Jan/13/'14, Aspen Winter Conference "Beyond quasiparticles: New paradigms for quantum fluids"

Valence fluctuation and strange metal phase in $YbAlB_4$

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- **Introduction: Kondo lattice vs. mixed valence systems**
- **Kondo lattice behavior in the mixed valence systems: β-, α-$YbAlB_4$**
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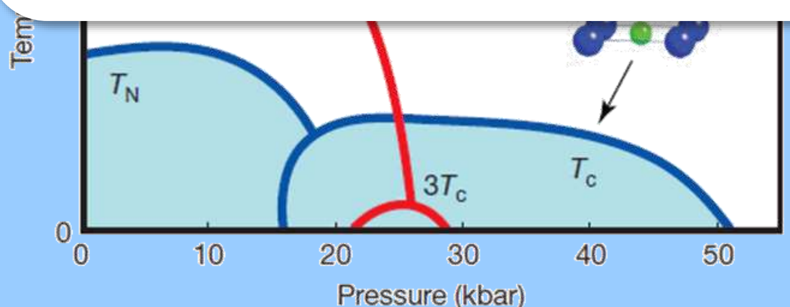
Kondo lattice vs. Mixed valence systems

"Kondo lattice" with integer valence

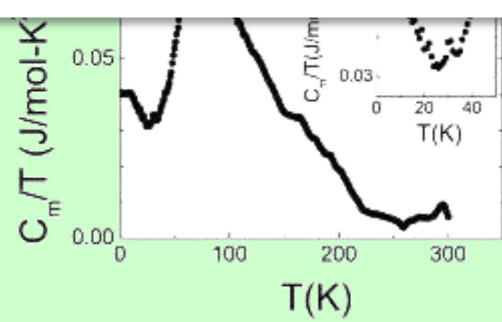
- Doniach like phase diagram
  Kondo vs. RKKY
- Quantum criticality based on critical spin fluctuations associated with **magnetic QCP**.



Mixed valence systems

- Large T_K
- Pauli paramagnetism below T_K
- γ (= C/T) value is not large.

Basically, no QC has been expected.



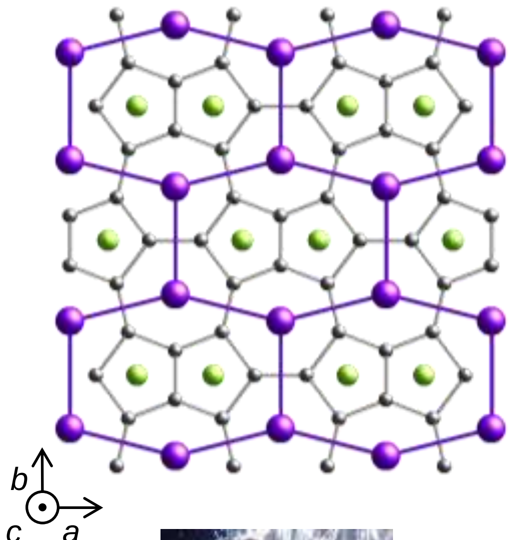
A. L. Cornelius *et al*., PRL **88**, 117201 (2002).

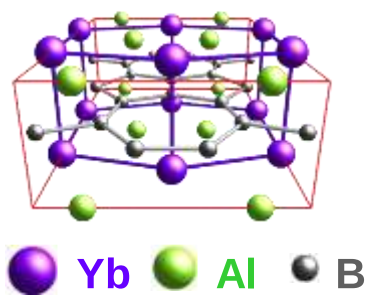
In contrast,

- **α-, β-$YbAlB_4$ provide unique examples of quantum criticality in the mixed valence systems.**
- **What is the origin ?**
- **Novel metallic state ?**

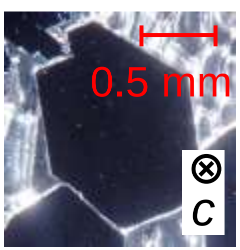
HF Compounds: β-$YbAlB_4$

- Yb form distorted hexagonal lattice.
- Layered but Yb-Yb distance is shortest in *c* axis.
- **The first heavy fermion SC (T_c = 80 mK) in Yb based system.**
- **Pronounced NFL behavior in the normal state @ B = 0.**

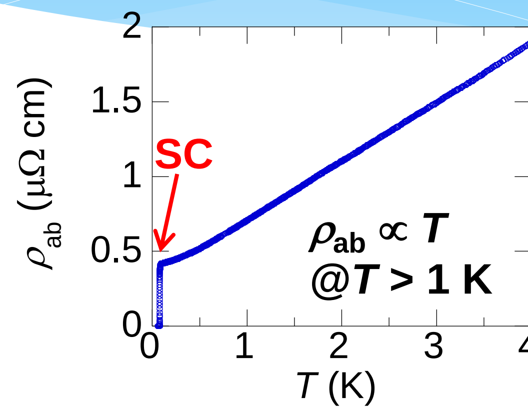


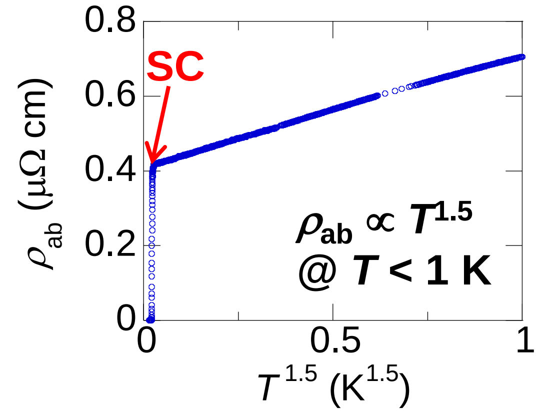


Space Group : *Cmmm,*
a = 7.3080 Å,
b = 9.3150 Å,
c = 3.4980 Å



Thickness: ~10 μm

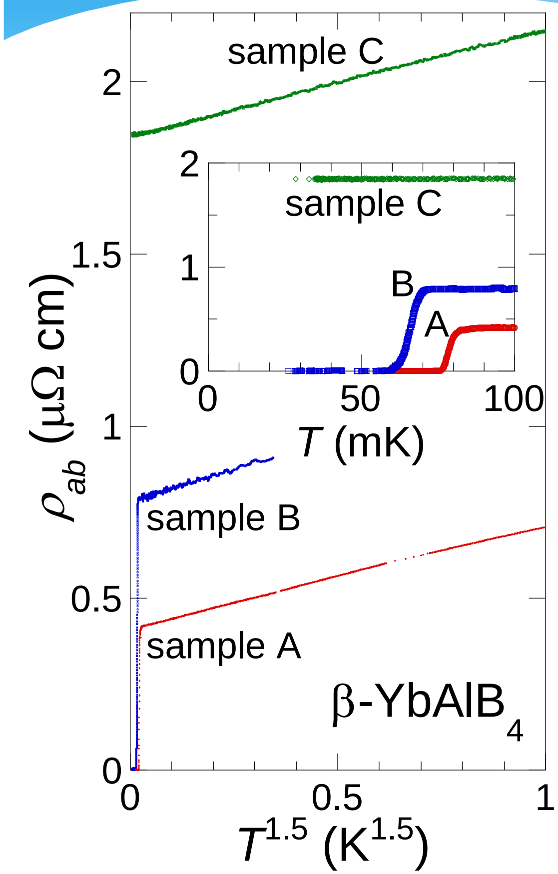


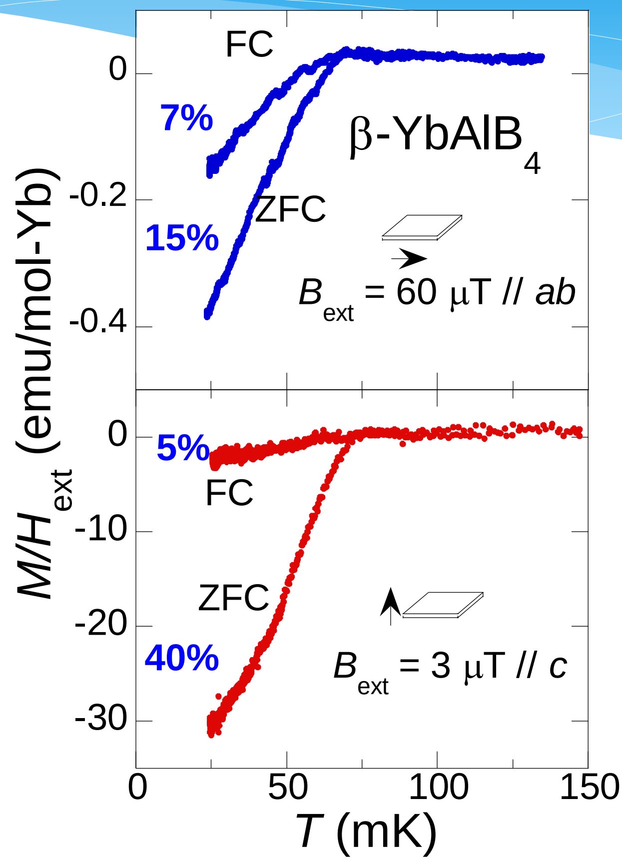


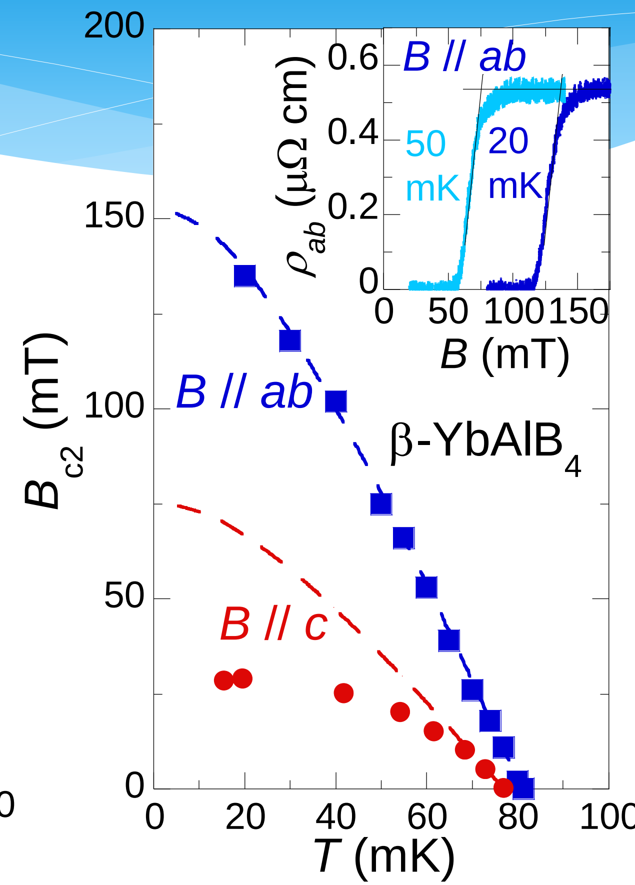
S. Nakatsuji *et. al.*, Nature Phys. **4**, 603-607 (2008).

