Wrocław, 2 Oct. 2014

Residual Meissner effect and other pre-pairing phenomena in the cuprate superconductors

T. Domański

M. Curie-Skłodowska University,

Lublin, Poland

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

Outline

Outline

- **Preliminaries**

/ pairing vs coherence /

Outline

- **Preliminaries**

  / pairing vs coherence /

- **Pre-pairing**

  / experimental evidence /

Outline

- **Preliminaries**
  / pairing vs coherence /
- **Pre-pairing**
  / experimental evidence /
- **Selected results**

Outline

- **Preliminaries**

  / pairing vs coherence /

- **Pre-pairing**

  / experimental evidence /

- **Selected results**

⇒ *Bogoliubov quasiparticles above* T_c

Outline

★ **Preliminaries**

/ pairing vs coherence /

★ **Pre-pairing**

/ experimental evidence /

★ **Selected results**

- *Bogoliubov quasiparticles above* T_c

⇒ *Diamagnetism above* T_c

Outline

- **Preliminaries**

  / pairing vs coherence /

- **Pre-pairing**

  / experimental evidence /

- **Selected results**

  - *Bogoliubov quasiparticles above* T_c
  - *Diamagnetism above* T_c

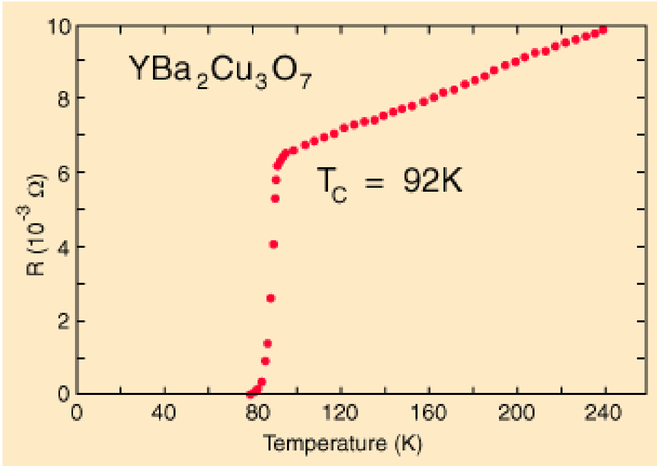
- **Summary**

1. Preliminaries

Superconducting state – properties

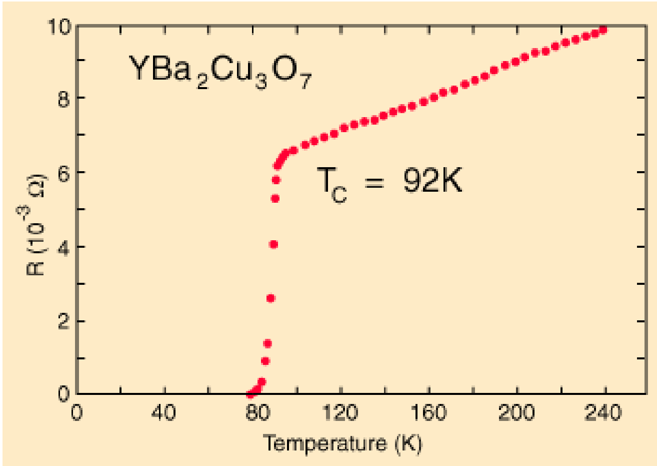
Superconducting state – properties

★ **ideal d.c. conductance**



Superconducting state – properties

★ **ideal d.c. conductance**



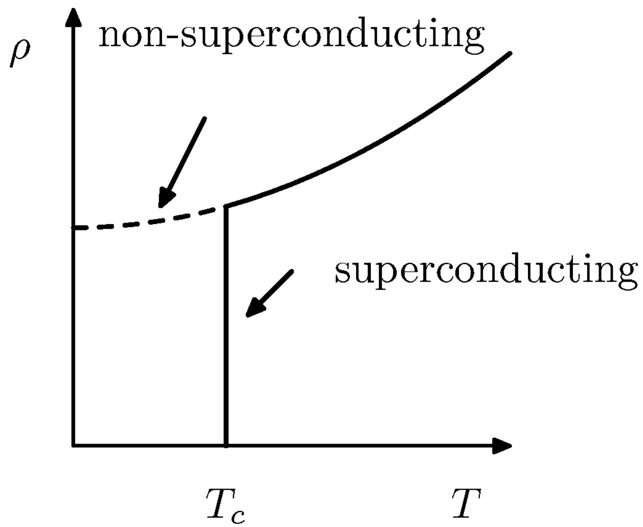
Normal conductors:

resistance $R = \rho \, \frac{l}{S}$

where $\rho \equiv 1/\sigma$

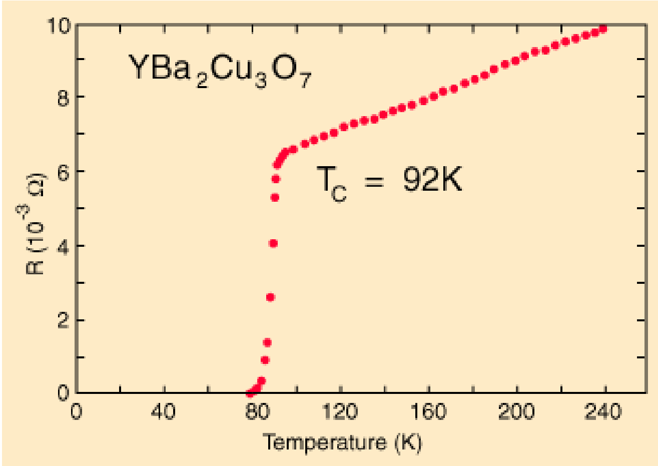
and $\sigma = \frac{ne^2\tau}{m}$

$\tau(T)$ **– relaxation time**



Superconducting state – properties

* **ideal d.c. conductance**



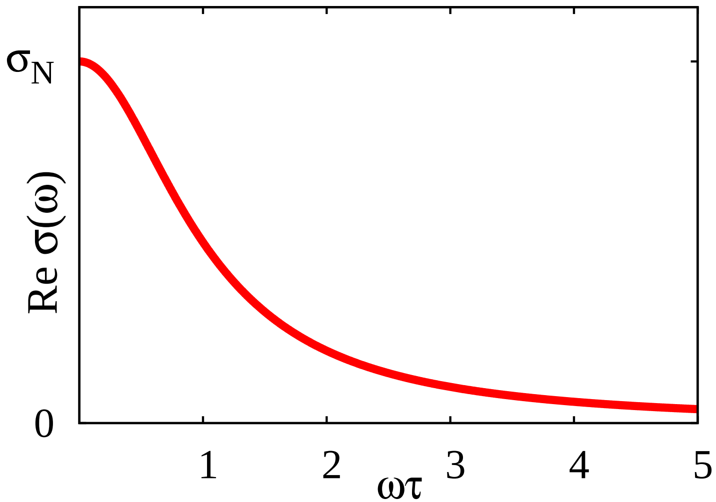
a.c. conductance

Drude conductance

$$\sigma(\omega) = \frac{ne^2\tau}{m} \frac{1}{1-i\omega\tau}$$

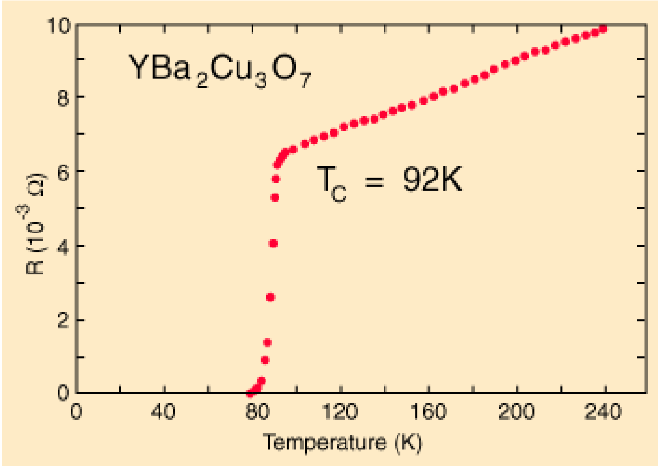
obeys the f-sum rule

$$\int_{-\infty}^{\infty} \mathrm{Re}\,\sigma(\omega) = \pi\,\frac{ne^2}{m}$$



Superconducting state – properties

⋆ **ideal d.c. conductance**



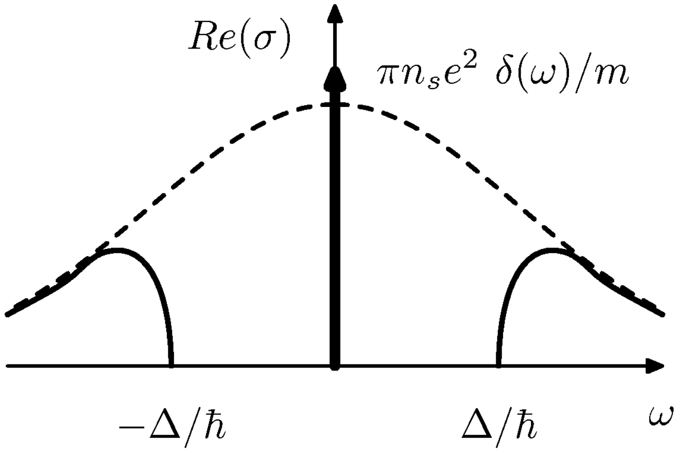
a.c. conductance

This f-sum rule

$$\int_{-\infty}^{\infty} \mathrm{Re}\ \sigma(\omega) = \pi\ \frac{ne^2}{m}$$

must be obeyed also below T_c, where

$$n = n_n + n_s$$

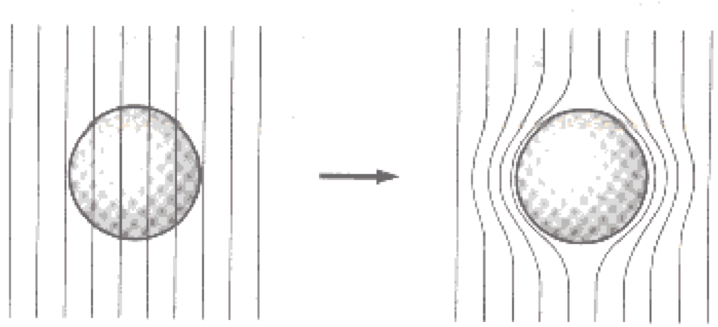


n_s – **superfluid density**

Superconducting state – properties (continued)

Superconducting state – properties (continued)

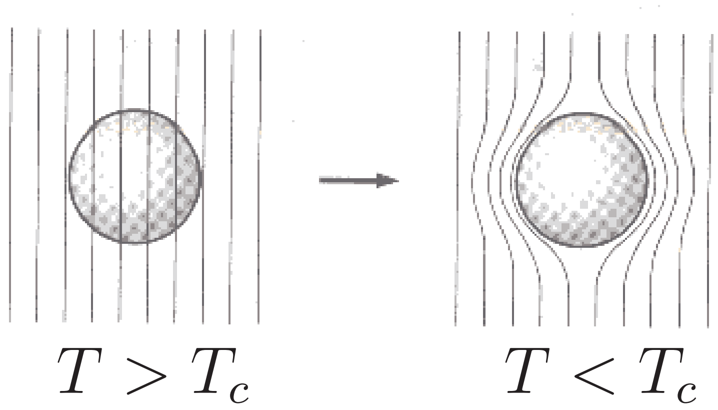
⋆ **ideal diamagnetism** /perfect screening of d.c. magnetic field/



$T > T_c$ $\quad\longrightarrow\quad$ $T < T_c$

Superconducting state – properties (continued)

★ **ideal diamagnetism** /perfect screening of d.c. magnetic field/



Meissner effect is described by the Londons' equation

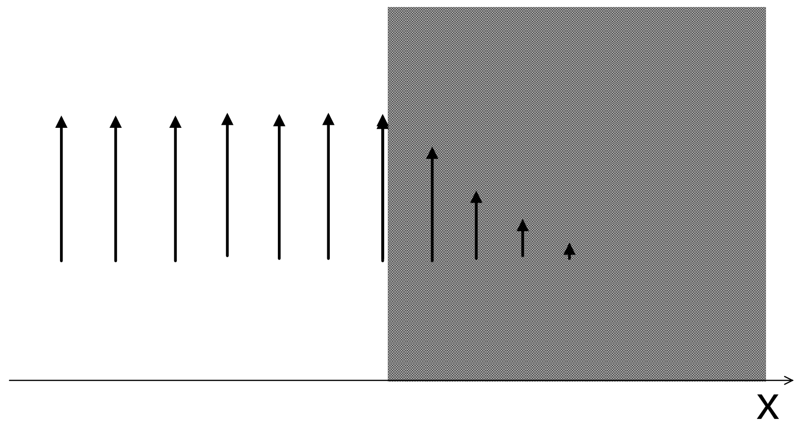
$$\vec{j} = -\frac{e^2 n_s(T)}{mc^2}\,\vec{A}$$

where the coefficient

$$\frac{e^2 n_s(T)}{mc^2} \equiv \rho_s(T) = \frac{1}{\lambda^2}$$

$\rho_s(T)$ **– superfluid stiffness**

$\lambda(T)$ – penetration depth



$$B(x) = B_0\, e^{-x/\lambda}$$

Superconducting state – basic concepts

Superconducting state – basic concepts

⇒ **ideal d.c. conductance**

Superconducting state – basic concepts

⇒ **ideal d.c. conductance**

⇒ **ideal diamagnetism (Meissner effect)**

Superconducting state – basic concepts

⇒ ideal d.c. conductance

⇒ ideal diamagnetism (Meissner effect)

can be regarded as two sides of the same coin.

Superconducting state – basic concepts

⇒ ideal d.c. conductance

⇒ ideal diamagnetism (Meissner effect)

can be regarded as two sides of the same coin.

Both effects are caused by the superfluid fraction

$$n_s(T)$$

Such superfluid fraction marks the coherence between paired electrons.

Such superfluid fraction marks the coherence between paired electrons.

Pairing mechanisms can be driven for instance by:

Such superfluid fraction marks the coherence between paired electrons.

Pairing mechanisms can be driven for instance by:

1. **exchange of phonons**

   / classical superconductors, MgB_2, ... /

Such superfluid fraction marks the coherence between paired electrons.

Pairing mechanisms can be driven for instance by:

1. **exchange of phonons**

   / classical superconductors, MgB_2, ... /

2. **exchange of magnons**

   / heavy fermion compounds /

Such superfluid fraction marks the coherence between paired electrons.

Pairing mechanisms can be driven for instance by:

1. **exchange of phonons**

   / classical superconductors, MgB_2, ... /

2. **exchange of magnons**

   / heavy fermion compounds /

3. **strong correlations**

   / exchange coupling $\frac{2t_{ij}^2}{U}$ *in the high* T_c *superconductors /*

Such superfluid fraction marks the coherence between paired electrons.

Pairing mechanisms can be driven for instance by:

1. **exchange of phonons**

   / classical superconductors, MgB_2, ... /

2. **exchange of magnons**

   / heavy fermion compounds /

3. **strong correlations**

   / exchange coupling $\frac{2t_{ij}^2}{U}$ in the high T_c superconductors /

.. **other exotic processes**

   / ultracold atoms, nuclei, gluon-quark plasma /

Such superfluid fraction marks the coherence between paired electrons.

Pairing mechanisms can be driven for instance by:

1. **exchange of phonons**

   / classical superconductors, MgB_2, ... /

2. **exchange of magnons**

   / heavy fermion compounds /

3. **strong correlations**

   / exchange coupling $\frac{2t_{ij}^2}{U}$ in the high T_c superconductors /

.. **other exotic processes**

   / ultracold atoms, nuclei, gluon-quark plasma /

Onset of the fermion pairing often goes hand in hand with appearance of the superconductivity/superfluidity but it doesn't have to be a rule.

Formal issues – generalities

Formal issues – generalities

The order parameter

$$\chi \equiv \langle \hat{c}_{\downarrow}(\vec{r}_i)\hat{c}_{\uparrow}(\vec{r}_j)\rangle$$

Formal issues – generalities

The order parameter

$$\chi \equiv \langle \hat{c}_{\downarrow}(\vec{r}_i)\hat{c}_{\uparrow}(\vec{r}_j)\rangle$$

is a complex quantity

$$\chi = |\chi| \, e^{i\theta}$$

Formal issues – generalities

The order parameter

$$\chi \equiv \langle \hat{c}_{\downarrow}(\vec{r}_i)\hat{c}_{\uparrow}(\vec{r}_j)\rangle$$

is a complex quantity

$$\chi = |\chi|\ e^{i\theta}$$

It has the following physical implications:

Formal issues – generalities

The order parameter

$$\chi \equiv \langle \hat{c}_{\downarrow}(\vec{r}_i)\hat{c}_{\uparrow}(\vec{r}_j)\rangle$$

is a complex quantity

$$\chi = |\chi| \, e^{i\theta}$$

It has the following physical implications:

$|\chi| \neq 0$ $\longrightarrow$ **amplitude causes the energy gap**

Formal issues – generalities

The order parameter

$$\chi \equiv \langle \hat{c}_{\downarrow}(\vec{r}_i)\hat{c}_{\uparrow}(\vec{r}_j)\rangle$$

is a complex quantity

$$\chi = |\chi| \, e^{i\theta}$$

It has the following physical implications:

$|\chi| \neq 0 \longrightarrow$ **amplitude causes the energy gap**

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

Critical temperature – classification

Critical temperature – classification

The complex order parameter

$$\chi = |\chi| \, e^{i\theta}$$

Critical temperature – classification

The complex order parameter

$$\chi = |\chi| \, e^{i\theta}$$

can vanish at $T \to T_c$ by:

Critical temperature – classification

The complex order parameter

$$\chi = |\chi| \, e^{i\theta}$$

can vanish at $T \to T_c$ by:

1. **closing the gap** . . . . **[conventional BCS superconductors]**

$$\lim_{T \to T_c} |\chi| = 0$$

Critical temperature – classification

The complex order parameter

$$\chi = |\chi| \, e^{i\theta}$$

can vanish at $T \longrightarrow T_c$ by:

1. **closing the gap** .... **[conventional BCS superconductors]**

$$\lim_{T\to T_c} |\chi| = 0$$

2. **disordering the phase** .... **[HTSC compounds, URh_2Si_2 (?)]**

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

Amplitude vs phase driven transition

scenario # 1

Amplitude vs phase driven transition

scenario # 1

⇒ **amplitude transition** */ classical superconductors /*

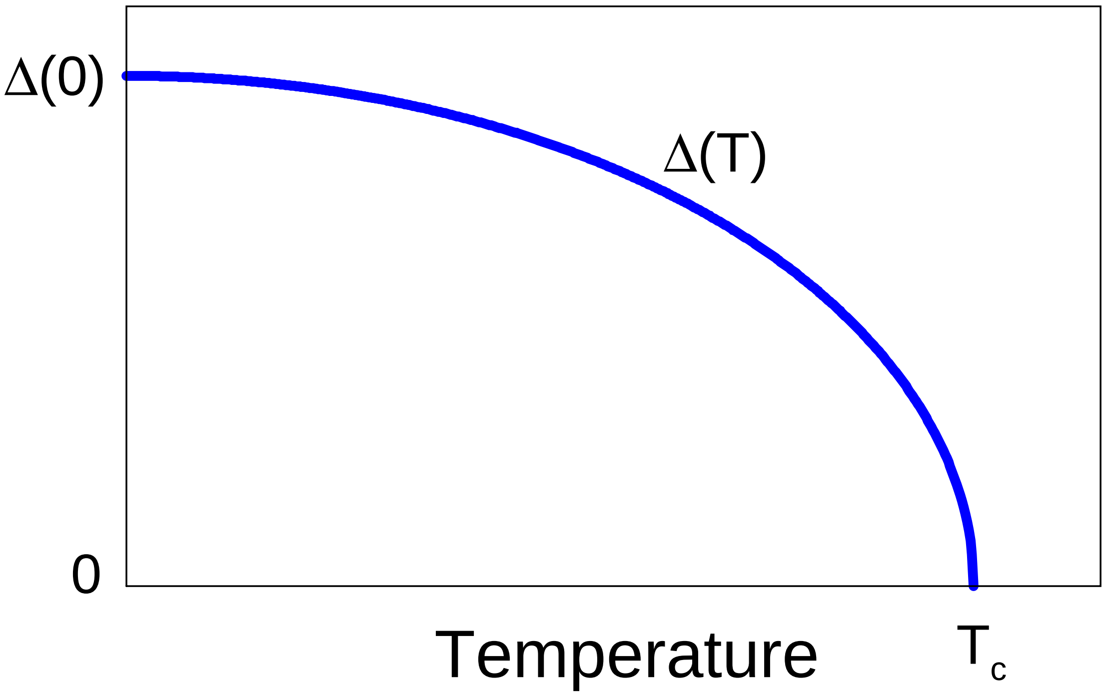
$$k_B\, T_c \simeq \frac{\Delta(0)}{1.76}$$

