The Abdus Salam International Centre for Theoretical Physics

2157-4

Workshop on Principles and Design of Strongly Correlated Electronic Systems

2 - 13 August 2010

Magnetism and Superconductivity in Pnictides

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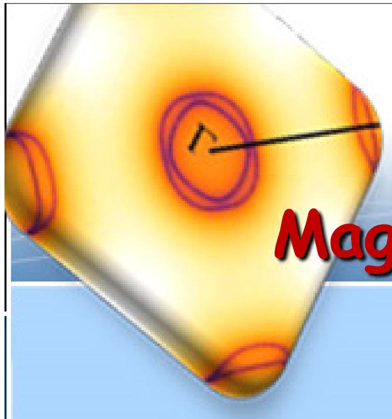

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Magnetism and Superconductivity in Pnictides

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Funded by the U.S. Department of Energy

USA TODAY

Swine flu, space interest scientists most in 2009

$ 100 question: What is the theory of iron-pnictides ?

- LDA + RPA: Mazin, Singh et al, Kuroki et al, Scalapino et al, Schmalian et al, …
- Weak coupling++: Chubukov, Eremin et al, DH Lee, Vishwanath et al, Cvetkovic et al, Bernevig, Thomale et al, …
- Mott limit: Si & Abrahams, Phillips et al, Sachdev et al, Kivelson et al, Zaanen & Sawatzky et al, Hu, Bernevig et al, Dagotto et al, …
- Assorted insights: Haule & Kotliar, Hirschfeld et al, Benfatto, Castellani et al, PA Lee & Wen, Raghu, SC Zhang, et al, Nagaosa & Ng, Gor'kov et al, FC Zhang & Rice, …

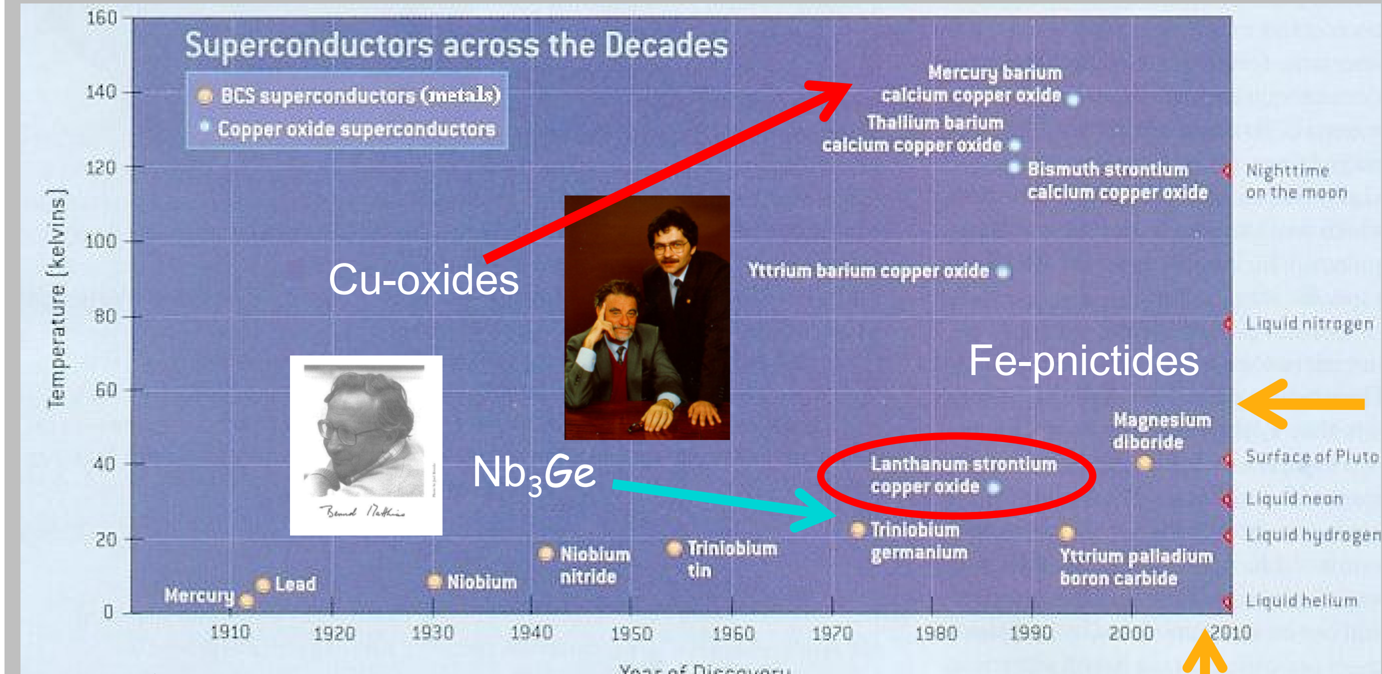
linked anti-angiogenesis to tumor growth.

•Graphene, single-atom layers of carbon that have semiconductor properties. They "look like a coming revolution in electronics," Pendlebury says. *Science* magazine included graphene on its "Top Ten" list of breakthroughs for the year.

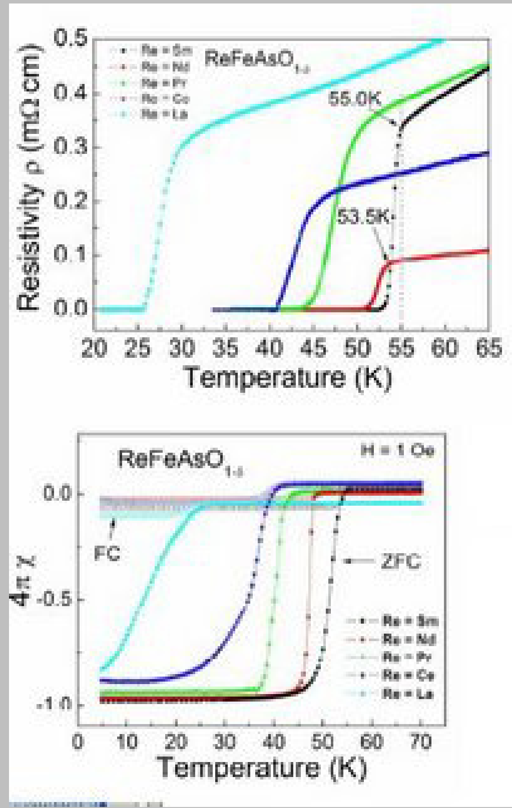
•Small RNA's, genetic materials that regulate genes in cells. They've emerged in "an astounding landscape" notes a highly-cited *Nature Reviews Molecular Cell Biology* survey led by V. Narry Kim of South Korea's Seoul National University. They have potential to treat diseases and reveal how genes work on a fundamental level inside cells. But not a big news item.

•Obesity gene, biology and diet studies. A *New England Journal of Medicine* report that found cutting calories, whatever their origin, mattered the most surprisingly high number of citations, considering it confirmed long-standing advice.

Superconductors → Hg → Nb_3Ge → cuprates → pnictides

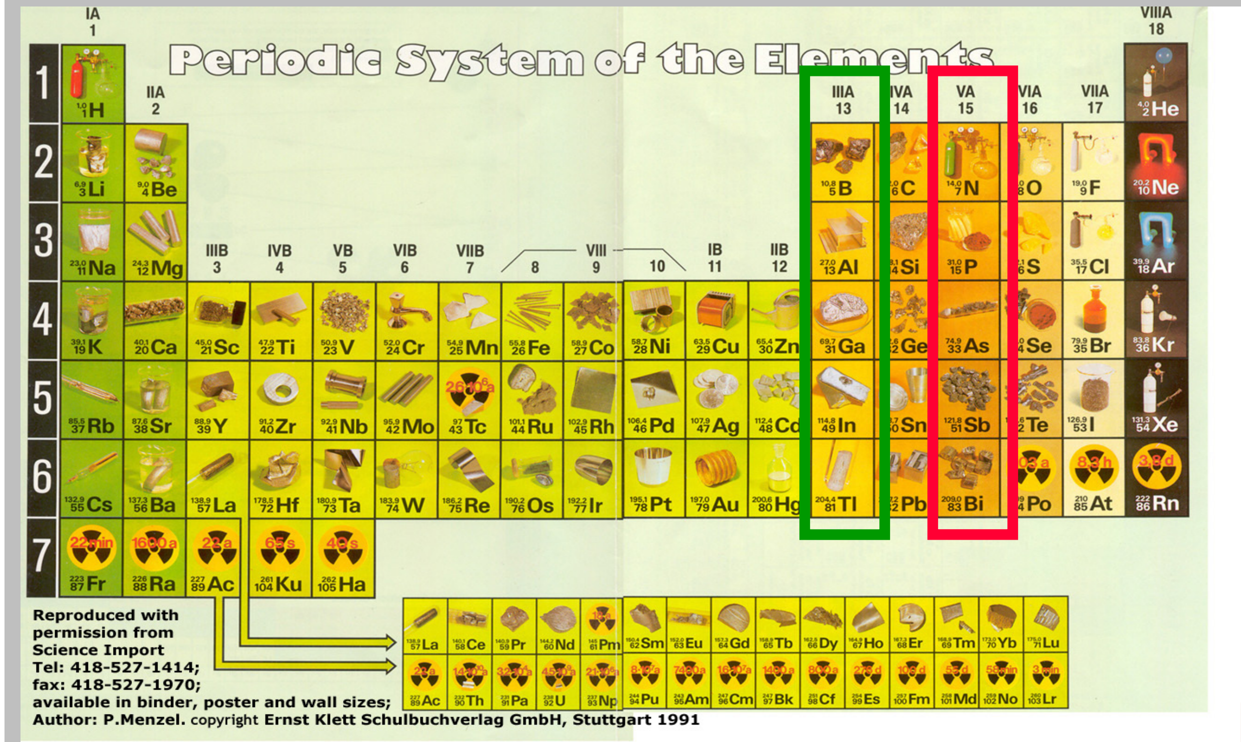


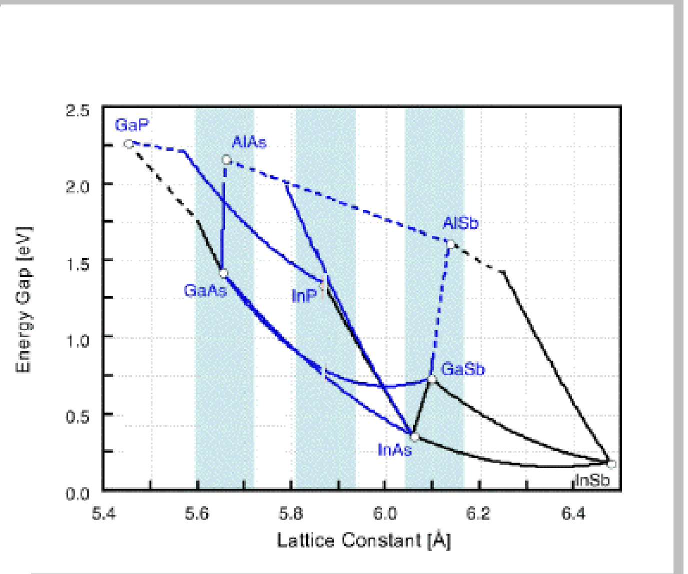
P. Canfield, Scientific American

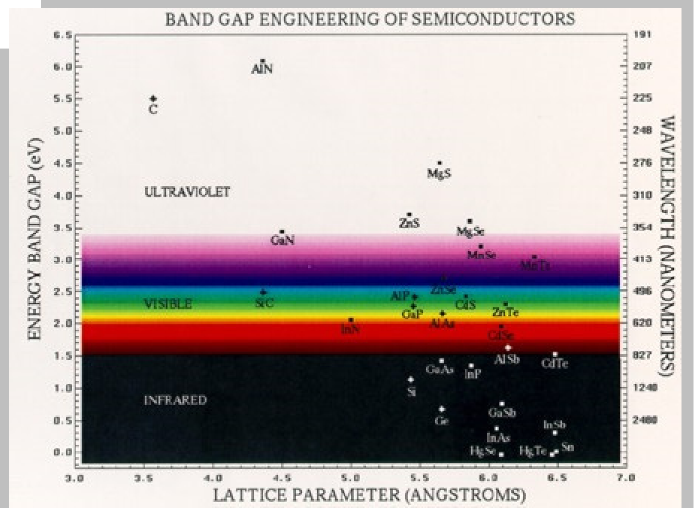


Greatest web-induced frenzy in history of condensed matter physics: 17 papers on arXiv in a single July '08 day. Comparable to the latest superstring "revolution" (Bagger-Lambert)

Pnictides πνίγειν (Greek for chocking, suffocation):
Semiconductors → Semimetals → Superconductors







Pnictides – elements from Group V of Periodic Table: nitrogen, phosphorus, arsenic, antimony and bismuth

III-V Semiconductors – formed by elements from Groups III and V: aluminium phosphide, aluminium arsenide, aluminium antimonide, gallium phosphide, gallium arsenide, gallium antimonide, indium phosphide, indium arsenide and indium antimonide plus numerous ternary and quaternary semiconductors.

Fe-pnictides: Semimetals → Superconductors

May 2006

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

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ナノテクノロジーの専門情報

日経ナノビジネスについて

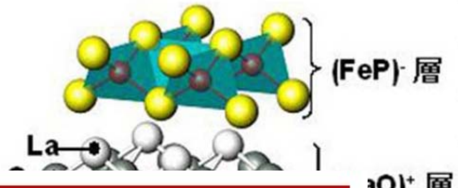
JSTと東工大、新しい酸化物超電導体LaOFePを発見

2006-07-18 (黒川 卓)

印刷用ページ

科学技術振興機構(JST)は東京工業大学と協同で、層状構造の新しい酸化物超電導体を発見した。酸化物超電導体としては遷移金属の銅(Cu)を含む物質がよく知られ、すでに産業界で実用化が始まっている。今回発見されたのは、Cuの代わりに遷移金属の鉄(Fe)を含む酸化超電導体。超電導転移する温度(Tc)は4Kと今のところ低いが、今後、構成元素の種類と組成比を変えることによってTcをさらに高められる可能性がある。

今回発見された超電導体の化学組成はLaOFeP(ランタン・鉄・リン酸化物)。JSTが進める「透明酸化物のナノ構造を活用した機能開拓と応用展開」プロジェクトで発見された。結晶構造は、LnOMPh(Ln=希土類元素、O=酸素、M=遷移金属、Ph=15族のP・As・Sbなど)で表記される物質群に属している。同プロジェクトの細野秀雄研究総括(東工大教授)らは、$(FeP)^-$層と$(LaO)^+$層が交互に積層したこの物質(Fig1)の超電導は$(FeP)^-$層が担っており、キャリアはFe^{2+}イオンの3d電子だと推定している。



←

Superconductivity at 43 K in Samarium-arsenide Oxides

$SmFeAsO_{1-x}F_x$

X. H. Chen* and T. Wu, G. Wu, R. H. Liu, H. Chen and D. F. Fang

Hefei National Laboratory for Physical Science at Microscale and Department of Physics, University of Science and Technology of China, Hefei, Anhui 230026, People's Republic of China

arXiv:0803.3603v1 [cond-mat.supr-con] 25 Mar 2008

(Dated: March 25, 2008)

nature International weekly journal of science

Letter

Nature 453, 761-762 (5 June 2008) | d

Superconductivity at

X. H. Chen1 (#a1), T. Wu1 (#a1)

1. Hefei National Laboratory for Phys

Correspondence to: X. H. Chen1 (#a1) C

Since the discovery of hig... been devoted to exploring... from Bardeen–Cooper–Sc... copper oxide supercondu... (ref. 2 (/nature/journal/v45... La–Nd, Sm and Gd) are n... $LaO_{1-x}F_xFeAs$ (ref. 3 (/natu... superconductivity in the r... measurements reveal a tr... high-temperature superc...

nature International weekly journal of science

go Advanced search

nature International weekly journal of science

Letter

Nature 459, 64-67 (7 May 2009) | doi:10.1038/nature07981; Received 4 November 2008; Accepted 13 March 2009

A large iron isotope effect in $SmFeAsO_{1-x}F_x$ and $Ba_{1-x}K_xFe_2As_2$

R. H. Liu1, T. Wu1, G. Wu1, H. Chen1, X. F. Wang1, Y. L. Xie1, J. J. Ying1, Y. J. Yan1, Q. J. Li1, B. C. Shi1, W. S. Chu2,3, Z. Y. Wu2,3 & X. H. Chen1

1. Hefei National Laboratory for Physical Sciences at Microscale and Department of Physics, University of Science and Technology of China, Hefei, Anhui 230026, China
2. Beijing Synchrotron Radiation Facility, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
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Accepted 5 May 2008; Published online 4 June 2008

...$F_{0.15}$

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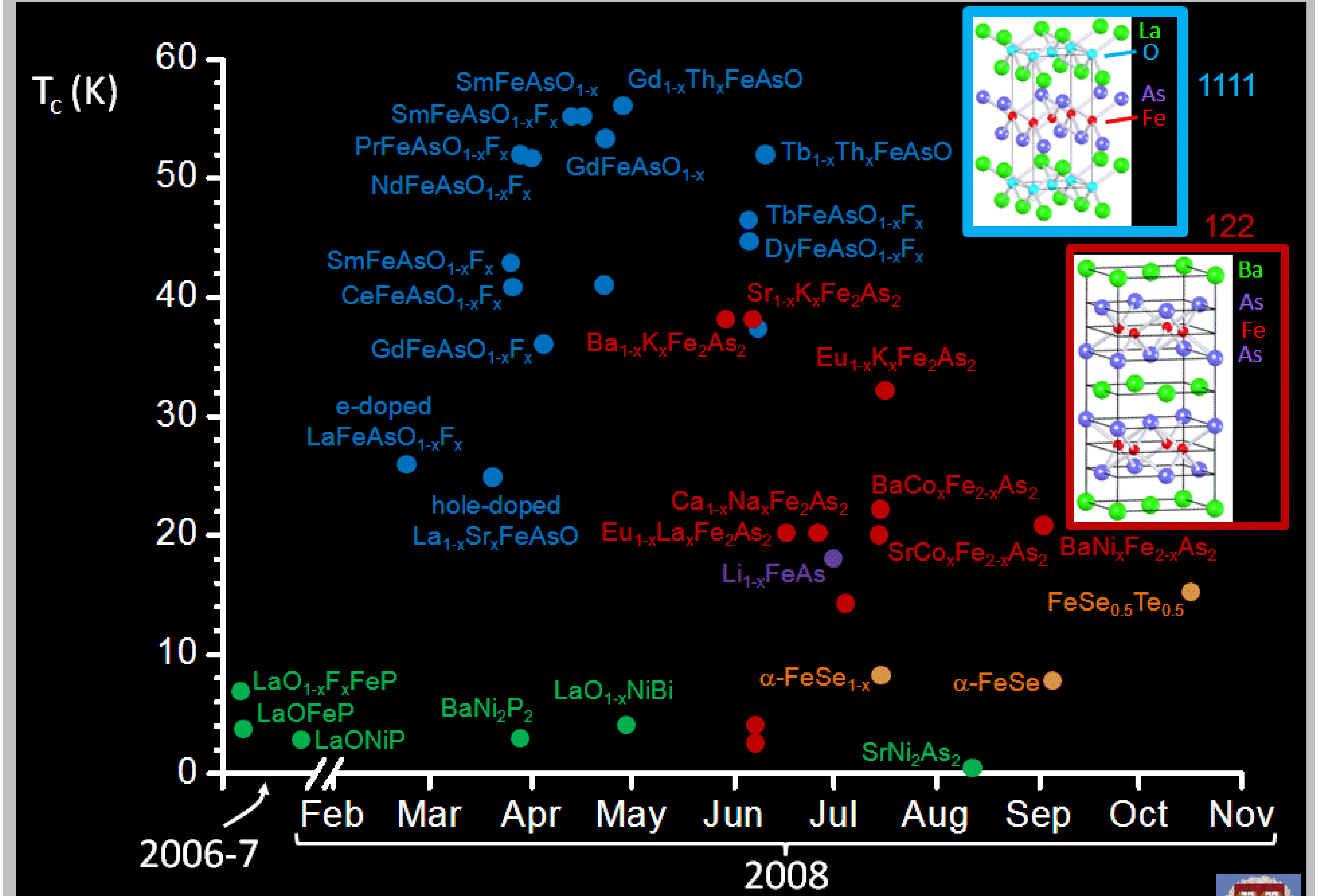
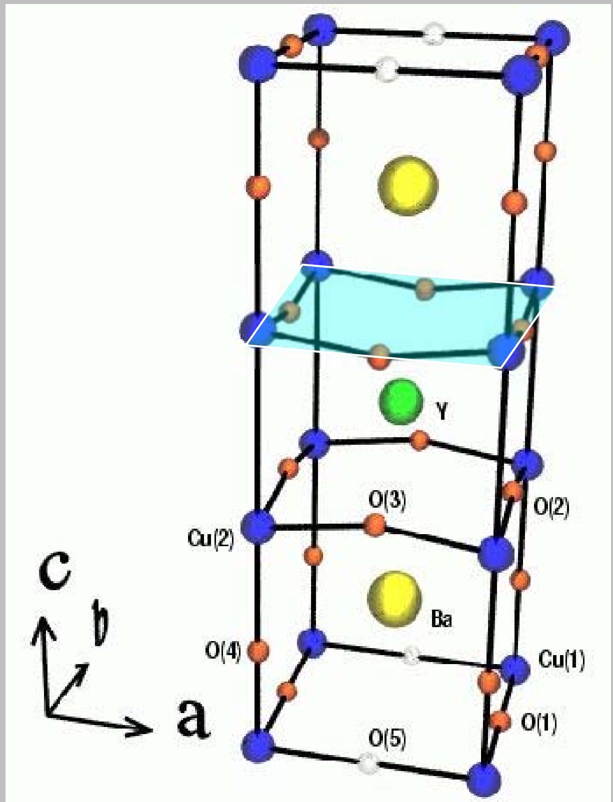
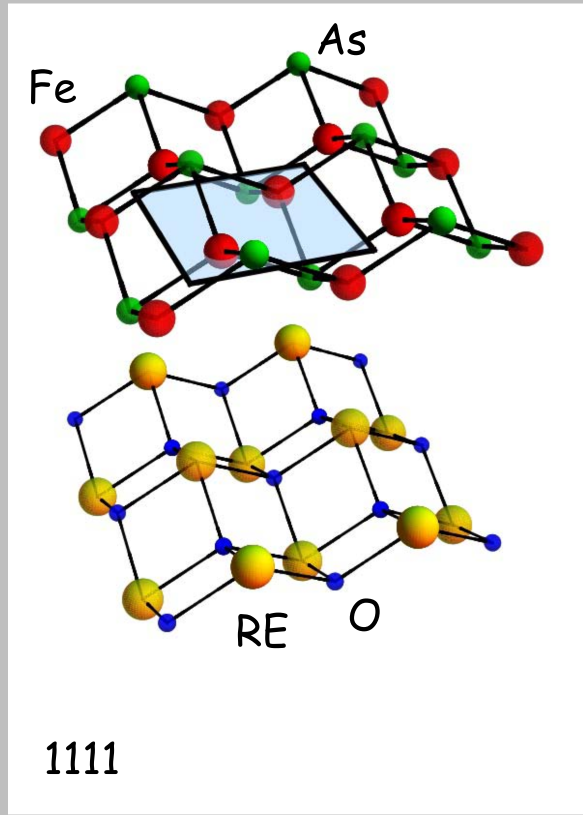
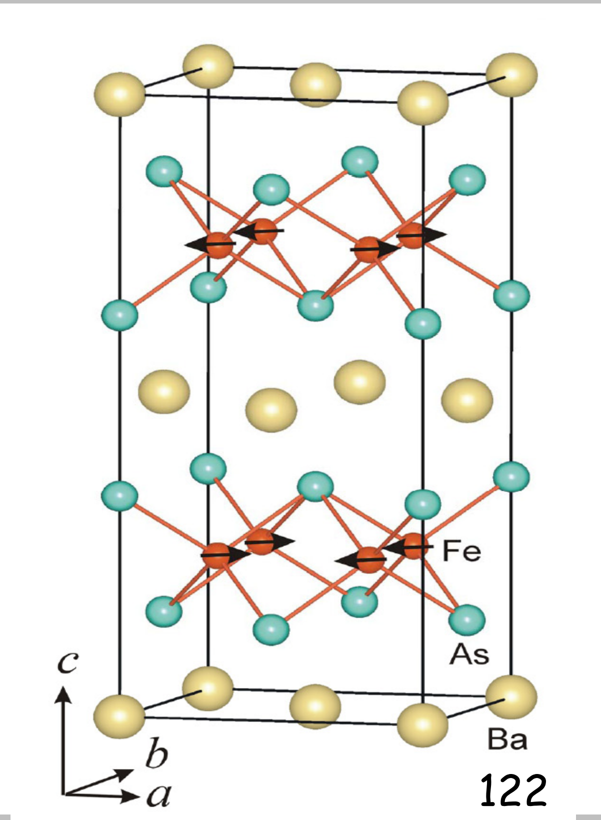


courtesy of J. Hoffman

Cu-oxides versus Fe-pnictides







Both have d-electrons in key role (Cu vs Fe)

