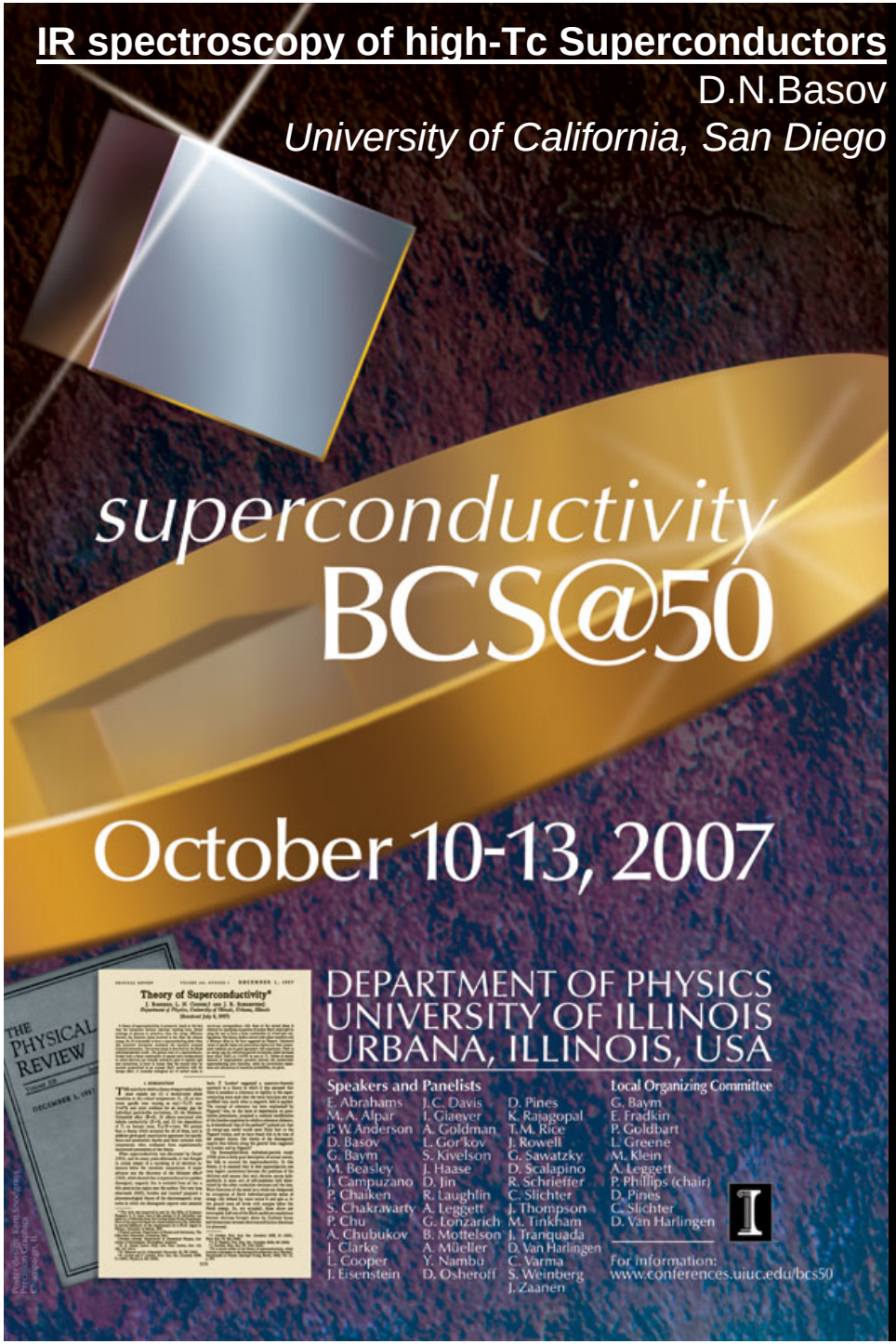
IR spectroscopy of high-Tc Superconductors

D.N.Basov
University of California, San Diego



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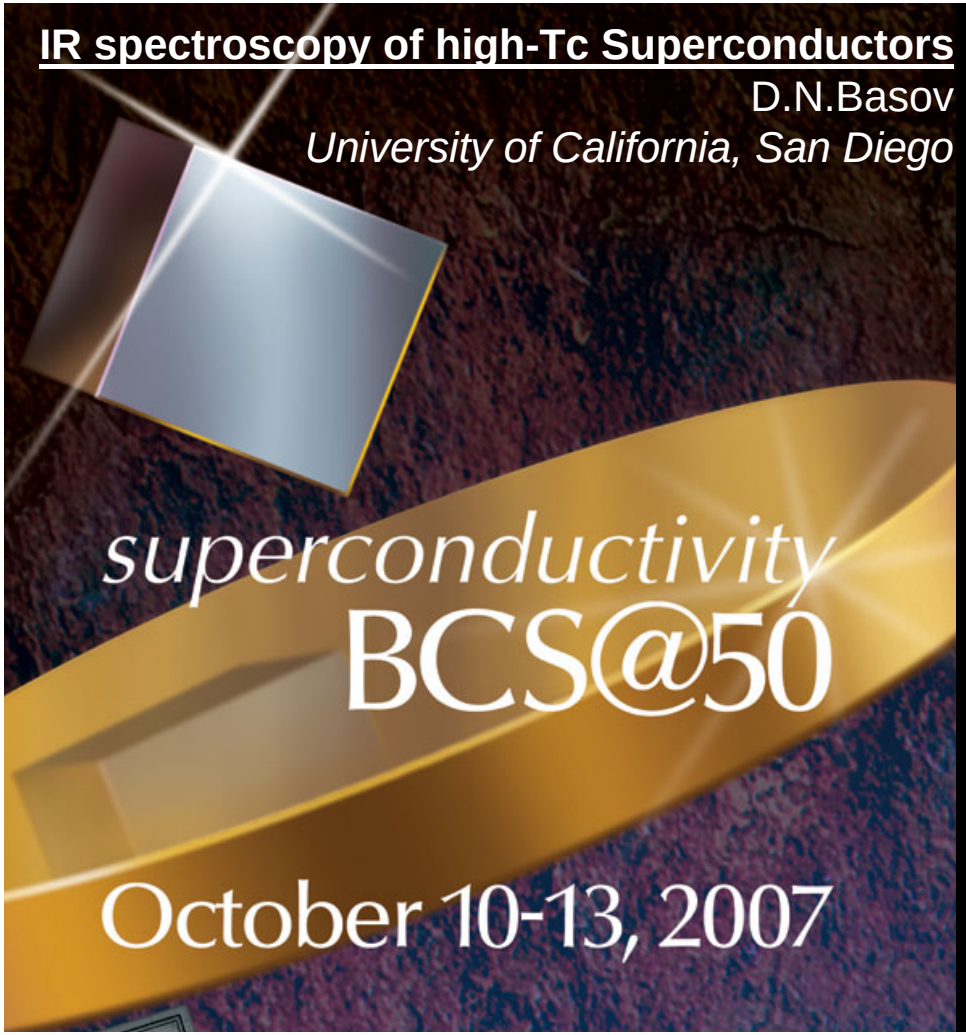


