Quantum Criticality in Iron-pnictide Superconductors

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OUTLINE

1. Evidence of a QCP in $BaFe_2(As_{1-x}P_x)_2$
   - Mass enhancement near x=0.3
2. Anomalous superconducting properties near the QCP

科研費
KAKENHI

Topological
Quantum
Phenomena

Collaborators

Transport properties
Penetration depth
Thermal conductivity
dHvA
Magnetic torque
Crystal growth

S. Kasahara
K. Hashimoto
Y. Mizumami
H. Shishido
Y. Kawamoto
D. Watanabe
Y. Matsuda

Band calc.

H. Ikeda

NMR

T. Iye
Y. Nakai
K. Ishida

Kyoto Univ. Japan

Critical fields, dHvA

C. Puzke
A. Serafin
P. Walmsley
A. Carrington

Univ. of Bristol, UK

dHvA

A.I. Coldea

Univ. of Oxford, UK

Penetration depth

K. Cho
M.Tanatar
R.Prozorov

Ames, USA

N. Salovich
R. W. Giannetta

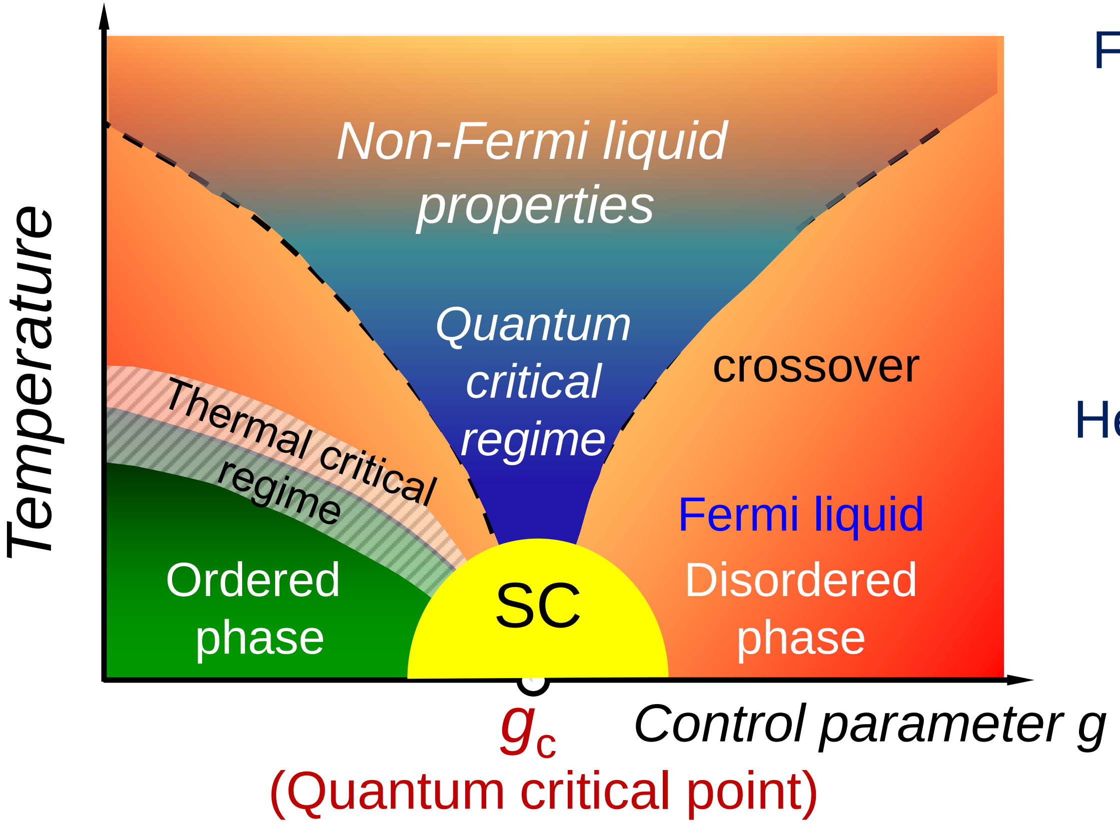
Univ. of Illinois at Urbana-Champaign, USA

Microwave

H. Kitano

Aoyama Gakuin, Japan

Quantum Critical Point (QCP)

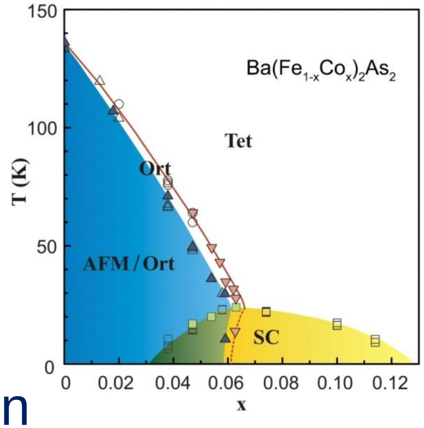


g: pressure, chemical substitution, magnetic field

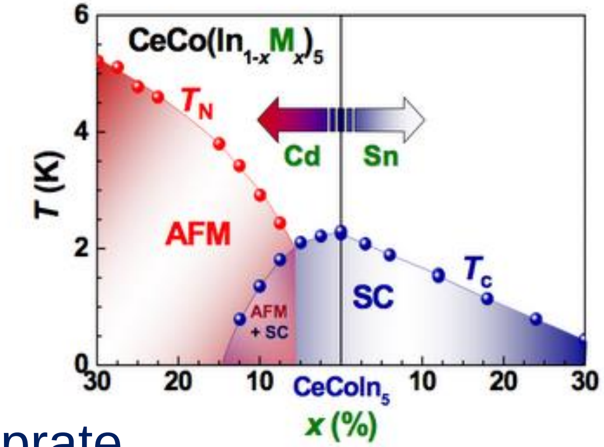
Does the QCP lie beneath the SC dome?

1. Mechanism of superconductivity
2. non-Fermi liquid properties
3. Coexistence of SC and magnetic (exotic) order

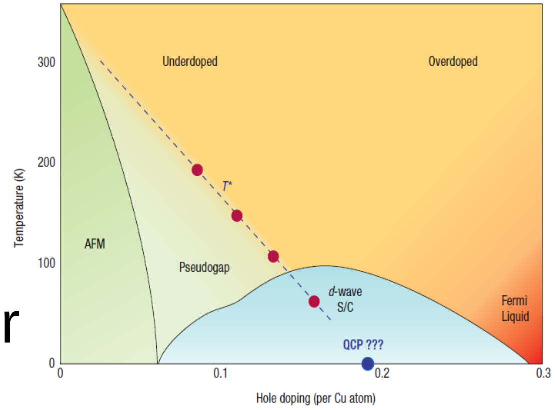
Fe-pnictide



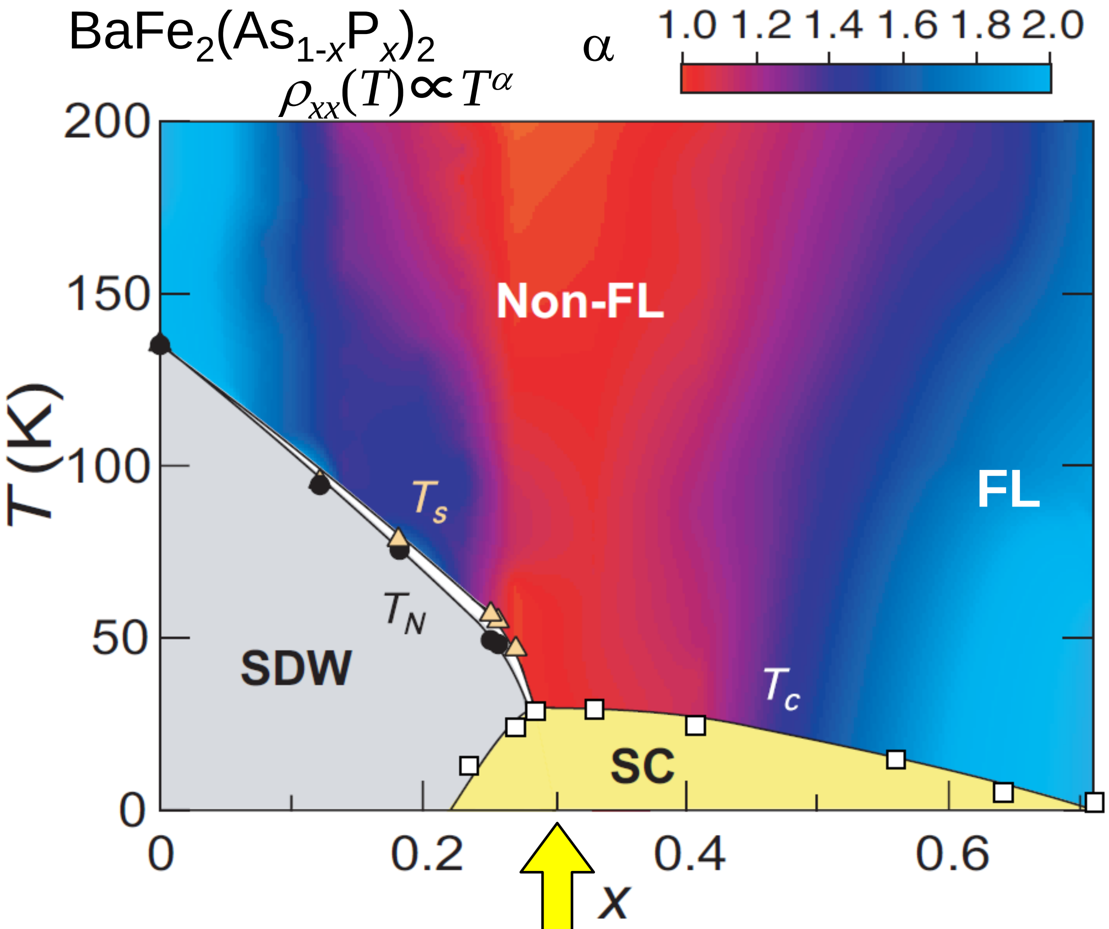
Heavy Fermion



Cuprate



Doping evolution of the transport property



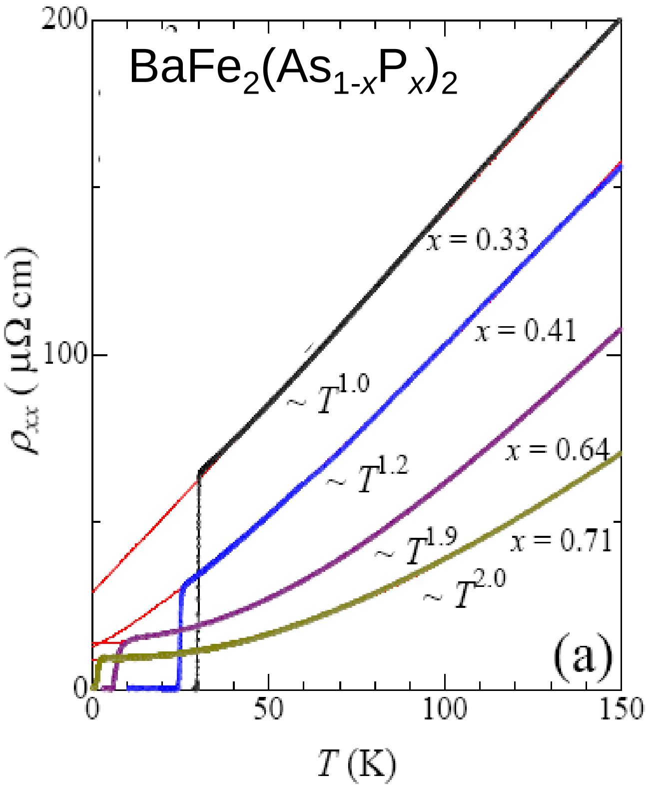
QCP ?

