EXPERIMENTAL PROOF OF MAGNETIC FLUX QUANTIZATION IN A SUPERCONDUCTING RING*

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EXPERIMENTAL EVIDENCE FOR QUANTIZED FLUX IN SUPERCONDUCTING CYLINDERS*

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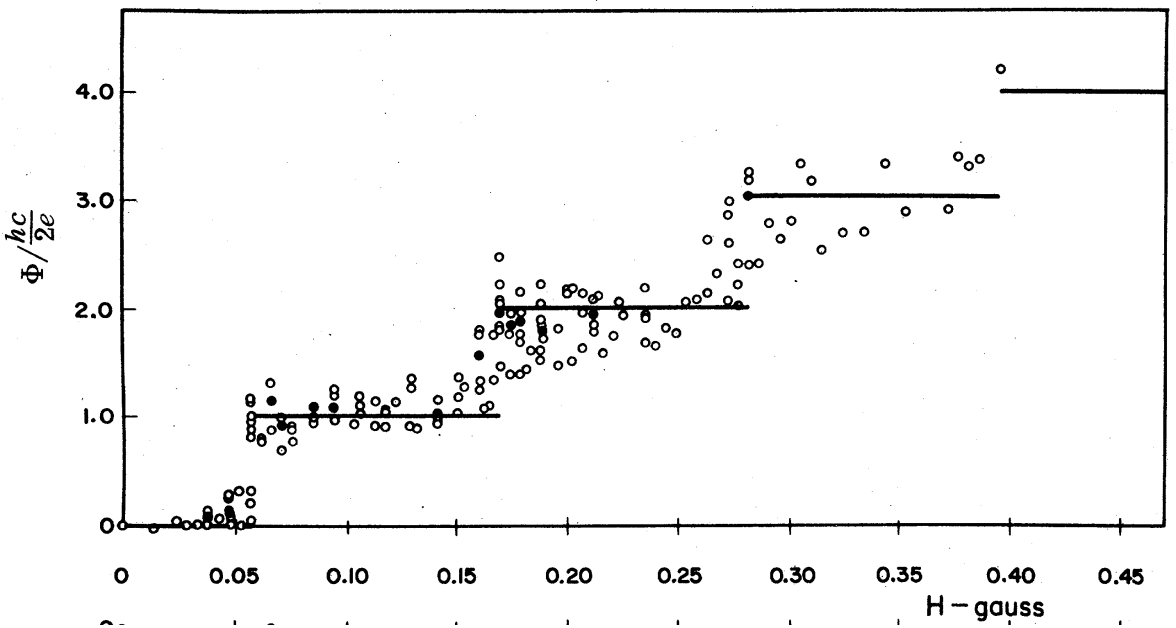
(Received June 16, 1961)



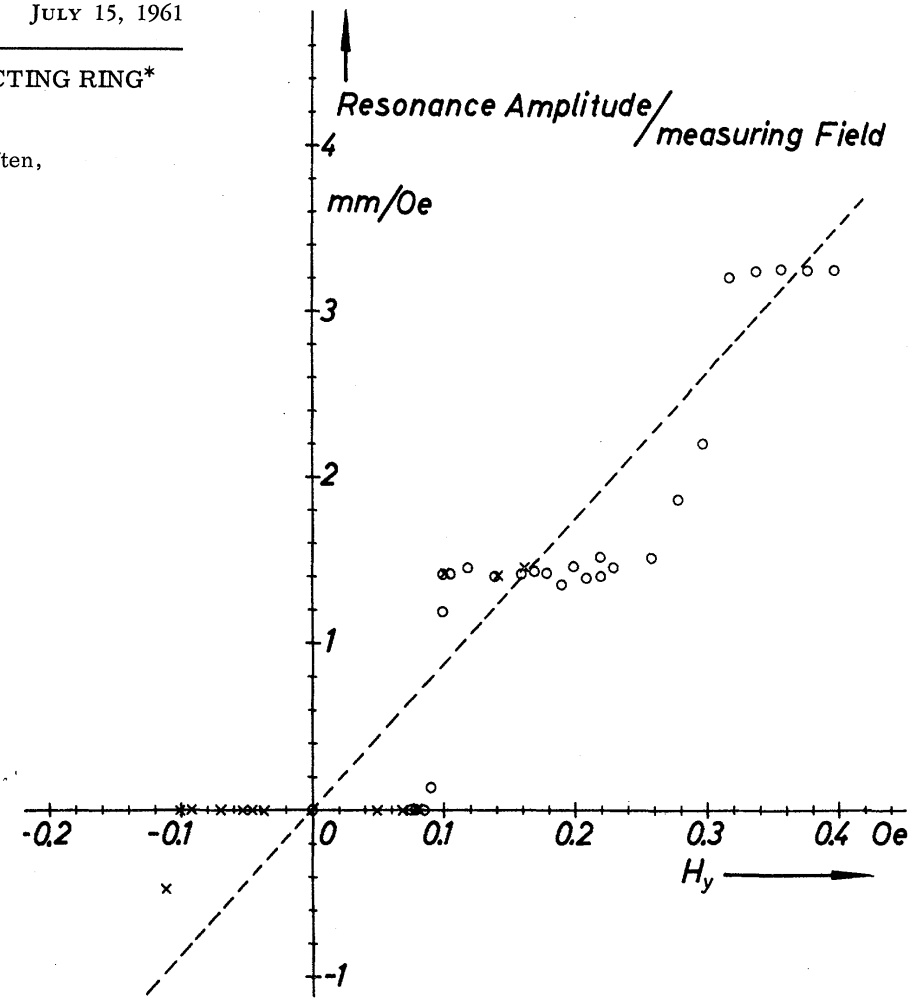
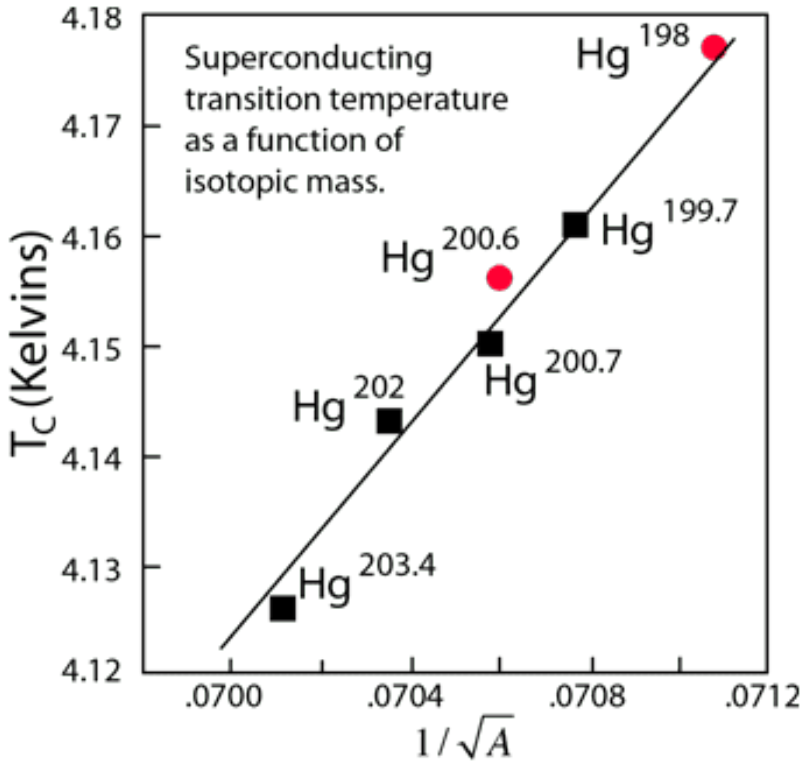


