Momentum Dependence of Eliashberg Function of Bi2212 from Laser ARPES

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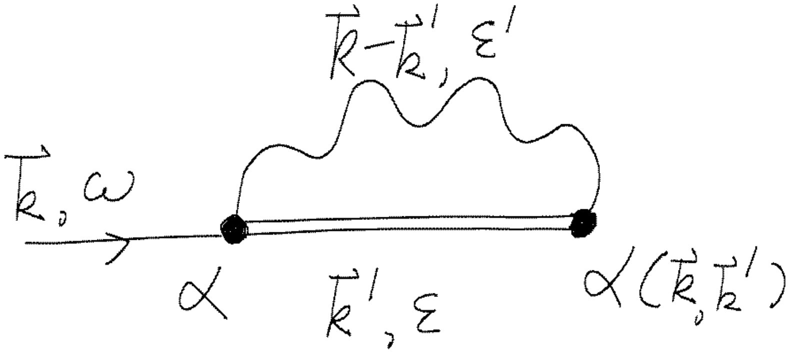
Han-Yong Choi
SKKU

Collaborators

Jin Mo Bok, Jae Hyun Yun / SKKU
Wentao Zhang, Xingjiang Zhou / CAS
Chandra Varma / UCR

Eliashberg function $\alpha^2 F(\vec{k},\omega)$ for HTCS?

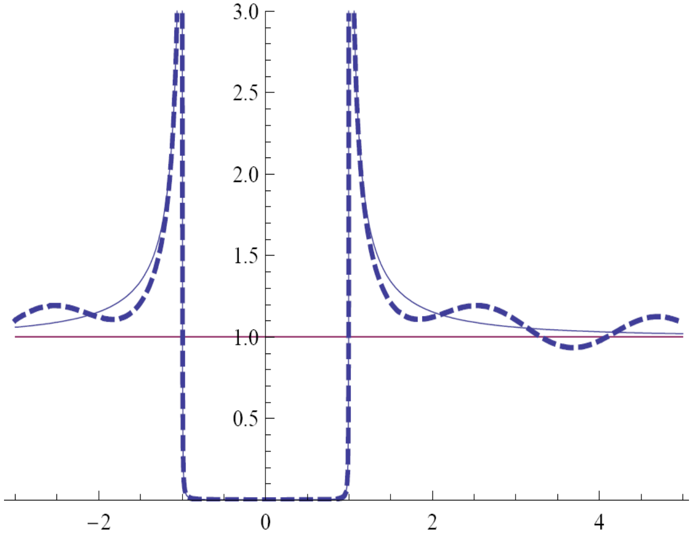


The mom-dependence of the self-energy → understand the transport and spectroscopic properties of cuprates.

Conventional isotropic SC

- McMillan-Rowell (1965).

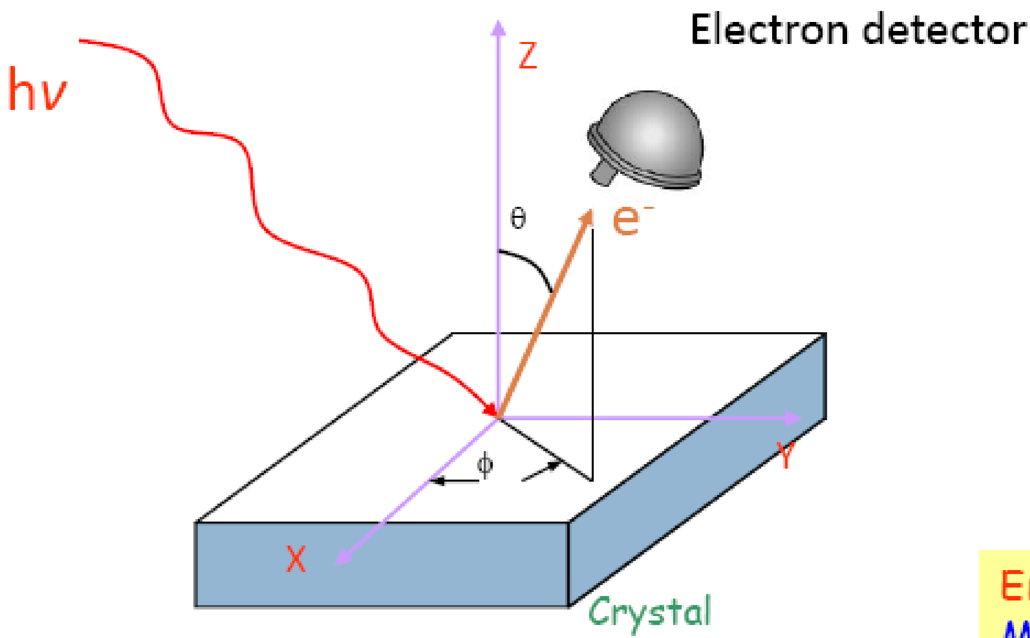
$$N_1(\omega) \equiv \mathrm{Re}\left[\frac{\omega}{\sqrt{\omega^2 - \Delta^2(\omega)}}\right]$$



- Fit $N_1(\omega)$ by inverting the Eliashberg eq. to extract $\alpha^2 F(\omega)$ and $\Delta(\omega)$.

- HTC complicated by mom anisotropy
  → mom resolved probe!!

Angle-Resolved Photoemission Spectroscopy (*ARPES*)



- Synchrotron Radiation
- Gas Discharge Lamp
  He I, hν=21.2 eV
  He II, hν=40.8 eV
- **VUV Laser**
  hν=6.994 eV

Photoemitted electrons in real space

E_{kin}, $K_{||}$

↓

Energy Conservation: $E_B = h\nu - E_{kin} - \Phi$

Momentum Conservation: $K_{||} = k_{||} + G_{||}$

↓

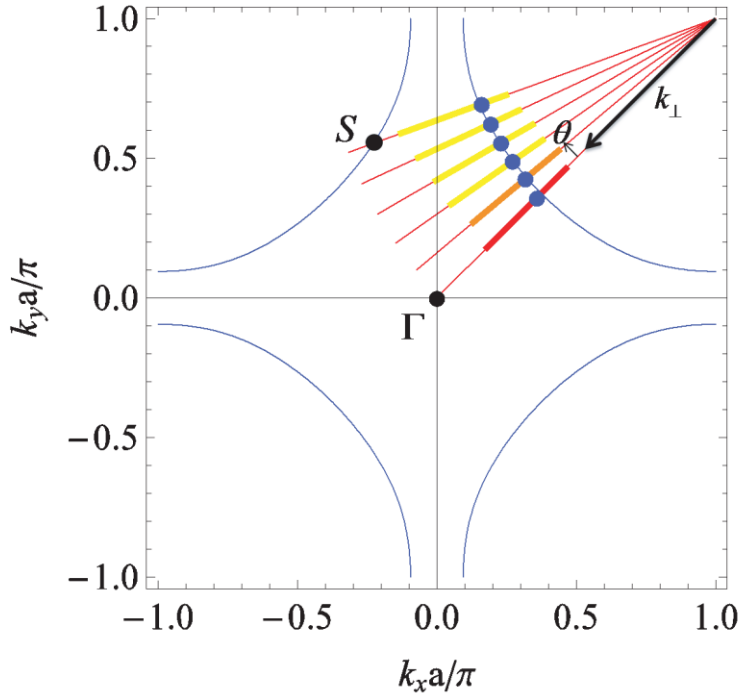
Electronic state in solid:

$\Psi(E_B, k_{||})$

Laser ARPES data on SUD Bi2212 (Tc=89K) from Zhou group@CAS

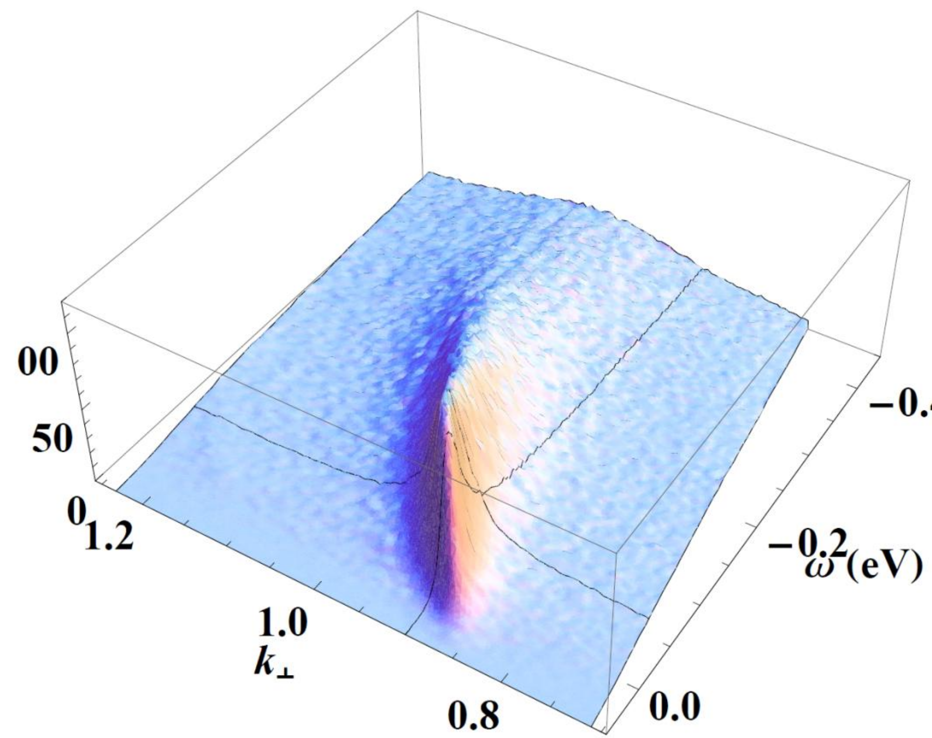
$$I_{ARPES}(\vec{k},\omega) = |M|^2 A(\theta, k_\perp, \omega) f(\omega)$$