S. Kasahara *et al*., PRB **81**, 184519 (2010).
A.E. Böhmer *et al*. Phys. Rev. B 86, 094521 (2012).

See also

S. Sachdev and B. Keimer, Physics Today (2011).

J. Dai, Q. Si, J.-X. Zhu, and E. Abrahams, PNAS (2009).



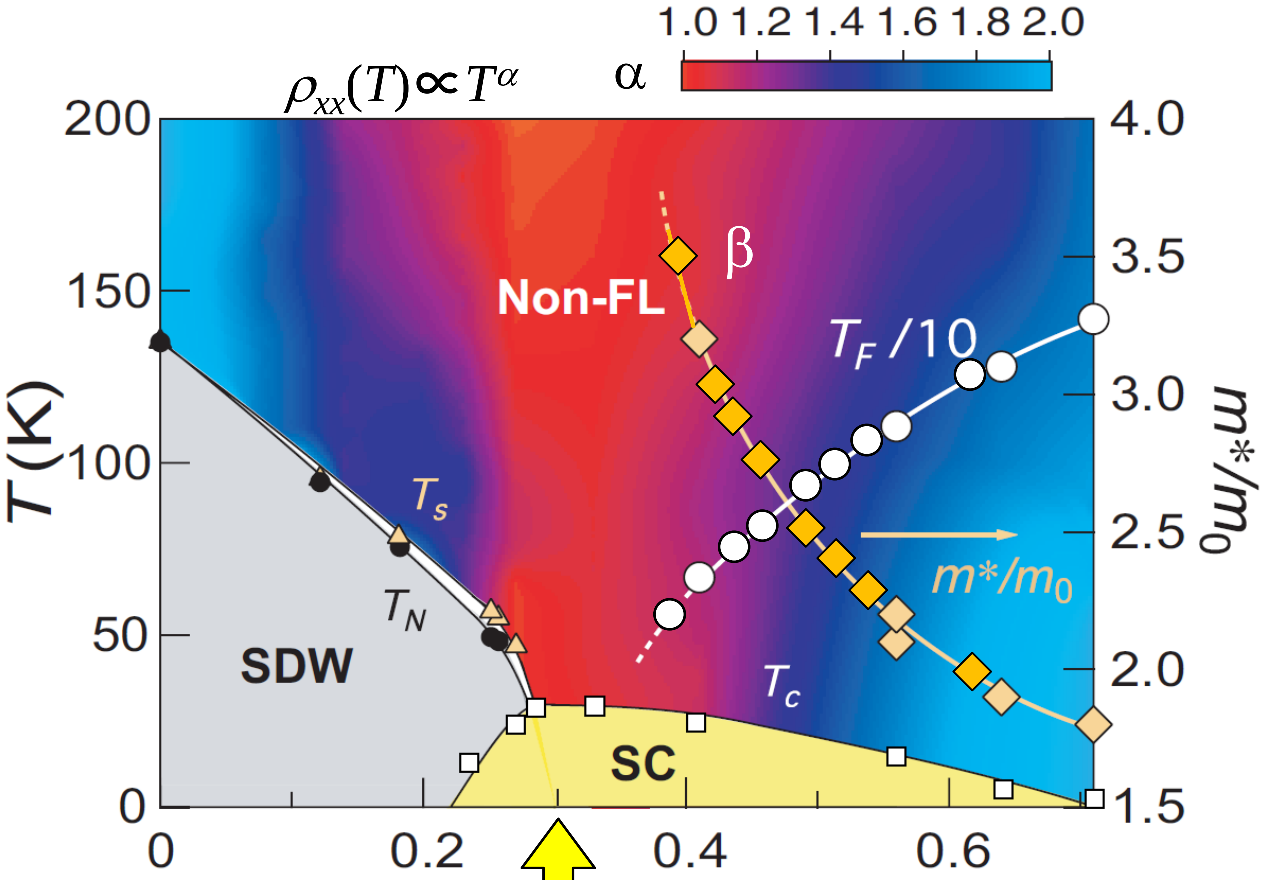
T-linear resistivity at *x*=0.33 just beyond the SDW end point

Hallmark of non-Fermi liquid

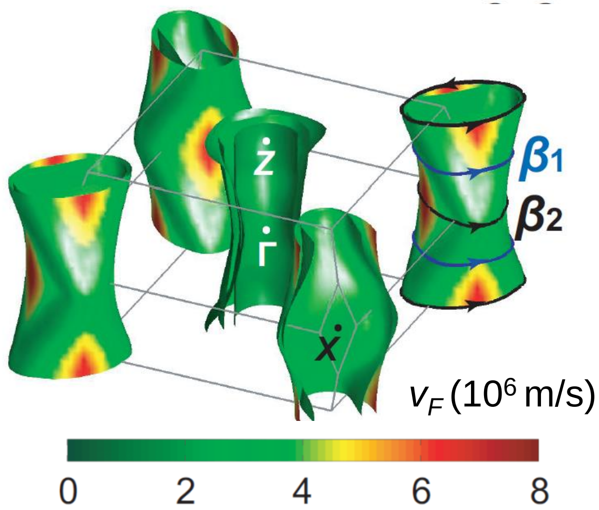
T^2-dependence at *x*=0.71

Fermi-liquid behavior

Fermi surface and mass renormalization



QCP ?

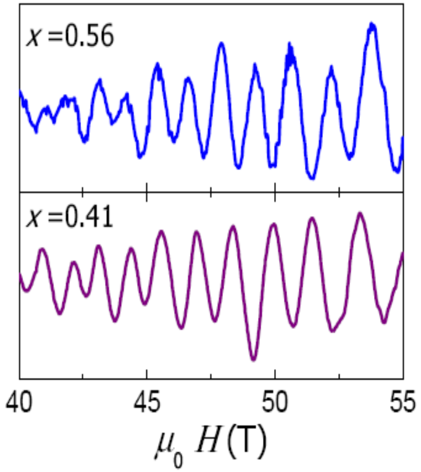


Effective mass m^*

Fermi temperature

$$T_F = \hbar eF / m^* k_B$$

dHvA



As *x* is tuned towards the maximum T_c,

Effective mass m^* is strongly enhanced

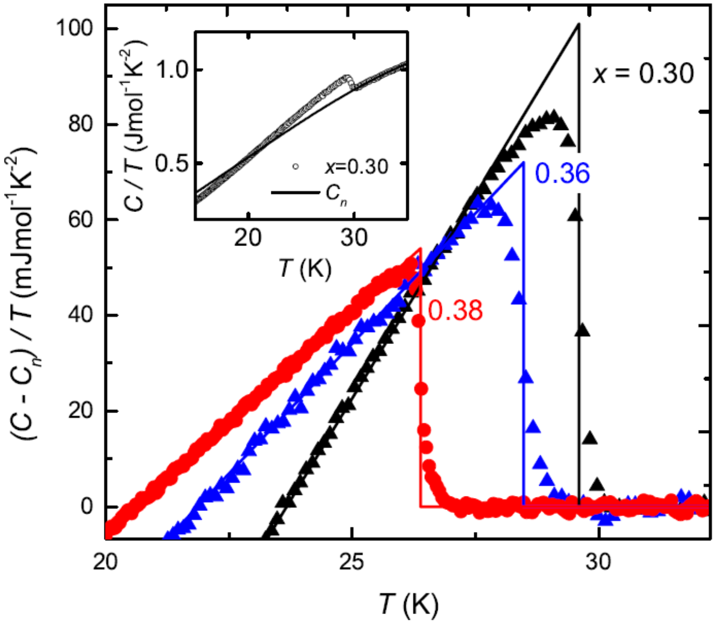
Fermi temperature $T_F = heF/m^* k_B$ tends to zero

H. Shishido *et al*., PRL (2009); B. J. Arnold *et al*., PRB (2011); P. Walmsley *et al*., PRL (2013).

Doping evolution of the specific heat jump at T_c

$BaFe_2(As_{1-x}P_x)_2$

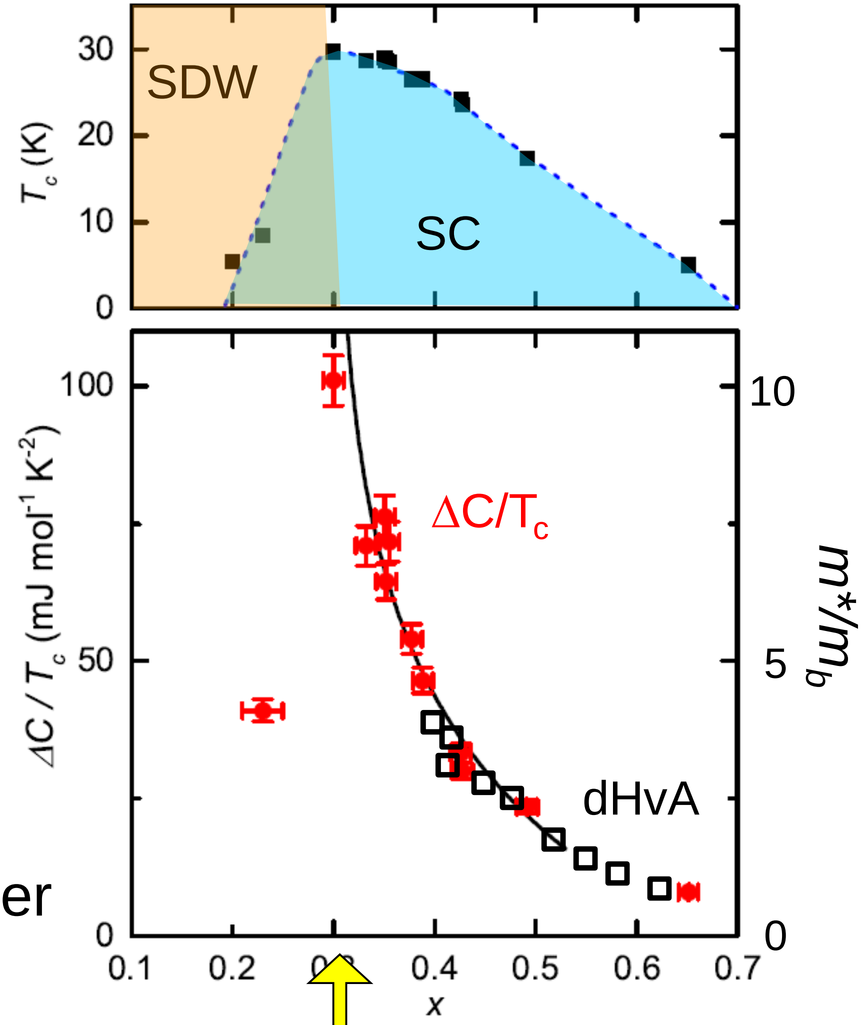
P. Walmsley *et al*., PRL (2013).



$$\frac{\Delta C}{T_c} \propto \gamma \propto m^*$$

The uniform mass enahancement over the Fermi surface

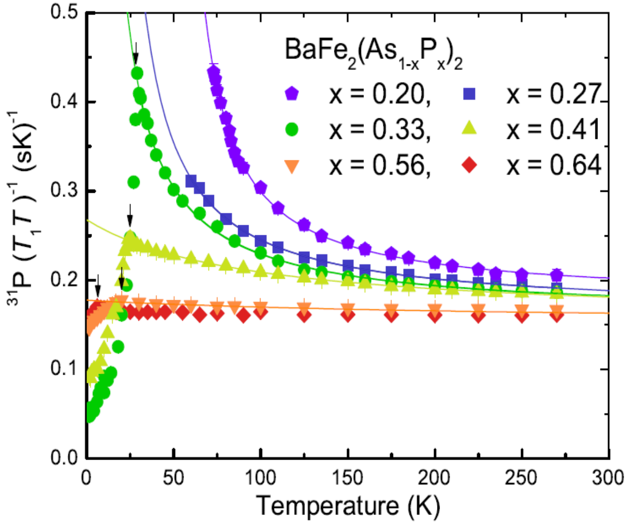
$$\frac{m^*}{m_b} = c_0 + c_1 \ln(x - x_c)$$

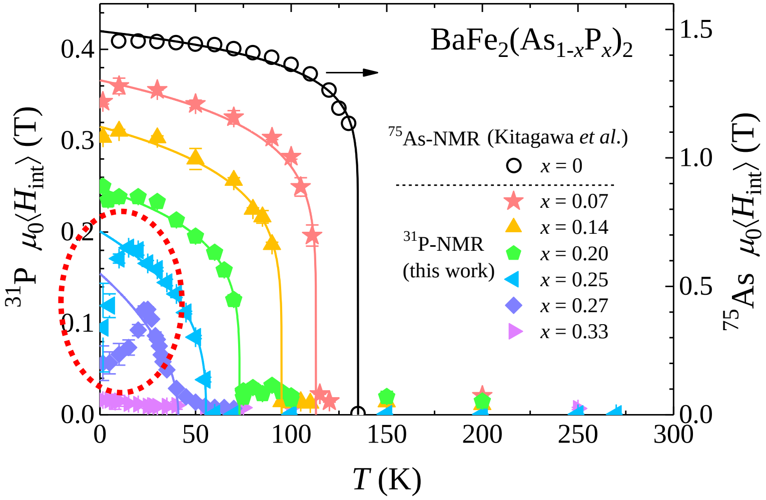


QCP?

