Determining gap nodal structure in isovalent doped $BaFe_2(As_{1-x}P_x)_2$

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Specific heat

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Penetration depth

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Outline

1. Introduction

2. "Iso-valent doping" system $BaFe_2(As_{1-x}P_x)_2$

3. Superconducting gap structure of $BaFe_2(As_{1-x}P_x)_2$
   - Evidence of line node
   - Pinpointing the position of line node

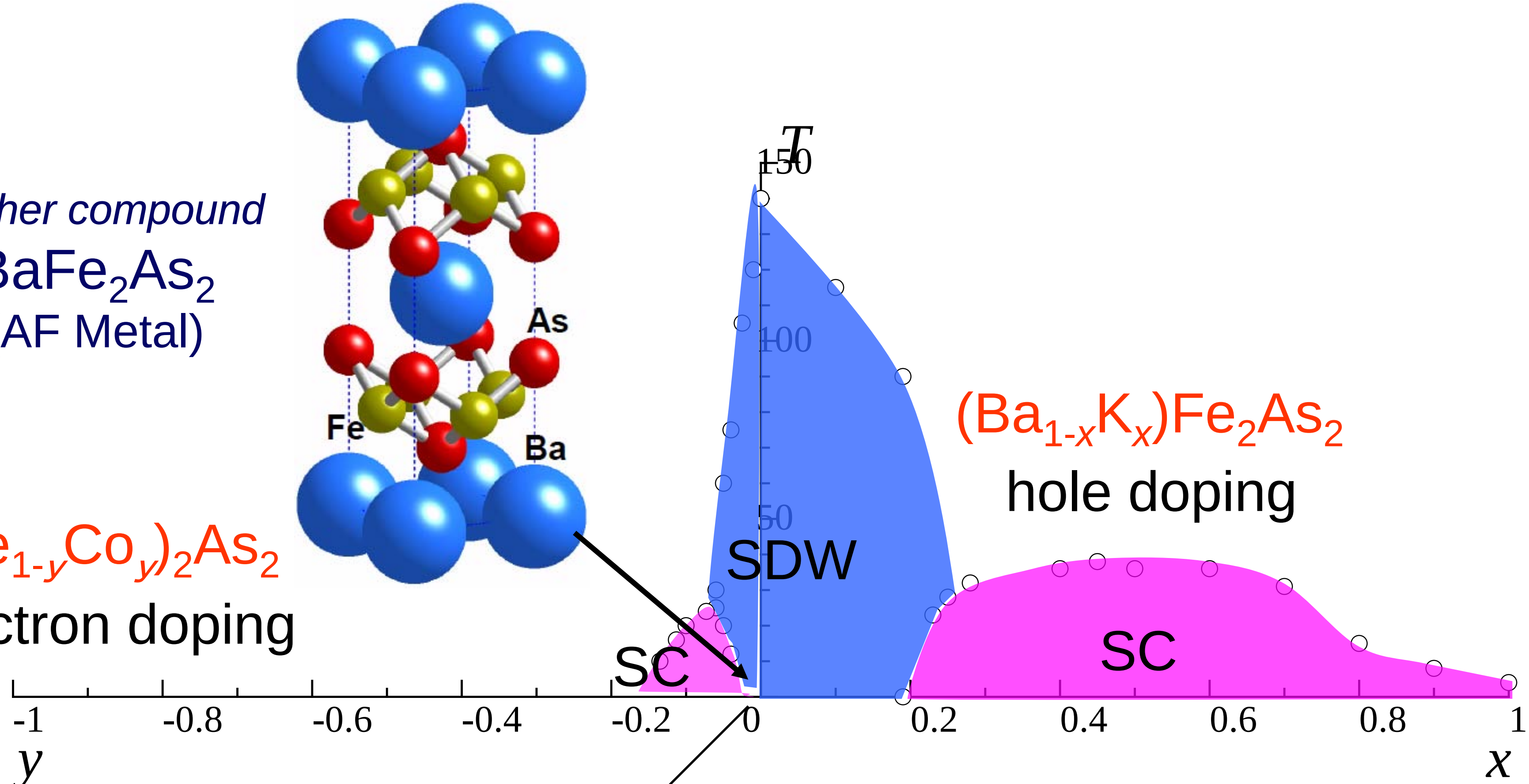
4. Summary

Superconductivity in $BaFe_2As_2$ systems

Mother compound

$BaFe_2As_2$

(AF Metal)



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

electron doping

$(Ba_{1-x}K_x)Fe_2As_2$

hole doping

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

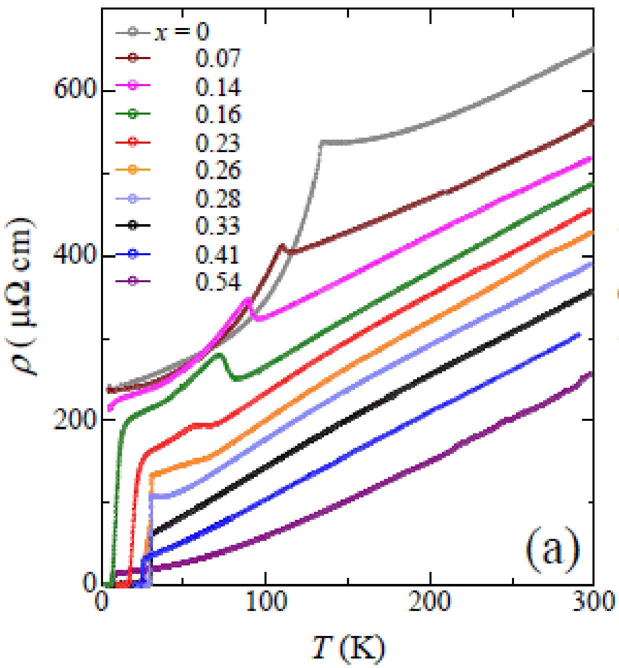
S. Jiang *et al.* JPCM (09)

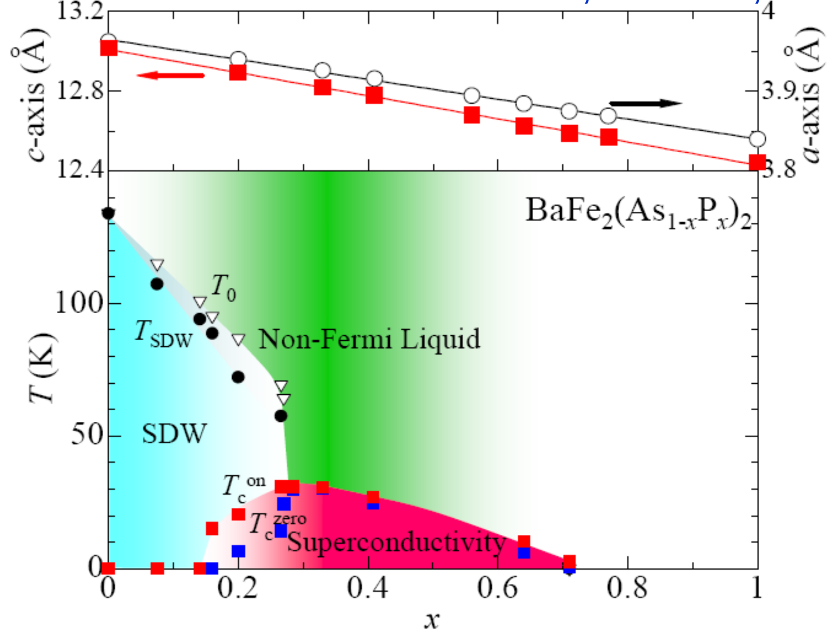
Iso-valent doping (Chemical Pressure)

Superconductinty by isovalent substitution of P for As

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

P-dope





Why is the isovalent doping important?

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

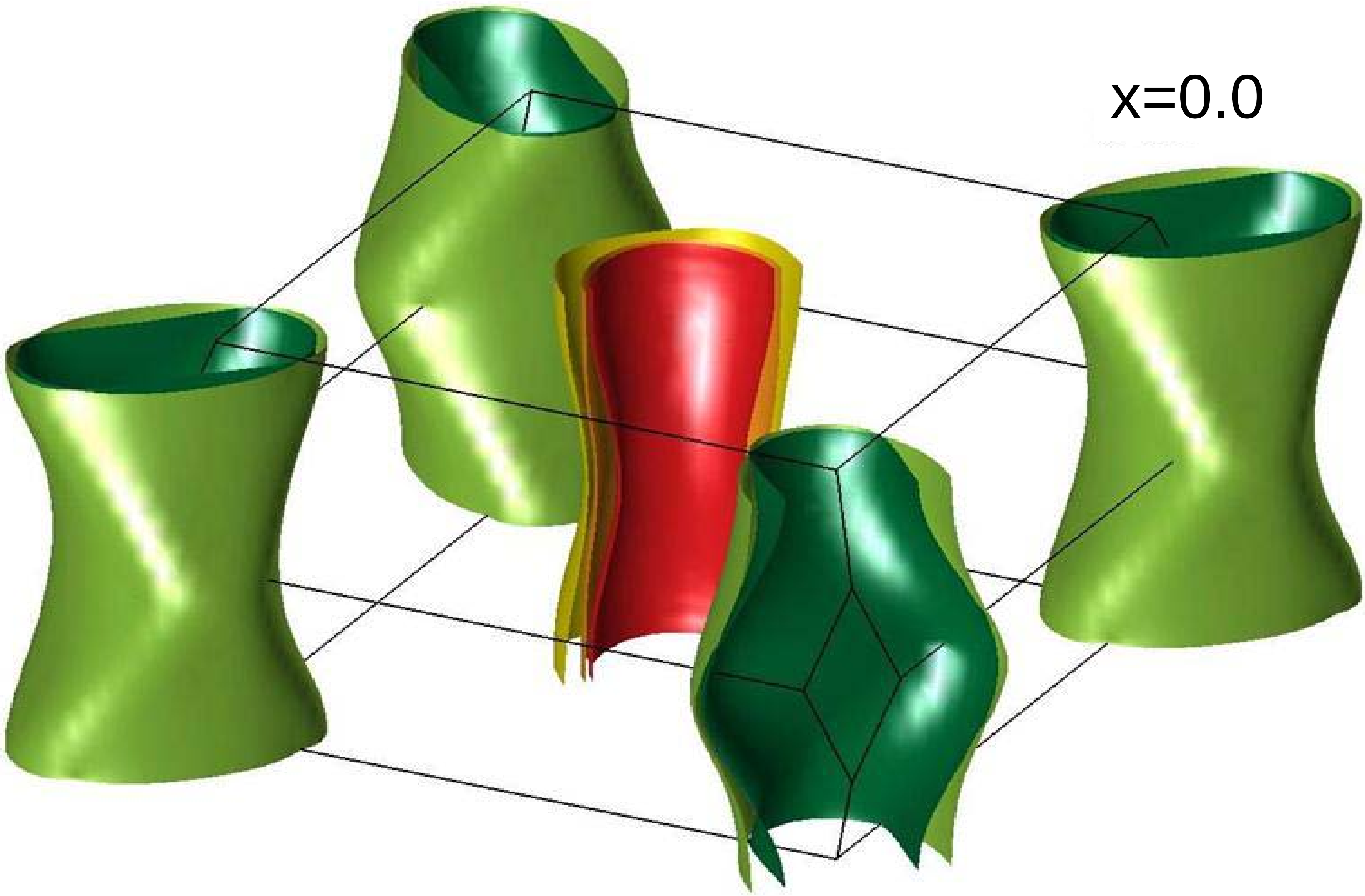
Volume of hole FSs=Volume of electron FSs

The magnetic characters can be tuned by *x* without doping carrier.

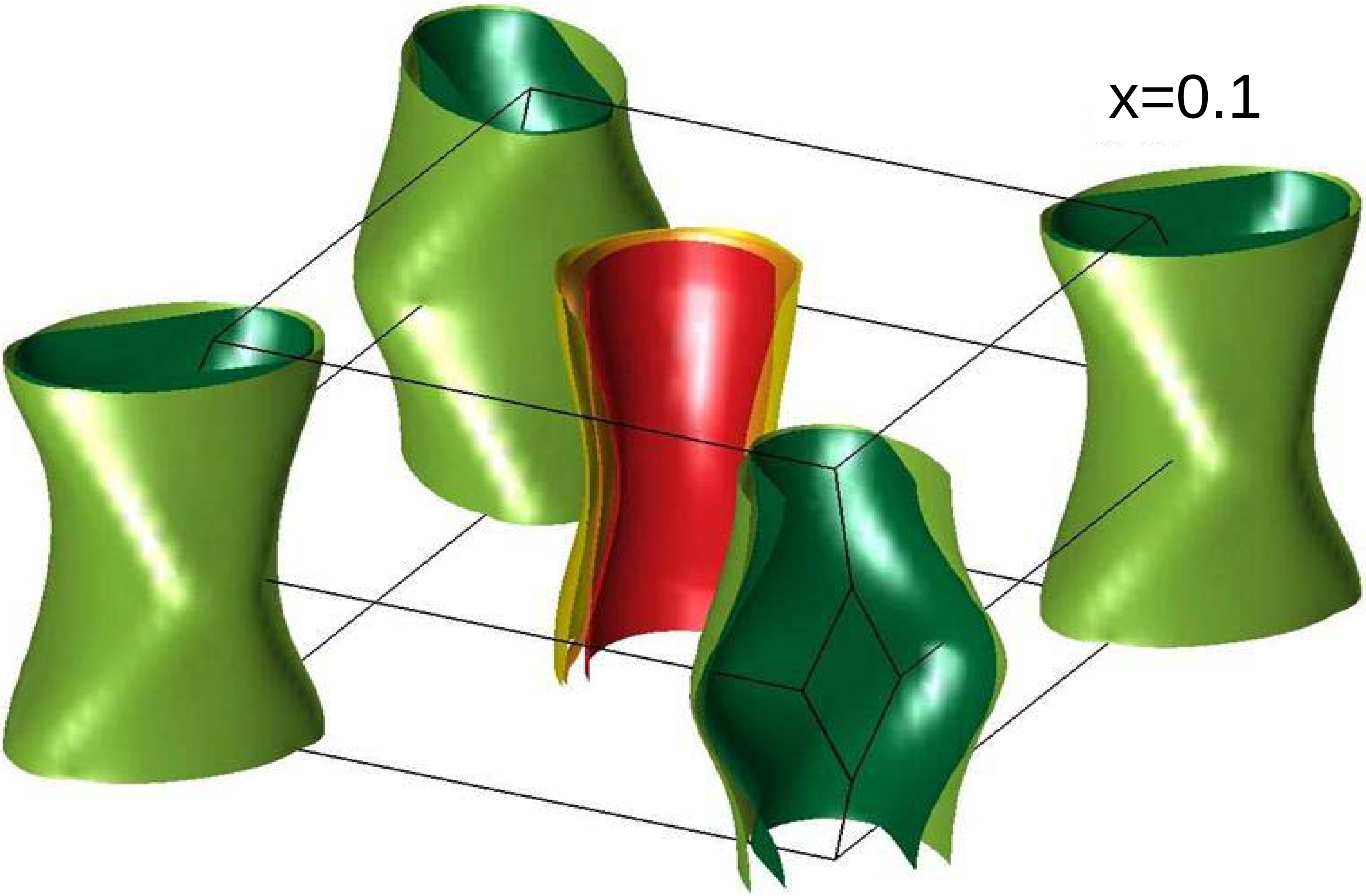
Very clean single crystals are available (quantum oscillations)

⇨ suitable for studying intrinsic physics among Fe-based SCs.

