Strength of the spin fluctuation mediated pairing interaction in $YBCO_{6.6}$

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Collaboration

Inelastic neutron scattering:
V. Hinkov, B. Keimer, MPI-FKF Stuttgart

ARPES:
S. Borisenko, A. Kordyuk, V.B. Zabolotnyy,
J. Fink, B. Büchner, IFW Dresden

Theory:
W. Hanke, University of Würzburg

DFG Research Unit 538

D.J. Scalapino, UCSB, Santa Barbara, USA

Nature Physics **5**, 217 (2009)

Conventional Superconductors

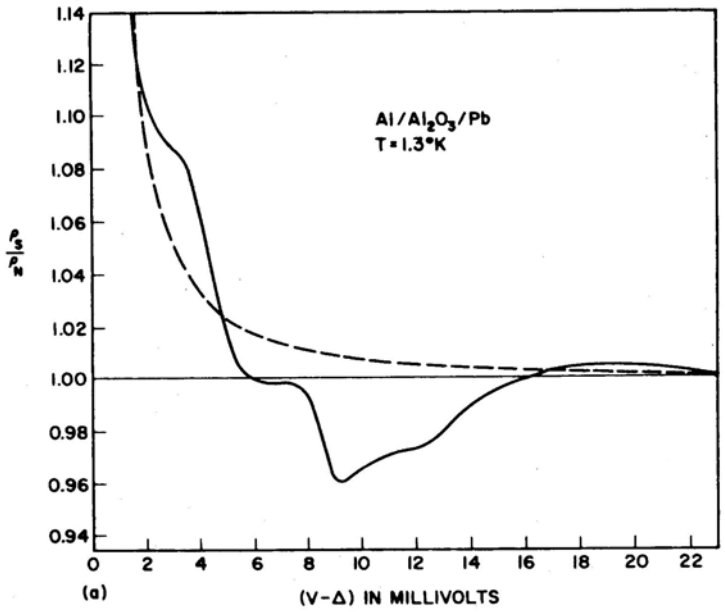
How do we know, that the pairing mechanism in the conventional superconductors is due to phonons ?

No chance in the BCS weak-coupling limit

Strong electron-phonon coupling:

„Fingerprints“ of the phonons appear in the electronic properties

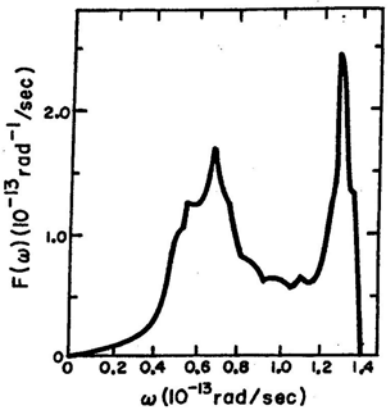
For example: tunneling density of states in lead



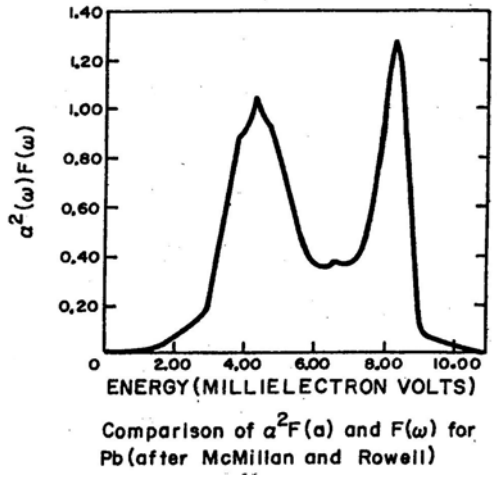
Inversion of tunneling data on lead
McMillan & Rowell (PRL 1965)

Inelastic neutron scattering
(Stedman et al.)

10^{13} rad/sec = 6 meV



Spectrum obtained by inversion
of Migdal-Eliashberg equations



- Strong „circumstantial evidence“ in favor of electron-phonon interaction

Can we do something similar in high-T_c cuprates ?

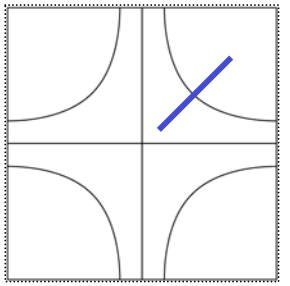
Problems:

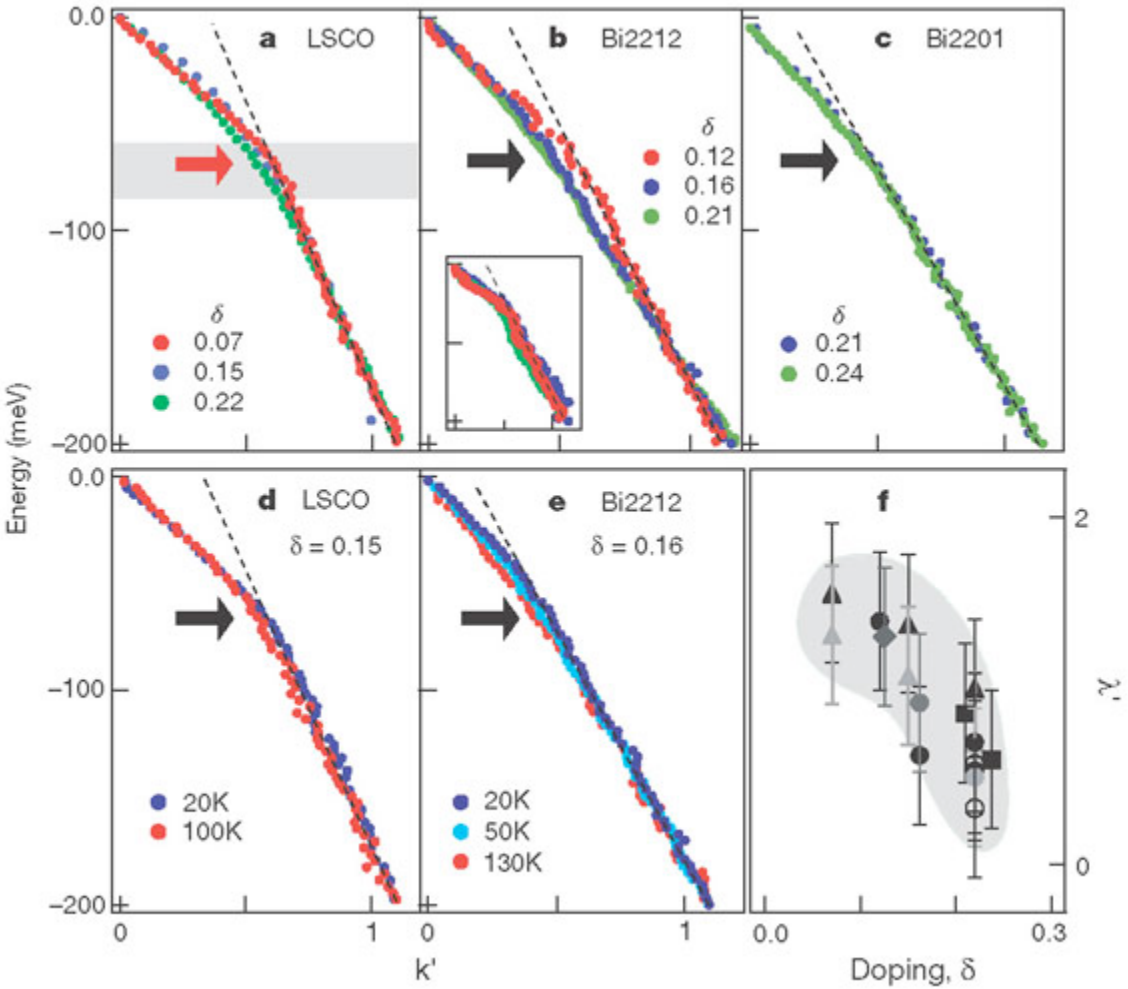
- Migdal's theorem still valid? $\Rightarrow \lambda \frac{\omega_D}{E_F}$ not small anymore
- *d*-wave superconductivity
- strong momentum dependence of the interaction
  - ➢ Use momentum resolved techniques: ARPES, INS
- Problem:

ARPES is usually done on BSCCO (high surface quality)
INS is usually done on YBCO (large single crystals)

Can we relate structures in INS and ARPES ?