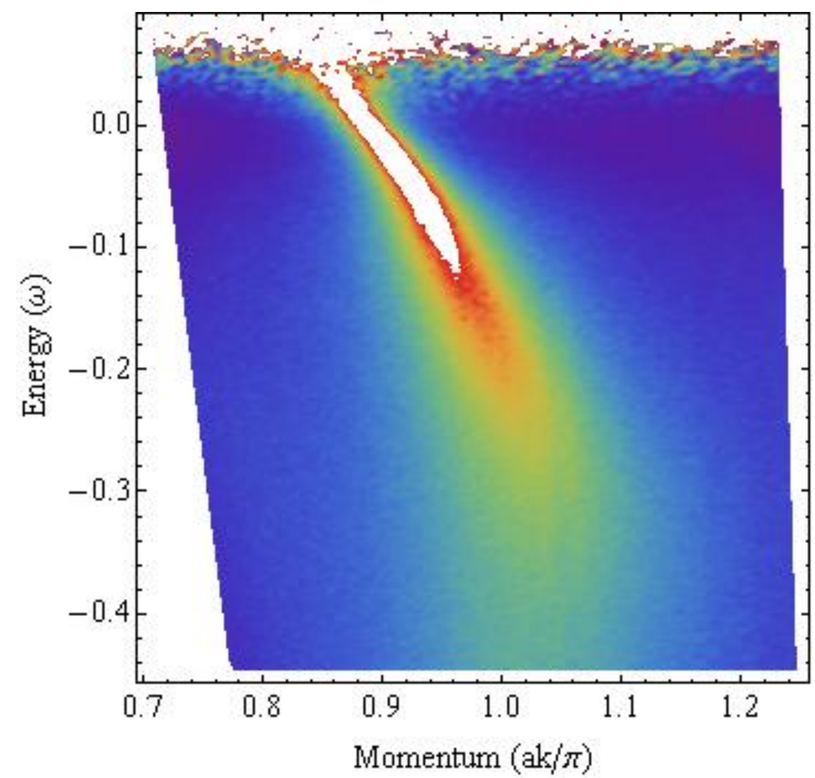
- **Tilt angles = 0, 5, 10, 15, 20, 25 degrees & *T*=107K.**



T=107K > *T*c=89 &

tilt angle=15 deg



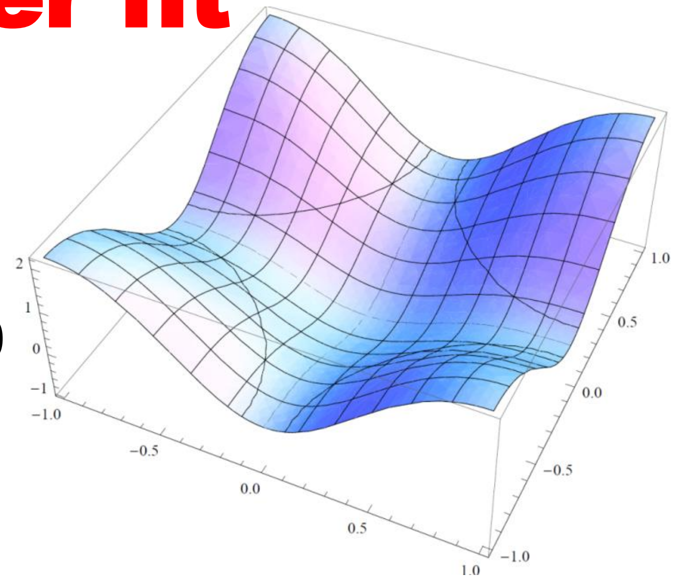


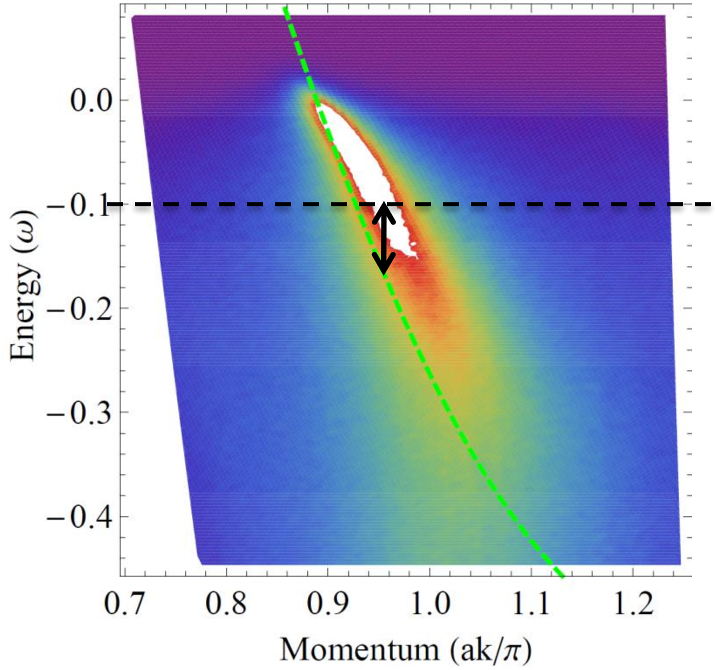
Self-energy

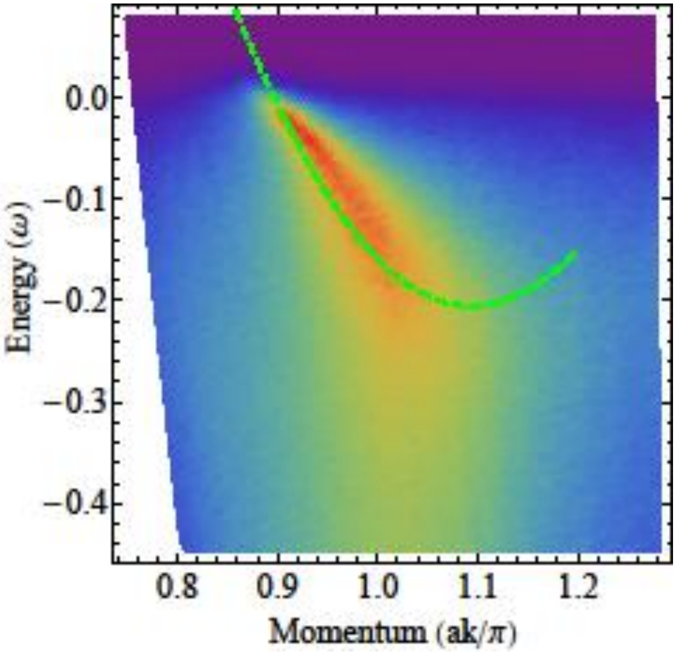
MDC 4 parameter fit

$$A(\theta, k_\perp, \omega) = -\frac{1}{\pi}\frac{\Sigma_2(\theta,\omega)}{\left[\omega - \xi(\vec{k}) - \Sigma_1(\theta,\omega)\right]^2 + \left[\Sigma_2(\theta,\omega)\right]^2}.$$

