

Constituents of the “kink” in high- T_c cuprates

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Outline

- **Introduction to ARPES**
- **Self-consistent analysis of ARPES spectra**
- **Nodal direction of cuprates**

Introduction to ARPES

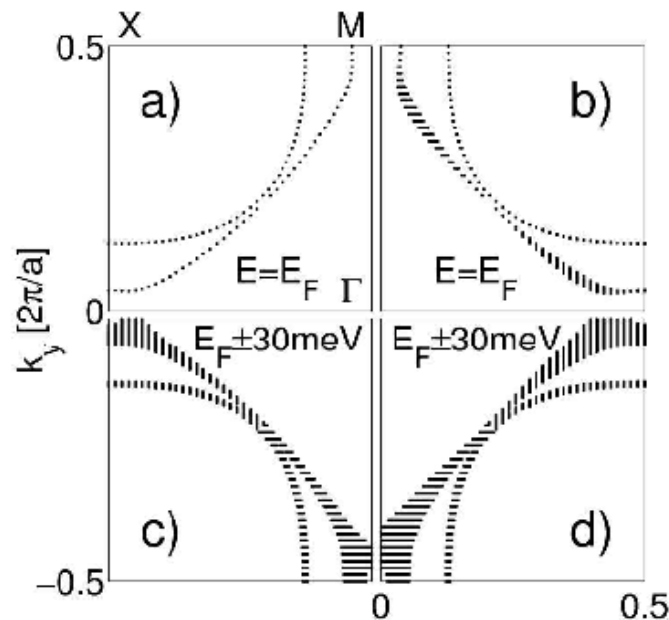
What do we measure?

Samples should be

- 1. Easily cleavable – perfect surface**

Samples should be

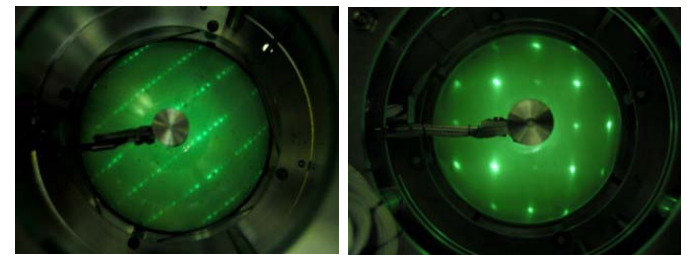
1. Easily cleavable – perfect surface
2. 2D – to neglect k_z dispersion



Bansil 2004

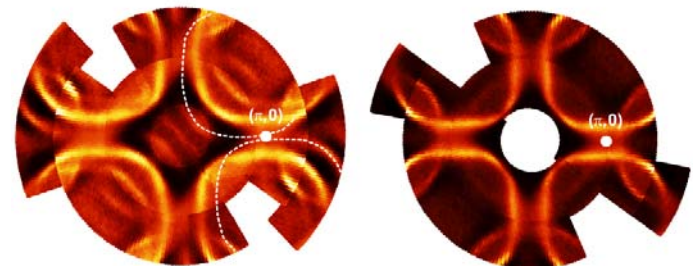
Samples should be

1. Easily cleavable – perfect surface
2. 2D – to neglect k_z dispersion
3. Free of superstructure



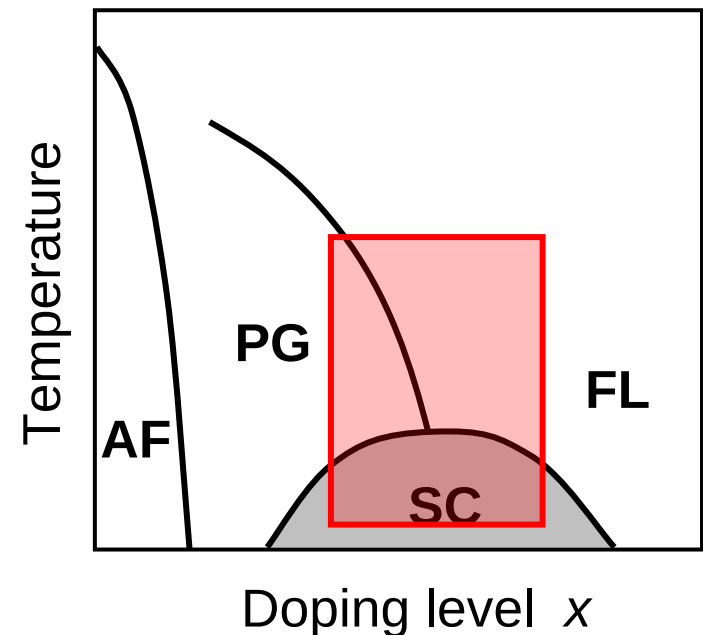
Bi2212

Pb-Bi2212



Samples should be

1. Easily cleavable – perfect surface
2. 2D – to neglect k_z dispersion
3. Free of superstructure
4. High T_c



Samples should be

1. Easily cleavable – perfect surface
2. 2D – to neglect k_z dispersion
3. Free of superstructure
4. High T_c

 Bi(Pb)-2212

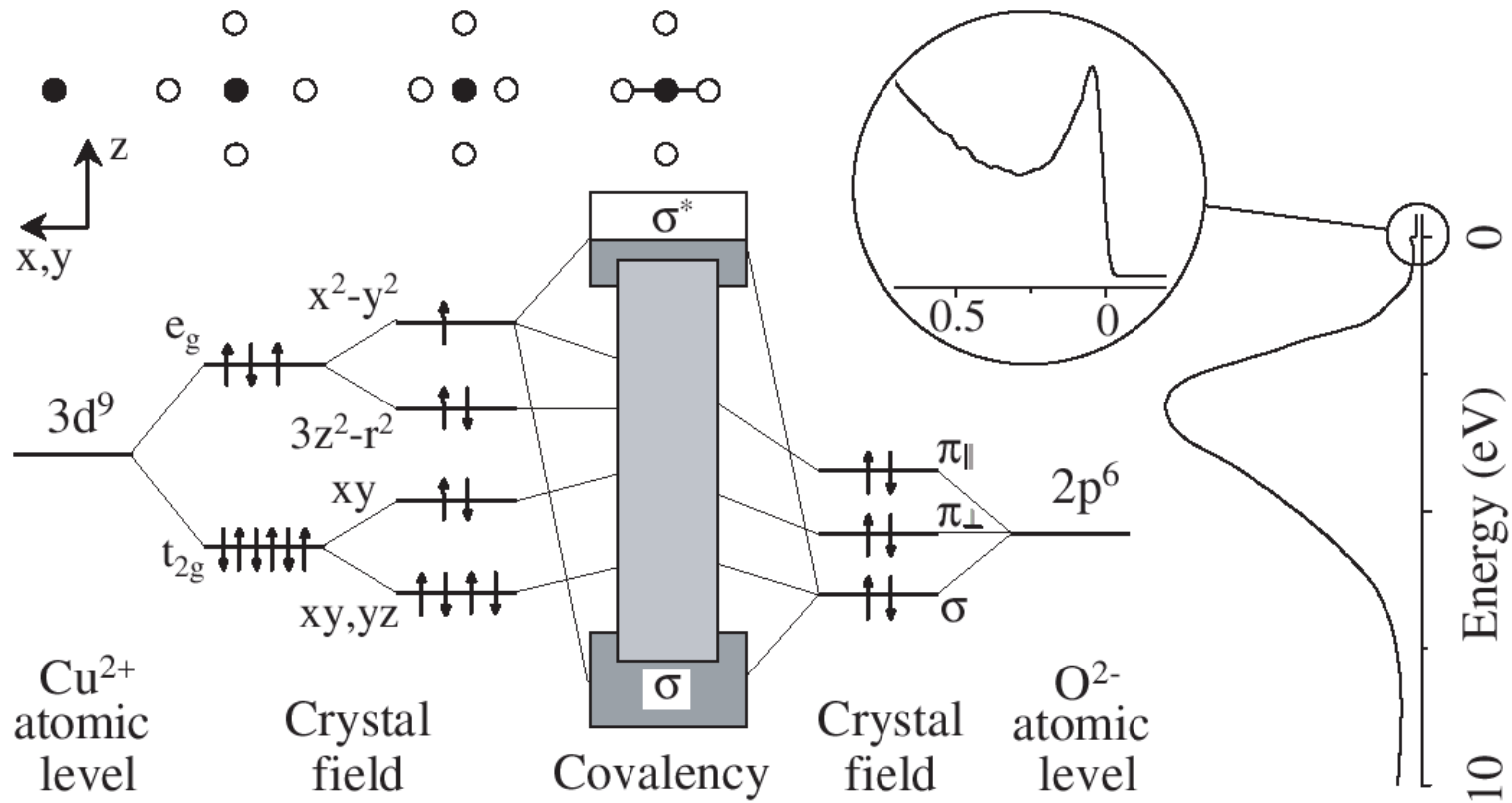
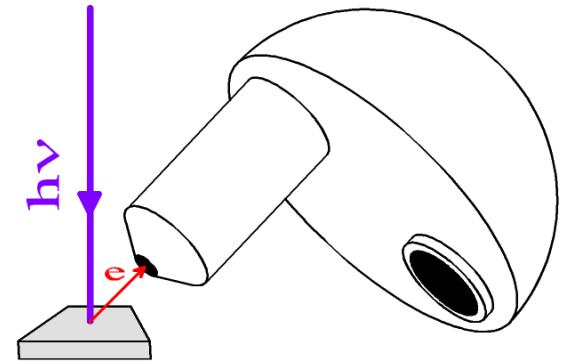
Samples should be

1. Easily cleavable – perfect surface
2. 2D – to neglect k_z dispersion
3. Free of superstructure
4. High T_c

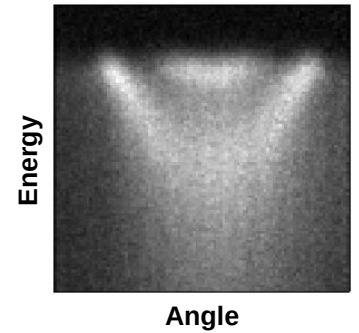
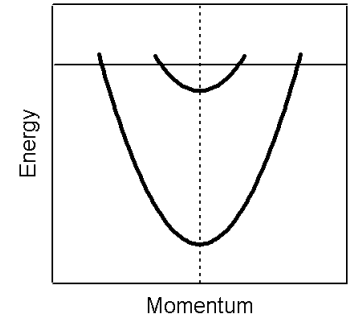
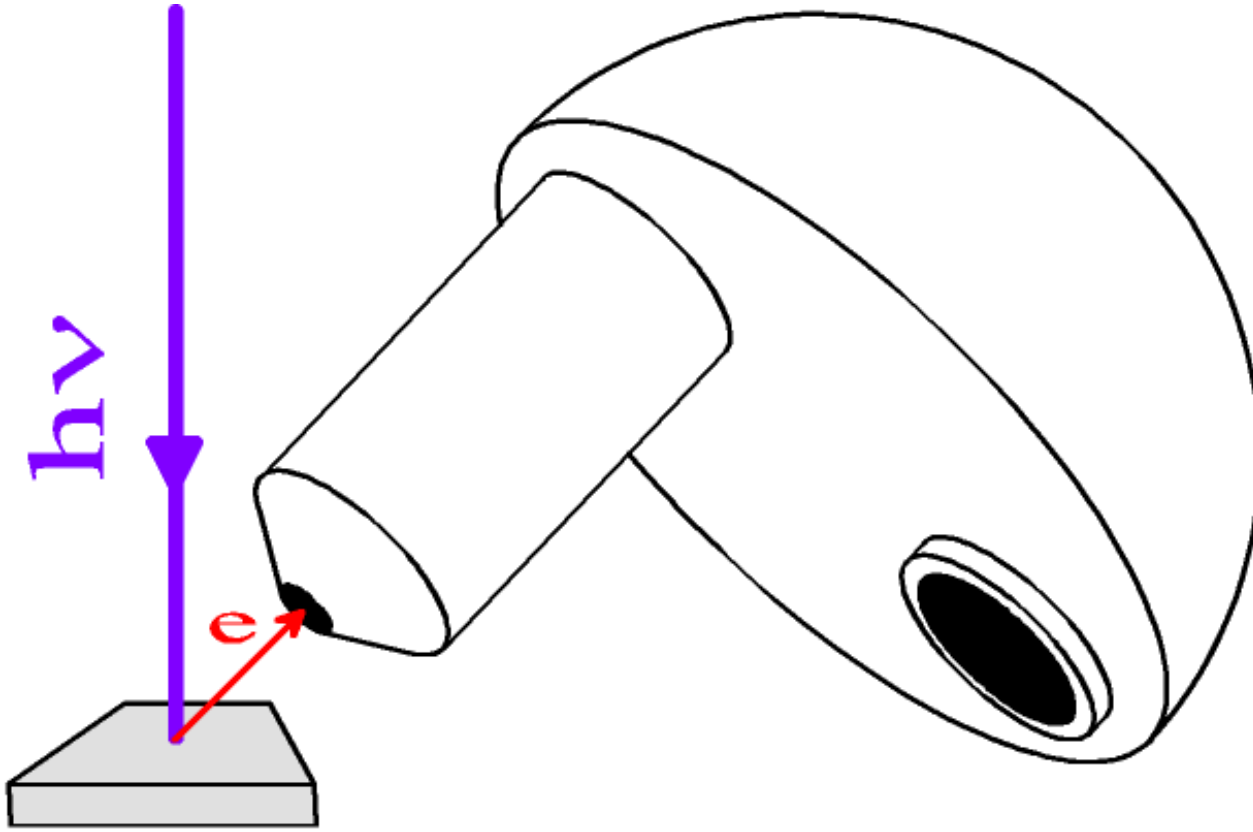
 Bi(Pb)-2212

but **bilayer splitting** – we need **different $h\nu$**

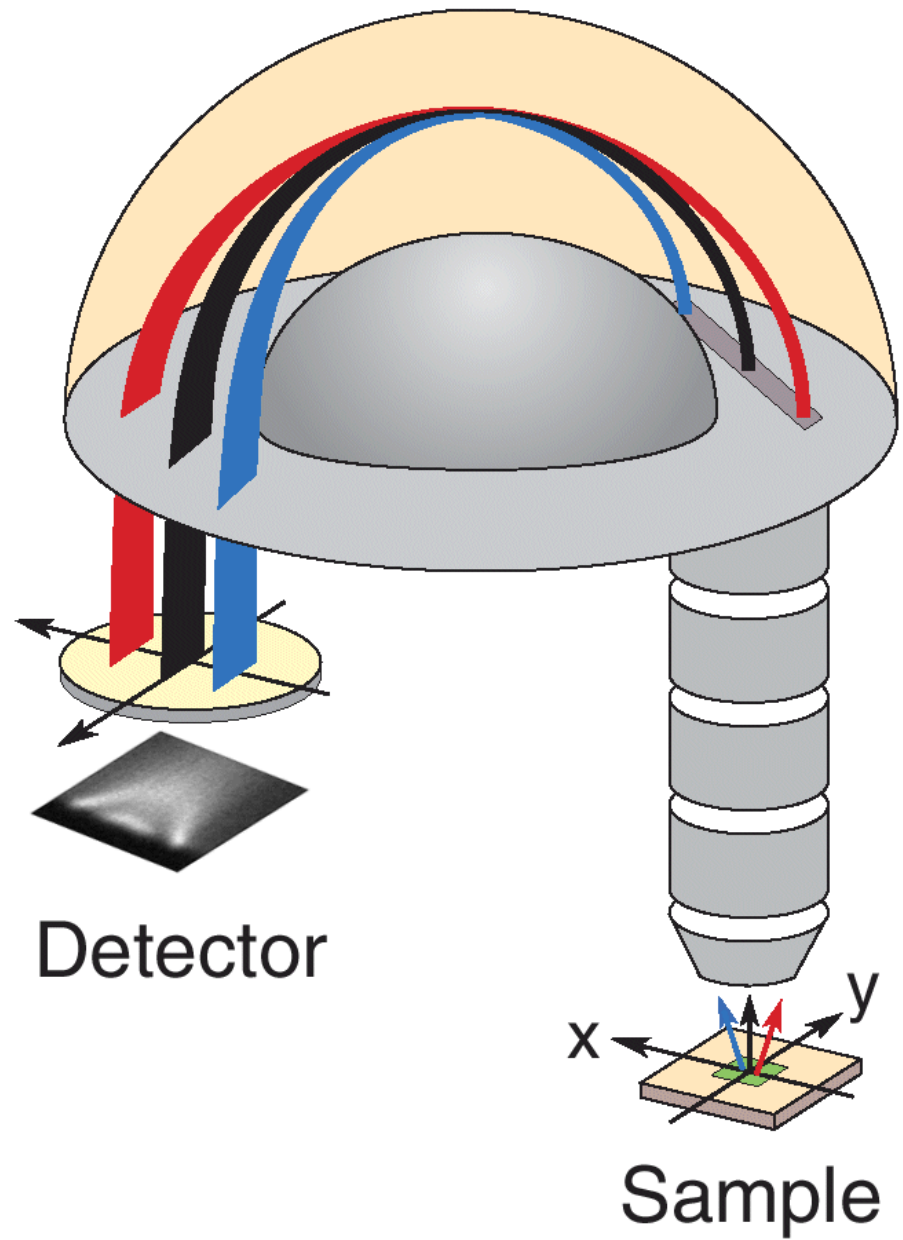
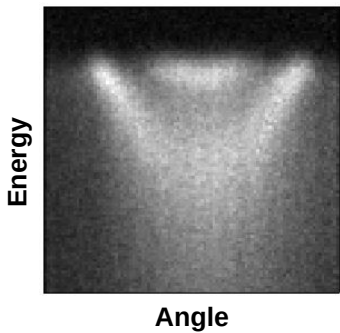
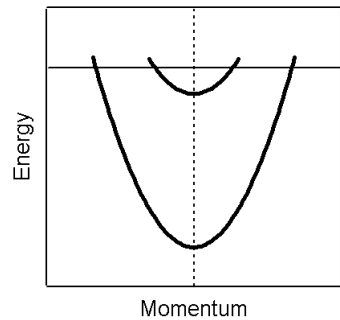
Photoemission Spectrum



