鉄系高温超伝導体

- 銅酸化物、重い電子系との比較
- 超伝導ギャップ構造
- 量子臨界点

鉄系高温超伝導体

銅酸化物、重い電子系との比較

超伝導ギャップ構造

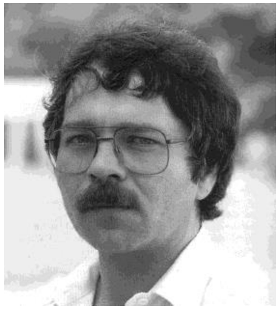
量子臨界点

High-T_c cuprates

Possible High T_c Superconductivity in the Ba – La – Cu – O System

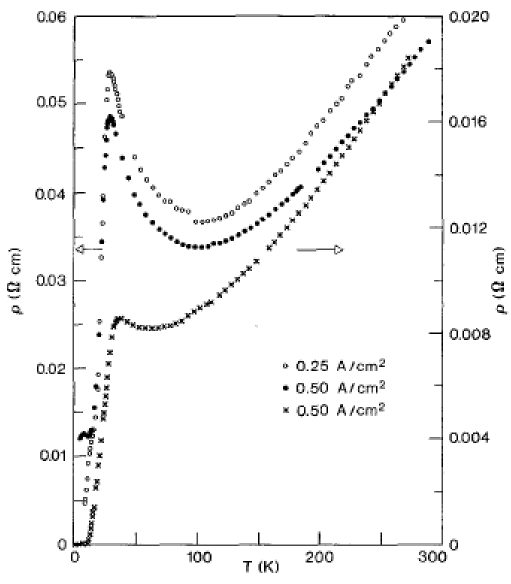
J.G. Bednorz and K.A. Müller
IBM Zürich Research Laboratory, Rüschlikon, Switzerland

Received April 17, 1986

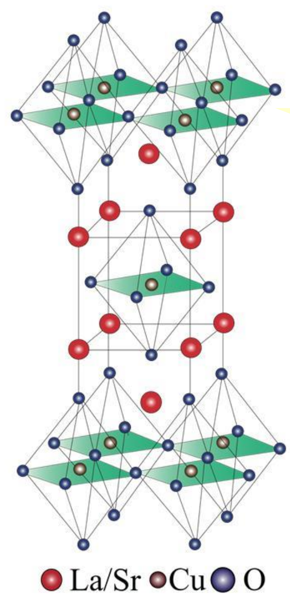


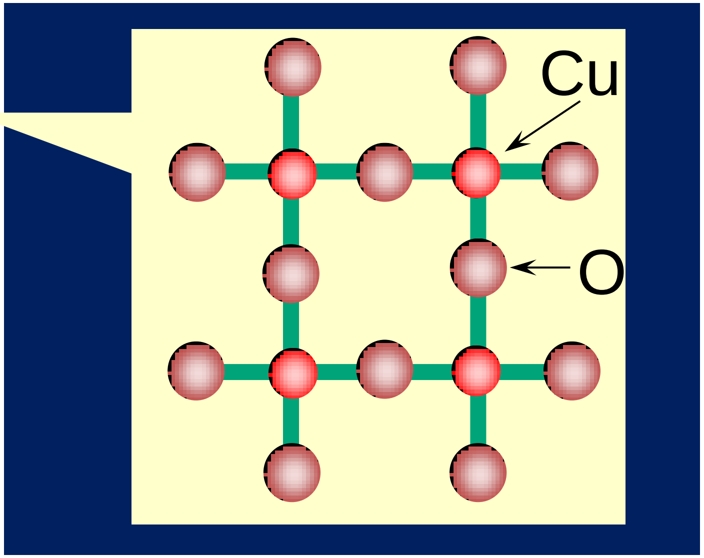
Metallic, oxygen-deficient compounds in the Ba – La – Cu – O system, with the composition $Ba_xLa_{5-x}Cu_5O_{5(3-y)}$ have been prepared in polycrystalline form. Samples with $x=1$ and 0.75, $y>0$, annealed below 900 °C under reducing conditions, consist of three phases, one of them a perovskite-like mixed-valent copper compound. Upon cooling, the samples show a linear decrease in resistivity, then an approximately logarithmic increase, interpreted as a beginning of localization. Finally an abrupt decrease by up to three orders of magnitude occurs, reminiscent of the onset of percolative superconductivity. The highest onset temperature is observed in the 30 K range. It is markedly reduced by high current densities. Thus, it results partially from the percolative nature, bute possibly also from $2D$ superconducting fluctuations of double perovskite layers of one of the phases present.

Superconductivity in CuO_2 planes



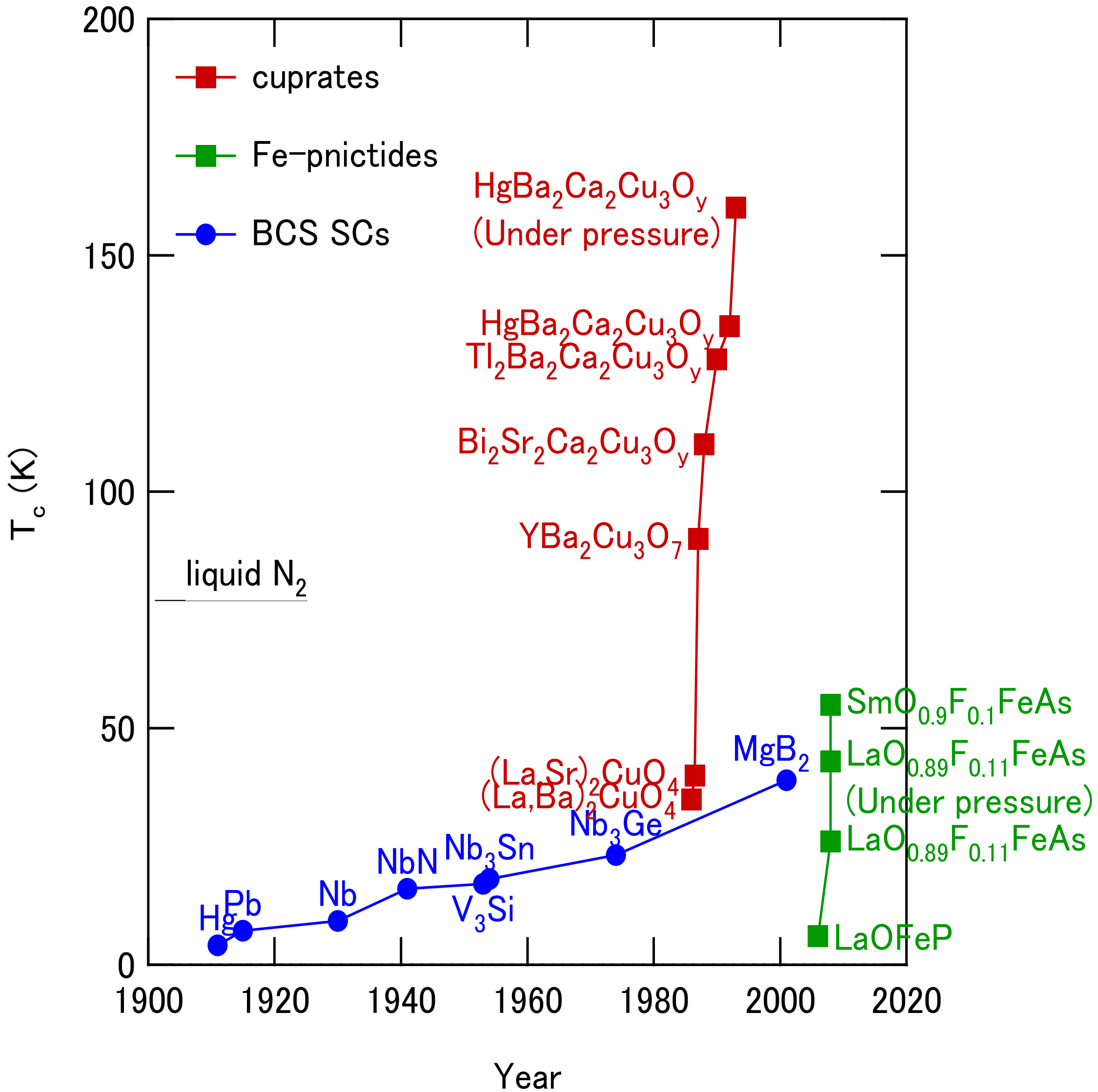
$La_{2-x}Sr_xCuO_4$





J. G. Bednorz and K.A. Müller, Zeitschrift für Physik B **64**, 189 (1986).

Fe-based high-T_c superconductors



Superconductivity in Fe-Pnictides — Discovery

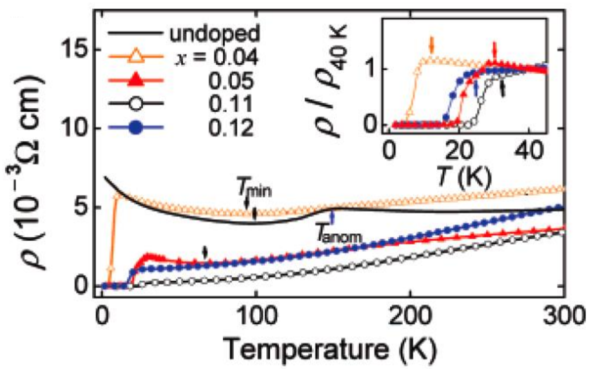
J|A|C|S
COMMUNICATIONS

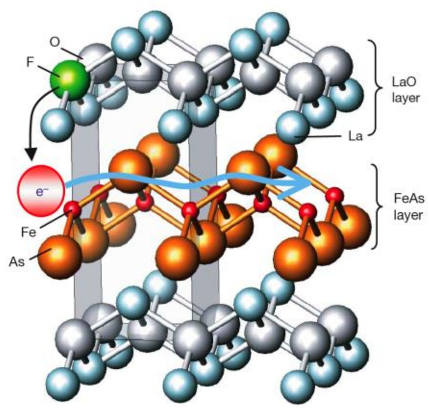
Published on Web 02/23/2008

Iron-Based Layered Superconductor $La[O_{1-x}F_x]FeAs$ ($x = 0.05-0.12$) with $T_c = 26$ K

Yoichi Kamihara,*[,†] Takumi Watanabe,[‡] Masahiro Hirano,[†,§] and Hideo Hosono[†,‡,§]

ERATO-SORST, JST, Frontier Research Center, Tokyo Institute of Technology, Mail Box S2-13, Materials and Structures Laboratory, Tokyo Institute of Technology, Mail Box R3-1, and Frontier Research Center, Tokyo Institute of Technology, Mail Box S2-13, 4259 Nagatsuta, Midori-ku, Yokohama 226-8503, Japan



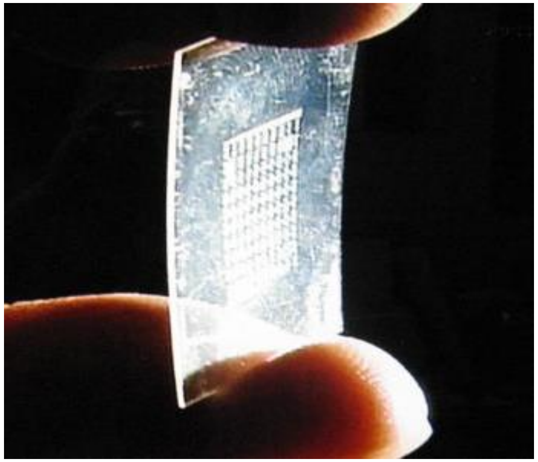


$LaFeAs(O_{1-x}F_x)$

Y. Kamihara *et al.*, JACS, **130**, 3296 (2008).

High-T_c superconductors

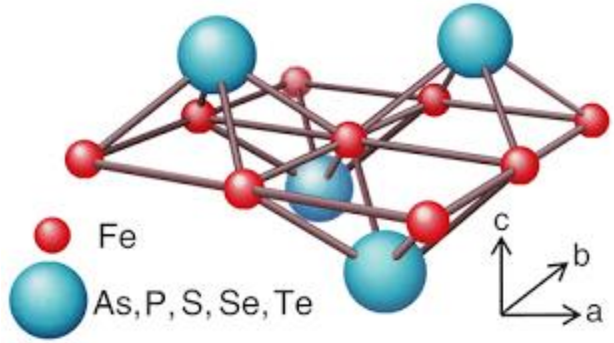
Hosono's group was not looking for superconductor, but trying to create new kind of transparent semiconductors for flat-panel display.



LaFePO	T_c=4 K
LaFeP(O,F)	T_c=7 K
LaFeAs(O,F)	T_c=26 K
SmFeAs(O,F)	T_c=56 K

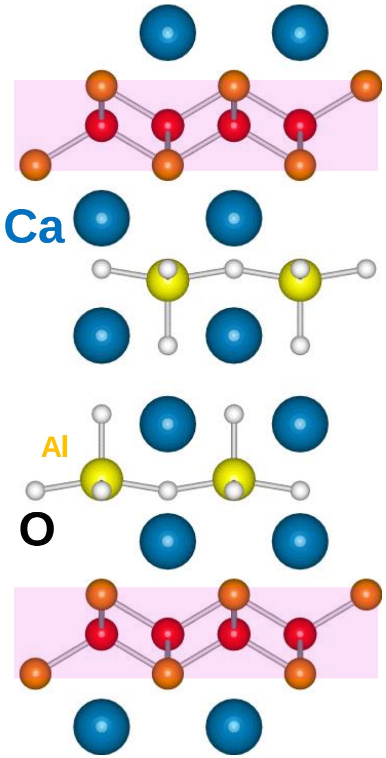
Only two months!

Fe-based high-T_c superconductors



2D square lattice of Fe

42622
(32522)

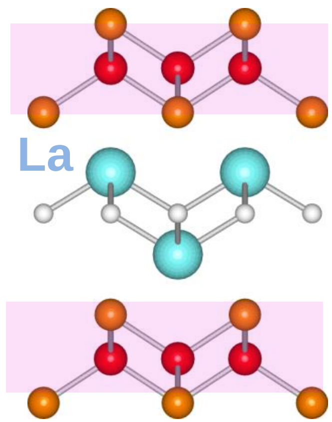


$(A_4M_2O_6)\ Fe_2As_2$

T_c(max)=47K

Zhu et al.(2009)
Ogino et al. (2009)

1111

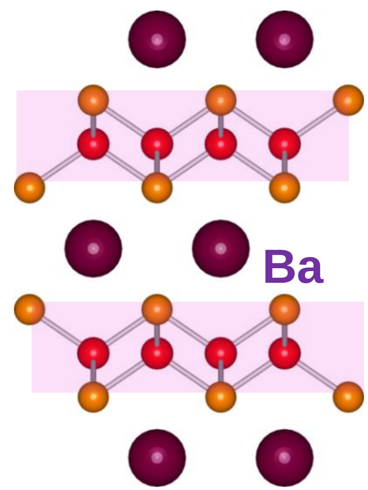


Ln FeAsO

T_c(max)=55K

Y. Kamihara et al.(2008)

122

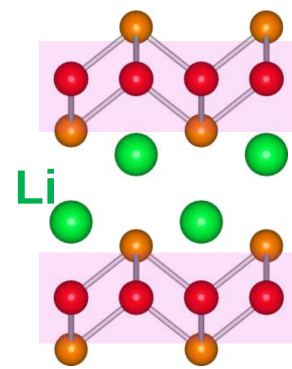


$BaFe_2As_2$

T_c(max)=38K

M. Rotter et al.(2008)

111

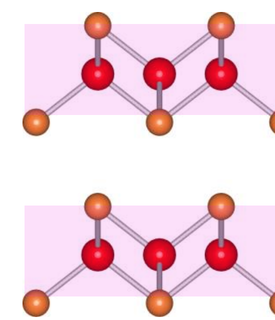


LiFeAs

T_c= 18 K

X.C.Wang et al.(2008)

11



FeSe

T_c= 8 K

F.C.Hsu et al.(2008)

Are iron-pnictides an Electron-Phonon Superconductor?

$$T_c \sim \omega_D e^{-\frac{1}{\lambda}}$$

$$\omega_D \sim 200\ \mathrm{K}$$

ω_D Debye frequency

$$\lambda \sim 0.2$$

λ Electron-phonon coupling

Comparable to the conventional metals

$\Rightarrow$ $T_c \sim 1\ \mathrm{K}$

Electron-phonon coupling is not sufficient to explain superconductivity in the whole family of Fe-As based superconductors

L. Boeri, O.V. Dolgov, and A.A. Golubov, PRL **101**, 026403 (2008).

Why are Fe-based HTSC important?

1. A new class of high temperature superconductors

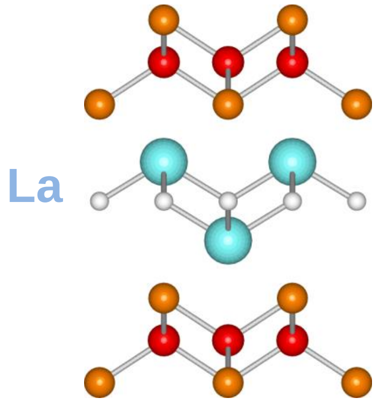
They knocked the cuprates off their pedestal as a unique class of high temperature superconductors.

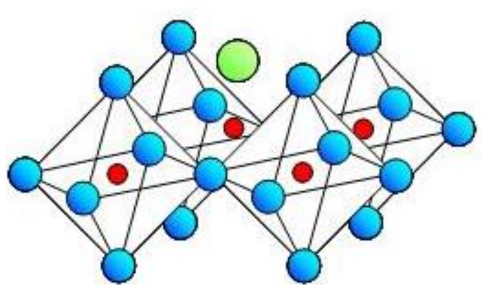
2. A new family of unconventional superconductors

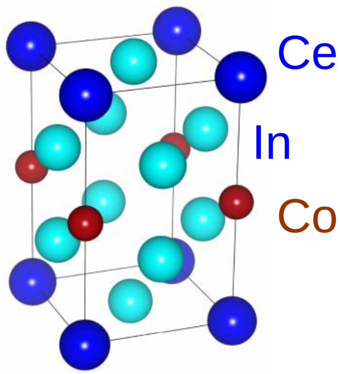
A possible new mechanism of high-T_c superconductivity

Three families of unconventional superconductor

Iron pnictide (Fe) | **Cuprate (Cu)** | **Heavy fermion compound (Ce, U)**







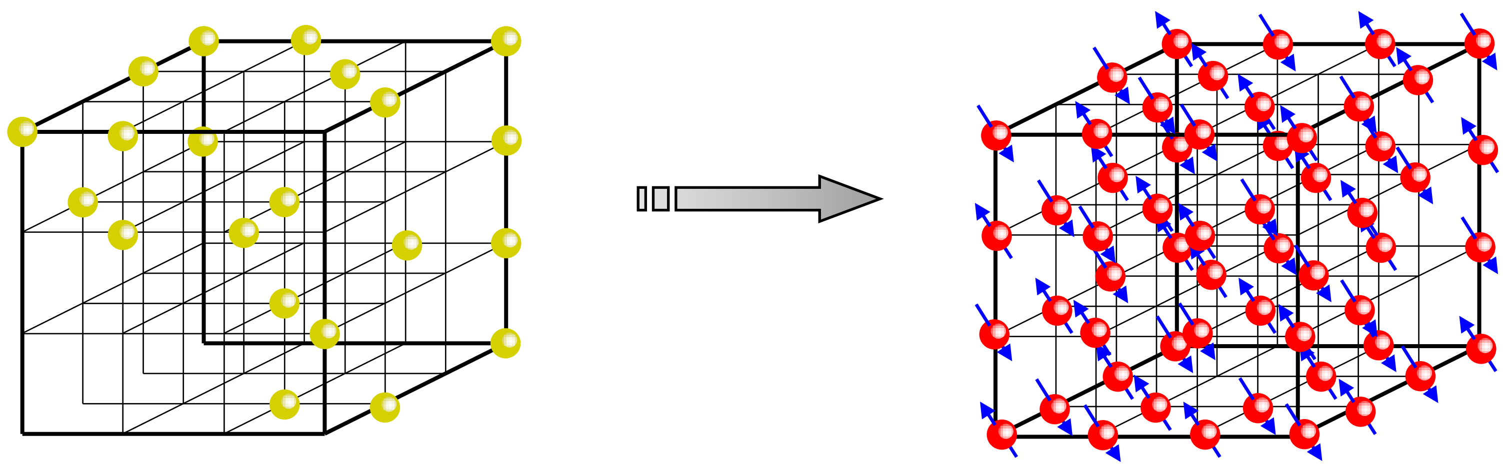
Weakly localized
3*d*-electrons

Strongly localized
3*d*-electrons

Very strongly localized
4*f*, 5*f* electrons

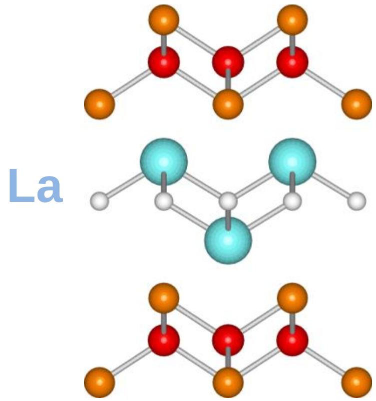
Weak correlation

Strong correlation

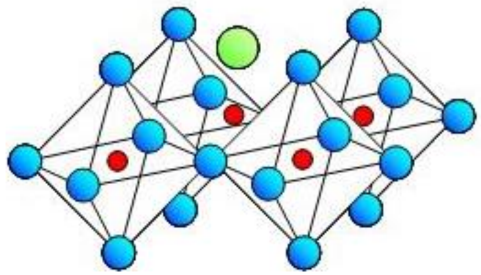


Three classes of unconventional superconductor

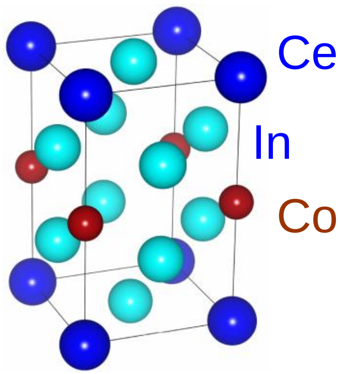
Iron pnictide (Fe)



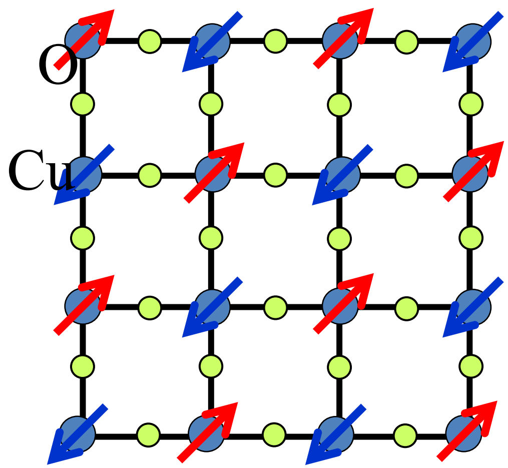
Cuprate (Cu)



Heavy fermion compound (Ce, U)

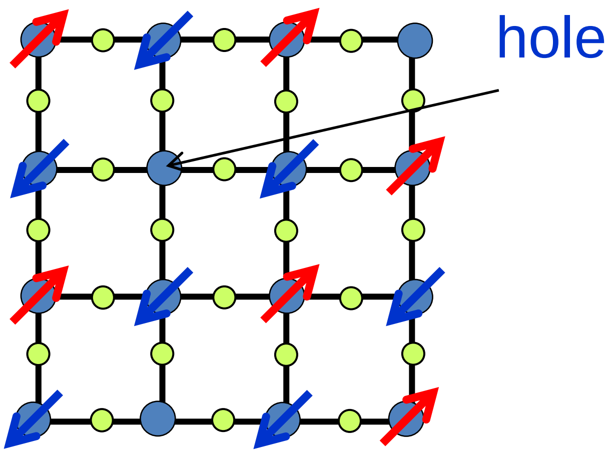


La_2CuO_4



Mott insulator

$(La_{1-x}Sr_x)_2CuO_4$ $La^{3+} \rightarrow Ba^{2+}$

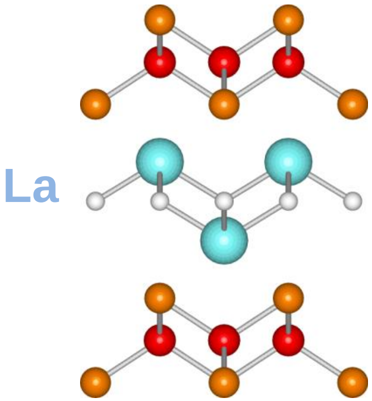


High-T_c superconductor

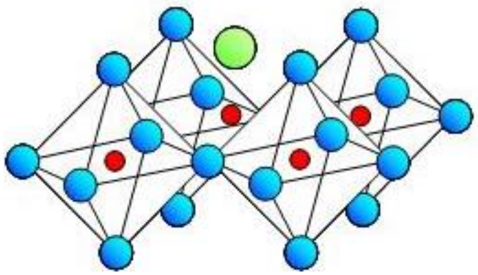
Carrier doping

Three families of unconventional superconductor

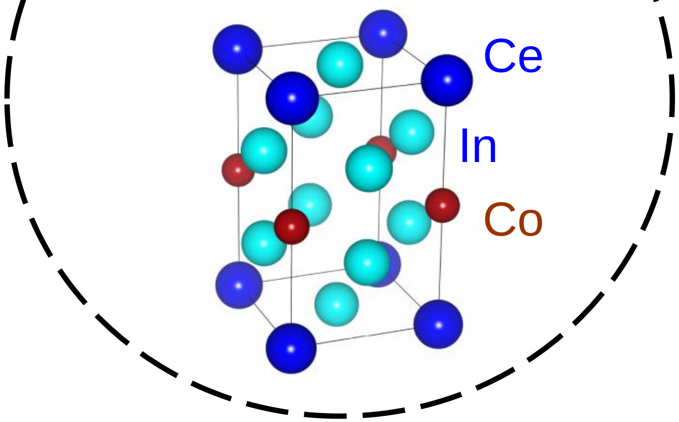
Iron pnictide (Fe)



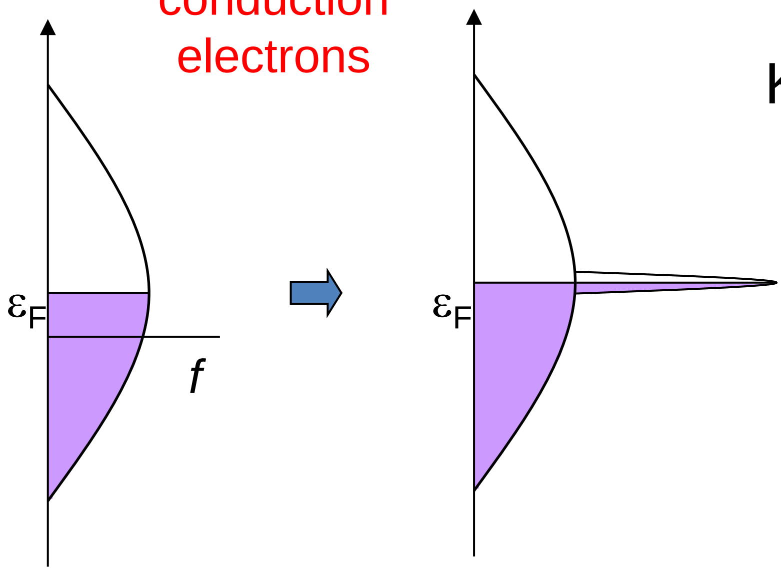
Cuprate (Cu)



Heavy fermion compound (Ce, U)



Hybridization with conduction electrons

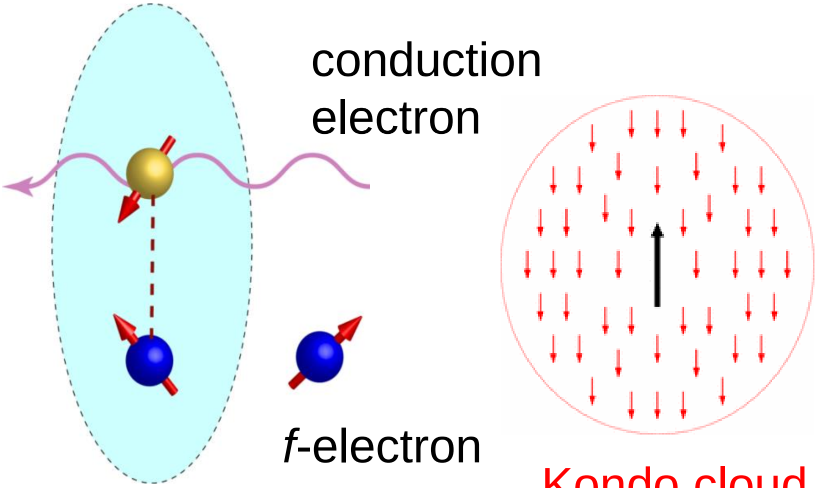


High temperature

Low temperature

Up to ~1000 times the free electron mass "Heavy Fermions"

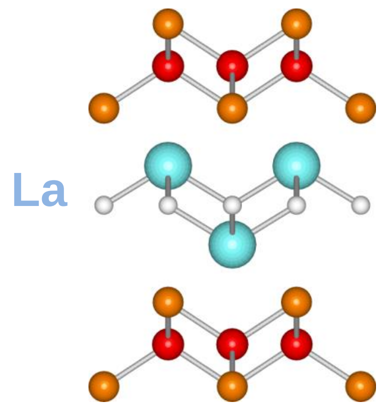
Kondo effect

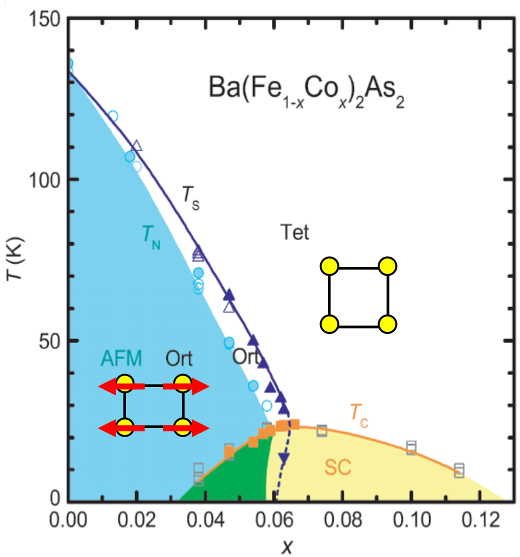


Kondo cloud

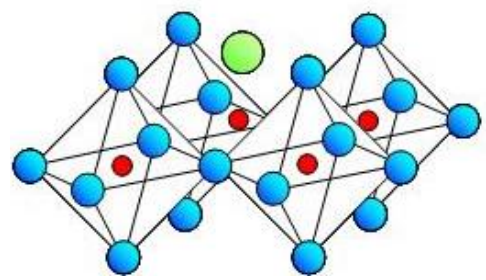
Three families of unconventional superconductor

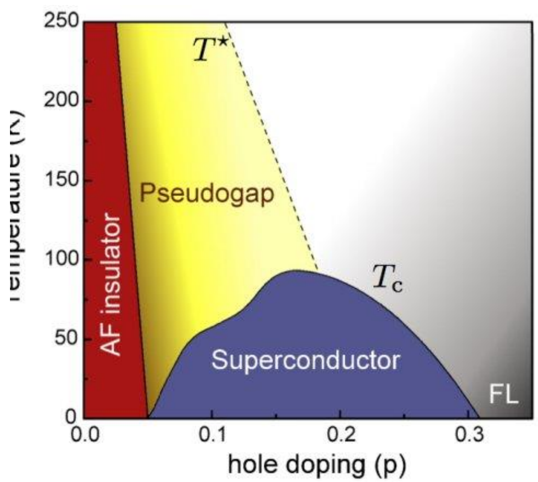
Iron pnictide (Fe)



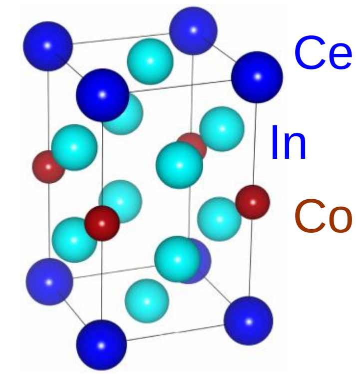


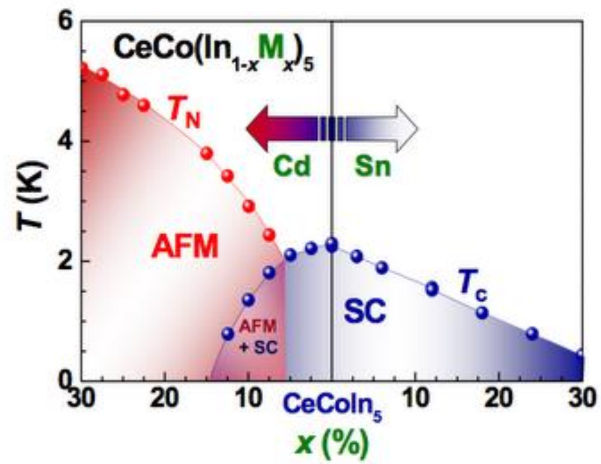
Cuprate (Cu)





Heavy fermion compound (Ce, U)



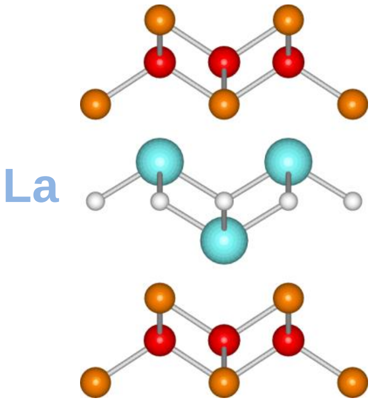


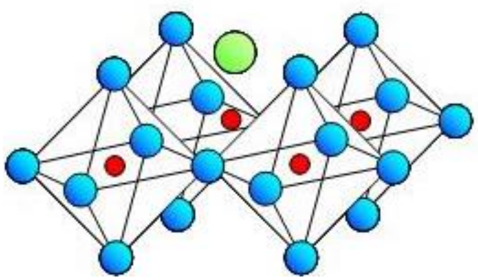
Superconductivity is induced by suppressing a magnetically ordered phase

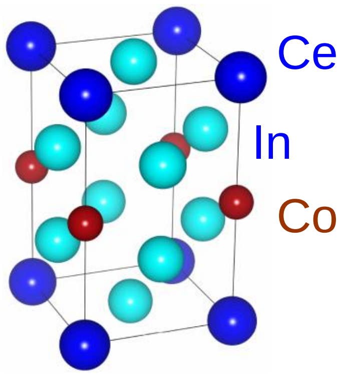
Magnetic fluctuations may bind the Cooper pairs

Three families of unconventional superconductor

Iron pnictide (Fe)	Cuprate (Cu)	Heavy fermion compound (Ce, U)



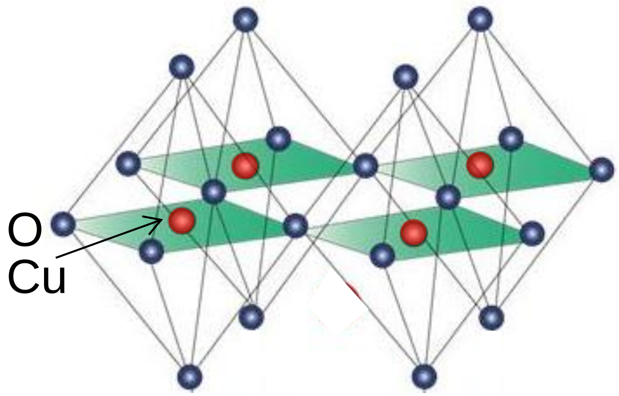




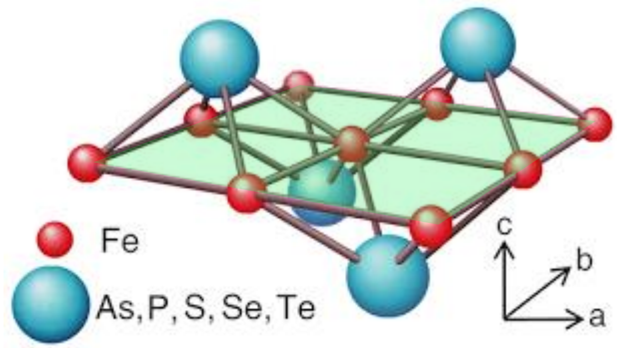
	Pnictide		Cuprate		Heavy Fermion
Electron correlation	strong	<	strong	<	very strong
Fermi surface	simple 2D		Very simple 2D		Complicated 3D
Magnetic structure	simple		simple		complicated
Physics	Multi-orbital		Mott		Kondo

