Field-induced quantum critical point and nodal superconductivity in the heavy-fermion superconductor Ce_2PdIn_8

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Outline：

1. Ultra-low-temperature heat transport measurement

2. Field-induced QCP and nodal superconductivity in Ce_2PdIn_8

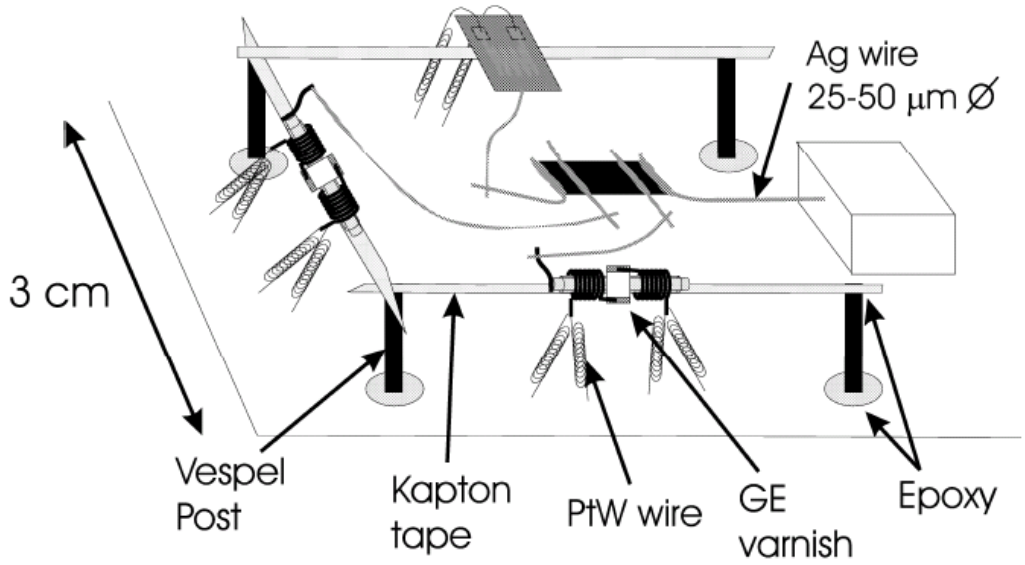
3. Research groups in Fudan University

Collaborators:

J. K. Dong, H. Zhang, X. Qiu, B. Y. Pan, Y. F. Dai, T. Y. Guan, S. Y. Zhou

D. Gnida, D. Kaczorowski
Institute of Low Temperature and Structure Research, Poland

1. Ultra-low-temperature heat transport measurement



^{3}He-^{4}He dilution fridge
T→7 mK; H→17 T

$$\kappa = \alpha \frac{\dot{Q}}{\Delta T}$$

$T \to 0$ separate κ_e and κ_{ph}

$$\kappa = \kappa_{electrons} + \kappa_{phonons} + \kappa_{magnons} + \kappa_{spinons} + \ldots$$

$$\kappa = 1/3\ C\ v\ l$$

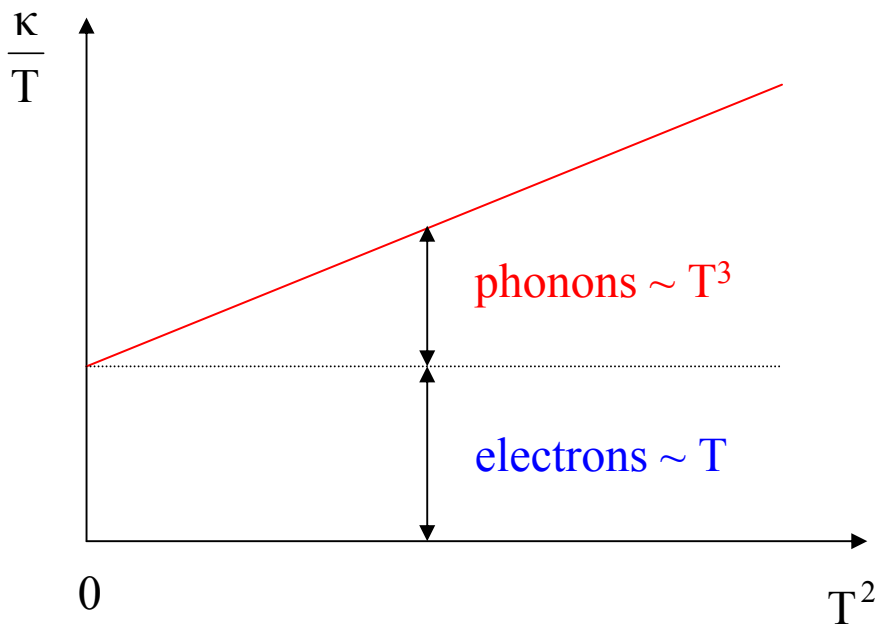
FERMIONS (Electrons)

$\kappa \propto C_e \propto T$

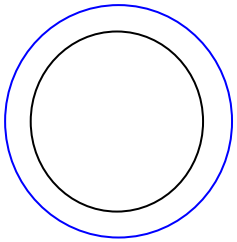
BOSONS (Phonons)

$\kappa \propto C_{ph} \propto T^3$

$$\kappa/T = A + BT^2$$

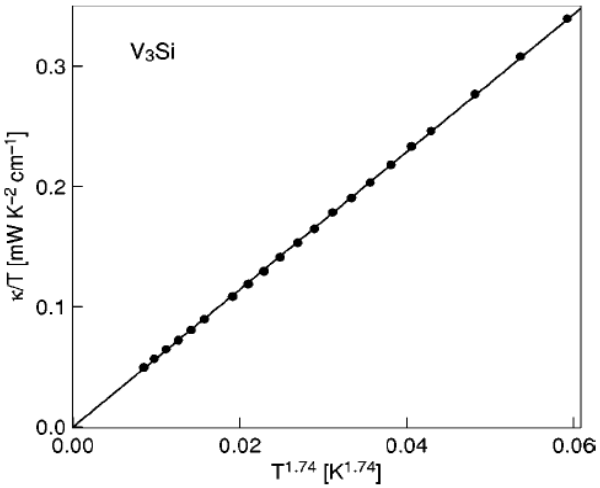


$T \to 0$ Superconducting gap probed by κ



s-wave gap

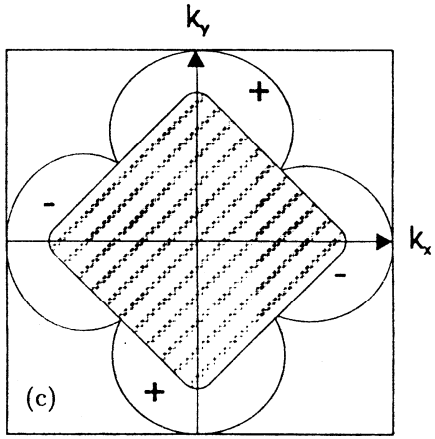
$\Delta = \Delta_0$



V_3Si， $T_c = 17$ K

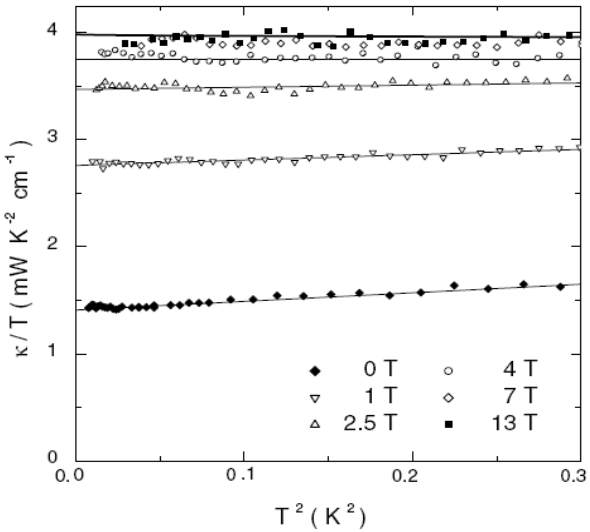
All electrons form Cooper pairs as $T \to 0$：

$\kappa_0/T = 0$



d-wave gap

$\Delta = \Delta_0 \cos(2\phi)$

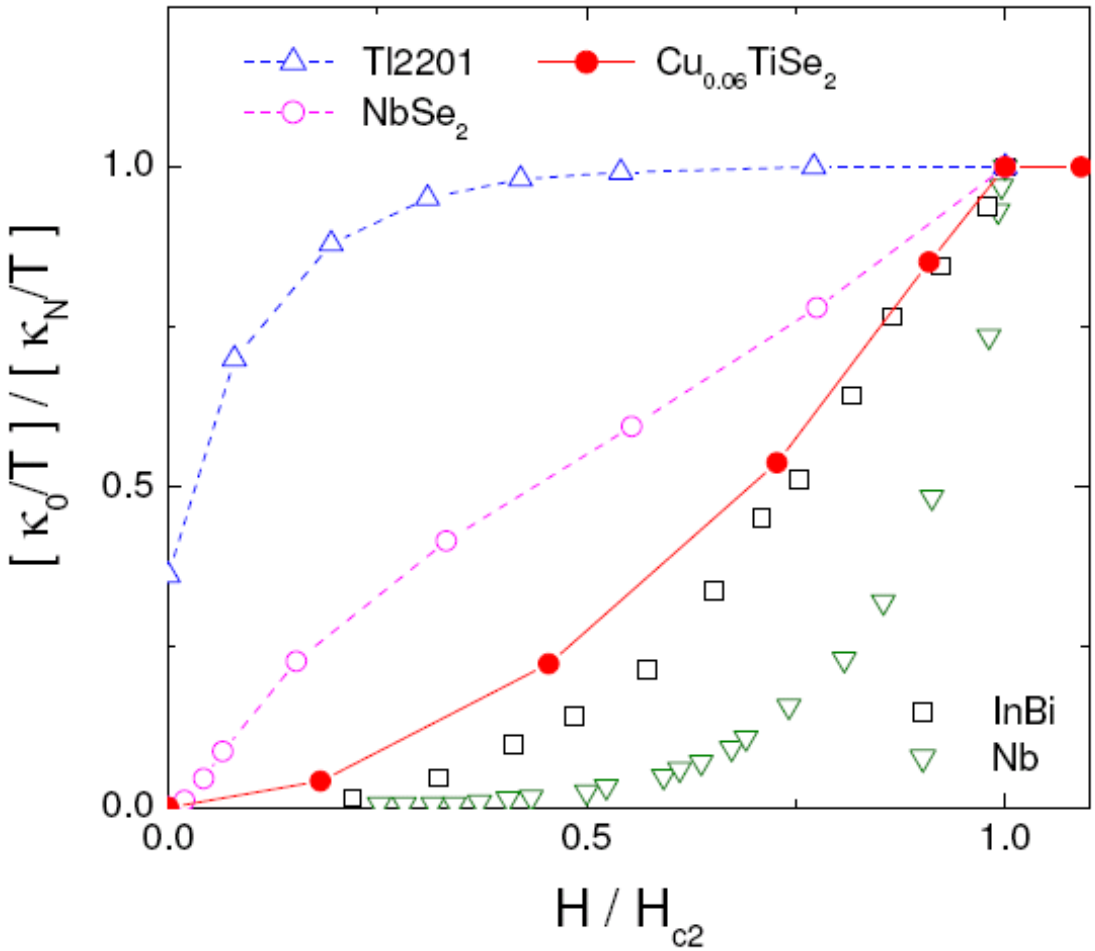


$Tl_2Ba_2CuO_{6+\delta}$， $T_c = 15$ K

Finite density of delocalized states at zero energy due to gap nodes and impurity:

