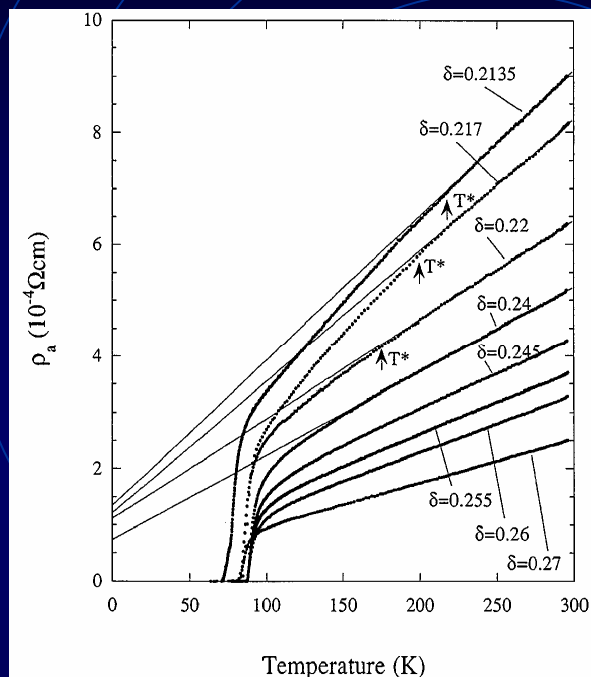
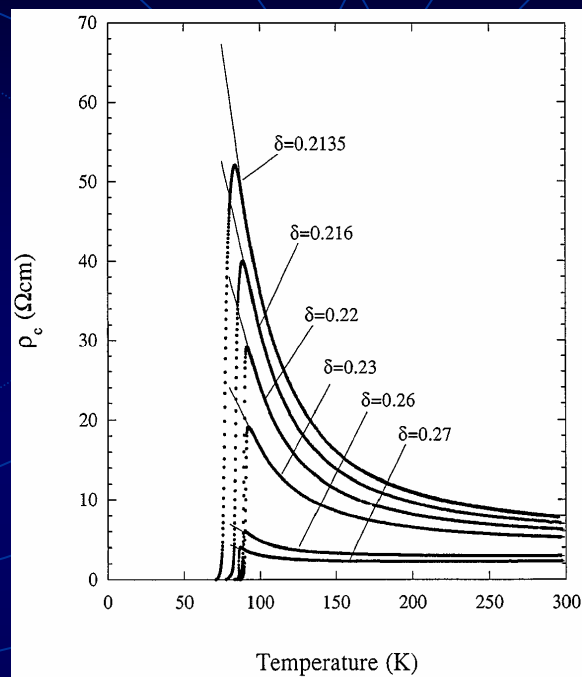


