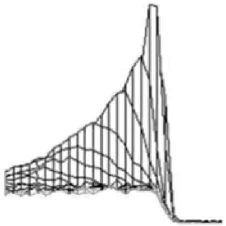


Constituents of the “kink” in high-Tc cuprates

Alexander Kordyuk

IFW Dresden, Germany
IMP Kiev, Ukraine

Outline

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

Introduction to ARPES

What do we measure?

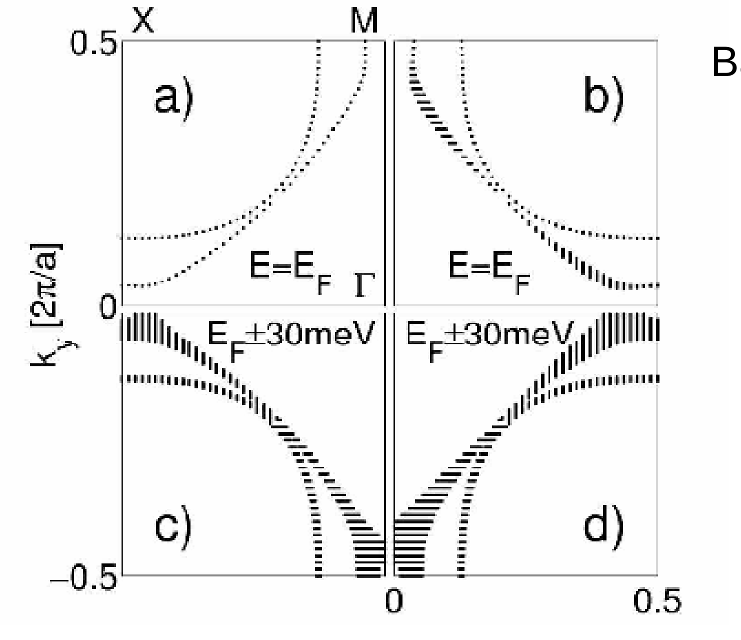
Samples should be

1. **Easily cleavable – perfect surface**

Samples should be

1. Easily cleavable – perfect surface

2. 2D – to neglect k_z dispersion



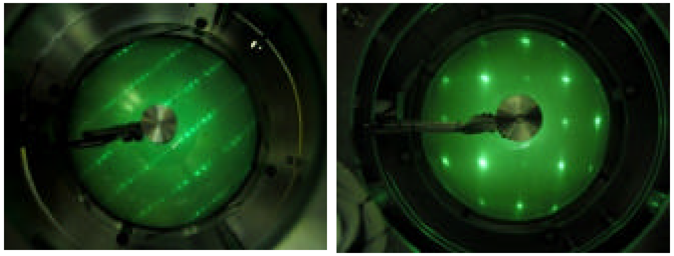
Bansil 2004

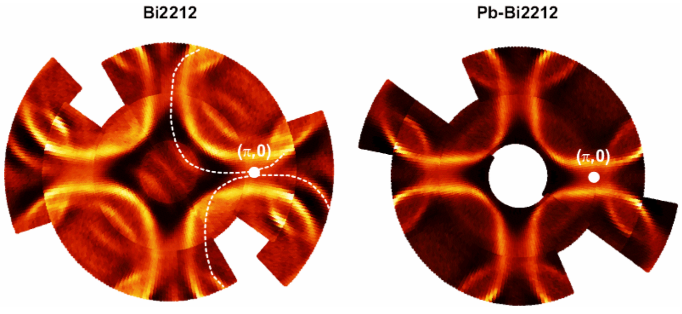
Samples should be

1. Easily cleavable – perfect surface

2. 2D – to neglect k_z dispersion

3. Free of superstructure





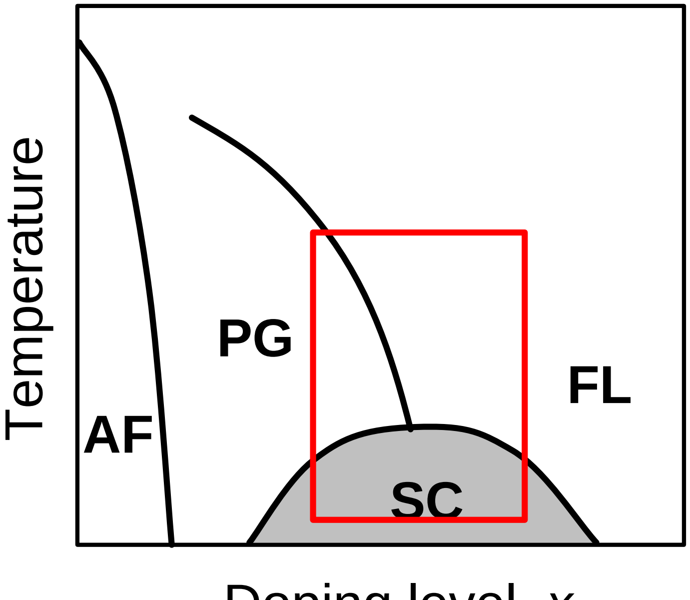
Samples should be

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

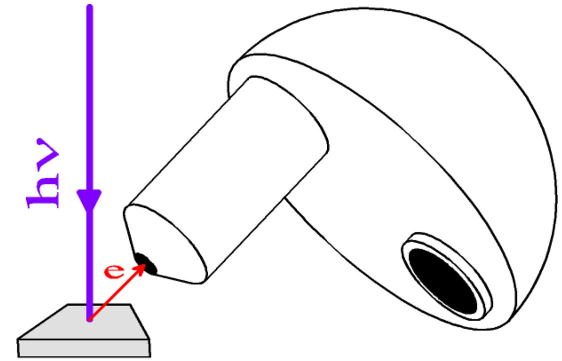
Samples should be

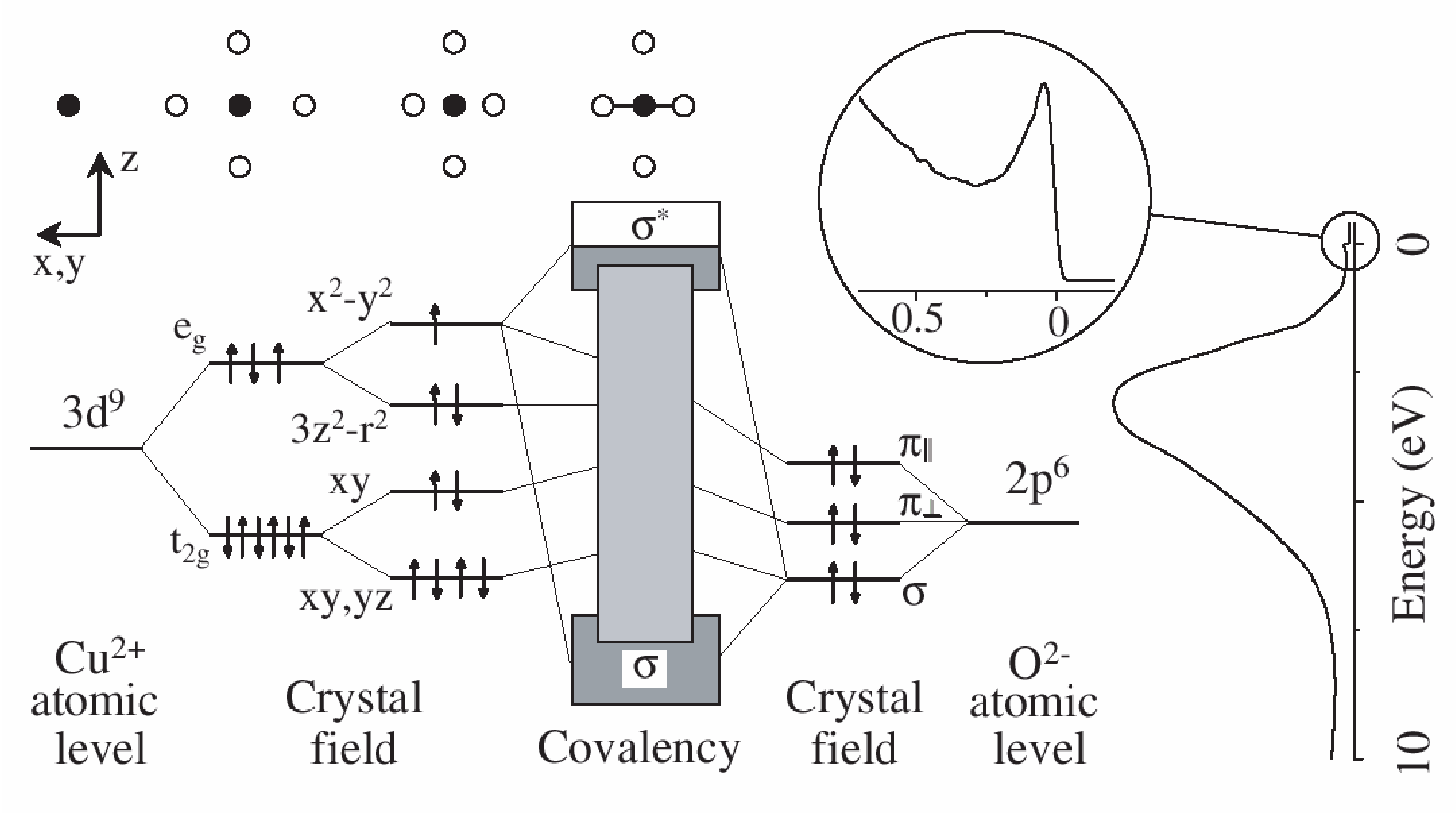
1. **Easily cleavable – perfect surface**
2. **2D – to neglect k_z dispersion**
3. **Free of superstructure**
4. **High T_c**

⇒ Bi(Pb)-2212

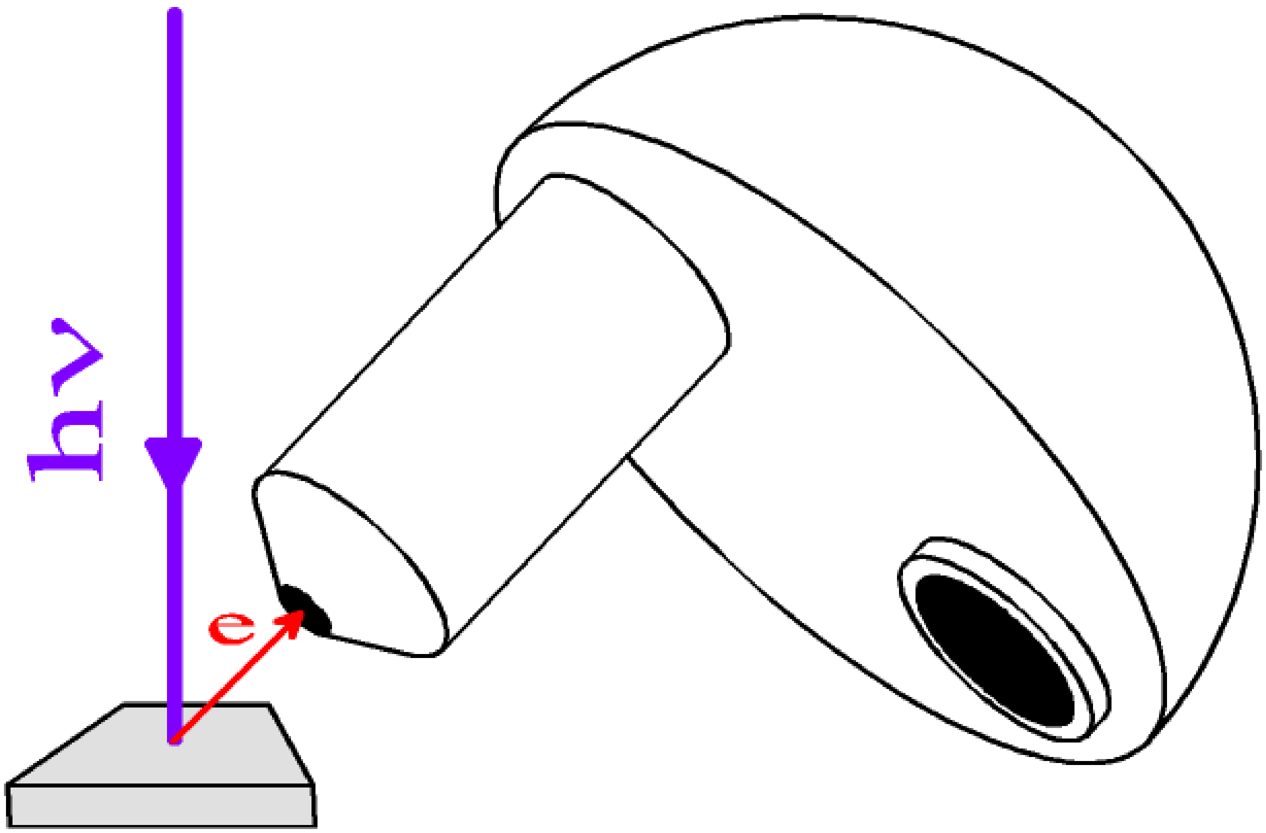
but bilayer splitting – we need different *hv*

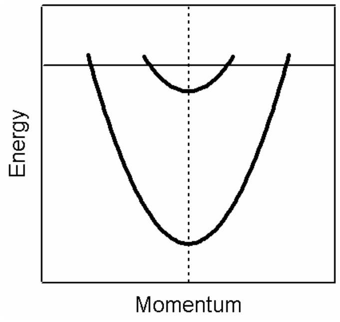
Photoemission Spectrum

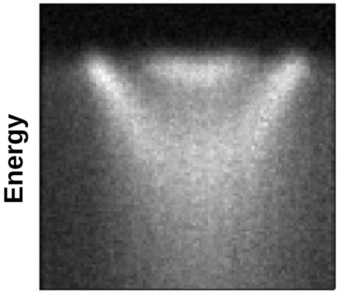




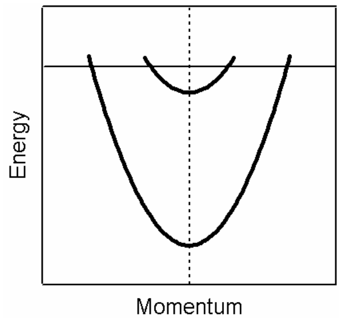
Angle-Resolved Photoemission (ARPES)