SC in β-YbAlB$_4$

K. Kuga, Y. Karaki, Y. Matsumoto, Y. Machida, and S. Nakatsuji, PRL**101**, 137004 (2008).





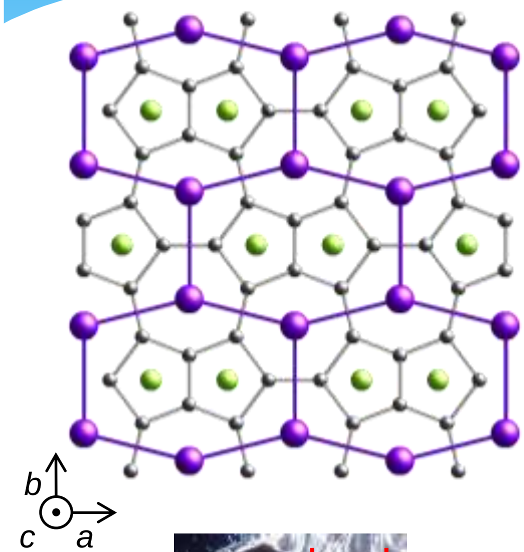


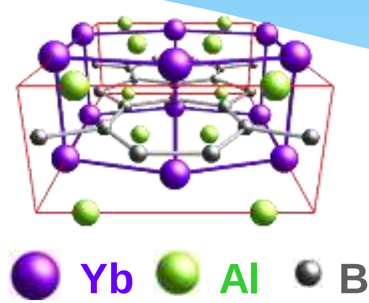
- Type-II SC in the clean limit (l = 1.2 μm > ξ = 0.06 μm) with T_c = 80 mK
- RRR dependence of T_c ⇒ **unconventional, non-s-wave SC ?**
- Considerable amounts of volume fractions → Bulk SC
- Anisotropic B_{c2} (*B // ab*: orbital critical fields, *B // c*: paramagnetic effect)
- $\partial \boldsymbol{B}_{c2} / \partial \boldsymbol{T}|_{T_c}$ = -2.6 T/K for *B // ab* → $\boldsymbol{m^*/m_0}$ **~ 180**

HF Compounds: β-, α-$YbAlB_4$

- Yb form distorted hexagonal lattice.
- Layered but Yb-Yb distance is shortest in *c* axis.

β-$YbAlB_4$





Space Group : *Cmmm*,
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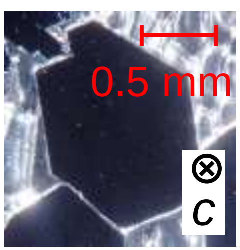
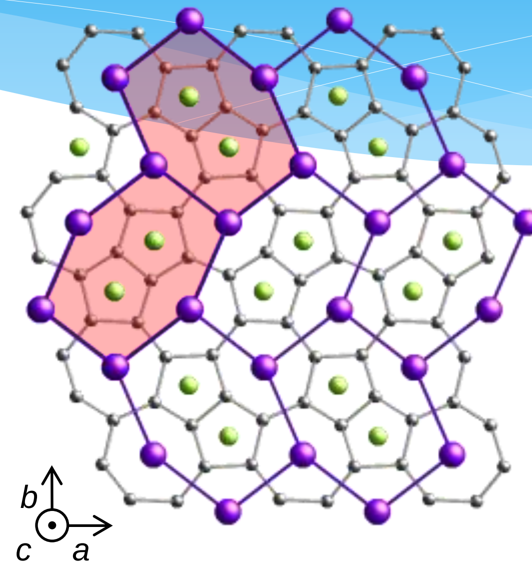
c = 3.4980 Å

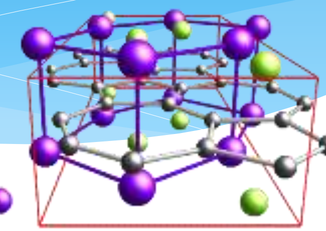


Thickness: ~10 μm

- The first HFSC (T_c = 80 mK) in Yb based system.
- Pronounced NFL behavior in the normal state @ *B* = 0.

α-$YbAlB_4$





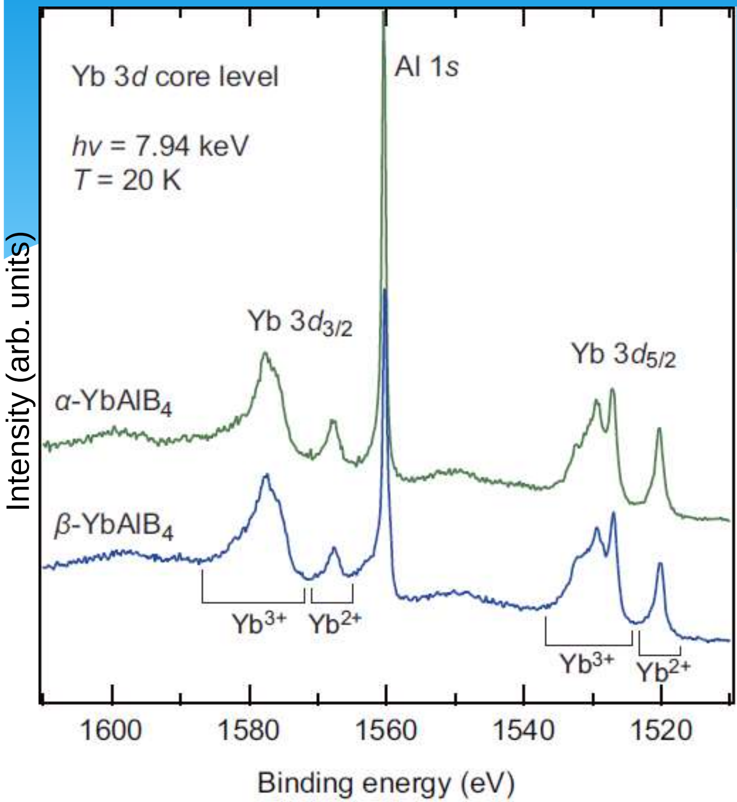
Space Group : *Pbam*
a = 5.9220(2) Å
b = 11.468(5) Å
c = 3.5060(5) Å

~ 1 x 1 x 3 mm^3

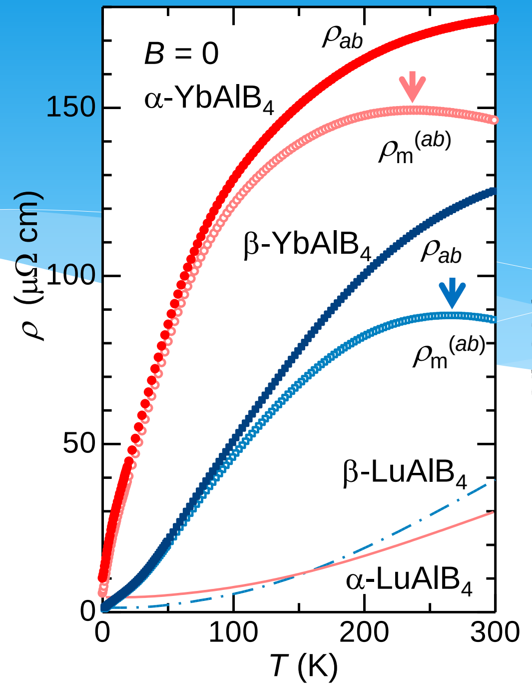
- FL ground state @ *B* = 0
- Close to QC ?
- Metamagnetic behavior @ *B* ~ 3 T

