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INTERNATIONAL ATOMIC ENERGY AGENCY
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SMR.959 - 17

MINIWORKSHOP ON STRONG ELECTRON CORRELATIONS
"Disorder and Interaction in Quantum Systems and Their Classical Analogs"

(1 - 19 July 1996)

"Non Fermi Liquid behaviour and d-wave superconductivity near charge instabilities"

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These are preliminary lecture notes, intended only for distribution to participants.

Non Fermi Liquid behavior and d-wave superconductivity near charge instabilities

The issue: are charge instabilities relevant in providing a consistent scenario for cuprate superconductors?

Collaborators

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two preliminary considerations

* Cuprates, normal phase $T > T_c$: linear resistivity, $\rho \sim T$
anomalously strong scattering

non Fermi Liquid

* models with short range forces
(forward scattering)

Fermi Liquid $d > 1$ dimensional crossover: C.C., Di Castro and Metzner PRL 72, 316 (94)

$\Rightarrow$ search for singular interactions in $d = 2$

$V(q) \sim \frac{1}{q^\alpha}$ $\alpha \geq 2(d-1)$

"simple" Coulomb forces $\sim \frac{1}{q}$ in $d = 2$ are not enough

Bares and Wen 93
Houghton et al 94
C.C, Di Castro and Maccarone 94

Short range forces, forward scattering

$\Rightarrow$ Fermi Liquid at $d = 2$

bosonization at $d = 2, 3, \ldots$ (Haldane (92))

in $d = 2 \Rightarrow$ FL $\left\{ \begin{array}{l} \text{Houghton and Marston (93)} \\ \text{Castro Neto and Fradkin (94)} \end{array} \right.$

renormalization group Feldman et al 94

* Ward Identities ; dimensional crossover for $1 \leq d \leq 2$

the approach is exact for $d \to 1$ (Dzyaloshinskii and Larkin (74))

$\Rightarrow$ Fermi Liquid $d > d_c \equiv 1$ (i.e. Luttinger liquid is restricted to $d = 1$)

Phase Separation: charge instability at $q = 0$, diverging compressibility

effective interaction among quasi-particles

$$\Gamma_{eff} \simeq - \frac{V}{q^2 + \kappa^2 - i\gamma \frac{\omega}{q}}$$

γ = damping parameter ($\sim 1/v_F$)

$\kappa^2 = \xi^{-2}$ inverse correlation length

at the transition $\kappa^2 \to 0$:

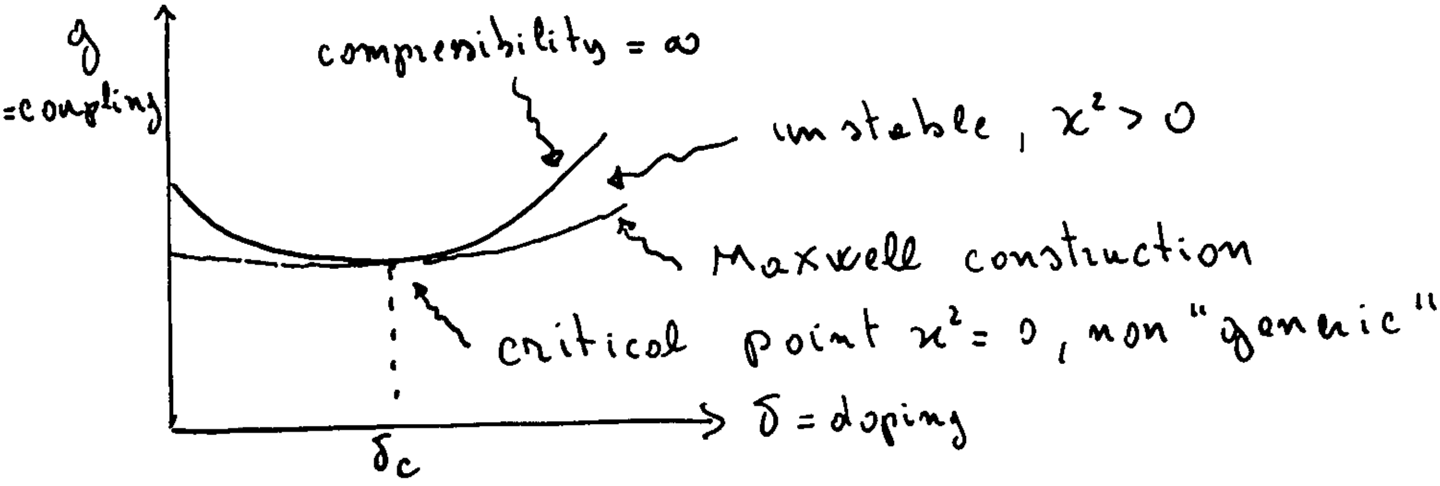
singular interaction, as in gauge theories

