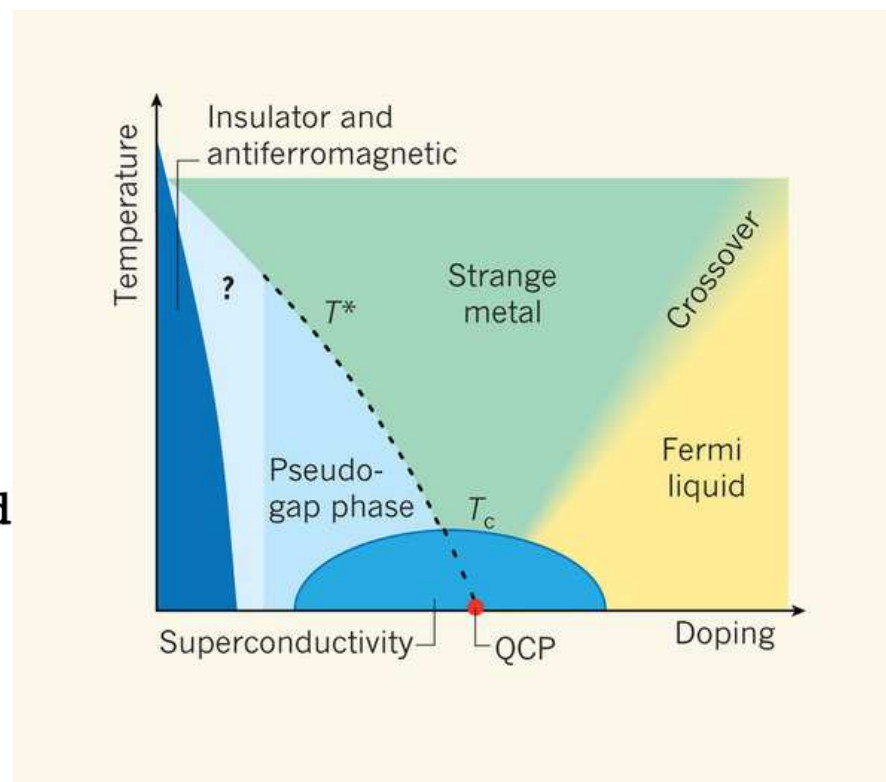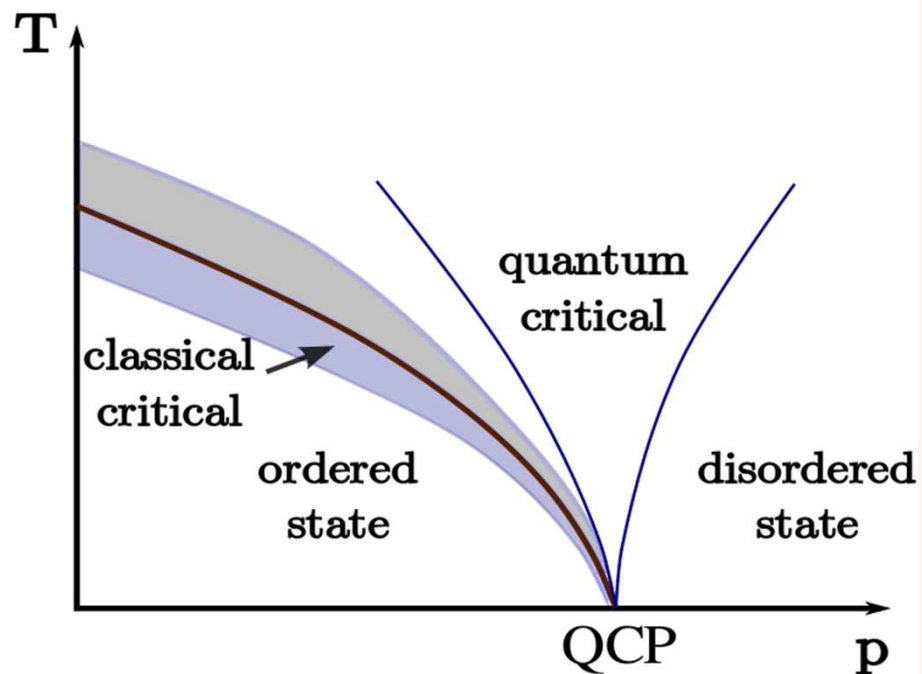# QCP in strongly correlated superconductors

Hong Xiao

IOP

QCP

Outline

- QCP in heavy fermion superconductor $CeCoIn_5$

- QC in mixed valence compound $Ce_{1-x}YbCoIn_5$

- First order QPT and possible QTCP in iron-based superconductor $Ba(Fe_{1-x}Co_x)As_2$

Outline

- QCP in heavy fermion superconductor $CeCoIn_5$

- Quantum criticality in mixed valence compound $Ce_{1-x}YbCoIn_5$

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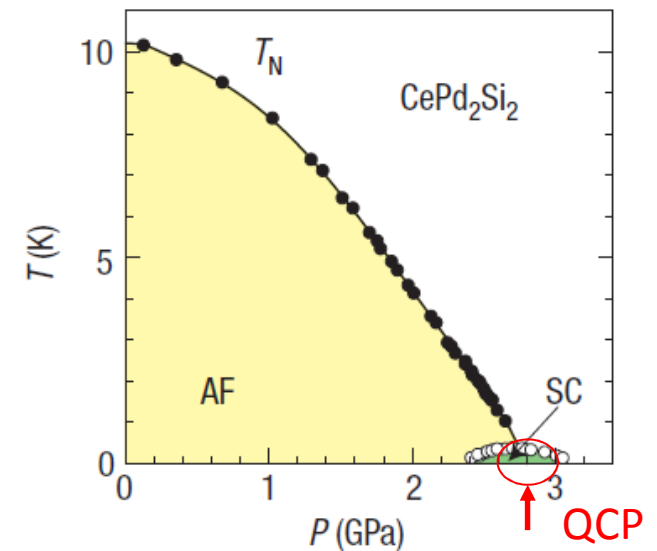
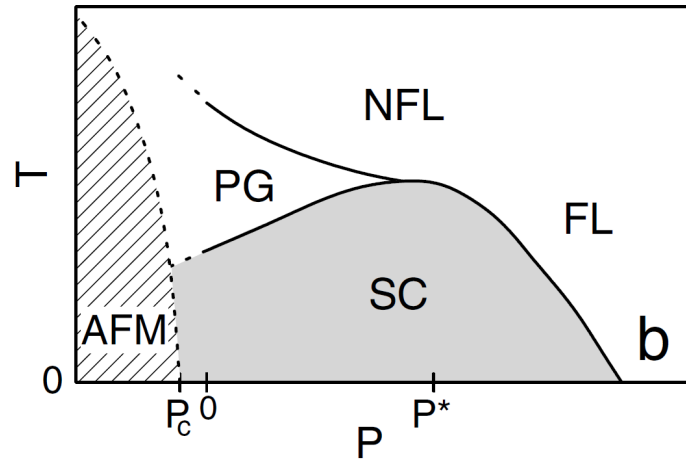# HFSC: Prototypical system to study QCP

Doping-tuned QCP
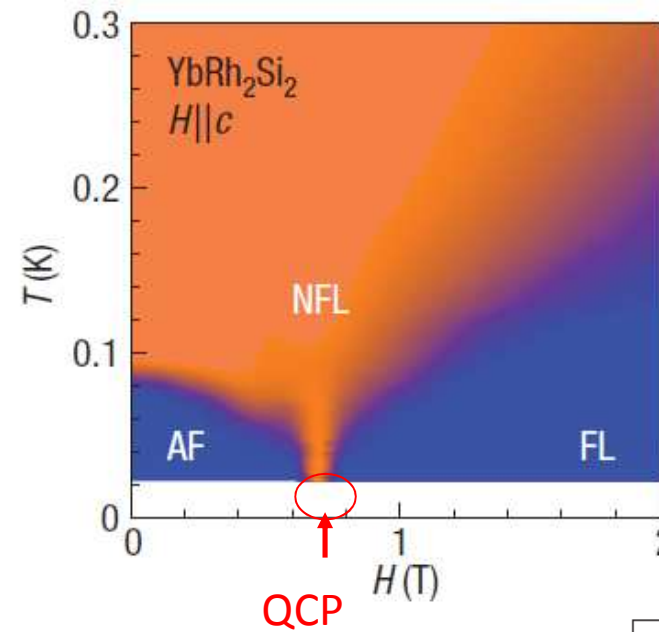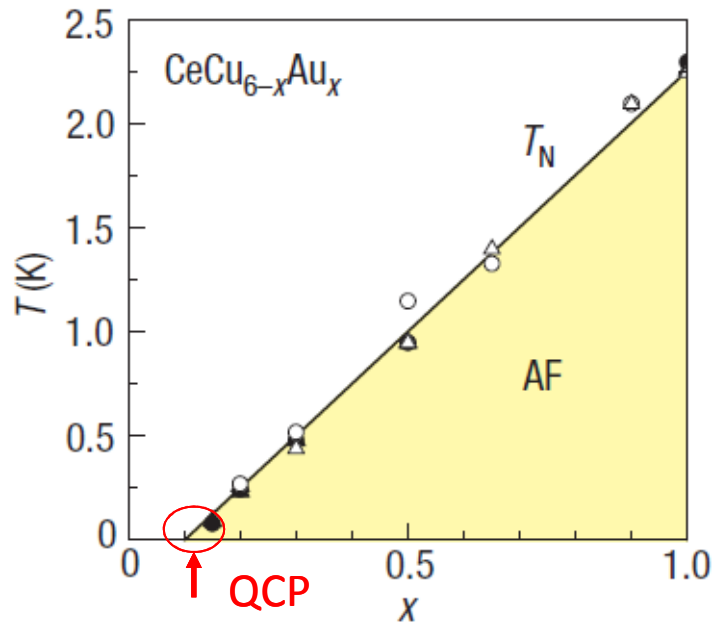
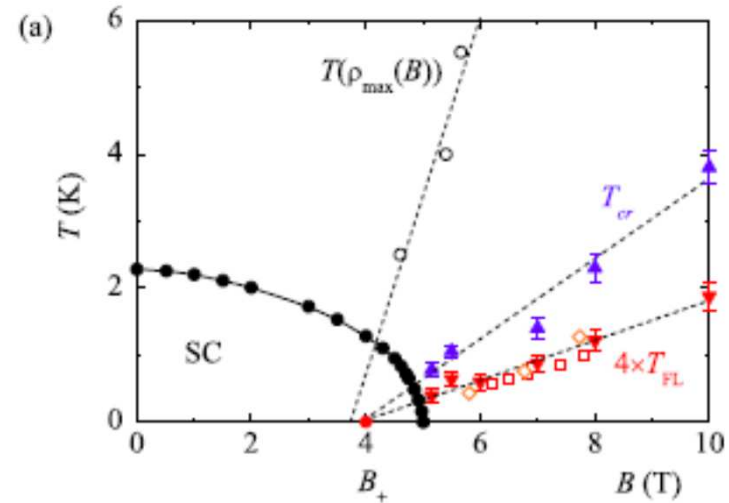**Field-tuned QCP**

Pressure-tuned QCP

Nature Phys. 4, 186 (2008)

QCP in CeCoIn$_5$

PRL 89, 157004 (2002)