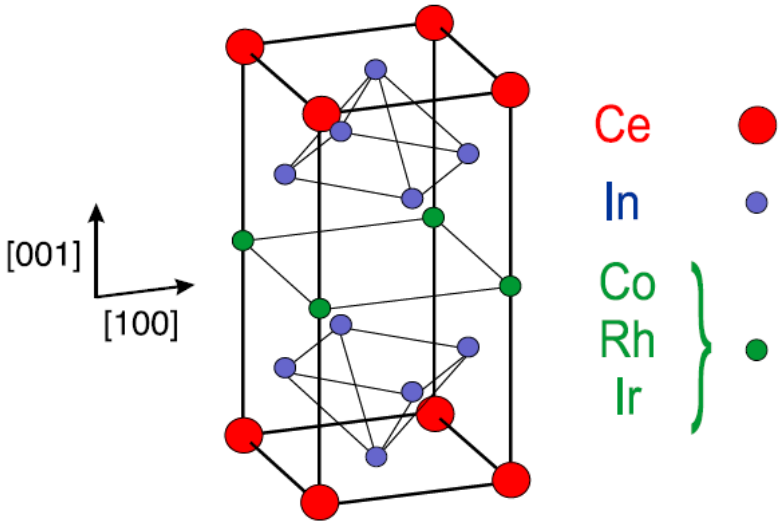
$\kappa_0/T = c$

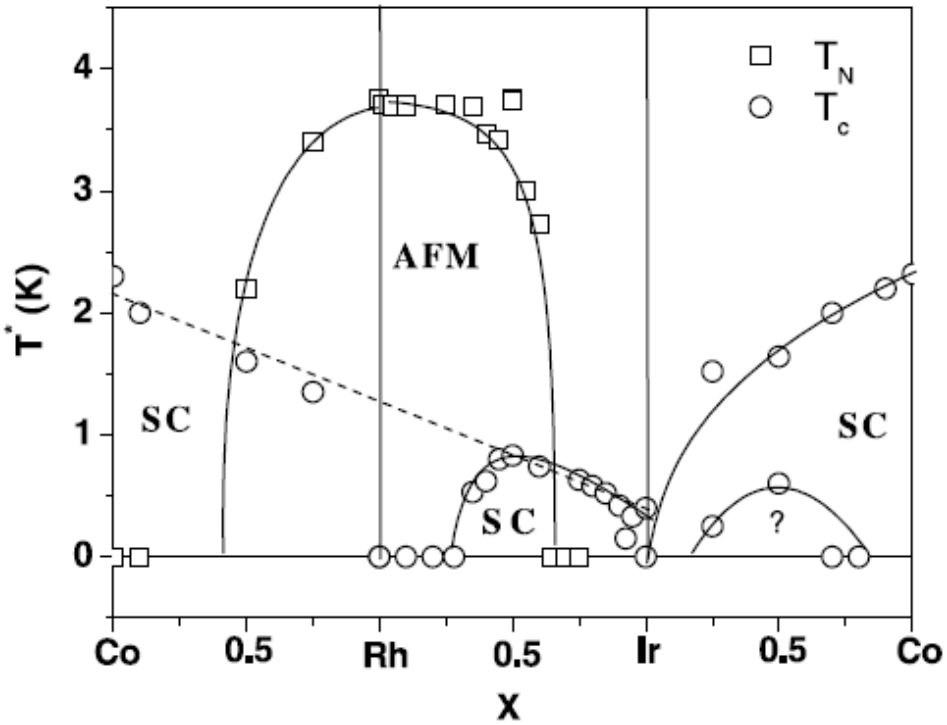
$\kappa_0/T(H)$ for different superconducting gap structures



S. Y. Li *et al.*, PRL **99**, 107001 (2007)

2. Field-induced QCP and nodal superconductivity in Ce_2PdIn_8





$CeRhIn_5$, T_N = 3.8 K;
$CeIrIn_5$, T_c = 0.4 K;
$CeCoIn_5$, T_c = 2.3 K.

$CeIn_3$, T_N = 10.1 K,
T_c = 0.2 K@26 kbar.

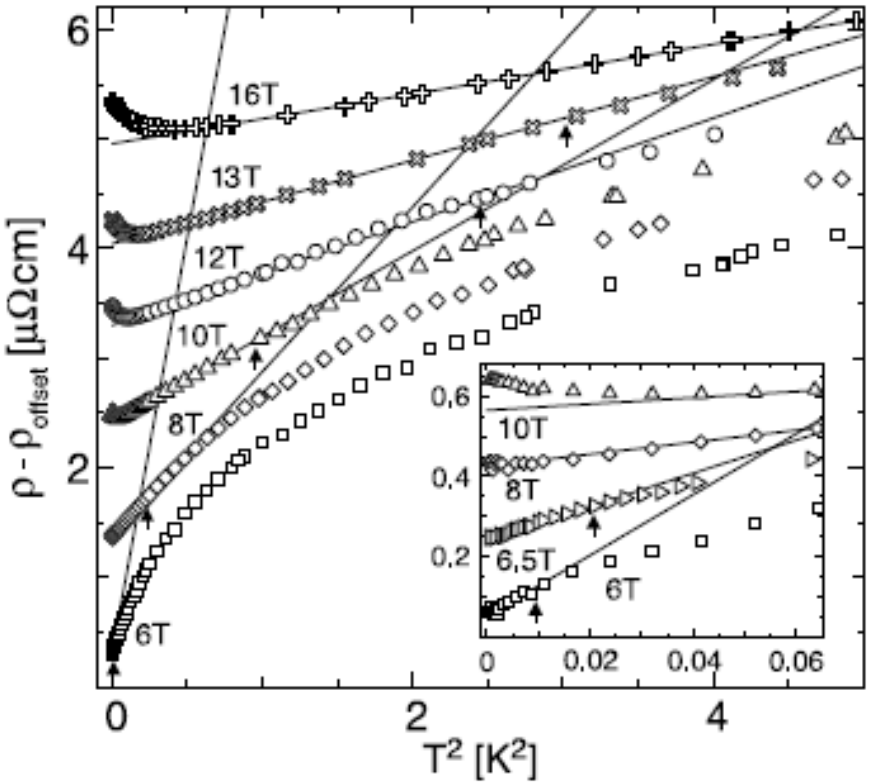
H. Hegger *et al.*, PRL **84**, 4986 (2000) Times cited: 551
C. Petrovic *et al.*, EPL **53**, 354 (2001) Times cited: 324
C. Petrovic *et al.*, JPCM **13**, L337 (2001) Times cited: 381

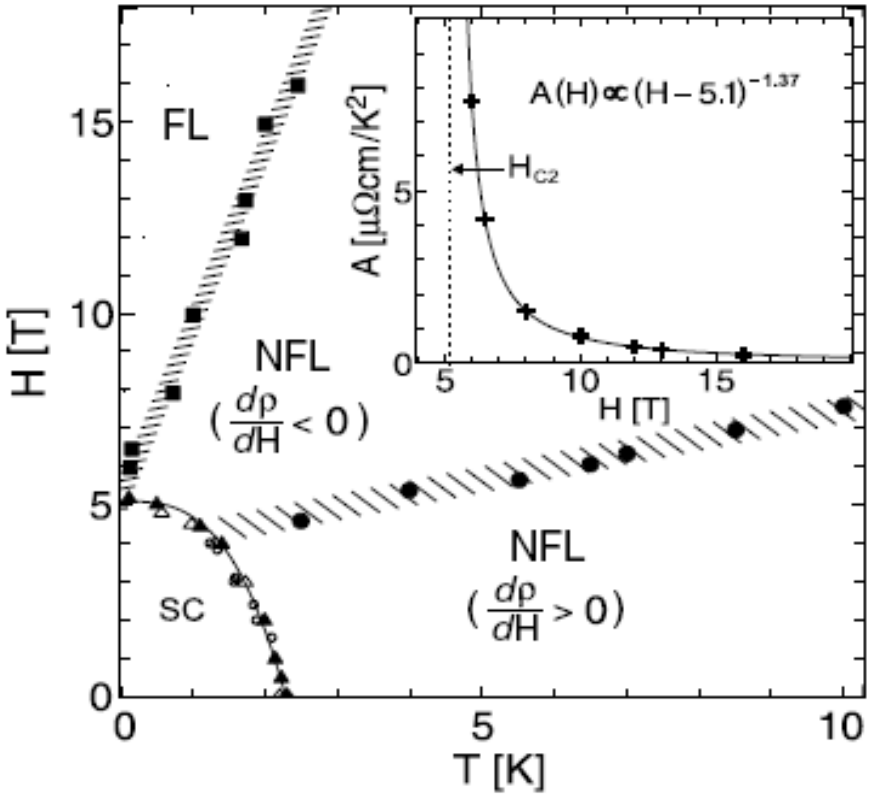
N. D. Mathur et al., Nature 394, 39 (1998) Times cited: 881