R. T. Macaluso *et al*., Chemistry of Materials **19** 1918 (2007)

Strong Valence Fluctuation in α, β-$YbAlB_4$

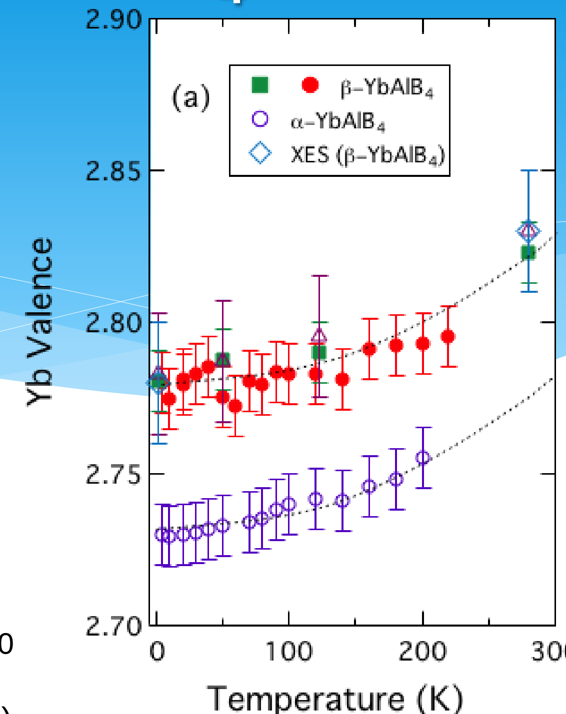


M. Okawa *et al.*, PRL **104**, 247201 (2010) .



$\rho_m = \rho\,(YbAlB_4)$ - $\rho(LuAlB_4)$

Y. Matsumoto *et al.*, PRB **84**, 125126 (2011).



Y. H. Matsuda *et al.*, JKPS **62**, 1778 (2013).

α-$YbAlB_4$: 2.73 ± 0.02

β-$YbAlB_4$: 2.75 ± 0.02

from HXPES

β phase is the first example of **QC in mixed valence system.**

Large *T* scale peculiar to mixed valence systems

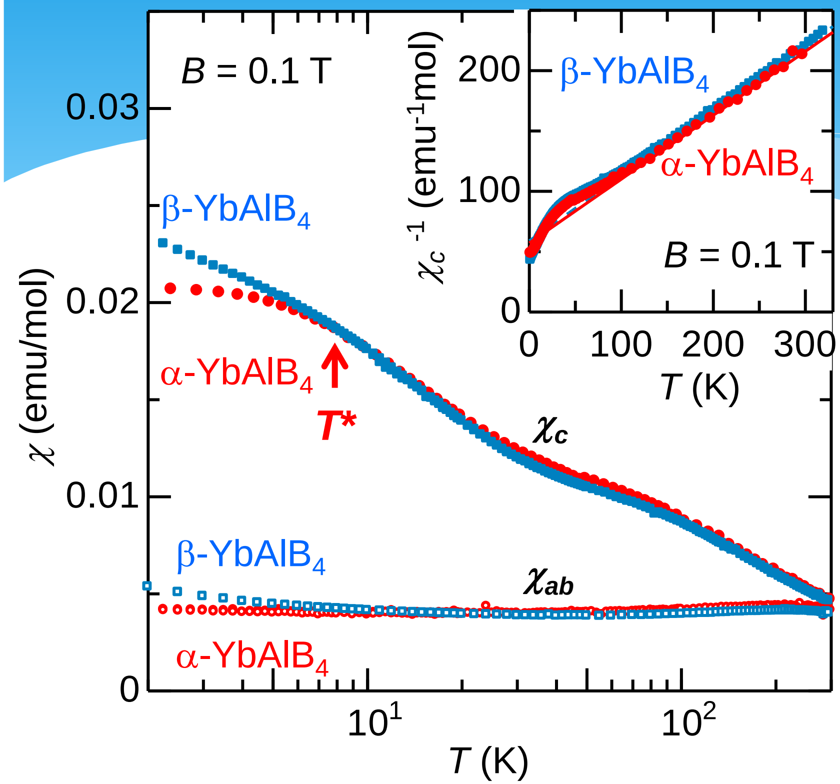
- Coherence peak of a resistivity **@ *T* ~ 200 ~ 250 K**
- ***T_0* ~ 200 K** obtained from *C.*

$$C_M / T = S_0 / T_0 \ln(T_0 / T)$$

- Yb valence measured by X-ray adsorption spectra revealed *T* scale of ~ 290 K.

Kondo lattice behavior with small T scale of ~ 8 K

Y. Matsumoto *et al.*, Science **331**, 316 (2011), Y. Matsumoto *et al.*, PRB **84**, 125126 (2011).



- Almost identical χ for α and β @ T > 8 K
- Ising like susceptibility with moments aligned along the *c*-axis
- **Curie-Weiss behavior in χ_c far below the valence fluctuation T scale**
- **Shoulder in χ_c @ T^* ~ 8 K**
  - ✓ Energy scale of Kondo lattice which emerges in low T.
  - ✓ Below T^* ~ 8 K,

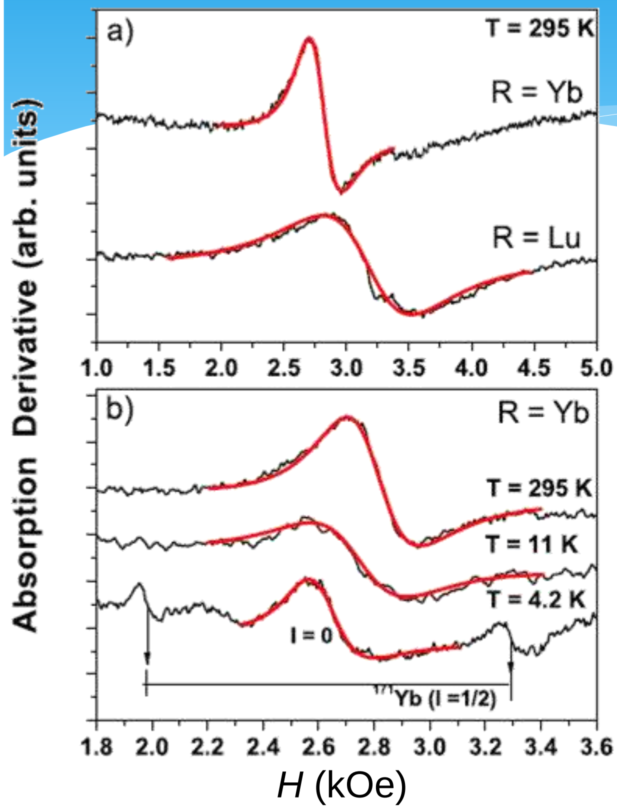
    α phase: FL ⇔ β phase: NFL
- ***C*/*T* ~ 130 mJ/K^2 mol @ 0.4 K**

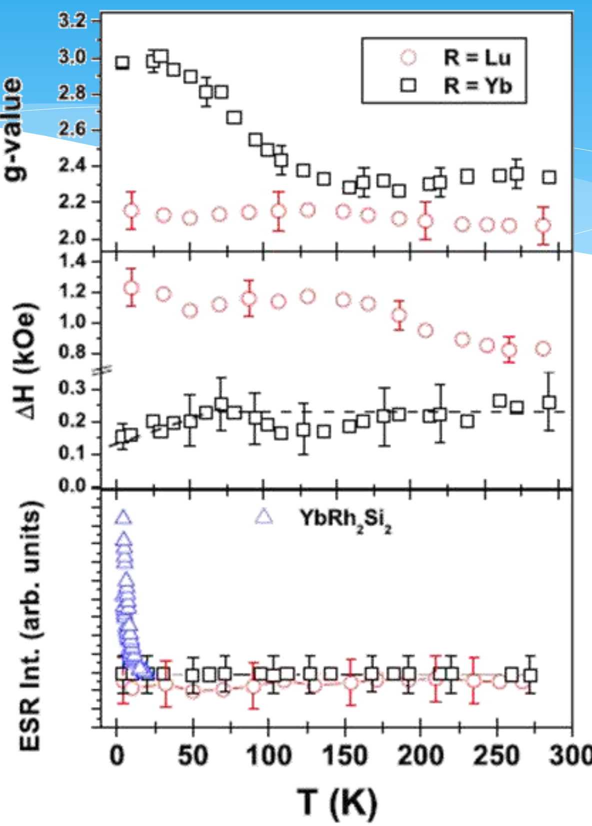
How does the small T scale 8 K coexists with large valence T scale of 200 ~ 300 K ?

Local moment behavior in ESR spectra of β-$YbAlB_4$

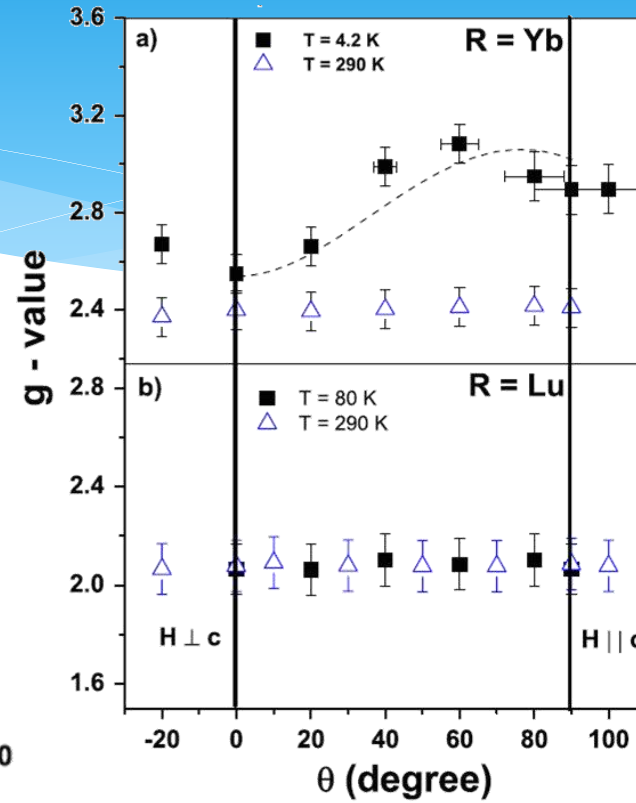
L. M. Holanda *et al.*, PRL **107**, 026402 (2011).