The ARPES kink





Phonons ?

A. Lanzara et al, Nature **412**, 510 (2001)

The “kink”

- Visible in both superconducting and normal state
- Constant energy as function of temperature, doping
- Looks like a phonon structure
- Cannot be explained by the resonance peak

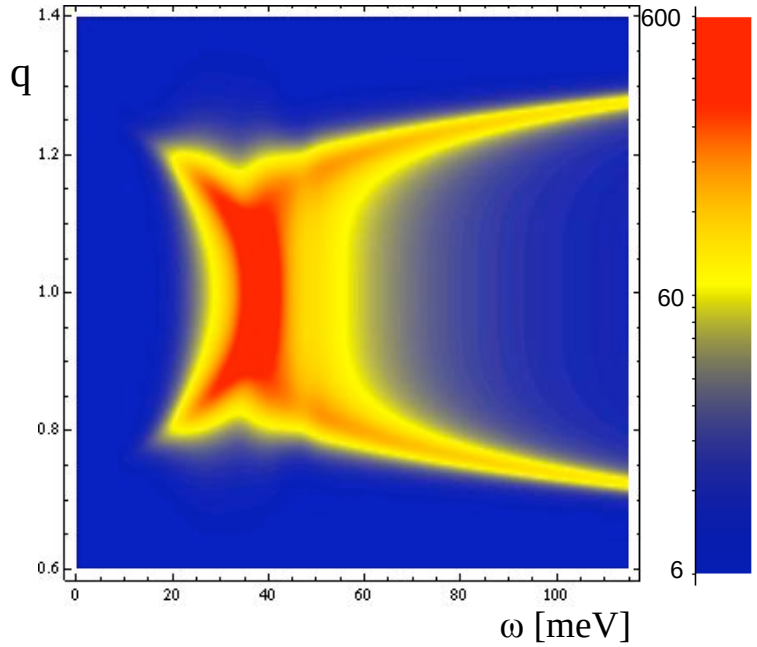
- Is it a phonon structure ?
- Is it strong enough to produce d-wave superconductivity ?
- Recent LDA calculations show that electron-phonon interaction is too weak to produce the kink

R. Heid et al, PRL **100**, 137001 (2008) F. Giustino et al, Nature **452**, 975 (2008)

New features of our study

- $YBCO_{6.6}$ samples from Stuttgart were investigated with high resolution INS.
- The same samples were measured by the Dresden group using ARPES
- V. Hinkov provided an analytical fitting formula for the measured spin excitation spectrum (fully momentum and frequency dependent) at T=5 K (s) and T=70 K (n).
- Using the fitting formula I have calculated ARPES spectra in order to relate structures of the two experimental techniques

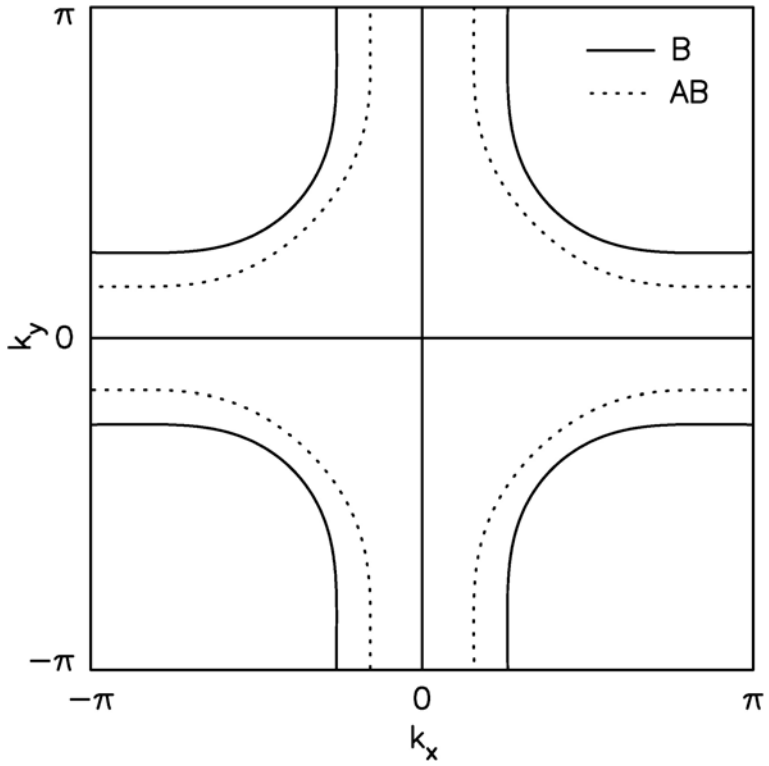
Properties of spin excitations



Momentum structure: hourglass shape

Properties of electrons

Renormalized Fermi surface from the ARPES measurements



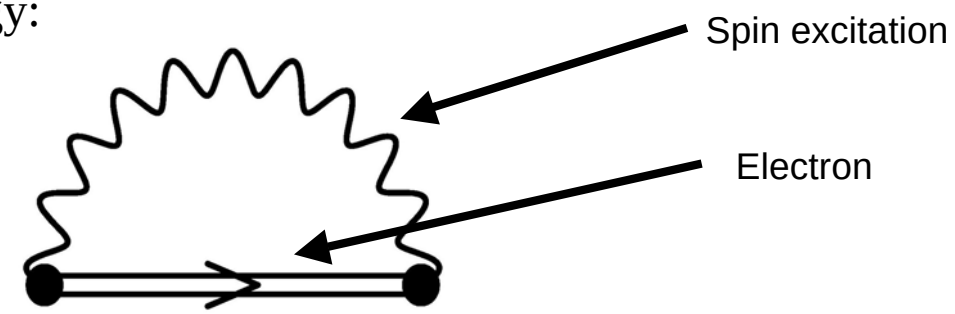
Two bands due to two planes per unit cell in YBCO

Theoretical calculation

Philosophy:

avoid theory as much as possible, take as much information from experiment as feasible

Calculate the electron self-energy:



Features:

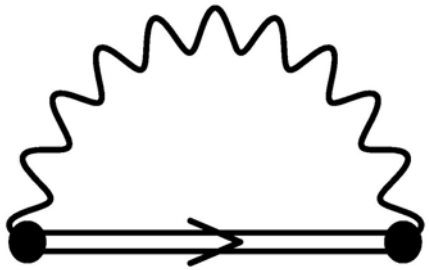
- full momentum and energy dependence taken into account
- a-b plane anisotropy
- double CuO_2 plane per unit cell taken into account
- self-consistent calculation of the self-energy
- renormalized Fermi surface is kept fixed during the calculation
- unrenormalized nodal Fermi velocity from LDA
- adjust coupling strength such as to reproduce renormalized nodal Fermi velocity

Am I allowed to do this ?

