

Photoemission Studies of Strongly Correlated Systems

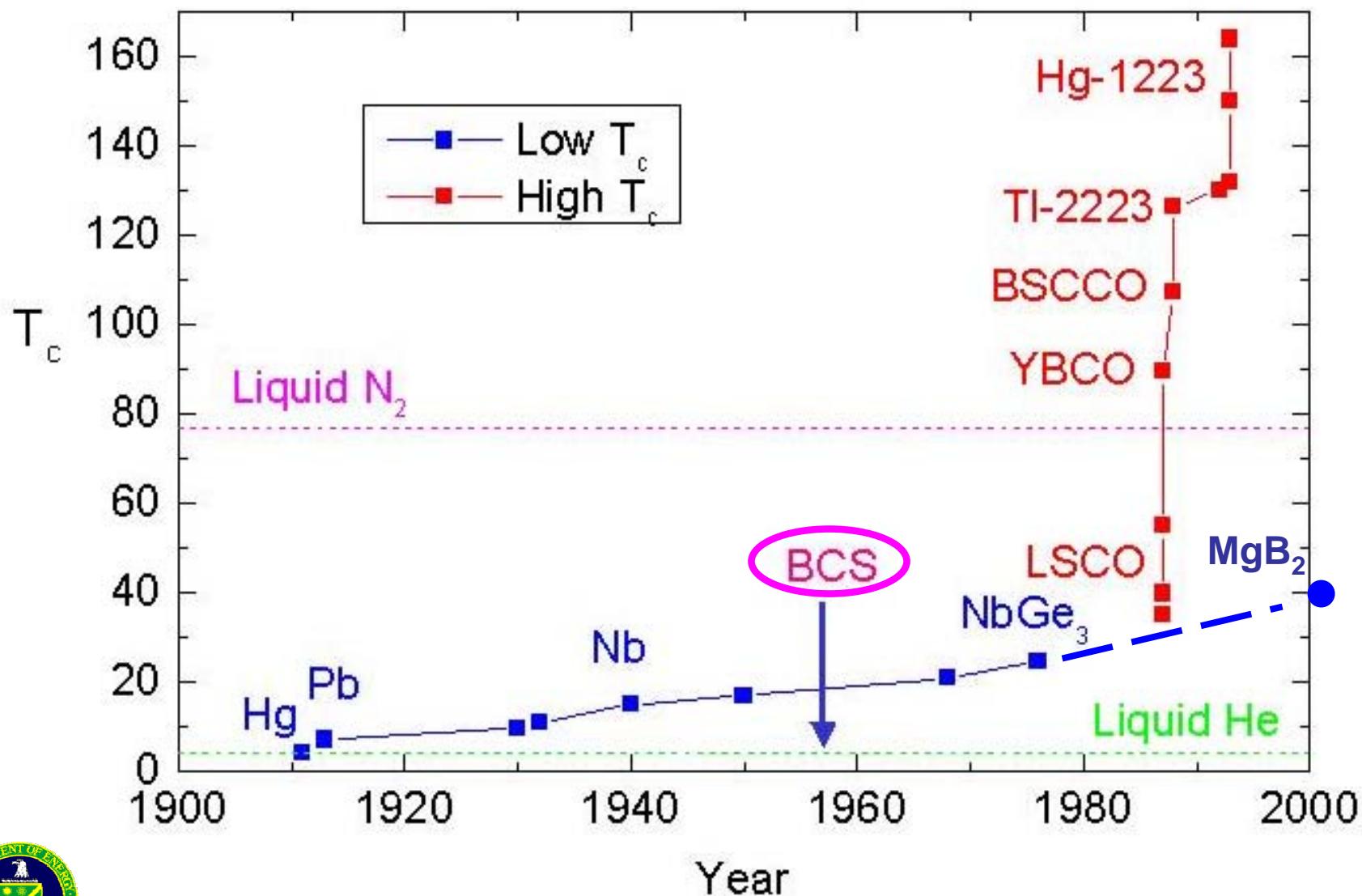
Peter D. Johnson

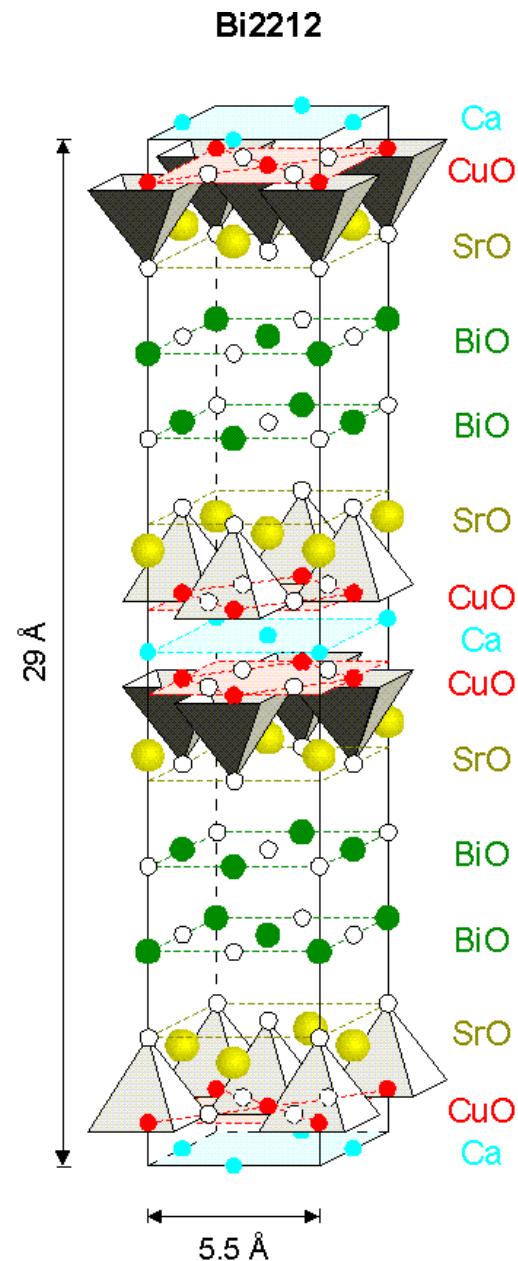
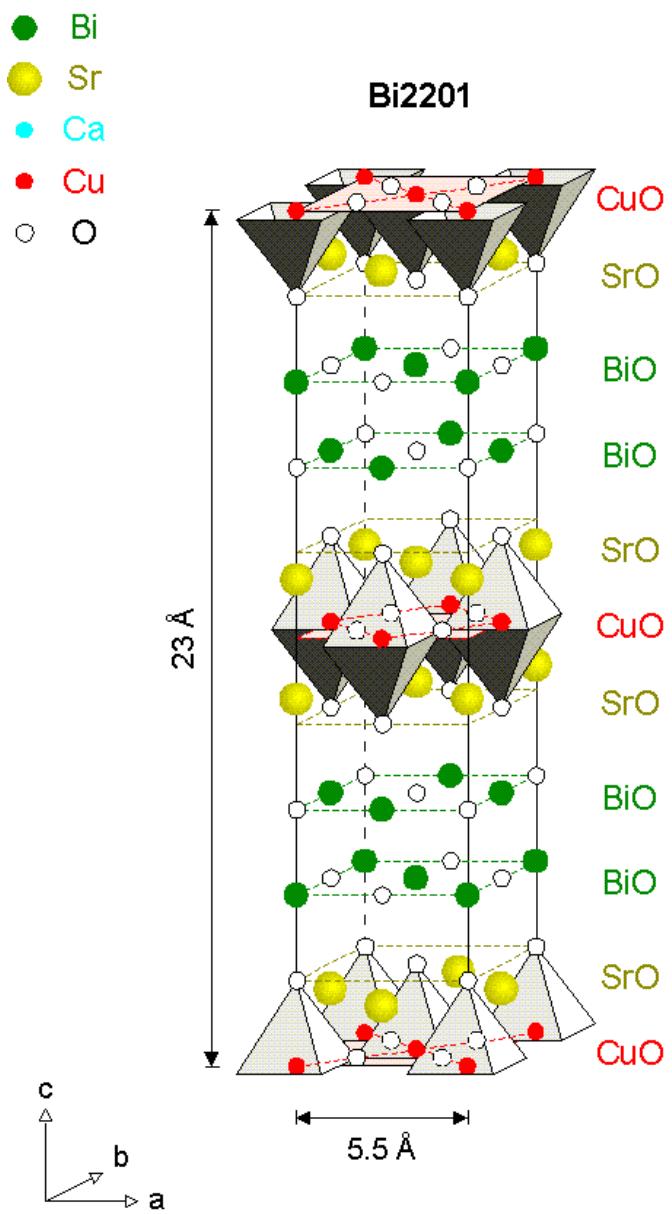
*Physics Dept.,
Brookhaven National Laboratory*

JLab March 2005

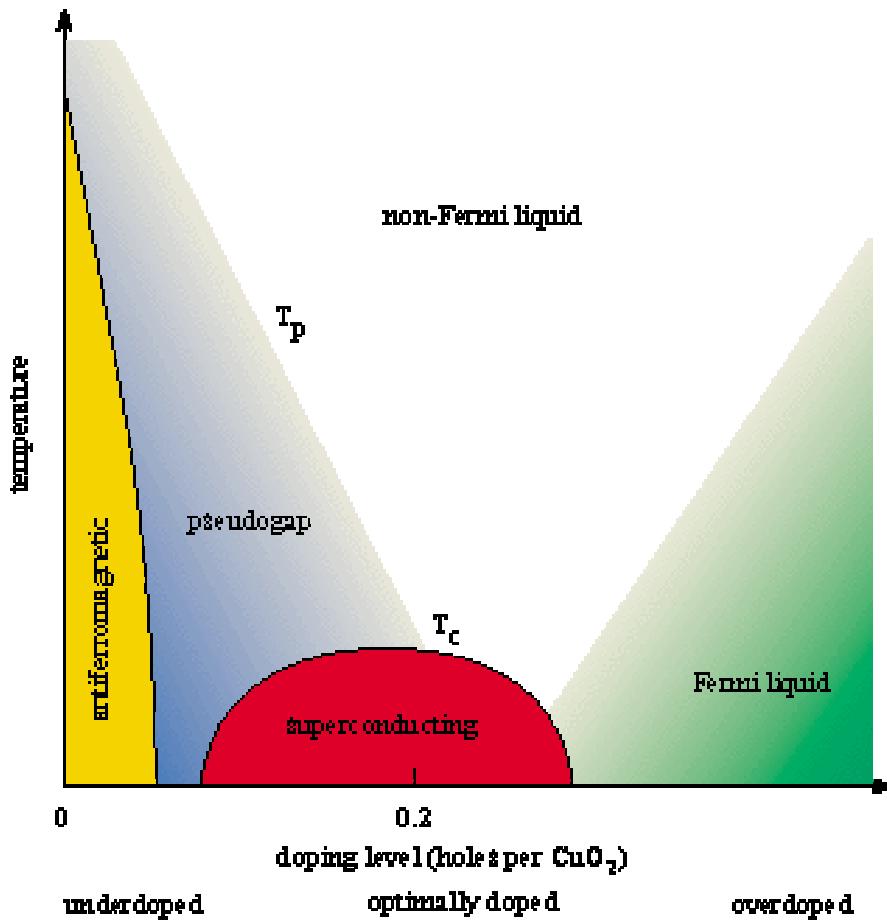


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High T_c Superconductor - Phase Diagram



