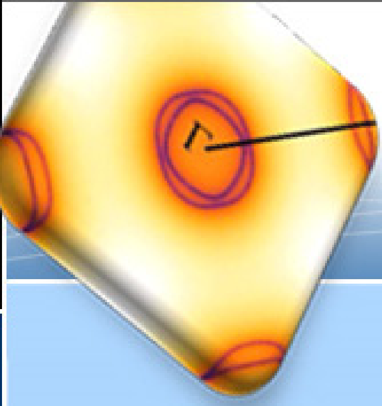


INSTITUTE FOR QUANTUM MATTER

A collaboration between JOHNS HOPKINS UNIVERSITY and PRINCETON UNIVERSITY

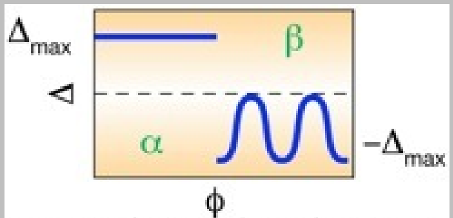
Spin and Orbital Flavors in Pnictides

Zlatko Tesanovic, Johns Hopkins University
zbt@pha.jhu.edu http://www.pha.jhu.edu/~zbt

Funded by the U.S. Department of Energy

Correlated superconductivity comes in (at least) two varieties:

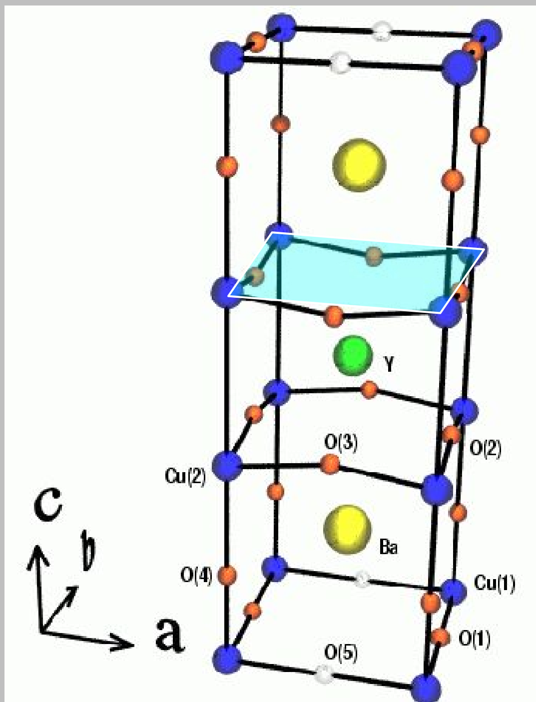
- Strongly correlated normal state exhibiting a "BCS-ish" pairing instability (?pnictides, ^{3}He, heavy fermions, organics, e-doped cuprates, …)
- Intrinsic strongly correlated SC, exerting major influence on surrounding "normal" state(s) (?pnictides, h-doped cuprates, …)

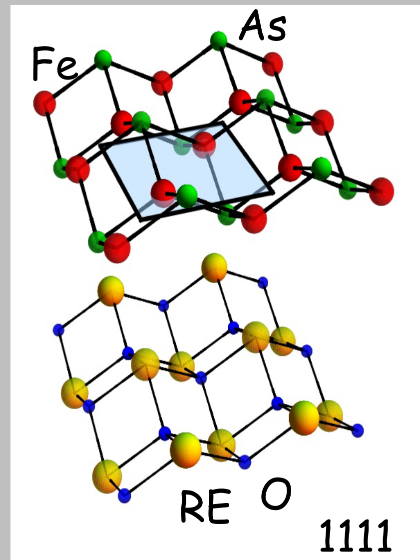


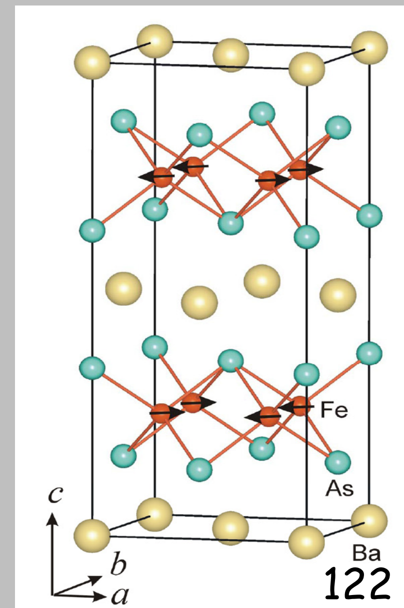
KITP Miniprogram: Iron-Based Superconductors (Jan 11-21, 2011)

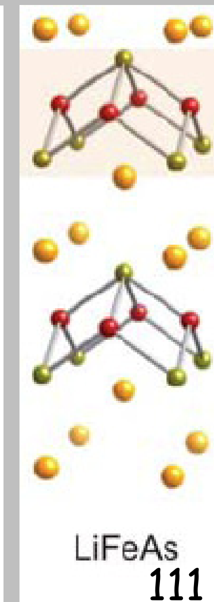
The Kavli Institute for Theoretical Physics
University of California, Santa Barbara

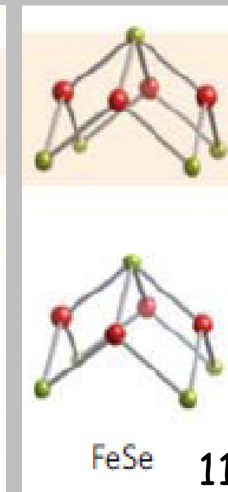
Correlated Superconductors: Cu-oxides vs Fe-pnictides











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

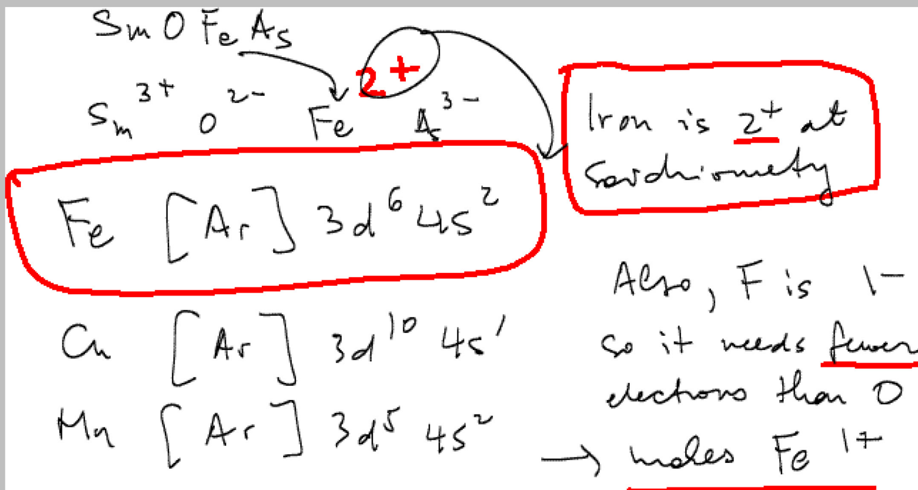
Both are layered (CuO_2 vs FeAs)

