Superconducting gap symmetry in $BaFe_2As_2$-based superconductors

Taka Shibauchi
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1. Observation of the “node lifting” by disorder in $BaFe_2(As,P)_2$
2. Evidence for sign-changing gaps between hole pockets in heavily hole-doped $(Ba,K)Fe_2As_2$

Collaborators

Transport properties
Penetration depth
Thermal conductivity
dHvA
Magnetic torque
Crystal growth

S. Kasahara
K. Hashimoto
Y. Mizumami
Y. Kawamoto
S. Kurata
T. Mikami
T. Yamashita
D. Watanabe
Y. Matsuda

Band calc.

H. Ikeda

Kyoto Univ. Japan

Penetration depth, dHvA

A. Serafin
P. Walmsley
A. Carrington

Univ. of Bristol, UK

Penetration depth

K. Cho
M. Tanatar
R. Prozorov

Ames, USA

Electron irradiation

M. Konczykowski
C. J van der Beek

Ecole Polytechnique, France

K-122 crsytals

T. Saito
H. Fukazawa
Y. Kohori

Chiba Univ., Japan

S. Ishida
K. Kihou
C. H. Lee
A. Iyo
H. Eisaki

AIST, Japan

Theory

A.B. Vorontsov

Montana

Y. Wang
A. Kreisel
P. J. Hirschfeld

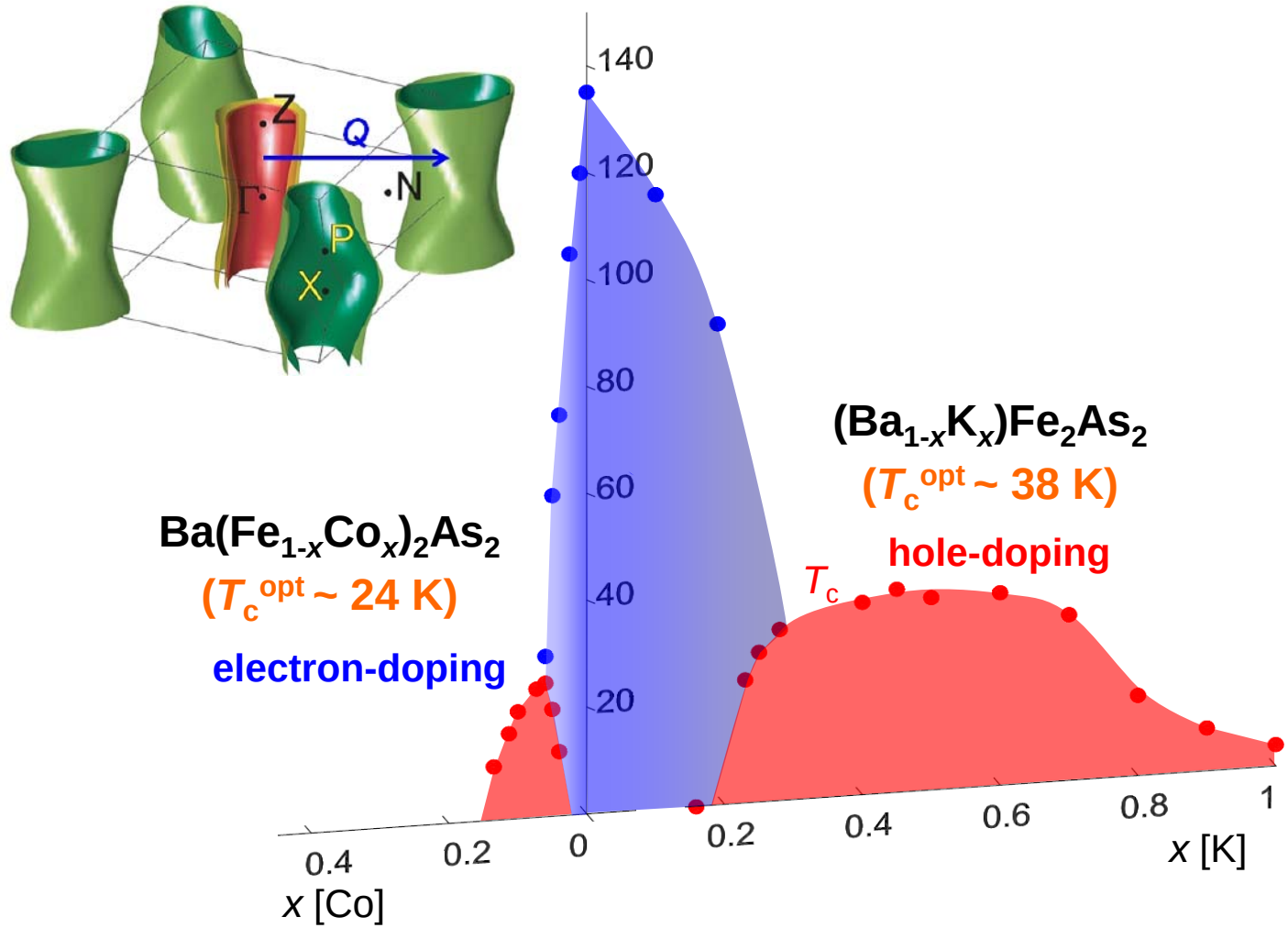
Univ. of Florida, USA

V. Mishra

Argonne Nat'l Lab, USA

Superconductivity in $BaFe_2As_2$ systems

Parent compound
$BaFe_2As_2$
(AF Metal)



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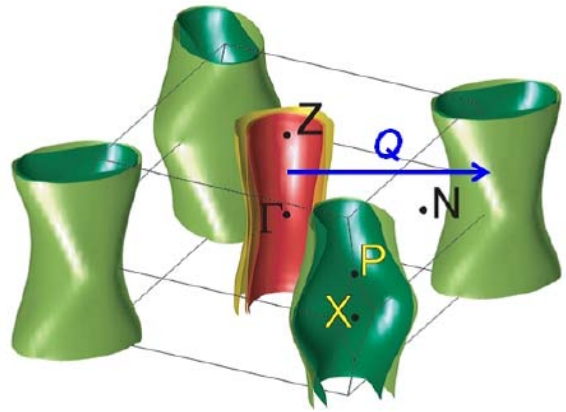

