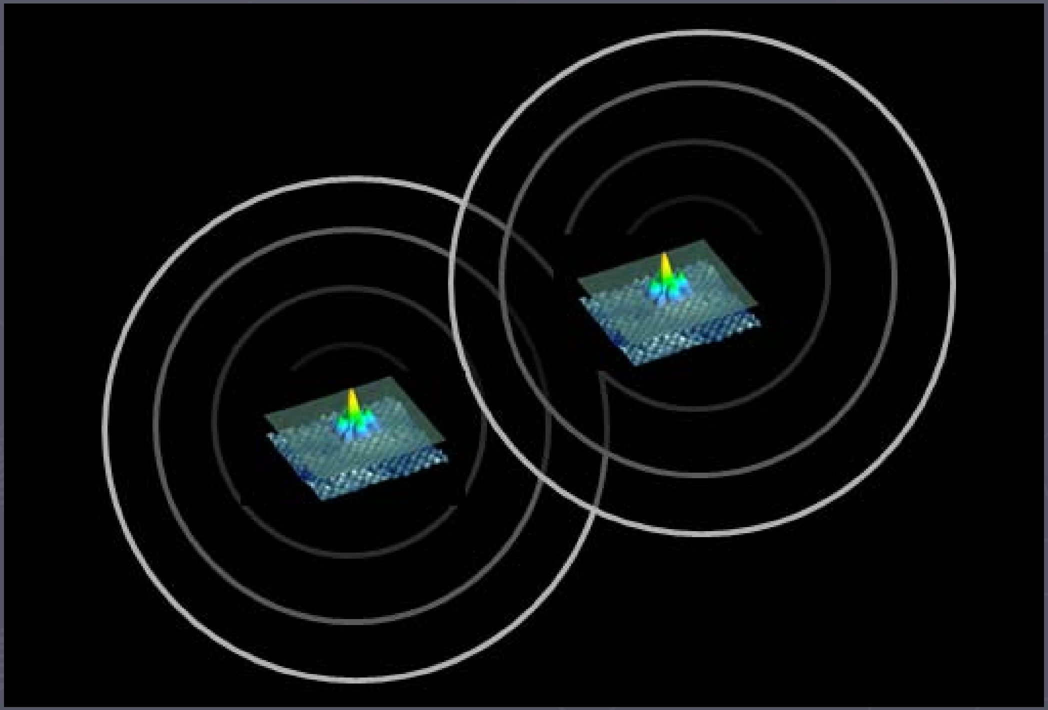
I. Review of Fe-based Superconductivity
II. Disorder effects in unconventional SC

P. Hirschfeld, U. Florida



Balatsky , Vekhter and Zhu, Rev Mod Phys 78, 373, (2006)
Alloul, Bobroff, Gabay, PH, Rev. Mod. Phys. 81, 45 (2009)

Maglab Theory Winter School January 2013

Anderson's theorem

P. W. Anderson, J.Phys. Chem. Solids 11, 26 (1959)

THEORY OF DIRTY SUPERCONDUCTORS

P. W. ANDERSON

Bell Telephone Laboratories, Murray Hill, New Jersey

(*Received* 3 *March* 1959)

Abstract—A B.C.S. type of theory (see BARDEEN, COOPER and SCHREIFFER, *Phys. Rev.* **108, 1175** (1957)) is sketched for very dirty superconductors, where elastic scattering from physical and chemical impurities is large compared with the energy gap. This theory is based on pairing each one-electron state with its exact time reverse, a generalization of the k up, $-k$ down pairing of the B.C.S. theory which is independent of such scattering. Such a theory has many qualitative and a few quantitative points of agreement with experiment, in particular with specific-heat data, energy-gap measurements, and transition-temperature versus impurity curves. Other types of pairing which have been suggested are not compatible with the existence of dirty superconductors.

In the presence of dirt one can still pair time-reversed members of Kramer's doublet: thermodynamics (T_c, gap, sp. ht., …) are not affected by nonmagnetic impurities

Abrikosov-Gor'kov theory

SOVIET PHYSICS JETP VOLUME 35 (8), NUMBER 6 JUNE, 1959

ON THE THEORY OF SUPERCONDUCTING ALLOYS

I. THE ELECTRODYNAMICS OF ALLOYS AT ABSOLUTE ZERO

A. A. ABRIKOSOV and L. P. GOR'KOV

Institute for Physics Problems, Academy of Sciences, U.S.S.R.

Submitted to JETP editor July 16, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) **35**, 1558-1571 (December, 1958)

In this paper we give the theory of superconductors containing impurities at the absolute zero. The dependence of the penetration depth on the impurity concentration is considered for small atomic concentrations. We have obtained the electrodynamic equations in an alternating field for superconductors with a mean free path which is smaller than the correlation length.

Many body formulation of disorder problem in superconductor assuming weak scattering agrees with Anderson conclusions

Abrikosov-Gor’kov theory cont’d

Skalski et al PR 136, A1500 1964

Pairbreaking in s-wave SC by magnetic impurities

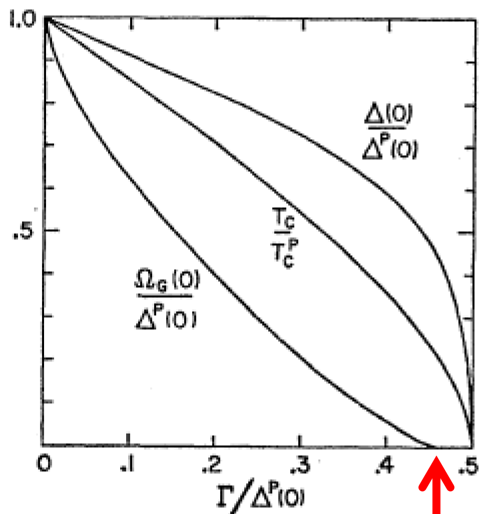


Fig. 2. The critical temperature T_c, the order parameter $\Delta(0)$, and the half-excitation energy gap $\Omega_G(0)$ at $T=0°$, plotted as a function of the inverse collision time Γ. The superscript P refers to the value when $\Gamma=0$.

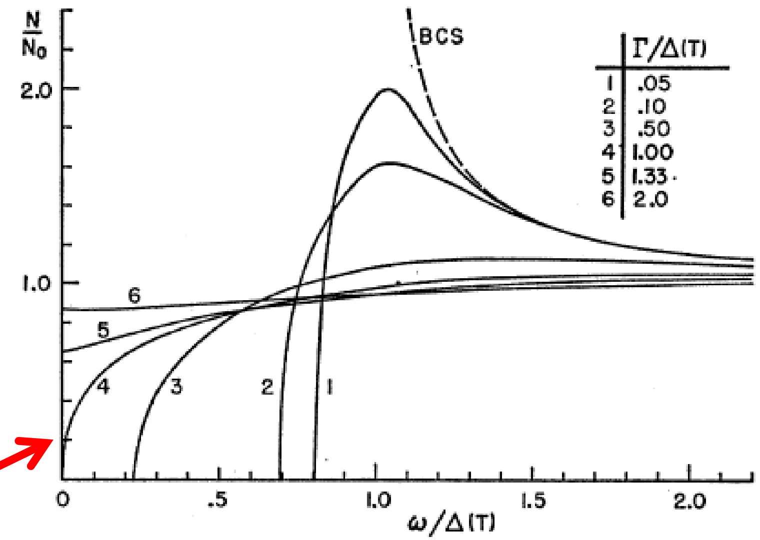


Fig. 4. The density of states in energy plotted as a function of the reduced energy for several values of the reduced inverse collision time Γ/Δ. $\Delta(T)$ is to be understood as $\Delta(T,\Gamma)$.

Gapless SC

Balian-Werthamer: p-wave superconductivity

PHYSICAL REVIEW VOLUME 131, NUMBER 4 15 AUGUST 1963

Superconductivity with Pairs in a Relative *p* Wave*†

R. BALIAN
Centre d'Etudes Nucléaires de Saclay, Gif-sur-Yvette (S.O.), France

AND

N. R. WERTHAMER
Bell Telephone Laboratories, Murray Hill, New Jersey

(Received 6 March 1963)

These conclusions are not, in general, true for the *p*-wave pair state. Since the interaction between the conduction electrons and an impurity is short ranged, probably localized to the immediate vicinity of the impurity site itself, the perturbation extends only over a distance comparable to the lattice spacing, and as we remarked earlier very large momentum transfers of order $2k_F$ are allowed. In fact, $|\lambda(\mathbf{k}-\mathbf{k}')|^2$ is certainly not such as to restrict $\hat{k}$ to the vicinity of $\hat{k}'$ in Eq. (70). The exact cancellation of the two last terms, therefore, occurs only for $\gamma=1$, that is for an *s*-wave state with nonmagnetic impurities. The prediction for the *p*-wave pair state, then, is that magnetic impurities would tend to depress the transition temperature to roughly the same degree as for the BCS state, and that in an equivalent concentration nonmagnetic impurities would lower T_c even more, since λ^2 is likely to be a good deal larger in this case.

Nonmagnetic impurities are pairbreaking in unconventional superconductors

Strong magnetic impurity creates bound state in s-wave SC

BOUND STATE IN SUPERCONDUCTORS WITH PARAMAGNETIC IMPURITIES

YU LUH

ABSTRACT

A generalized canonical transformation and a SCF method have been used to investigate the influence of isolated impurity atoms on the properties of superconductors. It has been found that a bound state of excitation exists around a paramagnetic impurity with its energy level in the energy gap. An analytical expression has been obtained for the corresponding wave function. The effect of electromagnetic absorption due to the bound state should appear as a precursory peak. The possible experimental verifications of the bound state through tunnelling effect and infrared absorption are discussed.

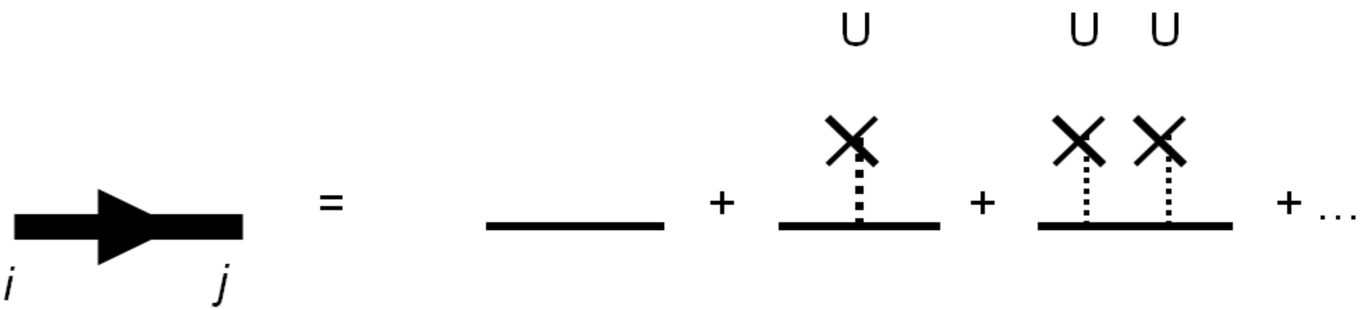
Futhermore, the excitations of continuous spectra around a nonmagnetic impurity and the spatial variation of the energy gap parameter have been considered.

Yu Lu, Acta Physica Sinica 21, 75 (1965)

see also

H. Shiba, Prog. Theor. Phys. 40, 435 (1968).
A. I., Rusinov, 1969, Zh. Eksp. i Teor. Fiz. 56, 2047, [Sov. Phys. JETP 29, 1101 (1969)].

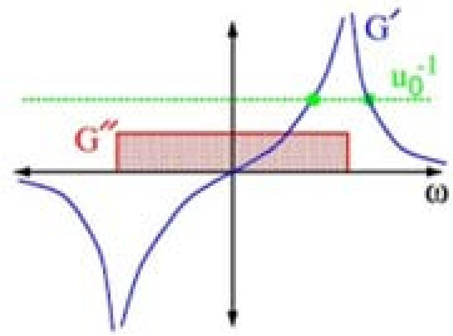
T-matrix for *single* nonmagnetic impurity



$$G = G^0 + G^0UG^0 + G^0UG^0UG^0 + \ldots$$

$$= G^0 + G^0TG^0, \quad \text{where}$$

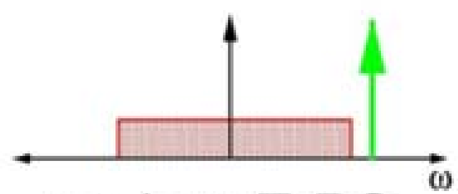
$$T = U + UG^0U + UG^0UG^0U + \ldots = U + UG^0T$$



Onsite potential

$$U(i) = u_0\delta(i - i_0)$$

$$T(\omega) = \frac{1}{u_0^{-1} - \sum_k G^0(k,\omega)}$$



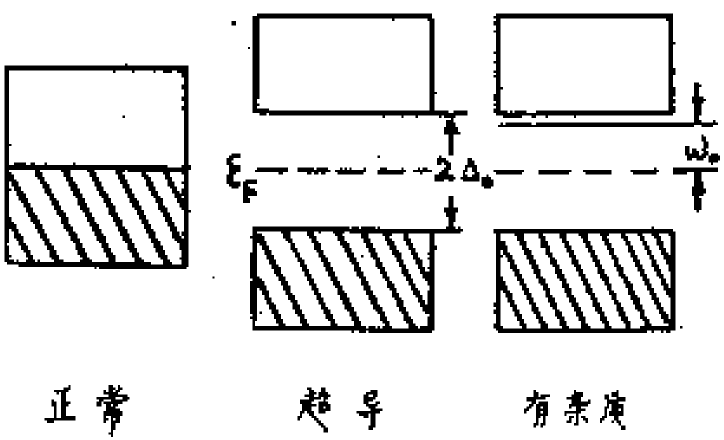
no low-E BS

Magnetic impurity bound state in s-wave SC

$$\underline{G}^0 = (\omega\tau_0 - \xi_k\tau_3 - i\sigma_2\Delta\tau_1)^{-1}$$

$$\underline{U} = u_s\vec{S}\cdot\vec{\alpha} = u_s\vec{S}\cdot\left[\frac{1+\tau_3}{2}\vec{\sigma} + \frac{1-\tau_3}{2}\sigma_2\vec{\sigma}\sigma_2\right]$$

$$\underline{T} = \underline{U} + \underline{U}\,\underline{G}^0\underline{T} = u_s\frac{G_0(1+u_s^2)\,\tau_0 + G_1(1-u_s^2)\,\tau_1}{1-2u_s^2\left(\dfrac{\Delta^2+\omega^2}{\Delta^2-\omega^2}\right)+u_s^4}$$



subgap state

Pole $\omega = \omega_0$

Impurity bound state in *s*-wave superconductor?

$$\underline{G}^0 = \begin{bmatrix} \langle cc^\dagger \rangle & \langle cc \rangle \\ \langle c^\dagger c^\dagger \rangle & \langle c^\dagger c \rangle \end{bmatrix} = \frac{\omega\tau_0 + \xi_k \tau_3 + \Delta \tau_1}{\omega^2 - \xi_k{}^2 - \Delta^2}$$

"Nambu propagator"

Impurity bound state in *s*-wave superconductor?

$$\underline{G}^0 = \begin{bmatrix} \langle cc^\dagger \rangle & \langle cc \rangle \\ \langle c^\dagger c^\dagger \rangle & \langle c^\dagger c \rangle \end{bmatrix} = \frac{\omega\tau_0 + \xi_k \tau_3 + \Delta\tau_1}{\omega^2 - \xi_k{}^2 - \Delta^2}$$

$$\underline{T} = \underline{U} + \underline{U}\,\underline{G}^0\,\underline{T} \qquad\qquad \underline{U} = u_0 \tau_3 \delta(i - i_0)$$

$$= \quad u_0\tau_3 \quad + \quad u_0\tau_3 \left[\Sigma_k \underline{G}^0(k,\omega) \right] \underline{T}$$

Impurity bound state in *s*-wave superconductor?

$$\underline{G}^0 = \begin{bmatrix} \langle cc^\dagger \rangle & \langle cc \rangle \\ \langle c^\dagger c^\dagger \rangle & \langle c^\dagger c \rangle \end{bmatrix} = \frac{\omega\tau_0 + \xi_k \tau_3 + \Delta\tau_1}{\omega^2 - \xi_k^2 - \Delta^2}$$

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$$= \quad u_0\tau_3 \quad + \quad u_0\tau_3\left[\Sigma_k \underline{G}^0(k,\omega)\right]\underline{T}$$

$$\Downarrow$$

$$\underline{T} = \frac{G_0\tau_0 - G_1\tau_1 - u_0^{-1}}{u_0^{-2} + G_1^2 - G_0^2};$$

$$G_\alpha(\omega) = \frac{1}{2}\mathrm{Tr}\,\Sigma_k \tau_\alpha \underline{G}^0(k,\omega)$$

$$= \begin{cases} \dfrac{-i\omega}{\sqrt{\omega^2 - \Delta^2}} & \alpha = 0 \\[2ex] \dfrac{i\Delta}{\sqrt{\omega^2 - \Delta^2}} & \alpha = 1 \end{cases}$$

Impurity bound state in *s*-wave superconductor?