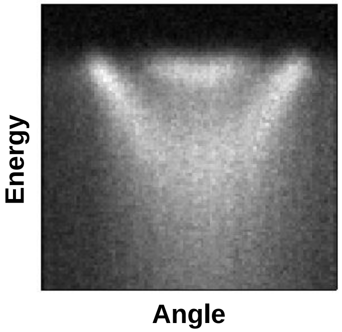


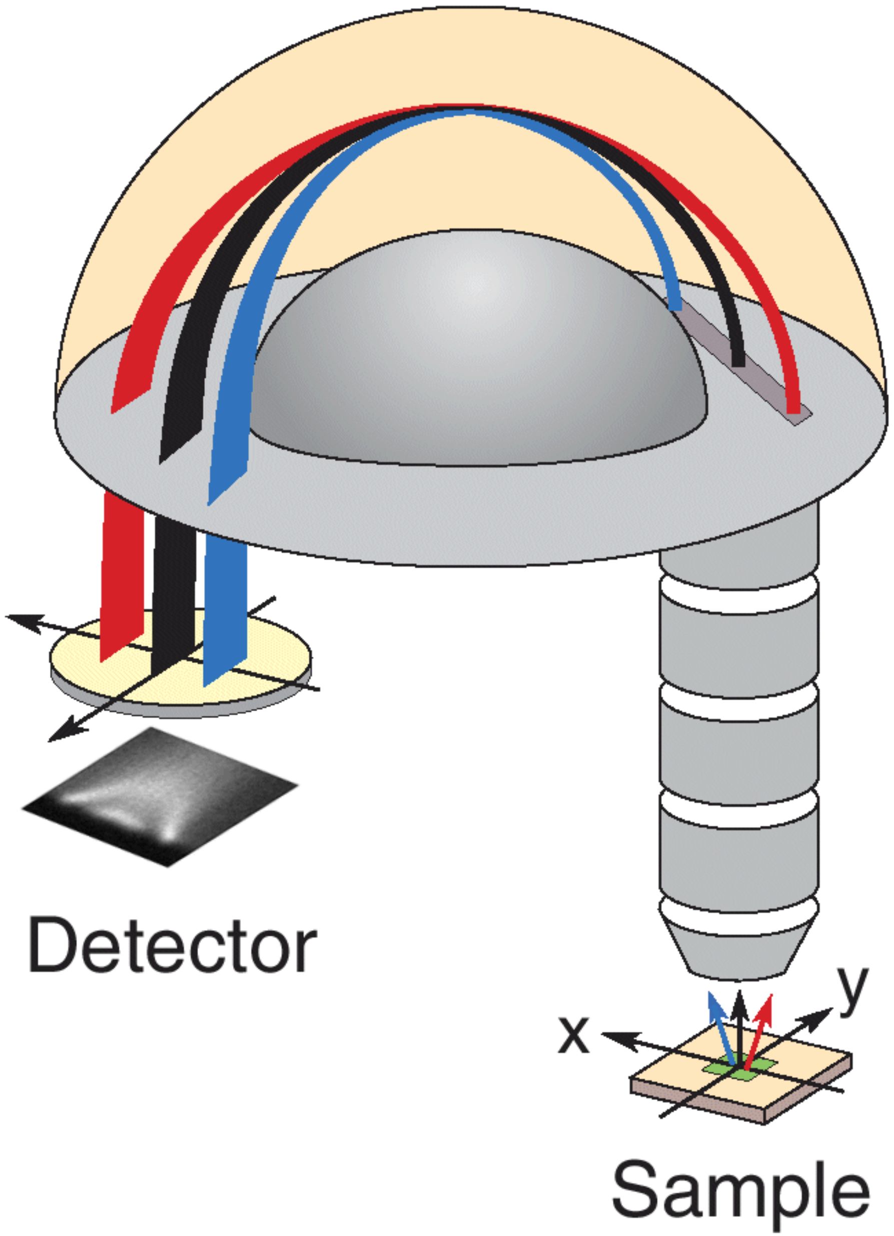




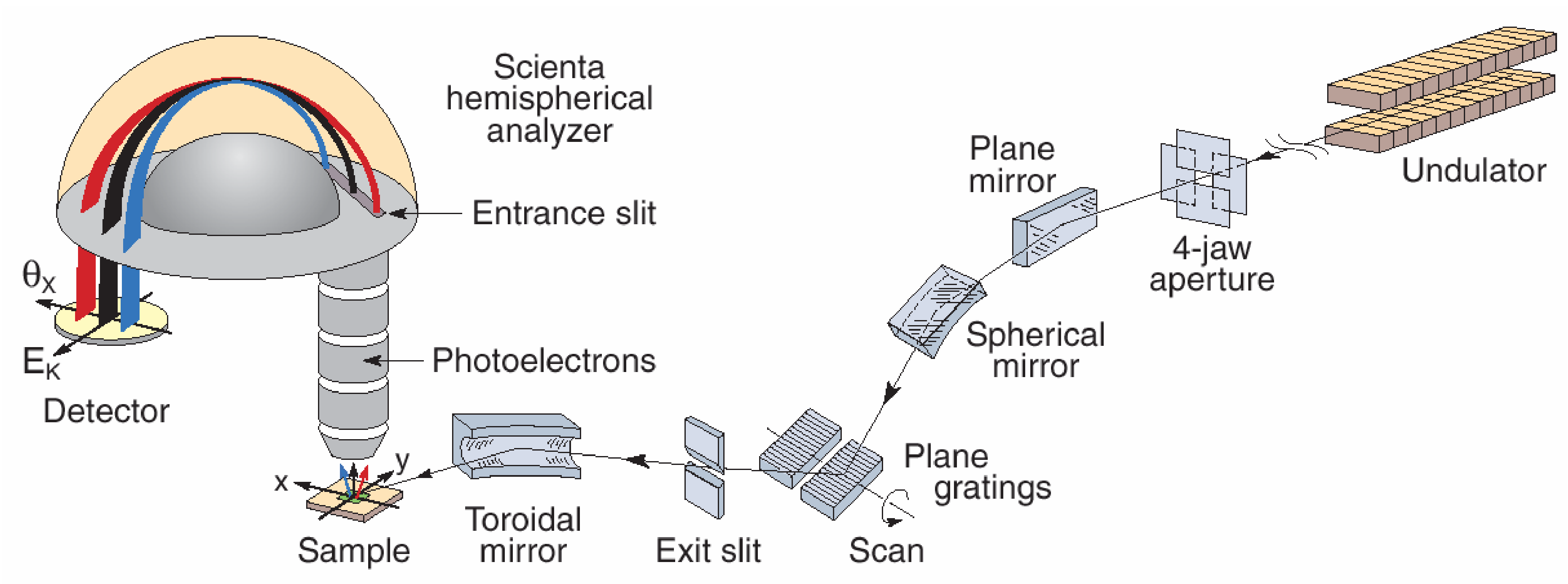
Angle Resolved Analyser





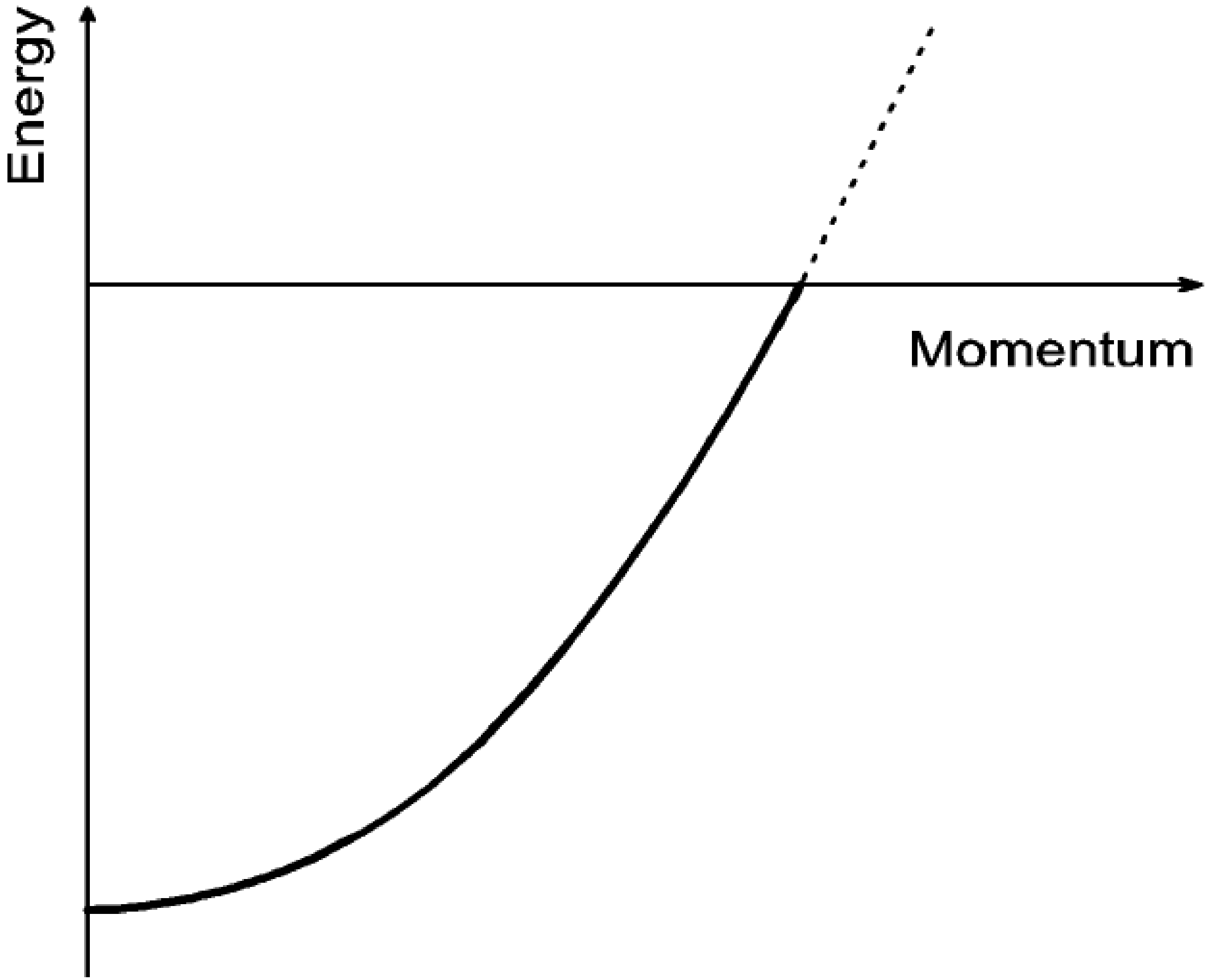


ARPES with Synchrotron Light

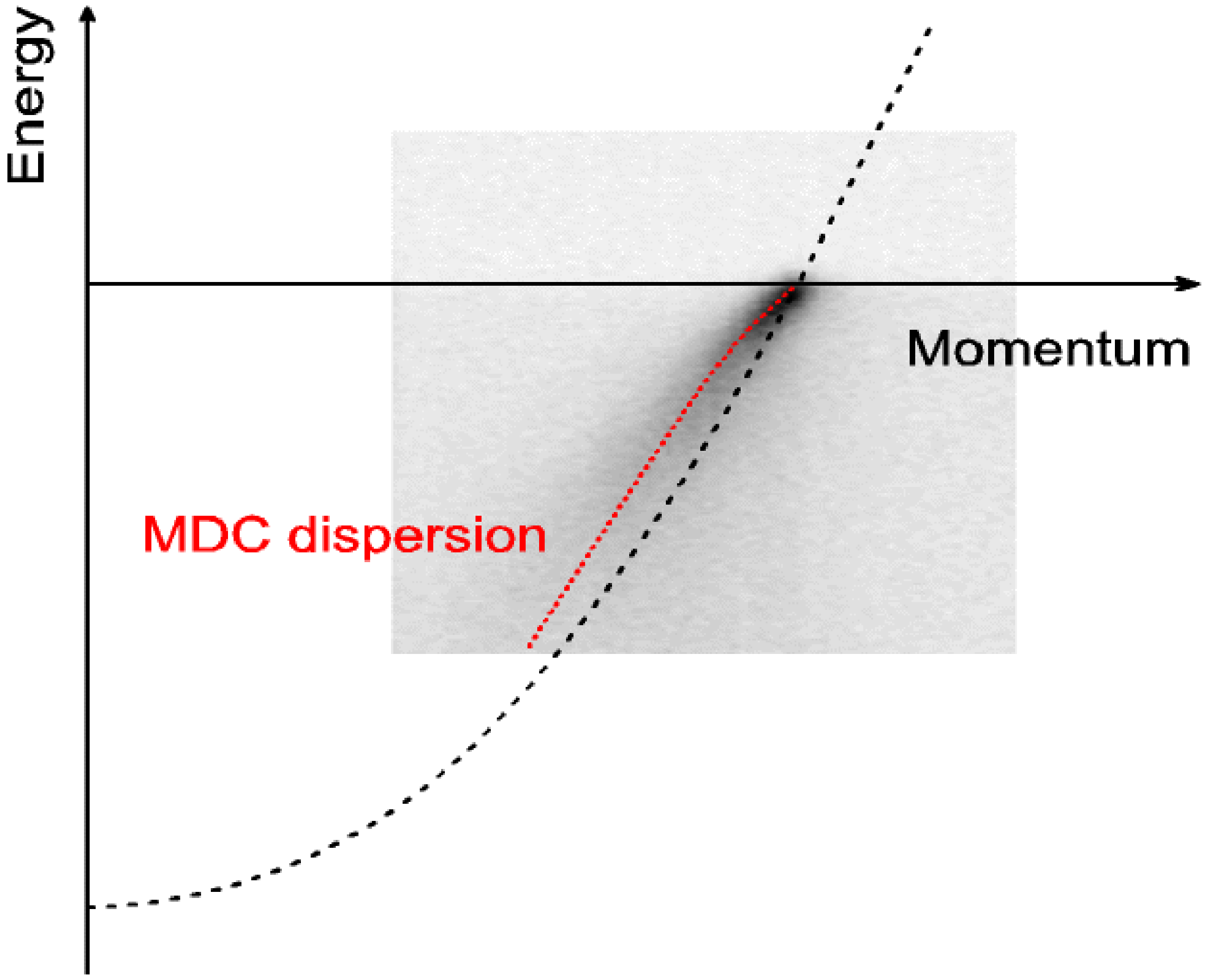


Damascelli *RMP* 2003

Basics: electron dispersion



Basics: electron dispersion



Photocurrent

geometrical prefactor

momentum and energy resolution

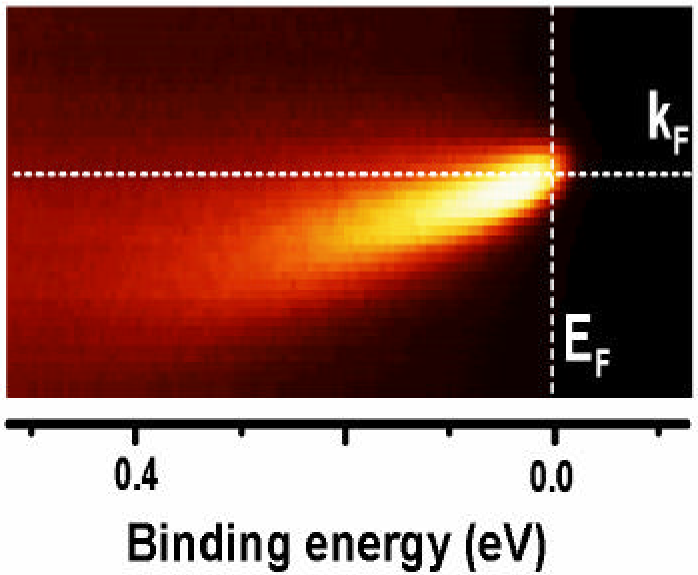
$$I(\mathbf{k},\omega)=G_{\mathbf{k}}\{M(\mathbf{k})[A(\mathbf{k},\omega)f(\omega)]\otimes R_{\omega,\mathbf{k}}+B(\omega)\}$$

matrix elements

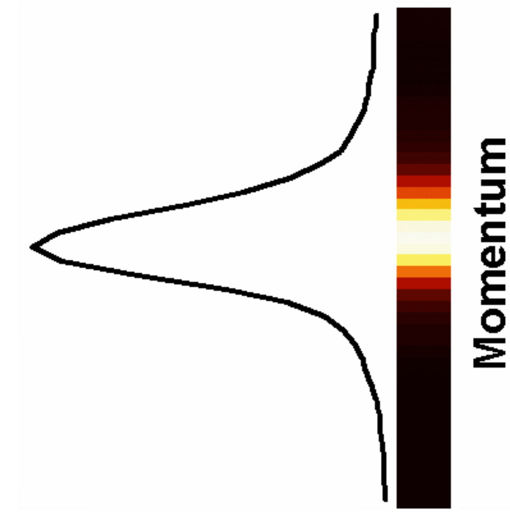
Fermi cutoff

extrinsic background

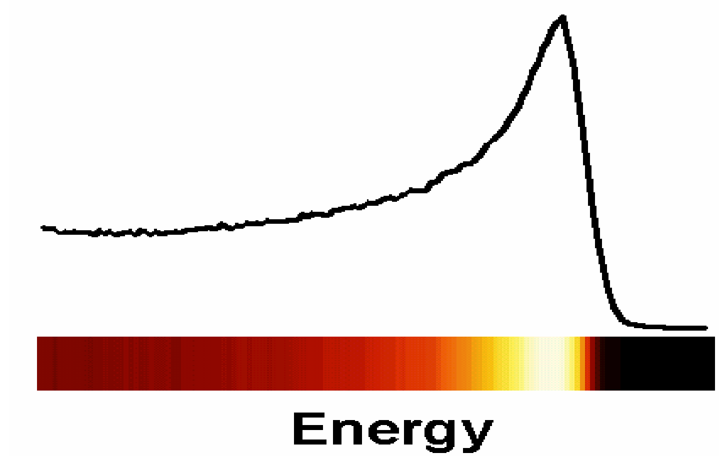
$I(k,w)$ - Energy Distribution Map



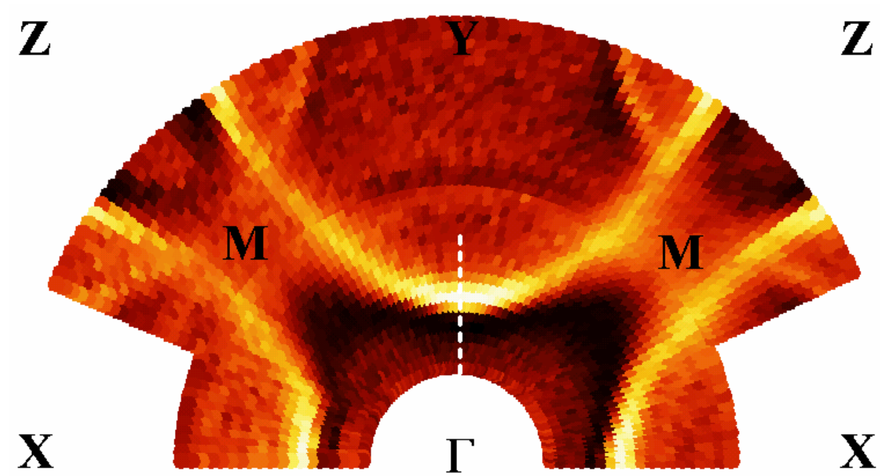
$I(k,w)$ - Momentum Distribution Curve



$I(k,w)$ - Energy Distribution Curve

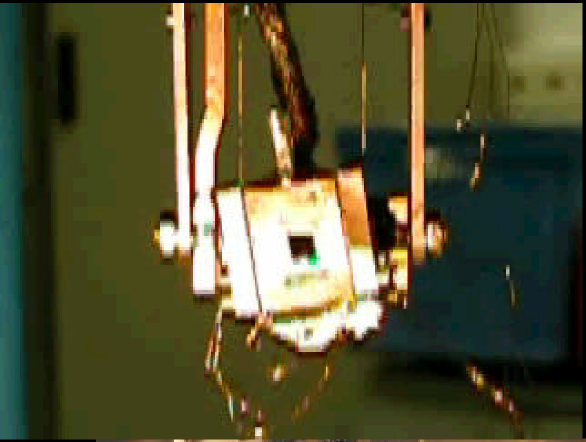


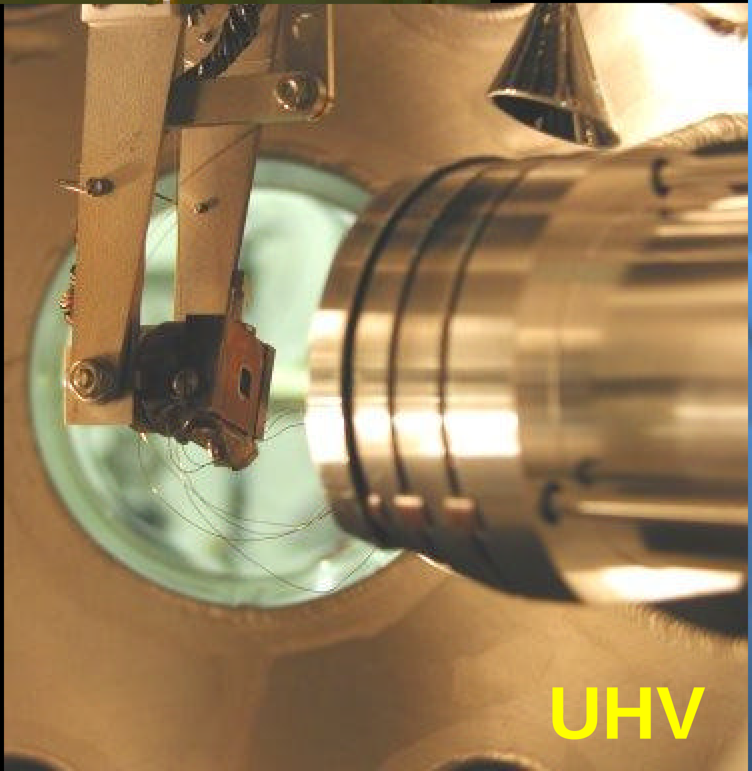
$I(k_x,k_y,w)$ - Momentum Distribution Map

