Y Kitaoka, *et al.*, *JPSJ* (2005); …

Superconductivity on Border of 4d-Electron Ferromagnetism

Quasi 2D Ferromagnet





Itinerant d Electrons*

$T_{SC}/T^* \approx 0.01\%$

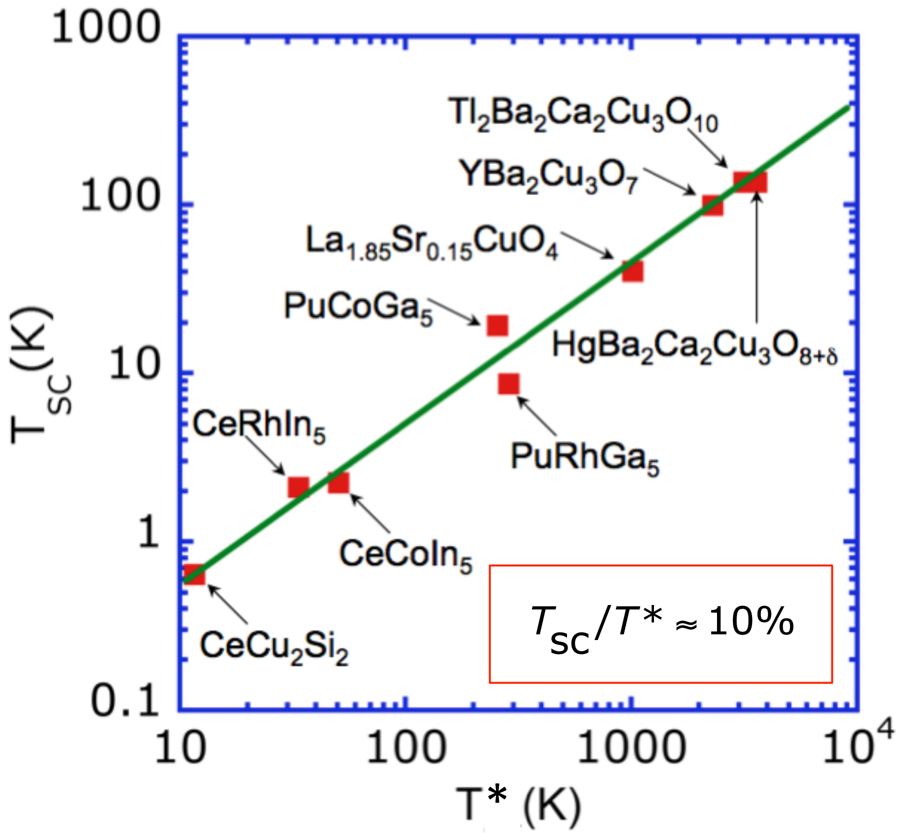
Ca_2RuO_4: PL Alireza, F Nakamura, SK Goh, Y Maeno, S Nakatsuji, YTC Ko, M Sutherland, S Julian & GGL, *J Phys: Condens. Matter* (2010)

Sr_2RuO_4: Y Maeno *et al., Nature* (1994)

*P Monthoux & GGL, *Phys. Rev. B* (1999); …

Unconventional Superconductivity on Border of Magnetism

e.g., DJ Scalapino, *Rev. Mod. Phys.* (2012) and references therein



T_{SC} = Superconducting Transition Temperature

T^* = Characteristic Spin-Fluctuation Temperature

Not too close to a quantum critical point:

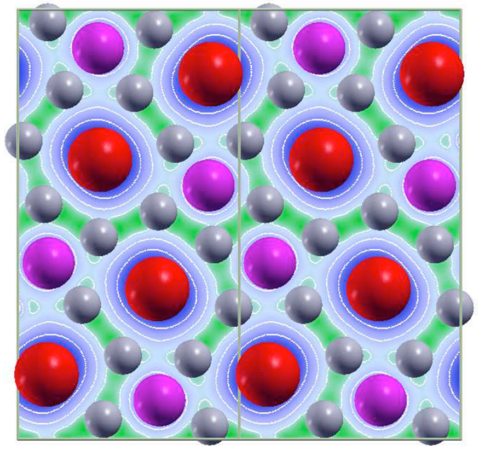
$$T^* \approx \frac{10^4\,\mathrm{K}}{\gamma\,/\,(\mathrm{mJ\ mol^{-1}K^{-2}})}$$

