The Abdus Salam
International Centre
for Theoretical Physics

2357-8

Innovations in Strongly Correlated Electronic Systems: School and Workshop

6 - 17 August 2012

Nematic transition and antiferromagnetic quantum critical point in BaFe2(As1-xPx)2

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JAPAN

Nematic transition and antiferromagnetic quantum critical point in $BaFe_2(As_{1-x}P_x)_2$

Taka Shibauchi
Department of Physics, Kyoto University

1. Quantum phase transition lurking inside the superconducting dome

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

2. Nematic transition above the dome

S. Kasahara *et al*., Nature **486**, 382 (2012).

3. Summary – A renewed phase diagram

Collaborators

Transport properties
Penetration depth
Thermal conductivity
dHvA
Magnetic torque
Crystal growth

S. Kasahara
K. Hashimoto
Y. Mizumami
H. Shishido
T. Terashima
Y. Matsuda

Band calc.

H. Ikeda

NMR

T. Iye
K. Ishida

Kyoto Univ. Japan

Penetration depth, dHvA

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

Synchrotron X-ray

K. Sugimoto

SPring-8,

T. Fukuda

JAEA, SPring-8, Japan

Theory (Nematic)

A. Nevidomskyy

Rice Univ. , USA

Ce_2PdIn_8 crystals

D. Gnida
D. Kaczorowski

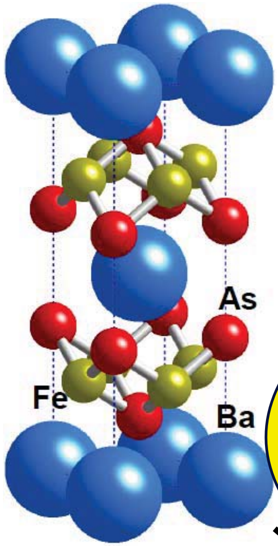
Polish Academy of Sciences, Poland

Superconductivity in $BaFe_2As_2$ systems

Mother compound

$BaFe_2As_2$

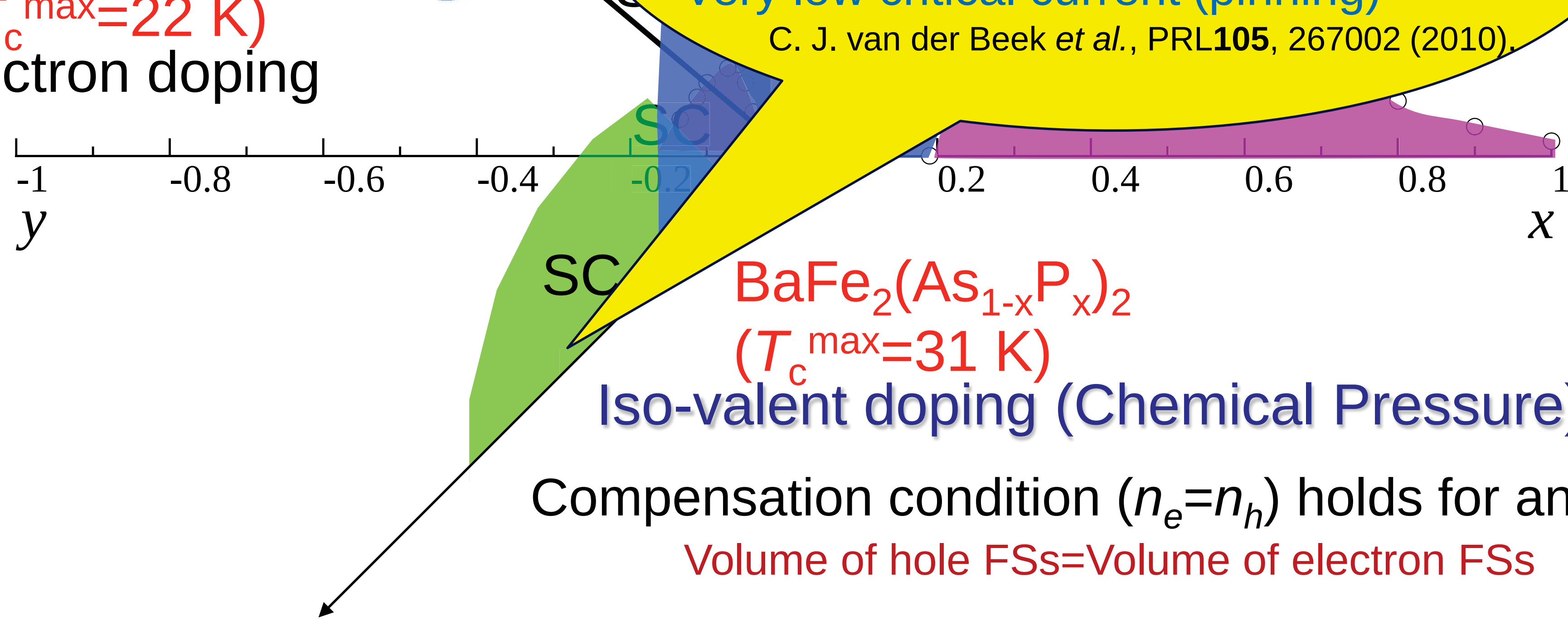
(AF Metal)



$Ba(Fe_{1-y}Co_y)_2As_2$

(T_c^{max}=22 K)

electron doping



Very clean and homogeneous

Quantum oscillations in a wide range of *x*

H. Shishido *et al*., PRL **104**, 057008 (2010).

B. J. Arnold *et al*., PRB **83**, 220504(R) (2011).

Very low critical current (pinning)

C. J. van der Beek *et al*., PRL**105**, 267002 (2010).

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

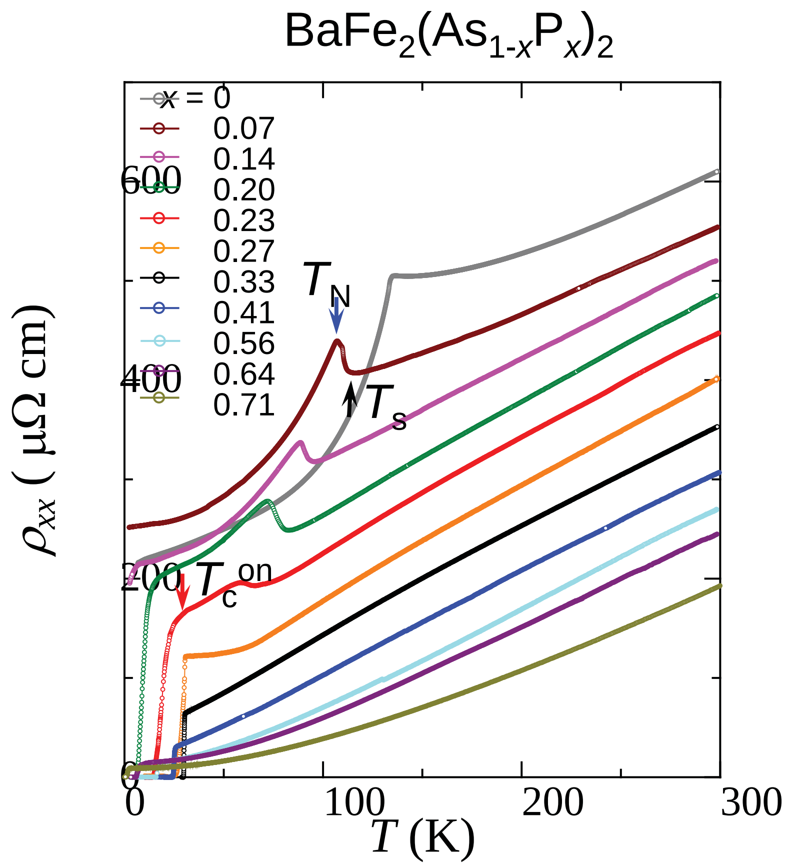
(T_c^{max}=31 K)

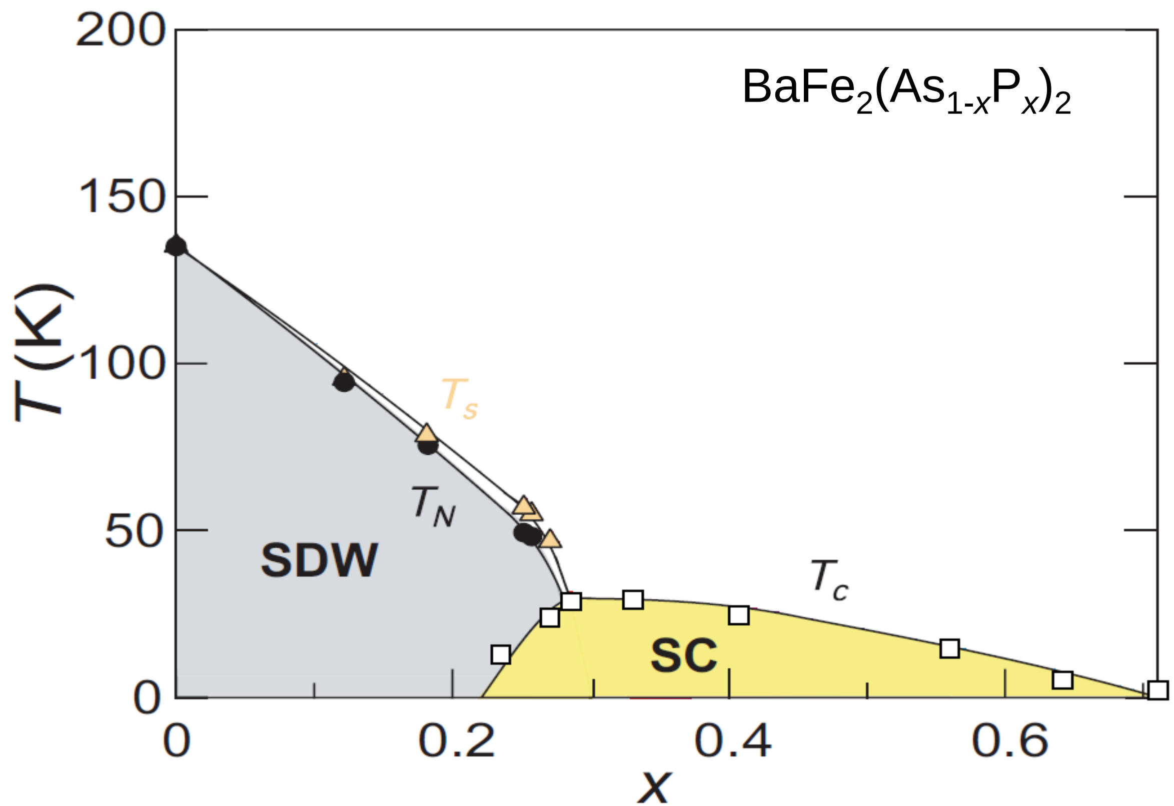
Iso-valent doping (Chemical Pressure)

Compensation condition (n_e=n_h) holds for any *x*.

Volume of hole FSs=Volume of electron FSs

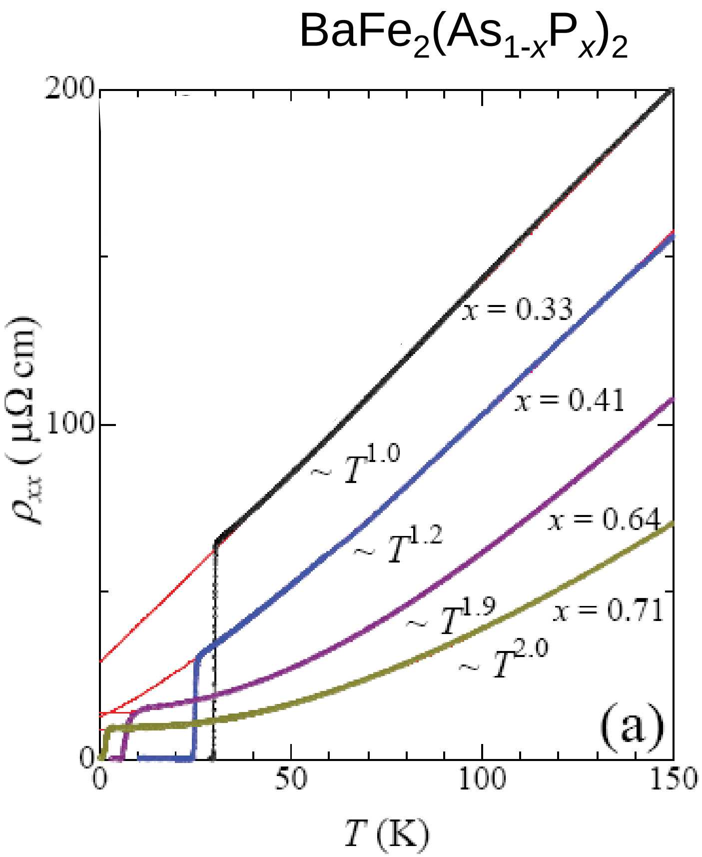
$BaFe_2(As_{1-x}P_x)_2$ is a clean system to study intrinsic properties

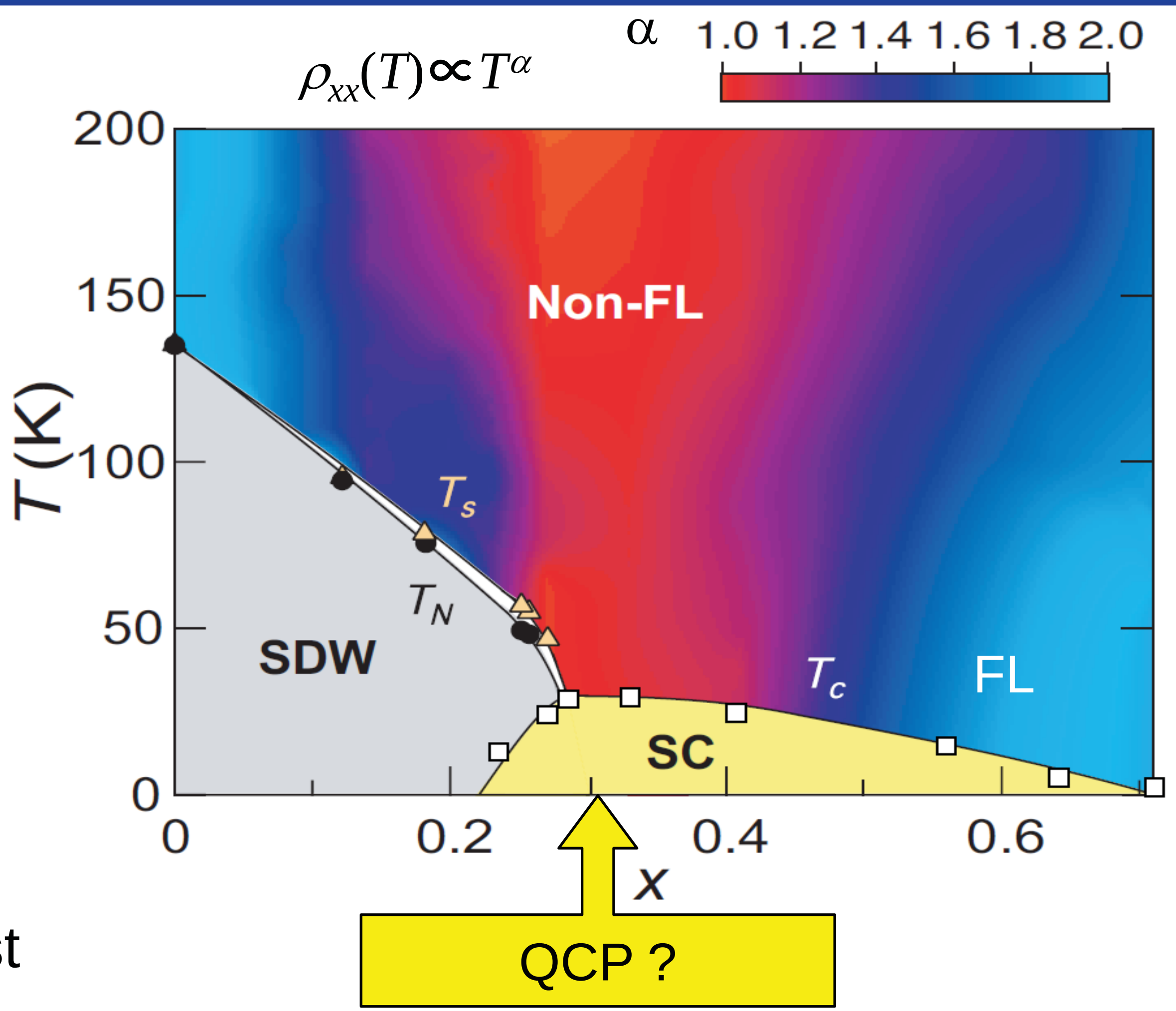




S. Kasahara, TS *et al*., PRB **81**, 184519 (2010).

Doping evolution of transport properties





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

Hallmark of non-Fermi liquid

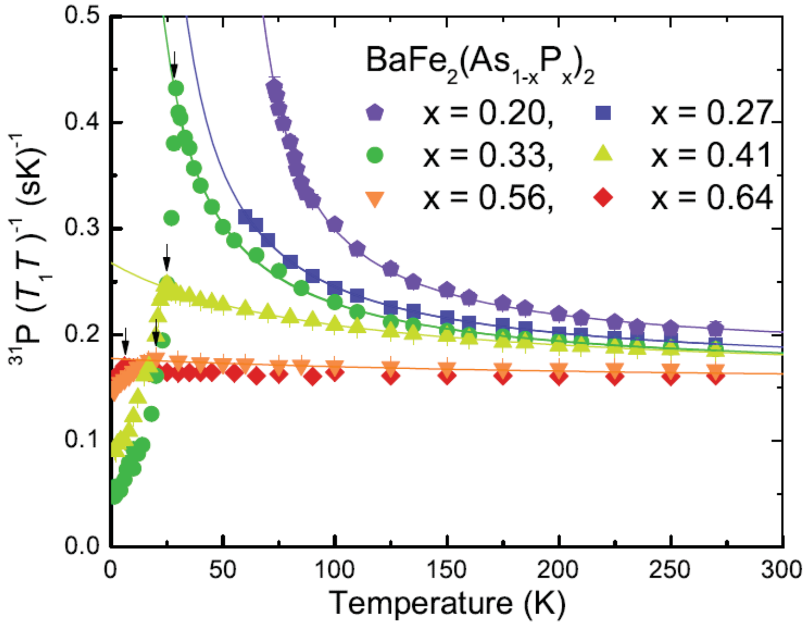
T^2-dependence at x=0.71

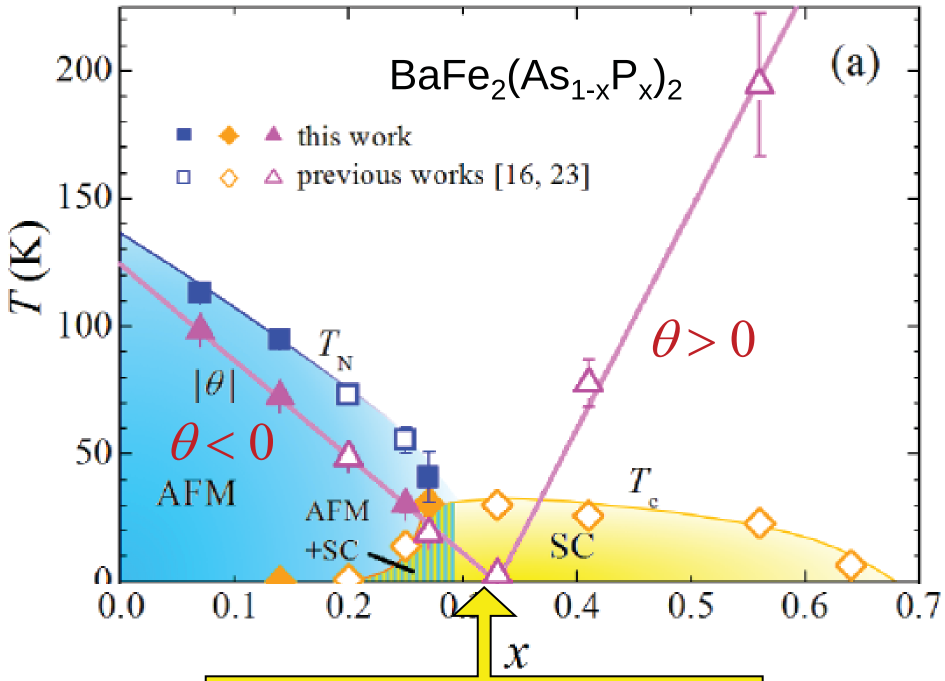
Fermi-liquid behavior

S. Kasahara, TS *et al*., PRB **81**, 184519 (2010).

See also J. Dai *et al*., PNAS (2009);
S. Sachdev and B. Keimer, Physics Today (2011).