$$\underline{G}^0 = \begin{bmatrix} \langle cc^\dagger \rangle & \langle cc \rangle \\ \langle c^\dagger c^\dagger \rangle & \langle c^\dagger c \rangle \end{bmatrix} = \frac{\omega\tau_0 + \xi_k \tau_3 + \Delta\tau_1}{\omega^2 - \xi_k^{\ 2} - \Delta^2}$$

$$\underline{T} = \underline{U} + \underline{U}\,\underline{G}^0\,\underline{T} \qquad \underline{U} = u_0 \tau_3 \delta(i - i_0)$$

$$= \quad u_0\tau_3 \quad + \quad u_0\tau_3 \left[\Sigma_k \underline{G}^0(k,\omega) \right] \underline{T}$$

$$\Downarrow$$

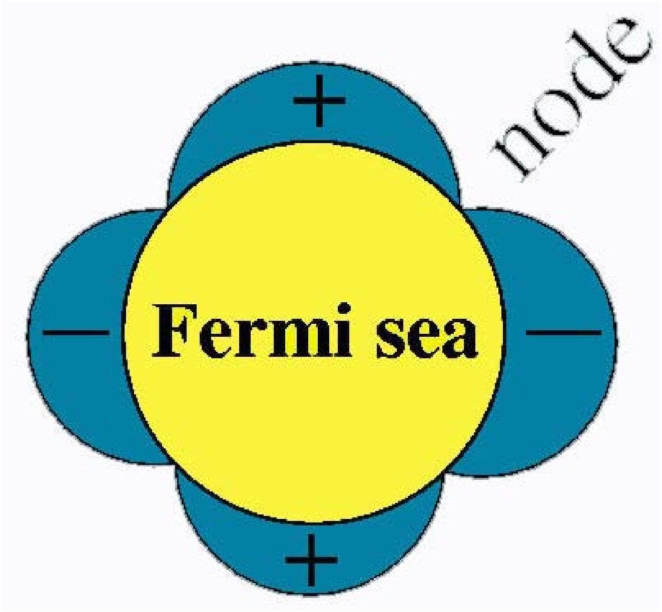
$$\underline{T} = \frac{G_0\tau_0 - G_1\tau_1}{\underbrace{u_0^{\ -2} + G_1^{\ 2} - G_0^{\ 2}}_{u_0^{-2}+1}};$$

No! no pole... (Anderson, AG)

$$G_\alpha(\omega) = \frac{1}{2} \mathrm{Tr}\, \Sigma_k \tau_\alpha \underline{G}^0(k,\omega)$$

$$= \begin{cases} \dfrac{-i\omega}{\sqrt{\omega^2 - \Delta^2}} & \alpha = 0 \\ \dfrac{i\Delta}{\sqrt{\omega^2 - \Delta^2}} & \alpha = 1 \end{cases}$$

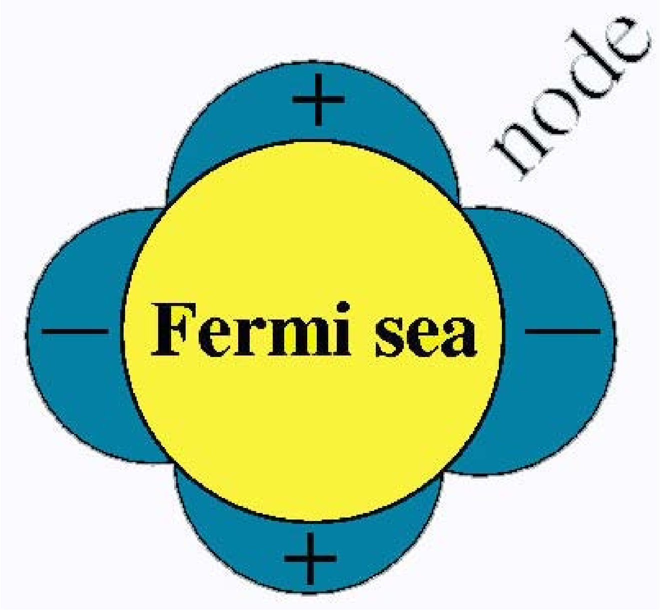
What about in *d*-wave superconductor?



$$\underline{G}^0 = \frac{\omega\tau_0 + \xi_k\tau_3 + \Delta(\phi)\tau_1}{\omega^2 - \xi_k{}^2 - \Delta(\phi)^2}$$

$$\Delta(\phi) = \Delta_0 \cos 2\phi$$

What about in *d*-wave superconductor?



$$\underline{G}^0 = \frac{\omega\tau_0 + \xi_k\tau_3 + \Delta(\phi)\tau_1}{\omega^2 - \xi_k{}^2 - \Delta(\phi)^2}$$

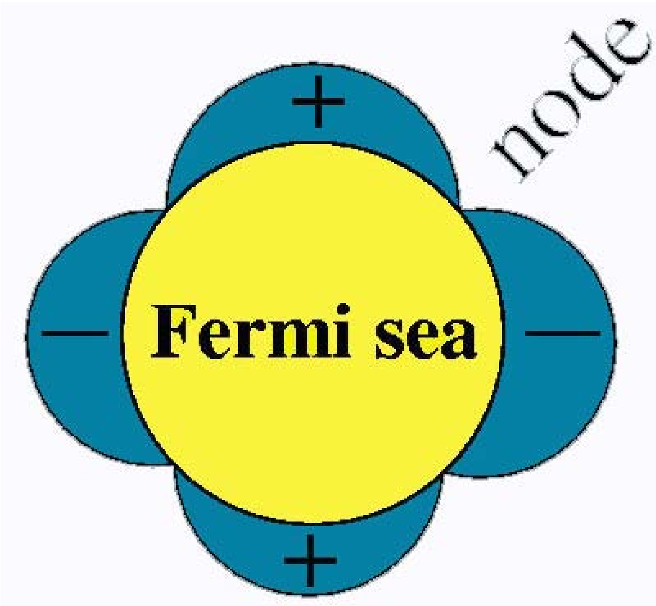
$$\Delta(\phi) = \Delta_0 \cos 2\phi$$

$$\underline{T} = \frac{G_0\tau_0 - G_1\tau_1 - u_0{}^{-1}}{u_0{}^{-2} + G_1{}^2 - G_0{}^2};$$

$$G_0(\omega) = \left\langle \frac{-i\omega}{\sqrt{\omega^2 - \Delta(\phi)^2}} \right\rangle_\phi$$

$$G_1(\omega) = \left\langle \frac{i\Delta(\phi)}{\sqrt{\omega^2 - \Delta(\phi)^2}} \right\rangle_\phi$$

Nonmagnetic impurity in *d- or s* -wave superconductor?



$$\underline{G}^0 = \frac{\omega\tau_0 + \xi_k\tau_3 + \Delta(\phi)\tau_1}{\omega^2 - \xi_k^{\ 2} - \Delta(\phi)^2}$$

$$\Delta(\phi) = \Delta_0 \cos 2\phi$$

$$\underline{T} = \frac{G_0\tau_0 - G_1\tau_1 - u_0^{\ -1}}{\underbrace{u_0^{\ -2} + G_1^{\ 2} - G_0^{\ 2}}_{u_0^{-2} - G_0^{2}}};$$

(The G_1 terms are crossed out in red.)

Possible pole...

$$G_0(\omega) = \left\langle \frac{-i\omega}{\sqrt{\omega^2 - \Delta(\phi)^2}} \right\rangle_\phi$$

$$G_1(\omega) = \left\langle \frac{i\Delta(\phi)}{\sqrt{\omega^2 - \Delta(\phi)^2}} \right\rangle_\phi = 0!$$

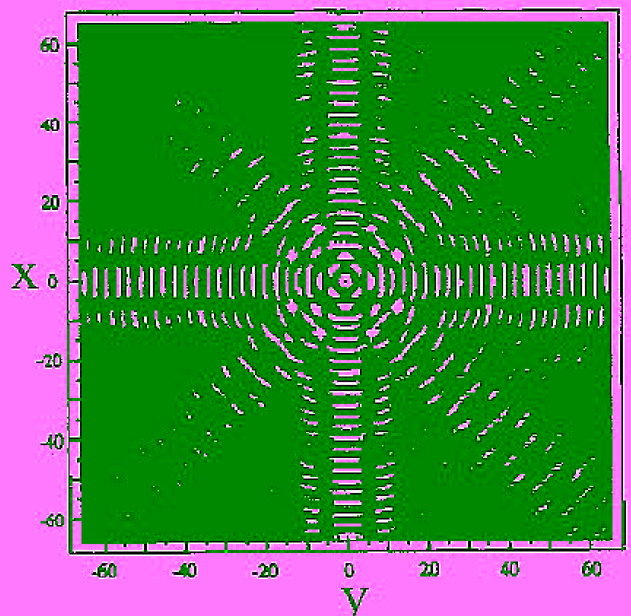
for d-wave

Bound states of nonmagnetic impurity in *d*-wave SC

Byers et al (1993):

Local DOS shows 4fold pattern

$\rho(x,y,E=1.1\Delta_0)$

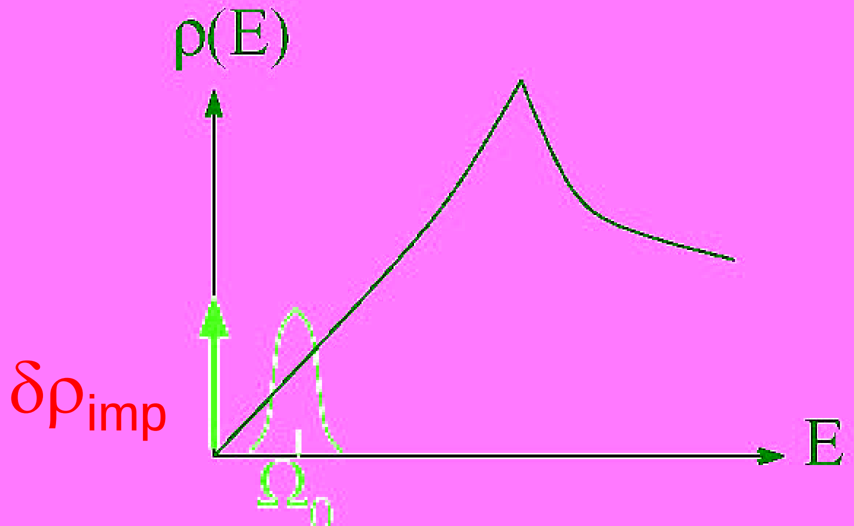


$$\rho(r,\omega) = -\frac{1}{\pi}\,\mathrm{Im}\,G(r,r;\omega)$$

Balatsky et al.(1995):

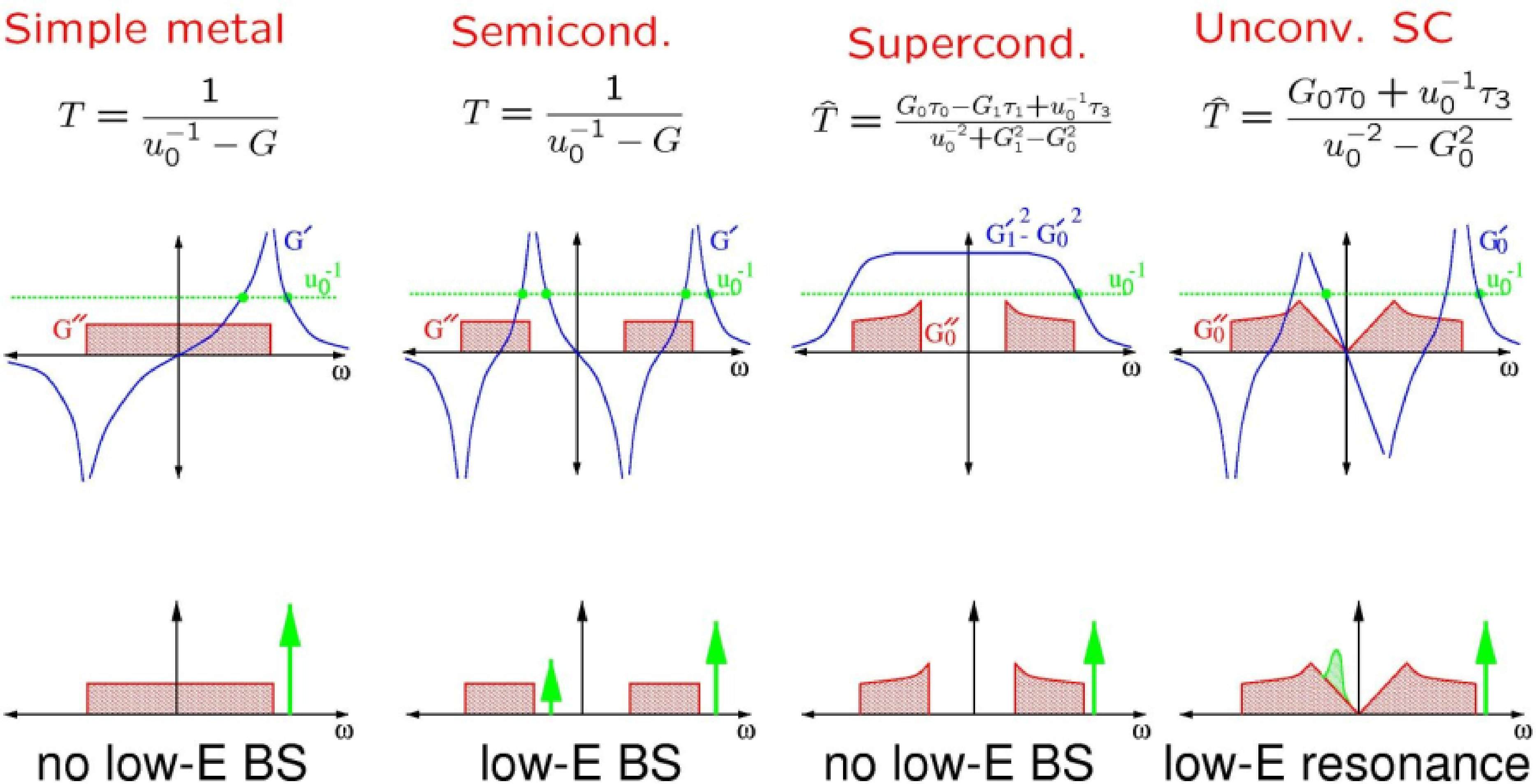
Bound state in resonant limit at

$$\Omega_0 = \Delta_0\,(2N_0 u_0 \log 8 N_0 u_0)^{-1}$$



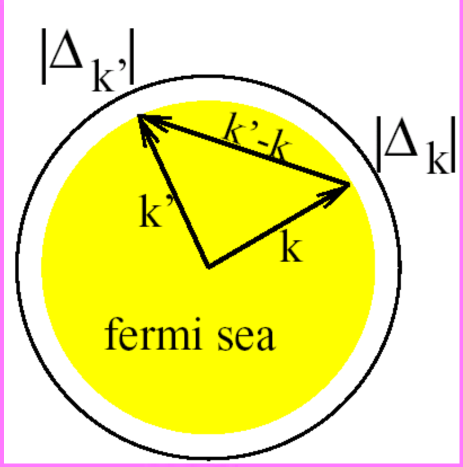
see also Stamp, 1986 (p-wave)

Nonmagnetic impurity bound states in various systems

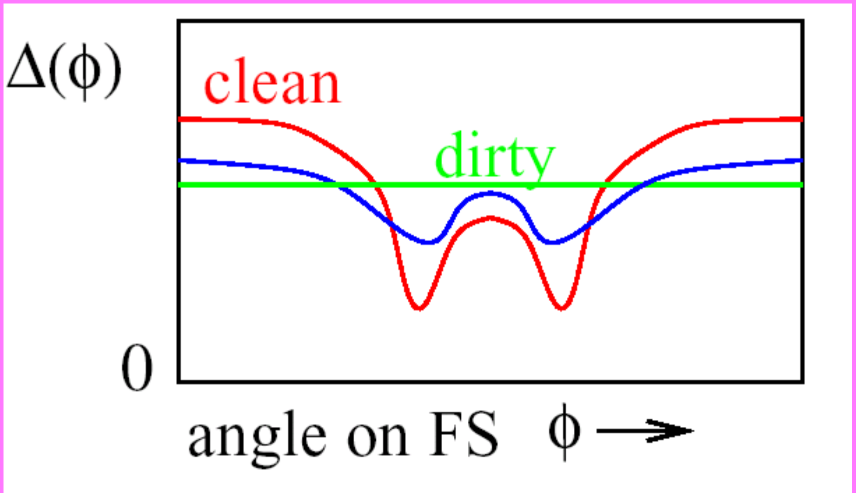


Finite nonmagnetic disorder in unconventional superconductors

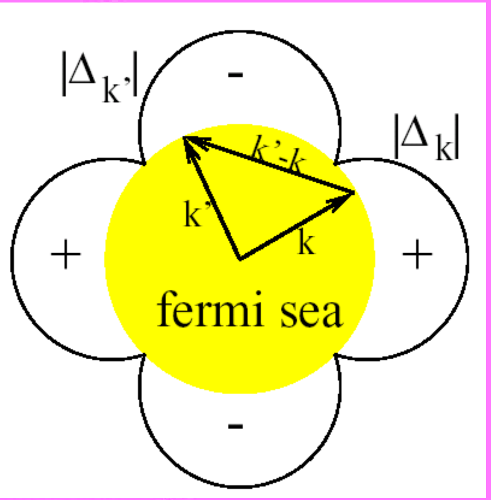
s-wave:
Impurities mix $\Delta_{\mathbf{k}}$ with $\Delta_{\mathbf{k}'}$:



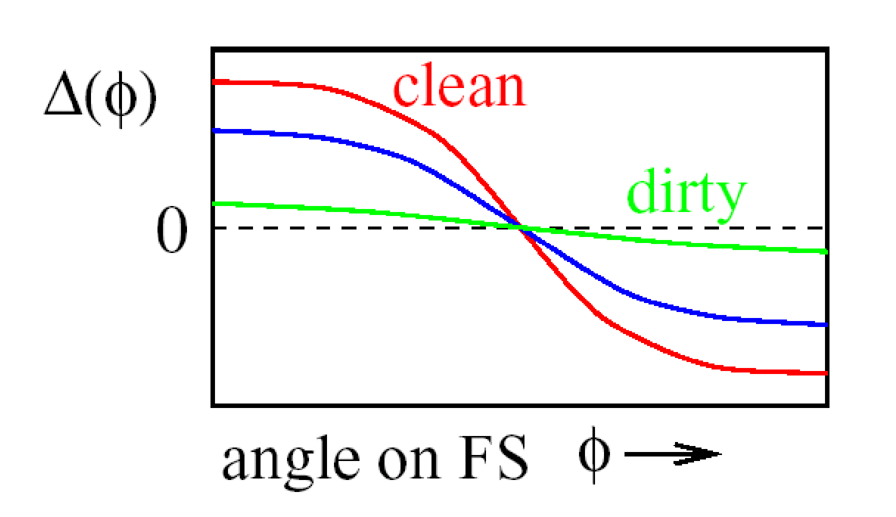
Anisotropy smeared out:



d-wave:
Mix $\Delta_{\mathbf{k}}$, $\Delta_{\mathbf{k}'}$ with signs $\pm$:



Gap supressed:



(Weak nonmagnetic) disorder and unconventional superconductors: destruction of gap nodes

Gor'kov and Kalugin, Sov. Phys. JETP 41, 253 (1985)
Rice and Ueda, *Theory of Heavy Fermions and Valence Fluctuations (Springer, 1985)*

Self-consistent treatment of average G:

Σ =

self-consistent Born

predictions for residual dos N(0) in p-wave states

``polar state" $\Delta(\theta)=\cos\theta$ N(0)>0 for infinitesimal disorder

``axial state" $\Delta(\theta)=\sin\theta$ N(0)>0 for critical disorder strength

triplet classes with point nodes (with moment) are `topologically stable'

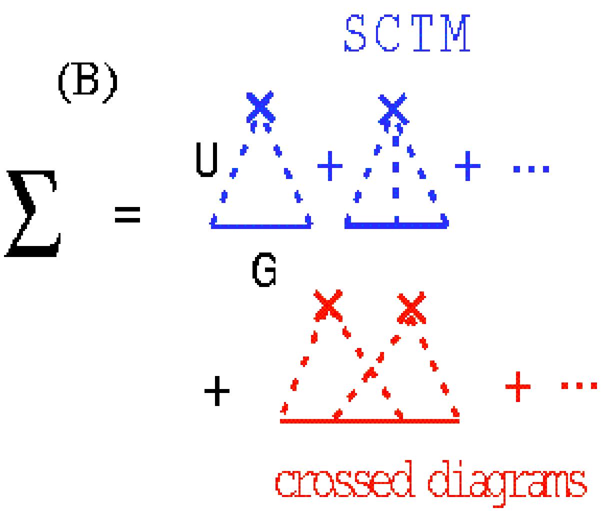
PH et al Sol St. Comm 59, 111 (1986)   Schmitt-Rink et al, PRL 57, 2575 (1986)

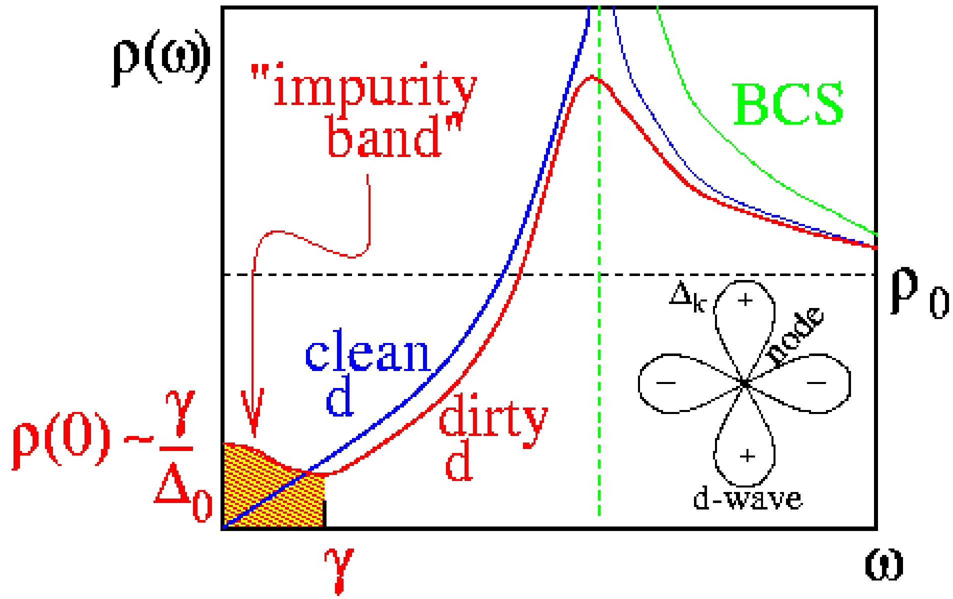
Disorder: self-consistent t-matrix approx. (“SCTMA”,“CPA”...)

Sum all multiple scattering diagrams from 1 impurity:

$$\underline{\Sigma} = n_i \underline{T}$$

$$\underline{T} = \underline{V} + \underline{V}\,\underline{G}\,\underline{T}$$



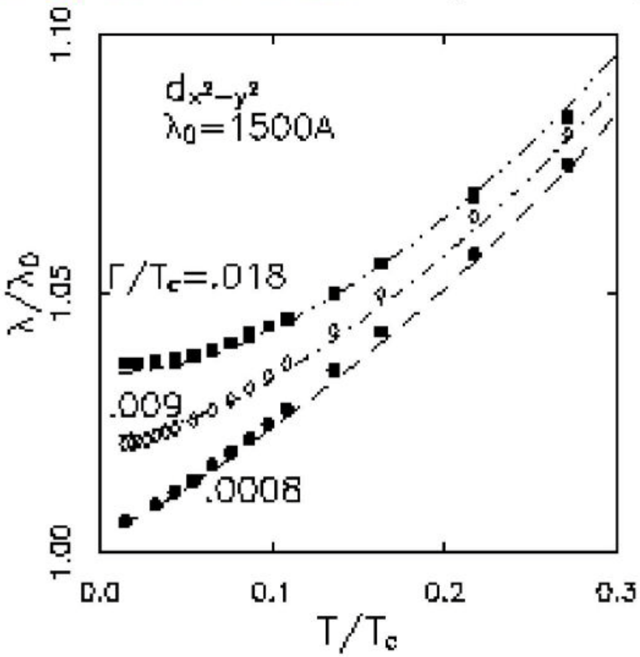


$$\rho(E \to 0) \simeq \rho_0 \left(\frac{\gamma}{\Delta_0}\right) \log\left(\frac{\Delta_0}{\gamma}\right)$$

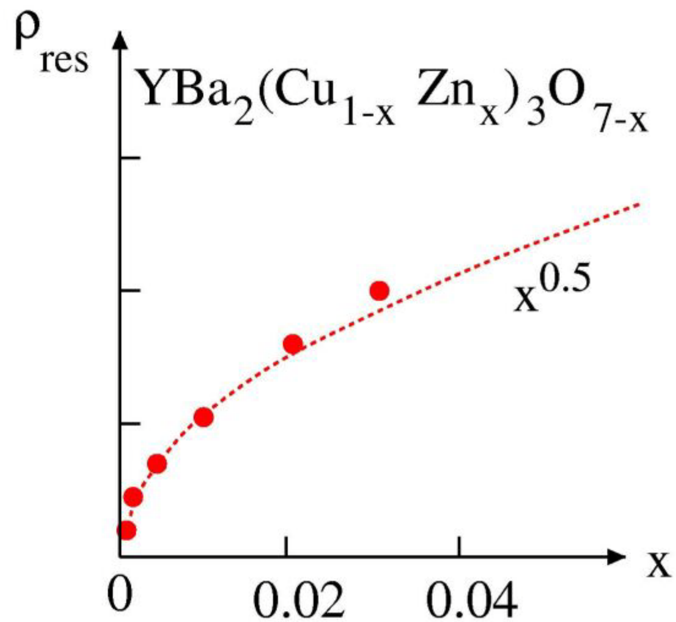
where γ is residual scattering rate, Δ_0 gap max, ρ_0 normal state DOS.

Experiments exhibit effect of residual DOS (YBCO):

Zhang et al. 1994 (μ wave):



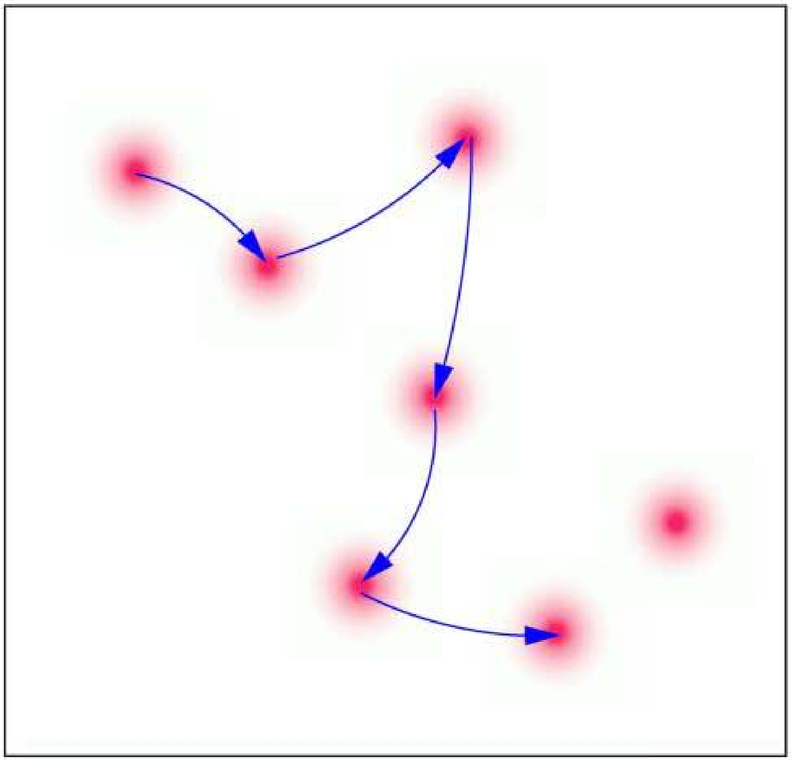
Kitaoka 1993 (NMR):



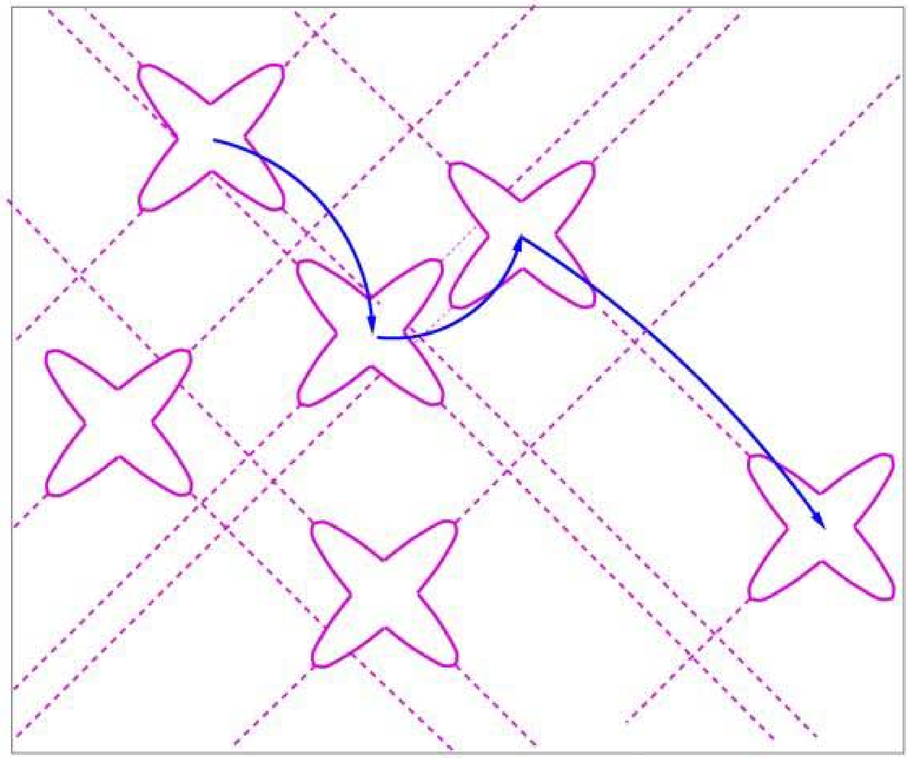
$\rho(0) \sim \gamma \simeq \sqrt{n_i \Delta_0 E_F}$ unitarity scattering limit $u_0 \gg E_F$

$\delta\lambda(T=0), \sqrt{1/T_1 T} \sim \rho(0)$

Origin of "impurity band" : hopping through tails of impurity states



Semiconductor

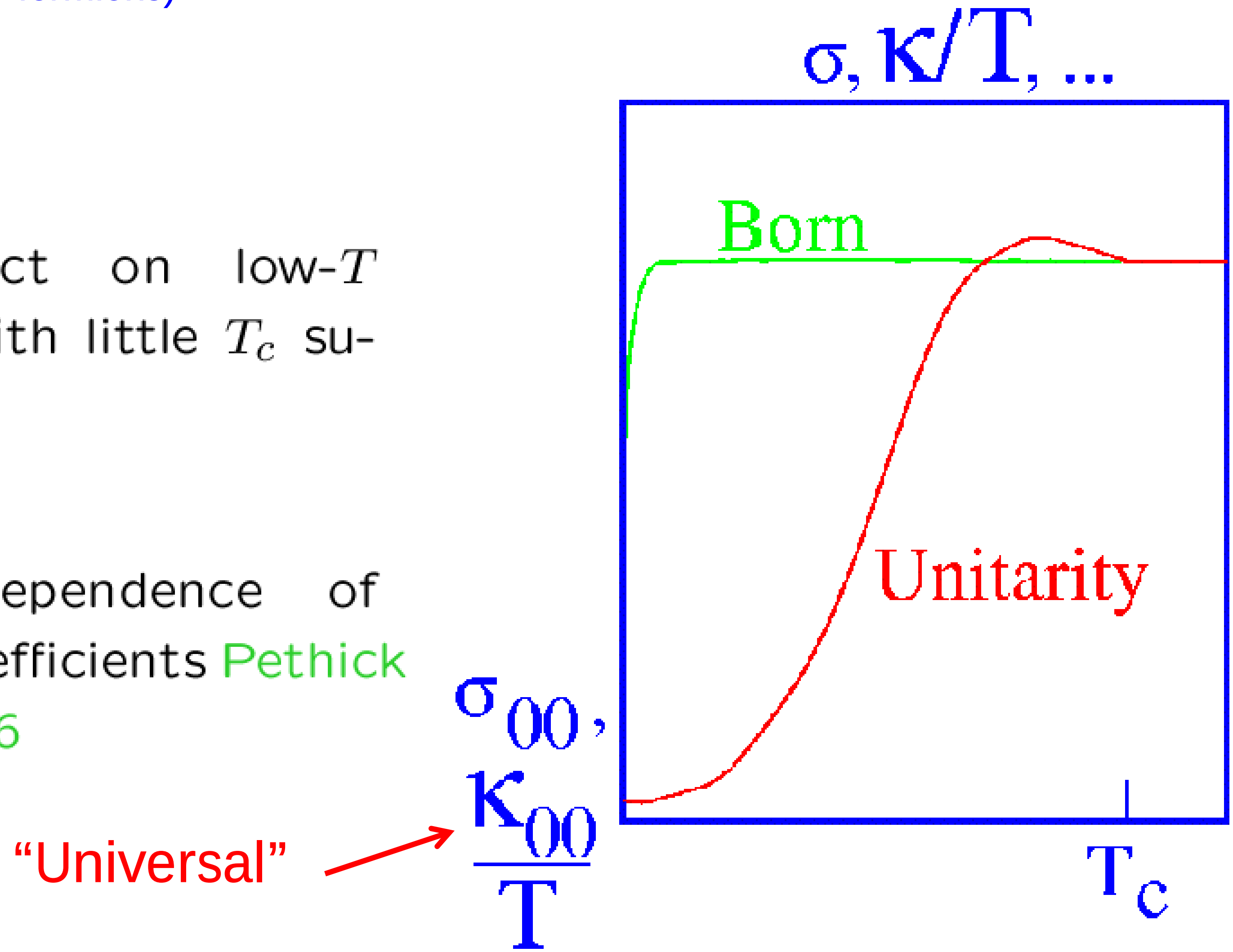


d-wave SC

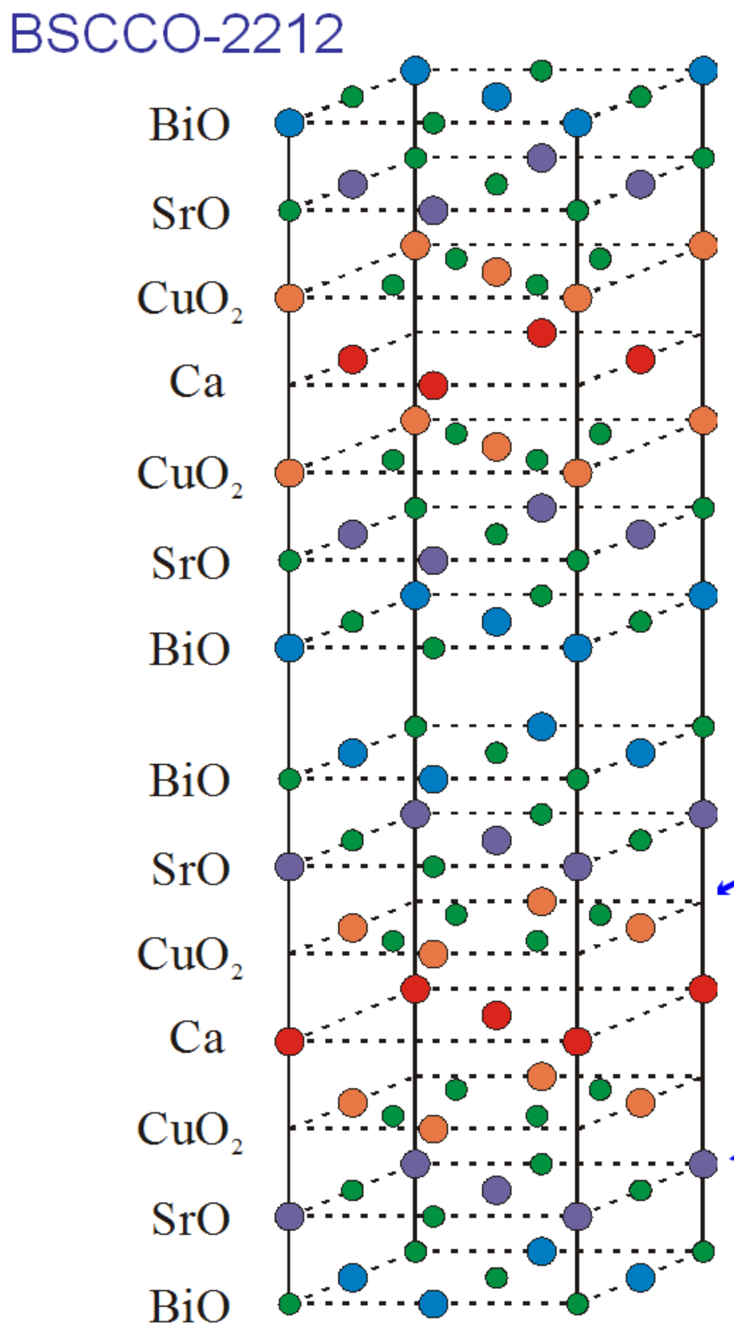
Experiments require near-unitarity impurity scattering