$\Rightarrow$ similar results:

non Fermi Liquid $\frac{1}{\tau} \sim \omega^{2/3}, T^{2/3}$ at $d = 2$

$\rho(T) \sim T^{4/3}$ for $T > T^* \sim \kappa^3/\gamma$

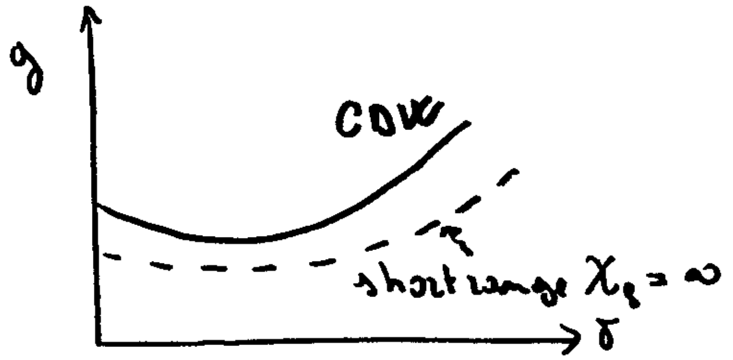
- However PS is usually first order



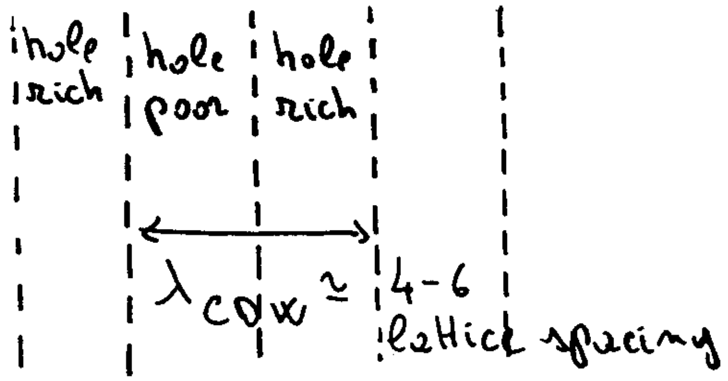
- long range forces $\sim \frac{1}{q}$ spoil PS

※ no charge segregation

PS + long range forces : incommensurate CDW



- second order transition (no cubic terms in the G.L. F_{eff})
- it is not a Fermi Surface instability, q_{CDW} is fixed by the balance between PS segregation and "electrostatic" cost to segregate changes.



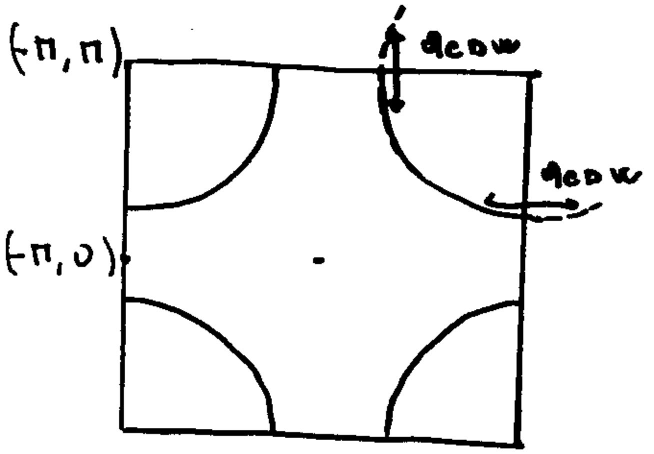
Hubbard - Holstein model : $q_{CDW} \simeq 1$ along $(\pm\pi, 0)$, $(0, \pm\pi)$ directions

