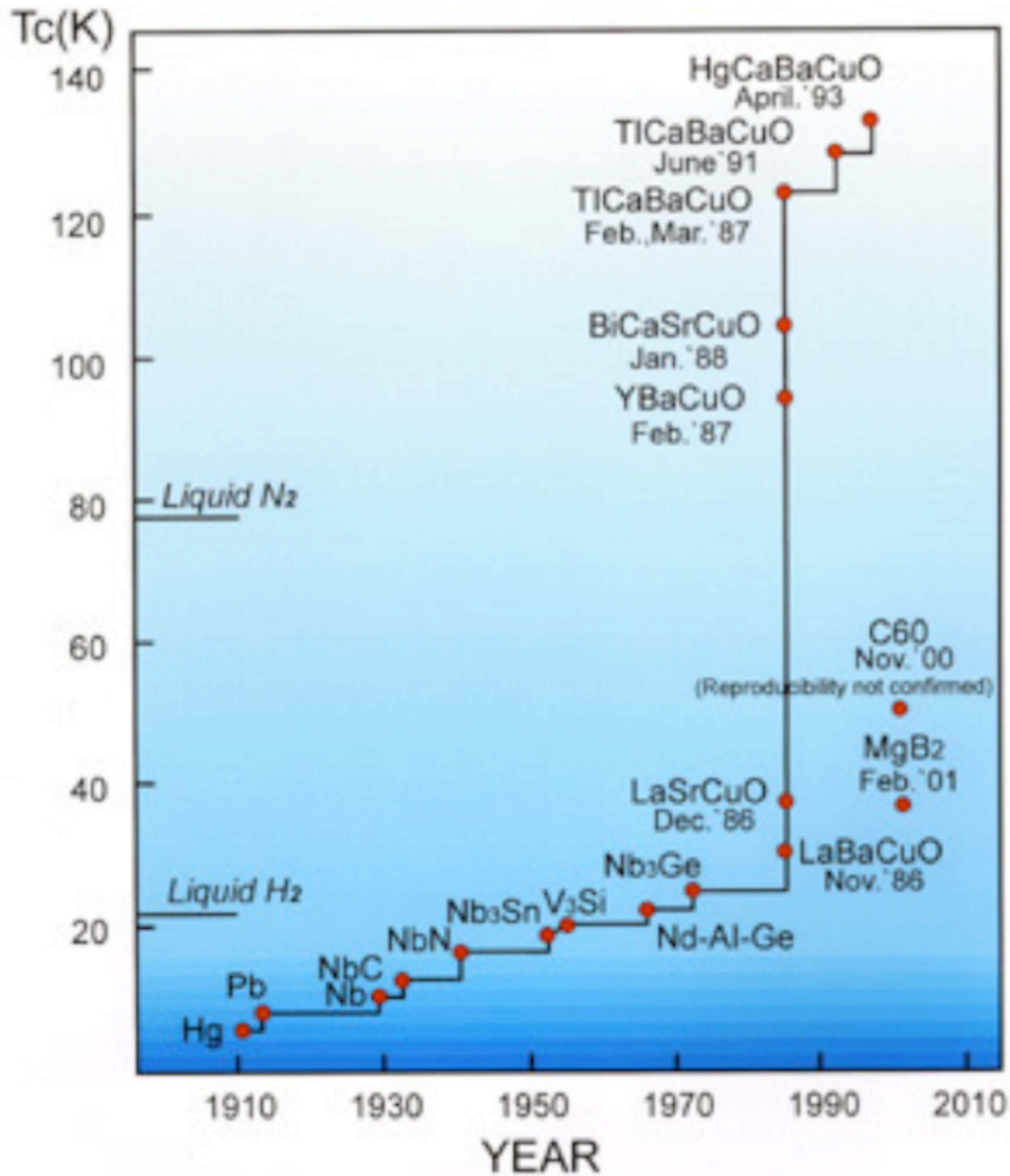
Introduction to superconductivity in the

Jules Carbotte
McMaster and CIFAR


Tc(K)
140
120
100
80
60
40
20
Liquid N_2
Liquid H_2
HgCaBaCuO April.`93
TlCaBaCuO June`91
TlCaBaCuO Feb.,Mar.`87
BiCaSrCuO Jan.`88
YBaCuO Feb.`87
C60 Nov.`00
(Reproducibility not confirmed)
MgB_2 Feb.`01
LaSrCuO Dec.`86
LaBaCuO Nov.`86
Nb_3Ge
Nd-Al-Ge
Nb_3Sn
V_3Si
NbN
NbC
Nb
Pb
Hg
1910
1930
1950
1970
1990
2010
YEAR

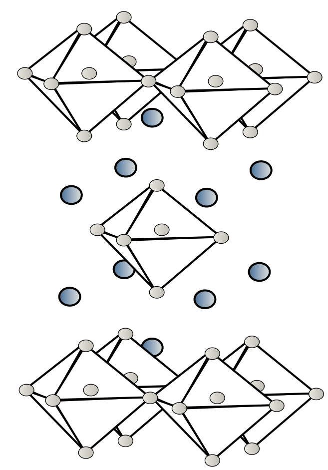
A Famous Discovery!

- **1986**

J.G. Bednorz and K.A. Müller

- **Nobel Prize 1987 – Fastest one ever!**

$La_{2-x}Ba_xCuO_4$



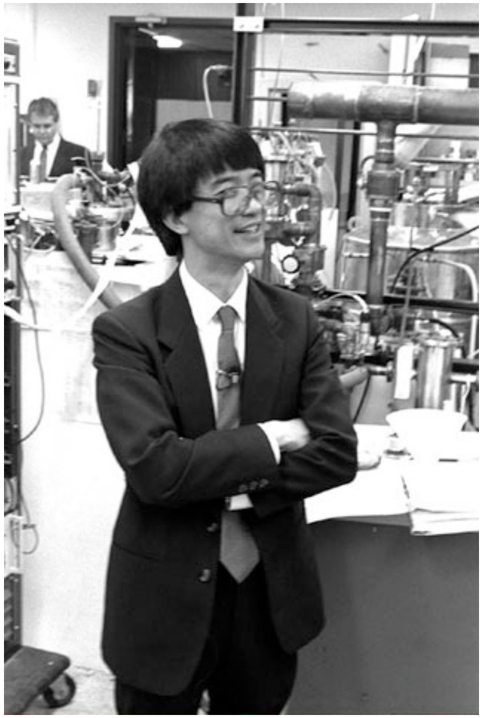
T_c ~36 K

Possible High T_c Superconductivity in the Ba–La–Cu–O System

J.G. Bednorz and K.A. Müller
IBM Zürich Research Laboratory, Rüschlikon, Switzerland

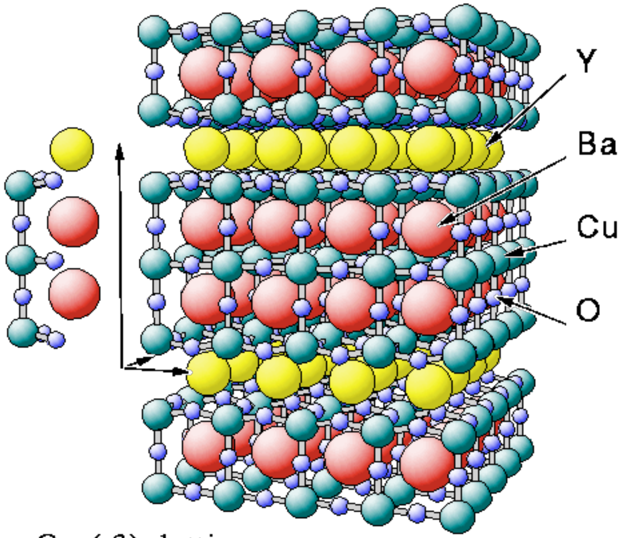
Received April 17, 1986

Breaking the Liquid Nitrogen Barrier!



- 1987

Paul Chu and co-workers



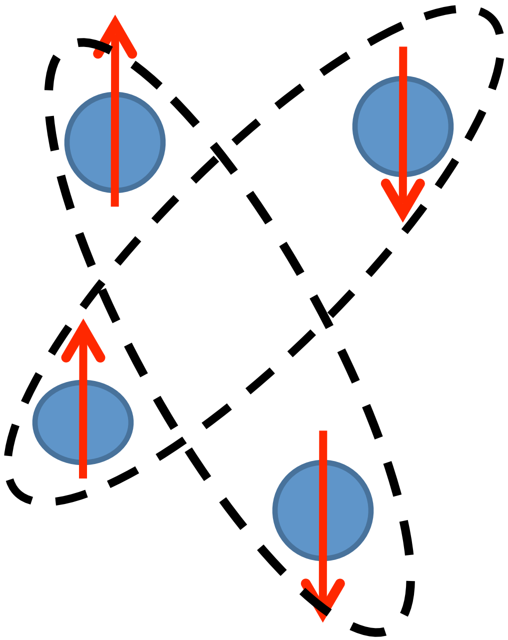
$YBa_2Cu_3O_7$ (.3) lattice

BALSAC plot

Based on idea of cooper pairs
equal and opposite momentum
and spins

Pairs overlap in r-space so many body condensate,all pairs in same wave function

Macromolecule,quantum mechanics at macroscopic level



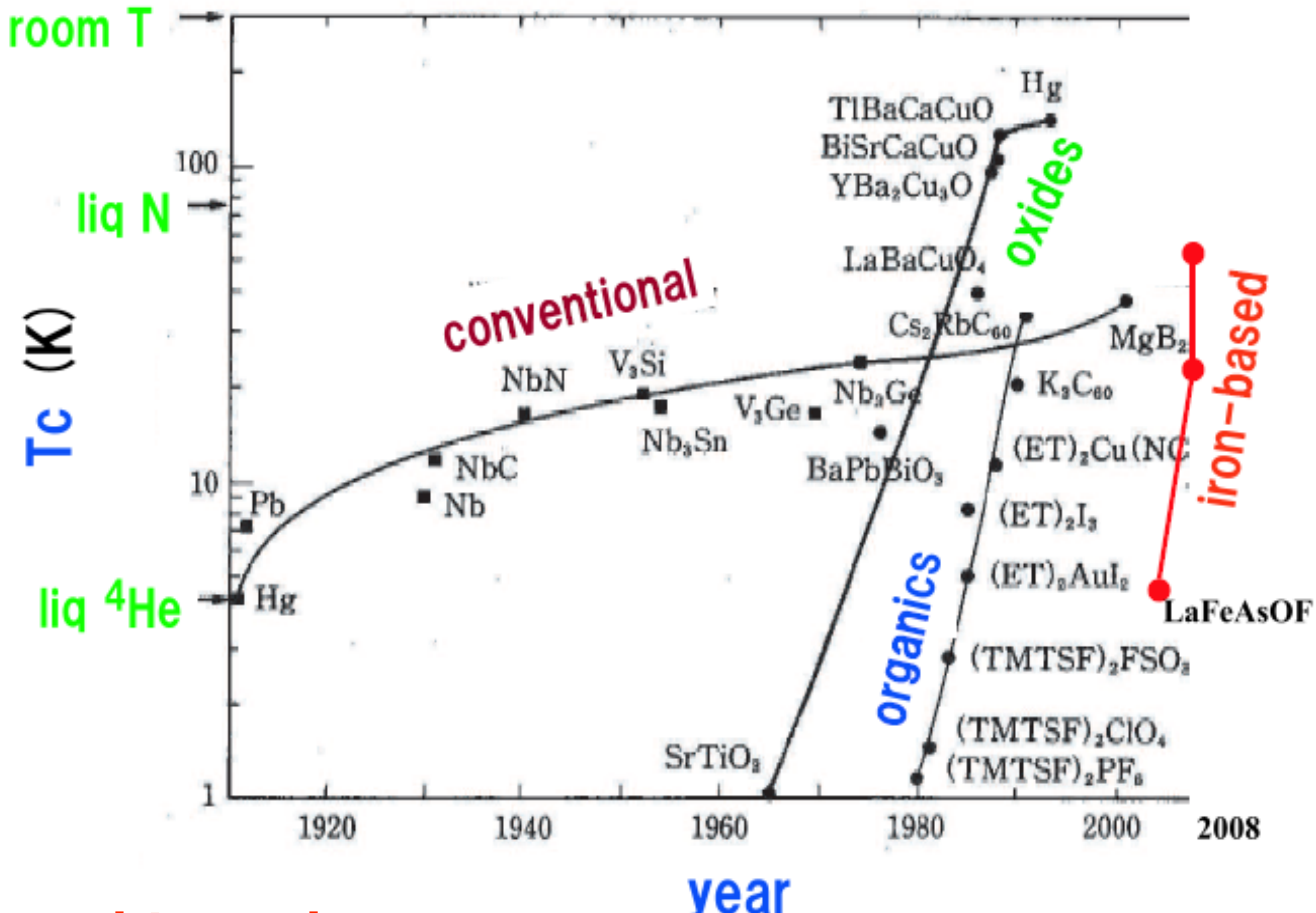
Coherence length much larger then free electron spacing

BCS theory 1957 physics nobel prize 1972

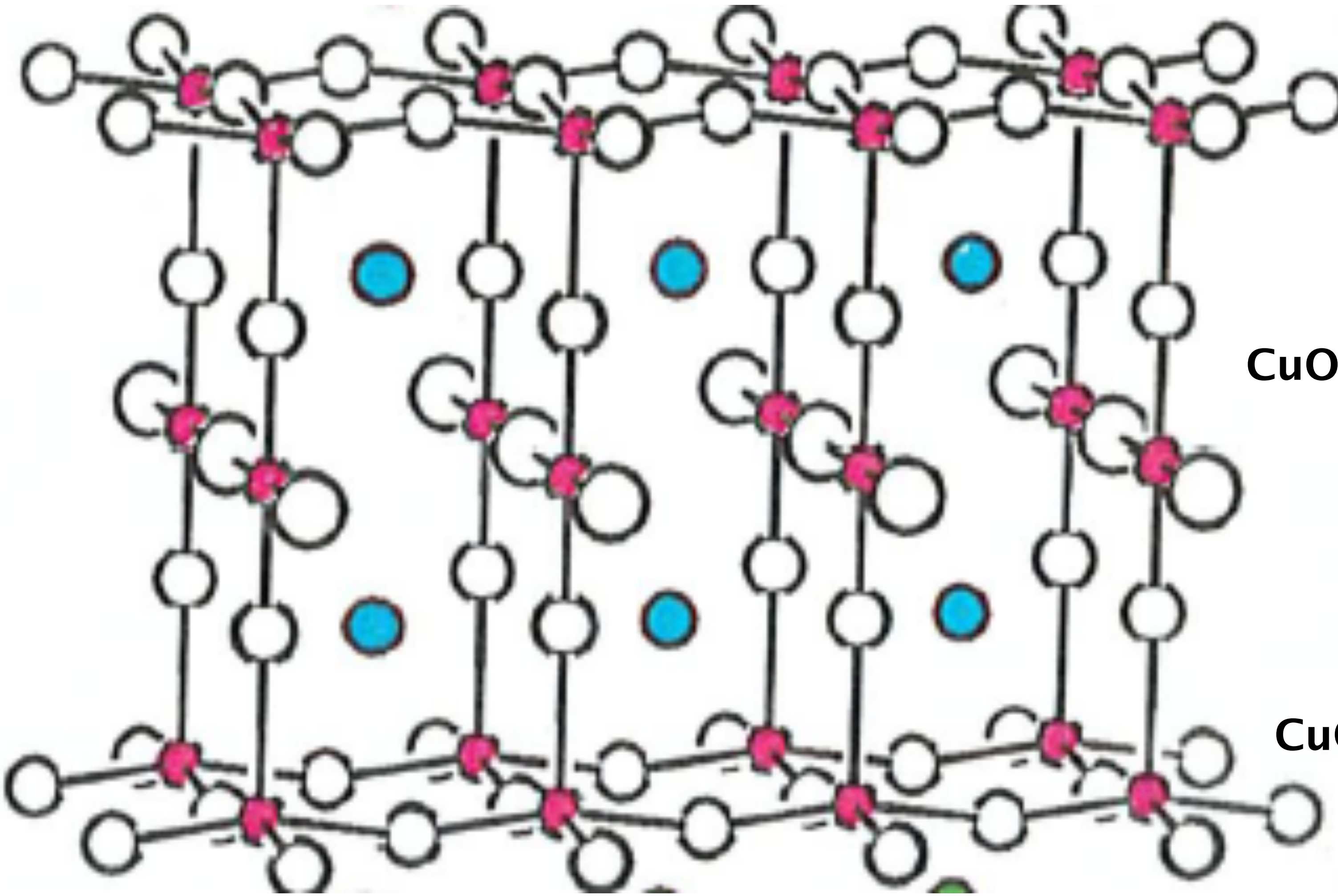
John Bardeen

Leon N. Cooper

John R. Schrieffer



Aoki cond-mat 0811.1656



123

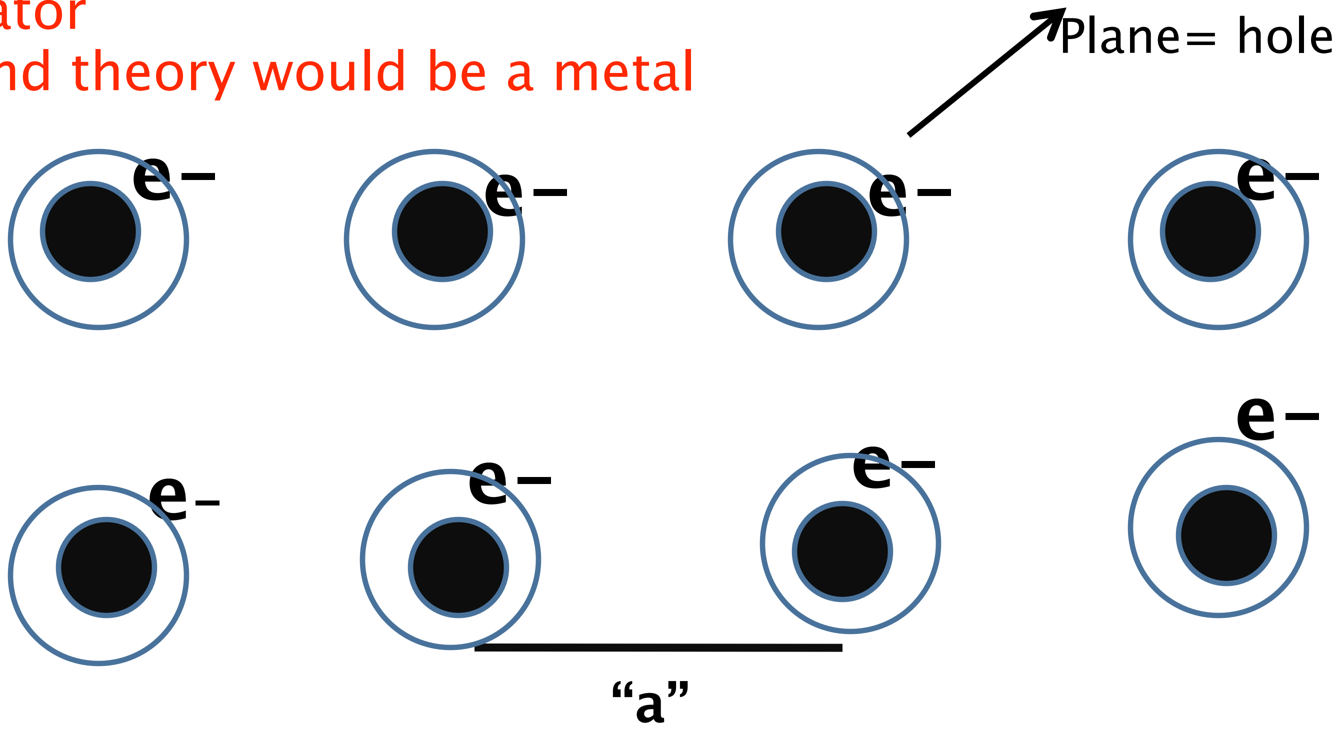
YBaCuO

Cu oxide plane is modeled with atoms on square lattice " a "with

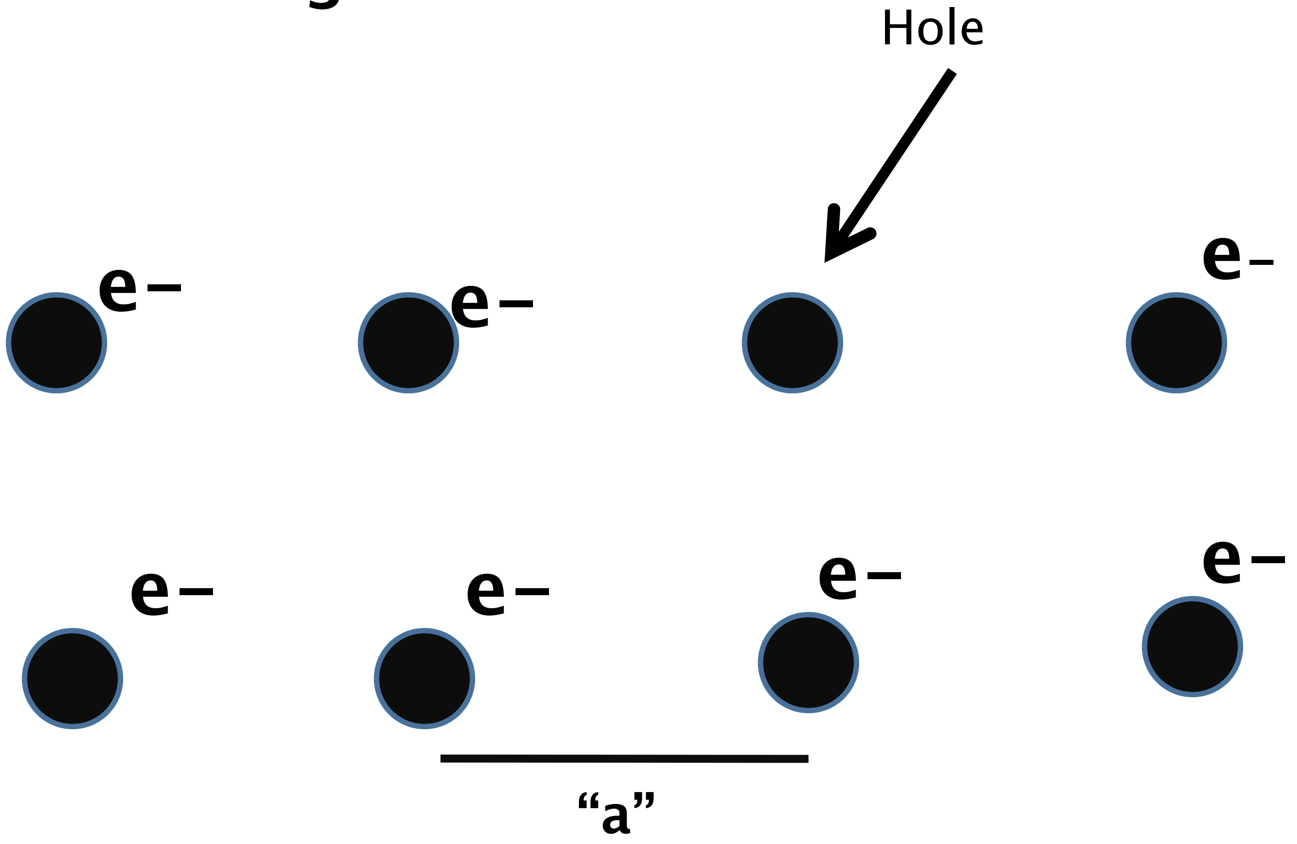
each site filled which corresponds to half filling of BZ

Measure doping from half filling as reference. Hole doping. MOTT insulator
in band theory would be a metal

