Intertwined orders in the Q-phase of superconducting $CeCoIn_5$

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- Pauli limiting in $CeCoIn_5$: phase diagram, first order SC transition, FFLO?
- Pressure and Cd doping effects on FFLO phase, 1^{st} order transition, and QCP.
- NMR studies: Curro, Mitrovic, Kumagai.
- Neutron diffraction studies: AFM order, relation to the applied magnetic field?
- Possible published scenarios for the Q-phase and some (unpublished) ideas.
- Thermal conductivity in the Q-phase in rotating magnetic field – *Duk Young Kim*

$\Rightarrow$ *intertwined orders in $CeCoIn_5$, with p-wave pair-density-wave (PDW).*

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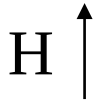
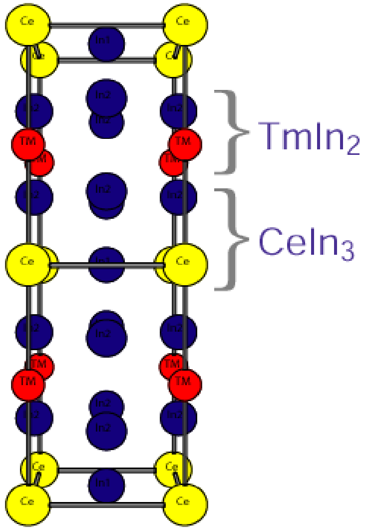
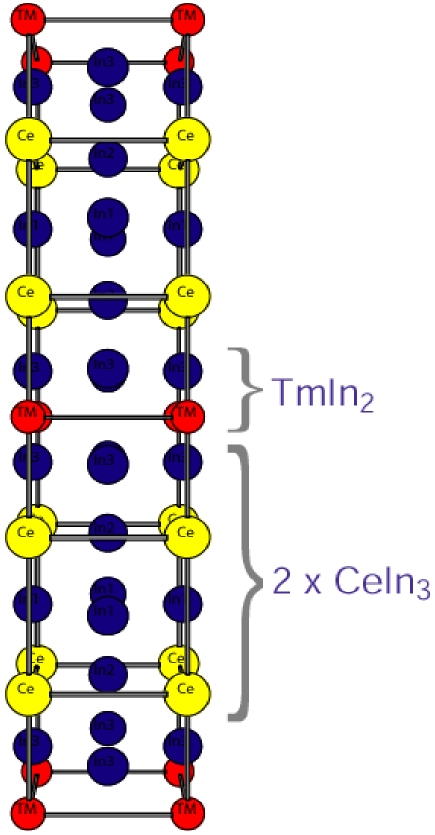
Crystal structures of the $Ce_nTm_mIn_{3n+2m}$ family

Tm = Rh,Co, or Ir

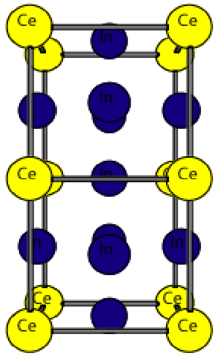




$CeTmIn_5$



Ce_2TmIn_8

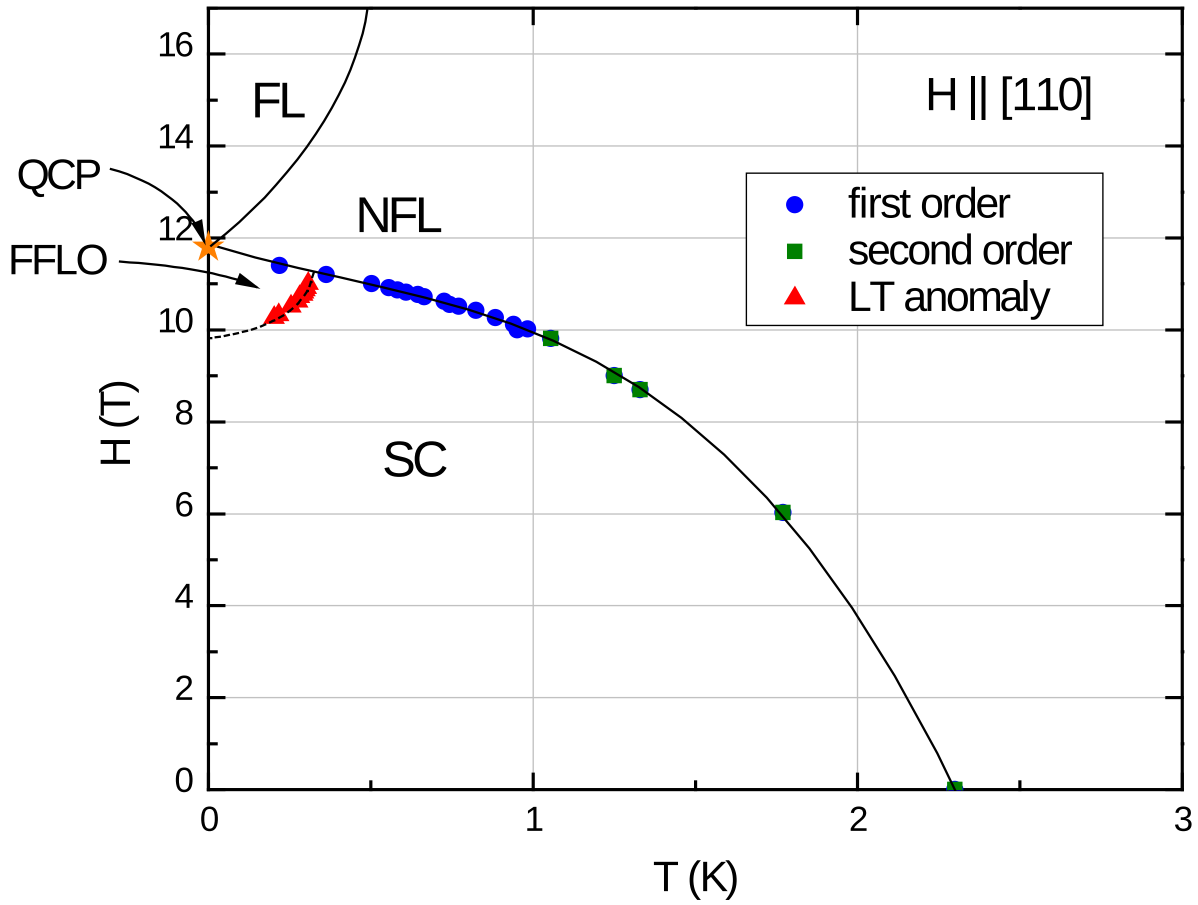


$CeIn_3$

Superconductors,
T_c up to 2.3 K at
ambient pressure

T_c < 200 mK
P ~ 25 kbar

H-T phase diagram of $CeCoIn_5$



Complex phase diagram :

1. coinciding QCP and H_{c2}
2. superconducting transition itself changes from second to first order
3. a new phase in the High Field-Low Temperature HFLT corner of SC phase.

Q's:

- origin of QCP?
- HFLT - possibly FFLO?
- relation between HFLT and QCP and its underlying magnetism?

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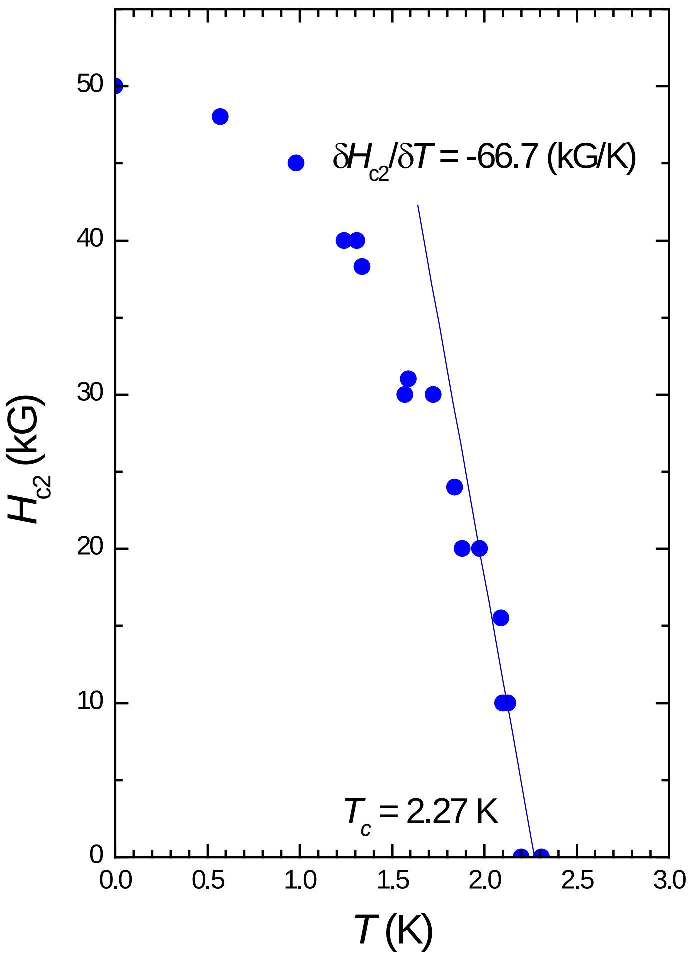
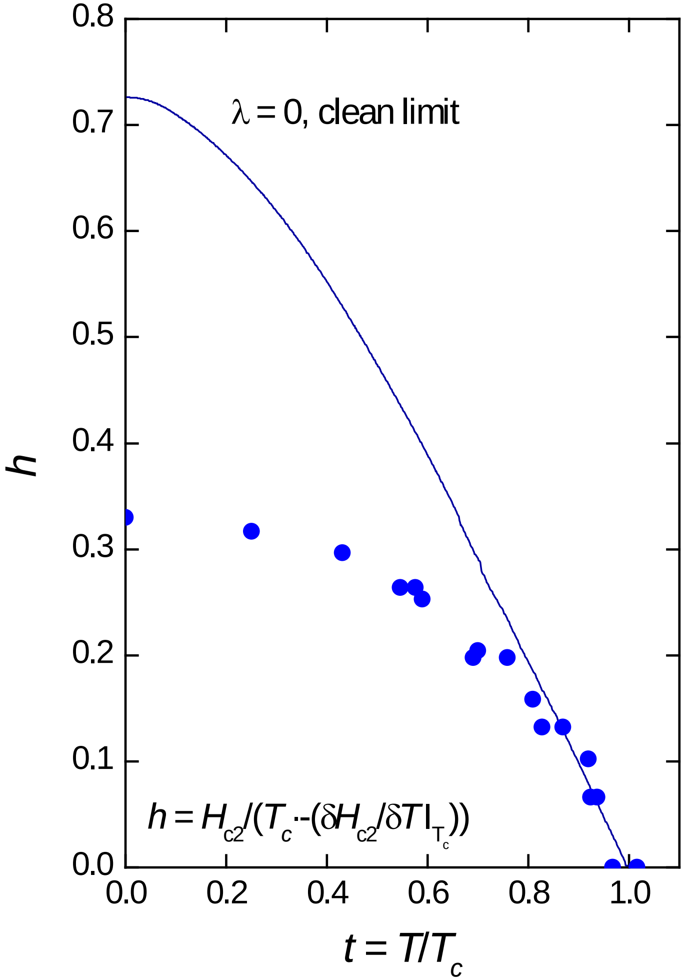
CeCoIn5 – upper critical field for *H* II c





E. Helfand and N.R. Werthamer Phys.Rev. **147** 313 (1967)

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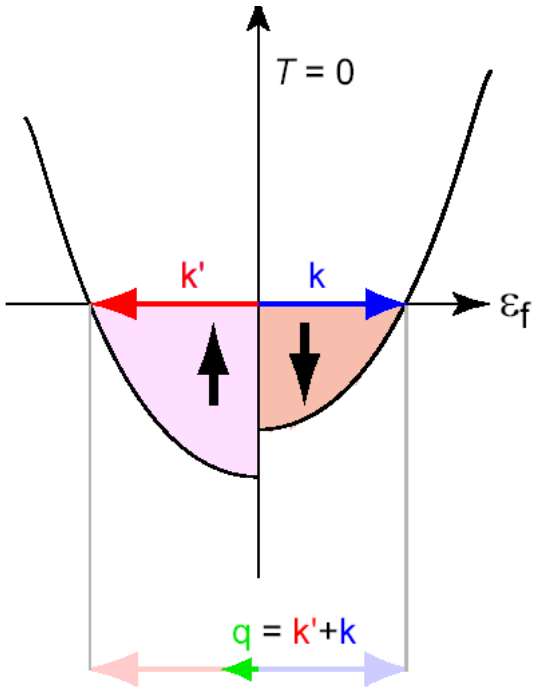
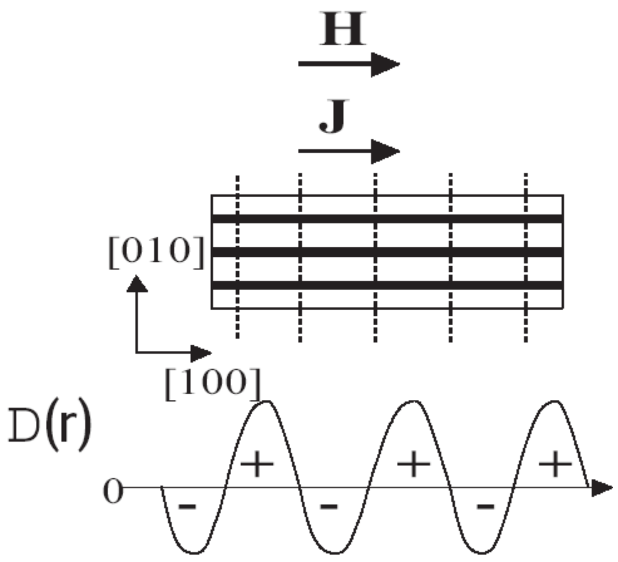
Fulde – Ferrell and Larkin – Ovchinnikov



Zeeman splitting of the spin up and spin down bands leads to formation of the SC Cooper pairs out of quasiparticle states with different magnitude k, and a resulting non-zero total momentum q. This results in a spatially varying order parameter and nodal (normal) planes.



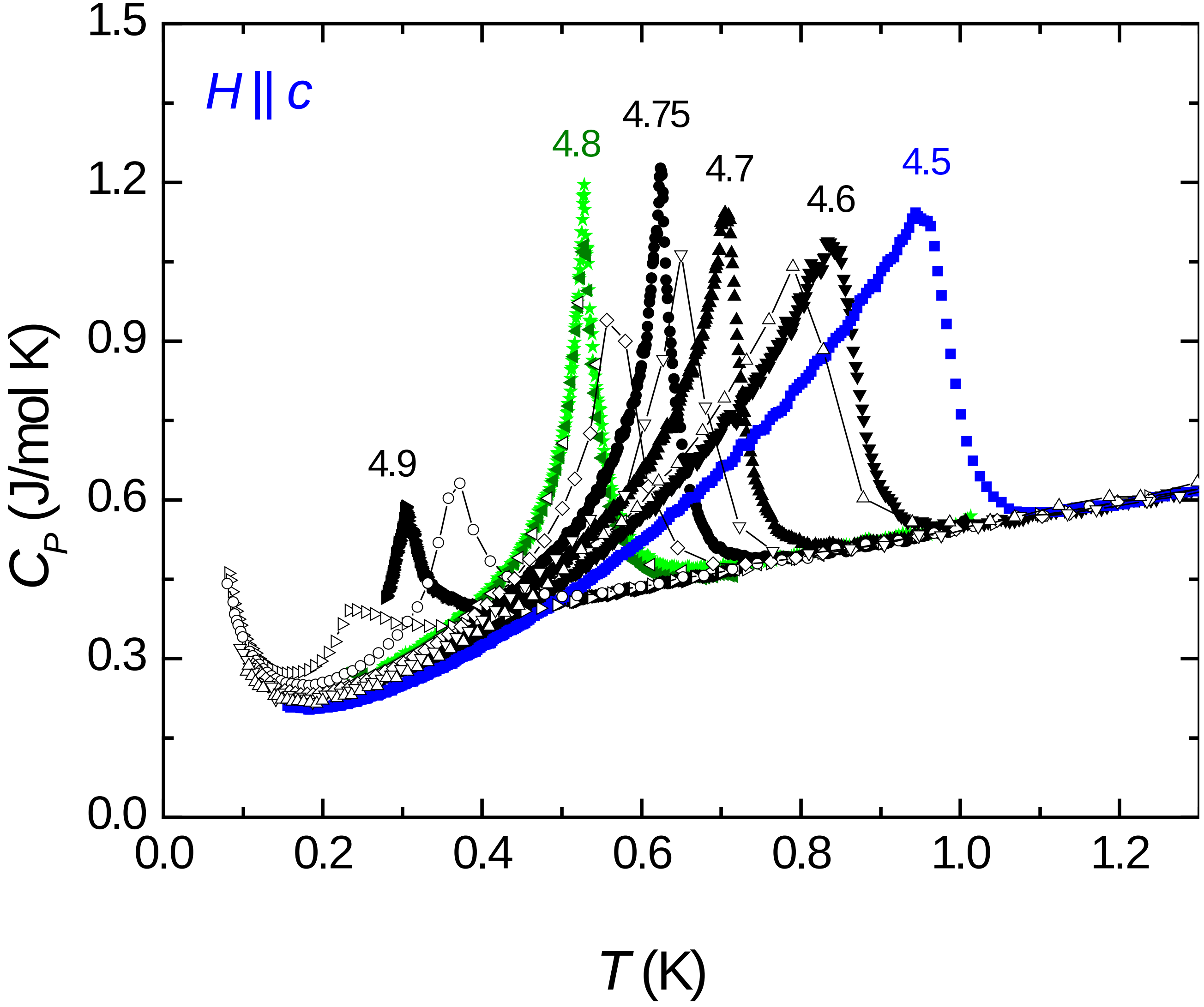
$\Delta(r) = |\Delta_q| e^{(iqr)}$ (FF)

P. Fulde and A. Ferrell Phys. Rev. 135, A550 (1964).

$\Delta(r) = |\Delta_q| \cos(qr)$ (LO)

A.I. Larkin and Yu.N. Ovchinnikov Zh. Eksp. Teor. Fiz. 47, 1136 (1964).

$CeCoIn_5$ – second order – first order



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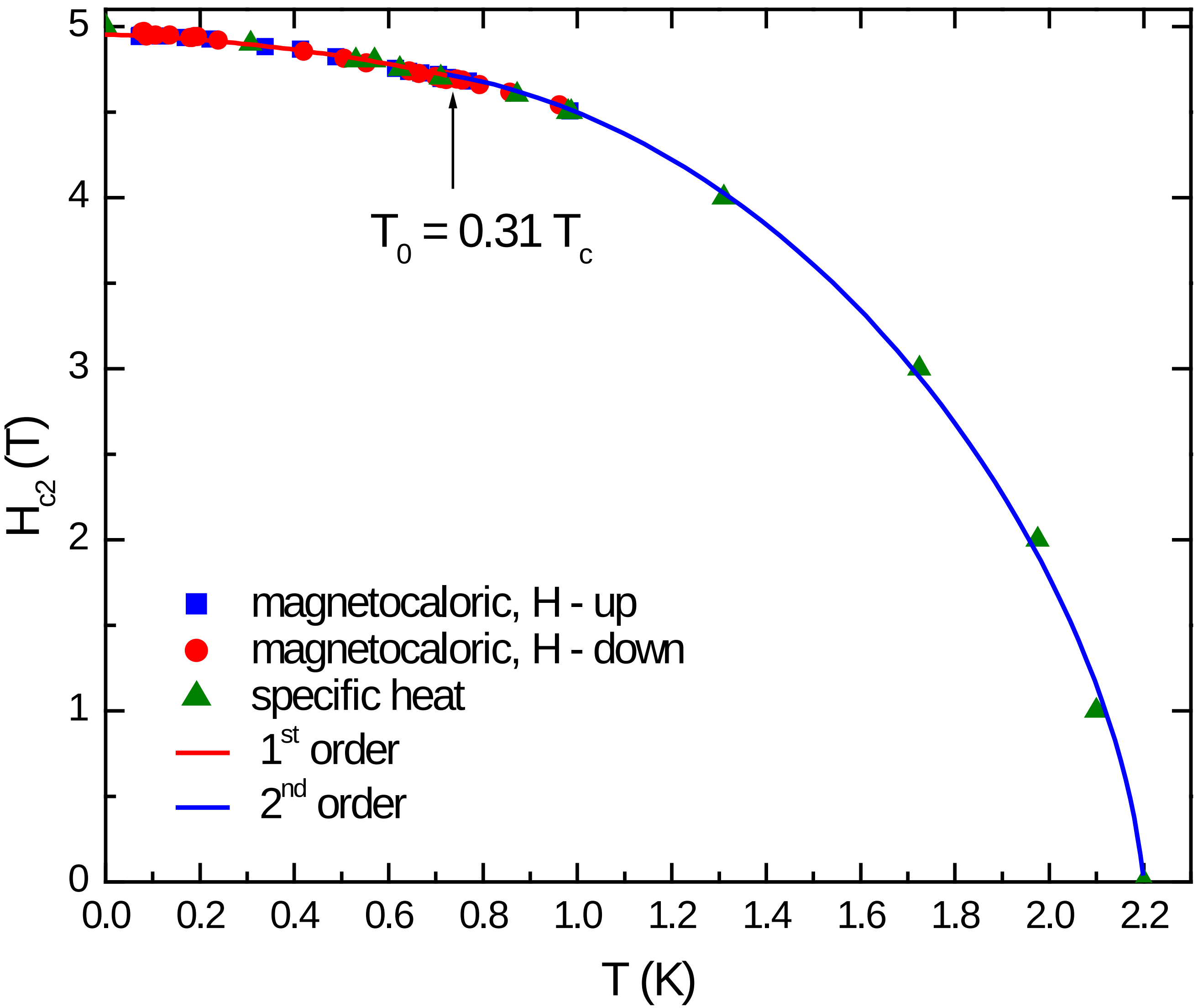
A. Bianchi *et al.*, Phys. Rev. Lett. **89**, 137002 (2002)

$CeCoIn_5$, H || [001]



A. Bianchi *et al.*, *Phys. Rev. Lett.* **89**, 137002 (2002).

H || [001]

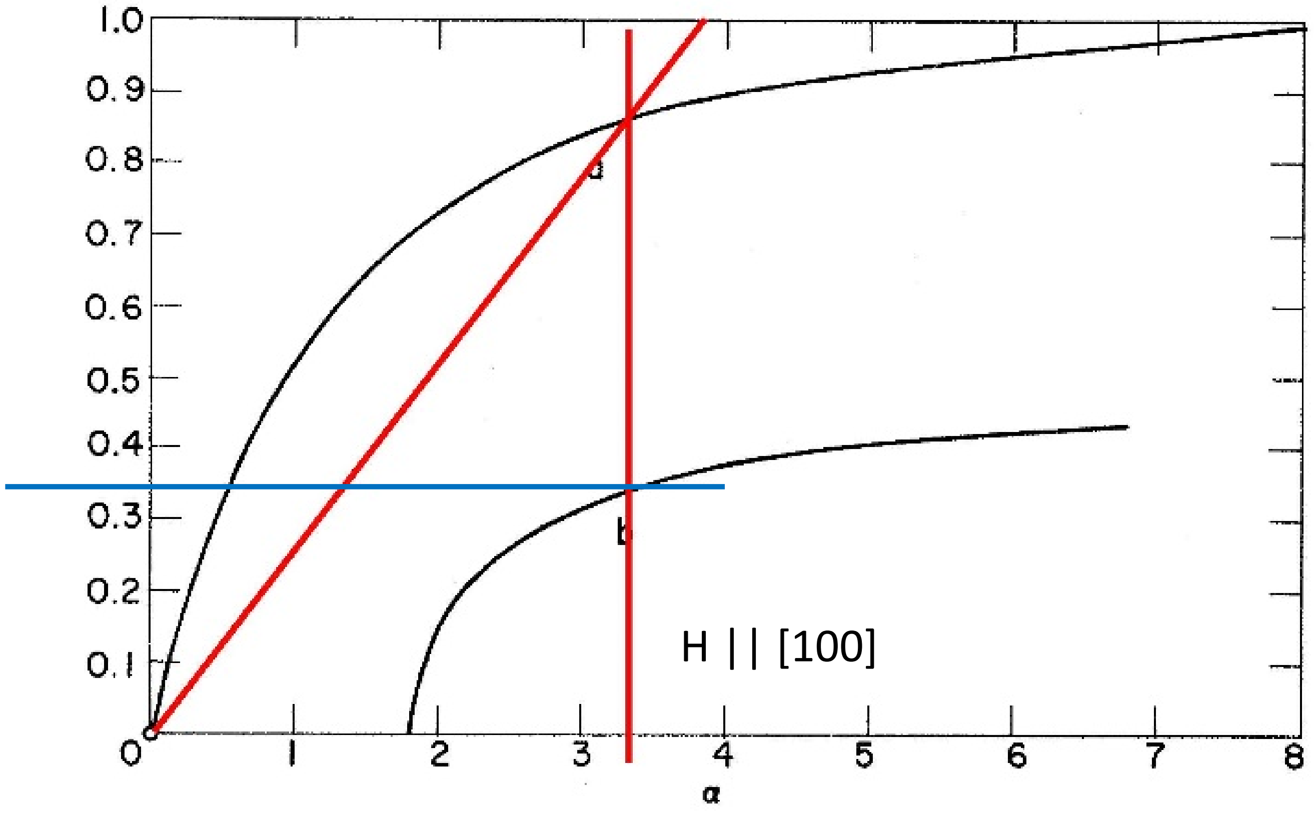


FIG. 1. (a) H_{c2}/H_p as a function of α. (b) $Q\xi_0$ as a function of α.