Fermi Liquid:-Excitations

Landau-Quasiparticles

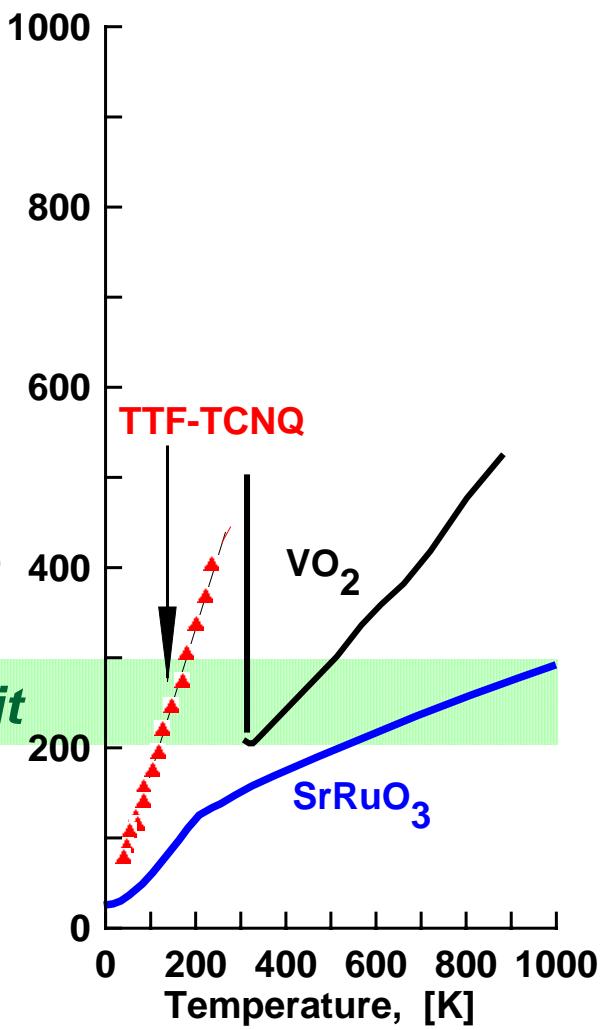
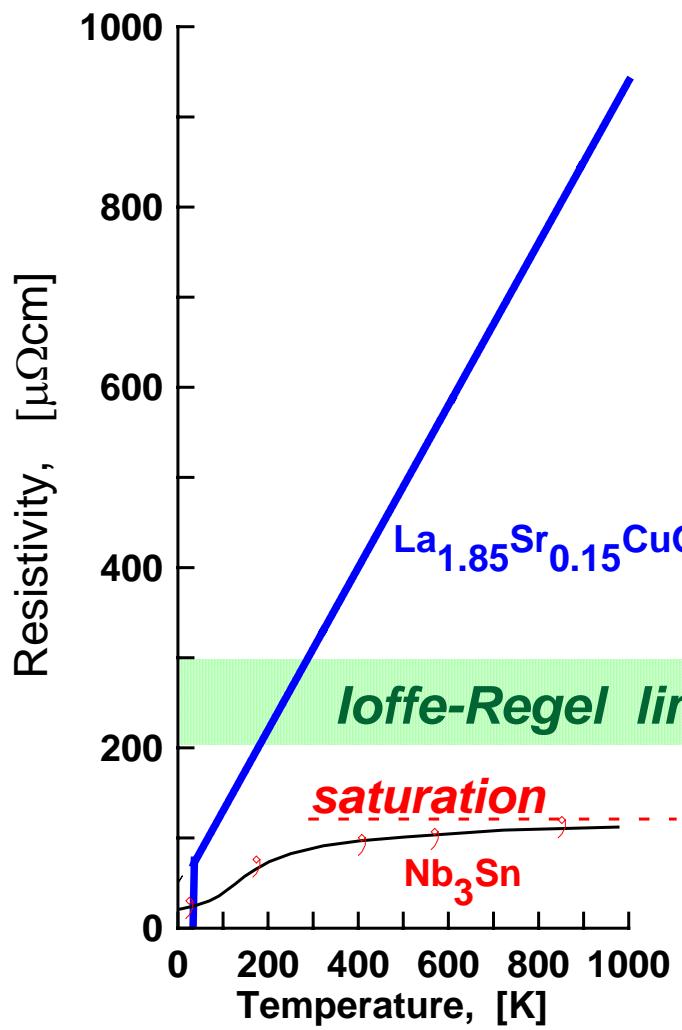
$$\Gamma(\omega, T) = 2\beta [(\pi k_B T)^2 + \omega^2]$$

$$\Delta E = \frac{\eta}{\tau} \leq \omega$$



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dc Transport in Synthetic Metals



Drude Model of Conductivity

$$\text{Conductivity} \quad \sigma = \frac{ne^2}{m^*} \tau$$

In a two-dimensional system

$$\sigma \propto k_F l$$

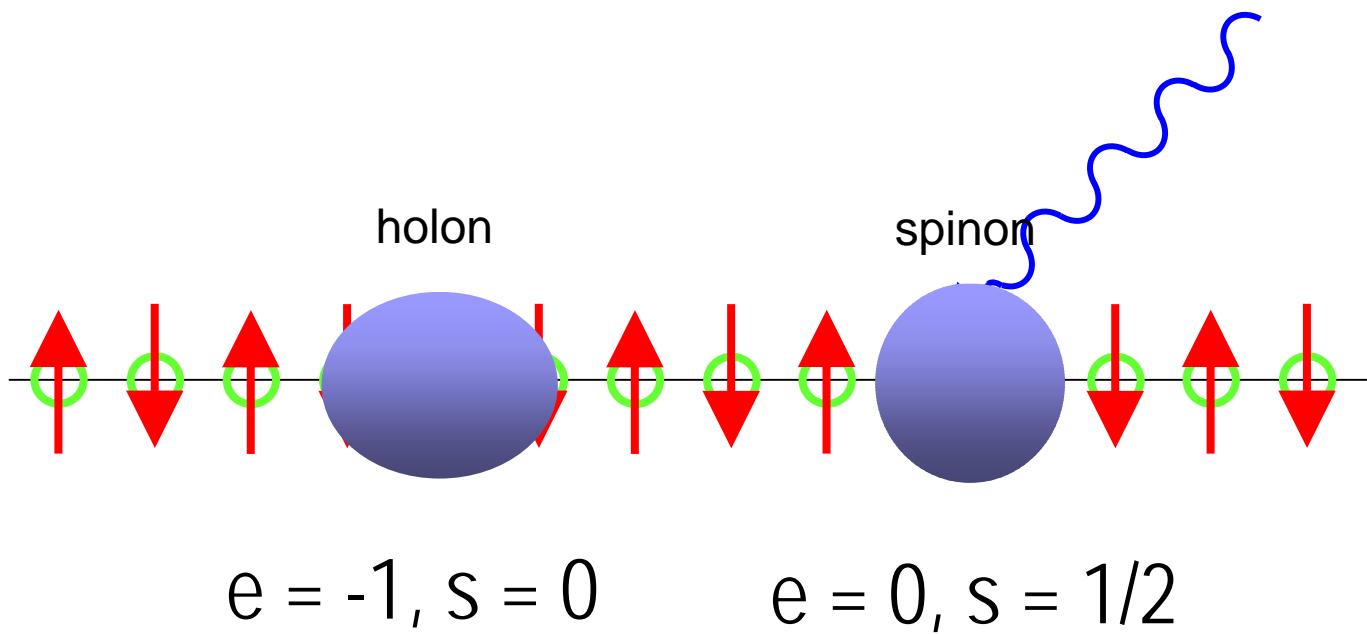
Thus the **resistivity ρ** is given by

$$\rho \propto \frac{1}{k_F l} = \frac{\Delta k}{k_F} \text{ or } \frac{\text{Im } \Sigma}{E_F}$$



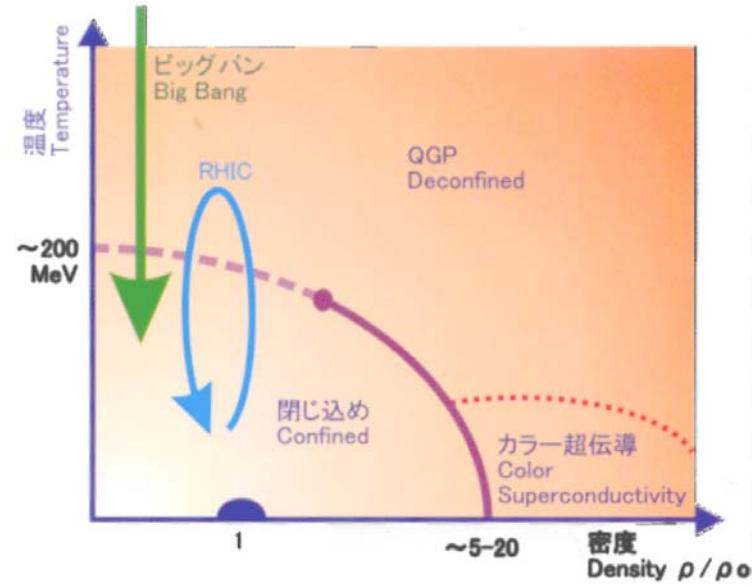
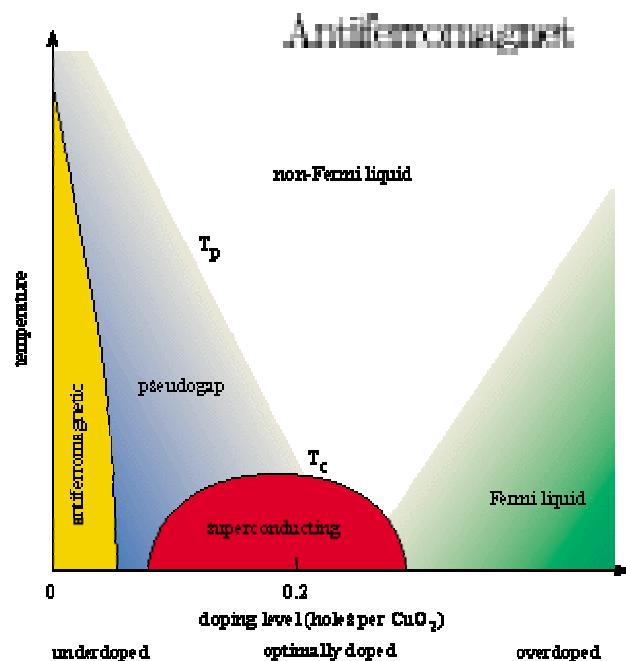
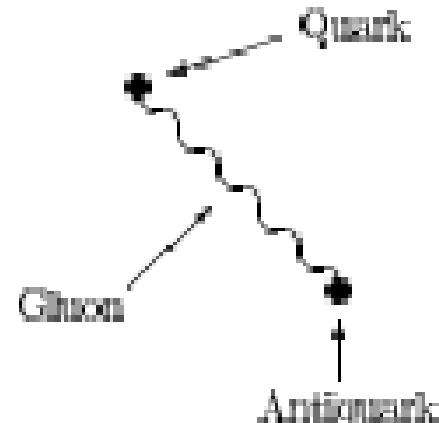
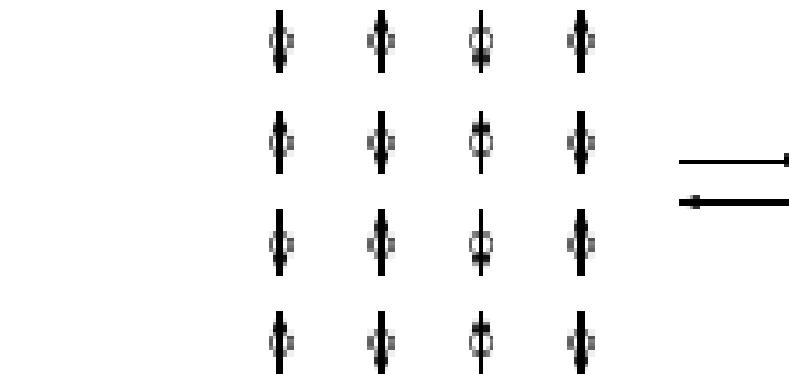
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Spin-charge separation



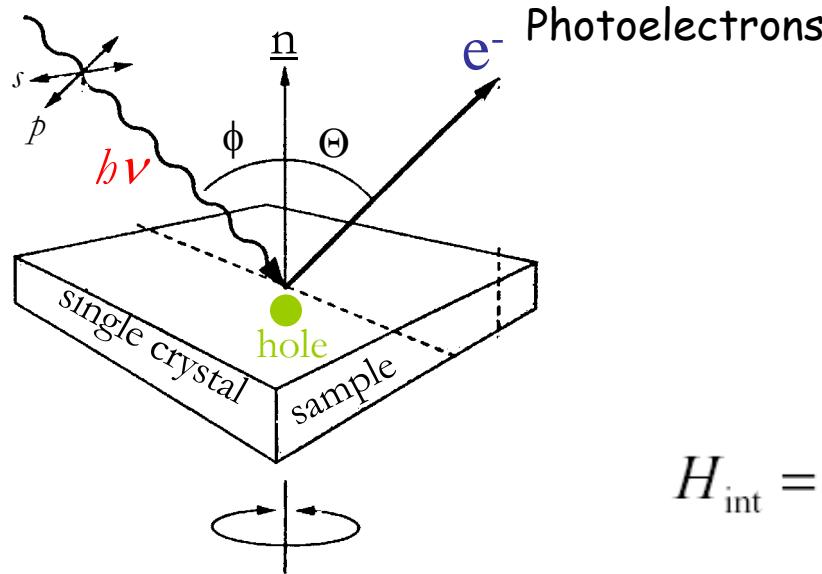
R. B. Laughlin 1998

"Parallels Between Quantum Antiferromagnetism and the Strong Interactions"



Photoemission is an excellent probe of low energy excitations

Incident Photons



$$H_{\text{int}} = \frac{e}{mc} \mathbf{A} \cdot \mathbf{p}$$

$$\omega = \frac{2\pi}{\eta} \left| \langle \psi_f | H_{\text{int}} | \psi_i \rangle \right|^2 \delta(E_f - E_i - h\nu)$$



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$$\omega = \frac{2\pi}{\eta} \left| \langle \psi_f | H_{\text{int}} | \psi_i \rangle \right|^2 \delta(E_f - E_i - h\nu)$$

$$\psi(r') = \psi_i(r') + \int dr G(r, r') H_{\text{int}}(r) \psi_i(r)$$

Spectral Response

$$A(k, E) = \frac{1}{\pi} \text{Im } G(k, E)$$

Free Electron Case:-

$$G(k, E) = \frac{1}{E - E_k^0 - i\delta} \quad A_0(k, E) = \delta(E - E_k)$$



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We introduce the *self-energy* Σ to take account of interactions

$$\text{Green's Function } G(E) = \frac{1}{E - \varepsilon} \Rightarrow \frac{1}{E - \varepsilon - \Sigma}$$

$$\text{Spectral Function } A(E) = \frac{1}{\pi} \text{Im} G(E) = \frac{1}{\pi} \frac{\Sigma''}{(E - \varepsilon - \Sigma')^2 + (\Sigma'')^2}$$

