Interference of Bogoliubov quasiparticles in the antinodal region of superconducting cuprates

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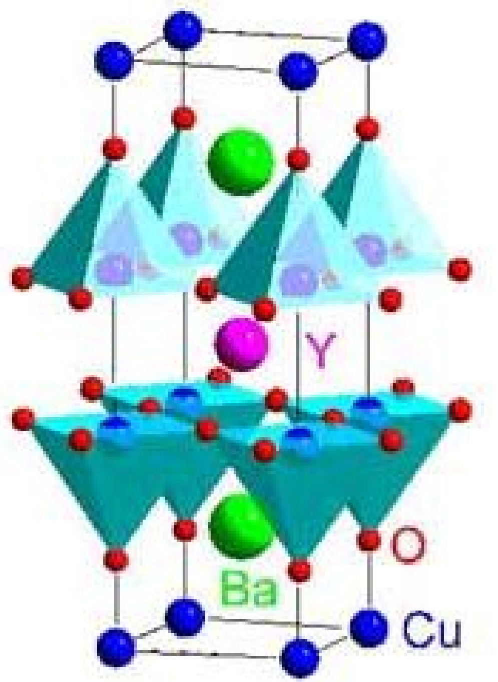
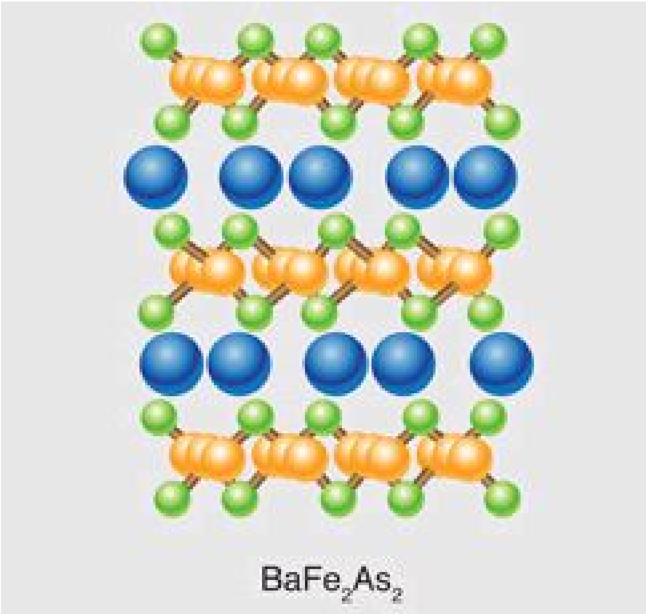
1. *Phase diagram of the cuprates*
2. *Superconducting pairing with large total momentum K.*
   Mirror nesting, kinematical constraint, oscillation of Coulomb potential.
3. *Coexisting of the Cooper and K-pairing channels.*
4. *Topology of superconducting order parameter.*
5. *FT-STM and AC-ARPES.*
6. *Interference of Bogoliubov quasiparticles in the nodal region.*
7. *Interference of Bogoliubov quasiparticles in the antinodal region.*
8. *Stripe and checkerboard structures.*

Crystal structure of cuprates and Fe-pnictides



$YBa_2Cu_30_7$



Phase diagram of high-T_c cuprates

Competing ordered states: proximity of the structure and energy of the ground state

Spin antiferromagnet (**AF**)

Weak pseudogap (**wPG**)

Orbital antiferromagnet (**DDW** – *charge current density wave*)

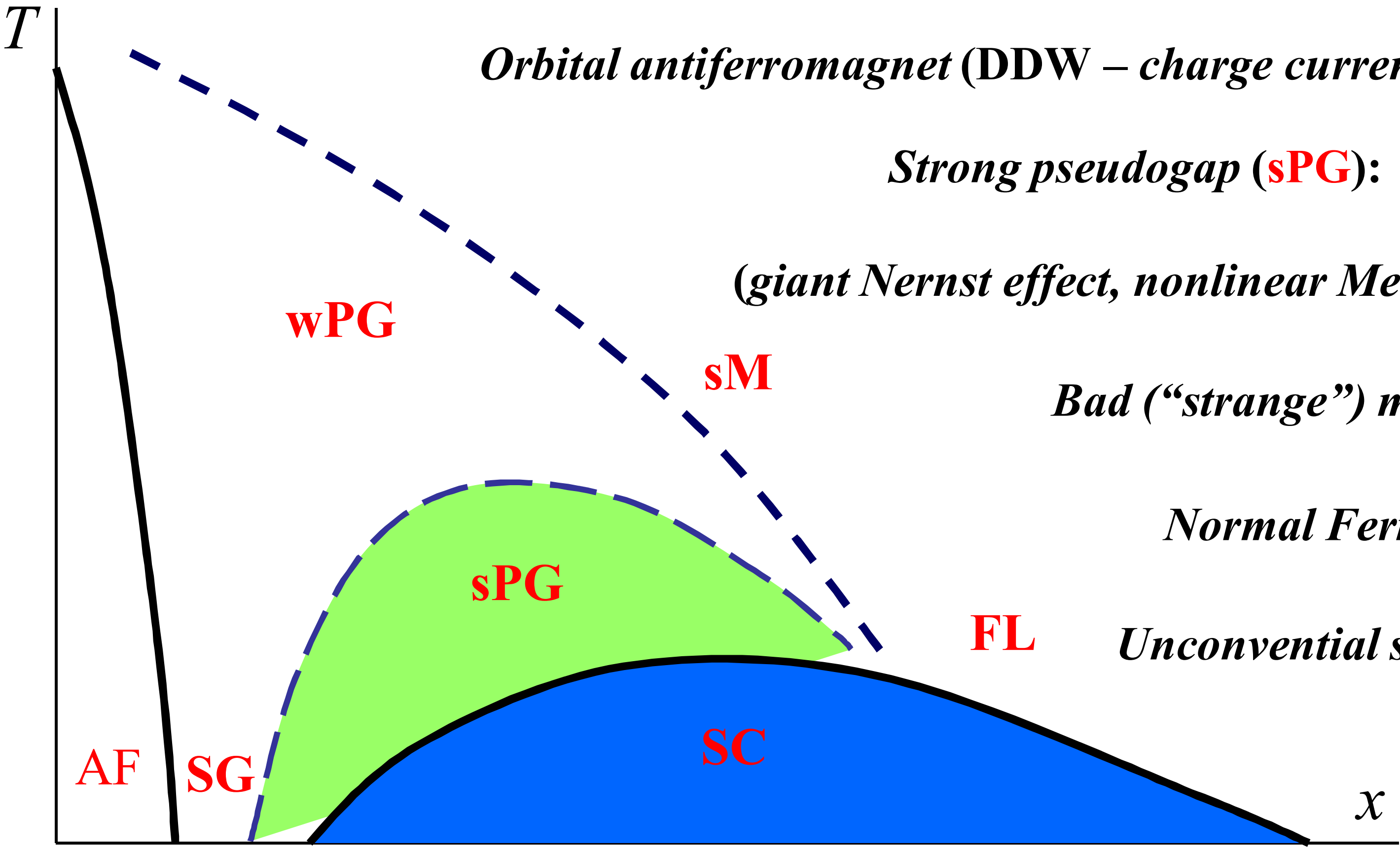
Strong pseudogap (**sPG**):

(*giant Nernst effect, nonlinear Meissner effect*)

Bad ("strange") metal (**sM**)

Normal Fermi liquid (**FL**)

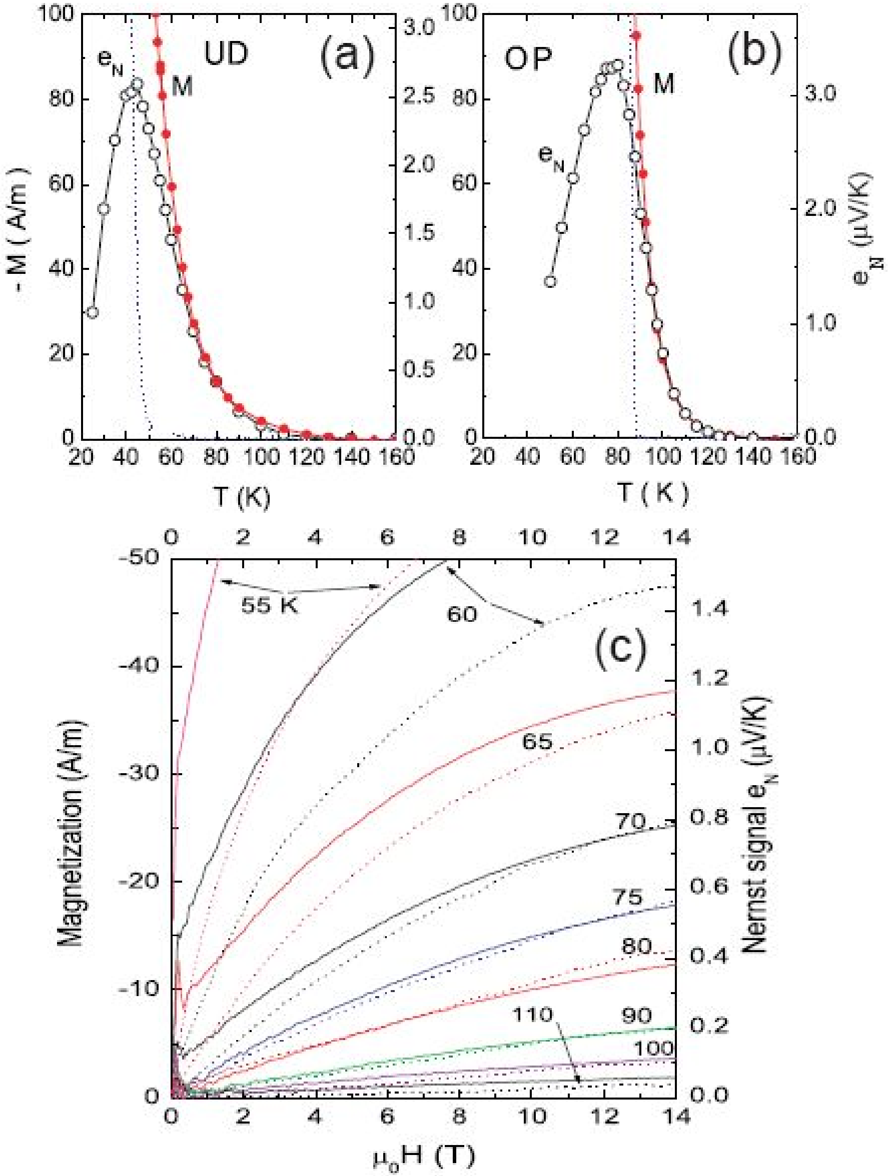
Unconvential superconductor (**SC**)



Anomalous diamagnetism and giant Nernst effect of the strong pseudogap state

$Bi_2Sr_{2-y}La_yCu_2O_6$, T_c=28 K

Nernst response is obsevable up to ≈ 100 K



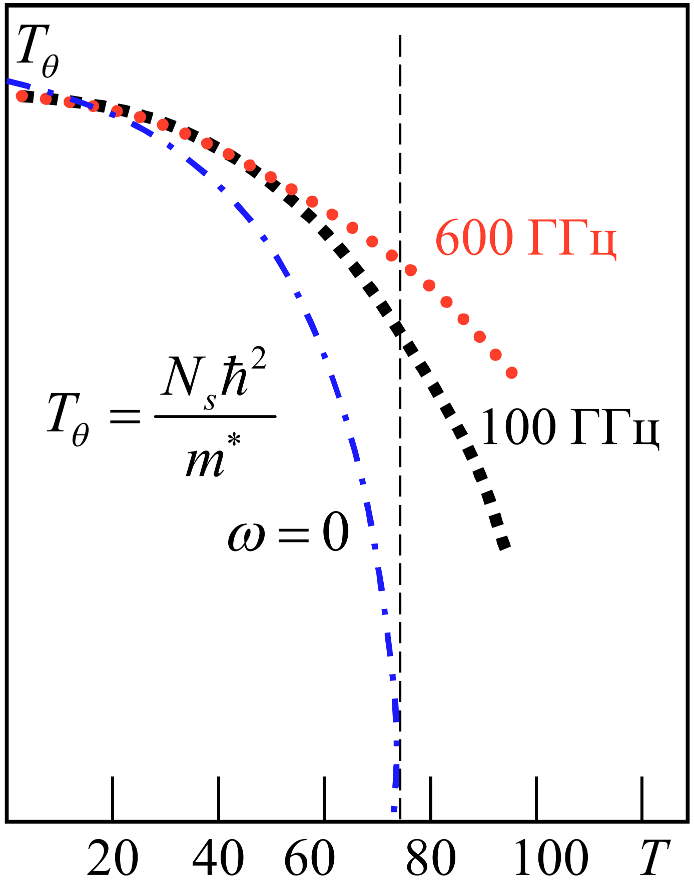
Anomalous diamagnetism, observable above the coherence loss temperature, disappears below weak pseudogap crossover temperature

Strong competition between superconducting and strong pseudogap states

Z.A. Xu et al., Nature **406**, 486 (2000)