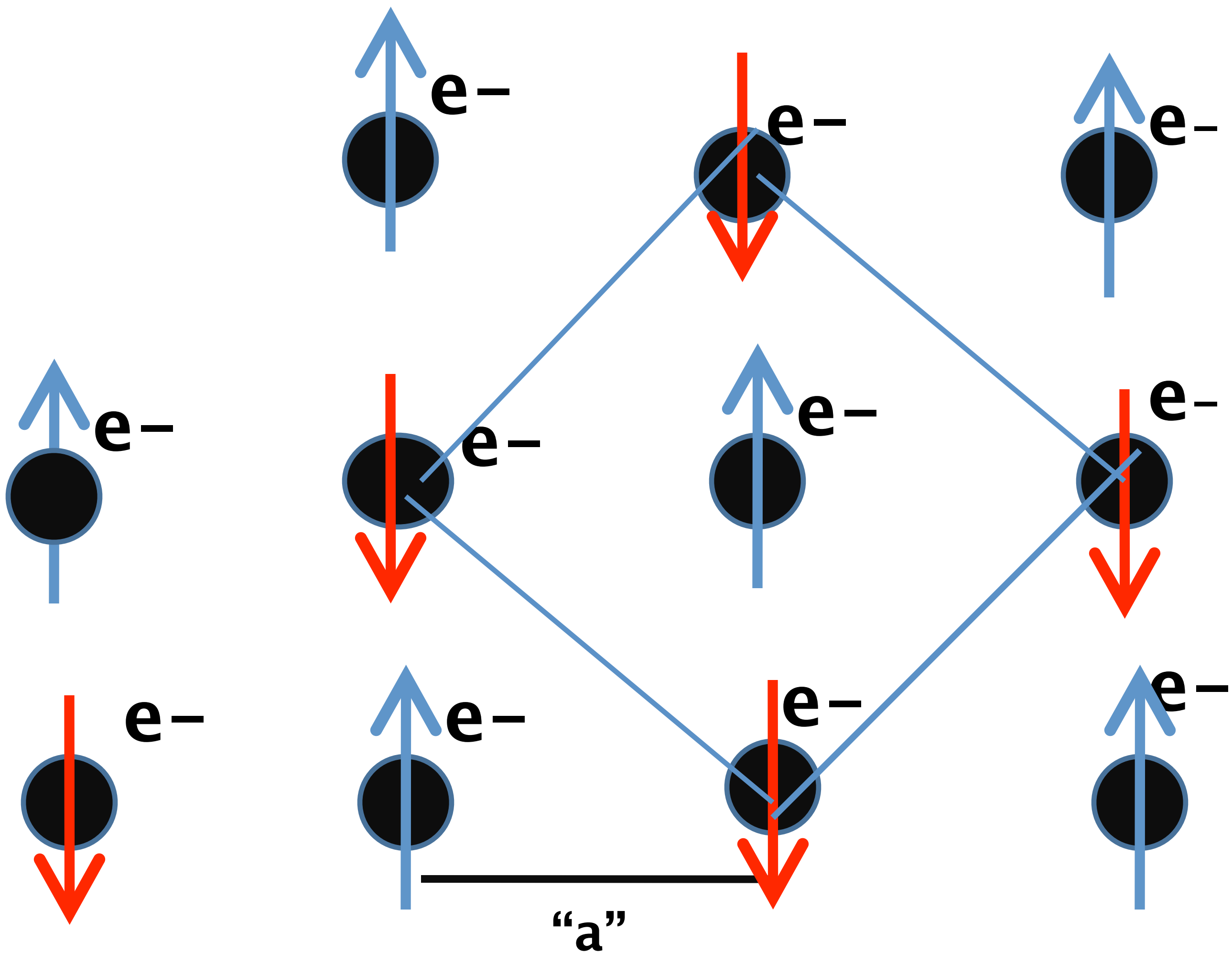
Send to other none CuO2
Plane= hole doping



**Electron cannot hop to occupied site because of Hubbard U [large
repulsive energy] . Can only hop to empty site
so at half filling MOTT insulator**



Antiferromagnet has twice the unit cell and half the BZ

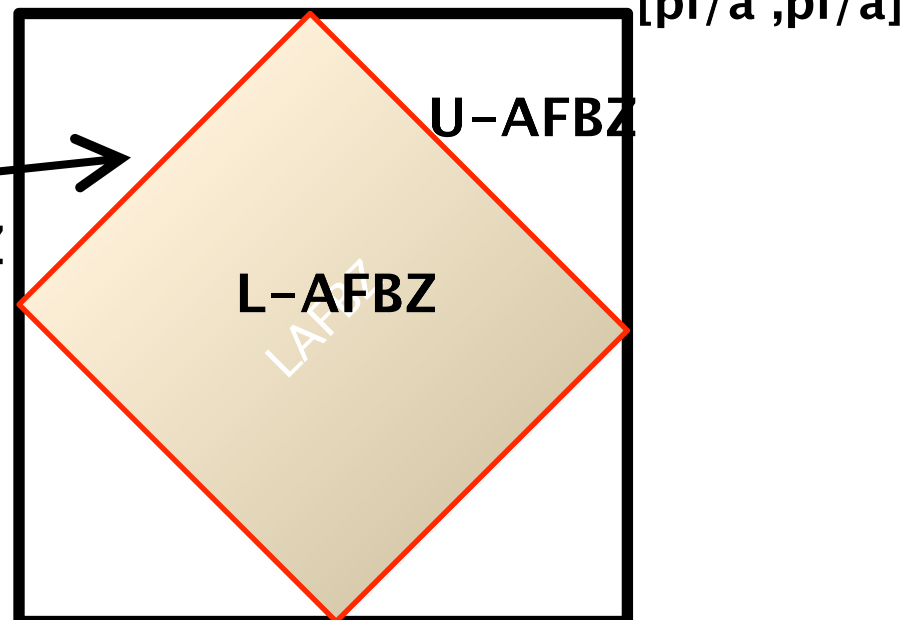


At half filling a metal in band theory

Copper –oxygen B Z

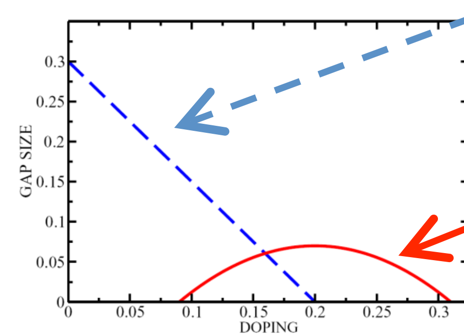
Mott insulator because of large **U**
no double occupancy

On AFMBZ



Leads to pseudogap

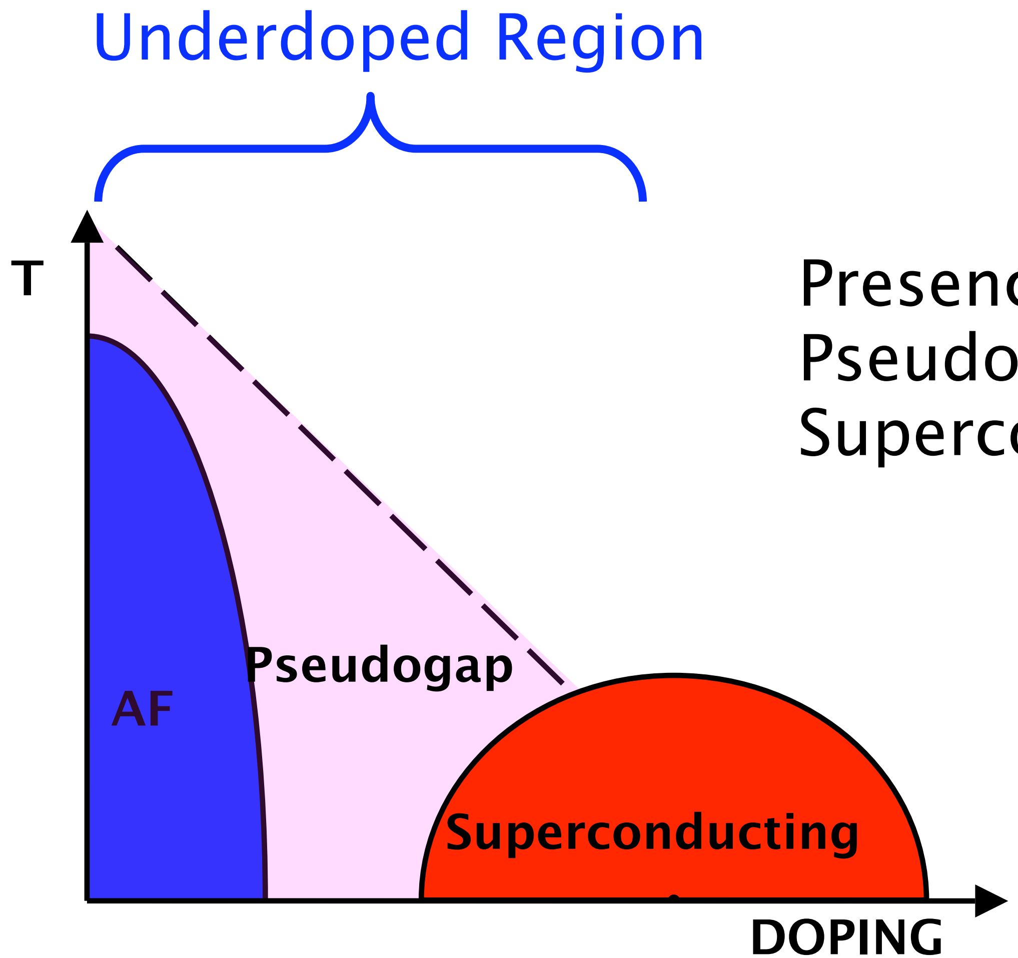
New energy scale PG



Supercon d dome

Gutzwiller factors narrow bands and account for
reduced coherence

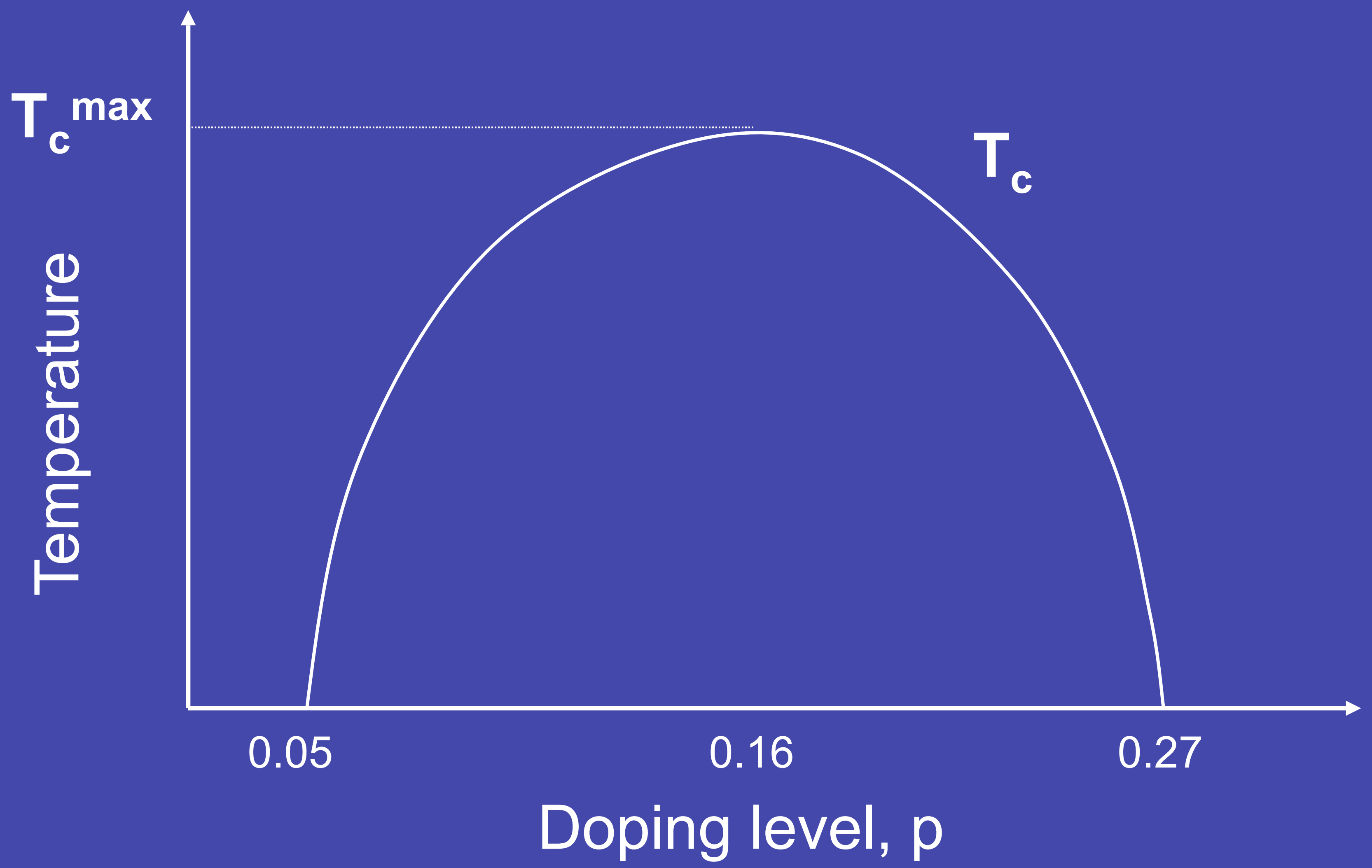
Phase Diagram of High T_C



Presence of both Pseudogap and Superconducting gap.