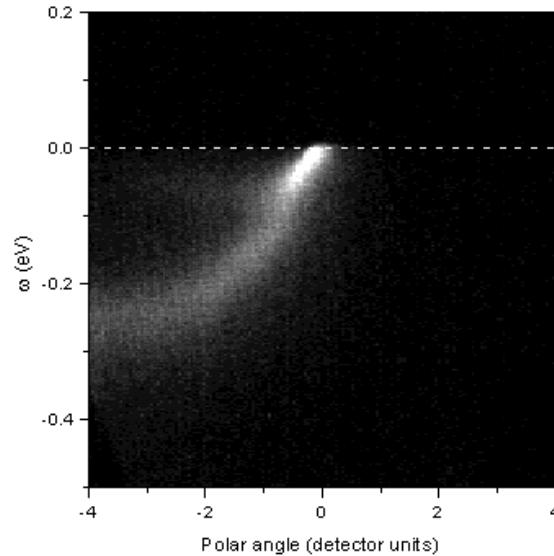
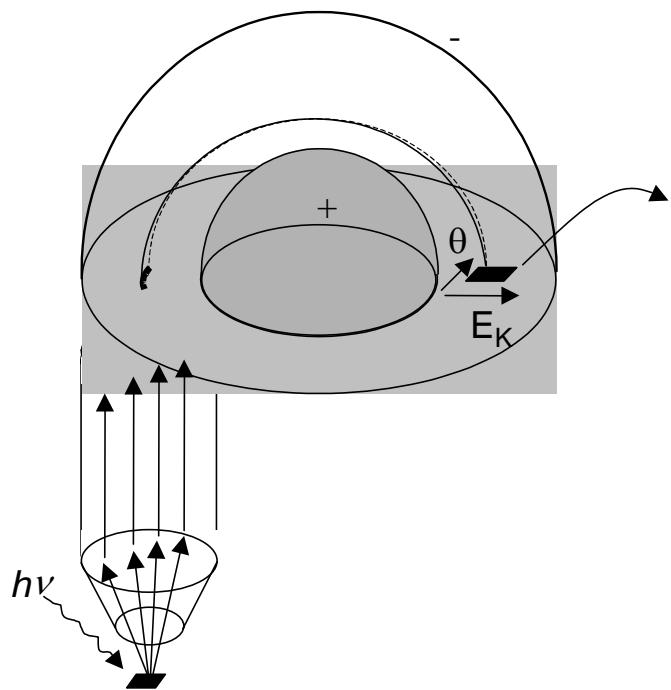
Photoemission peak at an energy $\varepsilon - \Sigma'$

Lifetime broadened to a width proportional to $2\Sigma'' = \Gamma$



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Photoelectron Spectrometer

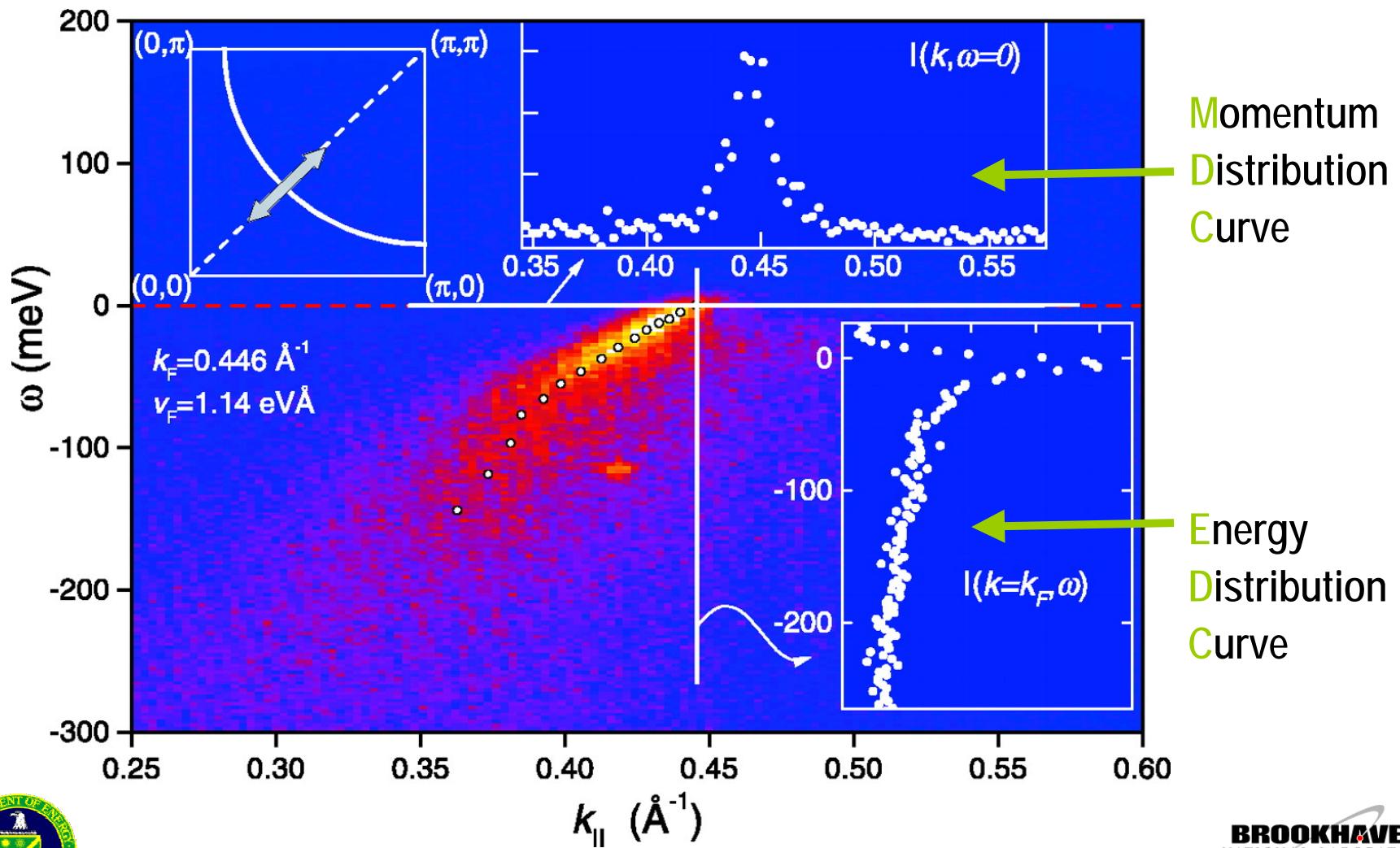


Resolution:- $\Delta E: \sim 5 \text{ meV}$
 $\Delta k: 0.015 \text{ \AA}^{-1}$



MDCs and EDCs

Science 285, 2110 (1999)



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MDCs and EDCs

MDC width $\Delta k = \frac{2\Sigma''}{v_0} = \frac{1}{\lambda}$ *Inverse Mean Free path*

EDC width $\Delta E = v\Delta k = \frac{\eta}{\tau}$ *Inverse Lifetime*

$$= \frac{2\Sigma''}{\left(1 - \frac{\partial\Sigma'}{\partial\omega}\right)}$$



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Drude Model of Conductivity

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In a two-dimensional system

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Thus the **resistivity ρ** is given by

$$\rho \propto \frac{1}{k_F l} = \frac{\Delta k}{k_F} \text{ or } \frac{\text{Im } \Sigma}{E_F}$$



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Photoemission Linewidths

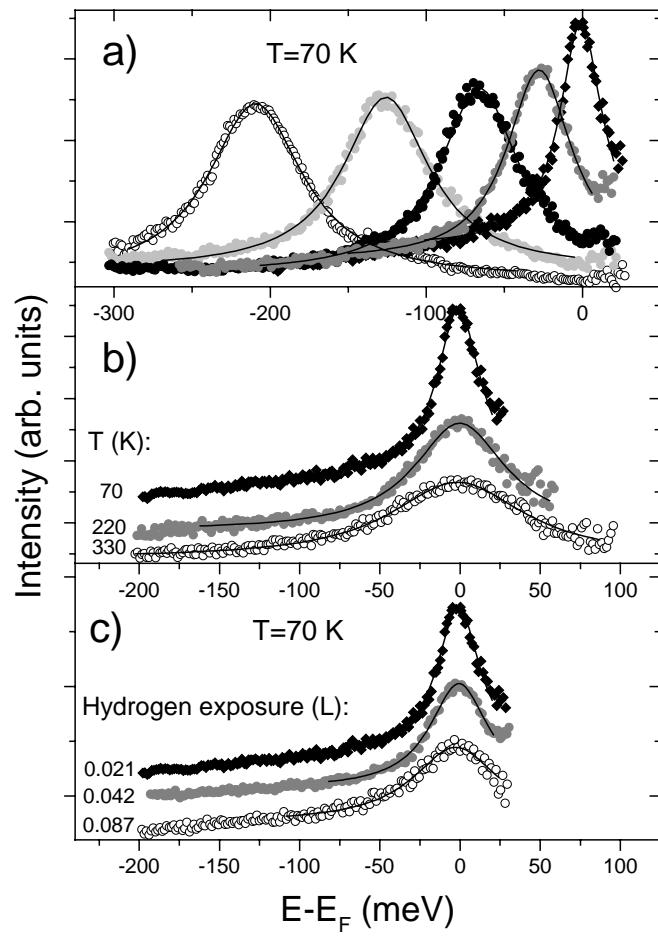
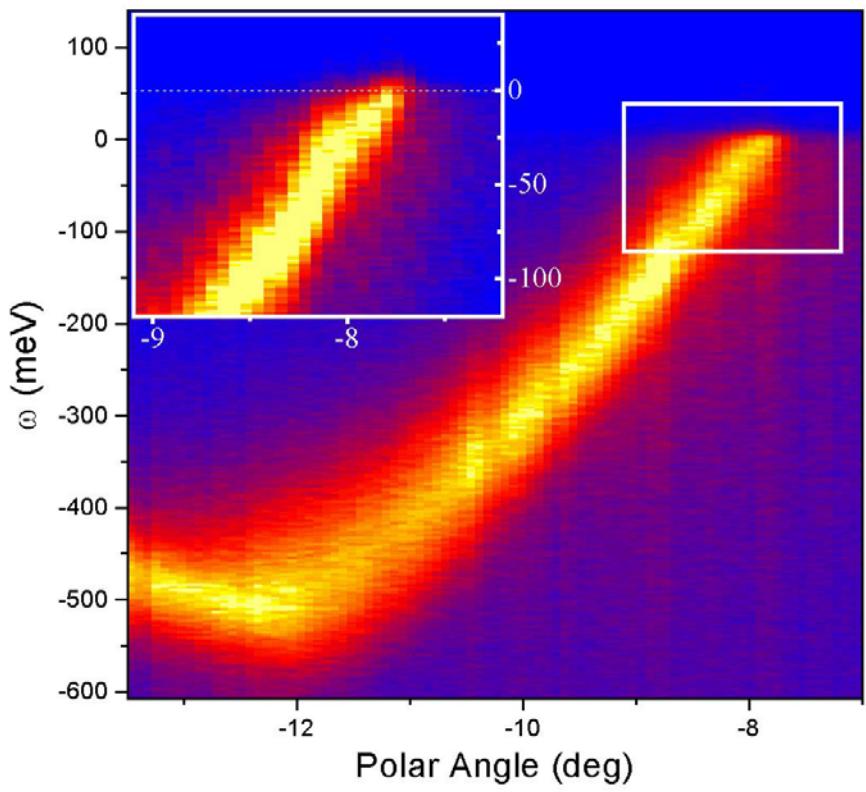
Linewidth
$$\Gamma = \frac{\frac{\Gamma_i}{|v_{i\perp}|} + \frac{\Gamma_f}{|v_{f\perp}|}}{\frac{1}{|v_{i\perp}|} + \frac{1}{|v_{f\perp}|}}$$

For a 2-Dimensional initial state $v_{i\perp} = 0$

$$\boxed{\Gamma = \Gamma_i}$$



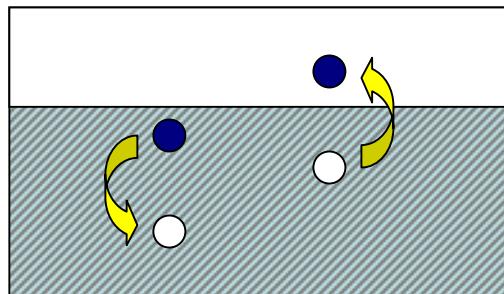
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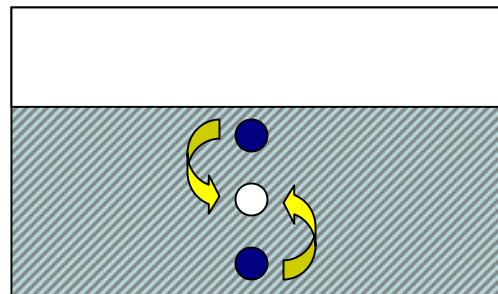
Phys. Rev. Lett. 83, 2085 (1999)

