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Signatures of the precursor superconductivity above T_c

T. DOMANSKI

M. Curie-Skłodowska University,

20-031 Lublin, Poland

http://kft.umcs.lublin.pl/doman

Outline

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- **Introduction**

/ pairing in the many-body systems /

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$\Rightarrow$ *basic properties*

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$\Rightarrow$ *description of pair fluctuations above* T_c

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$\Rightarrow$ *results for ARPES, STM and collective phenomena*

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- **Introduction**

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- **Conventional superconductors**

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- **HTSC cuprates**

  basic properties

  description of pair fluctuations above T_c

  results (ARPES, collective features, etc)

- **Summary**

I. Introduction

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Very often formation of the fermion pairs goes hand in hand with **superconductivity/superfluidity** but it needs not be the rule.

Hamiltonian of the pairing interactions

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The momentum representation:

$$\hat{H} = \sum_{\mathbf{k},\sigma} \xi_{\mathbf{k}} \hat{c}^{\dagger}_{\mathbf{k}\sigma} \hat{c}_{\mathbf{k}\sigma} \; + \sum_{\mathbf{k},\mathbf{k}'} V_{\mathbf{k},\mathbf{k}'} \; \hat{c}^{\dagger}_{\mathbf{k}\uparrow} \; \hat{c}^{\dagger}_{-\mathbf{k}\downarrow} \; \hat{c}_{-\mathbf{k}'\downarrow} \hat{c}_{\mathbf{k}'\uparrow}$$

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The real space representation:

$$\hat{H} = \sum_{i,j} \sum_{\sigma} t_{i,j} \hat{c}^{\dagger}_{i\sigma} \hat{c}_{j\sigma} + \sum_{i,j} V_{i,j} \; \hat{c}^{\dagger}_{i\uparrow} \; \hat{c}_{i\uparrow} \; \hat{c}^{\dagger}_{j\downarrow} \hat{c}_{j\downarrow}$$

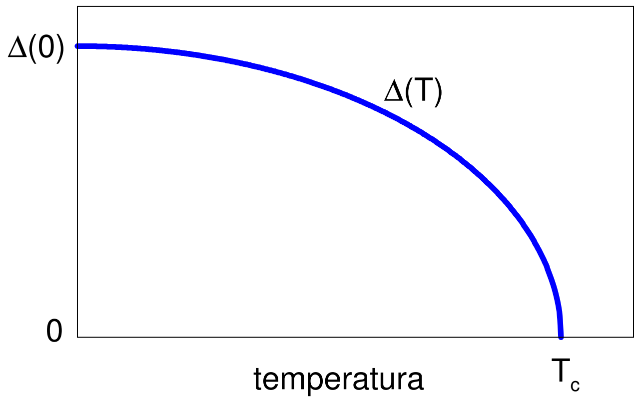
with attractive potential $V_{i,j} < 0$

II. Conventional superconductors

Major property

Major property

Pair formation and onset of their coherence coincide at T_c



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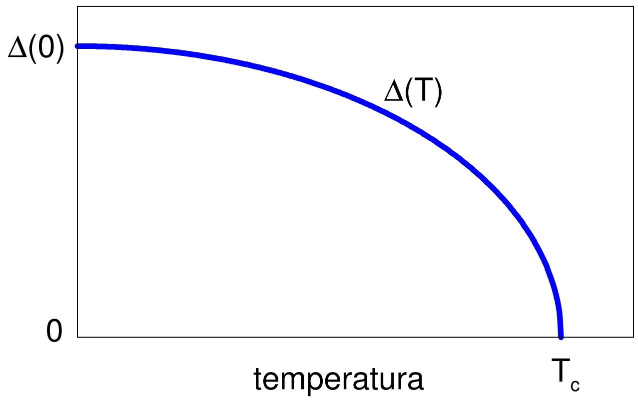
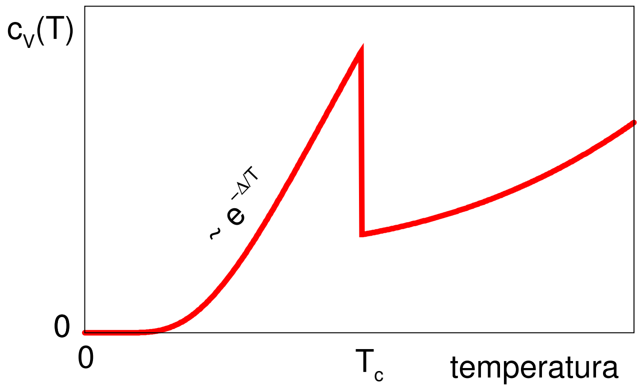


Pairing is responsible for the gap in the single particle spectrum

The order parameter $\longrightarrow$ 2-nd order phase transition



/ as classified by Landau /

Pair fluctuations

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Possible sources:

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1. **quantum fluctuations**

$$\hat{A}\hat{B} = \hat{A}\langle\hat{B}\rangle + \langle\hat{A}\rangle\hat{B} - \langle\hat{A}\rangle\langle\hat{B}\rangle + \delta\hat{A}\ \ \delta\hat{B}$$

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2. **topological**

In the low dimensional (dim$\leq$2) systems ODLRO does not establish.

There can appear only the power-law behaviour

$$\langle\hat{\psi}_{\downarrow}(\mathbf{r_1}) \; \hat{\psi}_{\uparrow} \; (\mathbf{r_2})\rangle \;\; \propto \;\; |\mathbf{r_1} - \mathbf{r_2}|^{-\theta(T)}$$

whith the phase stiffness $\theta \neq 0$ for $T \leq T_{KT}$.

J.M. Kosterlitz and P.J. Thouless, J. Phys. C **6**, *1181 (1973).*

Historical remarks: 1

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He predicted smearing of the specific heat jump near T_c but in an extremely narrow temperature region

$$\frac{\delta T}{T_c} \sim \left(\frac{a}{\xi}\right)^4 \sim 10^{-12} - 10^{-14}$$

a – interatomic distance,

ξ – correlation length.

V.L. Ginzburg, Sov. Solid State **2***, 61 (1968).*

Historical remarks: 2

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First experimental observation of the sc fluctuations above T_c has been obtained for **granular aluminium**.

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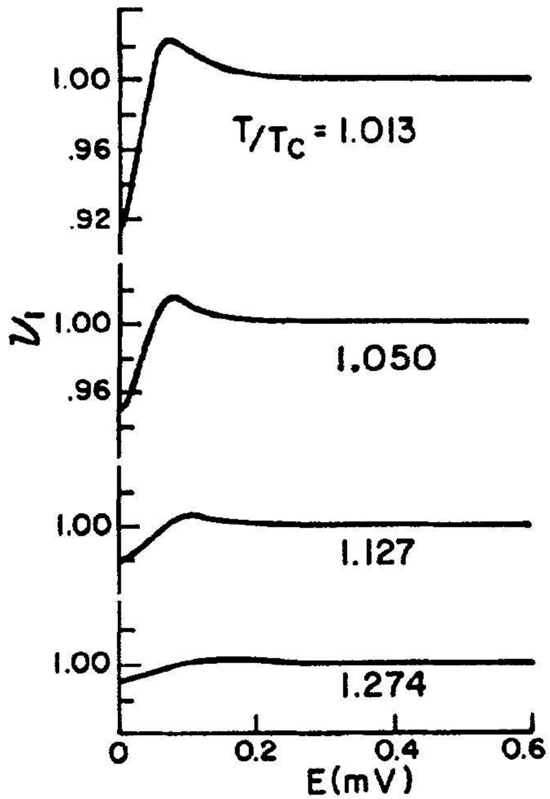

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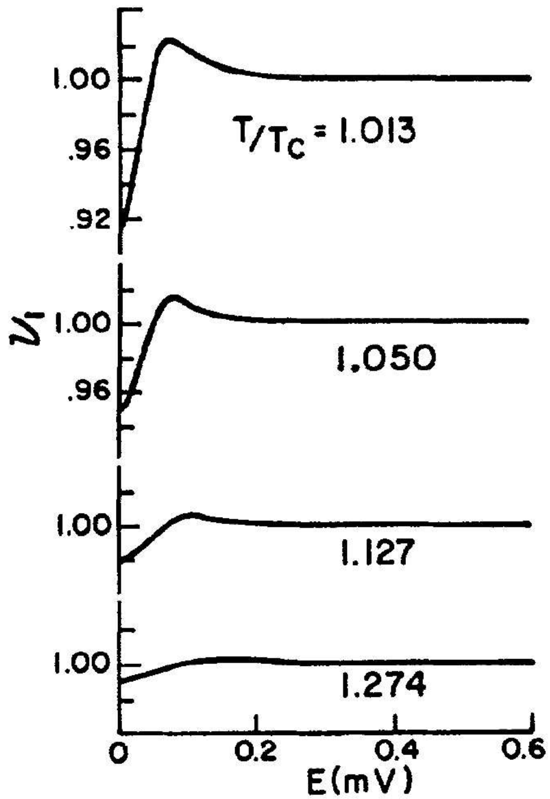

R.W. Cohen and B. Abels, Phys. Rev. ***168****, 444 (1968).*

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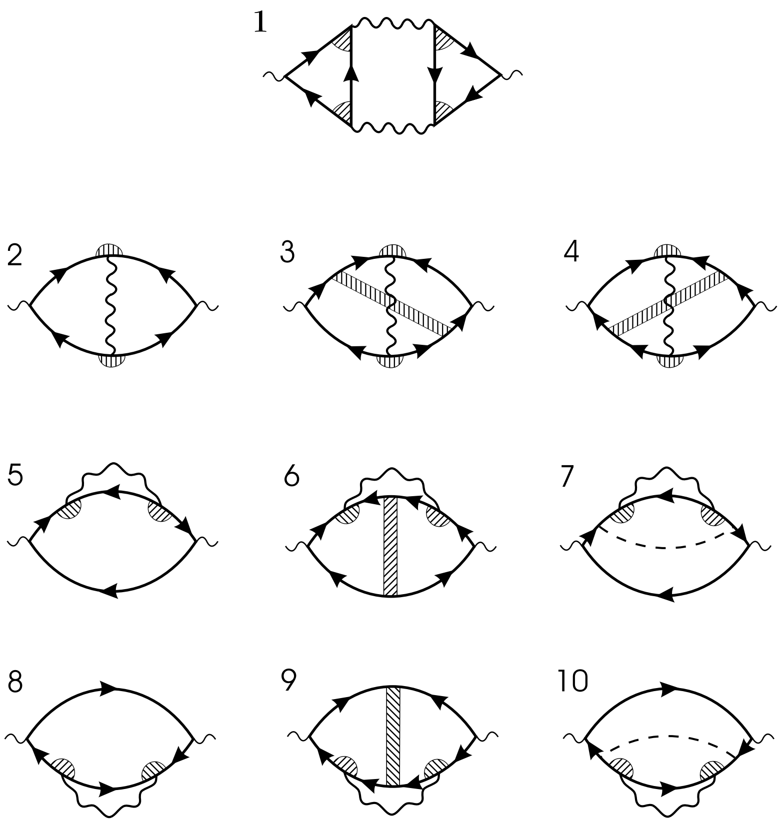