Exp: H_{c2} = 4.95 T; H_{c2}^0 = 13.2 T ➔ $\alpha/(H_{c2}/H_p) = (\sqrt{2}\ H_{c2}^0/H_p)/(H_{c2}/H_p) = \sqrt{2}\ H_{c2}^0/H_{c2}$ = 3.8

$\Rightarrow$ α = 3.3, H_p = 5.8 T, and T_0/T_c = 0.33. compare with experimental T_0/T_c = 0.31.

H ∥ [001]

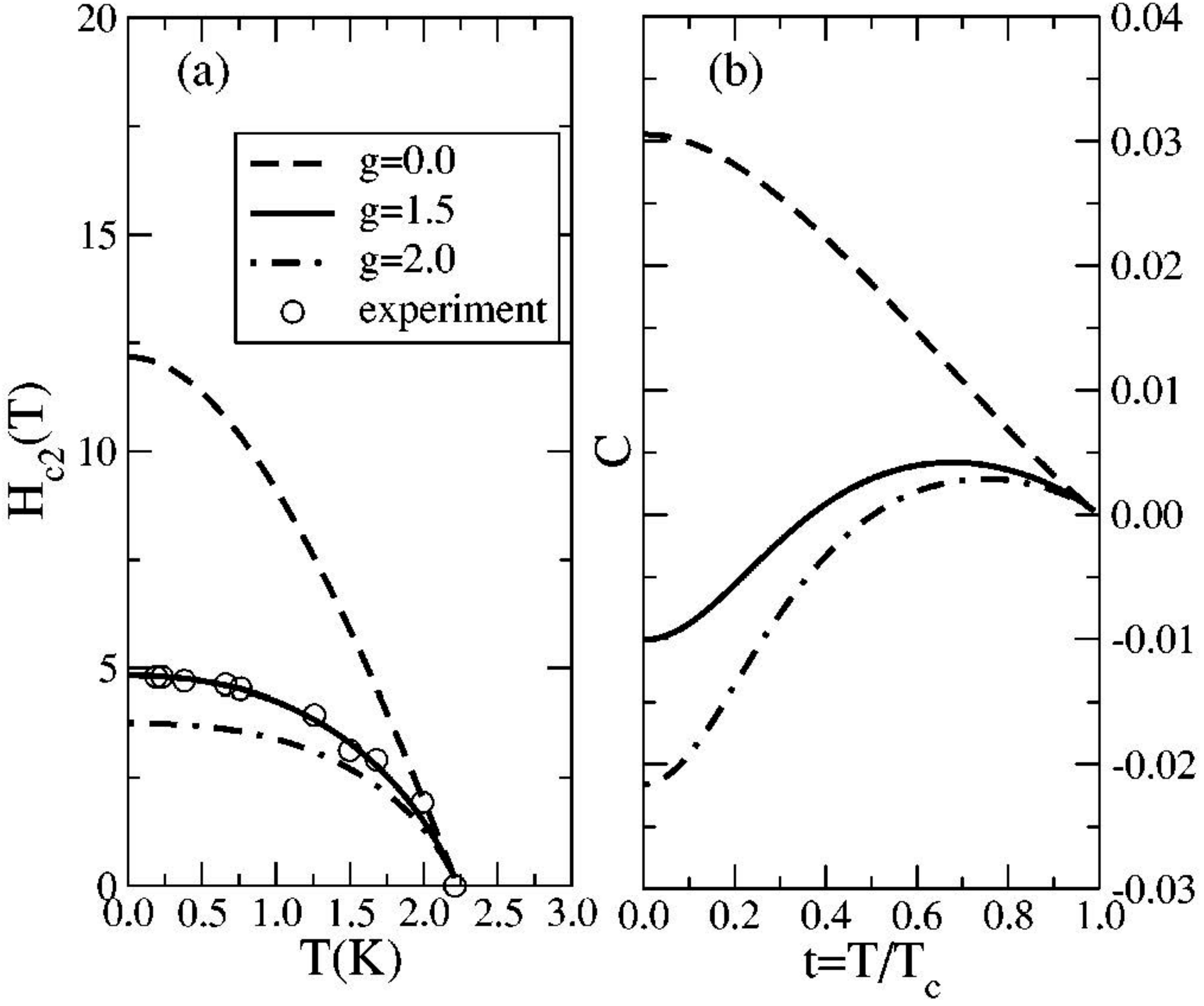


FIG. 1. Temperature dependence of (a) the upper critical field and (b) the admixture parameter C in a $d_{x^2-y^2}$-wave superconductor with g factors $g=0$, 1.5, and 2. The magnetic field is applied along the crystal c direction.

H_p = 5.5 T , α = 3.1 for H ∥ [001]
Compare to H_p = 5.8 T , α = 3.3, from GG with H_{orb} = 13.2 T

H. Won, K. Maki *et al.,* Phys. Rev. B **69**, 180504(R) (2004)

Onset of the first order SC transition for H||[100]

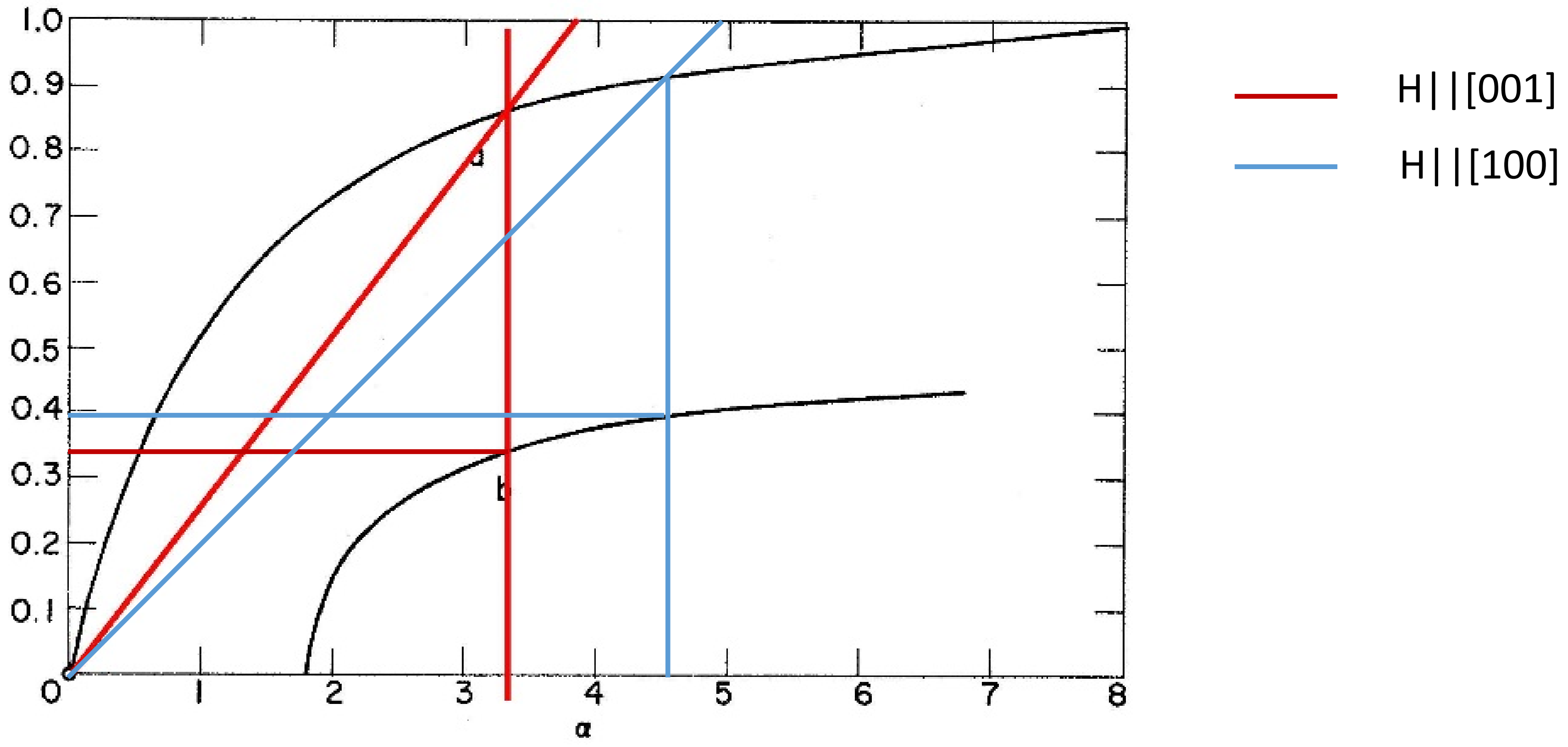


FIG. 1. (a) H_{c2}/H_p as a function of α. (b) $Q\xi_0$ as a function of α.

L.W. Gruenberg and L. Gunther PRL **16**, 996 (1966).

Exp: H_{c2} = 11.6T T; H_{c2}^0 = 40.3 T ➔ $\alpha/(H_{c2}/H_p) = (\sqrt{2}\, H_{c2}^0/H_p)/(H_{c2}/H_p) = \sqrt{2}\, H_{c2}^0/H_{c2} = 4.91$

α = 4.5, H_p = 12.7 T, and $t_0 = T_0/T_c$ = 0.39. (1) compare with experimental T_0/T_c = 0.31.

(2) Compare with Won and Maki (WM): α = 4.5, H_p = 12.8 T, $t_0 = T_0/T_c$ = 0.31.

Good agreement between GG and WM! GG misses experimental value of $t = T_0/T_c$ by about 25%.

H || [100]

α = 4.5, H_p = 12.8 T, $t_0 = T_0/T_c$ = 0.31.

Compare with GG:
α = 4.5, H_p = 12.7 T, $t_0 = T_0/T_c$ = 0.39.

p quantifies the presence of the FFLO
p$\rightarrow$0 at t = 0.31 – same as where the SC transition switches from second to first order!

This calculation is equivalent to Gruenberg and Gunther, but for d-wave superconductor!

H. Won, K. Maki *et al.*,
Phys. Rev. B **69**, 180504(R) (2004)

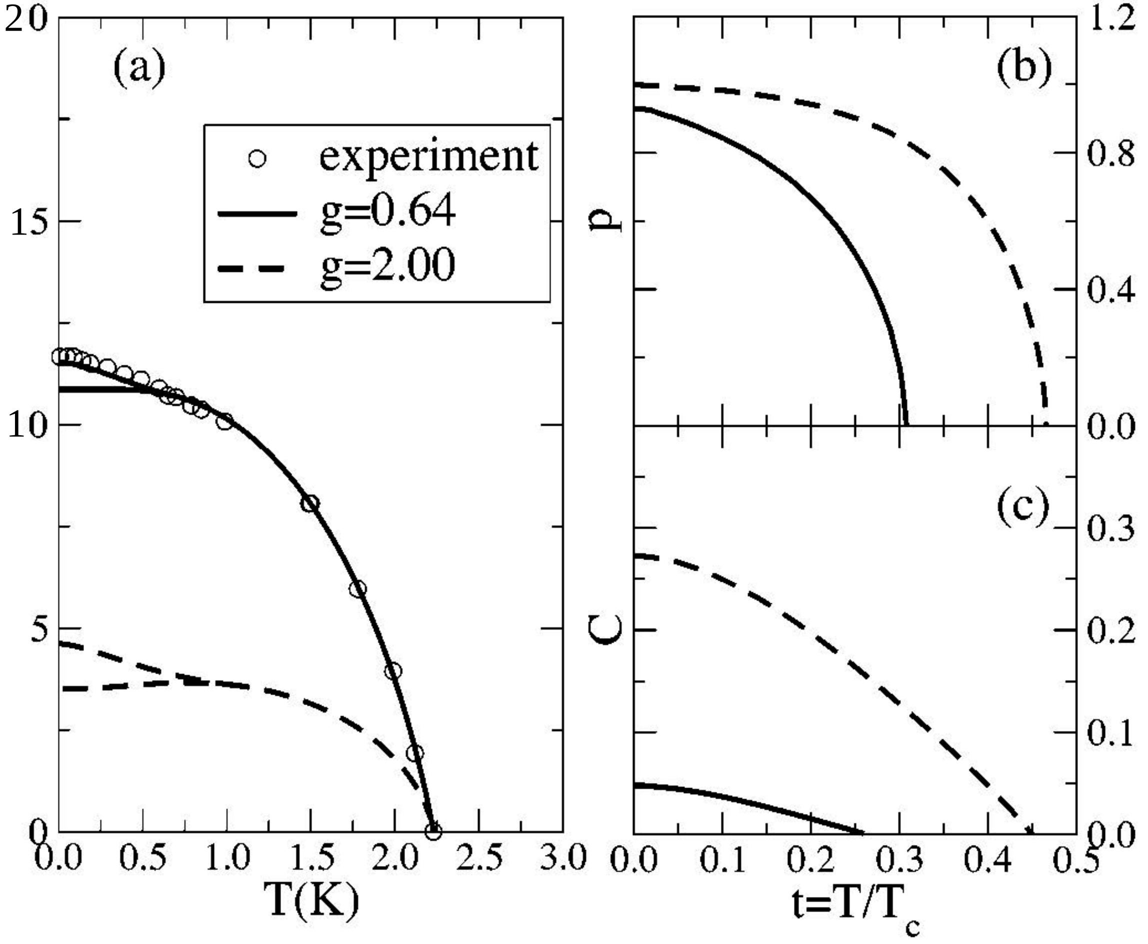


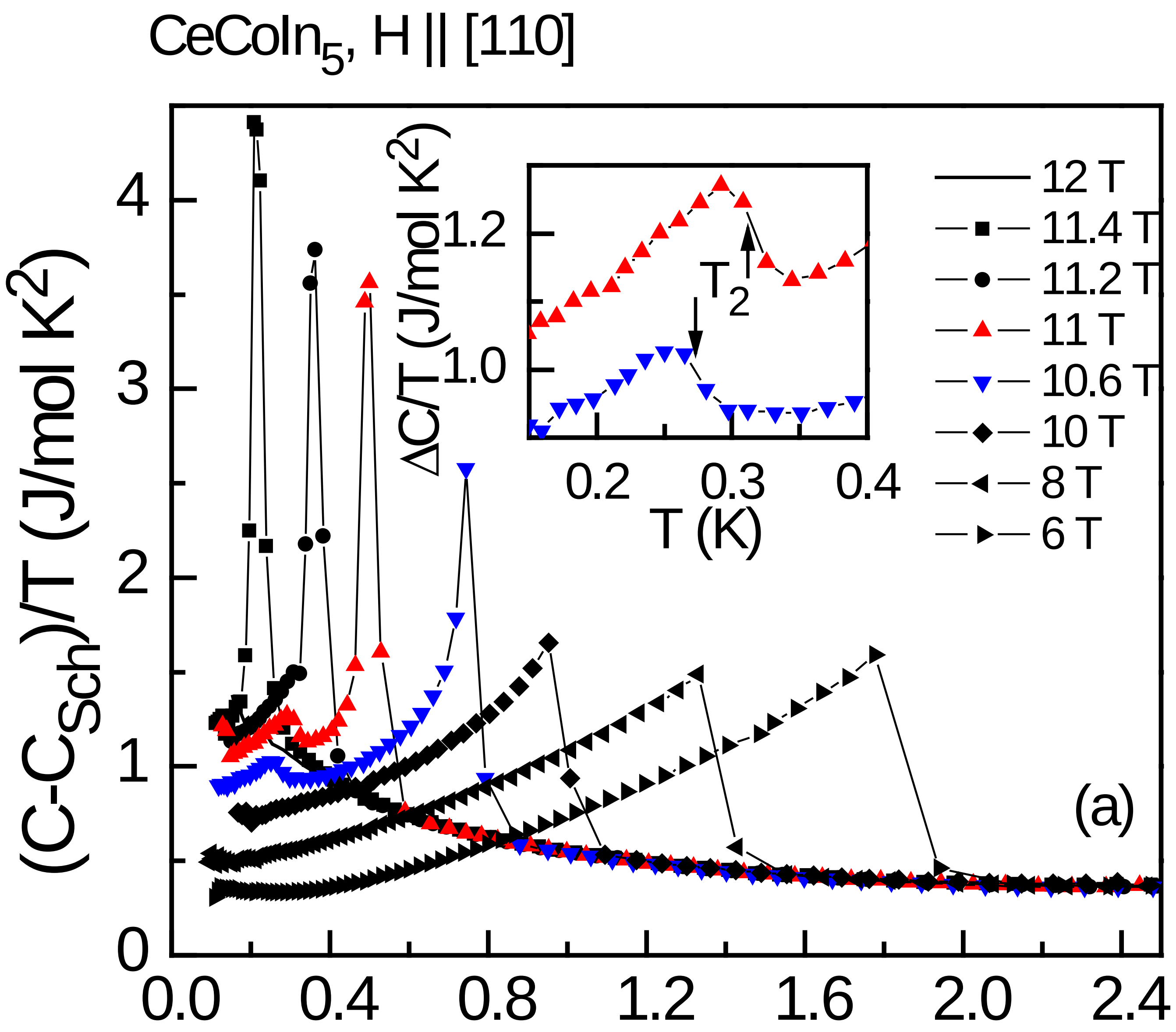
FIG. 2. Temperature dependence of (a) the upper critical field, (b) the $\vec{v}\cdot\vec{q}/(2H)=p\cos\phi$ term, and (c) the admixture parameter C in a $d_{x^2-y^2}$-wave superconductor with g factors $g=0.64$ (solid lines) and 2 (dashed lines). Here $t\equiv T/T_c$ is the reduced temperature. In (a) the lower curves represent $p(t)=0$, i.e., absence of FFLO, whereas the upper curves have $p(t=0)=0.9$. The magnetic field is applied along the crystal a direction. The experimental data (circles) are best described by $g=0.64$ and $p(t=0)=0.9$.