Scattering Rates: $(\vec{k}, \omega) \rightarrow (\vec{k} + \Delta\vec{k}, \omega + \Delta\omega)$

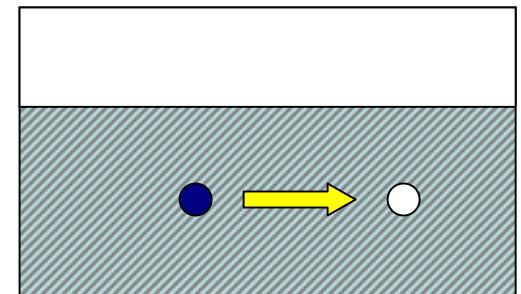
Electron-Electron



Electron-Phonon



Electron-Impurity



$$\Gamma_{el-el}(\omega, T) = 2\beta [(\pi k_B T)^2 + \omega^2]$$

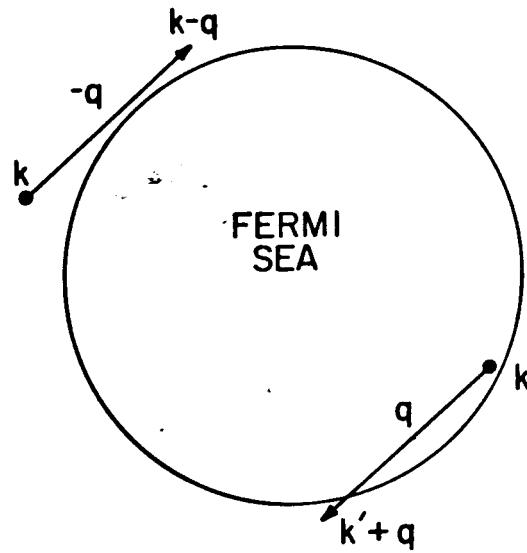
$$\Gamma_{el-ph}(\omega, T)$$

$$\Gamma_{el-im} \approx const$$

$$\Gamma = \Gamma_{el-el} + \Gamma_{el-ph} + \Gamma_{el-im}$$

Landau 1957 – Fermi Liquid

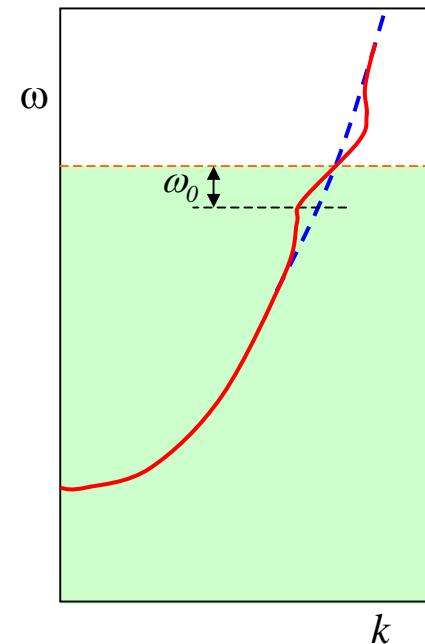
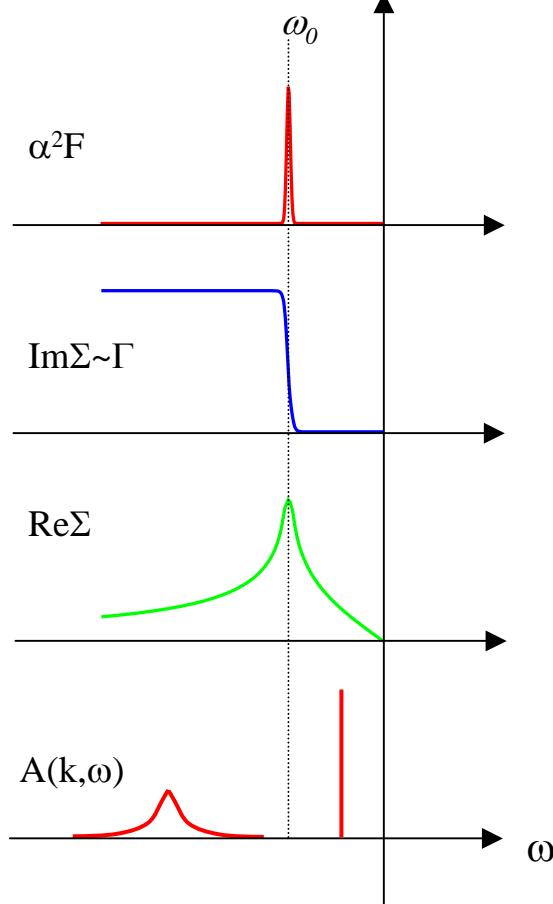
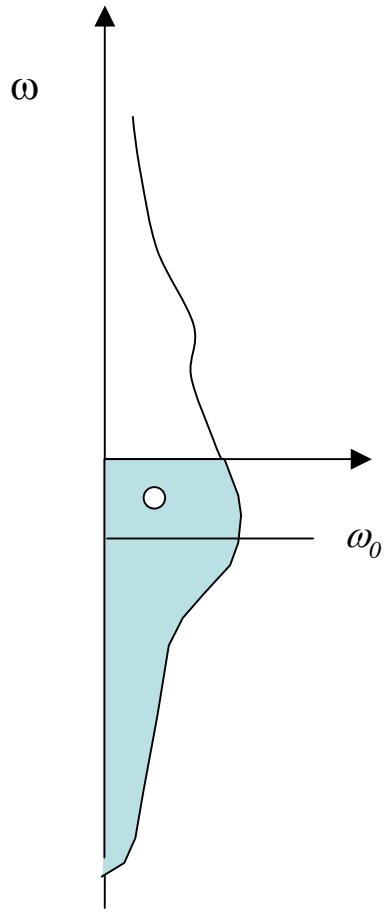
electron-electron scattering



Scattering rate or inverse lifetime

$$\Gamma = 2\beta[(\pi k_B T)^2 + \omega^2] \quad \Delta E = \frac{\eta}{\tau} \leq \omega$$

$$A(\mathbf{k}, \omega) \propto \frac{\text{Im} \Sigma(\mathbf{k}, \omega)}{[\omega - \varepsilon_{\mathbf{k}} - \text{Re} \Sigma(\mathbf{k}, \omega)]^2 + [\text{Im} \Sigma(\mathbf{k}, \omega)]^2}$$



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Electron-Phonon Coupling

Eliashberg Equation:-

$$\eta/\tau(\omega, T) = 2\pi\eta \int_0^{\omega_D} d\omega' \alpha^2 F(\omega') [1 - f(\omega - \omega') + 2n(\omega') + f(\omega + \omega')]$$

In the limit $T \rightarrow 0$

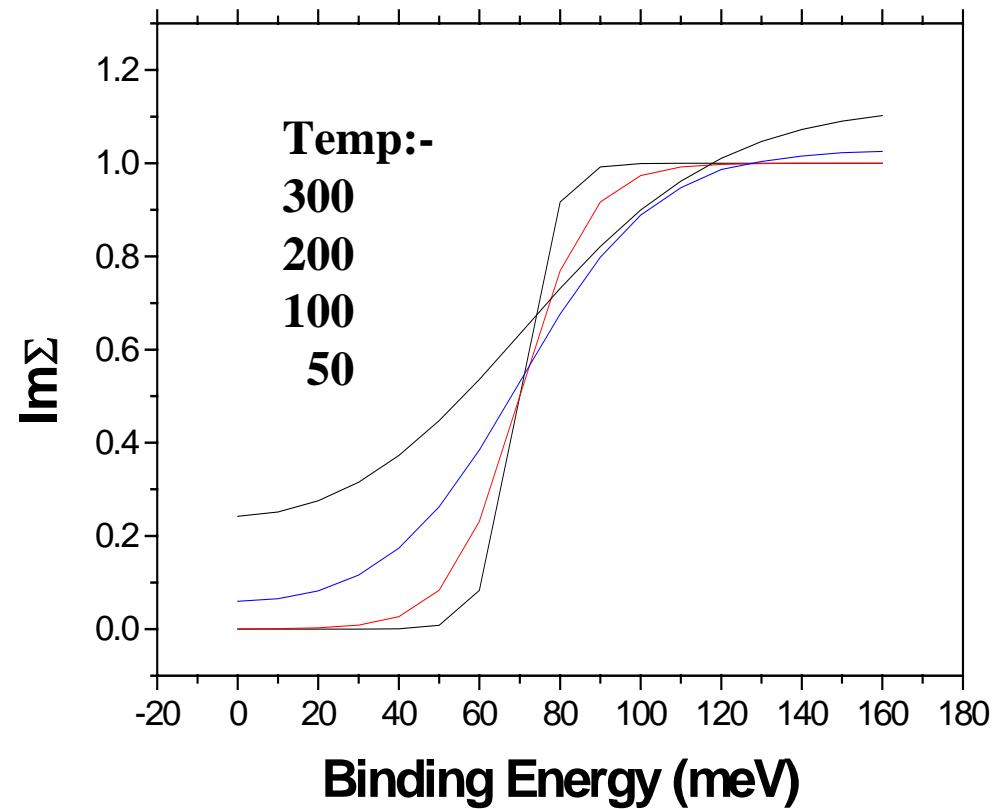
$$\Sigma_I(\omega) = \pi\eta \int_0^{|\omega|} \alpha^2 F(\omega') d\omega'$$



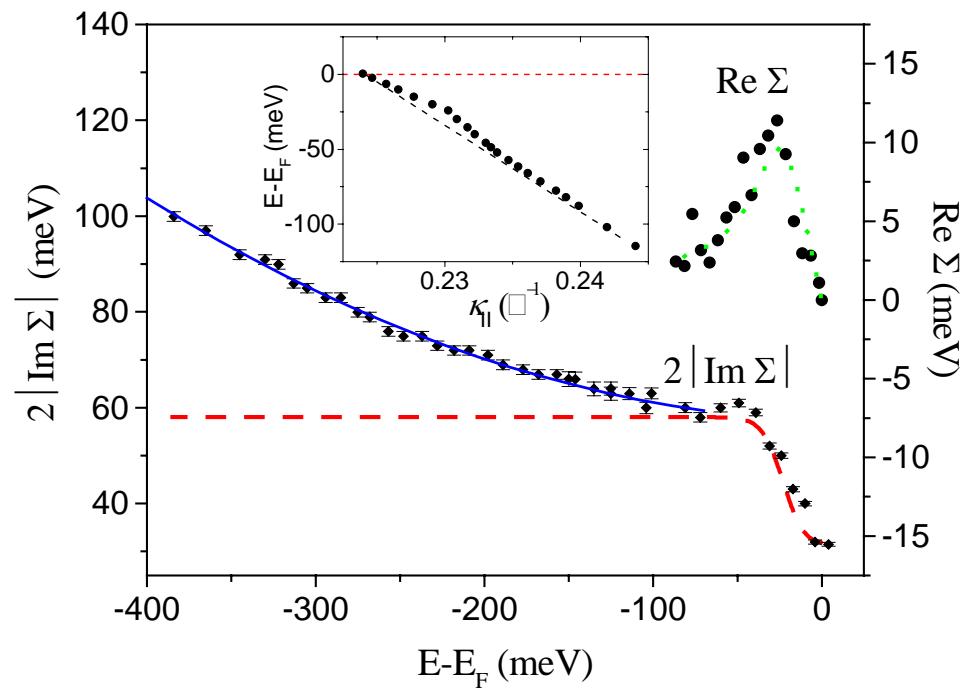
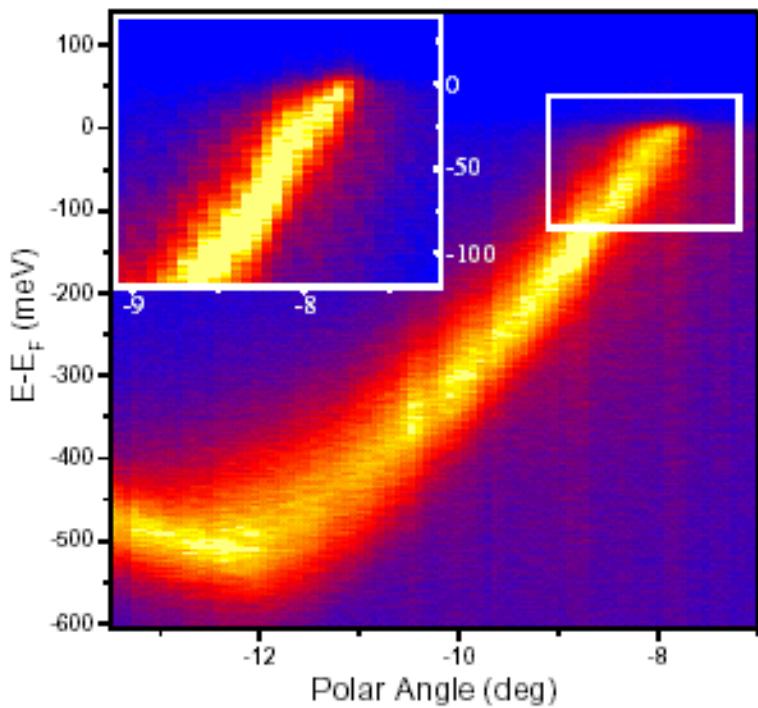
Temperature dependent scattering rates