Aslamazov-Larkin

Maki - Thompson

diagrams giving corrections to the density of states

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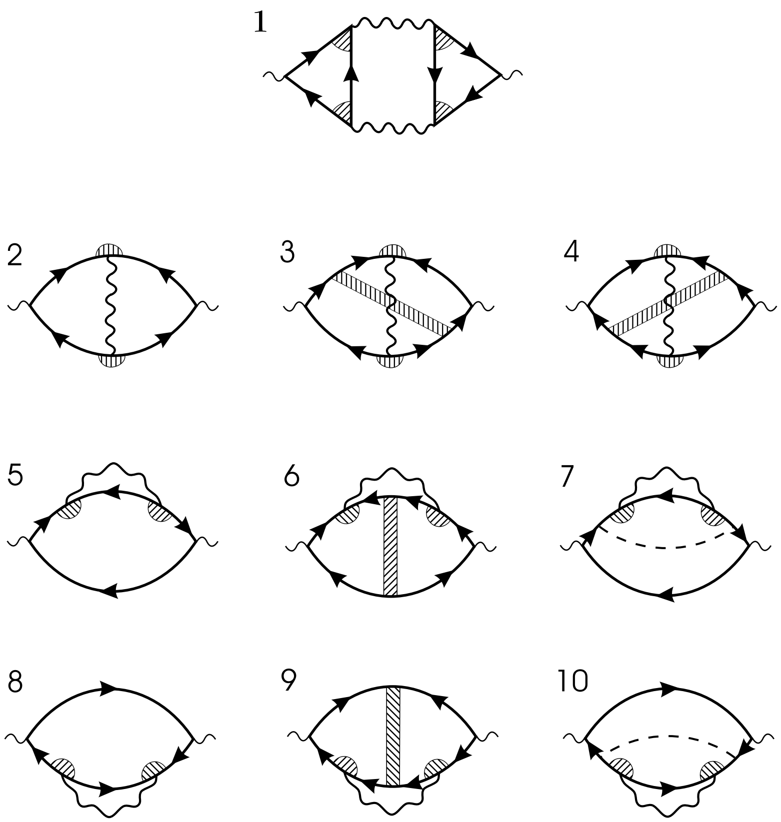


Aslamazov-Larkin

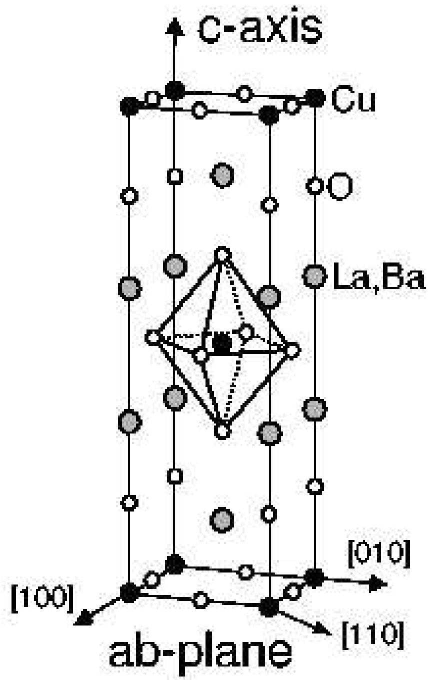
Maki - Thompson

diagrams giving corrections to the density of states

V.V. Dorin et al, *Phys. Rev. B* **48**, *12951 (1993).*

III. HTSC cuprates

1. The parent compounds are quasi-2D Mott insulators



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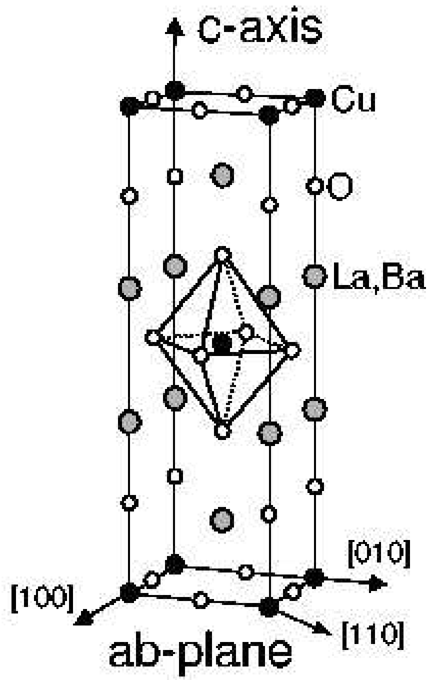

Important remark:

Spatial extent of the pairs is very short $\boldsymbol{\xi_{ab} \simeq 5}$ **Å**

2. Superconductivity appears upon doping by

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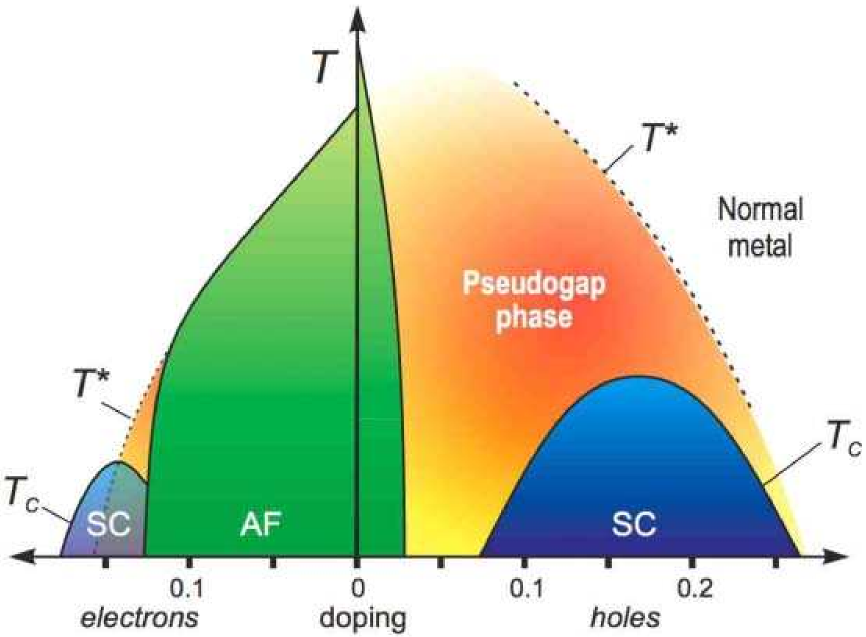

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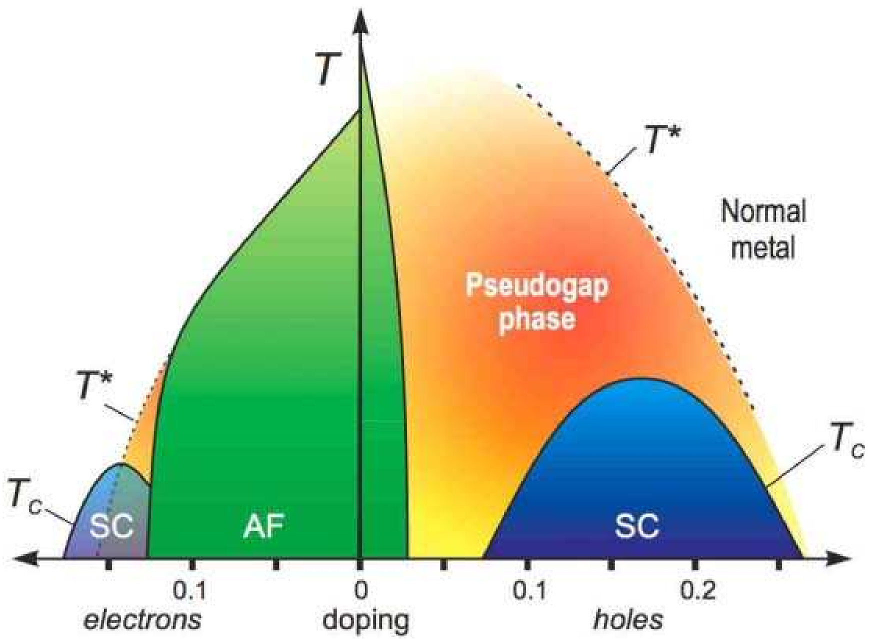

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A puzzle:

Why this diagram is asymmetric ?

3. Inhomogeneities

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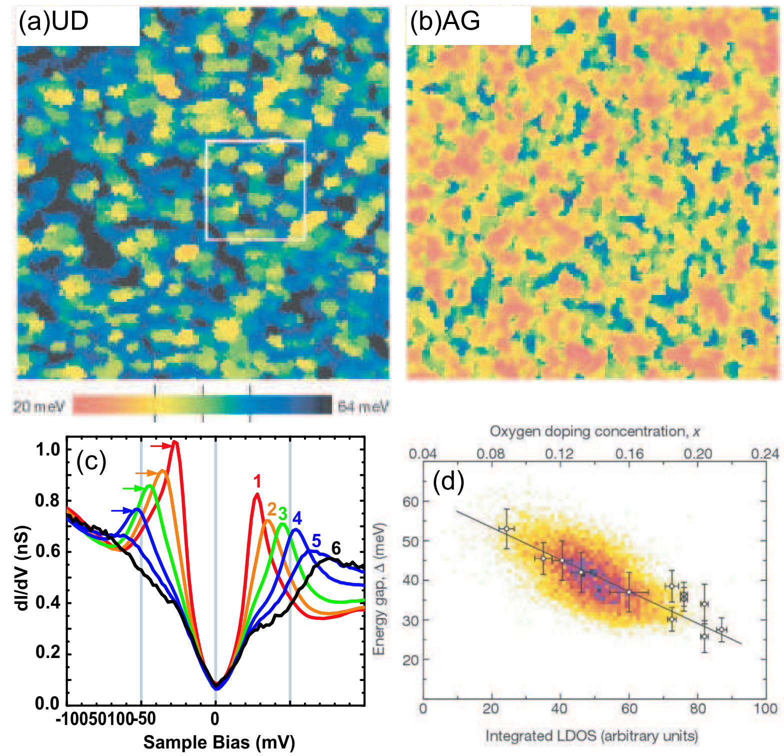
The new STM spectroscopy finds that the energy gap is inhomogenous.

/ K. McElroy et al, *Phys. Rev. Lett.* **94**, *197005 (2005) /*



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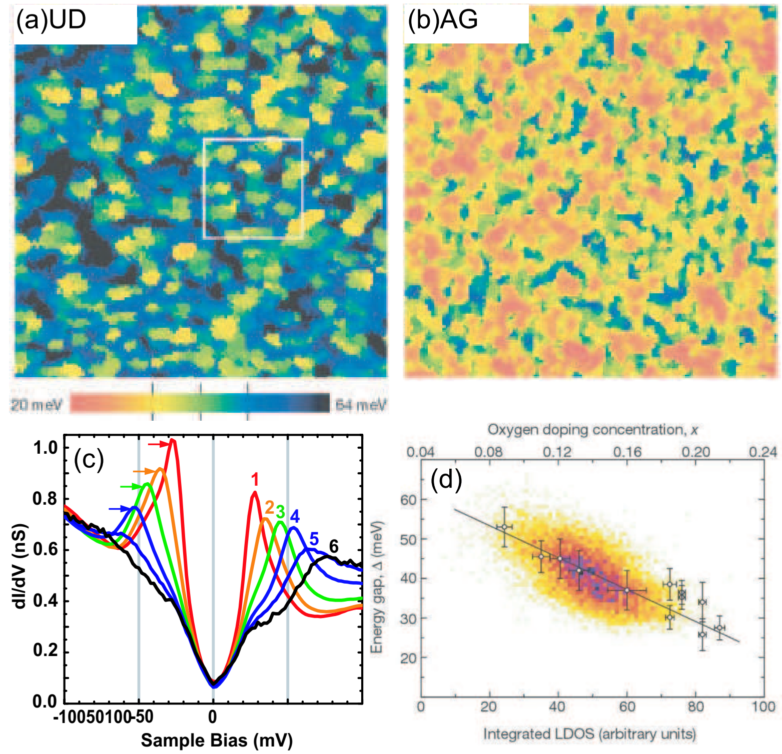

Notice:

Inhomogenous structure promotes the fluctuations

4. Pseudogap

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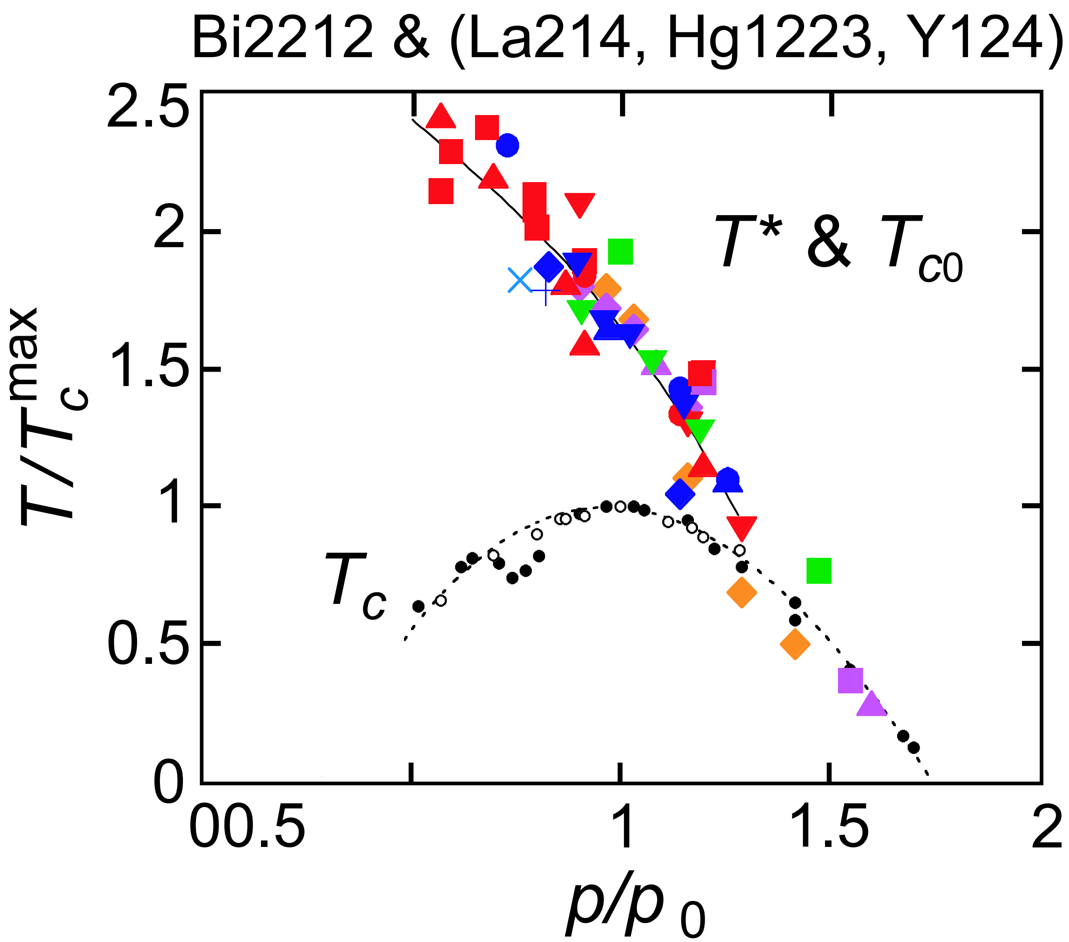
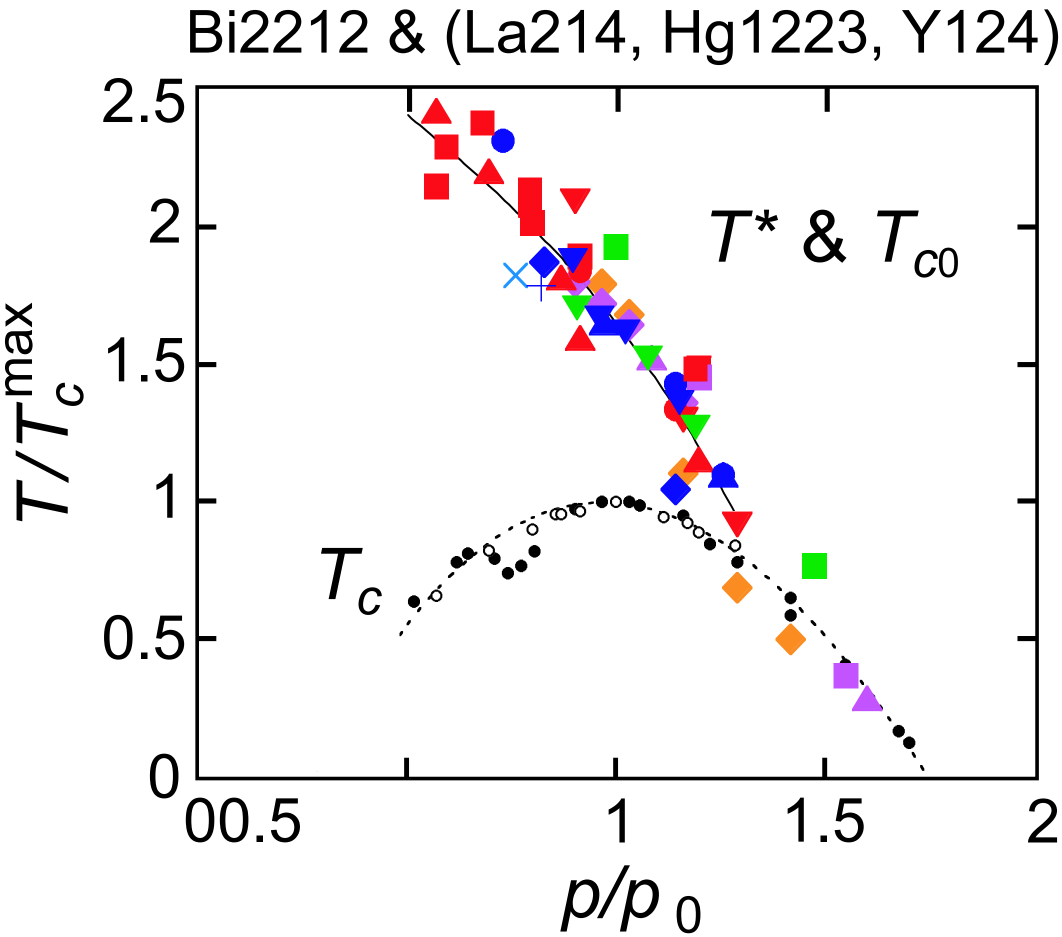


T. Nakano et al, *J. Phys. Soc. Jpn.* **67**, *2622 (2002).*

4. Pseudogap



T. Nakano et al, *J. Phys. Soc. Jpn.* **67**, *2622 (2002).*

What kind of mechanism is responsible for the pseudogap ?

Theoretical concepts

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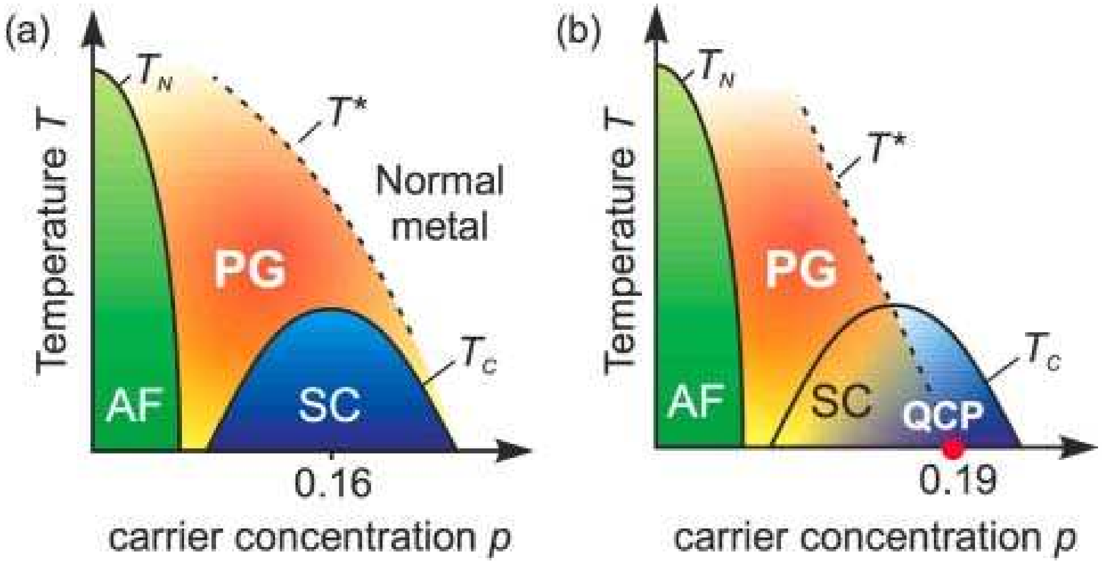

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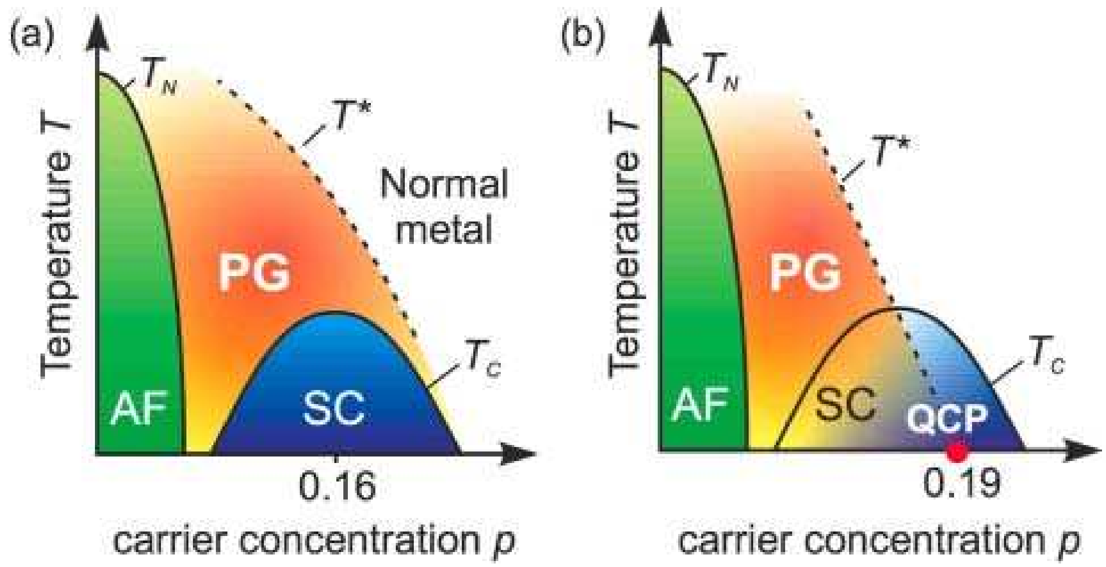
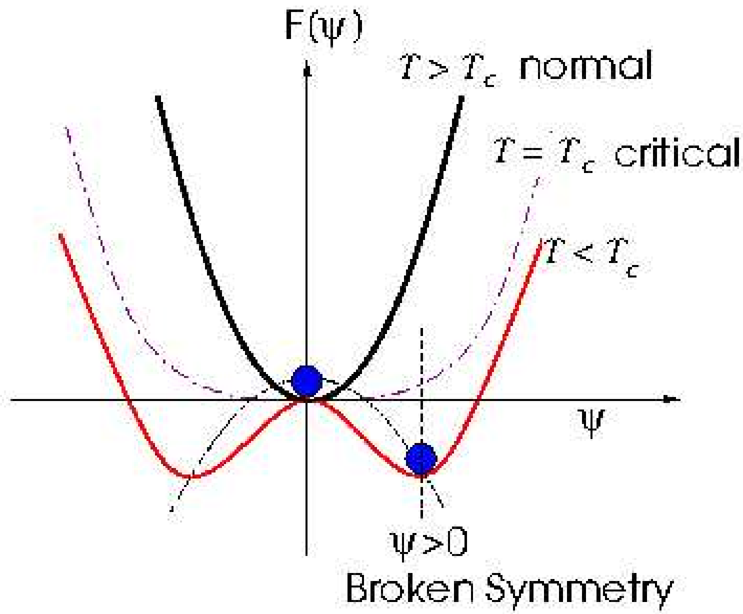


(a) Pseudogap is a ***precursor*** of the superconducting gap which is due to strong fluctuations (because of the reduced dimensionality, local pairing, etc).