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)



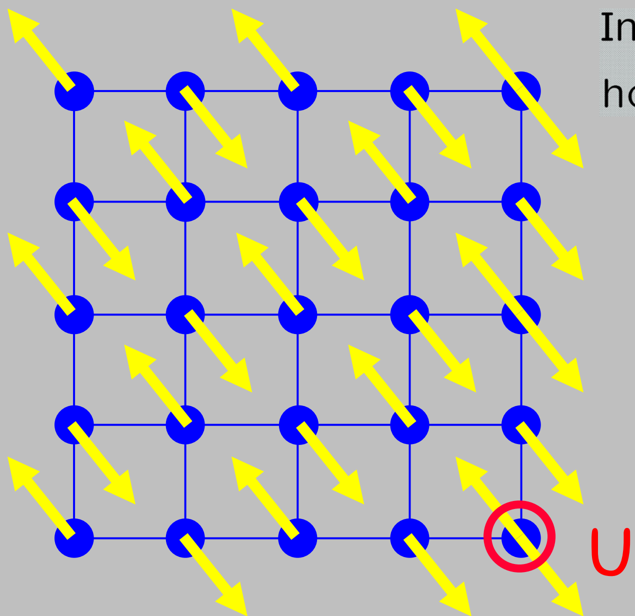
In CuO_2 a **single** hole in a filled 3d orbital shell

→ A suitable single band model might work

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

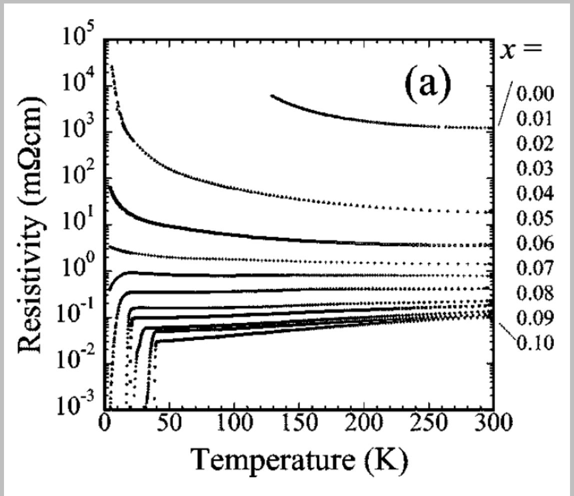
→ A multiband model is likely necessary

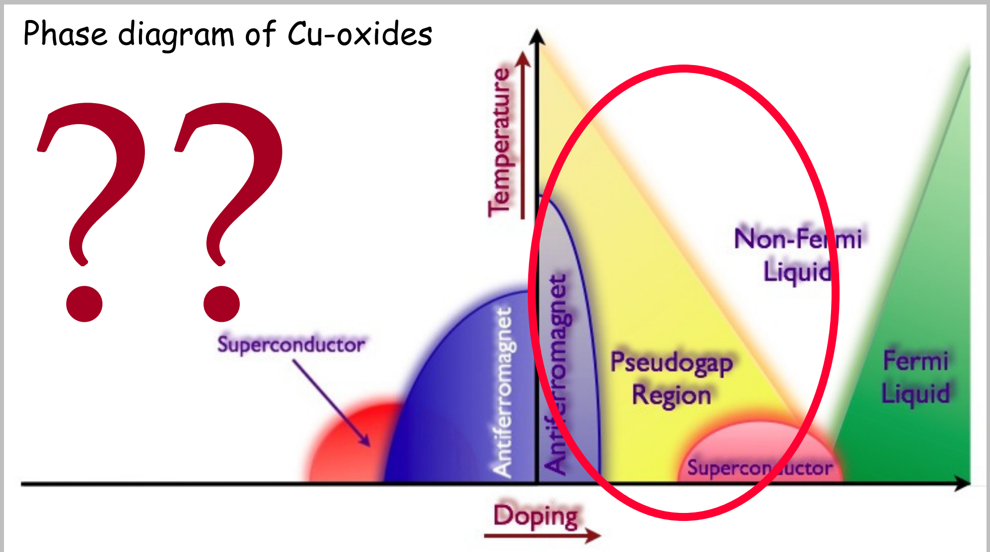
Cu-oxides: Mott Insulators → Superconductors