Similarities and differences between cuprates and pnictides

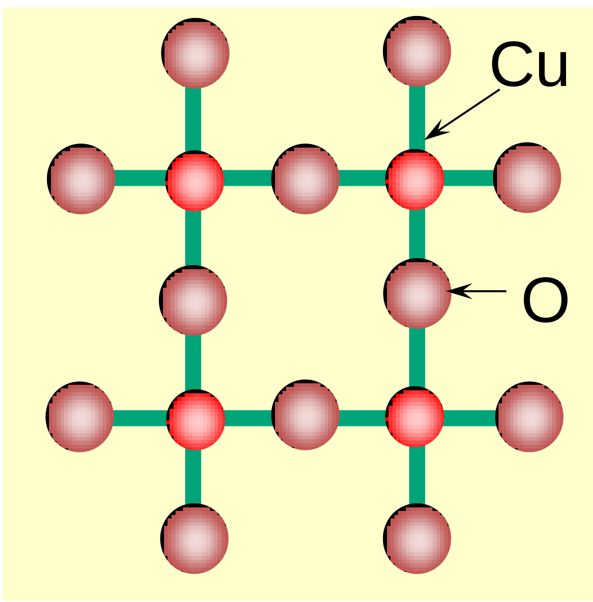
Cuprates

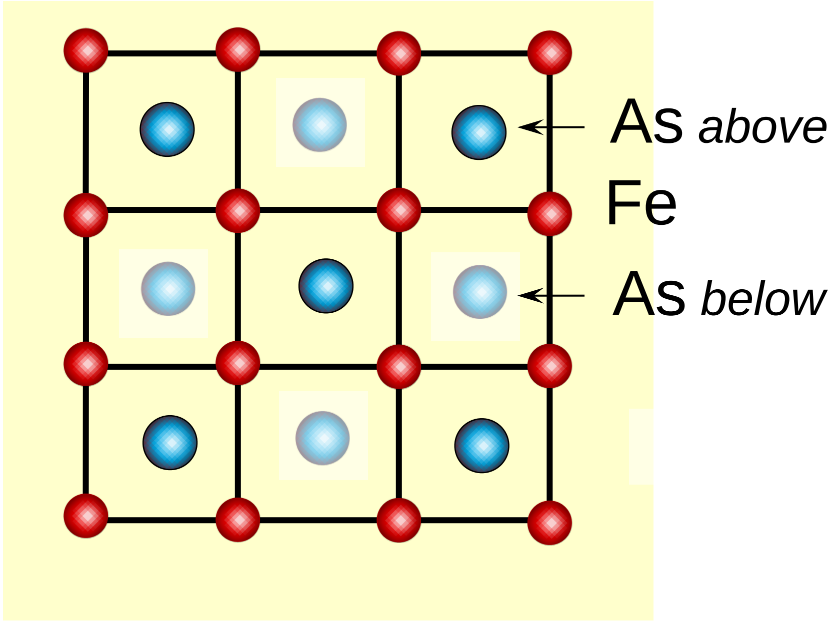


Fe-pnictides



Superconductivity in 2D planes

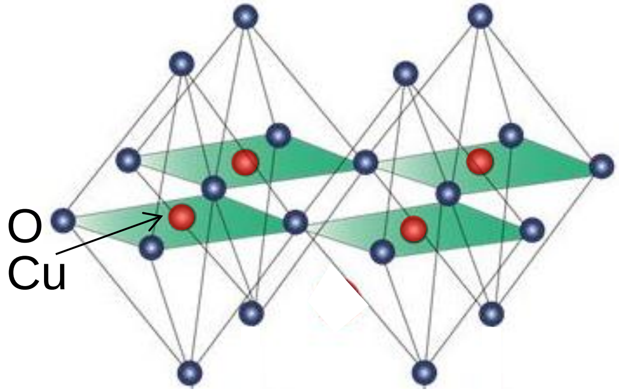




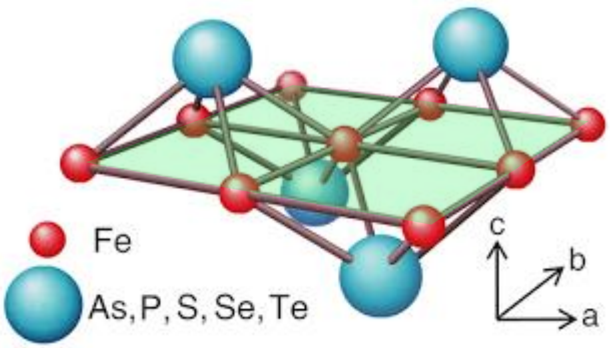
Enhanced fluctuations → suppression of magnetic order

Similarities and differences between cuprates and pnictides

Cuprates

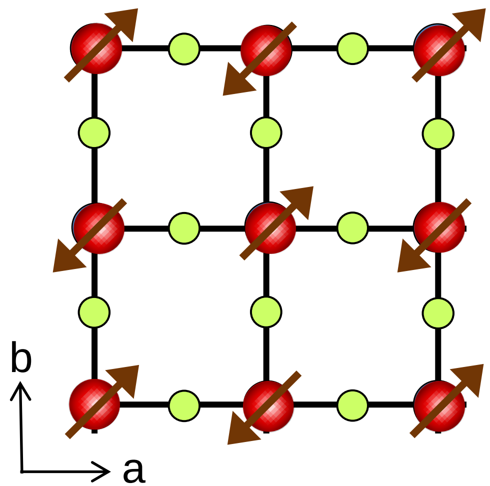


Fe-pnictides



Parent compound

AFM insulator



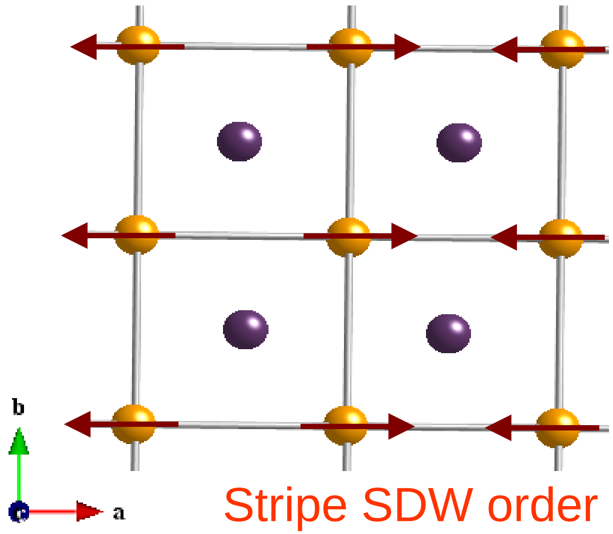
Cu

S=1/2 1 μ_B

~0.6 μ_B

2D quantum fluctuation

SDW metal

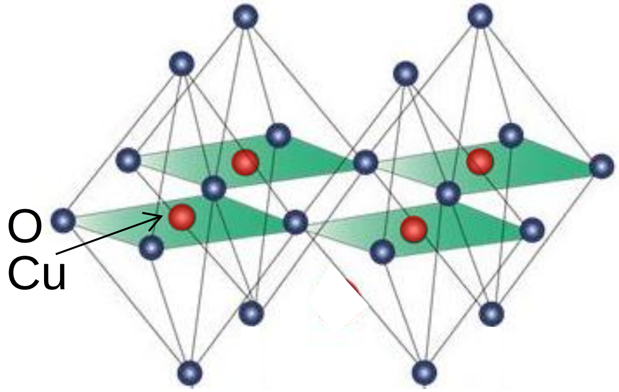


Stripe SDW order

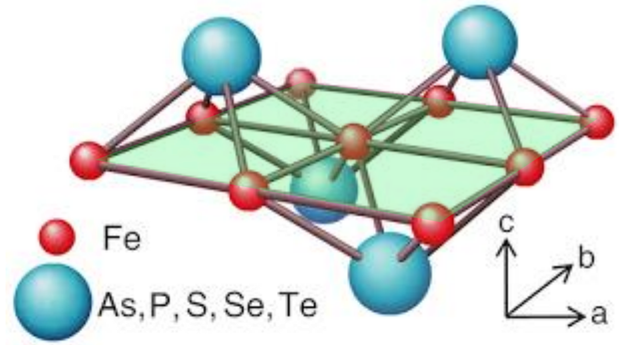
$BaFe_2As_2$ 0.8-1 μ_B

Similarities and differences between cuprates and pnictides

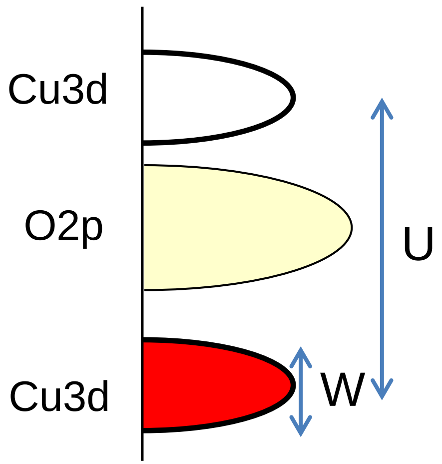
Cuprates



Fe-pnictides



Parent compound

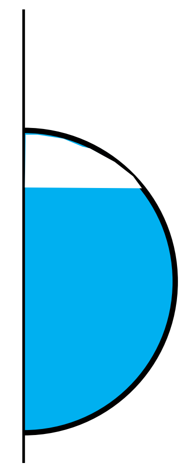


U : Coulomb ~ 8eV

W : Band width ~ 3eV

Strong electron-electron correlation

Mott insulator



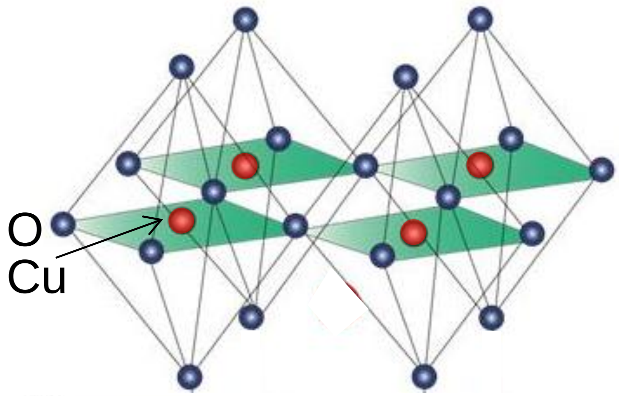
U~W~2-3 eV

Intermediate correlation

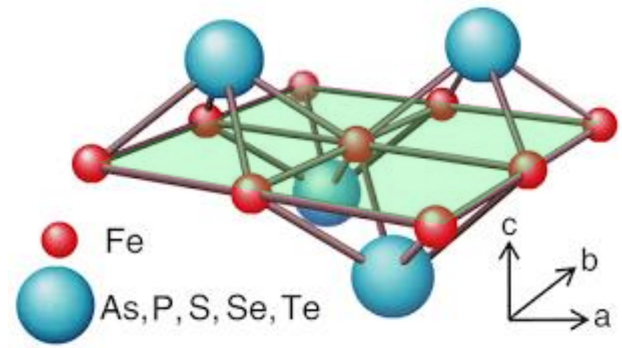
Spin density wave (SDW) metal

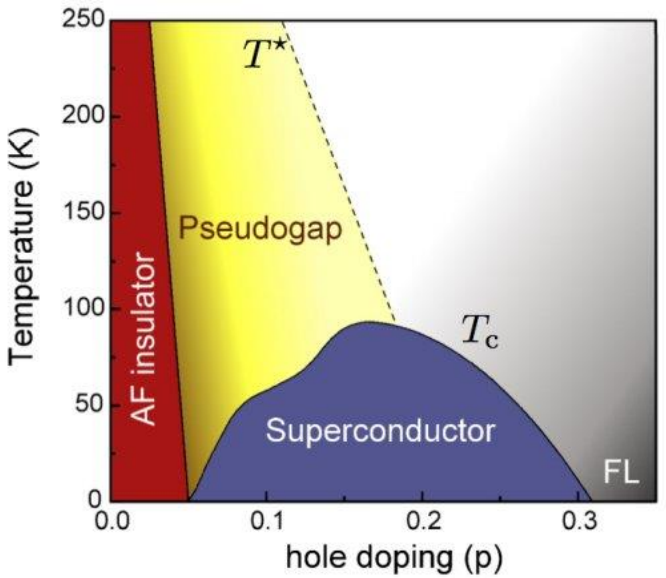
Similarities and differences between cuprates and pnictides

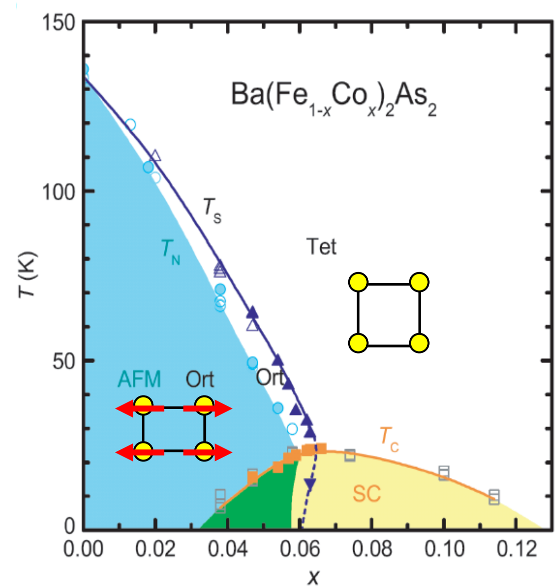
Cuprates



Fe-pnictides





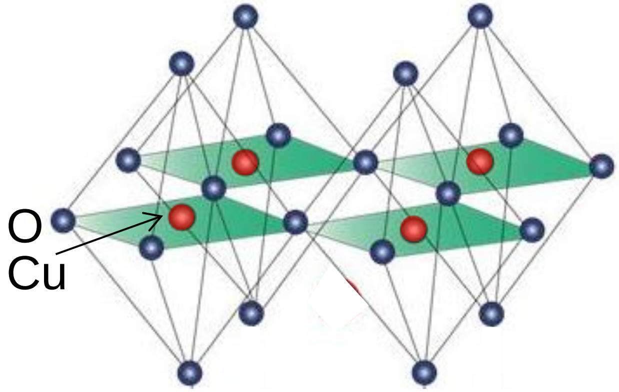


Superconductivity occurs in the vicinity of magnetic order

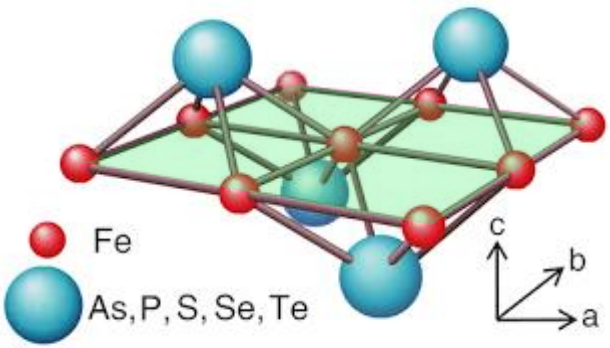
In Fe-pnictides, structural (T_S) and AFM transition (T_N) lines follow closely each other

Similarities and differences between cuprates and pnictides

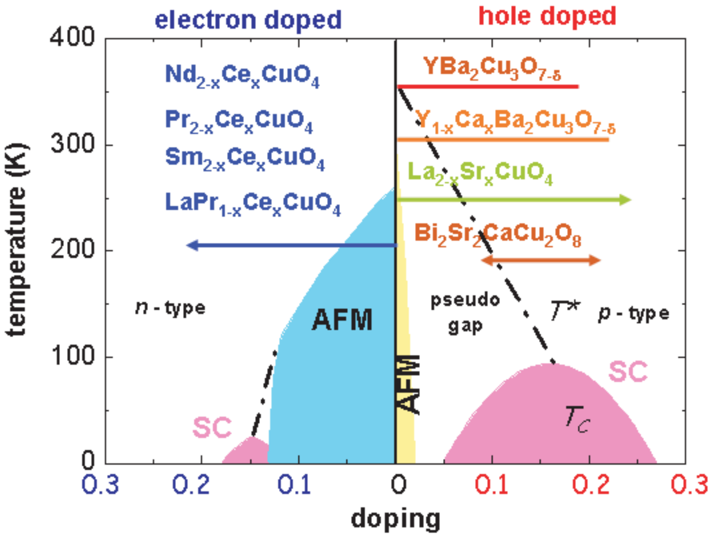
Cuprates



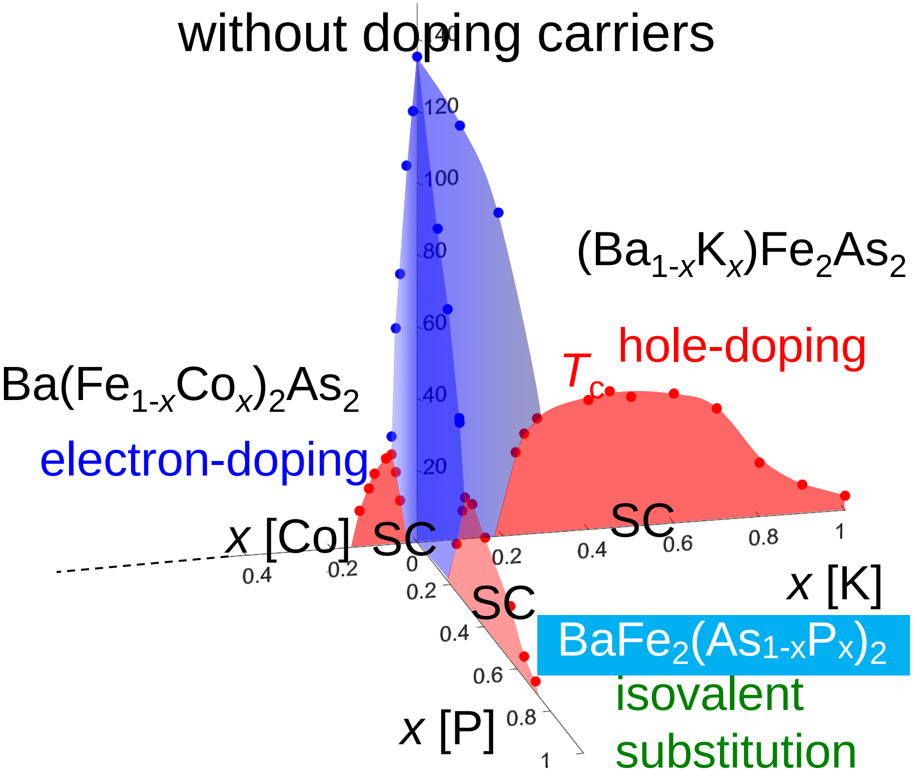
Fe-pnictides



Superconductivity induced by doping holes or electrons

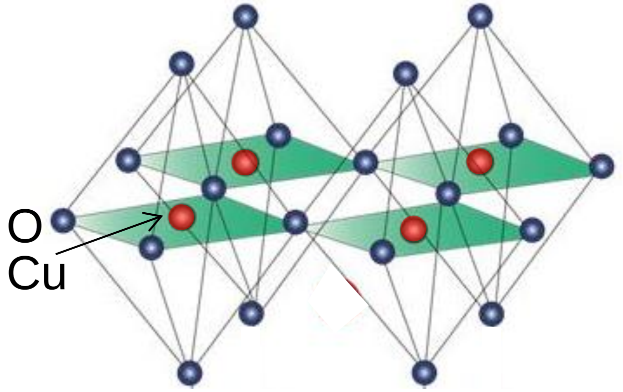


Ground state can be tuned without doping carriers

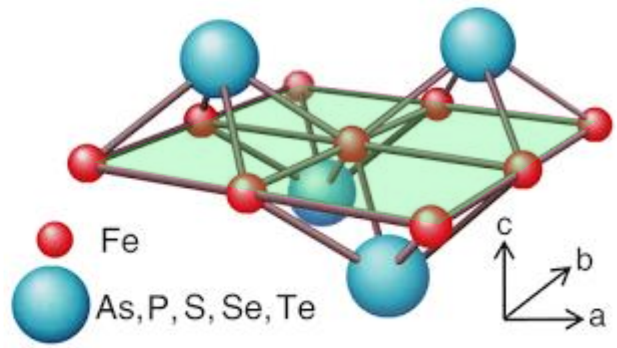


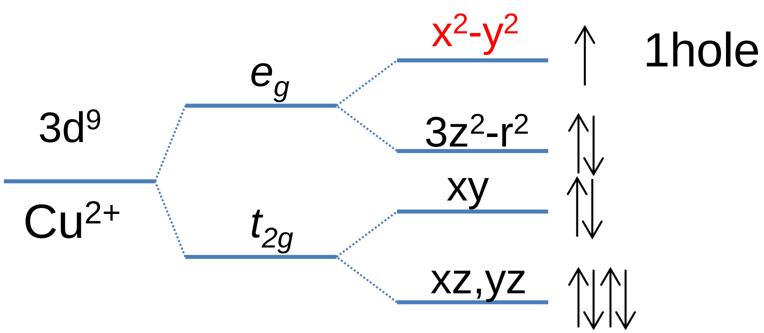
Similarities and differences between cuprates and pnictides

Cuprates

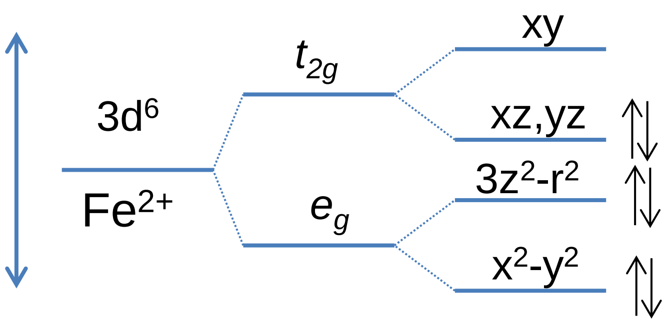


Fe-pnictides





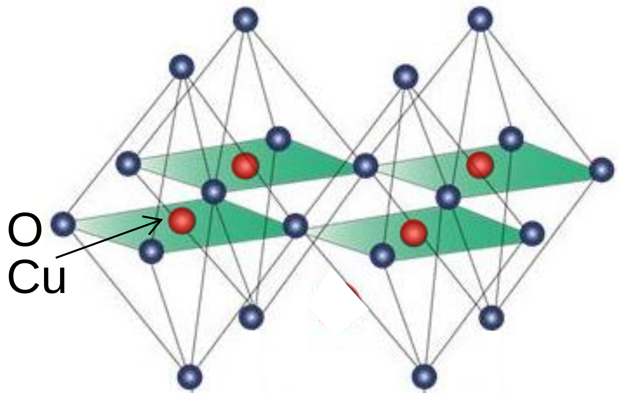
Large crystal field ~2-3 eV



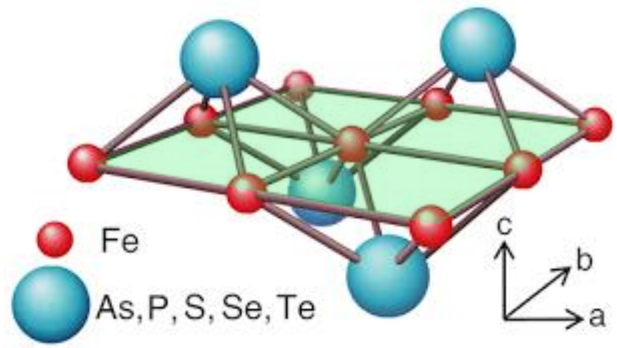
Small crystal field (~500meV)

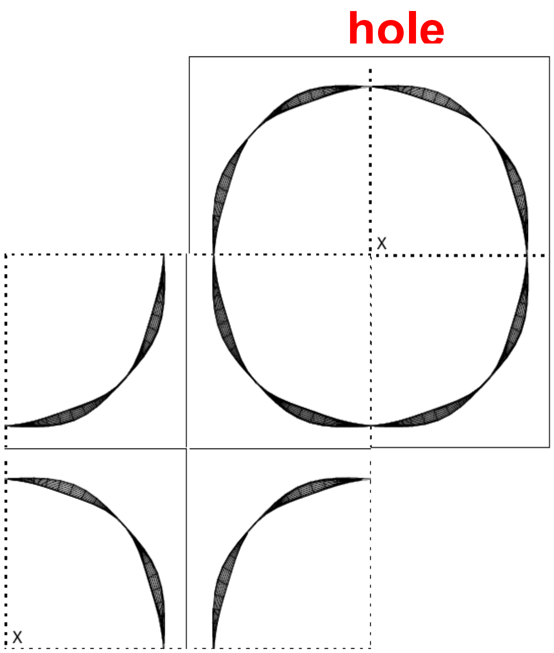
Similarities and differences between cuprates and pnictides

Cuprates

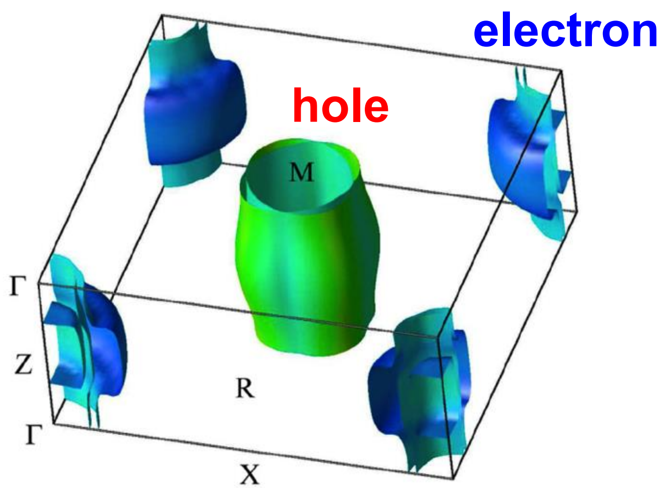


Fe-pnictides





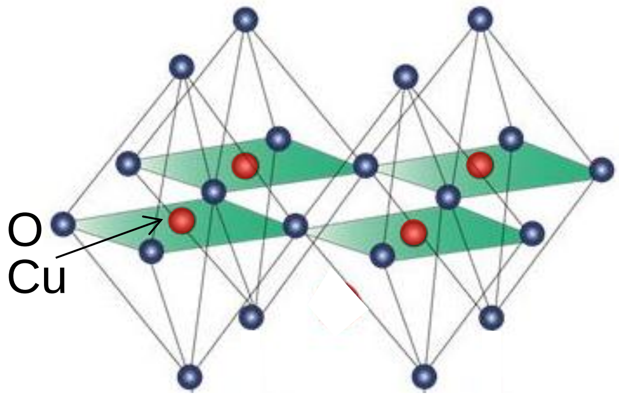
Only hole band



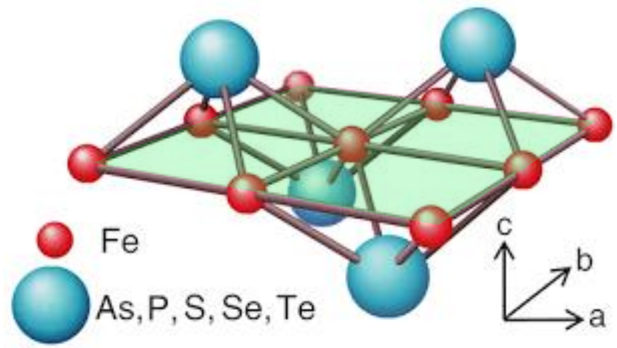
Well separated hole and electron bands

Similarities and differences between cuprates and pnictides

Cuprates

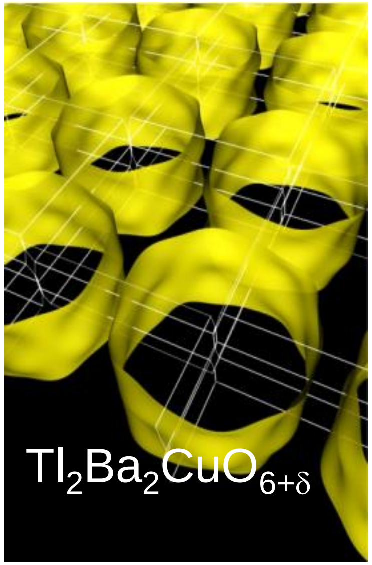


Fe-pnictides



One orbital

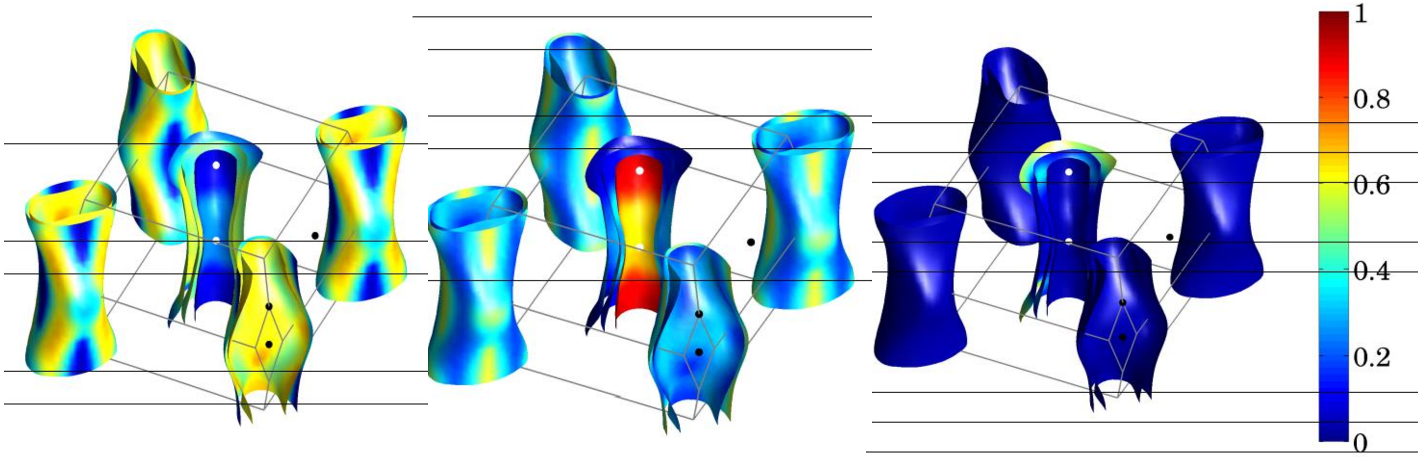
x^2-y^2



N. E. Hussey *et al.*, Nature (2003).

Mainly three orbitals

xz+yz | *xy* | *3z²-r²*



$BaFe_2As_2$

鉄系高温超伝導体

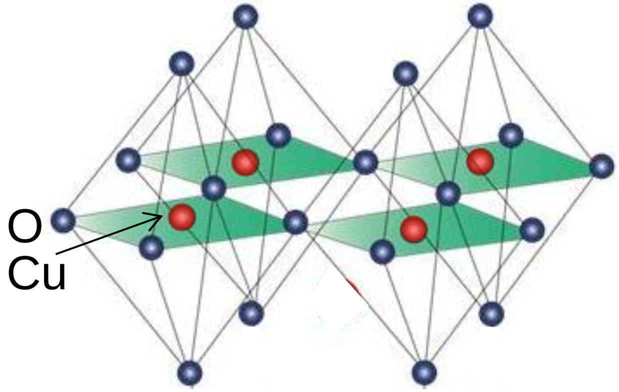
銅酸化物、重い電子系との比較

超伝導ギャップ構造

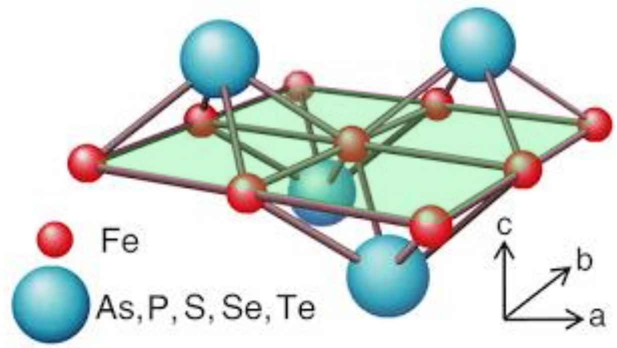
量子臨界点

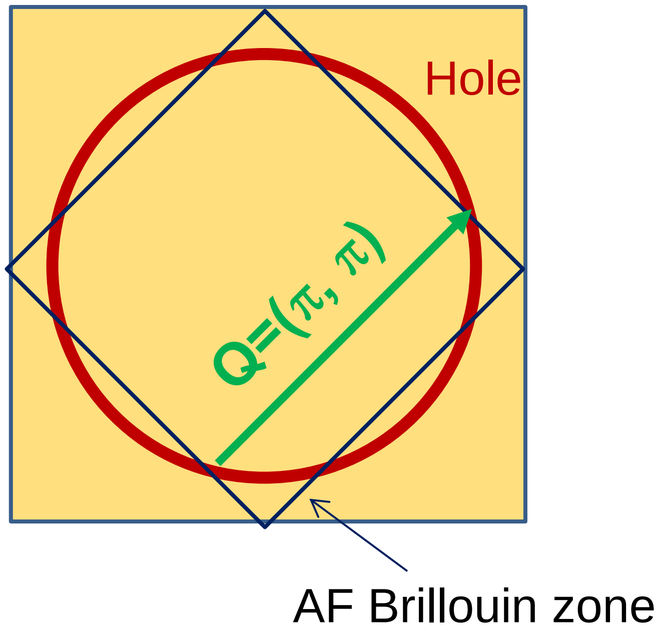
Similarities and differences between cuprates and pnictides

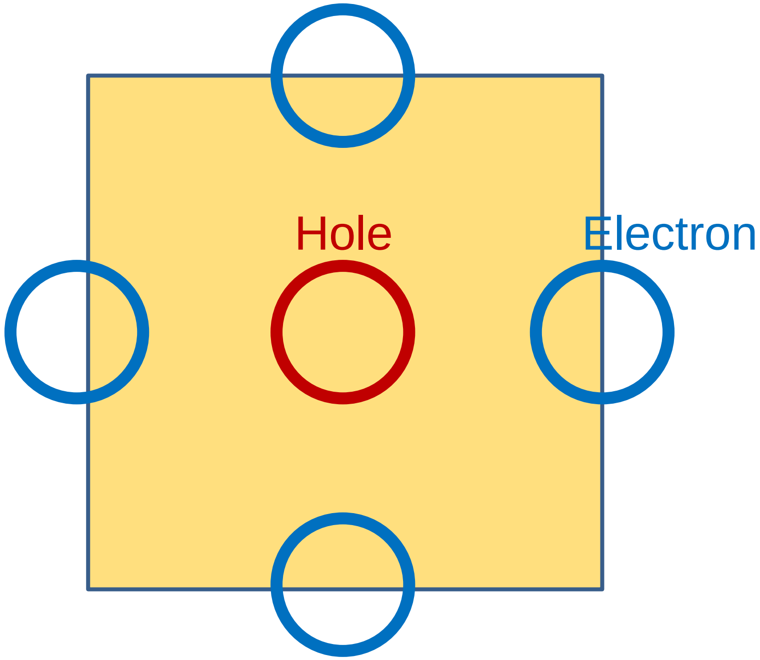
Cuprates



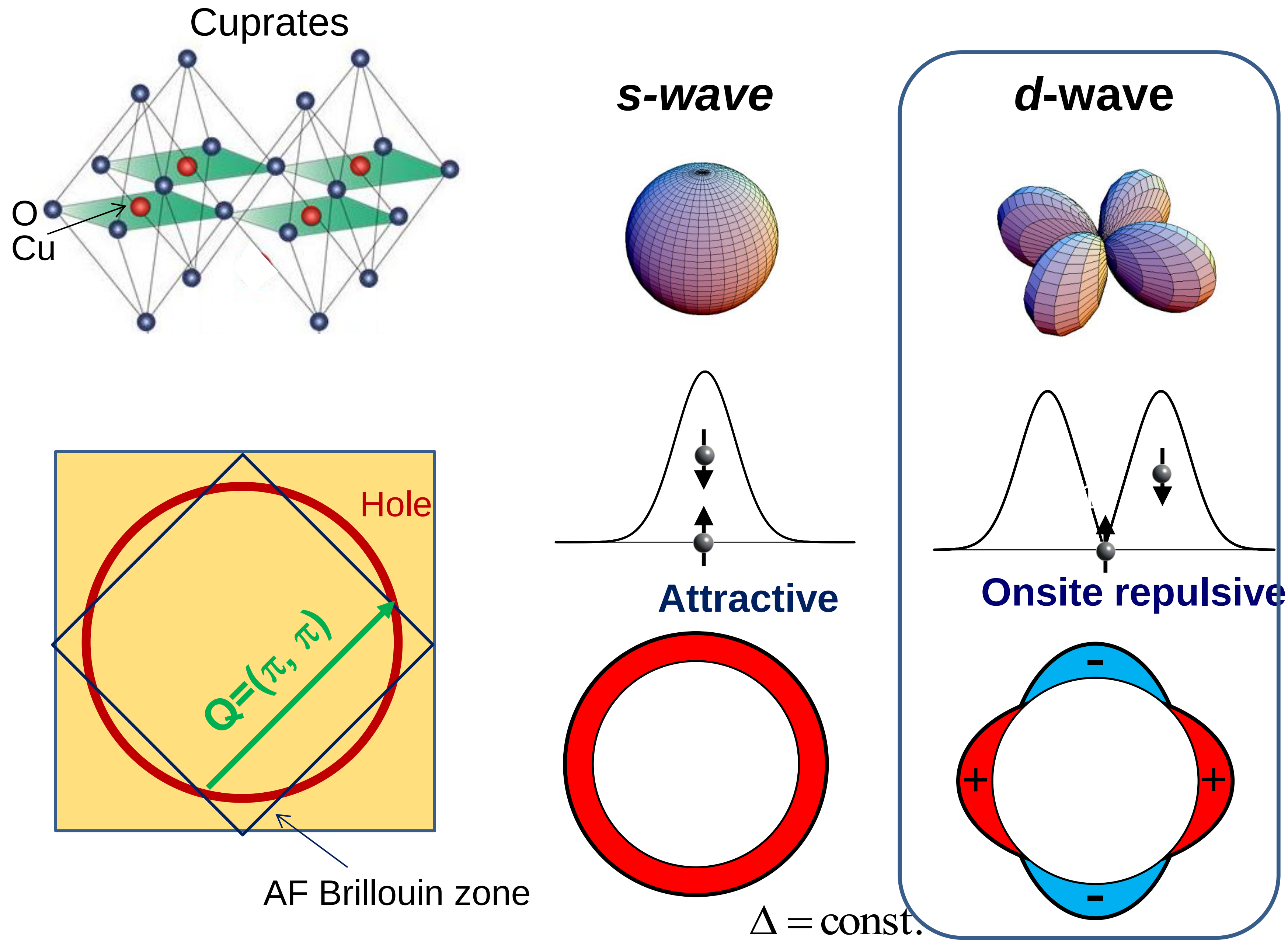
Fe-pnictides



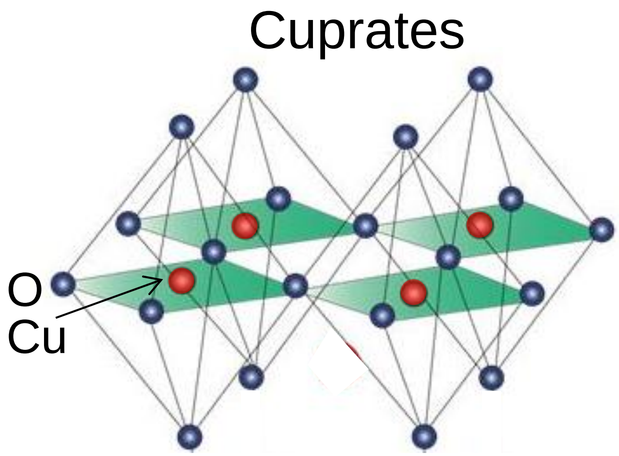


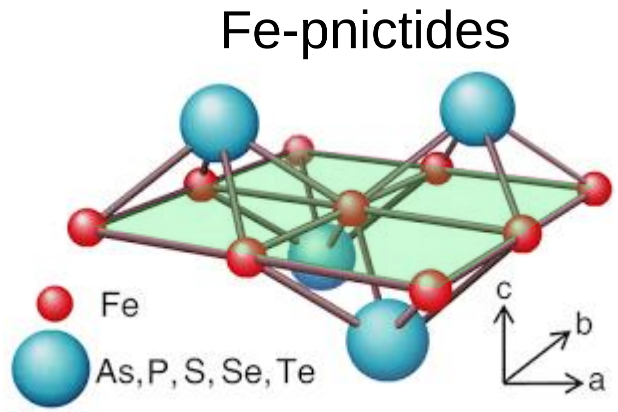


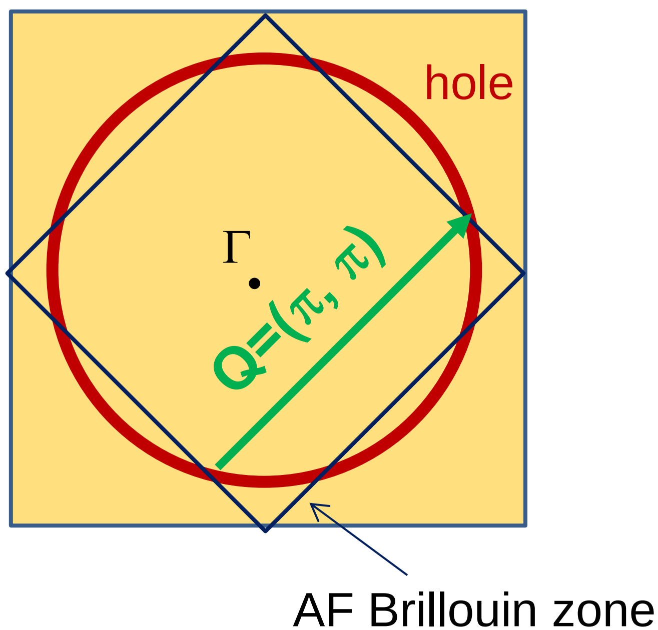
Similarities and differences between cuprates and pnictides

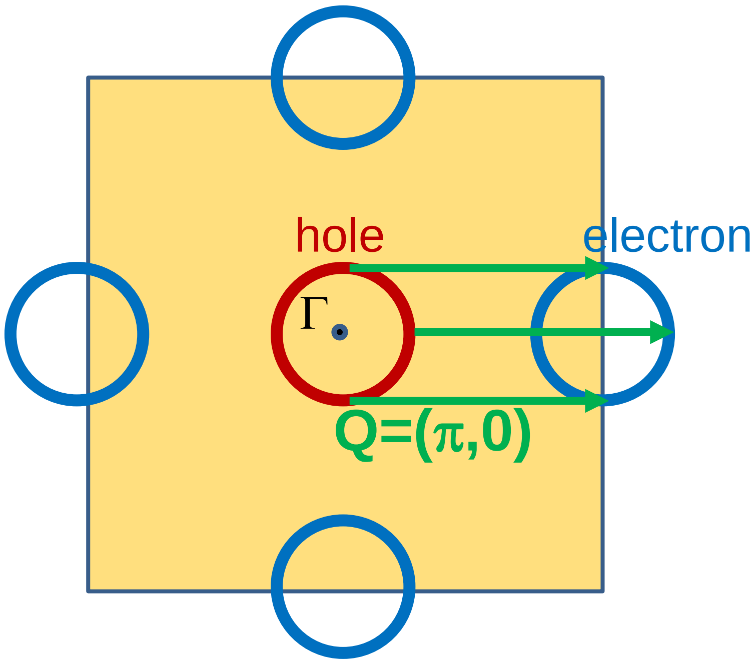


Similarities and differences between cuprates and pnictides



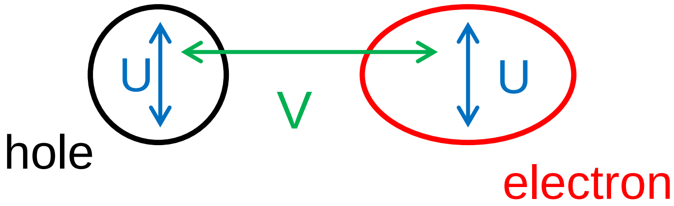


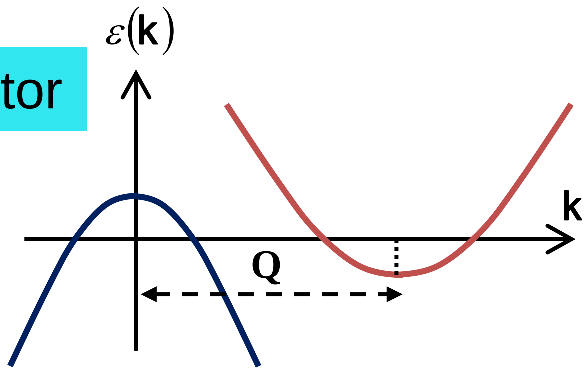




Iron pnictides: candidate for the SC state

Two band superconductor





disconnected Fermi surfaces

Gap equation

$$\Delta_e = -V\Delta_h \sum_q \frac{\tanh\frac{\varepsilon_q}{2T_c}}{\varepsilon_q} - U\Delta_e \sum_q \frac{\tanh\frac{\varepsilon_q}{2T_c}}{\varepsilon_q}$$

$$\Delta_h = -V\Delta_e \sum_q \frac{\tanh\frac{\varepsilon_q}{2T_c}}{\varepsilon_q} - U\Delta_h \sum_q \frac{\tanh\frac{\varepsilon_q}{2T_c}}{\varepsilon_q}$$

At T_c:

$$U = 0$$

$$|V|N(0)\ln\frac{W}{T_c} = 1$$

W: band width

$$\begin{pmatrix}\Delta_e \\ \Delta_h\end{pmatrix} = A\begin{pmatrix}0 & -1 \\ -1 & 0\end{pmatrix}\begin{pmatrix}\Delta_e \\ \Delta_h\end{pmatrix} \qquad A = \pm 1$$

$V > 0$ — repulsive — $A = +1$ — $\Delta_e = -\Delta_h$ — Sign change — $S_\pm$

$V < 0$ — attractive — $A = -1$ — $\Delta_e = \Delta_h$ — No sign change — S_{++}

Superconducting gap structure of iron pnictides

Gap structure is closely related to the pairing interaction

Full gap or nodal?