Doping evolution of the magnetic fluctuations (NMR)





AF-QCP ?

$$\frac{1}{T_1T} = a + \frac{b}{T+\theta}$$

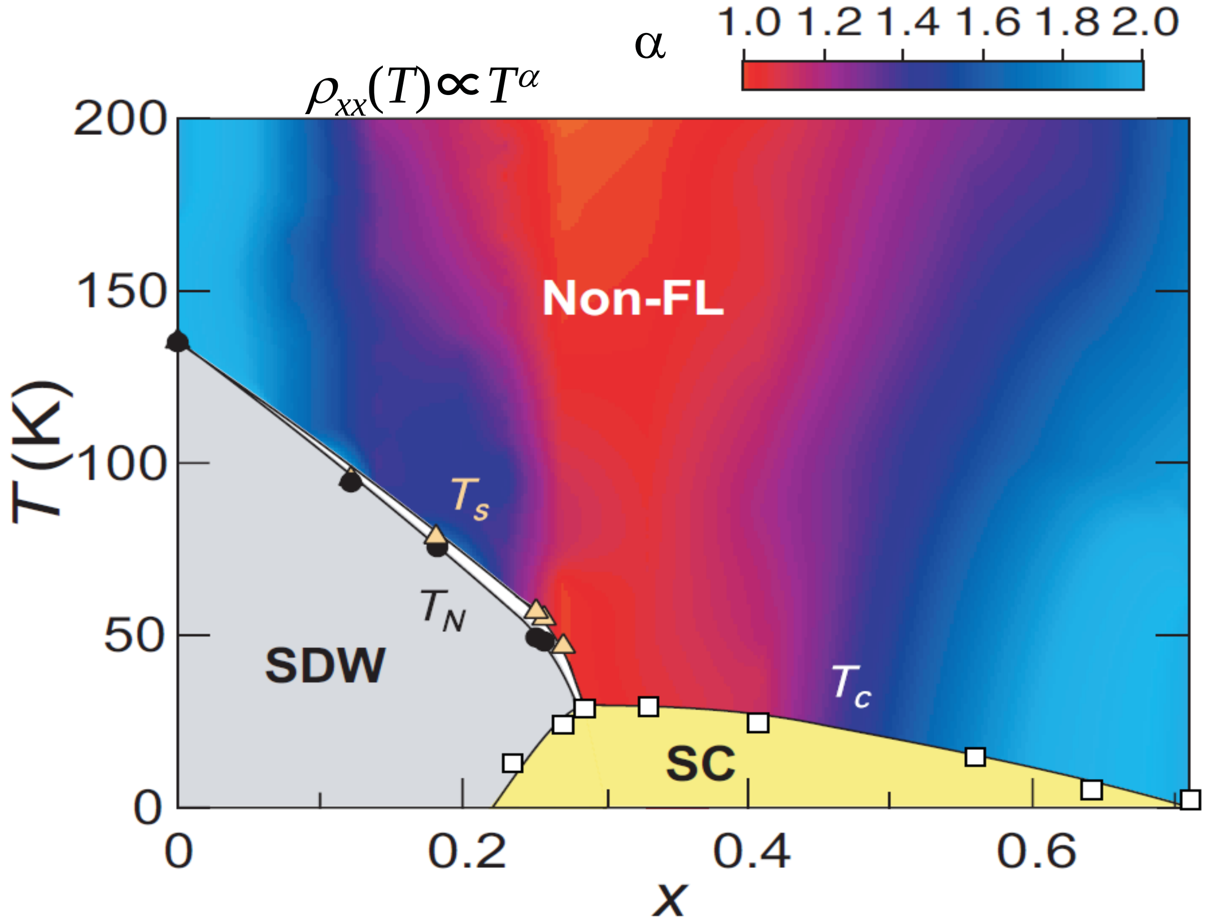
θ: Weiss temperature

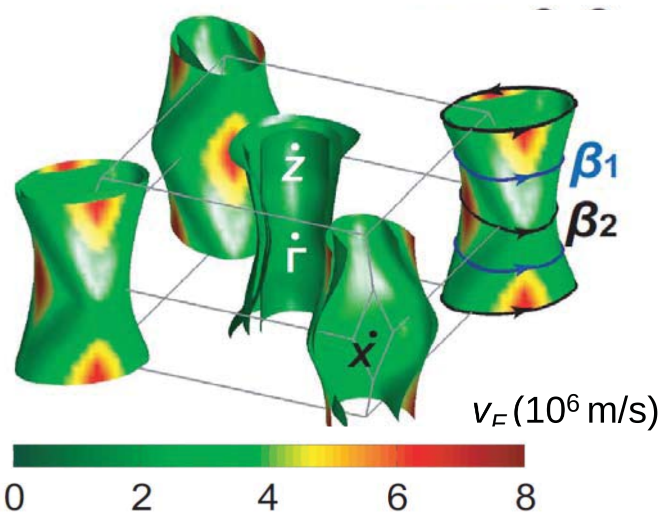
Y. Nakai *et al*. PRL (2010); T. Iye *et al*. PRB (2012)

θ goes to zero at x~0.3

<m> goes to zero at x~0.3

Doping evolution of electronic properties above T_c





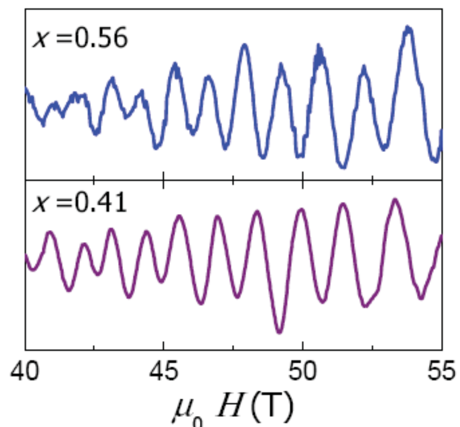
m^*

Effective mass

Fermi temperature

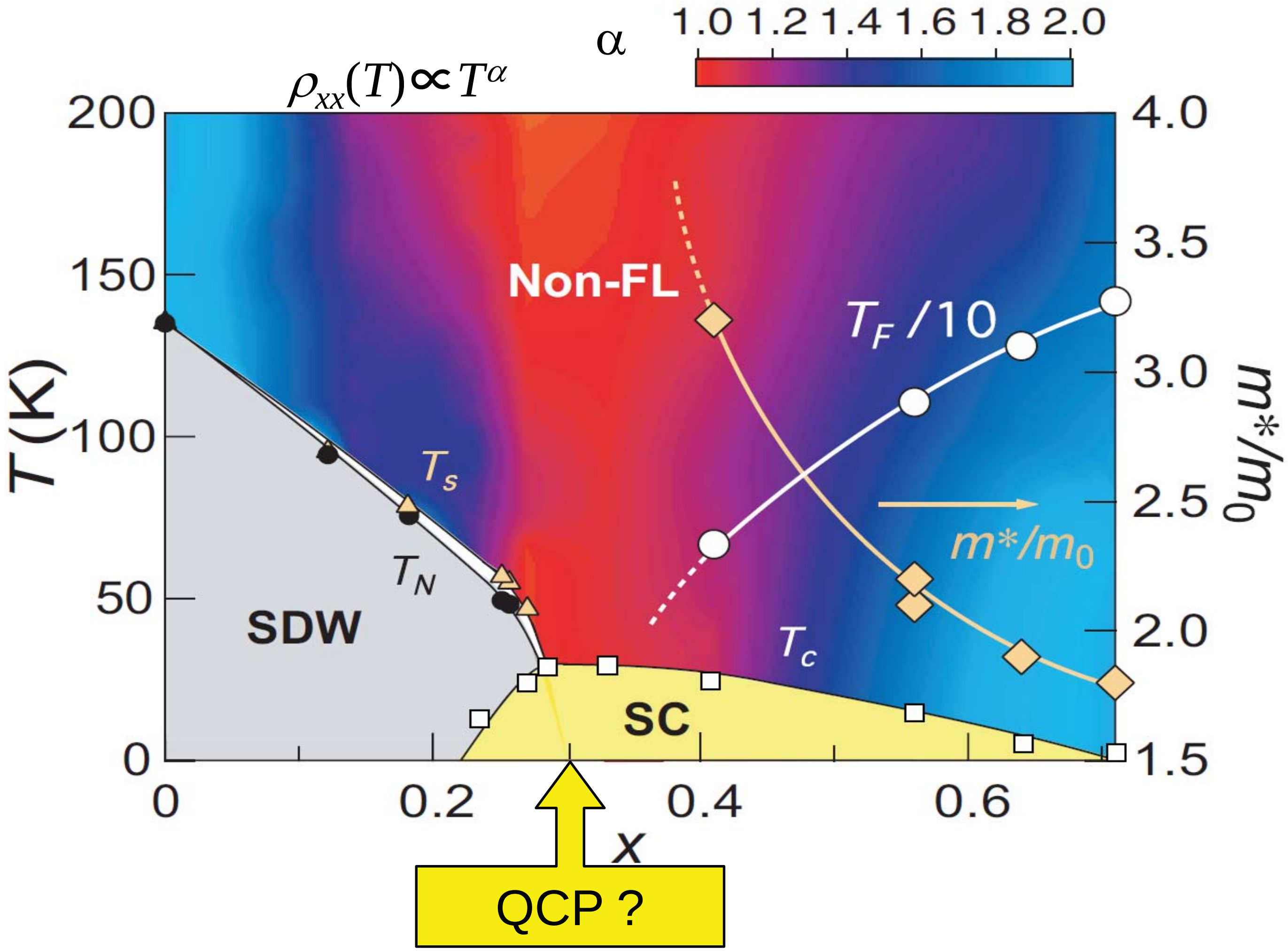
$$T_F = \hbar e F / m^* k_B$$

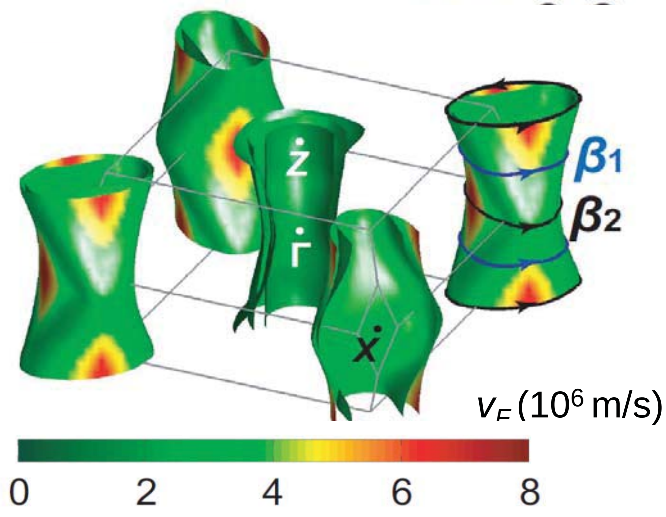
dHvA



H.Shishido *et al*. PRL (2009).

Doping evolution of electronic properties above T_c





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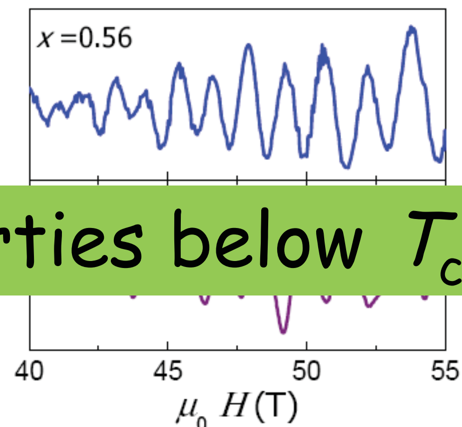
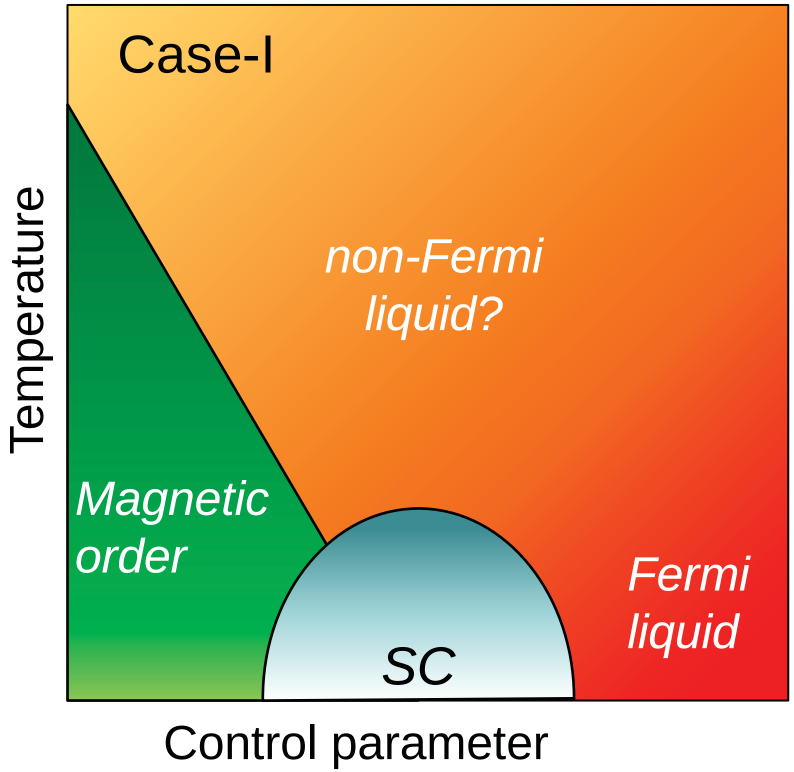


How does the QCP affects the SC properties below T_c?

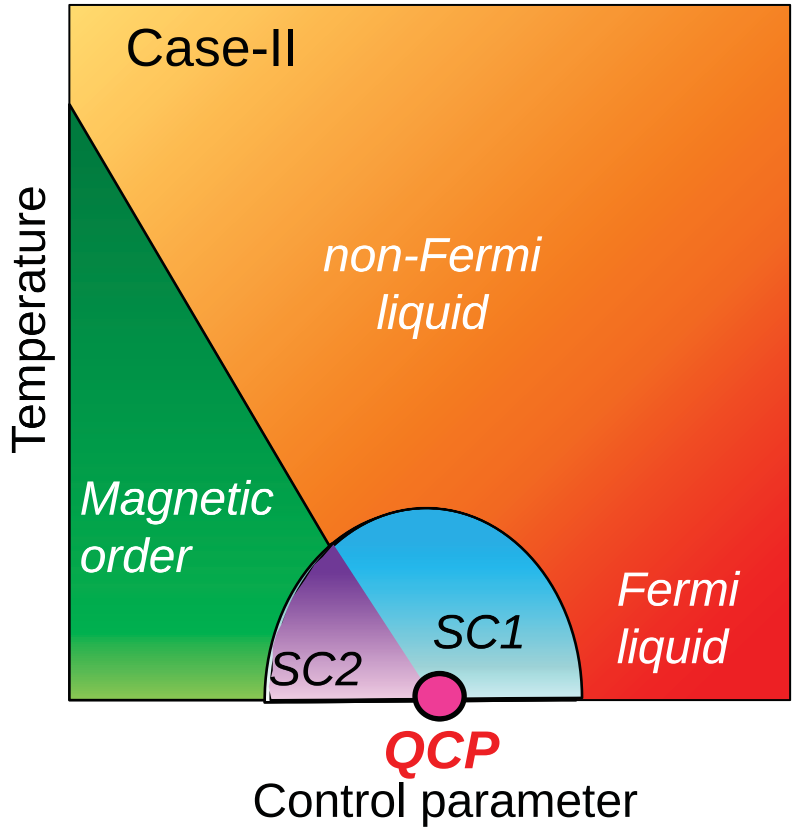
Fermi temperature $T_F = heF/m^*k_B$ tends to zero

H.Shishido *et al*. PRL (2009).

Does a QCP lie beneath the SC dome?



Criticality avoided by the transition to the SC state



QCP lying beneath the SC dome

A quantum phase transition inside the dome

⇓

Two different SC phases.

Superfluid density as a probe of QCP inside the SC dome

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

mass of superconducting electrons

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

density of superconducting electrons

1. Tunnel diode oscillator (13MHz, 70 mK)

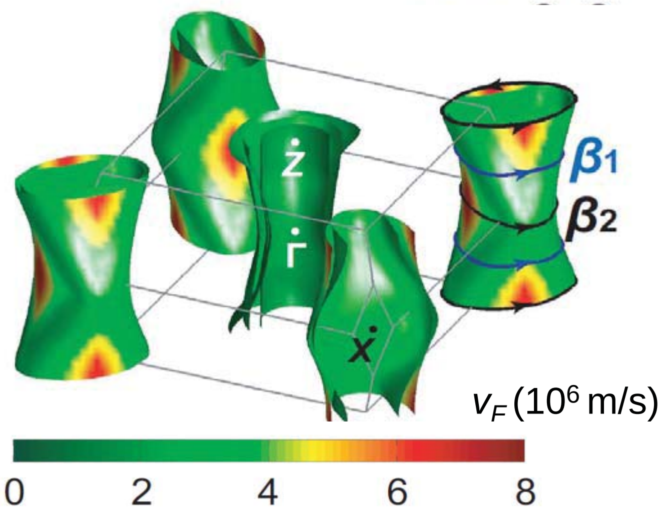
   Al coated method

2. Microwave surface impedance

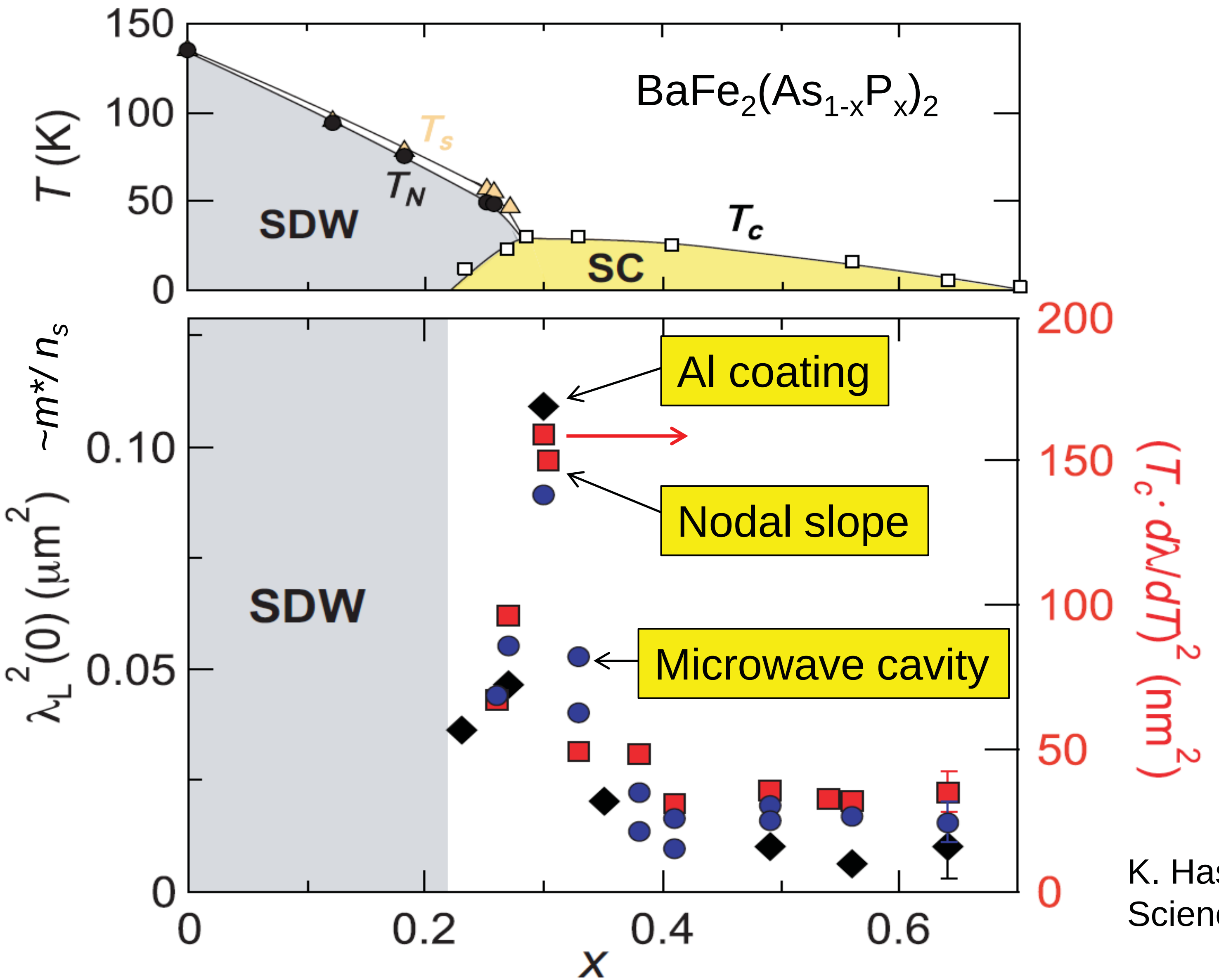
   Rutile cavity resonator (5 GHz, Q~10^6)

3. Nodal superconducting gap structure

   Slope of the *T*-dependence $\frac{\delta\lambda_L(T)}{\lambda_L(0)} \approx \frac{\ln 2}{\Delta} k_B T$



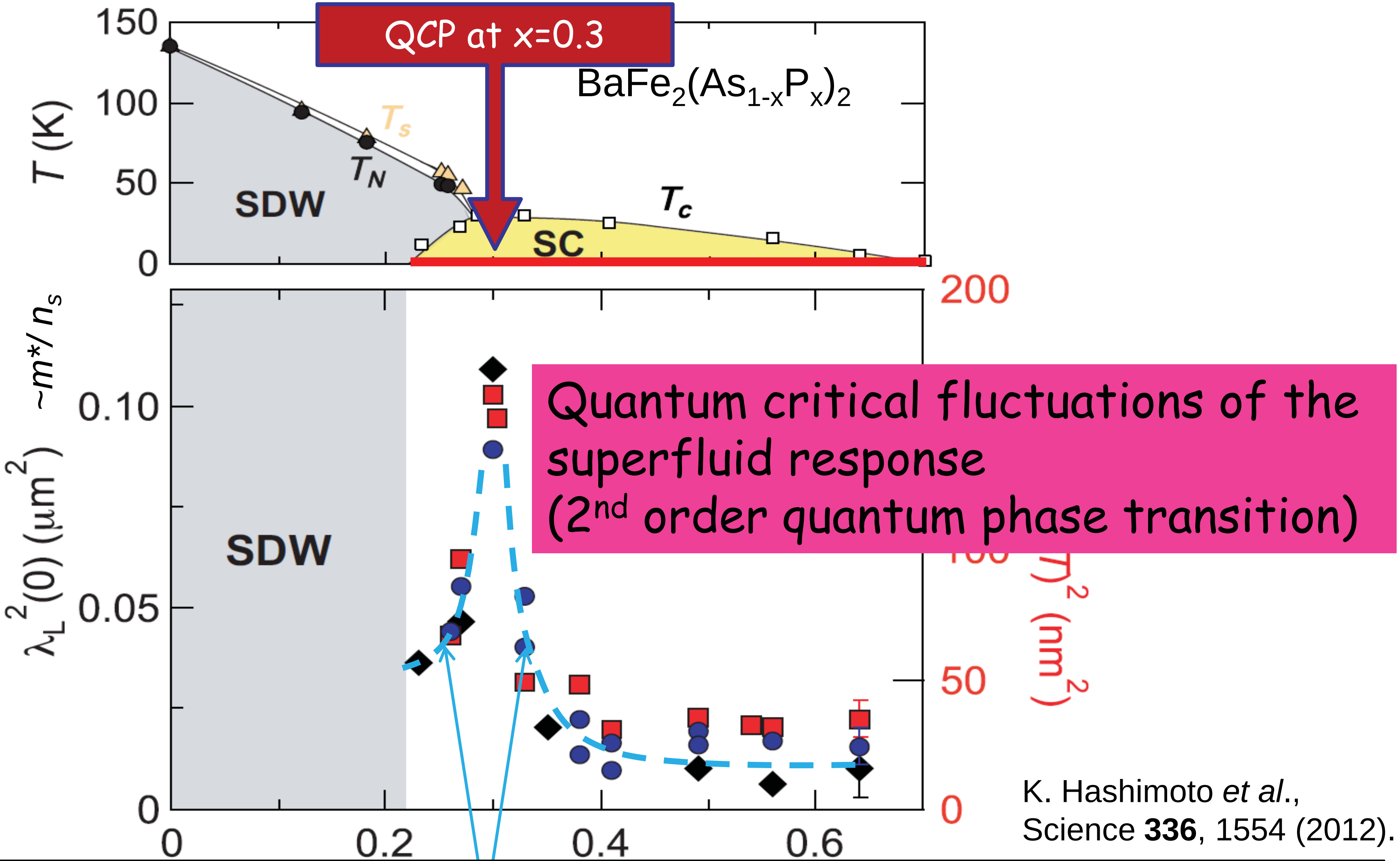
Doping evolution of the London penetration depth at T=0



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

All three methods give very similar x-dependence of $\lambda(0)$.

