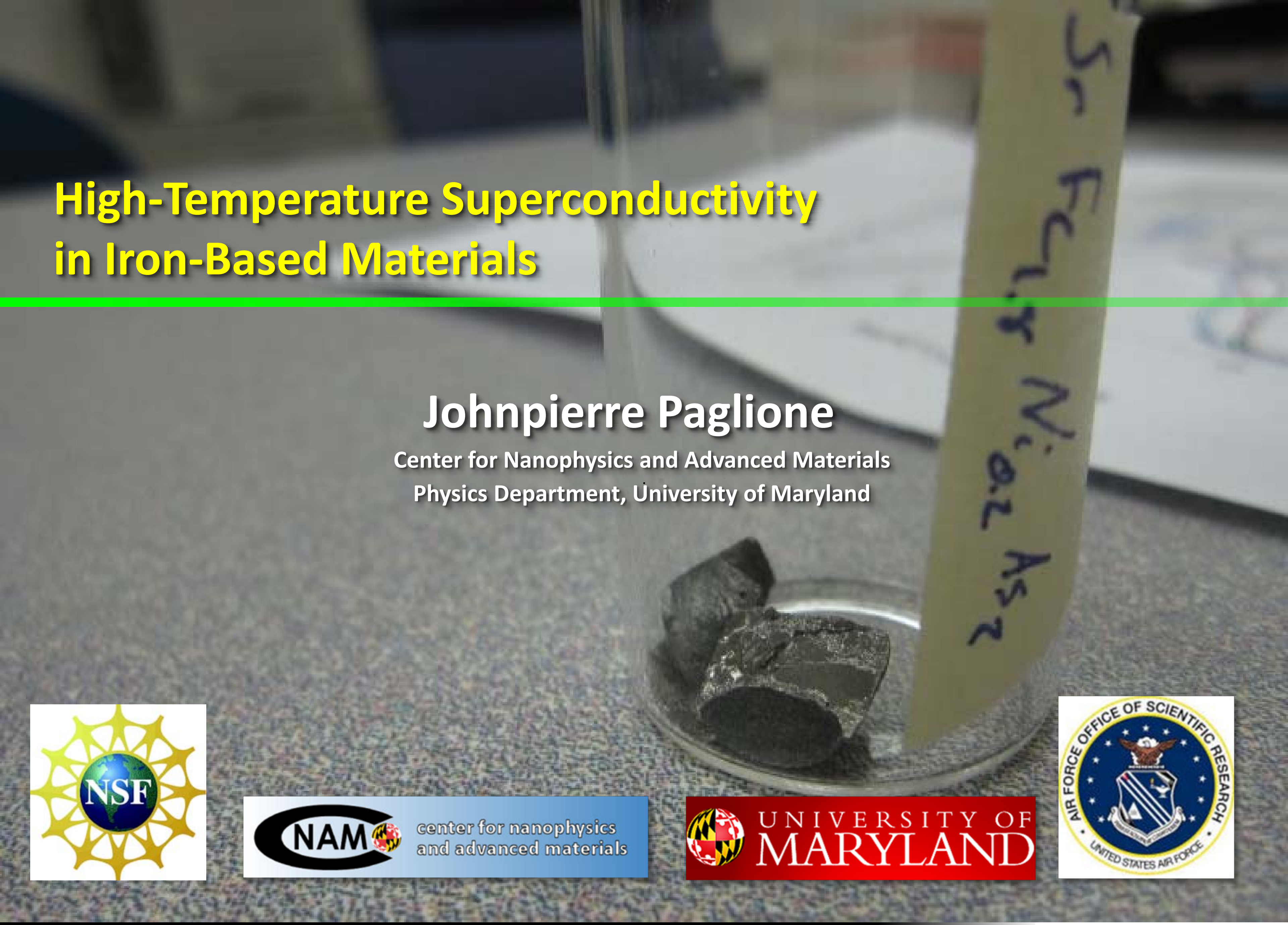
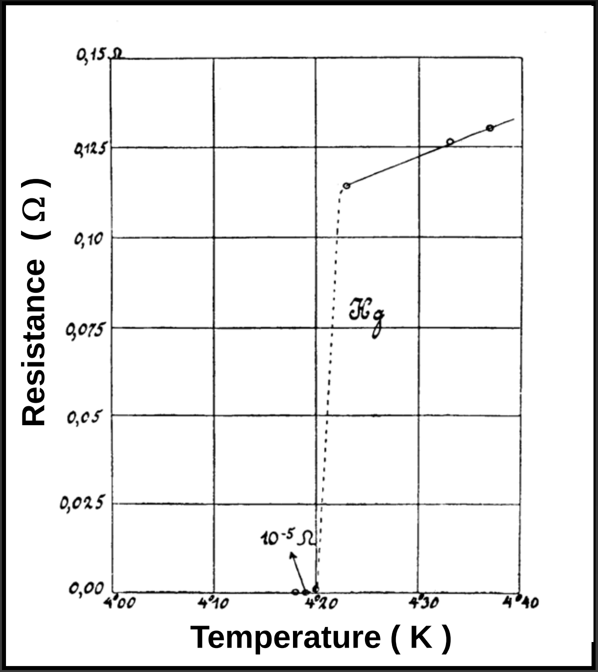


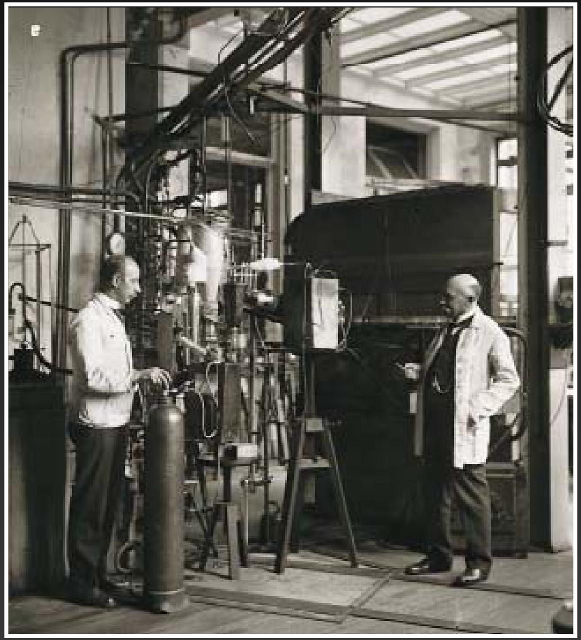
High-Temperature Superconductivity in Iron-Based Materials

Johnpierre Paglione

Center for Nanophysics and Advanced Materials
Physics Department, University of Maryland

Superconductivity in 1911

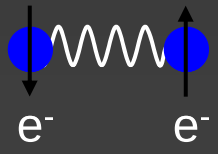




Gerrit Flim

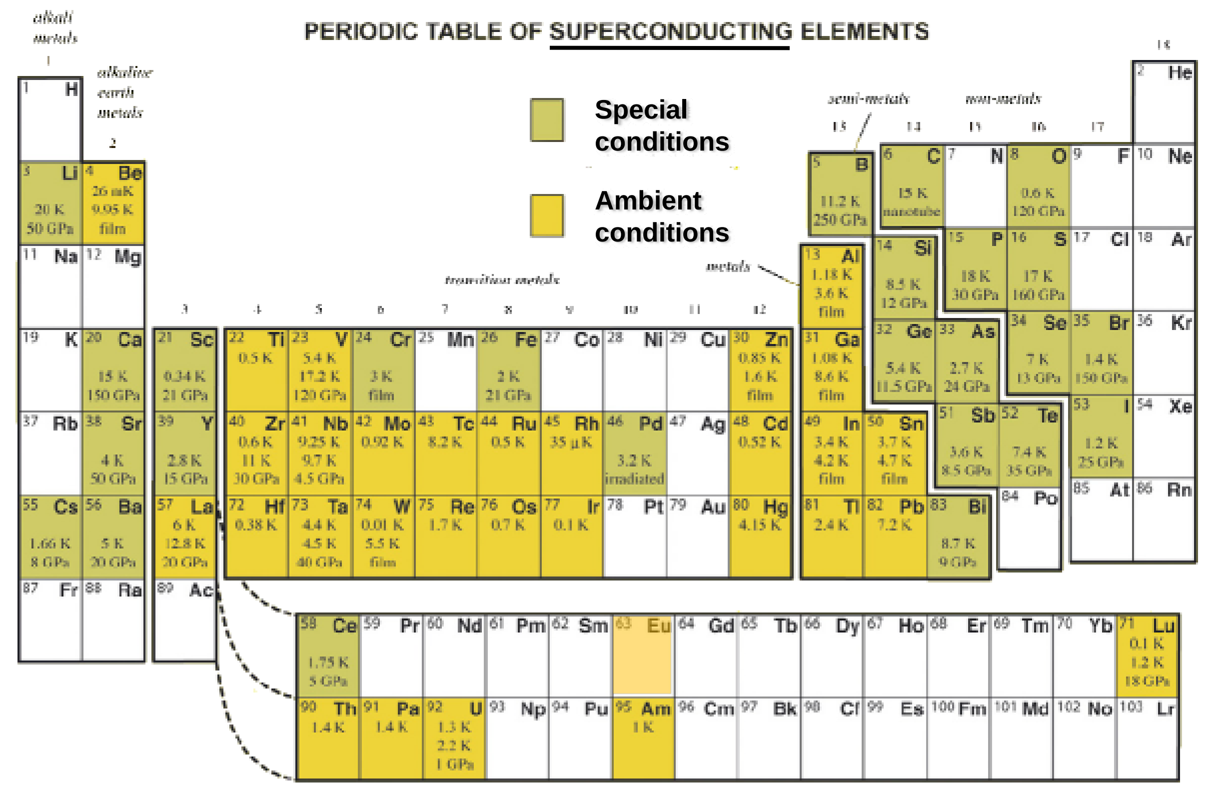
H. Kamerlingh Onnes

T_c = 4.2 K in elemental Hg



electrons "pair up"

Since then… very common!

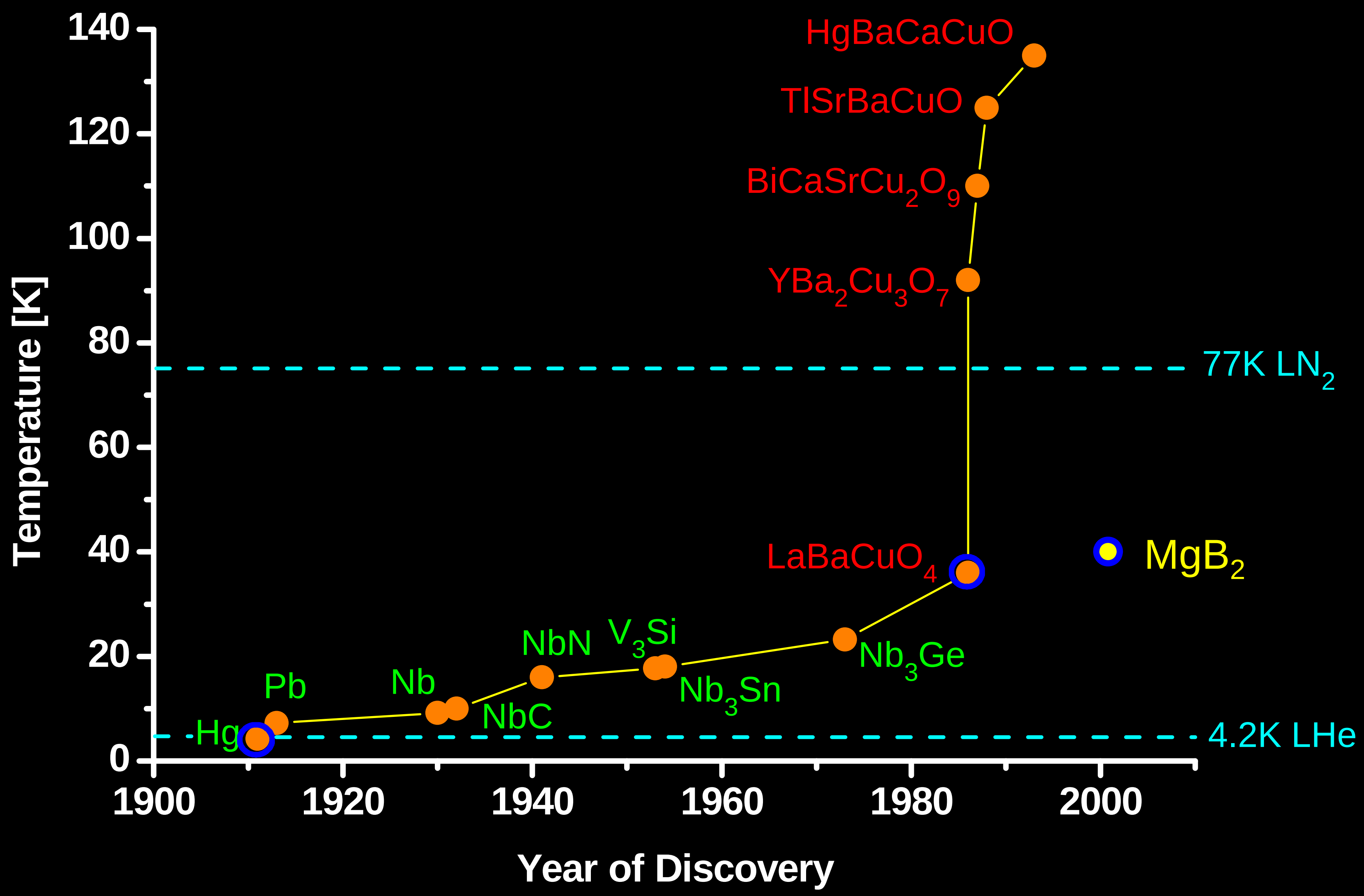


PERIODIC TABLE OF SUPERCONDUCTING ELEMENTS

Special conditions

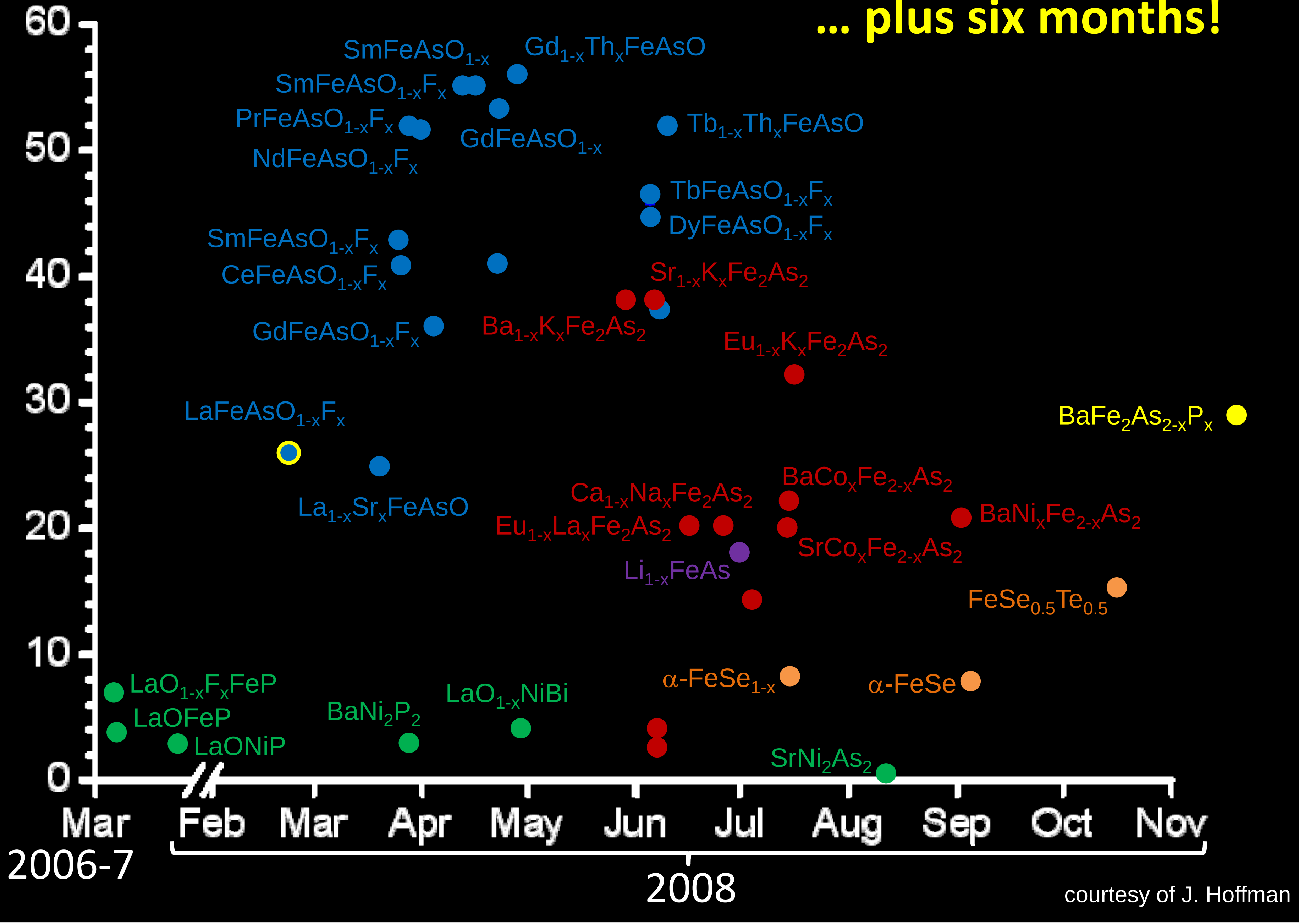
Ambient conditions

Evolution of superconductivity to 2008…



courtesy of J. Hoffman

… plus six months!



courtesy of J. Hoffman

Transparent Oxide Semiconductors…

Hideo HOSONO

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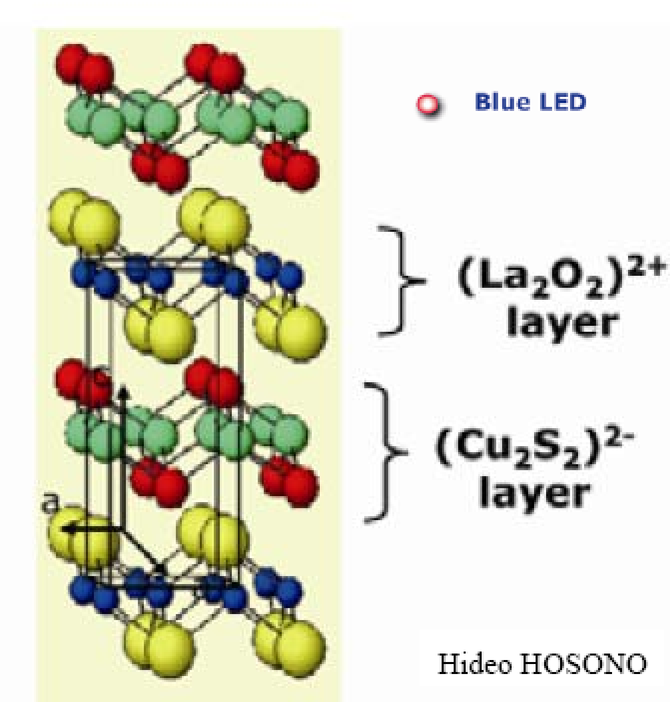
Nagatsuta 4259, Midori-ku, Yokohama 226-8503, JAPAN,

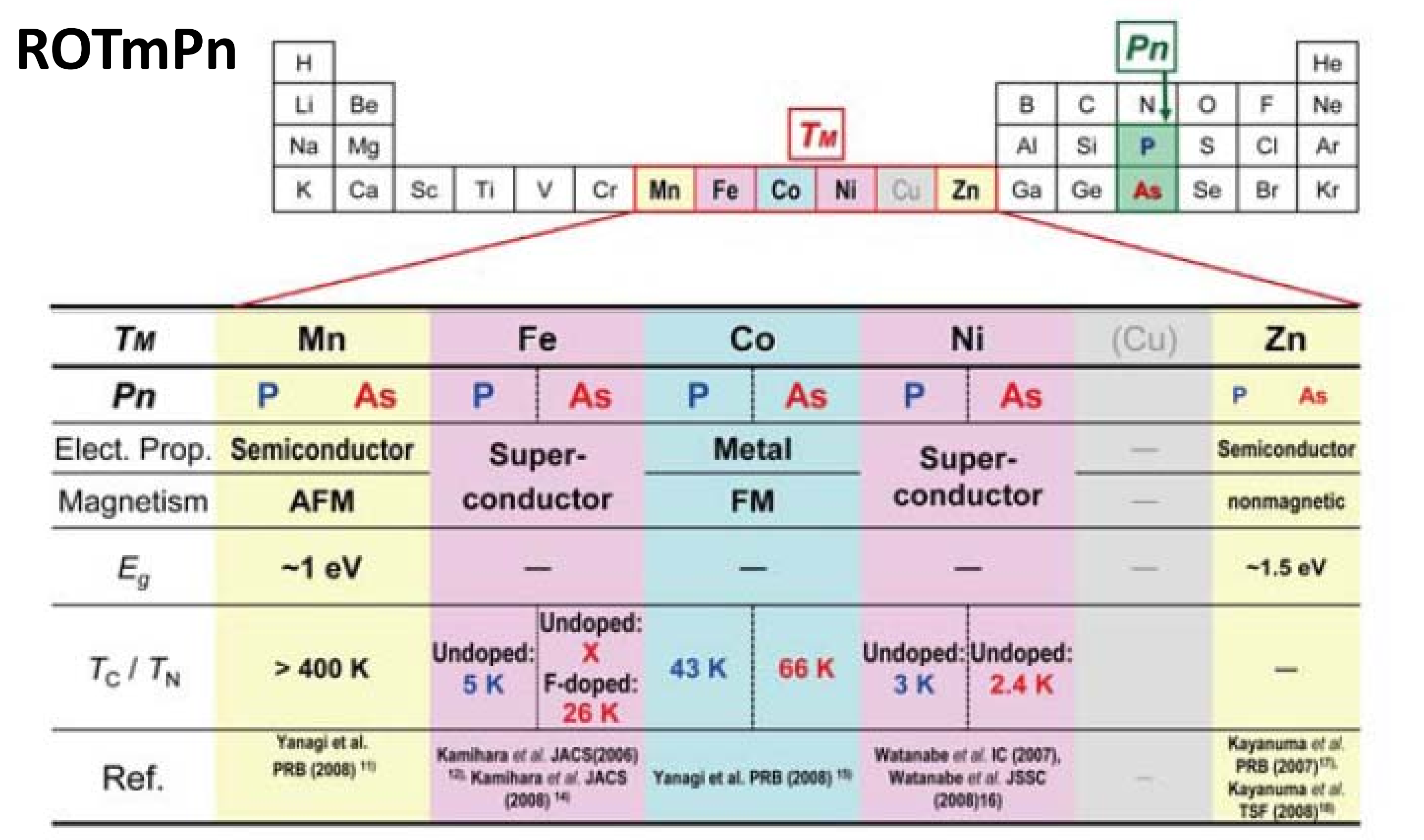
& Transparent Functional Oxide Project, ERATO-SORST, Japan Science and Technology Agency (JST), JAPAN



insulating

semiconducting

… to a wide assortment of behaviour



ROTmPn

TM	Mn		Fe		Co		Ni		(Cu)	Zn	
Pn	P	As	P	As	P	As	P	As		P	As
Elect. Prop.	Semiconductor		Super-conductor		Metal		Super-conductor		—	Semiconductor	
Magnetism	AFM				FM				—	nonmagnetic	
E_g	~1 eV		—		—		—		—	~1.5 eV	
T_C / T_N	> 400 K		Undoped: 5 K	Undoped: X F-doped: 26 K	43 K	66 K	Undoped: 3 K	Undoped: 2.4 K		—	
Ref.	Yanagi et al. PRB (2008) [11]		Kamihara *et al.* JACS(2006) [12], Kamihara *et al.* JACS (2008) [14]		Yanagi et al. PRB (2008) [15]		Watanabe *et al.* IC (2007), Watanabe *et al.* JSSC (2008)16)		—	Kayanuma *et al.* PRB (2007)[17], Kayanuma *et al.* TSF (2008)[18]	

Hosono (2008)