Manifestation of superconducting properties of the strong pseudogap

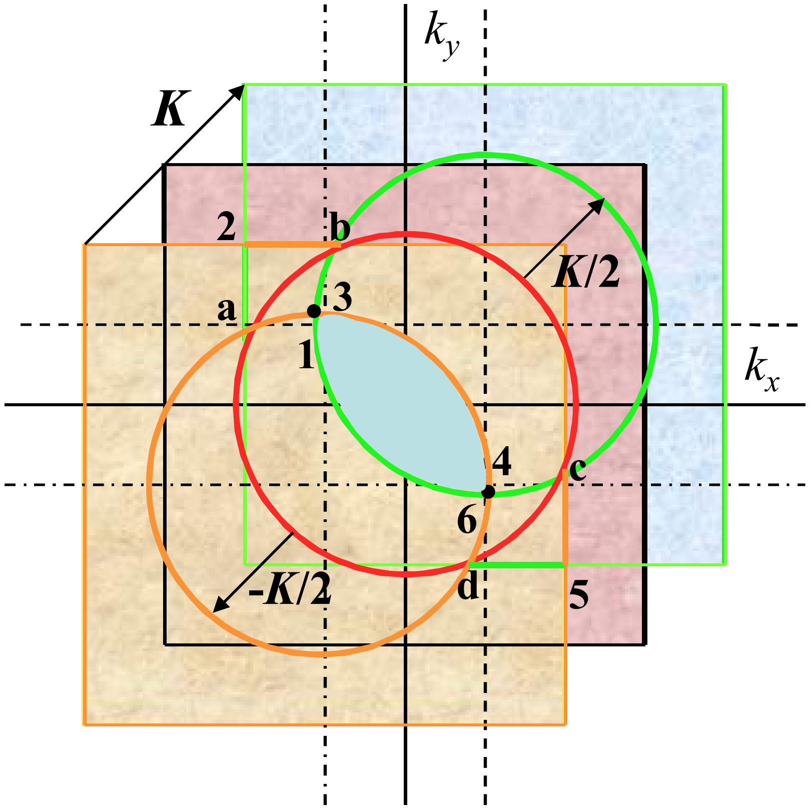
Frequency dependence of superfluid density N_s



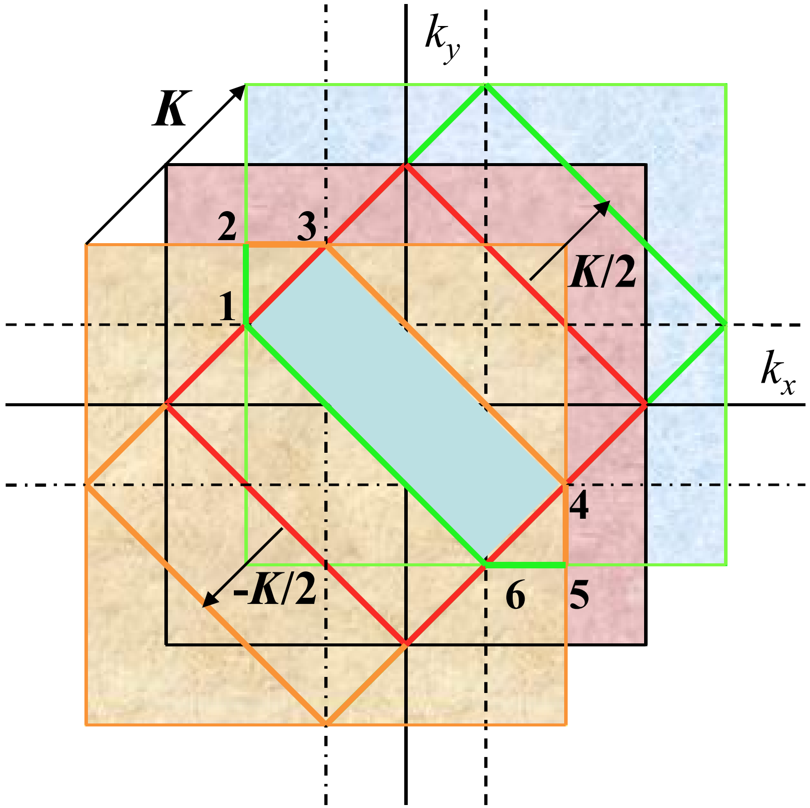
Superconducting pairing with large momentum (*K*-pairing)

Kinematical constraint. "Pair" Fermi contour

$$\varepsilon(k_x,k_y)=\frac{\hbar^2}{2m^*}\left(k_x^2+k_y^2\right)$$



$$\varepsilon(k_x,k_y)=-2t\left(\cos k_x+\cos k_y\right)$$

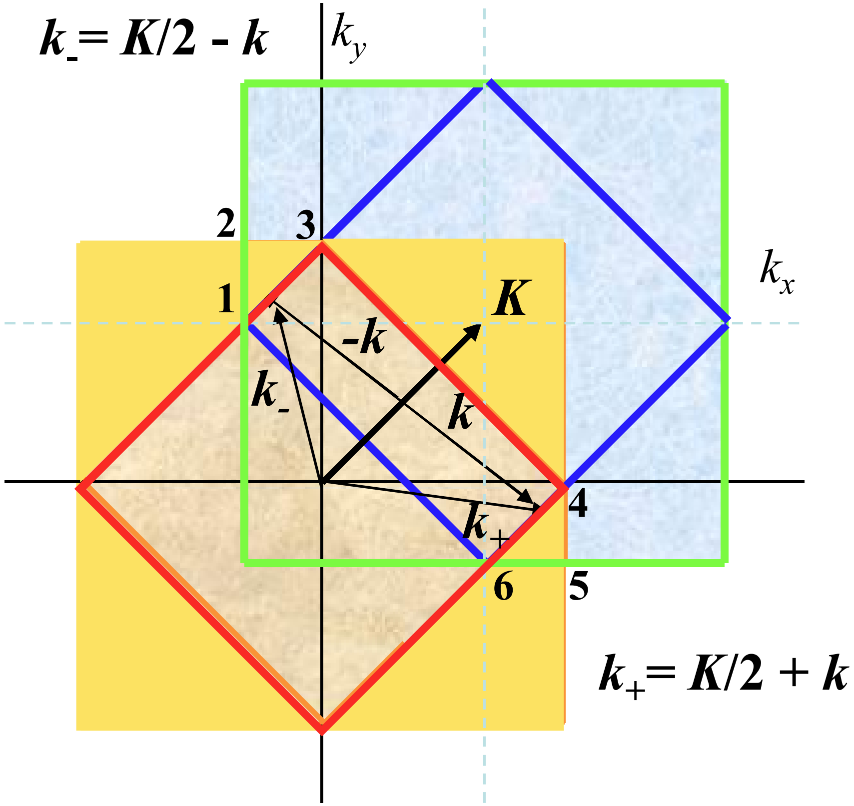


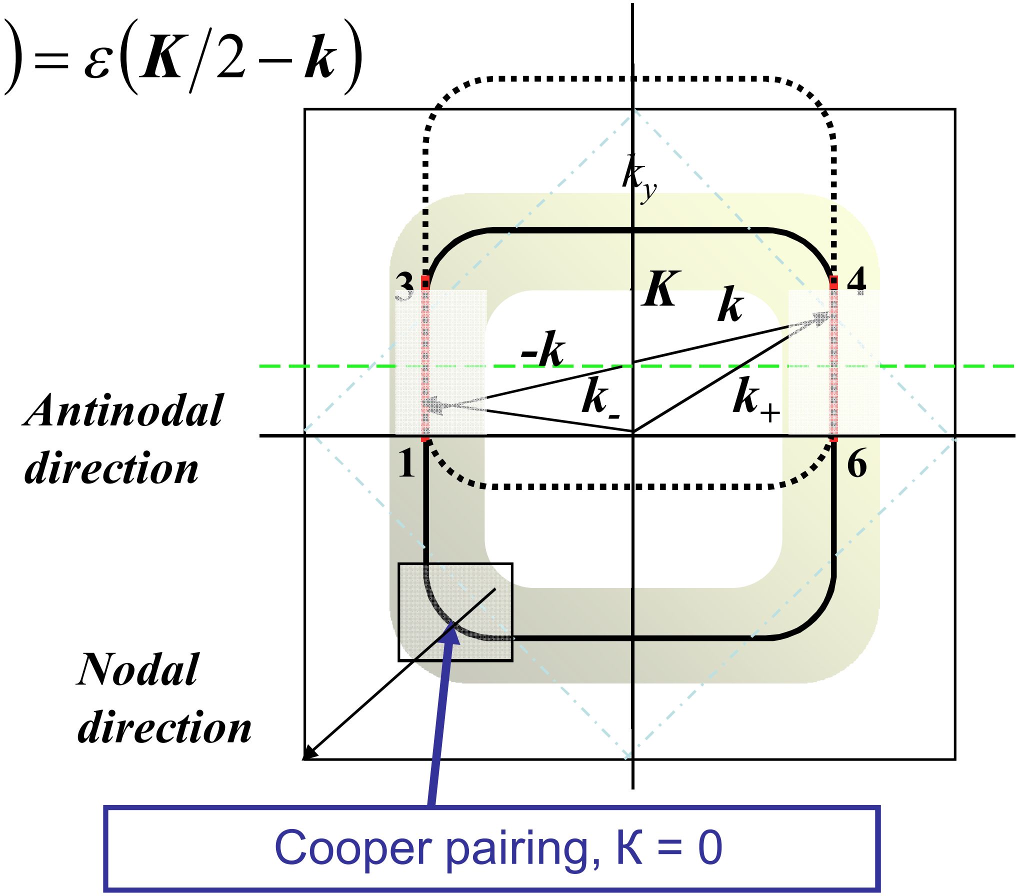
K-pairing. Mirror nesting

Kinematical constraint + *Insulation induced constraint*

logarithmic singularity in the SC K-pairing channel

$$\varepsilon\left(\boldsymbol{K}/2+\boldsymbol{k}\right)=\varepsilon\left(\boldsymbol{K}/2-\boldsymbol{k}\right)$$