Amplitude vs phase driven transition

scenario # 1

⇒ **amplitude transition** */ classical superconductors /*

$$k_B\, T_c \simeq \frac{\Delta(0)}{1.76}$$



Electrons' pairing is responsible for the energy gap $\Delta(T)$ in a single particle spectrum

$$\Delta(T_c) = 0$$

Appearance of the electron pairs is simultaneous with onset of their coherence

Amplitude vs phase driven transition

scenario # 2

Amplitude vs phase driven transition

scenario $\#$ 2

$\Rightarrow$ **phase-driven transition** */ high T_c cuprate oxides /*

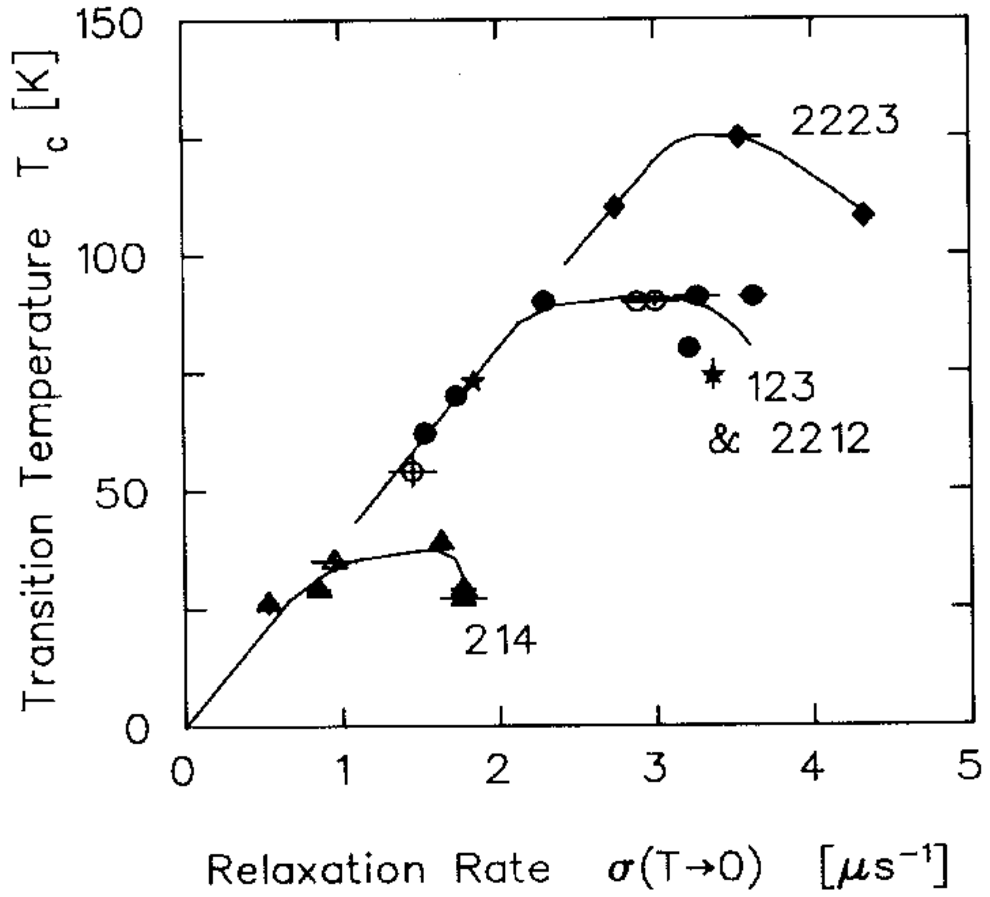
$T_c \not\sim \Delta(0)$

Amplitude vs phase driven transition

scenario # 2

⇒ **phase-driven transition** */ high T_c cuprate oxides /*

$$T_c \not\sim \Delta(0)$$



Y.J. Uemura et al, Phys. Rev. Lett. ***62****, 2317 (1989).*

Early experiments using the muon-spin relaxation indicated that in HTSC

$$T_c \propto \rho_s(0)$$

/ Uemura scaling /

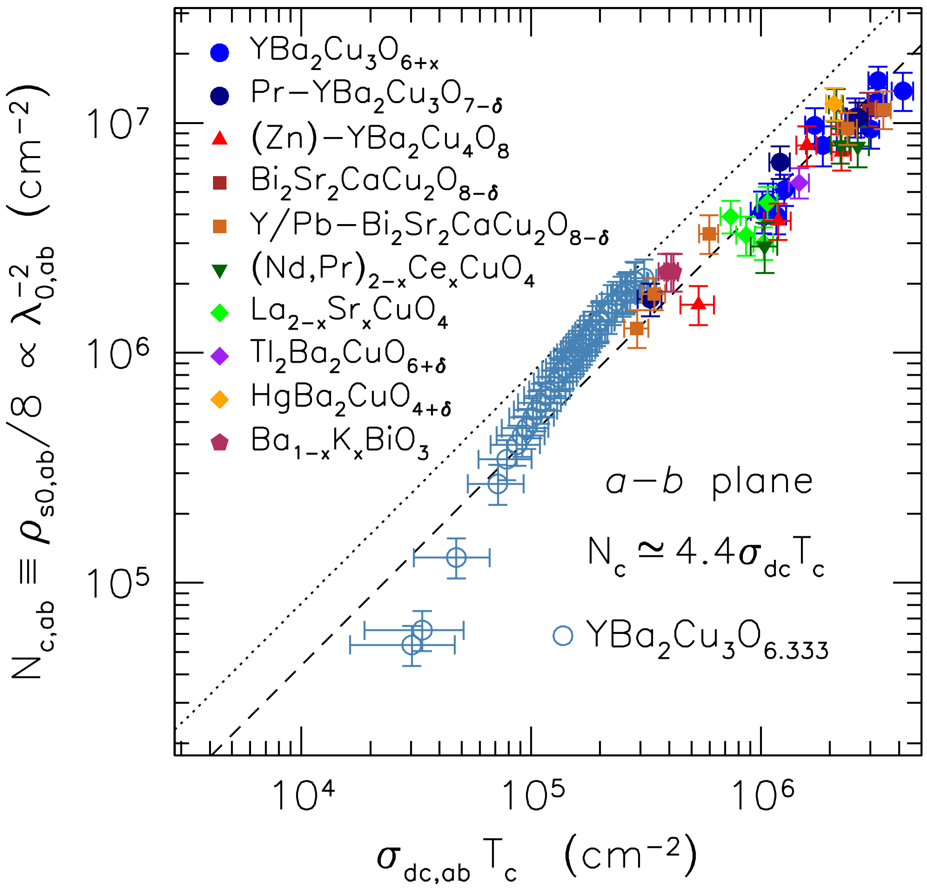
The superfluid stiffness $\rho_s(T)$ is here defined by

$$\rho_s(T) \equiv \frac{1}{\lambda^2(T)} = \frac{4\pi e^2}{m^* c^2} n_s(T)$$

Amplitude vs phase driven transition

scenario # 2

⇒ **phase-driven transition** */ high T_c cuprate oxides /* $T_c \not\sim \Delta(0)$



Recently such scaling has been updated from transport measurements

$$\frac{1}{8}\rho_s = 4.4\sigma_{dc}\, T_c$$

/ Homes scaling /

This new relation is valid for all samples ranging from the underdoped to overdoped region.

C.C. Homes, Phys. Rev. B **80***, 180509(R) (2009).*

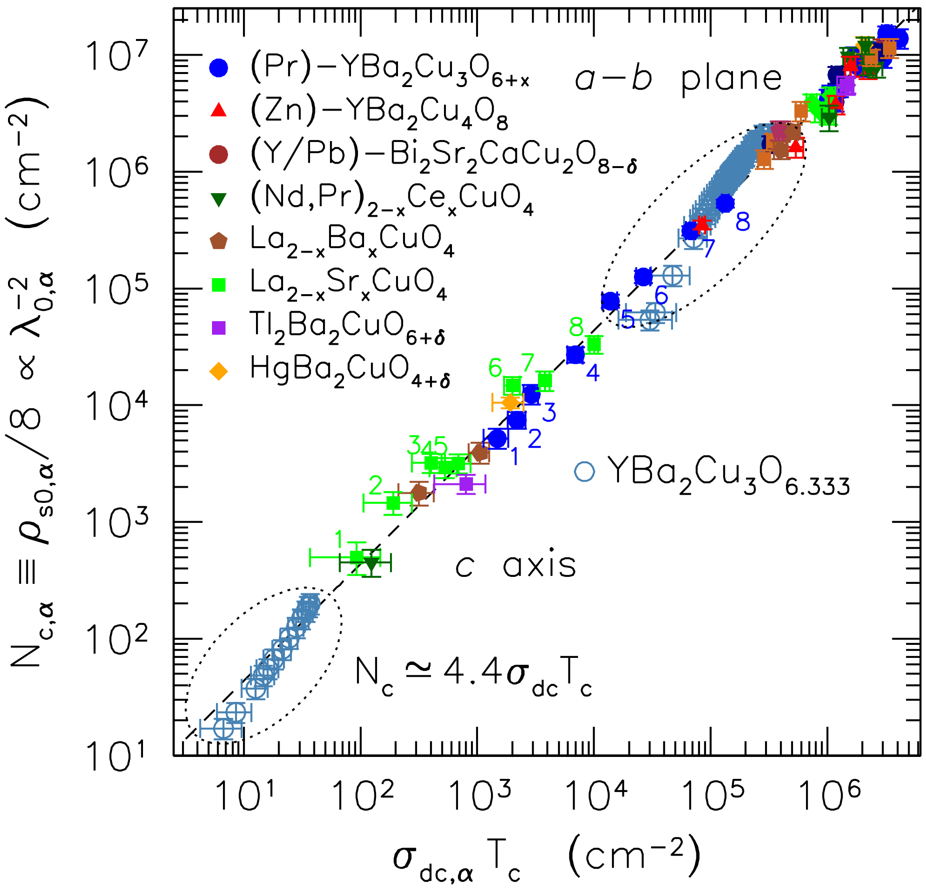
/ ab - plane /

Amplitude vs phase driven transition

scenario # 2

⇒ **phase-driven transition** */ high T_c cuprate oxides /*

$T_c \not\sim \Delta(0)$



C.C. Homes, Phys. Rev. B ***80****, 180509(R) (2009).*

Recently such scaling has been updated from transport measurements

$$\frac{1}{8}\rho_s = 4.4\sigma_{dc}\, T_c$$

/ Homes scaling /

This new relation is valid for all samples ranging from the underdoped to overdoped region.

/ c - axis /

2. Pre-pairing

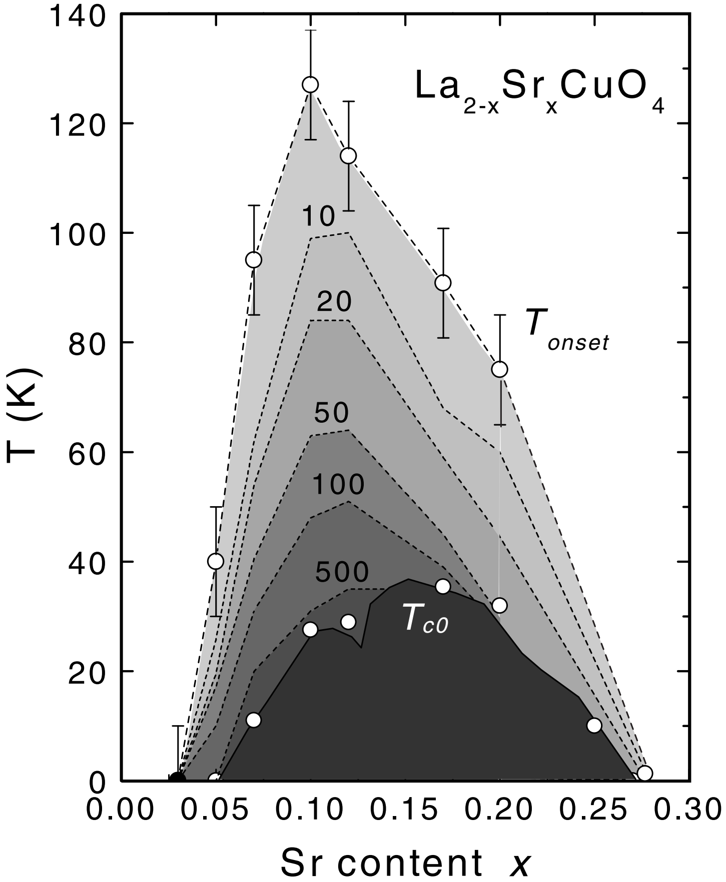
/experimental evidence/

Incoherent pairs above T_c

experimental fact $\#$ 1

Incoherent pairs above T_c

experimental fact # 1

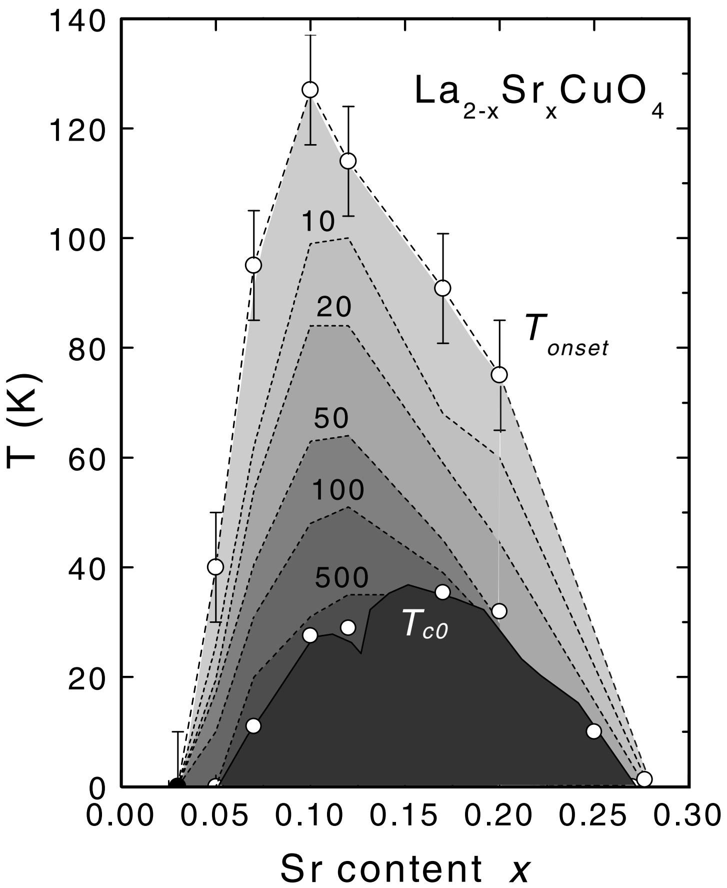


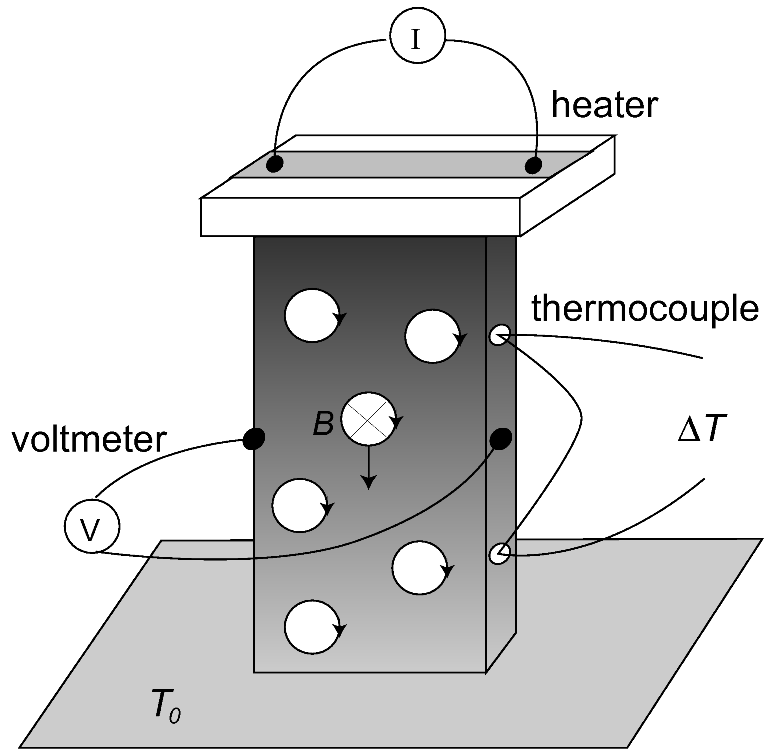
Phase slippage detected in the large Nernst effect.

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

Incoherent pairs above T_c

experimental fact # 1





Phase slippage detected in the large Nernst effect.

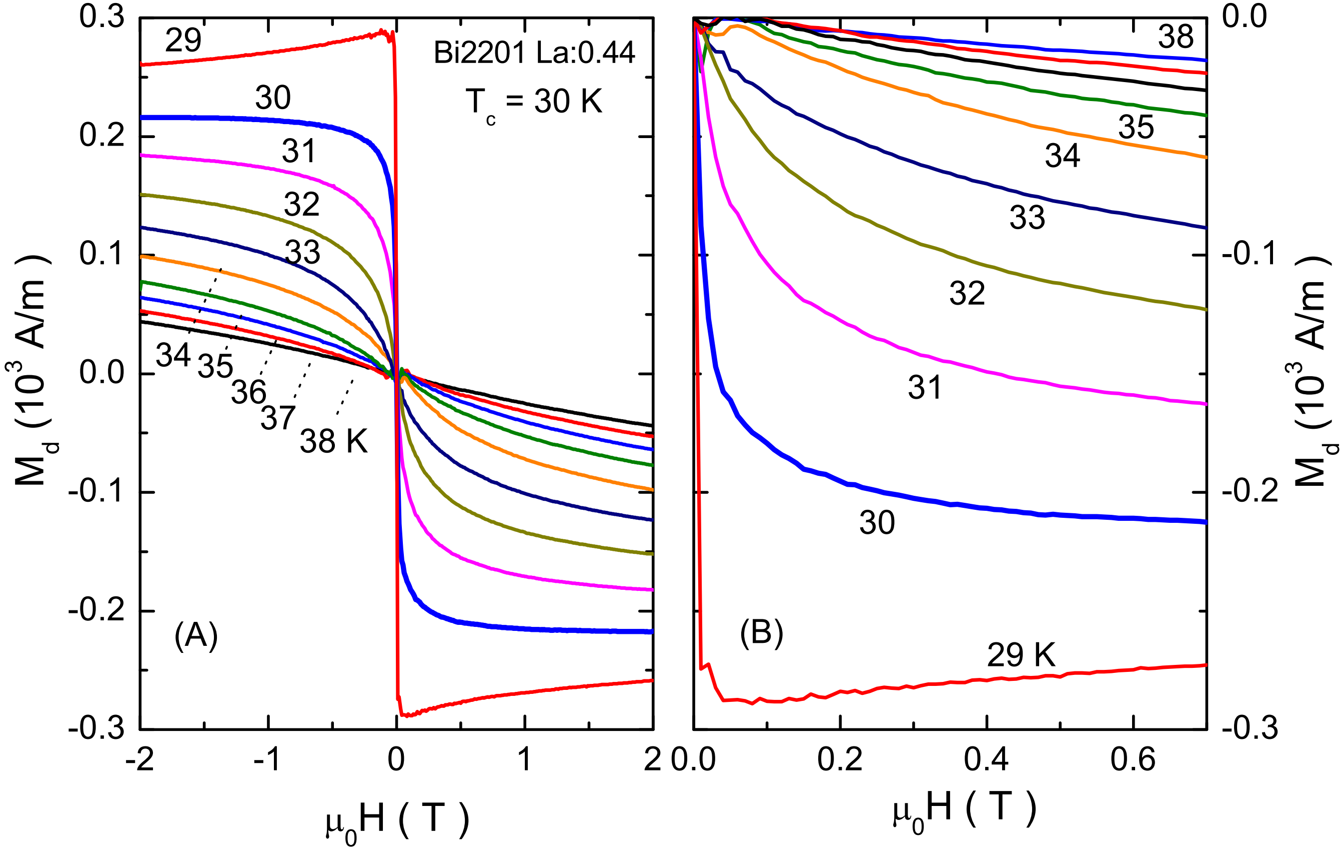
Y. Wang et al, *Science* **299**, *86 (2003).*

Incoherent pairs above T_c

experimental fact $\#$ 2

Incoherent pairs above T_c

experimental fact # 2



Van Vleck background $(A + BT)H$ *is subracted*

$$T_c = 30K$$

Enhanced diamagnetic response revealed above T_c by the high precission torque magnetometry.

