Dispersion anomalies in Cuprate Superconductors

Andrey Chubukov

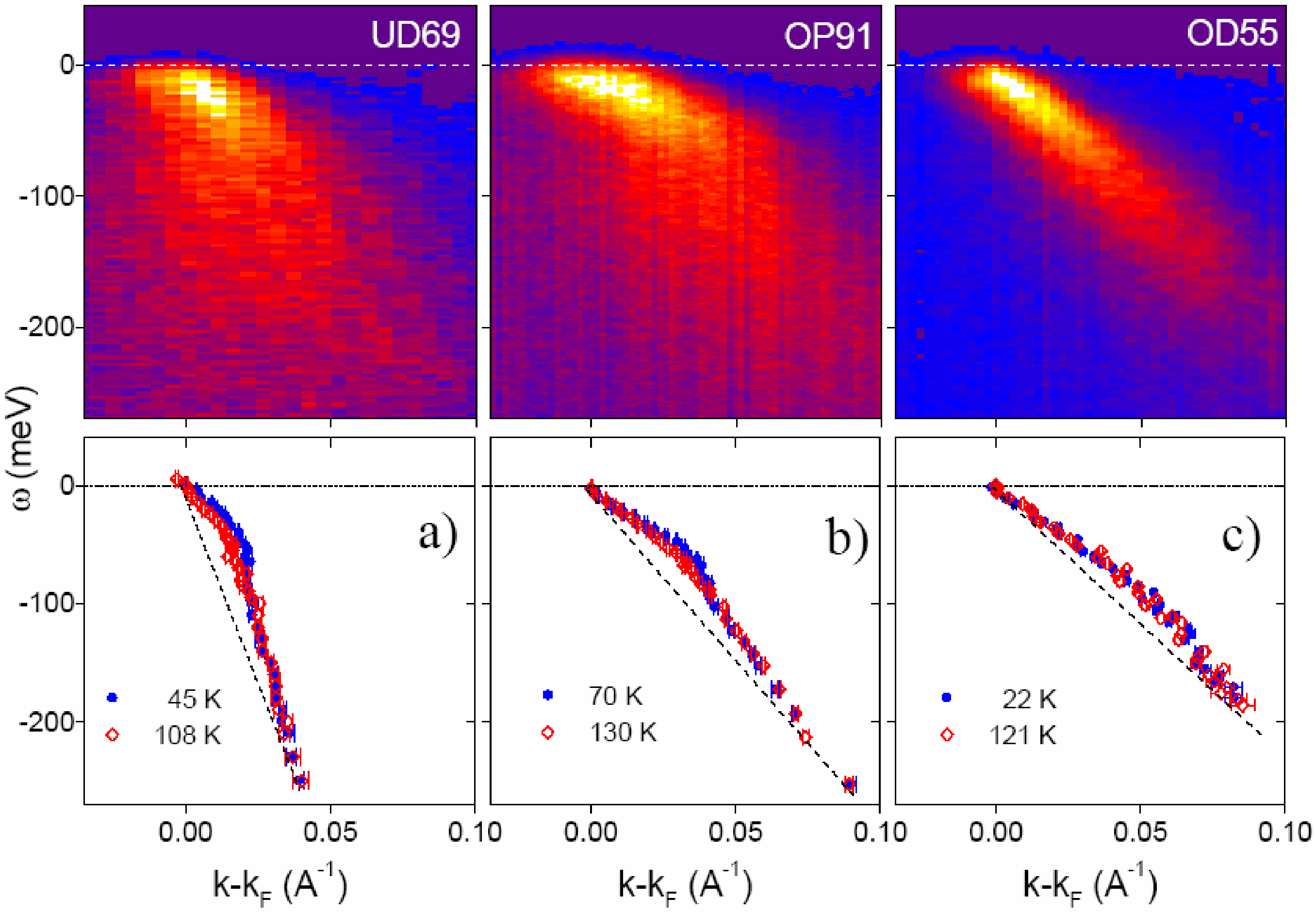
University of Maryland

Mike Norman

Argonne National Lab

CORPES05, Dresden, April 2005

kink in the dispersion

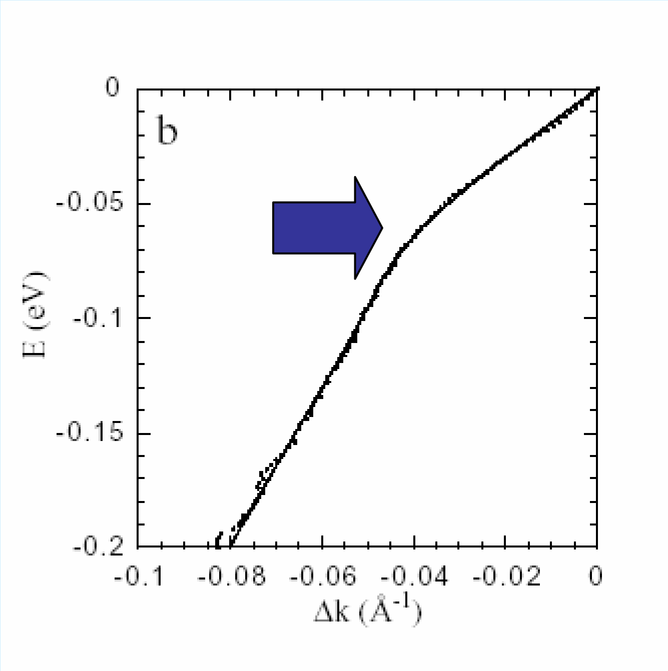


Nodal direction, Bi2212

P.D. Johnson, T. Valla, ...

kink in the dispersion

Nodal direction



T. Valla et al,

P. Bogdanov et al,

A. Kaminski et al,

A. Lanzara et al,

P.D. Johnson et al,

T. Sato et al,

T.K. Kim et al,

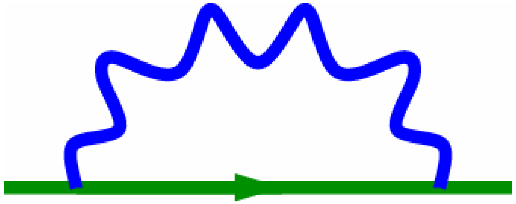
A.D. Gromko et al

Spin fluctuations or phonons?

A simple theory – fermions coupled to a bosonic mode

What should we expect?

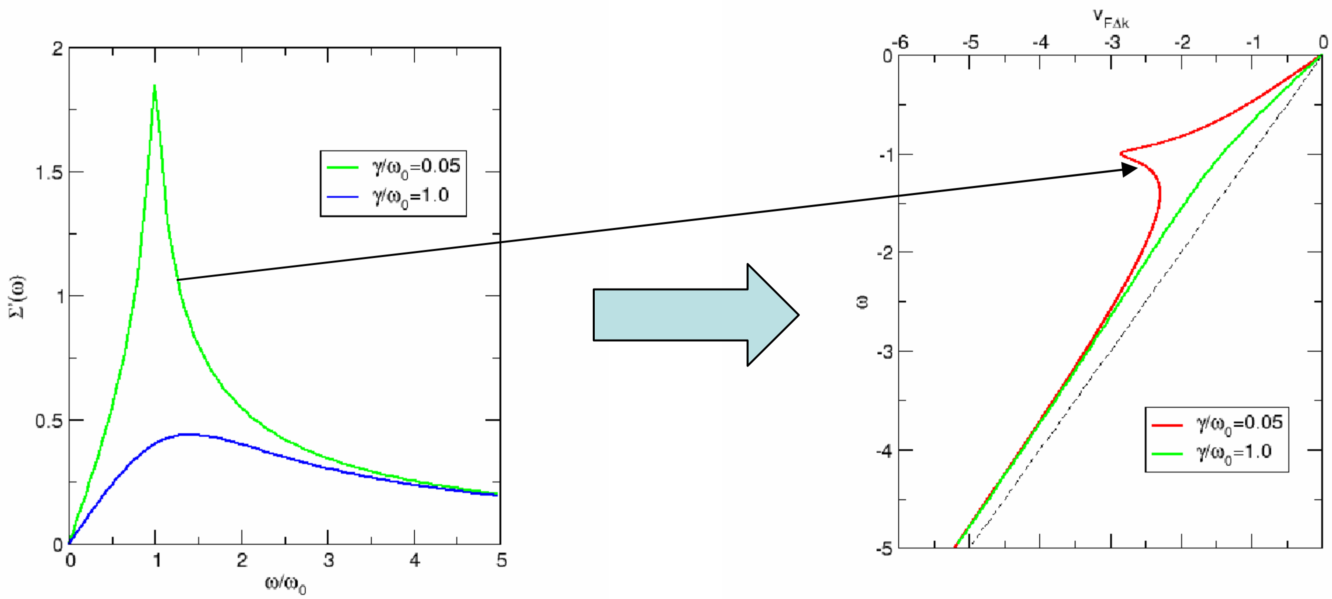
$$\chi(\omega) = \frac{1}{(\omega + \mathrm{i}\,\gamma)^2 - \omega_0^2}$$

$\Sigma(\omega) =$  $= \lambda\; T \sum_{\Omega} \int d\vec{q}\; \chi(\Omega)\, G(\vec{k} + \vec{q}, \omega + \Omega)$