Full gap

Does the gap change sign between the hole and electron pockets?

Is the major pairing interaction repulsive or attractive?

Nodal

⇨ Presence of repulsive interaction.

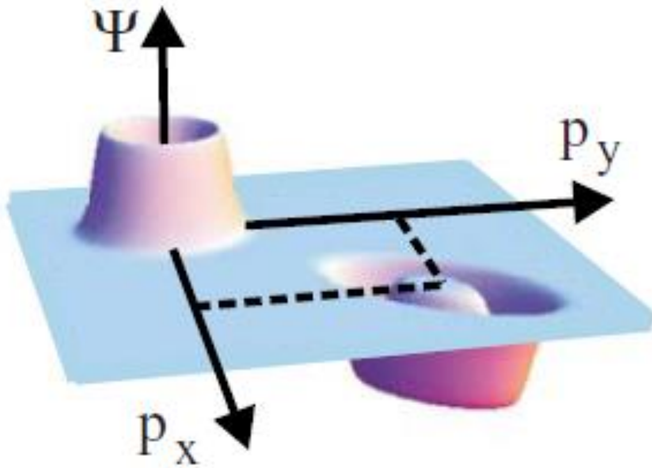
Is the node accidental or symmetry protected?

Accidental : presence of two (or more) competing pairing interactions

Iron pnictides: candidate for the SC state

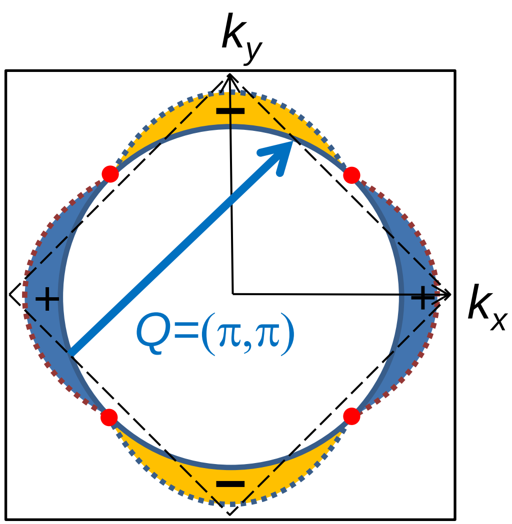
- Pairing due to purely repulsive electronic interaction (enhanced by spin fluctuations)

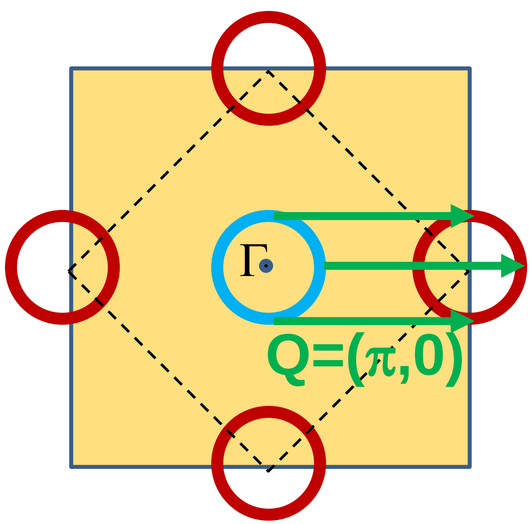
$$V > 0$$



s_{+-}

cf. *d*-wave cuprate





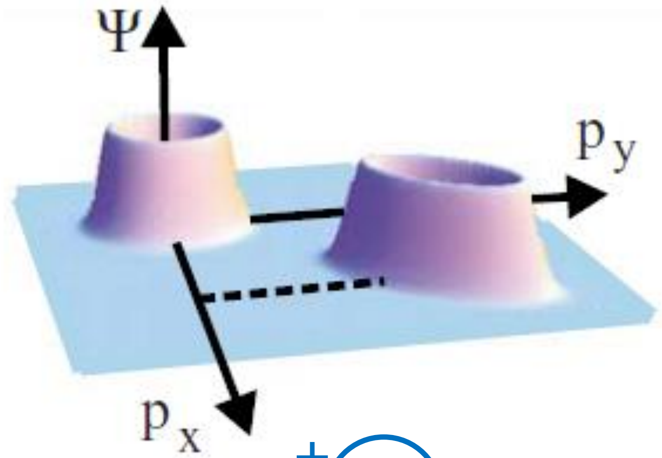
I. I. Mazin *et al.*, PRL **101**, 057003 (2008).
K. Kuroki *et al.*, PRL **101**, 087004 (2008).
& PRB **79**, 224511 (2009).
A. V. Chubkov *et al.*, PRB **80**, 140515(R) (2009).
S. Graser *et al.*, NJP **11**, 025016 (2009).
H. Ikeda, PRB **81**, 054502 (2010).
K. Seo *et al.*, PRL **101**, 206404 (2008).
F. Wang *et al.*, PRL **102**, 047005 (2009).

⋮

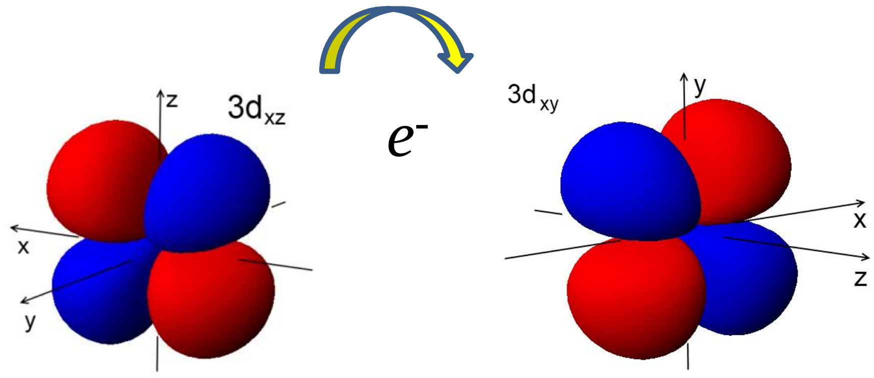
Iron pnictides: candidate for the SC state

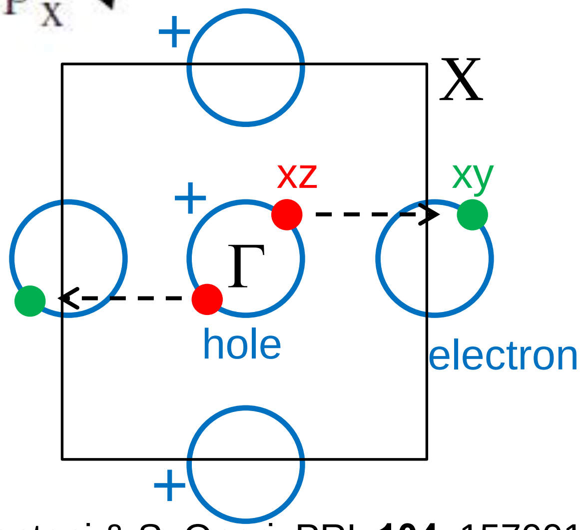
- Pairing due to attractive interaction caused by charge/orbital fluctuations.

S_{++} $V < 0$



Orbital fluctuations
(Quadrupole fluctuation)





Charge up   Charge down

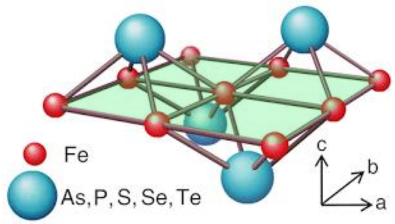
Occupation number of each orbit at each Fe site fluctuates

H. Kontani & S. Onari, PRL **104**, 157001 (2010).
F. Kruger *et al.*, PRB **79**, 054504 (2009).
Y. Yanagi *et al.*, PRB **81**, 054518 (2010).

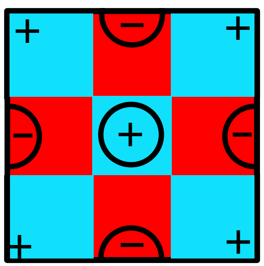
Iron pnictides: candidate for the SC state

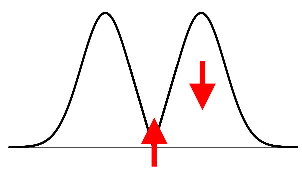
S_{+-}

Fe-pnictides

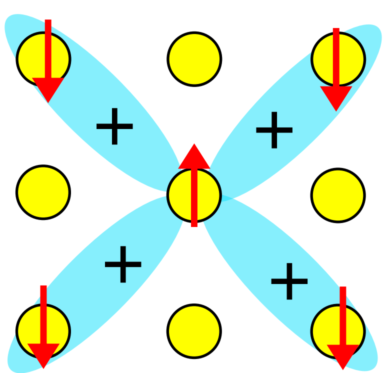


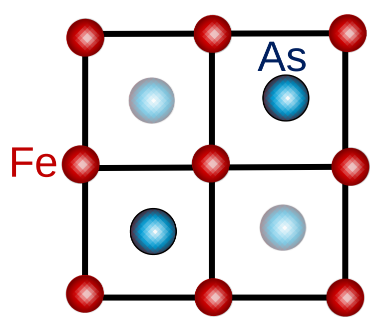
k-space (repulsive)





r-space

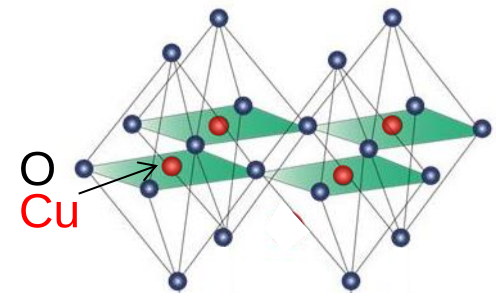




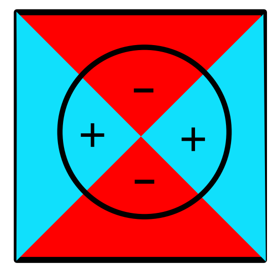
$$\Delta(\cos k_x \cos k_y)$$

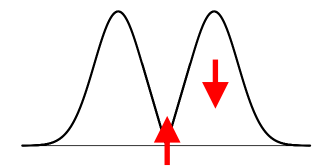
$d_{x^2-y^2}$

Cuprates

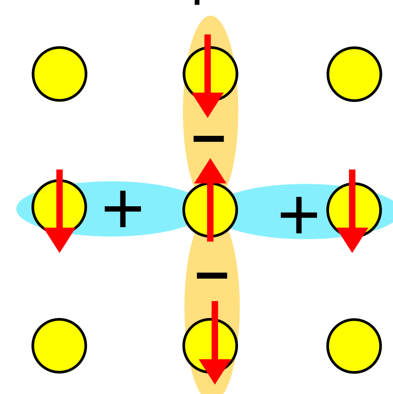


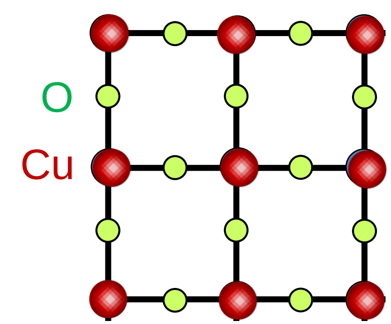
k-space (repulsive)





r-space



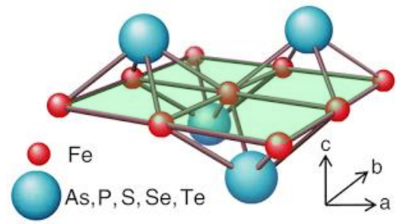


$$\Delta(\cos k_x - \cos k_y)$$

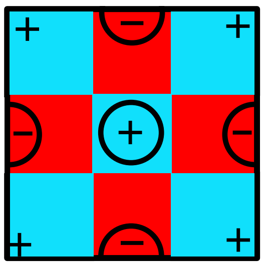
Iron pnictides: candidate for the SC state

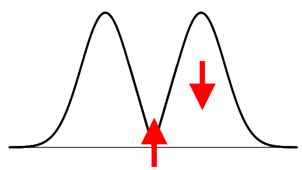
S_{+-}

Fe-pnictides

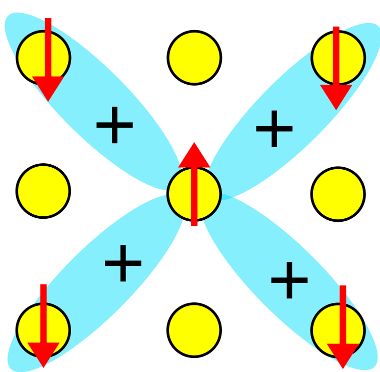


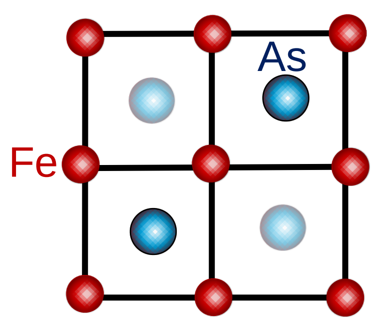
k-space (repulsive)





r-space

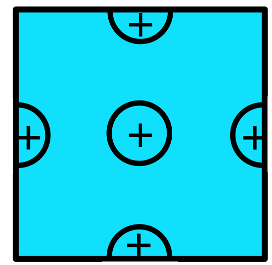


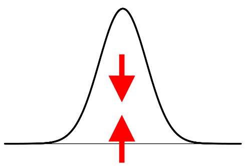


$$\Delta(\cos k_x \cos k_y)$$

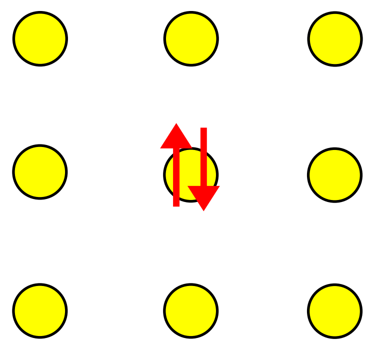
S_{++}

k-space (attractive)





r-space

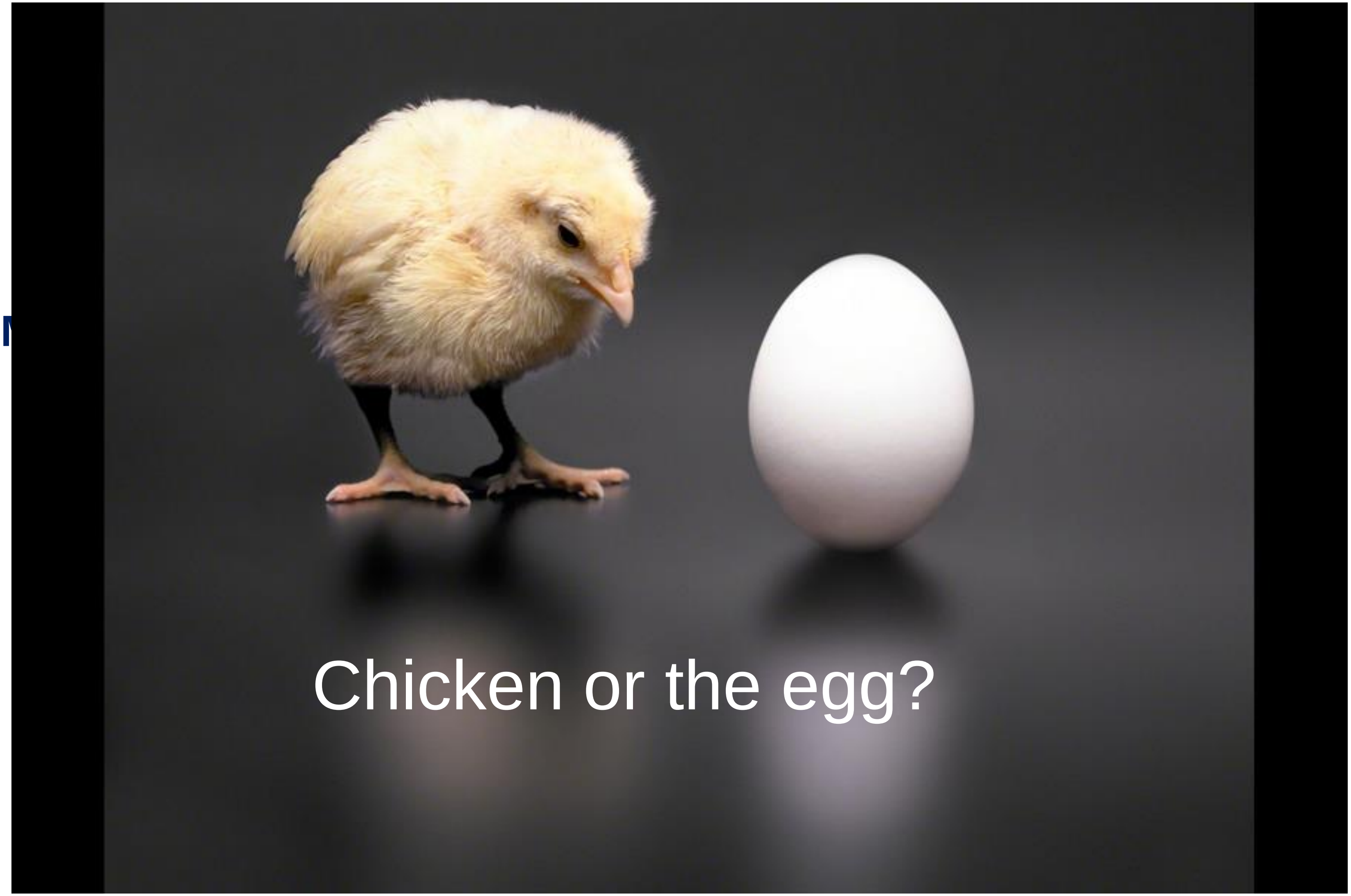


$$\Delta$$

Iron pnictides: candidate for the SC state

AF

ng



Spin fluctuations or orbital fluctuations?

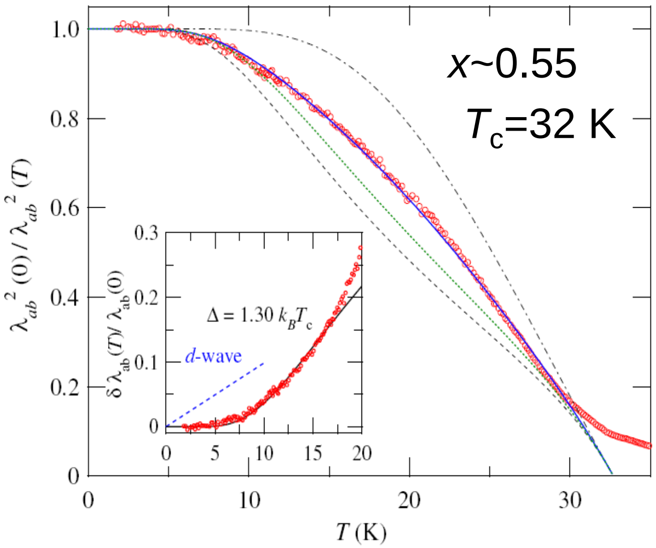
Gap structure of iron pnictides

Full gap or nodal?

Full gap superconductivity

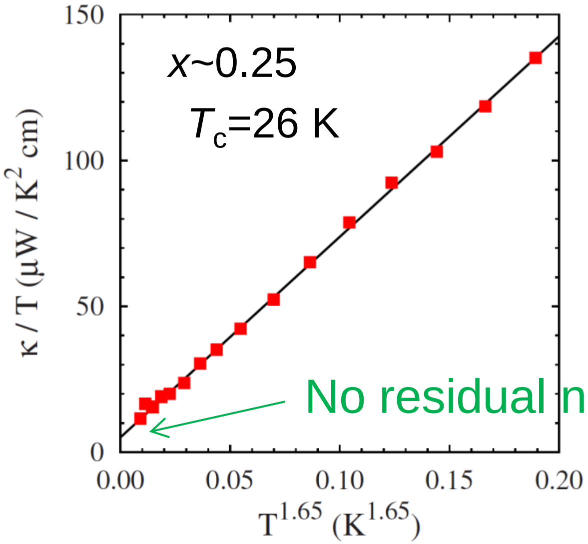
hole doped $Ba_{1-x}K_xFe_2As_2$

Penetration depth



K. Hashimoto, *et al.*, PRL **102**, 027001 (2009).

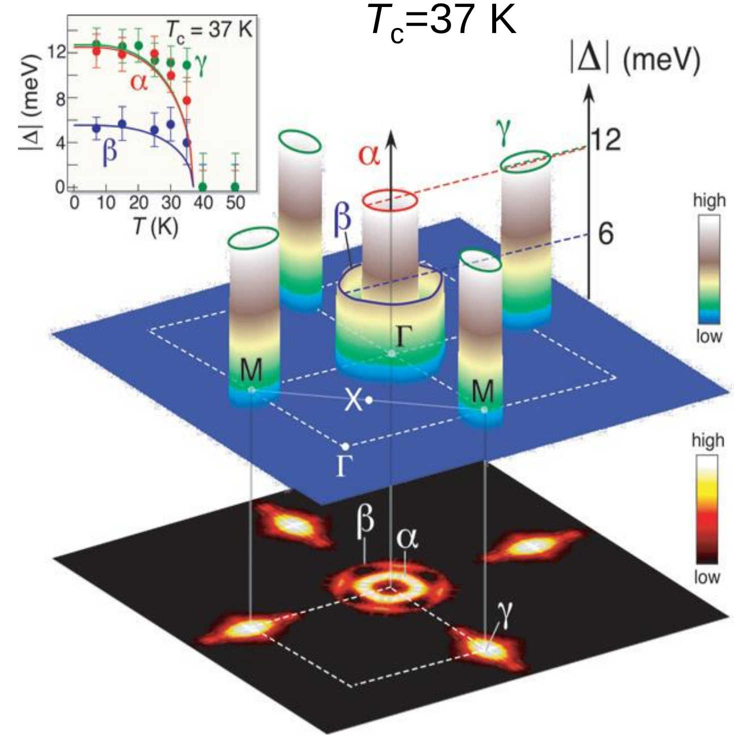
Thermal conductivity



No residual normal fluid

X.G. Luo *et al*. PRB 80, 140503 (2009).

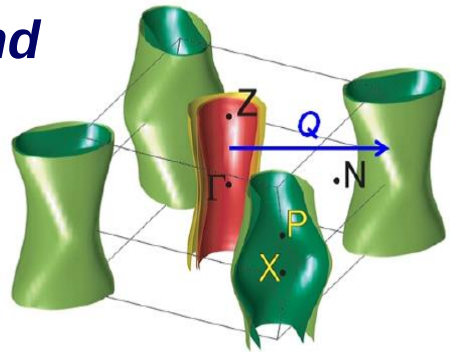
ARPES

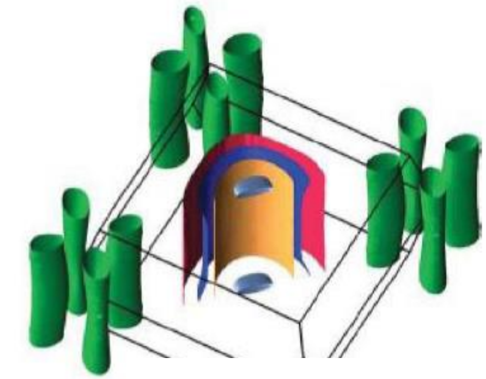


H. Ding *et al.*, EPL **83**, 47001 (2008).

Superconductivity in $BaFe_2As_2$ systems

Parent compound
$BaFe_2As_2$
(AF Metal)

