On the pseudogap model in...

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in collaboration with

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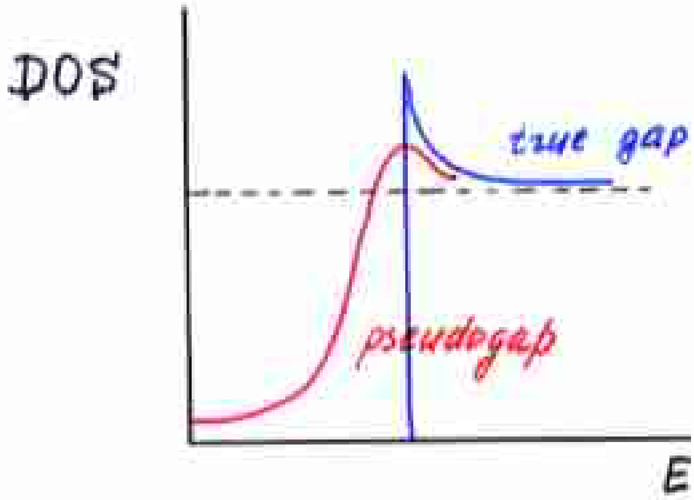
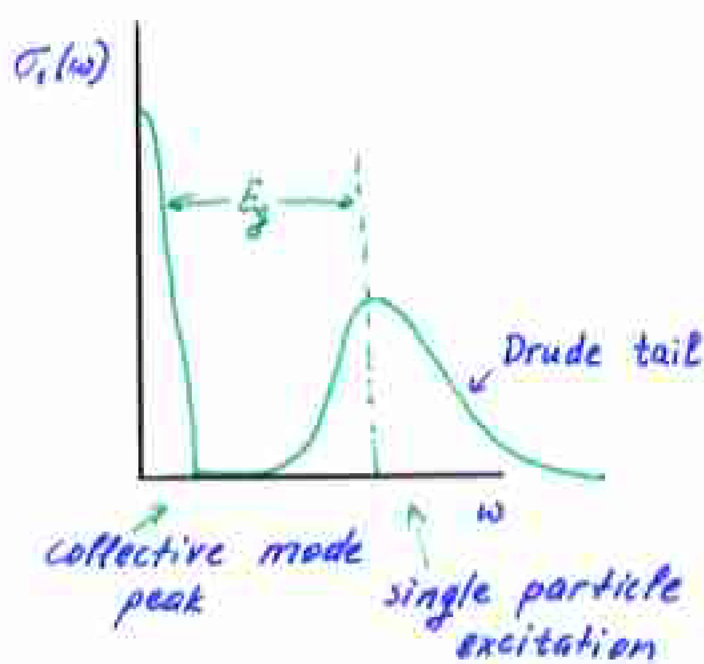
Plan

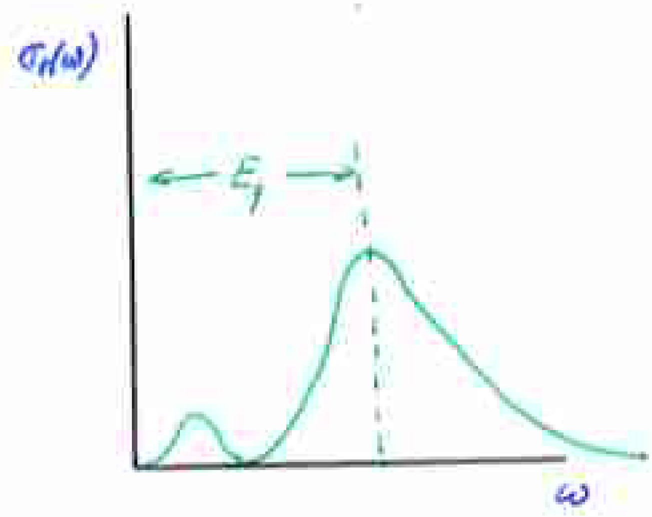
1. Unavoidable experimental overview
2. FGM - $\simeq 30$ years of history
3. Toy model of the pseudogap in cuprates
4. Effective action appoach $\to$
   issues of a "quenched" average
5. Conclusions



Back to 70-th

e.g. conductivity of 1D Peierls-Fröhlich conductor





Indeed observed in TTF-TCNQ (IR study)
(tetrathiofulvalene - tetracyanoquinodimethane)