(cuprates, heavy fermions)

- Strong effect on low-T properties with little T_c suppression
- Strong T-dependence of transport coefficients Pethick & Pines 1986



Impurities in cuprates



Probe the response of SC to a spin/charge local perturbation

Dilute Cu in-plane substitutions

- Ni^{2+} $3d^8$ spin 1
- Zn^{2+} $3d^{10}$ no spin
- Li^+ no spin

Out-of-plane defects: missing O, cation switching, …

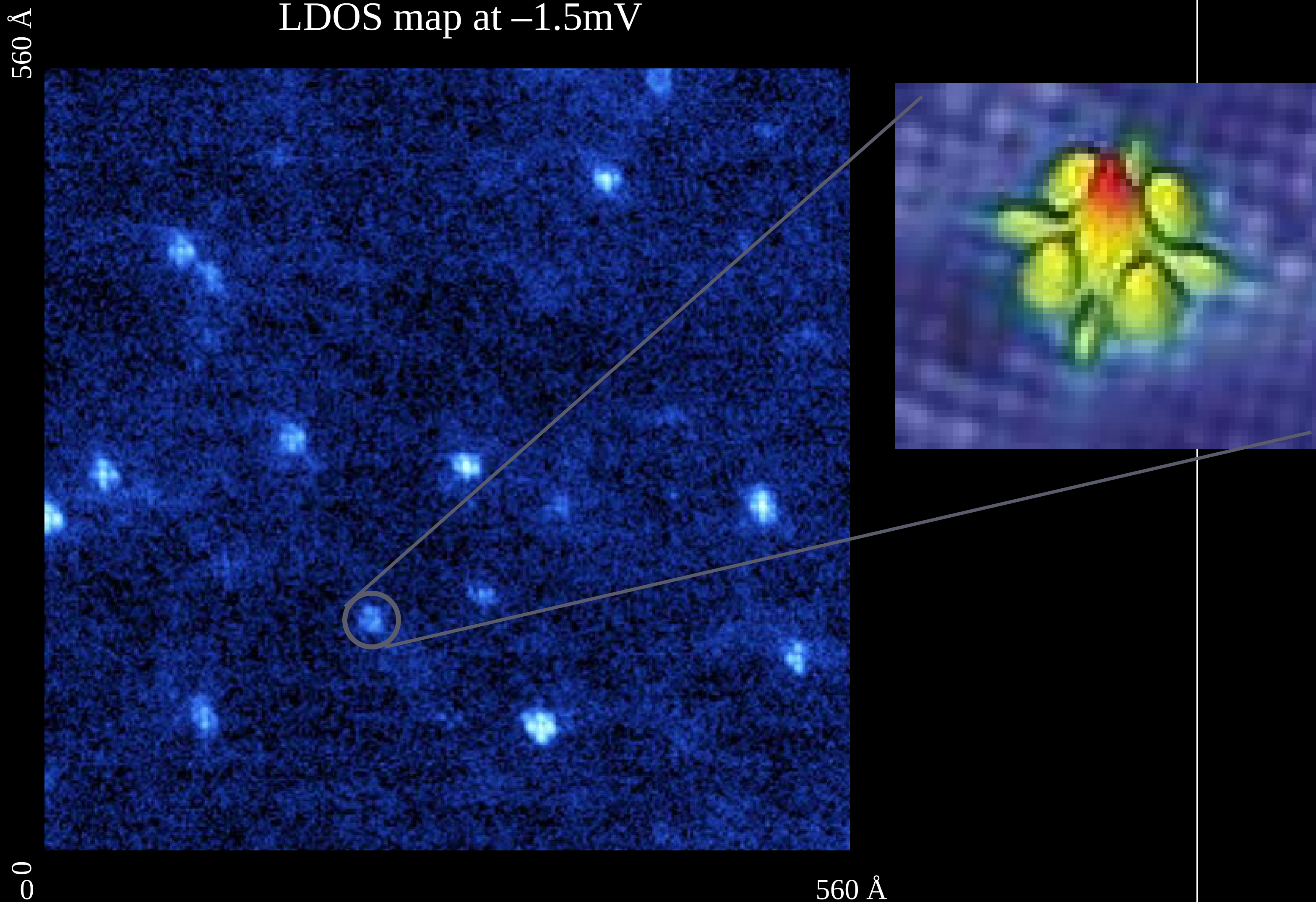
T = 4.2 K

200 pA, -200 mV

$Bi_2Sr_2Ca(Cu_{1-x}Zn_x)_2O_{8+\delta}$: x ≅ 0.3%

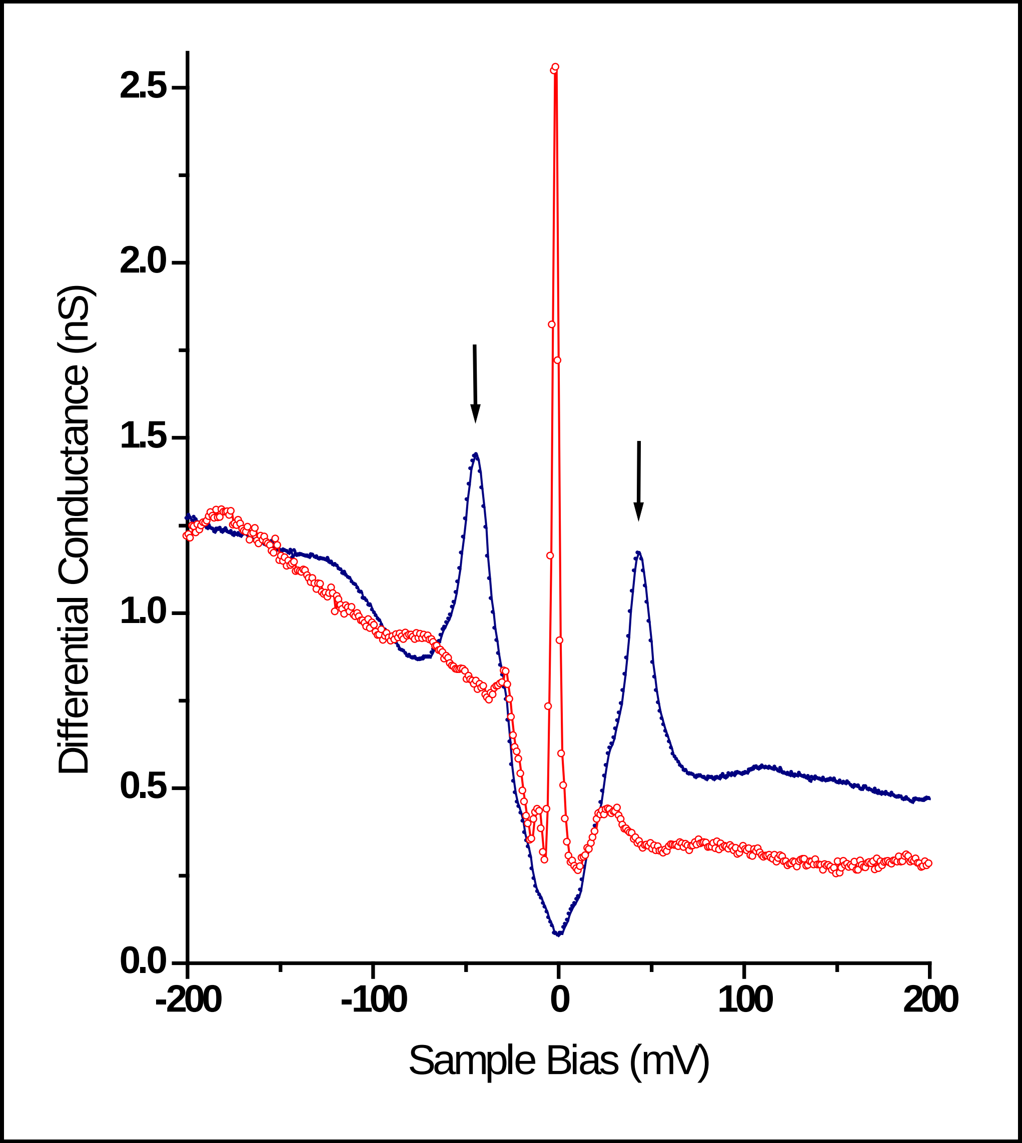
LDOS map at –1.5mV

~20
Zn atoms



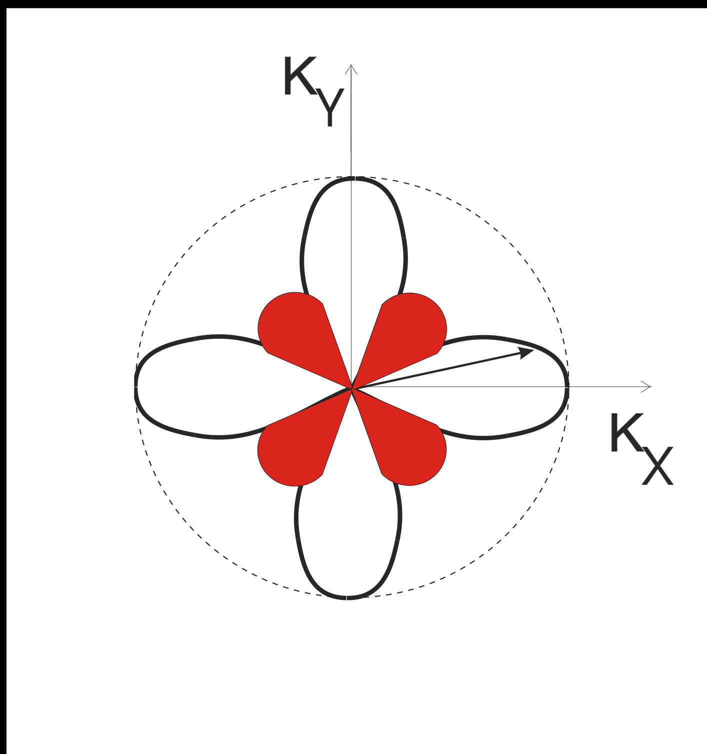
Pan et al, ***Nature*** **403,** 746 (2000).

Zn On-site LDOS spectrum: Ω_0=-1.5 meV

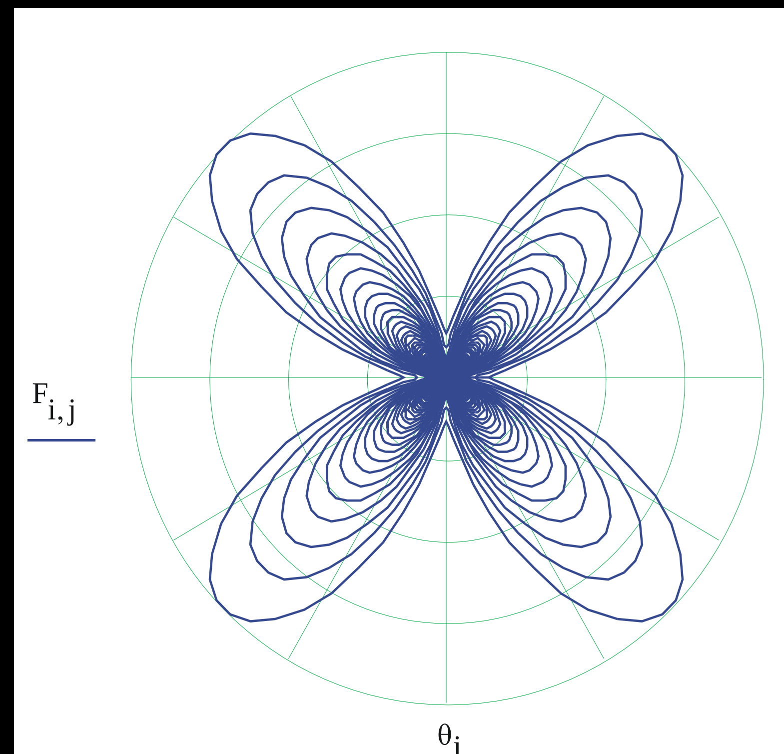


Pan et al, ***Nature*** **403,** 746 (2000).

k-space



r-space

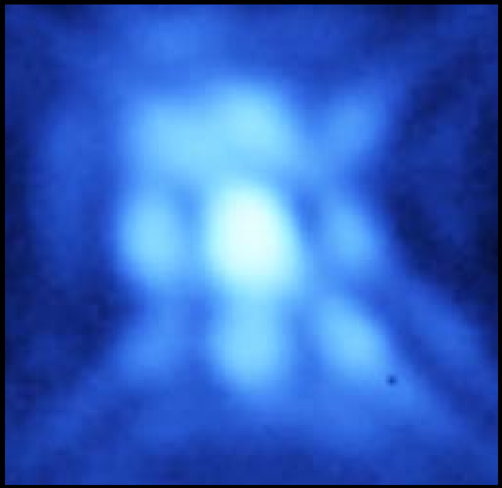


Data contrast with naïve expectation:
$|Y|^2$ should be a four-fold symmetric ‘star’ oriented with gap-nodes, maximum amplitude on nearest neighbor sites!

Spatial structure of these $|\Psi|^2$ not well understood.

Zn

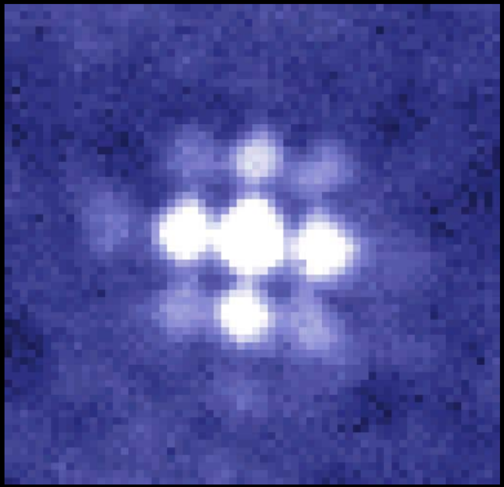
-1.2 mV



0 Å 30 Å

Ni

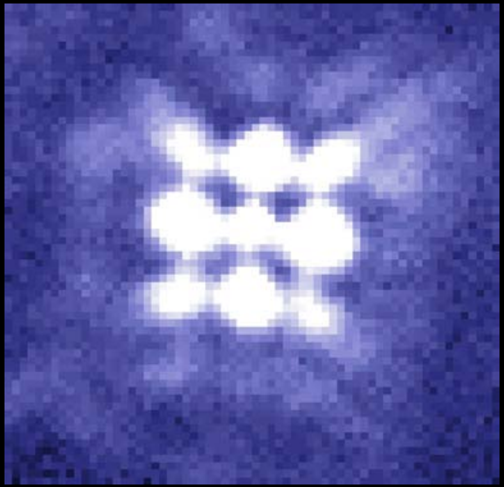
+9 mV



0 Å 32 Å

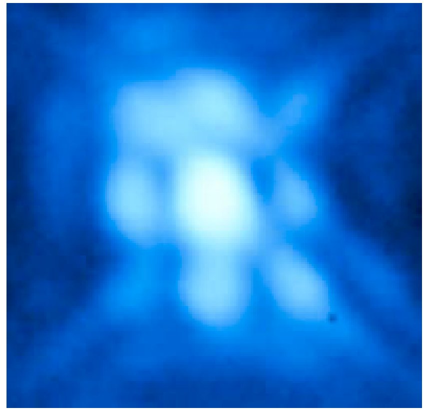
Cu:Vac.?