Superconductivity at 5 K in LaOFeP

J|A|C|S
COMMUNICATIONS

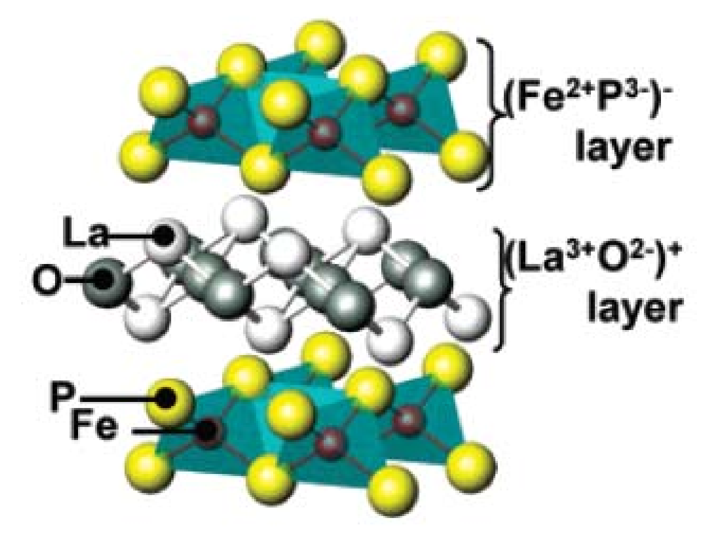
Published on Web 07/15/2006

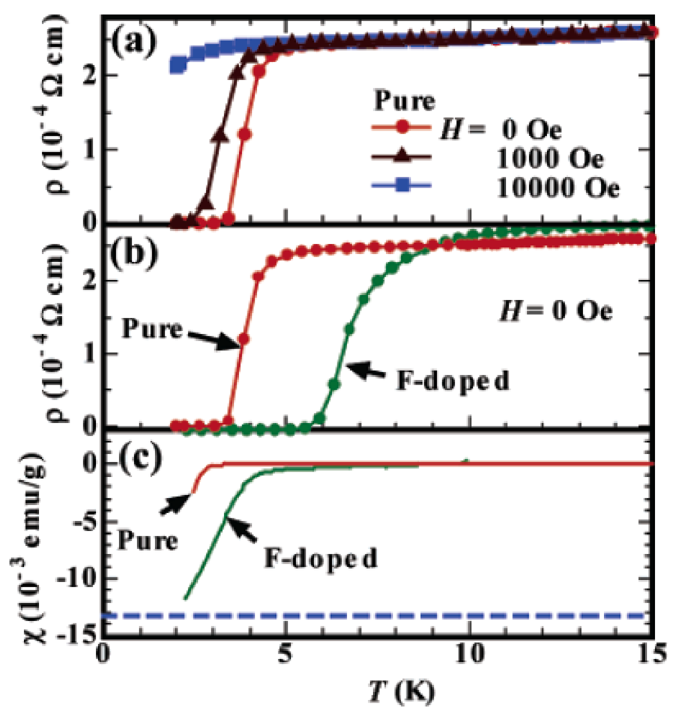
Iron-Based Layered Superconductor: LaOFeP

Yoichi Kamihara,† Hidenori Hiramatsu,† Masahiro Hirano,†,‡ Ryuto Kawamura,§ Hiroshi Yanagi,§
Toshio Kamiya,†,§ and Hideo Hosono*,†,‡

ERATO-SORST, JST, Frontier Collaborative Research Center, Tokyo Institute of Technology, Mail Box S2-13, 4259 Nagatsuta, Midori-ku, Yokohama 226-8503, Japan, Frontier Collaborative Research Center, Tokyo Institute of Technology, Mail Box S2-13, 4259 Nagatsuta, Midori-ku, Yokohama 226-8503, Japan, and Materials and Structures Laboratory, Tokyo Institute of Technology, Mail Box R3-4, 4259 Nagatsuta, Yokohama 226-8503, Japan

Received May 15, 2006; E-mail: hosono@msl.titech.ac.jp





Superconductivity at 26 K in LaOFeAs doped with Fluorine

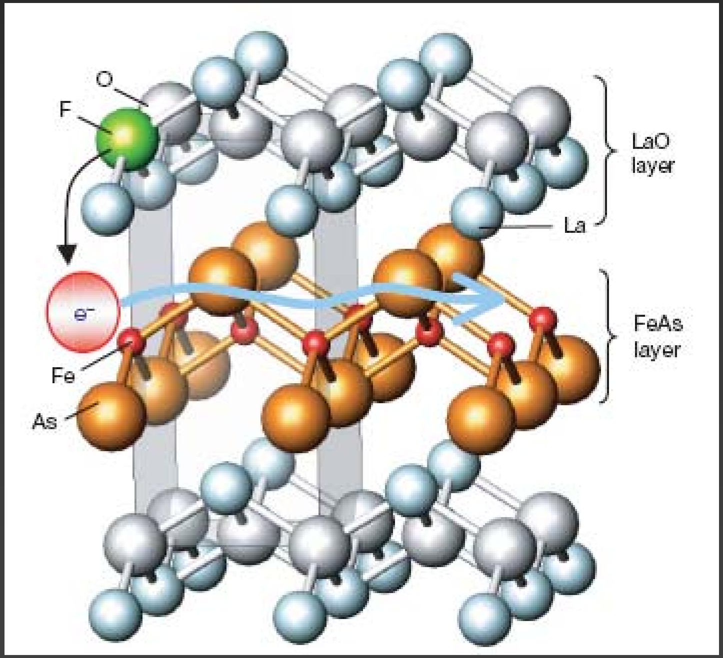
J|A|C|S COMMUNICATIONS

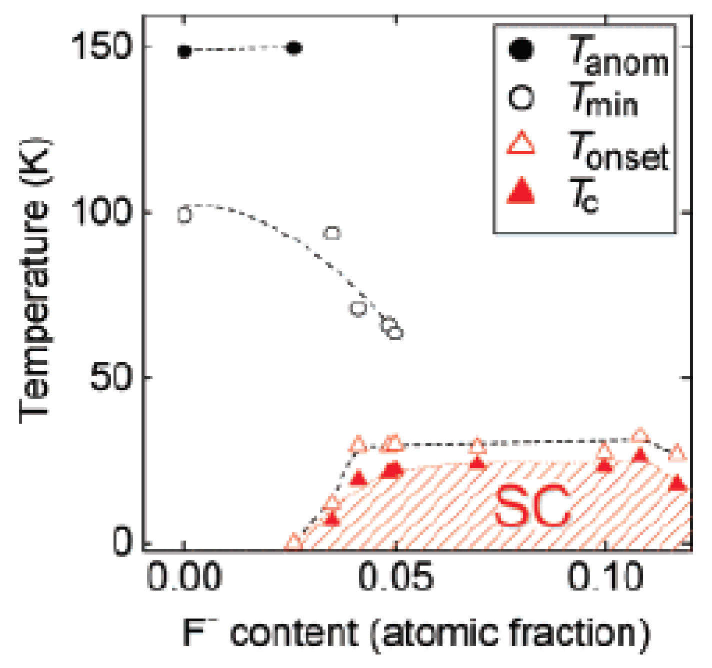
Published on Web 02/23/2008

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





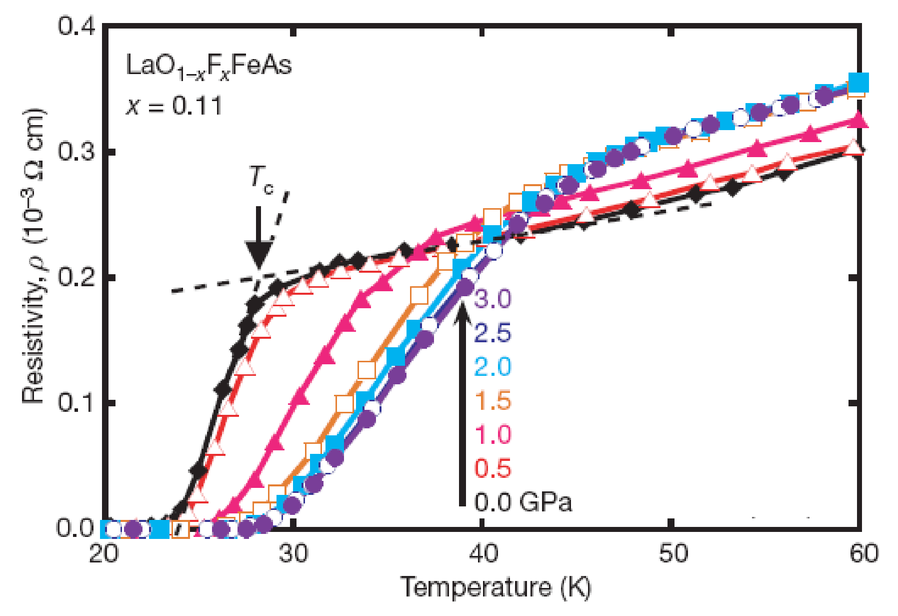
Superconductivity at <u>43 K</u> in La(O,F)FeAs under pressure

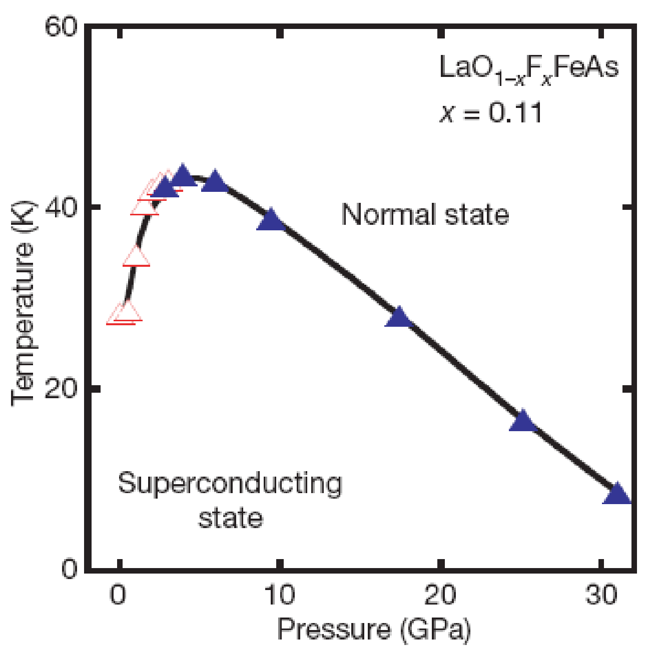
NATURE|Vol 453|15 April 2008

LETTERS

Superconductivity at 43 K in an iron-based layered compound $LaO_{1-x}F_xFeAs$

Hiroki Takahashi[1], Kazumi Igawa[1], Kazunobu Arii[1], Yoichi Kamihara[2], Masahiro Hirano[2,3] & Hideo Hosono[2,3]





Superconductivity
up to 56 K in doped ROFeAs, RFeAsF

epl A LETTERS JOURNAL EXPLORING THE FRONTIERS OF PHYSICS

September 2008

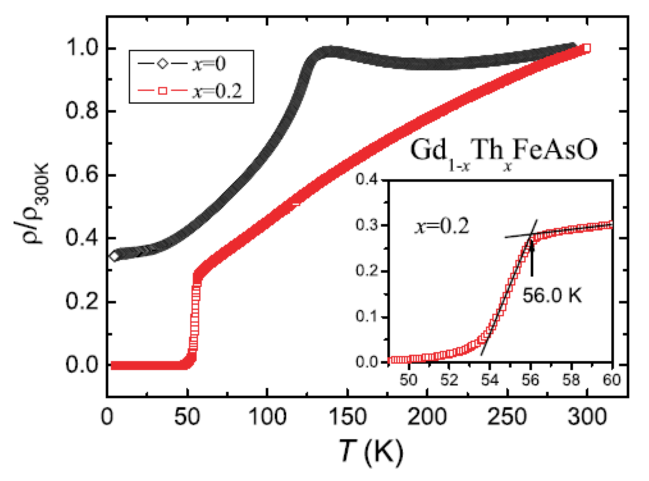
EPL, **83** (2008) 67006
doi: 10.1209/0295-5075/83/67006

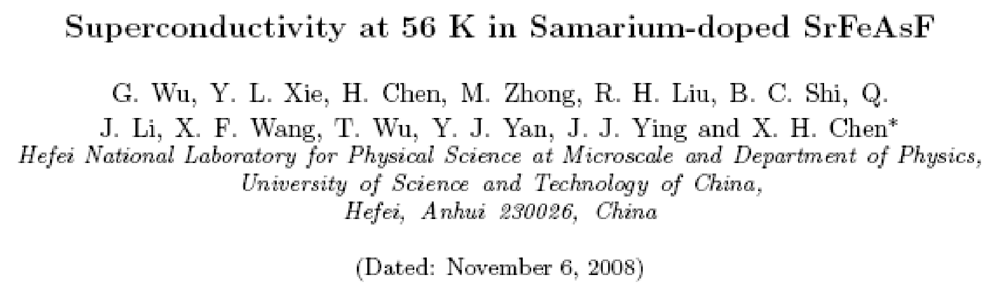
www.epljournal.org

Thorium-doping–induced superconductivity up to 56 K in $Gd_{1-x}Th_xFeAsO$

CAO WANG, LINJUN LI, SHUN CHI, ZENGWEI ZHU, ZHI REN, YUKE LI, YUETAO WANG, XIAO LIN, YONGKANG LUO, SHUAI JIANG, XIANGFAN XU, GUANGHAN CAO(a) and ZHU'AN XU(b)

Department of Physics, Zhejiang University - Hangzhou 310027, People's Republic of China

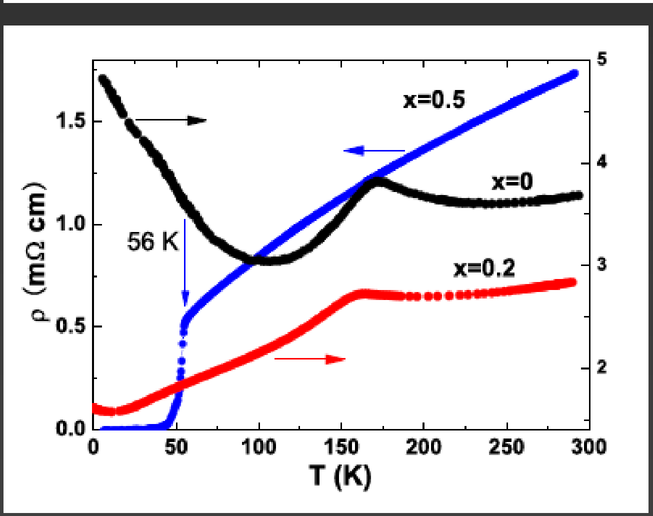


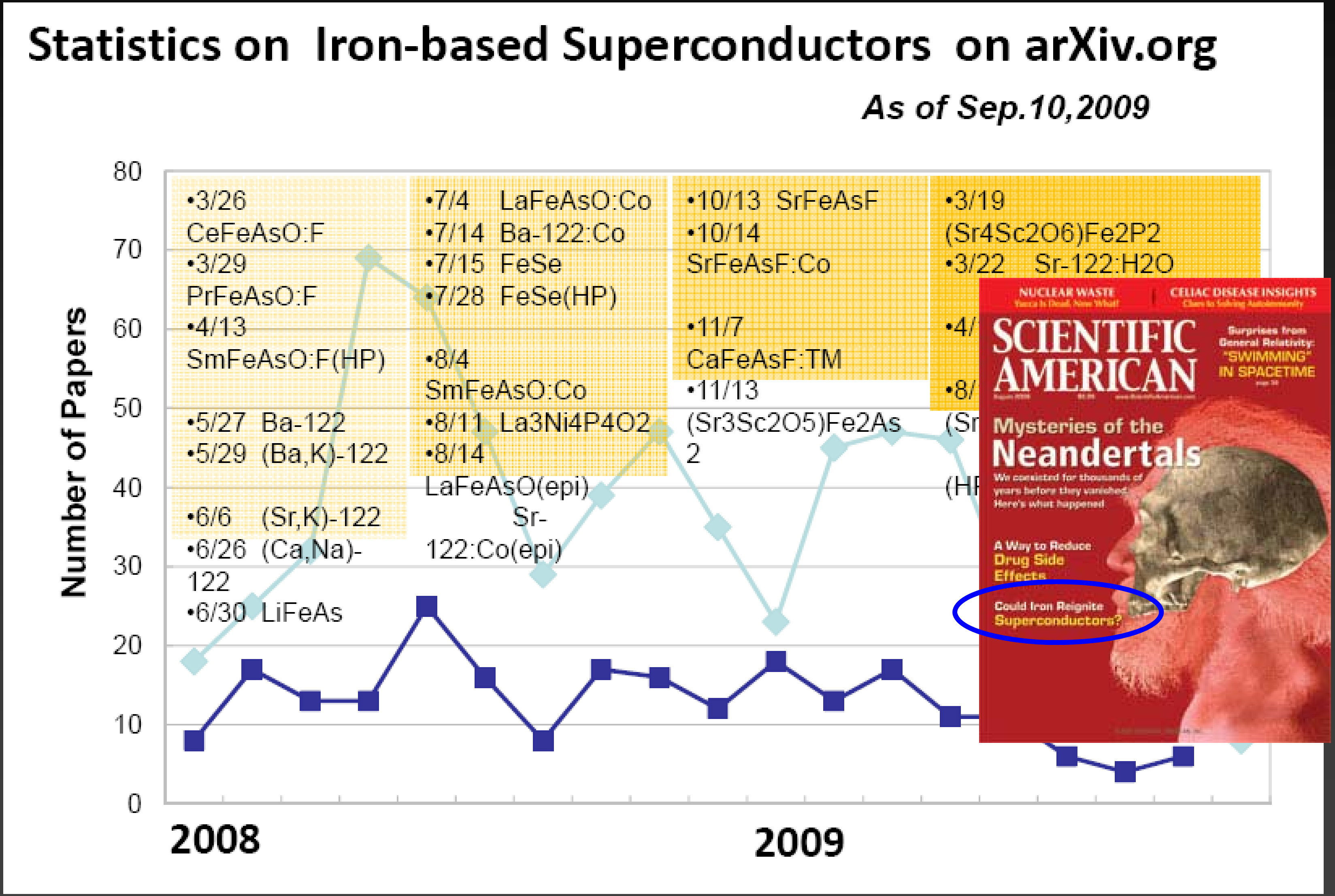


Superconductivity at 56 K in Samarium-doped SrFeAsF

G. Wu, Y. L. Xie, H. Chen, M. Zhong, R. H. Liu, B. C. Shi, Q. J. Li, X. F. Wang, T. Wu, Y. J. Yan, J. J. Ying and X. H. Chen*
Hefei National Laboratory for Physical Science at Microscale and Department of Physics, University of Science and Technology of China, Hefei, Anhui 230026, China

(Dated: November 6, 2008)





Statistics on Iron-based Superconductors on arXiv.org

As of Sep.10,2009

- •3/26 CeFeAsO:F
- •3/29 PrFeAsO:F
- •4/13 SmFeAsO:F(HP)
- •5/27 Ba-122
- •5/29 (Ba,K)-122
- •6/6 (Sr,K)-122
- •6/26 (Ca,Na)-122
- •6/30 LiFeAs

- •7/4 LaFeAsO:Co
- •7/14 Ba-122:Co
- •7/15 FeSe
- •7/28 FeSe(HP)
- •8/4 SmFeAsO:Co
- •8/11 La3Ni4P4O2
- •8/14 LaFeAsO(epi) Sr-122:Co(epi)

- •10/13 SrFeAsF
- •10/14 SrFeAsF:Co
- •11/7 CaFeAsF:TM
- •11/13 (Sr3Sc2O5)Fe2As2

- •3/19 (Sr4Sc2O6)Fe2P2
- •3/22 Sr-122:H2O
- •4/
- •8/
- (Sr
- (HP

Hosono – ISS (2010)

Outline of talks

Part 1:

a) iron-pnictide family album

b) Phase diagrams and tuning

c) Normal and superconducting state properties

Part 2:

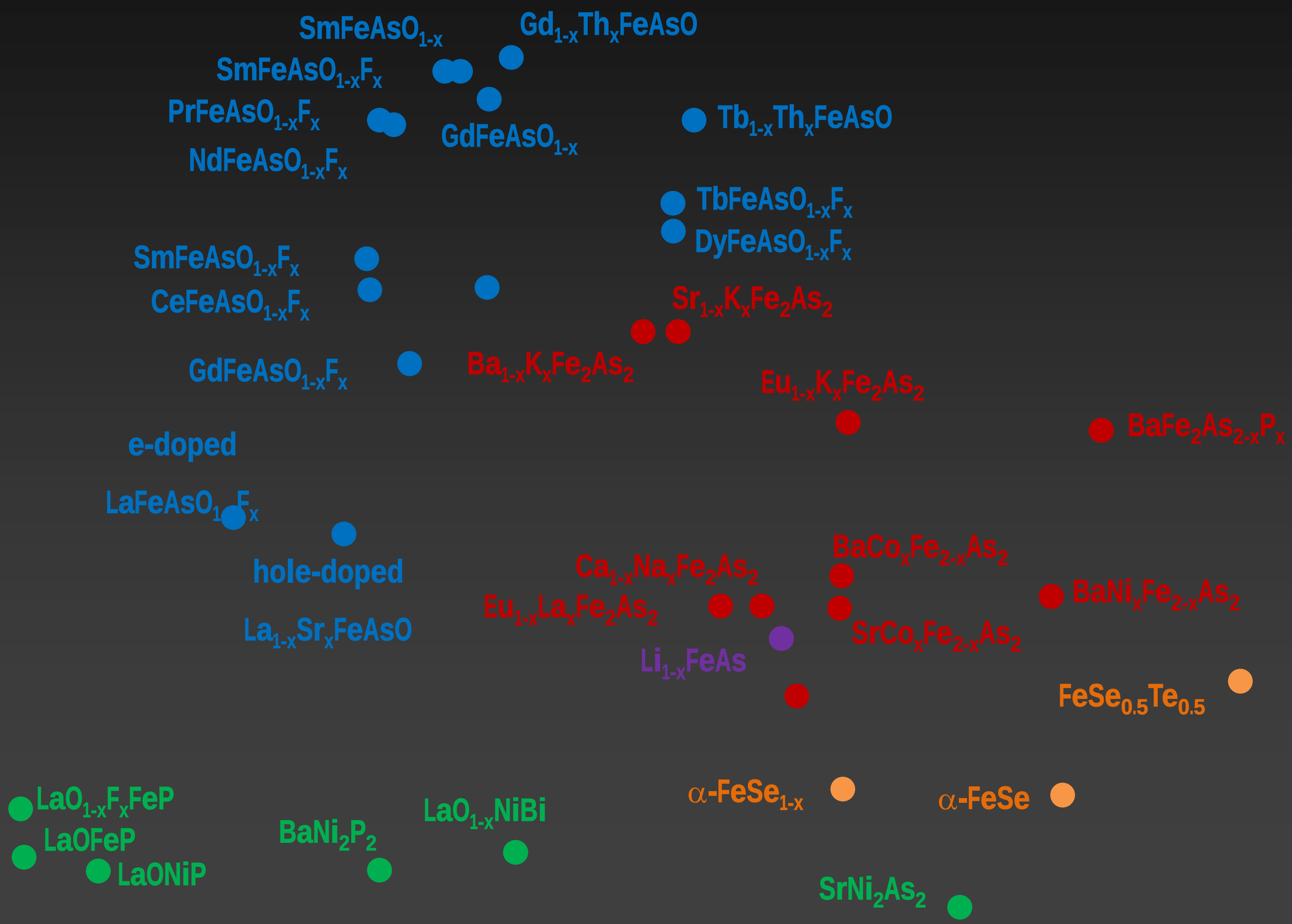
a) single-crystal growth

b) Ni- and Pt-doped $SrFe_2As_2$

c) SC in stoichiometric $SrFe_2As_2$

d) $(Ca,Sr,Ba)Fe_2As_2$ solid solutions

a) Iron-Pnictide family



$SmFeAsO_{1-x}$

$Gd_{1-x}Th_xFeAsO$

$SmFeAsO_{1-x}F_x$

$PrFeAsO_{1-x}F_x$

$GdFeAsO_{1-x}$

$Tb_{1-x}Th_xFeAsO$

$NdFeAsO_{1-x}F_x$

$TbFeAsO_{1-x}F_x$

$DyFeAsO_{1-x}F_x$

$SmFeAsO_{1-x}F_x$

$CeFeAsO_{1-x}F_x$

$Sr_{1-x}K_xFe_2As_2$

$GdFeAsO_{1-x}F_x$

$Ba_{1-x}K_xFe_2As_2$

$Eu_{1-x}K_xFe_2As_2$

$BaFe_2As_{2-x}P_x$

e-doped

$LaFeAsO_{1-x}F_x$

hole-doped

$BaCo_xFe_{2-x}As_2$

$Ca_{1-x}Na_xFe_2As_2$

$Eu_{1-x}La_xFe_2As_2$

$BaNi_xFe_{2-x}As_2$

$La_{1-x}Sr_xFeAsO$

$SrCo_xFe_{2-x}As_2$

$Li_{1-x}FeAs$

$FeSe_{0.5}Te_{0.5}$

$LaO_{1-x}F_xFeP$

$LaO_{1-x}NiBi$

α-$FeSe_{1-x}$

α-FeSe

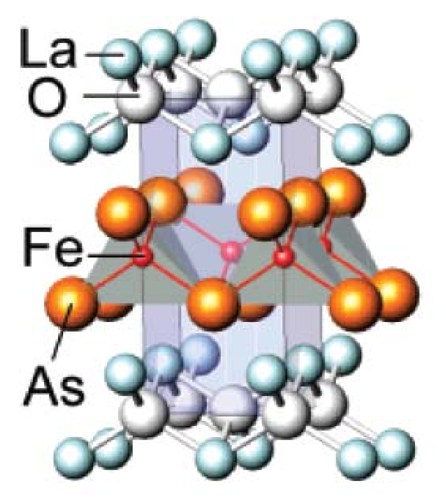
LaOFeP

$BaNi_2P_2$

LaONiP

$SrNi_2As_2$

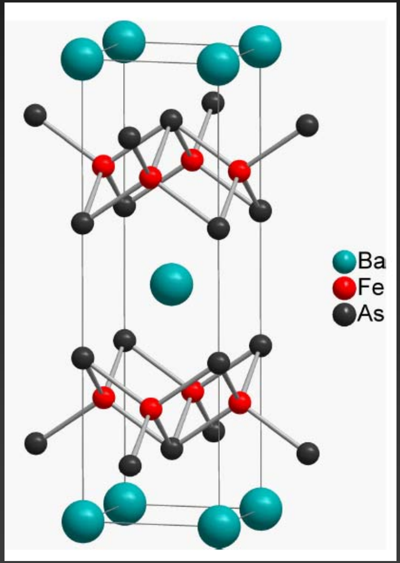
Crystal Structures



“1-1-1-1” (ZrCuSiAs)