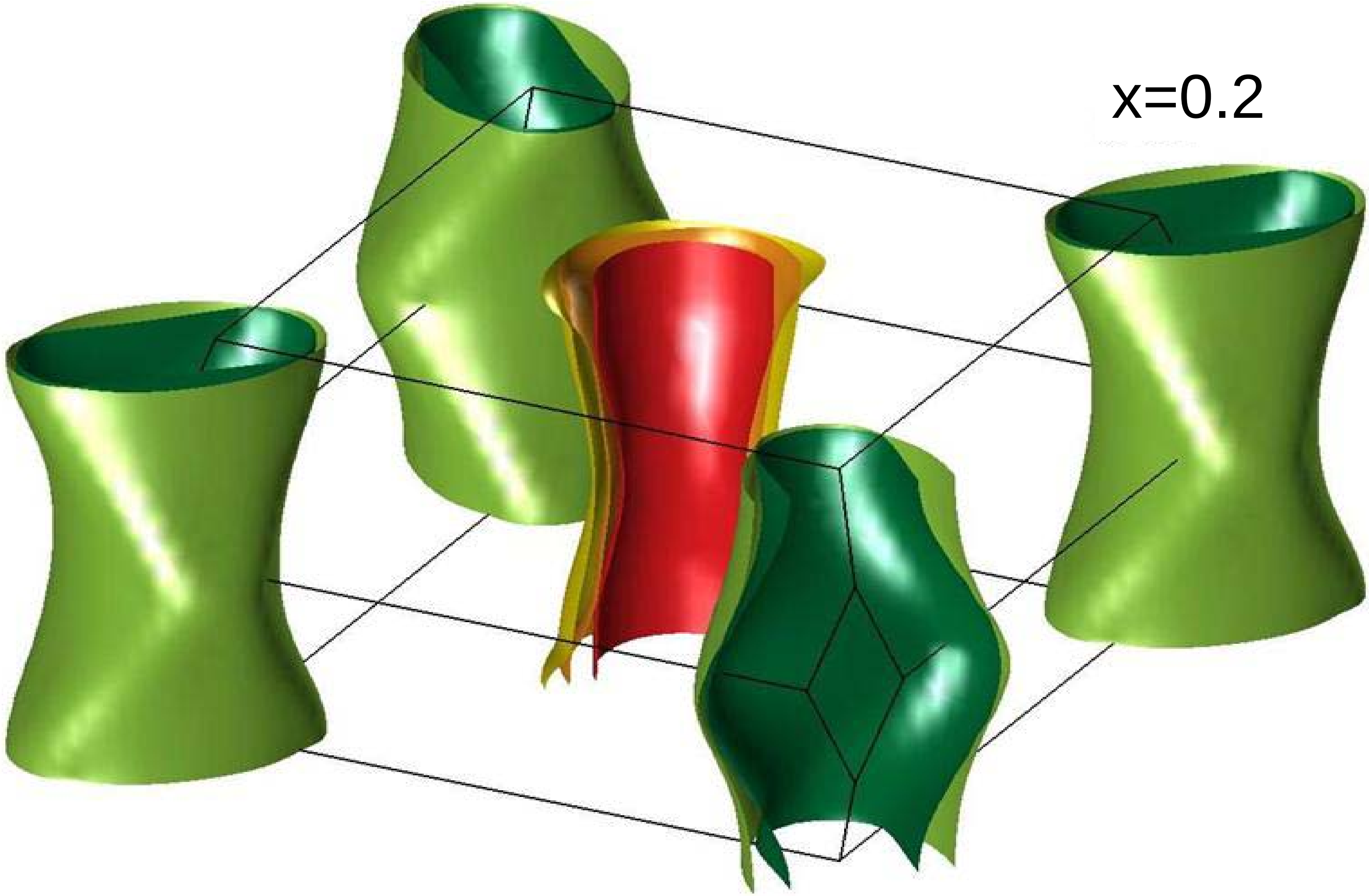
$BaFe_2(As_{1-x}P_x)_2$



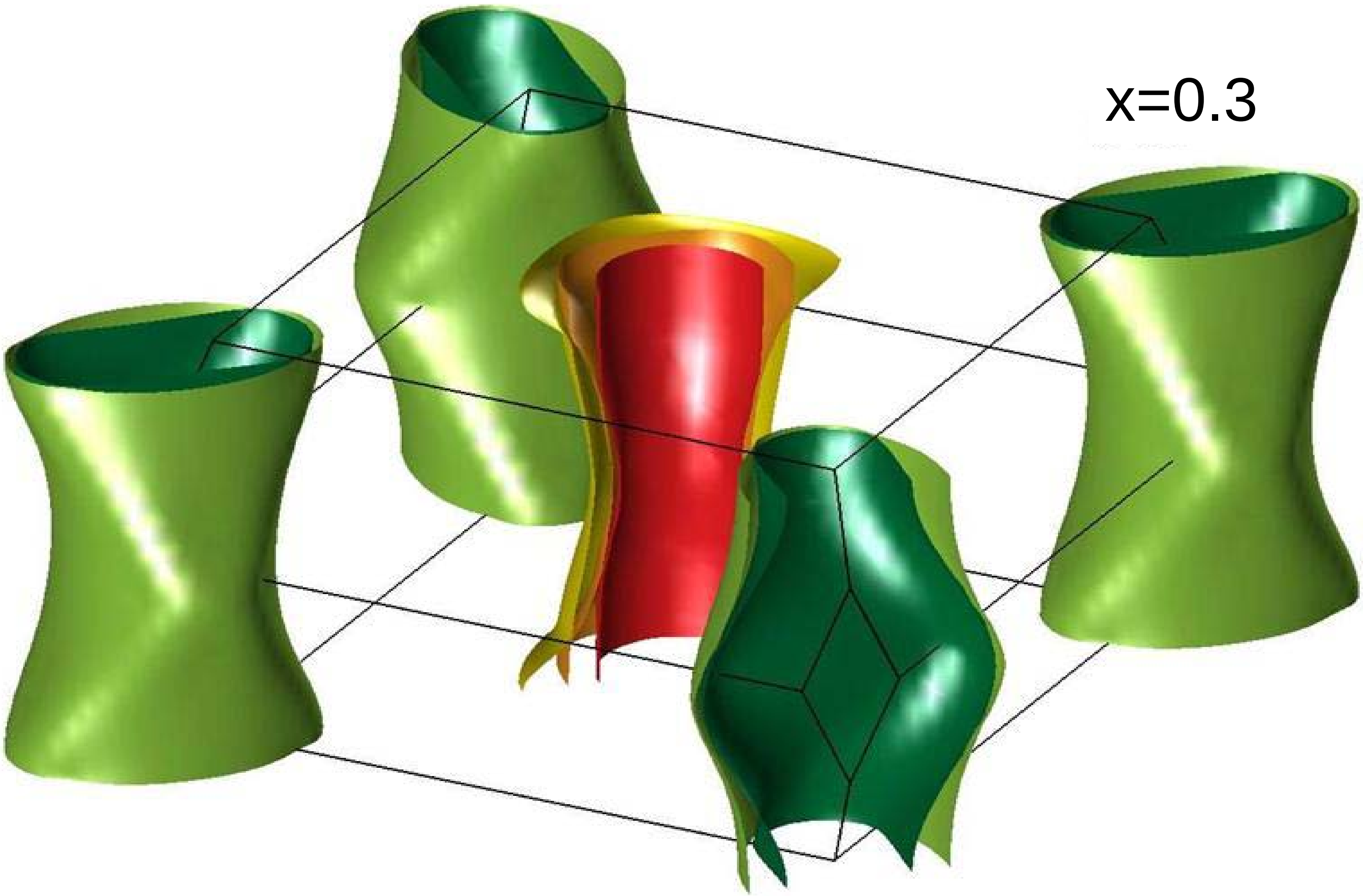
$BaFe_2(As_{1-x}P_x)_2$



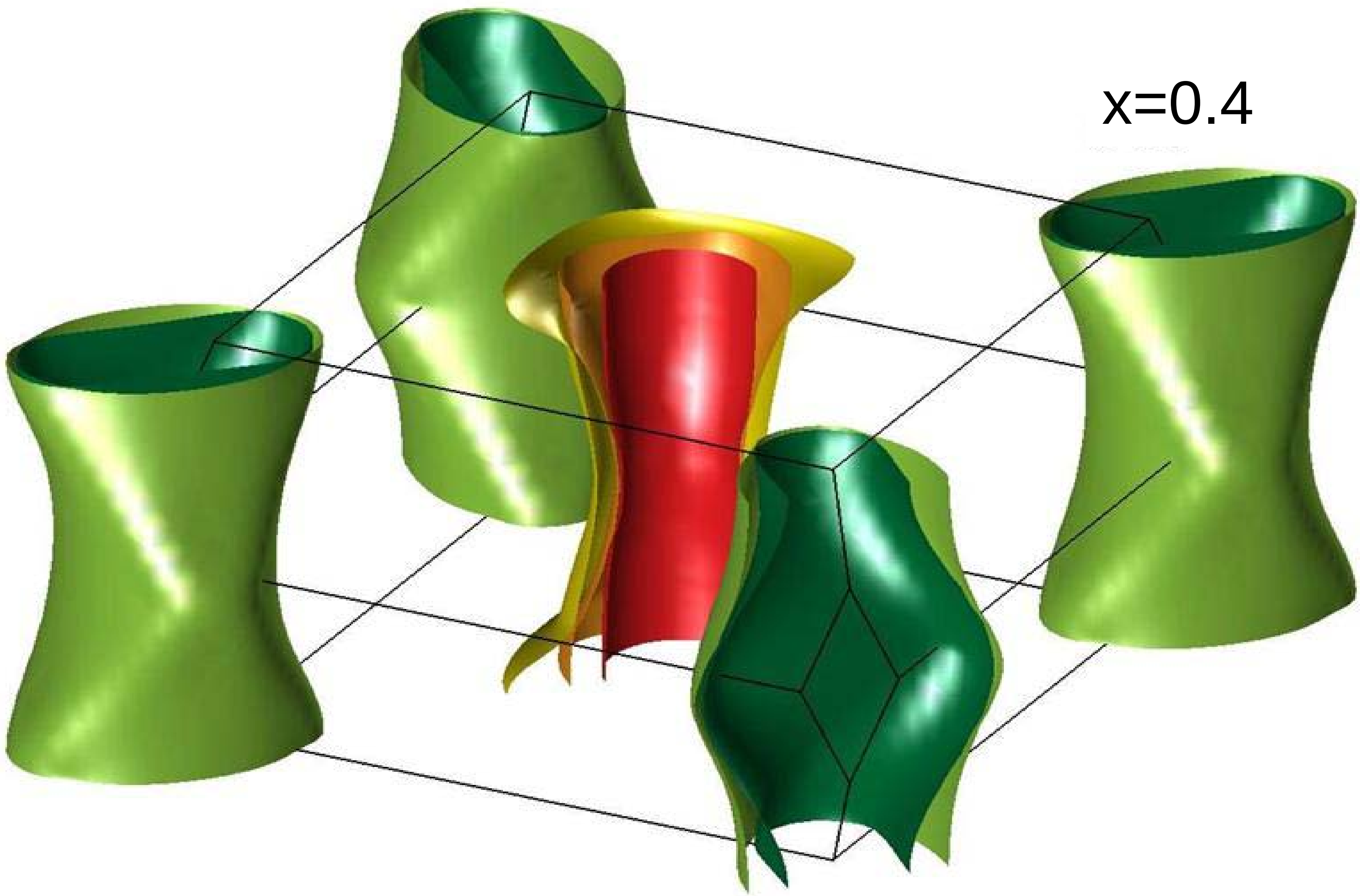
$BaFe_2 (As_{1-x}P_x)_2$



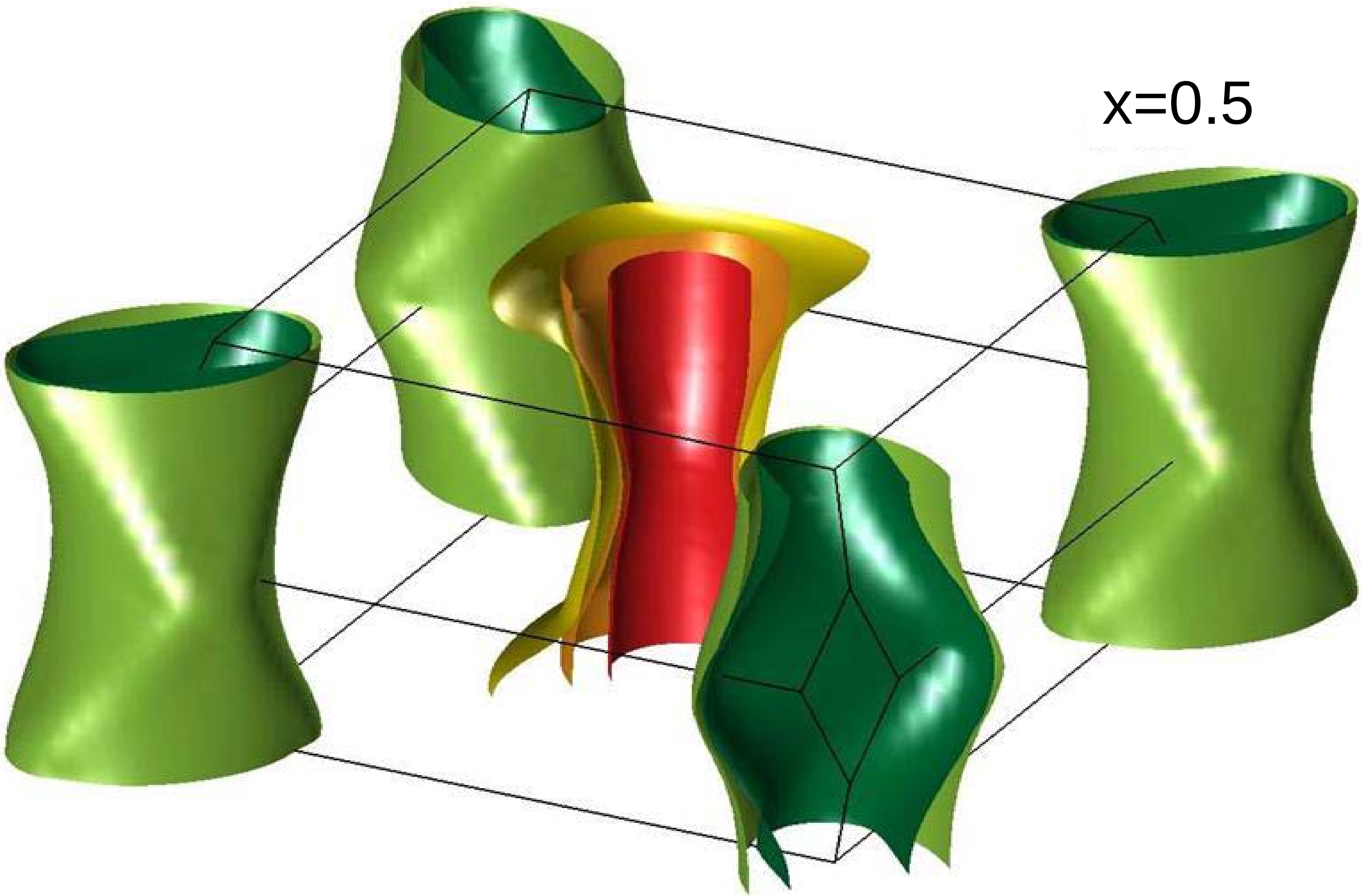
$BaFe_2 (As_{1-x}P_x)_2$



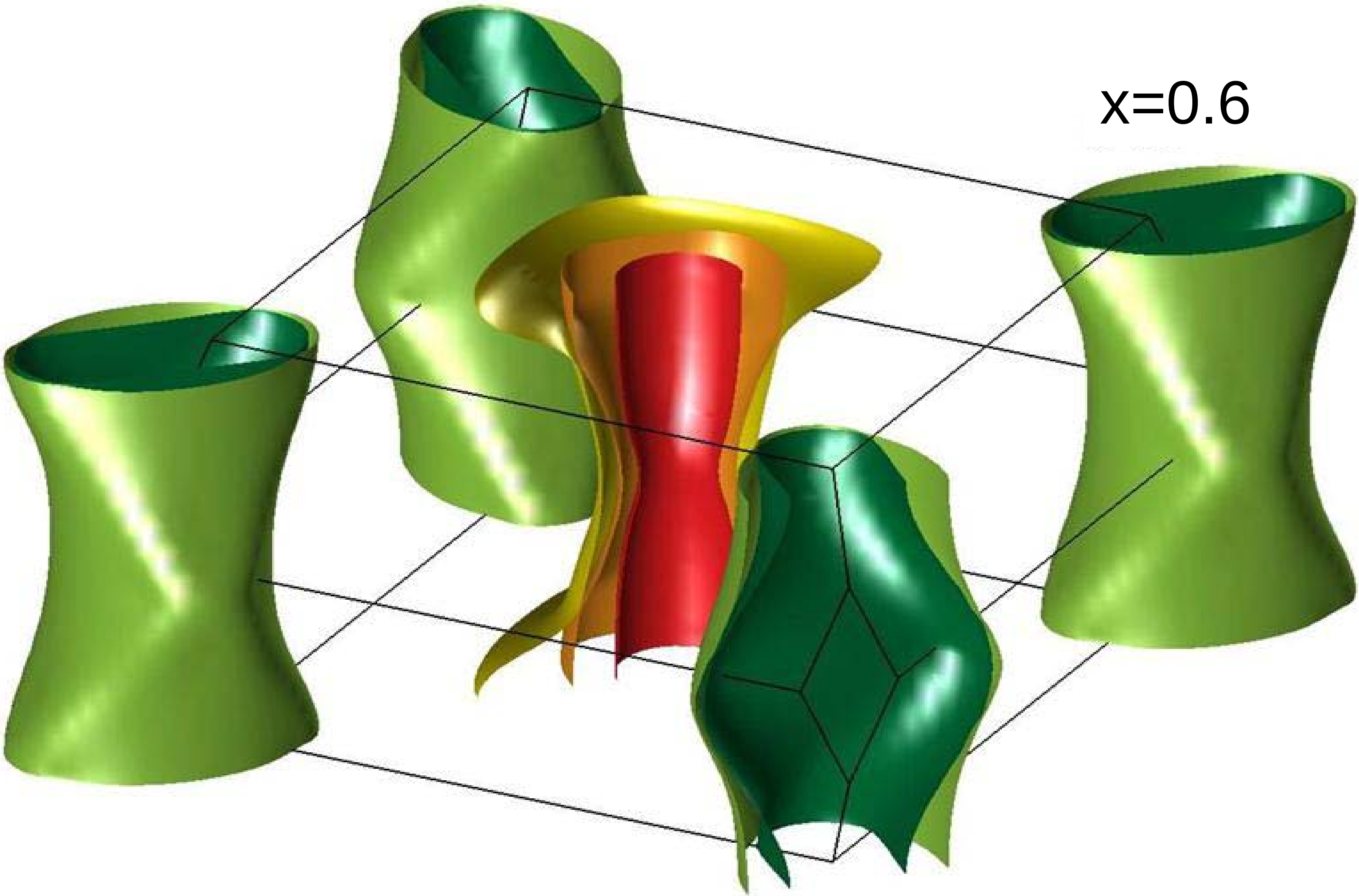
$BaFe_2(As_{1-x}P_x)_2$



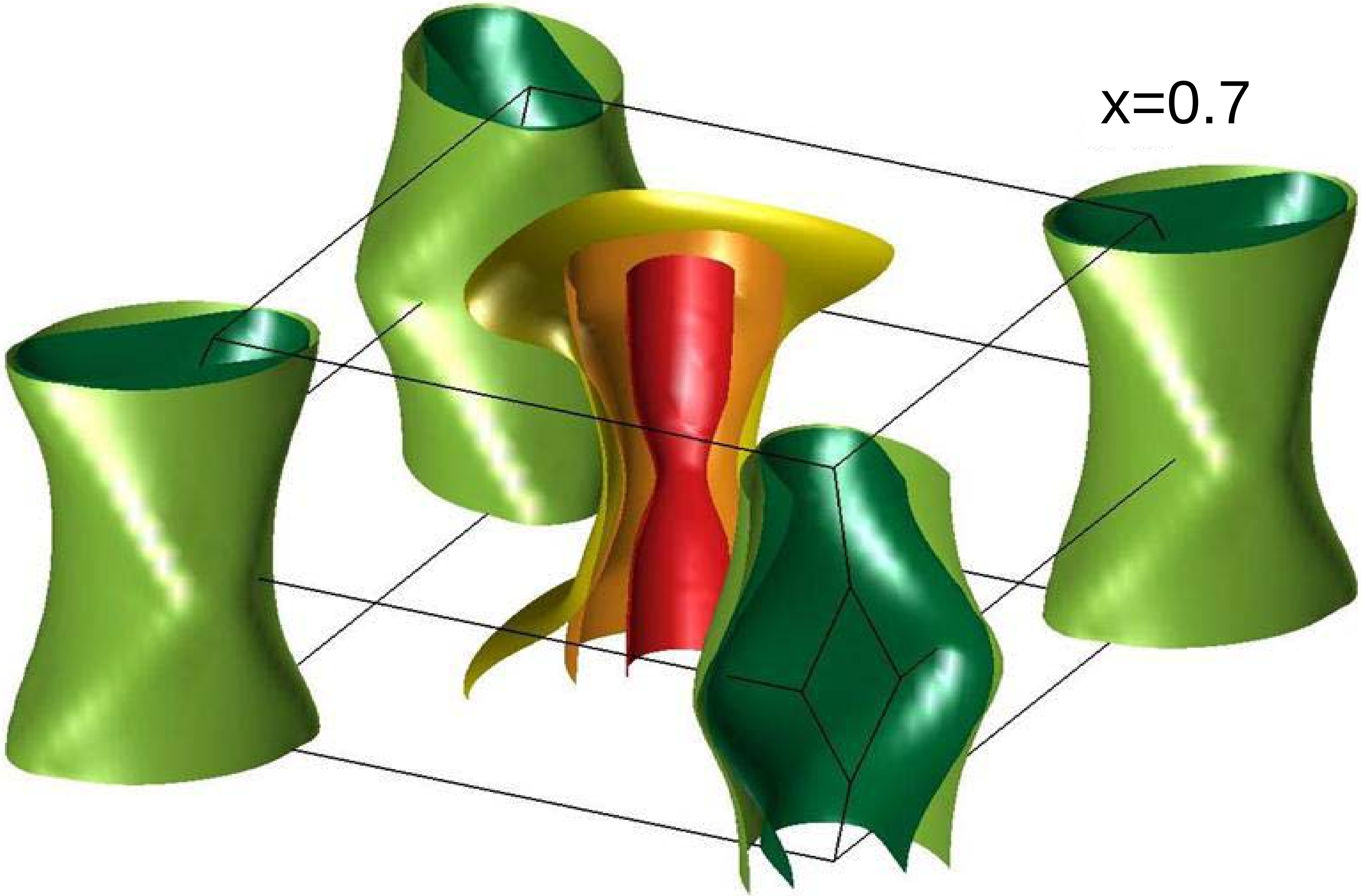
$BaFe_2 (As_{1-x}P_x)_2$



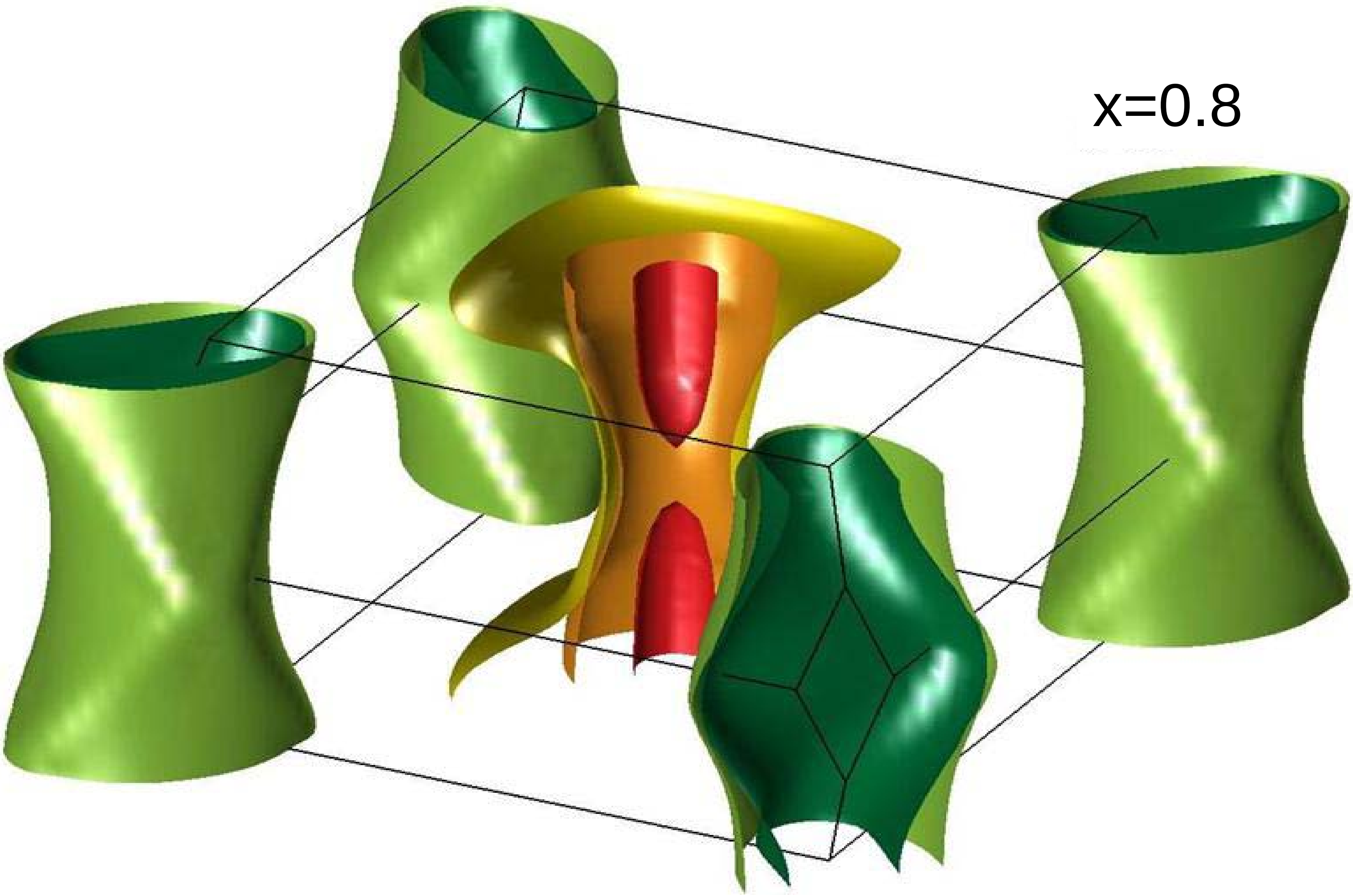
$BaFe_2(As_{1-x}P_x)_2$



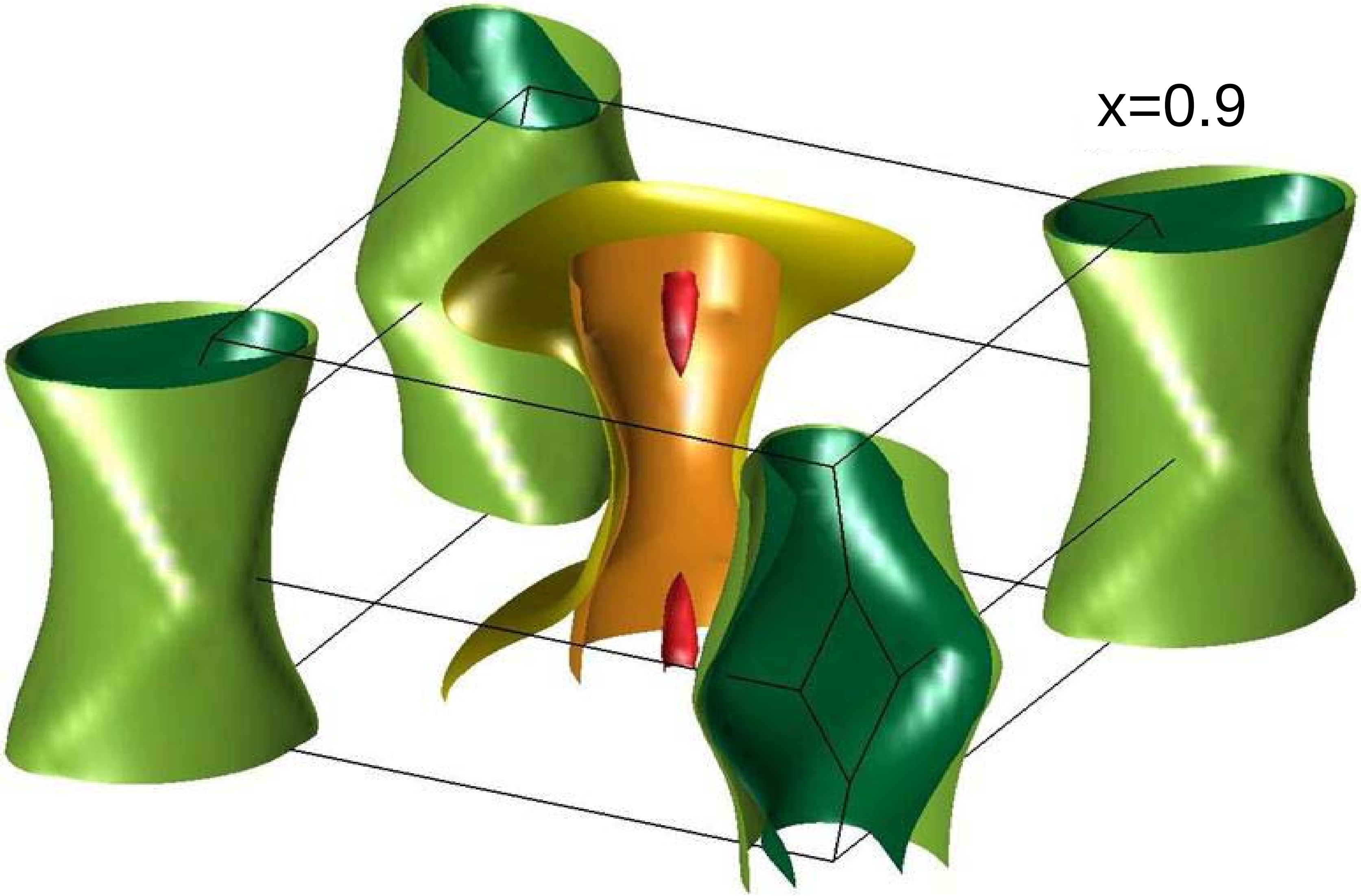