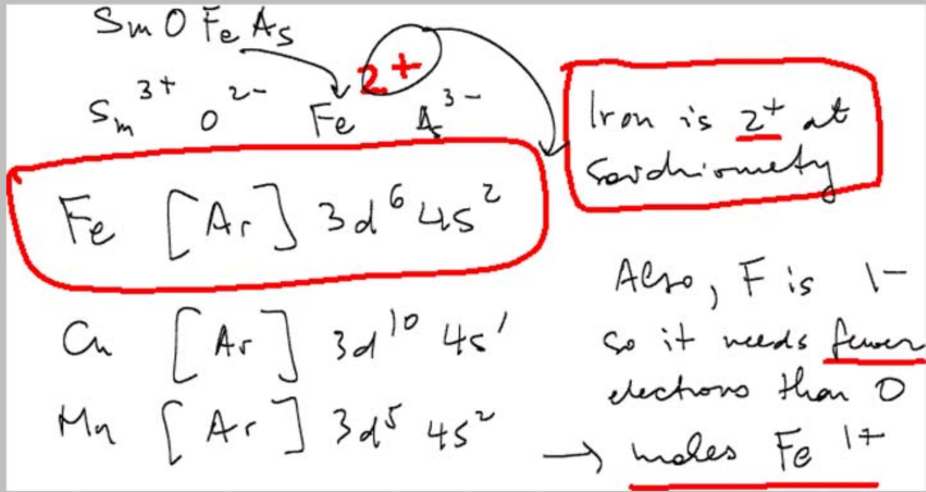
Both are layered (CuO_2 vs FeAs)

Both have AF and SC in close proximity

However, there are also many differences! This may add up to new and interesting physics

Key Difference: 9 versus 6 d-electrons

ZT, Physics **2**, 60 (2009)



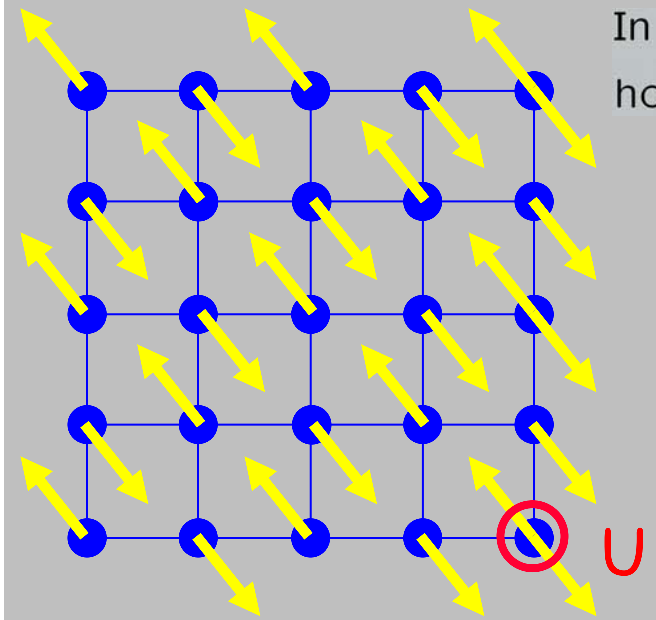
In CuO_2 a **single** hole in a filled 3d orbital shell

→ A suitable single band model might work

In FeAs large and **even** number of d-holes

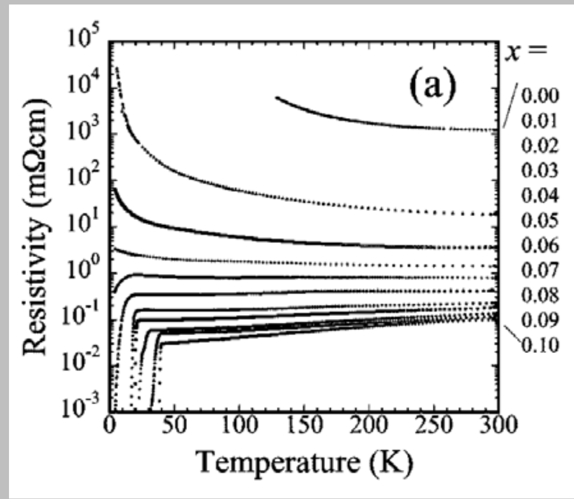
→ A multiband model is likely necessary

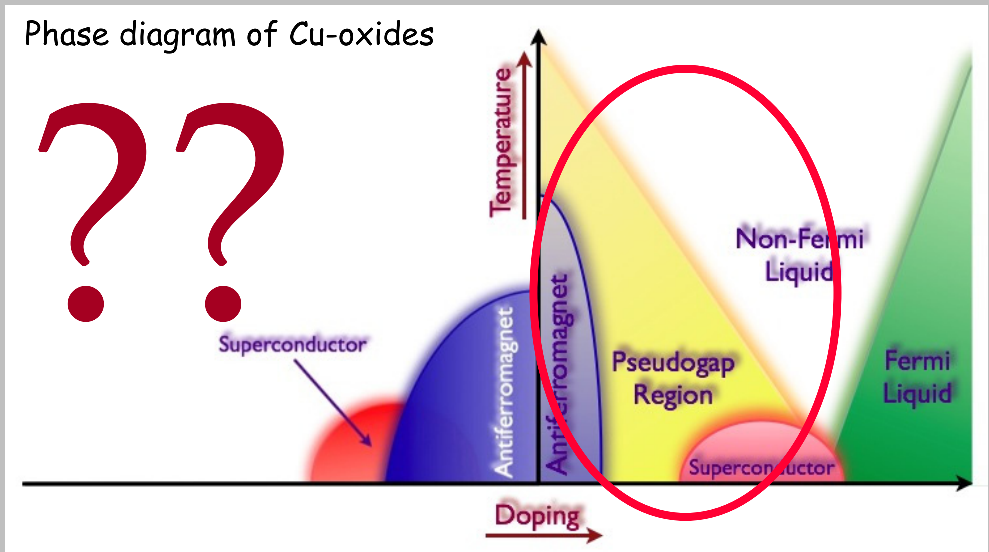
Cu-oxides: Mott Insulators → Superconductors



In a half-filled band Coulomb repulsion $Un_{i\uparrow}n_{i\downarrow}$ $(U \gg t)$ keeps holes in place $\Rightarrow$ Mott insulator + Neel antiferomagnet !!

Only when doped with holes (or electrons) do cuprates turn into superconductors





How Mott insulators turn into superconductors, particularly in the pseudogap region, remains one of great intellectual challenges of condensed matter physics

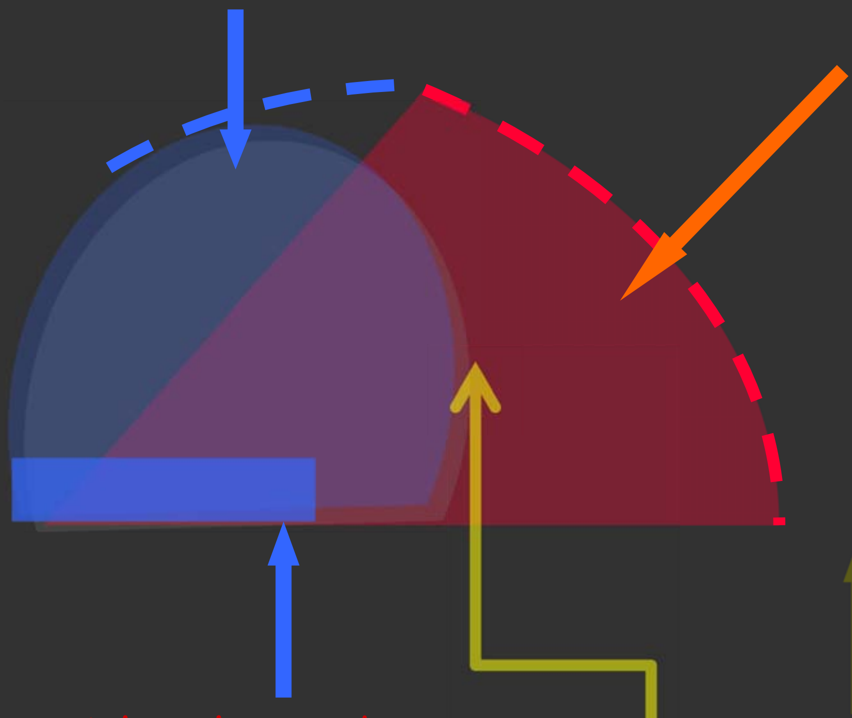
How Correlated Superconductors turn into Mott Insulators

ZT, Nature Physics **4**, 408 (2008)

Correlated superconductors have quantum (anti)vortex fluctuations

All superconductors have thermal fluctuations

Near T_c these are always phase fluctuations



BCS-Eliashberg-Migdal

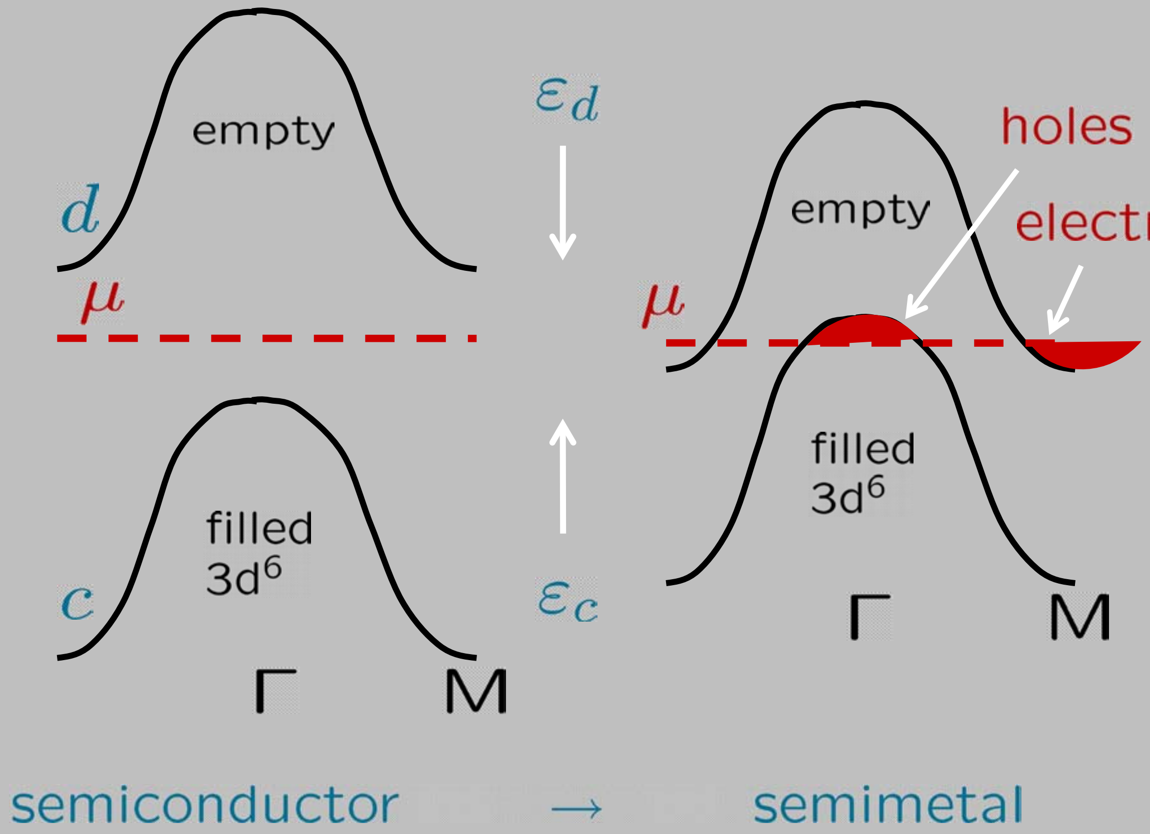
Ground state with enhanced pairing correlations but no SC !!
(gauge theories, QED_3, chiral SB, AdS/CMT,...
PW Anderson, Balents, MPA Fisher, Nayak, Franz, Vafek, Melikyan, ZT, Senthil & PA Lee)

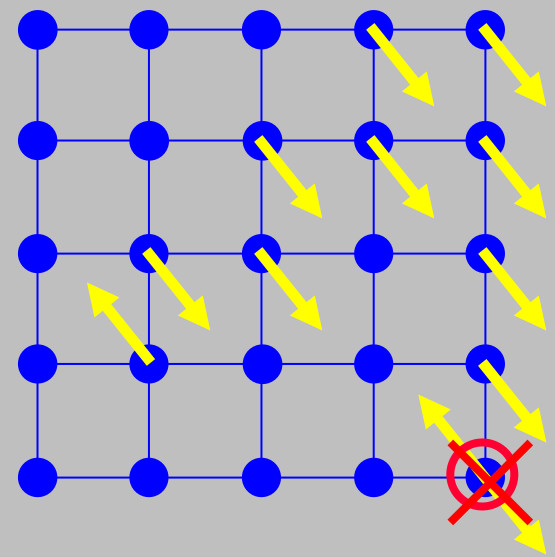
No such ground state in BCS theory (at weak coupling) !!

Optimal T_c in HTS is determined by quantum fluctuations

Fe-pnictides: Semimetals → Superconductors

$$\epsilon^c_{\vec{k}} = \varepsilon_c + t_c \cos(k_x a) + t_c \cos(k_y a)$$
$$\epsilon^d_{\vec{k}} = \varepsilon_d + t_d \cos(k_x a) + t_d \cos(k_y a)$$

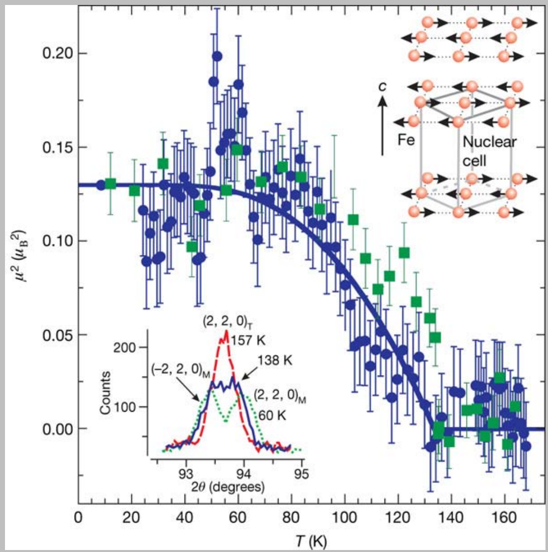




In contrast to CuO_2, all d-bands in FeAs are either nearly **empty** (electrons) or nearly **full** (holes) and far from being **half-filled**. This makes it easier for electrons (holes) to avoid each other.
→ **FeAs are less correlated than CuO_2 (correlations are still important !!)**

Phase diagram of Fe-pnictides

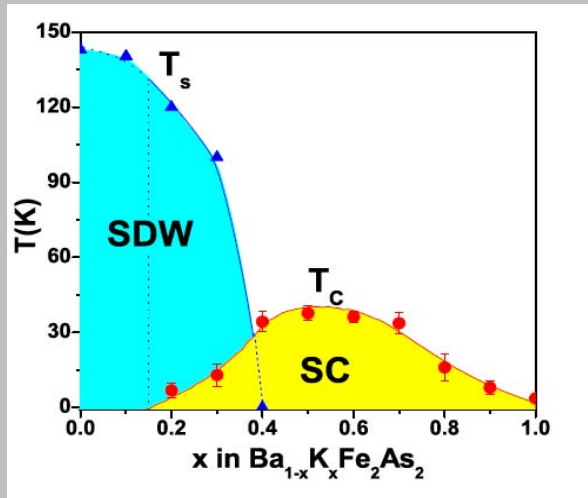
C. de la Cruz, *et al.*, Nature **453**, 899 (2008)

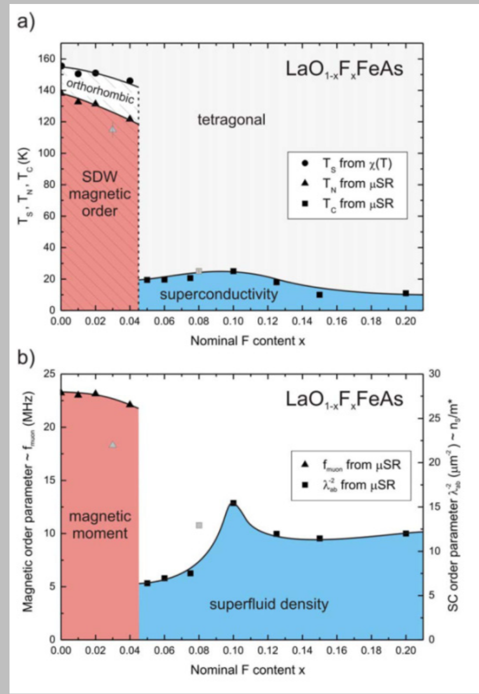


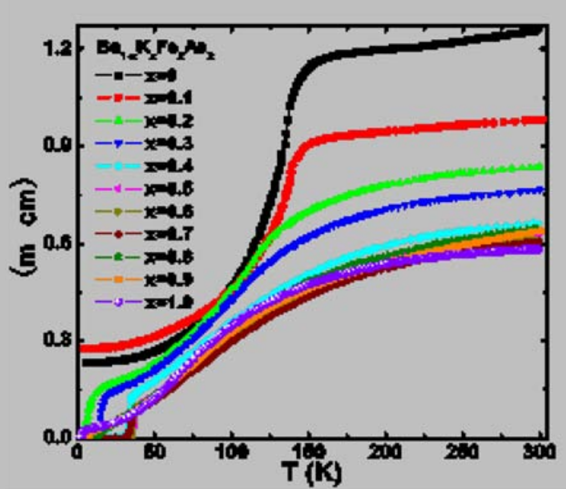
Like CuO_2, phase diagram of FeAs has SDW (AF) in proximity to the SC state.

SC coexists with SDW (AF) in 122 compounds →

H. Chen, *et al.*, arXiv/0807.3950

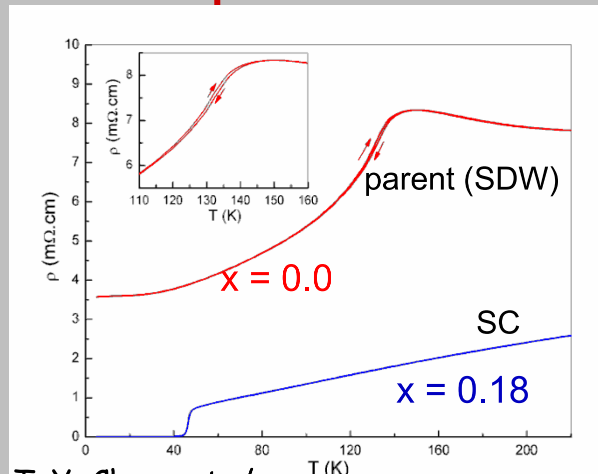






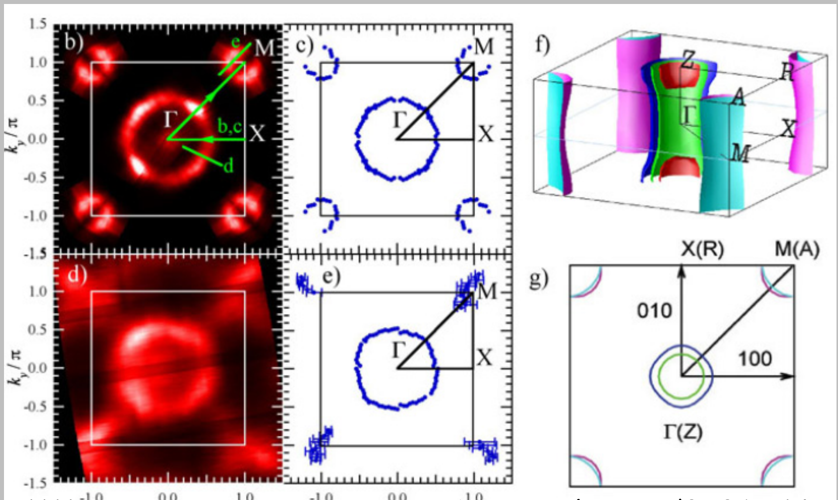
However, unlike CuO_2, all regions of FeAs phase diagram are (bad) metals !!