J. D. Thompson, Z. Fisk, JPSJ **81**, 011002 (2012)

QCP at H_{c2}

$\rho(T)$ of $CeCoIn_5$



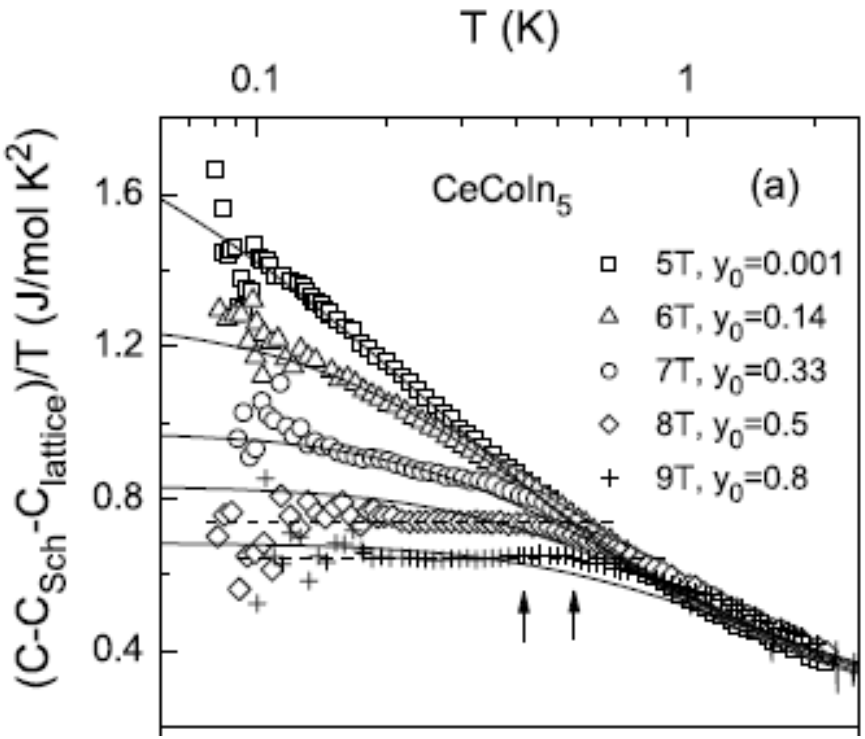


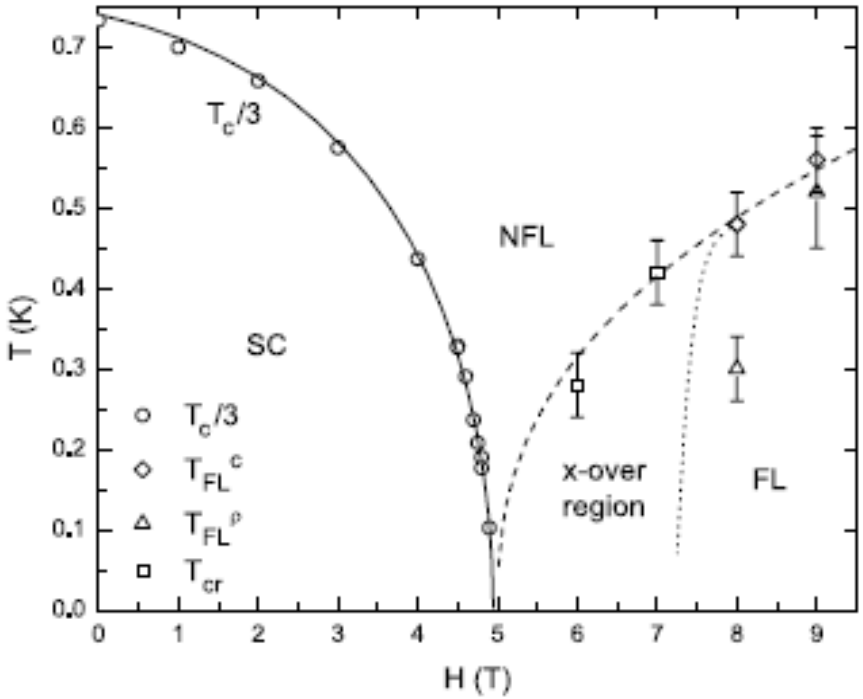
In $CeCoIn_5$, a field-induced AF QCP is located at H_{c2} = 5.1 T.

J. Paglione, Louis Taillefer *et al.*, PRL **91**, 246405 (2003)

QCP at H_{c2}

C(T) of $CeCoIn_5$

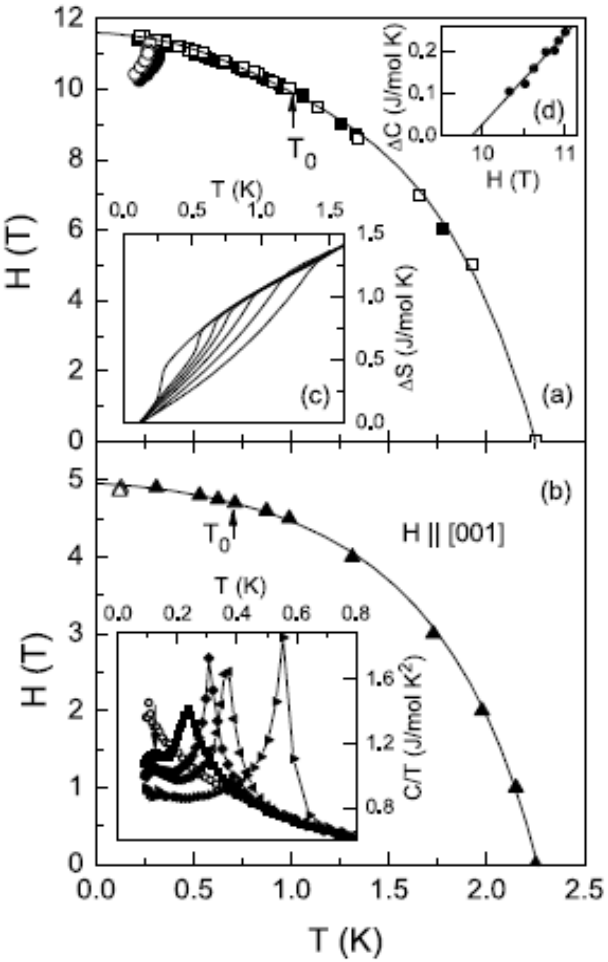




In $CeCoIn_5$, a field-induced AF QCP is located at H_{c2} = 5 T.

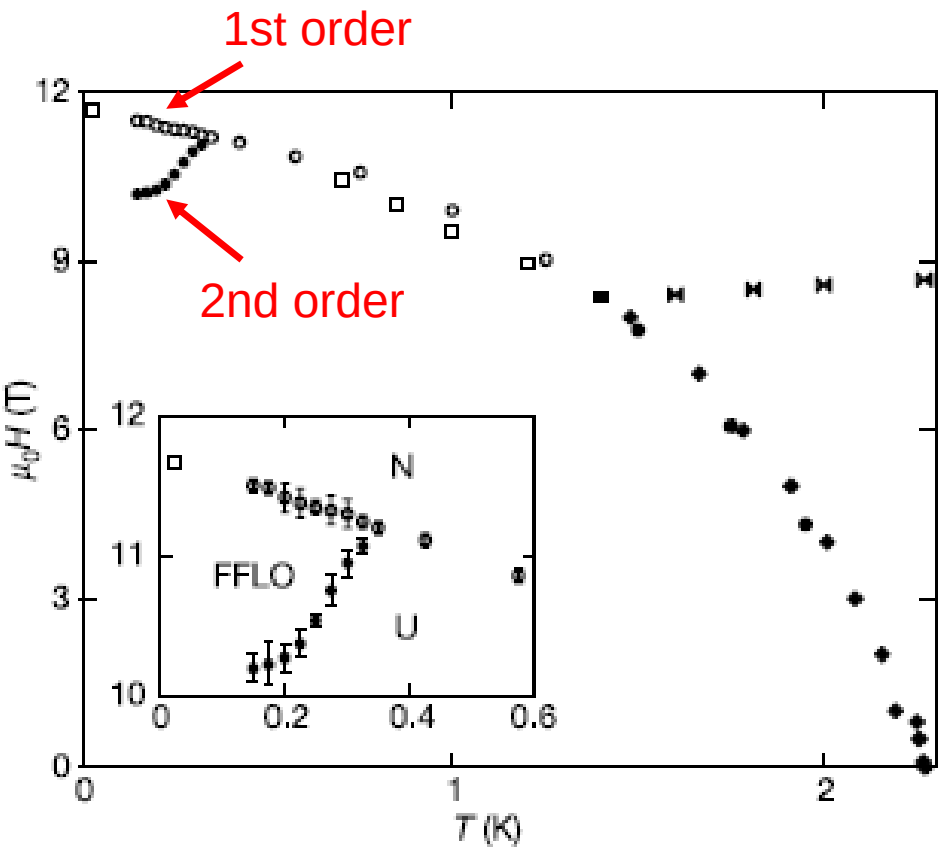
A. Bianchi *et al.*, PRL **91**, 257001 (2003)