Effective interaction $\Gamma_{eff} \simeq - \dfrac{V}{(\vec{q} - \vec{q}_{CDW})^2 + \varkappa^2 - i\gamma\omega}$

$\varkappa^2 = 0$ at $\delta_{c,CDW} \equiv \delta_c(g)$, generic Quantum Critical Point

Γ_{eff} like in AF fluctuation theory (Montoux and Pines (94))

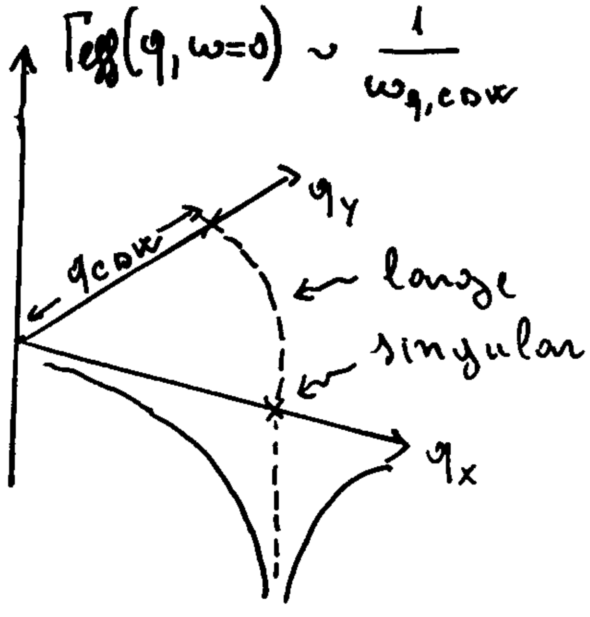
Similar outcome: near CDW instability non Fermi Liquid, "linear" resistivity for $T > T^* \simeq \kappa^2/\gamma$ ($\rho \sim T^{\frac{3}{2}}$ at $d=3$)



$\frac{1}{\tau_k} \sim \sqrt{T}$ "hot" points

$\frac{1}{\tau_k} \sim T^2$ "cold" points

Notice CDW comes out to be "not strongly" anisotropic



$\Gamma_{eff}(q,\omega=0) \sim \frac{1}{\omega_{q,CDW}}$

$\omega_{q,CDW} \simeq (|\vec{q}| - |q_{CDW}|)^2$

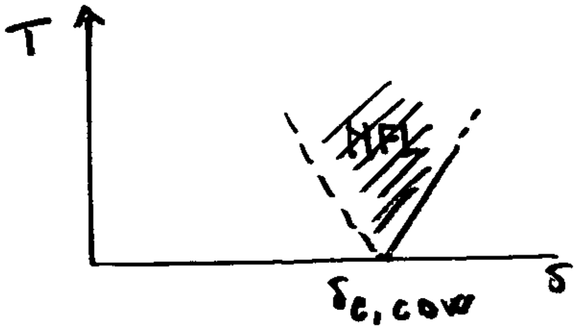
to be compared with

$\omega_{q,SDW} \simeq 2 + \cos q_x + \cos q_y$

(nesting effect)

Strong scattering near CDW is "more" generic

(cf Hlubina and Rice ('95 criticism to $\rho \sim T$ in AF theory)