Energy Gap Interpretation of Experiments on Infrared Transmission through Superconducting Films*

M. TINKHAM

Department of Physics, University of California, Berkeley, California

(Received September 4, 1956)

PHYSICAL REVIEW LETTERS
APRIL 15, 1959

DETERMINATION OF THE SUPERCONDUCTING SKIN DEPTH FROM THE ENERGY GAP AND SUM RULE*

M. Tinkham
Department of Physics, University of California, Berkeley, California

and

R. A. Ferrell
Physics Department, University of Maryland, College Park, Maryland

(Received March 11, 1959)

PHYSICAL REVIEW VOLUME 108, NUMBER 2 OCTOBER 15, 1957

Conductivity of Superconducting Films for Photon Energies between 0.3 and $40kT_c$*

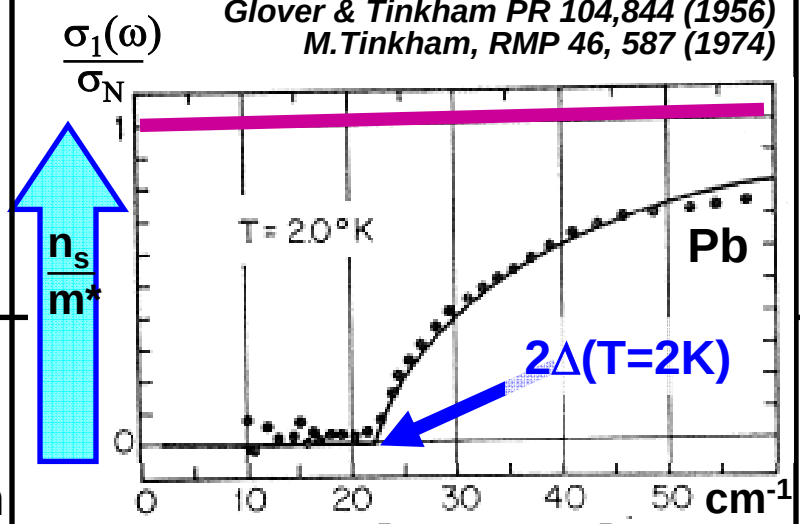
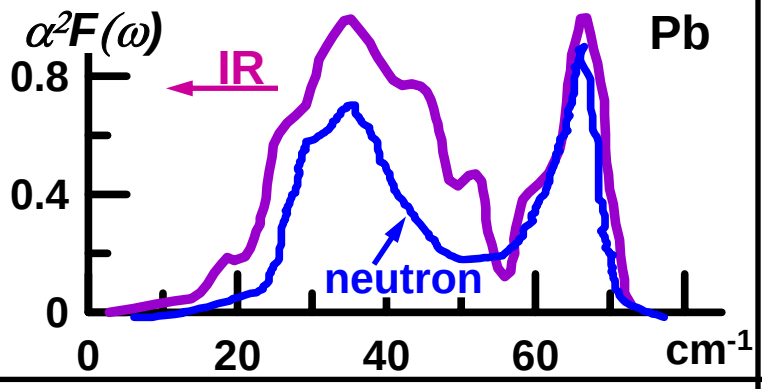
R. E. GLOVER, III,† *University of California, Berkeley, California and University of North Carolina, Chapel Hill, North Carolina*

AND

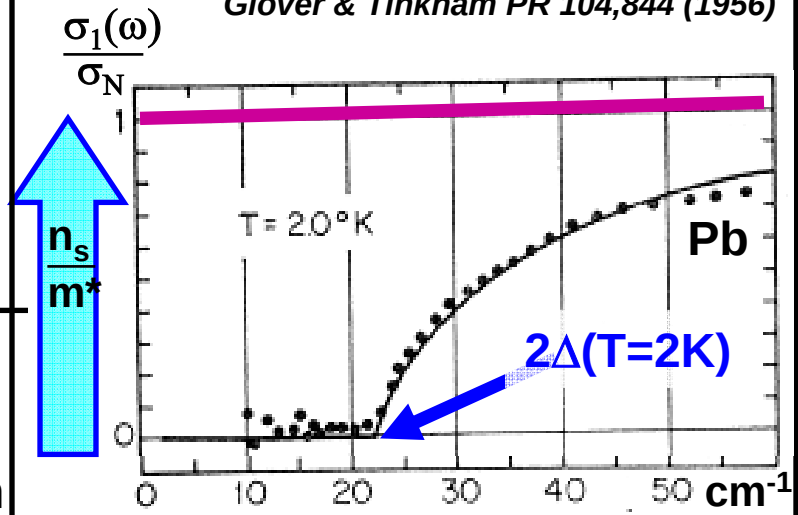
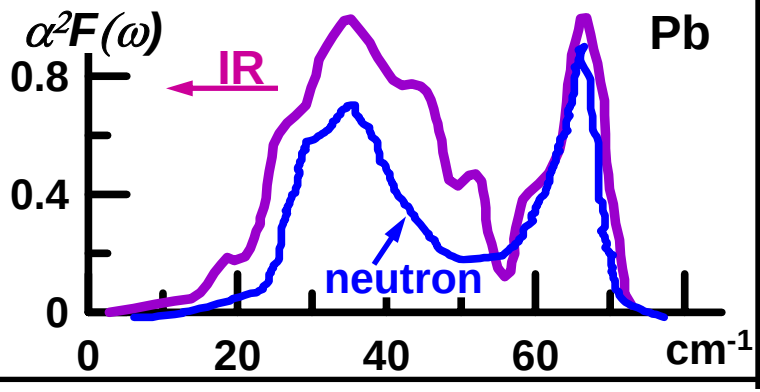
M. TINKHAM, *University of California, Berkeley, California*

(Received May 17, 1957)

Shedding Infrared Light on Superconductivity

	Elemental superconductors	High-T_c cuprates
Energy gap	*Glover & Tinkham PR 104,844 (1956)* *M.Tinkham, RMP 46, 587 (1974)* 	**pseudogap**
Superconducting condensate, penetration depth & sum rules	$\rho_s = \frac{n_s}{m^*} = \int d\omega \left[\sigma_1^N - \sigma_1^{SC}\right]$ *Ferrell-Glover-Tinkham sum rule*	**Energy scales: > 10^2-10^3 kT_c** $\rho_s = \int_{0+} d\omega \left[\sigma_1^N - \sigma_1^{SC}\right]$ **+ *ΔK***
Pairing "glue"	*R.R.Joyce and P.L. Richards PRL 24, 1007 (67)* *Farnworth and Timusk PRB10, 2799 (76)* 	**Phonons?** **Magnetic excitations?** **Both/Neither?** **"modes"?** **No glue is needed/wanted?**