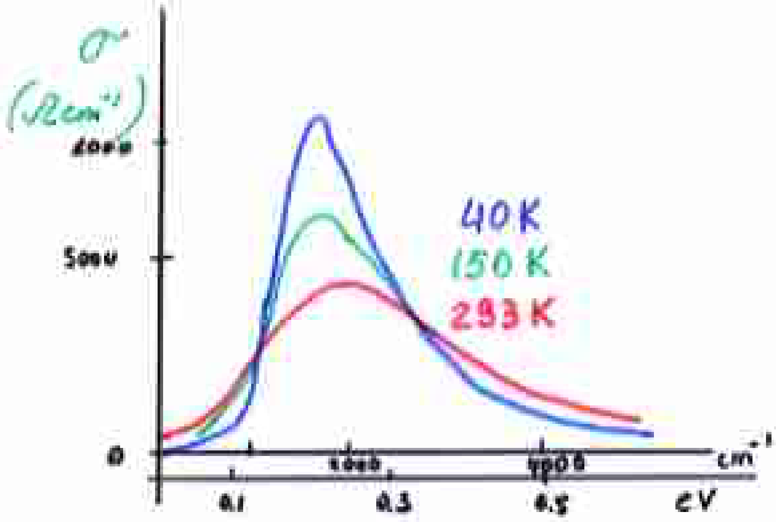
in $\sigma(\omega)$ & dielectric function

(Tanner et al. PRB 13, 3381 (1976)

Another example -

spectroscopical study of the Peierls transition in KCP ($K_2 Pt(CN)_4 Br_{0.3} \cdot 3(H_2O)$)

optical conductivity



Brüesch et al
PRB 12, 219 (1975)

Models with a true gap - incompatible with the observations

Most promising -
idea of a pseudogap at the FL due to coupling of the electrons to a soft phonon of $2k_F$

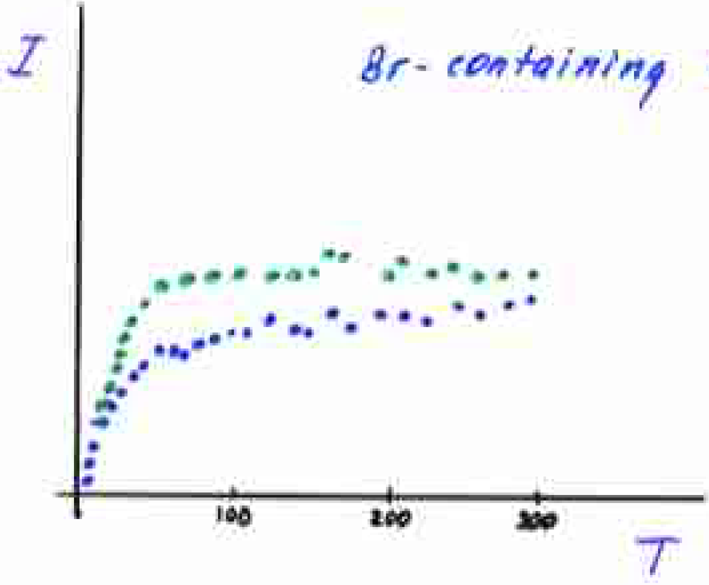
More recent examples

OLS $\varkappa - (ET)_2 X$

($\varkappa$ - (BEDT-TTF)$_2$ Cu [N(CN)$_2$]Cl $T_c = 12.5$ K, $P = 0.3$ kbar
quasi 2D

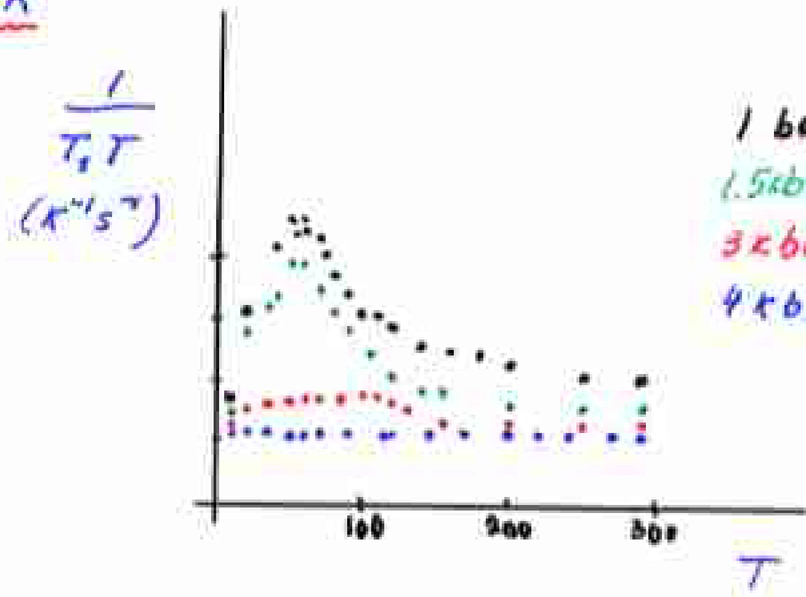
ESR , I - integral intensity ~ static magnetic susceptibility