β-$RAlB_4$ – fine powder (X-Band)





β-$RAlB_4$ – oriented crystals (X-Band)

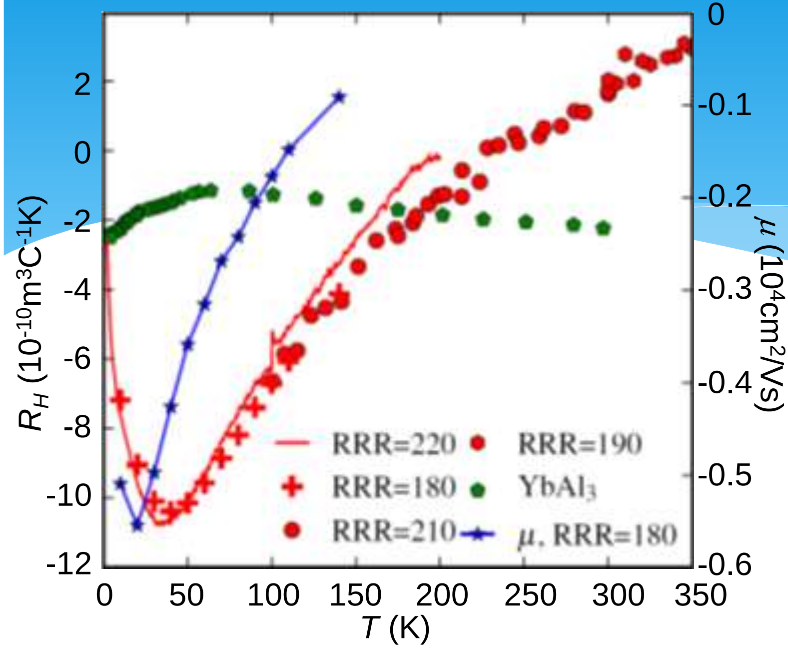


- ➢ ^{171}Yb hyperfine lines.
- ➢ *g* value increases from 2.4 to 3.0 below *T* ~ 100 K.
- ➢ anisotropy in *g* value

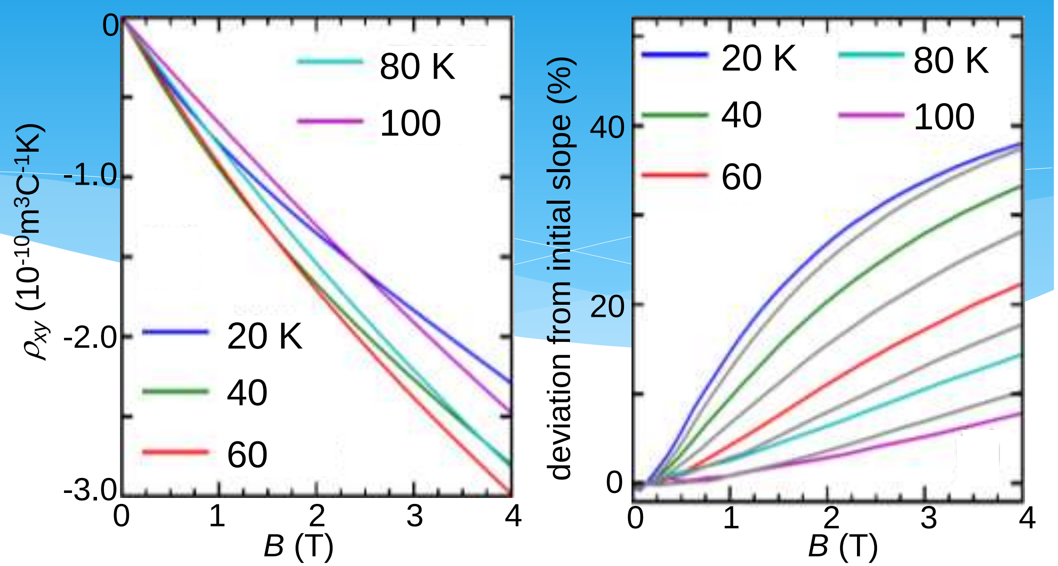
- ➢ *T* independent intensity which is typical in ESR signal for conduction electron.

Unique dual behavior

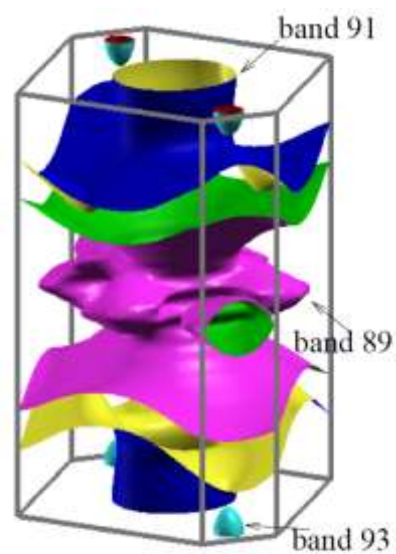
Two component Hall effect



E. C. T. O'Farrell, Y. Matsumoto, S. Nakatsuji, PRL **109**, 176405 (2012).



- Large T dependence of R_H
- R_H has a peak at T ~ 40 K ⇒ **Coherence develops below 40 K**.
- ρ_{xy} becomes non-linear in B below 100 K. This can be explained by **two band model** with
  1. **hole-like component** (band 89?) and
  2. **electron-like component with low carrier density** (band 91?).

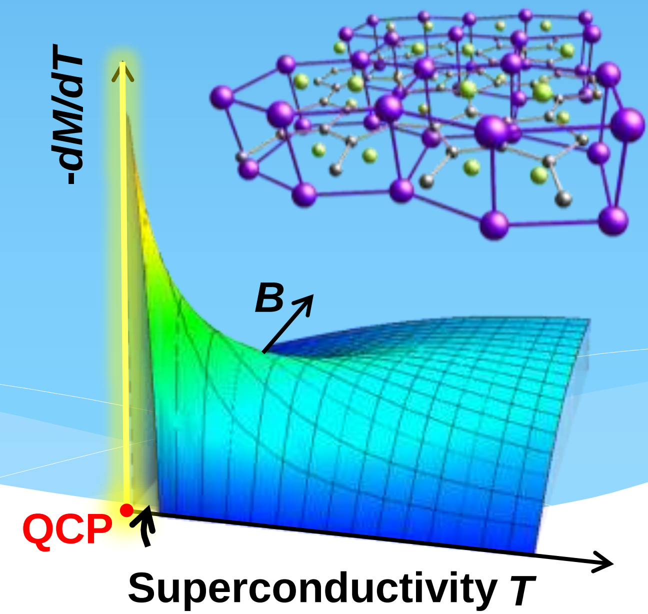


A. Nevidomsky and P. Coleman, PRL **102**, 077202 (2009). Also by E. C. T. O'Farrell *et al.*, H. Harima *et al*, and W. Pickett *et al.*

The elecrton-like component is responsible for the Kondo lattice behavior and QC ?

Quantum criticality without tuning in the mixed valence system β-$YbAlB_4$

Y. Matsumoto, S. Nakatsuji, K. Kuga, Y. Karaki, N. Horie, Y. Shimura, T. Sakakibara, A. H. Nevidomskyy, P. Coleman, Science **331**, 316 (2011).



NFL behavior @ $B = 0$ in β-$YbAlB_4$

S. Nakatsuji *et al.*, Nature Phys. **4**, 603-607 (2008).

***B* = 0:**

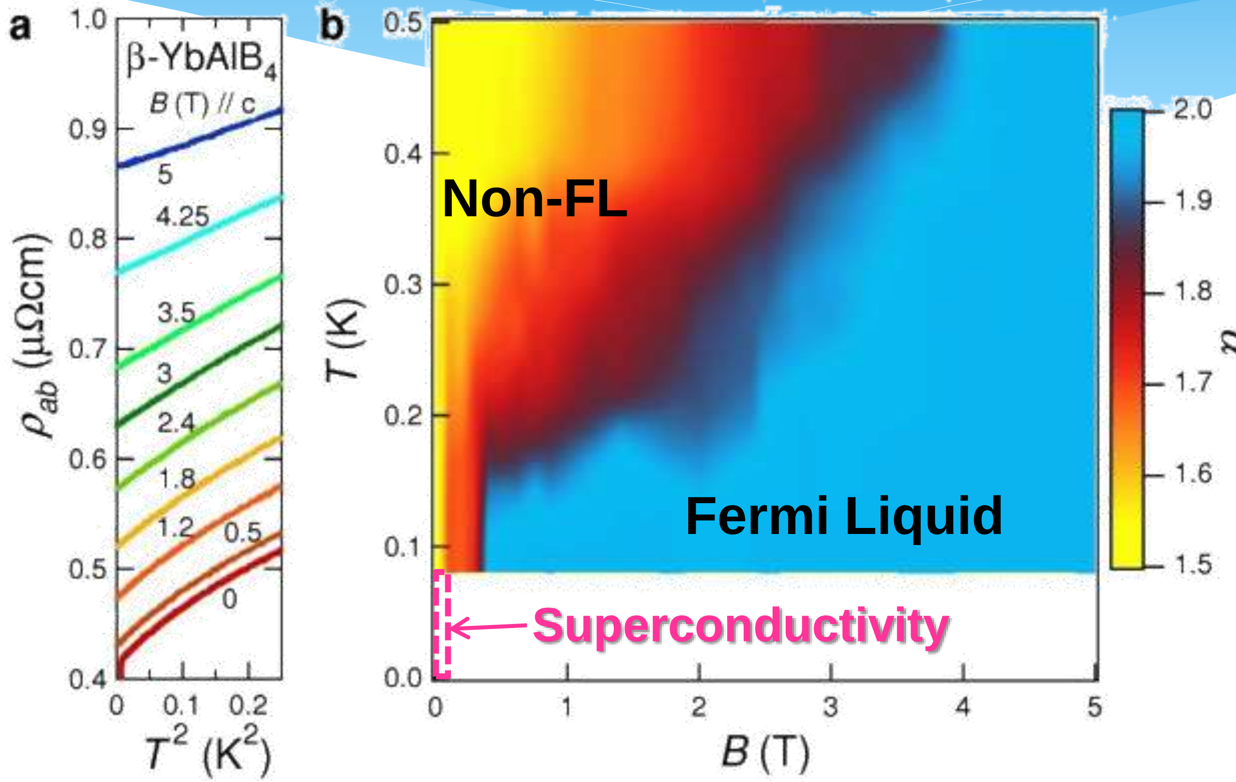
Non Fermi Liquid

- $\rho_{ab} \propto T^{1.5}$
- $M/H \propto T^{-0.5}$
- $C/T \propto \ln(T^*/T)$

In magnetic field:

Fermi Liquid

- $\rho_{ab} \propto T^2$
- M/H = const.
- C/T = const.