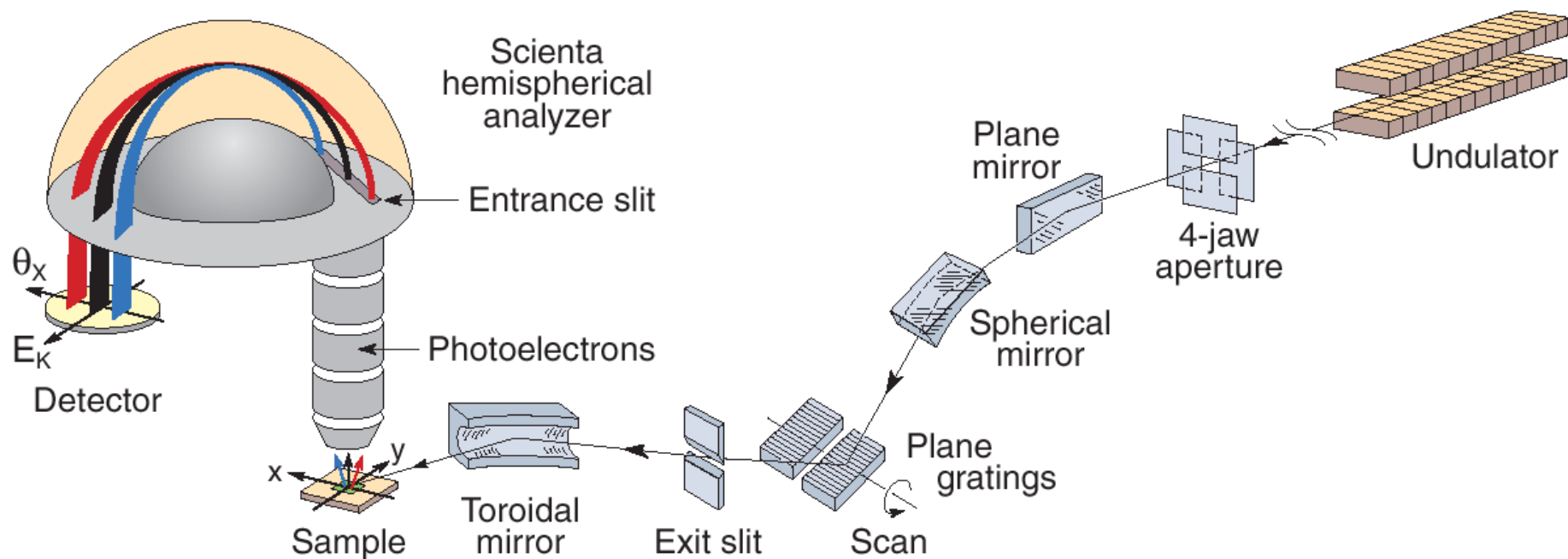
Angle-Resolved Photoemission (ARPES)



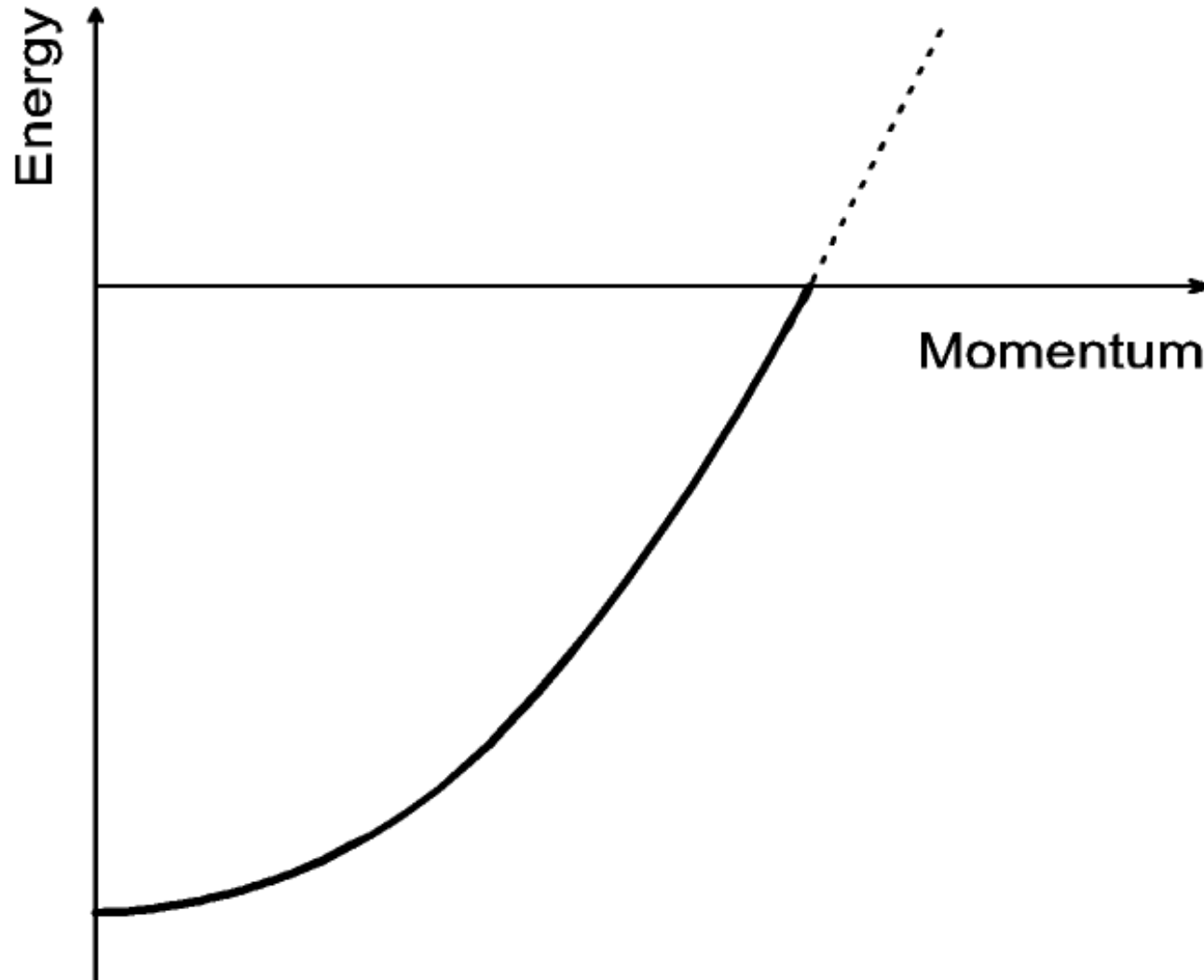
Angle Resolved Analyser



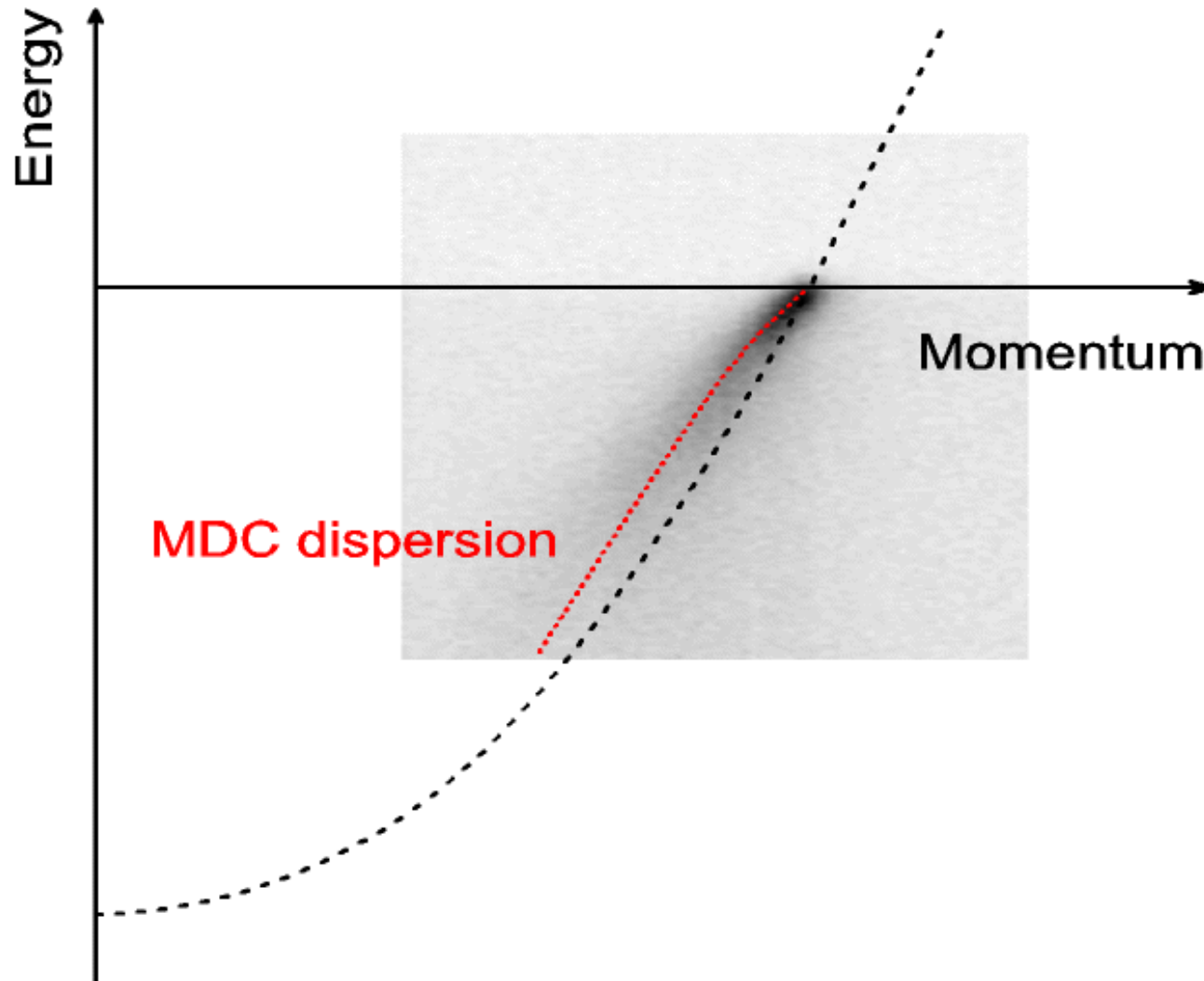
ARPES with Synchrotron Light



Basics: electron dispersion



Basics: electron dispersion



Photocurrent

geometrical prefactor

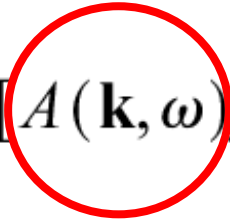
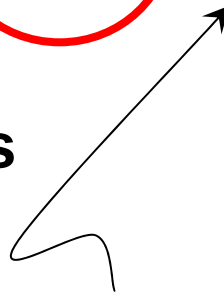
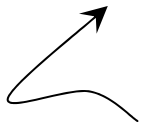
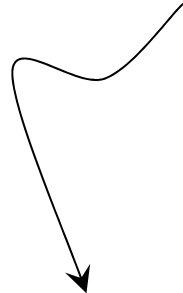
momentum and energy resolution

$$I(\mathbf{k}, \omega) = G_{\mathbf{k}} \{ M(\mathbf{k}) [A(\mathbf{k}, \omega) f(\omega)] \otimes R_{\omega, \mathbf{k}} + B(\omega) \}$$

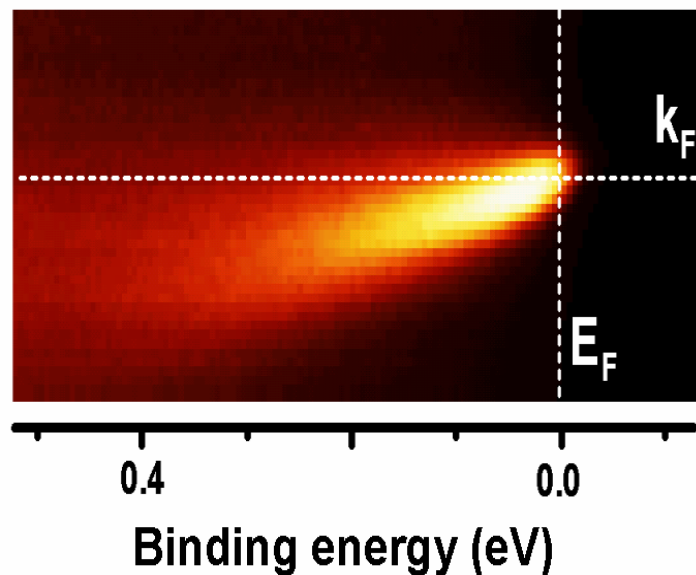
matrix elements

Fermi cutoff

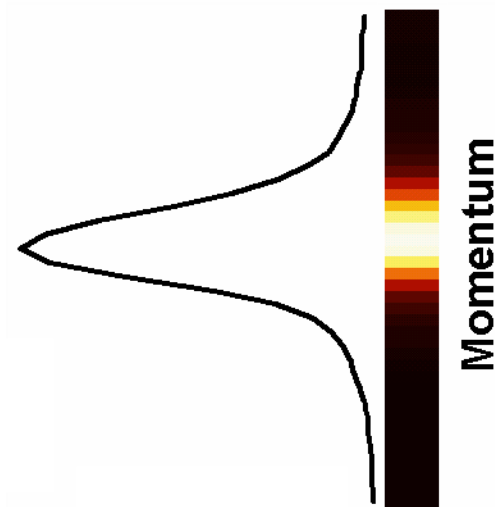
extrinsic background



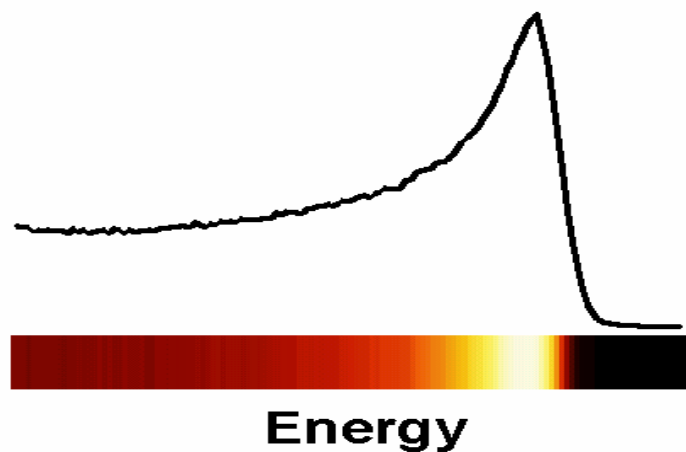
$I(k, \omega)$ - Energy Distribution Map



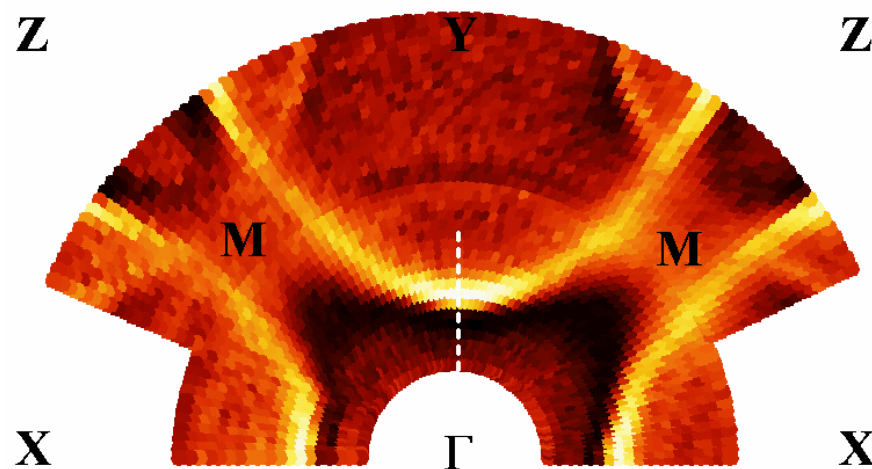
$I(k, \omega)$ - Momentum Distribution Curve



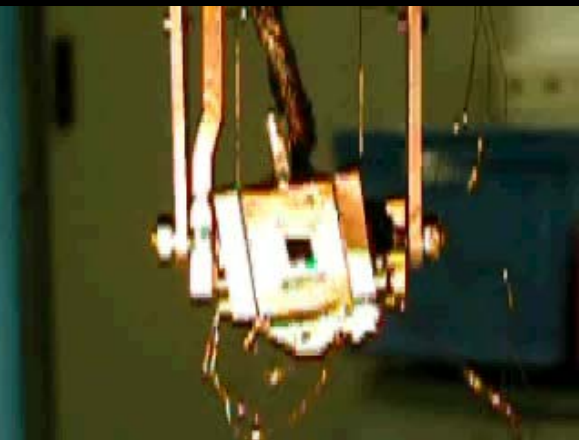
$I(k, \omega)$ - Energy Distribution Curve



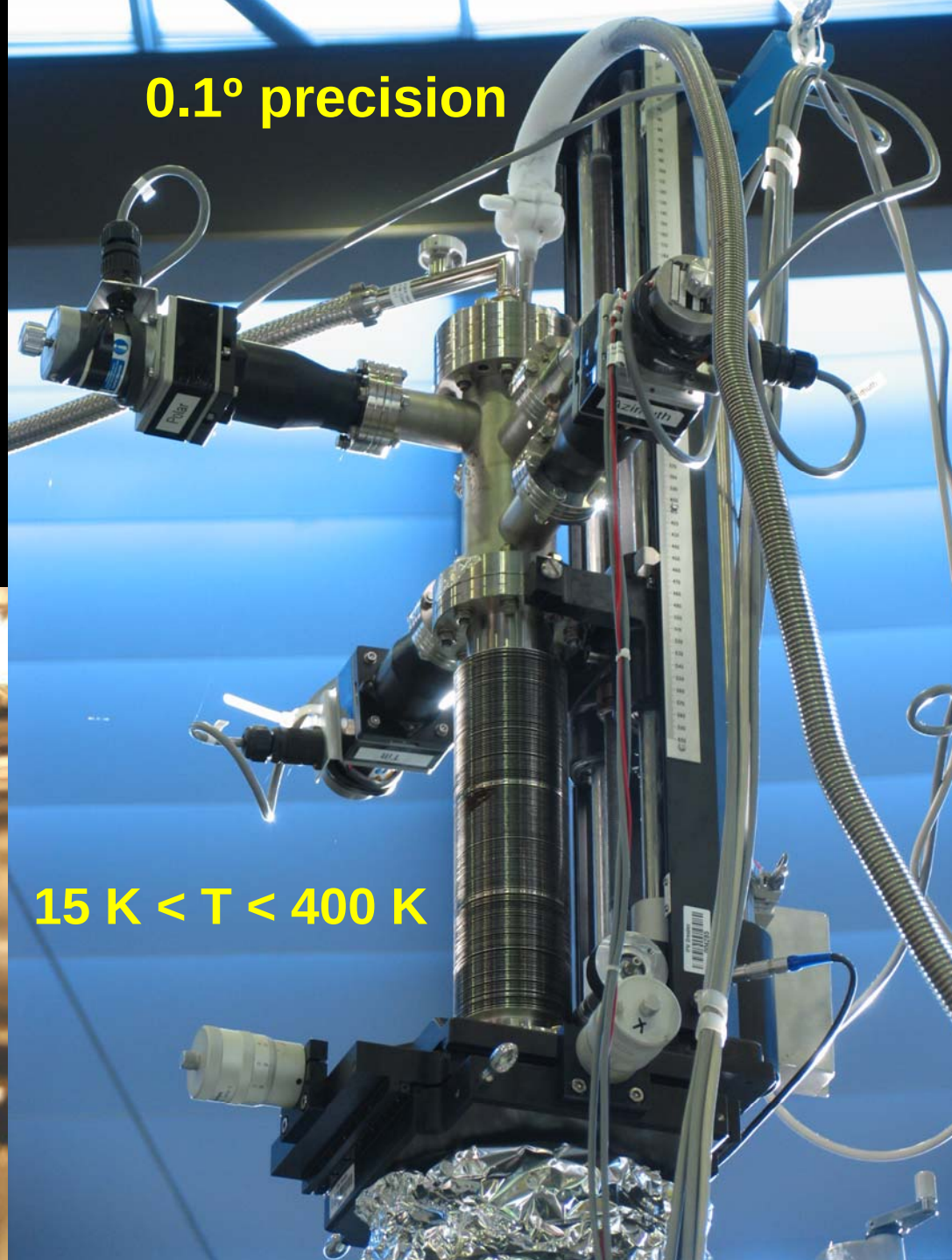
$I(k_x, k_y, \omega)$ - Momentum Distribution Map