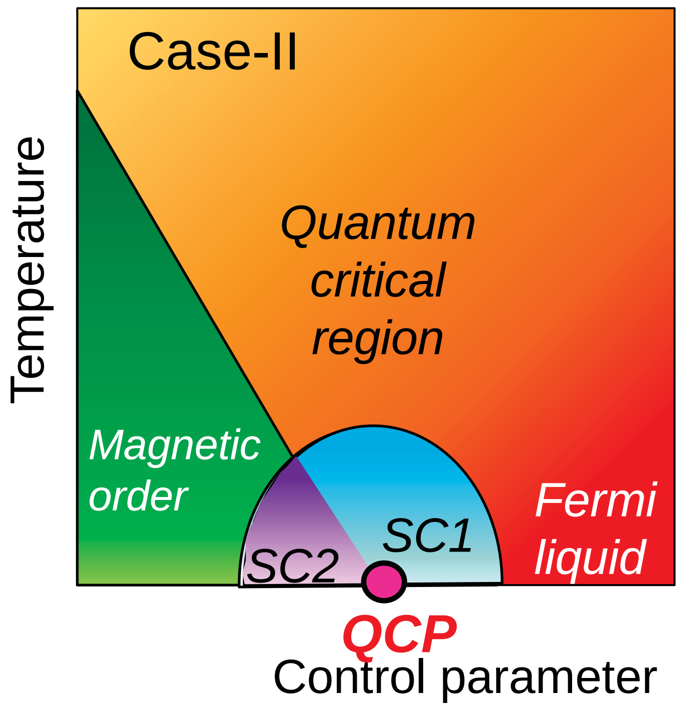
Doping evolution of the London penetration depth at T=0

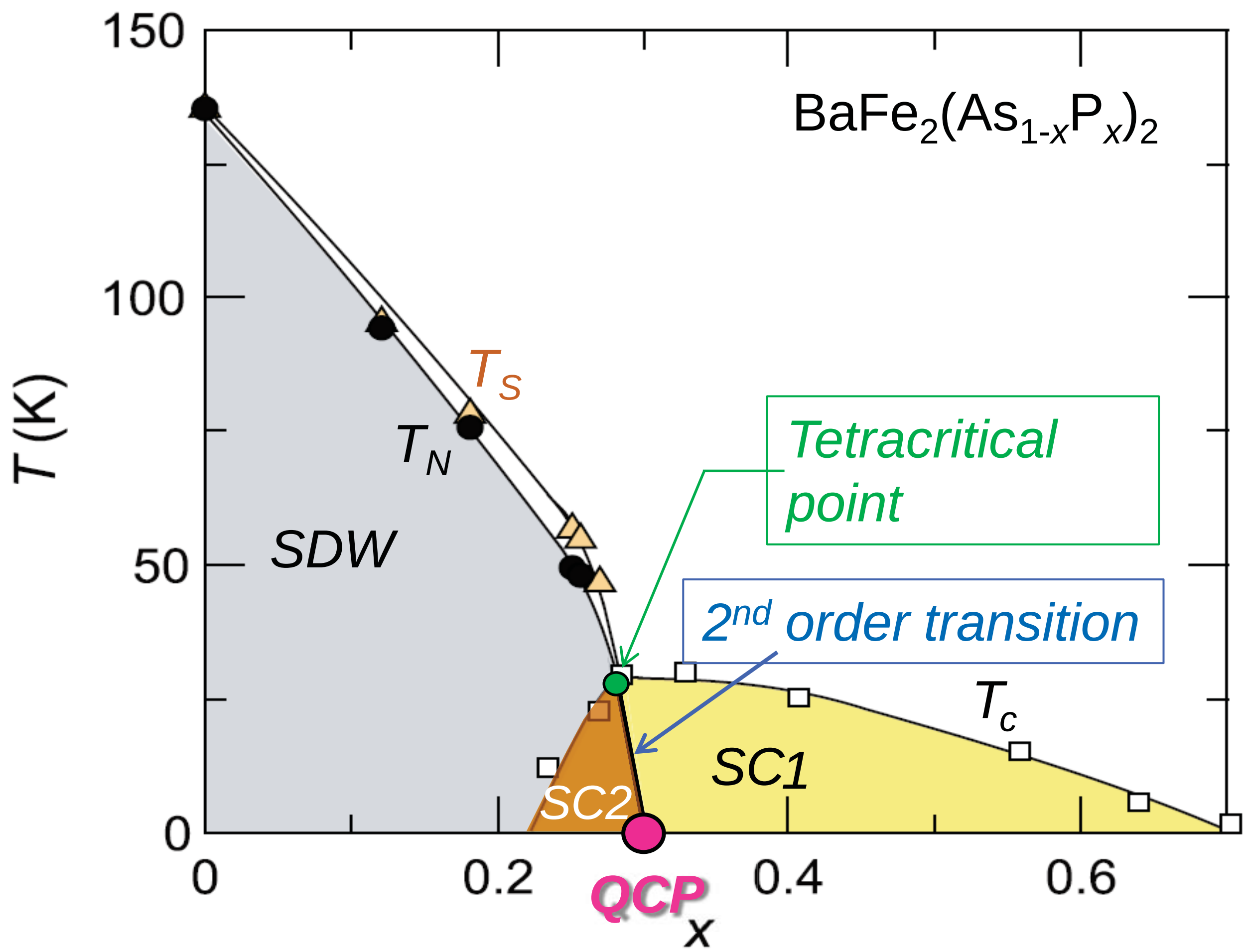


K. Hashimoto *et al*., Science **336**, 1554 (2012).

Striking enhancement of $\lambda_L^2(0)$ on approaching x=0.3 from *either* side.
The data represents the behavior at the zero temperature limit.

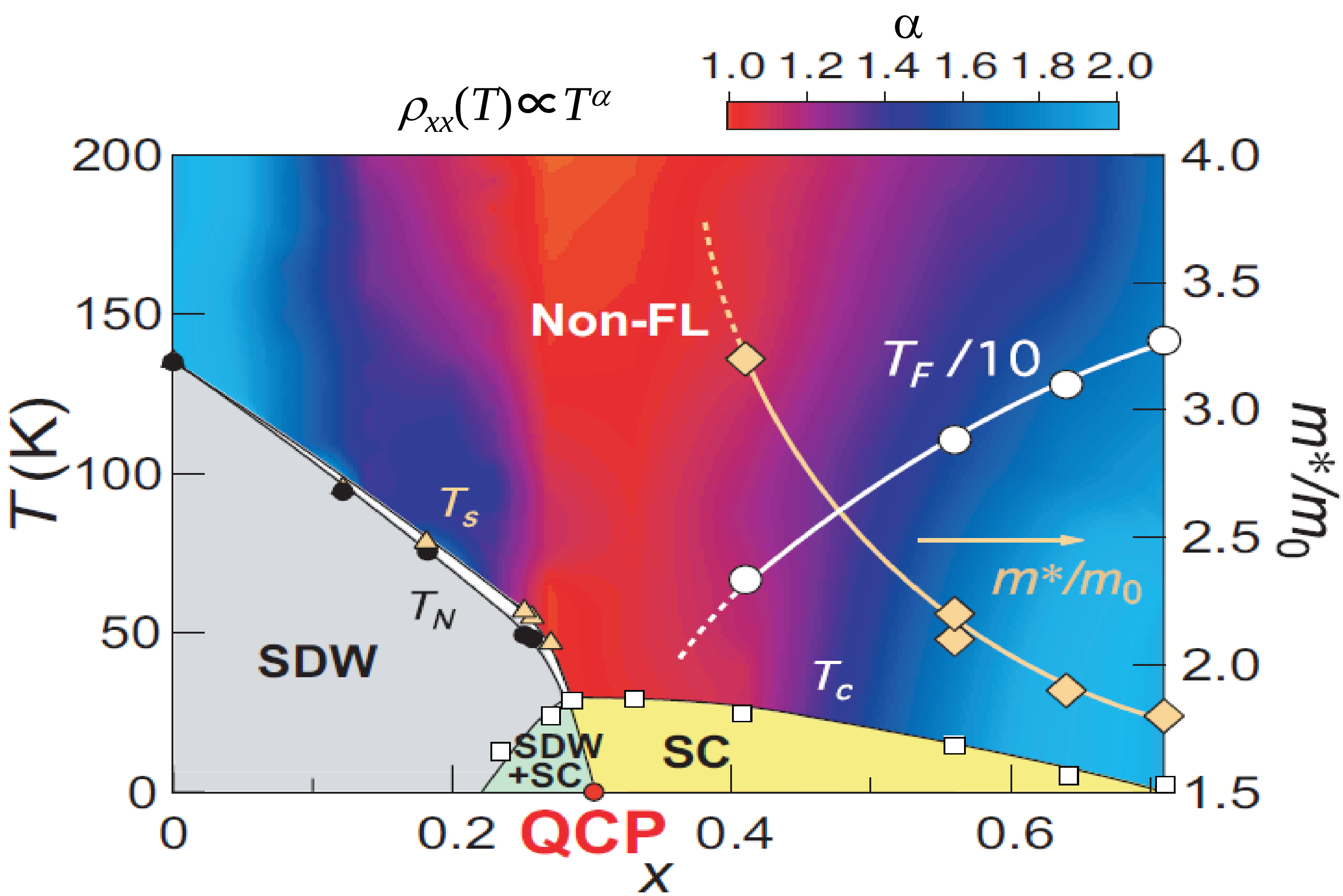
QCP at x=0.3





Two distinct SC phases

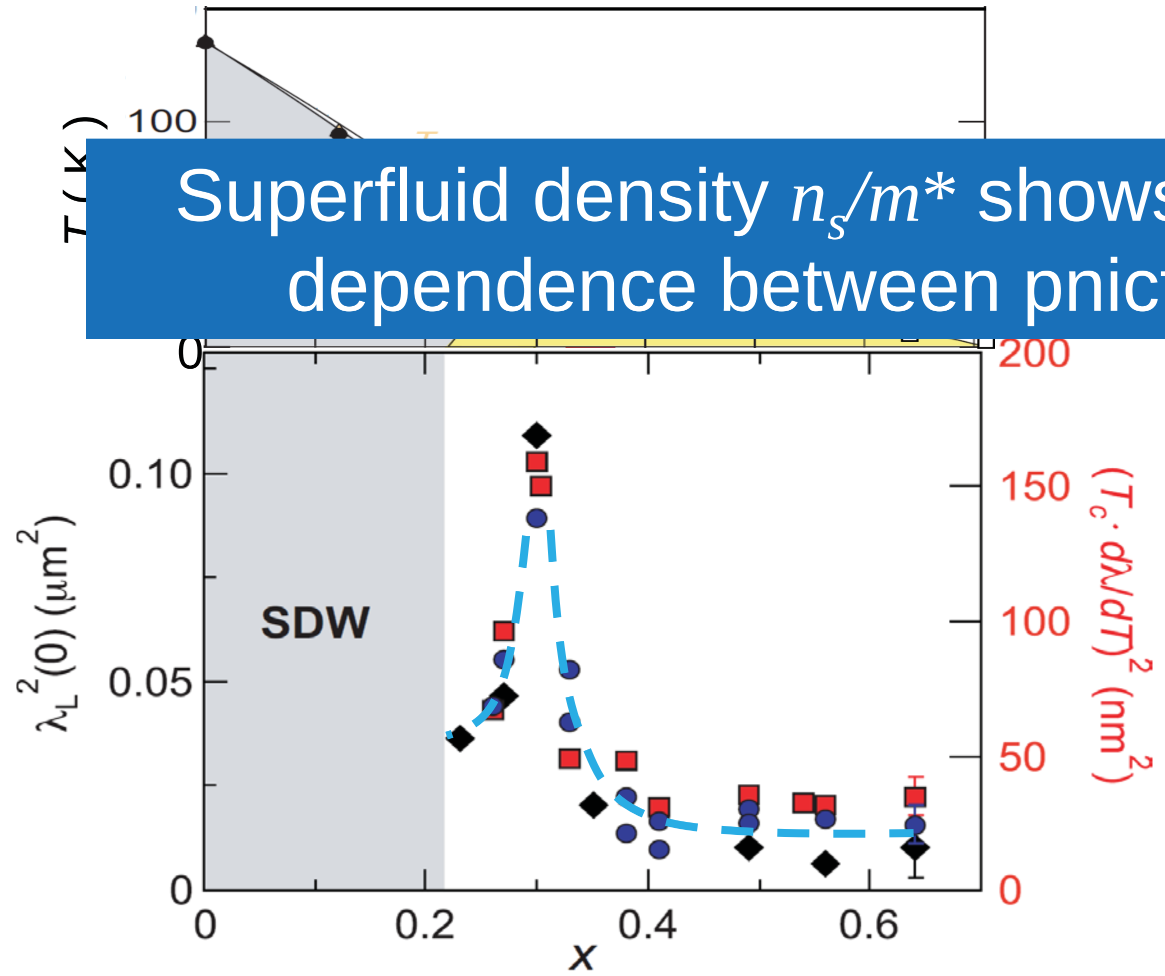
QCP at x=0.3



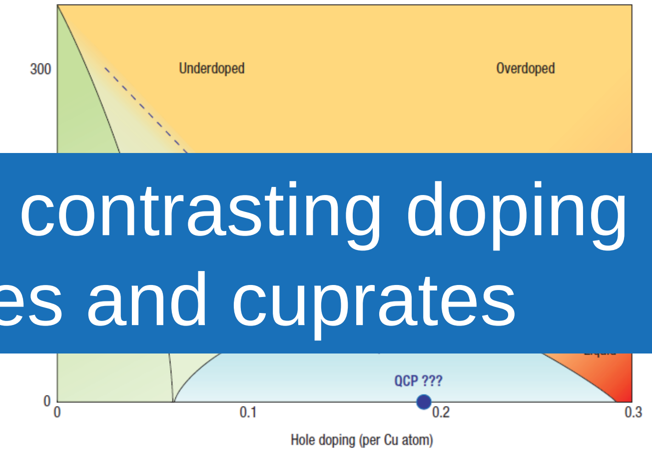
The mass enhancement, reduction of Fermi temperature and non-Fermi liquid behavior, all are associated with the finite-temperature quantum critical region linked to the QCP.

Doping evolution of the London penetration depth at T=0

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



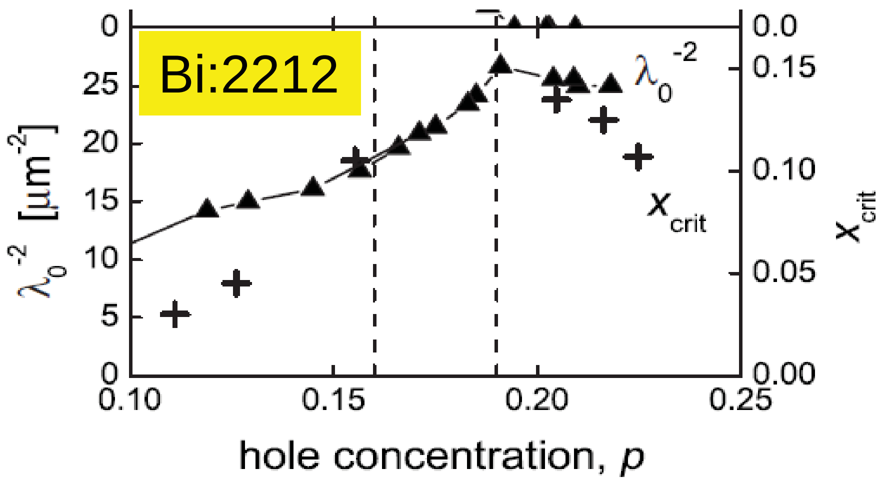
High-T_c cuprates



D.M. Broun, Nature Phys. (2008).

Superfluid density n_s/m^* shows a contrasting doping dependence between pnictides and cuprates

Bi:2212

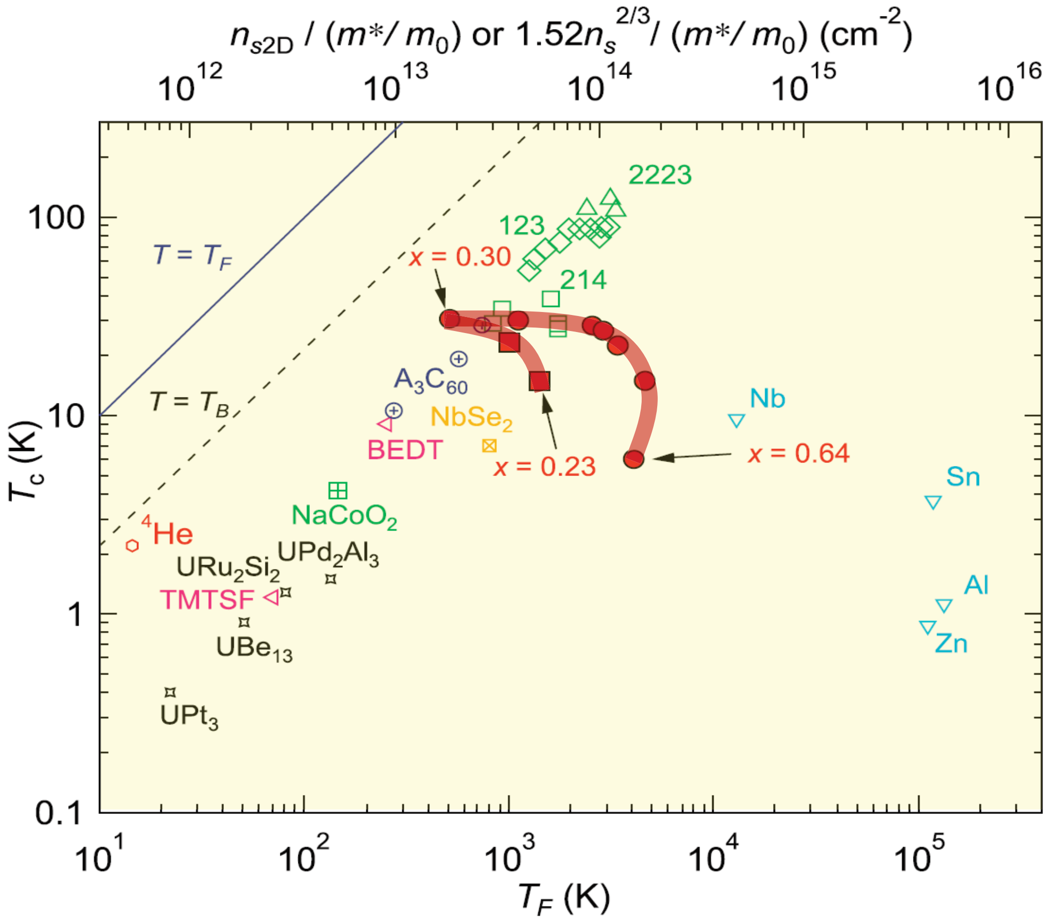


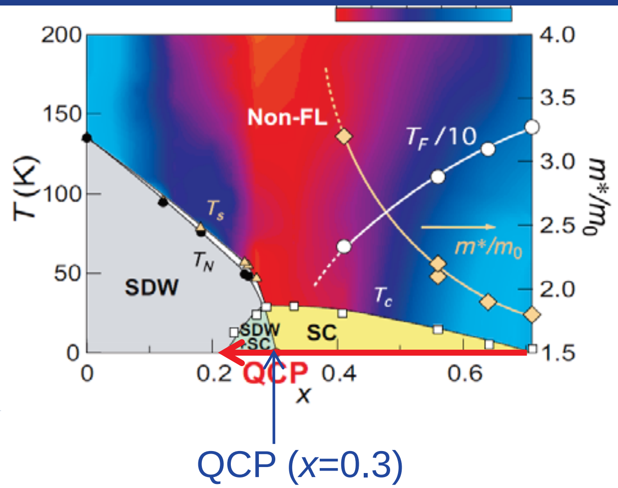
J. G. Storey *et al.*, PRB (2007).