Doping evolution of the magnetic properties (^{31}P NMR)

$1/T_1T \sim \chi(\pi,\pi)$



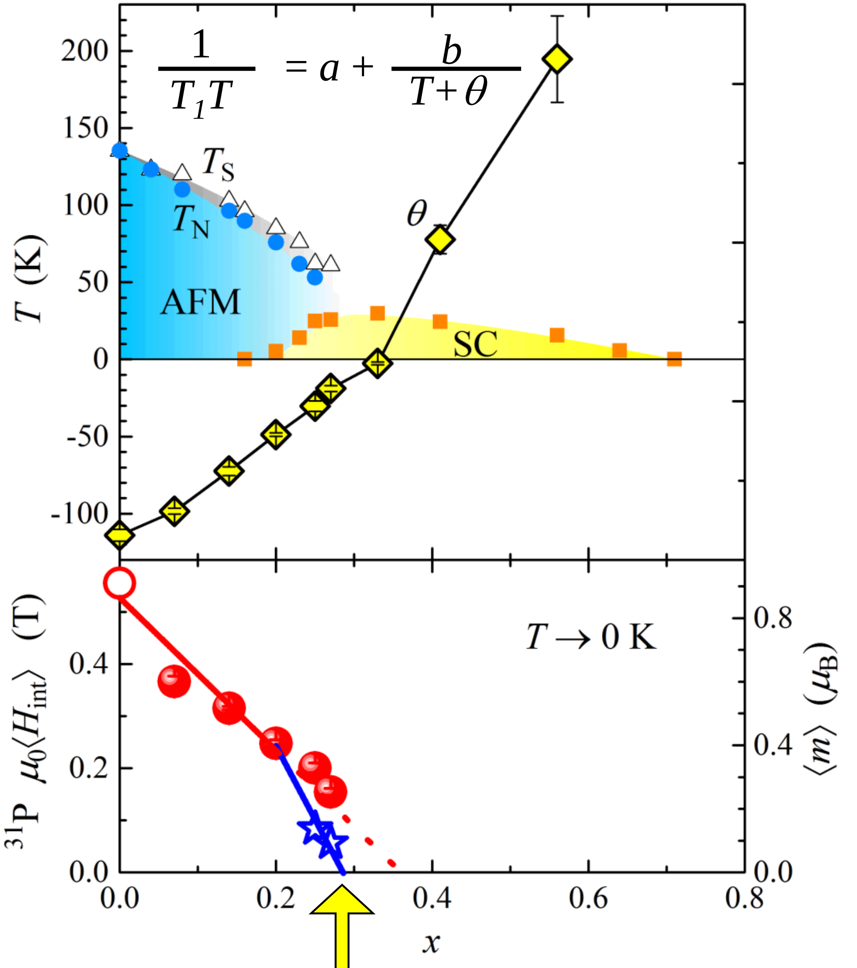


Coupling between magnetism and superconductivity

θ: Weiss temperature

θ goes to zero at x~0.32

Y. Nakai *et al*. PRL (2010).

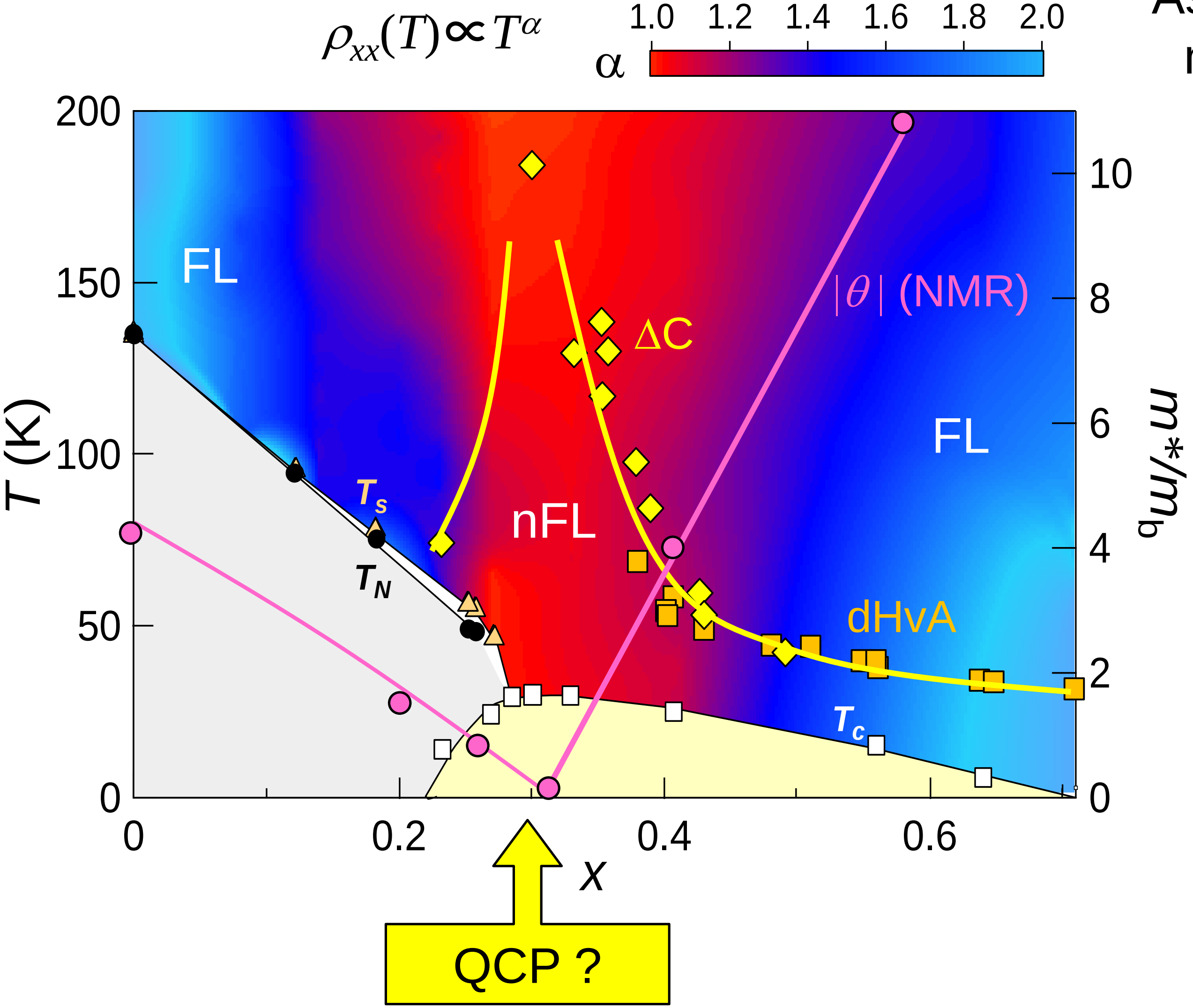


QCP?

T. Iye *et al*. (2014).

Magnetic moment vanishes at x=0.3

Doping evolution of normal-state properties



As *x* is tuned towards the maximum T_c at x=0.30

Hallmark of non-Fermi liquid behavior

Resistivity

Effective mass m^* is strongly enhanced

dHvA

Specific heat

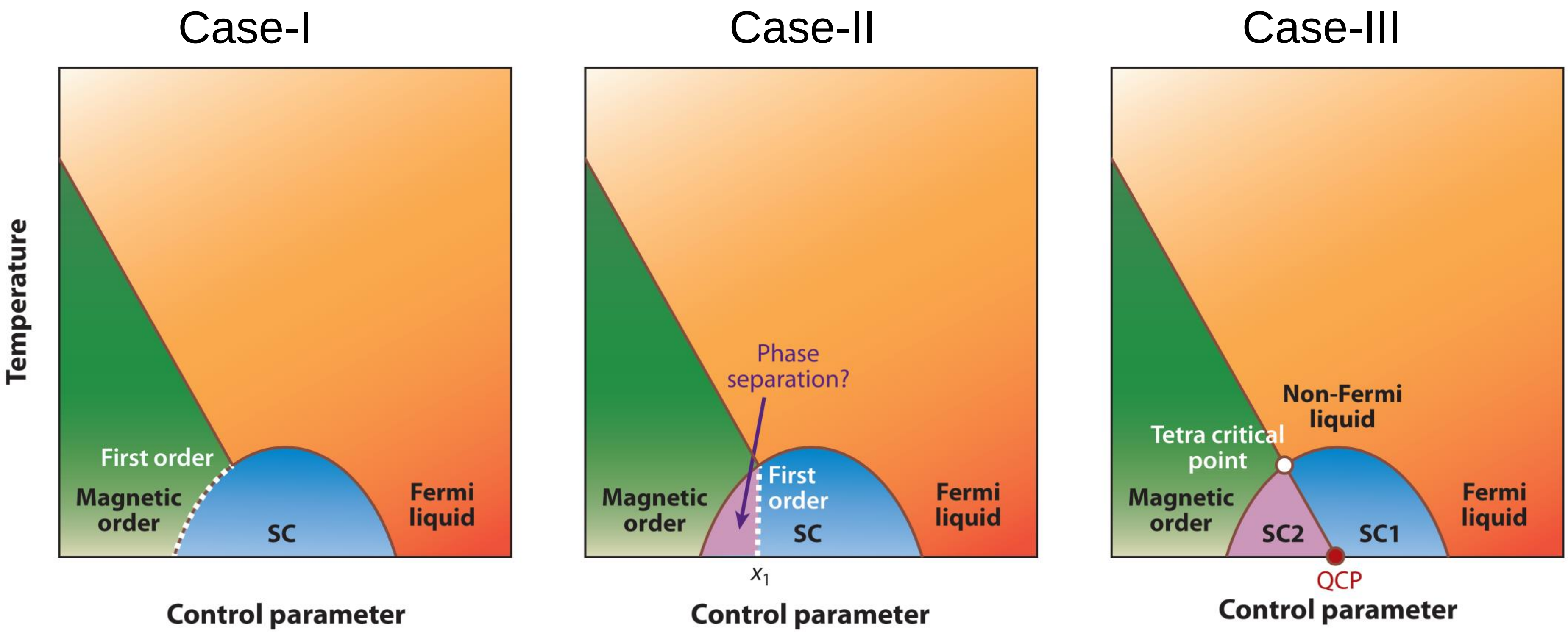
Weiss temperature goes to zero

Magnetic moment vansishes

NMR

We need evidence at zero temperature and zero field.