ROFeAs

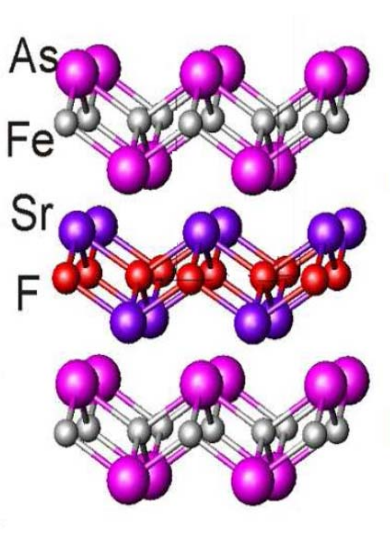
R= rare earth



“1-2-2” (ThCr$_2$Si$_2$)

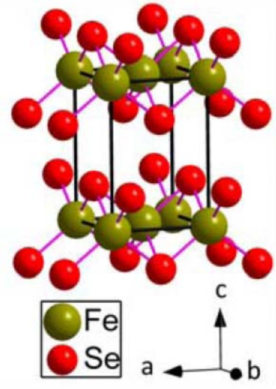
AFe$_2$As$_2$

A= alkali(ne)



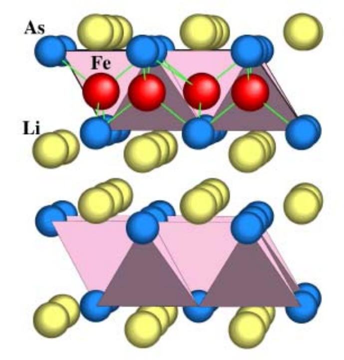
“1-1-1-1”

(A,R)FeAsF



binary

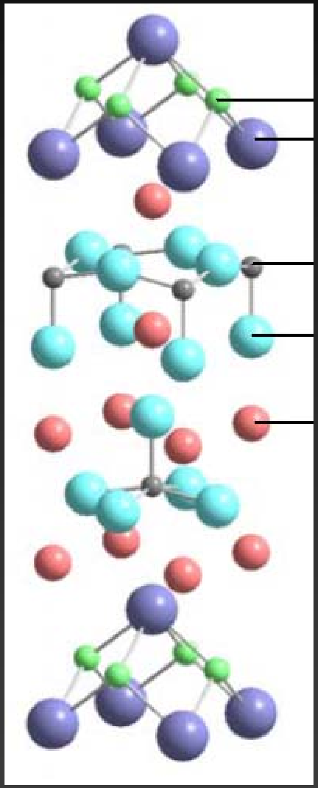
Fe(S,Se,Te)



“1-1-1”

AFeAs

Crystal Structures



Fe_2Pn_2 layers

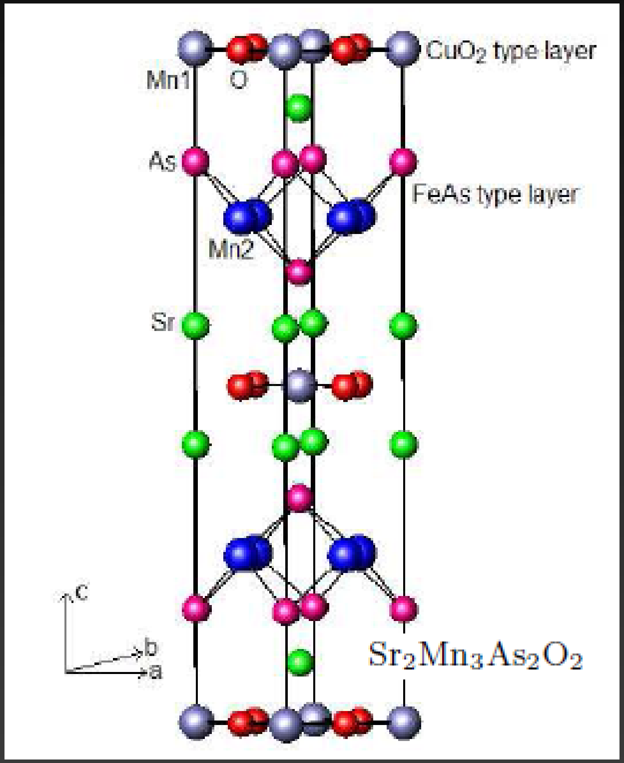
$Sr_4T_2O_6$ (T=V,Sc) perovskite layers

"42622"

Tetragonal P4/nmm

$Sr_4Sc_2O_6Fe_2P_2$ (T_c ~ 17 K)

$Sr_4V_2O_6Fe_2As_2$ (T_c ~ 35 K)

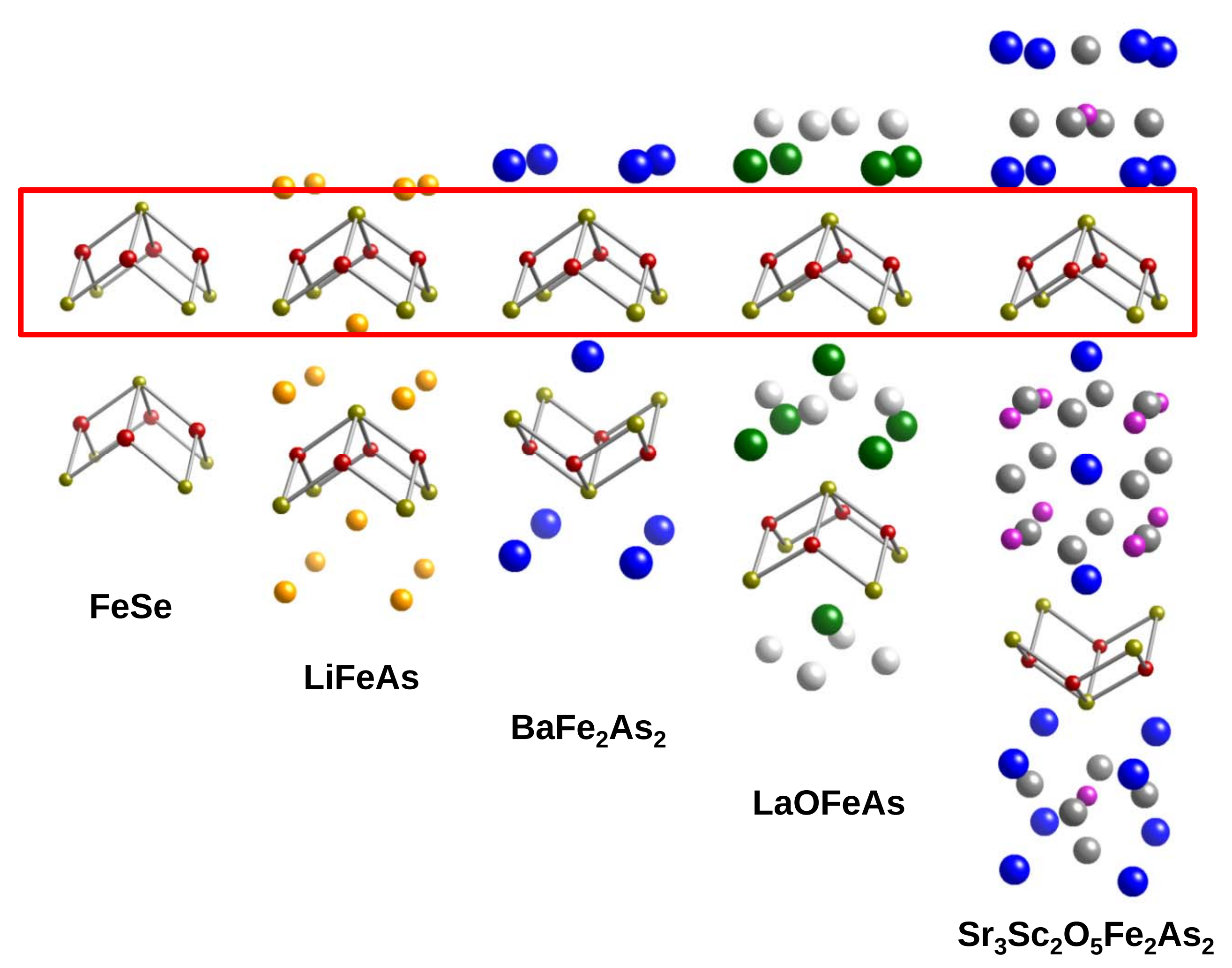


R. Nath *et al.* (2010)

FeAs/CuO_2-type layered I4/mmm

(not superconducting)

Crystal Structures



FeSe

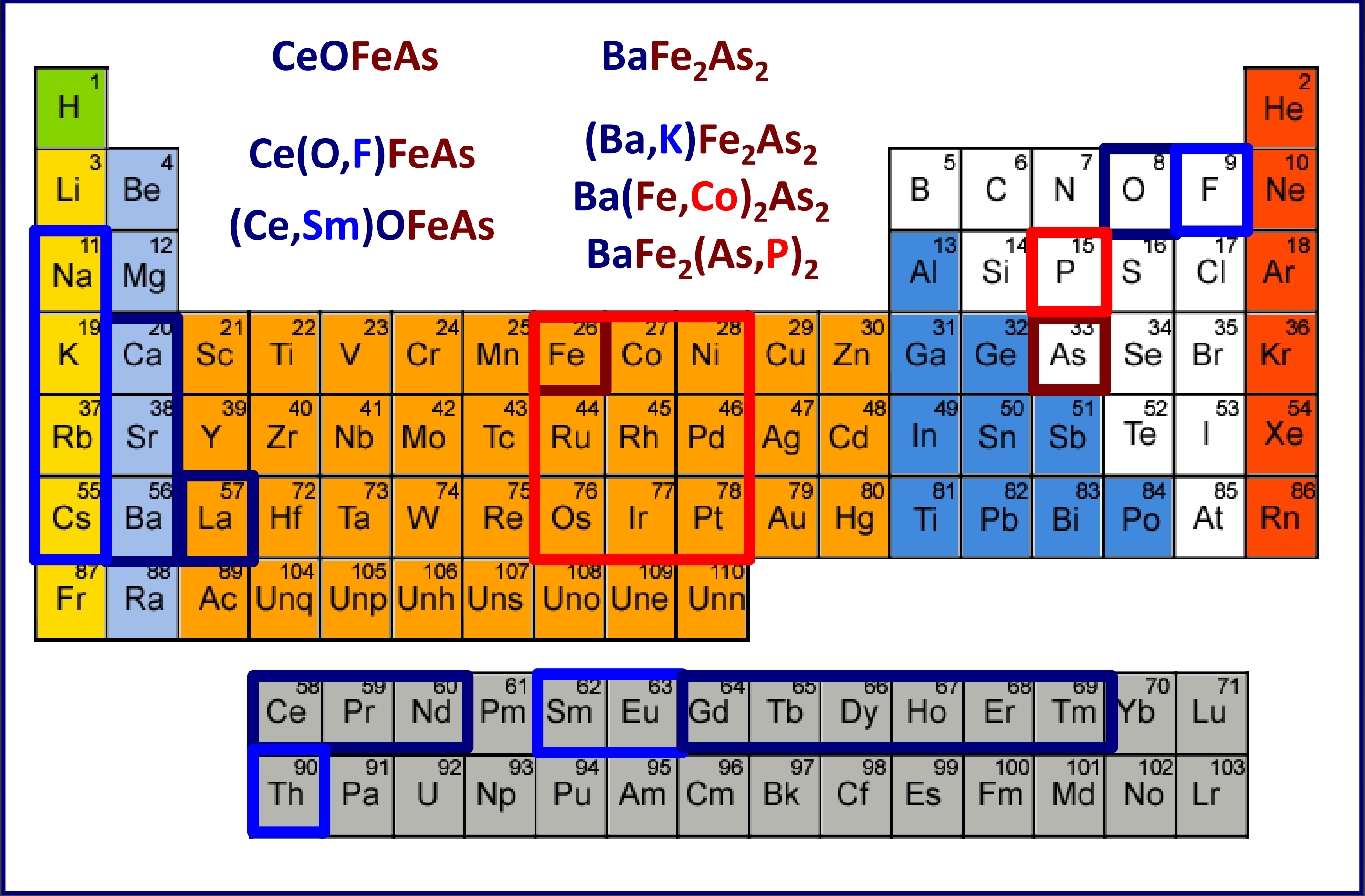
LiFeAs

$BaFe_2As_2$

LaOFeAs

$Sr_3Sc_2O_5Fe_2As_2$

Chemical substitution



CeOFeAs

Ce(O,F)FeAs

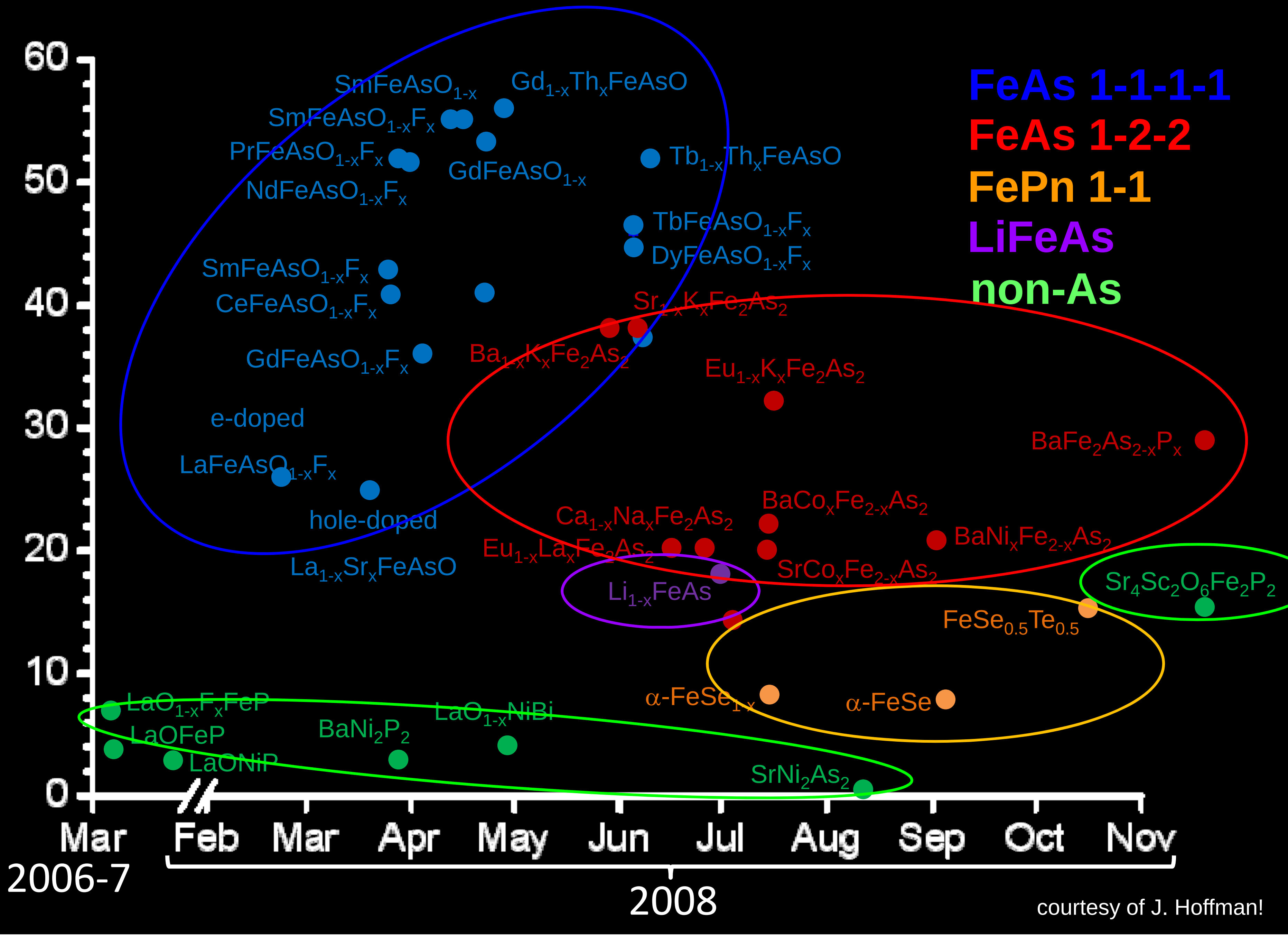
(Ce,Sm)OFeAs

$BaFe_2As_2$

$(Ba,K)Fe_2As_2$

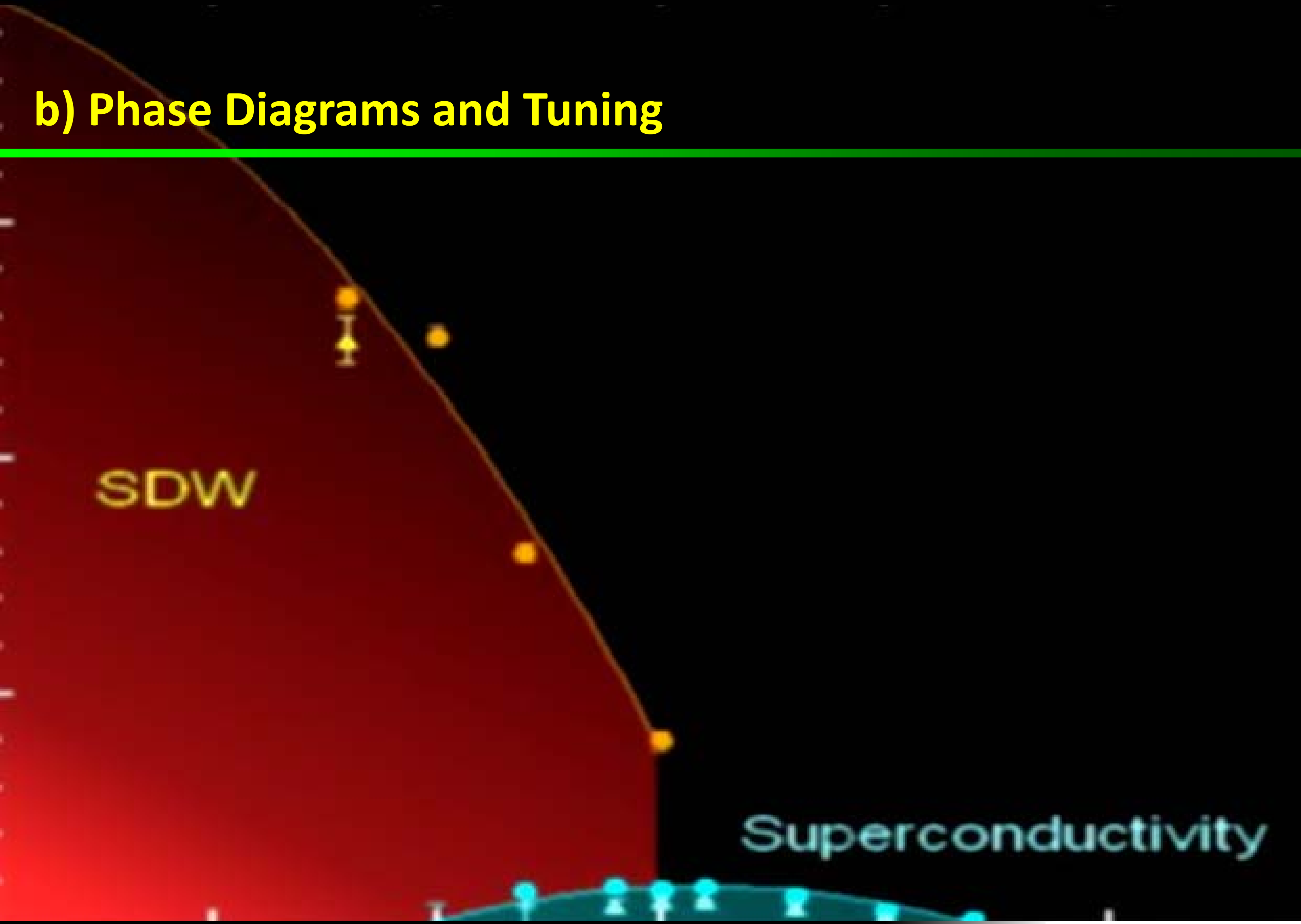
$Ba(Fe,Co)_2As_2$

$BaFe_2(As,P)_2$



courtesy of J. Hoffman!