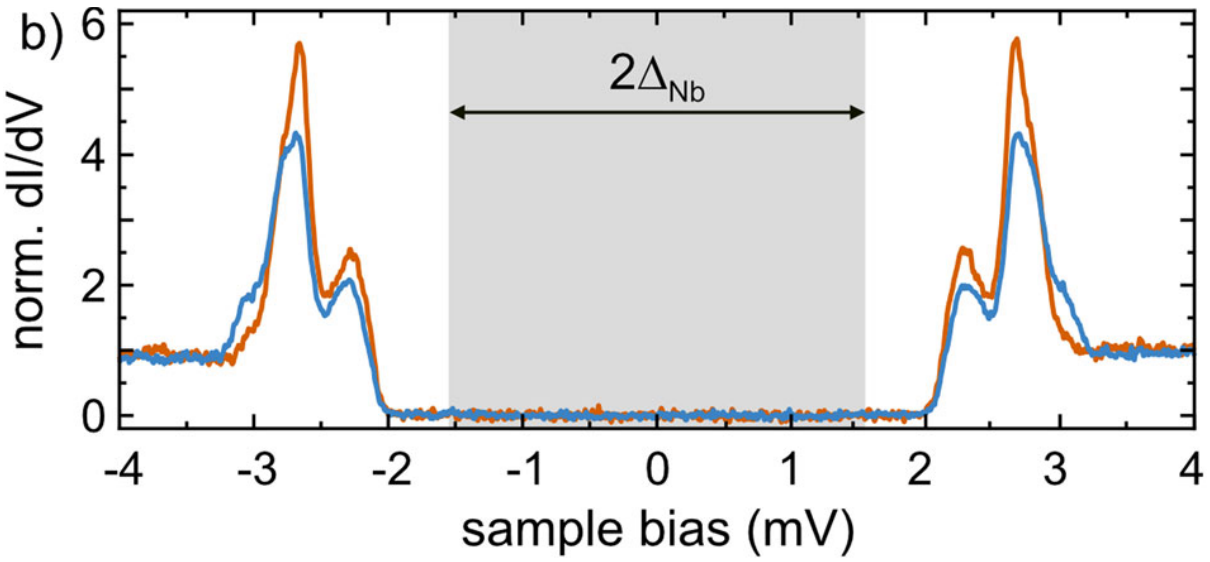
FIG. 2. Resonance amplitude divided by measuring field H_x as a function of the applied field H_y. The ordinate is proportional to the frozen-in flux. ×– First run; o– second run.

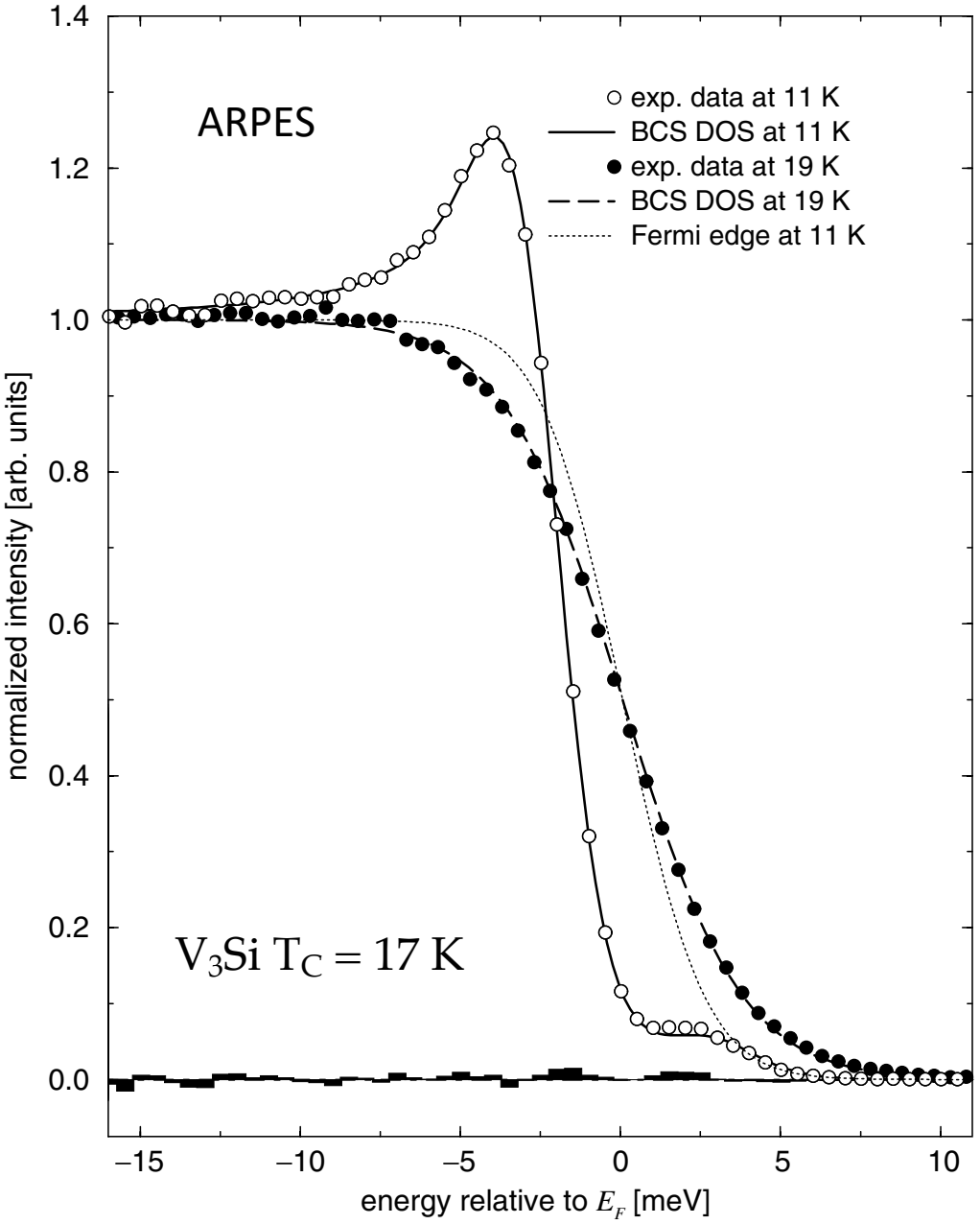


E. Maxwell, Phys. Rev. 78 477 (1950)

C. A. Reynolds, et al., Phys Rev. 78, 487 (1950)

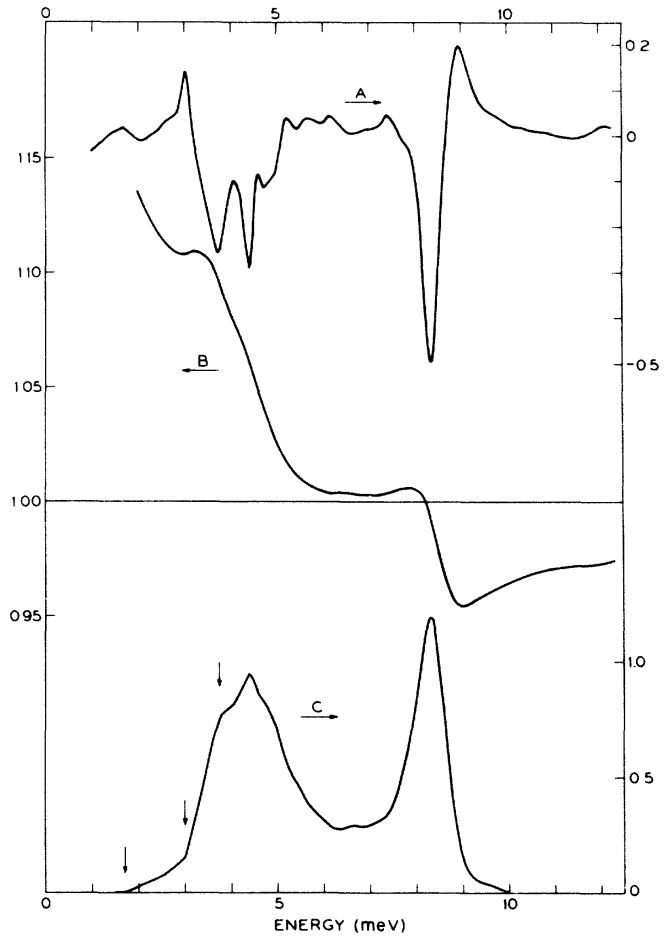
STM


b)
norm. dI/dV
$2\Delta_{Nb}$
sample bias (mV)