Normal state

The self-energy

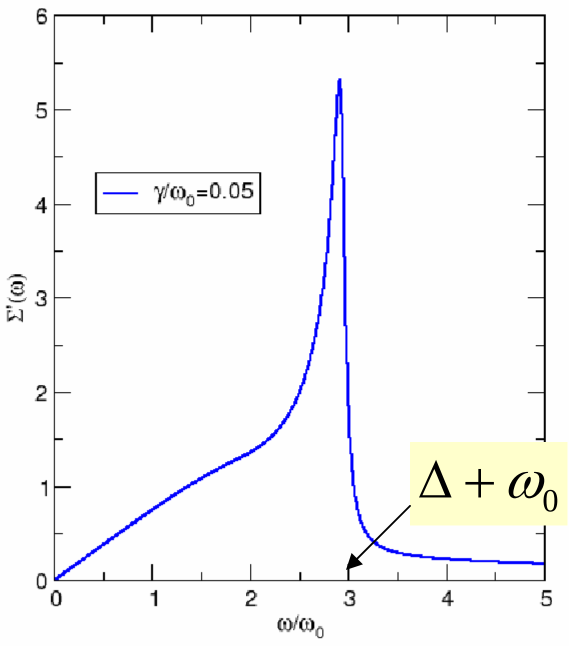
The dispersion



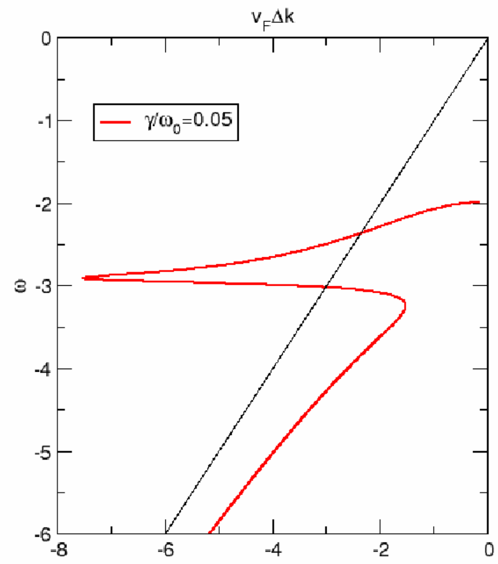
- the dispersion has an S-shape
- an S-shape can be eliminated by a large damping
- a large damping also reduces mass renormalization

Superconducting state

The self-energy

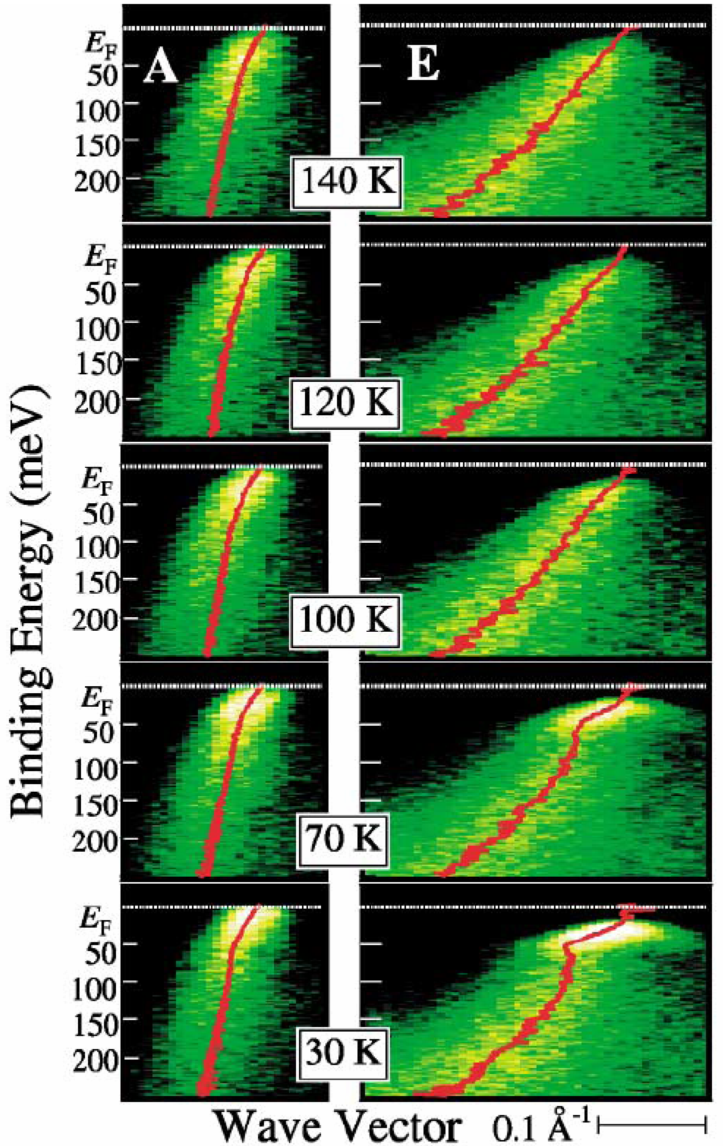


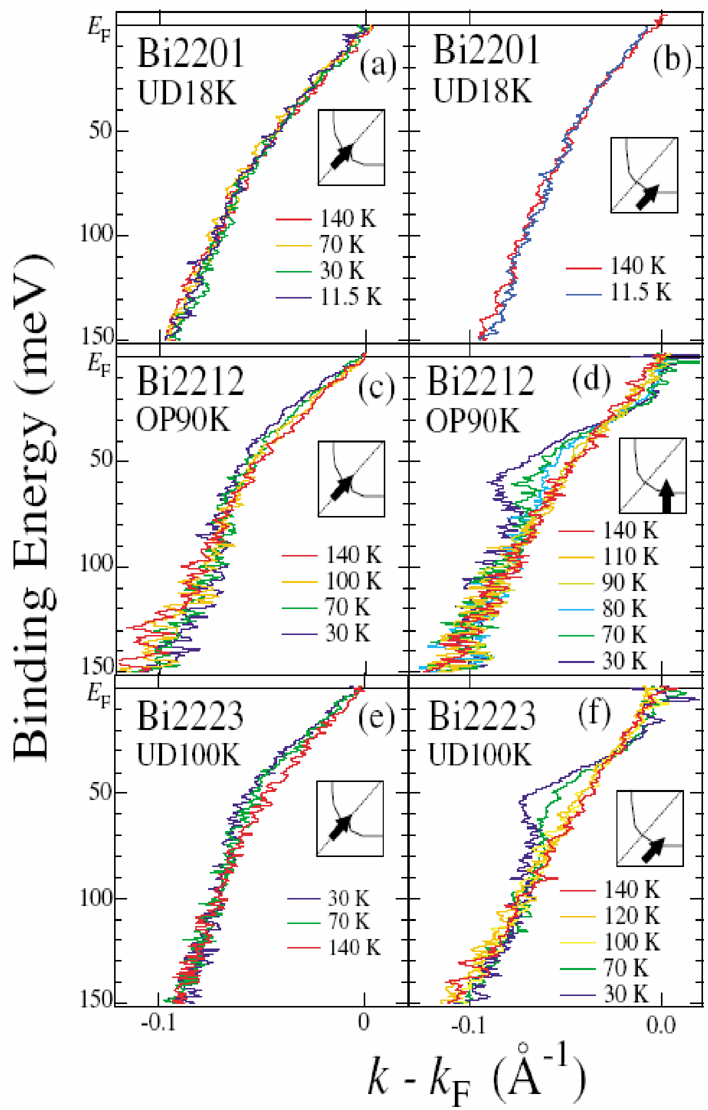
The dispersion



- the S-shape dispersion is even stronger
- high energy dispersion interpolates to k outside the Fermi surface

