Lublin, 16 XI 2010

Korelacje nadprzewodzące powyżej T_c

T. DOMAŃSKI

Uniwersytet M. Curie-Skłodowskiej

w Lublinie

Współpraca: J. Ranninger (CNRS, Grenoble)

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Signatures of the short-range superconducting correlations above T_c

T. DOMAŃSKI

M. Curie-Skłodowska University,

Lublin, Poland

Collaboration: J. Ranninger (CNRS, Grenoble)

Outline

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$\Rightarrow$ *Bogoliubov-type modes above* T_c

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- *Bogoliubov-type modes above* T_c
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$\Rightarrow$ *Diamagnetism above* T_c

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- ⋆ **Conclusions**

Preliminaries

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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.

Conventional superconductors – major property

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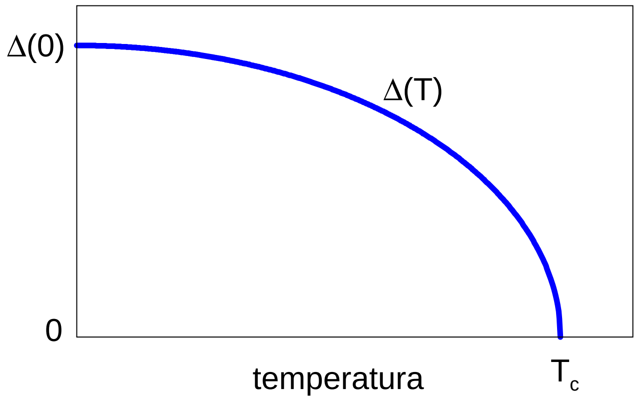
Pair formation and onset of their coherence coincide at T_c



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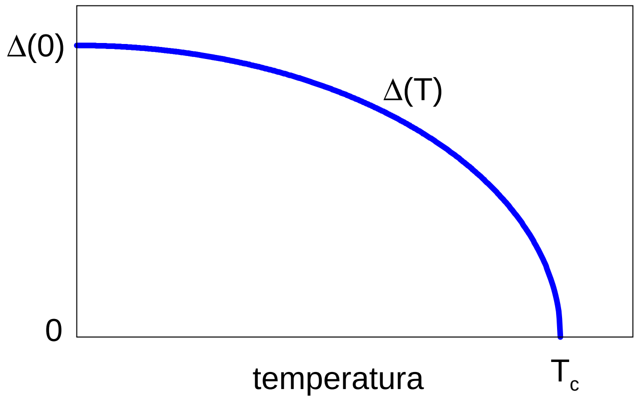
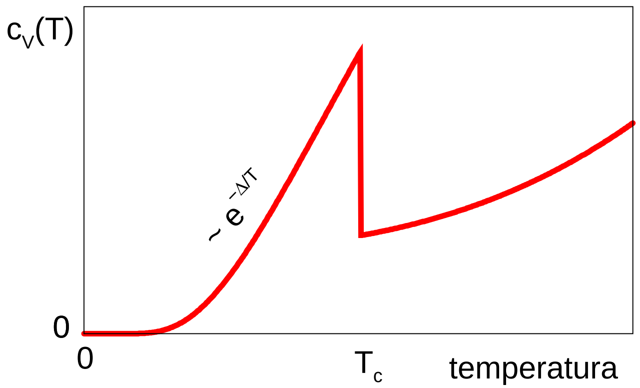


Pairing is responsible for the gap in the single particle spectrum

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



/ as classified by Landau /

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This is BE condensate of Cooper pairs !

Theoretical issues – generalities

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The order parameter

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$\nabla\theta \neq 0 \longrightarrow$ **phase slippage causes supercurrents**

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can be achieved at T_c either:

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or disordering the phase . . . . (the HTSC compounds)

$$\lim_{T\to T_c} \langle\theta\rangle = 0$$

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The first empirical observation of the sc fluctuations above T_c has been seen in **granular aluminium**.

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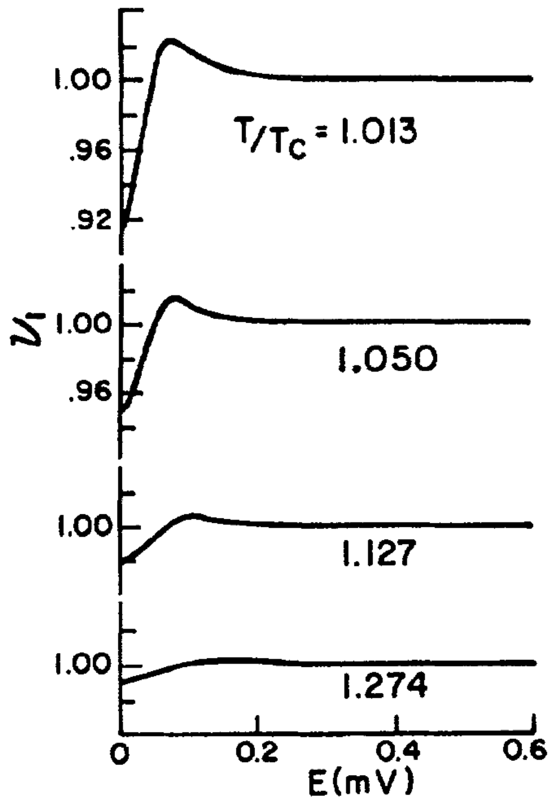
Tunneling conductance revealed a small pseudogap above T_c.



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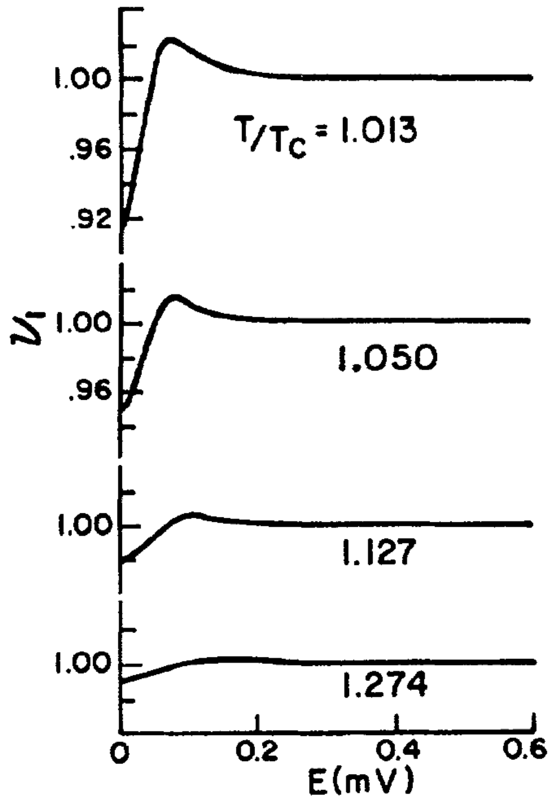
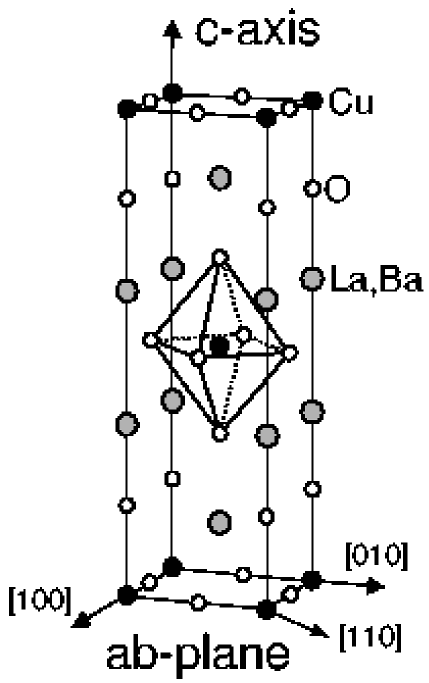


R.W. Cohen and B. Abels, Phys. Rev. **168***, 444 (1968).*

Experimental motivation

HTSC materials – structure

The parent compounds are quasi-2D Mott insulators



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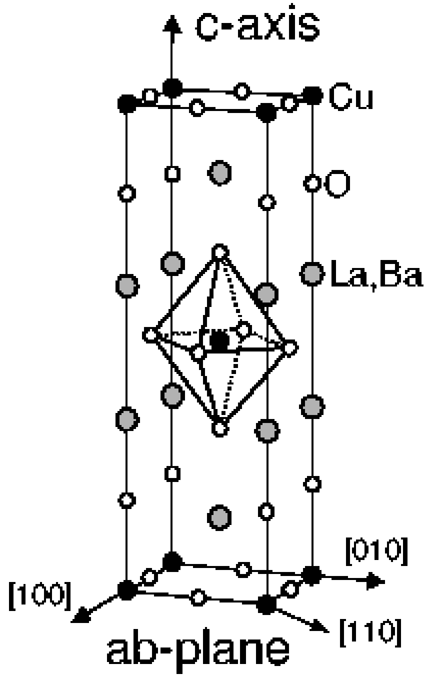

Important remark:

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

HTSC materials – effect of doping

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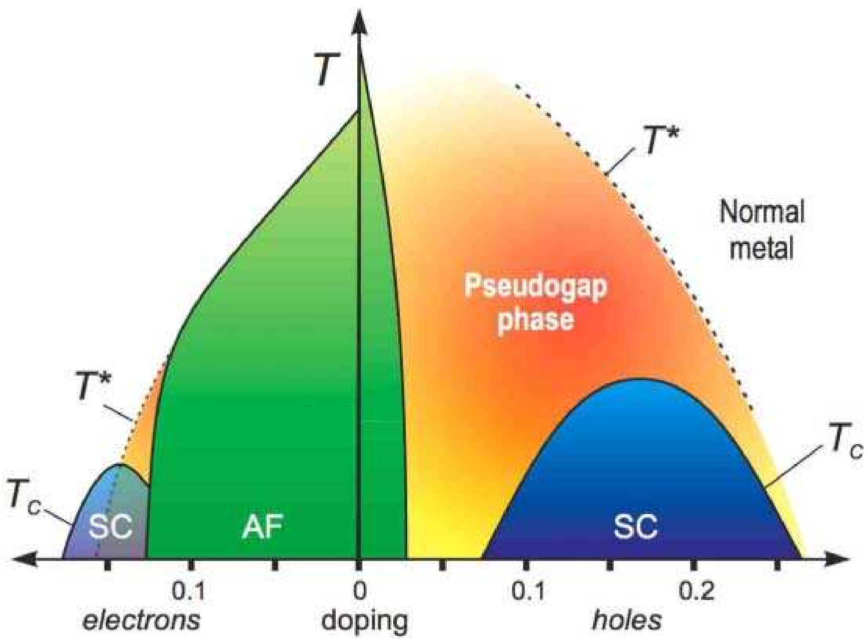
Superconductivity appears upon doping by

electrons or *holes*



O. Fisher et al, *Rev. Mod. Phys.* **79**, *353 (2007).*

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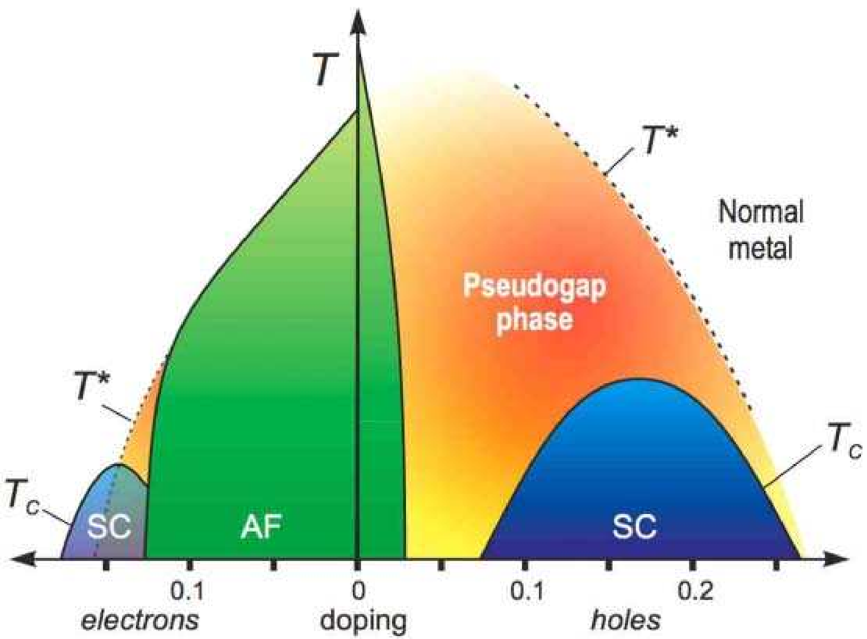

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Important remark:

What is an origin of the pseudogap ?