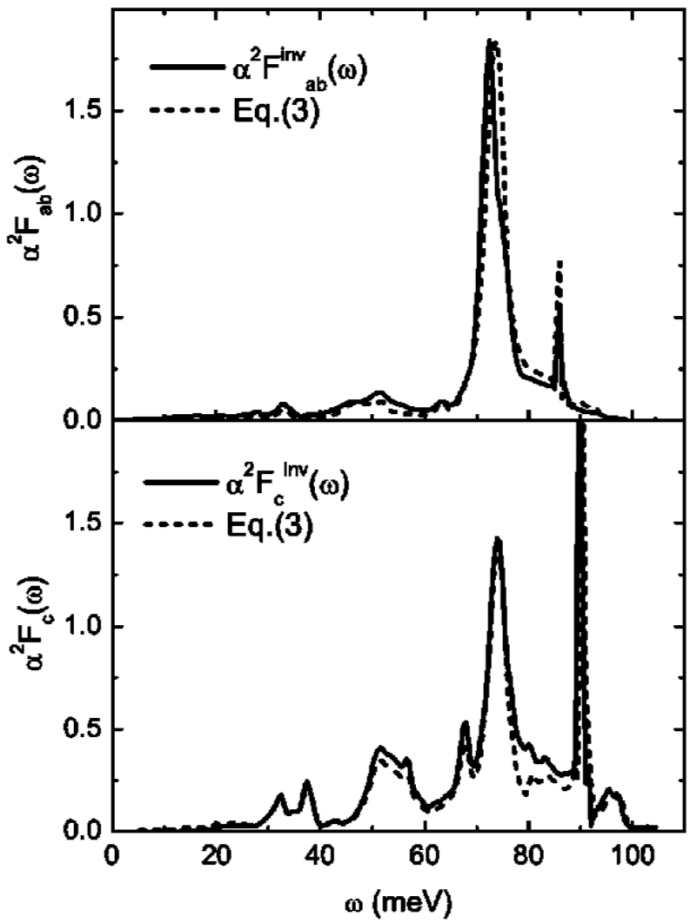

ARPES
exp. data at 11 K
BCS DOS at 11 K
exp. data at 19 K
BCS DOS at 19 K
Fermi edge at 11 K
normalized intensity [arb. units]
V_3Si $T_C = 17$ K
energy relative to E_F [meV]

Eliashberg function

Pb



MgB_2



LEAD PHONON SPECTRUM CALCULATED FROM SUPERCONDUCTING DENSITY OF STATES

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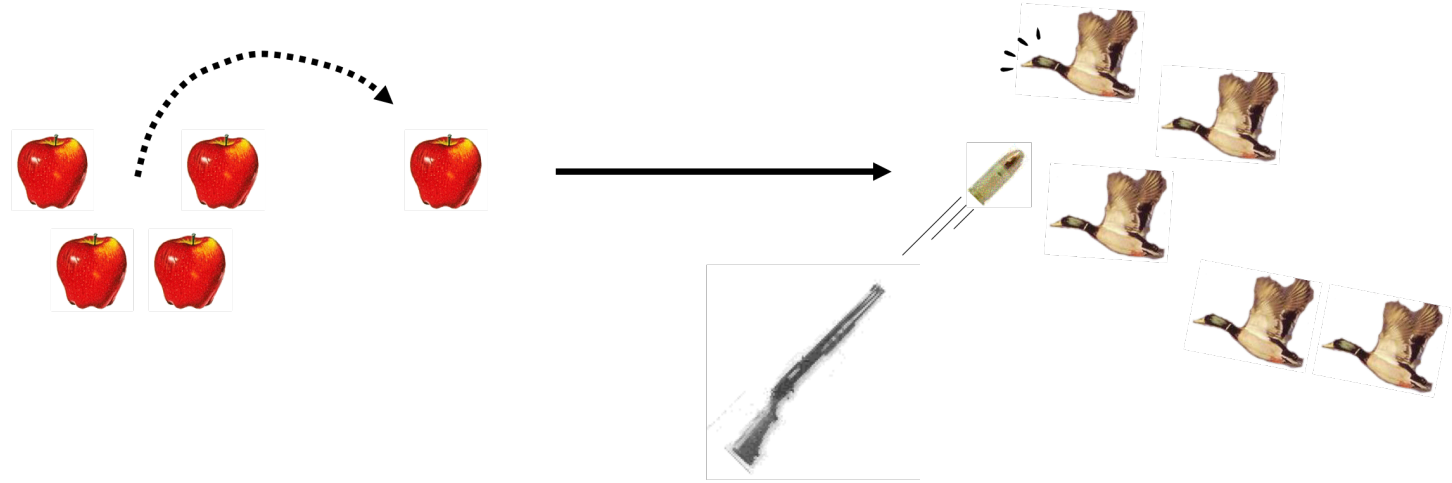
(Received 18 December 1964)



How can we detect interactions in ARPES?

Green's function: $G(\mathbf{k},E) = \dfrac{1}{E - E_{\mathbf{k}} - \Sigma(\mathbf{k},E)}$ indicates how the binding energies are modified

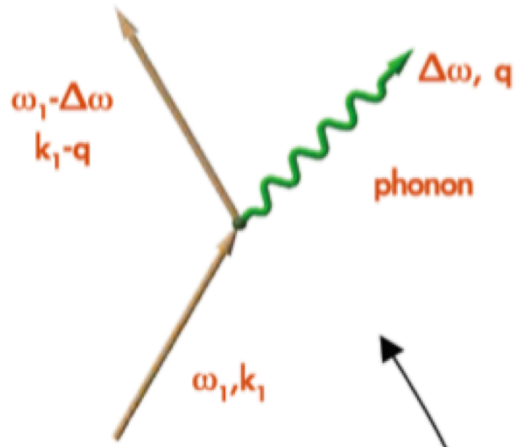
Spectral function: $A(\mathbf{k},E) = \dfrac{1}{\pi}\dfrac{Im\Sigma(\mathbf{k},E)}{\left[E - E_{\mathbf{k}} - Re\Sigma(\mathbf{k},E)\right]^2 + \left[Im\Sigma(\mathbf{k},E)\right]^2}$ indicates how the lines look

Self energy: $\Sigma(\mathbf{k},E) = \mathrm{Re}\Sigma(\mathbf{k},E) + \mathrm{Im}\Sigma(\mathbf{k},E)$ (zero for non interacting situation)

Change in energy

Change in lifetime (linewidth)

The carriers have a finite lifetime due to absorption and emission of phonons and other excitations