$BaFe_2(As_{1-x}P_x)_2$



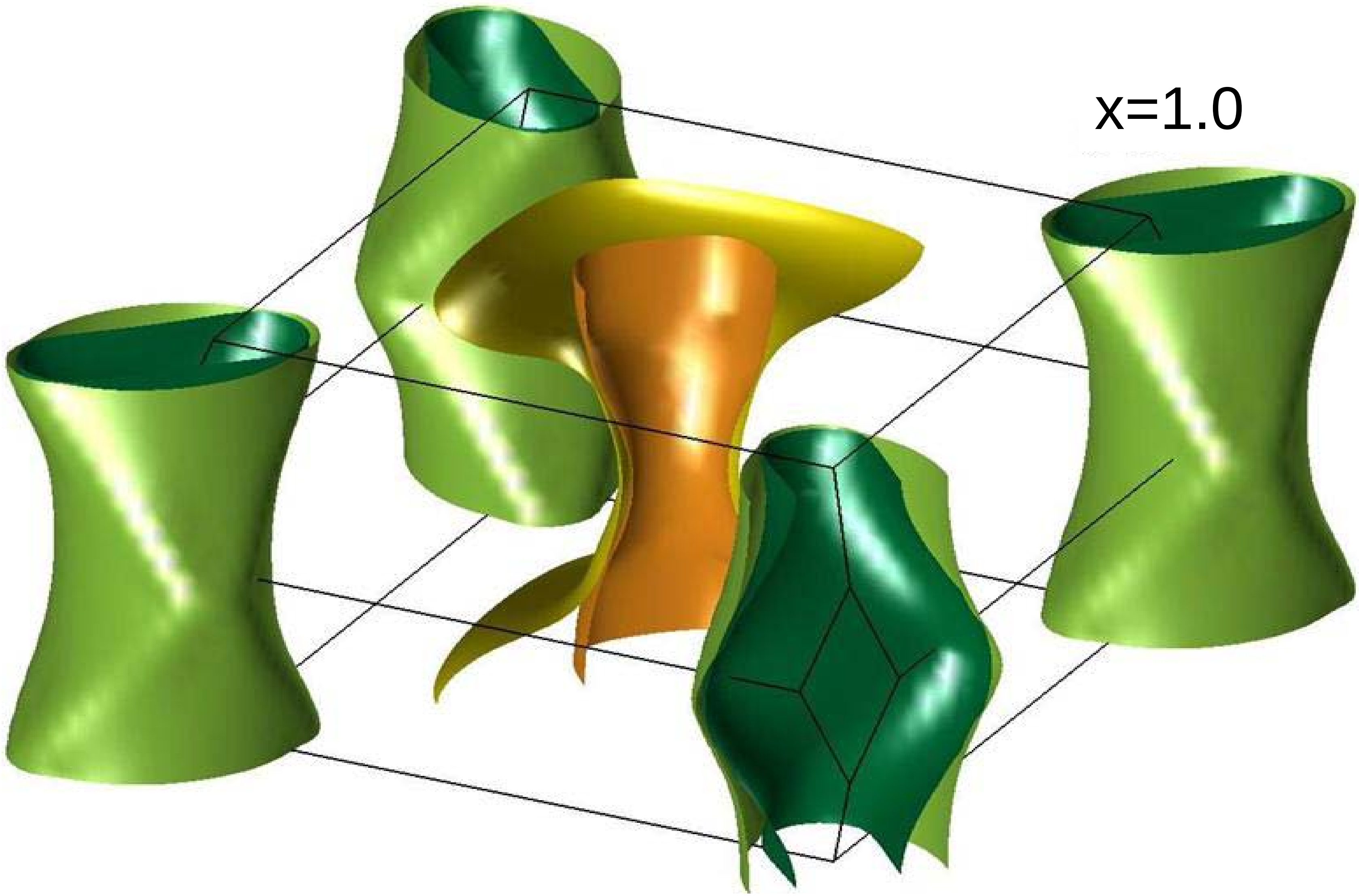
$BaFe_2(As_{1-x}P_x)_2$



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



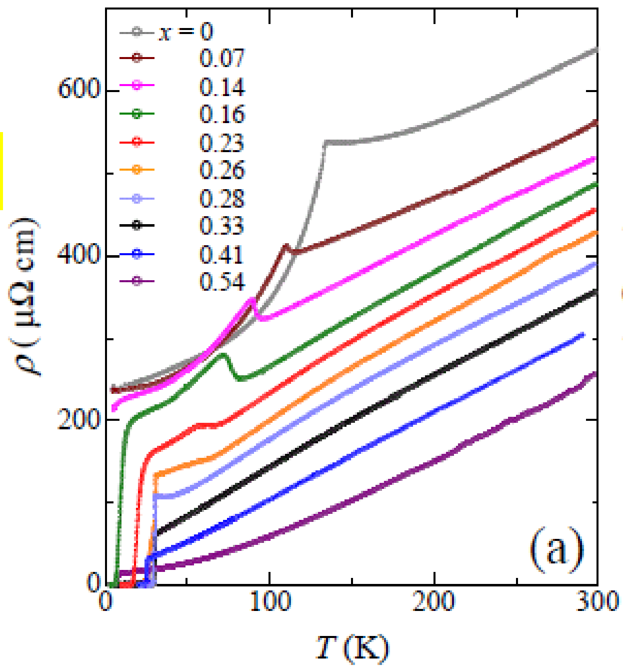
$BaFe_2\ (As_{1-x}P_x)_2$

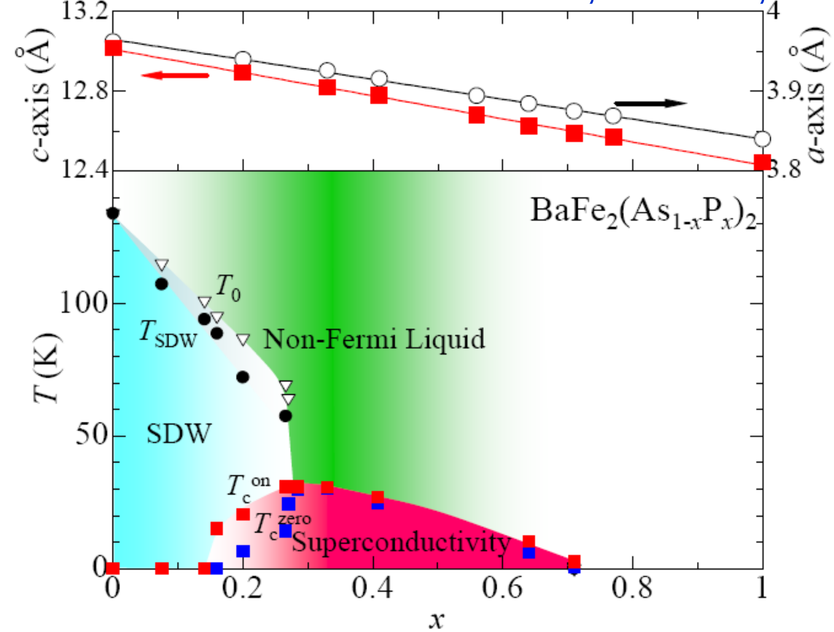


Superconductinty by isovalent substitution of P for As

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

P-dope





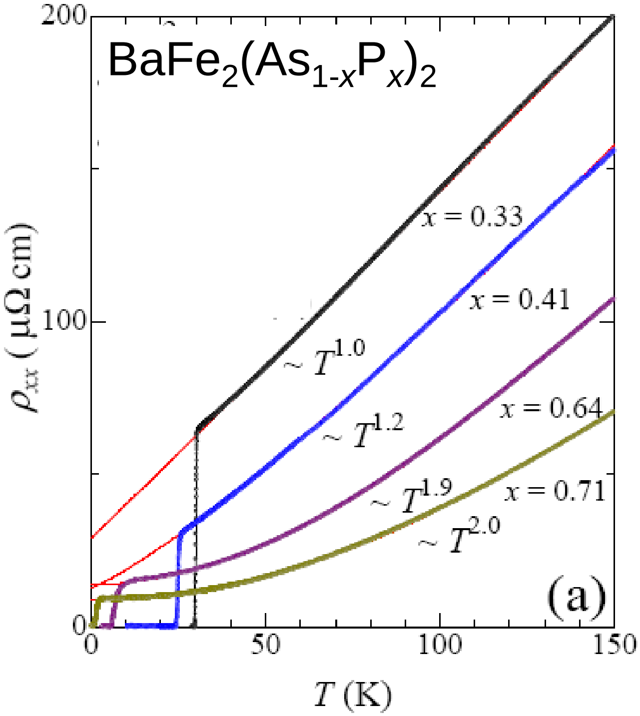
Compensation condition (n_e=n_h) holds for any *x*.