PRL 106, 087003 (2011)

$$\rho = \rho_0 + AT^2$$

$$A(H) \propto (H - 5.1)^{-1.37}$$
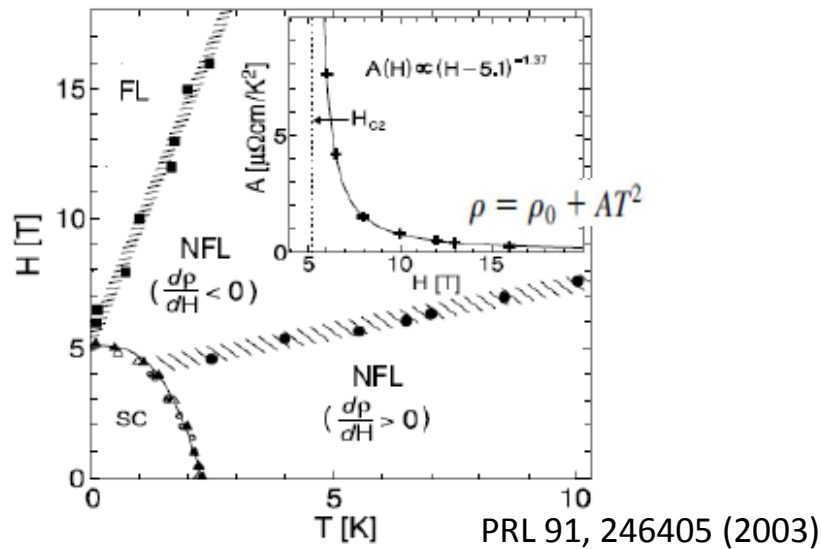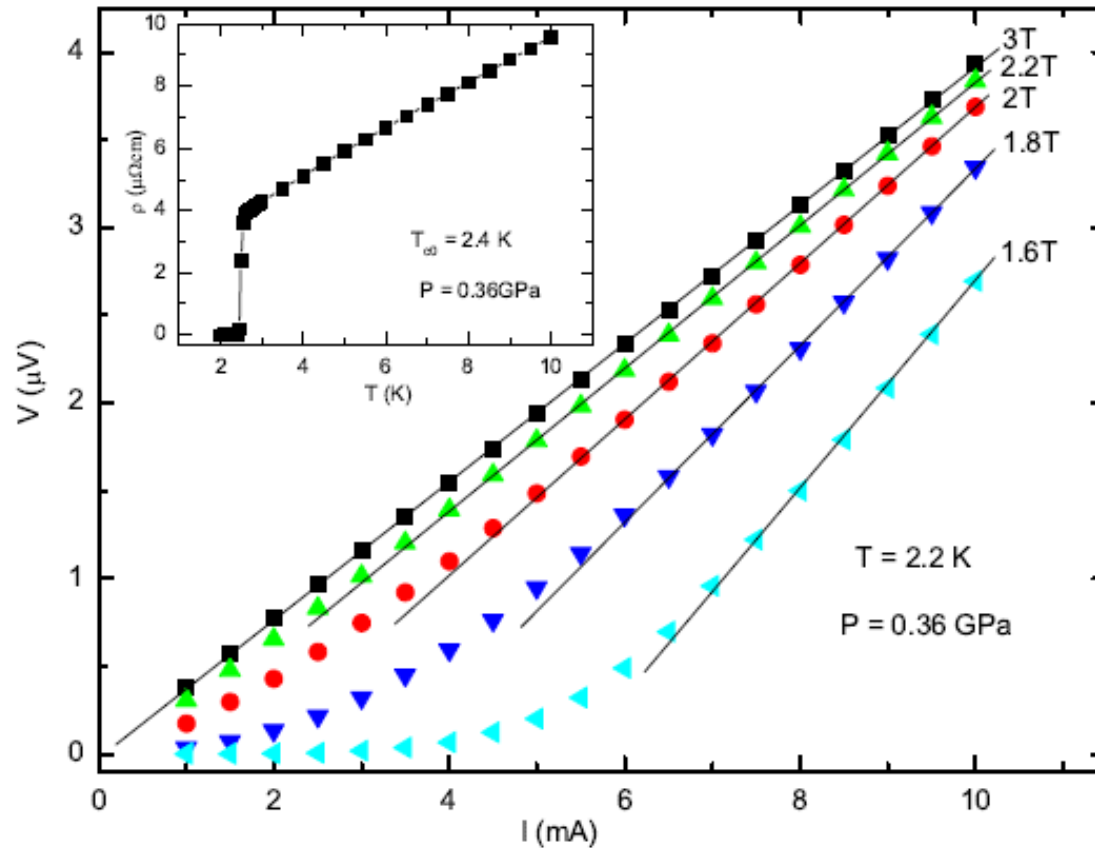
PRL 91, 246405 (2003)
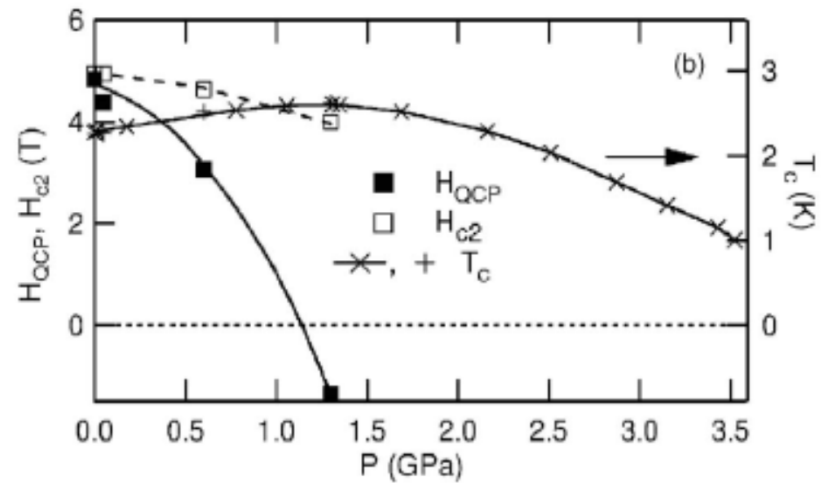
PRB 73, 064519 (2006)