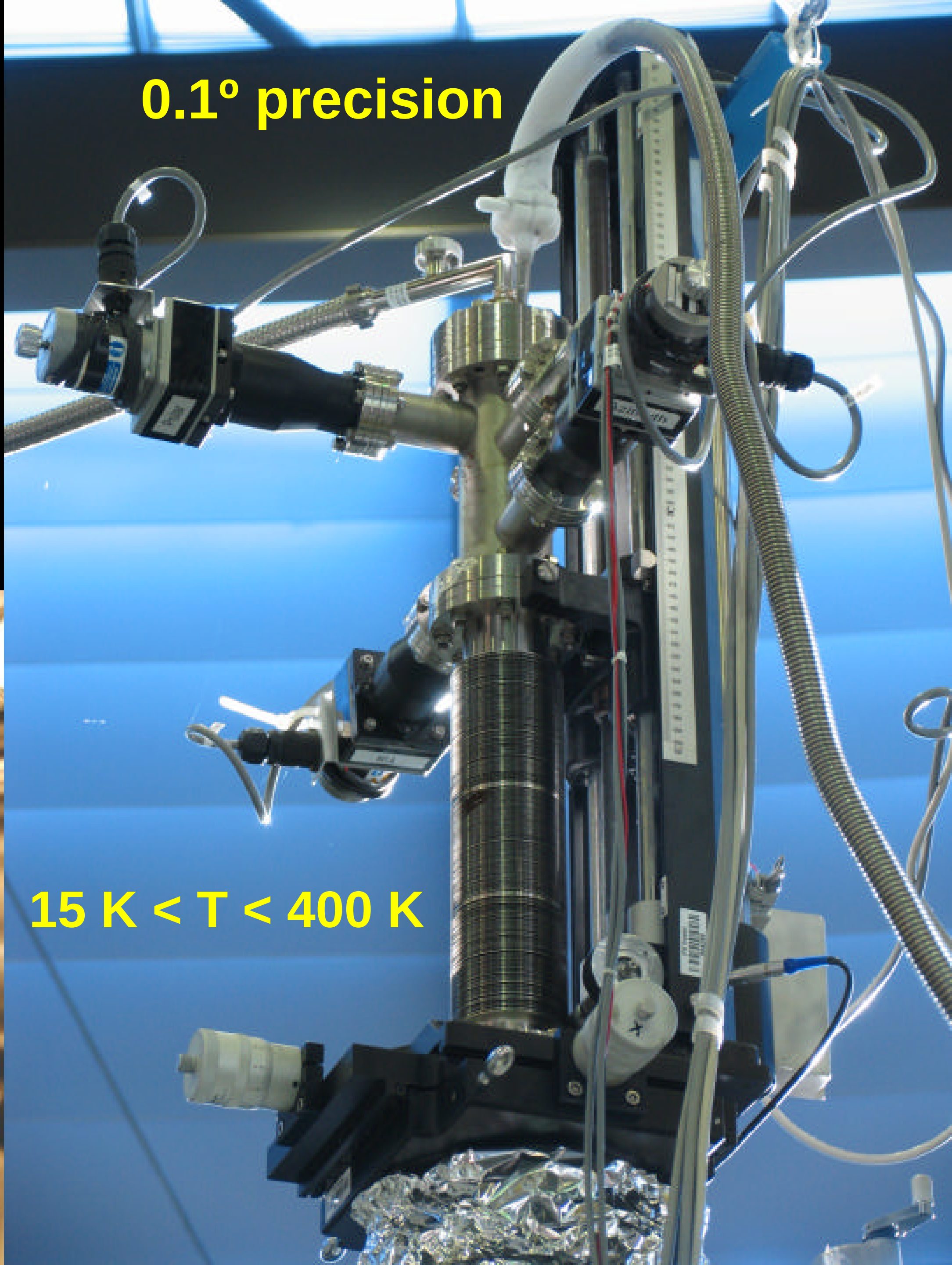


Borisenko *PRB* 2001

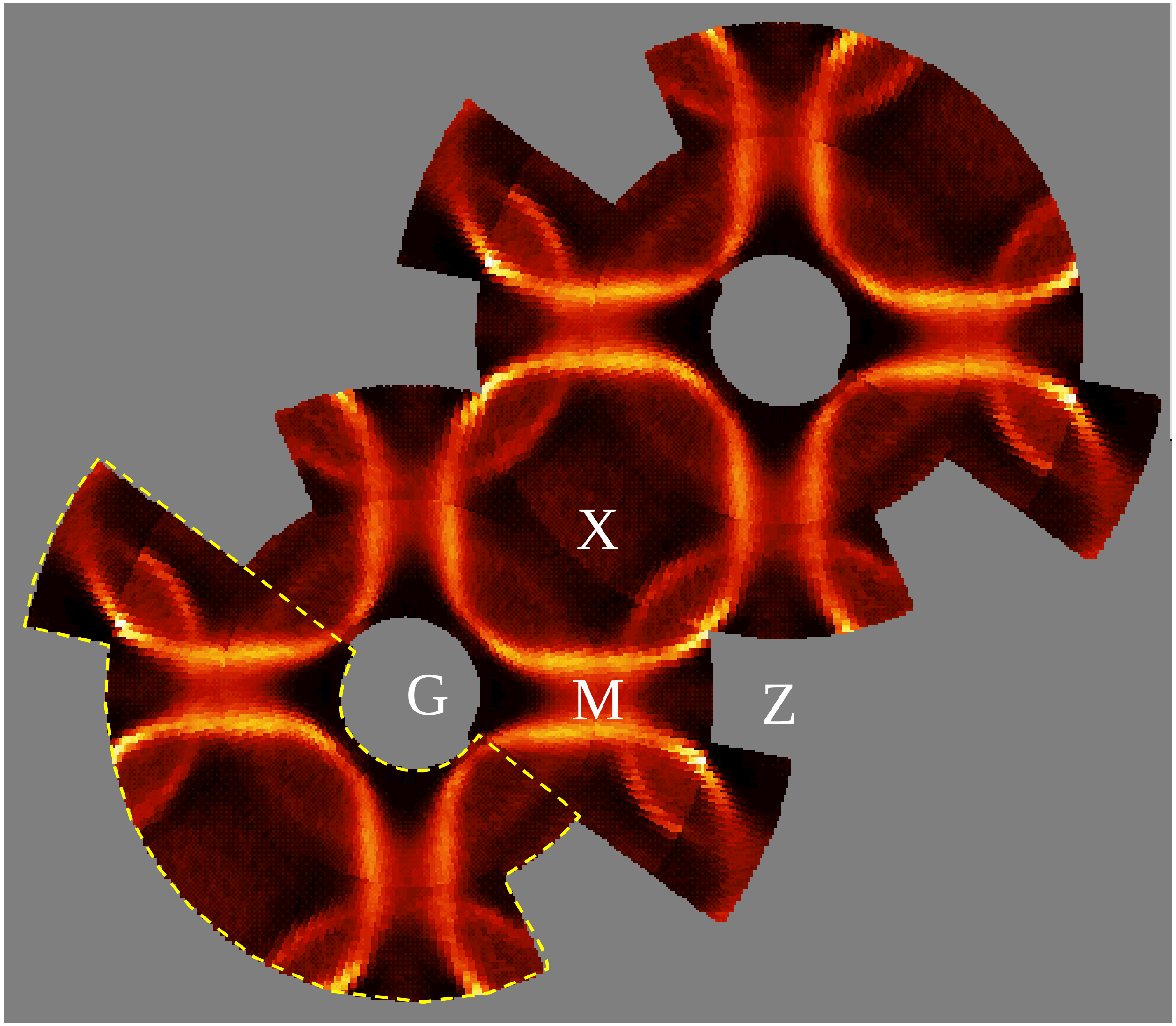
Precise Cryo-Manipulator

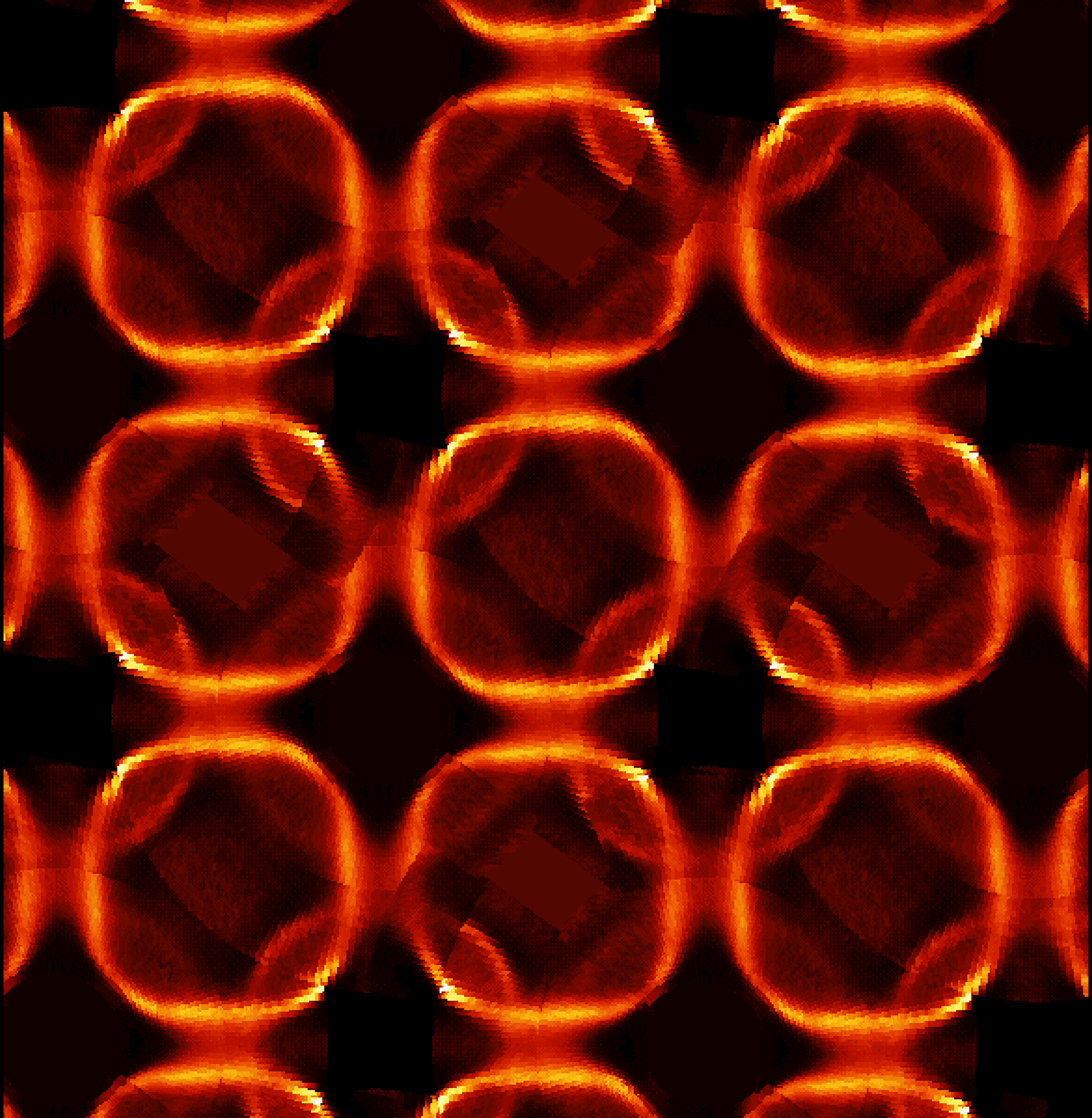




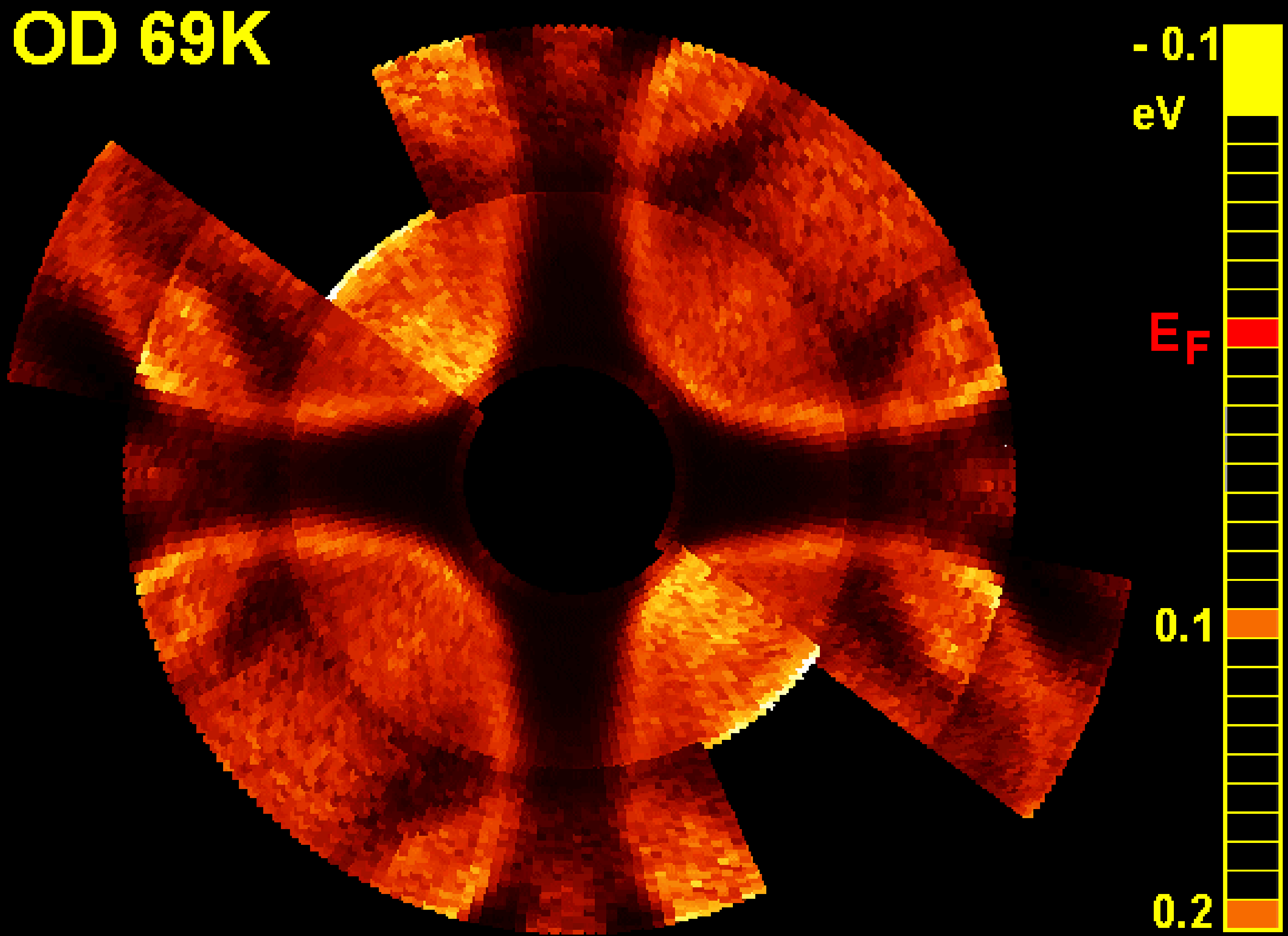


Fermi-surface map





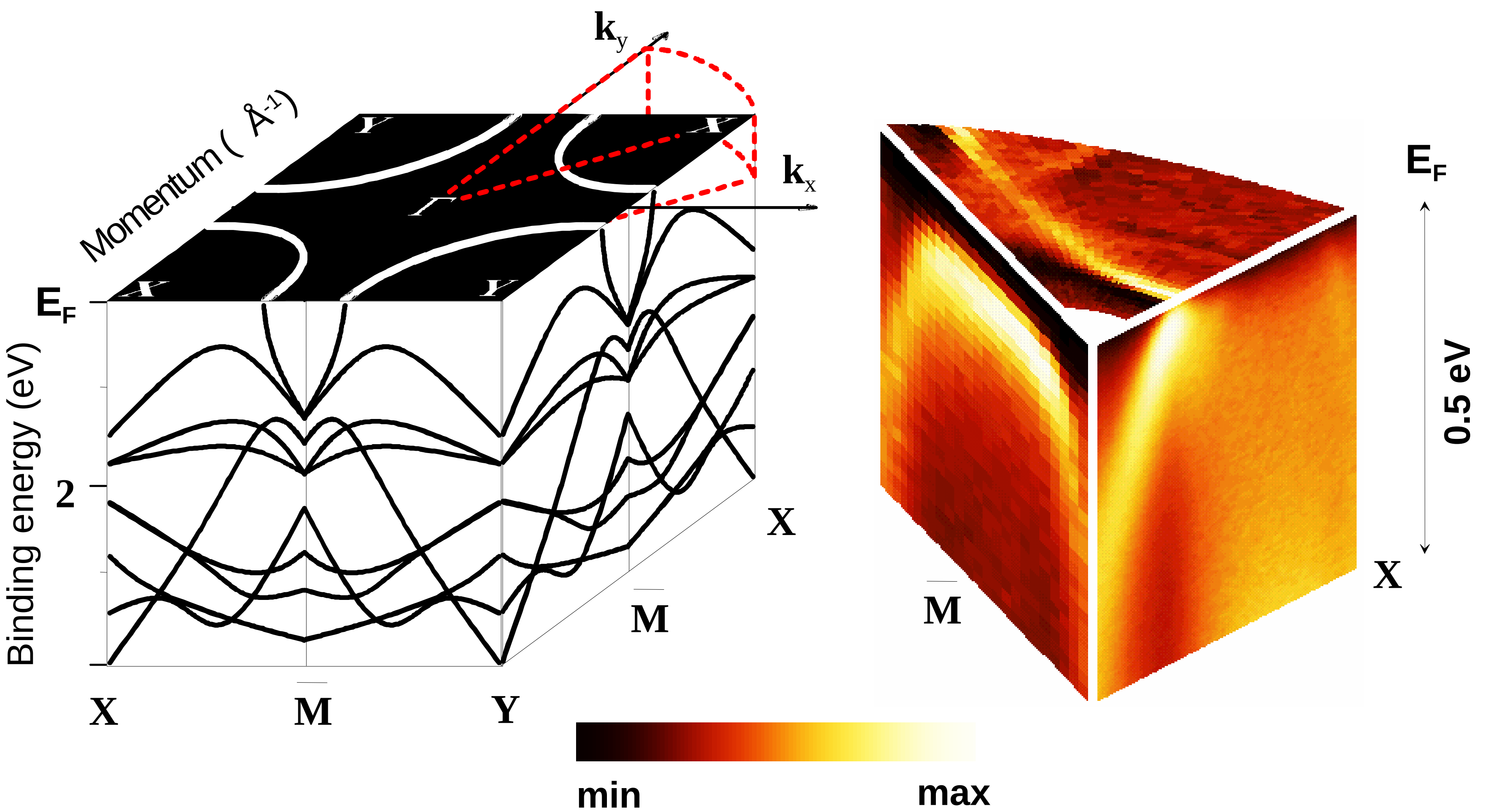
Momentum Distribution Map



300 K, 21.2 eV

Kordyuk 2000

Momentum-energy space

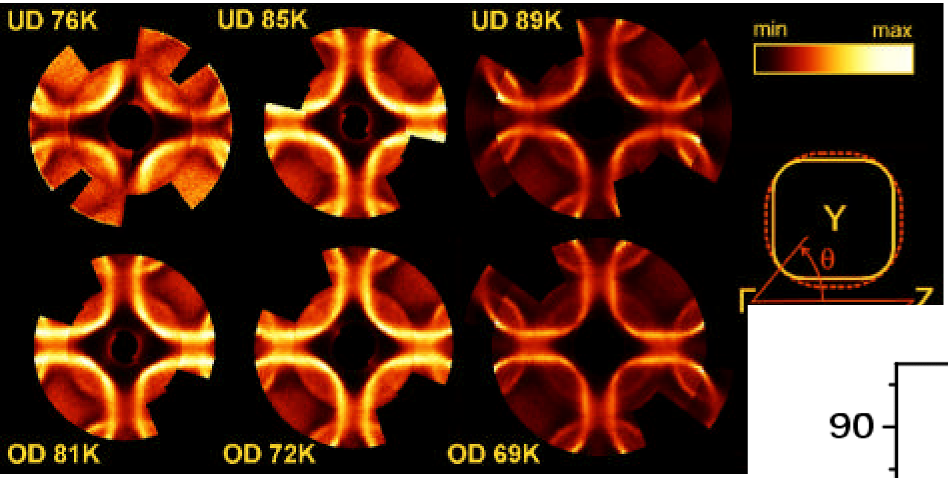


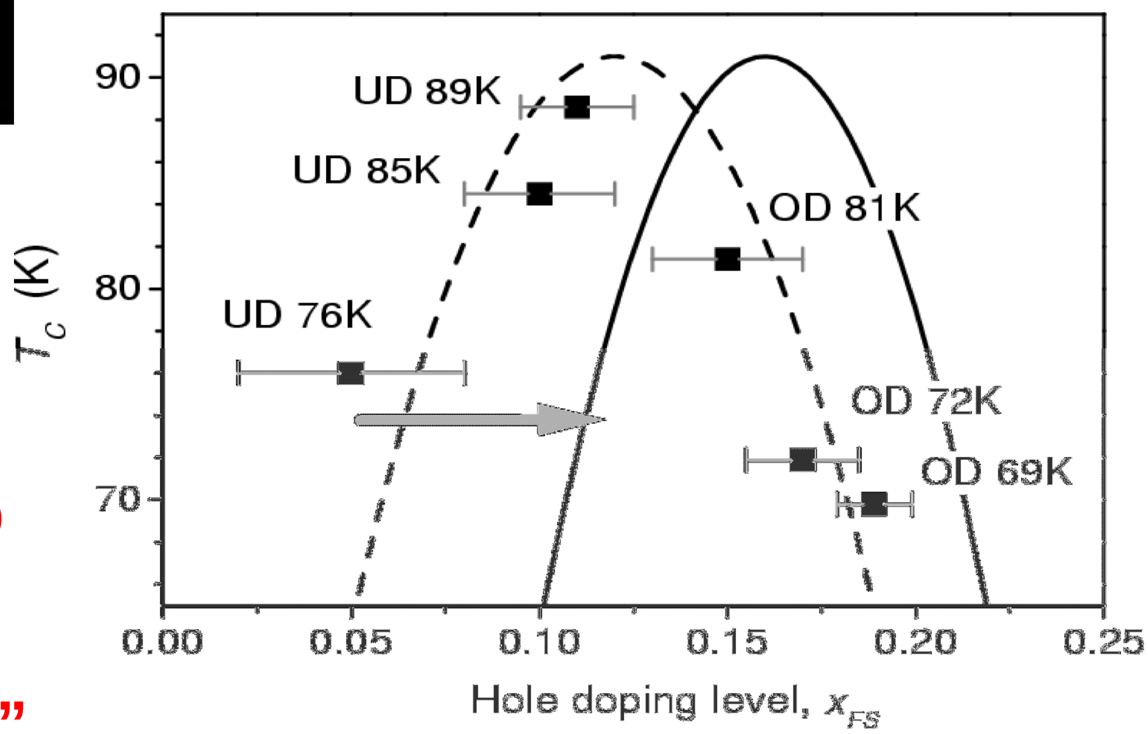
Borisenko *PRB* 2001

Bare band structure

What is underneath?