Proximity to incommensurate CDW

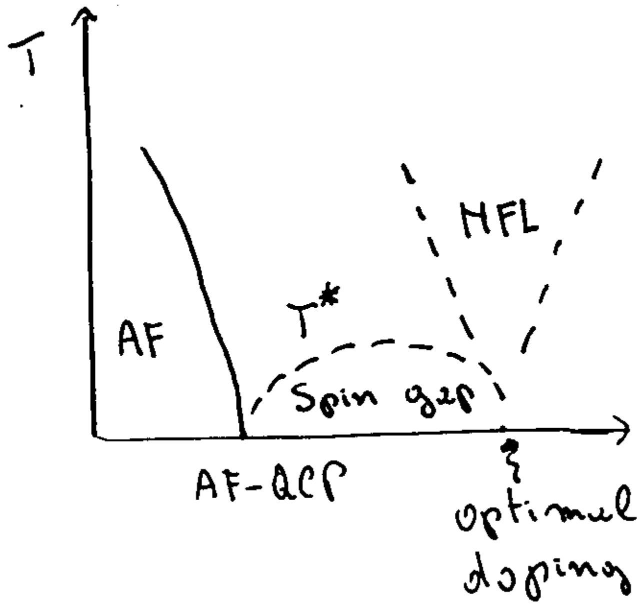
▨ non Fermi Liquid above the order-disorder transition (QCP) at $\delta_{c,CDW}$

※ Evidences for CDW in cuprates { various } not conclusive yet

※ relation with AF

CDW: unmotivated "variation" of AF-QCP ?

Barzykin and Pines (95) (see also Sachdev and Ye, 92)

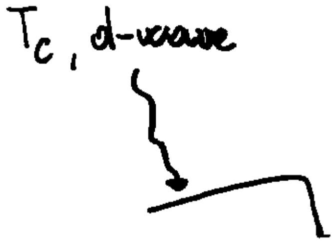


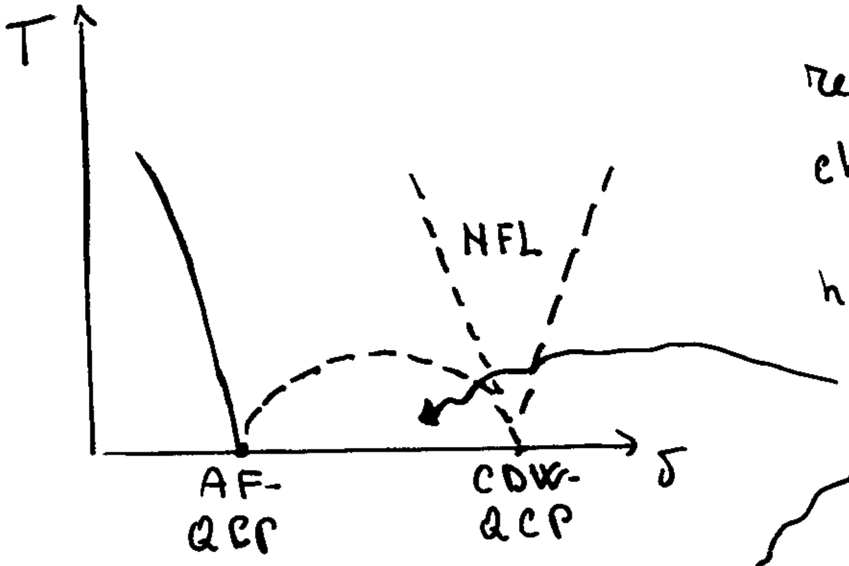
1. Optimal T_c (and "optimal" non Fermi Liquid) is <u>not</u> above the AF-QCP
2. Spin-gapped phase $T<T^*$, metallic

AF - paramagnetic metal

? dynamical index $z=2$
no spin gap

(Sachdev et al 95)


T_c, d-wave



region $T < T^*$:
charge dishomogeneity

hole rich, hole poor stripes

"ordered" phase for charge, "disordered" for spin

order on a mesoscopic scale or slow dynamical fluctuation

⁂ CDW supports extension of AF-fluctuations away from AF-QCP
⇓
(in the hole poor stripe