Incoherent pairs above T_c

experimental fact $\#$ 1

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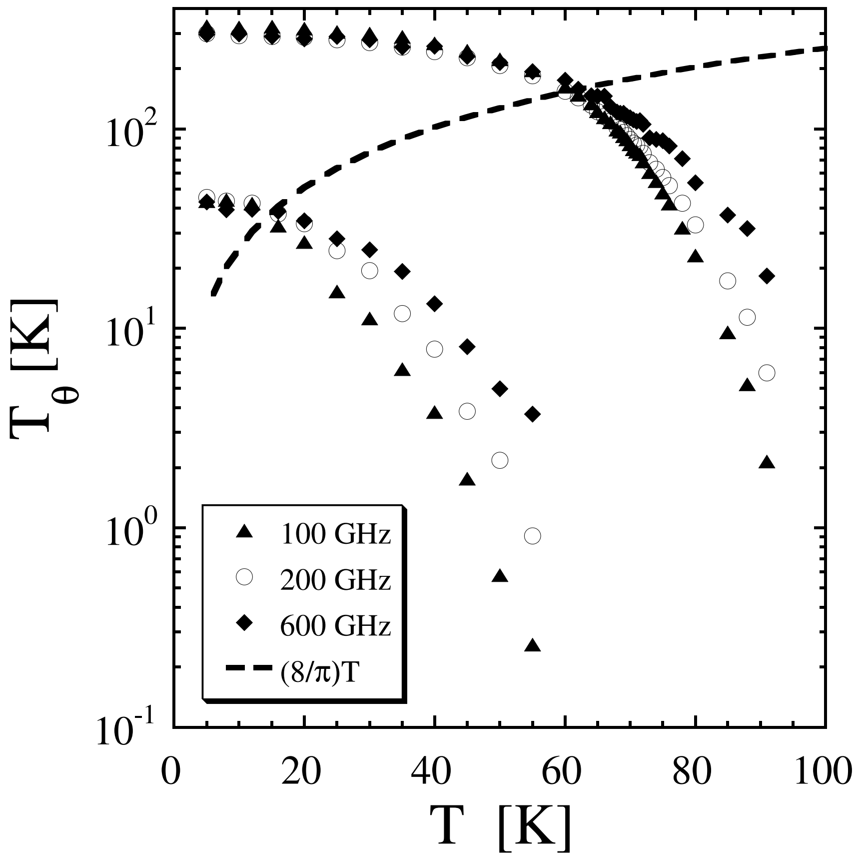
experimental fact # 1



Dynamic phase-stiffness $T_\theta = \omega \mathrm{Im}\sigma(\omega, T)/\sigma_Q$
observed at the ultrafast (teraHz) external ac fields.

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

Incoherent pairs above T_c

experimental fact $\#$ 2

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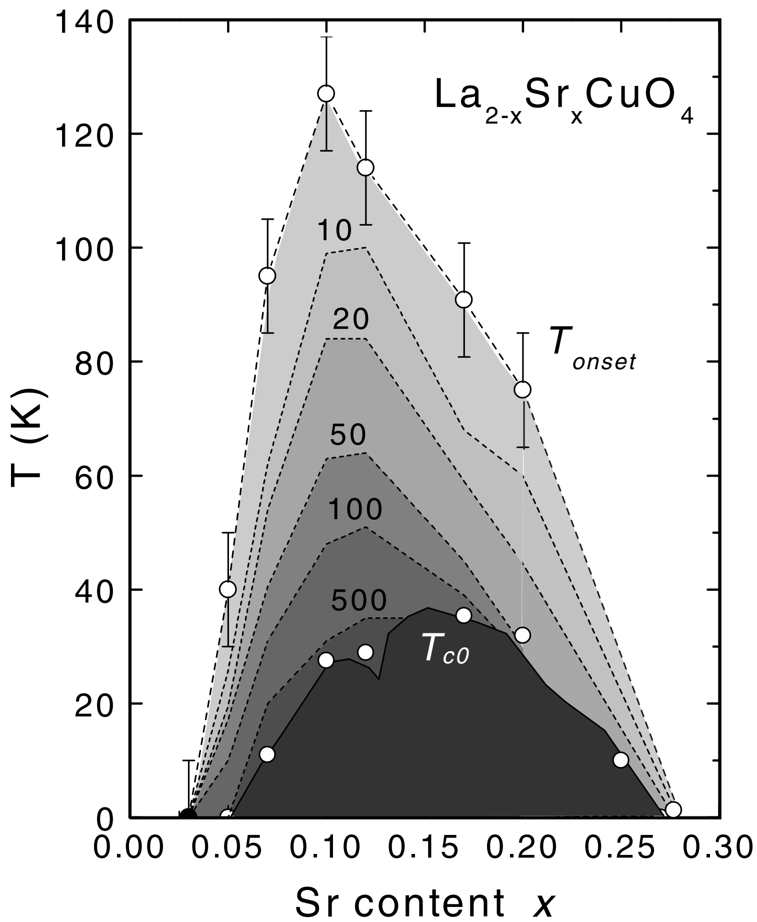
experimental fact # 2



Phase slippage detected in the large Nernst effect.

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

Incoherent pairs above T_c

experimental fact $\#$ 3

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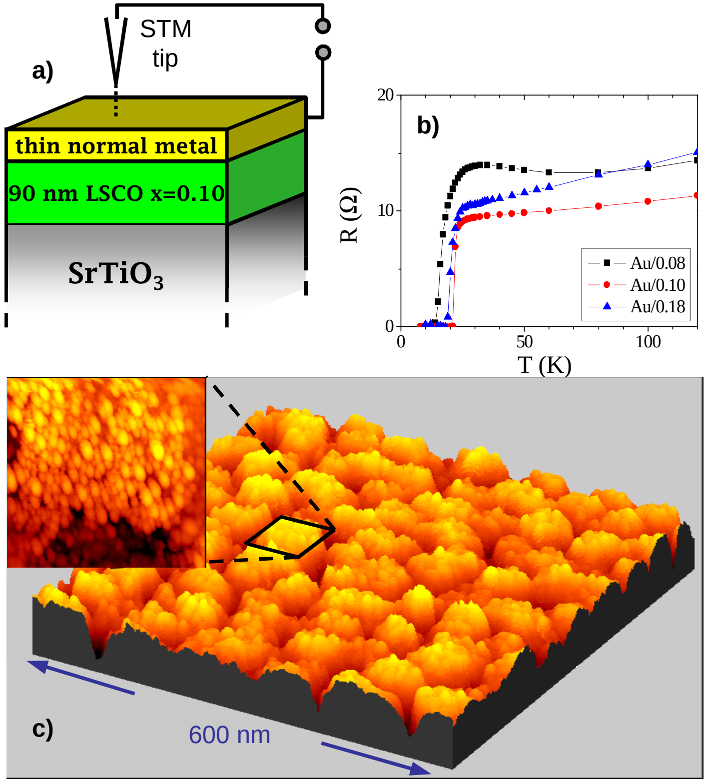


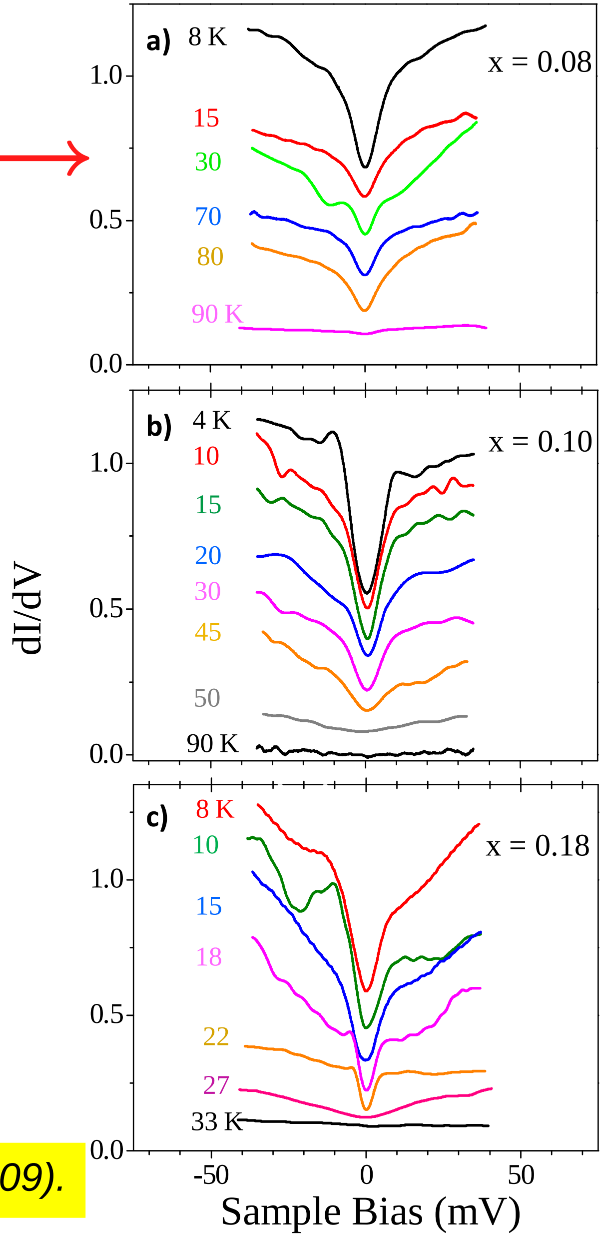
O. Yuli et al, *Phys. Rev. Lett.* **103**, *197003 (2009).*

Pseudogap induced above T_c in the ultrathin metallic slab deposited on $La_{2-x}Sr_xCuO_4$.

Incoherent pairs above T_c

experimental fact # 3

Measured LDOS →



Proximity induced pseudogap has been observed at temperatures far above T_c.

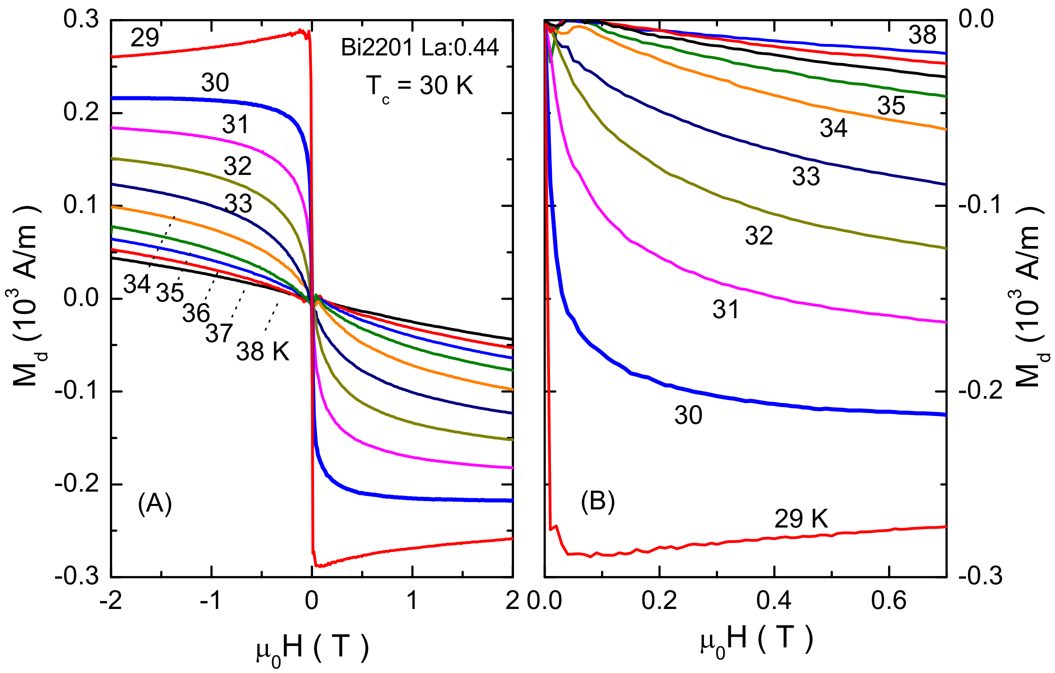
O. Yuli et al, *PRL* **103**, *197003 (2009).*