Fermi surface evolution with doping





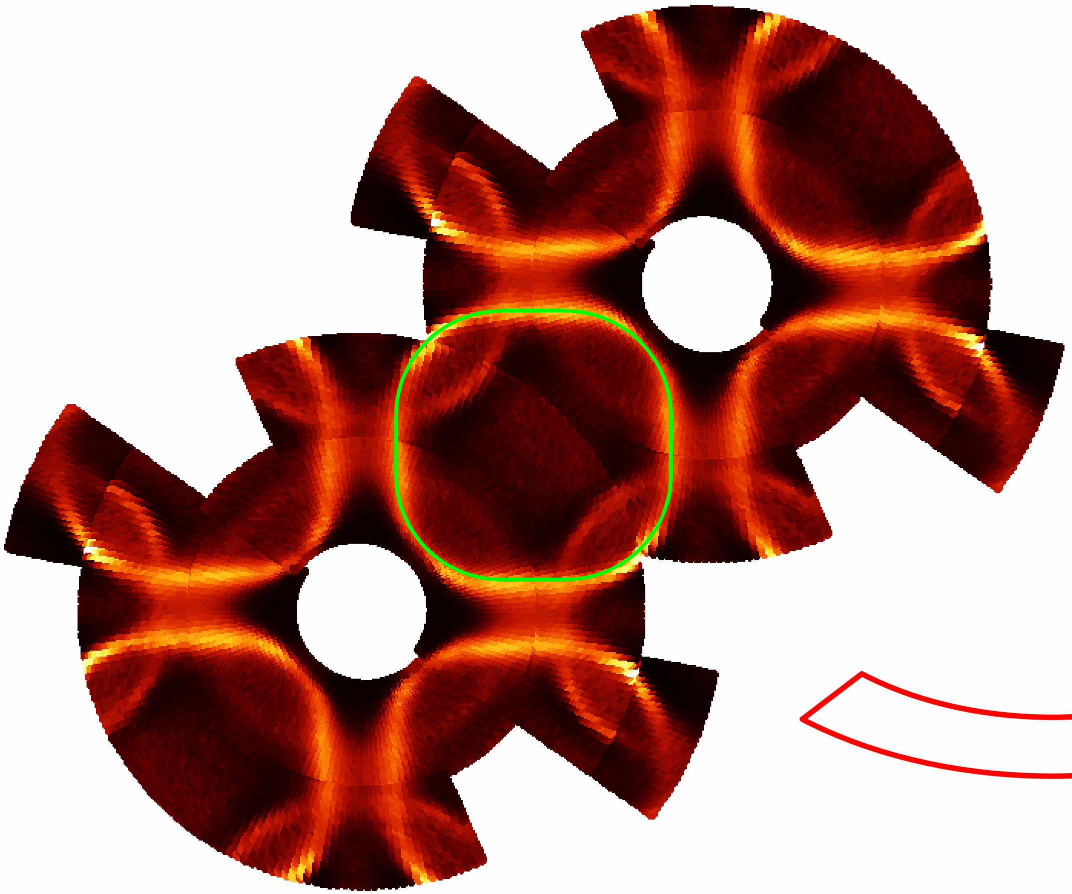
$$S_{FS} = (1 - x)/2$$

"Large Fermi surface"

Kordyuk *PRB* 2002

Band structure: TBF

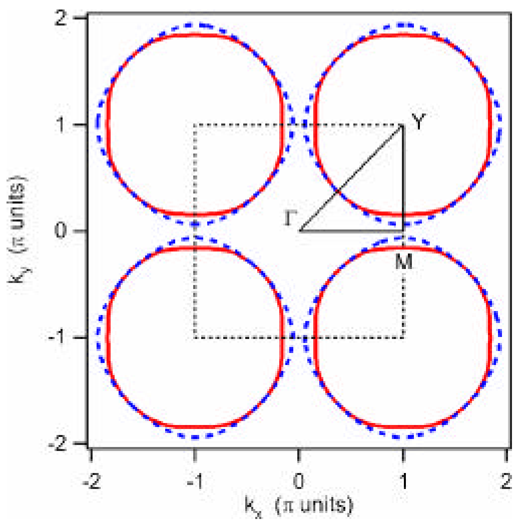
$$\varepsilon(k_x, k_y) = \Delta\varepsilon - 2t(\cos k_x + \cos k_y) + 4t' \cos k_x \cos k_y - 2t''(\cos 2k_x + \cos 2k_y)$$



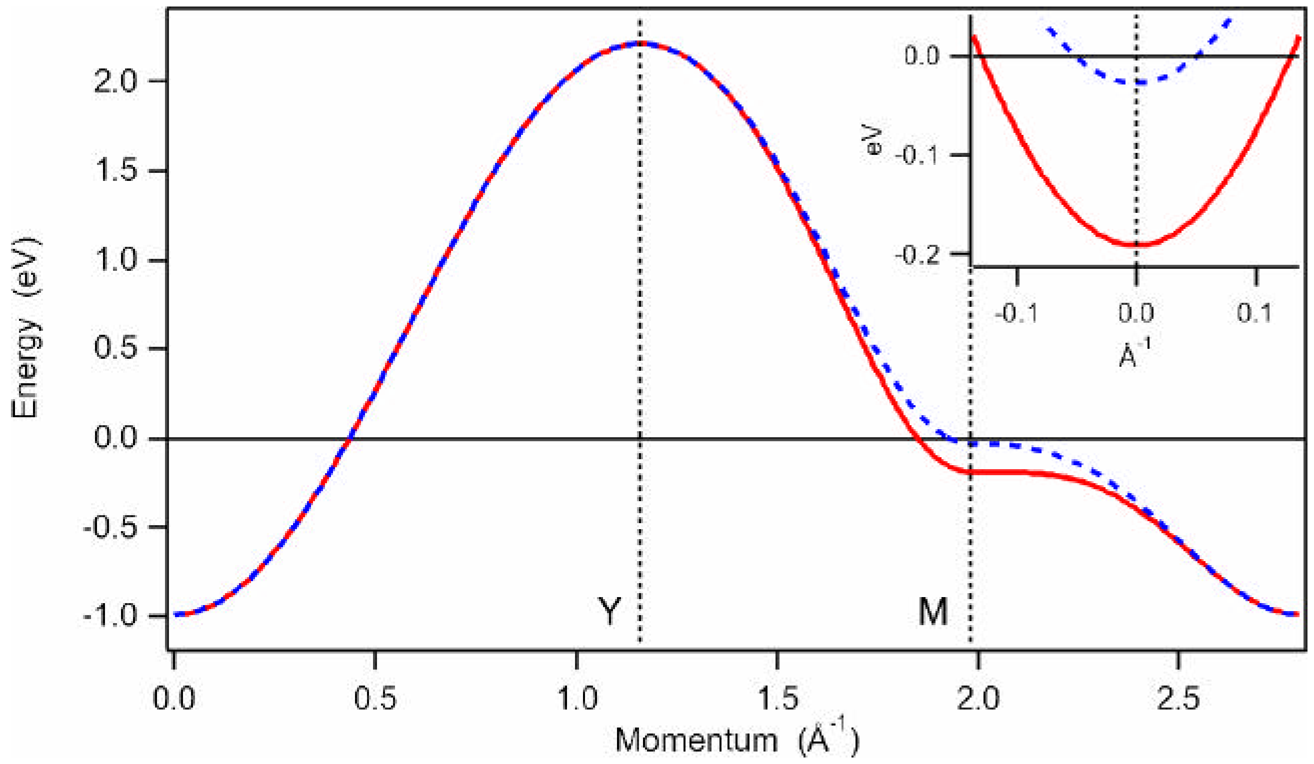
$$\Delta\varepsilon \approx 0.4\,\mathrm{eV}$$
$$t \approx 0.4\,\mathrm{eV}$$
$$t' \approx 0.1\,\mathrm{eV}$$
$$t'' \approx 0.05\,\mathrm{eV}$$

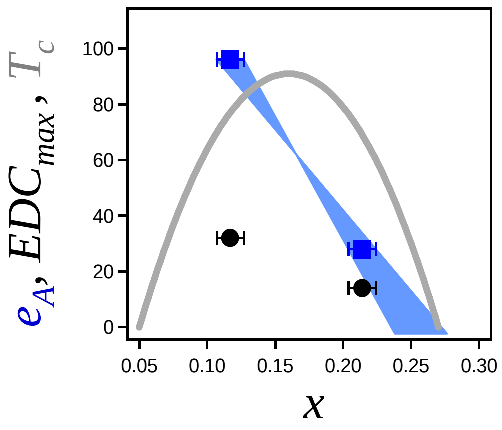
Kordyuk *PRB* 2003

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





Kordyuk *PRB* 2003

Good agreement with LDA

(no signature of Mott insulator)

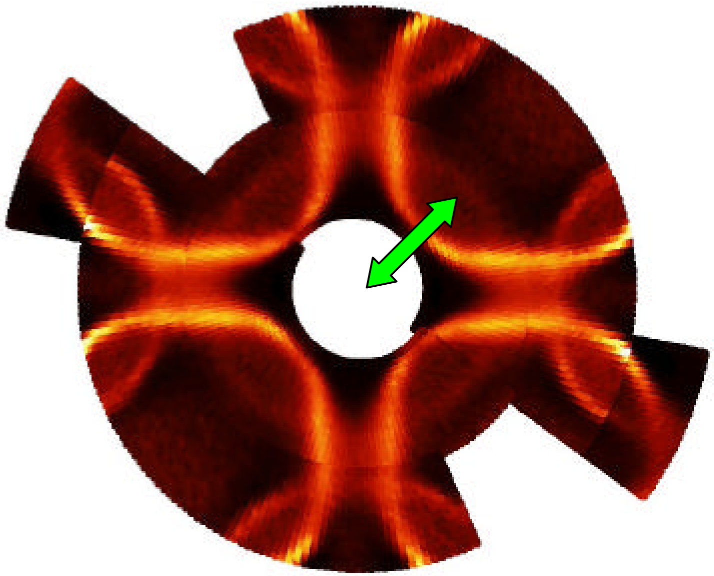
vHs is essential for HTSC

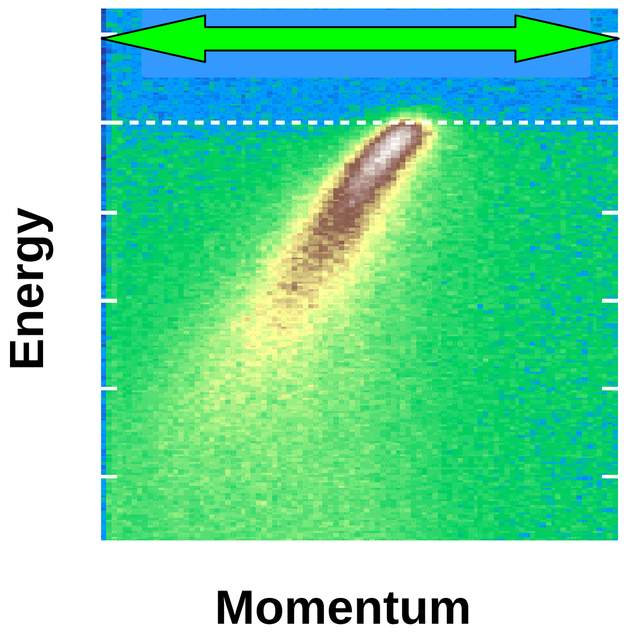
Quasiparticle spectral weight

What is relevant in ARPES spectra?

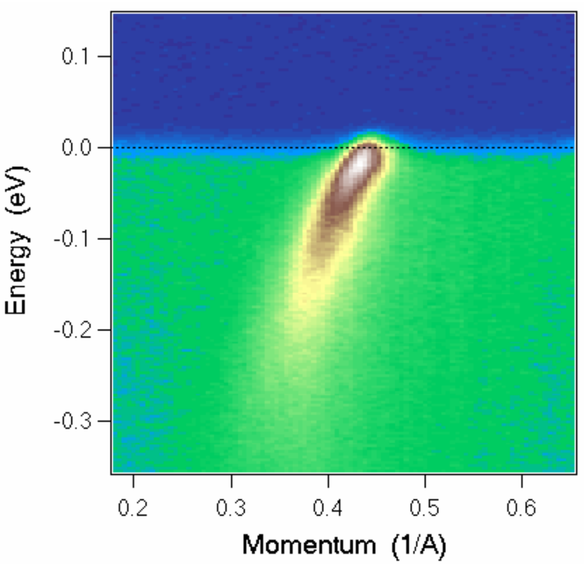
Nodal direction (GX)

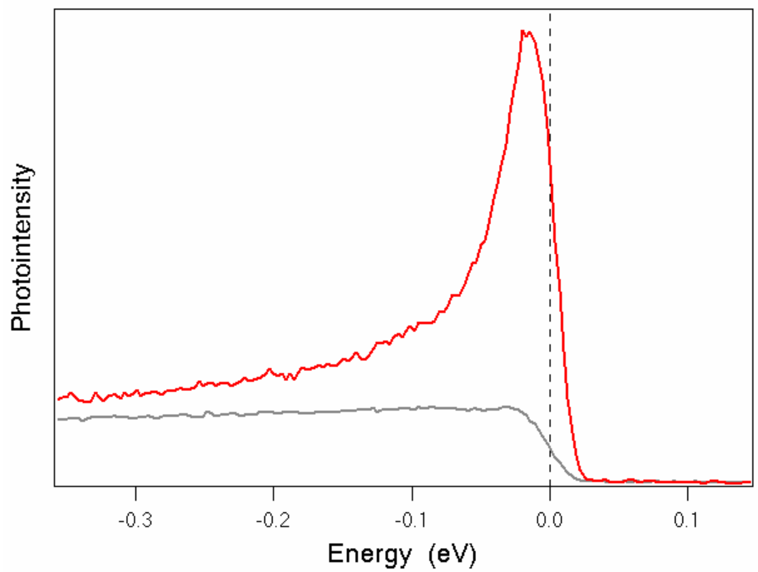
No gap, simple bare dispersion.