A direct probe is needed …

I-V measurements
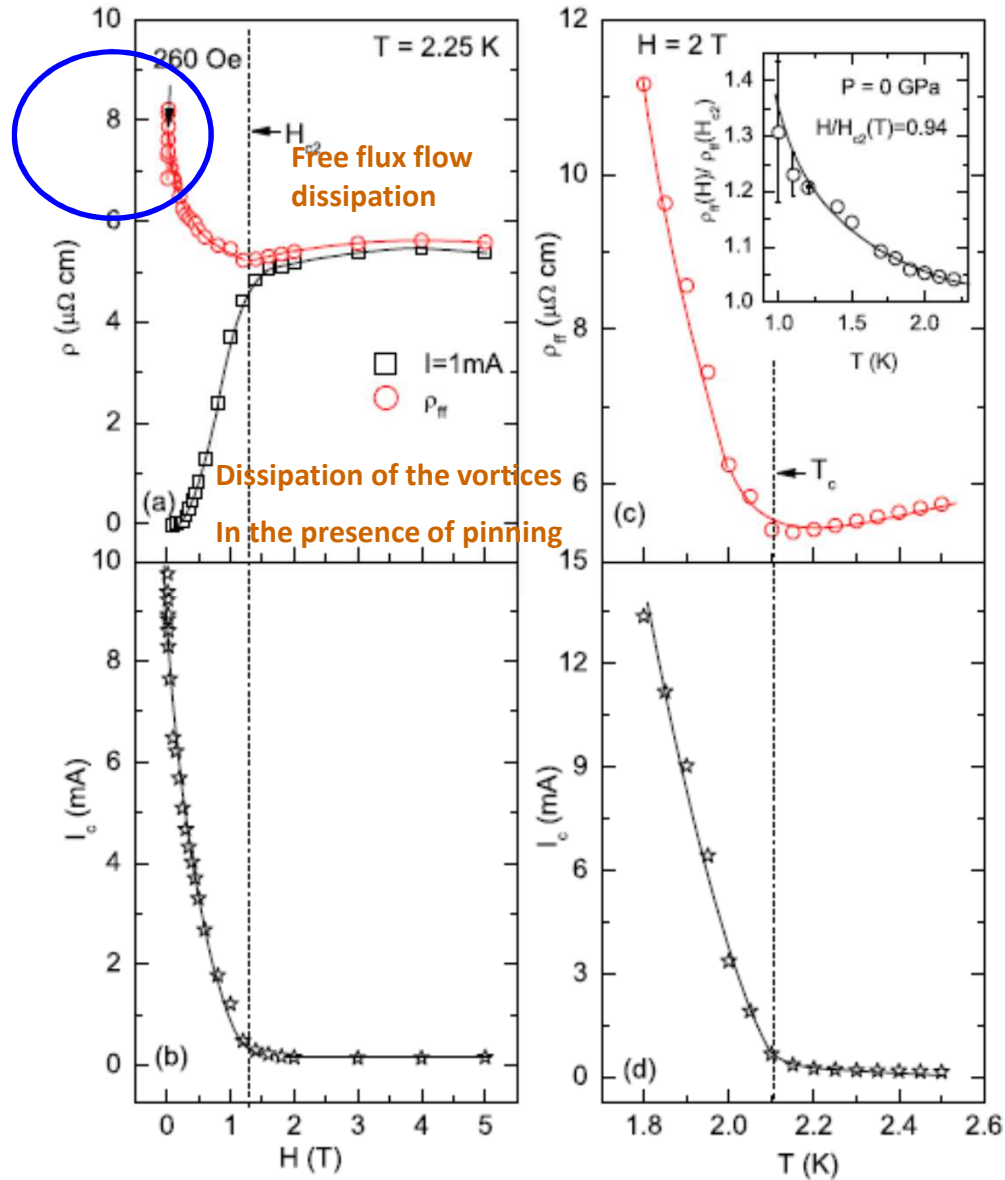

$$\rho_{ff} \equiv k \frac{dV}{dI}$$

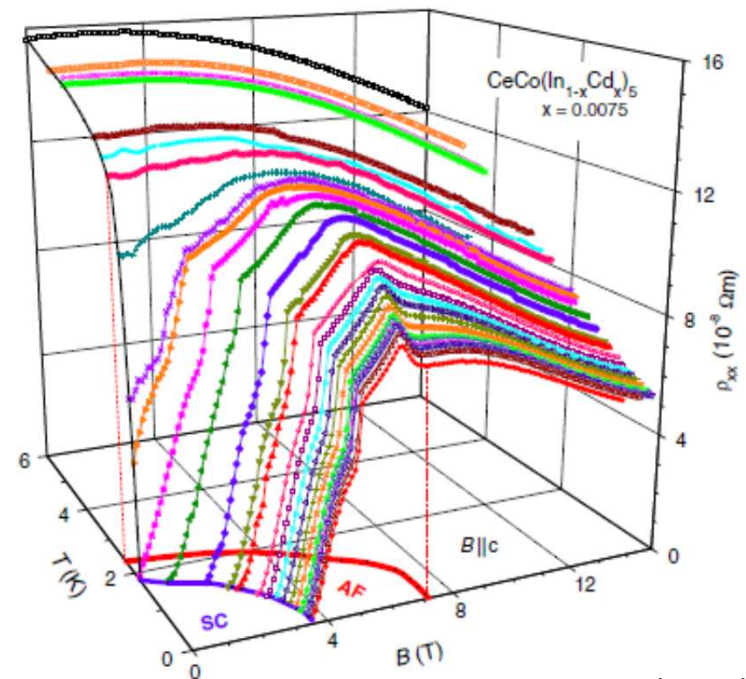$\dfrac{dV}{dI}$: the slope of the

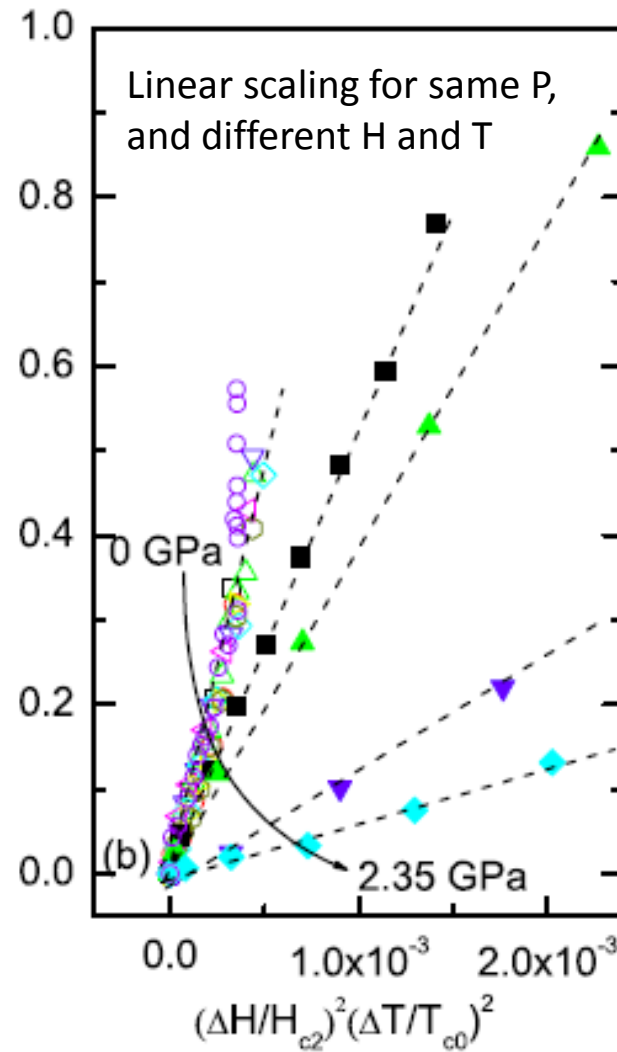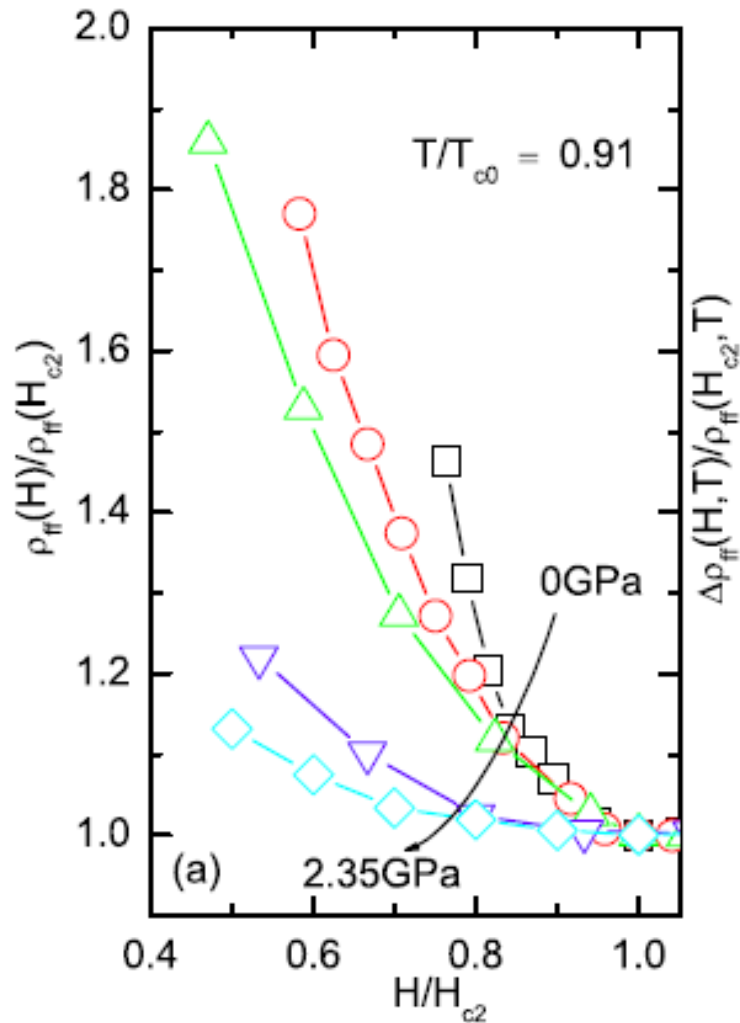linear region of the I-V curve

$$\rho_{ff} \approx \rho_n$$

PRL 108, 056401 (2012)

Abnormal vortex core resistivity

- ρ_{ff} ↑ sharply as T,H ↓

- $\rho_{ff} \approx \rho_n$

- Sharp ↑ in ρ_{ff} reflects the ↑ in the scattering of the quasiparticles in the vortex core due to critical AF fluctuations near T_N

Figure labels:
- (a) ρ (μΩ cm), 260 Oe, T = 2.25 K, H_{c2}, Free flux flow dissipation, Dissipation of the vortices In the presence of pinning, I=1mA, ρ_{ff}
- (b) I_c (mA), H (T)
- (c) ρ_{ff} (μΩ cm), H = 2 T, T_c; inset $\rho_{ff}(H)/\rho_{ff}(H_{c2})$, P = 0 GPa, $H/H_{c2}(T)$=0.94, T (K)
- (d) I_c (mA), T (K)
- $CeCo(In_{1-x}Cd_x)_5$, x = 0.0075, ρ_{xx} (10^{-8} Ωm), B||c, SC, AF, B (T), T (K)

Pressure suppress the abnormal behavior
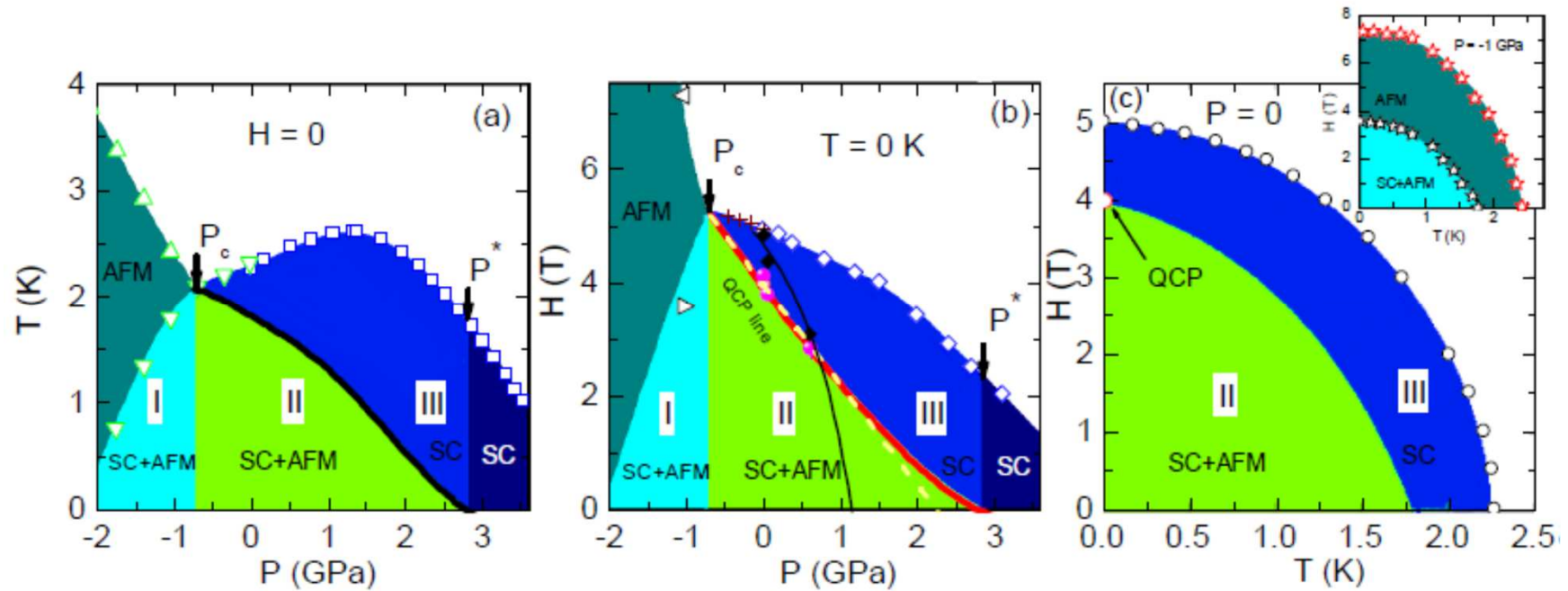

The abnormal behavior is greatly suppressed with P↑, due to the suppressed AF order inside the vortex core.

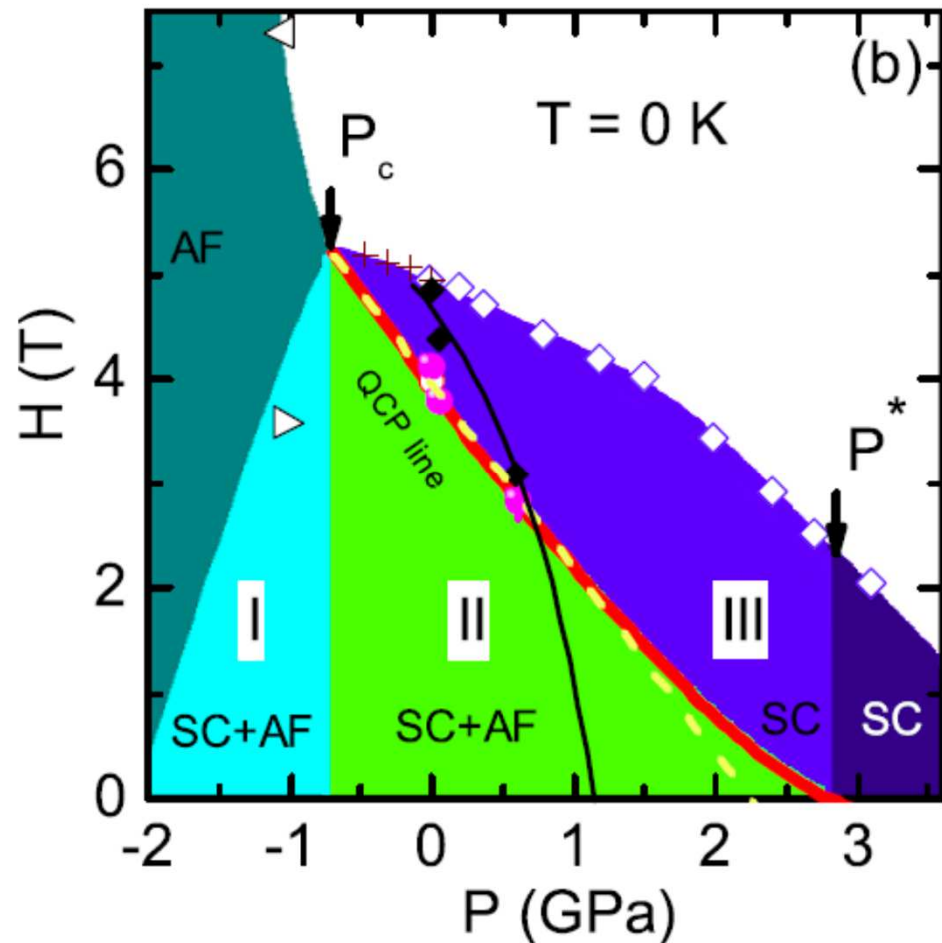AF phase boundary moves deeper inside the SC dome with P↑, diminishing the effect of critical fluctuations.