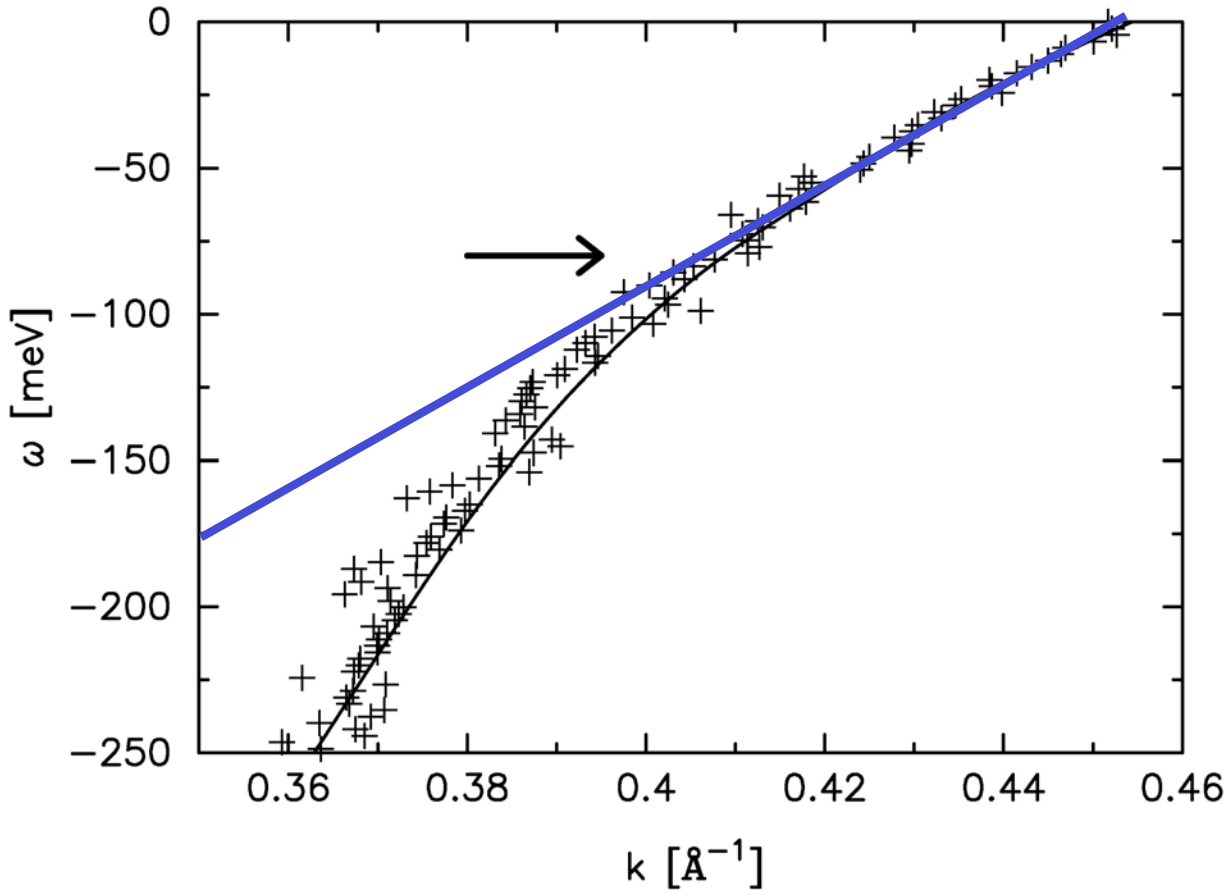
T.A. Maier, A. Macridin, M. Jarrell, and D.J. Scalapino, Phys. Rev. B **76**, 144516 (2007)

DCA-QMC calculations on the Hubbard model:

- calculate spin susceptibility $\chi(q,\omega)$ exactly
- Define effective interaction $V_{eff}\left(\vec{q},\omega\right)=\frac{3}{2}\bar{U}^2\chi\left(\vec{q},\omega\right)$
- Effective coupling strength obtained from fit to nodal dispersion
- Calculate T_c from the effective interaction
- This approximate T_c is within 30% of the exact DCA T_c.
- Essential point: the effective coupling strength is different from the bare one (contains “vertex corrections”)



Nodal dispersion



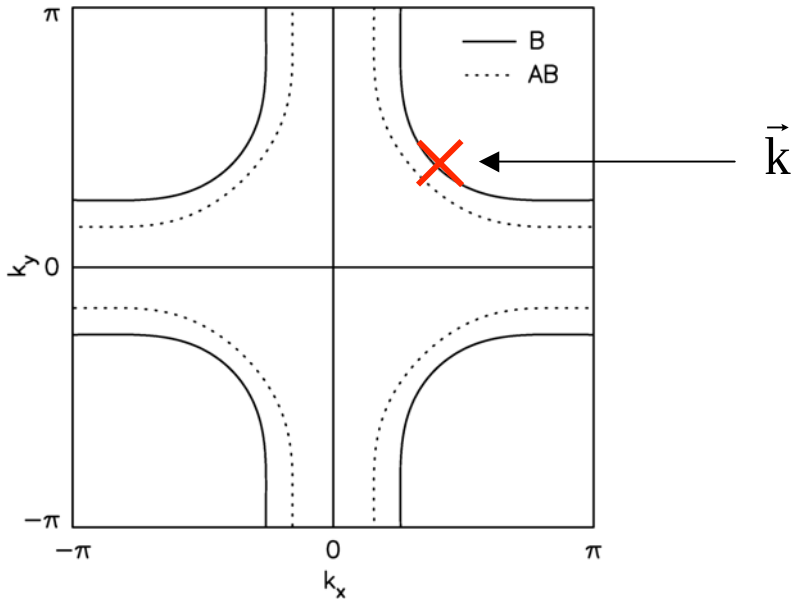
Nodal dispersion has a “kink”. Where does it come from? (No phonons here)

We can analyze, from which parts of the Fermi surface the kink is coming from.

Let's look at the T=0 imaginary part of the self-energy:

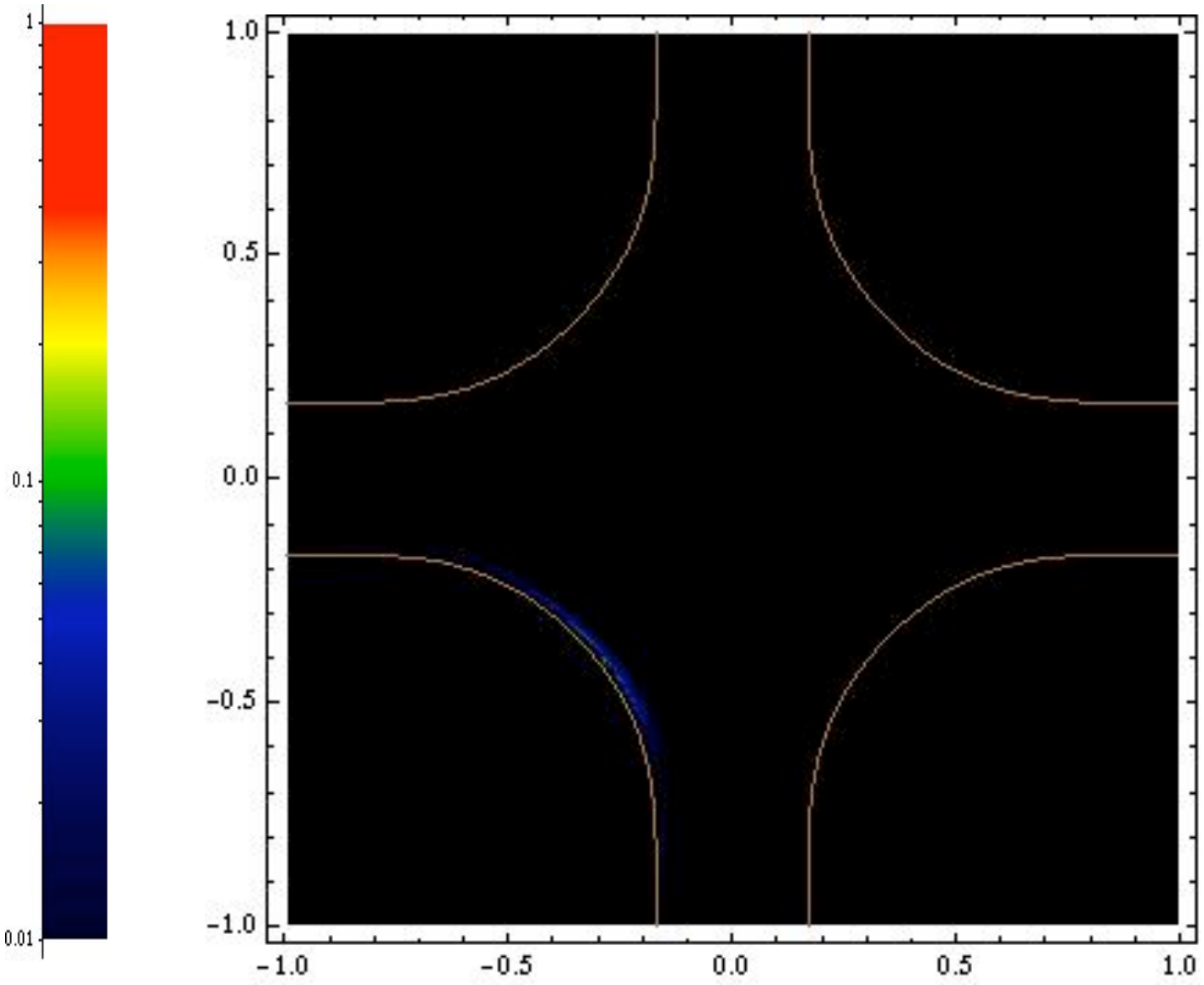
$$-\Sigma''^{(b)}_{T=0}\left(\vec{k},\omega<0\right)=\frac{g^2}{N}\sum_{\vec{k}',\omega<\varepsilon^{(a)}_{k'}<0}\chi''_0\left(\vec{k}-\vec{k}',\varepsilon^{(a)}_{k'}-\omega\right)$$