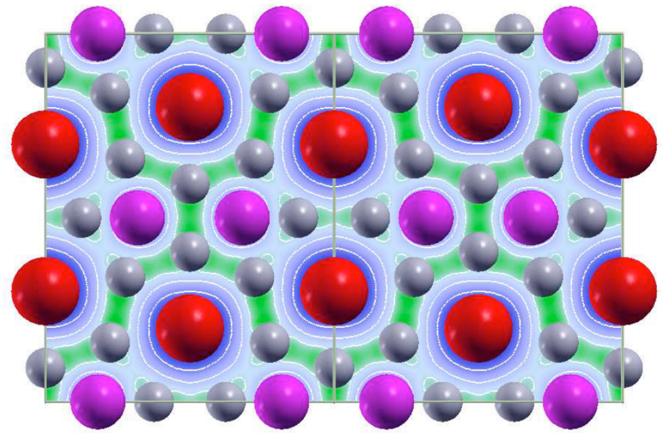
Systems with Reduced T_{SC} / T^*:

- Cubic f and d electron systems
  - Border of ferromagnetism
- Yb heavy electron systems (f-hole analogues of Ce)

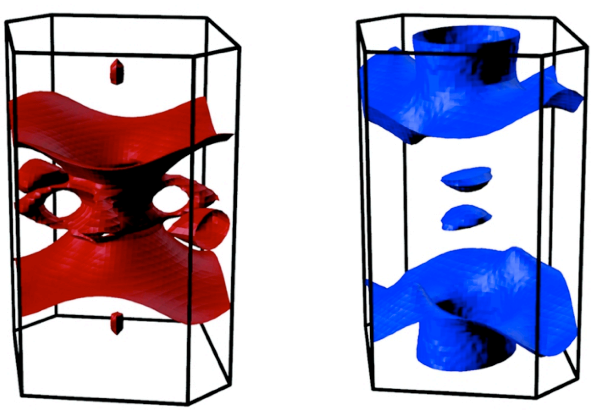
$YbAlB_4$: $T^{3/2}$ Resistivity & Superconducting Transition

α-$YbAlB_4$

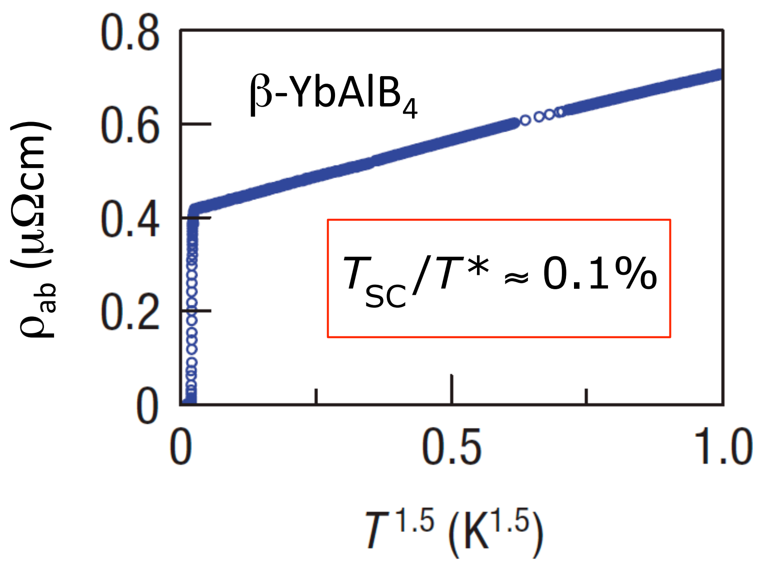




β-$YbAlB_4$



β-$YbAlB_4$ Fermi Surface



$YbRh_2Si_2$

$\frac{T_{SC}}{T^*} \leq 0.01\%$

E Shuberth *et al.*

S Nakatsuji *et al.*, *Nature Phys.* (2008), (2010); ECT O'Farrell *et al., Phys. Rev. Lett*. (2009);
DA Tompsett, ZP Yin, GGL & WE Pickett. , *Phys. Rev. B* (2010)
Critical Nodal Metal: A Ramires, P Coleman, AH Nevidomskyy & AM Tsvelik, *Phys. Rev. Lett*. (2012)

Why is Superconductivity Rare in Yb Heavy Fermion Systems?

- Compactness of f-orbitals in Yb: weak f-spd hybridization, crystal field splittings, double f-hole occupancy and intersite spin couplings
- Prevalence of ferromagnetic correlations (high Wilson ratios and ferromagnetic transitions) and valence transitions
- Role of f-level degeneracy together with crystal field splittings:

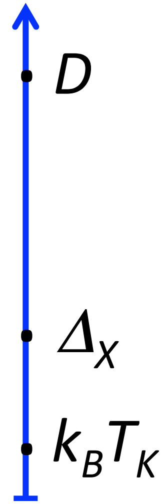
$$k_B T_K \approx D\exp(-1/\rho J) \;\rightarrow D\exp(-1/\rho J)\,(D/\Delta_X)^{(N/2)-1}$$

$$k_B T_{RKKY} \approx \rho J^2$$

N = orbital degeneracy for $\Delta_X = 0$ (N=6 for Ce, N=8 for Yb)