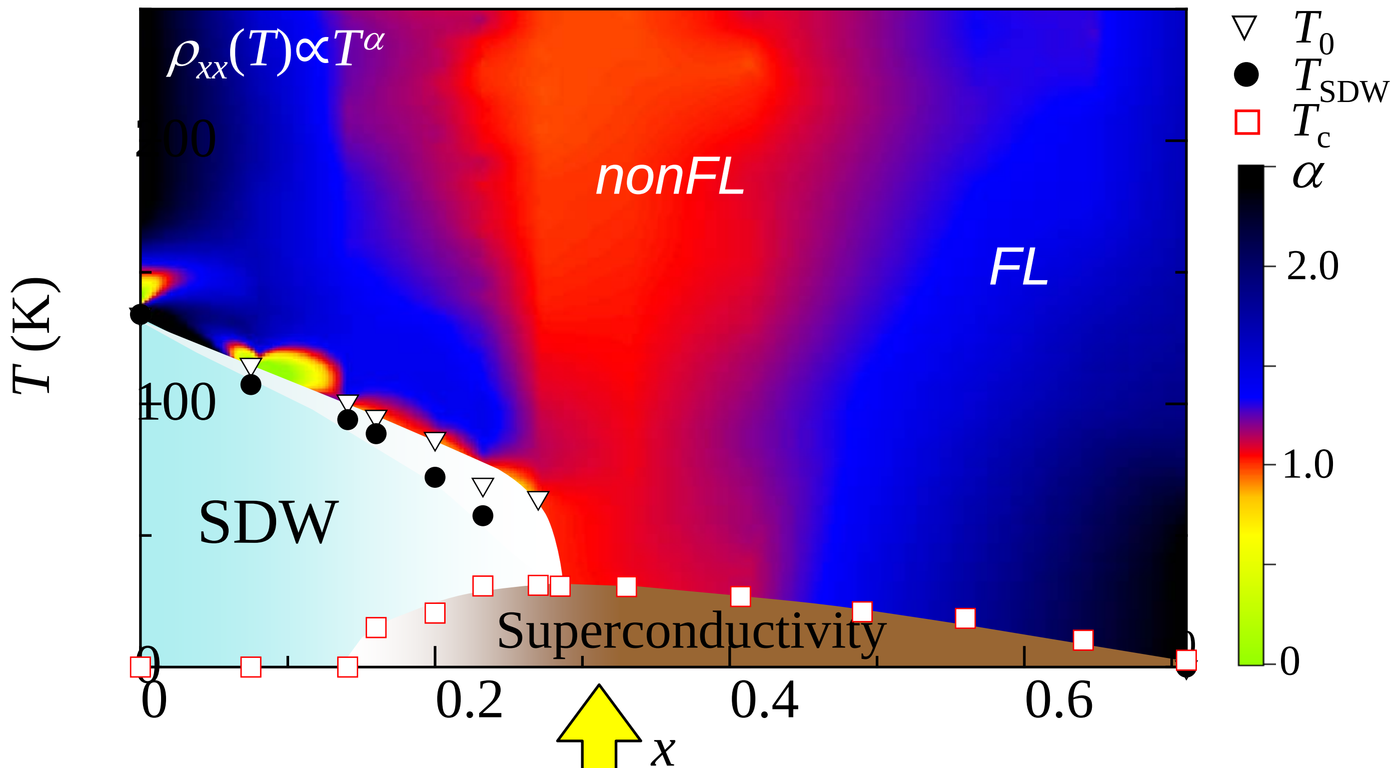
Volume of hole FSs=Volume of electron FSs

Hole band becomes more 3D-like but electron band is almost unchanged.

Nesting condition degrades with *x*.

Evolution of transport properties with doping





critical x value

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

Hallmark of non-Fermi liquid

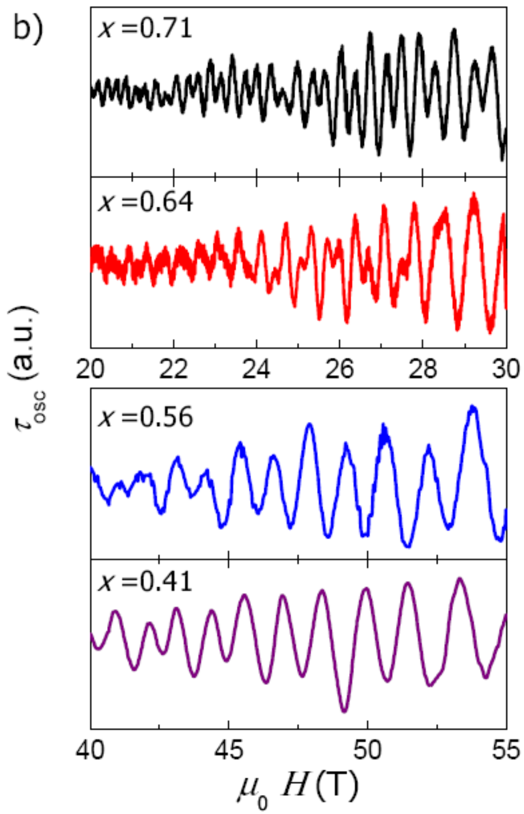
S. Kasahara *et al*., PRB **81**, 184519 (2010)

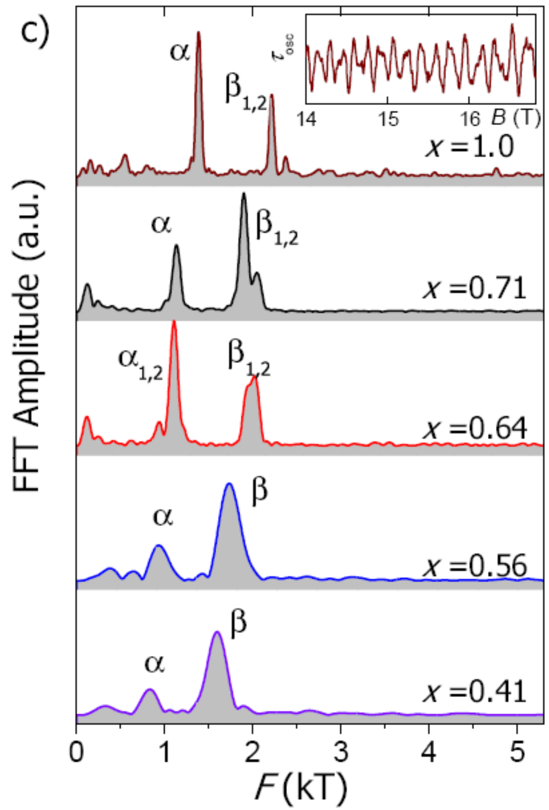
T^2-dependence at x=0.71

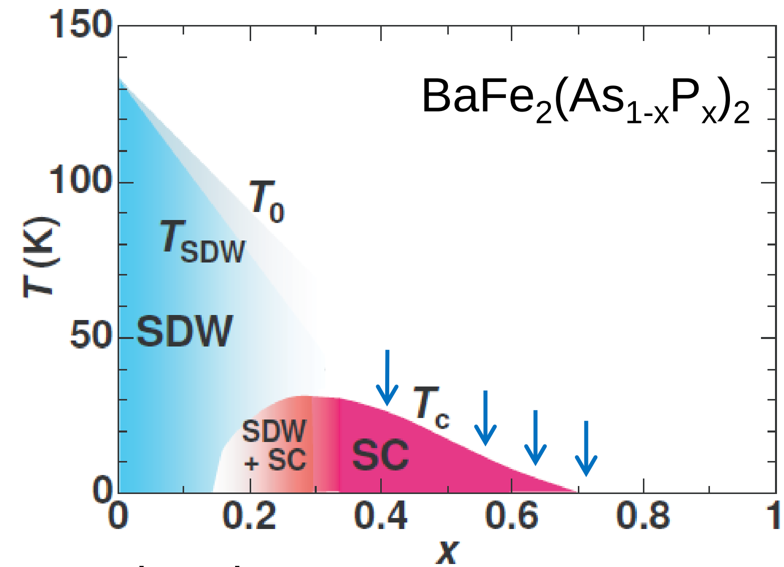
Fermi-liquid behavior

Evolution of the Fermi surface on entering the SC dome

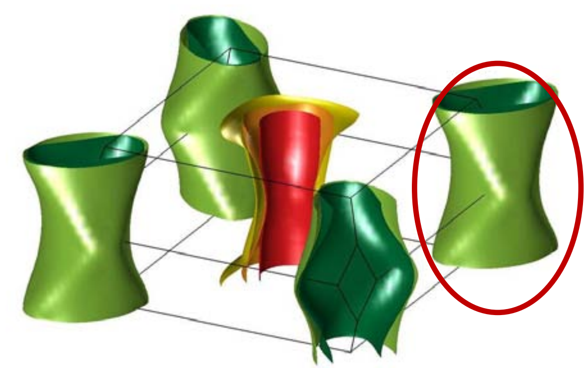
dHvA H. Shishido *et al*., PRL **104**, 057008 (2010)







Electron bands

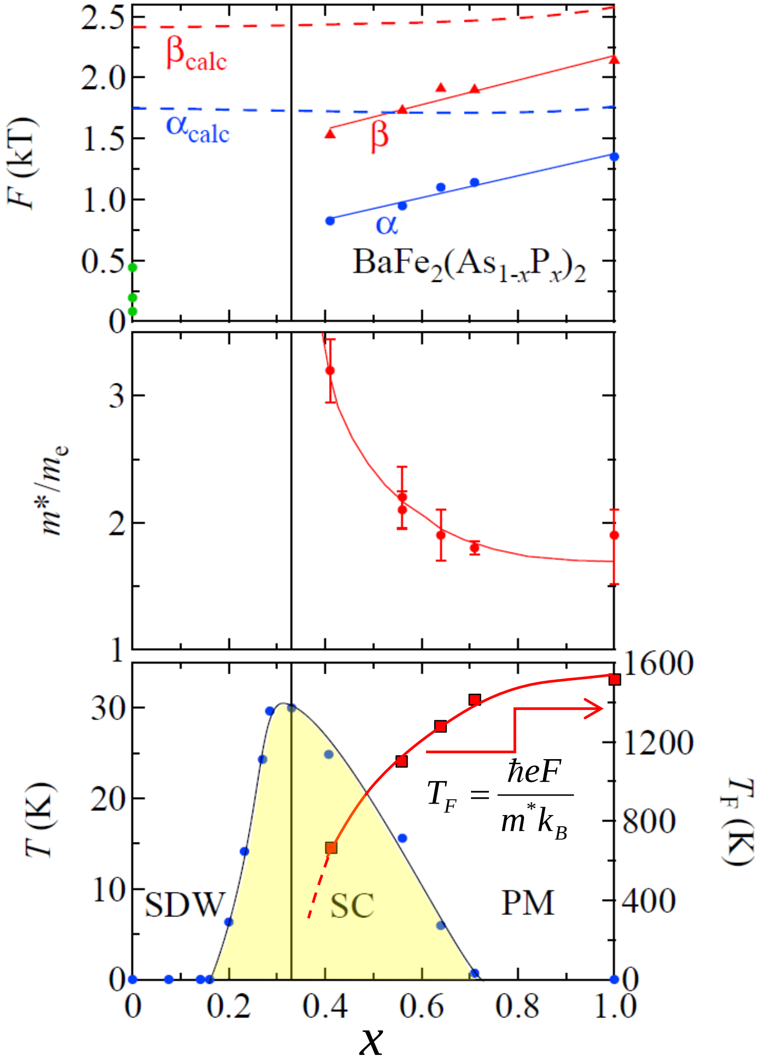


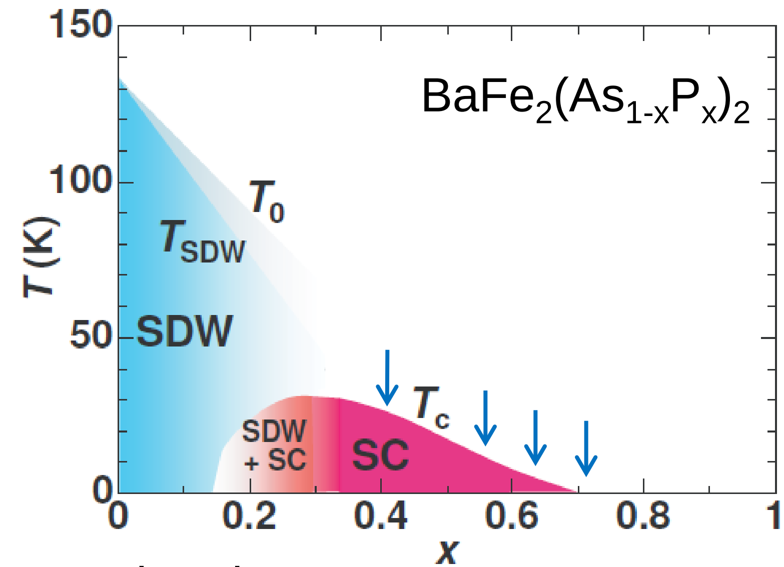
Hole band (x=0.63) , J.G. Analytis *et al*. PRL (10)

Very clean single crystals are available (quantum oscillations) ➡ suitable for studying intrinsic physics among Fe-based SCs.

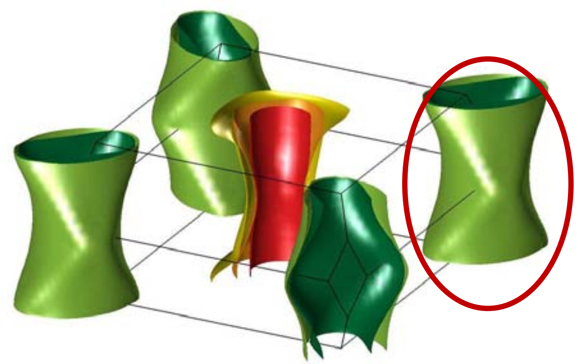
Evolution of the Fermi surface on entering the SC dome

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





Electron bands

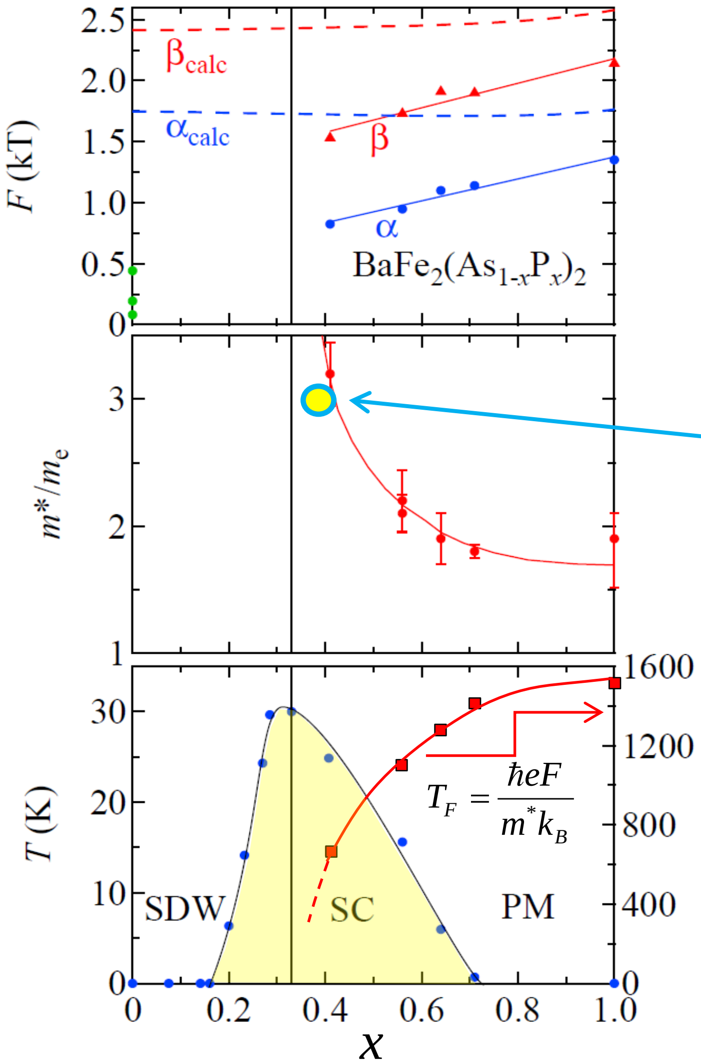


As x is tuned towards the maximum T_c,

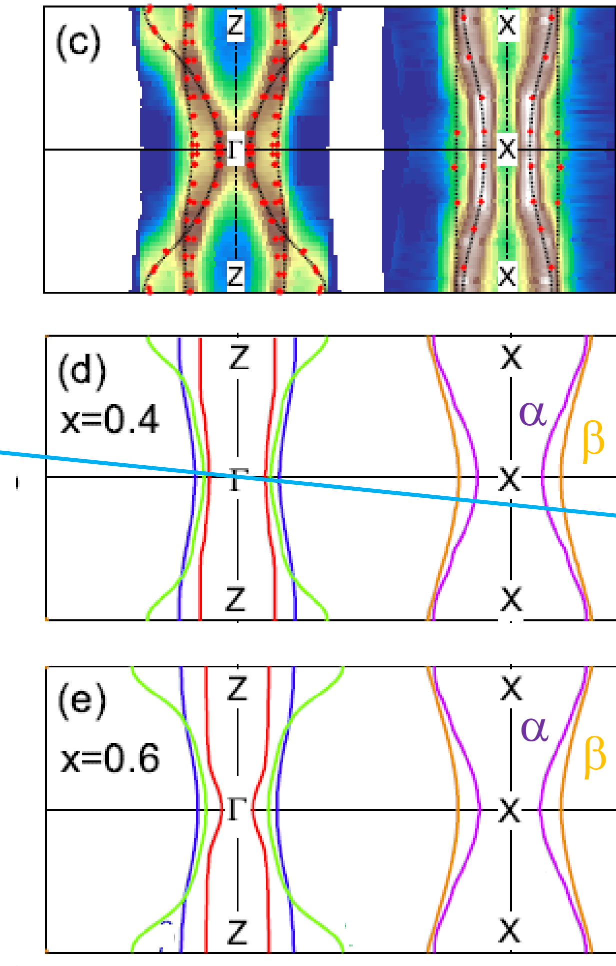
- Shrinkage of the FS occurs
- Effective mass m^* is strongly enhanced
- Fermi temperature $T_F = heF/m^*k_B$ decreases

Evolution of the Fermi surface on entering the SC dome

dHvA H. Shishido *et al.*, PRL(10)



ARPES T.Yoshida *et al*. PRL in press



$BaFe_2(As_{1-x}P_x)_2$
x=0.38

3D volume	k_z	2D area	m^*/m_e	m_b/m_e	m^*/m_b
3.9	Γ	3.9	3.8	1.3	2.9
	Z	3.8	2.5	1.2	2.1
6.0	Γ	1.0	2.6	0.9	2.9
	Z	16.3	3.9	2.3	1.7
5.3	X	5.3	2.8	0.71	3.9
3.4	X	3.0	2.0	0.93	2.1