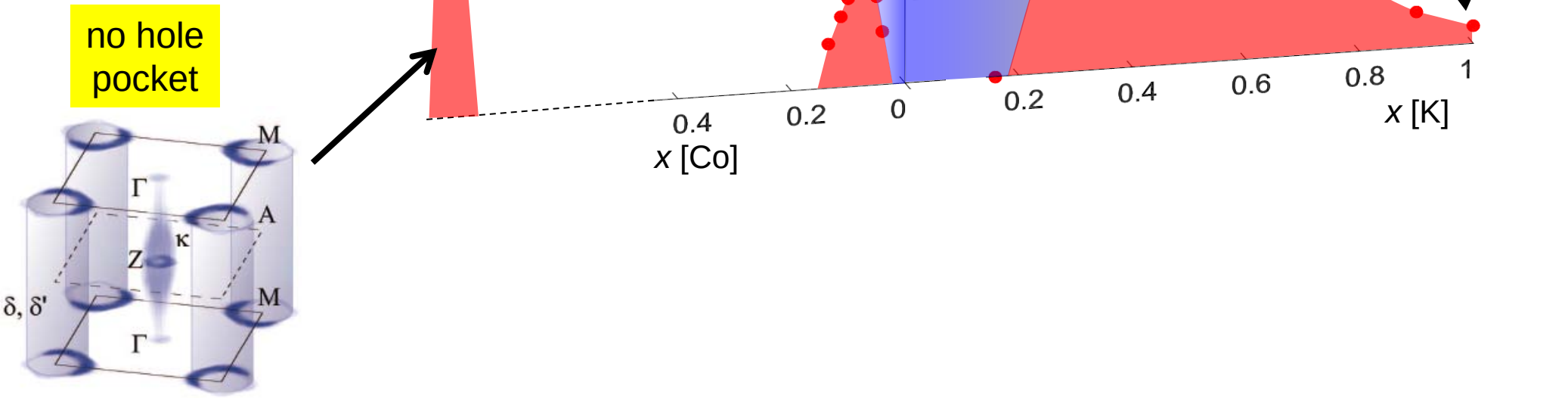

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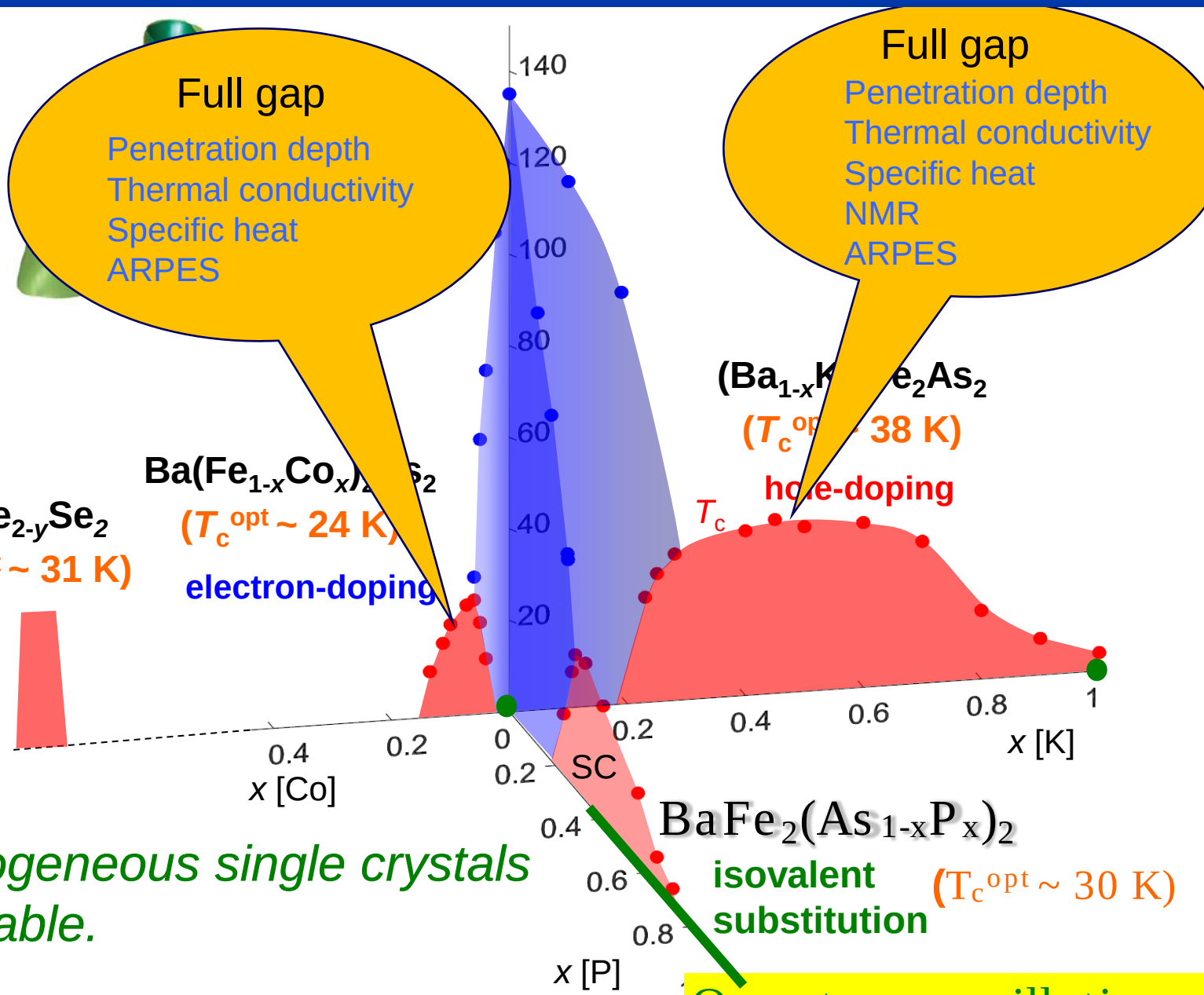
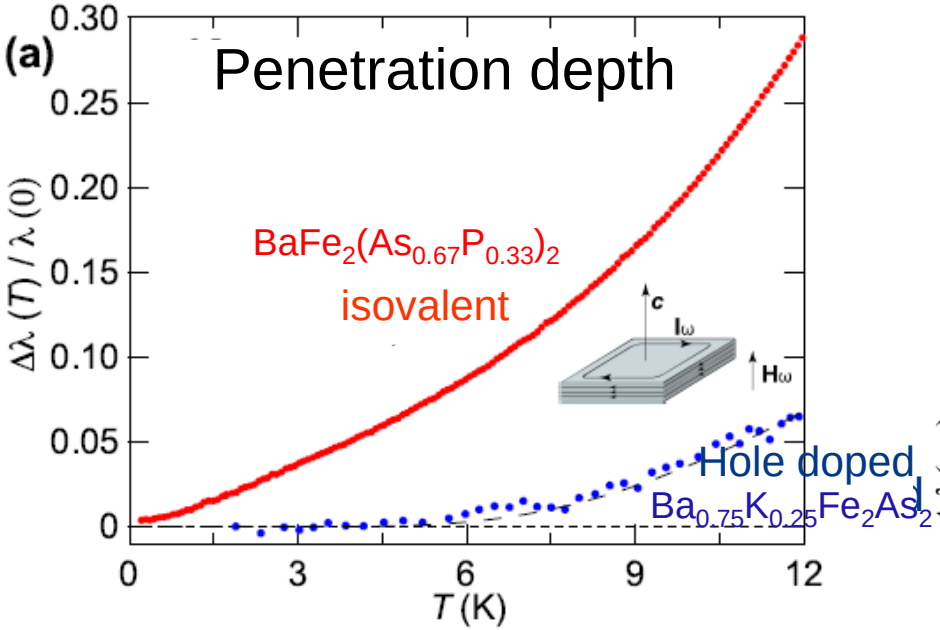
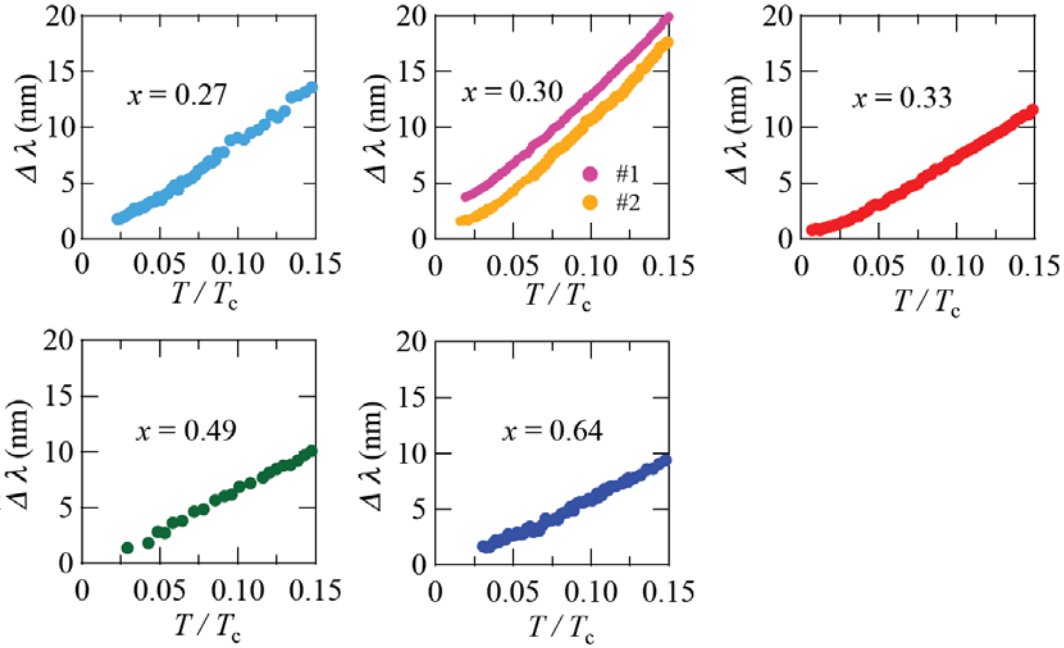


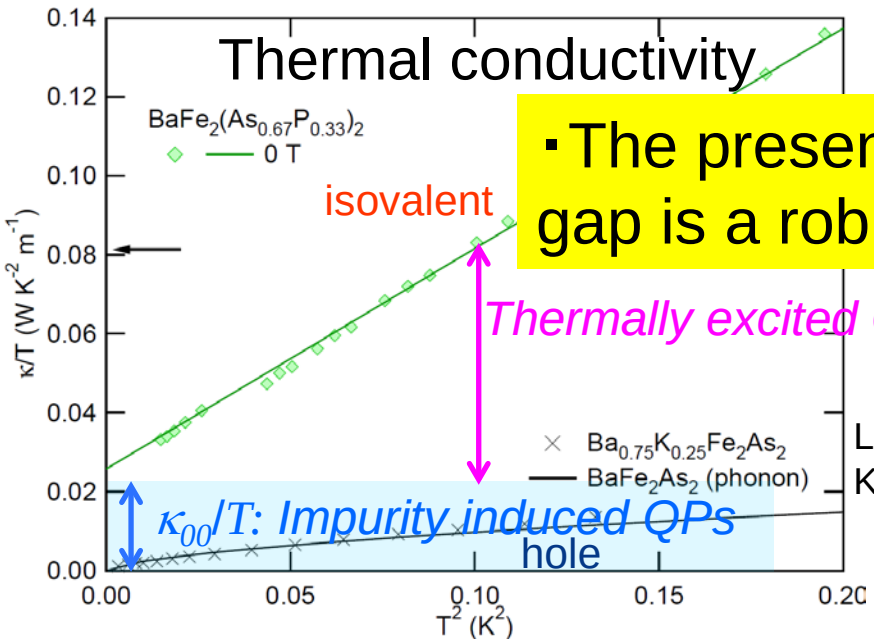
Clean and homogeneous single crystals have been available.

T. Shibauchi, A. Carrington, Y, Matsuda, arXiv:1304.6387 (2013).

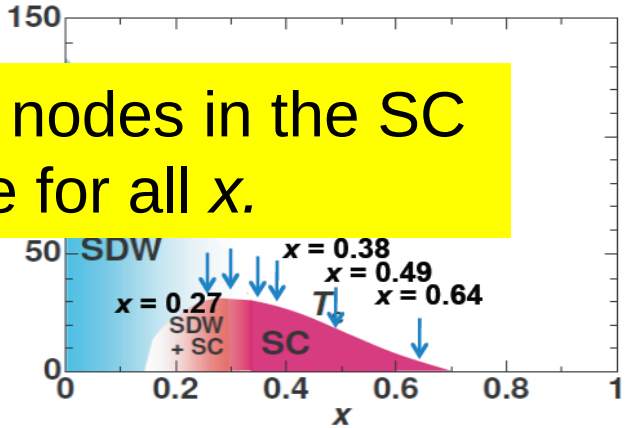
Gap structure of isovalent doped $BaFe_2(As_{1-x}P_x)_2$







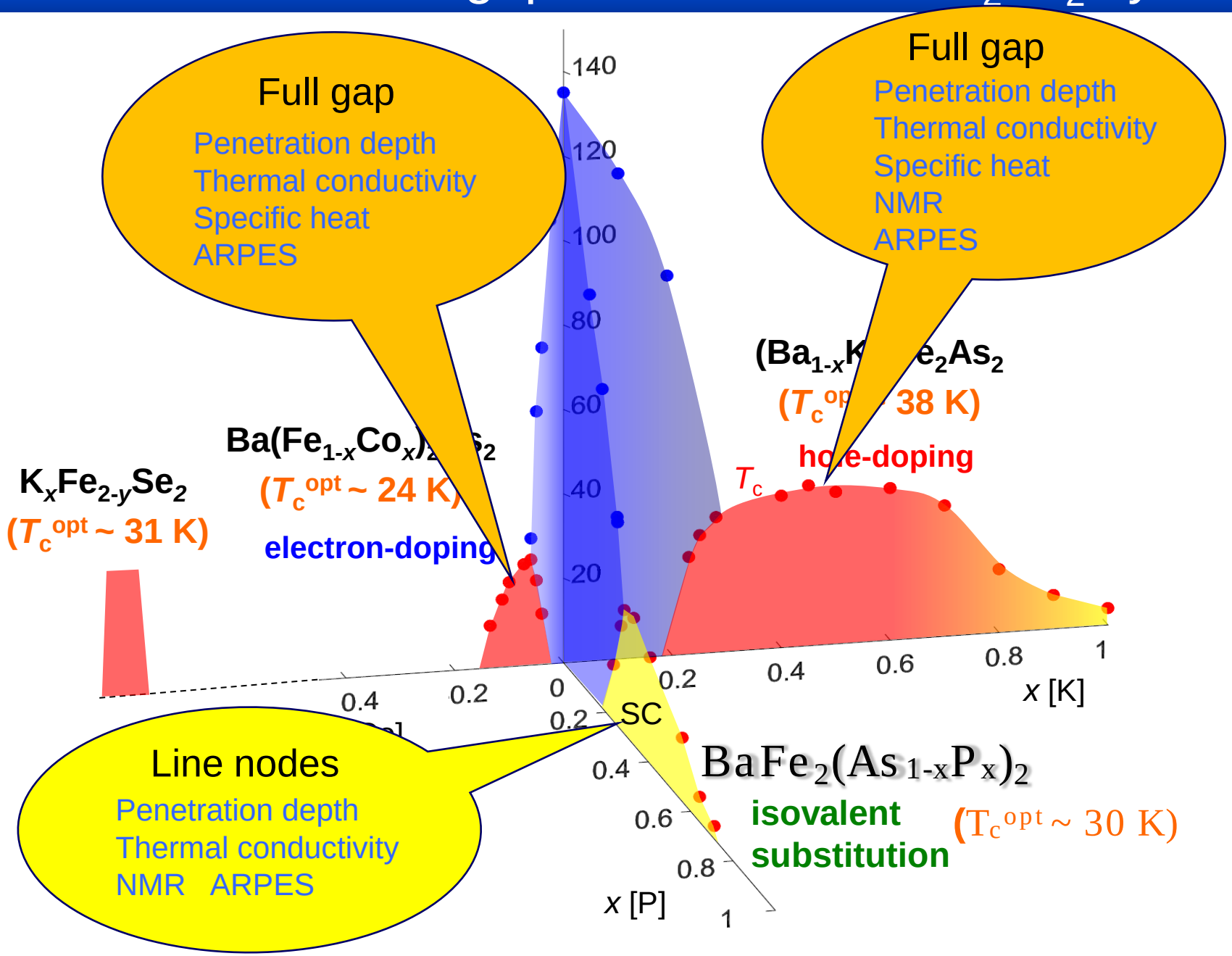
- The presence of line nodes in the SC gap is a robust feature for all *x*.