高温超导体c轴电阻的普适标度律

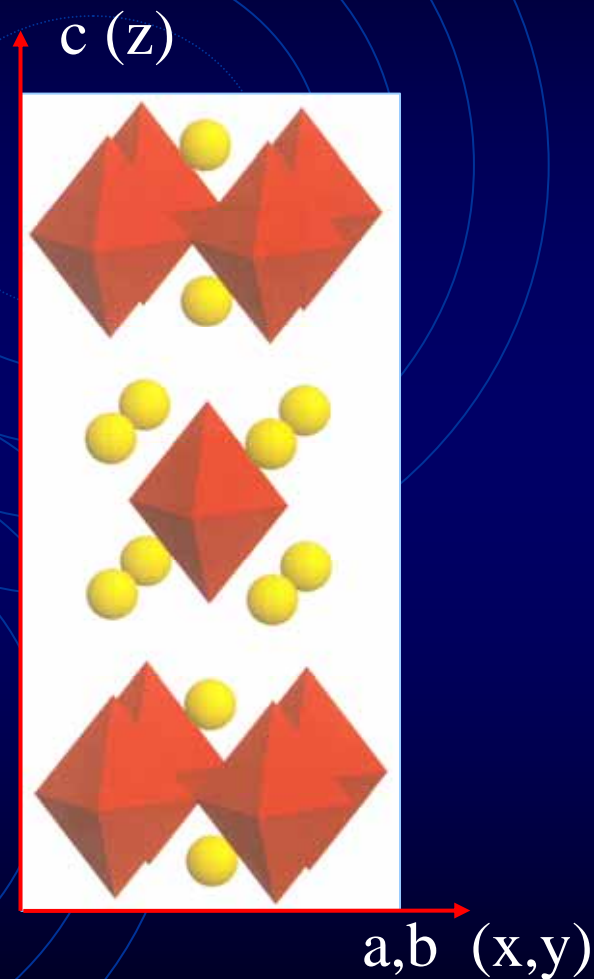
高温超导体c轴电阻的反常



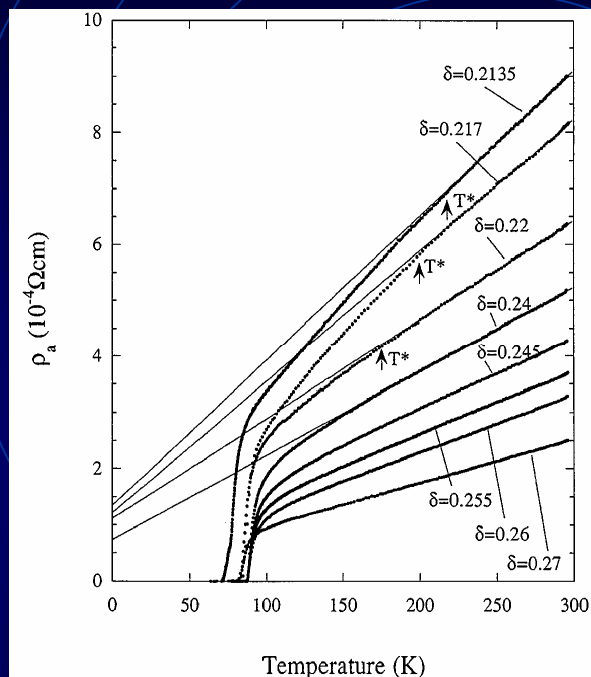
平面内电阻随温度降低而降低，典型的金属行为



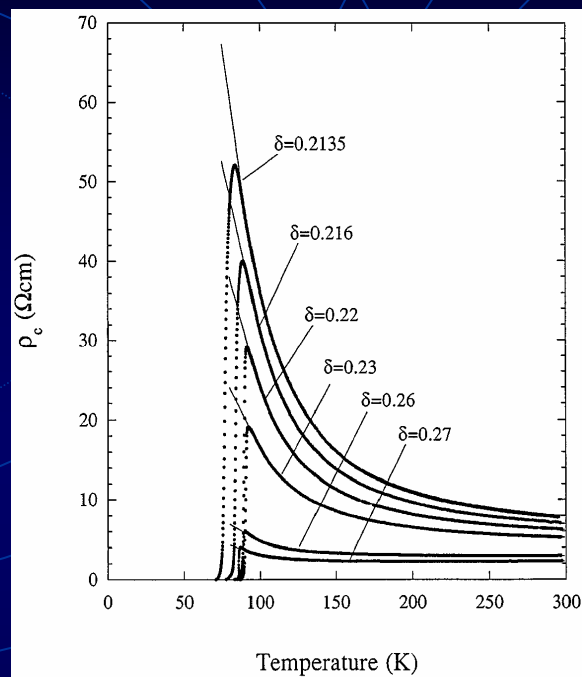
垂直平面方向电阻随温度降低而上升，典型的半导体行为



高温超导体c轴电阻的反常



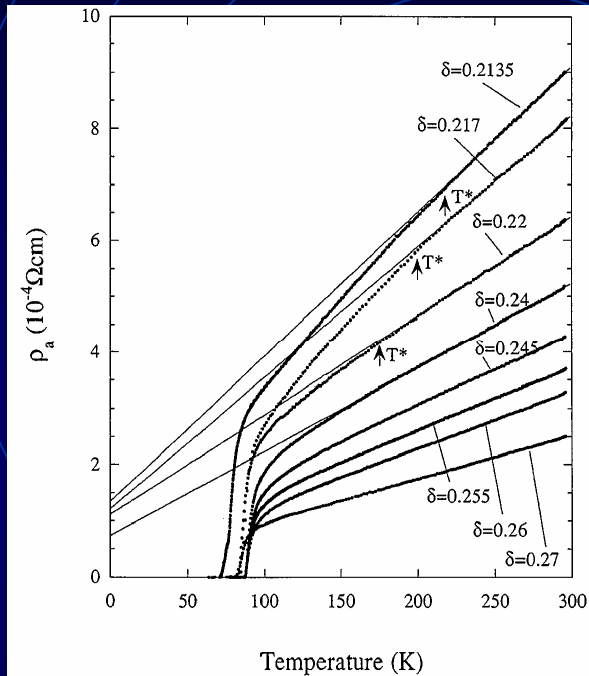
平面内电阻随温度降低而降低，典型的金属行为



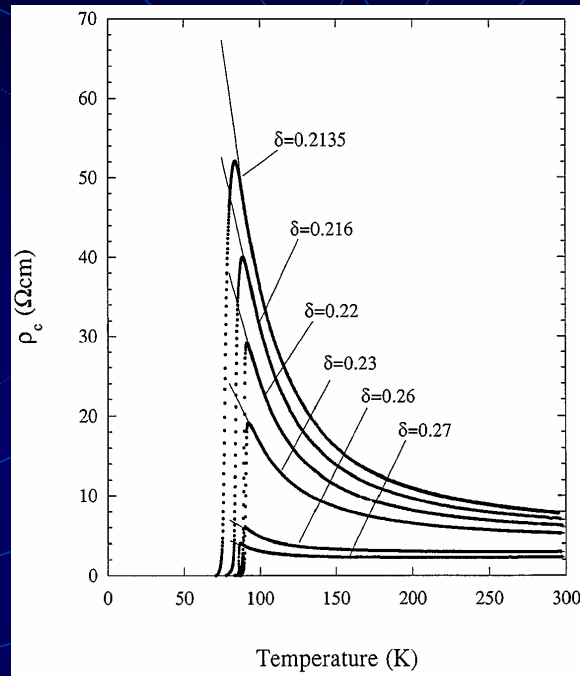
垂直平面方向电阻随温度降低而上升，典型的半导体行为

平行和垂直平面方向的电阻呈现出完全相反的变化行为，这个问题不能用能带论和电子弱局域化理论解释。

已有的物理解释



平面内电阻随温度降低而降低，典型的金属行为



垂直平面方向电阻随温度降低而上升，典型的半导体行为

动力学电荷禁闭



P.W. Anderson
1977 Nobel Laureate

电子的非相干隧穿



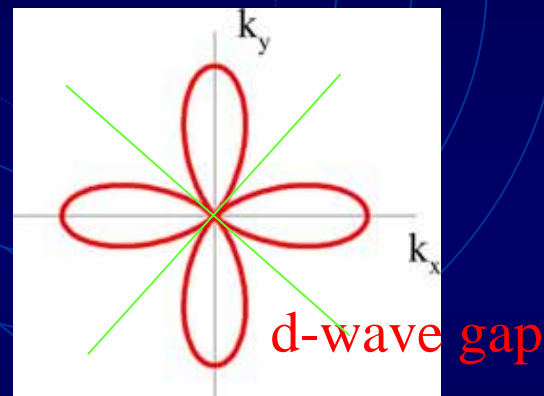
A.J. Leggett
2003 Nobel Laureate

新的物理图象

c-轴电阻的半导体行为是各向异性的层间电子跃迁与 $d(x^2-y^2)$ 波对称的赭能隙相互作用的结果

1. 赭能隙具有 $d(x^2-y^2)$ 对称性

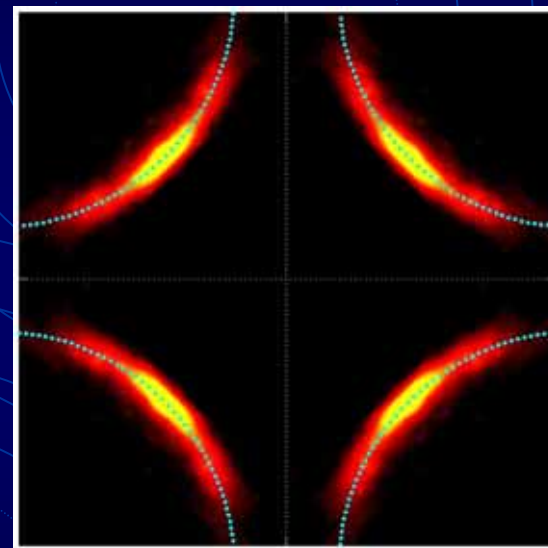
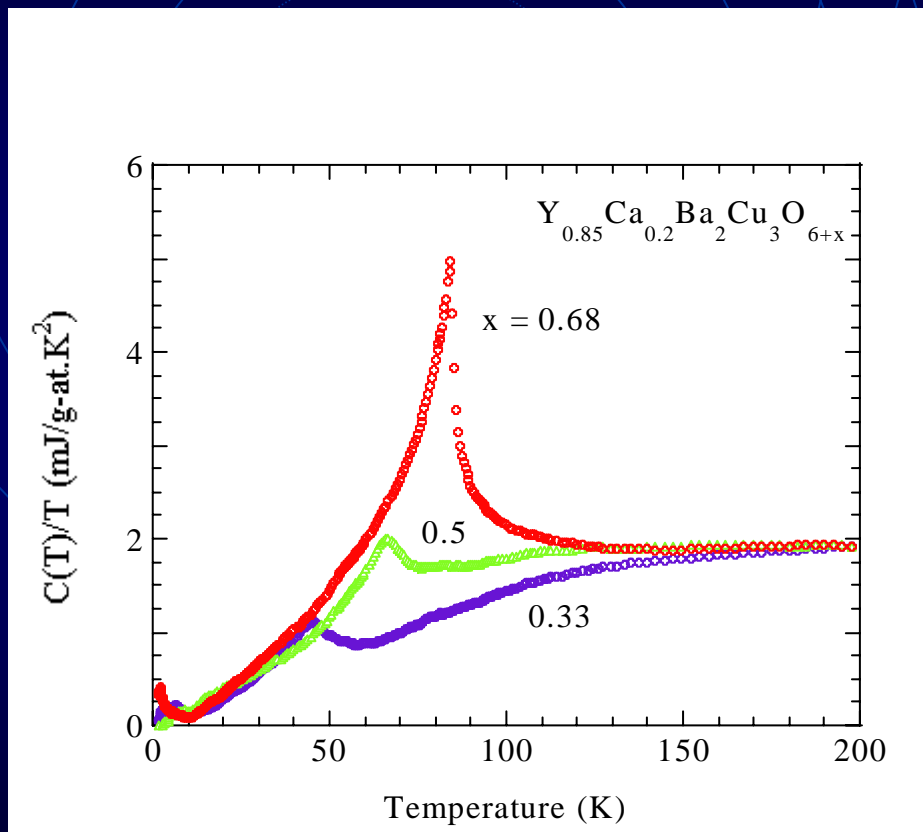
$$\Delta_k = \Delta (\cos k_x - \cos k_y)$$



2. c-轴电子跃迁积分强烈依赖 CuO_2 平面内电子的动量方向

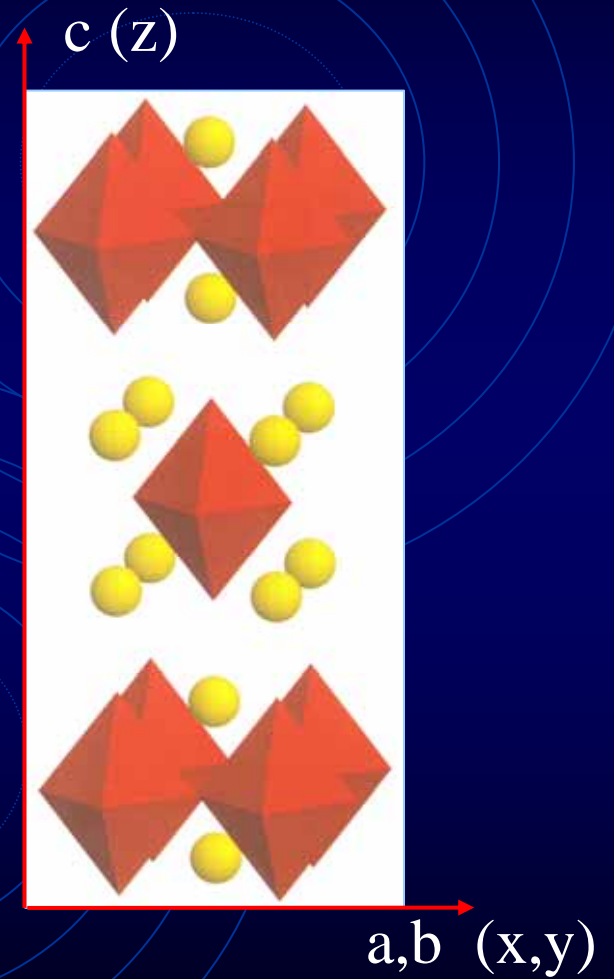
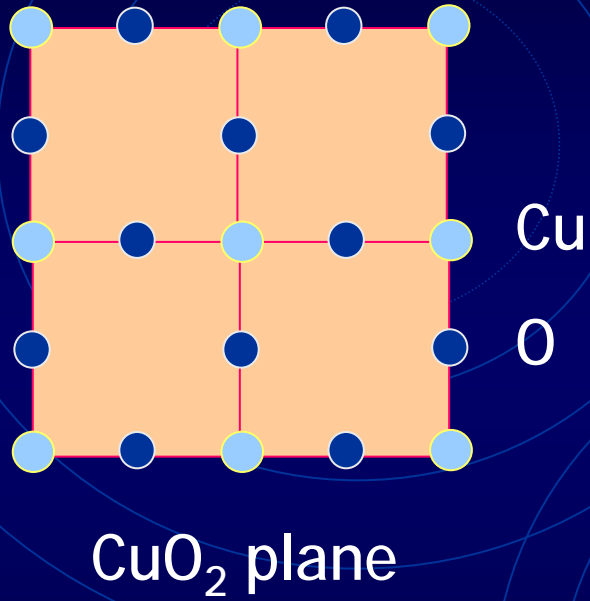
$$t_z \propto t_{\perp} (\cos k_x - \cos k_y)^2$$

赝能隙：正常态中出现的类超导能隙现象



费米面不连续

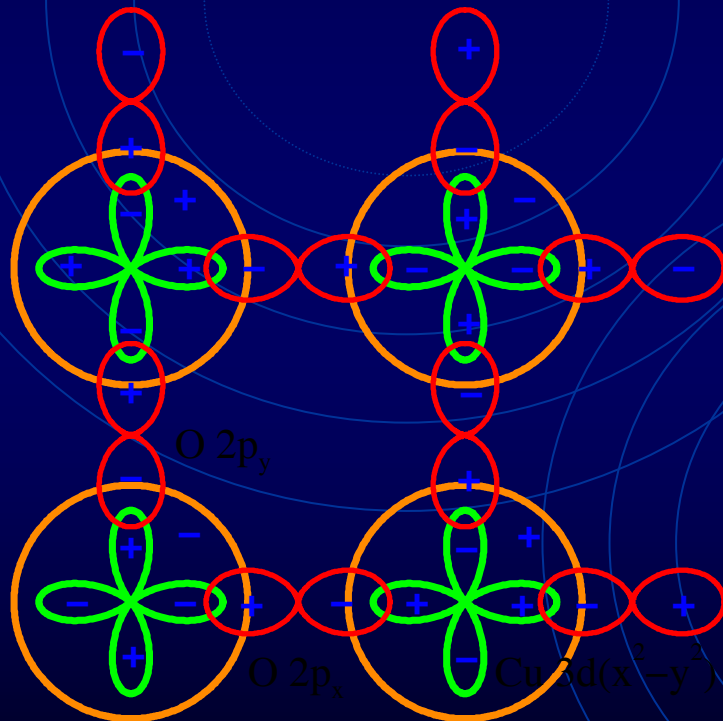
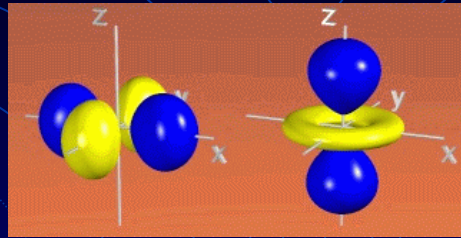
高温超导体的c轴电子结构



电子的层间跃迁过程

$$d_{x^2-y^2} = k_x^2 - k_y^2$$

$$\sim \cos k_x - \cos k_y$$



Cu 4s

O 2p_y

O 2p_x

Cu 3d(x²-y²)