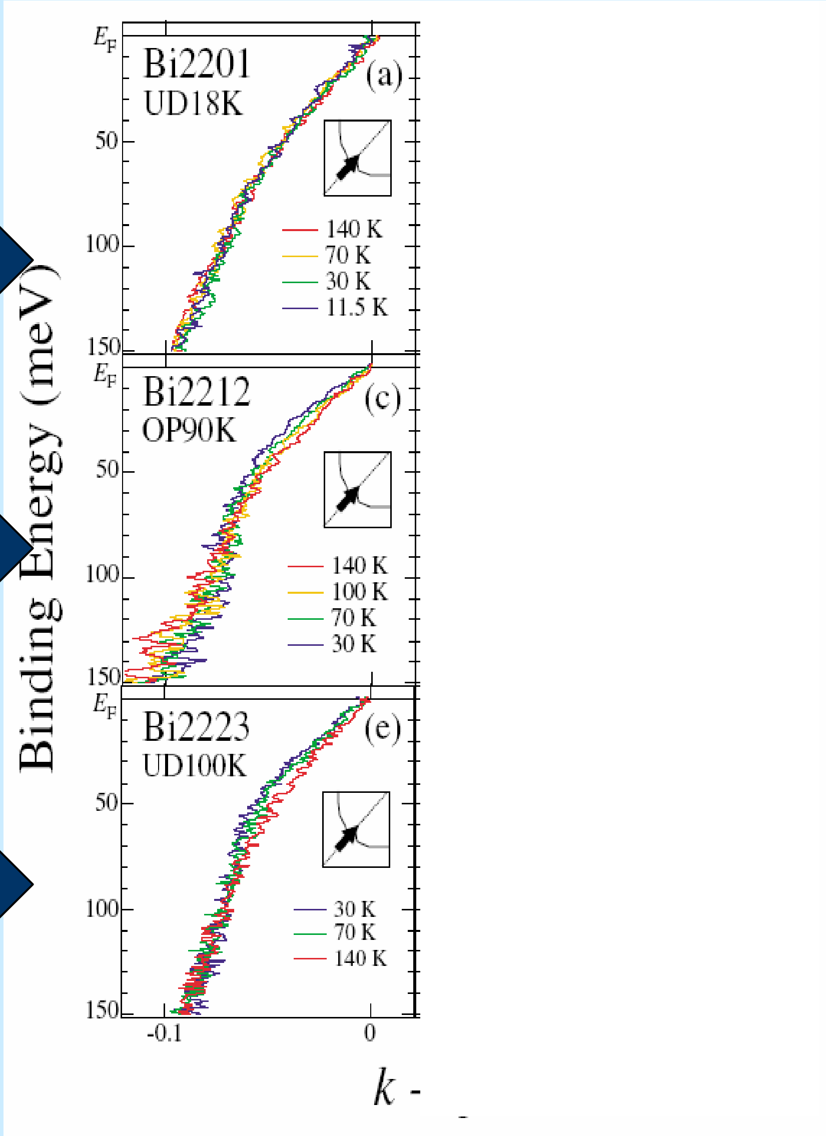
Experiment





Sato et al, 2003

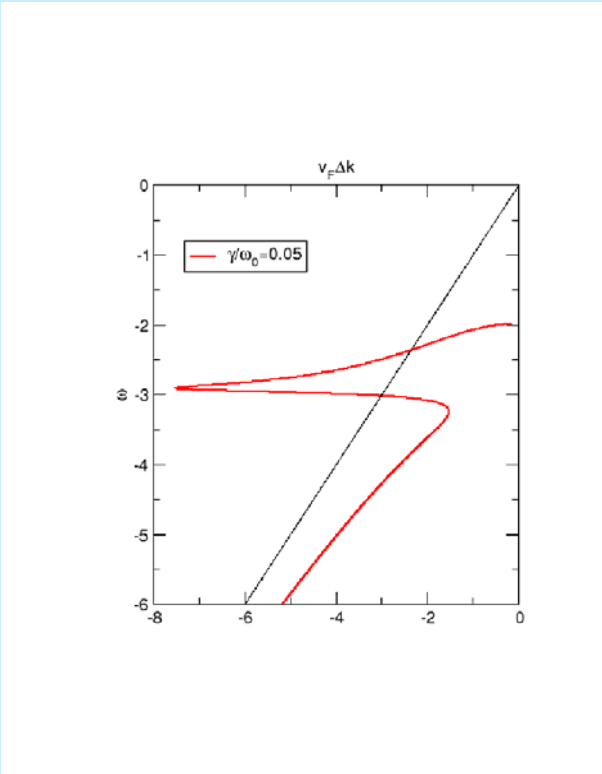
Nodal direction



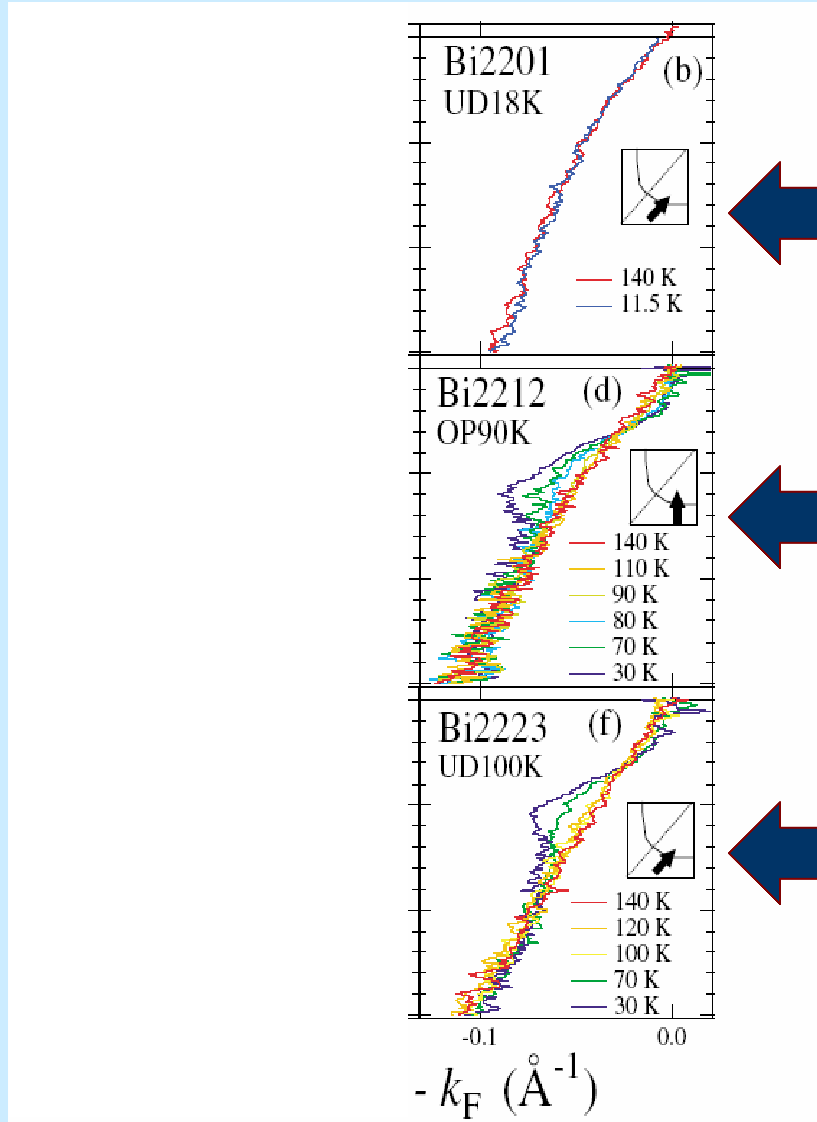
a crossover (a smooth "kink") in the normal state

some sharpening, but still rather smooth "kink" in the superconducting state

It doesn't look like a mode



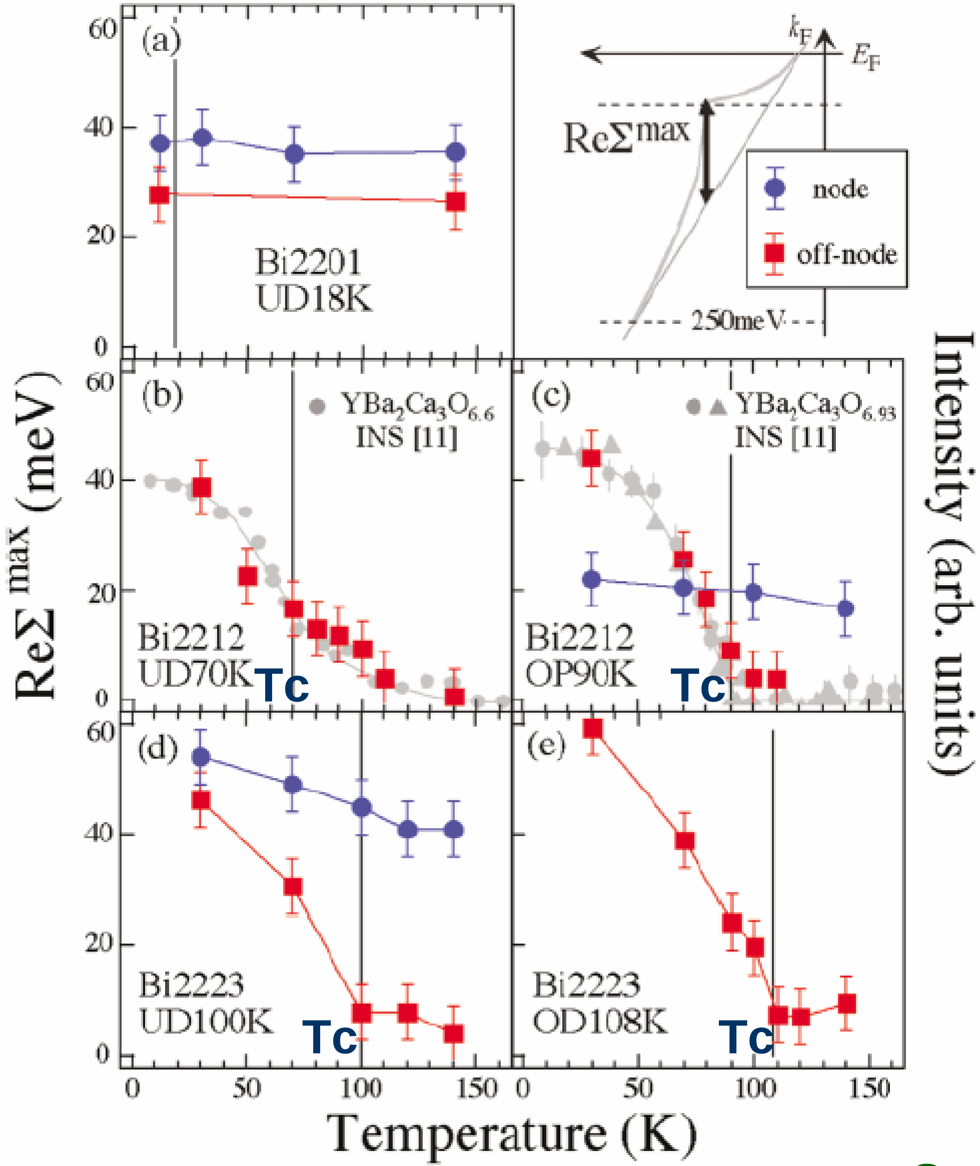
High energy dispersion interpolates to k inside Fermi surface



Antinodal direction

This looks like the effect of a mode, but not completely

S-shape dispersion is correlated with T_c (more accurately, with T*)



Sato et al, 2003

Theory: what are the options

Bosonic mode is independent on electrons (phonons)

- **one needs two different phonon modes (buckling and breathing)**
- **the coupling constant for the nodal direction must be small** $\lambda = 0.3$