(b) Pseudogap is not related to sc gap. It represents some other type of ordering which is ***competing*** with the sc phase.

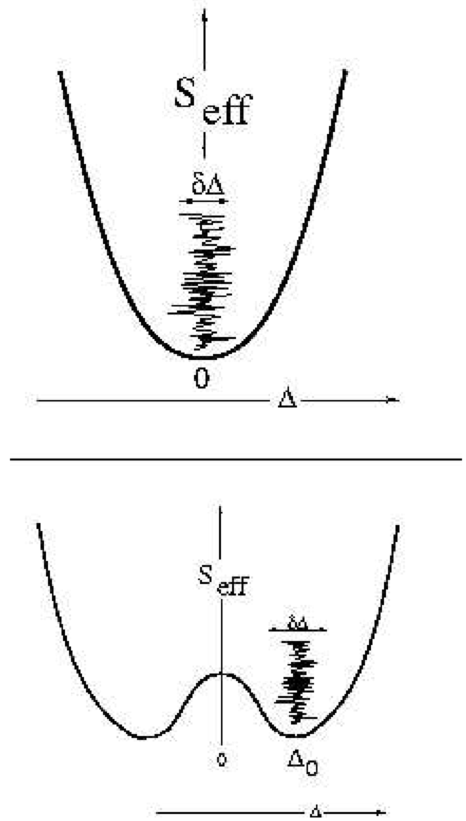
Pair fluctuations

Pair fluctuations



Usual mean field solution (i.e. the saddle point) neglects an influence of any fluctuations.

Pair fluctuations



One can describe the small fluctuations via Gaussian corrections.

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Without a specific pairing mechanism being established we propose to describe the coherent (for $T < T_c$) or incoherent (for $T > T_c$) fermion pairs using the phenomenological boson-fermion model.

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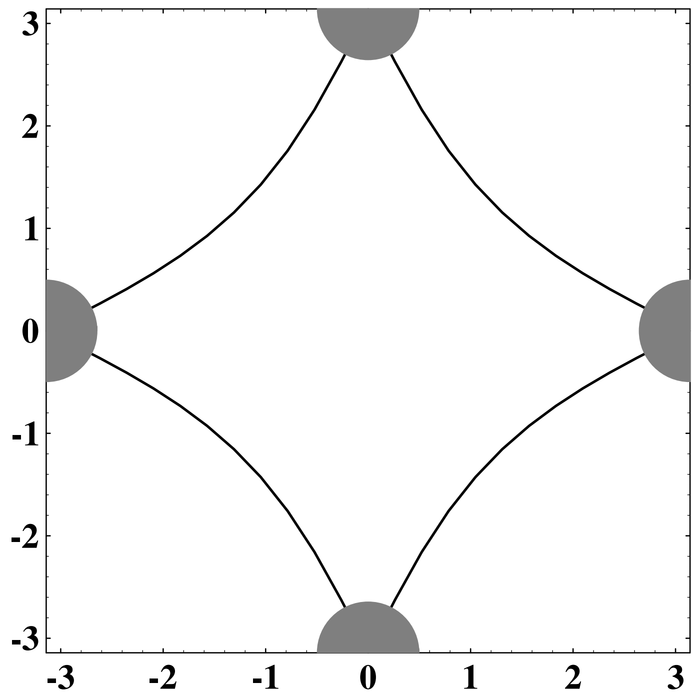

The dark areas denote such parts of the I-st Brillouin zone where the local (electron or hole) pairs exist.

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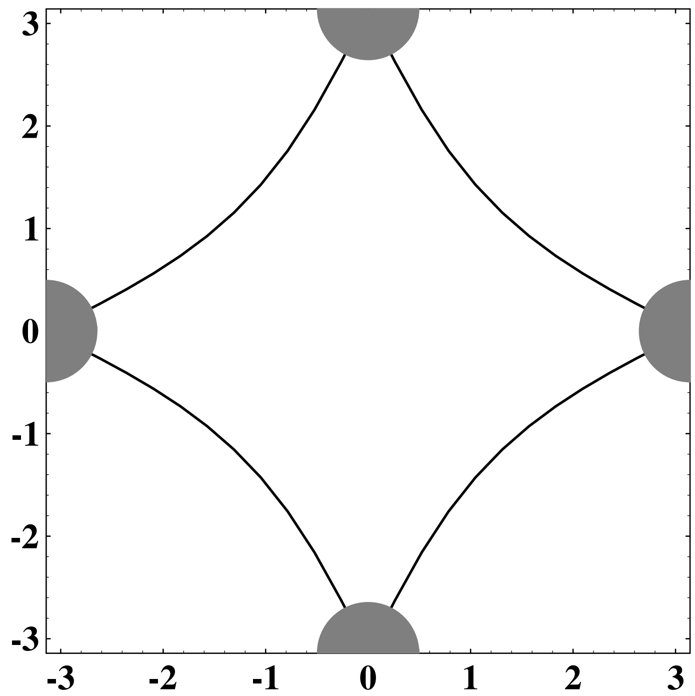

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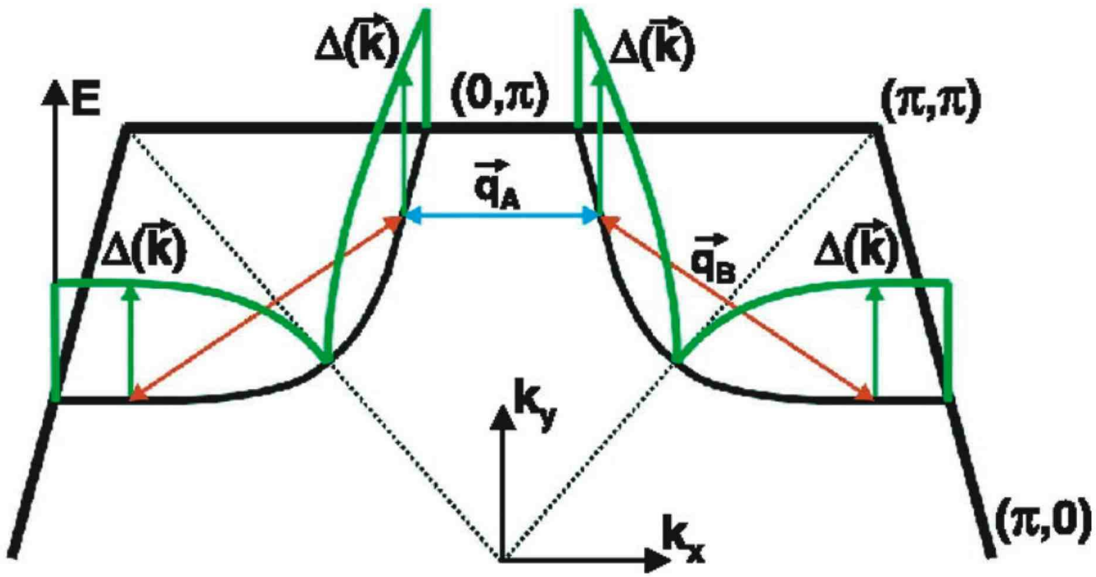
V.B. Geshkenbein, L.B. Ioffe and A.I. Larkin, Phys. Rev. B **55**, *3173 (1997).*

Anisotropic energy gap



d-wave type symmetry $\Delta_{\mathbf{k}} = \Delta(\cos k_x - \cos k_y)$ of the gap

J.E. Hoffman et al, *Science* **297**, *1148 (2002).*

The BF model (J. Ranninger, 1985):

$$
\begin{aligned}
H &= \sum_{\mathbf{k}\sigma} (\varepsilon_{\mathbf{k}} - \mu)\, c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \sum_{\mathbf{q}} (E_{\mathbf{q}} - 2\mu)\, b^{\dagger}_{\mathbf{q}} b_{\mathbf{q}} \\
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has been explored in the context of HTSC:

R. Micnas, J. Ranninger, S. Robaszkiewicz, Rev. Mod. Phys. **62***, 113 (1990).*

R. Friedberg and T.D. Lee, Phys. Rev. **B 40***, 423 (1989).*

C. Lannert, M.P.A. Fisher and T. Senthil, Phys. Rev. B **64***, 014518 (2001).*

E. Altman and A. Auerbach, Phys. Rev. B **65***, 104508 (2002).*

and for description of the superfluid ultracold atoms:

R.A. Duine and H.T.C. Stoof, Phys. Rep. **396***, 115 (2004).*

Q. Chen, J. Stajic, S. Tan and K. Levin, Phys. Rep. **412***, 1 (2005).*

Outline of the procedure

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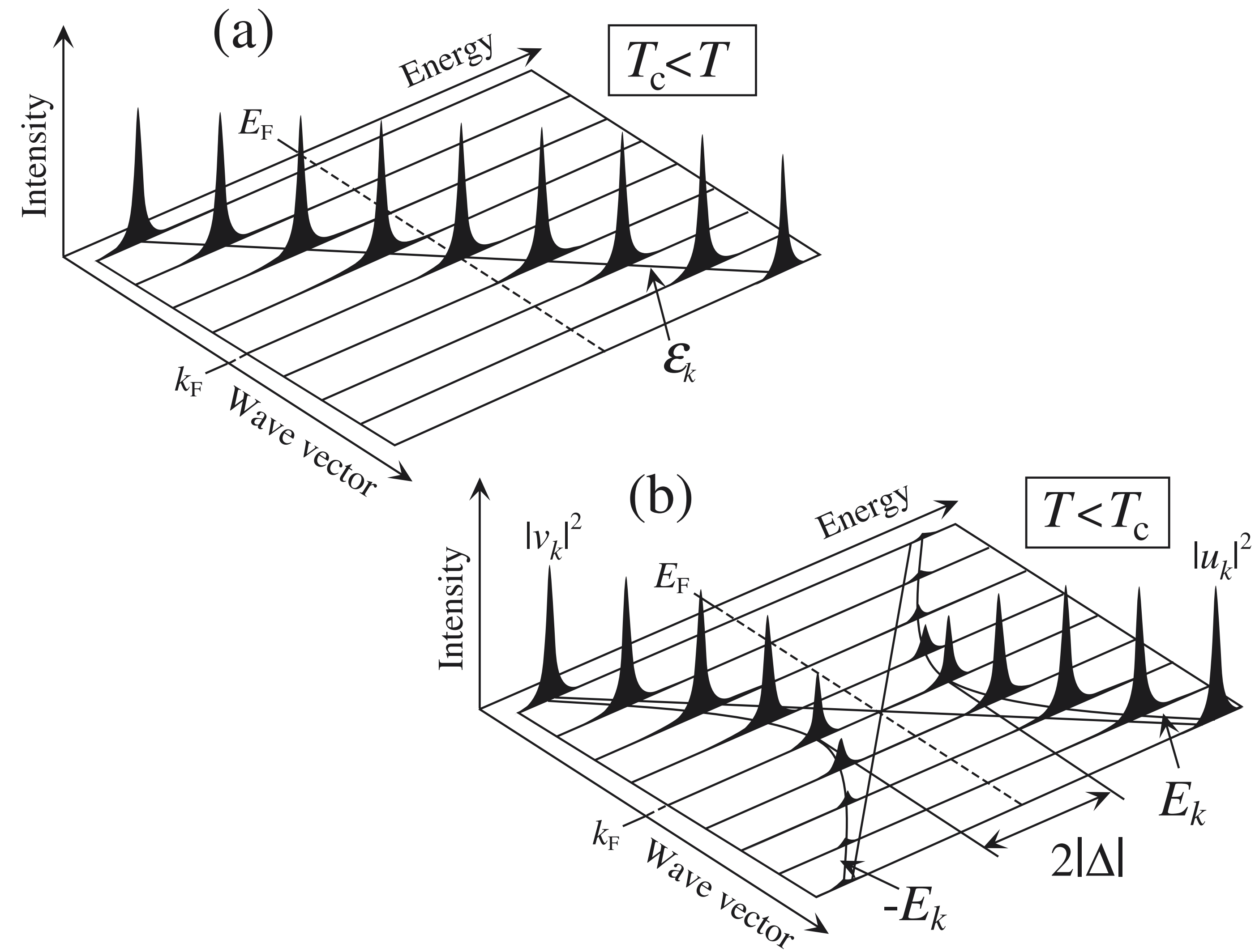
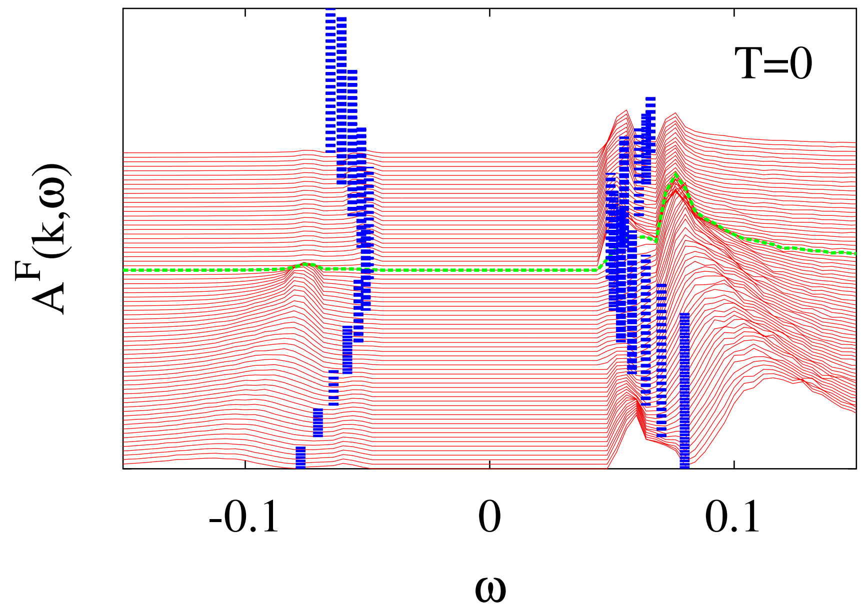
T. Domański and J. Ranninger, Phys. Rev. **B 63**, *134505 (2001).*