Precise Cryo-Manipulator



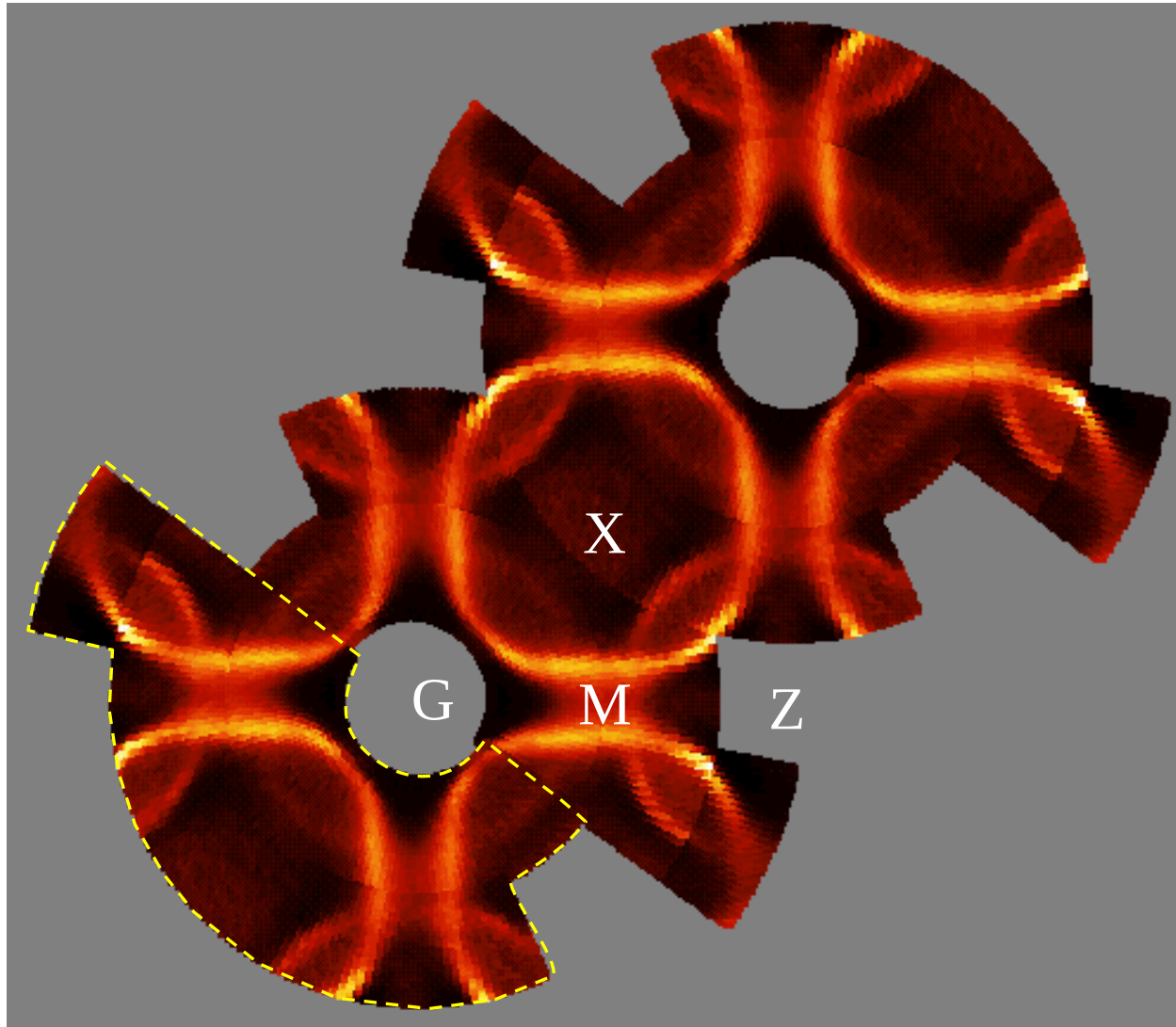
UHV

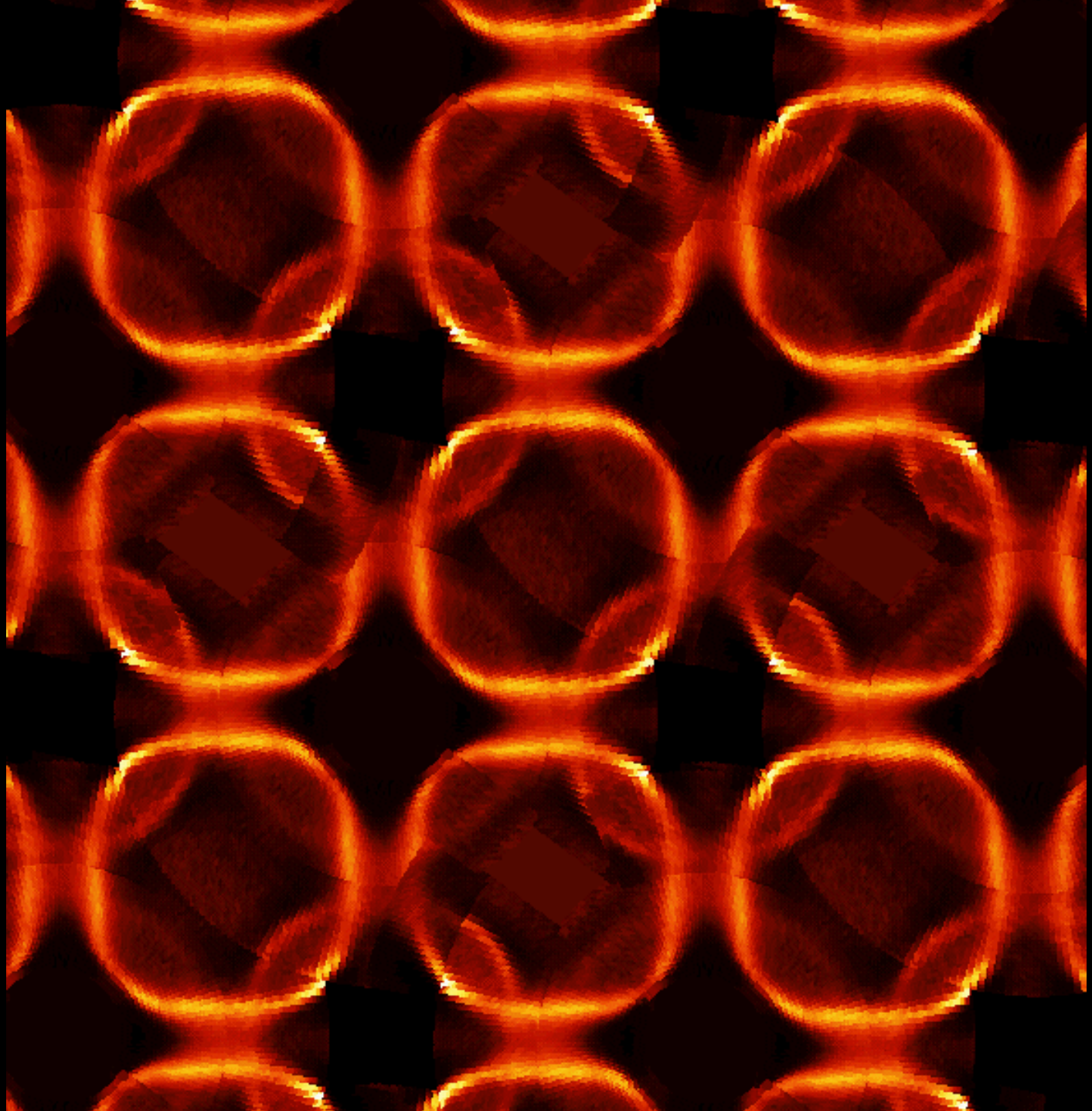


0.1° precision

$15\text{ K} < T < 400\text{ K}$

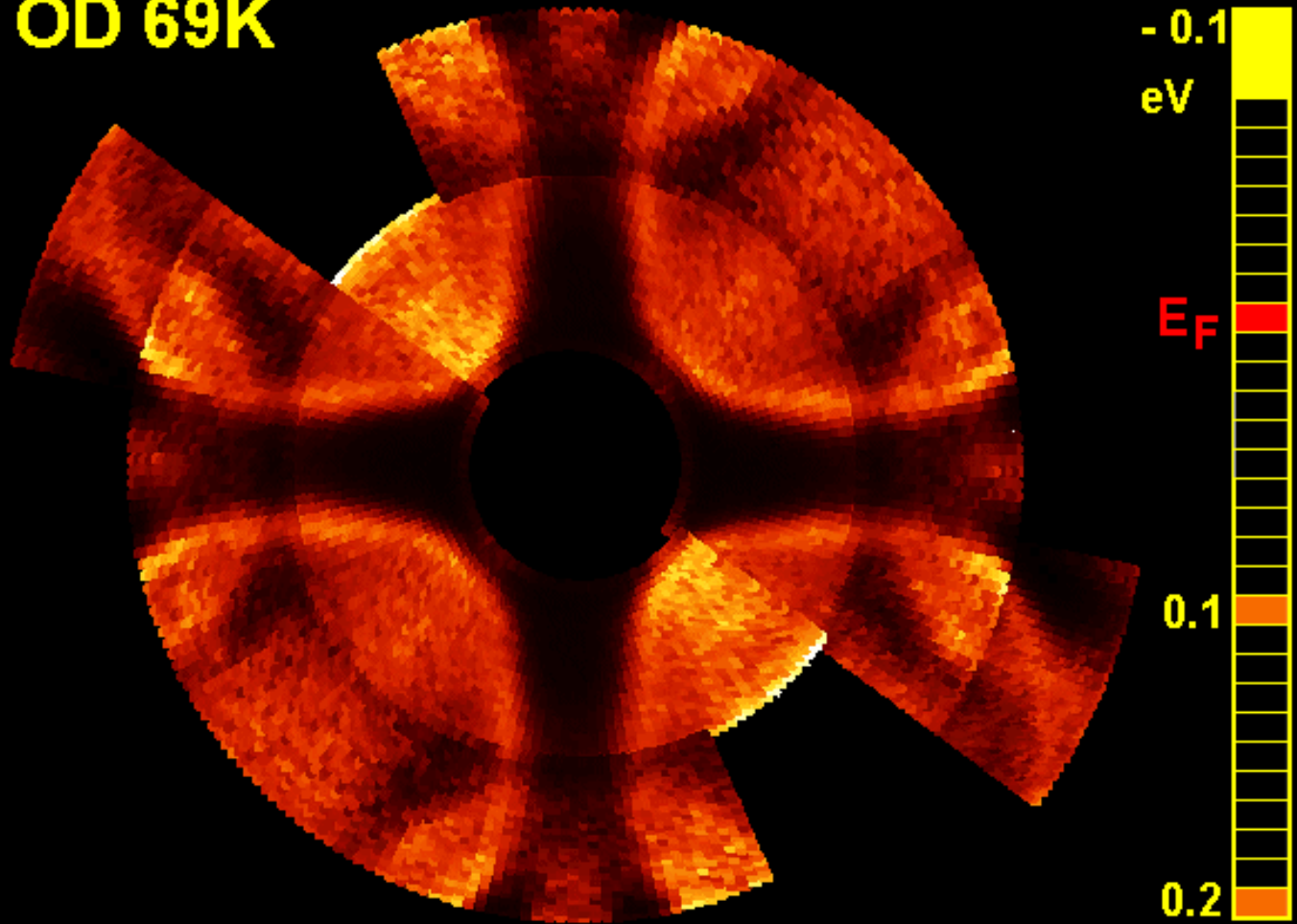
Fermi-surface map





Momentum Distribution Map

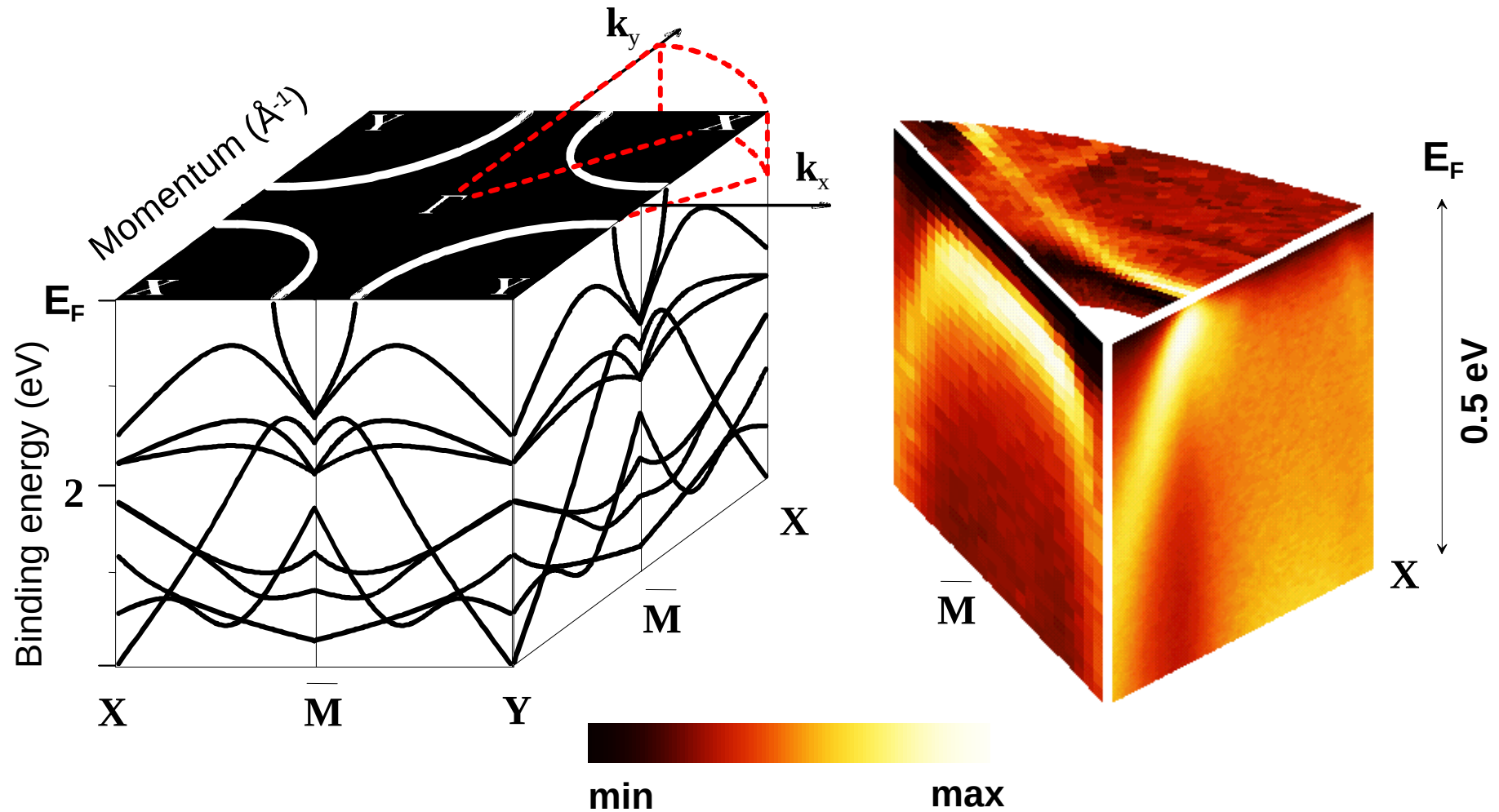
OD 69K



300 K, 21.2 eV

Kordyuk 2000

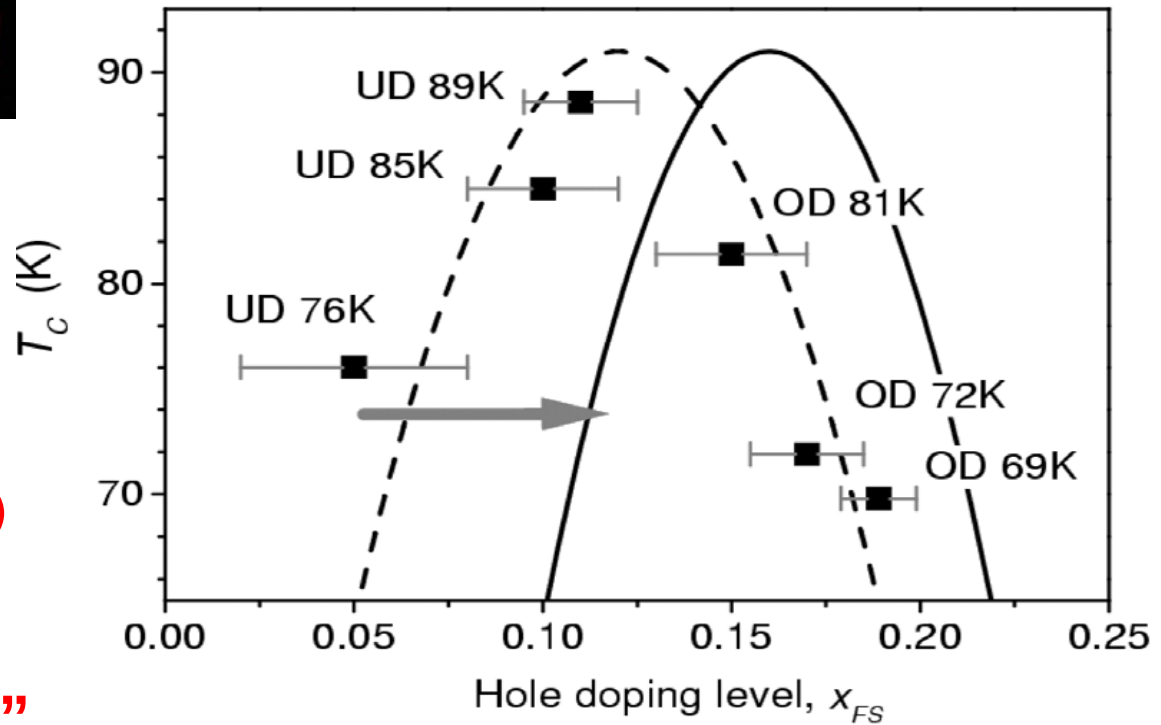
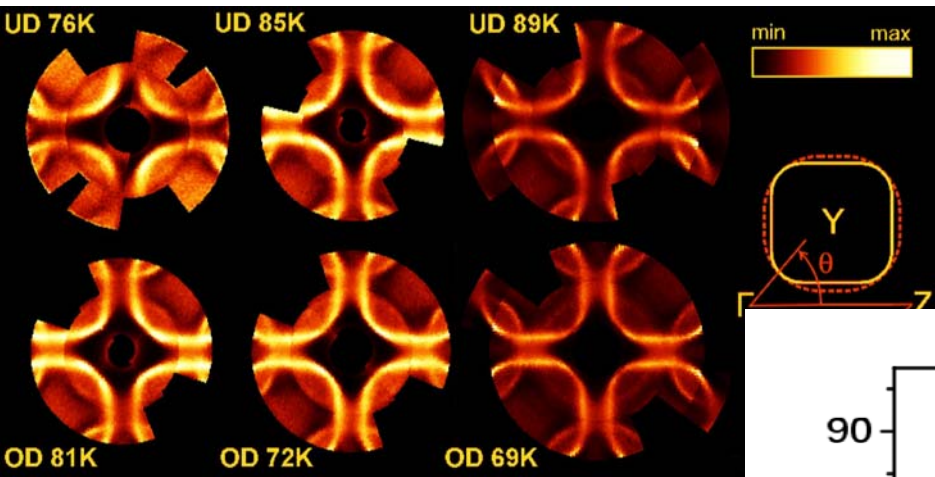
Momentum-energy space



Bare band structure

What is underneath?