Fitting critical field SC phase boundary as a function of temperature

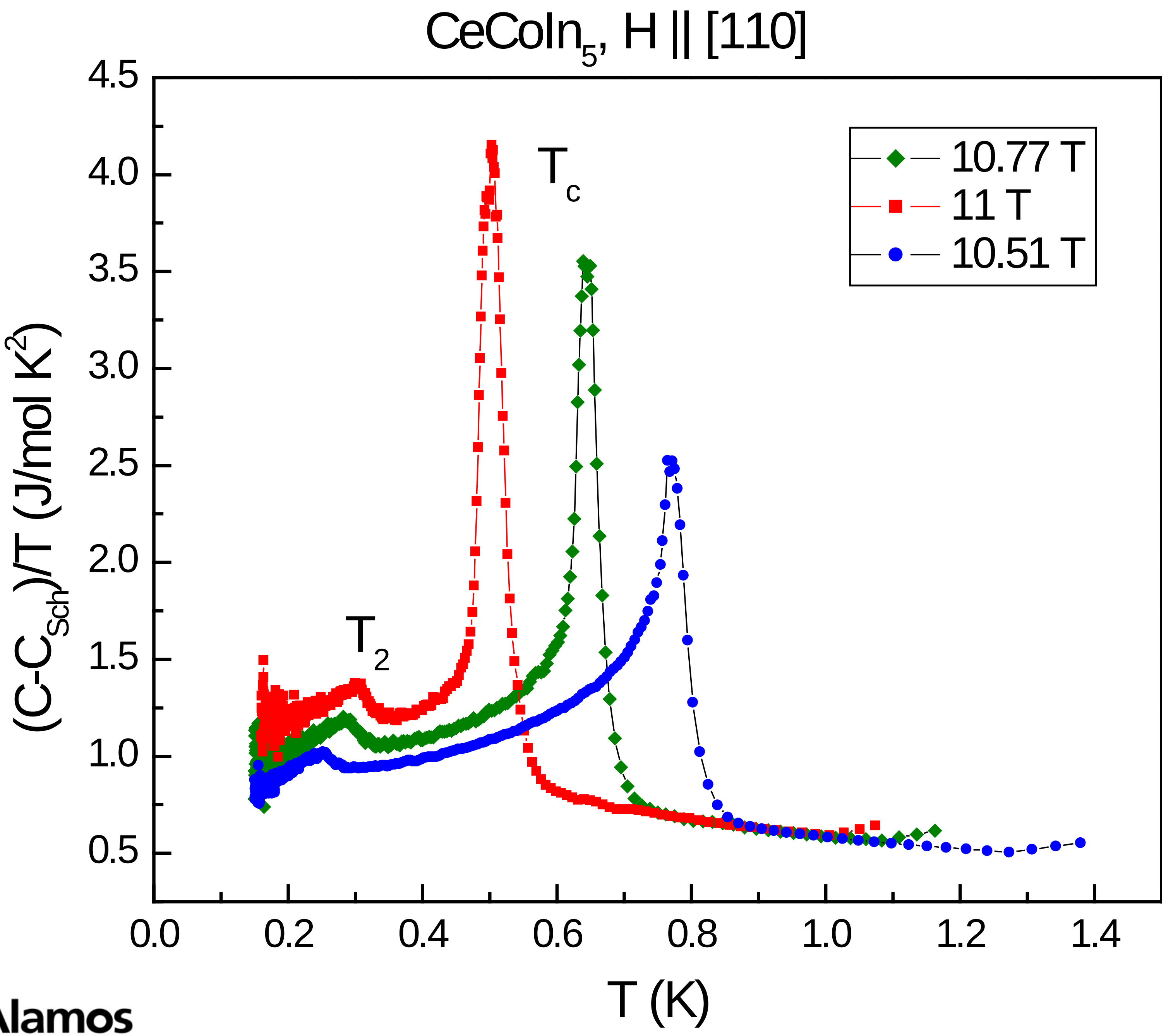
III. $H_{c2}(T)$ FOR $H \parallel$a

In order to match the experimental data for $H_{c2}(T)$ along the crystal a axis, we explore the effect of a $\vec{v} \cdot \vec{q}$ term arising from the formation of a FFLO state. Again, the equations for the upper critical field can be derived from weak coupling $d_{x2\text{-}y2}$-wave BCS theory. The differences of these results from the corresponding conventional s-wave superconductors are (i) the assumption of a quasi-2D Fermi cylindrical Fermi surface, and (ii) the admixture of higher Landau levels, as was first proposed by Luk'yanchuk and Mineev. Here we have extended this formalism to include (i) the $d_{x2\text{-}y2}$-wave symmetry of the superconducting order parameter, (ii) Pauli paramagnetism, (iii) FFLO pairing, and (iv) the orbital effect via the ansatz of **Gruenberg and Gunther.**

H. Won, K. Maki *et al.*, Phys. Rev. B **69**, 180504(R) (2004)



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



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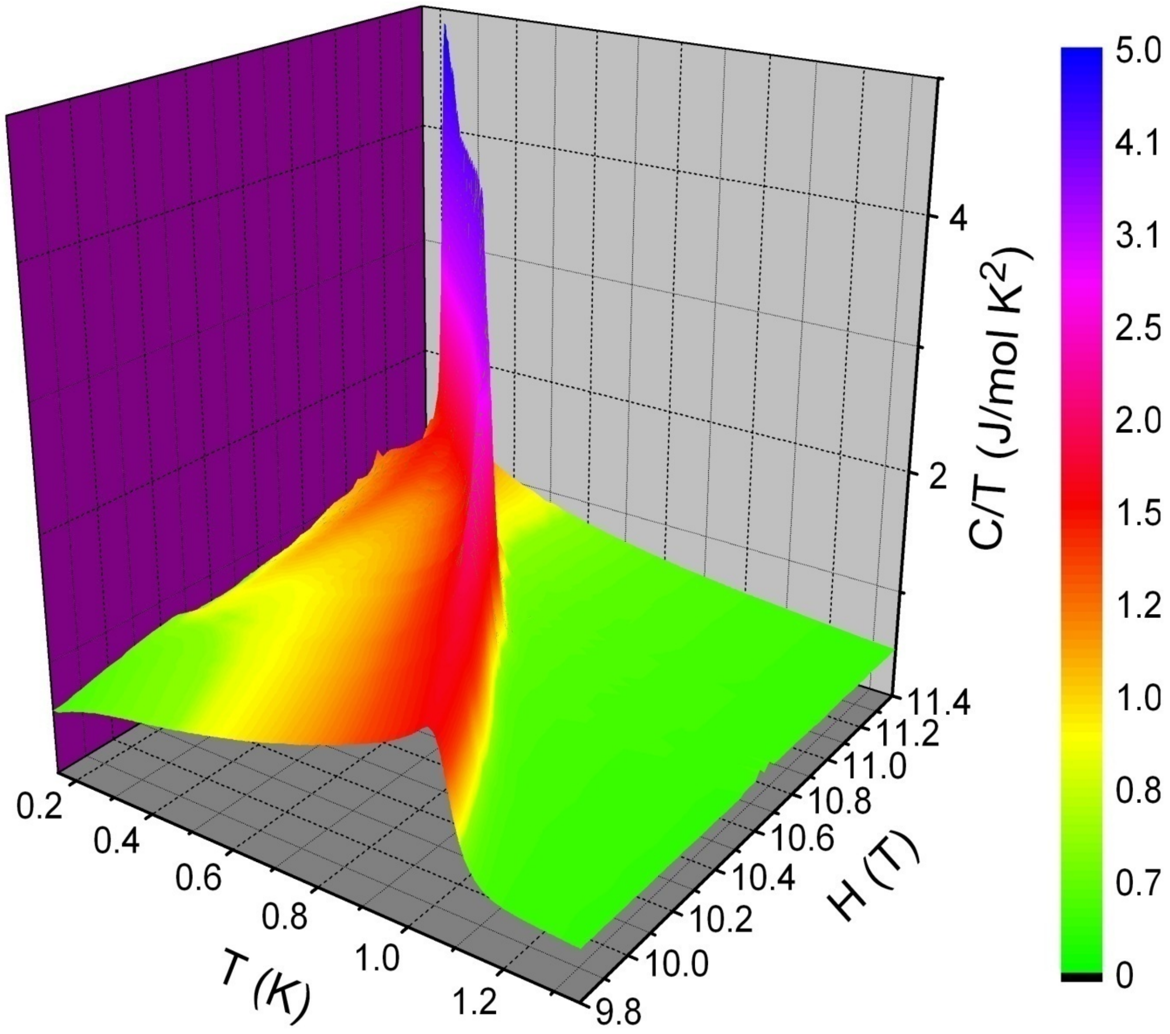
Specific heat of $CeCoIn_5$: SC and the high field phase



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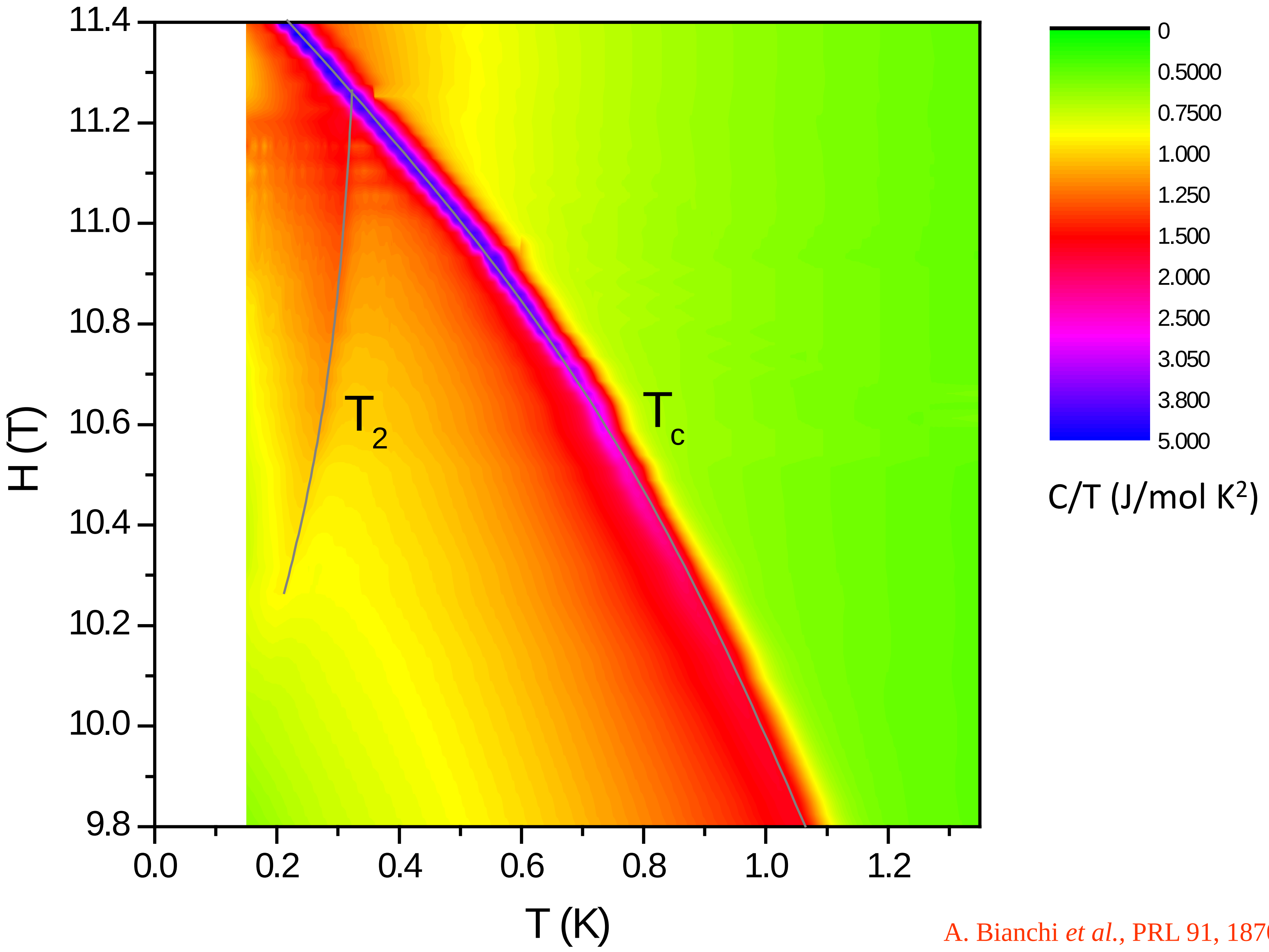
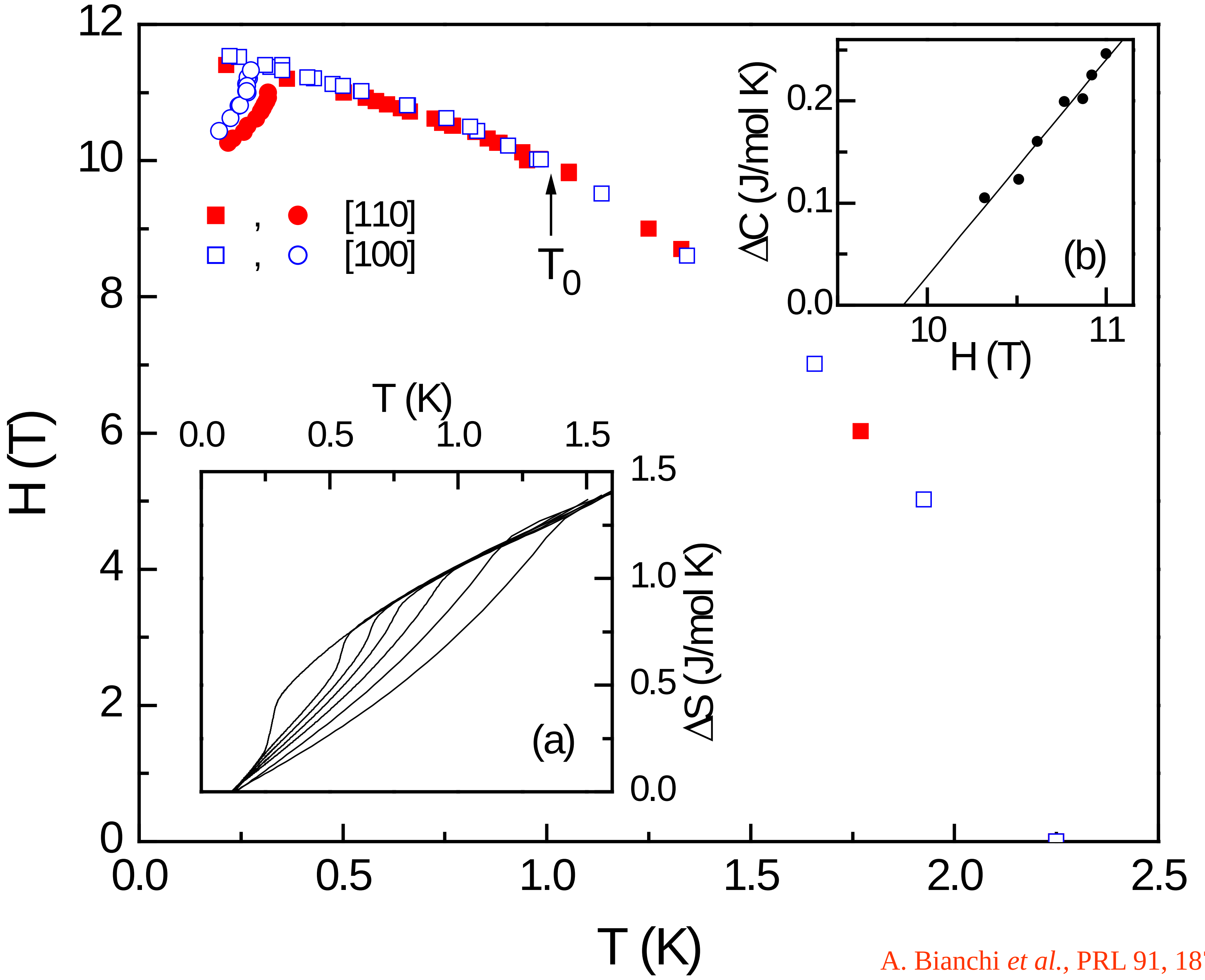
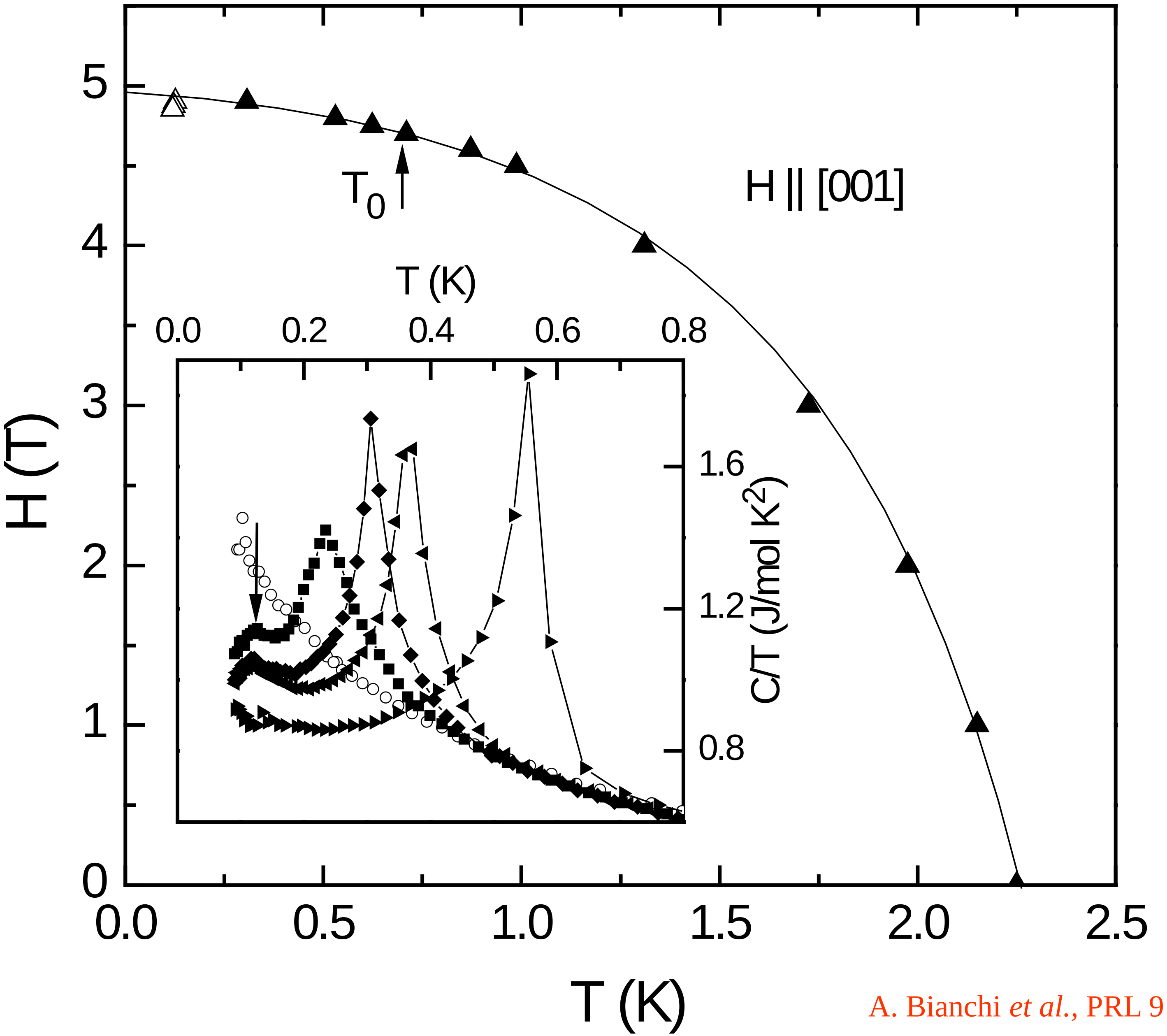
A. Bianchi *et al.*, PRL 91, 187004 (2003)



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

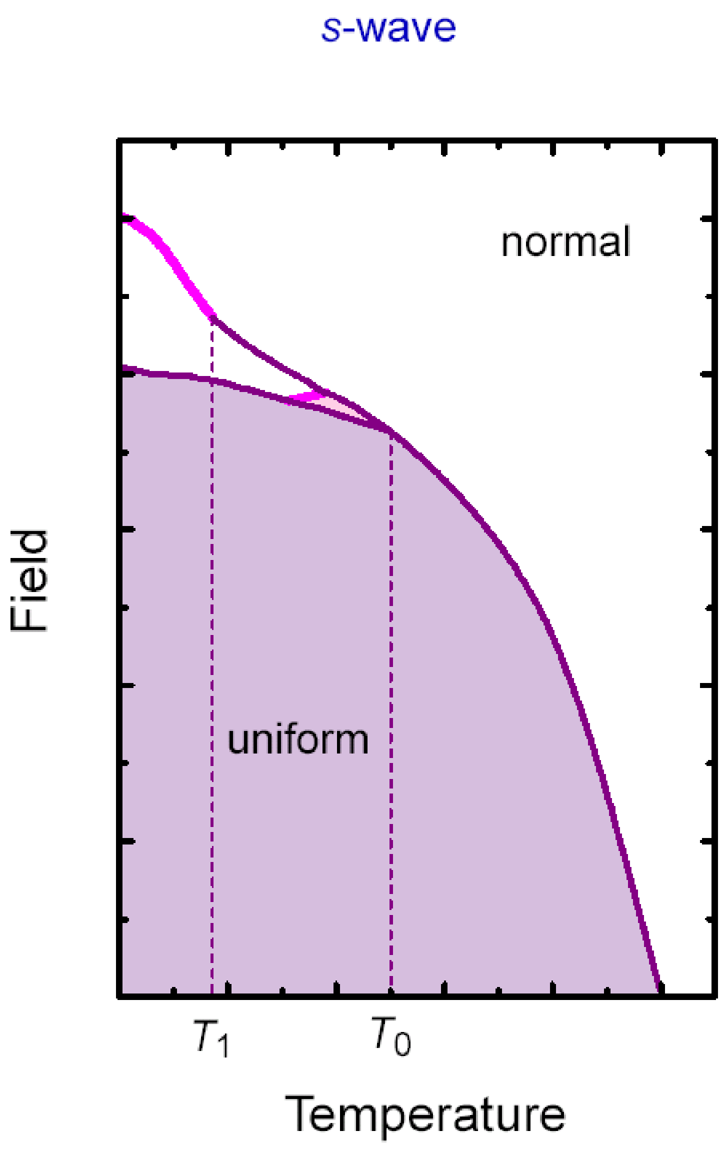


A. Bianchi *et al.*, PRL 91, 187004 (2003)

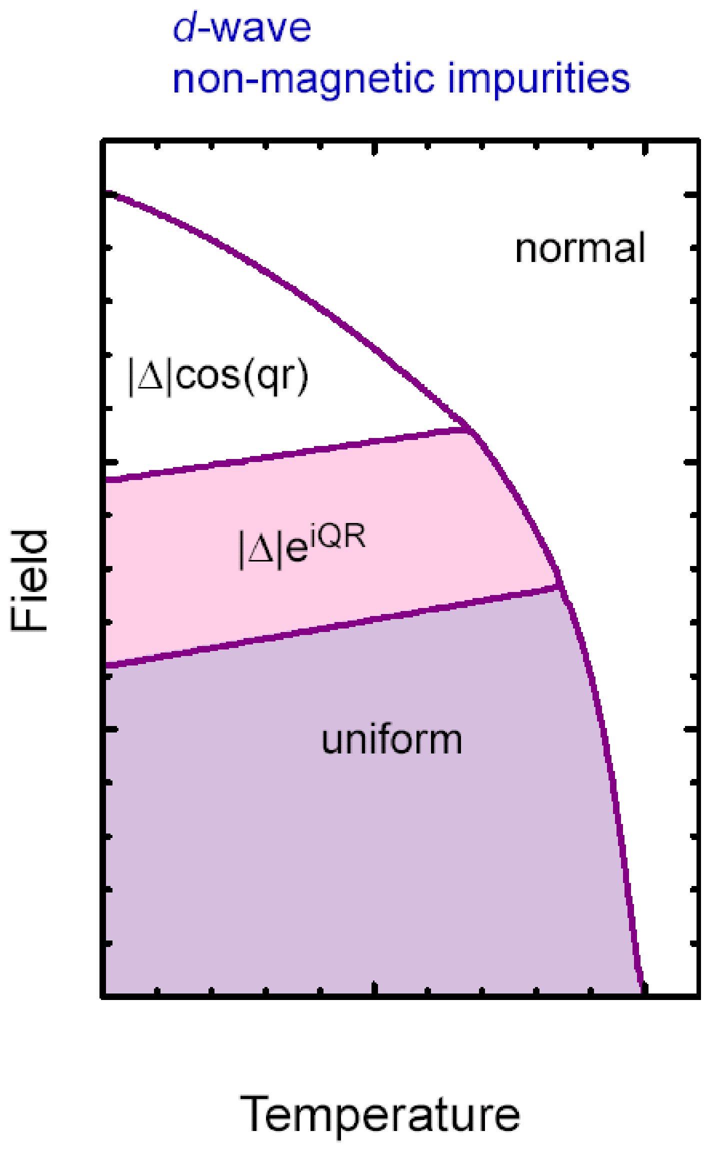


A. Bianchi *et al.*, PRL 91, 187004 (2003)

FFLO phase diagram?