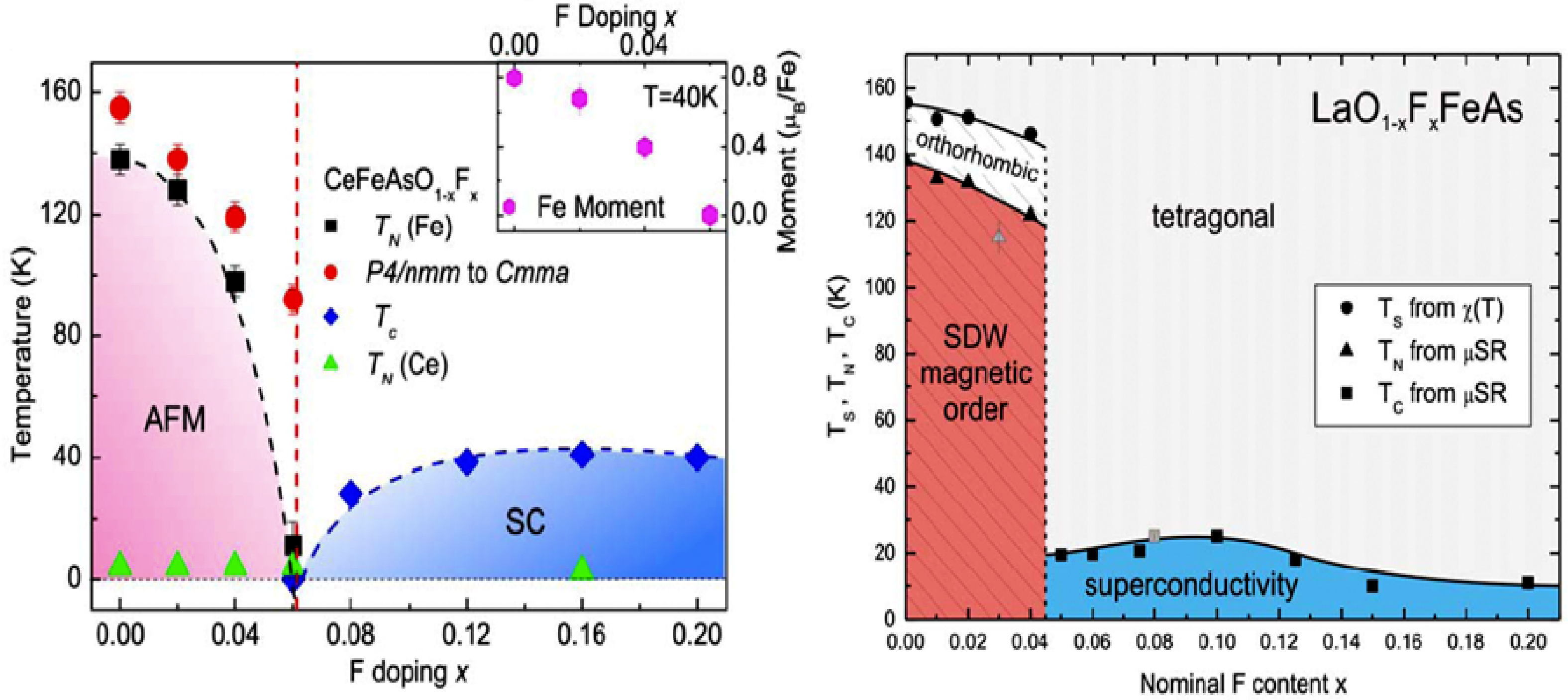
b) Phase Diagrams and Tuning



Tuning Phase Diagram

1-1-1-1 (polycrystals)

$RO_{1-x}F_xFeAs$



J. Zhao *et al.* (2008)

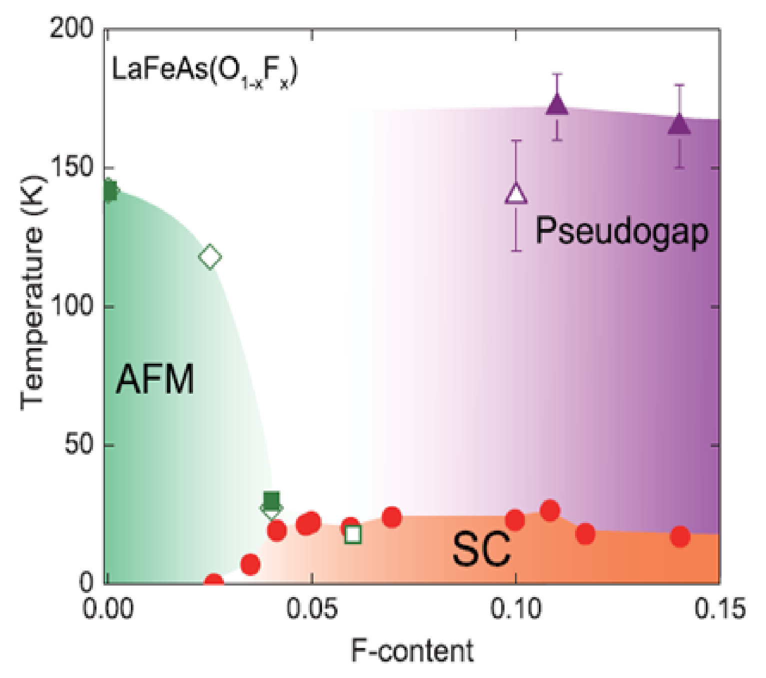
H. Luetkens *et al.* (2008)

No AFM/SC coexistence?

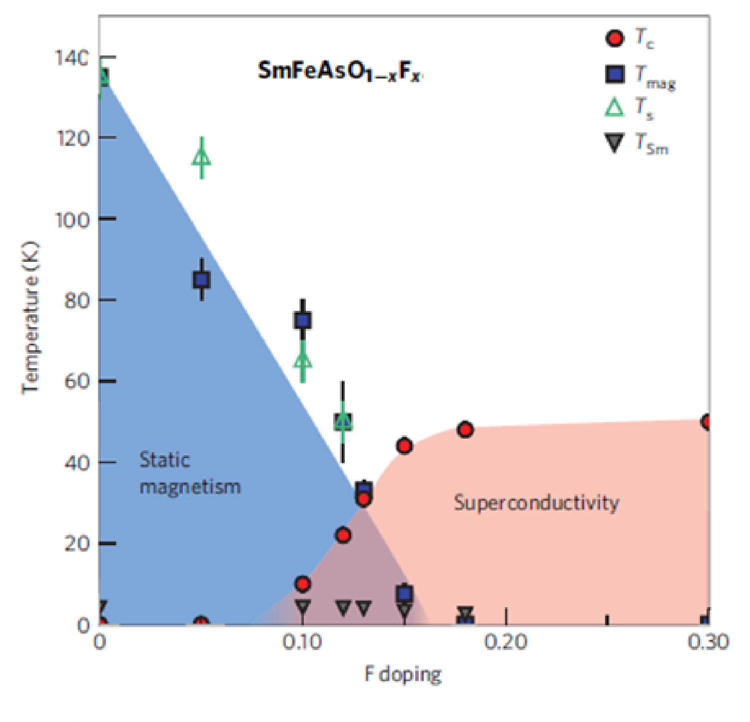
Tuning Phase Diagram

1-1-1-1 (polycrystals)

$RO_{1-x}F_xFeAs$



Y. Nakai *et al.* (2009)



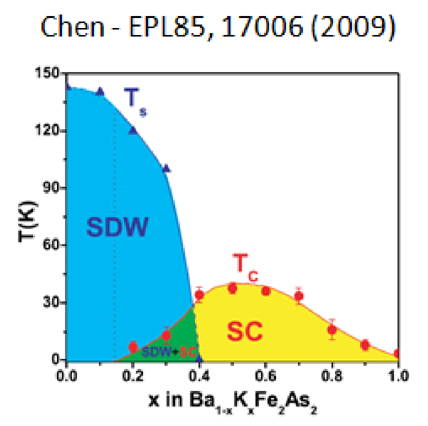
A. Drew *et al.* (2009)

AFM/SC coexistence?

Tuning Phase Diagram

1-2-2 (single crystals)

$Ba_{1-x}K_xFeAs_2$


Chen - EPL85, 17006 (2009)

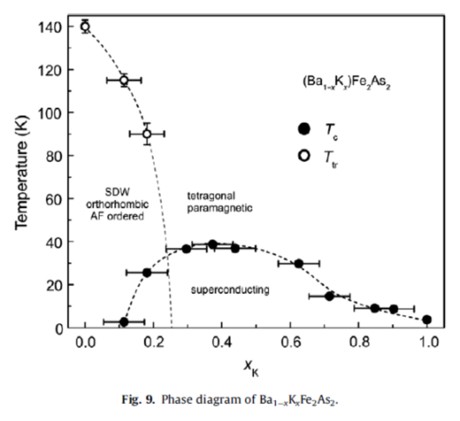


Fig. 9. Phase diagram of $Ba_{1-x}K_xFe_2As_2$.

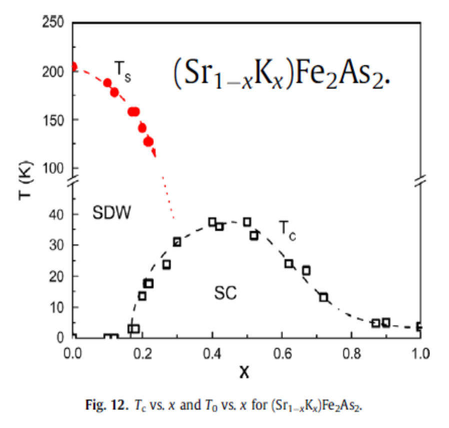
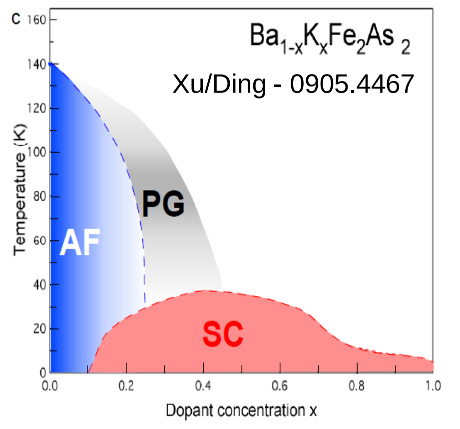
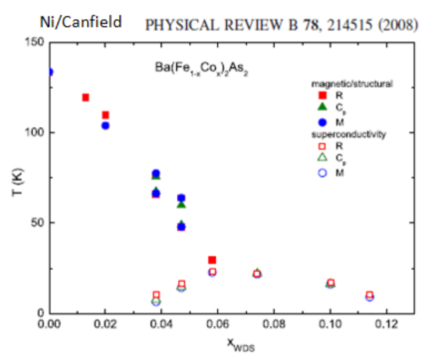
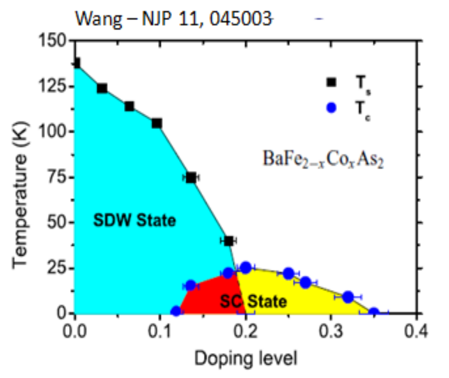


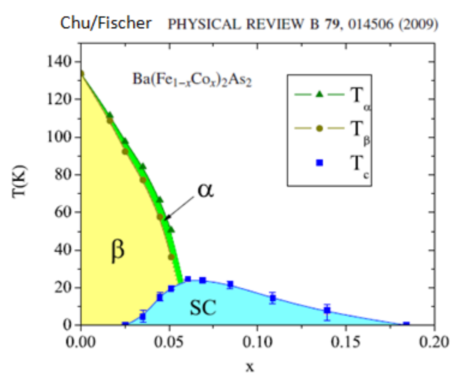
Fig. 12. T_c vs. x and T_0 vs. x for $(Sr_{1-x}K_x)Fe_2As_2$.

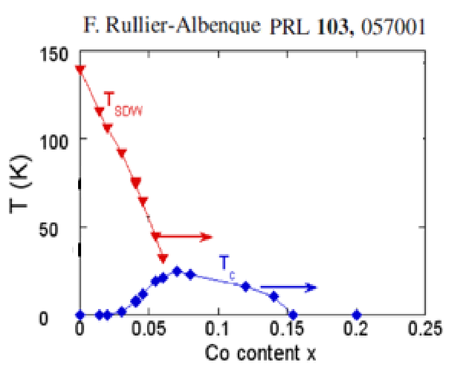

Xu/Ding - 0905.4467

$BaFe_{2-x}Co_xAs_2$


Ni/Canfield PHYSICAL REVIEW B 78, 214515 (2008)


Wang – NJP 11, 045003


Chu/Fischer PHYSICAL REVIEW B 79, 014506 (2009)


F. Rullier-Albenque PRL 103, 057001

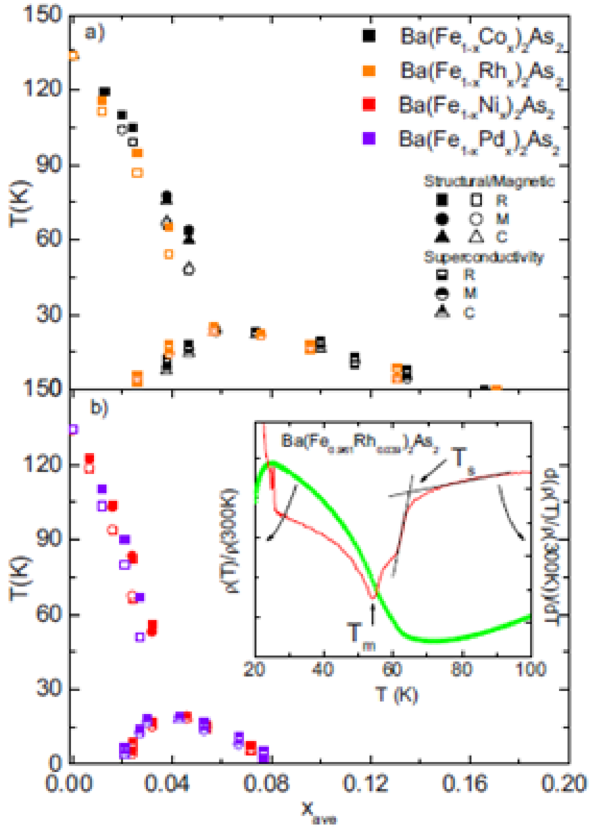
Tuning Phase Diagram

1-2-2 (single crystals)

$BaFe_{2-x}T_xAs_2$

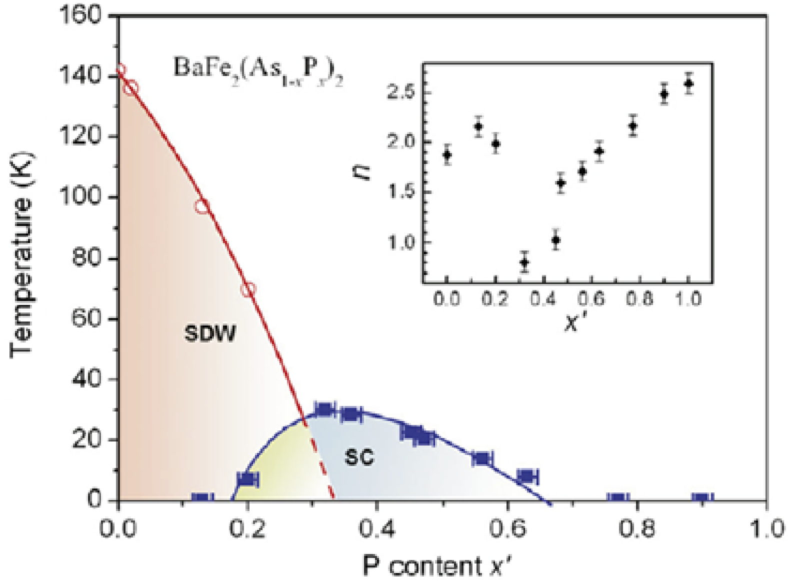
$BaFeAs_{2-x}P_x$

Thaler – PRB 80, 024511



Shuai Jiang

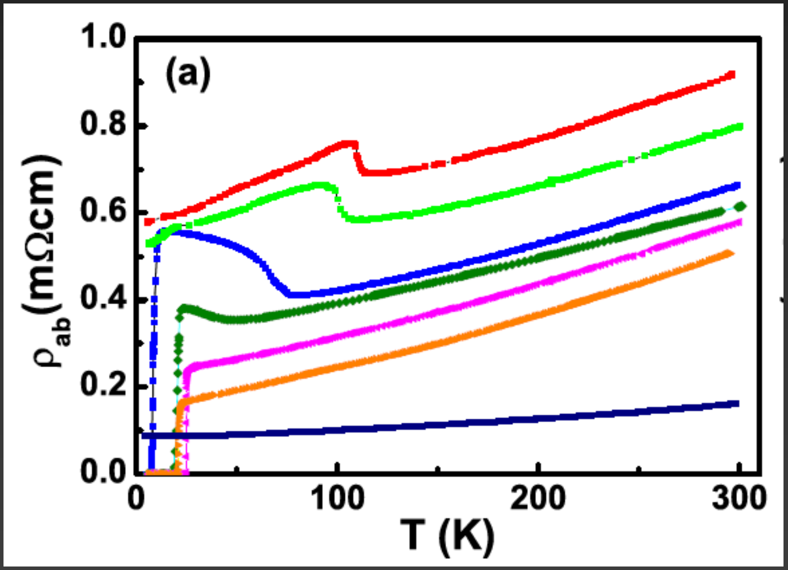
J. Phys.: Condens. Matter **21** (2009) 382203

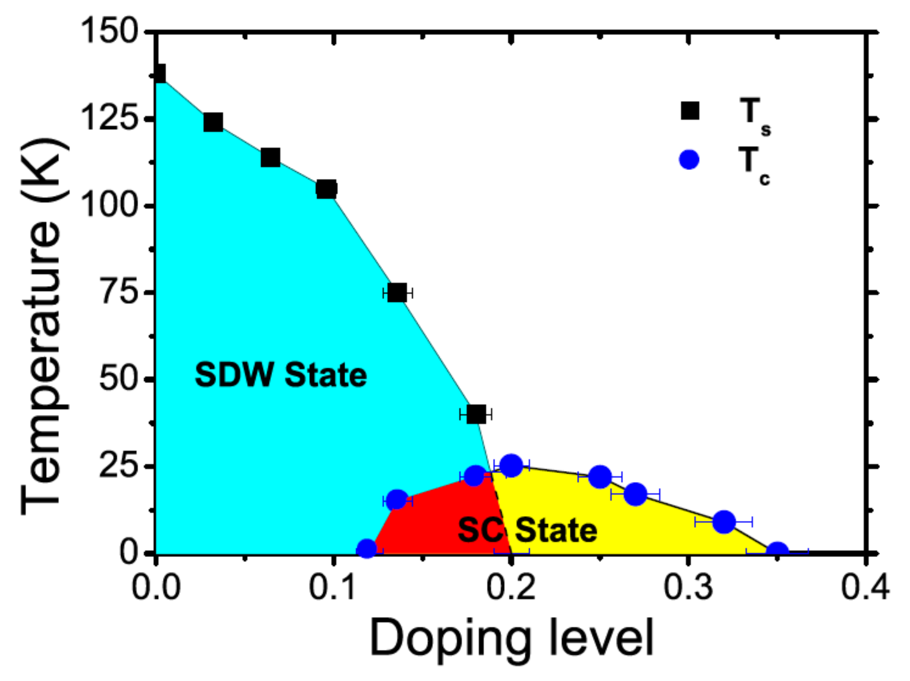


Tuning Phase Diagram

1-2-2 (single crystals)

$BaFe_{2-x}Co_xAs_2$



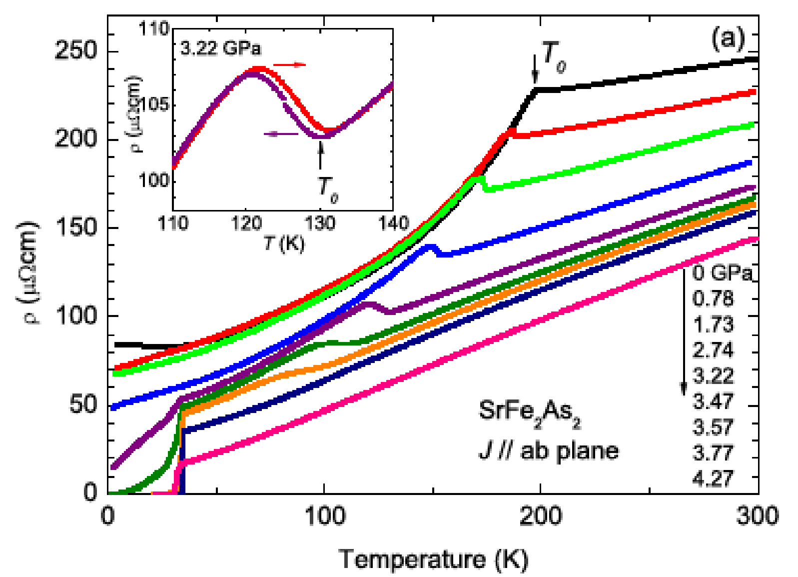


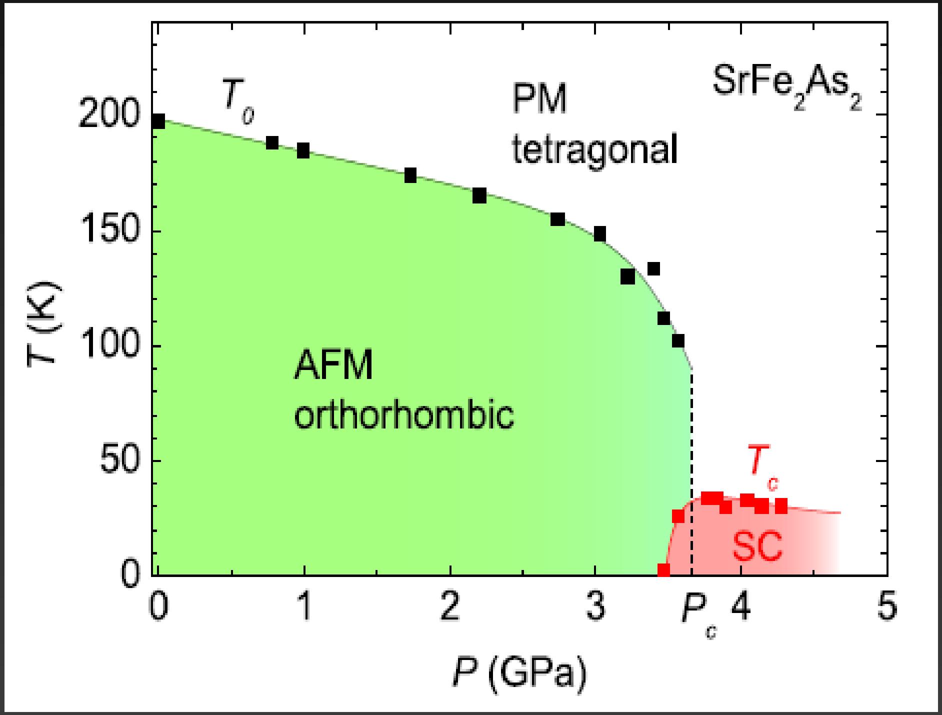
X.F. Wang *et al.* (2008)

Tuning Phase Diagram

1-2-2 (single crystals)

Pressure tuning

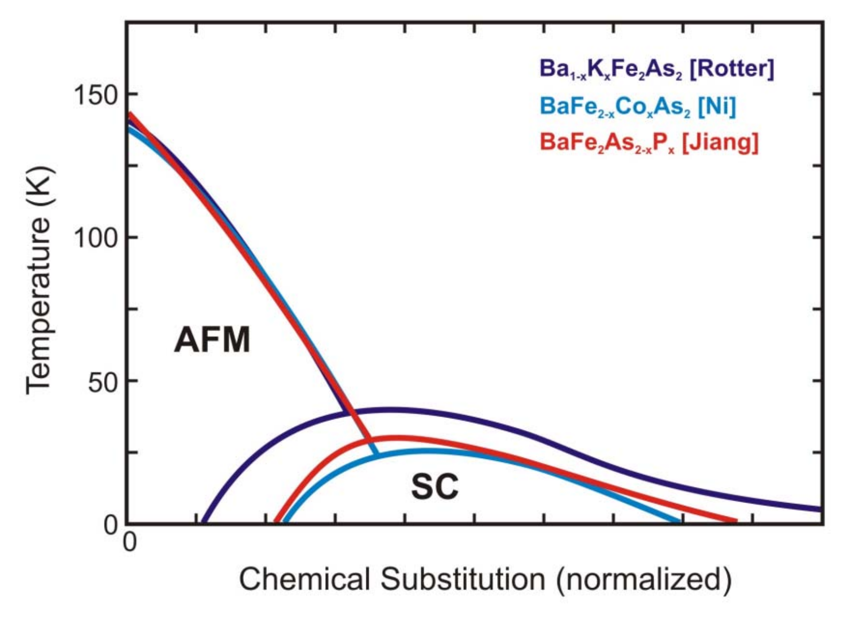


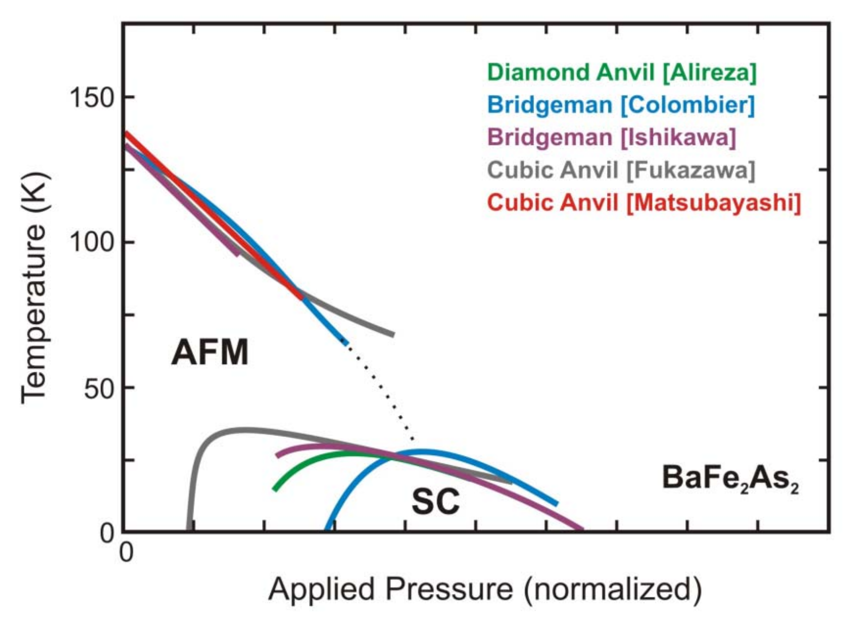


H. Kotegawa *et al.* (2008)

Tuning Phase Diagram

1-2-2 (single crystals)