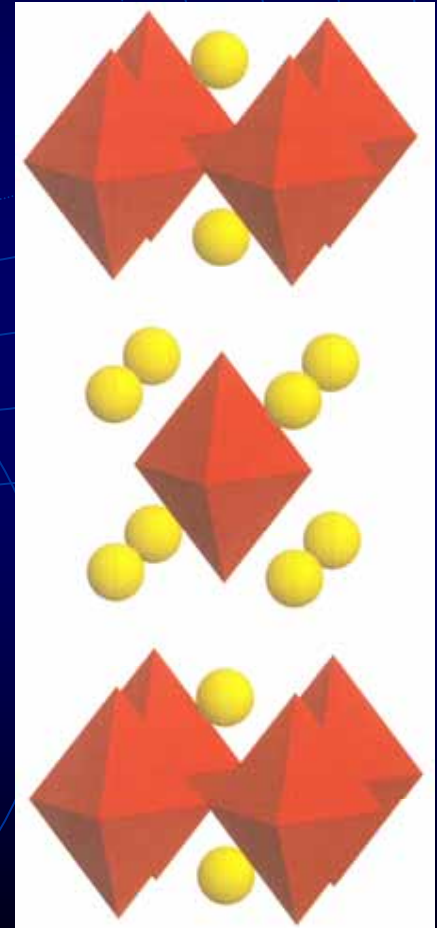
2nd layer

O 2p



1st layer

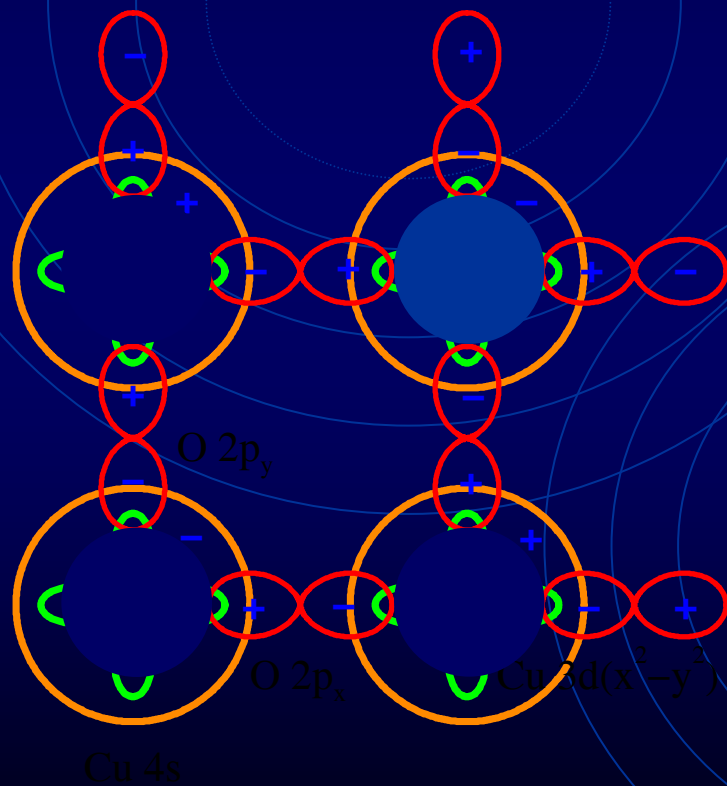
O 2p



层间跃迁矩阵元

Xiang, Wheatley, PRL 77,4632

$$d_{x^2-y^2} = k_x^2 - k_y^2 \sim \cos k_x - \cos k_y$$



$$t_z \propto t_{\perp} \left(\cos k_x - \cos k_y \right)^2$$

2nd layer

O 2p

Cu 4s

$$\cos k_x - \cos k_y$$

1st layer

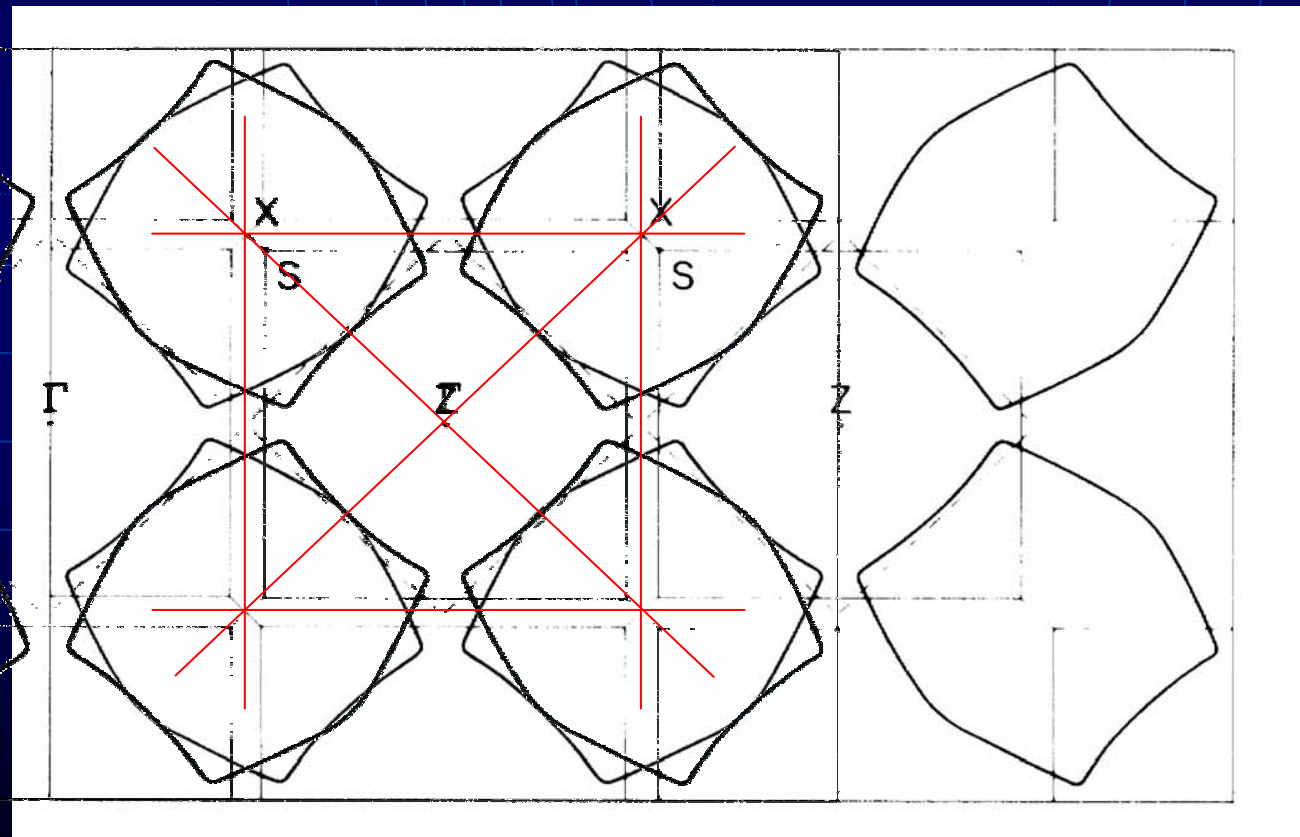
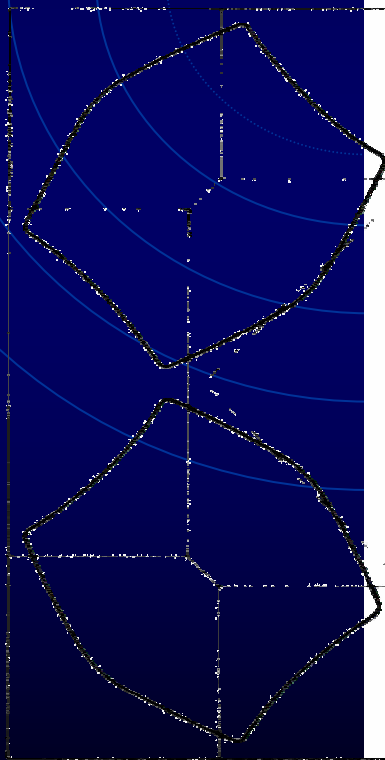
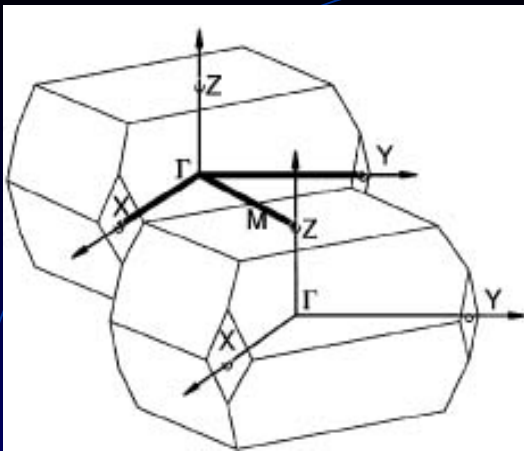
O 2p

Cu 4s

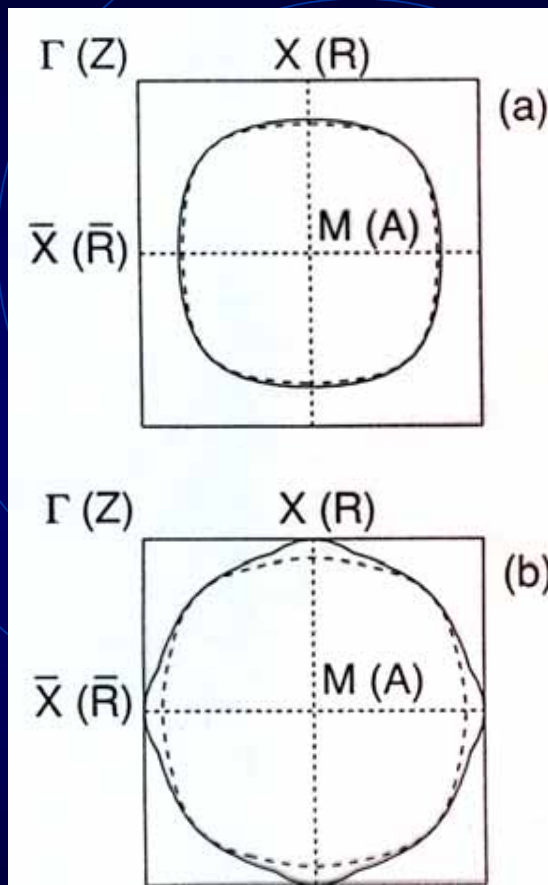
$$\cos k_x - \cos k_y$$

Fermi Surface of $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$

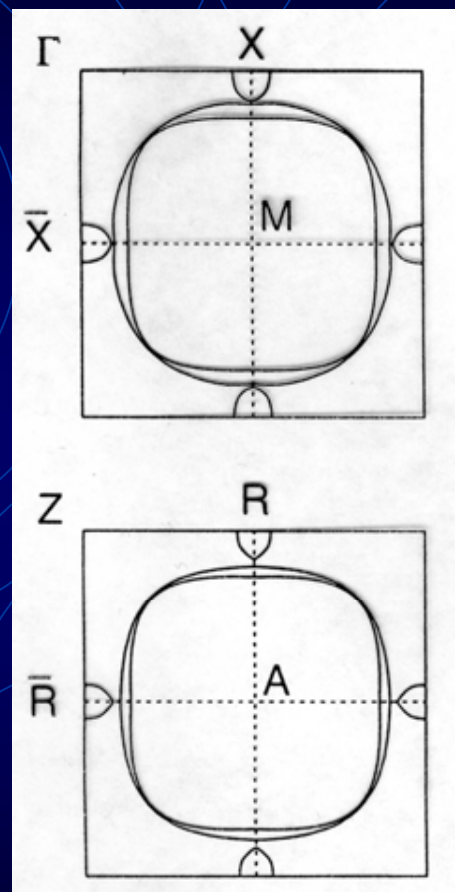
$$t_z \propto t_{\perp} \left(\cos k_x - \cos k_y \right)^2$$