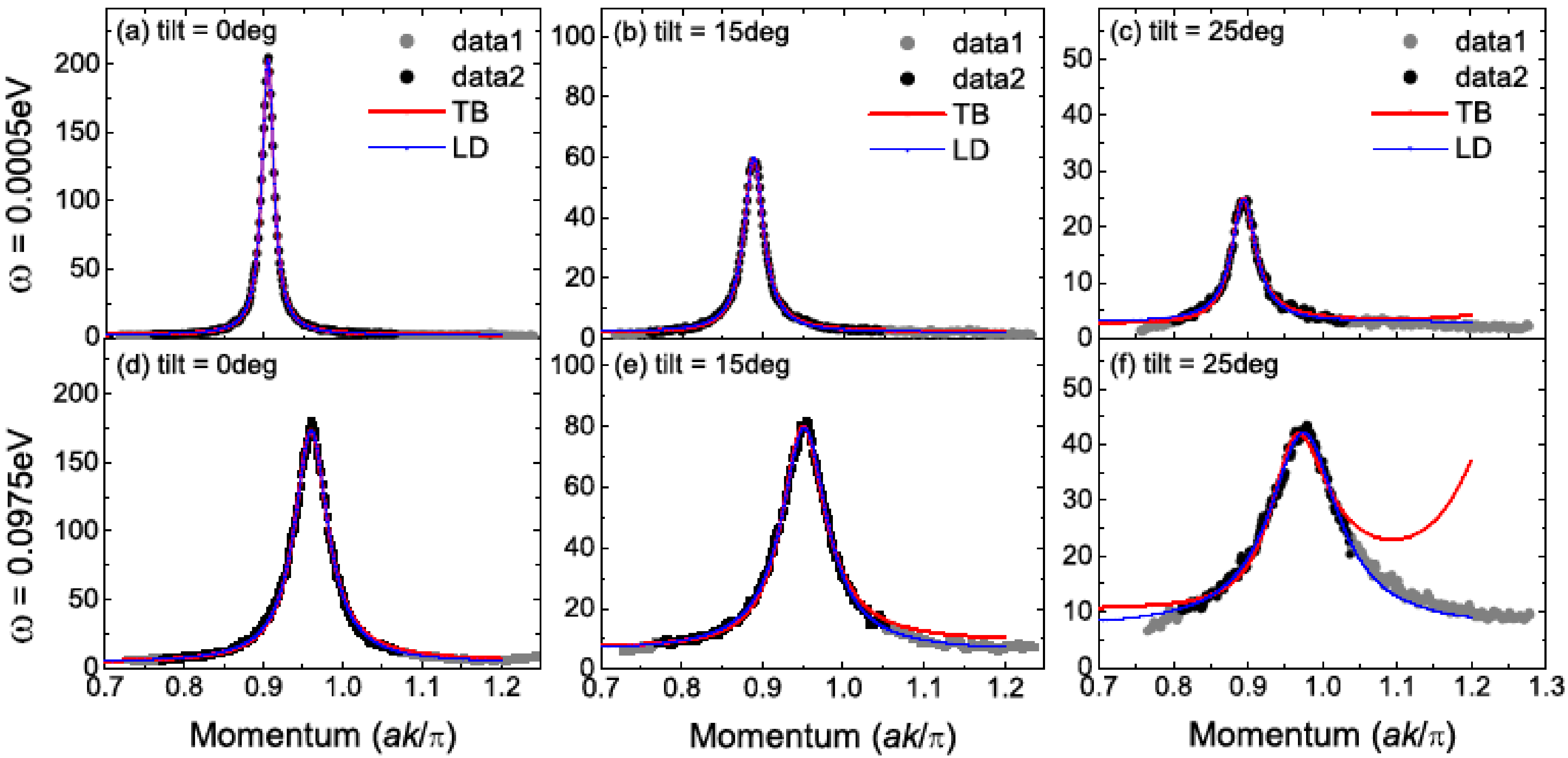
$$\xi(\vec{k}) = -2t[\cos(k_x a) + \cos(k_y a)] + 4t'\cos(k_x a)\cos(k_y a)$$
$$-2t''[\cos(2k_x a) + \cos(2k_y a)] - \mu.$$





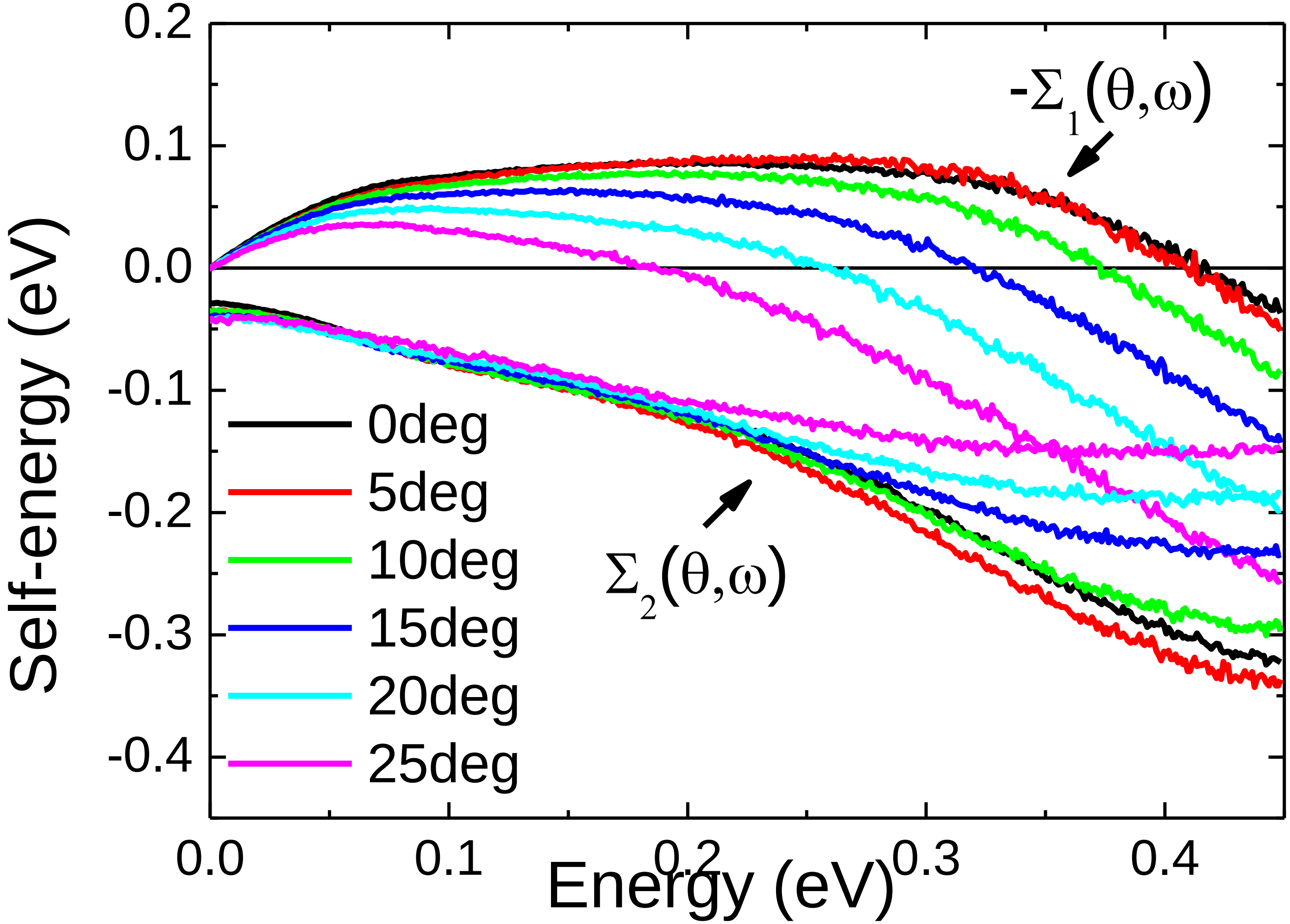


MDC fits



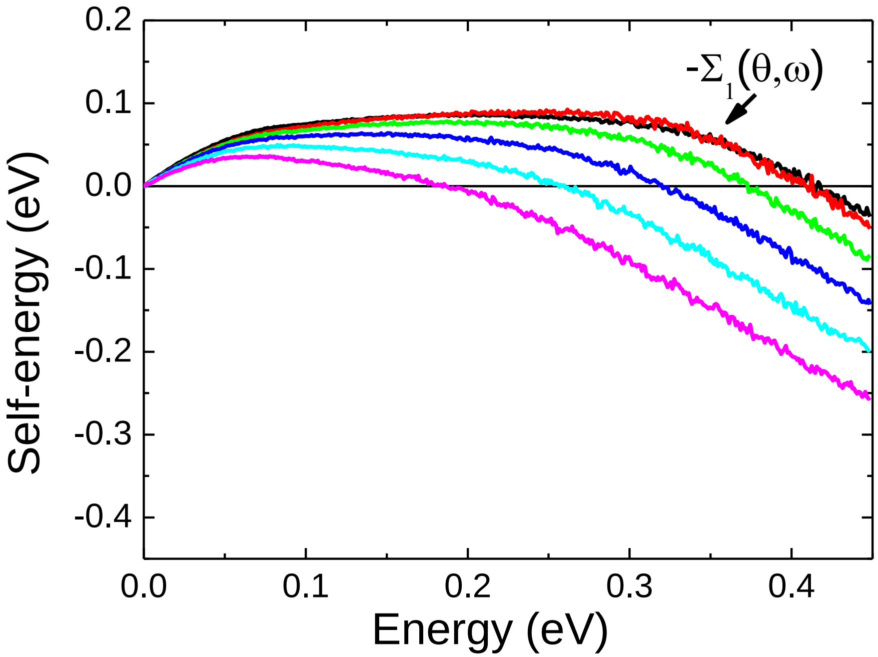
(a) tilt = 0deg
(b) tilt = 15deg
(c) tilt = 25deg
(d) tilt = 0deg
(e) tilt = 15deg
(f) tilt = 25deg
data1
data2
TB
LD
ω = 0.0005eV
ω = 0.0975eV
Momentum (ak/π)

Self-energy



-Σ1(θ,ω)
Σ2(θ,ω)
0deg
5deg
10deg
15deg
20deg
25deg
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
Self-energy (eV)
0.0
0.1
0.2
0.3
0.4
Energy (eV)