Fermi surface evolution with doping

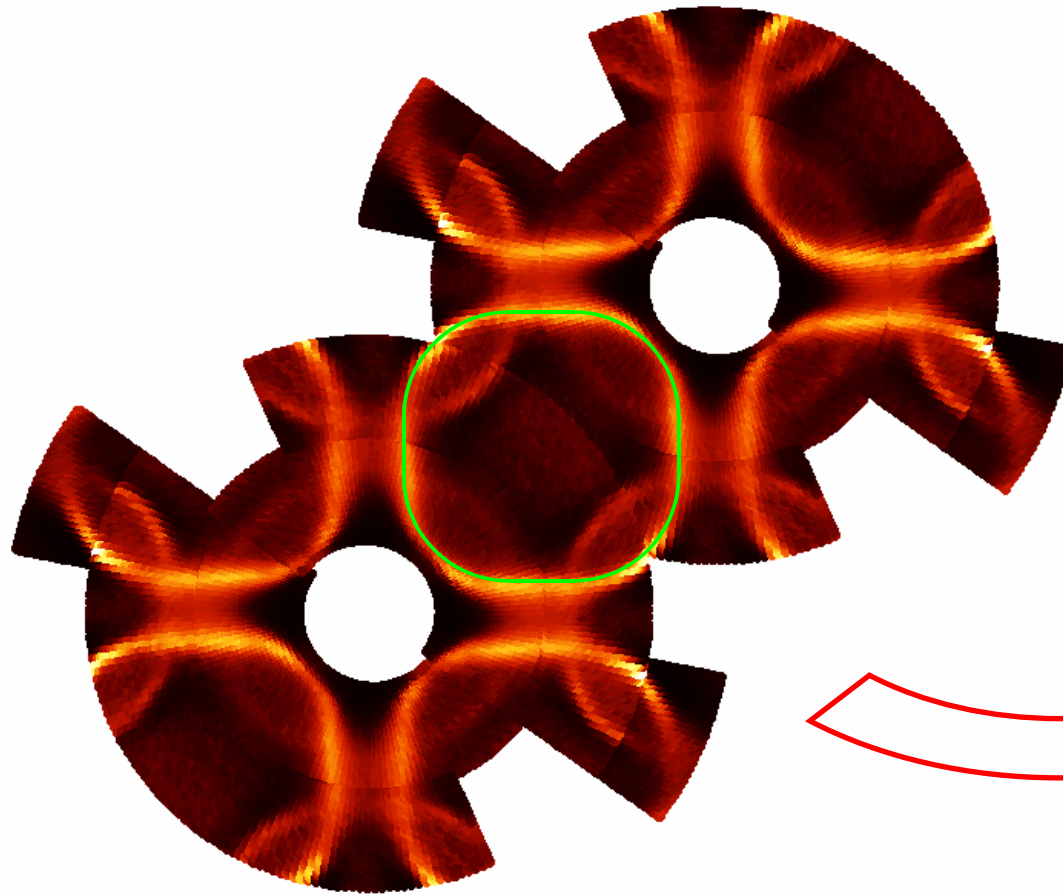


$$S_{FS} = (1 - x)/2$$

“Large Fermi surface”

Band structure: TBF

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

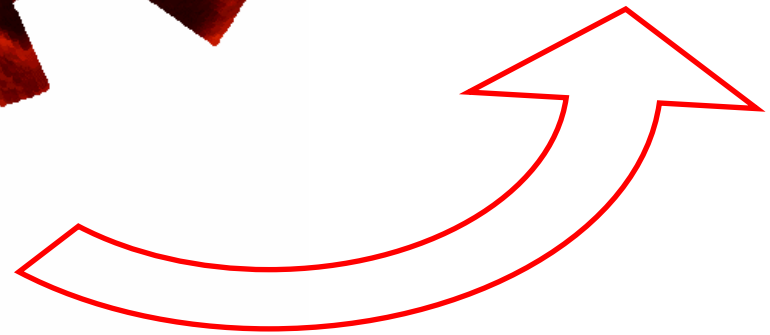


$$\Delta\varepsilon \approx 0.4 \text{ eV}$$

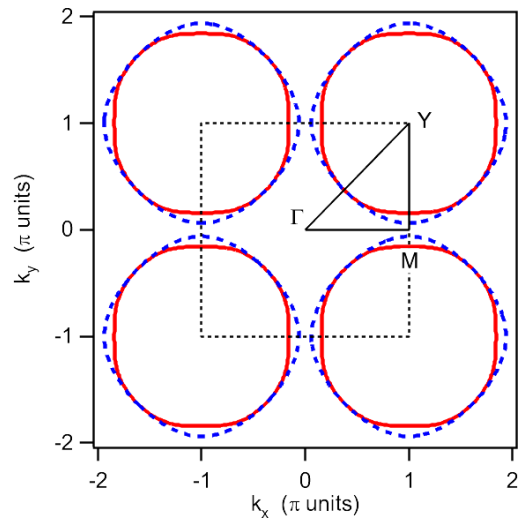
$$t \approx 0.4 \text{ eV}$$

$$t' \approx 0.1 \text{ eV}$$

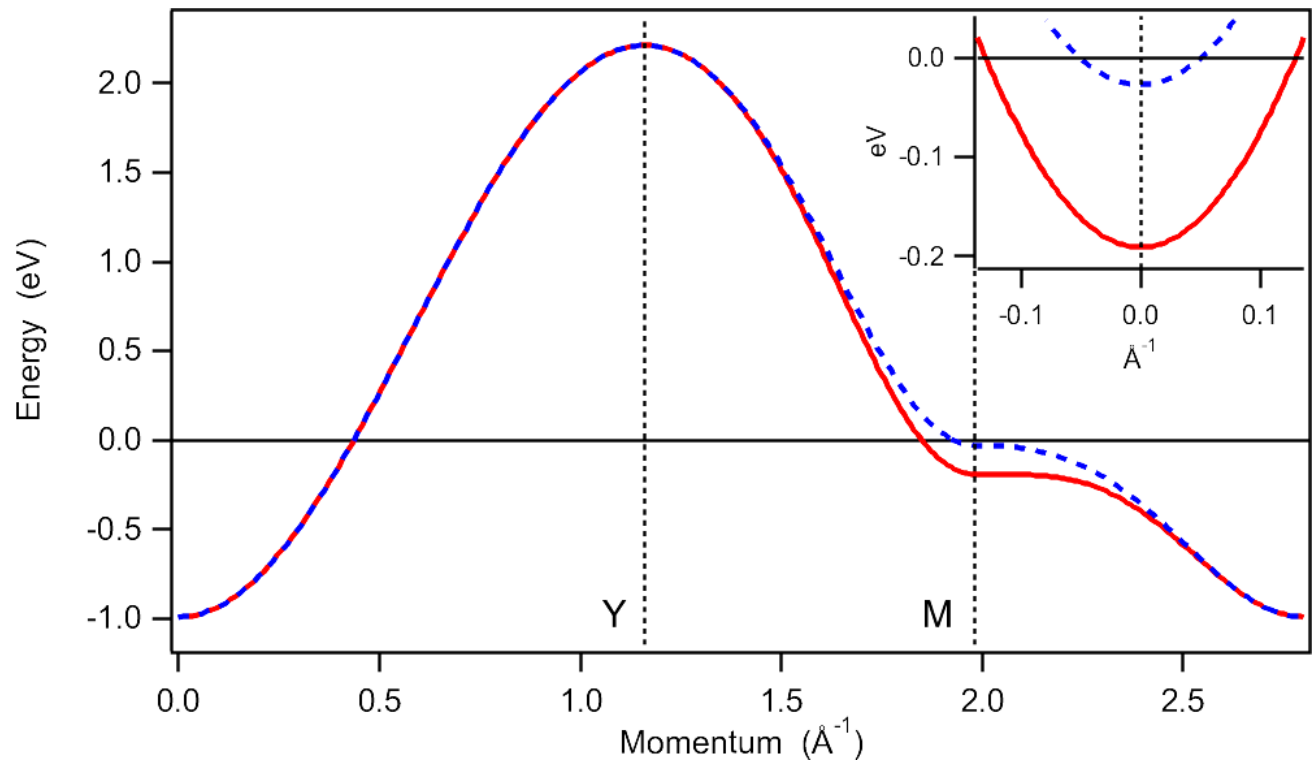
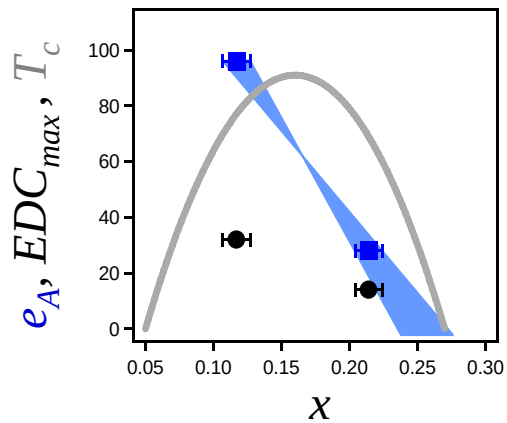
$$t'' \approx 0.05 \text{ eV}$$



Bare band structure



Sample	t (eV)	t' (eV)	t'' (eV)	$t_{\perp}$ (eV)	$\Delta\epsilon$ (eV)
OD 69 K	0.40	0.090	0.045	0.082	0.43
UD 77 K	0.39	0.078	0.039	0.082	0.29



Good agreement with LDA
(no signature of Mott insulator)

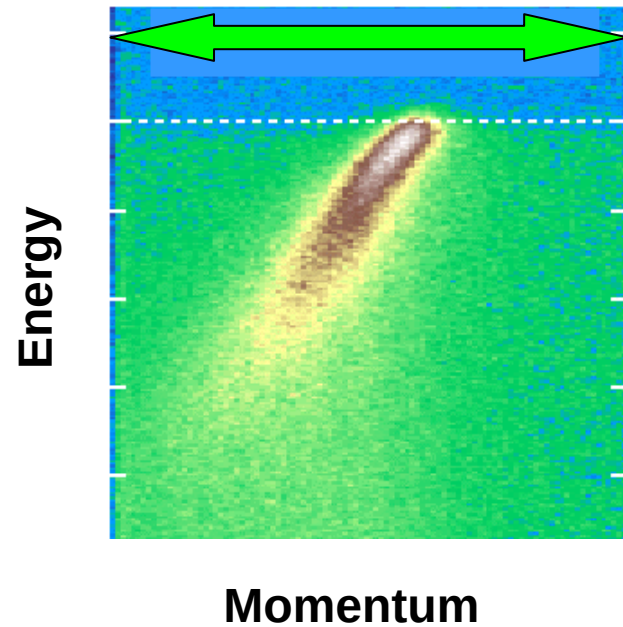
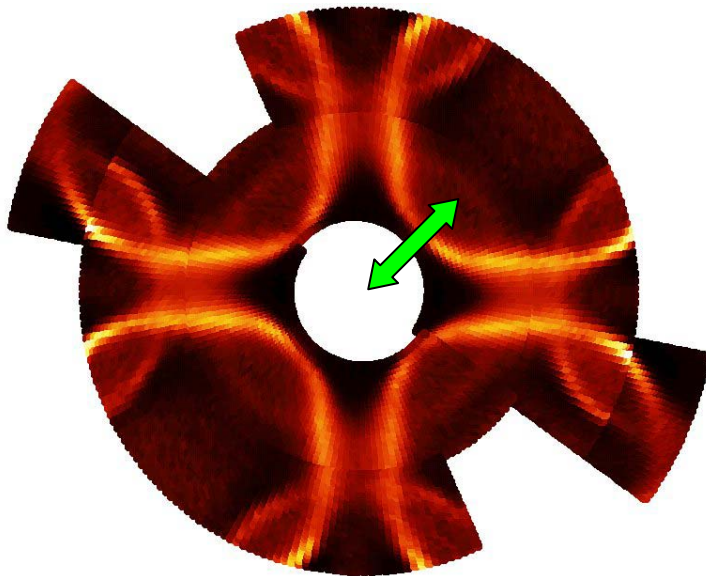
vHs is essential for HTSC

Quasiparticle spectral weight

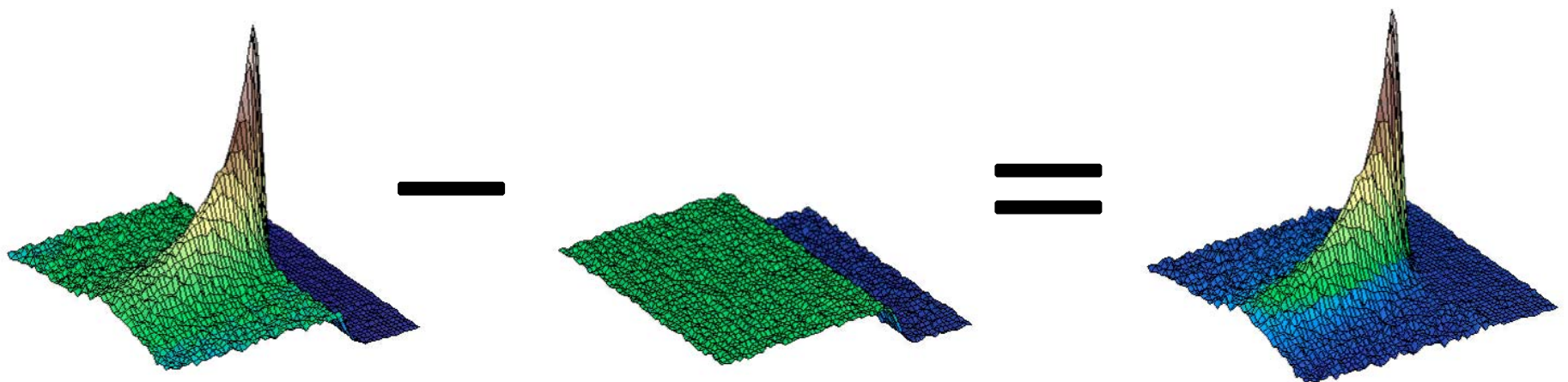
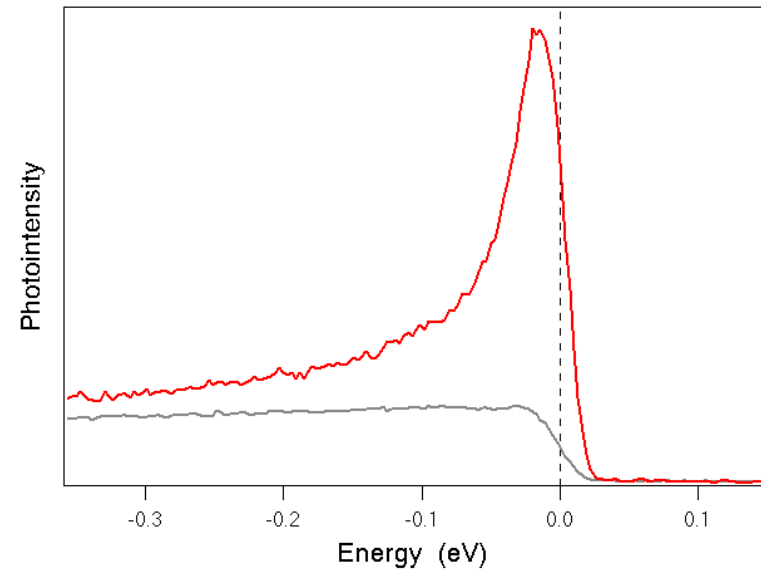
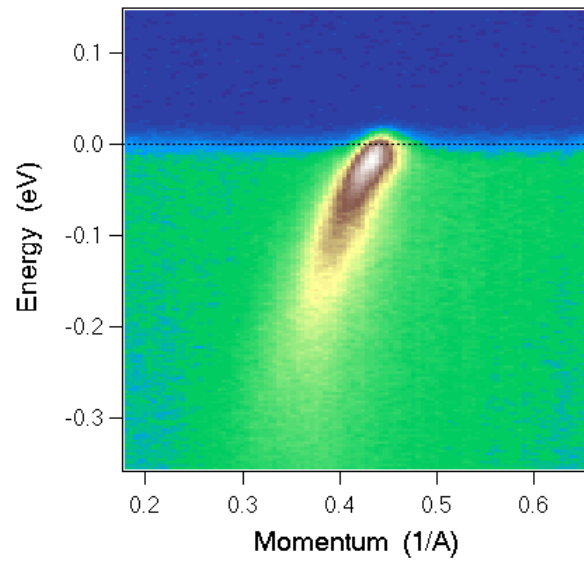
What is relevant in ARPES spectra?

Nodal direction (GX)

No gap, simple bare dispersion.