$\Delta\rho = \rho(T) - \rho(0) = T^{\alpha}$

FL behavior is recovered in magnetic field.

QCP at *B* = 0 under *P* = 0 ?

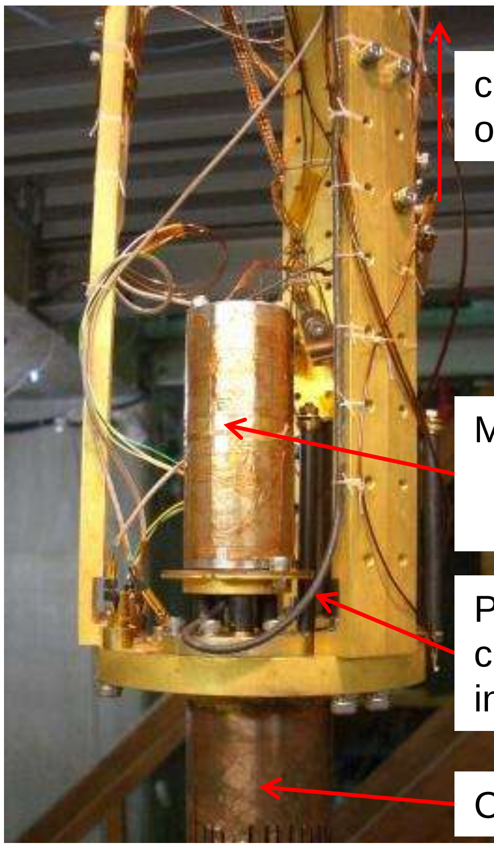
Normally, we have to tune *B* or *P* or doping to approach QCP.

ex) $YbRh_2Si_2$, $CeCoIn_5$, $CeCu_{5.9}Au_{0.1}$, …

SQUID magnetometer installed in a dilution fridge

ULT group @ ISSP, Univ. of Tokyo

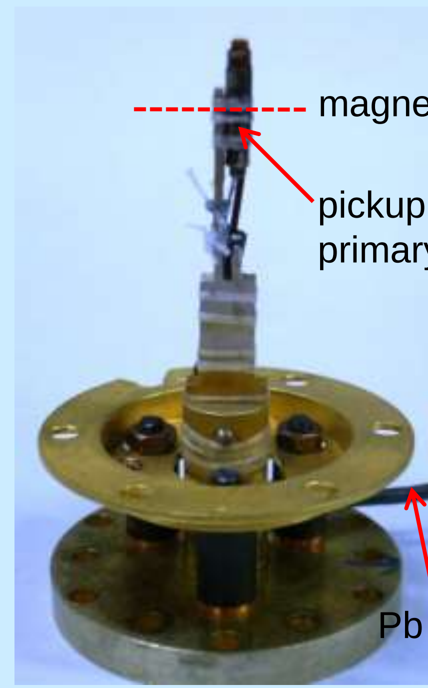
- High precision (**resolution: ~ 10^{-8} emu**)
- T range: **20 mK** ≤ T ≤ 4 K, B < 0.1 T
  T down to ~ 0.1 mK is also available by using nuclear demag
- AC susceptibility and DC magnetization can be measured.



Setup inside of the shielded magnet

pickup coils
viewed from above

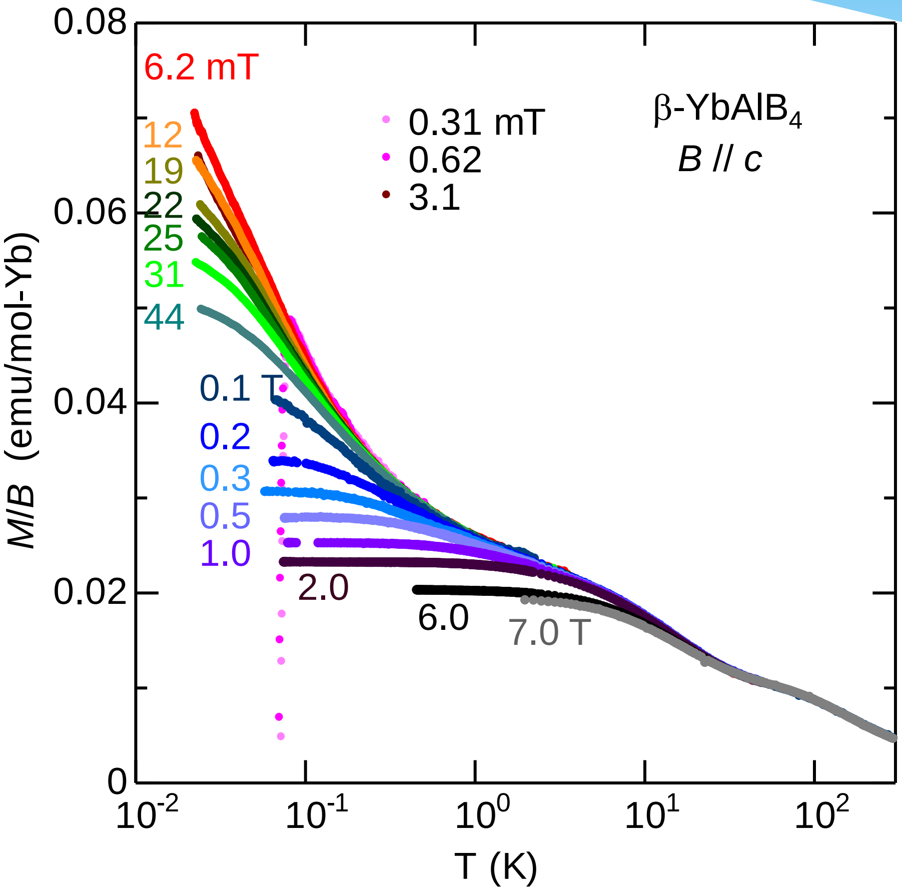
Samples:
0.82 mg,
RRR > 200

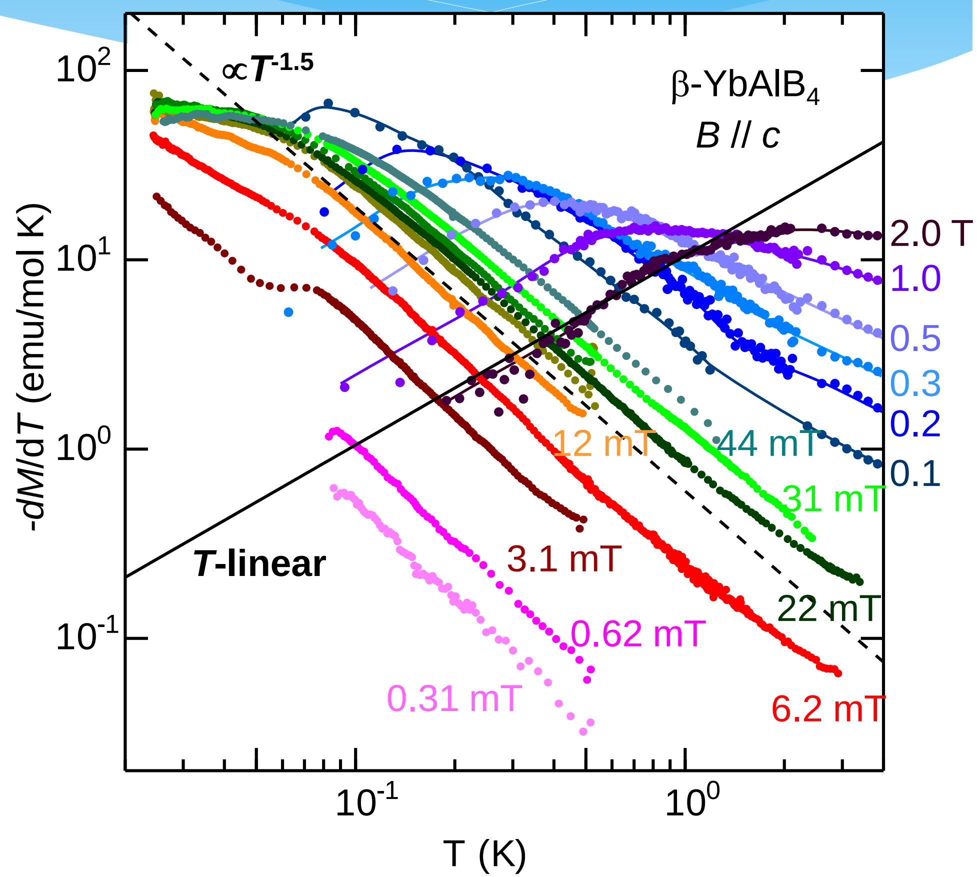


**Silver support
for pick up coils**

Diverging Susceptibility at $B \rightarrow 0$ (B // c)