$SmFeAsO_{1-x}F_x$

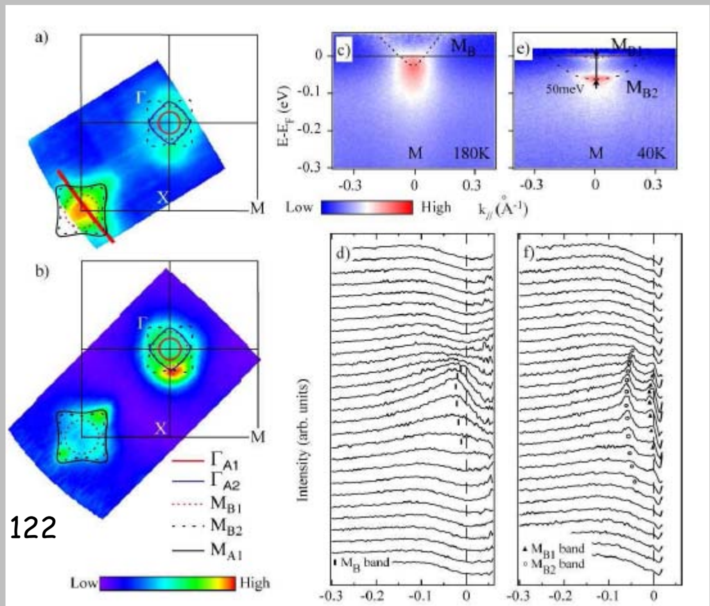


T. Y. Chen, *et al.*.

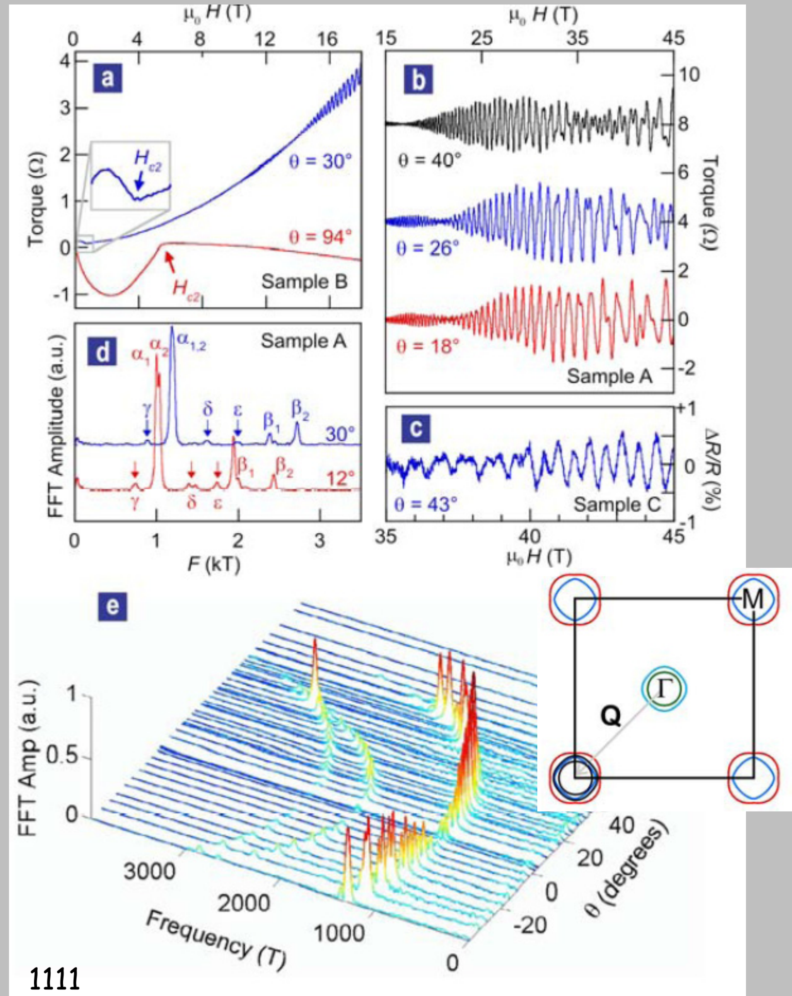
ARPES + dHvA



C. Liu, *et al.*, arxiv/0806.2147



L. X. Yang, *et al.*, arxiv/0806.2627

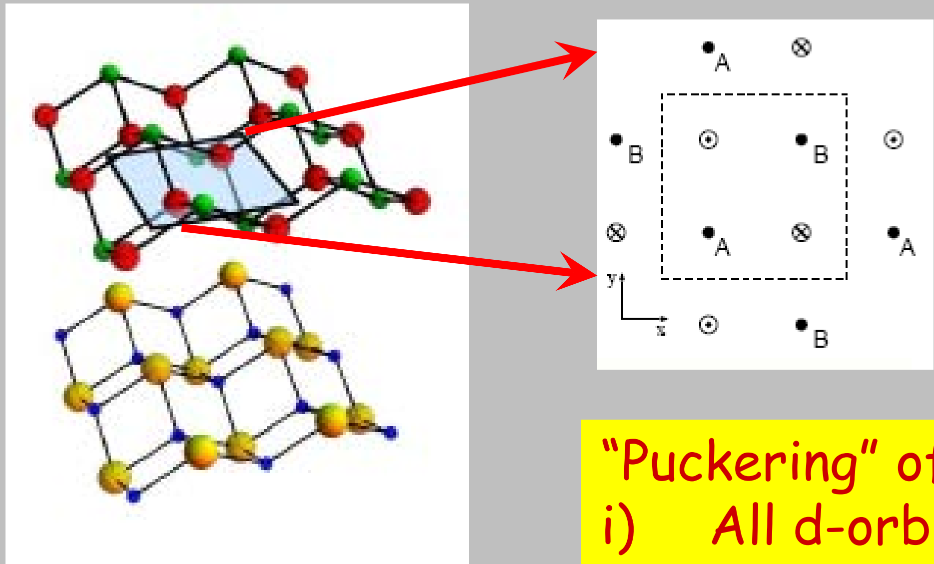


A. I. Coldea, *et al.*, arxiv/0807.4890

ARPES and dHvA see coherent (metallic) bands in rough agreement with LDA.

Minimal Model of FeAs Layers I

V. Cvetkovic and ZT, EPL **85**, 37002 (2009)
C. Cao, P. J. Hirschfeld, and H.-P. Cheng, PRB **77**, 220506 (2008)

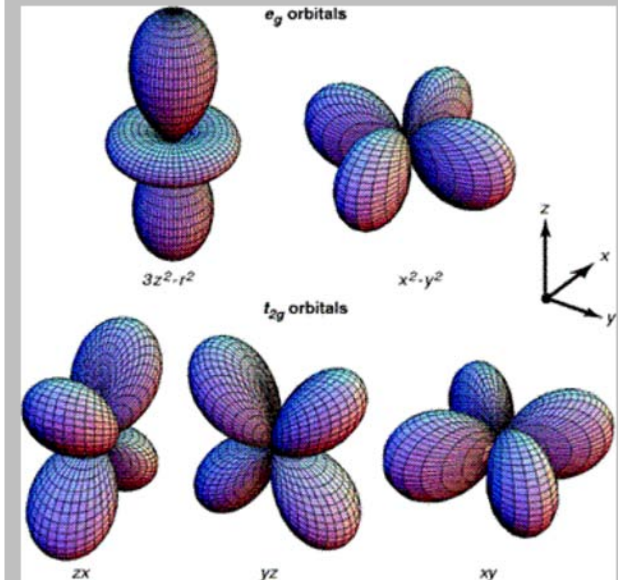


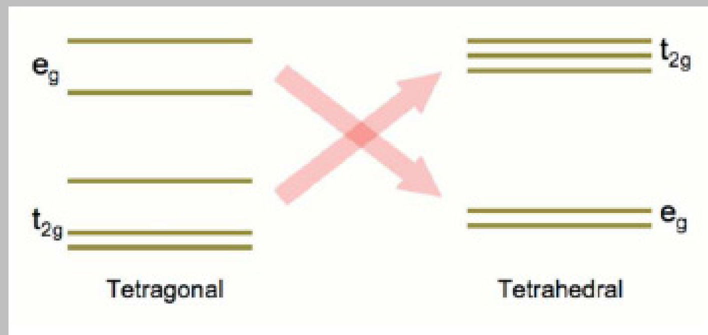
We consider effective 2D Fe model, with all 5 d-orbitals. As bands are below E_F but they contribute crucial terms to the "minimal" model

"Puckering" of FeAs planes is essential:

i) All d-orbitals are near E_F

ii) Large overlap with As p-orbitals below E_F
→ enhanced itinerancy of d electrons defeats Hund's rule and large local moment



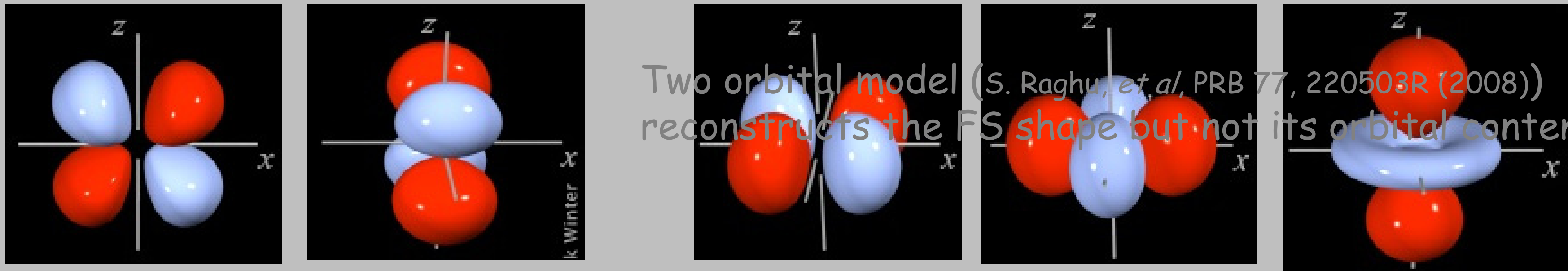


$$(5+3)\times 2 = 16\ (\div 2)\ \text{Wannier orbitals}$$

$$\Rightarrow \quad \text{"minimal" model} \quad \Rightarrow$$

Minimal Model of FeAs Layers II

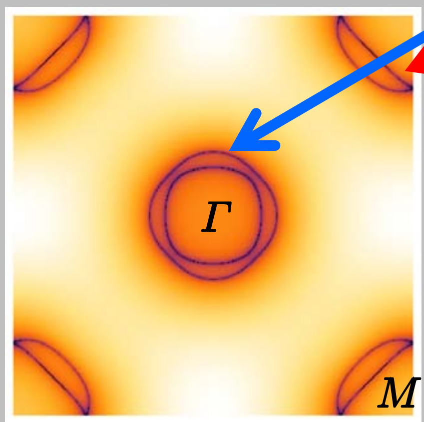
We consider an effective 2D model with 5 Fe + 3 As orbitals



d_{xz} d_{yz} d_{xy} d_{xx-yy} $d_{2zz-xx-yy}$

odd parity

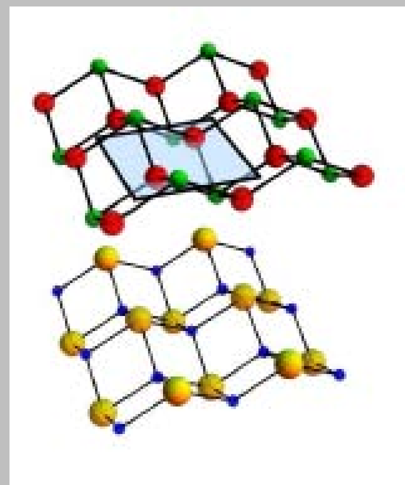
even parity



The importance of Fe 3d – As 4p hybridization:

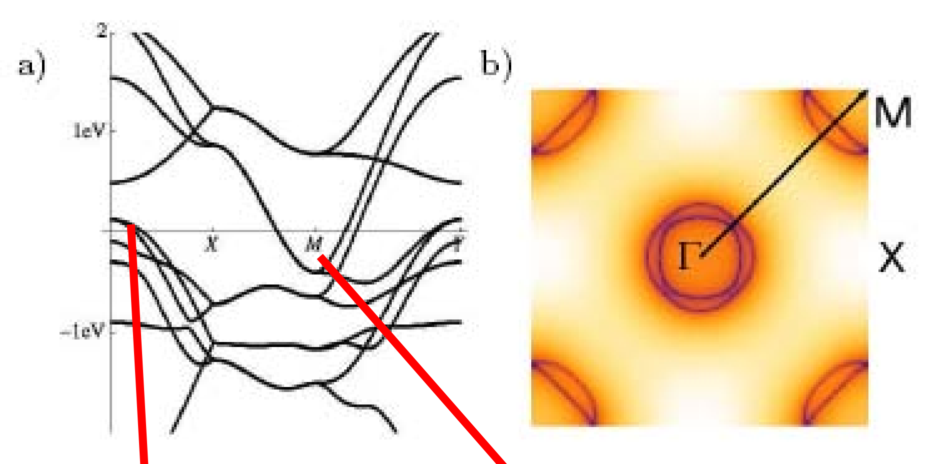
Without pnictide atoms many hopping processes would vanish by symmetry.

These symmetries are violated by pnictide puckering.



Minimal Model of FeAs Layers III

V. Cvetkovic and ZT, EPL **85**, 37002 (2009)
C. Cao, P. J. Hirschfeld, and H.-P. Cheng, PRB **77**, 220506 (2008)
K. Kuroki *et al*, PRL **101**, 087004 (2008)



hole FS
2 pockets (valleys)

electron FS
2 pockets (valleys)

Tight-binding model optimized for band structure + exps.
Only nearest neighbor Fe-As, Fe-Fe, and As-As hoppings are used.

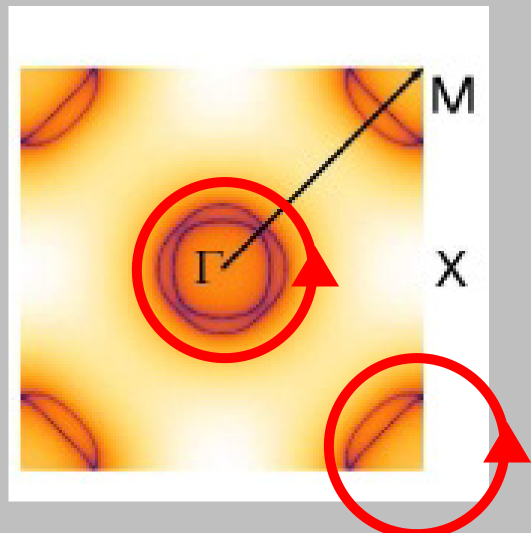
α	x^2-y^2	z^2	xy	xz
ϵ_α	-0.85	-1.4	-1.1	-1.15
$t^{Fe}_{\alpha,\alpha}$	-0.55	-0.5	-1.6	-0.55
$t_{\alpha,x/y}$	0.65	-1.4	1.5	3.2
$t_{\alpha,z}$	2.1	1.25		0.7

β	x	z
ϵ_β	-4.0	-4.0
$t^{As}_{\beta,\beta}$	-0.8	-0.45

$t^{Fe}_{z^2,xy} = 0.1$, $t^{Fe}_{xz,yz} = -0.75$, and $t^{As}_{x,y} = 0.8$.

Important: Near E_F e and h bands contain significant admixture of **all** five Wannier d-orbitals, d_{xz} and d_{yz} of **odd** parity (in FeAs plane) and the remaining three d-orbitals of **even** parity in FeAs plane →

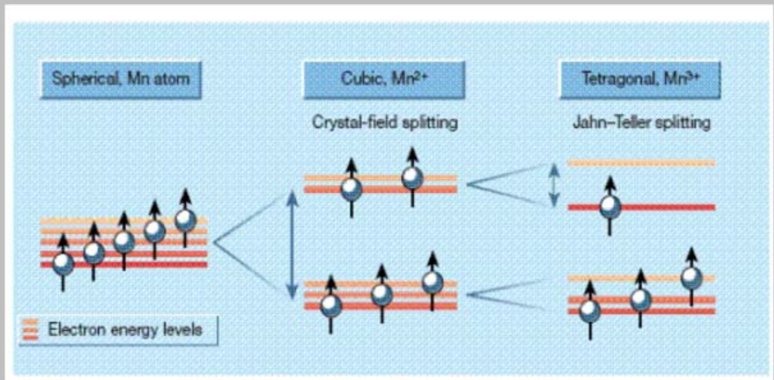
As one goes around the FS there is strong mixing of odd and even d-orbitals
⇒ no simple orbital "topology"

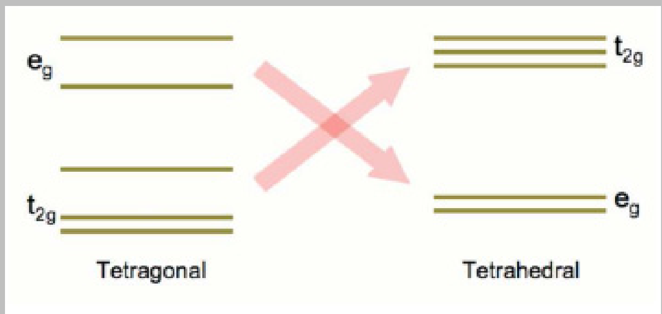


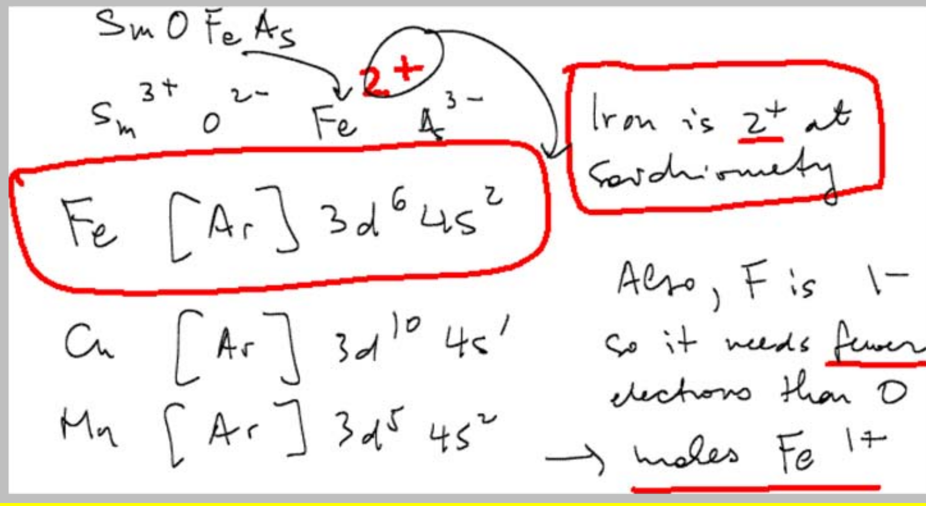
Hund's Rule Defeated (but Lurking!)

Hund's rule rules for Mn^{2+} :
all five d-electrons line up to minimize Coulomb repulsion → $S = 5/2$

Y. Singh *et al.*, arXiv/0907.4094 (MnAs)
Y. Z. Zhang *et al.*, PRB **81**, 094505 (2010)







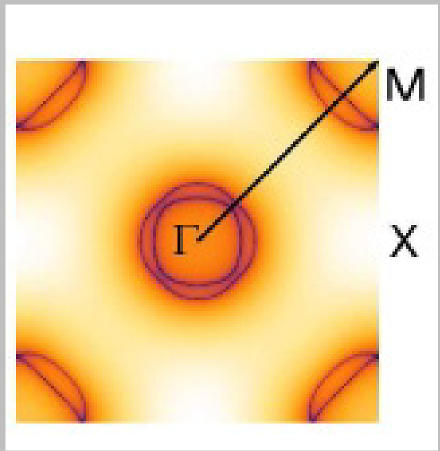
"Puckering" of FeAs planes is essential:

i) All d-orbitals are near E_F
ii) Large overlap with As p-orbitals below E_F → enhanced itinerancy of d electrons defeats Hund's rule and large local moment

Haule, Shim and Kotliar, PRL **100**, 226402 (2008)

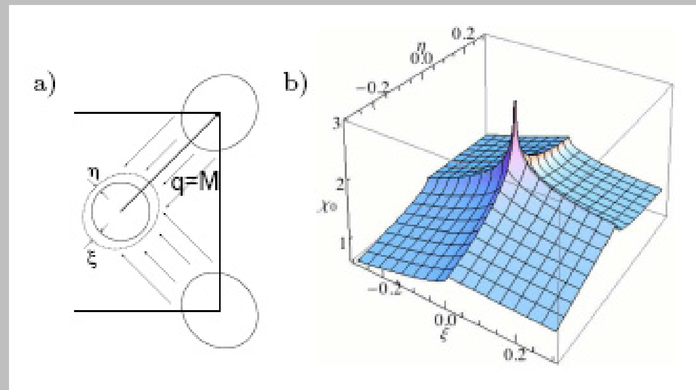
Nesting and Valley Density-Wave (VDW) in Fe-pnictides I

V. Cvetkovic and ZT, EPL **85**, 37002 (2009)
V. Cvetkovic and ZT, PRB **80**, 024512 (2009)
M. Korshunov and I. Eremin, PRB **78**, 140509 (2008)

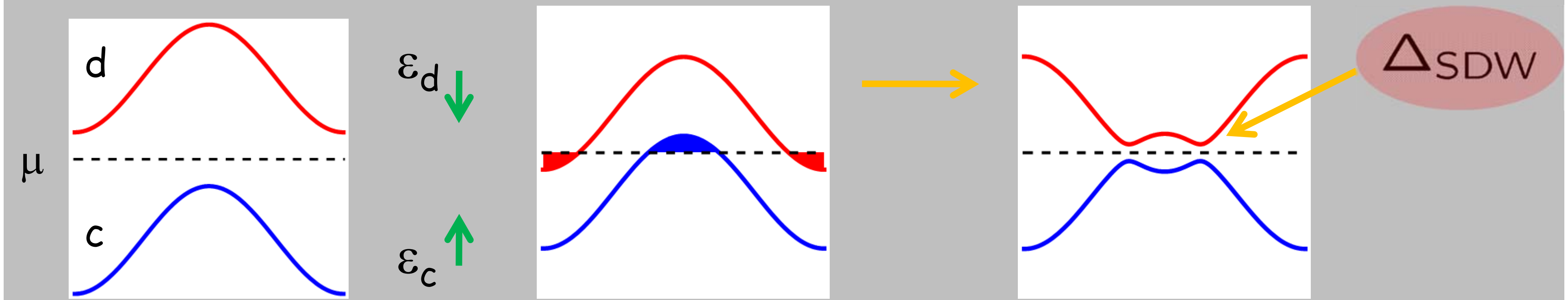


If hole (Γ) and electron bands (M) are identical
$\Rightarrow$ perfect nesting at $\mathbf{q} = \mathbf{M} = (\pi, \pi)$ $\Rightarrow$
strongly enhanced electron-hole excitations

$$\chi'_0(\mathbf{q}, \omega = 0) = 2\frac{m_e}{2\pi} \log \frac{\Lambda}{|\mathbf{q} - \mathbf{M}|},$$



Turning on moderate interactions →
VDW = itinerant multiband CDW (structural),
SDW (AF) and orbital orders at **q** = **M** = (π,π)