Br-containing salt



Kataev et al
Solid State Comm. 83, 435 (1992)

NMR



Mayaffre et al.
EPL 28, 205 (1994)

Knight shift, $1/T_1T$ - similar to $YBa_2Cu_3O_{6.63}$

higher pressure - more usual metallic behavior

TMD - transition metal dichalcogenides

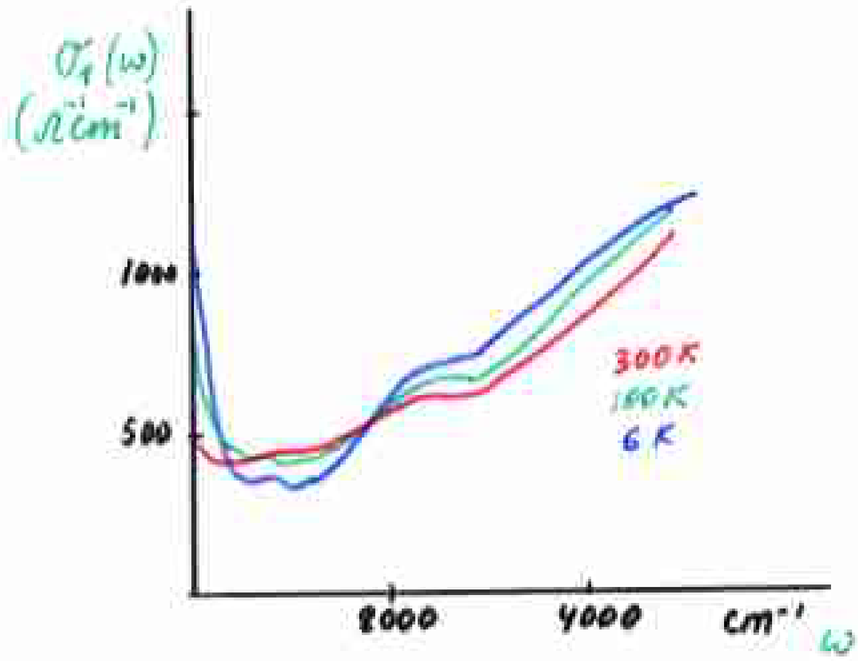
2H - MX_2

$M \to$ Ta, Nb; $X \to$ S, Se

2D, layered

optical response of 2H-$TaSe_2$

(Ruzicka et al, PRL **86**, 4136 (2001))



progressive development of pg like feature with T decreasing

also: resistivity & susceptibility - qualitatively similar to those of HTS

HTSC

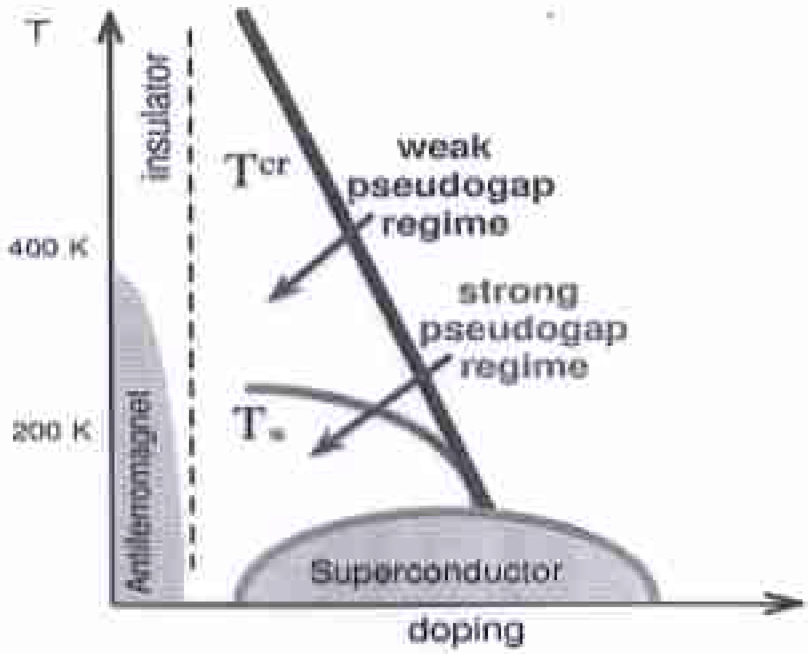


FIG. 1. Phase diagram of cuprates.