M. Houzet and A. Buzdin PRB **63**, 184521 (2001).



D. F. Agterberg and K. Yang J. Phys.: Cond. Mat. **13**, 9259 (2001).

Field-Induced Superconducting-Magnetic State in $CeCoIn_5$ – theory I.

$$V_\infty = C\Delta^{(e)}_{\mathbf{q}} M_{\mathbf{Q}_0+\mathbf{q}} \Delta^{(o)}_{-\mathbf{Q}_0}, \quad (1)$$

where $M_{\mathbf{Q}_0+\mathbf{q}}$, $\Delta^{(e)}_{\mathbf{q}}$, and $\Delta^{(o)}_{-\mathbf{Q}_0}$ denote the IC-SDW magnetization in the c-direction, the d-wave superconducting (SC) gap in the FFLO state, and an additional odd-parity "equal-spin" SC gap with finite center-of-mass momentum $-\mathbf{Q}_0$, $\mathbf{Q}_0 \equiv (0.5\pi/a, 0.5\pi/a, 0.5\pi/c)$, (the so-called π-paring),

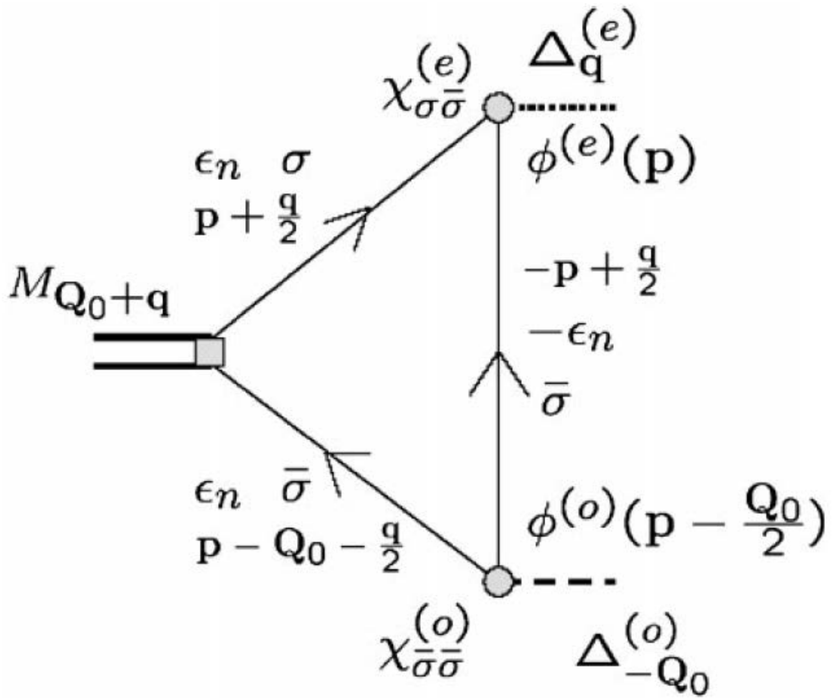


Fig. 1. Feynman diagram for the mode-coupling term eq. (1) among IC-SDW magnetization, $M_{\mathbf{Q}_0+\mathbf{q}}$, d-wave SC gap of FFLO state, $\Delta_{\mathbf{q}}$, and the so-called π-gap of odd-parity with center-of mass momentum $\mathbf{Q}_0$, $\Delta_{-\mathbf{Q}_0}$. The solid line presents the Green function of the quasiparticles in the normal state.

In the present model, the wave-vector of IC-SDW $\mathbf{Q}$ is not the same as that of FFLO $\mathbf{q}$, but is given by

$$\mathbf{Q} = \mathbf{Q}_0 + \mathbf{q}. \quad (10)$$

In the experiment of ref. 1, the FFLO wave vector is considered to be parallel to $(1, 1, 0)$ so that the expected IC-SDW wave vector is along $(0.5 + q, 0.5 + q, 0.5)$ direction in consistent with the experiment of ref. 1. However, if the FFLO vector was parallel to $(1, 0, 0)$ or $(0, 1, 0)$, the expected IC-SDW wave vector would be in $(0.5 + q, 0.5, 0.5)$ or $(0.5, 0.5 + q, 0.5)$ direction, respectively. This is a prediction of the present theory.

Kazumasa Miyake, J.Phys. Soc. Japan **77**, 123703 (2008)

Field-Induced Superconducting-Magnetic State in $CeCoIn_5$ – theory II.

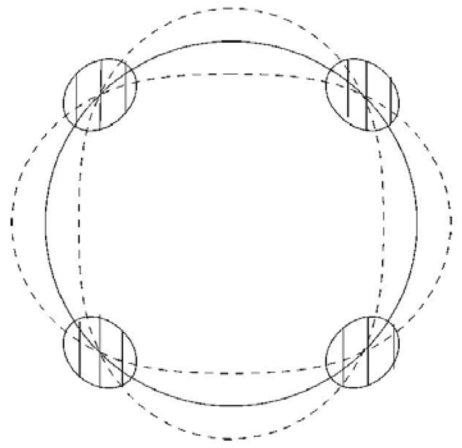


FIG. 1. Fermi surface pockets (shaded regions) produced by a Zeeman magnetic field. The electrons in the pockets are unpaired and spin polarized along the direction of the field. The dashed lines indicate the extent of the smearing of the Fermi surface by the superconducting order at zero field, and show that the lateral extrema of the "normal" pockets are bracketed by regions of paired electrons.

K. Yang & S. L. Sondhi, PRB 57 (1998)

Idea (Batista, Martin, Bulaevski): Nesting pockets of normal electrons around the nodes of the d-wave gap on the FS lead to AFM

Q: $M \propto H^2$ not observed in $CeCoIn_5$. Kondo effect, formation of the HF state?

Balatski: Magnetism couples to a gradient of the superconducting order parameter, similarly to the suggestion for URu_2Si_2, where the GL model is proposed that couples magnetic order to the gradient of the hidden order.

Needs microscopic foundation?

$$F[\Psi, \mathrm{M}] = F_{HO} + F_{AF} + F_C,$$

$$F_{HO}[\Psi] = a_1(T)\Psi^2 + \frac{1}{2}b_1\Psi^4 + \kappa_1|\nabla\Psi|^2,$$

$$F_{AF}[\mathrm{M}] = a_2(T)|\mathrm{M}|^2 + \frac{1}{2}b_2|\mathrm{M}|^4 + \kappa_2^{ijkl}\partial_j M_i \partial_l M_k,$$

ıts $a_1(T) = a_1(T - T_0)$ and $a_2(T) = a_2$. The coupling term is

$$F_C[\Psi, \mathrm{M}] = g_1\Psi^2|\mathrm{M}|^2 + g_2|\mathrm{M}|^2|\nabla\Psi|^2 + g_3|\mathrm{M}\cdot\nabla\Psi|^2.$$

S.–H. Baek et al., preprint

PHYSICAL REVIEW B **82**, 060510(R) (2010)

Antiferromagnetic ordering induced by paramagnetic depairing in unconventional superconductors

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(Received 16 June 2010; published 12 August 2010)

Antiferromagnetic (AFM) (or spin-density wave) quantum critical fluctuation enhanced just below $H_{c2}(0)$ have been often observed in d-wave superconductors with a strong Pauli paramagnetic depairing (PD) including $CeCoIn_5$. It is shown here that such a tendency of field-induced AFM ordering is a consequence of strong PD and should appear particularly in superconductors with a gap node along the AFM modulation. Two phenomena seen in $CeCoIn_5$, the AFM order in the Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state and the anomalous vortex lattice form factor in the high-field range below the FFLO state, are explained based on this peculiar PD effect.

H || [100] – FFLO is needed to explain the rise of H_{c2} at low T

Won and Maki (WM):

$\alpha = 4.5$, $H_p = 12.8$ T, $t_0 = T_0/T_c = 0.31$.

Compare with GG:

$\alpha = 4.5$, $H_p = 12.7$ T, $t_0 = T_0/T_c = 0.39$.

p signifies presence of the FFLO

$p \rightarrow 0$ at t = 0.31 – same as where the SC transition switches from second to first order!

This calculation is equivalent to Gruenberg and Gunther for an FFLO state in an *s*-wave superconductor, but for a *d*-wave superconductor!

H. Won, K. Maki *et al.*,
Phys. Rev. B **69**, 180504(R) (2004)

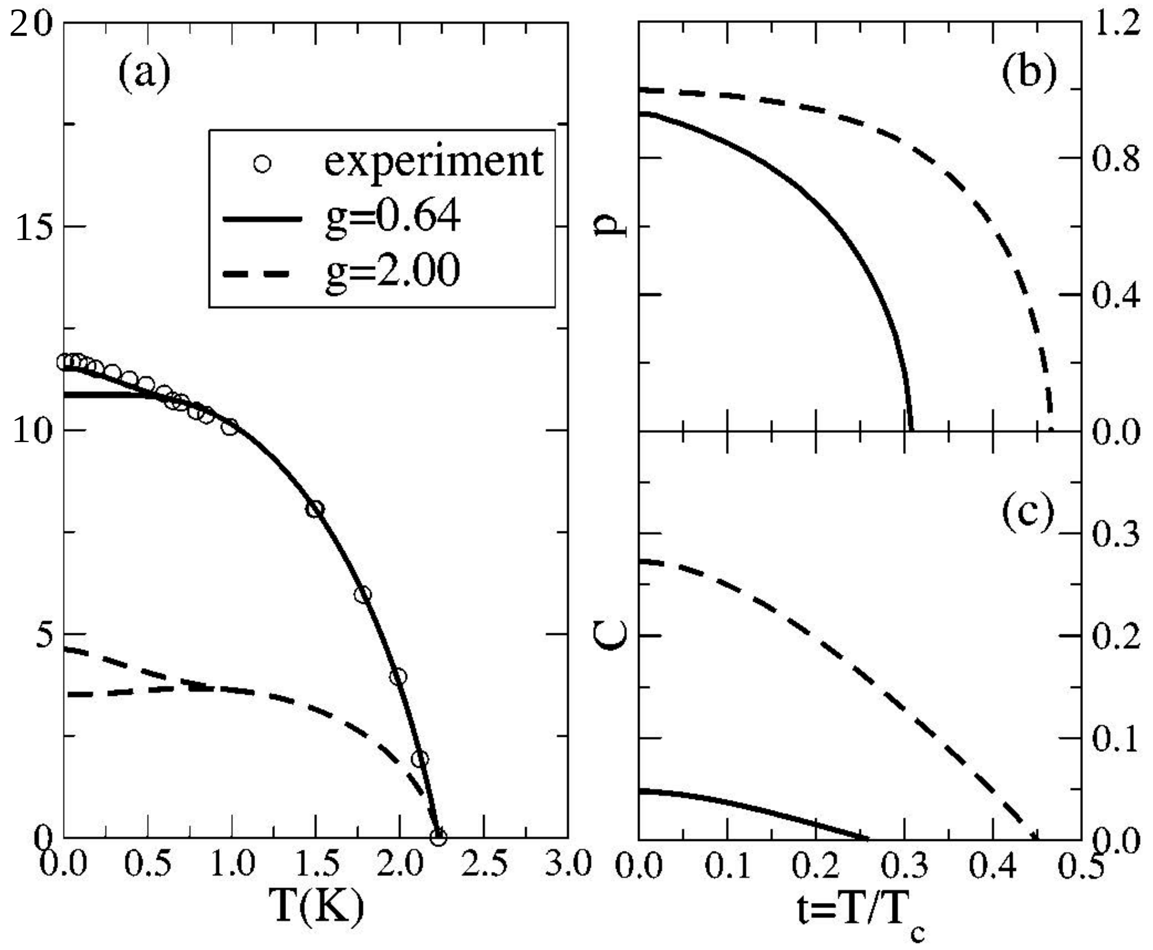
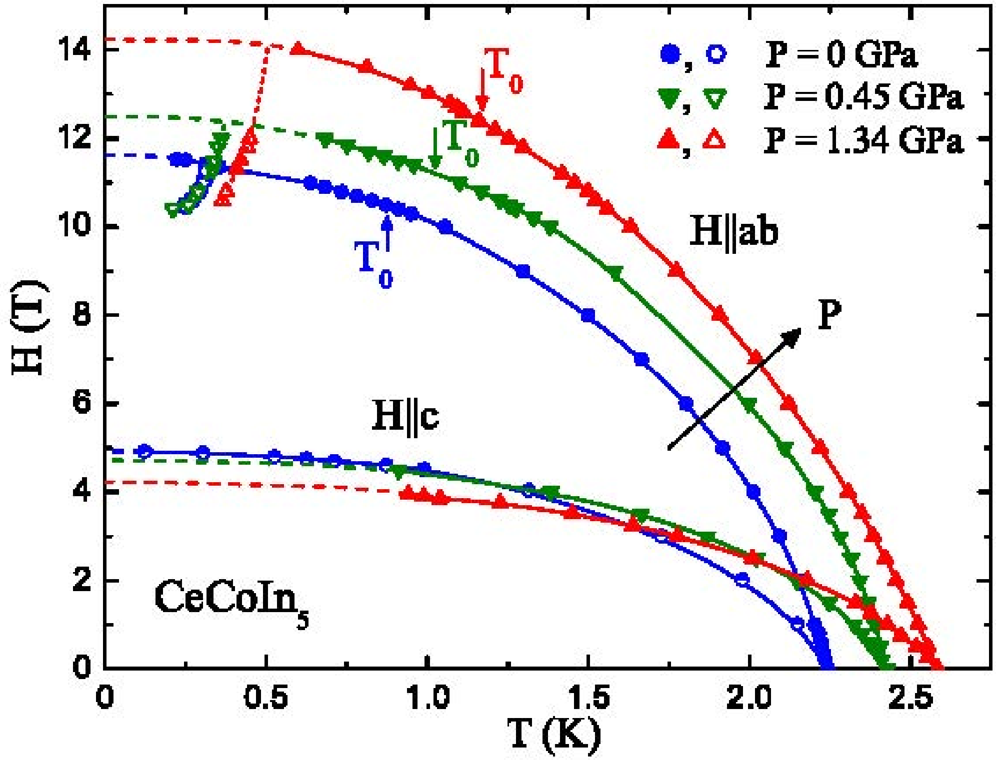
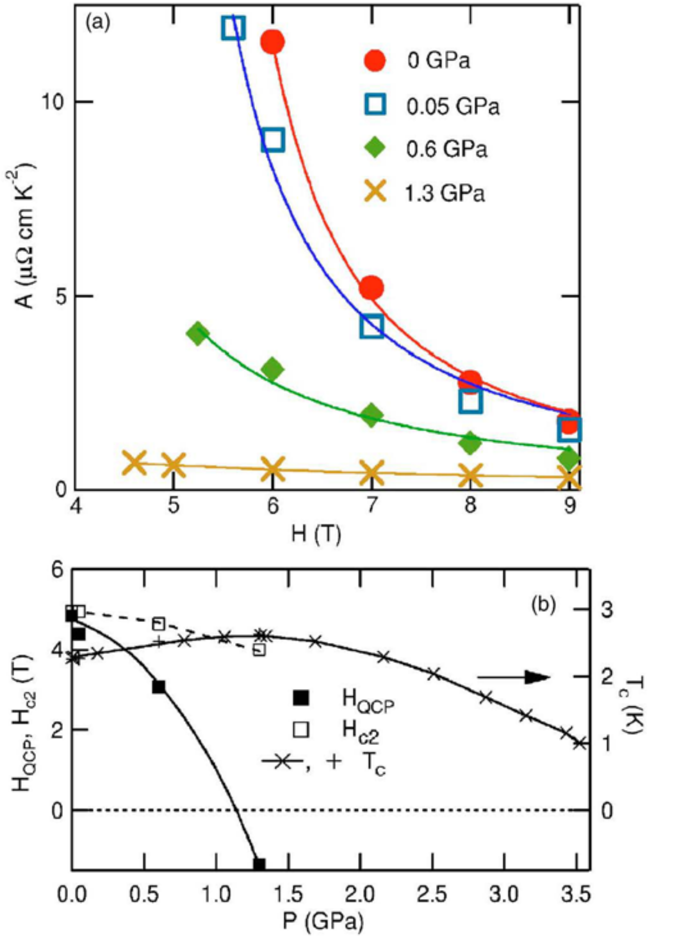


FIG. 2. Temperature dependence of (a) the upper critical field, (b) the $\vec{v}\cdot\vec{q}/(2H)=p\cos\phi$ term, and (c) the admixture parameter C in a $d_{x^2-y^2}$-wave superconductor with g factors $g=0.64$ (solid lines) and 2 (dashed lines). Here $t\equiv T/T_c$ is the reduced temperature. In (a) the lower curves represent $p(t)=0$, i.e., absence of FFLO, whereas the upper curves have $p(t=0)=0.9$. The magnetic field is applied along the crystal a direction. The experimental data (circles) are best described by $g=0.64$ and $p(t=0)=0.9$.

Pressure effects on FFLO and QCP in $CeCoIn_5$





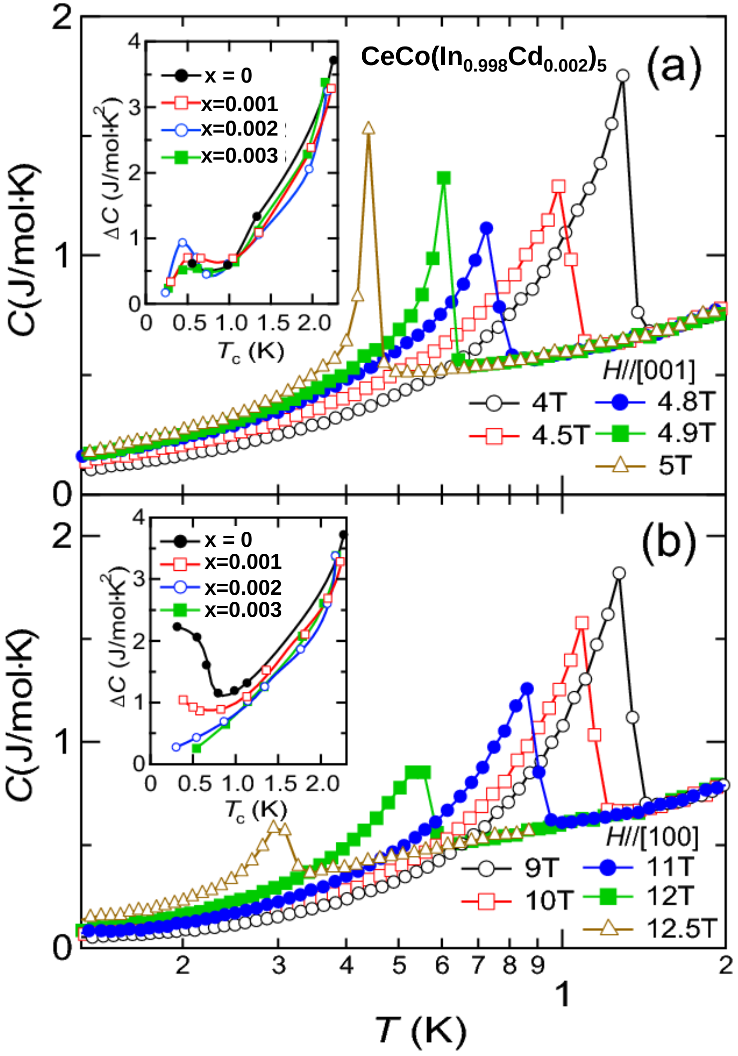
The first order character of the SC PT at high magnetic fields persists under pressure and the FFLO region in the phase diagram expands upon reducing the spin fluctuations, consistent with the model proposed by H. Adachi and R. Ikeda, Phys. Rev. B 68, 184510 (2003).

C. F. Miclea et al., PRL **96**, 117001 (2006)

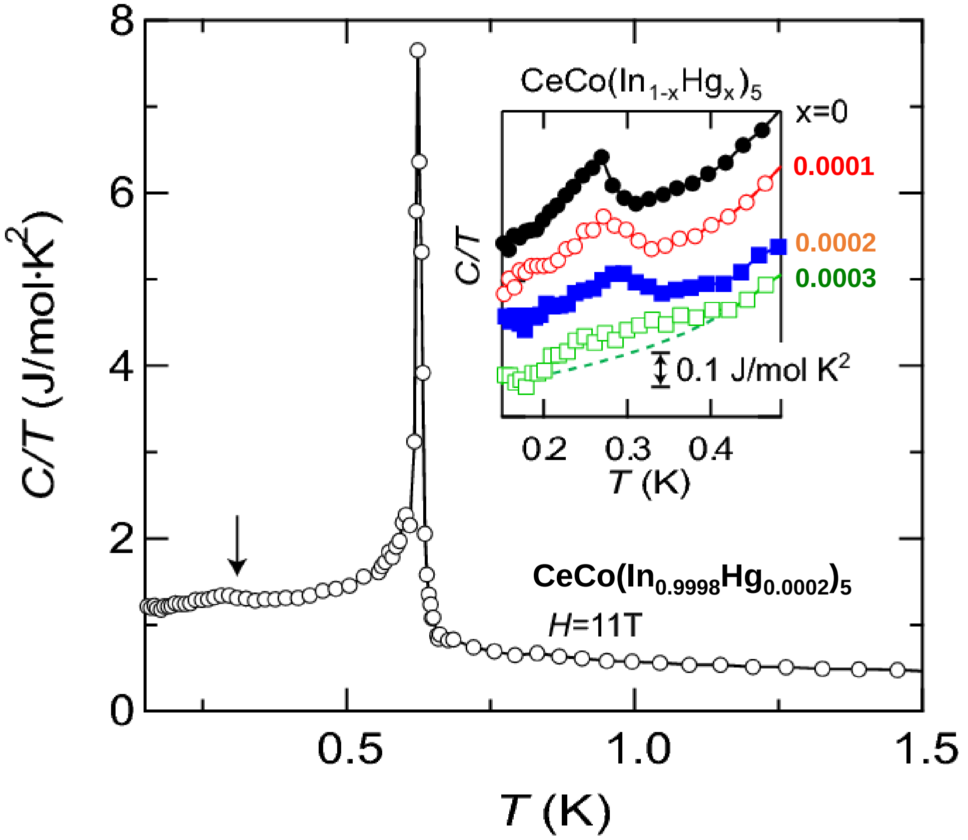
F. Ronning *et al.*, PRB **73**, 064519 (2006)

Pressure enhances the Q-phase and 1st to 2nd order of SC transition T_0 (and suppresses QCP) in support of the non-magnetic origin (FFLO?) of the Q-phase phase.