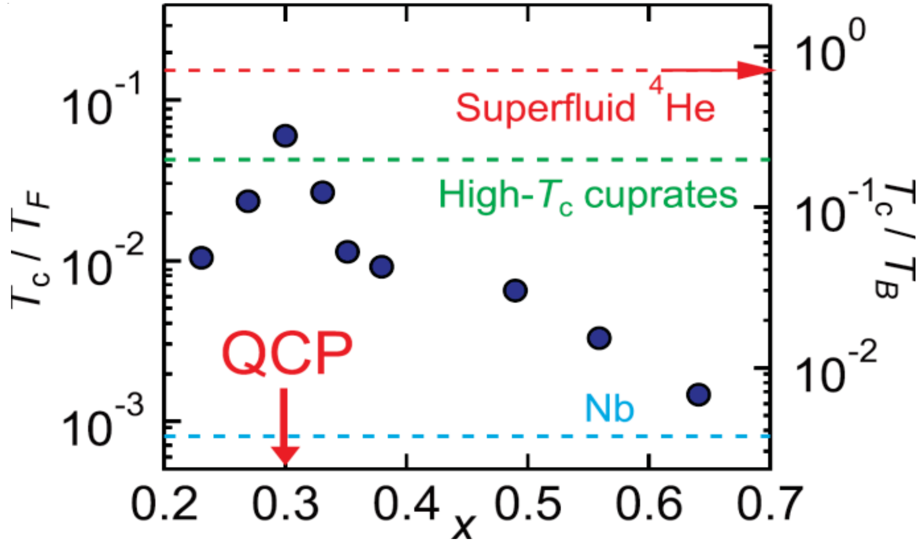
Bi:2212 : broad maximum in $1/\lambda_L^2(0)$ (enhancement of n_s/m^*) at p~0.19

$BaFe_2(As_{1-x}P_x)_2$: sharp peak in $\lambda_L^2(0)$ (suppression of n_s/m^*) at x=0.3

Doping evolution of the superfluid density (Uemura plot)







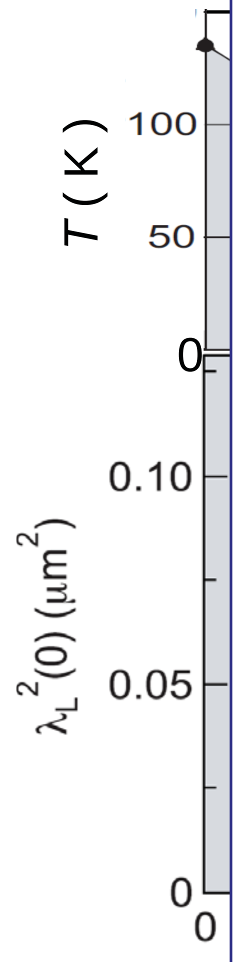
The strongest pairing interaction at the QCP.

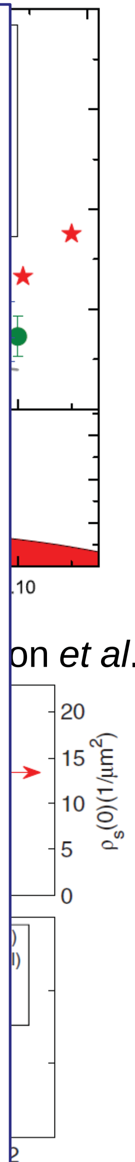
High-T_c SC may be driven by the QCP

Comparison with P-doped and Co-doped systems

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

$Ba(Fe_{1-x}Co_x)_2As_2$





...on *et al*. PRB (2010)

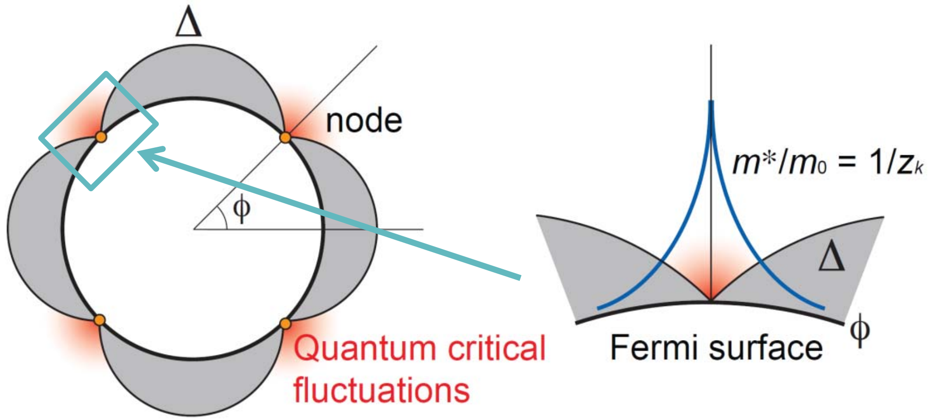
...an *et al.* PRL (2011)

1. Clean (homogeneous) vs Dirty (inhomogeneous)

SC gap map | STM | SC gap map

F. Massee, Ph.D thesis, Amsterdam

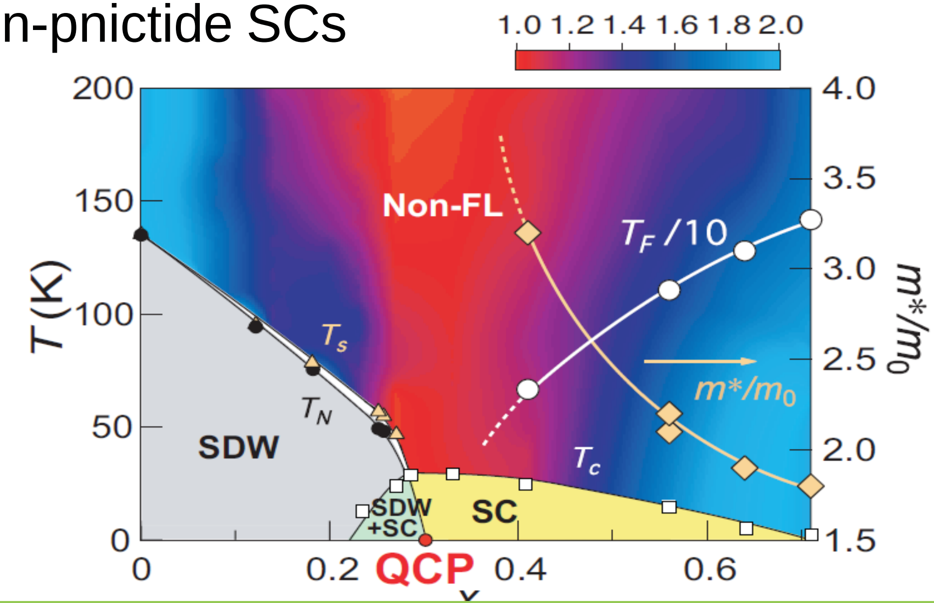
2. Nodal vs Nodeless



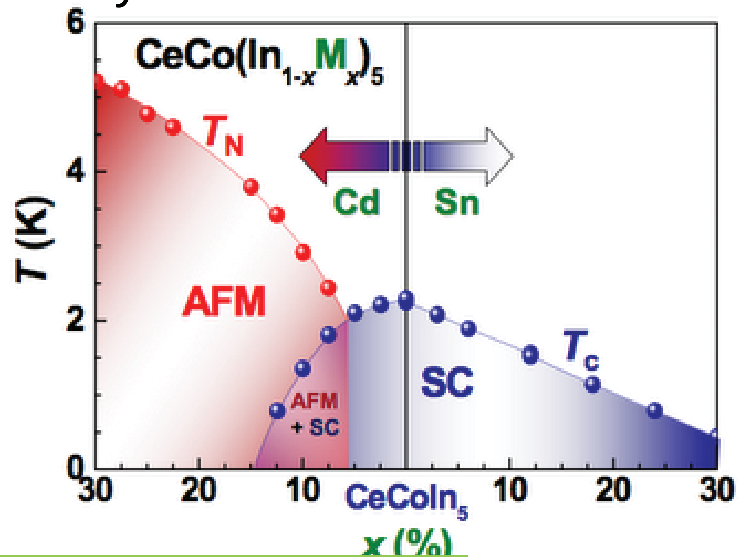
Critical ...
been re...

Nodal superconductors in the vicinity of AFM

Iron-pnictide SCs

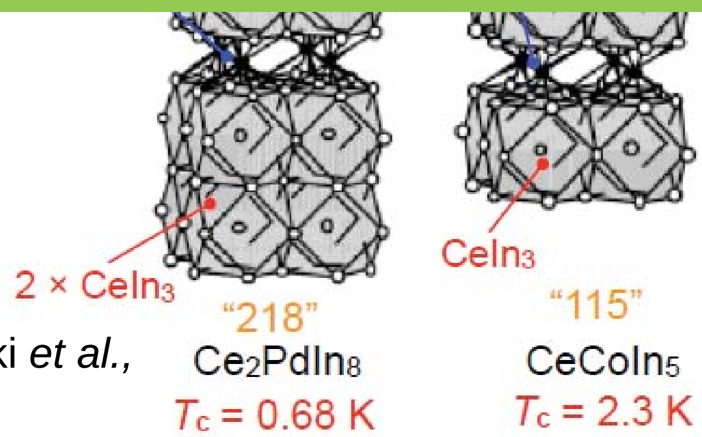


Heavy-Fermion SCs

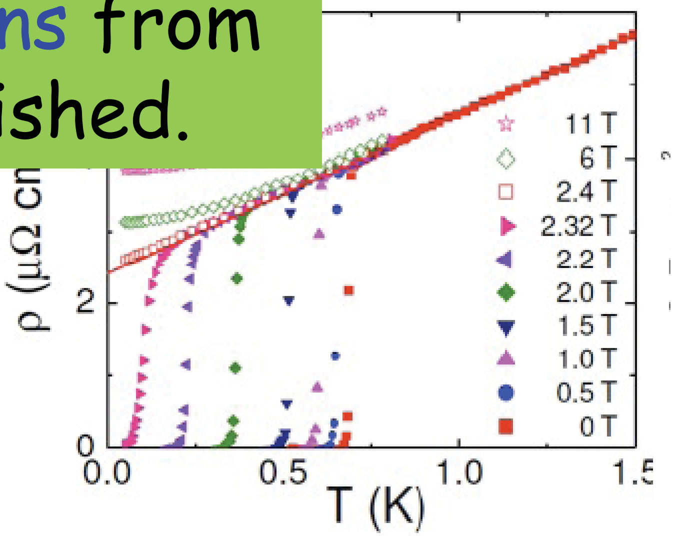


The effect of quantum fluctuations on the low-energy quasiparticle excitations from the SC ground state is not well established.

…ors with nodes



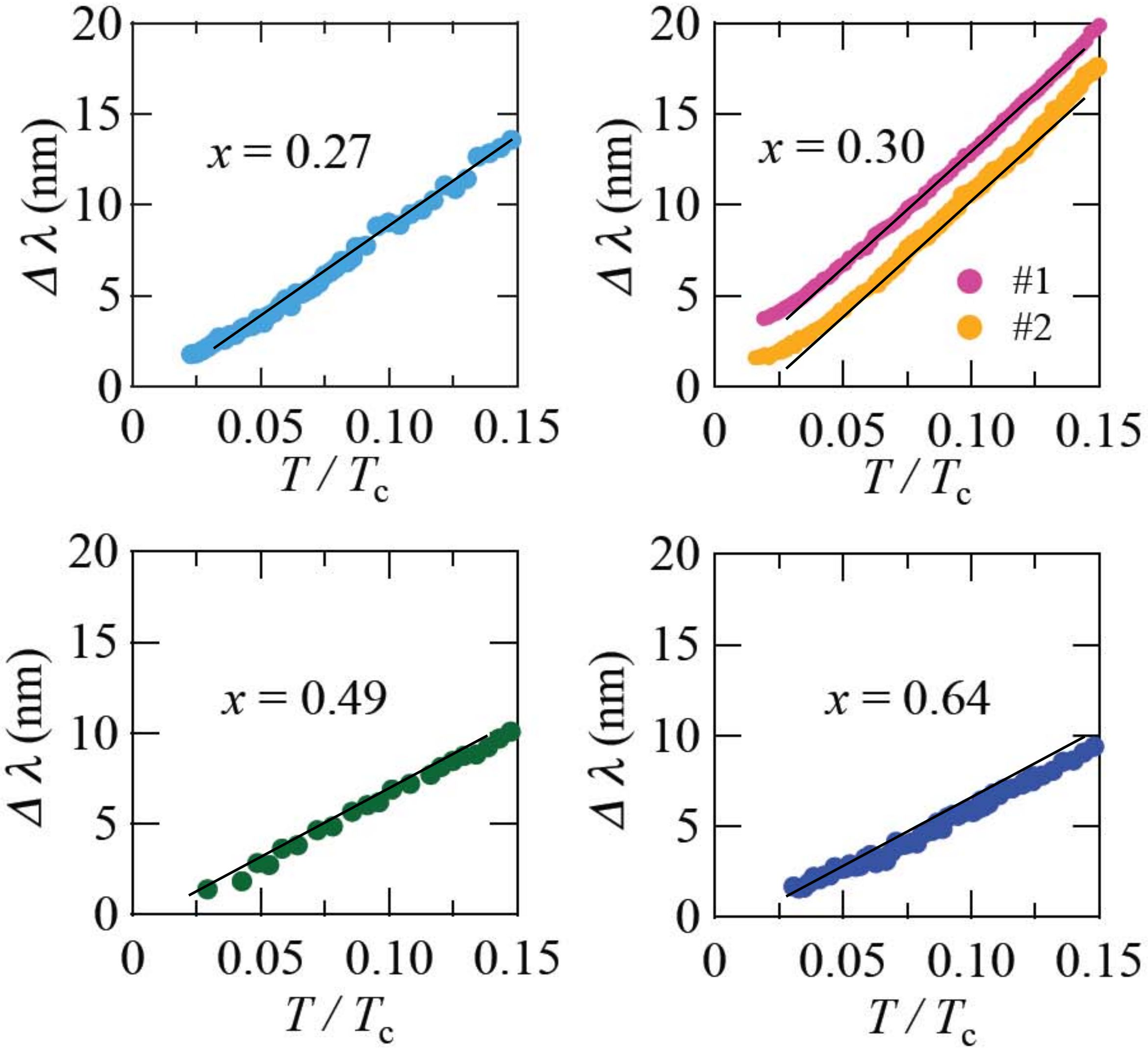
D. Kaczorowski *et al.*, PRL (2009).

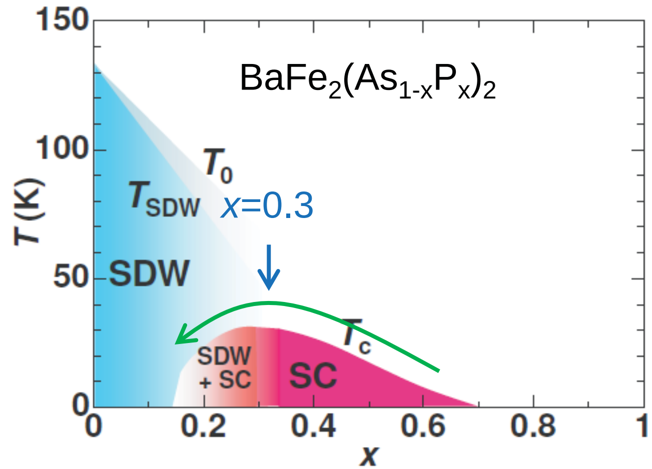


J. K. Dong *et al.*, PRX **1**, 011010 (2011).

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

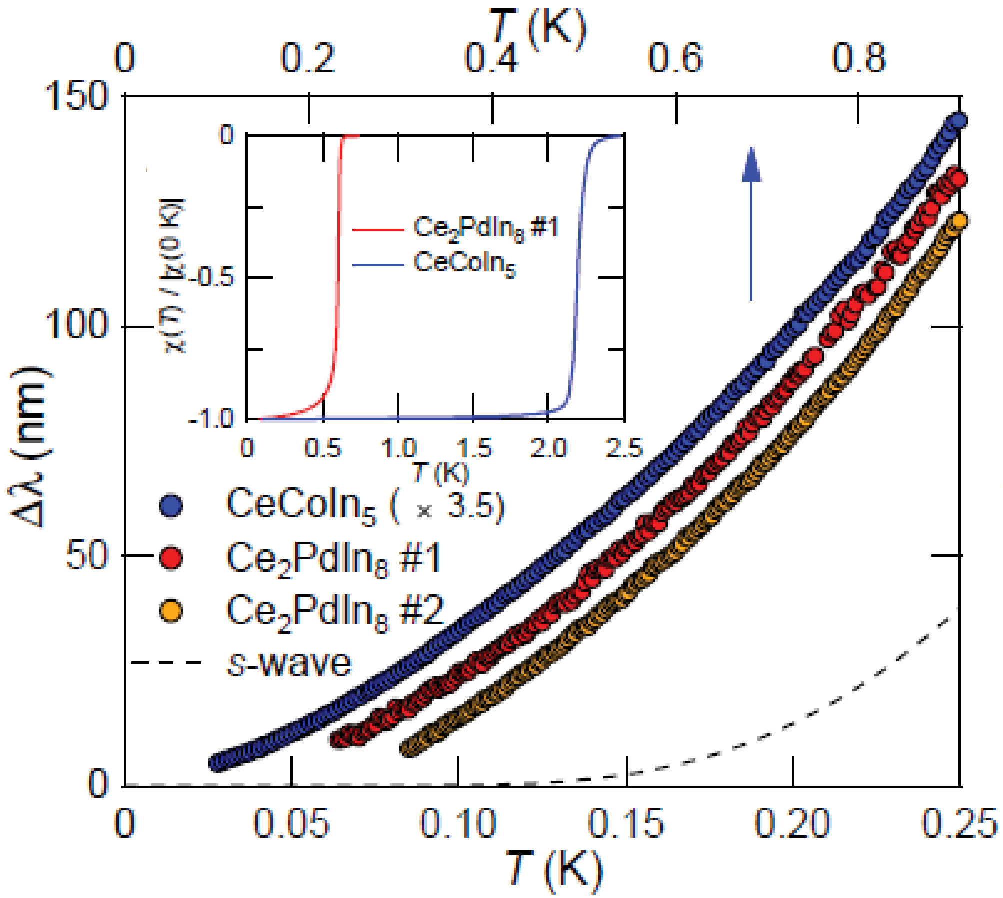
Robust line nodes over a wide range of *x*.