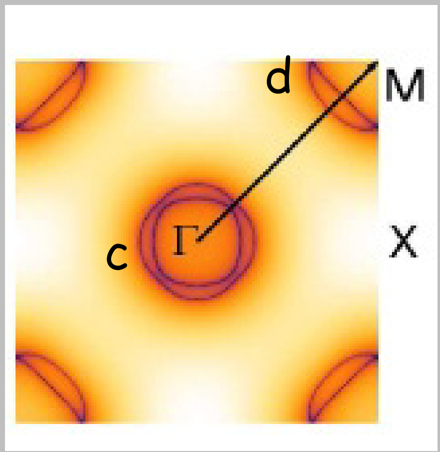


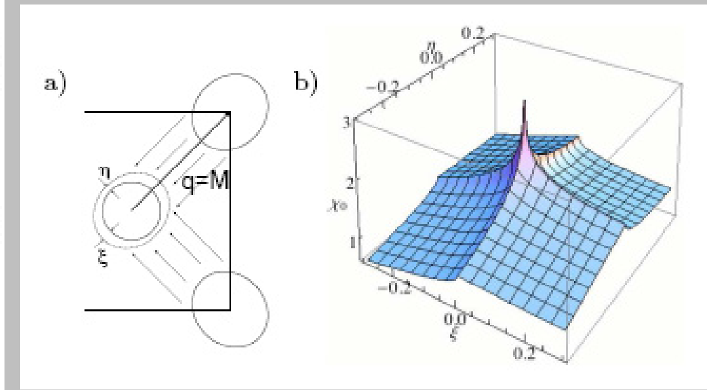
Semiconductor

Semimetal

SDW, CDW, ODW or
combinations thereof → VDW

Nesting and Valley Density-Wave (VDW) in Fe-pnictides II



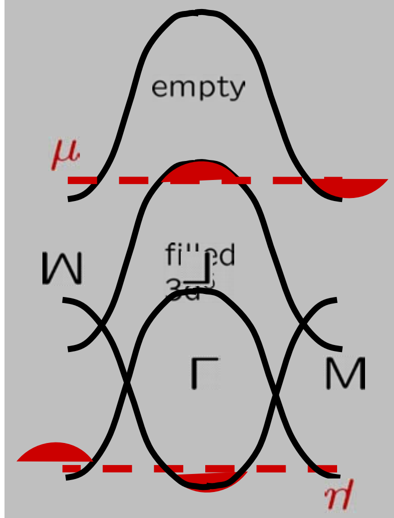


$$\chi_0'(\mathbf{q}, \omega = 0) = 2\frac{m_e}{2\pi} \log \frac{\Lambda}{|\mathbf{q} - \mathbf{M}|},$$

Consider the bare-bones model for interactions:

$$H = -\varepsilon_{\mathbf{k}} c_{\mathbf{k}}^{\dagger} c_{\mathbf{k}} + \varepsilon_{\mathbf{k}} d_{\mathbf{k}}^{\dagger} d_{\mathbf{k}} + U n_c^2 + U n_d^2 + W n_c n_d + (\cdots)$$

spinless fermions Intraband Interband



$\longrightarrow$

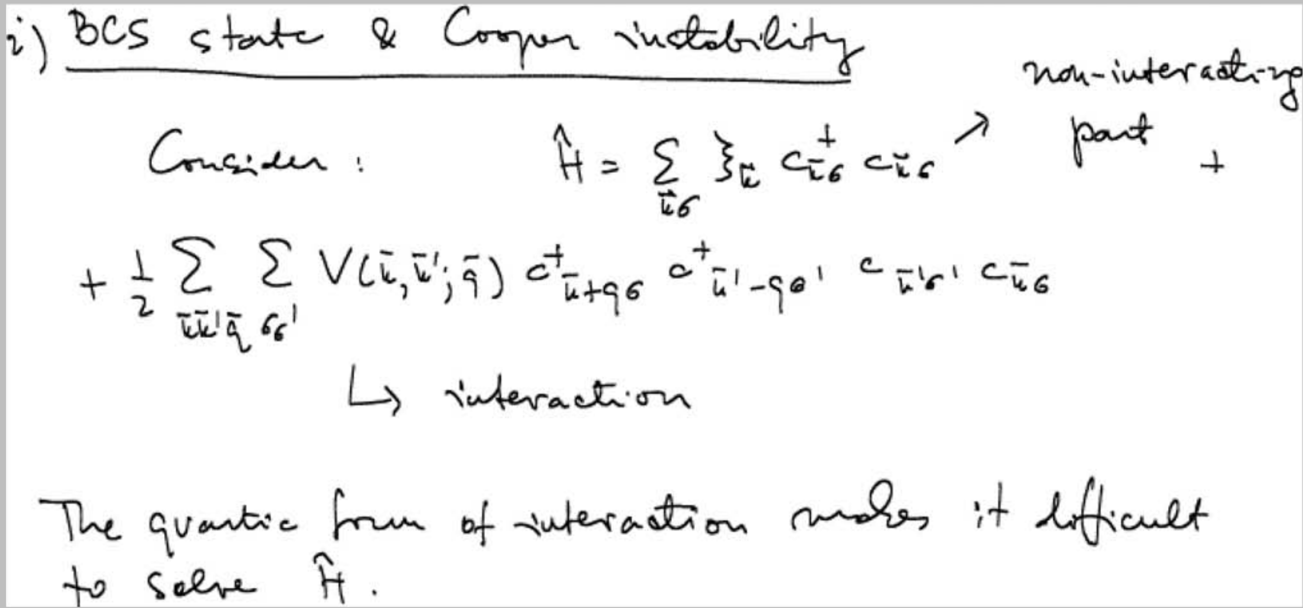
Particle-hole transformation

$$c \to h^{\dagger}\ , d \to e\ , n_c \to 1 - n_h\ , n_d \to n_e$$

$$H \to \varepsilon_{\mathbf{k}} h_{\mathbf{k}}^{\dagger} h_{\mathbf{k}} + \varepsilon_{\mathbf{k}} e_{\mathbf{k}}^{\dagger} e_{\mathbf{k}} - W n_h n_e + (\cdots)$$

Negative U Hubbard model: $(h, e) \leftrightarrow (f_{\uparrow}, f_{\downarrow})$

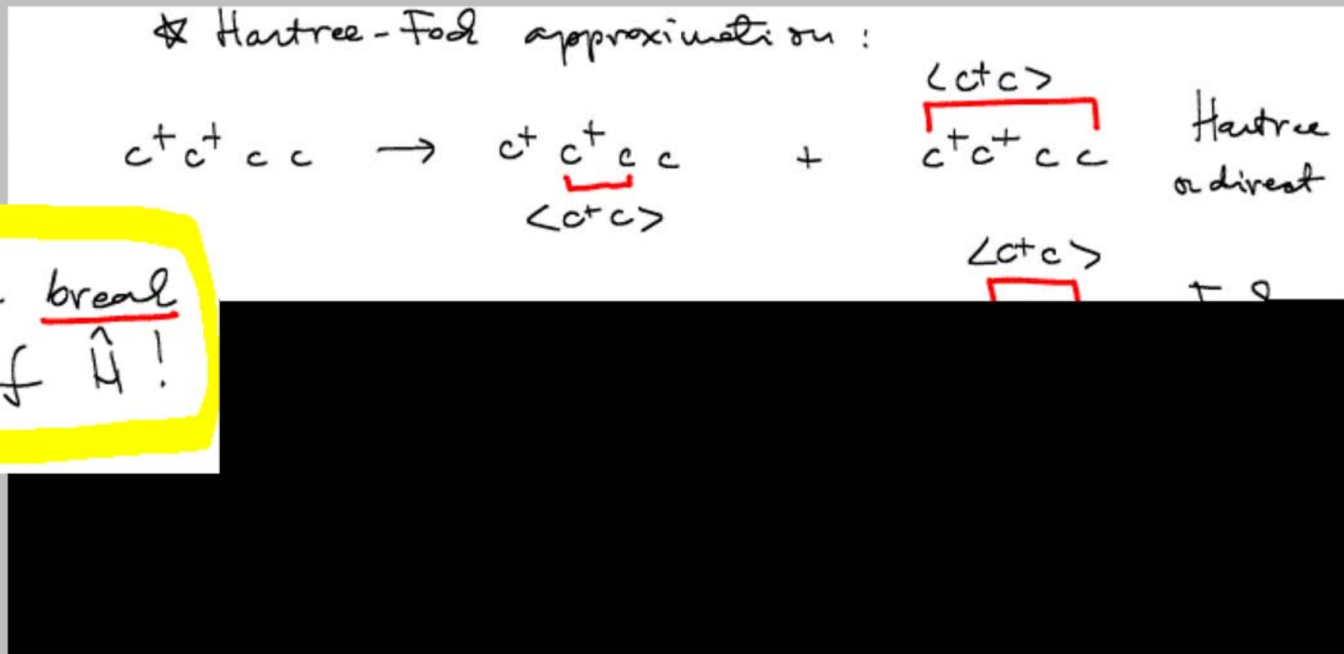
Many-Particle Problem in Quantum Matter



Once quartic interaction term is present, we don't know how to solve H, except in special cases

Numerous approximate methods have been developed over decades

Hartree-Fock mean-field theory is not trivial



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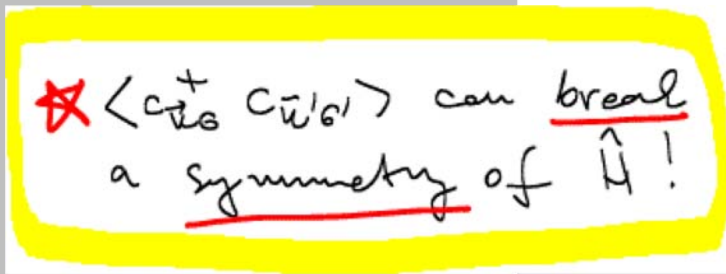


Quantum Phase Transitions

For example:

$\langle c^\dagger_{\vec{k}\sigma} c_{\vec{k}+\vec{Q}\sigma} \rangle \neq 0 \Rightarrow$ CDW

$\langle c^\dagger_{\vec{k}\sigma} c_{\vec{k}+\vec{Q}-\sigma} \rangle \neq 0 \Rightarrow$ SDW

... many other symmetry breaking states.

We can assume any form of the ground state, irrespective of whether it obeys the symmetries of H. As long as such Hartree-Fock state is determined self-consistently to have the lowest energy →

We have the true ground state

CDW breaks translational (lattice) invariance; SDW does the same plus, spin SU(2) symmetry.
All such states are allowed and can be the ground state with a suitable interaction.

☆ How about $\langle c^\dagger c^\dagger \rangle \neq 0$?

This breaks particle number conservation, $[\hat{H},\hat{N}]=0$!

Assume:

$$c^\dagger_{\vec{k}\sigma} c^\dagger_{\vec{k}'\sigma'} \rightarrow \langle c^\dagger_{\vec{k}\sigma} c^\dagger_{\vec{k}'\sigma'} \rangle + \underbrace{c^\dagger_{\vec{k}\sigma} c^\dagger_{\vec{k}'\sigma'} - \langle c^\dagger_{\vec{k}\sigma} c^\dagger_{\vec{k}'\sigma'} \rangle}_{\delta}$$

$$\downarrow$$

$$\langle c^\dagger_{\vec{k}\sigma} c^\dagger_{-\vec{k}-\sigma} \rangle \delta_{\vec{k},-\vec{k}'} \delta_{\sigma,-\sigma'}$$

and keep only terms $< O(\delta^2)$. Also, assume $V(\vec{k},\vec{k}';\vec{q}) \rightarrow -U$ attractive, short-range interaction

Tinkham, Intro to SC

$\langle c^\dagger_{\vec{k}\sigma} c^\dagger_{-\vec{k}-\sigma} \rangle \neq 0$

preserves spin SU(2) and translational invariance. It breaks U(1) particle number conservation

Hartree-Fock-BCS State

$$\hat{H} \to \hat{H}_{BCS} = \sum_{\vec{k}\sigma} \xi_{\vec{k}}\, c^+_{\vec{k}\sigma} c_{\vec{k}\sigma} + \Delta \sum_{\vec{k}} c^+_{\vec{k}\sigma} c^+_{-\vec{k}-\sigma} + h.c. + (1/U)\, \Delta^+ \Delta$$

where $\Delta = U \sum_{\vec{k}} \langle c_{-\vec{k}-\sigma}\, c_{\vec{k}\sigma} \rangle$ self-consistency condition

Ground state of H_{BCS} is the famous BCS wavefunction

→

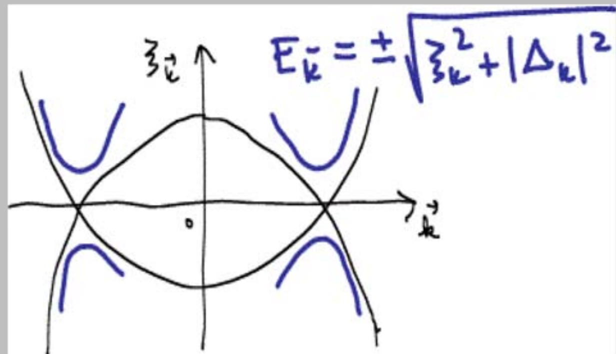
$$|\phi_0\rangle = \prod_k \left(u_k + v_k c^+_{k\uparrow} c^+_{-k\downarrow}\right)|0\rangle$$

Gap equation: $\Delta_{\mathbf{k}} = \sum_{\mathbf{k}'} V_{\mathbf{k}\mathbf{k}'} \frac{\Delta_{\mathbf{k}'}}{\sqrt{\epsilon^2_{\mathbf{k}'} + |\Delta_{\mathbf{k}'}|^2}}$

Ground state of H_{BCS} , $|\varphi_0\rangle$ is a superconductor !!

Hamiltonian for new Bogoliubov-deGennes (BdG) spinors: $[c^\dagger_\uparrow(\mathbf{r})\ ;\ c_\downarrow(\mathbf{r})]$

$$\mathcal{H}_{BdG} = \begin{pmatrix} \frac{(\mathbf{p}-(e/c)\mathbf{A})^2}{2m} - \epsilon_F & \Delta \\ \Delta^* & \epsilon_F - \frac{(\mathbf{p}+(e/c)\mathbf{A})^2}{2m} \end{pmatrix}$$

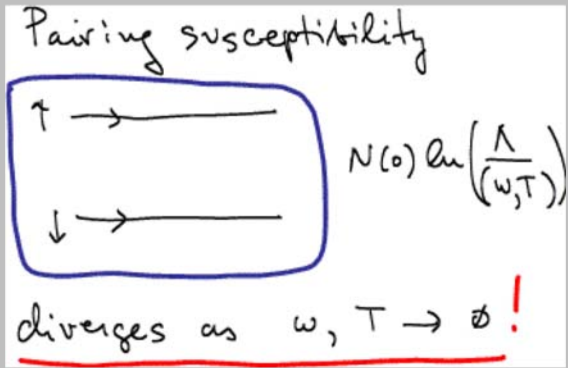


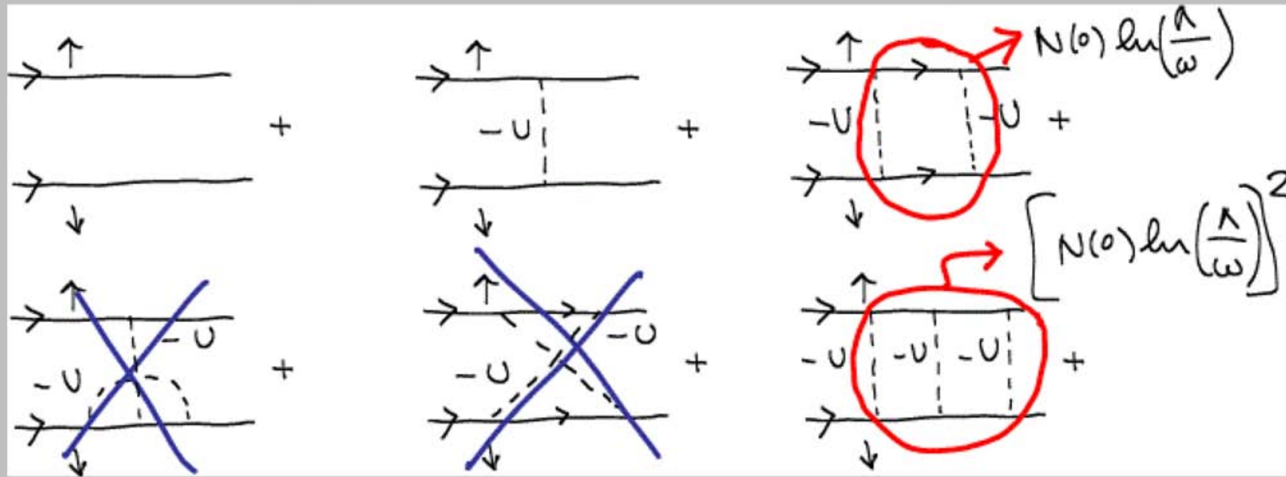
BdG quasiparticle spectrum:

$E_{\mathbf{k}} = \pm\sqrt{\xi^2_{\mathbf{k}} + |\Delta_{\mathbf{k}}|^2}$

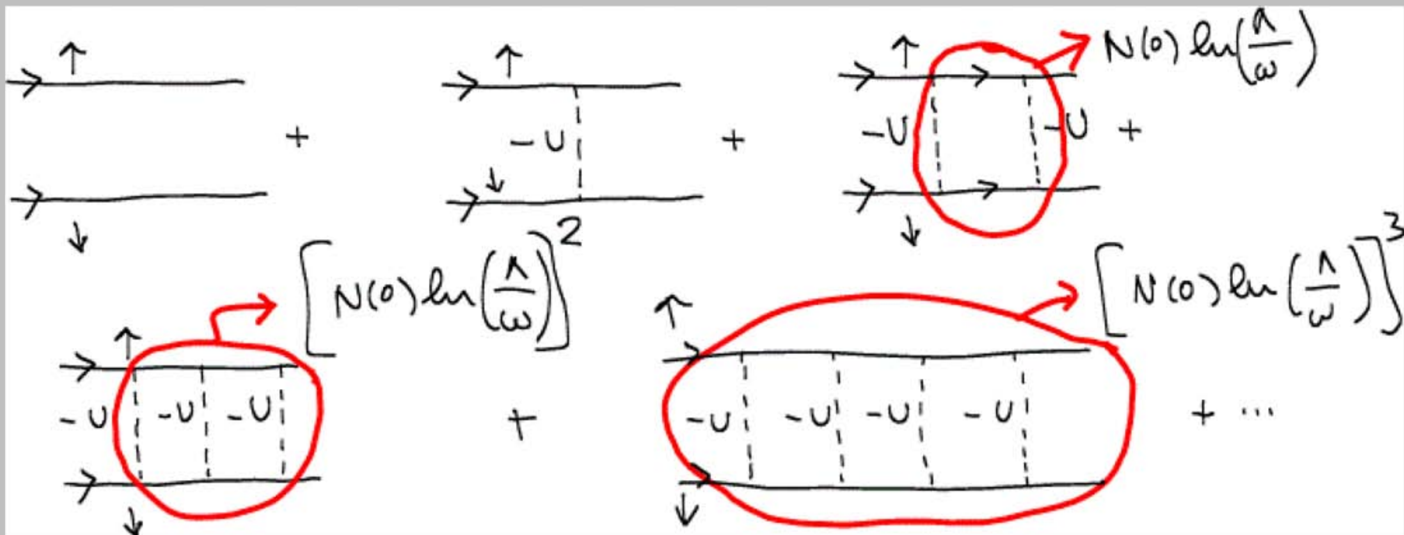
Cooper Instability

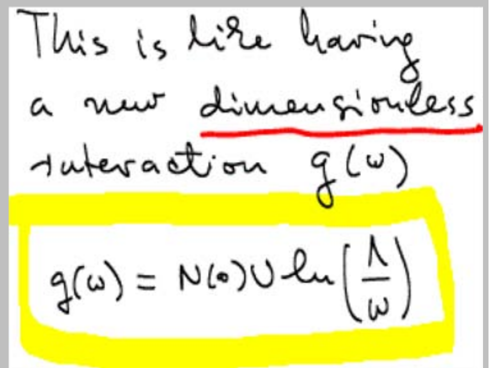
Origin of Cooper instability and BCS ground state is repeated scattering of two electrons (p-p channel) →





Keep only the most divergent diagrams at any given order in perturbation theory:





Poor-woman Renormalization Group (RG)

This is like having a new dimensionless interaction $g(\omega)$

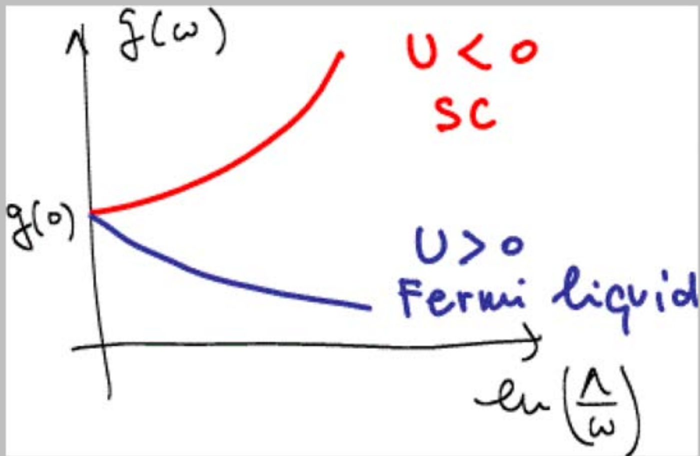
$$g(\omega) = N(0)U \ln\left(\frac{\Lambda}{\omega}\right)$$

To the leading order:

$$\frac{dg(\omega)}{d\ln\left(\frac{\Lambda}{\omega}\right)} \equiv \dot{g}(\omega) = \oplus\, g^2(\omega)$$

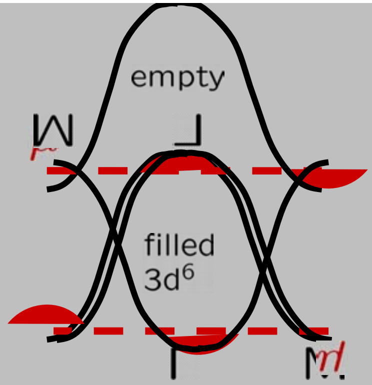
$\oplus$ for $U < 0$

$\ominus$ for $U > 0$



So, attractive pairing interaction ($U < 0$) grows as ω,T → 0 !!