Single particle spectrum of conventional superconductors consists of two Bogoliubov branches gapped around E_F (no fluctuation effects are here taken into account).

Bogoliubov-like spectrum

$T = 0$

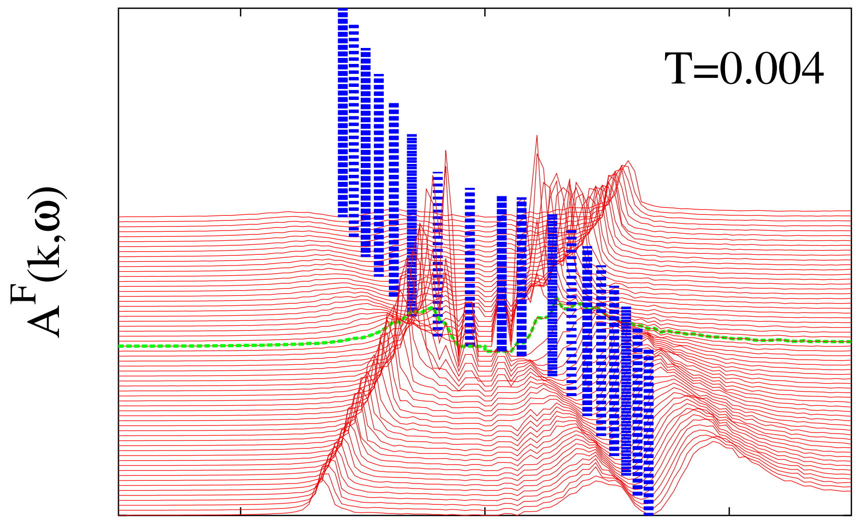


Below the critical temperature T_c there exist two branches of the single-particle excitation energies which (according to the BCS theory) occur at $\omega_{\mathbf{k}} = \pm\sqrt{(\varepsilon_{\mathbf{k}} - \mu)^2 + \Delta^2_{\mathbf{k}}}$.

T. Domański and J. Ranninger, Phys. Rev. Lett. **91***, 255301 (2003).*

Bogoliubov-like spectrum

$T_c < T < T^*$



Above T_c the Bogoliubov-type spectrum still survives but one of the branches (the shaddow) becomes overdamped. This means that fermion pairs have no longer an infinite life-time.

T. Domański and J. Ranninger, Phys. Rev. Lett. **91**, *255301 (2003).*

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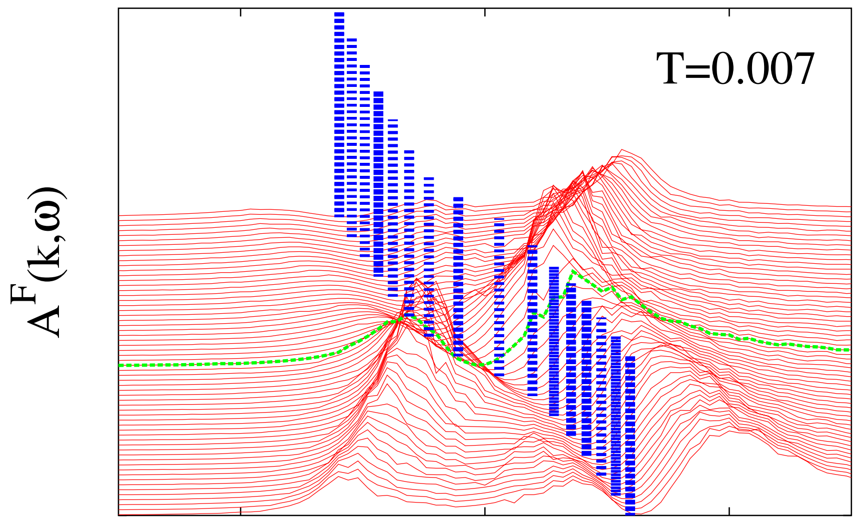

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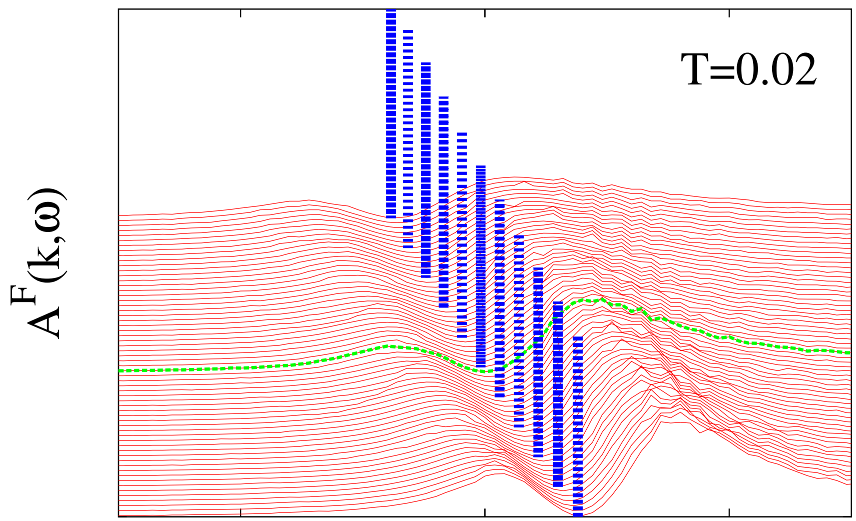
Bogoliubov-like spectrum

$T > T^*$

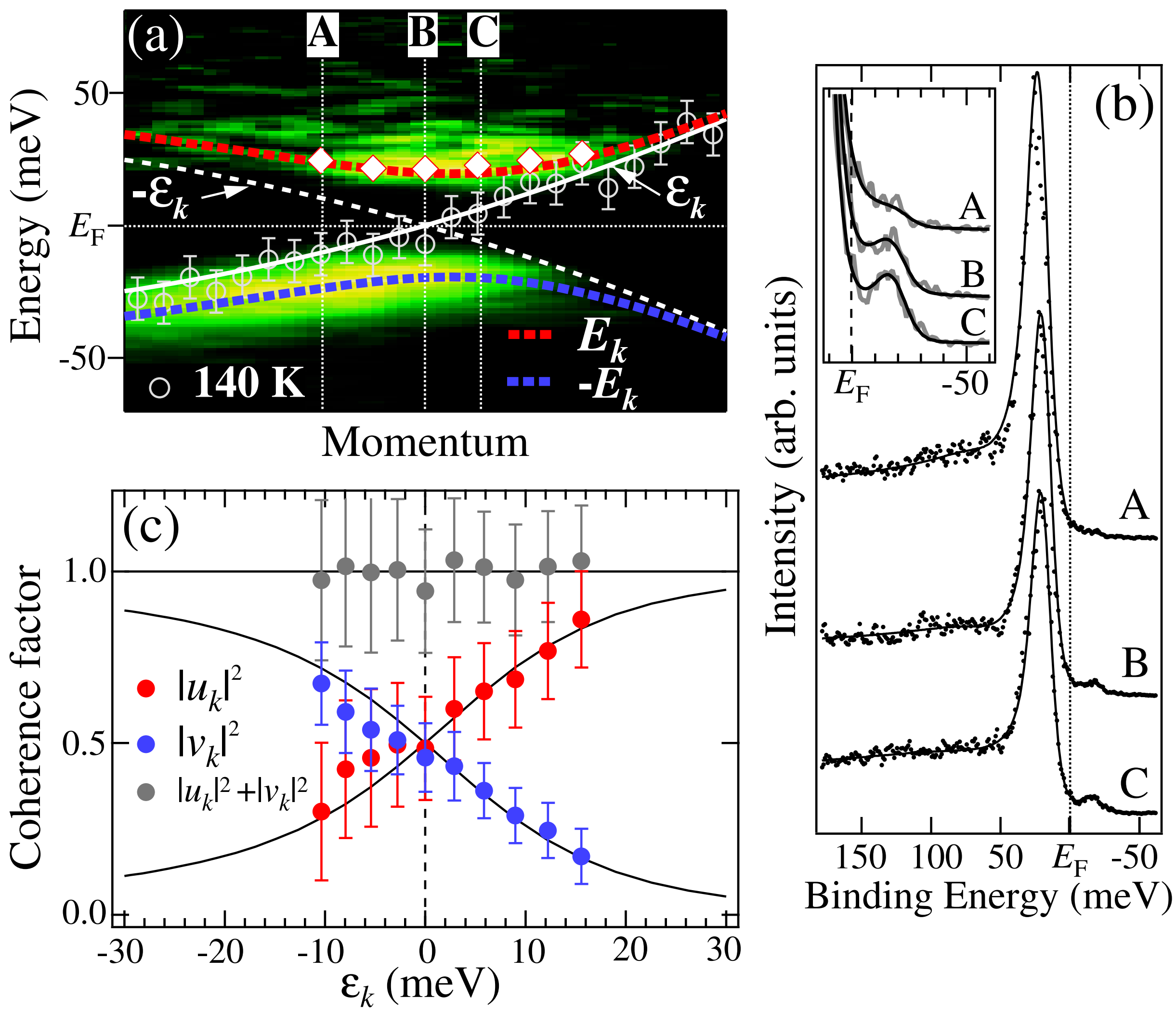


For temperatures far above T_c the Bogoliubov modes are gone and there remains only a single quasiparticle peak surrounded by an incoherent background.