Shedding Infrared Light on Superconductivity

	Elemental superconductors	High-T_c cuprates
Normal state	**Fermi liquid**	**1. Doped Mott insulators**
Energy gap	*Glover & Tinkham PR 104,844 (1956)*  $\rho_s = \frac{n_s}{m^*} = \int d\omega \left[\sigma_1^N - \sigma_1^{SC}\right]$ *Ferrell-Glover-Tinkham sum rule*	**2. pseudogap**
Superconducting condensate, penetration depth & sum rules		**3.** **Energy scales: > 10^2-10^3 kT_c** $\rho_s = \int_{0+} d\omega \left[\sigma_1^N - \sigma_1^{SC}\right]$ **+ ΔK**
Pairing "glue"	*R.R.Joyce and P.L. Richards PRL 24, 1007 (67)* *Farnworth and Timusk PRB10, 2799 (76)* 	**4.** **Phonons?** **Magnetic excitations?** **Both/Neither?** **"modes"?** **No glue is needed/wanted?**

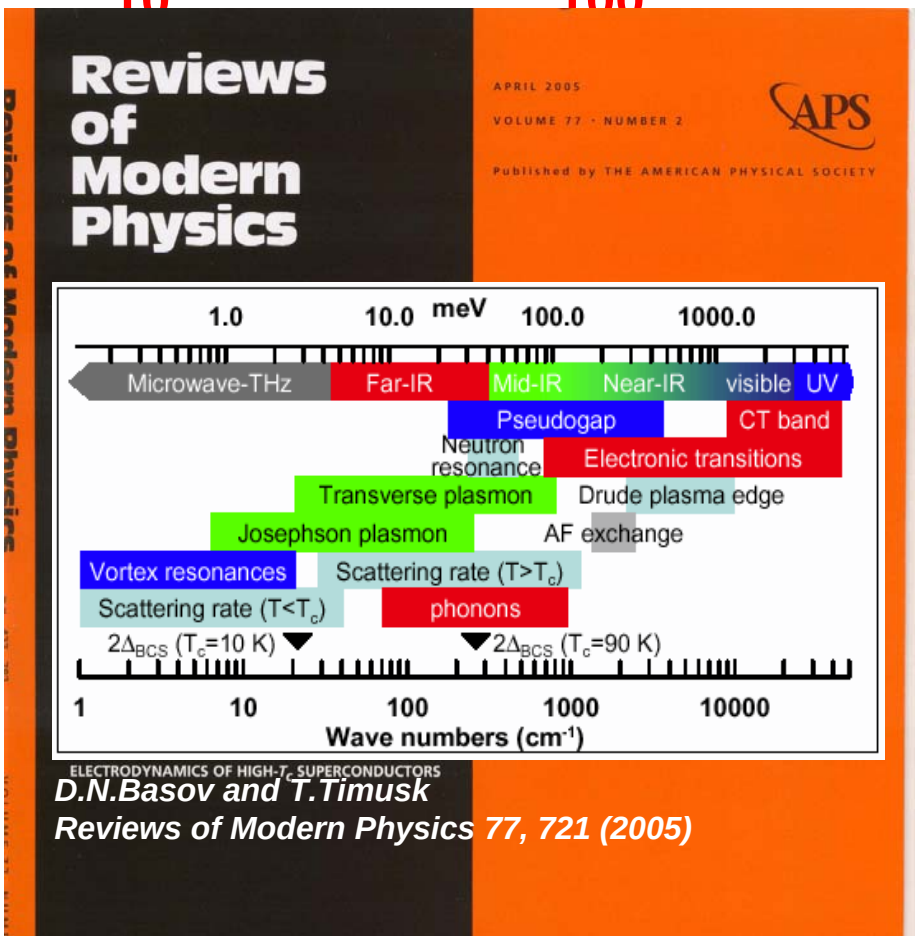
IR spectroscopy of high-Tc superconductors

1 10 100 1000 meV

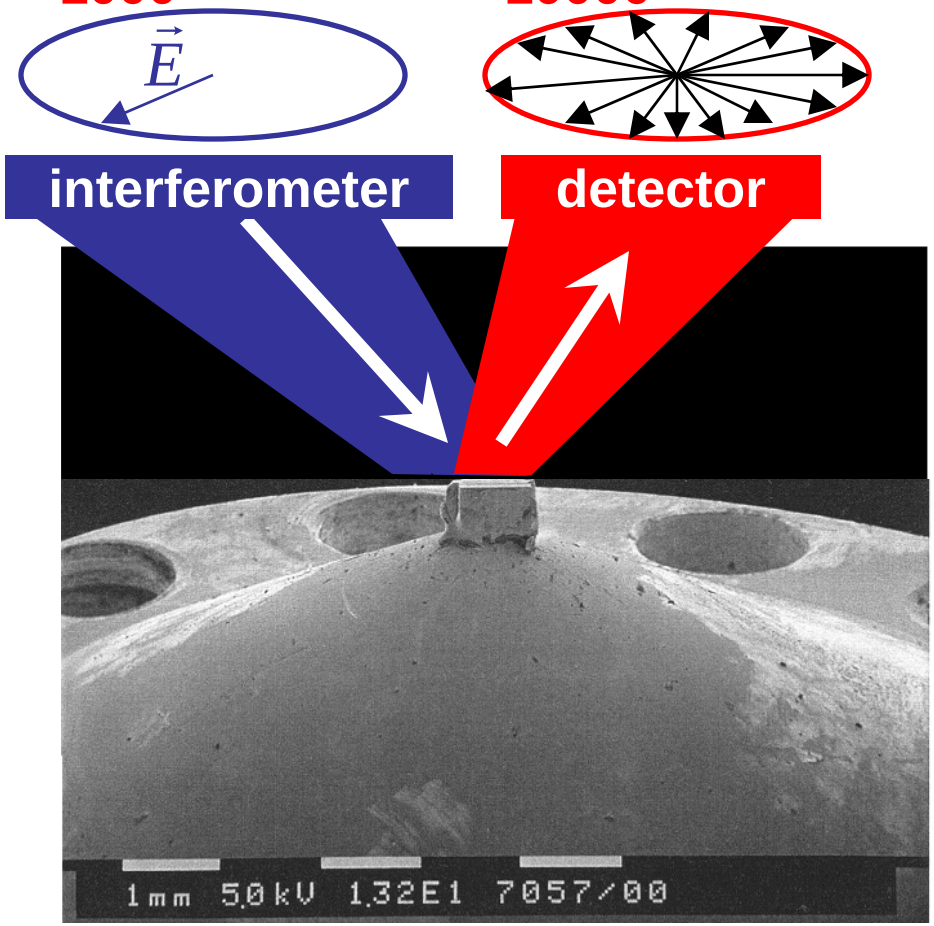
Sub-THz | **Far-IR** | **mid-IR - visible** | **UV**