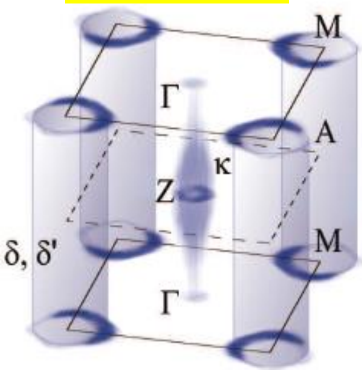


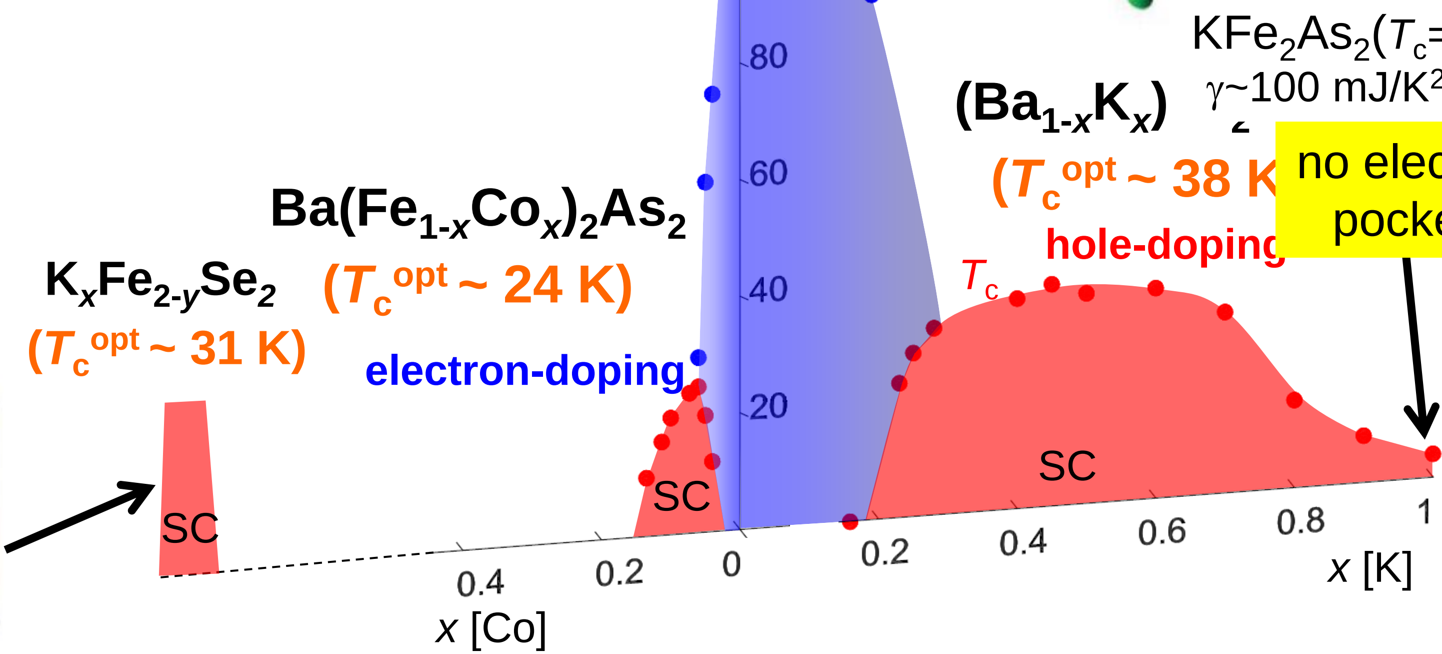


KFe$_2$As$_2$(T_c=3 K)
γ~100 mJ/K^{2}mol

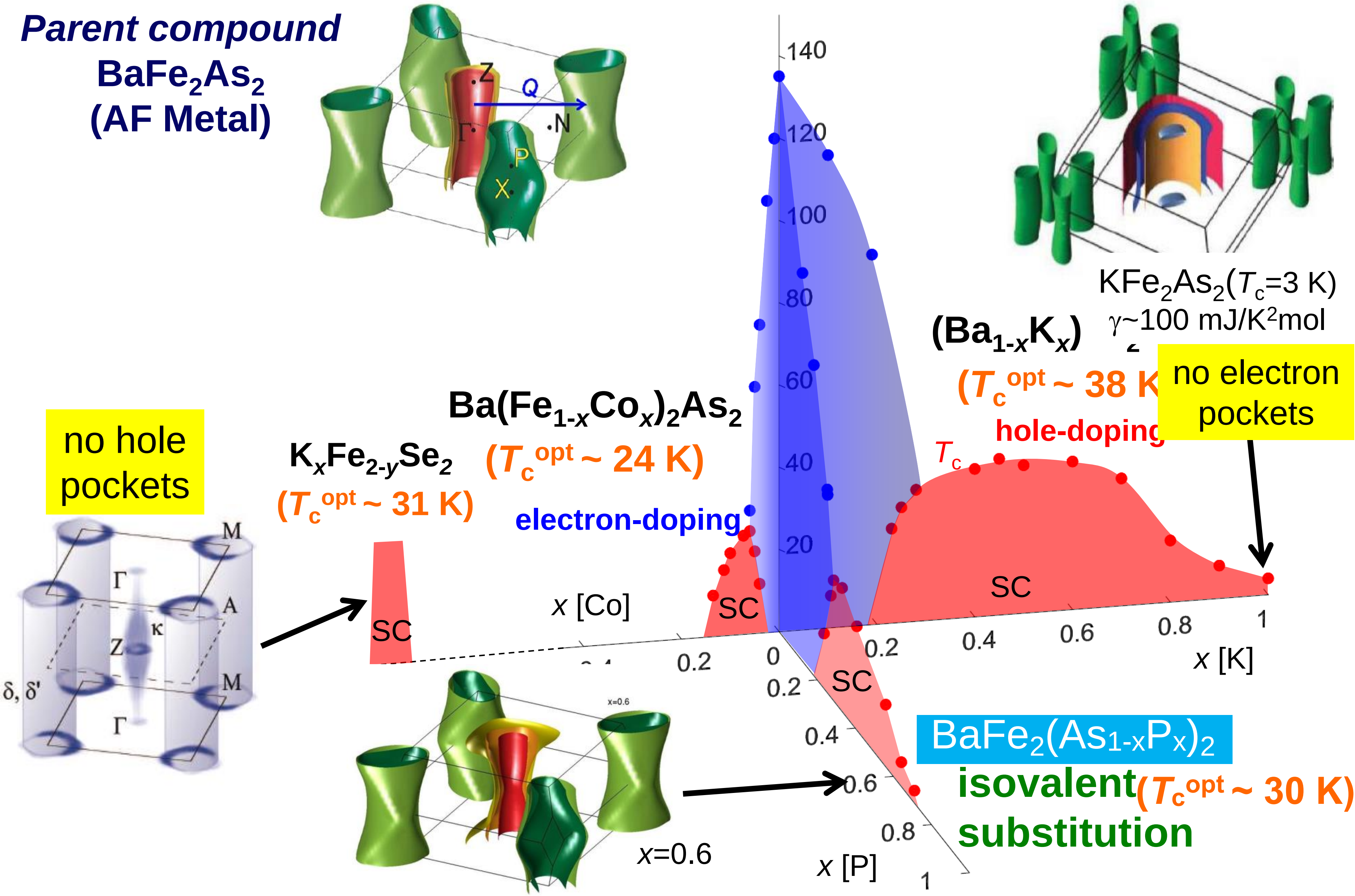
no electron pockets

no hole pockets



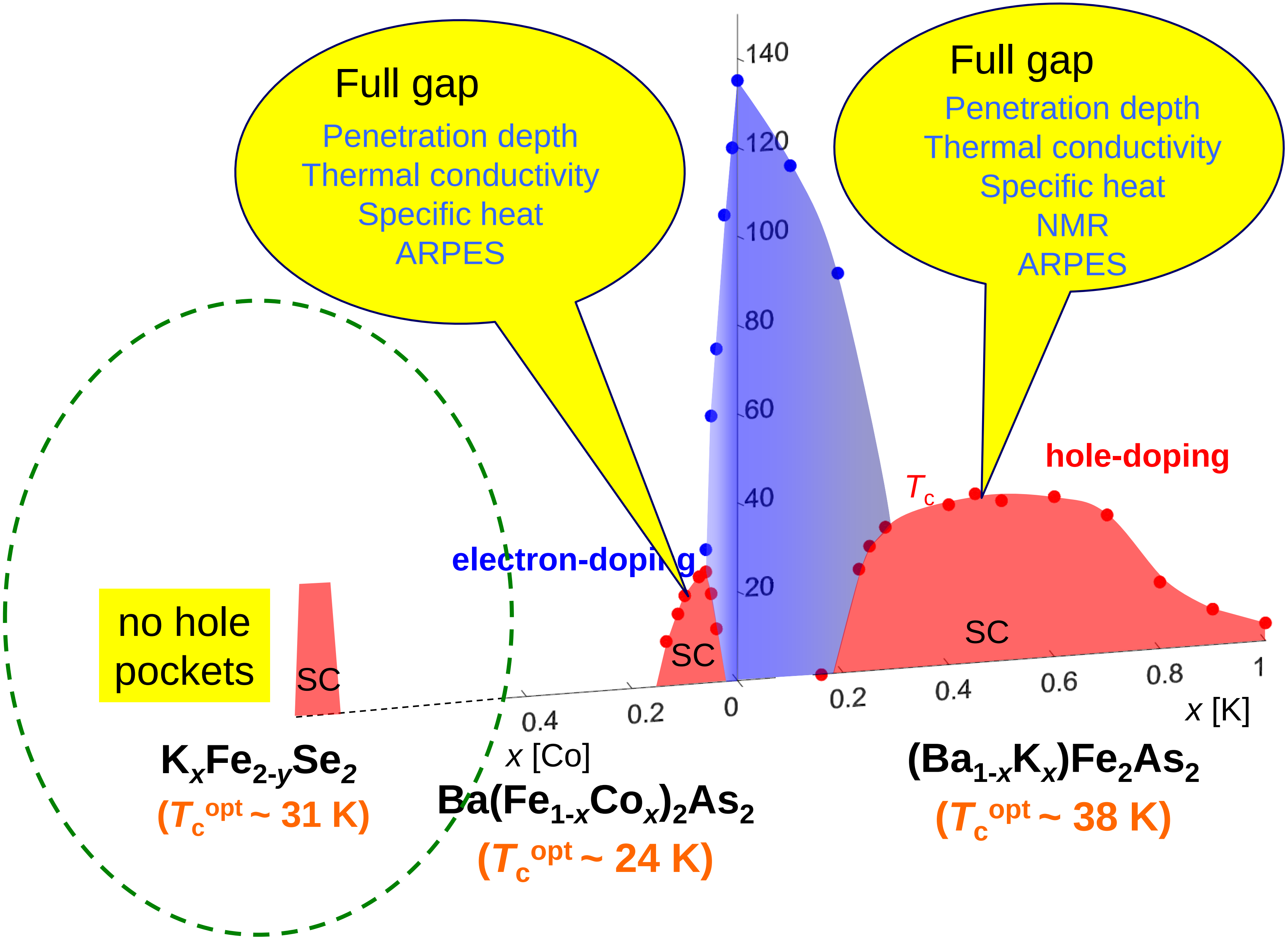


Superconductivity in $BaFe_2As_2$ systems

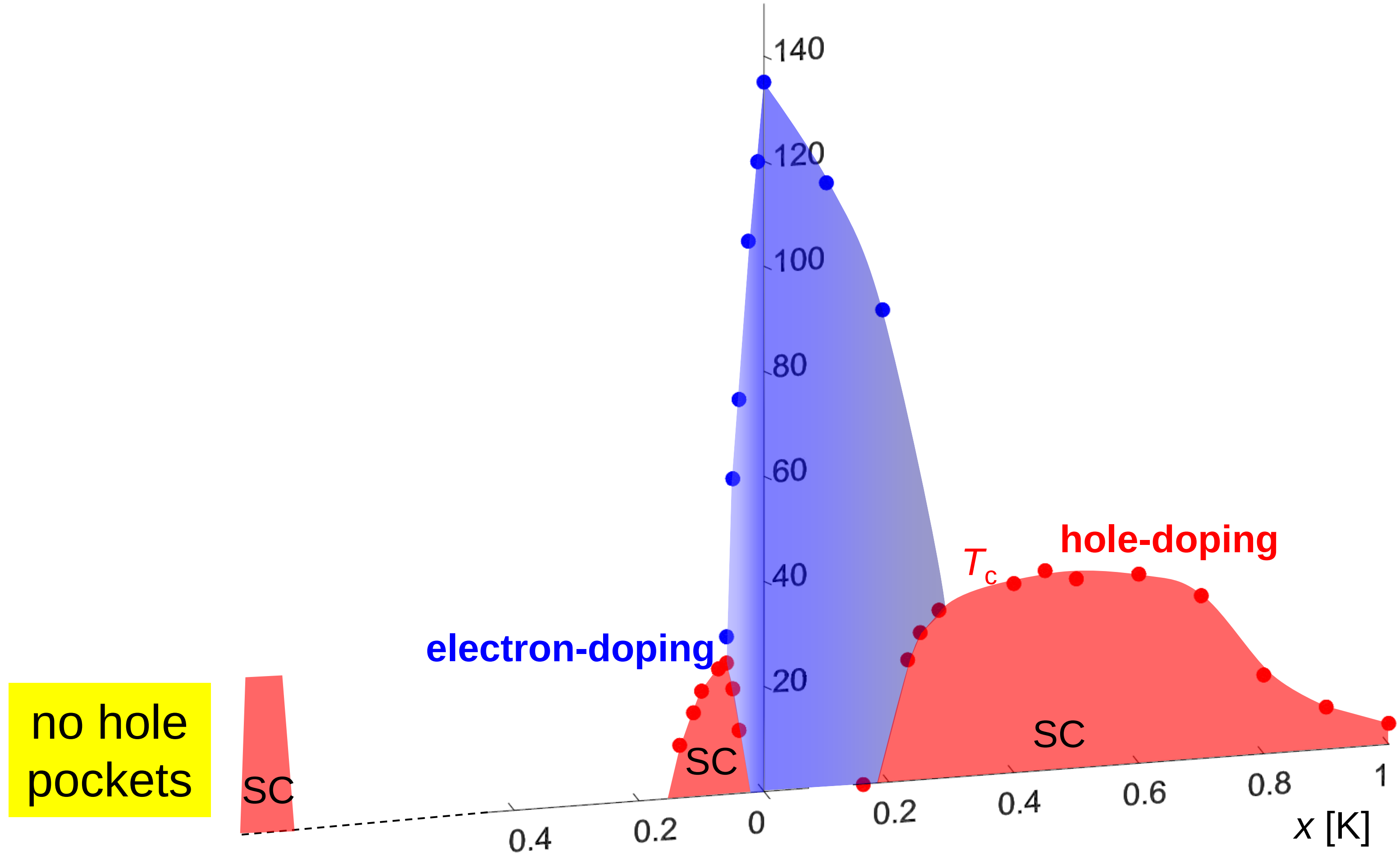


Ground state can be tuned without doping carriers

Superconducting gap structure of $BaFe_2As_2$ systems



Superconducting gap structure of $BaFe_2As_2$ systems

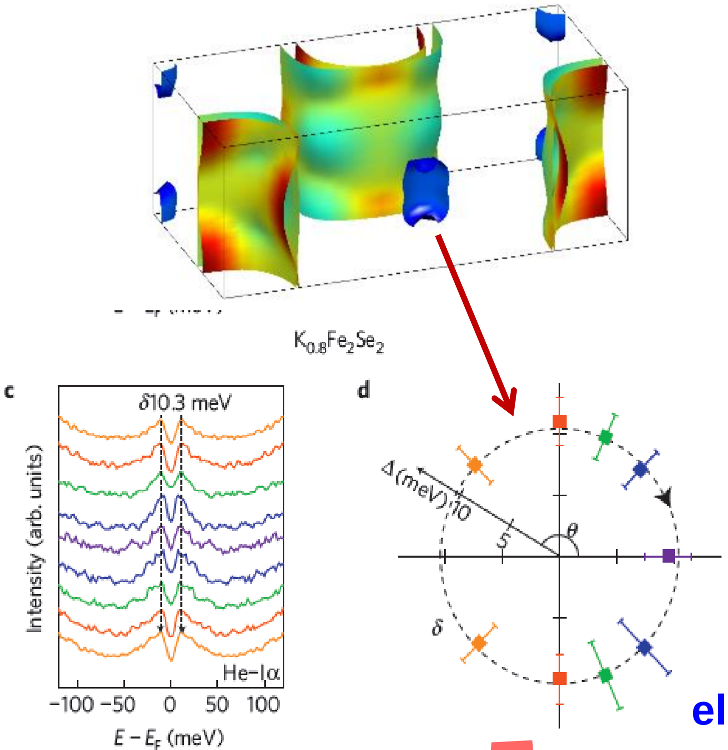


$K_xFe_{2-y}Se_2$
(T_c^{opt} ~ 31 K)

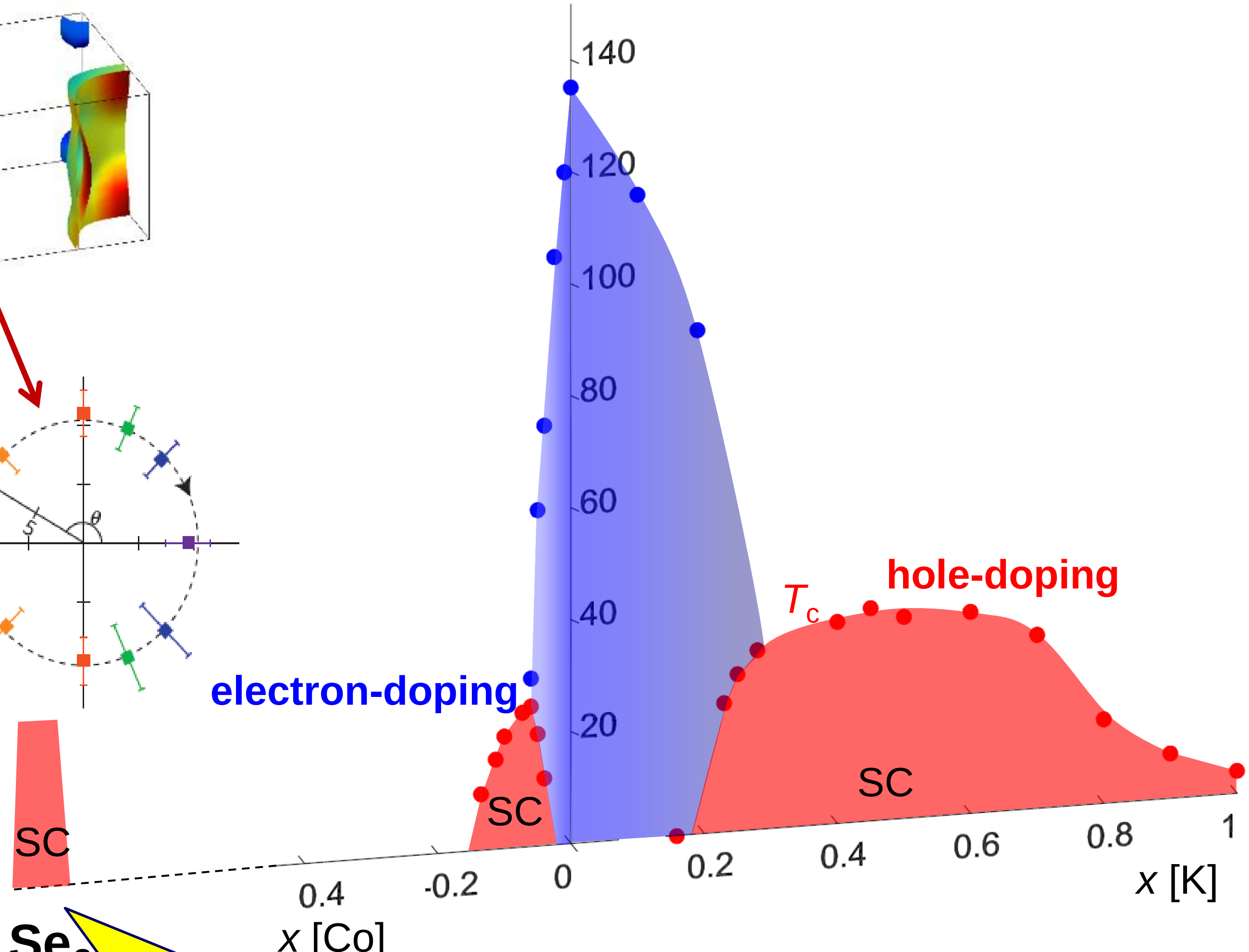
$Ba(Fe_{1-x}Co_x)_2As_2$
(T_c^{opt} ~ 24 K)

$(Ba_{1-x}K_x)Fe_2As_2$
(T_c^{opt} ~ 38 K)

SC gap structure in heavily electron doped systems



no hole pockets



$K_xFe_{2-y}Se_2$

(T_c^{opt} ~ 31 K)

Y. Zhang *et al.*, Nature Materials (2011).

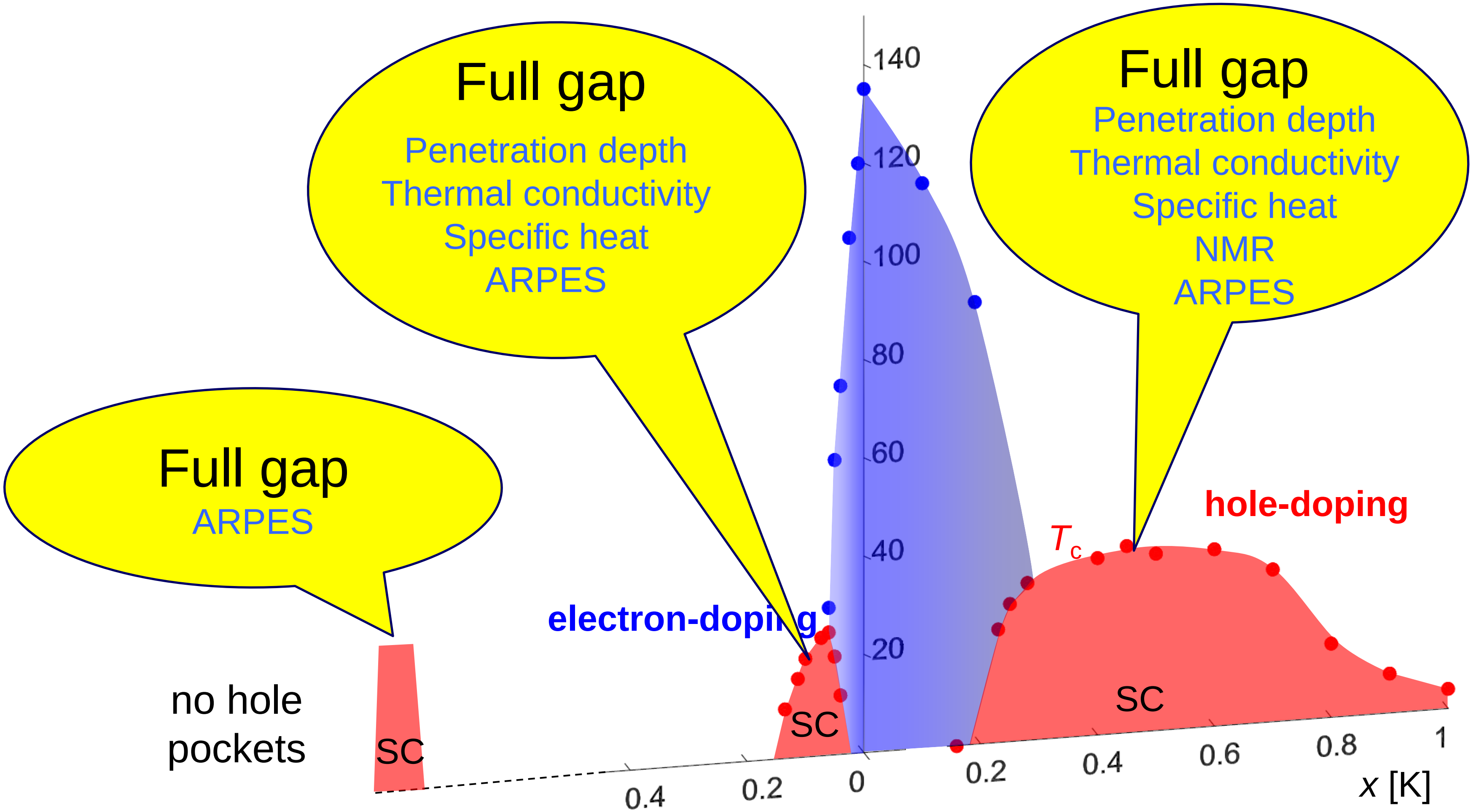
Full gap

Heavily electron doping

Full gap in inner electron pocket around *Z*-point

s-wave symmetry

Superconducting gap structure of $BaFe_2As_2$ systems



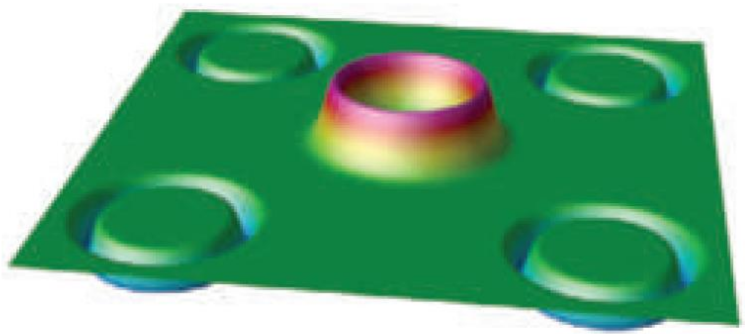
$K_xFe_{2-y}Se_2$
(T_c^{opt} ~ 31 K)

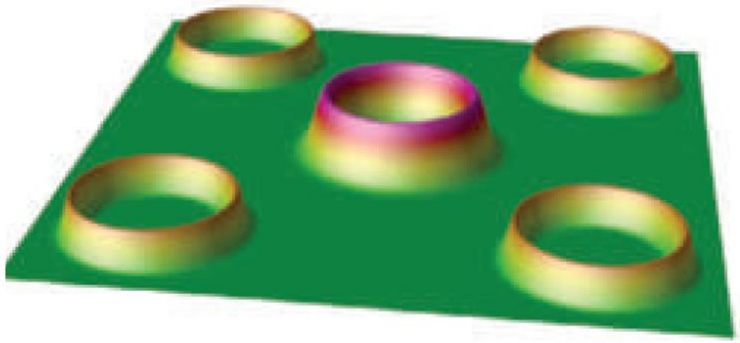
$Ba(Fe_{1-x}Co_x)_2As_2$
(T_c^{opt} ~ 24 K)

$(Ba_{1-x}K_x)Fe_2As_2$
(T_c^{opt} ~ 38 K)

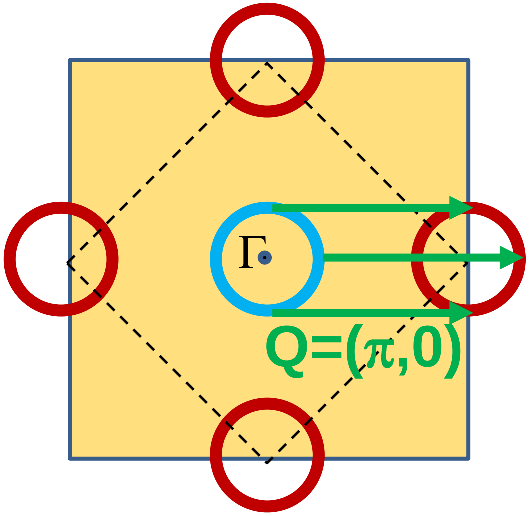
Sign change or no sign change?

S_{+-} or S_{++} ?

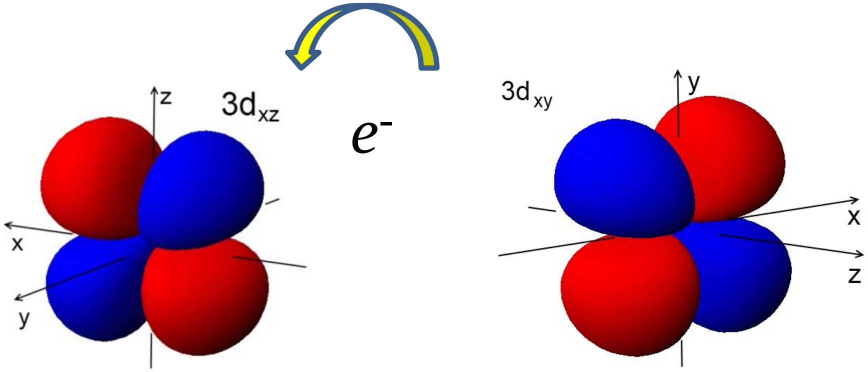




Spin fluctuations



Orbital fluctuations
(Quadrupole fluctuation)



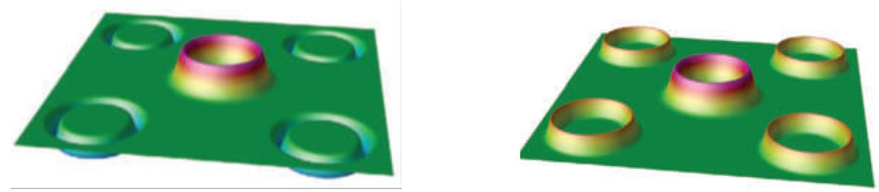
Charge up

Charge down

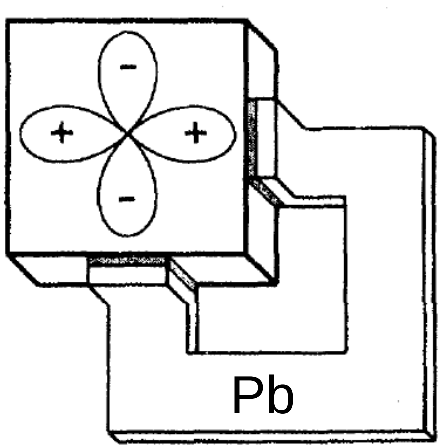
S+- or S++?

1. Phase sensitive test
2. NMR
3. Neutron scattering
4. Quasi-particle interference
5. Impurity effect

S+- or S++?: Phase sensitive tests



d-wave



PRL 102, 227007 (2009) PHYSICAL REVIEW LETTERS week ending 5 JUNE 2009

Possible Phase-Sensitive Tests of Pairing Symmetry in Pnictide Superconductors

D. Parker[1] and I. I. Mazin[1]

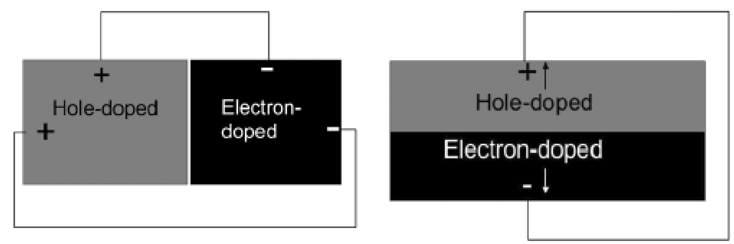
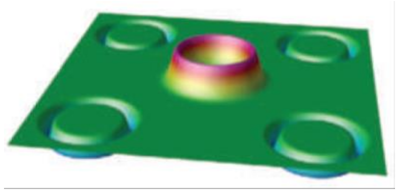


FIG. 3. A schematic view of the tunneling geometry for the proposed bicrystal experiments. Left: an *ab*-plane orientation with two possible lead orientations; right: a *c*-axis orientation.

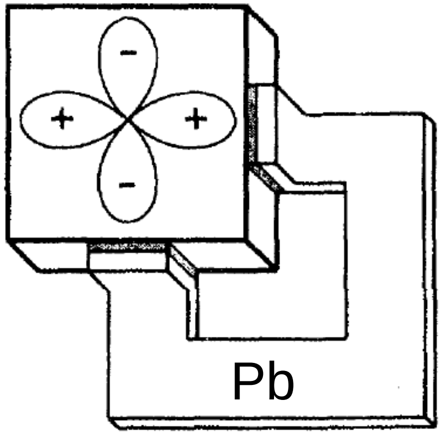
Practically very difficult to fabricate such junctions

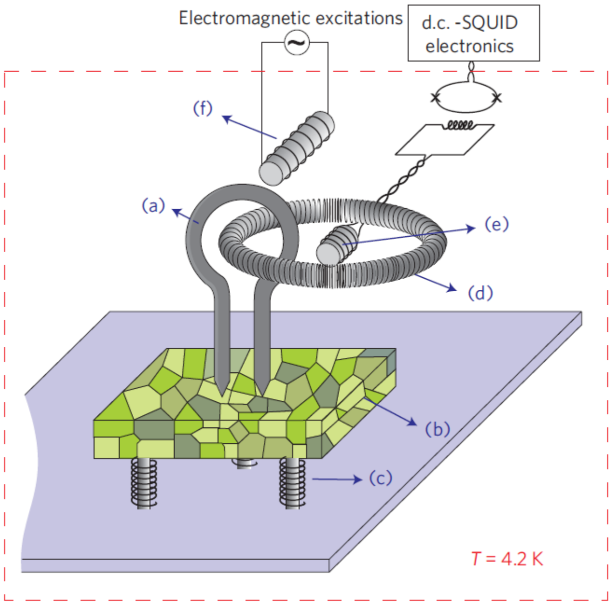
S+- or S++?: Phase sensitive tests



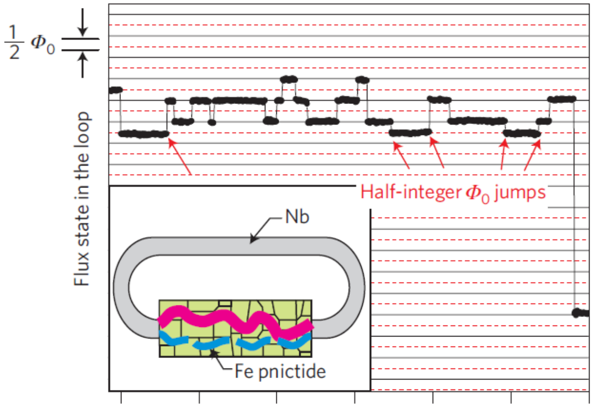
S_{+-}

d-wave





NdFeAsO$_{0.88}$F$_{0.12}$



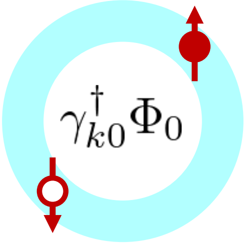
C.T. Chen et al. Nature Phys. (10)

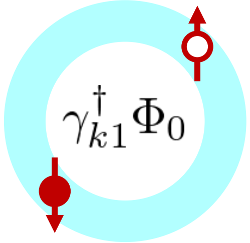
Experiments have been performed on polycrystals

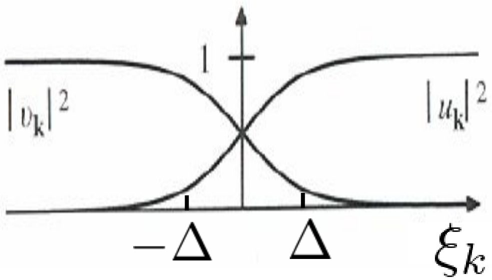
Sign change or no sign change?

Quasiparticle excitations from the SC ground state

$$\gamma^\dagger_{k0} = u_k c^\dagger_{k\uparrow} - v_k c_{-k\downarrow}$$
$$\gamma^\dagger_{k1} = u_k c^\dagger_{-k\downarrow} + v_k c_{k\uparrow}$$







$$|u_k|^2 = \frac{1}{2}\left(1 + \frac{\xi_k}{\sqrt{\Delta_k^2 + \xi_k^2}}\right) \qquad |v_k|^2 = \frac{1}{2}\left(1 - \frac{\xi_k}{\sqrt{\Delta_k^2 + \xi_k^2}}\right) \qquad \xi_k \equiv \frac{\hbar^2 k^2}{2m} - \varepsilon_F$$

B-quasiparticle: a superposition of an electron and a hole

$$\mathbf{k}\sigma \rightarrow \mathbf{k}'\sigma'$$

$$\mathcal{H}_1 = \sum_{k\sigma,k'\sigma'} B_{k\sigma,k'\sigma'} c^\dagger_{k\sigma} c_{k'\sigma'} - \begin{cases} B_{k\sigma,k'\sigma'} c^\dagger_{k\sigma} c_{k'\sigma'} \\ B_{-k'-\sigma',-k-\sigma} c^\dagger_{-k'-\sigma'} c_{-k-\sigma} \end{cases}$$

connected by time-reversal symmetry

Coherence factor

Scattering of QPs
$$(u_k u_{k'} \pm v_k v_{k'})^2 = \frac{1}{2}\left(1 \pm \frac{\Delta^2}{E_k E_{k'}}\right)$$

Creation and annihilation of two QPs
$$(v_k u_{k'} \pm u_k v_{k'})^2 = \frac{1}{2}\left(1 \pm \frac{\Delta^2}{E_k E_{k'}}\right)$$

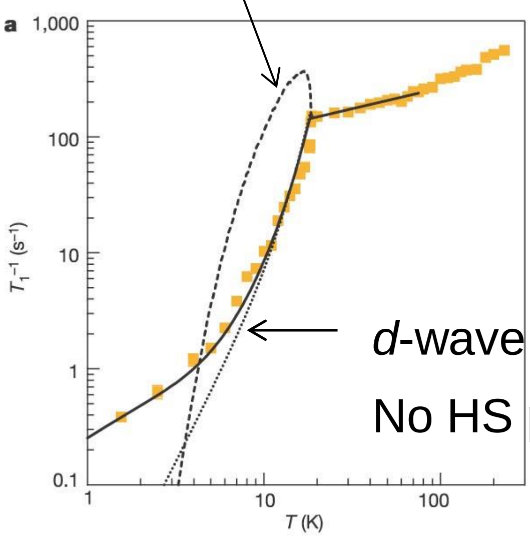
S+- or S++?: NMR

$$\frac{1}{T_1 T} \propto \sum_{kk'} \left(1 + \frac{\Delta_k \Delta_{k'}}{E_k E_{k'}}\right) \left[-\frac{\partial f(E_k)}{\partial E_k}\right] \delta(E_k - E_{k'})$$

s-wave

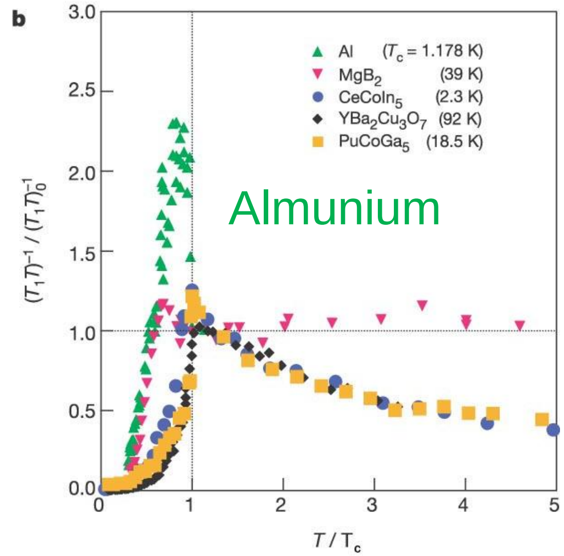
$$\frac{1}{T_1} \propto \int_{\Delta(T)}^{\infty} dE \, \frac{E^2 + \Delta^2}{\underline{E^2 - \Delta^2}} \, \text{sech}^2\left(\frac{E}{2T}\right)$$

Hebel-Slichter peak

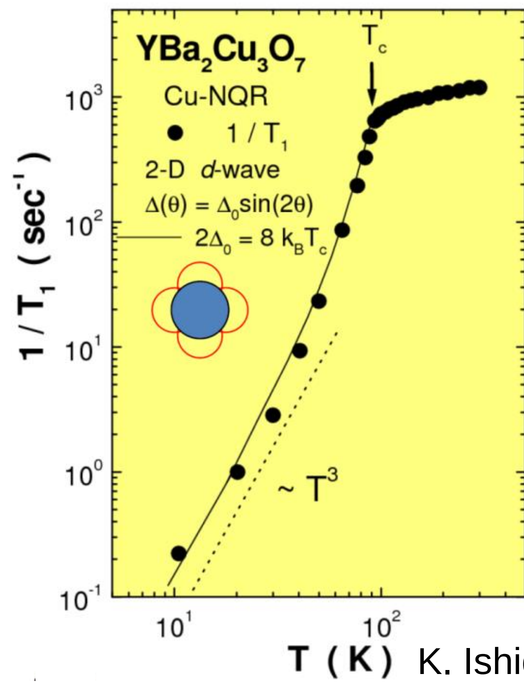


d-wave

No HS peak



N. Curro *et al*. Nature (12)



K. Ishida *et al*. JPSJ (93)

S+- or S++?: NMR

$$\frac{1}{T_1T} \propto \sum_{kk'} \left(1 + \frac{\Delta_k\Delta_{k'}}{E_kE_{k'}}\right)\left[-\frac{\partial f(E_k)}{\partial E_k}\right]\delta(E_k - E_{k'})$$

S_{++} $\Delta_k = \Delta_{k'} = \Delta$

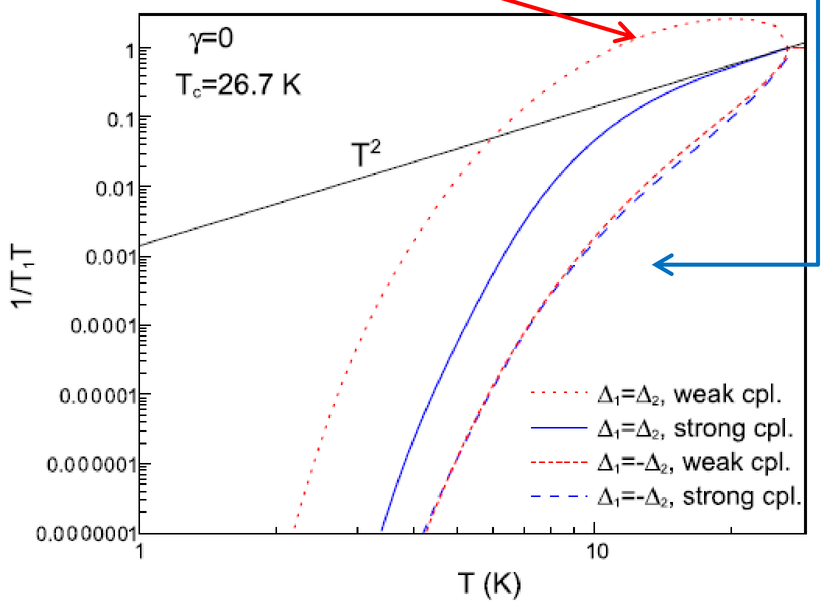
$$\frac{1}{T_1} \propto \int_{\Delta(T)}^{\infty} dE \, \frac{E^2+\Delta^2}{E^2-\Delta^2} \, \mathrm{sech}^2\left(\frac{E}{2T}\right)$$

S_{+-} $\Delta_k = -\Delta_{k'} = \Delta$

$$\frac{1}{T_1} \propto \int_{\Delta(T)}^{\infty} dE \, \mathrm{sech}^2\left(\frac{E}{2T}\right)$$

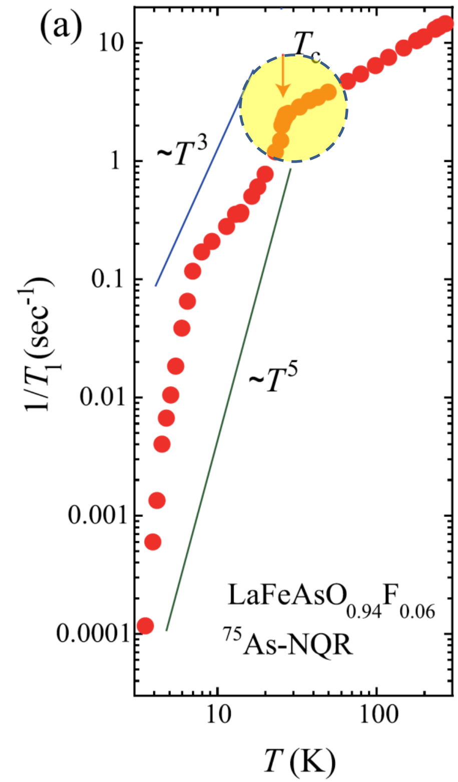
Hebel-Slichter peak

No HS peak



D. Parker *et al.* PRB (08)

No HS peak



T. Oka *et al.* PRL (12)

However, the HS peak readily disappears by inelastic scatterings, eg. Pb.

Absence of the coherence peak is not evidence of S_{+-}

S+- or S++?: Neutron resonance peak at *Q*

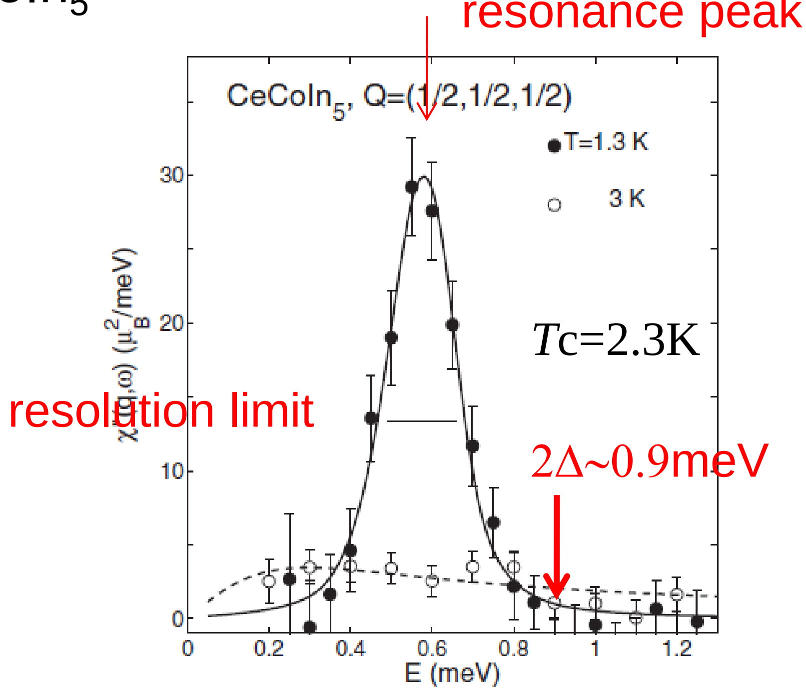
In the superconducting state

$$\mathrm{Im}\chi_0(\mathbf{q},\omega) = \frac{1}{4}\frac{1}{(2\pi)^3}\int d^3k\left(1 - \frac{\Delta_k\Delta_{k+q}}{E_{k+q}E_k}\right)\delta(\omega - E_{k+q} - E_k) \qquad E_{\mathbf{k}} = \sqrt{\xi_{\mathbf{k}}^2 + \Delta_{\mathbf{k}}^2}$$

The coherence factor becomes 2 for $\Delta_{\mathbf{k+Q}} = -\Delta_{\mathbf{k}}$

Sharp resonance peak at $\omega_{res} < 2\Delta$

$CeCoIn_5$ *d*-wave



Stock *et al.*, PRL **100**, 087001 (2008)

S+- or S++?: Neutron resonance peak at *Q*

In the superconducting state

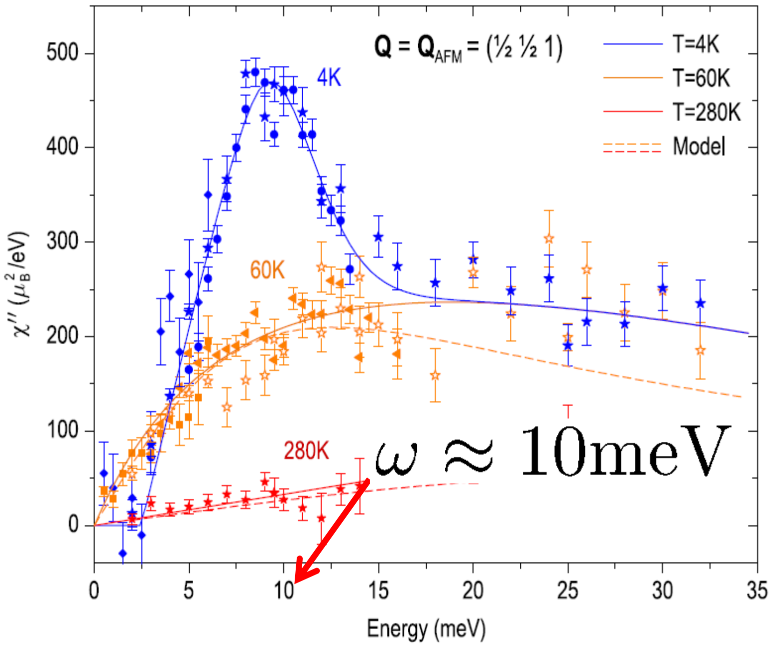
$$\mathrm{Im}\chi_0(\mathbf{q},\omega) = \frac{1}{4}\frac{1}{(2\pi)^3}\int d^3k \left(1 - \frac{\Delta_k \Delta_{k+q}}{E_{k+q}E_k}\right)\delta(\omega - E_{k+q} - E_k) \qquad E_{\mathbf{k}} = \sqrt{\xi_{\mathbf{k}}^2 + \Delta_{\mathbf{k}}^2}$$

The coherence factor becomes 2 for $\Delta_{\mathbf{k+Q}} = -\Delta_{\mathbf{k}}$

S_{+-} Sharp resonance peak at $\omega_{res} < 2\Delta$ ($\Delta_{el}+\Delta_{hole}$)

S_{++} Broad peak at $\omega_{res} > 2\Delta$ ($\Delta_{el}+\Delta_{hole}$)

$BaFe_{1.85}Co_{0.15}As_2$ Inosov *et al*., Nat. Phys. (10).