⇒ spin gap ("finite" system analogy Emery and Kivelson (93))

existence of charge stripes makes reasonable the picture of the spin disordered phase in terms of resonant singlets (cf non-linear σ-model)

dynamical index $z = 1$? reduction of particle-hole spin scattering

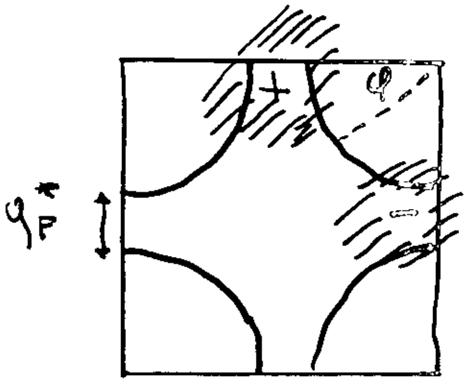
⁂ Non Fermi Liquid above a QCP (CDW)

⁂ in correspondence with the optimal T_c for superconductivity

Proximity to CDW

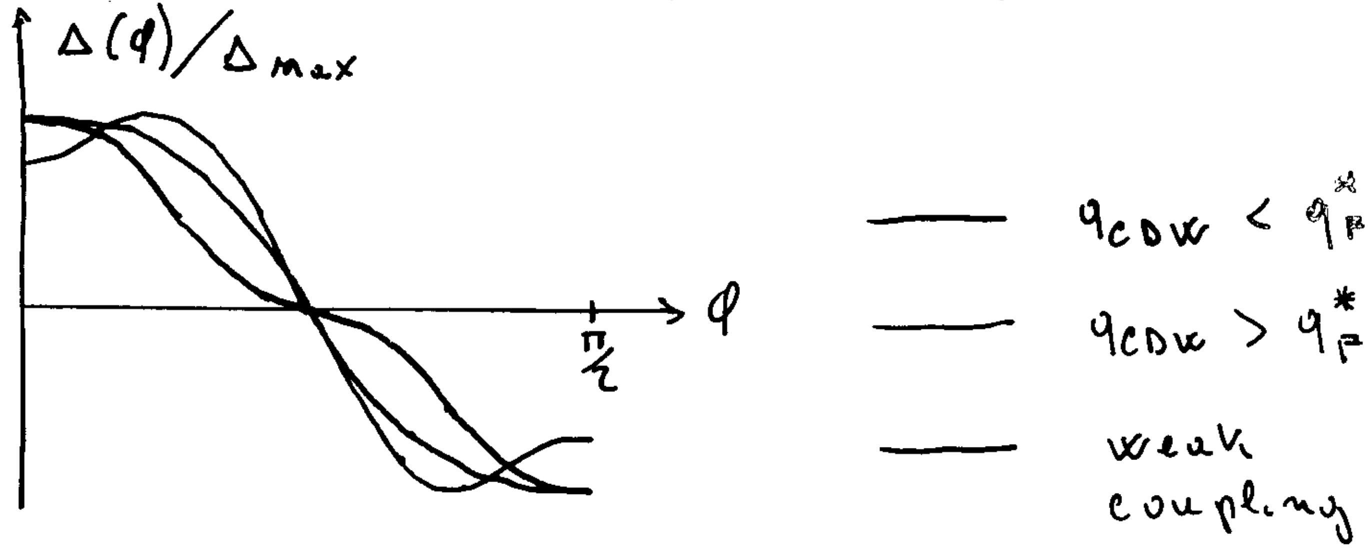
$$V_{\text{pairing}} = \Gamma_{\text{eff}}(\omega=0)$$

$$\simeq -\frac{V}{(\vec{q}-\vec{q}_{CDW})^2+\varkappa^2} + U$$



Pairing : d-wave

interplay between high density of states (around $(\pm\pi,0)$, $(0,\pm\pi)$), attraction at (small) q_{CDW}, repulsion at large q $\langle H_I\rangle = V_{kk'}\Delta_k\Delta_{k'}$