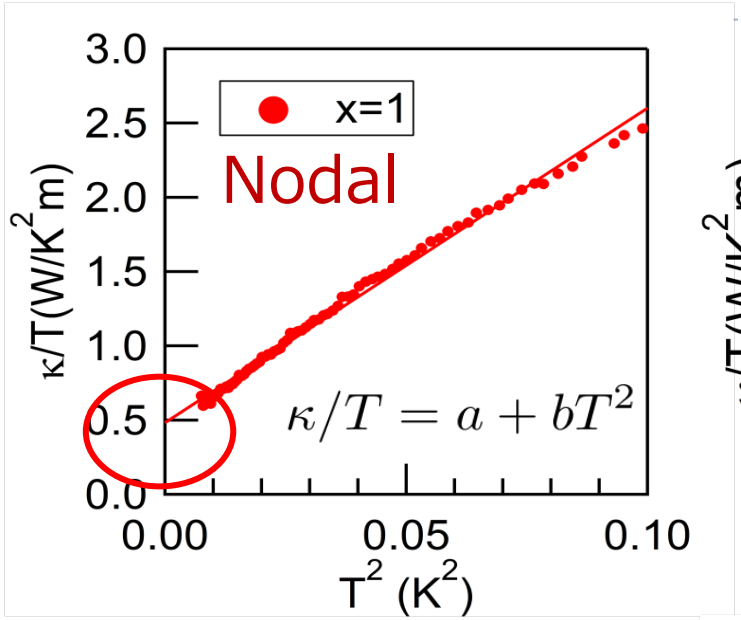
Luo *et al.*
Kurita *et al.*

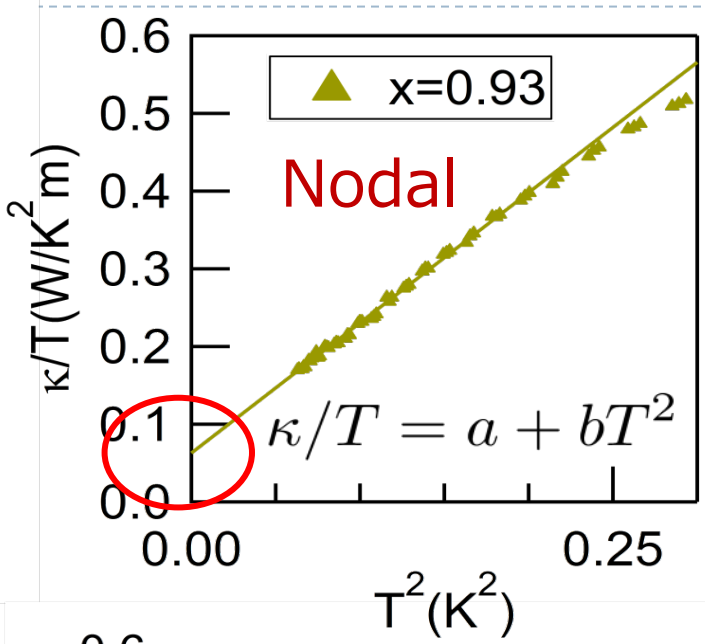
K. Hashimoto *et al.*, PRB (2010)
K. Hashimoto *et al.*, PRL (2009)
K. Hashimoto *et al.*, Science (2012)

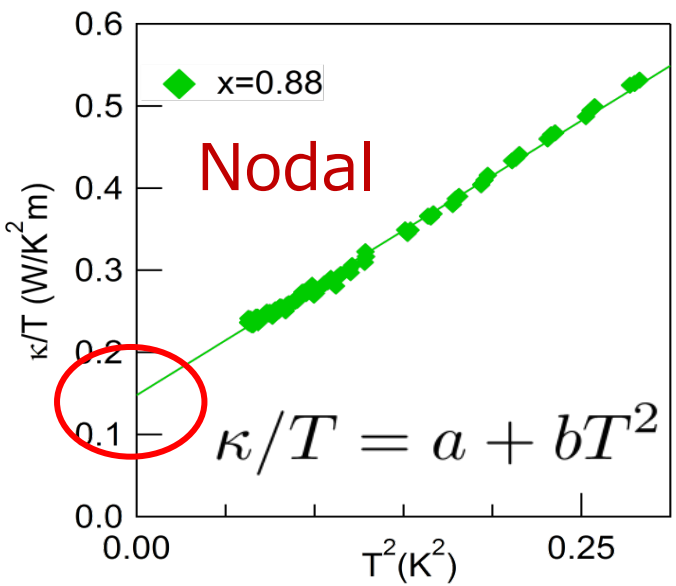
Non-universal gap structure in $BaFe_2As_2$ systems

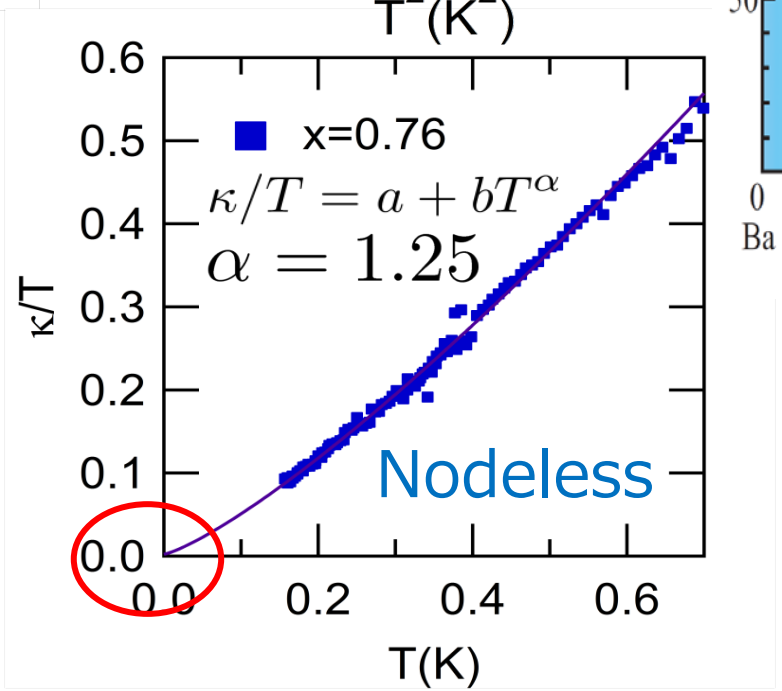


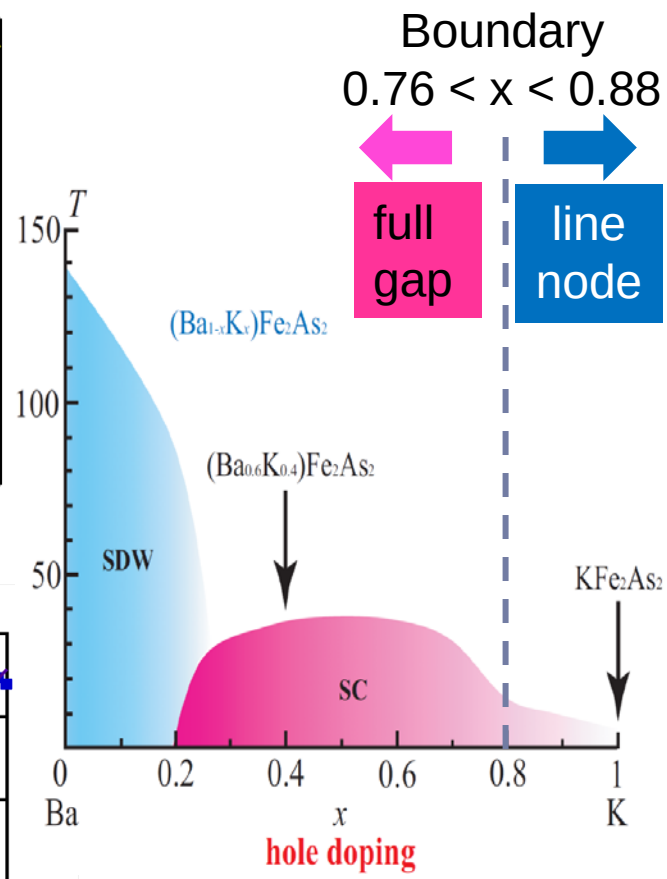
Gap structure of hole doped $Ba_{1-x}K_xFe_2As_2$







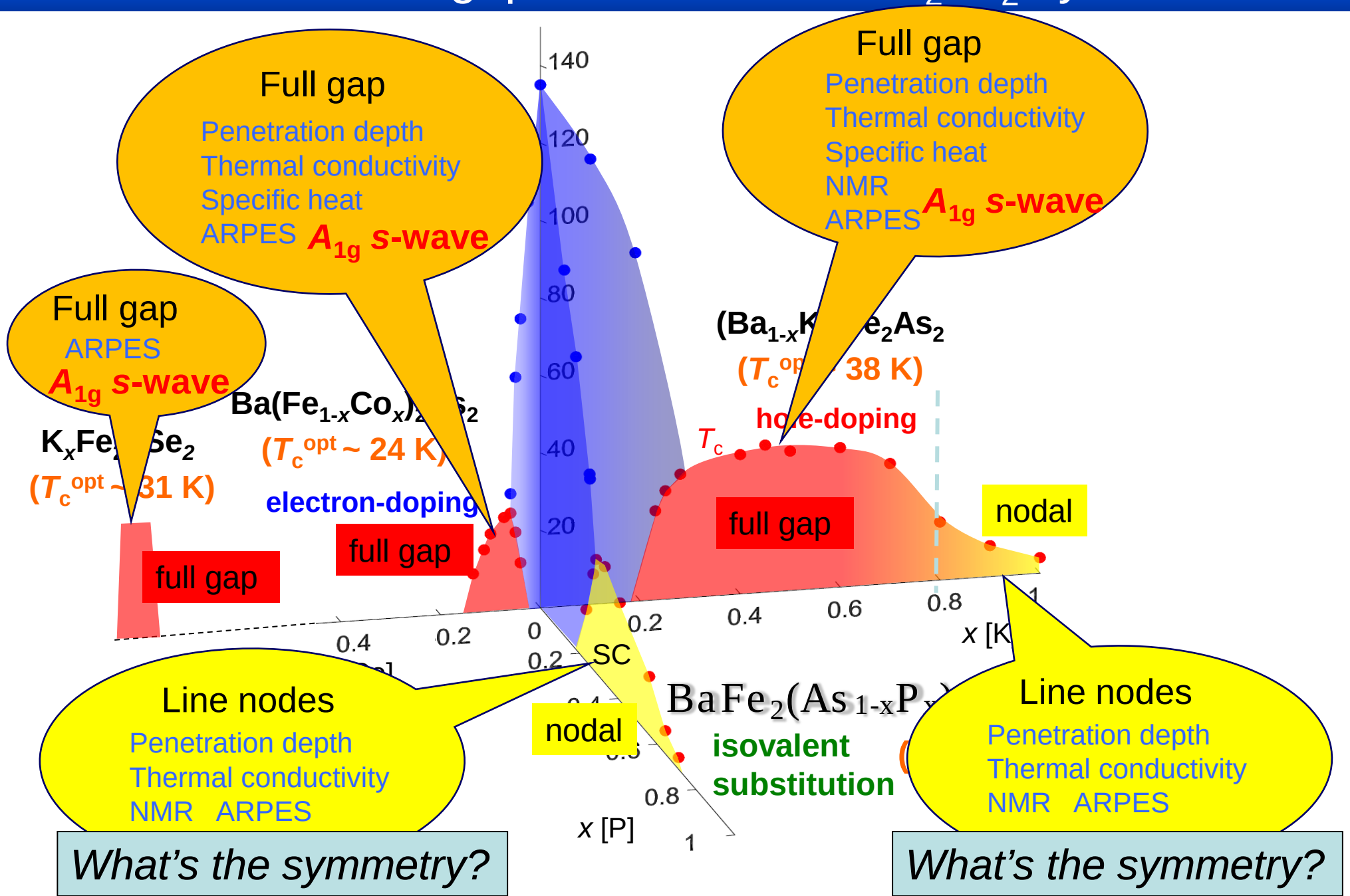




The gap structure changes at *x*~0.8.