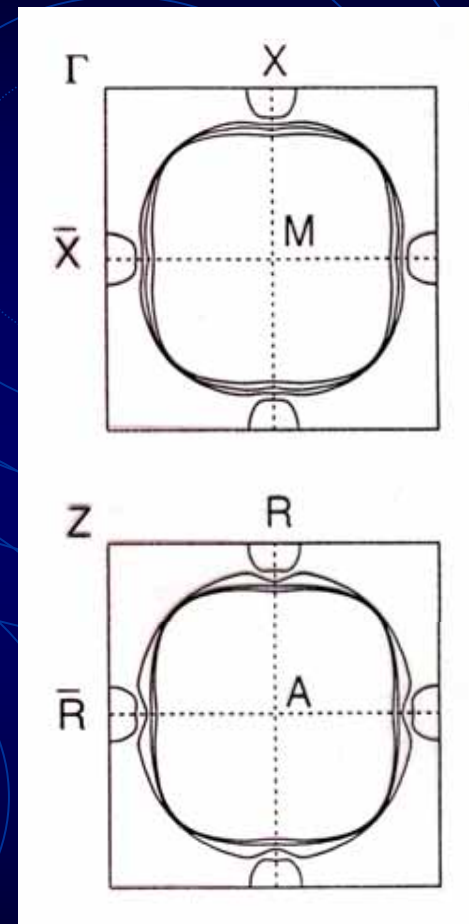
LDA Band Structure Results



Hg1201



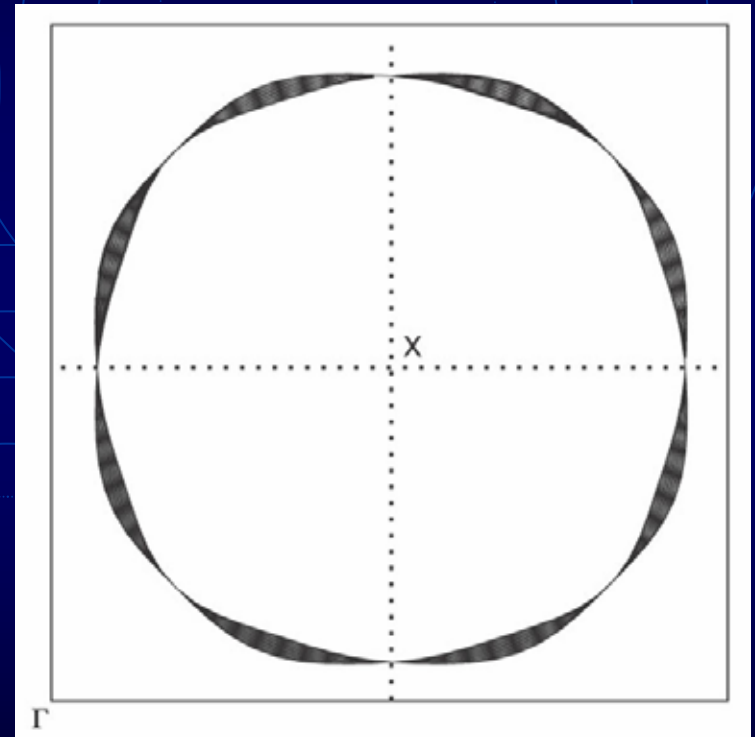
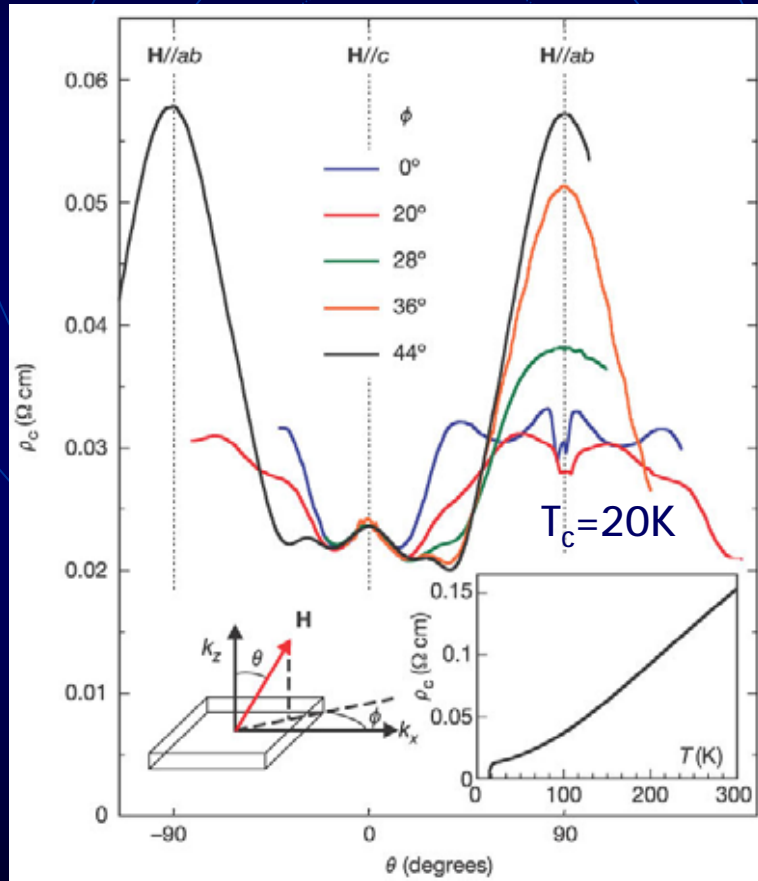
Hg1212



Hg1223

Coherent 3D Fermi surface measured by Polar Angular Magnetoresistance Oscillation

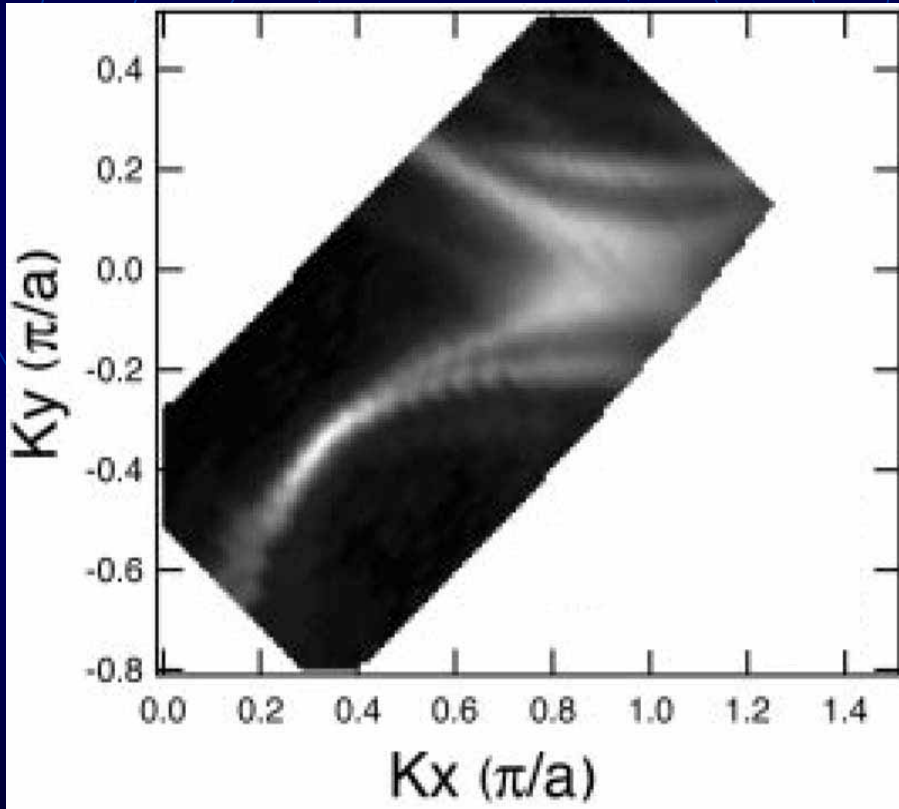
Hussey et al, Nature 425, 814 (03)



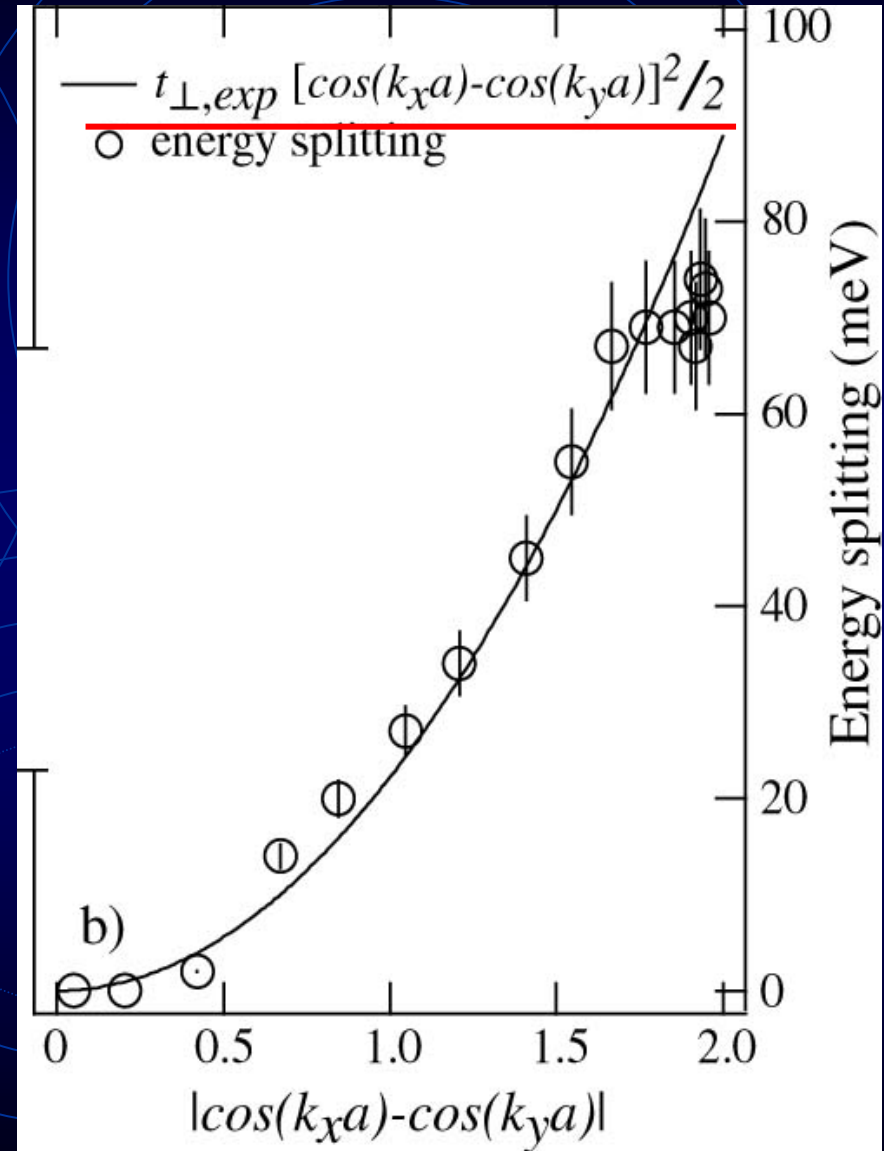
Projection of the FS onto the ab -plane

Polar AMRO, overdoped TI2201

Bilayer Split of Bi2212



Bogdanov et al, PRB **64**, 180505 (01)

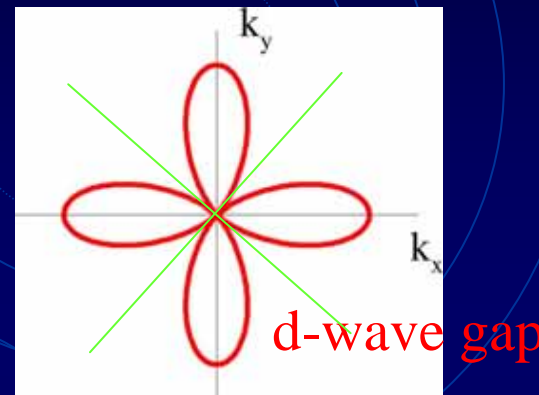


D L Feng et al, PRL **86**, 5550 (01)