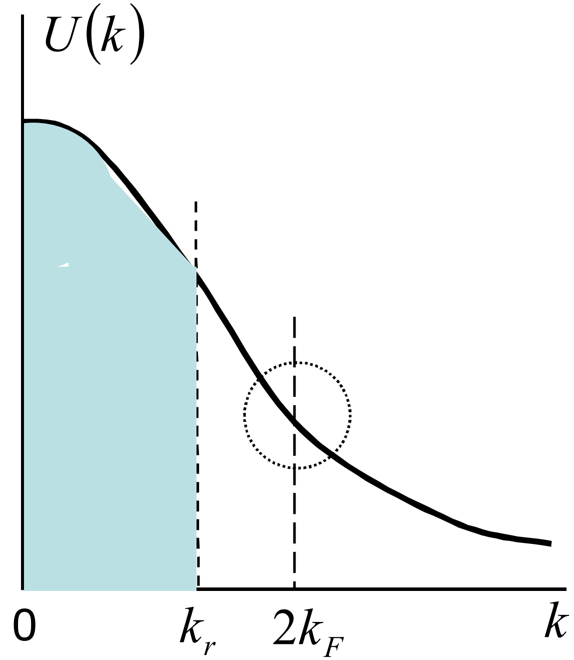


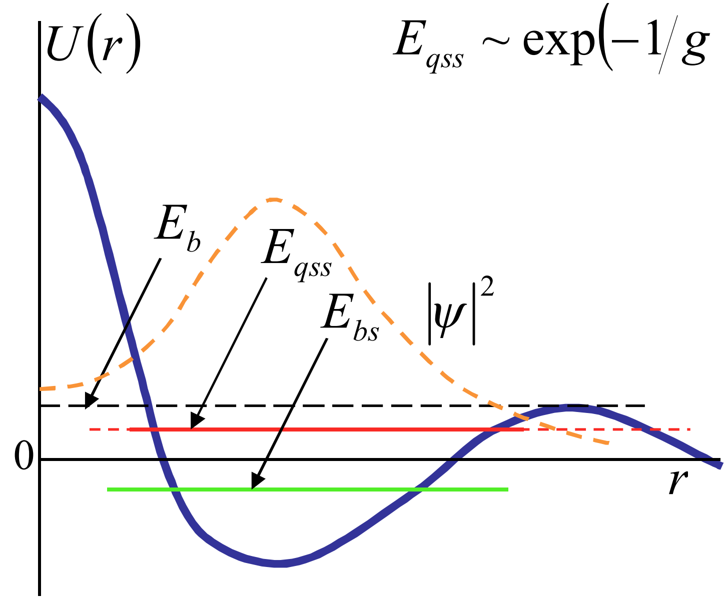
Pairing Coulomb repulsion

Bound state: $E_{bs} \sim \exp(-1/gU_0)$

Quasi-stationary states: $E \to E_{qss} - i\Gamma/2$

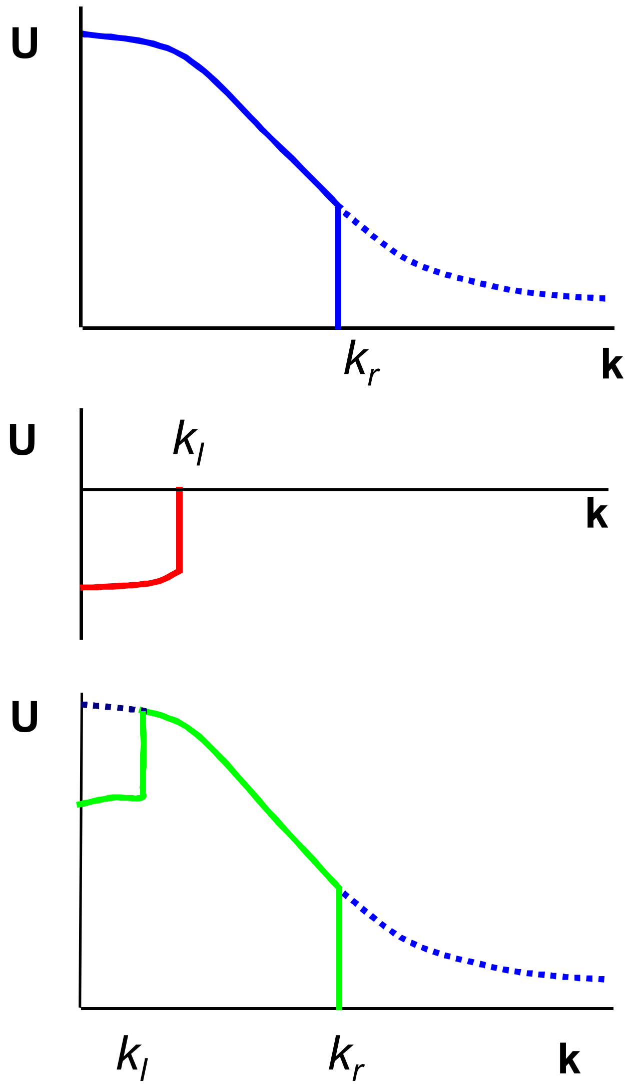
$E_{qss} \sim \exp(-1/g\, U_{qss})$

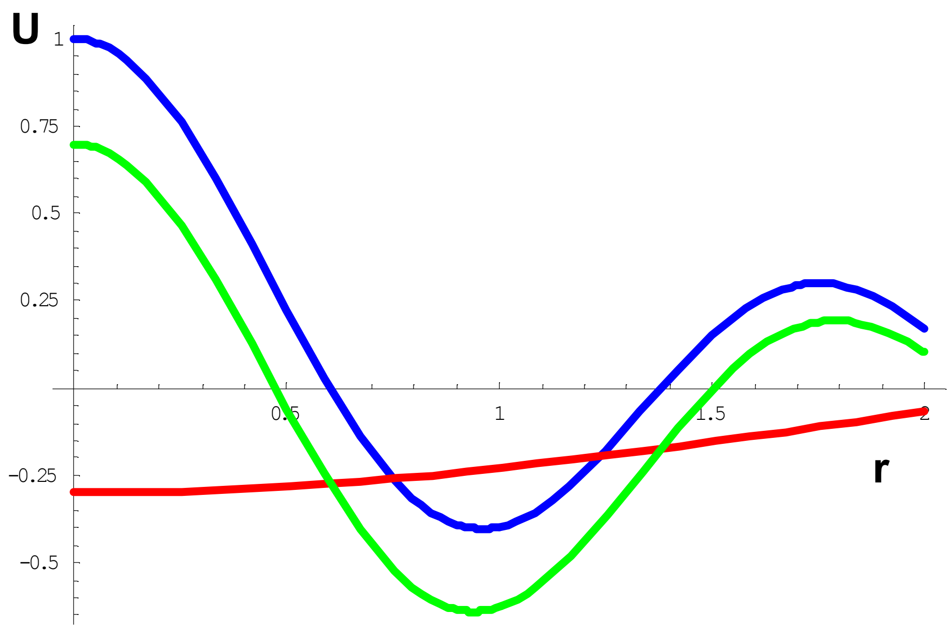




Asymmetry of tunnel current-voltage characteristic.
Analogy with Gamov's theory of alpha-decay

Symmetrization of oscilating potential by electron-phonon interaction (impurity scattering $k_l \sim 1/l$)

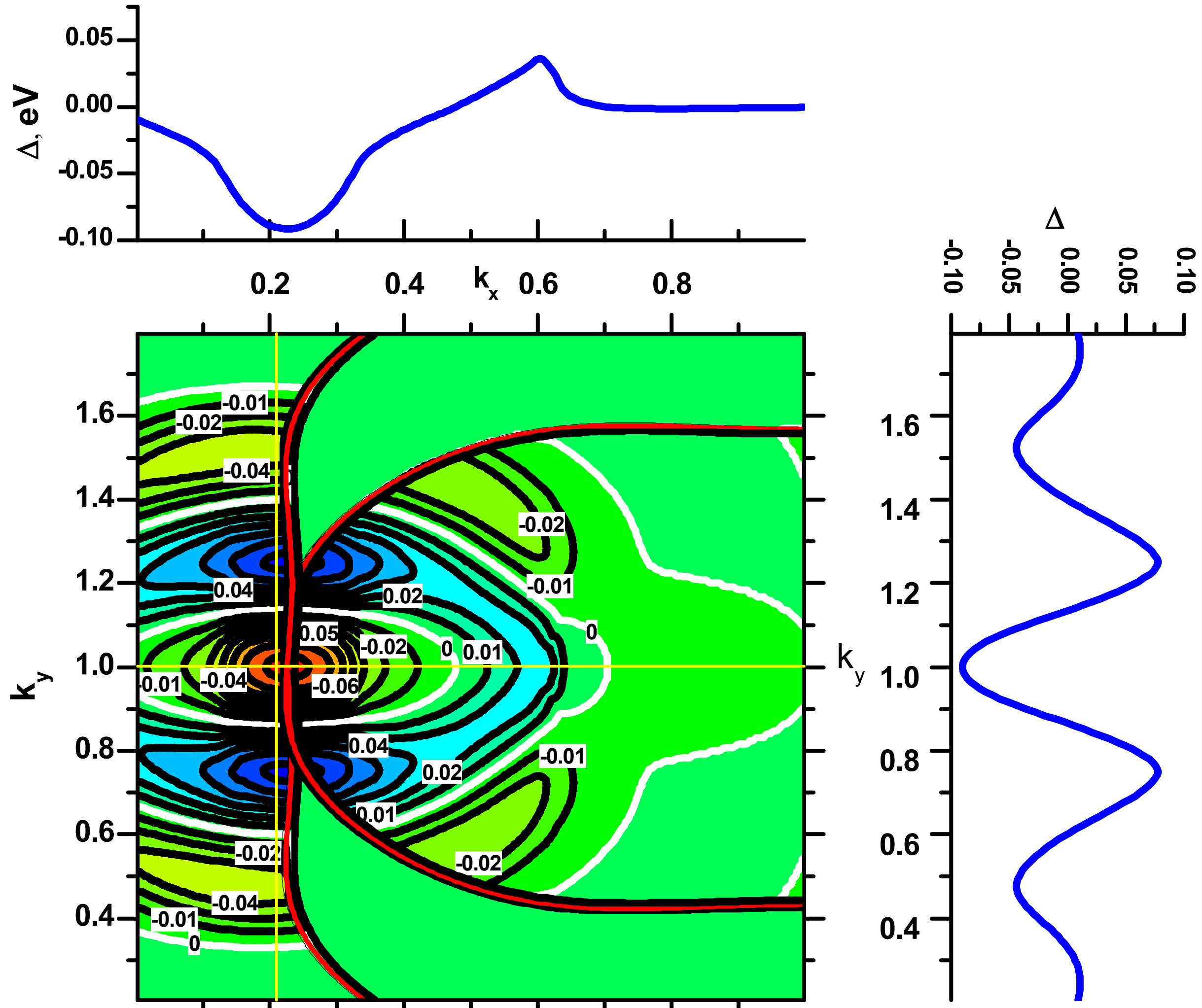




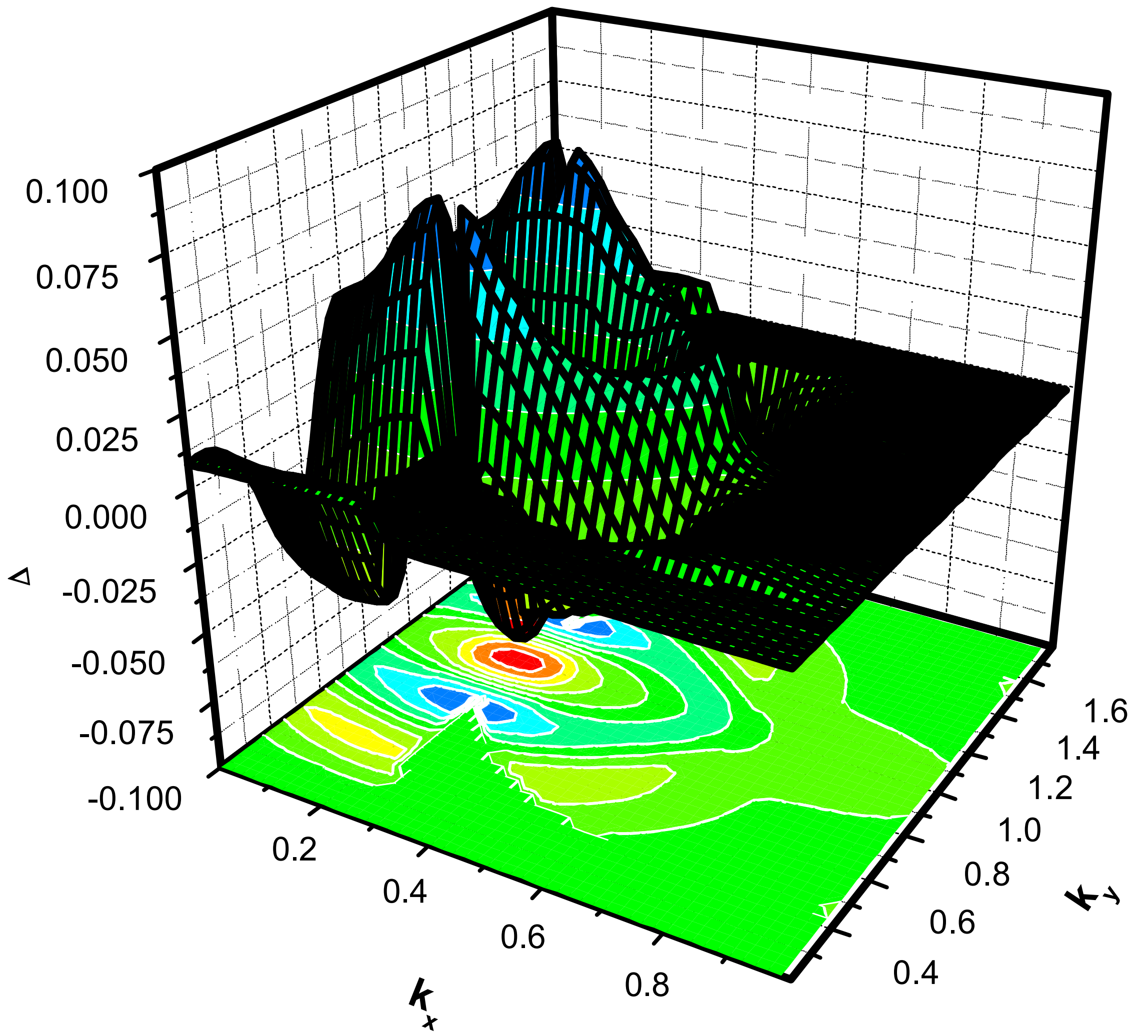
Topology of the superconducting order parameter

$$\Delta_K(\boldsymbol{k}) = -\frac{1}{2}\sum_{k'}\frac{U(\boldsymbol{k}-\boldsymbol{k}')\Delta_K(\boldsymbol{k}')}{\sqrt{\xi_K^2(\boldsymbol{k}')+|\Delta_K(\boldsymbol{k}')|^2}}$$

⌖ ***Essential dependence on the momentum of the relative motion of K-pair***

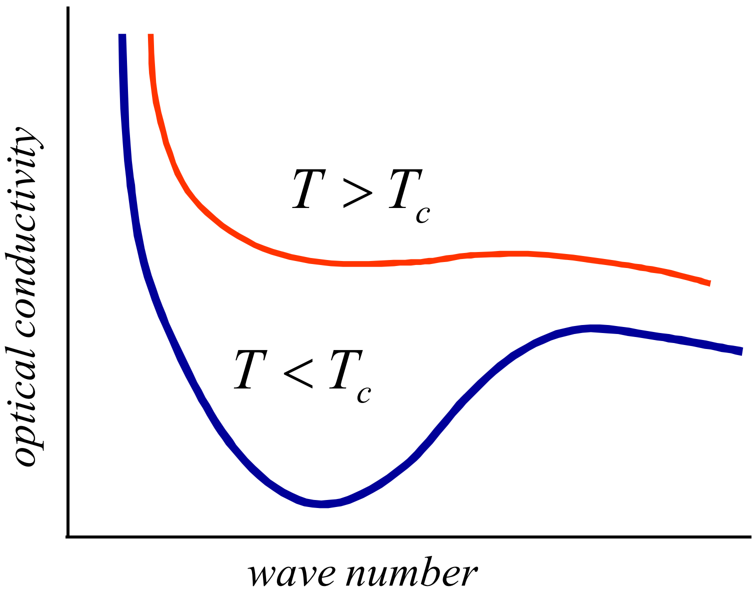


Topology of the superconducting order parameter



Optical conductivity. Superfluid density

D.N. Basov, T. Timusk, 2005



Effective number of carriers per planar Cu atom

Material	$T_c\ (K)$	N_{tot}	N_{Drude}	N_s	N_s/N_{tot}	N_s/N_{Drude}
$La_2CuO_{4.12}$	40	0.14	0.025	0.028	0.2	0.8
$Bi_2Sr_2CaCu_2O_8$	85	0.38	0.105	0.092	0.24	0.88
$Y\,0.35$	40	0.21	0.04	0.02	0.08	0.5
$P\,0.5, Y\,0.2$	35	0.23	0.05	0.017	0.07	0.34
$YBa_2Cu_3O_{7-\delta}$	92	0.44	0.093	0.082	0.19	0.89
Pr 0.15	75	0.375	0.073	0.054	0.14	0.74
Pr 0.35	40	0.25	0.045	0.02	0.08	0.44
$Tl_2Ba_2CaCu_2O_8$	110	0.54	0.13	0.115	0.21	0.88
Uncertanties	± 2	± 0.03	± 0.01	± 0.001	± 0.001	± 0.04