Linear scaling for same P, and different H and T

$T/T_{c0} = 0.91$

0GPa
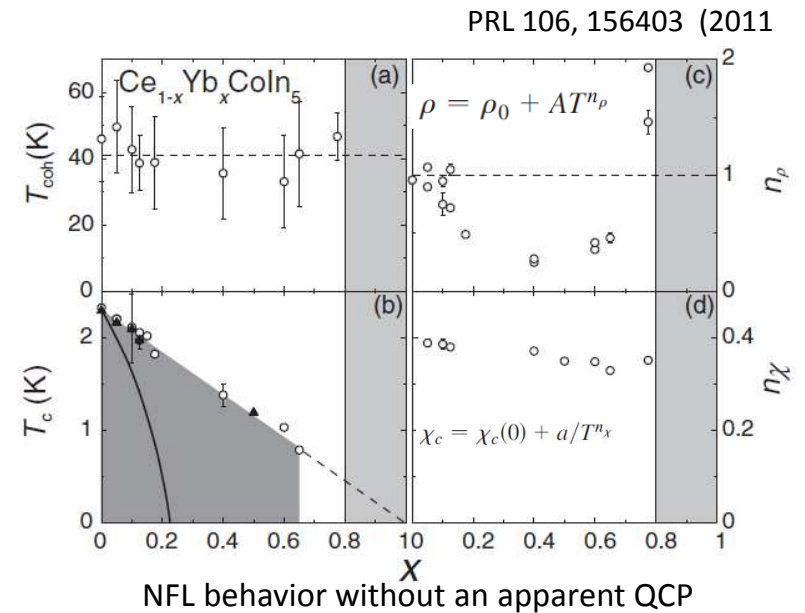
2.35GPa

0 GPa

2.35 GPa
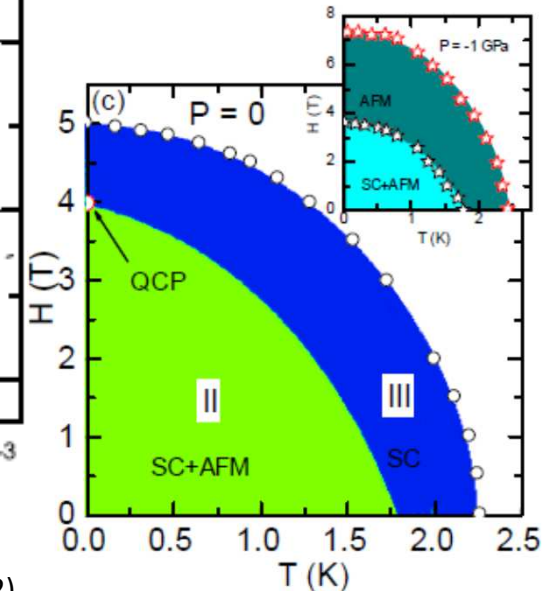
PRL 108, 056401 (2012)

Phase diagram

$$\frac{P - P_c}{P^* - P_c} = \left(1 - \frac{T_N}{T_{c0}}\right)\left(1 - \frac{H_N}{H_{c2}(T_N)}\right)$$

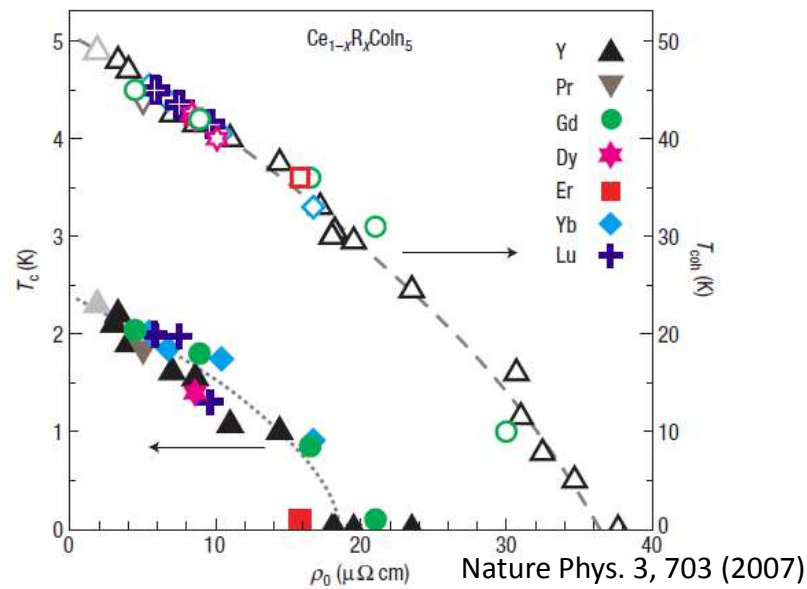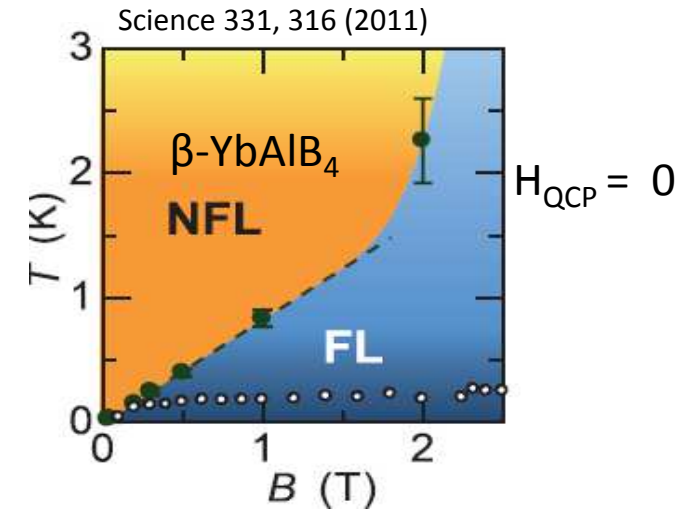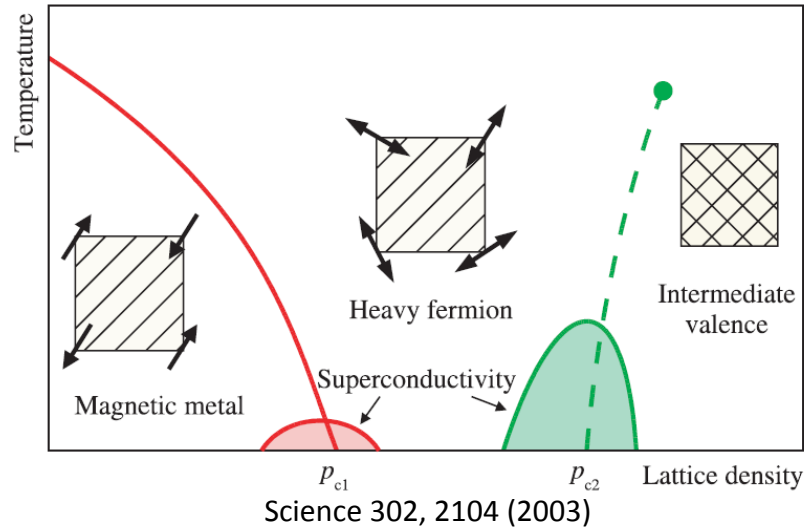# T = 0 K

$$\frac{P - P_c}{P* - P_c} = \left(1 - \frac{T_N}{T_{c0}}\right)\left(1 - \frac{H_N}{H_{c2}(T_N)}\right)$$

- Give the actual QCP line

- For $P<P_c$, the SC phase is inside the AF dome

- For $P>P_c$, the AF phase coexists with SC only inside the vortex cores

- SC and QC are close related

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- Quantum criticality in mixed valence compound $Ce_{1-x}YbCoIn_5$

- First order QPT and possible QTCP in iron-based superconductor $Ba(Fe_{1-x}Co_x)As_2$

Science 302, 2104 (2003)

Science 331, 316 (2011)

β-YbAlB$_4$

NFL

FL

$H_{QCP} = 0$

PRL 106, 156403 (2011

Ce$_{1-x}$R$_x$CoIn$_5$

Y	▲
Pr	▼
Gd	●
Dy	★
Er	■
Yb	◆
Lu	✚

Nature Phys. 3, 703 (2007)

Ce$_{1-x}$Yb$_x$CoIn$_5$

(a)

(b)

