Title: Superconducting gap symmetry in iron-pnictide superconductors: a thermal conductivity perspective

Date: Apr 26, 2011 02:30 PM

URL: http://pirsa.org/11040093

Abstract: The nature of the pairing mechanism in the recently discoverediron-pnictide family of superconductors remains an outstanding issue. To answer this question, it is instructive to know the symmetry of the superconducting energy gap. Low temperature thermal conductivity measurements provide a robust test of the presence or absence of low energy electronic quasiparticles that in turn can be used to characterise the symmetry of the gap function. In this talk, I will review what has been learnt so far from such measurements across several families of iron-pnictide superconductors, including our own recent results on the
stoichiometric material LaFePO.

Superconducting Gap Symmetry in Iron-based Superconductors: A Thermal Conductivity Perspective

Robert W. Hill

UNIVERSITY OF WATERLOO

uwaterloo.ca

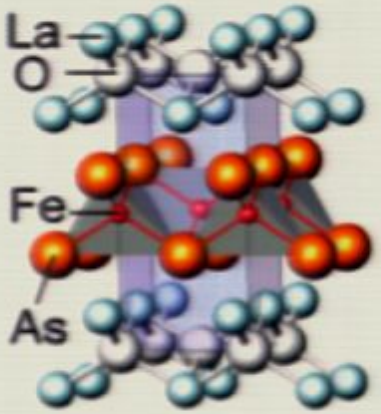
Acknowledgements

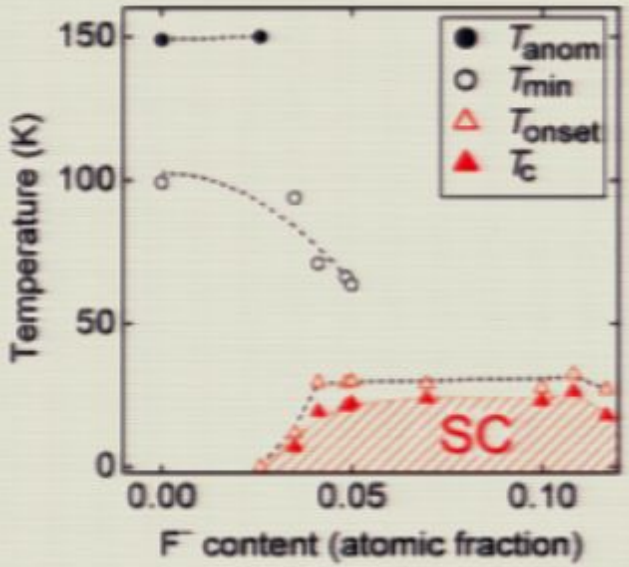
- Michael Sutherland (Cambridge)
- James Analytis (Stanford)
- Ian Fisher (Stanford)
- John Dunn (Waterloo, Oxford)
- Issam Alkhesho (Waterloo)
- William Toews (Waterloo)

UNIVERSITY OF WATERLOO

Iron-based Superconductors

- February 2008: Hosono and co-workers, superconductivity in LaFeAs(O,F), Tc~26 K

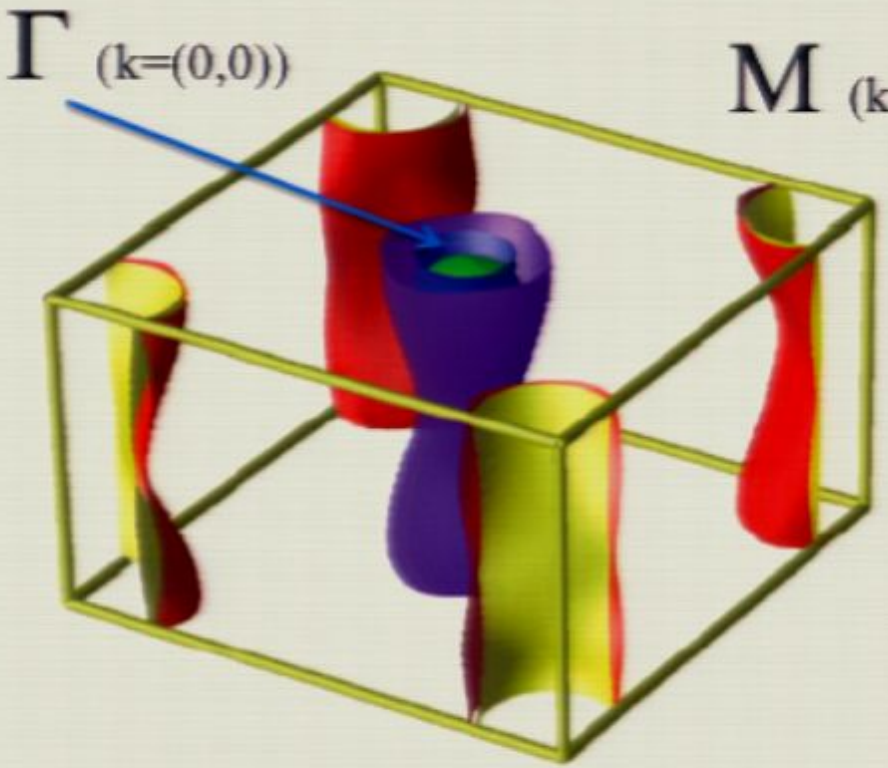




J. AM. CHEM. SOC. 2008, **130**, 3296-3297

UNIVERSITY OF WATERLOO

Fermi Surface



Bands crossing Fermi-level are derived from Fe *d*-orbitals

Four quasi-2D electron and hole cylinders:

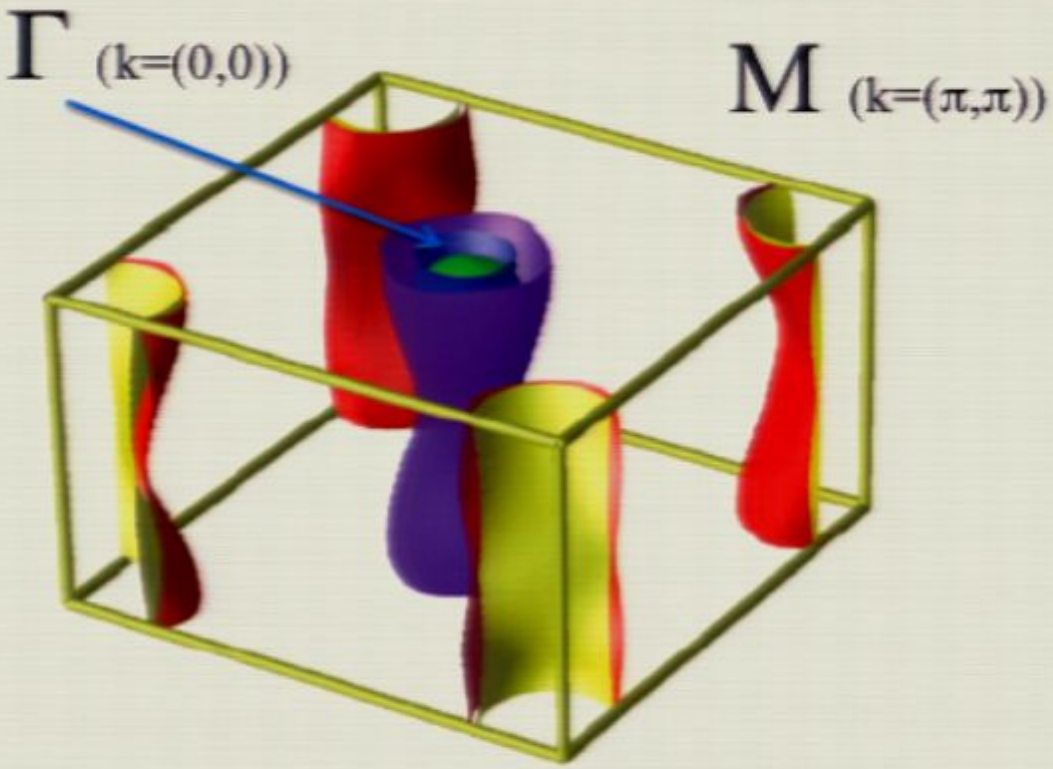
Two hole FS at Γ

Two electron FS at M

Mazin, I. I. & Schmalian, J. Physica C **469**, 614623 (2009)

UNIVERSITY OF WATERLOO

Fermi Surface



Bands crossing Fermi-level are derived from Fe *d*-orbitals

Four quasi-2D electron and hole cylinders:

Two hole FS at Γ

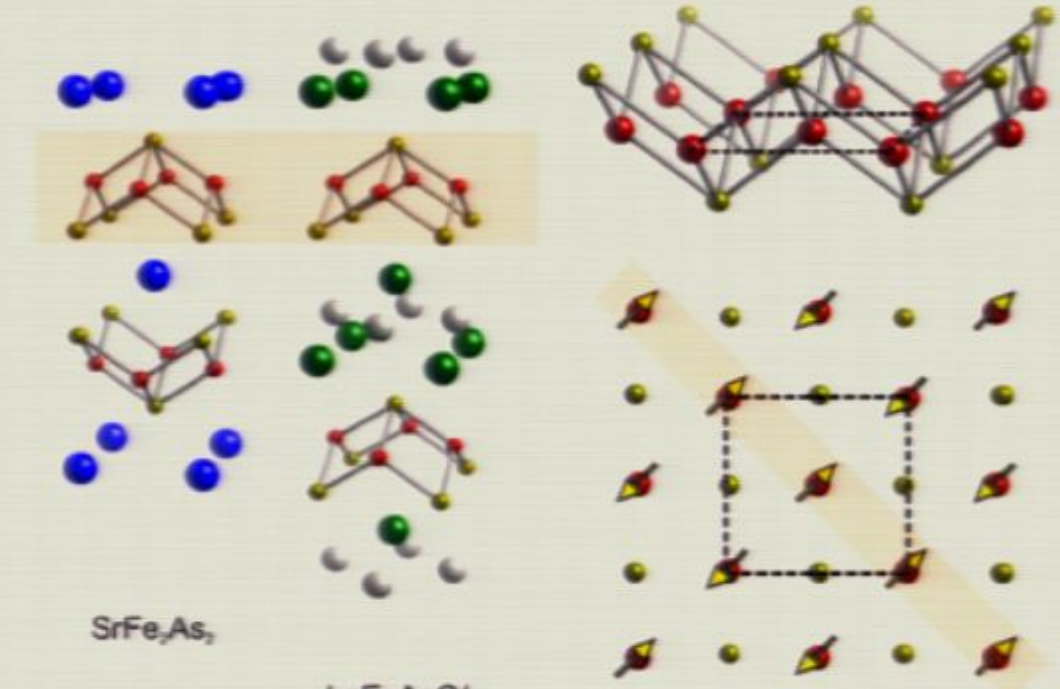
Two electron FS at M

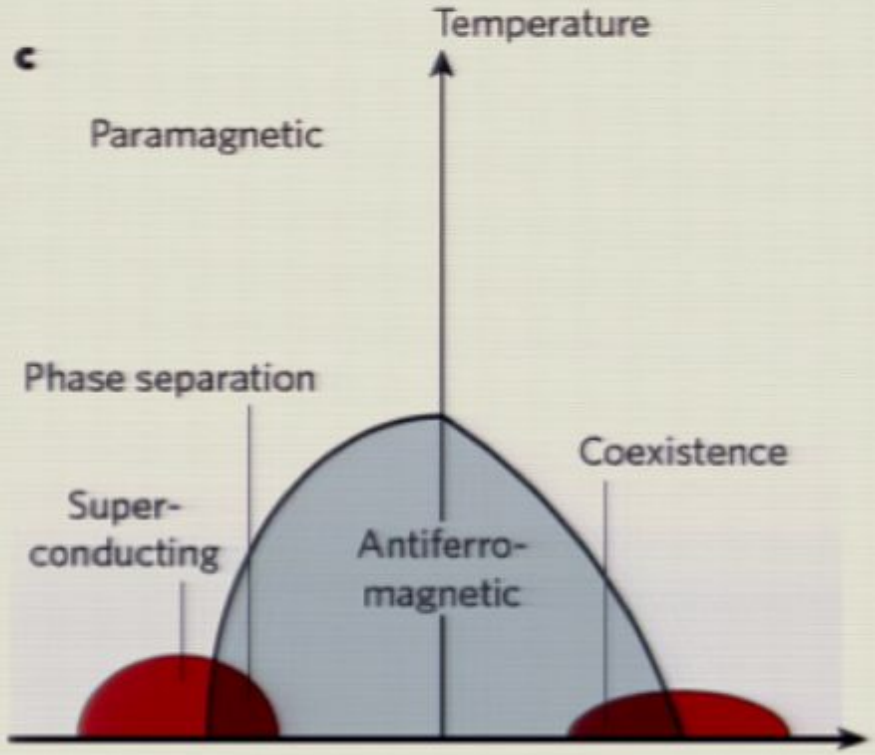
Mazin, I. I. & Schmalian, J. Physica C **469**, 614623 (2009)

UNIVERSITY OF WATERLOO

Iron-based Superconductors

Paglione and Greene, Nat. Phys. **6**, 645 (2010)

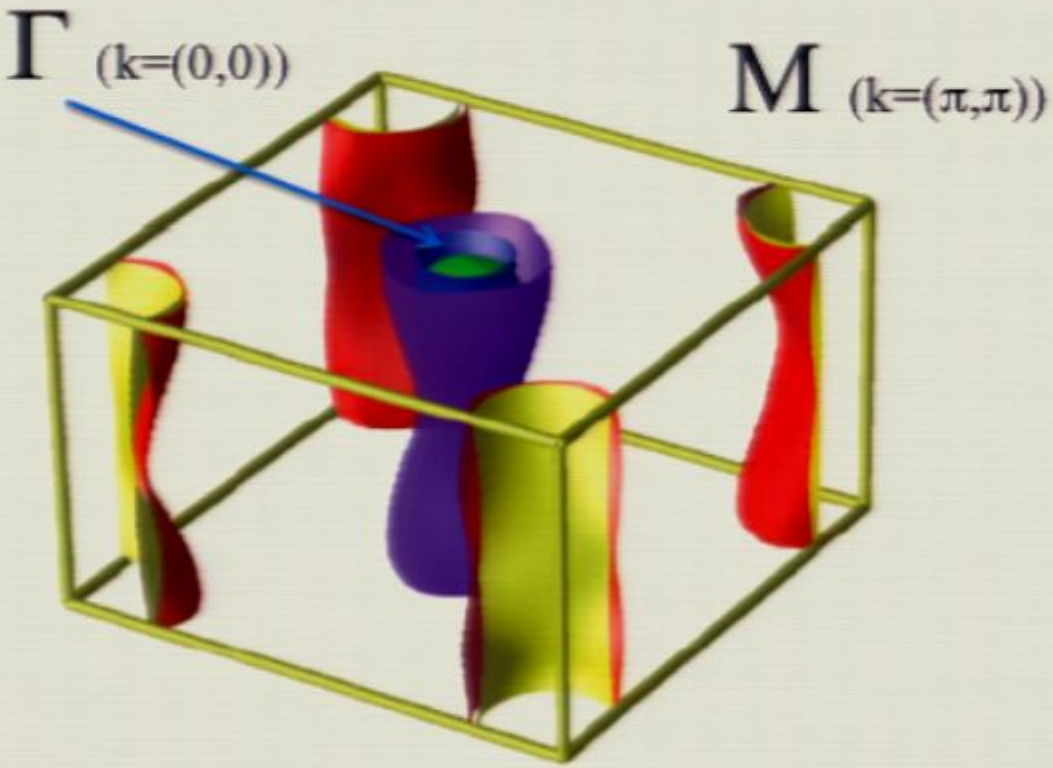




Mazin, Nature, **464**, 183 (2010)

UNIVERSITY OF WATERLOO

Fermi Surface



Bands crossing Fermi-level are derived from Fe *d*-orbitals

Four quasi-2D electron and hole cylinders:

Two hole FS at Γ

Two electron FS at M

Mazin, I. I. & Schmalian, J. Physica C **469**, 614623 (2009)

UNIVERSITY OF WATERLOO

Superconductivity

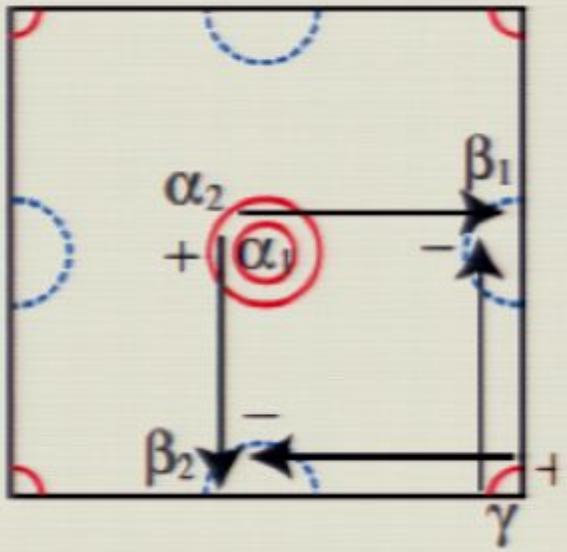
- Pairing is singlet – NMR (Knight shift) measurements

  Grafe, et al., Phys. Rev. Lett. 101, 047003 (2008).