Einstein mode

70 meV



Electron-Phonon Interaction in Molybdenum

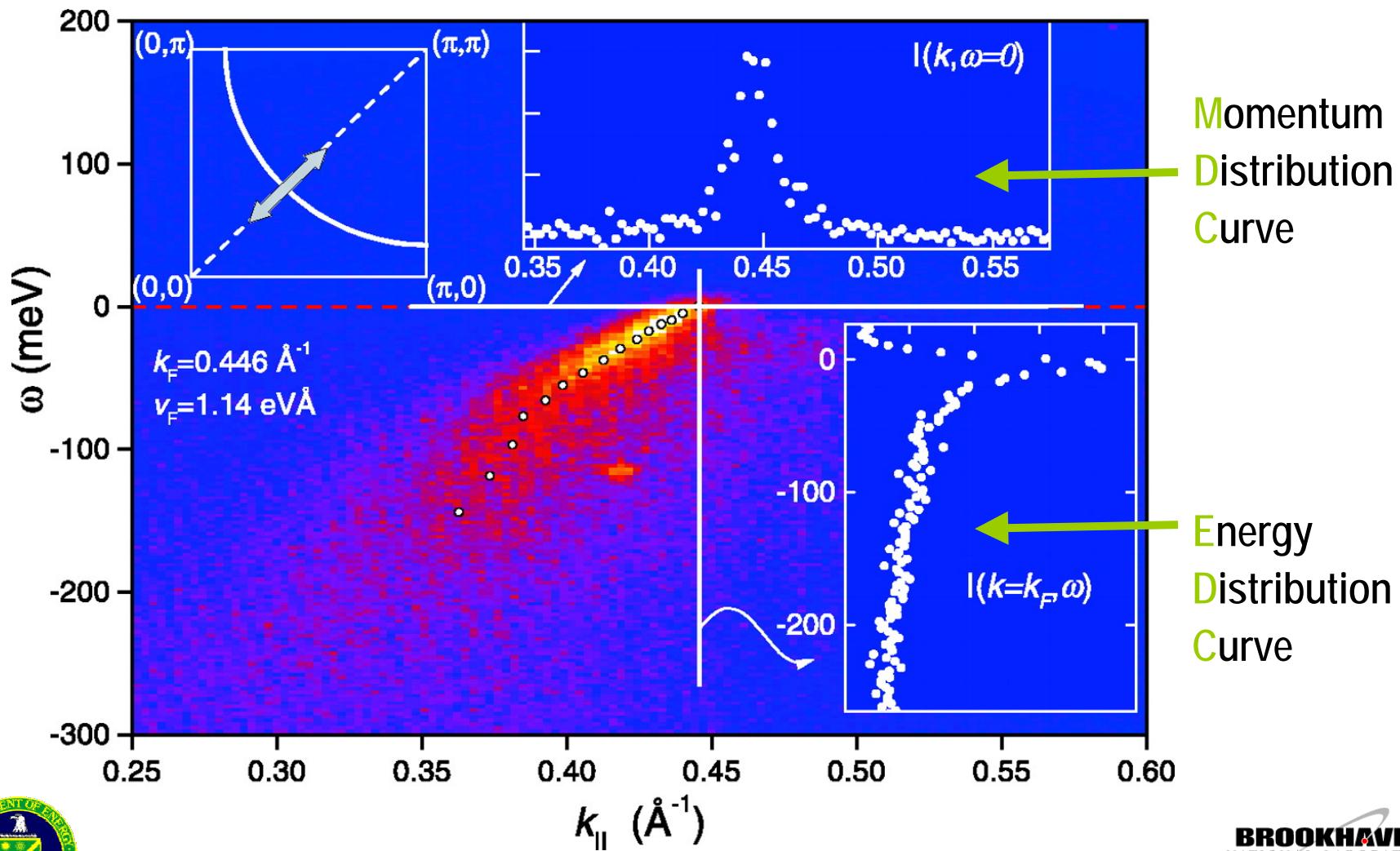


Phys. Rev. Lett. 83, 2085 (1999)

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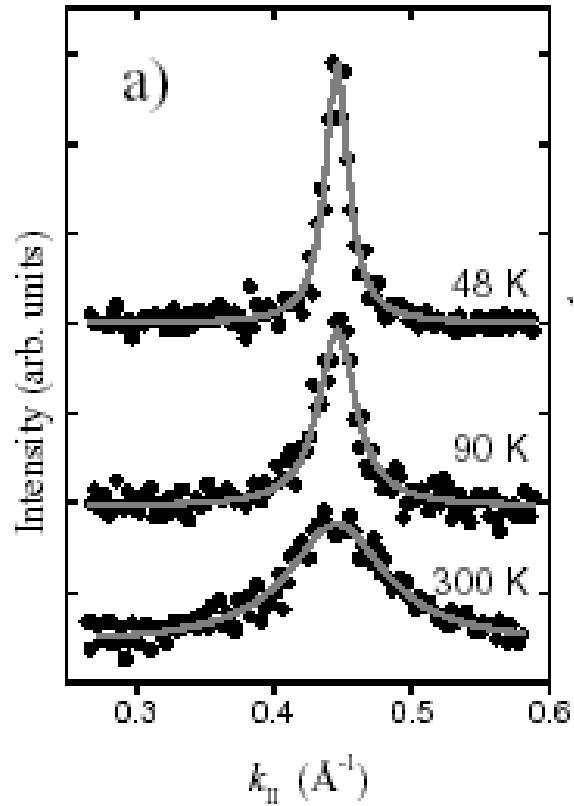
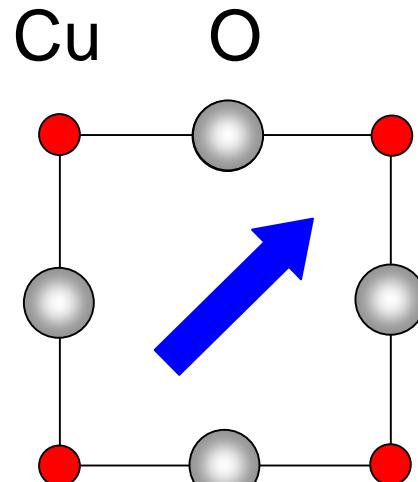
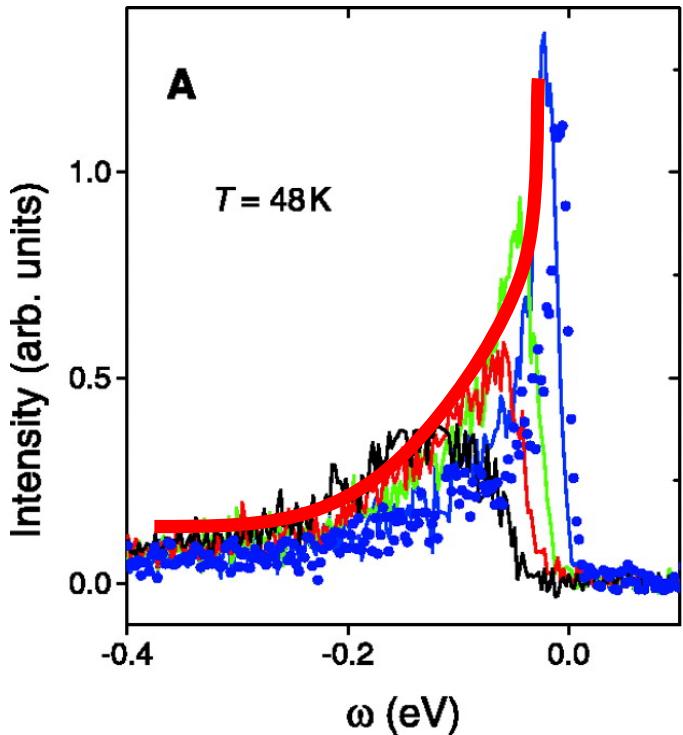
MDCs and EDCs

Science 285, 2110 (1999)



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Optimally Doped $Bi_2Sr_2CaCu_2O_{8+\delta}$

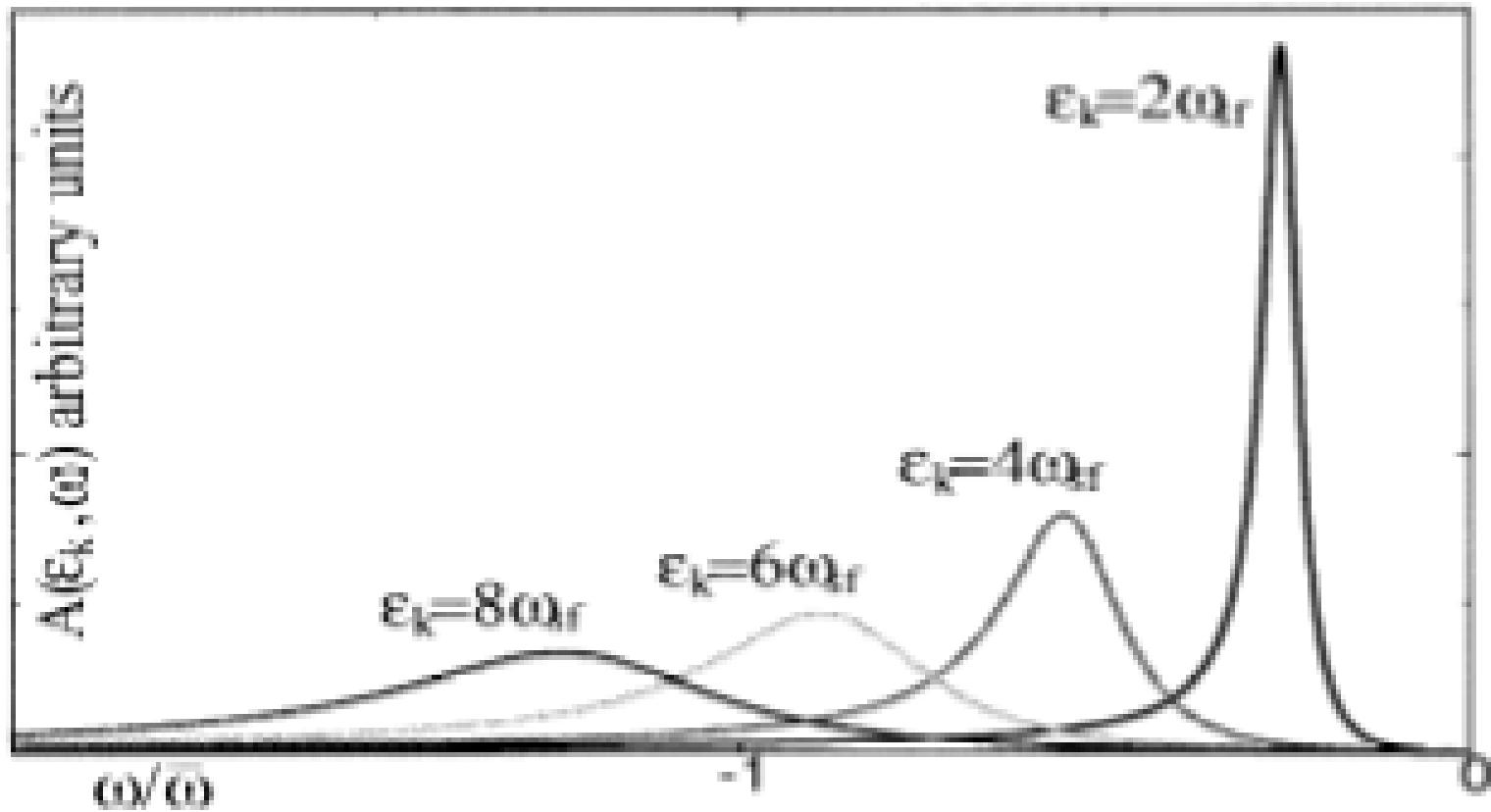


EDC's

MDCs near E_F



Science 285, 2110-2113 (1999)