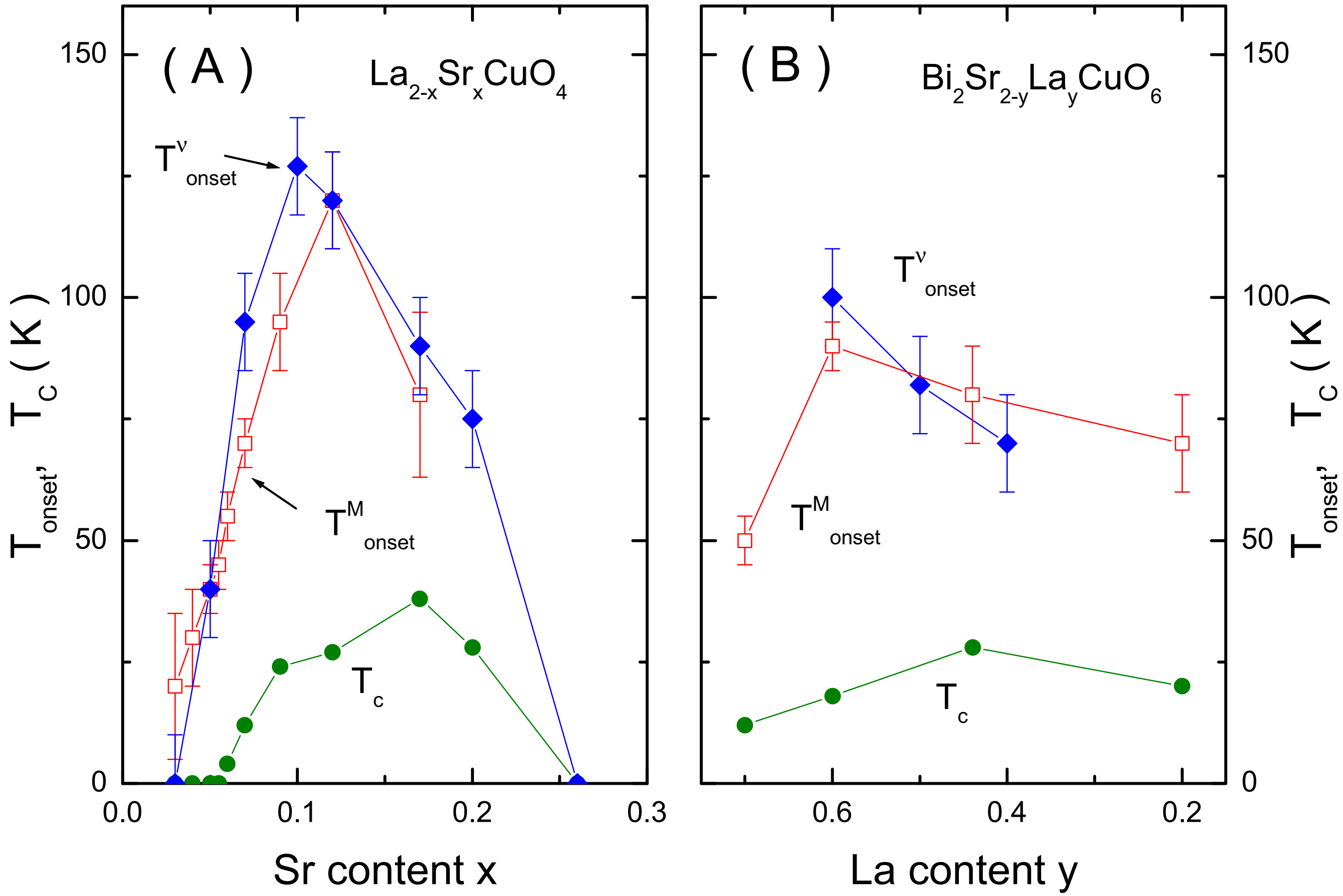
L. Li, ... and N.P. Ong, Phys. Rev. B **81**, *054510 (2010).* / Princeton University /

Incoherent pairs above T_c

experimental fact $\#$ 1 + 2

Incoherent pairs above T_c

experimental fact # 1 + 2



T^{ν} – onset of the Nernst effect

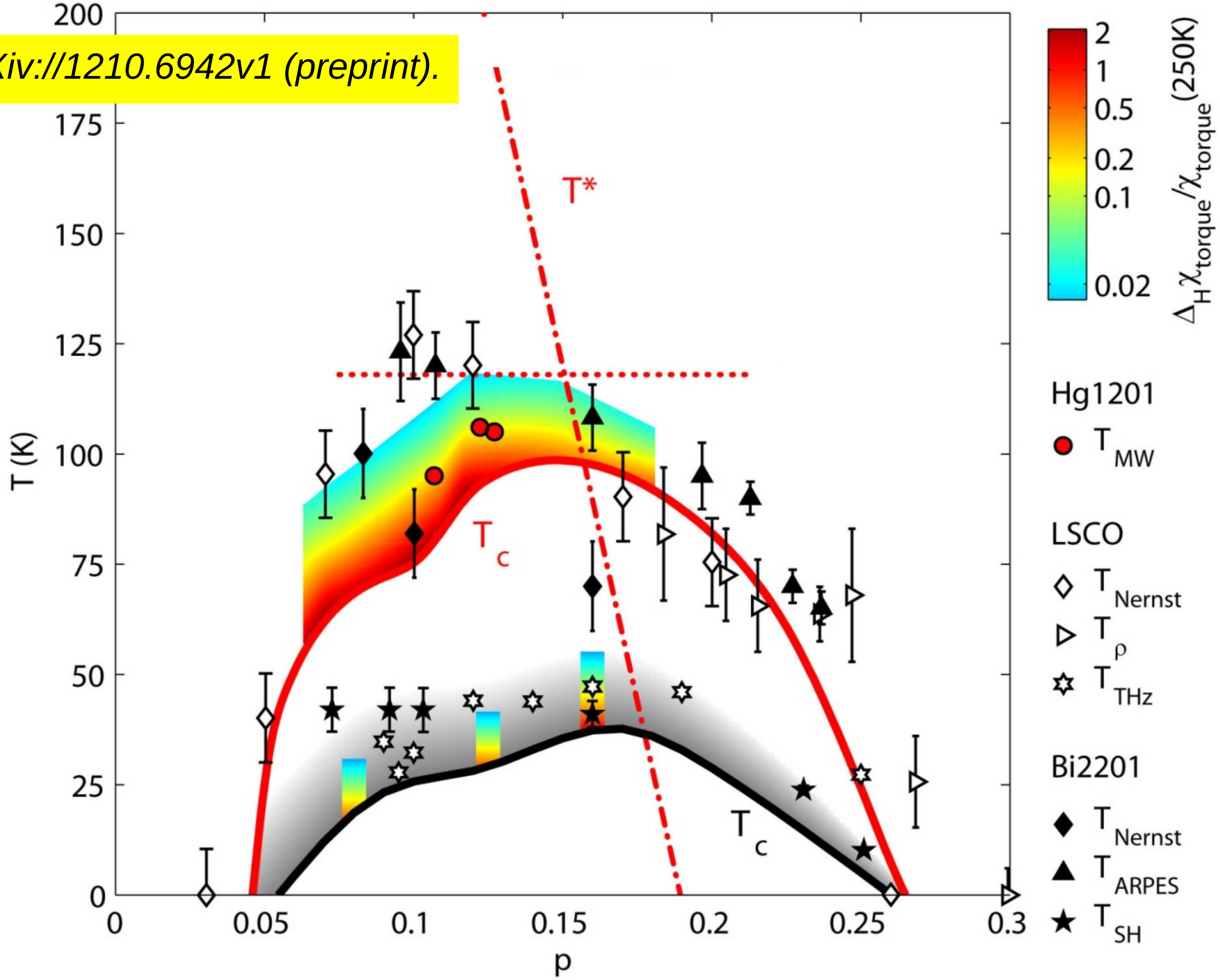
T^{M} – onset of the diamagnetism

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

Incoherent pairs above T_c

experimental fact # 1 + 2

G. Yu et al, arXiv://1210.6942v1 (preprint).



T_c – onset of the sc fluctuations

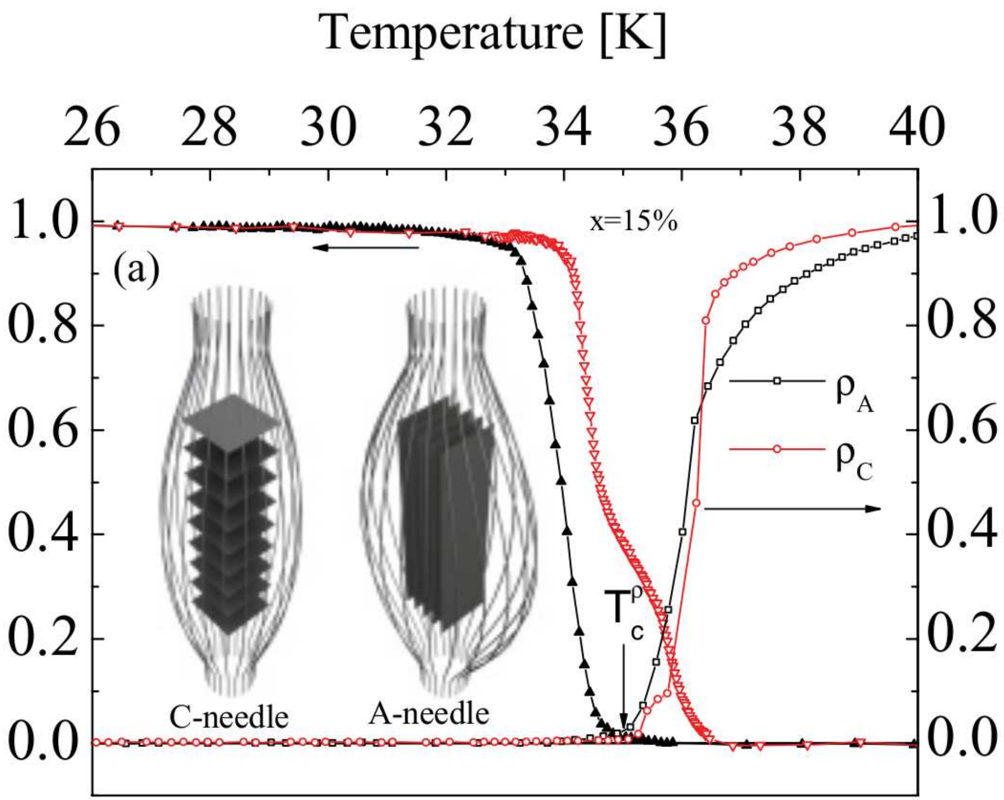
T_c – onset of the superconductivity

Incoherent pairs above T_c

experimental fact $\#$ 3

Incoherent pairs above T_c

experimental fact $\#$ 3

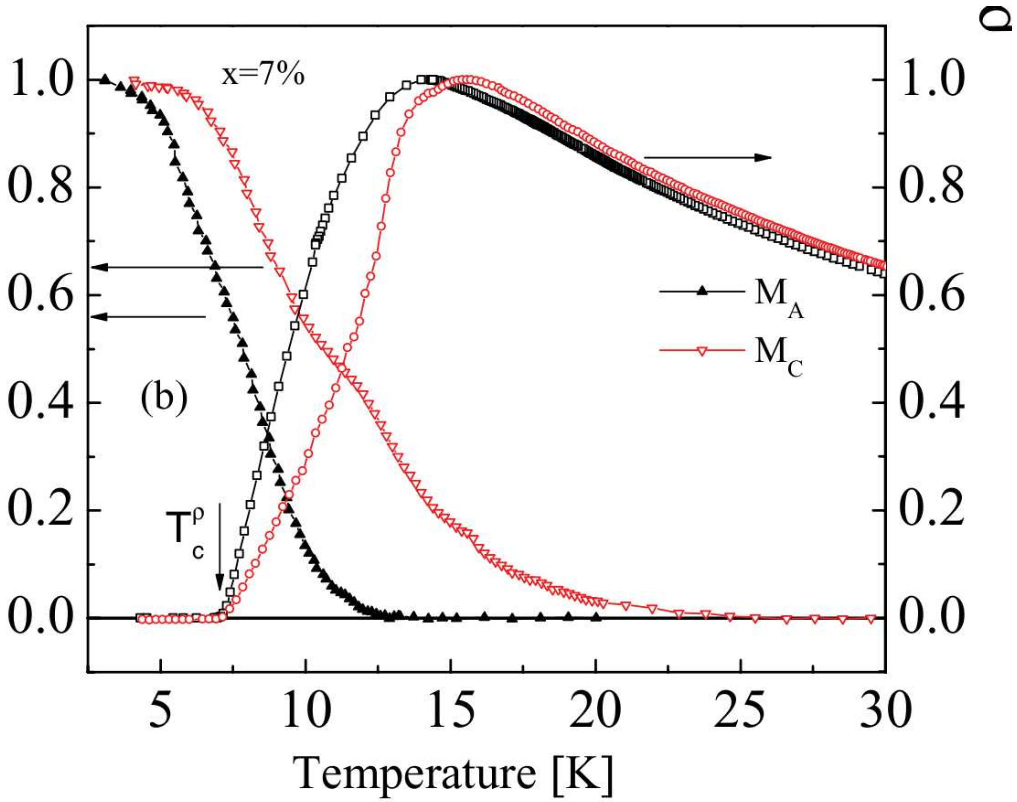


G. Drachuck et al, *Phys. Rev. B* **85**, *184518 (2012).*

/ Technion Group /

Magnetization measurements for the needle shape $La_{2-x}Sr_xCuO_4$ single crystals.

Incoherent pairs above T_c **experimental fact $\#$ 3**



G. Drachuck et al, *Phys. Rev. B* **85**, *184518 (2012).* / Technion Group /

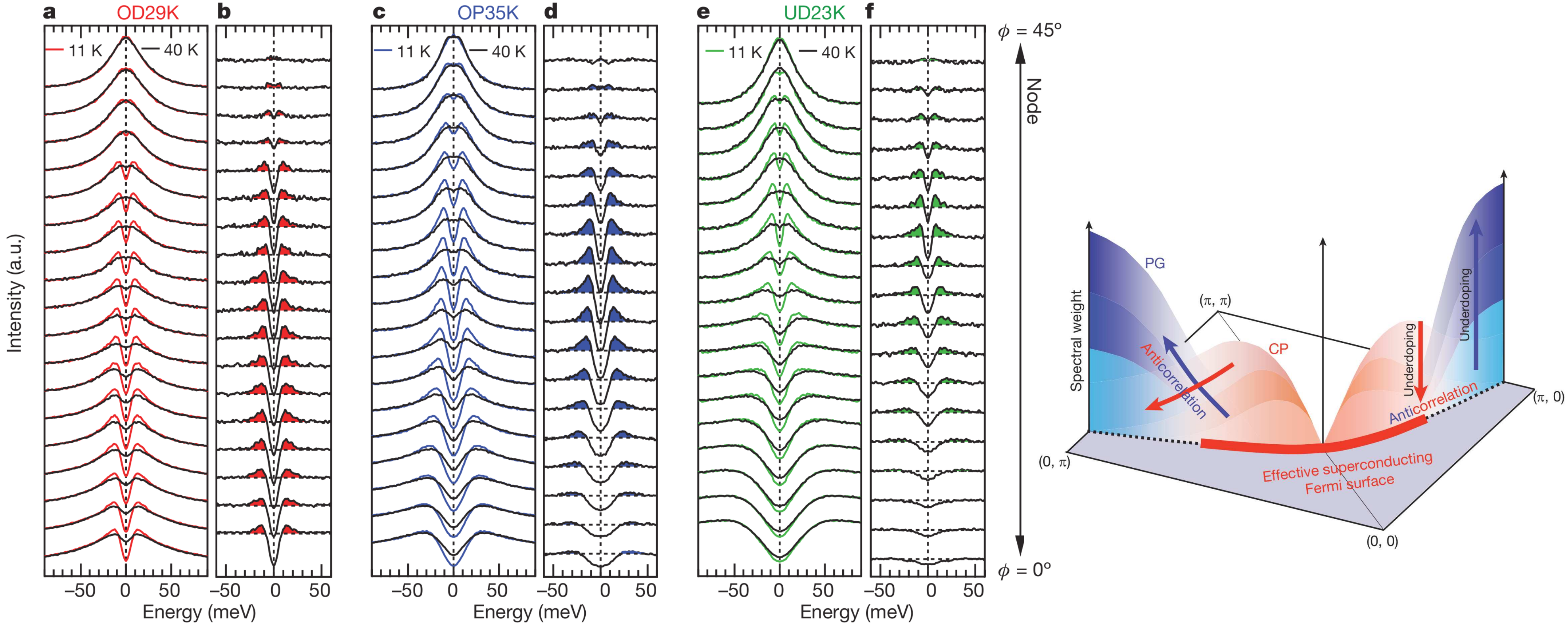
Magnetization measurements for the needle shape La$_{2-x}$Sr$_x$CuO$_4$ single crystals.

Incoherent pairs above T_c

experimental fact $\#$ 4

Incoherent pairs above T_c

experimental fact # 4

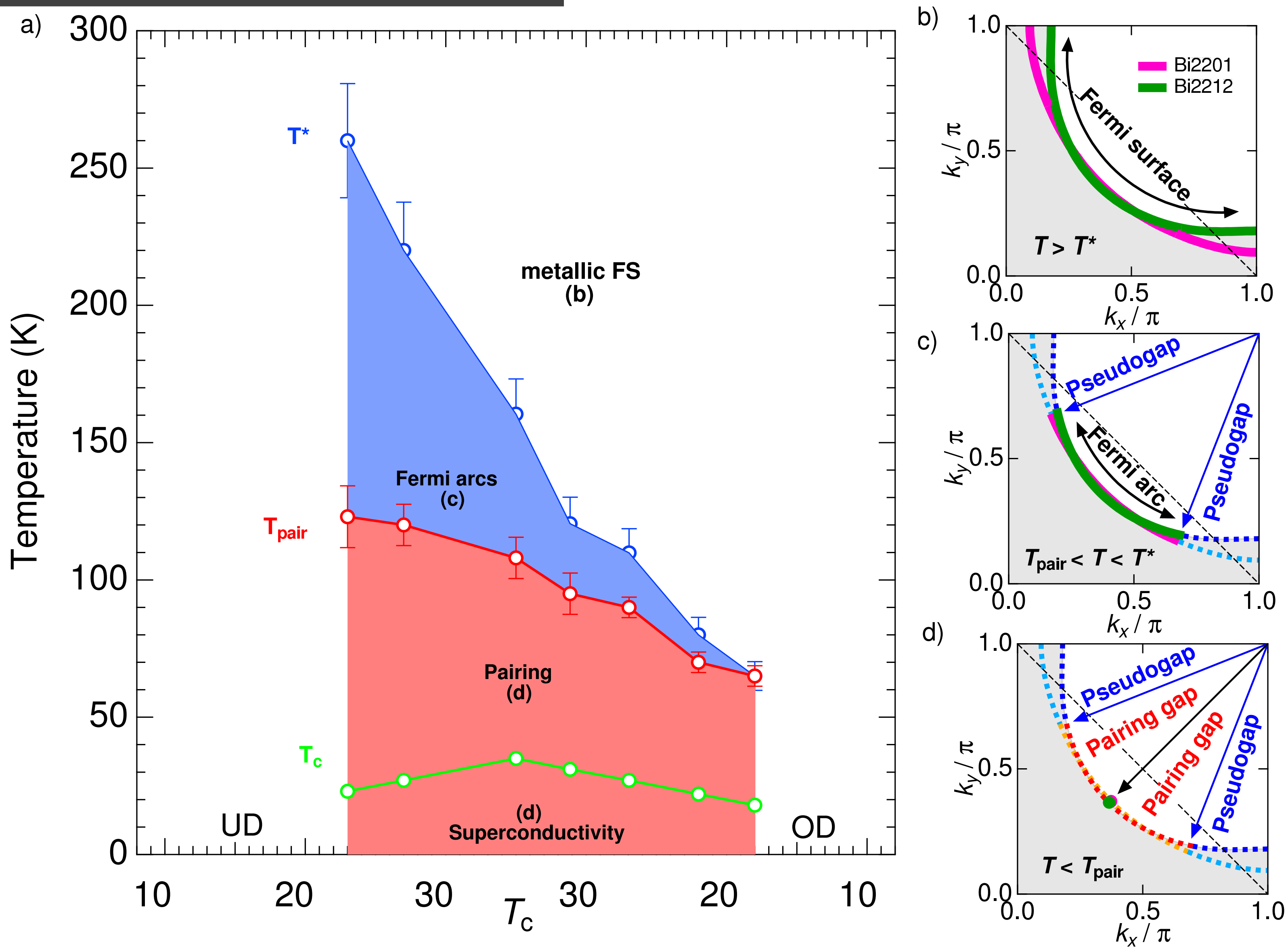


Transfer of the spectral weight in the single particle spectrum.