"Infrared" spectroscopy @ UCSD

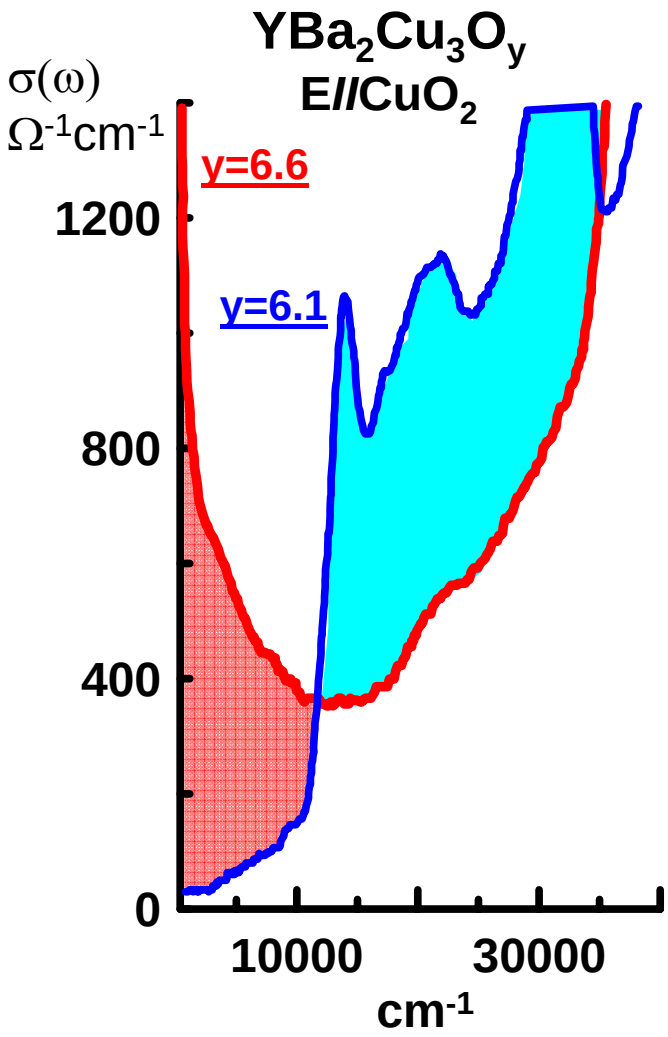
10 100 1000 10000 cm^{-1}

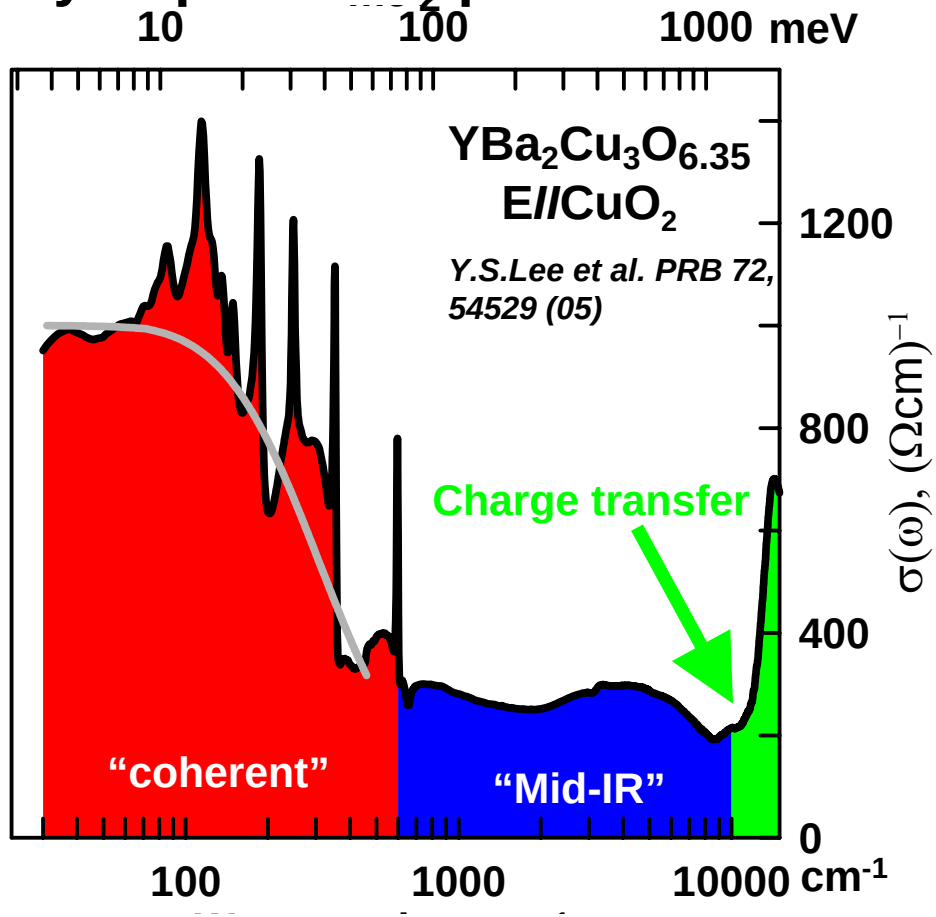


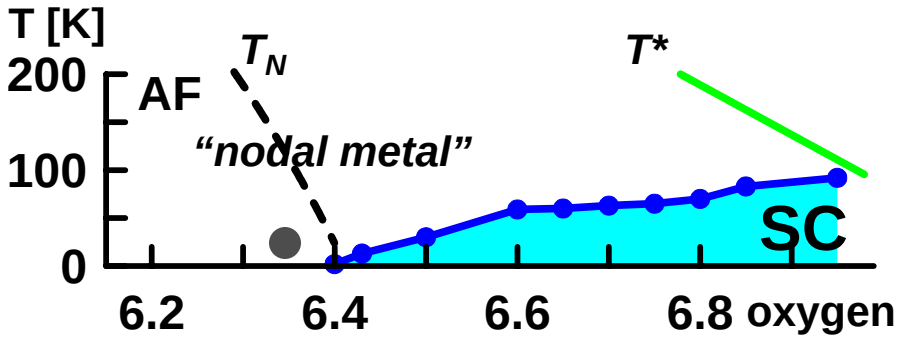
D.N.Basov and T.Timusk
Reviews of Modern Physics 77, 721 (2005)