FFLO Possible in $CeCoIn_5$



Specific heat

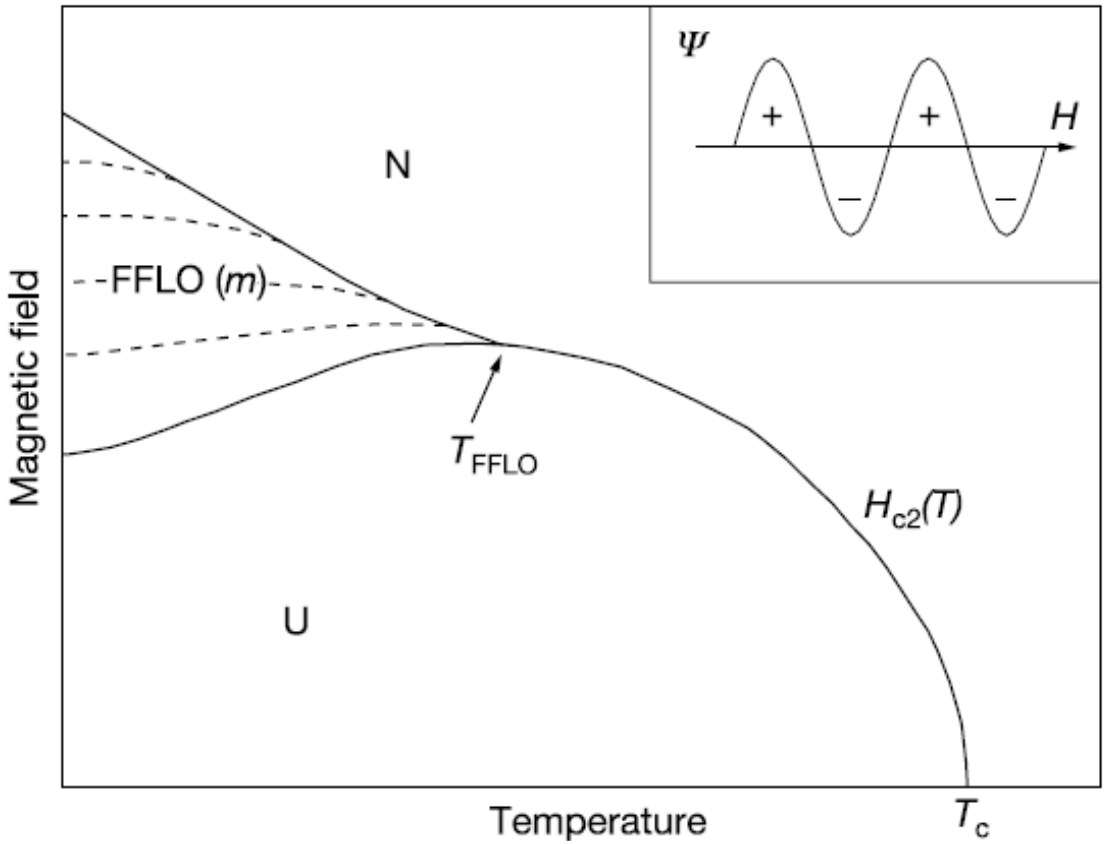
A. Bianchi *et al.*, PRL **91**, 187004 (2003)



Specific heat, magnetization,

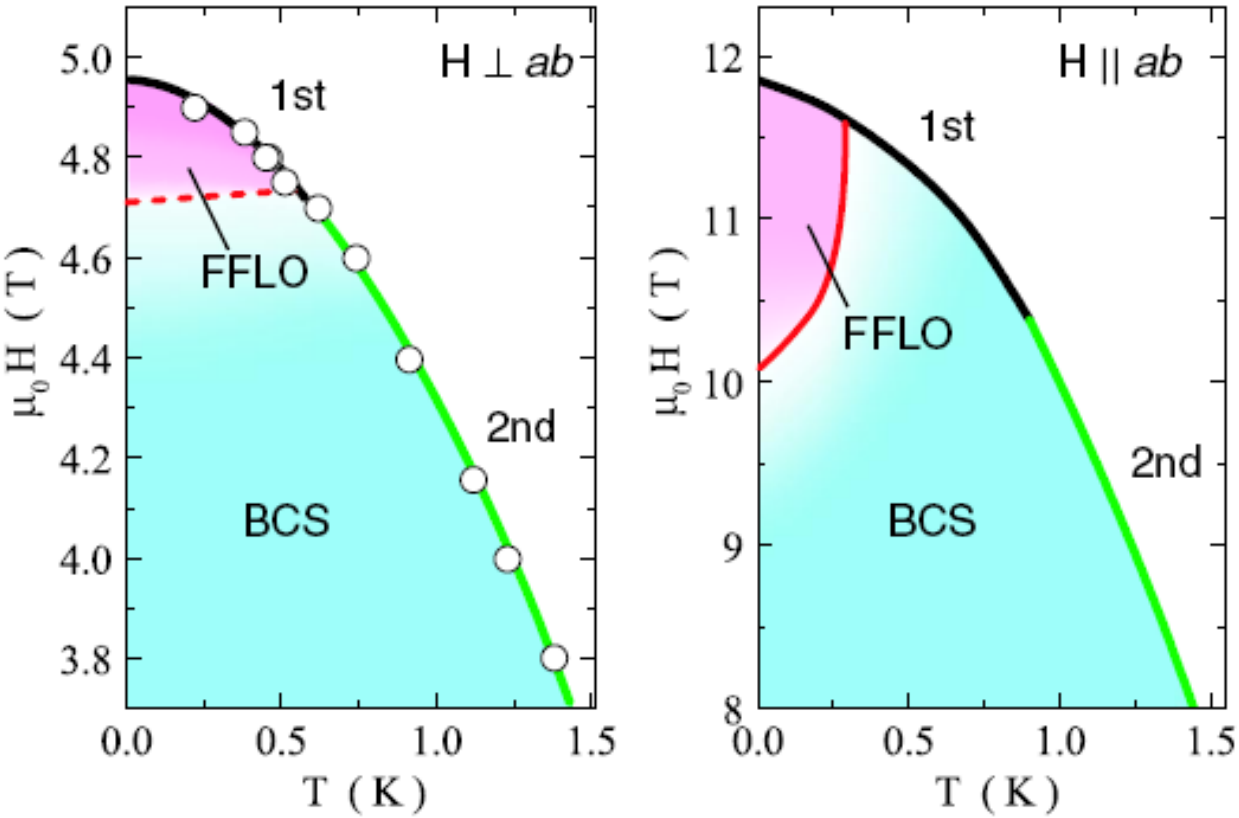
H. A. Raddovan *et al.*, Nature **425**, 51 (2003)

FFLO Spatial symmetry spontaneously broken



A novel superconducting phase with spatially inhomogeneous order parameter.
Predicted by Fulde, Ferrell, Larkin and Ovchinnikov in 1964.