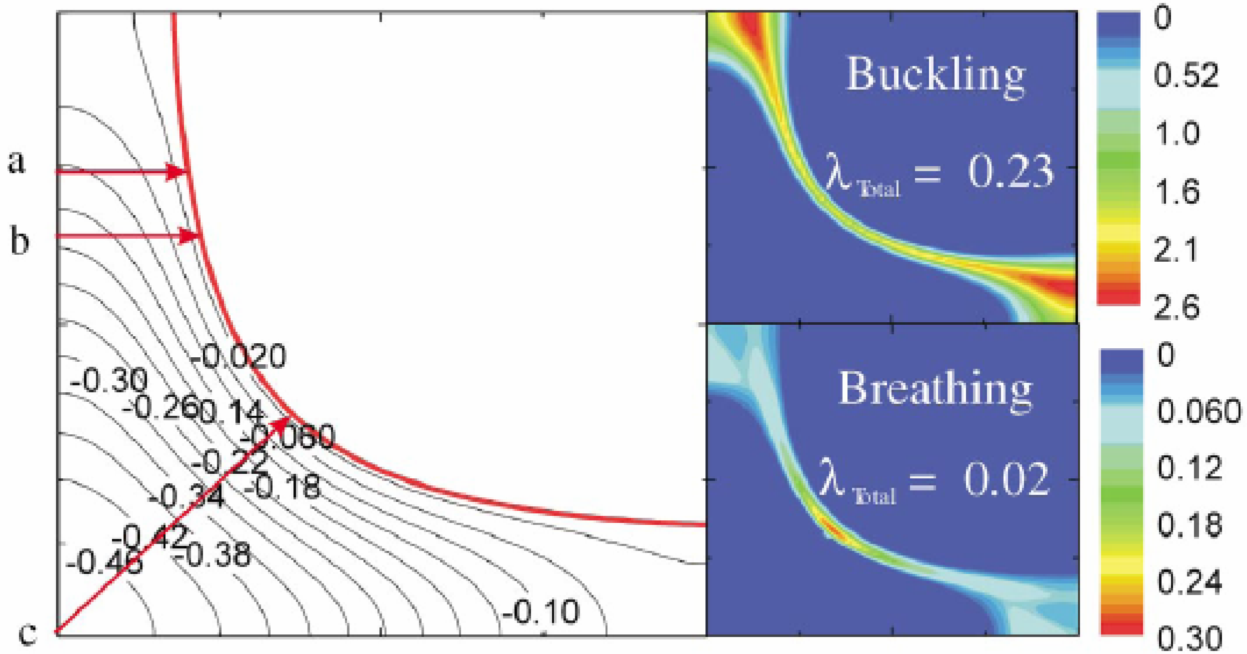
(Devereaux et al)

One needs some other mode to account for a large mass renormalization along the nodal direction

Bosonic mode is a collective mode of electrons (spin fluctuations)

“Mass media”: spin fluctuations == spin resonance
(and as such, they are not that different from phonons)

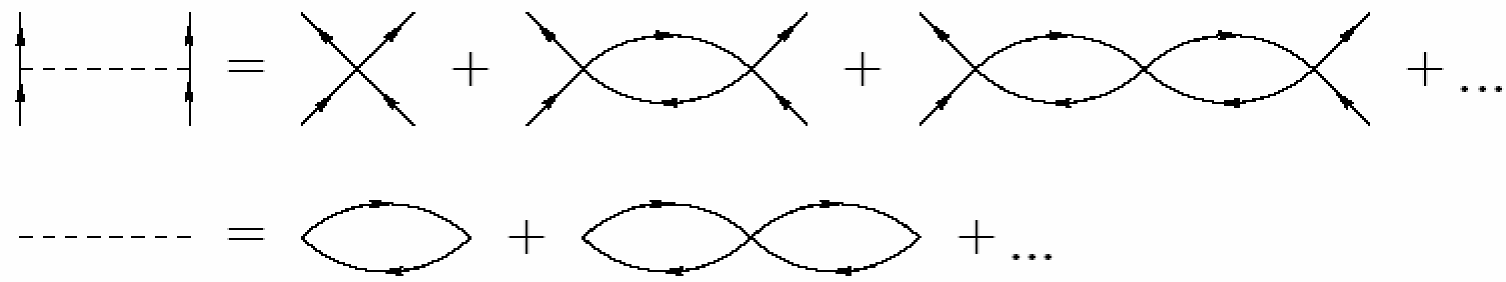
Actually, spin fluctuations are more complex

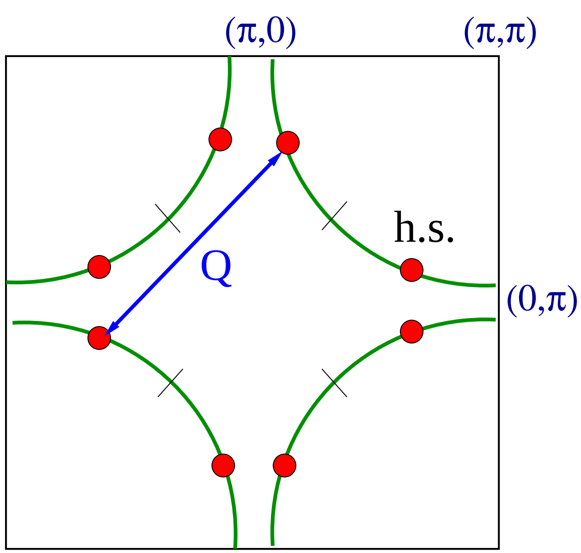


a
b
c
-0.020
-0.30
-0.26
-0.14
-0.060
-0.22
-0.34
-0.18
-0.42
-0.46
-0.38
-0.10
Buckling
λ Total = 0.23
0
0.52
1.0
1.6
2.1
2.6
Breathing
λ Total = 0.02
0
0.060
0.12
0.18
0.24
0.30

Collective spin fluctuations

$\chi(\mathrm{q},\omega) =$





In the normal state, spin fluctuations with momenta near (π,π) are Landau damped

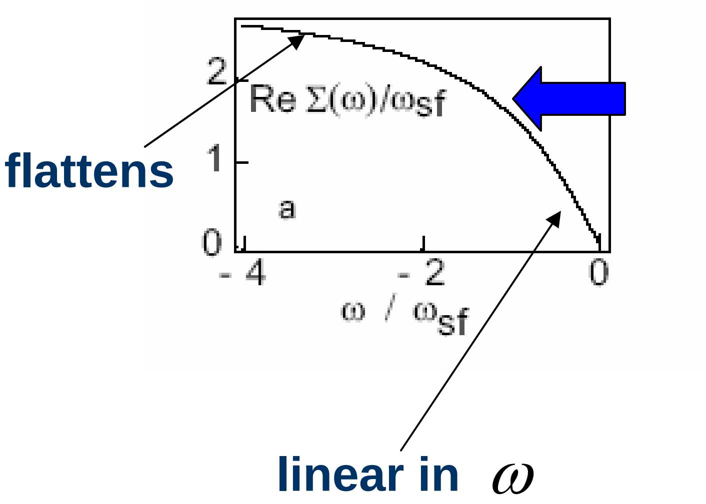
In the superconducting state spin damping is generally reduced due to gap opening, and spin fluctuations with momenta near (π,π) become sharp modes (spin waves)