Charge dynamics in weakly doped CuO_2 planes

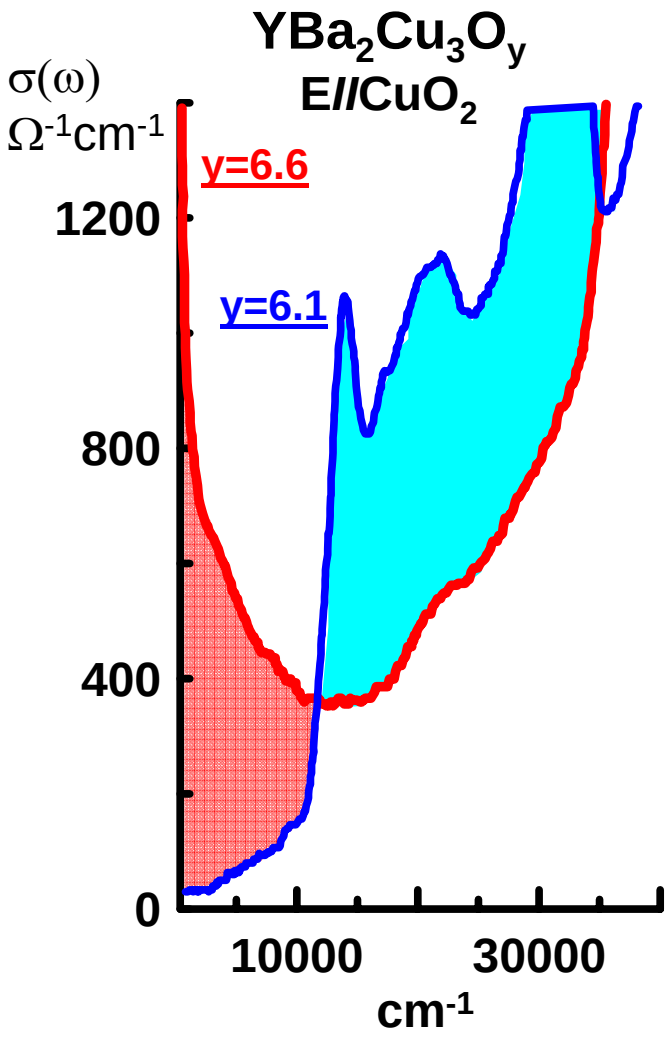


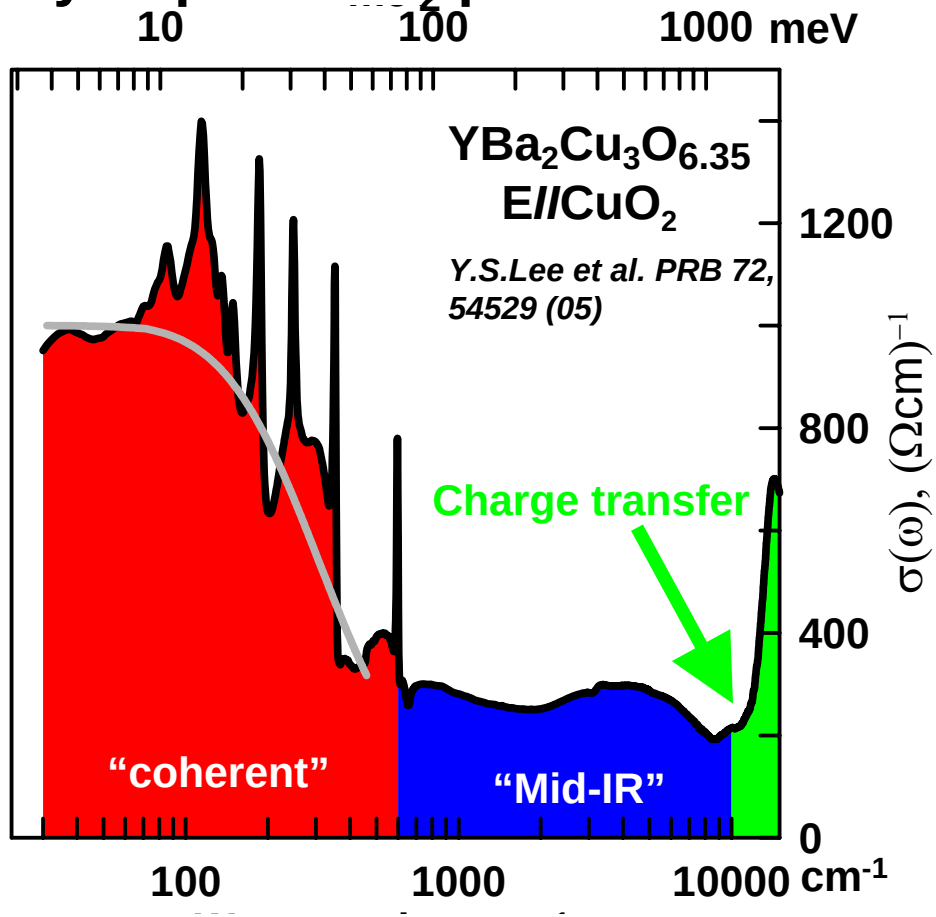


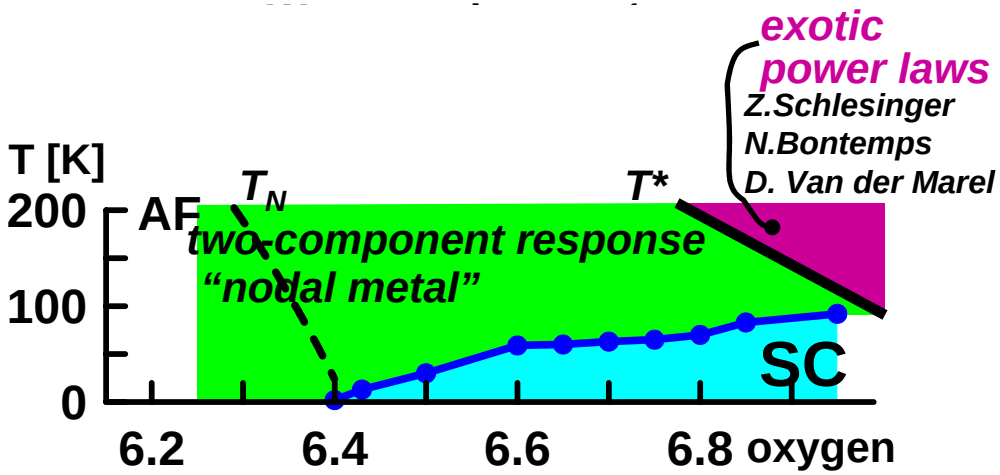


S.L.Cooper, D.Reznik, A.Kotz, M.A.Karlow, R.Liu, M.V.Klein, W.C.Lee, J. Gianitzakis, D.M.Ginsberg, B.W.Veal, and A.P.Paulikas PRB 47, 8233 (1993)

Charge dynamics in weakly doped CuO_2 planes







S.L.Cooper, D.Reznik, A.Kotz, M.A.Karlow, R.Liu, M.V.Klein, W.C.Lee, J. Gianitzakis, D.M.Ginsberg, B.W.Veal, and A.P.Paulikas PRB 47, 8233 (1993)