(c) $\rho = \rho_0 + AT^{n_\rho}$

(d) $\chi_c = \chi_c(0) + a/T^{n_\chi}$

NFL behavior without an apparent QCP

Whether QCP must be present in the material's phase diagram to induce NFL behavior and trigger SC?
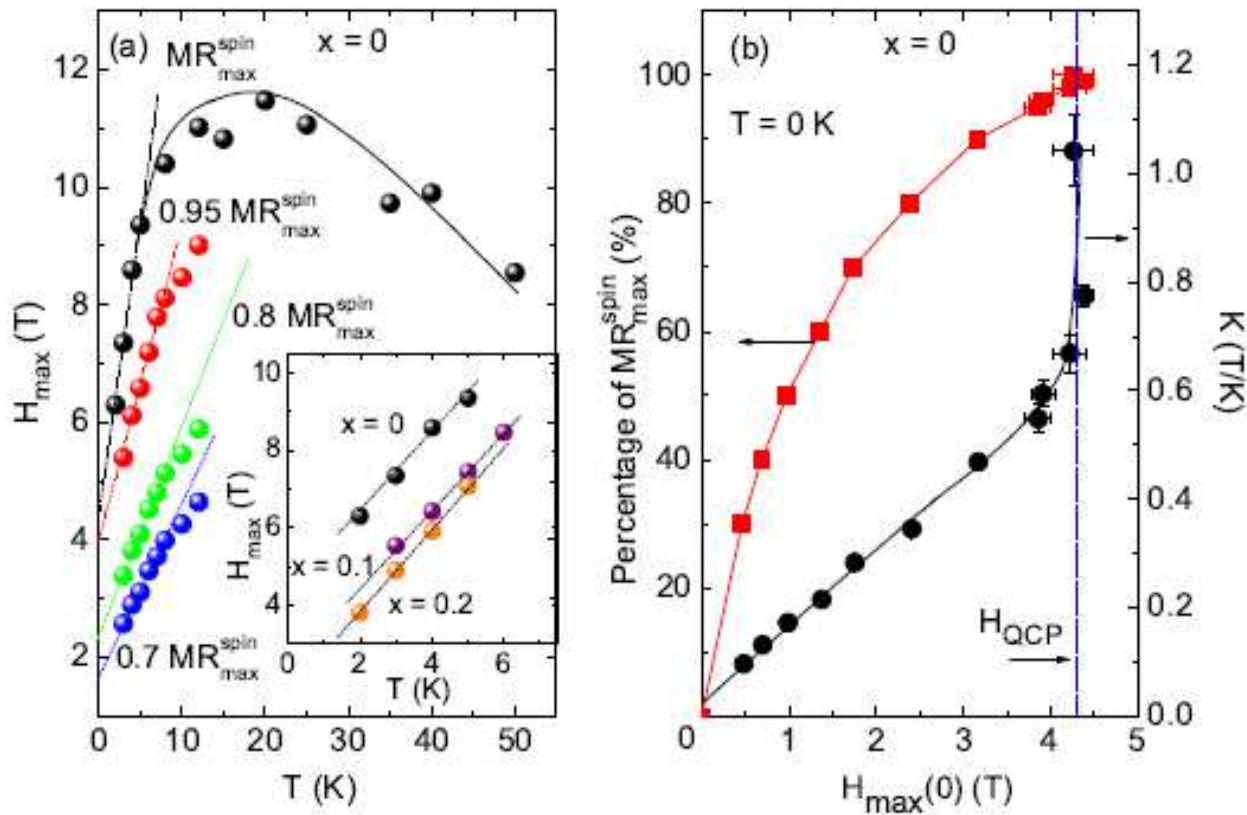
MR data in $Ce_{1-x}Yb_xCoIn_5$
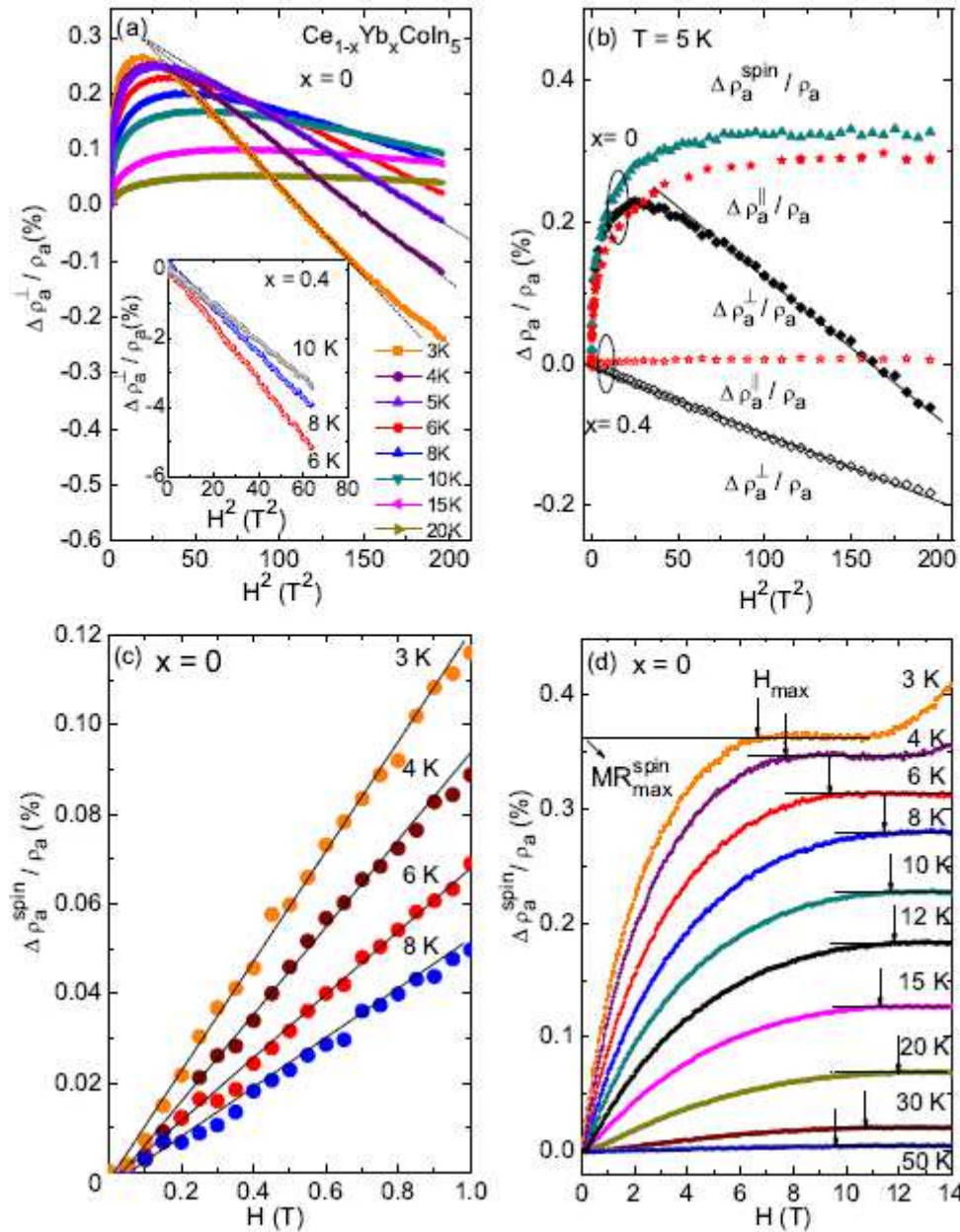
arXiv:1208.4308
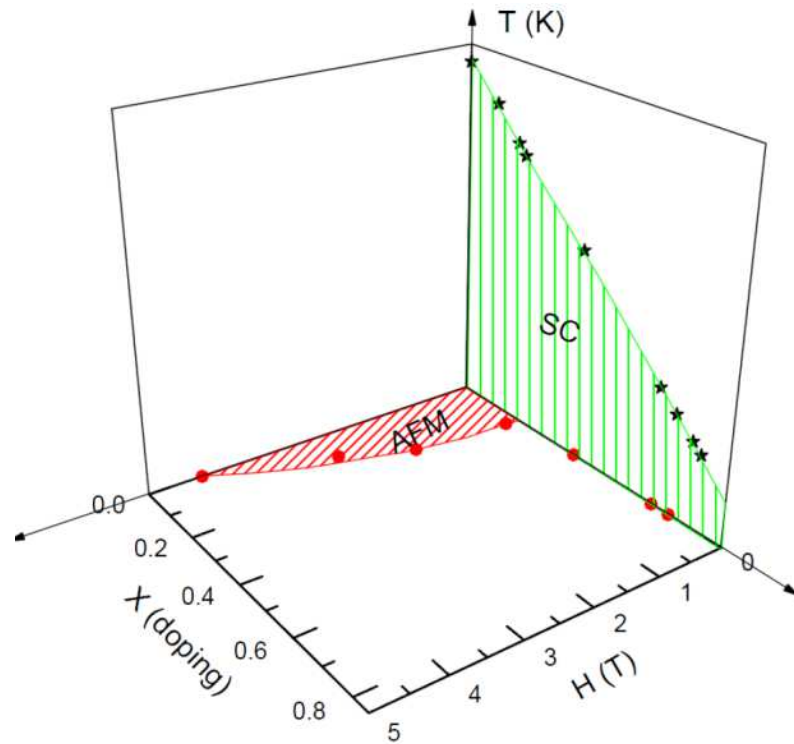
H$_{QCP}$

- Low T behavior : field quenching of AFM spin fluctuations
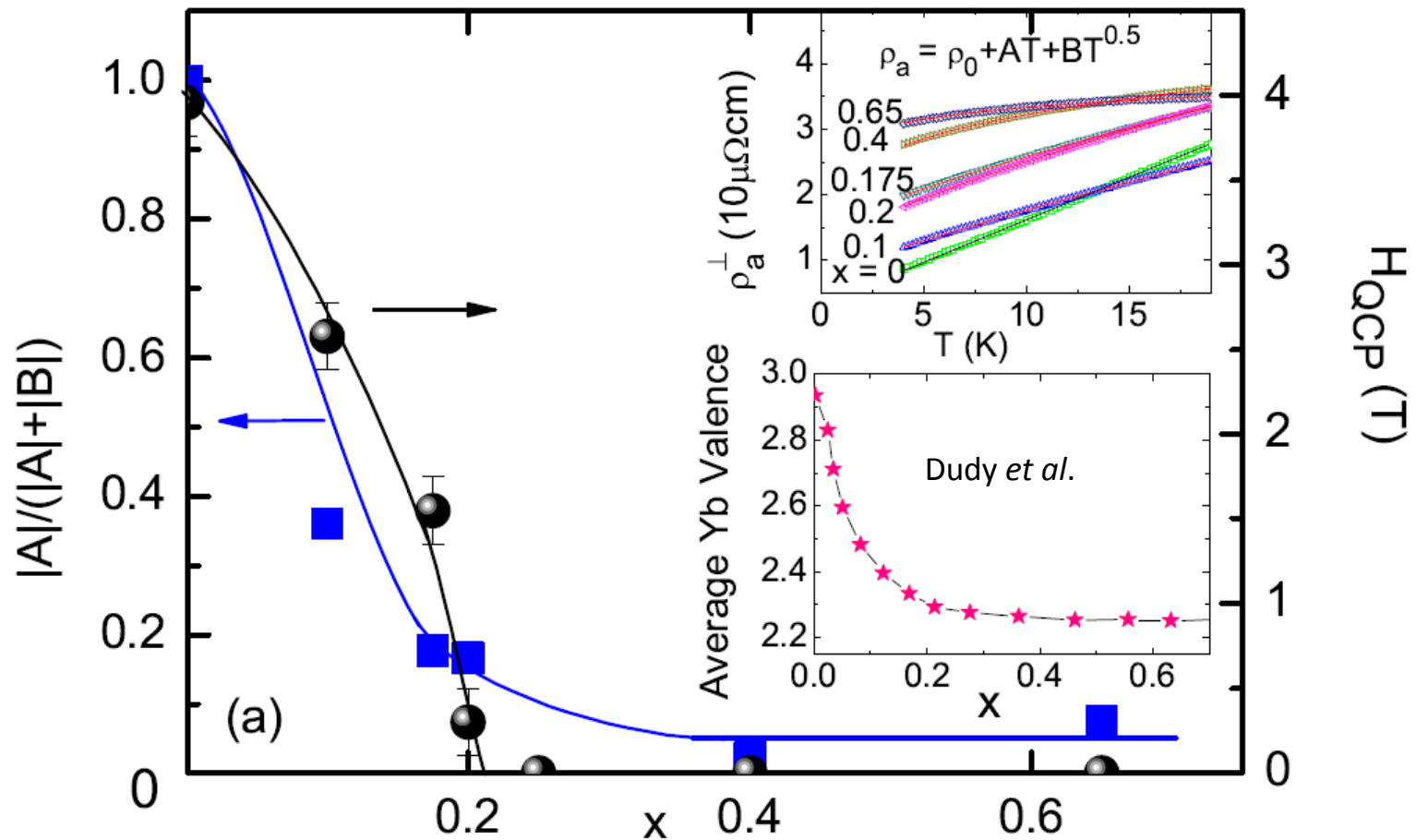
- At the QCP, the g-factor jumps.