Electron pocket

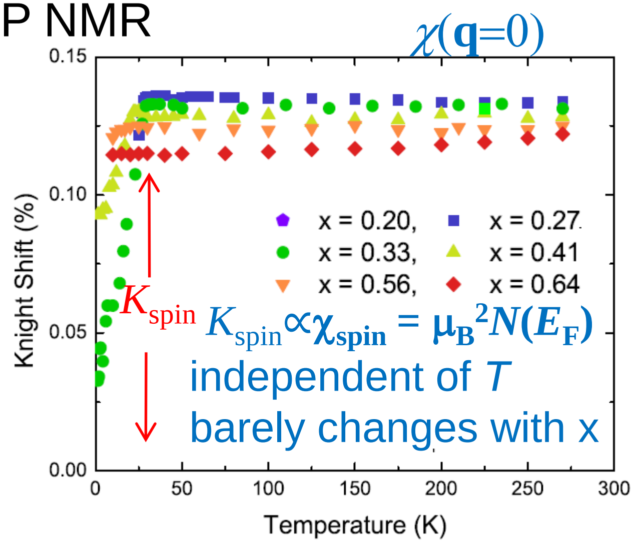
Electron correlation effect

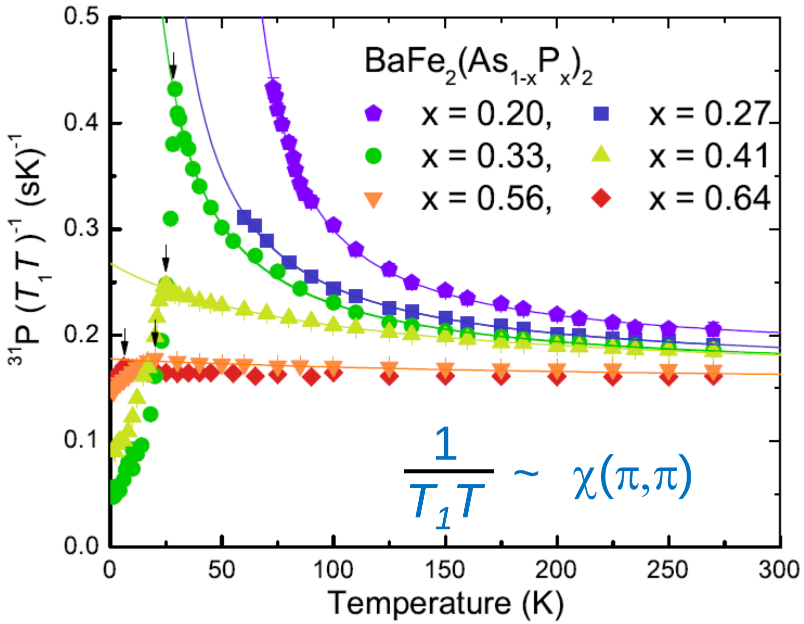
As x is tuned towards the maximum T_c,

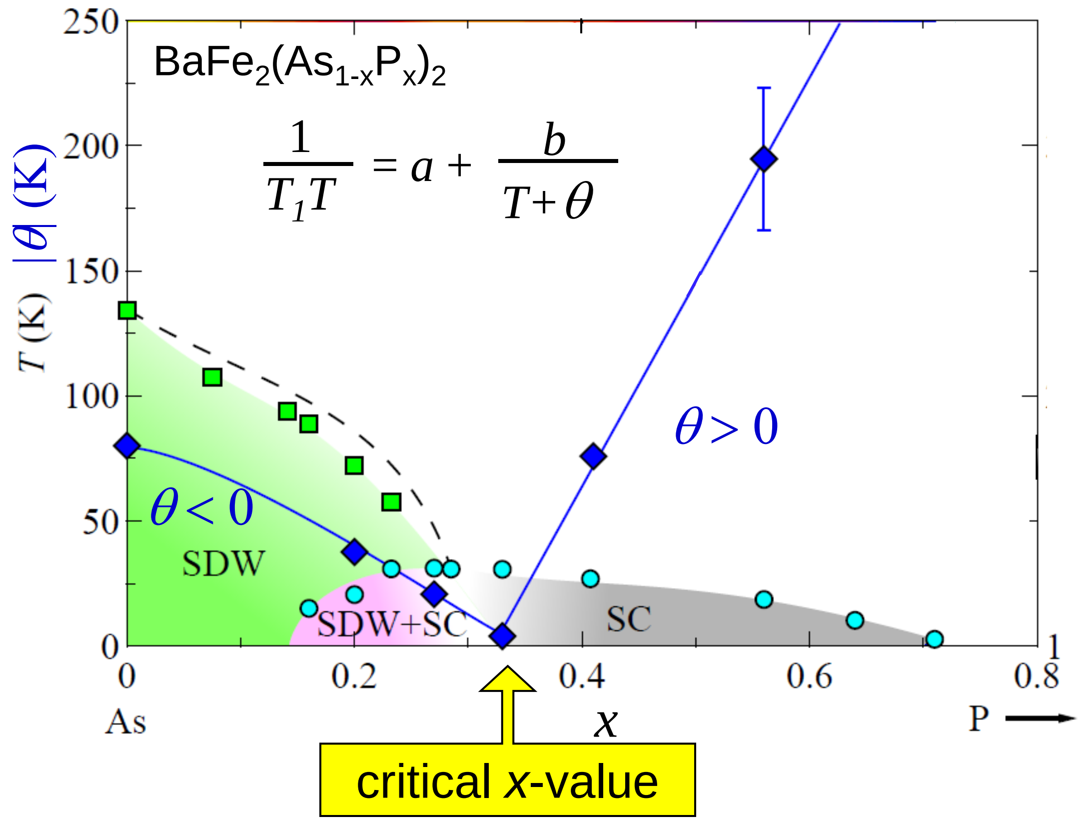
- Shrinkage of the FS occurs
- Effective mass m^* is strongly enhanced
- Fermi temperature $T_F = heF/m^* k_B$ decreases

Evolution of the magnetic fluctuations with doping (NMR)

^{31}P NMR





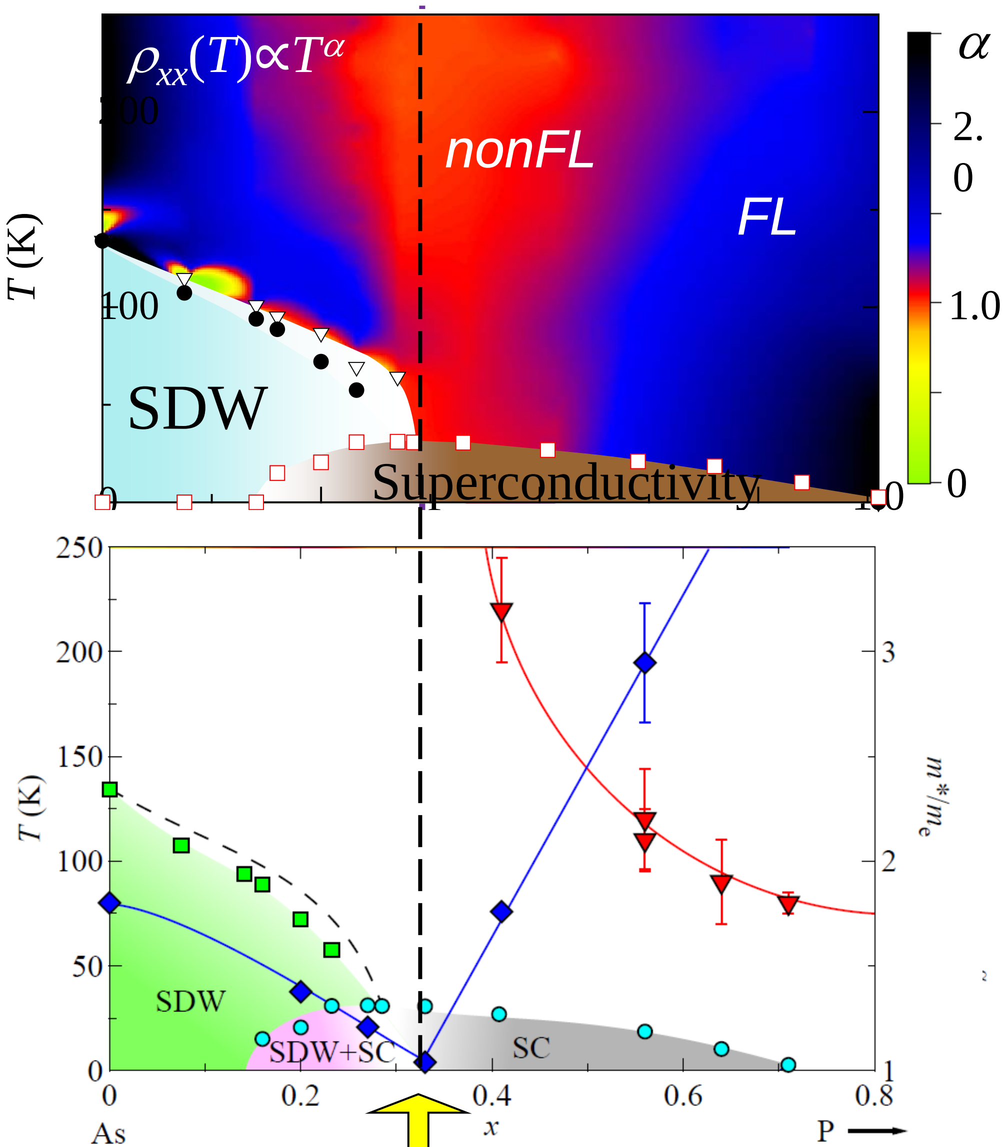


θ: Weiss temperature

θ goes to zero at x~0.33

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

Evolution of transport properties, magnetic properties, Fermi surface with doping in $BaFe_2(As_{1-x}P_x)_2$



AFM QCP at the end point of SDW

In the SC dome,

Strong enhancement of effective mass m^* (dHvA and ARPES) as x is tuned towards x_c=0.33

At a critical doping value x_c=0.33 close to the end point of SDW

T_c becomes maximun

Hallmark of non-Fermi in the transport coefficients

Weiss temperature θ (NMR) goes to zero

Non-Fermi liquid properties, magnetic fluctuations, electron correlations and superconductivity are intimately linked.

Superconducting gap structure of $BaFe_2(As_{1-x}P_x)_2$

Evidence of line node

Pinpointing the position of line node

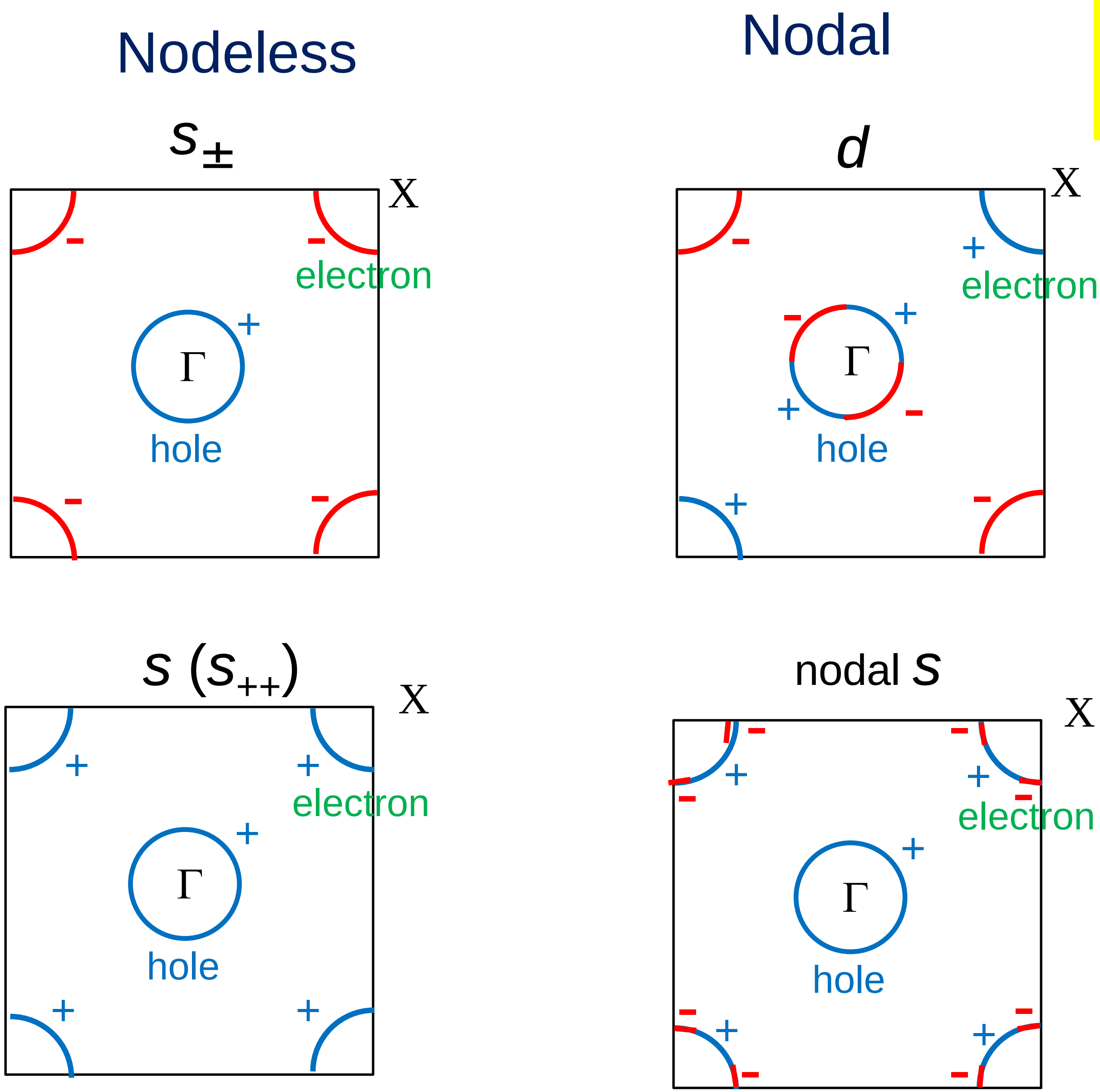
Possible gap functions (2D)

Large $\chi(\boldsymbol{q})$

↓

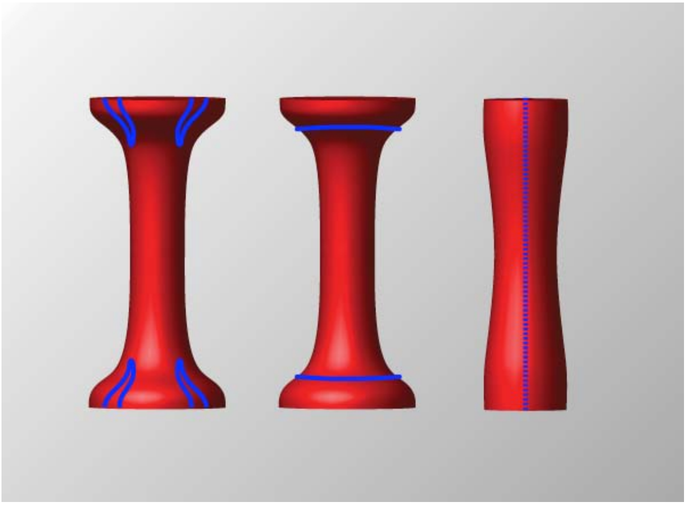
$\Delta(\boldsymbol{k}+\boldsymbol{q})\Delta(\boldsymbol{k}) < 0$

Sign change

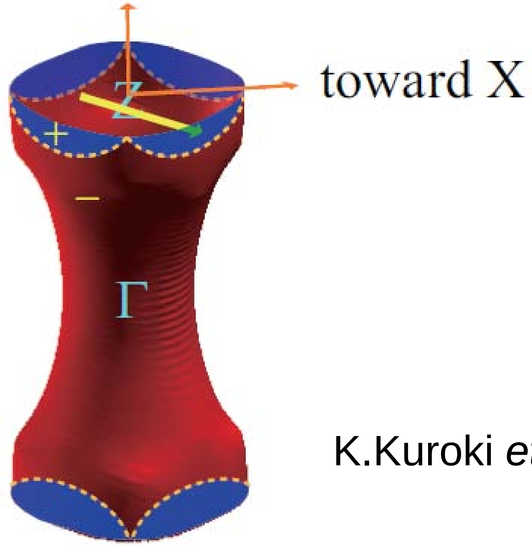


Possible gap functions (3D)

Node in the hole band



P.J. Hirschfeld and D.J. Scalapino, Physics **3**, 64 (2010)



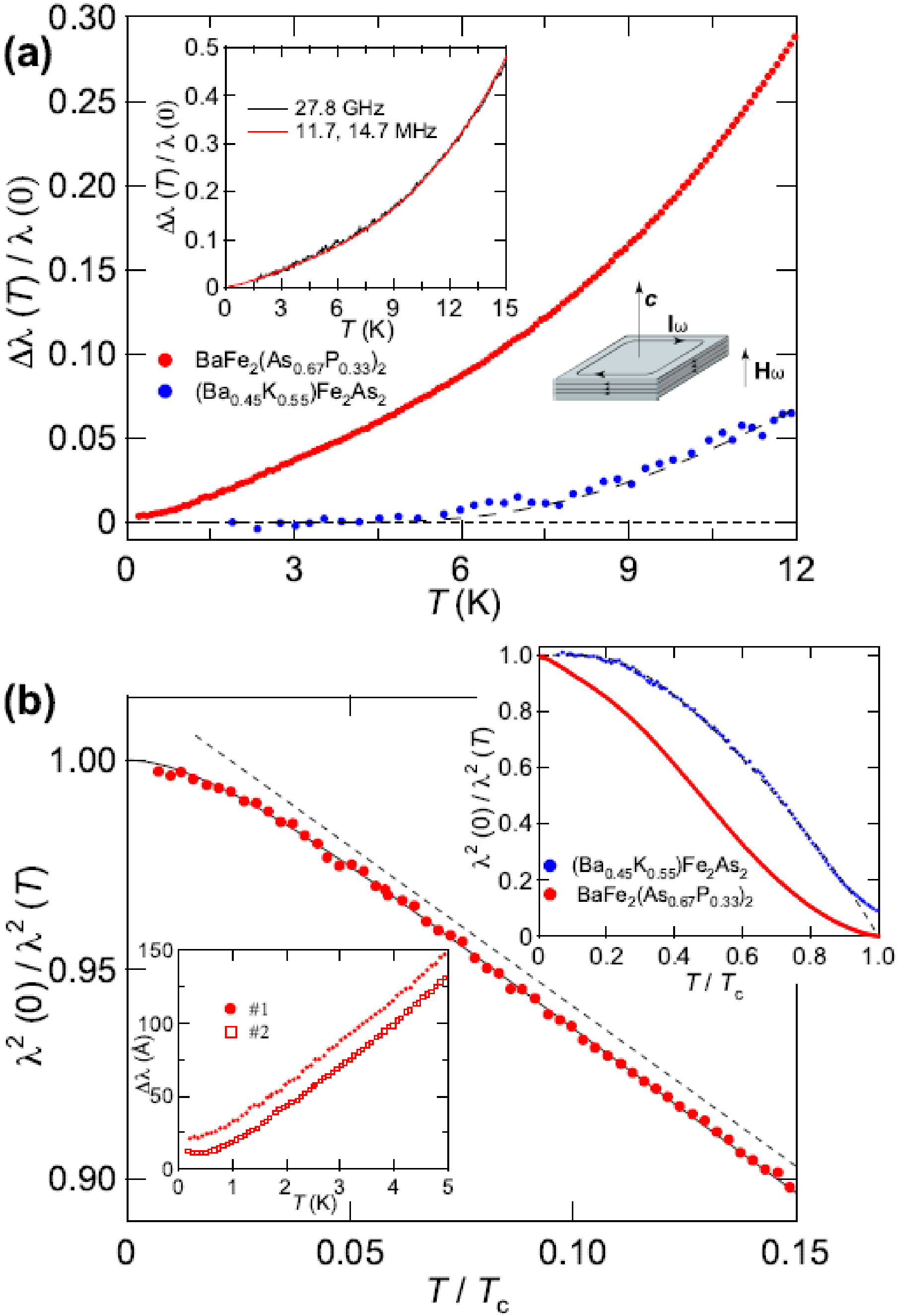
K.Kuroki *et al.* arXiv:1010.3542

Node in the electron band

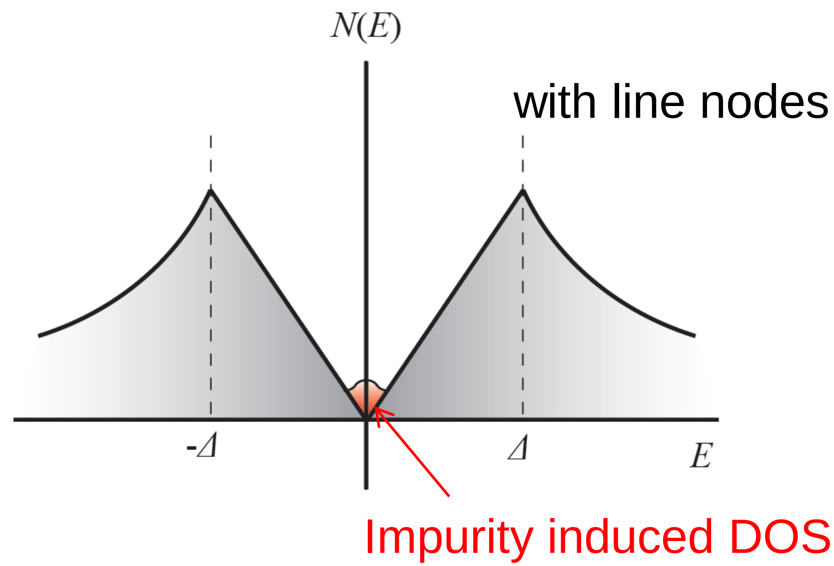
I.I. Mazin *et al.*, PRB (10)

Gap structure of $BaFe_2(As_{0.67}P_{0.33})_2$: penetration depth

K. Hashimoto *et al*., PRB **81**, 220501(R) (2010).



- T-linear penetration depth in $BaFe_2(As_{1-x}P_x)_2$ (T_c ~ 30 K, x=0.33) clearly indicates the line nodes in the gap.