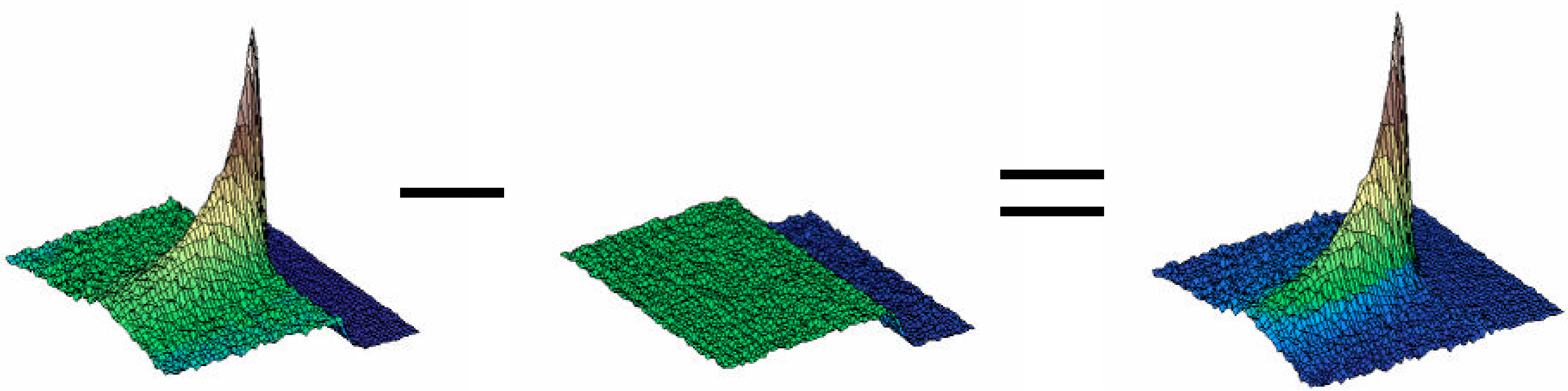




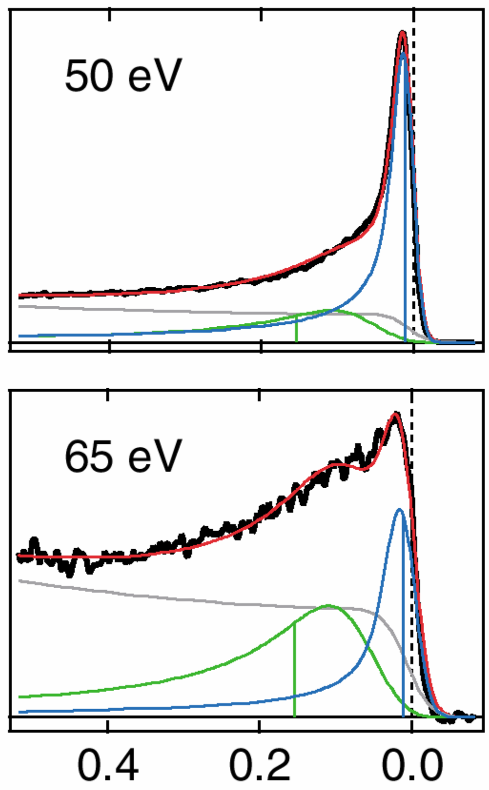
Extrinsic background



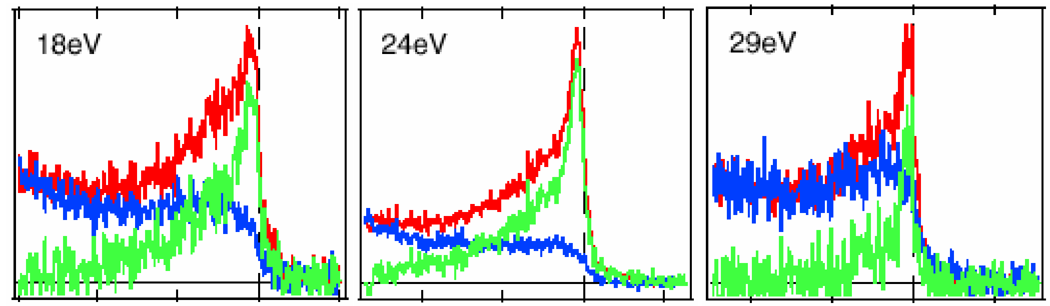




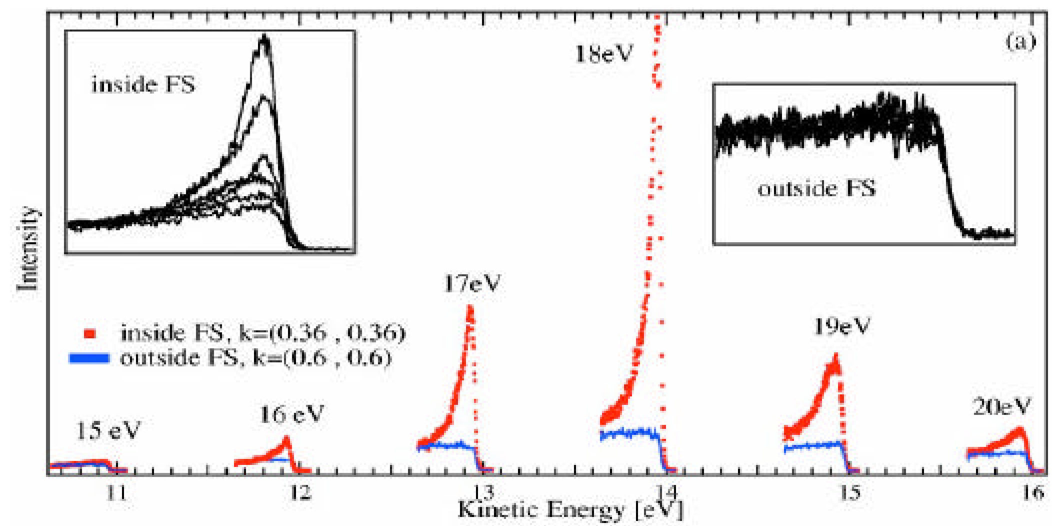
Extrinsic background
depends on excitation energy



Kordyuk *PRL* 2002

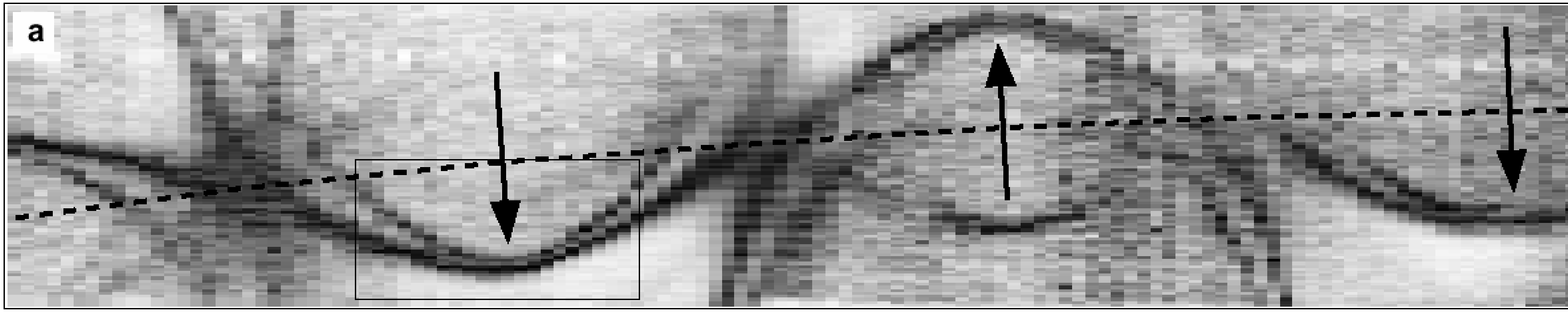


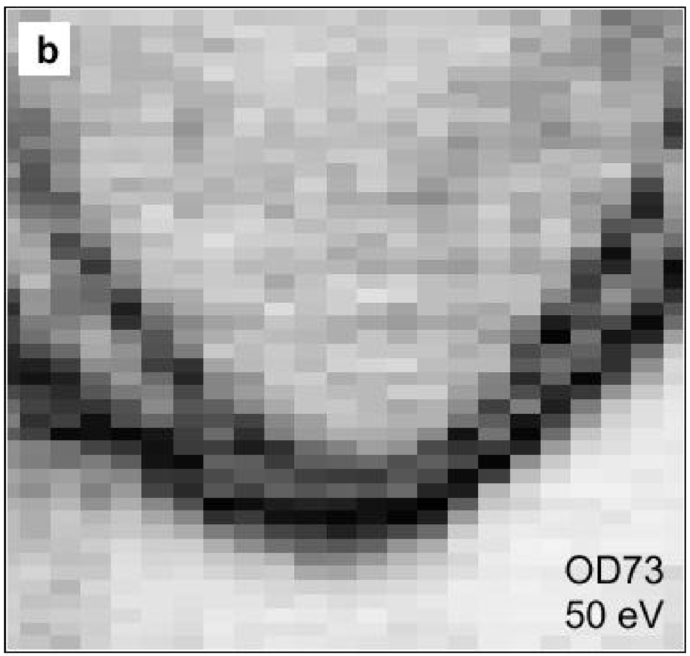
Borisenko *PhyC* 2004

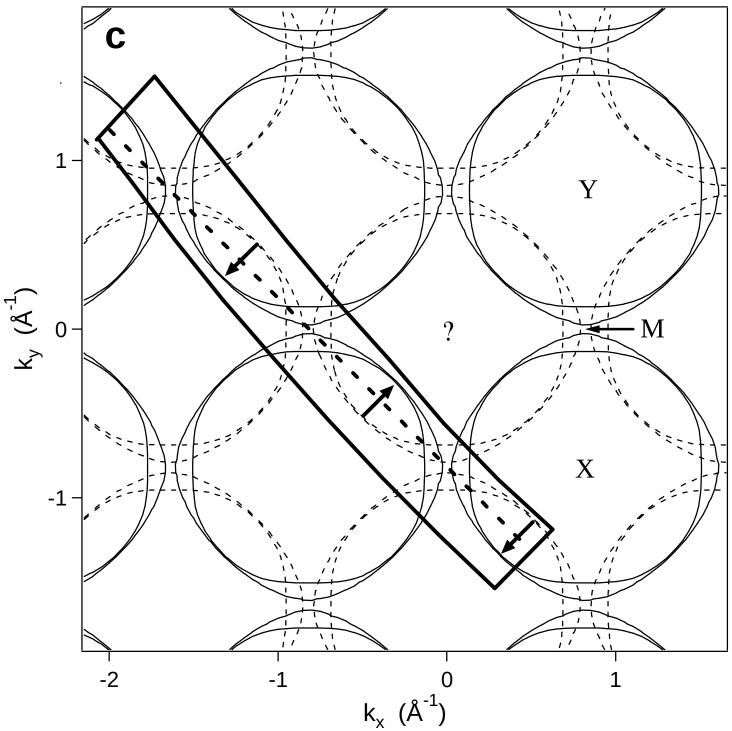


Kaminski *PRB* 2004

One more complication: nodal splitting



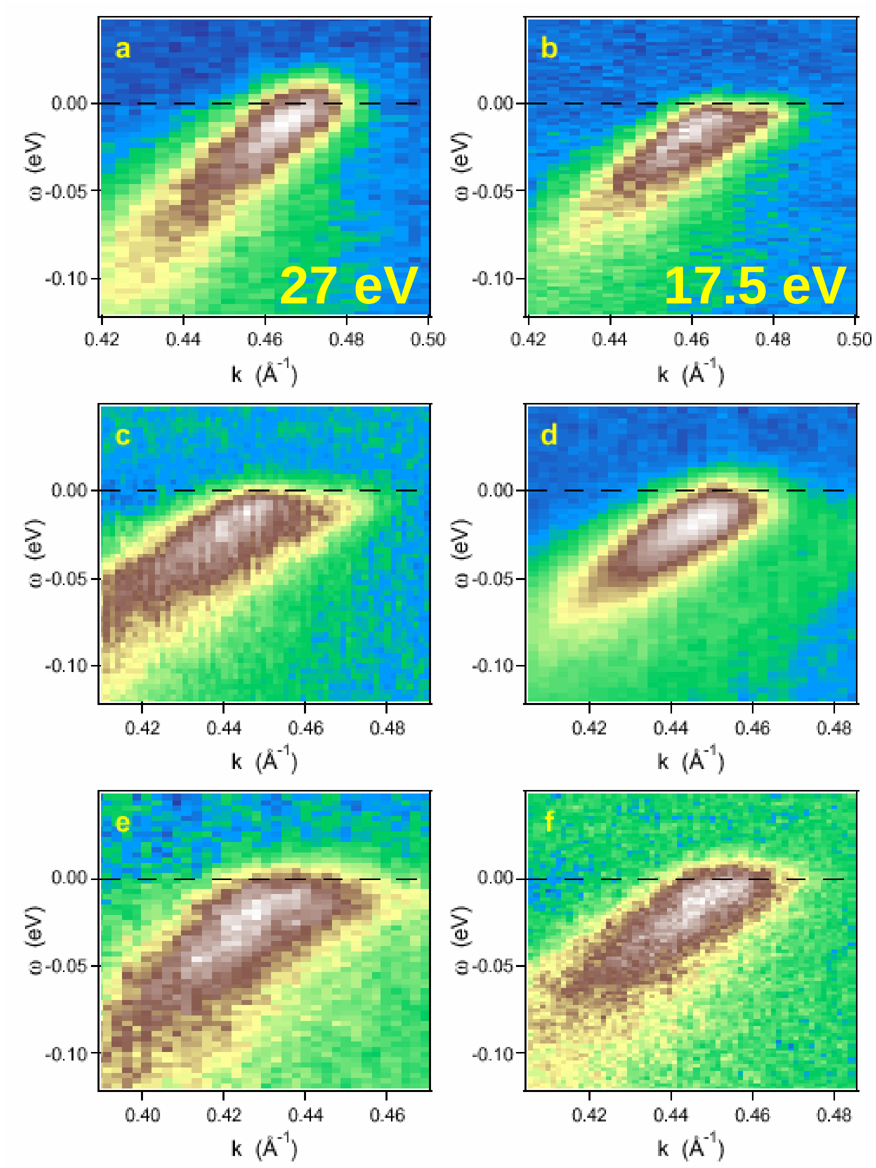


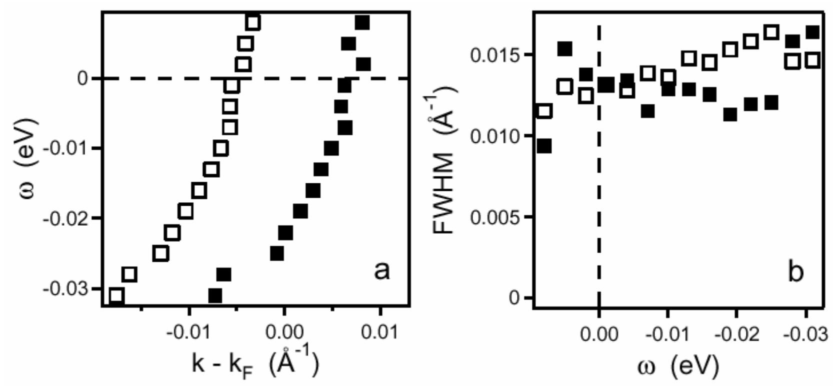


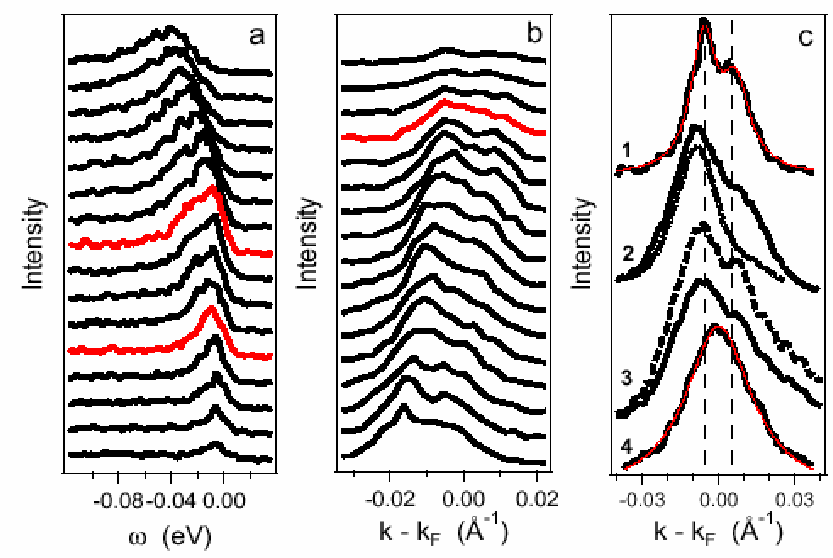
Kordyuk *PRB* 2004

Nodal splitting

$\Delta k = 0.012$ 1/Å
$\Delta\varepsilon = 50$ meV (bare!)







Kordyuk *PRB* 2004

IF

one use

superstructure-free high quality samples

with negligible k_z dispersion (Bi(Pb)-2212)

and

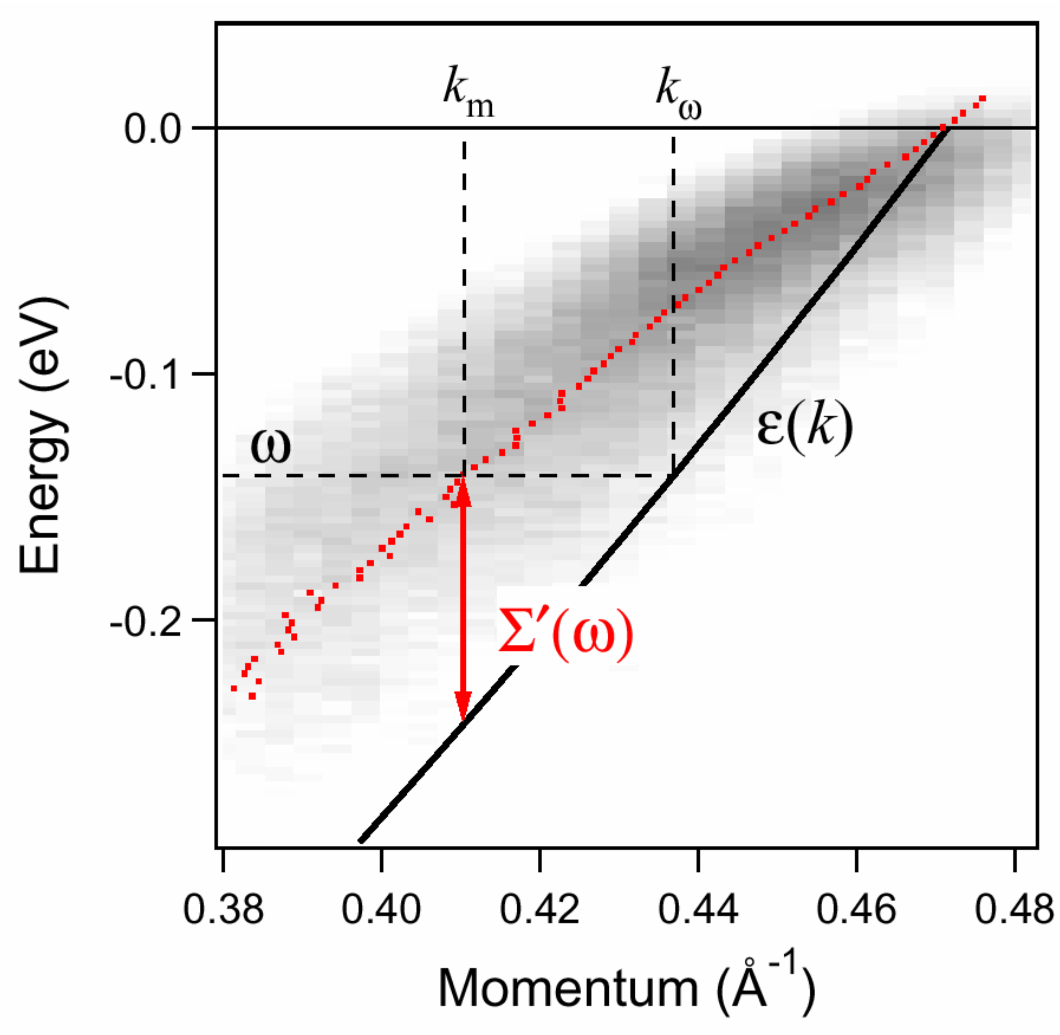
rid of the background

and bilayer splitting effect,

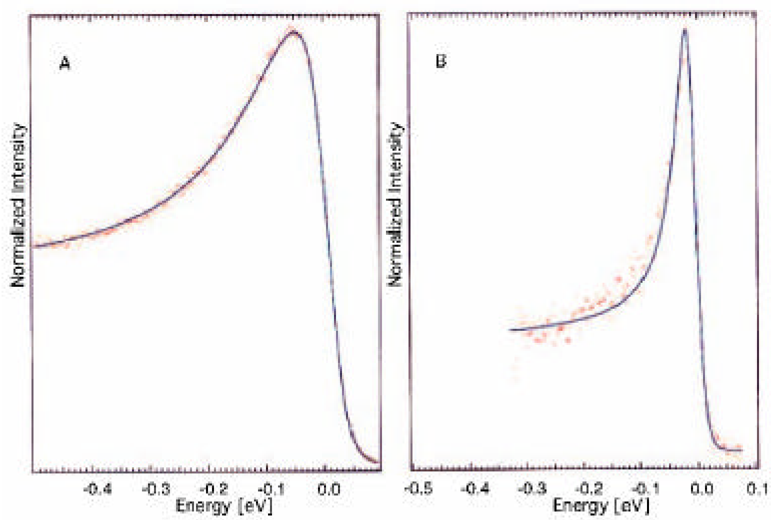
one may get an access to the

quasiparticle spectral function.