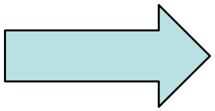
Normal state

$$\chi^{-1}(q,\omega) \sim [f(q) - i\frac{\omega}{\omega_{sf}}]$$

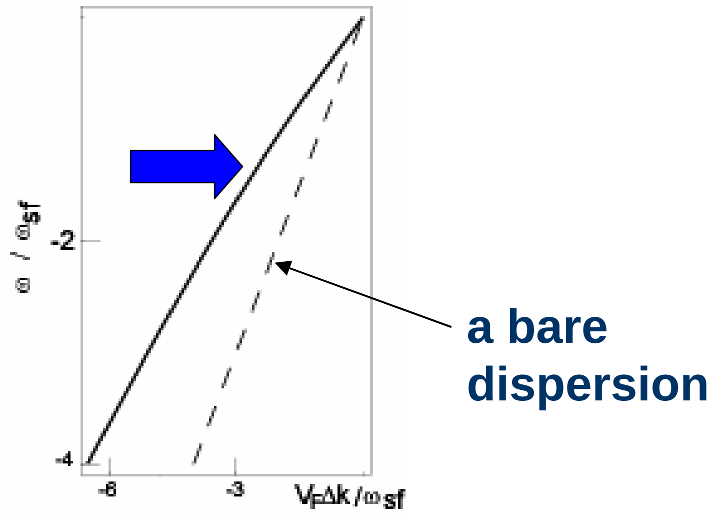
Overdamped mode

Self-energy





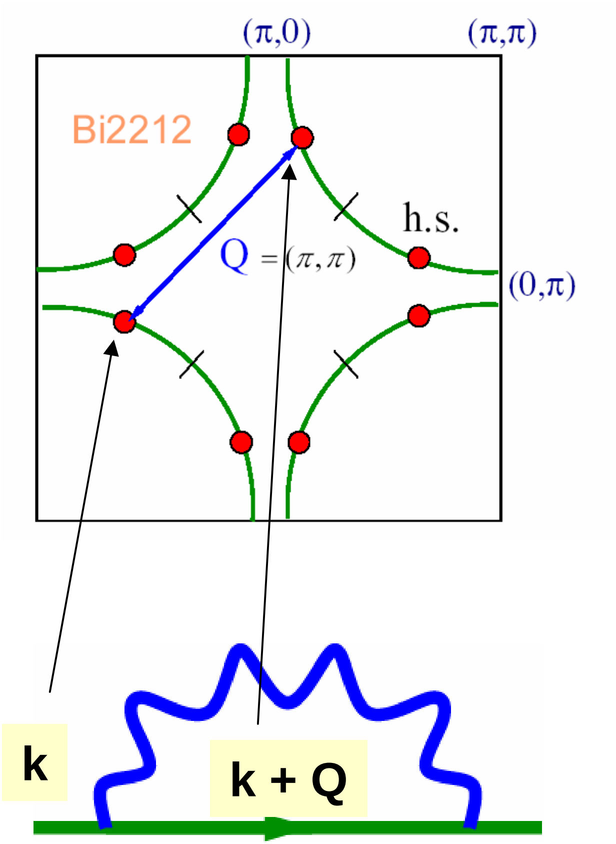
dispersion

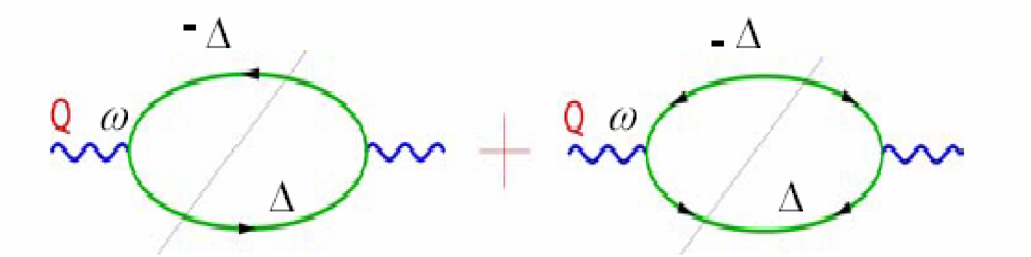


a smooth crossover in the fermionic dispersion

Superconducting state

1. antinodal region





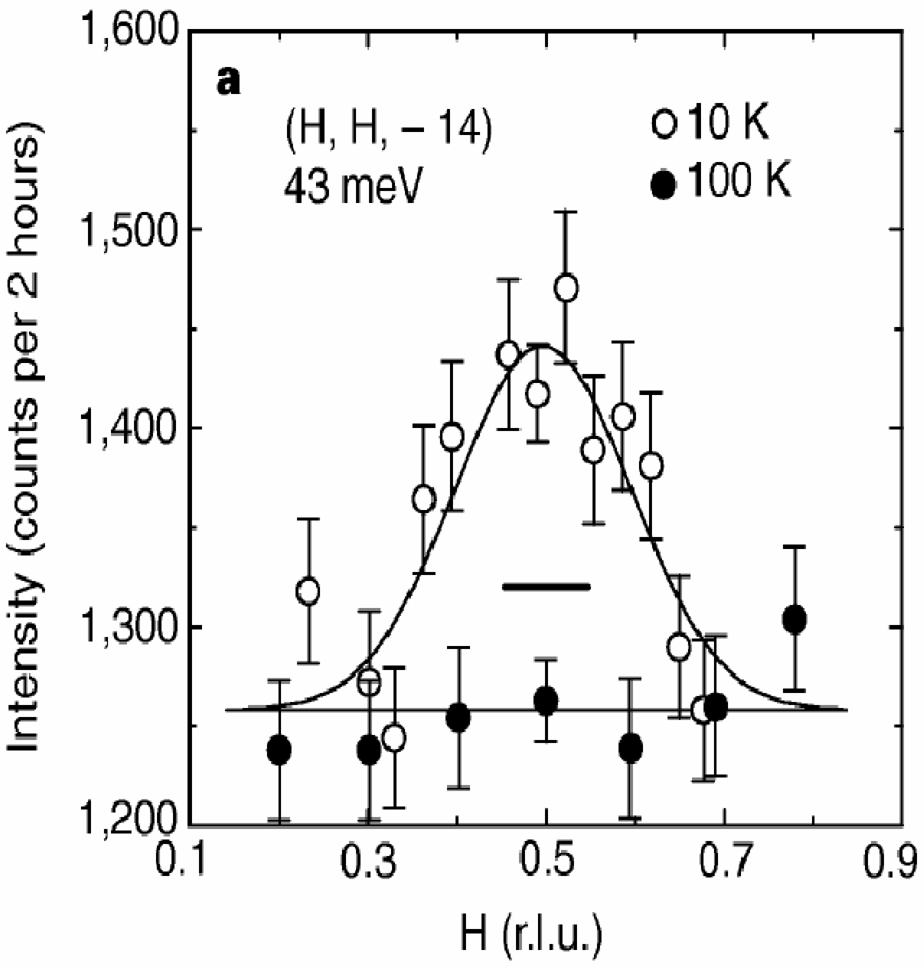
$$\chi(\omega) = \frac{Z}{\omega^2 - \omega_{res}^2}$$

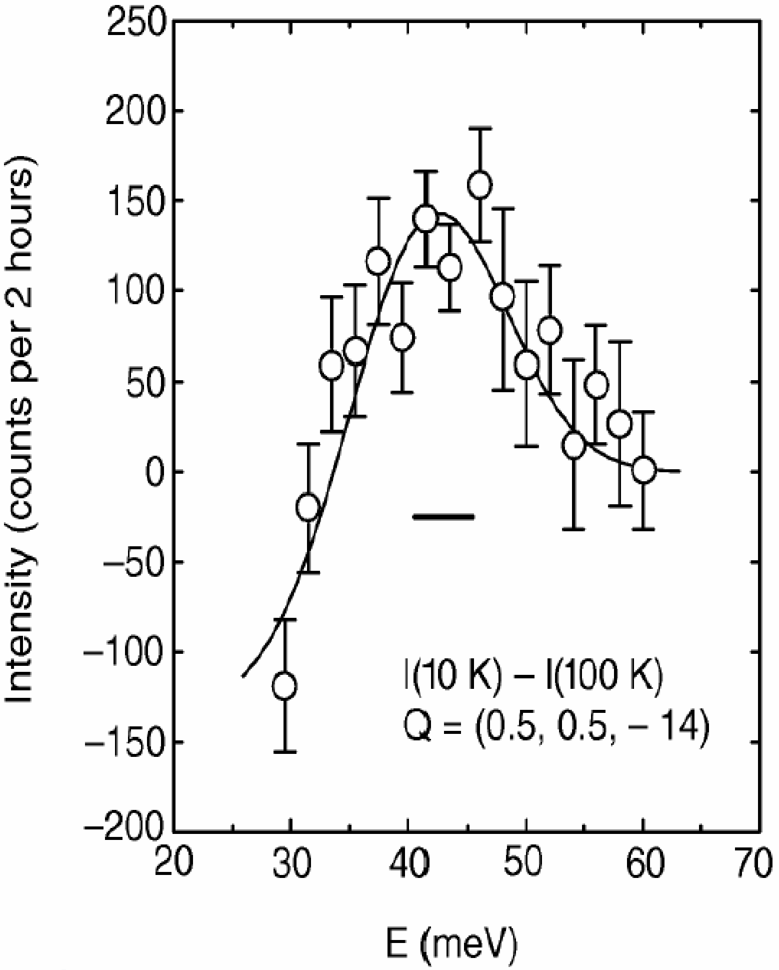
$$Z \propto \Delta$$

A collective spin-fluctuation mode at an energy $\omega_{res} < 2\Delta$

(a resonance peak)

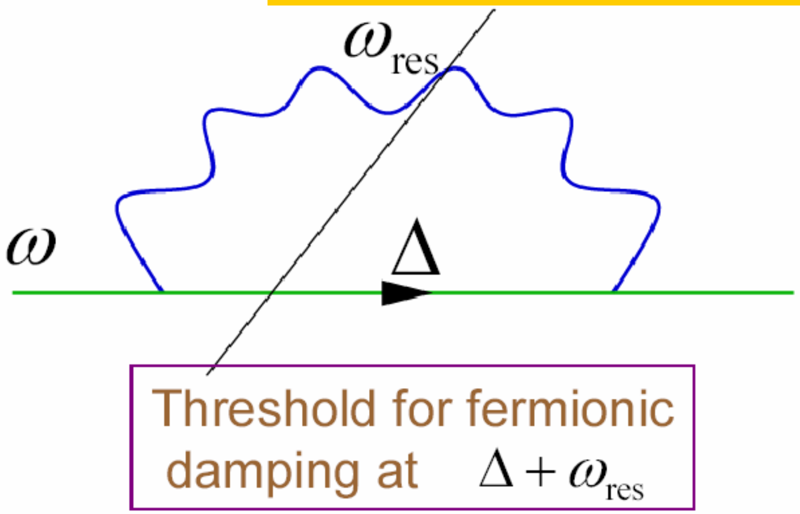
Resonance peak in a d-wave superconductor