Chemical potential shift: $\delta\mu \sim |\Delta|$

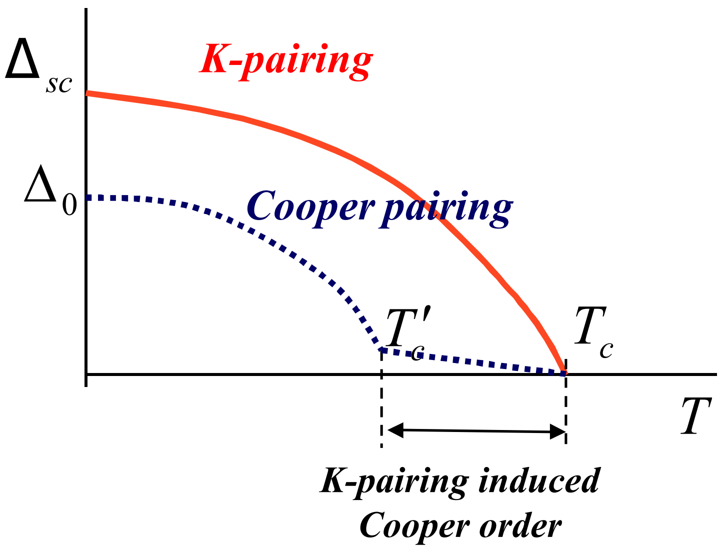
(instead of $\delta\mu \sim \Delta^2 / E_F$ ***in the BCS theory)***

G. Rietveld, N.Y. Chen, D. van der Marel, PRL 69, 2578 (1992)

$$\sigma_1(T > T_c) - \sigma_1(T < T_c) \neq 0, \quad \hbar\omega \sim 100\Delta$$ **("high energy problem",** *A. Leggett, 2006)*

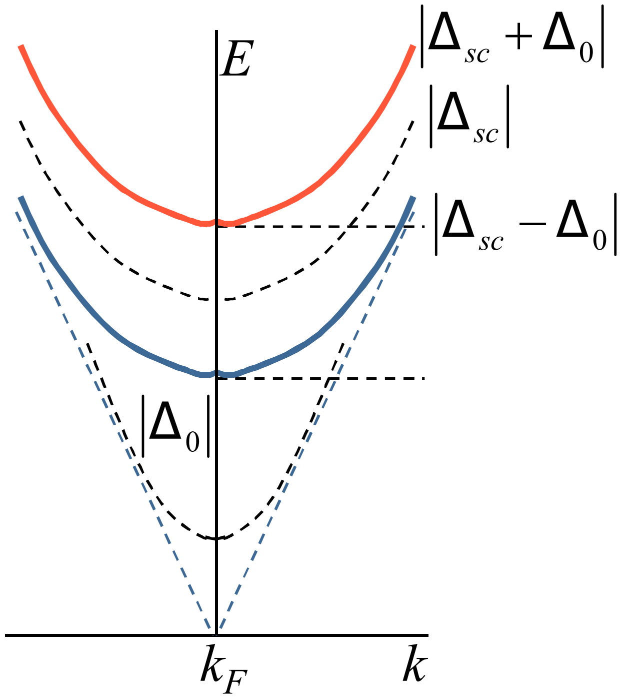
Two-gap quasi-particle spectrum

$$\left|\Delta_{sc} - \Delta_0\right| \qquad \left|\Delta_{sc} + \Delta_0\right| \qquad \Delta_{pg}$$



$$E_{\pm}(\boldsymbol{k}) = \sqrt{\xi_{\boldsymbol{K}}^2(\boldsymbol{k}) + \left|\Delta_{sc}(\boldsymbol{k}) \pm \Delta_0(\boldsymbol{k})\right|^2}$$

Redistribution of the spectral weight between the states with "large" and "small" superconducting gaps



Superfluid density of the biordered state

Superfluid density

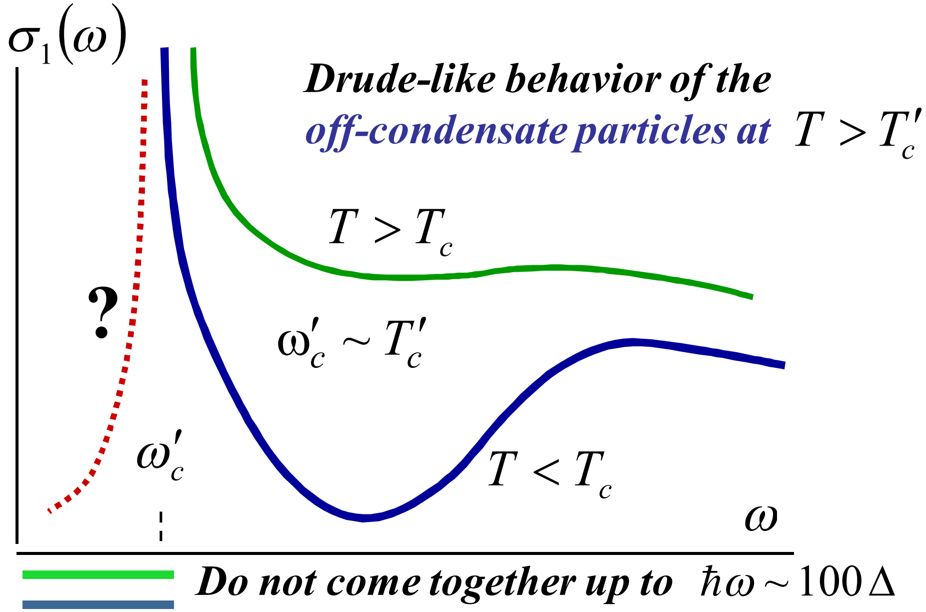
$0 < T < T'_c : \ \rho_s \sim 1$

$T'_c < T < T_c : \ \rho_s << 1$

Optical conductivity

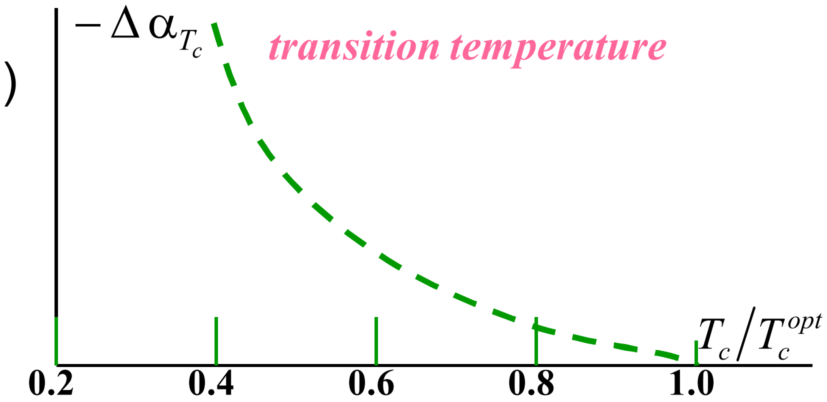
Chemical potential shift

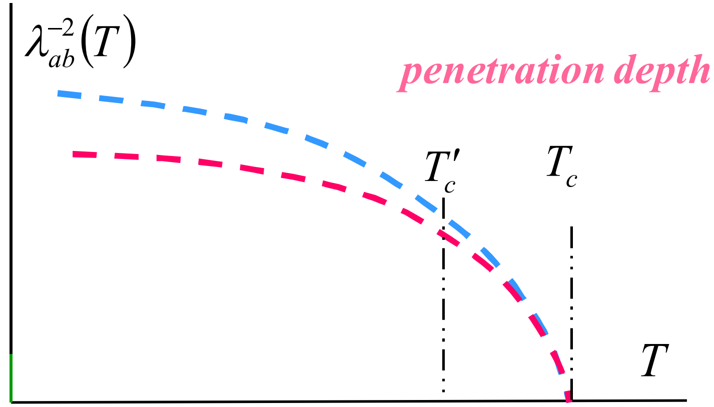
$\delta\mu \sim |\Delta|$ **(in the framework of *BCS theory*** $\delta\mu \sim \Delta^2/E_F$ **)**



Isotope effect

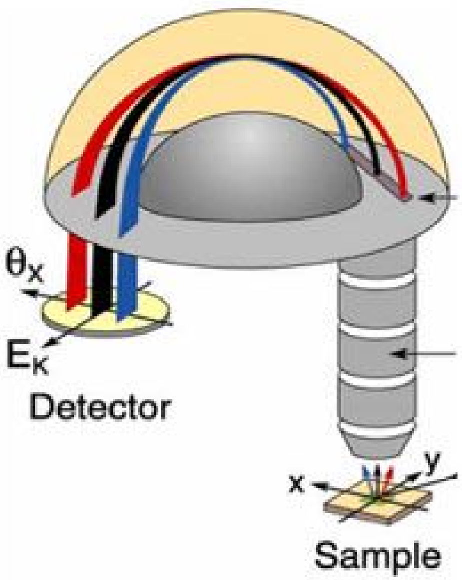
- ***Phonon suppression of the scattering with small momentum transfers***
- ***A contribution of the Cooper channel***

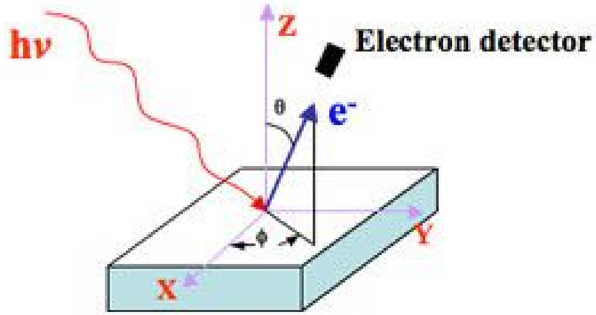


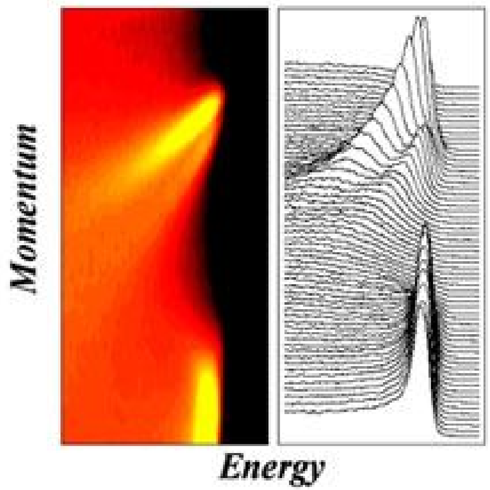


Study of the electron structure in the momentum space

Angle resolved photoemission spectroscopy (ARPES)

