Unadulterated spectral function of low-energy quasiparticles

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Low-Energy QuasiParticle spectrum $\Sigma = \Sigma' + i\Sigma''$

- Is quasiparticle approach valid ?
- ARPES **vs.** Transport ?
- Nature of interactions in HTSCs ?

Questions to behavior of $\boldsymbol{\Sigma'' \sim 1/\tau}$

- Offset at $\omega \rightarrow 0$ and at $T \rightarrow 0$?
- Behavior near T_C ?
- Evolution with doping?

Problems

- How to remove **resolution effects** accurately?

$$R\text{-}?$$

- How to disentangle **impurity scattering** from **quasiparticle interaction**?

$$\Sigma''_{int} = \Sigma'' - \Sigma''_{imp}$$

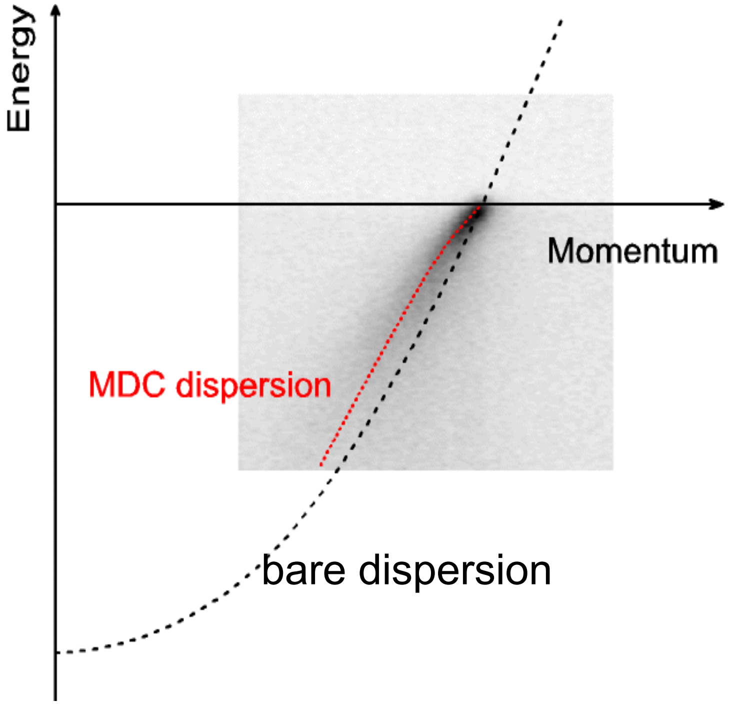
Total response function

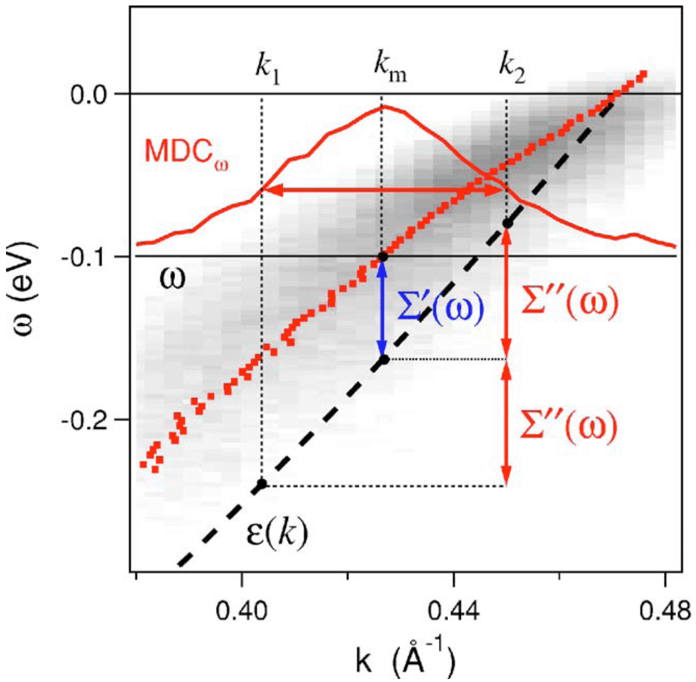
$$R = R_A \otimes R_S$$

- R_A – Analyzer
  - Remains constant
  - Easy to measure

- R_S – Sample Surface
  - Varies with space and time
  - Difficult to measure

Processing of ARPES Image





$A(\omega, k) \sim \mathrm{Im}(G(\omega, k))$

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

MDC(k) = A(ω, k), ω=*const*

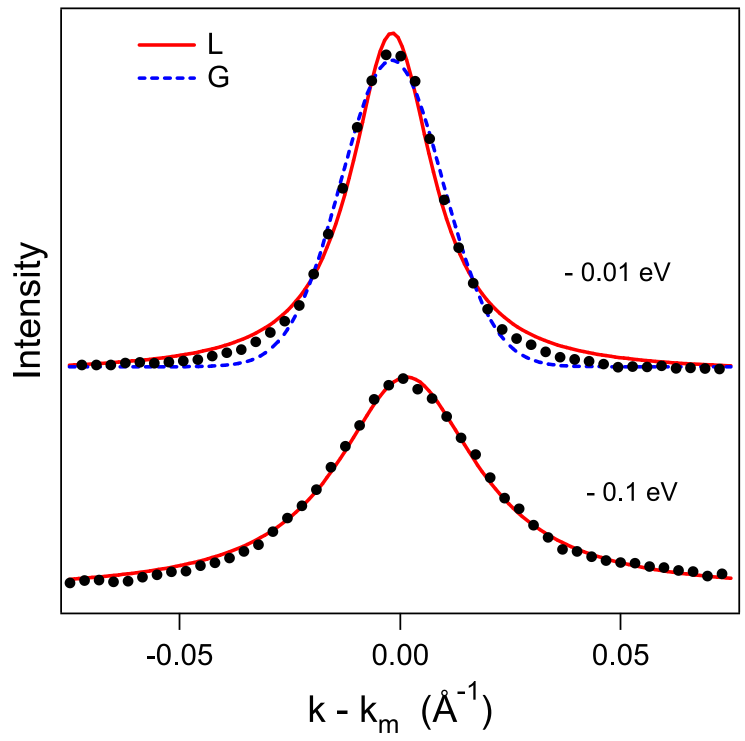
Spectral Function Extraction from ARPES Data

$$I(k, \omega) \propto A(k, \omega) \otimes R(k, \omega)$$

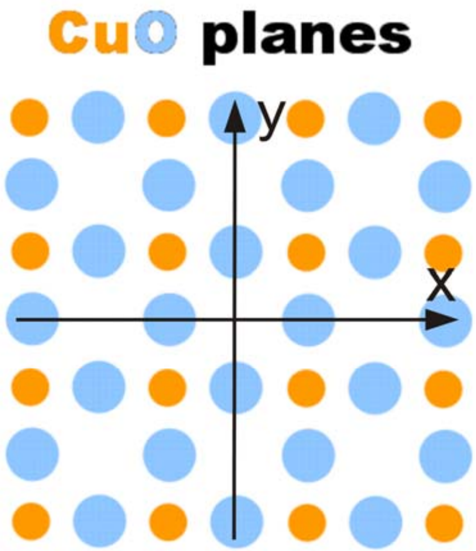
We measure $I(k, \omega)$

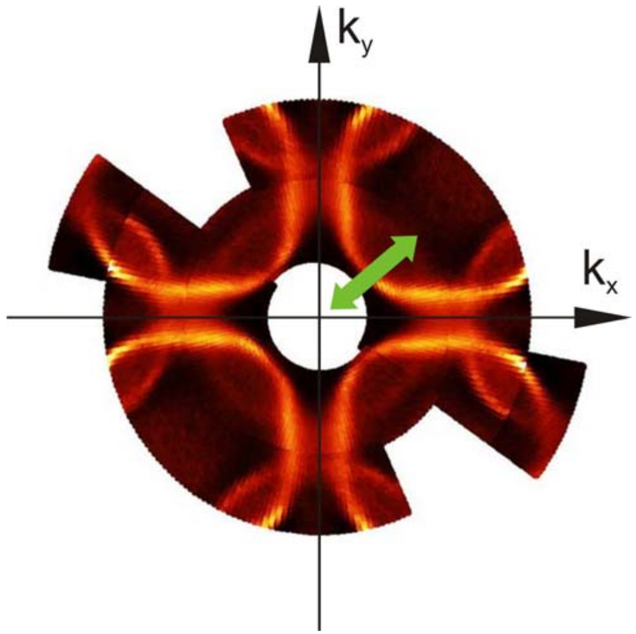
We are interested in $A(k, \omega)$

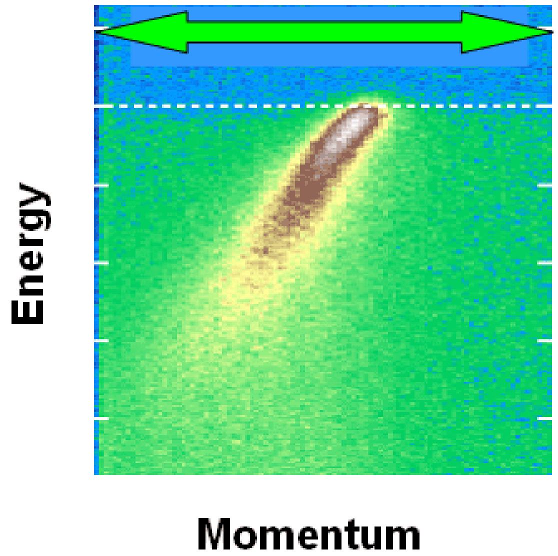
We need to remove $R(k, \omega)$



Nodal Direction







No gap

Momentum Resolution

$\Sigma(k,\omega)=\Sigma(\omega)$ M(k)=const $\varepsilon(k)$ linear

Without resolution effects MDC is perfect **lorentzian**:

$$L(k) = A(k,\omega_0) = -\frac{1}{\pi} \cdot \frac{\Sigma''(\omega_0)}{\left(v \cdot \left(k - k_{\max}\right)\right)^2 + (\Sigma''(\omega_0))^2}$$

Real MDC is a **convolution** between pure signal and resolution:

$$MDC(k) = L \otimes R = \int L(k-\kappa) \cdot R(\kappa) \cdot d\kappa$$

Where resolution is a **gaussian**: $R(k) = \frac{1}{\sigma\sqrt{\pi}} e^{-\frac{k^2}{\sigma^2}}$

Real MDC = Pure MDC
(Lorentzian)

$$\text{Real MDC} = \underset{\text{(Lorentzian)}}{\text{Pure MDC}} \otimes \underset{\text{(Gaussian)}}{\text{Resolution}}$$

Real MDC = Pure MDC $\otimes$ Resolution
(Lorentzian) (Gaussian)

Lorentzian $\otimes$ Gaussian = Voigt profile

Real MDC = Pure MDC $\otimes$ Resolution
(Lorentzian) (Gaussian)

Lorentzian $\otimes$ Gaussian = Voigt profile

What is **Voigt Profile**?

Voigt Profile

$$V(k) = L \otimes G = \int L(k-\kappa)\cdot G(\kappa)\cdot d\kappa$$

Where L is a lorentzian, and G is gaussian. HWHM $\mathbf{W_L}$ and $\mathbf{W_G}$

$$L(x) = \frac{1}{1 + x^2 / \boldsymbol{W_L}^2}, \qquad G(x) = \frac{\sqrt{\ln(2)}}{W_G\sqrt{\pi}} \exp(-\ln(2)\cdot x^2 / \boldsymbol{W_G}^2)$$

HWHM of Voigt profile, $\mathbf{W_V}$:

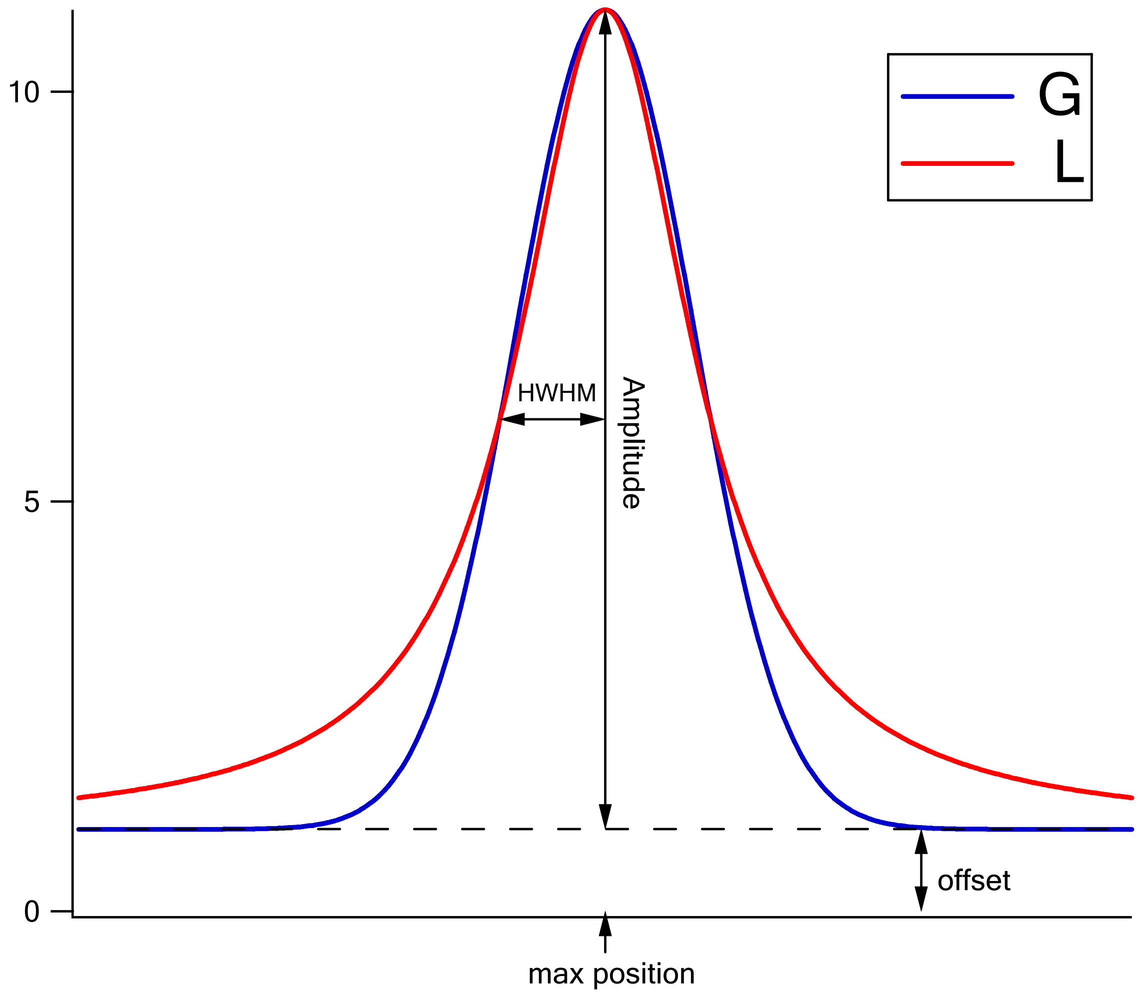
$$W_V \approx \frac{W_L}{2} + \sqrt{\frac{W_L^2}{4} + W_G^2}$$ error< 1.2 %

$$W_L << W_G \Rightarrow W_V \approx \frac{W_L}{2} + W_G$$

Lorentz, Gauss

L, G:

1. Offset
2. Max position
3. Amplitude
4. Width



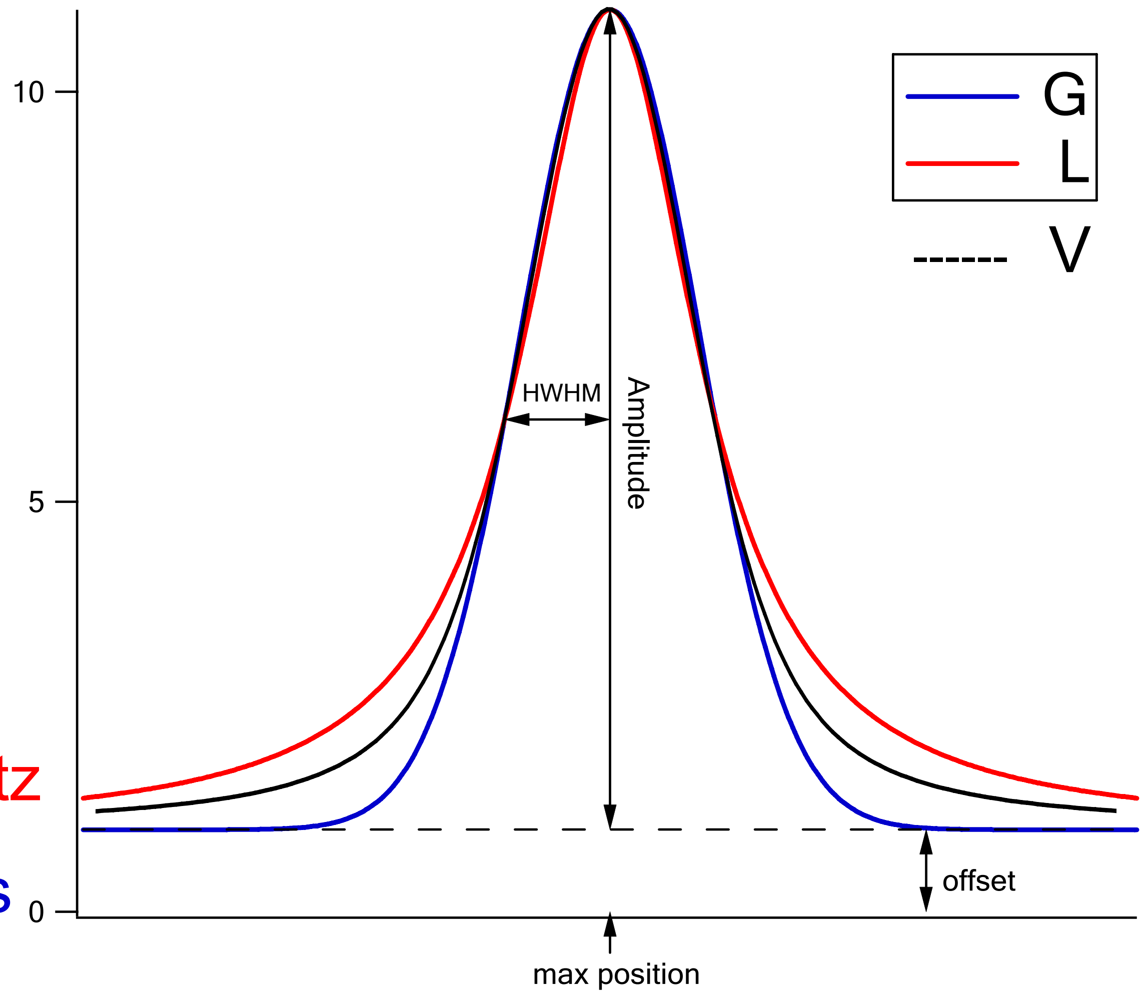
Lorentz, Gauss and Voigt

L, G:

1. Offset
2. Max position
3. Amplitude
4. Width

One more parameter:

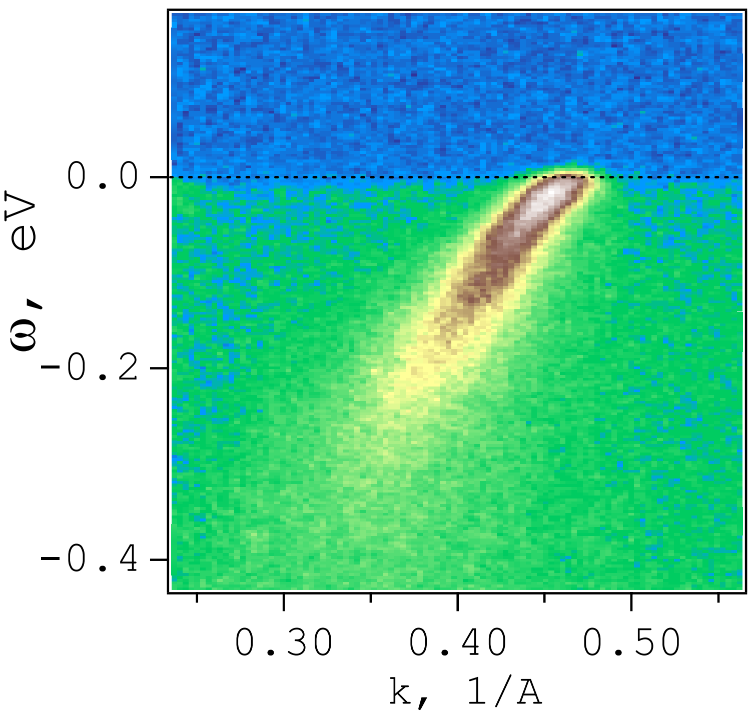
5. $\eta = W_G / W_L$



$\eta \to 0$ Voigt → Lorentz

$\eta \to \infty$ Voigt → Gauss

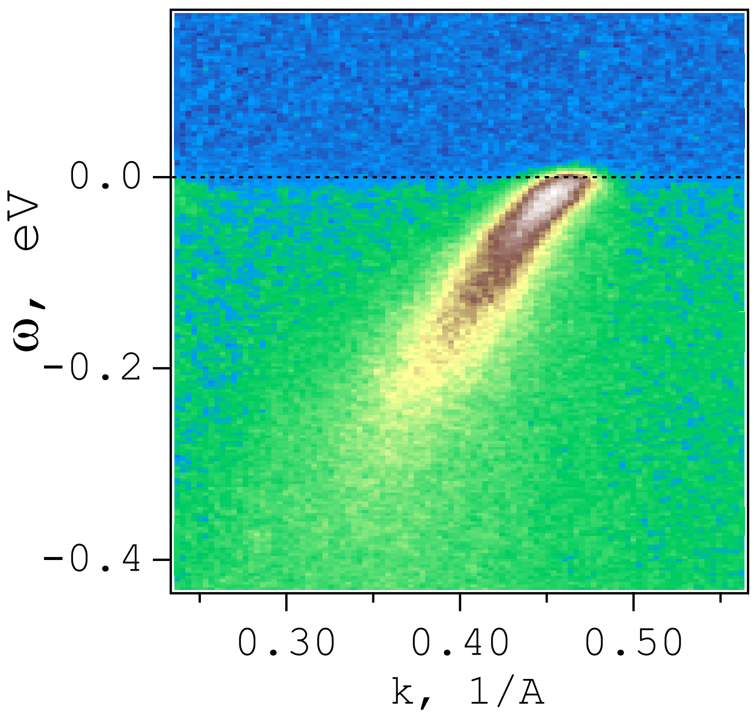
Old Procedure of Self Energy Extraction



Lorentz-Fit

Overall width

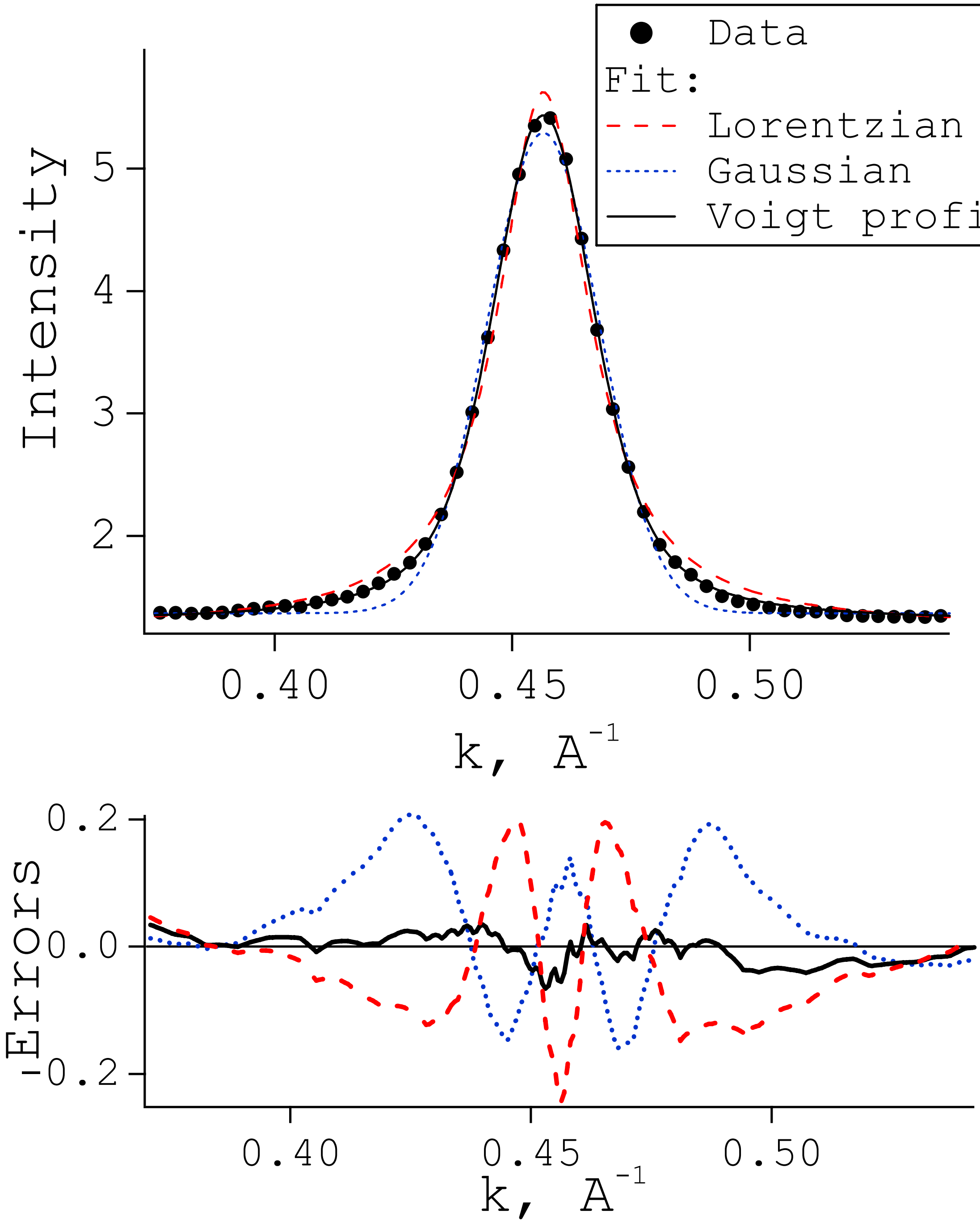
New Procedure of Self Energy Extraction



Lorentz-Fit → Overall width

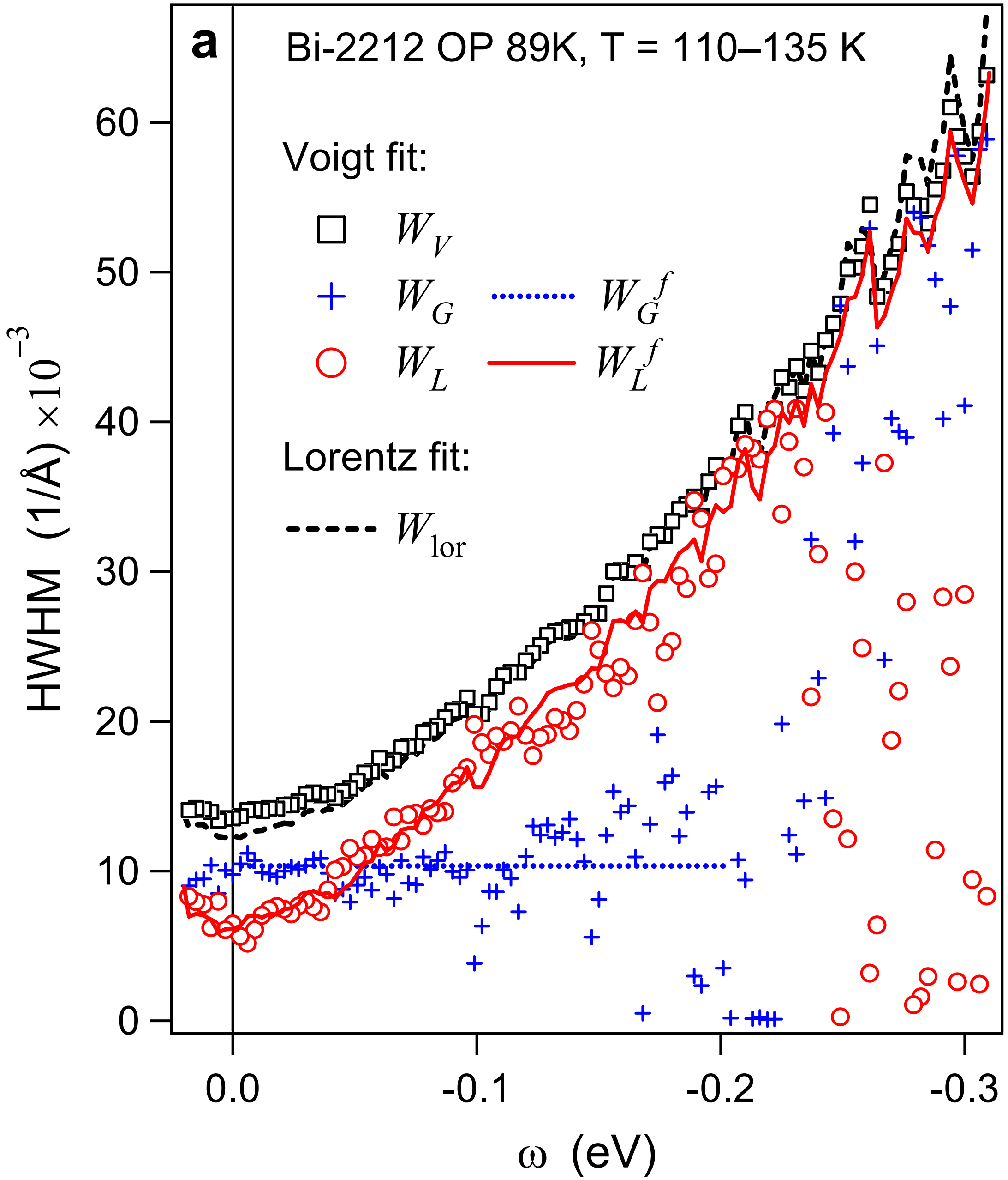
Voigt-Fit → Intrinsic width and resolution