D. Watanabe *et al.*
arXiv:1307.3408

Non-universal gap structure in $BaFe_2As_2$ systems



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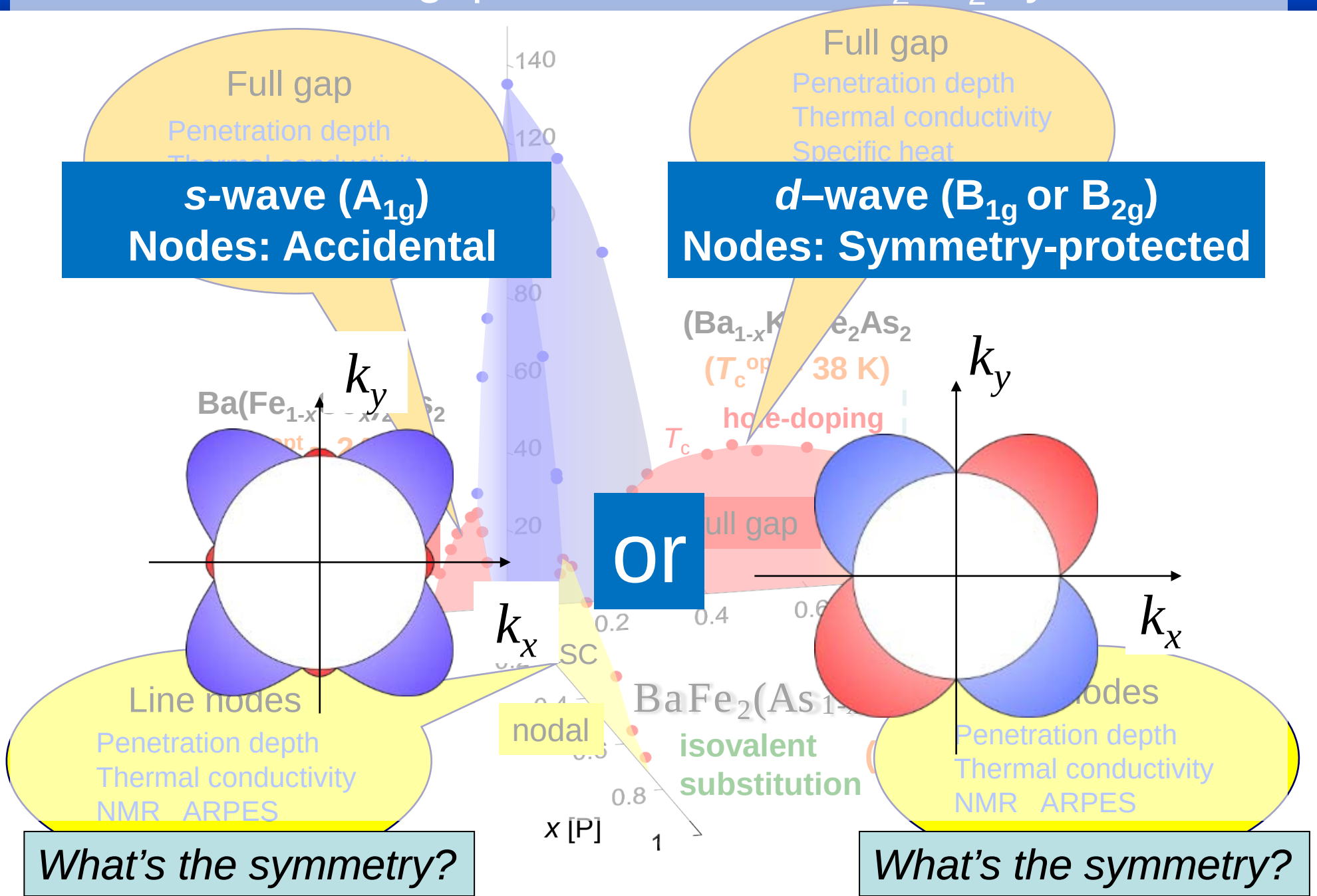
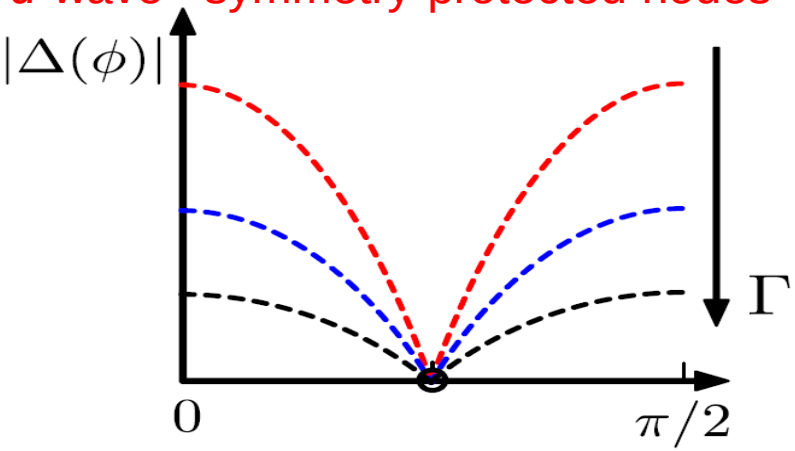


Are the nodes accidental or symmetry protected?

Impurity scattering dependence of gap structure can be a powerful probe of symmetry

Γ : impurity scattering rate

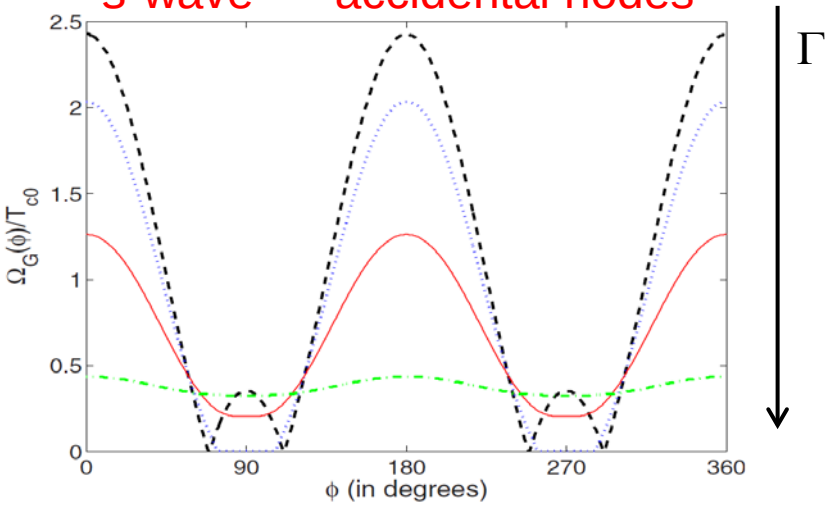
d-wave symmetry-protected nodes



J-Ph Reid *et al*., Supercond. Sci. Technol. **25**,084013 (2012).

Nodes are robust against disorder

s-wave accidental nodes



V. Mishra *et al*., PRB **79**, 094521 (2009).

Nodes can be lifted by disorder

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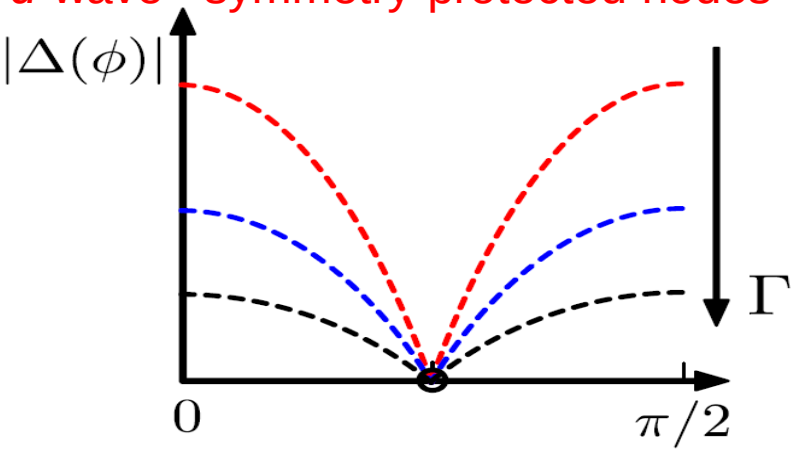
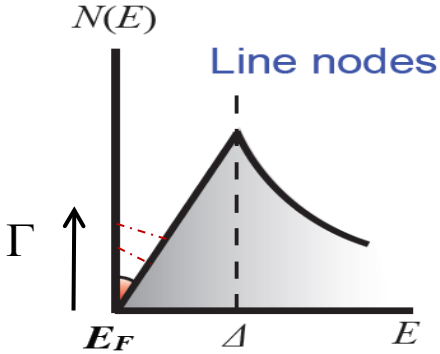
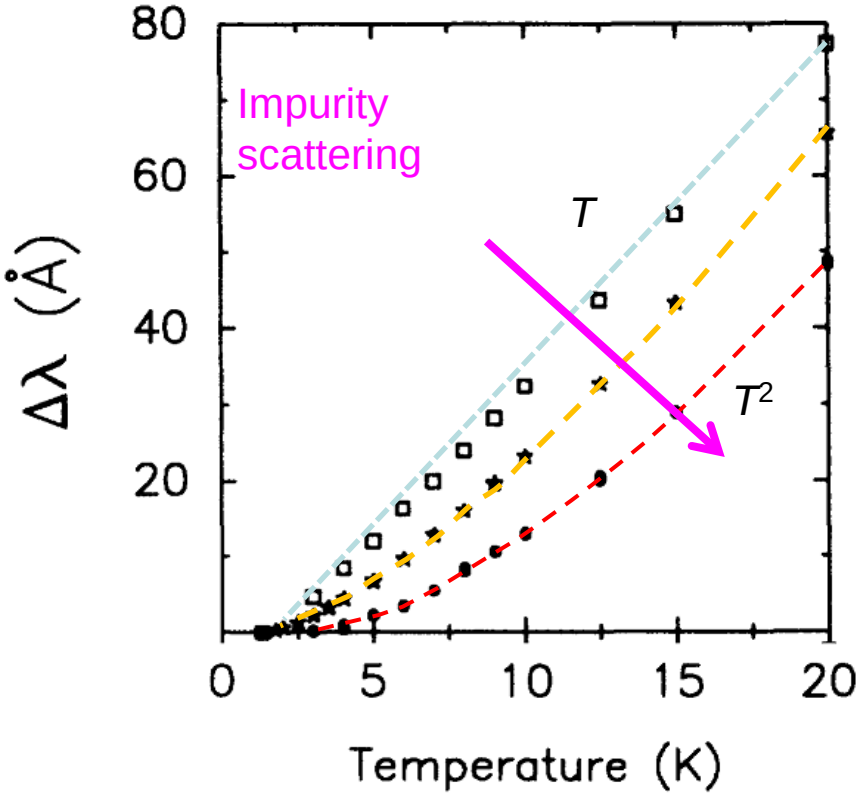


J-Ph Reid *et al.*, Supercond. Sci. Technol. **25**,084013 (2012).