两种各向异性相互作用会产生什么后果

1. 能隙具有 $d(x^2-y^2)$ 对称性

$$\Delta_k = \Delta (\cos k_x - \cos k_y)$$



2. c-轴电子跃迁积分强烈依赖 CuO_2 平面内电子的动量方向

$$t_z \propto t_{\perp} (\cos k_x - \cos k_y)^2$$

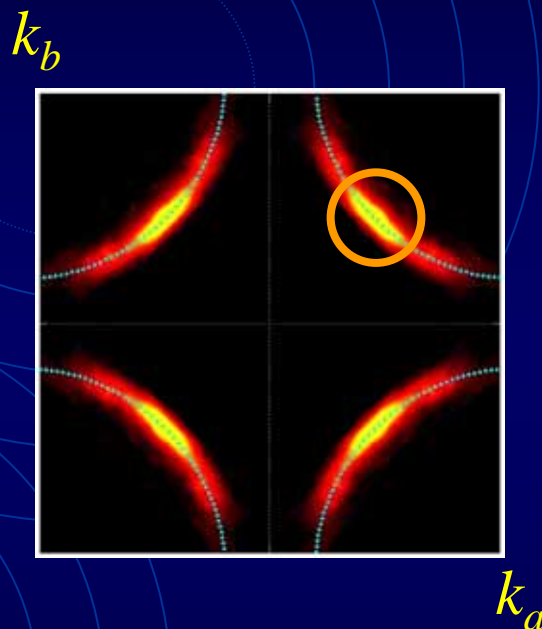
超导态：低能行为由能隙节点附近的准粒子决定

1. 电子沿c-轴方向的速度强烈依赖平面内的动量

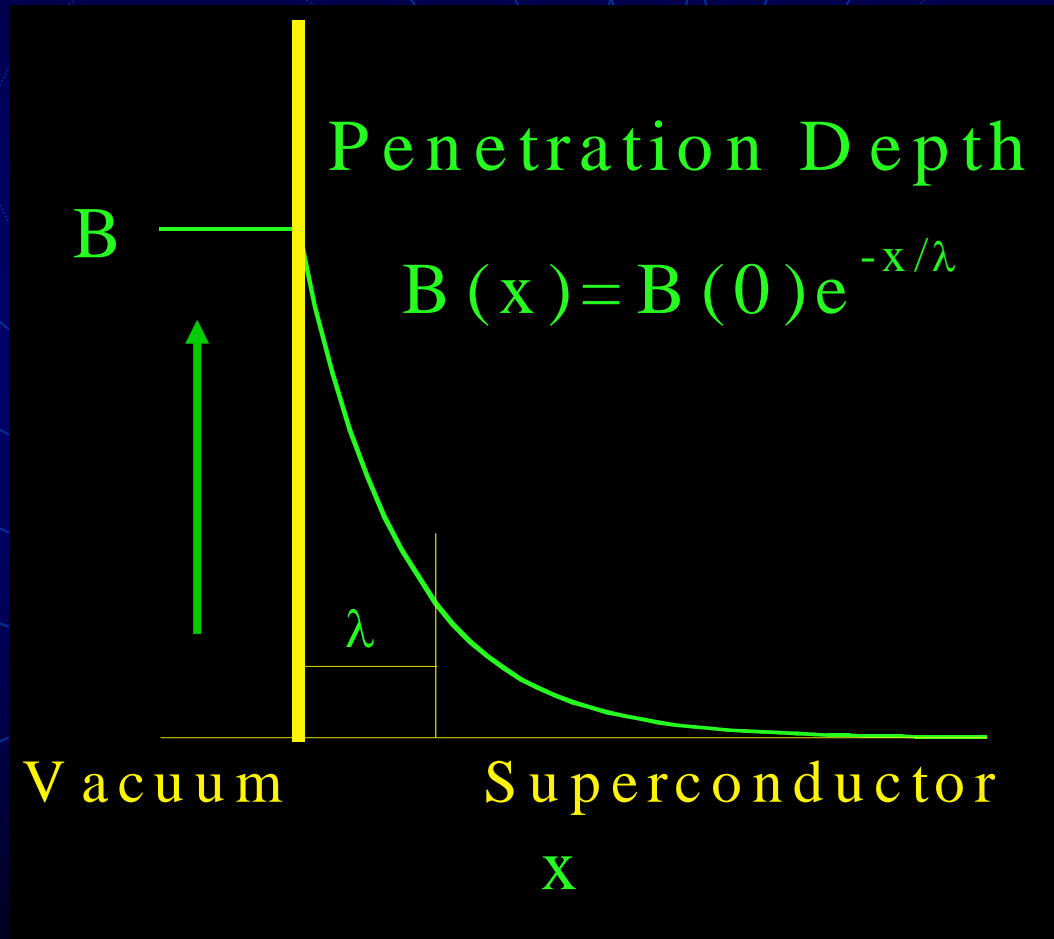
$$t_c \propto (\cos k_a - \cos k_b)^2$$

2. 超导及正常态的赭能隙具有d波对称性

$$\Delta_k = \Delta (\cos k_a - \cos k_b)$$



超流密度



CuO面内的超流密度

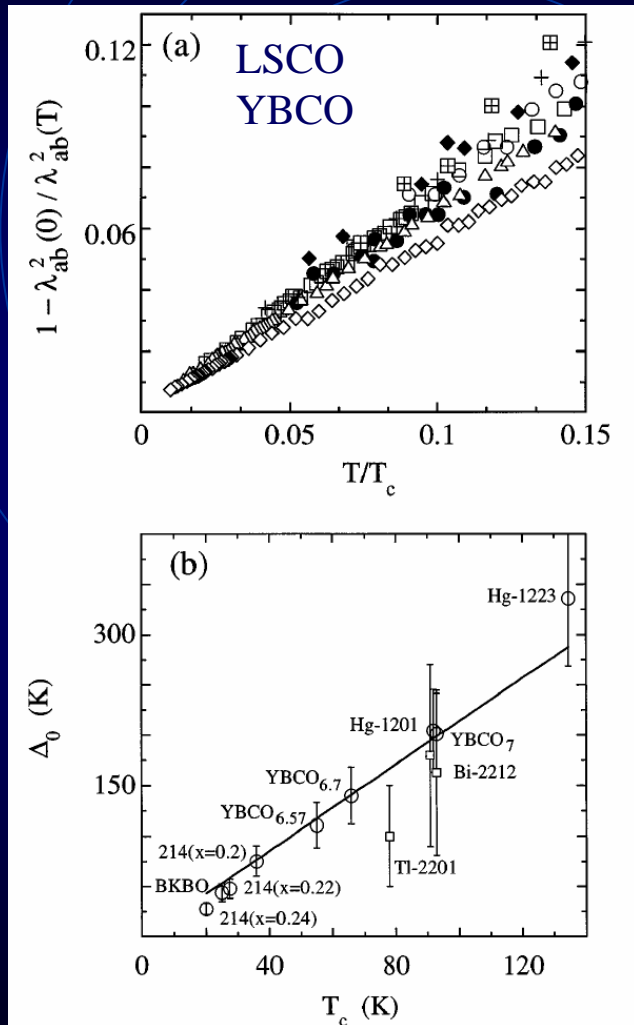
In-plane superfluid density
 \propto Density of states

$$\rho_{ab}^s \sim \int d^3k v_{ab}^2(k) \frac{\partial f(\lambda_k)}{\partial \lambda_k}$$

$$\sim \int d\omega \frac{\partial f(\omega)}{\partial \omega} \rho(\omega) \sim \rho(T)$$

Universal gap slope:

The gap slope at the nodal point is
 approximately proportional to T_c
 independent on doping

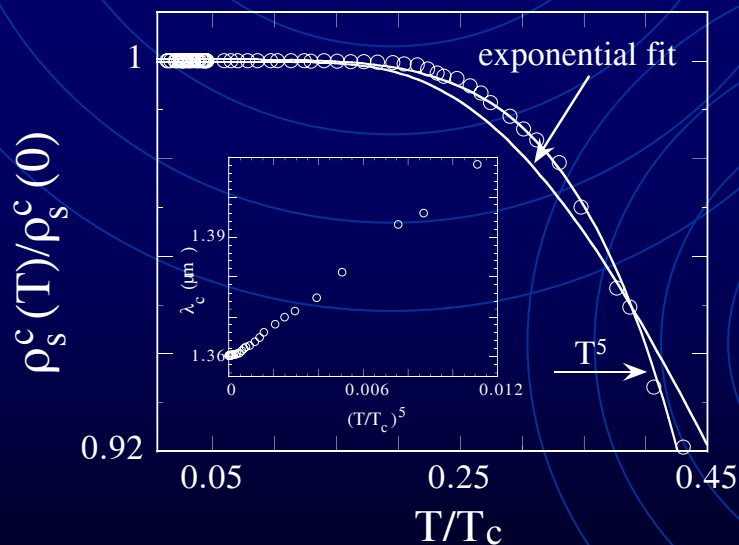


C轴方向超流密度：随温度 T^5 变化

$$\rho_c \sim \int d^3k v_c^2(k) \frac{\partial f(\lambda_k)}{\partial \lambda_k}$$

$$\sim \int d\omega \frac{\partial f(\omega)}{\partial \omega} \langle \cos^4 2\theta \rho(\omega, \theta) \rangle_{F.S.}$$

Xiang, Wheatley, PRL 77, 4632 (1996)



$$\rho_c \sim \lambda_c^{-2} \sim N(0) t_{\perp}^2 \left[1 - 450 \left(\frac{T}{T_c} \right)^5 \right]$$

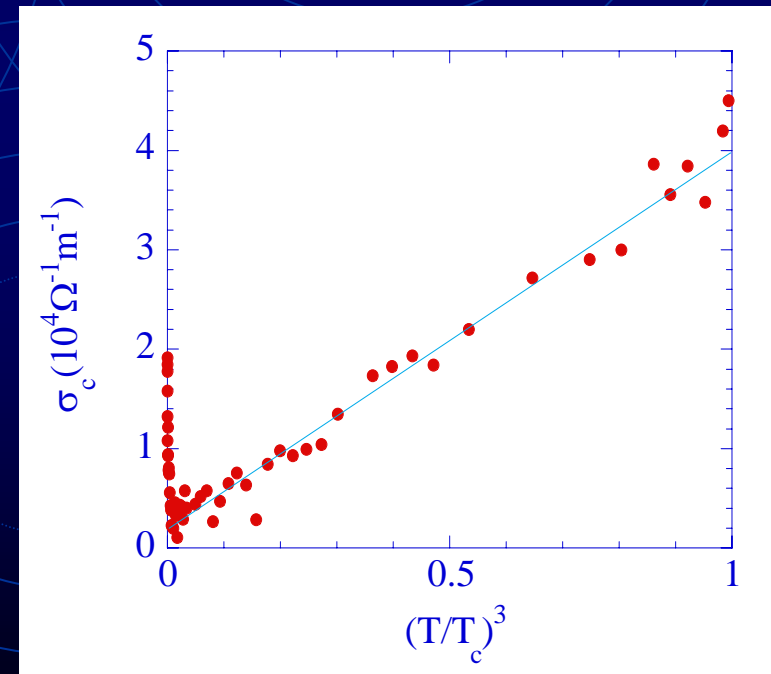
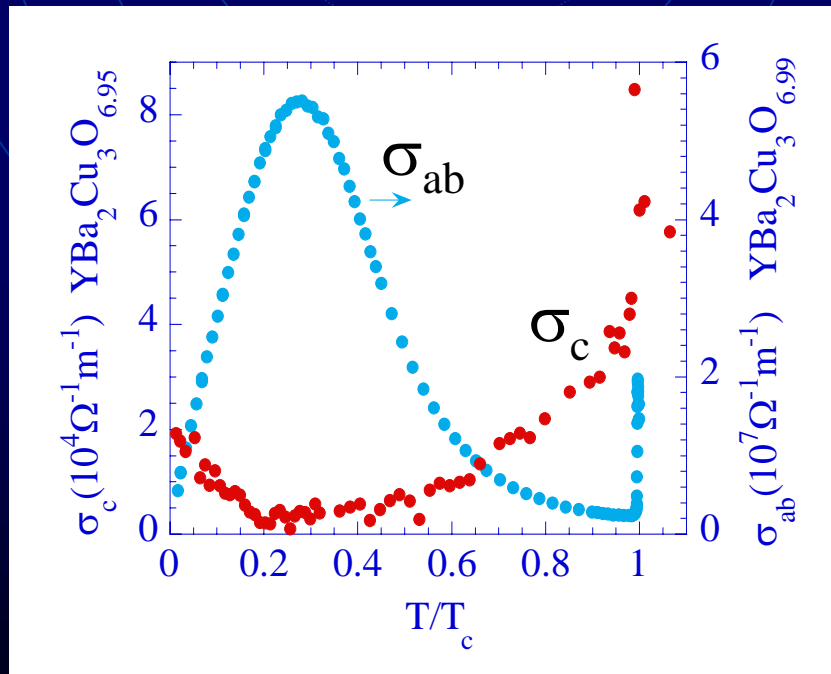
PRL 79, 2320 (1997)