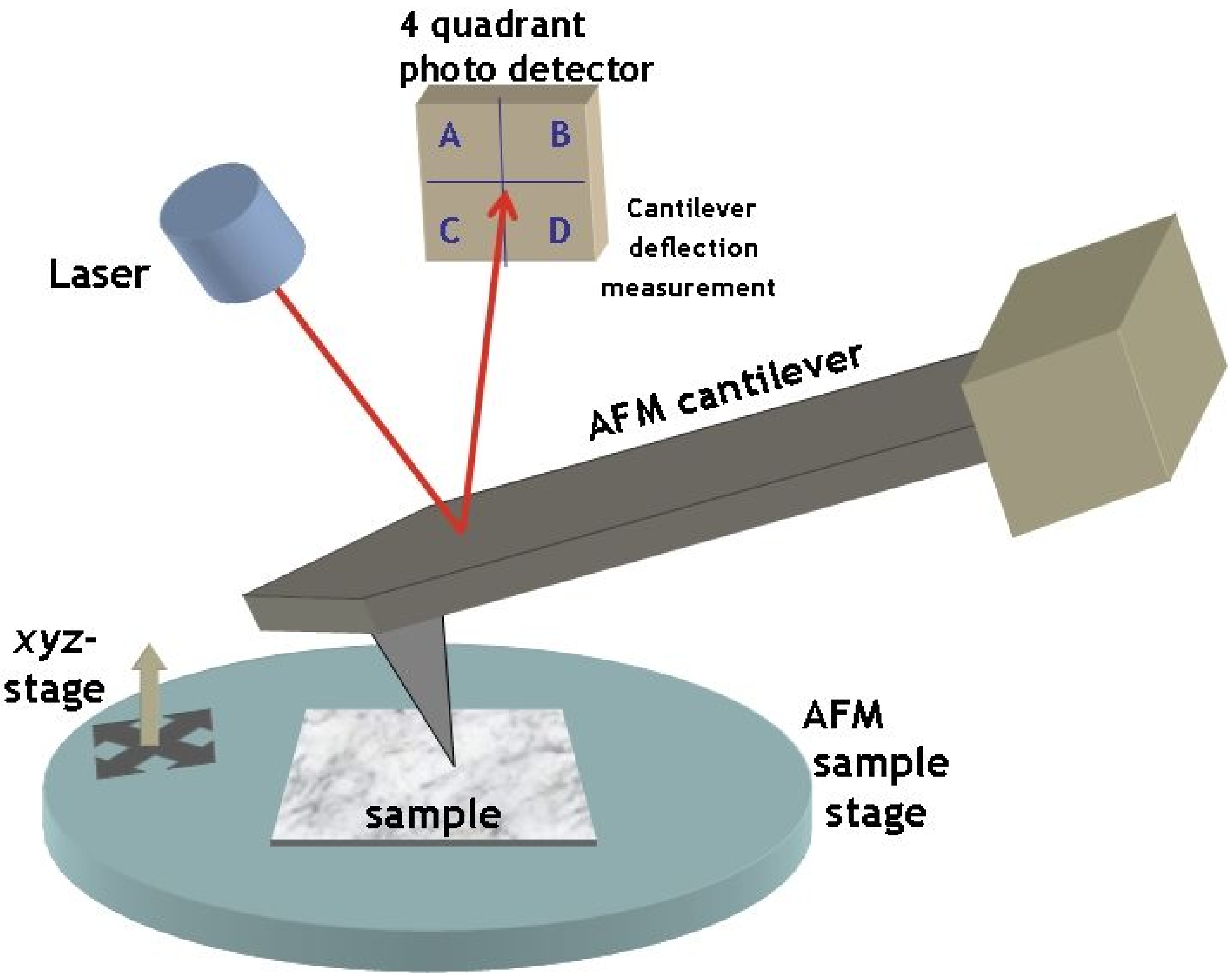






Geometry of an ARPES experiment.
The emission direction of the photoelectron is specified
by the polar (θ) and azimuth (φ) angles

Study of the electron structure in the real space



STM: invented by Gerd Karl Binnig and Heinrich Rohrer in earlier 1980 (Nobel prize, 1986).

A comparison of FT-STM and AC-ARPES

Fourier transform STM (FT-STM)

$$\frac{dI(V,r)}{dV} = G(V,r) \qquad G(r,\omega) = I_0 \left| M^{r}_{f,i} \right|^2 A(r,\omega)$$

$\omega = eV,\ A(r,\omega) -$ *local density of states (LDOS)*

$$A(k,\omega) = \sum_{r_l \in LxL} e^{ikr_l} A(r_l,\omega)$$ **- FT-STM**

Autocorrelated ARPES (AC-ARPES)

$$I(\hat{e},k,\omega) = I_0 \left| M^{\hat{e}}_{f,i} \right|^2 A(k,\omega) \qquad C(q,\omega) = \int A(k+q,\omega) A(k,\omega) d^2k$$

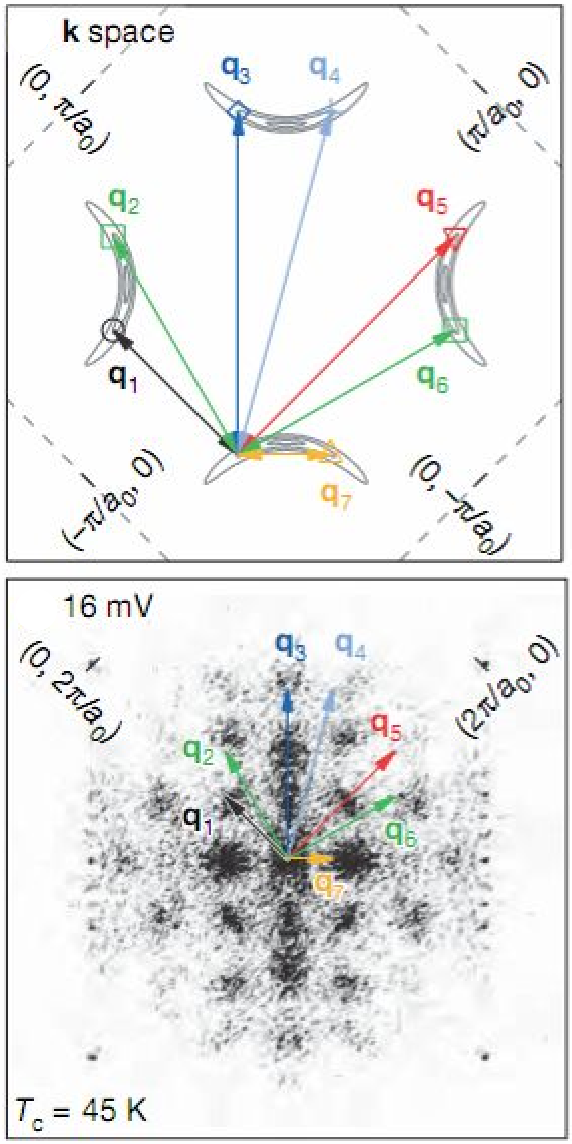
$C(q,\omega) -$ *joined density of states (JDOS)*

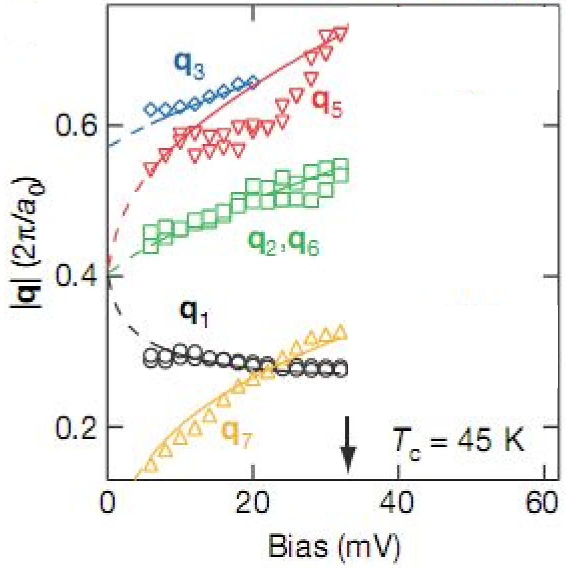
$$C(q,\omega) = -\frac{\delta\varepsilon(q)}{\pi} \operatorname{Im}\Lambda(q,\omega), \quad \Lambda(q,\omega) = \int d^2 r e^{iqr} G(r,\omega) G(-r,\omega)$$

$\left|\delta\varepsilon(q)\right|^2$ *- structure factor of the scattering center*

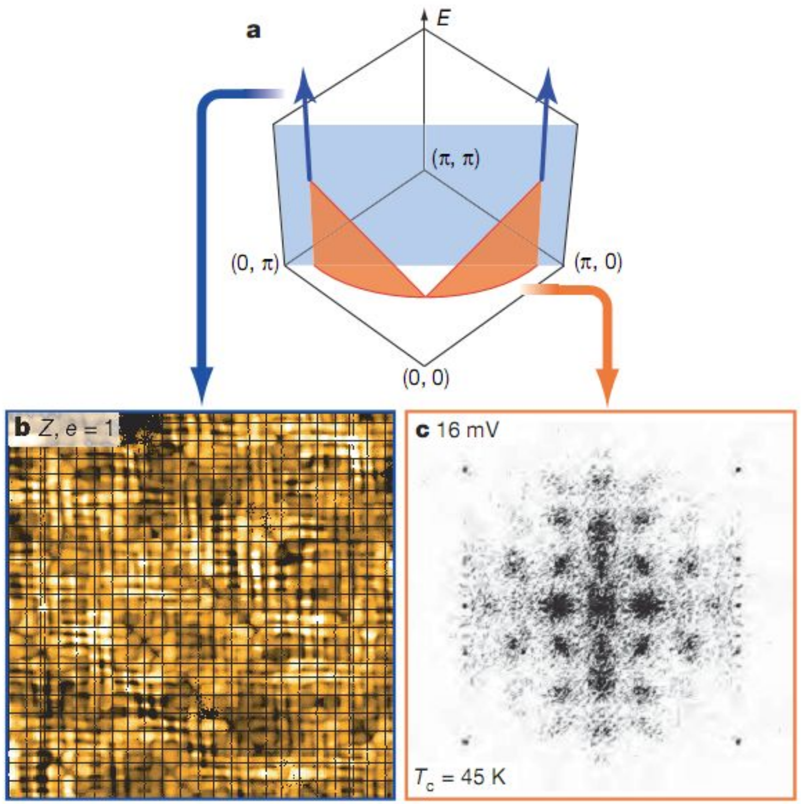
$\left|\operatorname{Im}\Lambda(q,\omega)\right|^2$ *- describes the quasi-particle interference*

Bogoliubov Quasi-particle (BQP) interference



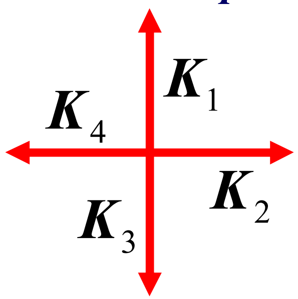


Imaging of the electron structure of high-T_c $Bi_2Sr_2CaCu_2O_{8+\delta}$ *in real space and momentum space:* Y. Kohsaka et al., *Nature* **454**, 1072 (2008)



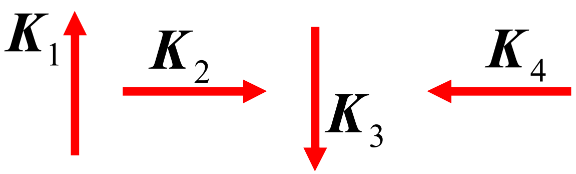
- ***pseudogap and superconducting states attributed with different regions of the momentum space***
- ***reduction of the rotation symmetry during transition from the superconducting state into the pseudogap one:*** $C_4 \rightarrow C_2$

Coherent superconducting state



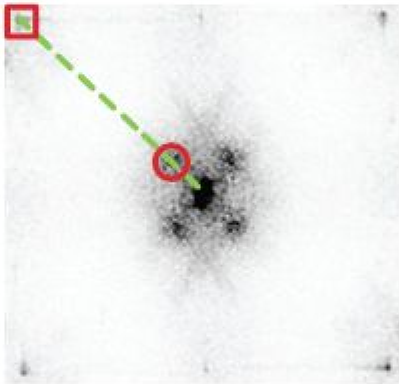
Checkerboard C_4 ***spatial structure of the superconducting state***

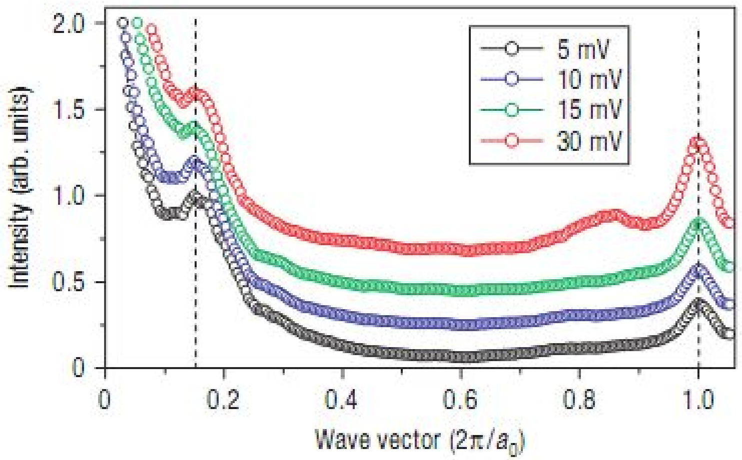
Non-coherent states of the strong pseudogap



Stripe C_2 ***electron structure of the strong pseudogap in the real space***

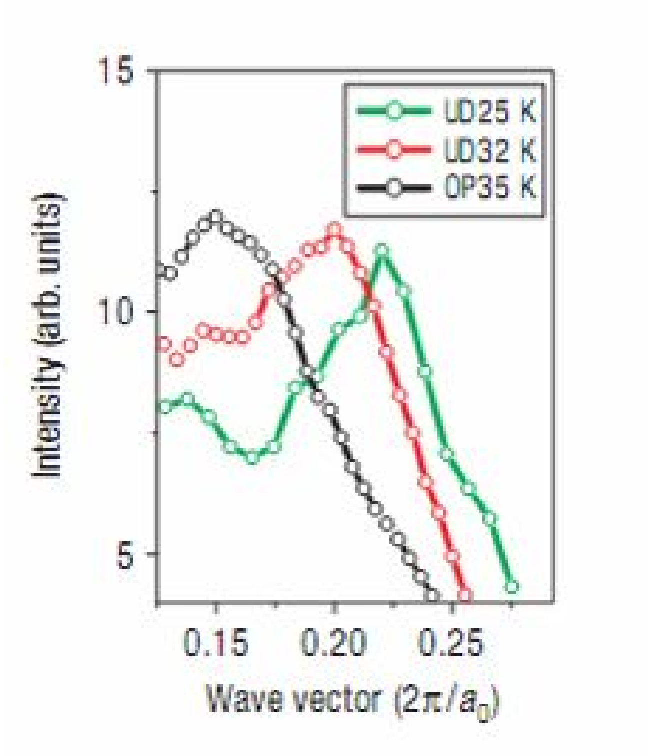
Anatomy of the checkerboard in optimally doped Bi-2201