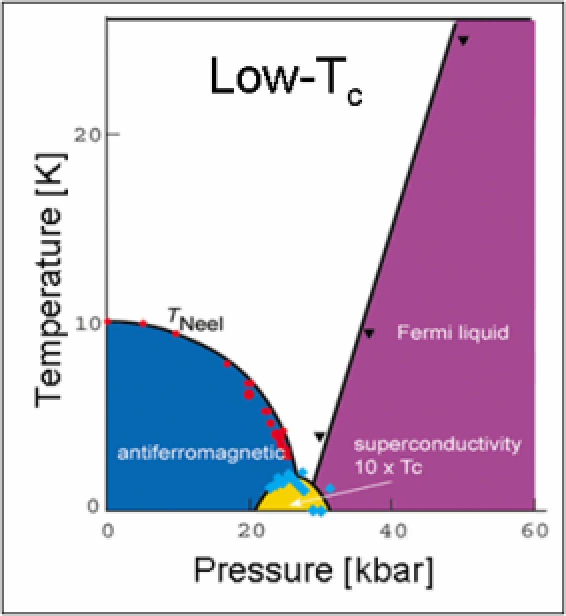


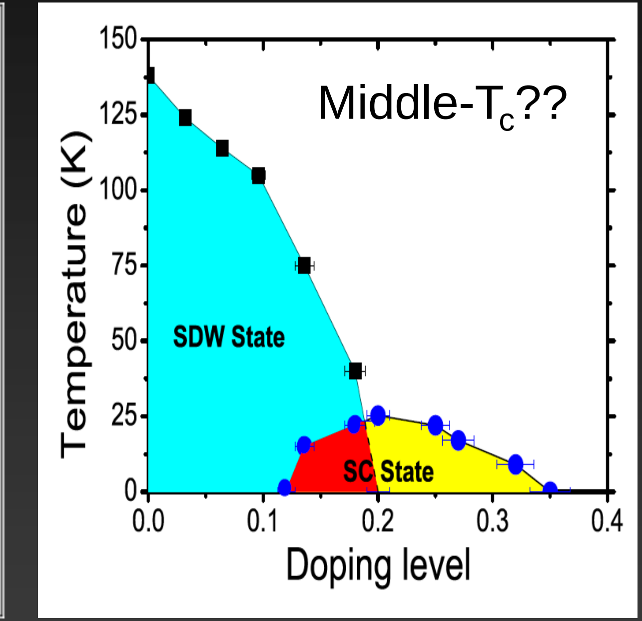


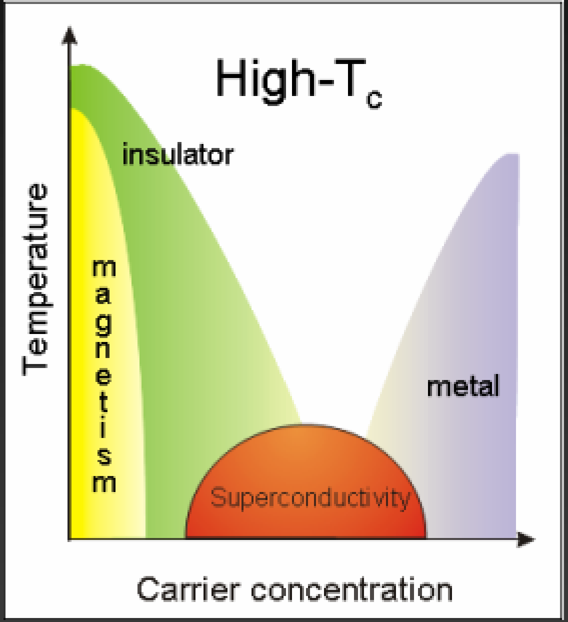
Universal Doping diagram? **Universal Pressure diagram?**

Tuning Phase Diagram

Quantum criticality??







Perhaps!

T-linear transport

Divergent thermopower

Anomalous scaling (non-BCS)

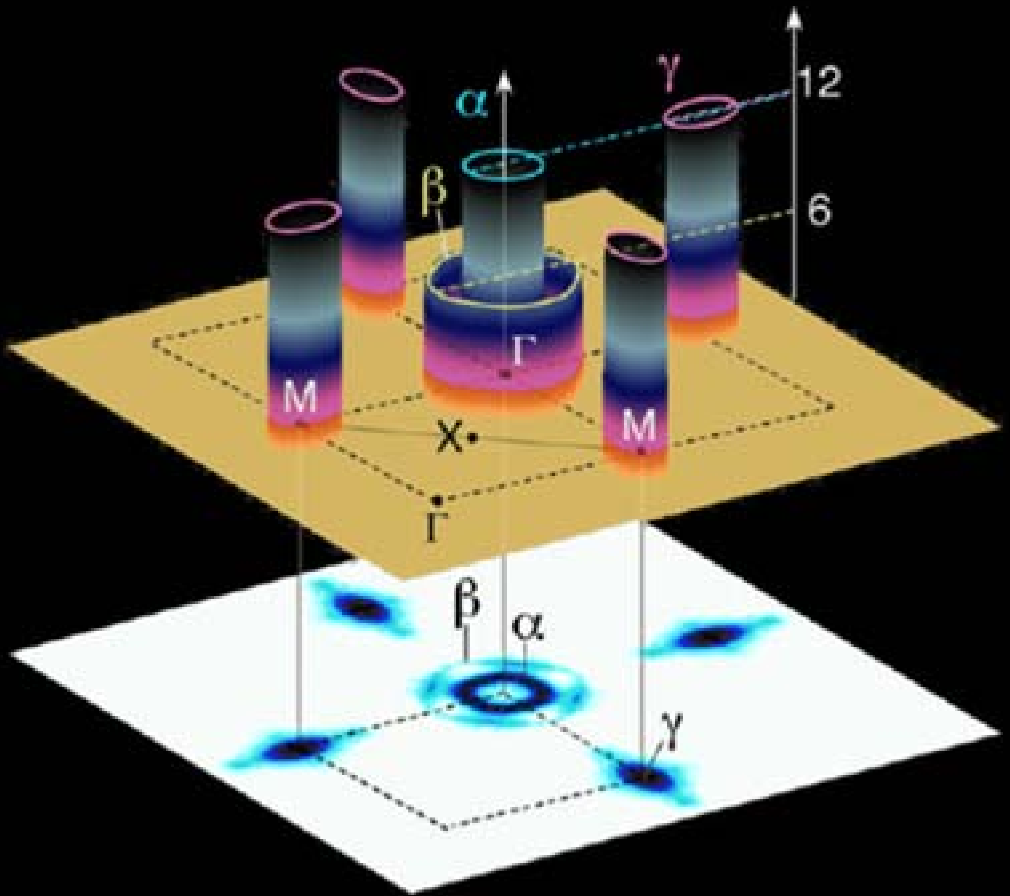
Perhaps Not!

Multi-band transport , WF law

Specific heat entropy balance

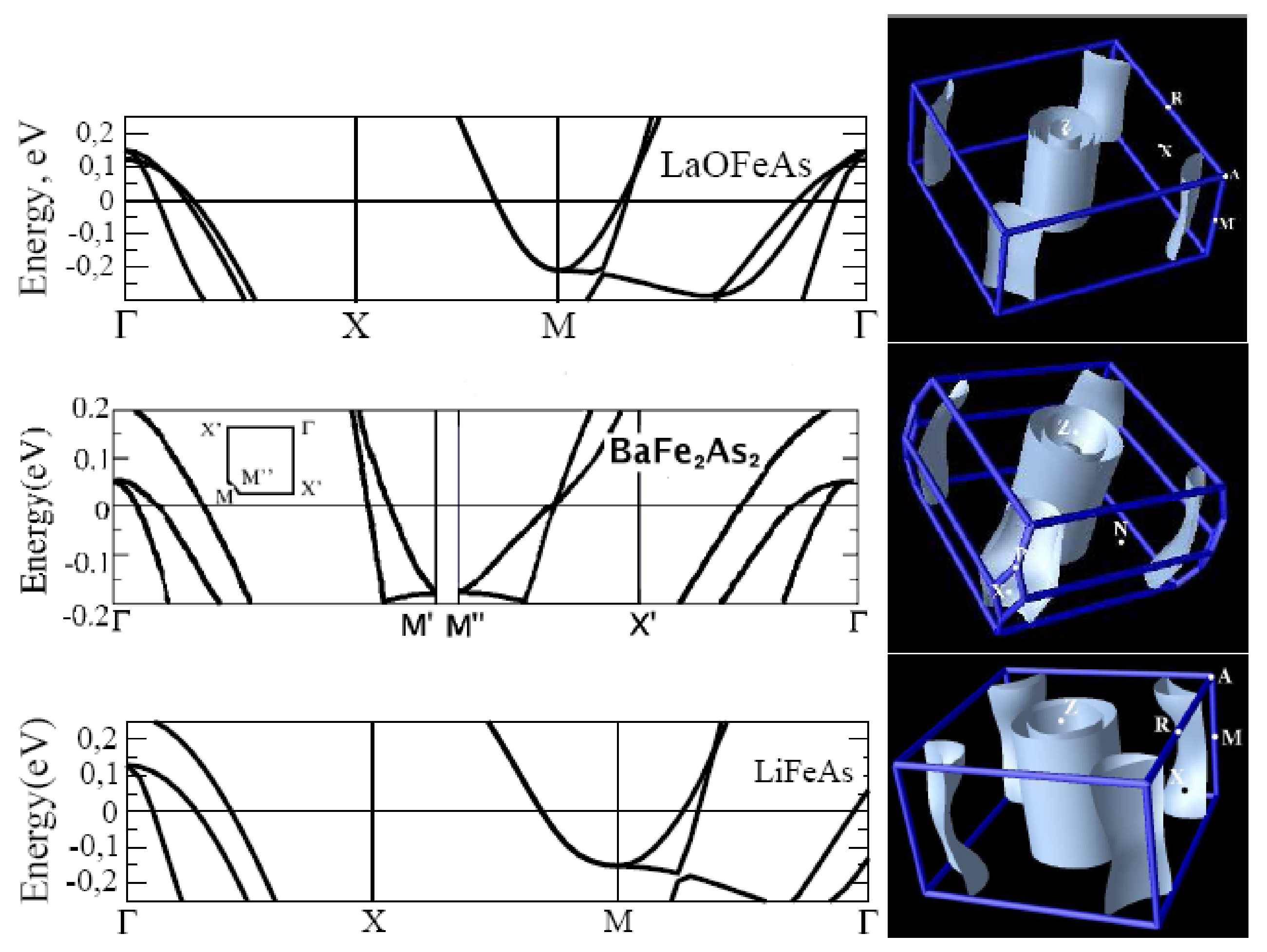
pair-breaking

c) Normal/SC State Properties



Normal State Properties

Quasi-2D band structure

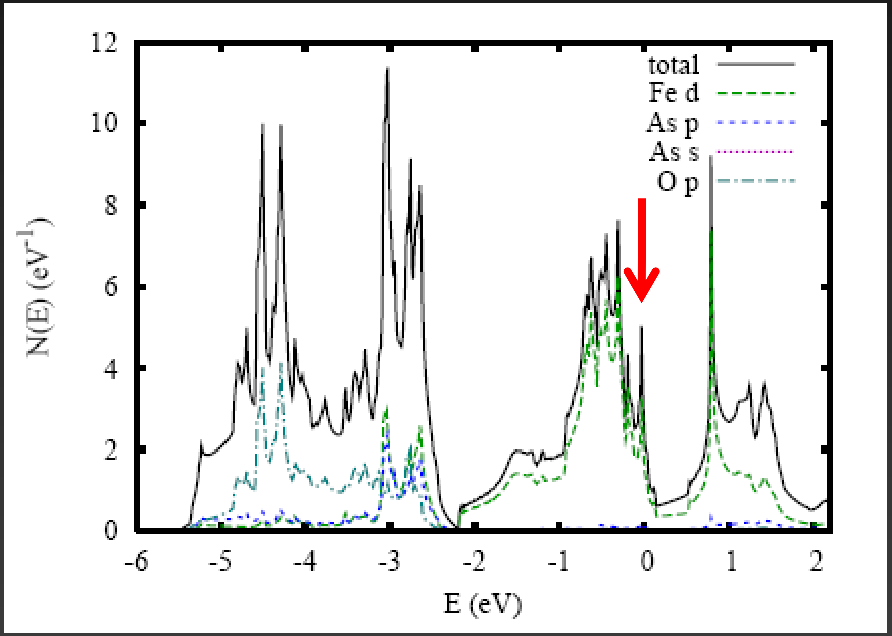


I.A. Nekrasov *et al.* (2008)

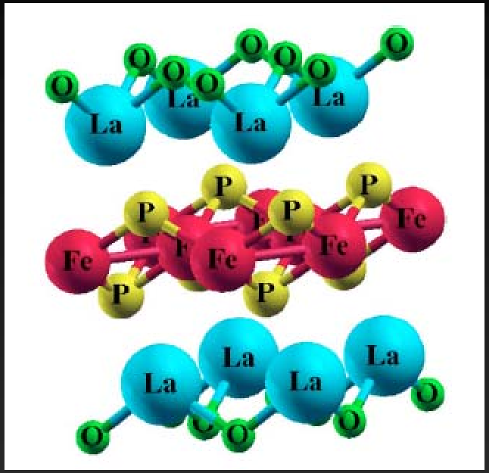
CeCoIn$_5$: Band Structure

Normal State Properties

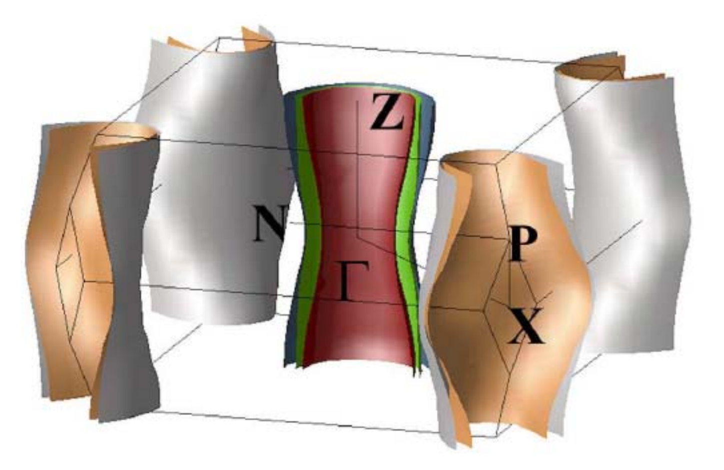
Fe-dominated DOS



D. J. Singh *et al.* (2008)



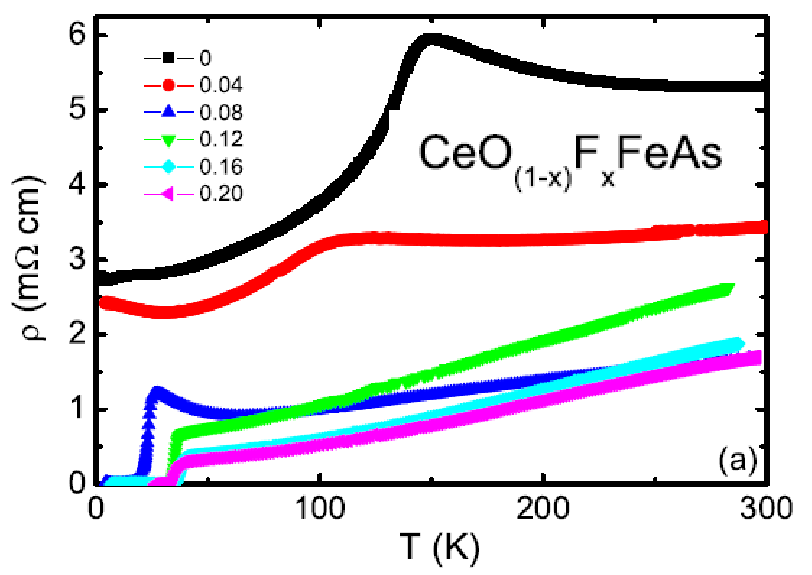
S. Lebègue *et al.* (2007)



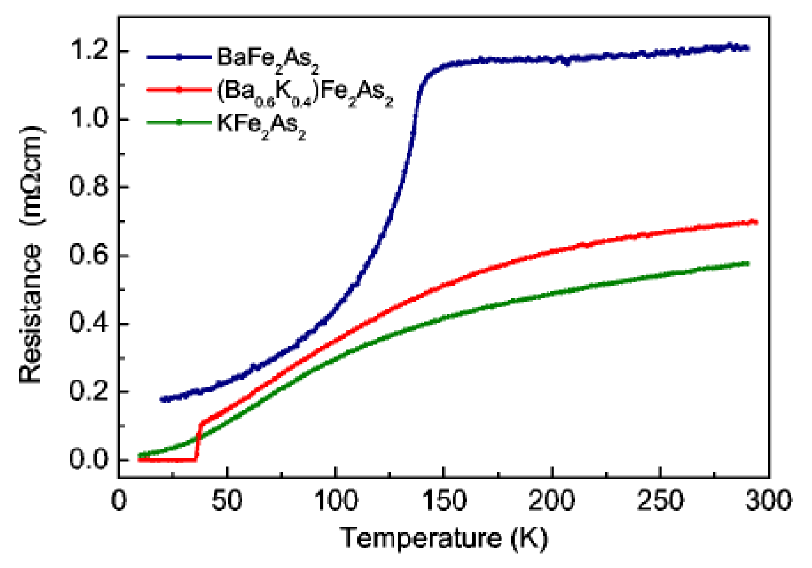
R.T. Gordon *et al.* (2007)

Normal State Properties

Metallic compounds



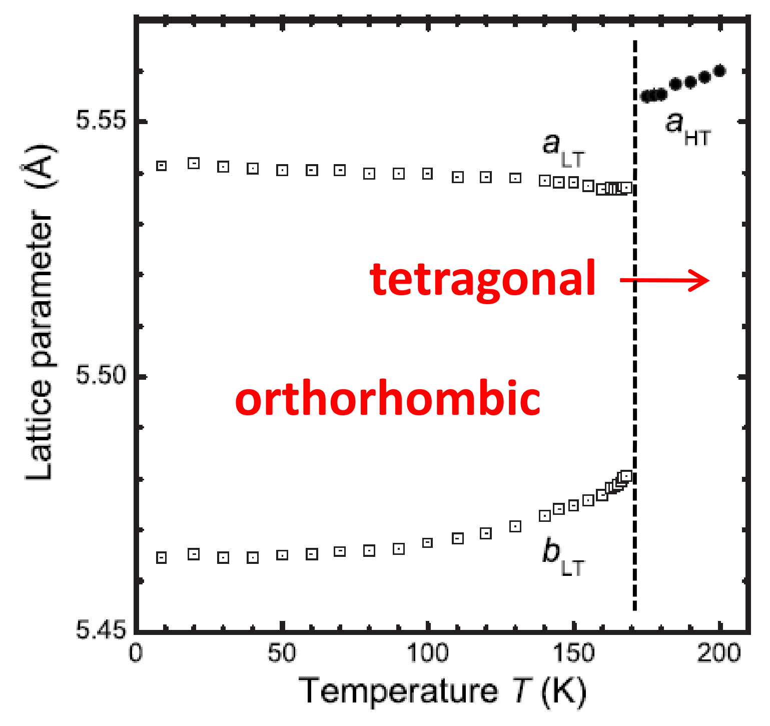
G.F. Chen *et al.* (2008)



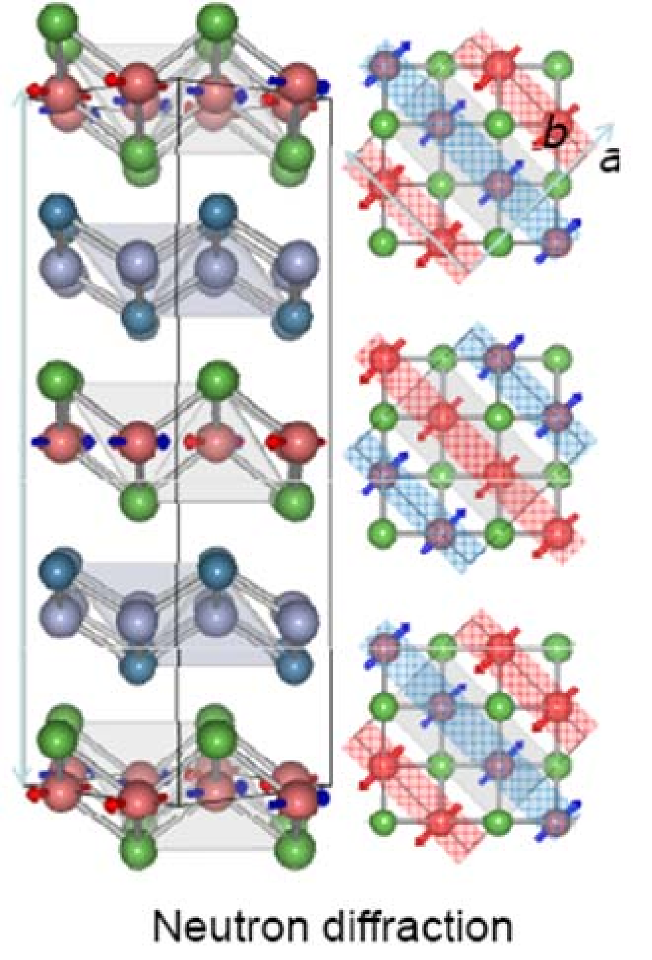
M. Rotter *et al.* (2008)