arXiv:1208.4308

Evolution of H$_{QCP}$

- SC is robust and survives over the whole Yb doping range

- Field-induced QCP is strongly suppressed with Yb doping and disappears for x>0.20

- SC and quantum criticality are likely to be decoupled in this system
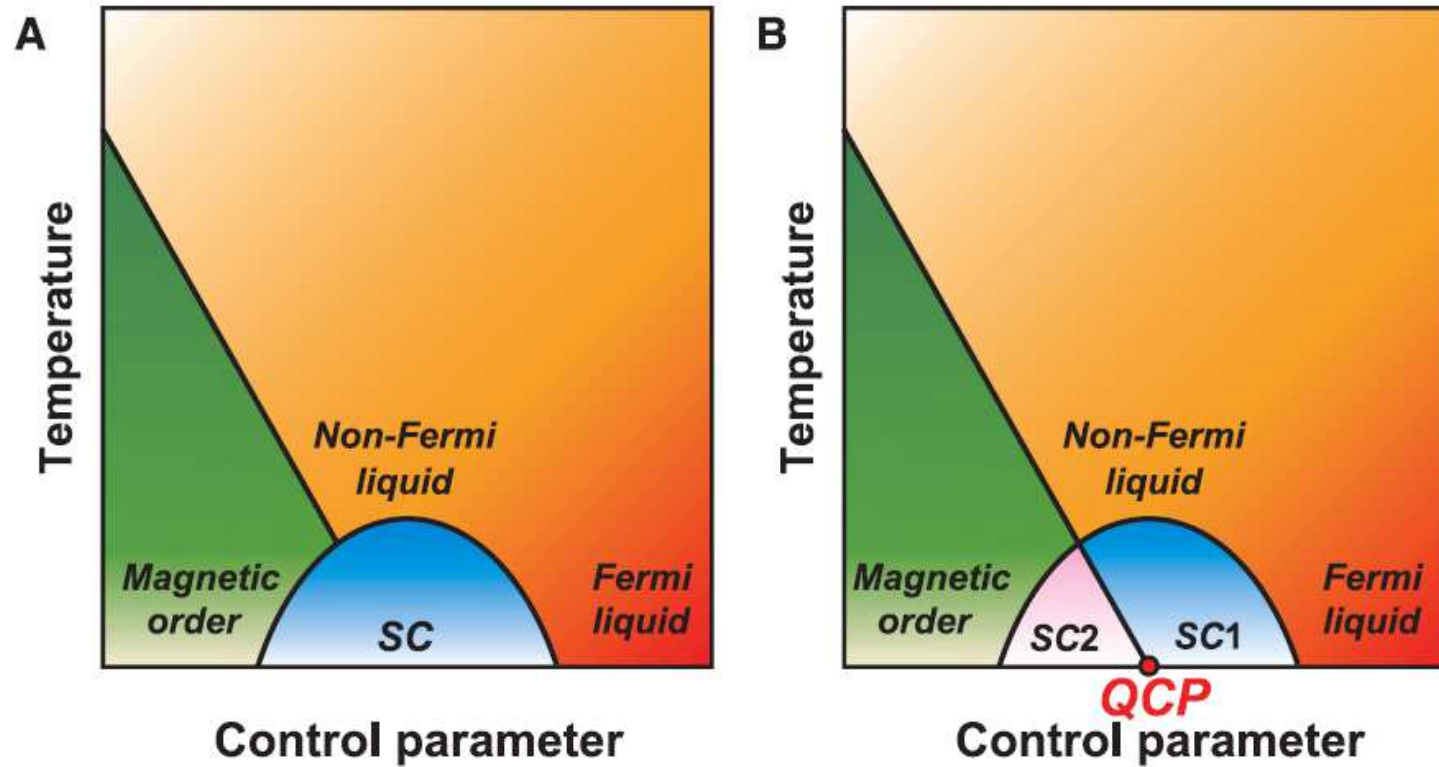
arXiv:1208.4308

Origin of NFL behavior

(a)

$\rho_a = \rho_0 + AT + BT^{0.5}$
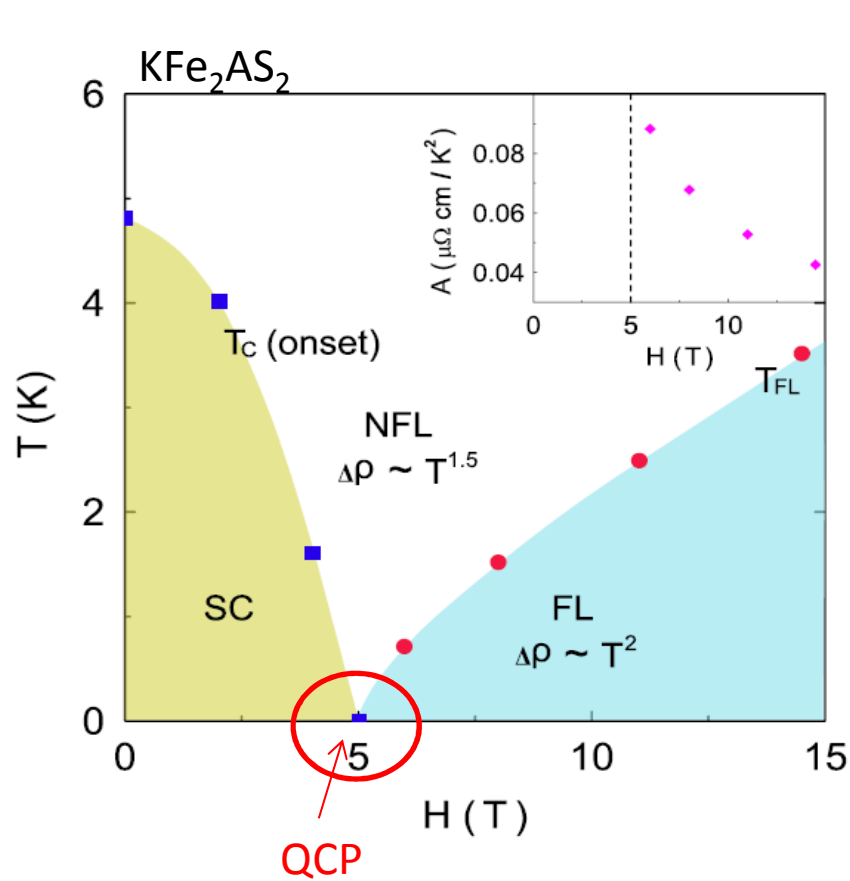
0.65
0.4
0.175
0.2
0.1
x = 0

Dudy *et al.*

arXiv:1208.4308

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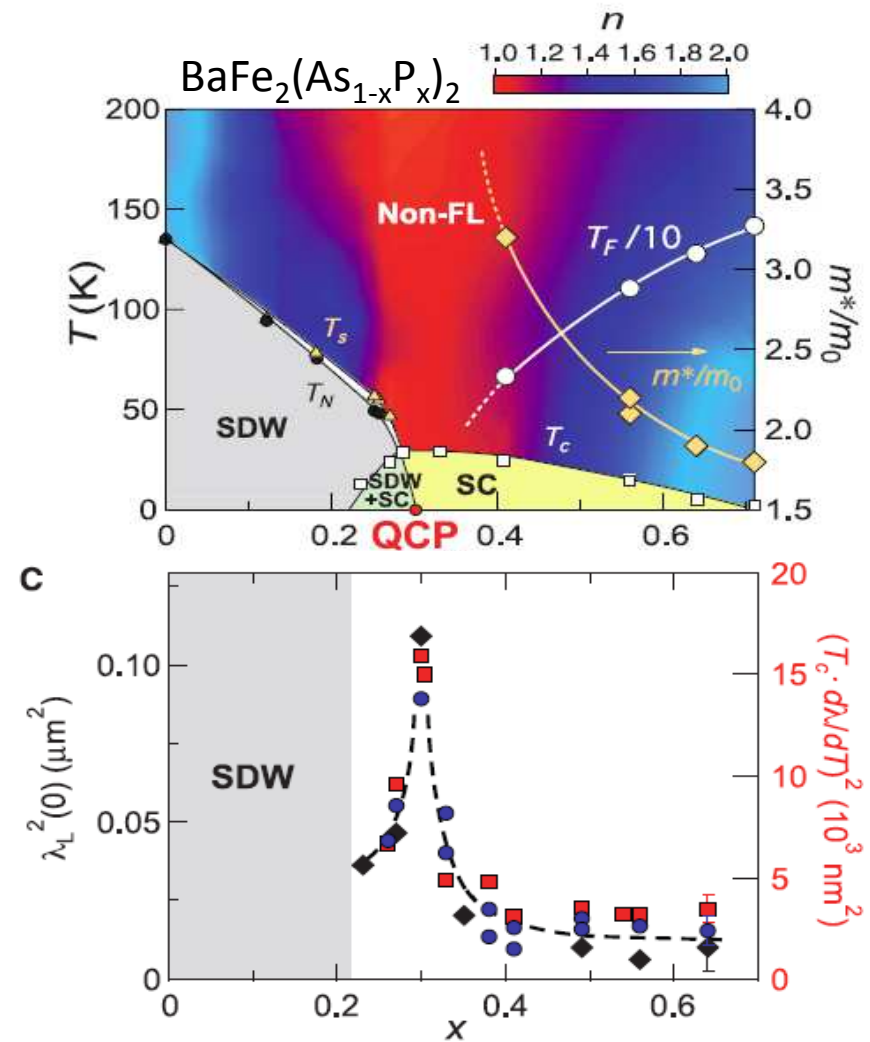
Iron-based SC
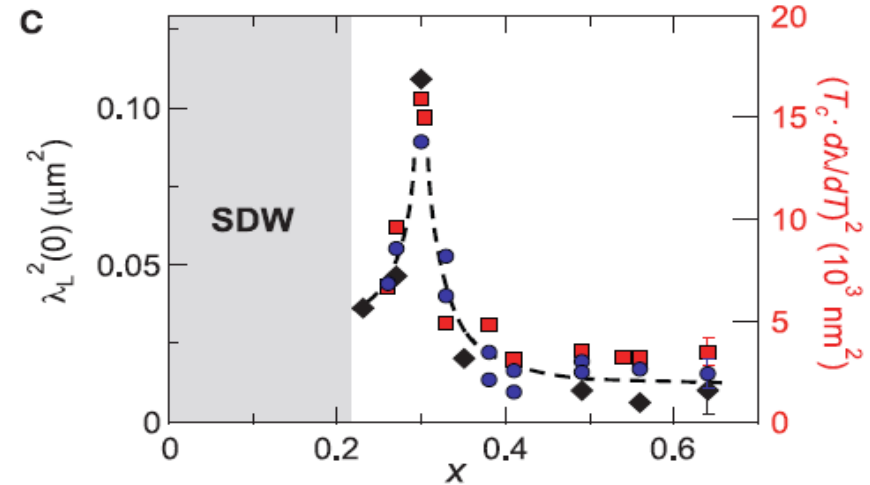

Science **336**, 1554 (2012)

Evidence for QCP

KFe$_2$AS$_2$

T_c (onset)