We put $\vec{k}$ at one node in the bonding band and plot the contributions as a function of $\vec{k}'$ in the antibonding band for different values of ω.



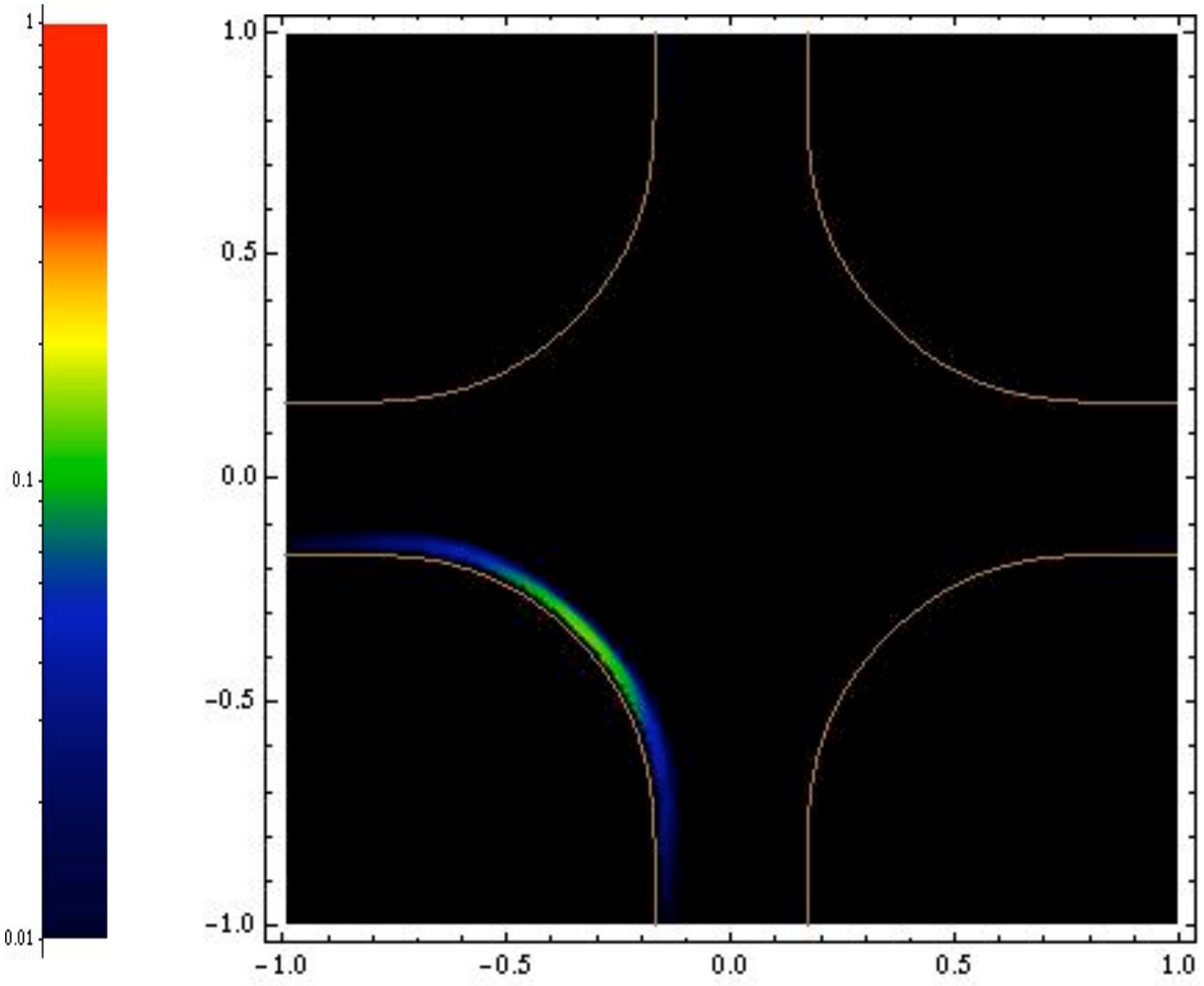
Contributions to the kink

ω=-20 meV



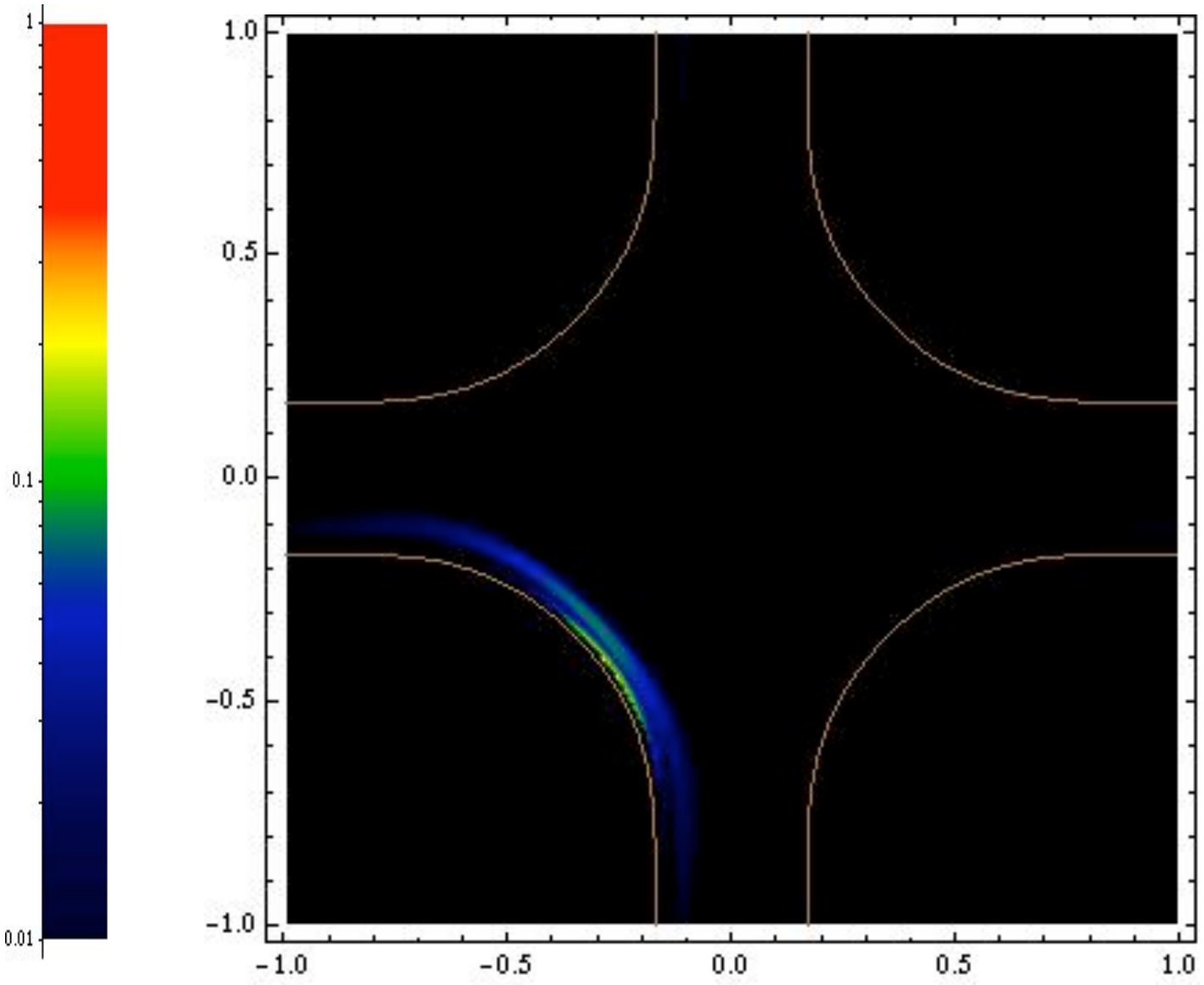
Contributions to the kink

ω=-40 meV