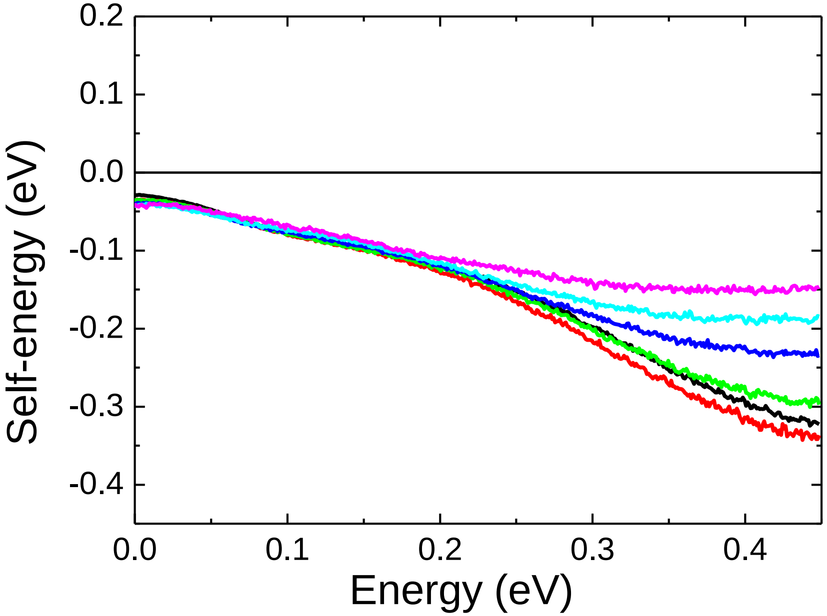
Real part



- **Zero crossing at smaller energy and the slope decreases as the angle increases.**

  ← Smaller band bottom energy.

Imaginary part



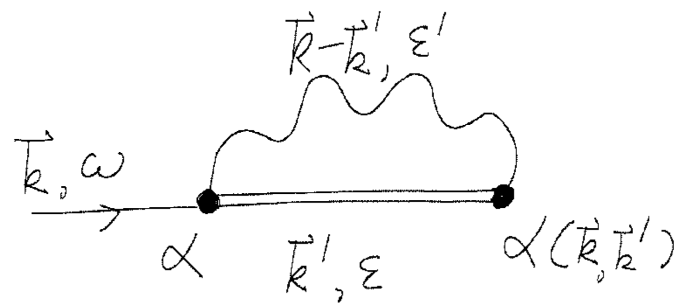
- $\mathrm{Im}\Sigma(\theta,\omega)=a+b\omega$ → **both elastic and inelastic parts are angle dependent.**
- **Nearly collapse ~0.2 eV.**

Fluctuation spectrum

Adaptive maximum entropy method

$$\Sigma(\vec{k},\omega) = \sum_{k'} \int d\varepsilon \int d\varepsilon' \frac{f(\varepsilon) + n(-\varepsilon')}{\varepsilon + \varepsilon' - \omega - i\delta}$$

$$A(\vec{k}',\varepsilon)\alpha^2(\vec{k},\vec{k}')F(\vec{k}-\vec{k}',\varepsilon')$$



$$\Sigma_1(\theta,\omega) = \int d\varepsilon' M(\omega,\varepsilon')\alpha^2 F(\theta,\varepsilon'),$$

$$M(\omega,\varepsilon') \equiv \int d\varepsilon \frac{f(\varepsilon) + n(-\varepsilon')}{\varepsilon + \varepsilon' - \omega}.$$

$$\Sigma_2(\theta,\omega) = \pi \int d\varepsilon' \left[f(\omega - \varepsilon') + n(-\varepsilon') \right] \alpha^2 F(\theta,\varepsilon').$$

$$\alpha^2 F(\theta,\epsilon') \equiv \left\langle \frac{\alpha^2(\theta,\theta')}{v_F(\theta')} F(\theta,\theta',\epsilon') \right\rangle_{\theta'}$$

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Adaptive MEM

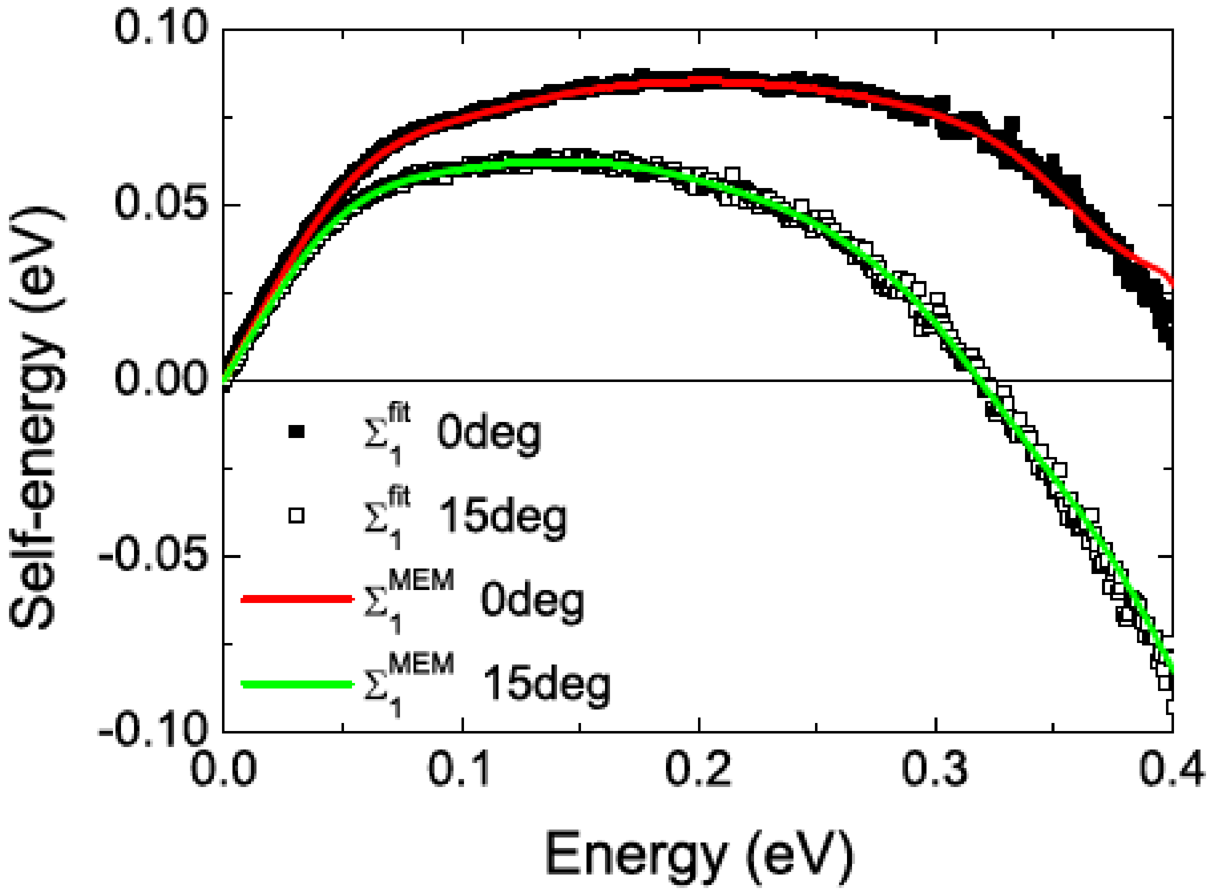
$$L = \frac{\chi^2}{2} - \alpha S.$$

$$\chi^2 = \sum_{i=1}^{N_D} \frac{[D_i - \Sigma_1(\omega_i)]^2}{\sigma_i^2}$$

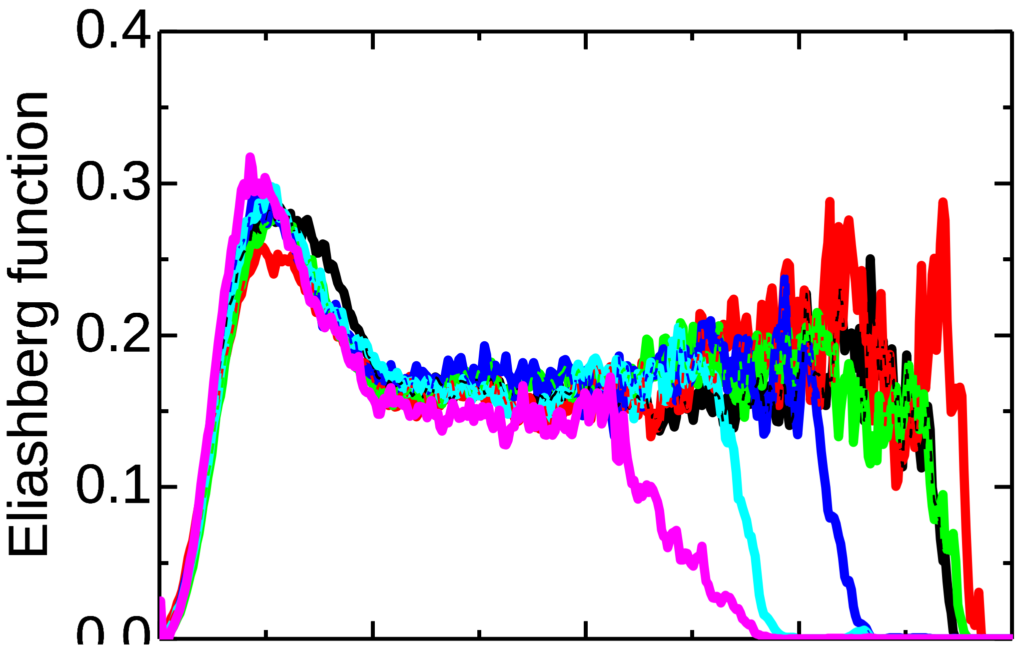
$$S = \int_0^\infty d\epsilon' \left[\alpha^2 F(\epsilon') - m(\epsilon') - \alpha^2 F(\epsilon') \ln \frac{\alpha^2 F(\epsilon')}{m(\epsilon')}\right]$$

$$\delta F_j = -\sum_k A_{jk}^{-1} \frac{\delta L}{\delta F_k}, \quad A_{jk} = \frac{\delta^2 L}{\delta F_j \delta F_k}$$