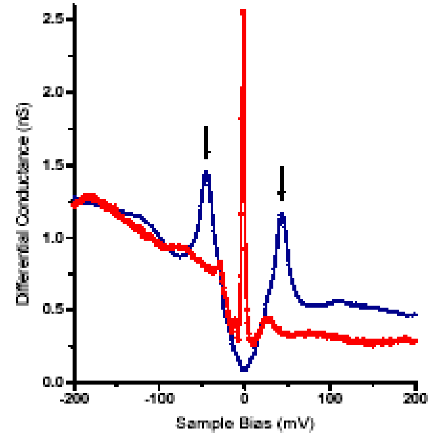
0 mV



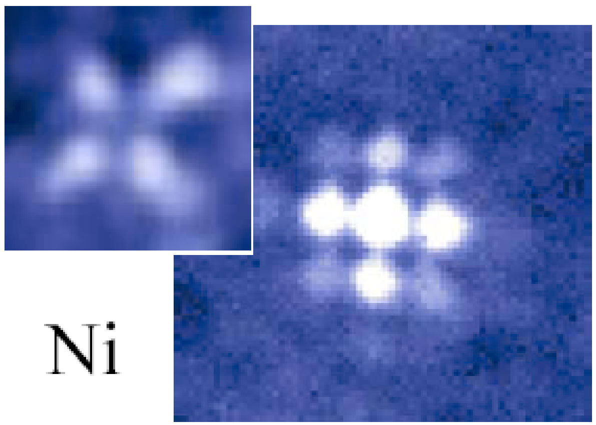
0 Å 32 Å

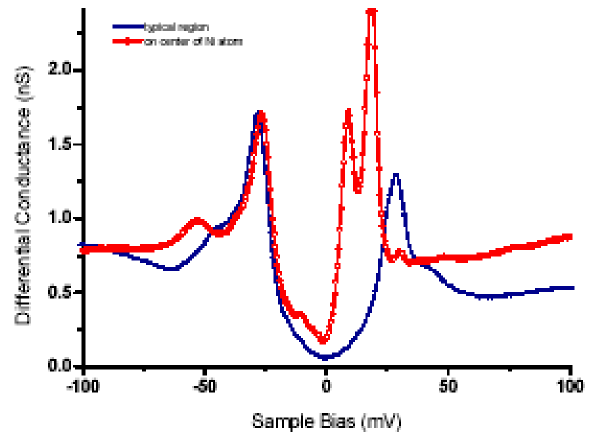
Zn



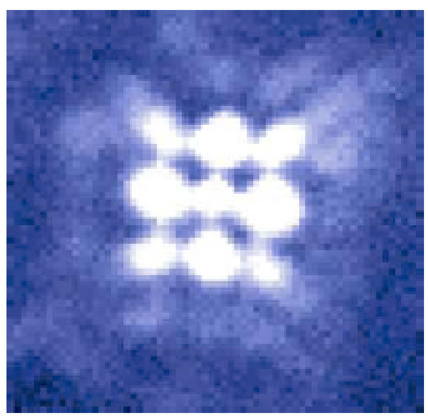

Differential Conductance (nS)
2.5
2.0
1.5
1.0
0.5
0.0
-200
-100
0
100
200
Sample Bias (mV)

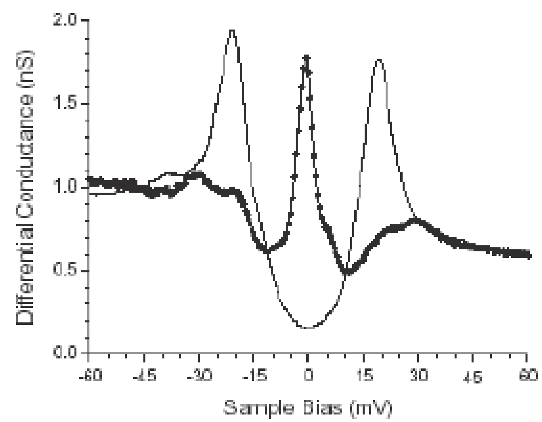
Ni




typical region
on center of Ni atom
Differential Conductance (nS)
2.0
1.5
1.0
0.5
0.0
-100
-50
0
50
100
Sample Bias (mV)

?




Differential Conductance (nS)
2.0
1.5
1.0
0.5
0.0
-60
-45
-30
-15
0
15
30
45
60
Sample Bias (mV)

Theories of impurity resonance spatial pattern

- “Chemistry”: M.E. Flatté et al. 2001, 03. Assume generalized extended impurity potential.

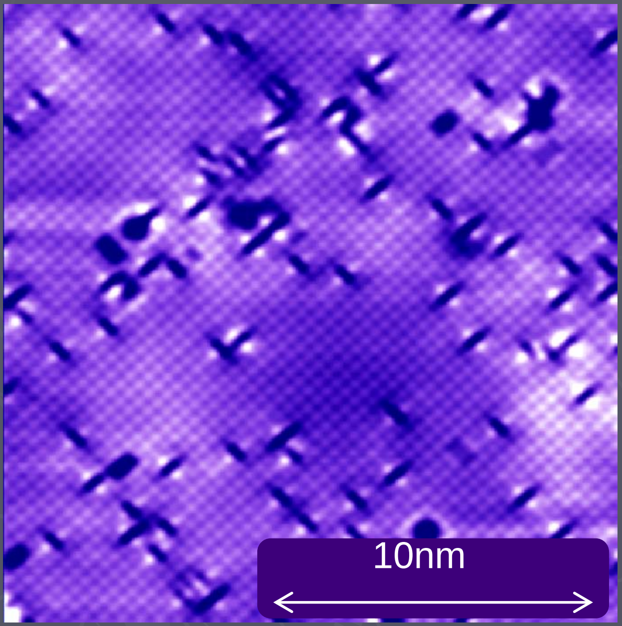
- “Filter”: C.S. Ting et al. 2001, Martin & Balatsky 2002. STM probes LDOS of neighboring Cu’s due to k-dependent tunneling matrix elements.

- “Correlations”: Polkovnikov et al 2001, … account for Kondo screening of correlation-induced local moment

Back to FeSC: intriguing defect states whose structure may reveal SC gap

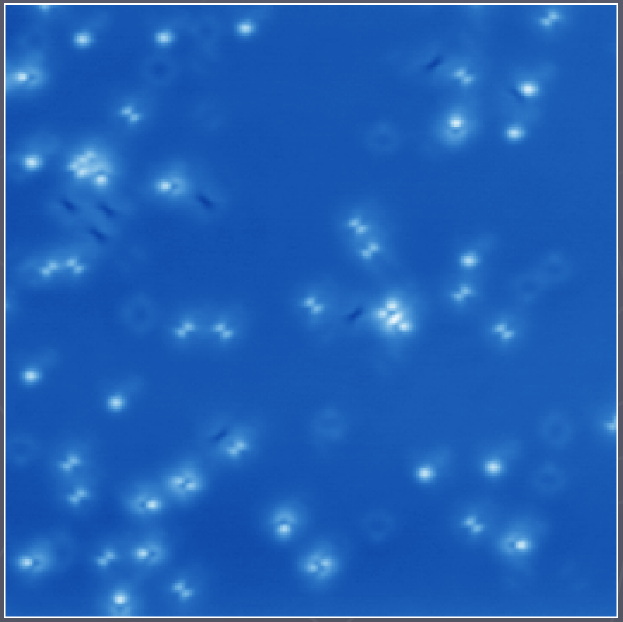
those shown believed to be Fe vacancies (J.E. Hoffman)

1111 (LaFeAsO)



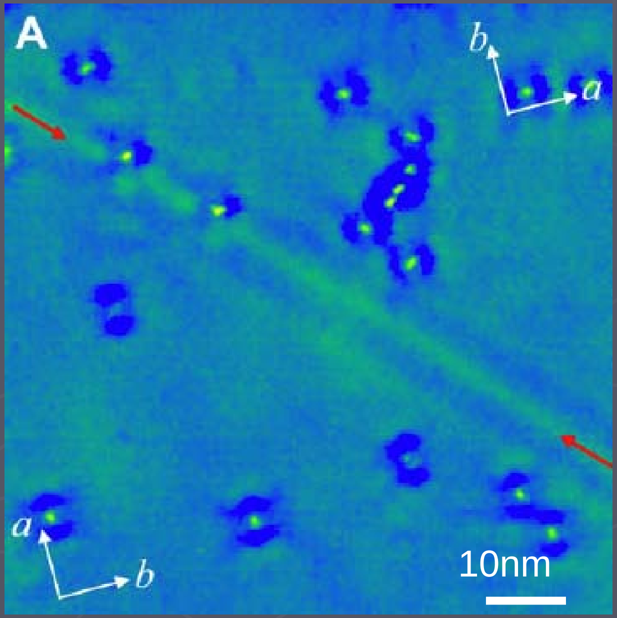
Zhou, PRL 106, 087001 (2011)

111 (LiFeAs)



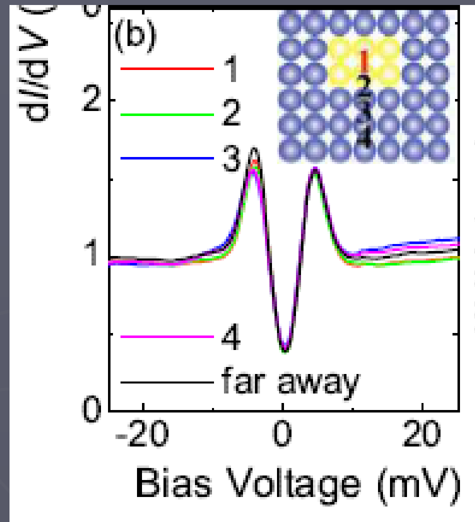
Hanaguri, unpublished

11 (FeSe)



Song, Science 332, 1410 (2011)

Sometimes no impurity bound states are seen

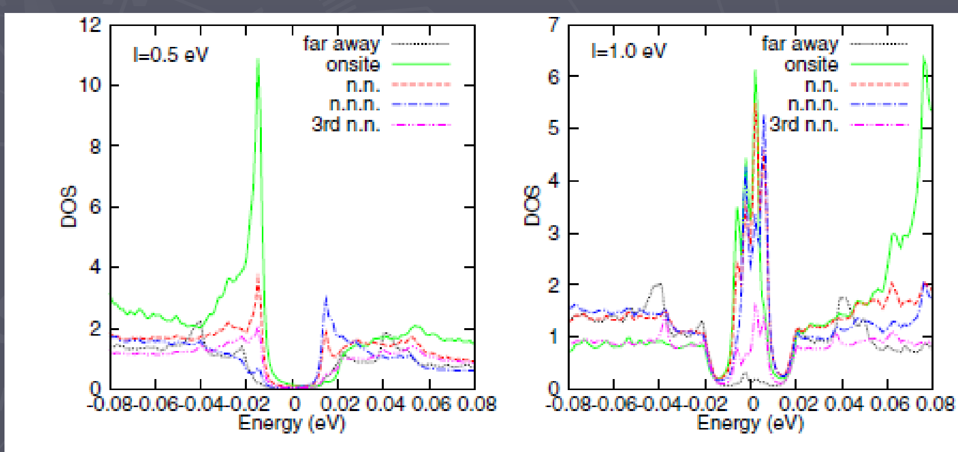


$Na(Fe_{1-x}Co_x)As$

Yang et al, PRB 86, 214512 (2012)

but it is not surprising!

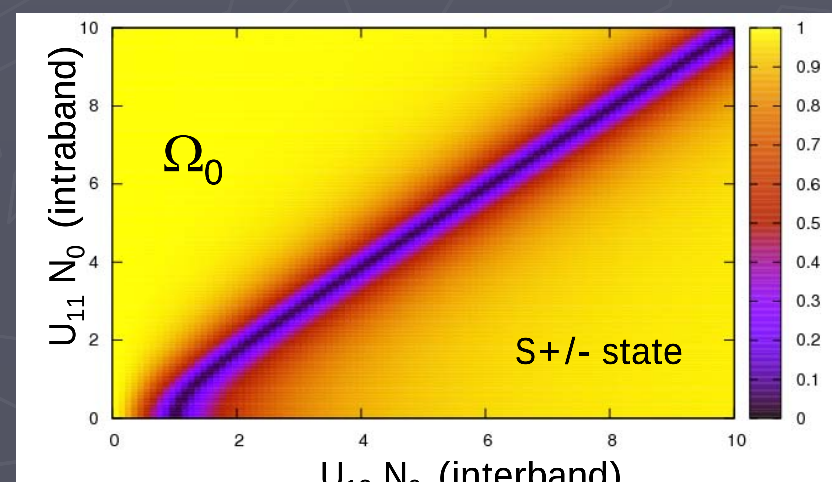
5-orbital BdG:
Kariyado and Ogata, JPSJ 79, 083704 (2010).



(a) (b)

bound states are hard to tune to low E

PH et al, ROPP 74, 124508 (2011)
Beaird et al PRB 86, 140507 (2012)



How to simplify many-parameter problem II:
use ab initio methods to determine intra/interband character of scattering?

- Ratio V_{inter}/V_{intra} important
- Impurity diagonal in orbital space has generically large interband component (Kontani 2009)
- Answer question with ab initio calculations for specific defects

	Mn	Co	Ni	Zn	Ru
xy	0.32	−0.39	−0.97	−7.88	−0.10
yz	0.27	−0.34	−0.84	−8.10	0.03
z^2	0.29	−0.36	−0.93	−7.96	−0.21
zx	0.27	−0.34	−0.84	−8.10	0.03
x^2-y^2	0.25	−0.33	−0.75	−8.22	0.16
Average	0.28	−0.35	−0.87	−8.05	−0.02
Ref. 36	1.27	−1.23	−2.42	-	1.95
ΔE_F	−0.004	0.011	0.032	0.084	0.062

Kemper et al 2009
for Co

band space:

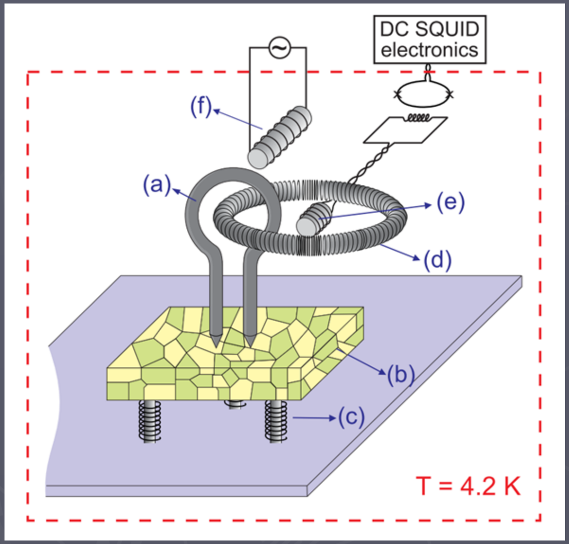
$$\frac{U_{12}}{U_{11}} \approx \frac{1}{3}$$

Kemper et al 2009, Nakamura et al 2010

Disagreement between Kemper, Nakamura, Elfimov... on Co potential?

s_{++} or s_{+-}? Few phase-sensitive expts.

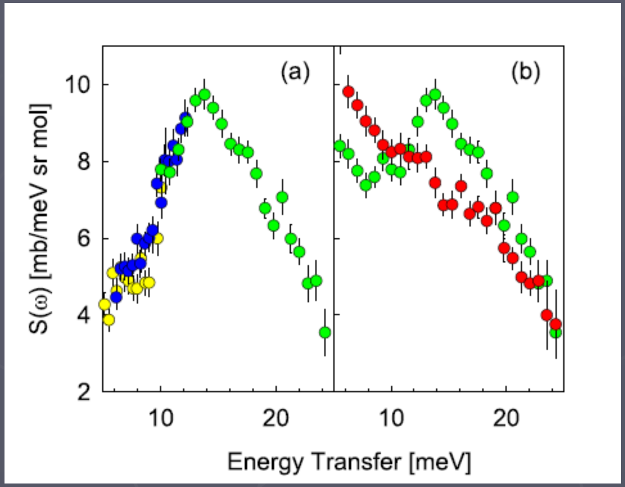
Chen et al, Nature 2010



$NdFeAsO_{0.88}F_{0.12}$

Half-integer fluxes detected (in a small fraction of loops)

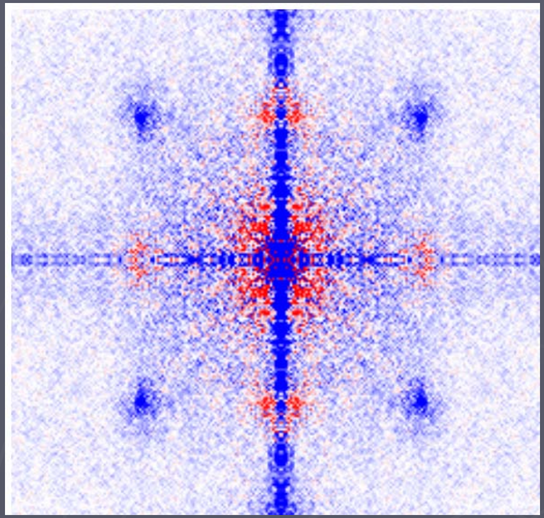
Christianson et al Nature 2008



$Ba_{0.6}K_{0.4}Fe_2As_2$

Enhanced susceptibility at Q below Tc ⇒ sign change of order parameter

Hanaguri et al Science 2010



Fe(Se,Te)

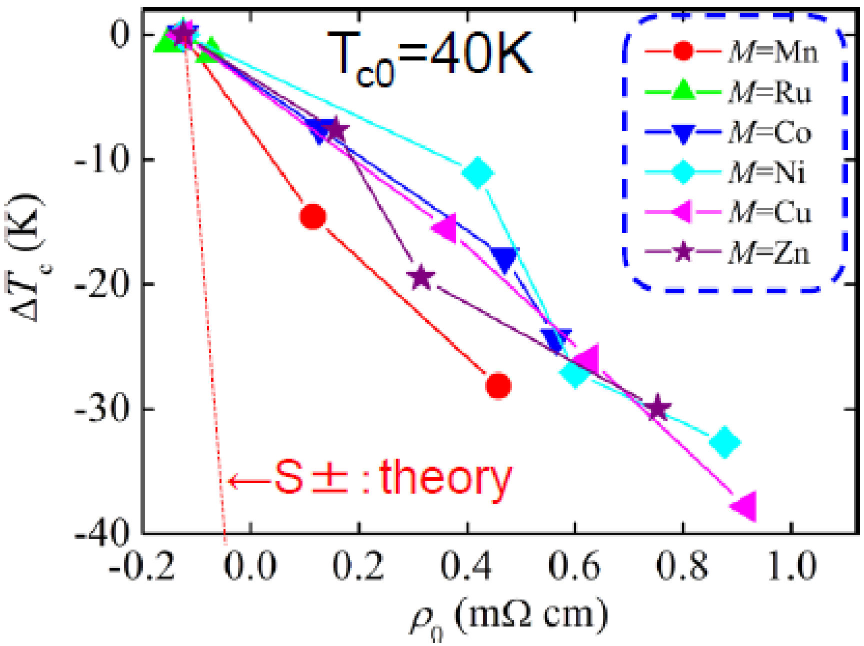
Field dependence of quasiparticle interference peaks depends on order parameter sign

Various critiques of all experiments, alternate scenarios: where is the  ?