For repulsive $U > 0$, the interaction → 0 and becomes irrelevant as ω,T → 0 → Fermi liquid (normal) ground state



Fictitious "Superconductor" → VDW in Fe-pnictides

$H \rightarrow \varepsilon_{\mathbf{k}} h^{\dagger}_{\mathbf{k}} h_{\mathbf{k}} + \varepsilon_{\mathbf{k}} e^{\dagger}_{\mathbf{k}} e_{\mathbf{k}} - W n_h n_e + (\cdots)$

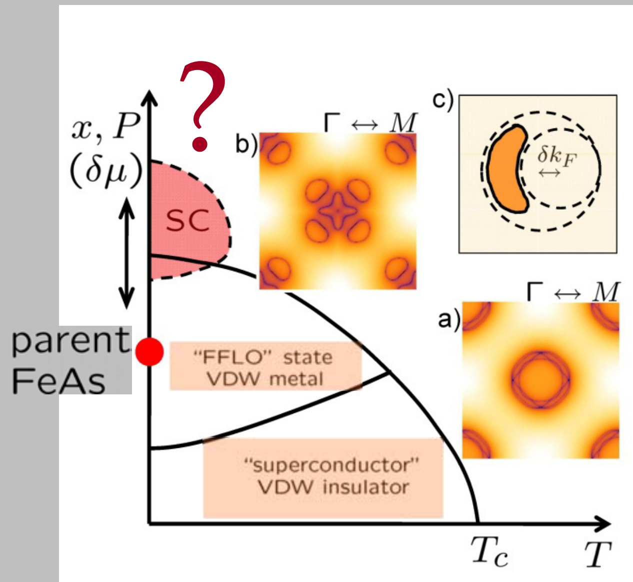
Negative U Hubbard model: $(h, e) \leftrightarrow (f_{\uparrow}, f_{\downarrow})$

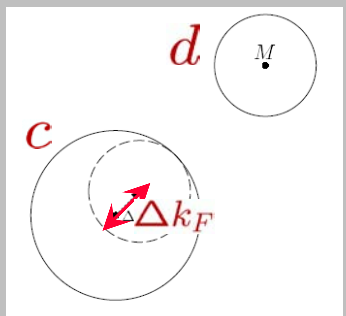
$\rightarrow \quad H = \sum_{\sigma} \varepsilon_{\mathbf{k}} f^{\dagger}_{\mathbf{k},\sigma} f_{\mathbf{k},\sigma} - W n_{f\uparrow} n_{f\downarrow} + (\cdots)$

Ground state is a "superconductor":

$\langle f_{\uparrow} f_{\downarrow} \rangle \neq 0 \quad \Rightarrow \quad \langle c^{\dagger} d \rangle \neq 0 \quad \Rightarrow$

insulating VDW (SDW/ODW/CDW) at $\mathbf{M} = (\pi, \pi)$





Genericaly, the c and d bands are different:

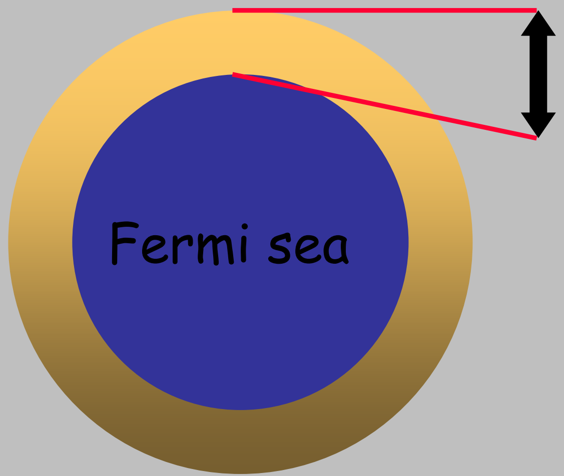
$k_{Fc} - k_{Fd} = \Delta k_F \neq 0 \quad \Rightarrow$ fictitious Zeeman magnetic field

⇒ "Fulde-Ferrell-Larkin-Ovchinikov", "breached pairing" states

⇒ metallic (incommensurate?) VDW (SDW/ODW/CDW)

What about real superconductivity ? $(\ldots)$

Pairing Gap Δ - Coastline of the Fermi Sea

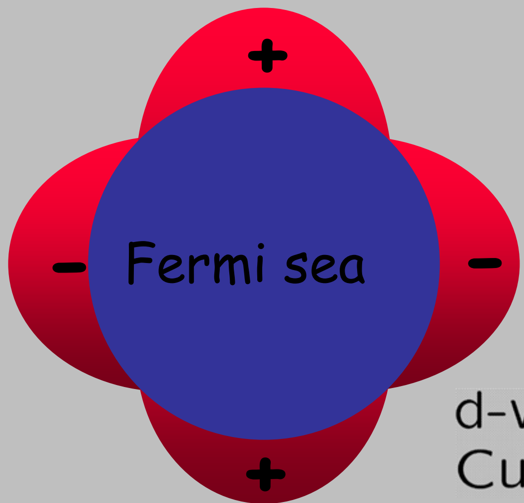


Superconducting gap Δ

Parting the waves
of the Fermi Sea

s-wave (isotropic)
Conventional SC (Nb, Pb, Al, $\cdots$)
$T_c < 25$K

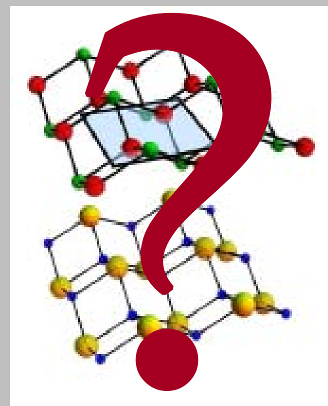
p-wave
Superfluid ^{3}He, SrRu (?)
$T_c \sim$ 1mK - 1K



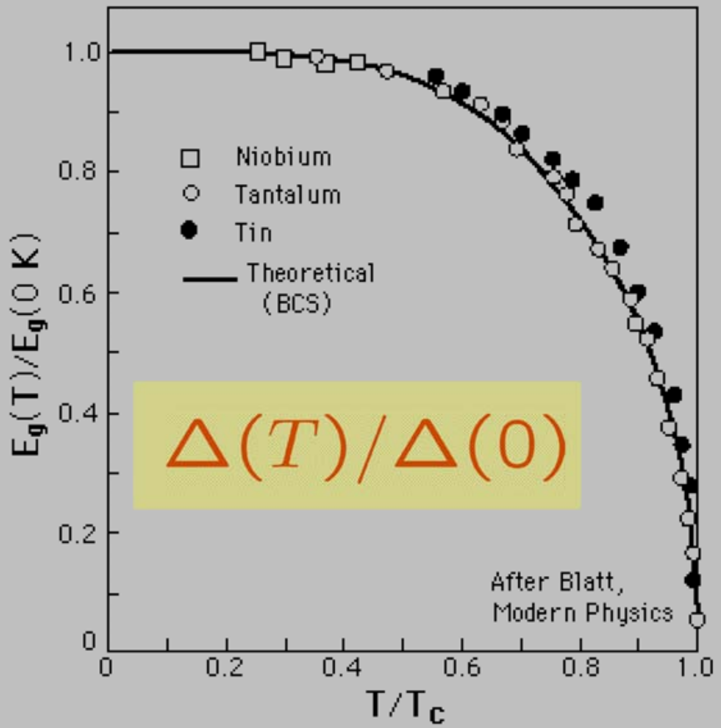
d-wave
Cuprate SC $T_c \sim 160$K

New REOFeAs SC
$T_c \sim 57$ K

$\Delta = ?$



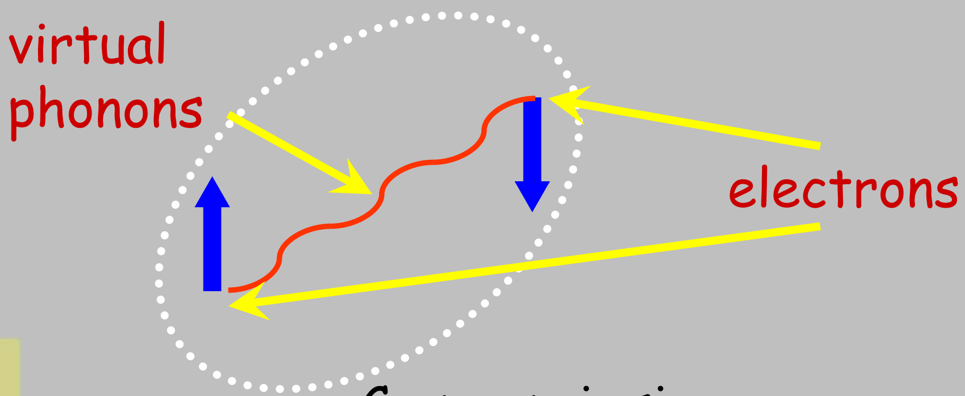
What can Δ tell us about superconducting state ?



$$2\Delta(0)/k_BT_c = 3.53$$

Universal BCS behavior

In conventional superconductors Δ is uniform along Fermi sea (s-wave)
This reflects the pairing interaction being attractive !!
Its origin is electron-electron interaction mediated by phonons !!

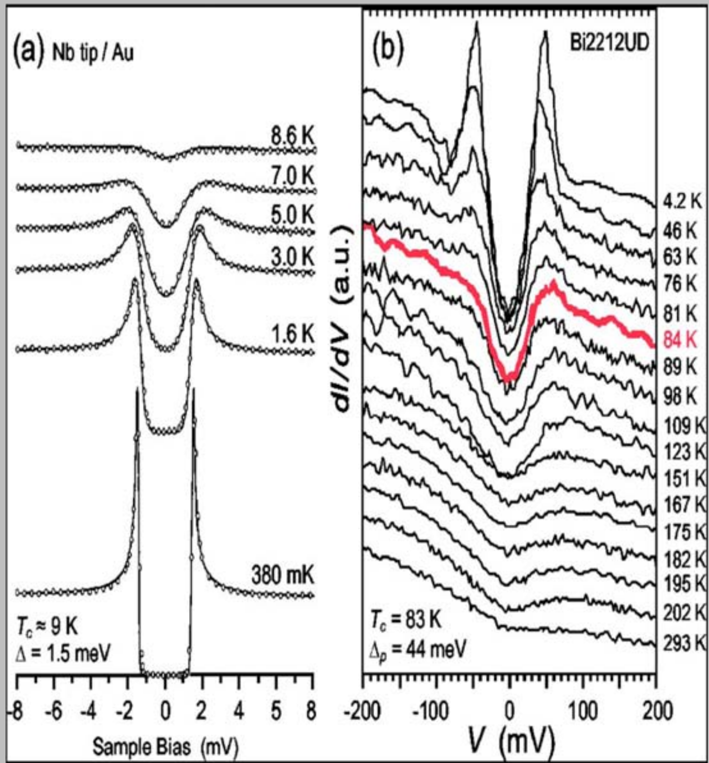


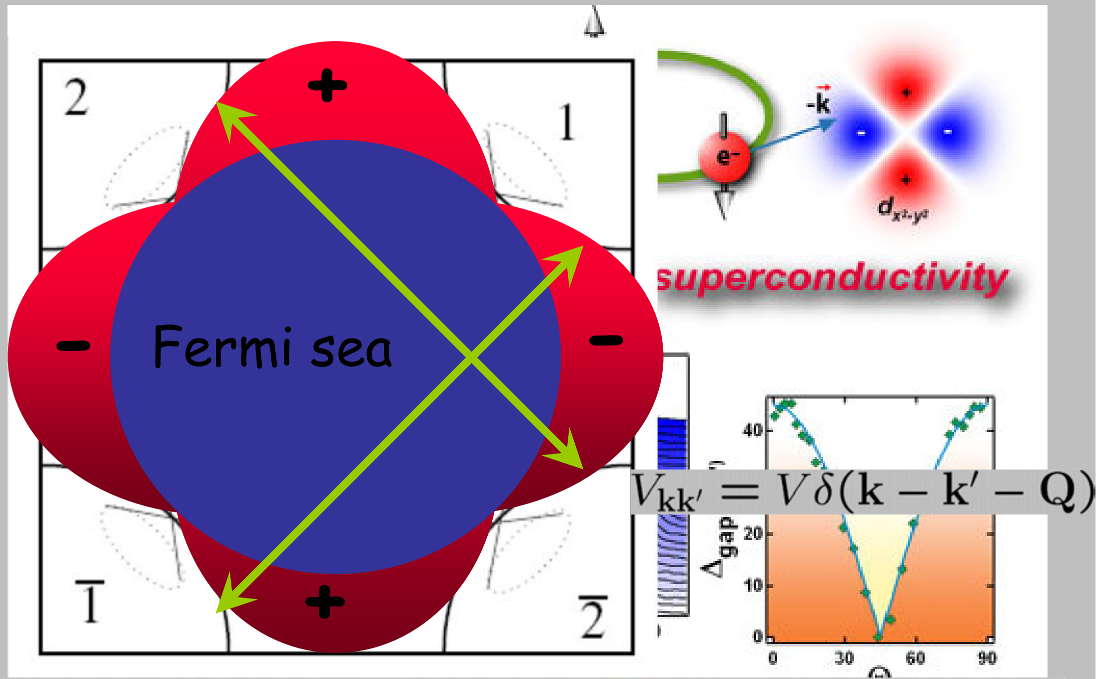
Cooper pair size
= coherence length ξ

Standard BCS theory works well in materials like Nb, Sn or Hg. In Pb and more complex systems (Nb_3Ge) one needs "strong coupling" theory ($2\Delta/T_c \sim$ 4-6)

What can Δ tell us about superconducting state ?

In cuprate superconductors Δ has nodes and $d_{x^2-y^2}$ symmetry. This suggests the basic interaction is repulsive !! The same is true of other nodal SCs



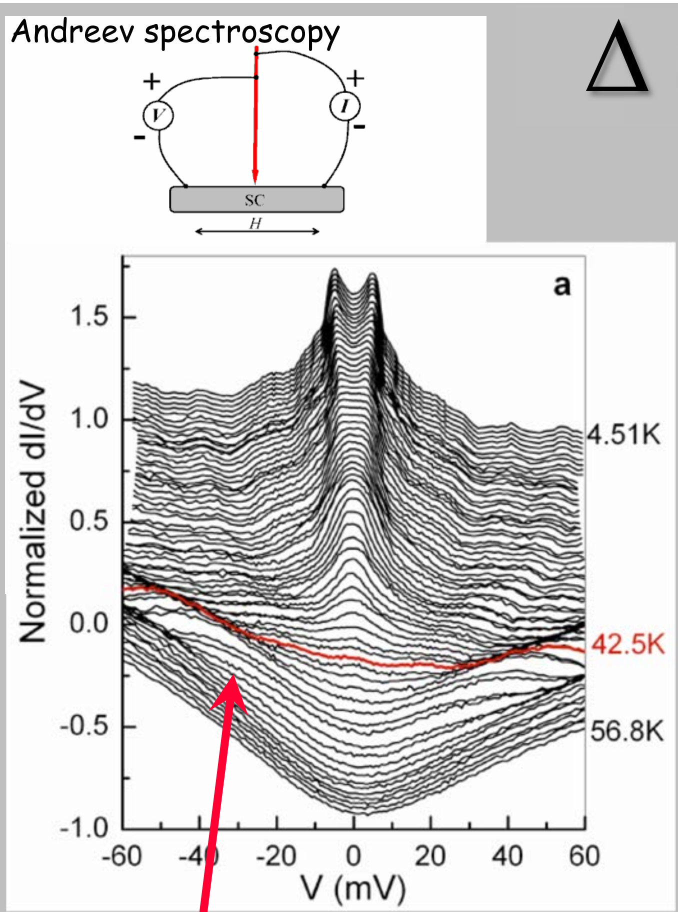


Gap equation $\Delta_{\mathbf{k}} = -\sum_{\mathbf{k}'} V_{\mathbf{k}\mathbf{k}'} \frac{\Delta_{\mathbf{k}'}}{\sqrt{\epsilon_{\mathbf{k}'}^2 + |\Delta_{\mathbf{k}'}|^2}}$

Furthermore, high temperature cuprate SCs exhibit a pseudogap behavior:
Δ remains finite even for $T > T_c$!
This reflects strong fluctuations !

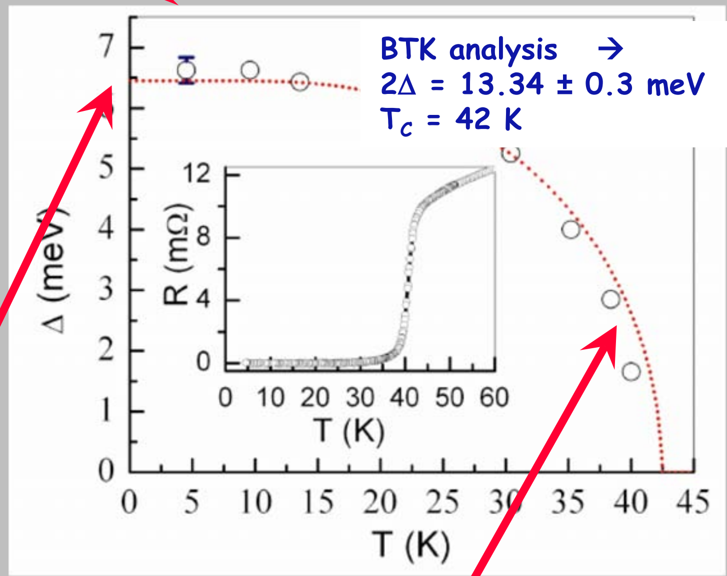
Results for FeAs mostly appear inconsistent with these features

Δ in FeAs superconductors I



T. Y. Chen *et al.*, Nature **453**, 1224 (2008)

$$\frac{2\Delta_{d(p)}(0)}{k_B T_c} = 4.28$$



No pseudogap !

Δ disappears at $T = T_c$

$2\Delta(0)/k_B T_c = 3.68 \sim 3.53$

Nodeless isotropic gap !

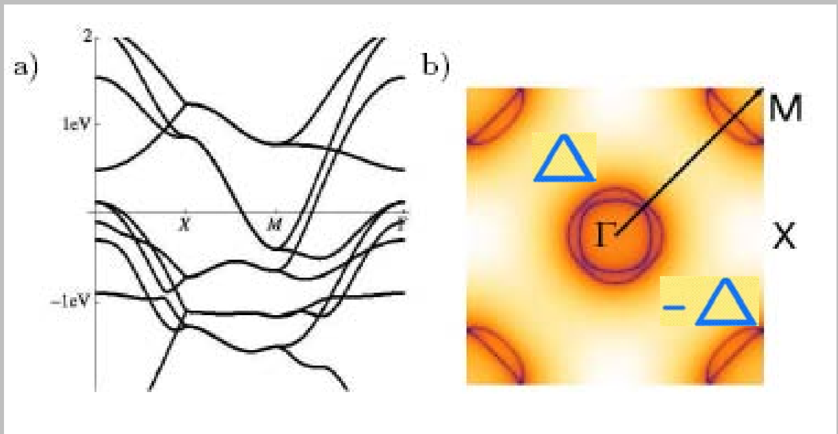
$\Delta(T)$ consistent with BCS theory

(sign/phase variation still possible!)

Conclusions: Nodeless superconducting gap and no pseudogap behavior. Very different from high T_c cuprate superconductors !!

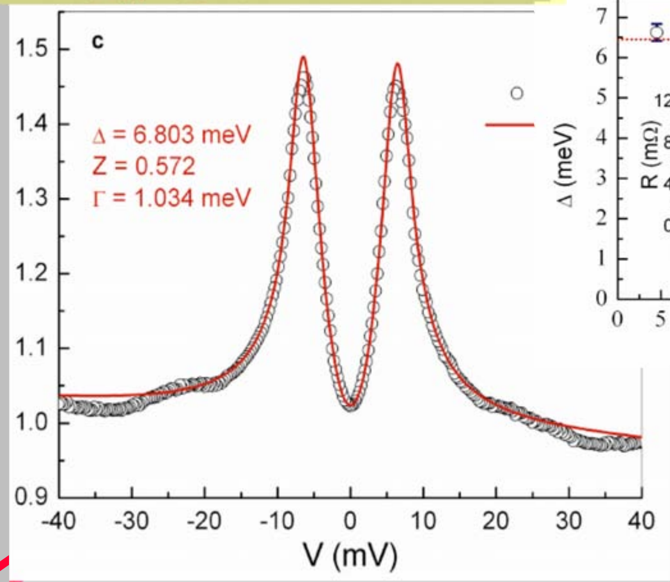
Δ in FeAs superconductors II

T. Y. Chen *et al.*, Nature **453**, 1224 (2008)

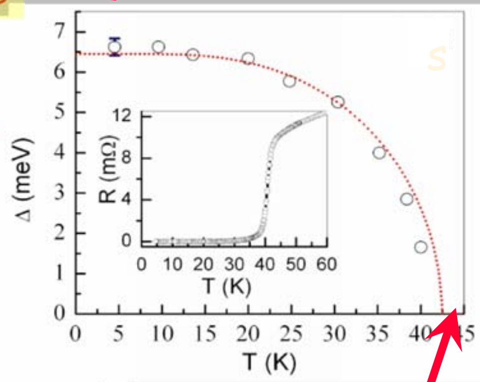


Fermi sea in FeAs materials
is more like Land o'Lakes.
It is multiply-connected.

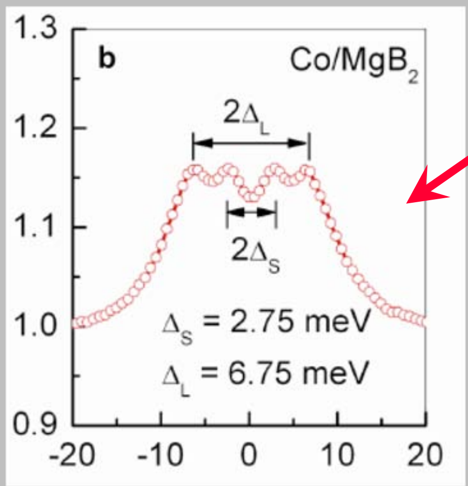
$2\Delta(0)/k_BT_c = 3.68 \sim 3.53$



$\frac{2\Delta_{d(p)}(0)}{k_BT_c} = 4.28$



$\Delta(T)$ BCS-like
no Pseudogap!

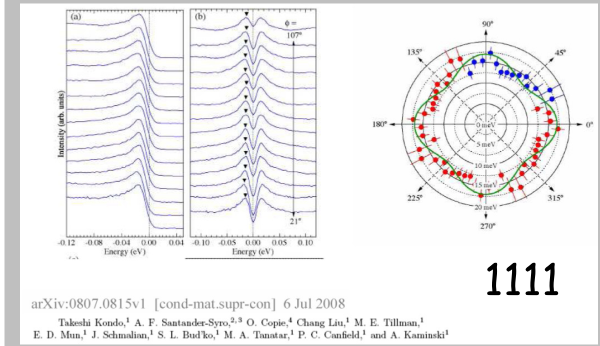


We see only a single isotropic BCS-like gap
If different Fermi "lakes" had significantly
different Δ we would see them

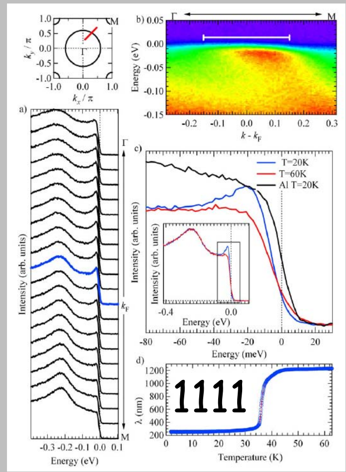
Only a "single" superconducting gap – but sign/phase could be different for holes and electrons. No pseudogap!