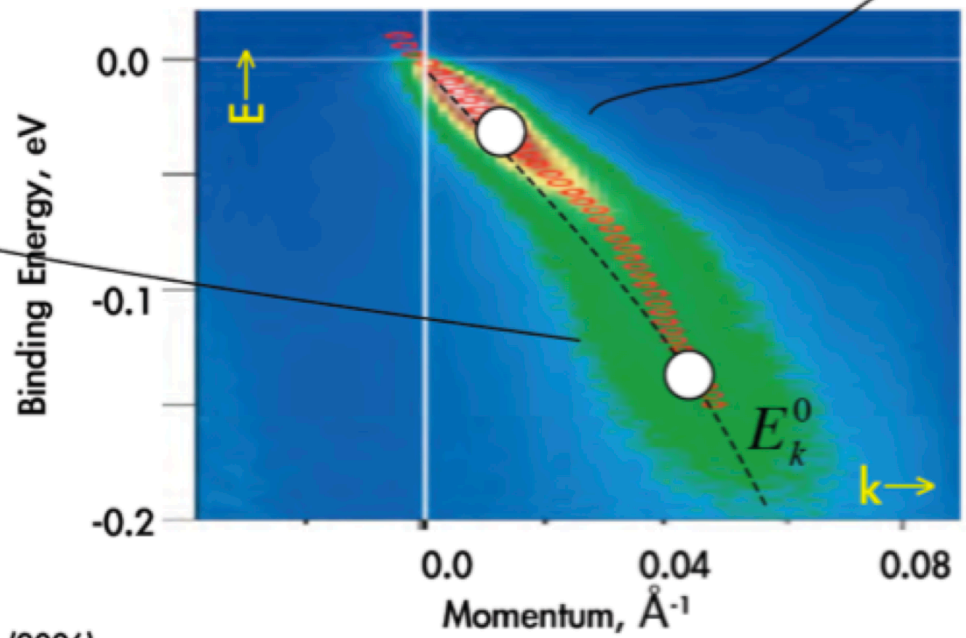
electron emits a phonon:
change of energy ω and momentum k

the measured state is broader in momentum and energy

electron emits and reabsorbs a phonon: change of mass

the mass of the carrier is increased

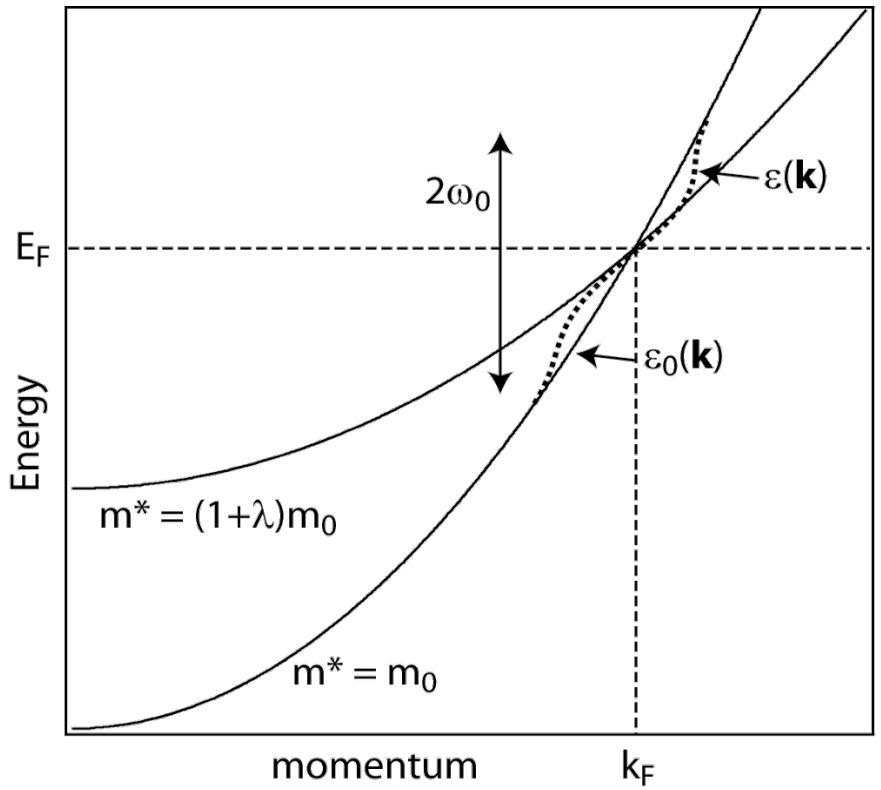
BSCCO Superconductor Results [1]



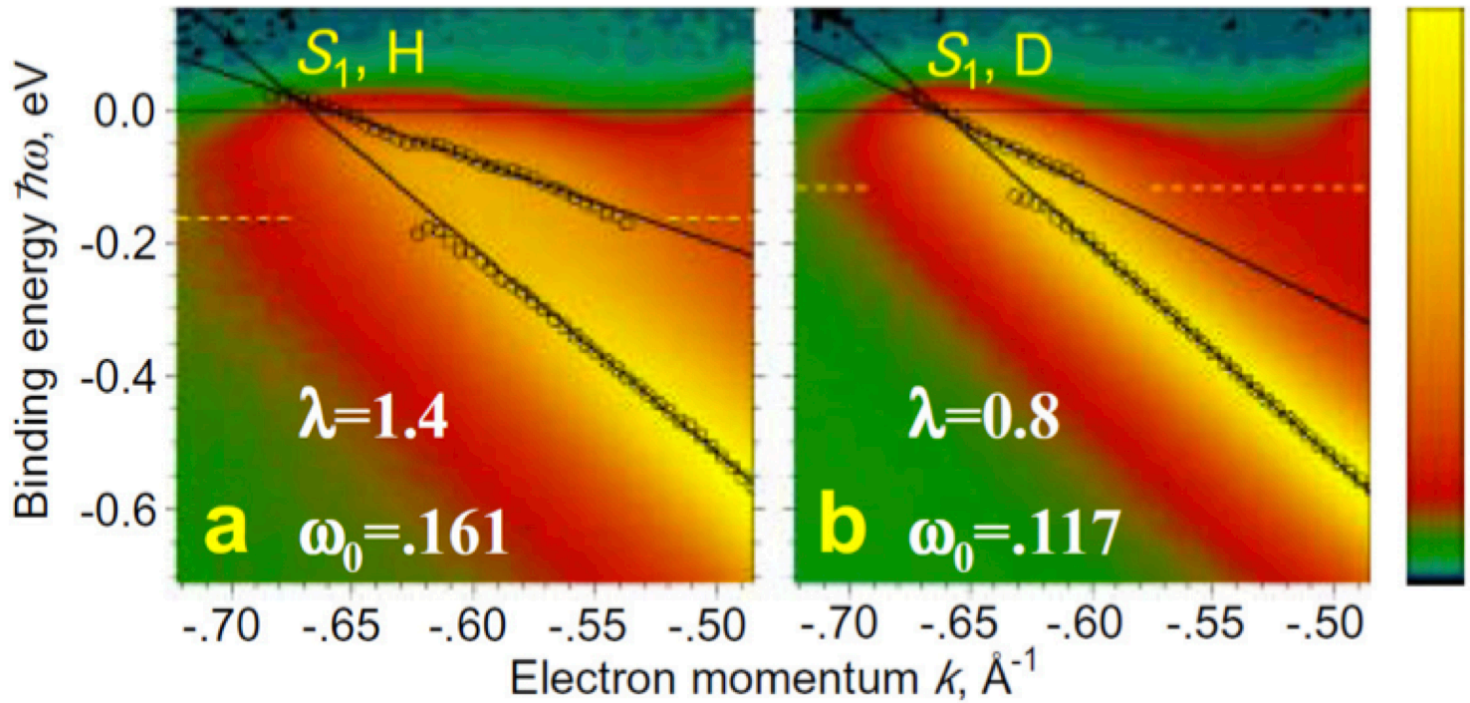
these processes are <u>fundamental</u> to understand superconductivity