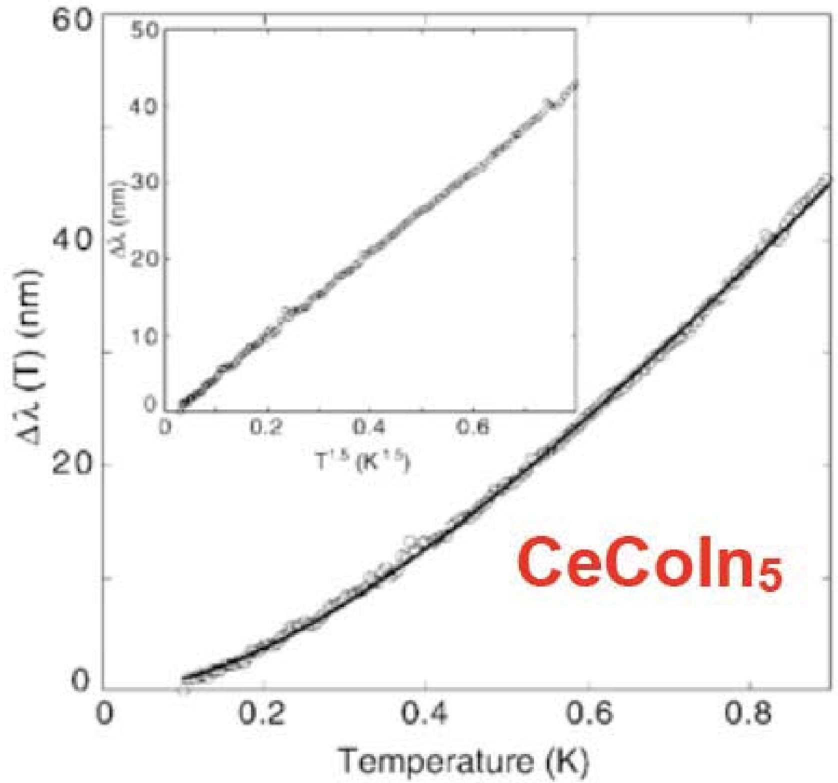




Deviations from the *T*-linear dependence near *x*=0.3

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



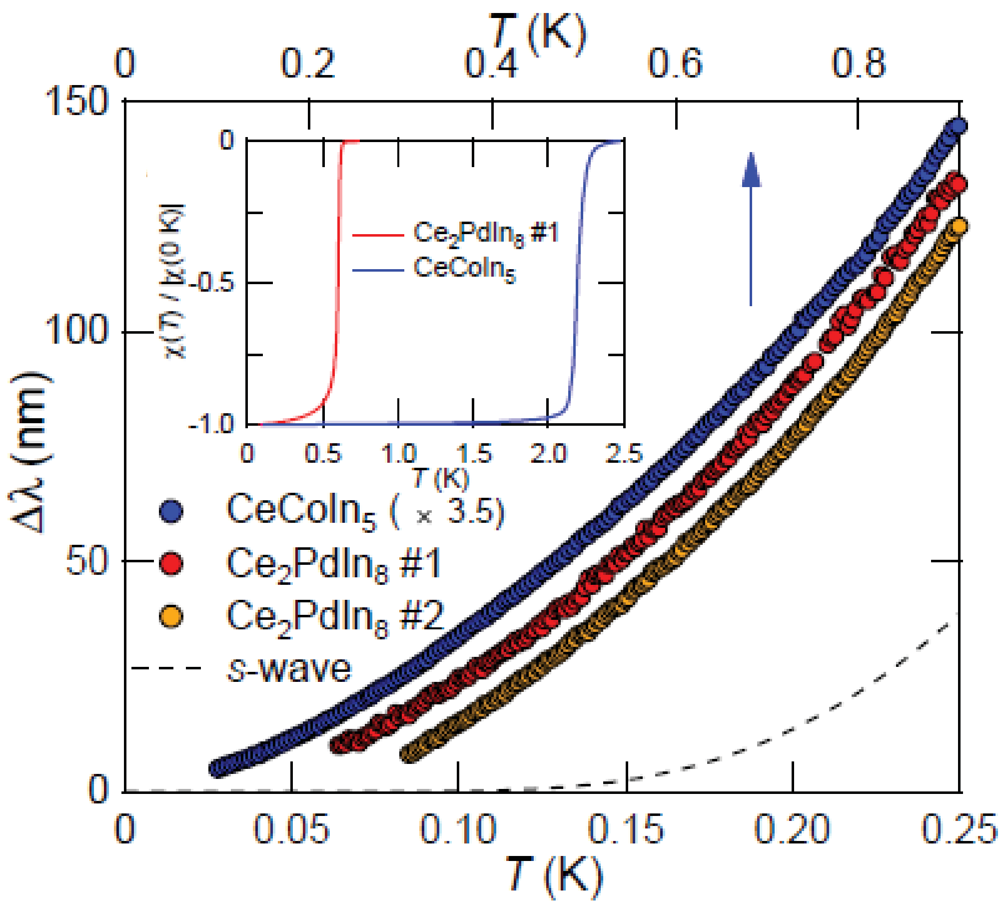


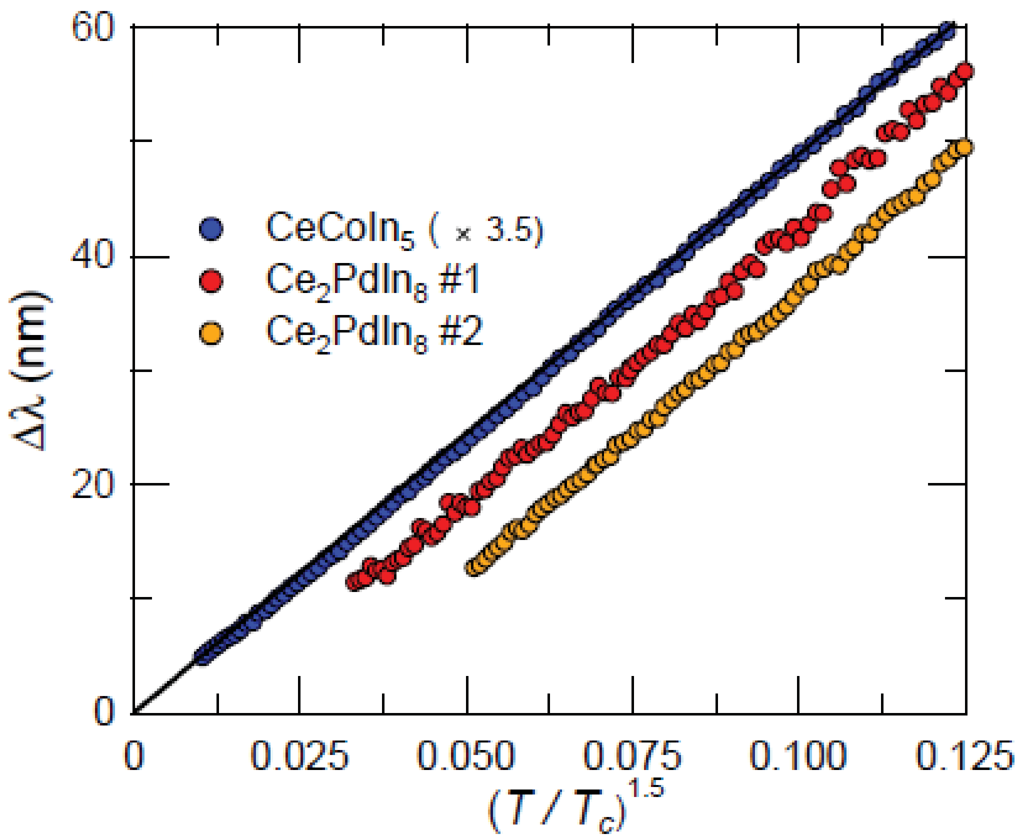
Deviations from the T-linear dependence

Consistent with previous studies.

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

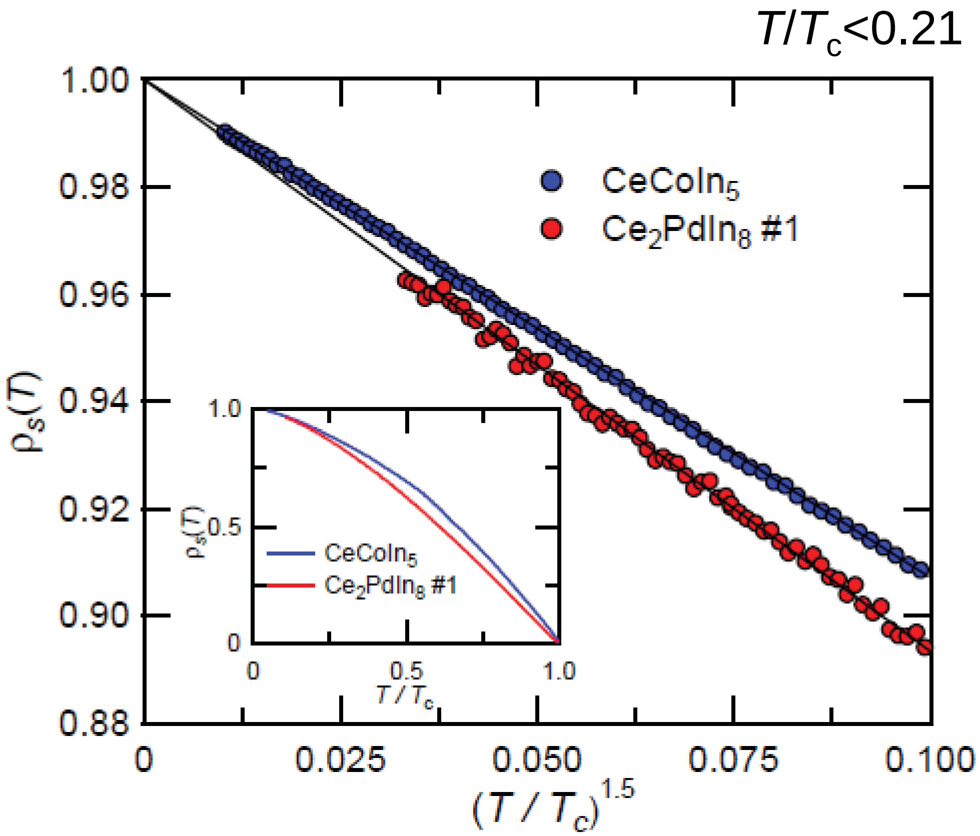
Anomalous λ(*T*) in $CeCoIn_5$ and Ce_2PdIn_8

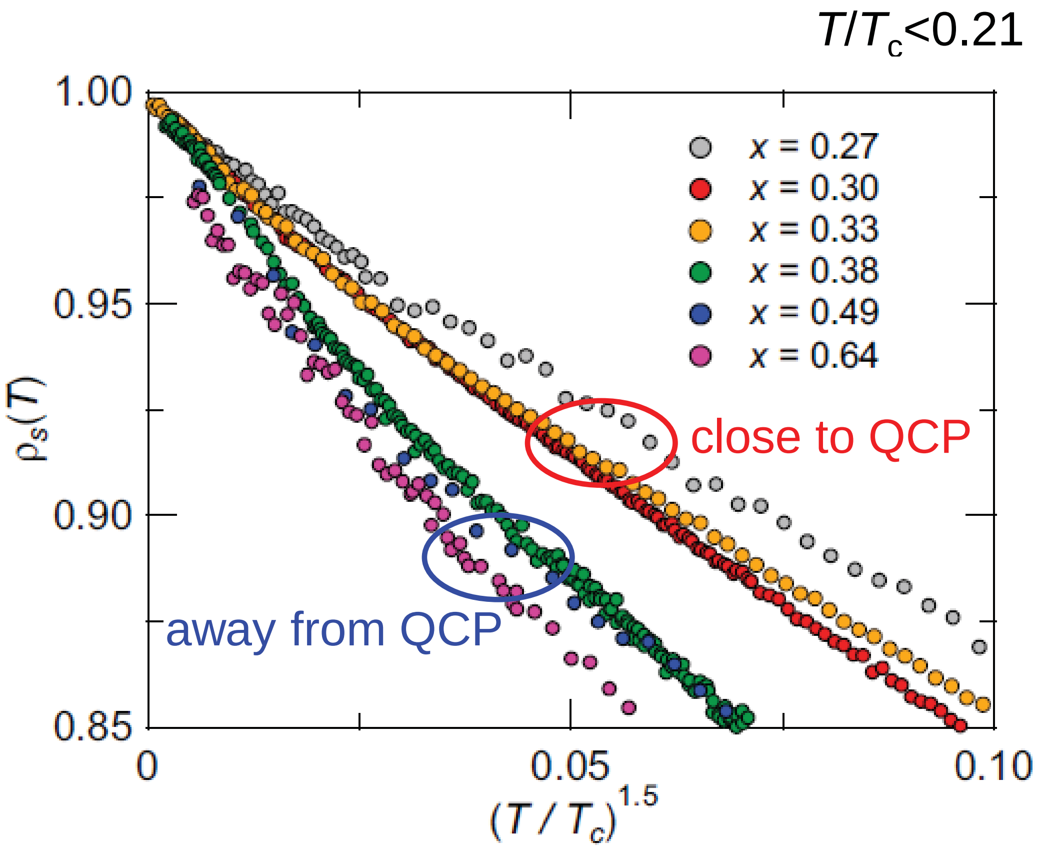




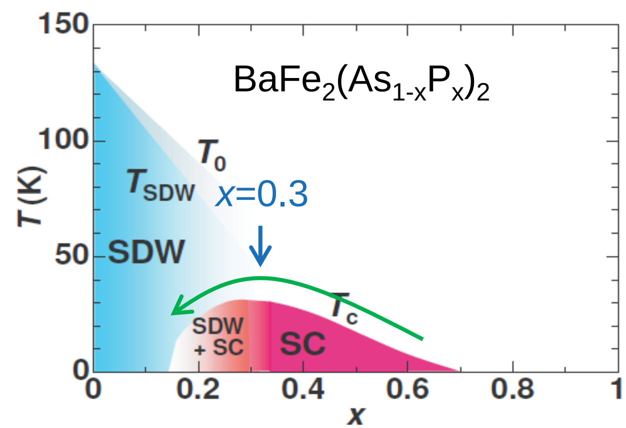
Anomalous non-integer 3/2 power-law dependence in a wide *T*-range

Anomalous superfluid density in `quantum critical' SCs

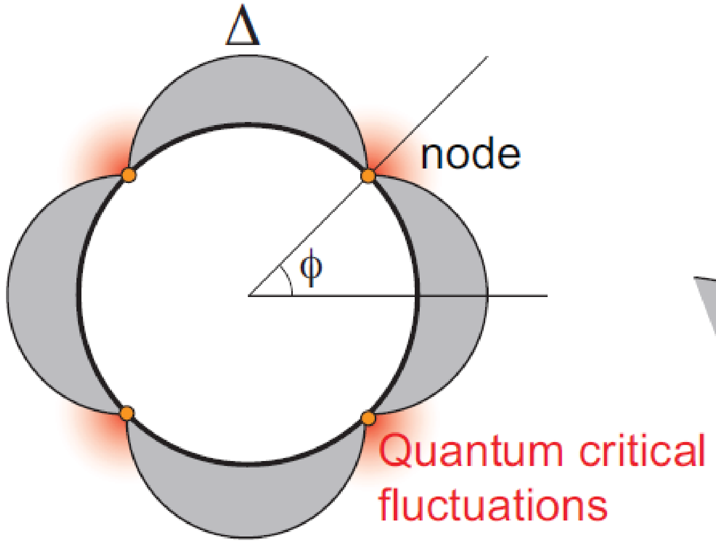


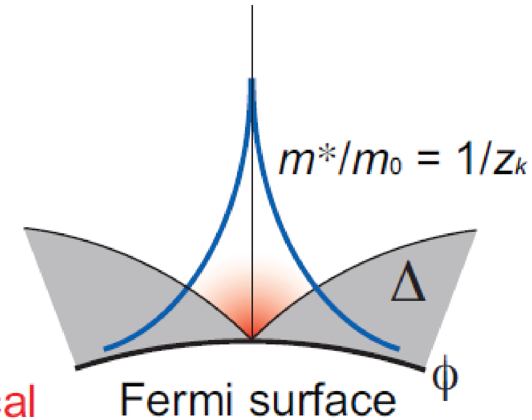


Anomalous non-integer power-law T dependence of superfluid density (except for the very low-T) is observed.



`Nodal quantum criticality' in unconventional SCs





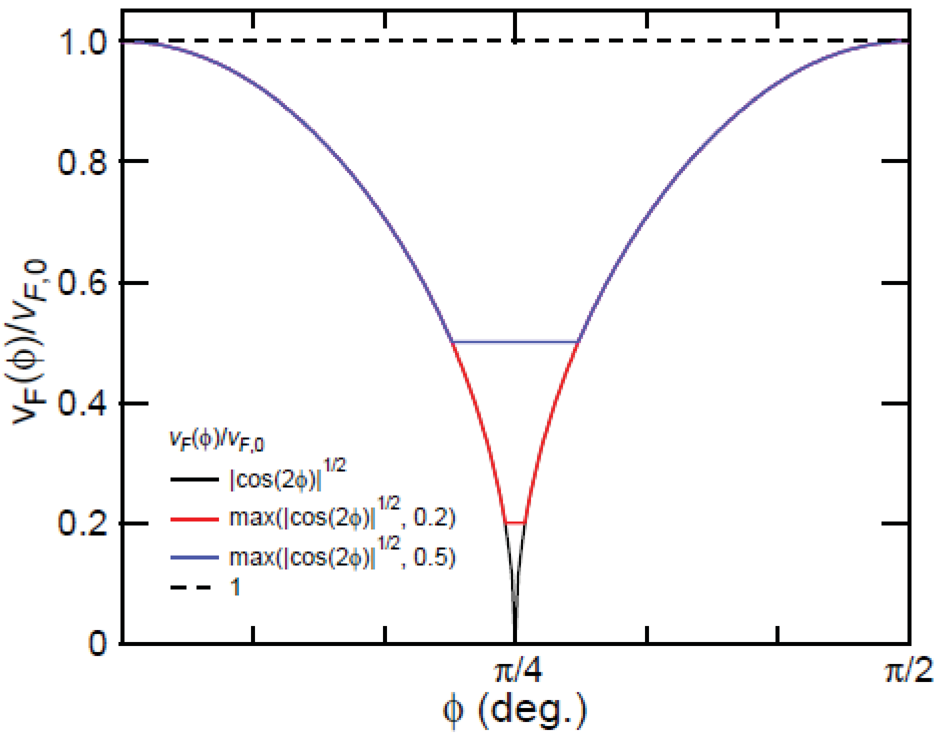
$$m^{*2} \propto (p - p_{\mathrm{QCP}})^{-\beta}$$

p: non-thermal parameter

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).

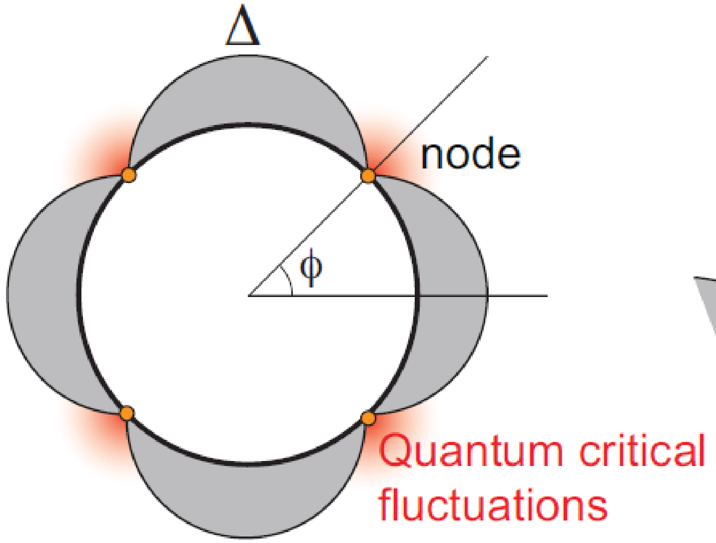
$$v_F(\boldsymbol{k}) \propto z_{\boldsymbol{k}} \propto 1/m^*(\boldsymbol{k}) \propto |\Delta(\boldsymbol{k})|^{\beta/2}$$

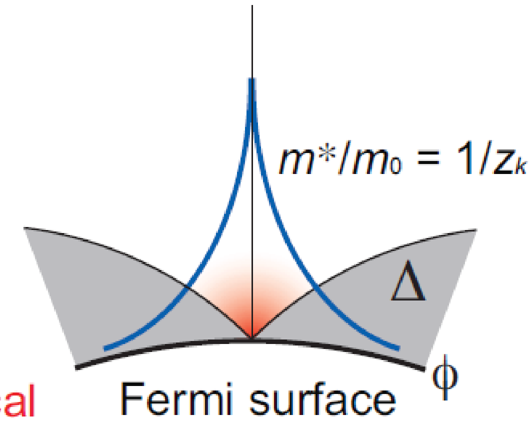


Low-energy quantum critical fluctuations
may be quenched by the SC gap formation.

Degree of quenching low-energy fluctuations
may be determined by the gap magnitude.

`Nodal quantum criticality' in unconventional SCs





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

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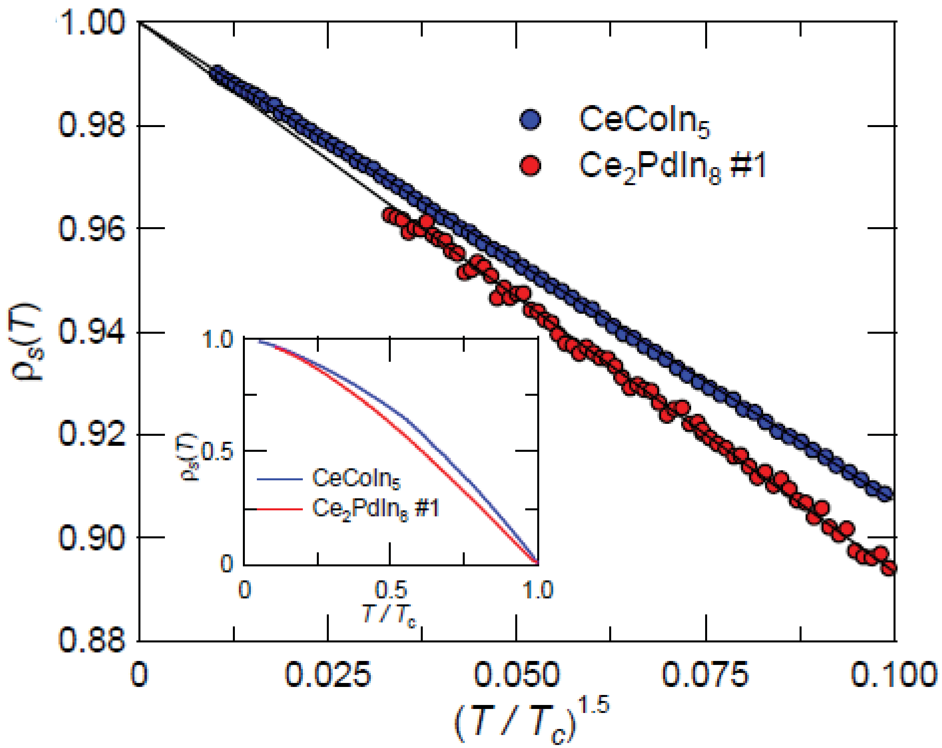
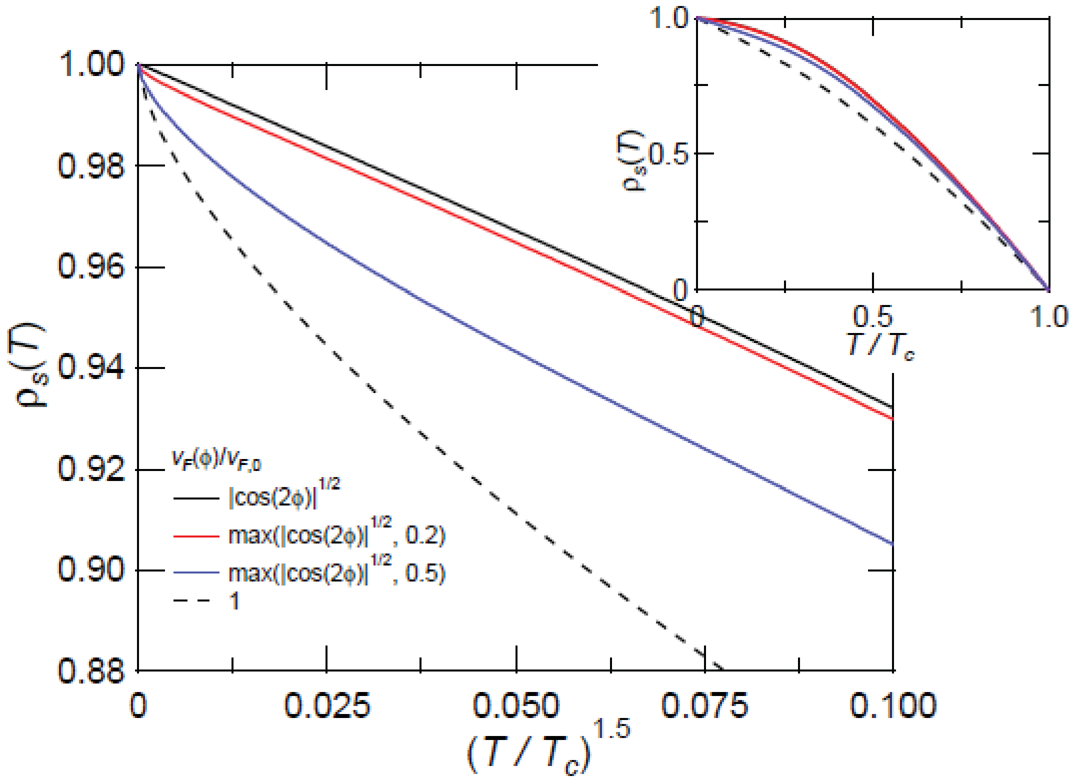
β~1 has been reported in β-$YbAlB_4$ and $YbRh_2Si_2$

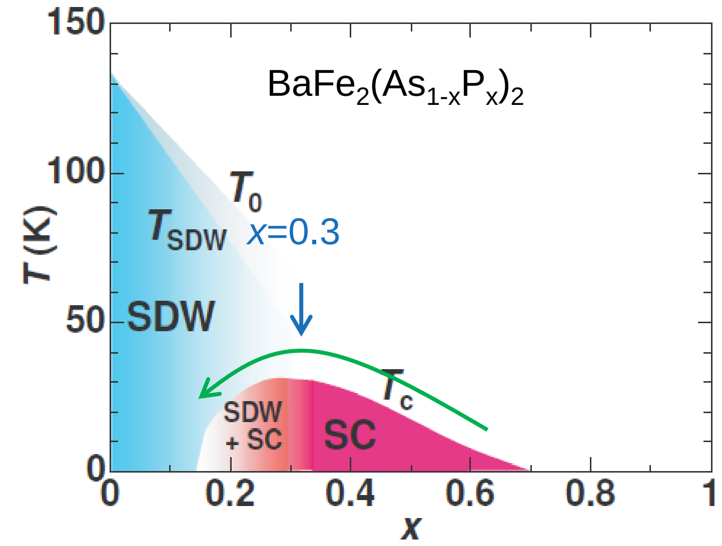
Y. Matsumoto *et al.*, Science (2011).
P. Gegenwart *et al.*, PRL (2002).