- **The constraint function *m* was updated → double iterations.**


0.10
0.05
0.00
-0.05
-0.10
0.0
0.1
0.2
0.3
0.4
Self-energy (eV)
Energy (eV)
Σ_1^{fit} 0deg
Σ_1^{fit} 15deg
Σ_1^{MEM} 0deg
Σ_1^{MEM} 15deg

Mom-dependent Eliashberg function



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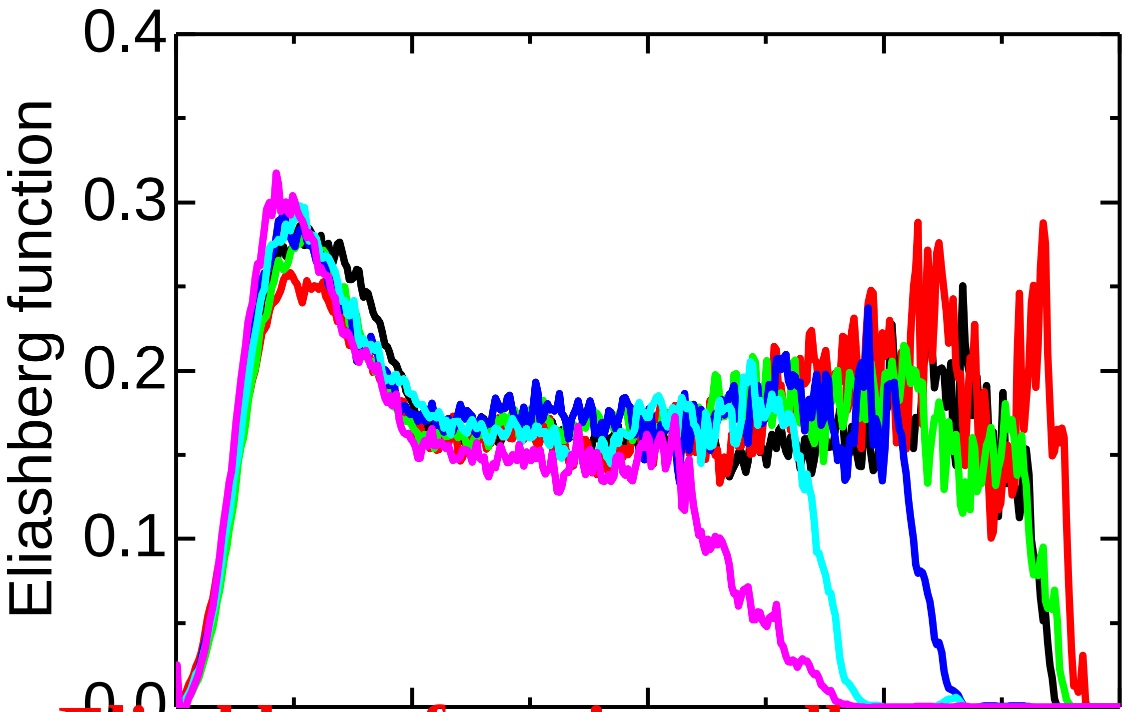
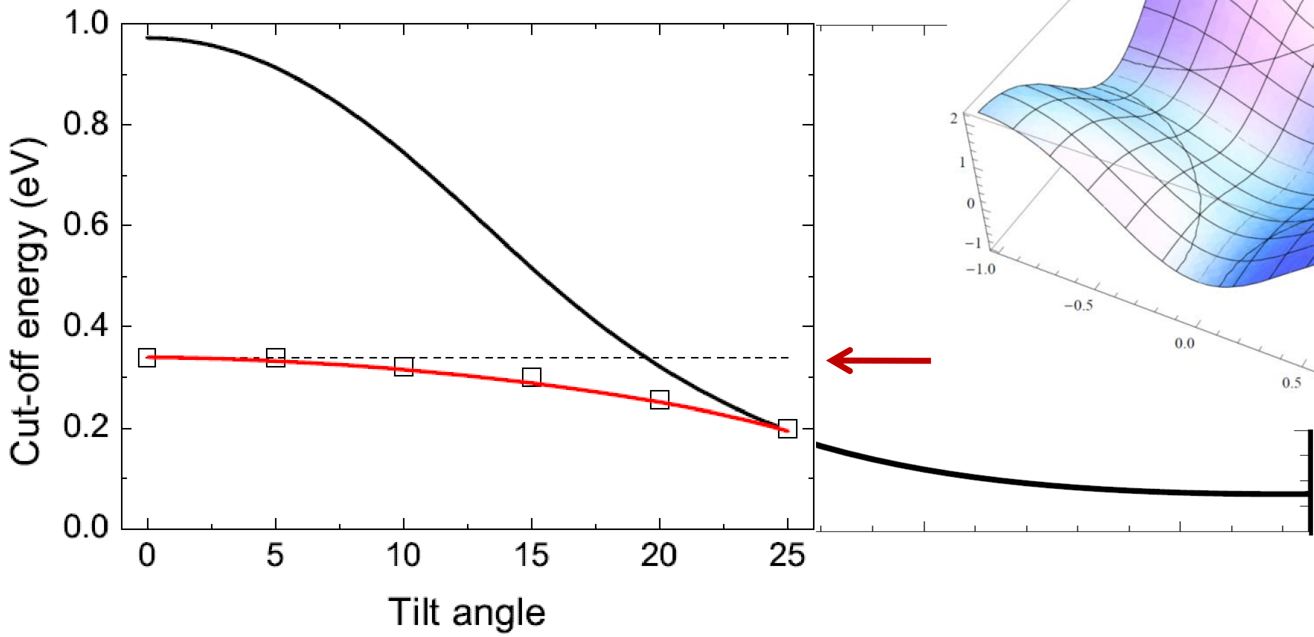
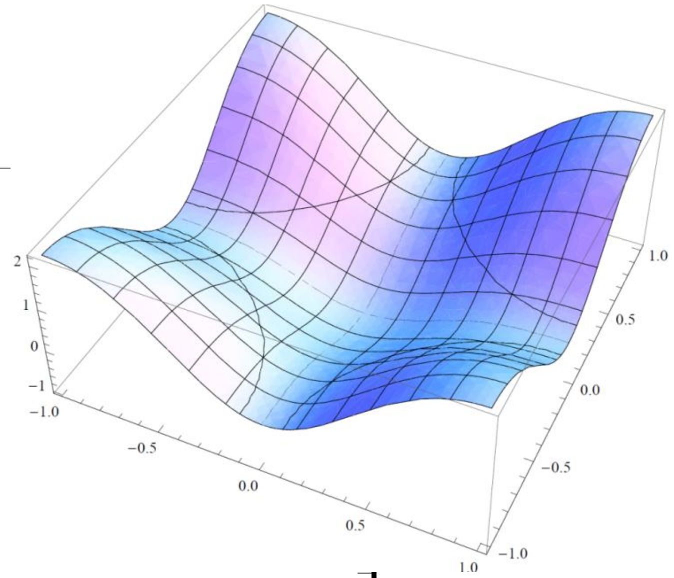


- **The Eliashberg functions collapse onto a single curve below the cut-off energy.**
- **The cut-off energy is angle dependent.**

The angle dependence of the cut-off energy





How the angle dependent cut-off energy comes about?