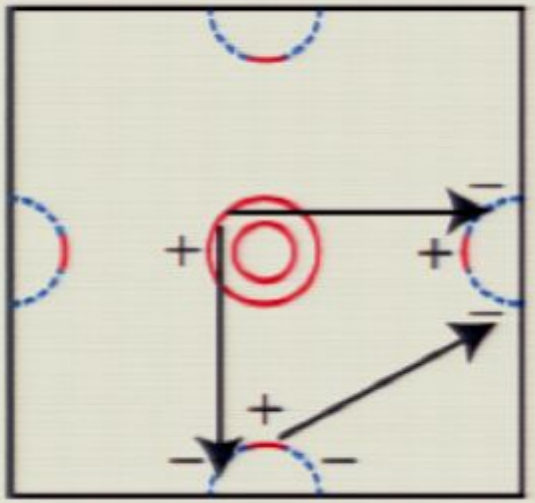
- Pairing through phonons unlikely because of weak electron-phonon interaction

  L. Boeri et al. Phys. Rev. Lett. **101**, 026403 (2008)

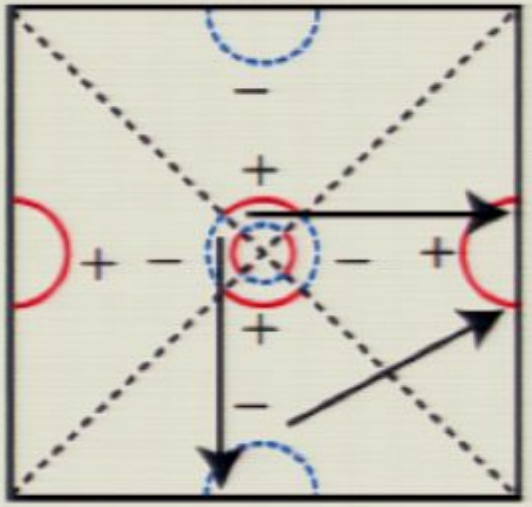
fully gapped $s\pm$wave



nodal $s\pm$wave



d-wave



Kuriki *et al*. Phys. Rev. B **79**, 224511 (2009)

Thermal conductivity in superconducting state

$$\kappa = \kappa_{electrons} + \kappa_{phonons}$$

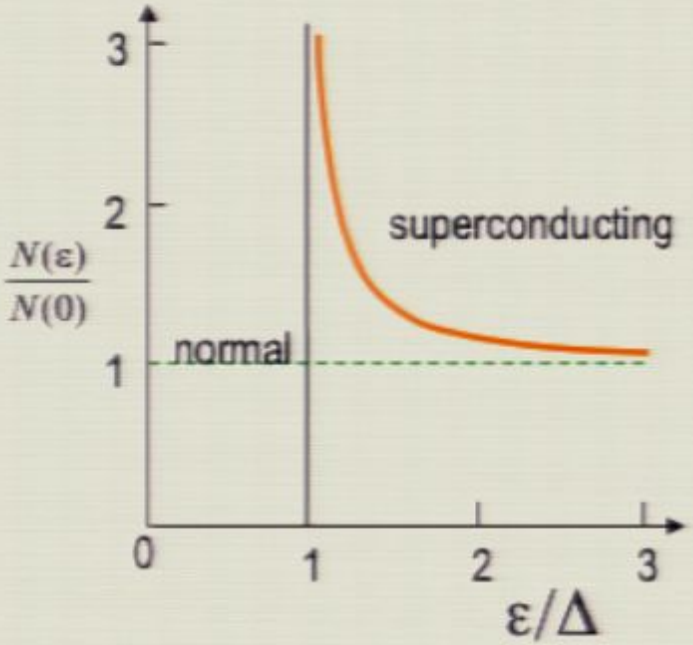
Separate contributions using temperature dependence in low temperature limit

Kinetic theory formulation: $\kappa = \frac{1}{3} c v l$

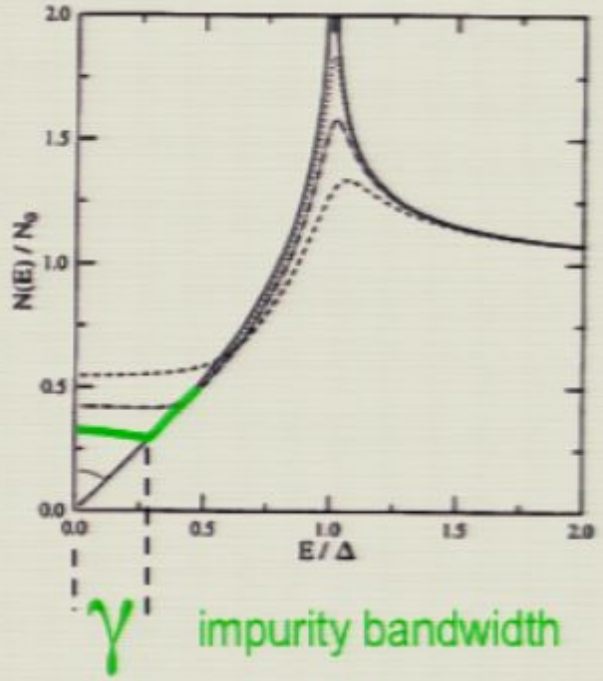
Phonons: $\kappa_{ph} = \frac{1}{3} \beta T^3 v_s l_0^{ph}$

Thermal conductivity: Nodal or fully-gapped?

s-wave – fully gapped



d-wave – nodal

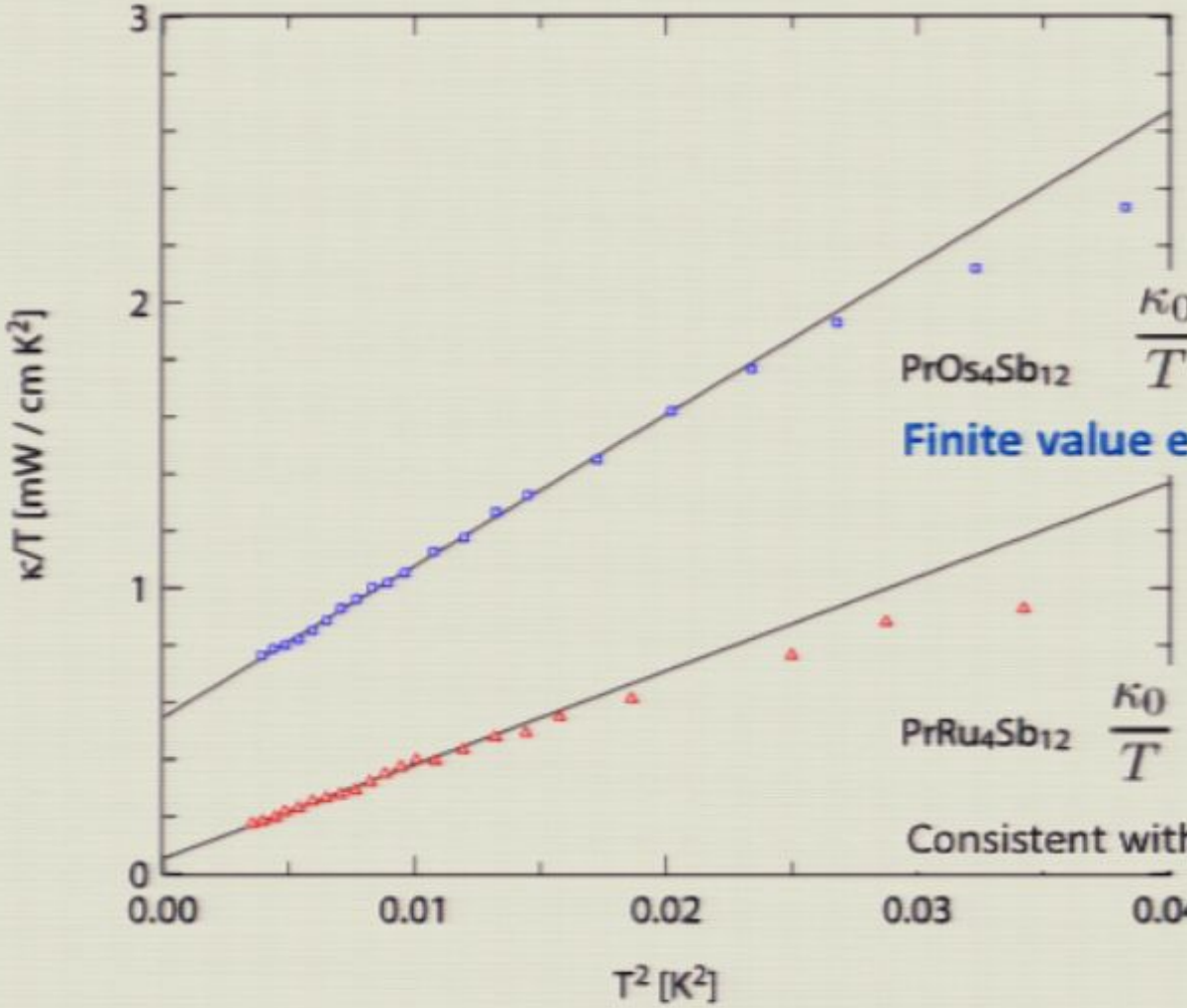


- activated behaviour at low T
- $\frac{\kappa_0}{T} \to 0$ as $T \to 0\,\mathrm{K}$

- $\kappa_e = \frac{1}{3}\gamma T v_F l_0^e$
- finite $\frac{\kappa_0}{T}$ → nodes