ARPES（bulk-sensitive）:

$$\Delta_{\mathrm{el}} + \Delta_{\mathrm{hole}} \approx 11.6\mathrm{meV}$$

Terashima *et al*., PNAS 2009

penetration depth:

$$\Delta_{\mathrm{el}} + \Delta_{\mathrm{hole}} \approx 8.4\mathrm{meV}$$

Luan *et al*., PRL 2011

specific heat:

$$\Delta_{\mathrm{el}} + \Delta_{\mathrm{hole}} \approx 7\mathrm{meV}$$

Hardy *et al*., EPL 2010

S+- or S++?: Neutron resonance peak at *Q*

In the superconducting state

$$\mathrm{Im}\chi_0(\mathbf{q},\omega) = \frac{1}{4}\frac{1}{(2\pi)^3}\int d^3k \left(1 - \frac{\Delta_k \Delta_{k+q}}{E_{k+q}E_k}\right)\delta(\omega - E_{k+q} - E_k) \qquad E_{\mathbf{k}} = \sqrt{\xi_{\mathbf{k}}^2 + \Delta_{\mathbf{k}}^2}$$

The coherence factor becomes 2 for $\Delta_{\mathbf{k}+\mathbf{Q}} = -\Delta_{\mathbf{k}}$

S_{+-} Sharp resonance peak at $\omega_{res} < 2\Delta$ ($\Delta_{el}+\Delta_{hole}$)

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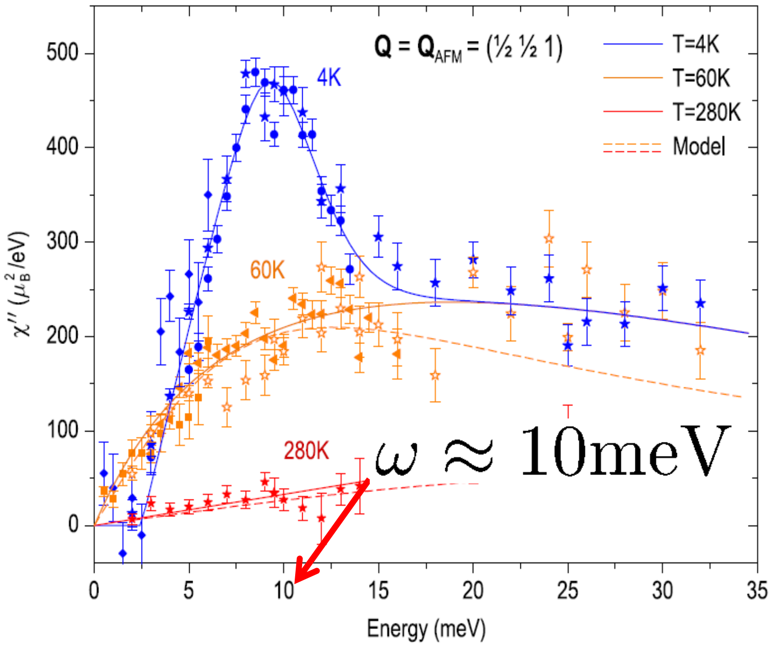
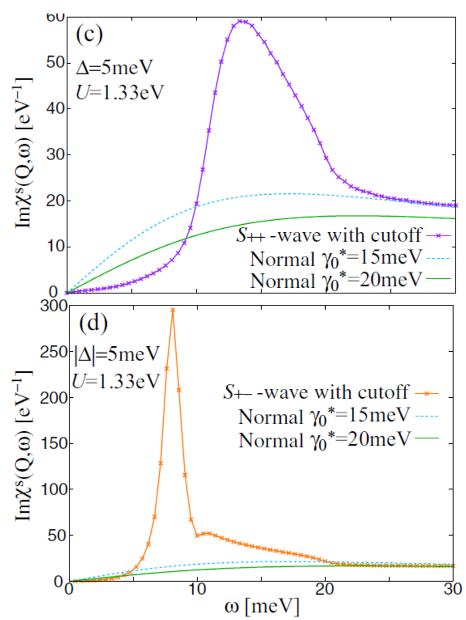
$BaFe_{1.85}Co_{0.15}As_2$ Inosov *et al*., Nat. Phys. (10).



S. Onari and H. Kontani, PRB (11)



Neutron scattering experiments can be explained by either models.

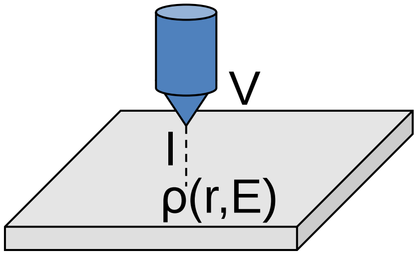
S+- or S++?: Quasiparticle interference (QPI)

Quasi-Particle Interference

Tunnel conductance

$$Z(\mathbf{r},E) \equiv \frac{dI/dV(\mathbf{r},+E)}{dI/dV(\mathbf{r},-E)} = \frac{\rho(\mathbf{r},+E)}{\rho(\mathbf{r},-E)} \Rightarrow Z(\mathbf{q},E)$$

FT



No impurity (no scattering) $Z(\mathbf{q},E) = 0$ for $\mathbf{q} \neq 0$

Nonmagnetic impurity

QP scattering probability (SC state)

$$w(\mathbf{k}\sigma \to \mathbf{k}'\sigma) \propto |V(\mathbf{k},\mathbf{k}')|^2 (u_k u_{k'} - v_k v_{k'})^2$$

Nonmagnetic (no spin flip)

matrix element

coherence factor

$$(u_k u_{k'} - v_k v_{k'})^2 = \frac{1}{2}\left(1 - \frac{\Delta_k \Delta_{k'}}{E_k E_{k'}}\right)$$

sign-preserving scattering

$\Delta_k \Delta_{k'} > 0$ $\quad (u_k u_{k'} - v_k v_{k'})^2$ small

sign-reversing scattering

$\Delta_k \Delta_{k'} < 0$ $\quad (u_k u_{k'} - v_k v_{k'})^2$ large

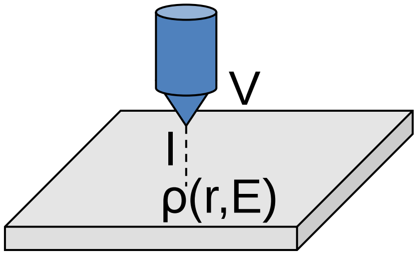
S+- or S++?: Quasiparticle interference (QPI)

Quasi-Particle Interference

Tunnel conductance

$$Z(\mathbf{r}, E) \equiv \frac{dI/dV(\mathbf{r}, +E)}{dI/dV(\mathbf{r}, -E)} = \frac{\rho(\mathbf{r}, +E)}{\rho(\mathbf{r}, -E)} \Rightarrow Z(\mathbf{q}, E)$$

FT



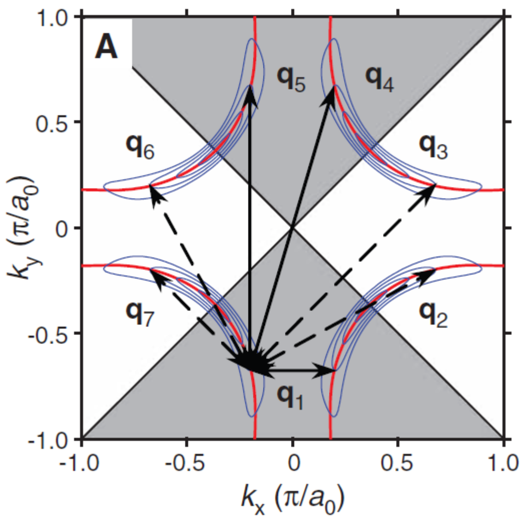
No impurity (no scattering) $Z(\mathbf{q}, E) = 0$ for $\mathbf{q} \neq 0$

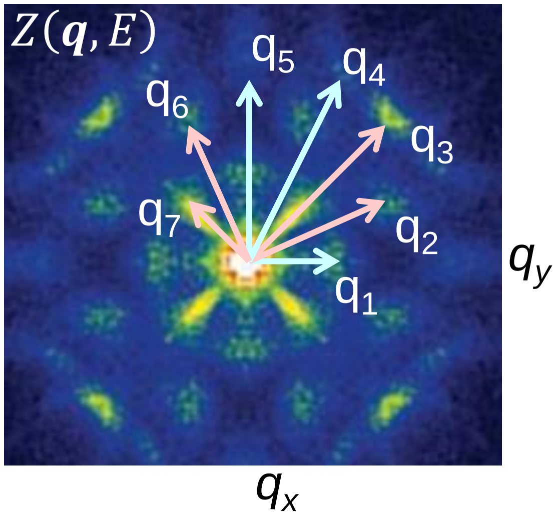
Nonmagnetic impurity

Cuprate : Octet Model

J. Hoffman *et al.*, Science (2002), K. McElroy, *et al.*, Nature (2003).

Δ_k and Δ_{k+q} { sign-preserving scattering => suppression; sign-reversing scattering => enhancement }





sign-preserving ($\mathbf{q}_1$, $\mathbf{q}_4$, $\mathbf{q}_5$)

sign-reversing ($\mathbf{q}_2$, $\mathbf{q}_3$, $\mathbf{q}_6$, $\mathbf{q}_7$)

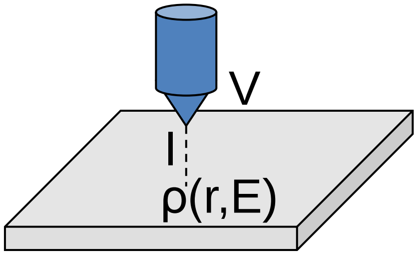
T. Hanaguri *et al*.

S+- or S++?: Quasiparticle interference (QPI)

Quasi-Particle Interference

Tunnel conductance

$$Z(\mathbf{r},E) \equiv \frac{dI/dV(\mathbf{r},+E)}{dI/dV(\mathbf{r},-E)} = \frac{\rho(\mathbf{r},+E)}{\rho(\mathbf{r},-E)} \xrightarrow{\text{FT}} Z(\mathbf{q},E)$$

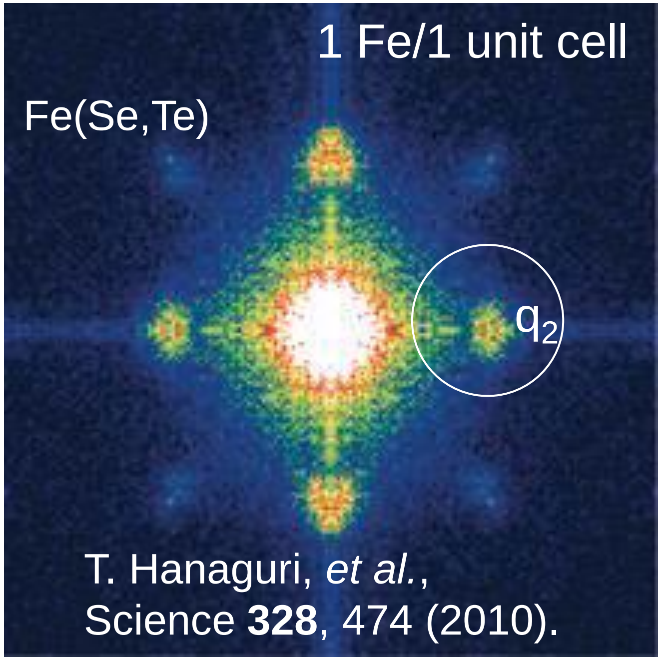


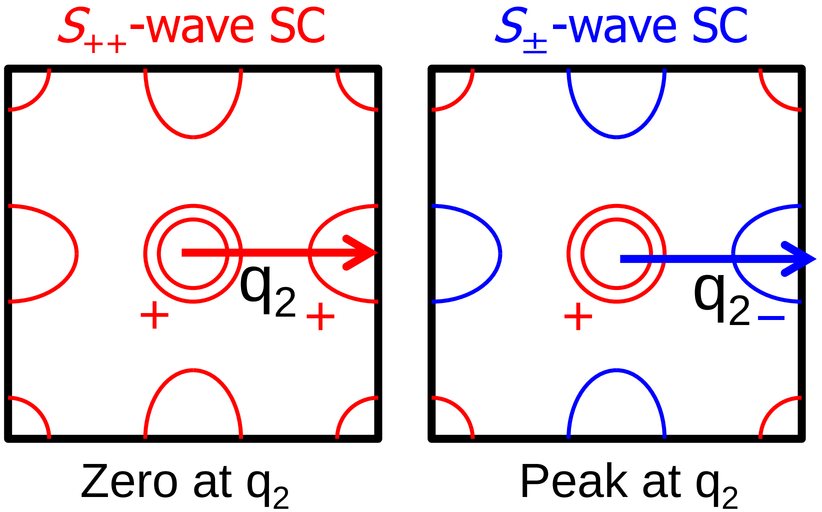
No impurity (no scattering) $Z(\mathbf{q},E)=0$ for $\mathbf{q}\neq 0$

Nonmagnetic impurity

Fe-based superconductor

Δ_k and Δ_{k+q} { sign-preserving scattering => suppression; sign-reversing scattering => enhancement

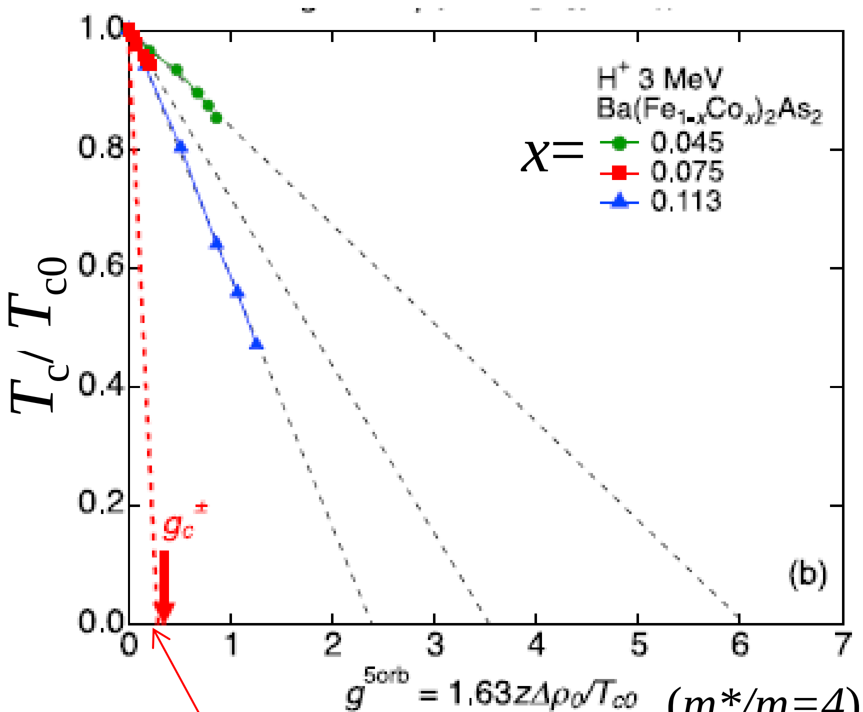




However, $\mathbf{q}_2$ spot can appear even in S++ case when $\Delta_e \neq \Delta_h$

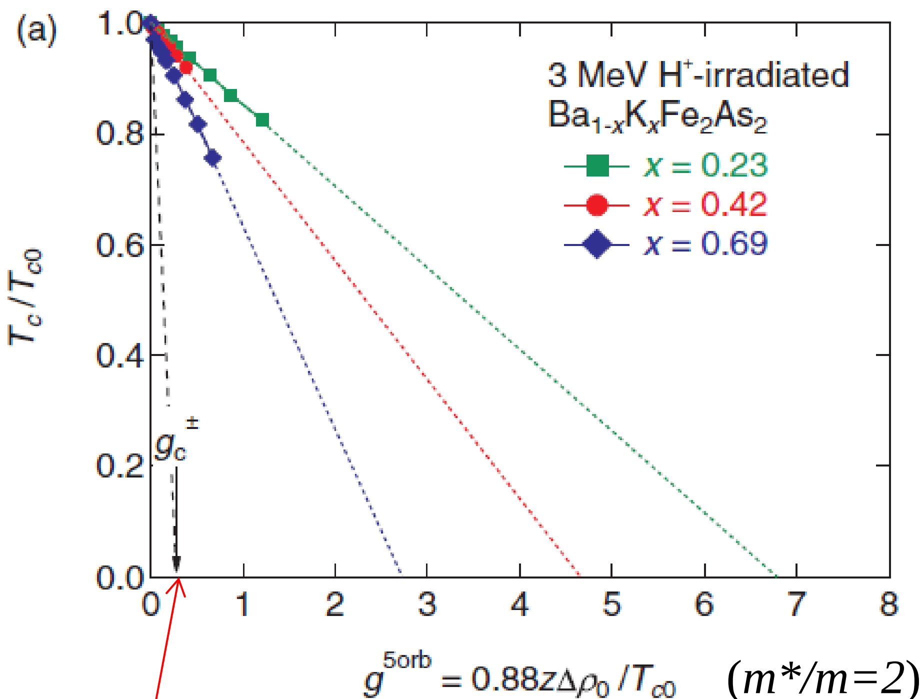
S+- or S++?: Impurity effect

$Ba(Fe_{1-x}Co_x)_2As_2$
Nakajima *et al.*, Phys. Rev. B 82, 220504(R)



(m*/m=4)
normalized scattering ratio

$Ba_{1-x}K_xFe_2As_2$
Taen *et al.*, Phys. Rev. B 88, 224514

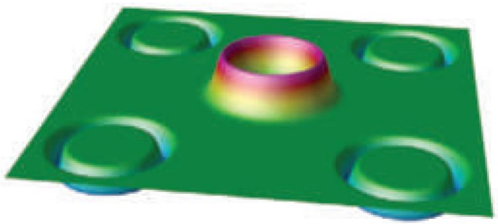


(m*/m=2)
normalized scattering ratio

theoretical prediction for S_{+-} wave (Onari and Kontani, PRL 2009)

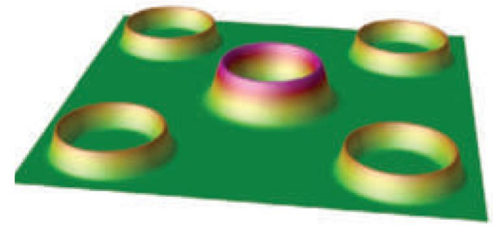
The robustness of the SC state against impurity contradicts with the S+- wave state.

S_{+-}



?

S_{++}



?

No conclusive experimental evidence so far

Are all iron-based high-T_c superconductors fully gapped?

If some are nodal

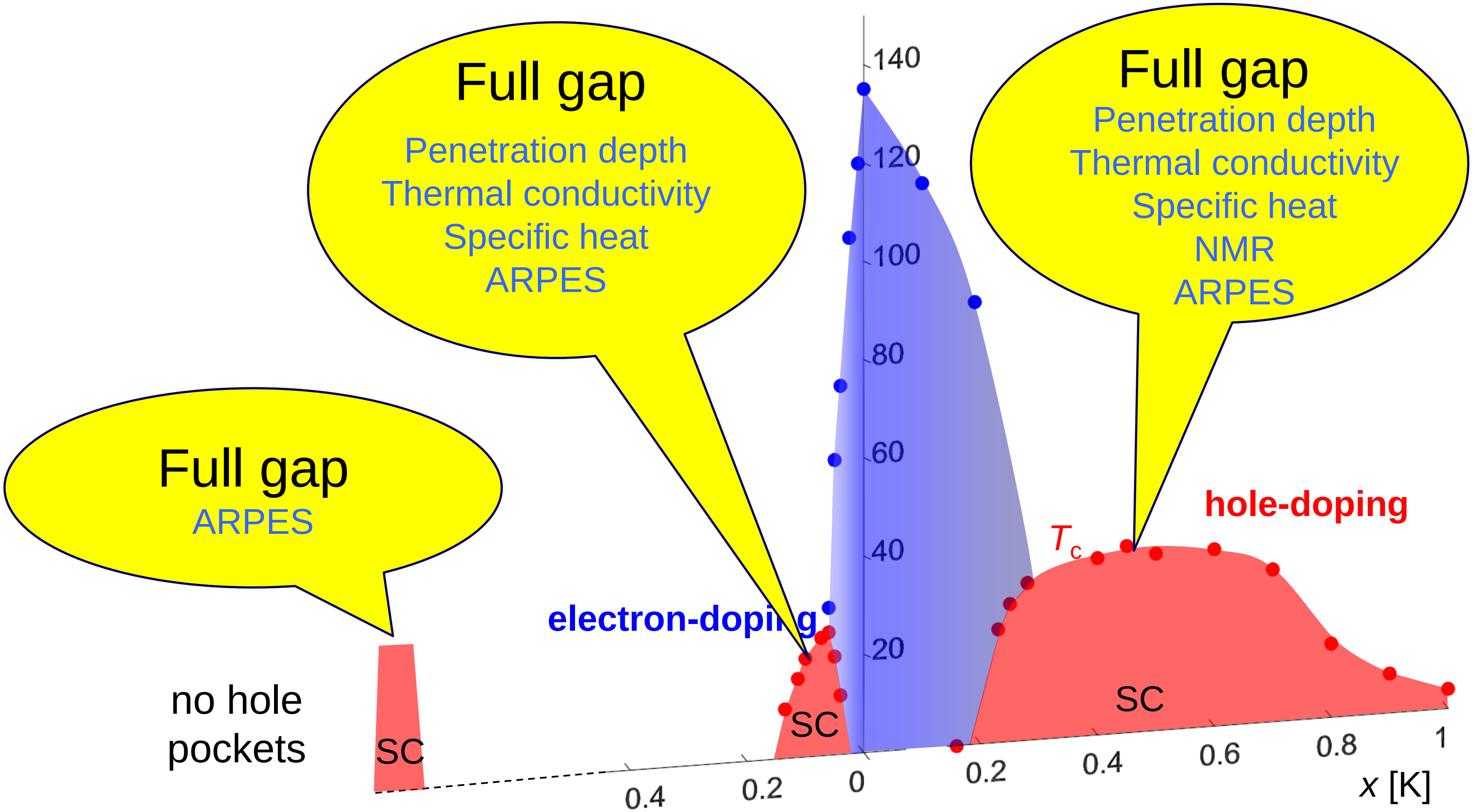
→ Presence of repulsive interaction

Accidental or symmetry protected?

If accidental

→ Presence of two (or more) competing pairing interactions

Superconducting gap structure of $BaFe_2As_2$ systems

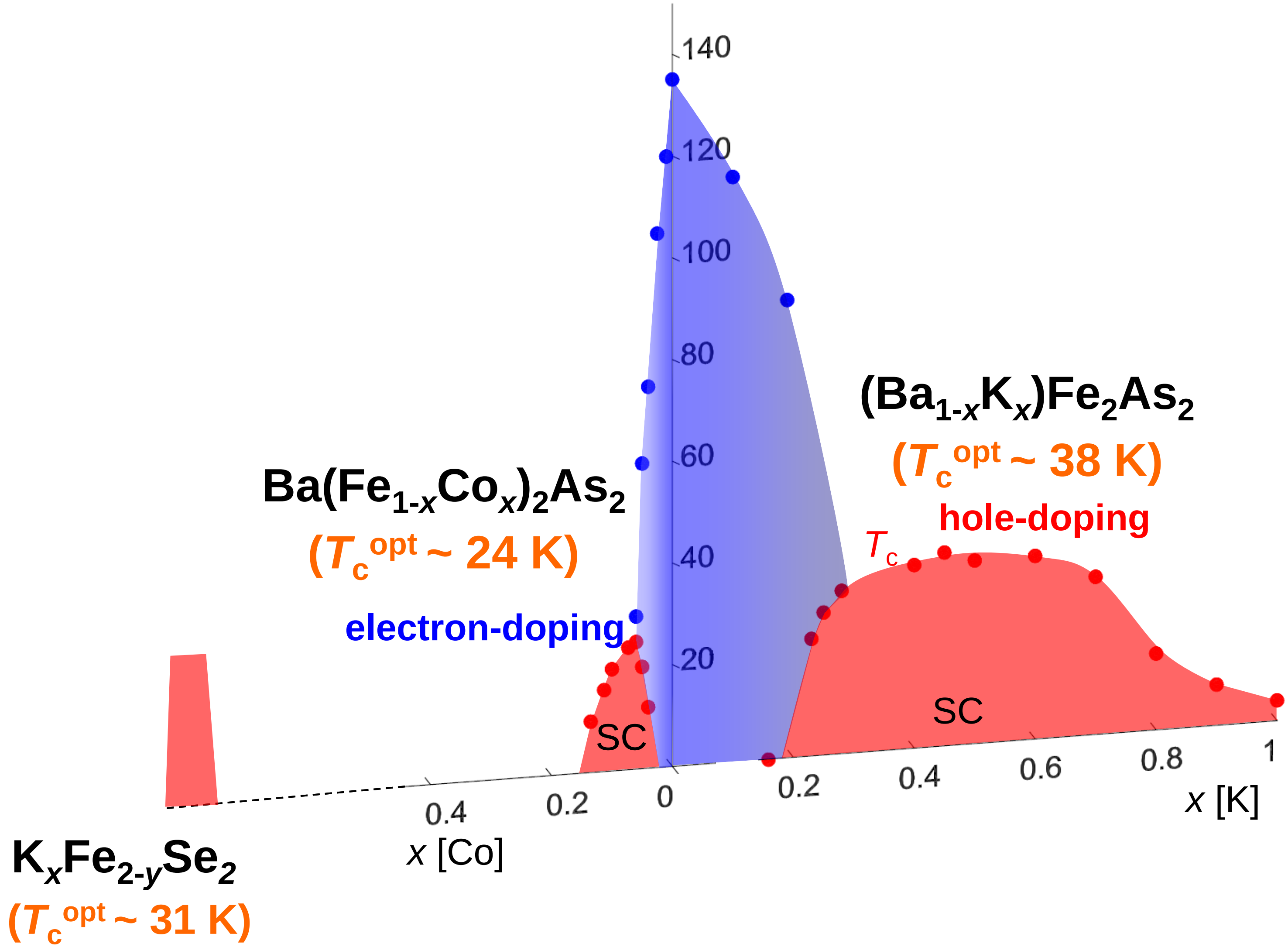


$K_xFe_{2-y}Se_2$
(T_c^{opt} ~ 31 K)

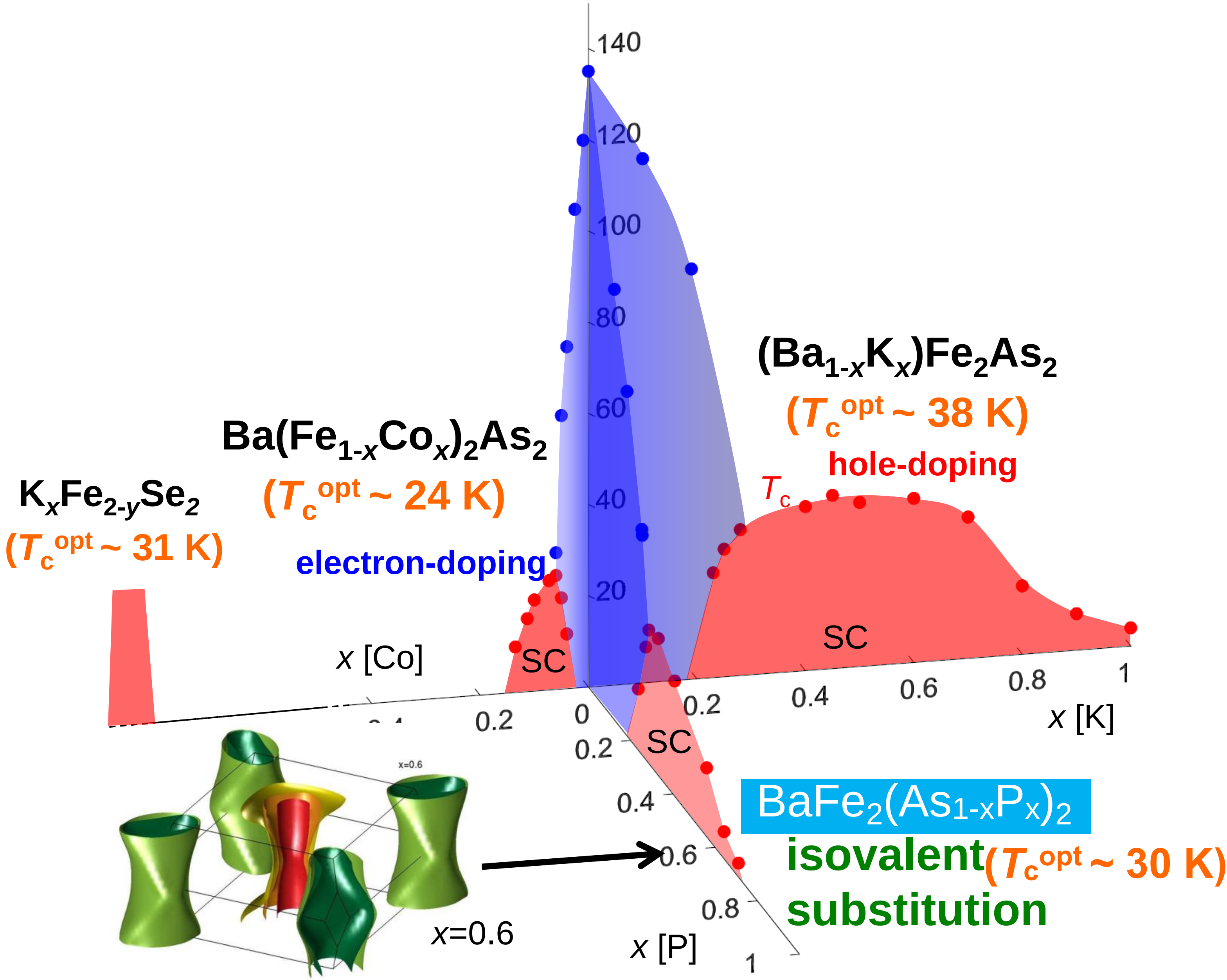
$Ba(Fe_{1-x}Co_x)_2As_2$
(T_c^{opt} ~ 24 K)

$(Ba_{1-x}K_x)Fe_2As_2$
(T_c^{opt} ~ 38 K)

SC gap structure in isovalent doped systems

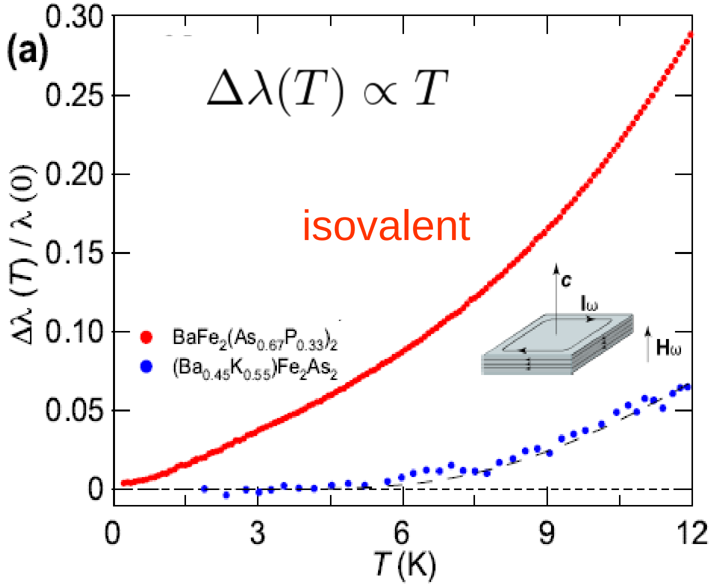


SC gap structure in isovalent doped systems

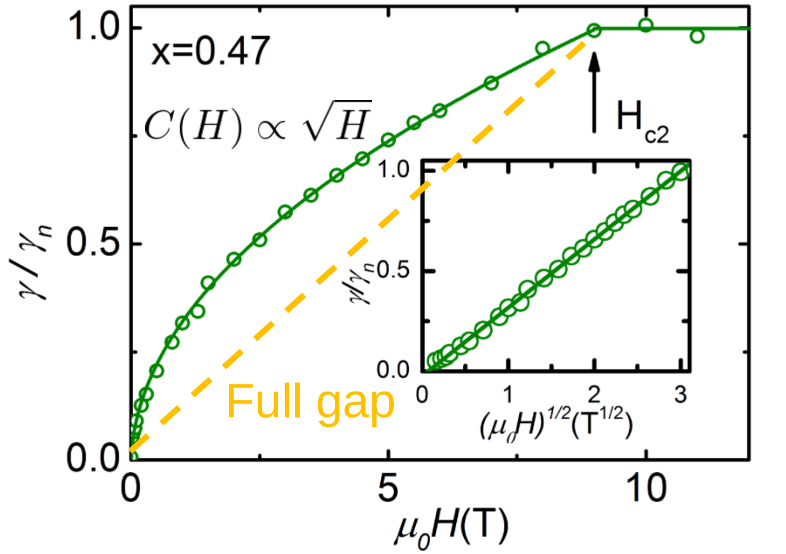


SC gap structure in isovalent doped systems

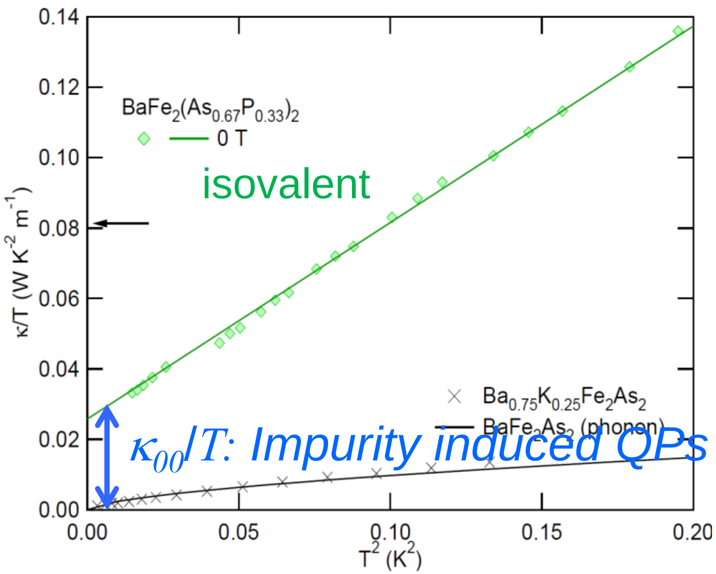
Penetration depth

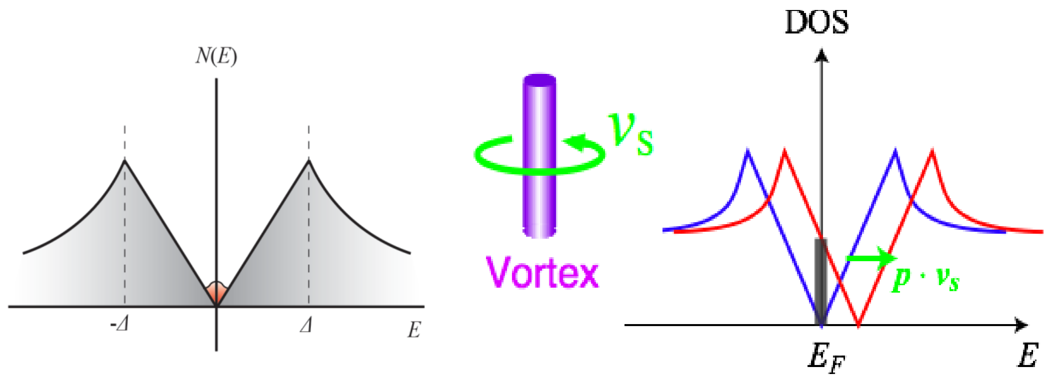


Specific heat $BaFe_2(As_{0.53}P_{0.47})_2$



Thermal conductivity



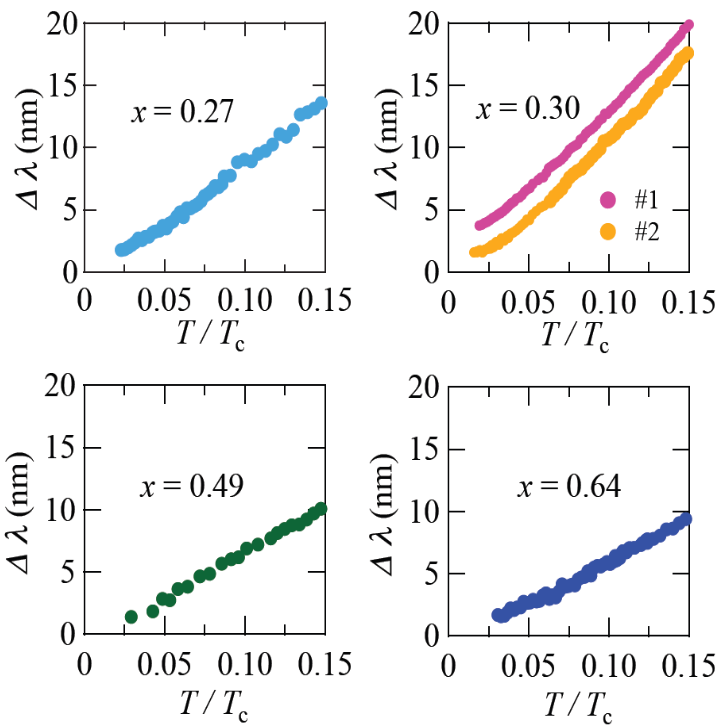


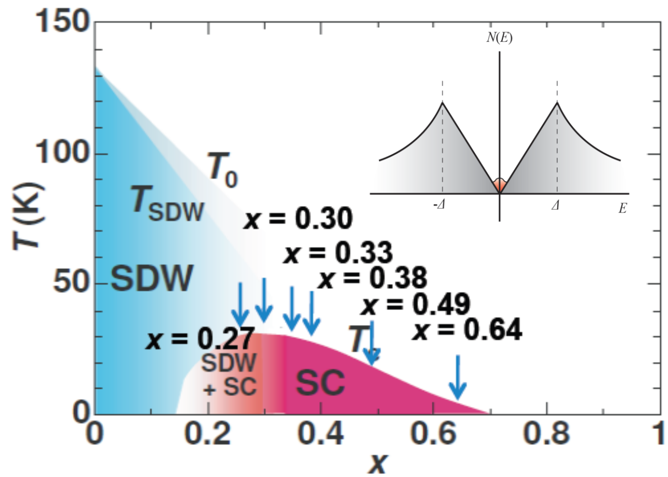
Luo *et al.*
Kurita *et al.*

Doppler shift

K. Hashimoto *et al.*, PRB (2010)
K. Hashimoto *et al.*, PRL (2009)
K. Hashimoto *et al.*, Science (2012)
A. Carrington *et al.* (2014)