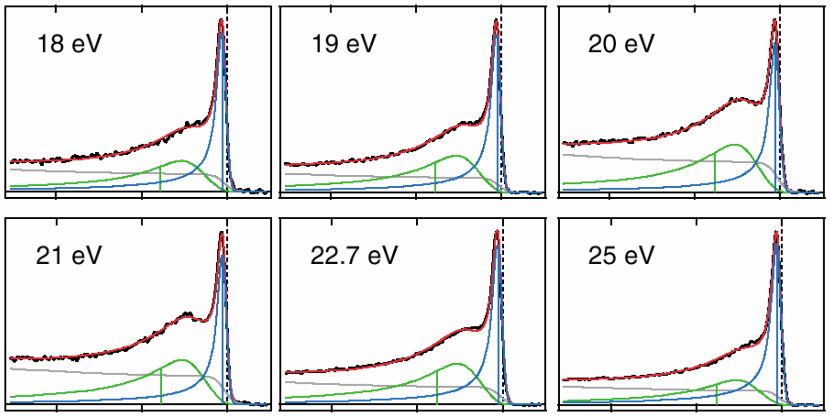
Quasiparticle spectral function



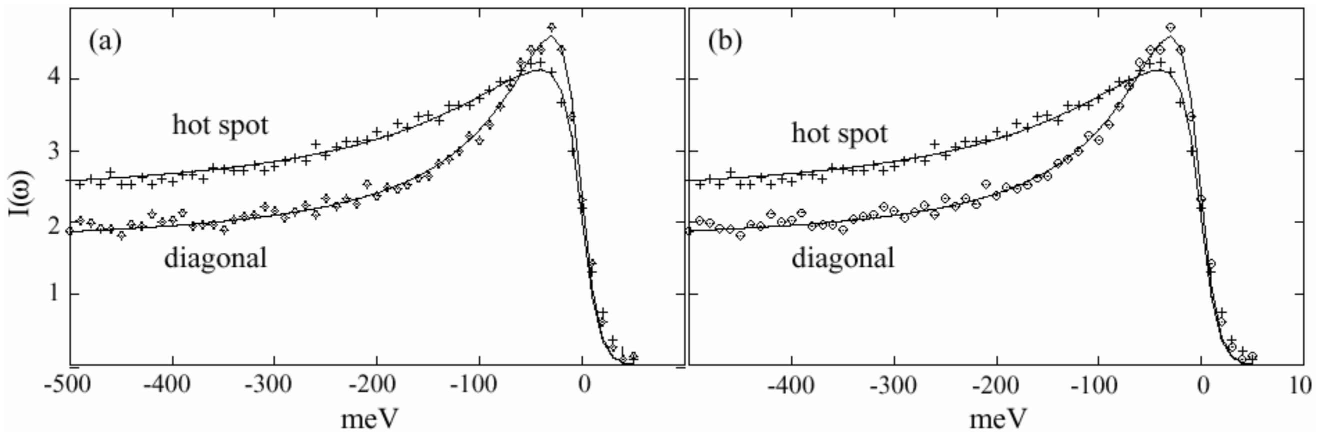
Quasiparticle spectral function



Abrahams *PNAS* 2000



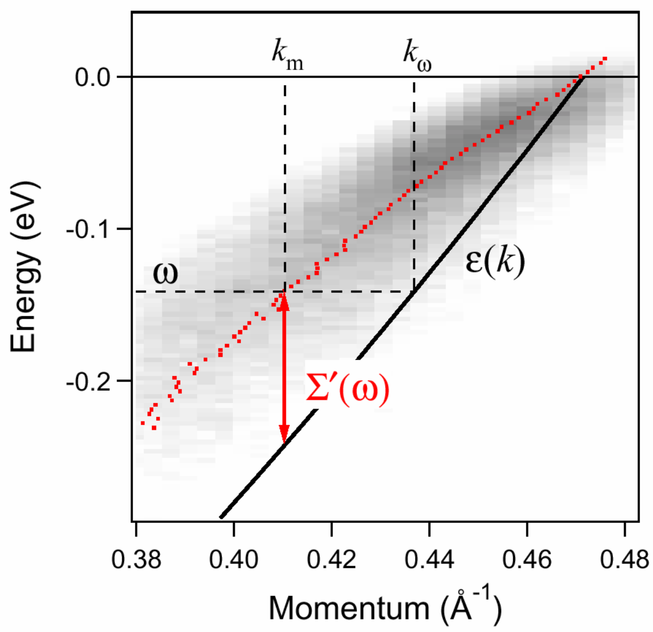
Kordyuk *PRL* 2002



Haslinger *EPL* 2002

Self-energy approach

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



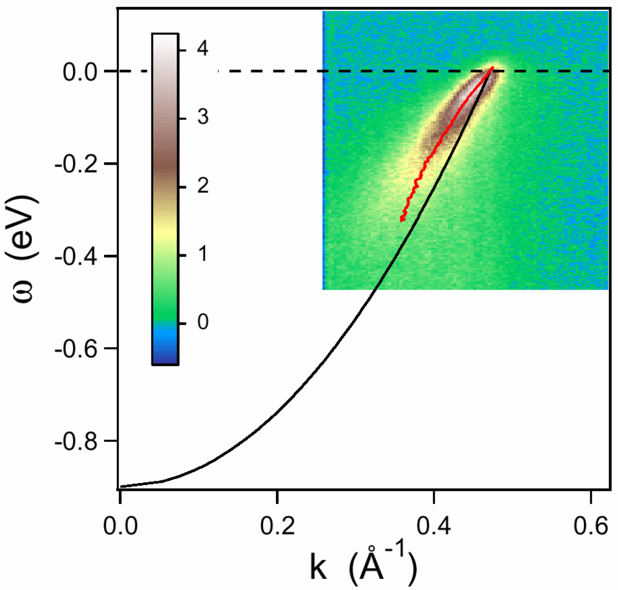
$$\Sigma'(\omega) = \omega - \varepsilon(k_m)$$

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

Self-energy approach: fitting procedure

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

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



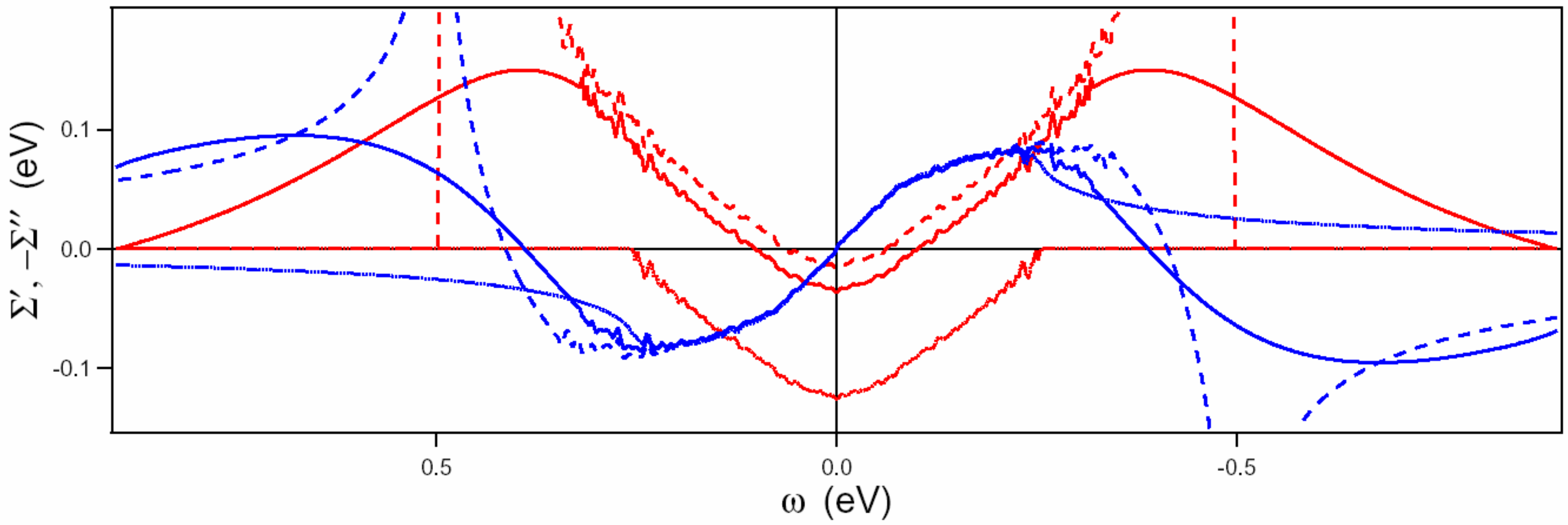
$$\Sigma'(\omega) = \mathrm{KK}\ \Sigma''(\omega)$$

Three parameters

bare band parameter: v_F or ω_0

tail parameters: ω_c and n

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



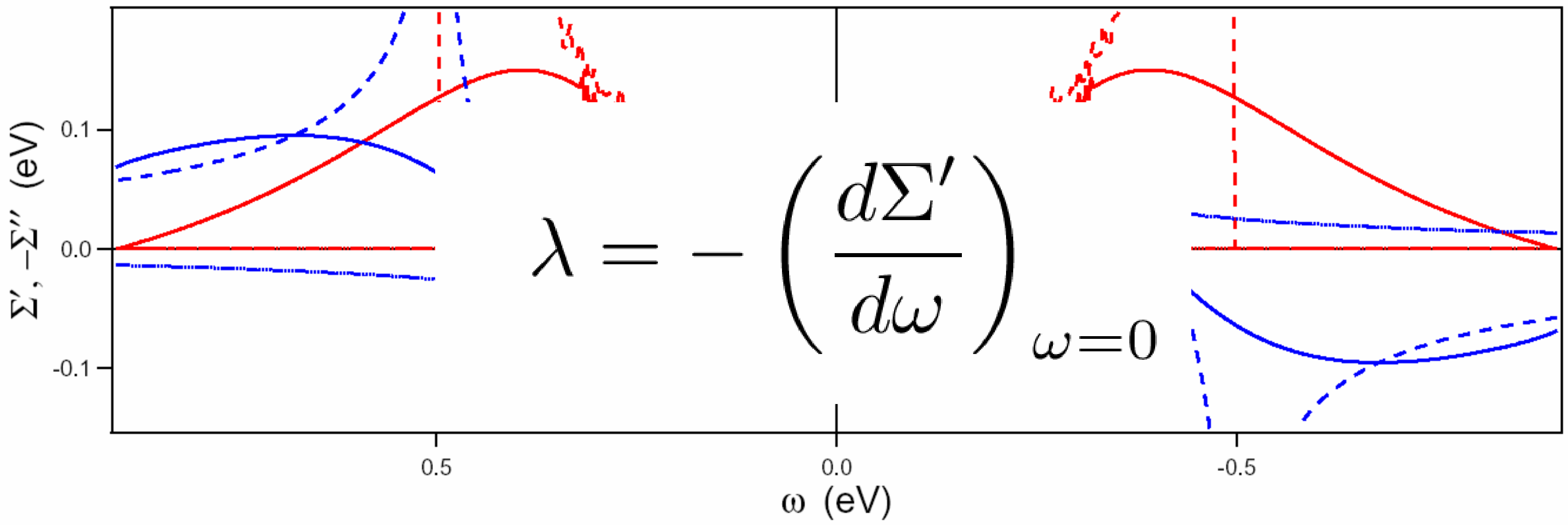
$$\Sigma''(\omega) = -\begin{cases} \alpha\omega^2 + C & \text{for } |\omega| < \omega_c, \\ 0 & \text{for } |\omega| > \omega_c, \end{cases}$$

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

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

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

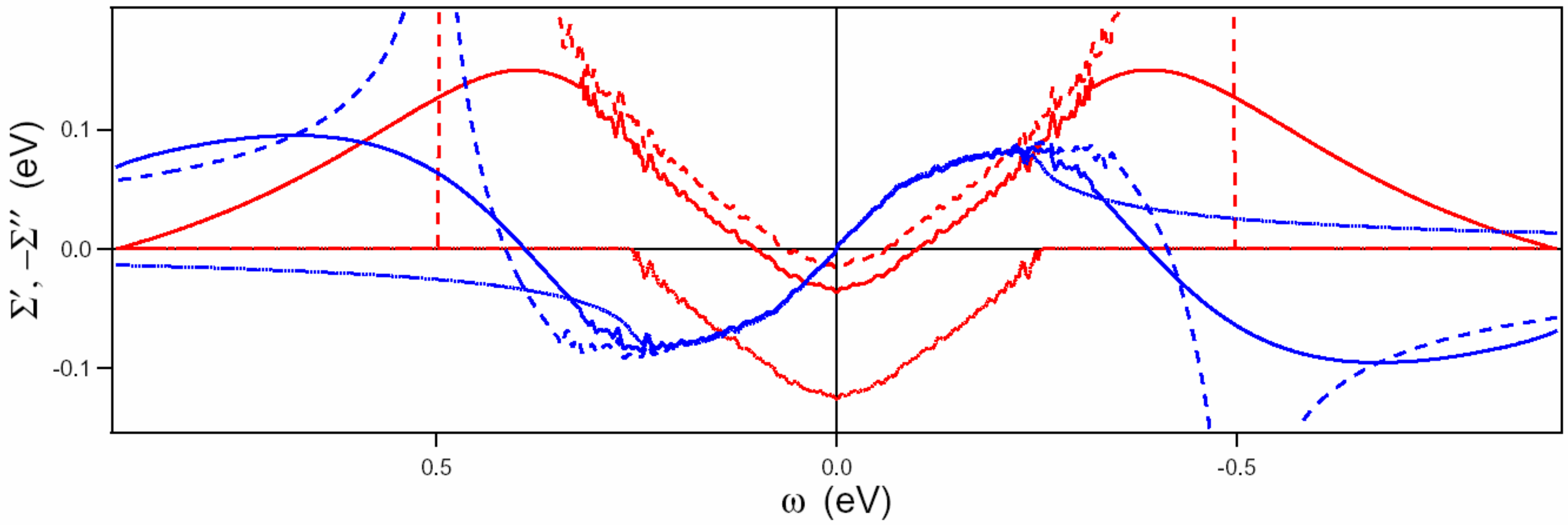
Kramers-Kronig transform $\Sigma'(\omega) = \text{KK}\ \Sigma''(\omega)$



$$\lambda = -\left(\frac{d\Sigma'}{d\omega}\right)_{\omega=0}$$

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

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

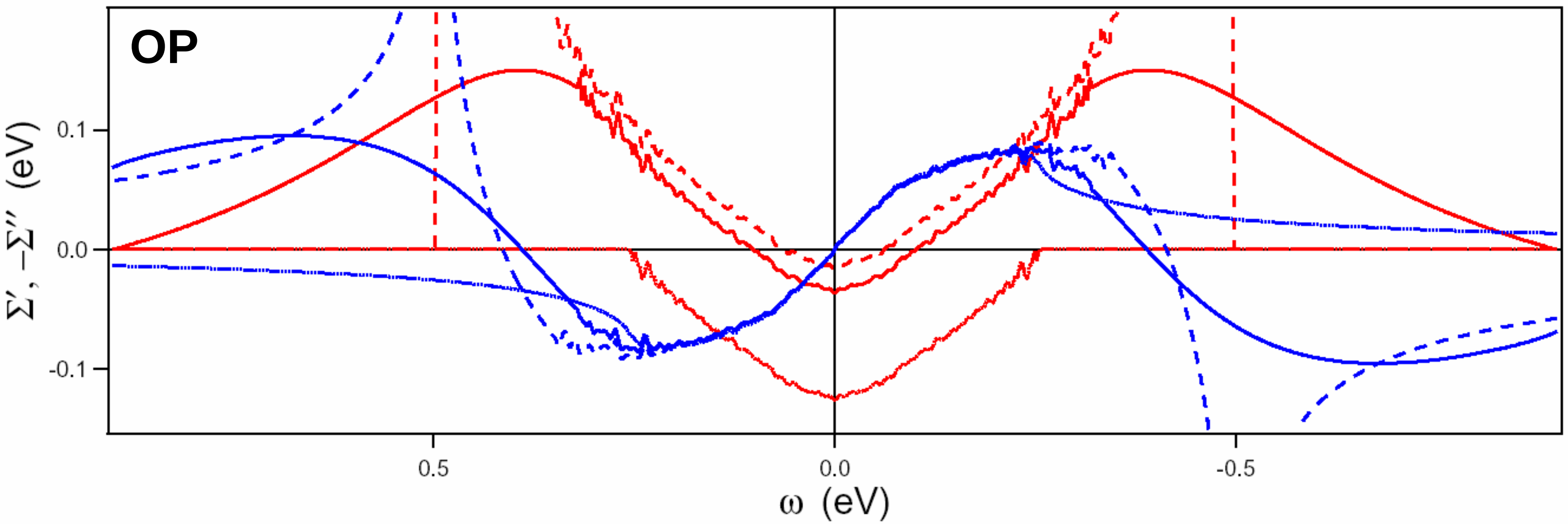


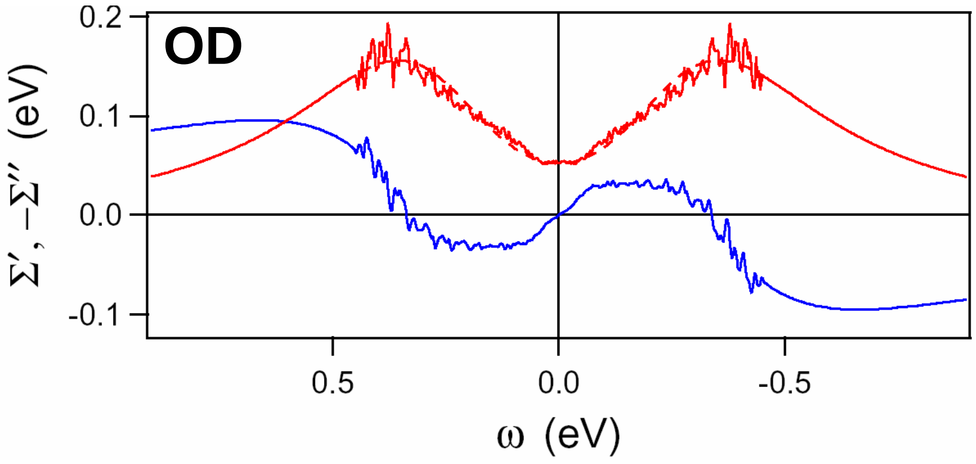
$$\Sigma''(\omega) = \begin{cases} \Sigma''_{width}(|\omega|) & \text{for } |\omega| < \omega_m, \\ \Sigma''_{mod}(\omega) & \text{for } |\omega| > \omega_m, \end{cases}$$

$$\Sigma''_{mod}(\omega) = -\frac{\alpha\,\omega^2 + C}{1 + \left|\frac{\omega}{\omega_c}\right|^n},$$