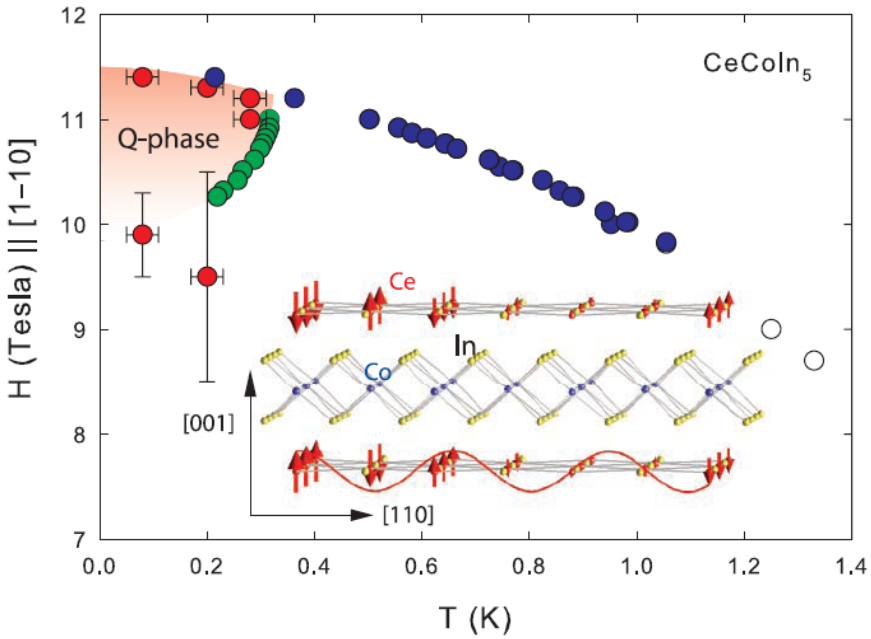
$CeCoIn_5$ Phase diagram

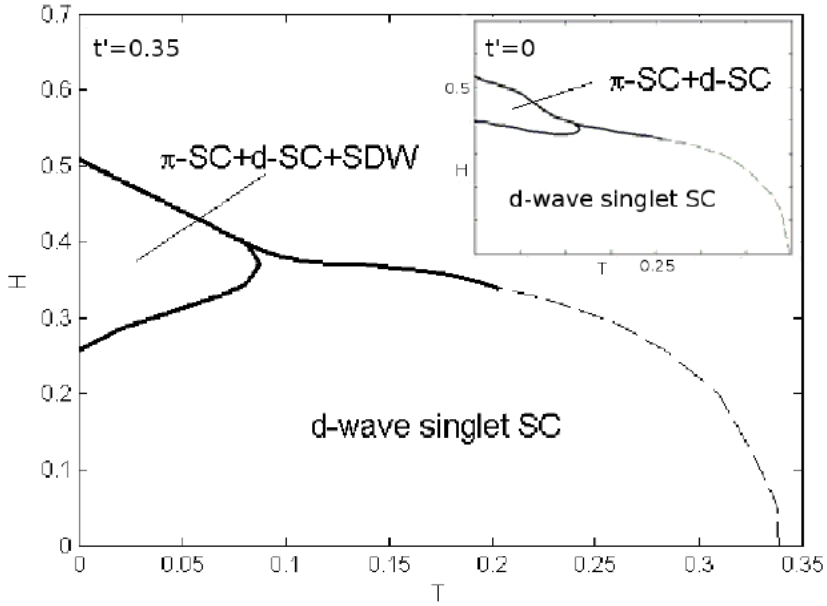


NMR

K. Kumagai *et al.*, PRL **97**, 227002 (2006)

Q phase neutron, NMR, μSR





M. Kenzelmann *et al.*, Science **321**, 1652 (2008)

A. Aperis *et al.*, PRL **104**, 216403 (2010)

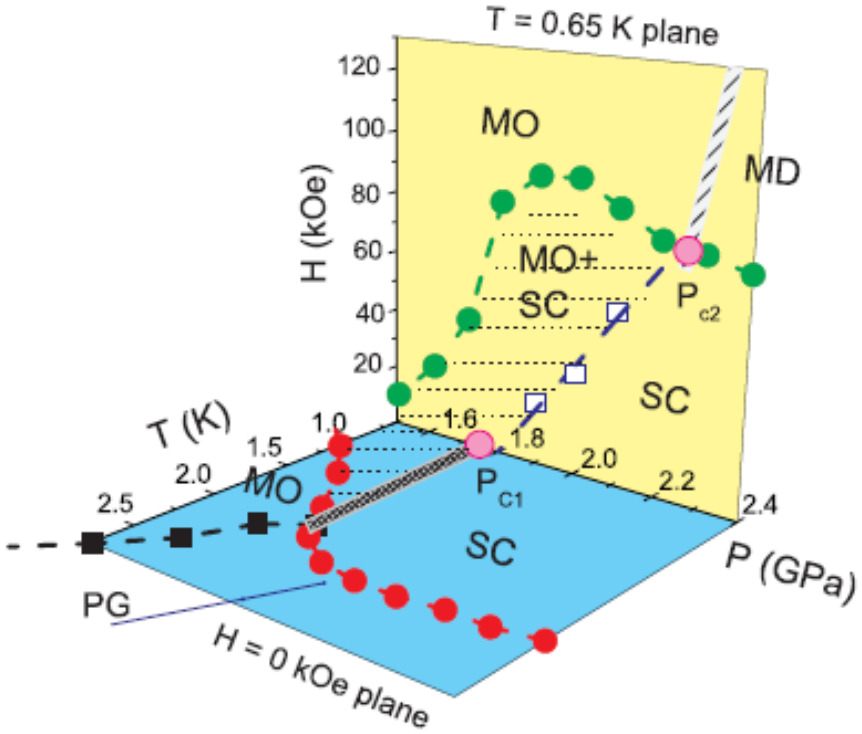
Coupled SDW and SC in the Q-phase for both H//ab and H//c

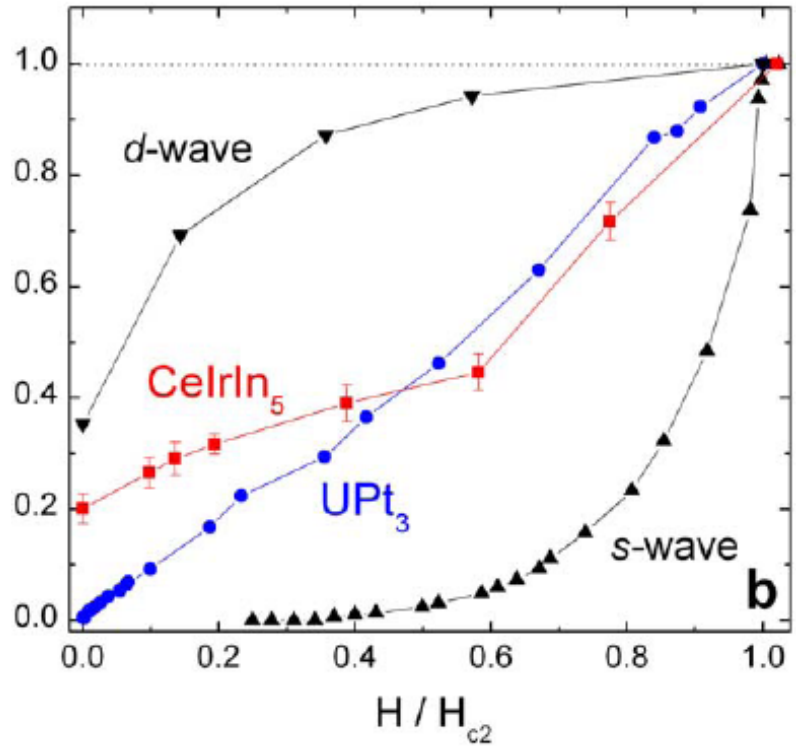
Orignin of Q phase? Really FFLO?

1 Nature, 2 Science, over 30 PRL CeCoIn5 papers on this issue

More compounds show this kind of phase diagram?

$CeMIn_5$ M = Rh, Ir





$CeRhIn_5$, field-induced magnetic order
Not coupled to superconductivity

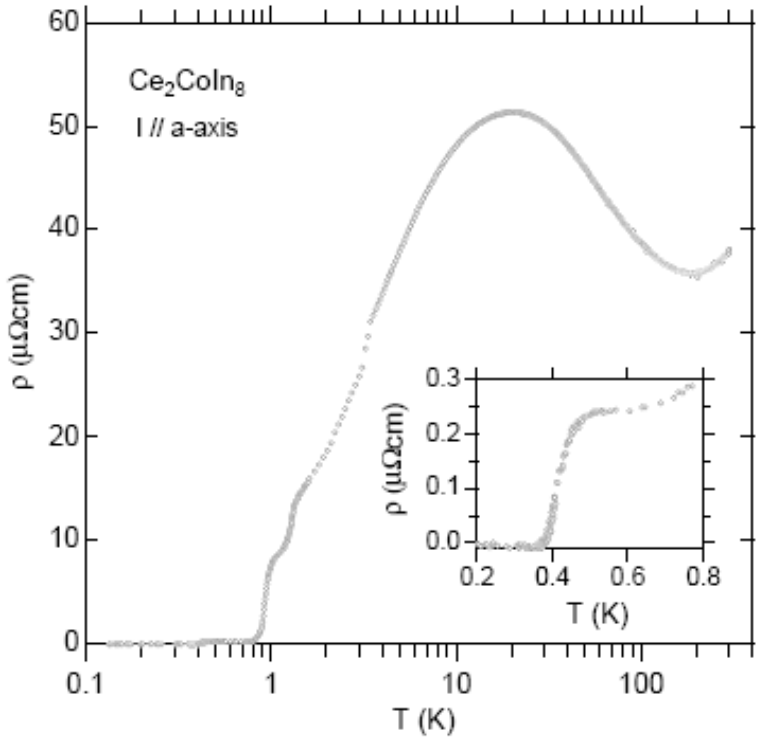
T. Park *et al.*, Nature **440**, 65 (2006)

$CeIrIn_5$, T_c ~ 0.4 K

H. Shakeripour *et al.*, NJP **11**, 055065 (2009)

Ce_2MIn_8 M = Co, Rh, Ir

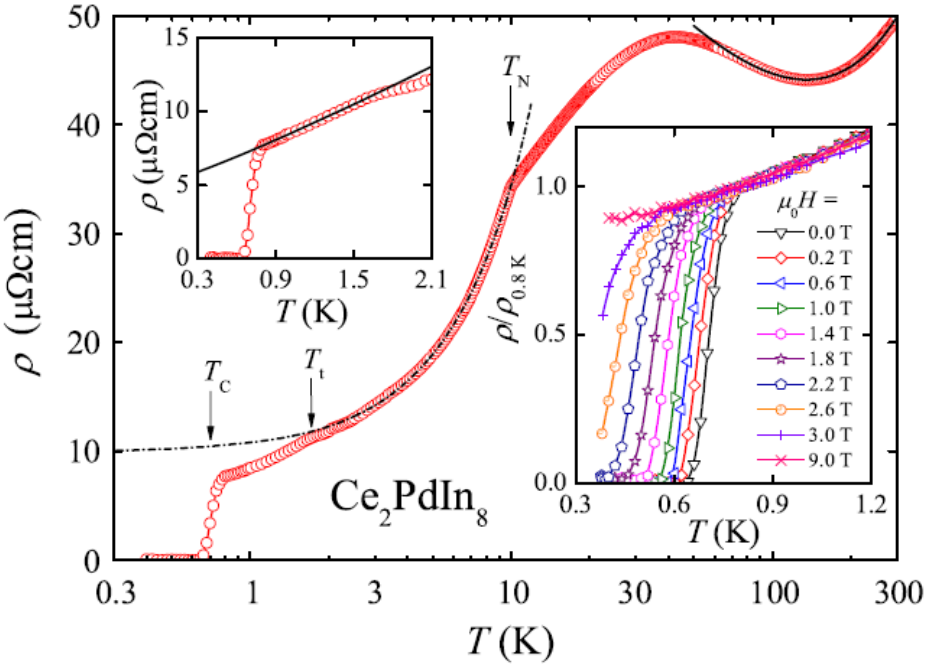
Ce_2RhIn_8, T_c ~ 2 K@2.3GPa; Ce_2IrIn_8, NSC

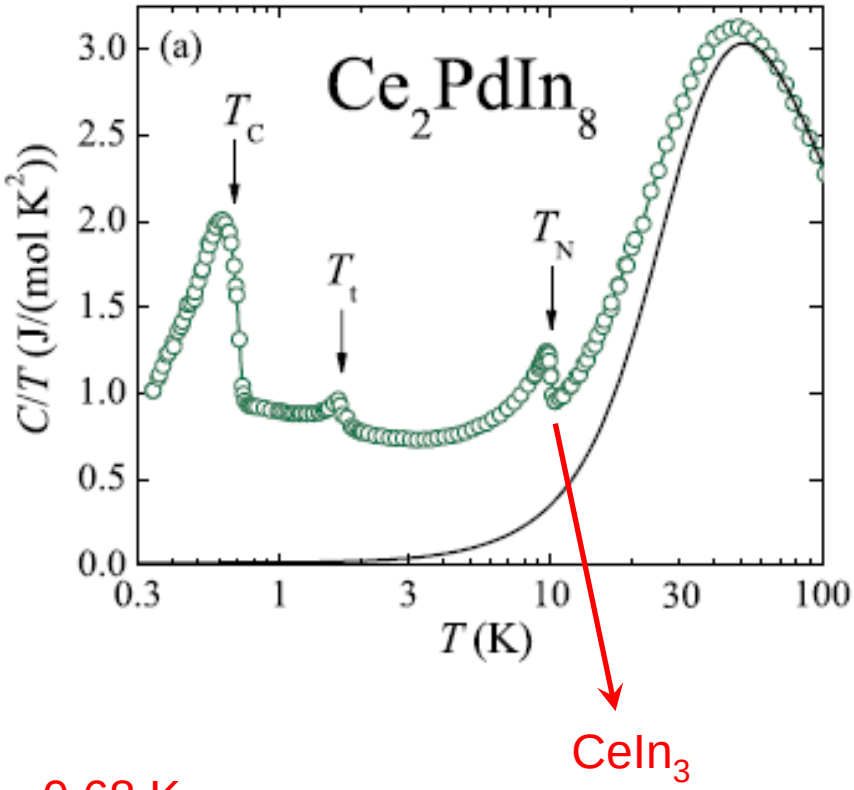


Ce_2CoIn_8, T_c ~ 0.4 K

Genfu Chen *et al.*, JPSJ **71**, 2836 (2002)