Y. Matsumoto *et al.*, Science **331**, 316 (2011).

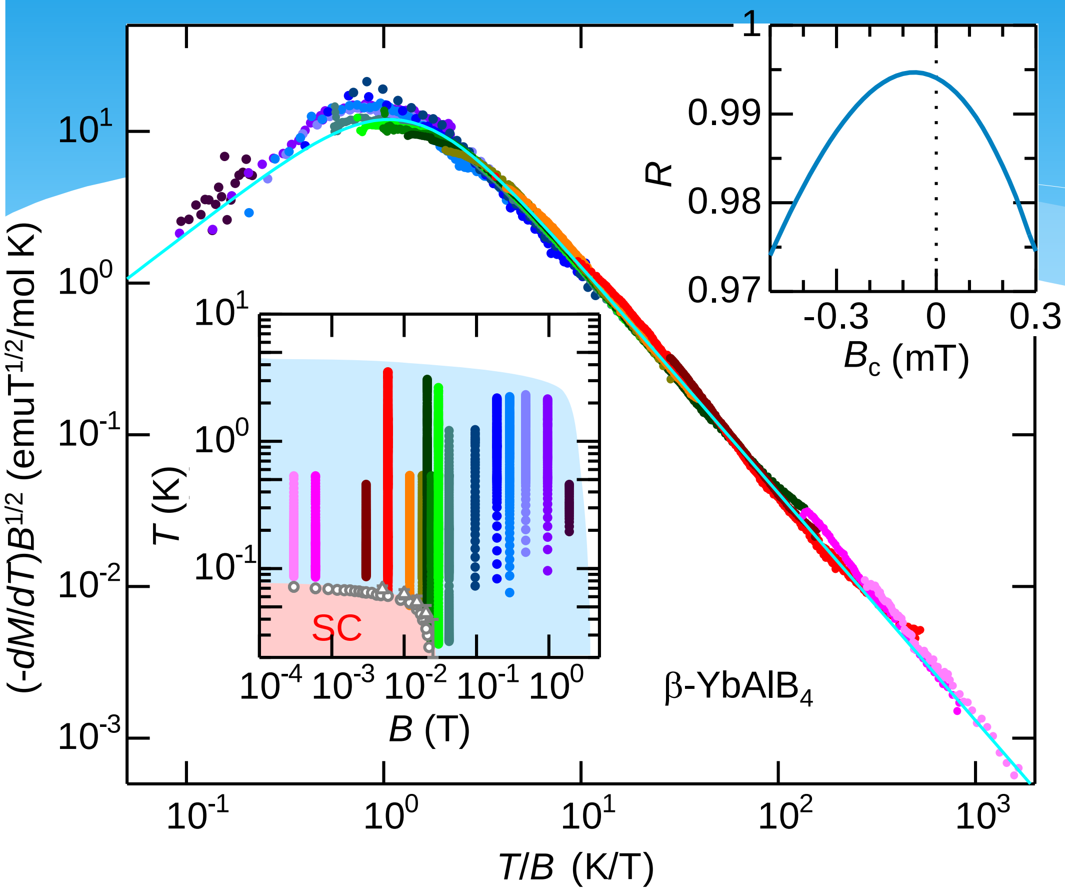




- At $T/B \gg 1$ (but below $T^* \sim 8$ K) **(NFL): $-dM/dT \propto T^{-1.5}$ ($M \propto$ const. + $T^{-0.5}$)**
- **At $T/B \ll 1$ (FL): $-dM/dT \propto T$**

T/B Scaling of Magnetization

Y. Matsumoto *et al.*, Science **331**, 316 (2011).



- **-dM/dT @ $B \leq 2$ T, $T \leq 3$ K satisfy following scaling equations.**

$$-\frac{\partial M}{\partial T} = B^{\alpha-2}\phi(T/B)$$

with $\alpha = 3/2$

Integrating both parts,

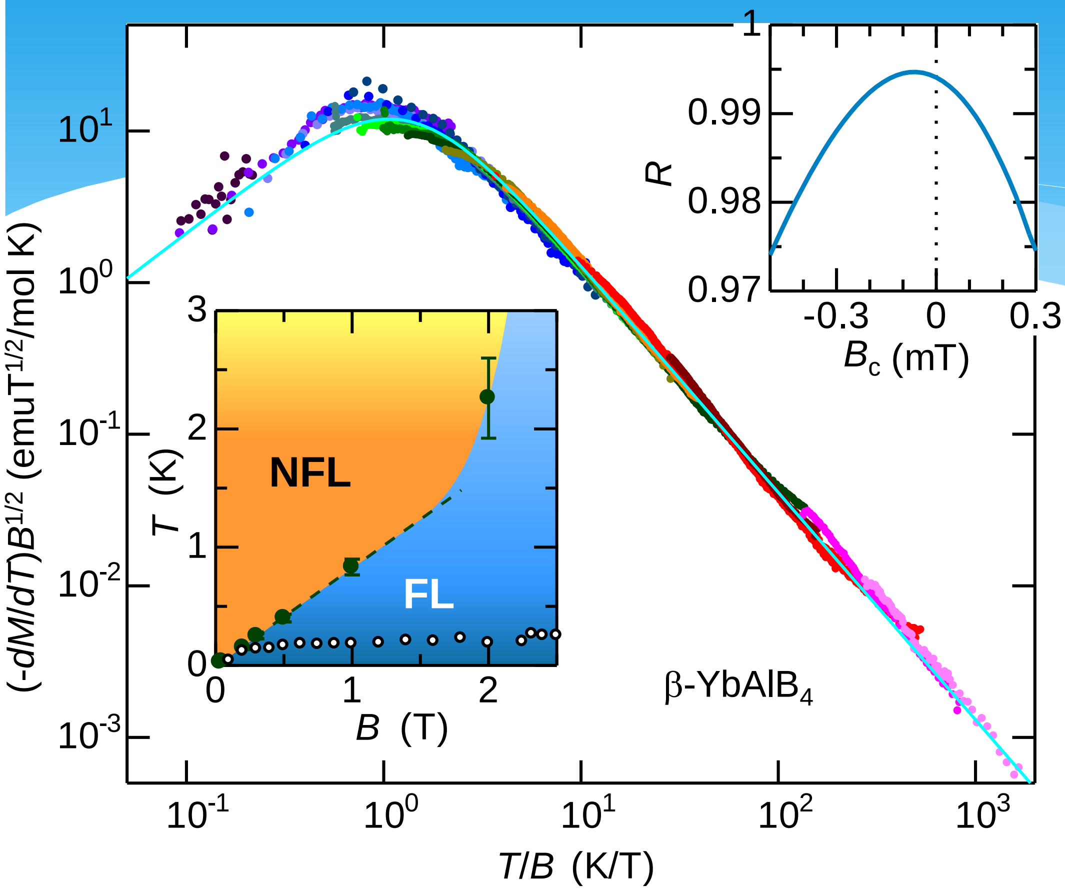
$$F = B^{\alpha} f(T/B)$$

$$\phi(x) = (\alpha-1)f'(x) - xf''(x)$$

- **Scaling observed over 4 orders of *T*/*B***
- **No intrinsic energy scale** (*T* and *B* are interchangeable) **@ $B \leq 2$ T, $T \leq 3$ K.**
- **QCP is not of a SDW type**

T/*B* Scaling of Magnetization

Y. Matsumoto *et al.*, Science **331**, 316 (2011).



- The data can be fitted to

$$\phi(x) = \Lambda x(A + x^2)^{-n}$$

with $x = T / (B - B_c)$

This satisfy the limiting behavior of $f(x)$, *i.e.*, $f(x) \propto \begin{cases} x^{\alpha} & (x >> 1, \text{NFL}) \\ \text{const} + x^2 & (x << 1, \text{FL}) \end{cases}$

The best fit was obtained with

$$\begin{cases} n = 1.25 \pm 0.01 \\ \quad (\alpha = 3/2 \pm 0.02) \\ B_c = 0.1 \pm 0.1 \text{ mT} \end{cases}$$

- **$|B_c| \leq 0.2$ mT (2 G)**
  - ✓ ***B_c is practically zero***
  - ✓ ***$\mu_0 H_{c2}/B_c > 100$***
  - ✓ ***Zero-field Quantum Criticality***

The first example of quantum criticality without tuning !!

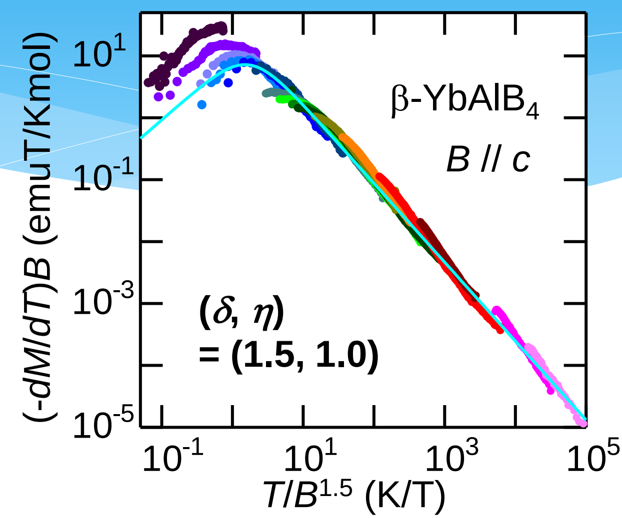
$T/(B-B_c)^{\delta}$ scaling with $\delta \neq 1$, $B_c \neq 0$?