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

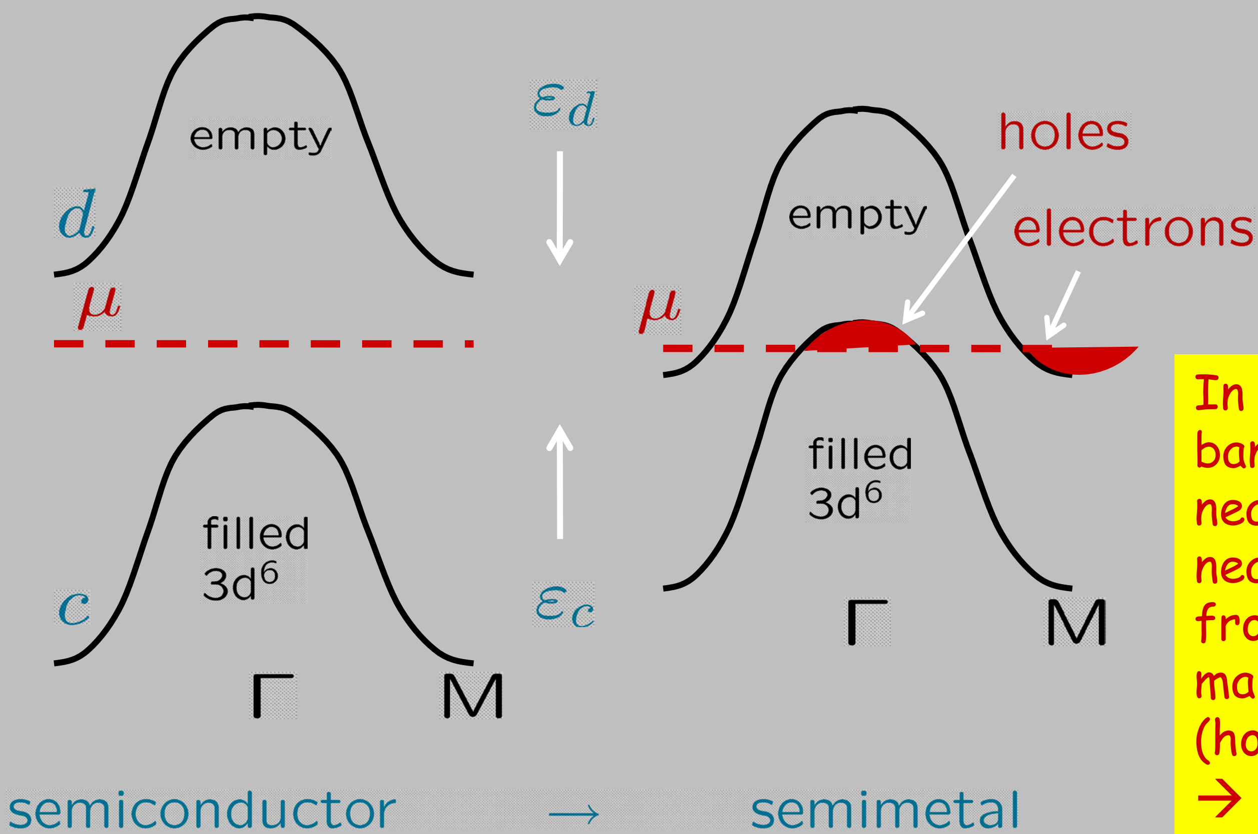


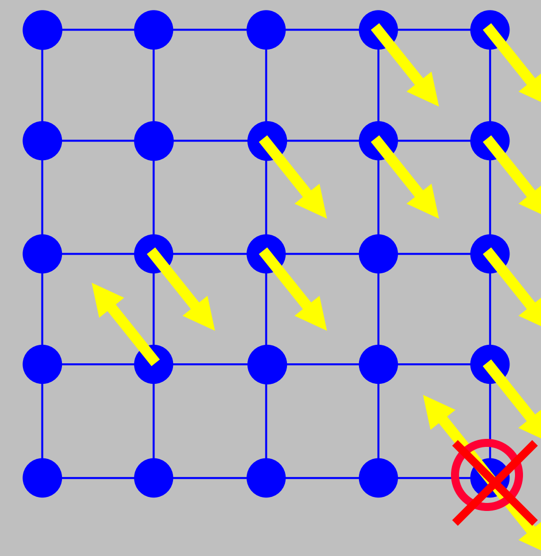


How Mott insulators turn into superconductors, particularly in the pseudogap region, remains one of great intellectual challenges of condensed matter physics

Fe-pnictides: Semimetals → Superconductors

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

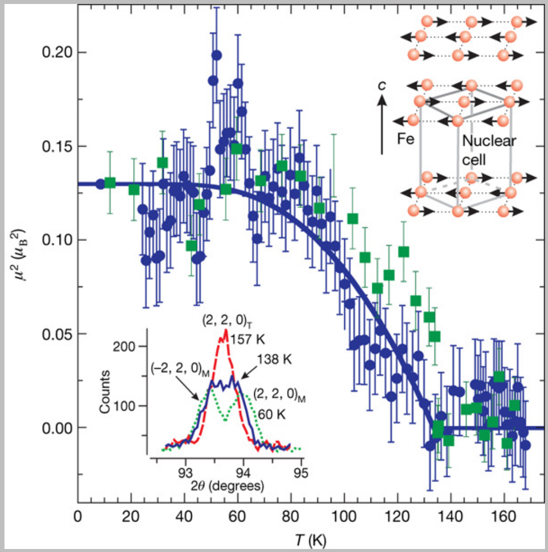




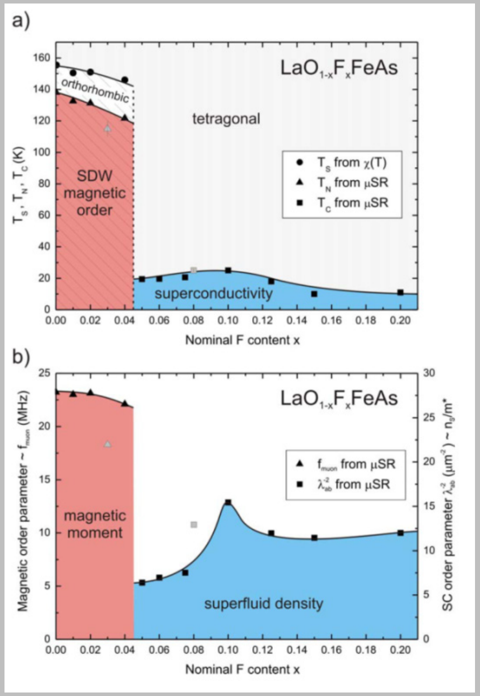
In contrast to CuO_2, all d-bands in FeAs are either nearly **empty** (electrons) or nearly **full** (holes) and far from being **half-filled.** This makes it easier for electrons (holes) to avoid each other.
→ **FeAs are less correlated than CuO_2 (correlations are still important !!)**

Phase diagram of Fe-pnictides

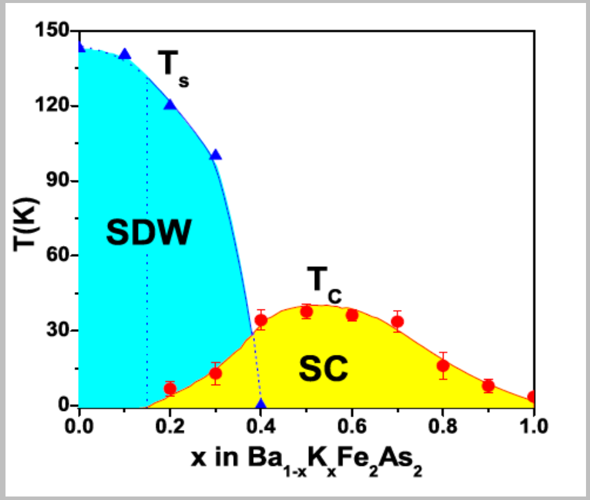
C. de la Cruz, *et al.*, Nature **453**, 899 (2008)



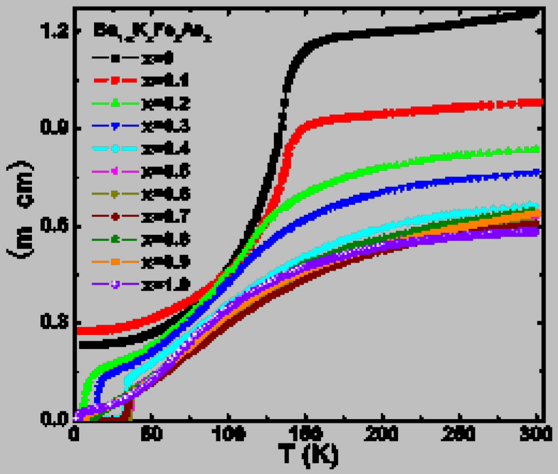
Like CuO_2, phase diagram of FeAs has SDW (AF) in proximity to the SC state.