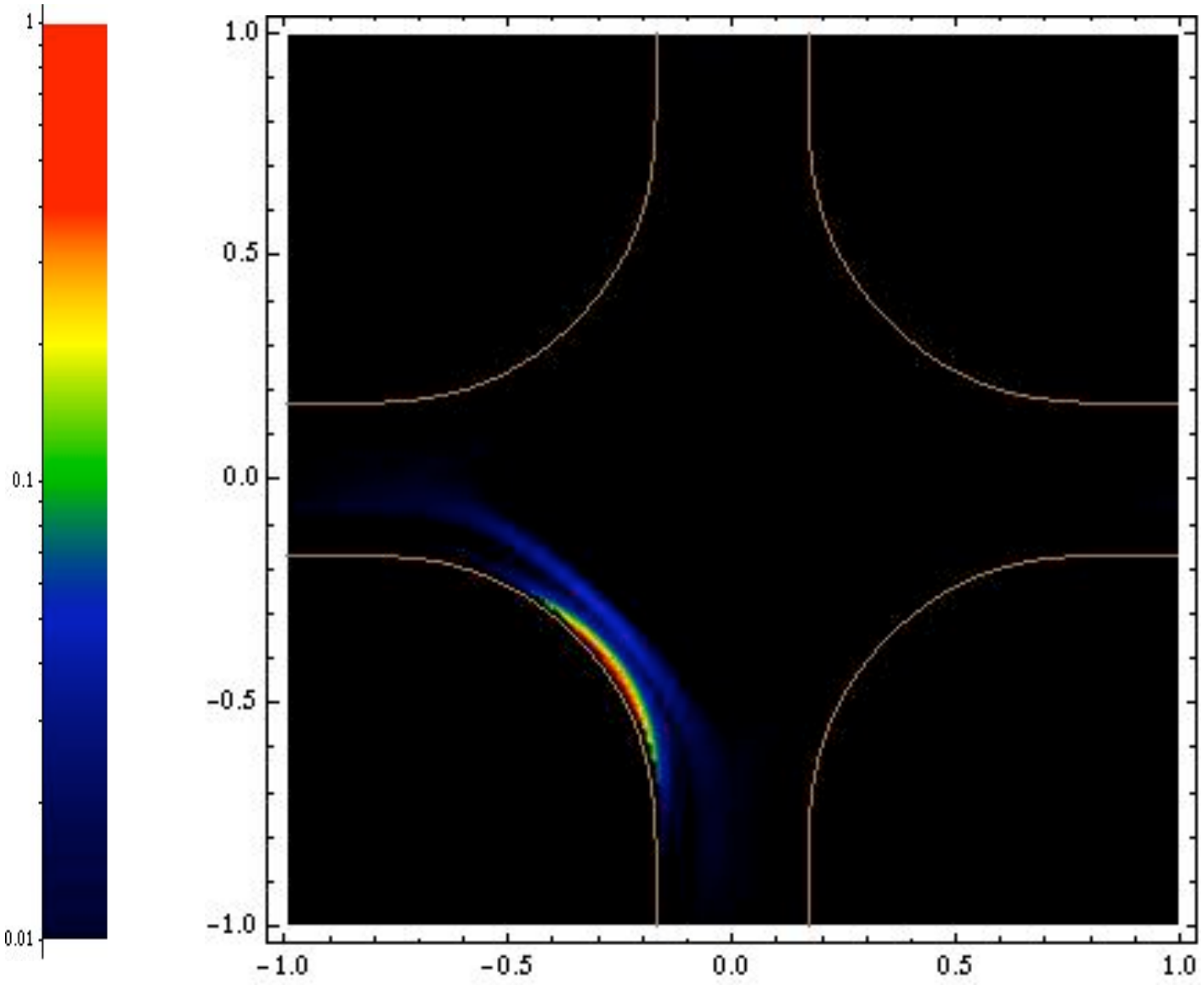
Contributions to the kink

ω=-60 meV



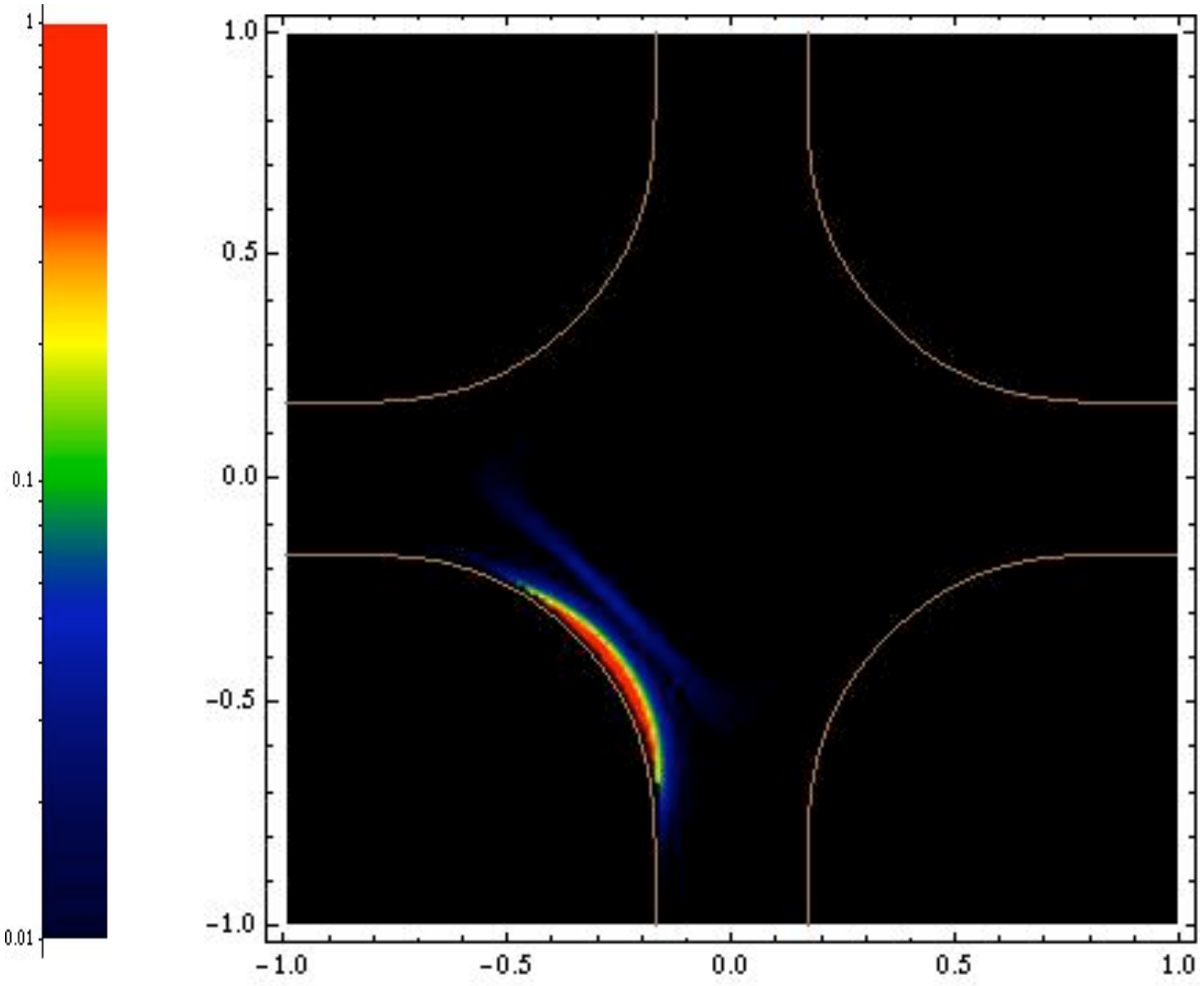
Contributions to the kink

ω=-80 meV



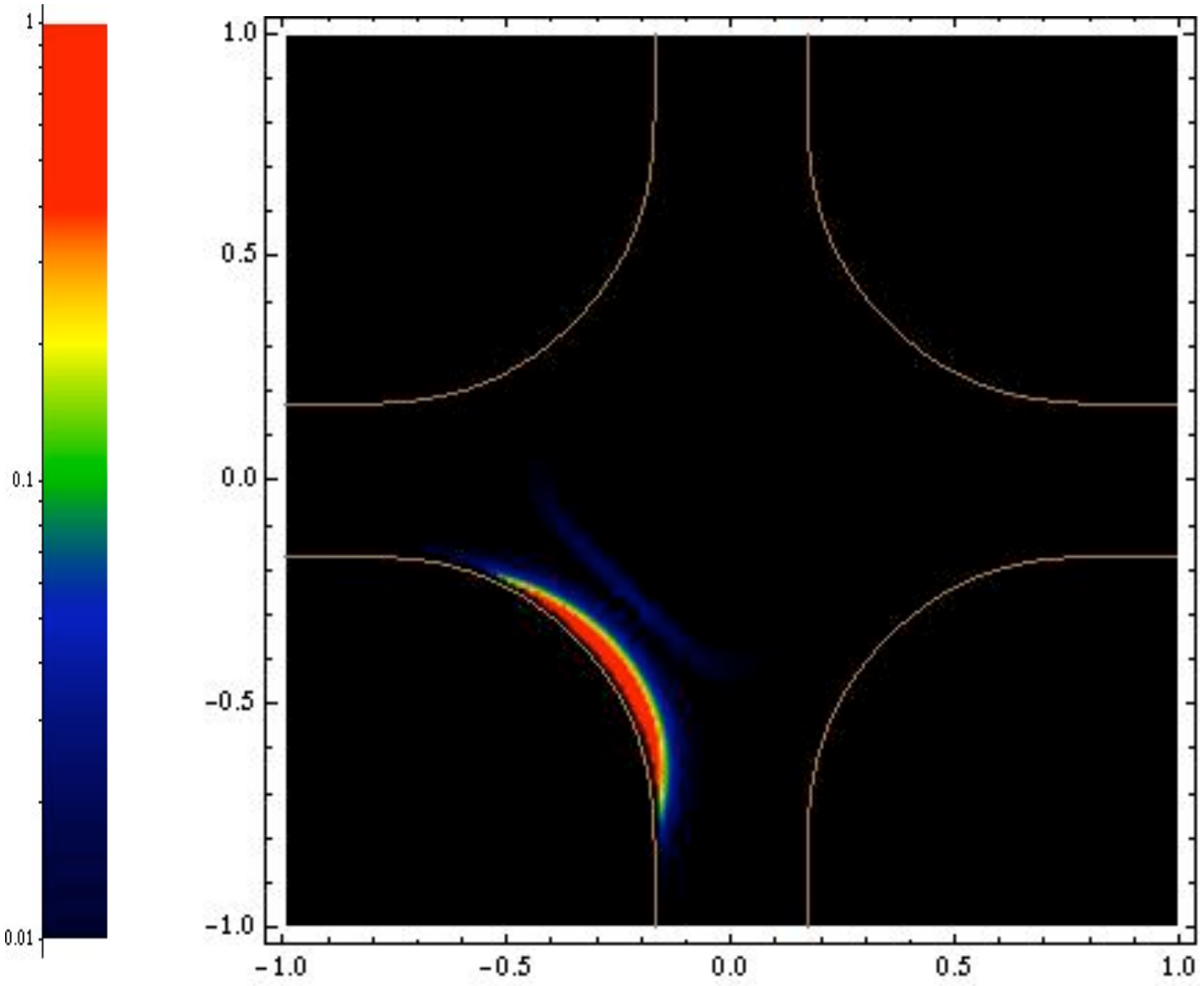
Contributions to the kink

ω=-100 meV



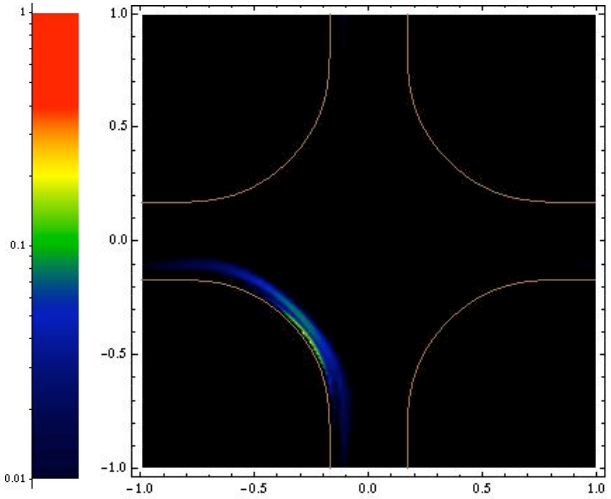
Contributions to the kink

ω=-120 meV