Hiroshi Kontani, M2S 2012

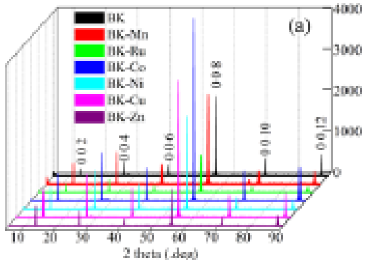
impurity effect in single crystal $(Ba,K)Fe_2As_2$

J.Li et al. PRB 85, 214509 (2012).



✓Vegard's law: good crystal

✓X-ray



other experiments:

1111 systems: Sato et al, JPSJ('08)
Ba122: Paglione et al, arXiv('12)
irradiation: Nakajima et al, PRB ('10)

Experiment:
T_c vanishes when
$\rho_{imp} > 500\mu\Omega cm$
$[l_{imp} \sim 3 Å]$

⟺

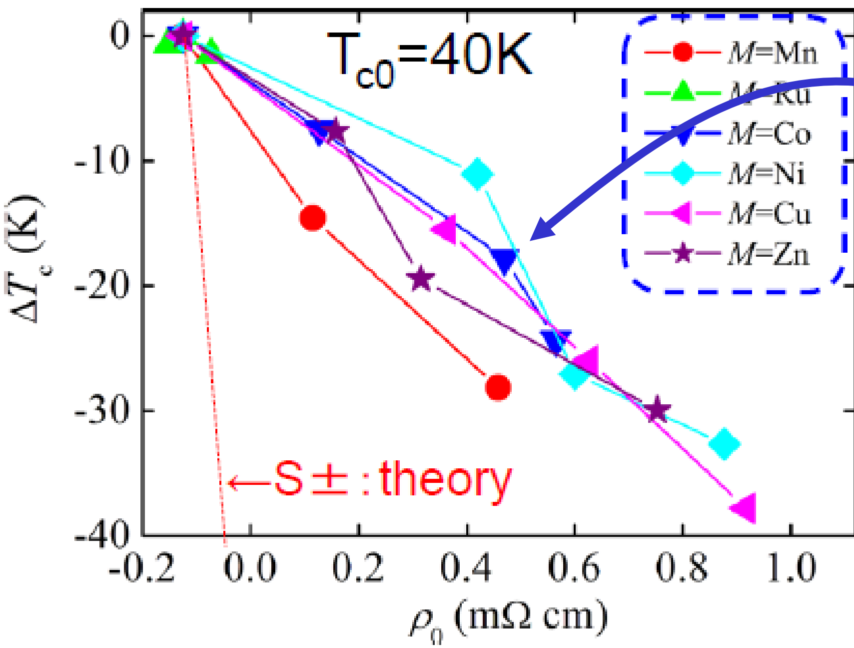
Theory:
S± wave state
disappears when
$\rho_{imp} = 20 \sim 40\mu\Omega cm$

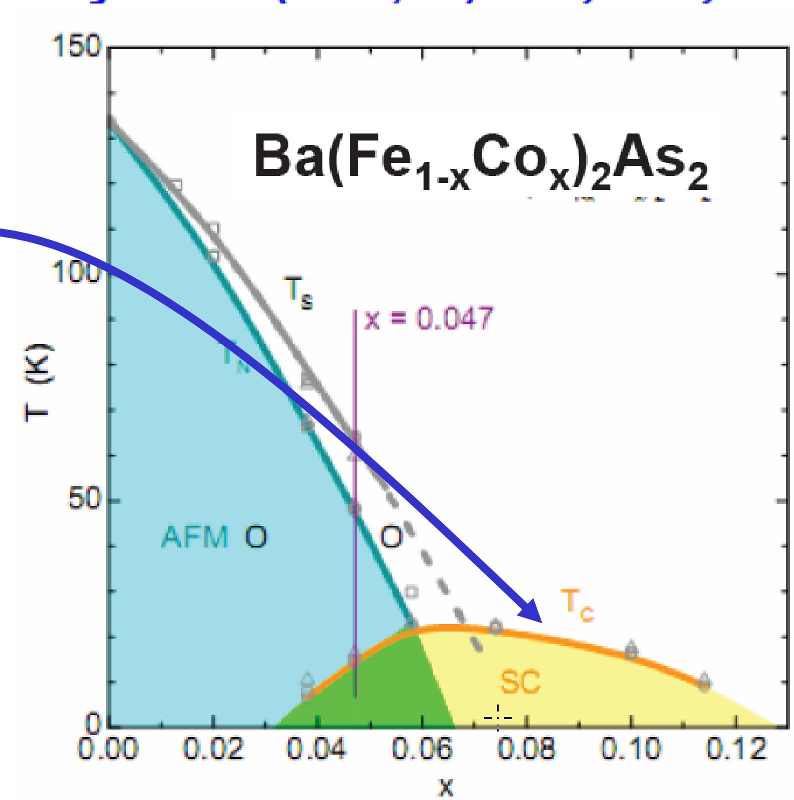
local impurity
on Fe-sites

Hiroshi Kontani, M2S 2012

impurity effect in single crystal $(Ba,K)Fe_2As_2$

J.Li et al. PRB 85, 214509 (2012).





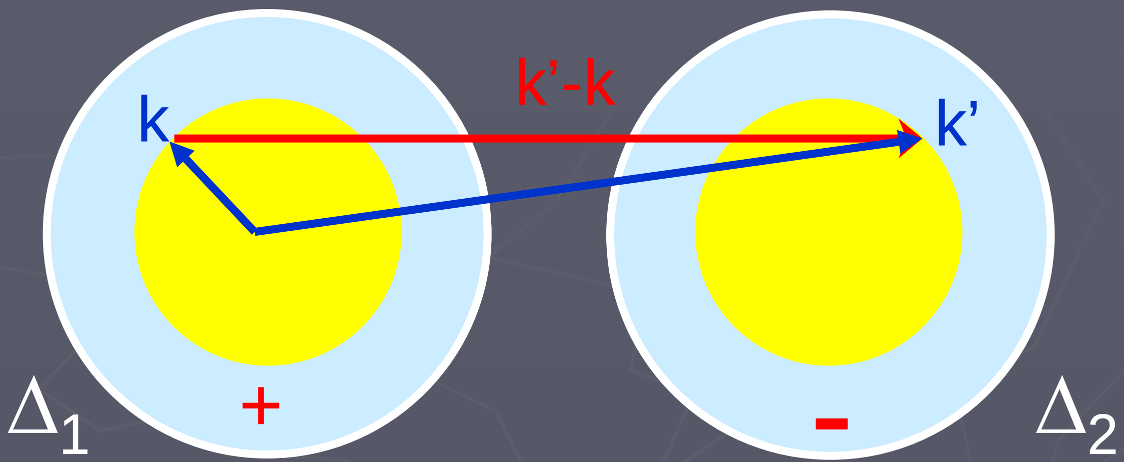
Experiment:
T_c vanishes when
$\rho_{imp} > 500\mu\Omega cm$
$[l_{imp} \sim 3\,Å]$

Theory:
S± wave state
disappears when
$\rho_{imp} = 20\sim40\mu\Omega cm$

local impurity
on Fe-sites

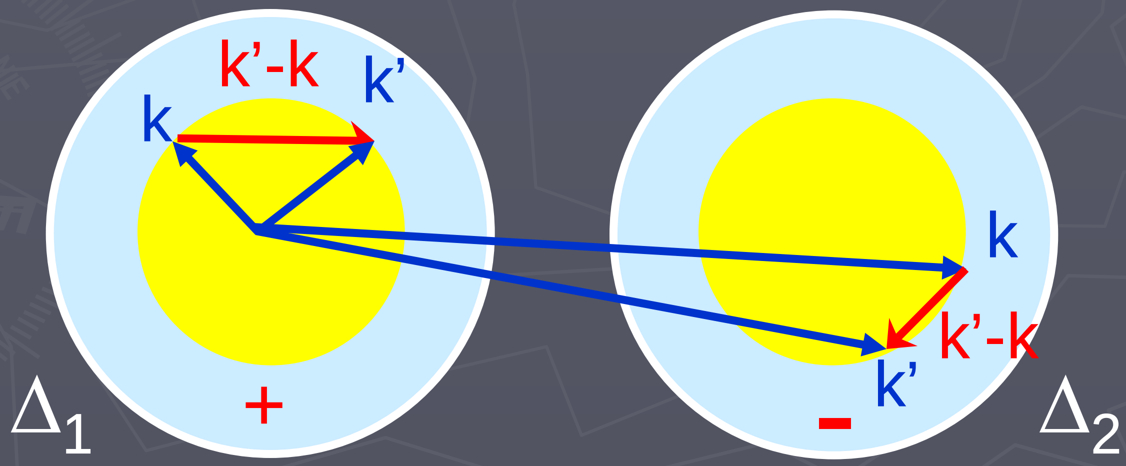
Inter- and intraband impurity scattering in 2-band $s_{+/-}$ system

Inter-



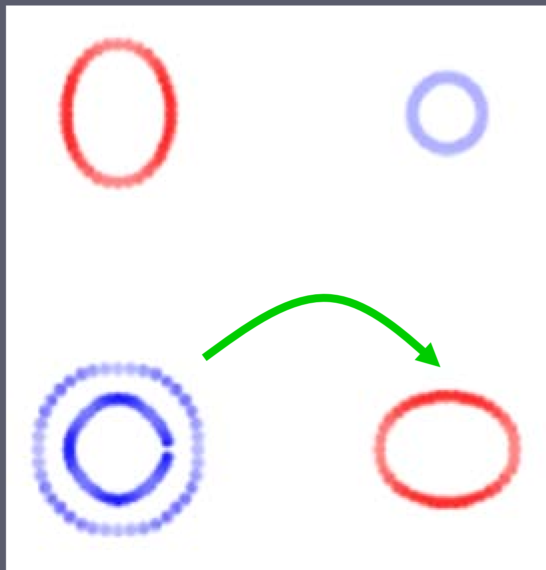
mixes + and – gaps, breaks pairs

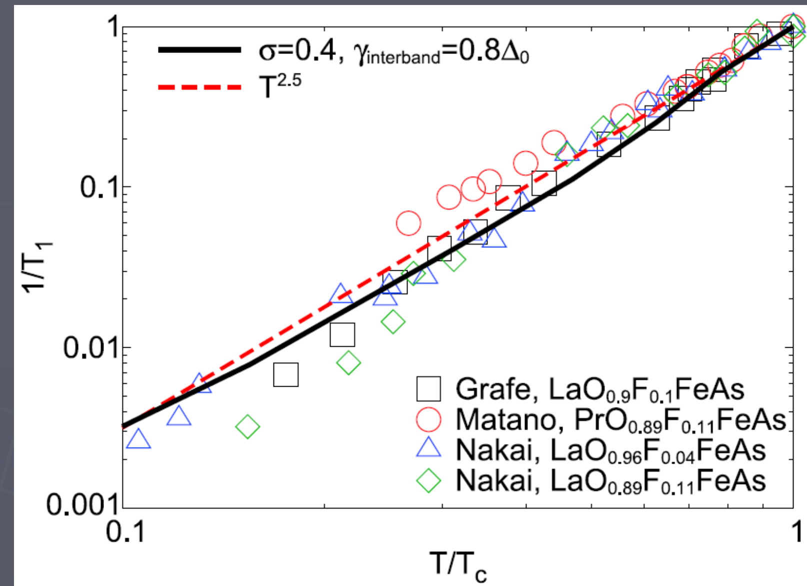
Intra-



no mixing of +/-
no pairbreaking

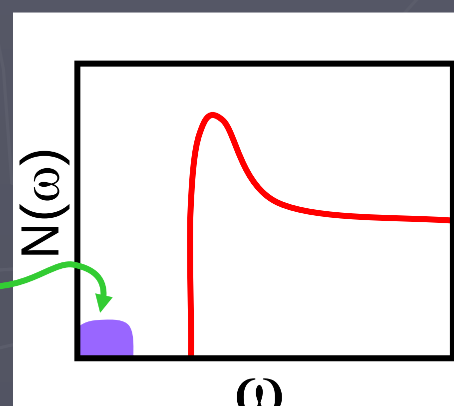
Scenario 1: isotropic $s_{+/-}$ state + interband impurity scattering $\Rightarrow$ low-E power laws





$$\frac{T_1^{-1}}{(T_1^{-1})_N} = 2\frac{T}{T_c}\int_0^\infty d\omega \left[\frac{-\partial f}{\partial \omega}\right]\left[\frac{N(\omega)}{N_0}\right]^2$$

$$\sim T \text{ if } N(\omega=0) = const$$



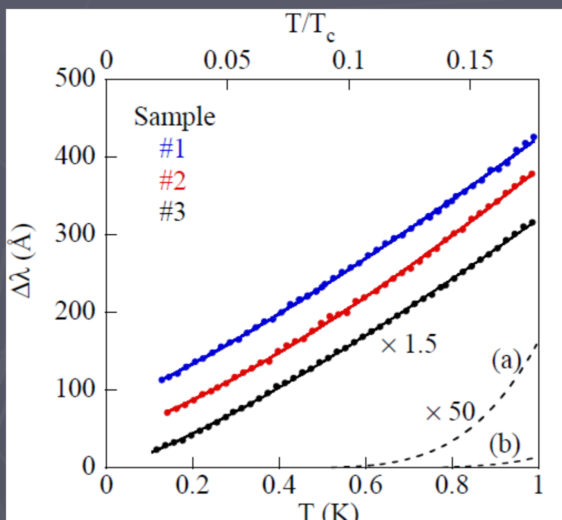
Parker et al PRB 2008
Chubukov et.al., PRB 2008
Vorontsov et al PRB 2009

$s_{+/-}$ state has full gap but interband scattering is pairbreaking due to bound state

Scenario 2: anisotropic states with intraband scattering

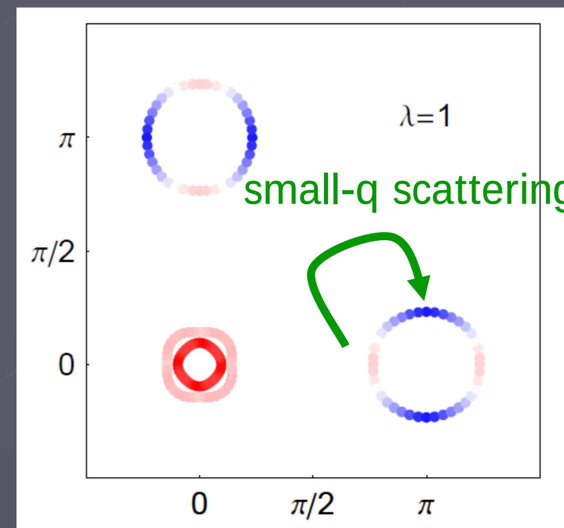
recall
Fletcher et al 2008 LaFePO T_c=6K

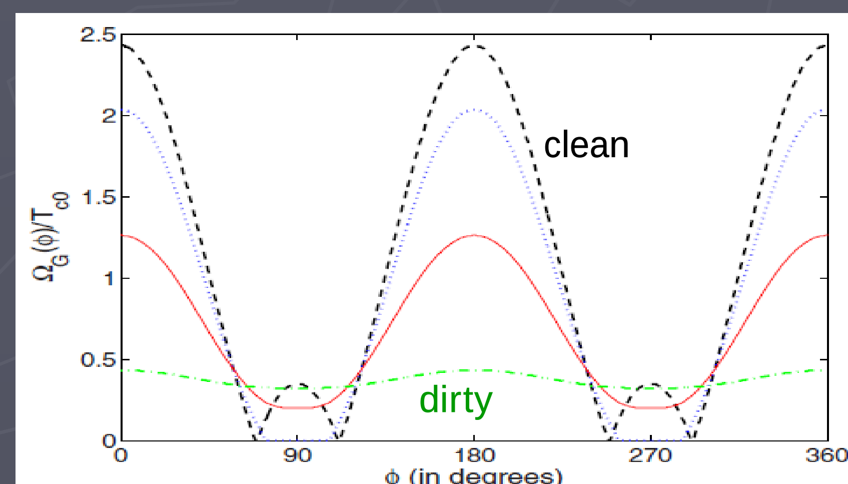
$\lambda \sim T \Rightarrow$ nodes!



intraband scattering averages gap anisotropy, "lifts" nodes!