MDC Shape



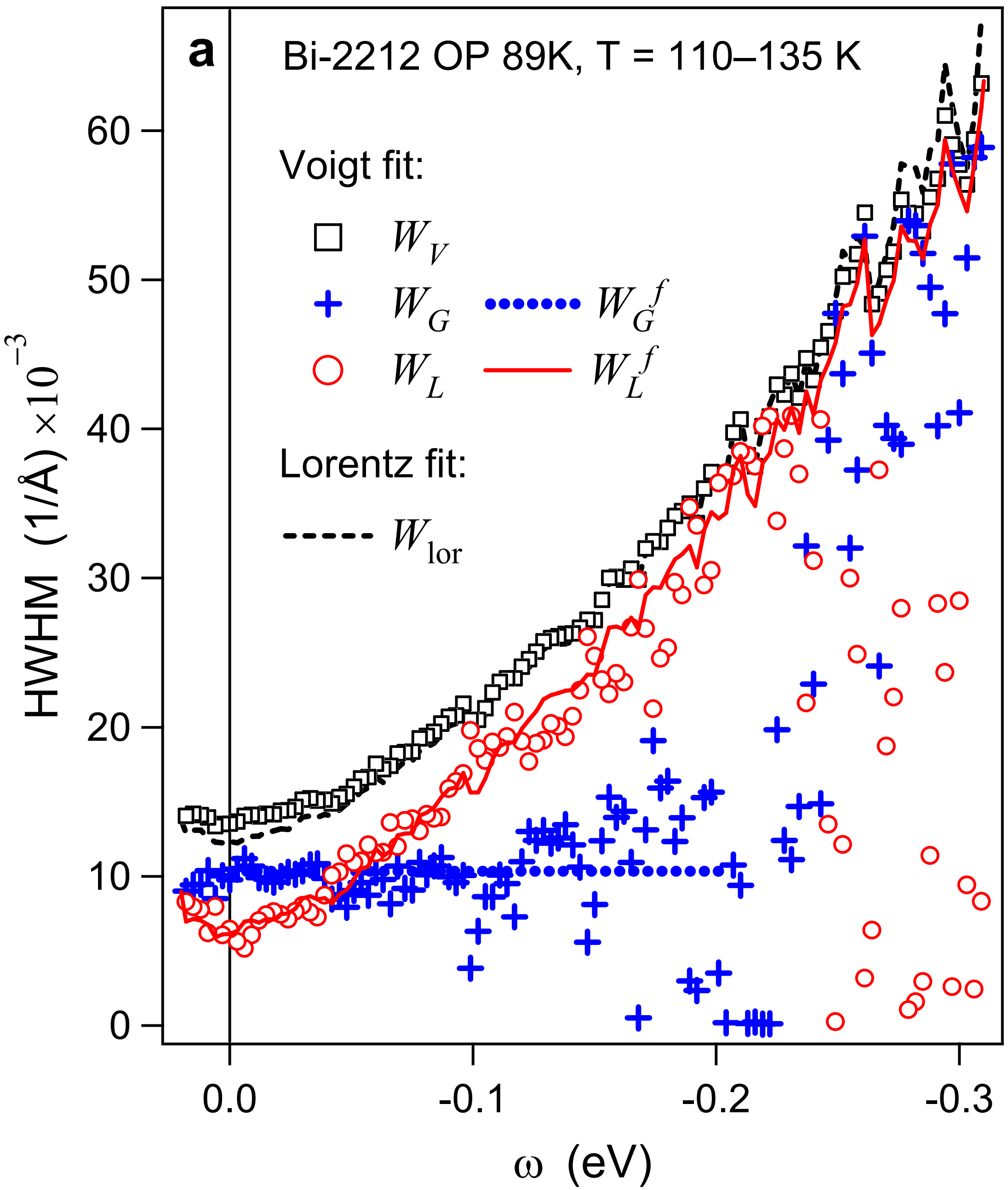
Data
Fit:
Lorentzian
Gaussian
Voigt profile
Intensity
2
3
4
5
0.40
0.45
0.50
k, A-1
Errors
0.2
0.0
-0.2
0.40
0.45
0.50
k, A-1

Σ(ω) from Voigt Fit



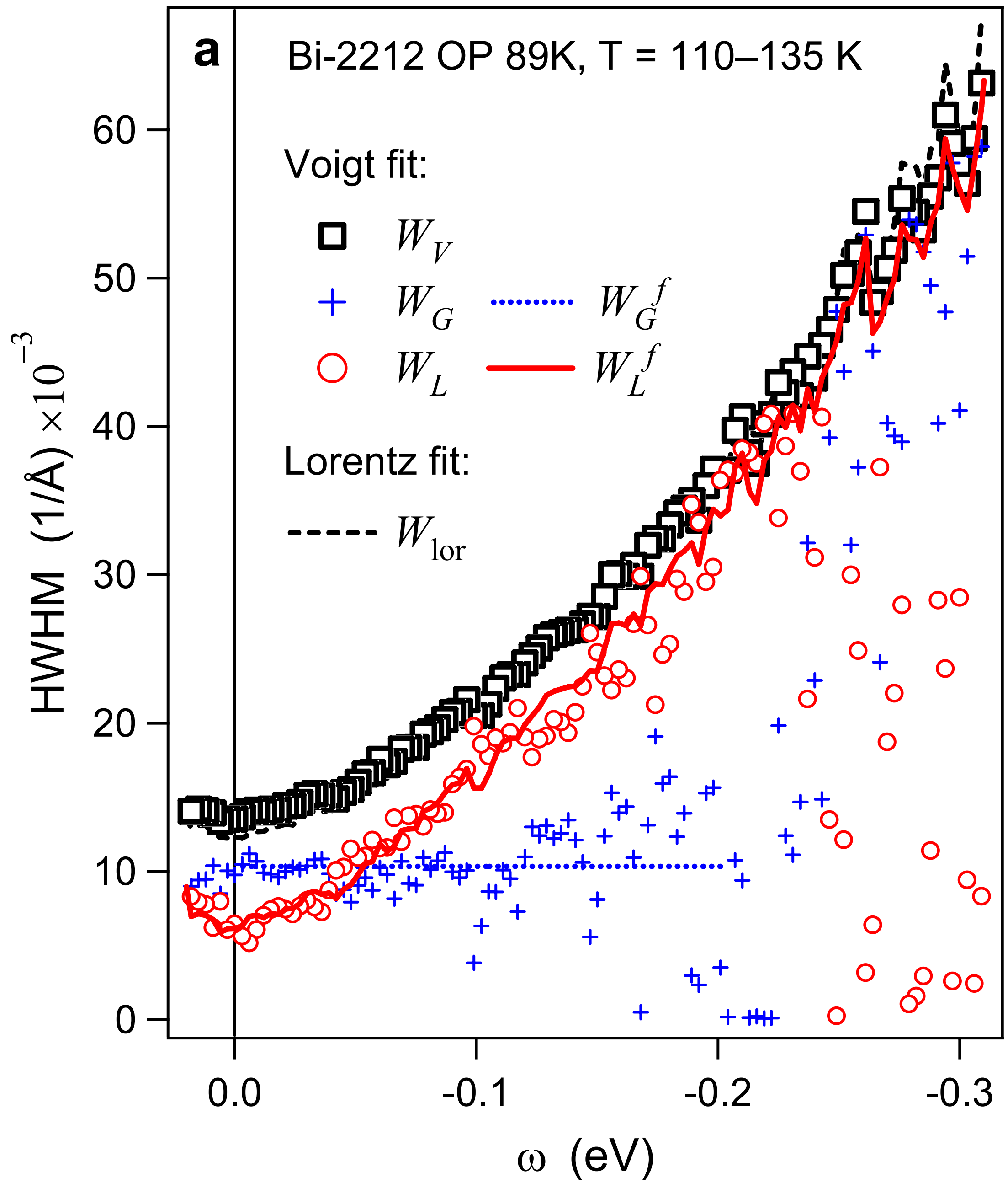
Σ(ω) from Voigt Fit

Resolution:
W_G=*const*



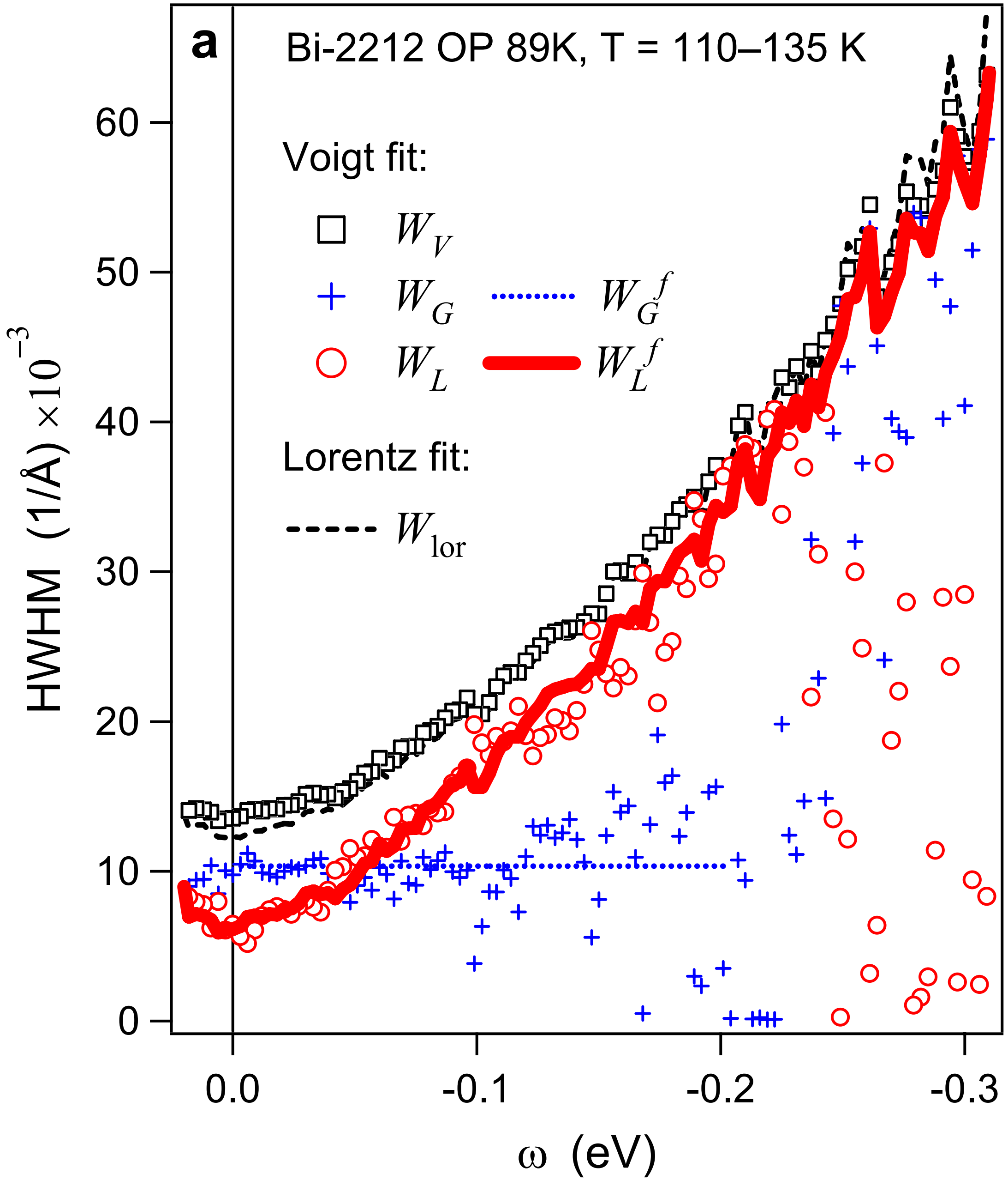
Σ(ω) from Voigt Fit

Overall width, W_V



Σ(ω) from Voigt Fit

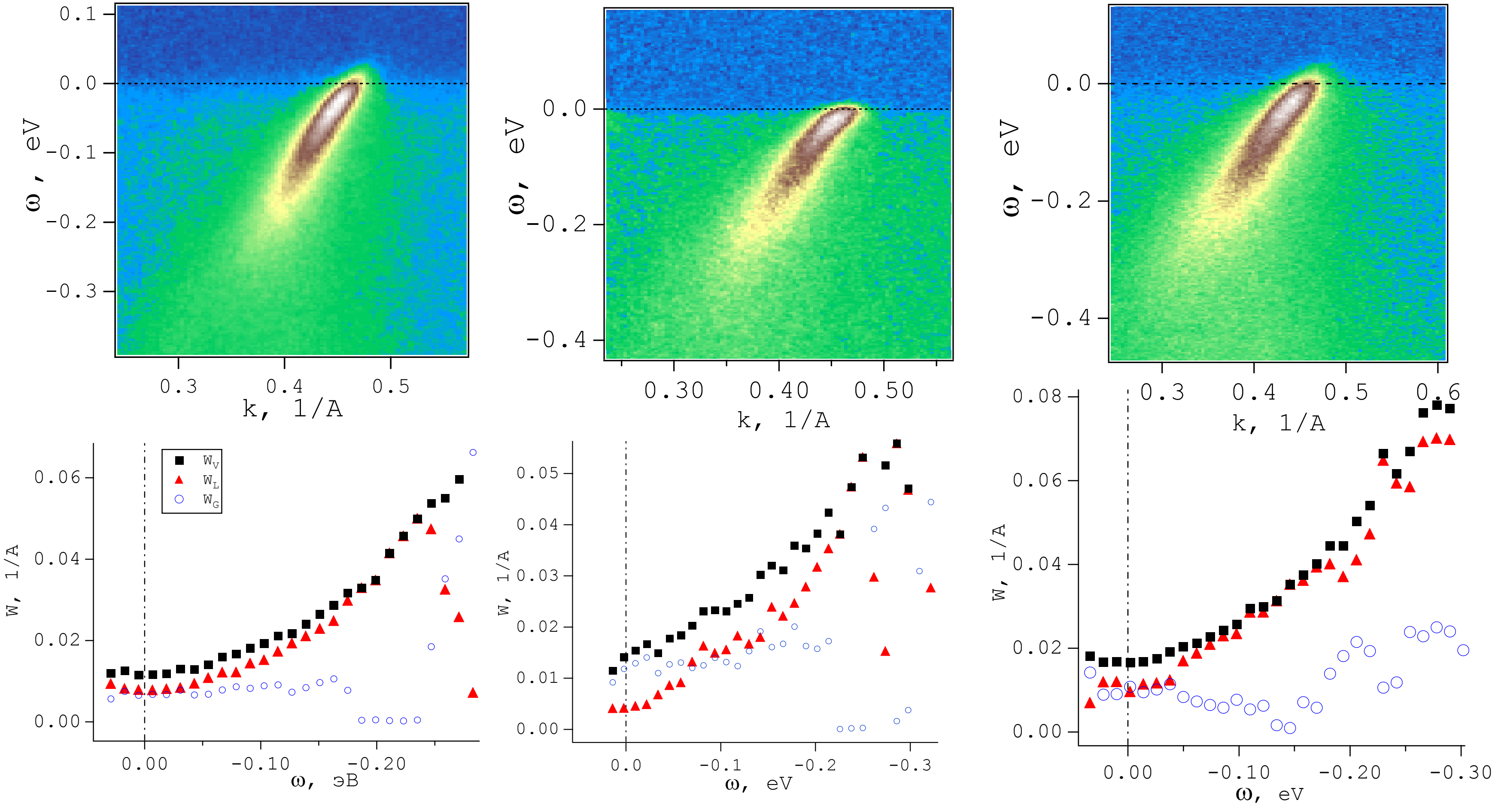
Intrinsic width, W_L



Examples of Voigt fit Application to ARPES Data

- BSCCO
  - x=0.21
  - x=0.16
  - x=0.12
- YBCO
- Temperature dependence
- Comparison to high-resolution data