UNIVERSITY OF WATERLOO

Example: filled-skutterudite materials



$PrOs_4Sb_{12}$ $\frac{\kappa_0}{T} = 0.46 \pm 0.07$ mW/K^{2}cm

Finite value establishes presence of nodes

$PrRu_4Sb_{12}$ $\frac{\kappa_0}{T} = 0.058 \pm 0.007$ mW/K^{2}cm

Consistent with fully gapped superconducting state

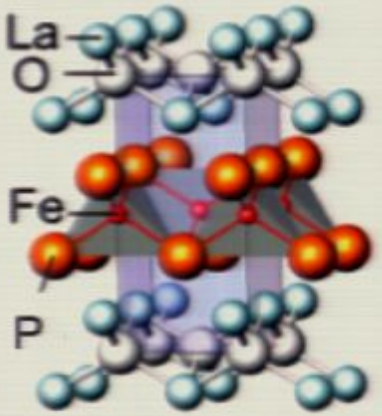
UNIVERSITY OF WATERLOO

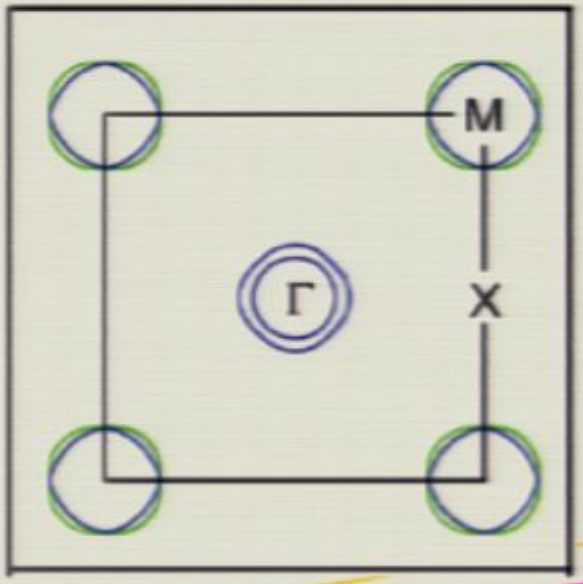
Hill et al., Phys. Rev. Lett. **101**, 237005 (2008)

LaFePO (1111 family)

- Stoichiometric superconductor, T_c = 7 K, non-magnetic groundstate
- Isostructural to LaFeAsO, non-superconducting (dope with F to get T_c~26 K)
- FS established from dHvA and ARPES
- Anisotropy in transport measurements ~ 15-20

- Single crystal sample
- RRR 85
- Small sample (100 x 75 x 25) μm^3
- Contacts made using evaporated gold pads

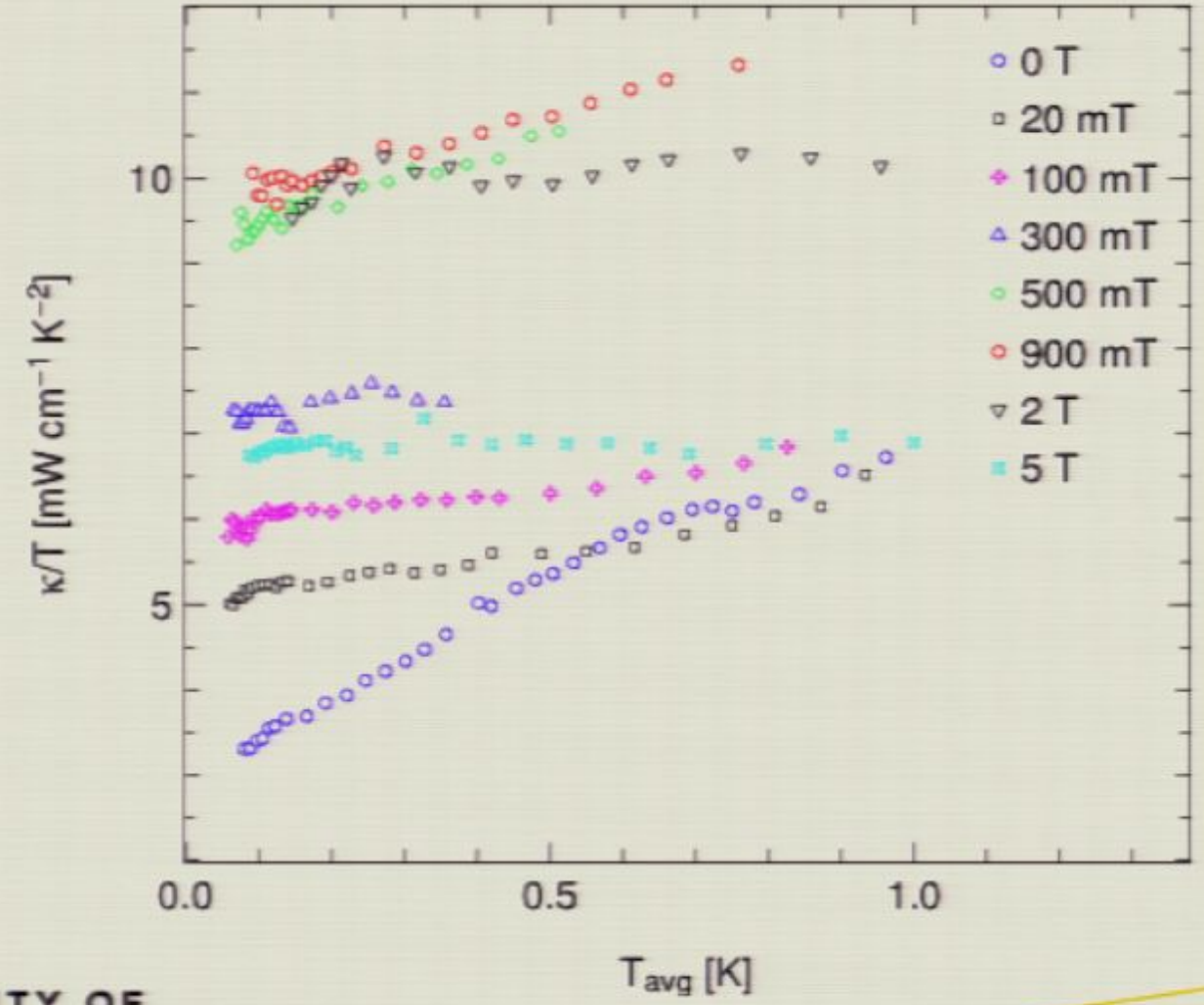




UNIVERSITY OF WATERLOO

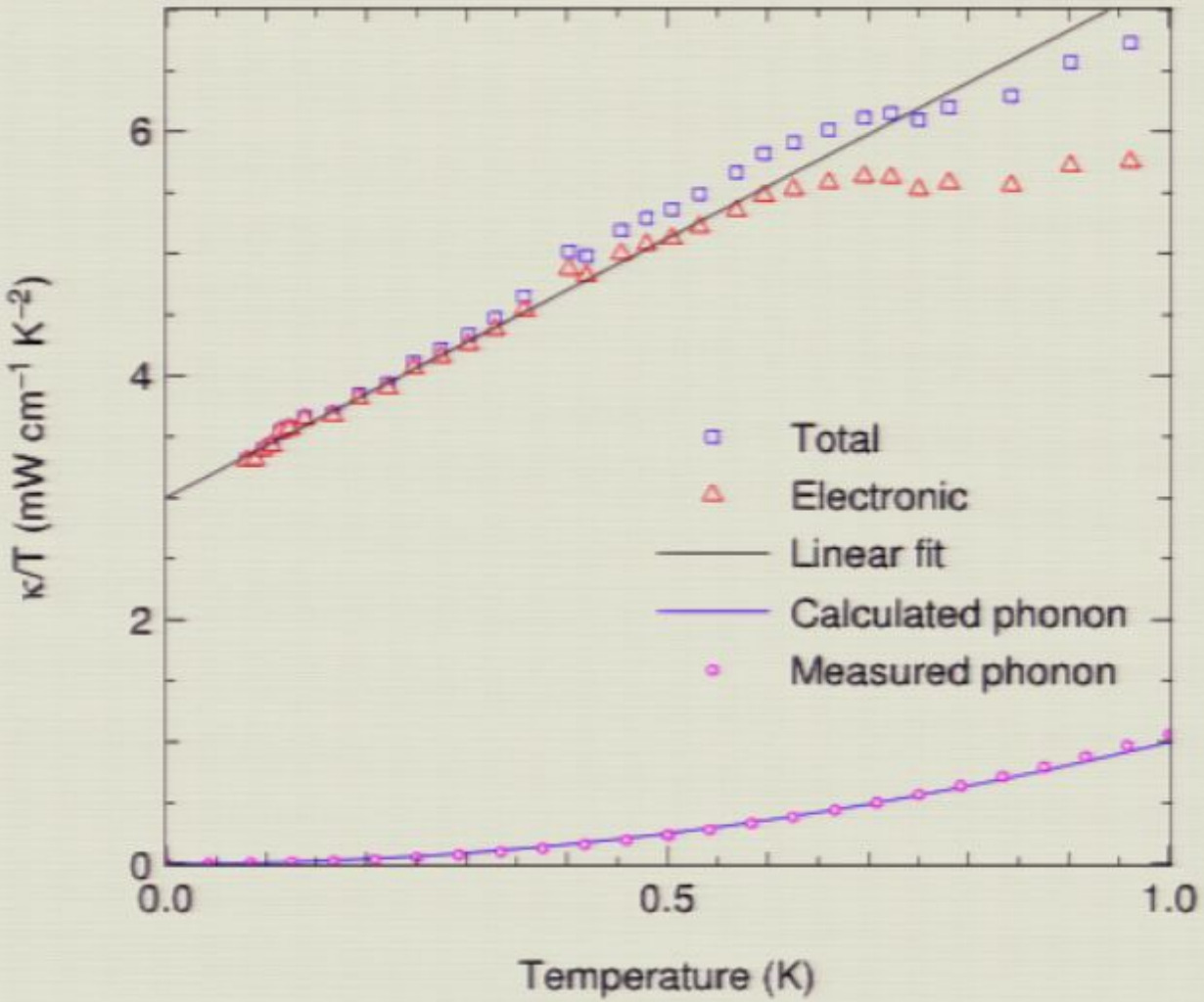
Carrington et al., Physica C **469** (2009) 459–468