Δ_X = crystal field splitting (2 to N-2, $k_B T_K < \Delta_X < D$)

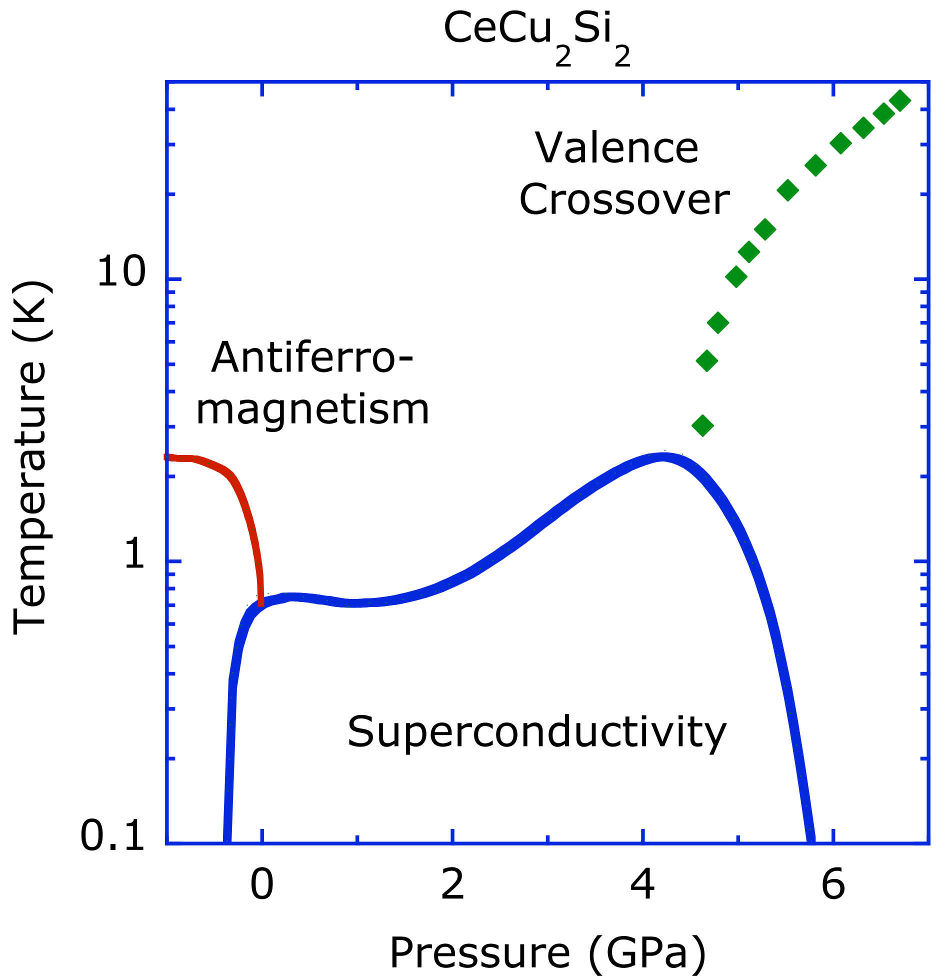
$T_{RKKY} \approx T_K$ yields J_{crit} which decreases with increasing N



S Doniach, *Phys. Rev. B* (1987); J Flouquet & H Harima (2009);
F Honda, T Onuki *et al.*, *J. Phys.: Conf. Ser.* (2012);

A Tsvelik, P Coleman & GGL (2014); ...