Kordyuk *PRB* 2005

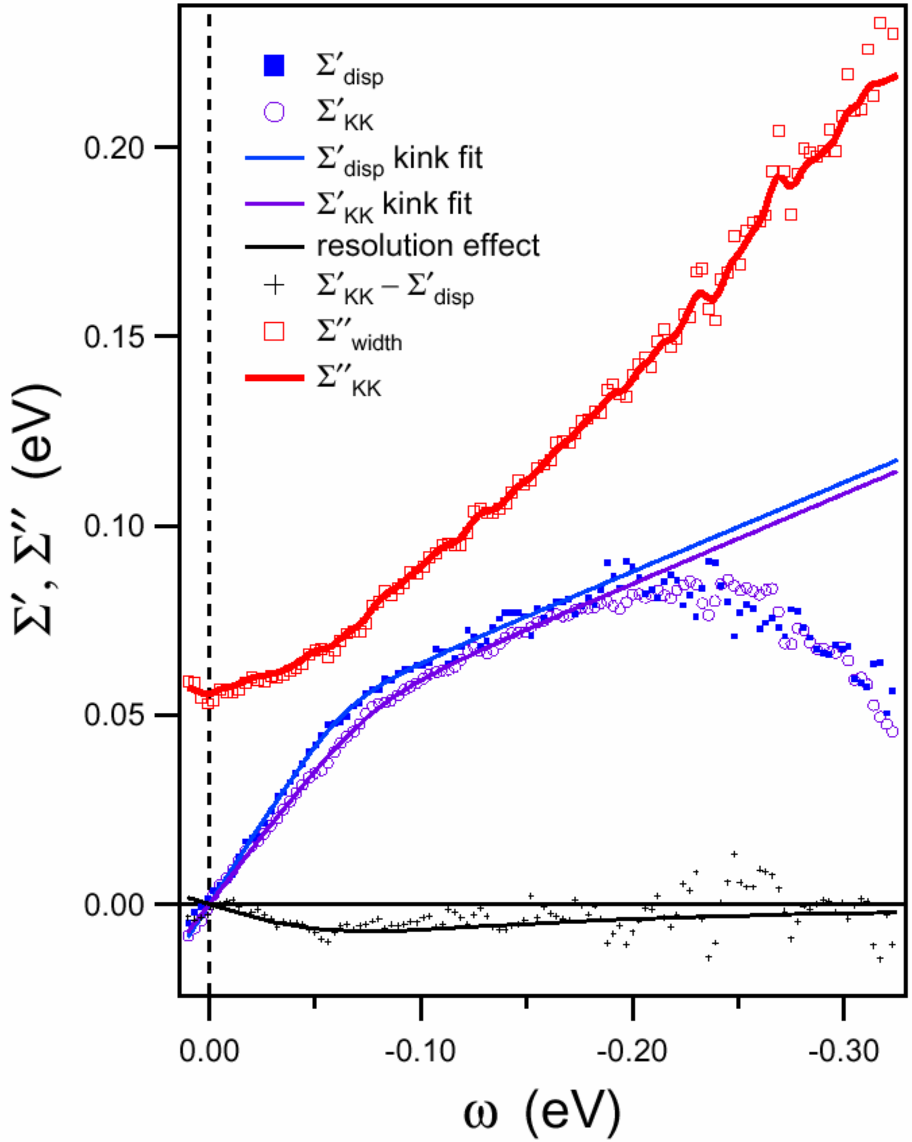
Kramers-Kronig transform $\Sigma'(\omega) = \mathrm{KK}\ \Sigma''(\omega)$