Cd and Hg doping studies of the high field part of the H-T phase diagram of $CeCoIn_5$

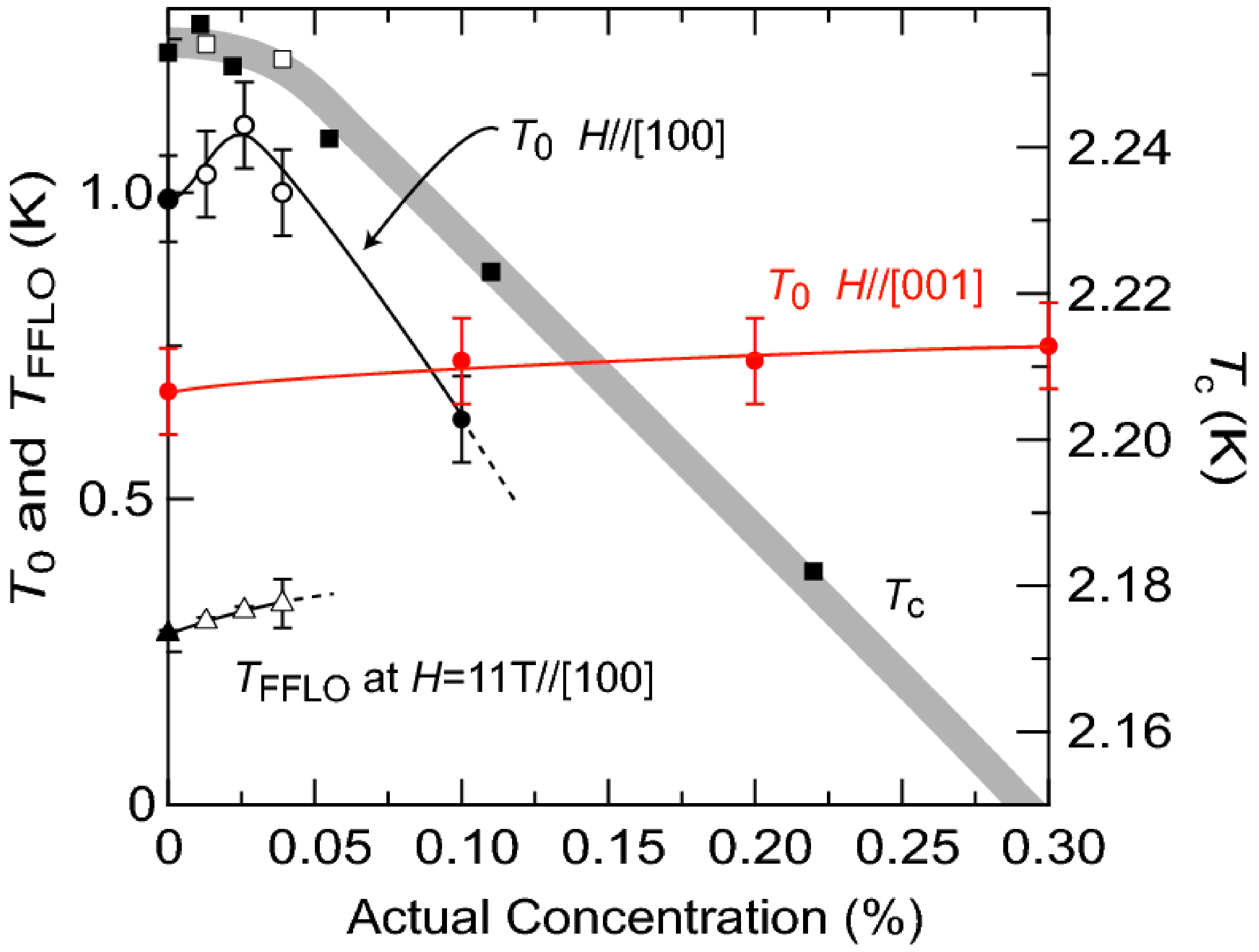


Y. Tokiwa *et al.*, PRL **101**, 037001 (2008)



Hg and Cd doping suppresses 1st order character of the SC transition for H||[100], an effect opposite to that of pressure. Lower level of Hg doping reveals HFLT anomaly, which is quickly suppressed with x = 0.0003 of actual concentration.

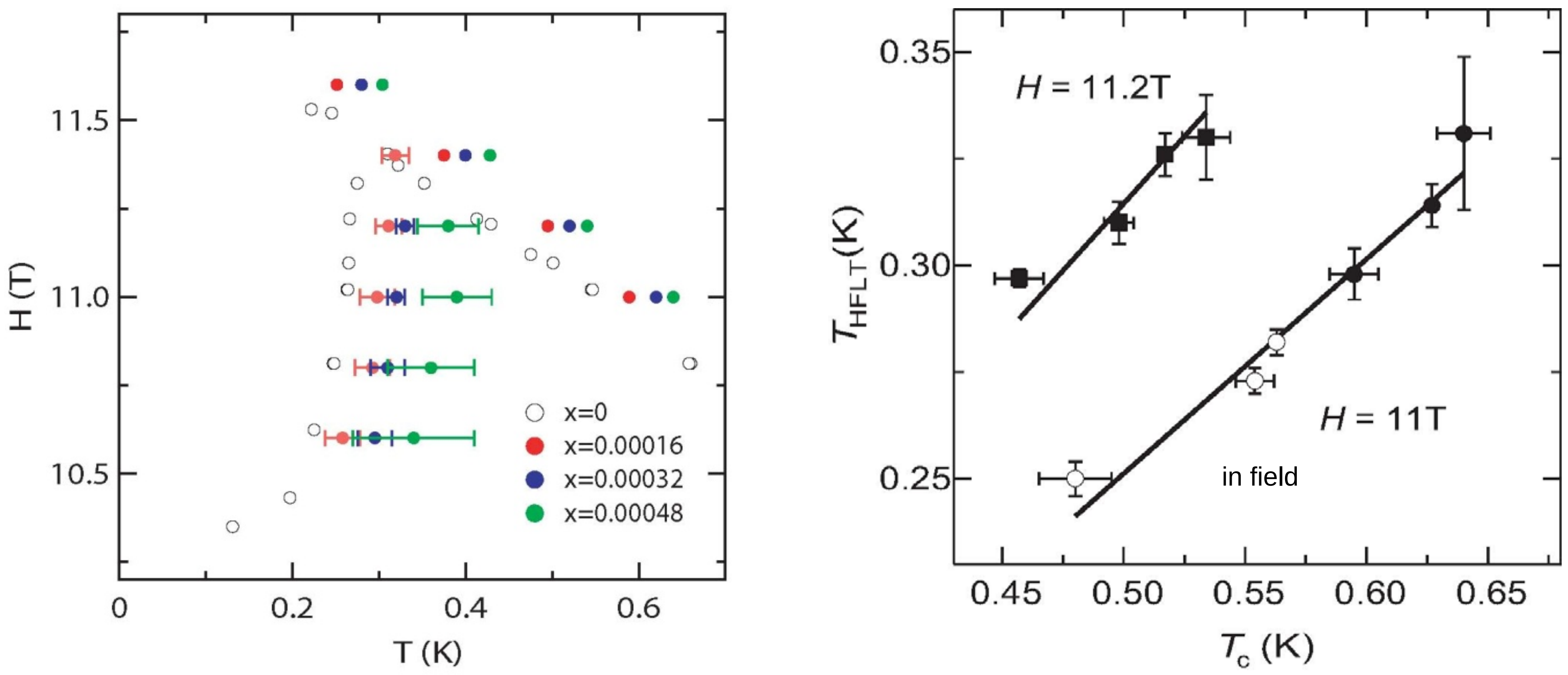
Cd and Hg doping studies of the high field part of the H-T phase diagram of $CeCoIn_5$



At low Cd and Hg concentrations T_c is constant, i.e. SC is in the independent impurity regime, where inter-impurity distance *d* is greater than two SC coherence lengths ξ. FFLO phase survives in exactly the same region, which implies that ξ is the relevant length scale for HFLT phase, expected for the FFLO state. In addition, if HFLT state is AFM in origin, impurities would be expected to stabilize such state, contrary to observations.

Y. Tokiwa *et al.*, PRL **101**, 037001 (2008)

Cd, Hg, and Sn doping studies of the H-T phase diagram of $CeCoIn_5$ – scaling of T_{HFLT} and $H_{c2}/T_c(H)$



For both Hg and Sn dopants HFLT phase scales with superconducting T_c in spite of the fact that large Hg doping leads to AFM state, and Sn does not.=> support for SC origin of HFLT.

PHYSICAL REVIEW B **81**, 060510(R) (2010)

Impurity-induced broadening of the transition to a Fulde-Ferrell-Larkin-Ovchinnikov phase

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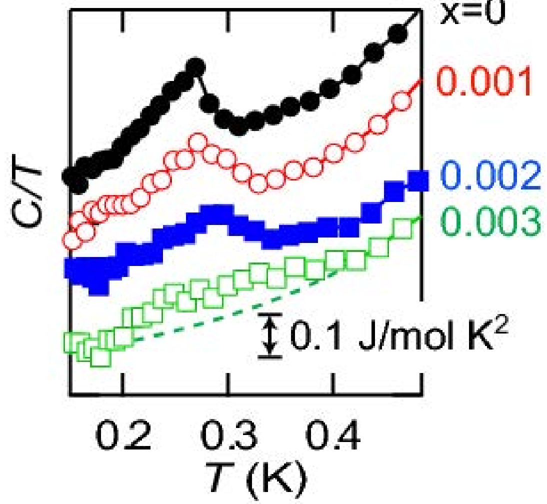
(Received 1 December 2009; revised manuscript received 11 January 2010; published 25 February 2010)

Recent study on doping effects in the heavy-fermion superconductor $CeCoIn_5$ has shown that a small amount of doping induces unexpectedly large broadening of the transition into the high-field and low-temperature (HFLT) phase of this material. To resolve this observation, effects of quenched disorder on the second-order transition into a longitudinal Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state are examined. The large broadening of the transition is naturally explained as a consequence of softness of each FFLO nodal plane. The present results strongly support the scenario identifying the HFLT phase of $CeCoIn_5$ with a longitudinal FFLO state.



Y. Tokiwa *et al.*, PRL **101**, 037001 (2008)

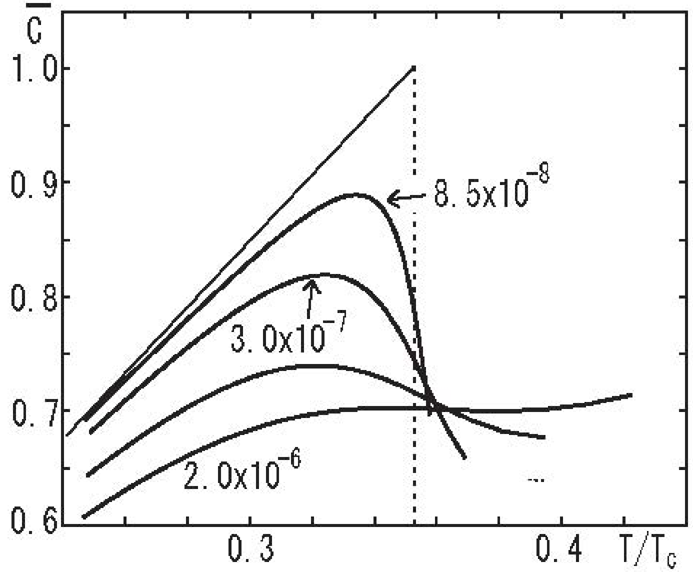
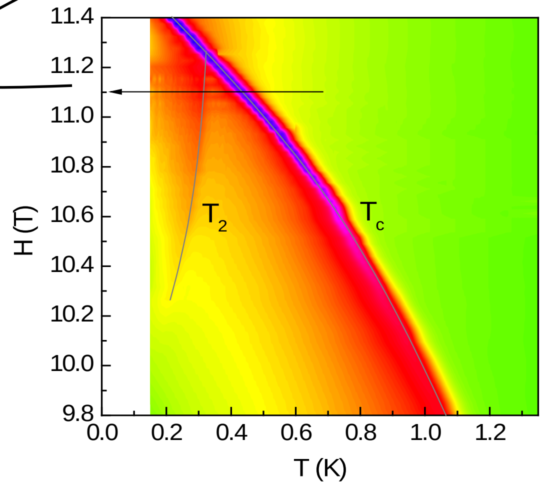


FIG. 1. Results of normalized heat capacity $\bar{C}(T)$ (thick solid curves) below $T_s(\delta_0)$ and at a fixed magnetic field following from Eq. (8) for $\delta_0=8.5\times10^{-8}$ (top), 3.0×10^{-7}, 1.0×10^{-6}, and 2.0×10^{-6} (bottom). Data in Ref. 7 on the coefficients in Eq. (1) at $H=0.5H_{orb}^{(2D)}(0)$ have been used, where $H_{orb}^{(2D)}(0)=0.56\phi_0/(2\pi\xi_0^2)$ is the two-dimensional (2D) orbital-limiting field, and ϕ_0 is the flux quantum. The right end of each curve corresponds to the result at each $T_s(\delta_0)$. The thin solid line denotes $\bar{C}(T)$ below $T_s=0.354T_c$ in the pure ($\delta_0=0$) case.

NMR – a case for local magnetic order



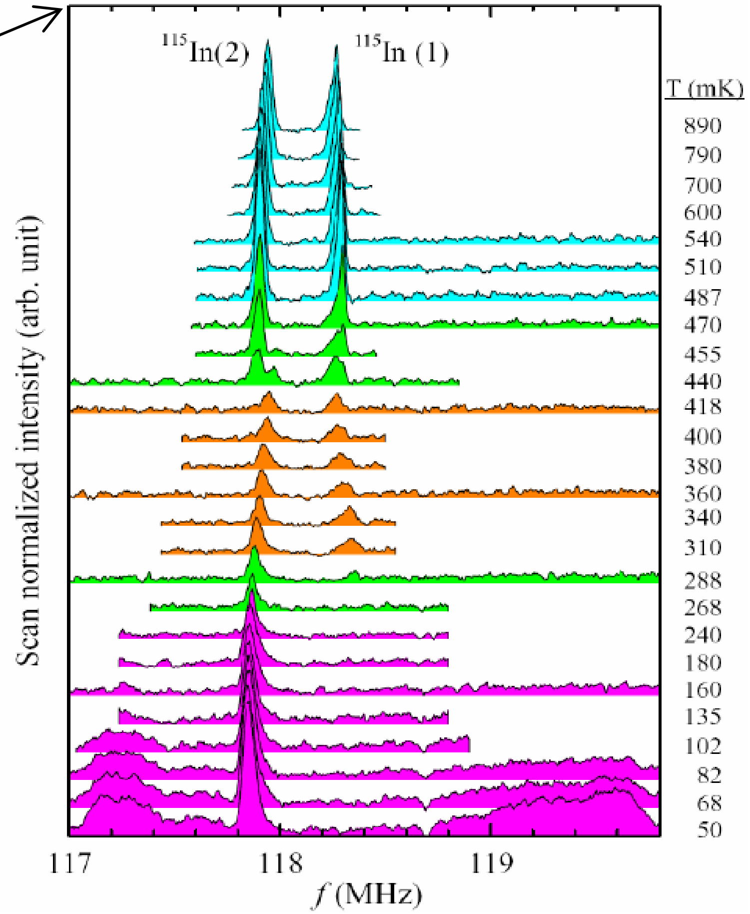


FIG. 2: NMR spectra of In(1) $\left(-\frac{5}{2} \leftrightarrow -\frac{7}{2}\right)$ and the In(2) $\left(-\frac{1}{2} \leftrightarrow -\frac{3}{2}\right)$ transitions in $CeCoIn_5$ at 11.1T. Note that the In(1) transition at 118.3MHz in the normal state shifts down in frequency discontinuously at T_c, whereas the In(2) shifts up in frequency, as observed previously in lower fields [16].

B.-L. Young et al., *Phys. Rev. Lett.* **98** , 36402 (2007).

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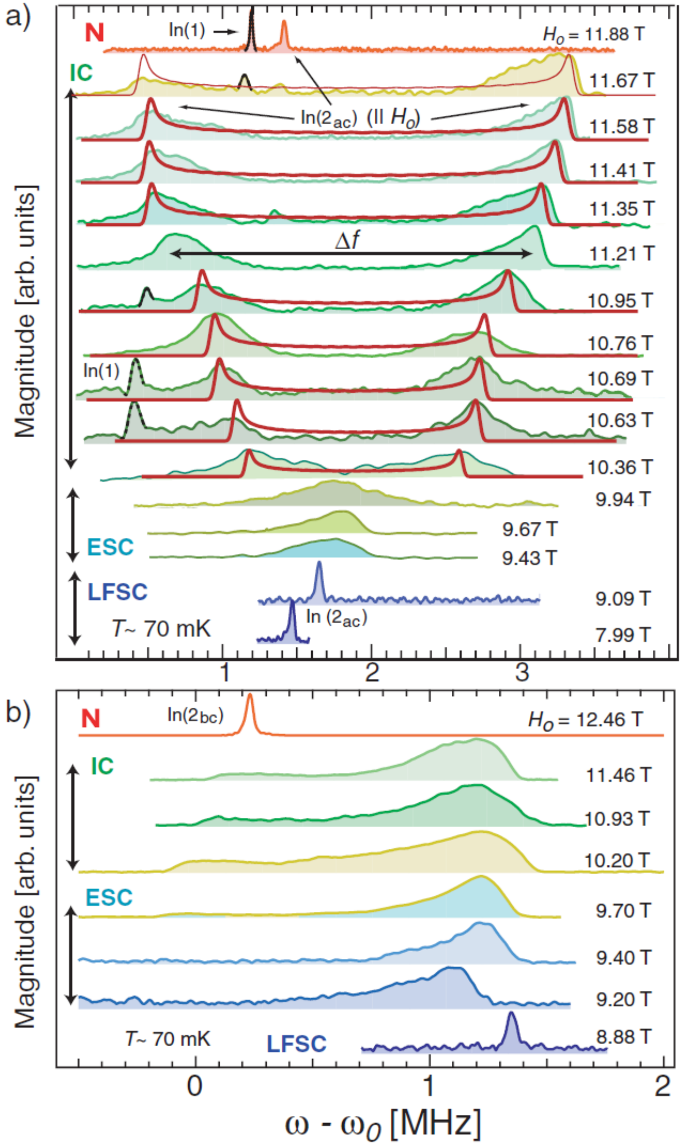
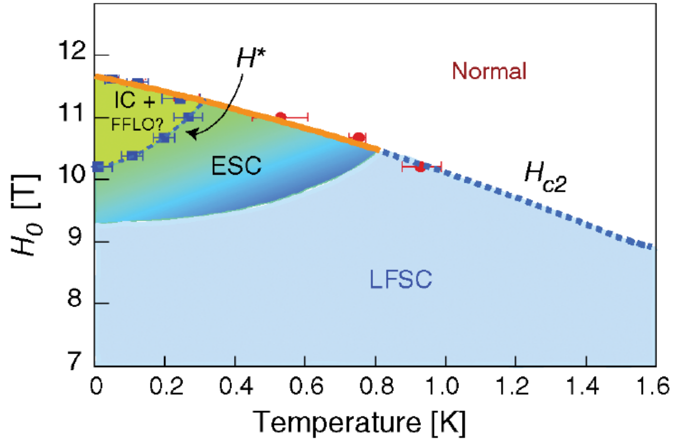
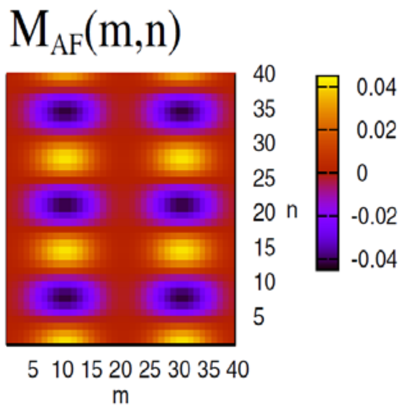
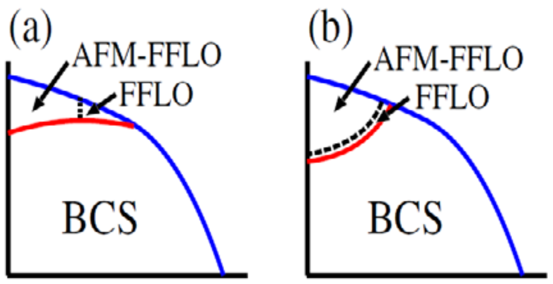
Intermediate Phase by Spin fluctuation



Koutroulakis, G. et al. , Phys. Rev. Lett. 104, 87001 (2010)







I. Yanase, Y. & Sigrist, M., J. Phys. Soc. Japan 78, 114715 (2009)

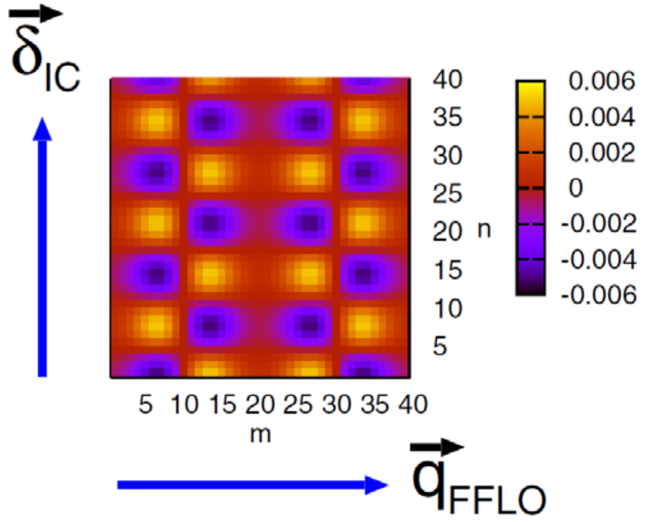
Consistent with FFLO state ?

$q_{FFLO} \perp Q$

Nodal plane || Q

$\kappa\ (J \perp Q)\ <\ \kappa\ (J \parallel Q)$

κ (J $\perp$ Nodal plane) < κ (J || Nodal plane)



The order parameter of the π-triplet paring in AFM-FFLO state

I. Yanase, Y. & Sigrist, M., J. Phys. Soc. Japan 78, 114715 (2009)

Evolution of Paramagnetic Quasiparticle Excitations Emerged in the High-Field Superconducting Phase of CeCoIn5

We show that the NMR spectra in this phase provide direct evidence for the emergence of the spatially distributed normal quasiparticle regions. The quantitative analysis for the field evolution of the paramagnetic magnetization and newly emerged low-energy quasiparticle density of states is consistent with the nodal plane formation, which is characterized by an order parameter in the Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state. The NMR spectra also suggest that the spatially uniform spin-density wave is induced in the FFLO phase.

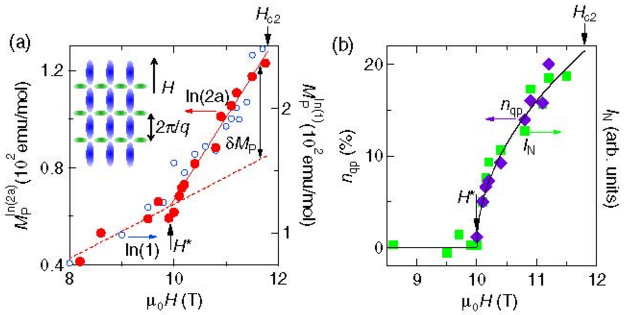


FIG. 4 (color online). (a) Field dependence of the paramagnetic magnetization M_p of the In(2a) (filled circles) and the In(1) (open circles) sites. Inset: Schematic quasiparticle structure in the FFLO state. The nodal planes with period of $2\pi/q$ appear perpendicular to the Abrikosov vortex lattice. (b) Field dependence of the DOS of the paramagnetic quasiparticles, n_{qp} and I_N, extracted from the In(2a) spectra. The solid line is a fit to $\sqrt{H - H^*}$ dependence.