SC gap structure in isovalent doped systems





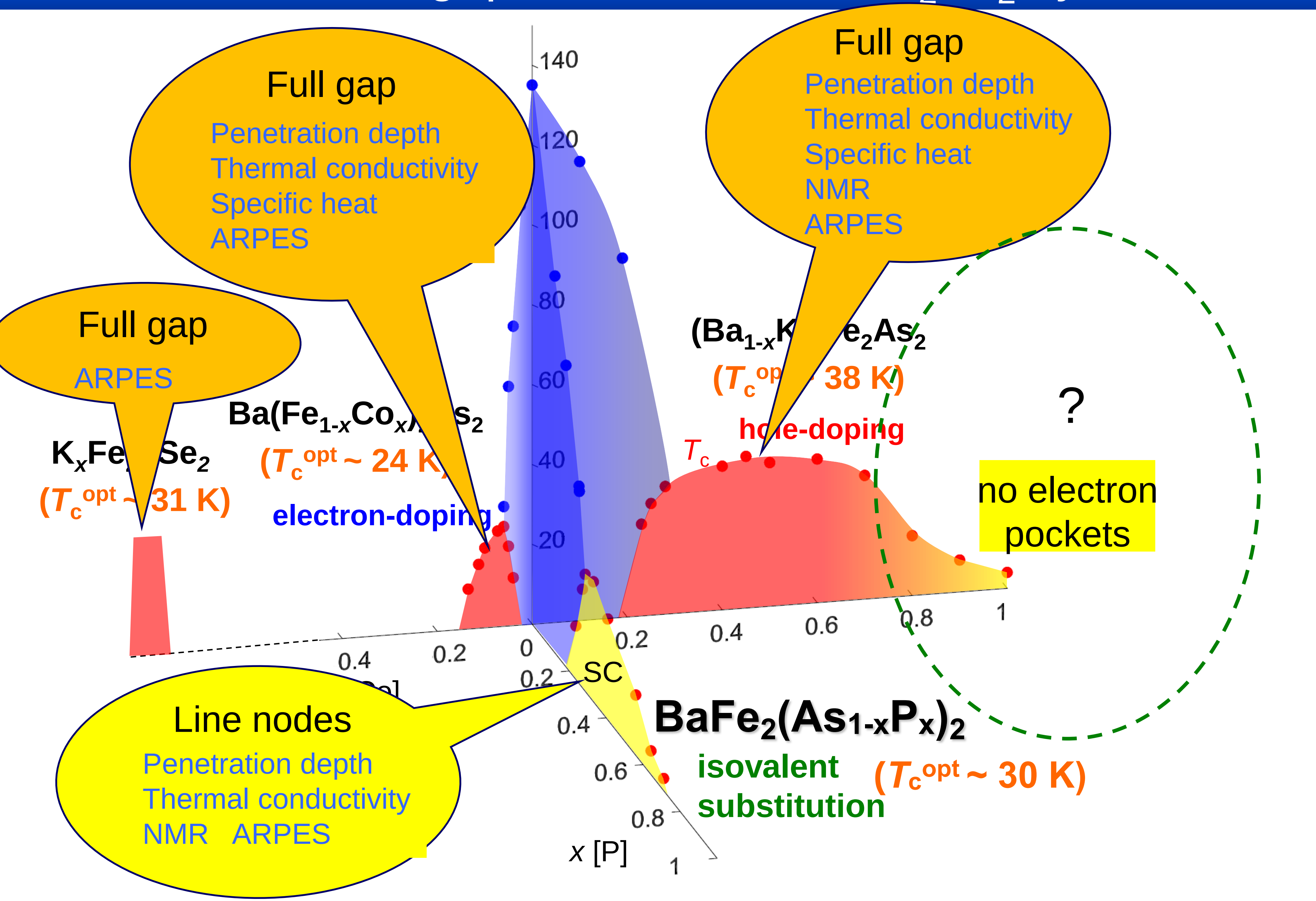
K. Hashimoto *et al*., Science (2012)

- The presence of line nodes is a robust feature for all *x*.

Presence of repulsive interaction

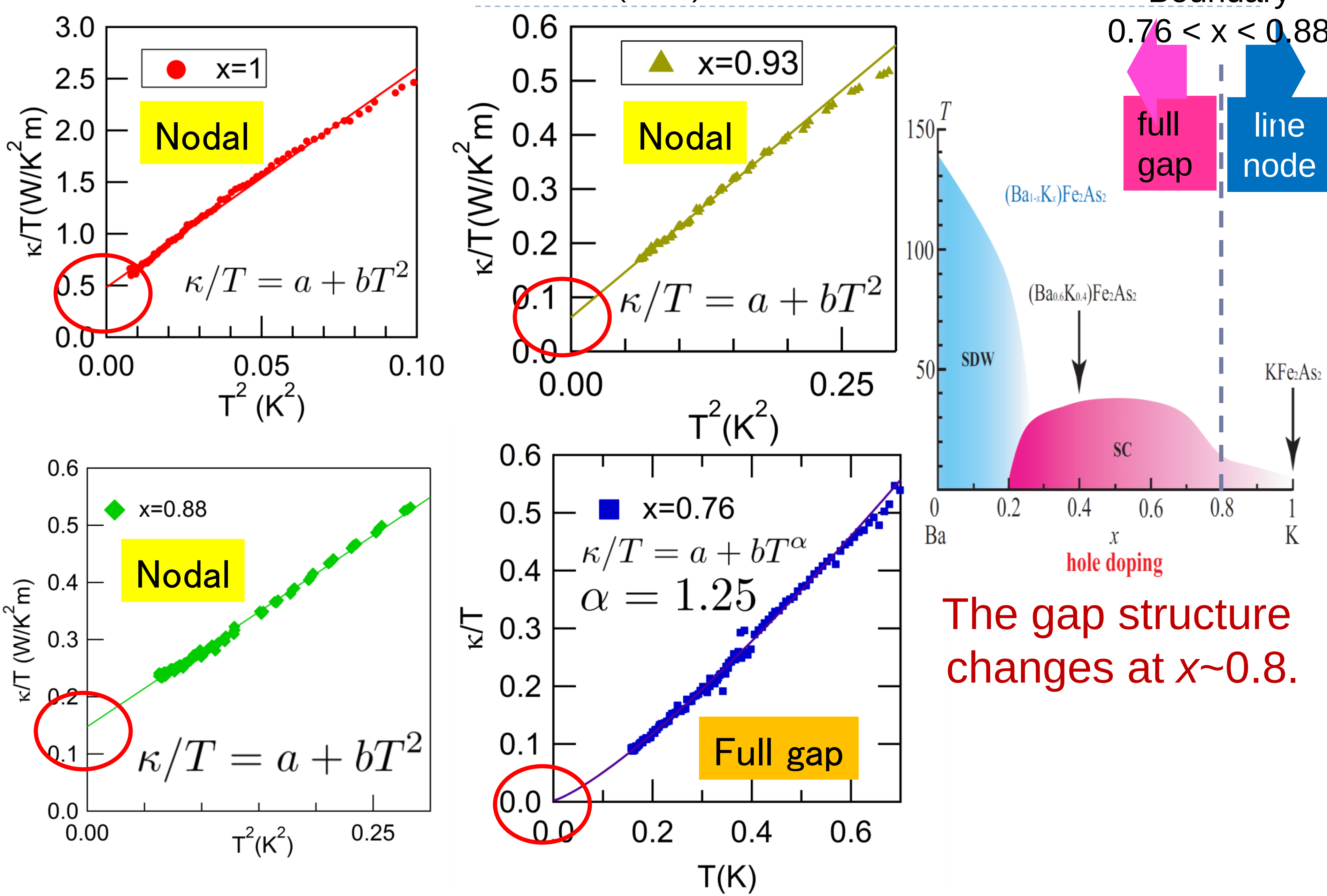
non-phononic (magnetic) pairing interaction

Non-universal gap structure in $BaFe_2As_2$ systems



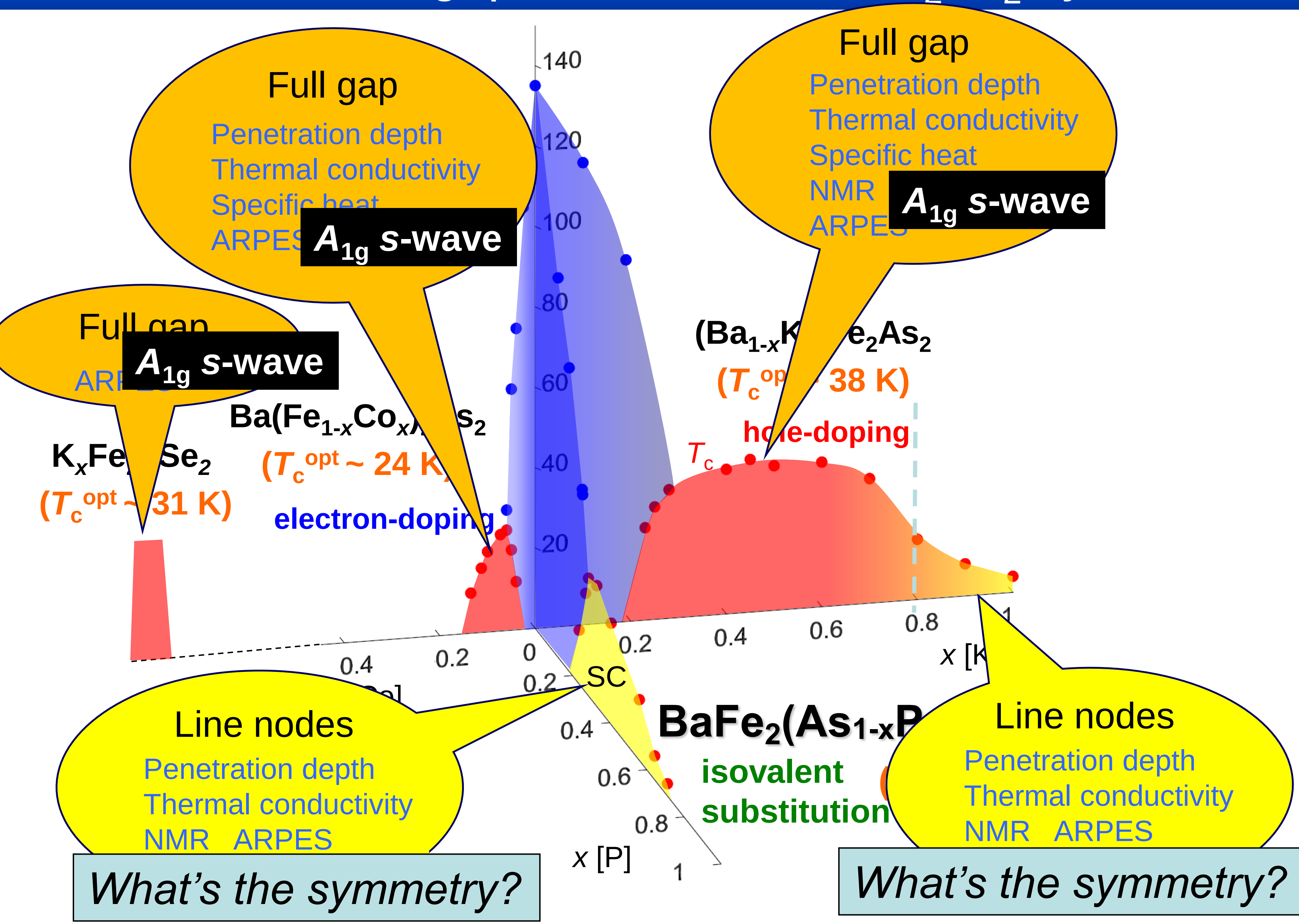
Gap structure of hole doped $Ba_{1-x}K_xFe_2As_2$

D. Watanabe *et al.* PRB (2014)

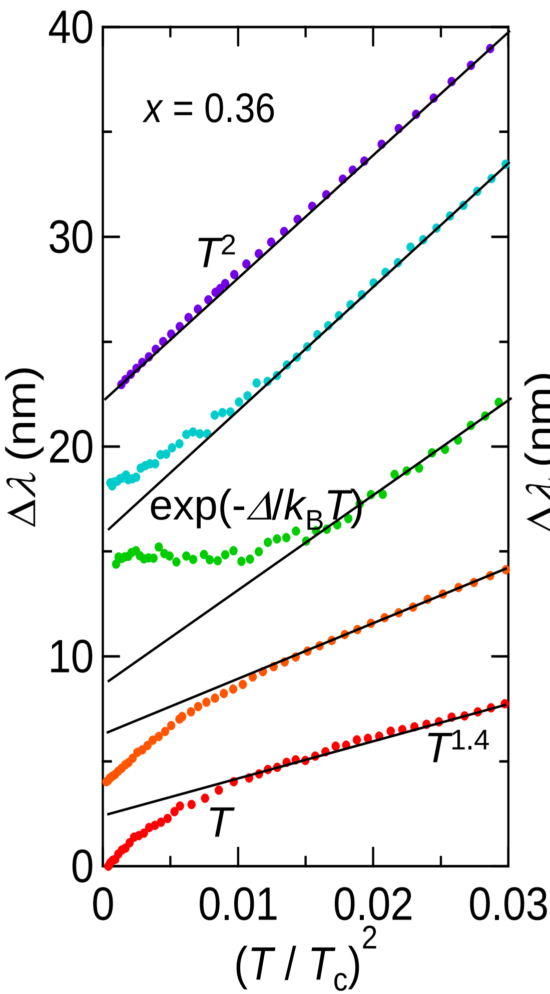


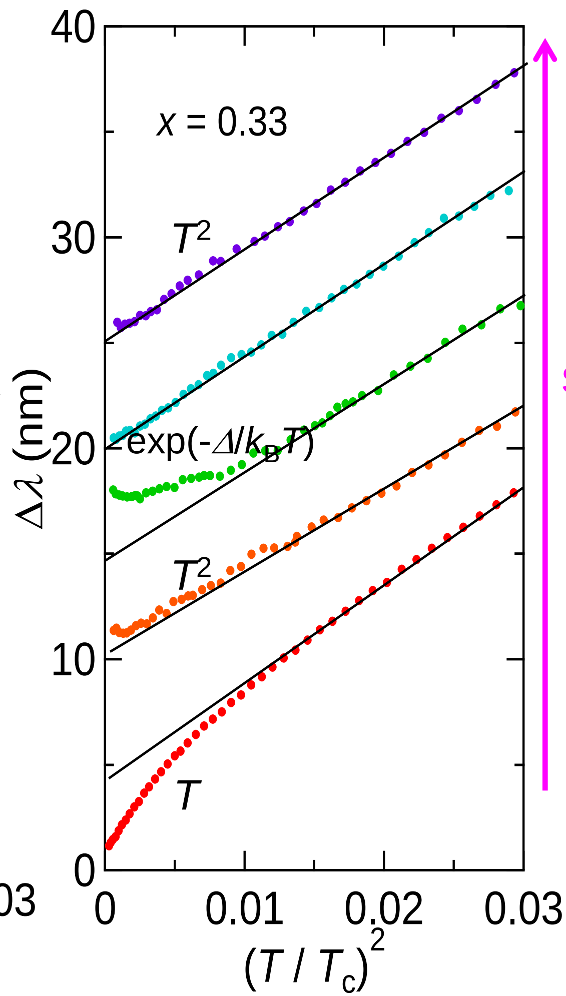
The gap structure changes at x~0.8.

Non-universal gap structure in $BaFe_2As_2$ systems

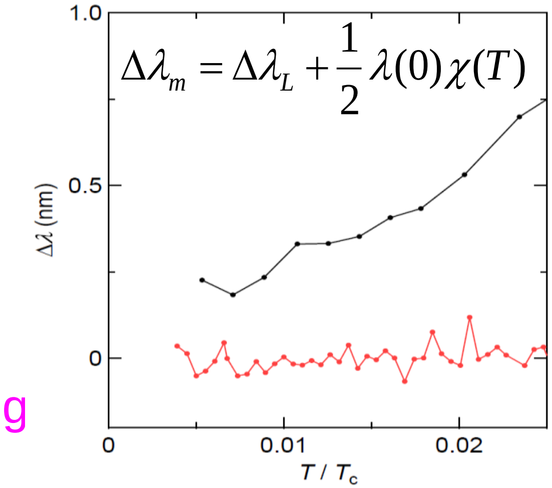


Observation of node lifting by disorder





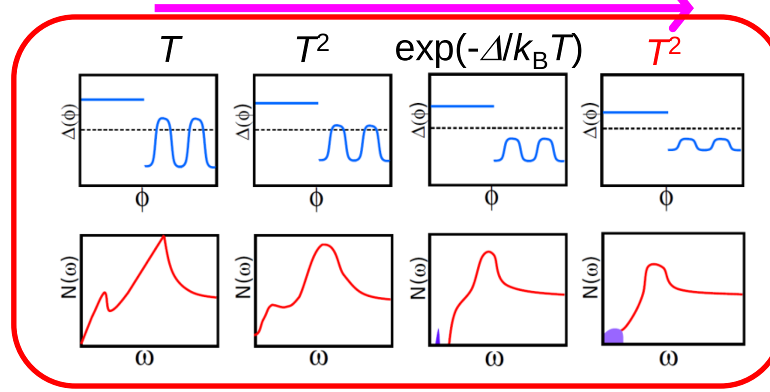
Impurity scattering



no evidence of Curie upturn down to ~80 mK

magnetic moment of point disorder is smaller than ~ 0.2-0.4μ_B

"*Nonmagnetic*" disorder



$\Delta\lambda$ changes with irradiation as

T → T^2 → exp(-Δ/k_BT) → T^2

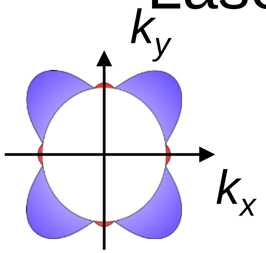
Y. Mizukami *et al.*

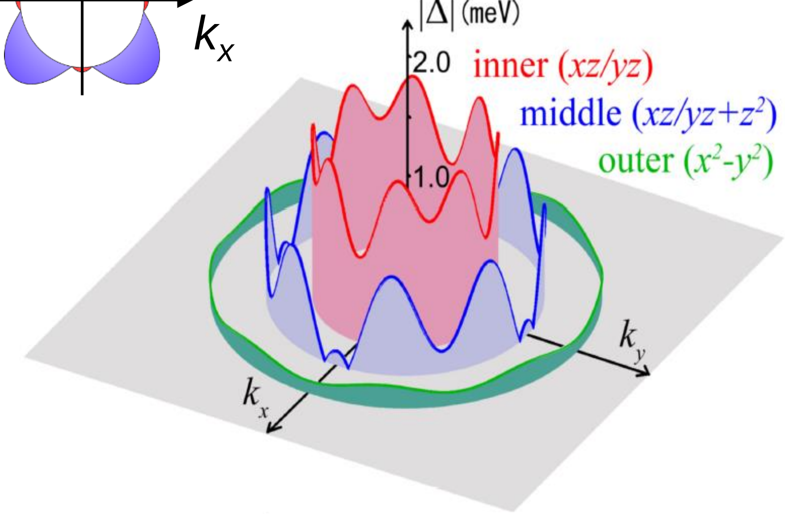
Y. Wang *et al.*, PRB **87**, 094504 (2013). ***S±***

Gap symmetry in KFe_2As_2

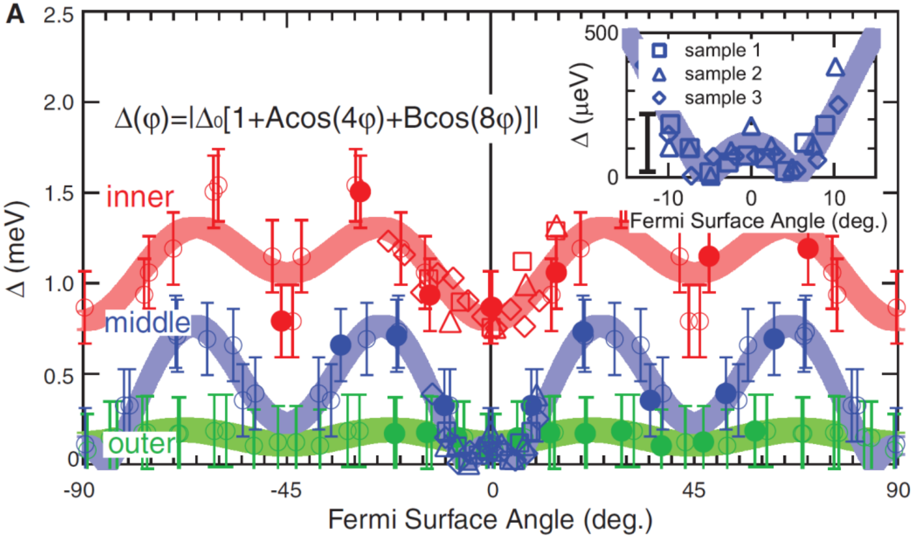
Nodal *s*-wave

Laser ARPES





Octet-Line Node

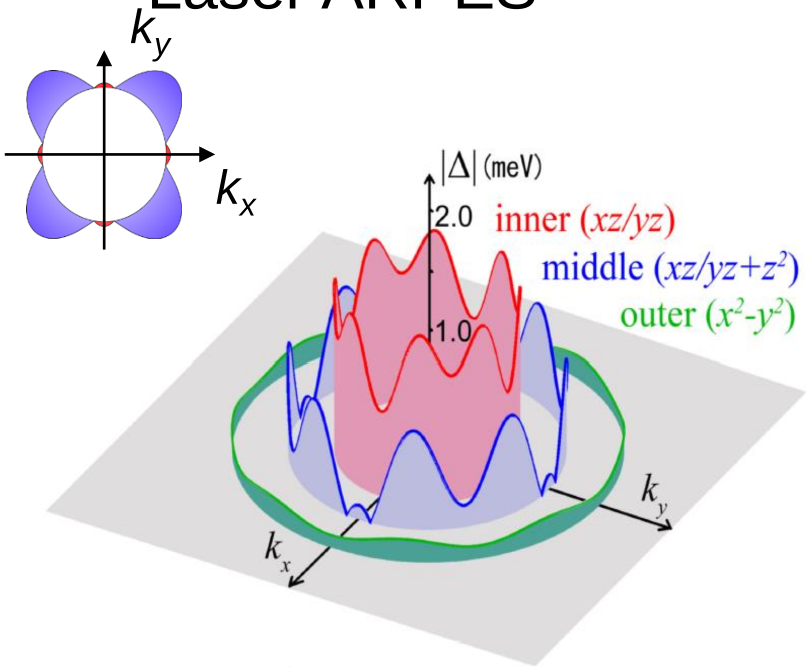


K. Okazaki *et al.*, Science (2012).

Gap symmetry in KFe_2As_2

Nodal *s*-wave

Laser ARPES



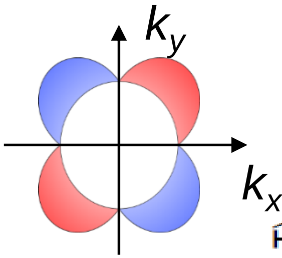
K. Okazaki *et al.*, Science (2012).

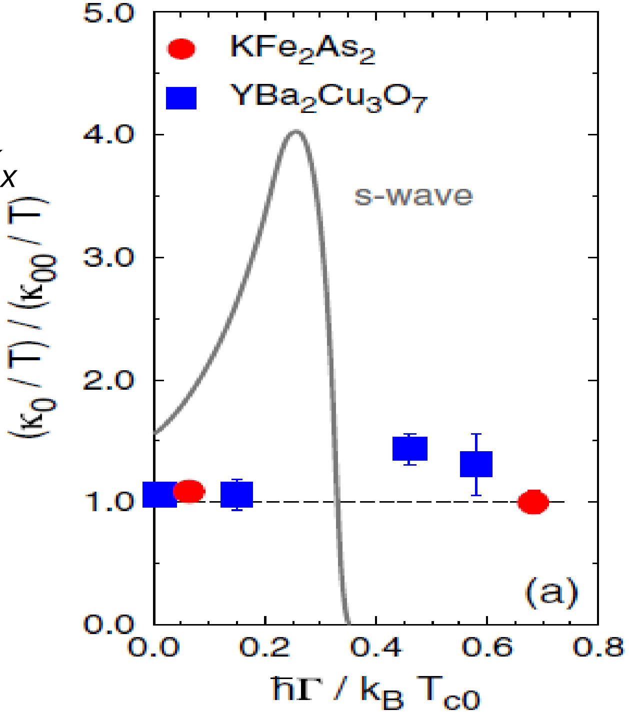
Specific heat

F. Hardy *et al*. JPSJ (2013)

***d*–wave**

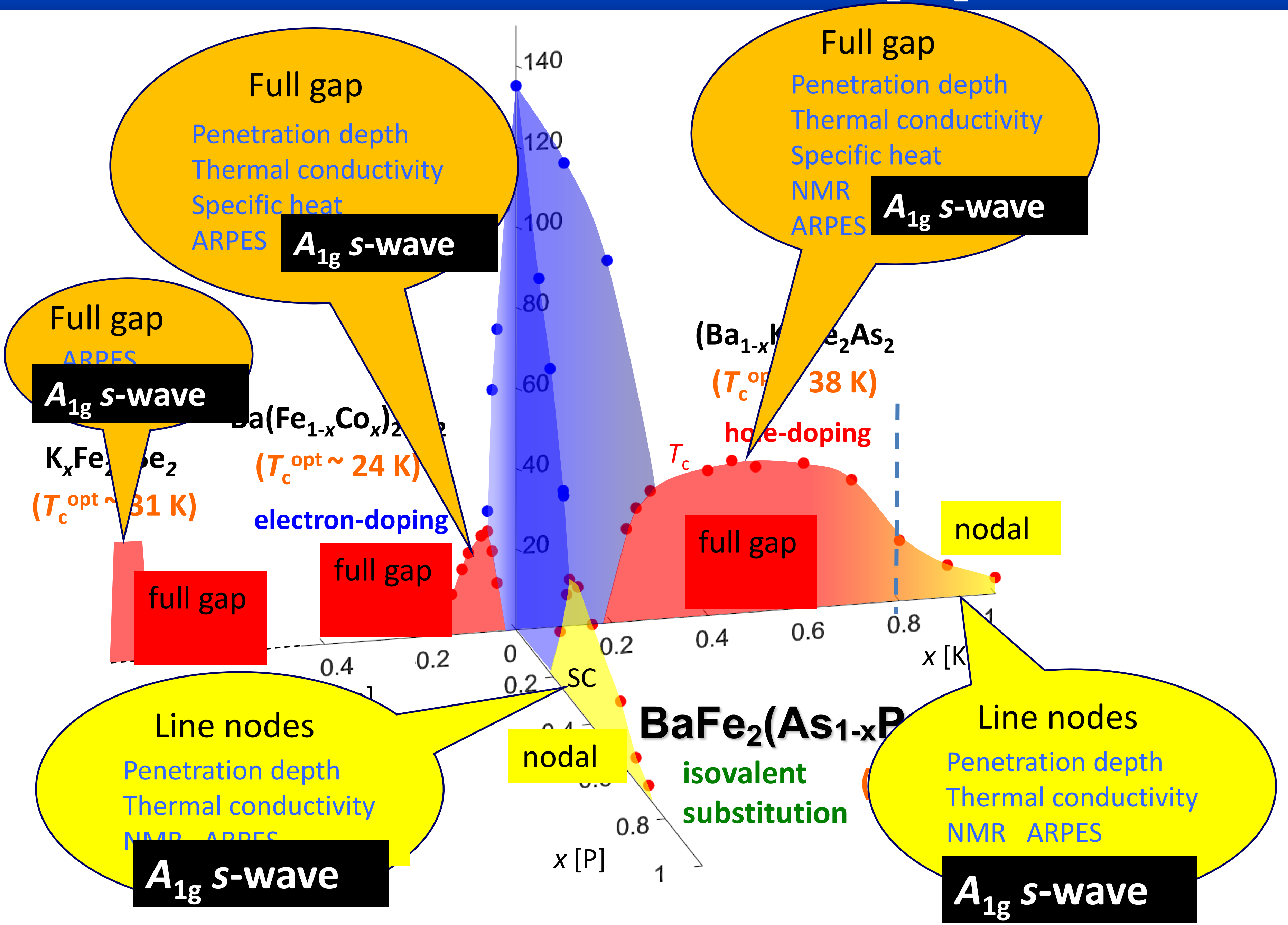
Thermal conductivity





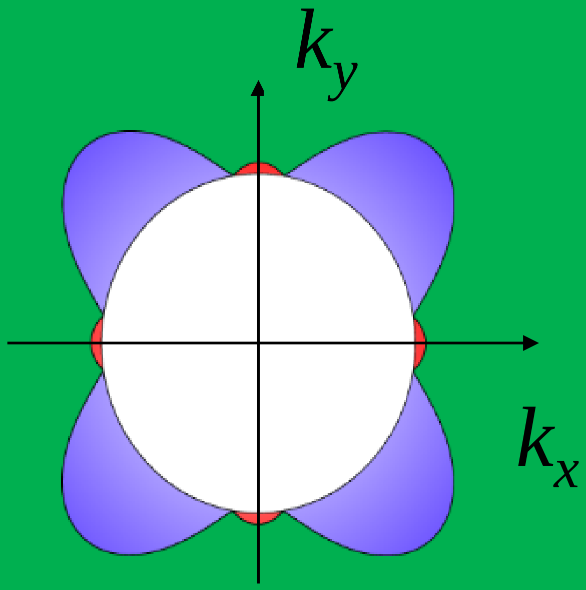
J.P.Reid *et al*. PRL (2012)

Non-universal gap structure in $BaFe_2As_2$ systems



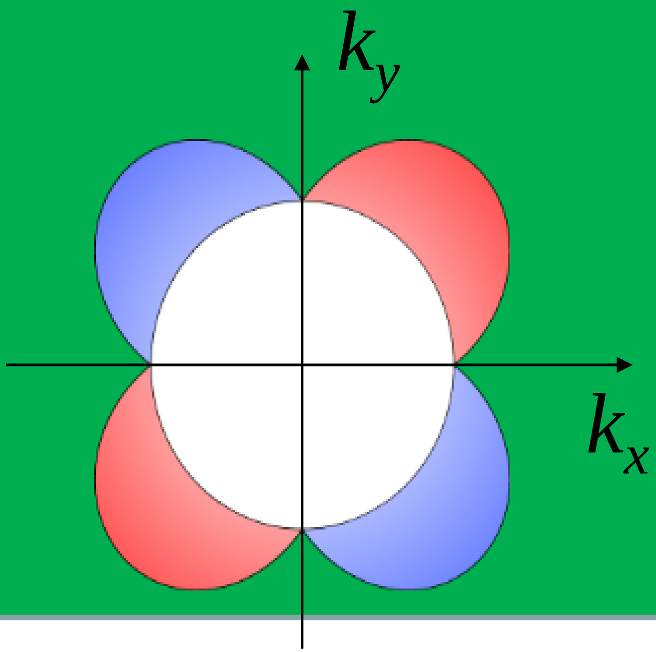
Non-universal gap structure in $BaFe_2As_2$ systems

_s_-wave (A_{1g})
Nodes: Accidental



or

_d_–wave (B_{1g} or B_{2g})
Nodes: Symmetry-protected



What's the symmetry?

What's the symmetry?

鉄系高温超伝導体

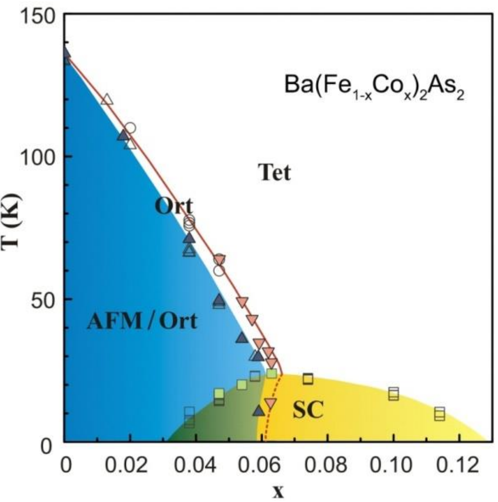
銅酸化物、重い電子系との比較

超伝導ギャップ構造

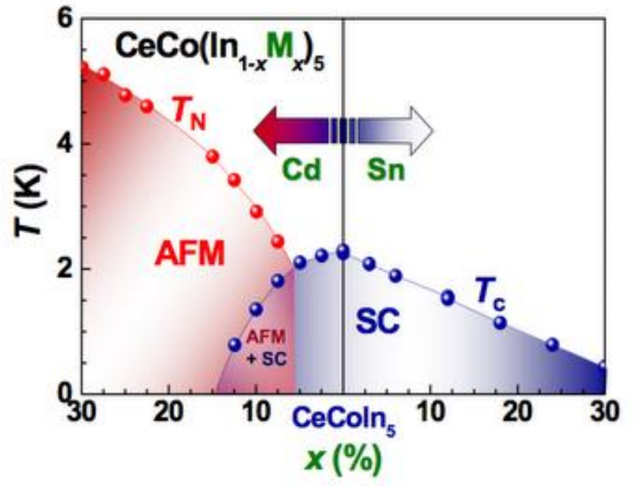
量子臨界点

Quantum Critical Point (QCP)

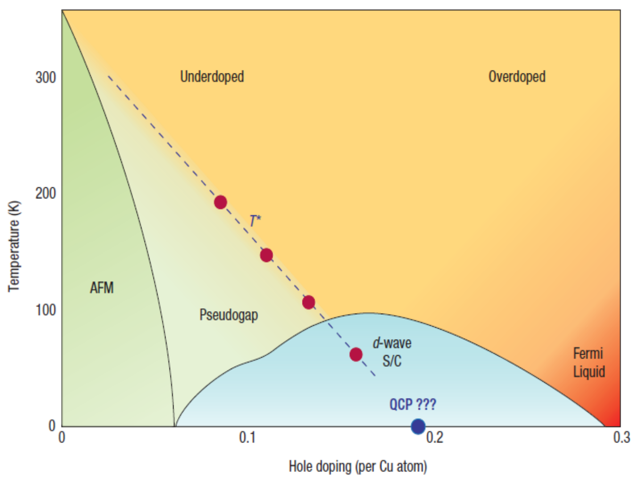
Fe-pnictide



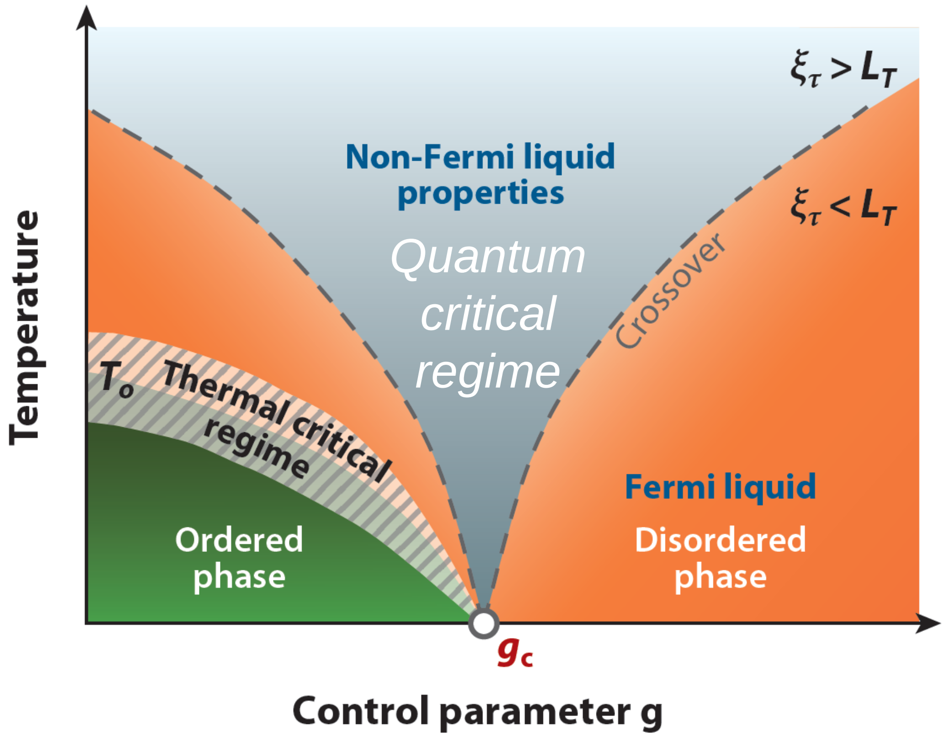
Heavy Fermion



Cuprate



Quantum Critical Point (QCP)



(Quantum critical point)

g: pressure, chemical substitution, magnetic field

S. Sachdev, Quantum Phase Transitions

Quantum time scale

$$\xi \propto |g - g_c|^\nu \qquad \xi_\tau \propto \xi^z$$

Thermal time scale

$$L_T = \frac{\hbar}{k_B T}$$

$\xi_\tau < L_T$

QP excitations are well defined

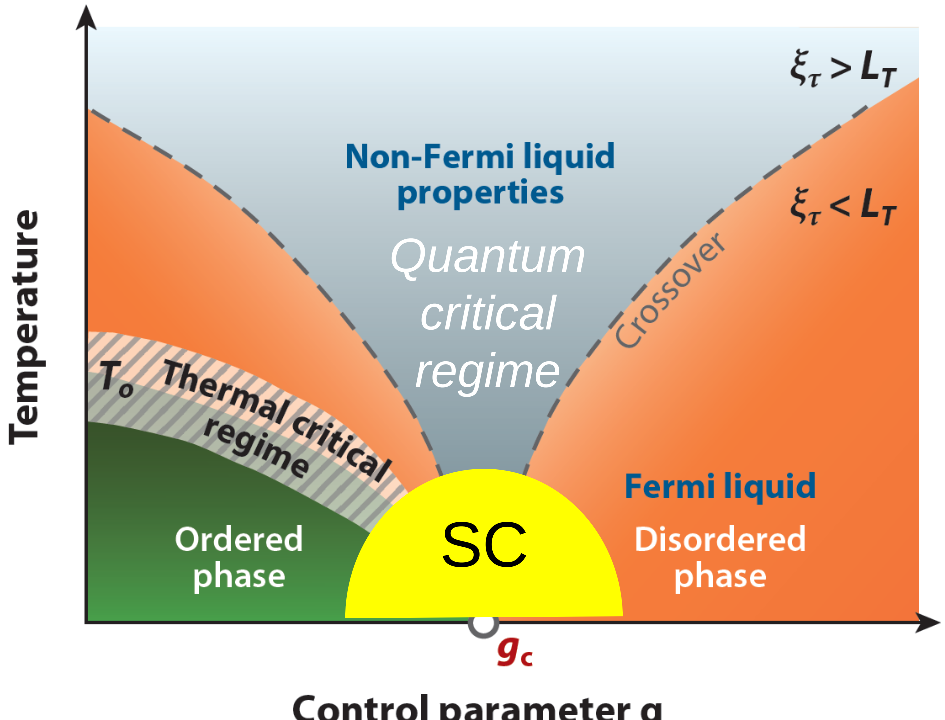
$\xi_\tau > L_T$

Physical properties are seriously influenced by QCP at $g=g_c$.