T. Kondo, R. Khasanov, T. Takeuchi, J. Schmalian & A. Kamiński, Nature **457***, 296 (2009).*

Incoherent pairs above T_c

experimental fact # 4



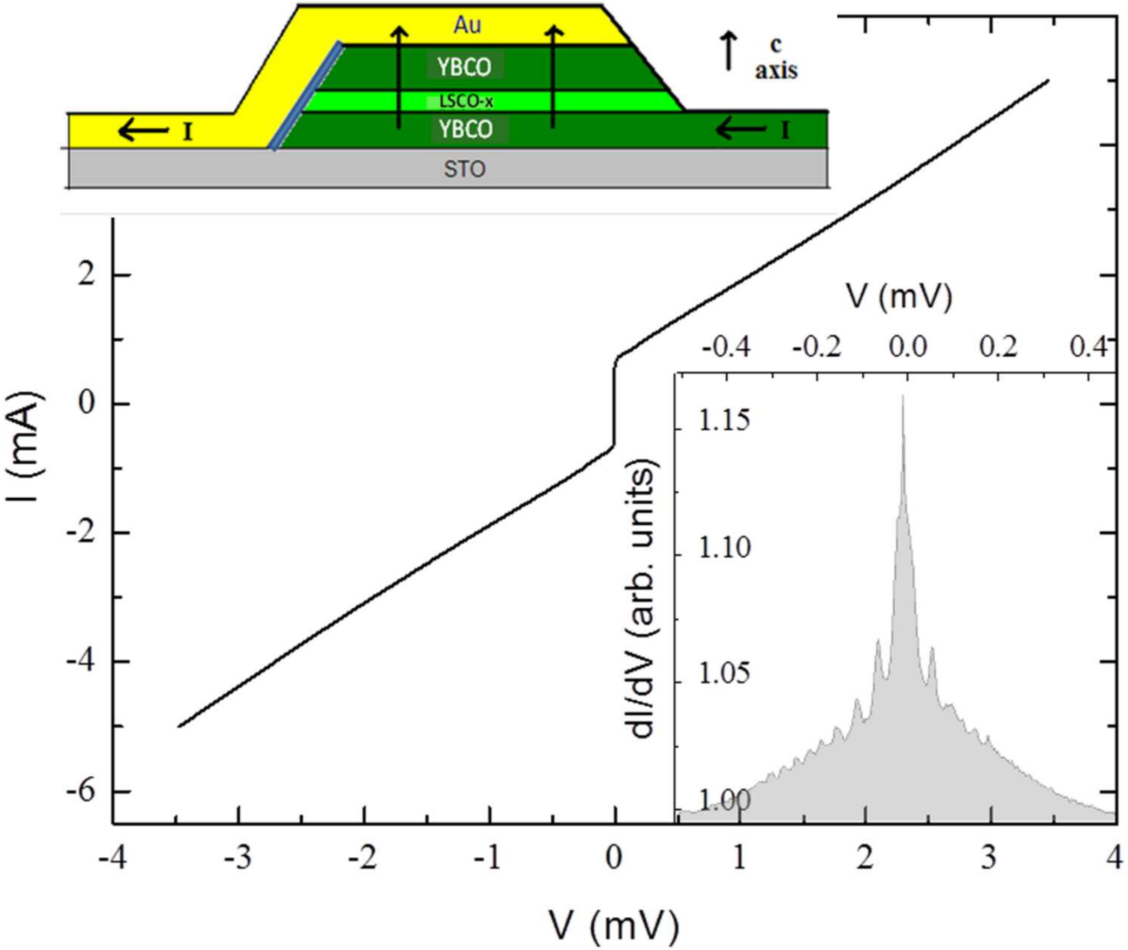
A. Kamiński, T. Kondo, T. Takeuchi, and G. Gu, arXiv://1403.0492 (2014) preprint.

Incoherent pairs above T_c

experimental fact $\#$ 5

Incoherent pairs above T_c

experimental fact # 5

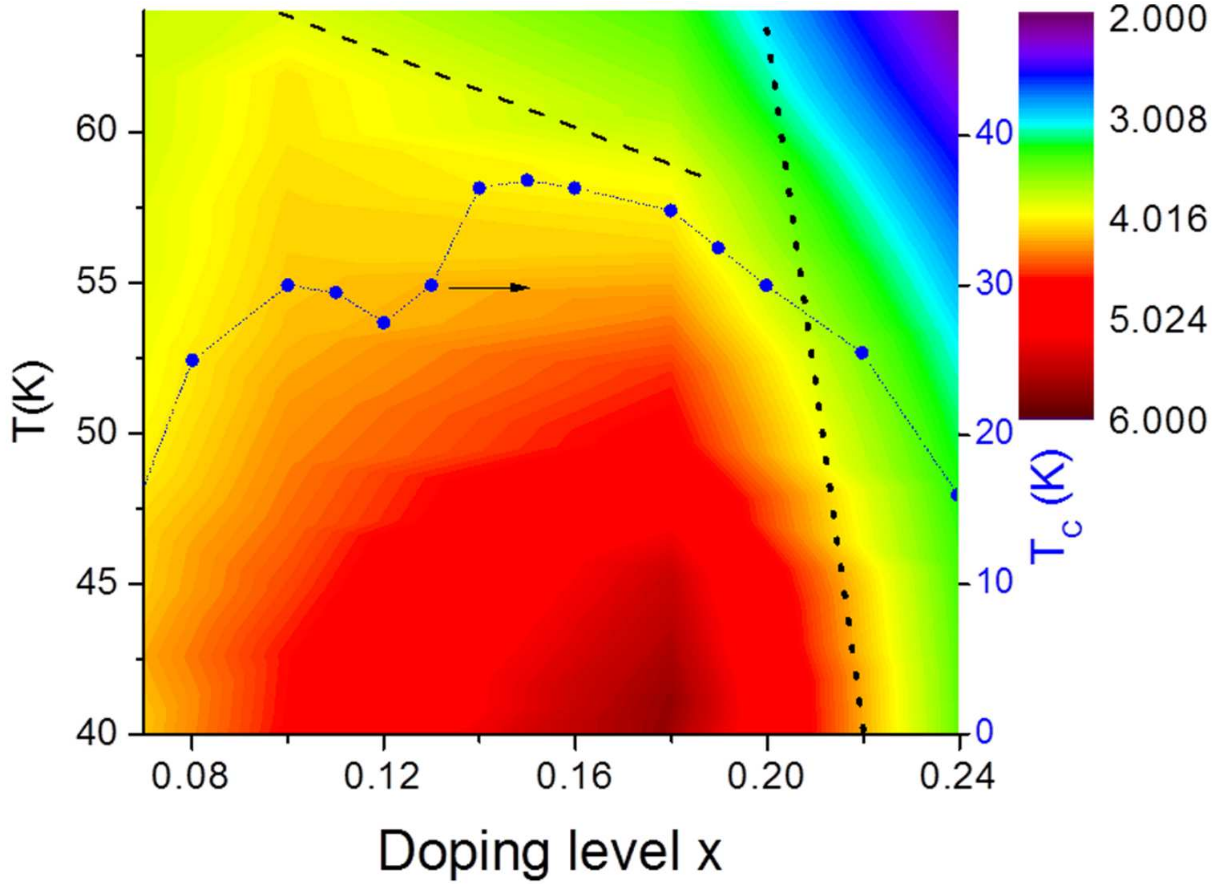


Josephson current in YBaCuO - LaSrCuO - YBaCuO junction with LaSrCuO being in the pseudogap state well above T_c

T. Kirzhner and G. Koren, Scientific Reports **4***, 6244 (2014).*

Incoherent pairs above T_c

experimental fact # 5



Phase diagram for the coherence length $\xi(T,x)$ appearing in the empirical law $I_c \propto \exp\left[-d/\xi\right]$ for Josephson current I_c.

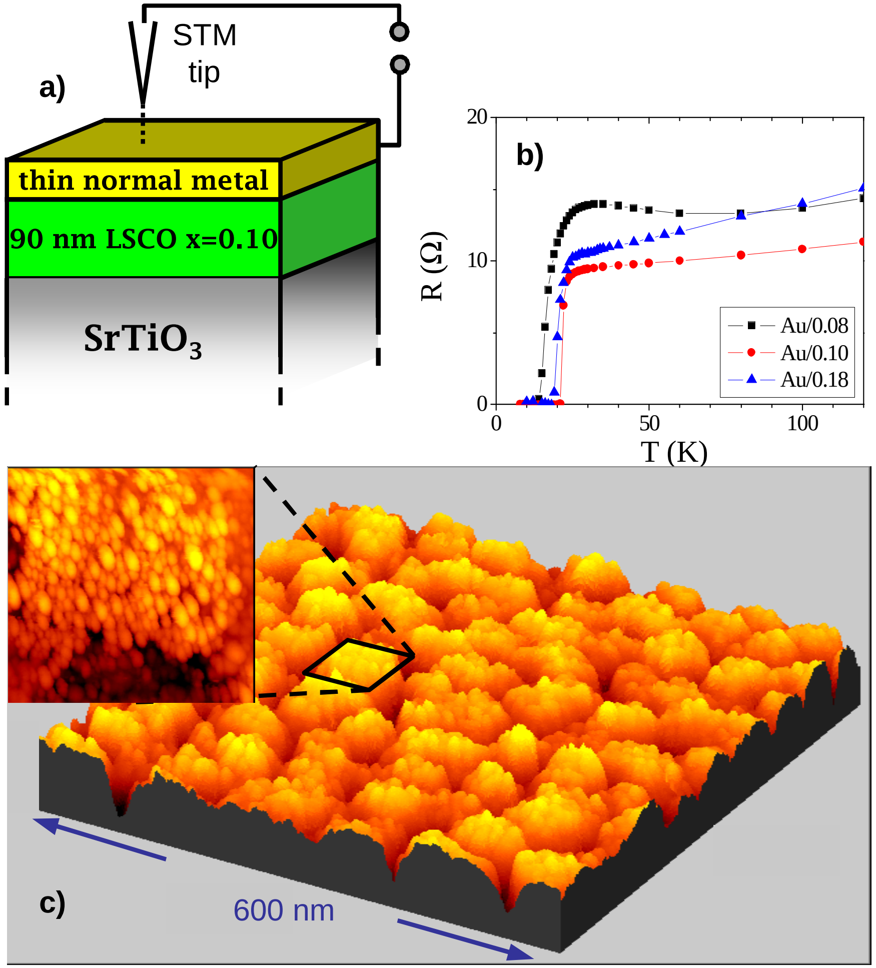
T. Kirzhner and G. Koren, Scientific Reports **4***, 6244 (2014).*

Incoherent pairs above T_c

experimental fact # 6

Incoherent pairs above T_c

experimental fact # 6



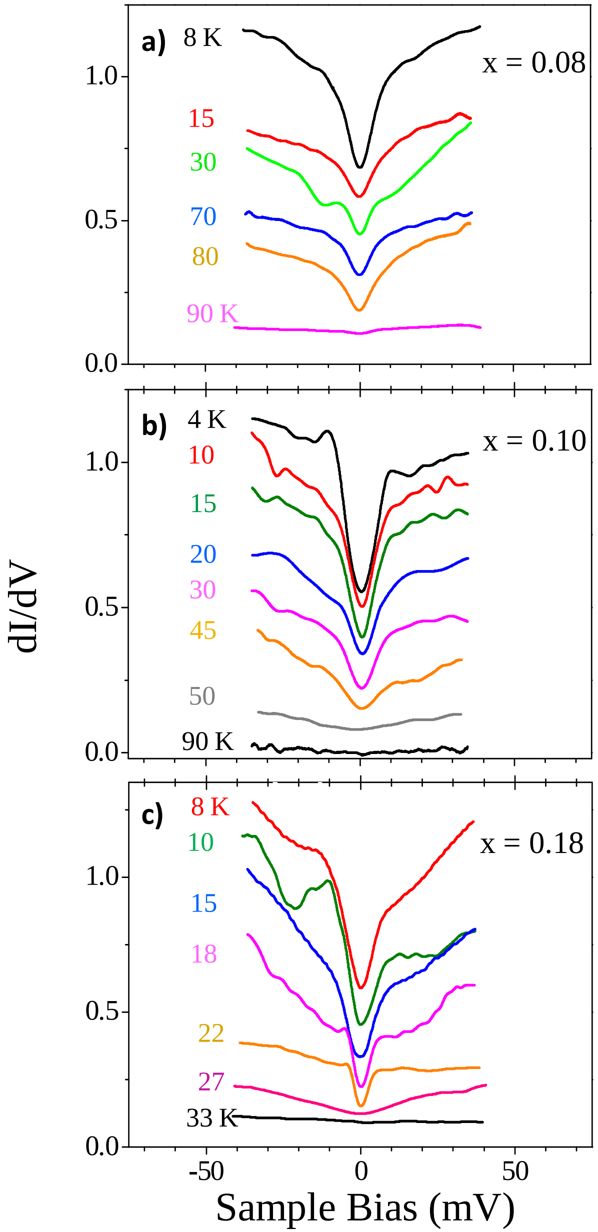
Pseudogap induced well above T_c in ultrathin metallic slab deposited on $La_{2-x}Sr_xCuO_4$.

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

Incoherent pairs above T_c

experimental fact # 6

Measured DOS ⟶



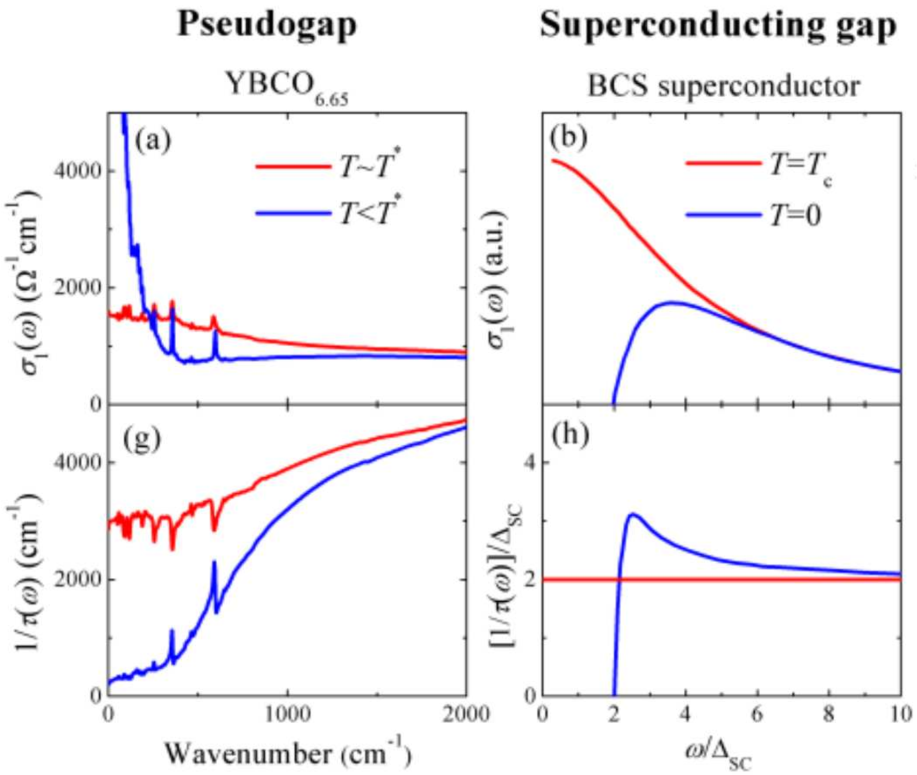
Proximity induced pseudogap observed far above T_c.

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

Incoherent pairs above T_c

experimental fact $\#$ 7

Incoherent pairs above T_c — experimental fact # 7

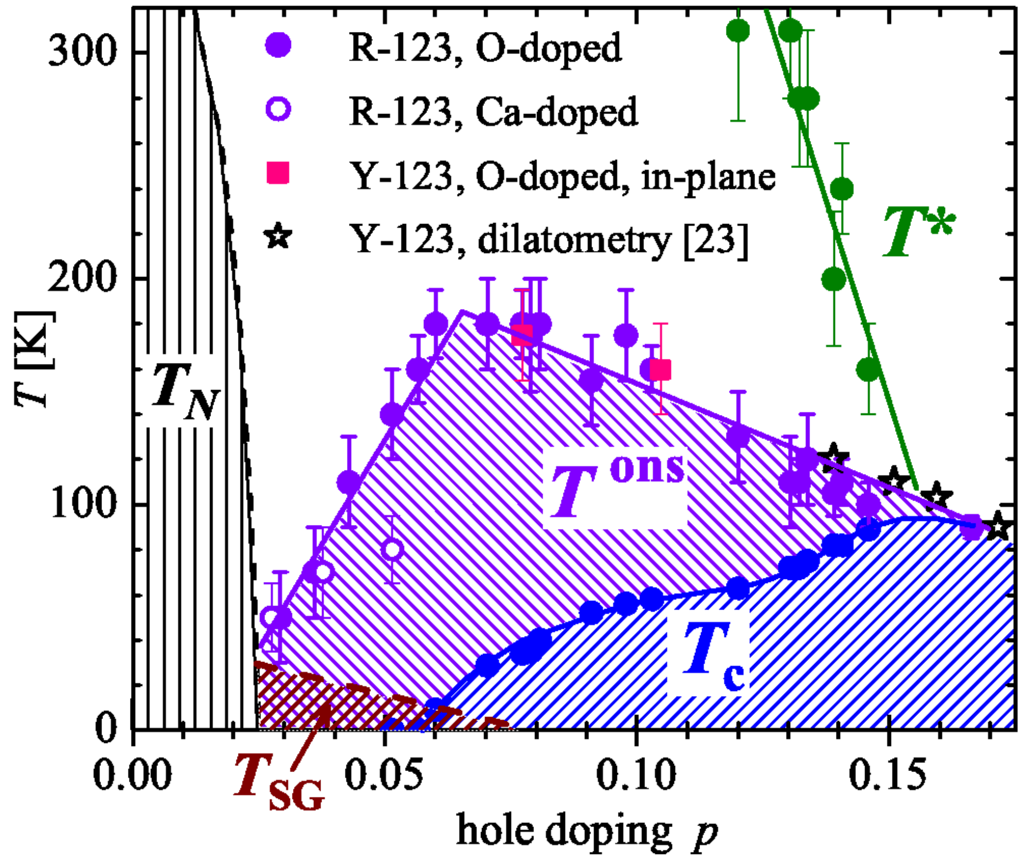


S.J. Moon et al, *Phys. Rev. B* **90**, *014503 (2014).*

Schematic view of the optical conductance in the pseudogap state of YBaCuO superconductor compared with conventional BCS materials.

Incoherent pairs above T_c

experimental fact # 7



A. Dubroka et al, *Phys. Rev. Lett.* **106**, *047006 (2011).*

Onset of the superfulid fraction observed in the c-axis optical measurements Re$\sigma_c(\omega)$.

Incoherent pairs above T_c

... continued

Incoherent pairs above T_c

... continued

⇒ **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**

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

⇒ **Bogoliubov quasiparticles detected above T_c in ARPES measurements for YBaCuO and LaSrCuO compounds**

Argonne (2008), Villigen (2009).

Incoherent pairs above T_c ... *continued*

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

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

⇒ **Bogoliubov quasiparticles detected above T_c in ARPES measurements for YBaCuO and LaSrCuO compounds**

Argonne (2008), Villigen (2009).