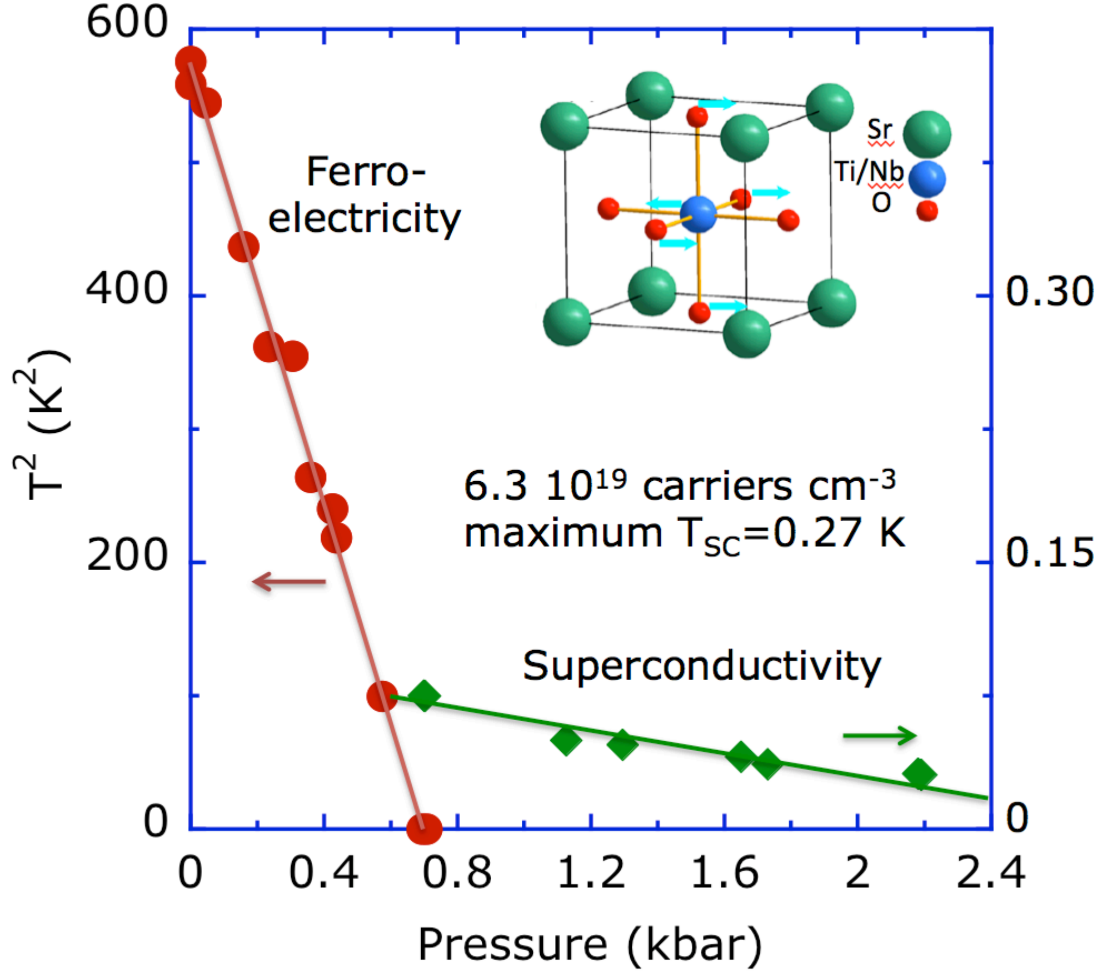
Double Superconducting Dome in $CeCu_2Si_2$



G Seyfarth, AS Ruetschi, K Sengupta, A Georges & D Jaccard, *EPL* (2012);
HQ Yuan, FM Grosche, M Deppe, C Geibel, G Sparn & F Steglich, *Science* (2003); …

Models: Onishi & Miyake, *J. Phys. Soc. Jpn.* (2001); P Monthoux & GGL, *Phys. Rev. B* (2004);
$CeNi_2Ge_2$: FM Grosche *et al.*, *J. Phys.-Cond. Matter* **12** (2000); A Demuer, *et al.*, *J. Phys.-Cond. Mat.* **14** (2002);
G Knebel, *et al.*, *High Pressure Research* **22** (2002); …

Ferroelectricity in $SrTi^{18}O_3$ & Superconductivity on Border of Ferroelectricity in Nb Doped $SrTiO_3$



EL Venturini *et al.*, *Phys. Rev. B* (2004); ER Pfeiffer & JF Schooley, *J. Low Temp. Phys.* (1970);
Ferroelectric Quantum Critical Point: R Roussev & AJ Millis, *Phys. Rev. B* (2003);
L Palova, P Chandra & P Coleman, *Phys. Rev. B* (2009);
SE Rowley, SS Saxena *et al.*, *Nature Phys.* (2014); …

Some Conditions Advantageous for Magnetically Mediated Superconductivity

High T^* on border of magnetism in the metallic state with:

- anisotropic (quasi-2D) electronic and magnetic structures;
- antiferromagnetic, or uniaxial ferromagnetic correlations;
- reduced or compatible orbital degeneracies;
- compatible charge couplings (cf. FeSe/$SrTiO_3$ interfaces).

Further Comments

- Can we explain the unusual and exceptional cases:

  ✧ very high T_{SC}/T^* in UBe_{13} & the related compound $PrTi_2Al_{20}$ with cubic rather than layered crystal structures;

  ✧ vanishing T_{SC}/T^* in many systems tuned to magnetic quantum critical points, including Cr and Pr metals?

- Can particularly strong pairing interactions arise in systems engineered to be on the border of coinciding antiferroelectric *and* antiferromagnetic quantum critical points?