More doping means more holes

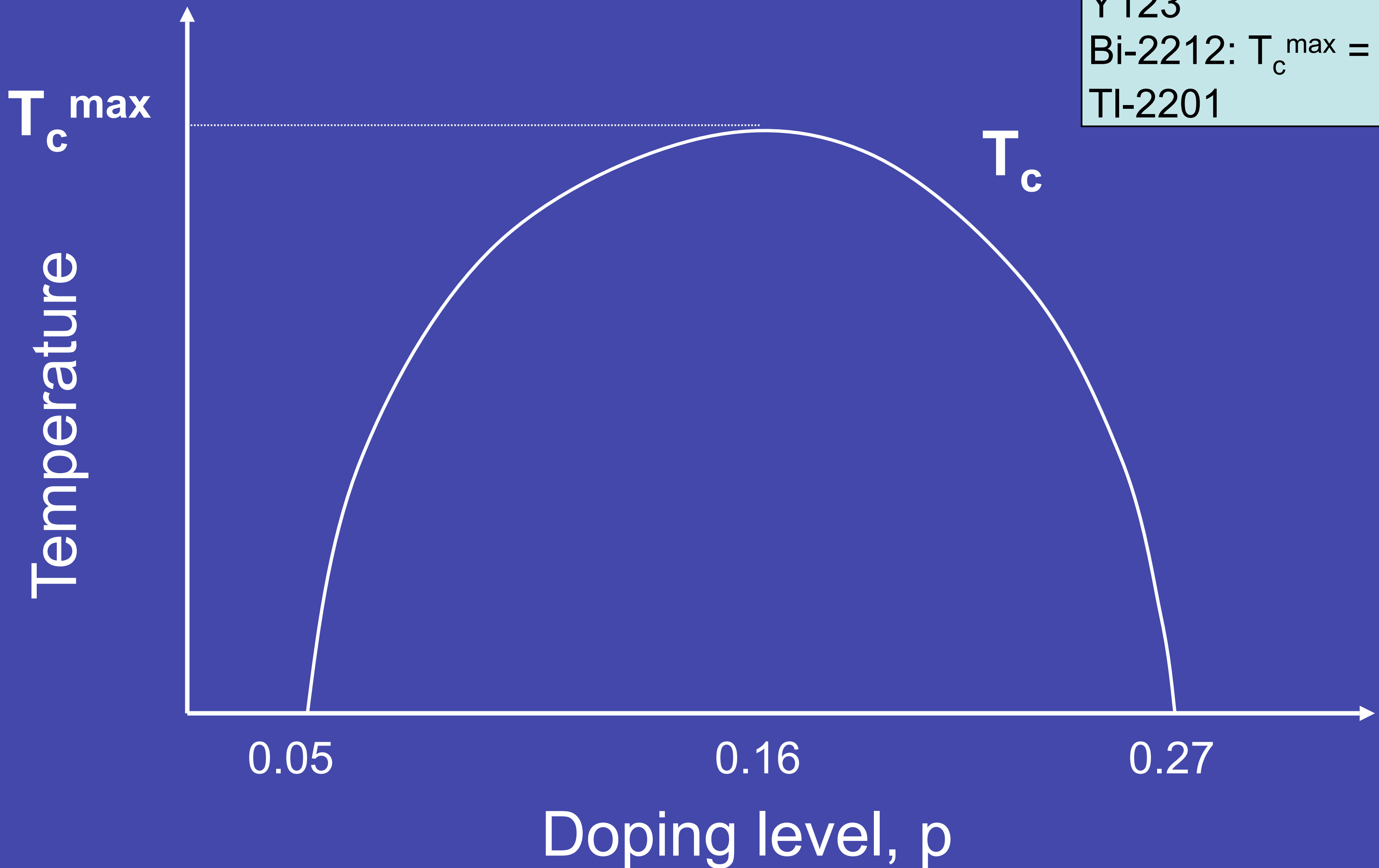
The superconducting dome



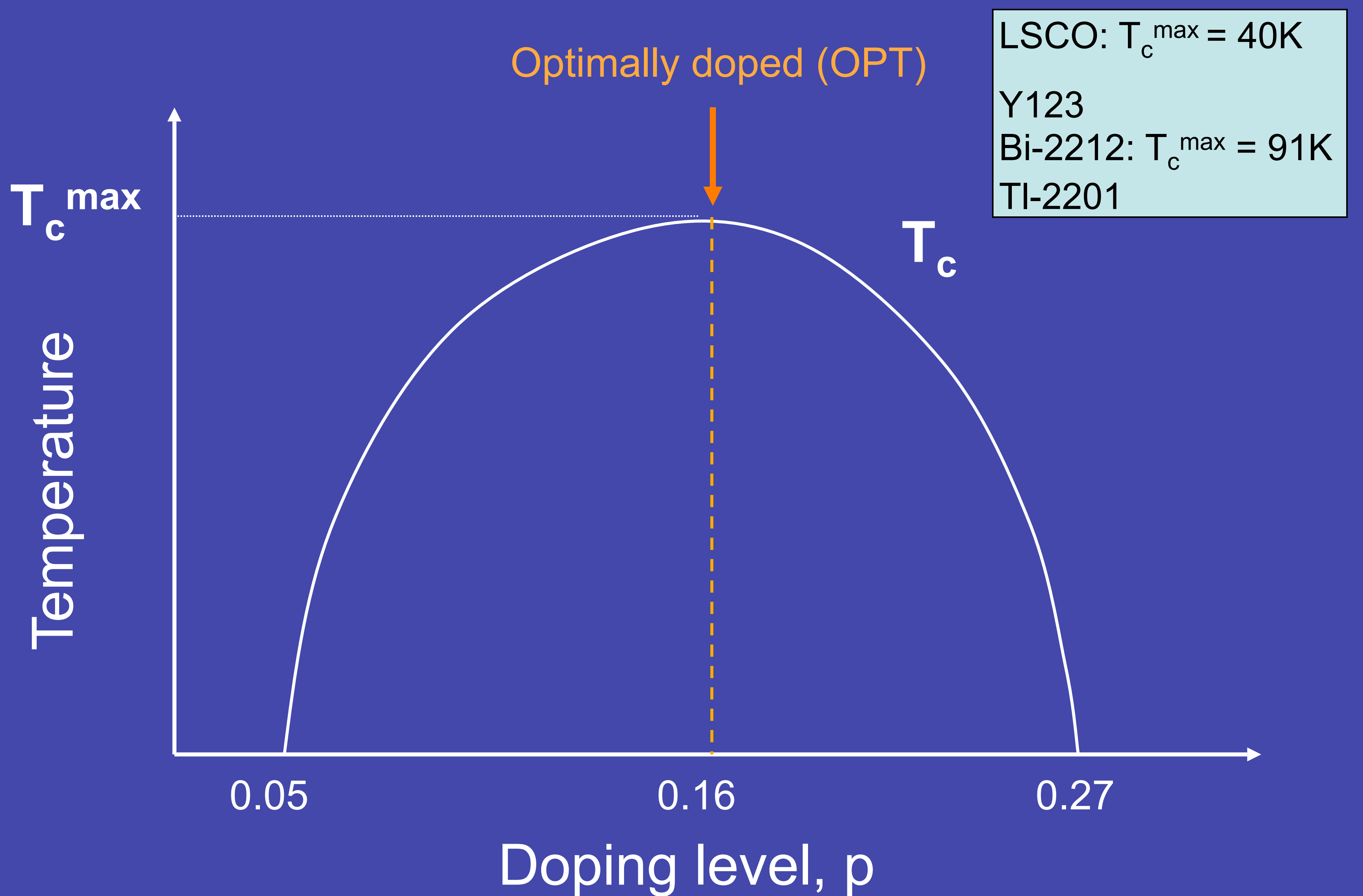
The superconducting dome

LSCO: T_c^{max} = 40K

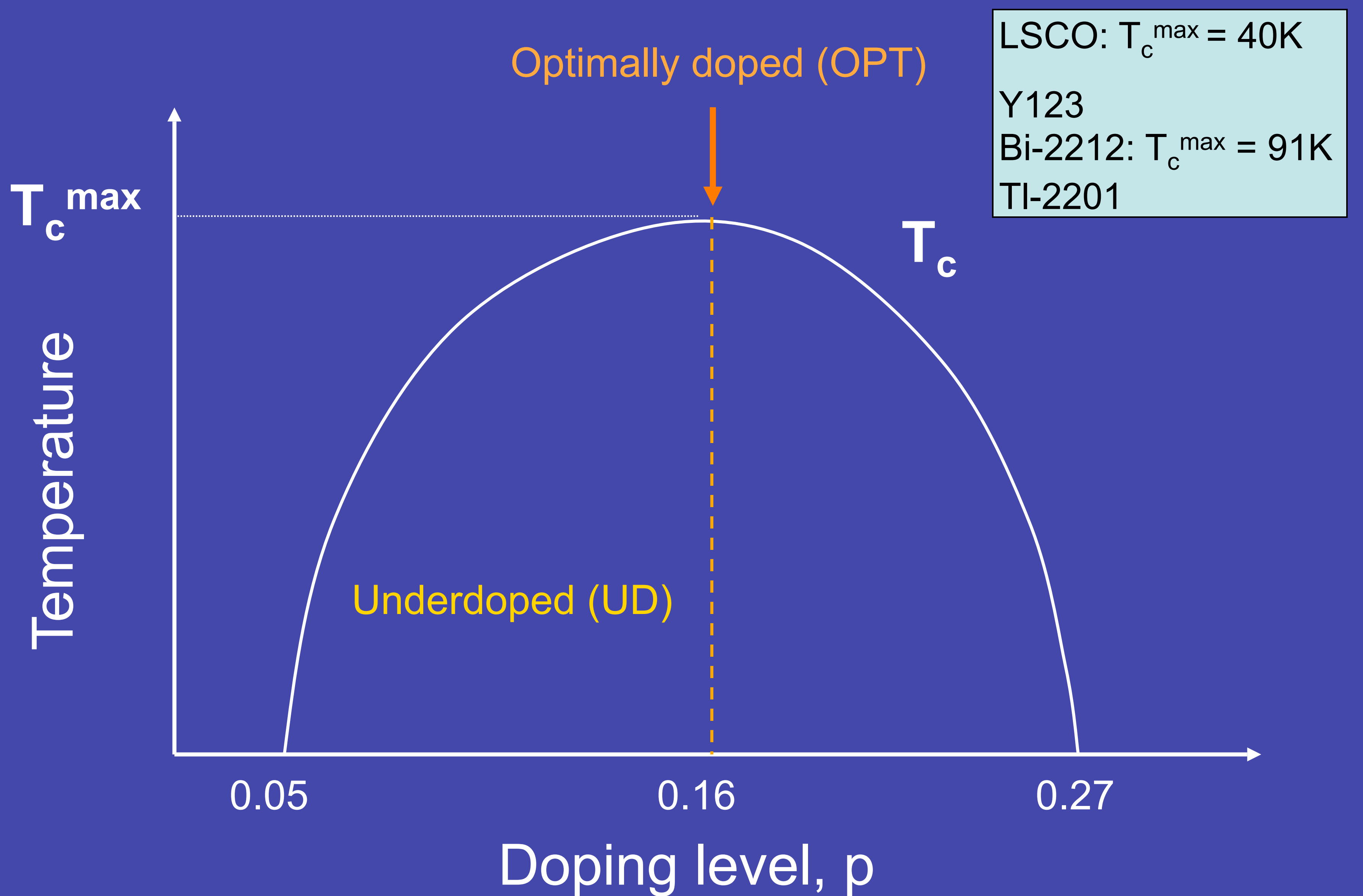
Y123
Bi-2212: T_c^{max} = 91K
Tl-2201



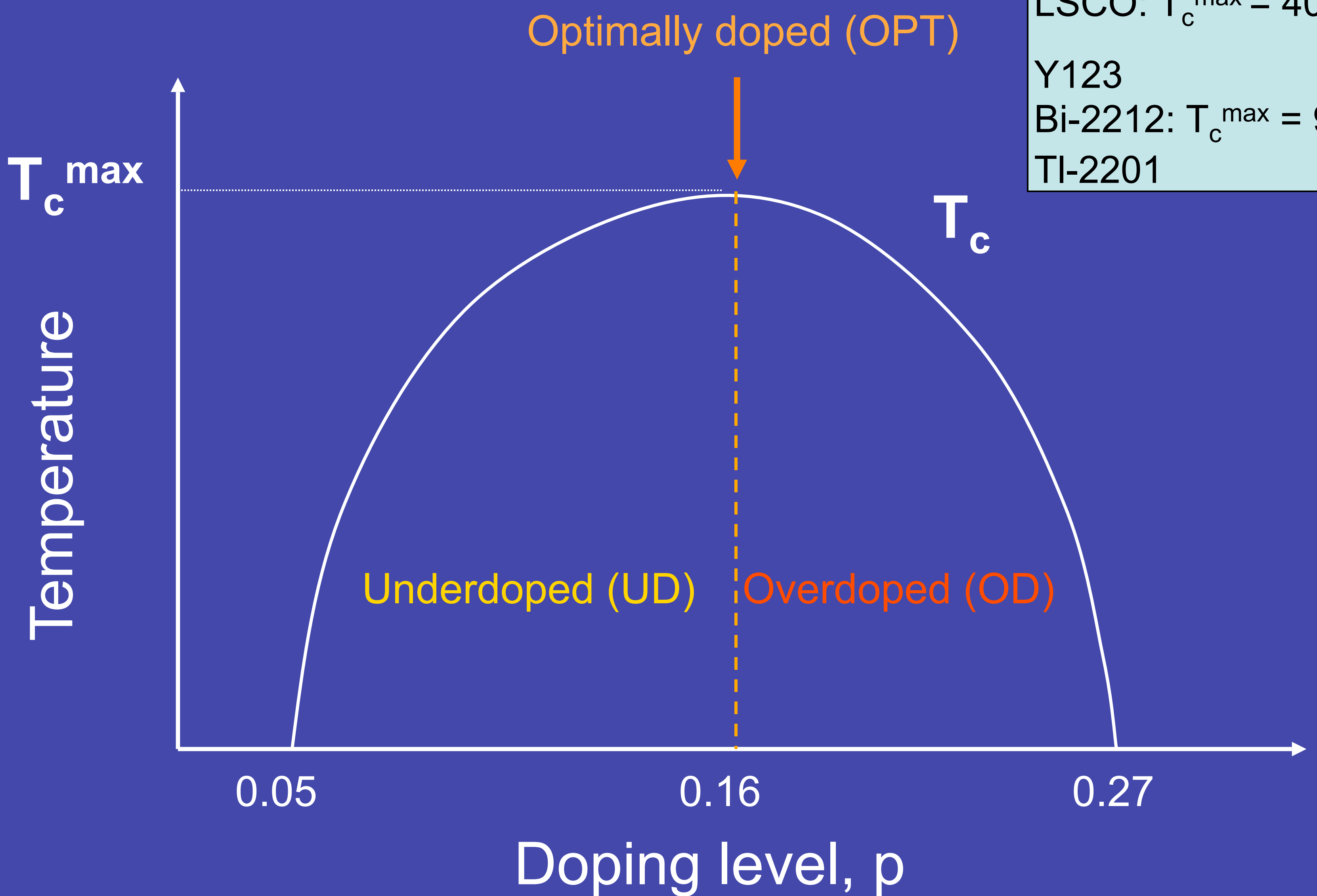
The superconducting dome



The superconducting dome



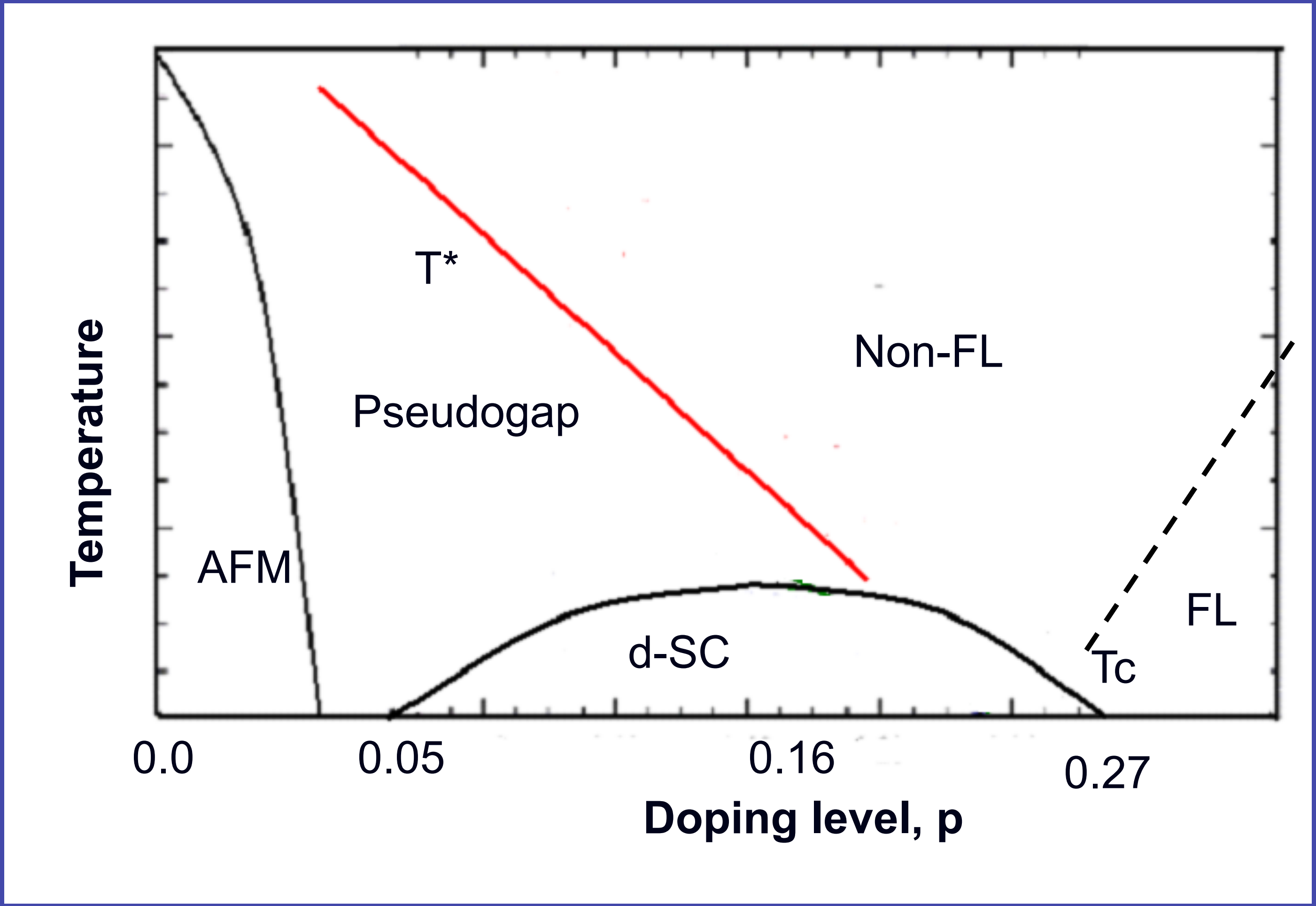
The superconducting dome



LSCO: T_c^{max} = 40K

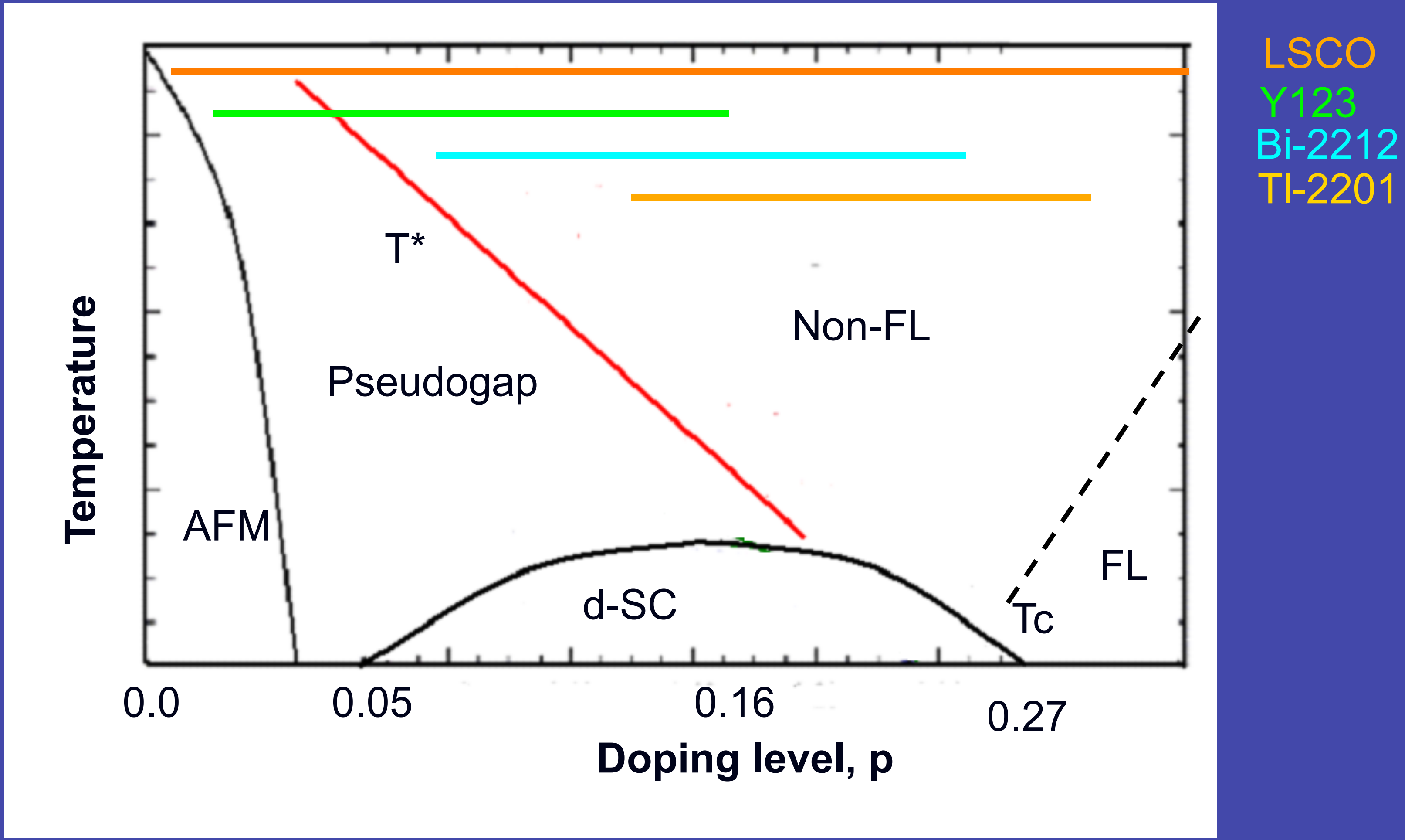
Y123
Bi-2212: T_c^{max} = 91K
Tl-2201

Phase diagram of the cuprates



Basov and Timusk, Rev. Mod. Phys **77**, 721 (2005)

Phase diagram of the cuprates

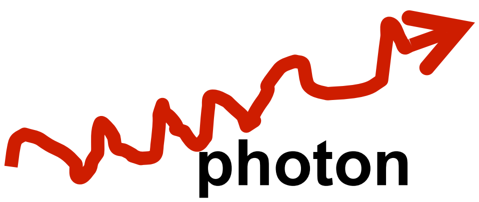


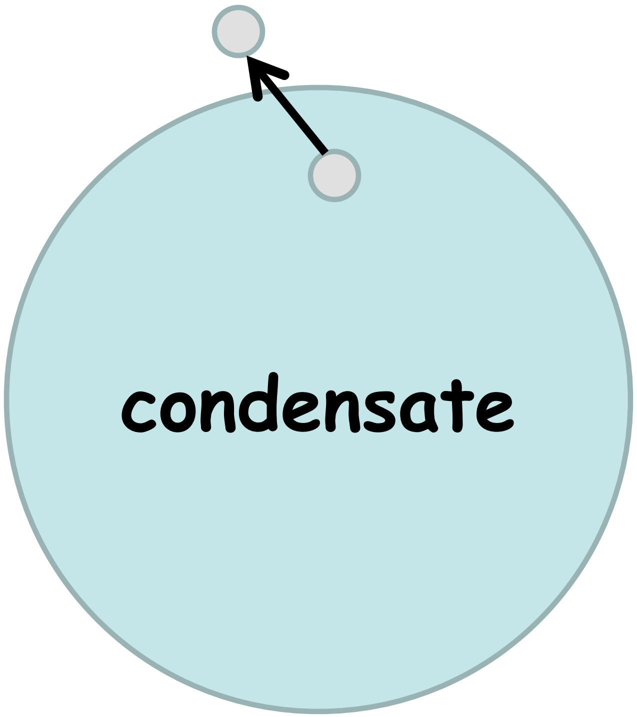
Basov and Timusk, Rev. Mod. Phys **77**, 721 (2005)

At zero temperature, no absorption till 2Δ, one Δ to pull an electron out of condensate and one more when it is placed back in. This process blocks states that can no longer be used to form condensate

Takes energy gap to pull an electron out of condensate or to put one in

Creates 2 excitations





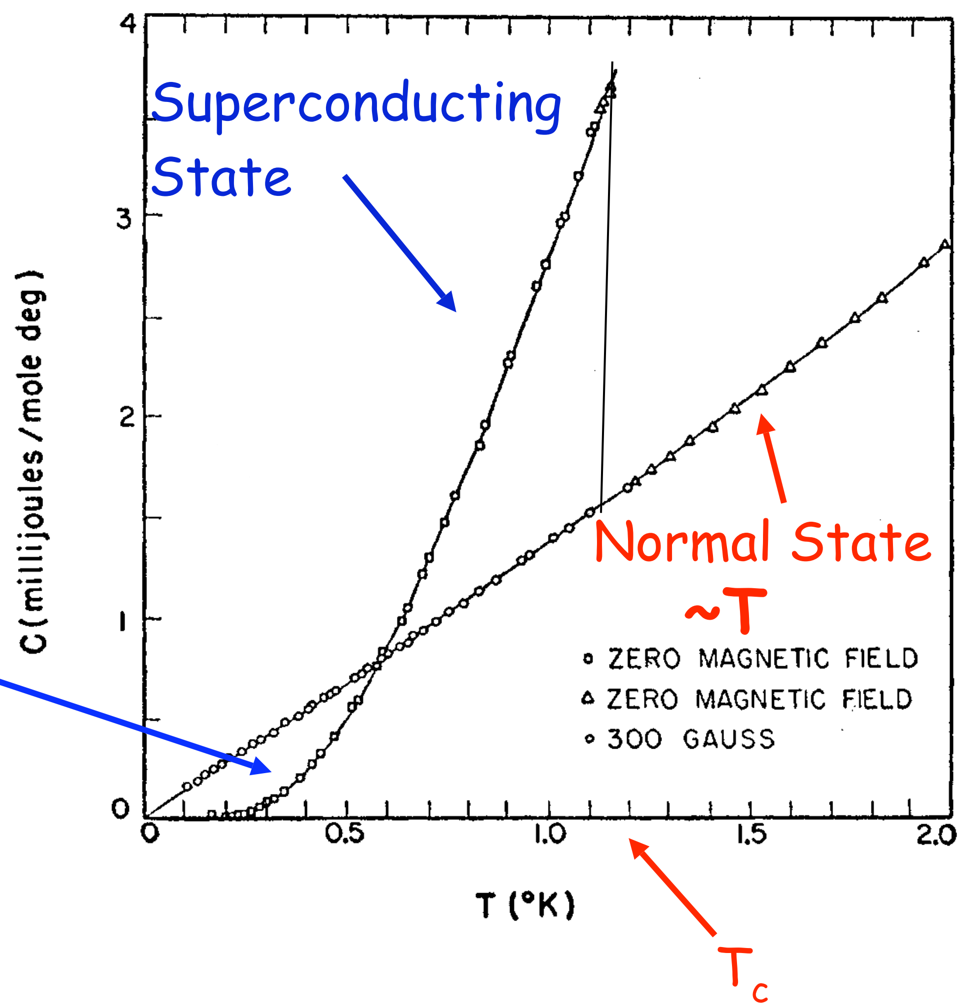
Macromolecule, all electrons bound together

Process requires twice gap

Classic BCS with s-wave gap

Specific Heat of Al

$$\Delta C(T) = -T \frac{d^2 \Delta F}{dT^2}$$



Note the exponential drop at low temperature and a jump at T_c

Second order phase transition

Phillips, Phys. Rev. **114**, 67 (1959)

Because of gap, takes energy delta Δ to release an electron from condensate and make an excitation [quasiparticle].

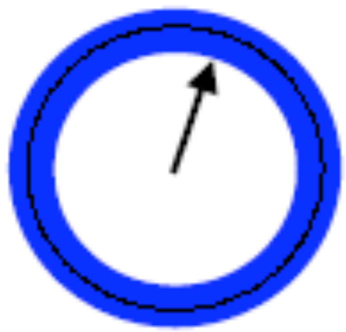
Specific heat is exponentially activated at low temperature.

$$C_S(T) \sim 2N(0)\Delta_0 k_B \sqrt{2\pi}\left(\frac{\Delta_0}{k_B T}\right)^{3/2} e^{-\Delta/k_B T}$$

Exponential activation

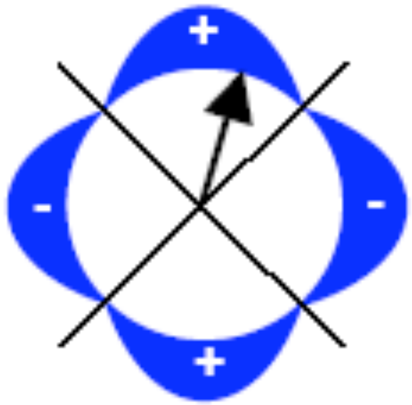
Note 1/T dependence, still exponential dominates at low T.

BCS (conventional) superconductors:



s-wave symmetry

Cuprate HTSC superconductors:



d-wave symmetry

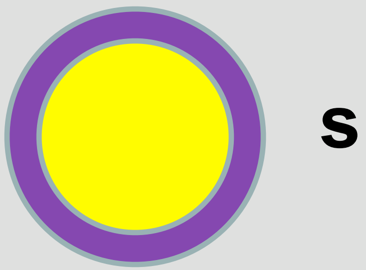
Kirill Samokhin,Brock University

Density of electronic states in s- and d-wave superconductor

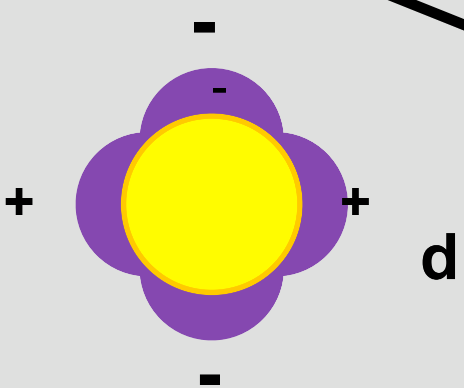
$$N(\omega) = \Re\mathrm{e}\left\{\frac{\omega}{\sqrt{\omega^2 - \Delta_0^2}}\right\}$$

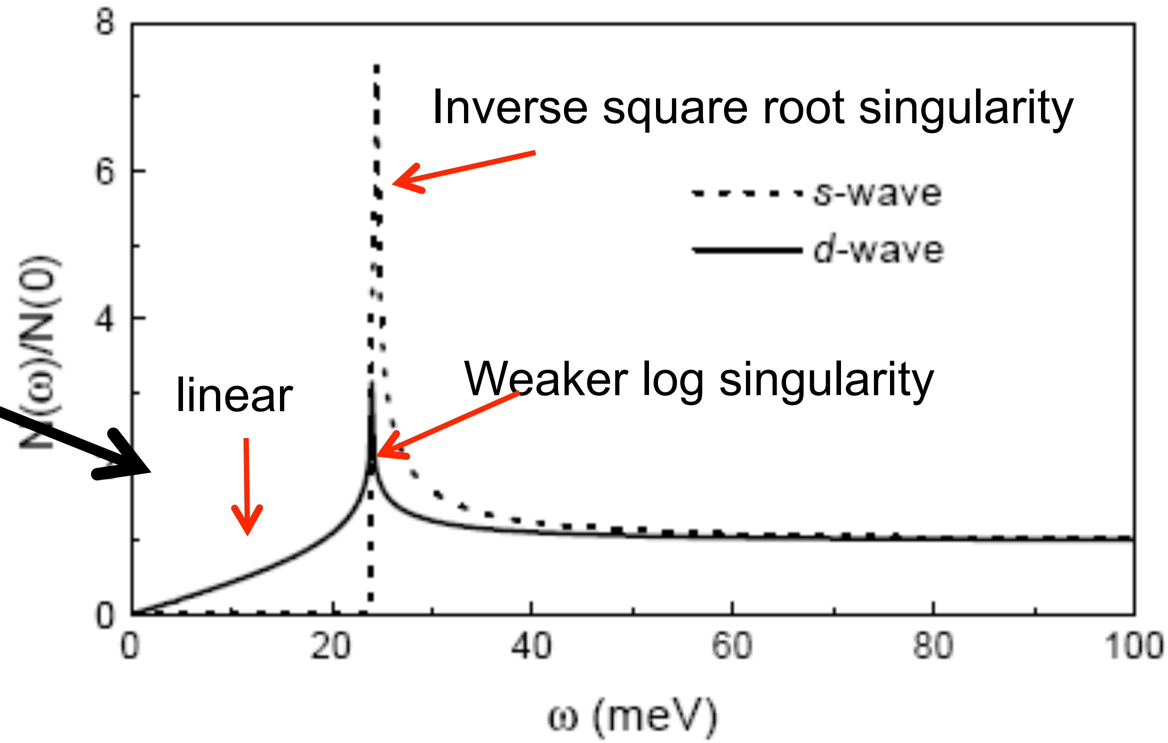
In d-wave distribution of gaps from 0 to maximum gap

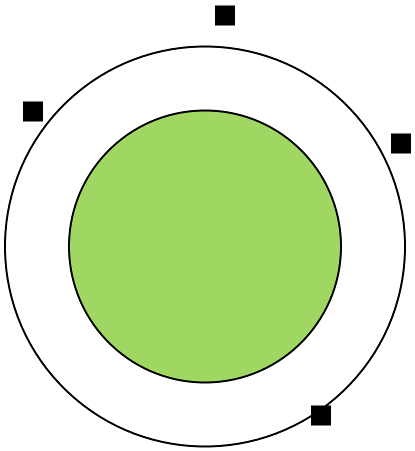
$\cos[2\theta]$



Just depression ,no real gap

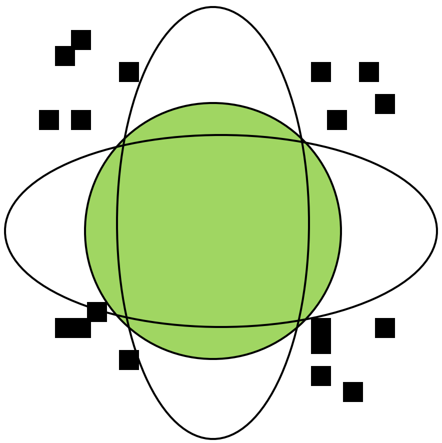






S-wave few excited electrons

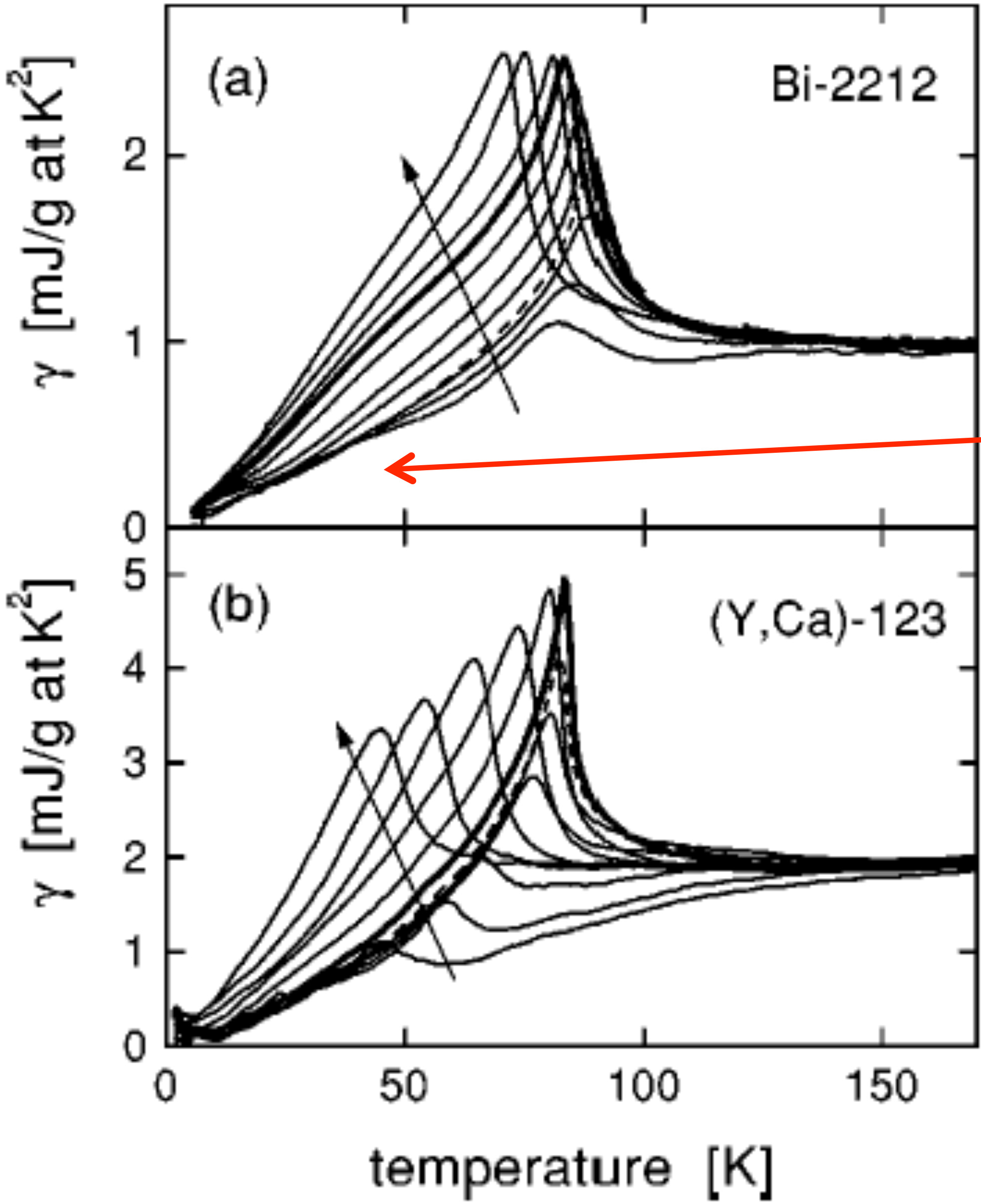
Temperature creates excitations out of ground state