实验结果与理论预言的比较

超导准粒子的低频电导：普适的 T^3 规律

$$\sigma_c \approx 10\sigma_{c,n}(0K) \left(\frac{T}{\Delta_0} \right)^3$$

Xiang, Hardy, PRB (2001)



正常态：导电行为由最大能隙处的电子激发决定

Su, Luo, Xiang (2006)

- 能隙 Δ 是控制低能电子激发行为的唯一能量尺度



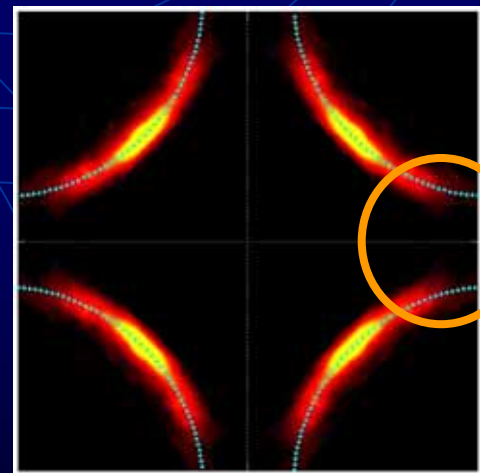
普适标度律

$$\rho_c(T) = \alpha_c g\left(\frac{T}{\Delta}\right)$$



$$g\left(\frac{T}{\Delta}\right) \approx \frac{T}{\Delta} \exp\left(\frac{\Delta}{T}\right)$$

k_b



k_a

c轴方向电阻

$$\sigma_c \sim \frac{1}{\Gamma} \int_{-\infty}^{\infty} d\omega \frac{\partial f(\omega)}{\partial \omega} \left\langle t_z^2(k) \rho(\omega, k) \right\rangle_{F.S} = \frac{1}{\Gamma} \int_{-\infty}^{\infty} d\omega \frac{\partial f(\omega)}{\partial \omega} N_c(\omega)$$

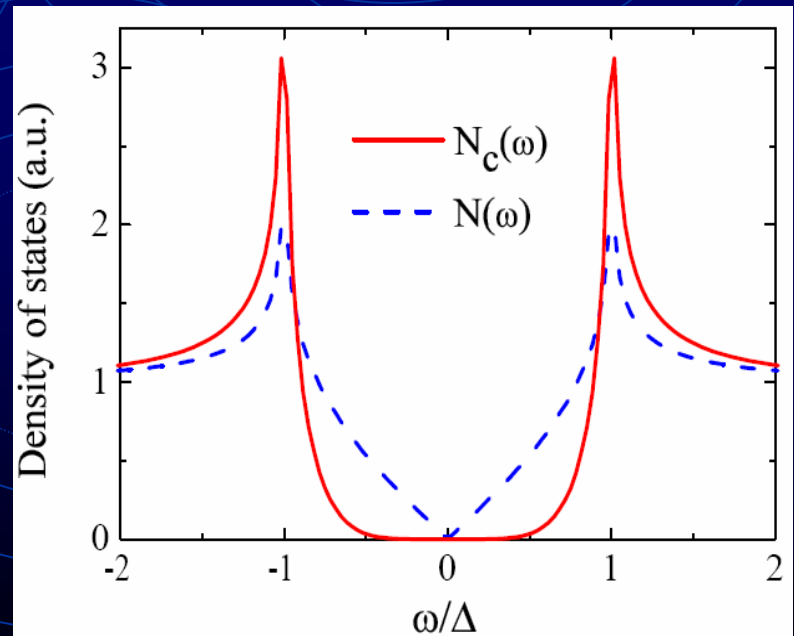


$$N_c(\omega) = \left\langle t_z^2(k) \rho(\omega, k) \right\rangle_{FS} \\ \approx N_0 \delta(\omega - \Delta)$$

$$\rho_c(T) = \sigma_c^{-1}(T) \propto T \exp\left(\frac{\Delta}{T}\right)$$

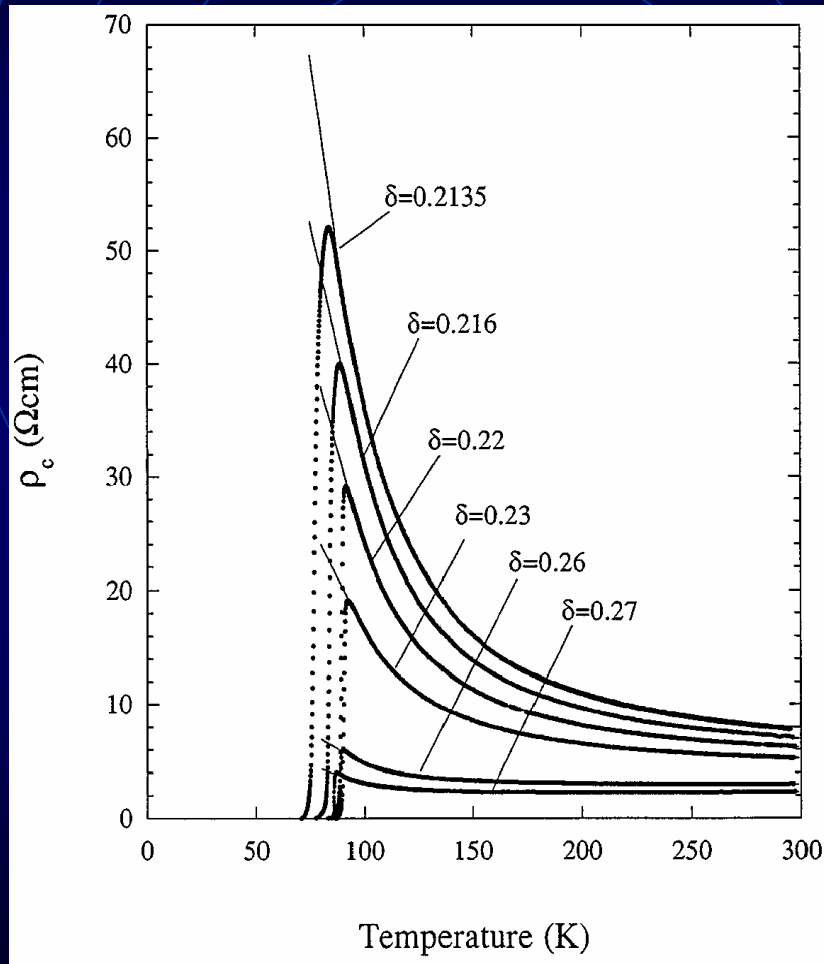


$$g\left(\frac{T}{\Delta}\right) \approx \frac{T}{\Delta} \exp\left(\frac{\Delta}{T}\right)$$