LaFePO: Thermal conductivity



UNIVERSITY OF WATERLOO

LaFePO: Thermal conductivity



Phonons

$$\frac{\kappa_{ph}}{T} = \frac{\kappa(20\ \mathrm{mT})}{T} - \frac{\kappa_0(20\ \mathrm{mT})}{T}$$

$$\kappa_{ph} = \frac{1}{3}\beta T^3 v_s l_{ph}$$

$= 1.2\ \mathrm{T}^3$ mW/Kcm (fitted)

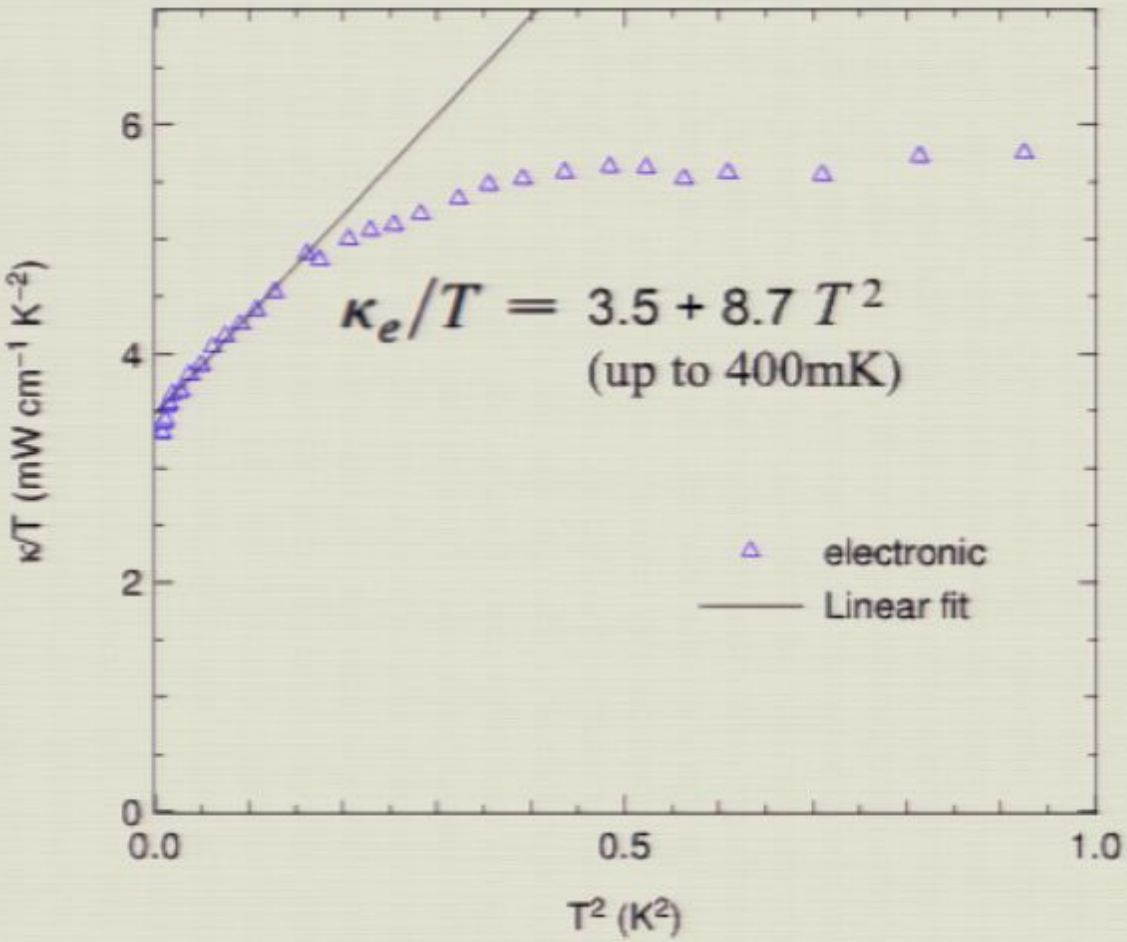
$= 1.0\ \mathrm{T}^3$ mW/Kcm (spec. heat

Electrons

$$\frac{\kappa_e}{T} = \frac{\kappa_{total}(H=0)}{T} - \frac{\kappa_{ph}}{T}$$

UNIVERSITY OF WATERLOO

LaFePO: *d*-wave?



Quasiclassical *d*-wave theory

Graf, Yip, Sauls and Rainer, PRB, **53**, 15147 (1996)

$$\frac{\kappa_e}{T}(T) = \frac{\kappa_{00}}{T}\left[1 + \frac{7\pi^2}{15}\left(\frac{a^2 T}{\gamma}\right)^2\right]$$

Universal linear term

$$\frac{\kappa_0}{T} = \left(\frac{4}{\pi}\frac{\hbar\Gamma}{\Delta_0}\frac{1}{\mu}\right)\frac{\kappa_n}{T}$$