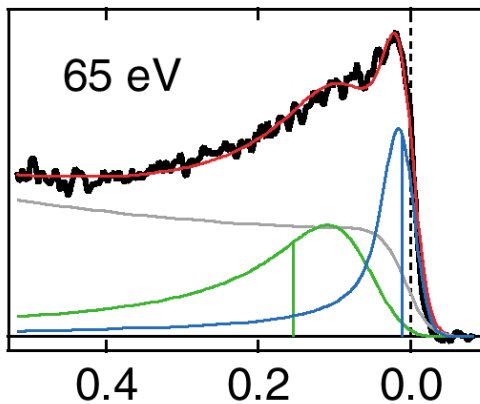
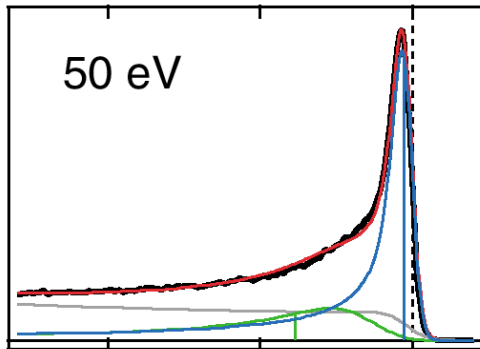


Extrinsic background

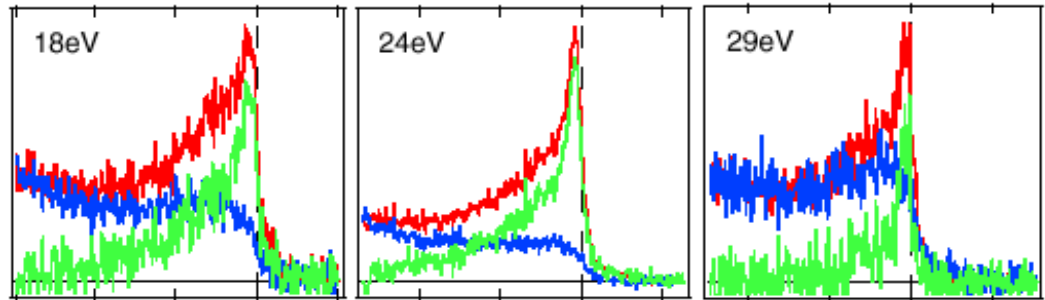


Extrinsic background

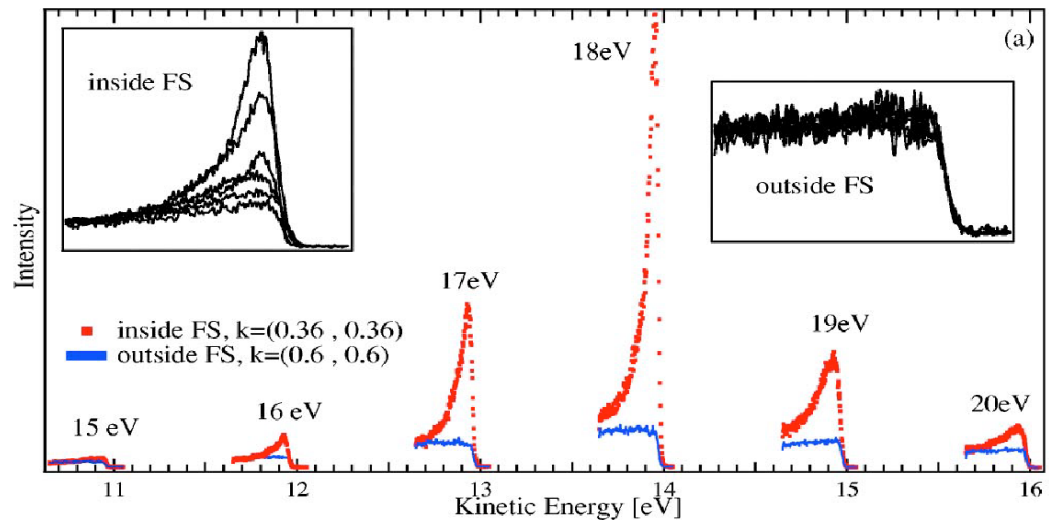
depends on excitation energy



Kordyuk *PRL* 2002

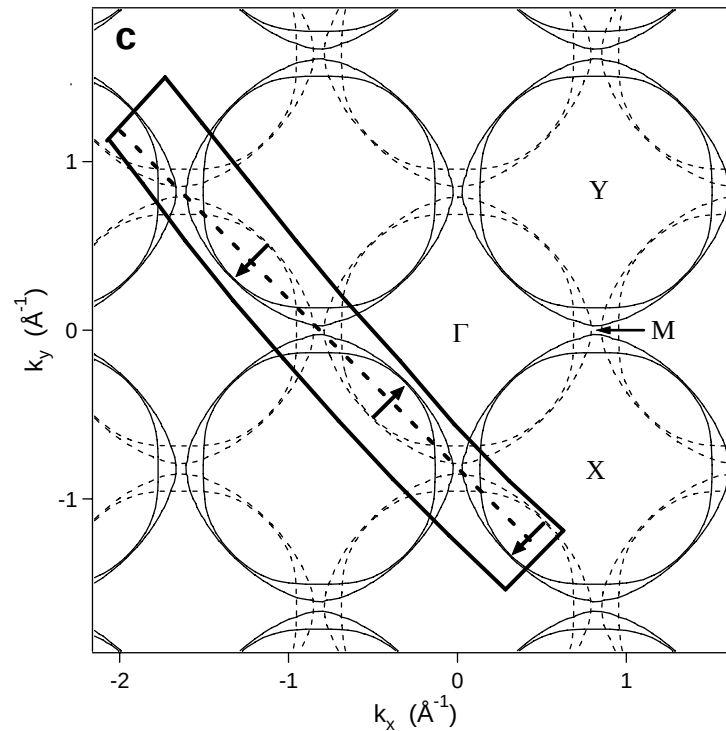
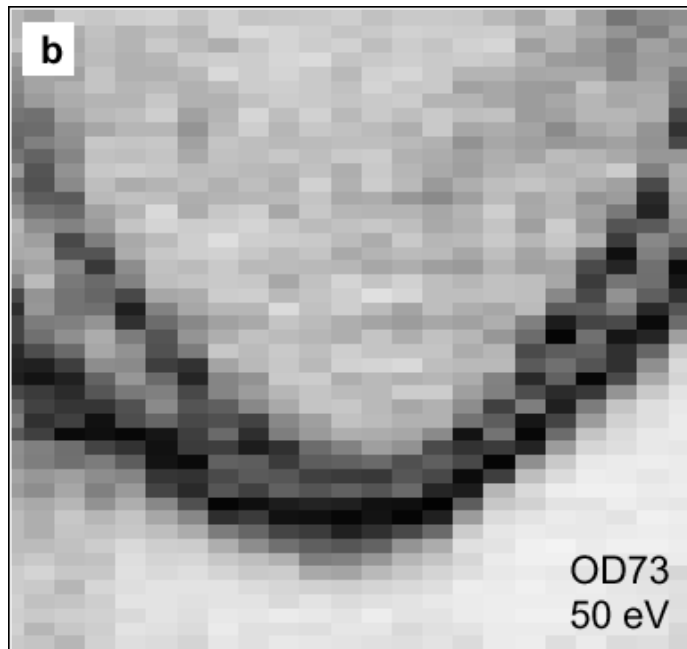
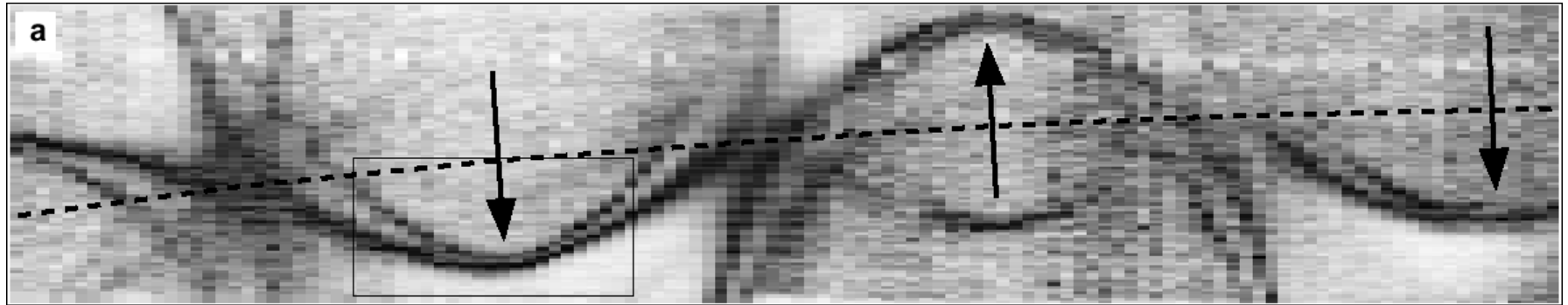


Borisenko *PhyC* 2004

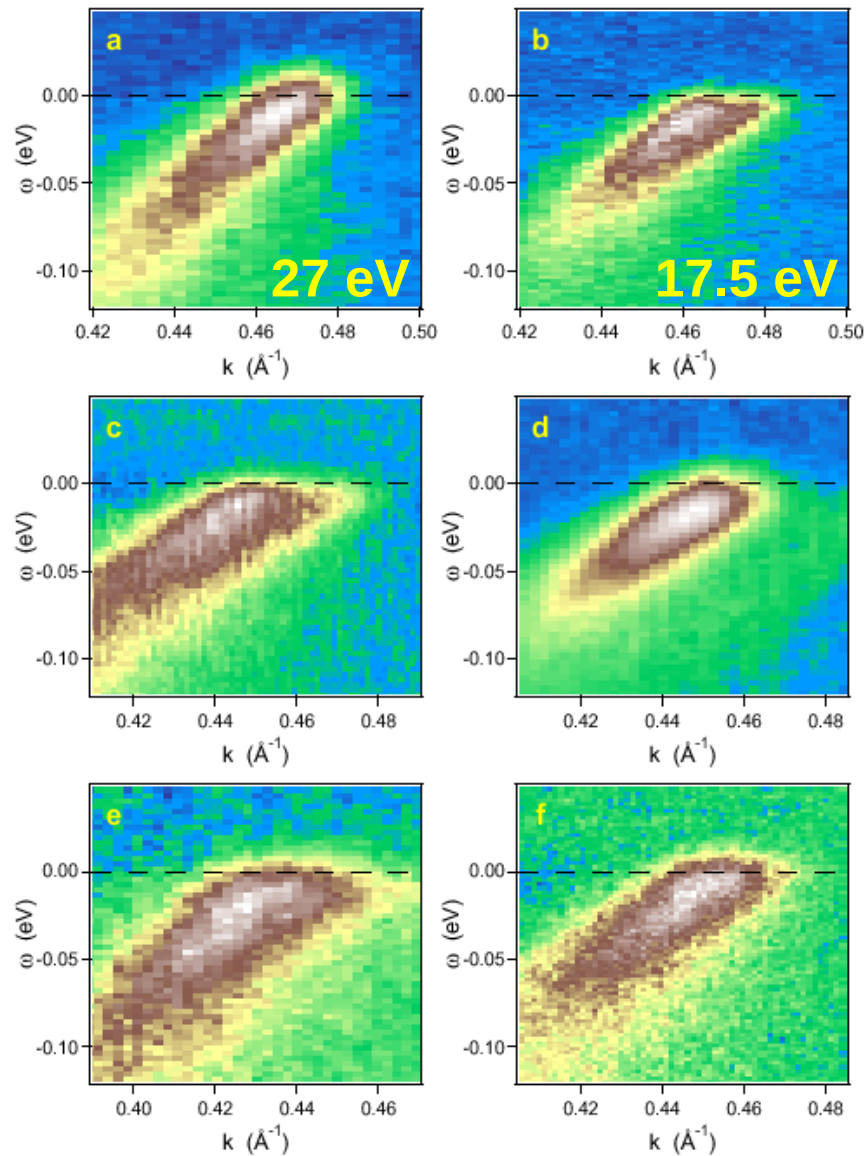


Kaminski *PRB* 2004

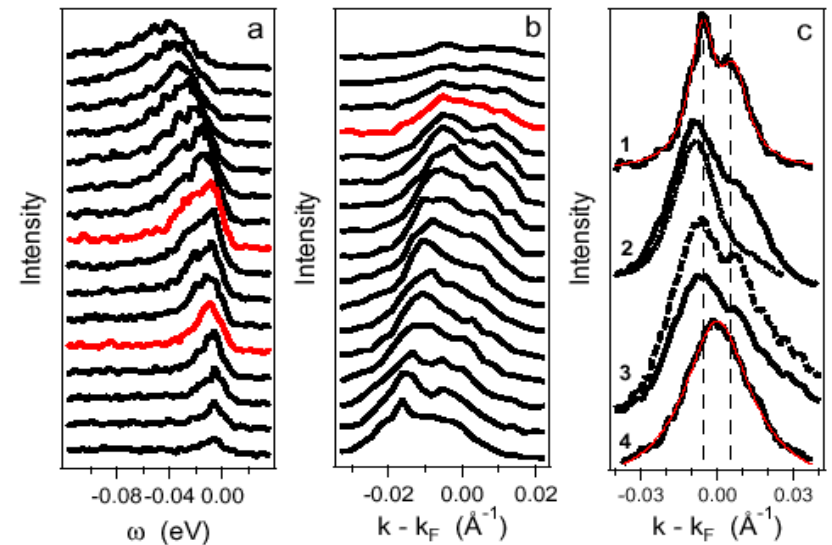
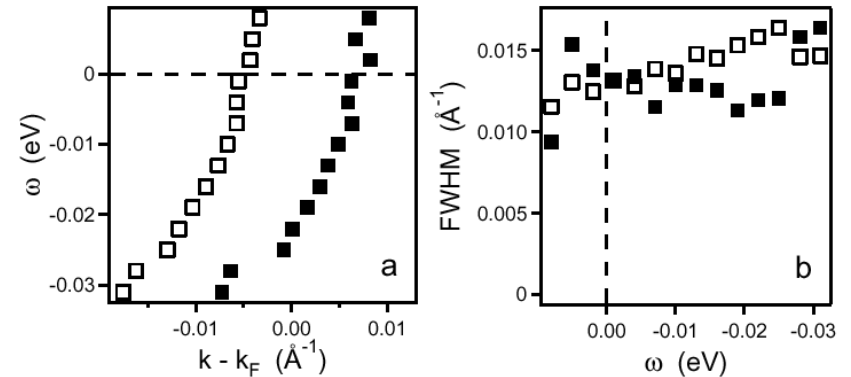
One more complication: **nodal splitting**



Nodal splitting



$\Delta k = 0.012 \text{ 1/\AA}$
 $\Delta \varepsilon = 50 \text{ meV (bare!)}$



IF

one use

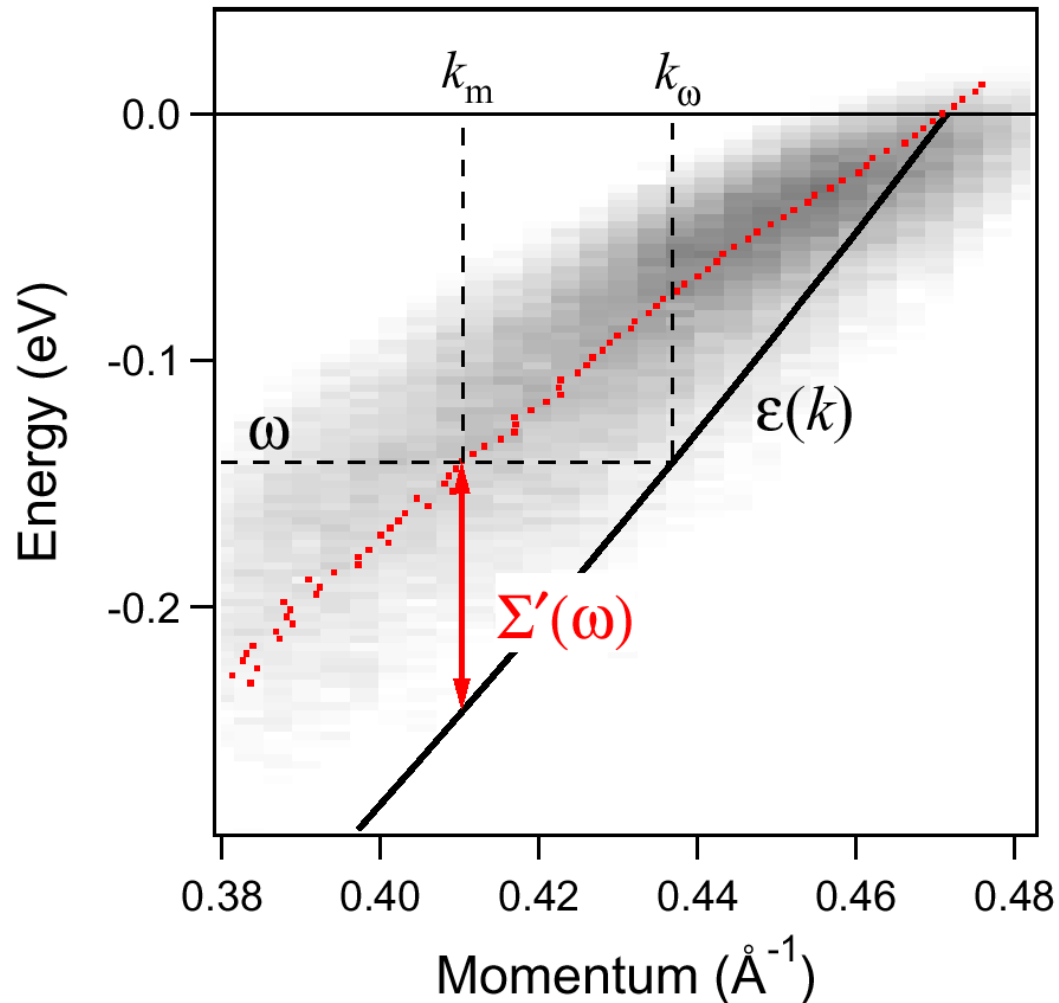
superstructure-free high quality samples
with **negligible k_z dispersion** (Bi(Pb)-2212)

and

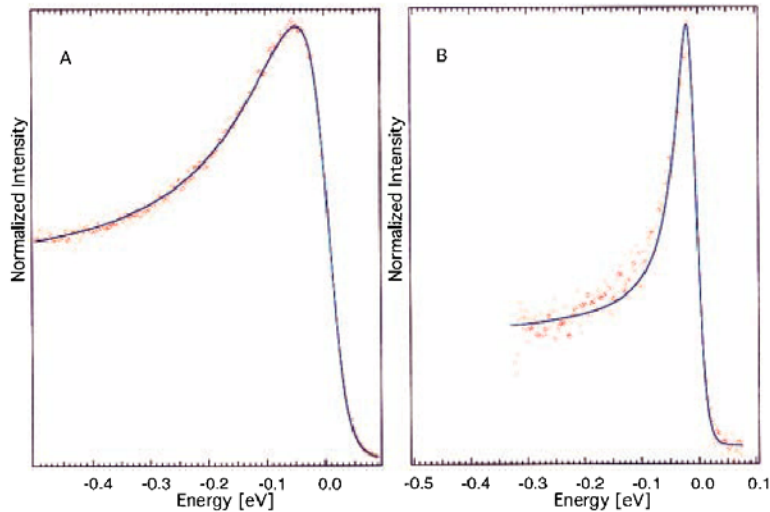
rid of the **background**
and **bilayer splitting effect**,

one may get an access to the
quasiparticle spectral function.