Incoherent pairs above T_c

experimental fact $\#$ 4

Incoherent pairs above T_c

experimental fact # 4

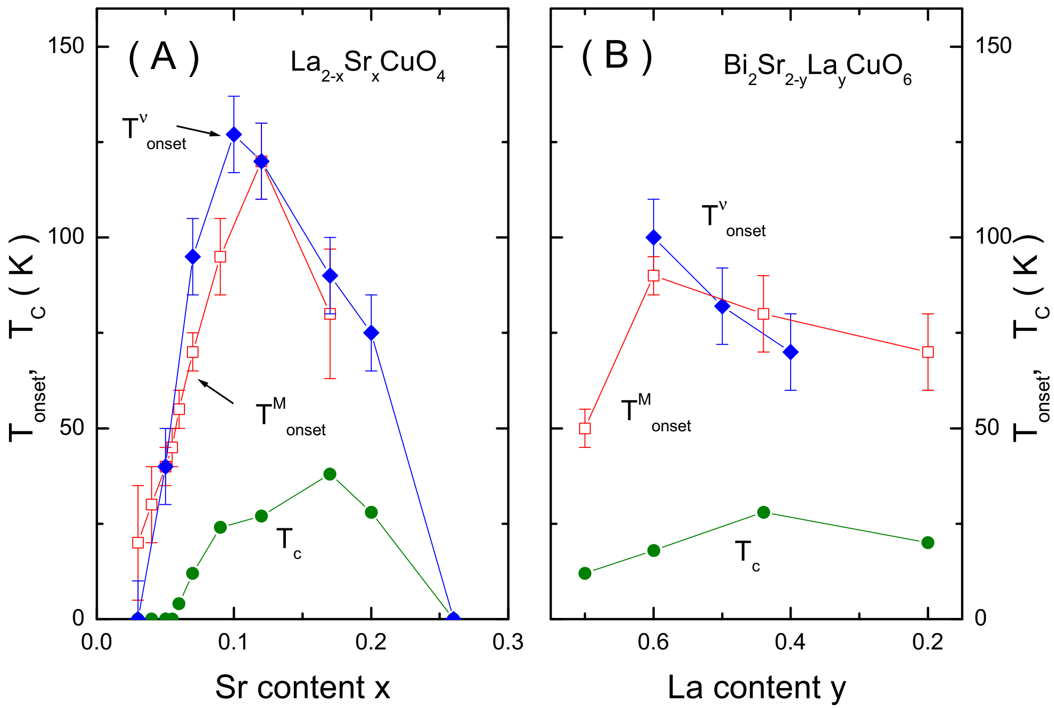


Onset of the diamagnetic response revealed by torque magnetometry.

L. Li, ... and N.P. Ong, Phys. Rev. B **81**, *054510 (2010).*

Incoherent pairs above T_c

experimental fact # 4



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Incoherent pairs above T_c

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$\Rightarrow$ **Josephson-like features seen above T_c in the tunneling**

N. Bergeal et al, *Nature Phys.* **4**, *608 (2008).*

Incoherent pairs above T_c ... *continued*

⇒ **Josephson-like features seen above T_c in the tunneling**

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⇒ **smooth evolution of the electronic spectrum observed by ARPES near the superconductor–insulator transition**

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U. Chatterjee et al, *Nature Phys.* **5**, *1456 (2009).*

⇒ **spectroscopic fingerprints of the Bogoliubov QPs seen by the unique octet patterns which survive up to $1.5T_c$**

J. Lee, ... and J.C. Davis, Science **325**, *1099 (2009).*

II. Model & methodology

Boson-Fermion model

$$\hat{H} = \sum_{i,j,\sigma} (t_{ij} - \mu\, \delta_{i,j})\, \hat{c}^{\dagger}_{i\sigma} \hat{c}_{j\sigma} + \sum_{l} \left(E_l^{(B)} - 2\mu \right) \hat{b}_l^{\dagger} \hat{b}_l + \sum_{i,j} g_{ij} \left[\hat{b}_l^{\dagger} \hat{c}_{i,\downarrow} \hat{c}_{j,\uparrow} + \text{h.c.} \right]$$

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Isotropic form of this model has been introduced 25 year ago by

J. Ranninger and S. Robaszkiewicz, Physica B **135**, *468 (1985).*

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[in the momentum space]

$$\hat{H} = \sum_{\mathbf{k}\sigma} (\varepsilon_{\mathbf{k}} - \mu)\, \hat{c}^{\dagger}_{\mathbf{k}\sigma} \hat{c}_{\mathbf{k}\sigma} + \sum_{\mathbf{q}} \left(E^{(B)} - 2\mu \right) \hat{b}^{\dagger}_{\mathbf{q}} \hat{b}_{\mathbf{q}} + \frac{1}{\sqrt{N}} \sum_{\mathbf{k},\mathbf{q}} g_{\mathbf{k},\mathbf{q}} \left[\hat{b}^{\dagger}_{\mathbf{q}} \hat{c}_{\mathbf{k},\downarrow} \hat{c}_{\mathbf{q}-\mathbf{k},\uparrow} + \text{h.c.} \right]$$

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

Ch.P. Enz, Phys. Rev. B 54, 3589 (1996);

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

...

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and ultracold atoms interacting with the Feshbach resonance by

Boson-Fermion model

[in the momentum space]

$$\hat{H} = \sum_{\mathbf{k}\sigma} (\varepsilon_{\mathbf{k}} - \mu)\, \hat{c}^{\dagger}_{\mathbf{k}\sigma} \hat{c}_{\mathbf{k}\sigma} + \sum_{\mathbf{q}} \left(E^{(B)} - 2\mu \right) \hat{b}^{\dagger}_{\mathbf{q}} \hat{b}_{\mathbf{q}} + \frac{1}{\sqrt{N}} \sum_{\mathbf{k},\mathbf{q}} g_{\mathbf{k},\mathbf{q}} \left[\hat{b}^{\dagger}_{\mathbf{q}} \hat{c}_{\mathbf{k},\downarrow} \hat{c}_{\mathbf{q}-\mathbf{k},\uparrow} + \text{h.c.} \right]$$

BF scenario has been considered in the context of HTSC by

R. Micnas, J. Ranninger, S. Robaszkiewicz, Rev. Mod. Phys. 62, 113 (1990);
R. Friedberg and T.D. Lee, Phys. Rev. B 40, 423 (1989);
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M. Holland *et al*, Phys. Rev. Lett. 87, 120406 (2001);
Y. Ohashi, A. Griffin, Phys. Rev. Lett. 89, 130402 (2002);
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);
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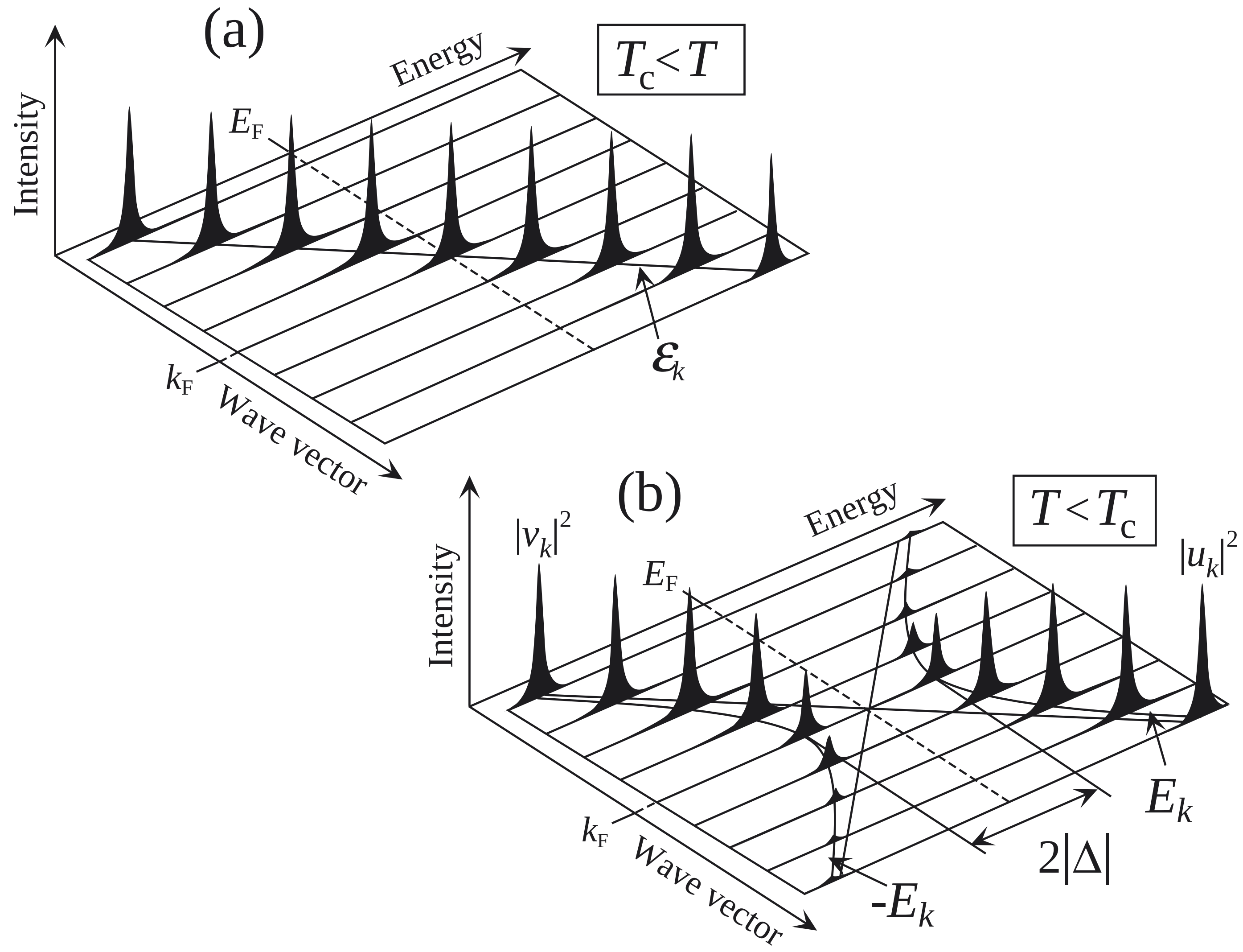
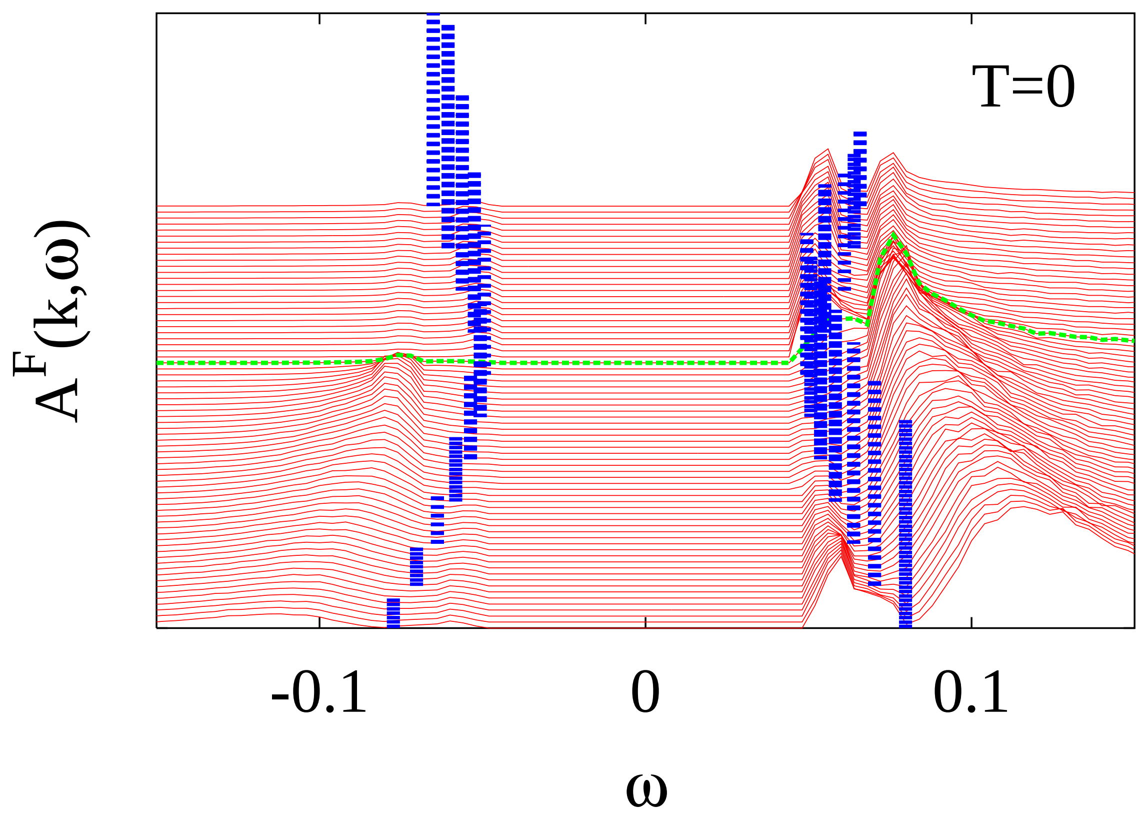
III. Selected results



Single particle spectra of conventional superconductors consist of the Bogoliubov branches separated around E_F by $2\Delta_{sc}$ (the fluctuation effects are neglected).