⇒ **Bogoliubov-type interference patterns in pseudogap state as the *fingerprint* of phase incoherent d-wave superconductivity preserved up to 1.5 T_c**

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

3. Selected results

/ below and above T_c /

Boson and fermion degrees of freedom

[spatial representation]

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

$$+ \sum_{i,j} g_{ij} \left[\hat{b}^{\dagger}_l \hat{c}_{i,\downarrow} \hat{c}_{j,\uparrow} + \text{h.c.} \right]$$

Boson and fermion degrees of freedom

[spatial representation]

$$\hat{H} = \sum_{i,j,\sigma} (t_{ij} - \mu\, \delta_{i,j})\, \hat{c}^\dagger_{i\sigma} \hat{c}_{j\sigma} + \sum_{l} \left(E_l^{(B)} - 2\mu \right) \hat{b}^\dagger_l \hat{b}_l$$

$$+ \sum_{i,j} g_{ij} \left[\hat{b}^\dagger_l \hat{c}_{i,\downarrow} \hat{c}_{j,\uparrow} + \text{h.c.} \right]$$

$$\vec{R}_l = (\vec{r}_i + \vec{r}_j)/2$$

Boson and fermion degrees of freedom

[spatial representation]

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

$$\vec{R}_l = (\vec{r}_i + \vec{r}_j)/2$$

This Hamiltonian describes a two-component system consisting of:

Boson and fermion degrees of freedom

[spatial representation]

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

$$+ \sum_{i,j} g_{ij} \left[\hat{b}^{\dagger}_l \hat{c}_{i,\downarrow} \hat{c}_{j,\uparrow} + \text{h.c.} \right]$$

$$\vec{R}_l = (\vec{r}_i + \vec{r}_j)/2$$

This Hamiltonian describes a two-component system consisting of:

$\hat{c}^{(\dagger)}_{i\sigma}$ **itinerant fermions** .... *(e.g. holes near the Mott insulator)*

Boson and fermion degrees of freedom

[spatial representation]

$$\hat{H} = \sum_{i,j,\sigma} (t_{ij} - \mu\, \delta_{i,j})\, \hat{c}^\dagger_{i\sigma} \hat{c}_{j\sigma} + \sum_l \left(E^{(B)}_l - 2\mu \right) \hat{b}^\dagger_l \hat{b}_l$$

$$+ \sum_{i,j} g_{ij} \left[\hat{b}^\dagger_l \hat{c}_{i,\downarrow} \hat{c}_{j,\uparrow} + \text{h.c.} \right]$$

$$\vec{R}_l = (\vec{r}_i + \vec{r}_j)/2$$

This Hamiltonian describes a two-component system consisting of:

$\hat{c}^{(\dagger)}_{i\sigma}$ **itinerant fermions** .... *(e.g. holes near the Mott insulator)*

$\hat{b}^{(\dagger)}_l$ **immobile local pairs** .... *(RVB defines them on the bonds)*

Boson and fermion degrees of freedom

[spatial representation]

$$\hat{H} = \sum_{i,j,\sigma} (t_{ij} - \mu\, \delta_{i,j})\, \hat{c}^{\dagger}_{i\sigma} \hat{c}_{j\sigma} + \sum_{l} \left(E^{(B)}_{l} - 2\mu \right) \hat{b}^{\dagger}_{l} \hat{b}_{l}$$

$$+ \sum_{i,j} g_{ij} \left[\hat{b}^{\dagger}_{l} \hat{c}_{i,\downarrow} \hat{c}_{j,\uparrow} + \text{h.c.} \right]$$

$$\vec{R}_l = (\vec{r}_i + \vec{r}_j)/2$$

This Hamiltonian describes a two-component system consisting of:

$\hat{c}^{(\dagger)}_{i\sigma}$ **itinerant fermions** ....*(e.g. holes near the Mott insulator)*

$\hat{b}^{(\dagger)}_{l}$ **immobile local pairs** ....*(RVB defines them on the bonds)*

interacting via:

Boson and fermion degrees of freedom

[spatial representation]

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

$$\vec{R}_l = (\vec{r}_i + \vec{r}_j)/2$$

This Hamiltonian describes a two-component system consisting of:

$\hat{c}^{(\dagger)}_{i\sigma}$ **itinerant fermions** .... *(e.g. holes near the Mott insulator)*

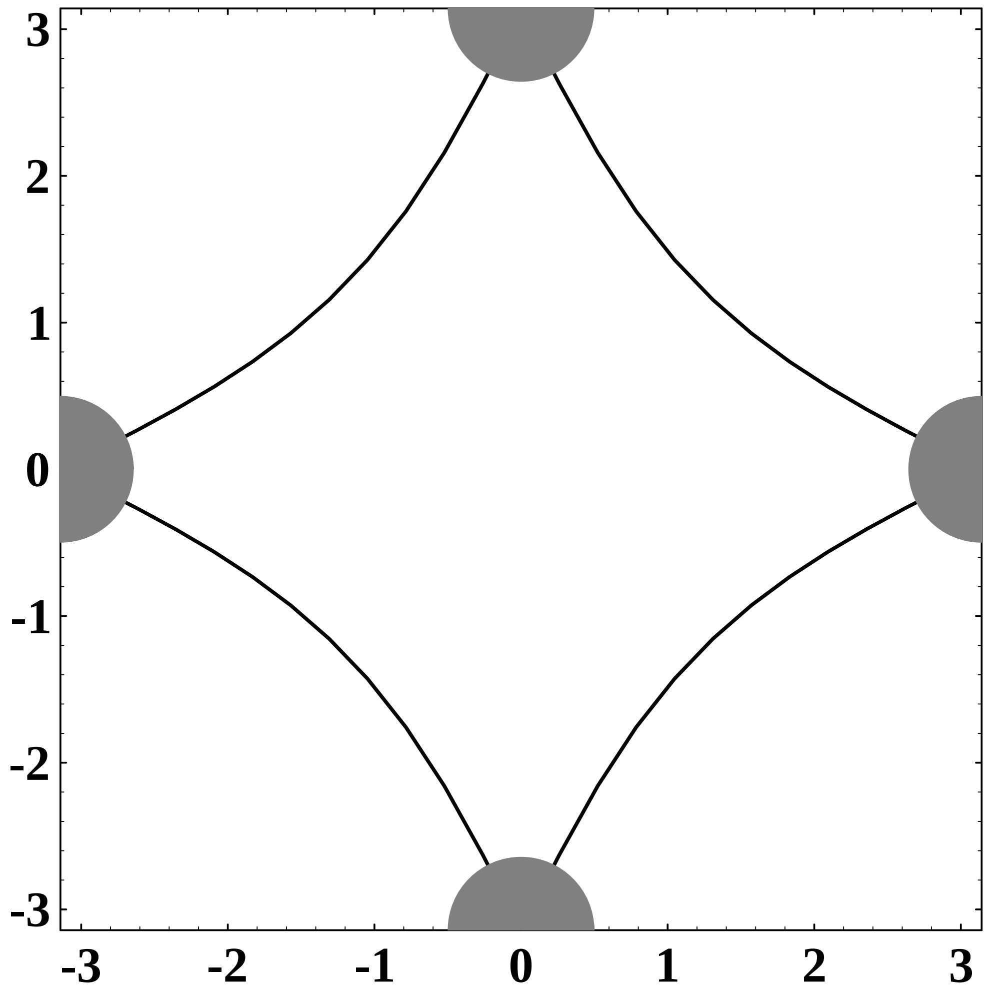
$\hat{b}^{(\dagger)}_l$ **immobile local pairs** .... *(RVB defines them on the bonds)*

interacting via:

$\hat{b}^{\dagger}_l \; \hat{c}_{i,\downarrow} \hat{c}_{j,\uparrow} \; + h.c.$ .... *(the Andreev-type scattering)*

Phenomenological arguments – supporting BF scenario

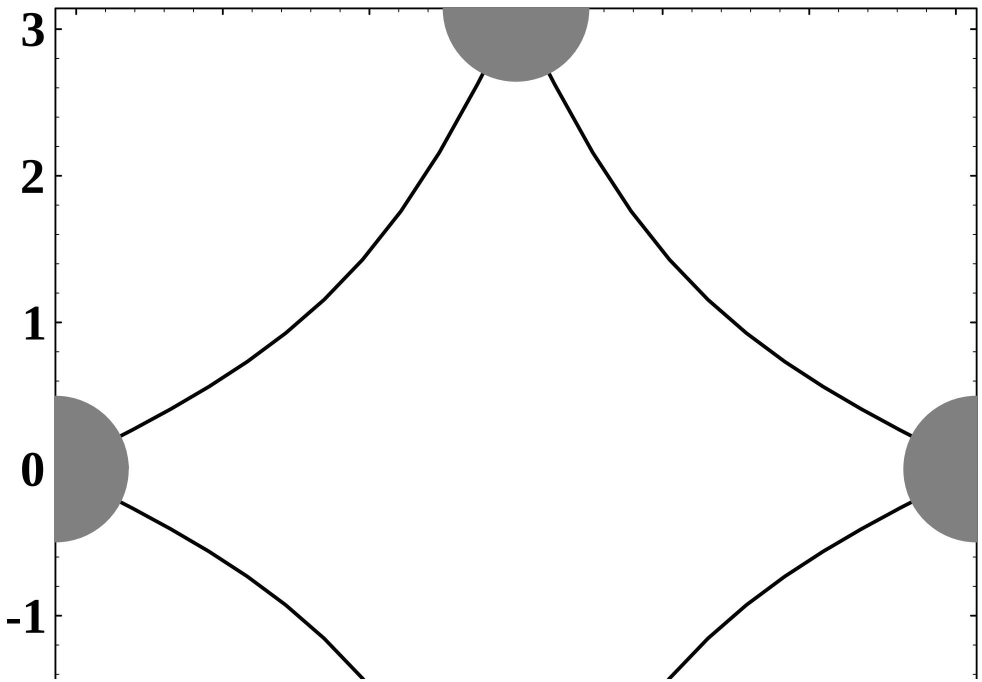
Phenomenological arguments – **supporting BF scenario**



paired & unpaired carriers

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

Phenomenological arguments – supporting BF scenario



paired & unpaired carriers

Received 27 Dec 2013 | Accepted 7 Jun 2014 | Published 11 Jul 2014

DOI: 10.1038/ncomms5353

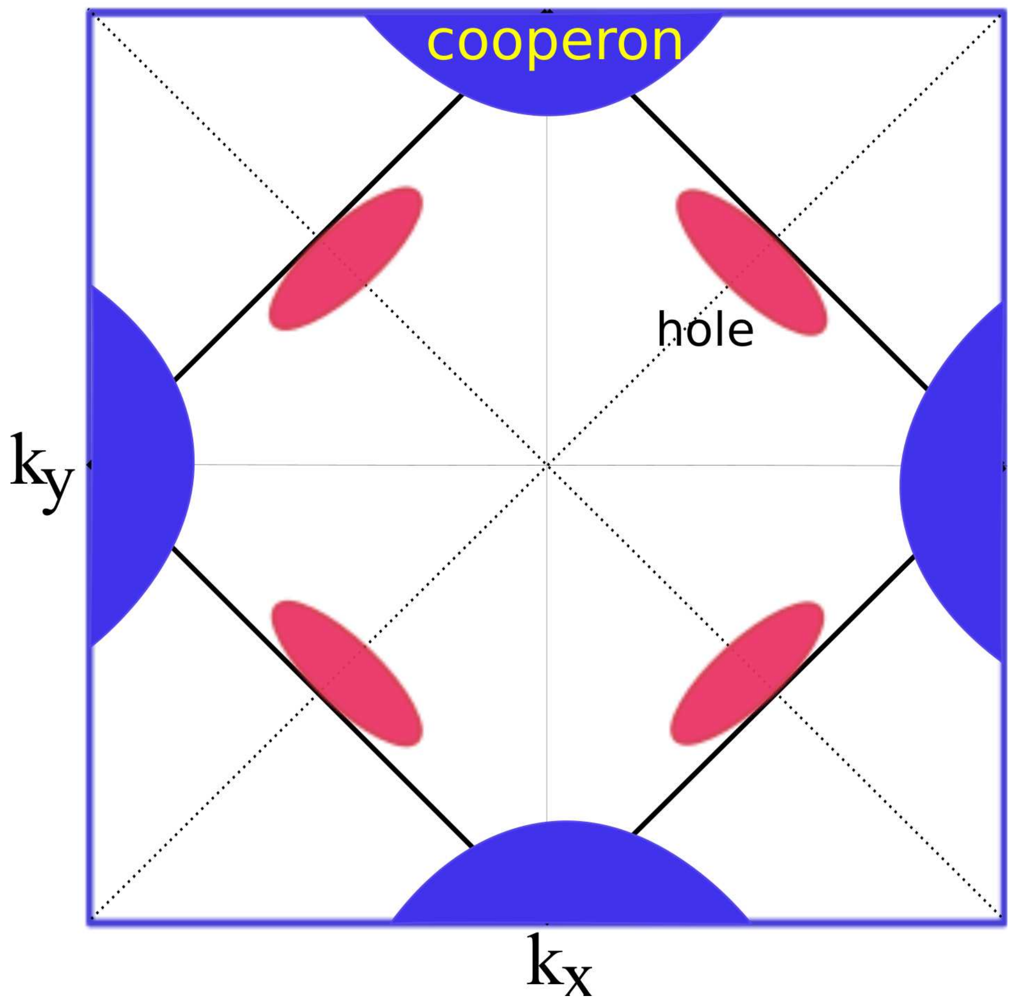
OPEN

Photo-enhanced antinodal conductivity in the pseudogap state of high-T_c cuprates

F. Cilento[1], S. Dal Conte[2,3,†], G. Coslovich[4,†], S. Peli[2,5], N. Nembrini[2,5], S. Mor[2], F. Banfi[2,3], G. Ferrini[2,3], H. Eisaki[6], M.K. Chan[7], C.J. Dorow[7], M.J. Veit[7], M. Greven[7], D. van der Marel[8], R. Comin[9,10], A. Damascelli[9,10], L. Rettig[11,†], U. Bovensiepen[11], M. Capone[12], C. Giannetti[2,3] & F. Parmigiani[1,4]

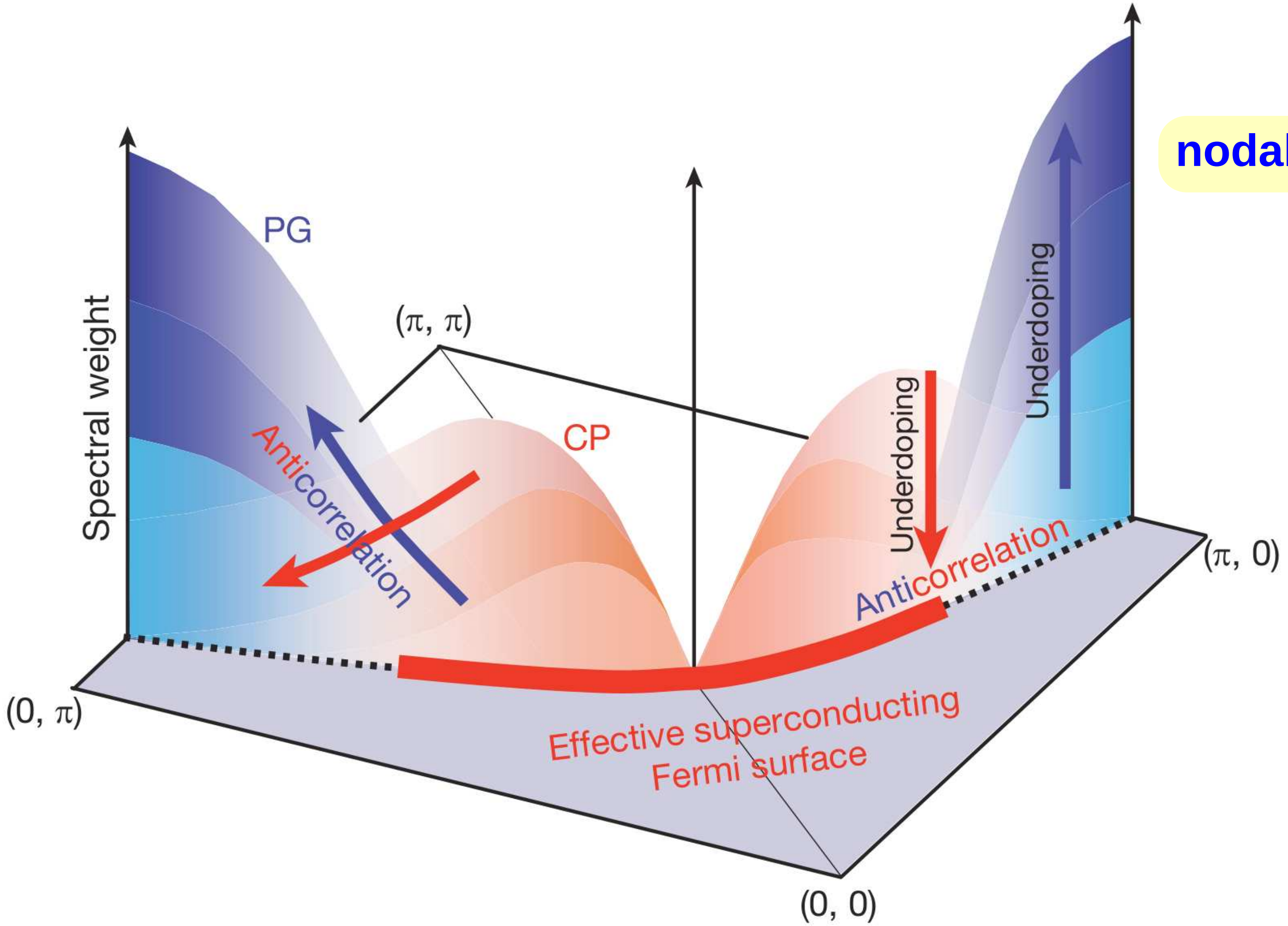
Phenomenological arguments – supporting BF scenario

K.-Y. Yang, E. Kozik, X. Wang, and M. Troyer, Phys. Rev. B **83***, 214516 (2011).*



cooperons & holes

Phenomenological arguments – supporting BF scenario



nodal–antinodal dichotomy

T. Kondo, R. Khasanov, T. Takeuchi, J. Schmalian & A. Kamiński, Nature **457***, 296 (2009).*

Bogoliubov quasiparticles

below and above T_c

BCS physics

The BCS ground state:

BCS physics

The BCS ground state:

$$|\text{BCS}\rangle = \Pi_{\mathbf{k}} \left(u_{\mathbf{k}} + v_{\mathbf{k}}\, e^{i\theta_{\mathbf{k}}}\, \hat{c}^{\dagger}_{\mathbf{k}\uparrow}\, \hat{c}^{\dagger}_{-\mathbf{k}\downarrow} \right) |\text{vac}\rangle$$

BCS physics

The BCS ground state:

$$|\mathrm{BCS}\rangle = \Pi_{\mathbf{k}} \left(u_{\mathbf{k}} + v_{\mathbf{k}}\, e^{i\theta_{\mathbf{k}}}\, \hat{c}^{\dagger}_{\mathbf{k}\uparrow}\, \hat{c}^{\dagger}_{-\mathbf{k}\downarrow} \right) |\mathrm{vac}\rangle$$

$v_{\mathbf{k}}$, $u_{\mathbf{k}}$ – coherence factors,

$\theta_{\mathbf{k}}$ – phase

BCS physics

The BCS ground state:

$$|\mathrm{BCS}\rangle = \Pi_{\mathbf{k}} \left(u_{\mathbf{k}} + v_{\mathbf{k}} \, e^{i\theta_{\mathbf{k}}} \, \hat{c}^{\dagger}_{\mathbf{k}\uparrow} \, \hat{c}^{\dagger}_{-\mathbf{k}\downarrow} \right) |\mathrm{vac}\rangle$$

$v_{\mathbf{k}}$, $u_{\mathbf{k}}$ – coherence factors,

$\theta_{\mathbf{k}}$ – phase

where

$$\left| v_{\mathbf{k}} \, e^{i\theta_{\mathbf{k}}} \right|^2 = \frac{1}{2} \left[1 - \frac{\varepsilon_{\mathbf{k}} - \mu}{\sqrt{(\varepsilon_{\mathbf{k}} - \mu)^2 + |\Delta|^2}} \right] = 1 - |u_{\mathbf{k}}|^2$$

BCS excitation spectrum

BCS excitation spectrum

The effective (Bogoliubov) quasiparticles :

$$\begin{aligned} \hat{\gamma}_{\mathbf{k}\uparrow} &= u_{\mathbf{k}}\, \hat{c}_{\mathbf{k}\uparrow} + v_{\mathbf{k}}\, \hat{c}^{\dagger}_{-\mathbf{k}\downarrow} \\ \hat{\gamma}^{\dagger}_{-\mathbf{k}\downarrow} &= -v_{\mathbf{k}}\, \hat{c}_{\mathbf{k}\uparrow} + u_{\mathbf{k}}\, \hat{c}^{\dagger}_{-\mathbf{k}\downarrow} \end{aligned}$$

BCS excitation spectrum

The effective (Bogoliubov) quasiparticles :

$$\begin{aligned} \hat{\gamma}_{\mathbf{k}\uparrow} &= u_{\mathbf{k}}\ \hat{c}_{\mathbf{k}\uparrow} + v_{\mathbf{k}}\ \hat{c}^{\dagger}_{-\mathbf{k}\downarrow} \\ \hat{\gamma}^{\dagger}_{-\mathbf{k}\downarrow} &= -v_{\mathbf{k}}\ \hat{c}_{\mathbf{k}\uparrow} + u_{\mathbf{k}}\ \hat{c}^{\dagger}_{-\mathbf{k}\downarrow} \end{aligned}$$

represent a coherent superposition of the particles and holes

BCS excitation spectrum

The effective (Bogoliubov) quasiparticles :

$$\begin{aligned} \hat{\gamma}_{\mathbf{k}\uparrow} &= u_{\mathbf{k}}\, \hat{c}_{\mathbf{k}\uparrow} + v_{\mathbf{k}}\, \hat{c}^{\dagger}_{-\mathbf{k}\downarrow} \\ \hat{\gamma}^{\dagger}_{-\mathbf{k}\downarrow} &= -v_{\mathbf{k}}\, \hat{c}_{\mathbf{k}\uparrow} + u_{\mathbf{k}}\, \hat{c}^{\dagger}_{-\mathbf{k}\downarrow} \end{aligned}$$

represent a coherent superposition of the particles and holes

$$A(\mathbf{k},\omega) = |u_{\mathbf{k}}|^2\, \delta(\omega - E_{\mathbf{k}}) + |v_{\mathbf{k}}|^2\, \delta(\omega + E_{\mathbf{k}})$$

BCS excitation spectrum

The effective (Bogoliubov) quasiparticles :