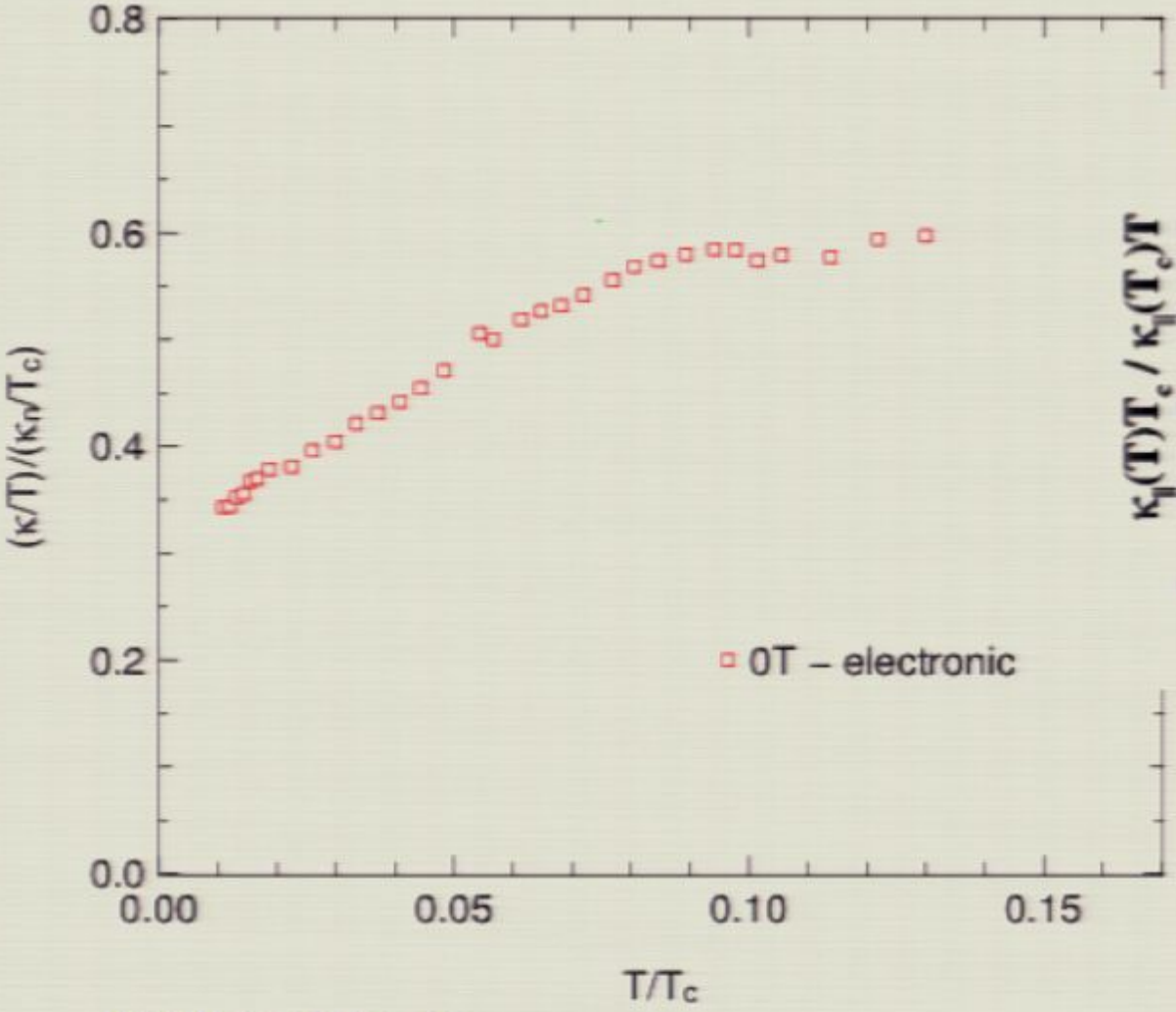
$= 2.9$ mW/K²cm

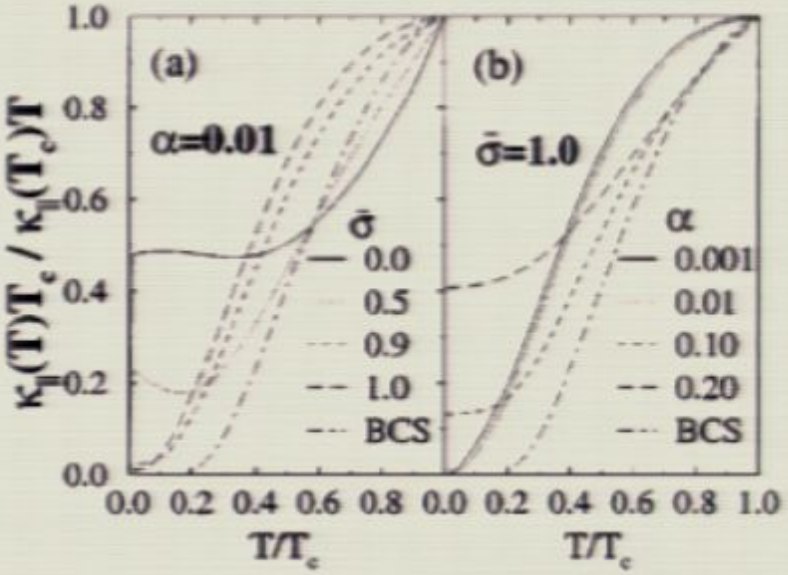
Use spec. heat: C/T = 10.6 mJ/K mol

Kohama et al. JPSJ **77** 094715 (2008)

UNIVERSITY OF WATERLOO

LaFePO: *d*-wave?

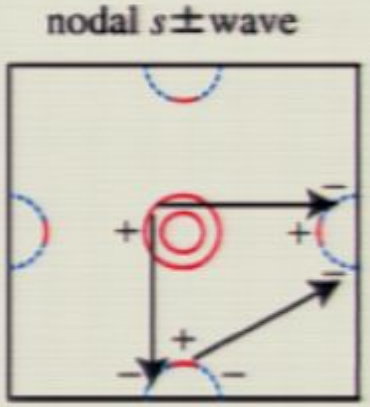




Graf, Yip, Sauls and Rainer
PRB, **53**, 15147 (1996)

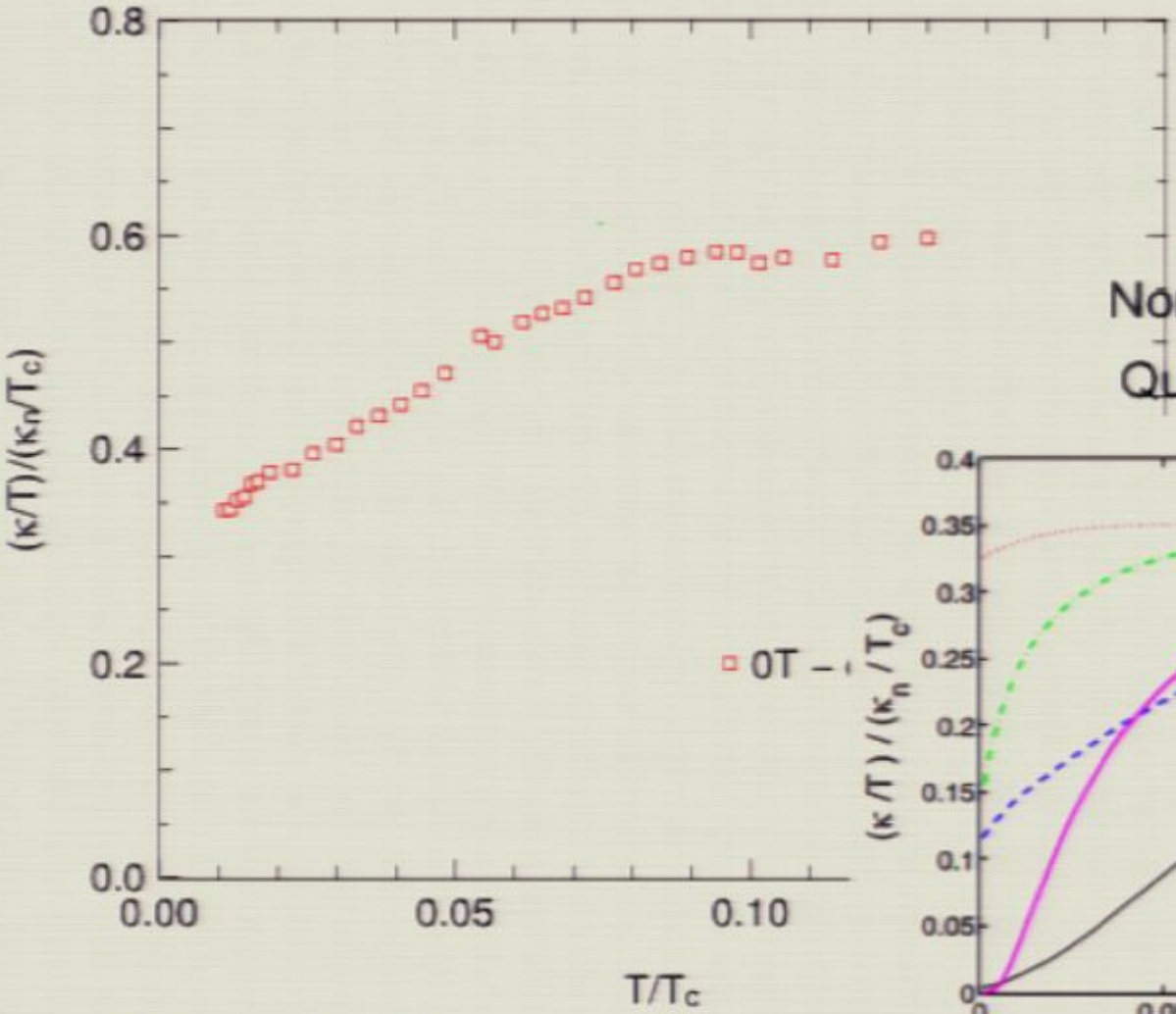
UNIVERSITY OF WATERLOO

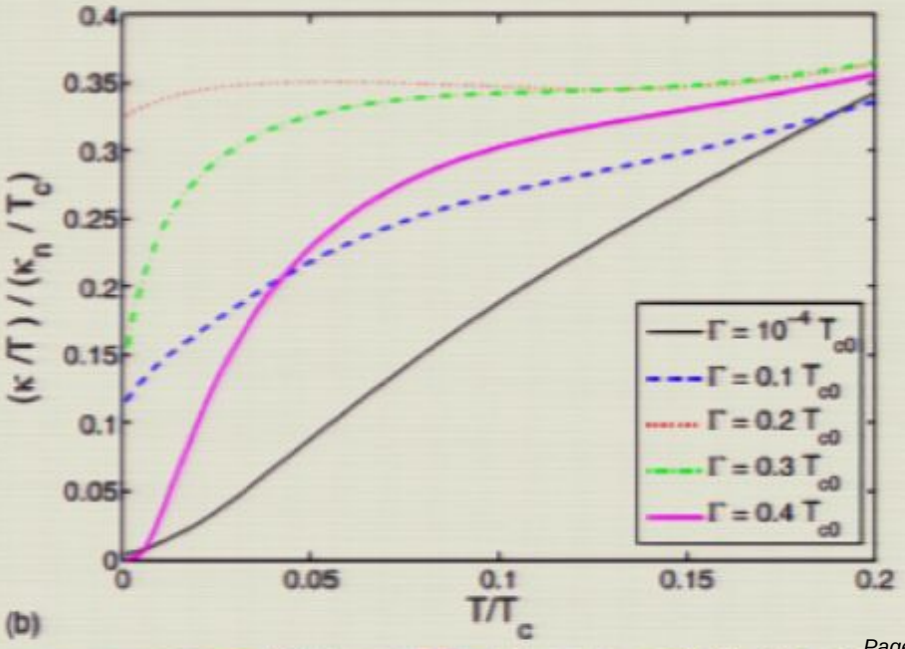
LaFePO: Nodal s+/- wave?