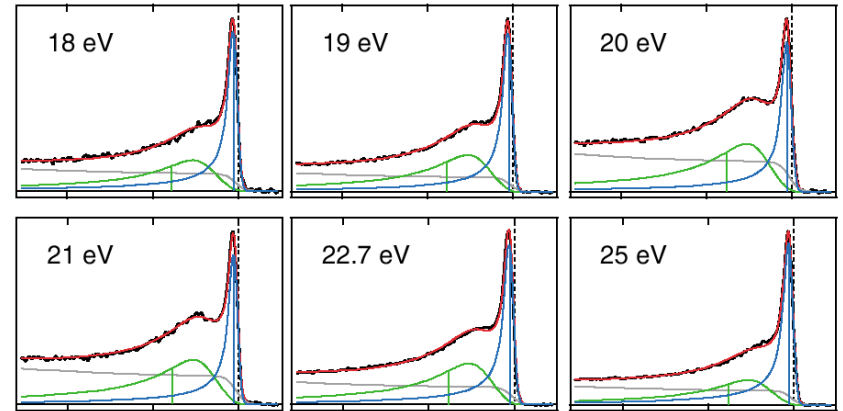
Quasiparticle spectral function



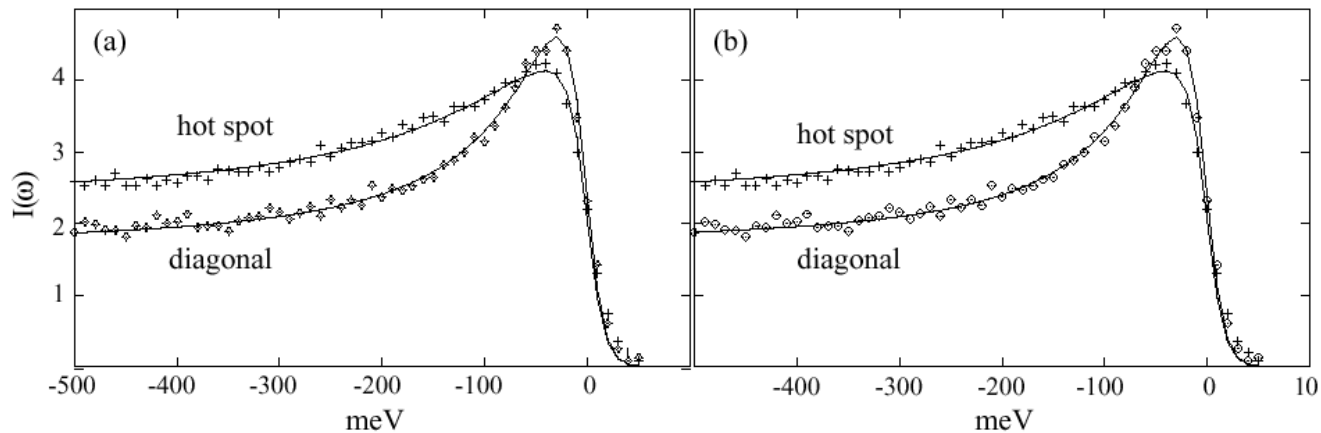
Quasiparticle spectral function



Abrahams *PNAS* 2000



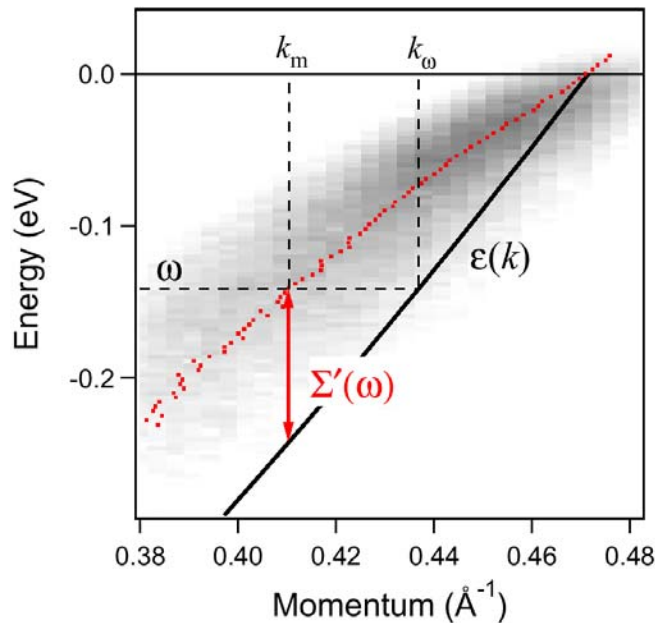
Kordyuk *PRL* 2002



Haslinger *EPL* 2002

Self-energy approach

$$A(\omega, \mathbf{k}) = -\frac{1}{\pi} \frac{\Sigma''(\omega)}{(\omega - \varepsilon(\mathbf{k}) - \Sigma'(\omega))^2 + \Sigma''(\omega)^2}$$



$$\Sigma'(\omega) = \omega - \varepsilon(k_m)$$

$$\Sigma''(\omega) = -v_F W(\omega)$$

Self-energy approach: fitting procedure

$$\Sigma'(\omega) = \frac{v_F}{2}(k_m^2(\omega) - k_F^2) + \omega,$$

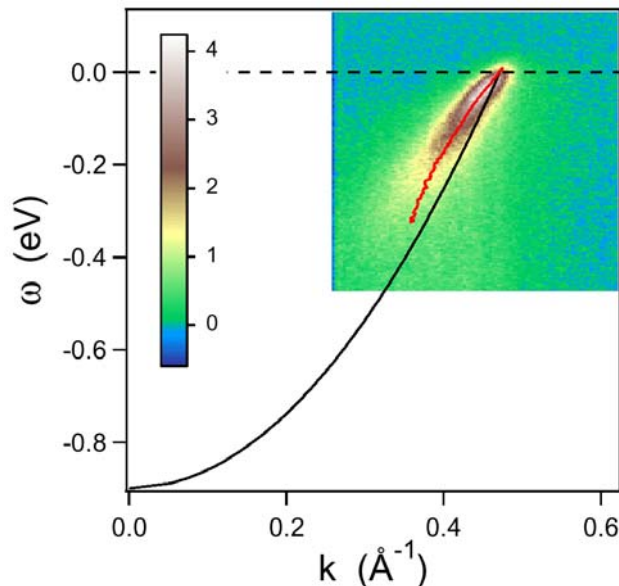
$$\Sigma''(\omega) = -v_F W(\omega) \sqrt{k_m^2(\omega) - W^2(\omega)}.$$

$$\Sigma'(\omega) = \text{KK} \Sigma''(\omega)$$

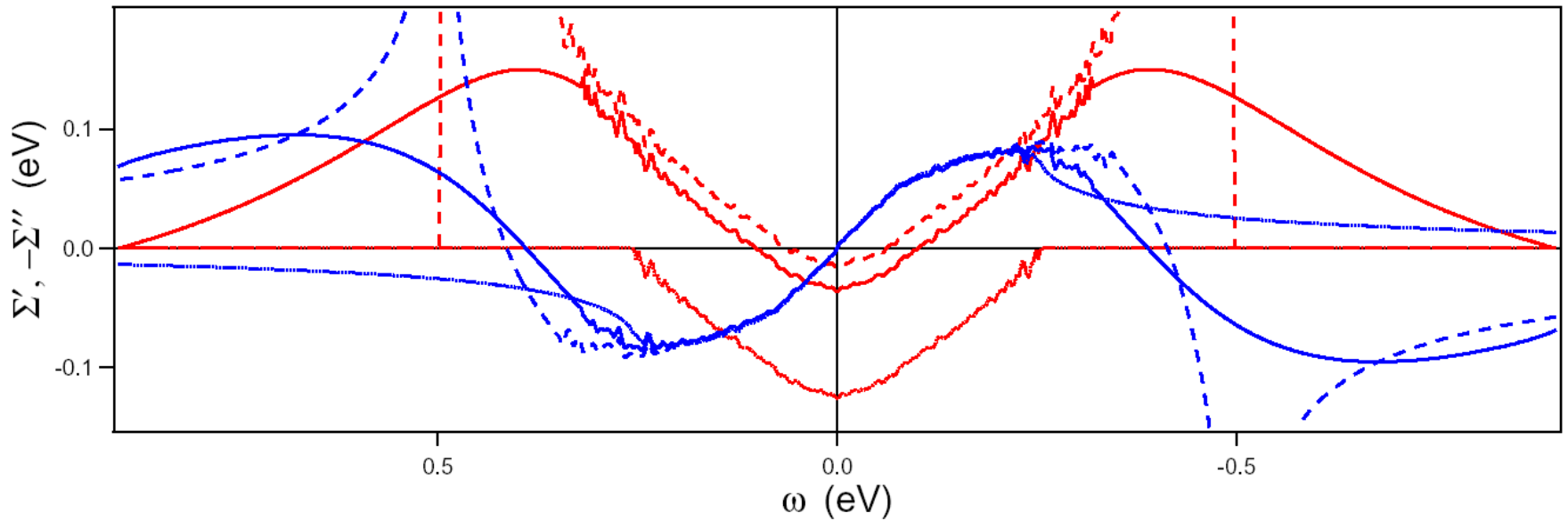
Three parameters

bare band parameter: v_F or ω_0

tail parameters: ω_c and n



Kramers-Kronig transform $\Sigma'(\omega) = \text{KK} \Sigma''(\omega)$



$$\Sigma''(\omega) = - \begin{cases} \alpha \omega^2 + C & \text{for } |\omega| < \omega_c, \\ 0 & \text{for } |\omega| > \omega_c, \end{cases}$$

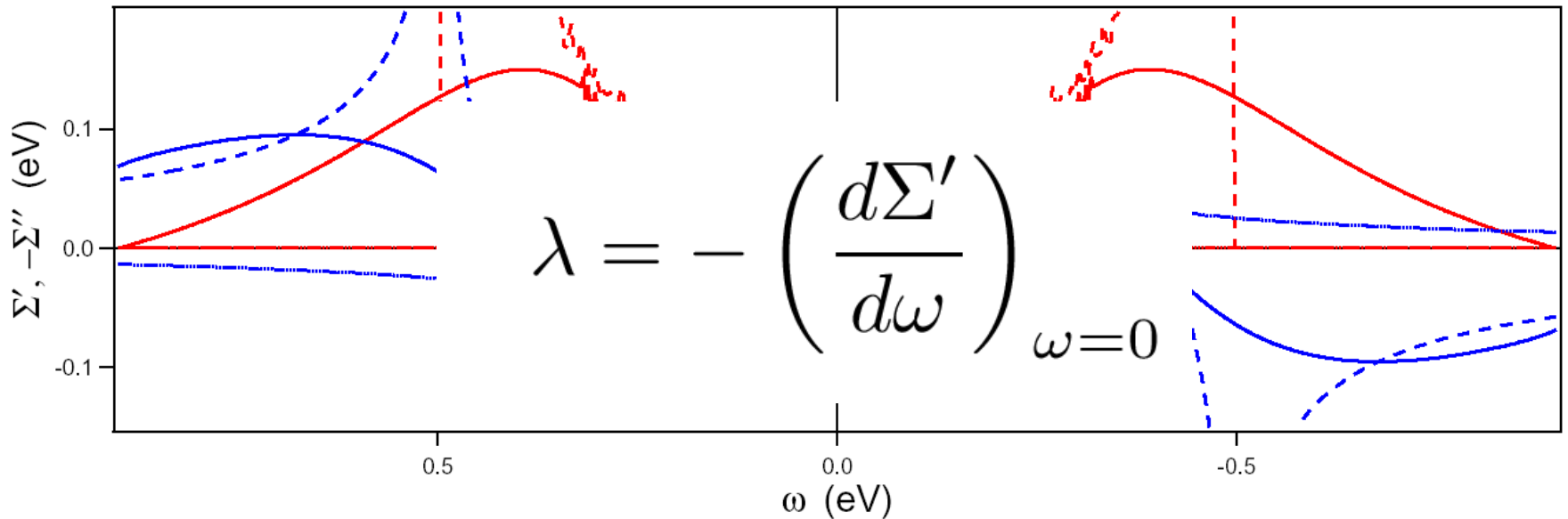
$$\Sigma''(\omega) = - \begin{cases} \alpha \omega^2 + C & \text{for } |\omega| < \omega_c, \\ \alpha \omega_c^2 + C & \text{for } |\omega| > \omega_c, \end{cases}$$

$$\lambda = \frac{2}{\pi} \left(\alpha \omega_c - \frac{C}{\omega_c} \right) \approx \frac{2}{\pi} \alpha \omega_c$$

$$\lambda = 4 \alpha \omega_c / \pi$$

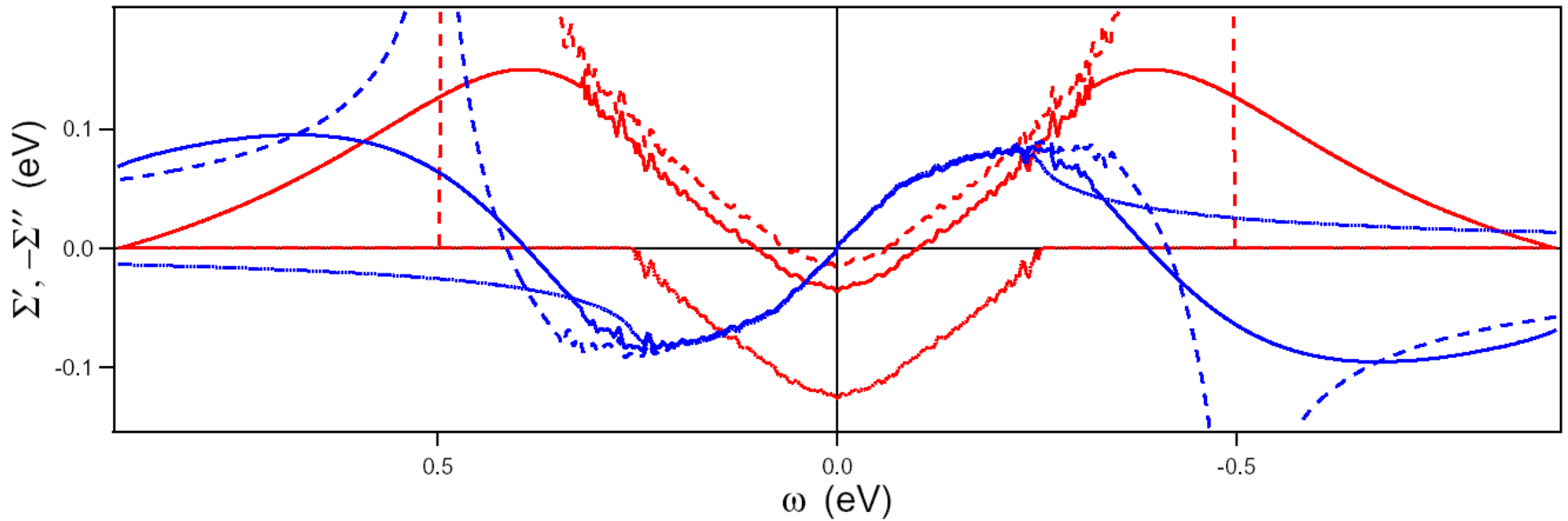
Kramers-Kronig transform

$$\Sigma'(\omega) = \text{KK} \Sigma''(\omega)$$



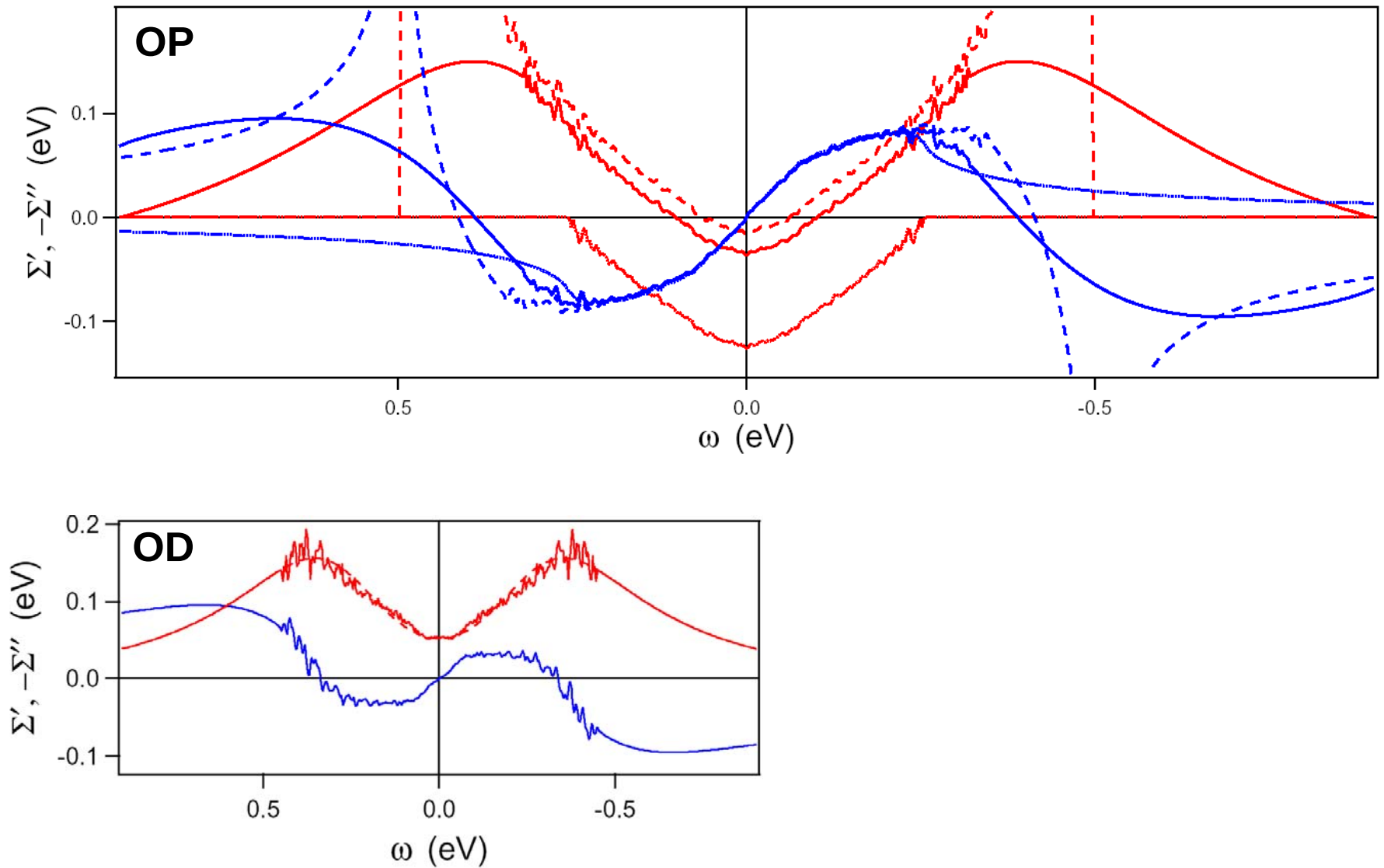
$$\lambda = \frac{-2}{\pi} \int_0^{\infty} \frac{\Sigma''(\omega) - \Sigma''(0)}{\omega^2} d\omega$$