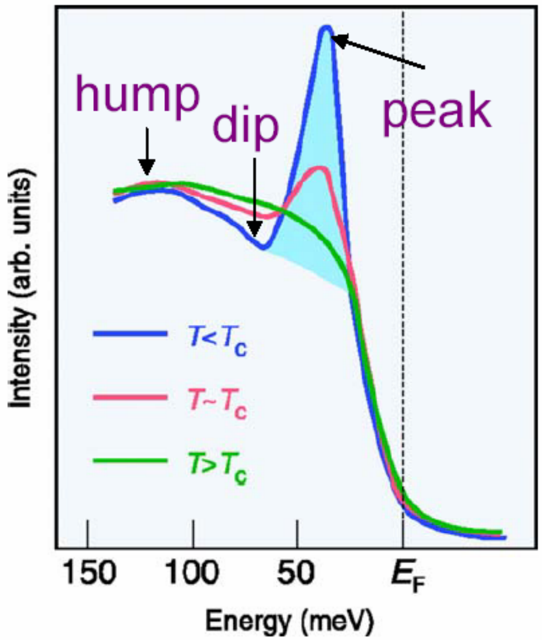


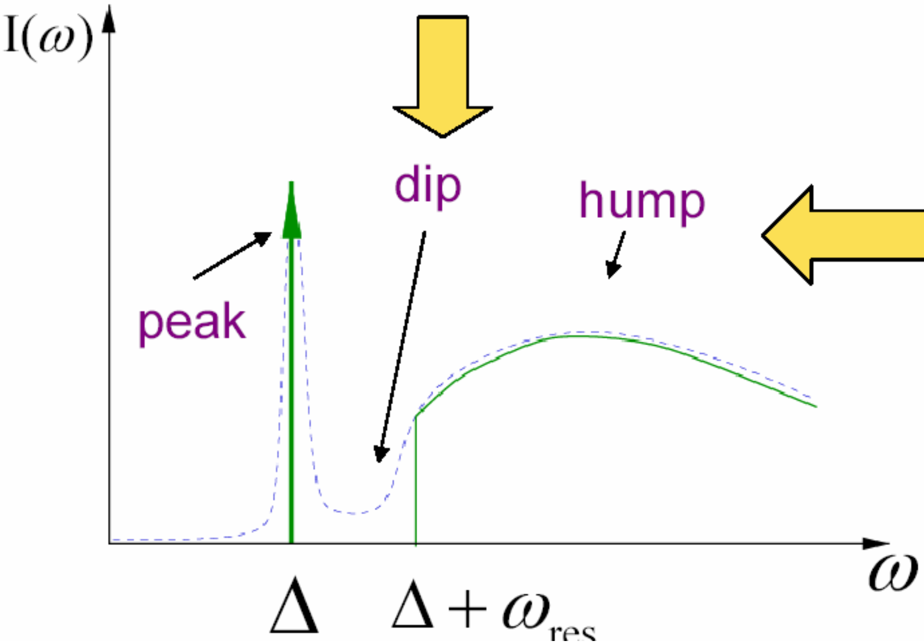


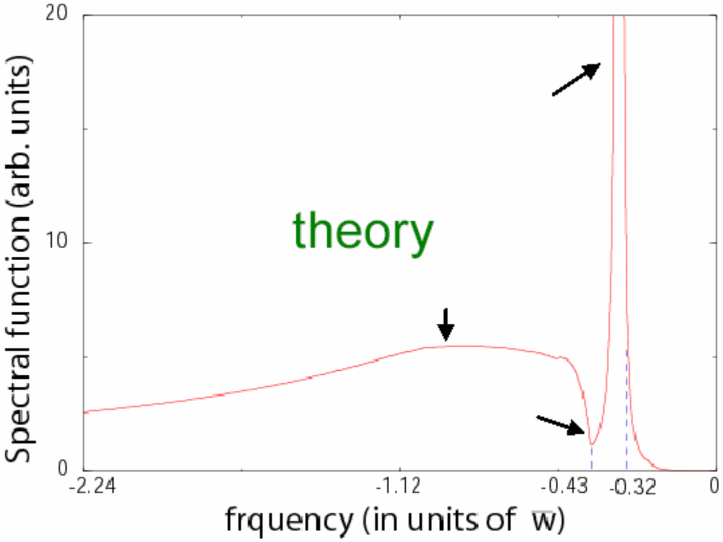
Keimer et al, Bi2212

Feedback on antinodal fermions



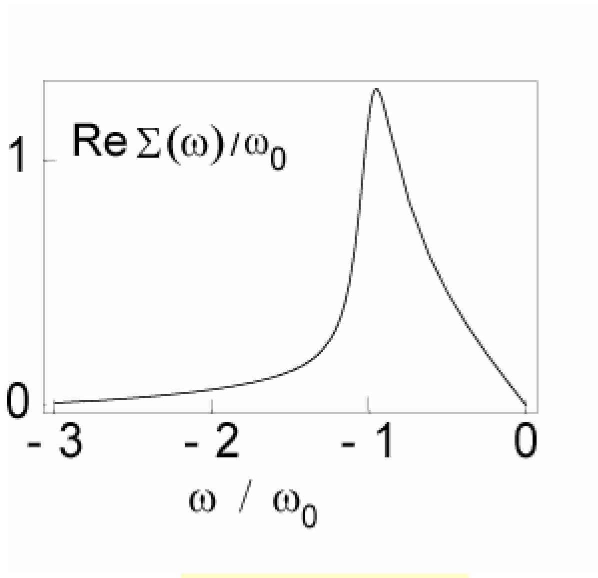






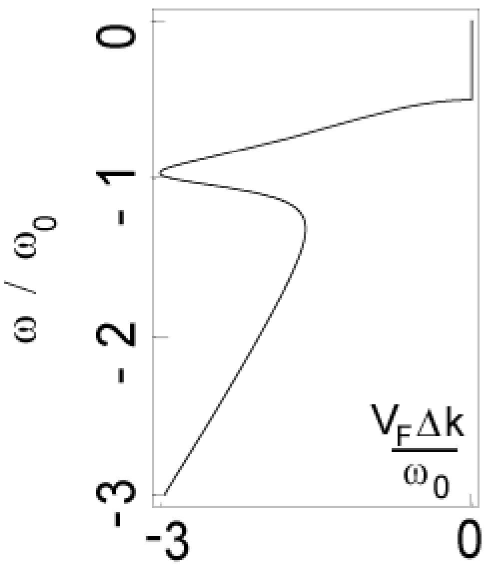
Feedback effect on Re $\Sigma(\omega)$

Antinodal self-energy



$\omega_0 = \Delta + \omega_{res}$

Antinodal dispersion

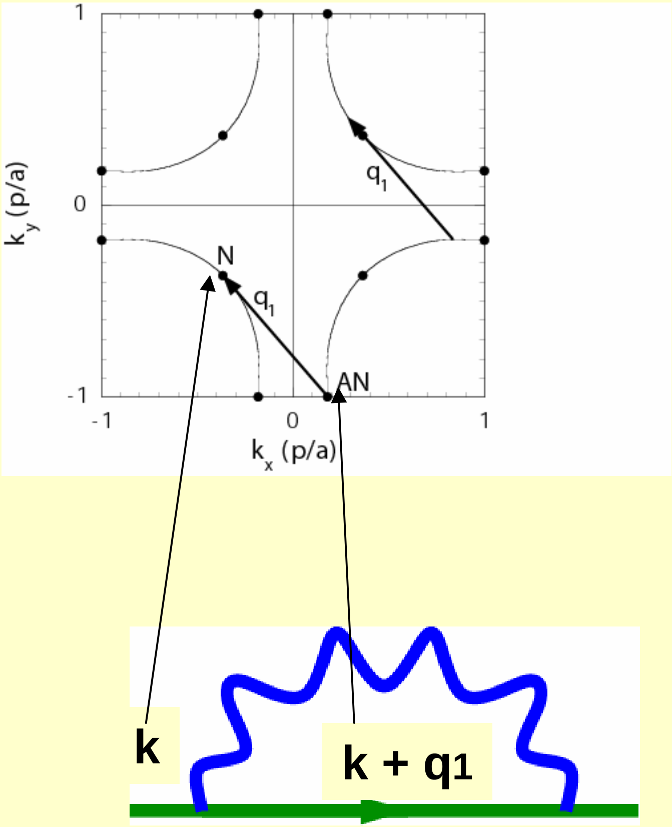


S – shape dispersion!

Interpolates to k inside Fermi surface

Superconducting state

2. nodal direction



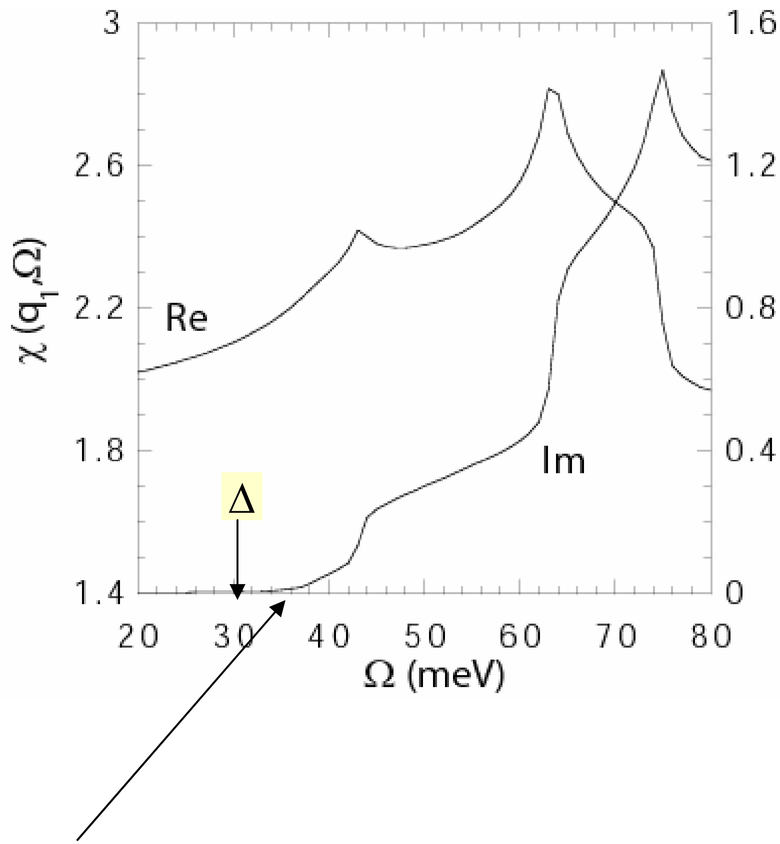
The main scattering is between nodal and antinodal regions