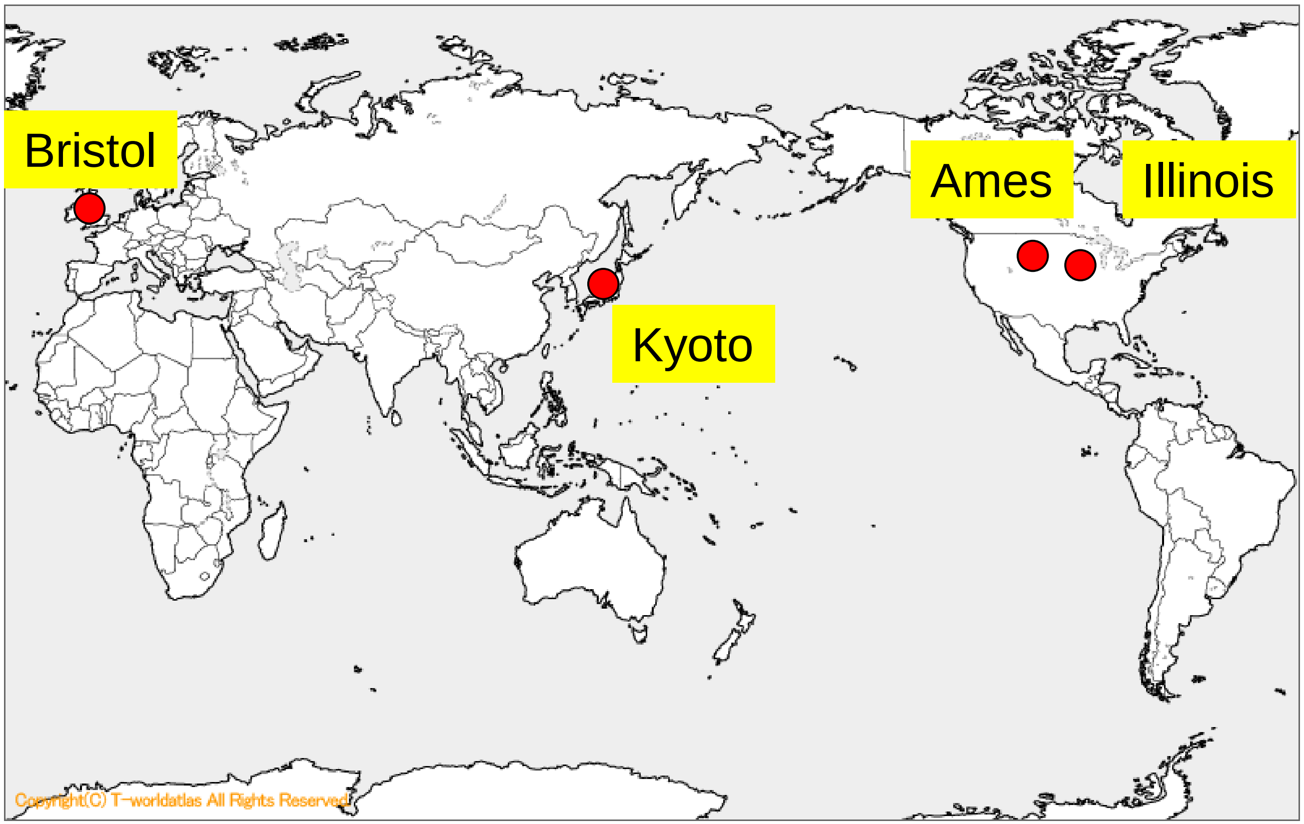


$\Delta\lambda(T) \sim T^2/(T+T^*)$ T^*=1.3 K

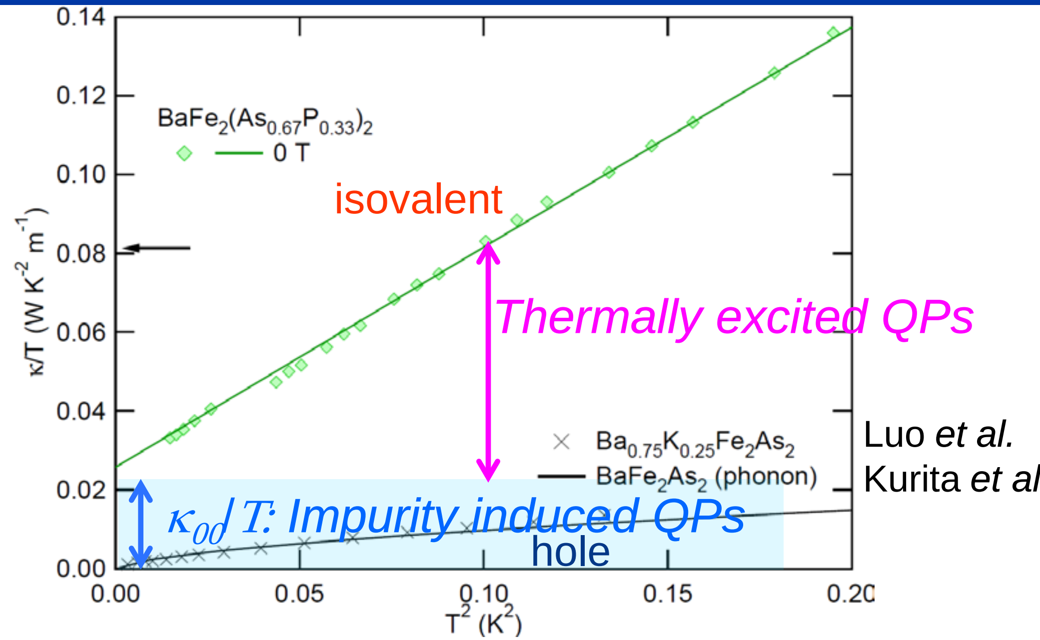
cf. clean YBCO T^*~1 K

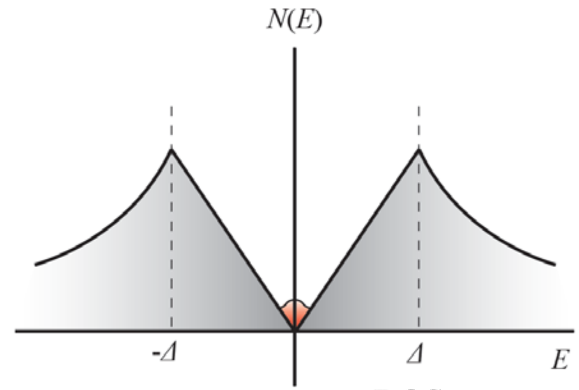
Gap structure of $BaFe_2(As_{0.67}P_{0.33})_2$: penetration depth

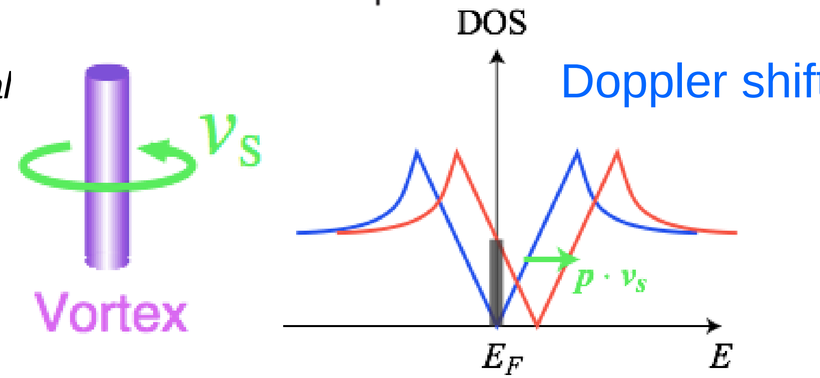
The *T*-linear dependent penetration depth of $BaFe_2(As_{0.67}P_{0.33})_2$ (T_c=31K) has been confirmed in four laboratories

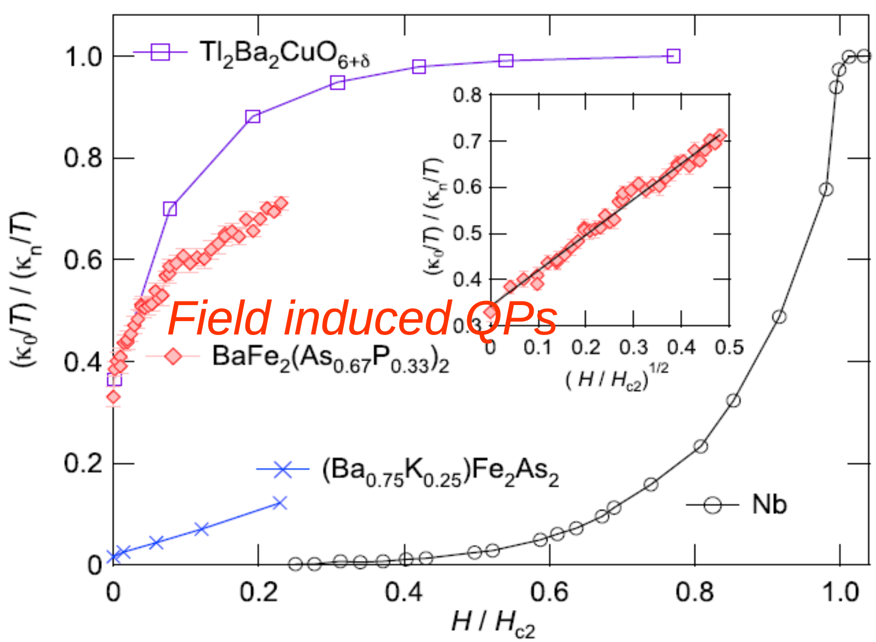


Gap structure of $BaFe_2(As_{0.67}P_{0.33})_2$: thermal conductivity







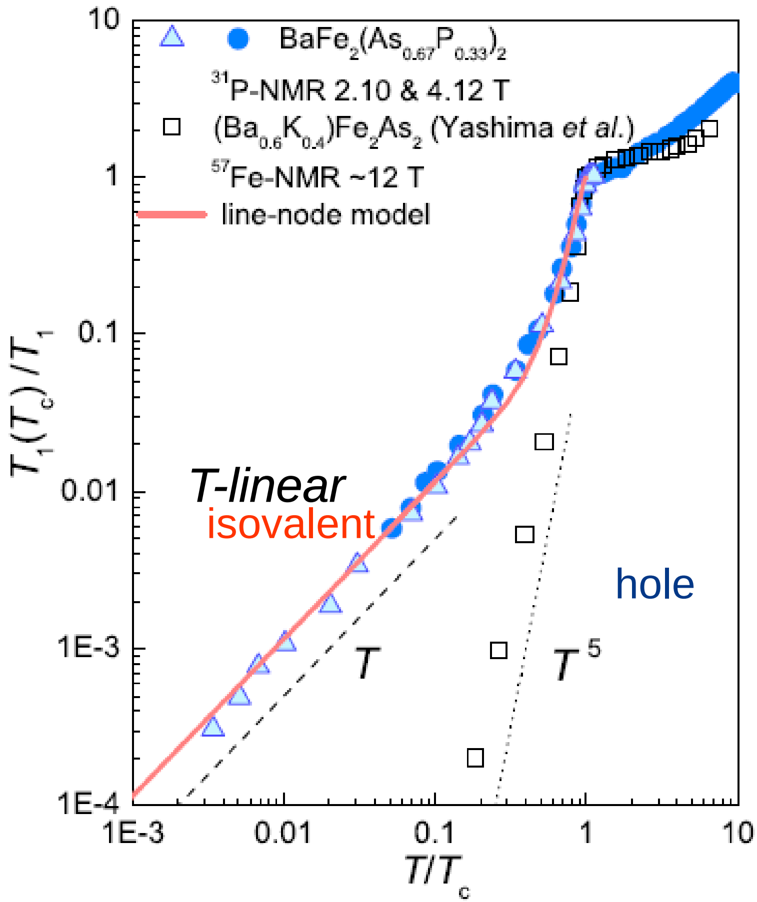


- Finite κ_0/T in the $T \rightarrow 0$ K limit
- Thermally excited QPs
- Steep increase with H

$$\kappa/T(T \rightarrow 0) \sim \sqrt{H}$$

Clear evidence for *line node with sign change* in $BaFe_2(As_{1-x}P_x)_2$

Gap structure of $BaFe_2(As_{0.67}P_{0.33})_2$: NMR

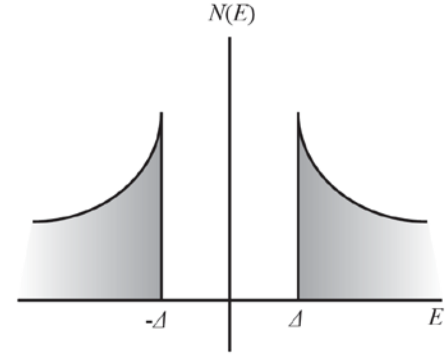


Y.Nakai *et al*. PRB (2010)

Hole dope

$(Ba_{1-x}K_x)Fe_2As_2$

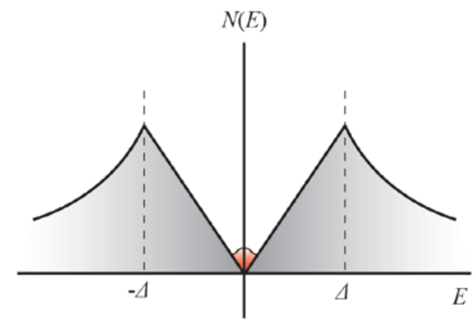
Full gap



Isovalent dope

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

Line node



T_1T becomes constant at very low temperature

Residual DOS due to line node

NMR results are consistent with the penetration depth and thermal conductivity

Superconducting gap structure of $BaFe_2(As_{1-x}P_x)_2$

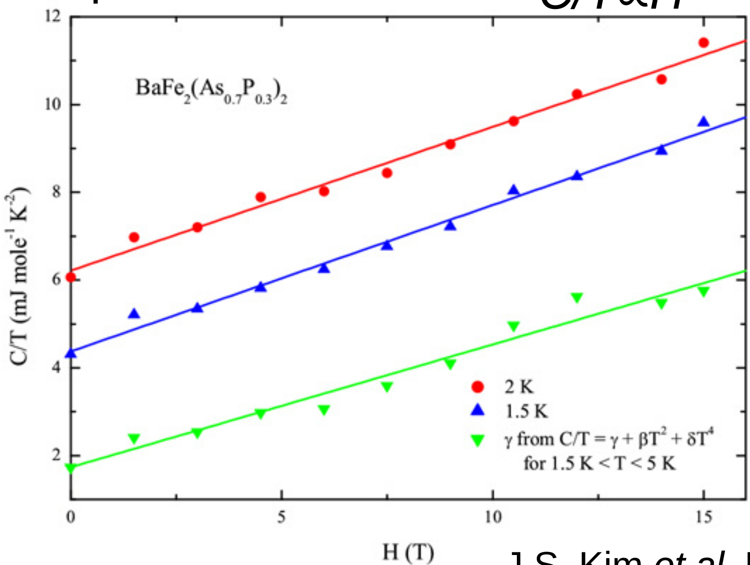
Evidence of line node

Pinpointing the position of line node

Where is the line node ?
Gap structure probed by specific heat and thermal conductivity

Specific heat

C/T∝*H*

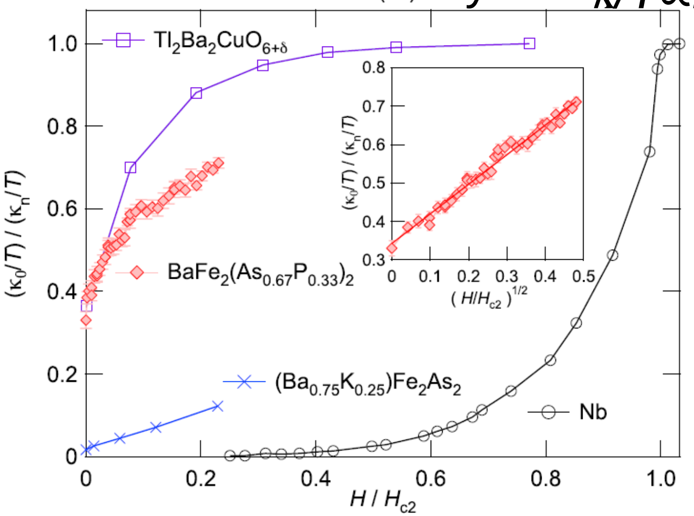


J.S. Kim *et al.* PRB (10)