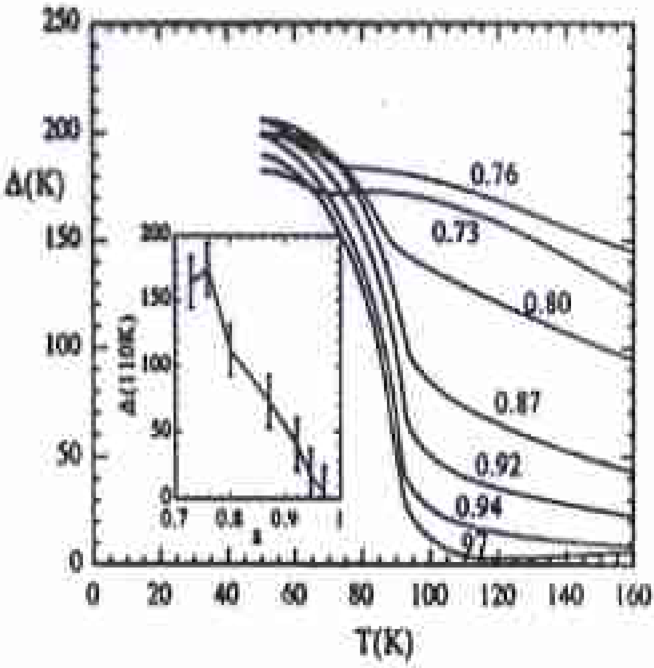


FIG. 2. Temperature dependence of the energy gap for $YBa_2Cu_3O_{6+x}$ samples from specific heat measurements, (Loram et al, 1994).

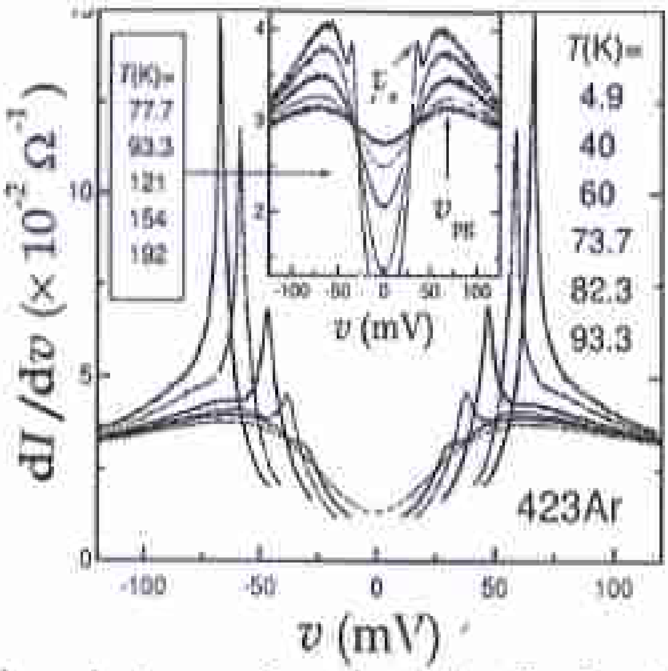


FIG. 3. Differntial conductance of nearly optimally doped Bi-2212, (Krasnov et al, 2000)

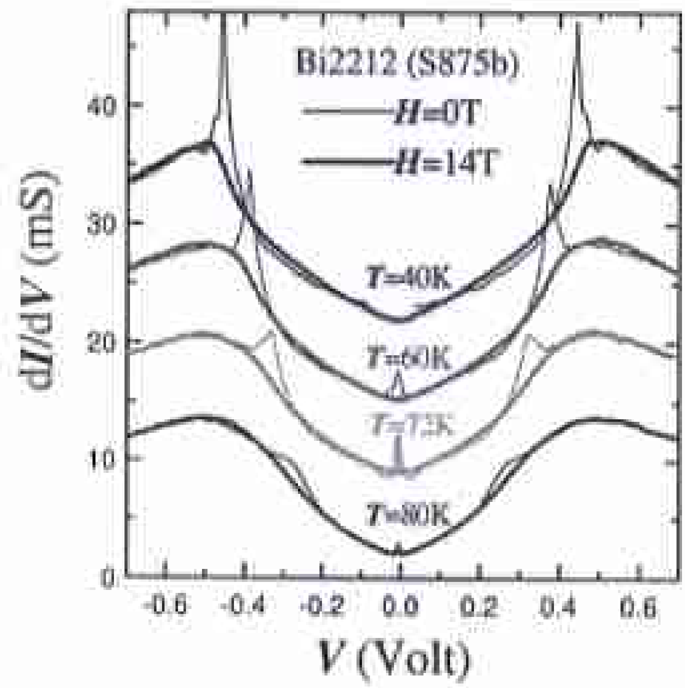


FIG. 4. Differential conductance in magnetic field, (Krasnov et al, 2000).