Kramers-Kronig transform $\Sigma'(\omega) = \text{KK} \Sigma''(\omega)$

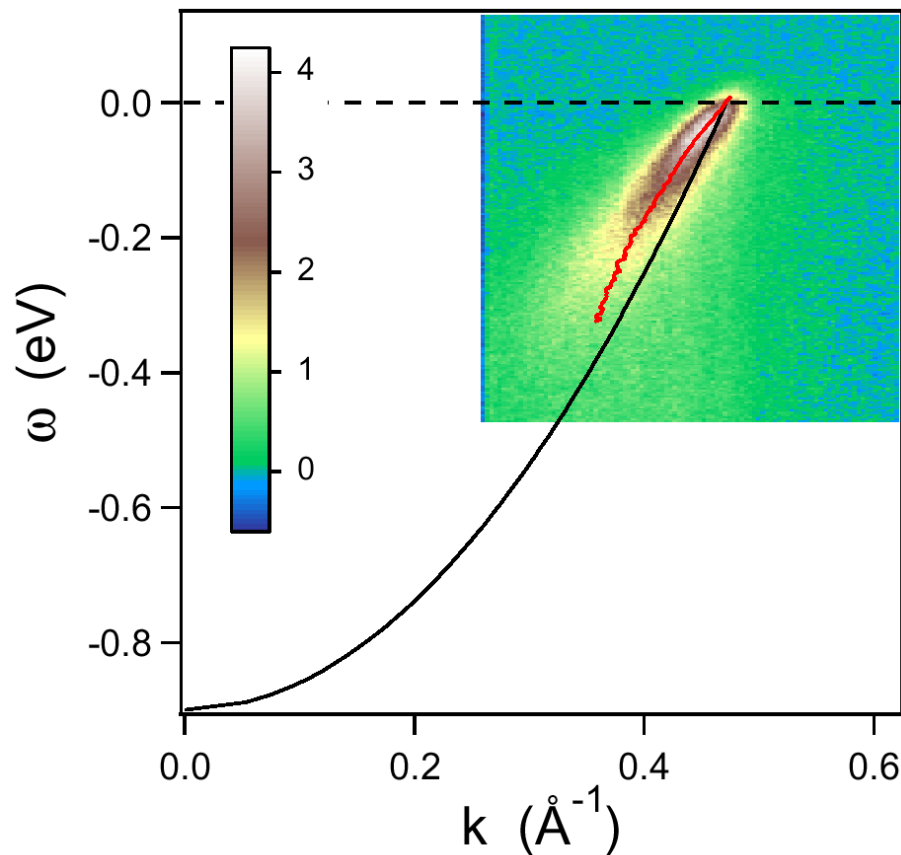
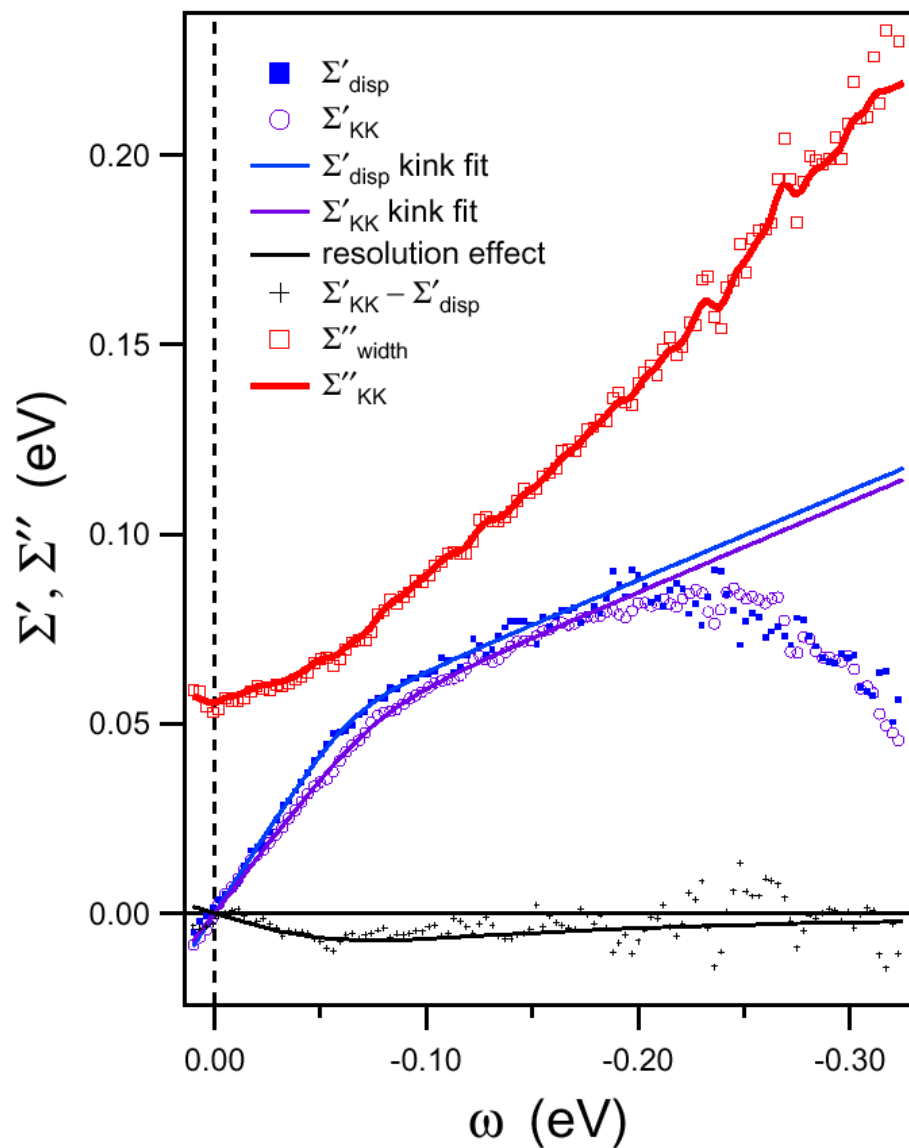


$$\Sigma''(\omega) = \begin{cases} \Sigma''_{width}(|\omega|) & \text{for } |\omega| < \omega_m, \\ \Sigma''_{mod}(\omega) & \text{for } |\omega| > \omega_m, \end{cases} \quad \Sigma''_{mod}(\omega) = -\frac{\alpha \omega^2 + C}{1 + \left| \frac{\omega}{\omega_c} \right|^n},$$