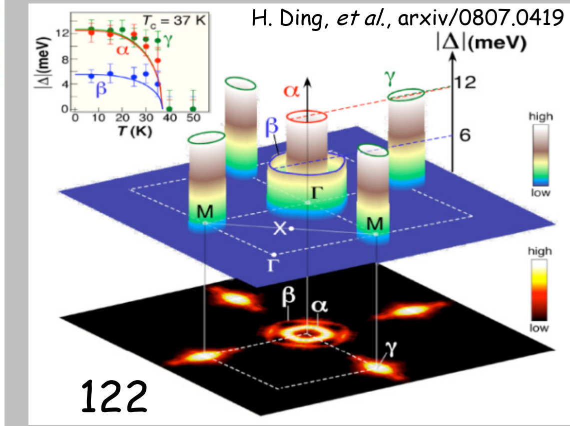
Conclusions: Conventional phonon-mechanism is unlikely but so is Mott limit-induced repulsion of the cuprate d-wave kind. We have something new !!

Emerging consensus (PCAR, ARPES, STM, μw, SQUID, …): nodeless "single" Δ in 1111, "two" Δ's in 122, nodes in lower T_c SC ??

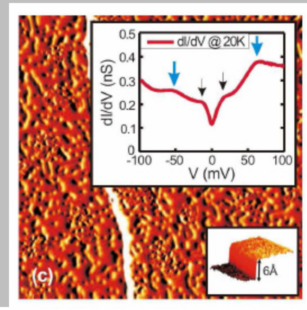


C. Liu, et al. arxiv/0806.2147

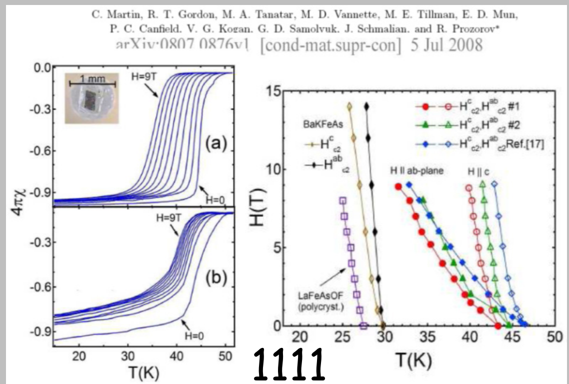


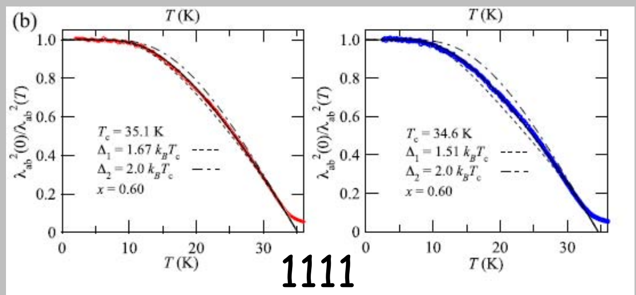


NMR sees nodal behavior ($\sim T^2$) in 1111

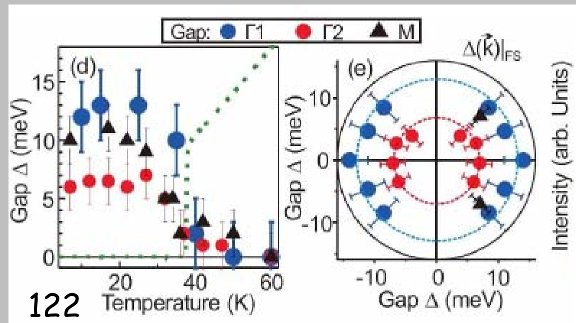


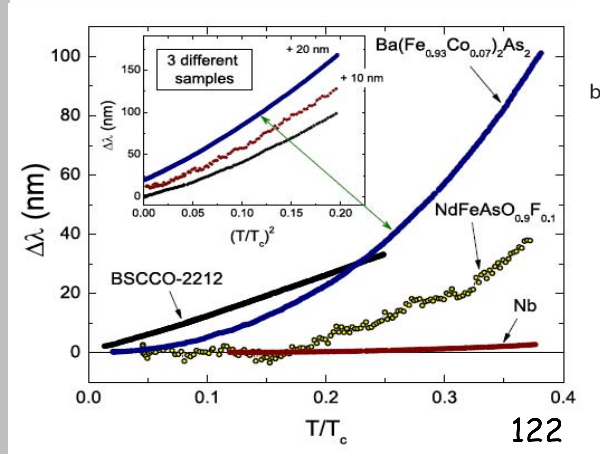
L. Wray, *et al.*, PRB **78** 184508 (2008),



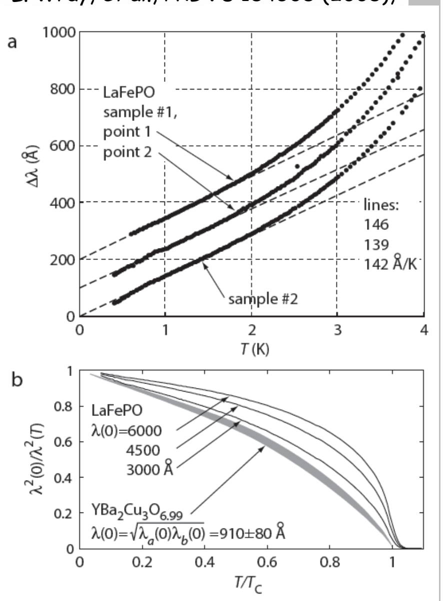


K. Hashimoto, *et al.*, PRL **102** 017002 (2009),





R. T. Gordon *et al.*, arxiv/0810.2295

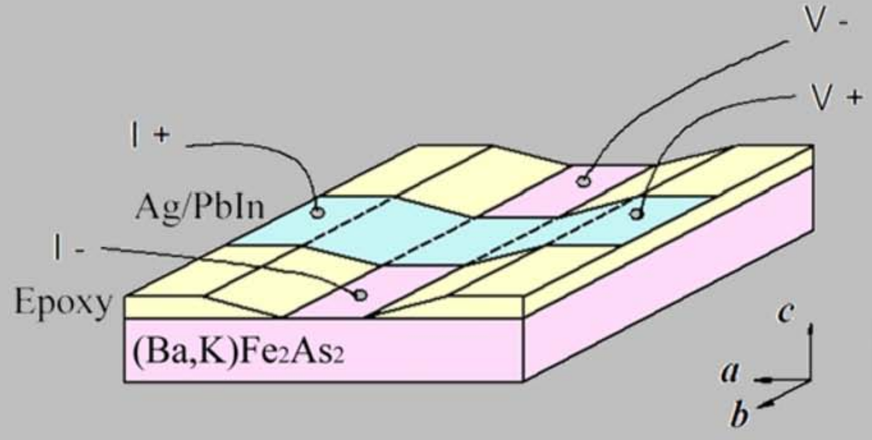


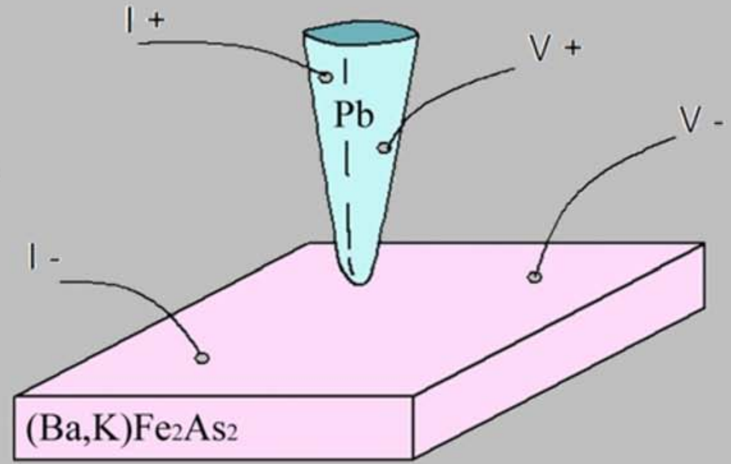
C. Hicks, *et al.*, arxiv/0903.5260

Multiband superconductivity in Fe-pnictides !?

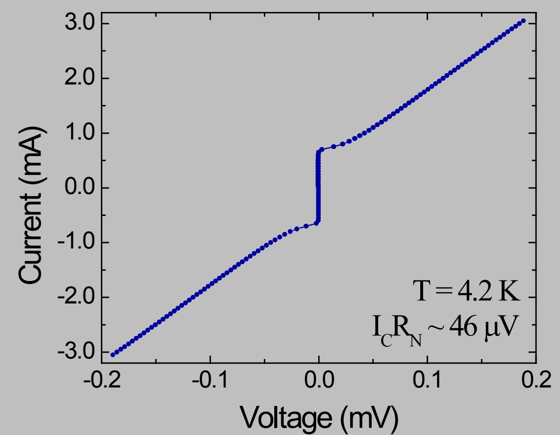
Josephson Effect Between FeAs and Pb

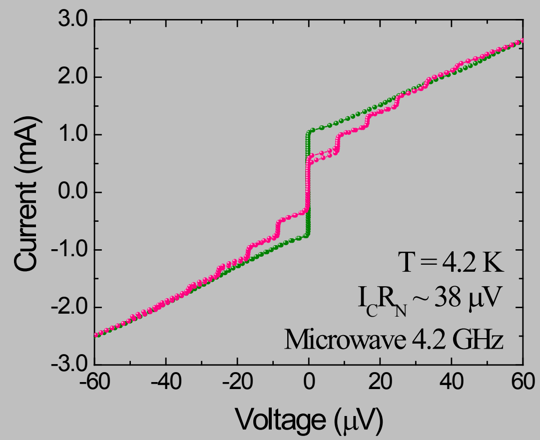
X. Zhang *et al.*, PRL **102**, 147002 (2009)





Point Contact Junction





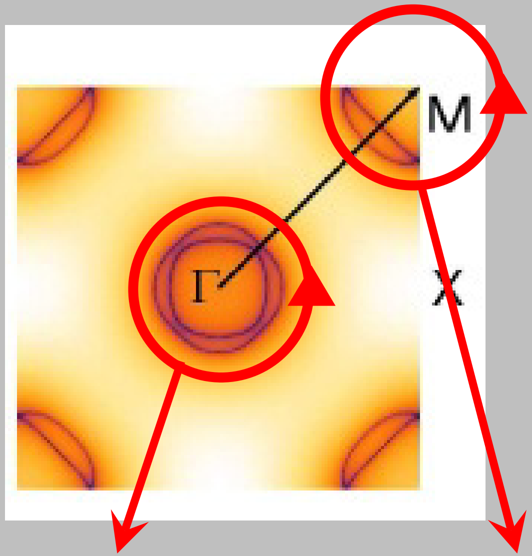
- I-V characteristics are resistively like a shunted junction
- Shapiro steps were observed under microwave irradiation

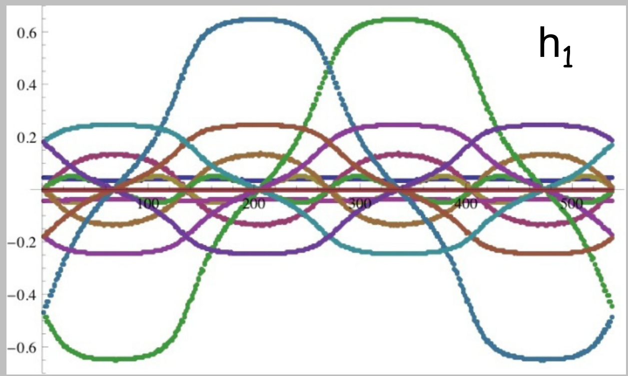
Strong indication of s-wave like SC state

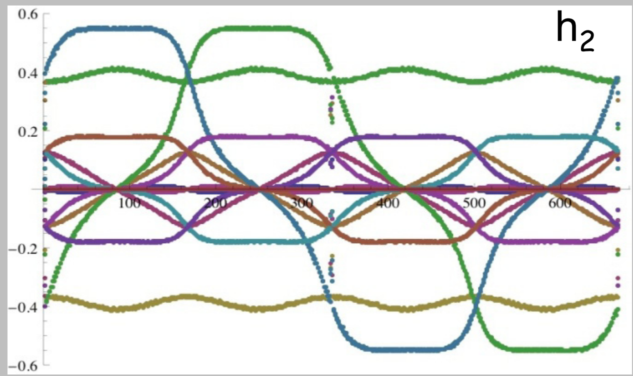
NAM center for nanophysics and advanced materials

courtesy of R. Greene

Minimal Model of FeAs Layers IV



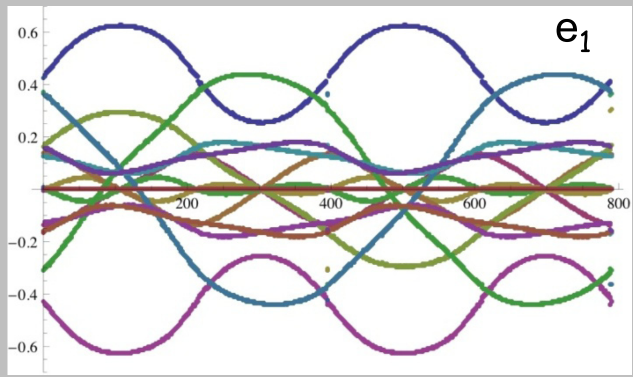




hole FS
2 pockets (valleys)

electron FS
2 pockets (valleys)

As one goes around the FS there is
strong mixing of odd and even d-orbitals
$\Rightarrow$ rich orbital content



FeAs are different from CuO_2

Charge carriers are more itinerant and less localized on atomic sites. Multiband description is necessary, unlike an effective single band model of cuprates

Interactions in FeAs I

High multiband itinerancy implies significant metallic screening

Yang *et al*, PRB **80**, 014508 (2009):
U_d not larger than ~ 2 eV, $J_{\mathrm{Hund}} \sim 0.8$ eV
from X-ray absorption
$\Rightarrow$ moderate correlations $U_d \sim t$, $J_{\mathrm{Hund}} < U_d$

Consider $\frac{1}{2}\int d^2r d^2r' V(\mathbf{r},\mathbf{r}')n(\mathbf{r})n(\mathbf{r}')$, where $V(\mathbf{r},\mathbf{r}')$ is the screened Coulomb repulsion $\Leftrightarrow$ Hubbard-like Hamiltonian with U_d and J_{Hund} reflecting atomic limit Coulomb correlations

$$H_{\mathrm{FeAs}} = -\sum_{ij,\alpha\beta} t_{ij}^{\alpha\beta} c_{i\alpha}^{\dagger} c_{j\beta} + \sum_{i,\alpha} \epsilon_i^{\alpha} c_{i\alpha}^{\dagger} c_{i\alpha} + \frac{1}{2} U_d \sum_i n_{di}^2 - J_{\mathrm{Hund}} \sum_i \mathbf{S}_{di}^2 + (\cdots)$$

Sawatzky *et al* discuss various interorbital interactions $(\cdots)$

Effective interaction at the Fermi surface:

$$\sum_{\mathbf{k},\mathbf{k}',\mathbf{q}} \Gamma_{\alpha,\beta,\gamma,\delta}(\mathbf{k},\mathbf{k}';\mathbf{q}) f_{\mathbf{k}+\mathbf{q},\alpha}^{\dagger} f_{\mathbf{k}'-\mathbf{q},\beta}^{\dagger} f_{\mathbf{k}',\delta} f_{\mathbf{k},\gamma}$$

$\Gamma_{\alpha,\beta,\gamma,\delta}(\mathbf{k},\mathbf{k}';\mathbf{q}) \rightarrow$ U, W, G_1, G_2

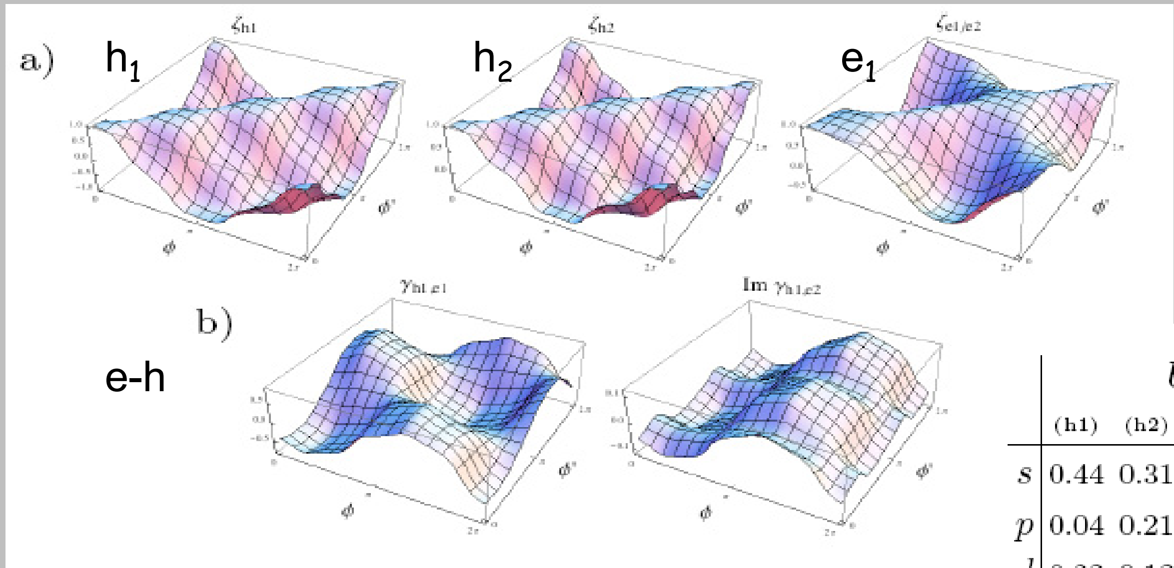
All flavor conserving (U,W) and flavor mixing (G_1,G_2) vertices

Interactions in FeAs II

V. Cvetkovic and ZT, PRB **80**, 024512 (2009); arXiv:0808.3742

A. V. Chubukov *et al*, PRB **78**, 134512 (2008)

vertices change significantly around Fermi surface:



k-space "Josephson" terms:

$$\rightarrow \; G_2 c^\dagger c^\dagger d d + h.c.$$

All interaction vertices @ FS: interband, intraband, mixed (typical sizes U, $W \gg G_1$, G_2)

	U				W				G_1	G_2
	(h1)	(h2)	(e1)	(e2)	(h1,e1)	(h1,e2)	(h2,e1)	(h2,e2)	(h1,e1)	(h1,e1)
s	0.44	0.31	0.35	0.35	0.21	0.25	0.27	0.29	0.14	0.14
p	0.04	0.21	0.17	0.20	0.22	0.21	0.22	0.22	0.01	0.01
d	0.22	0.12	0.09	0.10	0.11	0.13	0.09	0.11	0.03	0.02

Effective vertex at the FS:

$$\Gamma_{\alpha,\beta,\gamma,\delta}(\mathbf{k},\mathbf{k}';\mathbf{q}) \;\; (\mathbf{k},\mathbf{k}' \in \text{ FS}) \;\; \rightarrow \;\; V_s + V_p p_4(\varphi) p_4(\varphi') + V_d d_4(\varphi) d_4(\varphi')$$

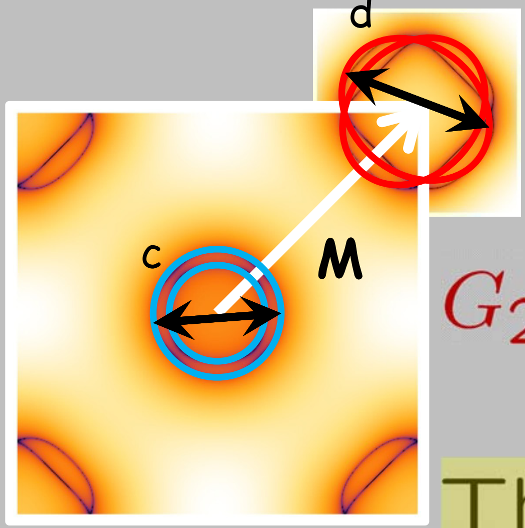
V_s, V_p, and V_d are C_4 version of s-, p- and d-wave coupling constants

Typically, we find W_s is dominant → Valley density-wave(s) (VDW) in FeAs

$G_2 c^\dagger c^\dagger d d$ These "Josephson" terms are not crucial for SDW → **Could they be the cause of SC ?**

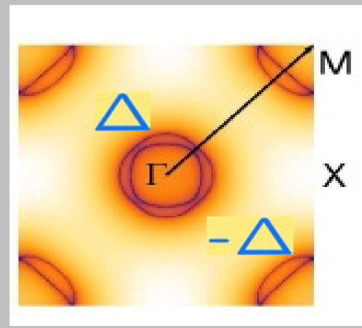
Two Kinds of Interband Superconductivity

ZT, Physics **2**, 60 (2009)



Interband pairing acts like Josephson coupling in k-space.
If G_2 is repulsive → antibound Cooper pairs (s'SC)

$$G_2 c^\dagger c^\dagger d d$$



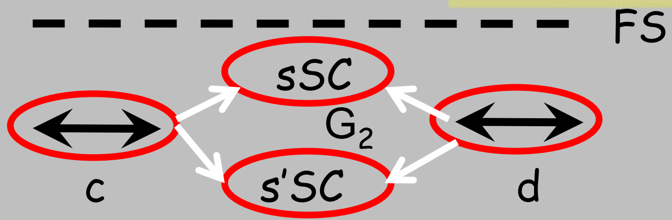
The Problem: Need

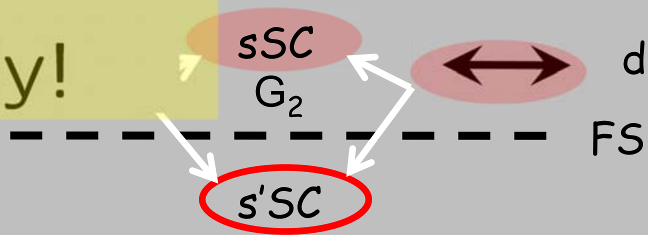
$$G_2 > \sqrt{U_c U_d}$$

Most unlikely!

Type-A interband S

trinsic) interband SC:





$(c_\uparrow c_\downarrow \ , \ d_\uparrow d_\downarrow) \quad \rightarrow \Psi_c \ , \Psi_d$

intraband Cooper pairing
further enhanced by G_2

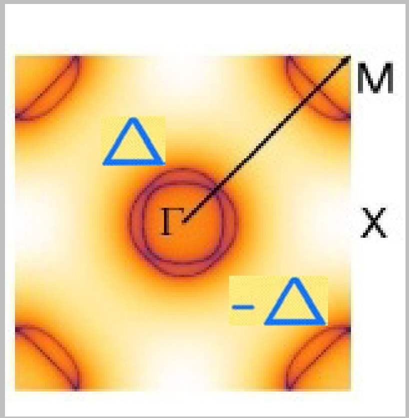
$(c_\uparrow c_\downarrow - d_\uparrow d_\downarrow)$

intrinsic interband Cooper pairs !

Single SC order parameter $\Psi_{s'}$!!