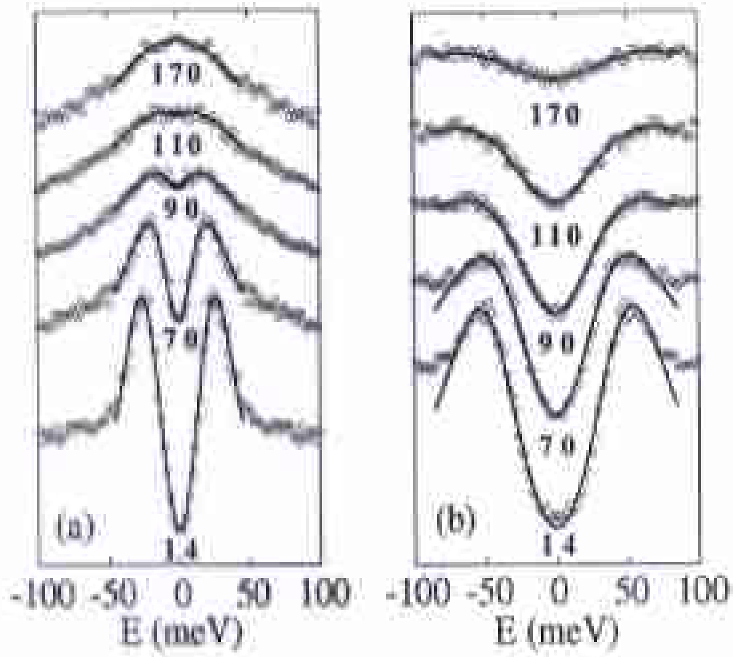


FIG. 5. ARPES spectra for overdoped Bi-2212 with $T_c = 82K$ (a) and underdoped sample with $T_c = 83K$ (Norman et al, 1998).

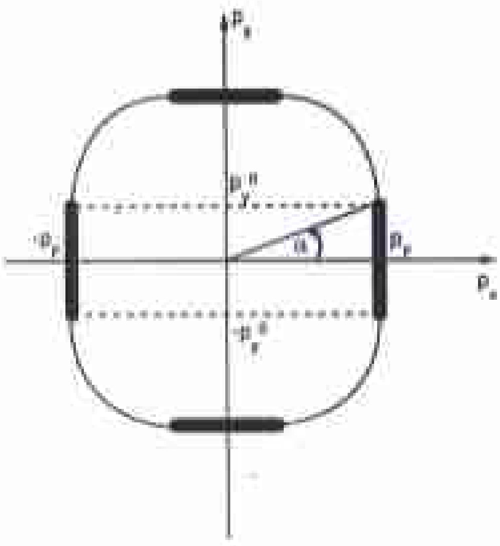


FIG. 6. Fermi surface in the model of "hot" regions

Theory : historical overview

Lee, Rice, Anderson (1973) – FGM
(fluctuation gap model)

OP fluctuations => suppression of DOS

1D Peierls chain

$$H = \sum_{p\sigma} \epsilon_p c^+_{p\sigma} c_{p\sigma} + \sum_q \omega_q b^+_q b_q + \sum_{p\sigma q} g(q)\, c^+_{p+q\sigma} c_{p\sigma} (b_q + b \dots$$

=> $2k_F$ instability =>

gap at T_p (static CDW)

remnant of the gap at $T > T_p$ = pseudogap
(Mott '74)
due to fluctuations

BUT : Σ → 

=> approximate solution

M. Sadovskii (1974)

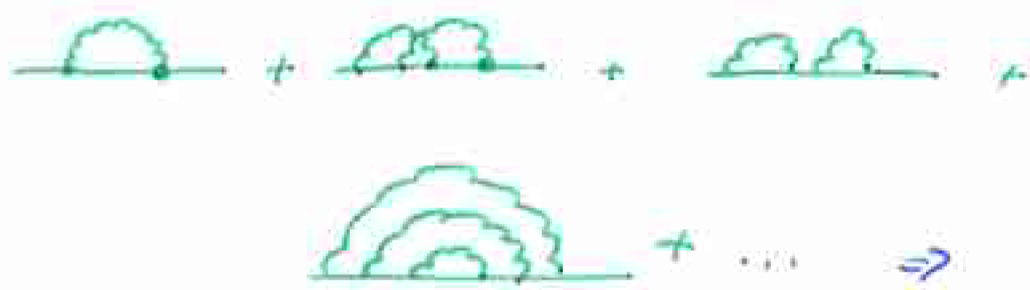
fluctuations : Gaussian, static
(≡ classical approx)

in the limit $\xi \to \infty$ (ξ - correlation length)
+ incommensurate case $\Rightarrow$
exact solution

effective interaction

$$V_{eff} \sim \Delta_{pg}^2 \cdot S(q) \; ; \; S(q) \sim \delta(q \pm 2k_F)$$

$\Sigma \to$



one-electron Green's function

$$G(\varepsilon \xi_p) = \int_0^\infty dz\, e^{-z} \frac{i\varepsilon_n + \xi_p}{(i\varepsilon_n)^2 - \xi_p^2 - z\,\Delta_{pg}^2}$$

$\Downarrow$

DOS, spectral density...