T. Domański and J. Ranninger, Phys. Rev. Lett. **91**, *255301 (2003).*

Experimental data (Japanese group)

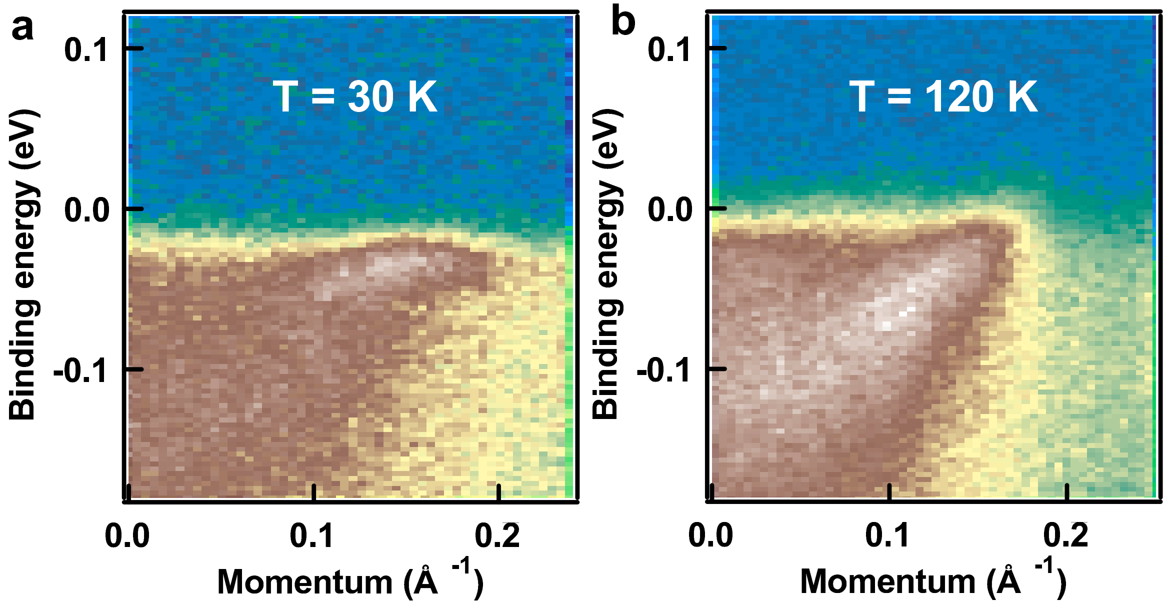
$T < T_c$

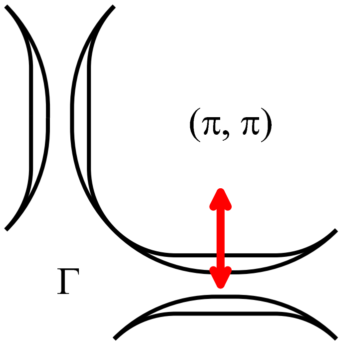


H. Matsui, T. Sato, and T. Takahashi, Phys. Rev. Lett. **90**, *217002 (2003).*

Experimental data (Dresden group)

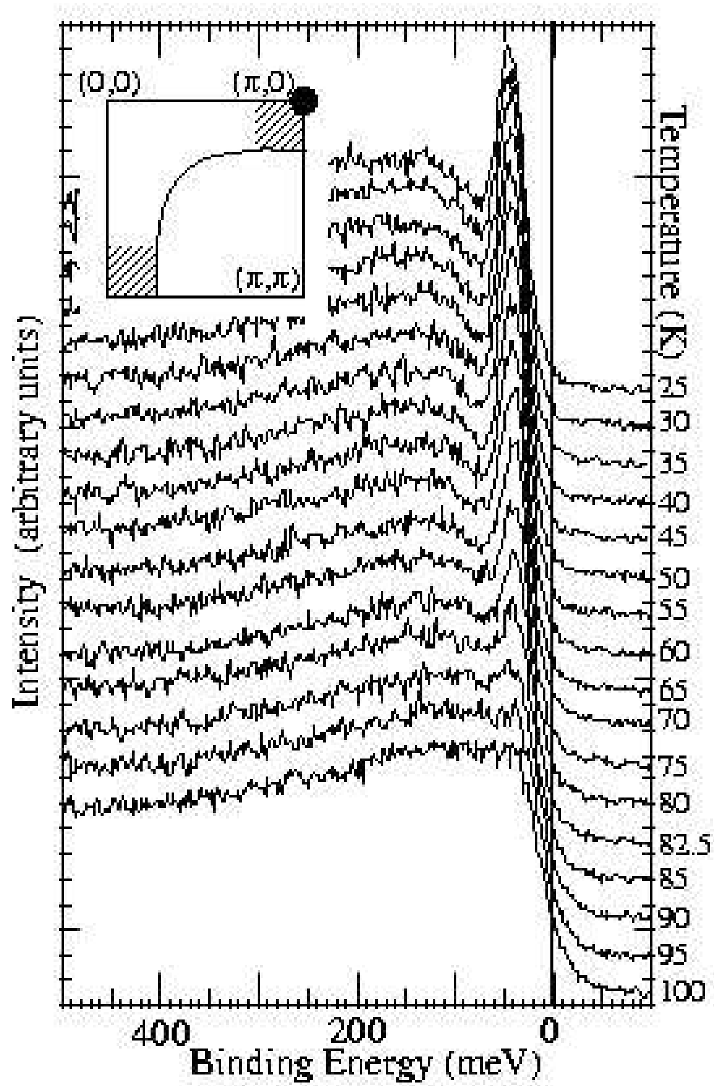
$T < T_c$ $T_c < T$





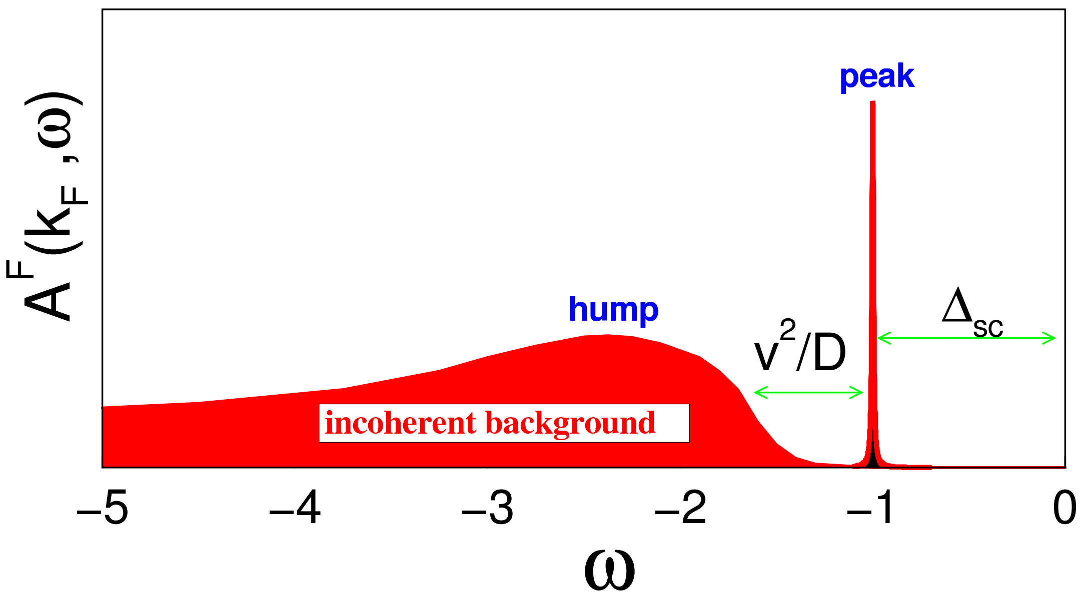
T. Eckl et al, *Phys. Rev. B* **70**, *094522 (2004).*

The peak-dip-hump structure



A.G. Loeser, Z.-X. Shen et al, *Phys. Rev. B* **56**, *14185 (1997).*

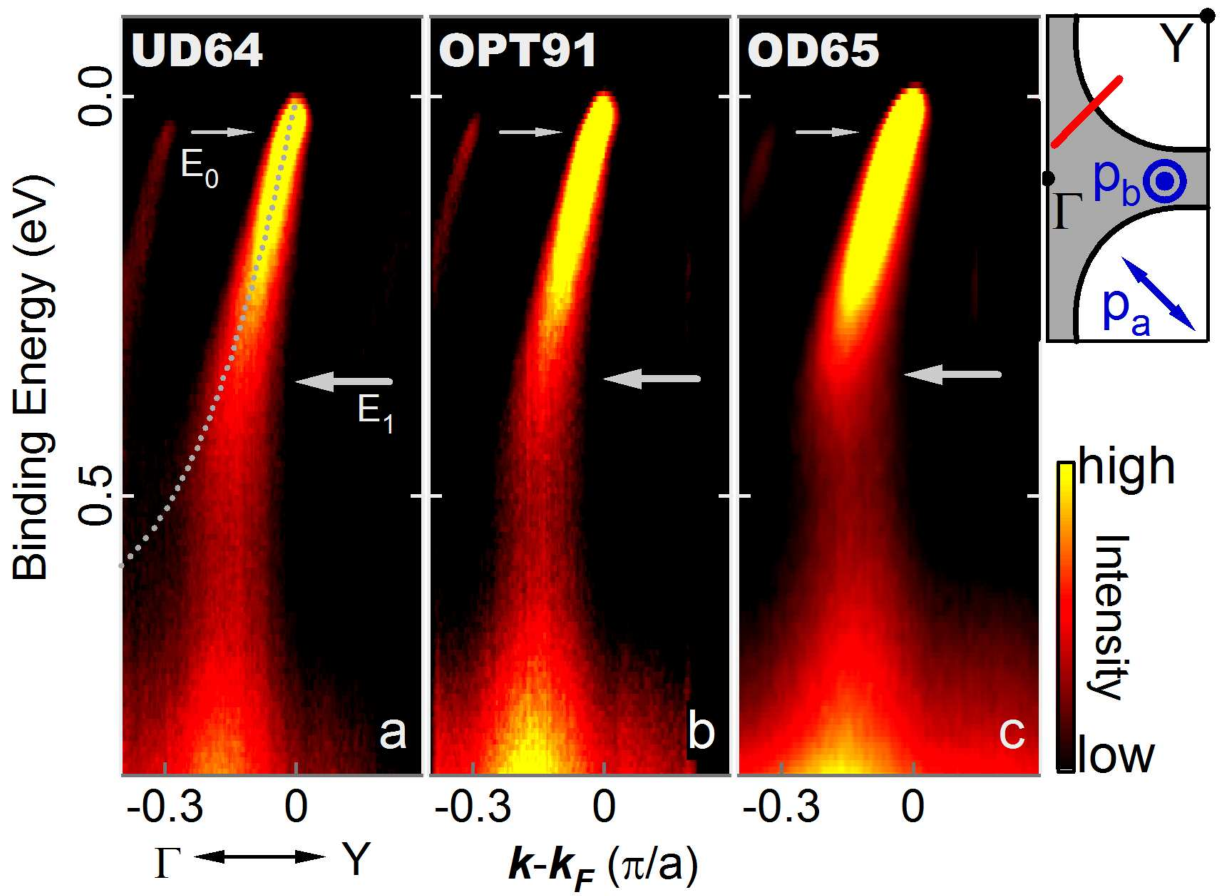
Spectral function for $T < T_c$



Schematic view of the spectral function in the antinodal direction for temperatures $T < T_c$ obtained using the boson-fermion model .