Normal State Properties

Structural/magnetic transition



N. Ni *et al.* (2008)



Neutron diffraction

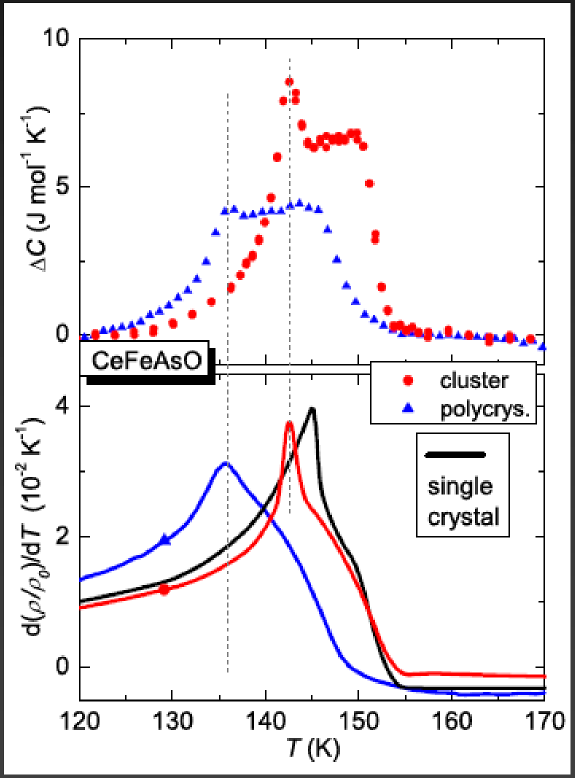
structural transition

AFM transition

Normal State Properties

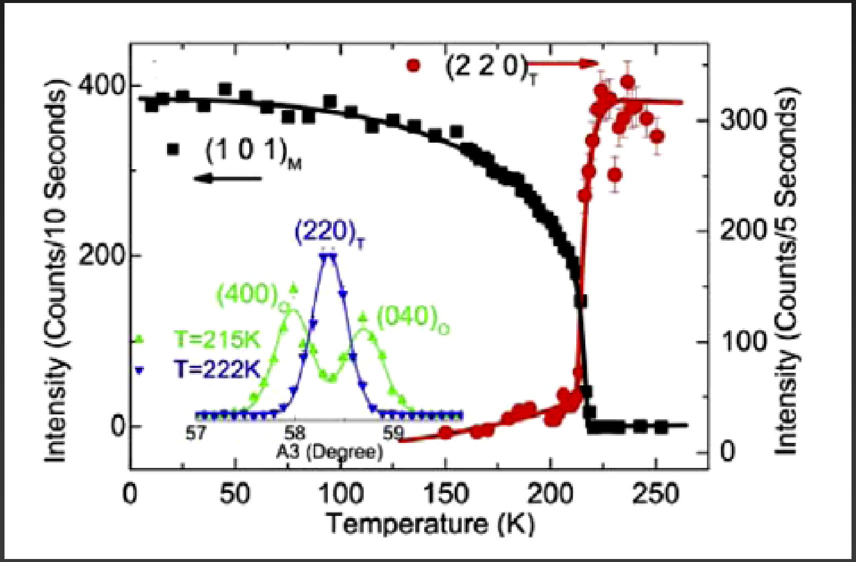
Structural/magnetic transition

CeFeAsO



A. Jesche *et al.* (2008)

$SrFe_2As_2$



J. Zhao *et al.* (2008)

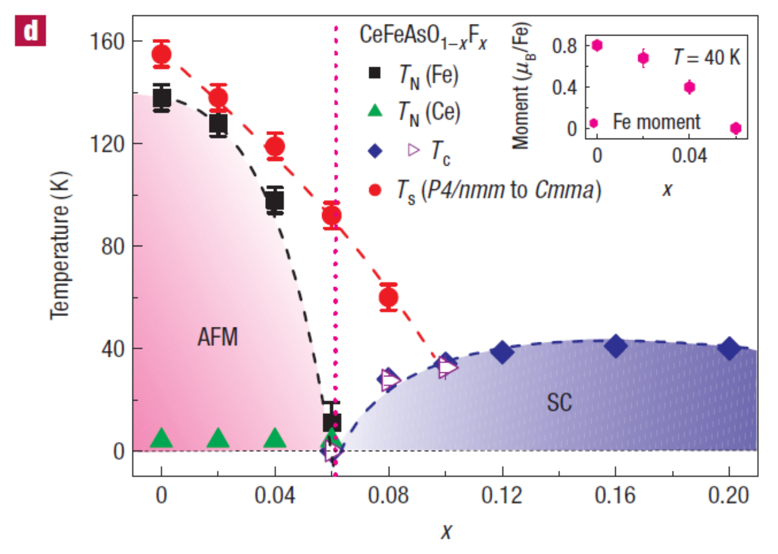
decoupled transitions

coincident transitions

Normal State Properties

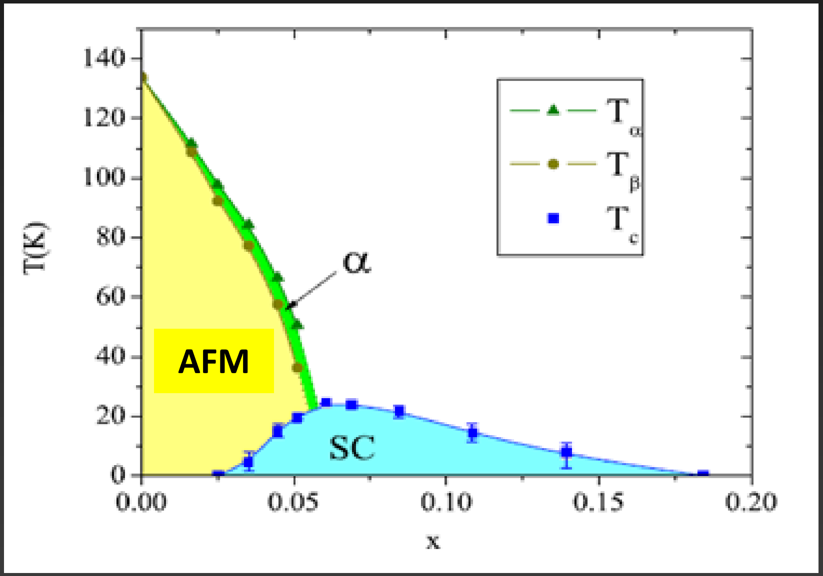
Structural/magnetic transition

CeFeAs(O,F)



J. Zhao *et al.* (2008)

Ba(Fe,Co)$_2$As$_2$



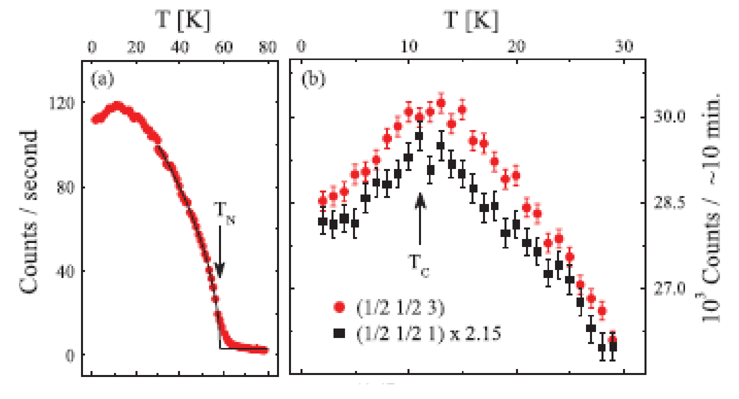
Chu *et al.* (2009)

Remains decoupled with doping

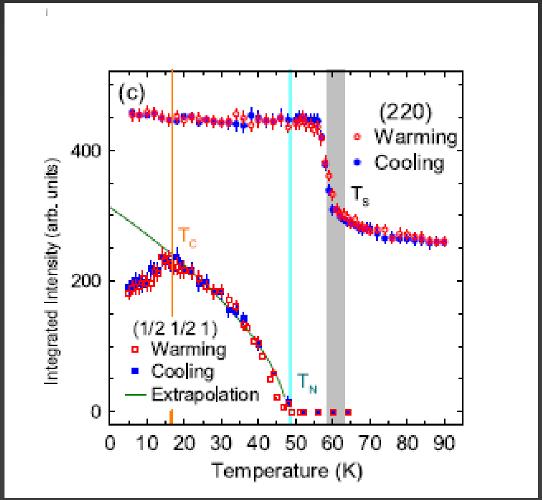
Decouples with doping

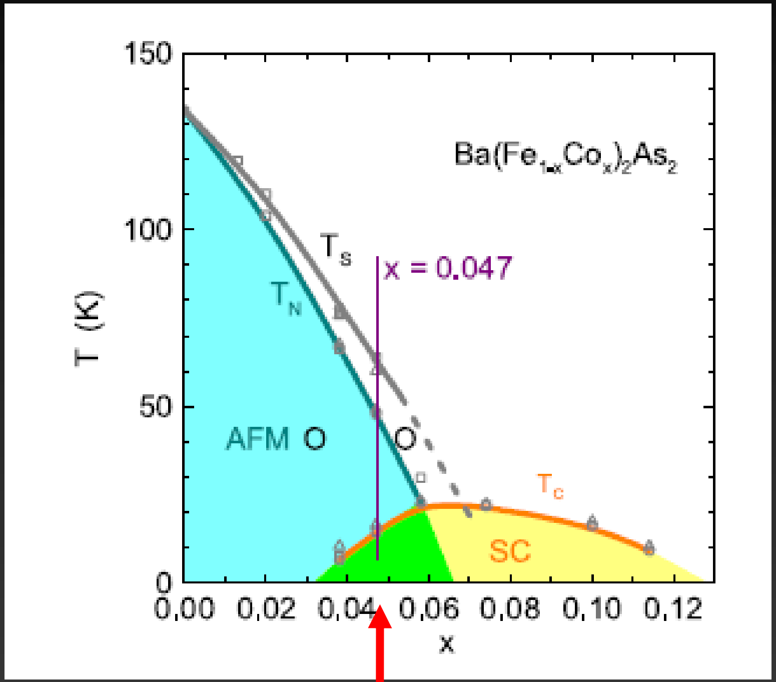
Normal State Properties

Structural/magnetic transition



A.D. Christianson *et al.* (2009)





D.K. Pratt *et al.* (2009)

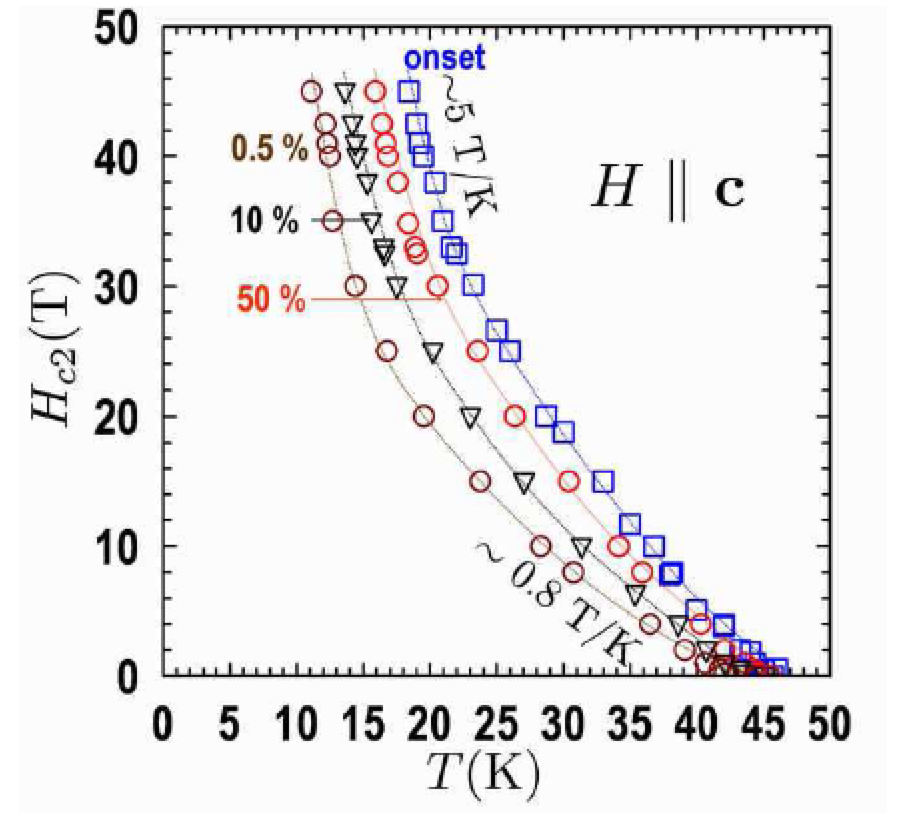
Competitive coexistence

Superconducting state properties

Upper critical field

- ~ 50 - 100 Tesla
- Less anisotropic than cuprates
- better pinning

$NdO_{0.7}F_{0.3}FeAs$

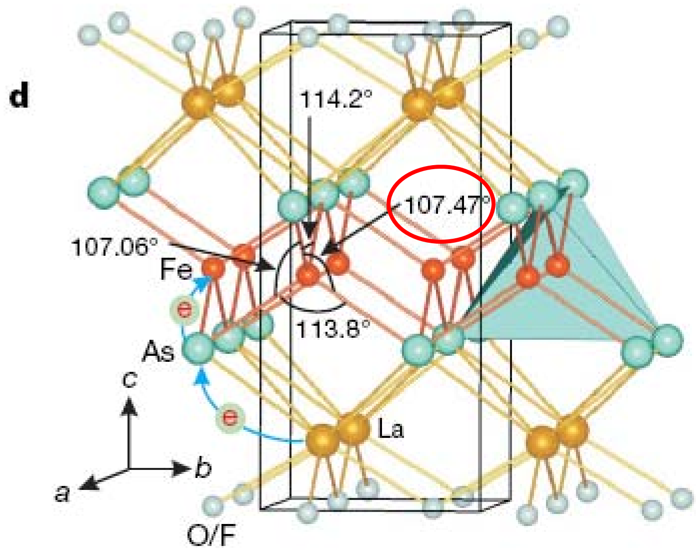


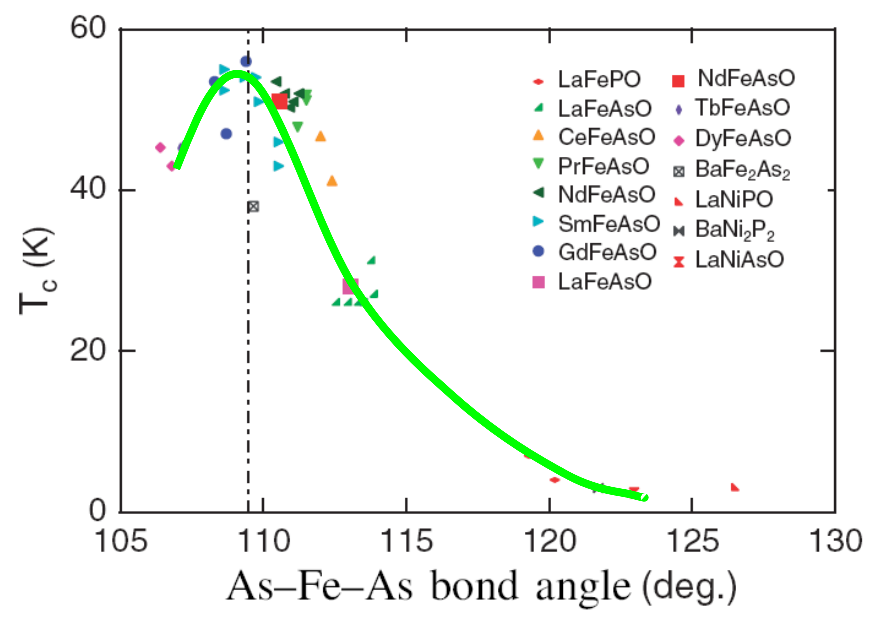
J. Jaroszynski *et al.* (2008)

Superconducting state properties

Structural tuning?

Fe-As-Fe bond angle





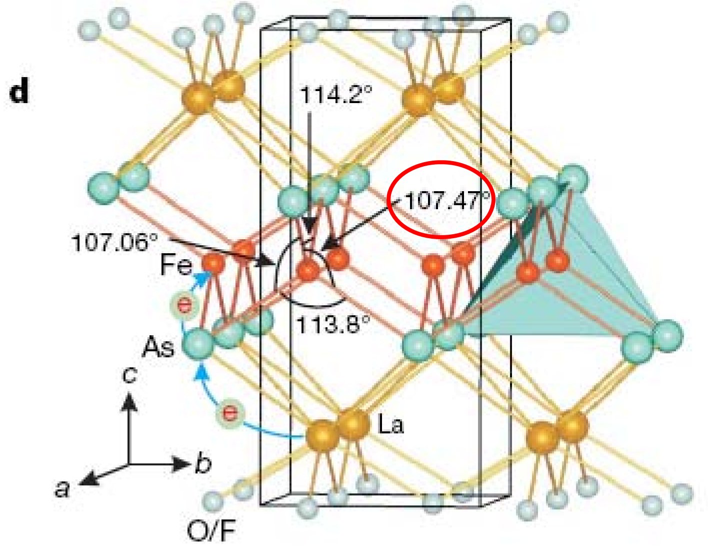
T_c vs As-Fe-As angle

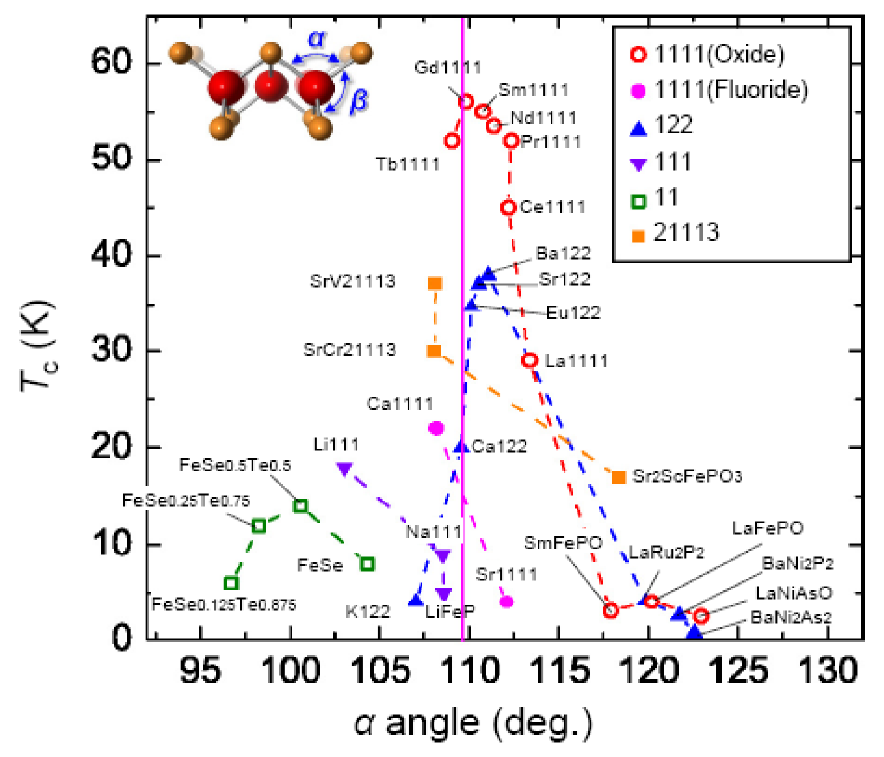
J. Zhao *et al.* (2008)

Superconducting state properties

Structural tuning?

Fe-As-Fe bond angle





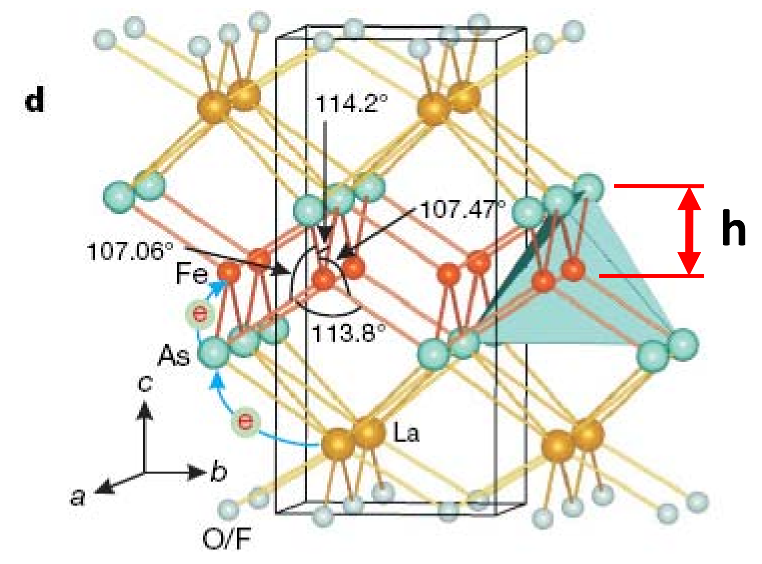
T_c vs **As-Fe-As angle**

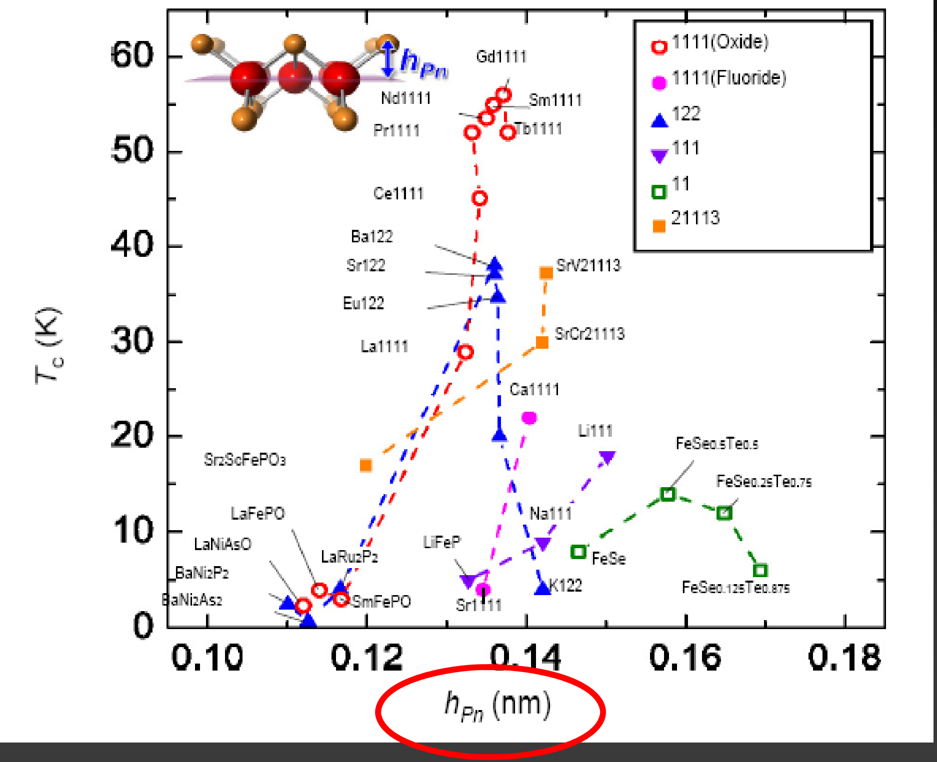
Hosono – ISS (2010)

Superconducting state properties

Structural tuning?