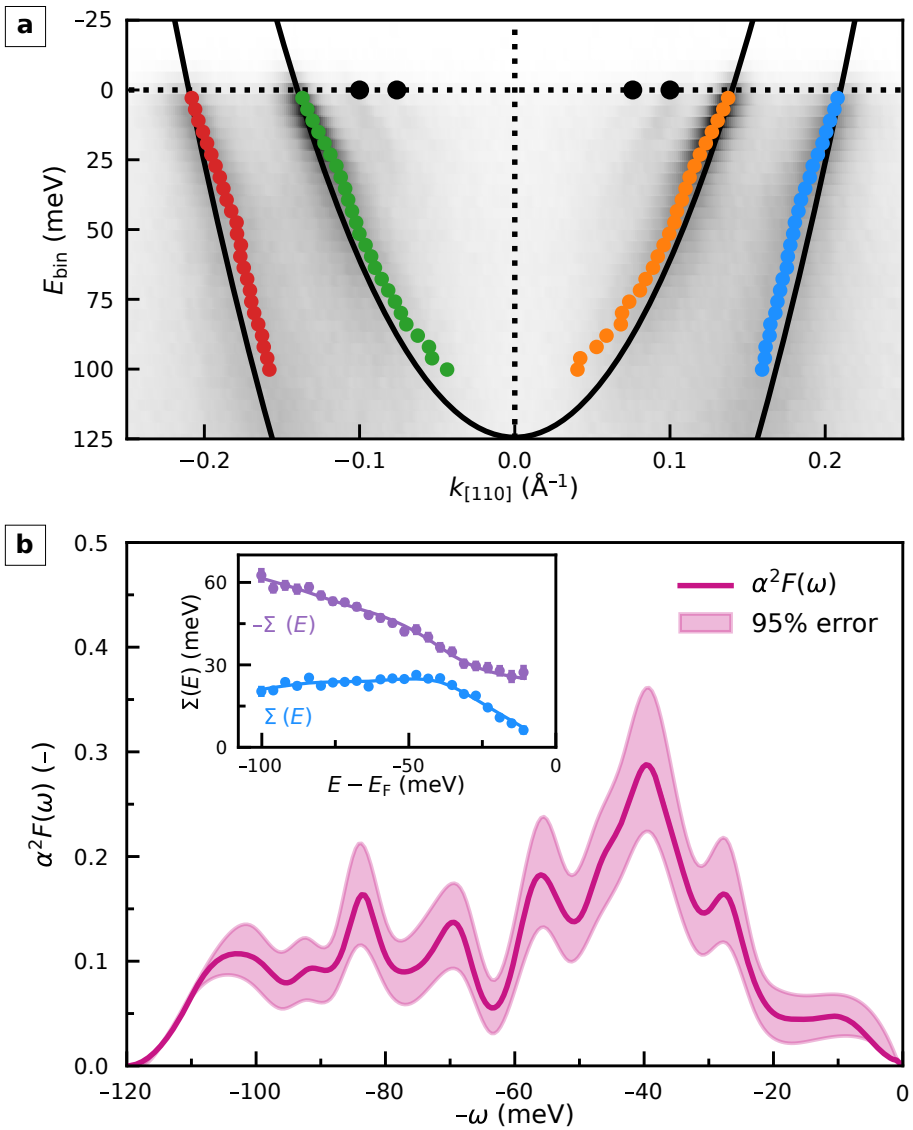
there is no direct way to probe these processes except through ARPES measurments

[1] Koralek et al, Phys. Rev. Lett. 96, 017005 (2006)



Hydrogen and deuterium on W, influence on surface state





$\Sigma^{\mathrm{im}}(E) \approx \mathrm{i}\Sigma^{\mathrm{im}\prime\prime}$ [20]. We assume that $\Sigma^{\mathrm{ph}}(E)$ is dominated by the Fan-Migdal self-energy [21] with negligible momentum dependence in the range of the extracted self-energies, whereas in a treatment of the phonons up to second order in the phonon displacements, the Debye-Waller term [21] is captured inside the bare band $\varepsilon(\mathbf{k})$. Subsequently, $\alpha^2F(\omega)$ is obtained from inverting the following integral [22]:

$$\Sigma^{\mathrm{ph}}(E) = \int_0^\infty \mathrm{d}\omega\alpha^2F(\omega)K(E,\omega), \tag{11}$$

where we use the following expression for the bosonic kernel [22]:

$$K(E,\omega) = \int_{-\infty}^{\infty} \mathrm{d}\nu \left[\frac{f(-\nu)+n(\omega)}{E-\omega-\nu+\mathrm{i}\eta} + \frac{f(\nu)+n(\omega)}{E+\omega-\nu+\mathrm{i}\eta}\right], \tag{12}$$

where η is an infinitesimal value from the analytic continuation [23] that we set to 10^{-5} meV.

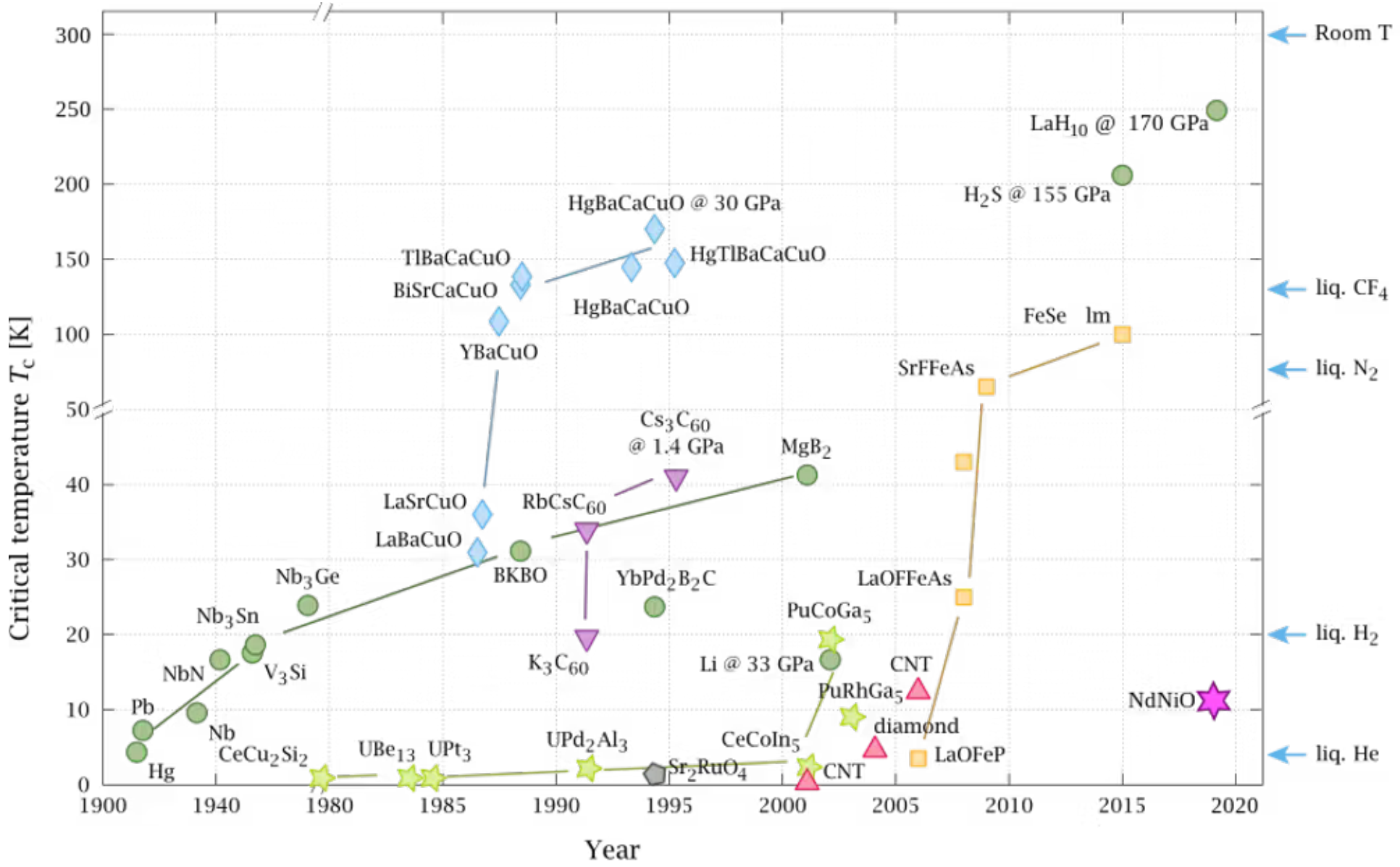
We reduce the integration range of Supplementary Eq. (12) by assuming that scattering only occurs from the band bottom $E_{\mathrm{F}} - E_{\mathrm{bot}}$ to an equivalent energy $E_{\mathrm{bot}} + E_{\mathrm{F}}$:

$$K(E,\omega) = \int_{E_{\mathrm{F}}-E_{\mathrm{bot}}}^{E_{\mathrm{F}}+E_{\mathrm{bot}}} \mathrm{d}\nu \left[\frac{f(-\nu)+n(\omega)}{E-\omega-\nu+\mathrm{i}\eta} + \frac{f(\nu)+n(\omega)}{E+\omega-\nu+\mathrm{i}\eta}\right], \tag{13}$$

which can then be integrated to give the following analytic expression [24]:

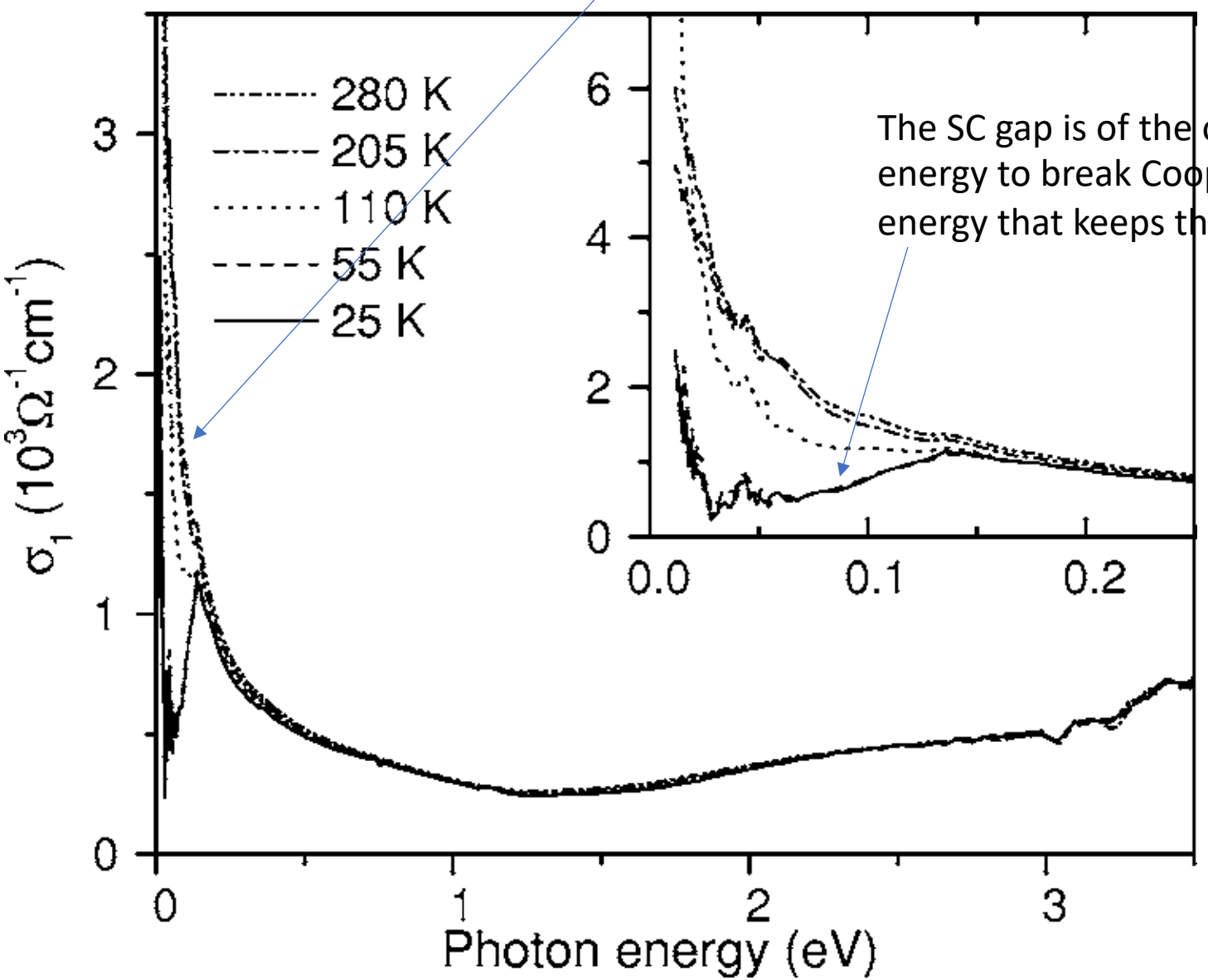
$$\begin{aligned} K(E,\omega) = -\mathrm{i}\pi + \psi\left(\frac{1}{2} - \mathrm{i}\frac{E-E_{\mathrm{F}}-\omega+\mathrm{i}\eta}{2\pi k_{\mathrm{B}}T}\right) - \psi\left(\frac{1}{2} - \mathrm{i}\frac{E-E_{\mathrm{F}}+\omega+\mathrm{i}\eta}{2\pi k_{\mathrm{B}}T}\right) + \ln\left(\frac{E-E_{\mathrm{F}}+\omega+E_{\mathrm{bot}}+\mathrm{i}\eta}{E-E_{\mathrm{F}}+\omega+E_{\mathrm{bot}}+\mathrm{i}\eta}\right) \\ + n(\omega)\left[\ln\left(\frac{E-E_{\mathrm{F}}-\omega+E_{\mathrm{bot}}+\mathrm{i}\eta}{E-E_{\mathrm{F}}-\omega-E_{\mathrm{bot}}+\mathrm{i}\eta}\right) + \ln\left(\frac{E-E_{\mathrm{F}}+\omega+E_{\mathrm{bot}}+\mathrm{i}\eta}{E-E_{\mathrm{F}}+\omega-E_{\mathrm{bot}}+\mathrm{i}\eta}\right)\right], \end{aligned} \tag{14}$$

where $\psi(x)$ is the digamma function.