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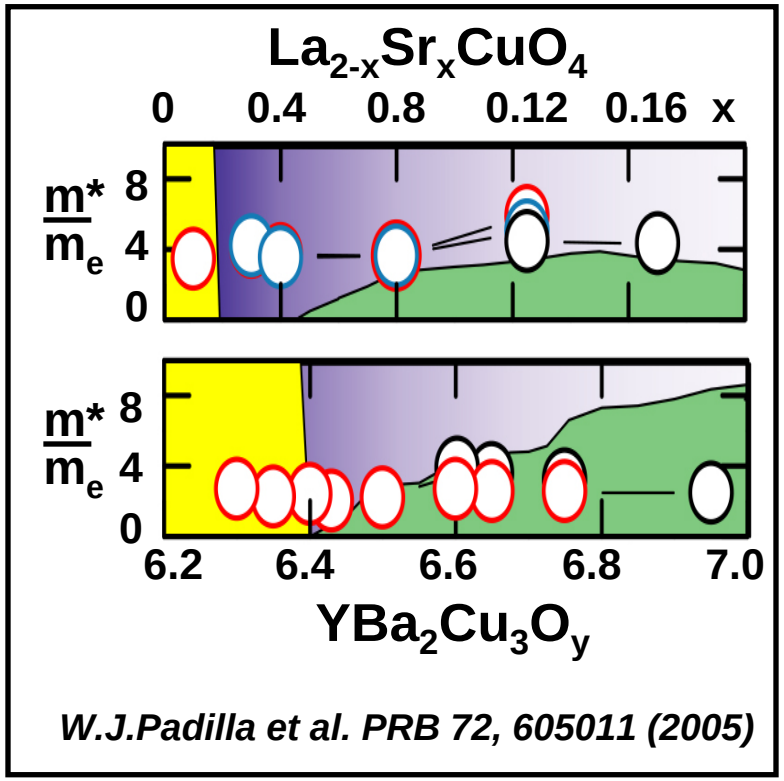
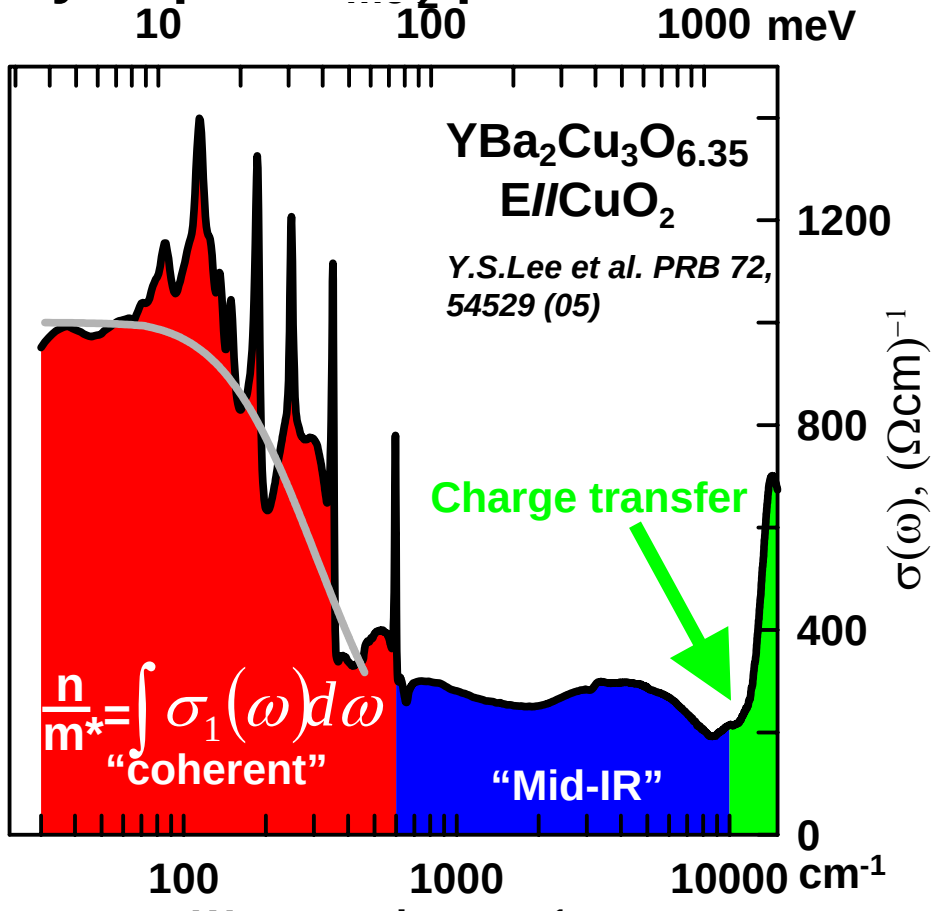
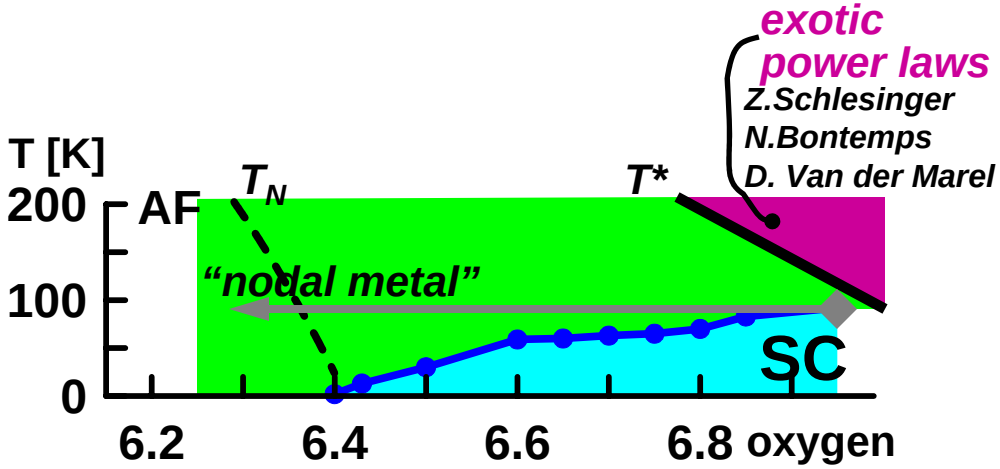




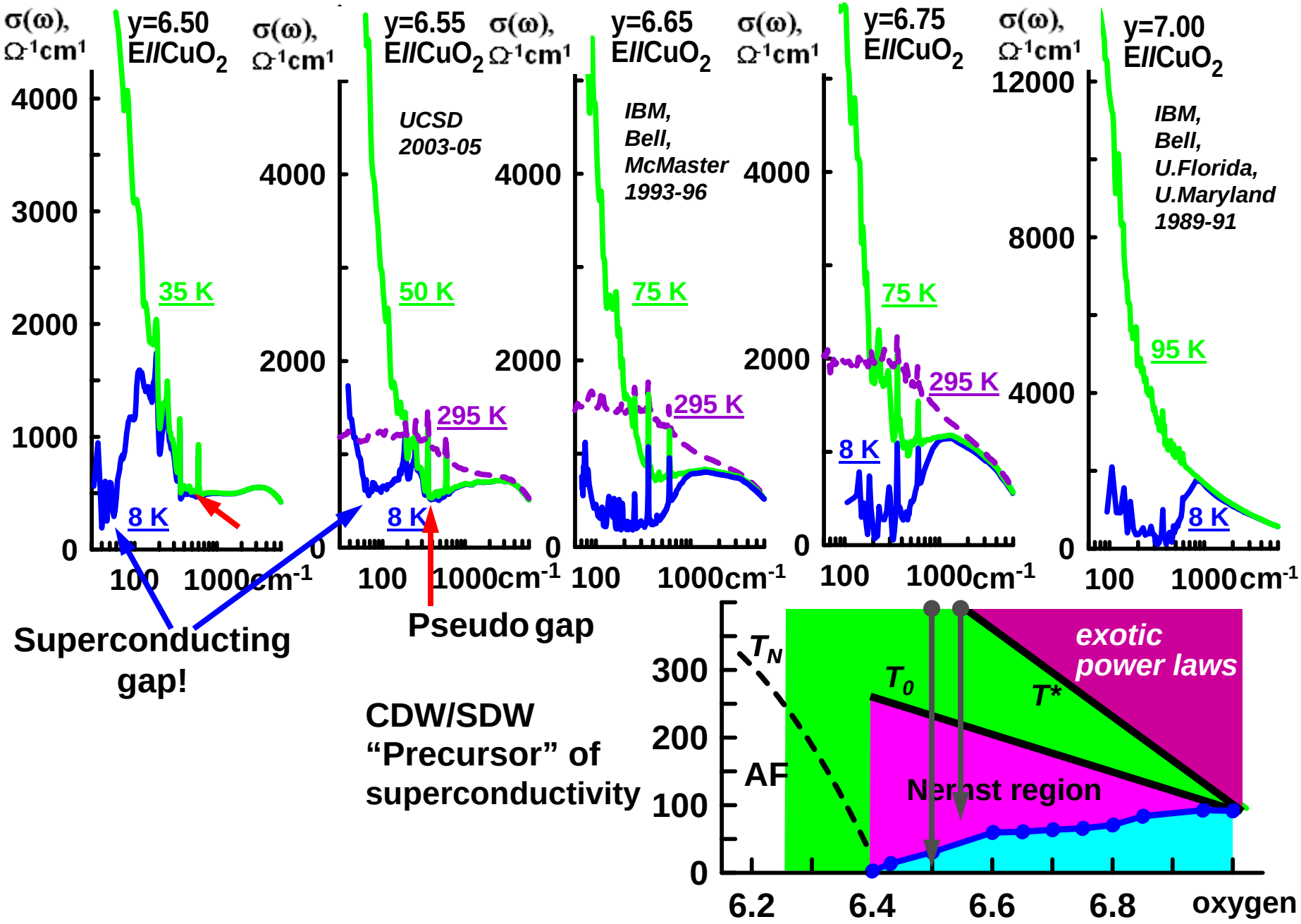
Light quasiparticles across the phase diagram:

Penetration depth, Mobility

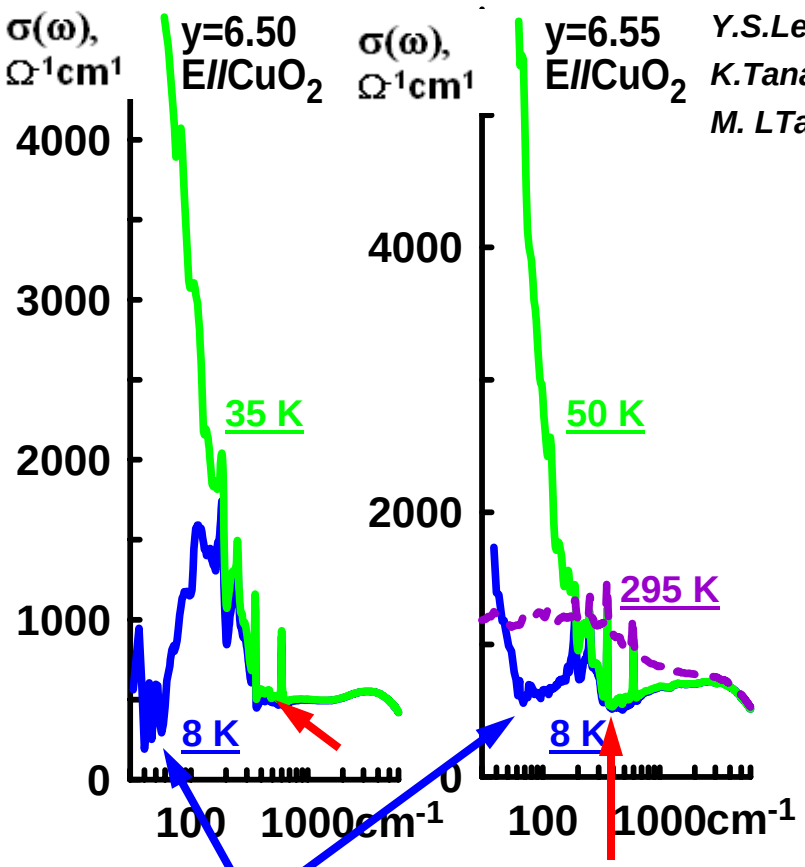
Quantum oscillations



Pseudogap and superconducting gap: $YBa_2Cu_3O_y$



Pseudogap and superconducting gap



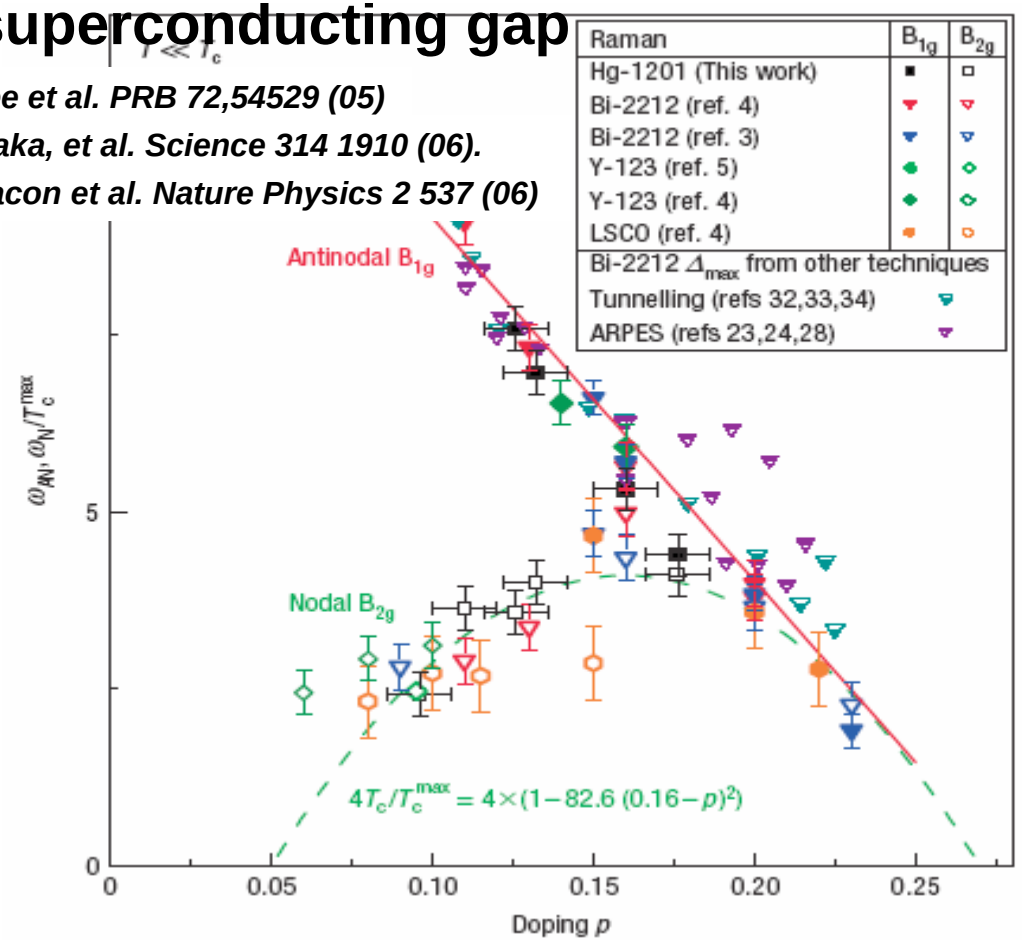
Superconducting gap!