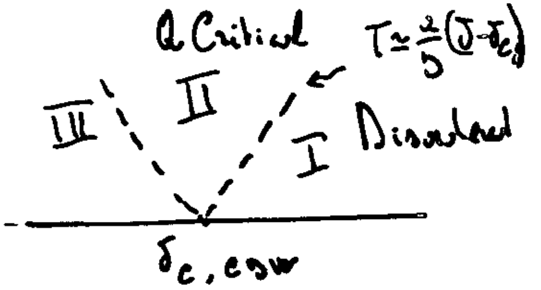


local minima : specific feature of relevant q-structure of V_{pairing} at finite $q\,(\neq(\pi,\pi)\,?)$

weak coupling : flat region around $\varphi \simeq \frac{\pi}{4}$

Superconducting critical temperature near charge instability (CDW) $V_{pairing} \simeq -\frac{V}{(\vec{q}-\vec{q}_{CDW})^2+\varkappa^2} + U$

$T_c(\delta) \equiv T_c(\varkappa^2, \text{band parameters})$



$\varkappa^2(\delta,T) \simeq \max\left(a(\delta-\delta_{c,CDW}), bT\right)$

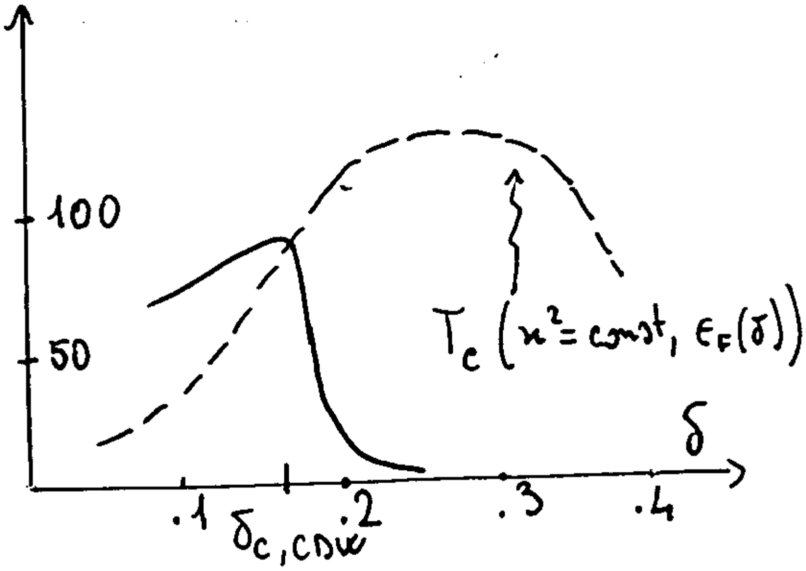
(Millis PRB 93)

- $\varkappa^2 \simeq \varkappa^2(\delta)$ in I : strong variation of T_c with δ
- $\varkappa^2 \simeq \varkappa^2(T)$ in II (and in III if not real charge order): smooth variation of T_c

maximum T_c at optimal doping $\simeq \delta_{c,CDW}$

$$T_c^{max} \simeq T_c\left(\varkappa^2(\delta_{c,CDW}, T_c)\right)$$

<u>not</u> at δ_{VH}, i.e. when ϵ_F = Van Hove singularity



band parameters: Bi-2212

interaction param.

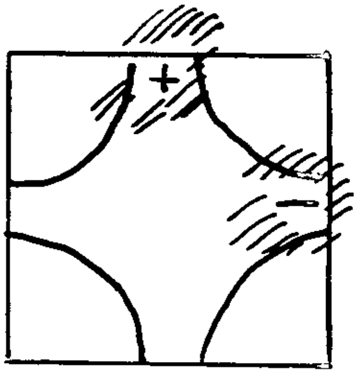
$$\begin{cases} q_{CDW} \simeq 1 \\ V \simeq 0.1 \text{ eV} \end{cases}$$