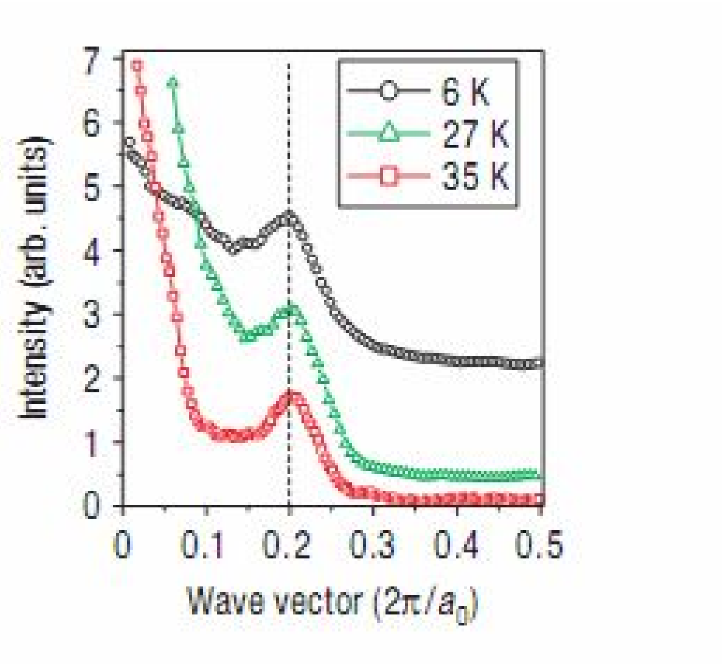




W.D.Wise et al. , Nature Physics, V4, p.696, 2008. Charge-density-wave origin of cuprate Checkerboard visualized by scanning tunnelling microscopy.

Doping dependence of the checkerboard

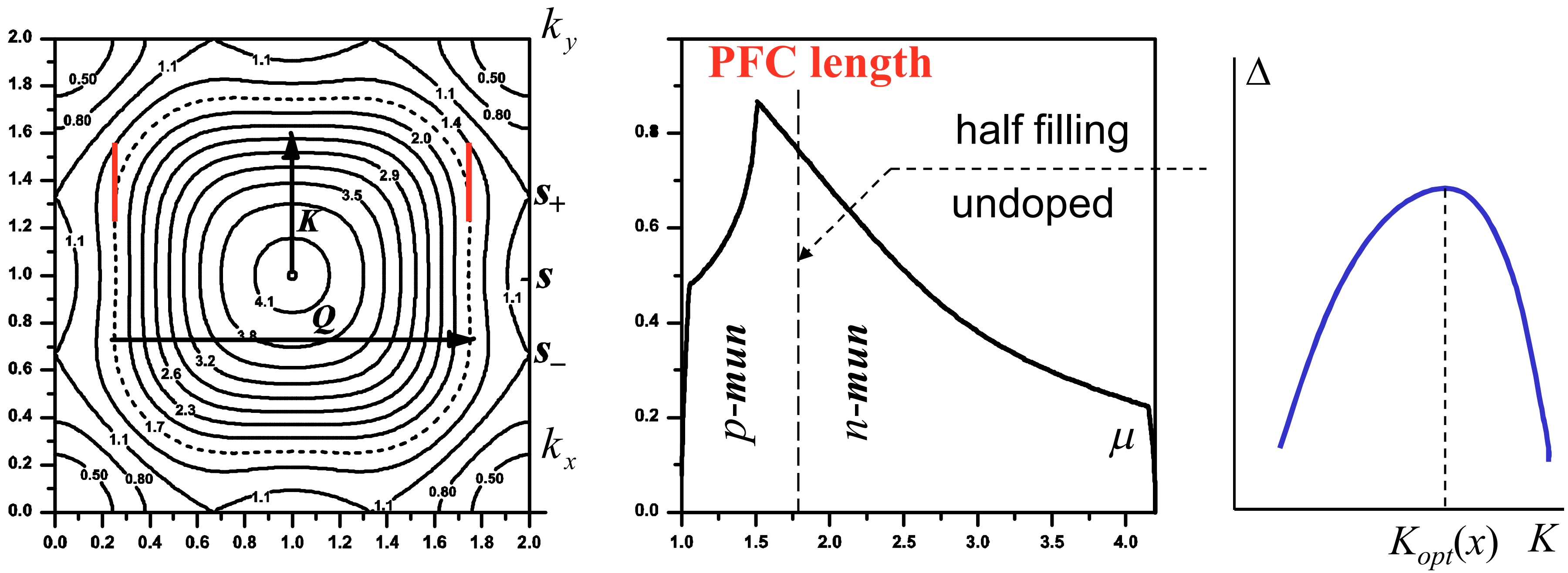




Temperature independence of the checkerboard

Distorted mirror nesting

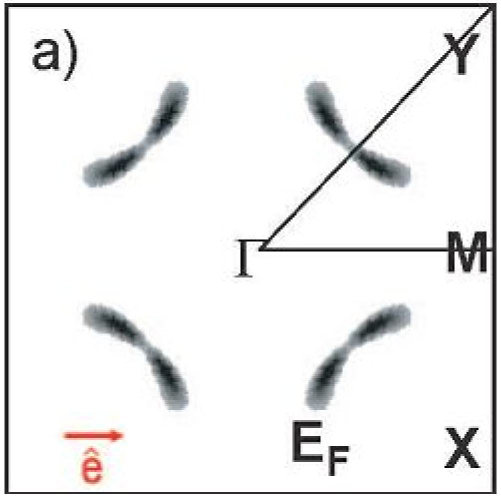
$$\varepsilon(k_x, k_y) = -2t(\cos k_x + \cos k_y) - 4t'\cos k_x \cos k_y - 2t''(\cos 2k_x + \cos 2k_y)$$



$$\Delta = \sqrt{\Delta_0(\Delta_0 - \delta)}$$

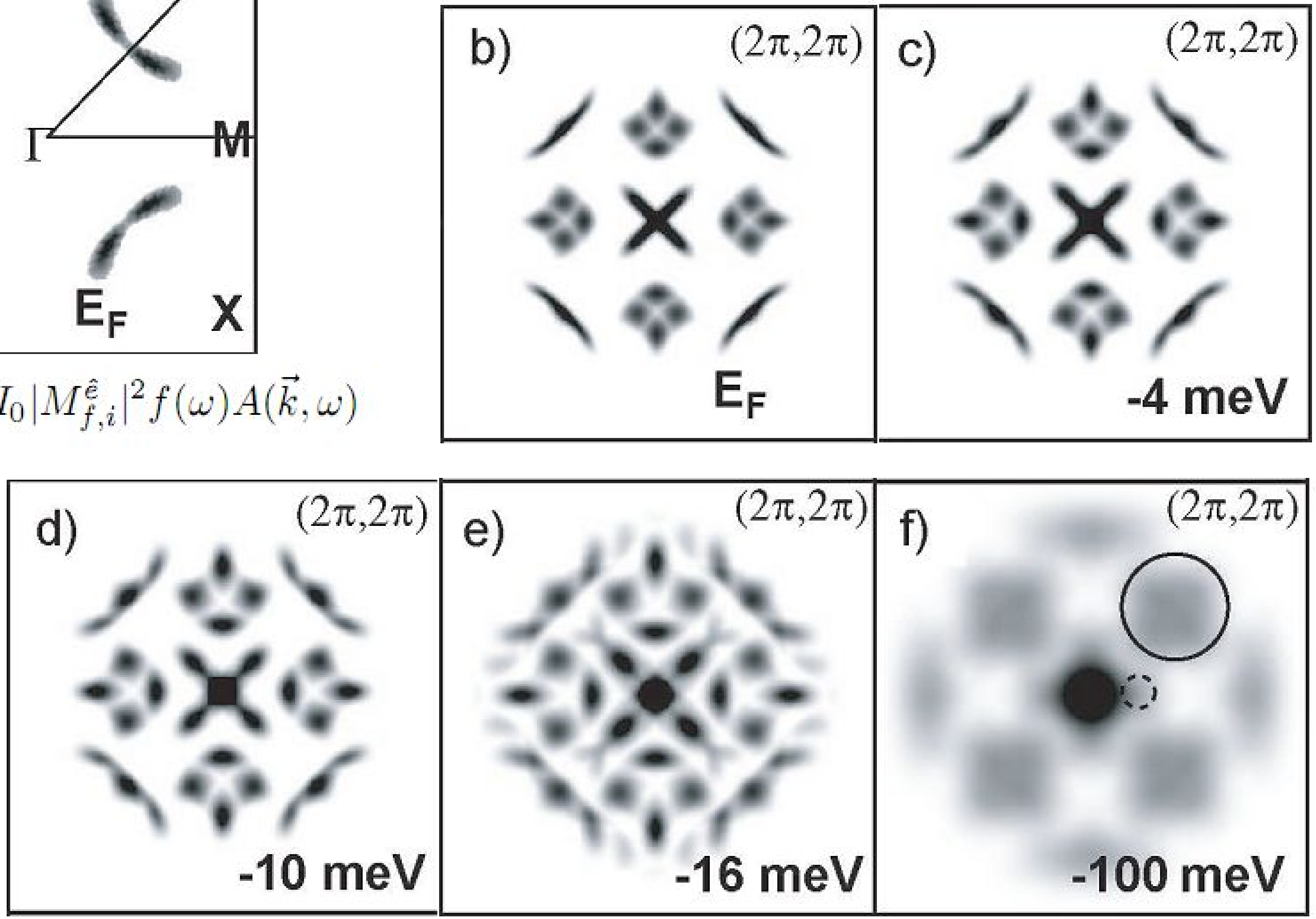
δ - mean-squared deviation of an isoline from perfect mirror nesting

A Comparison between Real and Momentum Space Photoemission Spectroscopies (*Phys. Rev. Lett. 96, 067005 (2006)*)



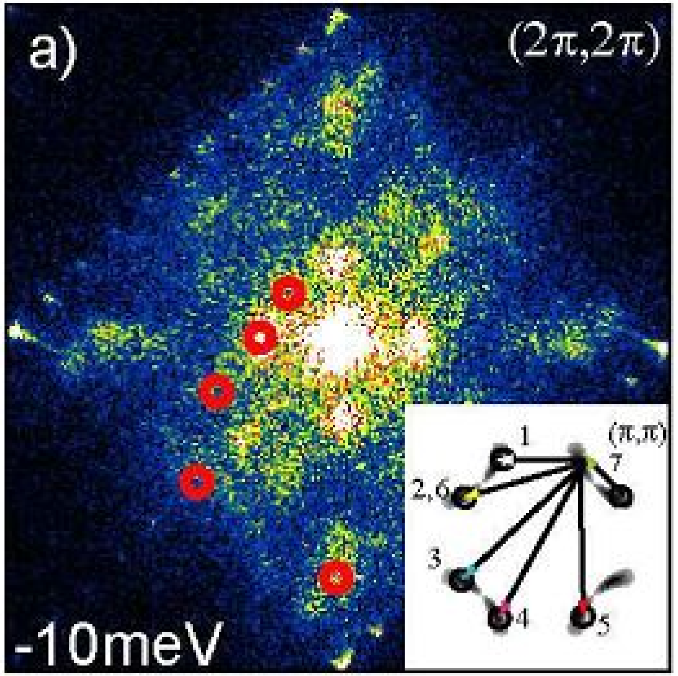
$$I(\hat{e}, \vec{k}, \omega) = I_0 |M^{\hat{e}}_{f,i}|^2 f(\omega) A(\vec{k}, \omega)$$

a) ARPES; b) – f) AC- ARPES

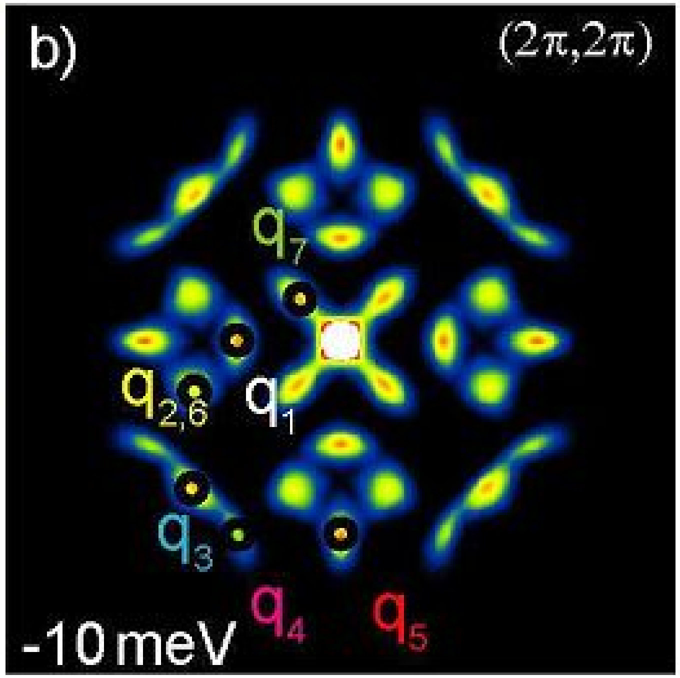


$$\mathrm{JDOS}(\vec{q}, \omega) = \int A(\vec{k} + \vec{q}, \omega) A(\vec{k}, \omega) \ d^2k.$$