D-wave more excited electrons only around nodes

Specific heat for many dopings

Increasing doping



0.13 to 0.21

Linear in T

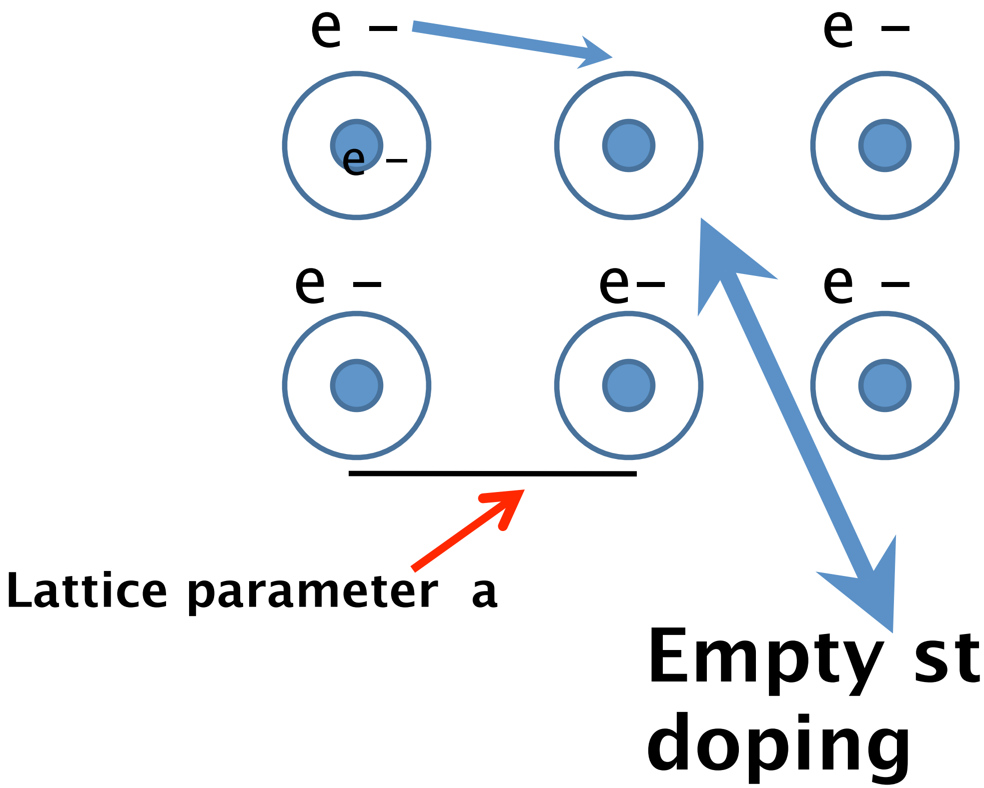
0.08 to 0.23

Specific heat
gamma
Is C{T}/T

Loram et. al. PRB 69 ,060502 [2004]

Cuprates are near half filling for the CuO2 Brillouin Zone
In band theory this would be a metal
Because of MOTT physics its an insulator at half filling

Mott physics

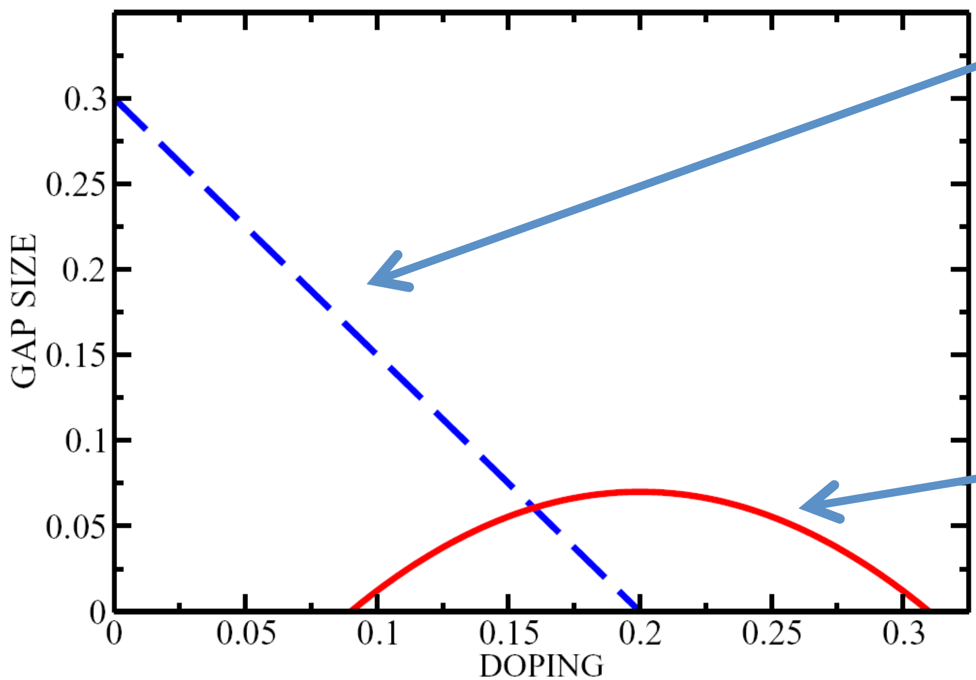


Hopping to empty site is ok
Hopping to filled site is energetically not favorable because of Hubbard U
big on site repulsion
NO double occupancy

Use the model of **Yang, Rice and Zhang**

[YRZ] PRB73 ,174501 [2006] based on RVB resonating valence bond,

spin liquid, has a quantum critical point [QCP]
at doping x=0.2 where a pseudogap develops in the electror
structu ched



Pseudo gap

Superconducting gap

Illes et.al. PRB 79 ,100505 [2009]

Pseudo gap modifies electronic structure
Fermi surface reconstruction

Use the model of **Yang, Rice and Zhang**

[YRZ] PRB73 ,174501 [2006] based on RVB resonating valence bond,

spin liquid, has a quantum critical point [QCP]

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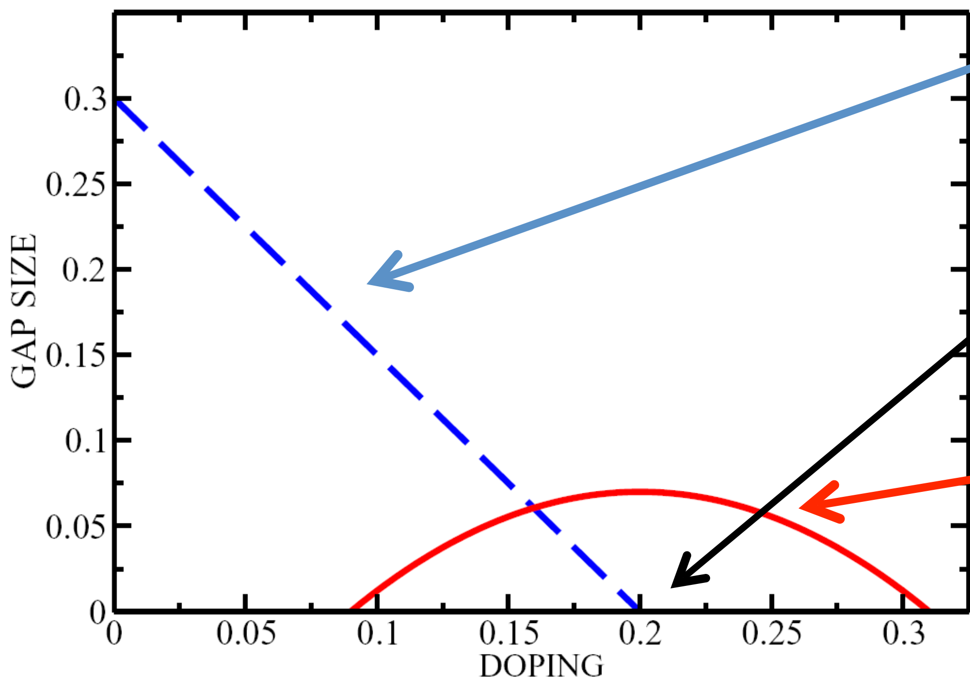

Pseudo gap

QCP x=0.2

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Illes et.al. PRB 79 ,100505 [2009]

Pseudo gap modifies electronic structure

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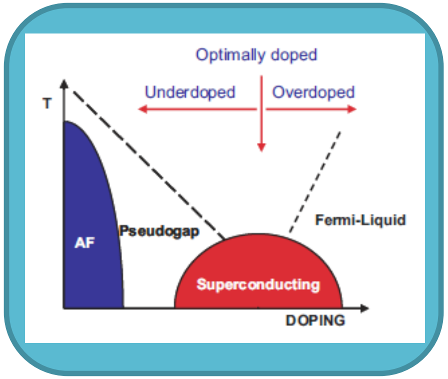
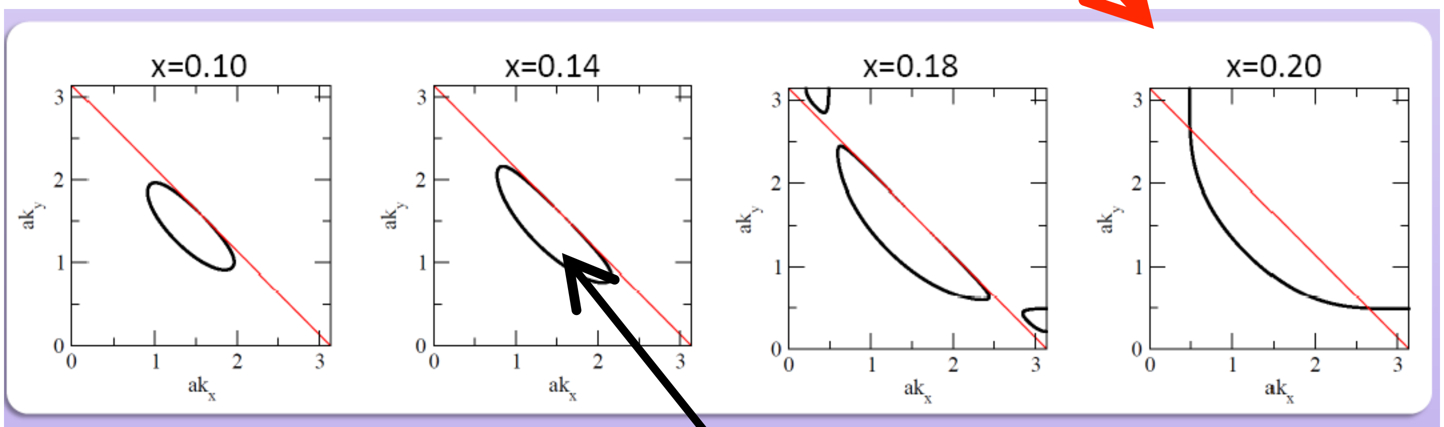


Usual large Fermi surface of Fermi liquid theory for tight binding bands near half filling

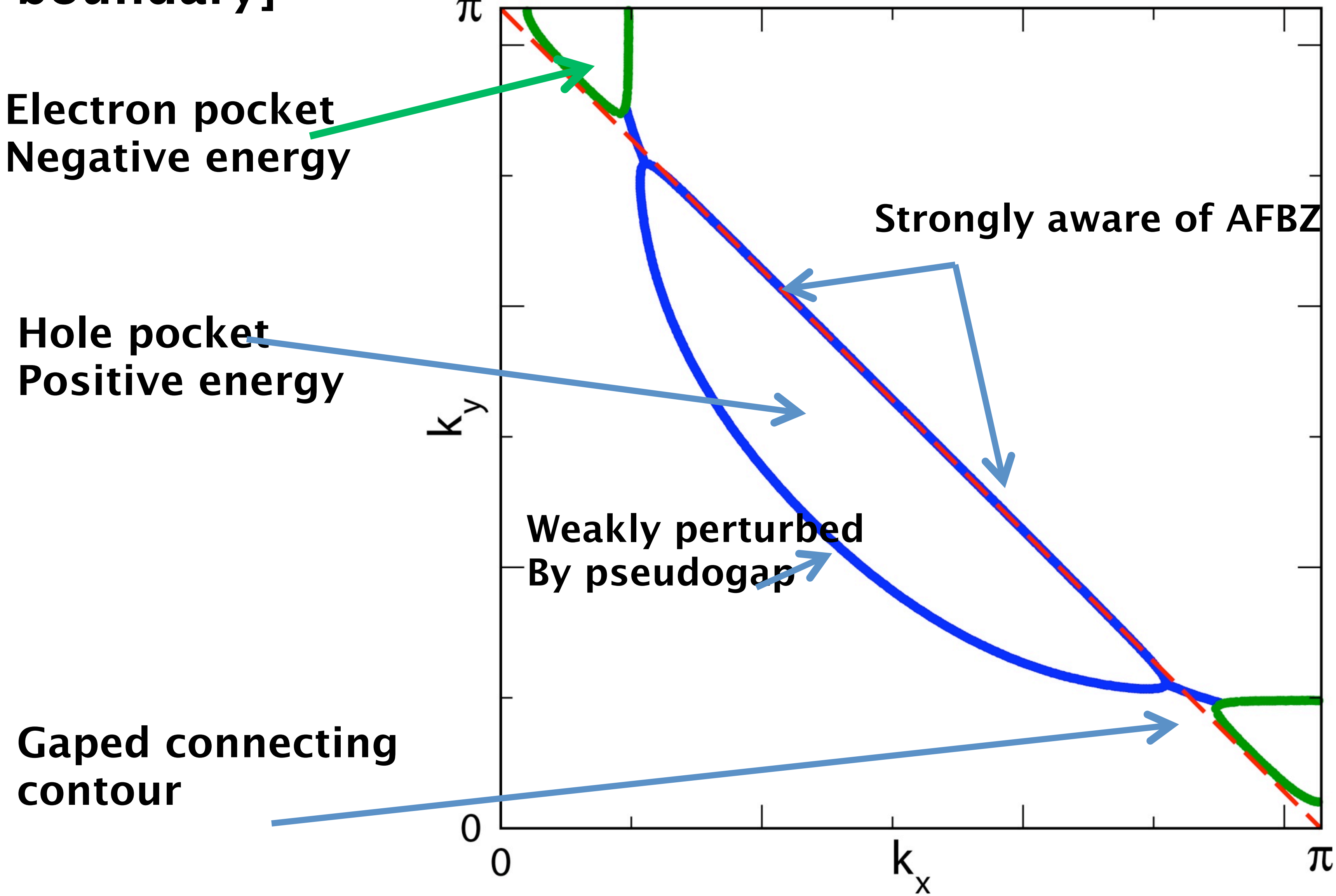
Top right corner of Two-D Cu-O2 B.Z.



Reconstructed Fermi surface due to pseudogap and approach to Mott Insulator ; metallicity is reduced

Luttinger hole pocket,small fermi surface
front is weighted order 1, back little weight
Fewer zro energy excitations

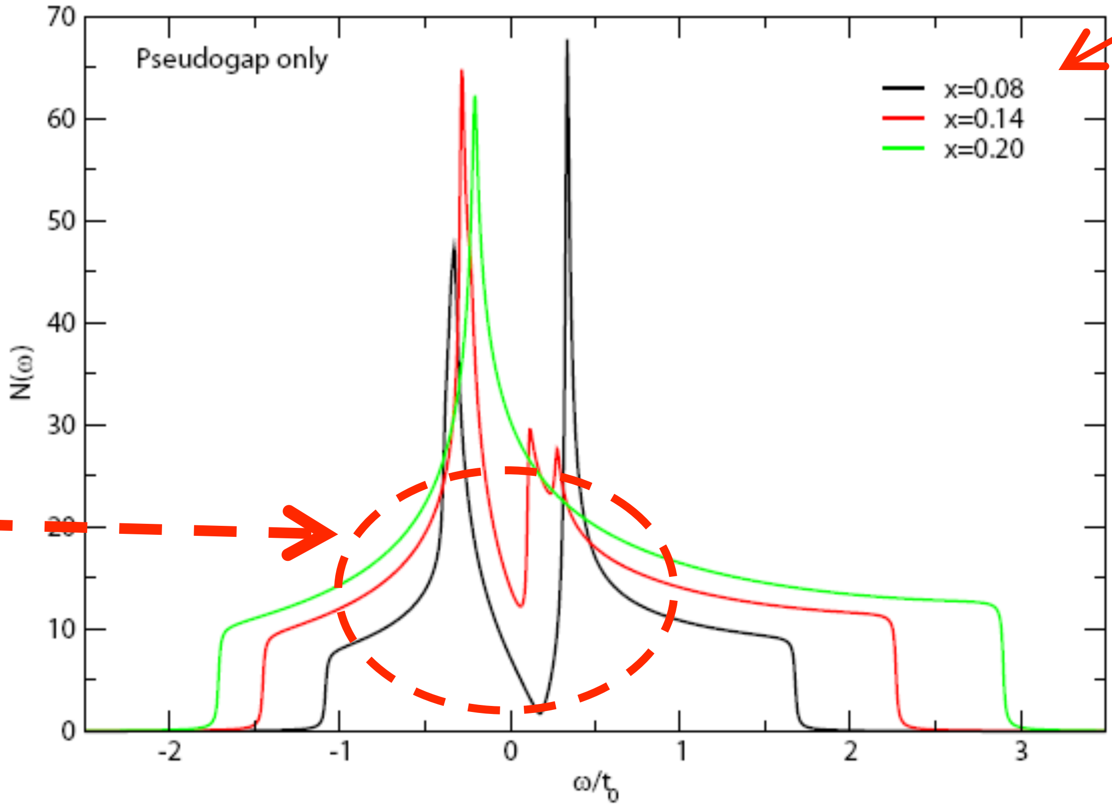
For x=0.19 can have holes and electron pockets [near B Z boundary]



Second energy scale associated with Mott transition to ins

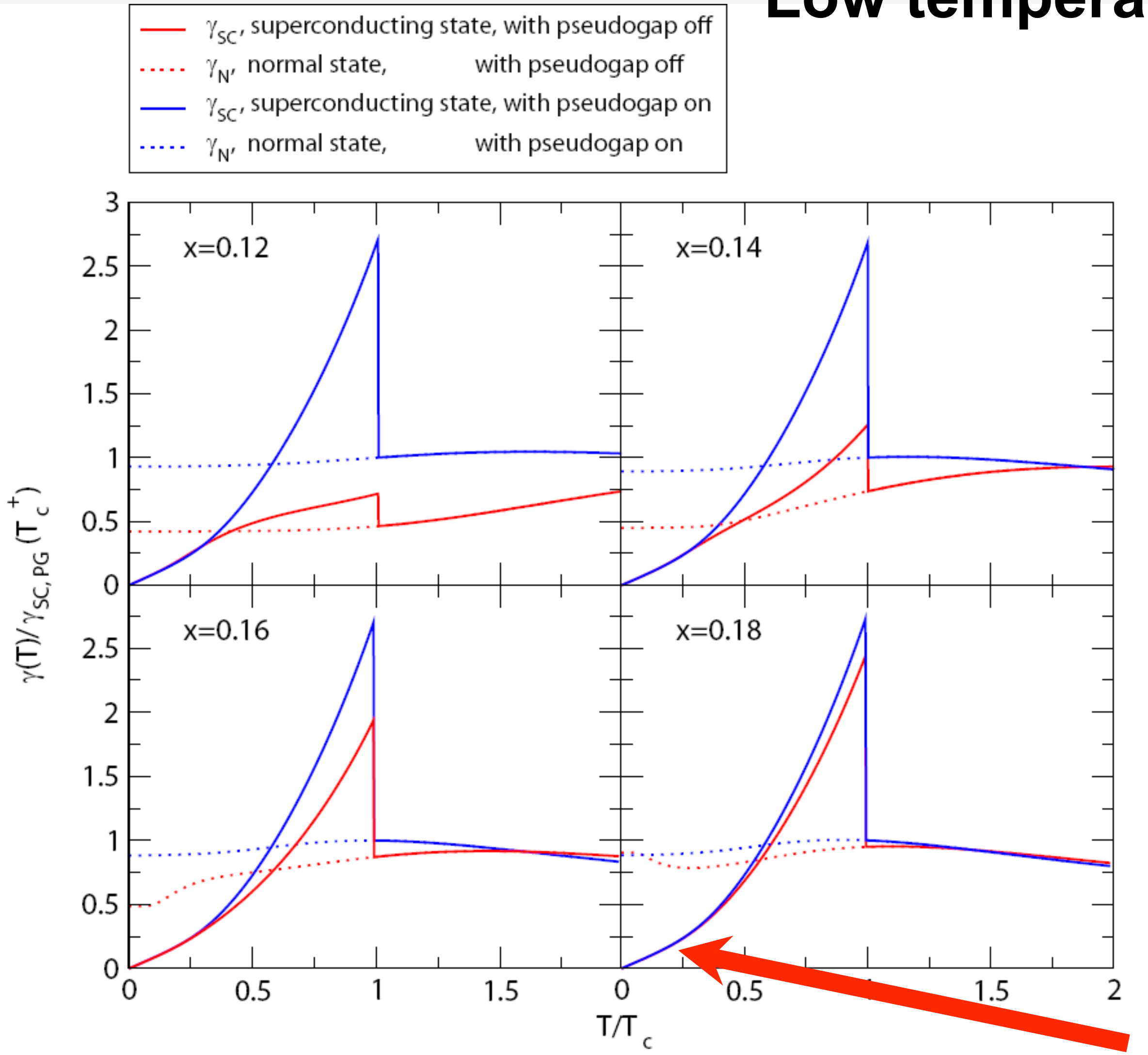
Density of states N[w]

doping

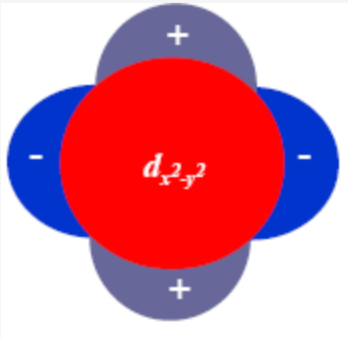


Look here,new Energy scale

Pseudogap does not change Low temperature law or its slope



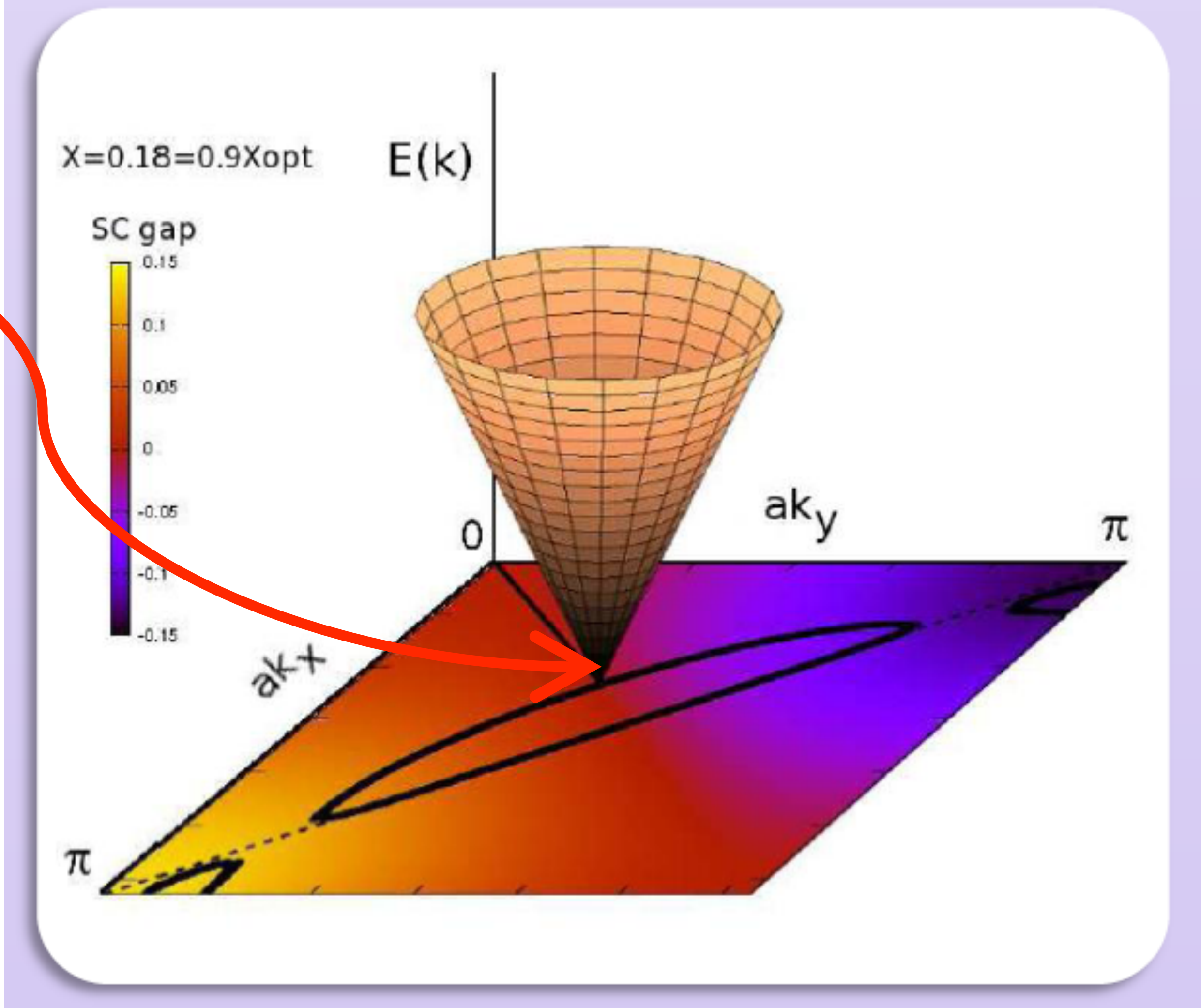
Gama is specific heat over temperature



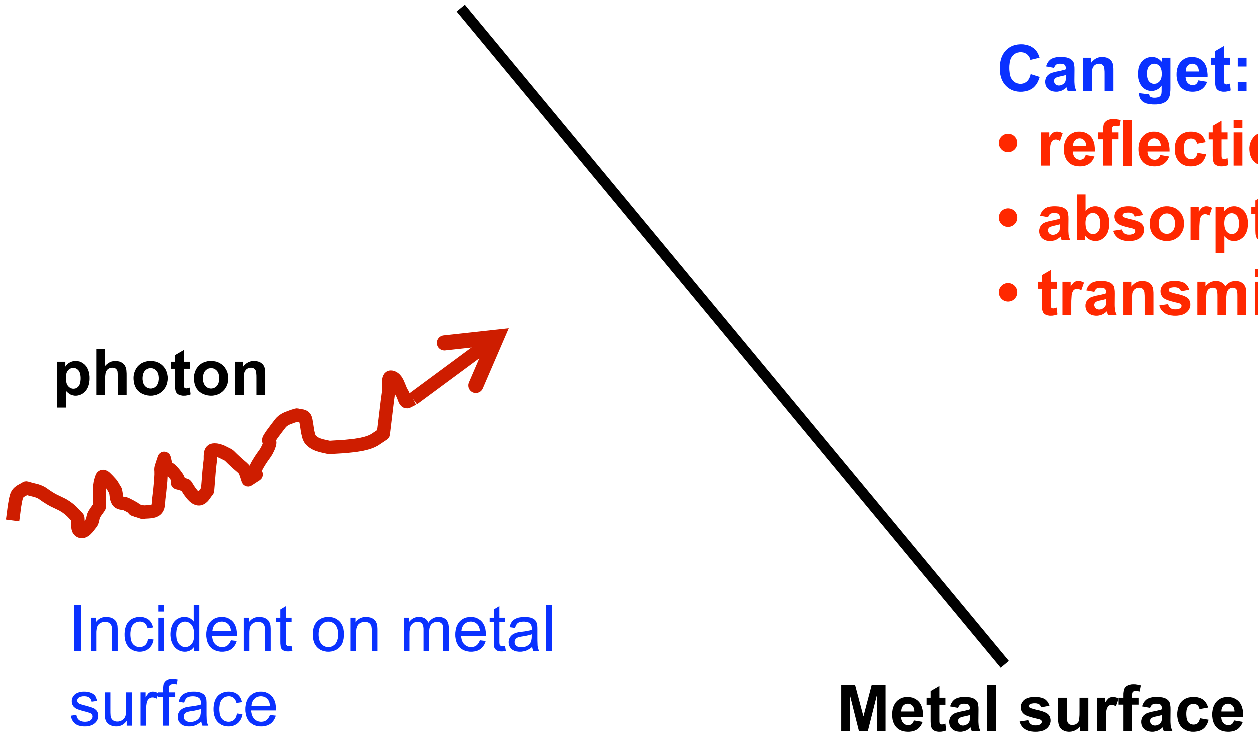
Linear ,NO change

Of course ,the gutzwiller coherence factor will come in additionally

***Dirac* point is only active spot at low temperature**



Optical Properties in BCS



Can get:

- **reflection**
- **absorption**
- **transmission**

In conventional superconductors, tunneling has been method of choice to get information on gap and phonons

Optics has been hard, good metals reflectance near 1

In poor metals such as oxides, optics has been great!

Reflectance is an experimentally measured quantity

From it can get optical the conductivity as a function of energy

Has real and imaginary part

Real part is absorptive part

Interested in conductivity in energy range of gap and phonon energies: far infrared

DRUDE model

No damping term
no absorption

electron charge

electron mass

$$m\frac{d\mathbf{v}}{dt} = e\mathbf{E} - \frac{m}{\tau}\mathbf{v}$$

velocity

elastic scattering time

$$\mathbf{J} = ne\mathbf{v}$$

$$\mathbf{E} = \mathbf{E}_0 \exp[-i\omega t]$$

electric field

$$\mathbf{J}(\omega) = \sigma(\omega)\mathbf{E}(\omega)$$

n: electron density

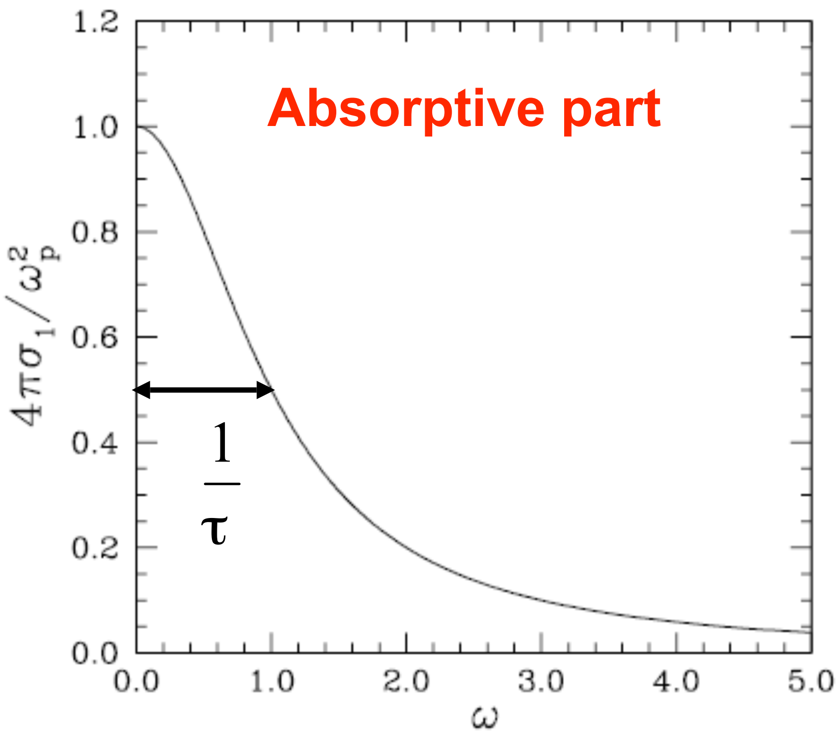
$$\sigma(\omega) = \frac{\sigma_0}{1 - i\omega\tau}$$

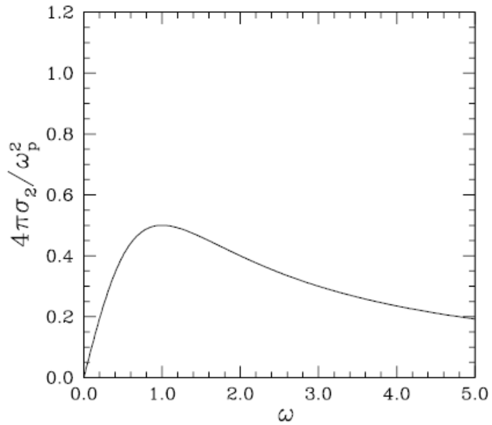
Drude Conductivity

DC value

$$\sigma_0 = ne^2\tau / m$$

Real [left] and imaginary [right] part of DRUDE conductivity





Width at half maximum is optical scattering rate **$1/\tau$** – here it is 1.0

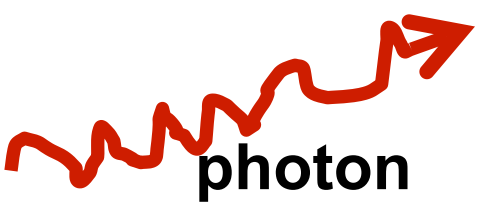
Plasma frequency ω_p

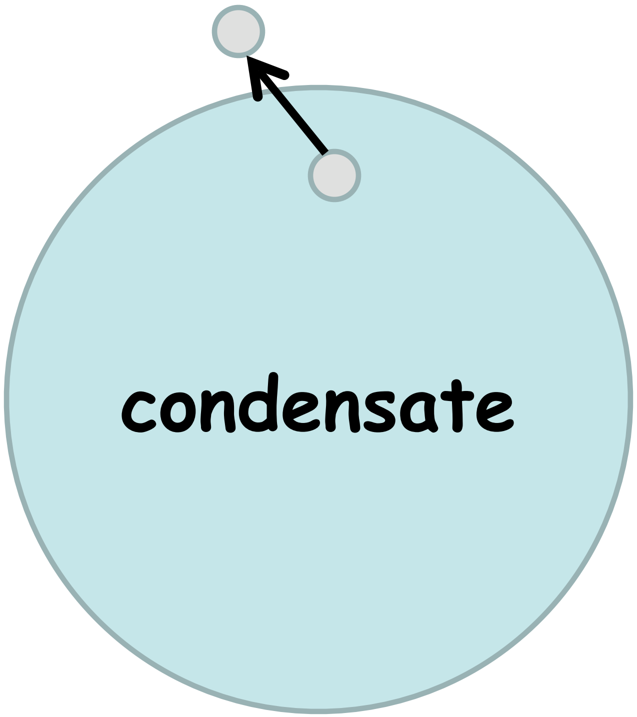
$$\frac{\omega_p^2}{4\pi} \equiv \frac{ne^2}{m}$$

$$\sigma_0 = ne^2\tau/m$$

At zero temperature, need one Δ to pull an electron out of condensate and one more to place it back in.
This process blocks states that can no longer be used to form condensate

Takes energy gap to pull an electron out of condensate or to put one in





Macromolecule, all electrons bound together

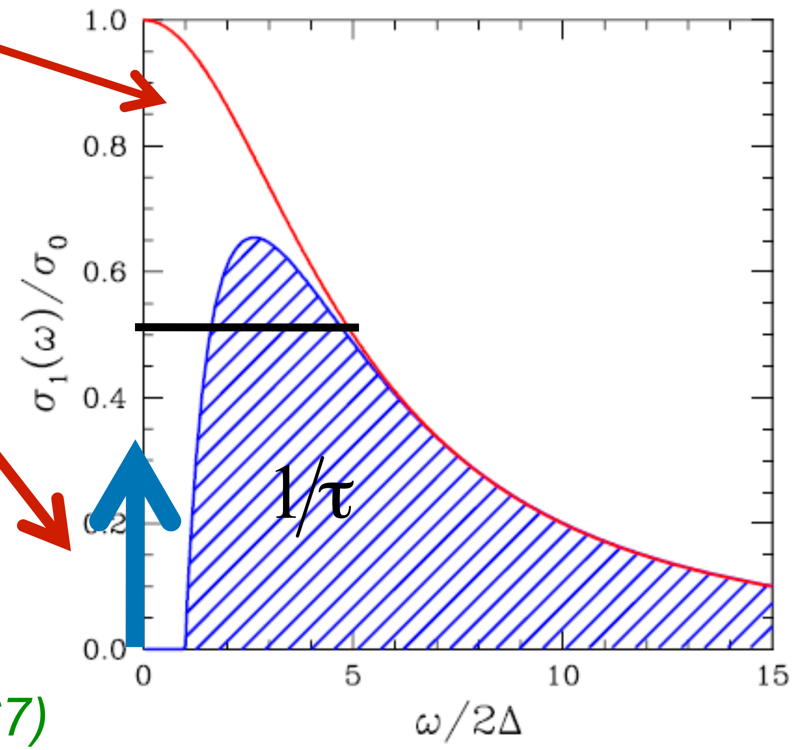
Real part of conductivity s-wave superconductor

Missing area goes into a delta function at origin

Optical spectral weight conserved

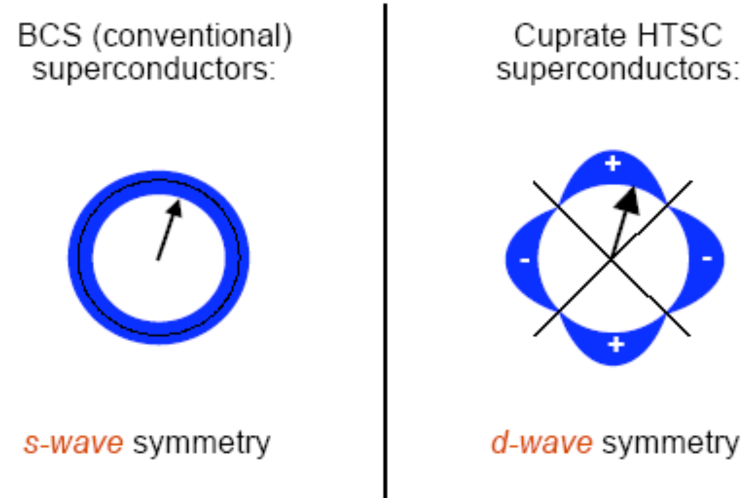
$1/\tau >> \Delta$

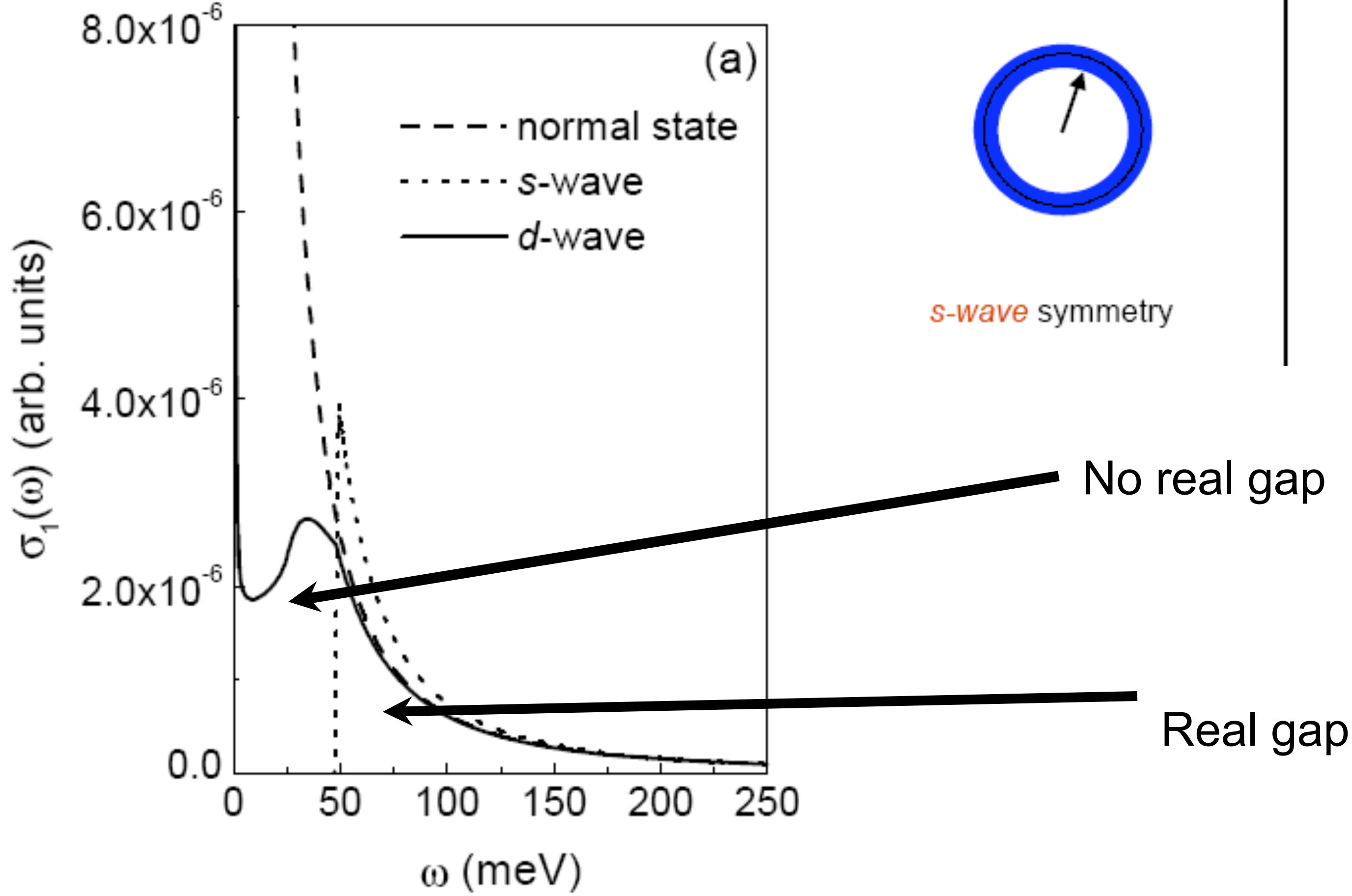
Fairly dirty case



Nam, Phys. Rev. ***156****, 487 (1967)*

Comparison of real part of conductivity in s- and d-wave BCS at zero temp.





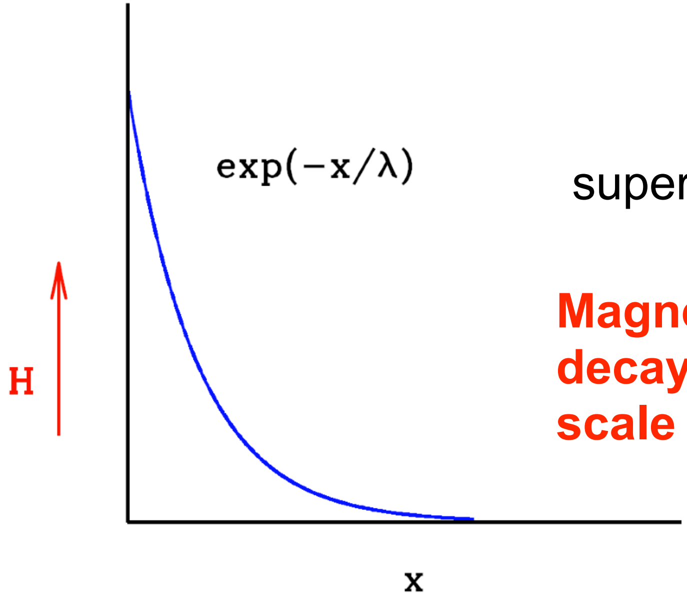
E. Schachinger and J.P. Carbotte, Models in Methods of High-Tc Superconductivity, Vol 2, Edited by J K Srivastava and S M Rao, pp73-169

Optical conductivity has real and imaginary part
Real part is absorptive part

In superconducting state, imaginary part is related to the penetration depth

$$\frac{1}{\lambda^2(T)} = \lim_{\omega \to 0} \frac{4\pi}{c^2}\omega\sigma_2(\omega) \qquad \lambda_L^{-2}(T) \cong \left(4\pi n_s(T)e^2 / mc^2\right)$$

Free space



superconductor

Magnetic field decays on length scale of penetration depth

Low temperature behaviour of superfluid density in s- and d-wave

s-wave is exponentially activated

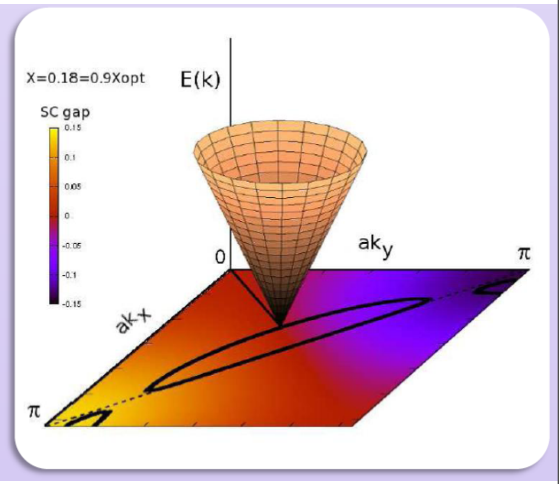
d-wave is linear in temperature

s-wave

$$\frac{1}{\lambda^2(T)} = \frac{4\pi n e^2}{mc^2}\left[1 - \sqrt{\frac{2\pi\Delta_0}{k_B T_c}}\, e^{-\frac{\Delta_0}{k_B T}}\right]$$

$$\frac{1}{\lambda^2(T)} = \frac{4\pi n e^2}{mc^2}\left[1 - \frac{2\ln(2)}{\Delta_0} k_B T\right]$$

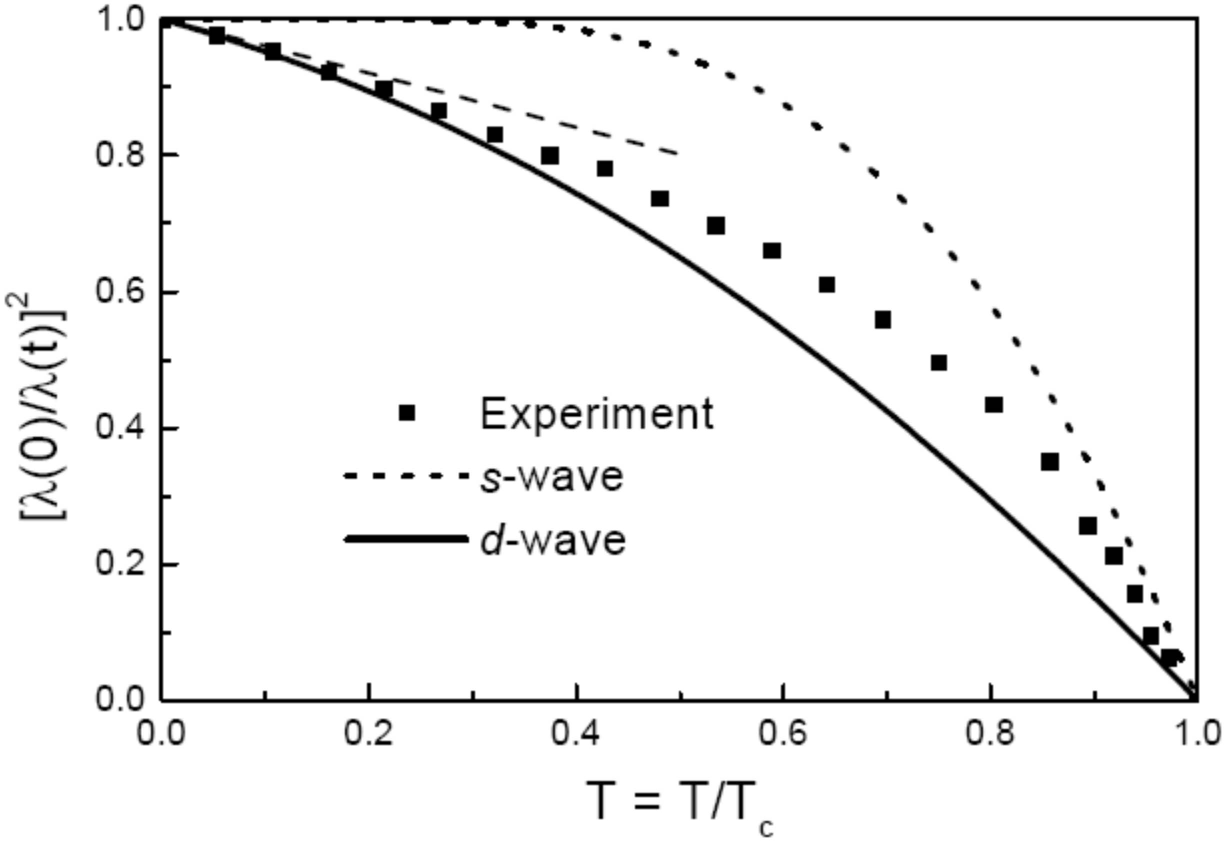
d-wave



Inverse square of London penetration depth is proportional to superfluid density

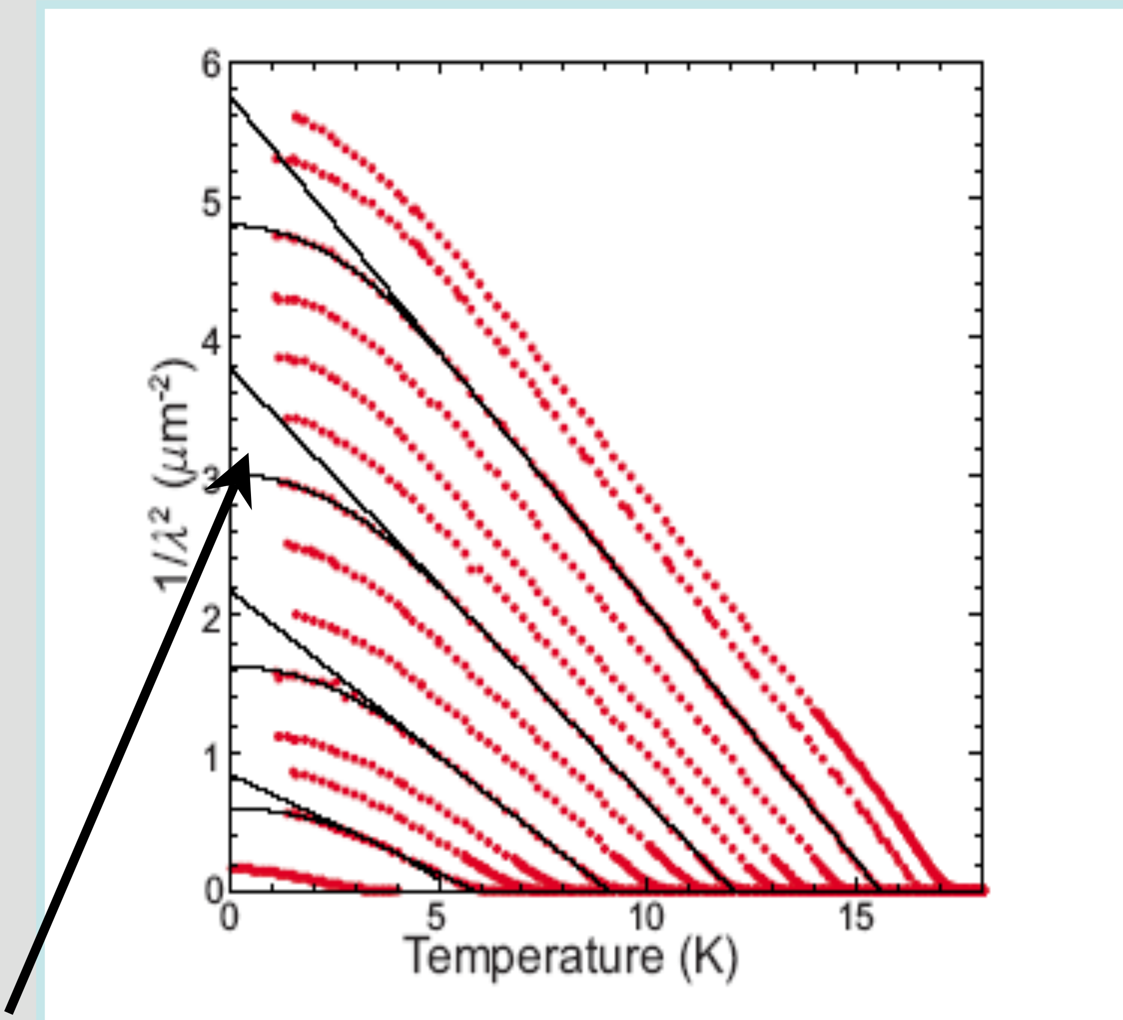
Comparison of London penetration depth for s- and d-wave symmetry in BCS