NFL
$\Delta\rho \sim T^{1.5}$

T_{FL}

SC

FL
$\Delta\rho \sim T^2$

QCP

Field tuned QCP coincident with H$_{c2}$

PRL **104**, 087005 (2010)

BaFe$_2$(As$_{1-x}$P$_x$)$_2$

Non-FL

T_F/10

T_s

T_N

SDW

SDW
+SC

SC

T_c

QCP

m^*/m_0

SDW

Science **336**, 1554 (2012)

Absence of QCP in BaFe$_{2-x}$Ni$_x$As$_2$
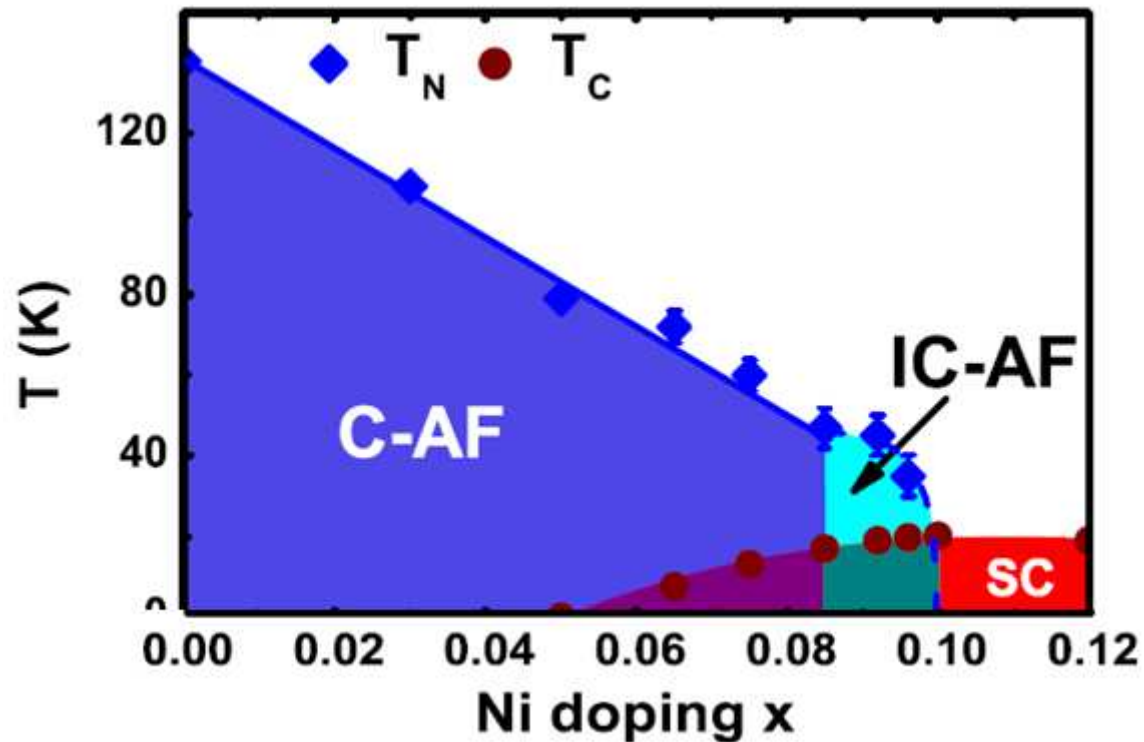
- The static AF order in changes abruptly from a commensurate wave vector for x = 0.085 to an incommensurate wave vector with short-range order for x = 0.092, 0.096.

- T$_N$ suddenly vanishes at x = 0.1 from T$_N$~35K for x = 0.096. The IC AF to SC phase transition appears to be first order
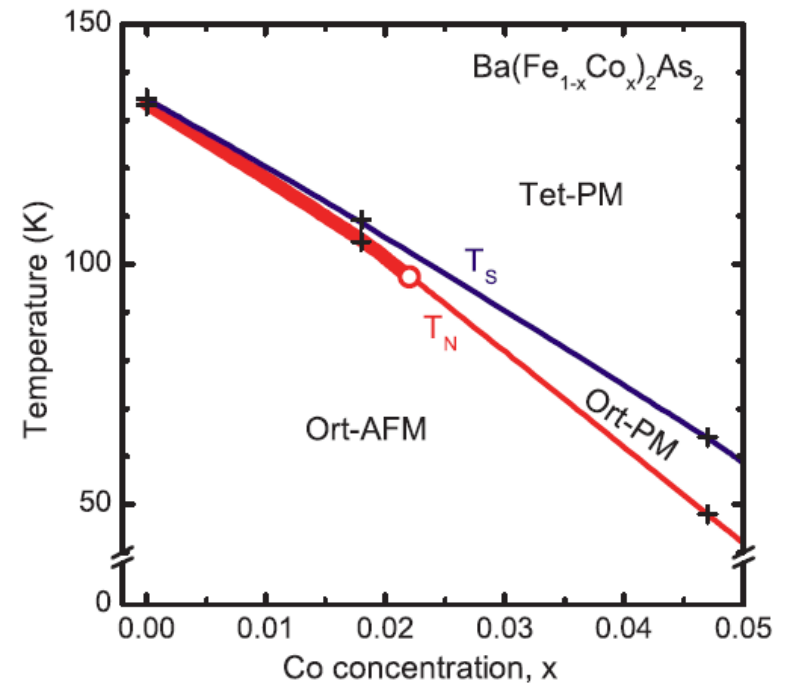
PRL **108**, 247002 (2012)
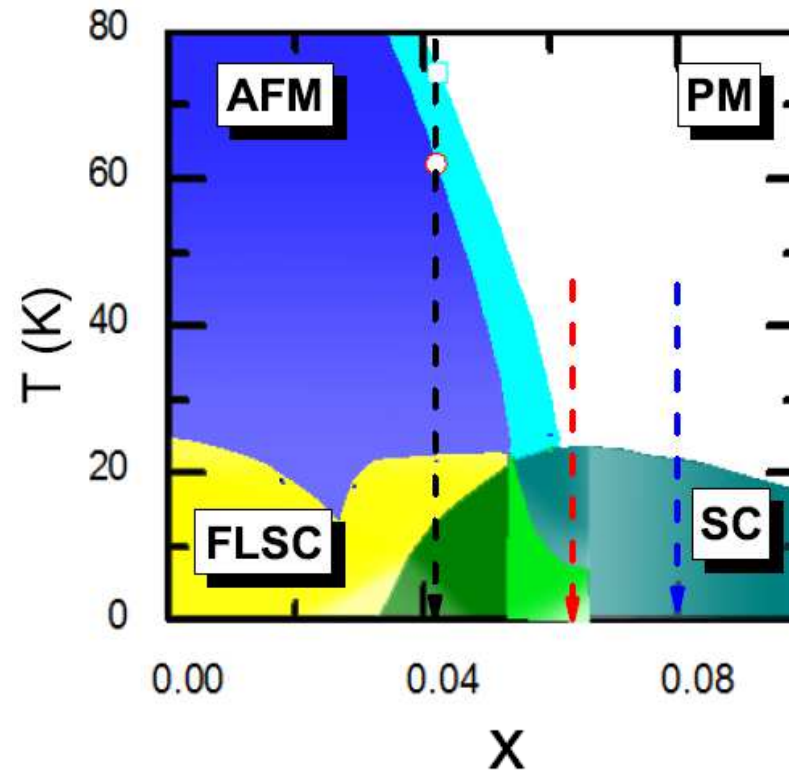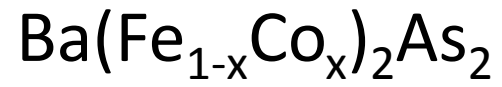
Tricritical point in Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$
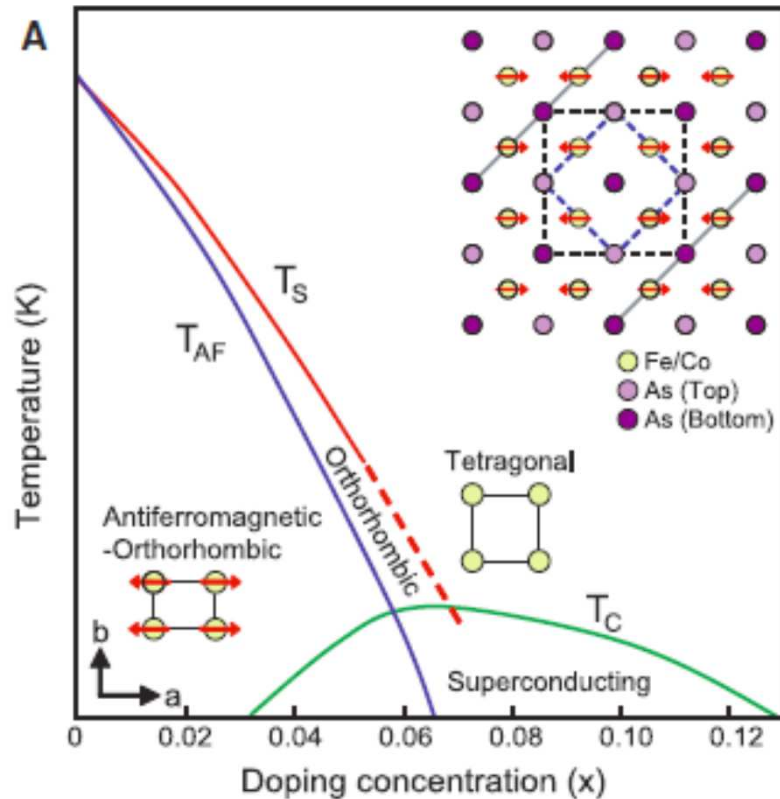
Science **327**, 181 (2010)
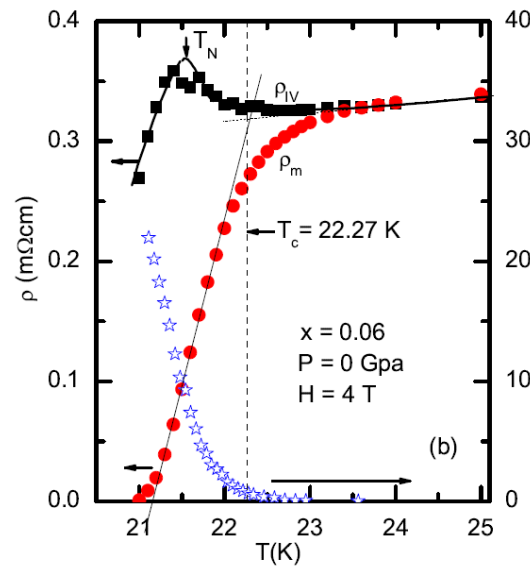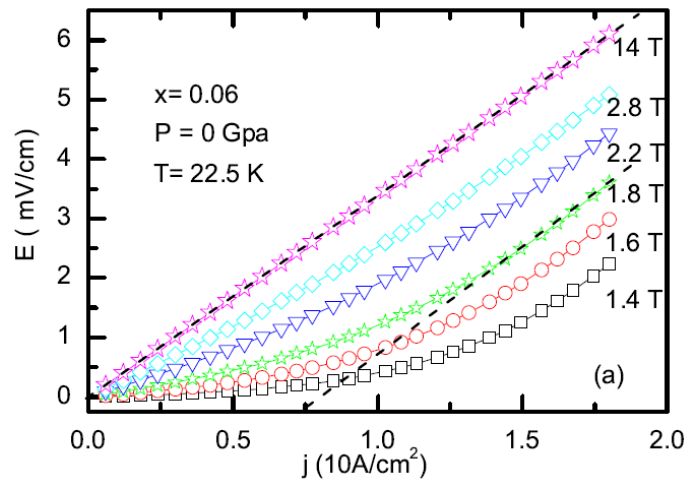
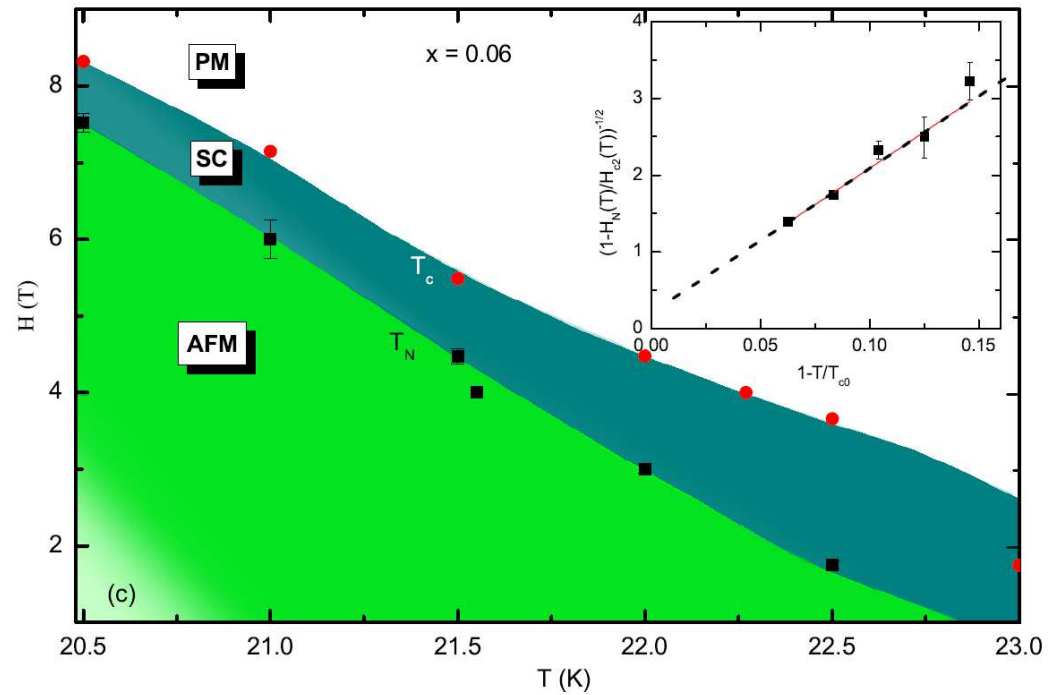- a magnetic tricritical point at $x \approx 0.022$