Nodes are robust against disorder



Zn doped $YBa_2Cu_3O_{6.95}$



D. A. Bonn *et al.*, PRB **50**,4051 (1993).
P. J. Hirschfeld and N. Goldenfeld, PRB **48**, 4219 (1993).

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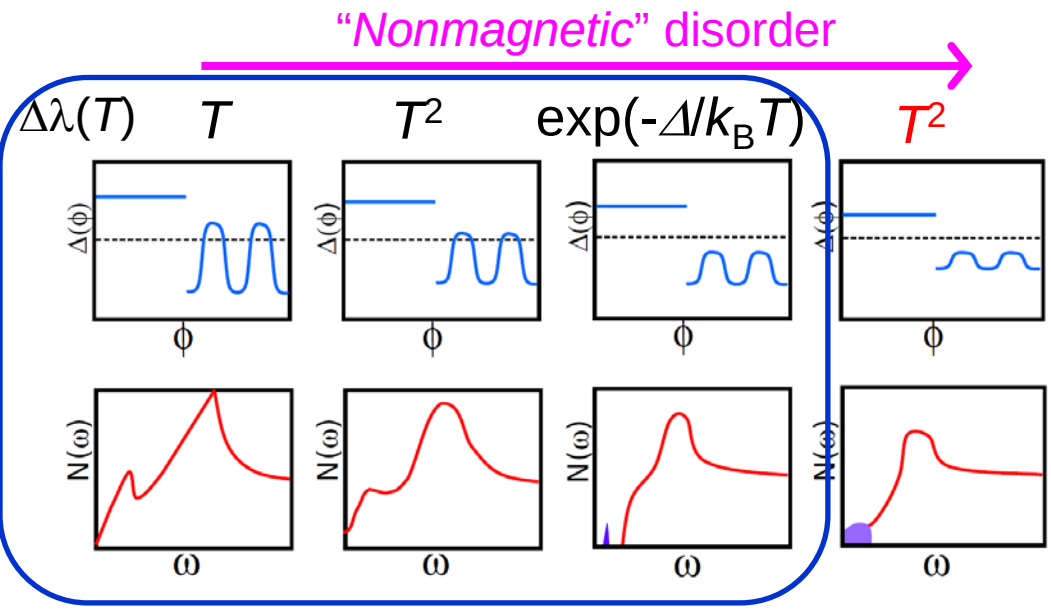
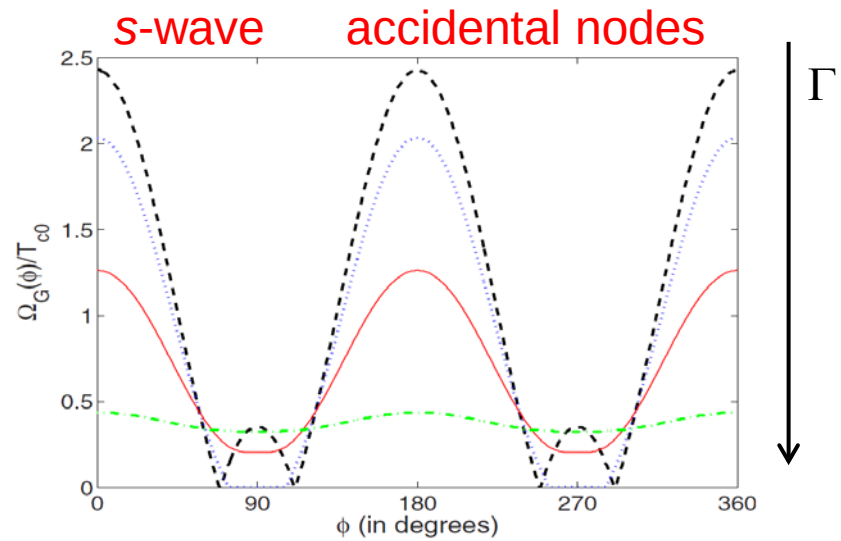
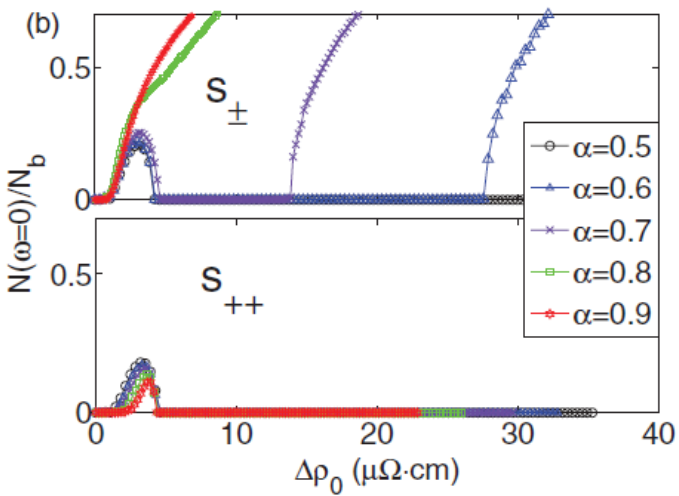




V. Mishra *et al.*, PRB **79**, 094521 (2009).

Nodes can be lifted by disorder

S++



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

Are the nodes accidental or symmetry protected?

Impurity scattering dependence of gap structure can be a powerful probe of symmetry

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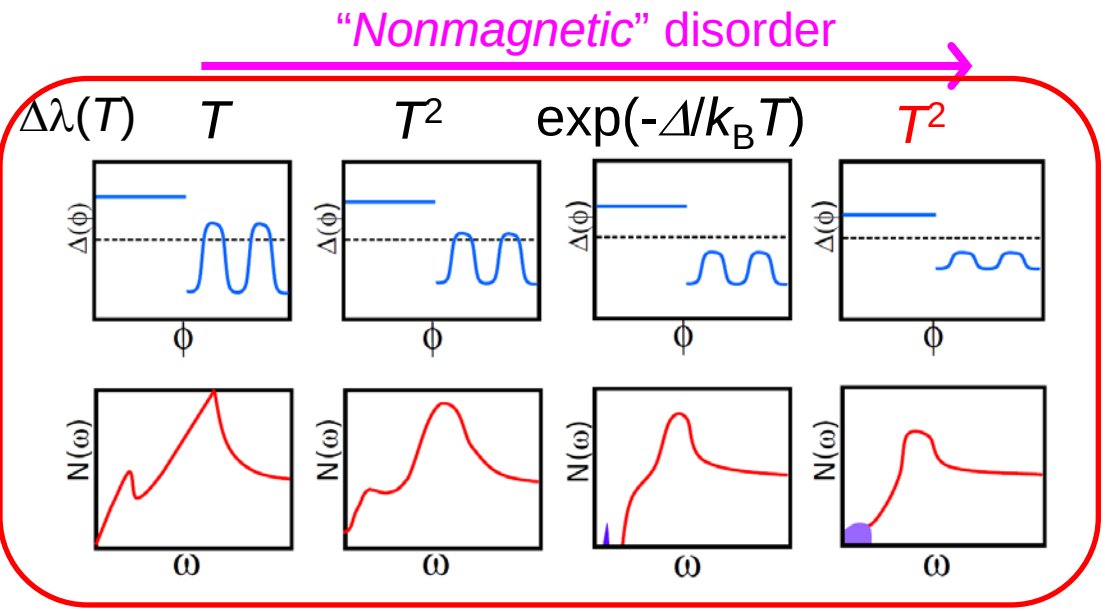
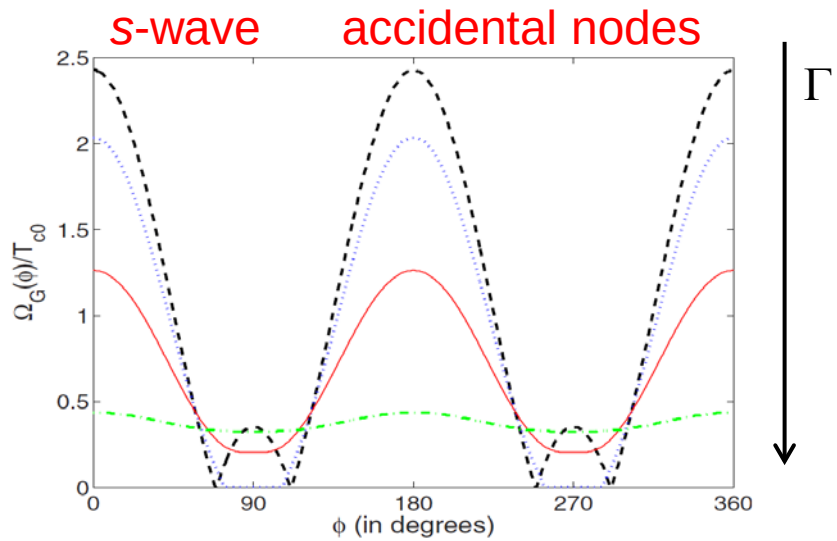
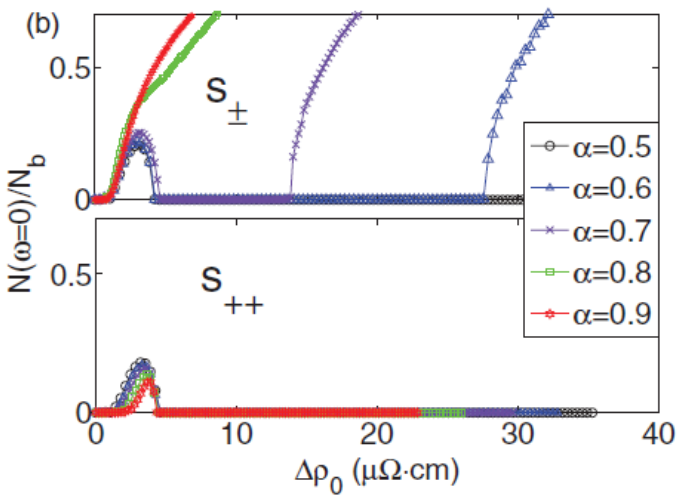




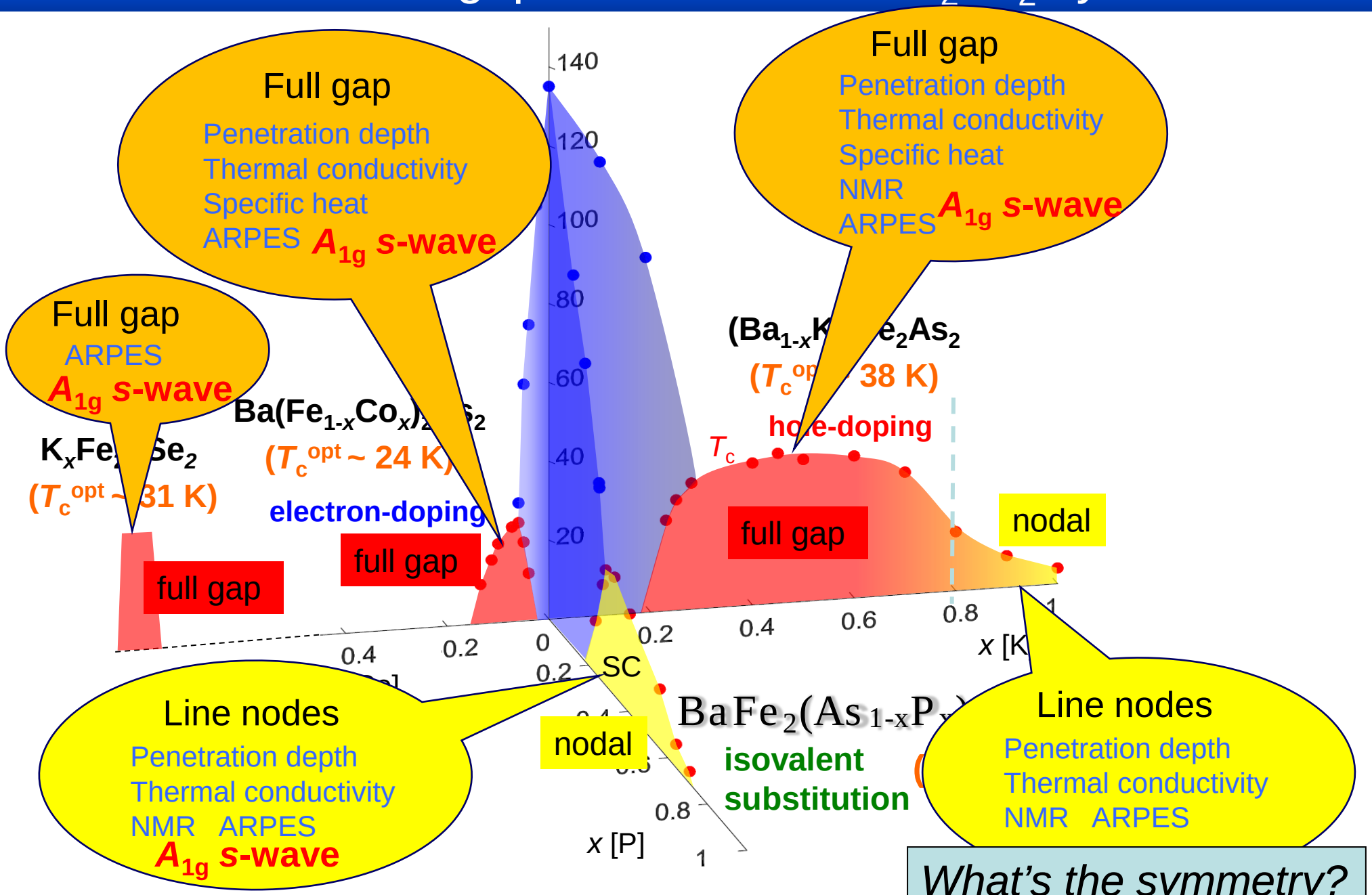
V. Mishra *et al.*, PRB **79**, 094521 (2009).