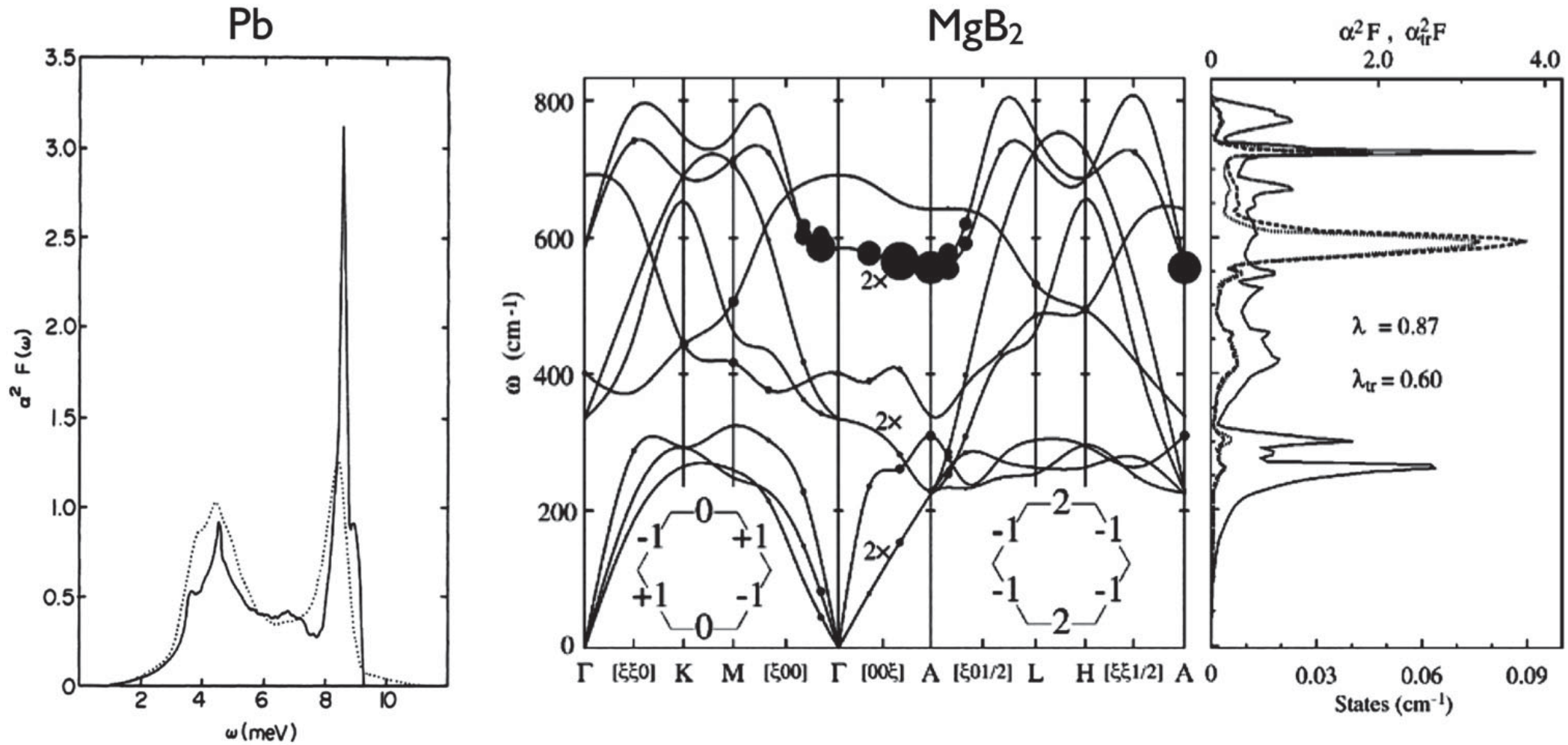

Critical temperature T_c [K]
Year
300
250
200
150
100
50
40
30
20
10
0
1900
1940
1980
1985
1990
1995
2000
2005
2010
2015
2020
Room T
liq. CF_4
liq. N_2
liq. H_2
liq. He
LaH_{10} @ 170 GPa
H_2S @ 155 GPa
HgBaCaCuO @ 30 GPa
TlBaCaCuO
HgTlBaCaCuO
BiSrCaCuO
HgBaCaCuO
YBaCuO
FeSe lm
SrFFeAs
Cs_3C_{60} @ 1.4 GPa
MgB_2
LaSrCuO
$RbCsC_{60}$
LaBaCuO
BKBO
Nb_3Ge
$YbPd_2B_2C$
LaOFFeAs
Nb_3Sn
$PuCoGa_5$
K_3C_{60}
Li @ 33 GPa
CNT
NbN
V_3Si
$PuRhGa_5$
NdNiO
Pb
Nb
diamond
$CeCoIn_5$
$CeCu_2Si_2$
UBe_{13}
UPt_3
UPd_2Al_3
LaOFeP
Hg
Sr_2RuO_4
CNT

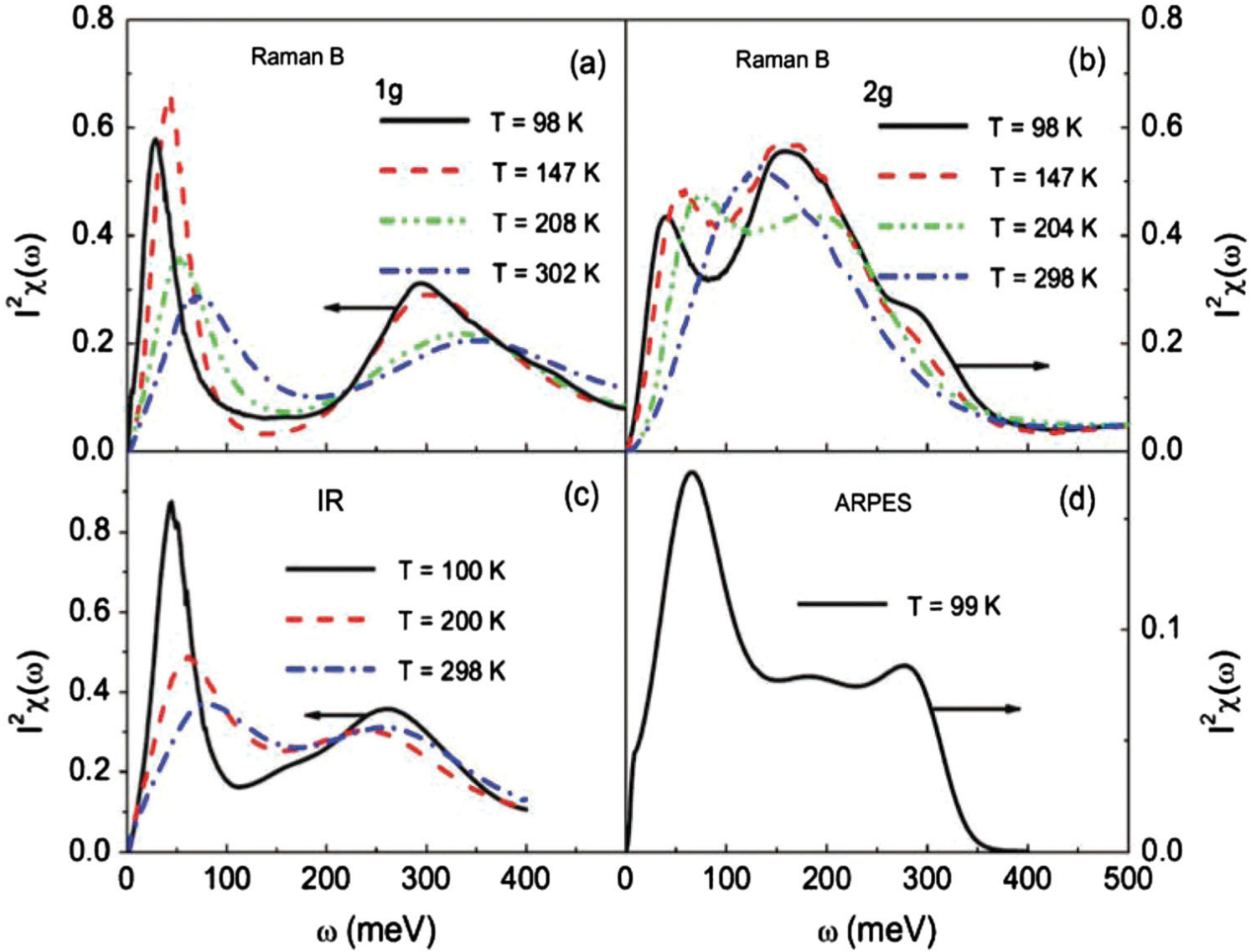
What does optics can tell me?

The conductivity is non-Drude, not a simple Fermi liquid



The SC gap is of the order of 60 meV energy to break Cooper pairs, thus energy that keeps them together…..