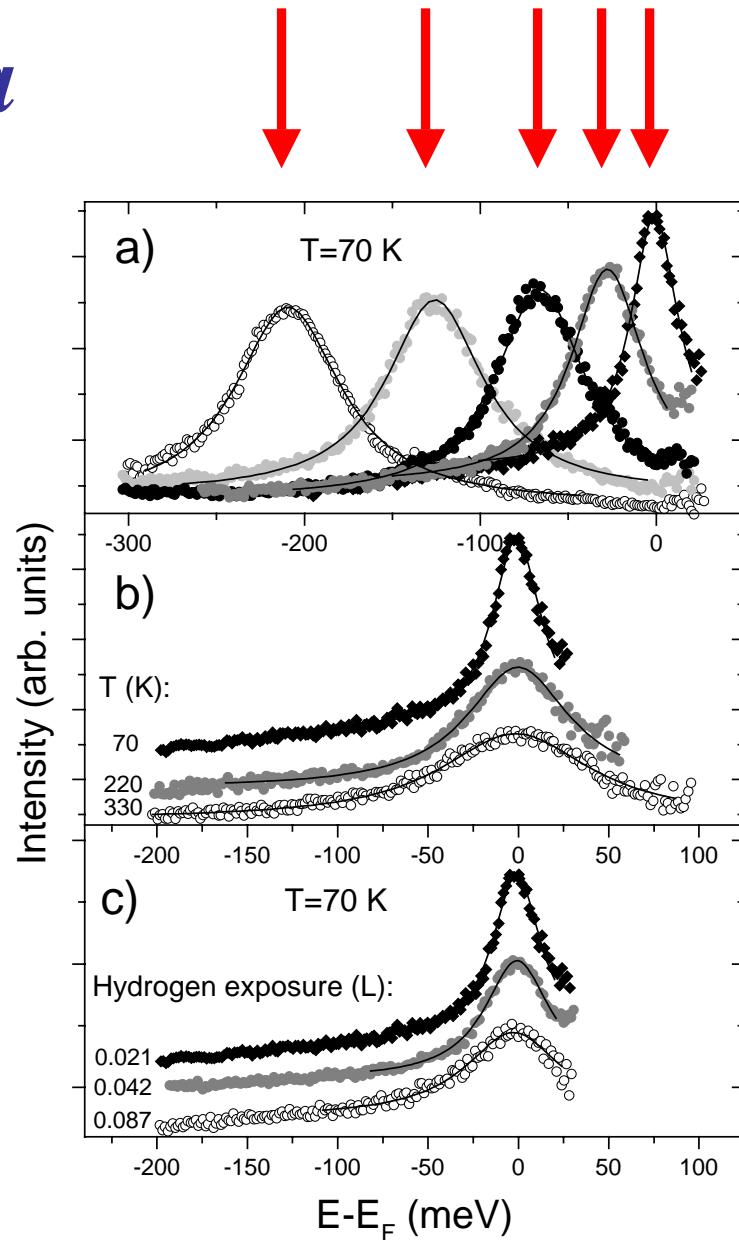


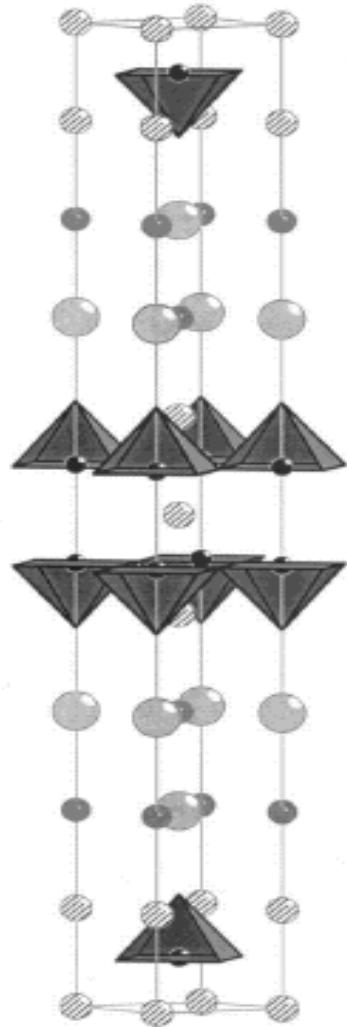
Abanov et al. J. Elect. Spectr. 117, 129 (2001)



The Molybdenum Data

Phys. Rev. Lett. 83, 2085 (1999)





(Bi₂O₂)

(MO)

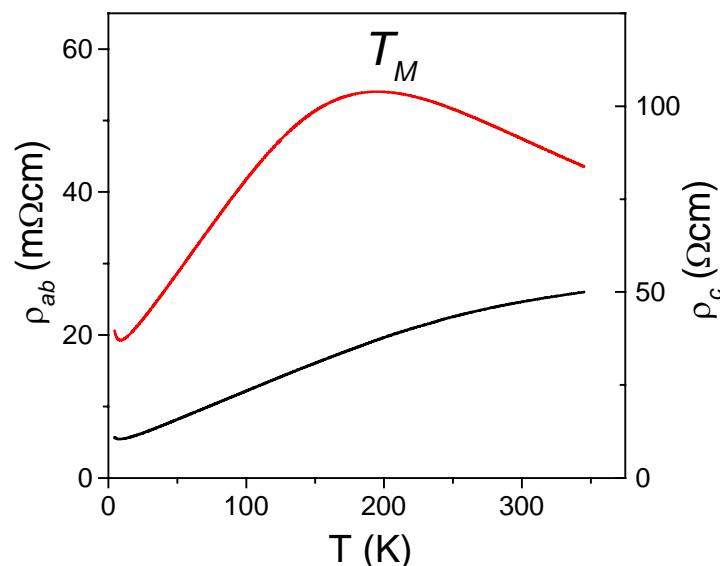
(Co₂O₂)

(M [])

(Co₂O₂)

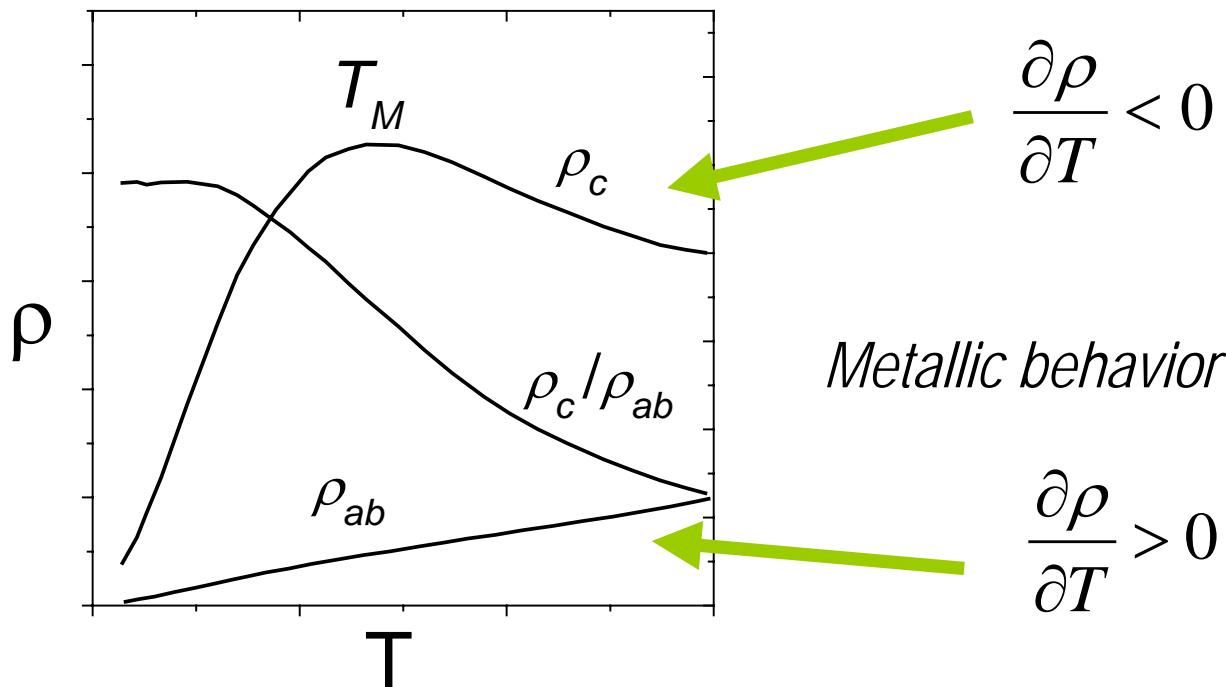
(MO)

(Bi₂O₂)



A number of the layered strongly-correlated materials show such anisotropic transport properties:

Insulating behavior

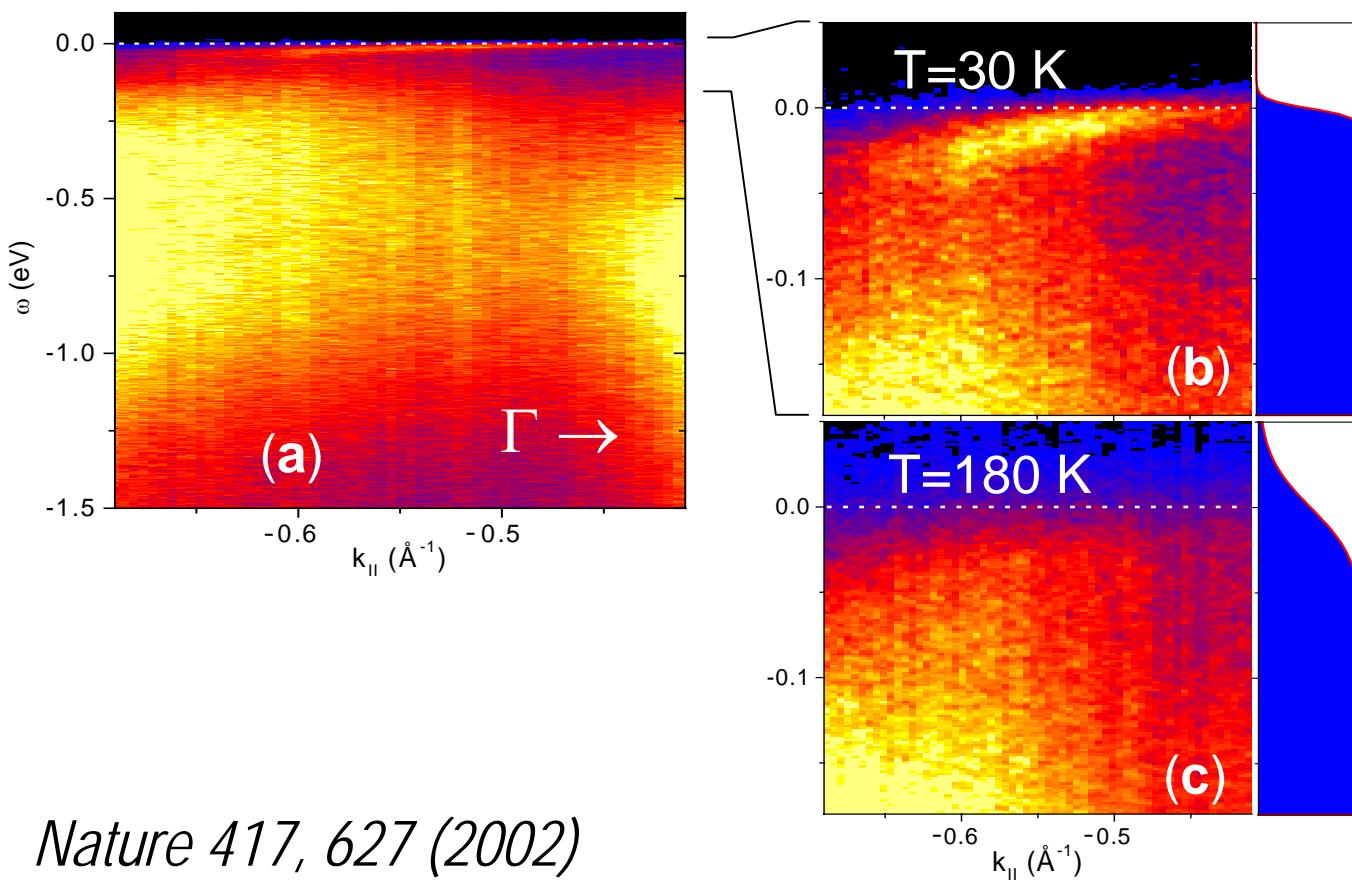


$$\frac{\partial \rho}{\partial T} < 0$$

Metallic behavior

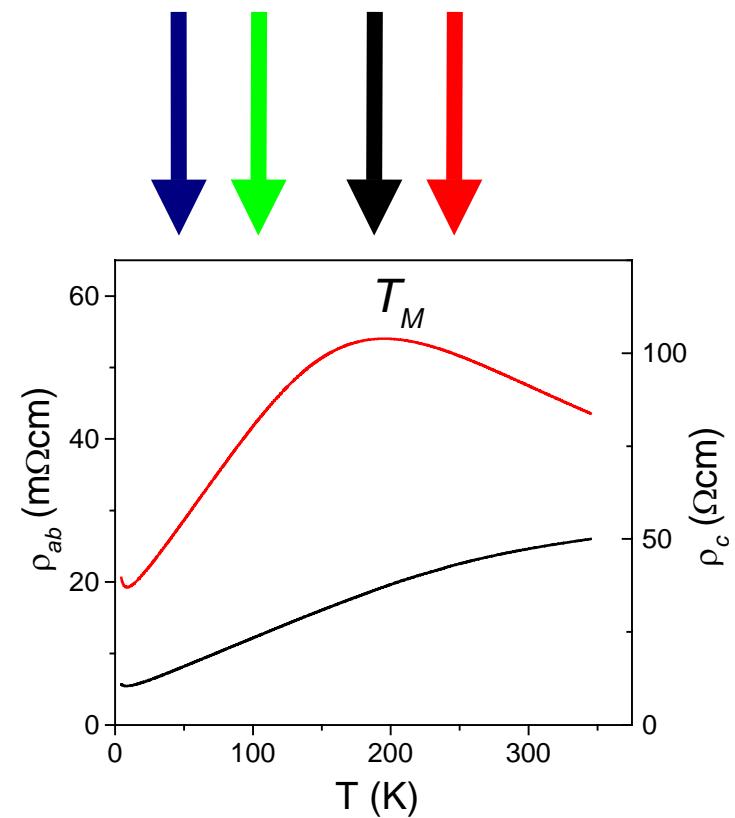
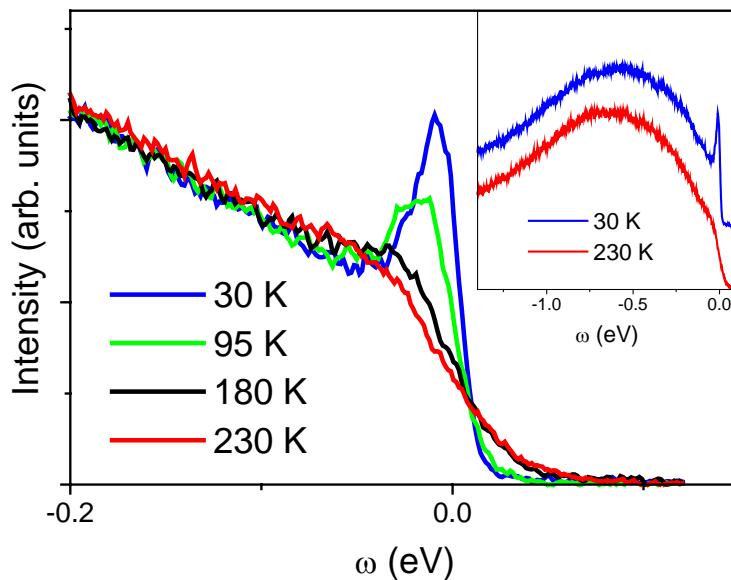
$$\frac{\partial \rho}{\partial T} > 0$$





Nature 417, 627 (2002)





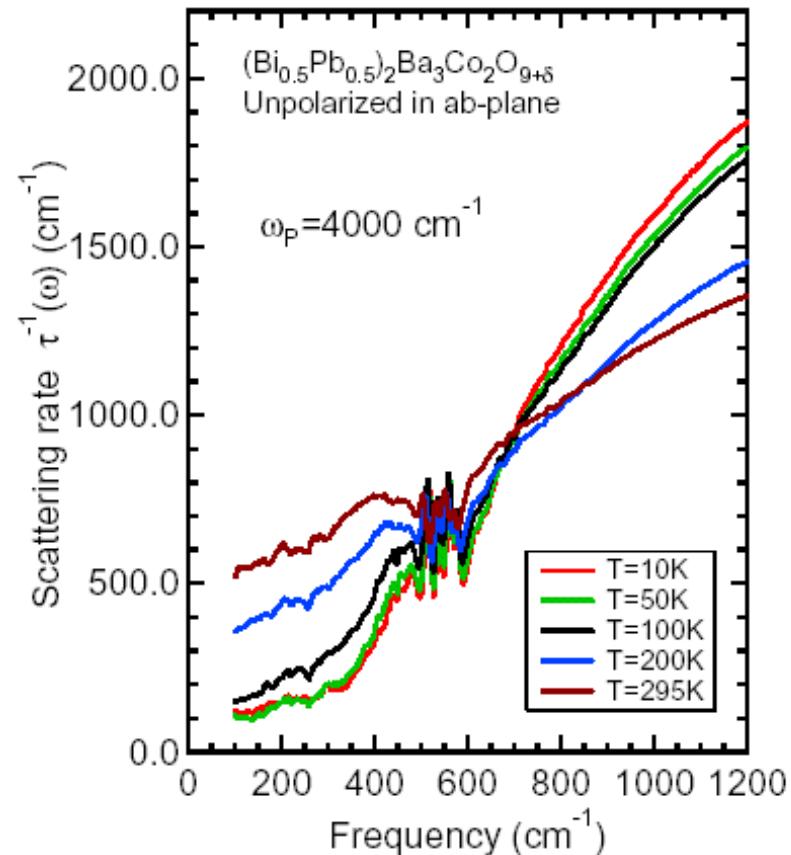
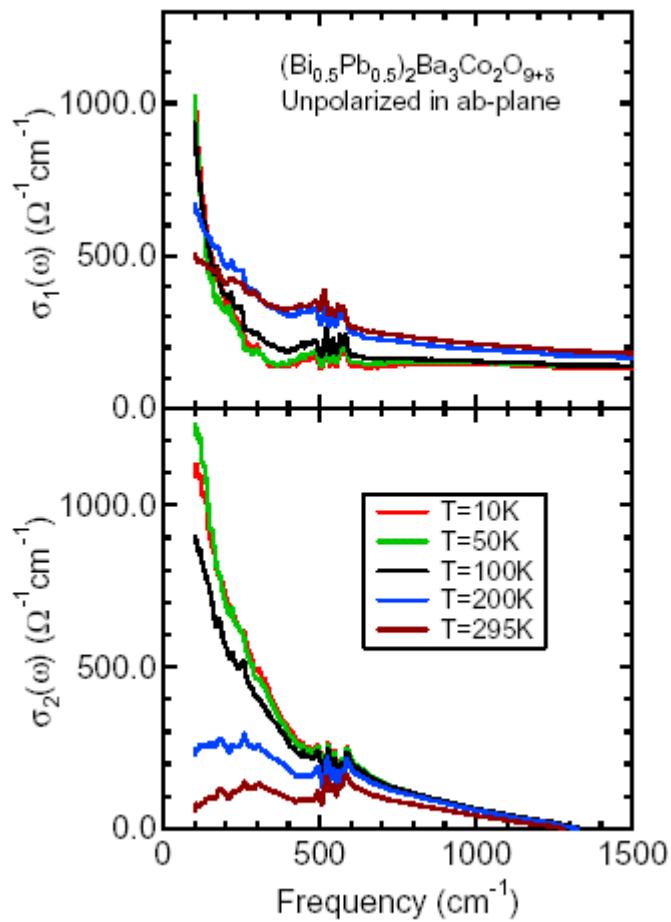
The appearance of in-plane coherent excitations strongly correlates with the dimensional crossover observed in transport measurements

$$\sigma_c(T, \omega = 0) \propto \int \frac{d^2k}{(2\pi)^2} t_\perp(k)^2 G_R(k, \omega) G_A(k, \omega) \frac{\partial f(\omega)}{\partial \omega}$$



Green's Function $\sim Z / (\omega - \varepsilon_k - i\Gamma)$

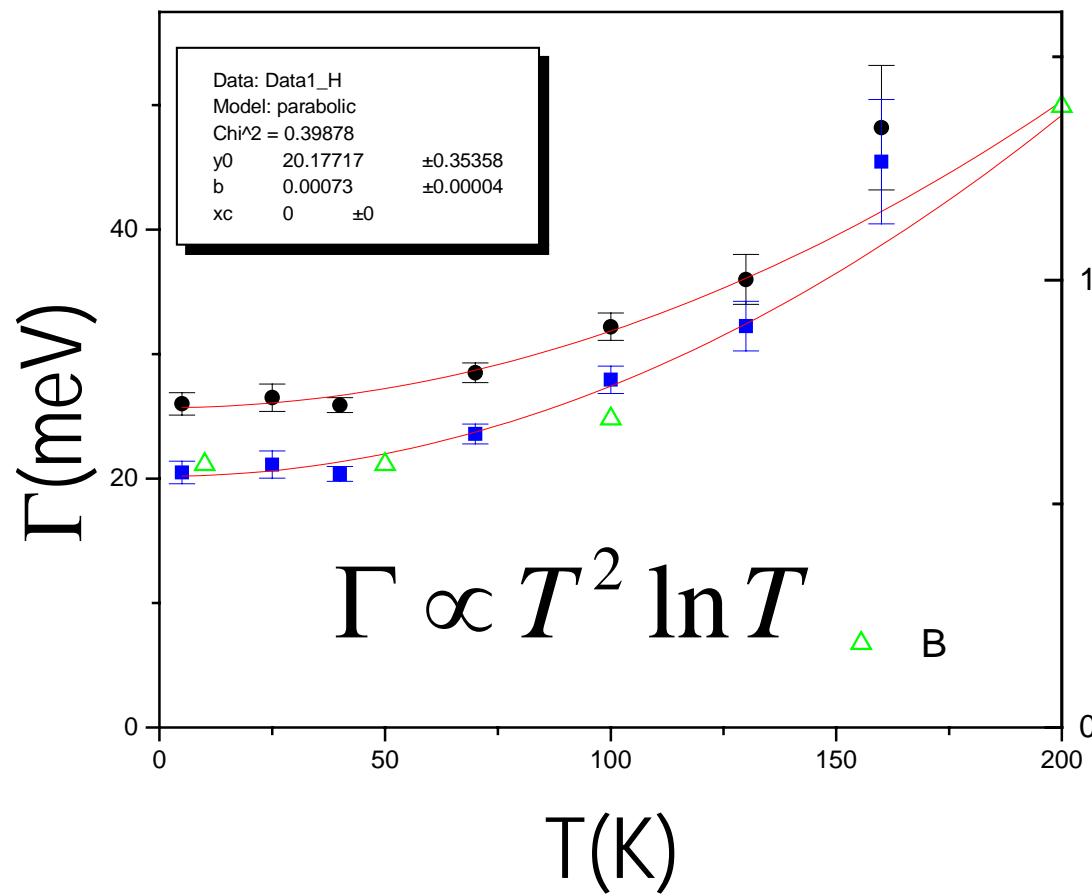
Optical Conductivity Measurements



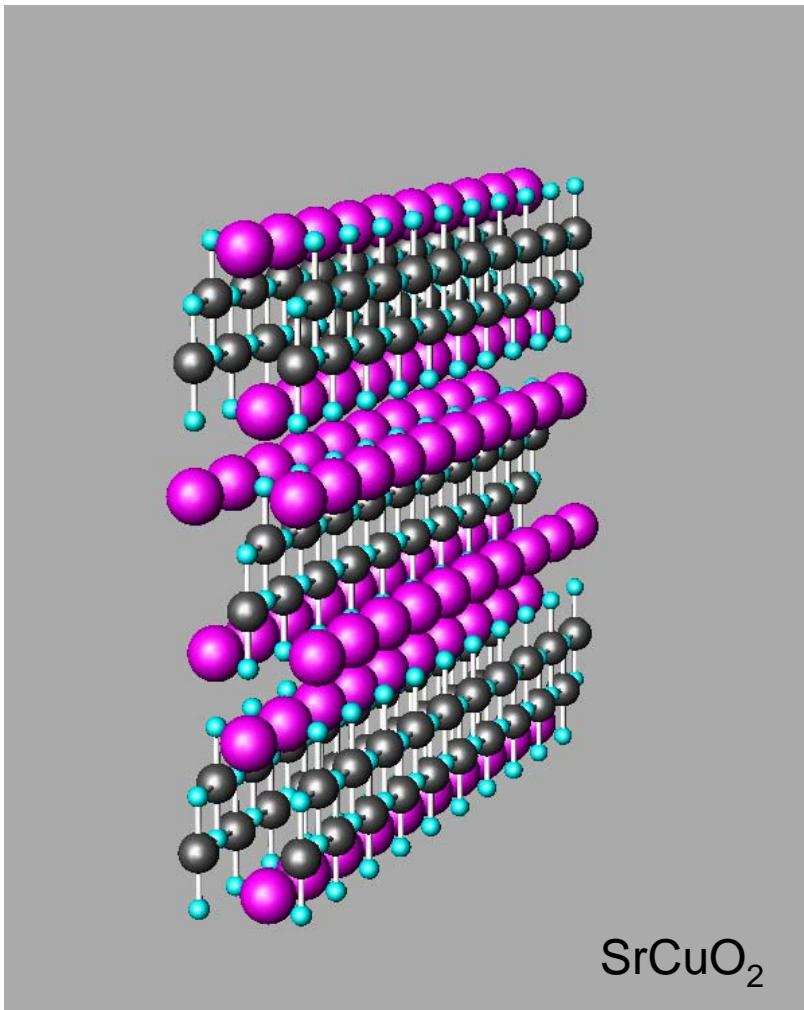
J. Tu et al.