Examples on BSCCO



x=0.21, *T* = 100 K   x=0.16, *T* = 40 K   x=0.12, Low T

Voigt Fit in application to YBCO

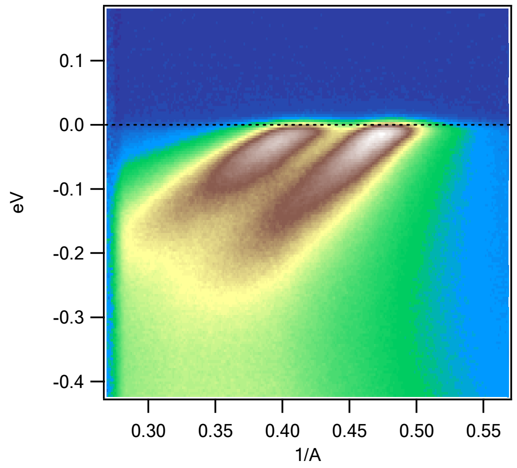


Image1,24 K

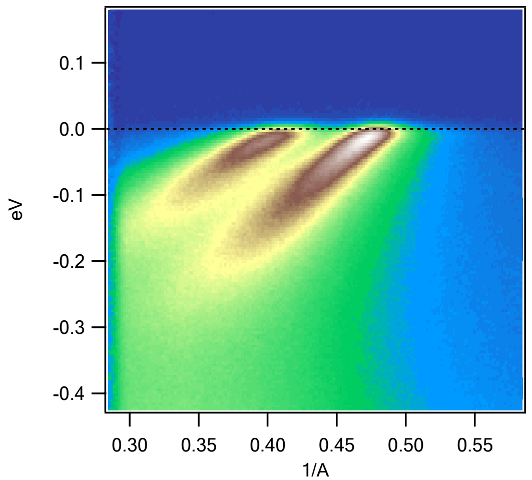
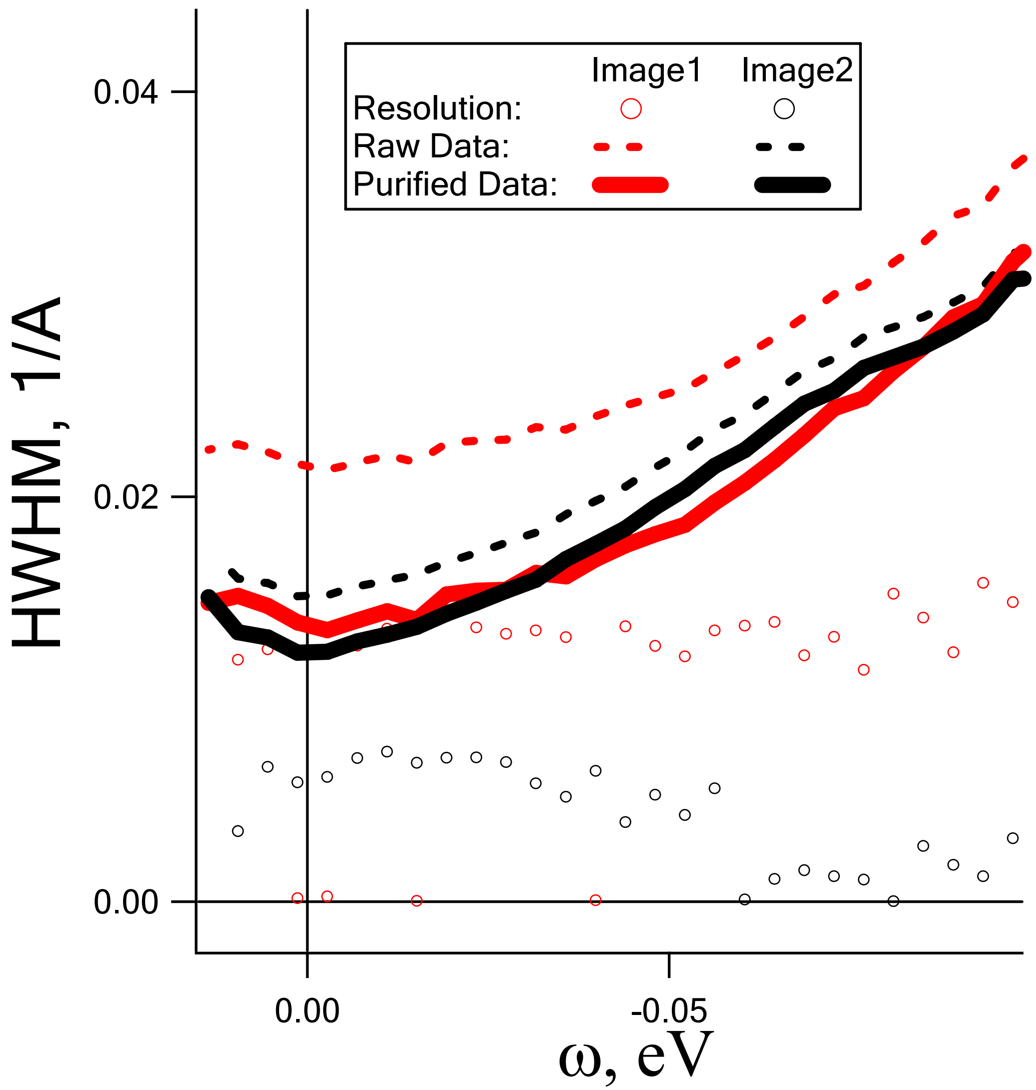
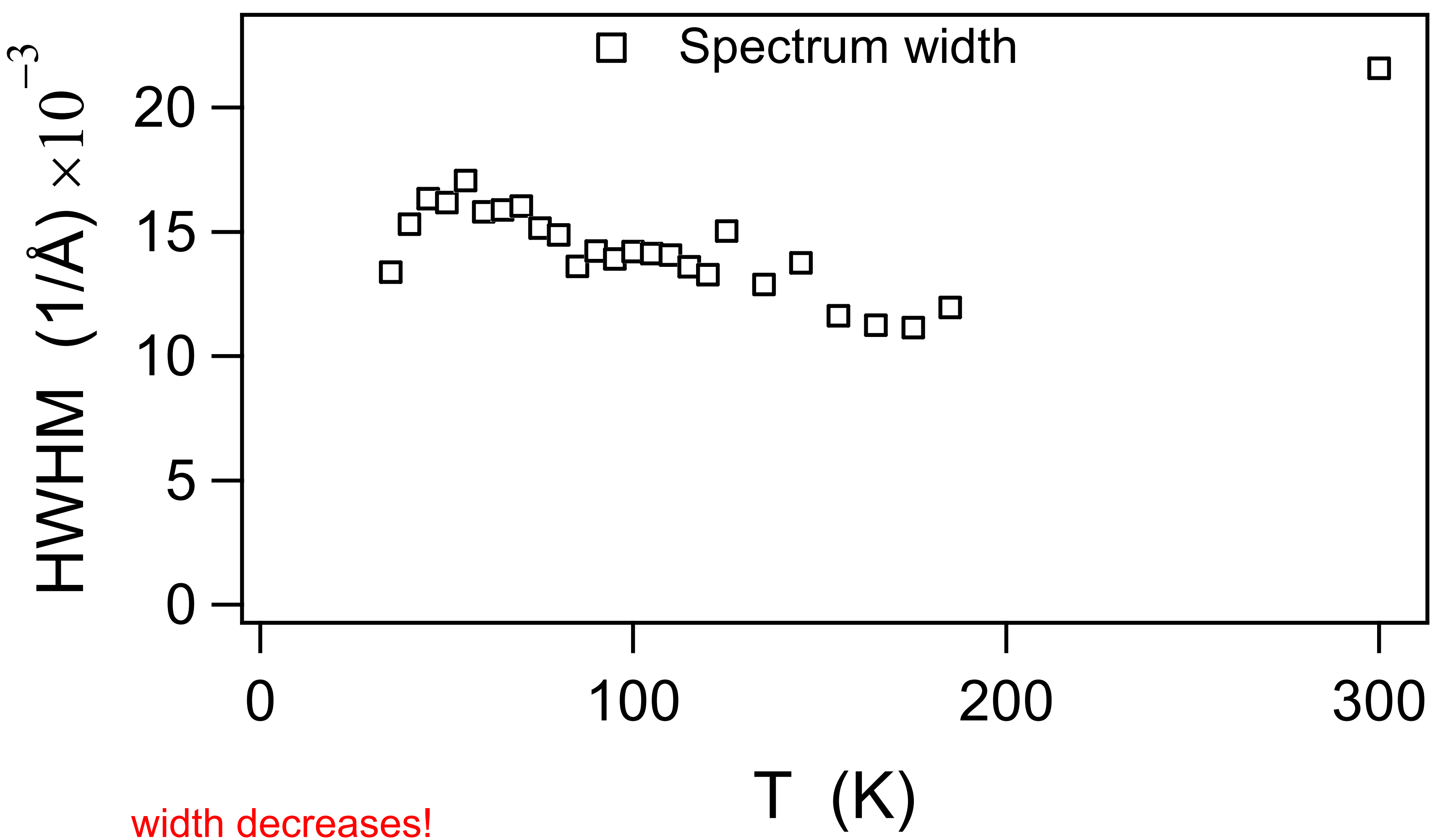


Image2,24 K



Temperature dependence of scattering rate

$\Sigma''(\omega=0,T)$



width decreases!

Temperature dependence of scattering rate

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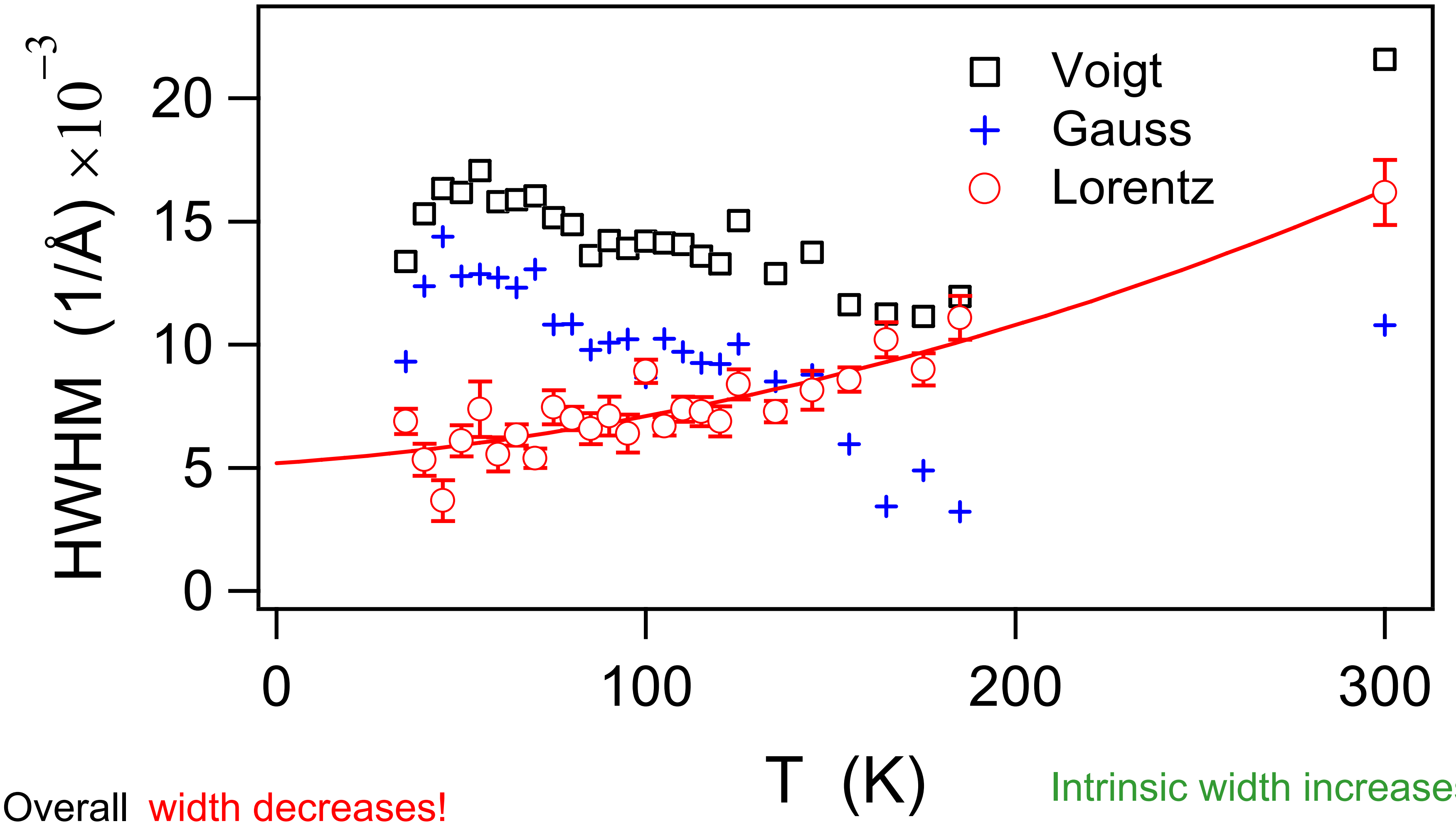


Overall width decreases!