Ce_2PdIn_8 new 218 compound





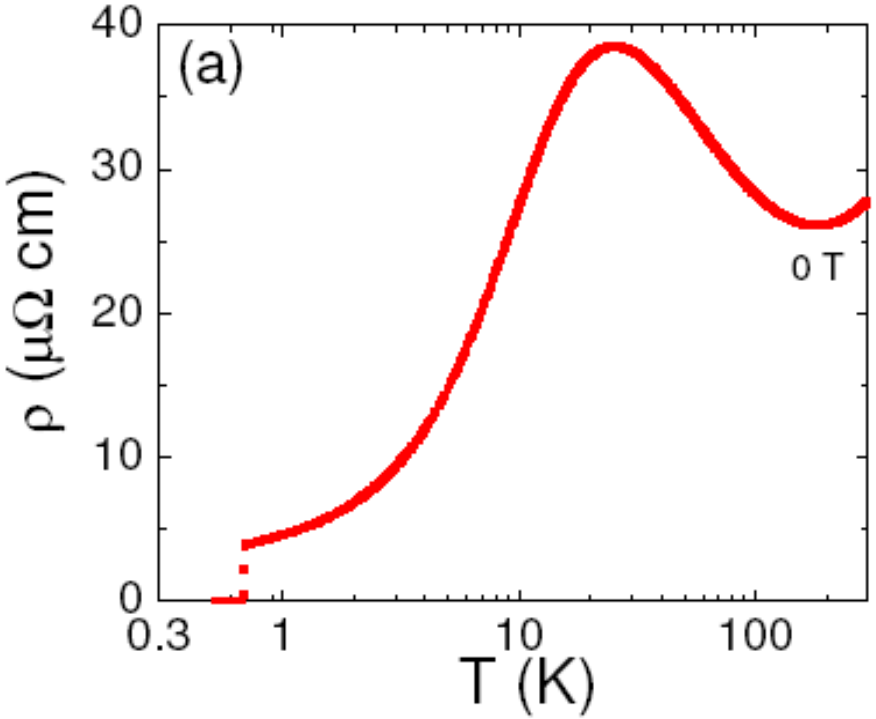
Ce_2PdIn_8, T_c ~ 0.68 K

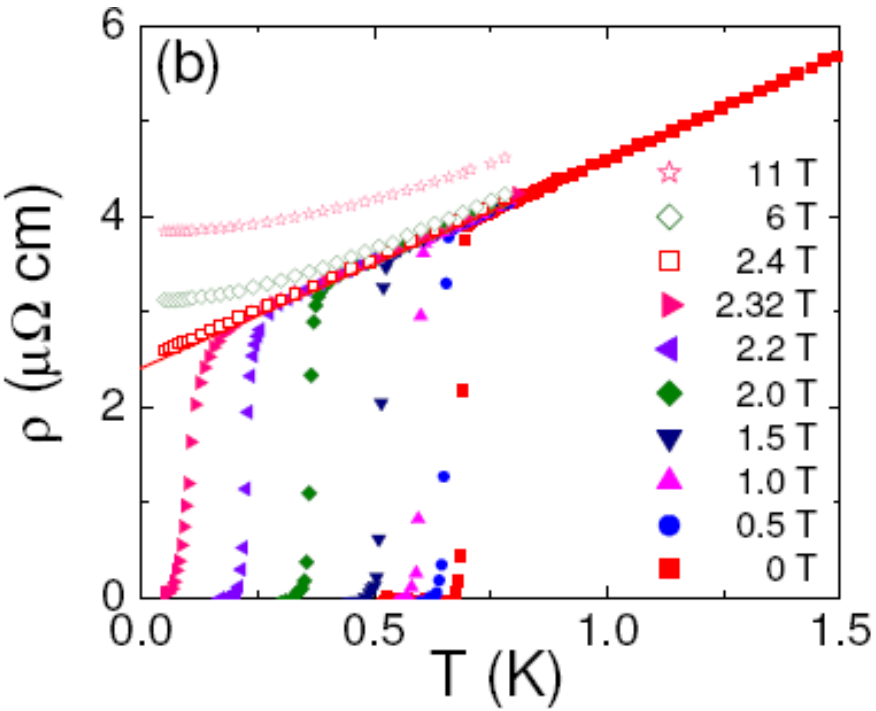
D. Kaczorowski *et al.*, PRL **103**, 027003 (2009)

ρ(T)

Ce_2PdIn_8

Very thin crystals: t = 40 μm; no $CeIn_3$ phase





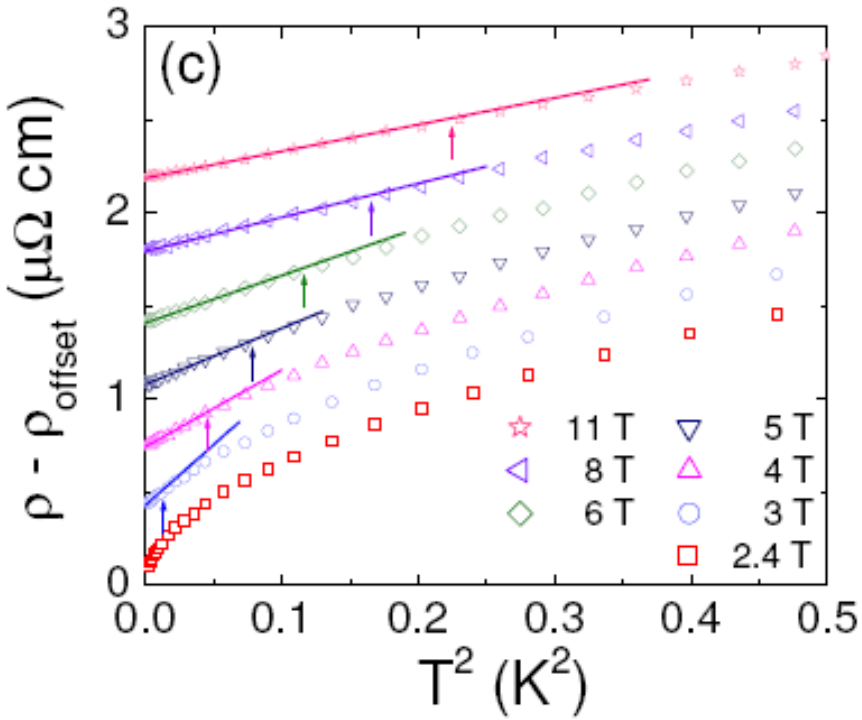
Tc = 0.68 K, ΔTc = 20 mK,

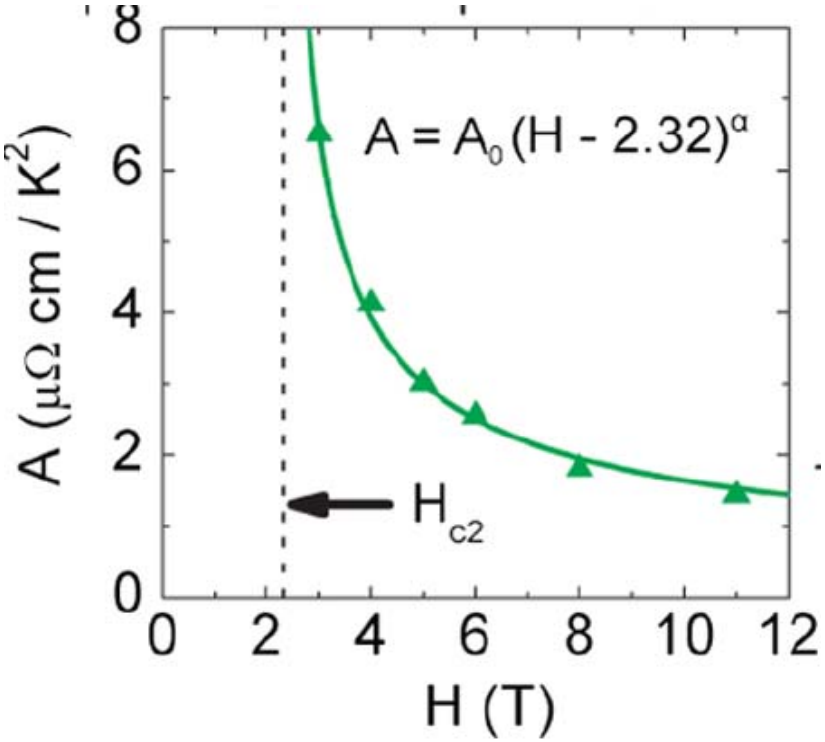
bulk H_{c2} = 2.32 T, H_{c2}(onset) = 2.4 T

ρ ~ T at H_{c2}(onset)= 2.4 T.