$H^{1/2}$-component is less than 5% of the total specific heat

Thermal conductivity

κ/T∝*H*$^{1/2}$

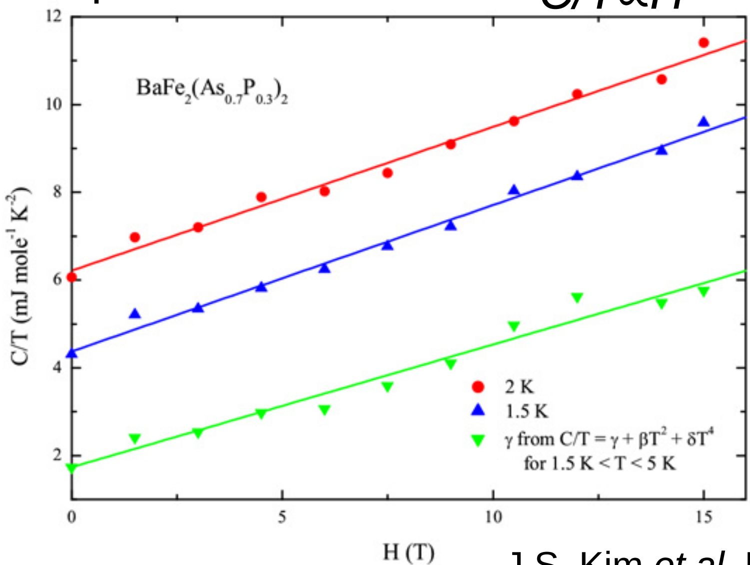


K. Hashimoto *et al*., PRB (10).

$H^{1/2}$-component is more than 30% of the total thermal conductivity

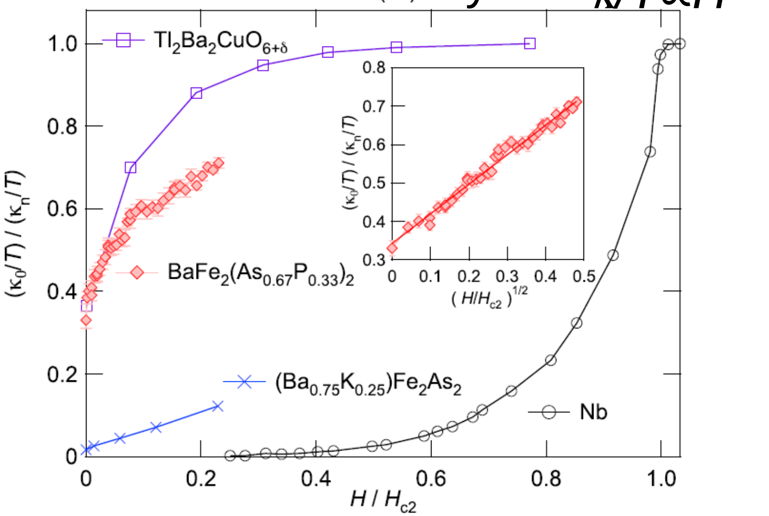
Where is the line node ?
Gap structure probed by specific heat and thermal conductivity

Specific heat $C/T \propto H$



J.S. Kim *et al.* PRB (10)

Thermal conductivity $\kappa/T \propto H^{1/2}$

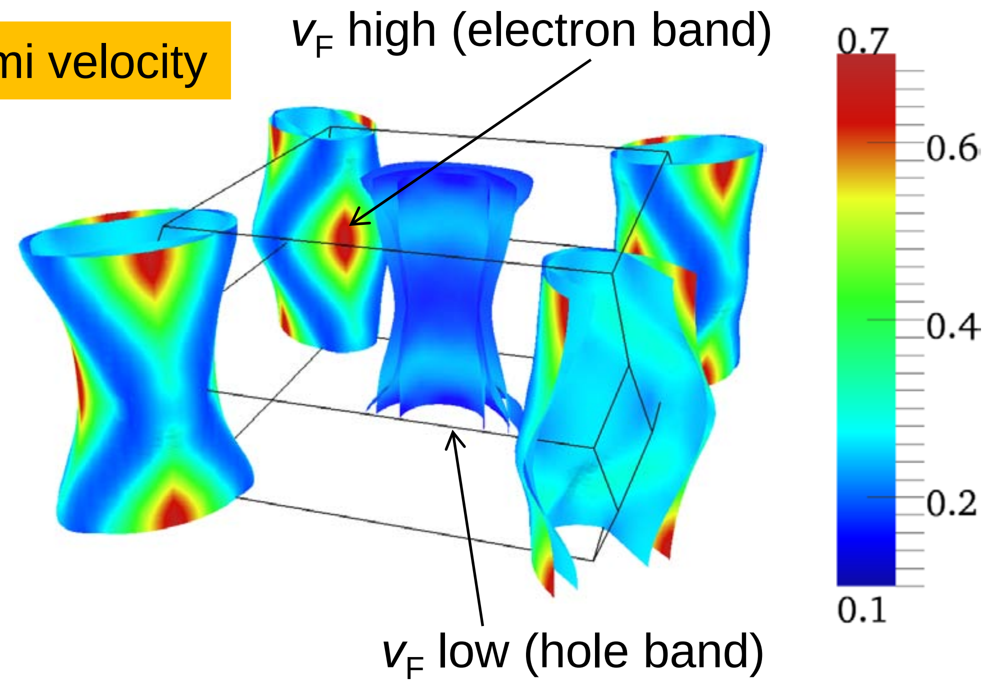


K. Hashimoto *et al*., PRB (10).

In the mutiband system,

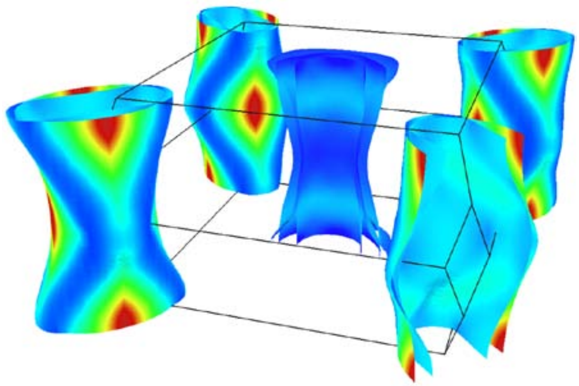
specific heat is dominated by the heavy mass band
heat conductivity is dominated by light mass band

Fermi velocity

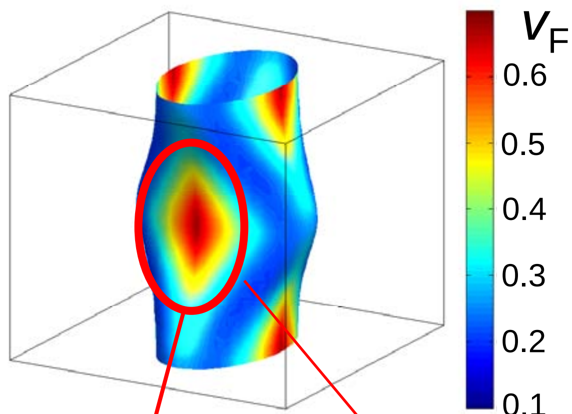


Specific heat is dominated by hole band
Thermal conductivity is dominated by the electron band

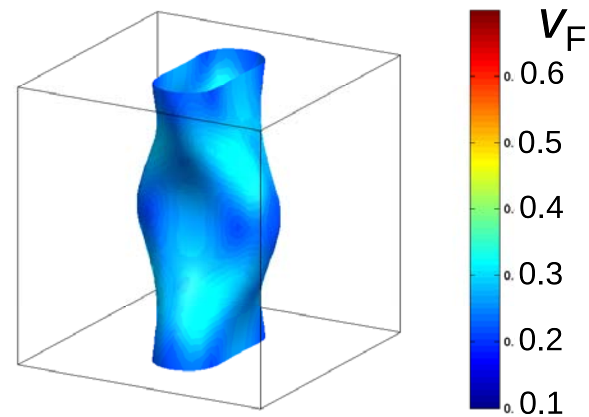
Where is the line node ?



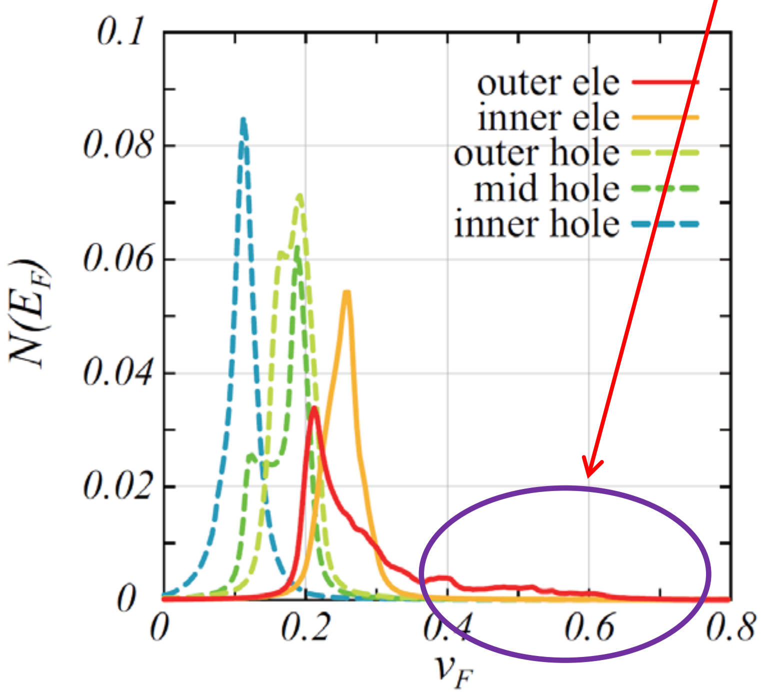
Outer electron band



Inner electron band

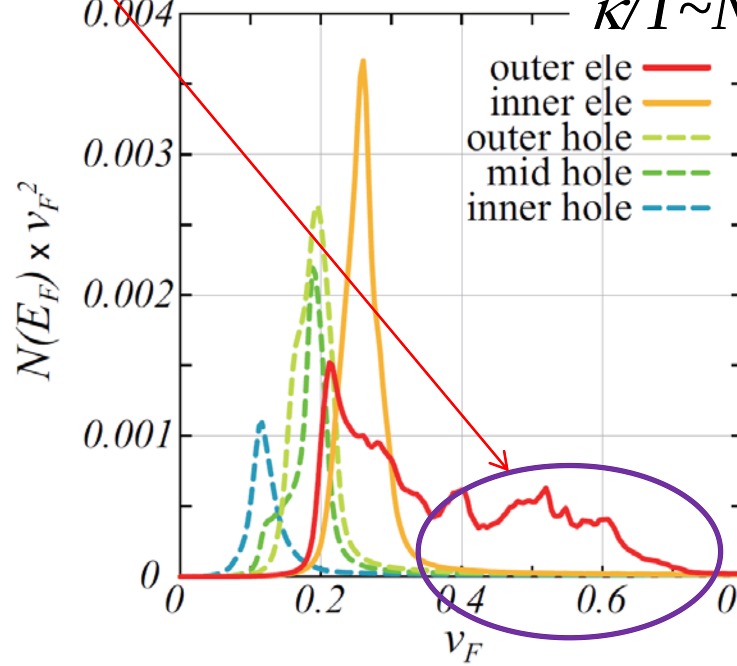


Less than 5% of total DOS



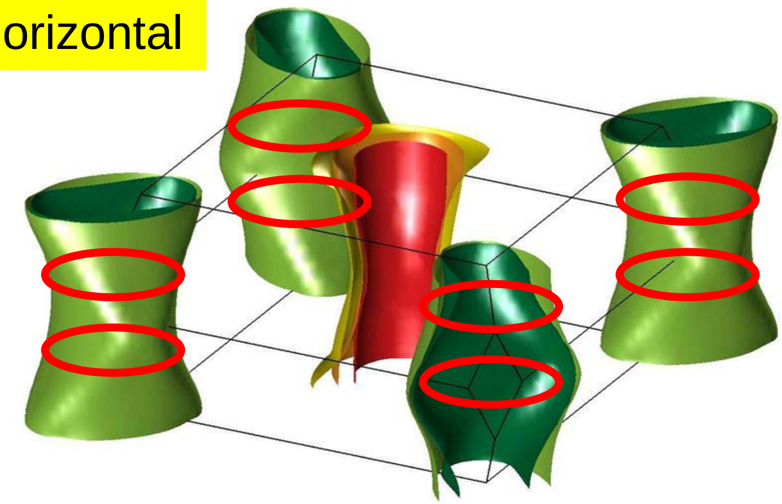
More than 20% of total thermal conductivity

$\kappa/T \sim N(E_F) v_F^2 \tau$



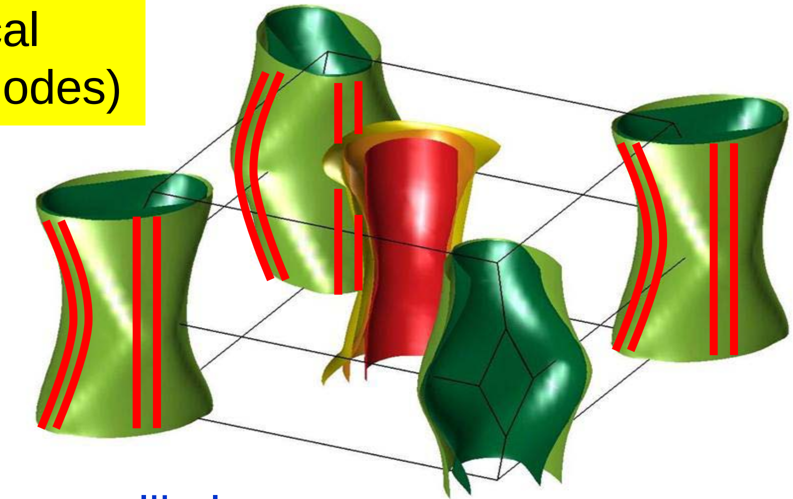
Where is the line node in $BaFe_2(As_{0.67}P_{0.33})_2$ (T_c=31 K) ?
Pinpointing line node by angle-resolved thermal conductivity

i) Horizontal



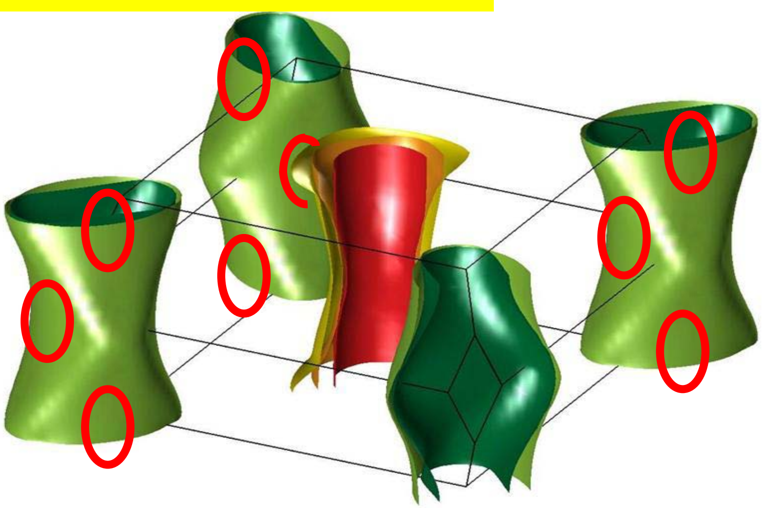
incompatible with the angle-resolved thermal conductivity

ii) Vertical
(8 line nodes)

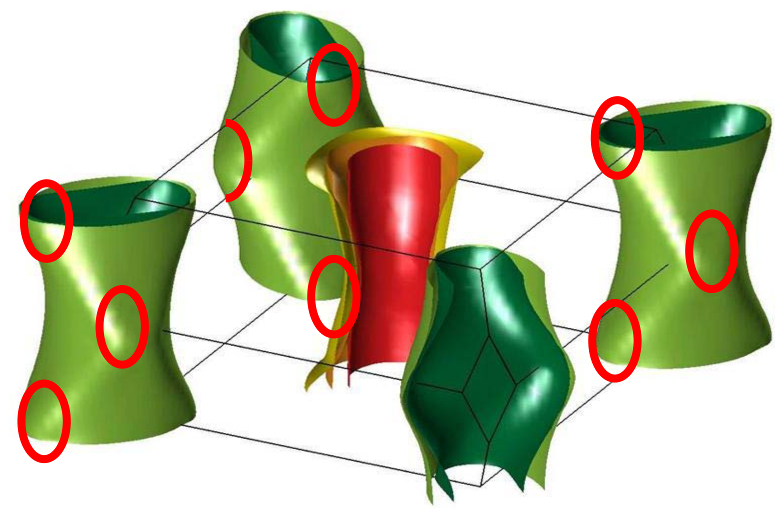


Seems unlikely
Has a symmetry higher than electron FS

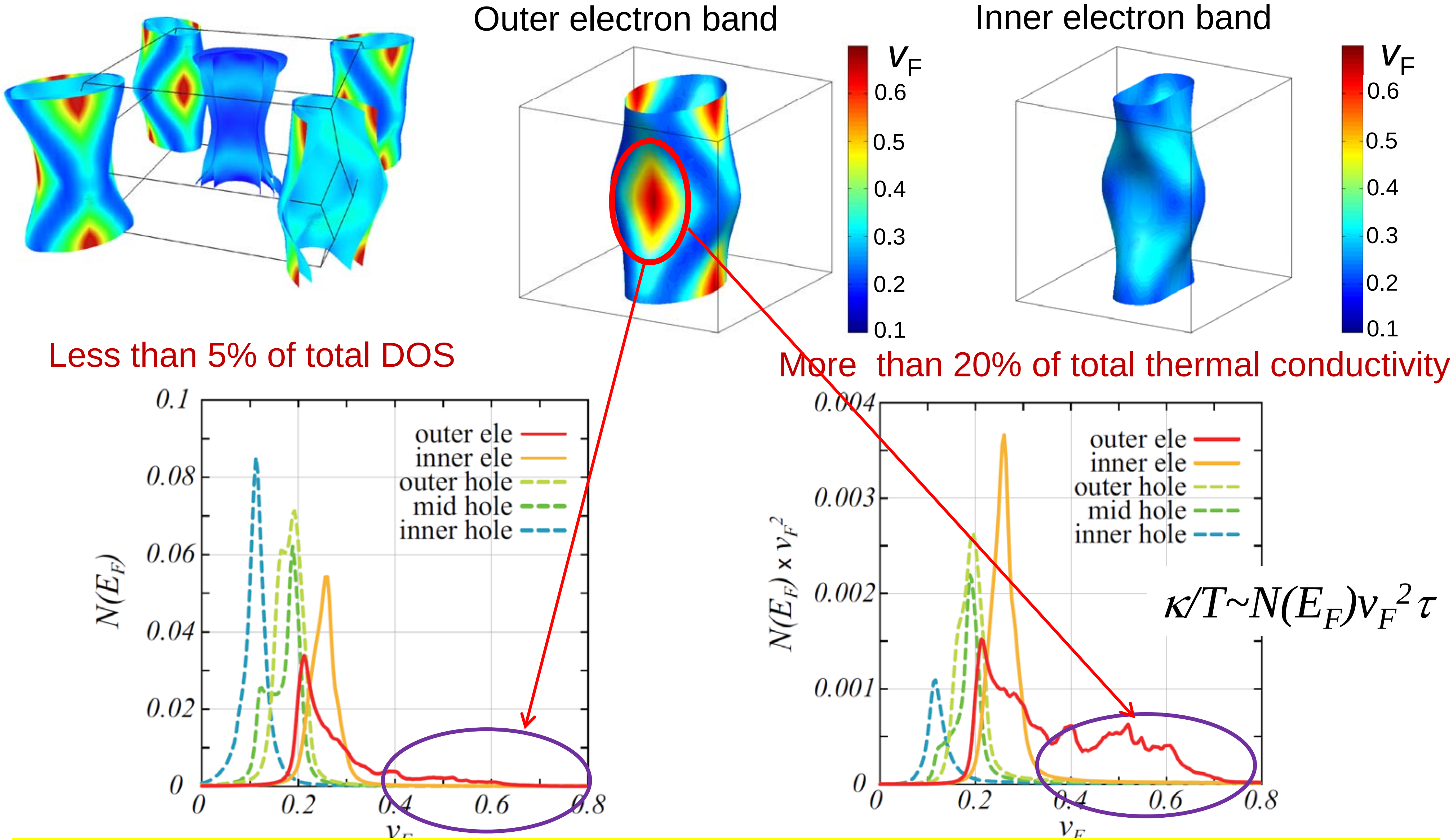
iii)Loop (Flat part of the FS)



iv)Loop (High curvature part of the FS)