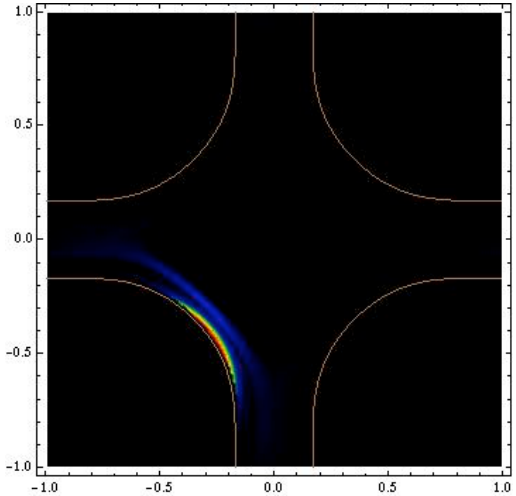


Contributions to the kink

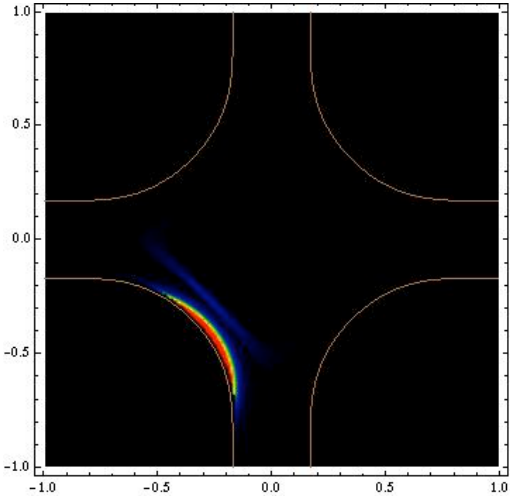
ω=-60 meV



ω=-80 meV



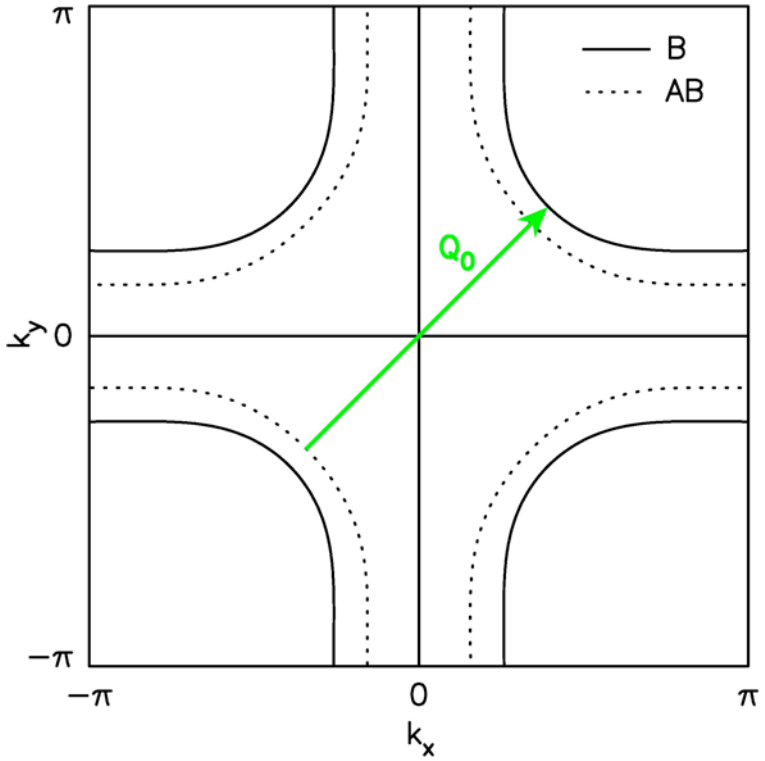
ω=-100 meV

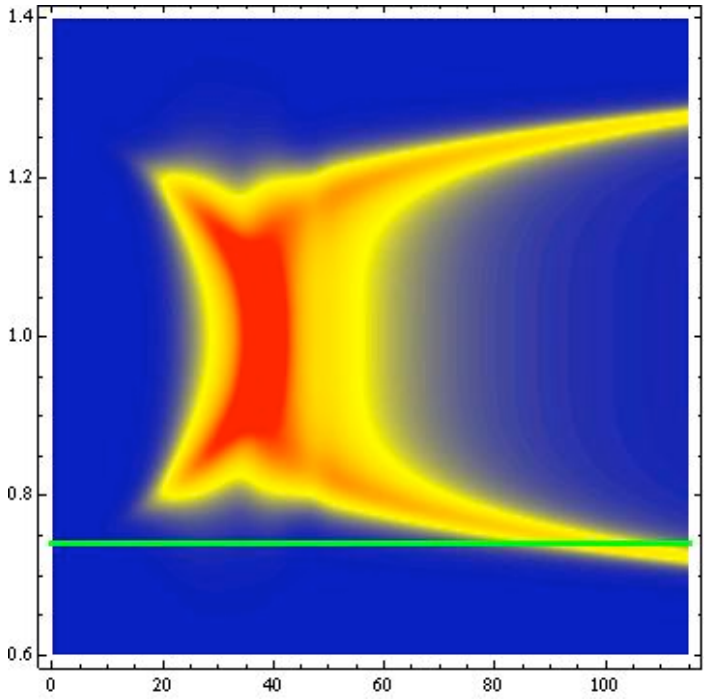


The contributions are coming from the opposite node in the other band.

There is a strong onset at about -80 meV.