Price : • interaction is infinitely retarded
• fully renormalized
• no interaction in between the classical fluctuations

Schmalian, Pines, Stojković (1998)

extension of the model to 2D + spins

O. Tchernyshyov (1998)

1D model with finite ξ revisited
finite correlation length problems

Millis, Monien (1999)

comparison of different approaches to the pseudogap problem
'FLEX', WKB approx. etc.

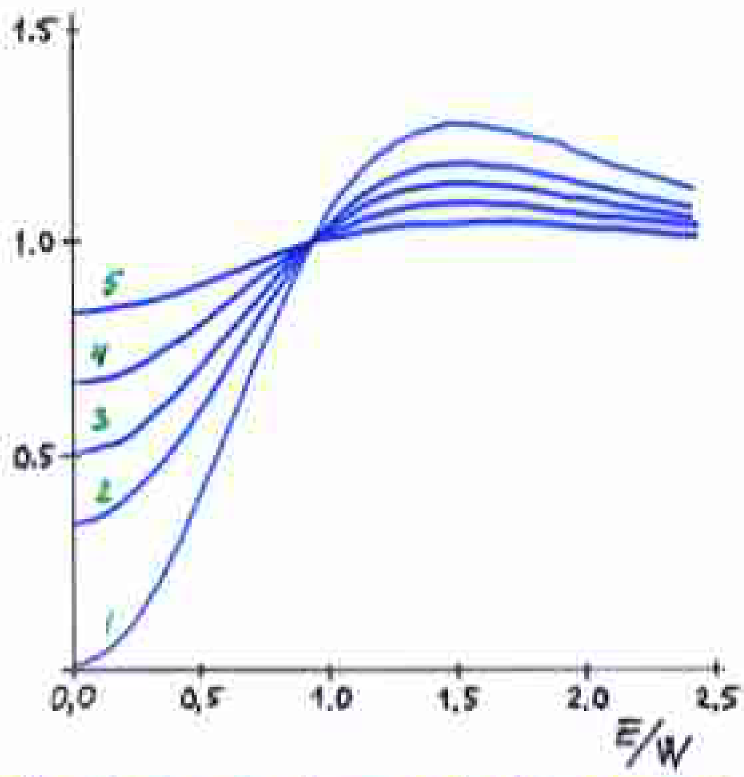
conclusion: Sadovskii model for finite ξ – reasonably good approx.

Bartosch, Kopietz (2000)

- tricky exact solution of finite correlation length model

Results of toy-model of the pseudogap

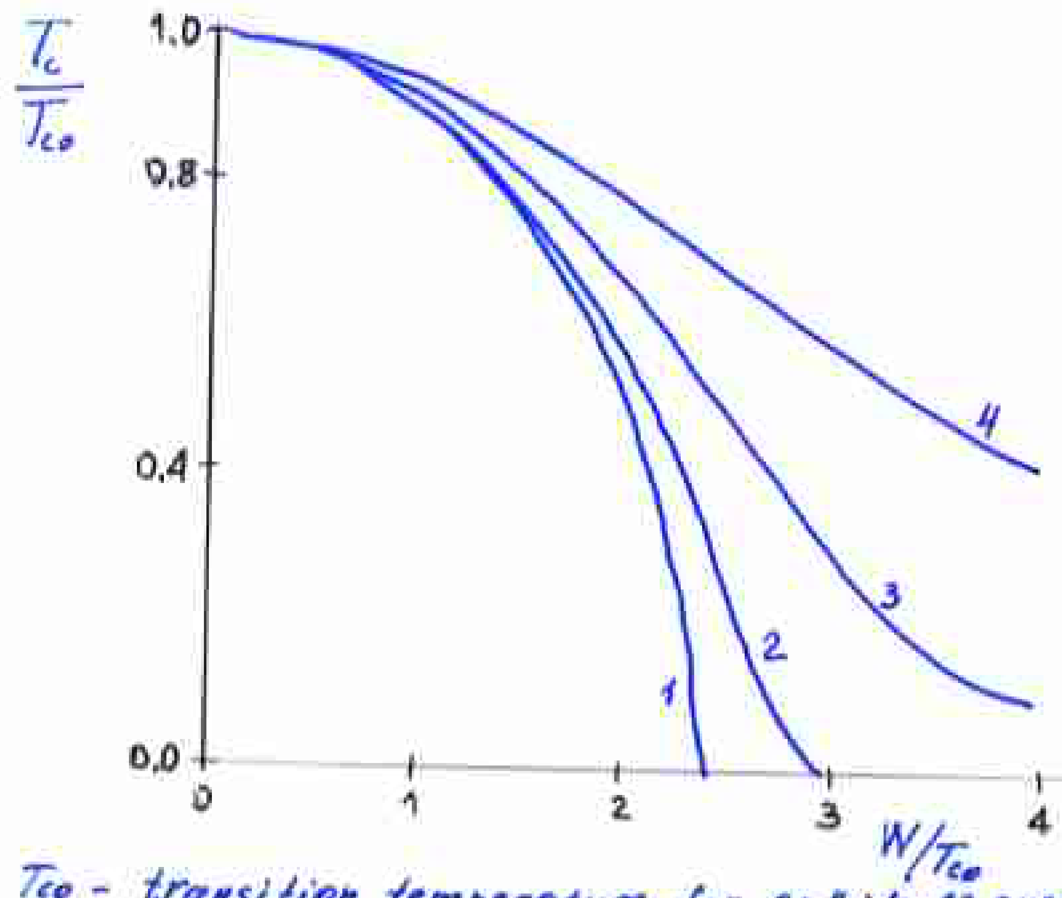
Electronic DOS for "hot" regions of different size