Phase diagrams of unconventional superconductors



Avoided criticality by the SC dome

QCP within the SC dome

$BaFe_2(As_{1-x}P_x)_2$

K. Hashimoto *et al.*, Science (2012).

T. Shibauchi, A. Carrington, and Y. Matsuda,
Annu. Rev. Condens. Matter Phys. **5**, 113-135 (2014).

Doping evolution of the London penetration depth at T = 0 K

London penetration depth λ_L is the quantity that can probe the electronic structure at zero temperature limit.

Number of superfluid

$$\lambda_L^{-2}(0) = \frac{\mu_0 n_s e^2}{m^*}$$

Mass of superfluid

1. Al coated method

Tunnel diode oscillator (13MHz, 70 mK)

2. Microwave surface impedance

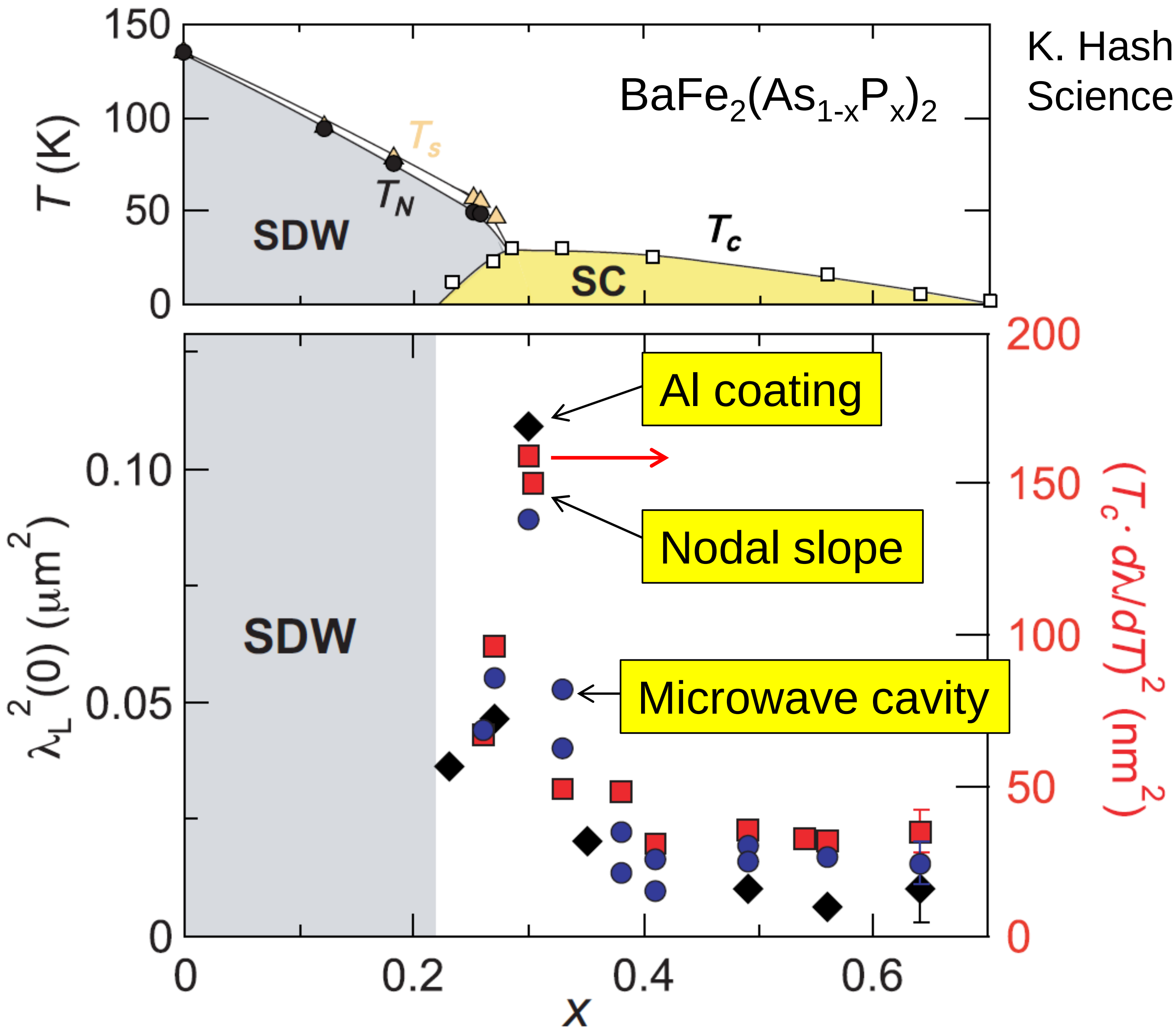
Rutile cavity resonator (5 GHz, Q~10^6, 350 mK)

3.Nodal superconducting gap structure

Line node

$$\frac{\delta\lambda_L(T)}{\lambda_L(0)} \approx \frac{\ln 2}{\Delta} k_B T$$

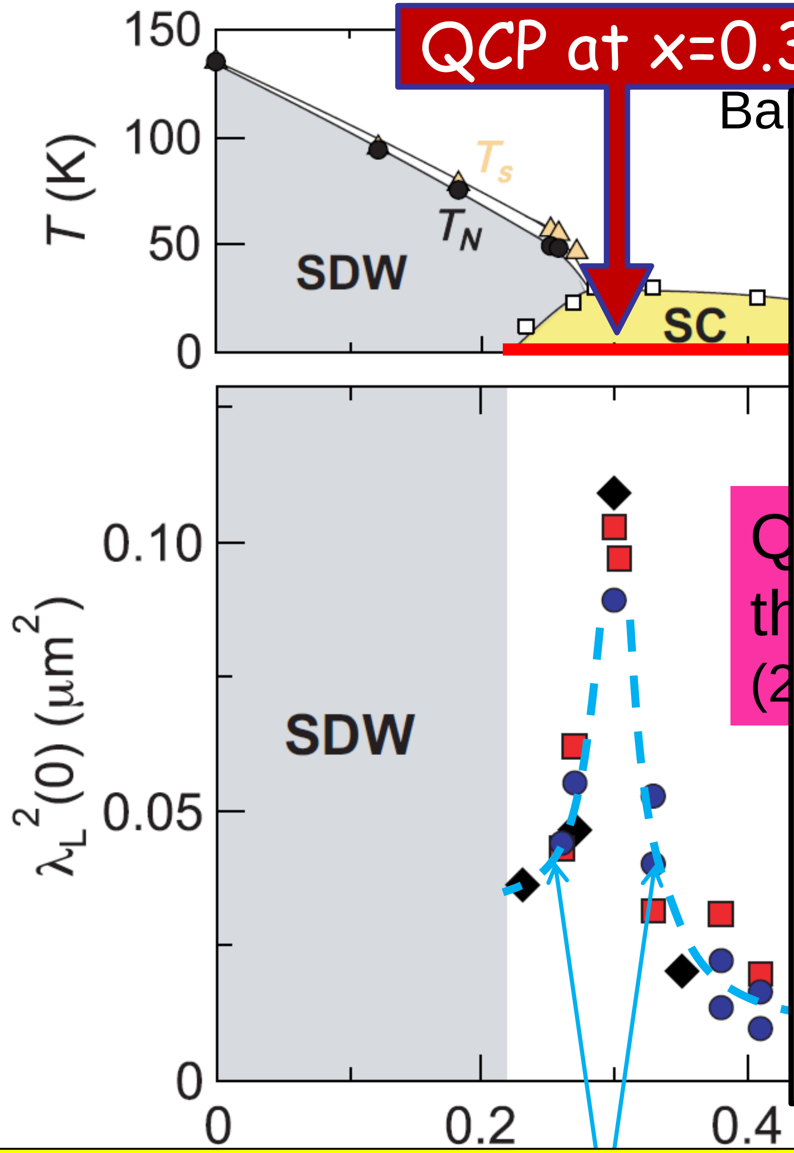
Doping evolution of the London penetration depth at T=0

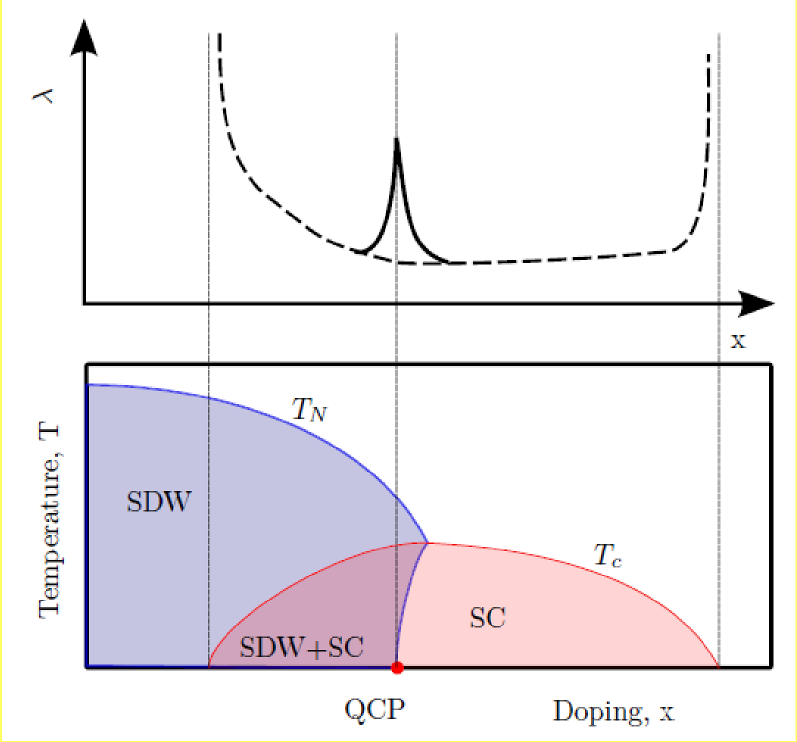


K. Hashimoto *et al.*,
Science **336**, 1554 (2012).

All three methods give very similar x-dependence

Doping evolution of the London penetration depth at *T*=0





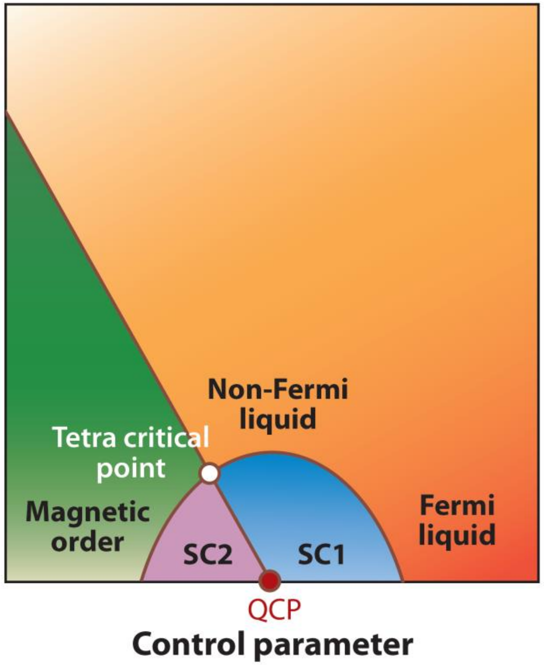
Mass renormalization of superfluid by critical magnetic fluctuations