Pb
$\alpha^2 F(\omega)$
ω (meV)
MgB_2
ω (cm^{-1})
Γ [$\xi\xi$0] K M [ξ00] Γ [00ξ] A [ξ01/2] L H [$\xi\xi$1/2] A
2×
2×
2×
$\alpha^2 F$, $\alpha^2_{tr} F$
λ = 0.87
λ_{tr} = 0.60
States (cm^{-1})



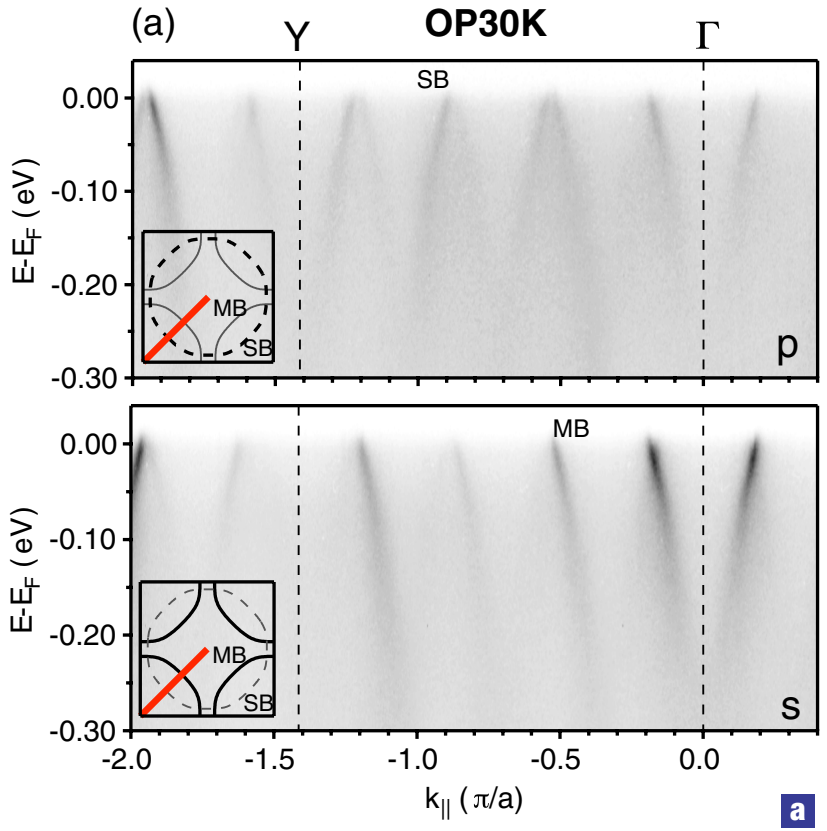
Modes at energies beyond highest phonon energy

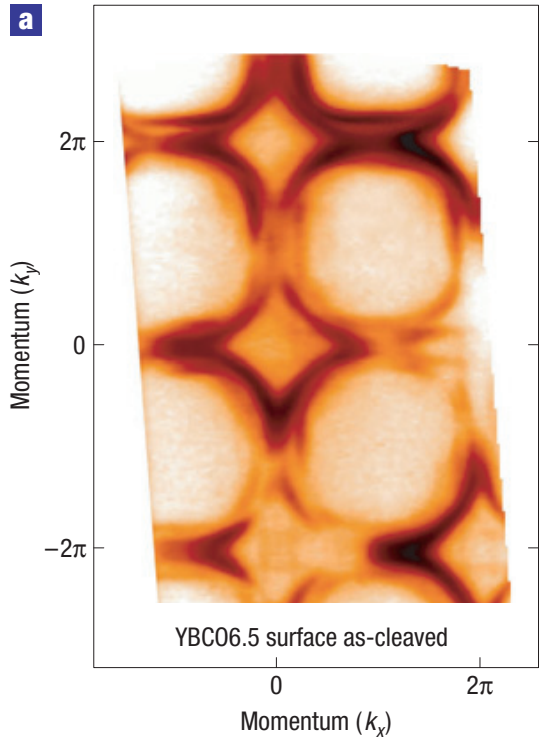
All ARPES data shows nice Fermi surfaces with well-defined bands

Clearly mettalic and Fermi liquid

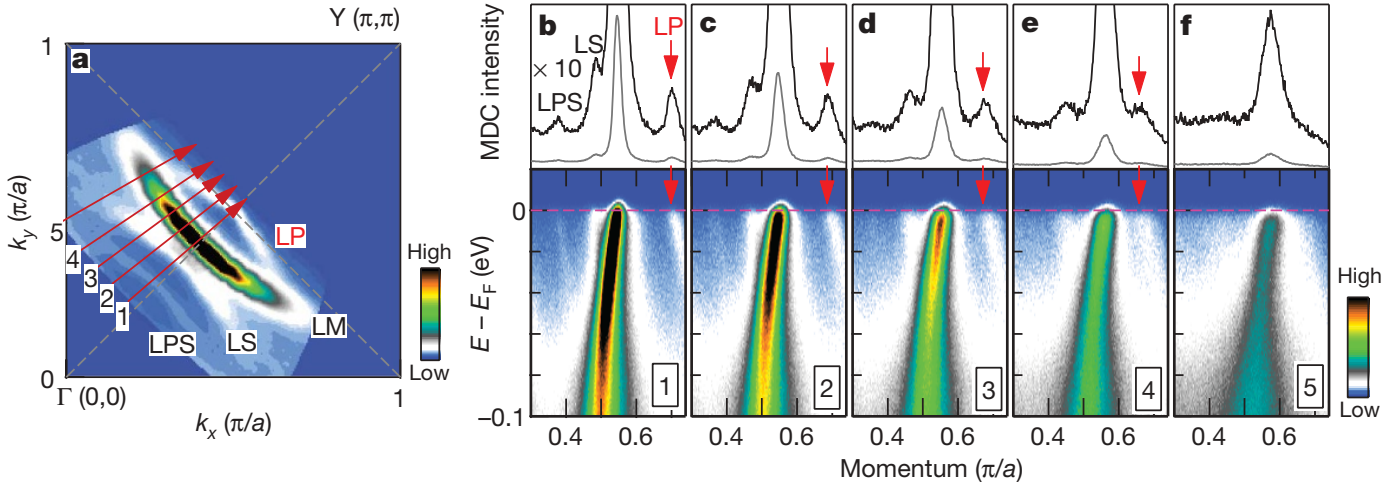
In contrast to optical conductivity

What are these bands???

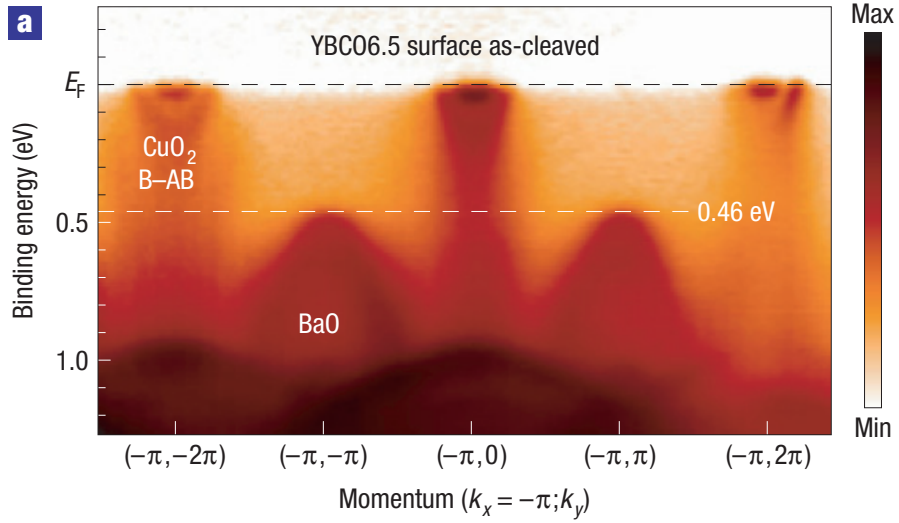




DOI: 10.1103/PhysRevLett.106.127005



doi:10.1038/nature08521



DOI: 10.1038/nphys998

d-wave superconducting gap

Bi2Sr2CaCu2O8+x TC = 87 K