Role of the upper branch



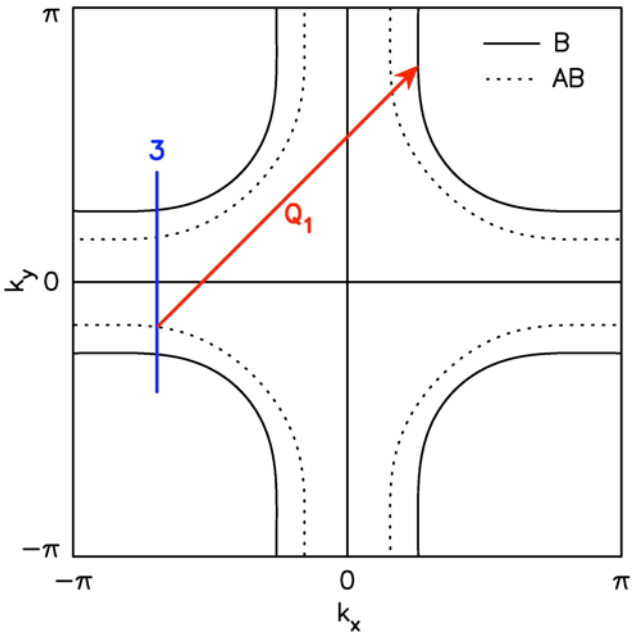


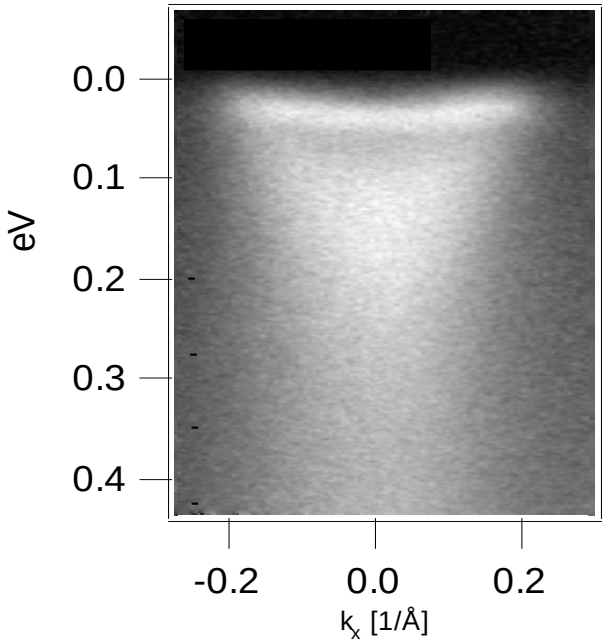
The kink structure is apparently dominated by scattering processes from the momentum vector Q_0 (interband node-to-node scattering).
This is coming from the “upper branch” of the hourglass spin excitations !