Non-universal linear term

Qualitatively similar T dependence



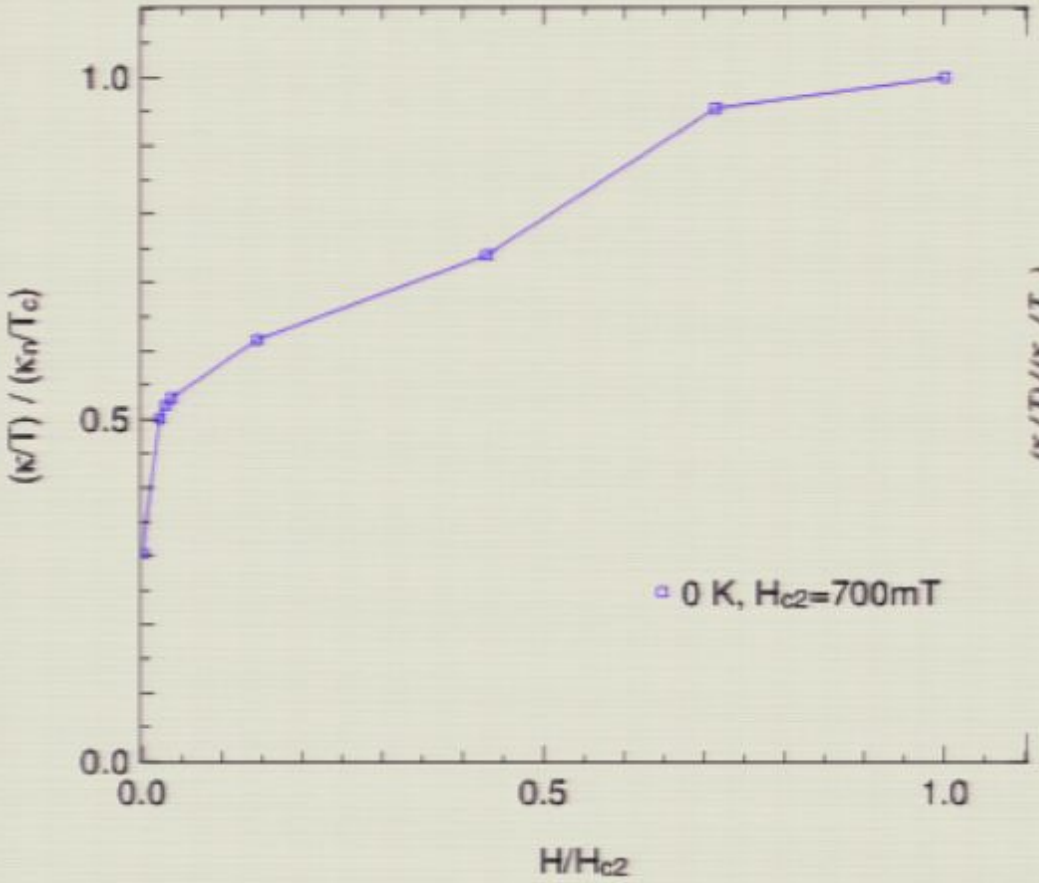


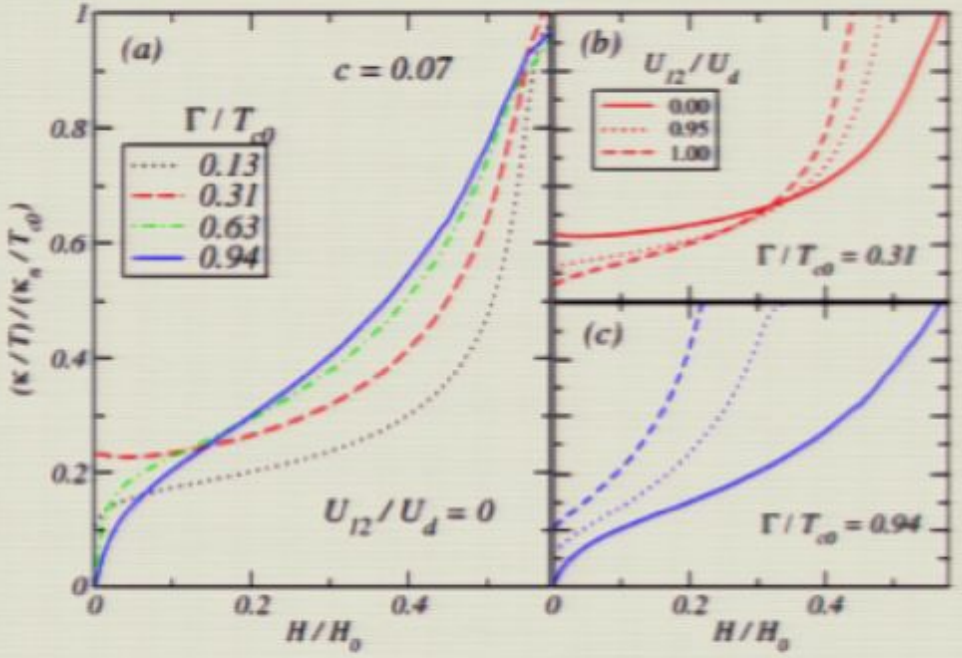
(b)

UNIVERSITY OF WATERLOO

Mishra, et al., Phys. Rev. B **80**, 224525 (2009)

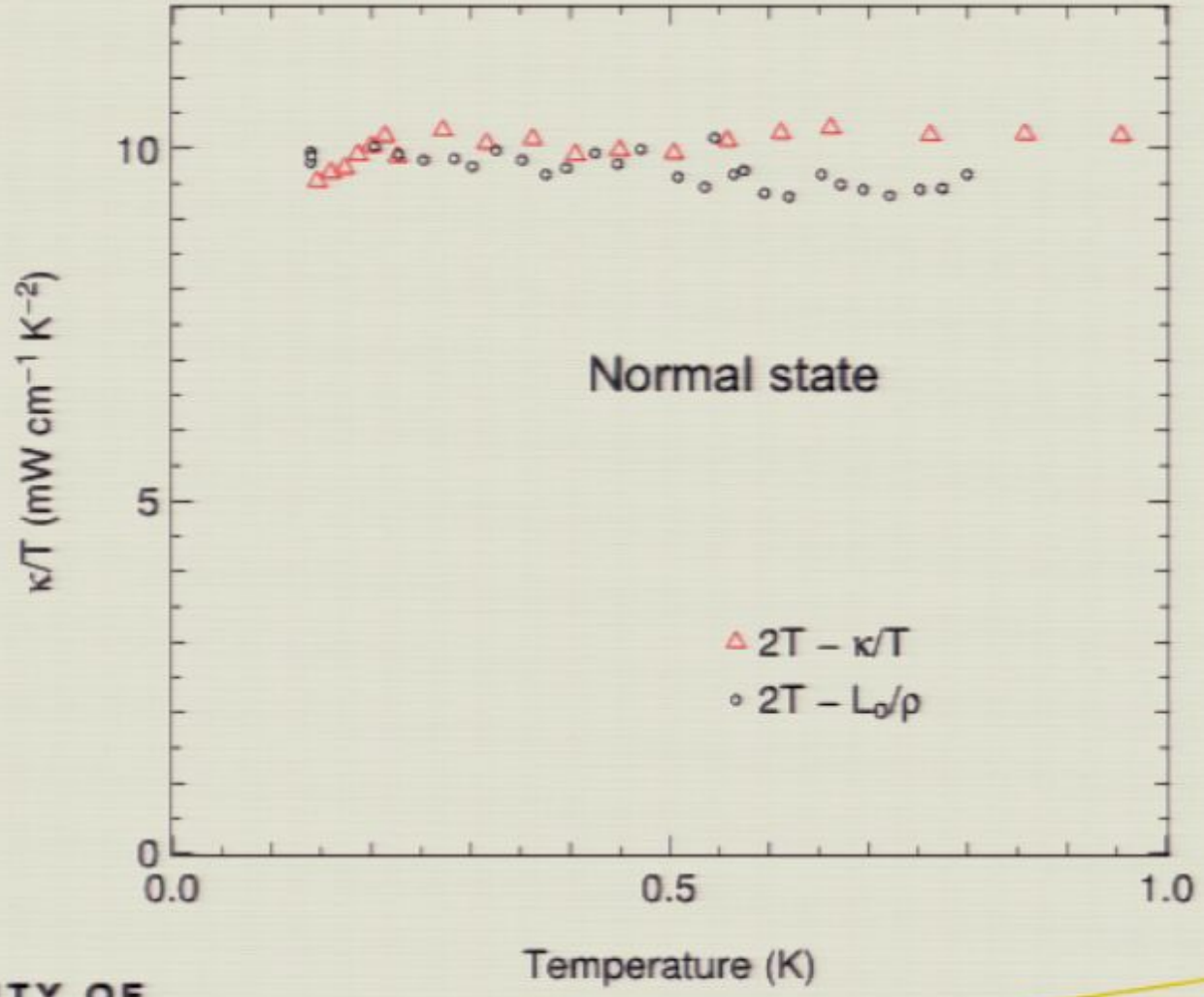
LaFePO: Field Dependence





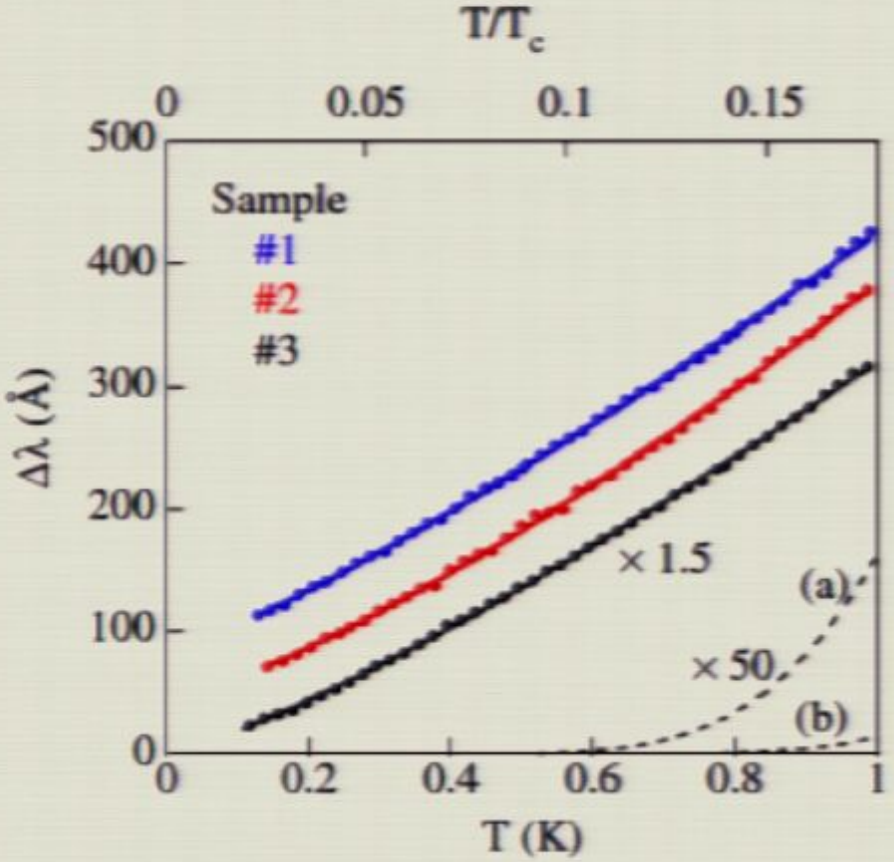
Mishra, et al., Phys. Rev. B **80**, 224525 (2009)