FT-STM intensity

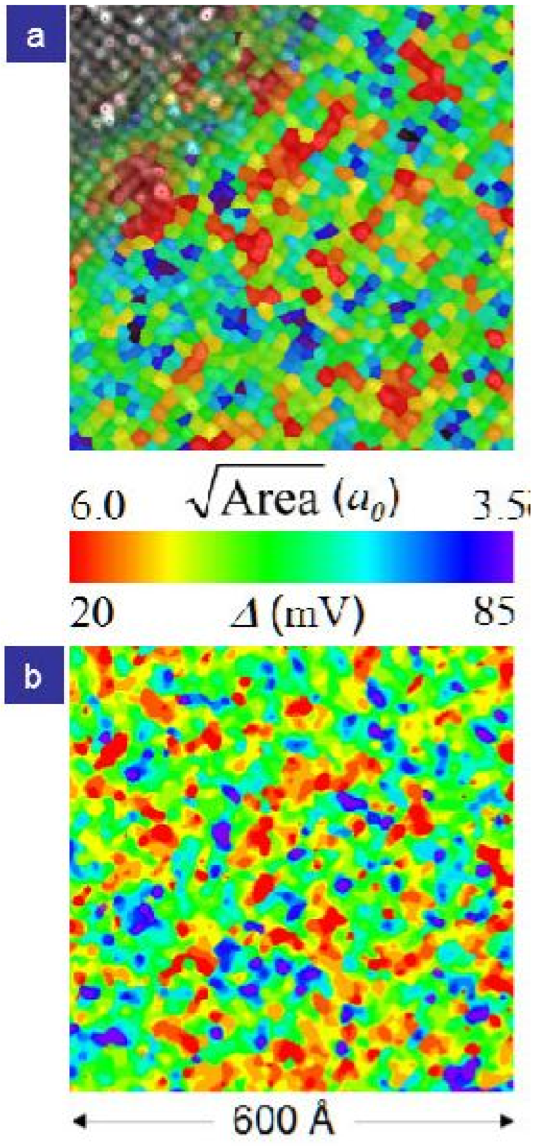


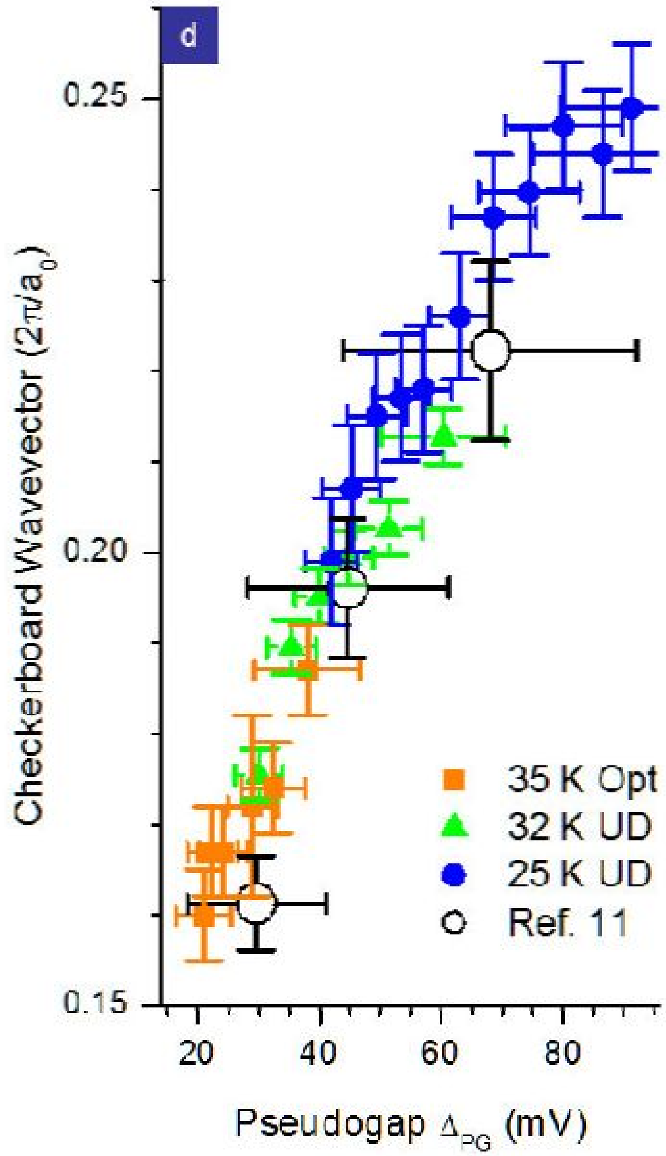
AC-ARPES



Local variations of the Bi-2201 *checkerboard*.

W. D. Wise at al, Cond-mat/0811.1585

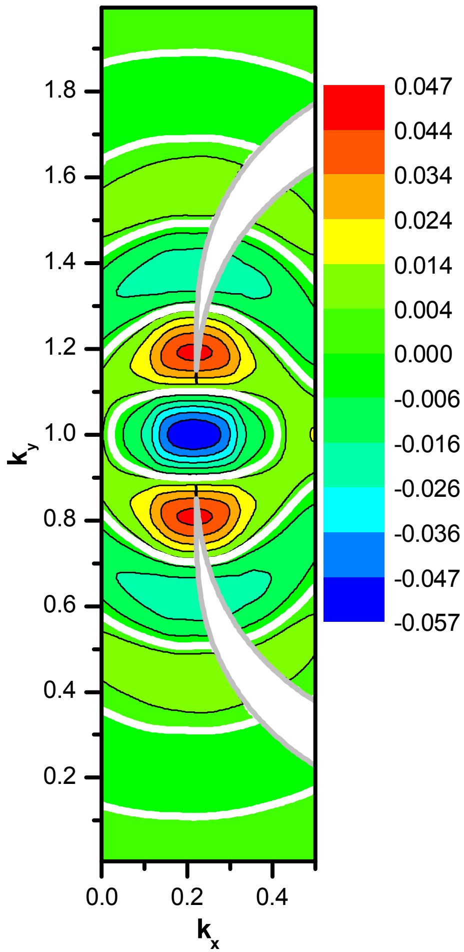




Superconducting antinodal state

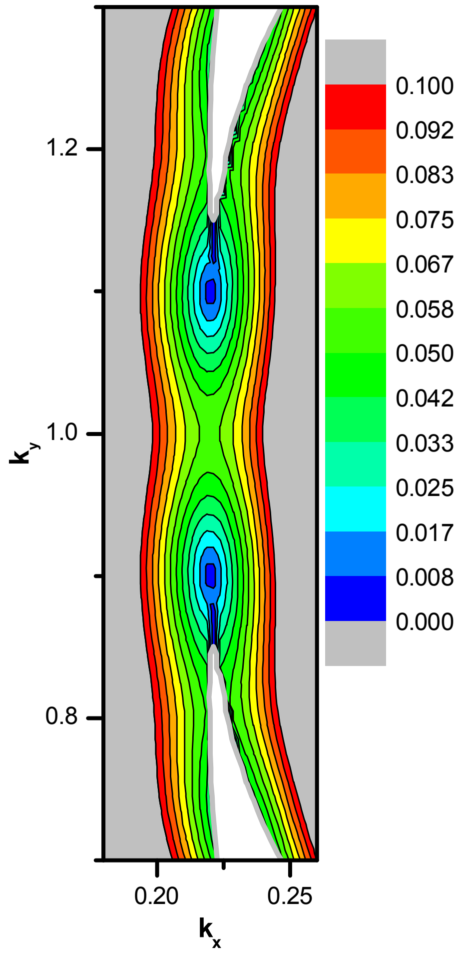
Symmetric (with respect to k_y) solution

$$\Delta(k_x, k_y) = \Delta(k_x, -k_y)$$



Isolines of quasi-particle dispersion

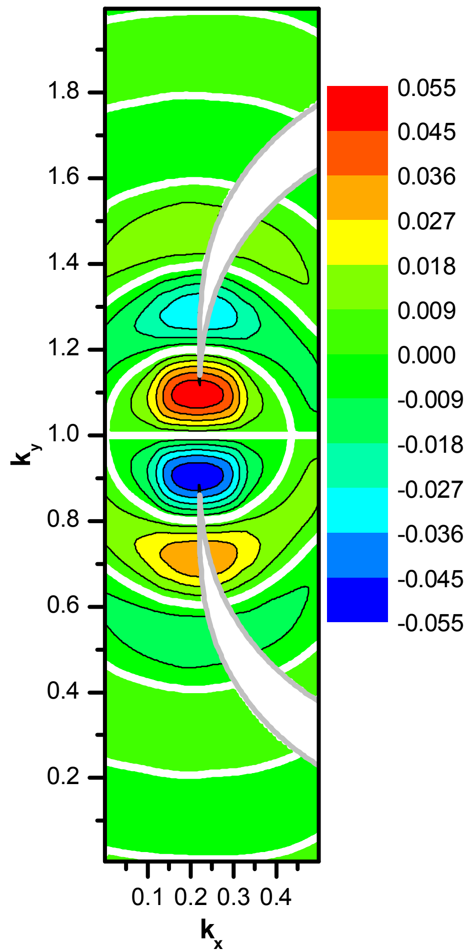
$$E(\boldsymbol{k}) = \sqrt{\xi^2(\boldsymbol{k}) + \Delta^2(\boldsymbol{k})}$$



Pseudogap antinodal state

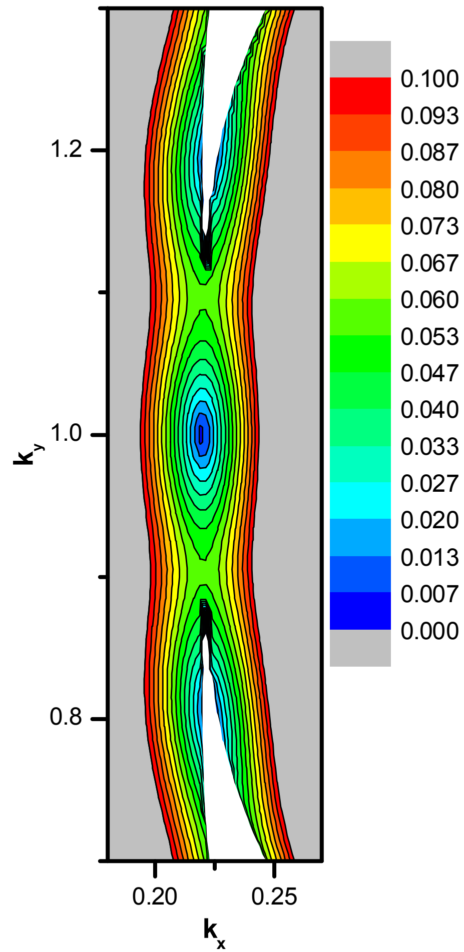
Asymmetric (with respect to k_y) solution

$$\Delta(k_x,k_y) = -\Delta(k_x,-k_y)$$



Isolines of quasi-particle dispersion

$$E(\boldsymbol{k}) = \sqrt{\xi^2(\boldsymbol{k}) + \Delta^2(\boldsymbol{k})}$$



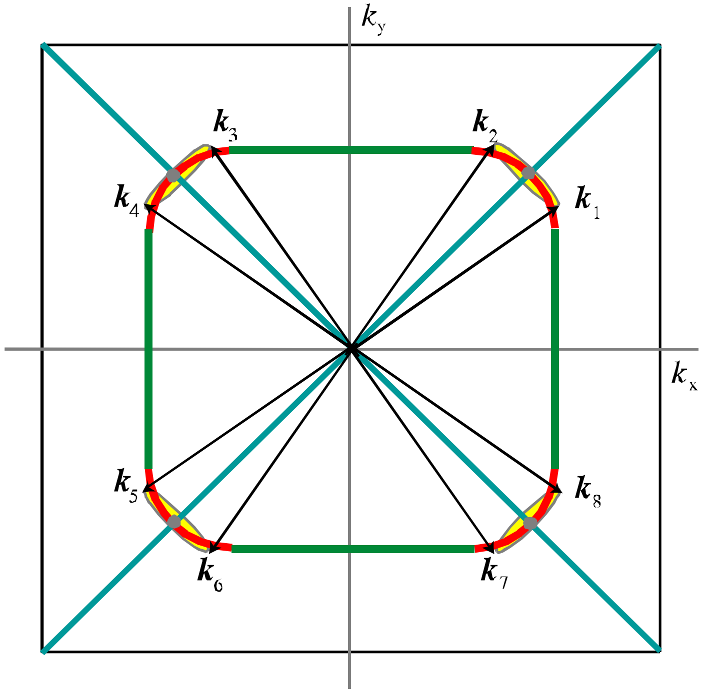
Closed isolines of the quasi-particles spectrum in the nodal and antinodal regions