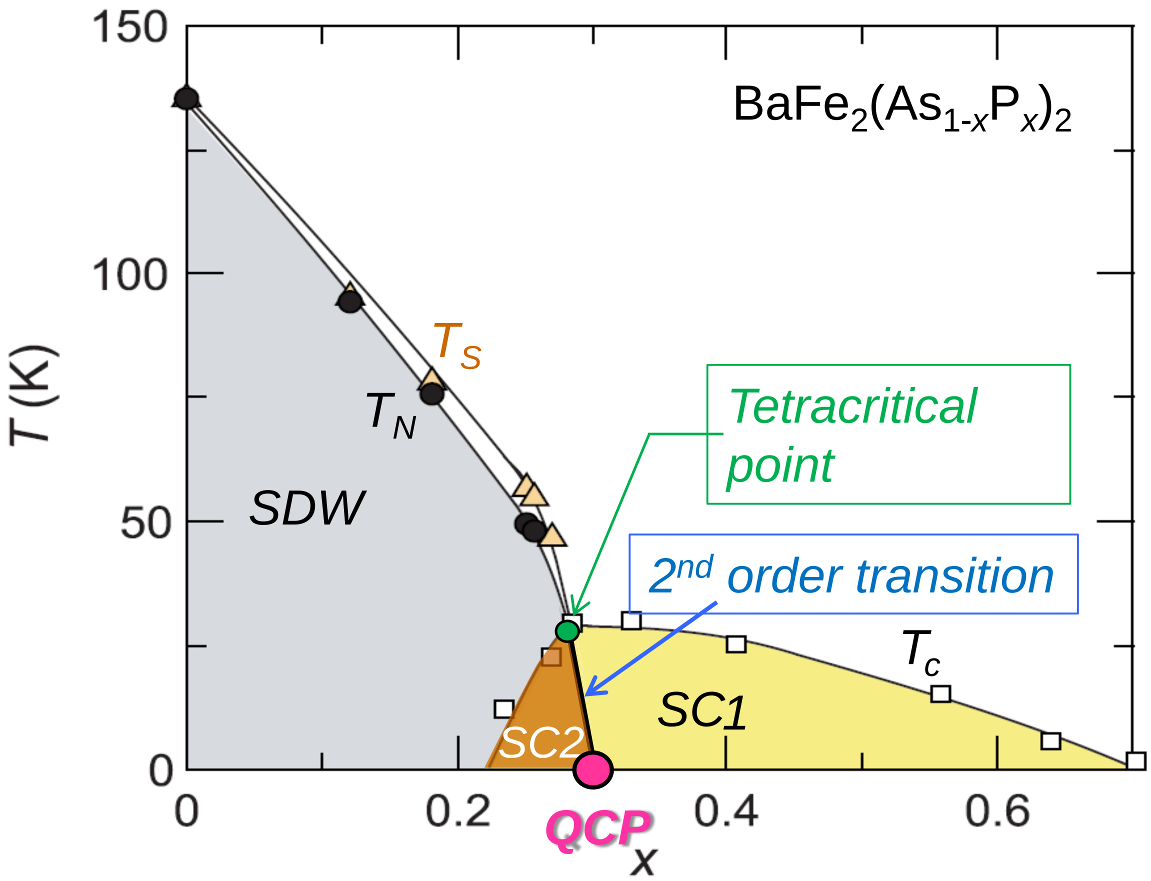
A. Levchenko *et al*. PRL (2013), T. Nomoto, H. Ikeda, PRL (2013); K. Hashimoto *et al*., PNAS (2013).

Striking enhancement of $\lambda_L^2(0)$ on approachi

The data represents the behavior at the zero temperature limit.

QCP lies beneath the dome





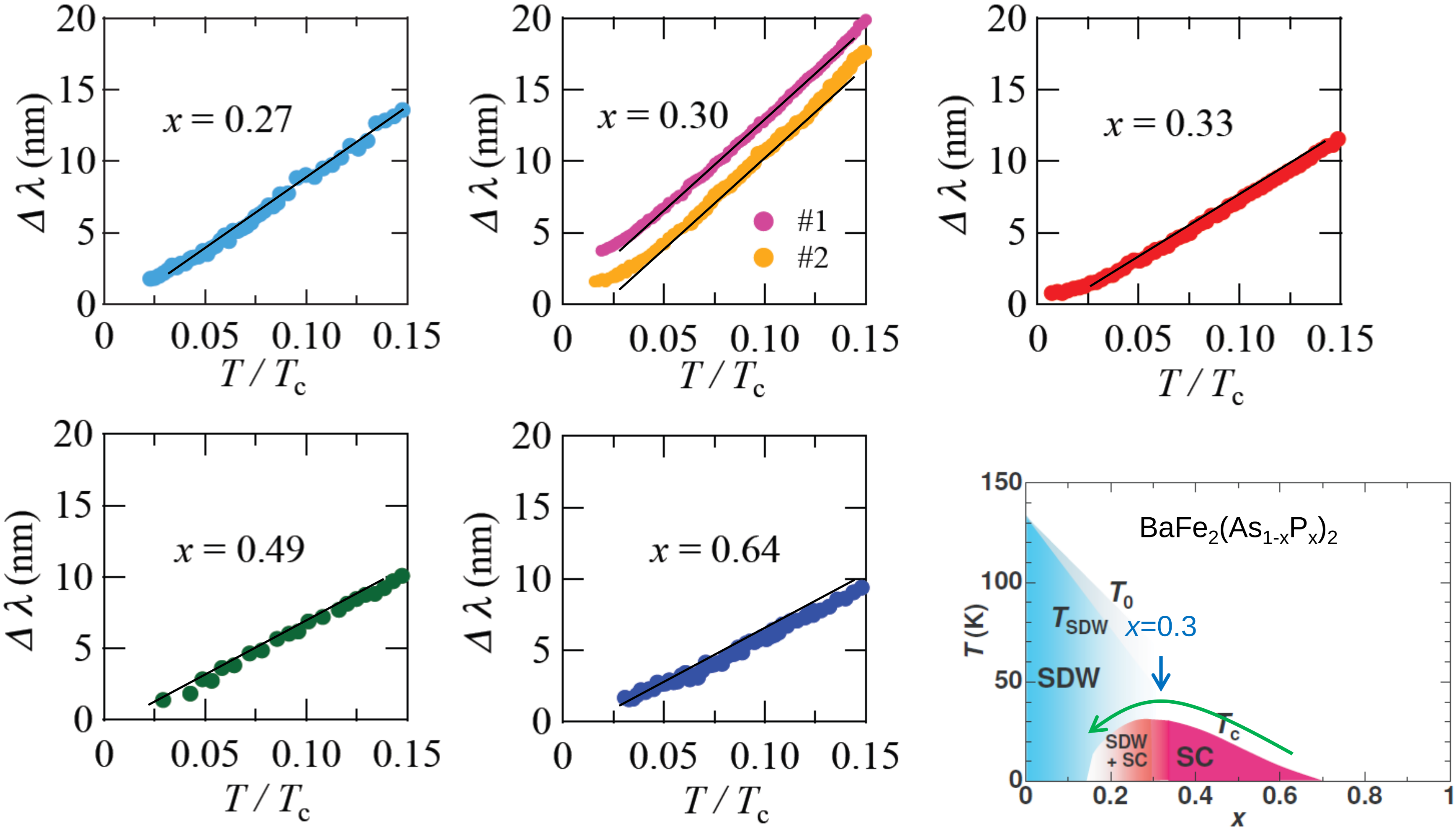
1. The QCP is the origin of the non-Fermi liquid behavior above T_c.

2. Unconventional SC coexists with AFM on a microscopic level.

3. The quantum critical fluctuations help to enhance superconductivity.

Doping evolution of $\lambda(T)$ in $BaFe_2(As,P)_2$

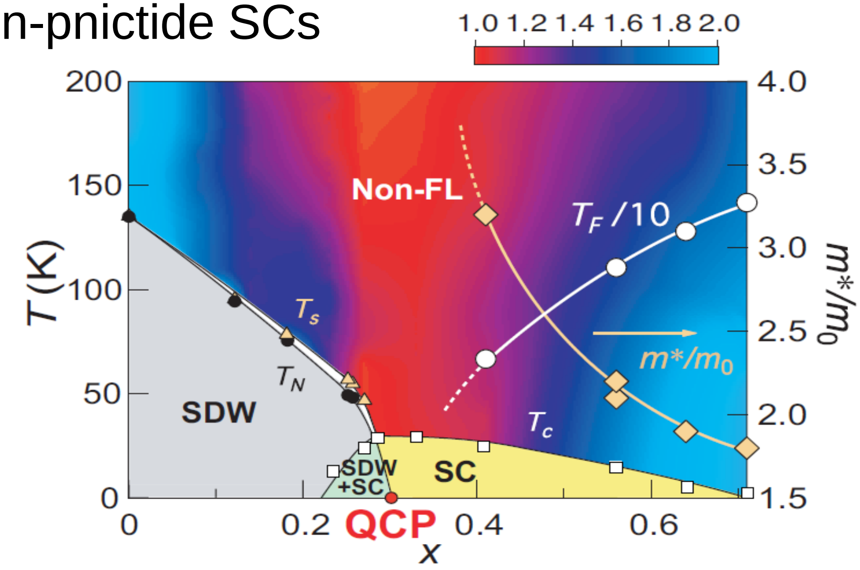
Robust line nodes over a wide range of *x*.



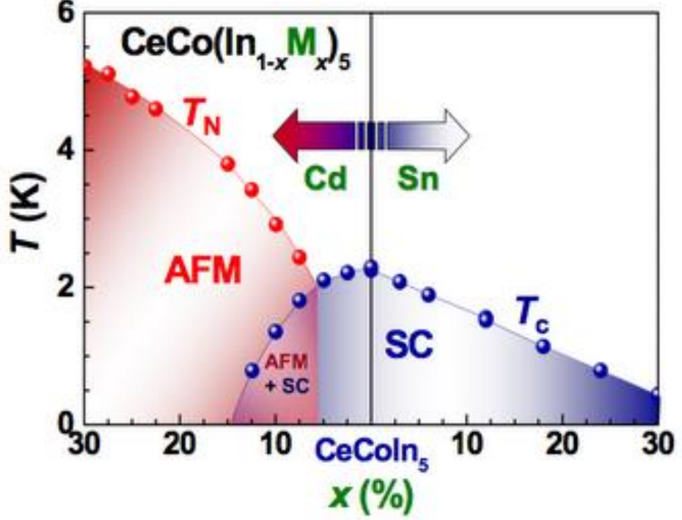
Deviations from the *T*-linear dependence near *x*=0.3