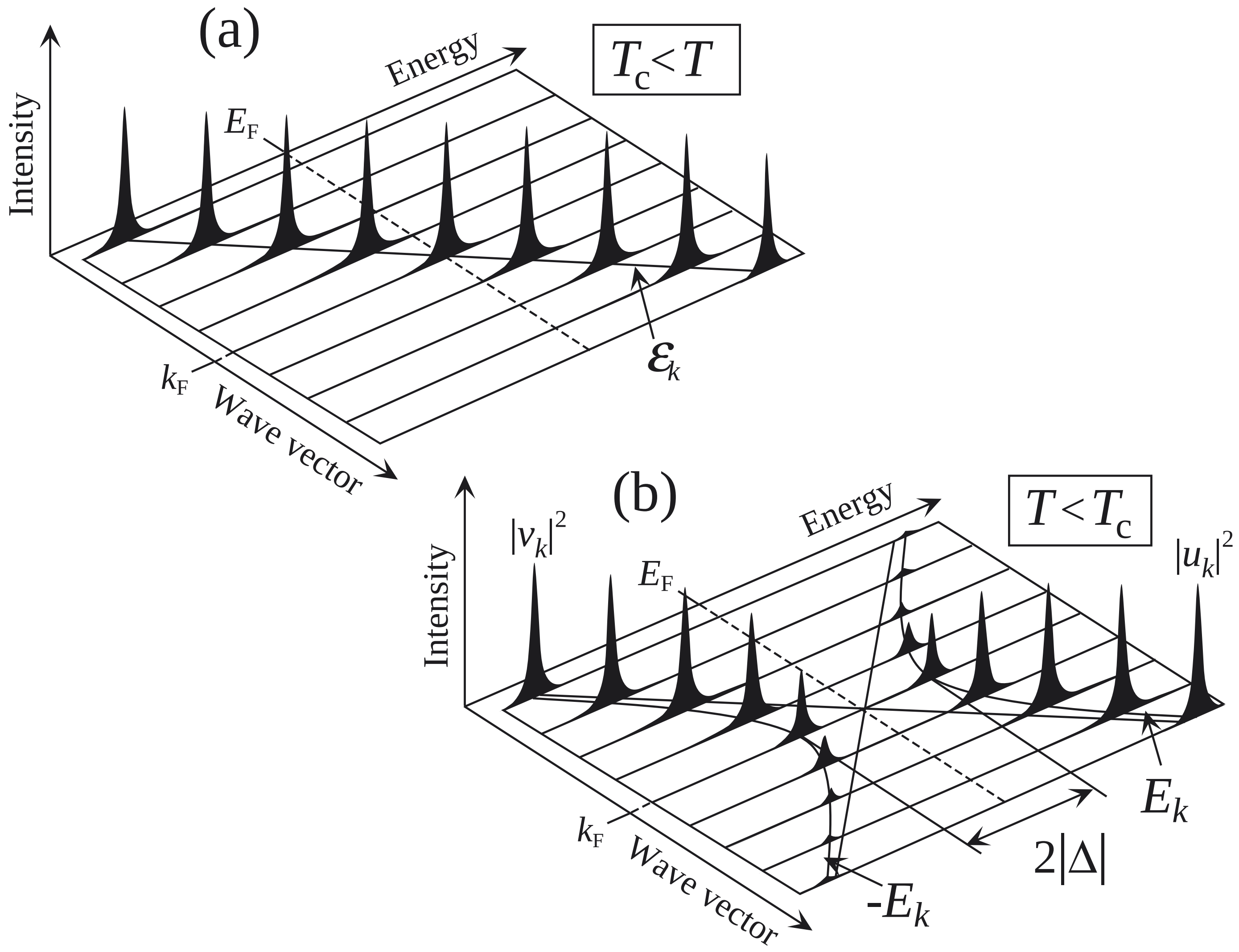
$$\begin{aligned} \hat{\gamma}_{\mathbf{k}\uparrow} &= u_{\mathbf{k}}\, \hat{c}_{\mathbf{k}\uparrow} + v_{\mathbf{k}}\, \hat{c}^{\dagger}_{-\mathbf{k}\downarrow} \\ \hat{\gamma}^{\dagger}_{-\mathbf{k}\downarrow} &= -v_{\mathbf{k}}\, \hat{c}_{\mathbf{k}\uparrow} + u_{\mathbf{k}}\, \hat{c}^{\dagger}_{-\mathbf{k}\downarrow} \end{aligned}$$

represent a coherent superposition of the particles and holes

$$A(\mathbf{k},\omega) = |u_{\mathbf{k}}|^2\, \delta(\omega - E_{\mathbf{k}}) + |v_{\mathbf{k}}|^2\, \delta(\omega + E_{\mathbf{k}})$$

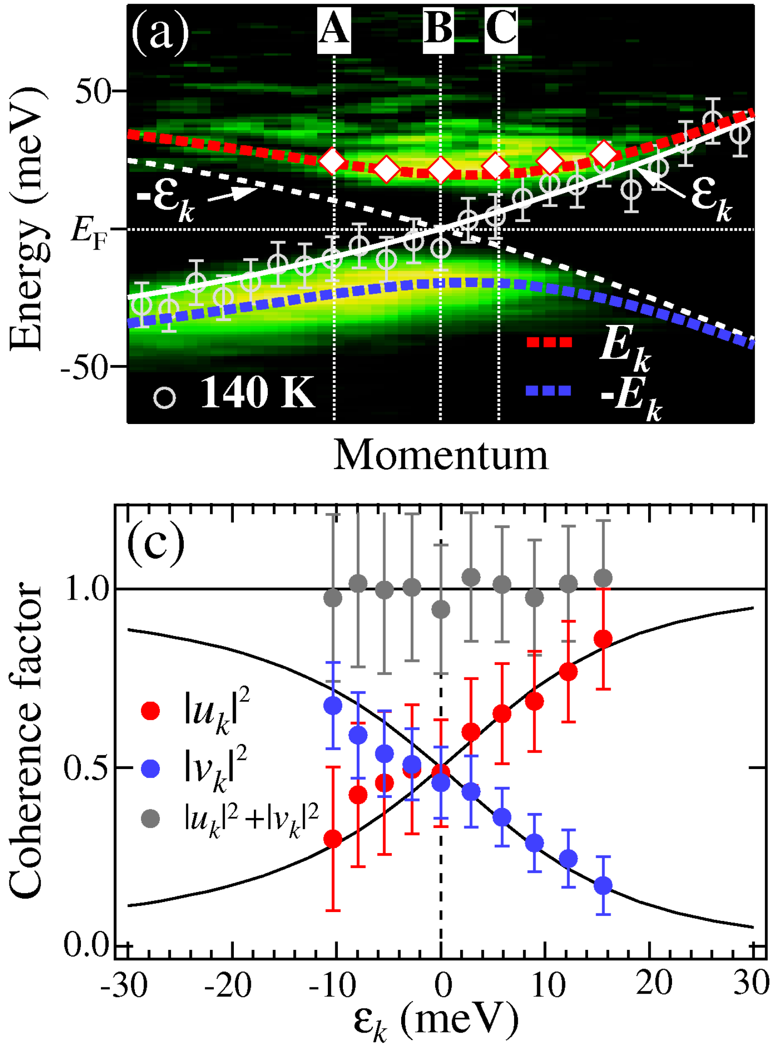
Occupancy of the momentum k is given by

$$n_{\mathbf{k}} = |u_{\mathbf{k}}|^2\, f_{FD}(E_{\mathbf{k}}) + |v_{\mathbf{k}}|^2\, \underbrace{f_{FD}(-E_{\mathbf{k}})}_{1-f_{FD}(E_{\mathbf{k}})}$$



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

Experimental data for cuprates – below T_c



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

Beyond the BCS approximation

Beyond the BCS approximation

We have generalized the Bogoliubov ansatz taking into account the non-condensed (preformed) pairs

Beyond the BCS approximation

We have generalized the Bogoliubov ansatz taking into account the non-condensed (preformed) pairs

$$\hat{c}_{\mathbf{k}\uparrow}(l) = u_{\mathbf{k}}(l)\,\hat{c}_{\mathbf{k}\uparrow} + v_{\mathbf{k}}(l)\,\hat{c}^{\dagger}_{-\mathbf{k}\downarrow} + \frac{1}{\sqrt{N}}\sum_{\mathbf{q}\neq 0}\left[u_{\mathbf{k},\mathbf{q}}(l)\,\hat{b}^{\dagger}_{\mathbf{q}}\hat{c}_{\mathbf{q}+\mathbf{k}\uparrow} + v_{\mathbf{k},\mathbf{q}}(l)\,\hat{b}_{\mathbf{q}}\hat{c}^{\dagger}_{\mathbf{q}-\mathbf{k}\downarrow}\right], \tag{1}$$

$$\hat{c}^{\dagger}_{-\mathbf{k}\downarrow}(l) = -v^{*}_{\mathbf{k}}(l)\,\hat{c}_{\mathbf{k}\uparrow} + u^{*}_{\mathbf{k}}(l)\,\hat{c}^{\dagger}_{-\mathbf{k}\downarrow} \frac{1}{\sqrt{N}}\sum_{\mathbf{q}\neq 0}\left[-v^{*}_{\mathbf{k},\mathbf{q}}(l)\,\hat{b}^{\dagger}_{\mathbf{q}}\hat{c}_{\mathbf{q}+\mathbf{k}\uparrow} + u^{*}_{\mathbf{k},\mathbf{q}}(l)\,\hat{b}_{\mathbf{q}}\hat{c}^{\dagger}_{\mathbf{q}-\mathbf{k}\downarrow}\right], \tag{2}$$

Beyond the BCS approximation

We have generalized the Bogoliubov ansatz taking into account the non-condensed (preformed) pairs

$$\begin{aligned} \hat{c}_{\mathbf{k}\uparrow}(l) &= u_{\mathbf{k}}(l)\,\hat{c}_{\mathbf{k}\uparrow} + v_{\mathbf{k}}(l)\,\hat{c}^{\dagger}_{-\mathbf{k}\downarrow} \\ &+ \frac{1}{\sqrt{N}}\sum_{\mathbf{q}\neq 0}\left[u_{\mathbf{k},\mathbf{q}}(l)\,\hat{b}^{\dagger}_{\mathbf{q}}\hat{c}_{\mathbf{q}+\mathbf{k}\uparrow} + v_{\mathbf{k},\mathbf{q}}(l)\,\hat{b}_{\mathbf{q}}\hat{c}^{\dagger}_{\mathbf{q}-\mathbf{k}\downarrow}\right], \end{aligned} \tag{1}$$

$$\begin{aligned} \hat{c}^{\dagger}_{-\mathbf{k}\downarrow}(l) &= -v^{*}_{\mathbf{k}}(l)\,\hat{c}_{\mathbf{k}\uparrow} + u^{*}_{\mathbf{k}}(l)\,\hat{c}^{\dagger}_{-\mathbf{k}\downarrow} \\ &\frac{1}{\sqrt{N}}\sum_{\mathbf{q}\neq 0}\left[-v^{*}_{\mathbf{k},\mathbf{q}}(l)\,\hat{b}^{\dagger}_{\mathbf{q}}\hat{c}_{\mathbf{q}+\mathbf{k}\uparrow} + u^{*}_{\mathbf{k},\mathbf{q}}(l)\,\hat{b}_{\mathbf{q}}\hat{c}^{\dagger}_{\mathbf{q}-\mathbf{k}\downarrow}\right], \end{aligned} \tag{2}$$

with the boundary conditions

$u_{\mathbf{k}}(0)=1$ **and** $v_{\mathbf{k}}(0)=v_{\mathbf{k},\mathbf{q}}(0)=u_{\mathbf{k},\mathbf{q}}(l)=0$

Beyond the BCS approximation

We have generalized the Bogoliubov ansatz taking into account the non-condensed (preformed) pairs

$$\hat{c}_{\mathbf{k}\uparrow}\ (l) \;=\; u_{\mathbf{k}}(l)\ \hat{c}_{\mathbf{k}\uparrow} \ + v_{\mathbf{k}}(l)\ \hat{c}^{\dagger}_{-\mathbf{k}\downarrow} + \frac{1}{\sqrt{N}} \sum_{\mathbf{q}\neq 0} \left[u_{\mathbf{k},\mathbf{q}}(l)\ \hat{b}^{\dagger}_{\mathbf{q}} \hat{c}_{\mathbf{q}+\mathbf{k}\uparrow} \ + v_{\mathbf{k},\mathbf{q}}(l)\ \hat{b}_{\mathbf{q}} \hat{c}^{\dagger}_{\mathbf{q}-\mathbf{k}\downarrow} \right], \tag{1}$$

$$\hat{c}^{\dagger}_{-\mathbf{k}\downarrow}(l) \;=\; -v^{*}_{\mathbf{k}}(l)\ \hat{c}_{\mathbf{k}\uparrow} \ + u^{*}_{\mathbf{k}}(l)\ \hat{c}^{\dagger}_{-\mathbf{k}\downarrow} \quad \frac{1}{\sqrt{N}} \sum_{\mathbf{q}\neq 0} \left[-v^{*}_{\mathbf{k},\mathbf{q}}(l)\ \hat{b}^{\dagger}_{\mathbf{q}} \hat{c}_{\mathbf{q}+\mathbf{k}\uparrow} \ + u^{*}_{\mathbf{k},\mathbf{q}}(l)\ \hat{b}_{\mathbf{q}} \hat{c}^{\dagger}_{\mathbf{q}-\mathbf{k}\downarrow} \right], \tag{2}$$

with the boundary conditions

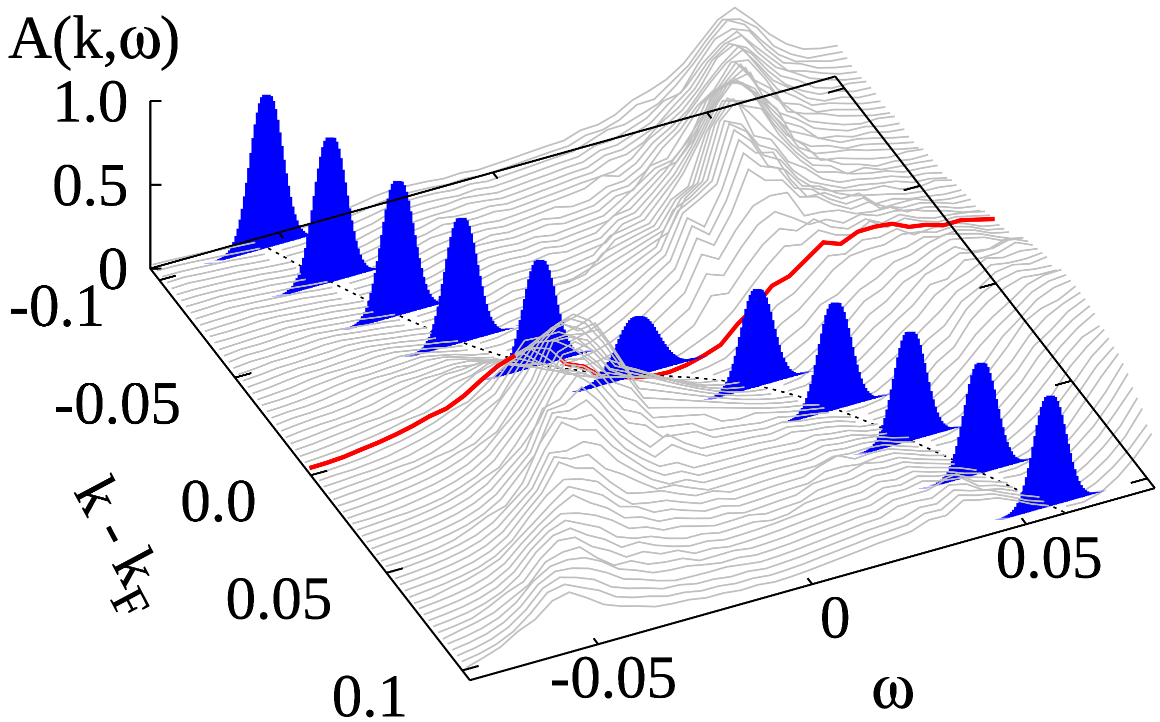
$u_{\mathbf{k}}(0) = 1$ and $v_{\mathbf{k}}(0) = v_{\mathbf{k},\mathbf{q}}(0) = u_{\mathbf{k},\mathbf{q}}(l) = 0$

and we determined the fixed point values $\lim_{l\rightarrow\infty} u_{\mathbf{k}}(l) \equiv \tilde{u}_{\mathbf{k}}$ etc from the coupled set of flow equations

$$\frac{\partial}{\partial l} u_{\mathbf{k}}(l)\ , \quad \frac{\partial}{\partial l} v_{\mathbf{k}}(l)\ , \quad \frac{\partial}{\partial l} u_{\mathbf{k},\mathbf{q}}(l)\ , \quad \frac{\partial}{\partial l} v_{\mathbf{k},\mathbf{q}}(l)\ .$$

Effective spectrum above T_c

$T_c < T < T^*$

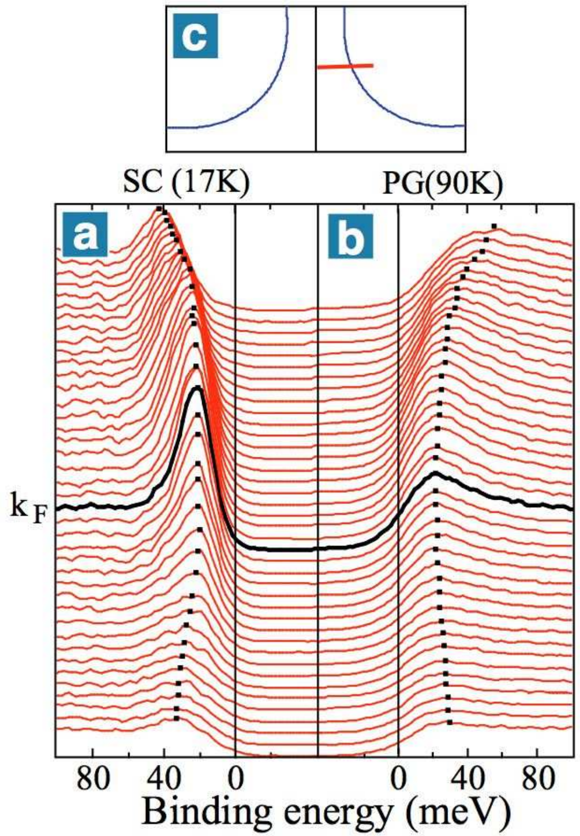


T. Domański and J. Ranninger, Phys. Rev. Lett. **91***, 255301 (2003).*

Evidence for Bogoliubov QPs above T_c

Evidence for Bogoliubov QPs above T_c

J. Campuzano group (Chicago, USA)

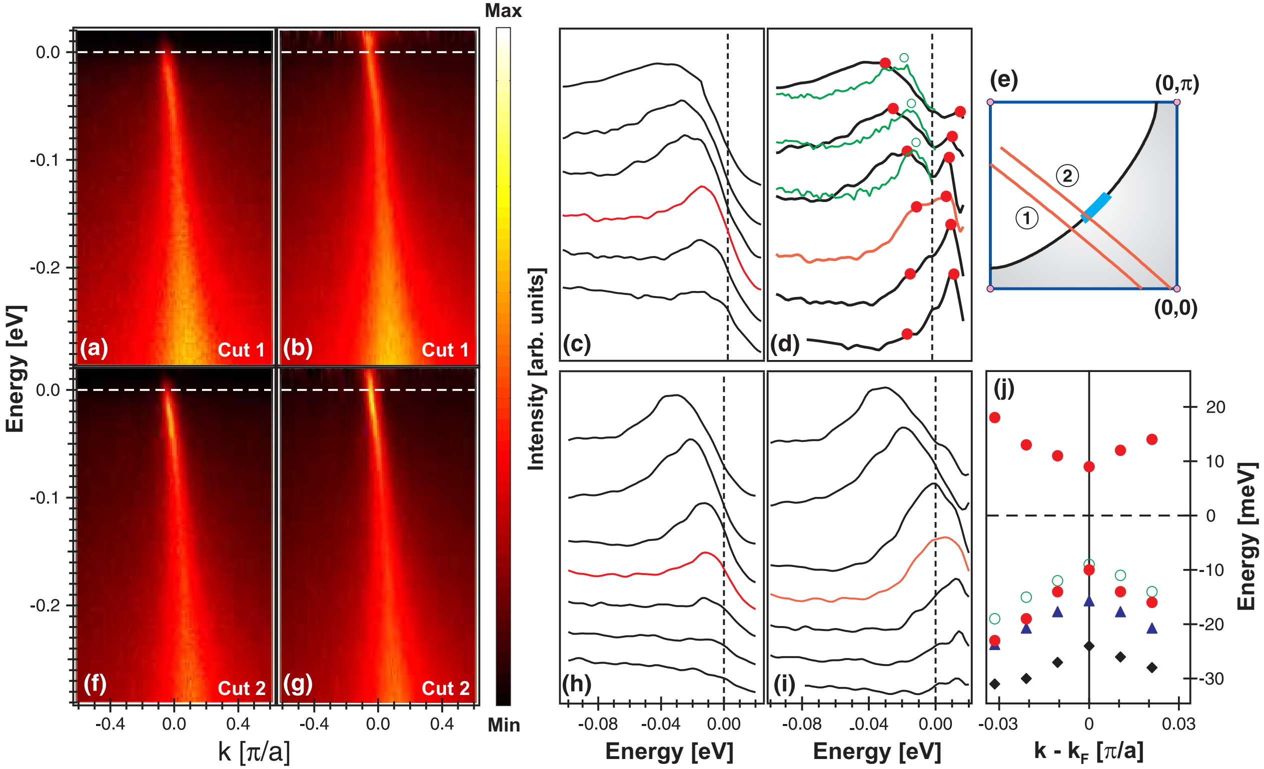


Results for: $Bi_2Sr_2CaCu_2O_8$

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

Evidence for Bogoliubov QPs above T_c

PSI group (Villigen, Switzerland)