Nodes can be lifted by disorder



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

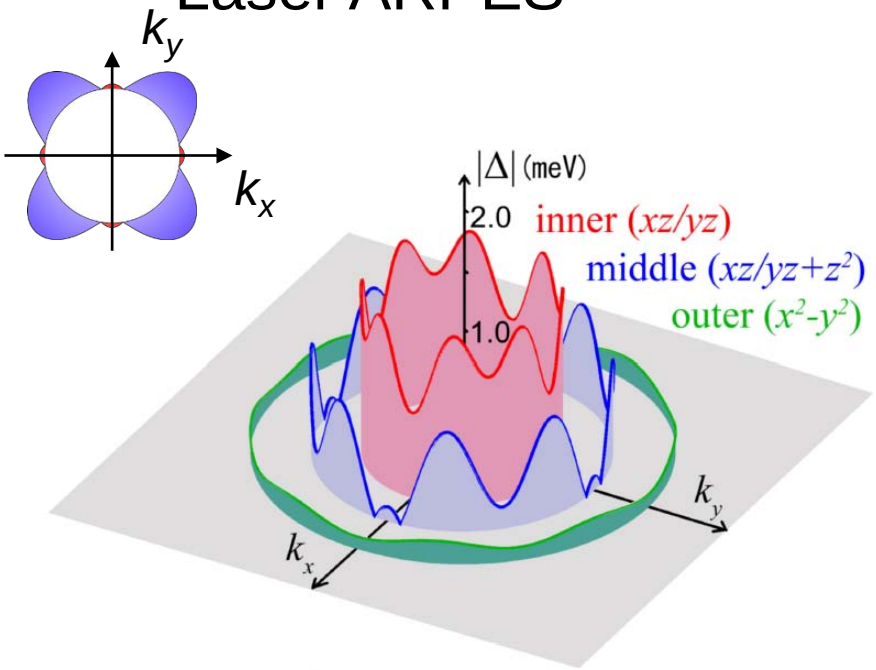
Non-universal gap structure in $BaFe_2As_2$ systems



Gap symmetry in KFe_2As_2

Nodal *s*-wave

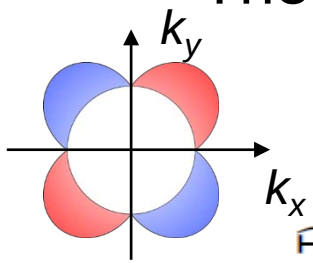
Laser ARPES

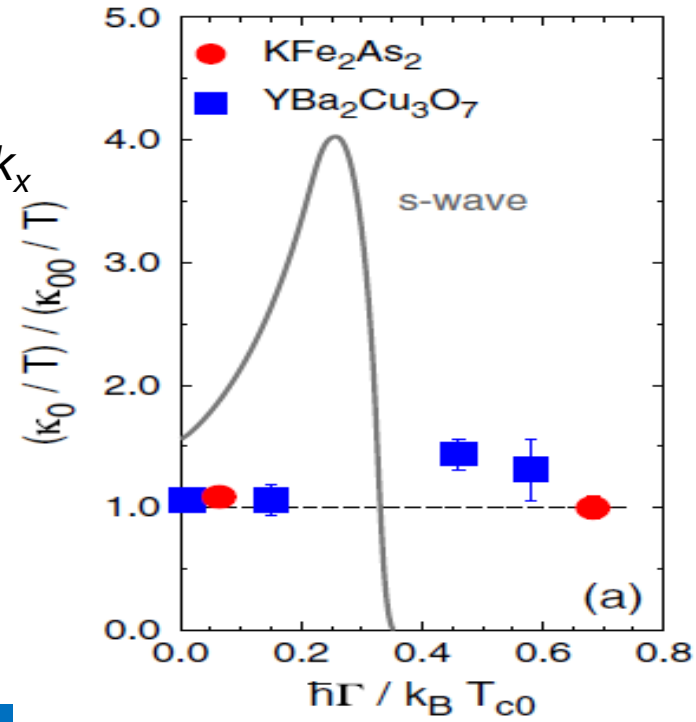


K. Okazaki *et al.*, Science **337**, 1314 (2012).

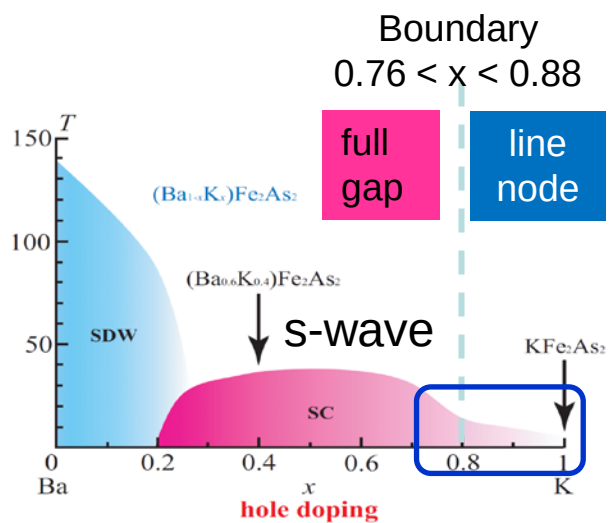
d–wave

Thermal conductivity





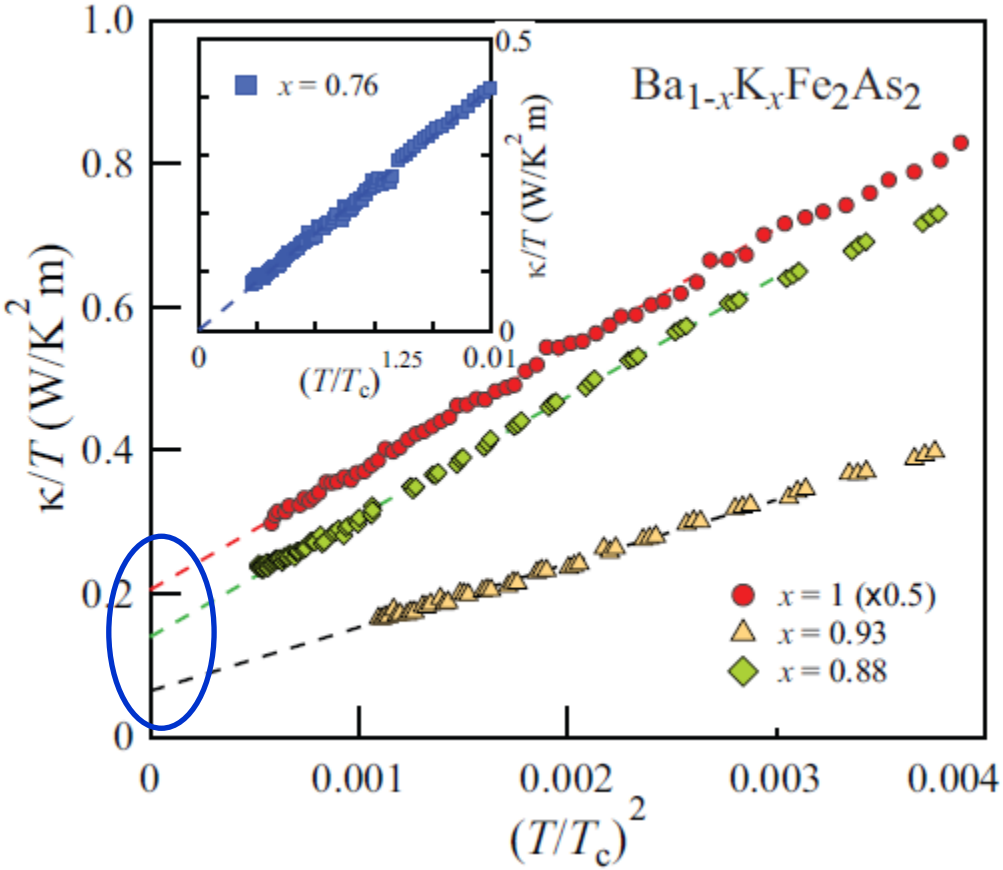
J.-P. Reid *et al.*, PRL **109**, 087001 (2012)



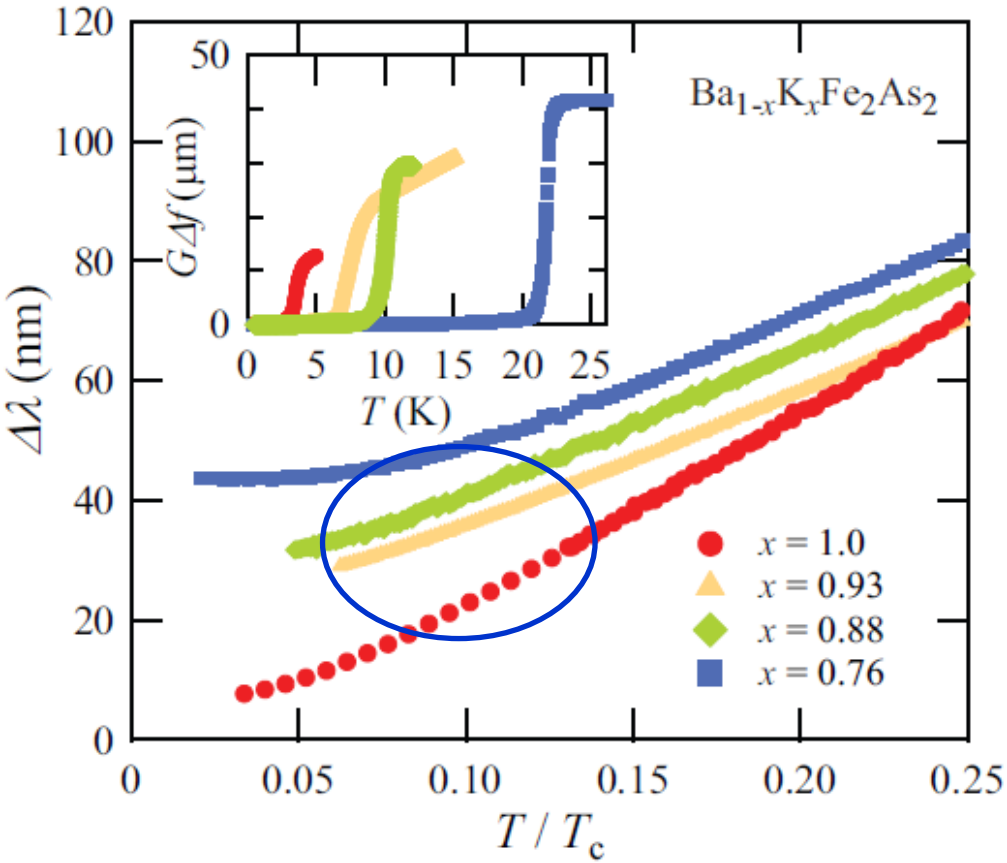
Doping evolution of quasiparticle excitations