Nodal superconductors in the vicinity of AFM

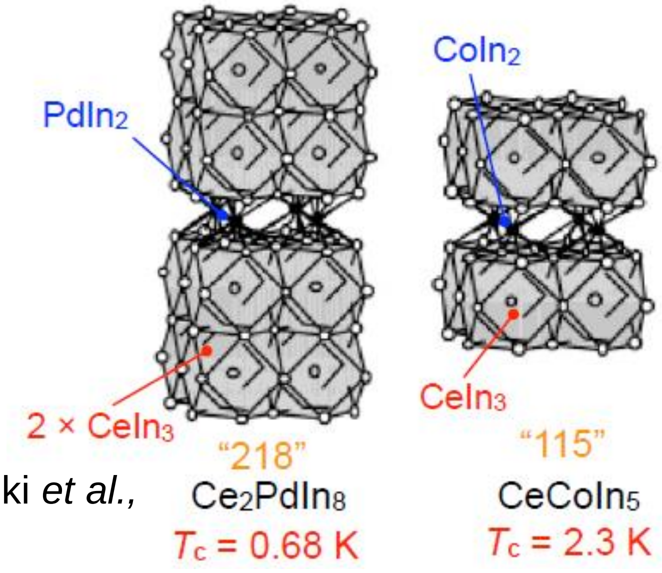
Iron-pnictide SCs



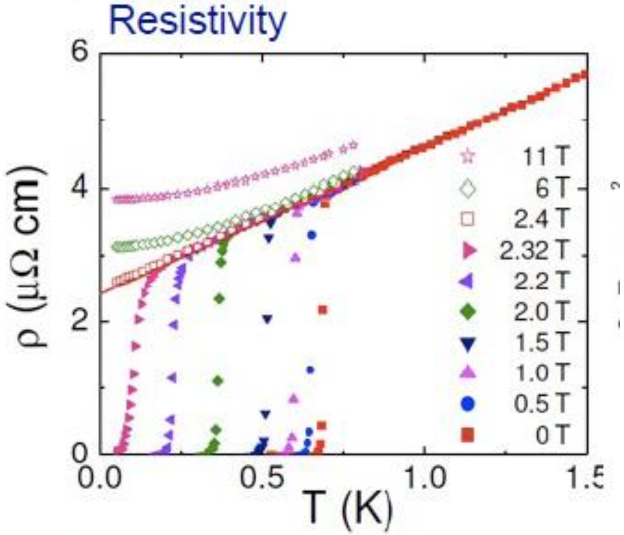
Heavy-Fermion SCs



prototypical `quantum critical' superconductors with nodes

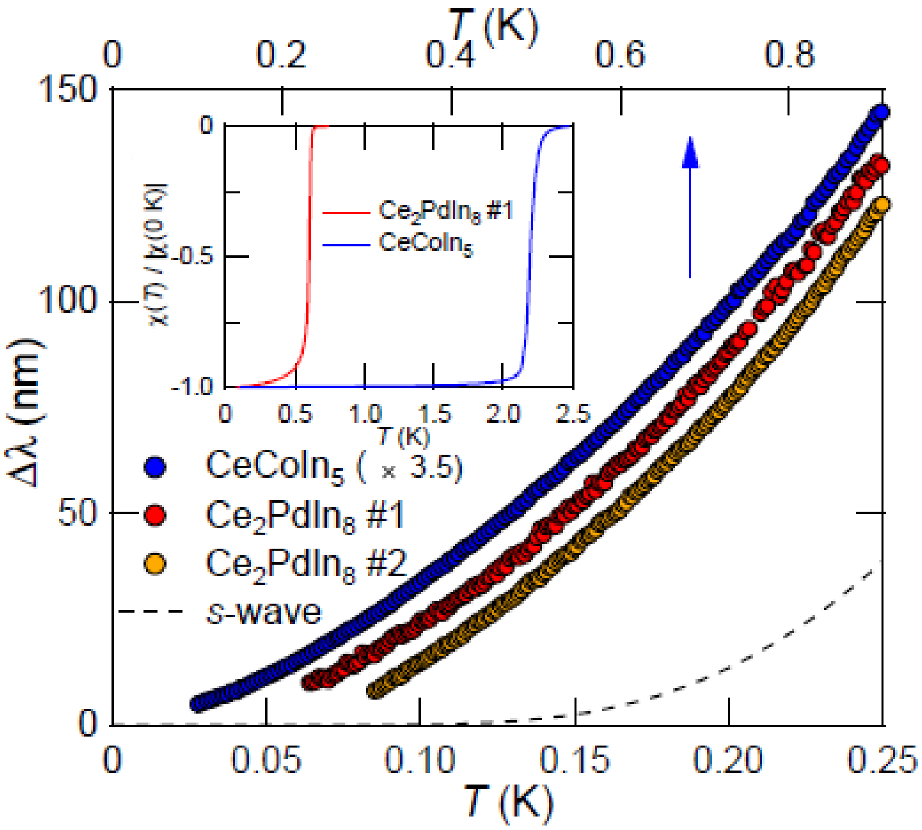


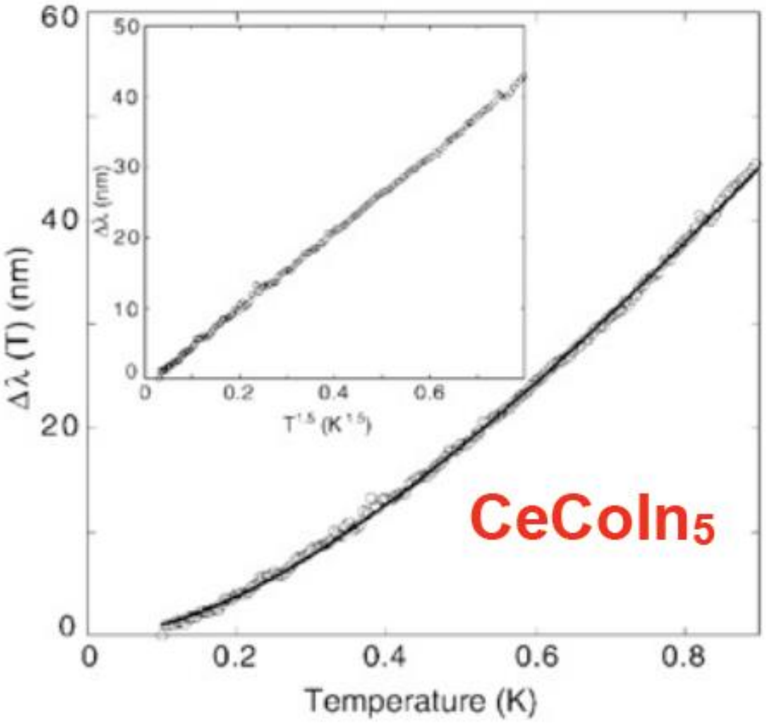
D. Kaczorowski *et al.*, PRL (2009).



J. K. Dong *et al.*, PRX **1**, 011010 (2011).

Anomalous $\lambda(T)$ in $CeCoIn_5$ and Ce_2PdIn_8



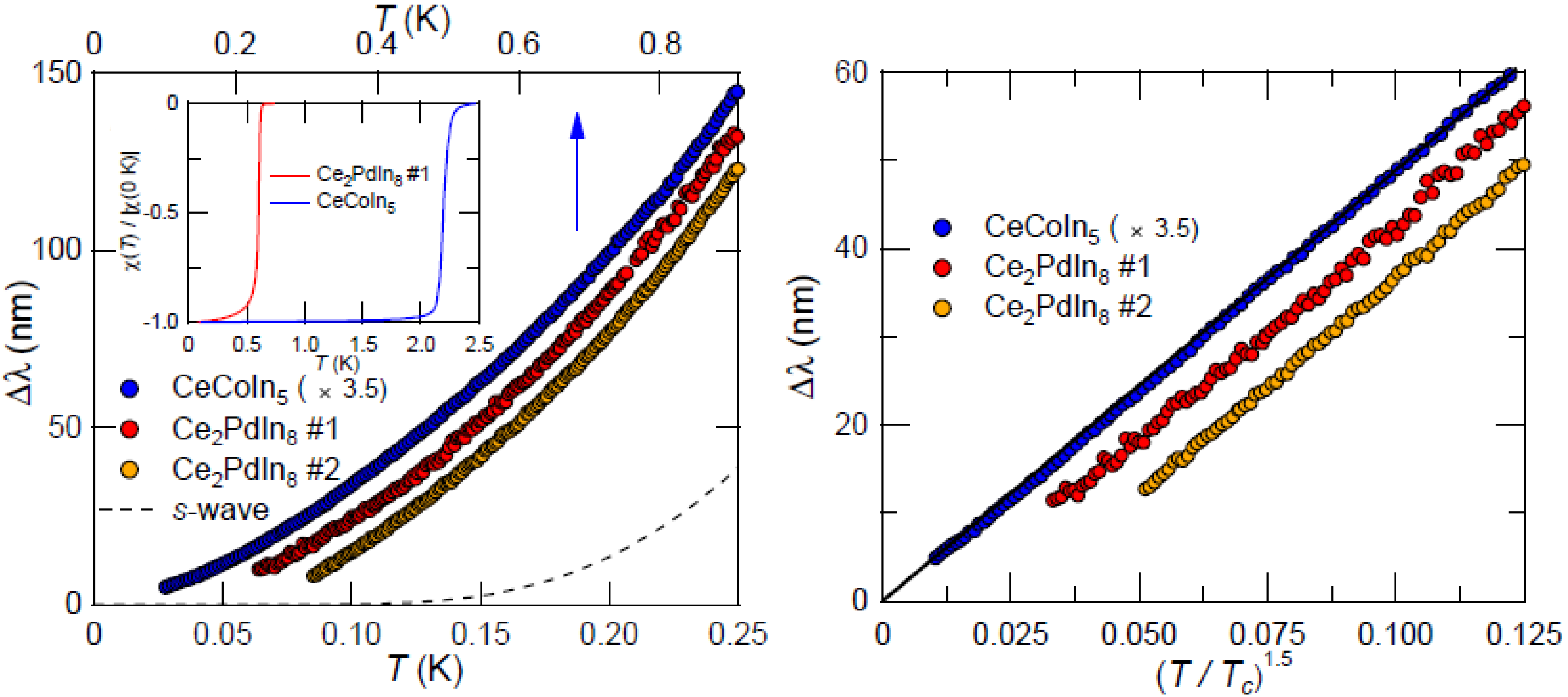


Deviations from the *T*-linear dependence

Consistent with previous studies.