Penetration depth is distance an external magnetic field can penetrate into a superconductor [screening supercurrents are set up]



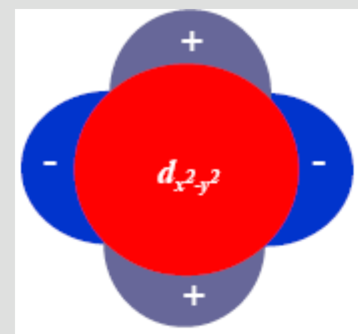
*Experimental data in YBCO: D. A. Bonn et al, PRB **50**, 4051 (1994)*

Highly underdoped orthoII YBCO



Pure d-wave
linear in T
at low temp

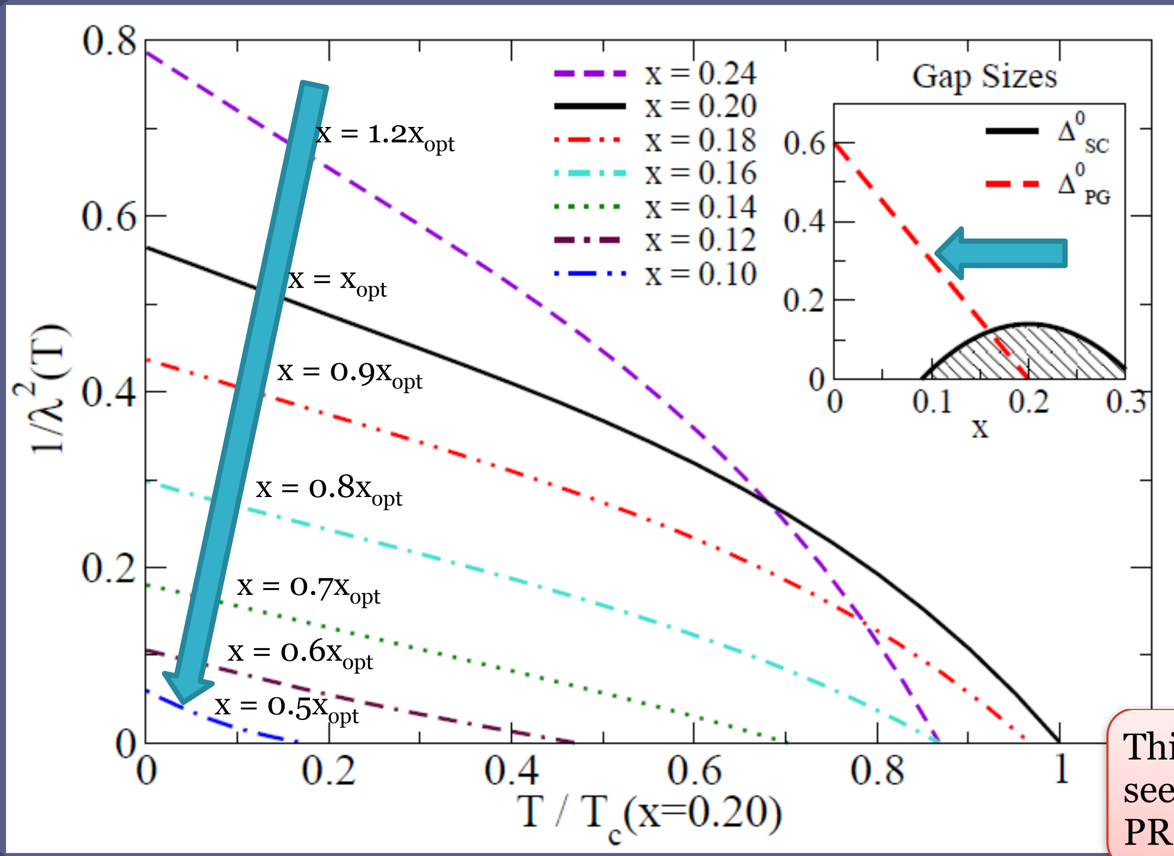
Dirty d-wave
Crossover to
T2**
due to scattering



Crossover from linear to quadratic

Huttema et.al. PRB 80,104509 [2009]

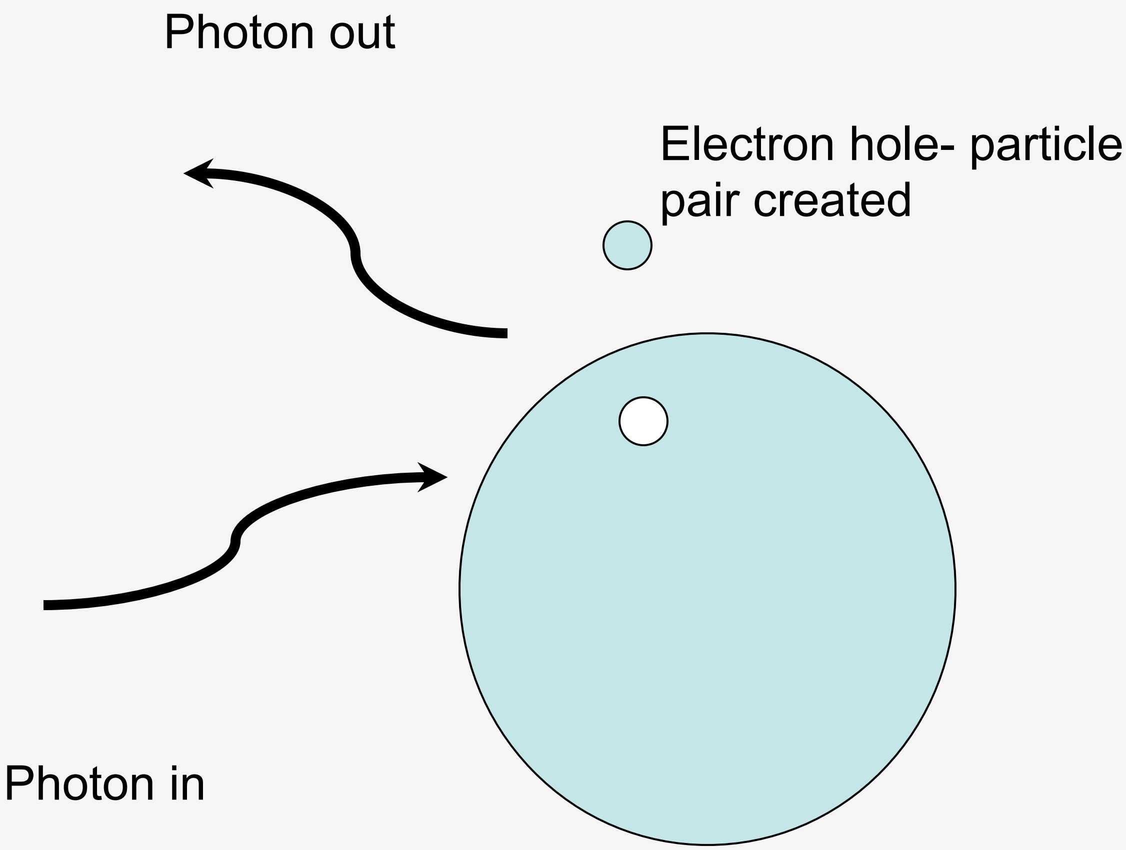
$1/\lambda^2(T)$ For Various Dopings

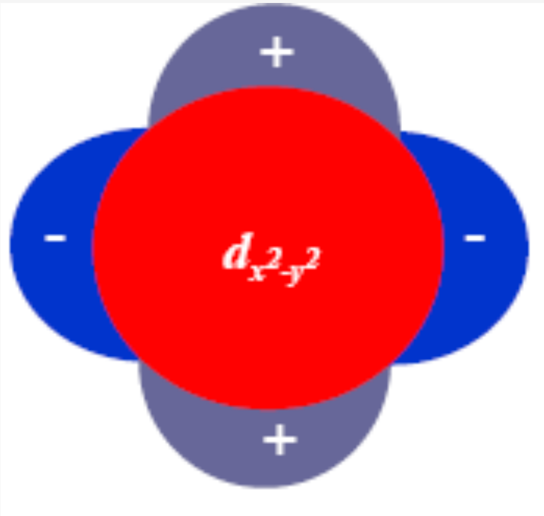


This trend is seen in experiment see Anukool et al. (Cambridge) PRB **80**, 024516 (2009)

Fisher et.al. G-McM-group

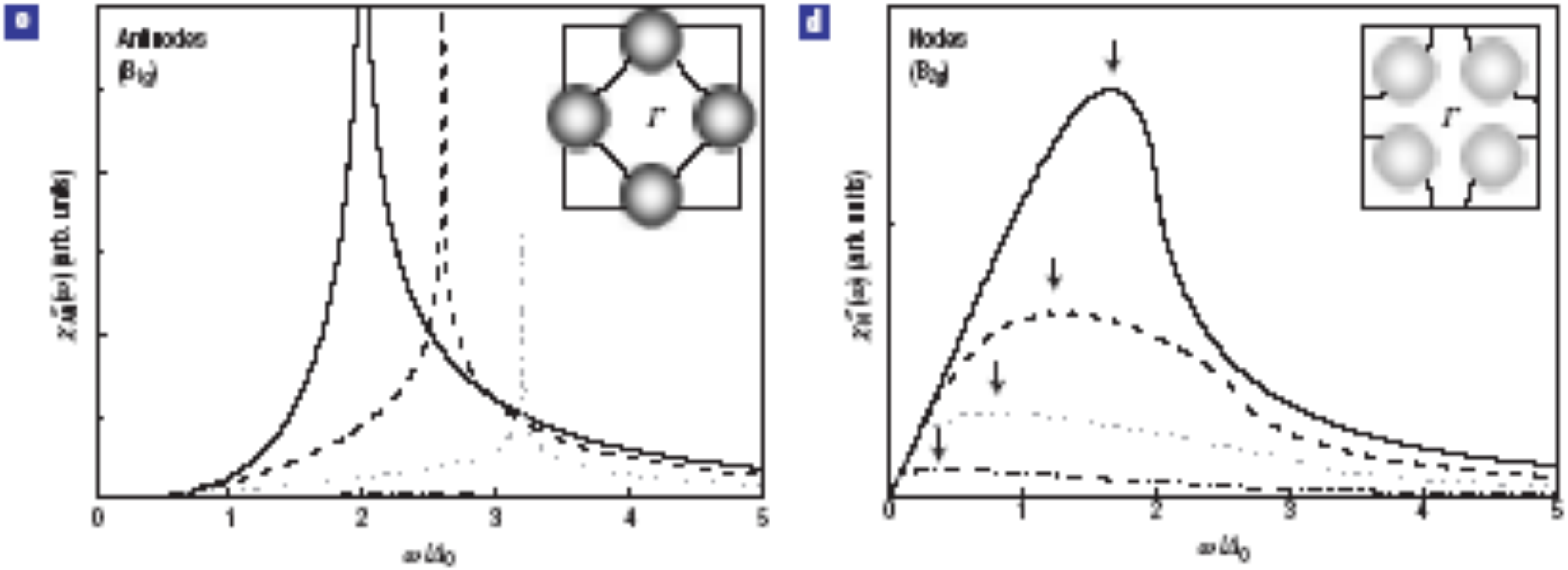
Raman in d-wave superconductor





Depends on polarization of the light , nodal, antinodal are different

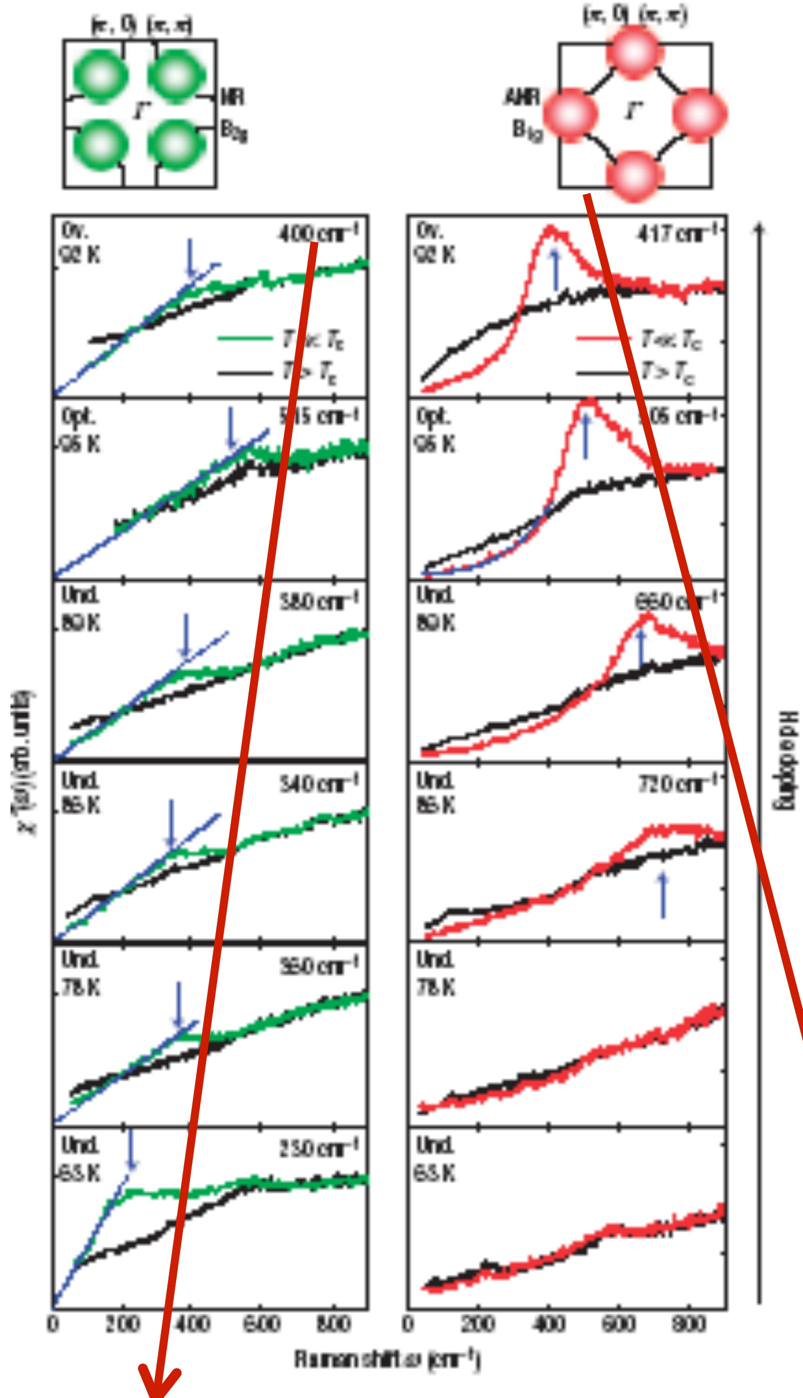
Raman scattering



Different polarization of light ,have different sampling factors [images different parts of k-space]

B1g samples most antinodal and B2g nodal direction

Le Tacon el.al. Nature Physics 2 ,537[2006]

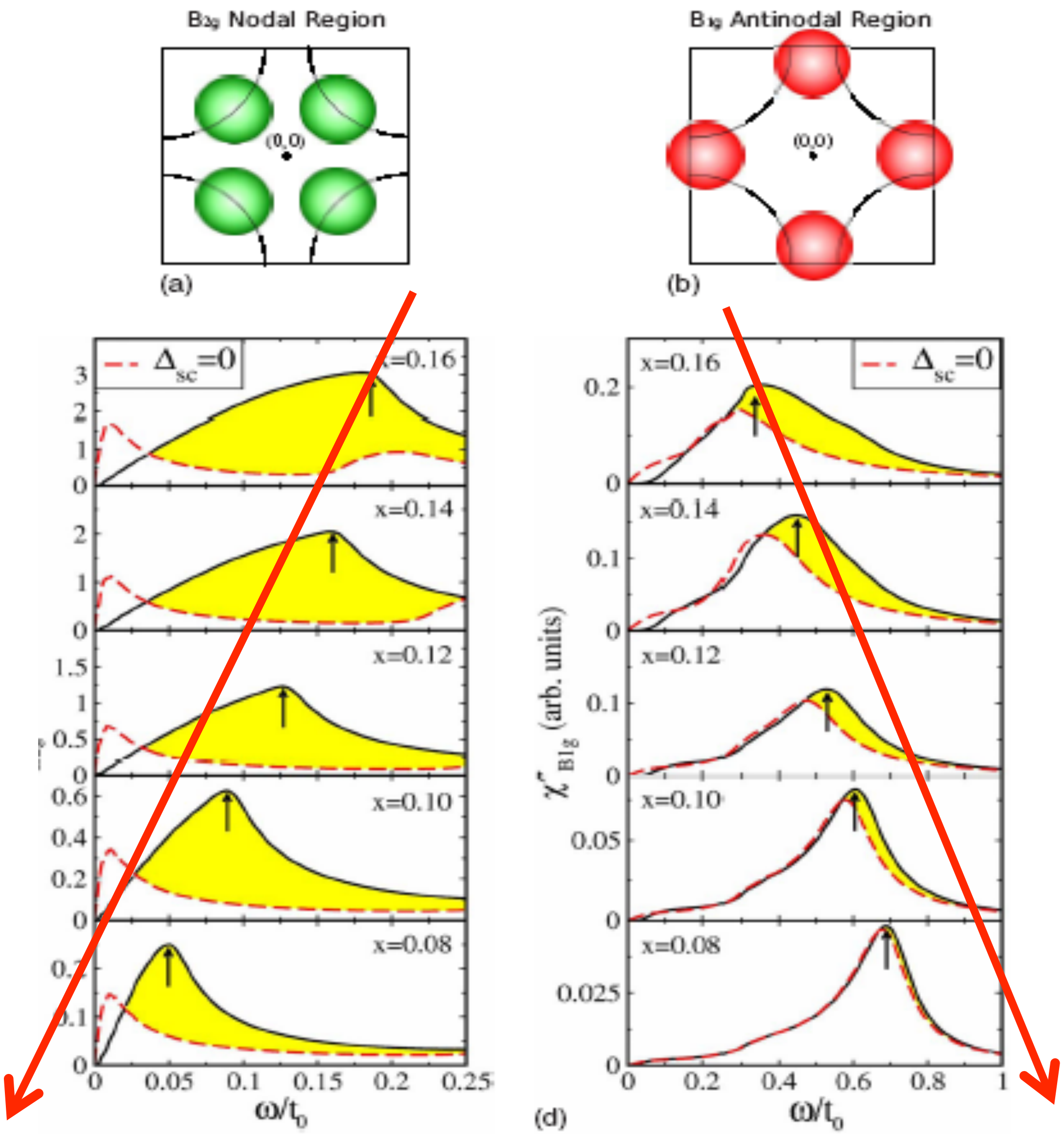


Peak energy scale down

Peak energy scale up

Less doping ,more MOTT

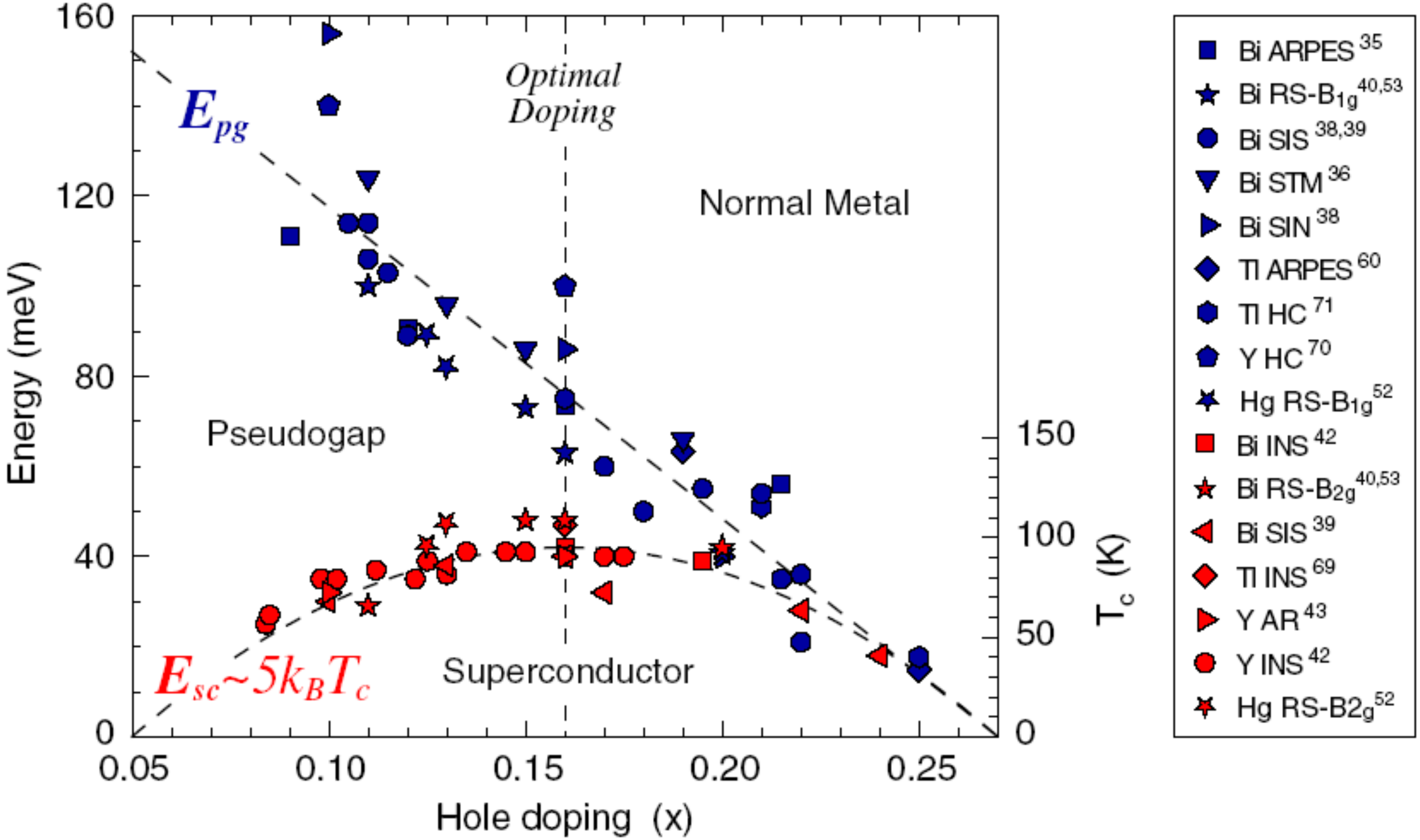
YRZ theory of underdoped cuprates



Leblanc et.al.
PRB 81,064504
[2010]

G-McM-group

Both scales are part of YRZ model
No pseudogap in nodal direction
Can dominate anti-nodal direction



Hufner et. Al. Rep. Prog. Phys. 71, 062501 [2008]