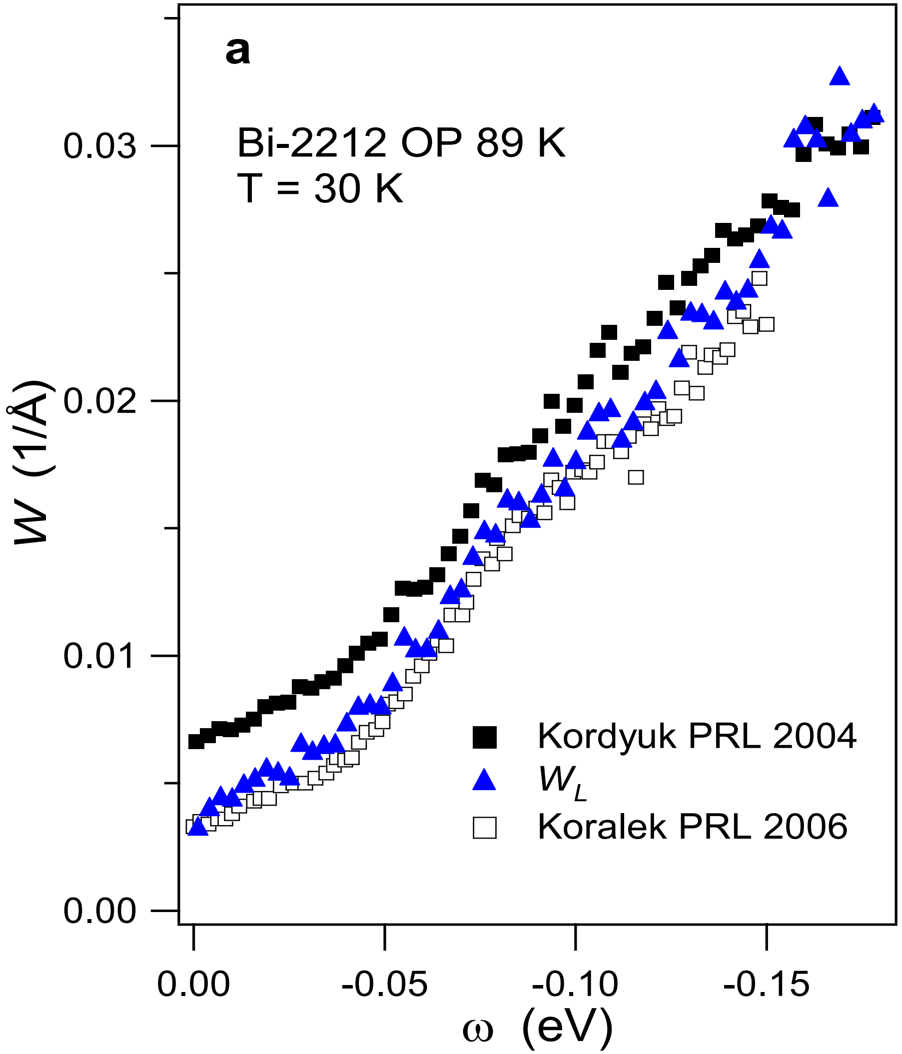
Intrinsic width increases

Comparison to the low-energy high-resolution data

$R \sim (h\nu - \phi)^{-1/2}$

$R_{6eV\ LASER}/R_{27eV\ synchrotron} = 0.25$

J. D. Koralek *et al.*, PRL 2006



Justification of Voigt Fit procedure

A. MDC Lineshape

B. ω-dependence: WG(ω)=const

C. YBCO: different images give same result while exposed to Voigt Fit procedure

D. T-dependence: while WG exhibits almost random and strange behavior, WL(T) always increases with temperature

E. Purified by Voigt Fit data coincides with high-resolution data (Koralek PRL 2006)

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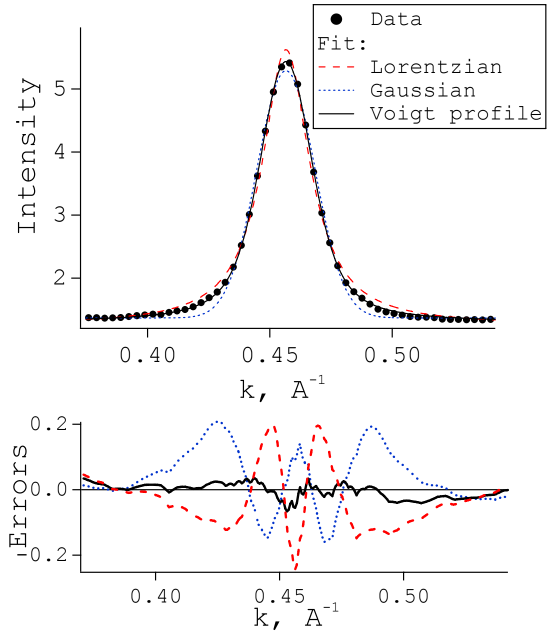

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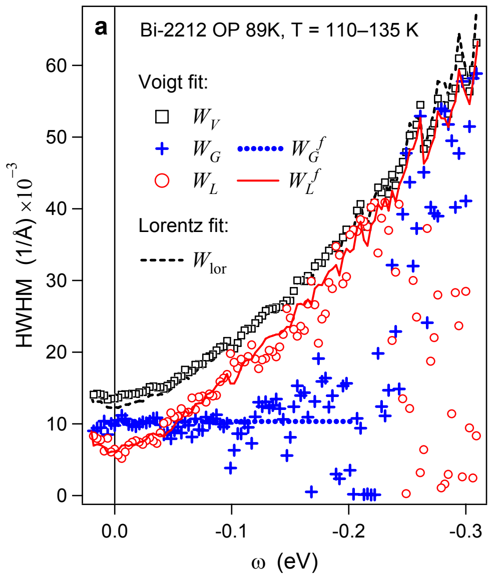

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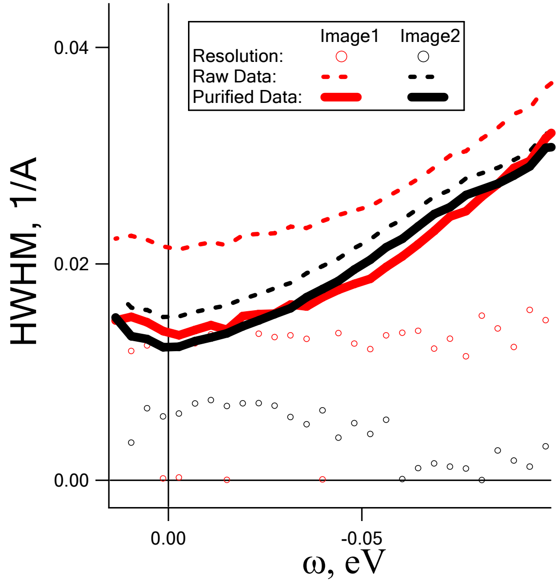

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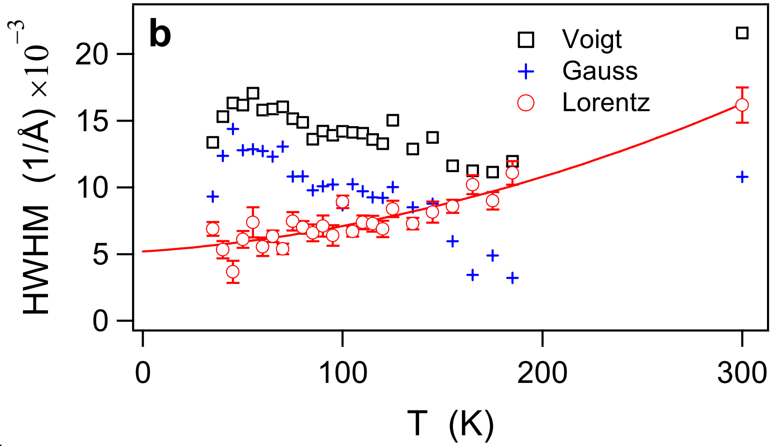

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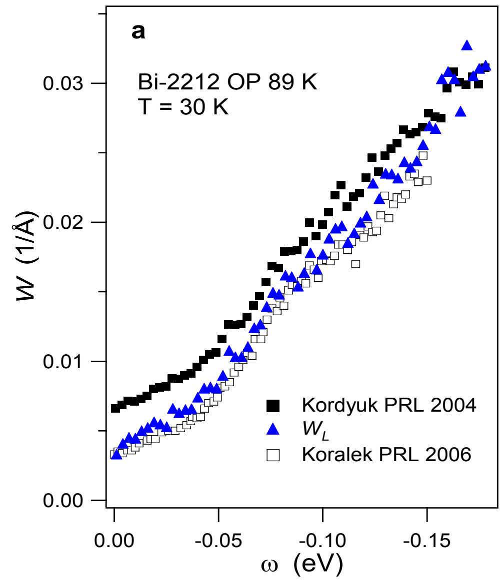

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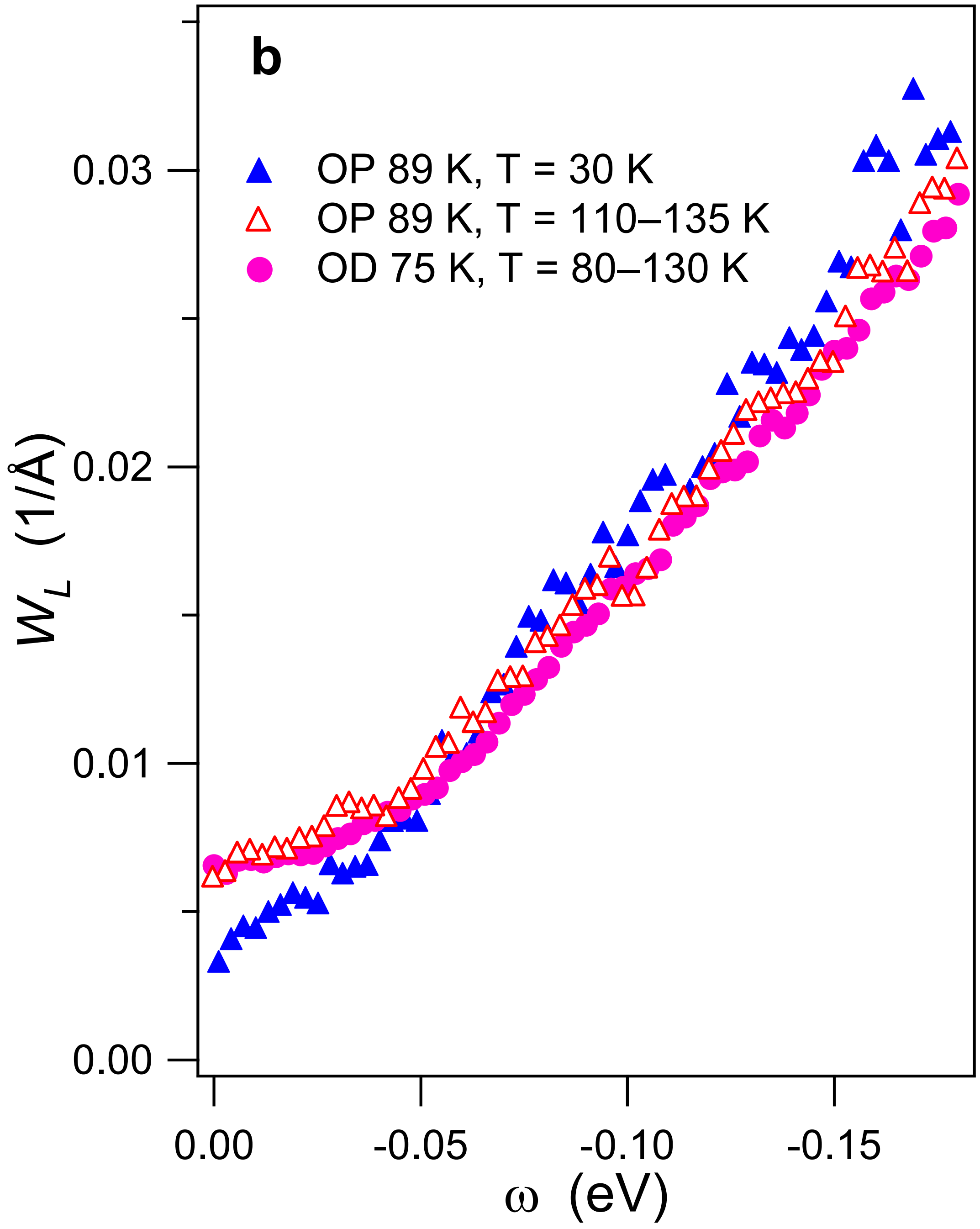
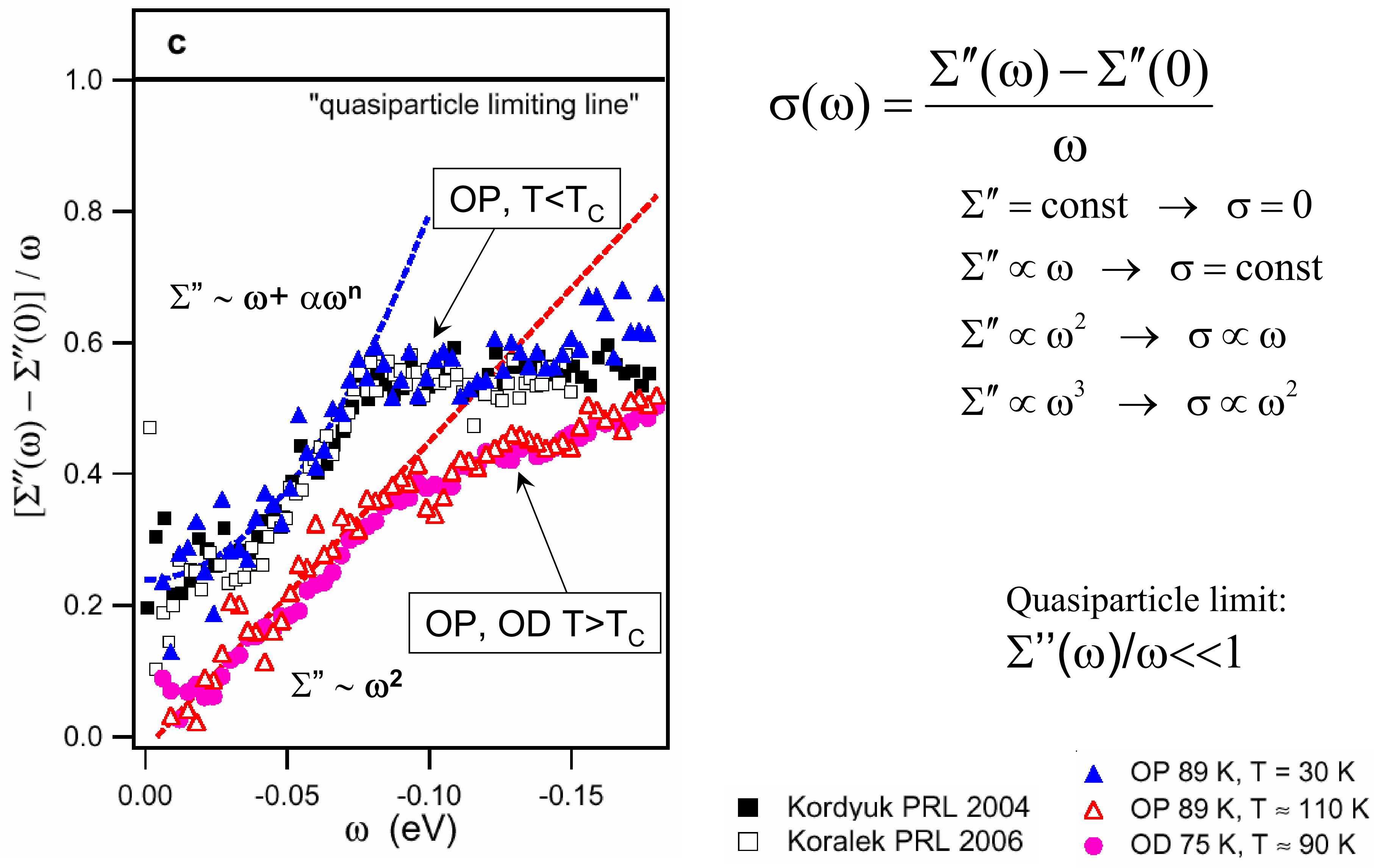
Most interesting part ☺