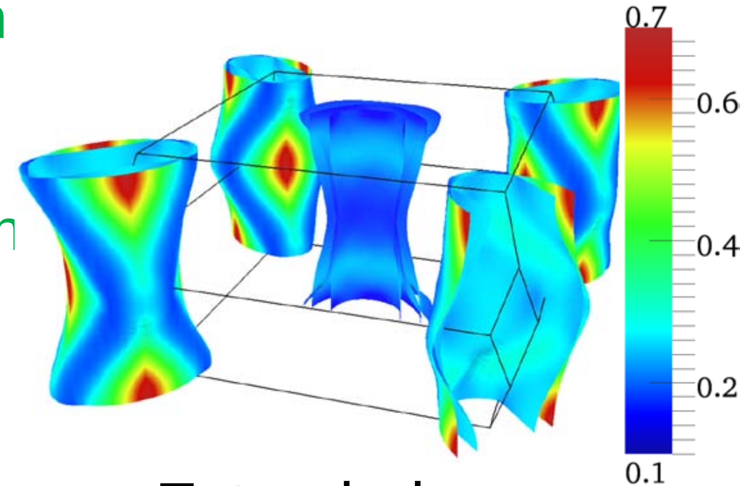


Where is the line node in $BaFe_2(As_{0.67}P_{0.33})_2$ (T_c=31 K) ?



Line node are most likely to be located at the region with the largest Fermi velocity (flat part) in the electron sheet

Summary of the nodal structure of $BaFe_2(As_{1-x}P_x)_2$



Extended s-wave

Penetration depth measures large v_F region

Node in the electron band

Thermal conductivity measures large v_F region

Node in the electron band

Specific heat measures large DOS region

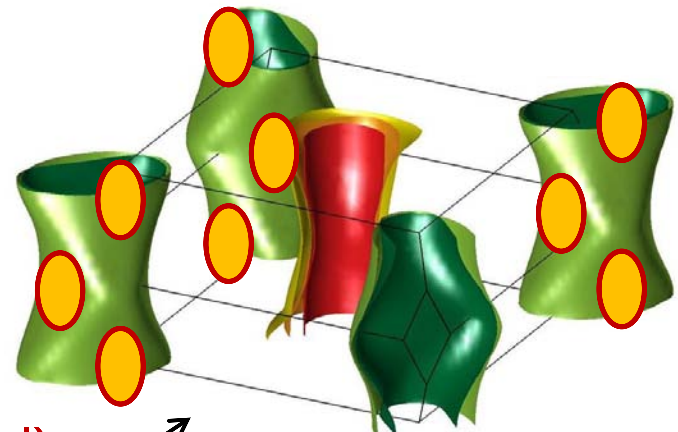
No evidence of nodes in the hole band

ARPES measures particular hole FS

No nodes at hole FS

Angular-resolved thermal conductivity

Node locates near ΓX-line (Fe-Fe bond)

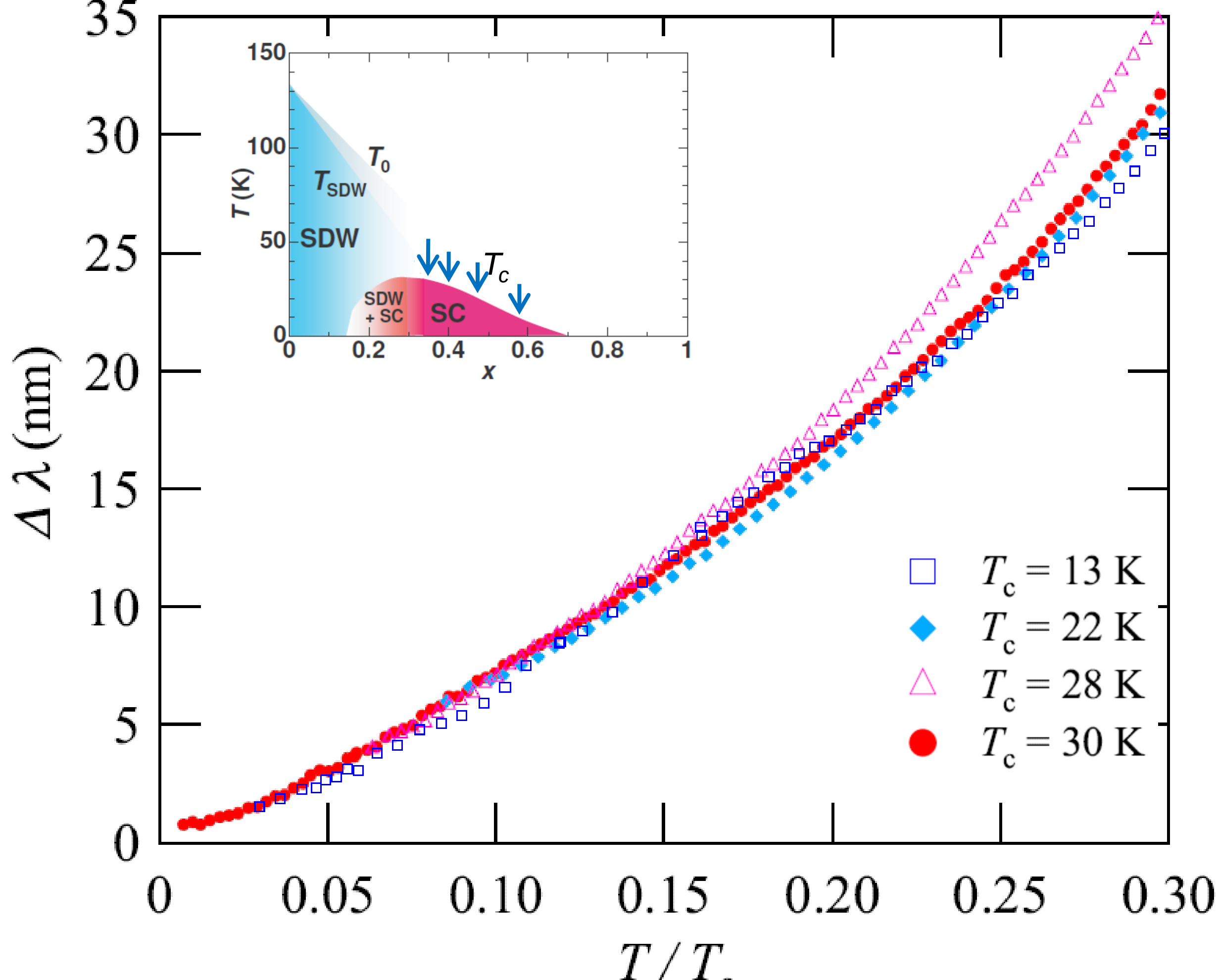


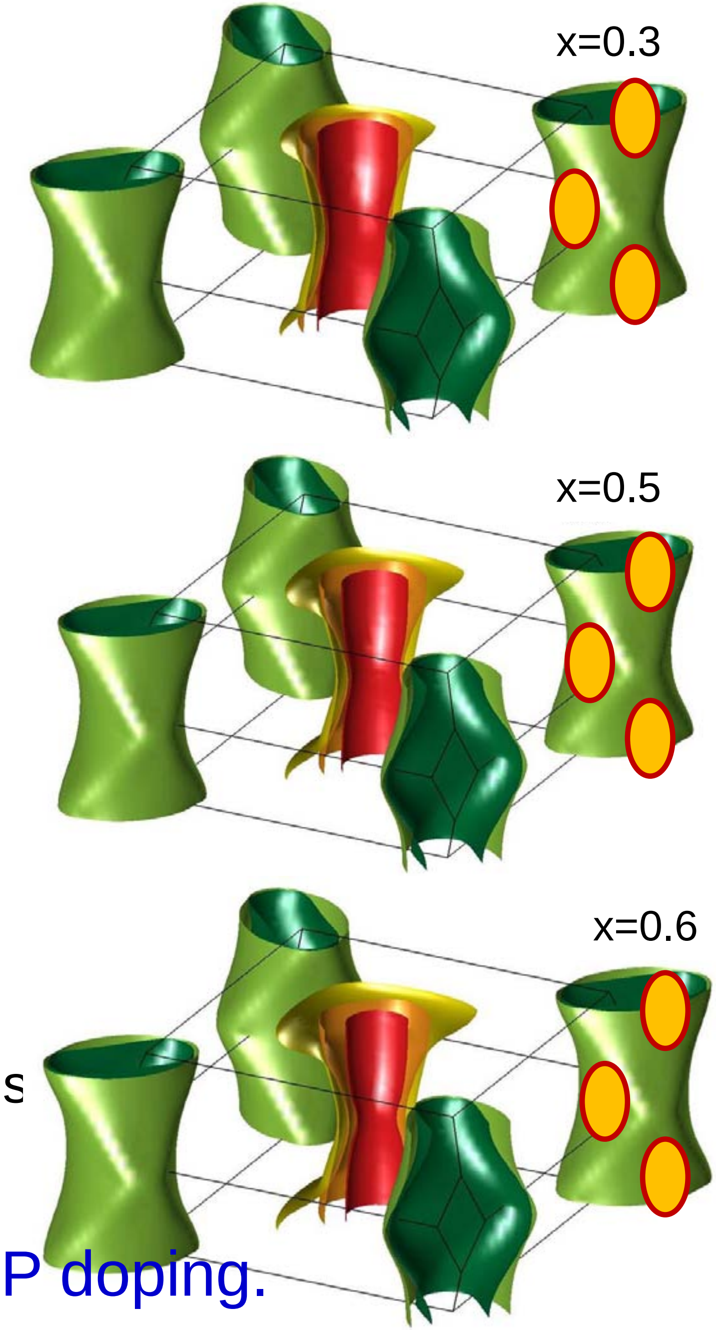
All results above are consistent with this nodal structure

Line node are most likely to be located at the region with the largest Fermi velocity (flat part) in electron sheet

Doping dependence of the gap structure

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





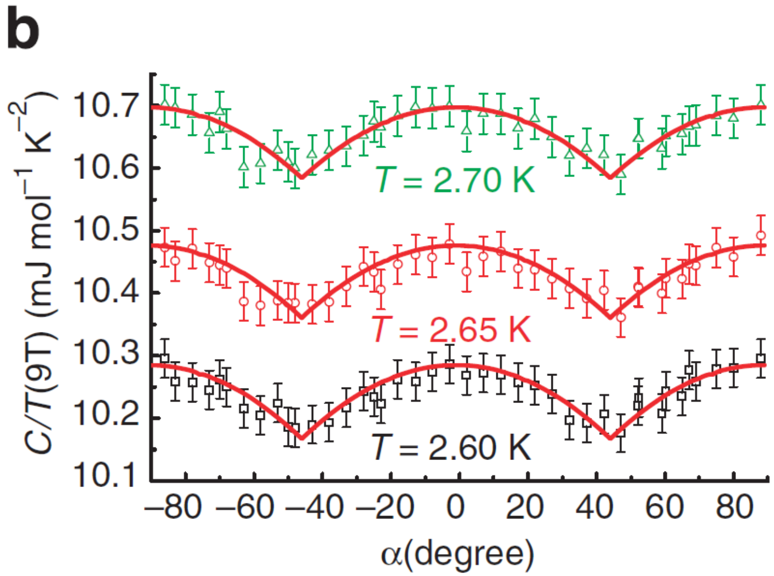
$\Delta\lambda(T)$ behavior is very similar in different doping levels

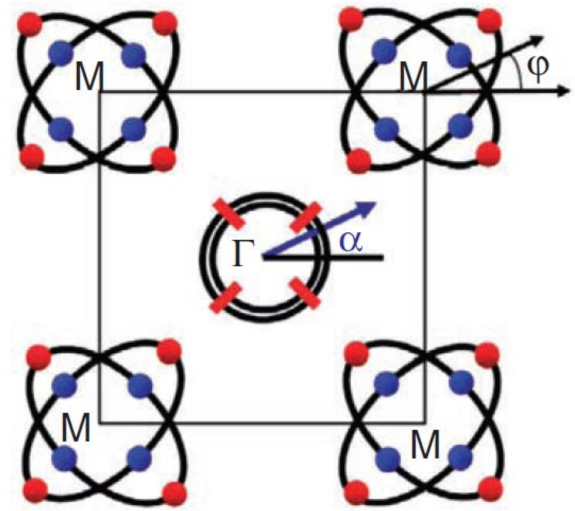
$$\Delta\lambda \sim N_0(\hat{\boldsymbol{k}}_n)\frac{T}{T_c}$$

The location of line node remains same with P doping.

$FeSe_{0.45}Te_{0.55}$

Angle-resolved specific heat



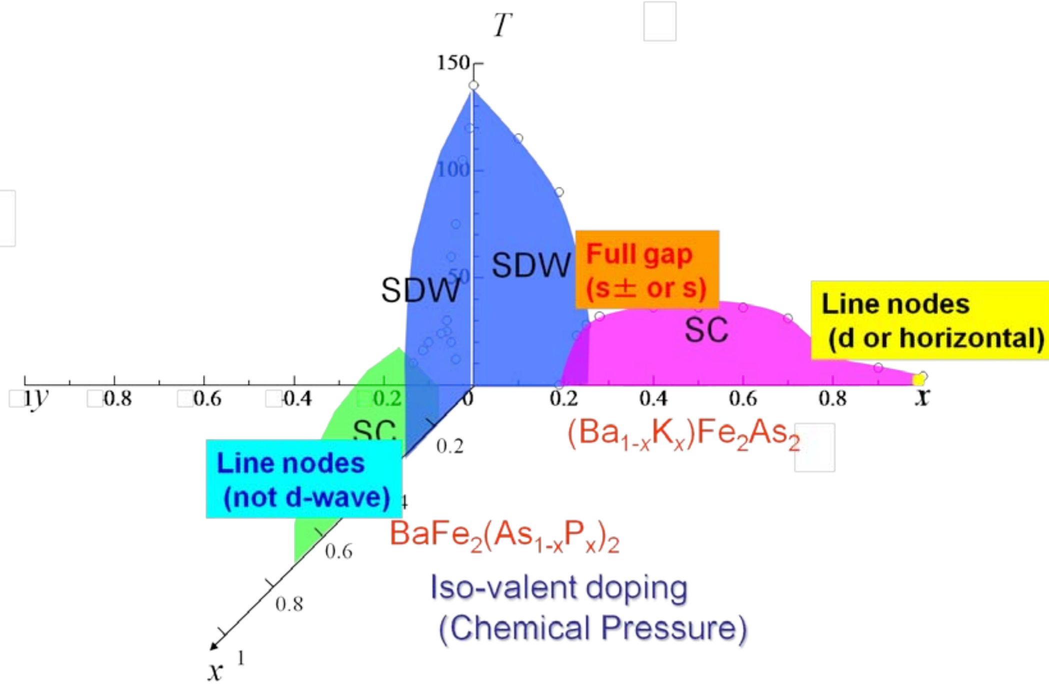


Gap minimum (not node) along the ΓM (Fe-Fe bond) direction

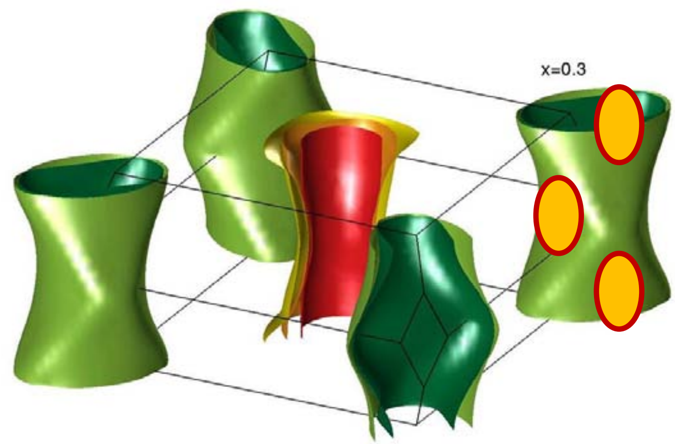
B.Zeng *et al*. Nature Communi. (10)

Summary
Determining gap nodal structure in isovalent doped $BaFe_2(As_{1-x}P_x)_2$

Thermal conductivity, penetration depth and NMR all consistently support the presence of line nodes in the superconducting gap.



Combined the above results with angle-resolved thermal conductivity, heat capacity, Laser ARPES, ARPES and band calculation, the line nodes are most likely to be located at the region with the largest Fermi velocity (flat part) in electron band.



The location of line node remains same with P doping.