Mishra et al PRB 2009





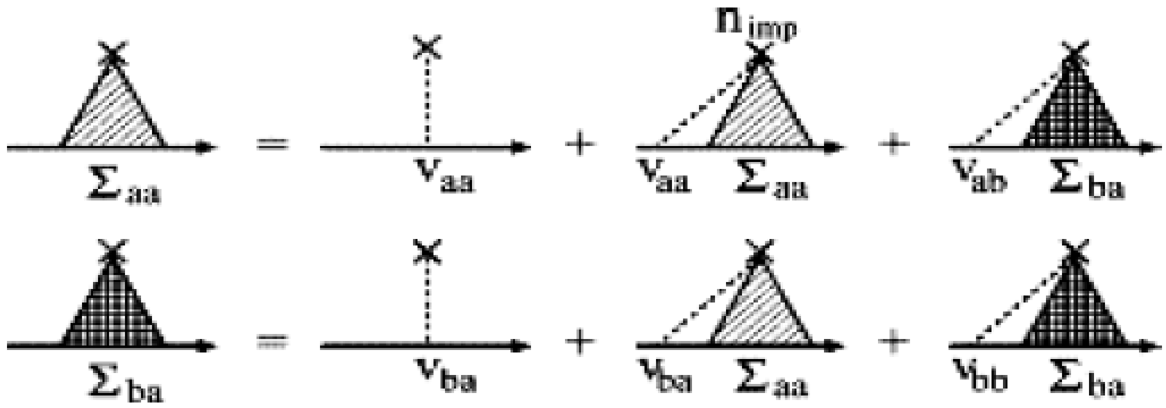
Simplest problem: T_c suppression in $s_{+/-}$ state

naïve expectations:

- interband scattering will suppress T_c faster
- T_c suppression will depend on interband/intraband scattering potential ratio u/v
- T_c suppression will depend on ratio/signs of interband/intraband pairing $\lambda_{inter}/\lambda_{intra}$ as well

2-band disorder problem

self-consistent t-matrix approx.



$$\hat{v} = \begin{pmatrix} u_{aa} & v \\ v & u_{bb} \end{pmatrix}$$

Interband and intraband impurities

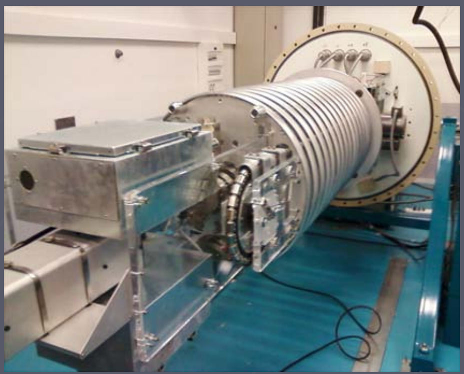
$$\sigma = \frac{\left(\pi\sqrt{N_a N_b}\, v\right)^2}{1 + (\pi\sqrt{N_a N_b}\, v)^2}$$

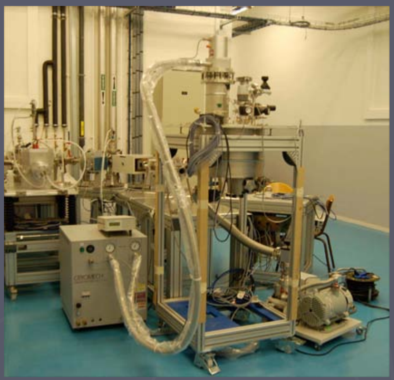
$\gamma = 2n\sigma/N(0)$ is the normal-state scattering rate, n is the impurity concentration, υ is the interband impurity potential, σ is the impurity strength ($\sigma \rightarrow 0$: Born limit, $\sigma = 1$: unitary limit)

Preosti, Muzikar PRB 54, 3489 1996; Golubov, Mazin, Phys. Rev. B 55, 15146 1997

M.L.Kulić, O.V.Dolgov, PRB, **60**, 13062 (1999); Y. Ohashi, Physica C, **412-414**, 41(2004)

Electron irradiation at LSI (Irradiated Solids Lab)--Paris





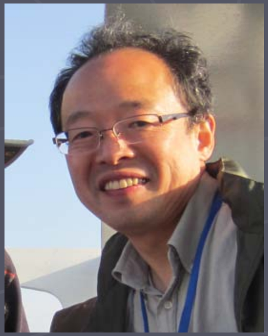
SIRIUS

Pelletron
Facility
At LSI

http://emir.in2p3.fr/LSI http://www.lsi.polytechnique.fr/accueil/equipements/accelerateur-sirius/

- vacancy – interstitial (Frenkel) pairs
- different sublattices are affected, depending on beam energy
- initial paper: arXiv:1209.3586 with 2.5MeV electrons: dominant Fe vacancies

Shibauchi



Matsuda

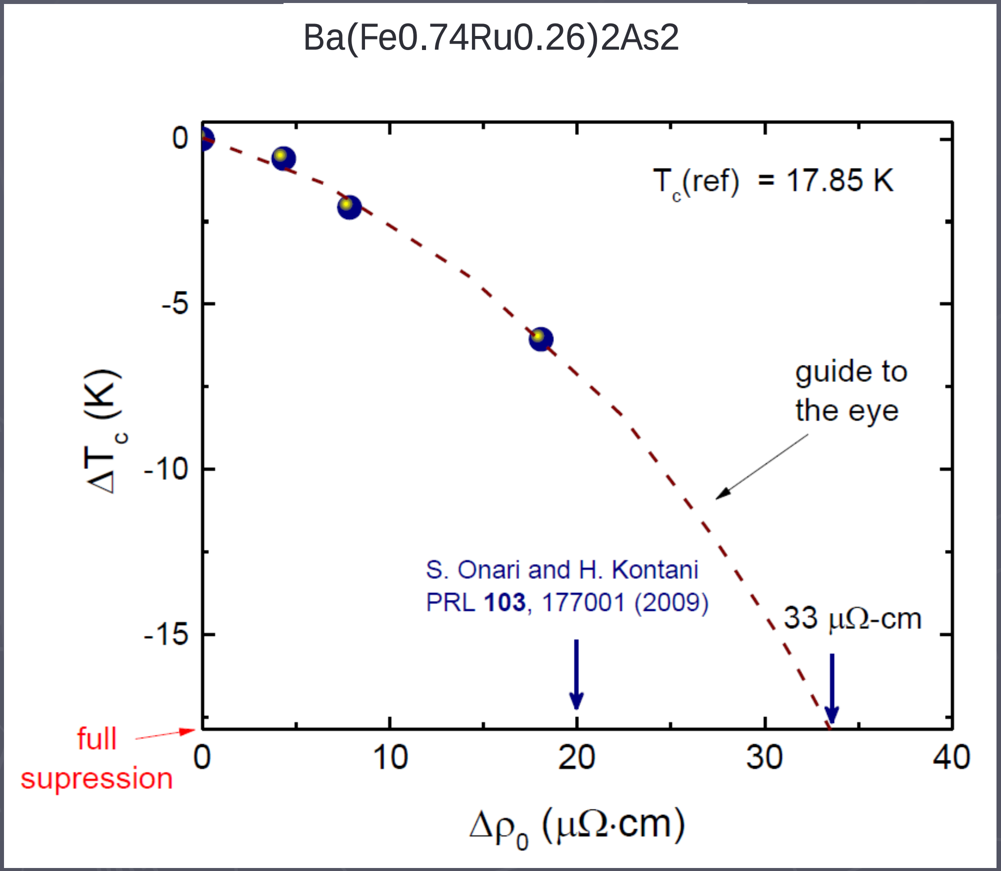
Rullier-Albenque

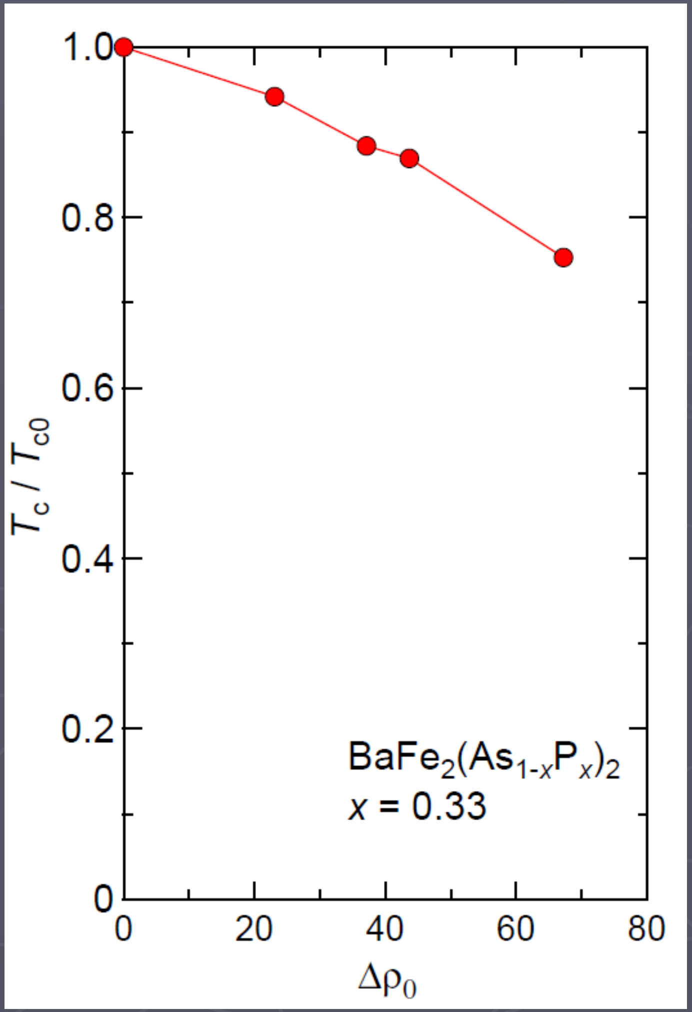
Prozorov

also: C. van der Beek, M. Konczykowski

Thanks: C. van der Beek

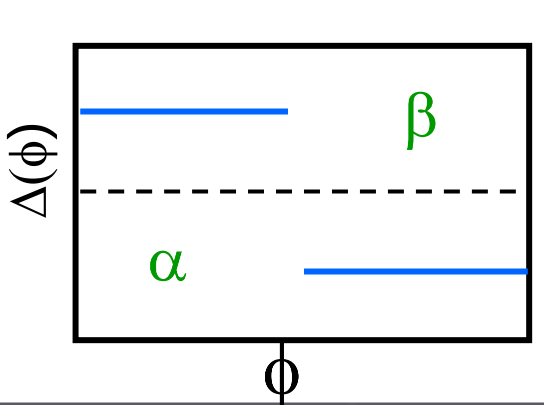
e- irradiation experiments

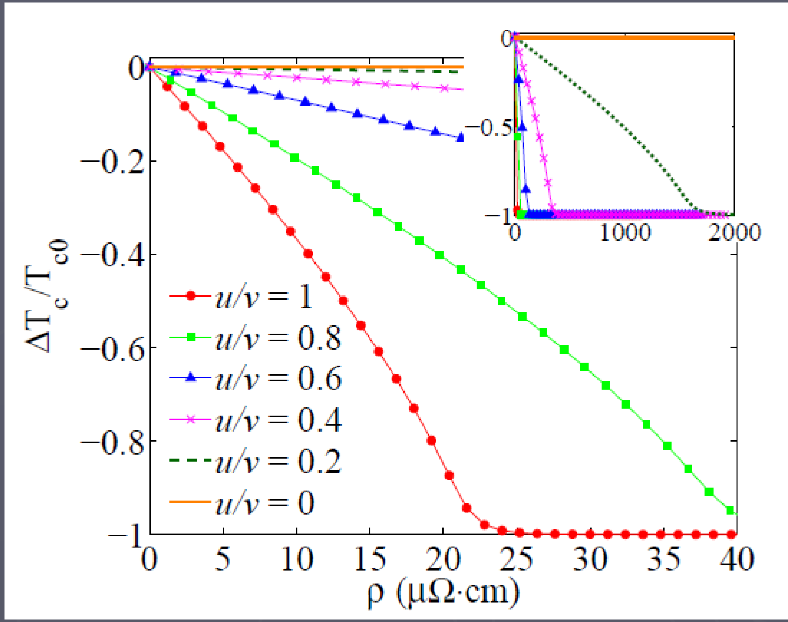




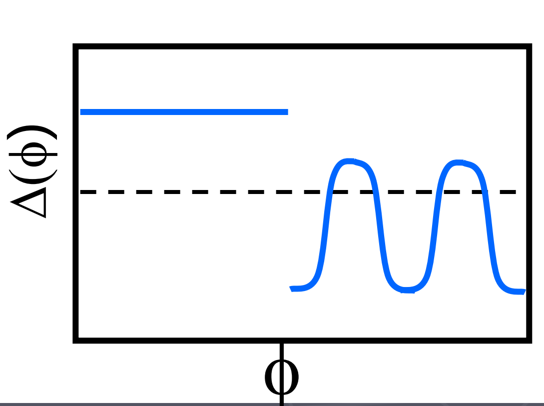
theory

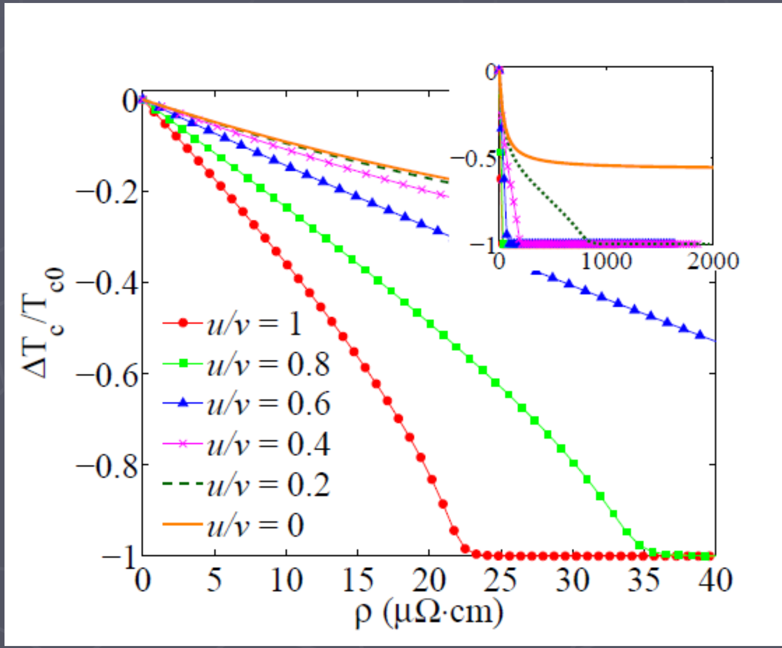
Wang et al 2012 (unpublished)





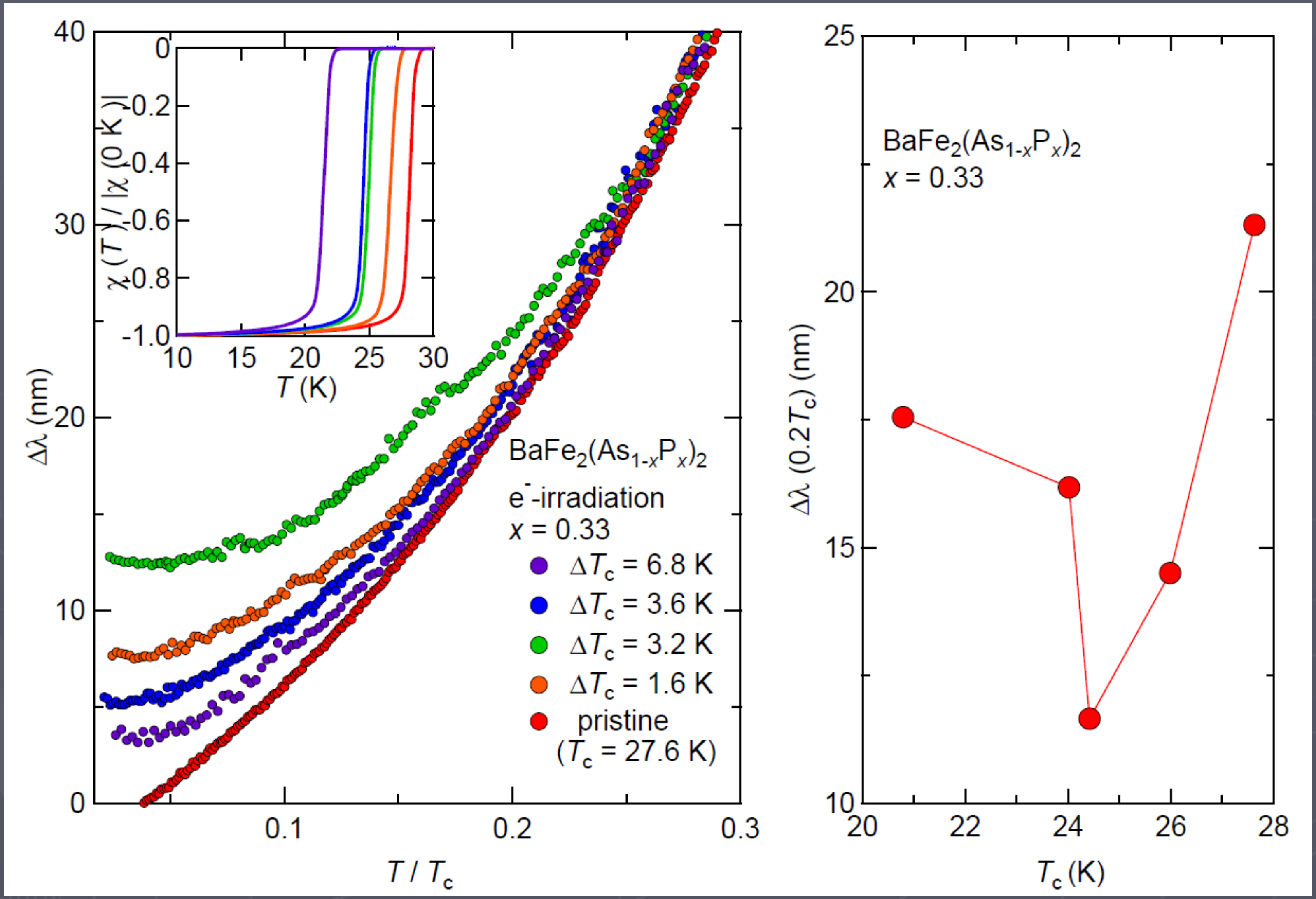
u = inter band impurity potential
v = intra band impurity potential





Critical $\Delta\rho_0$'s range from 20μΩ–cm to mΩ-cm!