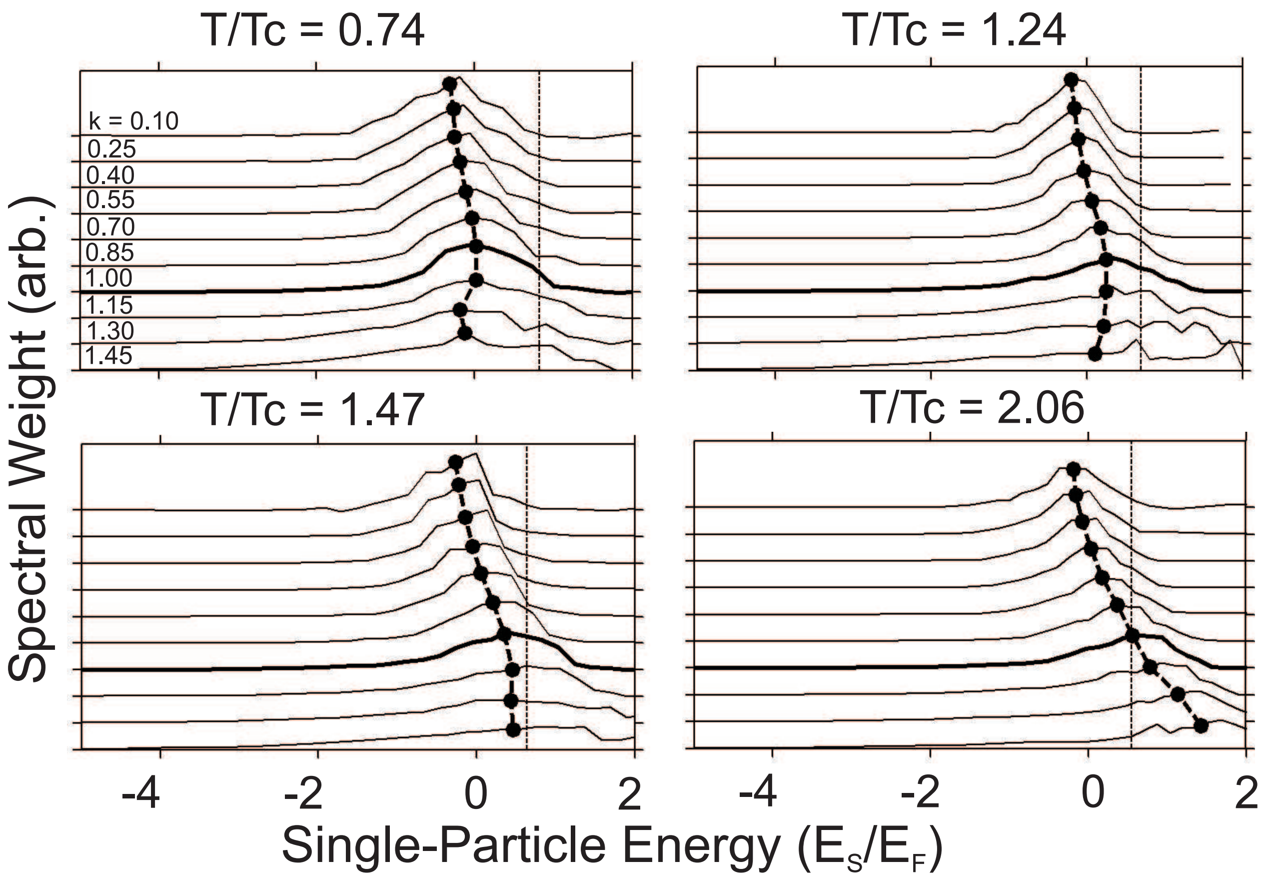


Results for: $La_{1.895}Sr_{0.105}CuO_4$

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

Evidence for Bogoliubov QPs above T_c

D. Jin group (Boulder, USA)



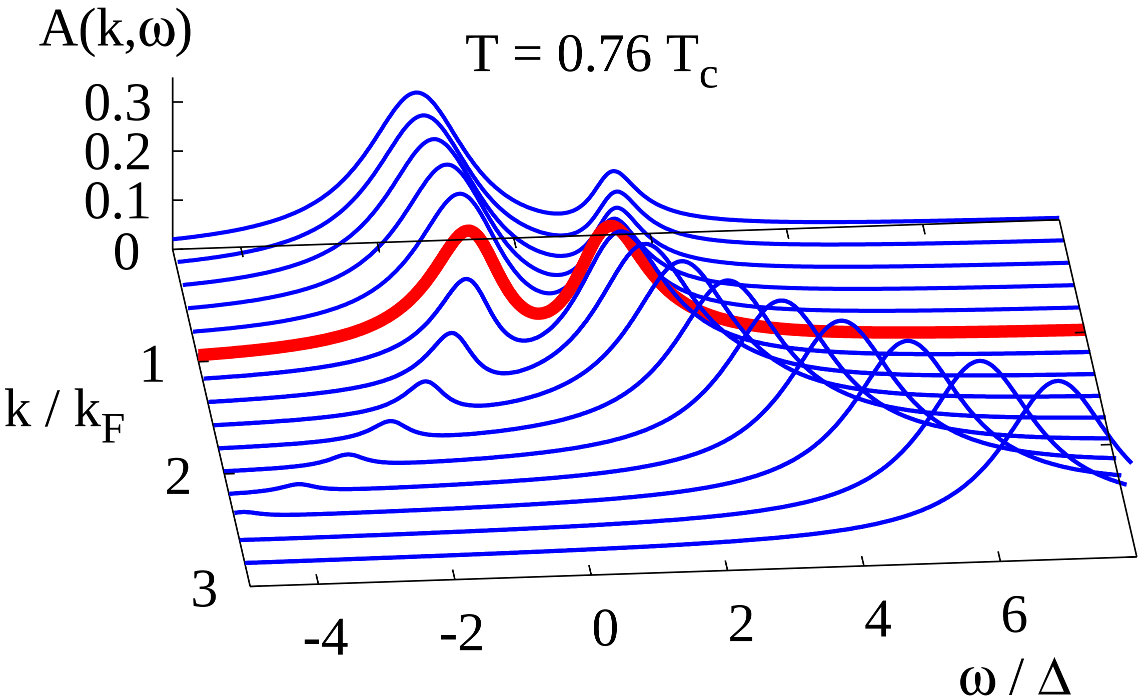
Results for: ultracold ^{40}K atoms

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

Bogoliubov QPs above T_c

Bogoliubov QPs above T_c

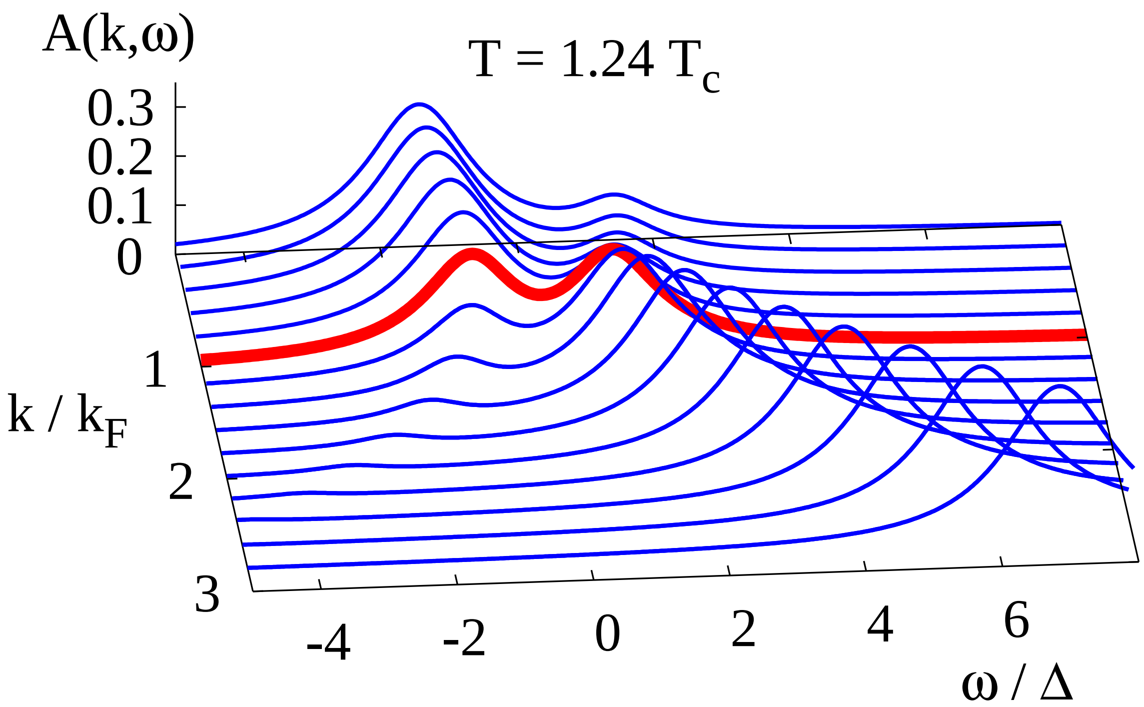
Reproducing experimental line-shapes of the ultra-cold fermion atoms



T. Domański, Phys. Rev. A **84**, *023634 (2011).*

Bogoliubov QPs above T_c

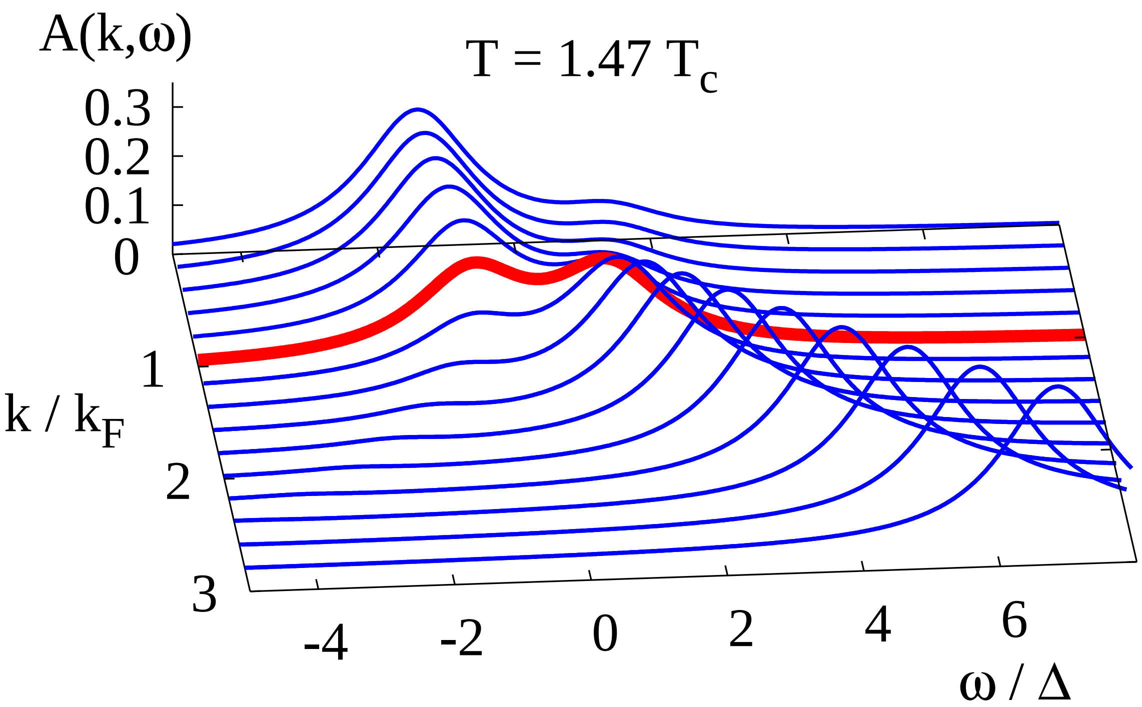
Reproducing experimental line-shapes of the ultra-cold fermion atoms



T. Domański, Phys. Rev. A ***84****, 023634 (2011).*

Bogoliubov QPs above T_c

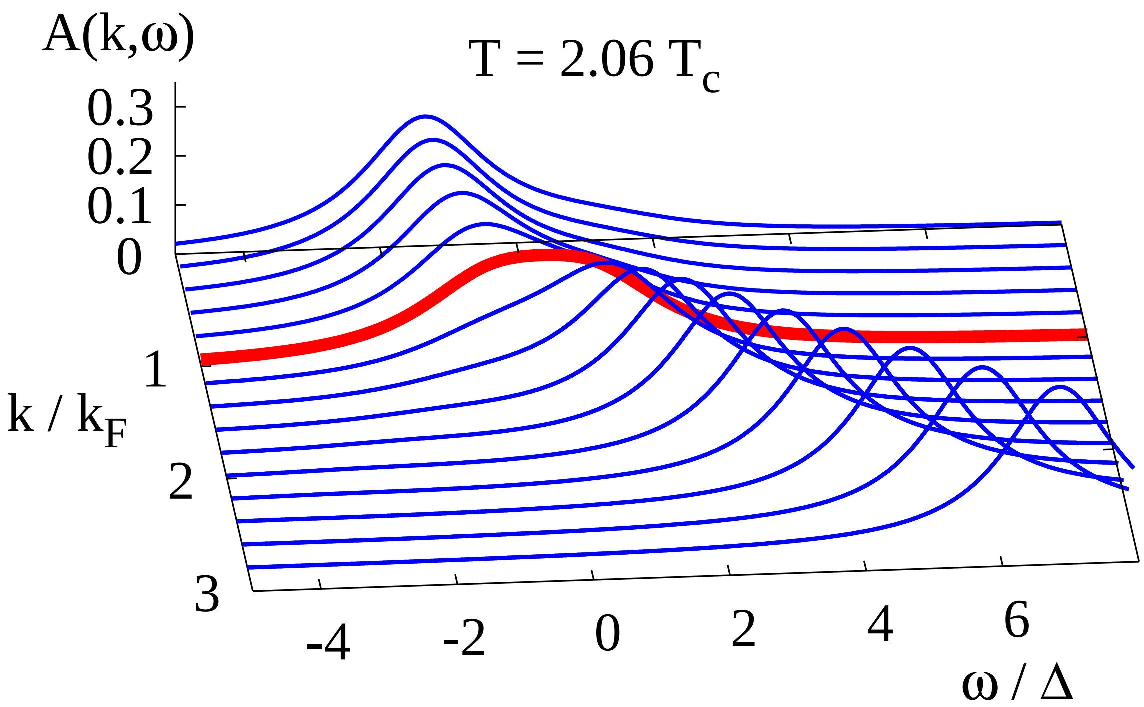
Reproducing experimental line-shapes of the ultra-cold fermion atoms



T. Domański, Phys. Rev. A **84***, 023634 (2011).*

Bogoliubov QPs above T_c

Reproducing experimental line-shapes of the ultra-cold fermion atoms



T. Domański, Phys. Rev. A **84**, *023634 (2011).*

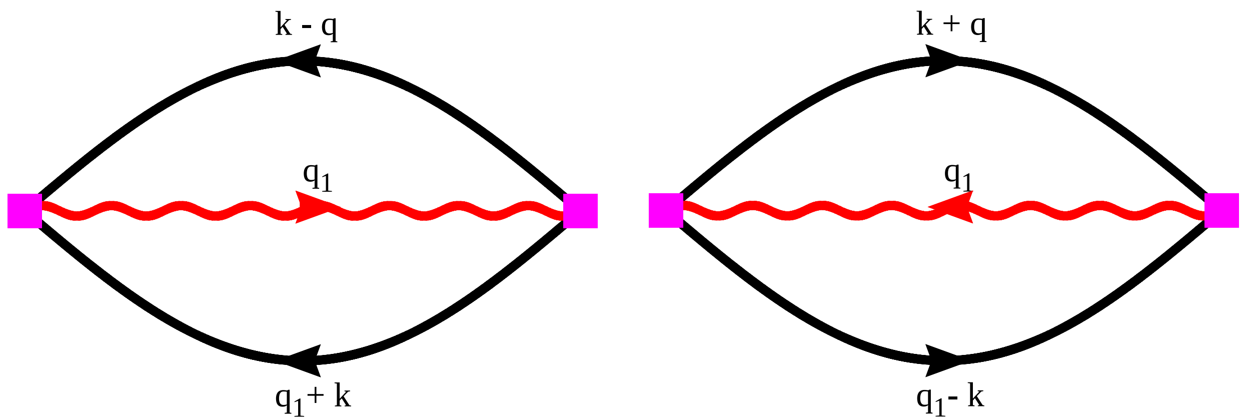
Diamagnetism

its origin above T_c

Diamagnetic response above T_c

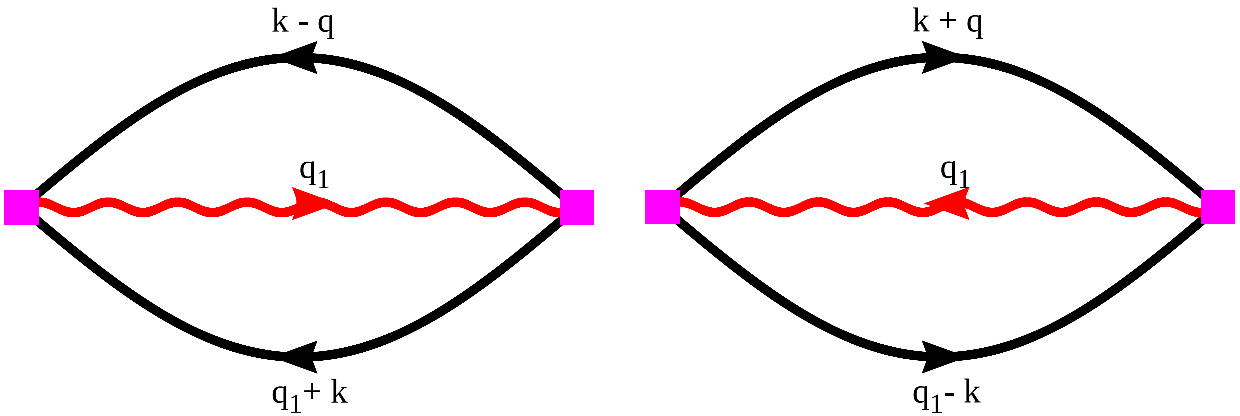
Diamagnetic response above T_c

The anomalous contributions

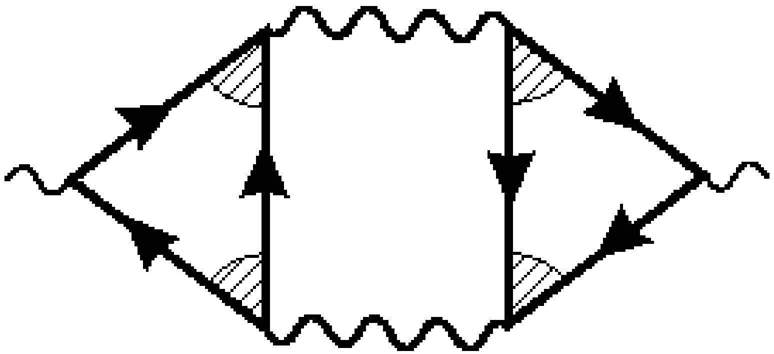


Diagramatic response above T_c

The anomalous contributions

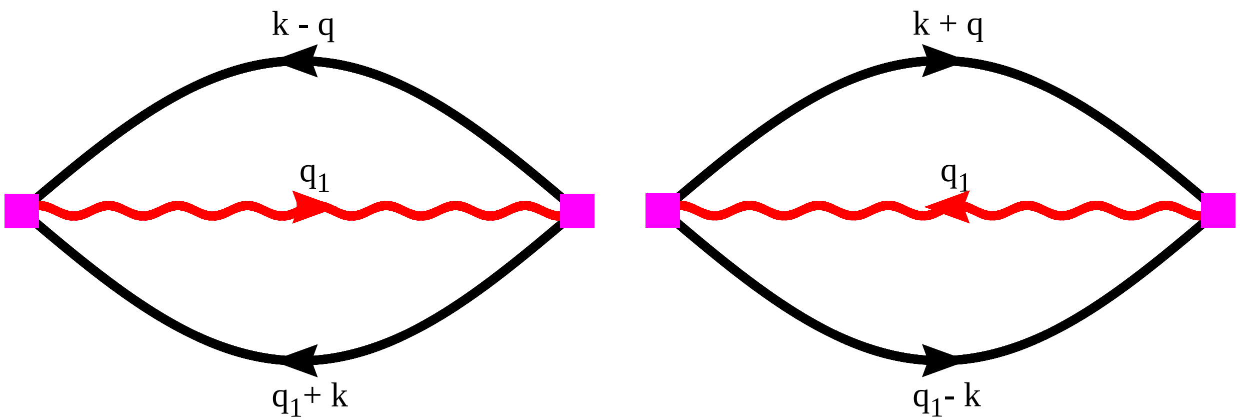


resemble the Aslamasov-Larkin diagram

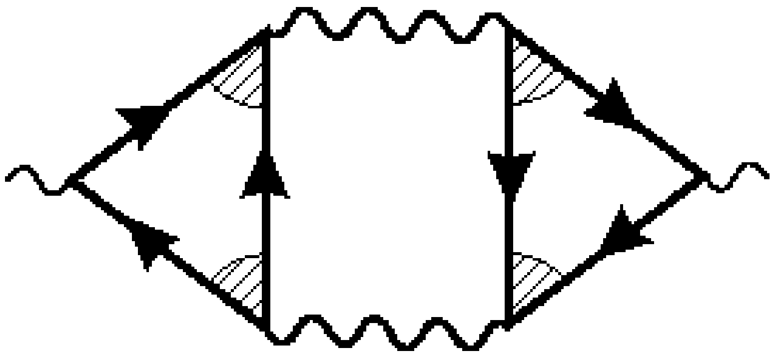


Diamagnetic response above T_c

The anomalous contributions



resemble the Aslamasov-Larkin diagram



enhancing the conductance/diamagnetism above T_c.