S. Ozcan *et al.*, Europhys. Lett **62** 412 (2003).

Anomalous $\lambda(T)$ in $CeCoIn_5$ and Ce_2PdIn_8

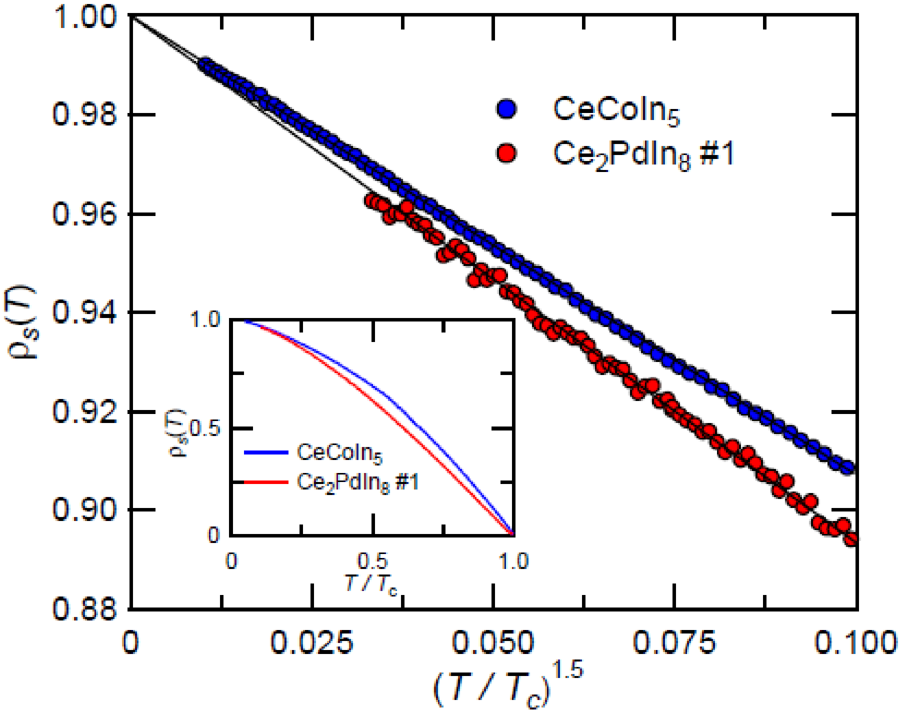


Anomalous non-integer 3/2 power-law dependence in a wide *T*-range

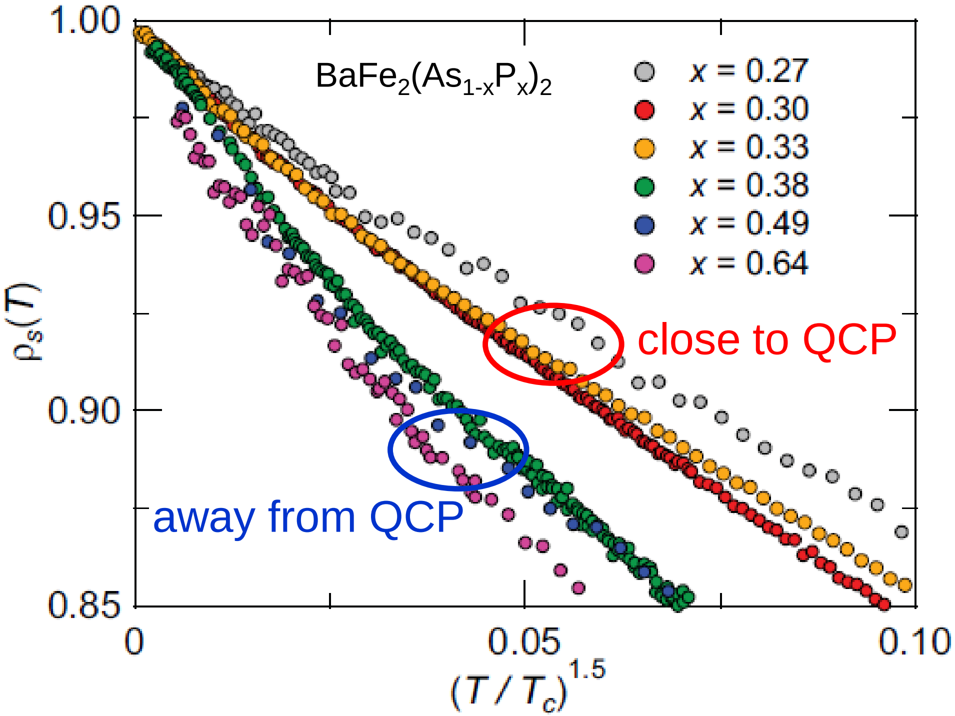
K. Hashimoto *et al*., PNAS **110**, 3293 (2013).

Anomalous superfluid density in `quantum critical' SCs

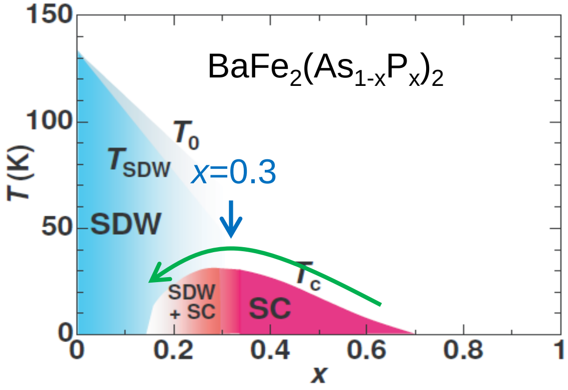
$\rho_s(T) = \lambda^2(0) / \lambda^2(T)$ $T/T_c<0.21$



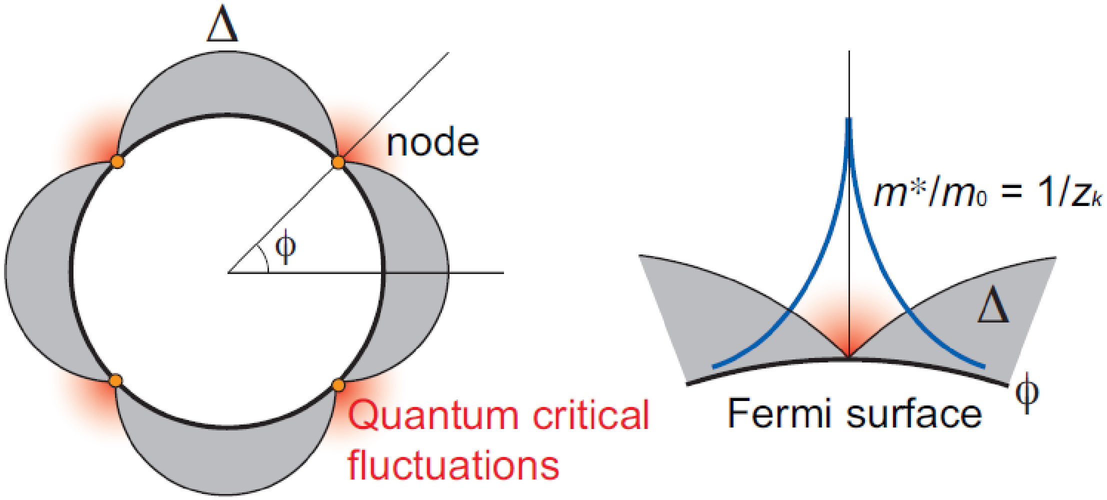
$T/T_c<0.21$



Anomalous non-integer power-law *T* dependence of superfluid density (except for the very low-*T*) is observed.

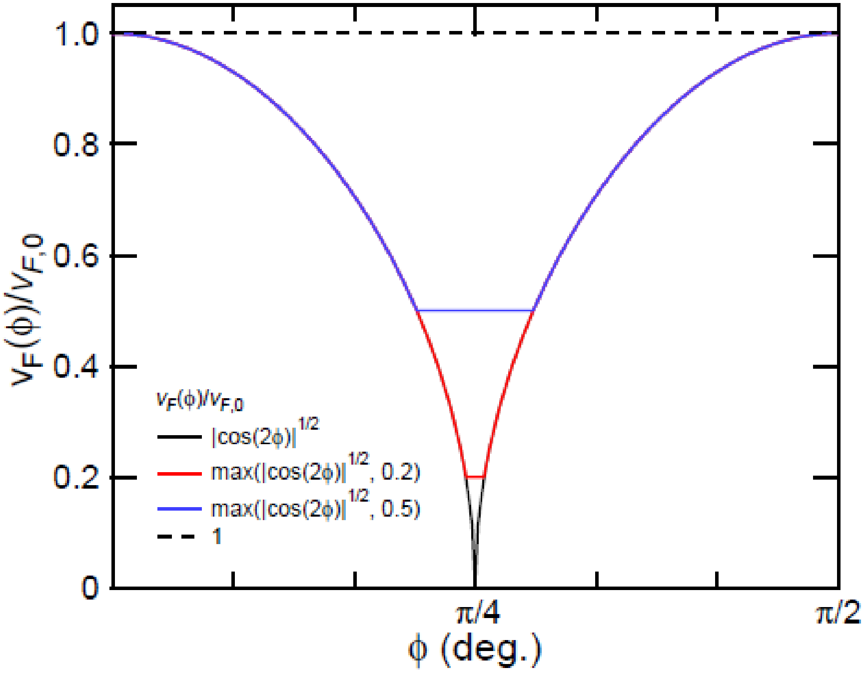


`Nodal quantum criticality' in unconventional SCs



Below T_c...
Low-energy quantum critical fluctuations may be quenched by the SC gap formation.

Fermi surface is not gapped at the nodes, which leads to momentum-dependent mass enhancement.



$$m^{*2} \propto (p - p_{\mathrm{QCP}})^{-\beta}$$

p: non-thermal parameter → gap magnitude

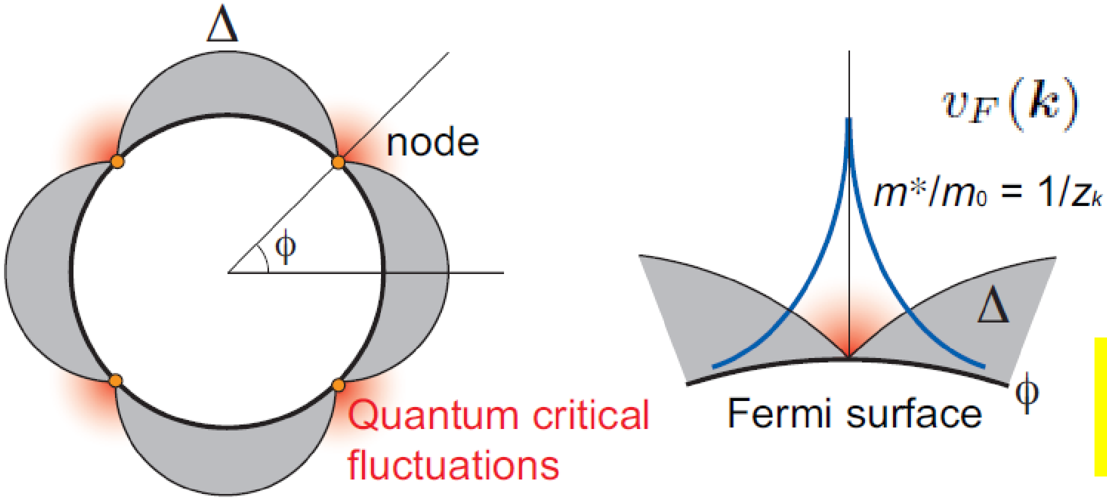
$$v_F(\boldsymbol{k}) \propto z_{\boldsymbol{k}} \propto 1/m^*(\boldsymbol{k}) \propto |\Delta(\boldsymbol{k})|^{\beta/2}$$

β~1 has been reported
in β-$YbAlB_4$ and $YbRh_2Si_2$

Y. Matsumoto *et al.*, Science (2011).
P. Gegenwart *et al.*, PRL (2002).

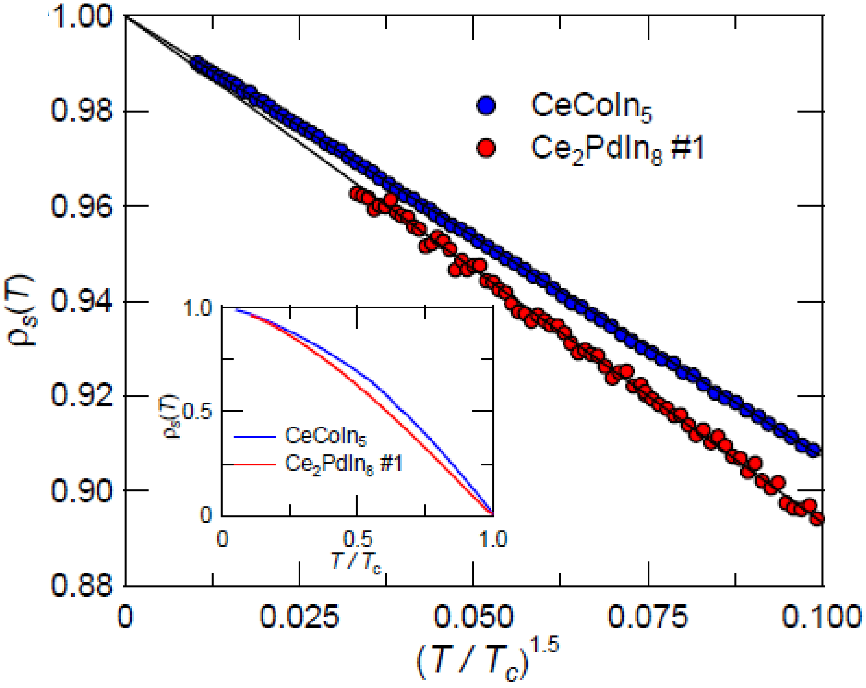
`Nodal quantum criticality' in unconventional SCs