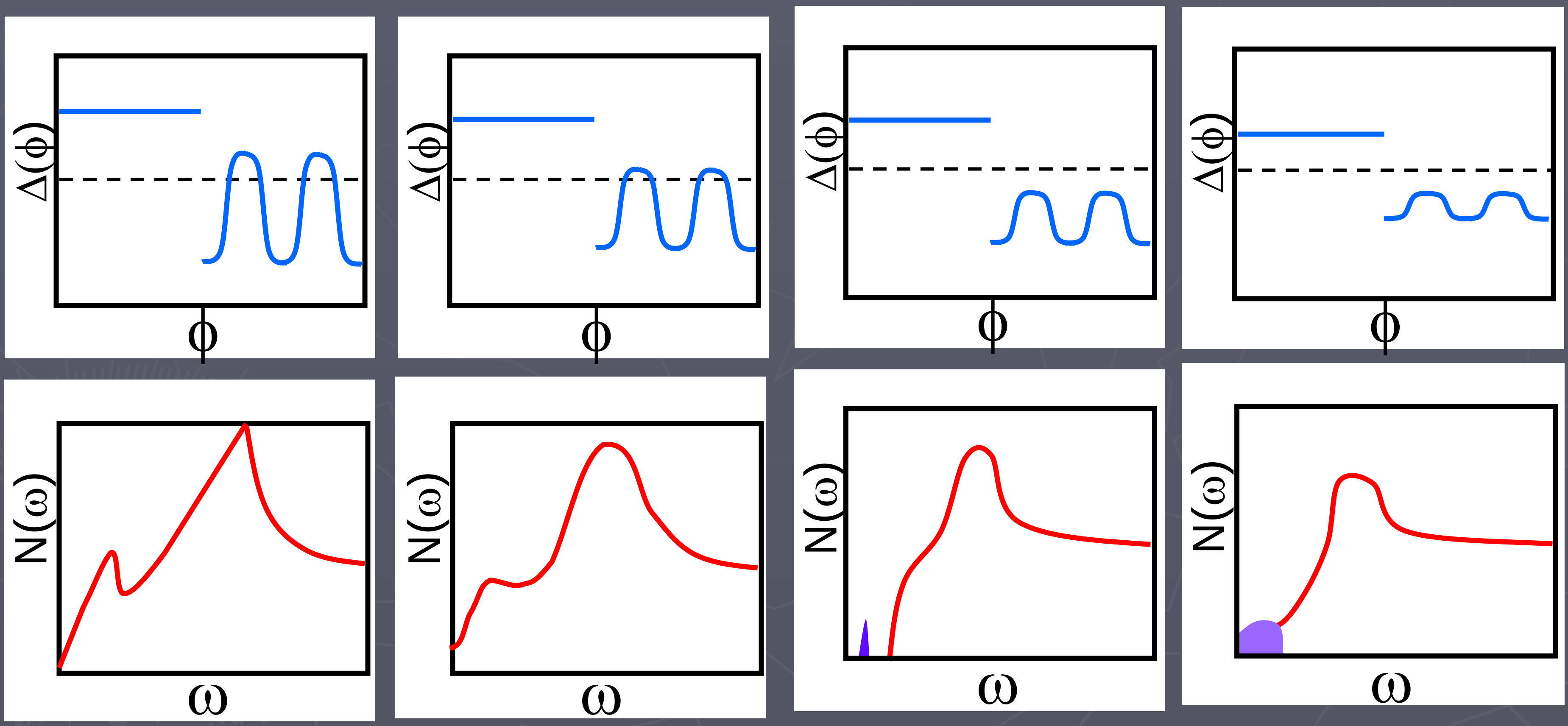
e- irradiation of $BaFe_2(As,P)_2$



Nonmonotonic change of low T dependence: T $\rightarrow$ exp(-Δ/T) $\rightarrow$ T^2

DOS, $\Delta\lambda$, T_1^{-1} with increasing disorder: mixed inter and intraband scattering

disorder→

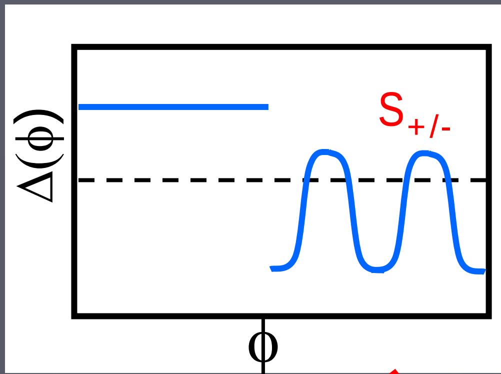


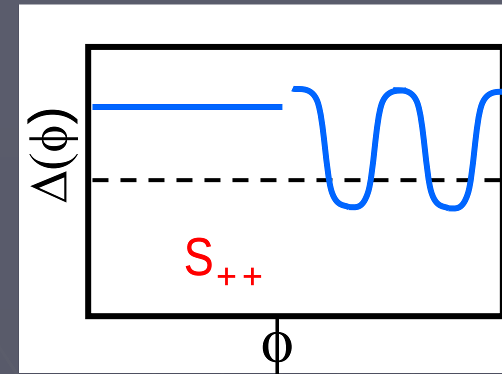
$\Delta\lambda \sim T \quad \rightarrow \quad T^2 \quad \rightarrow \quad e^{-\Delta/T} \quad \rightarrow \quad T^2$

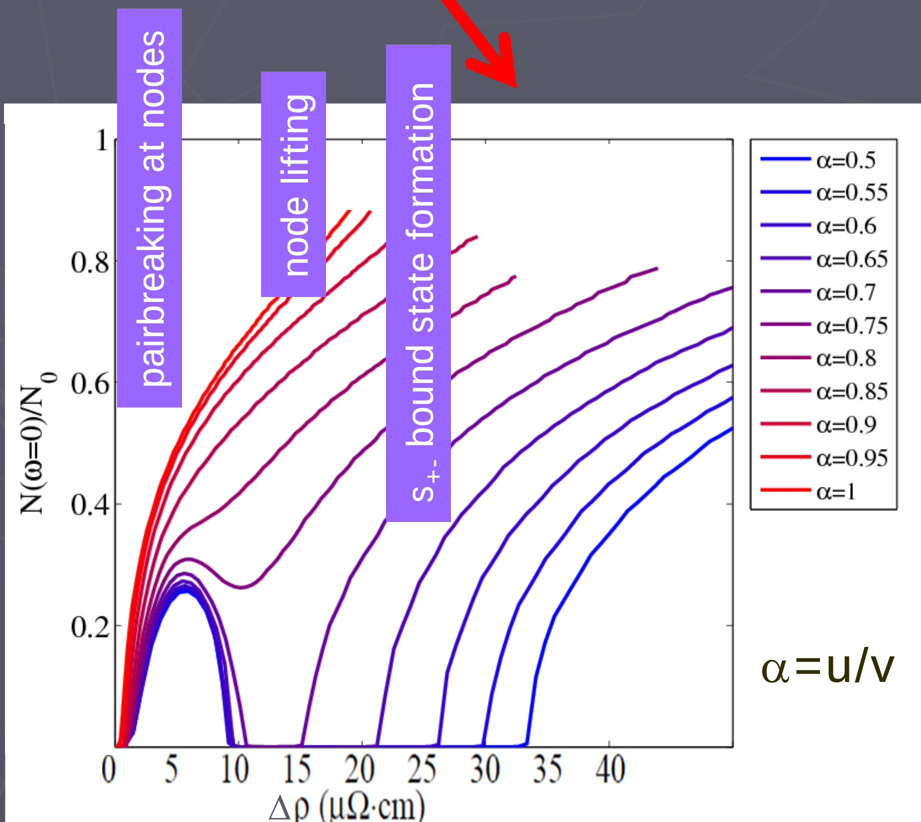
$T_1^{-1} \sim T^3 \quad \rightarrow \quad T \quad \rightarrow \quad e^{-\Delta/T} \quad \rightarrow \quad T$

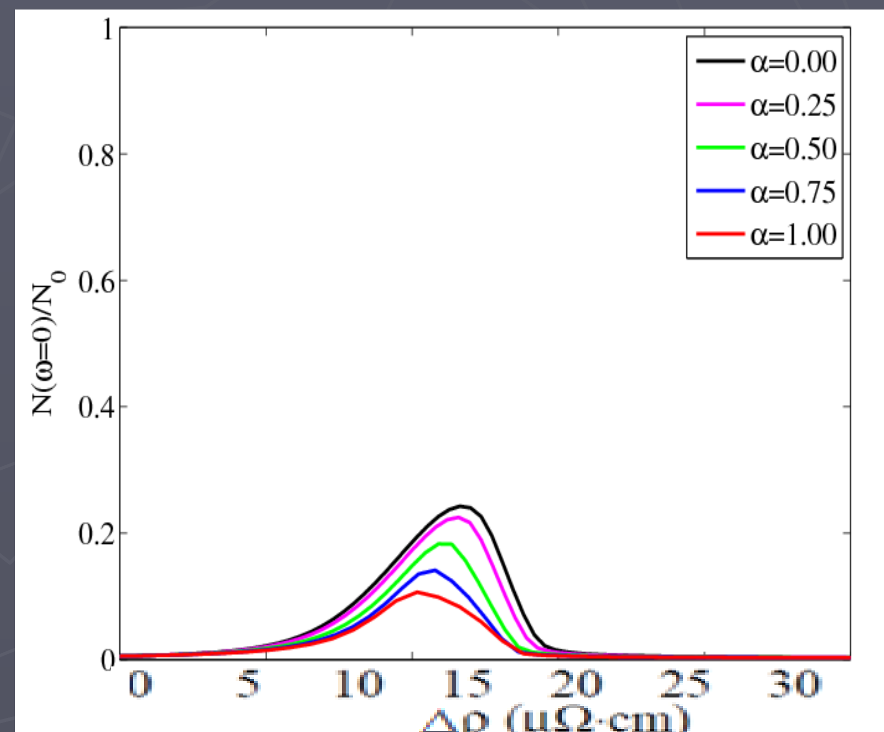
Theory of nonmonotonic λ(T)-variations

Wang et al 2012 (unpublished)



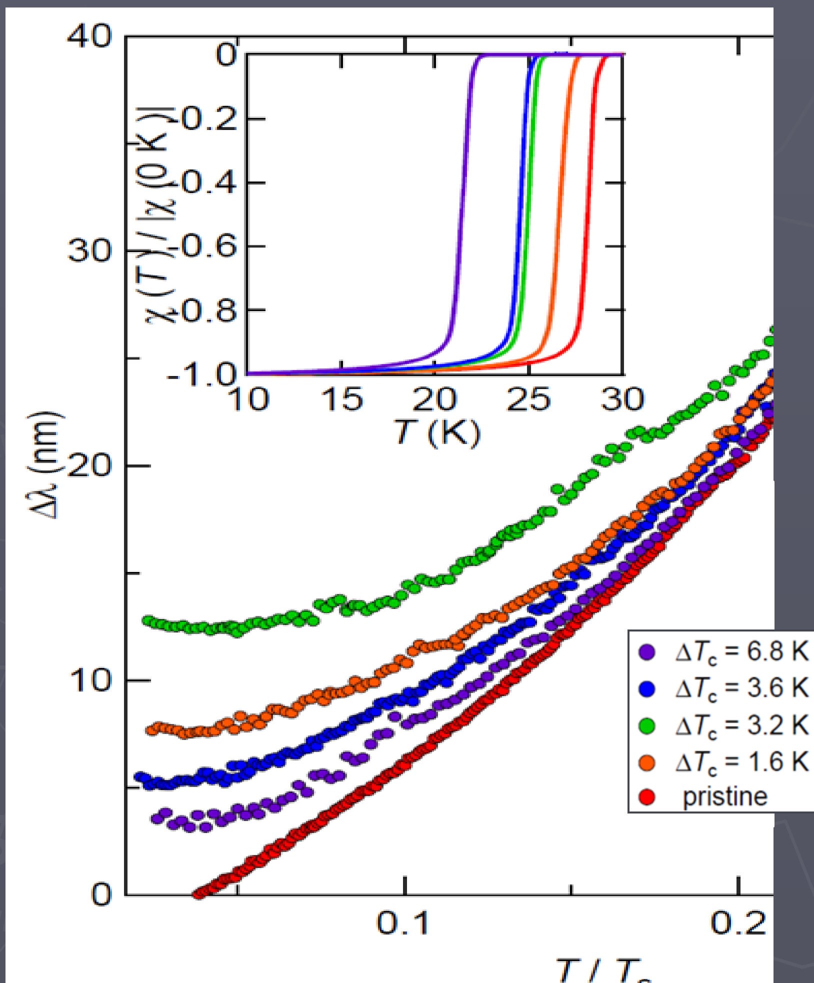


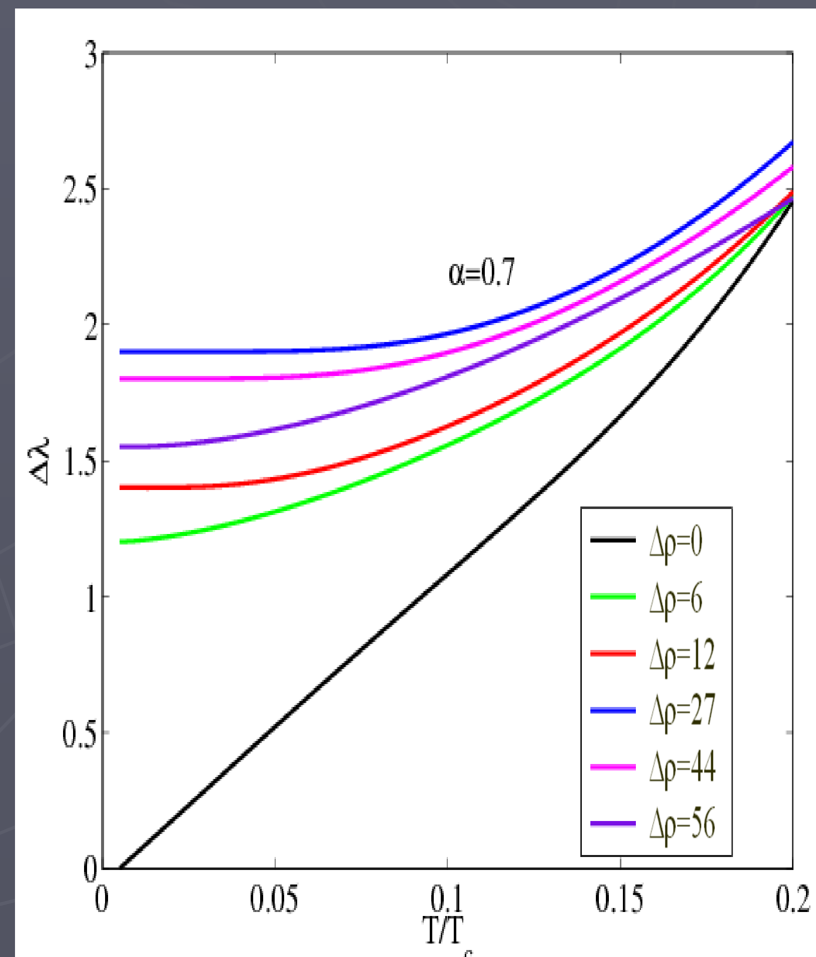




Only s+/- can explain data!

Comparison: expt vs. theory





Conclusions

- Unconventional superconductors are generically sensitive to nonmagnetic disorder
- impurity bound states may be good probes of superconducting gap structure; mysteries remain
- e- irradiation experiments: T_c suppression, penetration depth experiments strong evidence for sign-changing Δ in FeSC
- To use disorder analysis to determine order parameter structure, need to reduce # parameters – ab initio methods?