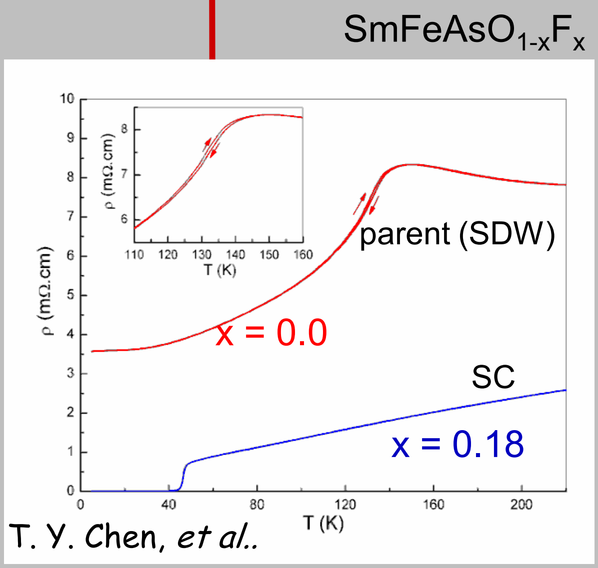
H. Chen, *et al.*, arXiv/0807.3950



SC coexists with SDW (AF) in 122 compounds →



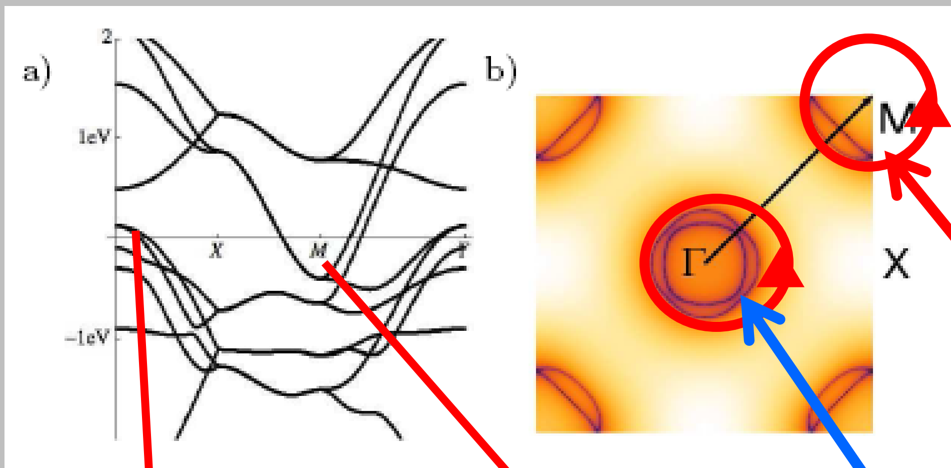
However, unlike CuO_2, all regions of FeAs phase diagram are (bad) metals !!



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

Minimal Model of FeAs Layers

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)

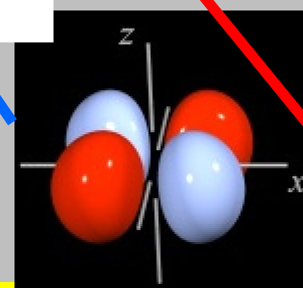


hole FS
2 pockets (valleys)

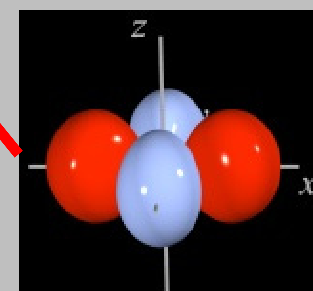
electron FS
2 pockets (valleys)

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

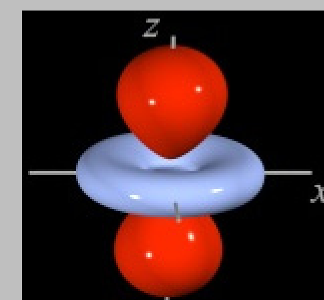
d_{xy}



d_{xx-yy}

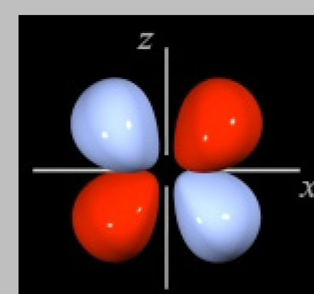


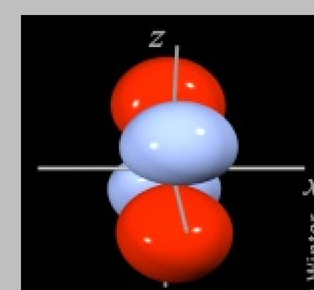
$d_{2zz-xx-yy}$



even parity

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 →



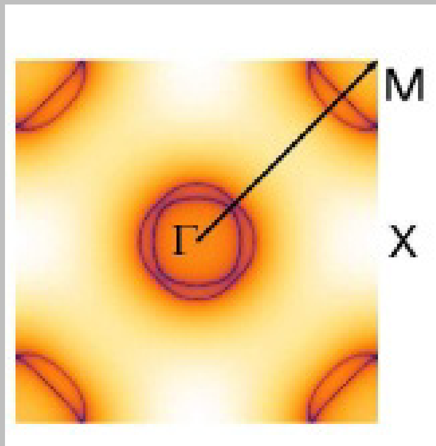


d_{xz} odd parity d_{yz}

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

Nesting in Fe-pnictides

Cvetkovic & ZT, Korshunov & Eremin

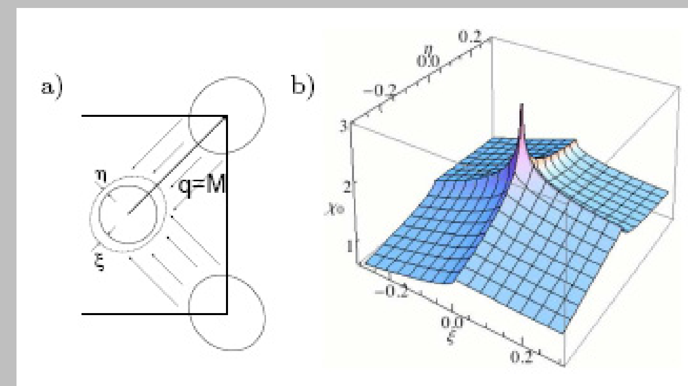


If hole (Γ) and electron bands (M) are identical

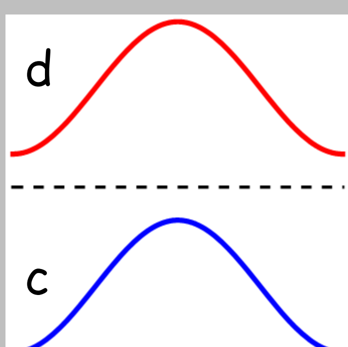
$\Rightarrow$ perfect nesting at $\mathbf{q} = \mathbf{M} = (\pi, \pi)$ $\Rightarrow$

strongly enhanced electron-hole excitations

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

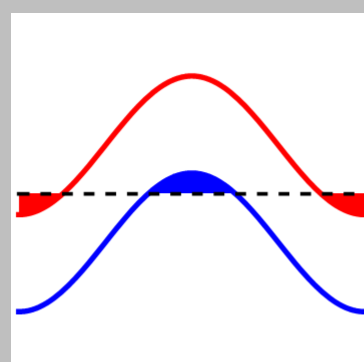


Turning on moderate interactions →
VDW = itinerant multiband CDW (structural),
SDW (AF) and orbital orders at **q** = **M** = (π,π)

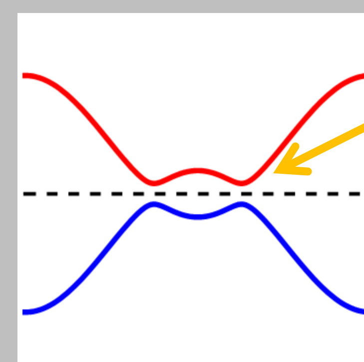


ε_d ↓

ε_c ↑



→



Semiconductor

Semimetal

SDW, CDW, ODW or combinations thereof → VDW

Interactions in FeAs I

V. Cvetkovic and ZT, PRB **80**, 024512 (2009);
J. Kang and ZT, arXiv:1011.2499

High multiband itinerancy implies significant metallic screening

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

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

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

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

Effective interaction at the Fermi surface:

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

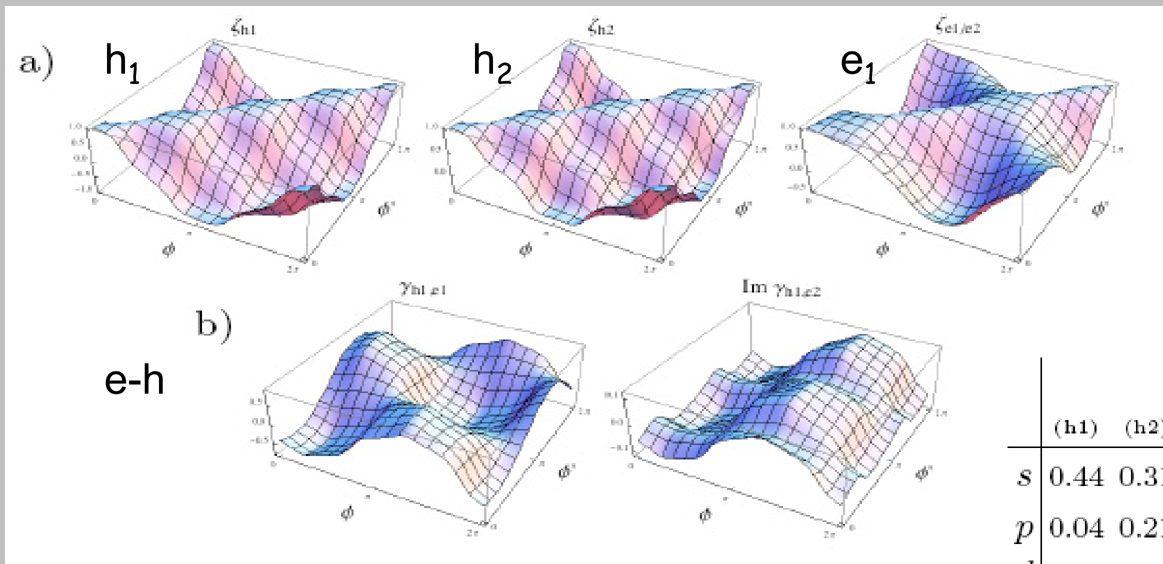
$\Gamma_{\alpha,\beta,\gamma,\delta}(\mathbf{k},\mathbf{k}';\mathbf{q}) \rightarrow$ U, W, G_1, G_2

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

Interactions in FeAs II

vertices exhibit significant orbital dependence around FS:

Hirschfeld, Kuroki, Bernevig, Thomale, Chubukov, Eremin,



k-space "Josephson" terms:

$$\rightarrow \quad G_2 c^\dagger c^\dagger dd + h.c.$$

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:

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

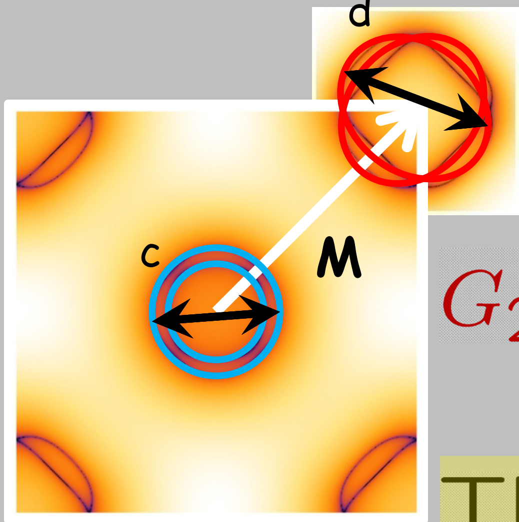
V_s, V_p, and V_d are C_4 version of s-, p- and d-wave coupling constants

$G_2 c^\dagger c^\dagger dd$ These "Josephson" terms are not crucial for SDW

→ **Could they be the cause of SC ?**

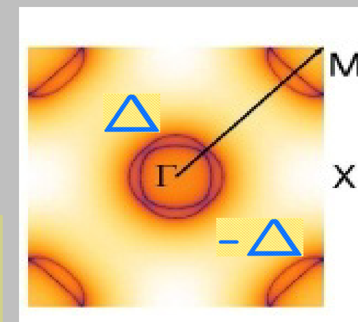
Two Kinds of Interband Superconductivity

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



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

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

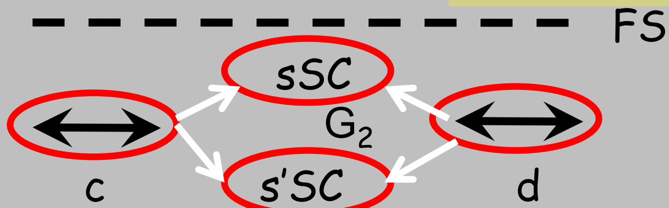


The Problem: Need

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

Most unlikely!

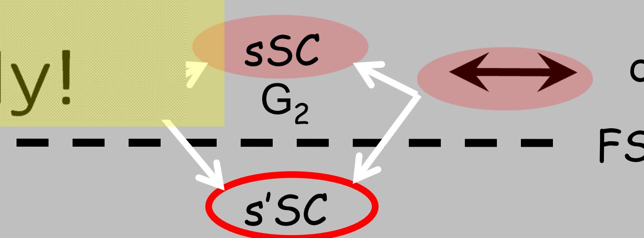
Type-A interband S



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

intraband Cooper pairing further enhanced by G_2

trinsic) interband SC:



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

intrinsic interband Cooper pairs !

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

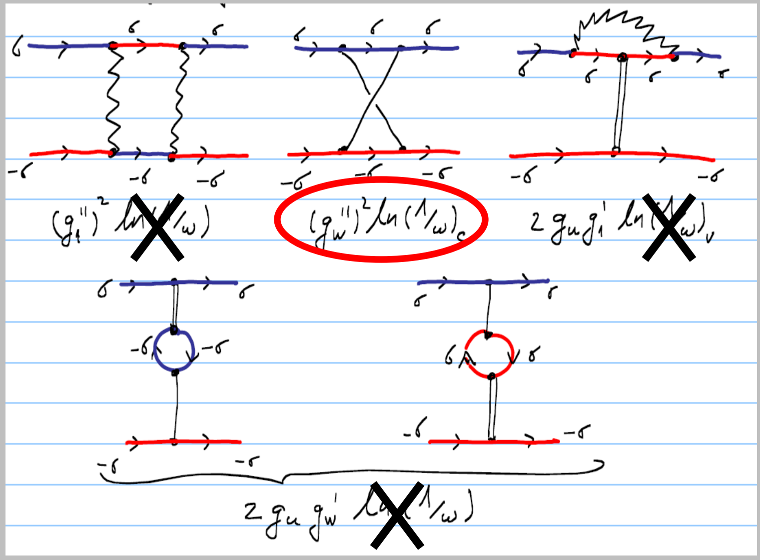
Interactions in FeAs III

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

The condition for interband SC is actually **milder**:
suffices to have $G_2^* > U^*$ **even if** G_2 << U