ρ(T)

Ce_2PdIn_8



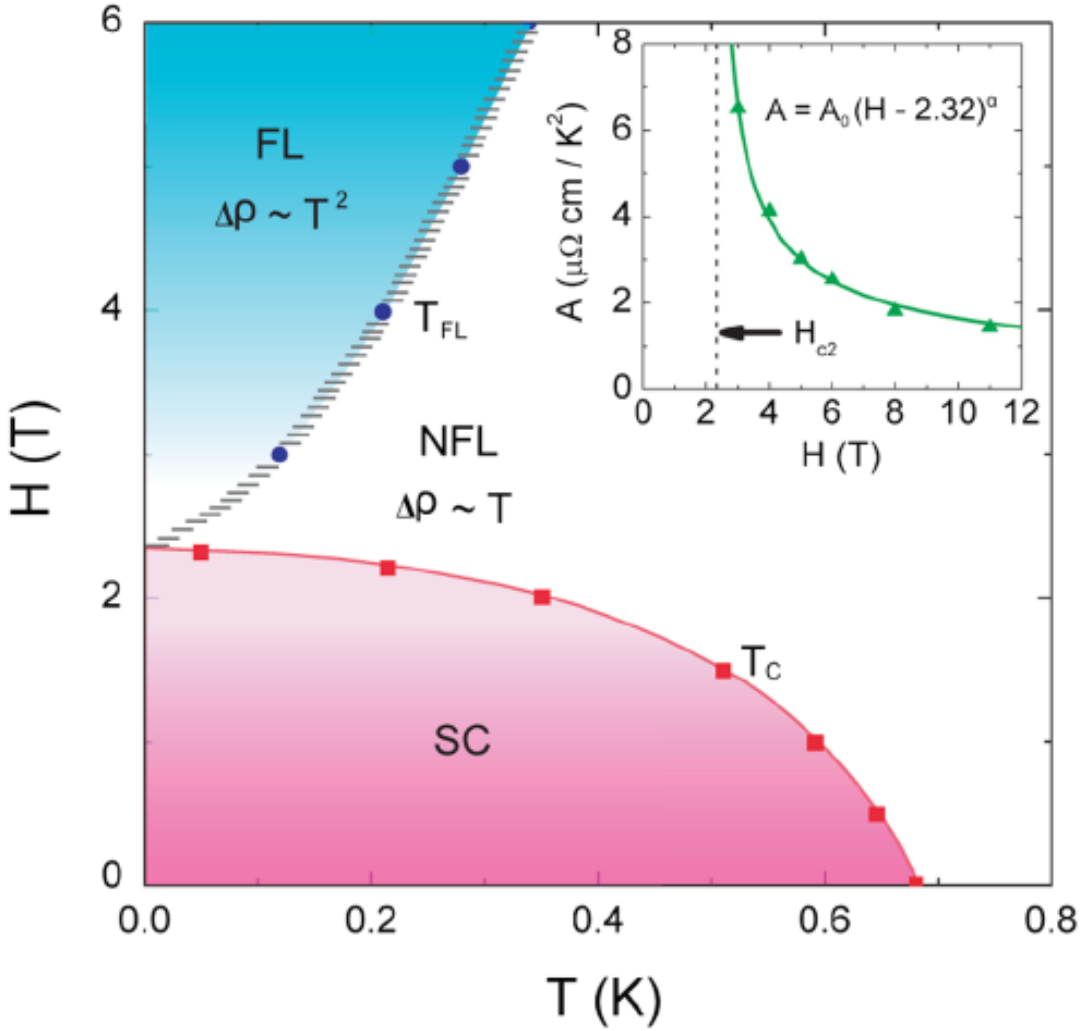


$\rho \sim AT^2$ at $H > H_{c2}$

$A \propto A_0 (H - H_{c2})^{\alpha}$

Phase diagram

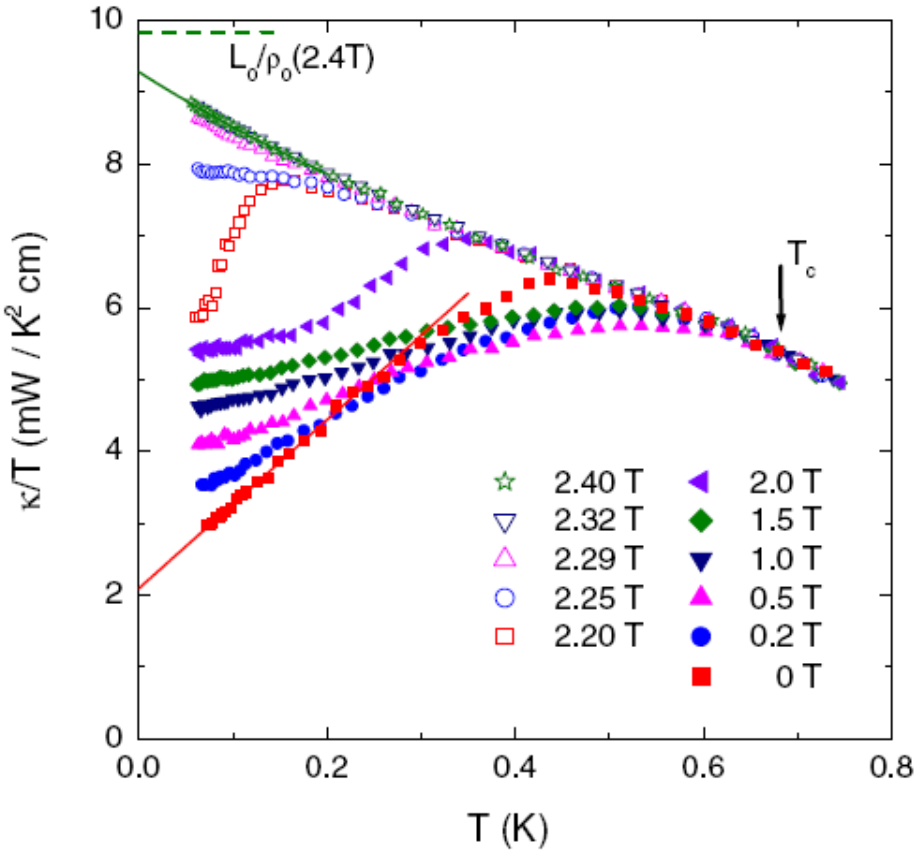
Ce_2PdIn_8

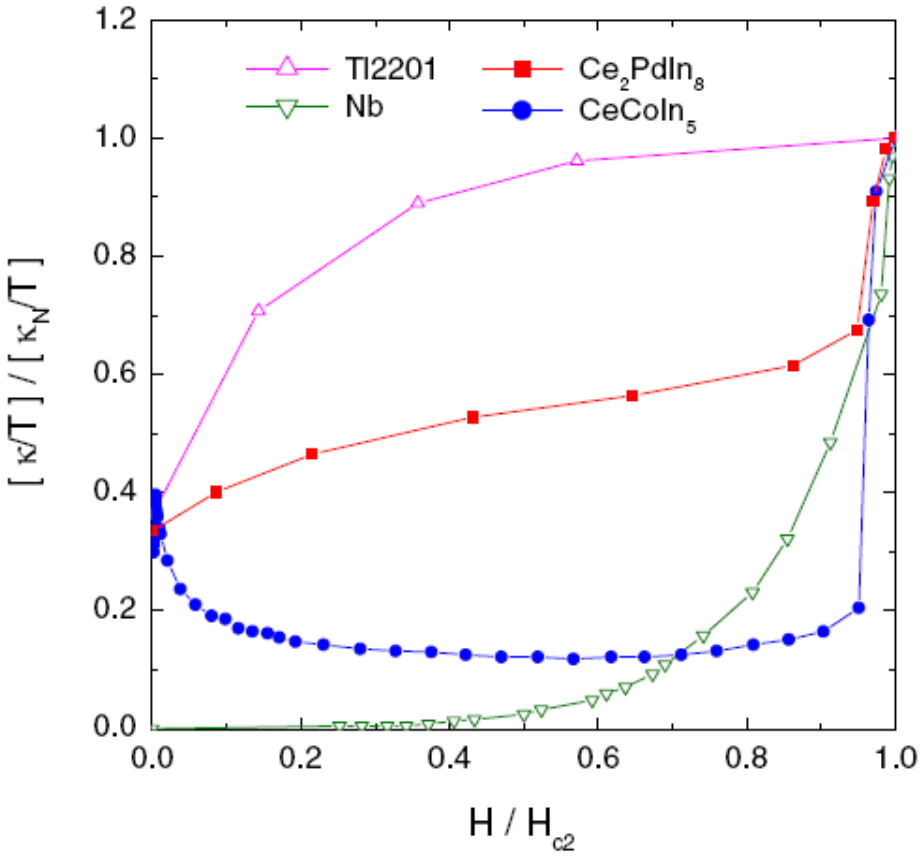


In Ce_2PdIn_8, a field-induced AF QCP is located at H_{c2} = 2.32 T.

κ(T)

Ce_2PdIn_8





Gap with nodes, likely d-wave

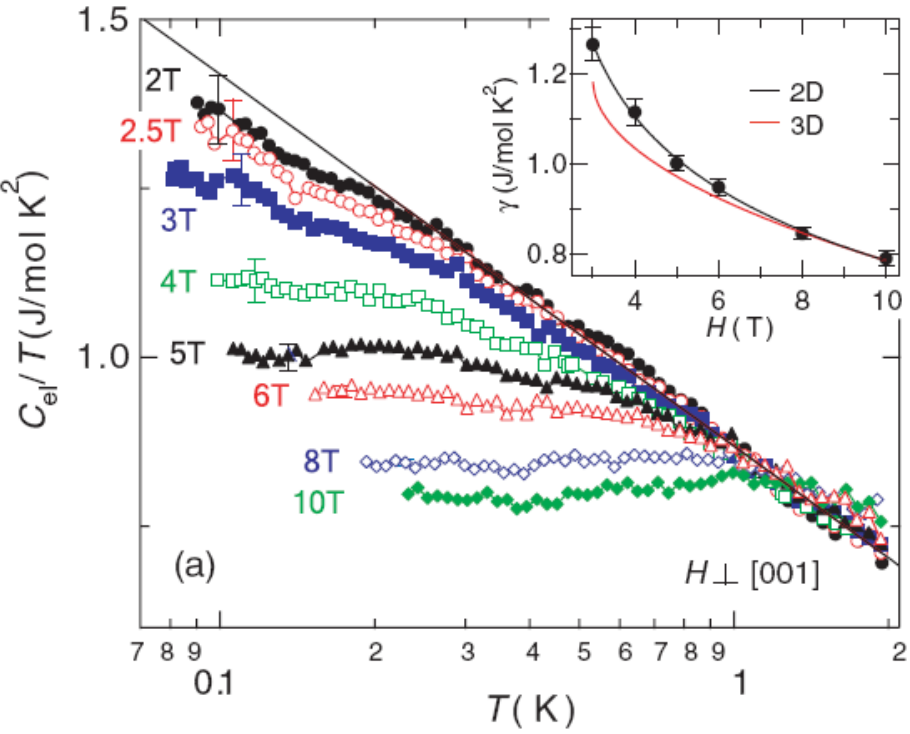
A first-order phase transiton near H_{c2} = 2.32 T.