$$E(\boldsymbol{k}) = \sqrt{\xi^2(\boldsymbol{k}) + \Delta^2(\boldsymbol{k})}$$

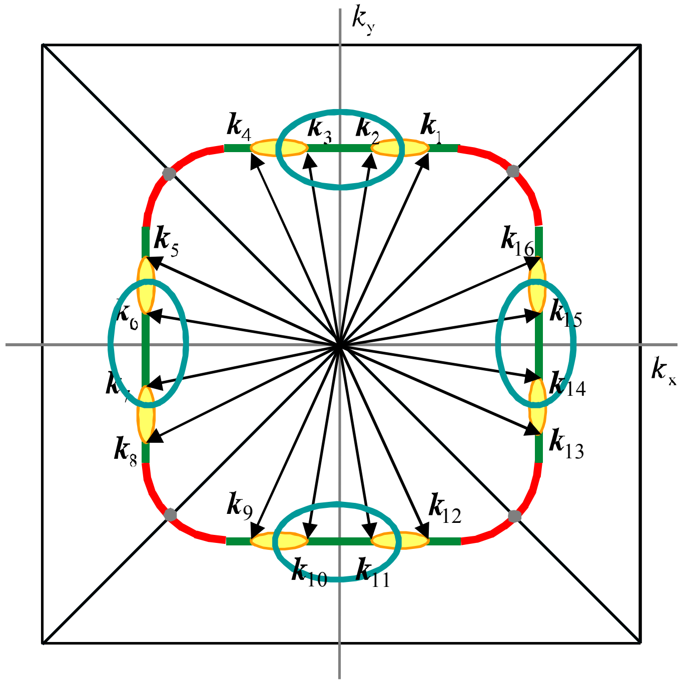
Singular points of quasi-particle dispersion:

$\xi(\boldsymbol{k})=0$ ***(Fermi contour),*** $\Delta(\boldsymbol{k})=0$ ***(nodal line)***

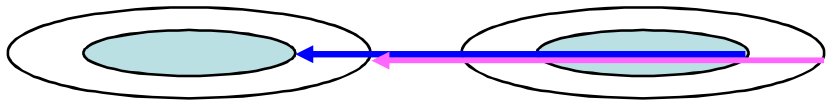
Nodal region: "banana"-like isolines



Antinodal region: pairs of closed isolines



Fixed (energy independent) scattering momentum



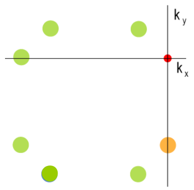
$\boldsymbol{q}=\boldsymbol{k}_3-\boldsymbol{k}_1=$const

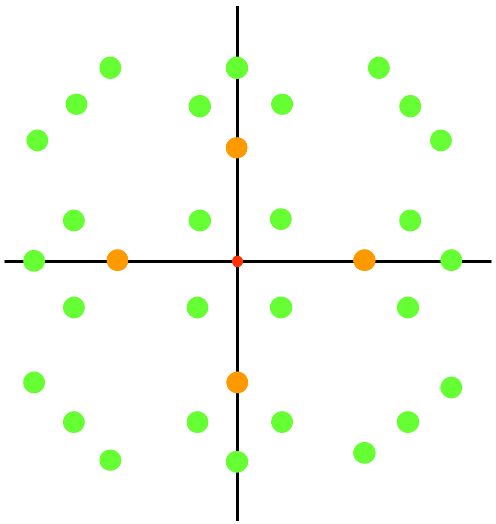
Nodal and antinodal quasi-particle interference patterns in the momentum space

Nodal region:
no fixed scattering momenta

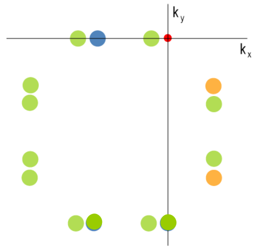
Antinodal region:
four fixed scattering momenta → Checkerboard spatial ordering

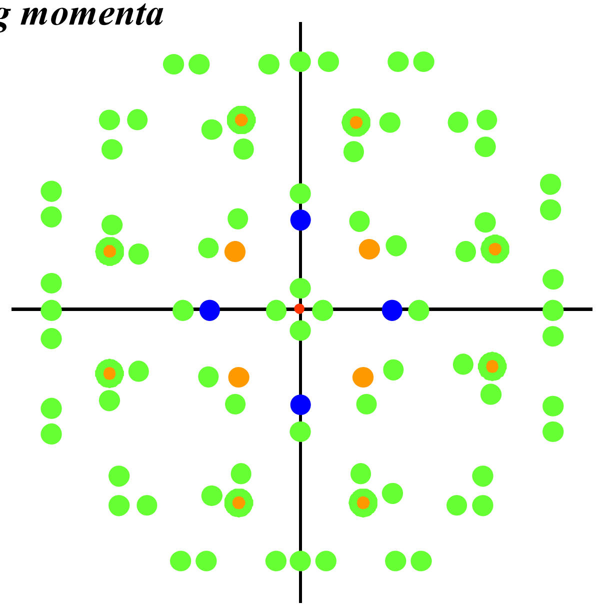
Principal scattering momenta:
"octet" model

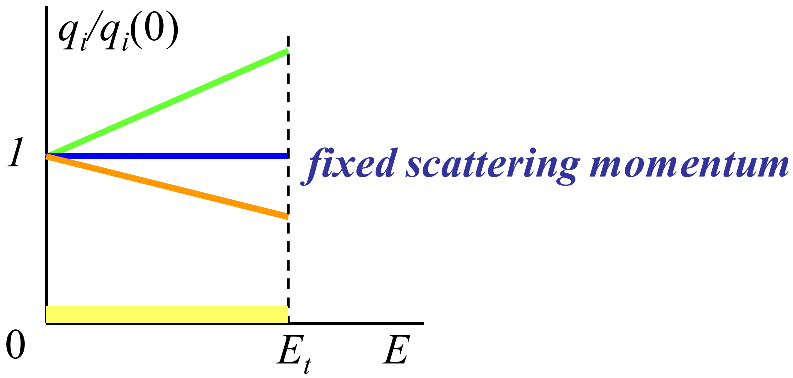




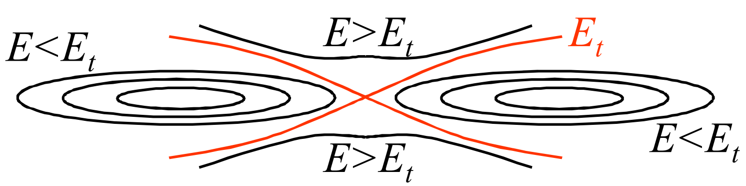
Principal scattering momenta







Topological transition



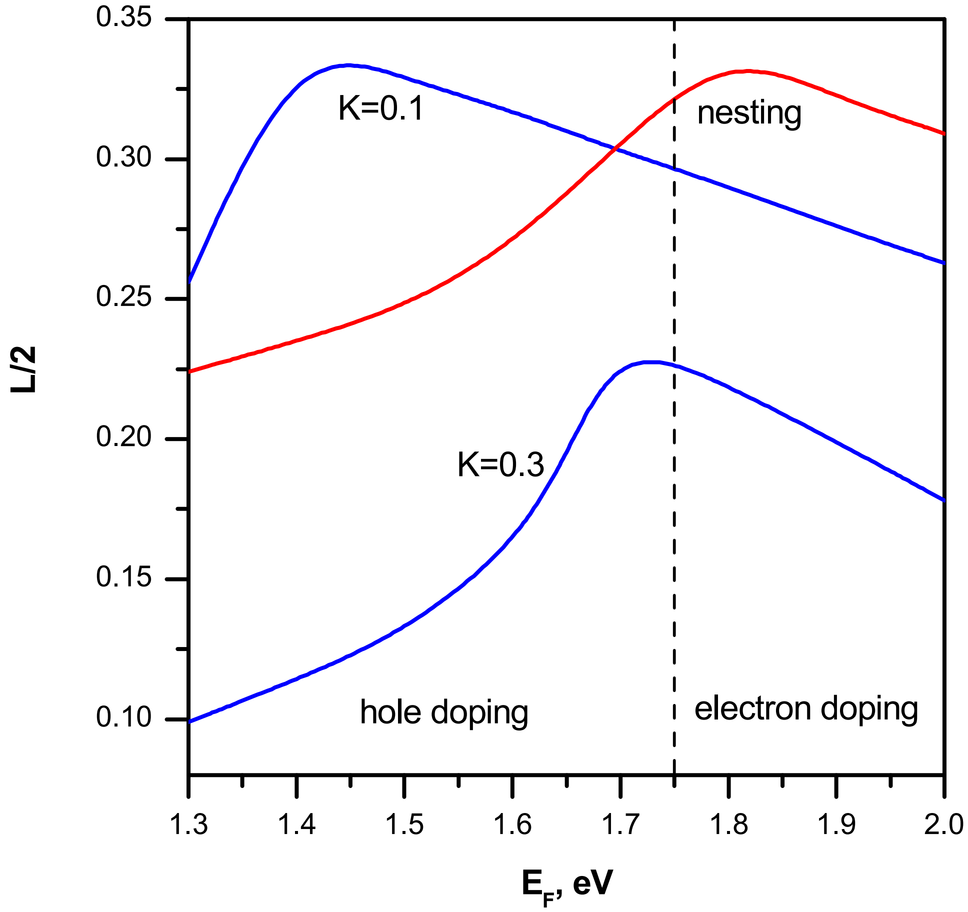
Length of electron-electron and electron-hole pair fermi contours

Mirror nesting

$$\varepsilon(K/2+k)=\varepsilon(K/2-k)$$

Nesting

$$\varepsilon(k)=-\varepsilon(k+Q_1)$$



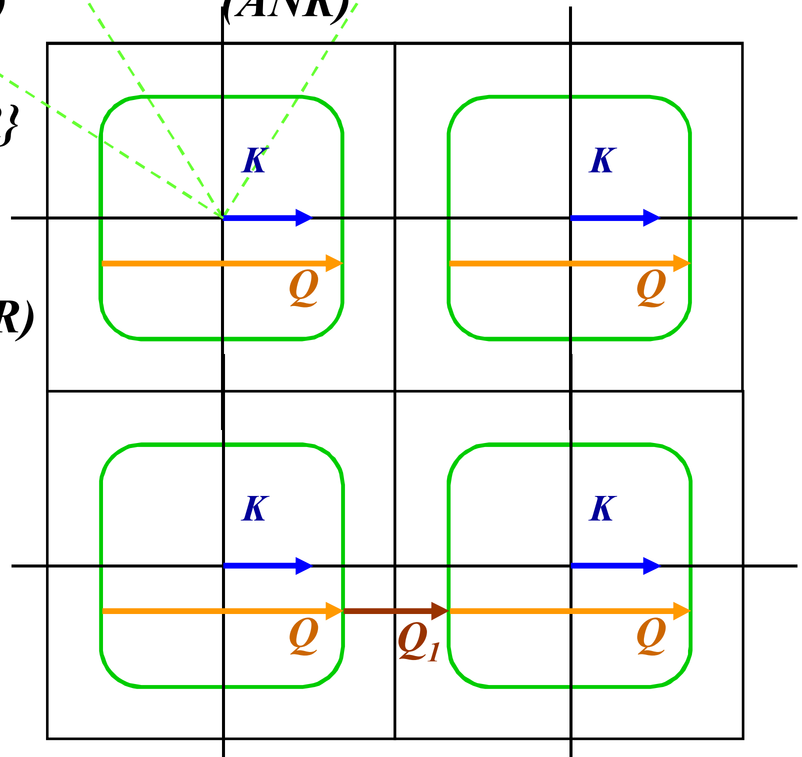
Nesting and mirror nesting:

a competition between insulating and superconducting states

Biordered superconducting state (coexistence of Cooper and K-pairing channels)

- ***Cooper channel*** (*K*=0): ***phonon mediated pairing (NR}***
- ***K-pairing channel*** (*K*≠0): ***Coulomb pairing (ANR)***

Insulating-pairing channel (Q_1≠0): CDW, DDW ***(ANR)***



Q+Q₁= reciprocal lattice vector

Mirror nesting — ***K≈Q₁*** — ***Nesting***

Cooper and K-pairing. Weak CDW (DDW) as Cooper and K-pairing induced order

CDW (DDW) and Cooper pairing. K-pairing as CDW (DDW) and Cooper pairing induced order

Strongly mixed biordered superconducting and insulating states

V.I. Belyavsky, Yu.V. Kopaev, Nguyen Ngoc Tuan, *JETP* **105**, 726 (2007)

A.I. Rusinov, Do Chan Kat, Yu.V. Kopaev, *Sov. Phys. JETP* **38**, 991 (1974).

Yu.V. Kopaev, in *The problem of High-Temperature Superconductivity* (Eds. V.L. Ginzburg, D.A. Kirzhnits) New York: Consultants Bureau (1982), Ch.5