Σ''(ω) behavior in vicinity of Fermi-level



Reduced self-energy function



$$\sigma(\omega) = \frac{\Sigma''(\omega) - \Sigma''(0)}{\omega}$$

$$\Sigma'' = \text{const} \quad \rightarrow \quad \sigma = 0$$

$$\Sigma'' \propto \omega \quad \rightarrow \quad \sigma = \text{const}$$

$$\Sigma'' \propto \omega^2 \quad \rightarrow \quad \sigma \propto \omega$$

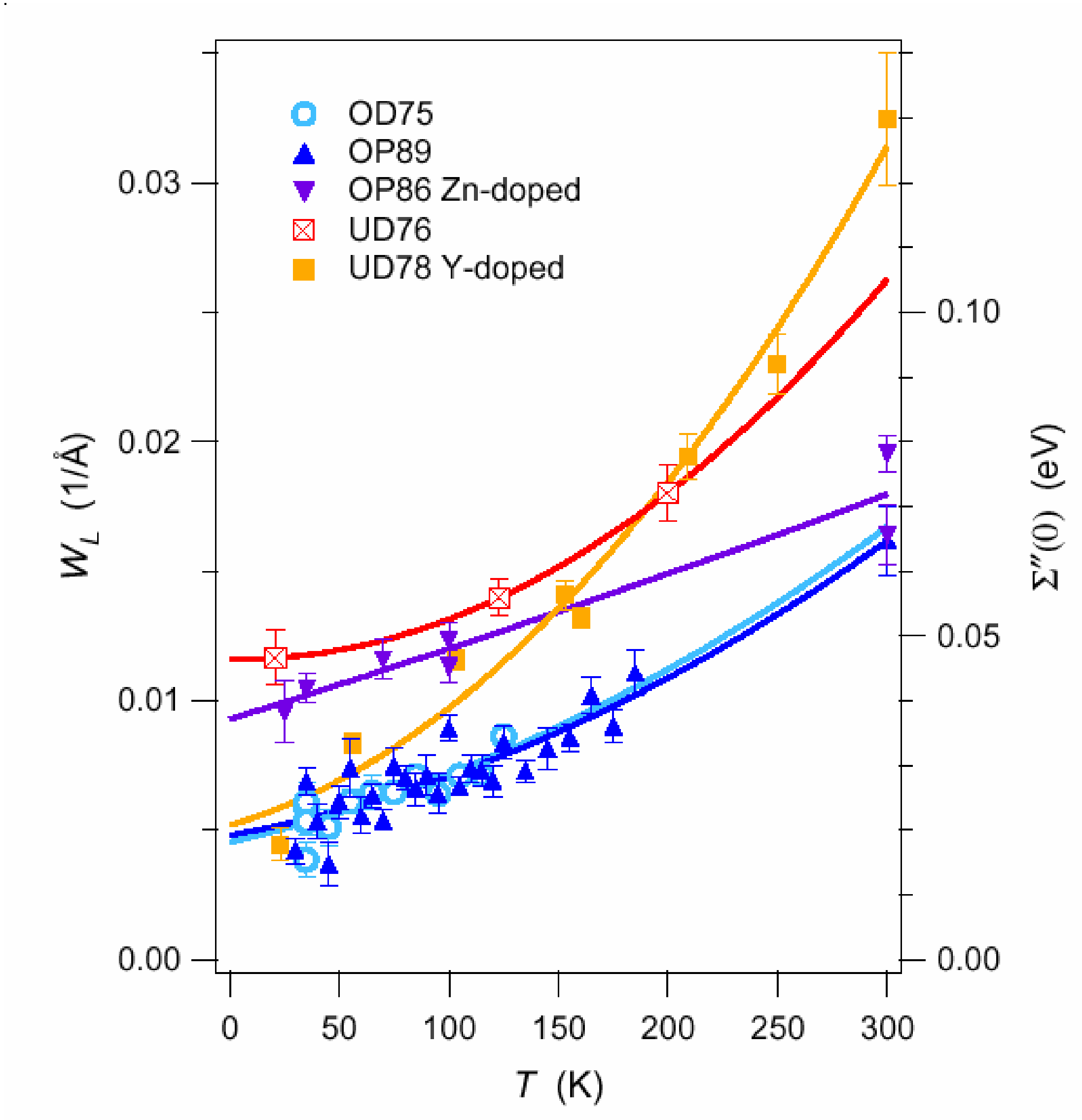
$$\Sigma'' \propto \omega^3 \quad \rightarrow \quad \sigma \propto \omega^2$$

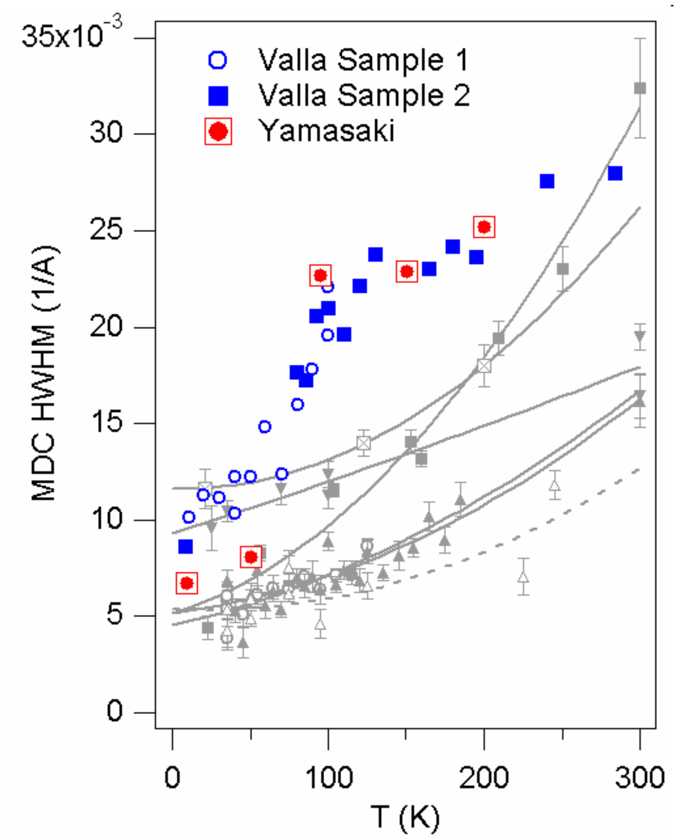
Quasiparticle limit:

$\Sigma''(\omega)/\omega \ll 1$

Evtushinsky *Physical Review B* 2006

Temperature dependence of scattering rate



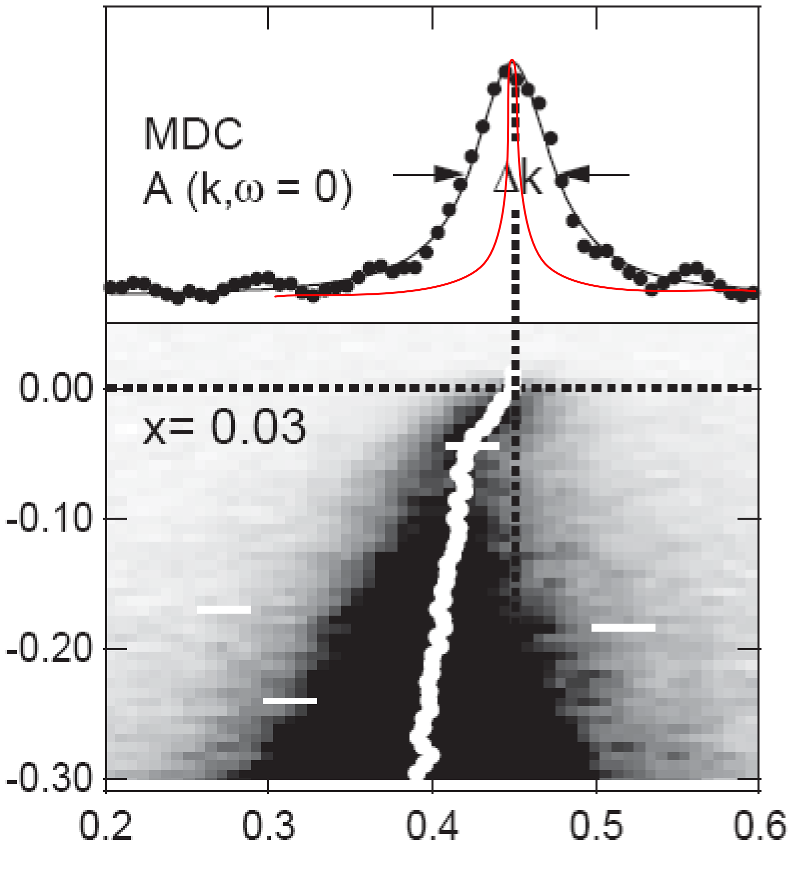


T.Valla *Physical Review B*, 2006

T. Yamasaki et al., cond-mat/0603006

ARPES
vs.
Transport

MDC Width: **0.030** vs **0.004** 1/Å



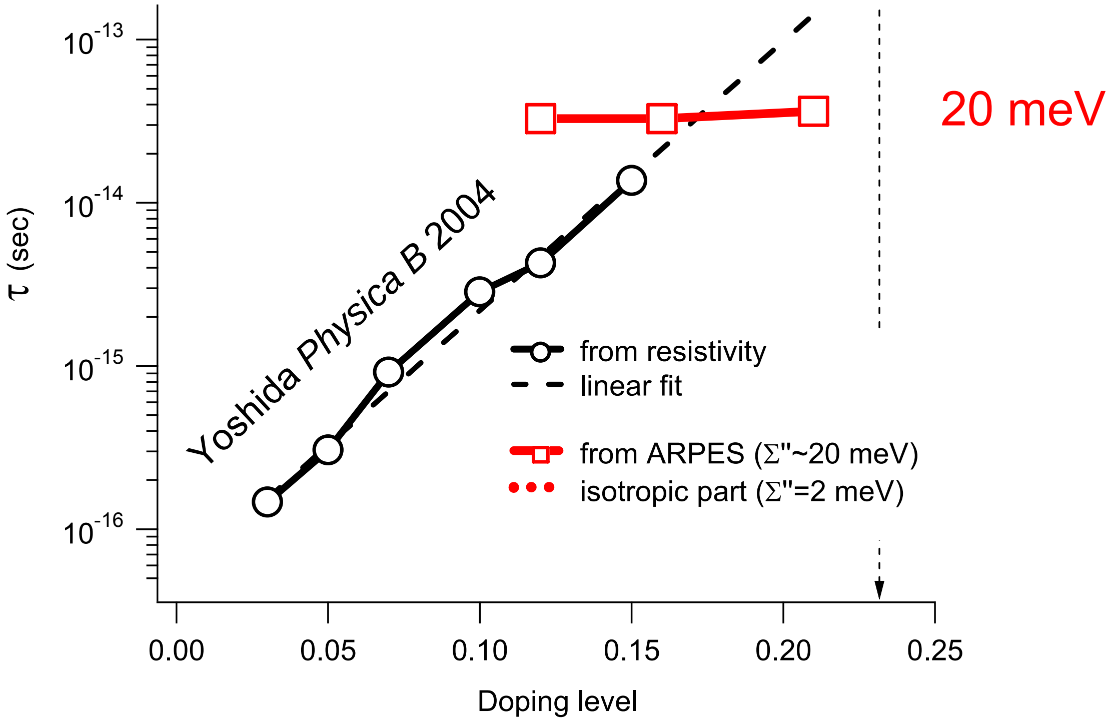
Yoshida's MDC used to calculate resistivity.
HWHM=**0.03** 1/Å
Compare to result, obtained by Voigt-fit procedure:
0.004 1/Å**.**