Ordinary phase transition – driven by thermal fluctuations

Quantum phase transition – driven by zero temperature quantum fluctuations associated with Heisenberg's Uncertainty Principle

Quantum Critical Point (QCP)



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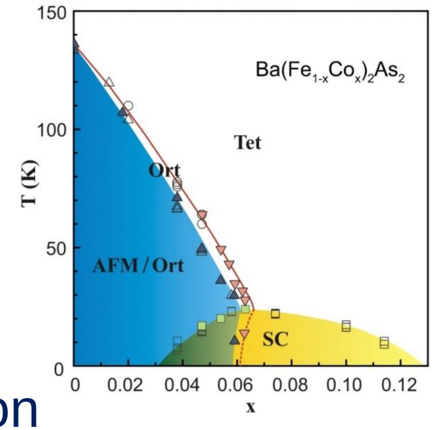
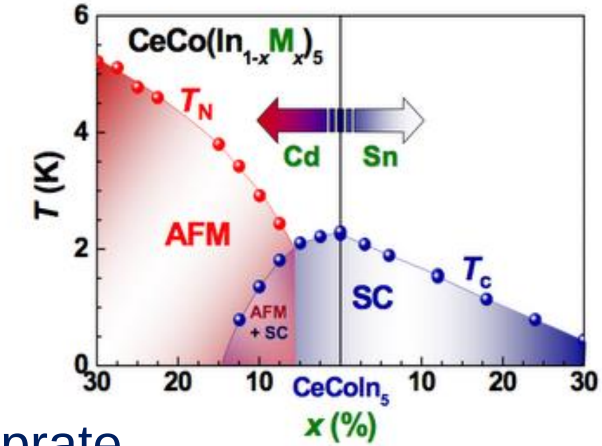
S. Sachdev, Quantum Phase Transitions

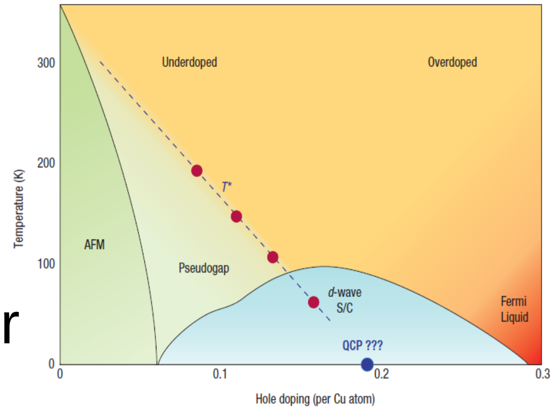
Fe-pnictide



Heavy Fermion



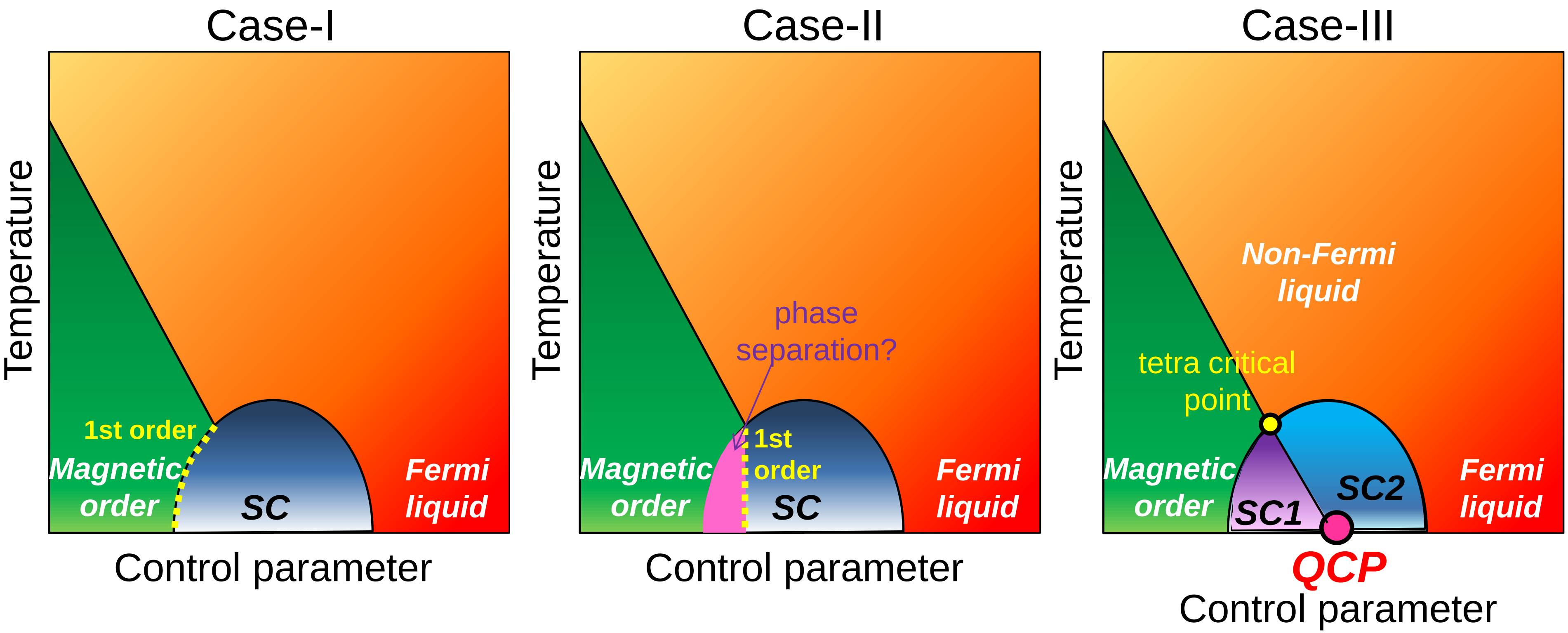
Cuprate



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

What lies beneath the SC dome?



Criticality avoided by the transition to the SC state

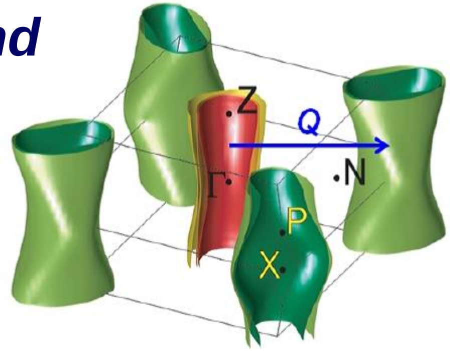
QCP lying beneath the SC dome

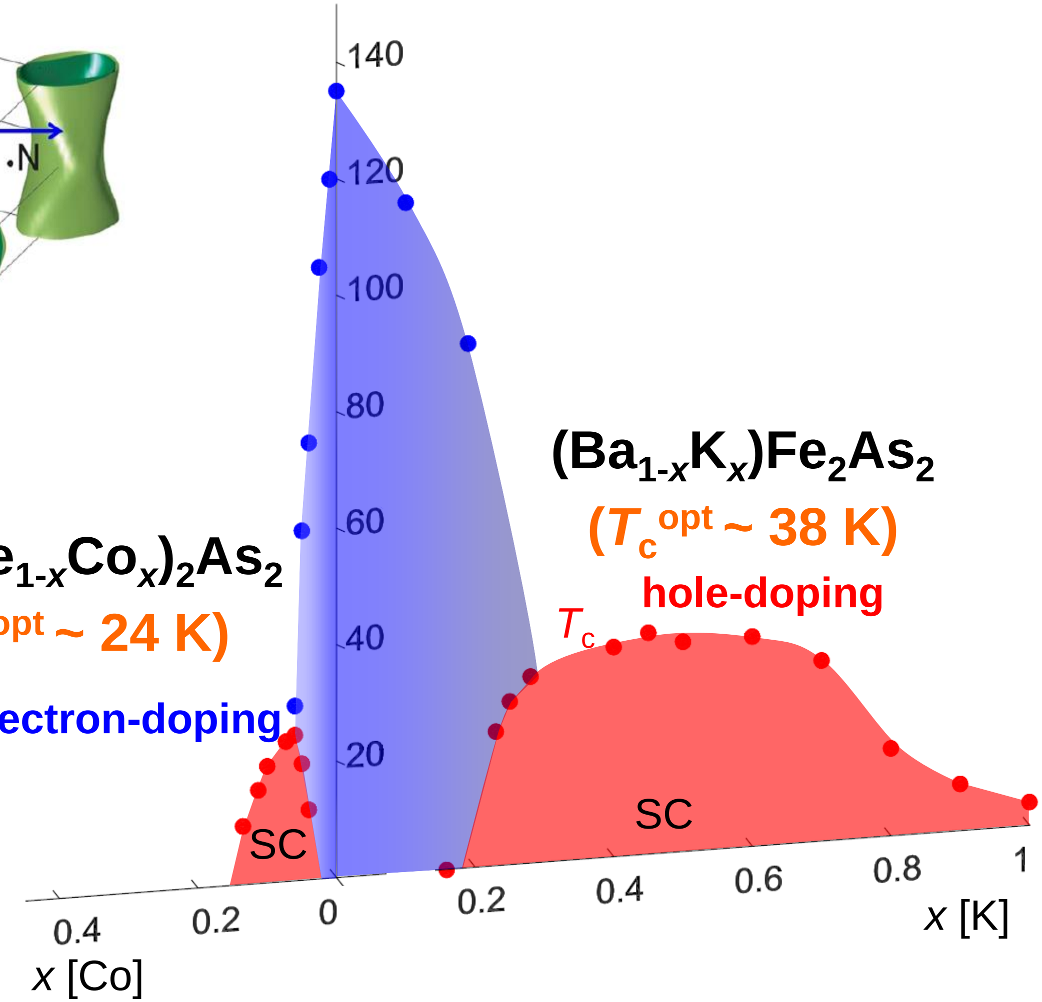
Superconductivity in $BaFe_2As_2$ systems

Parent compound

$BaFe_2As_2$

(AF Metal)





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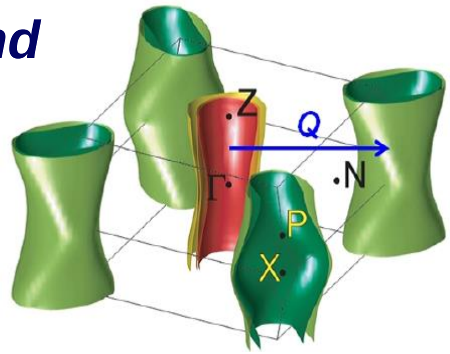
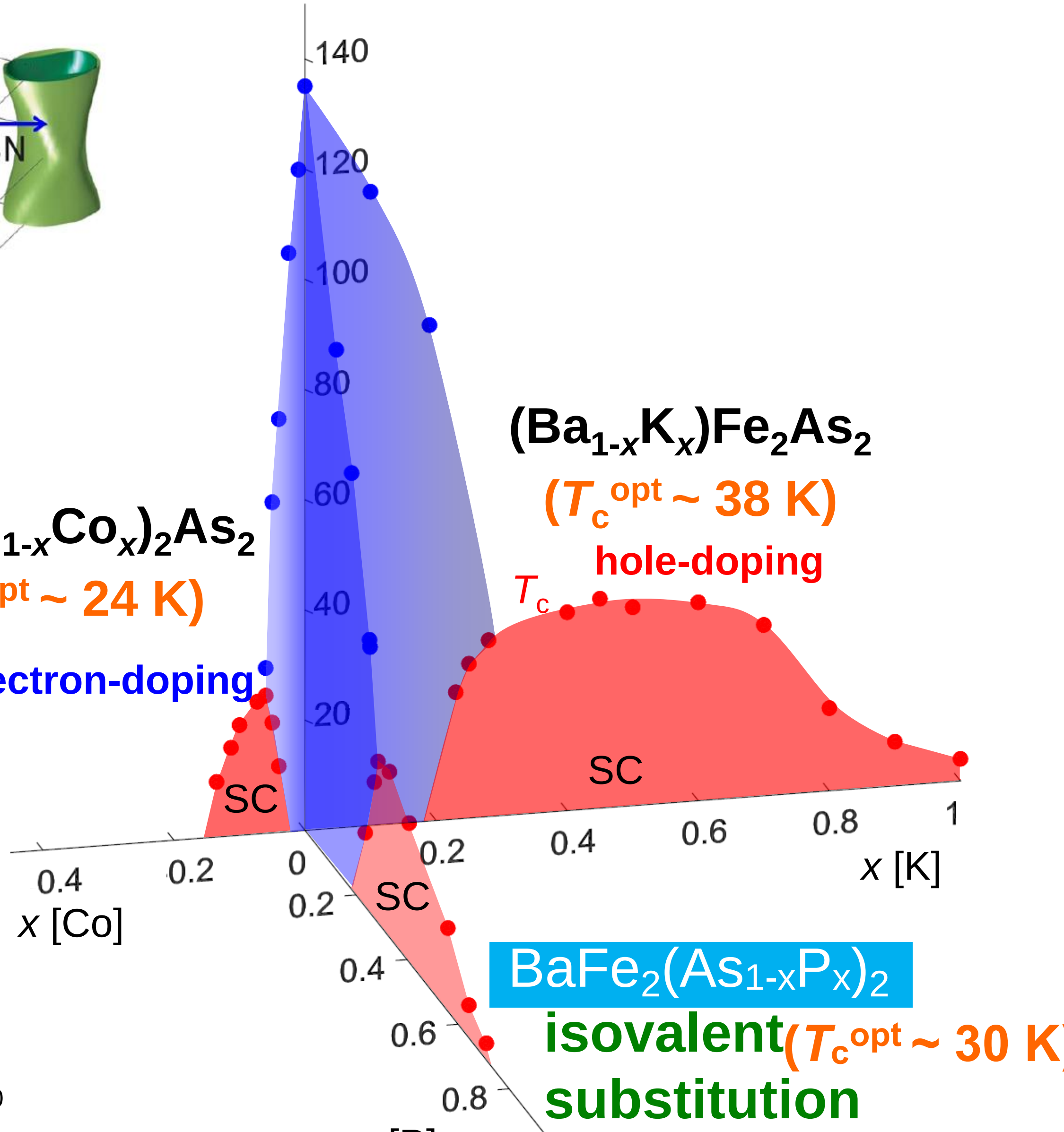
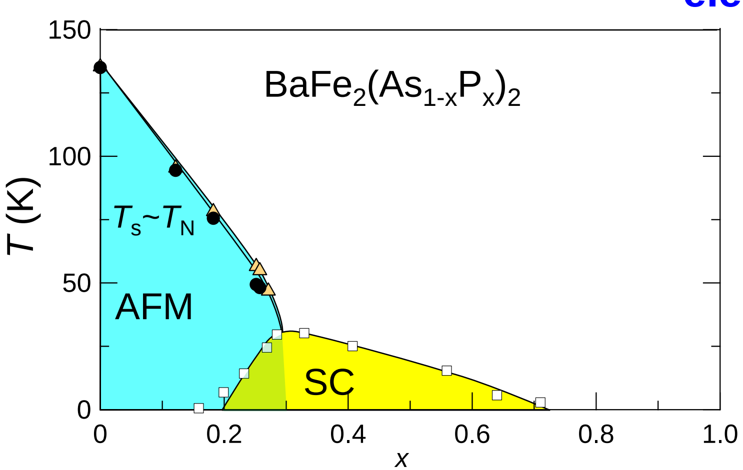


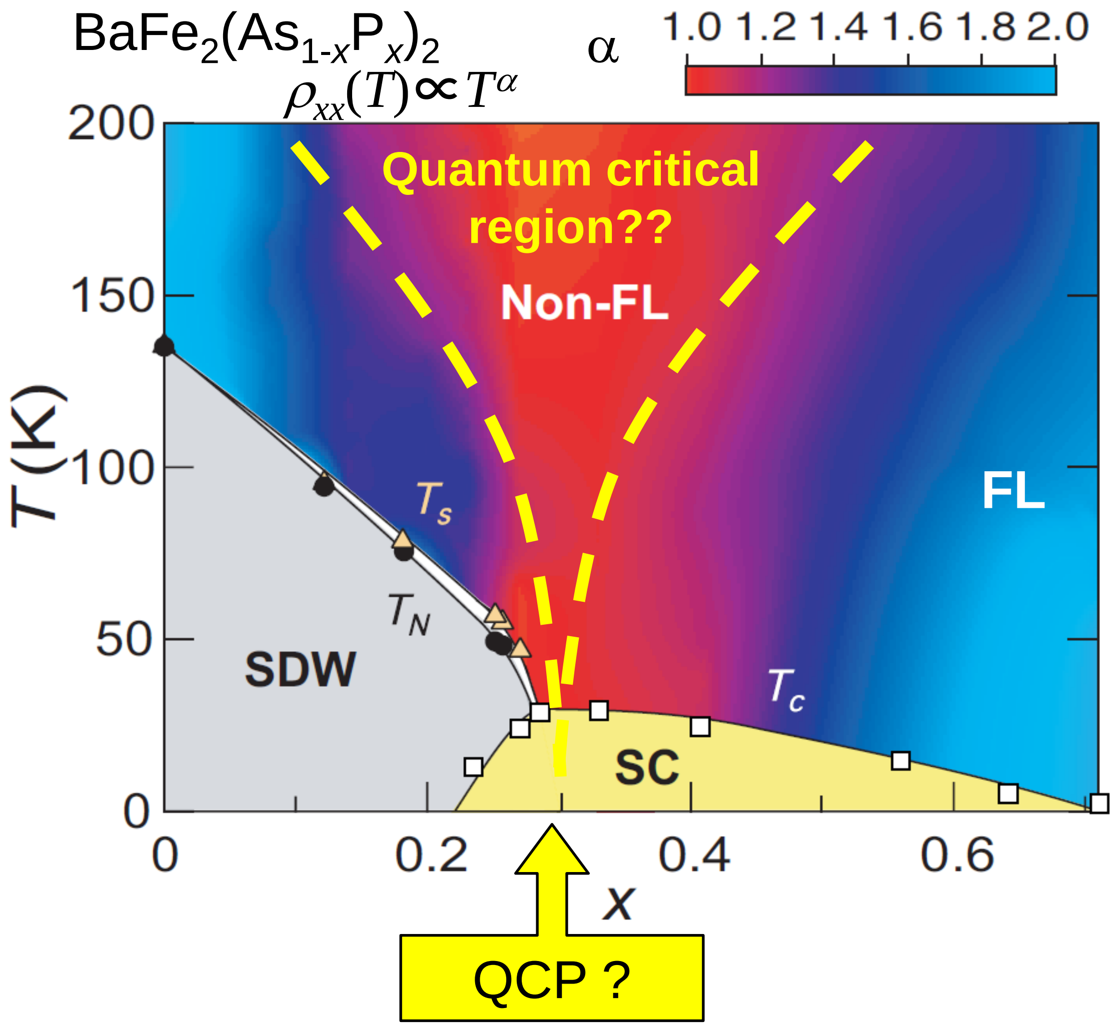


S. Jiang *et al*. JPCM (09)

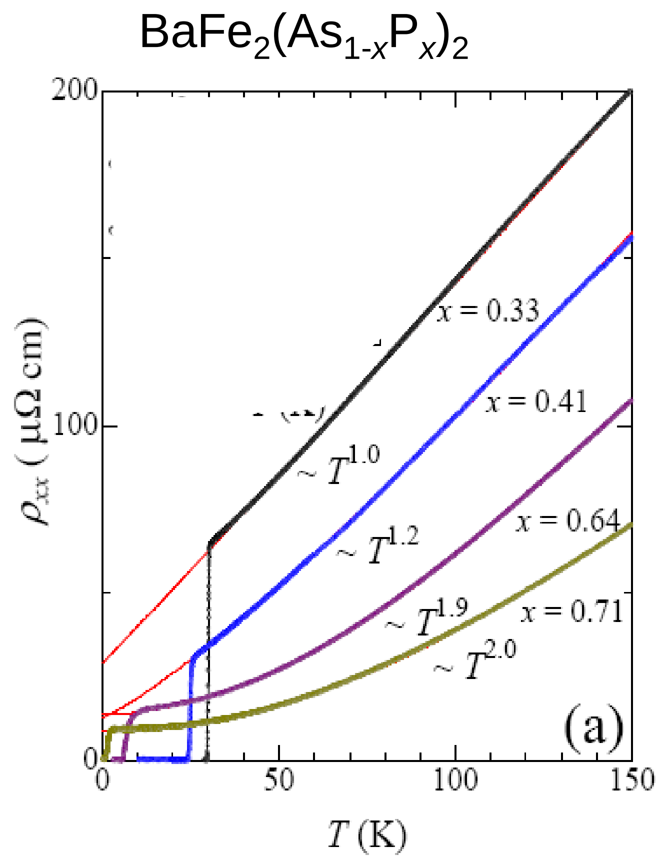


Ground state can be tuned without doping carriers

Doping evolution of the transport property



S. Kasahara *et al*., PRL (10)



T-linear resistivity at *x*=0.33 just beyond SDW end point (x_c=0.3)

Hallmark of non-Fermi liquid

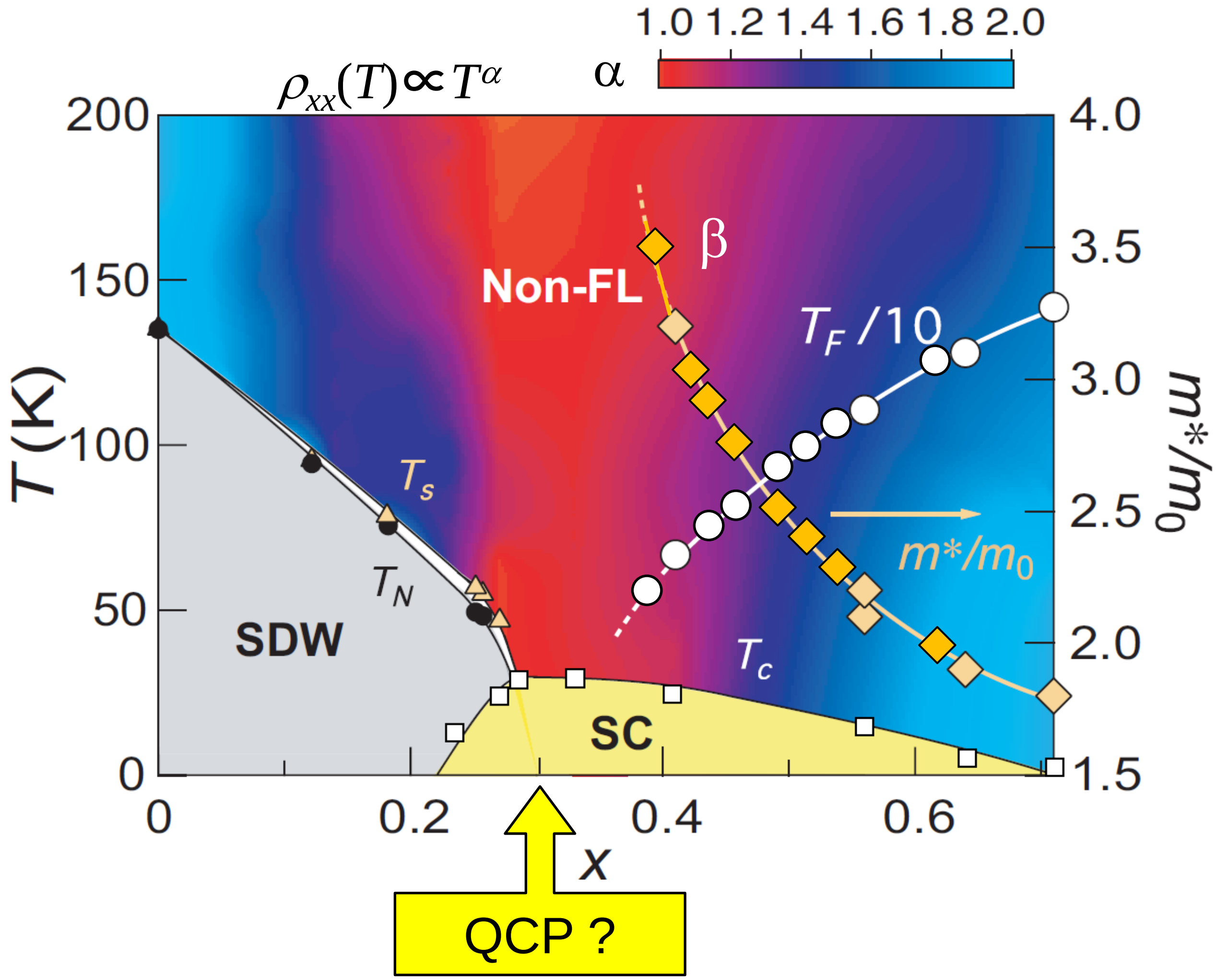
T^2-dependence at *x*=0.71

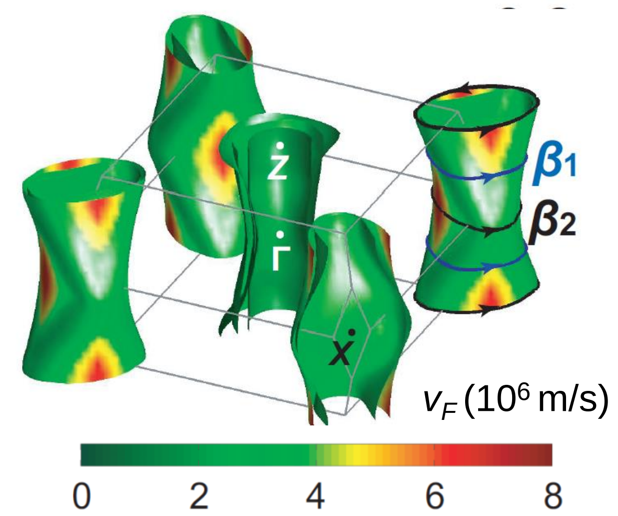
Fermi-liquid behavior

See also

S. Sachdev and B. Keimer, Physics Today (11)

Fermi surface and mass renormalization



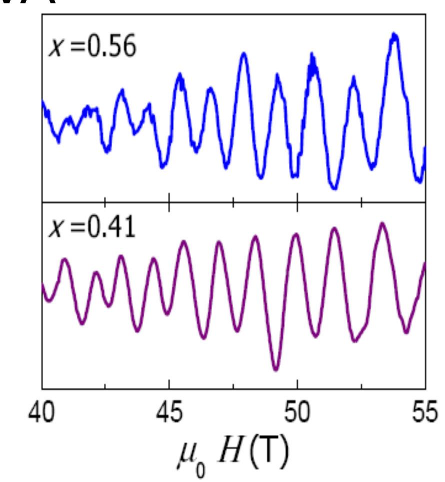


Effective mass

Fermi temperature

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

dHvA



As x is tuned towards the maximum T_c,

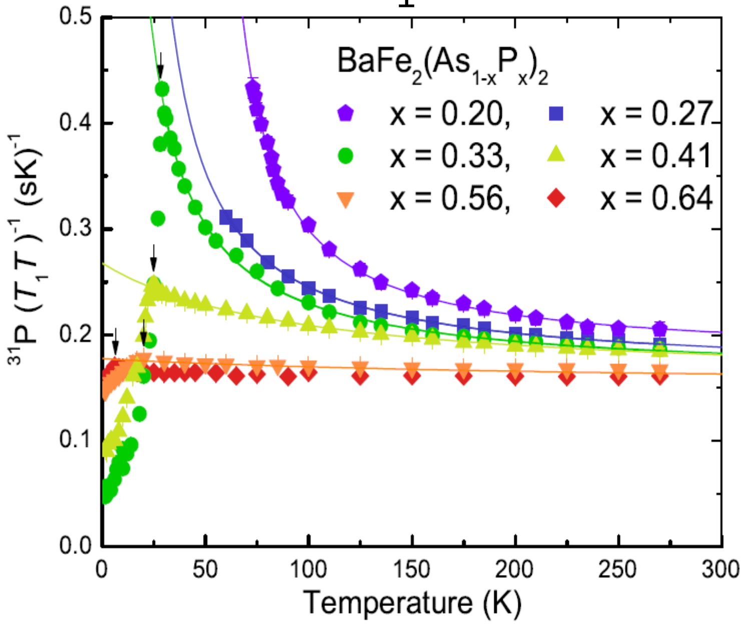
Effective mass m^* is strongly enhanced

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

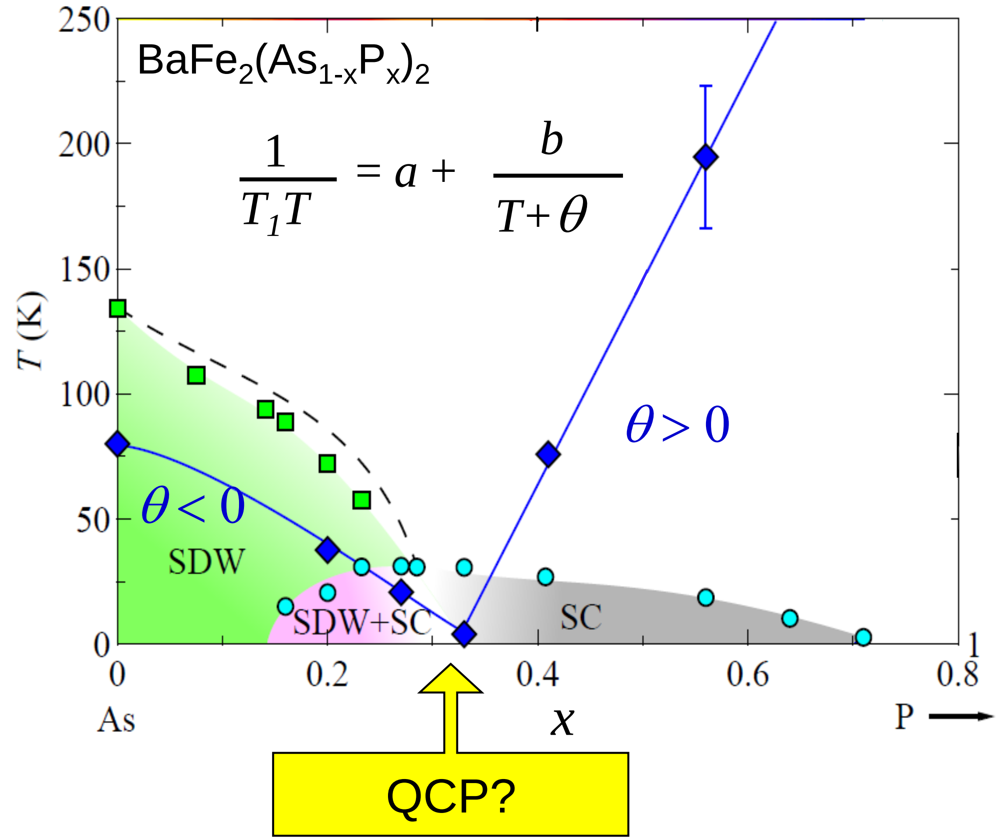
H.Shishido, Y.M. *et al*. PRL (09) P. Walmsley, Y.M. *et al*. PRL(13)

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

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



θ: Weiss temperature

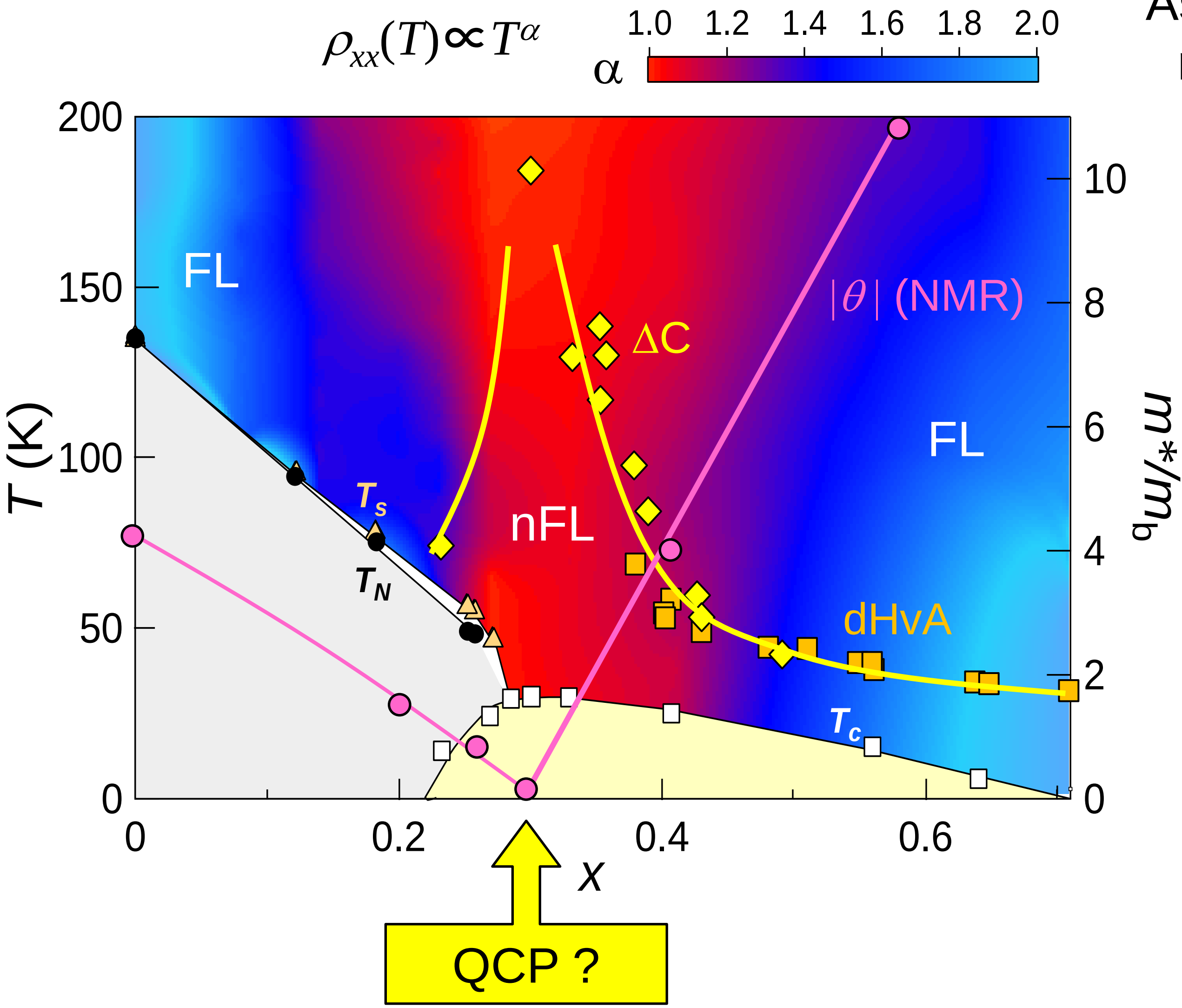


θ goes to zero at x~0.3

Dynamical susceptibility diverse at T=0 K.

Y. Nakai *et al*. PRL (10)

Doping evolution of normal electrons



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

NMR

We need evidence at zero temperature and zero field.