Effective spectrum: BF model

$T < T_c$



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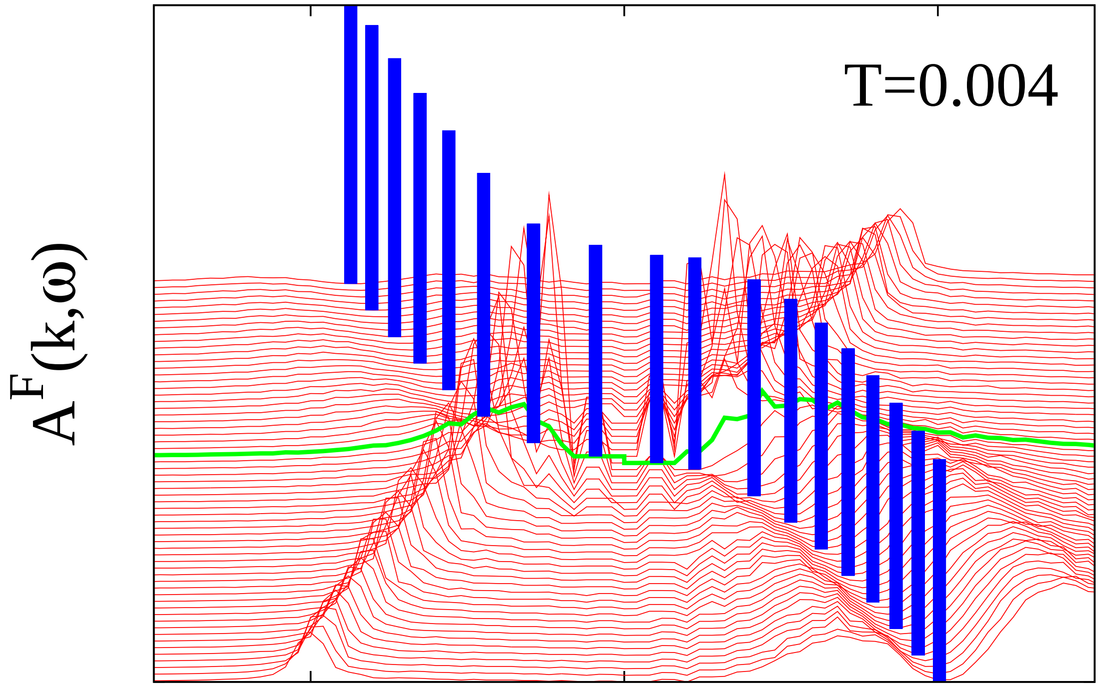

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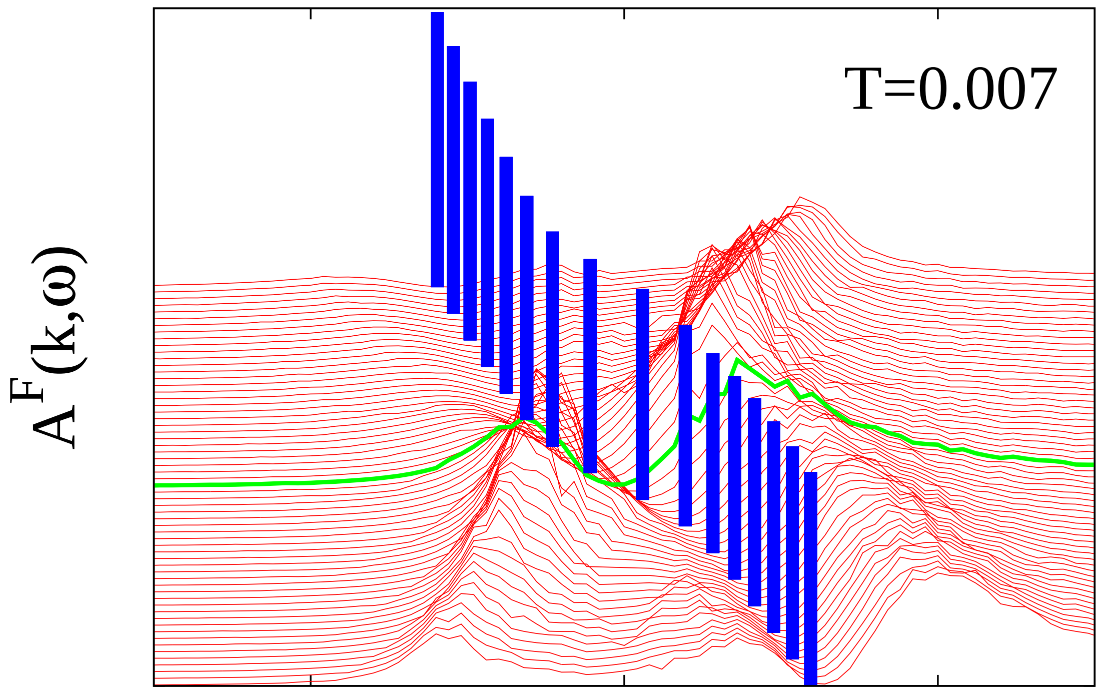

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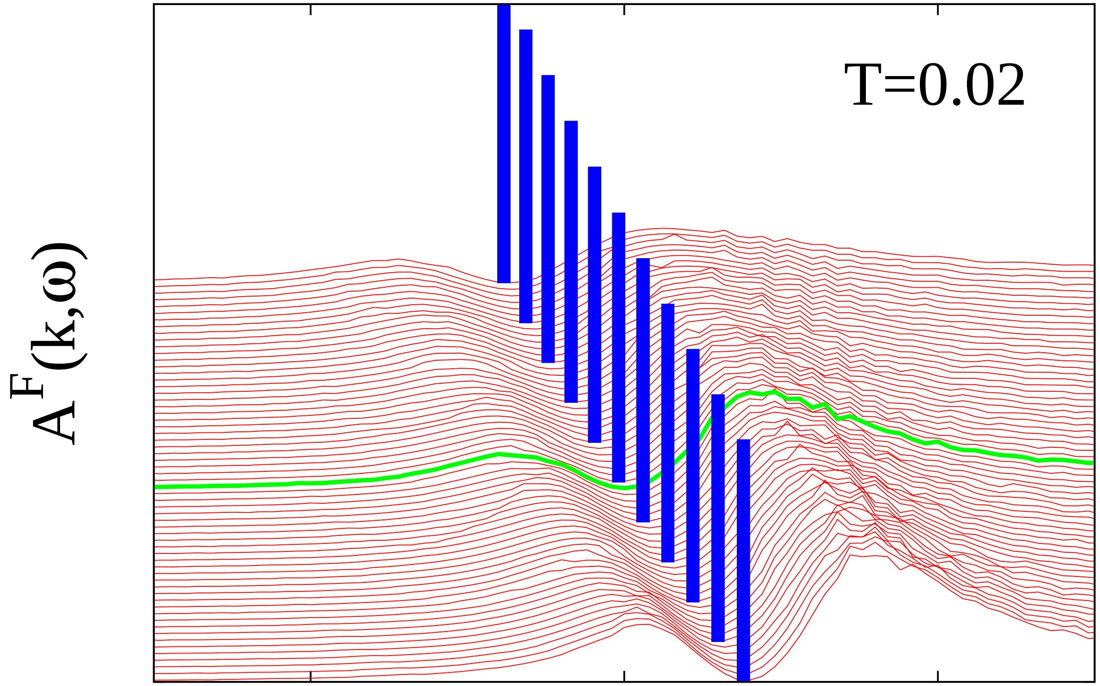

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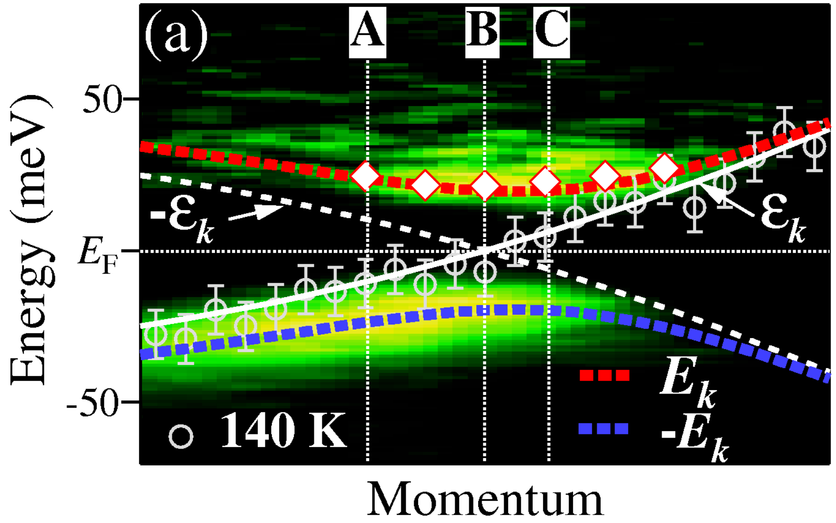
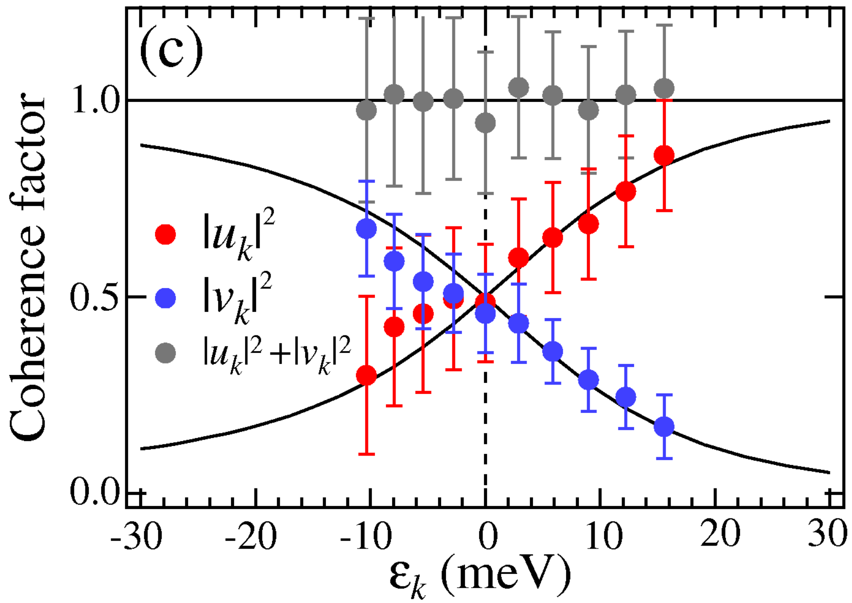
Experimental data for $T < T_c$





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

Date: Tue, 27 Feb 2007 19:05:55 +0900

From: Hiroaki Matsui <h.matsui@arpes.phys.tohoku.ac.jp>

To: Tadeusz Domanski <doman@kft.umcs.lublin.pl>

Dear Dr. Domanski,

...