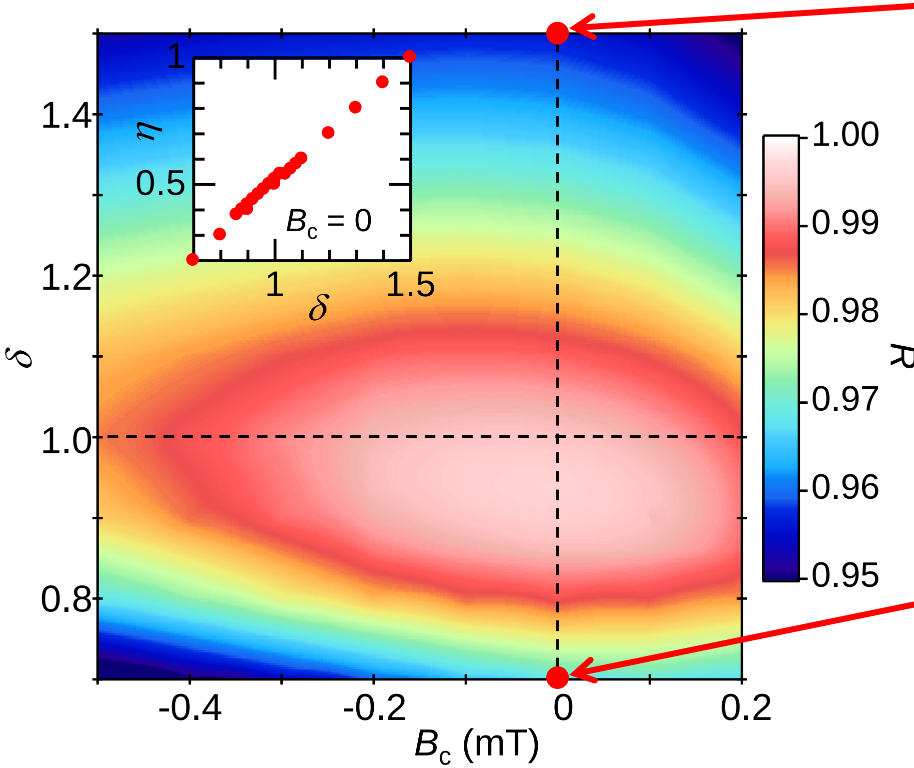
More general form was checked.

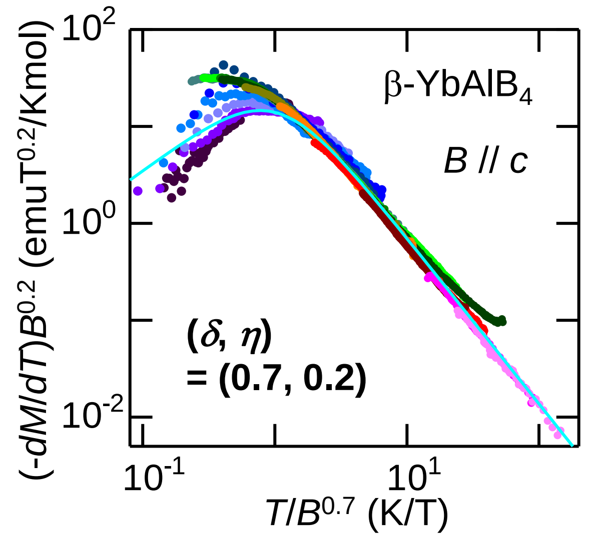
$$-\frac{dM}{dT} = (B - B_c)^{-\eta}\,\phi\left(\frac{T}{(B - B_c)^{\delta}}\right)$$

The best fit is obtained with
$(B_c, \delta) = (-0.02 \pm 0.20\ \text{mT}, 0.94 \pm 0.12)$

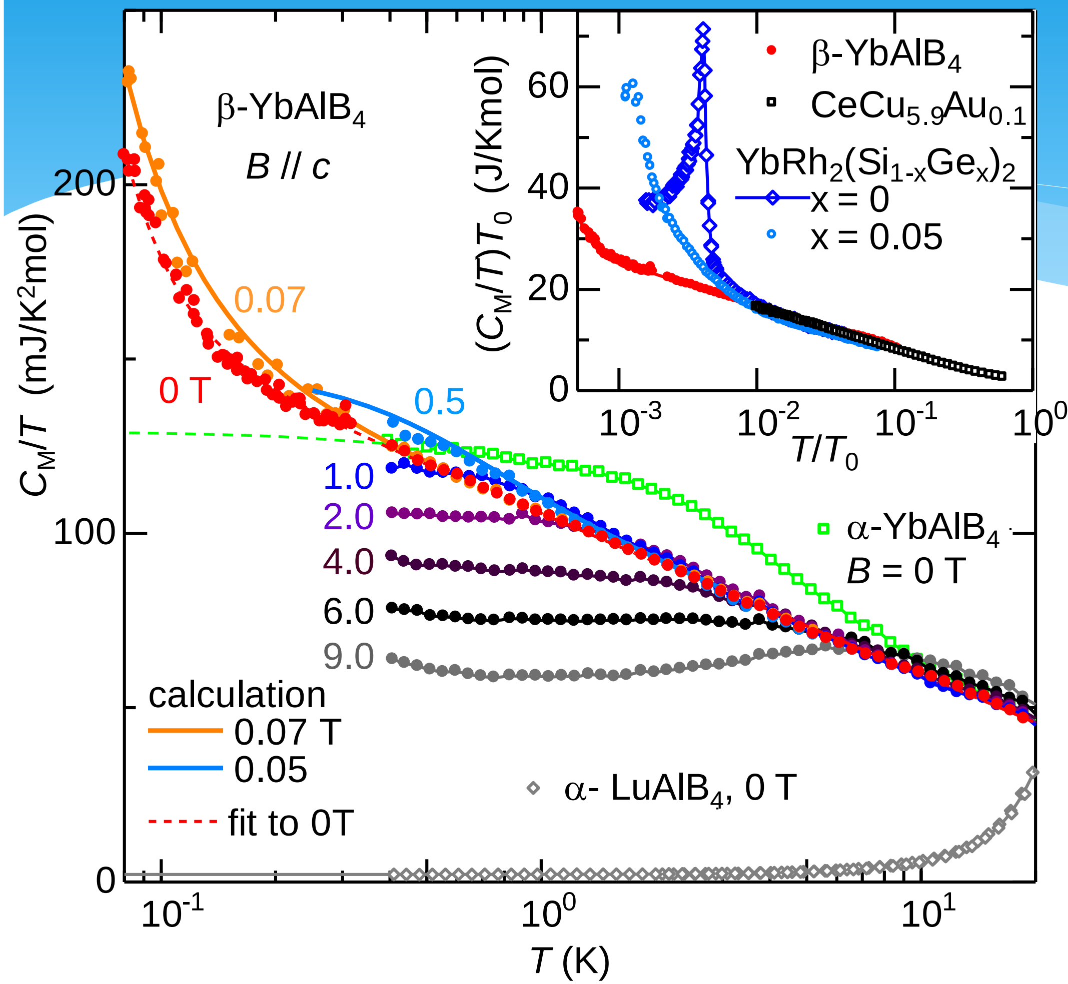
⇒ ***T/B* scaling is most likely!**







Specific Heat



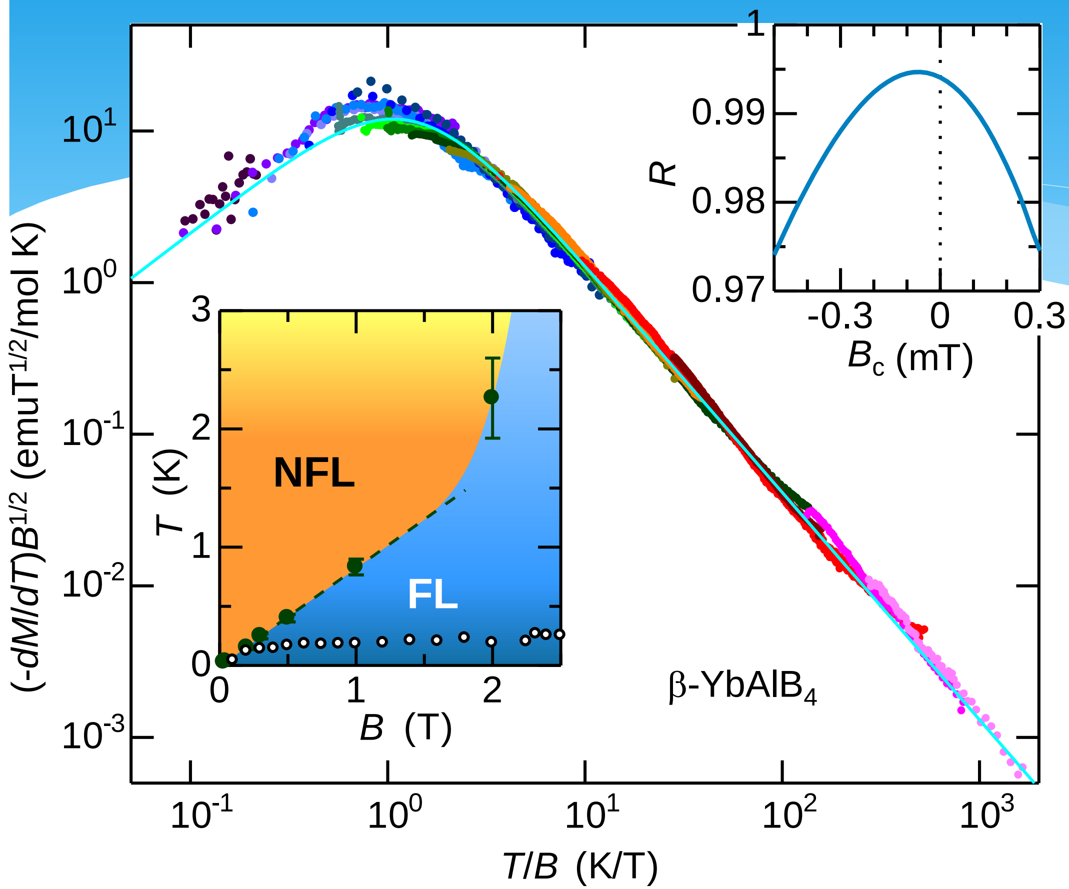
Y. Matsumoto *et al*., Science **331**, 316 (2011).