RG Theory of Interband Mechanism of SC in FeAs

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

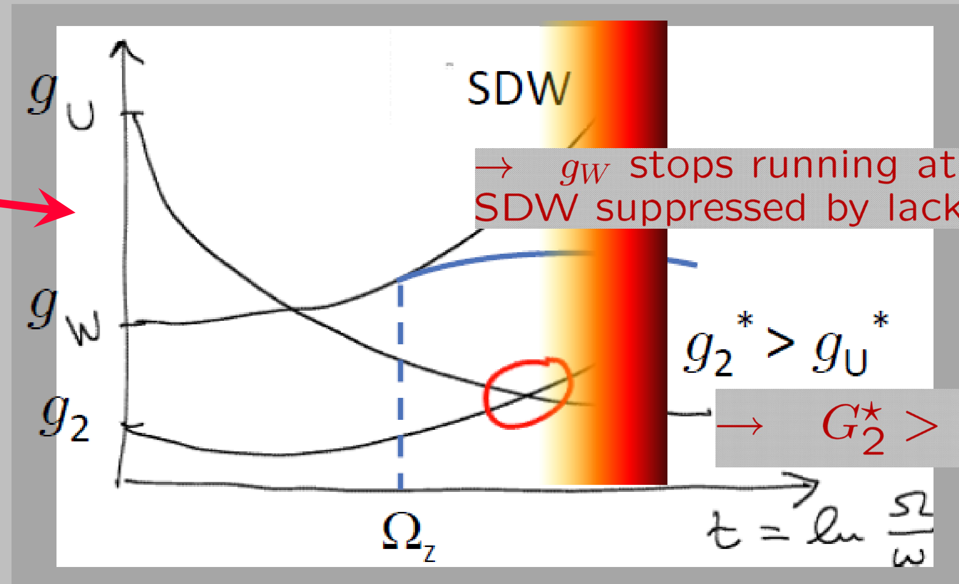
RG flows (near SDW):

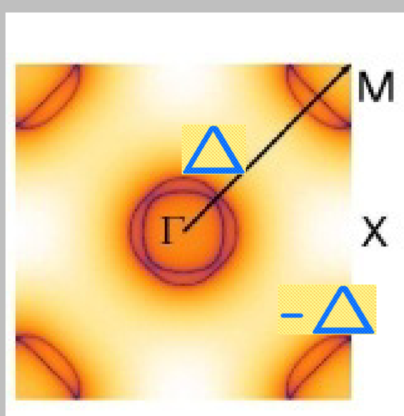
$$\dot{U} = -U^2 - G_2^2$$

$$\dot{G}_2 = -2G_2U + 4G_2W$$

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

$$\dot{U} \pm \dot{G}_2 = -(U \pm G_2)^2$$

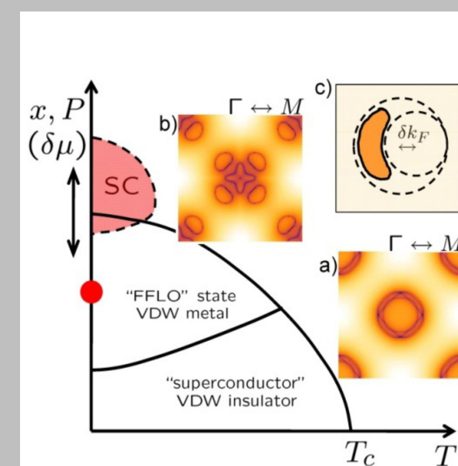




$$G_2 < \sqrt{U_c U_d}$$

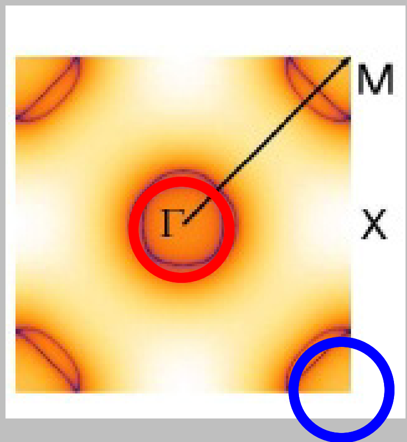
$$G_2^\star > \sqrt{U_c^\star U_d^\star}$$

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



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

What is a (THE) Model for Iron-Pnictides ? → U(4)×U(4) Theory of Valley-Density Wave (VDW)



The first question: Itinerant or Localized? ⇒
Itinerant starting point for high T_c Fe-pnictides

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

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

This is highly idealized. In the real world:

- Pockets are not of same size (particularly h_2)
- Their shape differs ("elliptical" e versus "circular" h)

Eremin, Knolle

Key assumption I:

Differences among (e, h) pockets $\ll$ effective bandwidth $D \sim E_F$

Furthermore, in real world, Γs have strong orbital content:

- Vertices U, W, G_1, and G_2 differ for $e(h)$ pockets
- They have significant angular variation $\delta\Gamma$ around FS

Hirschfeld, Kuroki, Bernevig, Thomale, Chubukov, Eremin,

Key assumption II:

$U, W \sim D \gg G_1, G_2$
$\delta(U, W) \ll (U, W)$

for moderate correlations
$U_d \sim t,\ J_{\text{Hund}} \ll U_d$

U(4)×U(4) Theory of Valley-Density Wave (VDW)

V. Cvetkovic and ZT, PRB **80**, 024512 (2009);
J. Kang and ZT, arXiv:1011.2499

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

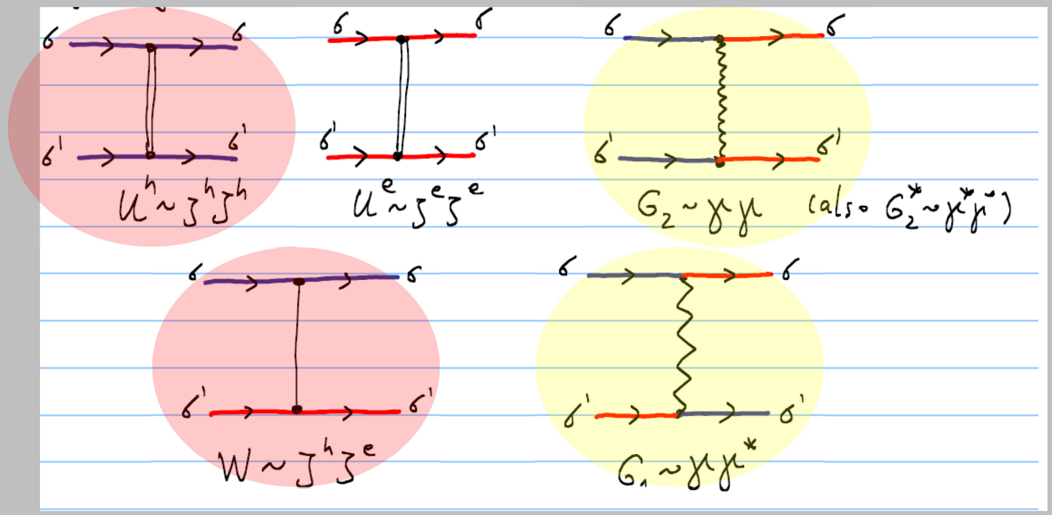
$$H_0 = \sum_{\mathbf{k},\sigma} \xi^{(0)}_{\mathbf{k}} [\sum_\alpha h^{(\alpha)\dagger}_{\mathbf{k}} h^{(\alpha)}_{\mathbf{k}} + \sum_\beta e^{(\beta)\dagger}_{\mathbf{k}} e^{(\beta)}_{\mathbf{k}}]$$