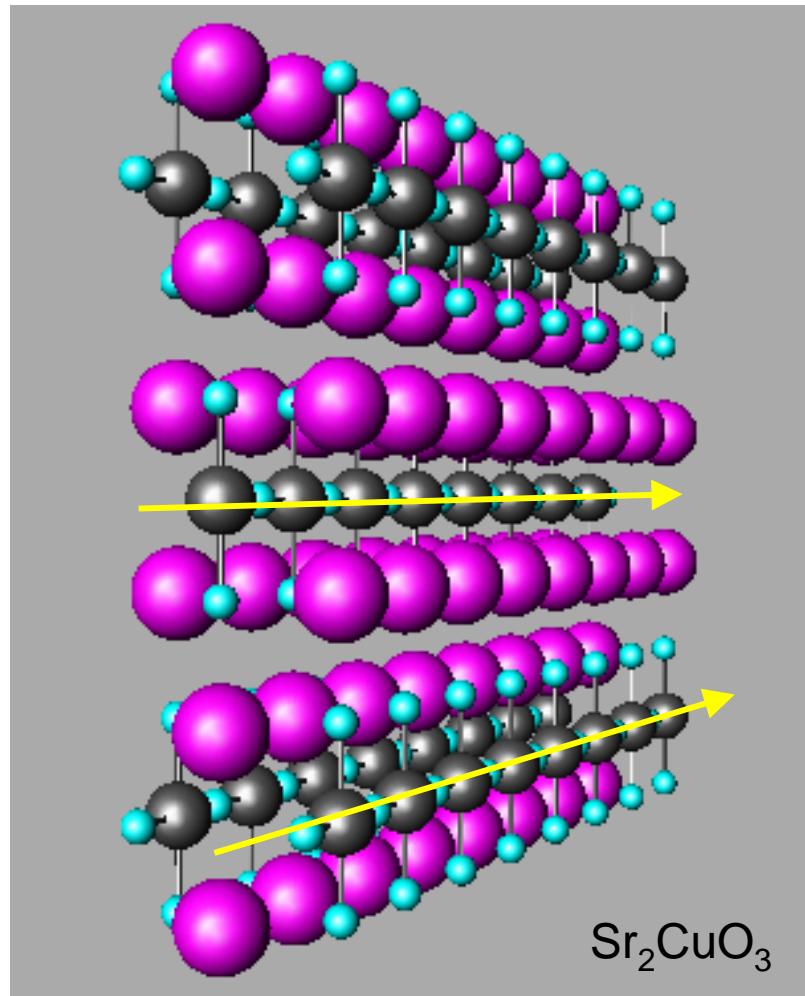
The coherent excitations behave like Fermions



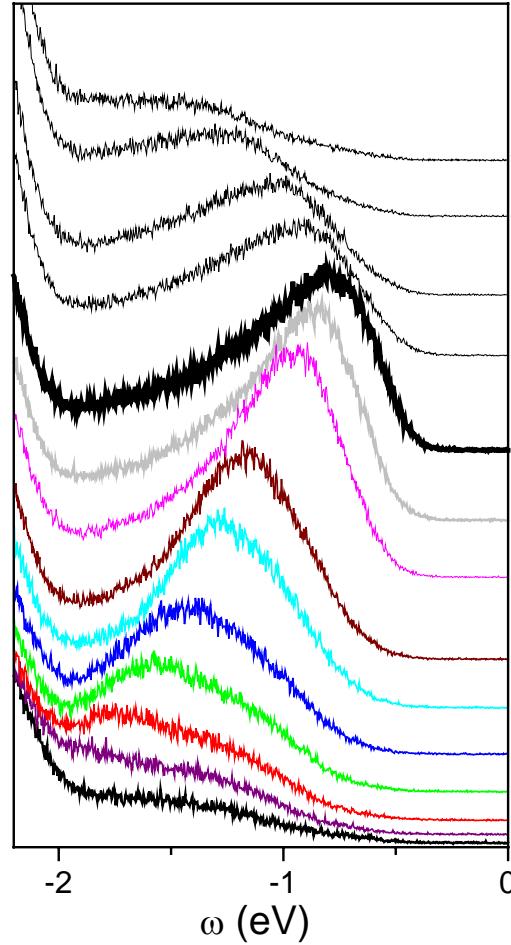
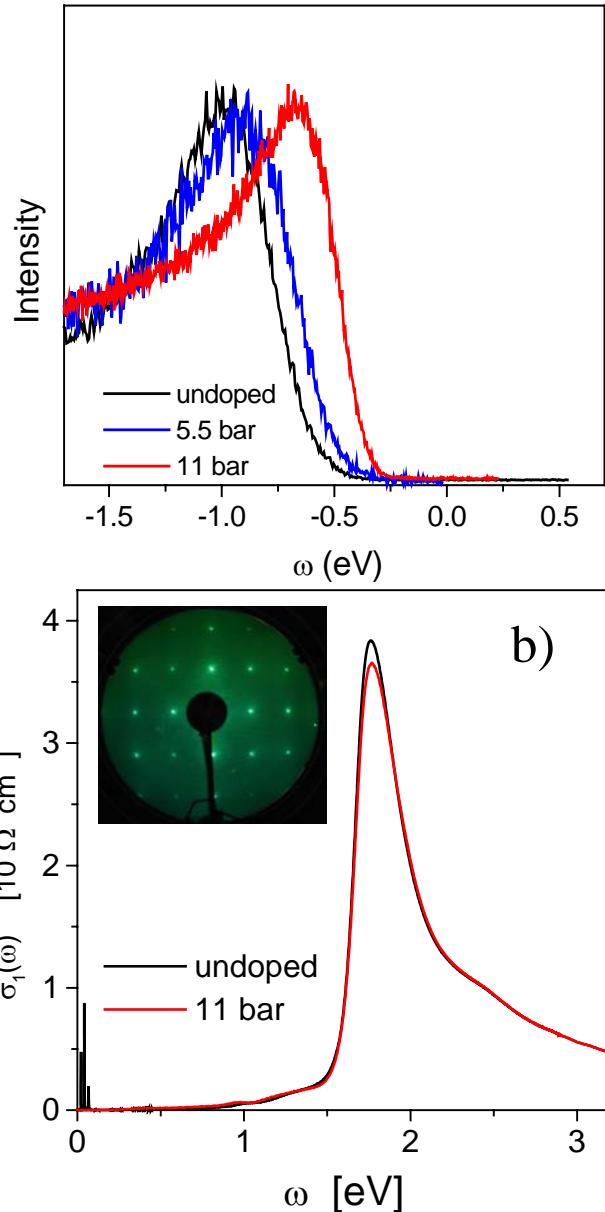
Crystal structure of chain cuprates



SrCuO_2



Sr_2CuO_3

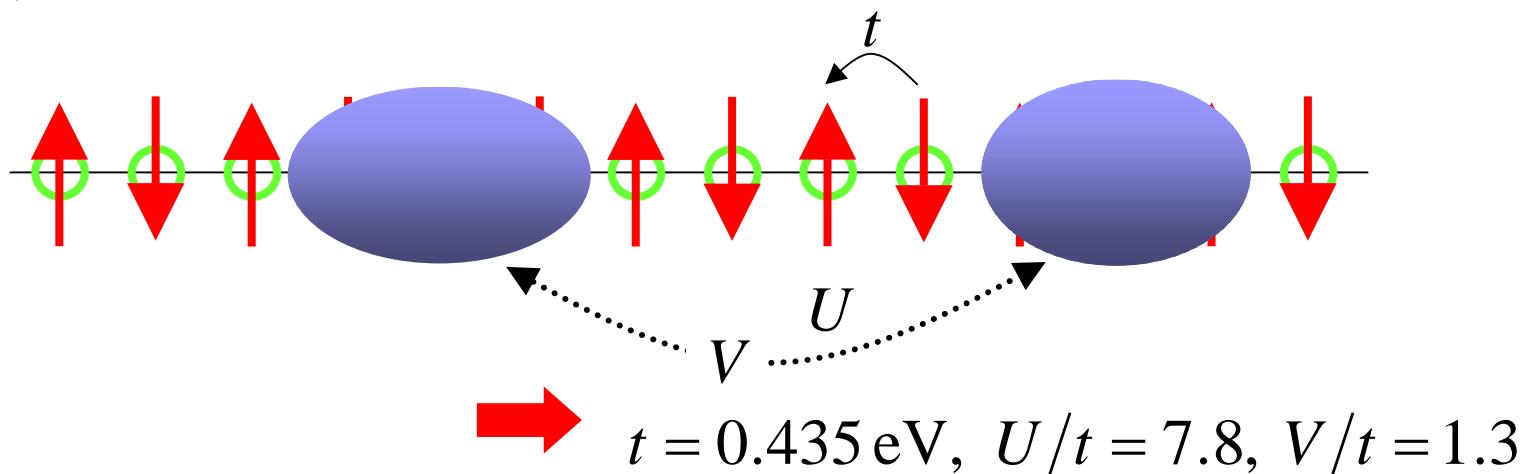


Doping with oxygen allows the clear identification of the spinon branch

1D Hubbard model calculation

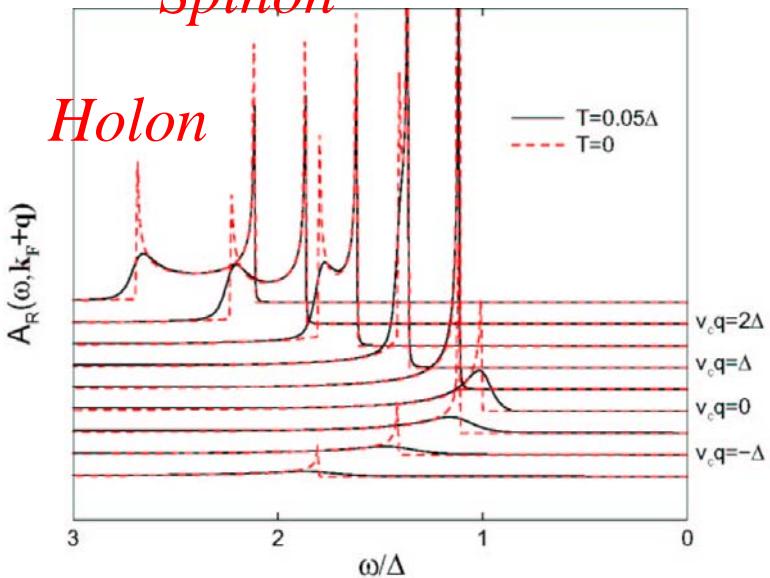
- Extended Hubbard model (half-filled, one band)

$$H = -t \sum_{l,\sigma} (\hat{c}_{l,\sigma}^+ \hat{c}_{l+1,\sigma} + \hat{c}_{l+1,\sigma}^+ \hat{c}_{l,\sigma}) + U \sum_l \hat{n}_{l,\uparrow} \hat{n}_{l,\downarrow} + V \sum_l (\hat{n}_l - 1)(\hat{n}_{l+1} - 1)$$

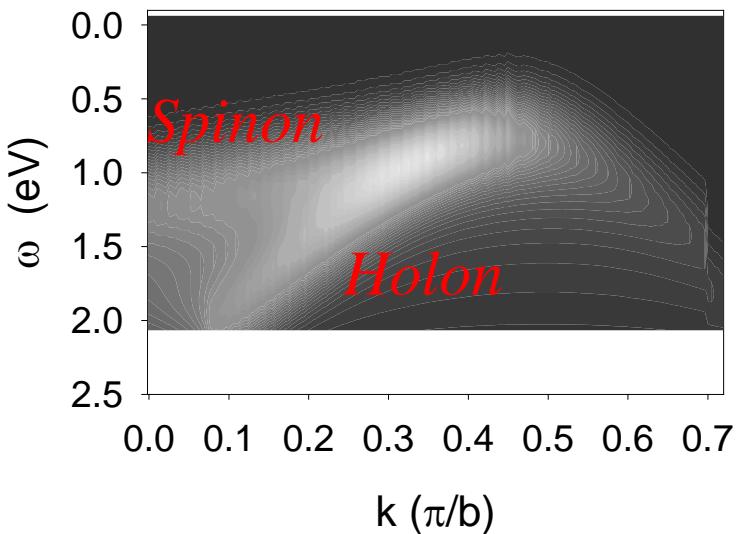


- Dynamical density matrix renormalization group (DDMRG)
 - Optical conductivity
 - Neutron scattering
 - Density-density correlation function $N(q,\omega)$

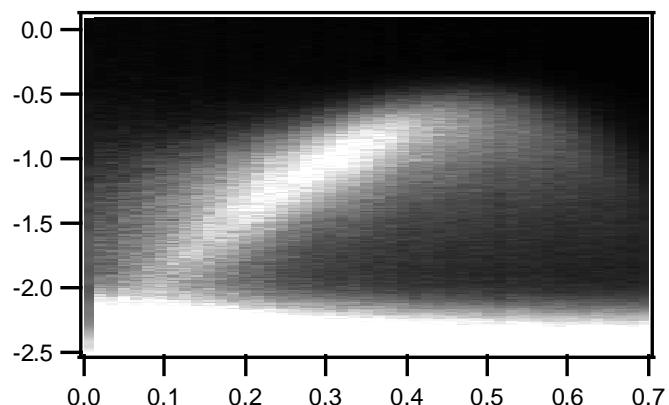
Studies of 1-D $Sr_2CuO_{3+\delta}$ at BN L Spinon



Theoretical predictions



Photoemission Expt



T. Valla
T. Kidd
A. Fedorov
G.D. Gu
S.L. Hulbert

Physics Dept., BNL

Q. Li
A.R. Moodenbaugh

Materials Science Dept., BNL

N. Koshizuka

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Princeton University



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THE END



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