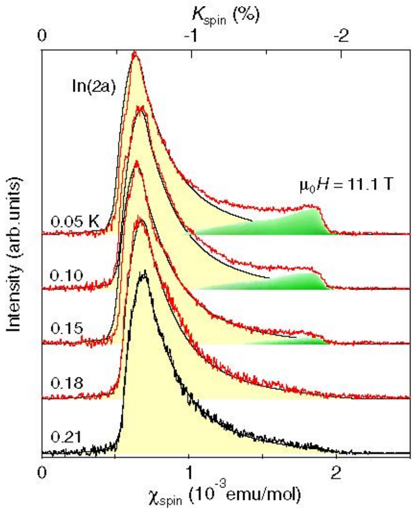


FIG. 3 (color online). Temperature evolution of the In(2a) spectrum in HL (0.05–0.18 K) and BCS (0.21 K) phases at $\mu_0H = 11.1$ T. The peak intensity of each spectrum is normalized. Thin black lines indicate the spectrum at $T = 0.21$ K just above T^*. The (green) shaded regions in the low-temperature data indicate the quasiparticle spectrum formed in the HL phase.

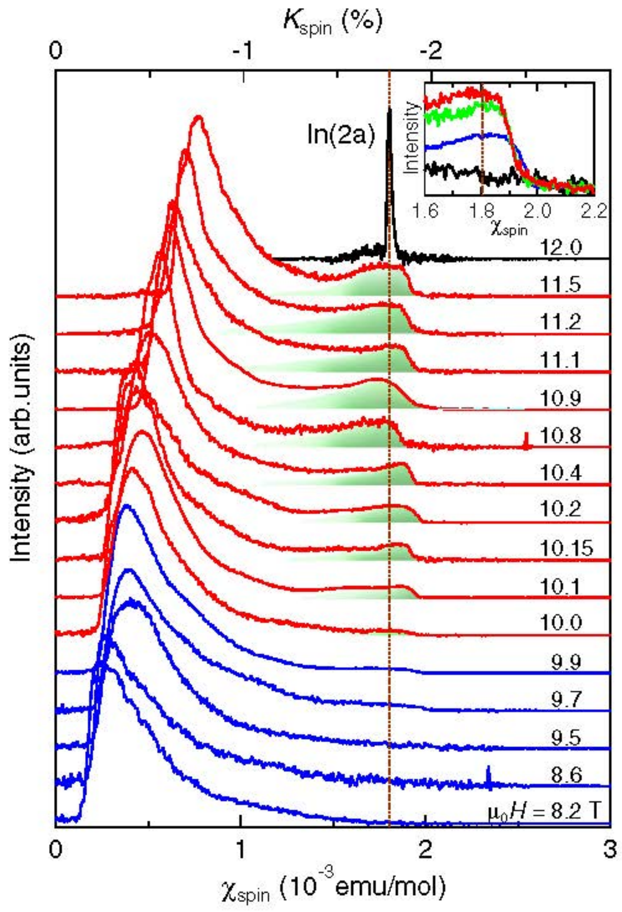


FIG. 2 (color online). Field evolution of the NMR spectra at the In(2a) site at $T = 0.05$ K in the normal (12.0 T), HL (10.0–11.5 T), and BCS (8.2–9.9 T) states. The integrated intensity of each spectrum below H_{c2} is normalized. The spin susceptibility (lower scale) is obtained by $\chi_{spin} = K_{spin}/A_{hf}$ with $K_{orb} = 1.95\%$. The (green) shaded region indicates the quasiparticle spectrum emerged in the HL phase. Inset: Zoom of spectra near the edge structure at $\mu_0H = 9.5$ (black), 10.2 (blue), 11.1 (green), and 11.2 T (red) from bottom to top. Dotted lines indicate the peak position in the normal state.

K. Kumagai, H. Shishido, T. Shibauchi, and Y. Matsuda PRL 106, 137004 (2011)

Additional support for an FFLO scenario

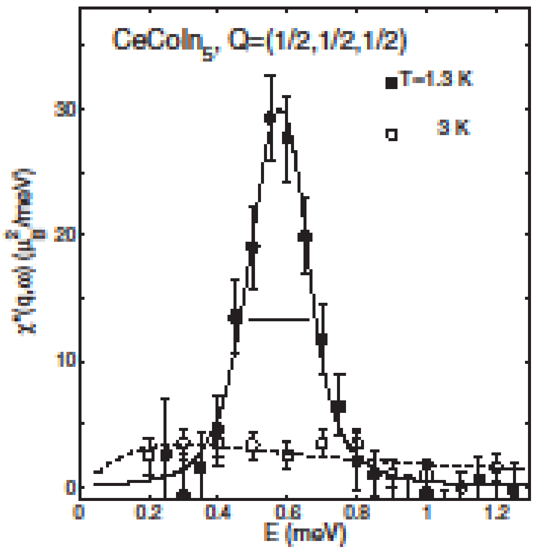
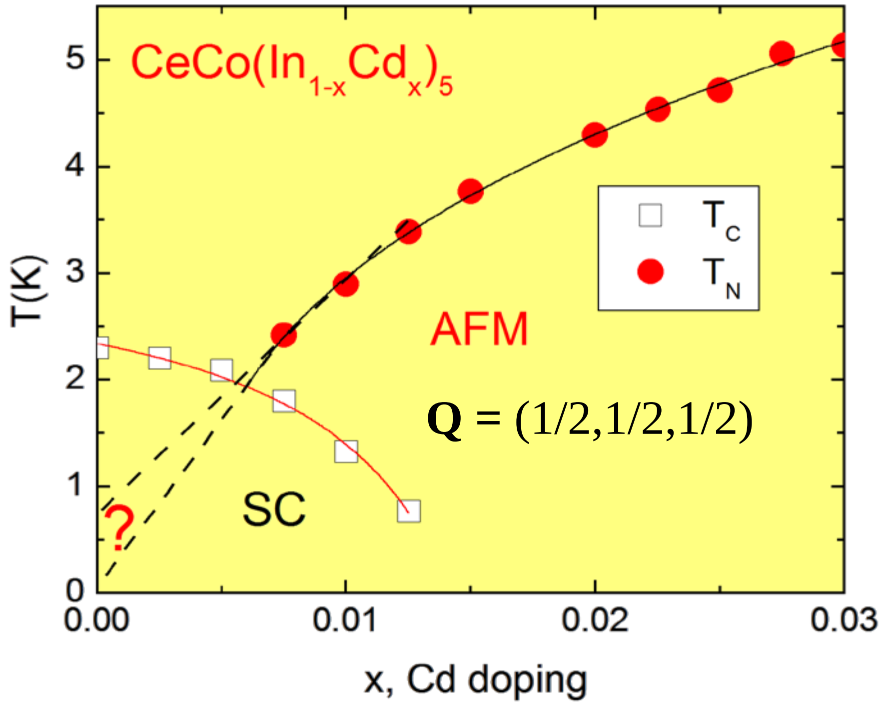


FIG. 1. The imaginary part of the dynamic susceptibility at $\mathbf{Q} = (\frac{1}{2}\frac{1}{2}\frac{1}{2})$ is plotted in the normal (3 K) and in the superconducting (1.35 K) states. A background taken at $\mathbf{Q} = (0.3, 0.3, 0.5)$ and $\mathbf{Q} = (0.7, 0.7, 0.5)$ was subtracted. The horizontal bar is the resolution width.

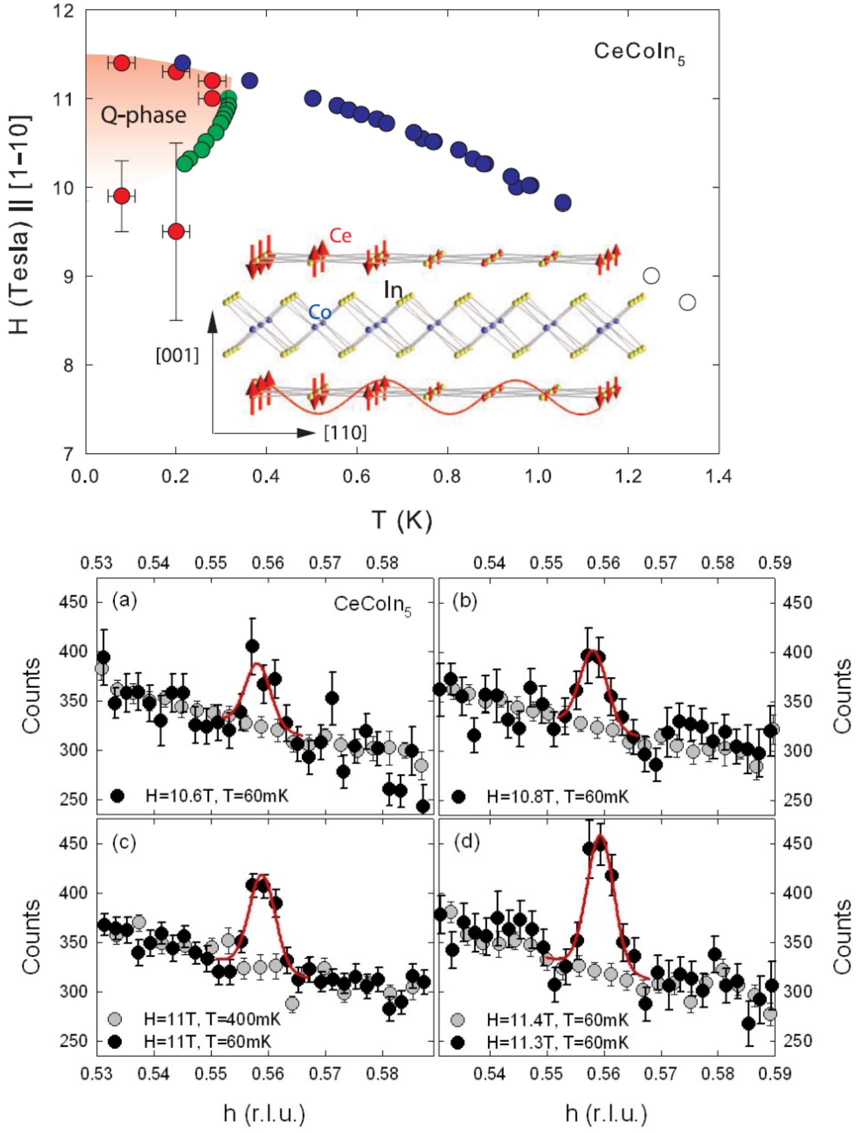
C. Stock, C. Broholm, PRL **100,** 087001 (2008)



L.Pham *et al.*, PRL **97**, 056404 (2006)

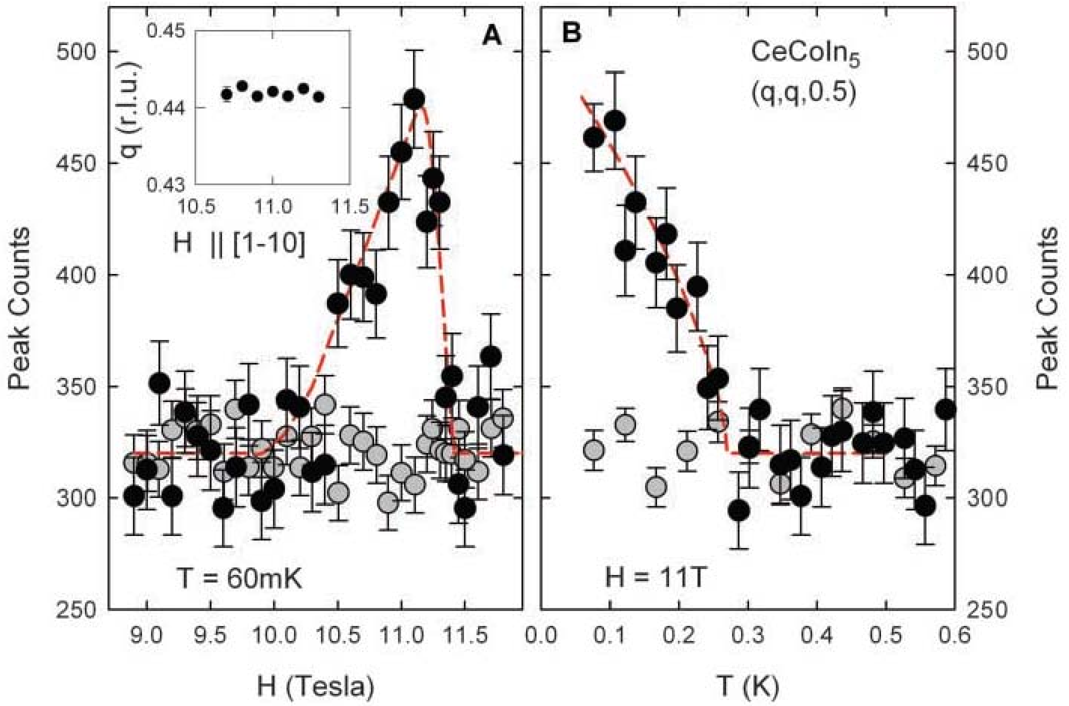
- Superconducting HFLT state shifts the AFM ordering wave vector Q by a small amount from (1/2,1/2,1/2) (K. Miyake ?) - FFLO?
- Ultrasound measurements by T. Watanabe, Y. Matsuda et al. , Phys. Rev. B 70, 020506 (2004): softening of the vortex lattice at transition into HFLT phase – understood to be a result of interaction between vortices and FFLO nodal planes.
- Doping studies (in the next few slides): small amount of doing destroy HFLT state – unlikely if origin of the HFLT state is AFM order
- Broad NMR lines in the HFLT state at the lowest temperatures.

Field-Induced Superconducting-Magnetic State in $CeCoIn_5$



(h,h,0.5) scans

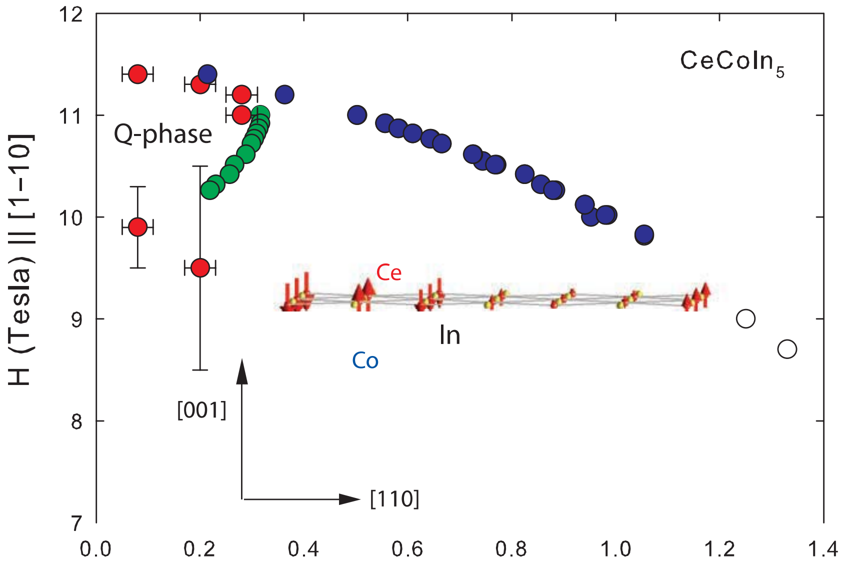
Neutron scattering identified the AFM order as an amplitude-modulated spin-density-wave (SDW) with an ordering wave-vector Q = (0.44,0.44,0.5)



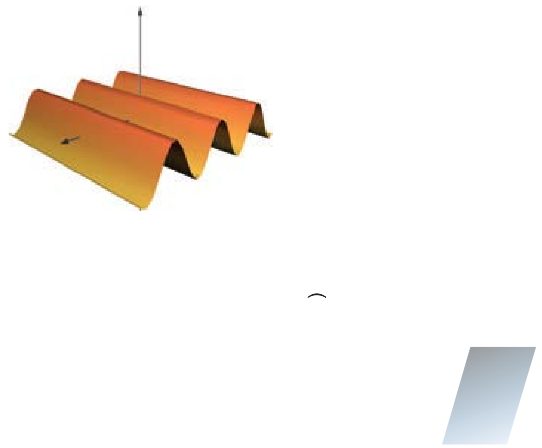
M. Kenzelmann, et al., *Science* **321**, 1652 (2008)

Q-Phase of $CeCoIn_5$

Spin-Density-Wave in the Superconducting state



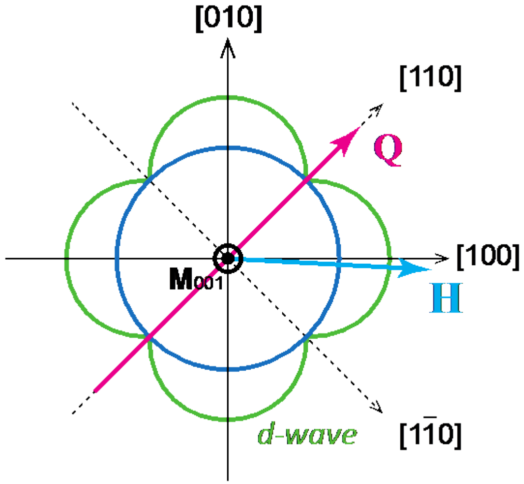
M. Kenzelmann *et al.*, Science **321**, 1652 (2008)

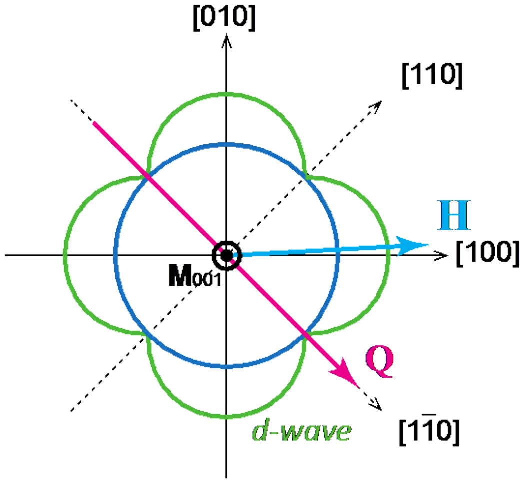


S. Gerber *et al.* Nat. Phys. **10**, 1038 (2014)

- Magnetic moment along the c axis
- Incommensurate propagation vector **Q** = (q, ±q, 1/2)
- Single domain
- First order domain switching between [110] and [1$\bar{1}$0] within ≈0.1 °.

Switching of the Spin-Density-Wave in CeCoIn5



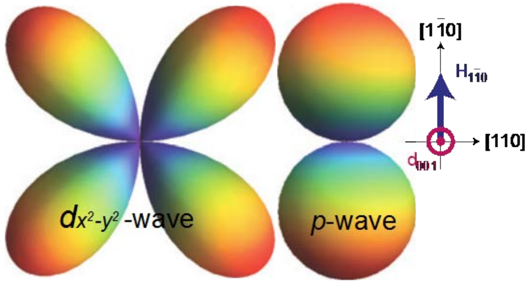


S. Gerber *et al.* Nat. Phys. **10**, 1038 (2014)

Theoretical proposals for hypersensitive switching

p-wave PDW

- S. Gerber *et al.* Nat. Phys. **10**, 1038 (2014)
- D. F. Agterberg, *et al.*, Phys. Rev. Lett. 102, 207004 (2009)



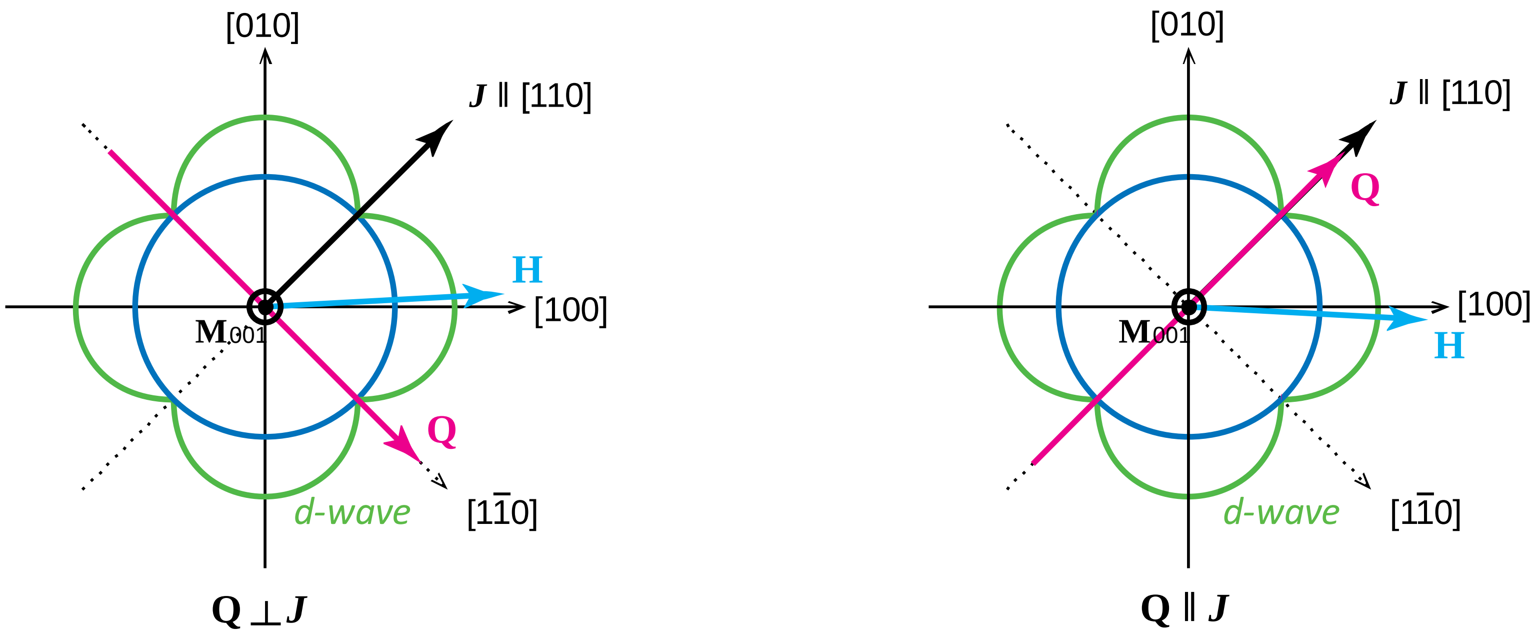
Spin-Orbital coupling

- V. P. Mineev, arXiv:1509.04915 (2015)