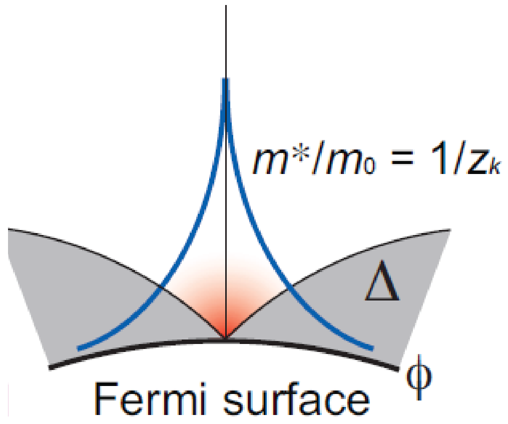
$$v_F(\boldsymbol{k}) \propto z_{\boldsymbol{k}} \propto 1/m^*(\boldsymbol{k}) \propto |\Delta(\boldsymbol{k})|^{\beta/2}$$





`Nodal quantum criticality' in unconventional SCs





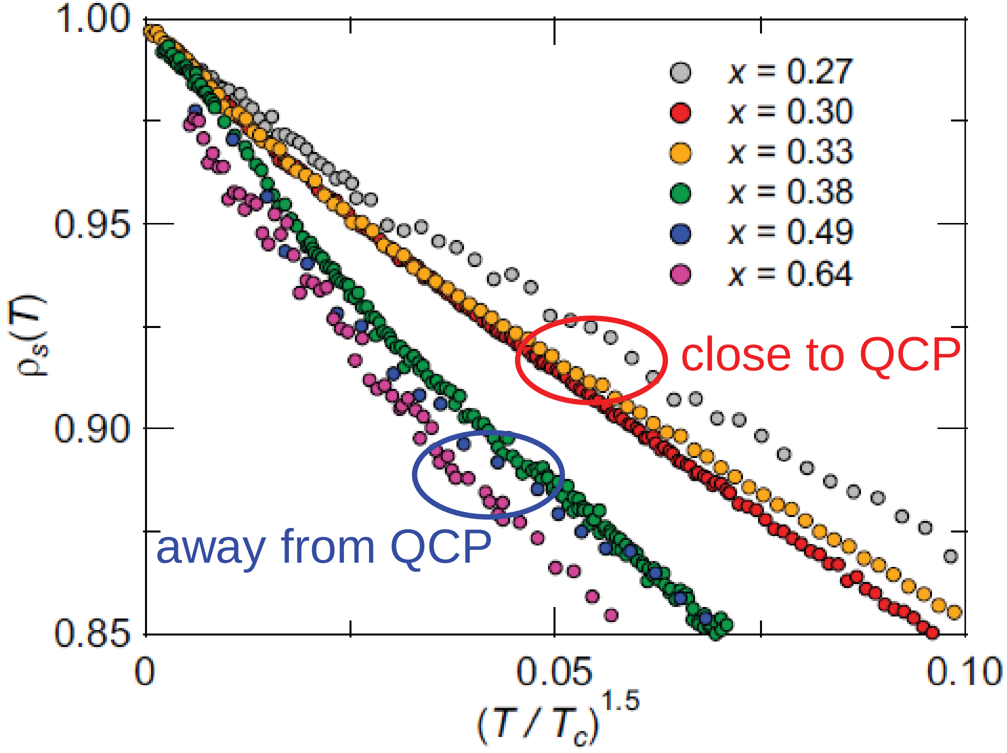
$$m^{*2} \propto (p - p_{\rm QCP})^{-\beta}$$

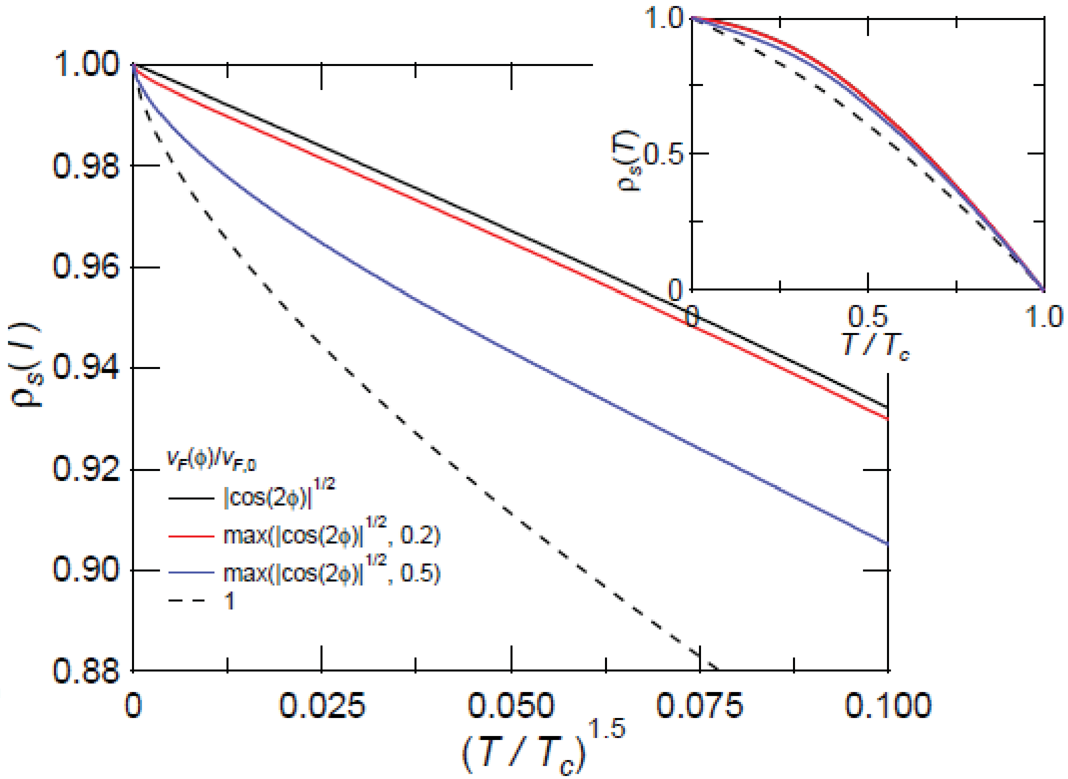
p: non-thermal parameter

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).

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





Nematic transition and antiferromagnetic quantum critical point in $BaFe_2(As_{1-x}P_x)_2$

Taka Shibauchi

Department of Physics, Kyoto University

1. Quantum phase transition lurking inside the superconducting dome

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

2. Nematic transition above the dome

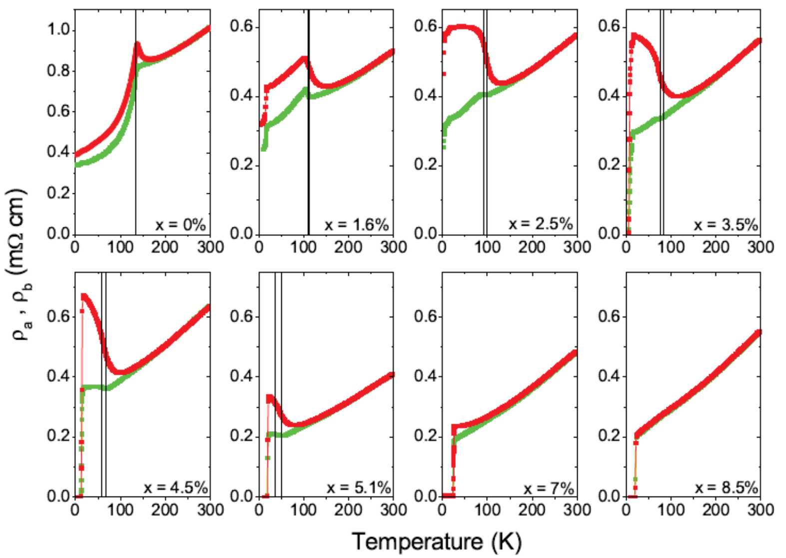
S. Kasahara *et al.*, Nature **486**, 382 (2012).

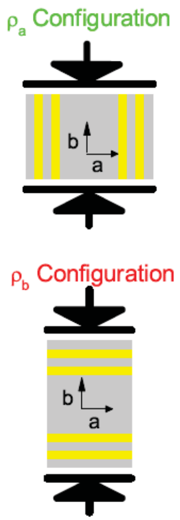
3. Summary – A renewed phase diagram

Experiments suggesting in-plane anisotropy at $T>T_s$

★**Resistivity** J. Chu *et al*. Science (2010).

Detwinned by uniaxial pressure

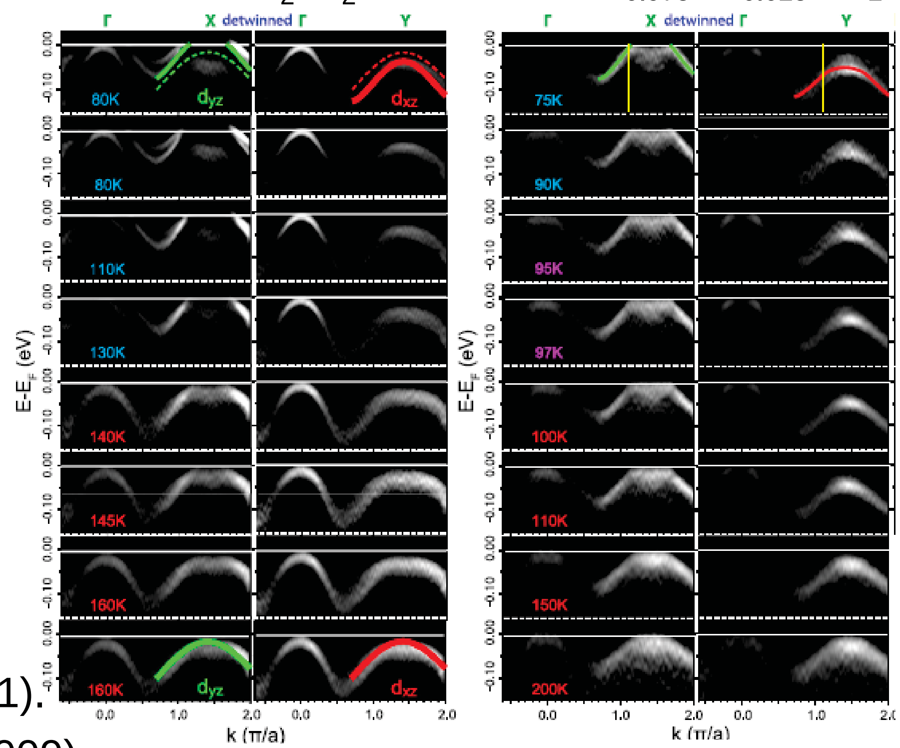


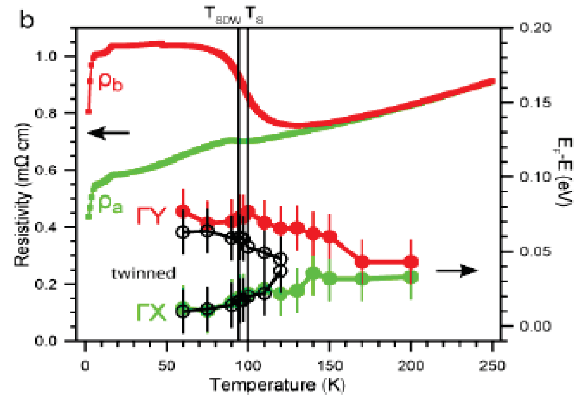


$\rho_b > \rho_a$ **above** T_s

★ **ARPES** M. Yi *et al*., PNAS (2011).

$BaFe_2As_2$ $Ba(Fe_{0.975}Co_{0.025})As_2$





★ **Optical Conductivity** A. Dusza *et al*., EPL (2011).
M. Nakajima *et al*., PNAS (2011).

★ **Neutron Scattering** J. Zhao *et al*., Nature Phys. (2009).
L. W. Harriger *et al*., PRB (2011).

★ **X-Ray Diffraction** E.C. Blomberg *et al*., PRB (2012).

In-plane anisotropy seems to extend above T_s in crystals under uniaxial strain.

Experiments suggesting in-plane anisotropy at $T>T_s$

Uniaxial pressure itself breaks the rotational symmetry and may induce the in-plane anisotropy.

To address whether unidirectional self-organization of electrons (nematicity) occurs above T_s or not, we need experiments *without* uniaxial pressure.

What the magnetic torque tells us

$$\boldsymbol{\tau} = \mu_0 \boldsymbol{M} V \times \boldsymbol{H}$$

$$M_i = \sum_j \chi_{ij} H_j$$

$\boldsymbol{\tau}$: magnetic torque
V: sample volume
$\boldsymbol{M}$: magnetization
$\boldsymbol{H}$: applied Field

Magnetic Torque: Thermodynamic Quantity

★ Micro-cantilever
Very high sensitivity

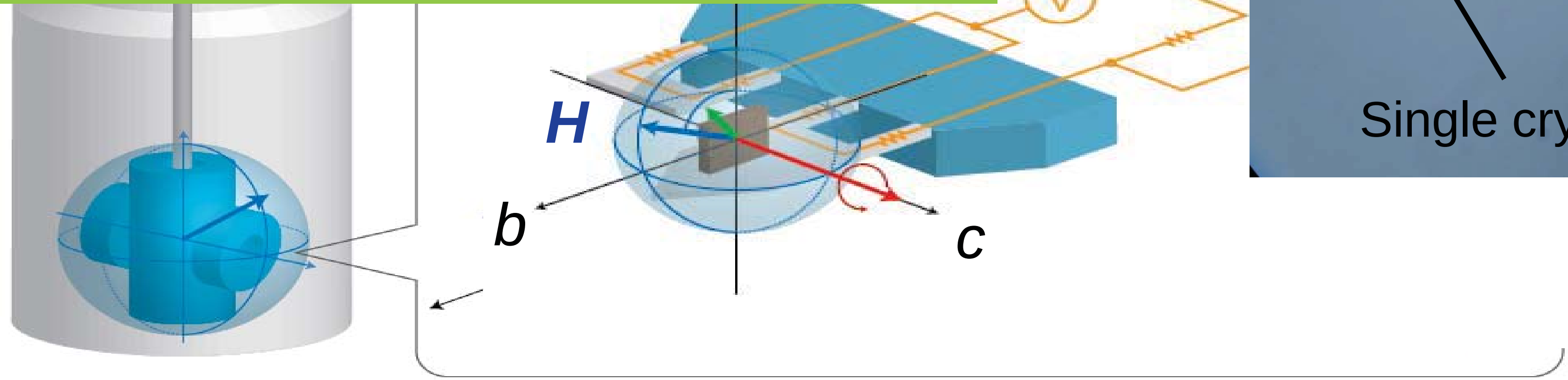
torque	5×10^{-12} e.m.u.
SQUID	10^{-8} e.m.u.

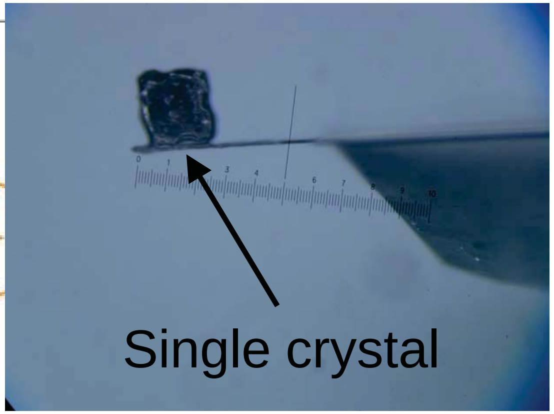
> 10^3 !!
(at $\mu_0 H$=4T)

★ A tiny pure single crystal
(Typical crystal dimensions: 70 x 70 x 30 um^3)

★ Precise control of the field directions within *ab* plane

In tiny crystals, we have a good chance to have imbalance of the domains without applying pressure.



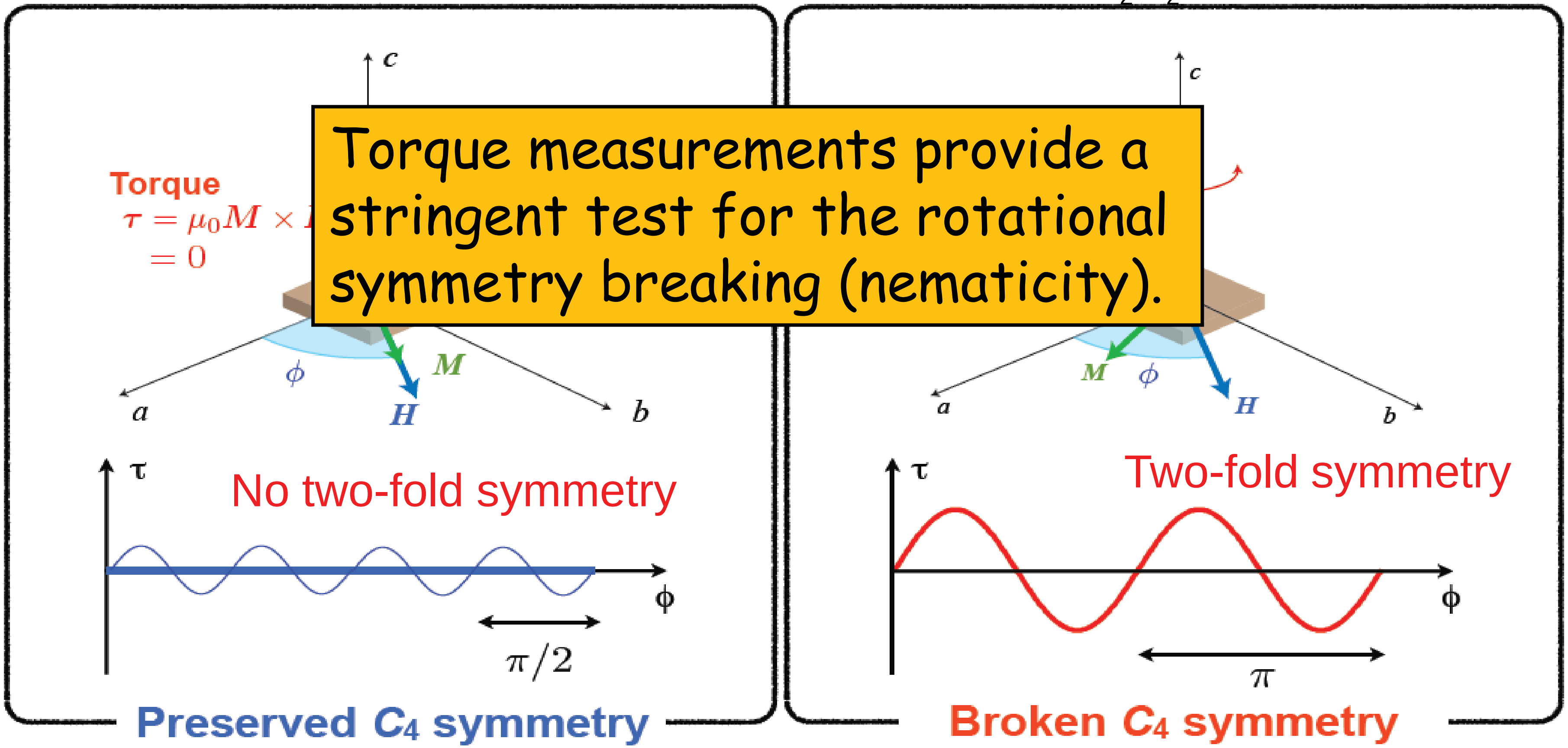


Vector magnet & Mechanical rotator

What the magnetic torque tells us

H rotation within the *ab* plane

see R. Okazaki, TS *et al.*, Science (2011) for URu_2Si_2 results.