LaFePO: Wiedemann-Franz Law



LaFePO: other experiments

Penetration depth



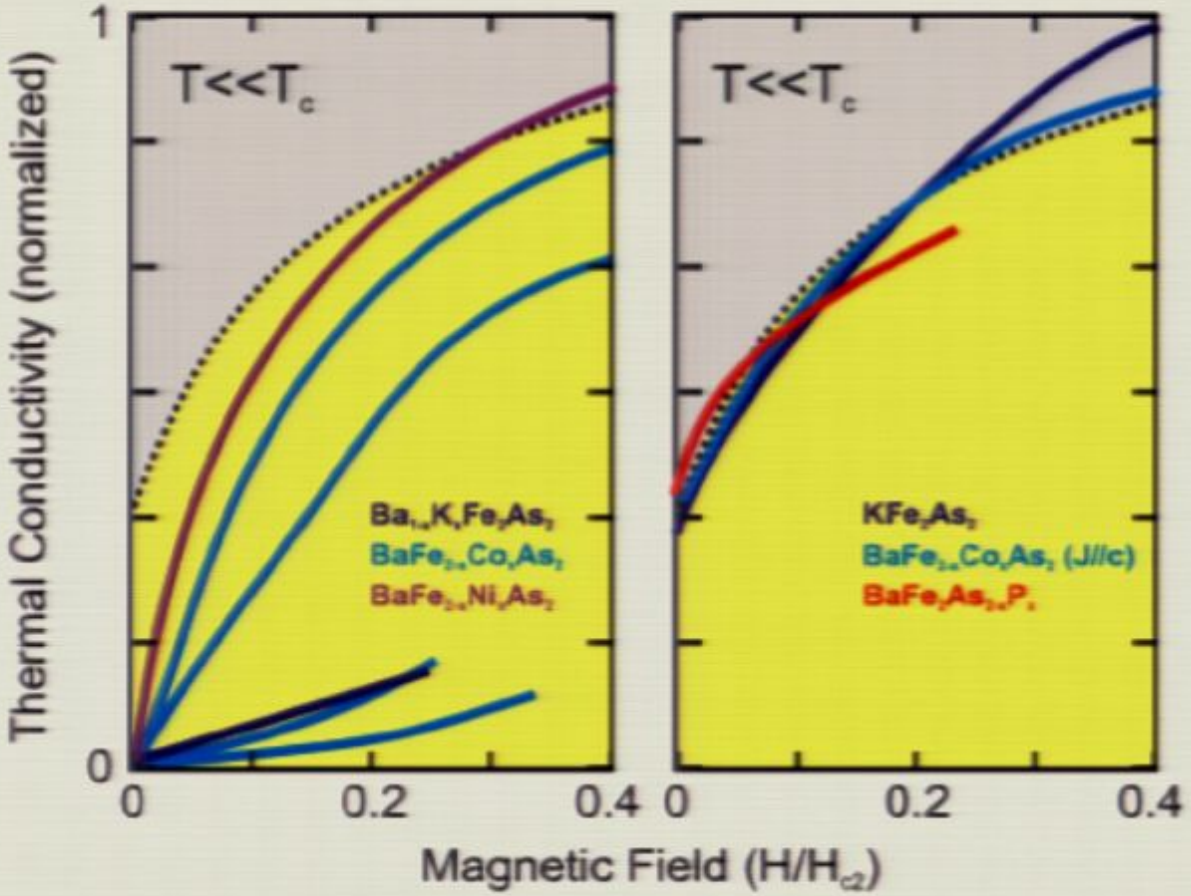
Power law T dependence

Consistent with nodes

Fletcher et al., PRL **102**, 147001 (2009)

UNIVERSITY OF WATERLOO

Thermal conductivity in other iron-based superconductors



Paglione and Greene, Nat. Phys. **6**, 645 (2010)

UNIVERSITY OF WATERLOO

Summary and Conclusions

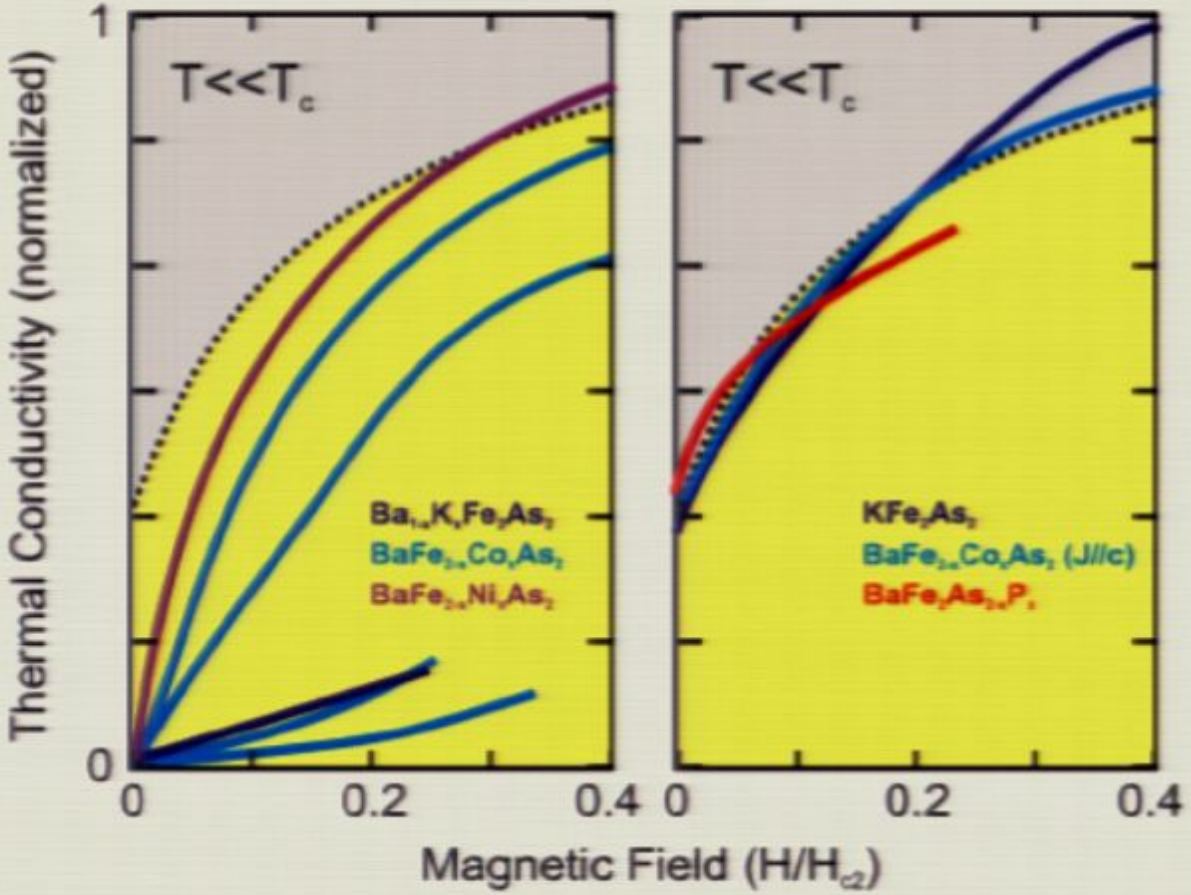
LaFePO

- Finite residual electronic conduction in zero temperature limit
  - evidence for nodes in superconducting gap.
- Quantitatively consistent with universal *d*-wave value
  - *However*, electronic temperature dependence qualitatively inconsistent (not T^3).
- Qualitatively consistent with nodal s+/- wave.
  - *Require methodical impurity dependence and numerical quantitative analysis.*

In broader picture of iron-based superconducting families, the sensitivity of the gap topology to Fermi surface details (because of a magnetic coupling mechanism) makes the observation of both nodes and fully-gapped structure a possibility within the same s+/- symmetry order parameter.

UNIVERSITY OF WATERLOO

Thermal conductivity in other iron-based superconductors



Paglione and Greene, Nat. Phys. 6, 645 (2010)

UNIVERSITY OF WATERLOO