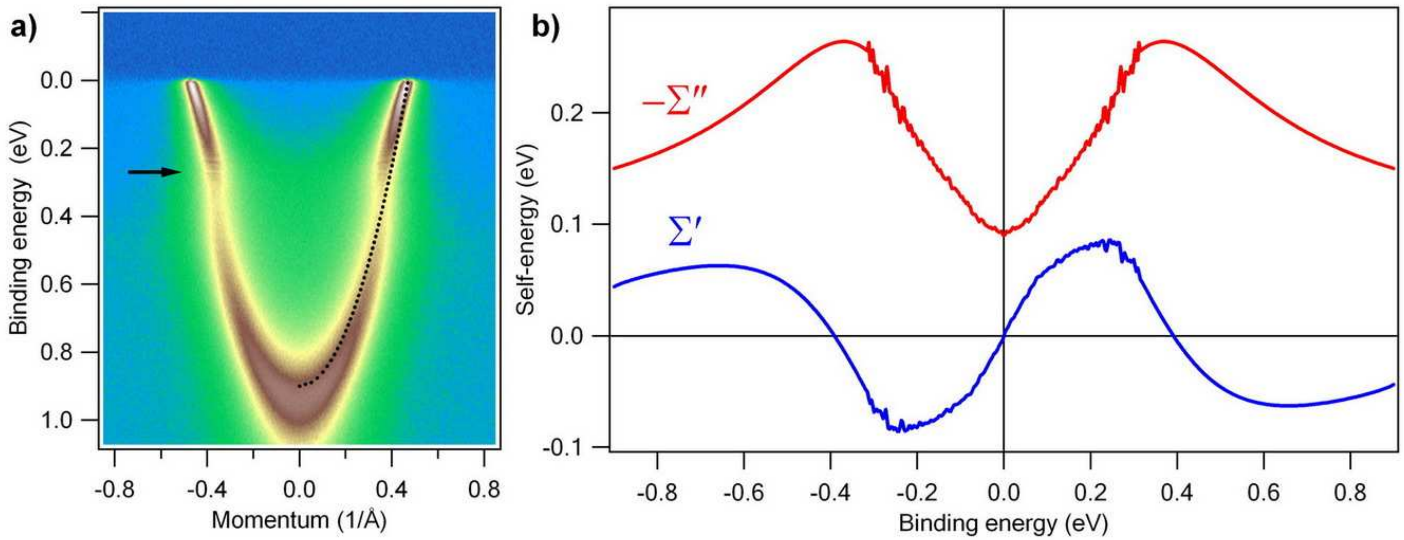
T. Domański and J. Ranninger, Phys. Rev. B **70***, 184513 (2004).*

The phenomenon of "waterfalls"



J. Graf et al, *Phys. Rev. Lett.* **98**, *067004 (2006).*

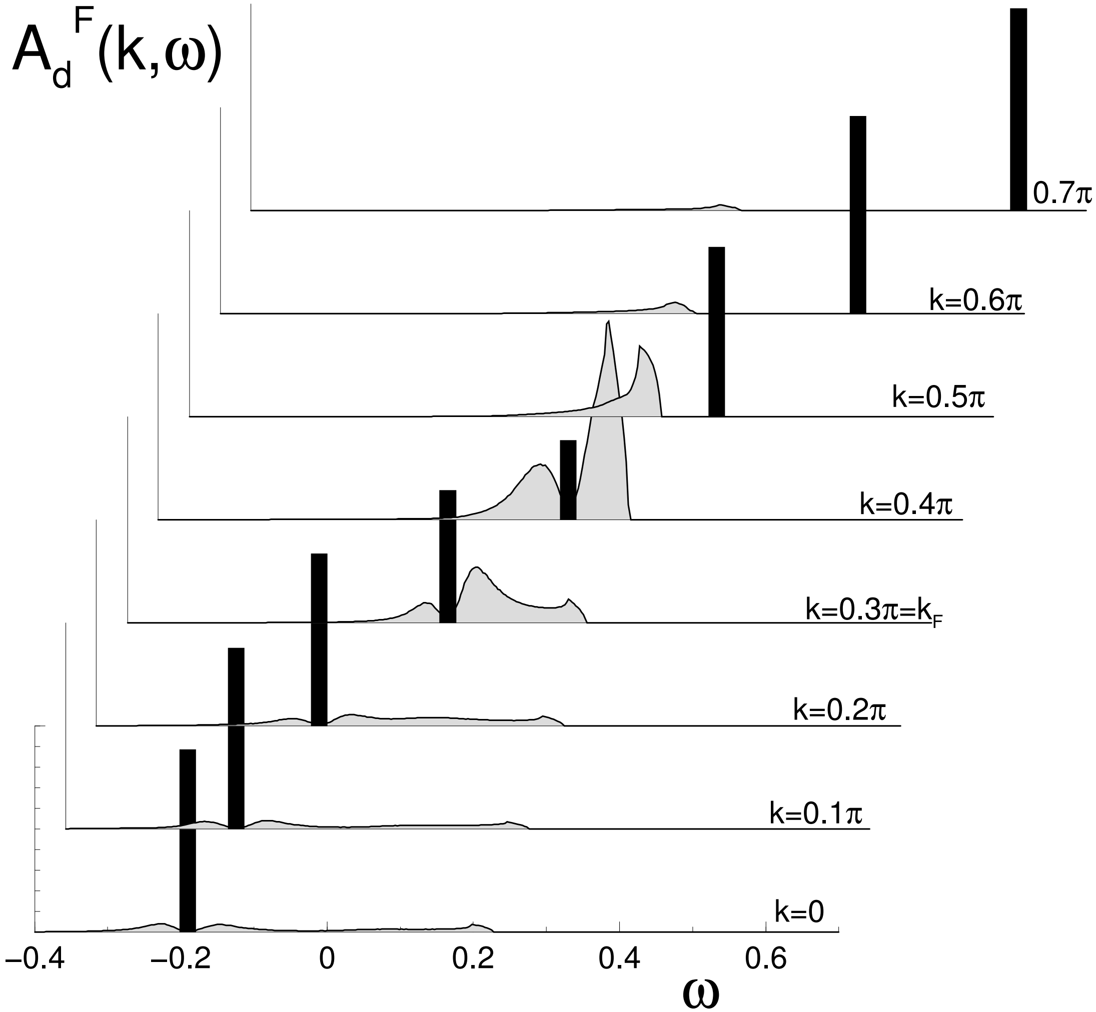
Physical implications of the "waterfalls"



D.S. Ionosov et al, *cond-mat/0703223; A.A. Kordyuk* et al, *cond-mat/0702374.*

"Waterfalls" can result from coupling to bosonic mode

$T > T^*$



T. Domański and J. Ranninger, Phys. Rev. B **70**, *184503 (2004).*

Collective phenomena

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We also investigated the pair correlation function

$$\left\langle \sum_{\mathbf{k}} c_{\mathbf{k}\downarrow}(\tau) c_{\mathbf{q}-\mathbf{k}\uparrow}(\tau) \sum_{\mathbf{k}'} c^{\dagger}_{\mathbf{q}-\mathbf{k}'\uparrow} c^{\dagger}_{\mathbf{k}'\downarrow} \right\rangle$$

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consisting of:

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- and the incoherent background $\mathcal{A}^{inc}_{\mathbf{k}}(\omega)$.

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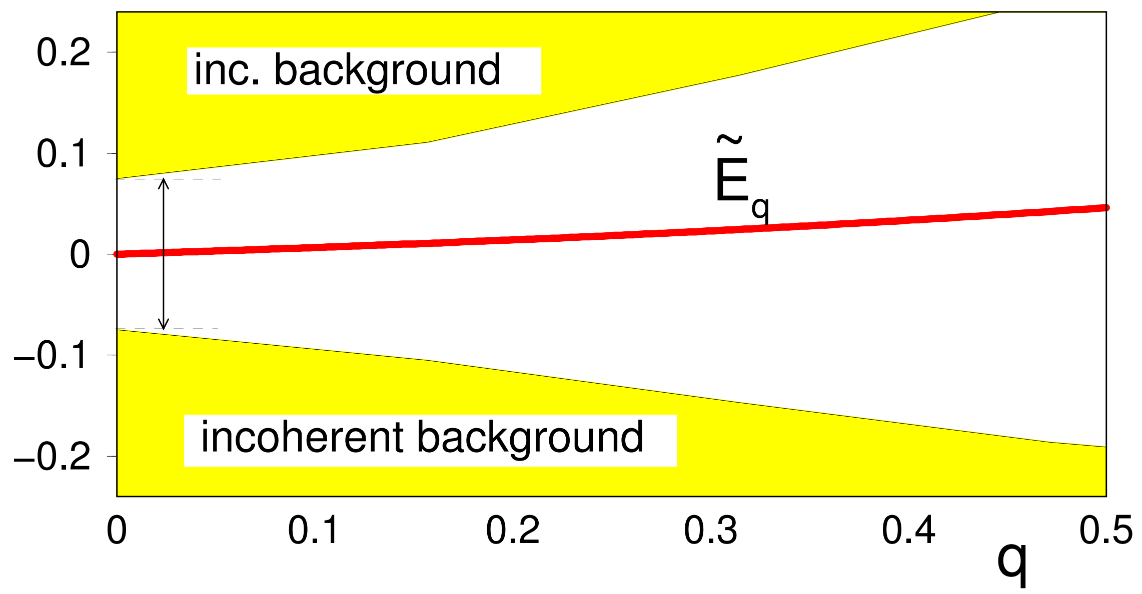
T. Domański and J. Ranninger, Phys. Rev. B **70**, *184513 (2004).*

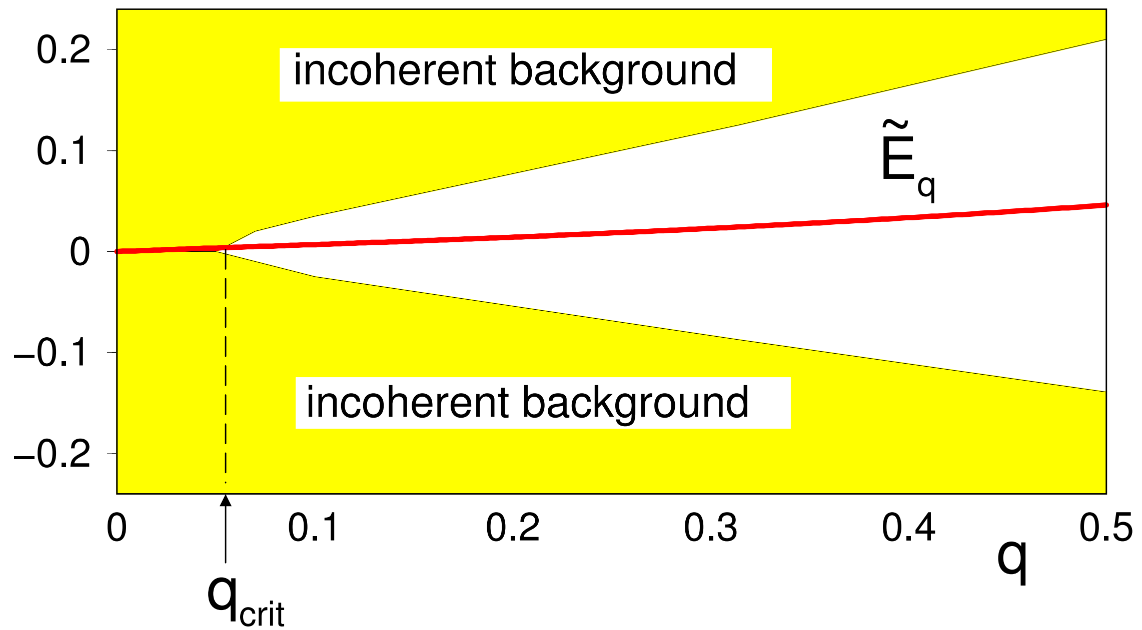
The pair spectrum for $T < T_c$



The quasiparticle peak is well separated from the incoherent background and, in the limit $\mathbf{q} \to \mathbf{0}$, has a characteristic dispersion $\tilde{E}_{\mathbf{q}} = c\,|\mathbf{q}|$. This Goldstone mode is a hallmark of the symmetry broken state.

Such a unique situation could be observed in the case of ultracold fermion atoms, otherwise the Coulomb repulsions lift this mode to the high plasmon frequency.