Interplay of Valley Density-Wave (VDW) and SC in FeAs I

V. Stanev, J. Kang, ZT, PRB **78**, 184509 (2008)



The condition for interband SC is actually milder:

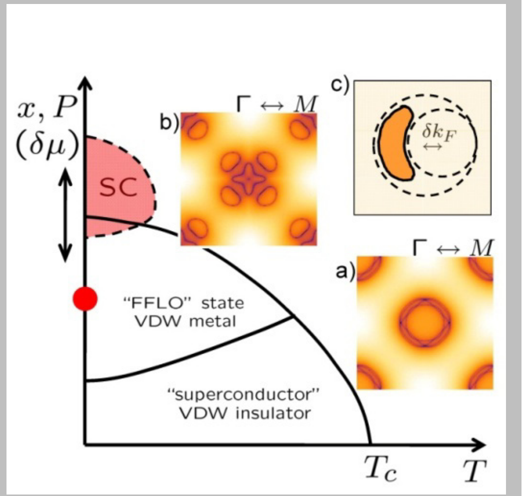
$G_2 < \sqrt{U_c U_d}$ but $G_2^\star > \sqrt{U_c^\star U_d^\star}$

$$U^\star_{c,d} = \frac{U_{c,d}}{1+U_{c,d}\log(\omega_{C2}/\omega_{C1})}$$

ω_{C1} (ω_{C2}) - Inter (intra) band energy scales

RG calculations indicate, near a VDW state:

G_2 grows, while $U_{c(d)}$ is suppressed



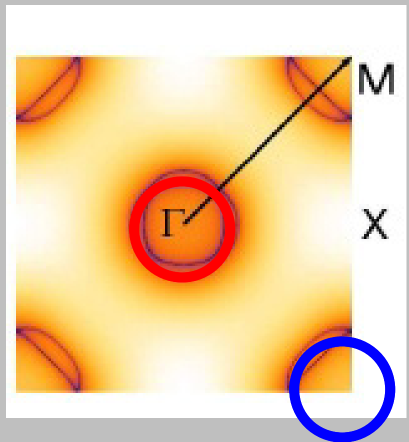
A. V. Chubukov *et al*, PRB **78**, 134512 (2008)

In Fe-pnictides interband superconductivity (s' or s+- state) is a strong possibility (perhaps with little help from phonons)

I. I. Mazin *et al.*, PRL **101**, 057003 (2008); M. Parish, J. Hu, and B. A. Bernevig, PRB **78**, 144514 (2008)

Hierarchy of Energy Scales U, W >> G_1, G_2
→ Unified Model of Valley Density-Wave (VDW)

Unified model N = 4 → SU(4)XSU(4)
V. Cvetkovic and ZT, PRB **80**, 024512 (2009)



$$H_0 = \sum_{\mathbf{k},\sigma} \xi^{(0)}_{\mathbf{k}} [\sum_\alpha h^{(\alpha)\dagger}_{\mathbf{k}} h^{(\alpha)}_{\mathbf{k}} + \sum_\beta e^{(\beta)\dagger}_{\mathbf{k}} e^{(\beta)}_{\mathbf{k}}]$$

All e and h bands are identical ⇒ H_0 has SU(8) internal symmetry

Orbital flavor-conserving vertices (U, W) reduce this to U(4)×U(4):

	T_S (K)	T_N (K)	m_{ord} (μ_B)
LaFeAsO	155	137	0.36
CeFeAsO	155	140	0.83
PrFeAsO	153	127	0.48
NdFeAsO	150	141	0.9
CaFeAsF	134	114	0.49
SrFeAsF	175	120	
$CaFe_2As_2$	173	173	0.8
$SrFe_2As_2$	220	220	0.94-1.0
$BaFe_2As_2$	140	140	0.9

$$H_{\text{int}} \to U^{(h)} \sum_{\alpha\alpha'\sigma\sigma'} h^{(\alpha)\dagger}_\sigma h^{(\alpha')\dagger}_{\sigma'} h^{(\alpha')}_{\sigma'} h^{(\alpha)}_\sigma + U^{(e)} \sum_{\beta\beta'\sigma\sigma'} e^{(\beta)\dagger}_\sigma e^{(\beta')\dagger}_{\sigma'} e^{(\beta')}_{\sigma'} e^{(\beta)}_\sigma +$$
$$2W \sum_{\alpha\beta\sigma\sigma'} e^{(\beta)\dagger}_{\sigma'} h^{(\alpha)\dagger}_\sigma h^{(\alpha)}_\sigma e^{(\beta)}_{\sigma'} + (\cdots)$$

$U(4)\times U(4)$ symmetry is reasonable since U and W do not vary much in different (e, h) channels

	(h1)	(h2)	(e1)	(e2)	(h1,e1)	(h1,e2)	(h2,e1)	(h2,e2)	(h1,e1)	(h1,e1)
s	0.44	0.31	0.35	0.35	0.21	0.25	0.27	0.29	0.14	0.14
p	0.04	0.21	0.17	0.20	0.22	0.21	0.22	0.22	0.01	0.01
d	0.22	0.12	0.09	0.10	0.11	0.13	0.09	0.11	0.03	0.02

Finally, flavor-mixing vertices $G_{1,2}(\ll U, W)$ have the highest symmetry that physics will allow:

$$(\ldots) \to 2G_1 \sum_{\alpha\beta\sigma\sigma'} (\sigma\sigma') e^{(\beta)\dagger}_\sigma h^{(\alpha)\dagger}_{-\sigma} h^{(\alpha)}_{-\sigma'} e^{(\beta)}_{\sigma'} +$$
$$G_2 \sum_{\alpha\alpha'\beta\beta'\sigma\sigma'} (\sigma\sigma') h^{(\alpha)}_{-\sigma} e^{(\beta)}_\sigma h^{(\alpha')}_{-\sigma'} e^{(\beta')}_{\sigma'} \epsilon^{\alpha\alpha'} \epsilon^{\beta\beta'} + h.c.$$

VDW in Fe-pnictides is a (nearly) highly symmetric combination: SDW/CDW/ODW

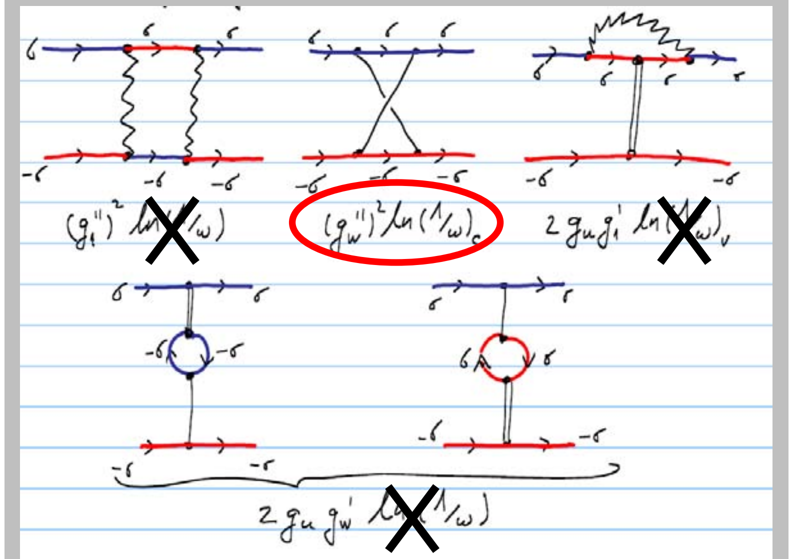
Interactions in FeAs III

V. Cvetkovic & ZT (RG) ; A. V. Chubukov, I. Eremin *et al* (parquet);
F. Wang, H. Zhai, Y. Ran, A. Vishwanath & DH Lee (fRG)
R. Thomale, C. Platt, J. Hu, C. Honerkamp & A. Bernevig (fRG)

Effective interaction at the Fermi surface:

$$\sum_{\mathbf{k},\mathbf{k}',\mathbf{q}} \Gamma_{\alpha,\beta,\gamma,\delta}(\mathbf{k},\mathbf{k}';\mathbf{q}) f^\dagger_{\mathbf{k}+\mathbf{q},\alpha} f^\dagger_{\mathbf{k}'-\mathbf{q},\beta} f_{\mathbf{k}',\delta} f_{\mathbf{k},\gamma} \quad \rightarrow \quad \boxed{U, W, G_1, G_2}$$

$$\begin{aligned}
g_U(\omega) &= g_U - g_U^2 \ln\left(\frac{\Lambda}{\omega}\right)_{pp} - g_2^2 \ln\left(\frac{\Lambda}{\omega}\right)_{pp}, \\
g_2(\omega) &= g_2 - 2g_2 g_U \ln\left(\frac{\Lambda}{\omega}\right)_{pp} + 2g_2 g'_W \ln\left(\frac{\Lambda}{\omega}\right)^c_{ph} + \\
& \quad 2g_2 g''_W \ln\left(\frac{\Lambda}{\omega}\right)^v_{ph} - 2g_2 g''_1 \ln\left(\frac{\Lambda}{\omega}\right)_{ph}, \\
g'_W(\omega) &= g'_W + (g'_W)^2 \ln\left(\frac{\Lambda}{\omega}\right)_{ph} + g_2^2 \ln\left(\frac{\Lambda}{\omega}\right)_{ph}, \\
g''_W(\omega) &= g''_W + (g''_W)^2 \ln\left(\frac{\Lambda}{\omega}\right)_{ph}, \\
g'_1(\omega) &= g'_1 - 2g'_1 g''_1 \ln\left(\frac{\Lambda}{\omega}\right)_{ph} + 2g'_1 g''_W ln\left(\frac{\Lambda}{\omega}\right)^v_{ph}, \\
g''_1(\omega) &= g''_1 - (g'_1)^2 \ln\left(\frac{\Lambda}{\omega}\right)_{ph} - (g''_1)^2 \ln\left(\frac{\Lambda}{\omega}\right)_{ph} - \\
& \quad g_2^2 \ln\left(\frac{\Lambda}{\omega}\right)_{ph} + 2g''_1 g''_W \ln\left(\frac{\Lambda}{\omega}\right)^v_{ph}, \qquad (15)
\end{aligned}$$



If G_1 , G_2 << U, W
→
relevant vertices: U, W, & G_2

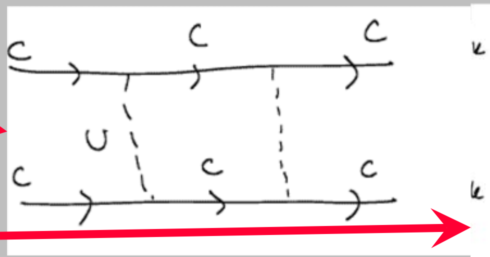
Interplay of VDW and SC in FeAs II

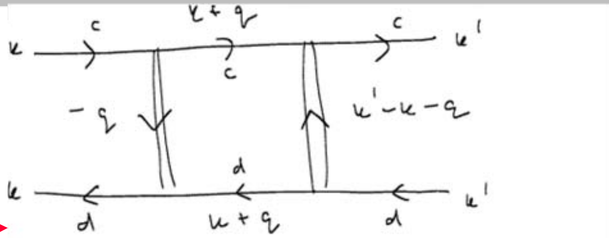
RG (near VDW):

$$\dot U = -U^2 - G_2^2$$

$$\dot G_2 = -2G_2U + 4G_2W$$

$$\dot W = +W^2 + G_2^2 \qquad (G_1 \to 0)$$





$$\int d^2q\, G_d(k+q)\, G_c(k+q)$$

$$\int d^2p\, G_d(p)\, G_c(p) \propto \ln\frac{\Omega}{\omega}$$

Proximity to VDW is crucial:

$$\dot U \pm \dot G_2 = -(U \pm G_2)^2 \pm 4WG_2$$

$$\dot W = W^2 + G_2^2$$

If $W \to 0$ then $\dot U \pm \dot G_2 = -(U \pm G_2)^2$

SC only for $G_2 > U$!!

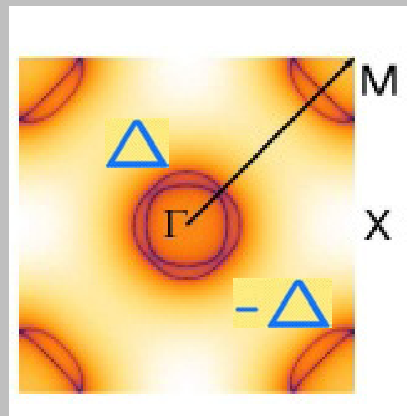
This is true interband SC since U > 0 – different from U < 0 :

$(c_\uparrow c_\downarrow - d_\uparrow d_\downarrow)$

interband Cooper pairs !

$(c_\uparrow c_\downarrow \ , \ d_\uparrow d_\downarrow)$

intraband Cooper pairs



RG Theory of Interband Mechanism of SC in FeAs

V. Cvetkovic and ZT, PRB **80**, 024512 (2009)

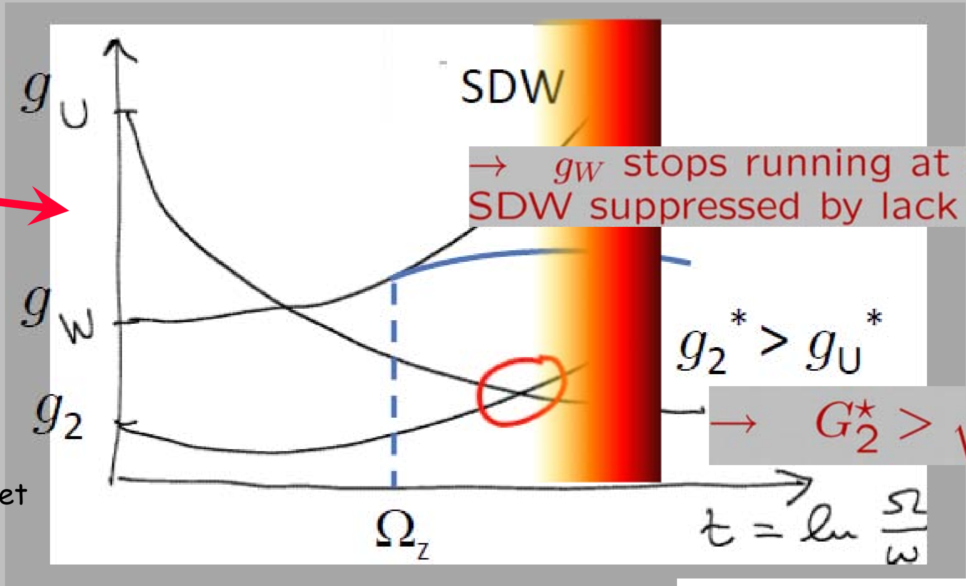
RG flows (near SDW):

$$\dot U = -U^2 - G_2^2$$

$$\dot G_2 = -2G_2 U + 4G_2 W$$

$$\dot W = +W^2 + G_2^2 \quad (G_1 \to 0)$$

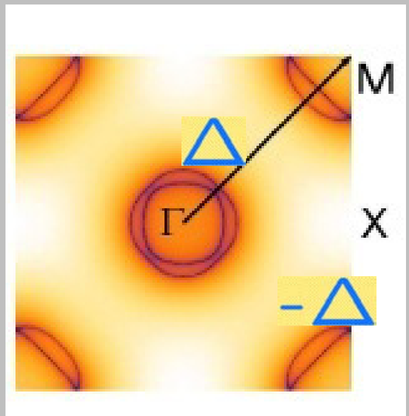
A. V. Chubukov *et al*, PRB **78**, 134512 (2008) parquet
F, Wang *et al*, PRL **102**, 047005 (2009) fRG
R. Thomale *et al*, PRB **80**, 180505(R) (2009) fRG



$\rightarrow$ g_W stops running at $\Omega = \Omega_z$;
SDW suppressed by lack of nesting

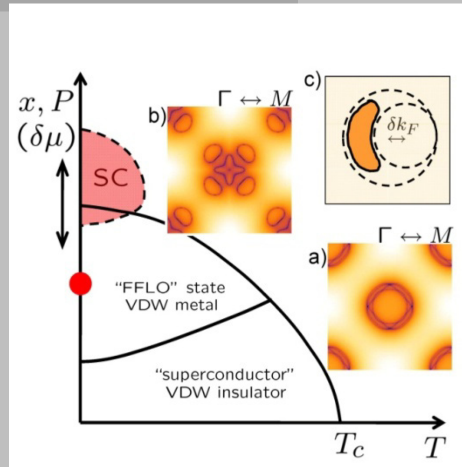
$g_2^* > g_U^*$

$\rightarrow \quad G_2^\star > \sqrt{U_c^\star U_d^\star}$



$$G_2 < \sqrt{U_c U_d}$$

$$G_2^\star > \sqrt{U_c^\star U_d^\star}$$



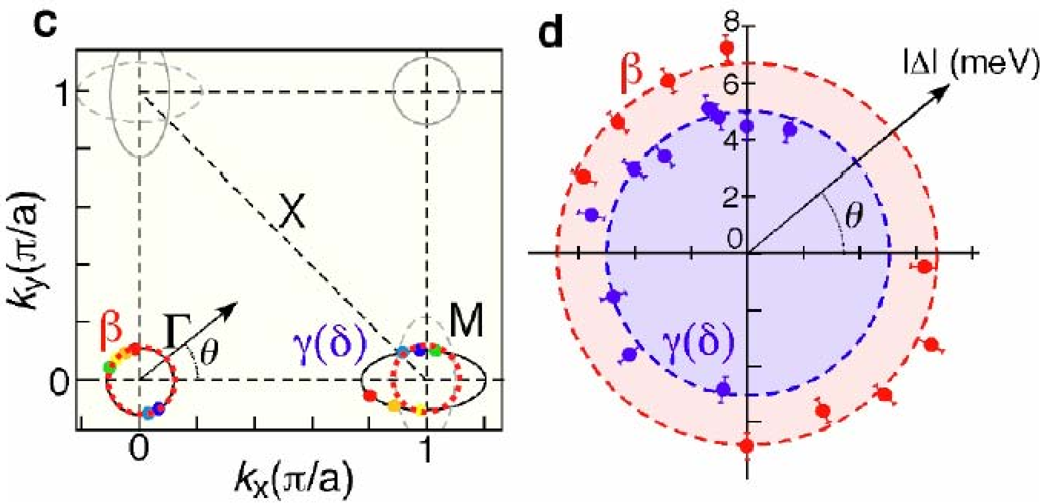
$$\rightarrow \quad T_c \sim \Omega_z \exp(-1/(g_2^\star - \sqrt{\mu_c^\star \mu_d^\star}))$$

In Fe-pnictides interband superconductivity (s' or s+- state) is a strong possibility but there is some fine tuning with SDW/CDW/ODW

Correlation between SC and Nesting (ARPES)

H. Ding group (CAS Beijing & BC)

In optimally electron doped samples, quasi FS nesting between the outer (β) hole pocket and the electron pockets

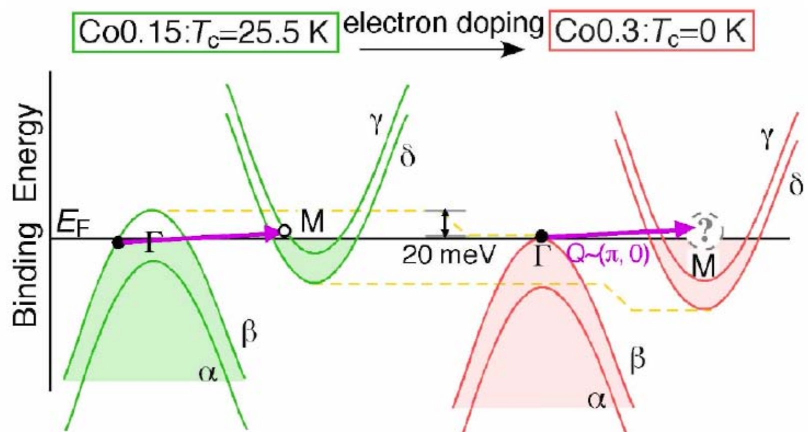


Strong pairing also happens to these FSs!

$$2\Delta/k_BT_c = 6,\ 4.5 \quad \text{for} \quad \beta,\ \gamma(\delta)$$

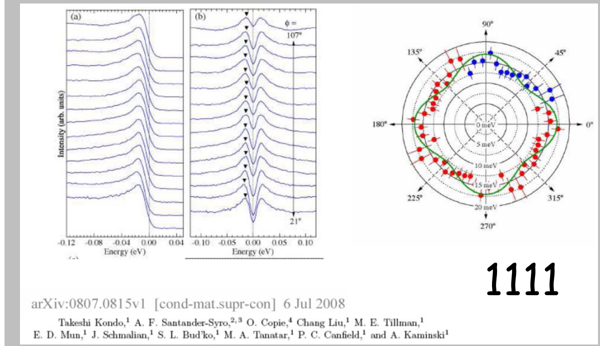
K. Terashima *et al.*, PNAS 106,

- Large SC gaps for well-nested hole and electron pockets
- SC collapses as one dopes away from near nesting
- Holds for both hole and electron doping

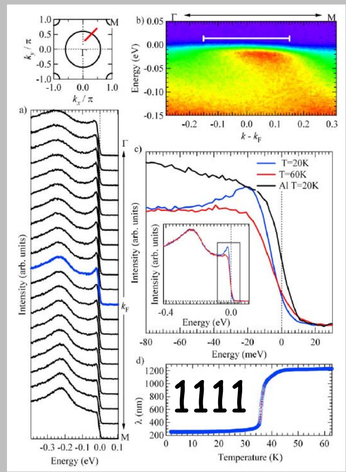


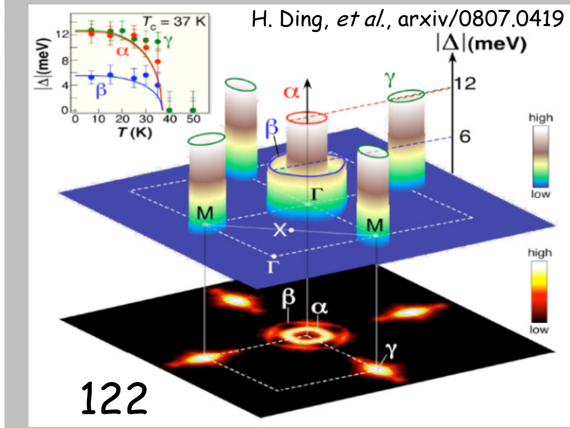
Nodeless SC correlates with degree of nesting and SC disappears as h(e) Fermi pockets are doped away.

Emerging consensus (PCAR, ARPES, STM, μw, SQUID, …): nodeless "single" Δ in 1111, "two" Δ's in 122, nodes in lower T_c SC ??