Fe-As-Fe bond angle





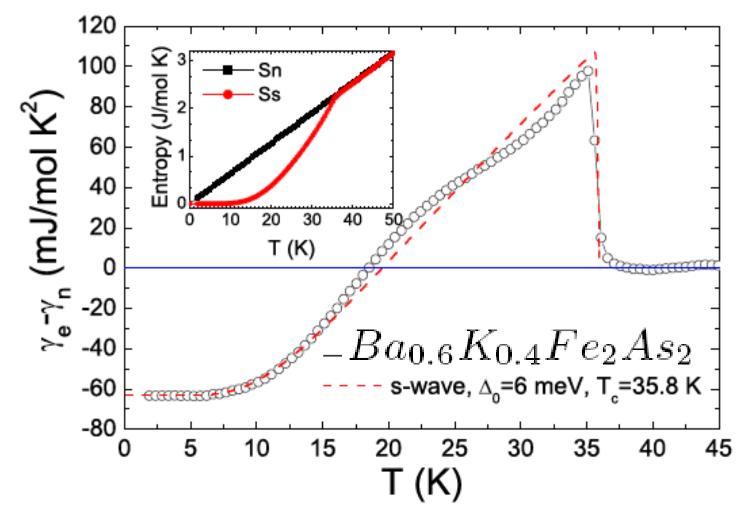
T_c vs **anion height**

Hosono – ISS (2010)

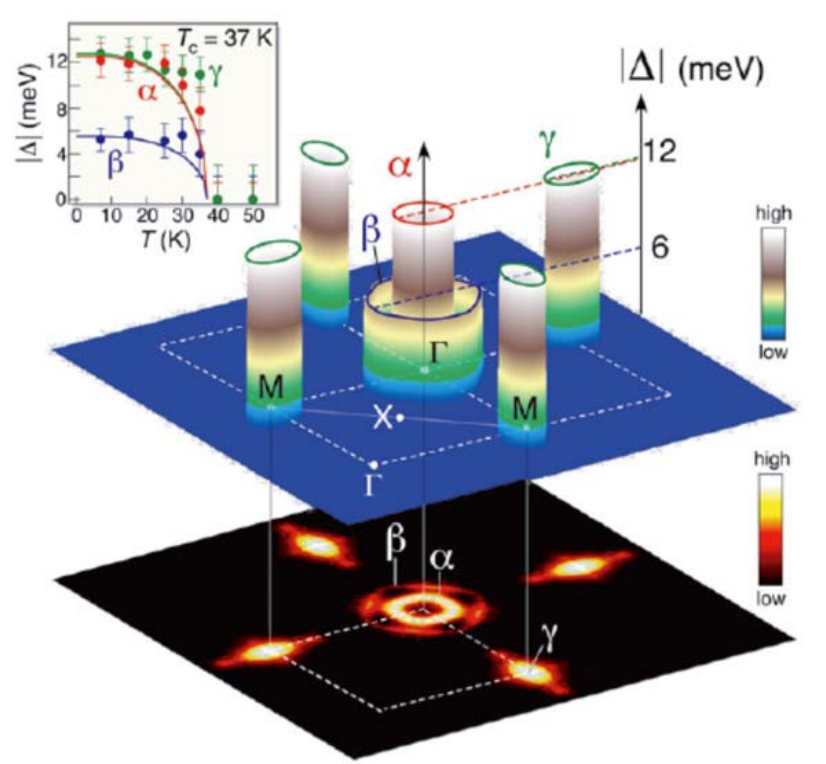
Superconducting state properties

Conventional BCS?

fully gapped s-wave



G. Mu *et al.* (2008)

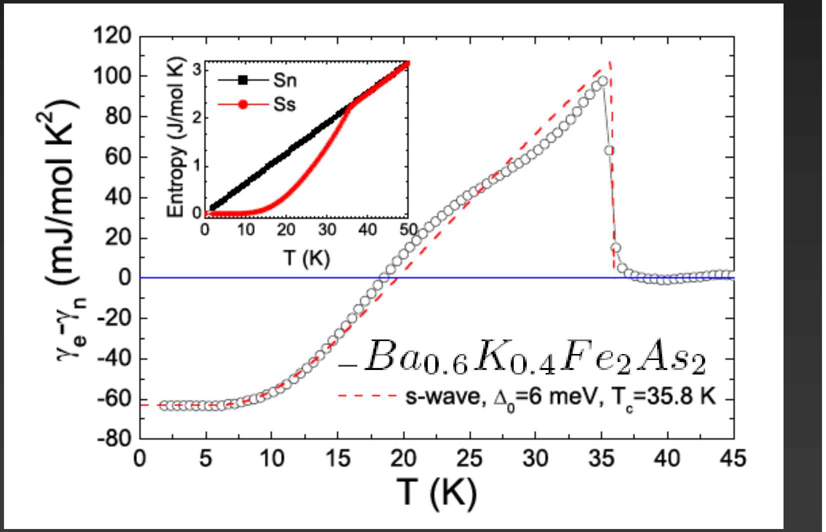


Ding *et al.* (2008)

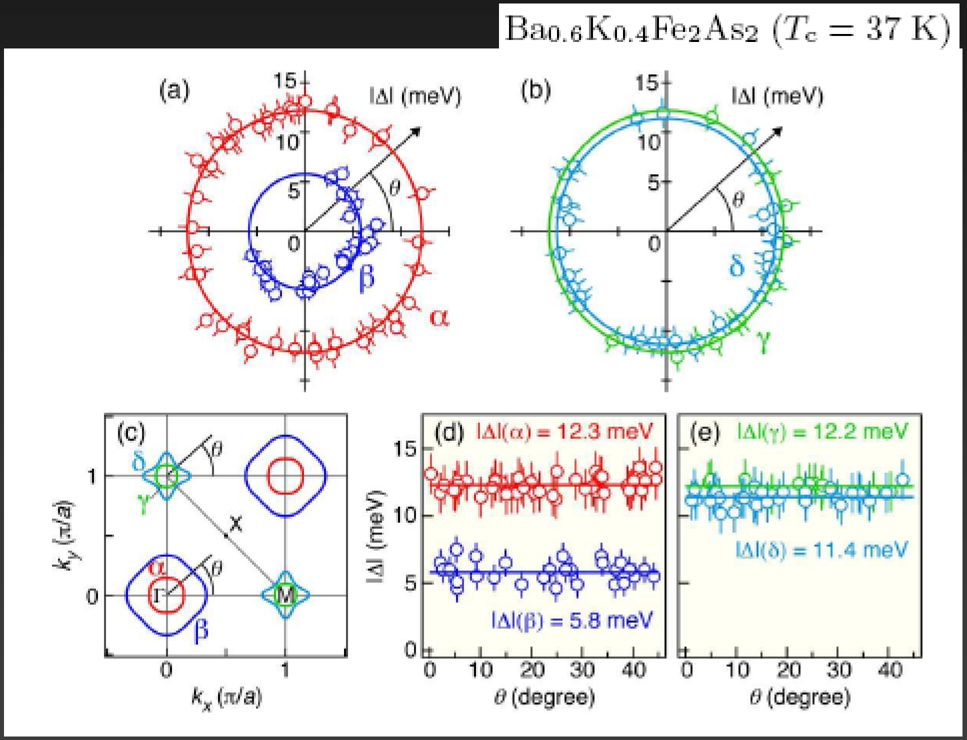
Superconducting state properties

Conventional BCS?

fully gapped s-wave



G. Mu *et al.* (2008)



K. Nakayama *et al.* (2008)

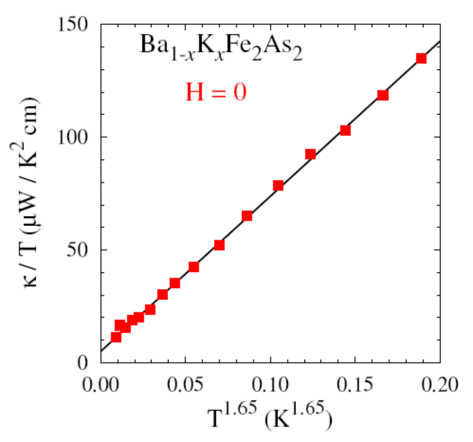
Superconducting state properties

Conventional BCS?

Thermal conductivity:

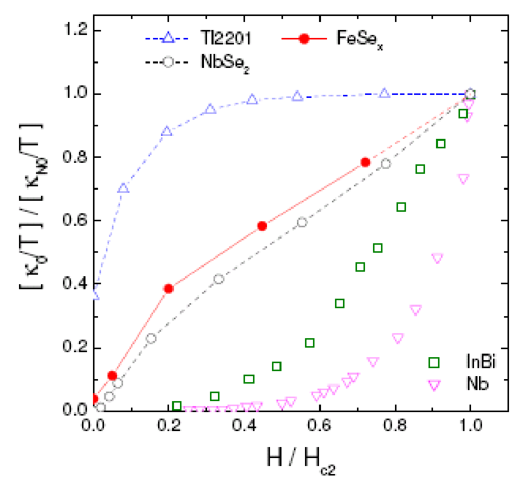
No (H=0) low-energy quasiparticles

$Ba_{1-x}K_xFe_2As_2$



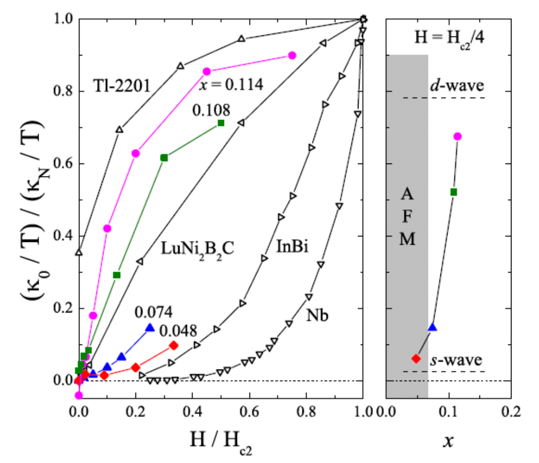
X.G. Luo *et al.* (2009)

FeSe



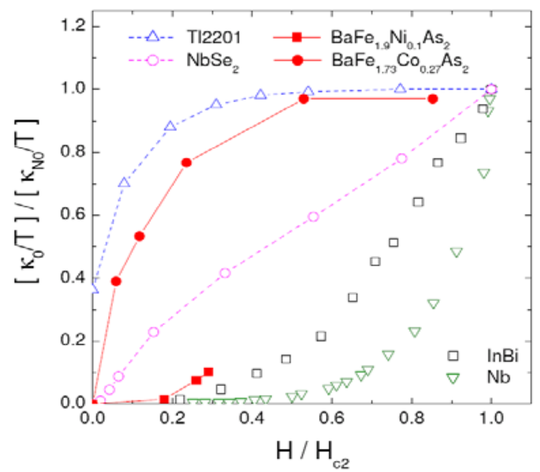
J.K. Dong *et al.* (2009)

$BaFe_{2-x}Co_xAs_2$



M.A. Tanatar *et al.* (2009)

$BaFe_{2-x}Ni_xAs_2$

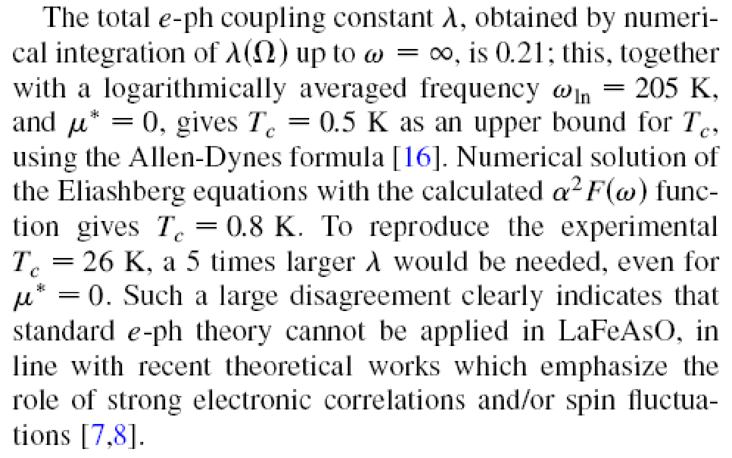


L. Ding *et al.* (2009)

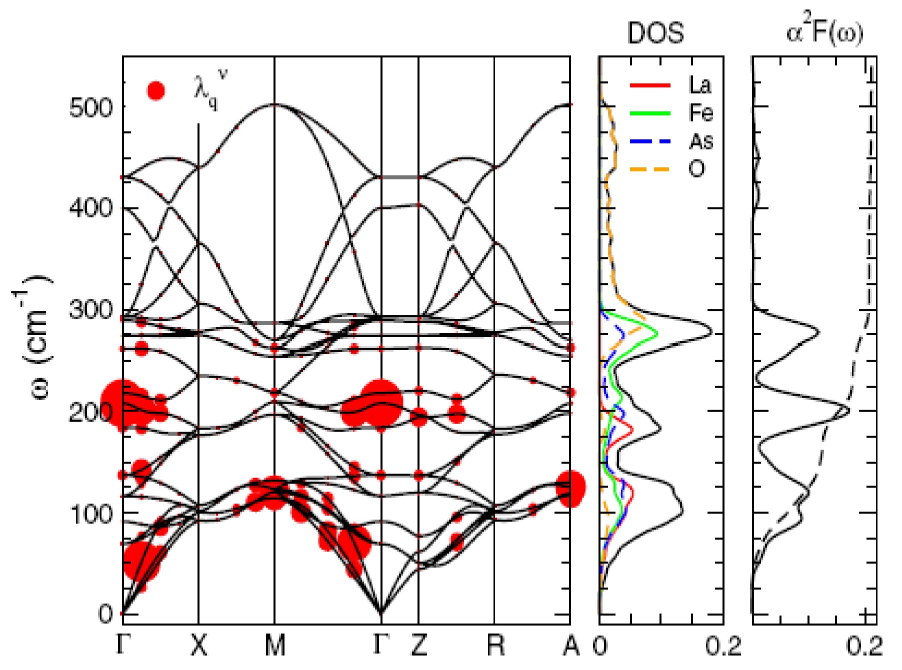
Superconducting state properties

Or unconventional?

Likely not (only) phonons…



The total e-ph coupling constant λ, obtained by numerical integration of $\lambda(\Omega)$ up to $\omega = \infty$, is 0.21; this, together with a logarithmically averaged frequency $\omega_{\ln} = 205$ K, and $\mu^* = 0$, gives $T_c = 0.5$ K as an upper bound for T_c, using the Allen-Dynes formula [16]. Numerical solution of the Eliashberg equations with the calculated $\alpha^2F(\omega)$ function gives $T_c = 0.8$ K. To reproduce the experimental $T_c = 26$ K, a 5 times larger λ would be needed, even for $\mu^* = 0$. Such a large disagreement clearly indicates that standard e-ph theory cannot be applied in LaFeAsO, in line with recent theoretical works which emphasize the role of strong electronic correlations and/or spin fluctuations [7,8].

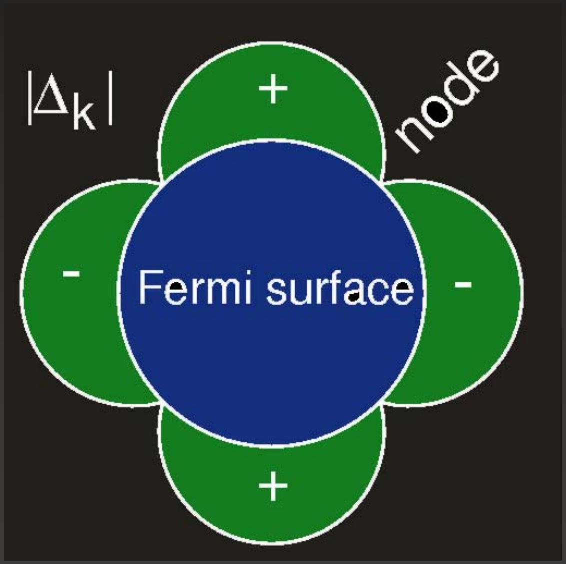


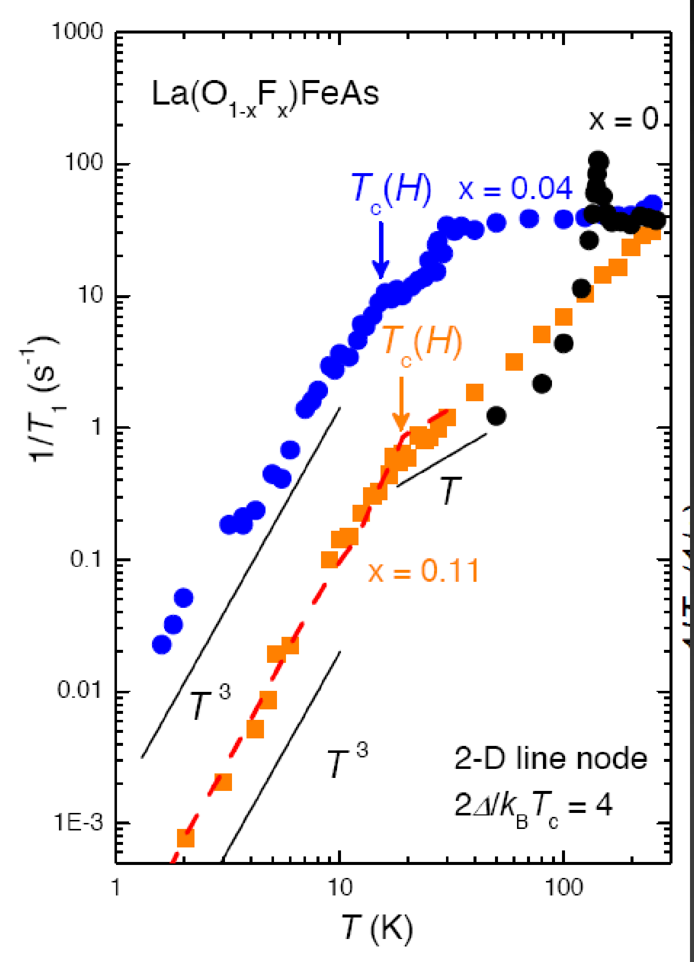
L. Boeri *et al.* (2008)

Superconducting state properties

Or unconventional?

Power law in T1-NMR



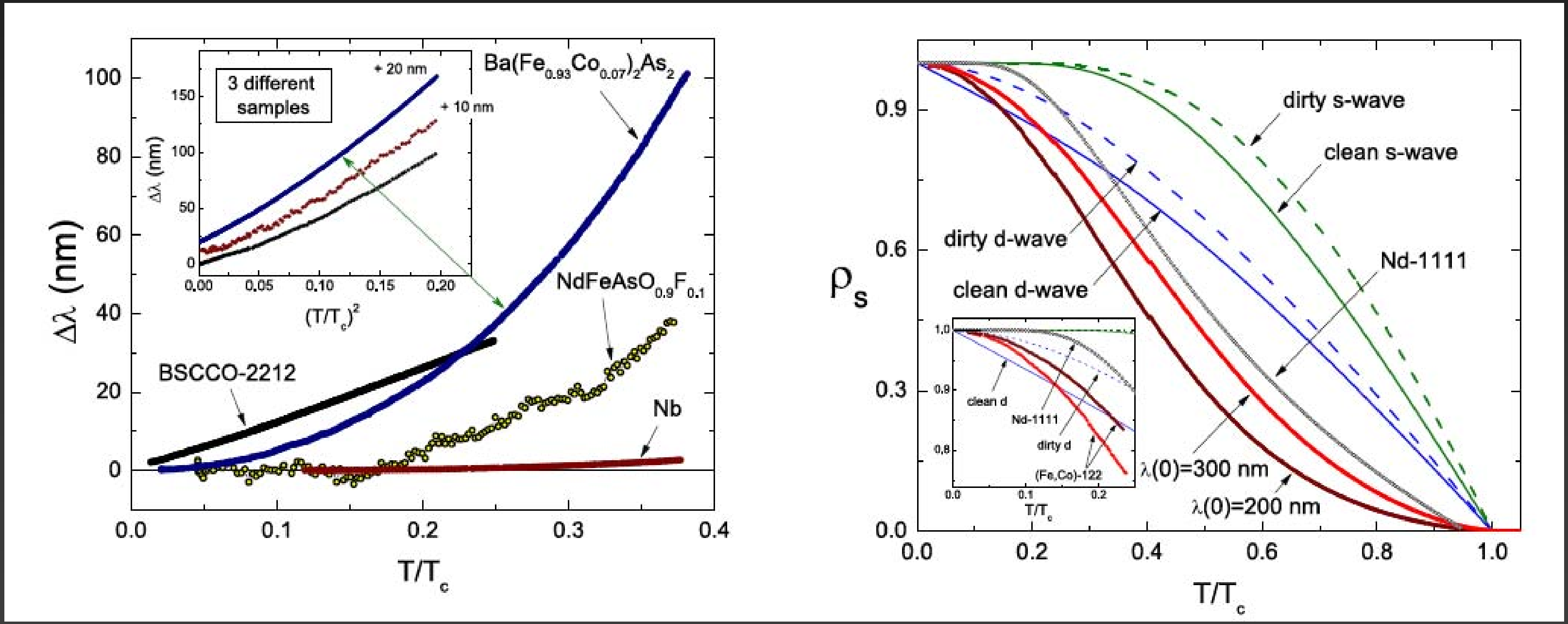


Y. Nakai *et al.* (2008)

Superconducting state properties

Or unconventional?

Varying penetration depth



R.T. Gordon *et al.* (2008)

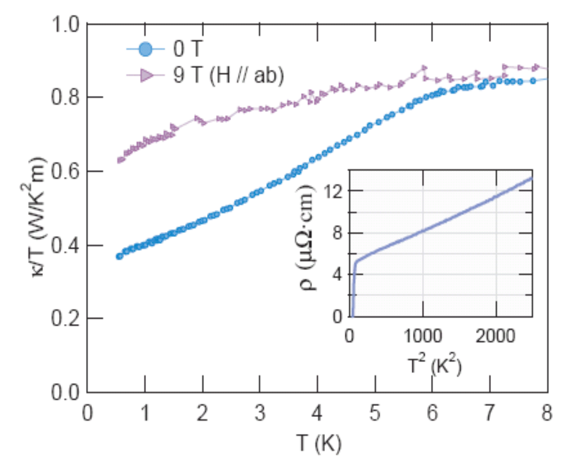
Superconducting state properties

Or unconventional?

Thermal conductivity:

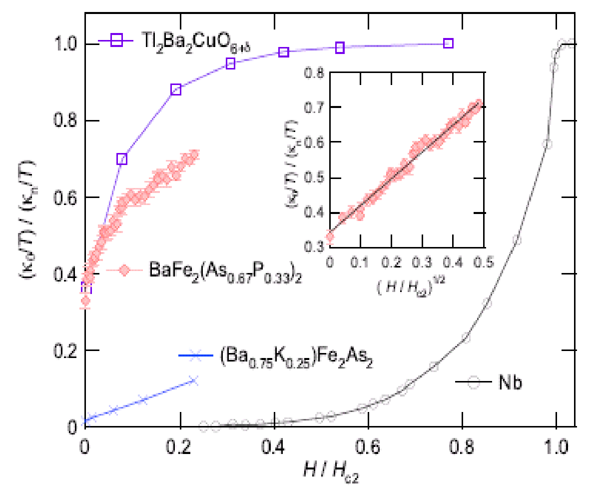
low-energy quasiparticles!

LaFePO



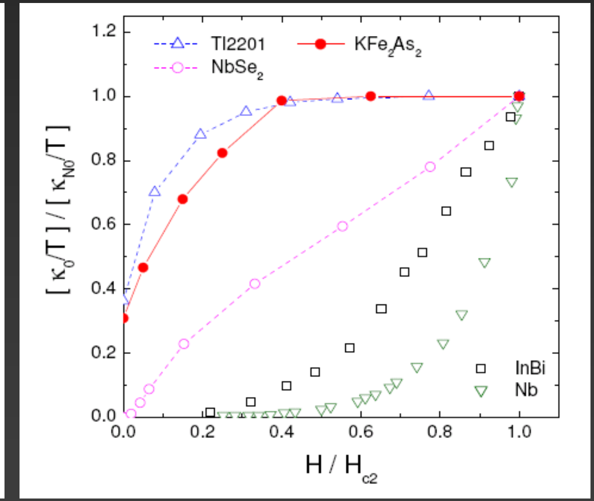
M. Yamashita *et al.* (2009)

$BaFe_2As_{2-x}P_x$



K. Hashimoto *et al.* (2009)

$Sr_{1-x}K_xFe_2As_2$ (x=1)



J.K. Dong *et al.* (2009)

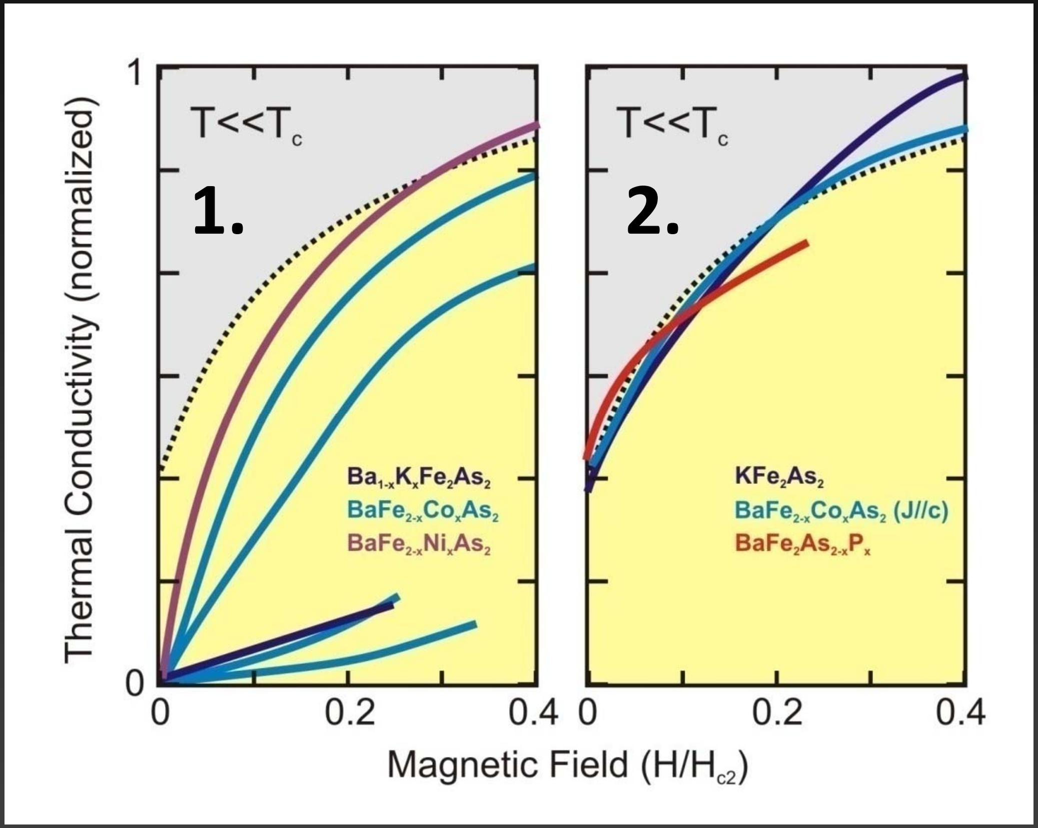
Superconducting state properties

Or unconventional?