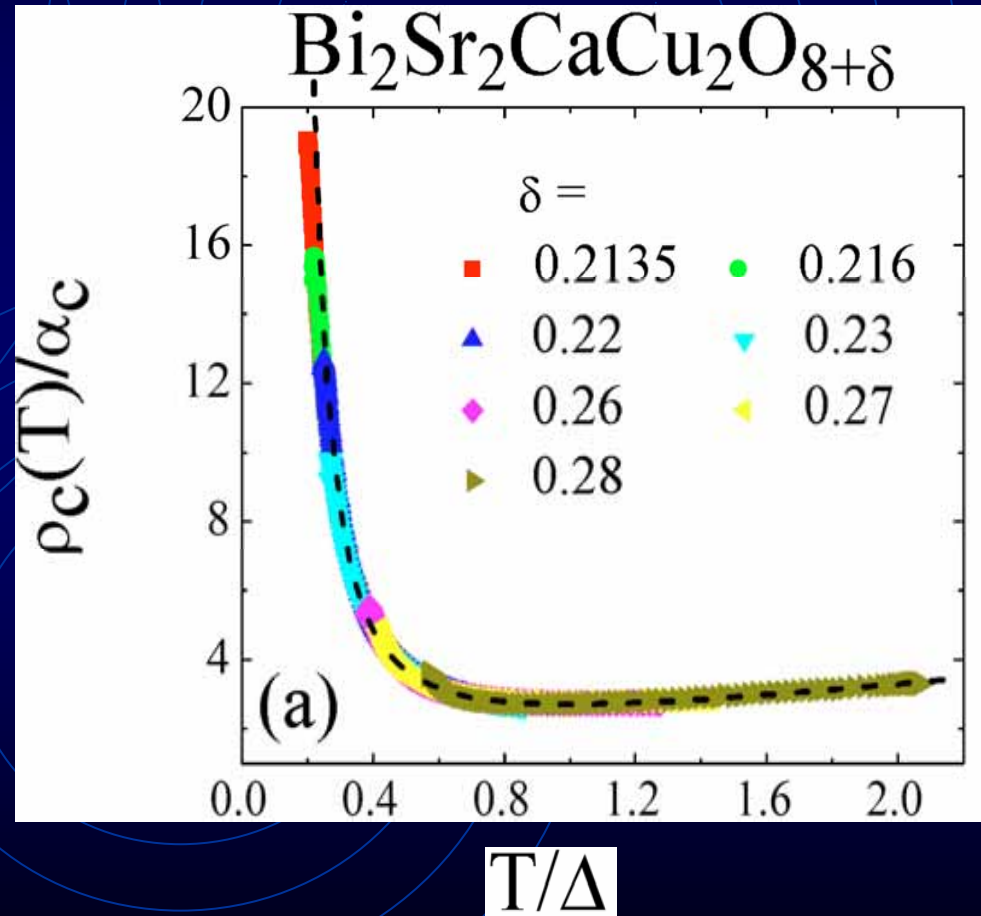


Normal state c-axis resistivity: Experimental Data

Bi2212

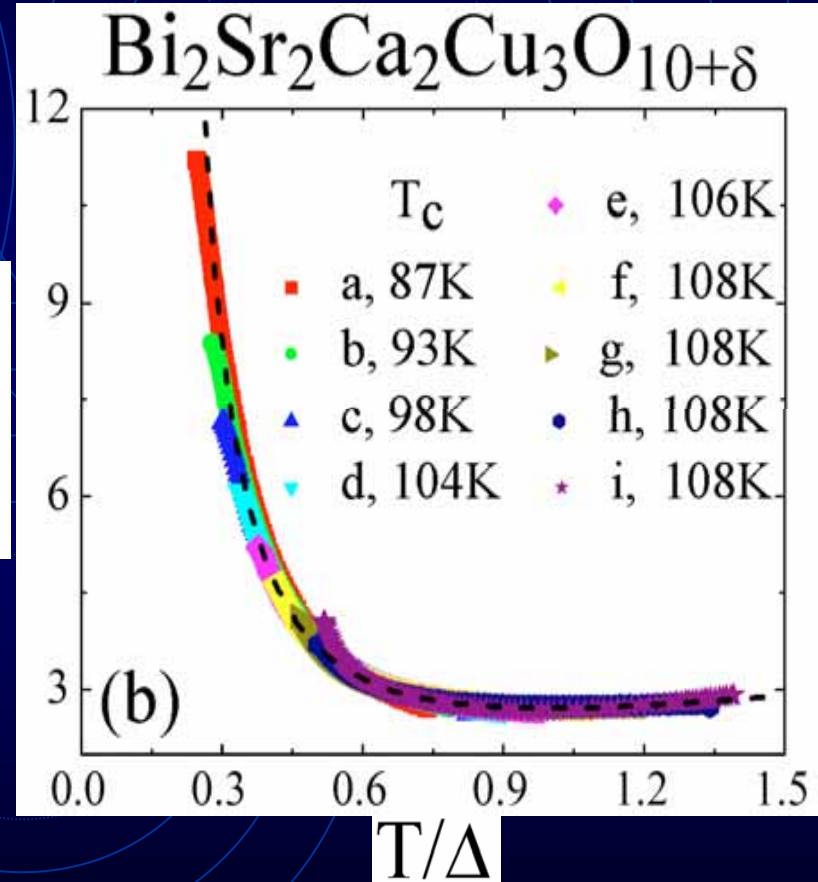
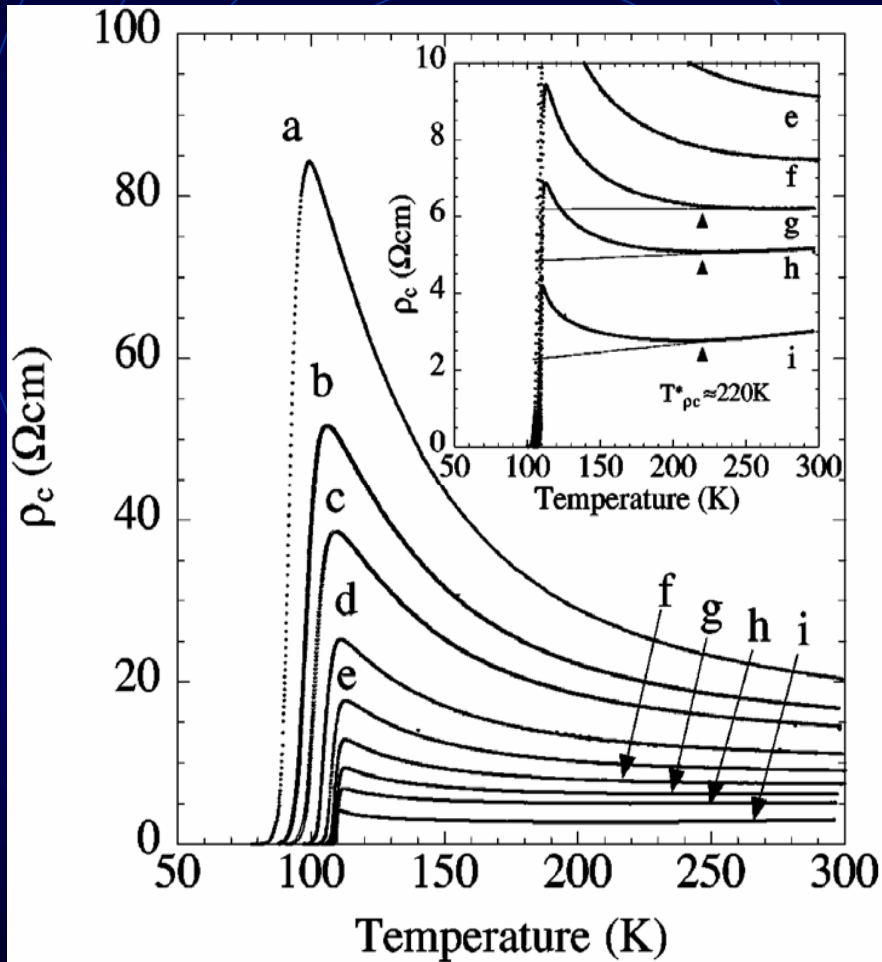


Dashed lines: $g(x) = x \exp\left(\frac{1}{x}\right)$

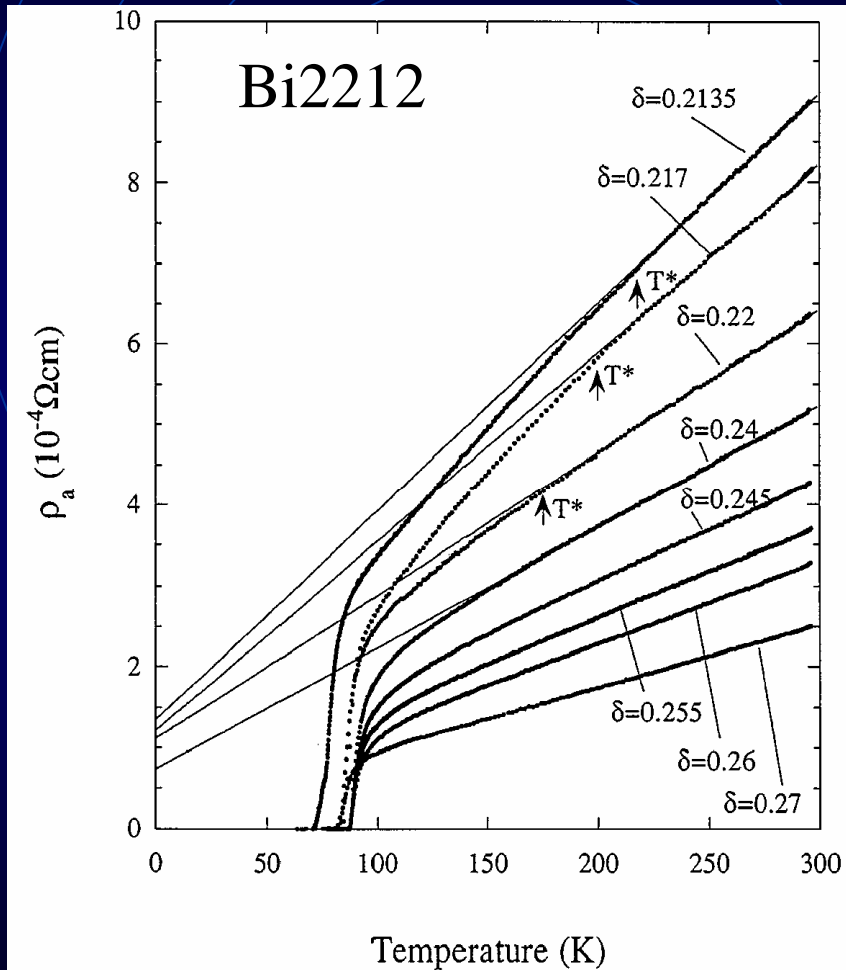


Normal state c-axis resistivity: Scaling Behavior

Bi2223



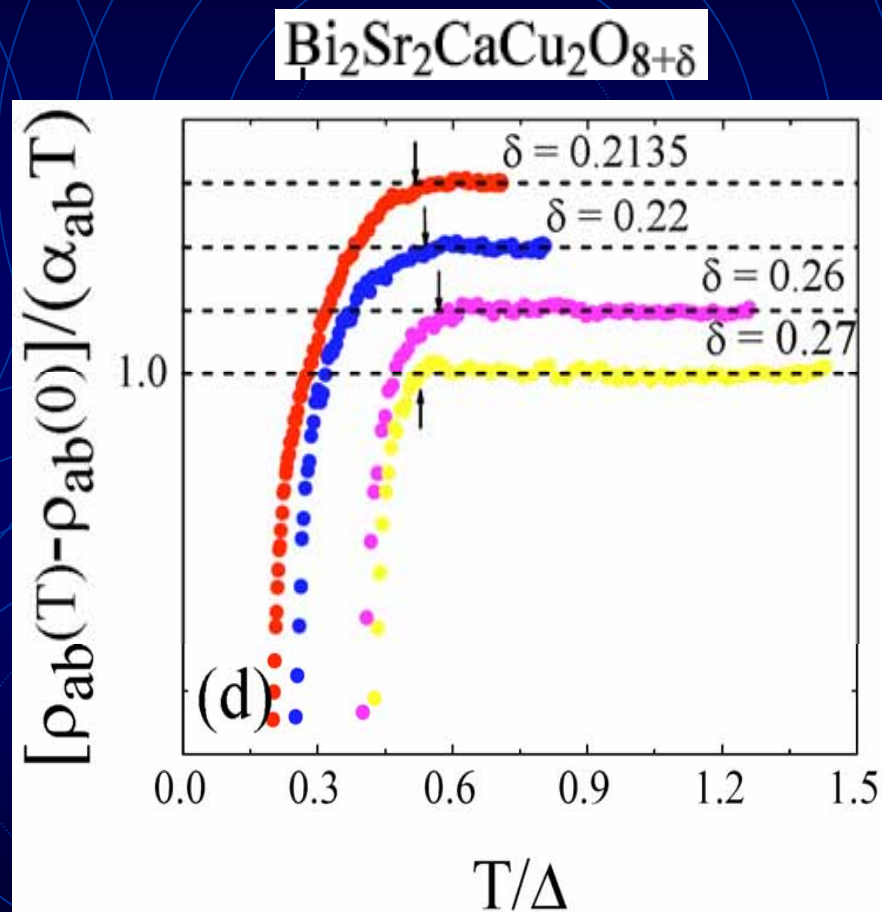
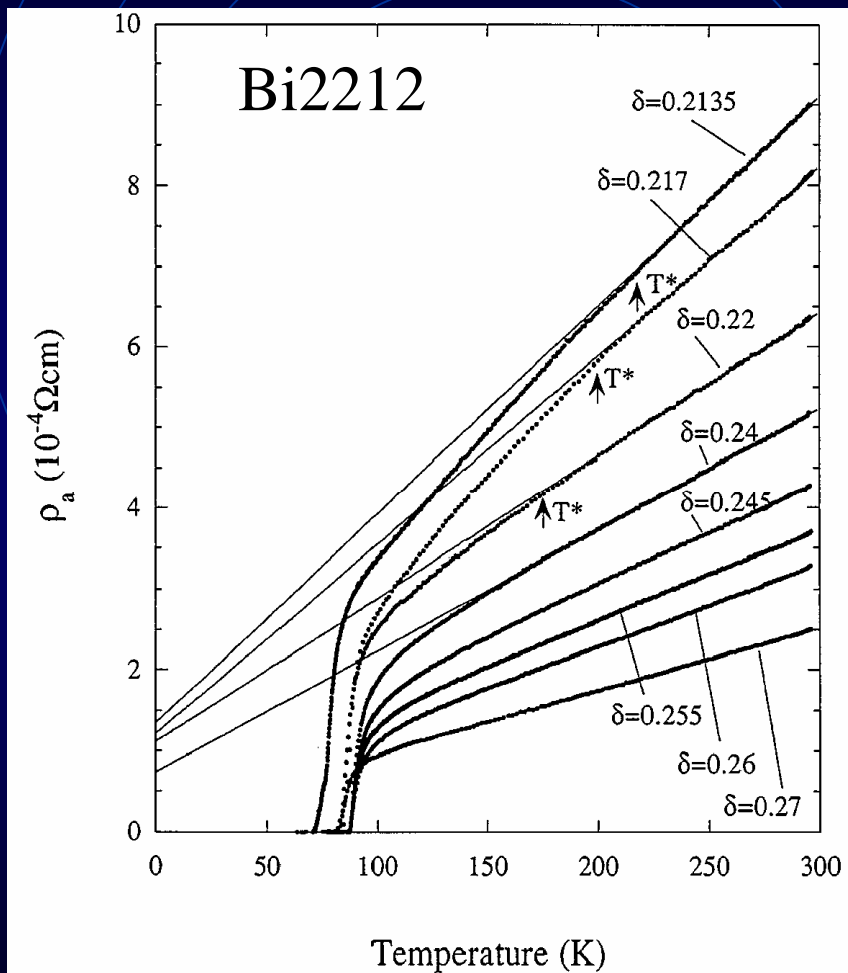
Is Δ really the pseudogap energy scale?