Yoshida *Physica B* 2004

τ from ARPES and Resistivity

$$\rho_0 = \frac{m^*}{ne^2\tau} \approx \frac{k_F}{ne^2\eta}\frac{\Sigma''_{im}}{v_r}$$

$$n \sim 1 - x$$

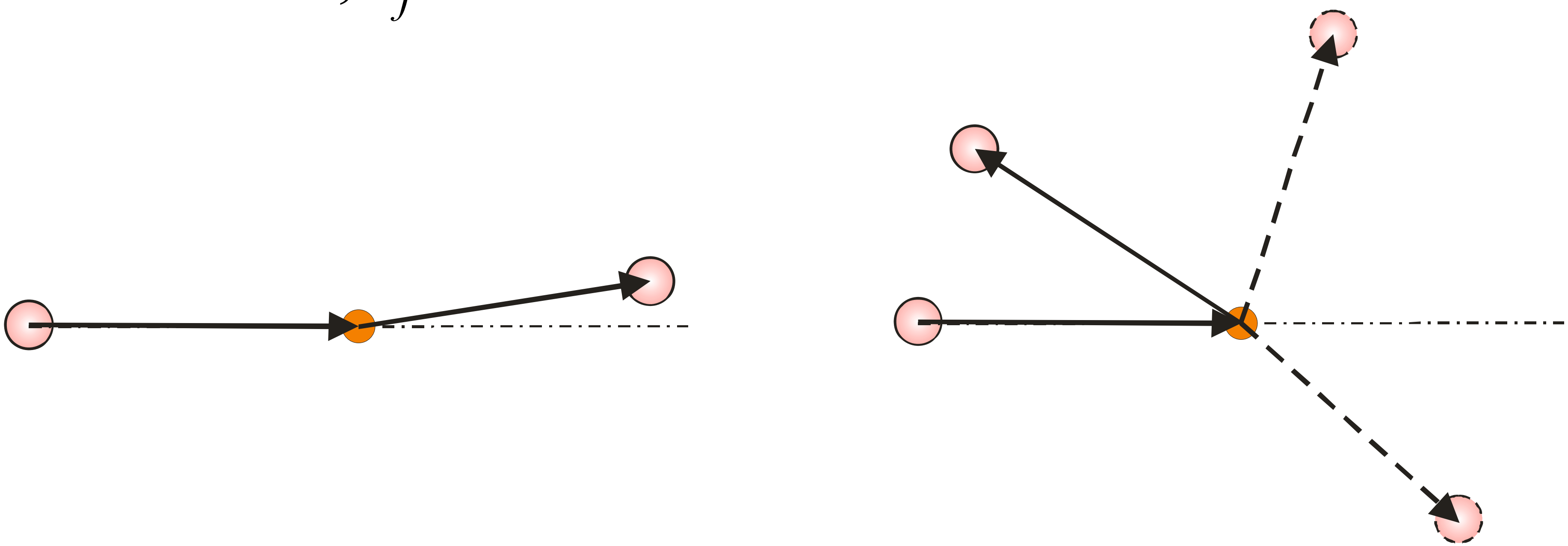


$$\tau = \frac{\eta}{\Sigma''(0)}$$

Forward and Isotropic Scattering

Forward, τ_f

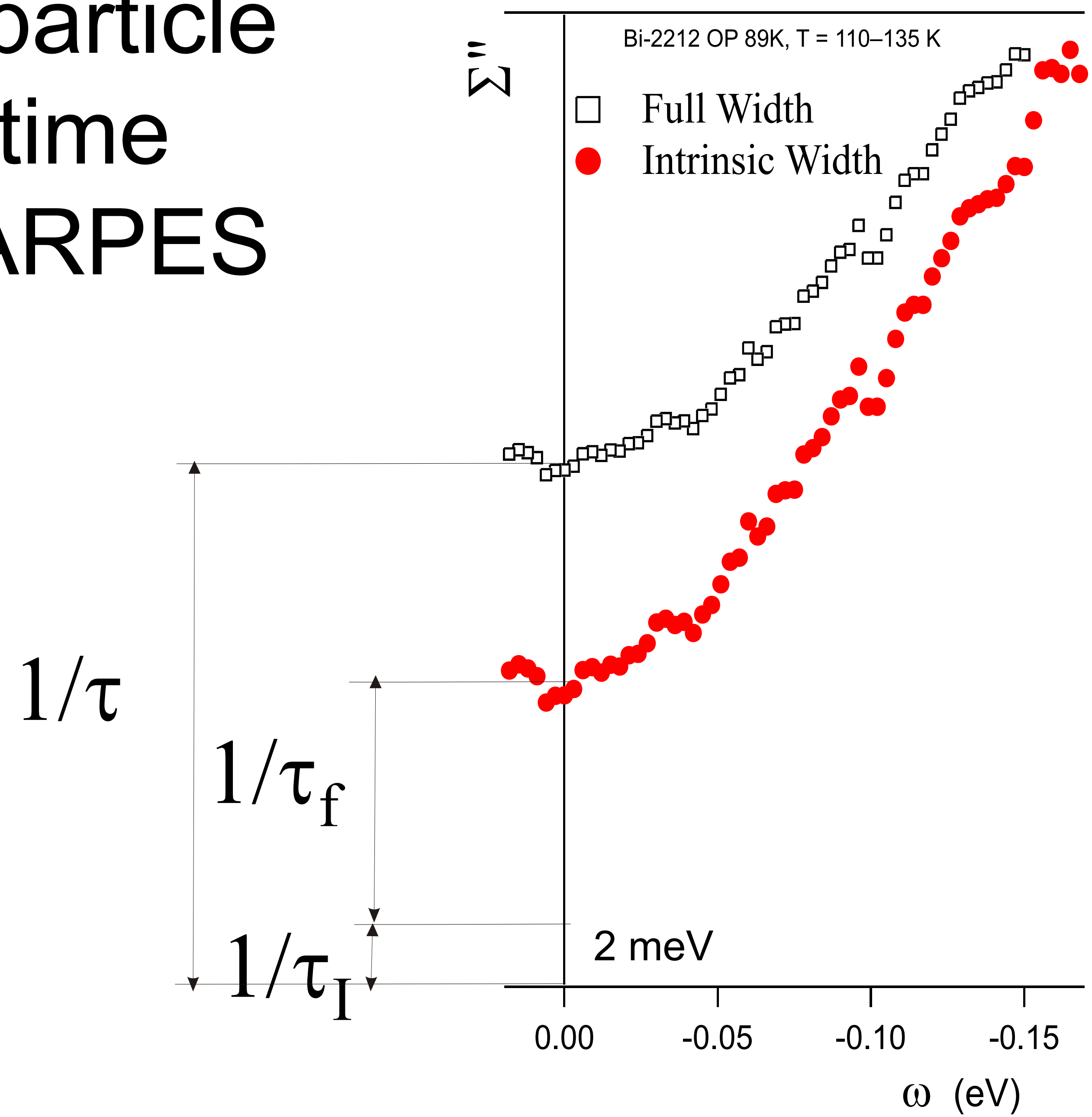
Isotropic, τ_I



ARPES: $\tau^{-1} = \tau_I^{-1} + \tau_f^{-1}$

Transport: $\tau^{-1} = \tau_I^{-1} + \alpha \cdot \tau_f^{-1}$, $\alpha << 1$

Quasiparticle Lifetime from ARPES

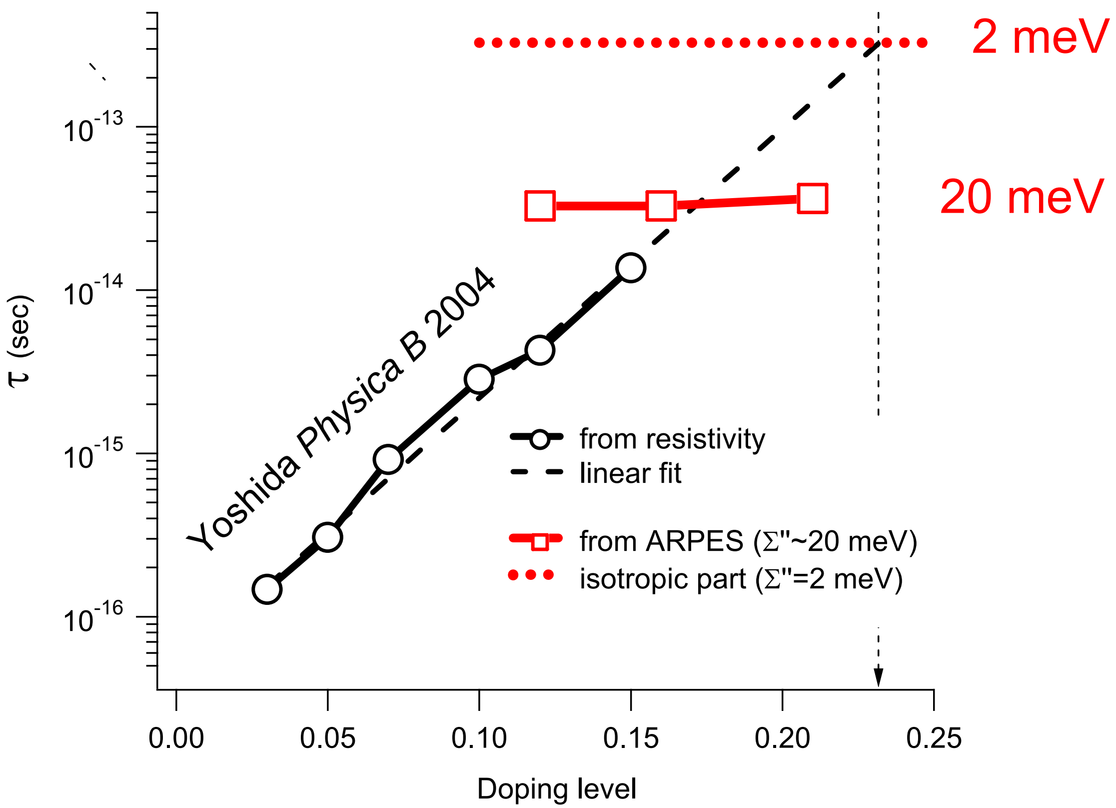


Impurity scattering

$$\rho_0 = \frac{m^*}{ne^2\tau} \approx \frac{k_F}{ne^2\eta}\frac{\Sigma''_{im}}{v_r}$$

forward and isotropic (unitary)?

$$n \sim 1 - x$$



$$n(x)\ ?$$

inhomogeneity

Resistivity from ARPES

Simple Drude formula: $\sigma = \dfrac{ne^2\tau}{m^*}$

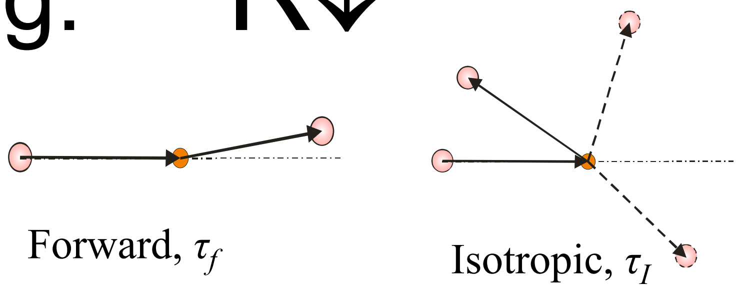
Note that *m** is calculated from renormalized dispersion.
n=(1-x)

How resistivity changes if we take in to account some extra features?

Two kinds of scattering: R↓

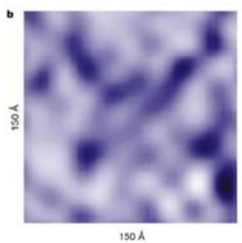
ARPES: $\tau^{-1} = \tau_I^{-1} + \tau_f^{-1}$

Transport: $\tau^{-1} = \tau_I^{-1} + \alpha \cdot \tau_f^{-1}$, $\alpha \ll 1$



Inhomogeneity: R↑

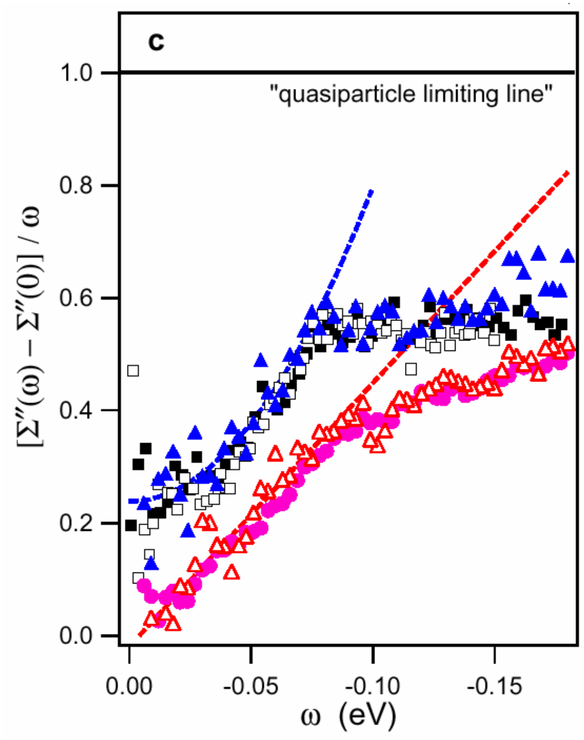
$n \sim (1-V_m)\, n_d + V_m\, n_m$
V_m – metallic phase volume



Conclusions

- Quasiparticles are well-defined
- Non-zero $\Sigma''(T=0) \approx 16$ meV
- No drop at T_C
- Σ“ depends rather on dopants than on x
- To compare to transport we need to disentangle isotropic and forward contributions

Conclusions



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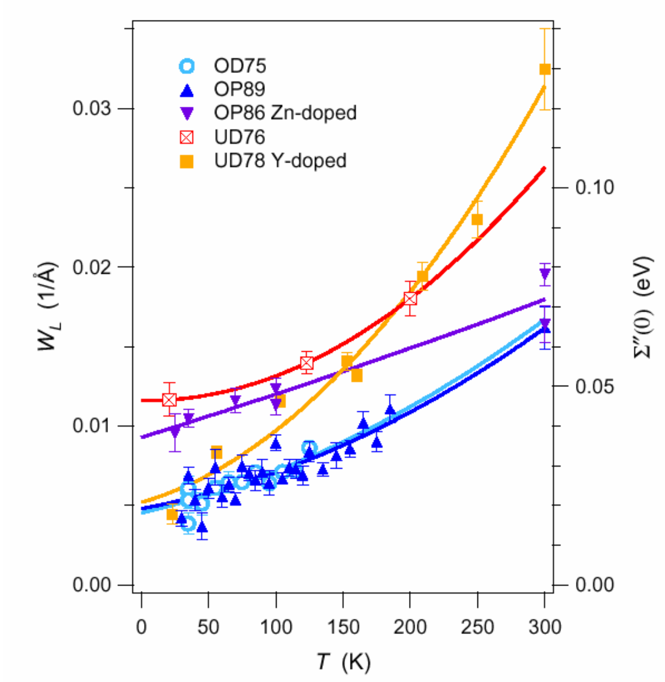

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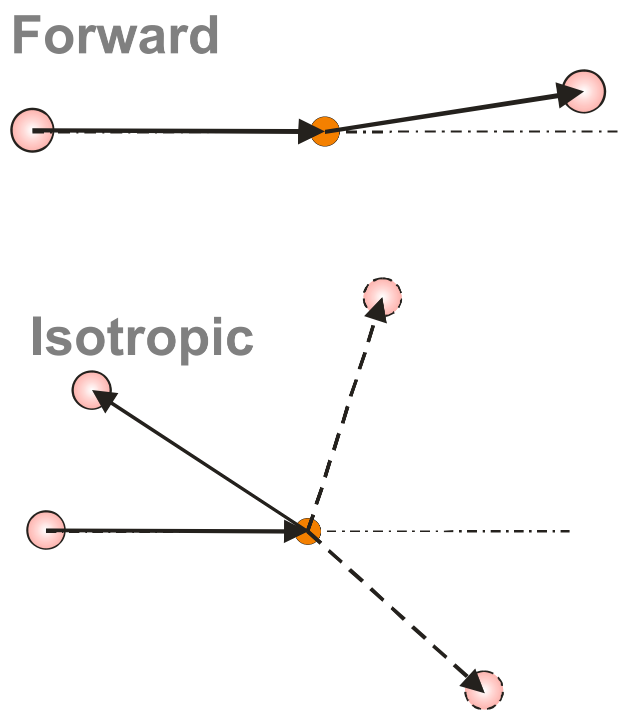