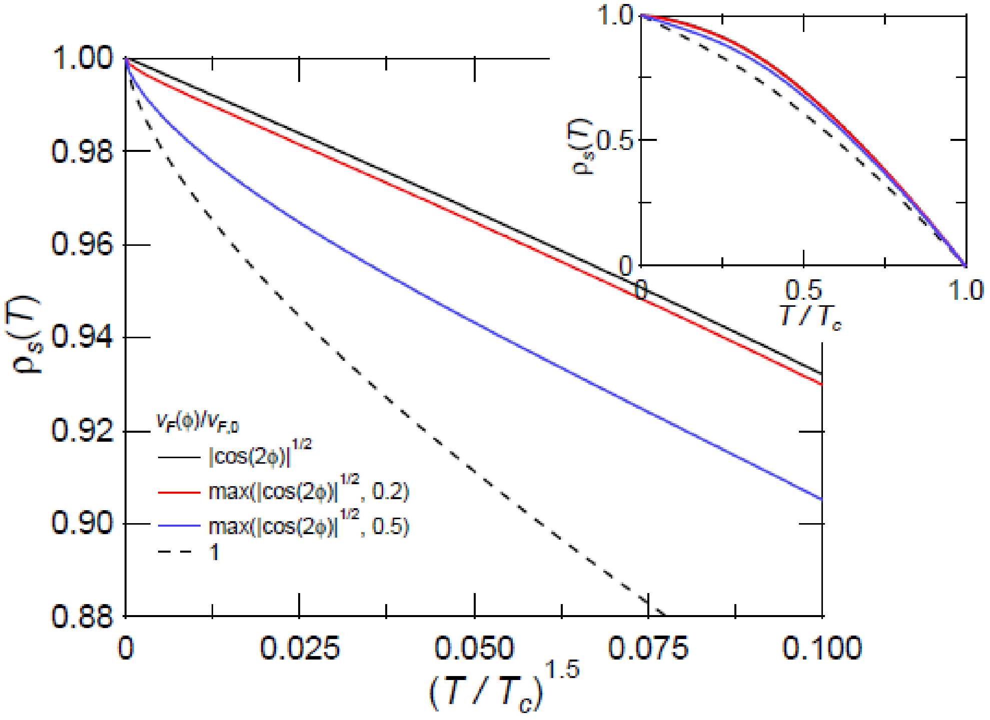
K. Hashimoto *et al*., PNAS (2013).



$$v_F(\boldsymbol{k}) \propto z_{\boldsymbol{k}} \propto 1/m^*(\boldsymbol{k}) \propto |\Delta(\boldsymbol{k})|^{\beta/2}$$

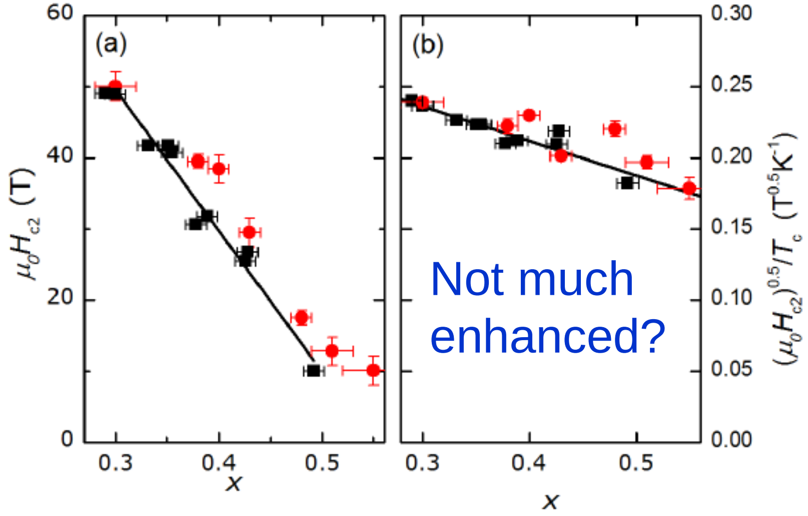
In nodal SCs, quantum criticality may appear in momentum space.





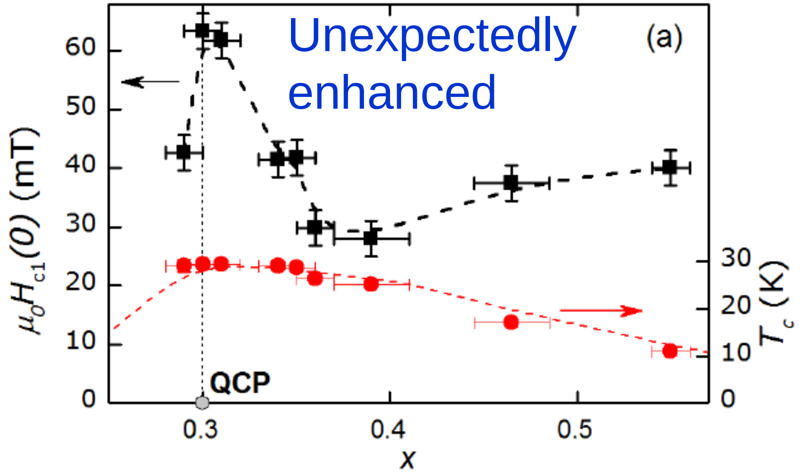
Anomalous critical fields in quantum critical SCs

$$H_{c2} = \frac{\phi_0}{2\pi\mu_0\xi_{GL}^2} \propto (\boxed{m^*}\Delta)^2$$



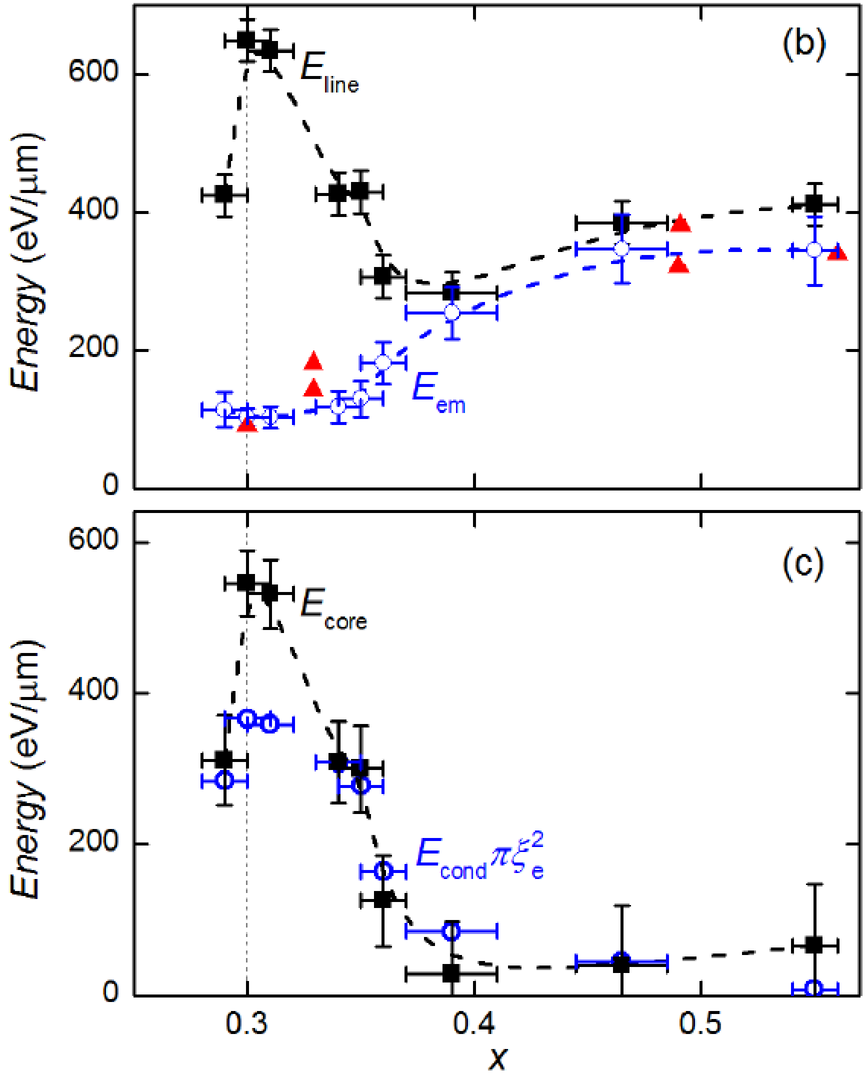
Not much enhanced?

$$H_{c1} = \frac{\phi_0}{4\pi\mu_0\boxed{\lambda^2}}\left(\ln(\kappa) + 0.5\right)$$
$$= (E_{em} + E_{core})/\phi_0$$



Unexpectedly enhanced

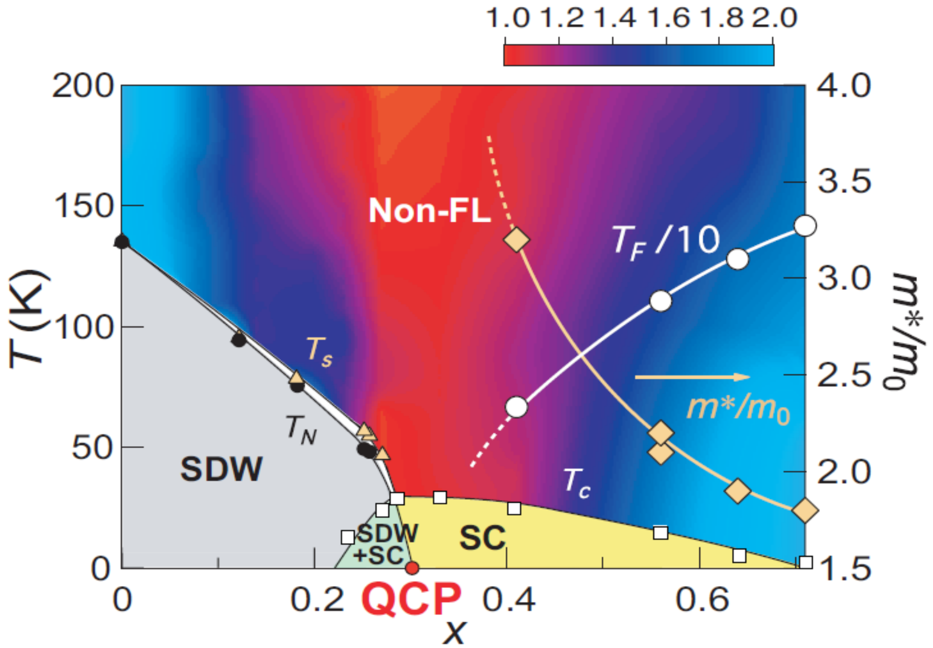
C. Putzke *et al.*, arXiv:1402.1323



Unusual vortices with enhanced core energy
Microscopic mixing of AFM and SC?

Summary: BaFe$_2$(As$_{1-x}$P$_x$)$_2$ A clean system to study the QCP

Quantum critical point

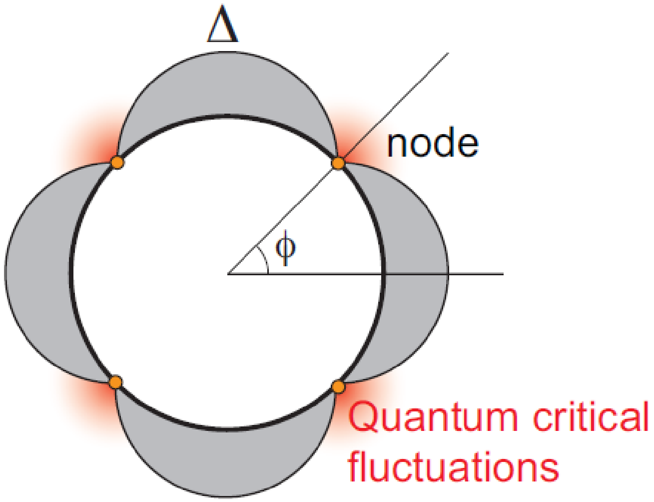


Several anomalies in the normal state
A sharp peak in penetration depth at T=0

A QCP lurking inside
the superconducting dome

T. Shibauchi, A. Carrington, and Y. Matsuda,
Annu. Rev. Condens. Matter Phys. **5**, 113 (2014).

Anomalous SC properties near the QCP



Possible nodal quantum criticality and unusual vortex state due to microscopic mixing of AFM and SC

K. Hashimoto *et al*., PNAS **110**, 3293 (2013).

C. Putzke *et al*., arXiv:1402.1323