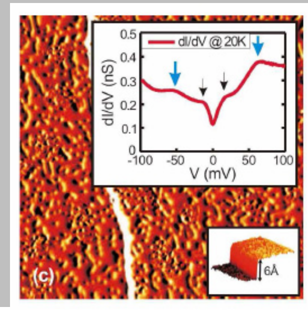


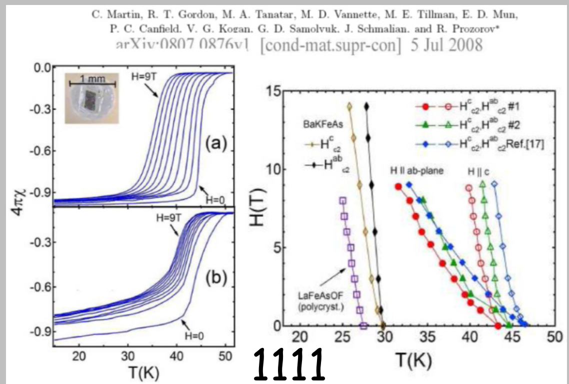
C. Liu, et al. arxiv/0806.2147

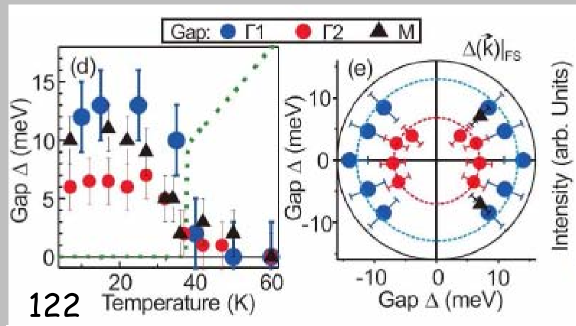




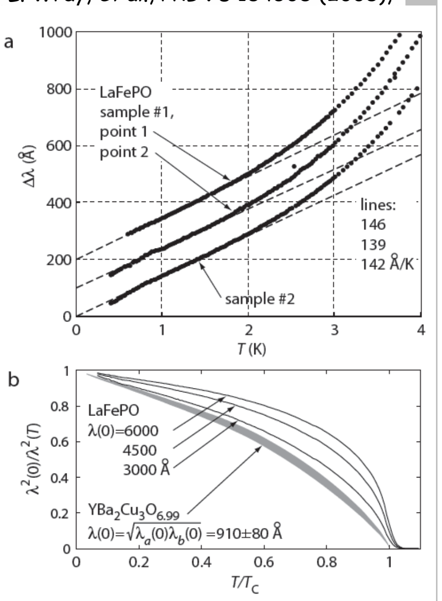
NMR sees nodal behavior ($\sim T^2$) in 1111



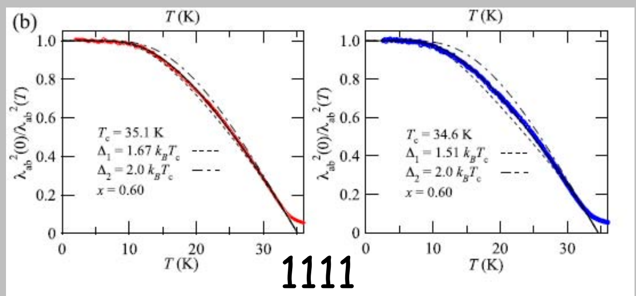




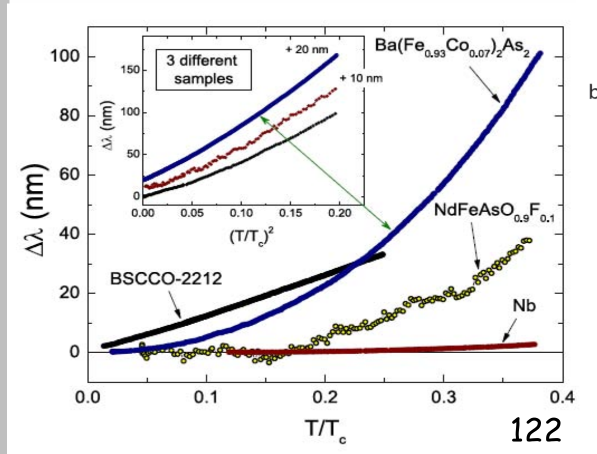
L. Wray, et al., PRB **78** 184508 (2008),



C. Hicks, et al., arxiv/0903.5260



K. Hashimoto, et al., PRL **102** 017002 (2009),

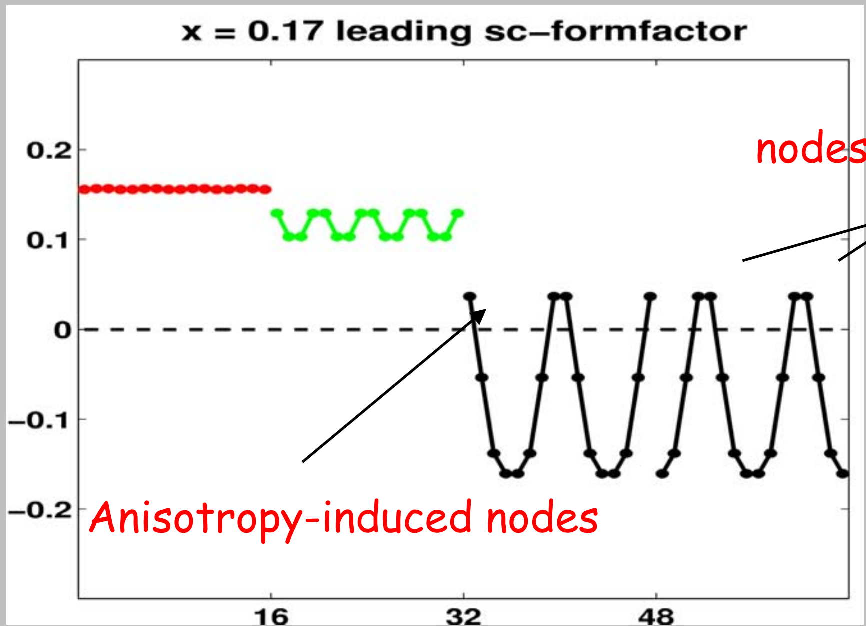


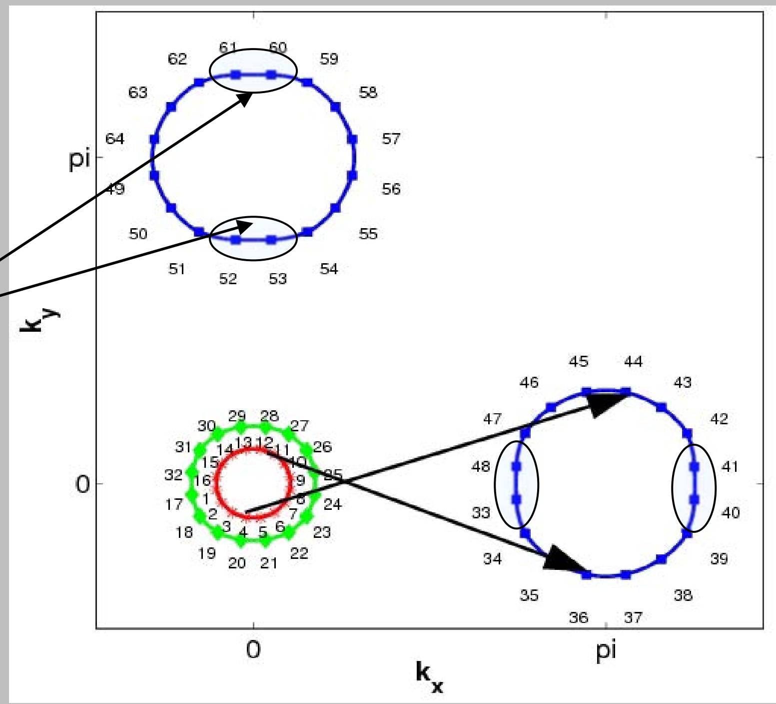
R. T. Gordon et al., arxiv/0810.2295

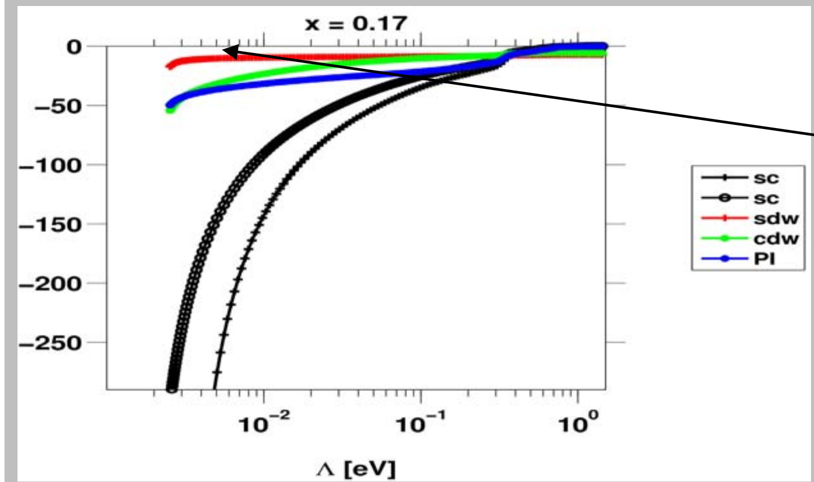
Multiband superconductivity in Fe-pnictides !?

Nodal SC from Orbital Structure (fRG)

R. Thomale, C. Platt, W. Hanke & A. Bernevig, arXiv:1002.3599;
also, F. Wang, D. H. Lee *et al*; K. Kuroki *et al*

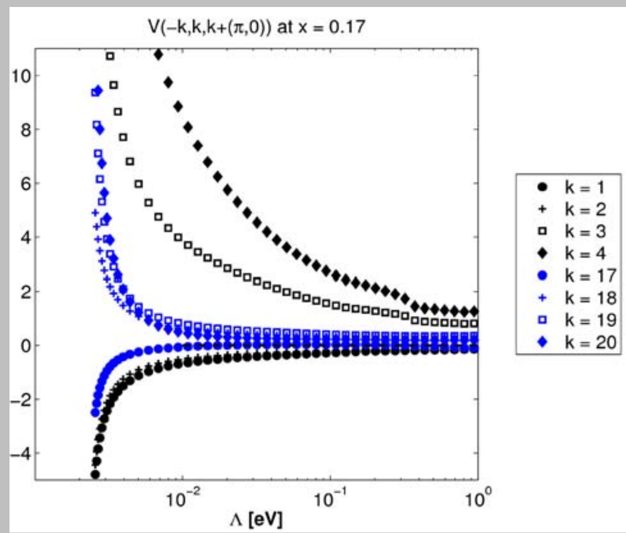






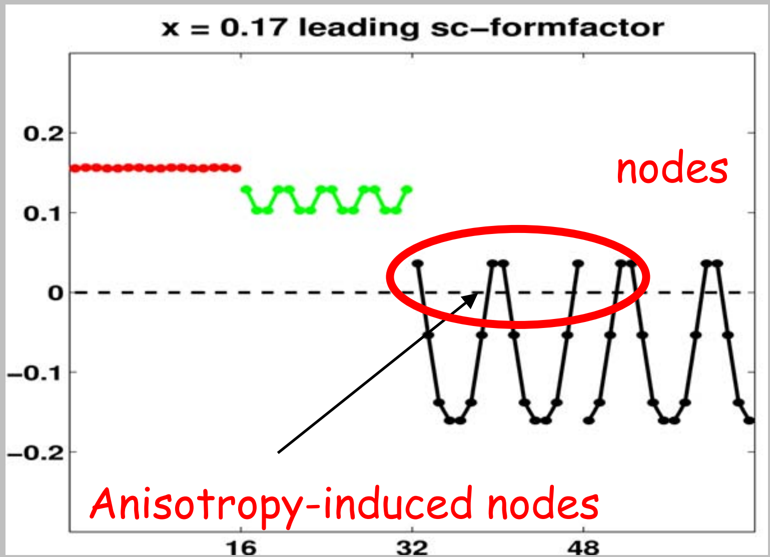
Change of orbital character in electron pockets reduces SDW fluctuations

Nodal s+- is the dominant instability as $T \to T_c$



Accidental Gap Nodes and Zeroes in Iron-Pnictides I

V. Stanev *et al.*, arXiv:1006.0447



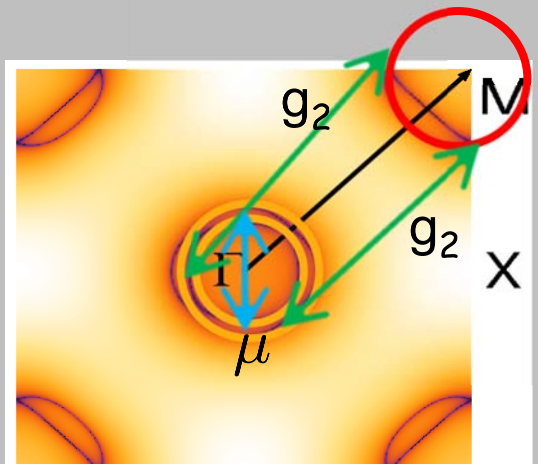
These nodes are accidental and NOT protected by any symmetry – SC state is still s+- or s'. They are caused by strong orbital anisotropy of pairing interaction.

Such nodal s' states arise in various calculations (fRG, RG, etc) near $T = T_c$. But do these accidental nodes survive as $T \to 0$?!

Consider interband interaction:

$$g_2(k,k') = \lambda_0 + \lambda_n \cos 4\theta$$

$$\to \boxed{\Delta_e(\theta) \equiv \Delta_0 + \Delta' \cos 4\theta}$$



$$\Delta_h = -\int_0^\Lambda d\xi \int_0^{2\pi} \frac{d\theta}{2\pi} \frac{\tanh(E_e/2T)}{E_e}(\lambda_0 + \lambda_n \cos 4\theta)\Delta_e - \mu \int_0^\Lambda d\xi \frac{\tanh(E_h/2T)}{E_h}\Delta_h$$

$$\Delta_0 = -\mu \int_0^\Lambda d\xi \int_0^{2\pi} \frac{d\theta}{2\pi} \frac{\tanh(E_e/2T)}{E_e}\Delta_e - \lambda_0 \int_0^\Lambda d\xi \frac{\tanh(E_h/2T)}{E_h}\Delta_h$$

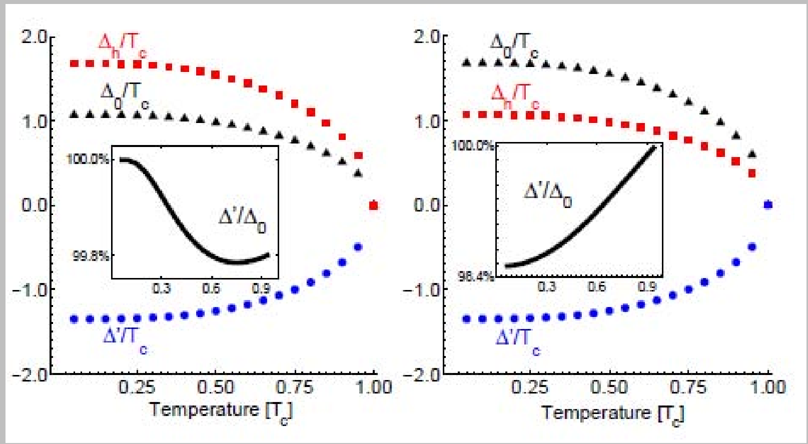
$$\Delta' = -\lambda_n \int_0^\Lambda d\xi \frac{\tanh(E_h/2T)}{E_h}\Delta_h \; , \qquad (1)$$

The problem: Gap equations can wipe out accidental nodes for $T \ll T_c$ →

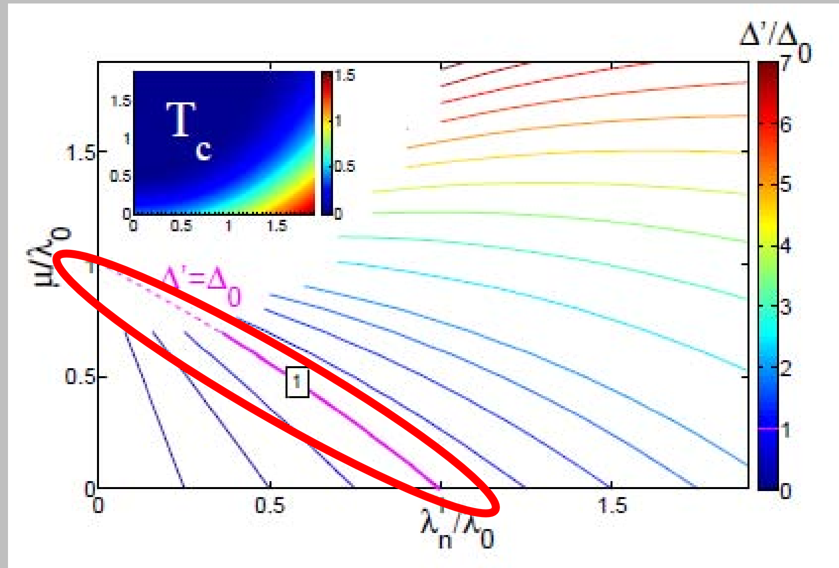
Accidental Gap Nodes and Zeroes in Iron-Pnictides II

V. Stanev *et al.*, arXiv:1006.0447

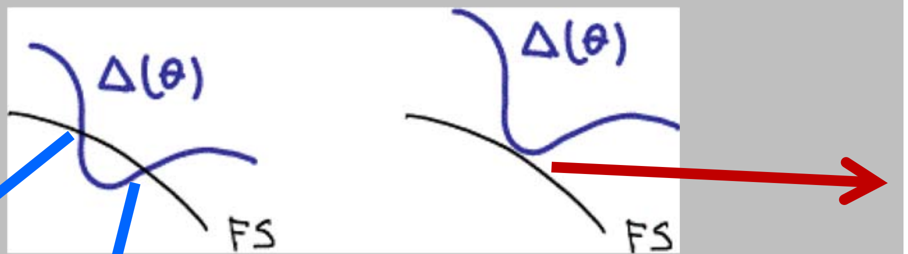
These accidental nodes appear “robust” as T → 0

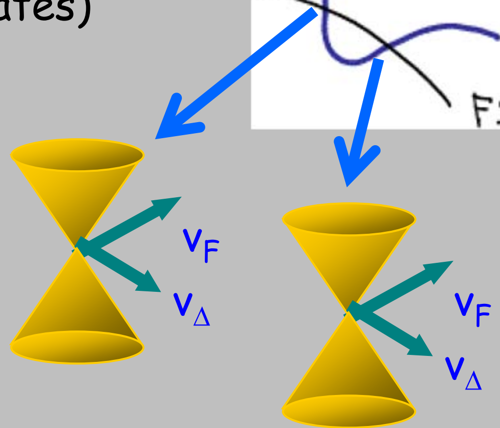


$$\Delta_e(\theta) \equiv \Delta_0 + \Delta' \cos 4\theta$$

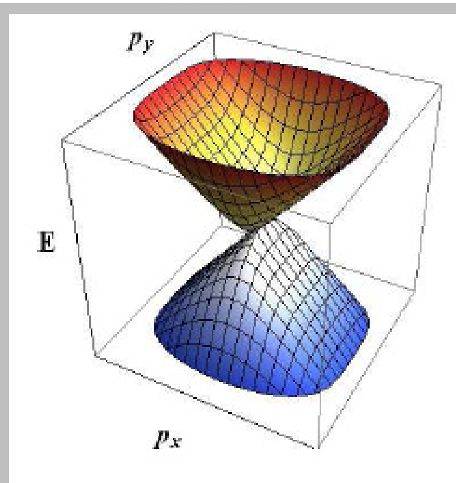


Accidental nodes
→ Dirac points
(cuprates)





Spectroscopy and low T thermodynamics dominated by accidental zeroes →



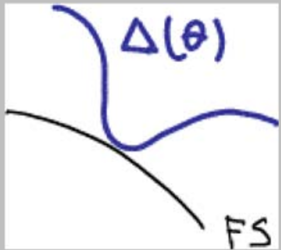
Zero-point BdG quasiparticles $\Delta(\theta) \sim \theta^2$

Critical "Zero-Point" Quasiparticle Scaling

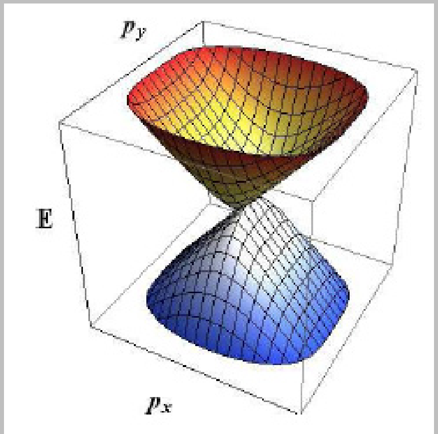
V. Stanev *et al.*, arXiv:1006.0447

$\Delta' = \Delta_0$ defines a line of quantum phase transitions in (T, H) phase diagram →
Critical scaling of zero-point BdG quasiparticles

$$\mathcal{H}_{\rm BdG} = \begin{bmatrix} \frac{\mathbf{p}^2}{2m} - \epsilon_F & \hat{\Delta}(\mathbf{r}) \\ \hat{\Delta}(\mathbf{r}) & -\frac{\mathbf{p}^2}{2m} + \epsilon_F \end{bmatrix} \approx \begin{bmatrix} v_F p_x & \frac{8\Delta_0}{p_F^2} p_y^2 \\ \frac{8\Delta_0}{p_F^2} p_y^2 & -v_F p_x \end{bmatrix}$$



$$\Rightarrow \quad E = \pm\sqrt{(v_F p_x)^2 + (8\Delta_0 p_y^2/p_F^2)^2}$$



Spectroscopy and thermodynamics dominated by zero-point scaling
←→ Different from Dirac and Simon-Lee scaling in cuprates

$$N(E) \sim {\rm Re}\left(\int d\theta \frac{E}{\sqrt{E^2 - \Delta(\theta)^2}}\right) \sim \sqrt{E}$$

$$C(T) \approx \frac{1}{T^2}\int_0^\infty dE E^2 N(E) \frac{1}{\cosh^2(E/2T)} \propto T^{3/2}$$

$$\chi_s(T)/\chi_n \approx \frac{1}{T}\int_0^\infty dE N(E) \frac{1}{\cosh^2(E/2T)} \propto T^{1/2}$$

$$\frac{(T_1)_n}{(T_1)_s} \approx \frac{1}{T}\int_0^\infty dE N(E)^2 \frac{1}{\cosh^2(E/2T)} \propto T$$

$$\lambda(T) = \sqrt{\frac{c^2 m}{4\pi e^2 \rho_s(T)}} \approx \lambda_0 + \lambda_1 T^{1/2}$$

At finite H new form of scaling replaces nodal Simon-Lee scaling:

$$N(E \to 0, H) \sim H^{1/3+\eta} \qquad N(0) \sim H^{1/2}$$

$$C(H,T) \sim T H^{1/3+\eta}$$

Conclusions

- Iron pnictides are semimetals turned superconductors
- Correlations are significant, hence a SDW in parent compounds, but weaker than in cuprates
- Both magnetism and superconductivity are intrinsically multiband in nature – s′ interband SC is a likely possibility near a nesting-driven SDW
- Orbital anisotropy of pairing interaction can lead to anisotropic SC gap with accidental nodes/zeroes → quantum critical "zero-point" scaling replaces Dirac-SL scaling seen in cuprates

→ new physics, beyond the "standard" model?

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