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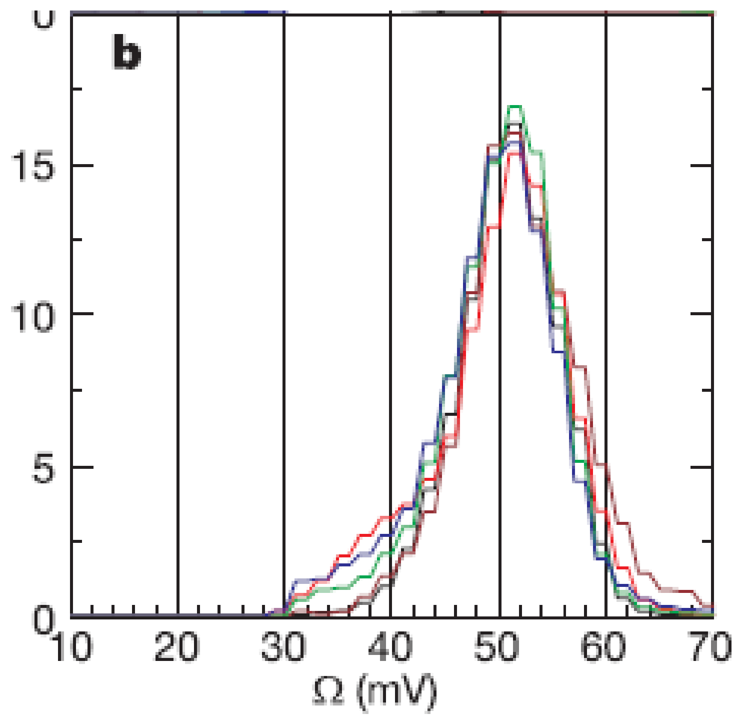
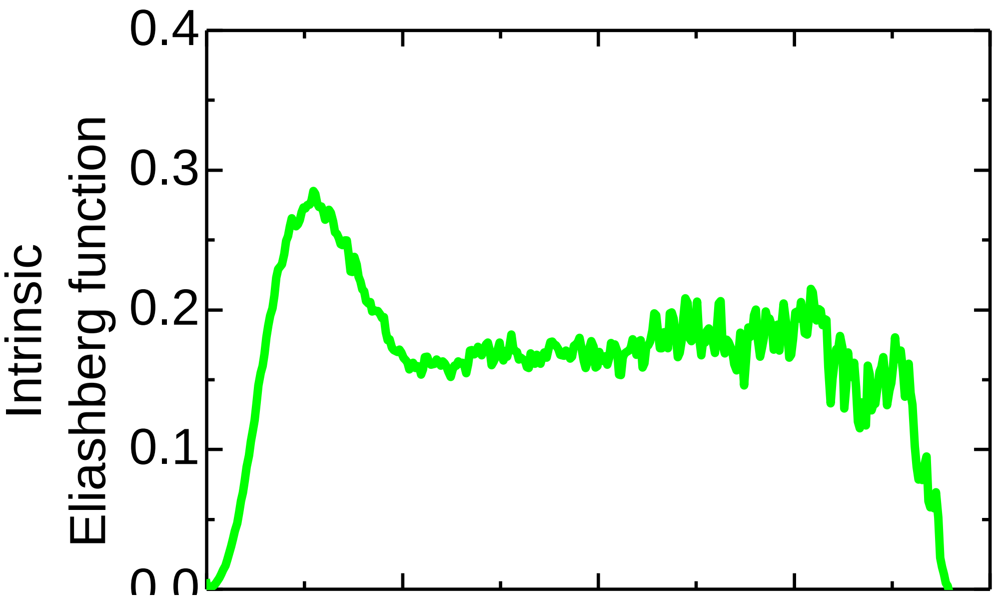
Lee *et al*, tunneling on Bi2212 Nature (2006)



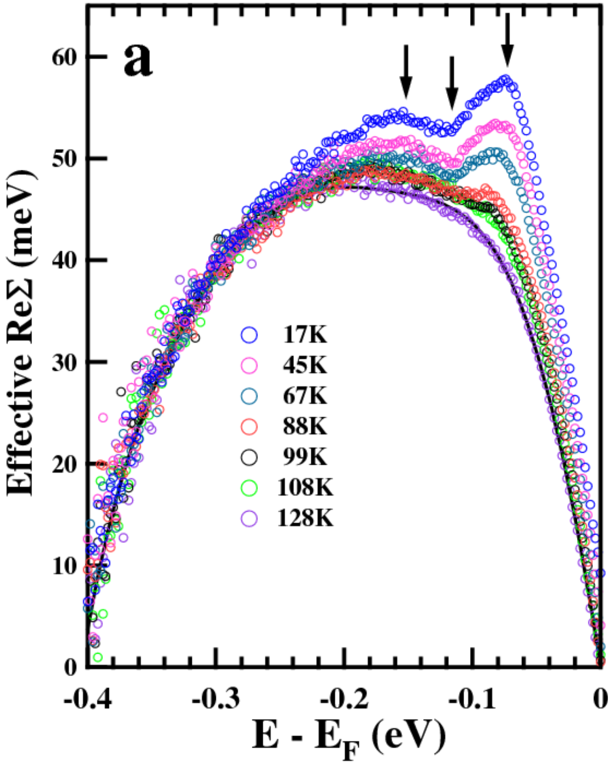
Intrinsic mom-independent Eliashberg function

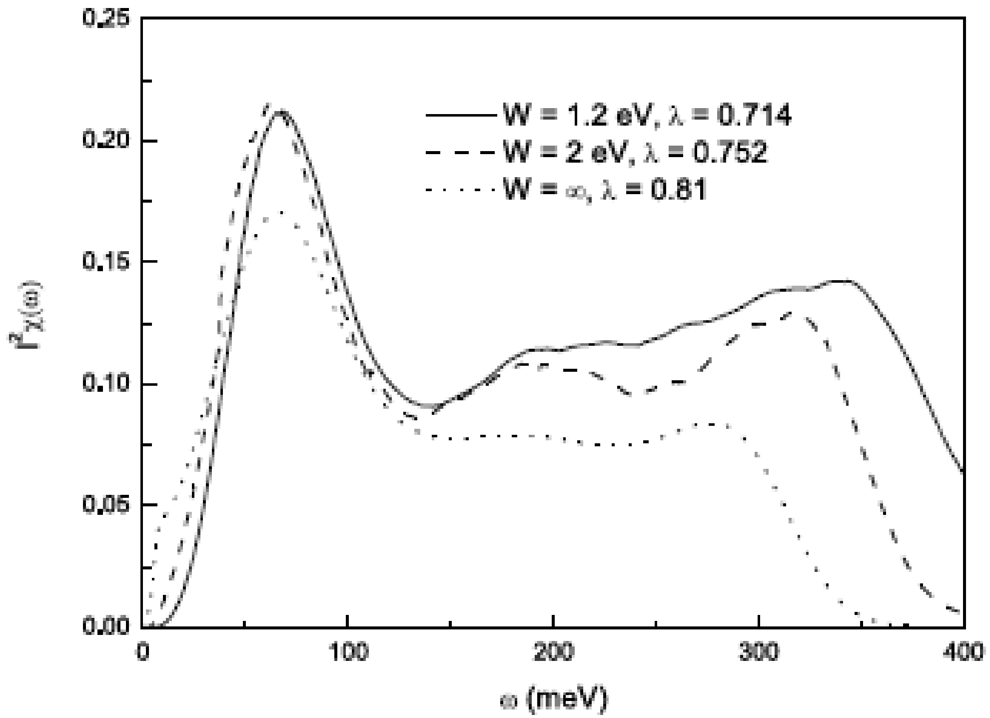


- **Intrinsic cut-off ~ 0.35--0.4 eV.**
- **Intrinsic** $\lambda = 2\int_0^\infty d\omega \frac{\alpha^2 F(\omega)}{\omega} \approx 1.5.$

Zhang & Zhou *et al*, PRL (2008)

Schachinger & Carbotte PRB (2008)