In high temperatures above the pseudogap phase, the in-plane resistivity varies linearly with T

$$\rho_{ab}(T) = \rho_{ab}(0) + \alpha_{ab}T$$

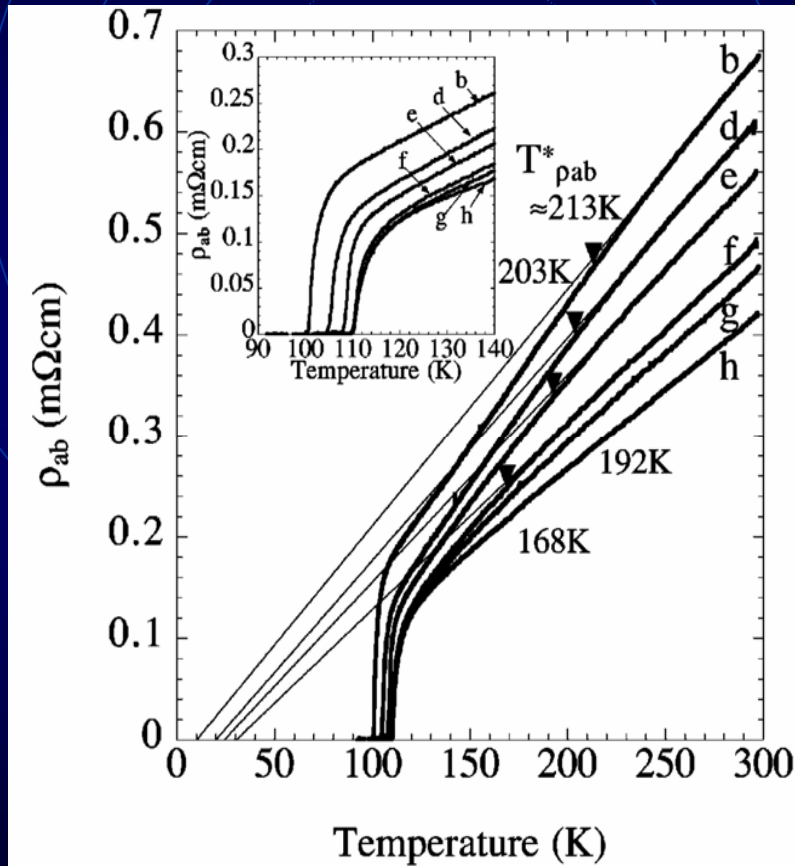
Is Δ really the pseudogap energy scale?



$$\rho_{ab}(T) = \rho_{ab}(0) + \alpha_{ab} T$$

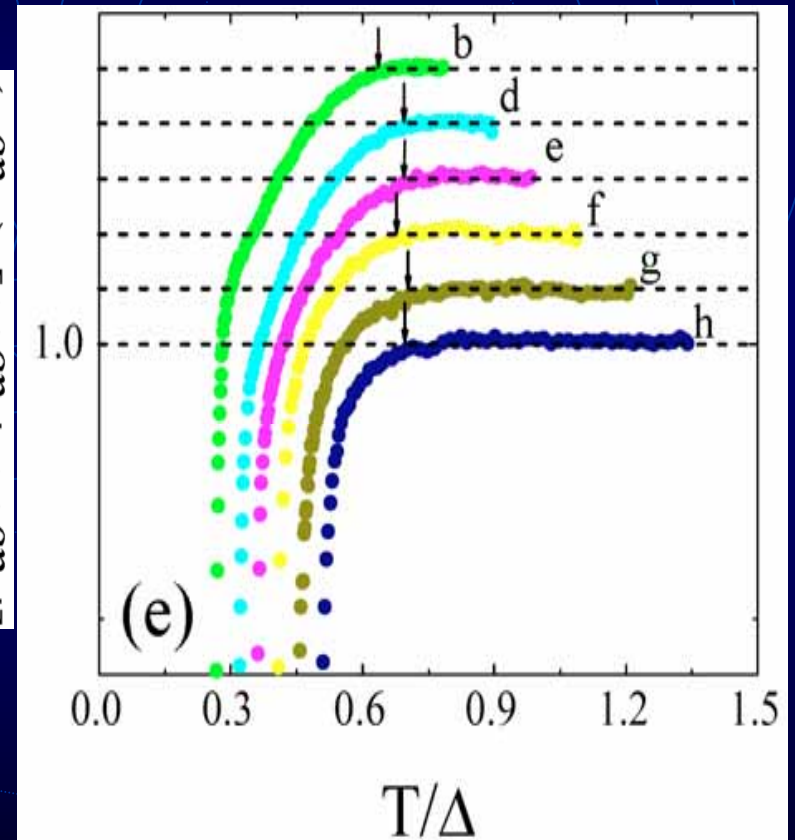
Is Δ really the pseudogap energy scale?

Bi2223

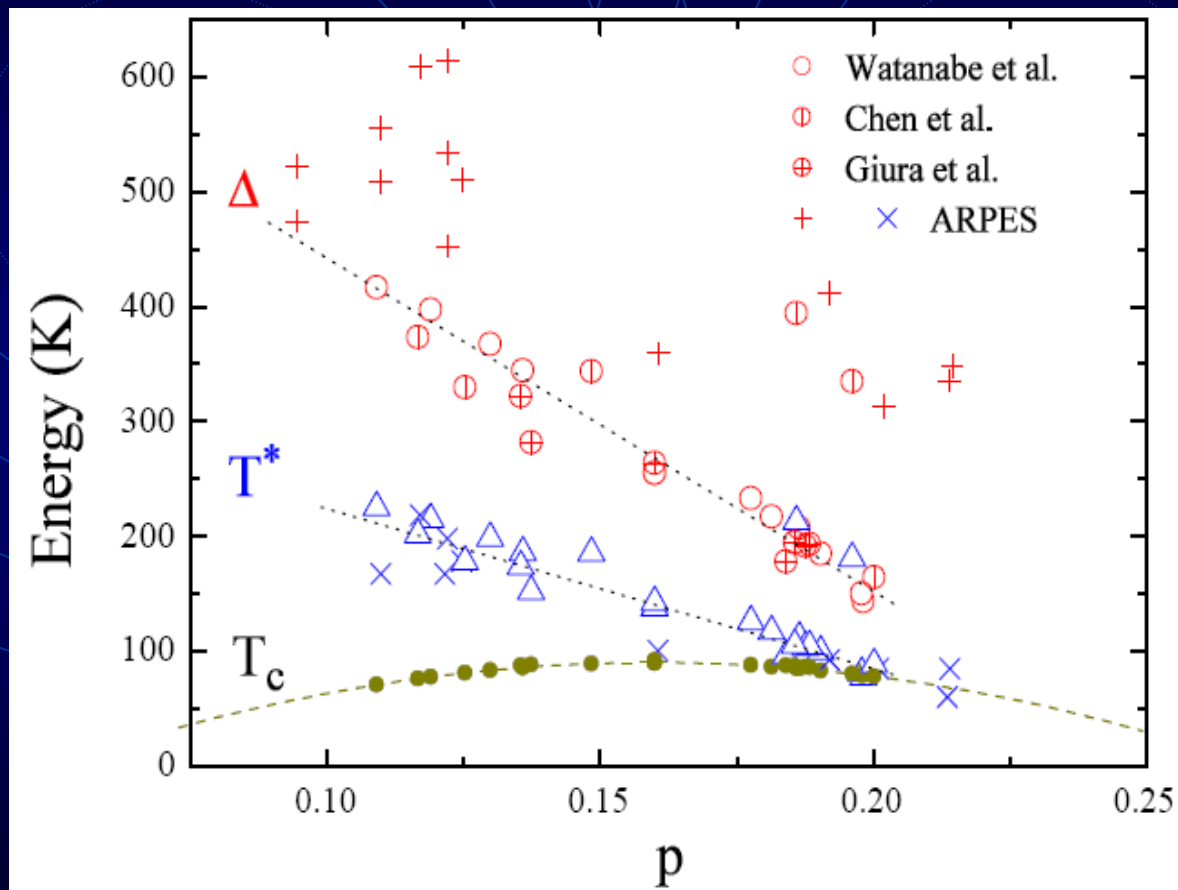


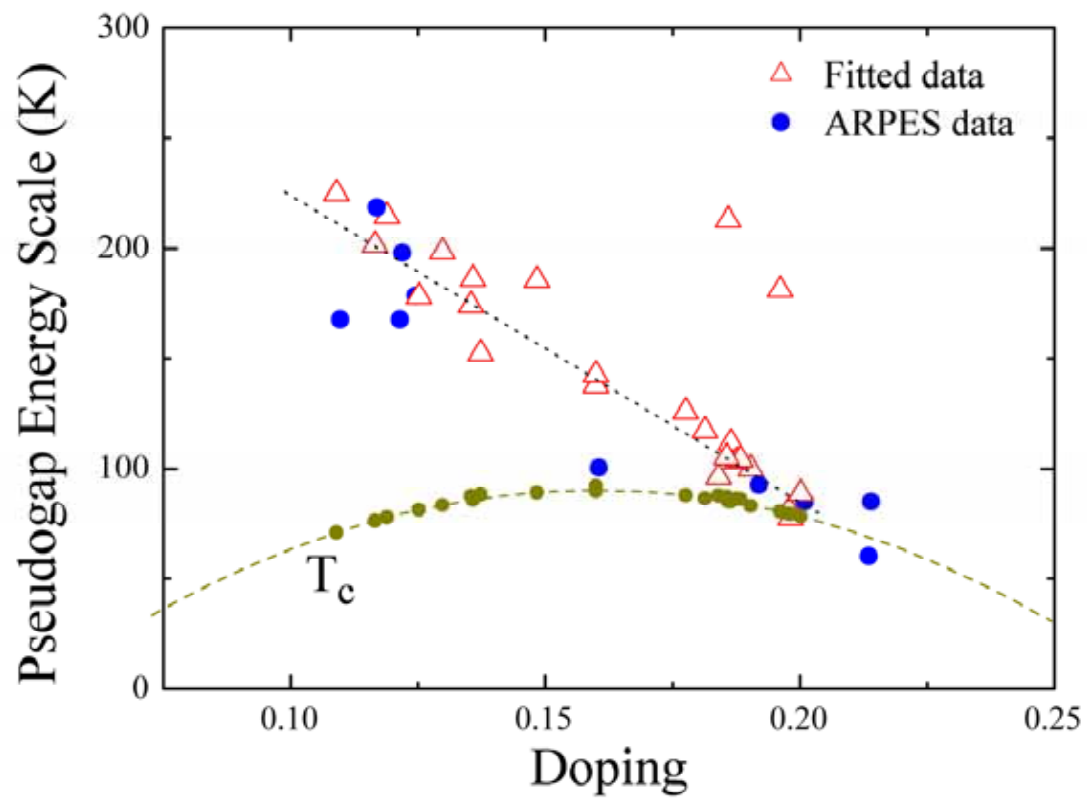
$\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+\delta}$

$$[\rho_{ab}(T) - \rho_{ab}(0)] / (\alpha_{ab} T)$$



Pseudogap versus Doping





Summary

- 高温超导体的c轴电阻的反常是赅能隙与电子层间跃迁的强各向异性的相互作用造成的
- 层间动力学存在普适性
- 表征层间电子运动，赅能隙是唯一的控制参量

结束语

物理的可靠性随着检验总量的增加而增加，但随着理论中引入的参数增加而减少。

彭恒武