There are two gaps . Superconducting gap

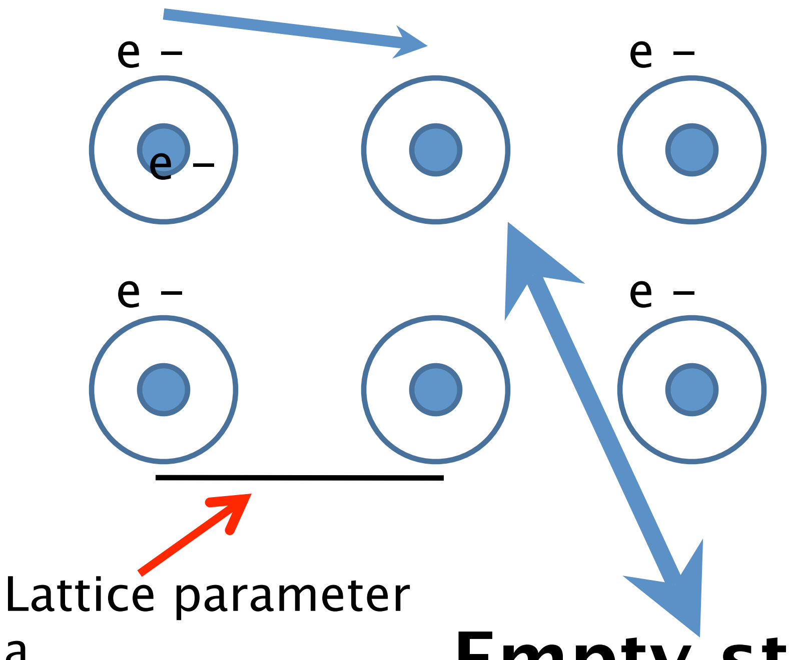
and a normal state gap associated with loss of

metalicity as Mott transition to insulating state

is approached

Hard to escape there are two gaps in underdoped cuprates
one superconducting gap ,the other a pseudogap associated with Mott physics

Mott physics

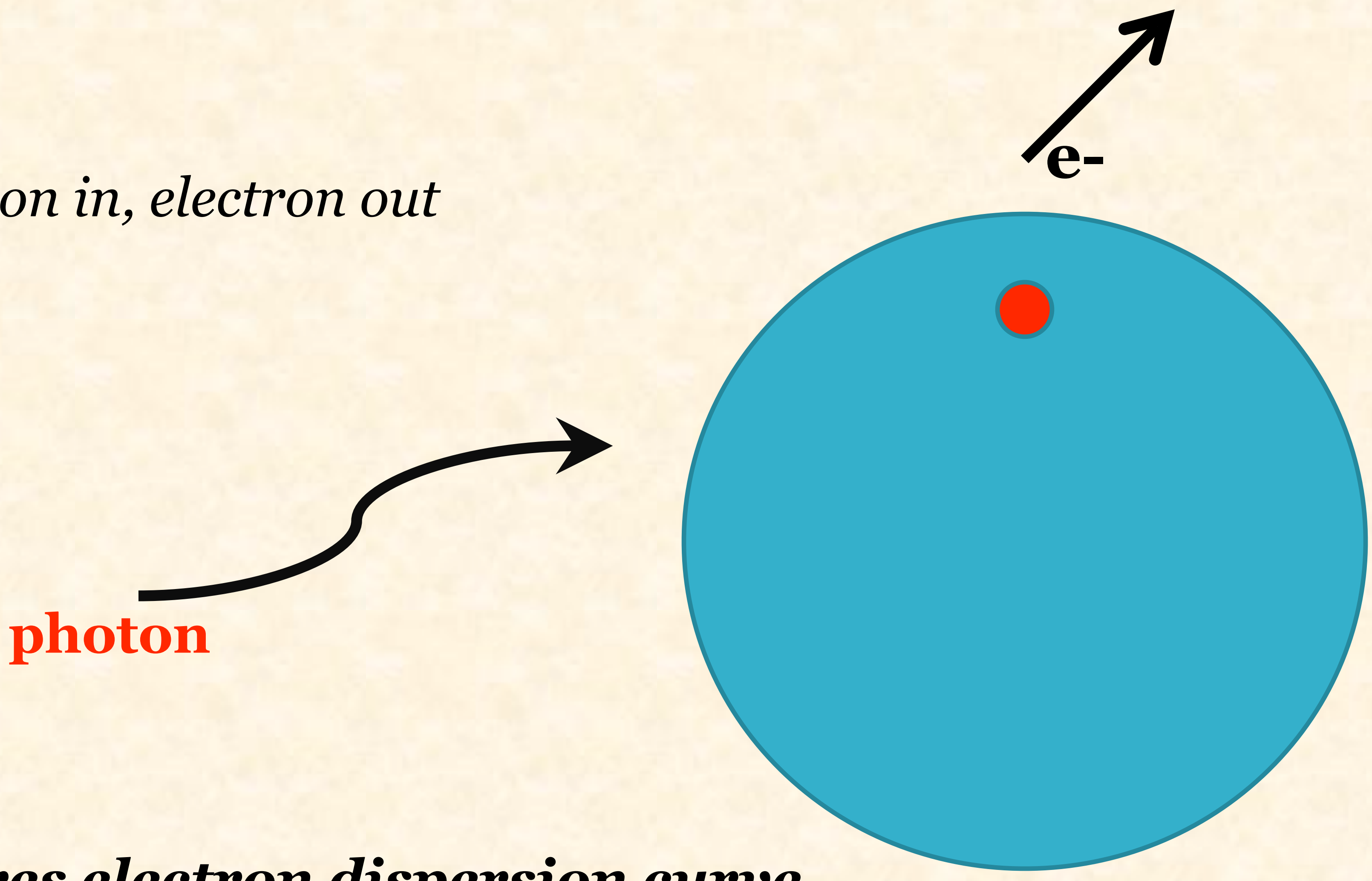


Hopping to empty site is ok
Hopping to filled site is energetically not favorable because of Hubbard U
big on site repulsion
NO double occupancy

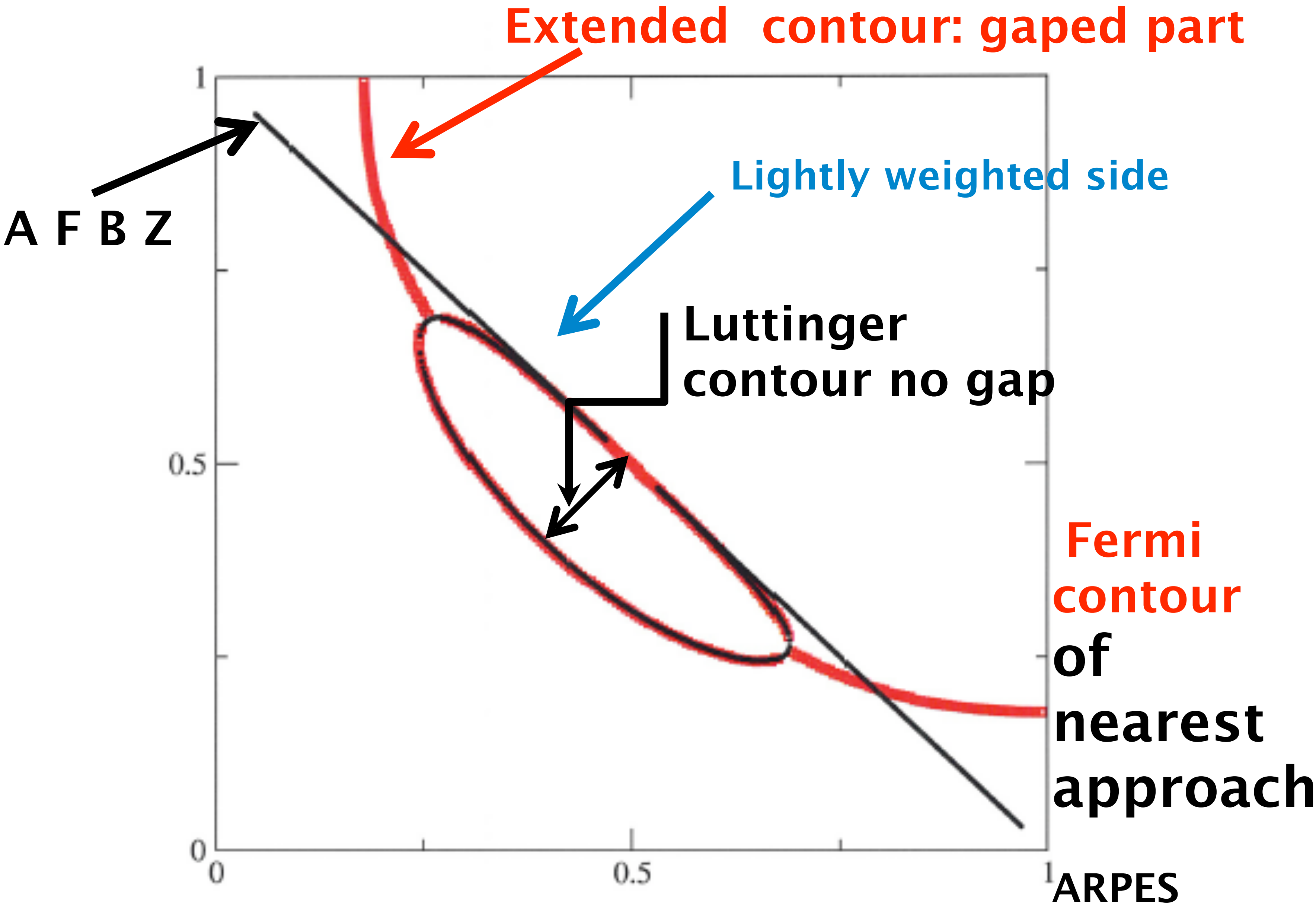
Empty state, hole doping

Angular resolved photo emission ARPES

Photon in, electron out



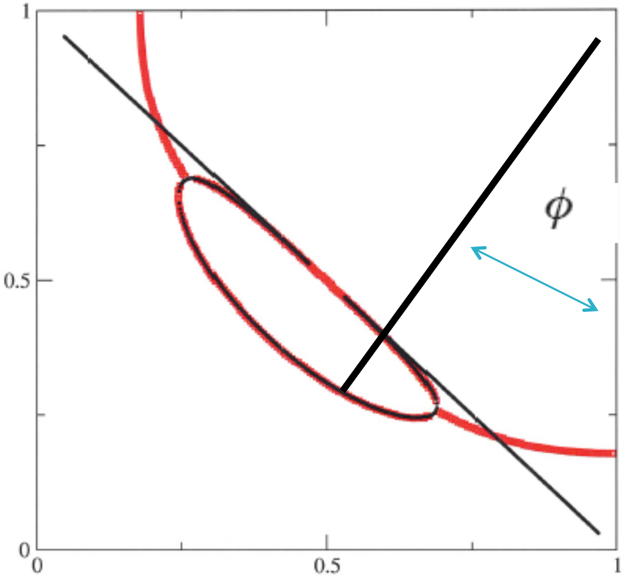
Measures electron dispersion curve

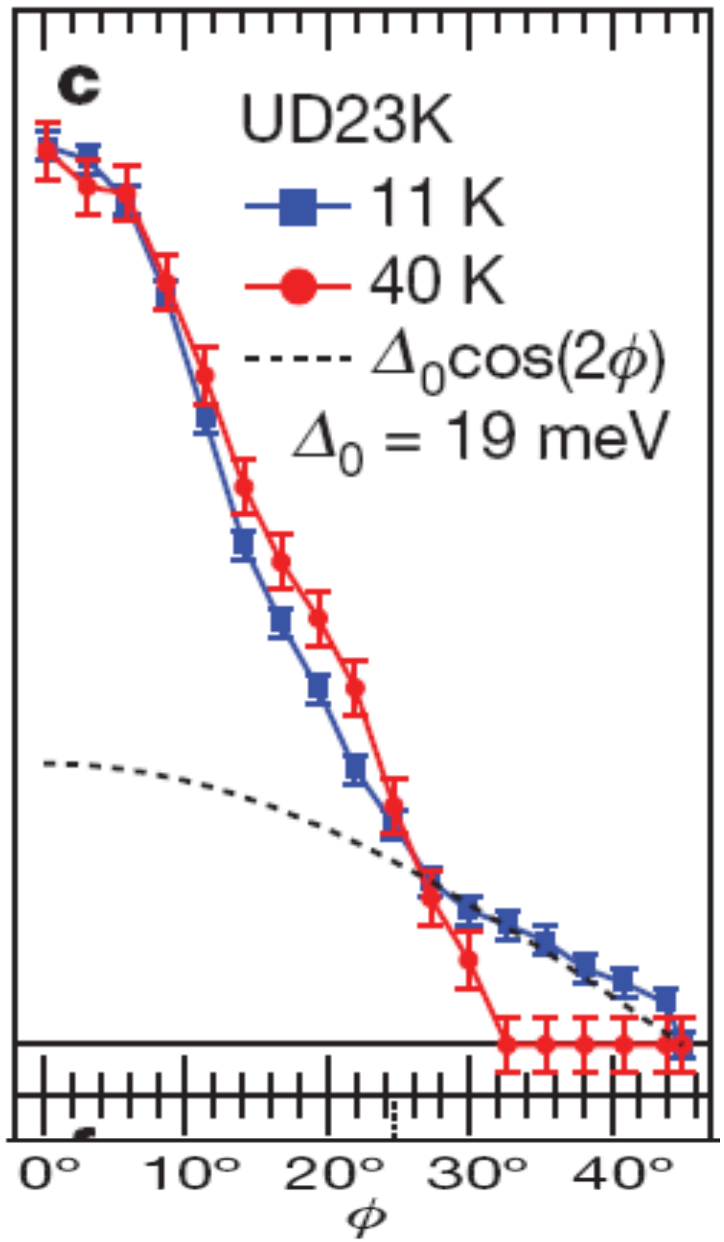


Measure along red contour and front part of luttinger fermi surface ,back has little weight

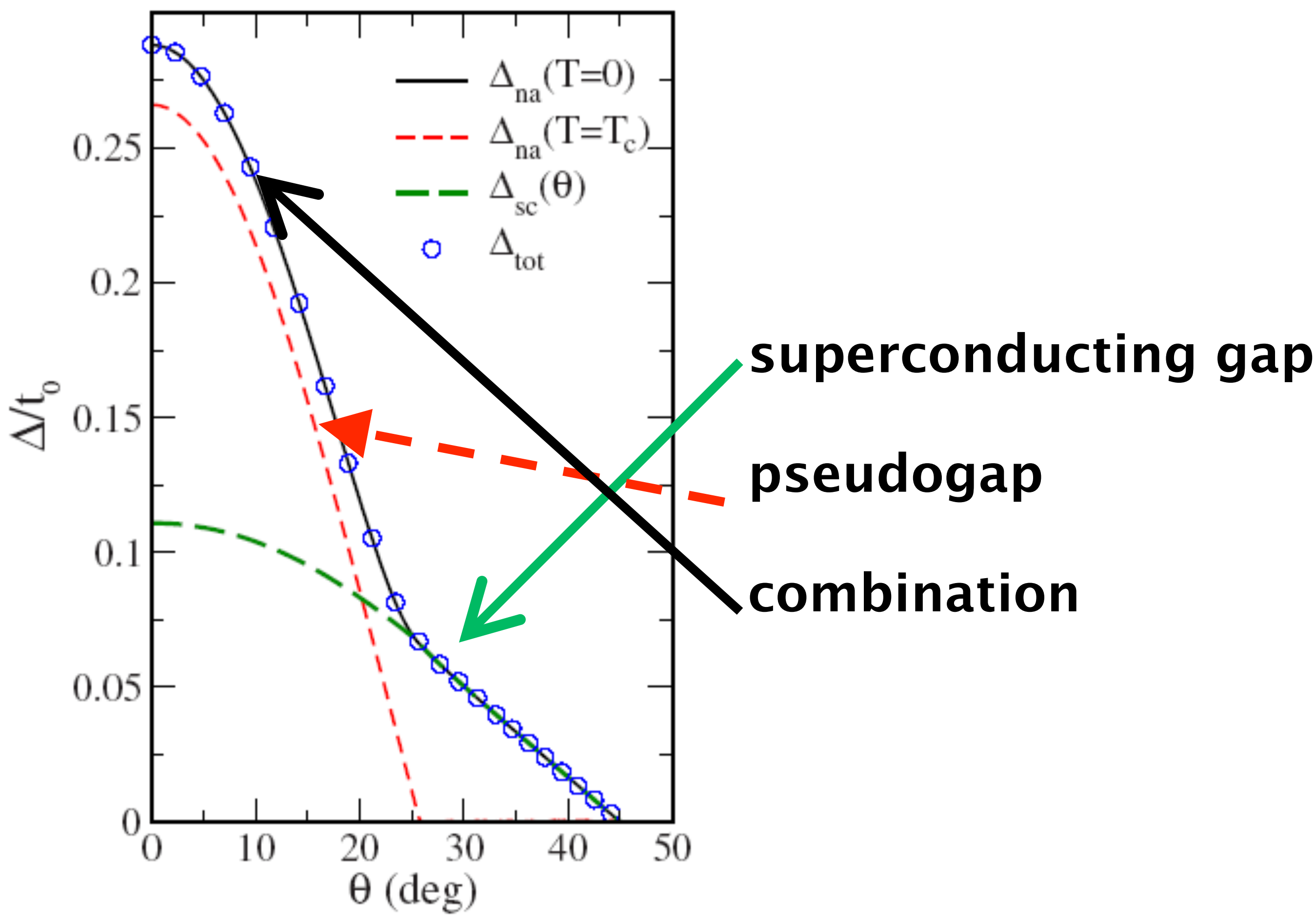
Kondo et. al. Nature, 457,296 [2009]

ARPES



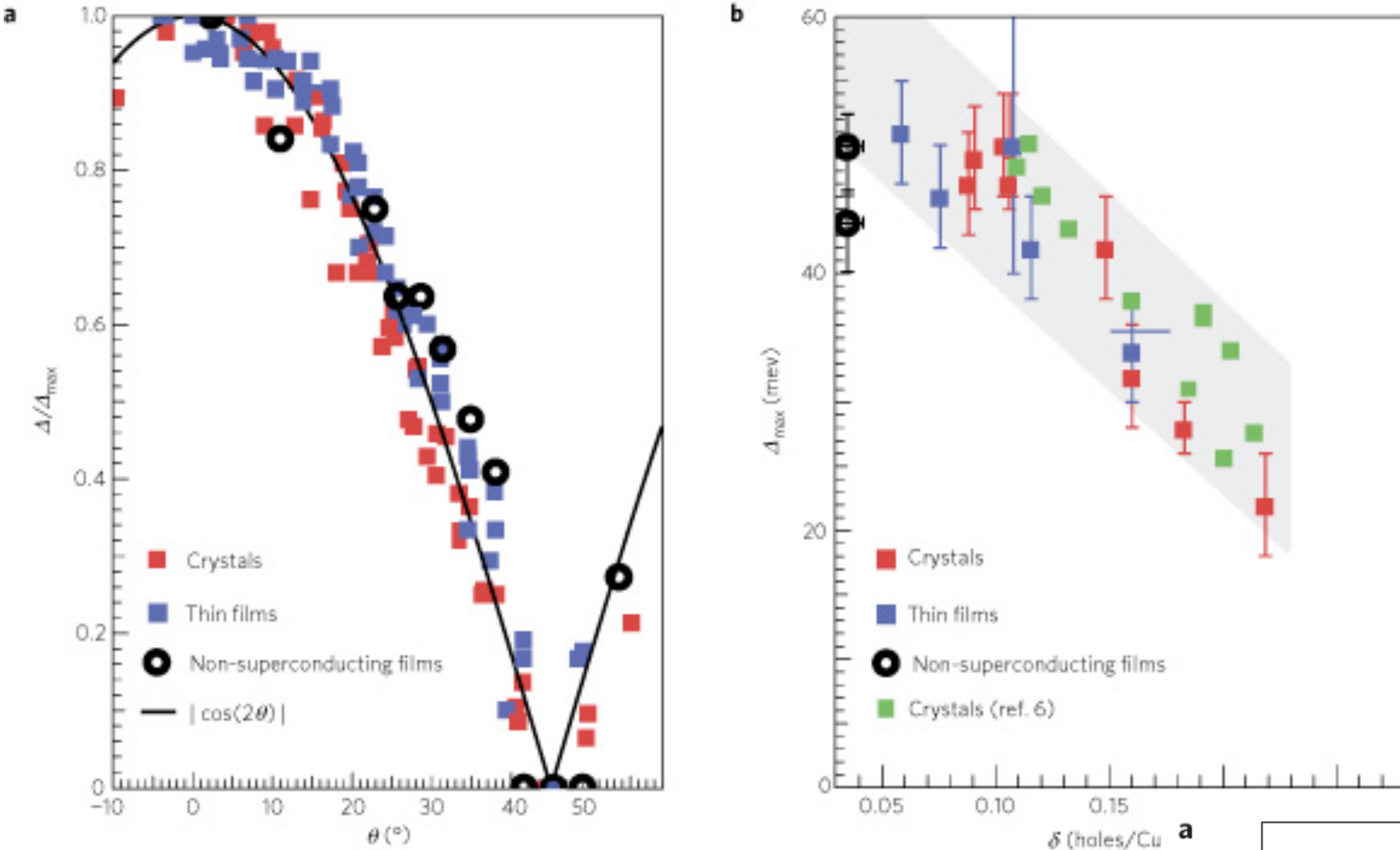


YRZ theory applied to ARPES ,Leblanc et.al. Phys. Rev. B 81, 064504 [2010]

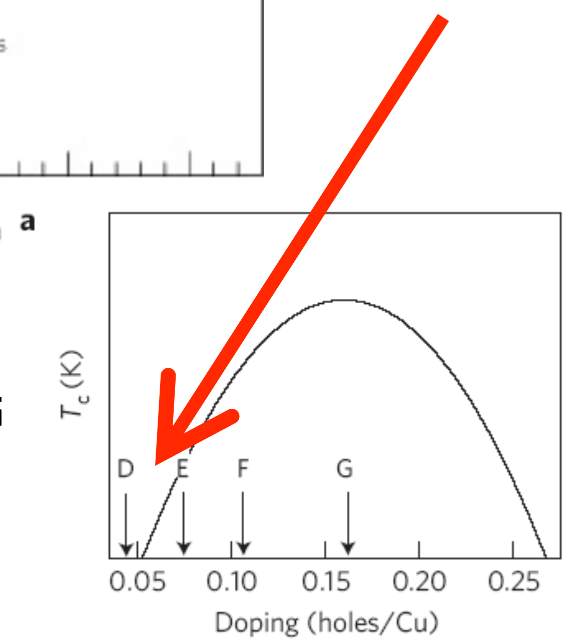


Total is square root of sum of squares of pseudogap [na]and superconducting gap

Chatterjee et.al. Nature Physics 6,99 [2010]



Highly underdoped Bi2212 NO sign of second or arcs around 45 degree from luttingr pockets