α:
1 → π/4;
2 → π/6;
3 → π/8;
4 → π/12;
5 → π/24.

N(0) - DOS of free electrons at the FL

T_c - dependence for "hot" regions of different sizes, incommensurate case, d-wave pairing



α:
1 → π/4
2 → π/6
3 → π/8
4 → π/12

T_{c0} - transition temperature for an "ideal" system without pseudogap

Basic idea

FGM: OP fluctuations – classical, time-independent =>

distribution of gap sizes

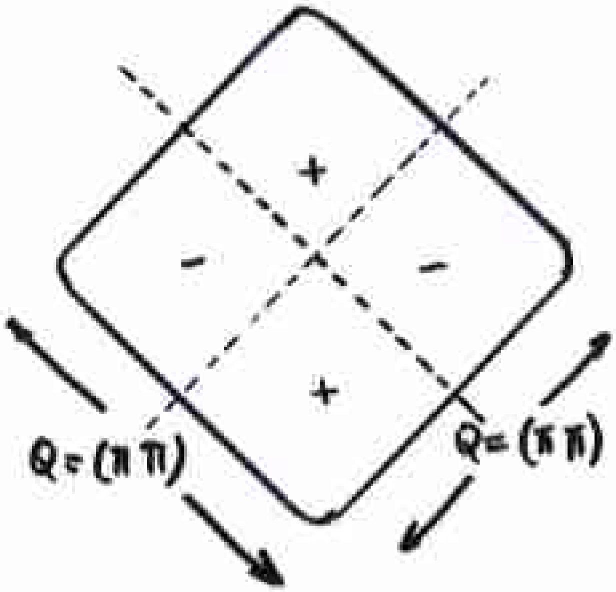
=>

? origin of this kind of distribution?

pseudogap modes – source of quenched (frozen in) disorder=>

quenched-averaged free energy etc.

Nested F.S.



Pairing in the presence of a pseudogap

quenched average Free energy

$$F = \frac{1}{\sqrt{2}} \int_{-\infty}^{\infty} dz\, e^{-z^2/2} \Big\{ -2T \sum_{n,\, k \in \frac{1}{2} Bz} \ln \big(\omega_n^2 + \epsilon_{k+Q/2}^2 + \Delta_{k+Q/2}^2 + (z w_k)^2 \big] + \frac{\Delta^2}{g} \dots$$

$$\frac{\partial F}{\partial \Delta} = 0 \Rightarrow T_c\text{-equation}$$

$$H[\phi] = H_0 + W \sum_{qk} c^+_{k-q} c_k \phi_q$$

classical field of OP fluctuations

distribution function

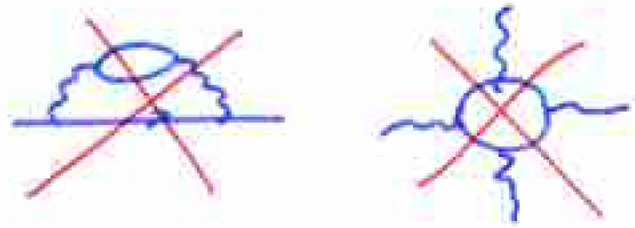
$$P[\phi] = e^{-\beta \sum \frac{\phi_q \phi_q}{2S(q)}} \Rightarrow$$