Phys. Rev. B **83**, 134522 (2011)

Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$

I-V measurements
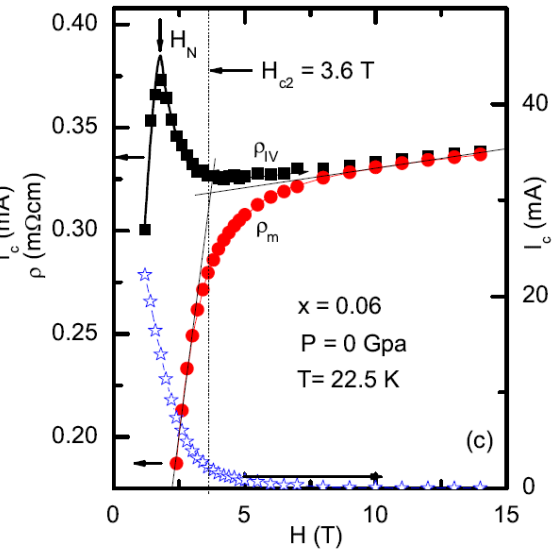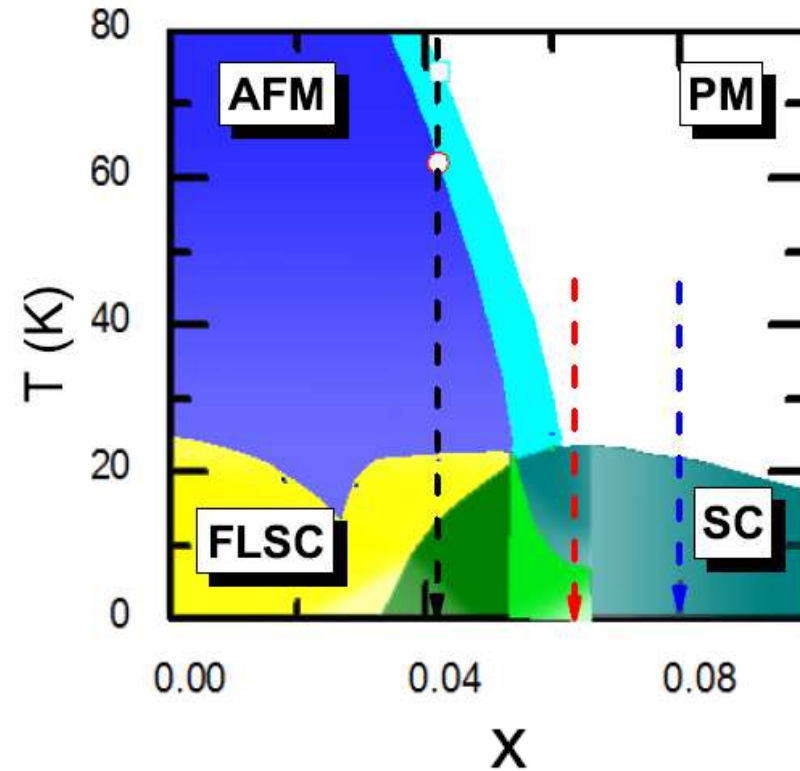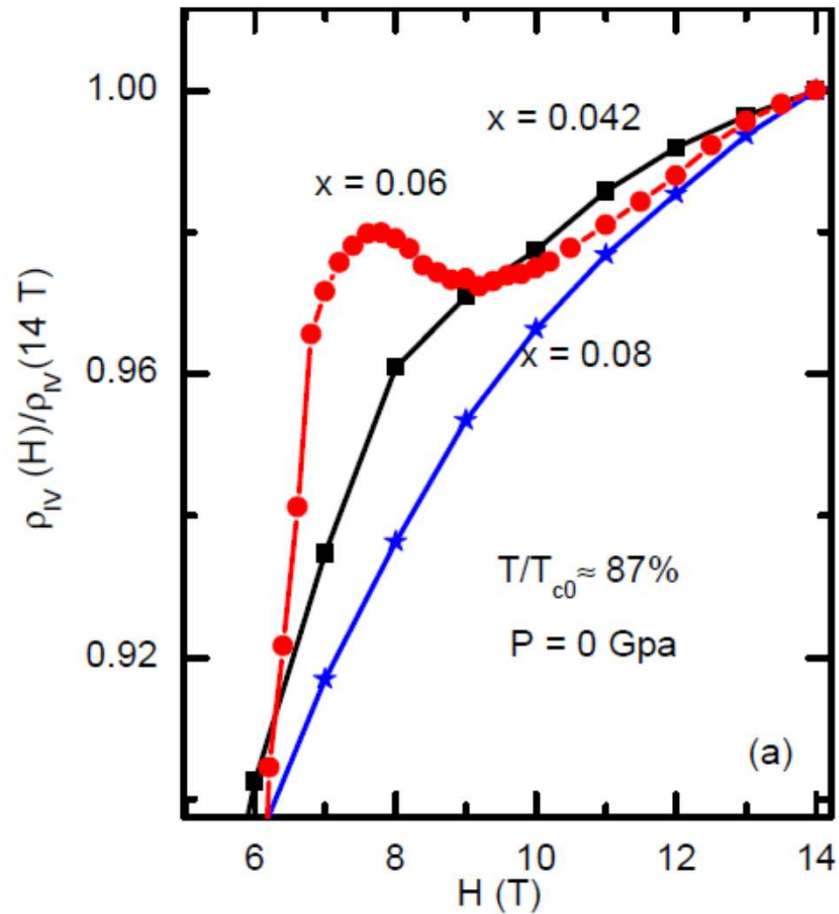
X = 0.06, AFM inside SC

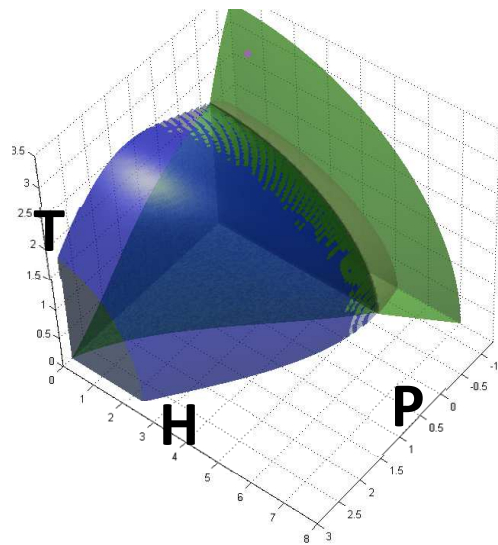

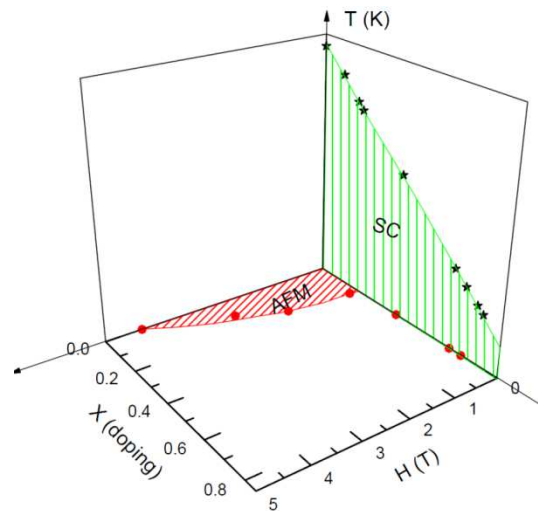Unpublished

X = 0.06, AFM inside SC

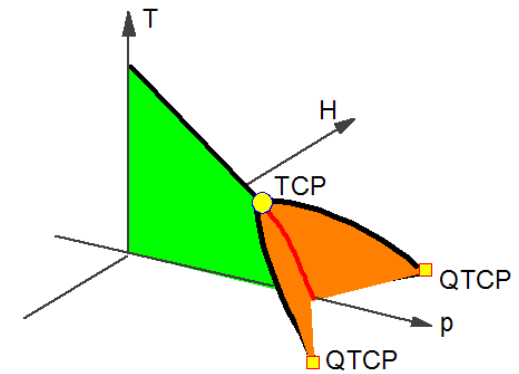Unpublished

Summary

$$\frac{P - P_c}{P^* - P_c} = \left(1 - \frac{T_N}{T_{c0}}\right)\left(1 - \frac{H_N}{H_{c2}(T_N)}\right)$$

CeCoIn$_5$ Ce$_{1-x}$Yb$_x$CoIn$_5$ Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$

The origin of unconventional SC could be much more profound and need to be further explored.