Torque measurements provide a stringent test for the rotational symmetry breaking (nematicity).

$$M_i = \sum_j \chi_{ij} H_j$$

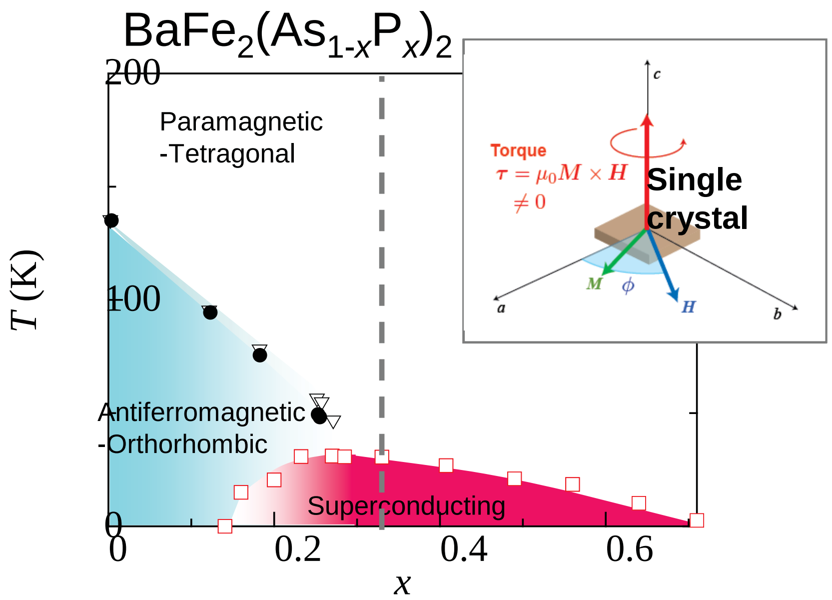
$$\boldsymbol{\tau} = \mu_0 M V \times \boldsymbol{H}$$

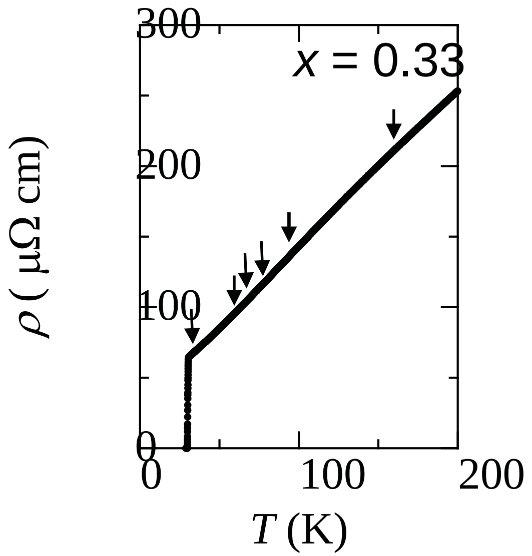
$$\tau = \frac{1}{2}\mu_0 H^2 V[(\chi_{aa} - \chi_{bb})\sin 2\phi - 2\chi_{ab}\cos 2\phi]$$

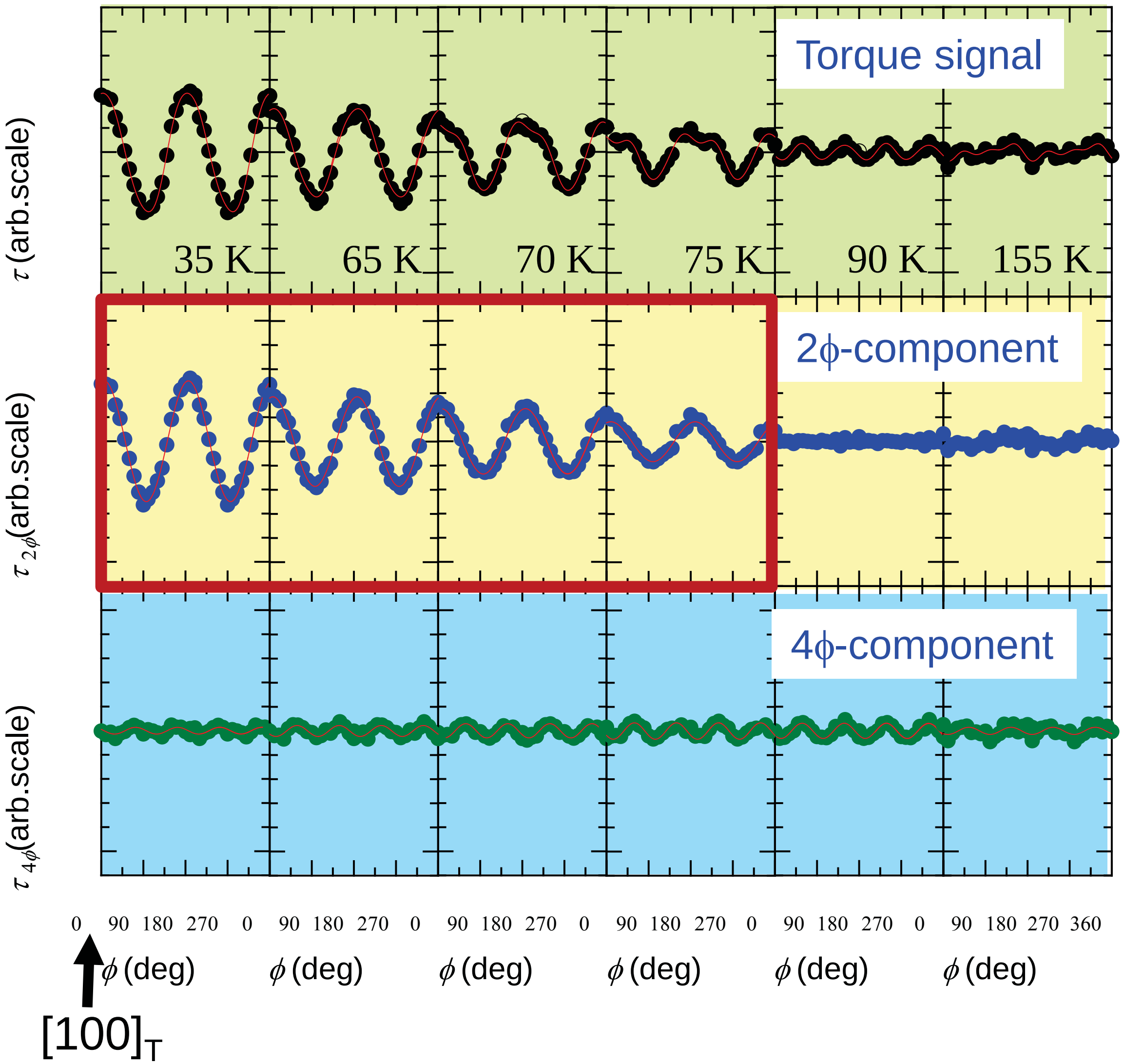
$\chi_{aa} = \chi_{bb}$ and $\chi_{ab} = 0$

$\chi_{aa} \neq \chi_{bb}$ and/or $\chi_{ab} \neq 0$

In-plane torque magnetometry

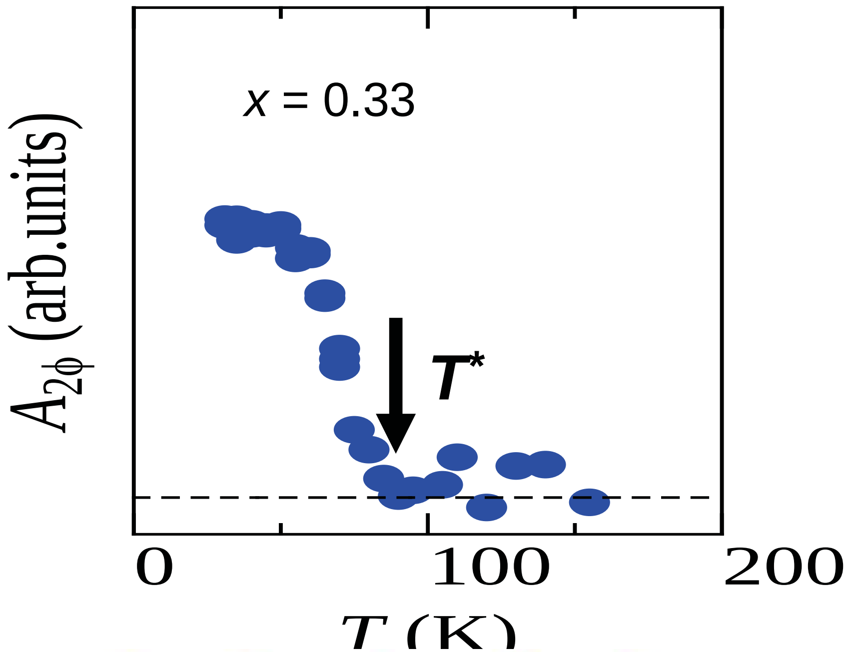


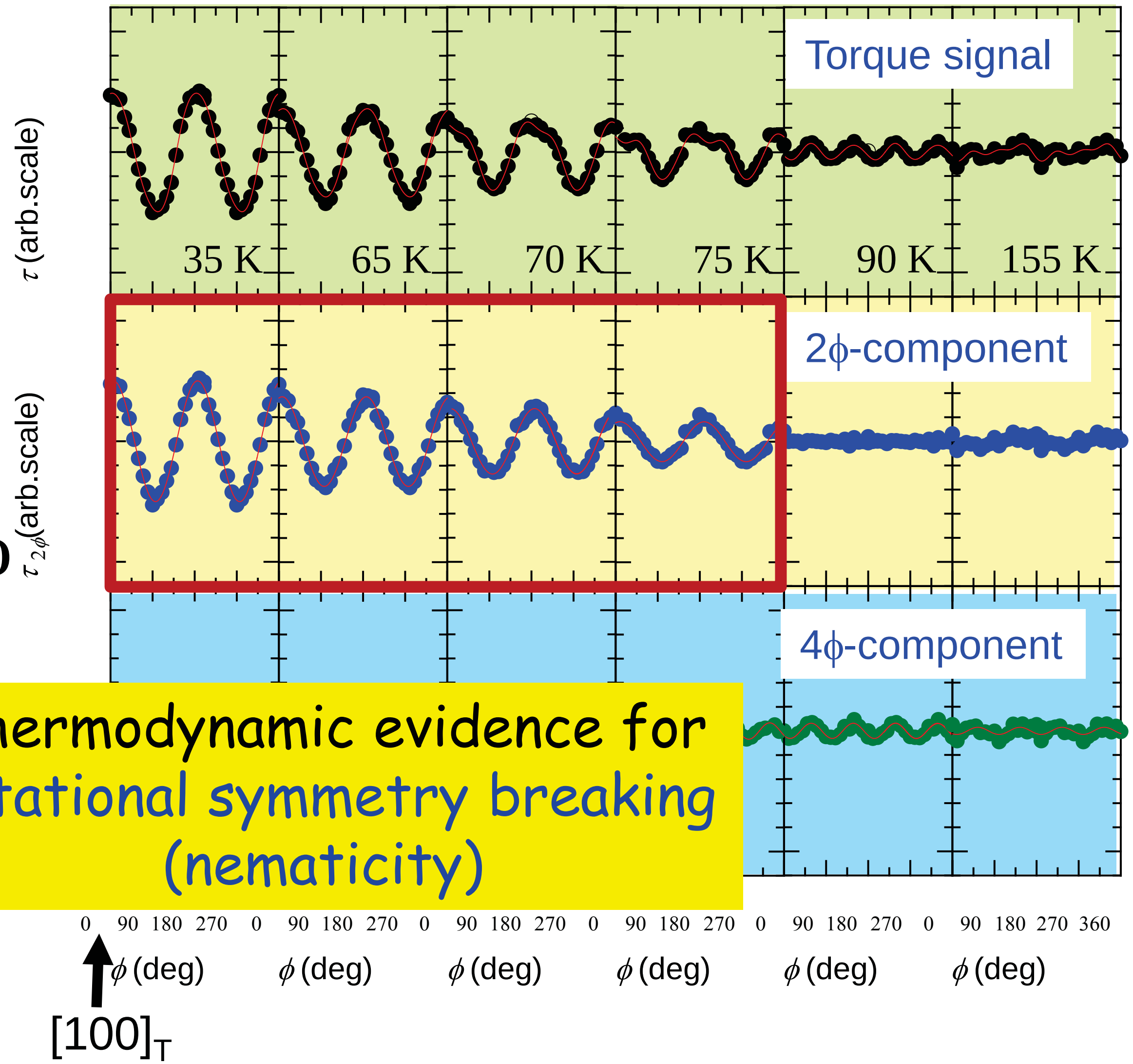




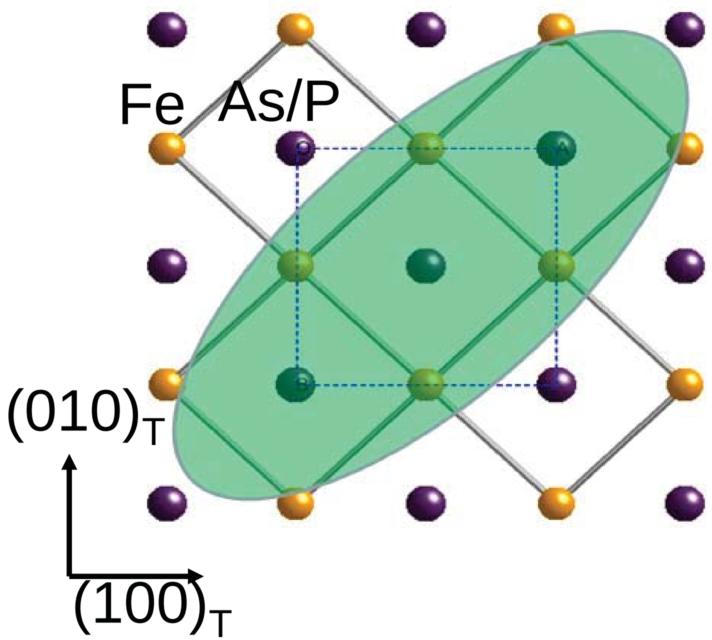
·2ϕ component at low temperatures

In-plane torque magnetometry





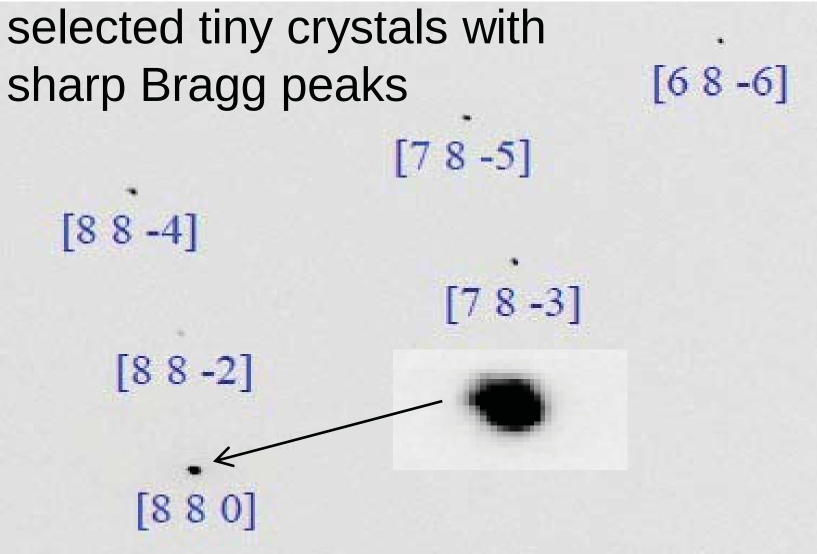
Thermodynamic evidence for rotational symmetry breaking (nematicity)



$$\tau = \frac{1}{2}\mu_0 H^2 V[(\chi_{aa} - \chi_{bb})\sin 2\phi - \boxed{2\chi_{ab}\cos 2\phi]}$$

$\chi_{ab} \neq 0$

Synchrotron XRD: Detection of a tiny lattice distortion



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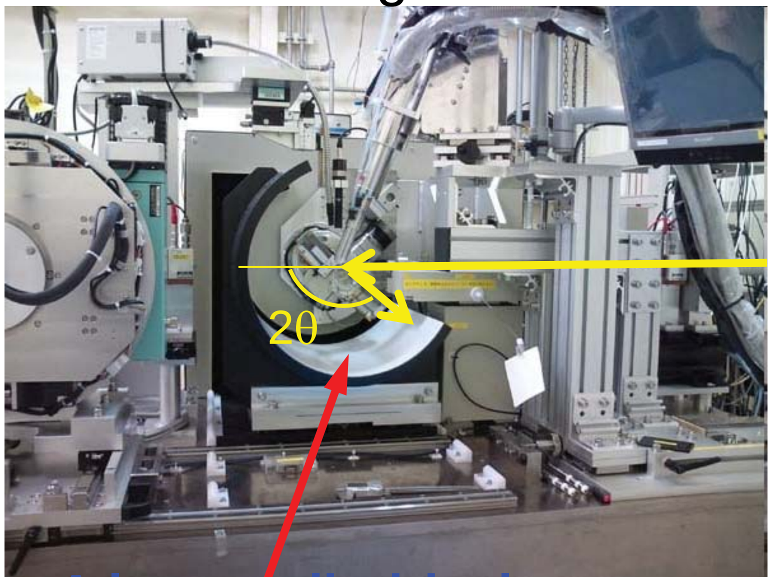
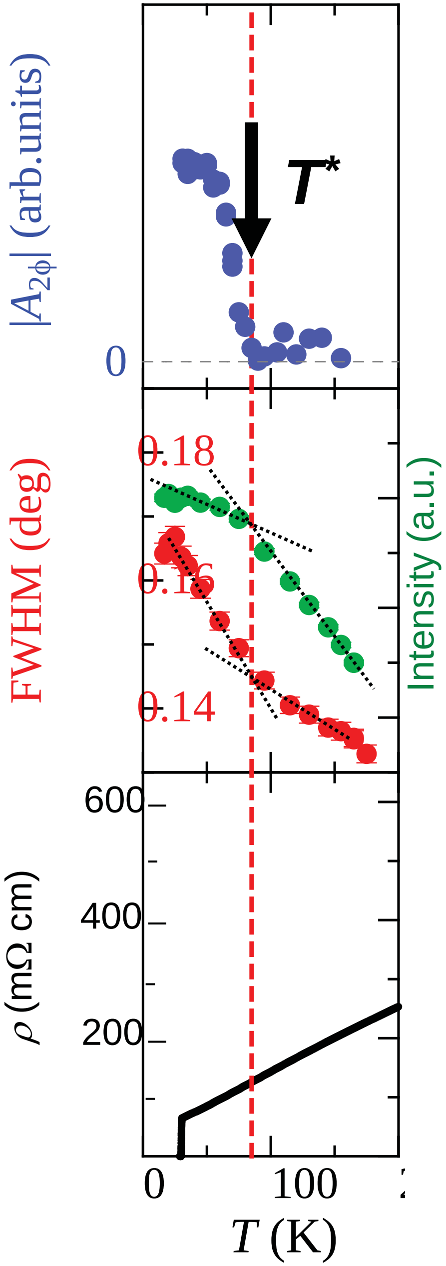
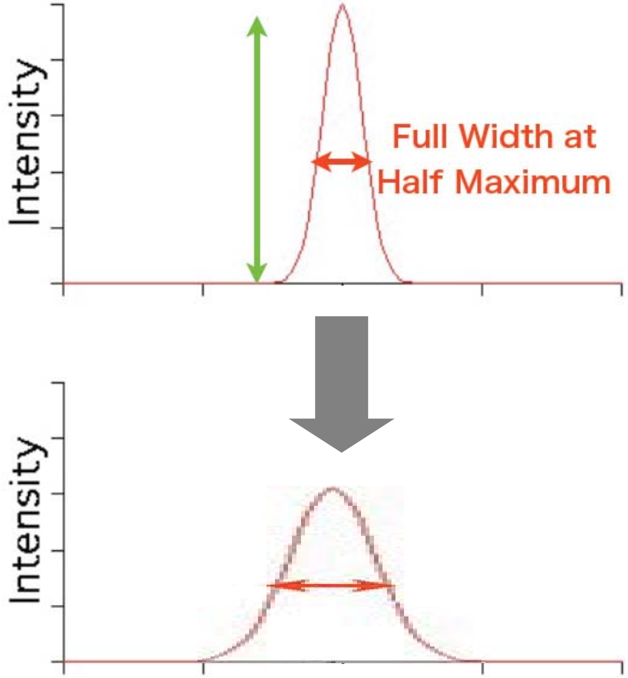