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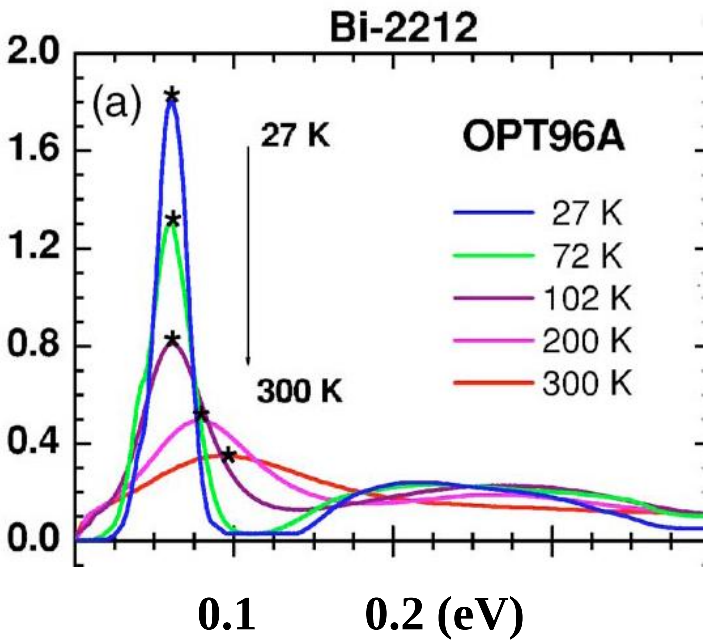
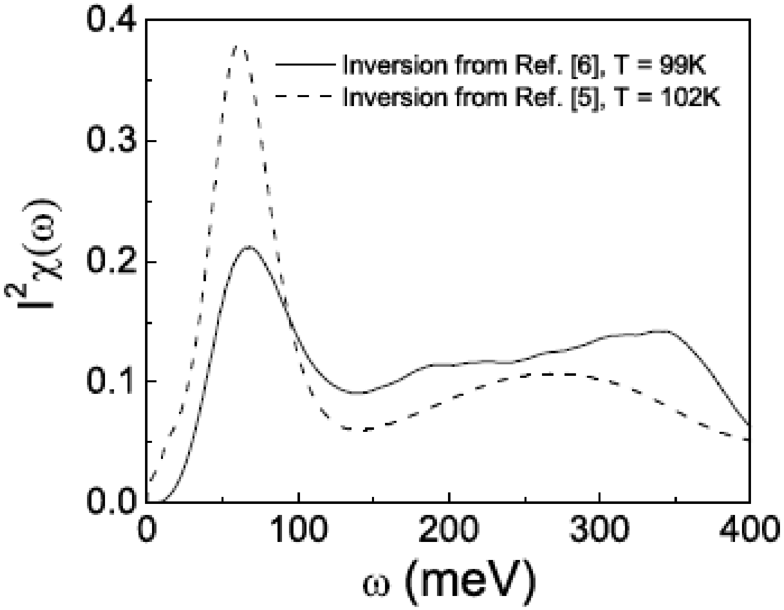
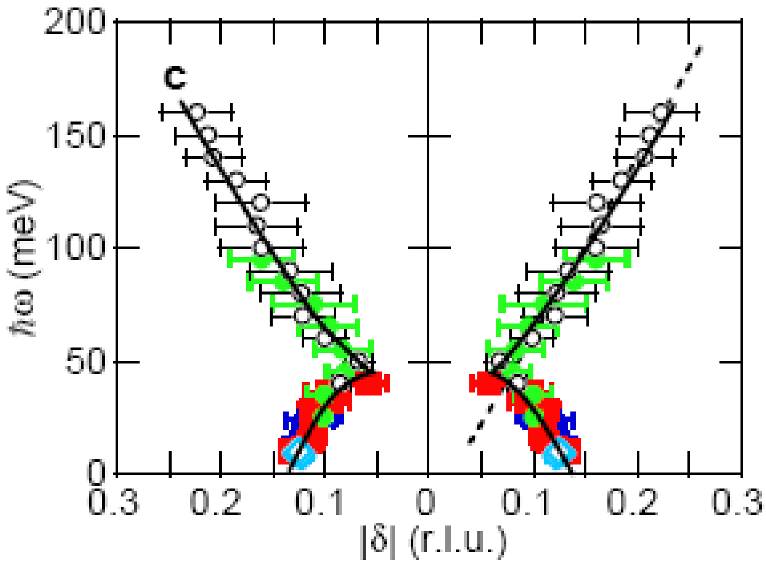
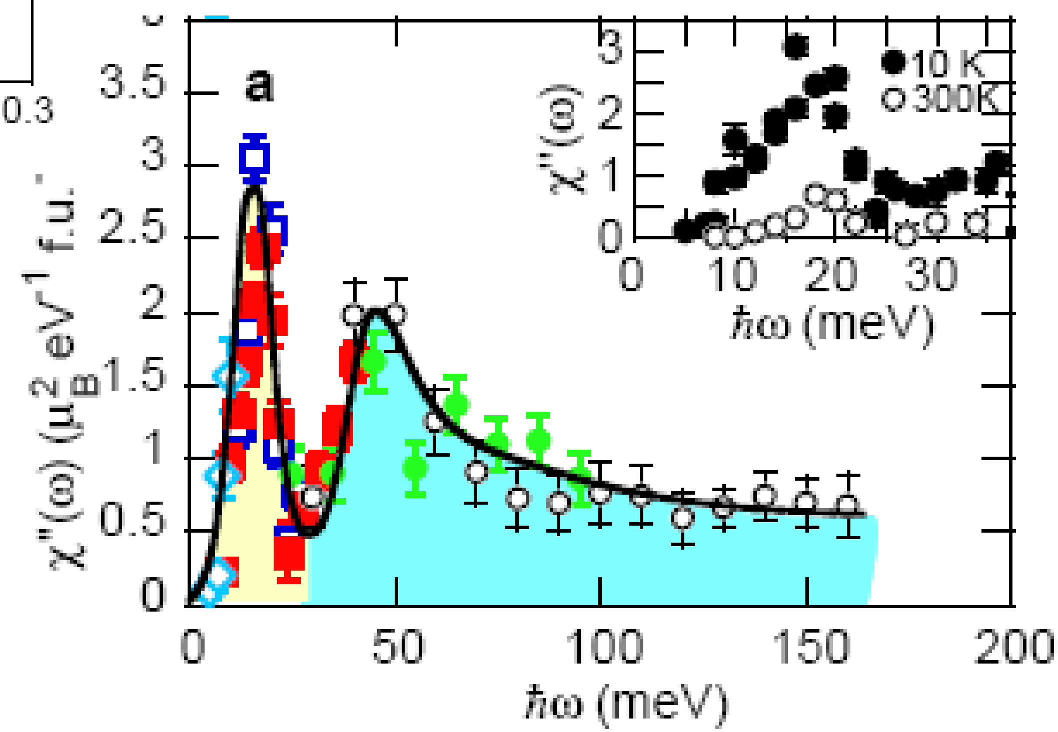
Hwang & Timusk, PRB (2007)





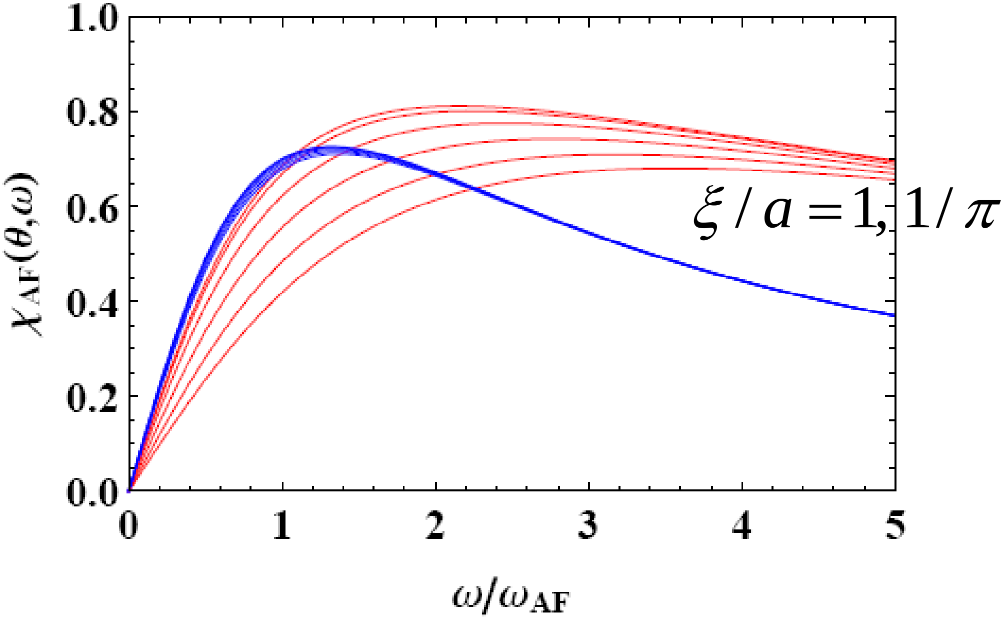
Vignolle *et al.* Nature Phys (2007)





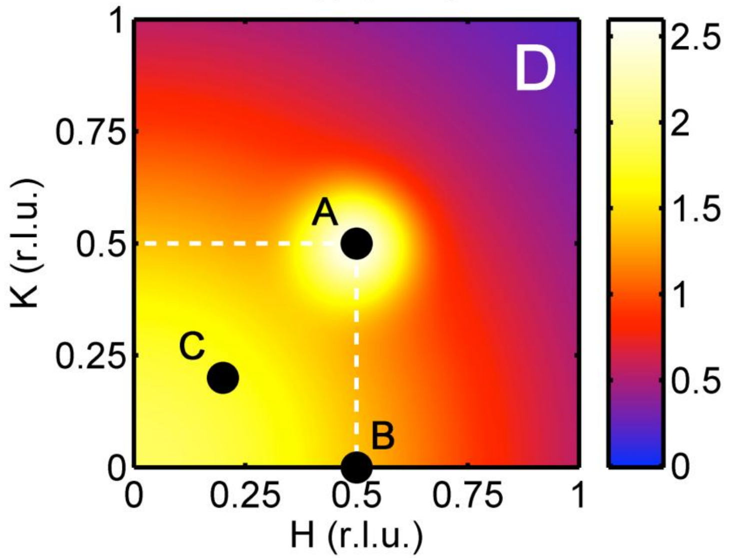
The angle independence of the Eliashberg fucntion: Implications for AFM fluctuations