Doping evolution of QP excitations in $(Ba,K)Fe_2As_2$

thermal conductivity

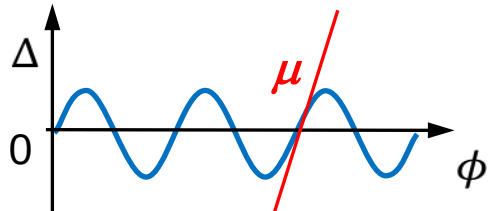


penetration depth

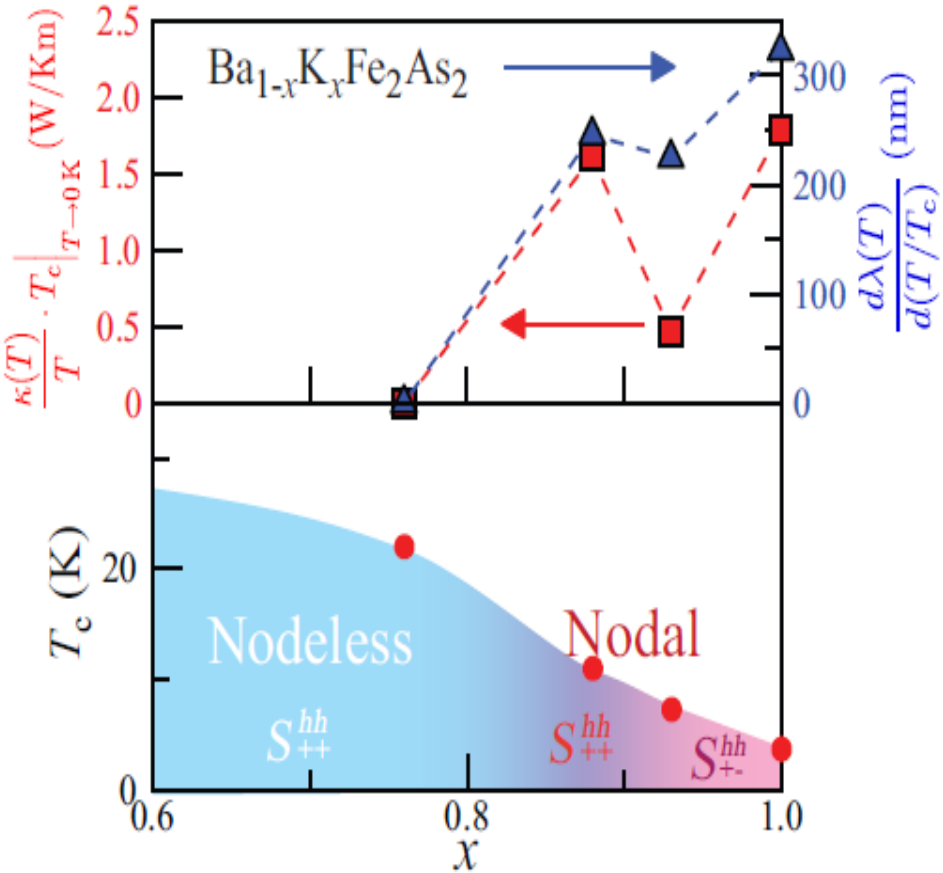


$$(\kappa/T)\cdot T_c|_{T\to 0\,\mathrm{K}} = aN_F v_F^2 \mu^{-1}, \qquad (d\lambda/dT)\cdot T_c \propto \mu^{-1}.$$

$$\mu = \frac{1}{\Delta_0}\left|\frac{d\Delta(\phi)}{d\phi}\right|_{\phi_{node}}$$



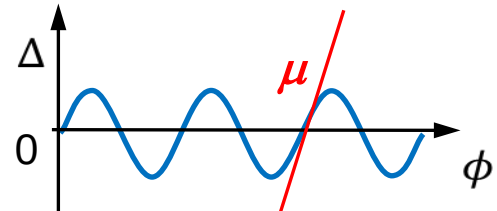
Doping evolution of QP excitations in $(Ba,K)Fe_2As_2$



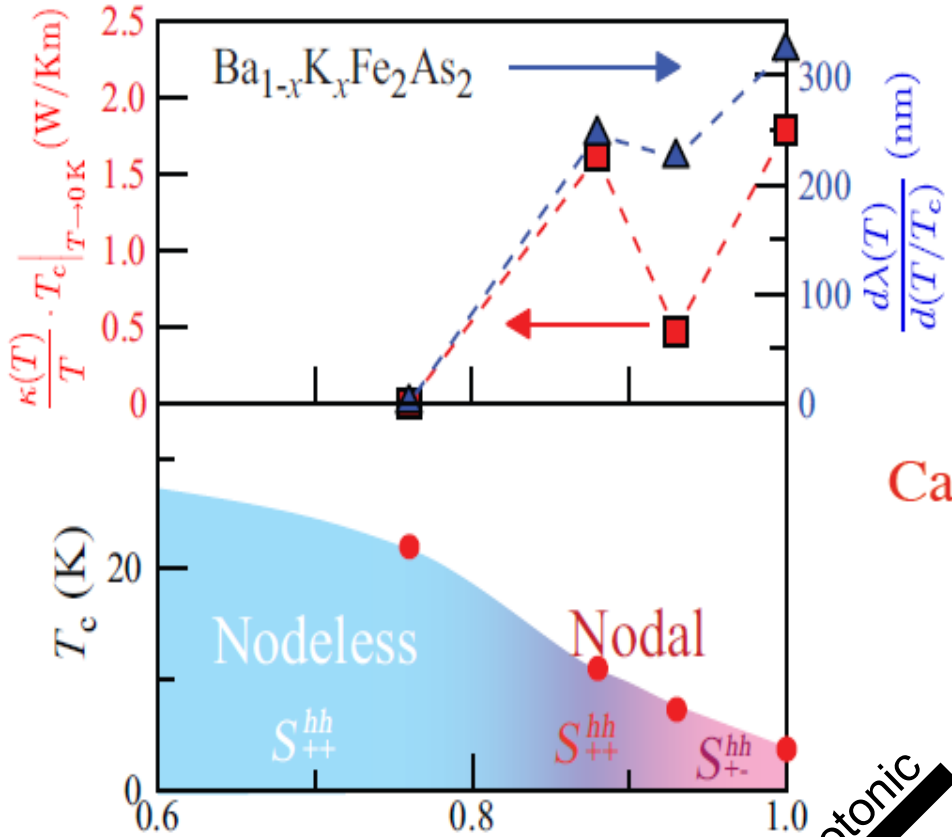
Non-monotonic *x* dependence of QP excitations: Evidence for doping-dependent μ

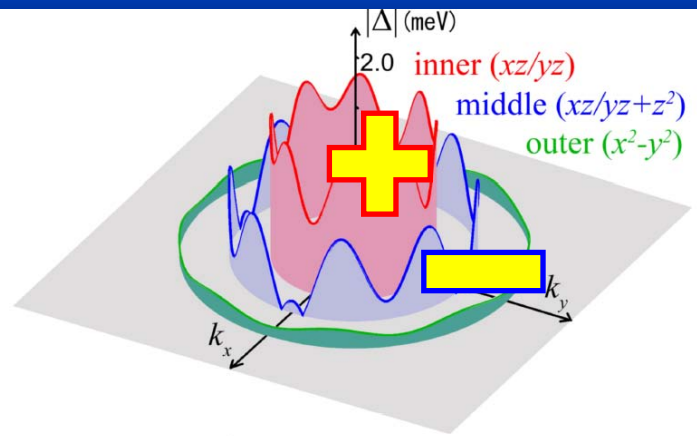
$$(\kappa/T)\cdot T_c|_{T\to 0\,\mathrm{K}} = aN_F v_F^2 \mu^{-1}, \qquad (d\lambda/dT)\cdot T_c \propto \mu^{-1}.$$

$$\mu = \frac{1}{\Delta_0}\left|\frac{d\Delta(\phi)}{d\phi}\right|_{\phi_{node}}$$

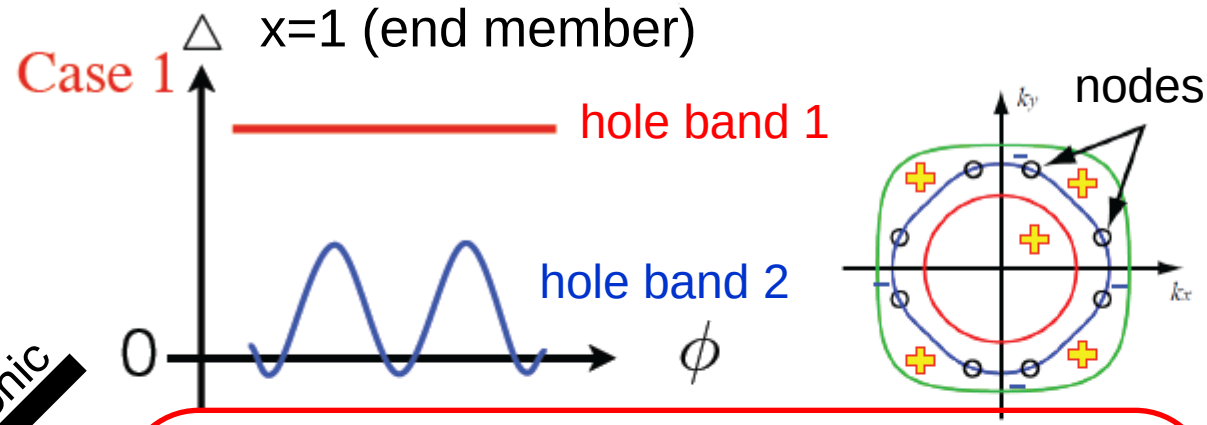


Symmetry in the overdoped $(Ba_{1-x}K_x)Fe_2As_2$ systems



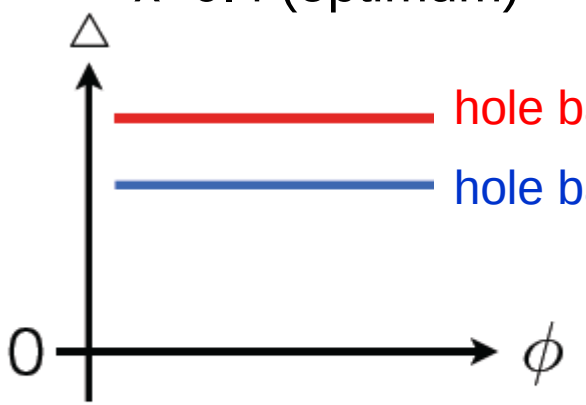


x=1 (end member)