J. K. Dong *et al.*, PRX **1**, 011001 (2011)

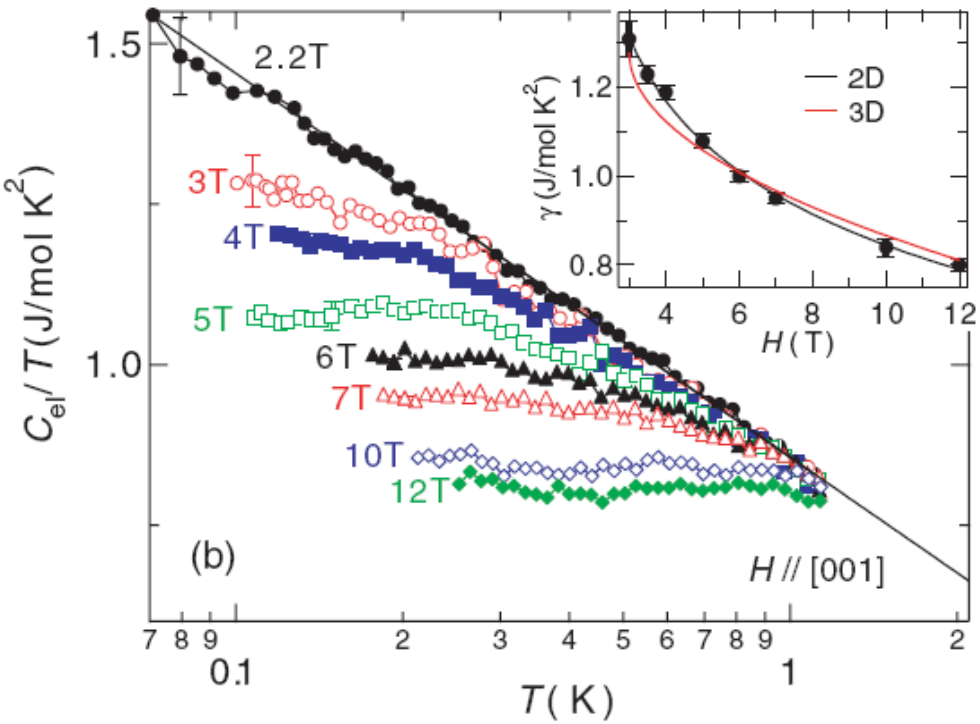
C/T

Ce_2PdIn_8

H || ab



H || c

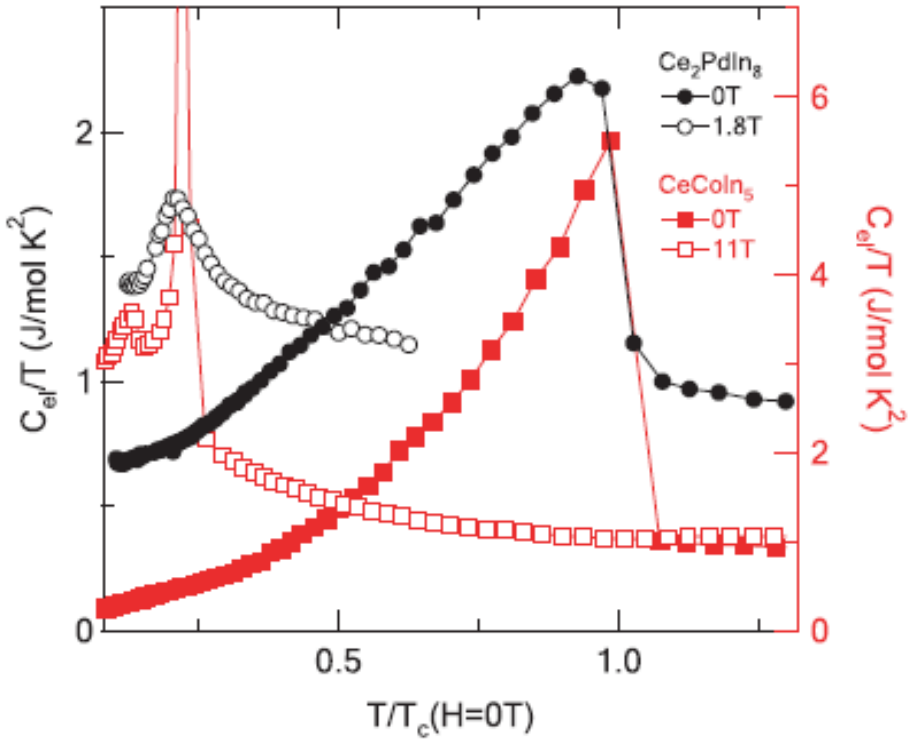


Field-induced QCP near H_{c2} in both H || c and H || ab

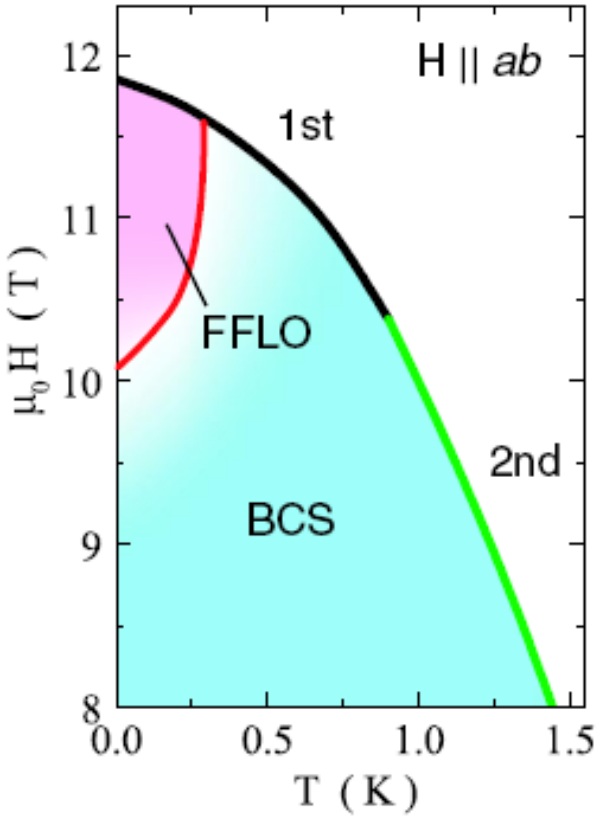
Y. Tokiwa, P. Gegenwart *et al.*, PRB **84**, 140507(R) (2011)

C/T

Ce_2PdIn_8



$CeCoIn_5$



No second phase was detected in Ce_2PdIn_8 by C/T.
Hope with probes sensitive to magnetic order (NMR, μSR, ...),
maybe in next generation of cleaner and larger single crystals.

Y. Tokiwa, P. Gegenwart *et al.*, PRB **84**, 140507(R) (2011)

Summary on Ce_2PdIn_8

Based on ρ and κ of Ce_2PdIn_8, we find:

A field-induced AF QCP near H_{c2} = 2.32 T;

Nodal superconductivity, likely d-wave;

First-order transition near H_{c2} = 2.32 T.

Ce_2PdIn_8 is another promising compound to study the "Q-phase, FFLO state", as in $CeCoIn_5$. The comparison between them may provide the key to understand the origin of Q phase, and the possible FFLO state.

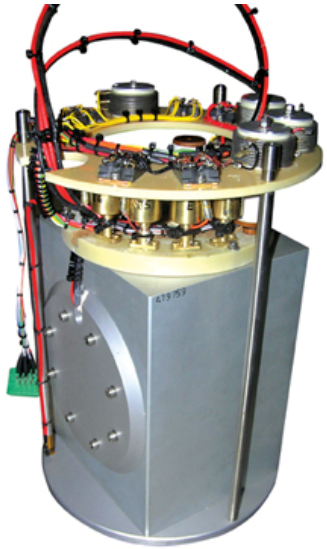
J. K. Dong *et al.*, PRX **1**, 011001 (2011)

3. Research groups in Fudan University

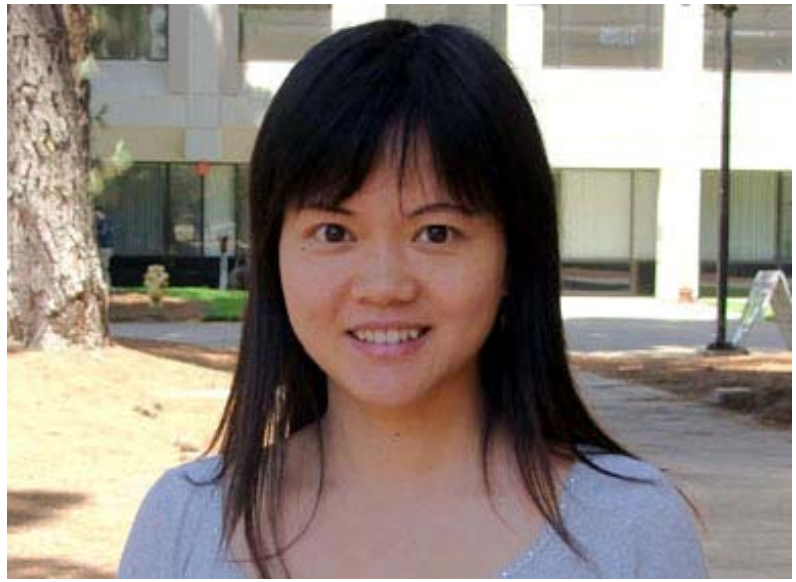
Prof. Shiyan Li -------- **Ph. D** **X. H. Chen's group in USTC**
Postdoc **Louis Taillefer's group**

Experiments: **ultra-low-T resistivity and thermal conductivity**

Main interests: **superconducting gap structure;**
quantum criticality (Wiedemann-Franz law at QCP)



dilution fridge: 7 mK;
vector magnet: 9T–3T



Prof. Lei Shu -------- **Ph. D** **MacLaughlin's group in Riverside**
Postdoc **Brian Maple's group**

Experiments: **ultra-low-T specific heat; μSR**

Main interests: **superconducting gap structure;**
quantum criticality

Prof. Donglai Feng

Ph. D Z. X. Shen's group
Postdoc Sawatsky's group

Experiments: ARPES

Prof. Jun Zhao

Ph. D Pengcheng Dai's group
Miller Fellow Birgeneau's group

Experiments: neutron scattering

Thank your for your attention!

Collaborations are welcome!