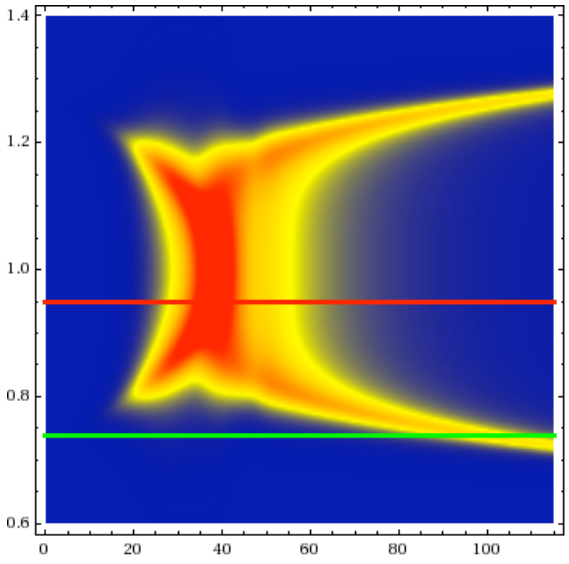
Upper branch is universal, common to all high-T_c cuprates, temperature and doping independent. → new explanation of the kink

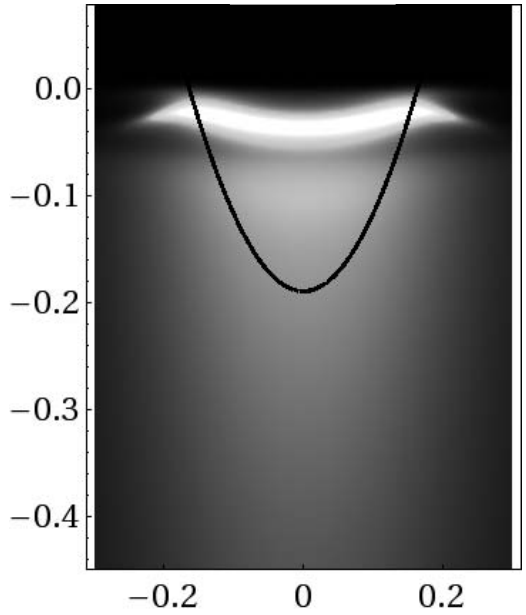
Peak-dip-hump structure

Cut #3

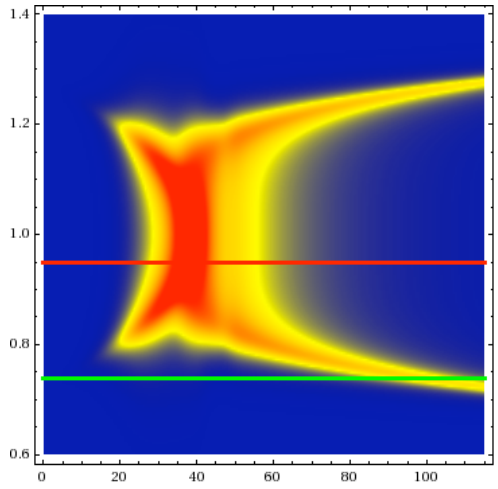


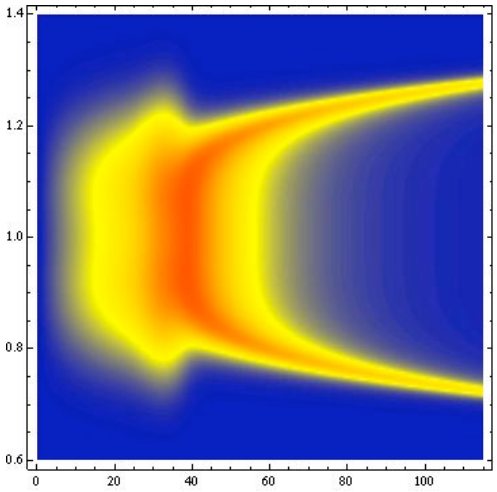






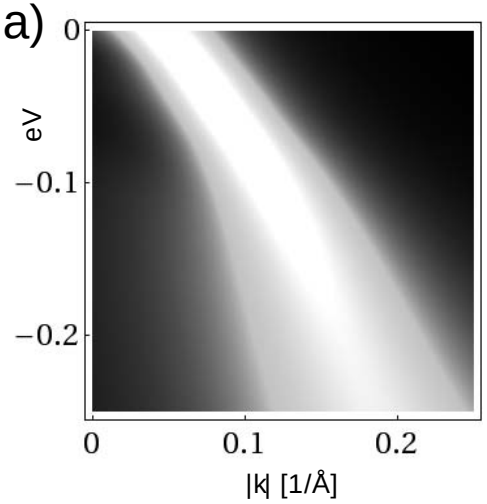
Comparison above and below T_c





Cut #1

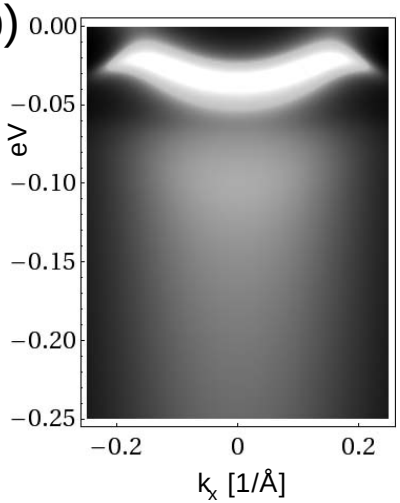
a)



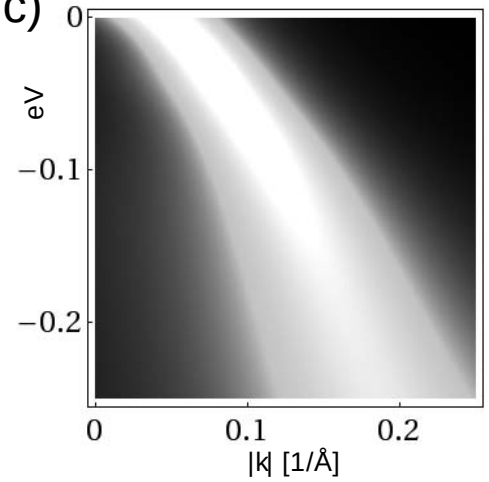
T=5 K

Cut #3

b)

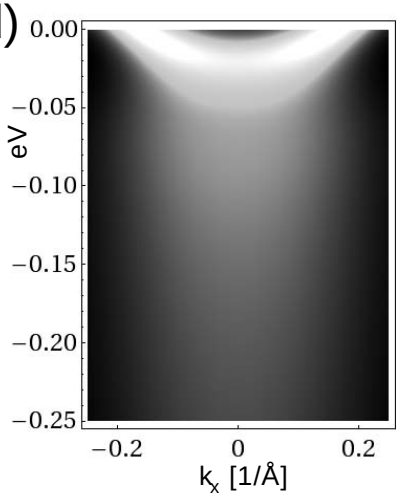


c)



T=70 K

d)



Calculation of T_c

The coupling constant comes out to be $\overline{U}$=1.6 eV.

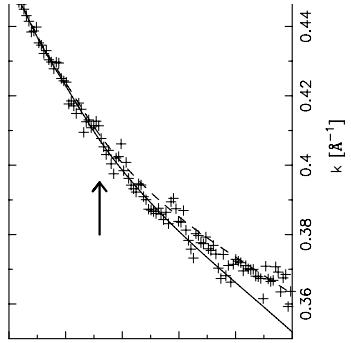
The d-wave eigenvalue at 70 K is found to be 1.39.

Assuming a constant spin excitation spectrum above 70 K this corresponds to a T_c of 174 K.

Discussion

Several effects have been neglected. What might be their impact ?
We have checked:

- Reduce unrenormalized nodal Fermi velocity by 20%:
  T_c drops to 140 K



- Inclusion of a 30 meV anisotropic pseudogap:
  T_c increases by 20%
- Cut off the spin excitation spectrum at 200 meV:
  T_c decreases by 1 K
- Inclusion of phonons with λ_{ph}=0.3:
  T_c drops by 10%

It turns out that within this calculation T_c is hard to suppress. Part of the reason for this is that the renormalized nodal dispersion provides a „boundary condition“ that can only be fulfilled with sufficient interaction strength.

Summary

Phenomenological approach: try to rely only on experimental data

- new interpretation of the kink
- high value of T_c
- most realistic calculation so far
- stable results
- ARPES structures can be related to structures in the spin excitation spectrum