$$\chi_{q_1}(\Omega) = \frac{Z}{\Omega^2 - \omega_{res}^2}$$

Residue of the resonance peak at q_1

$$Z \propto \left[\Delta_N \, \Delta_{AN}\right]^{1/2} = 0$$

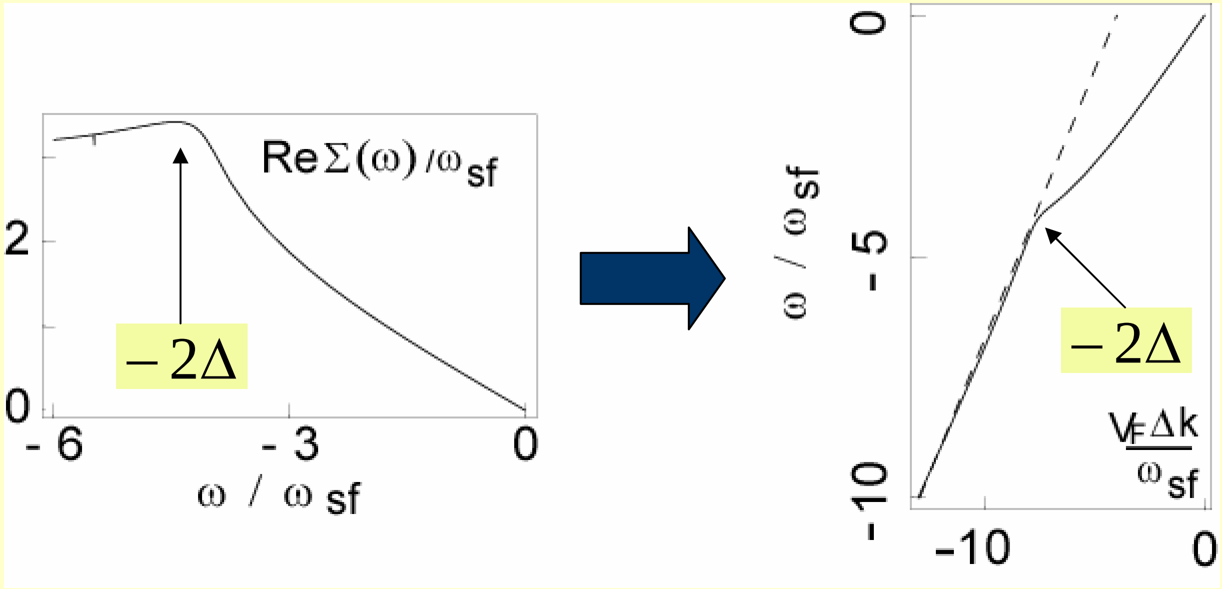
A nodal fermion DOES NOT couple to the resonance peak



$$\chi^{-1}(\Omega) \propto 1 - i\sqrt{\Omega^2 - \Delta^2}/\omega_{sf}$$

Nodal self-energy

Nodal dispersion



$$\Sigma^{'}(\omega)-\Sigma^{'}(-2\Delta)\ \propto(\omega+2\Delta)\log\frac{\Delta}{|\omega+2\Delta|}$$

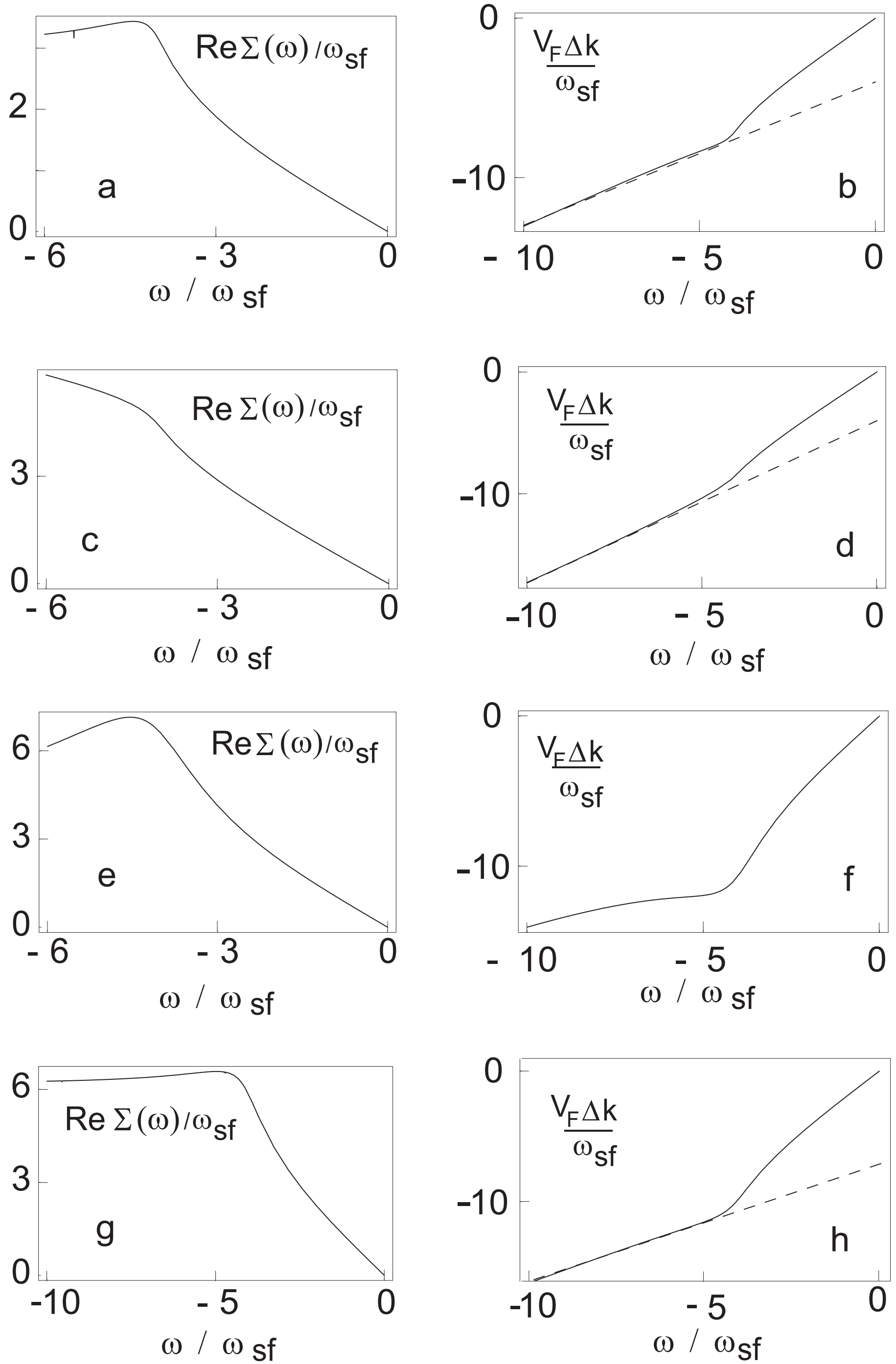
There is a true kink at $\omega = 2\Delta$, but no S-shape dispersion