We completely agree with you on that detecting the normal state BQP in the UD cuprates has a huge potential impact on the pseudogap problem. As you know, this kind of measurement is not very easy because the ARPES peak is broad in UD at anti-node and high-temperature. We do not have the data at present, but we are trying to realize such an experiment by selecting the conditions.

Thank you very much for contacting us.

Sincerely yours,

H. Matsui

Evidence for Bogoliubov QPs above T_c

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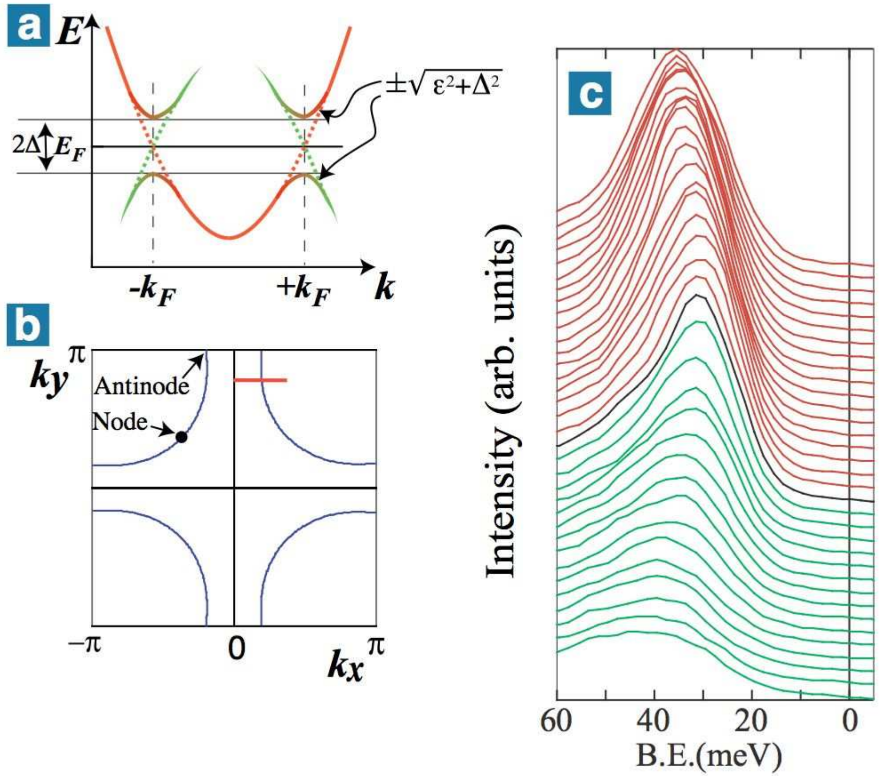

Results for: $Bi_2Sr_2CaCu_2O_8$

A. Kanigel et al, Phys. Rev. Lett. **101**, *137002 (2008).*

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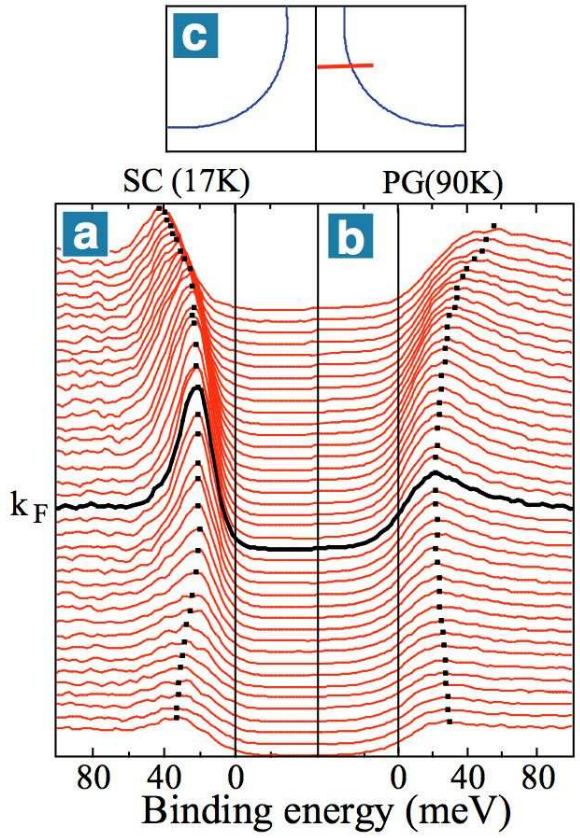

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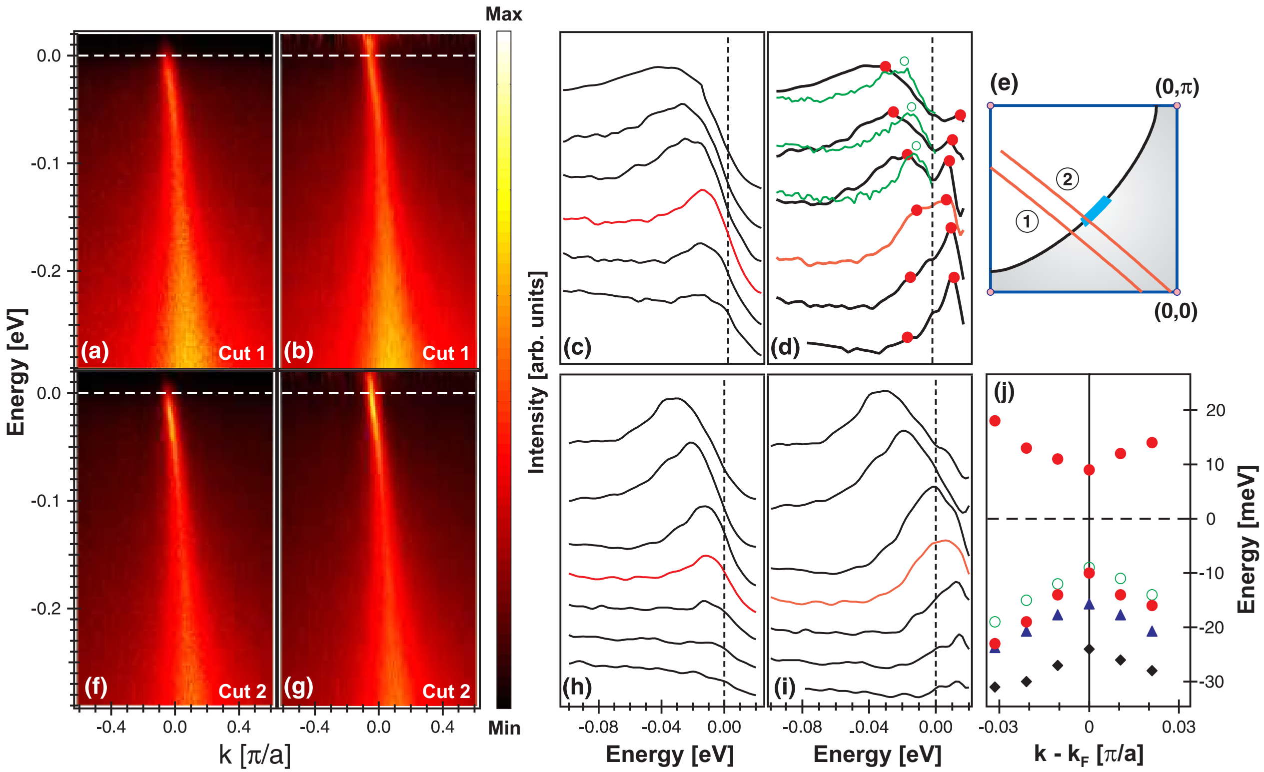
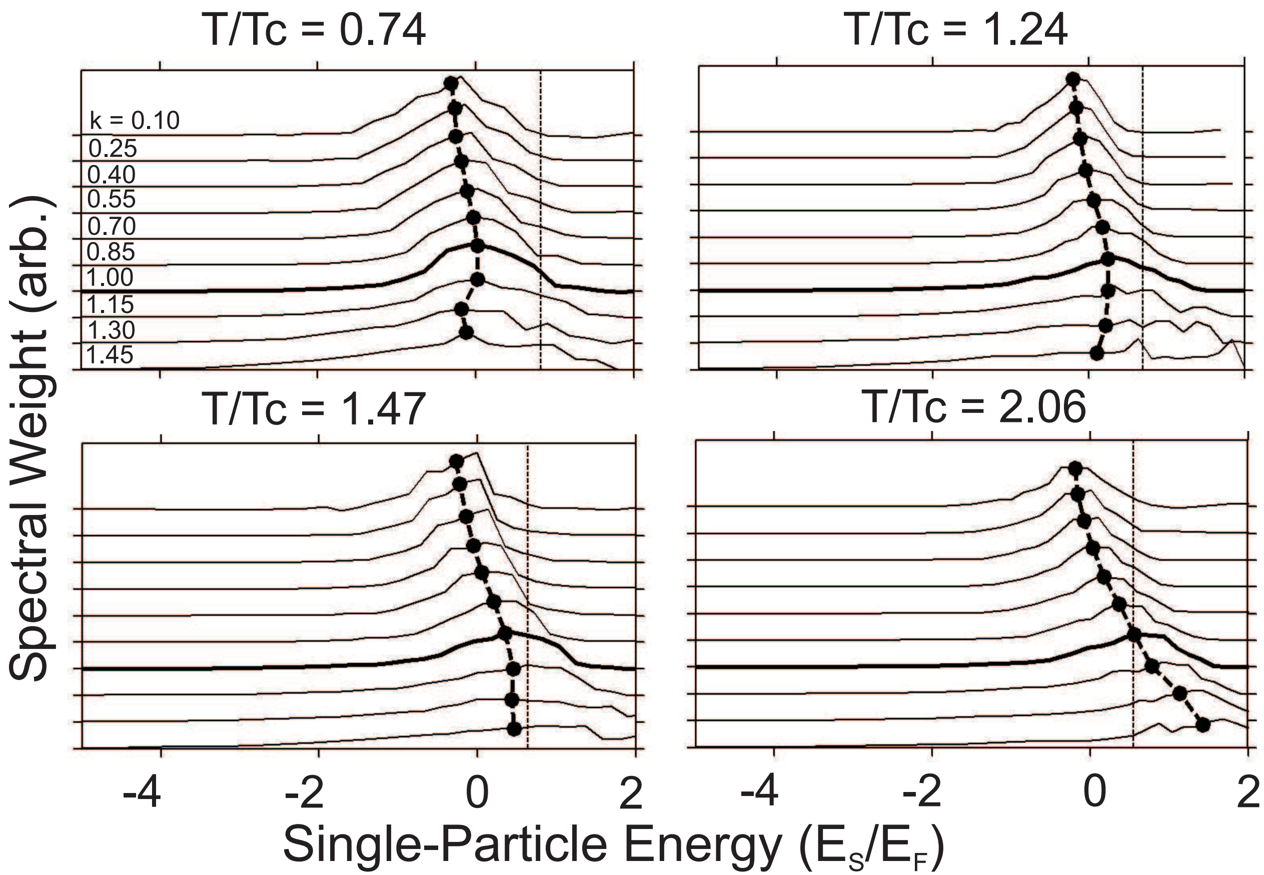


Results for: $La_{1.895}Sr_{0.105}CuO_4$

M. Shi et al, Eur. Phys. Lett. **88**, *27008 (2009).*

Evidence for Bogoliubov QPs above T_c

D. Jin group (Boulder, USA)



Results for: ultracold ^{40}K atoms

J.P. Gaebler et al, Nature Phys. **6**, *569 (2010).*

Date: Mon, 31 Mar 2008 13:57:05 +0300

From: Amit Kanigel <amitk@physics.technion.ac.il>

To: Tadeusz Domanski <doman@kft.umcs.lublin.pl>

Dear Prof. Domanski,

I'm really happy for your remarks. I read your paper (the PRL) and indeed found it very interesting. I must apologize and admit that I was not aware of the paper. While writing my paper I looked quite intensively for theoretical models predicting BG-like dispersion and for some reason I missed your work. Although the paper was already submitted I hope I'll have the chance to put in a reference to your work before publication.

If you have no objection, after I'll read the longer paper I might have few questions for you regarding the Boson-Fermion model.