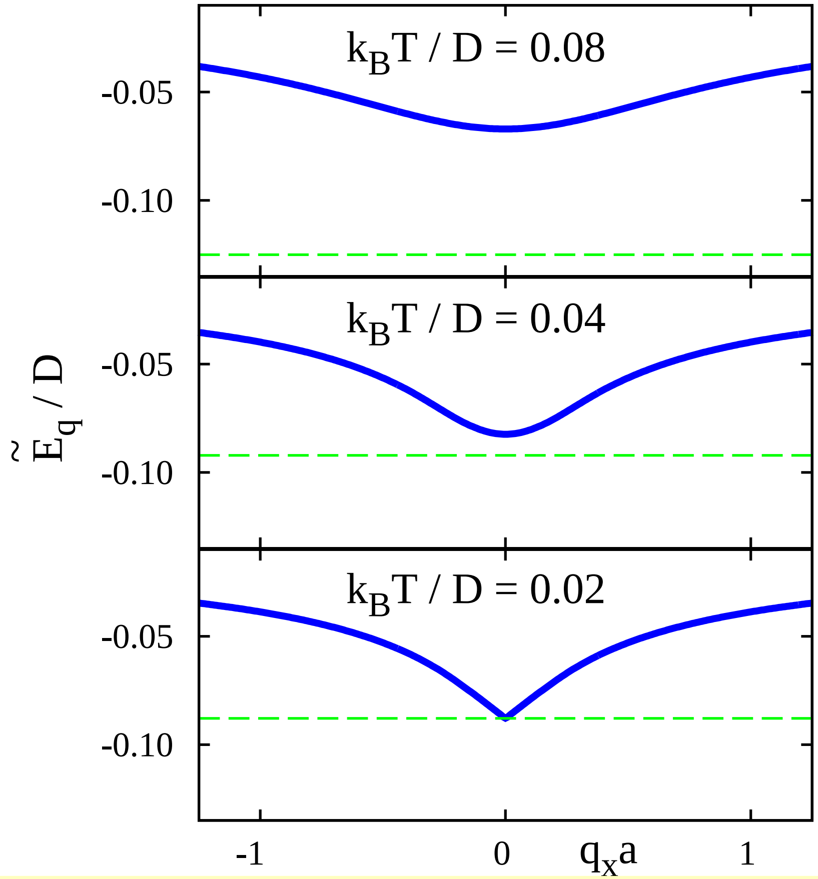
Onset of diamagnetism above T_c

Onset of diamagnetism above T_c

Onset of the diamagnetism coincides with appearance of the collective features in the fermion/boson spectrum.

Onset of diamagnetism above T_c

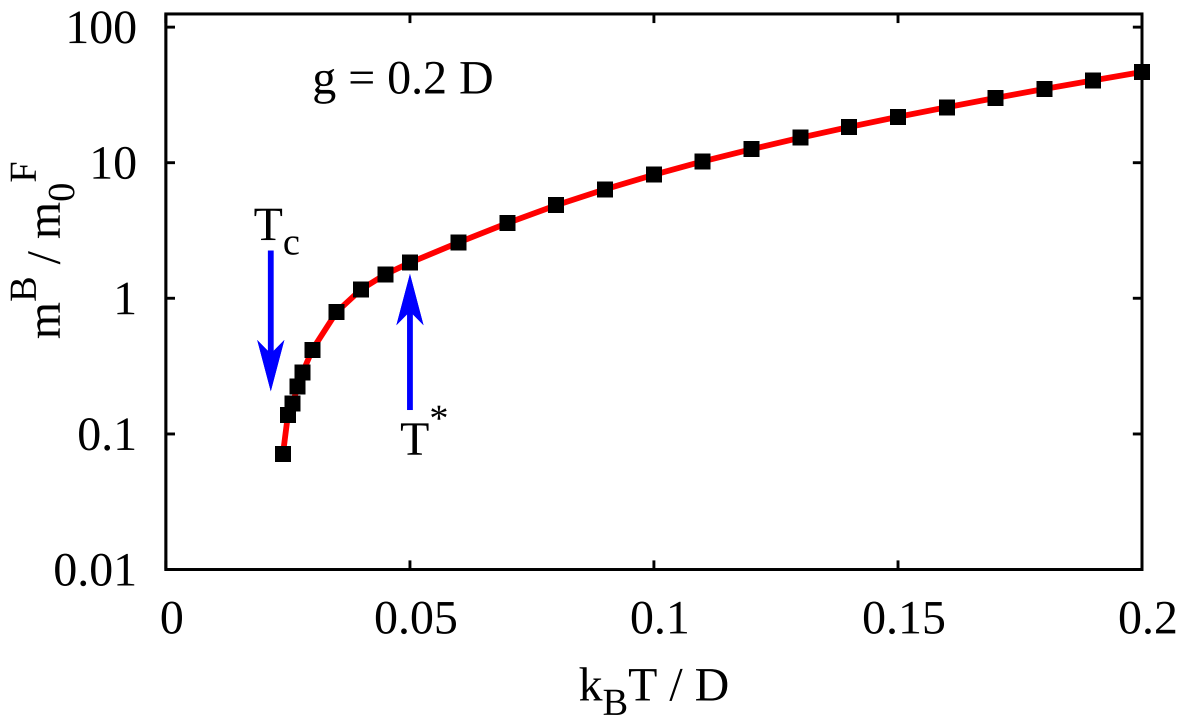
Onset of the diamagnetism coincides with appearance of the collective features in the fermion/boson spectrum.



Qulitative changes of the preformed pairs' spectrum.

Onset of diamagnetism above T_c

Onset of the diamagnetism coincides with appearance of the collective features in the fermion/boson spectrum.



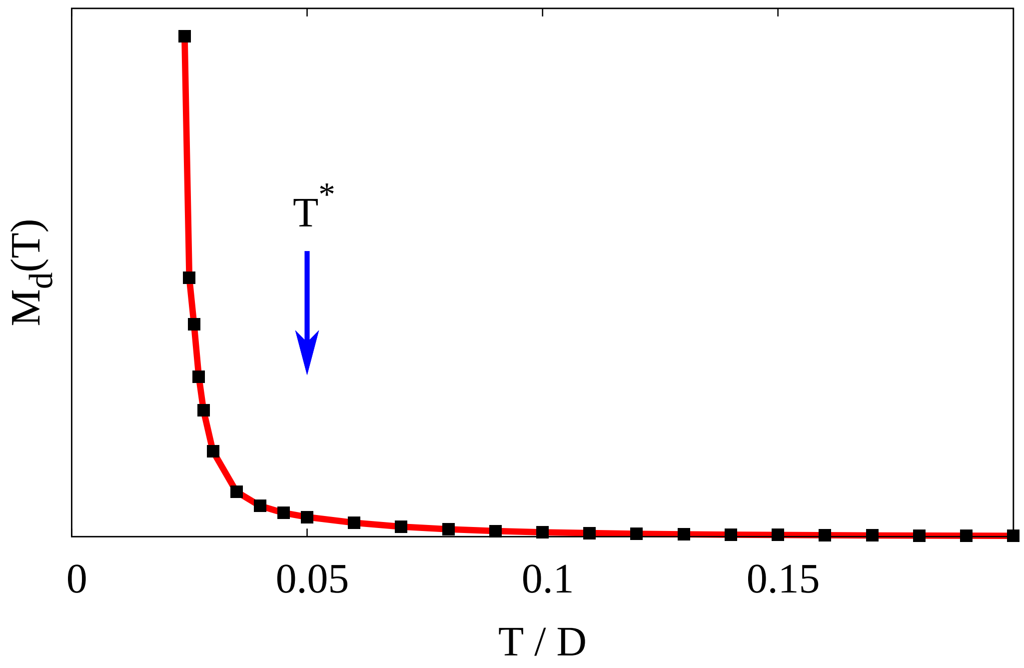
Effective mass m_B of the preformed pairs

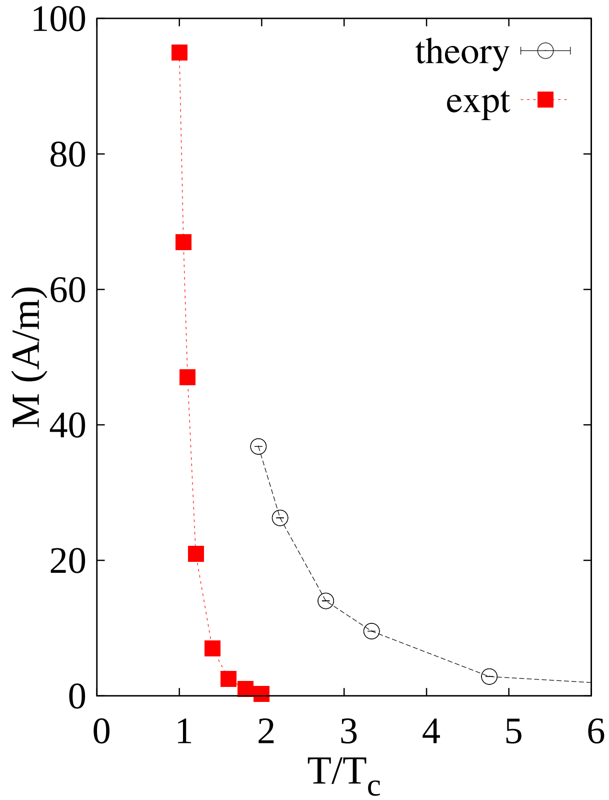
M. Zapalska and T. Domański, Phys. Rev. B ***84****, 174520 (2011).*

Onset of diamagnetism above T_c

Onset of the diamagnetism coincides with appearance of the collective features in the fermion/boson spectrum.

M. Zapalska and T. Domański (2014).

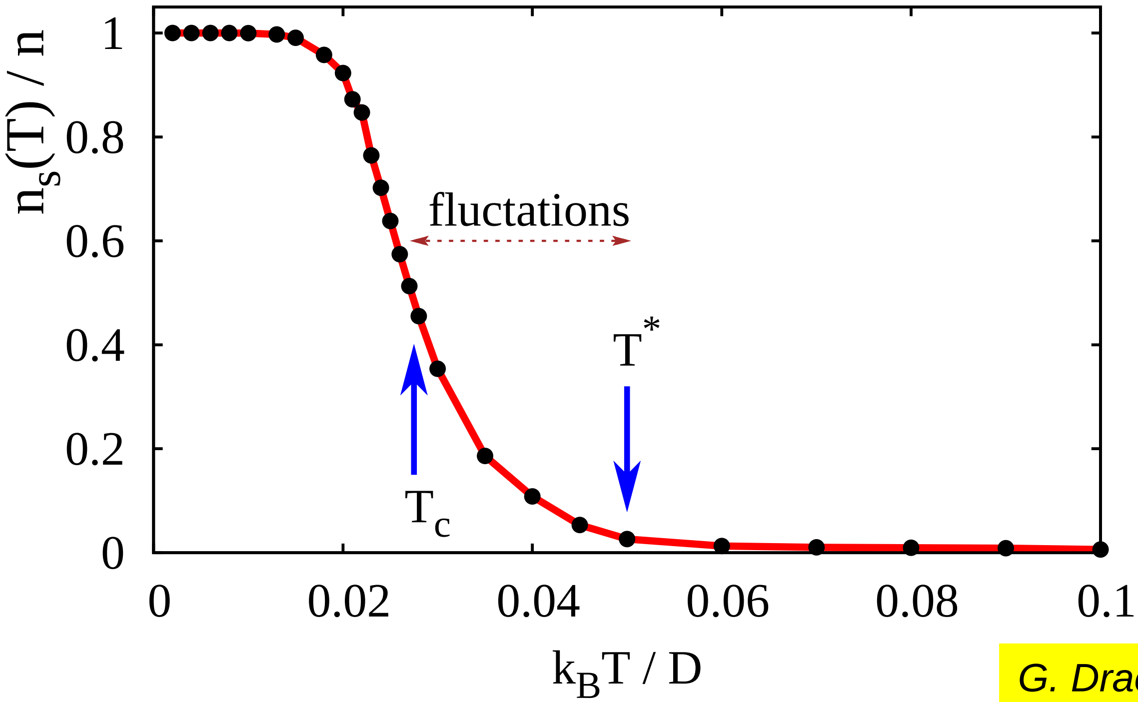


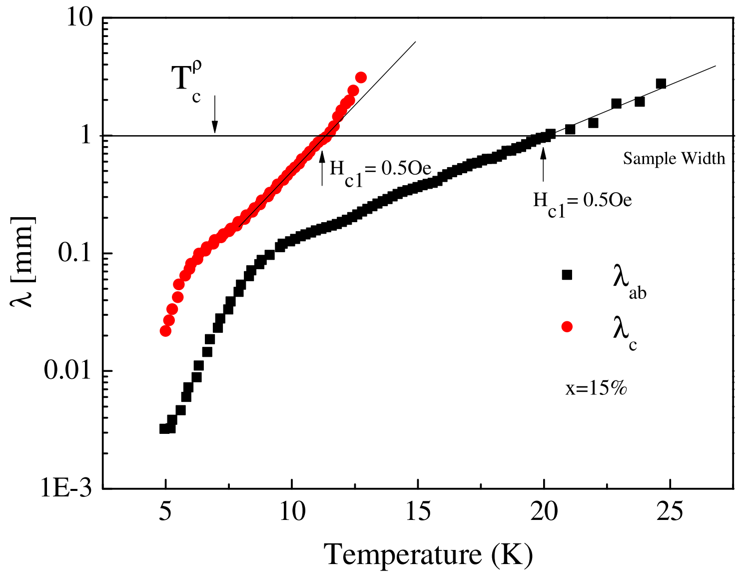


K.-Y. Yang, ... and M. Troyer, Phys. Rev. B ***83****, 214516 (2011).*

Onset of diamagnetism above T_c

Onset of the diamagnetism coincides with appearance of the collective features in the fermion/boson spectrum.





G. Drachuck et al, *Phys. Rev. B* **85**, *184518 (2012).*

$$J_x(\mathrm{q} \to 0, 0) = -\frac{e^2 n_s(T)}{m} A_x(\mathrm{q} \to 0, 0)$$

M. Zapalska and T. Domański, Phys. Rev. B **84**, *174520 (2011).*

Diamagnetic response above T_c

Diamagnetic response above T_c

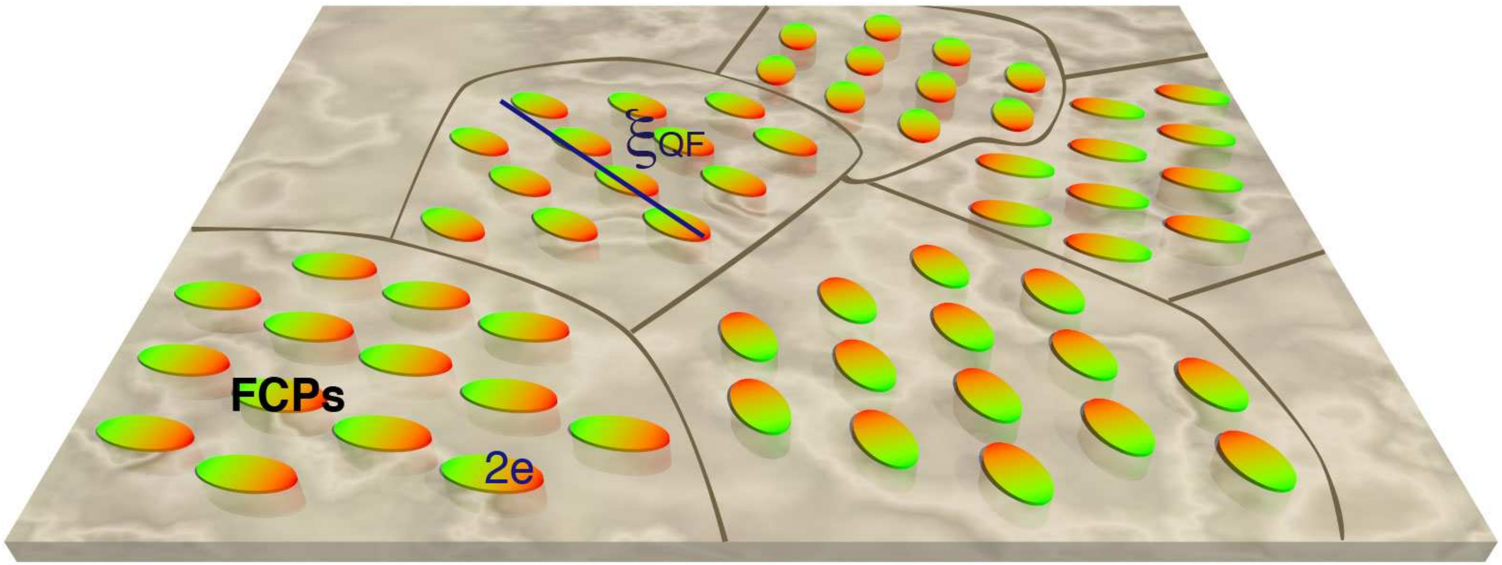
Residual diamagnetism originates from collective behavior of the pre-formed pairs.

Pair susceptibility is enhanced at T_{sc} and it ultimately diverges at some lower T_c.

Diamagnetic response above T_c

Residual diamagnetism originates from collective behavior of the pre-formed pairs.

Pair susceptibility is enhanced at T_{sc} and it ultimately diverges at some lower T_c.



Cartoon illustrating the vortex liquid above T_c.

Summary

Summary

- **A number of experimental data provide a clear evidence for the pre-existing pairs above T_c**

Summary

- A number of experimental data provide a clear evidence for the pre-existing pairs above T_c

$\Rightarrow$ **residual diamagnetism**

/ torque magnetometry, magnetization of needle samples /

Summary

- **A number of experimental data provide a clear evidence for the pre-existing pairs above T_c**

$\Rightarrow$ **residual diamagnetism**

/ torque magnetometry, magnetization of needle samples /

$\Rightarrow$ **Bogoliubov quasiparticles**

/ ARPES, Josephson effect, FT-STM /

Summary

- A number of experimental data provide a clear evidence for the pre-existing pairs above T_c

⇒ **residual diamagnetism**

/ torque magnetometry, magnetization of needle samples /

⇒ **Bogoliubov quasiparticles**

/ ARPES, Josephson effect, FT-STM /

- Short-range superconducting correlations

Summary

- **A number of experimental data provide a clear evidence for the pre-existing pairs above T_c**

$\Rightarrow$ **residual diamagnetism**

/ torque magnetometry, magnetization of needle samples /

$\Rightarrow$ **Bogoliubov quasiparticles**

/ ARPES, Josephson effect, FT-STM /

- **Short-range superconducting correlations**

$\Rightarrow$ **are responsible for the sc-like features**

Summary

- A number of experimental data provide a clear evidence for the pre-existing pairs above T_c

$\Rightarrow$ **residual diamagnetism**

/ torque magnetometry, magnetization of needle samples /

$\Rightarrow$ **Bogoliubov quasiparticles**

/ ARPES, Josephson effect, FT-STM /

- Short-range superconducting correlations

$\Rightarrow$ **are responsible for the sc-like features**

$\Rightarrow$ **even though ODLRO is absent above T_c**

Summary

- A number of experimental data provide a clear evidence for the pre-existing pairs above T_c

$\Longrightarrow$ **residual diamagnetism**

/ torque magnetometry, magnetization of needle samples /

$\Longrightarrow$ **Bogoliubov quasiparticles**

/ ARPES, Josephson effect, FT-STM /

- Short-range superconducting correlations

$\Longrightarrow$ **are responsible for the sc-like features**

$\Longrightarrow$ **even though ODLRO is absent above T_c**

T h a n k y o u