Effective interaction at the Fermi surface:

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

Flavor-conserving vertices U and W

$U, W \sim D$



Flavor-changing vertices G_2 and G_1

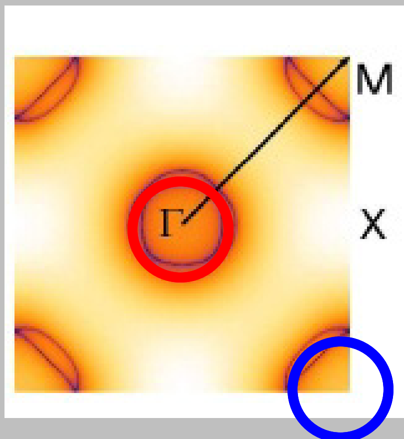
~~$G_2, G_1 \ll D$~~

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

→ U(4)×U(4) symmetry → unified spin and pocket/orbital flavors

Hierarchy of RG Energy Scales U, W >> G_1, G_2 → U(4)×U(4) Theory of Valley-Density Wave (VDW)

V. Cvetkovic and ZT, PRB **80**, 024512 (2009); J. Kang and ZT, arXiv:1011.2499



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

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

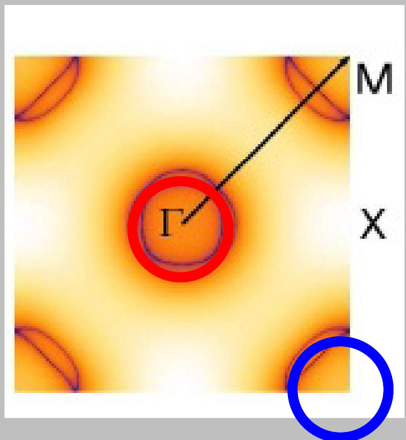
Finally, flavor-mixing vertices $G_{1,2} (\ll U, W)$ have the highest symmetry that physics will allow:

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

VDW in Fe-pnictides is a (nearly) U(4)×U(4) symmetric combination: SDW/CDW/ODW

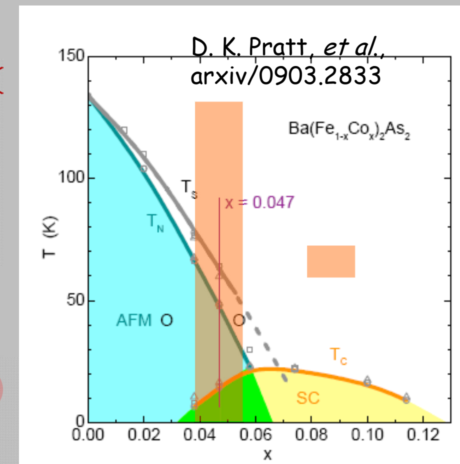
Hierarchy of RG Energy Scales U, W >> G_1, G_2 → U(4)×U(4) Theory of Valley-Density Wave (VDW)

V. Cvetkovic and ZT, PRB **80**, 024512 (2009); J. Kang and ZT, arXiv:1011.2499



Key assumptions:

Flavor-conserving vertices $(U, W) \sim D$; $\delta U, \delta W \ll D$; Flavor-changing vertices $G_1, G_2 \ll D$; Similarly, differences among (e, h) pockets $\ll D$ → U(4)×U(4) symmetric theory at high energies:



$$\exp\left(-W\sum c^\dagger_\mu c_\mu d^\dagger_\nu d_\nu\right) \to \Delta_{\mu\nu} \leftrightarrow \langle c^\dagger_\mu d_\nu \rangle$$

$$\int \mathcal{D}\Delta \exp\left\{-\sum_{\mu\nu}\left[\frac{1}{W}|\Delta_{\mu\nu}|^2 - \Delta^*_{\mu\nu} c^\dagger_\mu d_\nu + h.c.\right]\right\} .$$

U(4)×U(4) symmetric free energy:

$$F = \alpha \mathcal{T}r(\Delta^\dagger\Delta) + \frac{1}{2}\beta \mathcal{T}r(\Delta^\dagger\Delta\Delta^\dagger\Delta) \to \Delta = \Delta_0 \mathcal{U}$$

$\mathcal{U}$ is a 4×4 unitary matrix → all combinations SDW/CDW/PDW

U(4)×U(4) symmetry at high energies → Spin and pocket/orbital flavors all mixed → VDW ground state (any combination of SDW/CDW/ODW)

At low energies, numerous terms break this U(4)×U(4) symmetry

U(4)×U(4) Symmetry vs Reality

J. Kang and ZT, arXiv:1011.2499

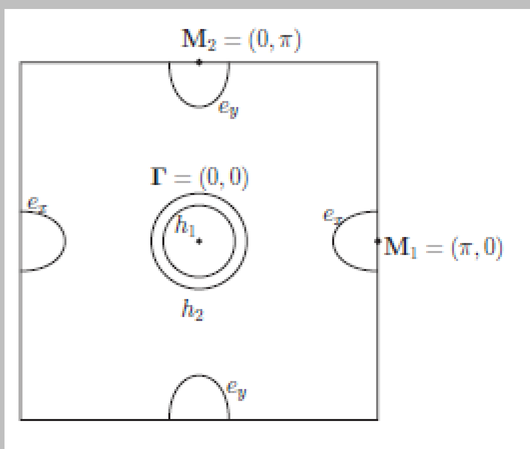
At low energy, numerous terms break U(4)×U(4) symmetry.
We consider their influence at the leading order

Most important symmetry breaking terms are $G_{1,2}$ ($\ll U, W$). $G_1 < G_2$ for $J_{\text{Hund}} \ll U_d$.