- $C_M/T \sim \ln(T_0/T)$ @ $T \geq 0.2$ K with $T_0 = 200$ K
  - $CeCu_{5.9}Au_{0.1}$: 6.2 K
  - $YbRh_2Si_2$: 24 K
- **Further increase below 0.2 K**
  - **QC without tuning**
- The scaling indicates $C_{QC}/T \propto T^{-0.5}$.
  - Difficult to extract due to the nuclear contribution.
- **Small increase @ $B \leq 0.5$ T is consistent with the scaling**. This can be checked by Maxwell's relations.

$$\left(\frac{\partial S}{\partial B}\right)_T = \left(\frac{\partial M}{\partial T}\right)_B$$

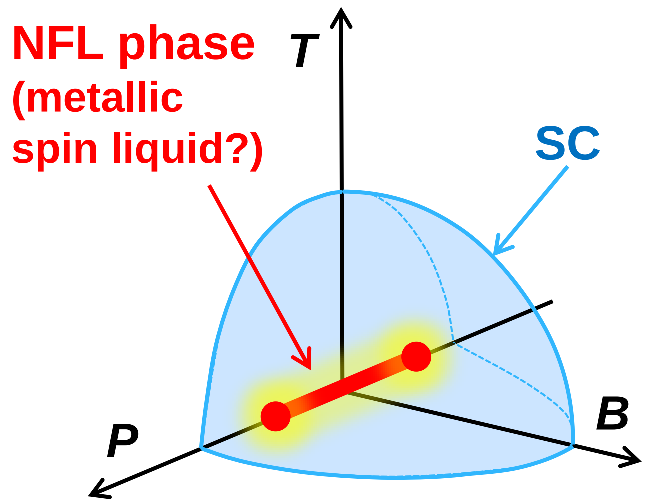
$$\Rightarrow \frac{C}{T} = \int_0^B \frac{\partial^2 M}{\partial T^2} dB + \left(\frac{C}{T}\right)_{B=0}$$

Why $B_c = 0$?



Y. Matsumoto *et al*., Science **331**, 316 (2011).

1. Fine tuned to QCP?
2. **Non-fermi liquid phase or Quantum Critical Phase**, More natural than the above accidental scenario.

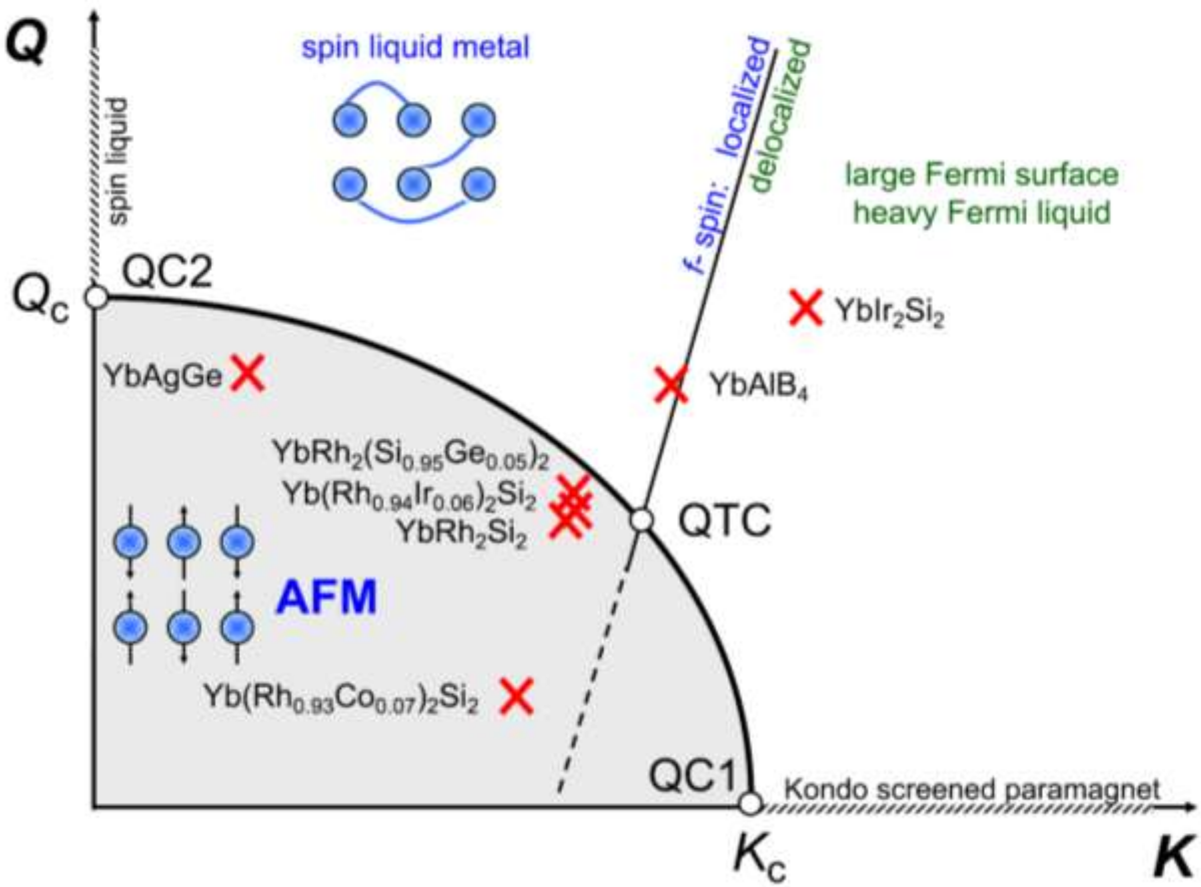


- **What happens under pressure ?**
- **NFL behavior robust against pressure ?**

What is the origin ?

Topological phase transition at P_c?

- Partial Mott localization of the *f*-electrons ?
- Spin liquid metal @ ambient pressure ?



J. Custers *et al*., PRL **104**, 186402 (2010).
References therein.

What is the origin ?

Kondo break down QCP at mixed valence

J. H. Pixley, S. Kirchner, K. Ingersent, Q. Si, PRL **109**, 086403 (2010).

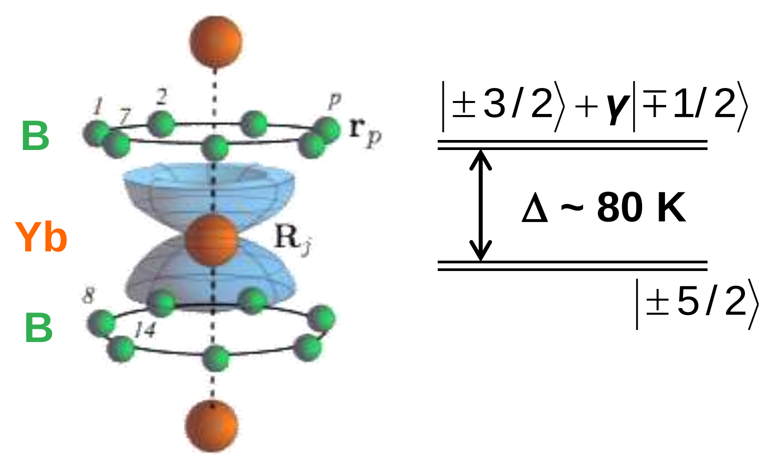
Valence quantum criticality?

S. Watanabe, K. Miyake, PRL **105**, 186403 (2010).

Anisotropic hybridization effect ?

A. Nevidomsky and P. Coleman, PRL **102**, 077202 (2009), A. Ramires *et al*., PRL **109**, 176404 (2012).

- **A hybridization node along the *c*-axis**
  CEF ground doublet $|J_z = \pm 5/2 >$ based on the local Yb site symmetry
- *c*-*f* hybridization $V(\mathbf{k}) \sim (k_x \pm i k_y)^2$
- **2D heavy band with a dispersion $E(\mathbf{k}) \sim |V(\mathbf{k})|^2 \sim (k_\perp)^4$ explains QC in β-$YbAlB_4$, if $E_f = 0$?**



- Topological phase transition
- **Highly anisotropic resistivity in α-$YbAlB_4$ with $\rho_{ab}/\rho_c \sim 11$ @ LT**
  Consistent with hybridization node along the *c*-axis

Y. Matsumoto, K. Kuga, T. Tomita, Y. Karaki and S. Nakatsuji, PRB **84**, 125126 (2011).

Summary

- In spite of the **strong valence fluctuation** with characteristic T scale of **200-300 K**, the both α- and β-$YbAlB_4$ exhibit **Kondo lattice behavior** with low-T scale of ***T* ~ 8 K***.
- Contrasting behavior below $T^* \sim 8$ K

  α phase: FL ⇔ **β phase: QC without tuning + SC**

- ***T/B* scaling of magnetization** observed over 4 decades of T/B in β-$YbAlB_4$ → **QC without tuning**
- Resistivity measurements under P revealed **strange metal phase extends up to P_c ~ 0.4 GPa**
- **Strange metal phase detached from magnetic order**
- What is the origin ?
  - ✓ topological phase transition?
  - ✓ valence? …