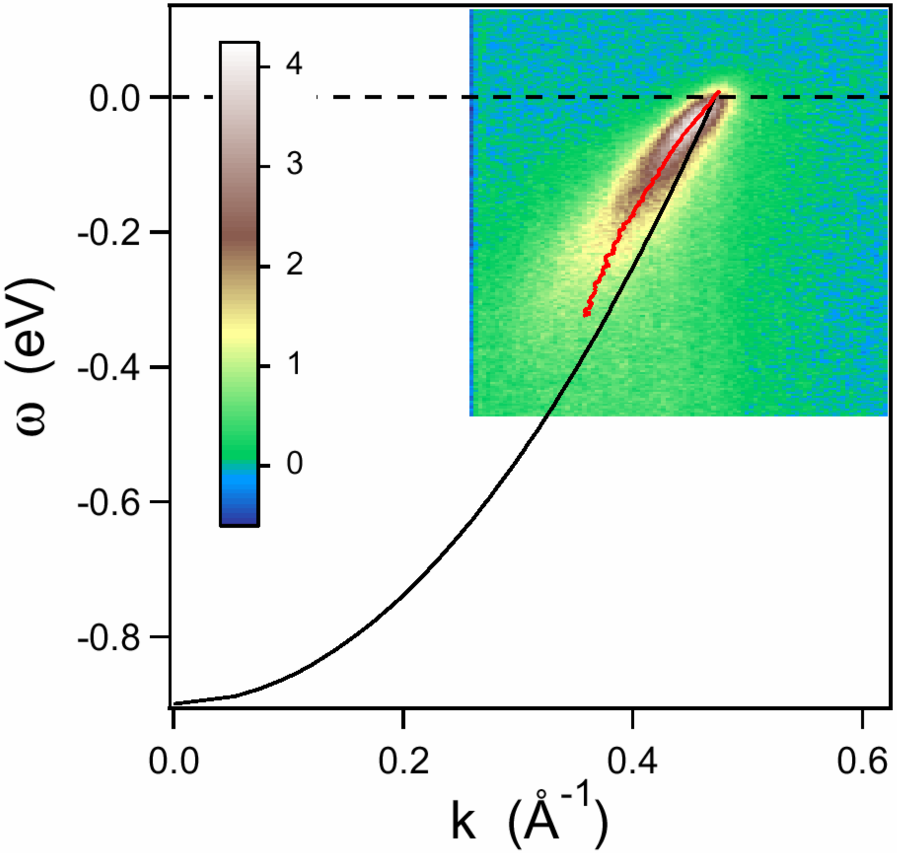




Kordyuk *PRB* 2005

Real Self-Energy



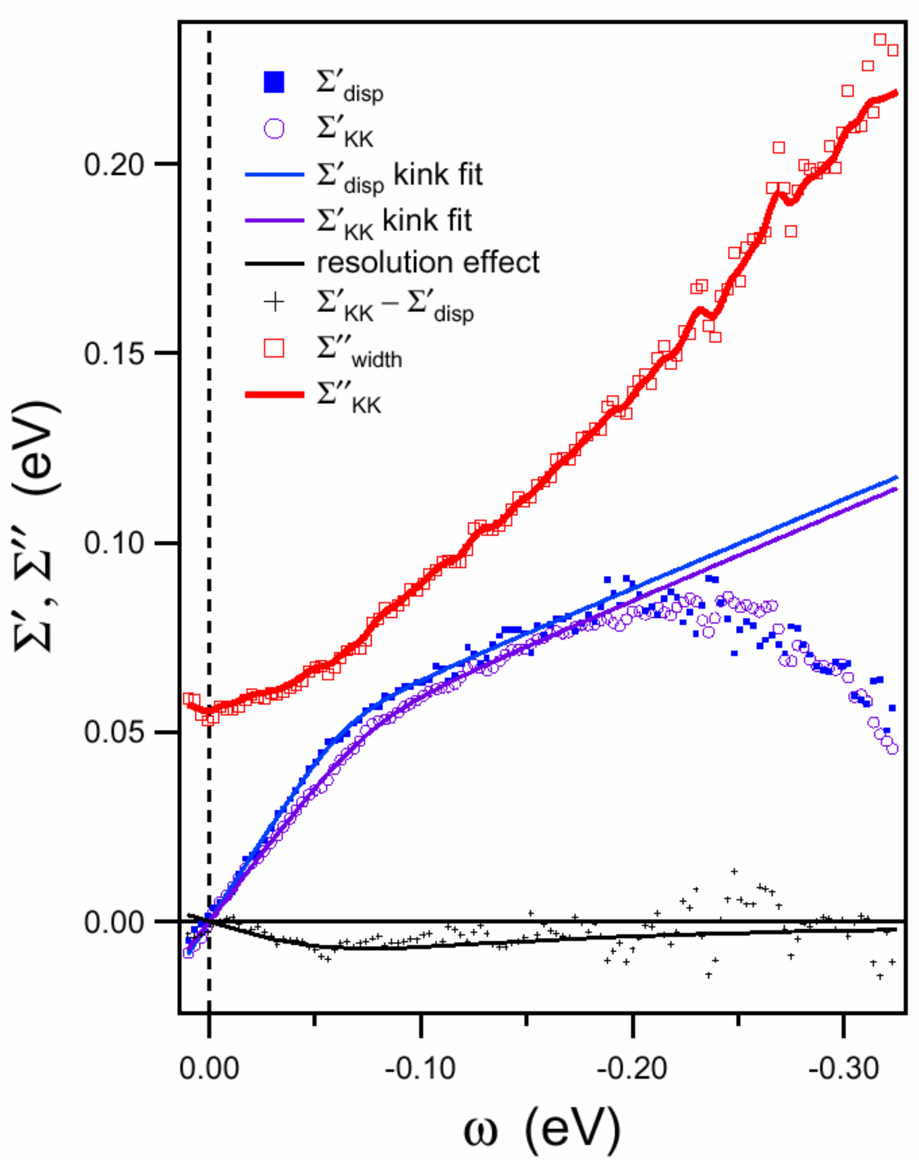


$$v_F = 3.82 \pm 0.17 \text{ eVÅ}$$

$$\lambda = 0.87 \pm 0.12$$

Kordyuk *PRB* 2005

Real Self-Energy



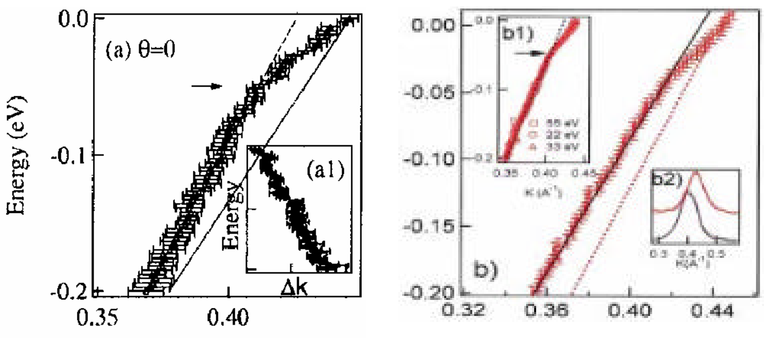
Self-consistency:
LDA + self-energy

Well defined quasi-particles

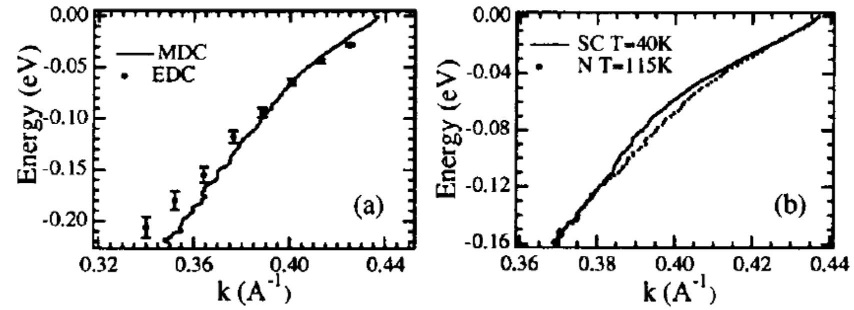
Kink phenomenology

Kordyuk *PRB* 2005

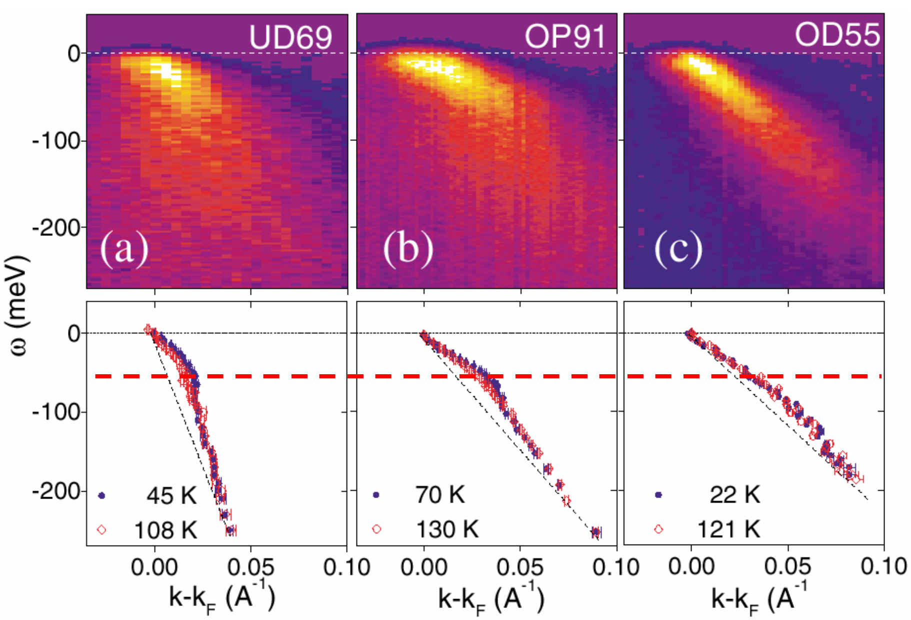
„Kinks“



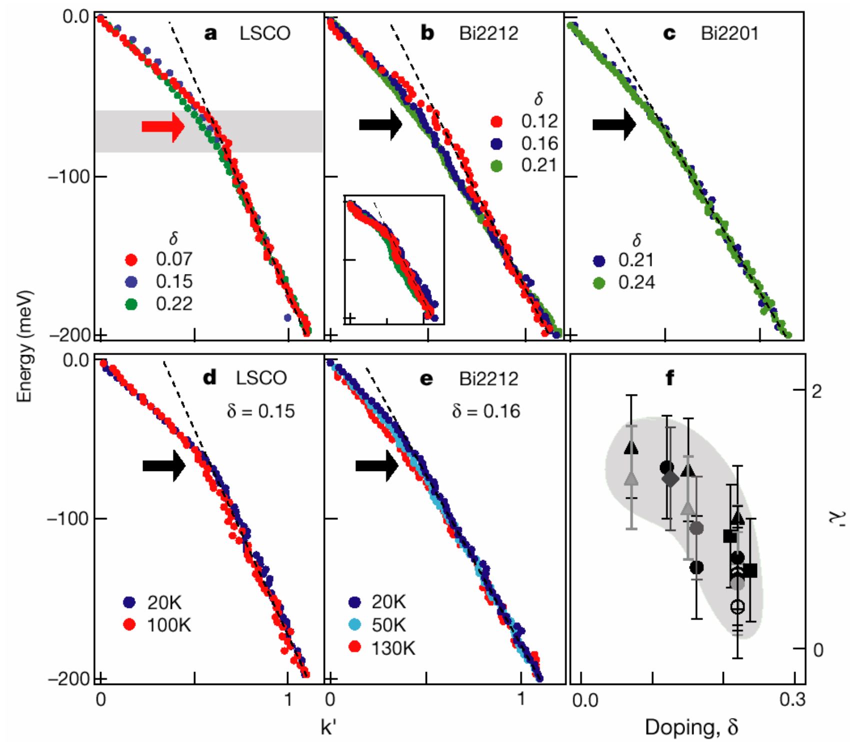
Bogdanov *PRL* 2000



Kaminski *PRL* 2001

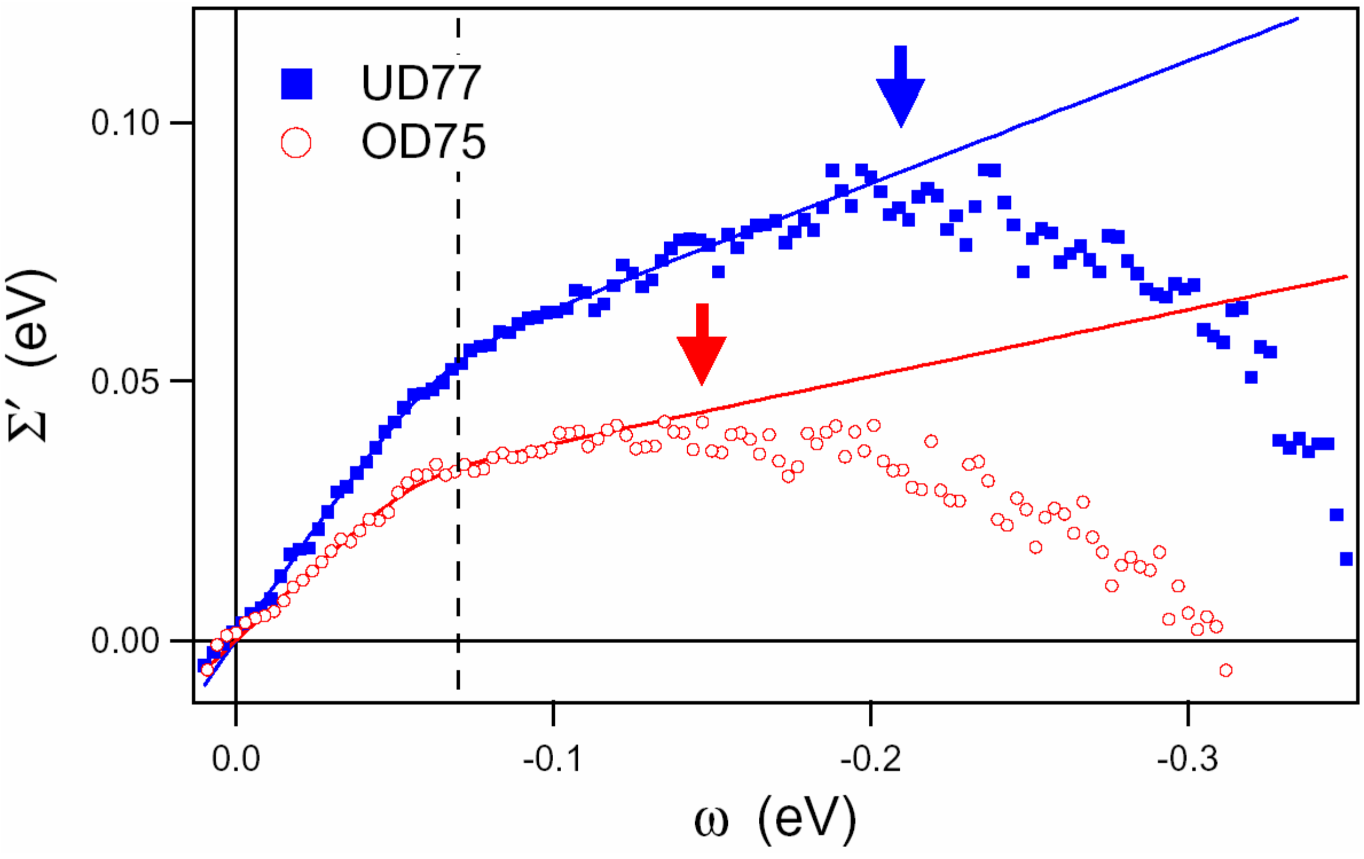


Johnson *PRL* 2001



Lanzara *Nature* 2001

Phenomenology of the kink

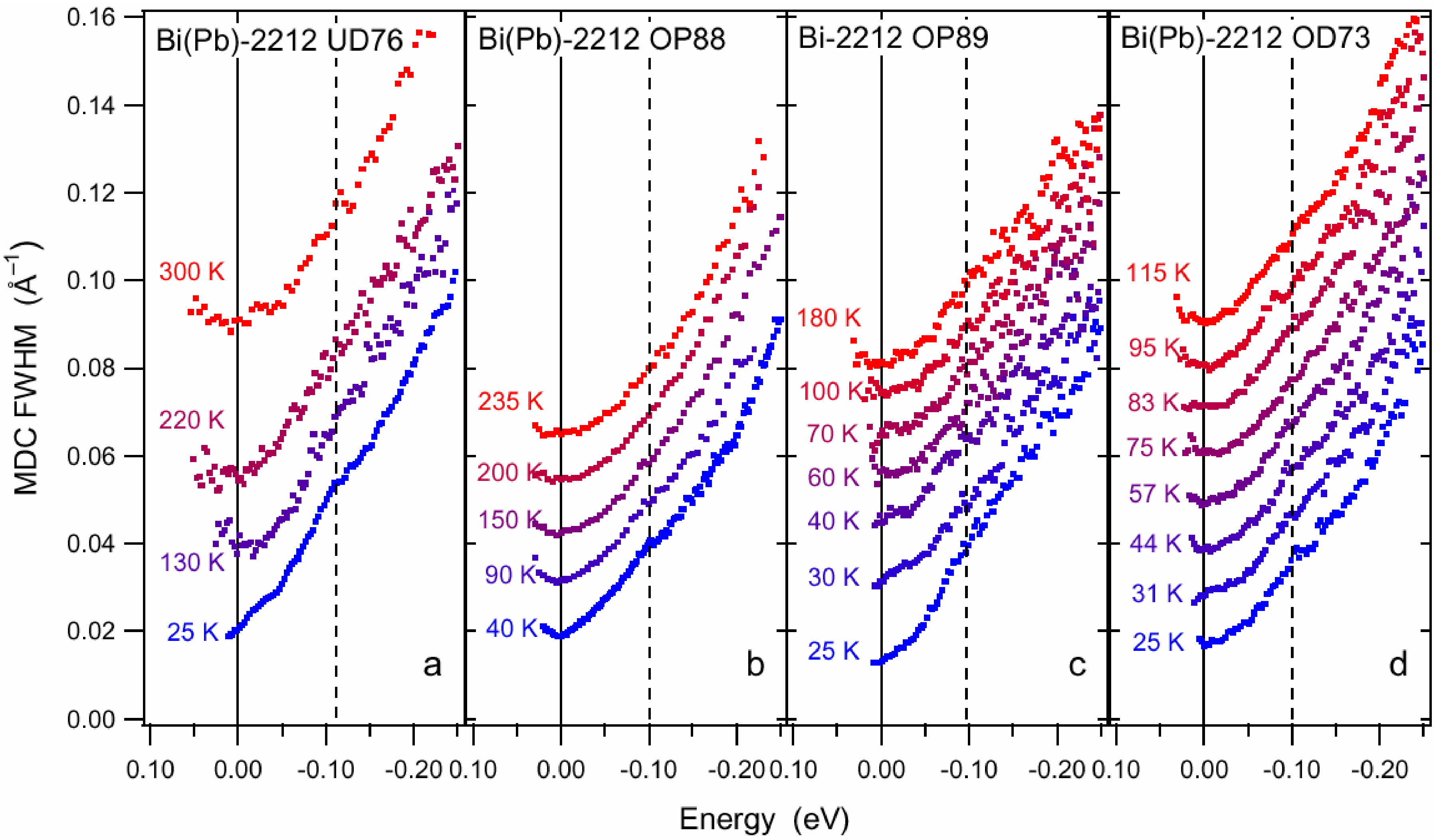


Kordyuk *PRB* 2005

Quasiparticle scattering rate

What is the main scatterer?

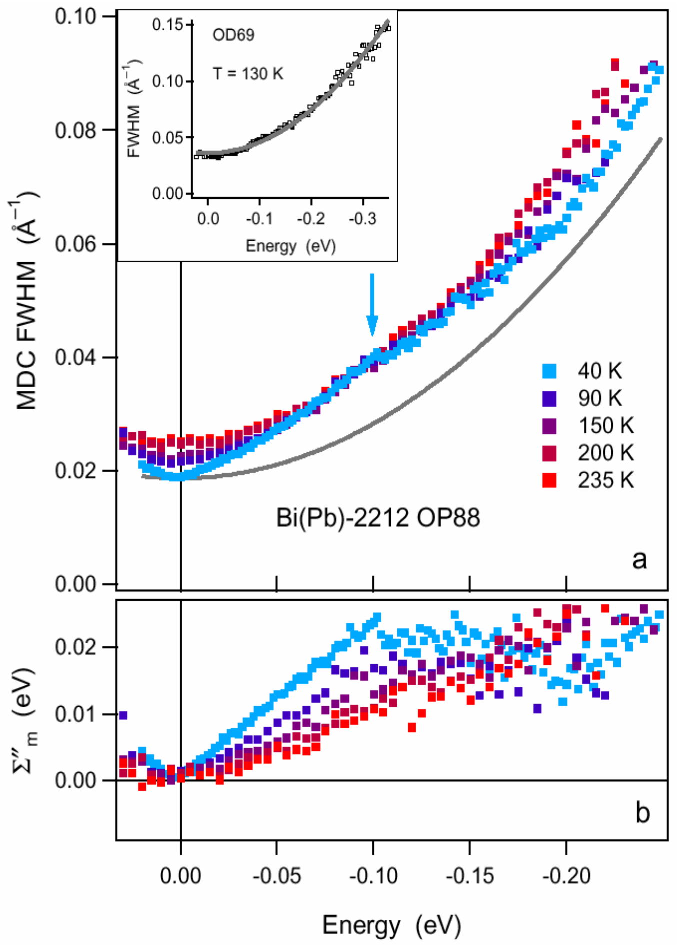
Scattering rate kink



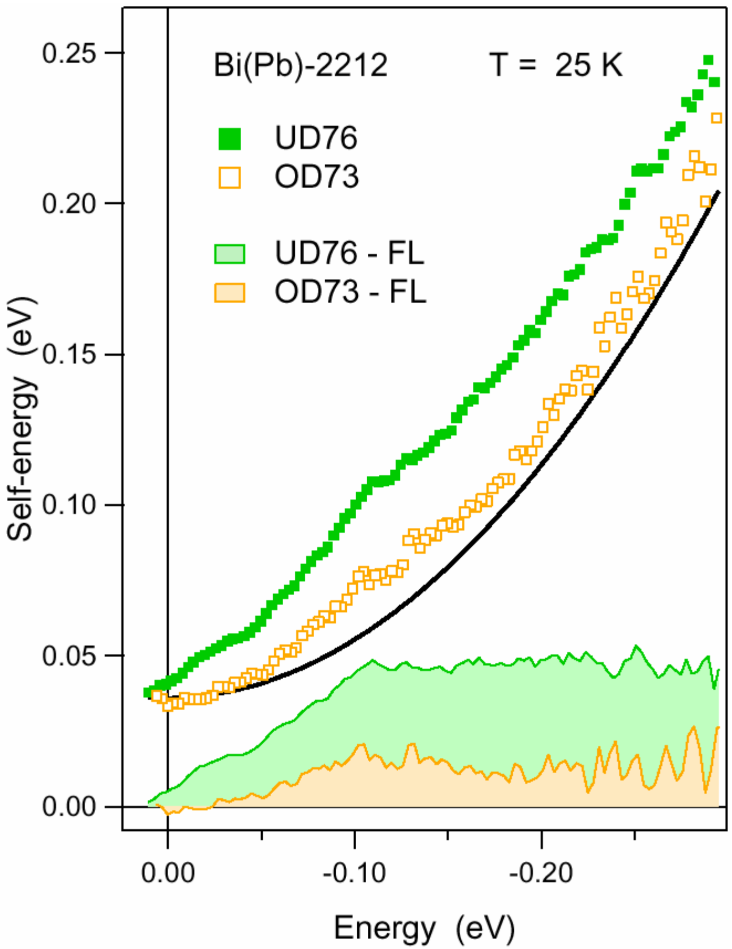
Kordyuk *PRL* 2004

Scattering rate:

T-dependence

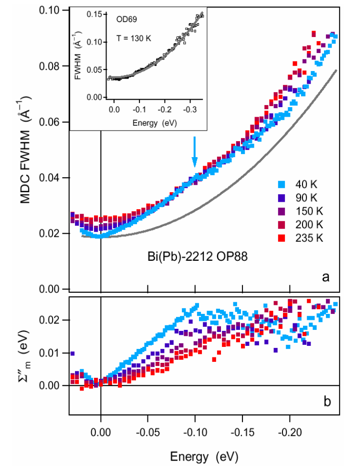


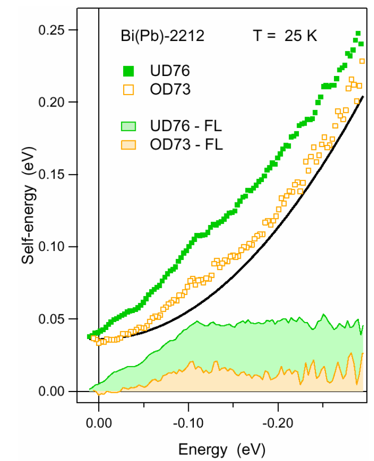
Doping dependence



Kordyuk *PRL* 2004

Scattering rate:
Some conclusions

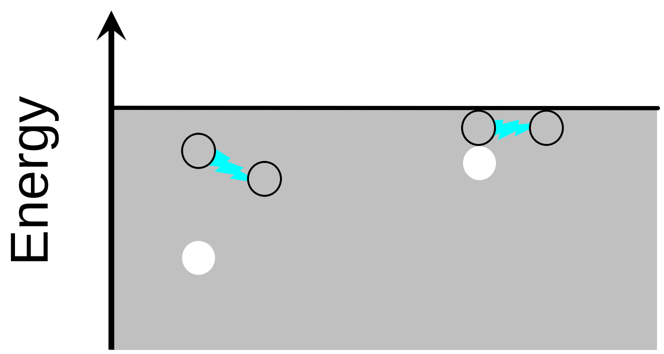


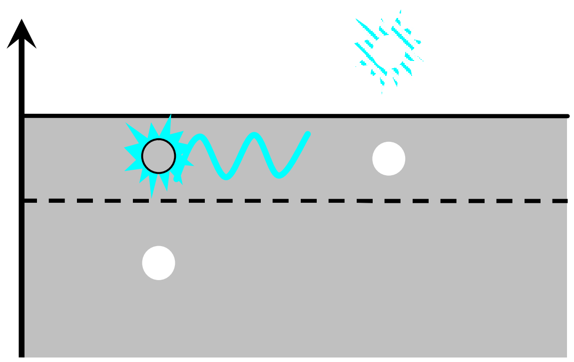


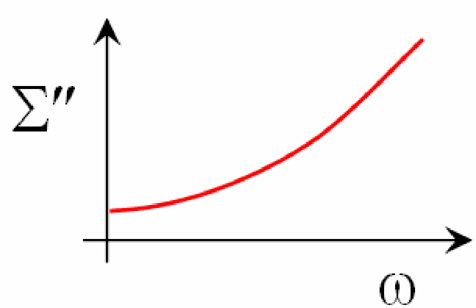
There are two channels:

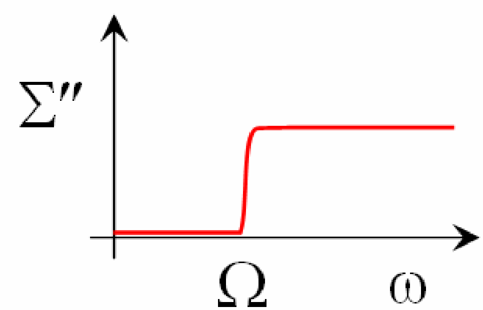
1st electron-electron scattering and

2nd electron-boson scattering

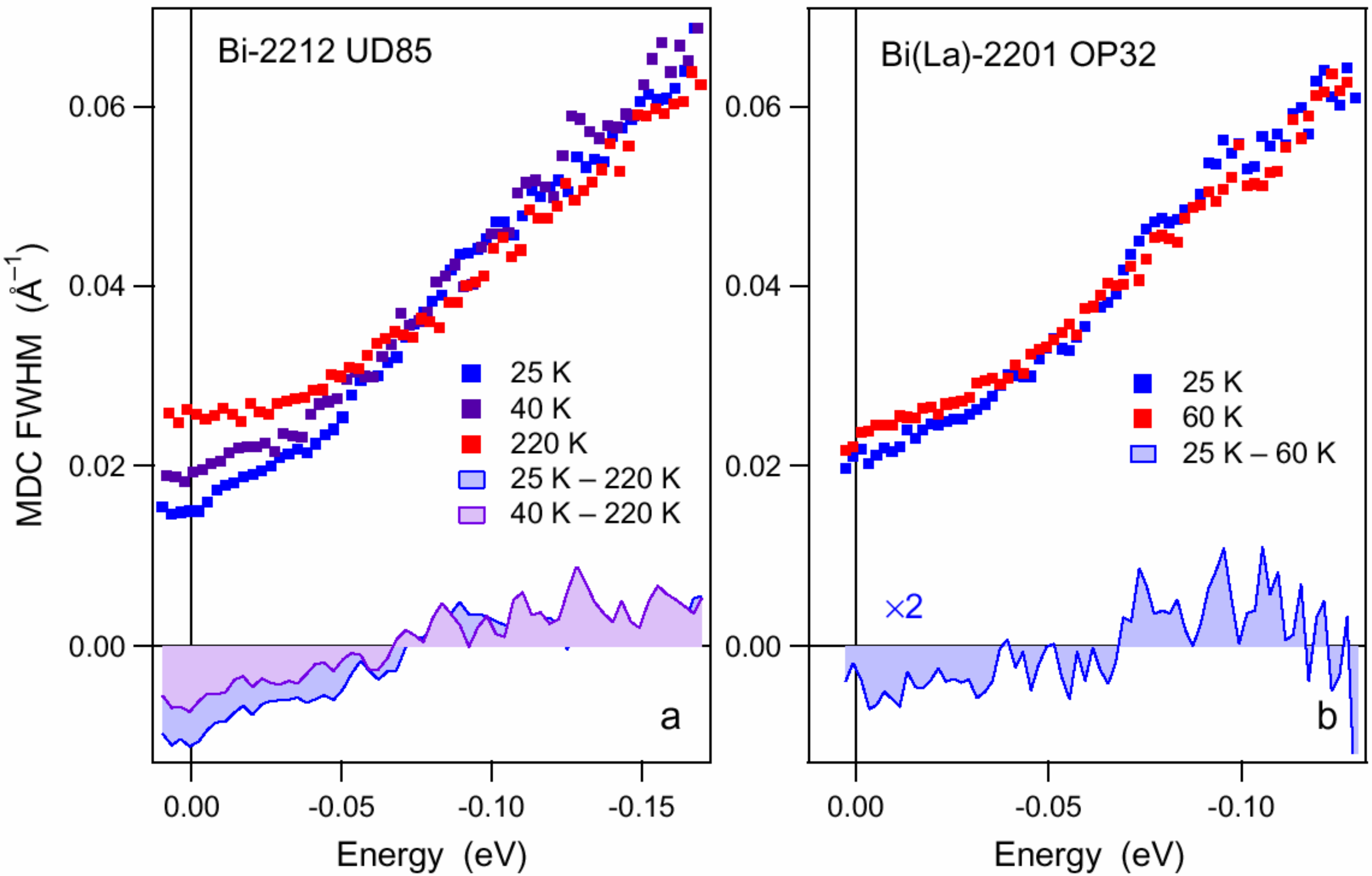








Scattering rate kink



Kordyuk *PRL* 2004

Nodal electrons couple to ...

Doping dependence: **UD↑**

OD↓

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 $\mathrm{Re}\Sigma(\omega)$ due to vHs approaching Fermi level.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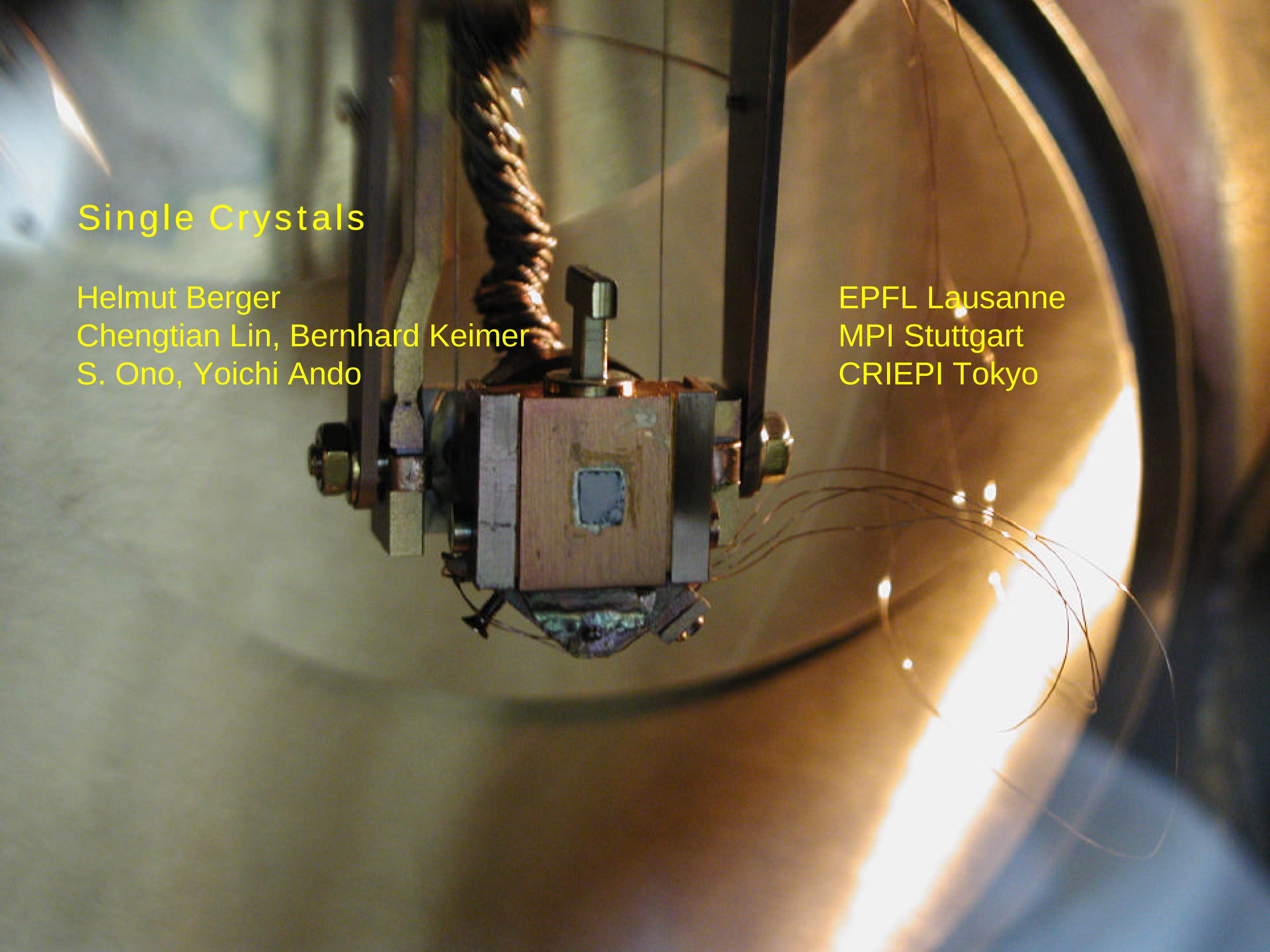
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THE END