$\varkappa^2(\delta_{c,CDW}, T_c) \simeq 0.1$

Proximity to PS

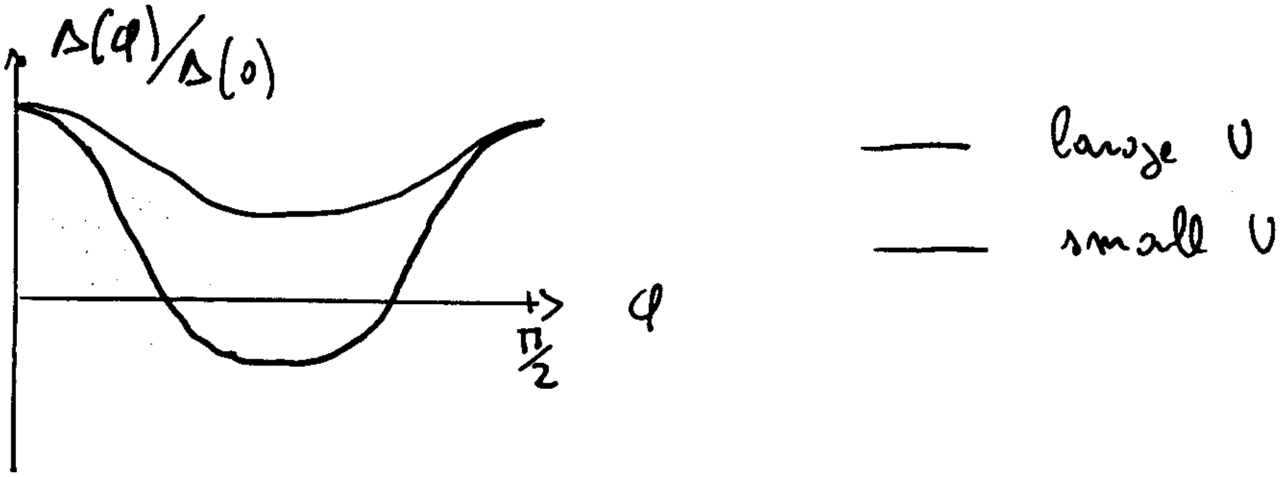
$$V_{\text{pairing}} = \Gamma_{\text{eff}}(\omega = 0) \simeq -\frac{V}{q^2+\kappa^2} + U$$

Pairing : d-wave



large attraction $k-k' = q \simeq 0$
(momentum decoupling,
Abrikosov 95, Varelogiannis et al 96) vs repulsion at large q

Also anisotropic s-wave



However d-wave has lower energy for
$U > U^* \simeq .1 - .05\ t$

* no change of sign for $U < U^*$
(see also Abrikosov 95)

Experimental evidences for CDW in cuprates

- CDW in the related compound $La_{2-x-y} Nd_y Sr_x CuO_4$ $x=.12; y=.4$

  Tranquada et al, Nature 95

  see also $La_{2-x} Ba_x CuO_4$ at $x = \frac{1}{8}$

$\Rightarrow$ when CDW is pinned (commensurate) the system becomes semiconducting

- PS in $La_2 CuO_{4+y}$ (Jorgensen et al (88))

  mobile oxygen allows for charge segregation

- Superstructures in Bi- and Tl-compounds

  usually: out of plane / "insulating" planes

$\Rightarrow$ superstructures in CuO_2-planes also?

$La_{1.85} Sr_{0.15} CuO_4$: Bianconi et al PRL 76, 3412 (96)

Exafs, (π, π) direction, $\lambda \simeq 6a$

for $T \leq 100K$

ordered/disordered domains

static / dynamic

relevance of deformations, of fluctuations

Conclusions

- proximity to a charge instability (CDW): singular scattering leading to a non Fermi Liquid
- scenario for cuprates: spin disordered phase (gapped) $\Longleftrightarrow$ charge "ordered" phase
- optimal doping in correspondence of CDW-QCP $\Longleftrightarrow$ highest T_c where "best" non Fermi Liquid behavior

Still needed

* conclusive experimental evidence for stripe superstructure

static (ordered vs disordered domains)

dynamic