Best regards,

Amit

Angular dependence of the gap

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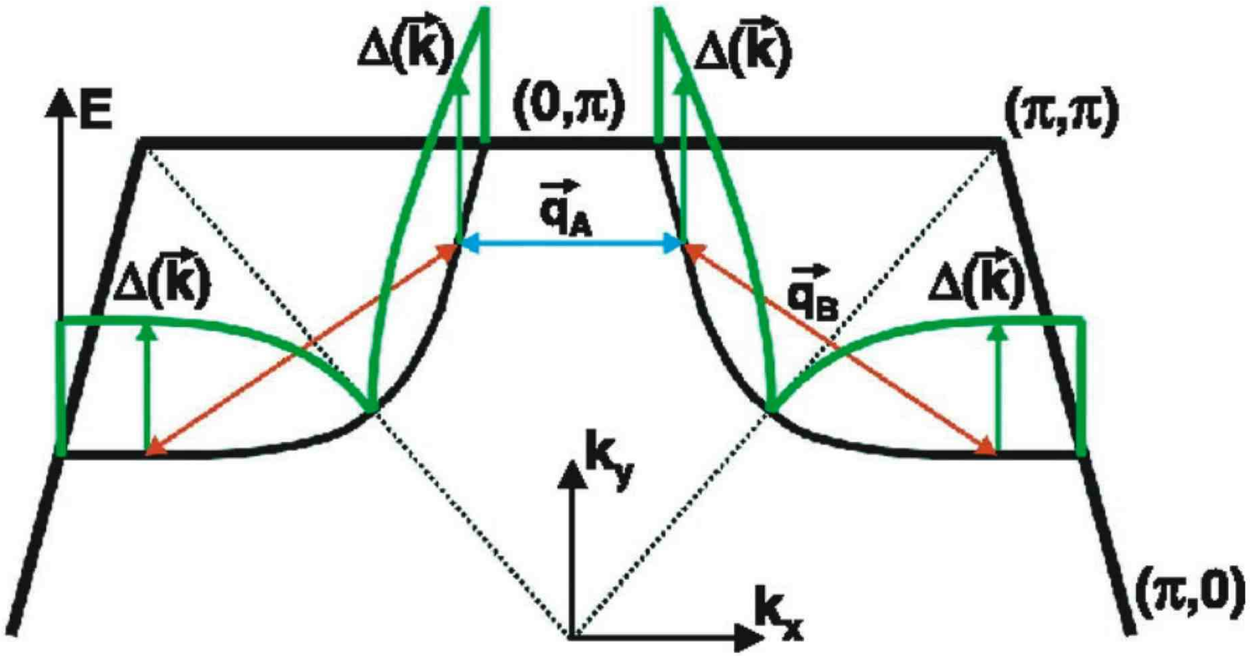

J.E. Hoffman et al, *Science* **297**, *1148 (2002).*

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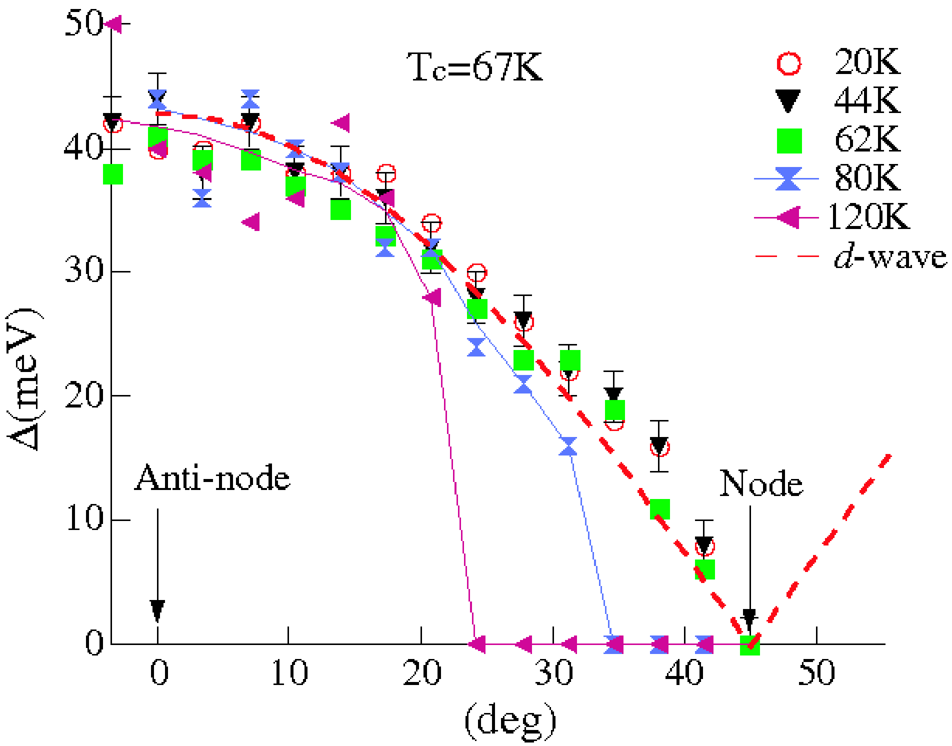

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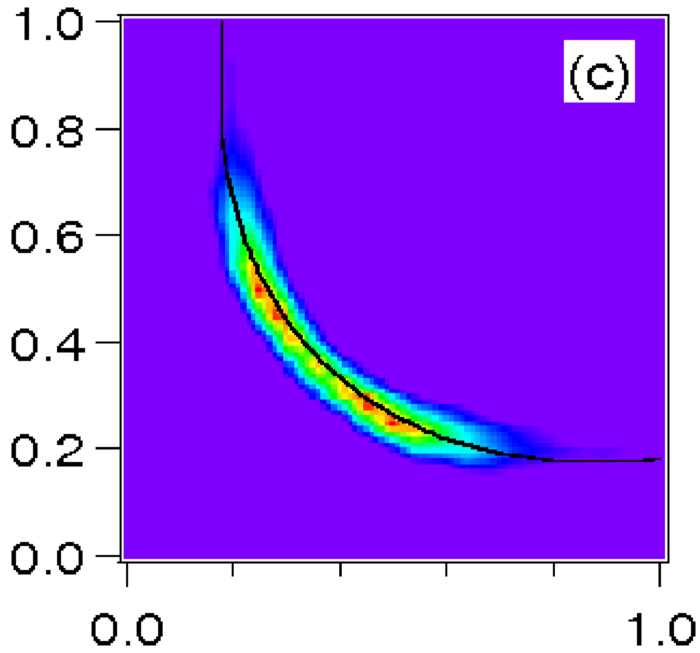

Pieces of the Fermi surface near the antinodal area are missing.

"Death of a Fermi surface" *K. McElroy, Nature Physics* **2***, 441 (2006)* .

B-F study of the angular variation

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We have examined the effect of anisotropic B-F coupling $g_{\vec{k}} = g\ [\cos(k_x) - \cos(k_y)]$ using the realistic dispersion $\varepsilon_{\vec{k}} = -2t\,[\cos(k_x) + \cos(k_y)] - 4t' \cos(k_x) \cos(k_y)$.

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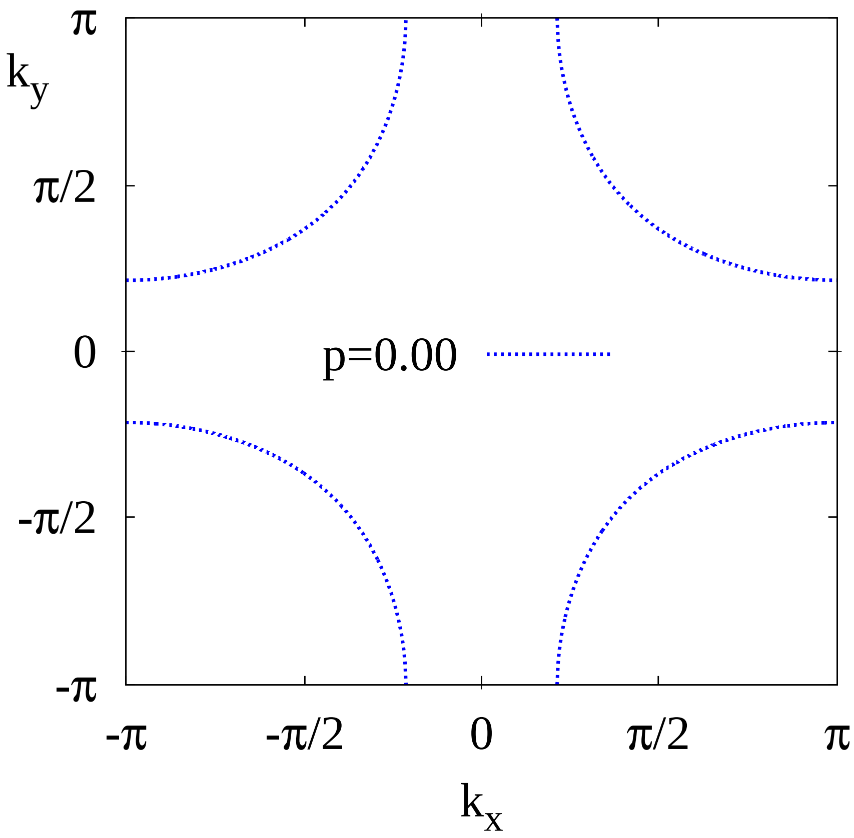

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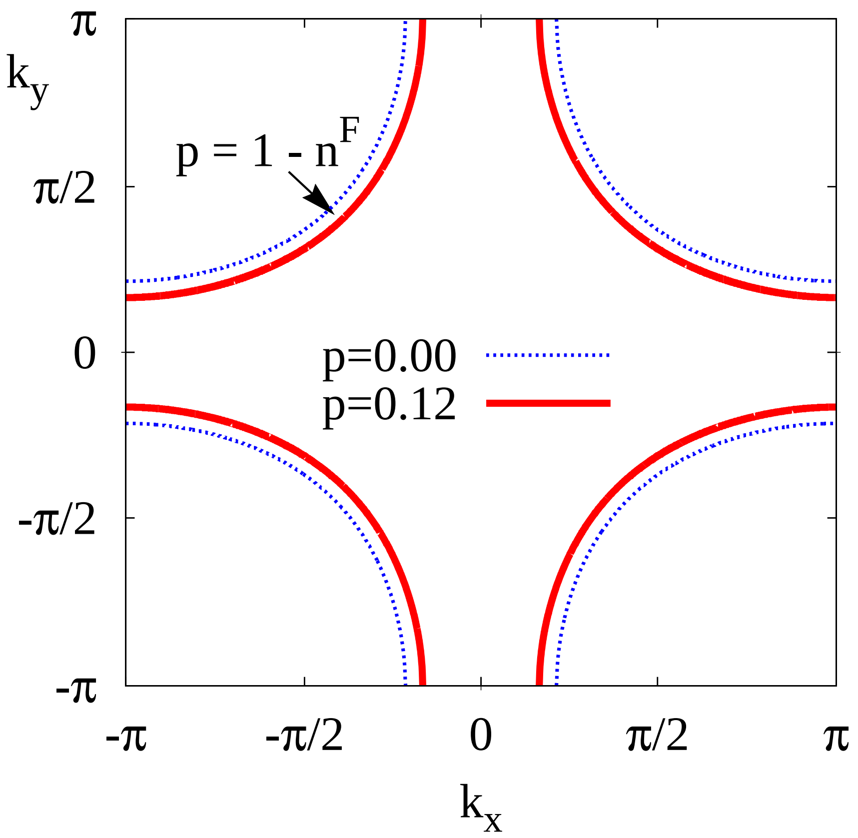