Kramers-Kronig transform $\Sigma'(\omega) = \text{KK} \Sigma''(\omega)$



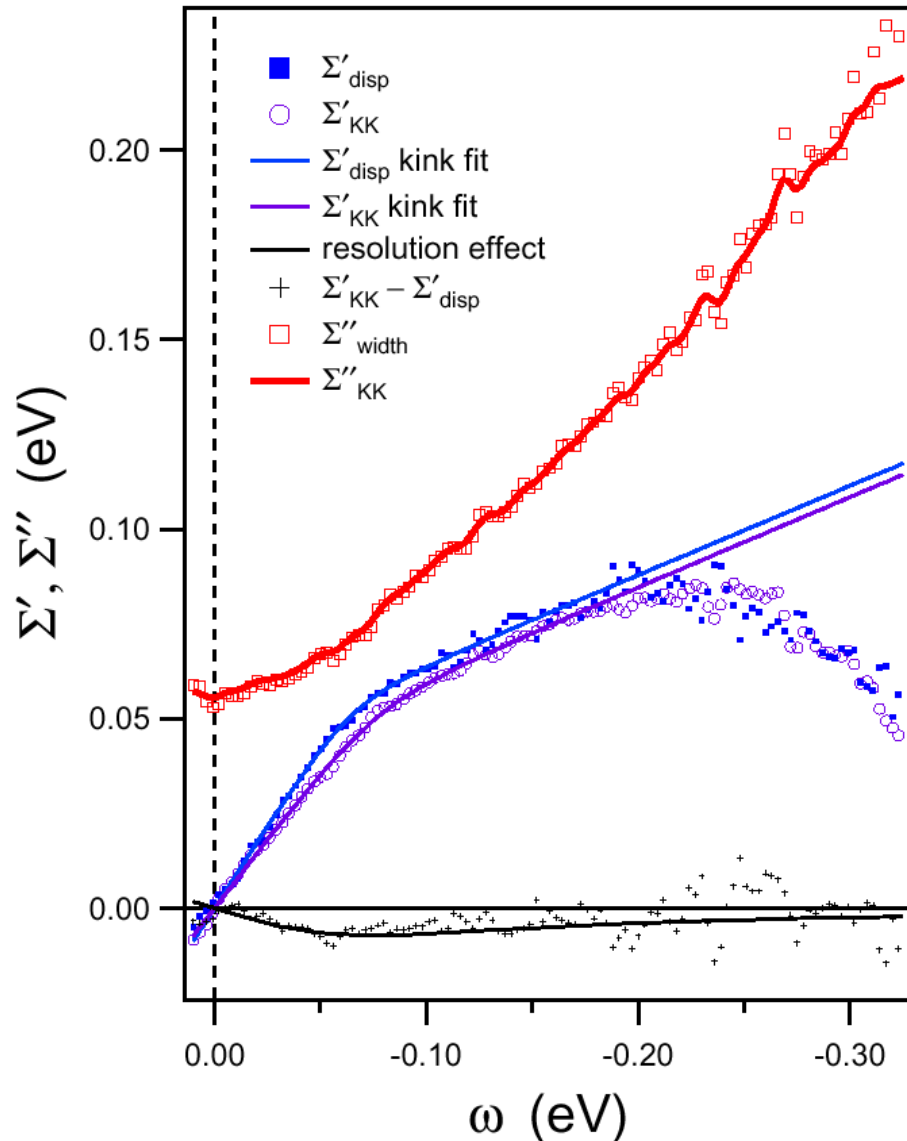
Real Self-Energy



$$v_F = 3.82 \pm 0.17 \text{ eV\AA}$$

$$\lambda = 0.87 \pm 0.12$$

Real Self-Energy

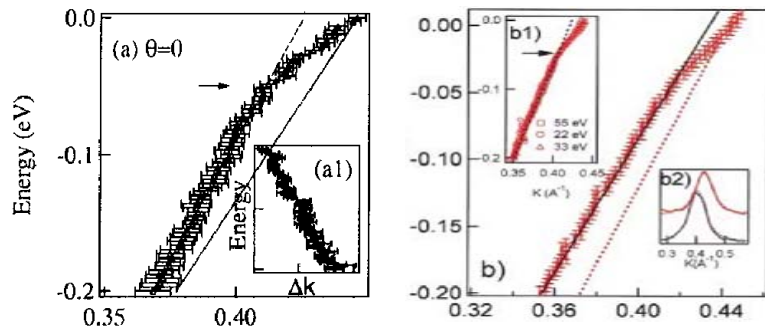


Self-consistency:
LDA + self-energy

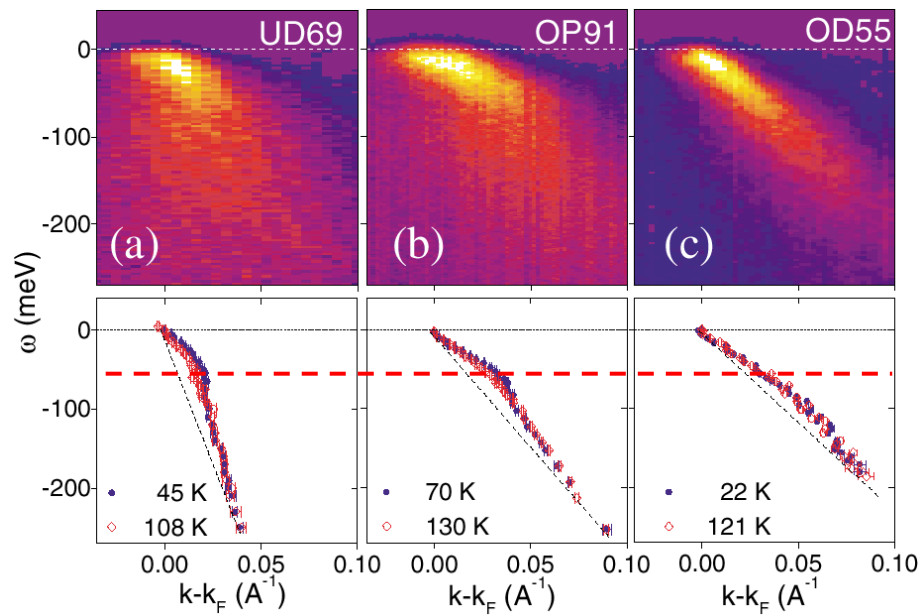
Well defined quasi-
particles

Kink phenomenology

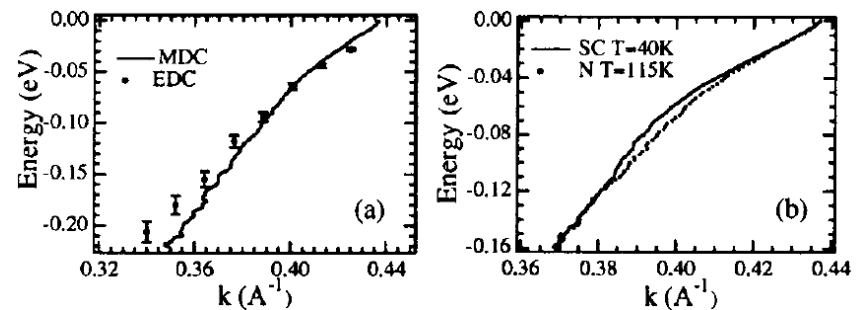
„Kinks“



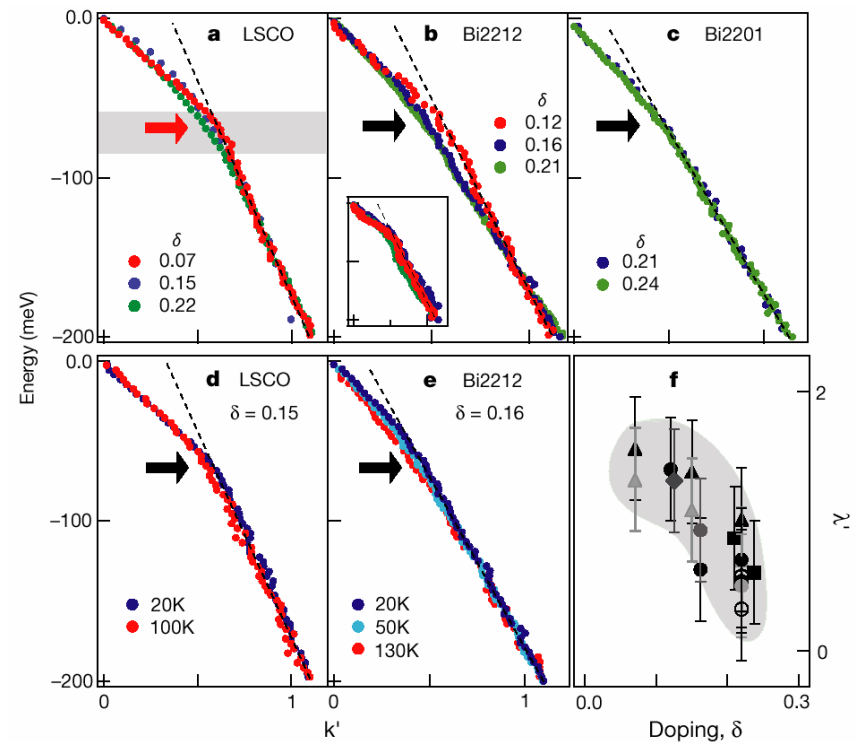
Bogdanov *PRL* 2000



Johnson *PRL* 2001

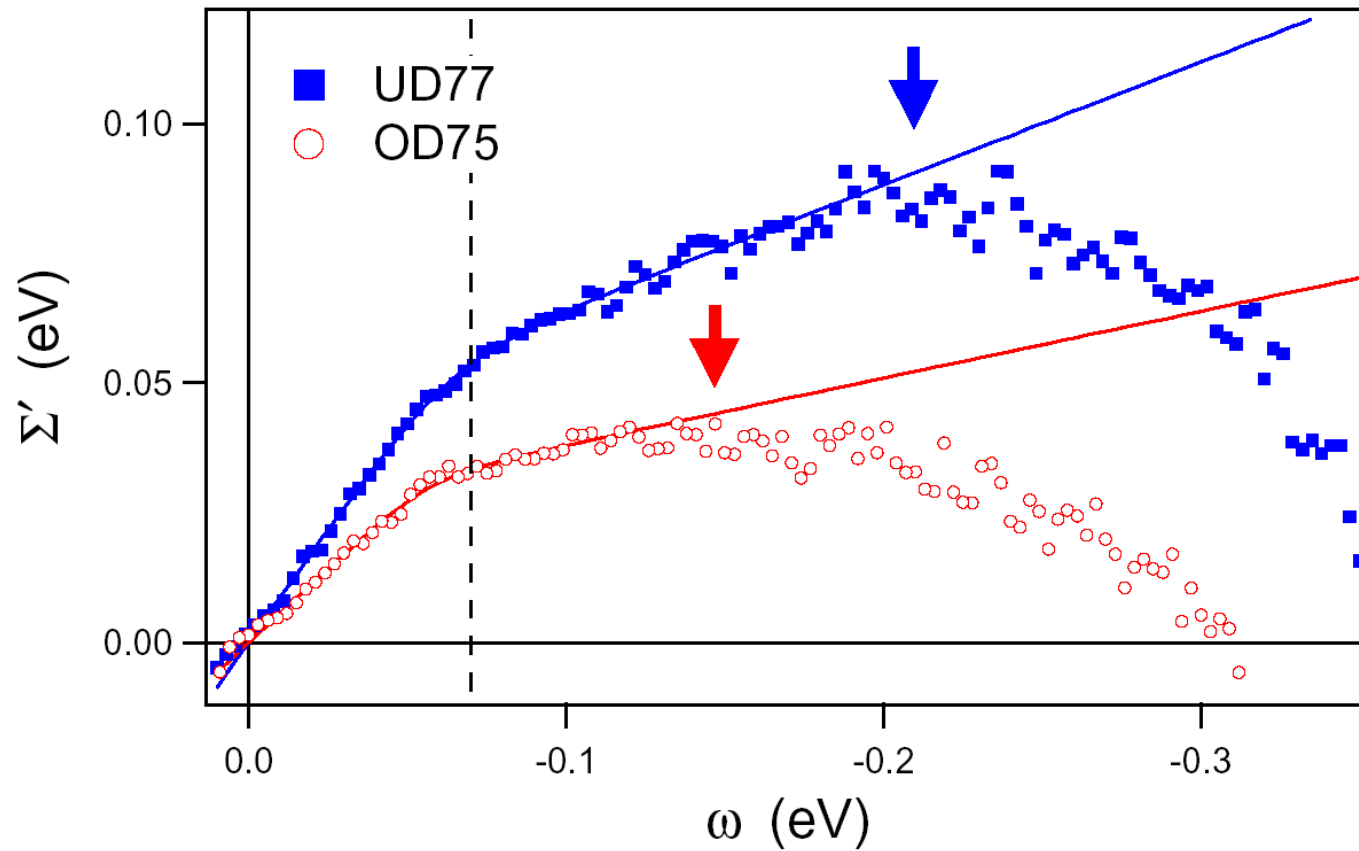


Kaminski *PRL* 2001



Lanzara *Nature* 2001

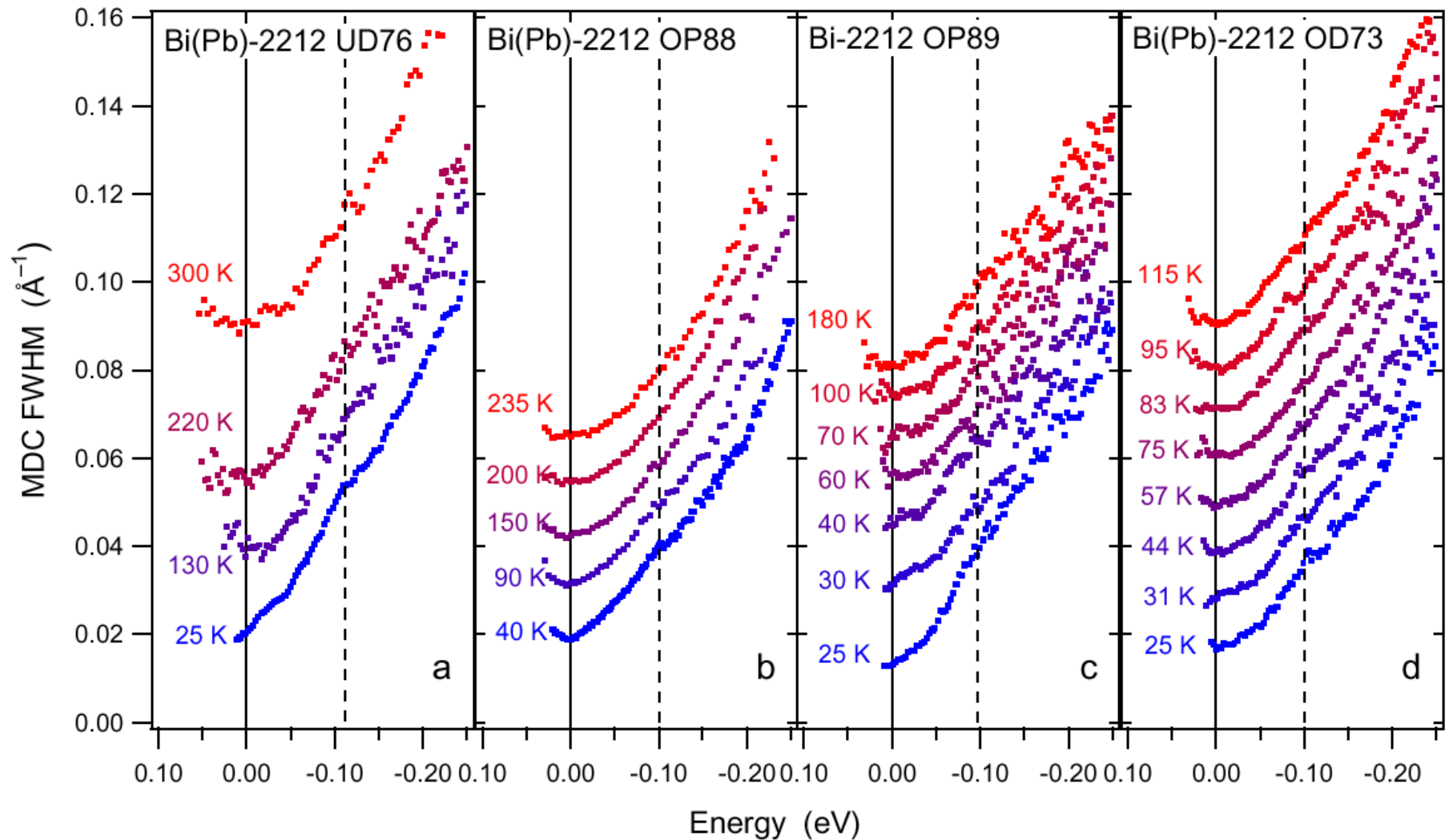
Phenomenology of the kink



Quasiparticle scattering rate

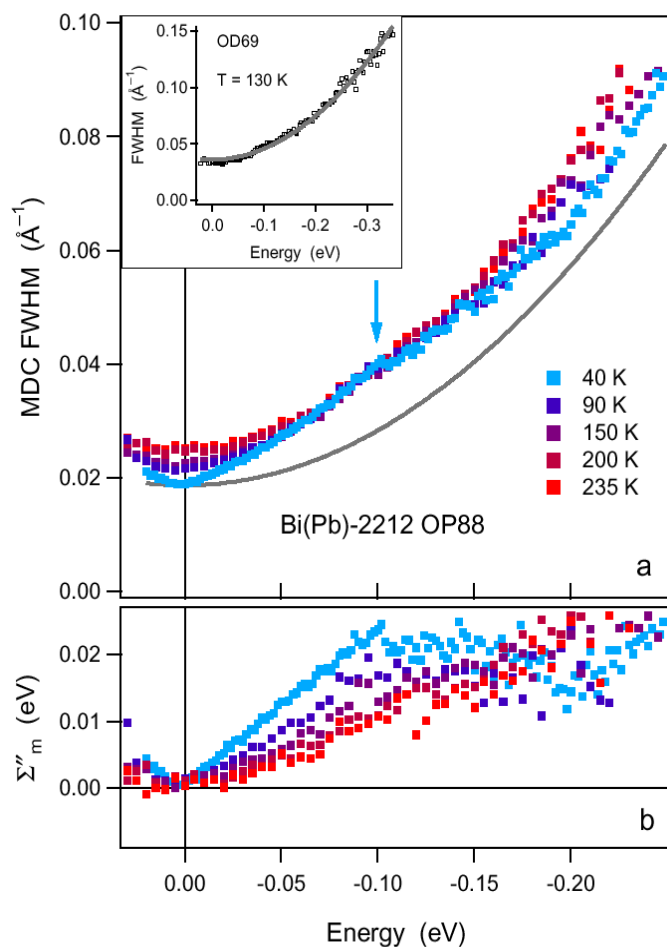
What is the main scatterer?

Scattering rate kink

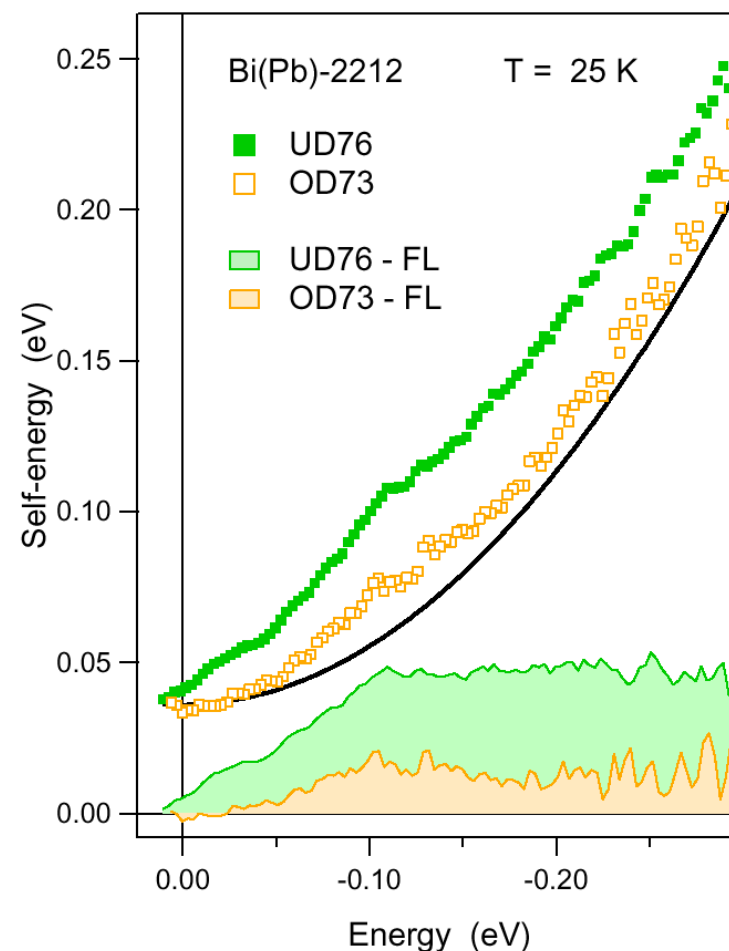


Scattering rate:

T-dependence

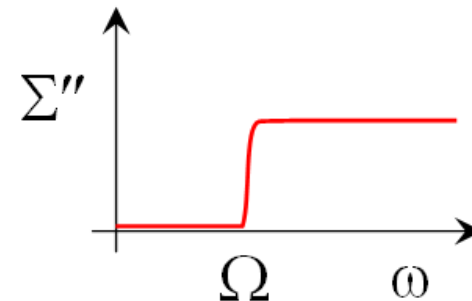
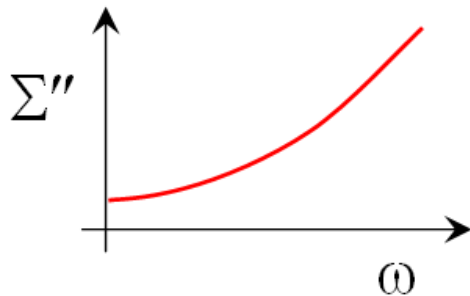
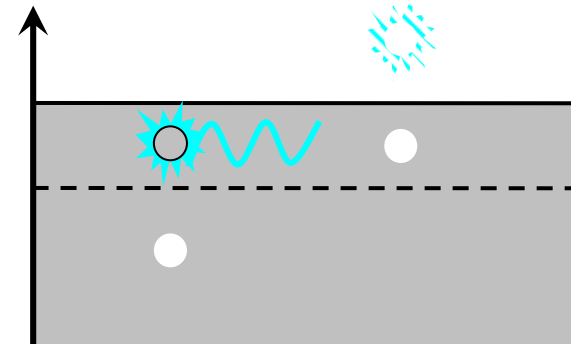
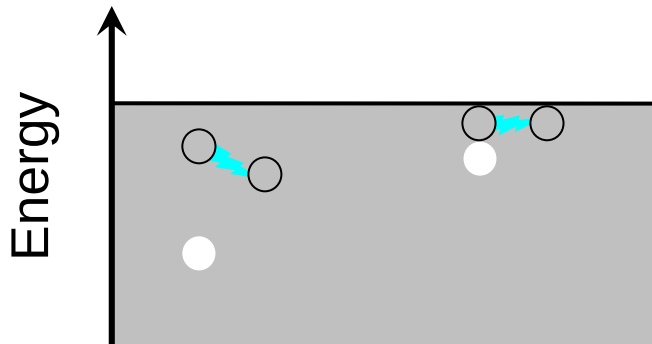
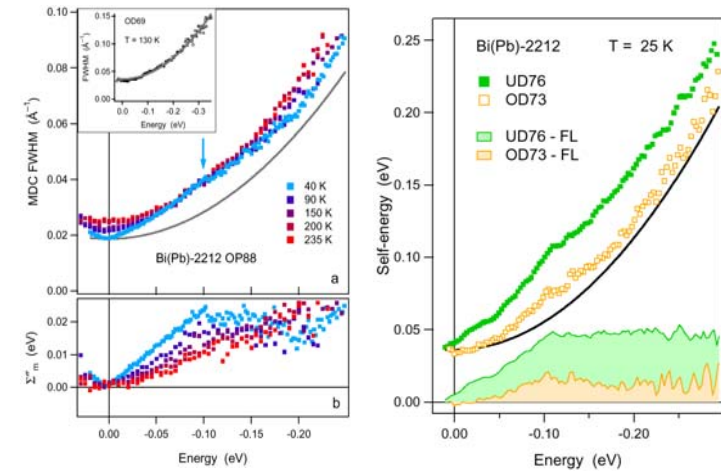


Doping dependence

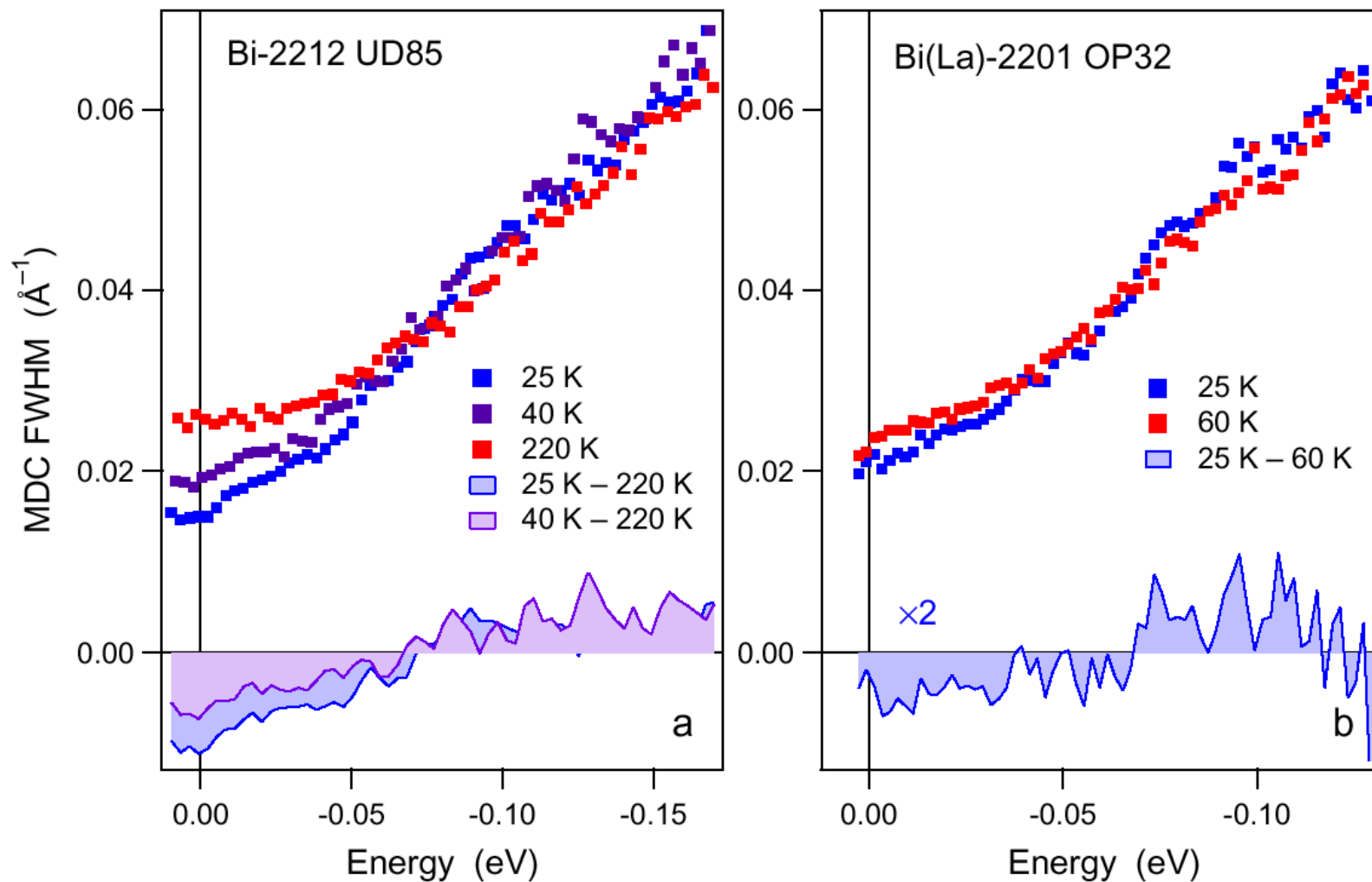


Scattering rate: Some conclusions

There are two channels:
1st electron-electron scattering and
2nd electron-boson scattering



Scattering rate kink



Nodal electrons couple to ...

Doping dependence: **UD** $\uparrow$
OD $\downarrow$

Temperature dependence:
 $< T_c$ for **OD**
 $< T^*$ for **UD**

Parity: **odd boson**

spin
fluctuations

Conclusions

“Careful and systematic analysis” of ARPES data implies KK consistency.

“Kink” needs to be quantified!

Meanwhile, under “kink” we imply the kinked **doping and temperature dependent part** of the self-energy. Besides the huge Auger-like scattering this is the **main interaction channel** seen by ARPES.

Kink appears below T^* line on the T - x phase diagram.

Irrelevant “kink” can have many reasons: e.g., superstructure, bilayer splitting, superconducting gap or, for overdoped samples, a sharp maximum of the $\text{Re}\Sigma(\omega)$ due to vHs approaching Fermi level.

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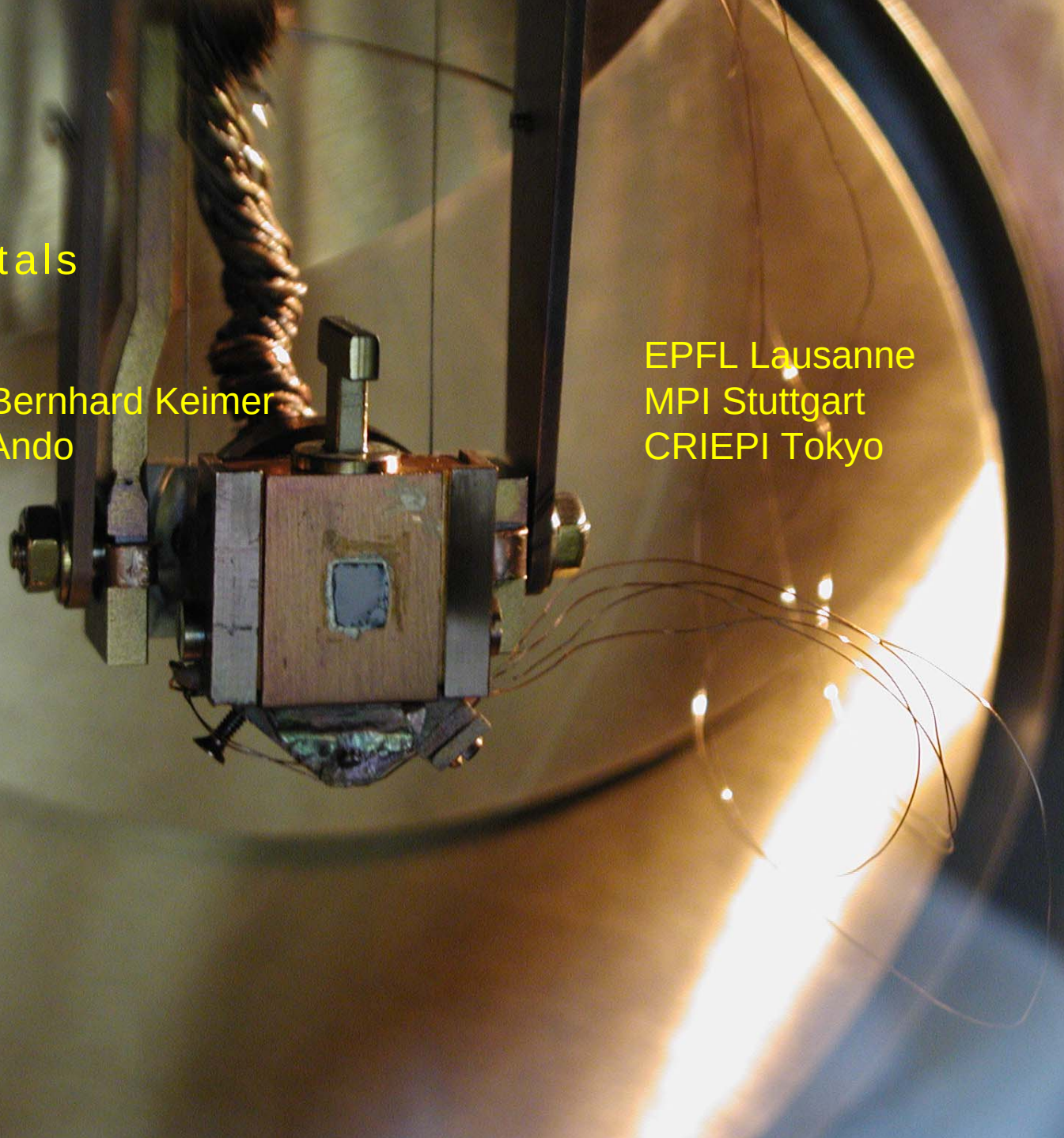
Timur Kim, Mark Golden



Single Crystals

Helmut Berger
Chengtian Lin, Bernhard Keimer
S. Ono, Yoichi Ando

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CRIEPI Tokyo



Synchrotron Light

Rolf Follath

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A photograph of three men in a laboratory or workshop. The man in the center, wearing glasses and a dark zip-up jacket, is smiling at the camera. He is flanked by two other men who are slightly out of focus. The background is filled with technical equipment, including a large blue cabinet, metal shelving, and various cables. The floor is light-colored and reflective. The text "THE END" is overlaid in yellow capital letters across the center of the image.

THE END