Correction to free energy $\delta F[G_2]$:

$$\sim \Pi(0)^2 \left\{ G_2^{eh_1} \left(\Delta_{11}\Delta_{22} + \Delta_{13}\Delta_{24} - \Delta_{12}\Delta_{21} - \Delta_{14}\Delta_{23}\right) + G_2^{eh_2} \left(\Delta_{31}\Delta_{42} + \Delta_{33}\Delta_{44} - \Delta_{32}\Delta_{41} - \Delta_{34}\Delta_{43}\right) + h.c \right\},$$

i) G_2 fixes phases of different DWs.
One expects $G_2^{eh_1}, G_2^{eh_2} > 0$, as prerequisite for high T_c s^{+-} SC.
Hence, the ground state is either *real* SDW or *imaginary spin-singlet* DW(s)



Correction to free energy $\delta F[G_1]$:

$$G_1 = \begin{pmatrix} G_1^{11} & \mathcal{R}eG_1^{12} \\ \mathcal{R}eG_1^{21} & G_1^{22} \end{pmatrix}$$

$$\Pi(0)^2 \{ G_1^{11} \left(|\Delta_{11} + \Delta_{22}|^2 + |\Delta_{13} + \Delta_{24}|^2\right) + G_1^{22} \left(|\Delta_{31} + \Delta_{42}|^2 + |\Delta_{33} + \Delta_{44}|^2\right) + [G_1^{12}(\Delta_{11}^* + \Delta_{22}^*)(\Delta_{31} + \Delta_{42}) + h.c.] + [G_1^{12}(\Delta_{13}^* + \Delta_{24}^*)(\Delta_{33} + \Delta_{44}) + h.c.] \} . \quad (4)$$

For $J_{\text{Hund}} \ll U_d$ typically $\lambda_1 \sim 0$

ii) Two real eigenvalues of G_1 $\rightarrow \lambda_1$, λ_2
if $\lambda_1, \lambda_2 > 0$ $\rightarrow$ *two* real SDWs.
if $\lambda_1, \lambda_2 < 0$ $\rightarrow$ *two* imaginary SSDWs.
if $\lambda_1 < 0$ and $\lambda_2 > 0$ $\rightarrow$ one real SDW and one imaginary SSDW.

Since $\lambda_1 \sim 0$ el-ph interaction or dynamical polarization from Pn bands could easily lead to $\lambda_1 < 0$ → Pnictides are near $\lambda_1 = 0$ QCP !!

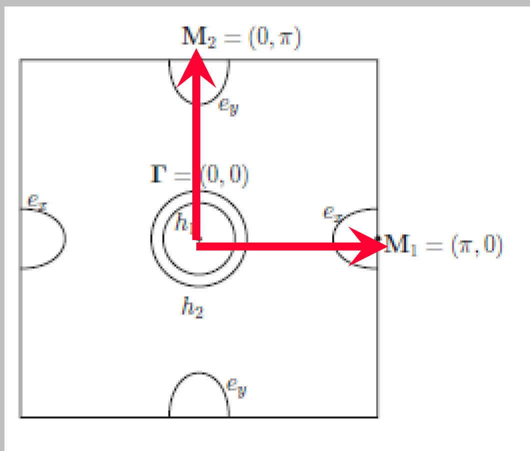
"Near" U(4)×U(4) Symmetry and Experiments

J. Kang and ZT, arXiv:1011.2499

"Direction" of U(4)×U(4) symmetry breaking fixed by flavor-mixing vertices $G_{1,2} (\ll U, W)$:

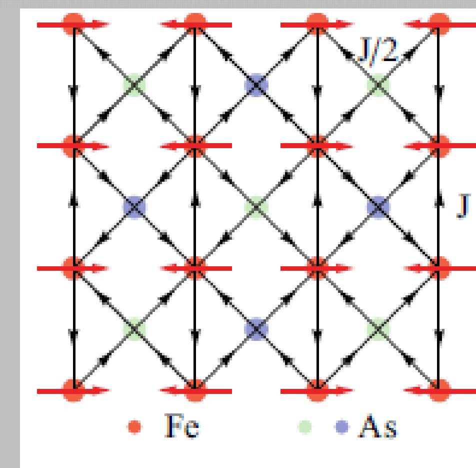
$$2G_1 \sum_{\alpha\beta\sigma\sigma'} (\sigma\sigma') e_{\sigma}^{(\beta)\dagger} h_{-\sigma}^{(\alpha)\dagger} h_{-\sigma'}^{(\alpha)} e_{\sigma'}^{(\beta)} +$$

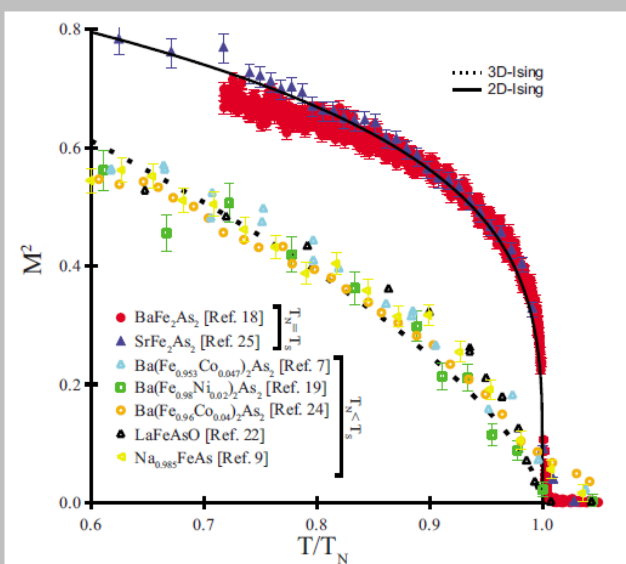
$$G_2 \sum_{\alpha\alpha'\beta\beta'\sigma\sigma'} (\sigma\sigma') h_{-\sigma}^{(\alpha)} e_{\sigma}^{(\beta)} h_{-\sigma'}^{(\alpha')} e_{\sigma'}^{(\beta')} \epsilon^{\alpha\alpha'} \epsilon^{\beta\beta'} + h.c.$$



Two main predictions:
i) SDW along x accompanied by imaginary PWD along y → orbital/charge currents

ii) Structural transition driven by PDW → $T_s \geq T_N$.





PHYSICAL REVIEW B **81**, 014501 (2010)

Universal magnetic and structural behaviors in the iron arsenides

Stephen D. Wilson,[1] C. R. Rotundu,[1] Z. Yamani,[2] P. N. Valdivia,[3] B. Freelon,[4] E. Bourret-Courchesne,[1] and R. J. Birgeneau[1,3,4]

Orbital "AF" → Can this modulated current pattern be observed by neutrons? μSR?

A·S·P·E·N
Center for Physics

Supported by the National Science Foundation

Click on http://www.aspenphys.org/
and go to Applications

Application deadline: Monday, January 31, 2011 !!

June 26 – July 24

A New Century of Superconductivity: Iron Pnictides and Beyond

Organizers:
Elihu Abrahams , University of California, Los Angeles
Meigan Aronson, Brookhaven National Laboratory
Jiangping Hu, Purdue University
Richard Greene, University of Maryland
Zlatko Tesanovic*, Johns Hopkins University

With the first century of superconductivity drawing to a close, a new frontier arose – the iron-based high-temperature superconductors. These materials have deep implications for fundamental physics. Their discovery opens a new path to explore the still-elusive phenomenon of high-Tc superconductivity and to address many fundamental questions related to the origin of the electron pairing in other unconventional superconductors, such as the cuprates, the heavy-fermions and the organics: What is the origin of the pairing and does it lead to the same or different pairing gap symmetries and why? What are the possible competing orders, like magnetism, and their origins? What are the limits on superconducting transition temperatures? The Workshop will focus on an in-depth theoretical exploration of these and related issues, assisted by guidance from several leading experimentalists, and in high celebratory spirit as we enter the new century of superconductivity.