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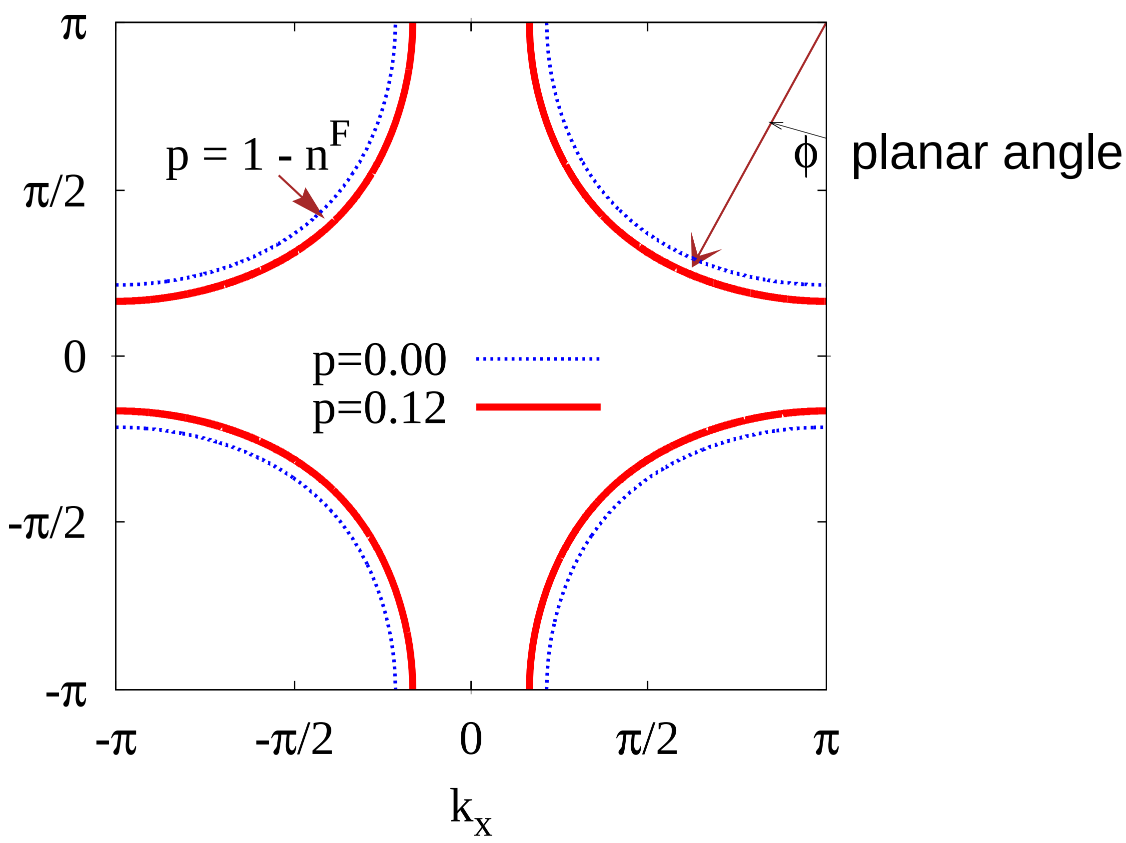

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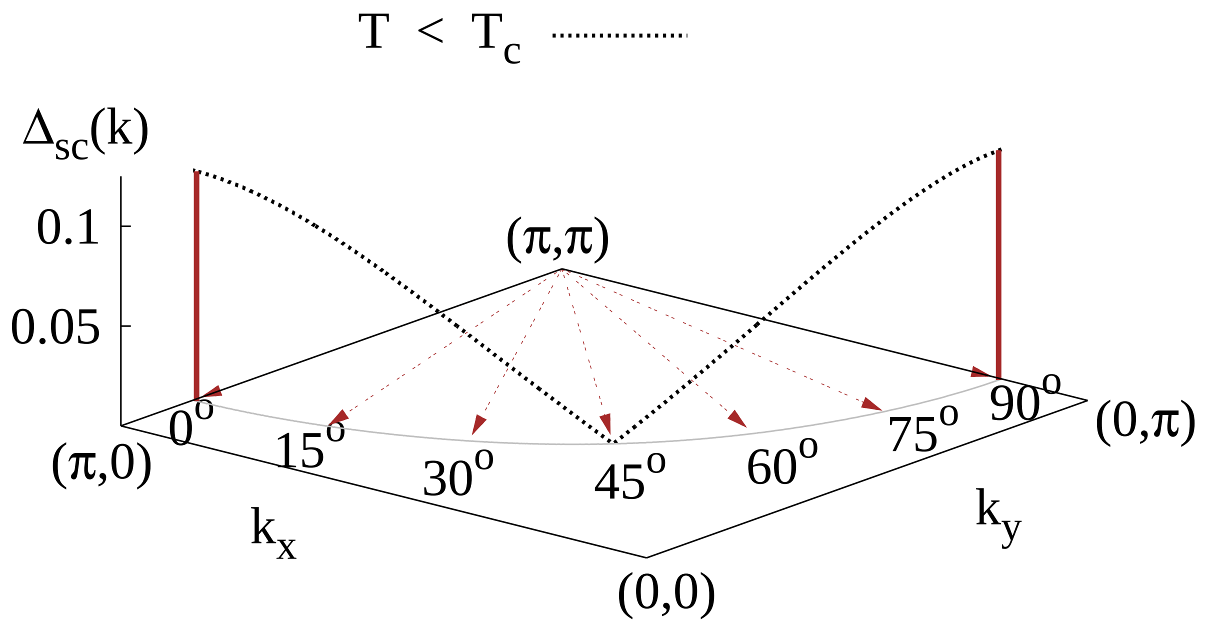

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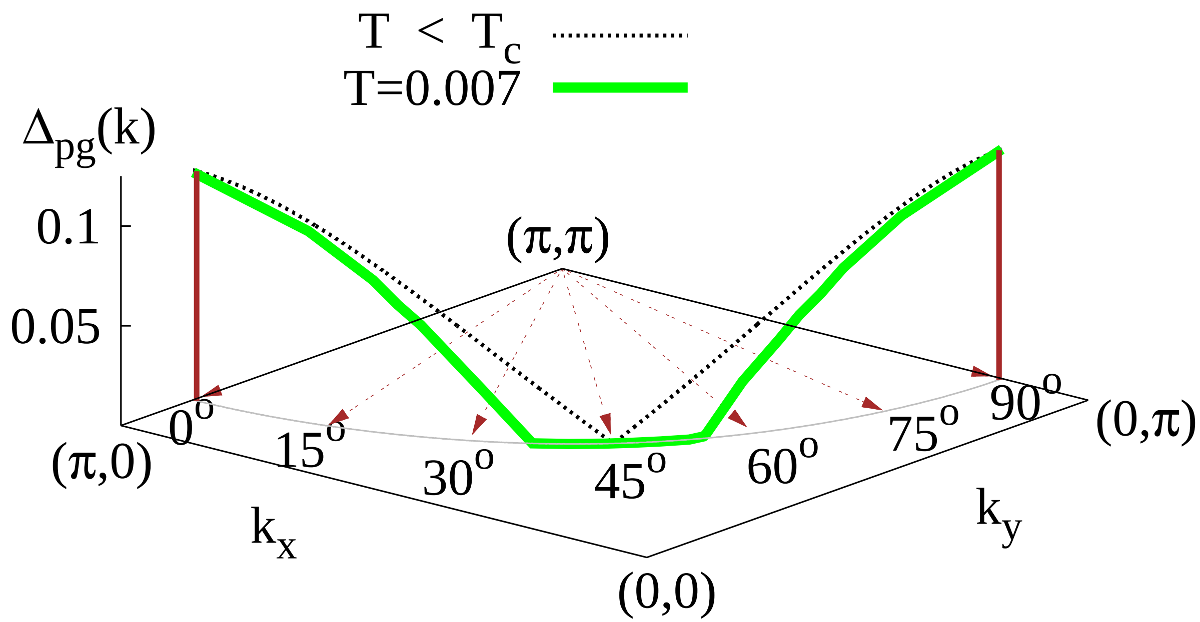

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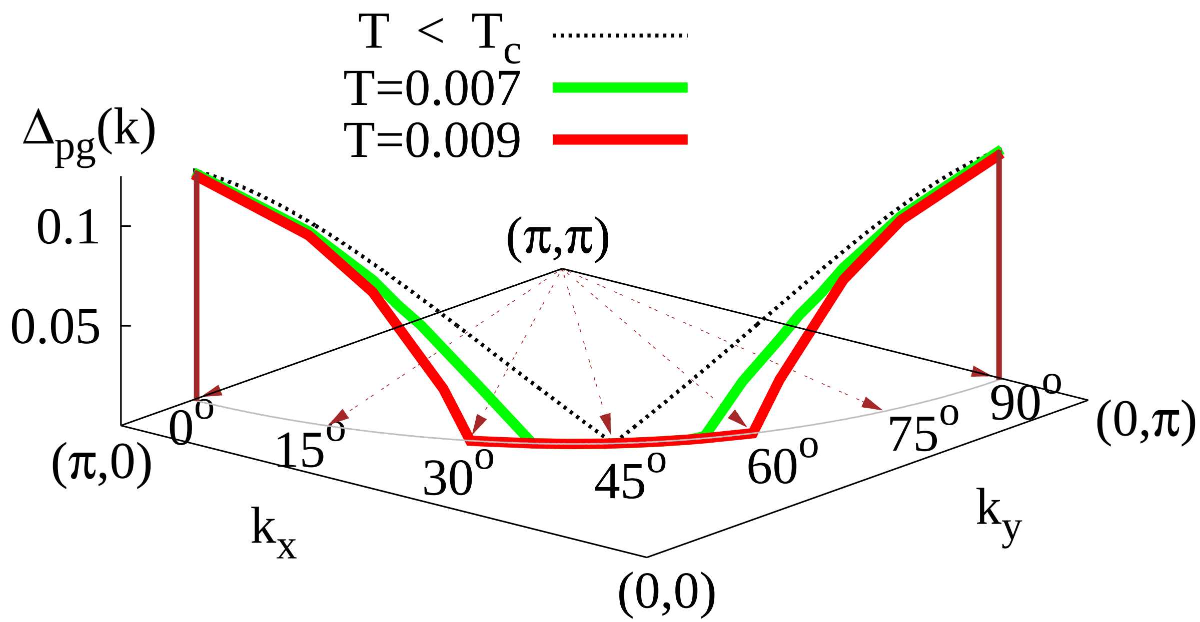

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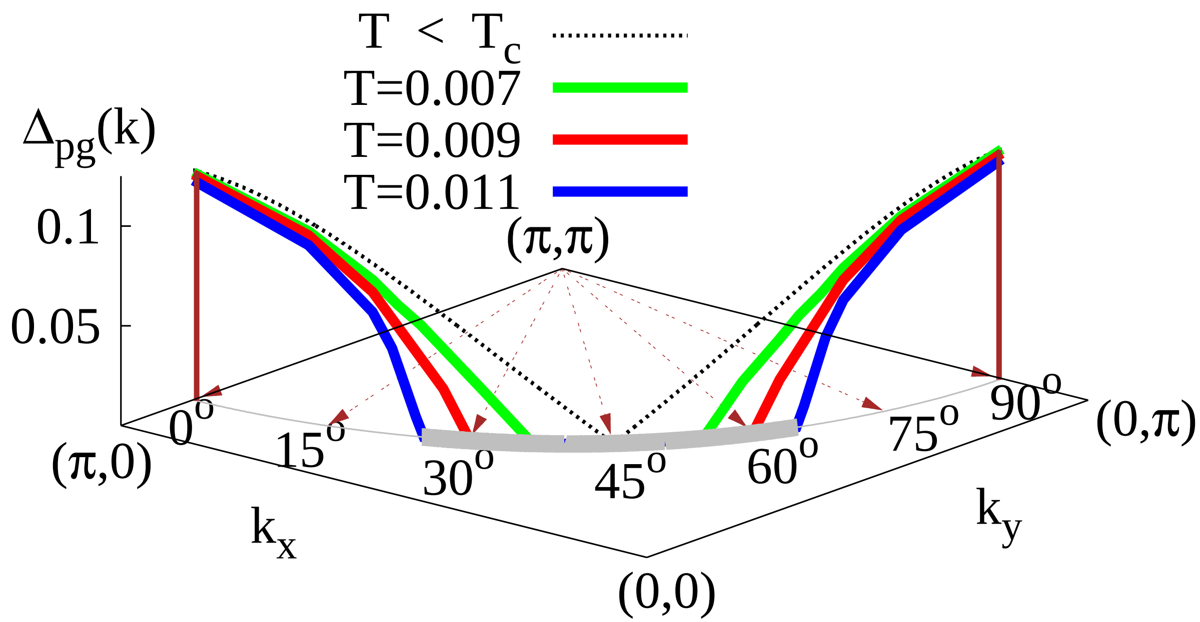