A large cylindrical imaging-plate camera





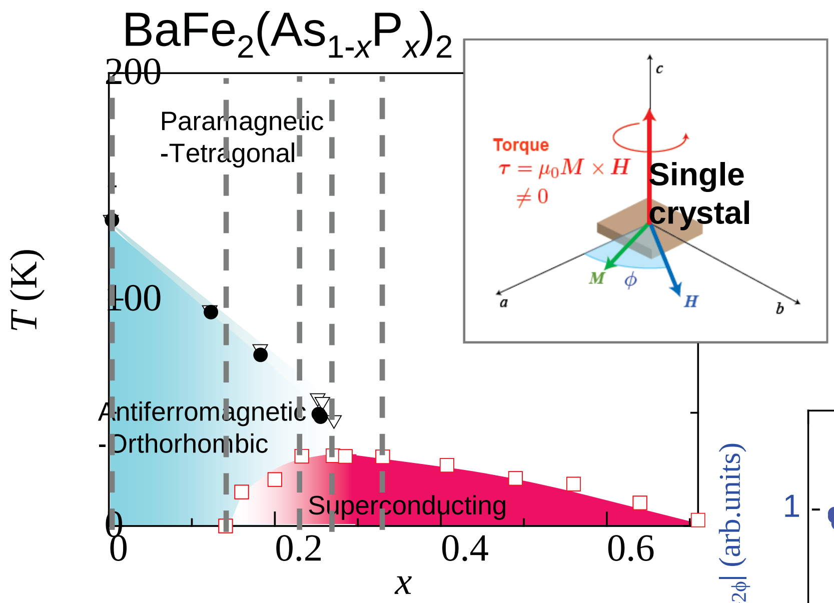
Broadening of the Bragg Peak

$(7\ 7\ 0)_T$ or $(8\ 8\ 0)_T$

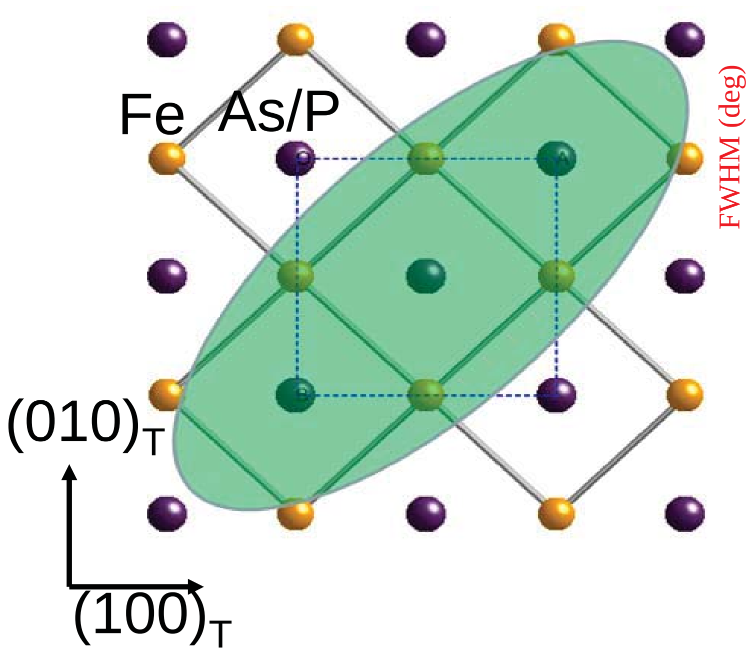
at high angle 2θ > 120 deg

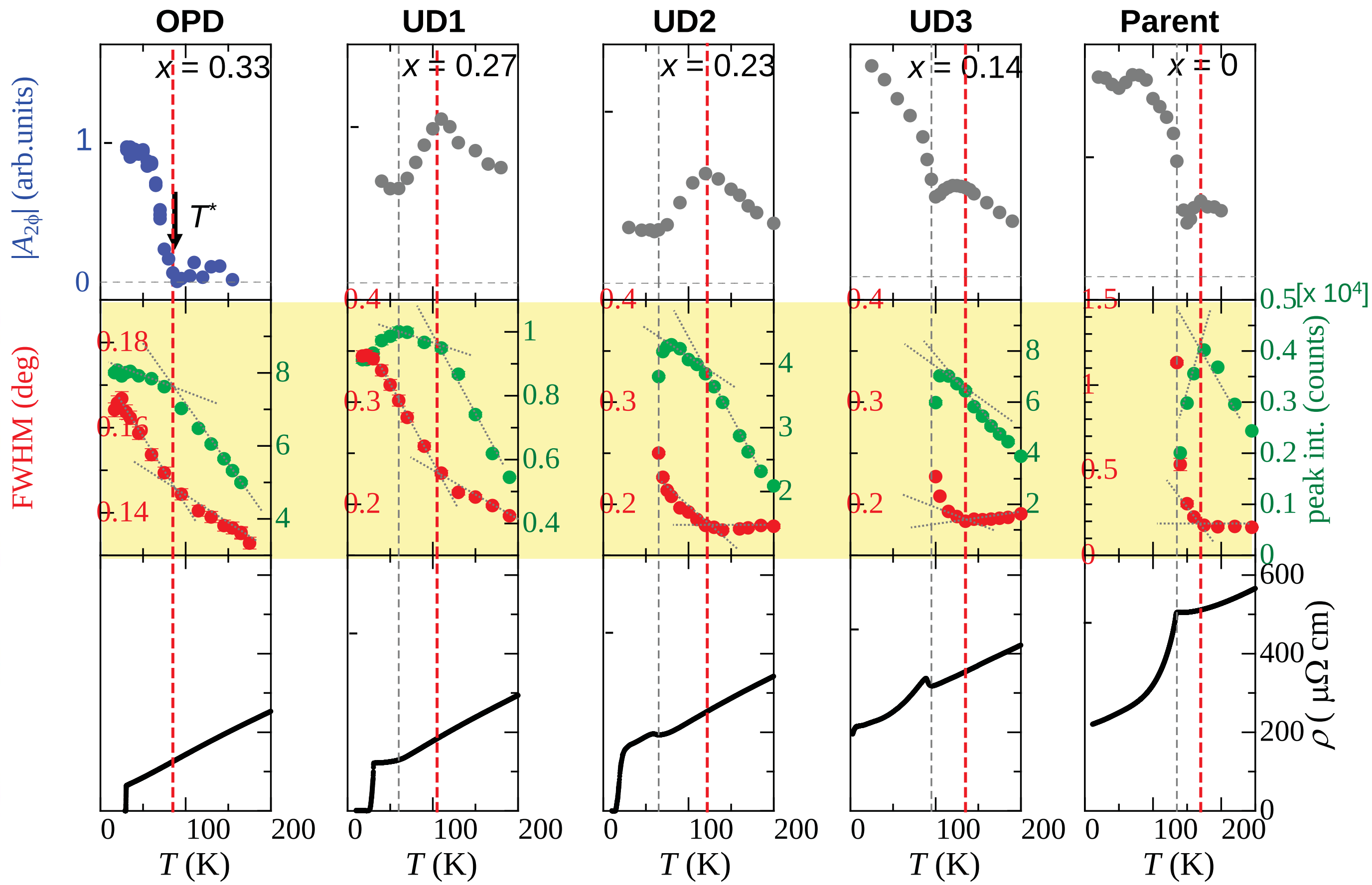
Tiny orthorhombic distortion associated with the nematic phase transition at T^*.

Evolution with doping

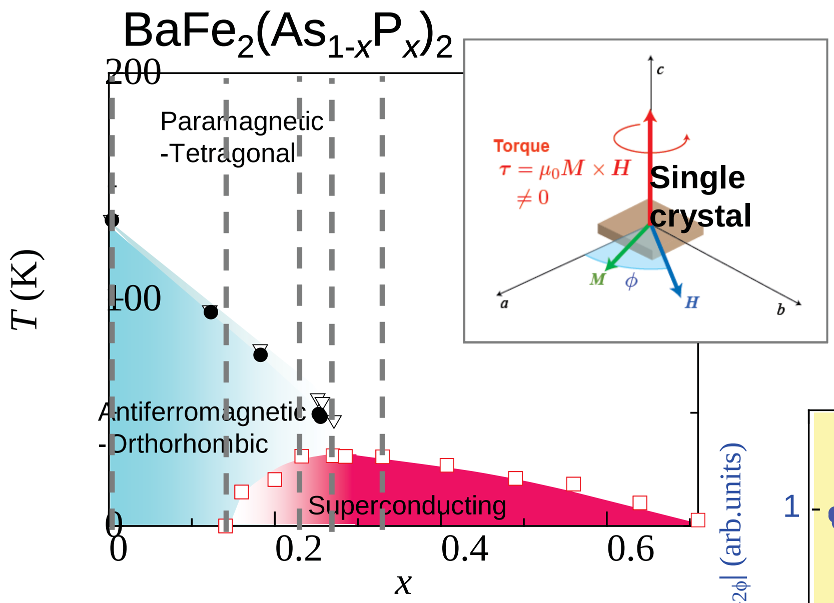


Systematic change in T^* with x

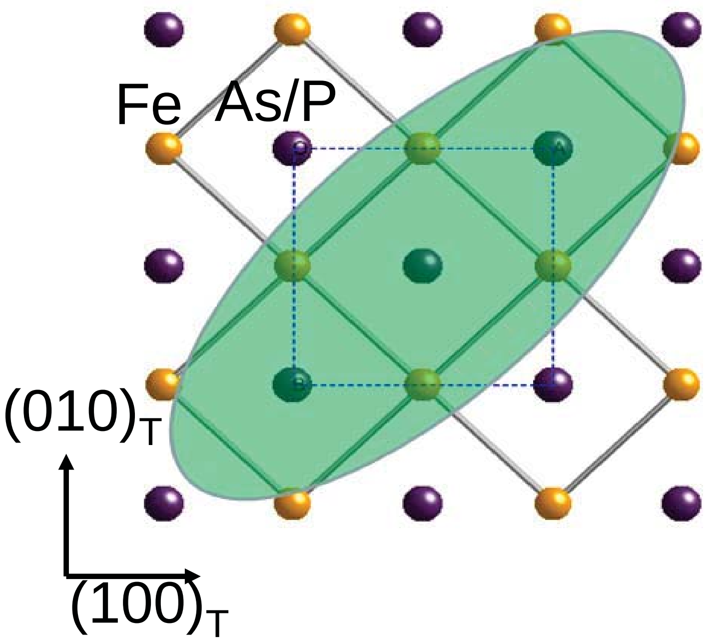


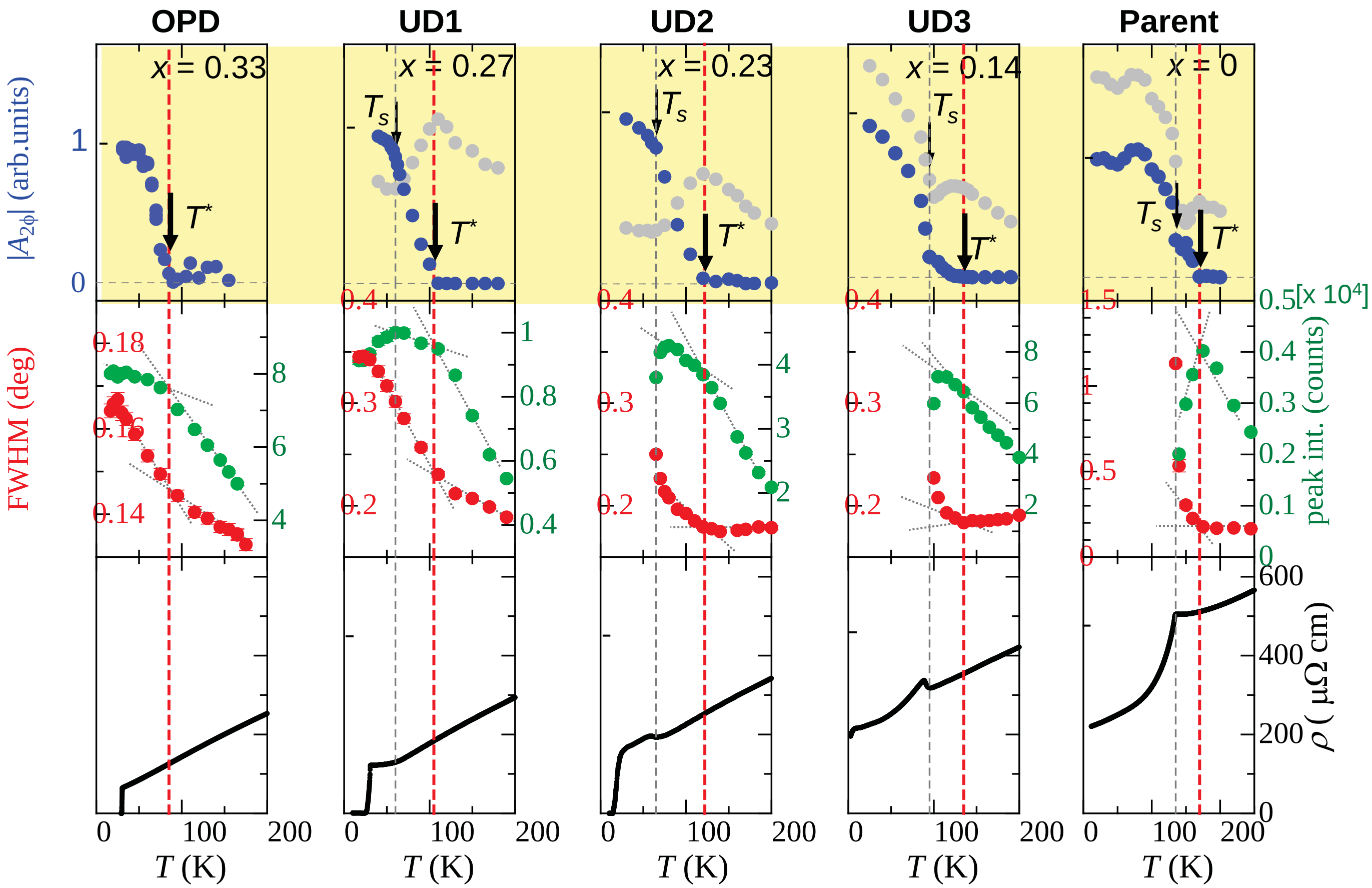


Evolution with doping



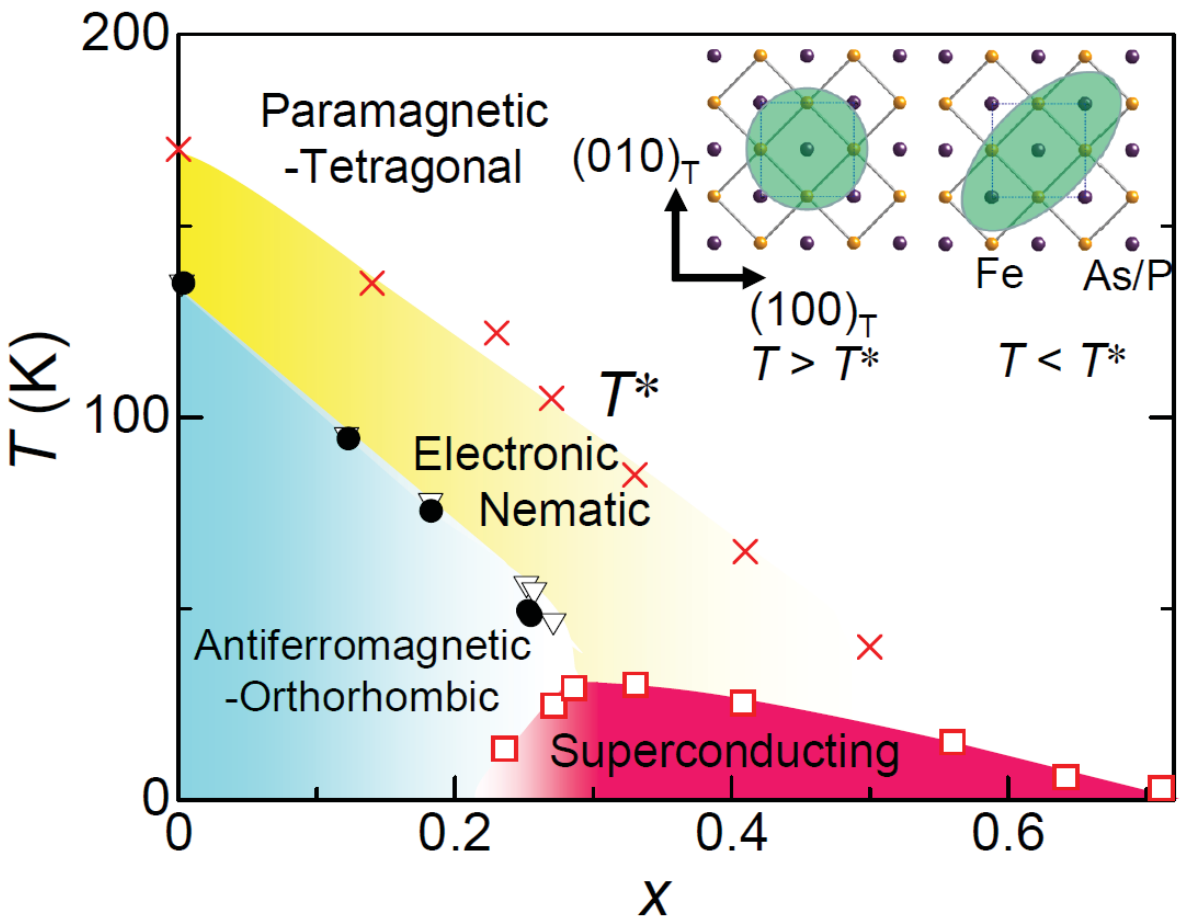
Systematic change in *T** with *x*





Phase diagram

S. Kasahara *et al*., Nature **486**, 382 (2012).



Electronic nematic phase persists over a wide range of doping

Pseudogap phase ? Orbital ordering?

Optical conductivity, S. J. Moon *et al*., PRL (2012).

Point contact spectroscopy, H. Z. Arham *et al*., PRB (2012).

ARPES, T. Shimojima *et al*., (unpublished).

Nematic and meta-nematic transitions

Landau free energy

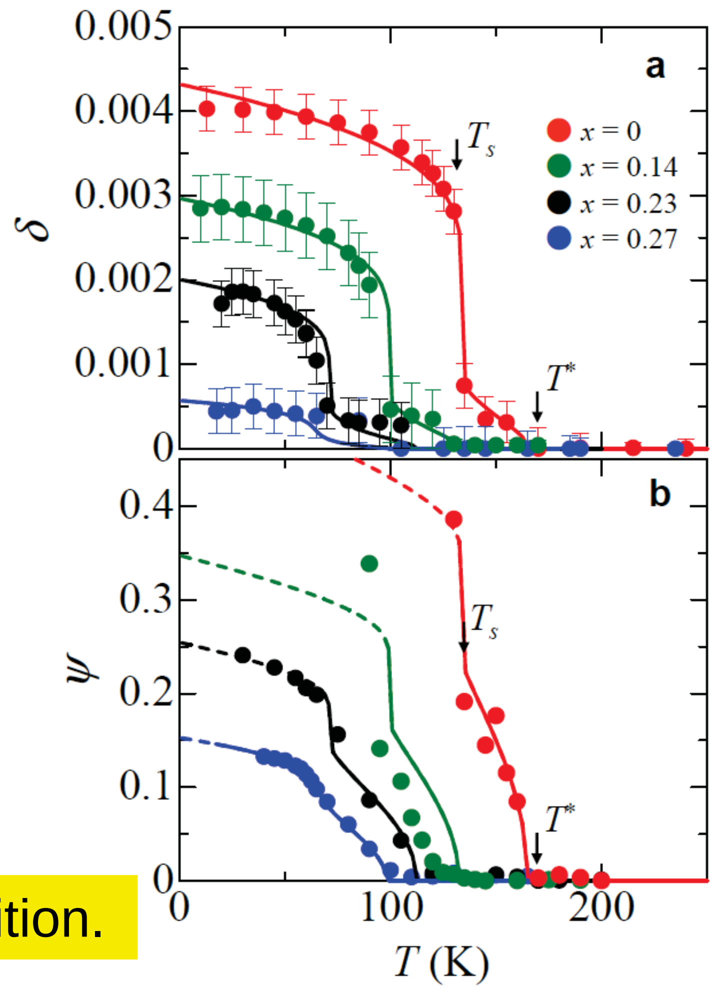
A. H. Nevidomskyy

$$F[\delta,\psi] = \left[t_s\delta^2 - u\delta^4 + v\delta^6\right] + \left[t_p\psi^2 + w\psi^4 + \mathcal{O}(\psi^6)\right] - g\,\psi\cdot\delta$$

Structural term Electronic term Coupling

Two order parameters

$$\begin{cases} \delta = \frac{a-b}{a+b} & \text{: Orthorhombic distortion} \\ \psi \propto A_{2\phi} & \text{: Nematic order parameter} \end{cases}$$



T^*: Non-zero δ and ψ

Broken C_4 symmetry

T_s: Finite jump of δ and ψ

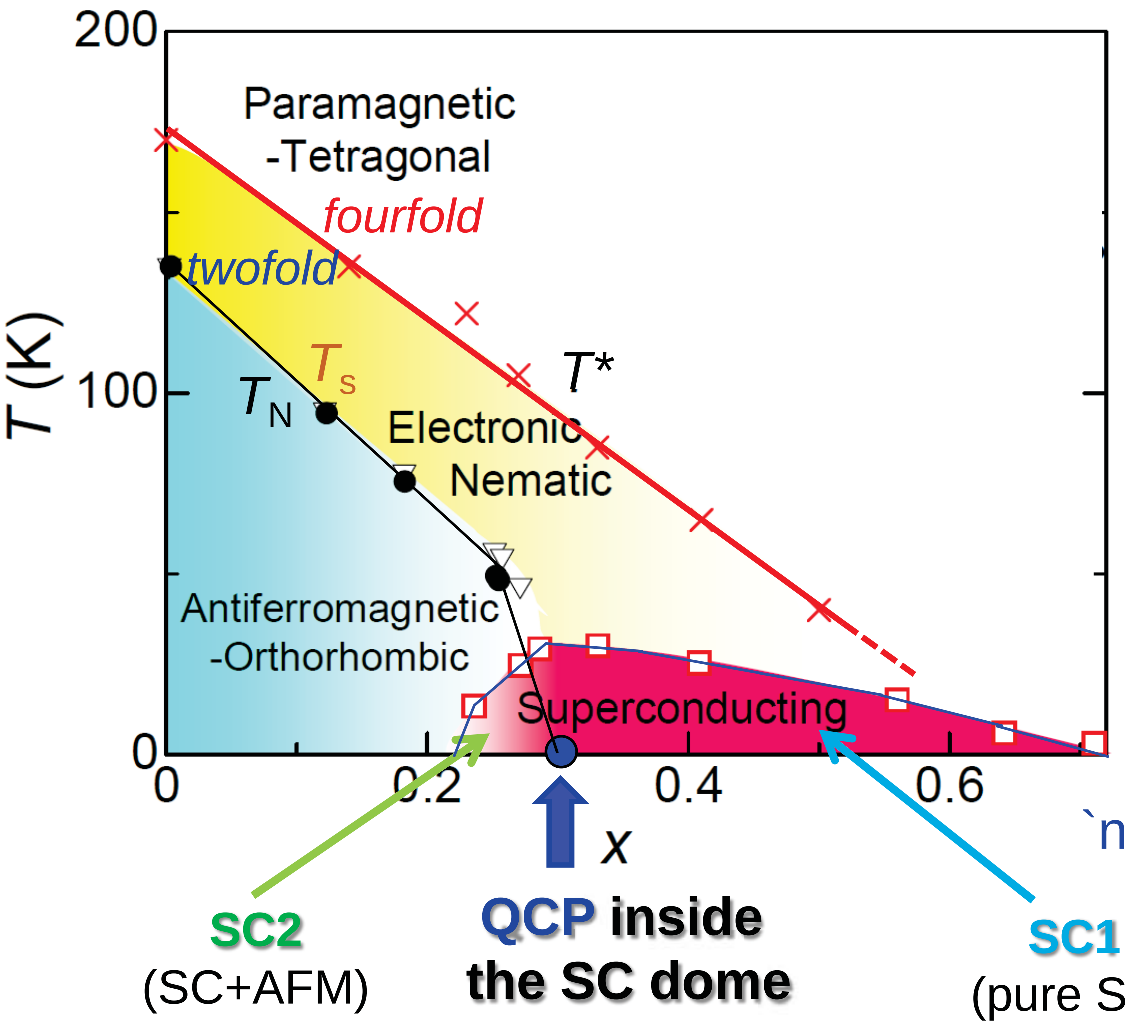
True nematic transition at T^*

`Meta-nematic transition' at T_s

$T^*>T_s$ implies an electronic origin of the nematic transition.

Summary: Renewed phase diagram in $BaFe_2(As_{1-x}P_x)_2$

S. Kasahara *et al*., Nature **486**, 382 (21 June 2012).
K. Hashimoto *et al*., Science **336**, 1554 (22 June 2012).



5 different phases

`nodal qauntum criticality'

The nematicity appears to be a requisite for SC, and the high-T_c SC may be associated with the AF-QCP.