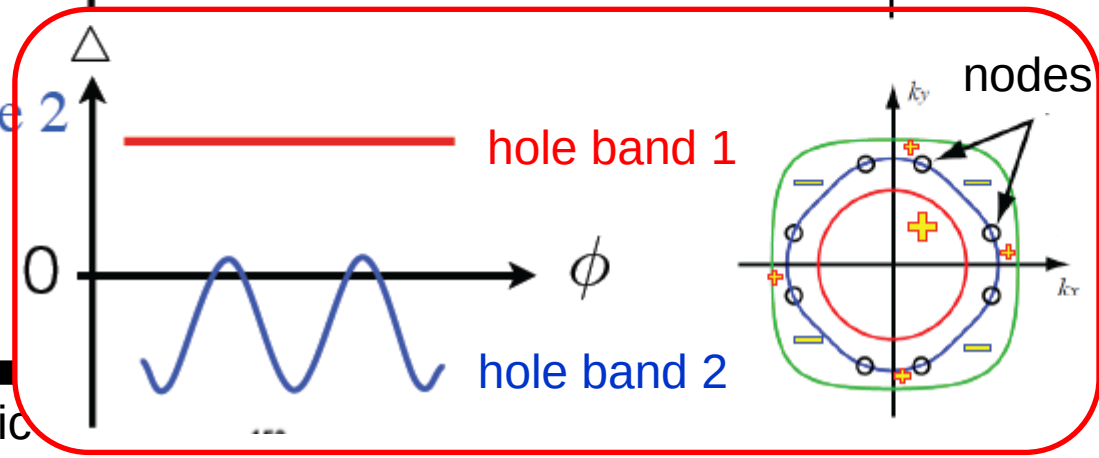


monotonic

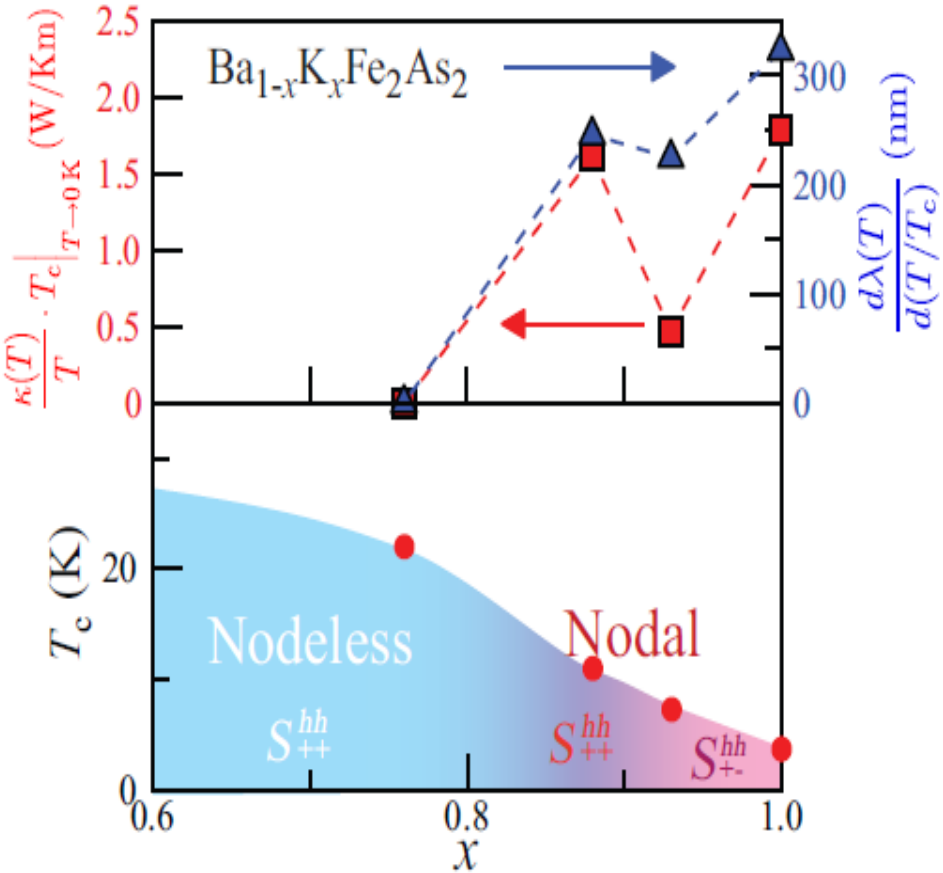
x=0.4 (optimum)

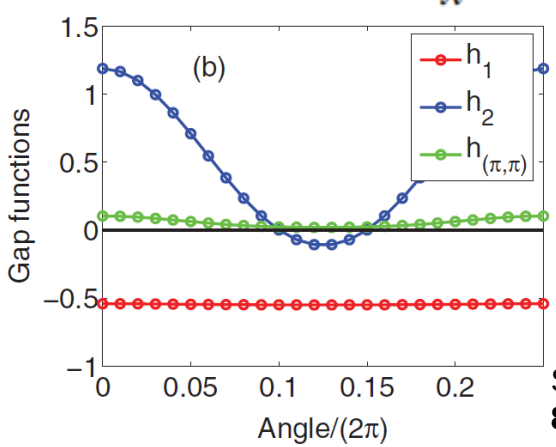


non-monotonic



Doping evolution of QP excitations in $(Ba,K)Fe_2As_2$



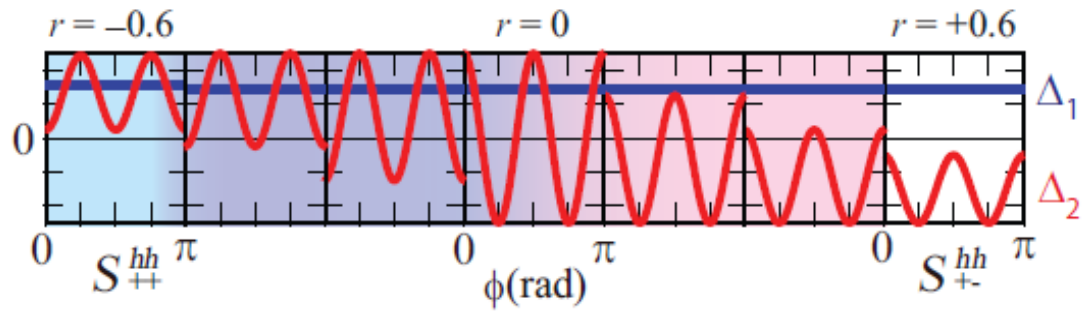


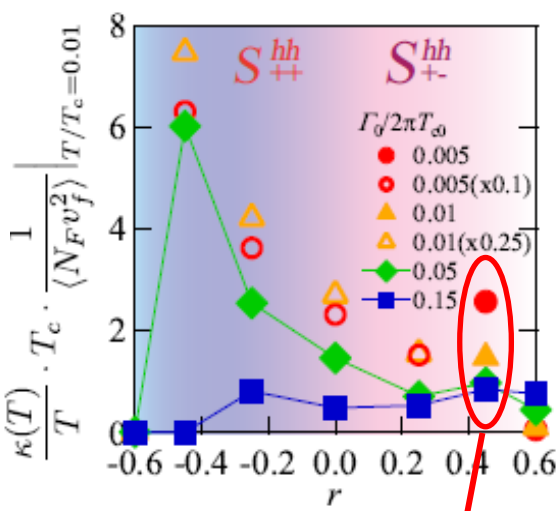
S. Maiti *et al.*, Phys. Rev. B **85**, 014511 (2012).

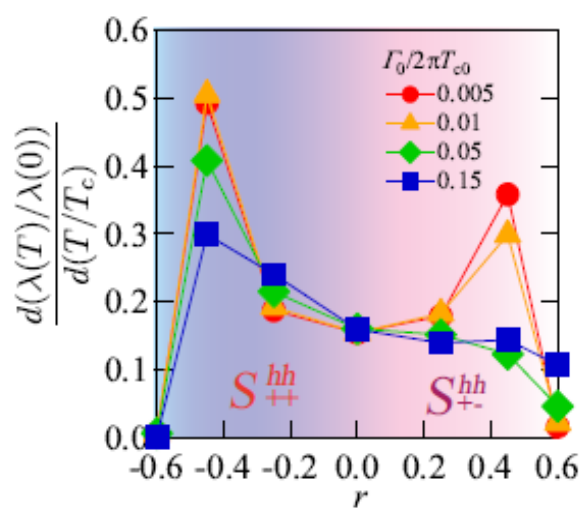
Two-band calculations

A. V. Vorontsov

$$\Delta_1(\phi) = \Delta_{10},$$
$$\Delta_2(\phi) = -\mathrm{sgn}(r)\Delta_{20}\{|r| - (1-|r|)\cos 4\phi\}.$$

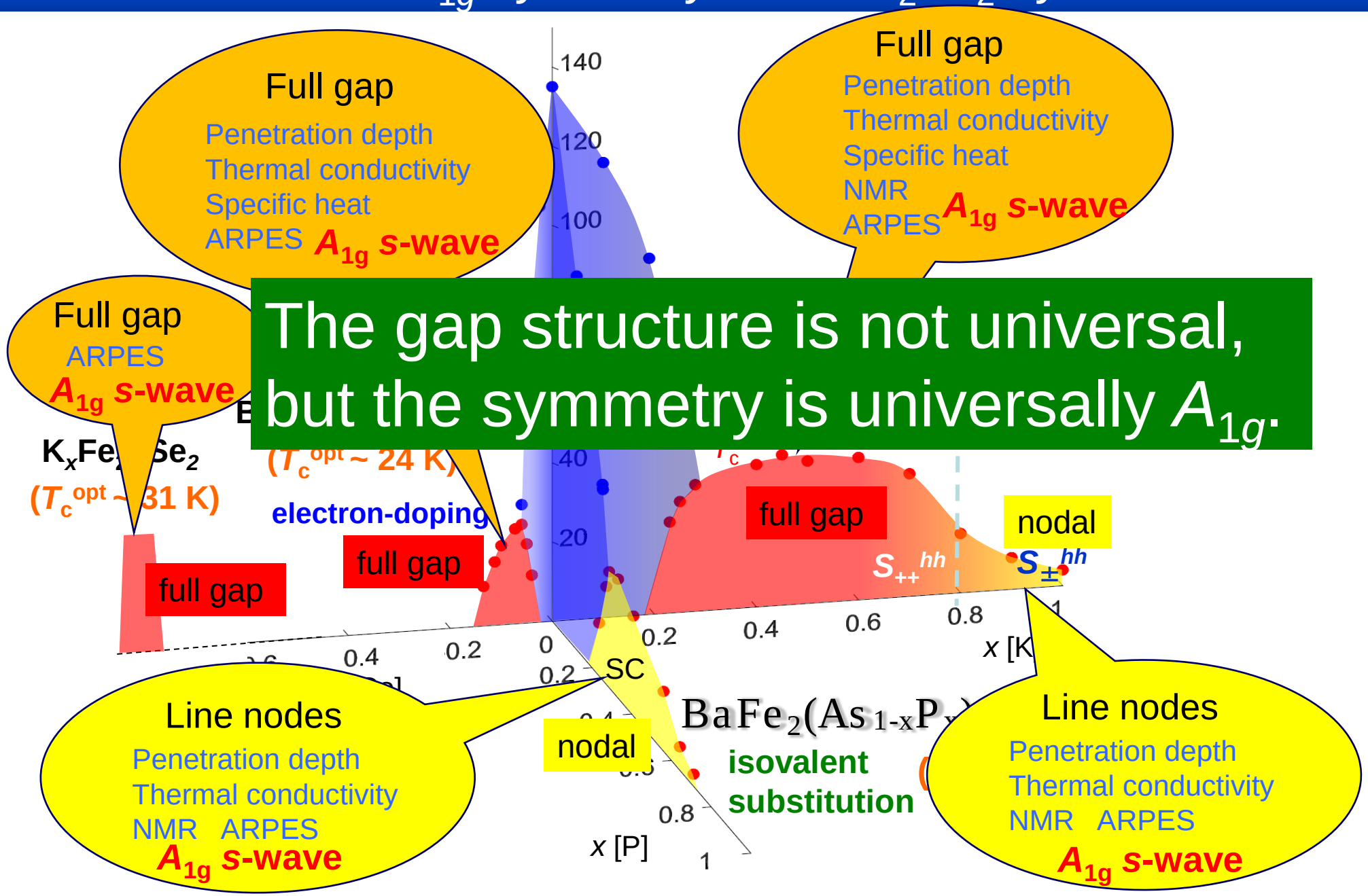






The residual thermal conductivity does not strongly depend on impurity scattering in the $S_{\pm}^{hh}$ side.

Universal A_{1g} symmetry in $BaFe_2As_2$ systems



Summary

1) In $BaFe_2(As,P)_2$ systems, the point disorder introduced by electron irradiation changes the low-energy quasiparticle excitations, providing bulk evidence for lifting accidental nodes by impurity scattering.

2) In overdoped $(Ba,K)Fe_2As_2$ systems, the anomalous non-monotonic doping dependence of low-energy quasiparticle excitations is observed, which can be consistently explained by the continuous change

nodal $s^{hh}_{\pm}$ → nodal s^{hh}_{++} → nodless s^{hh}_{++}

with decreasing hole doping.

3) In $BaFe_2As_2$-based superconductors, the gap structure is non-universal, but the gap symmetry is universally A_{1g}.