Flat susceptibility

Ornstein-Zernike, Eliashberg

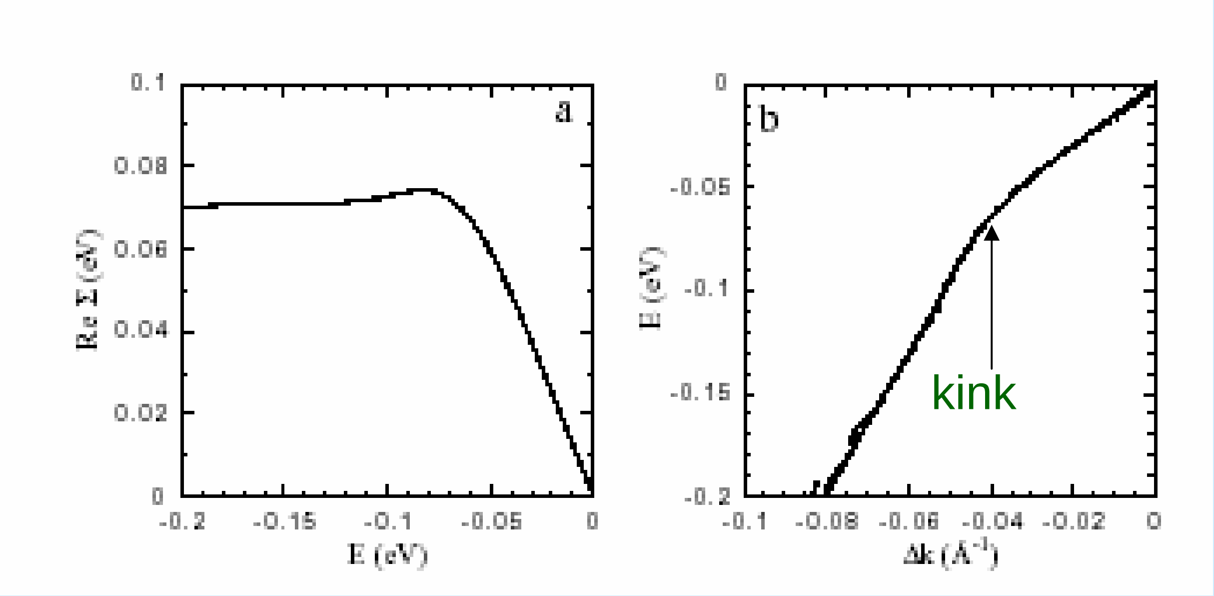
Ornstein-Zernike, anti- Eliashberg

With umklapp scattering

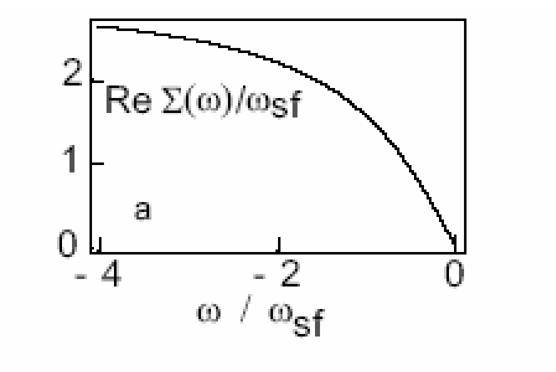


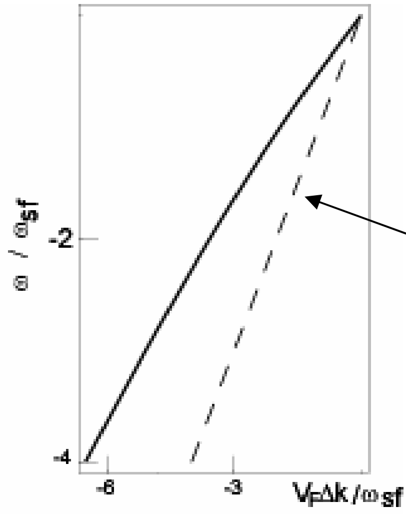
Superconducting state

Nodal dispersion



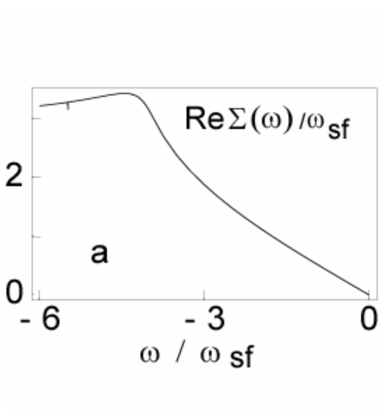
Normal state

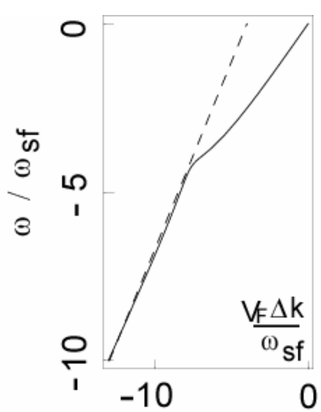




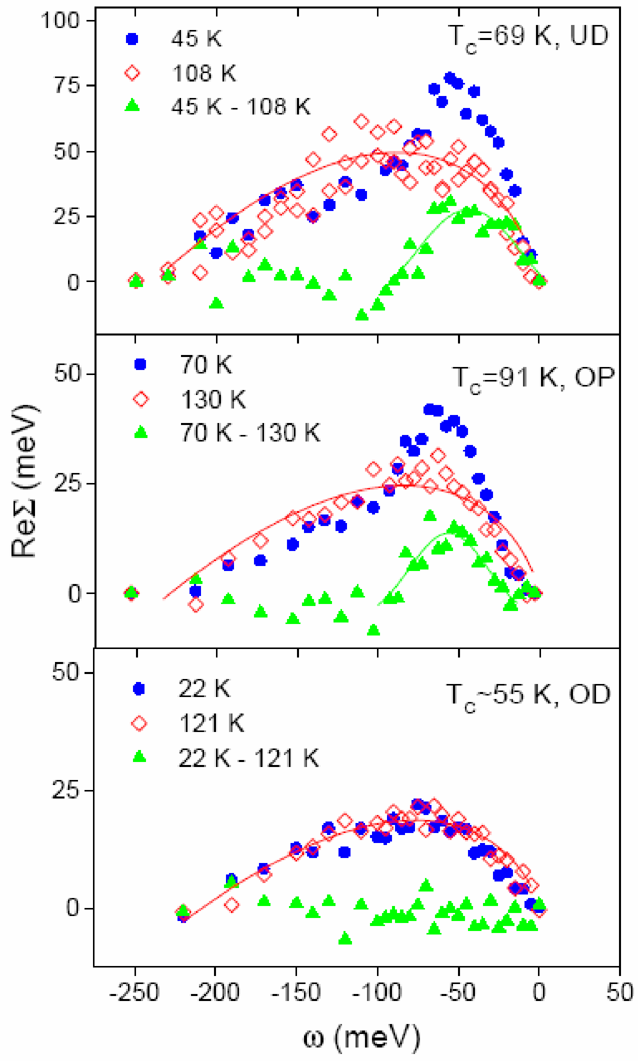
a bare dispersion

Superconducting state, nodal direction

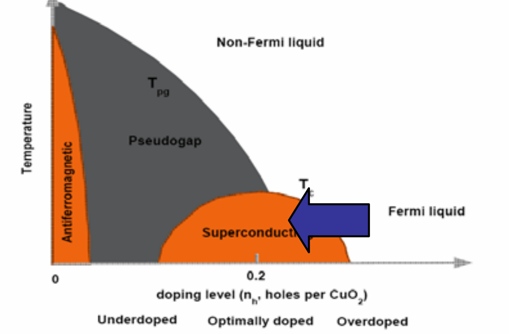




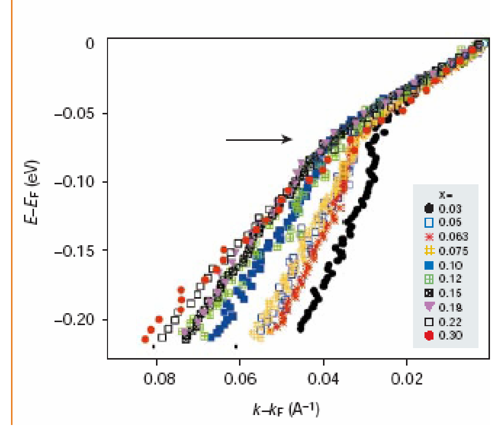
Real part of the self-energy, extracted from ARPES data



P.D. Johnson et al



The doping dependence



1. S-shape along antinode should increase with underdoping

The susceptibility at (π,π) increases

2. Nodal direction, low frequencies

$$V_F^* = V_F/(1+\lambda(q_1))$$

$$q_1 \neq (\pi,\pi), \quad \lambda(q_1) \sim 1$$

nodal velocity is weakly doping independent

(Dessau, Shen)

2. Nodal direction, high frequencies

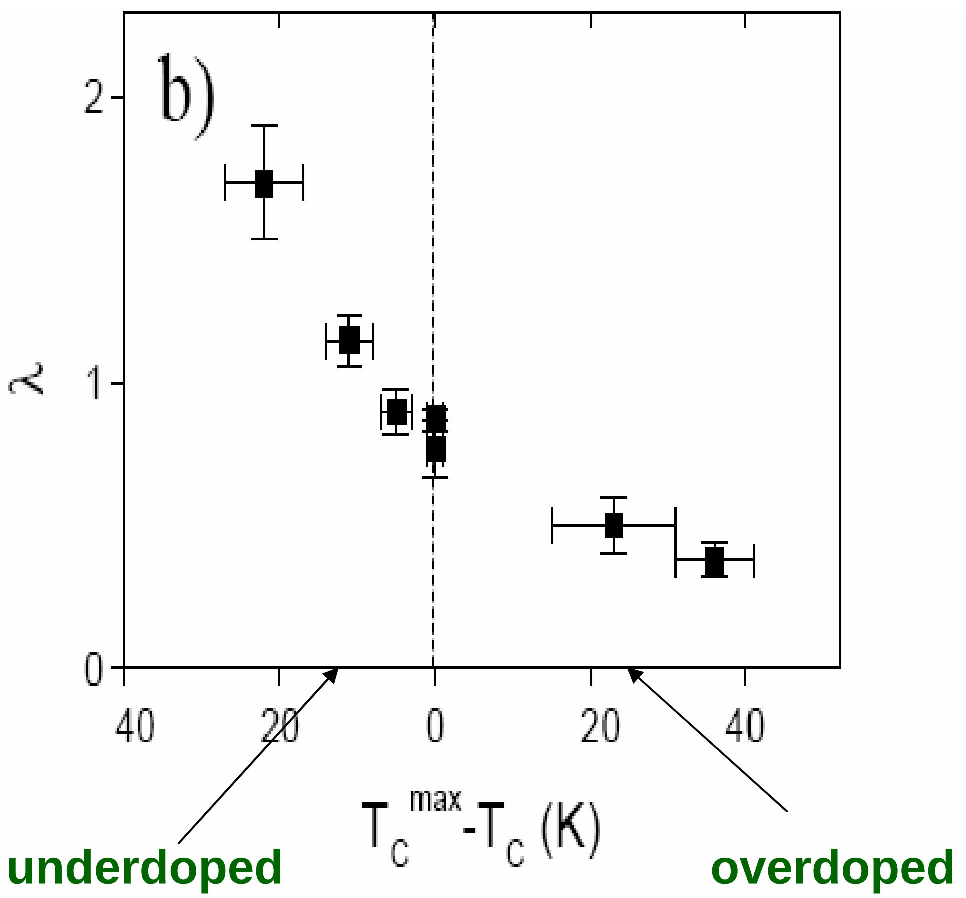
Mott (or SDW) physics

$$\Sigma(k,\omega) = \frac{\Delta^2}{\omega - \varepsilon_{k+\pi}}$$

$$\omega = \varepsilon_k - \frac{\Delta^2}{\varepsilon_{k+\pi} - \varepsilon_k}, \quad \varepsilon_k < 0, \quad \varepsilon_{k+\pi} > 0$$

Randeria et al

Coupling vs doping (nodal direction)



Conclusions

Dispersion anomalies in the cuprates can be explained by the interaction with spin fluctuations

Normal state:

- **overdamped spin fluctuations**
- **a smooth crossover in the dispersion**

Superconducting state:

- Antinodal fermions couple to spin resonance

An S - shape dispersion near $\Delta + \omega_{\text{res}}$

- Nodal fermions do not couple to spin resonance

No S - shape dispersion

A kink at 2Δ