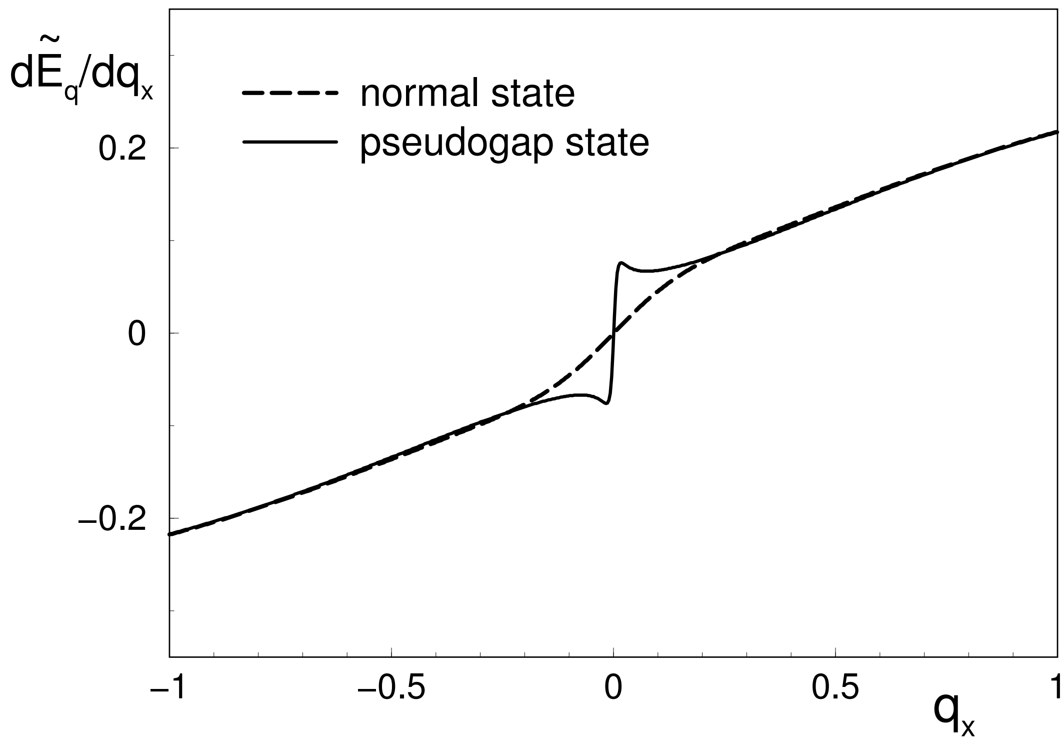
The pair spectrum for $T^* > T > T_c$



Above the transition temperature (for $T^* > T > T_c$):

- *the qusiparticle peak overlaps at small momenta with the incoherent background,*
- *for $\mathbf{q} \to \mathbf{0}$ the Goldstone mode disappears,*
- *remnant of the Goldstone mode is seen above $\mathbf{q}_{crit}$.*

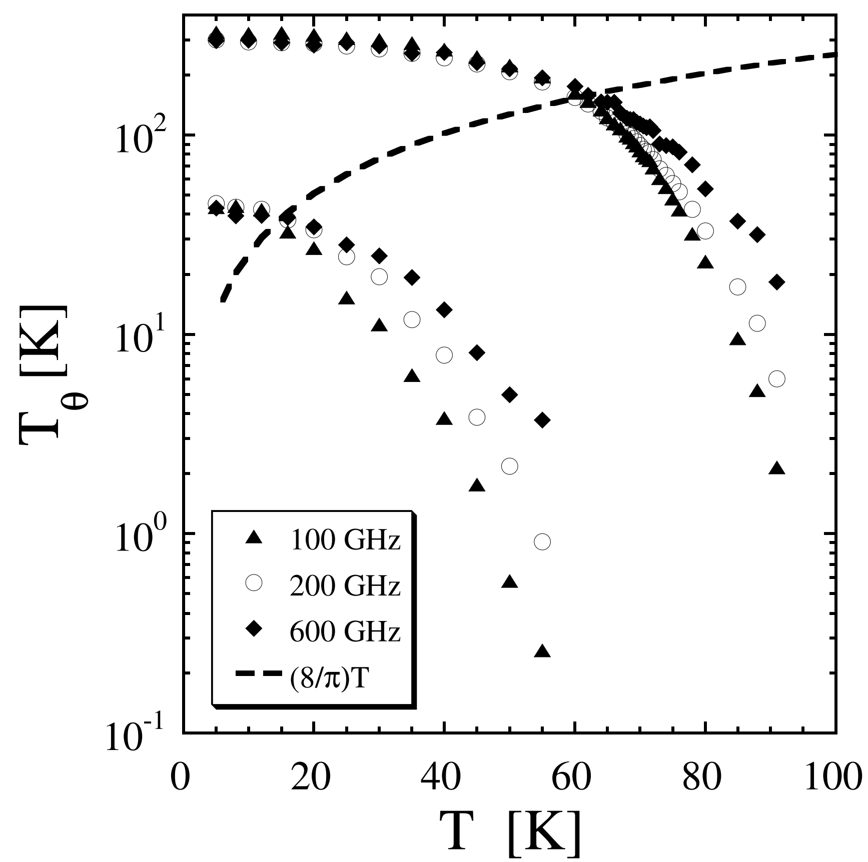
The pair spectrum for $T^* > T > T_c$



Remnant of the Goldstone branch in the dispersion of fermion pairs above T_c .

T. Domański and A. Donabidowicz, (2007) in print.

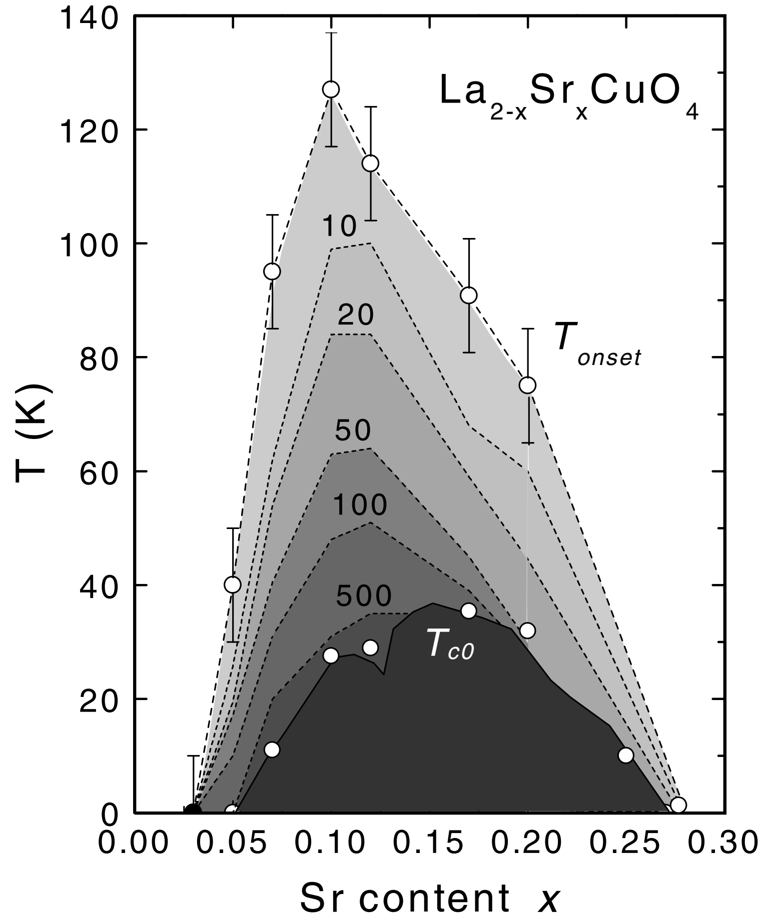
Experimental evidence: 1



Residual Meissner effect observed experimentally with use of the ultrafast magnetic fields.

J. Corson et al, *Nature* **398**, *221 (1999).*

Experimental evidence: 2



The large Nernst effect measured above T_c.

Y. Wang et al, *Science* **299**, *86 (2003).*

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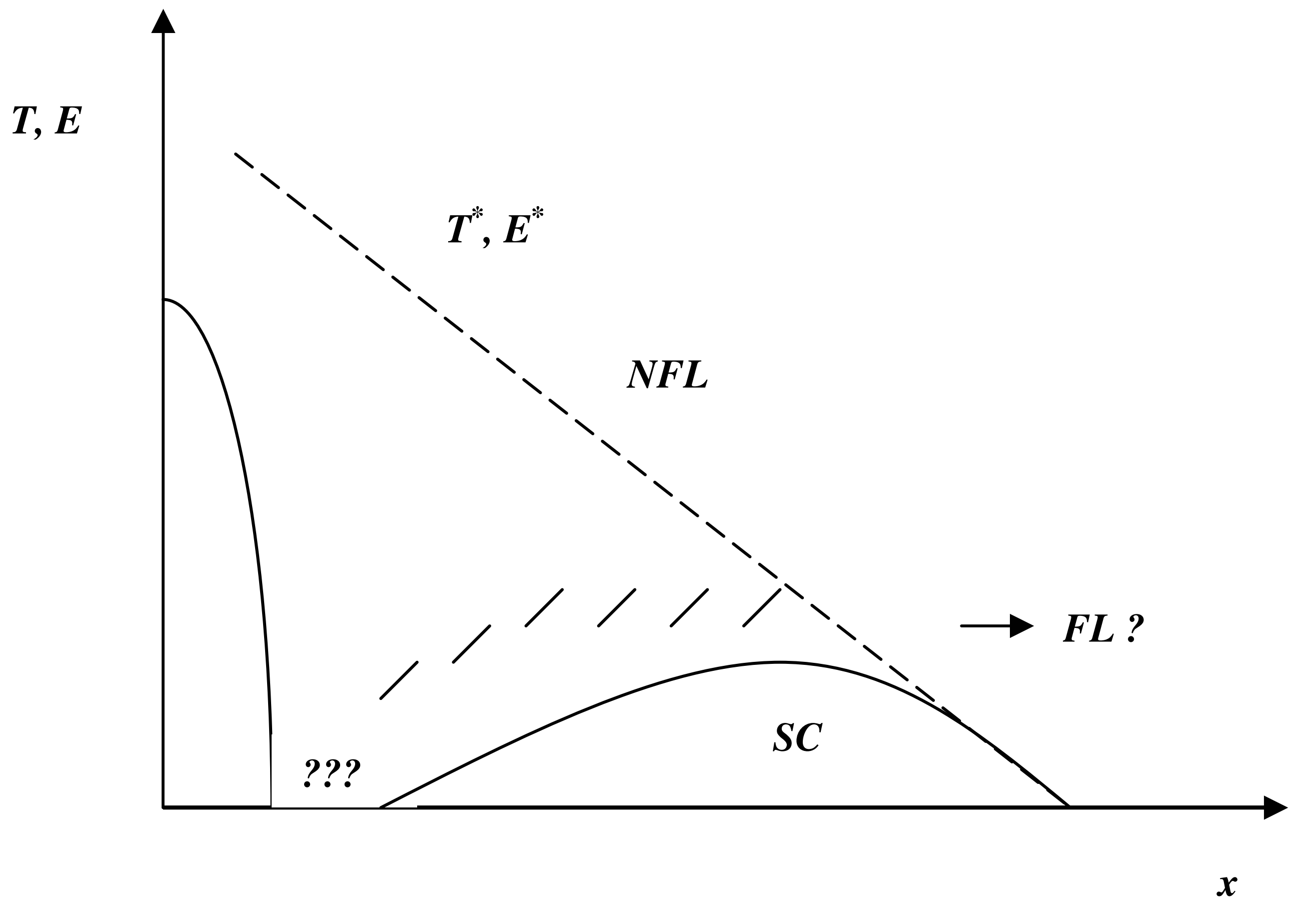
Precursor effects are robust for all superconductors but their temperature extent varies from case to case.

Resonating Valence Bonds

Why not ?



P.W. Anderson, Phys. Rev. Lett. **96**, *017001 (2006).*