Thermal conductivity:

1. Low-energy (gapped) excitations

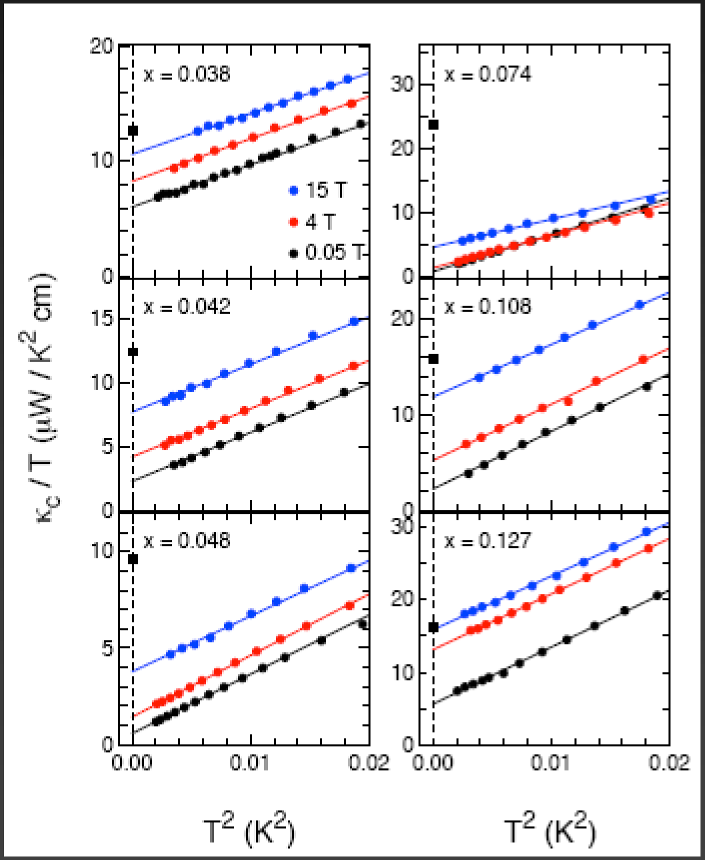
2. Nodal excitations

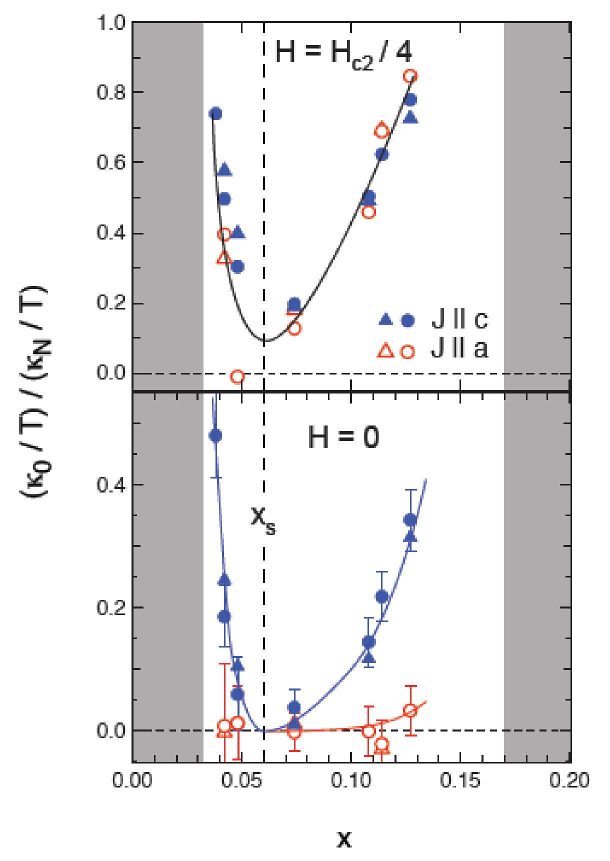


Superconducting state properties

Or unconventional?

BaFe$_{2-x}$Co$_x$As$_2$ (c-axis current)





J.P. Reid *et al.* (2010)

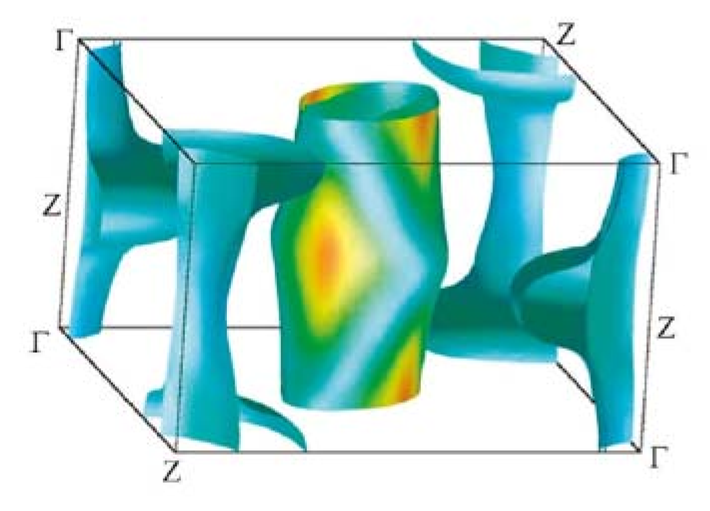
Superconducting state properties

Or unconventional?

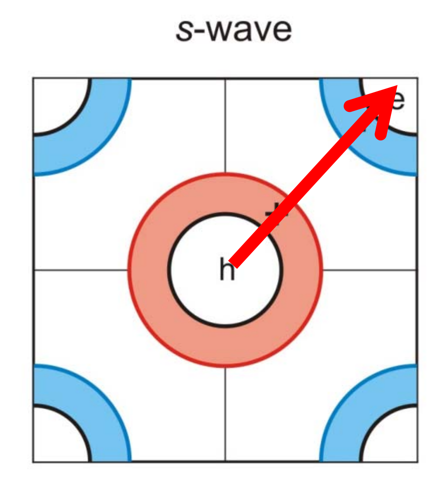
Multi-band

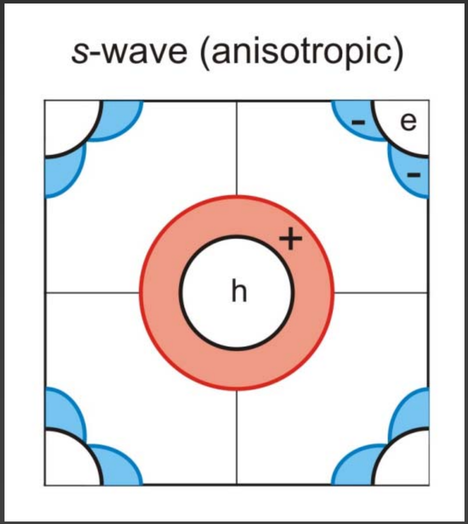
"extended s" or s+/-

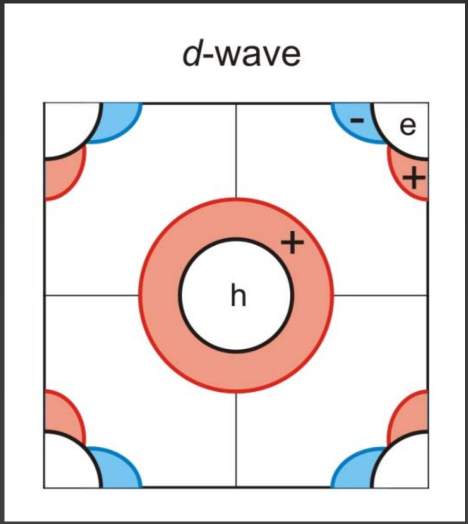
order parameter



D.J. Singh (2008)


s-wave


s-wave (anisotropic)


d-wave

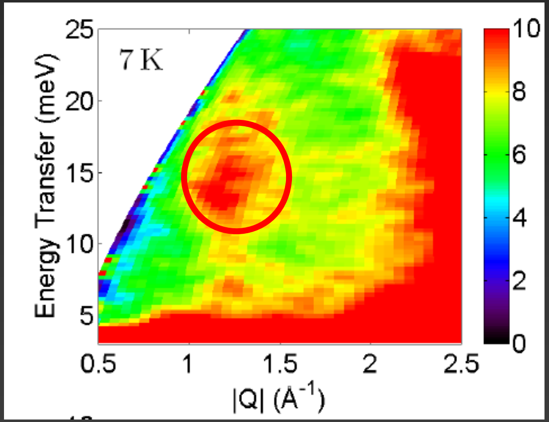
Superconducting state properties

Magnetic Resonance

$Ba_{1-x}K_xFe_2As_2$

T_c = 37 K, E = 14 meV

→ $2\Delta \approx 4.4K_BT_c$

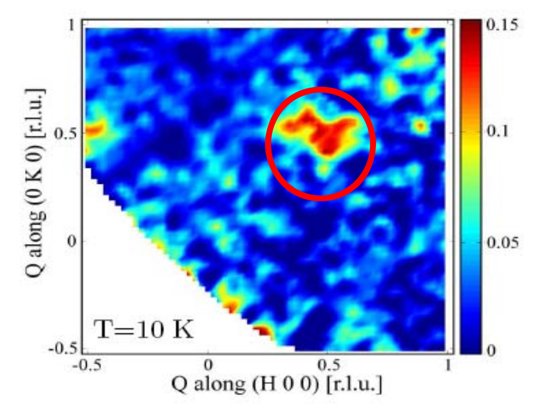


A.D. Christianson *et al.* (2008)

$BaFe_{2-x}Co_xAs_2$

T_c = 22 K, E = 9.6 meV

→ $2\Delta \approx 5K_BT_c$

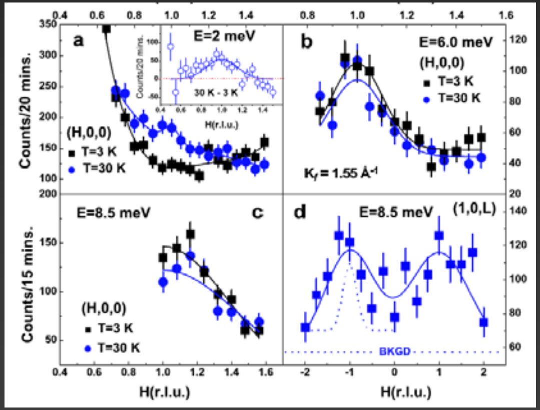


M.D. Lumsden *et al.* (2008)

$BaFe_{2-x}Ni_xAs_2$

T_c = 20 K, E = 8.5 meV

→ $2\Delta \approx 5K_BT_c$



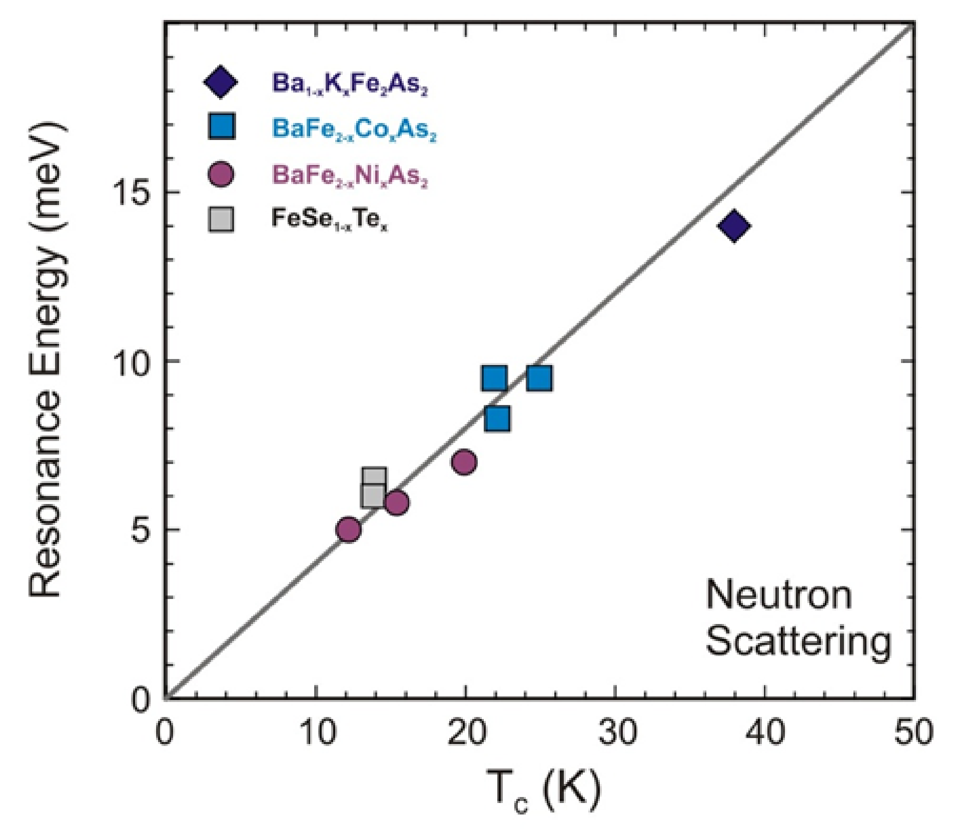
S. Chi *et al.* (2008)

Superconducting state properties

Magnetic Resonance

- reduced magnon damping

- intrinsic magnetic mechanism



Superconducting state properties

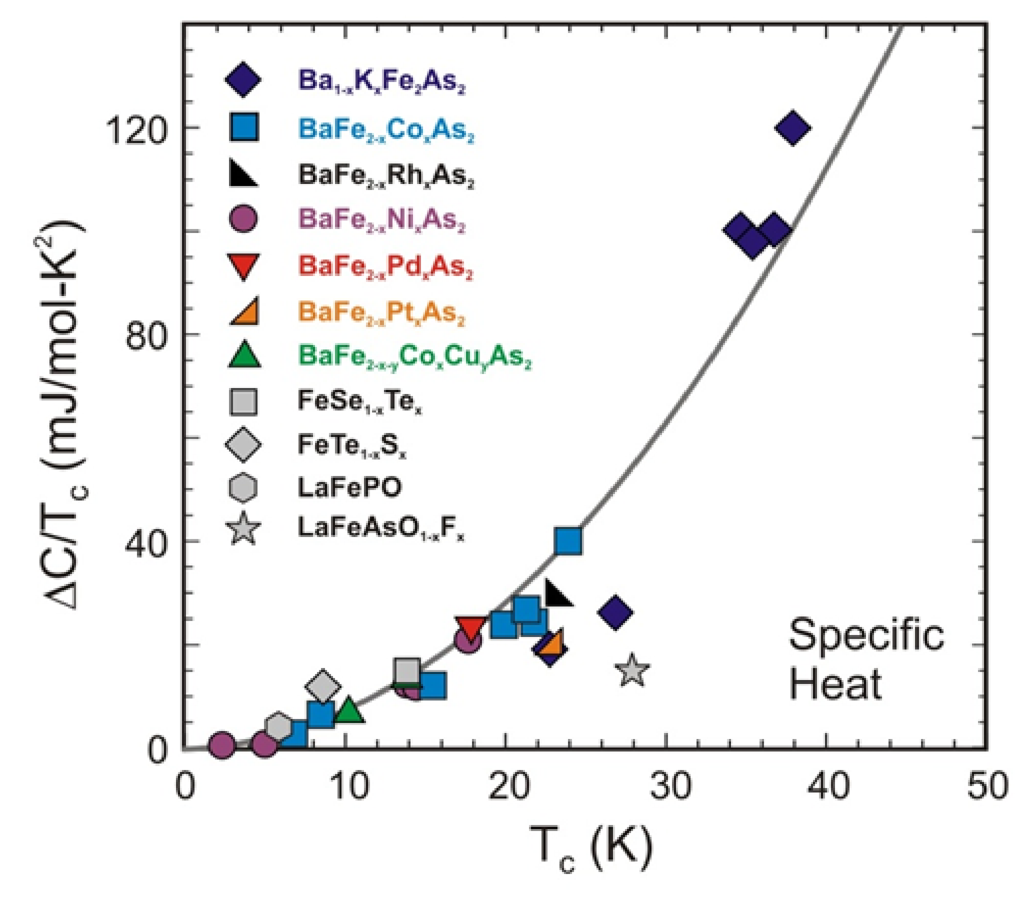
Specific Heat Scaling

- pair-breaking origin

(Kogan)

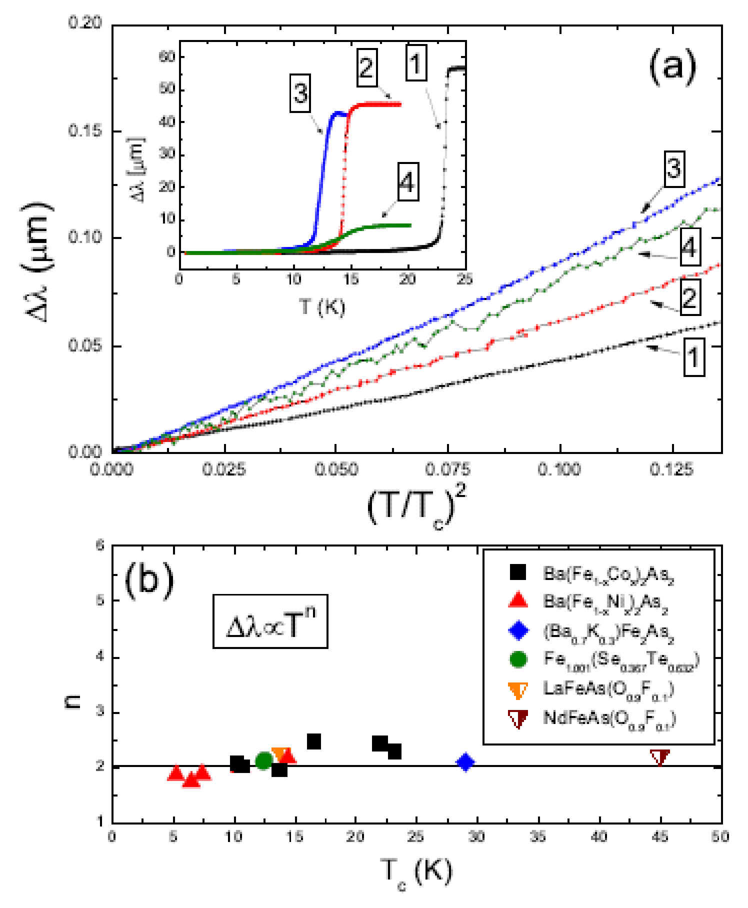
-Quantum critical scaling

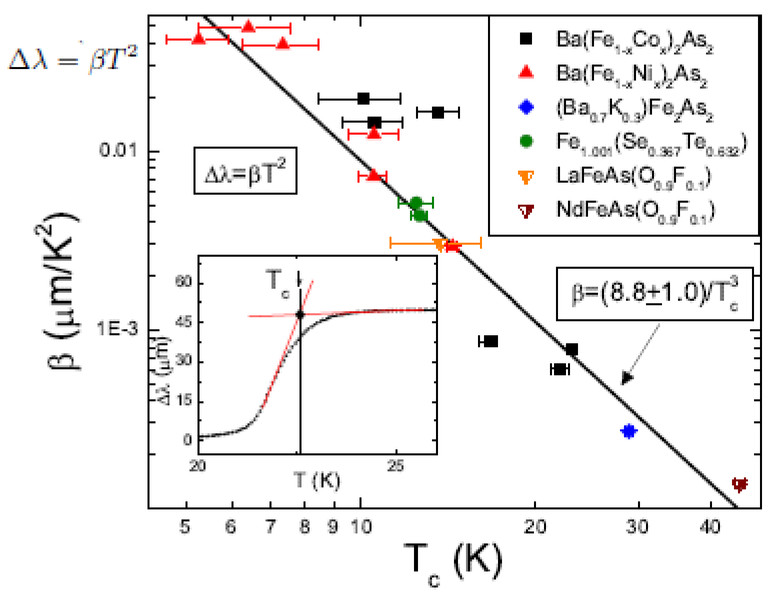
(Zaanen)



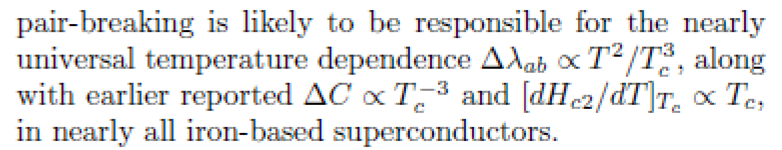
Superconducting state properties

Penetration Depth Scaling





R.T. Gordon *et al.* (2009)



To conclude, analysis of the low-temperature behavior of the London penetration depth shows that a strong pair-breaking is likely to be responsible for the nearly universal temperature dependence $\Delta\lambda_{ab} \propto T^2/T_c^3$, along with earlier reported $\Delta C \propto T_c^{-3}$ and $[dH_{c2}/dT]_{T_c} \propto T_c$, in nearly all iron-based superconductors.

Part 1: Conclusions

a) iron-pnictide family album

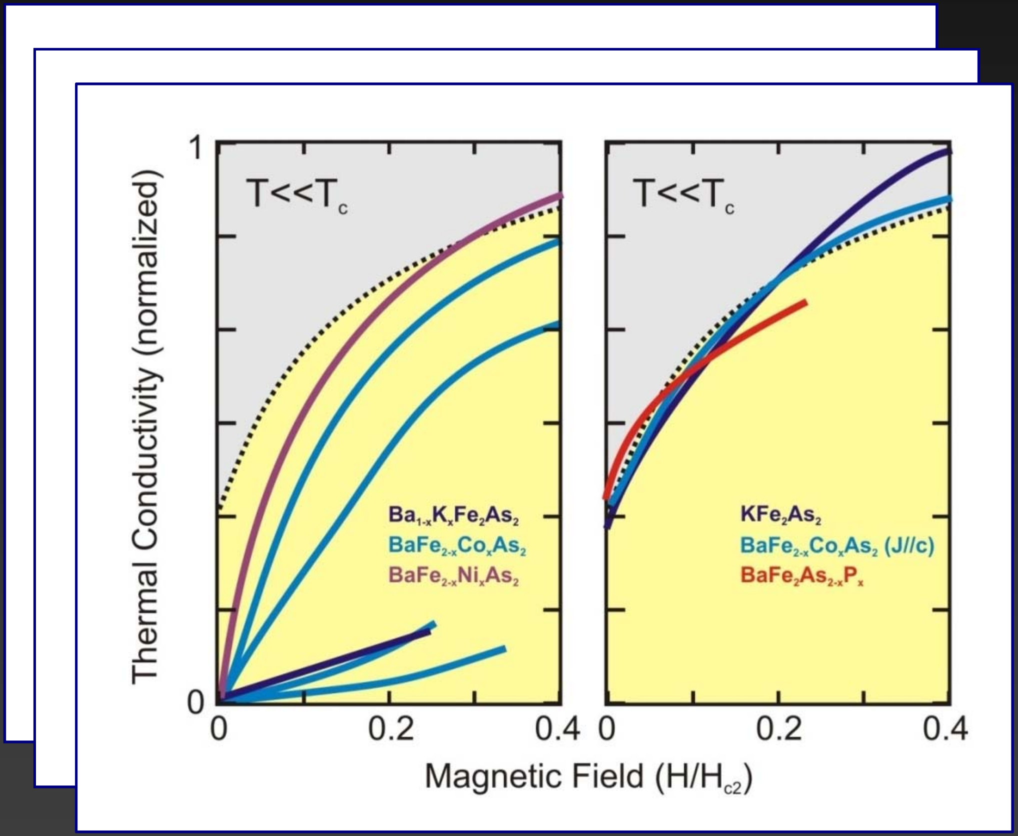
- Large phase space to explore!
- Overall chemistry good
- Lots of potential for new discoveries

b) phase diagrams and tuning

- Role of doping/pressure
- Subtle magnetic/structural tuning
- Quantum criticality?

c) normal/SC state properties

- Fully gapped AND nodal-like
- Varying OP symmetry?
- Scaling propeties



J.P. and R.L. Greene, Nature Physics (in progress)

The Team

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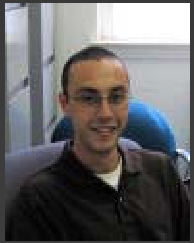

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