Doping evolution of the London penetration depth at T=0

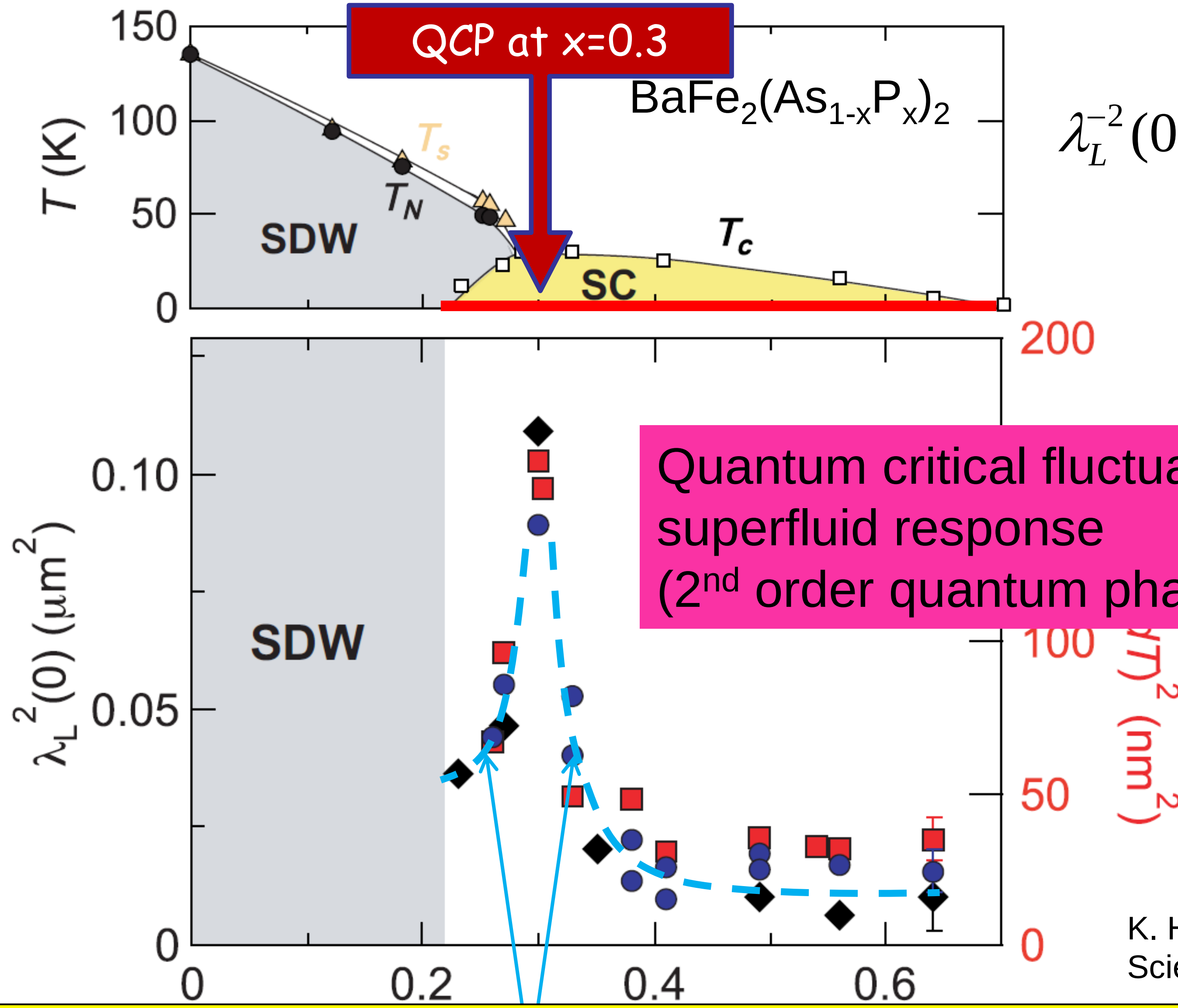
London penetration depth λ_L is the quantity that can probe the electronic structure at zero temperature limit.

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

Number of superfluid

Mass of superfluid

Doping evolution of the London penetration depth at T=0



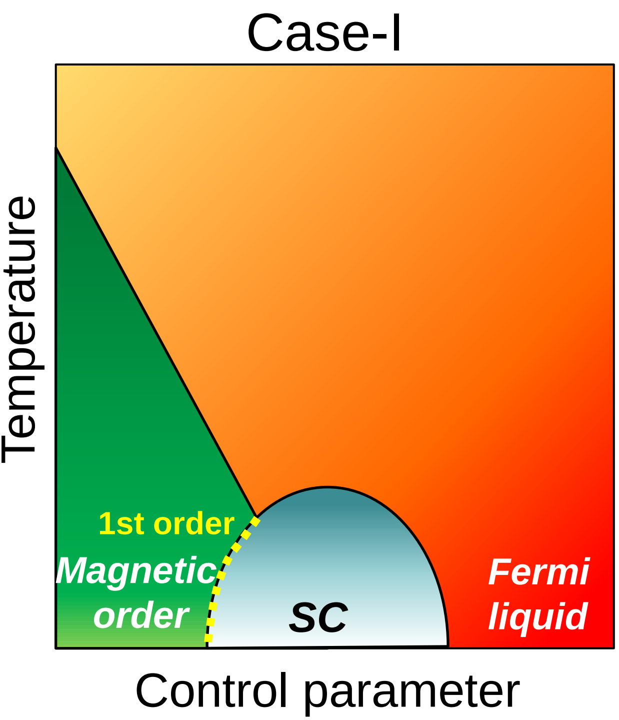
$$\lambda_L^{-2}(0) = \frac{\mu_0 n_s e^2}{m^*}$$

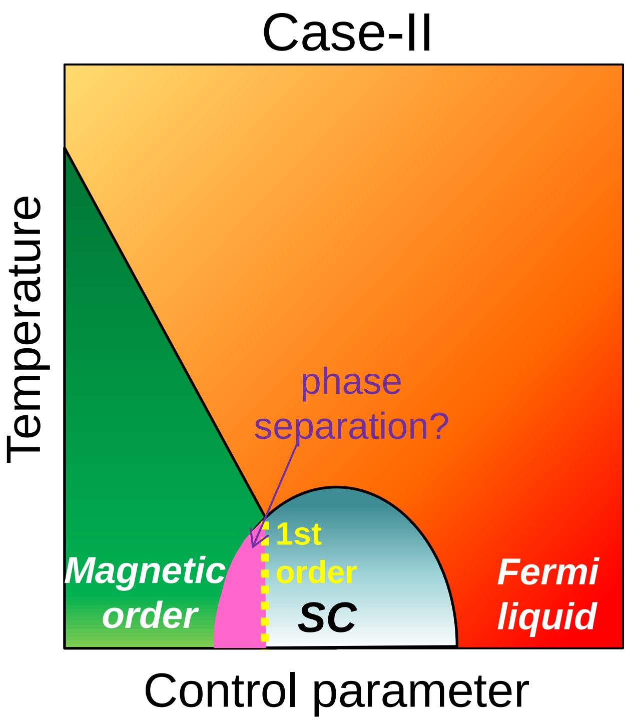
Quantum critical fluctuations of the superfluid response
(2nd order quantum phase transition)

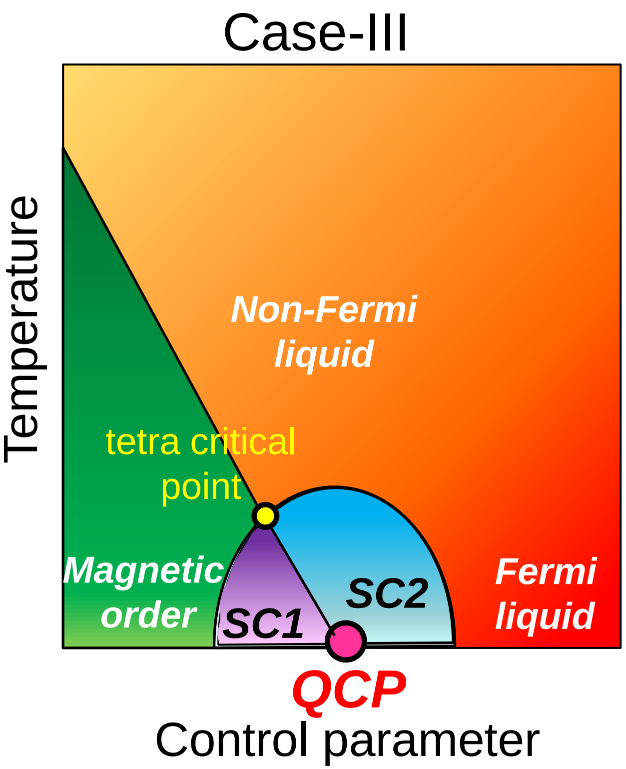
K. Hashimoto *et al.* Science (12)

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.

What lies beneath the SC dome?







$CeIn_3$,$CePd_2Si_2$

NMR

T. Kawasaki *et al*. J. Phys. Soc. Jpn (04)

$CeRhIn_5$

Specific heat

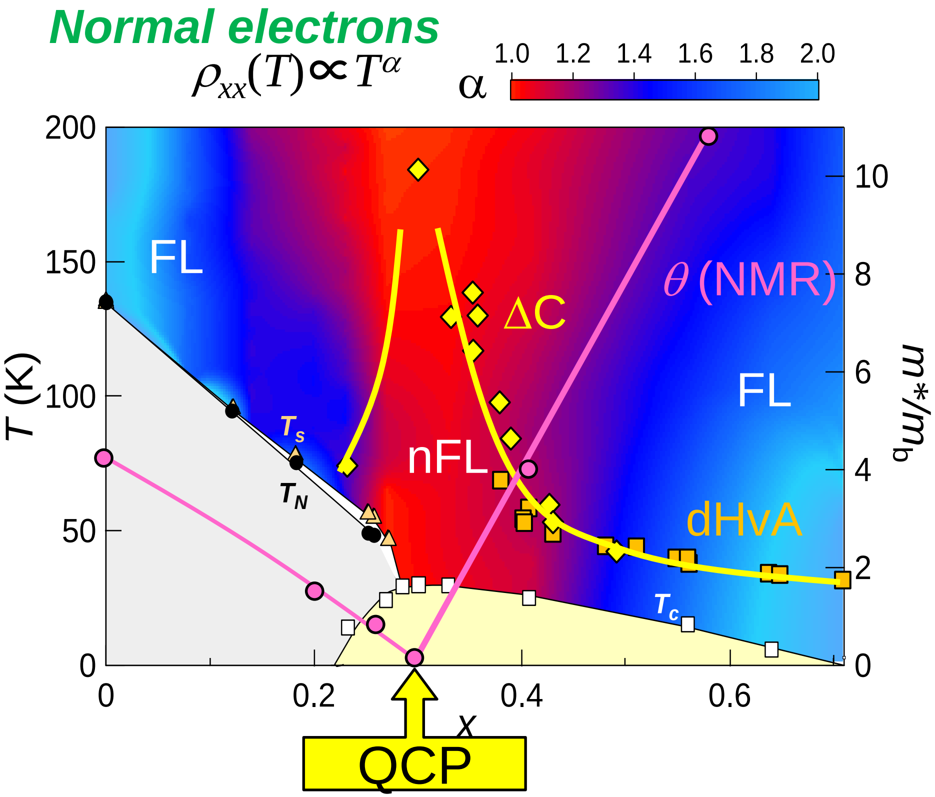
T. Park *et al*. Nature (06)

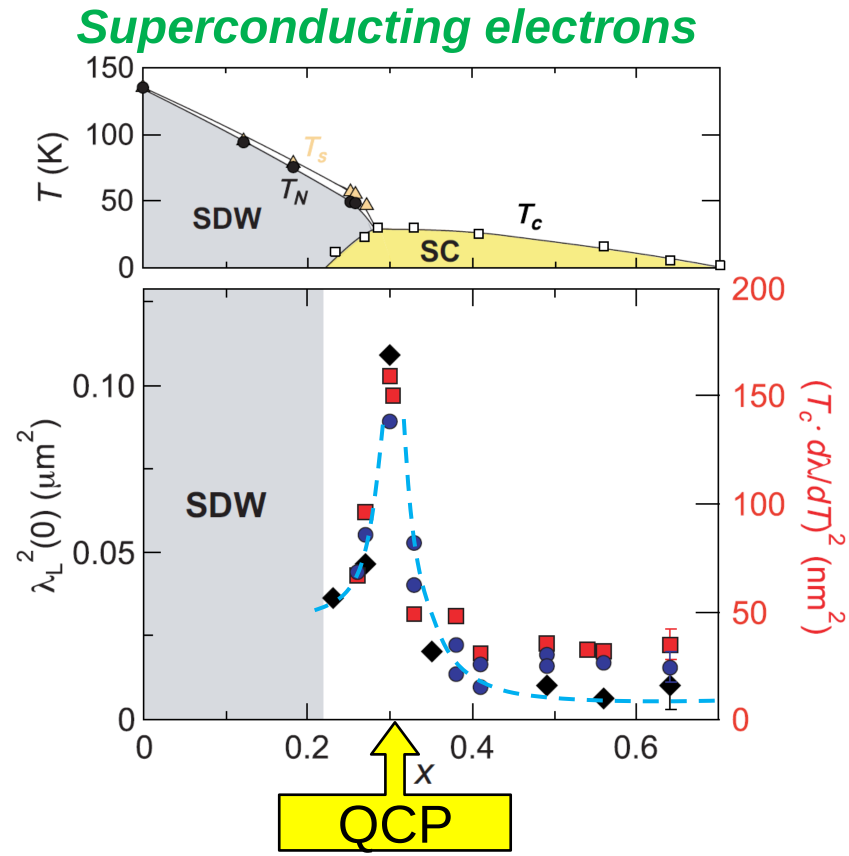
G. Knebel *et al*. Phys. Rev. B (06)

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

K. Hashimoto *et al*. Science (12)

QCP lies beneath the dome





Hallmark of non-Fermi liquid behavior

S. Kasahara, Y.M. *et al*. PRB (10)

Enhancement of normal electron mass

H. Shishido, Y.M. *et al*. PRL (10), P. Walmsley, Y.M. *et al*. PRL(13)

Vanishing of Weiss temperature

Y. Nakai *et al*. PRL (10)

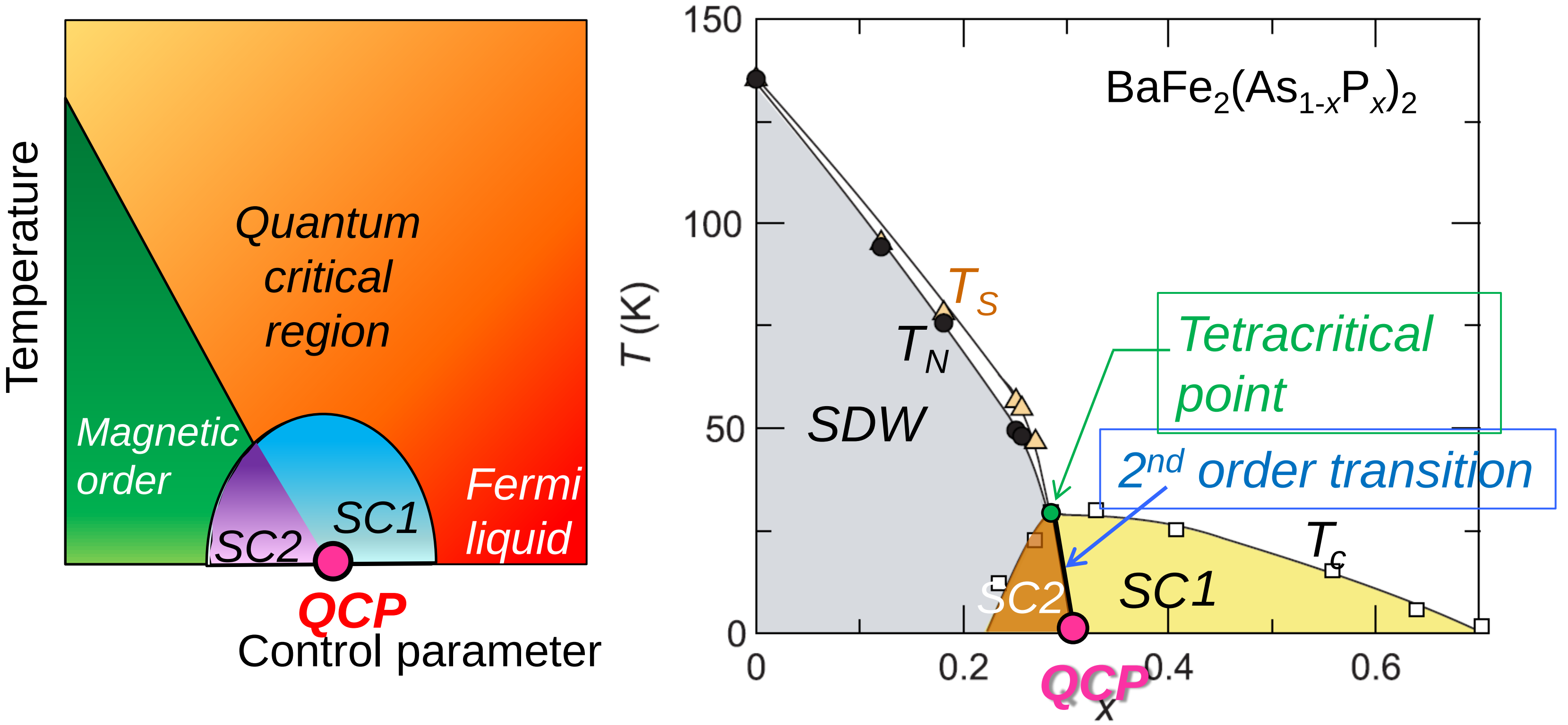
Striking enhancement of superfluid mass

K. Hashimoto, Y.M. *et al*. Science (12), PNAS (13)

QCP lies beneath the superconducting dome

T. Shibauchi, A. Carrington and Y. M., Annu. Rev. Condens. Matter Phys. 5, 113 (14)

QCP lies beneath the dome

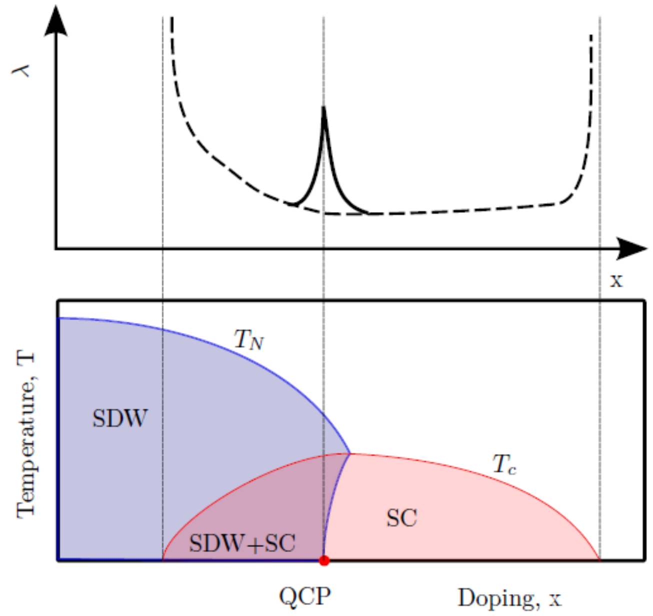


1. The QCP is the origin of the non-Fermi liquid behavior above T_c.

2. Microscopic coexistence of superconductivity and SDW.

3. The quantum critical fluctuations help to enhance the high-T_c superconductivity.

Singularity of the London penetration depth at QCP



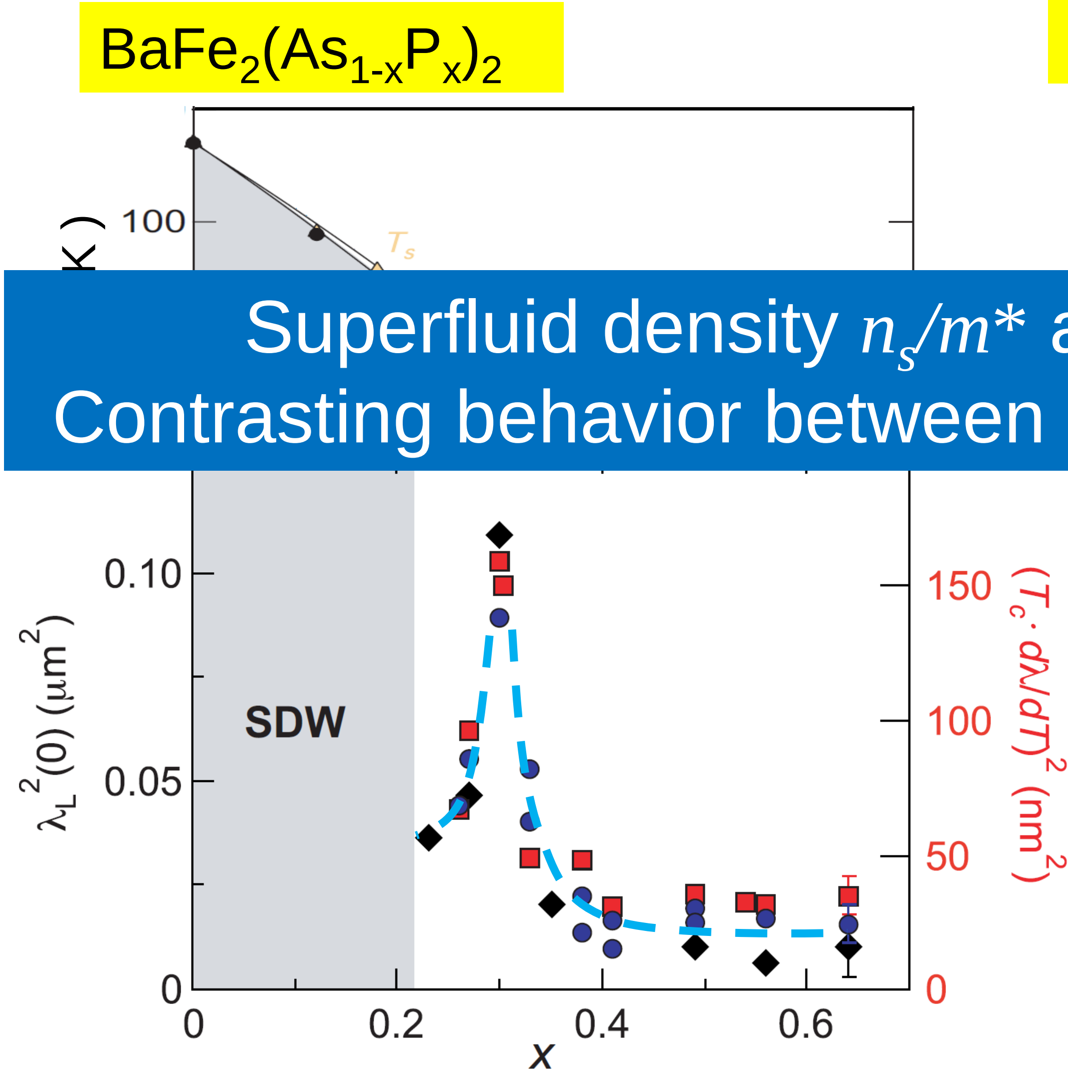
1) Mass renormalization of superfluid by critical magnetic fluctuations

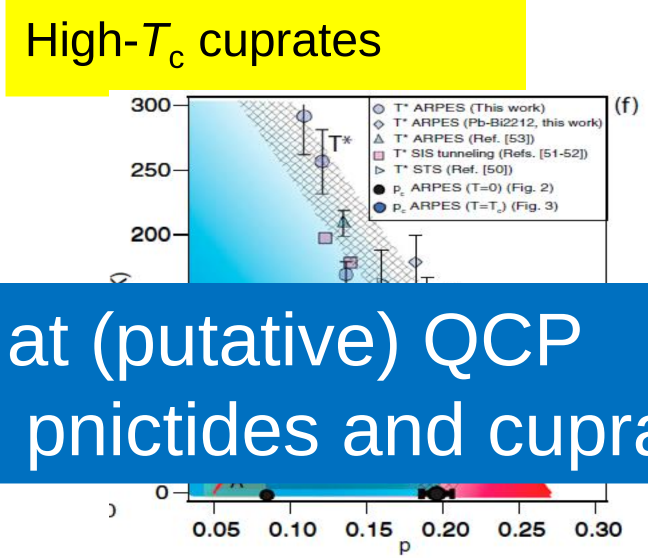
A. Levchenko, M. G. Vavilov, M. Khodas, and A. V. Chubukov, PRL (13)
T. Nomoto and H. Ikeda, PRL (13)

2) SDW fluctuations + nematic order

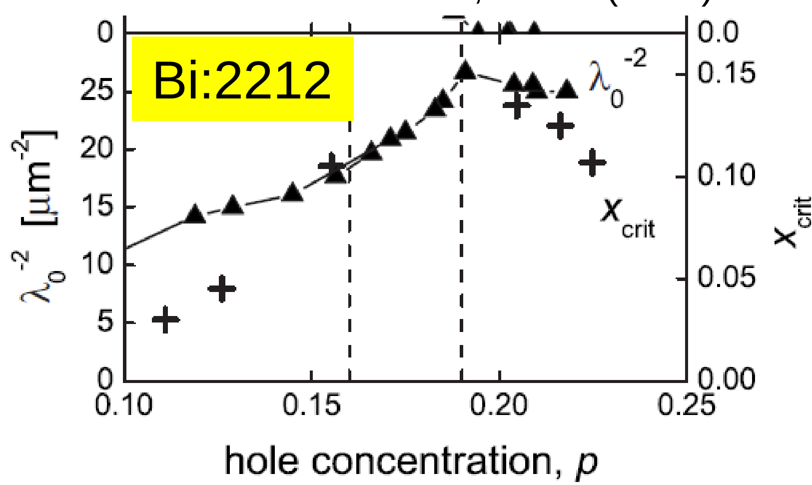
D.Chowdhury, B. Swingle, E. Berg, and S. Sachdev, PRL (13)

Doping evolution of the London penetration depth at T=0





I. M. Vishik *et al*., PNAS (2012).



J.G.Storey *et al*. PRB (07)

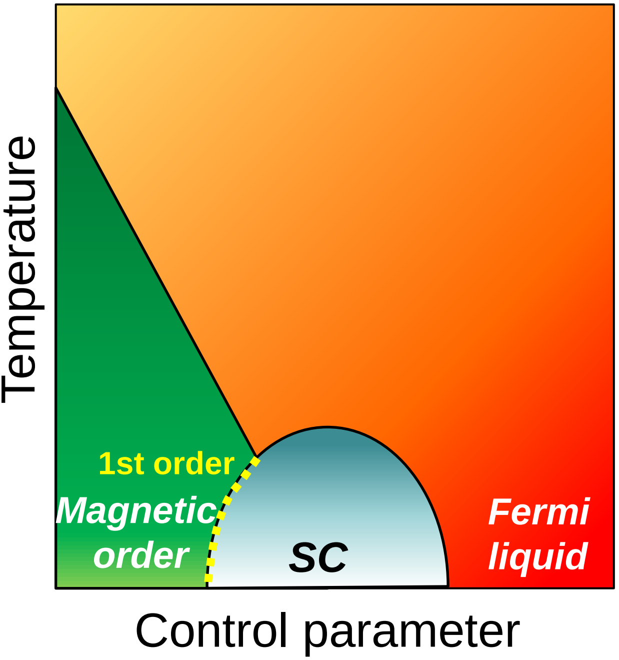
Superfluid density n_s/m^* at (putative) QCP
Contrasting behavior between pnictides and cuprates

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

What lies beneath the SC dome?

Case-I

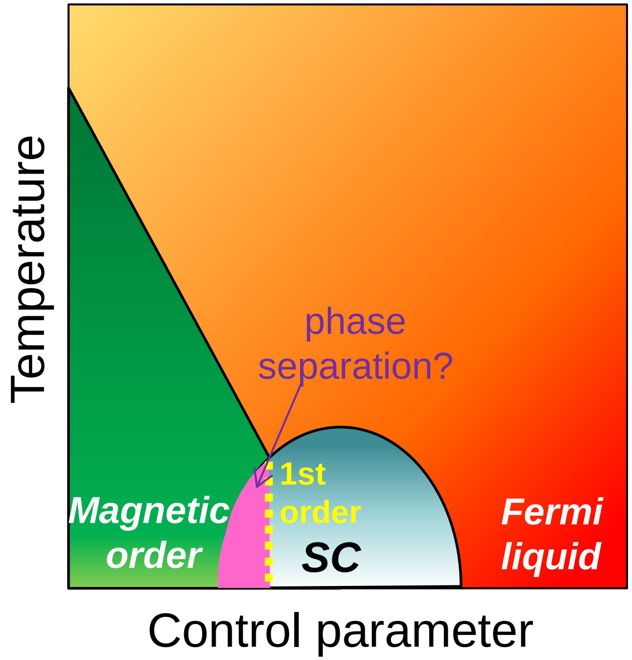


CeIn$_3$,CePd$_2$Si$_2$

NMR

T. Kawasaki *et al*. J. Phys. Soc. Jpn (04)

Case-II



CeRhIn$_5$

Specific heat

T. Park *et al*. Nature (06)

G. Knebel *et al*. Phys. Rev. B (06)

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

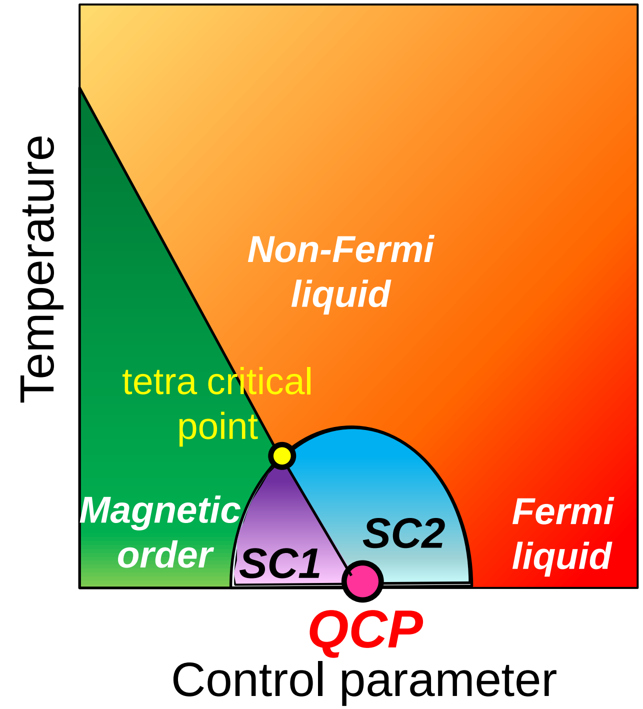
Neutron

Xingye Lu *et al*. PRL (13)

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

No anomaly in λ_L

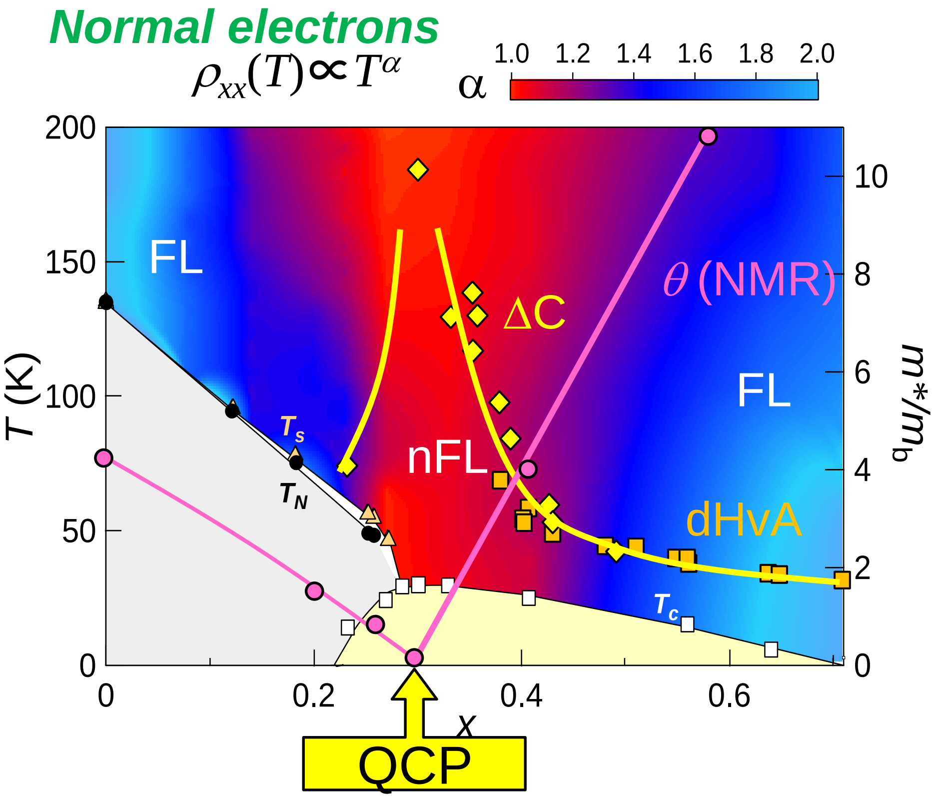
Case-III

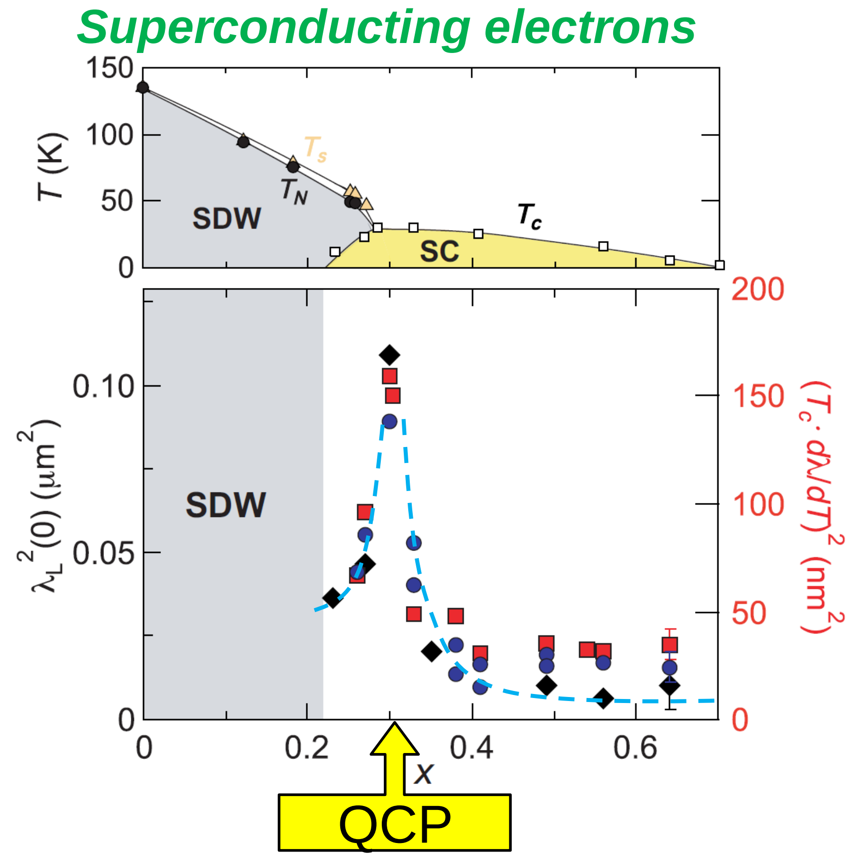


BaFe$_2$(As$_{1-x}$P$_x$)$_2$

K. Hashimoto *et al*. Science (12)

QCP lies beneath the dome





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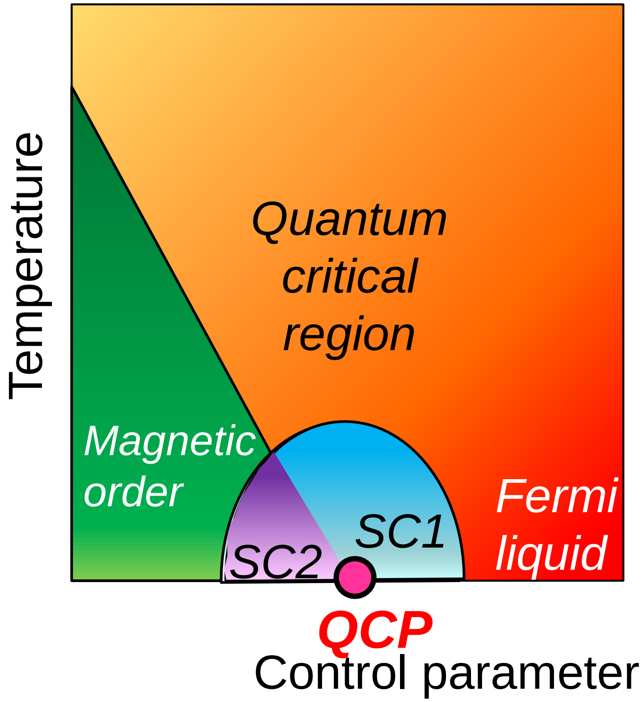
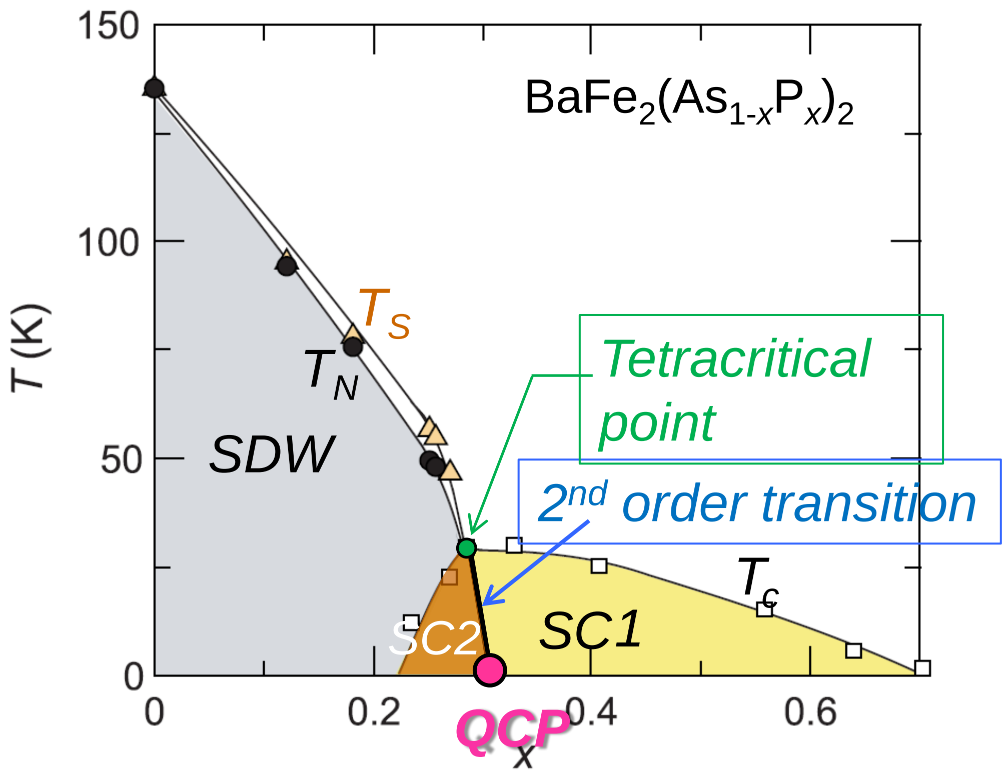
K. Hashimoto *et al*. Science (12), PNAS (13)

QCP lies beneath the superconducting dome

T. Shibauchi, A. Carrington and Y. Matsuda, Annu. Rev. Condens. Matter Phys. 5, 113 (14)

QCP lies beneath the dome





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

2. Microscopic coexistence of superconductivity and SDW.

3. The quantum critical fluctuations help to enhance the high-T_c superconductivity.