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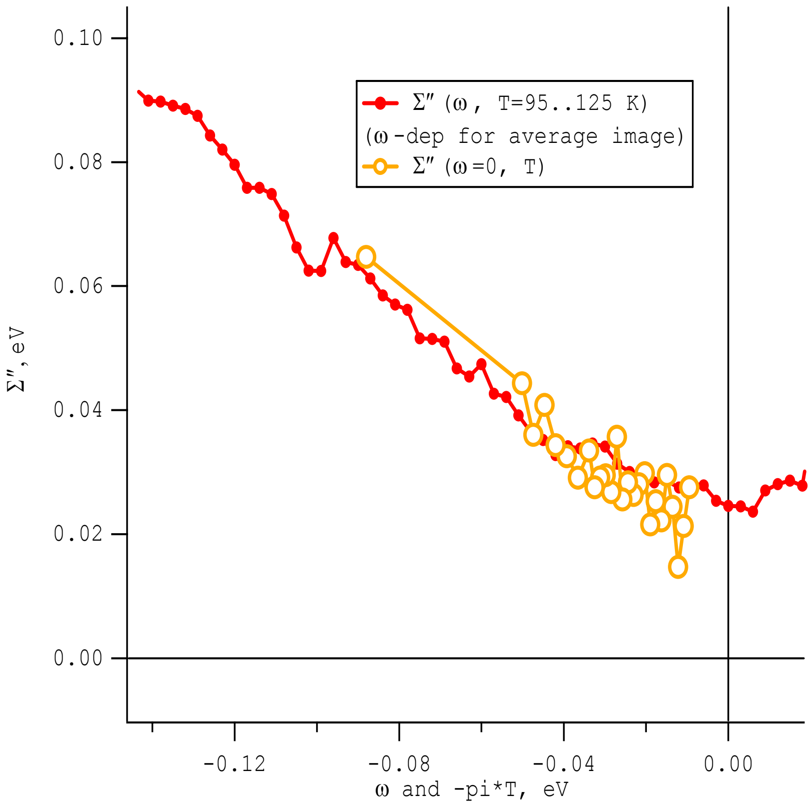
Σ"(ω,T) asymmetry

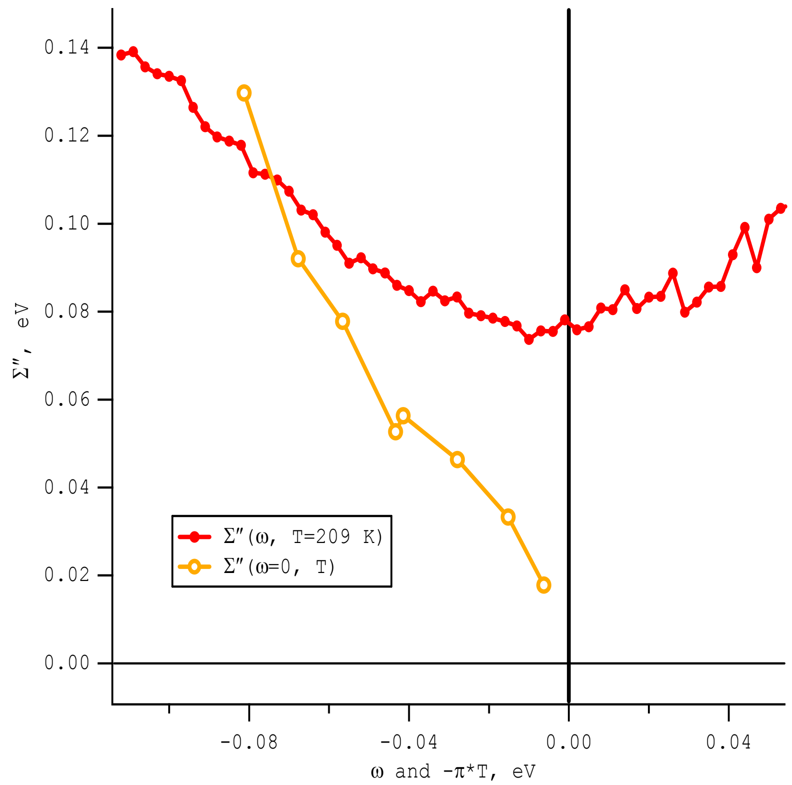
Σ"(ω,T)= **S**(ω)+**S**(πT) ⟶

Σ"(ω =0,T)= **S**(πT)

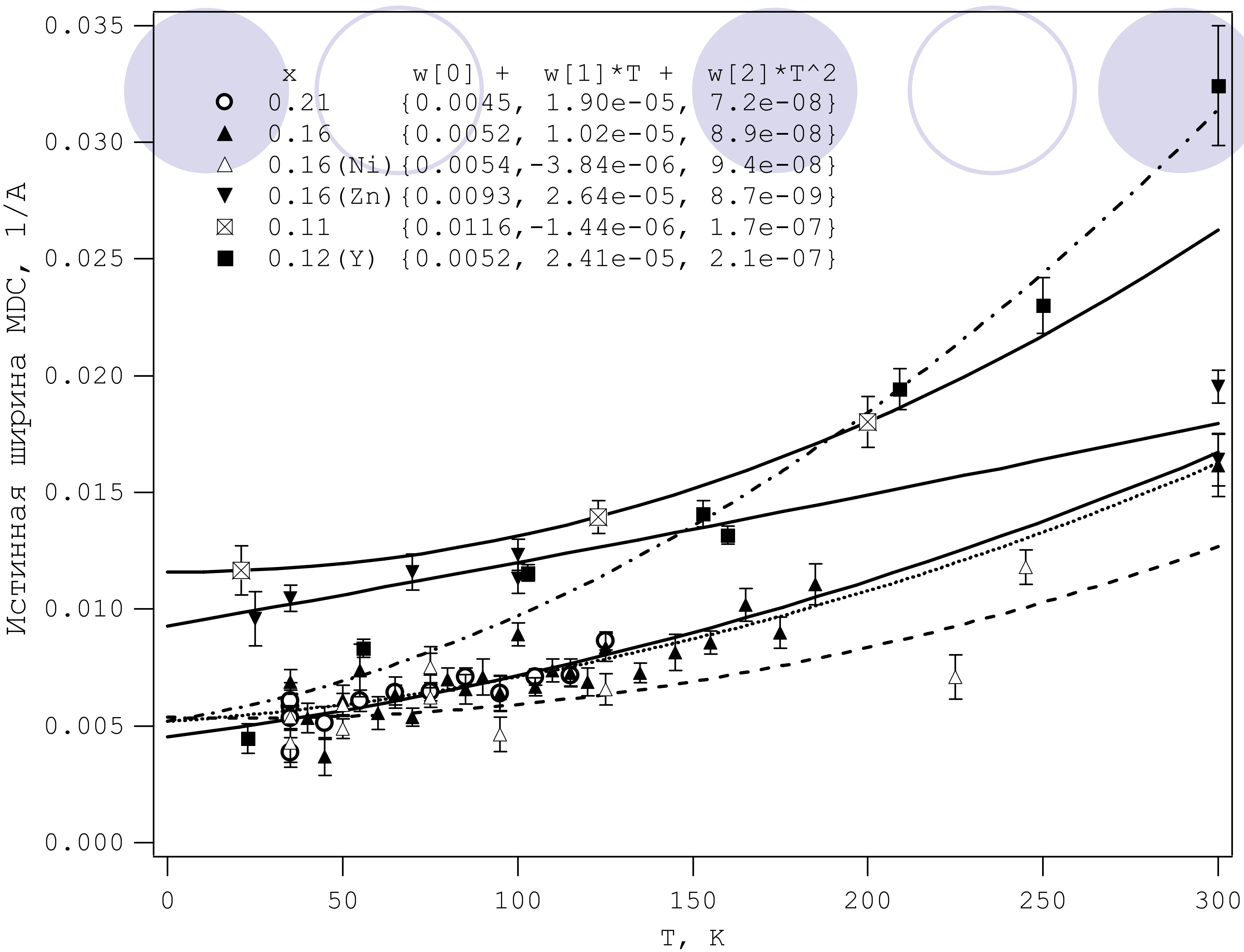
Σ"(ω,T=const)= **S**(ω)+const



OP (KEI)



Y-doped (YDLY)



x w[0] + w[1]*T + w[2]*T^2
0.21 {0.0045, 1.90e-05, 7.2e-08}
0.16 {0.0052, 1.02e-05, 8.9e-08}
0.16(Ni){0.0054,-3.84e-06, 9.4e-08}
0.16(Zn){0.0093, 2.64e-05, 8.7e-09}
0.11 {0.0116,-1.44e-06, 1.7e-07}
0.12(Y) {0.0052, 2.41e-05, 2.1e-07}
Истинная ширина MDC, 1/A
T, K
0.000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0
50
100
150
200
250
300

Energy resolution in Foigt fit

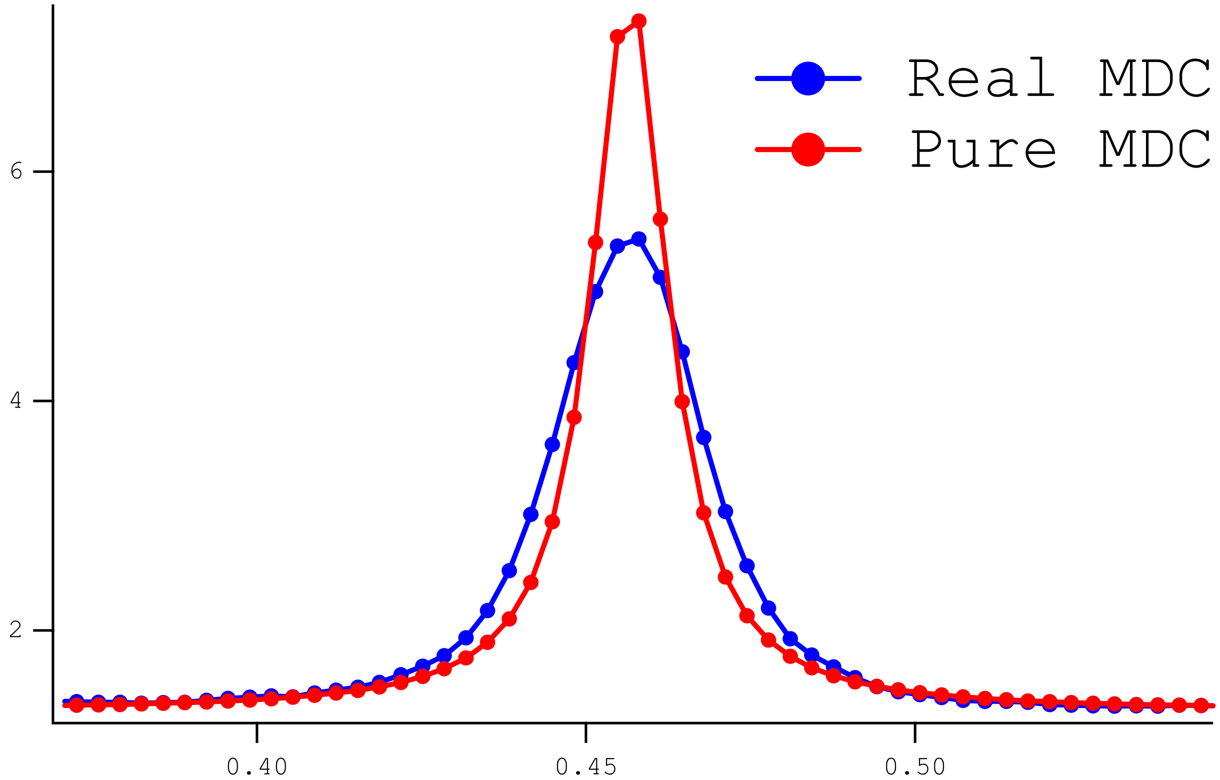
$$I(k, \omega) \propto A(k, \omega) \otimes R(k, \omega)$$

$$R(k, \omega) = R_k \otimes R_\omega$$

Energy resolution has almost the same effect on the MDC shape as momentum resolution, so both R_ω and R_k are taken into account by Voigt-fit procedure.

Pure MDC – Lorentzian

Real MDC = pure MDC ⊗ Resolution - Voigt



Scattering mechanisms

$$\text{Gap} \rightarrow \text{DOS} \rightarrow \Sigma''$$

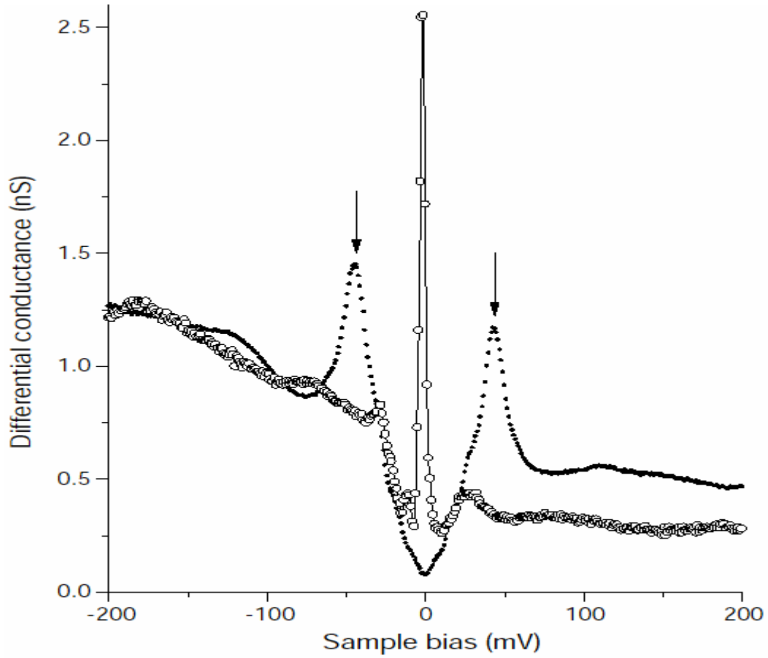
opening change change

Inelastic e - e scattering :

$$\Sigma''_{in}(\omega) \propto \iint d\omega_1 d\omega_2 DOS(\omega_1) DOS(\omega_2) DOS(\omega - \omega_1 - \omega_2)$$

$\Sigma''_{in}(\omega) \sim \omega^2$, $T>T_C$

$\Sigma''_{in}(\omega) \sim \omega^n$, $n \geq 3$, $T<T_C$



Scattering on impurities :

$$\Sigma''_{imp}(\omega) \propto \int DOS(\omega - \Omega) \cdot N_{imp}(\Omega) \cdot d\Omega$$

- $\Sigma''_{imp}(\omega) \sim DOS(\omega) \sim const$, $T>T_C$
- $\Sigma''_{imp}(\omega) \sim \omega$, $T<T_C$