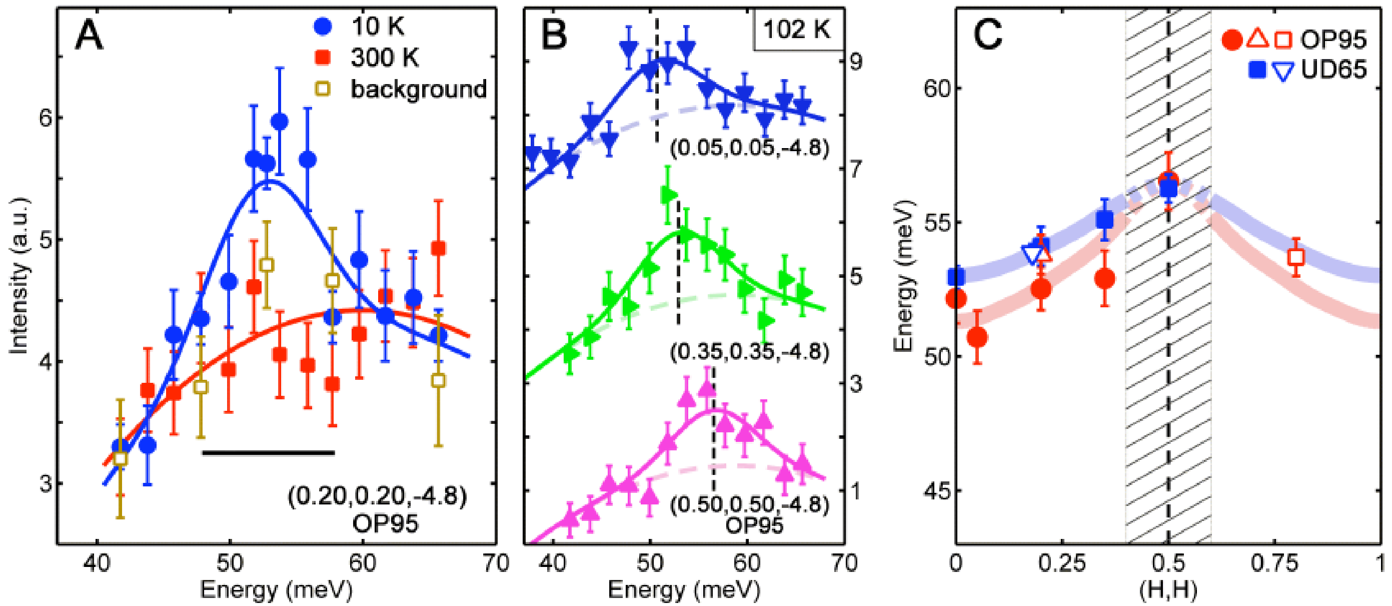
$$\chi_{AF}(\mathbf{k},\mathbf{k}',\omega) = \frac{\alpha\xi^2\,\omega/\omega_{AF}}{((\mathbf{k}-\mathbf{k}'-\mathbf{Q})^2\xi^2+1)^2+(\omega/\omega_{AF})^2}.$$



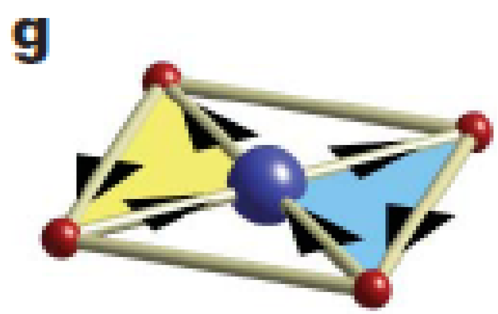
Li, Bourges, Greven, tbp Science

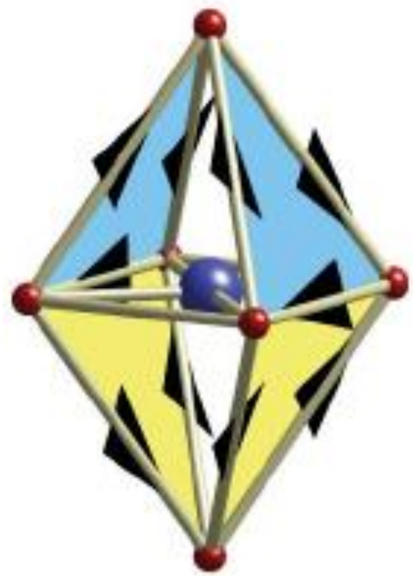
- nearly mom-independent magnetic excitation with comparable total spectral weight with the resonance mode.





Loop currents order, Varma *et al*, PRL (1999, 2007)





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Summary & remarks

- The Eliashberg functions collapse onto a single curve independent of the angle below the cut-off energy.
- The cut-off energy is angle dependent.
- How they come about?

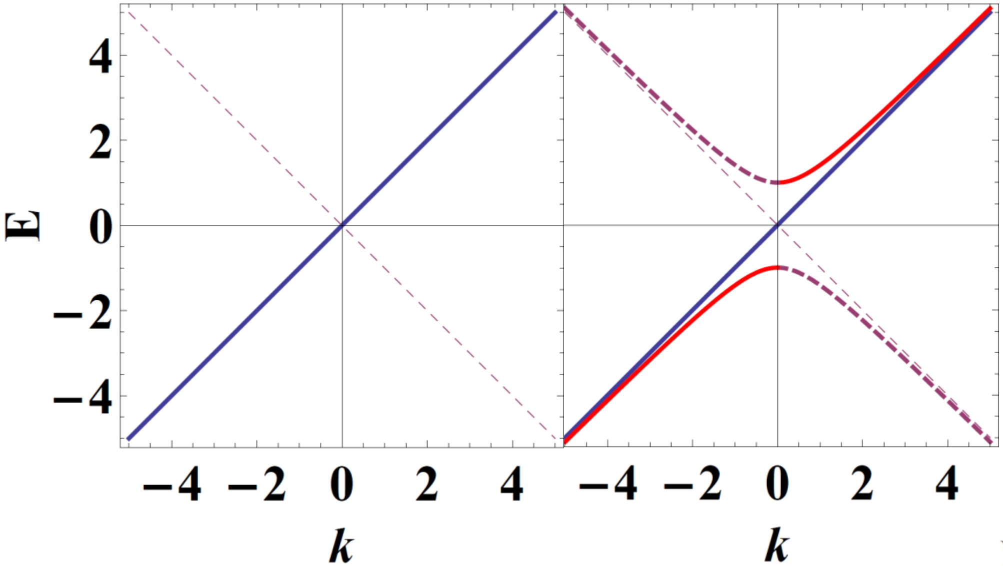
(cont'd)

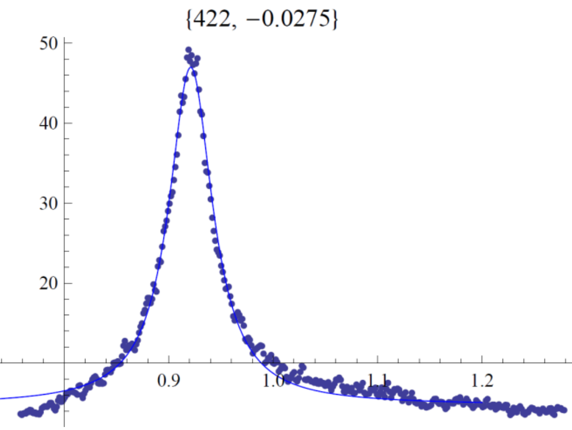
- **Eliasberg theory valid? →**

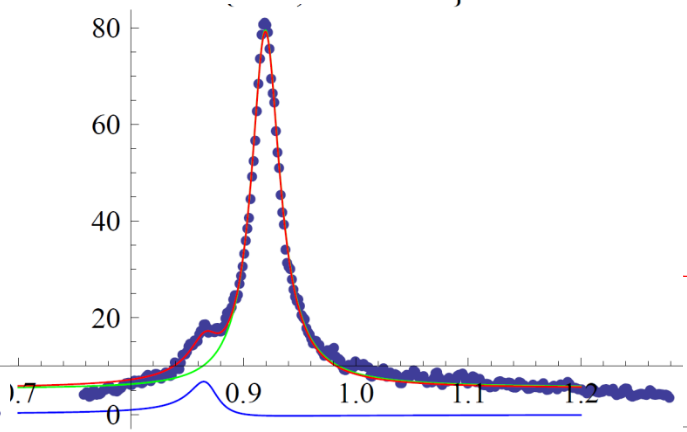
  $O(\omega_c / W) \approx 1/5.$

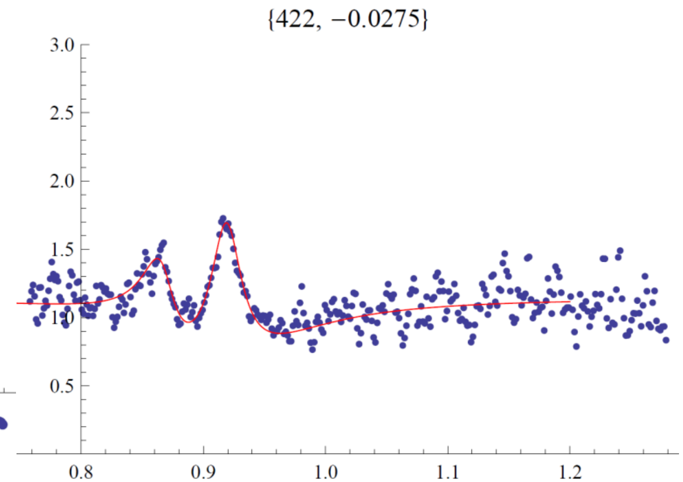
- **The doping evolutions?**
- **What about the *T* evolutions? SC state?**

SC state: 6 parameter fit









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Thanks!