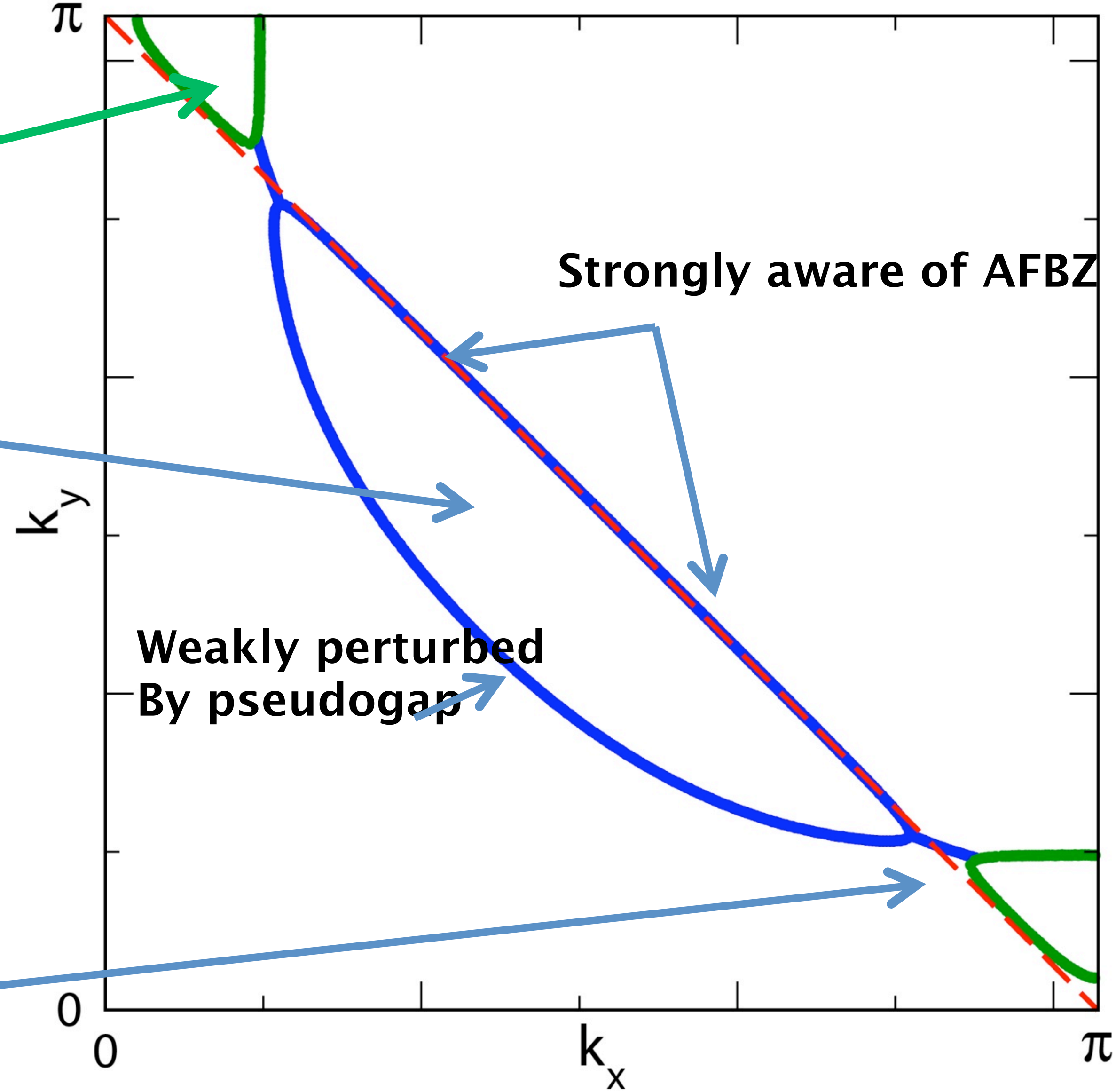
END

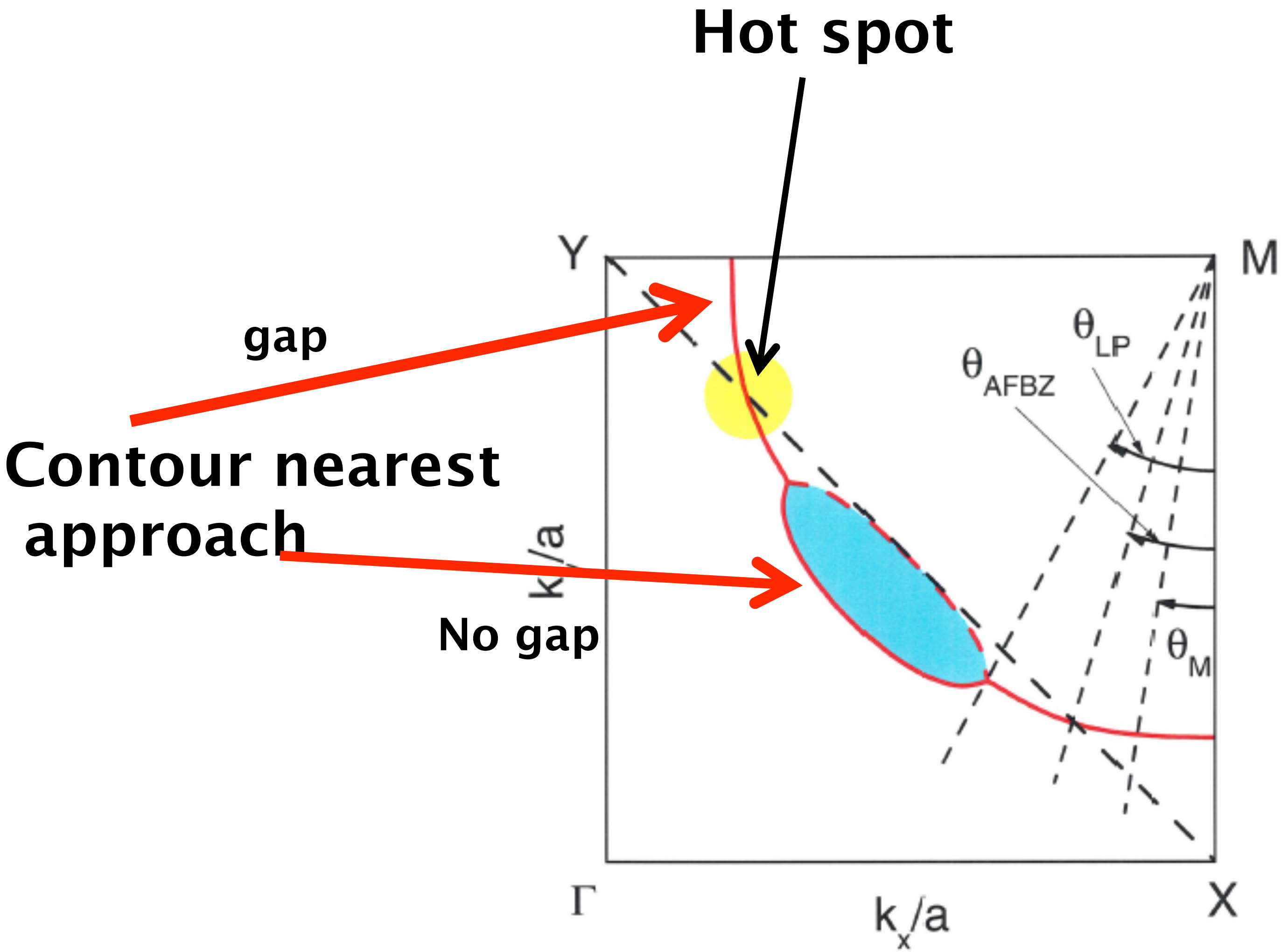
For x=0.19 can have holes and electron pockets [near B Z boundary]

Electron pocket
Negative energy

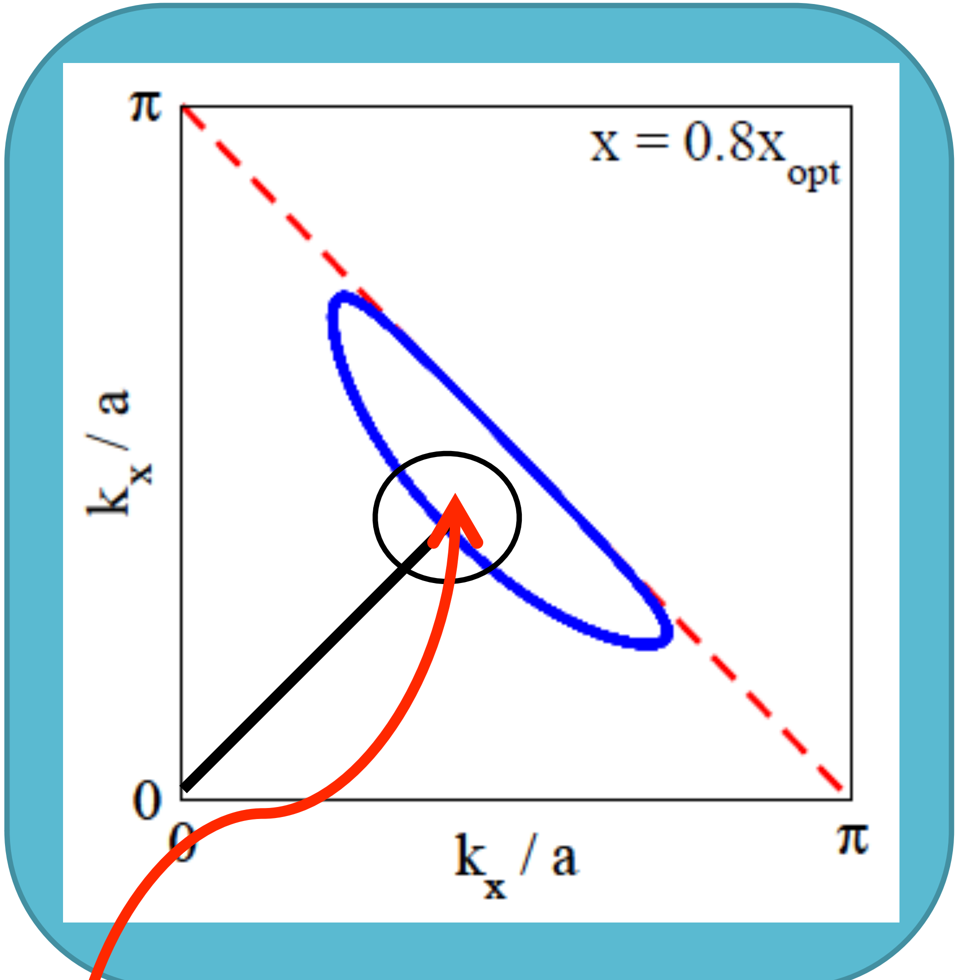
Hole pocket
Positive energy

Gaped connecting
contour

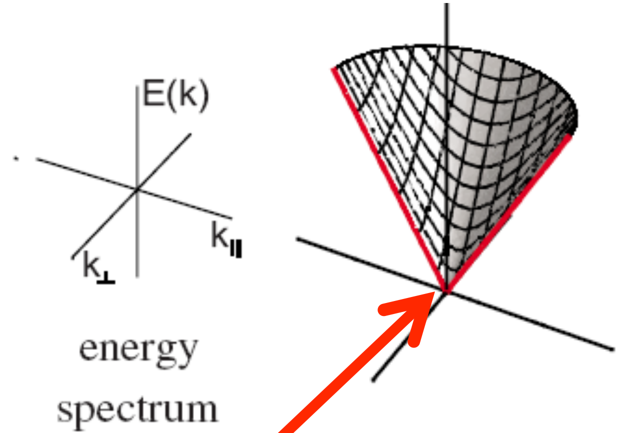




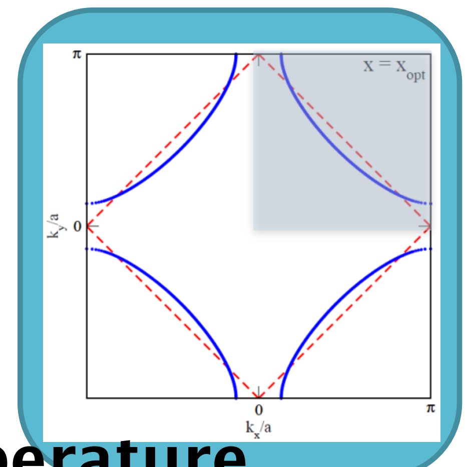
ARPES measures dispersion curves for occupied states. Can “see” if there are states of zero energies [real Fermi surface] .



x = 0.16

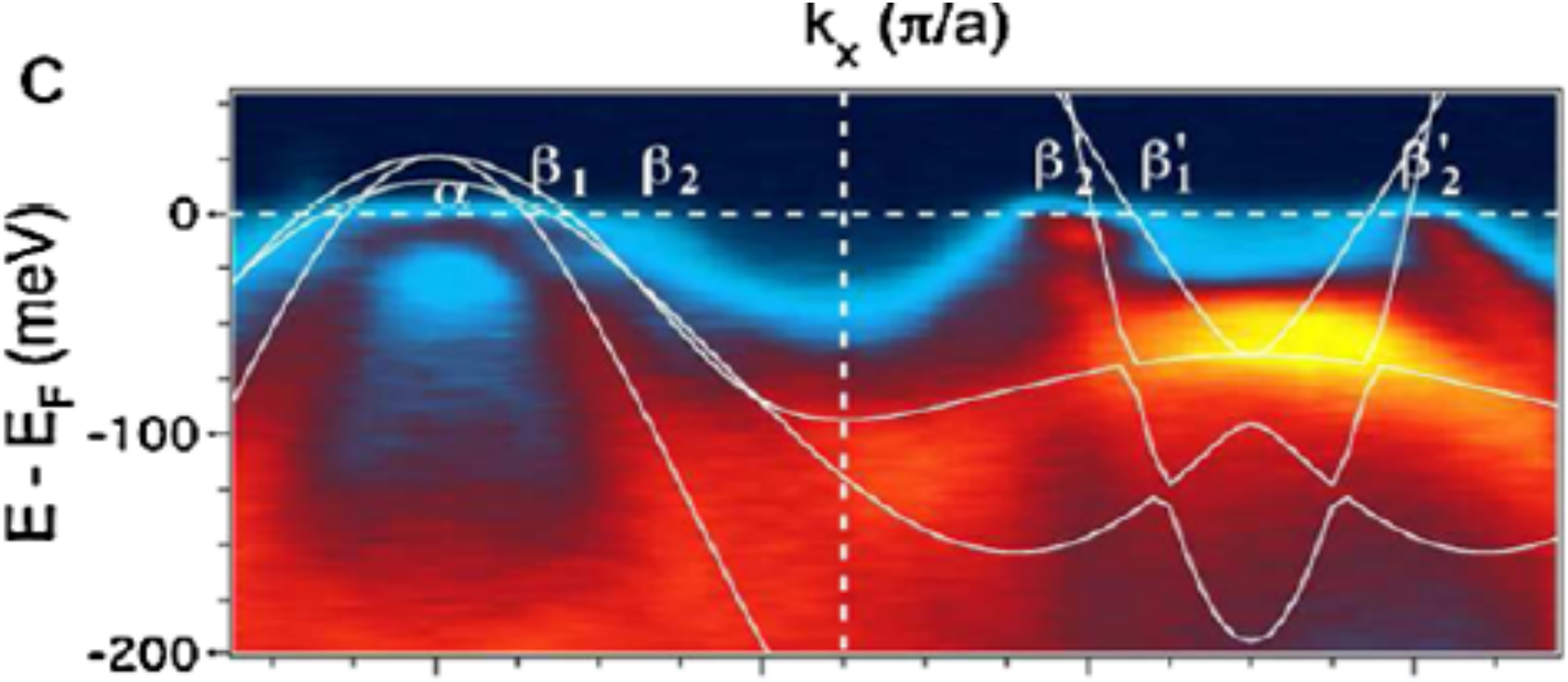


Dirac point



Dirac point is only active spot at low temperature

x = 0.20


C
k_x (π/a)
E - E_F (meV)
0
-100
-200
α
β_1
β_2
β'_2
β'_1
β'_2

Discovery of superconductivity 1911

Kamerlingh-Onnes
1911

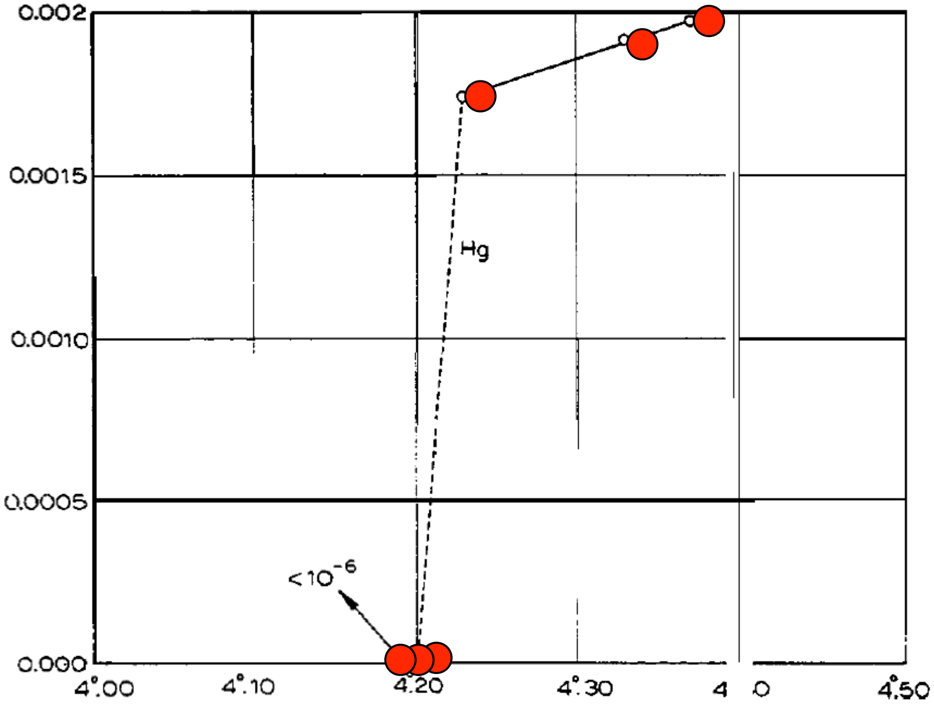
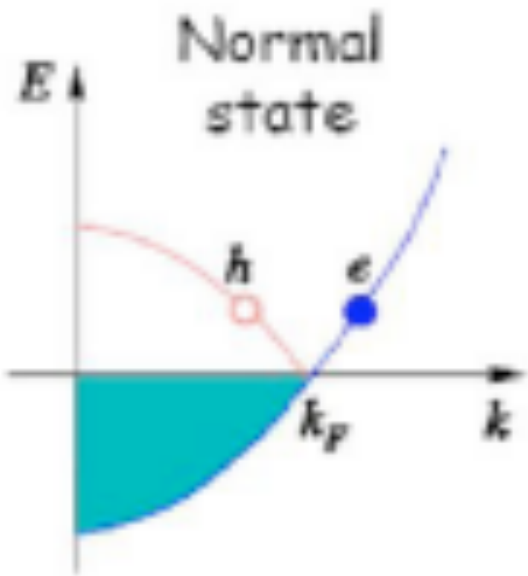


Fig. 17.

Temperature excites electrons out of fermi sea,create particle hole excitations



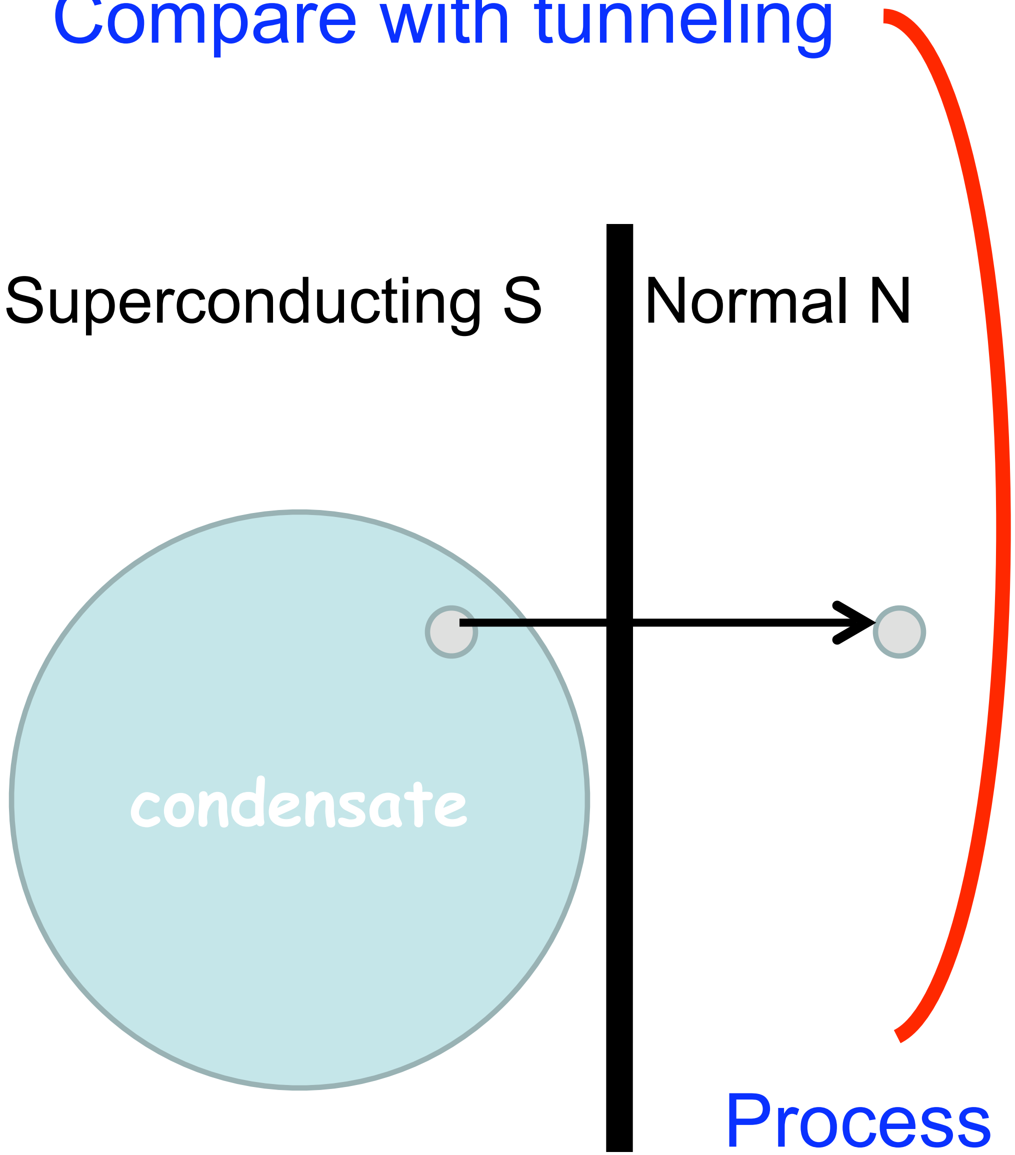
Number is N[0] *T*T
Internal energy U change
goes like above and

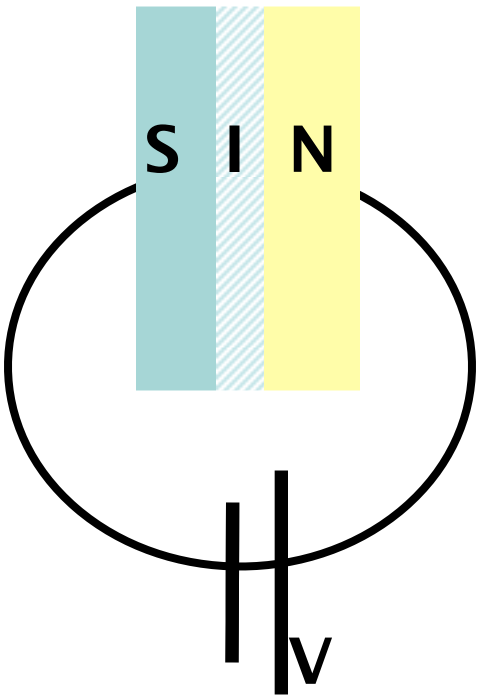
Specific heat like T

In s-wave superconducting state there is a gap and so
exponential activation

In a d-wave superconductor have distribution of gaps and DOS N[w] is linear in w so U goes like T3 and specific heat like T**2**

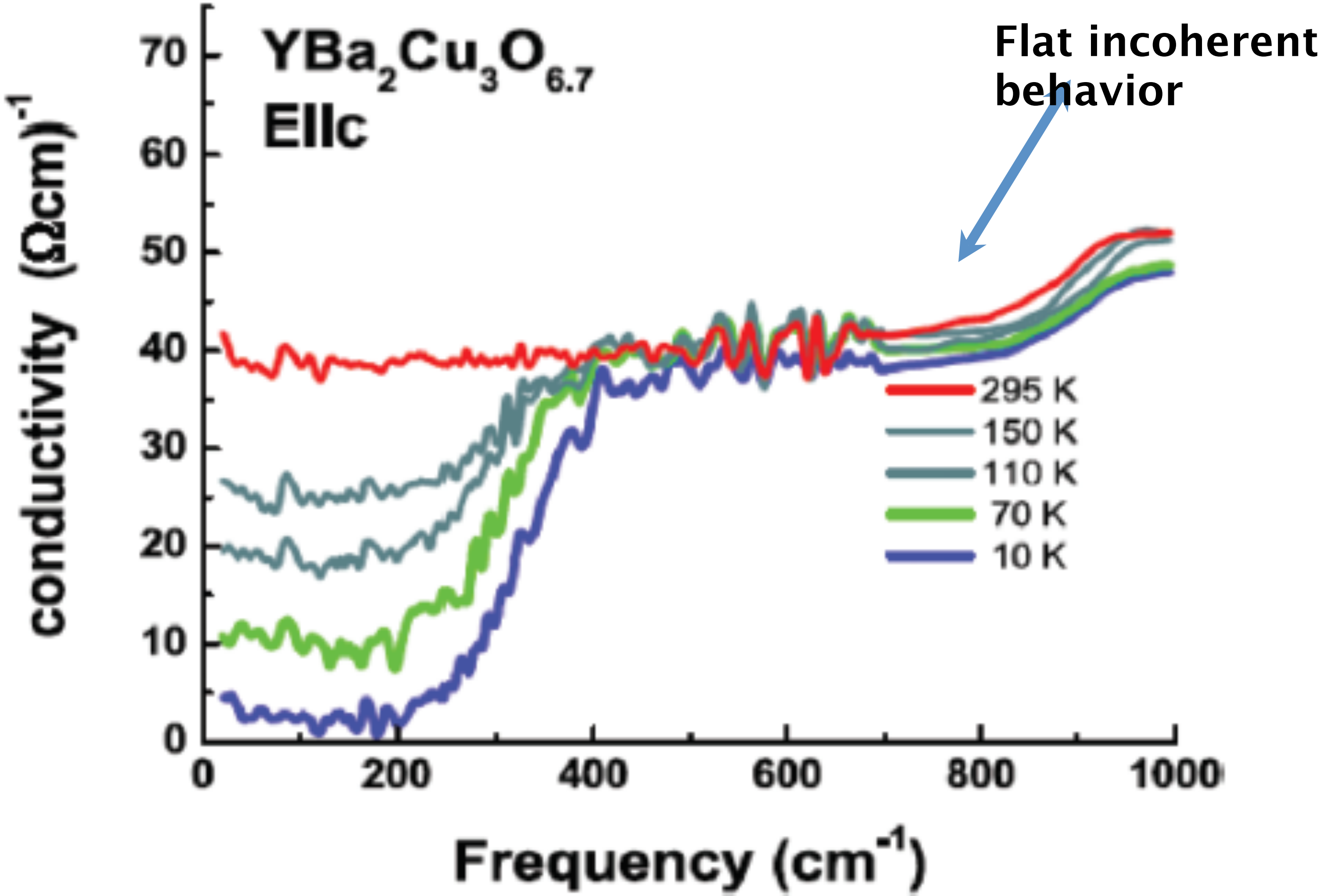
Compare with tunneling





Process requires only one gap

Hard to miss second gap ,perhaps seen best in c-axis optics
It is there in normal state above Tc



D Basov-group