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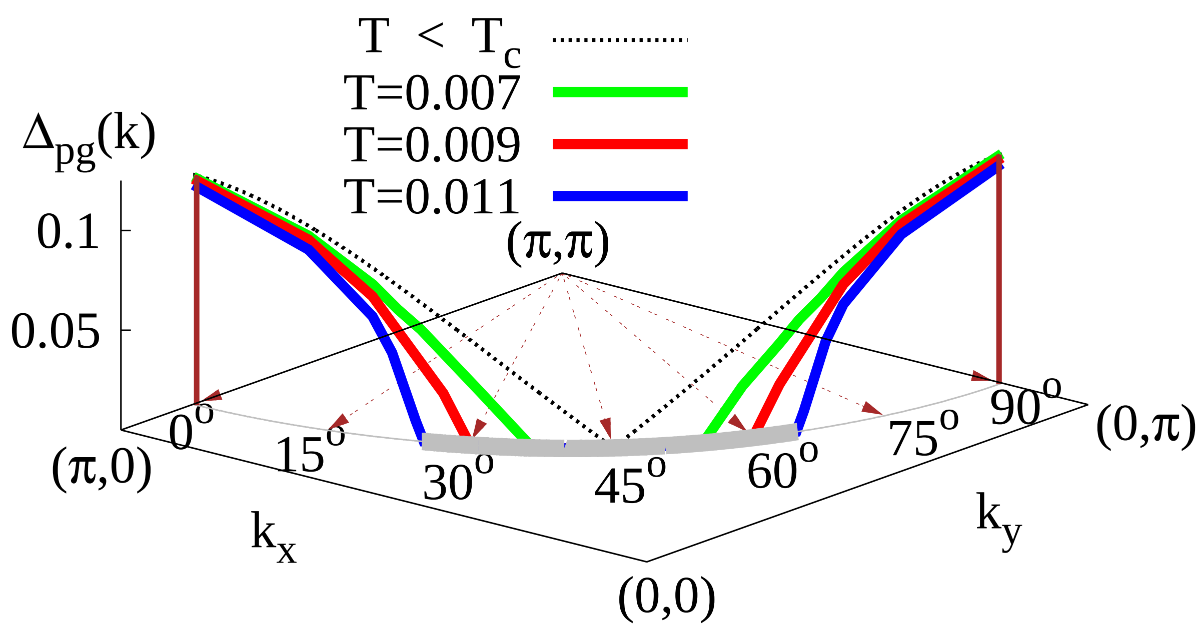

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J. Ranninger, T. Domański, Phys. Rev. B **81***, 014514 (2010).*

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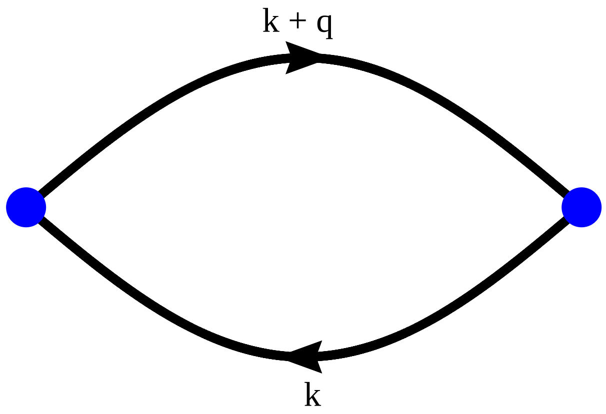

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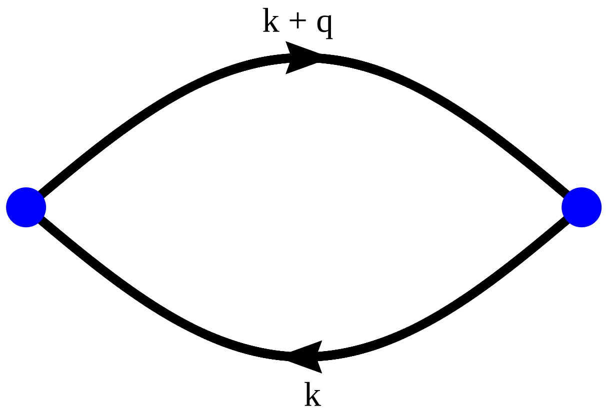

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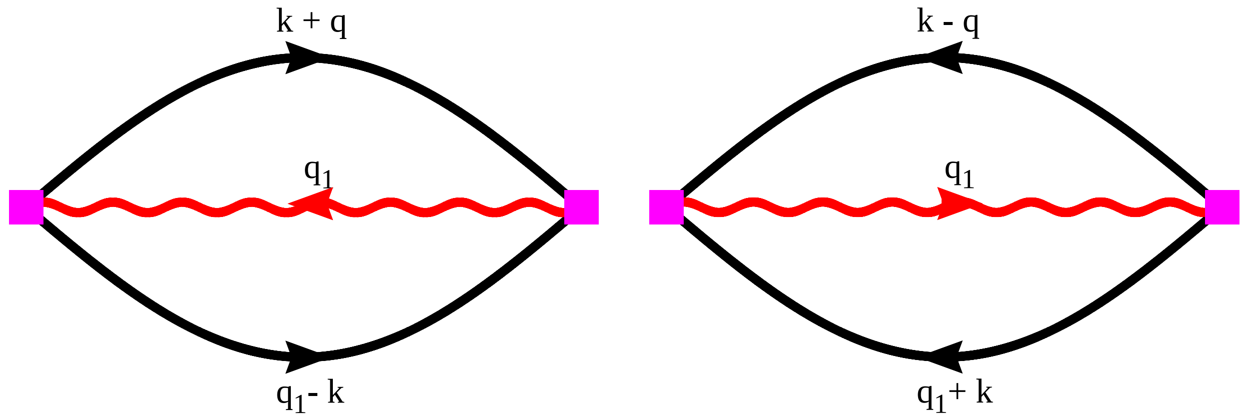

anomalous diagrams

Each vertex has to be determined from the flow equations.

T. Domanski and J. Ranninger, (2010).

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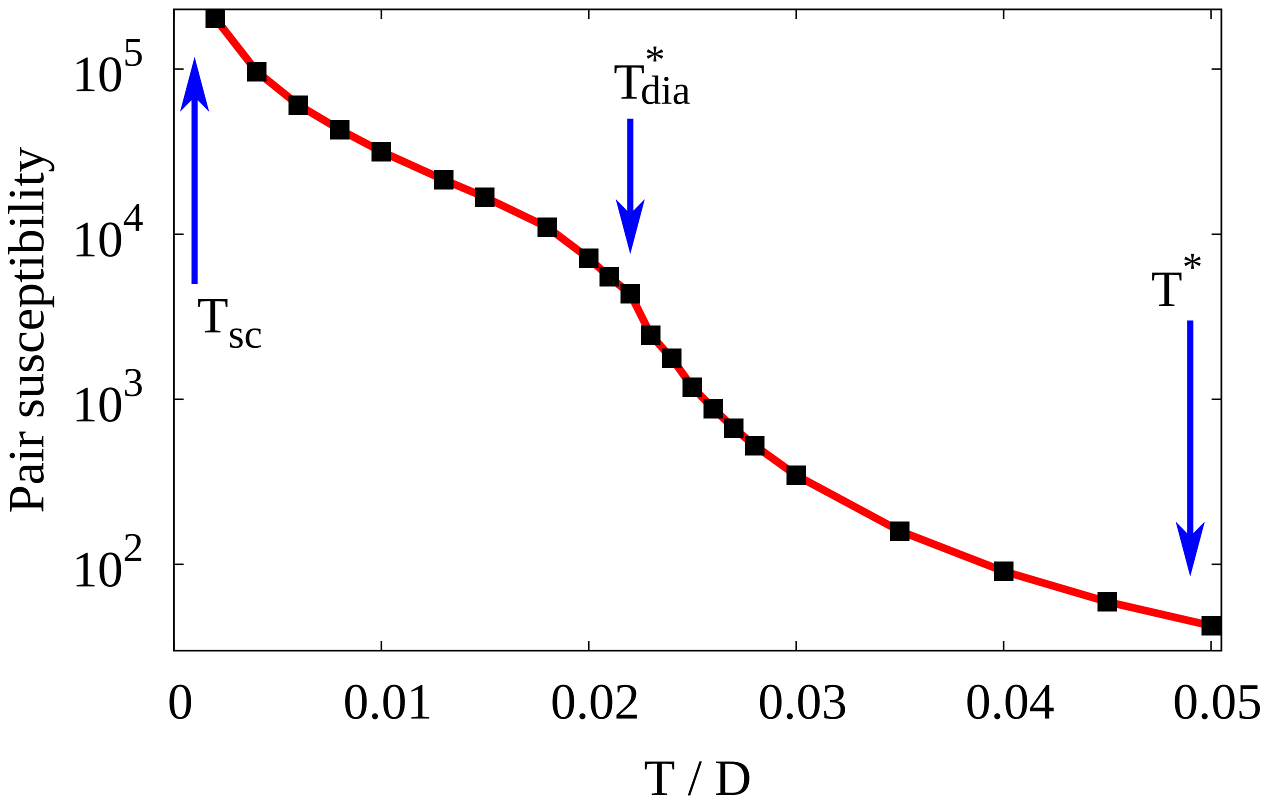

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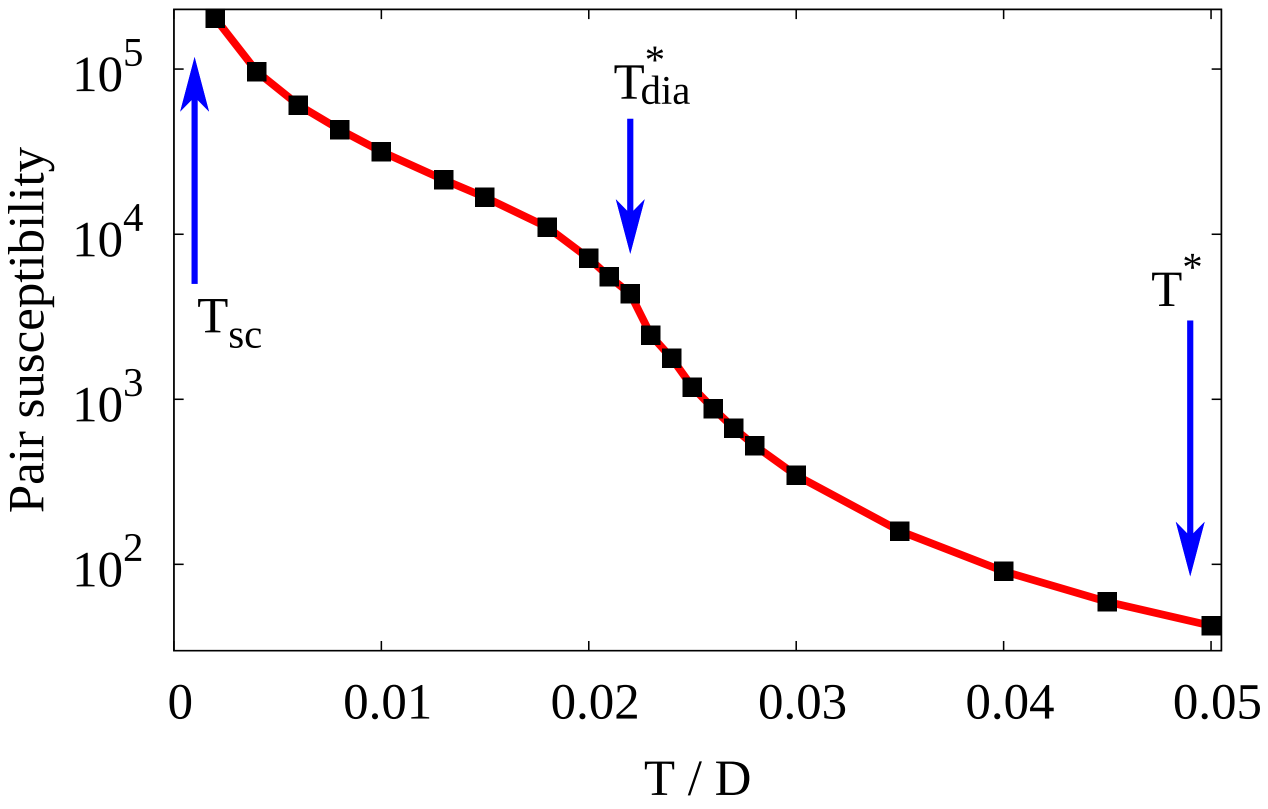

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