effective interaction

$$V_{eff}(q) = -W^2 S(q)$$

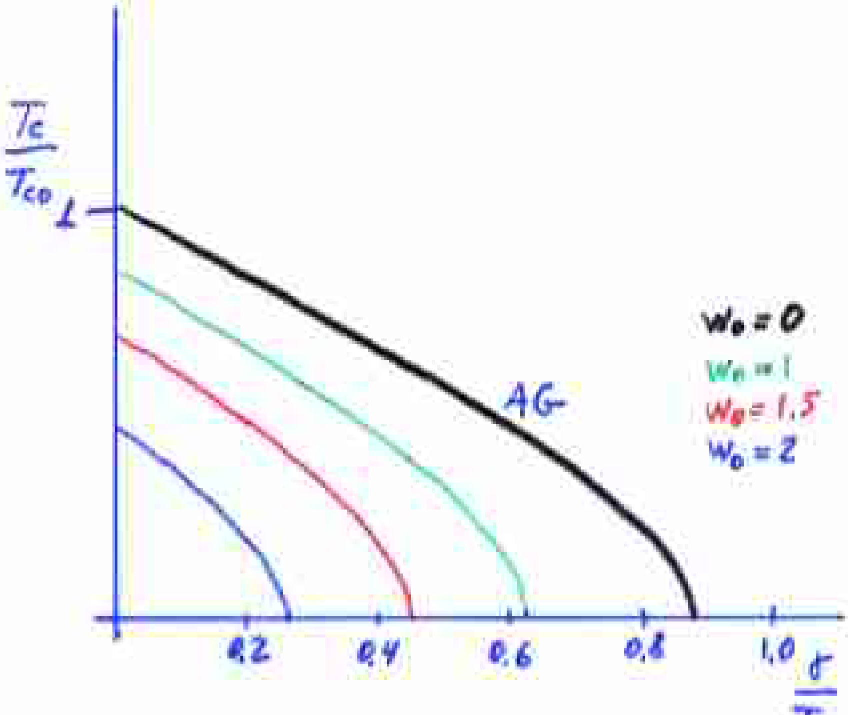
average over $P[\phi]$

partition function ? free energy

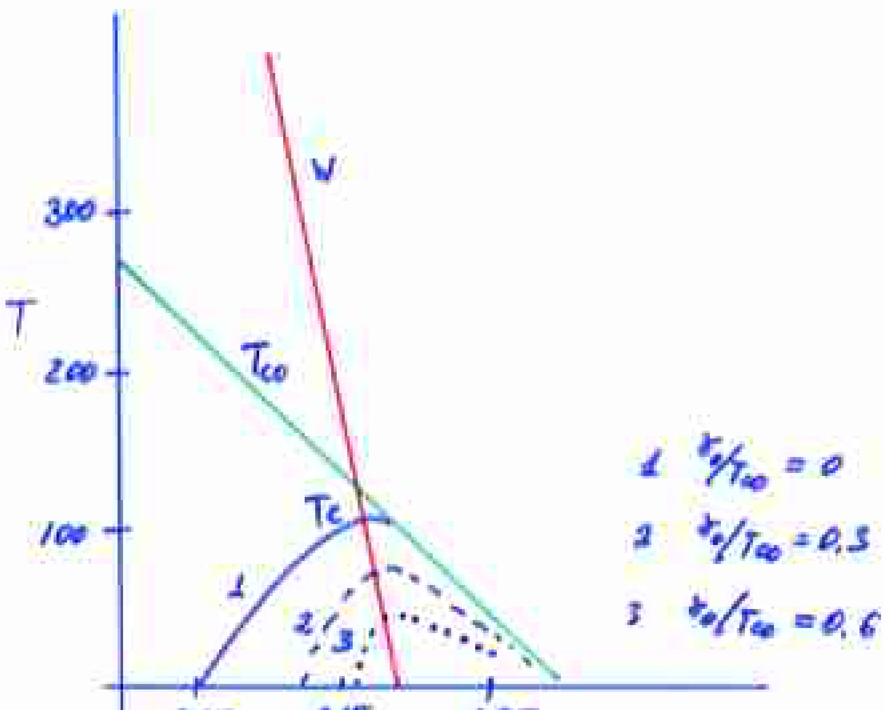
but  $\Rightarrow$

quenched average

$$F = -T \int P[\phi] \ln Z[\phi]$$



T_c vs impurity scattering



Toy phase diagram

Finite correlation length

Kopietz et al. approach

$$\Psi(x) = A\, e^{i\vec{Q}\vec{x}}$$

$A \to$ Gaussian random variable

$Q \to$ Lorentzian distribution $\Rightarrow$

$$F = -2T \int dz\, e^{-z}\ \mathrm{Tr}\ \ln\left[\tilde{\omega}_n^2 + (\epsilon_{k+Q/2})^2 + 2z W^2\right]$$

$$\downarrow$$

$$\omega_n + \frac{v_F}{2\xi}\omega_n$$

effect of finite corr. length ~ elastic impurity scattering potential

Conclusions

1. Nice phenomenological model of a system with a pseudogap

2. Large class of treatments of the pg problem may be formulated in terms of quenched average

Problems:

- no frequency dependence in the fluctuations
- classical modes are strictly non interacting