FFLO-Based

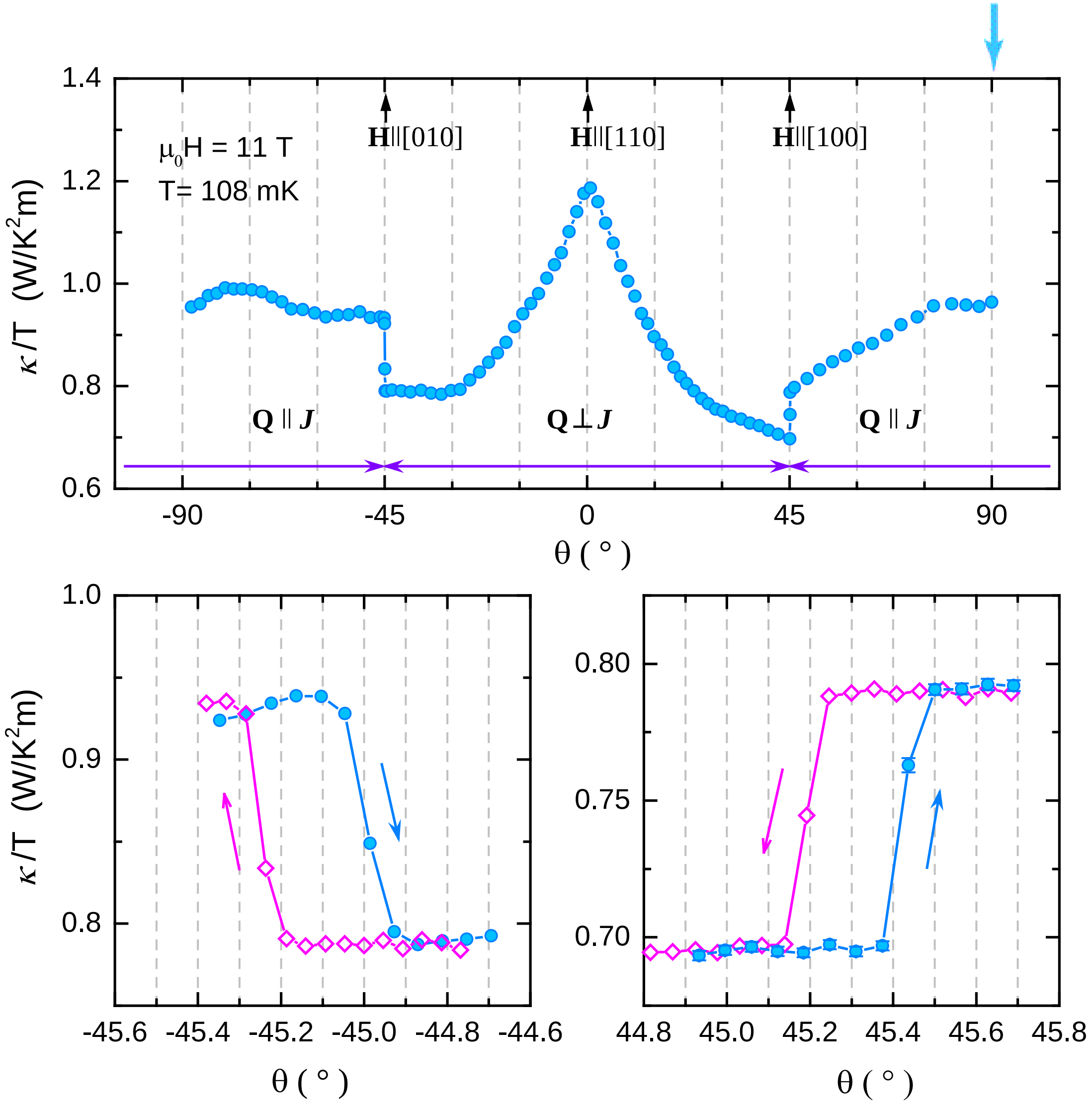
- Y. Hatakeyama & R. Ikeda, Phys. Rev. B **91**, 94504 (2015)

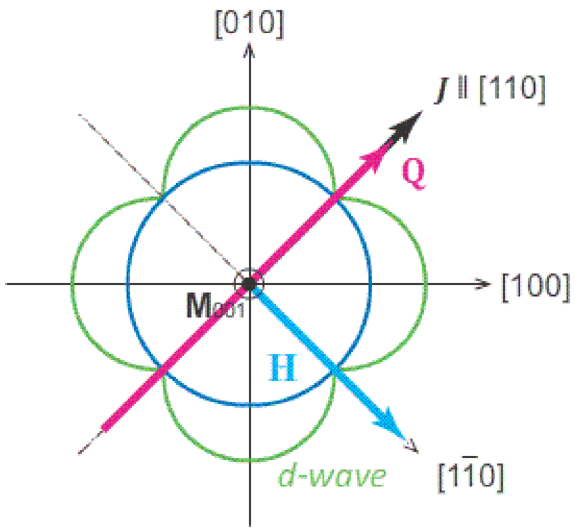
Thermal Transport Measurement to probe the Switching



Heat Current (*J*) along the Nodal direction [110]

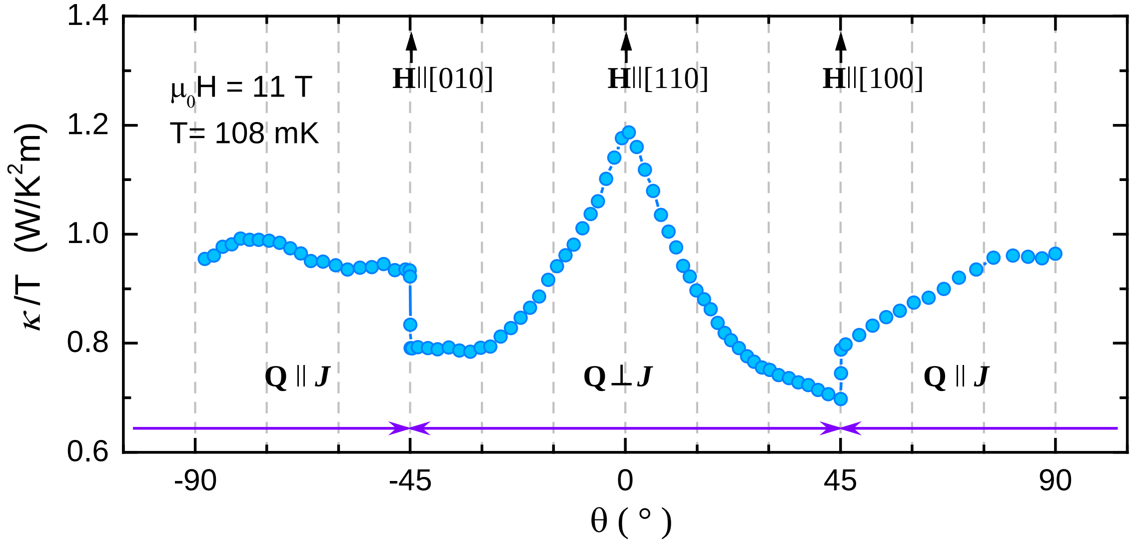
Thermal Conductivity Jump with the Q Switching

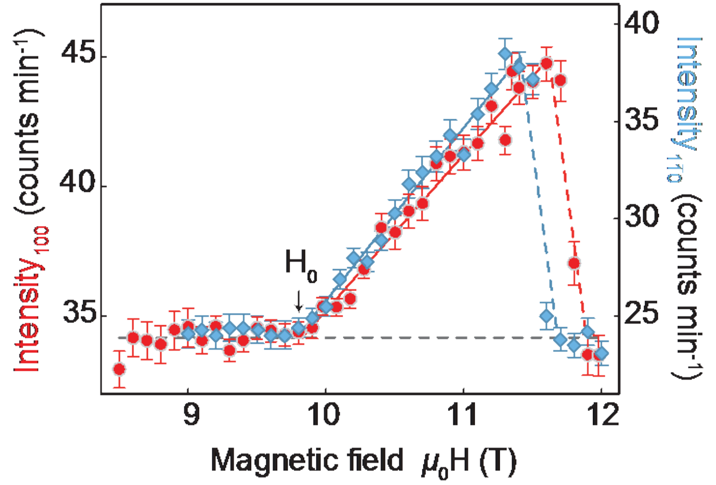




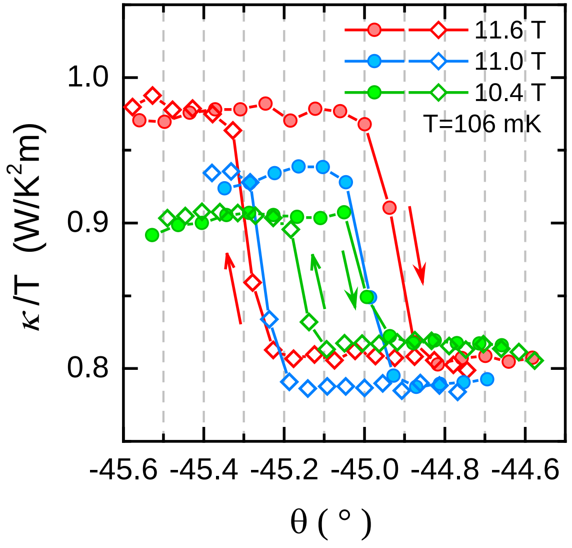
S. Gerber *et al.* Nat. Phys. **10**, 1038 (2014)

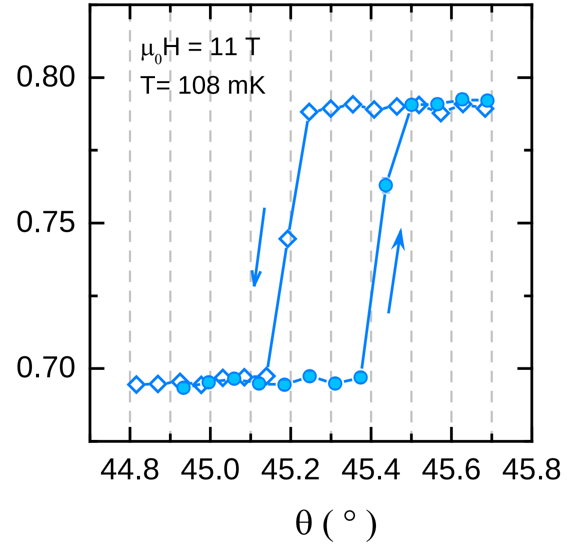
Thermal Conductivity Jump with the Q Switching



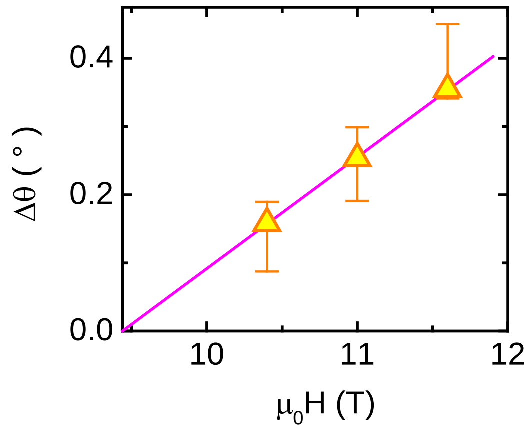


S. Gerber *et al.* Nat. Phys. **10**, 1038 (2014)

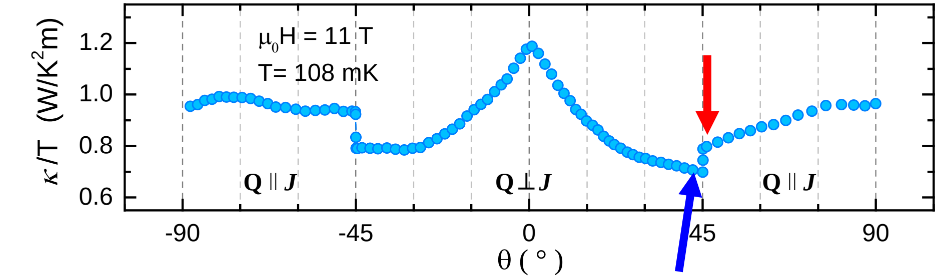


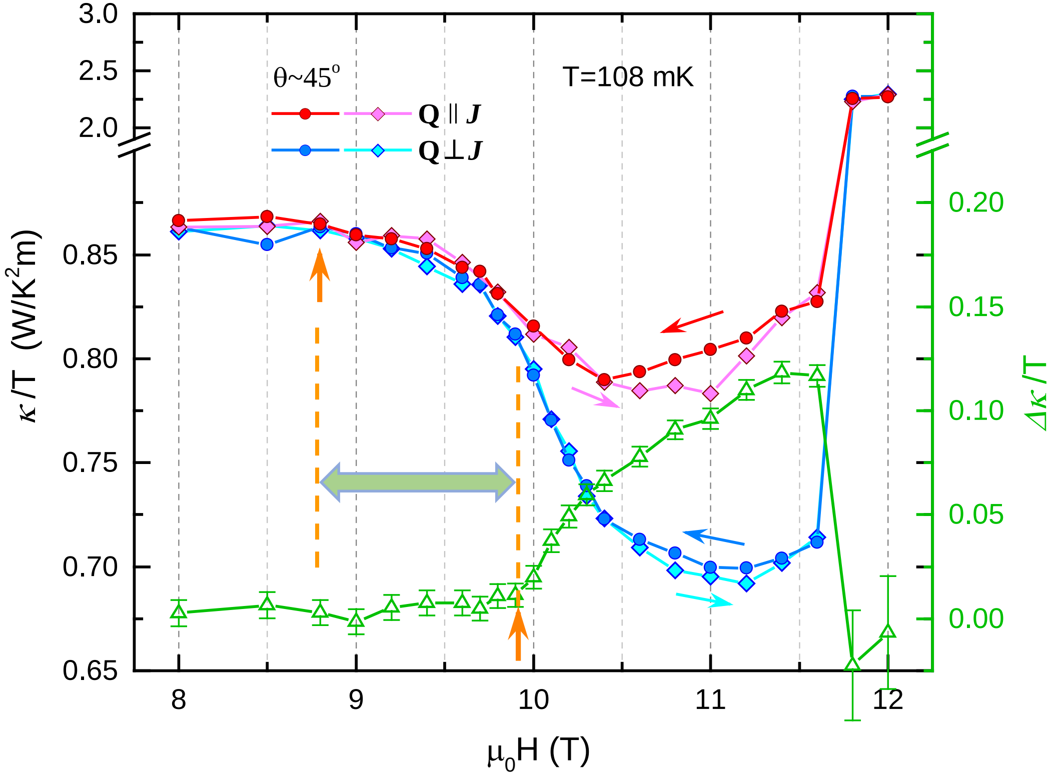


Hysteresis width as a function of field



Suppression of κ in the Q-phase

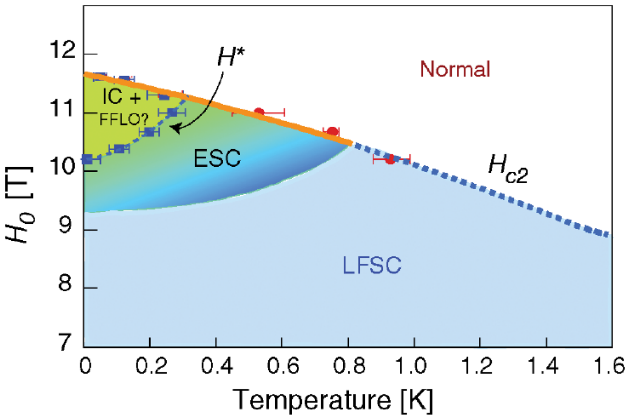




In the Q-phase,
thermal conductivities for both directions decrease.

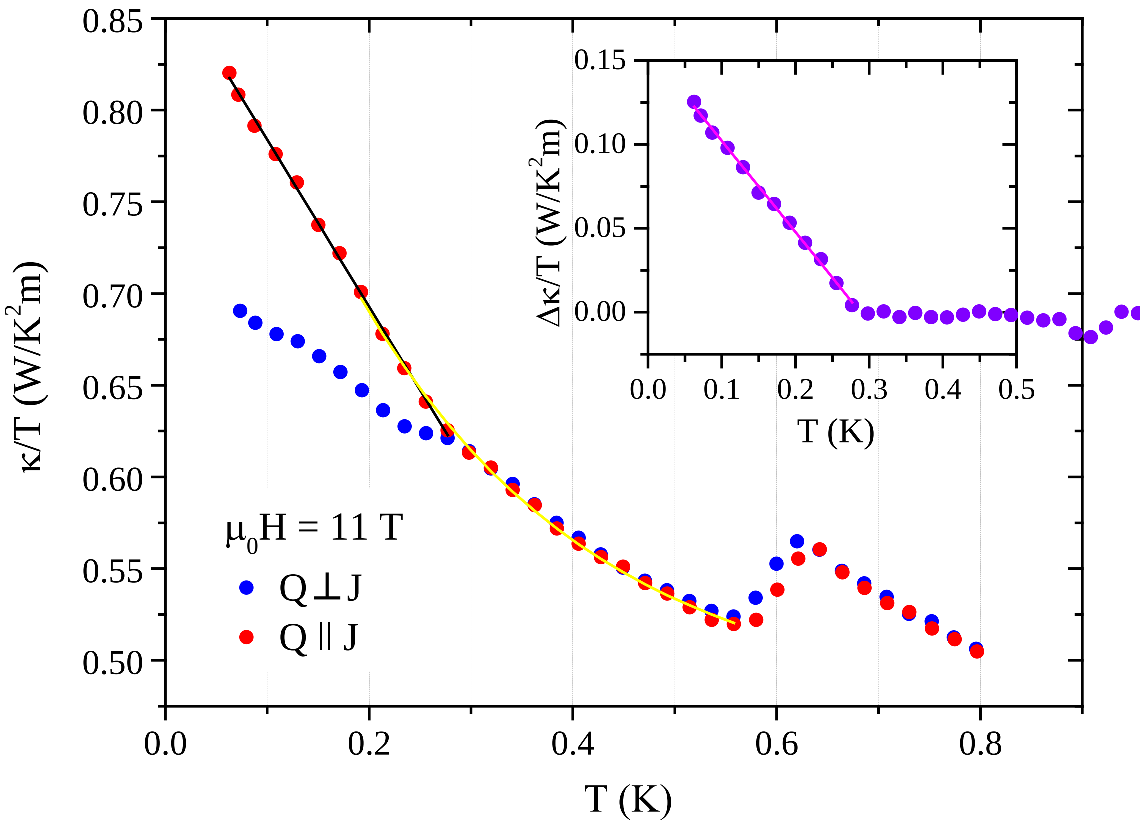
$$\kappa(\mathbf{Q}\perp \boldsymbol{J}) < \kappa(\mathbf{Q}\parallel \boldsymbol{J})$$

Compatible with the NMR spectrum broadening



Koutroulakis, G. *et al.* , Phys. Rev. Lett. **104**, 87001 (2010)

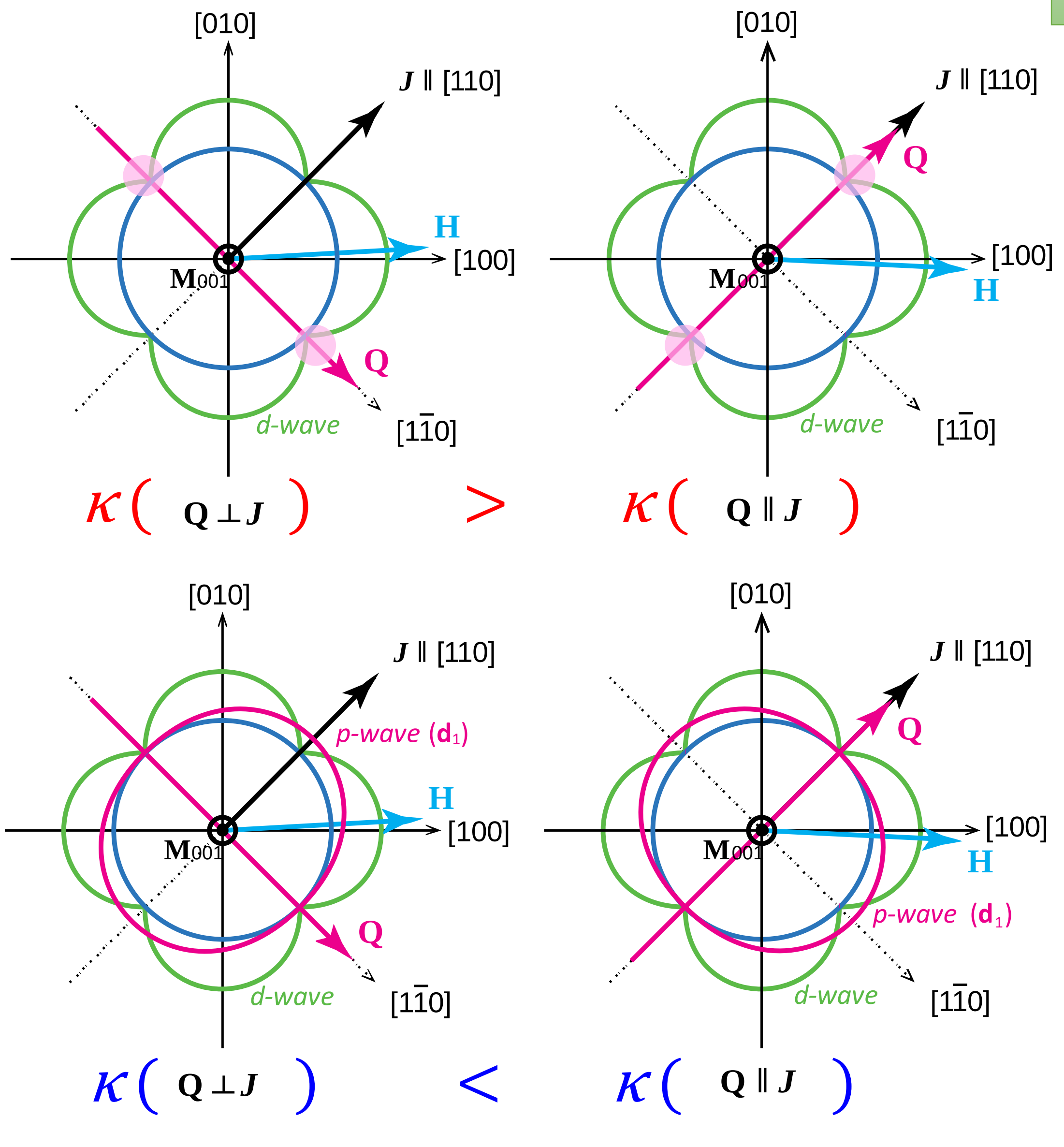
T – dependence of thermal conductivity of CeCoIn5 across the Q-phase



- Only κ (J ⊥ Q) has an anomaly.
- $\kappa/T \sim exp(-\frac{T}{T0})$ above 0.2 K
- Δκ/T decreases linearly in T

Mechanism of the Q-phase

$\kappa(\,\mathbf{Q}\perp \boldsymbol{J}\,) \;<\; \kappa(\,\mathbf{Q} \parallel \boldsymbol{J}\,)$ - Experiment



Switching of SDW can be explained by **spin-orbital coupling**.

V. P. Mineev, arXiv:1509.04915 (2015)

⇒ SDW alone is not enough!

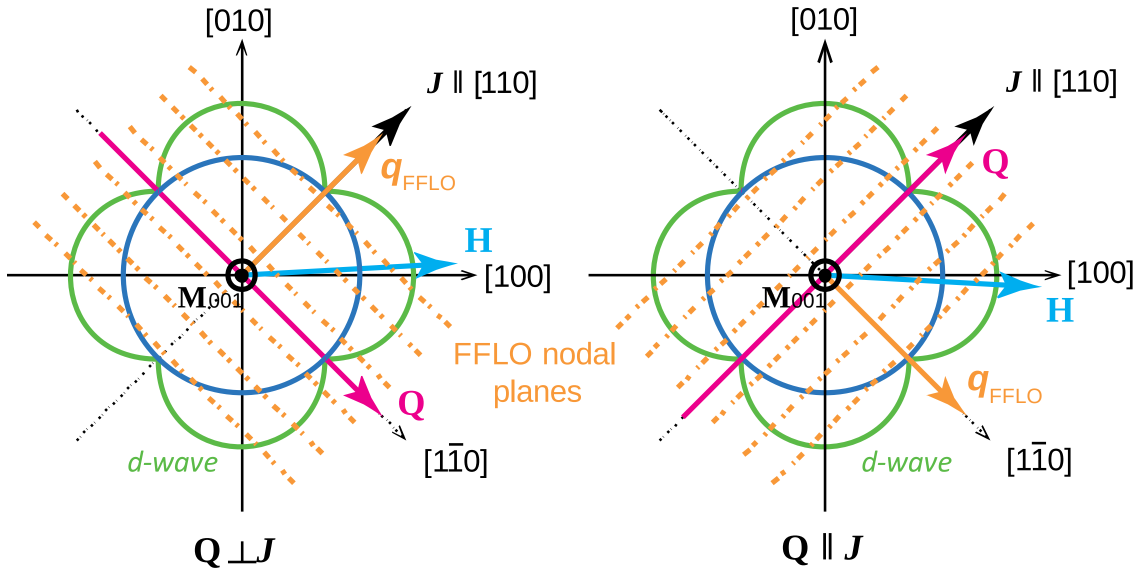
The *p*-wave PDW will suppress the thermal conductivity $\kappa(\,\mathbf{Q}\perp \boldsymbol{J}\,)$.

Fulde-Ferrell-Larkin-Ovchinnikov State

Y. Hatakeyama & R. Ikeda, Phys. Rev. B **91**, 94504 (2015)

- Hypersensitivity is due to the interaction between FFLO and SDW with $\boldsymbol{q}_{\mathrm{FFLO}} \parallel \mathbf{H}$.

The thermal conductivity results can be explained with $\boldsymbol{q}_{\mathrm{FFLO}}$ along the nodes and $\boldsymbol{q}_{\mathrm{FFLO}} \perp \mathbf{Q}$.



$$\kappa(\mathbf{Q} \perp \boldsymbol{J}) < \kappa(\mathbf{Q} \parallel \boldsymbol{J})$$

Summary

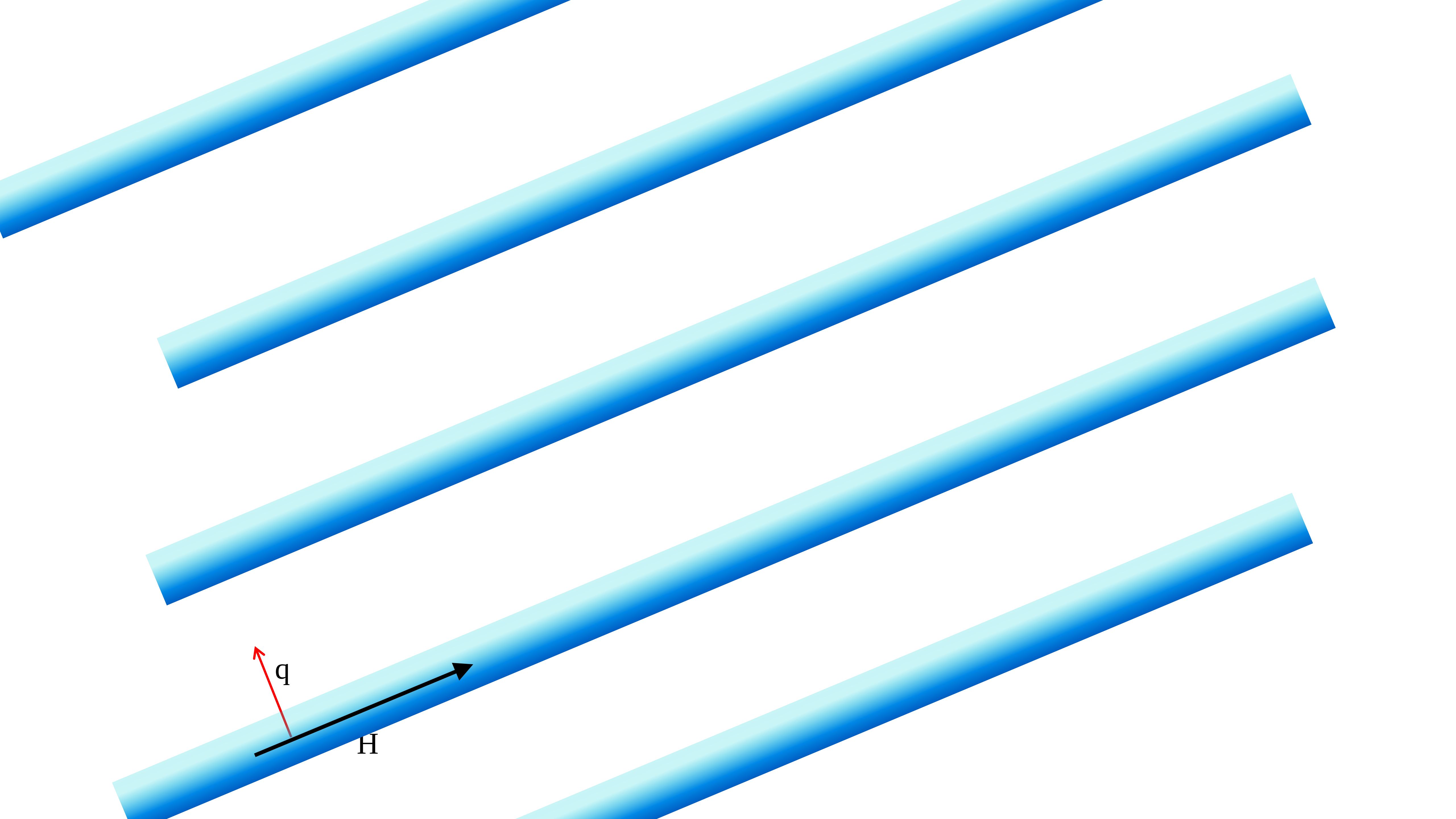
- The thermal conductivity in the Q-phase of $CeCoIn_5$ showed a discontinuous change in accordance with the SDW switching.

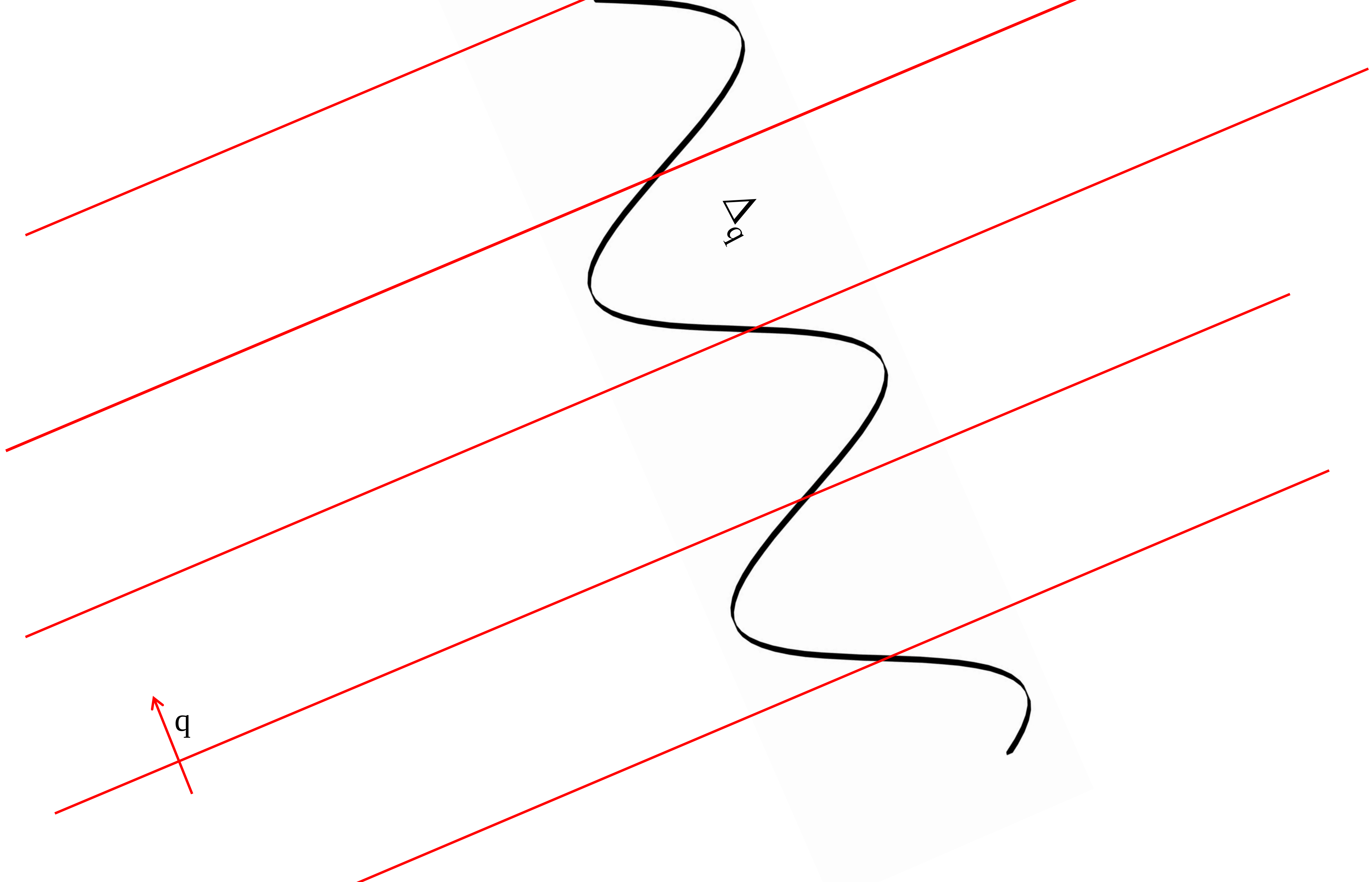
- The hypersensitivity and the thermal conductivity in rotating field demand the third order intertwined with superconducting *d*-wave and SDW:

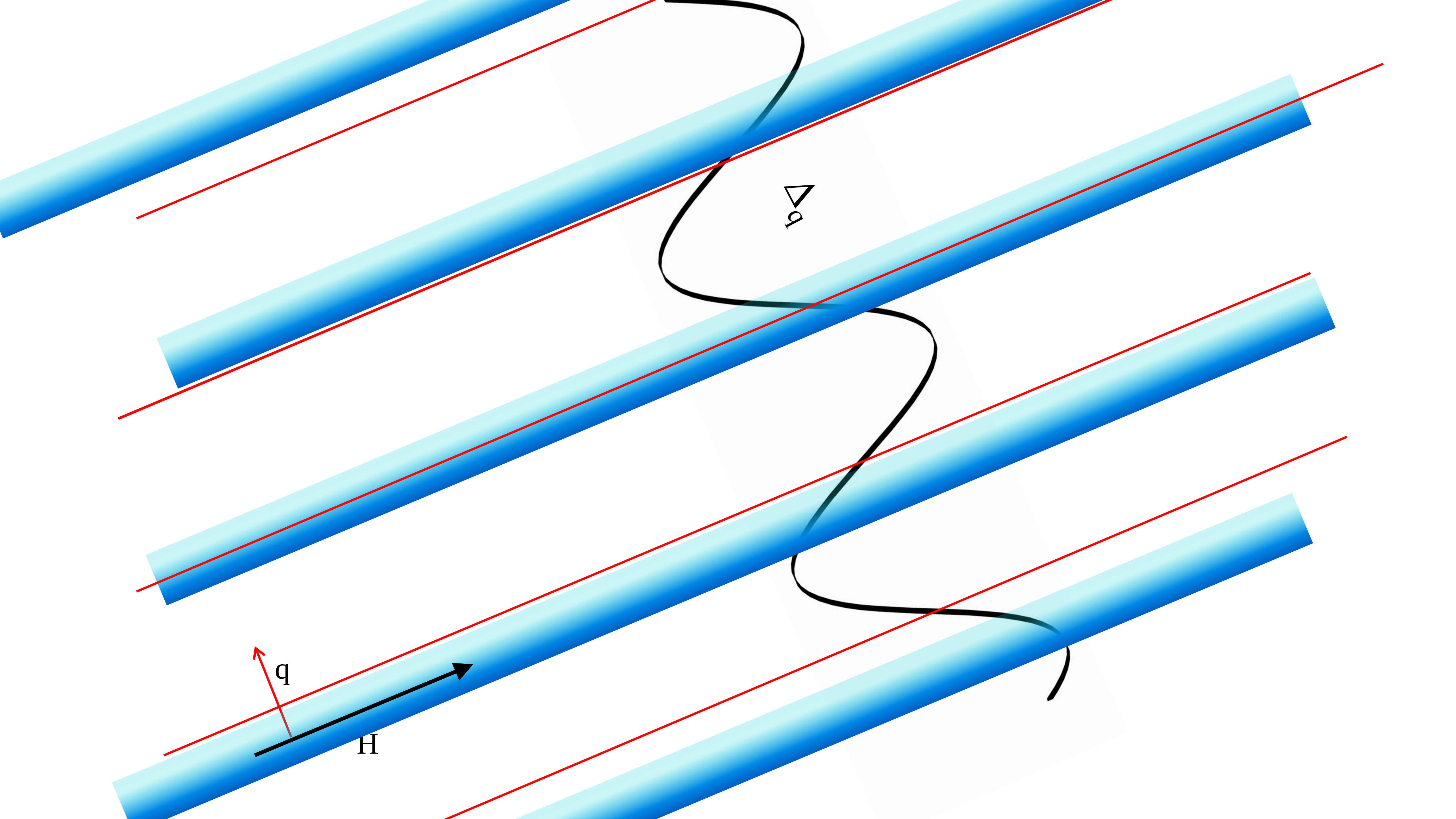
  ✓ SDW (SOC) + *p*-wave PDW

  ✓ FFLO ~~$\boldsymbol{q}_{\mathrm{FFLO}} \parallel \mathbf{H}$~~

  $\boldsymbol{q}_{\mathrm{FFLO}} \parallel$ *d*-wave nodes, $\boldsymbol{q}_{\mathrm{FFLO}} \perp \mathbf{Q}$

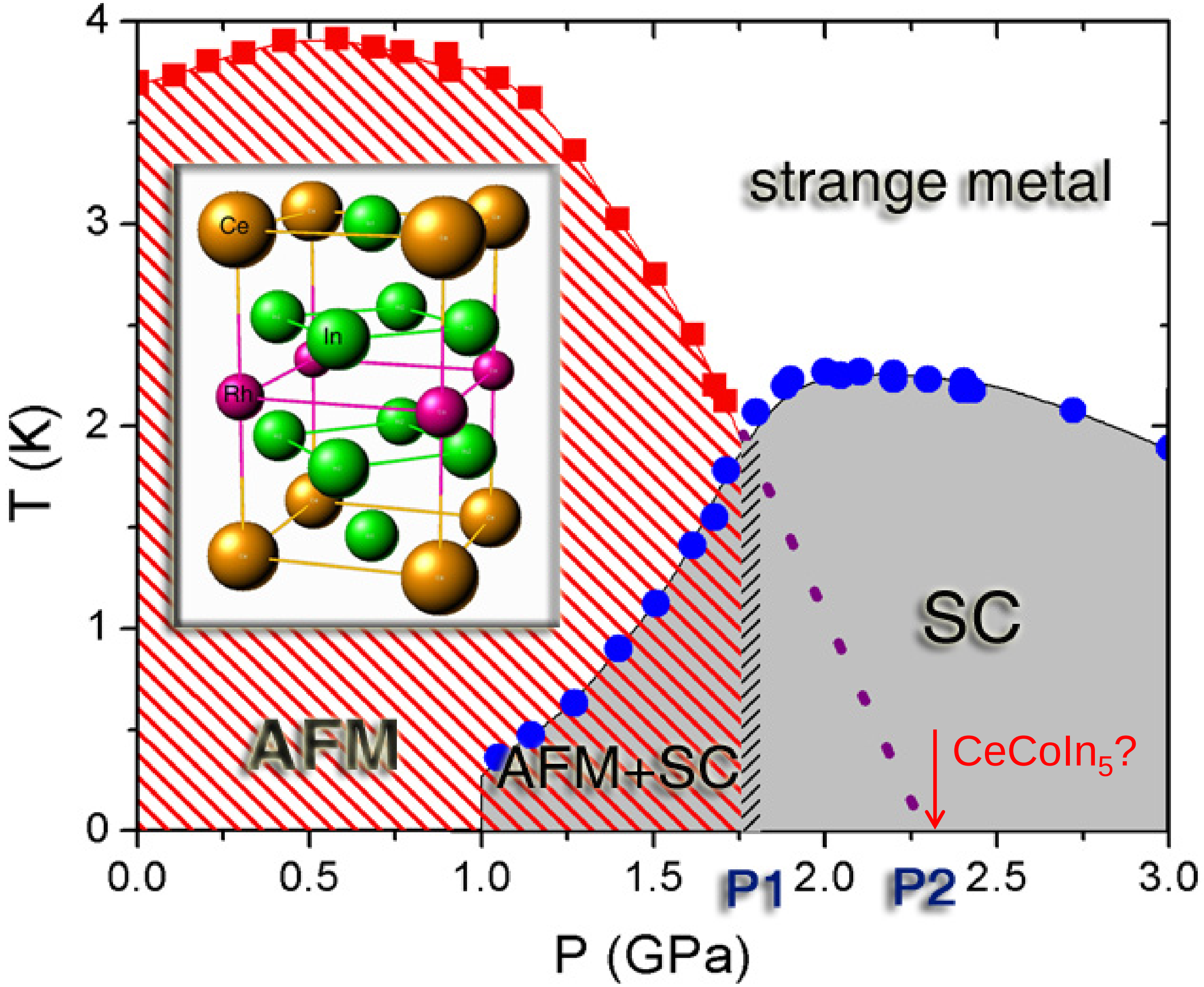

q
H


∇q
q

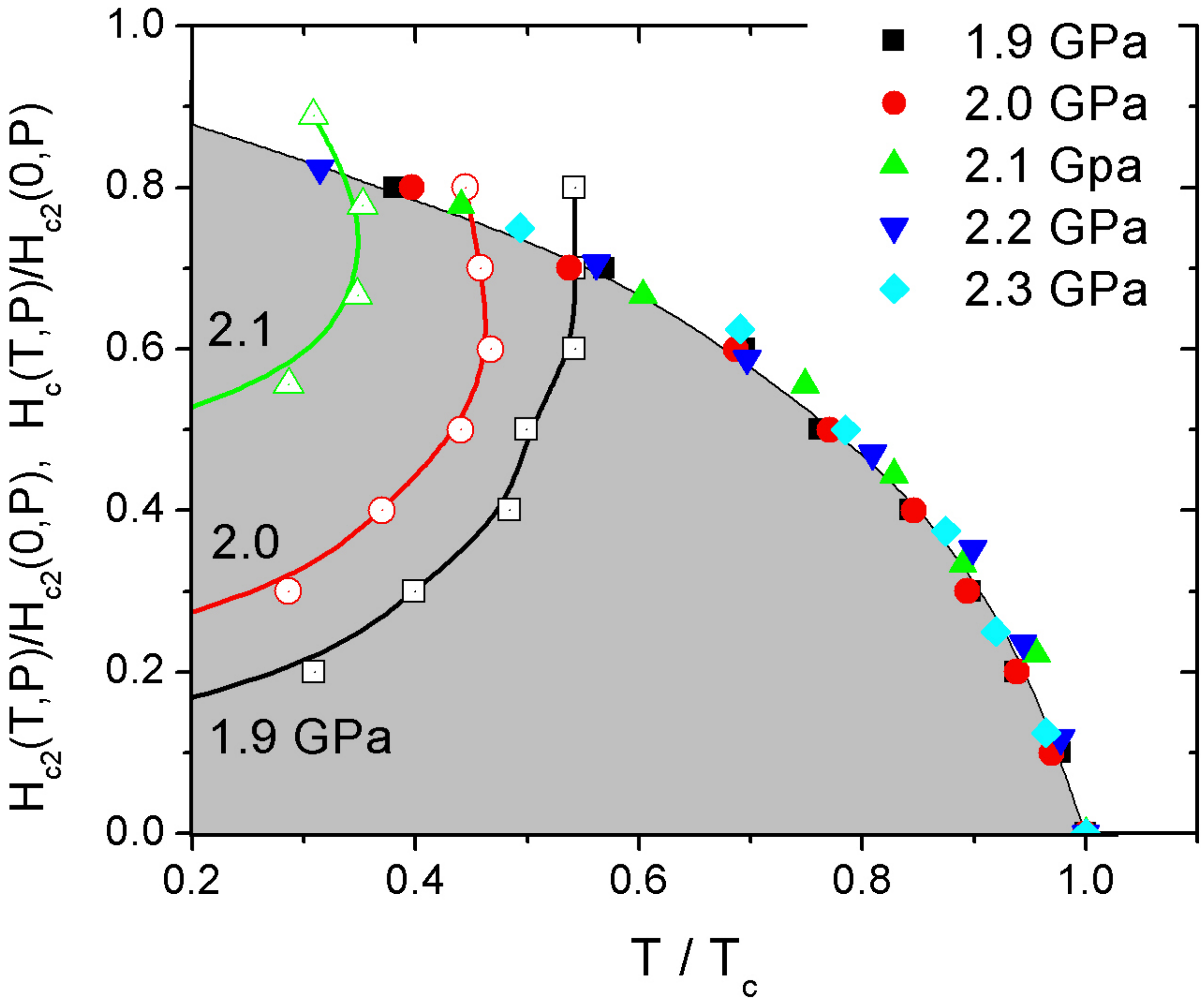


q
H

$CeRhIn_5$



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



Tuson Park *et al.*, unpublished.

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Conclusions I

•Cd, Hg, and Sn doping is a powerful way to tune and probe both H_{c2} and the HFLT state in $CeCoIn_5$. Minute amounts of impurities suppress HFLT phase.

•Phase diagrams of lightly Hg and Sn doped $CeCoIn_5$, both $T_c(H)$ and $T_{HFLT}(H)$ can be scaled on a single phase diagram at high fields, suggesting strong connection between superconductivity and the origin of the HFLT state.

•Whether or not the HFLT phase of magnetic or FFLO origin it is ***unique***, the magnetism is stabilized *only* in a SC state, and does not extend into normal state: such situation is opposite to the canonical "competition between SC and magnetism" paradigm.

• Pauli paramagnetism and proximity to QCP are key to understanding high field properties of $CeCoIn_5$

Conclusions II

•Thermal conductivity in rotating magnetic field revealed the presence of a third “intertwined” order in the Q-phase of $CeCoIn_5$

•Natural candidate for the third order is a *p*-wave pair-density-wave (PDW) superconducting order.

•FFLO scenario still maybe possible, but with a significant modification/requirement that qFFLO must lie along the nodes of the d-wave sc order parameter, and not be forced to lie parallel to magnetic field.

• Pauli paramagnetism and proximity to QCP are key to understanding high field properties of $CeCoIn_5$