Pseudo gap

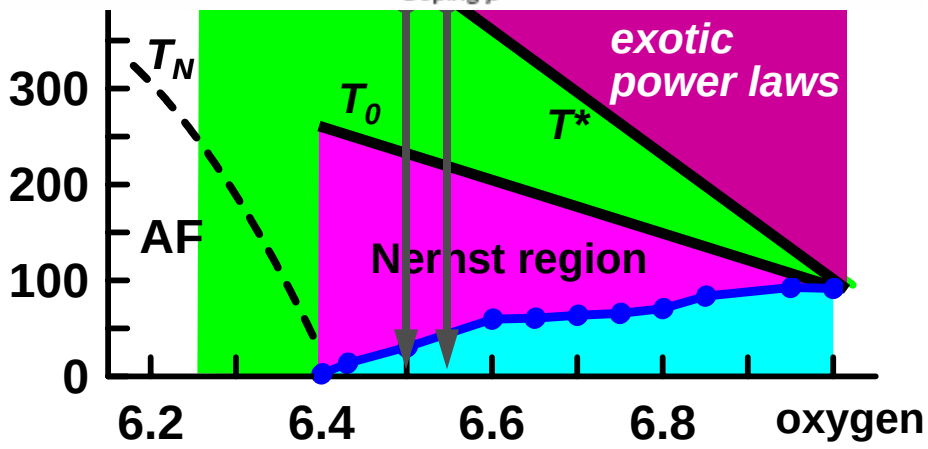
Y.S.Lee et al. PRB 72,54529 (05)

K.Tanaka, et al. Science 314 1910 (06).

M. LTacon et al. Nature Physics 2 537 (06)



CDW/SDW "Precursor" of superconductivity



Pseudogap and superconducting gap

Y.S.Lee et al. PRB 72,54529 (05)

K.Tanaka, et al. Science 314 1910 (06).

M. LTacon et al. Nature Physics 2 537 (06)

REVIEWS OF MODERN PHYSICS, VOLUME 78, JANUARY 2006

Doping a Mott insulator: Physics of high-temperature superconductivity

Patrick A. Lee

Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

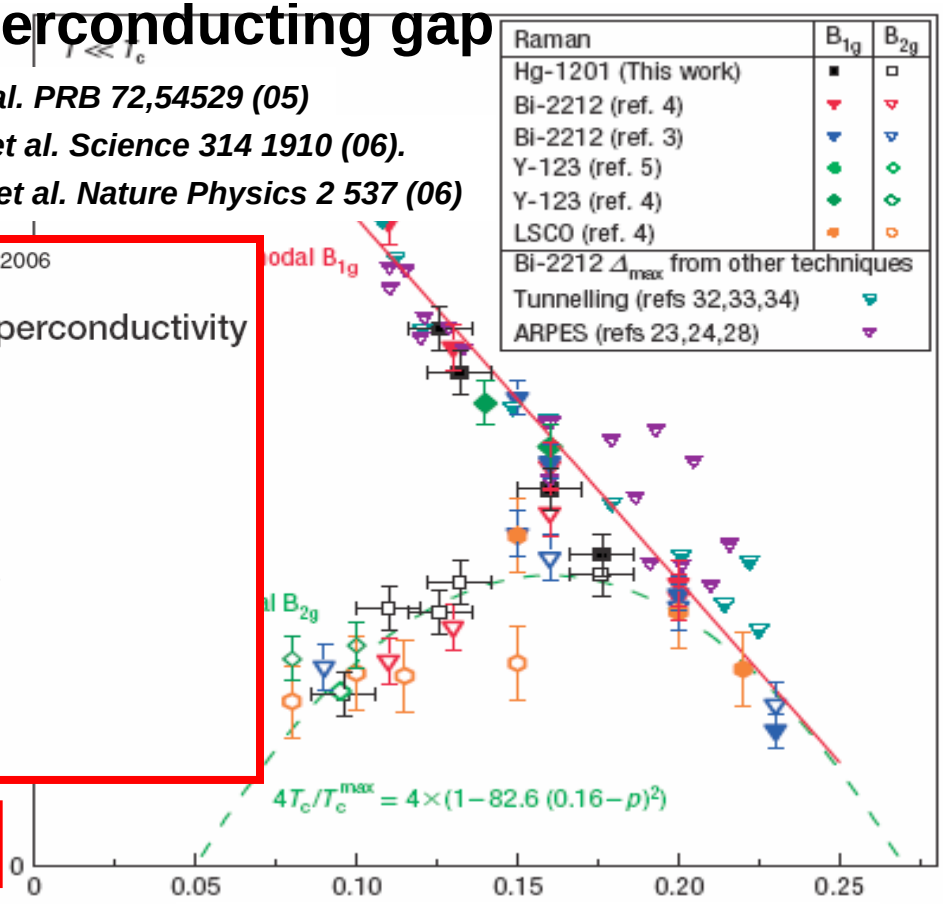
Naoto Nagaosa

CREST, Department of Applied Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan and Correlated Electron Research Center, AIST, Tsukuba Central 4, Tsukuba 305-8562, Japan

Xiao-Gang Wen

Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

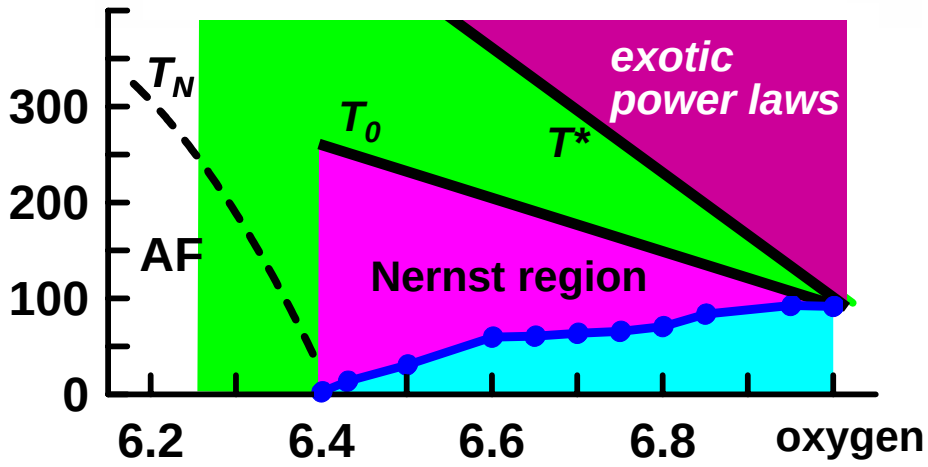
(Published 6 January 2006)



Pseudogap phenomenology

"thermal"

"new state of matter"



A.Paramekanti, M.Randeria and N. Trivedi PRL87, 217002 (2001)

Kristjan Haule and Gabriel Kotliar PRB 2007.

Sum rules and high energy effects at the onset of superconductivity

COMMENTARY

What DO we know about high T_c?

ANTHONY J. LEGGETT

Nature-Physics 2, 134 (2006)

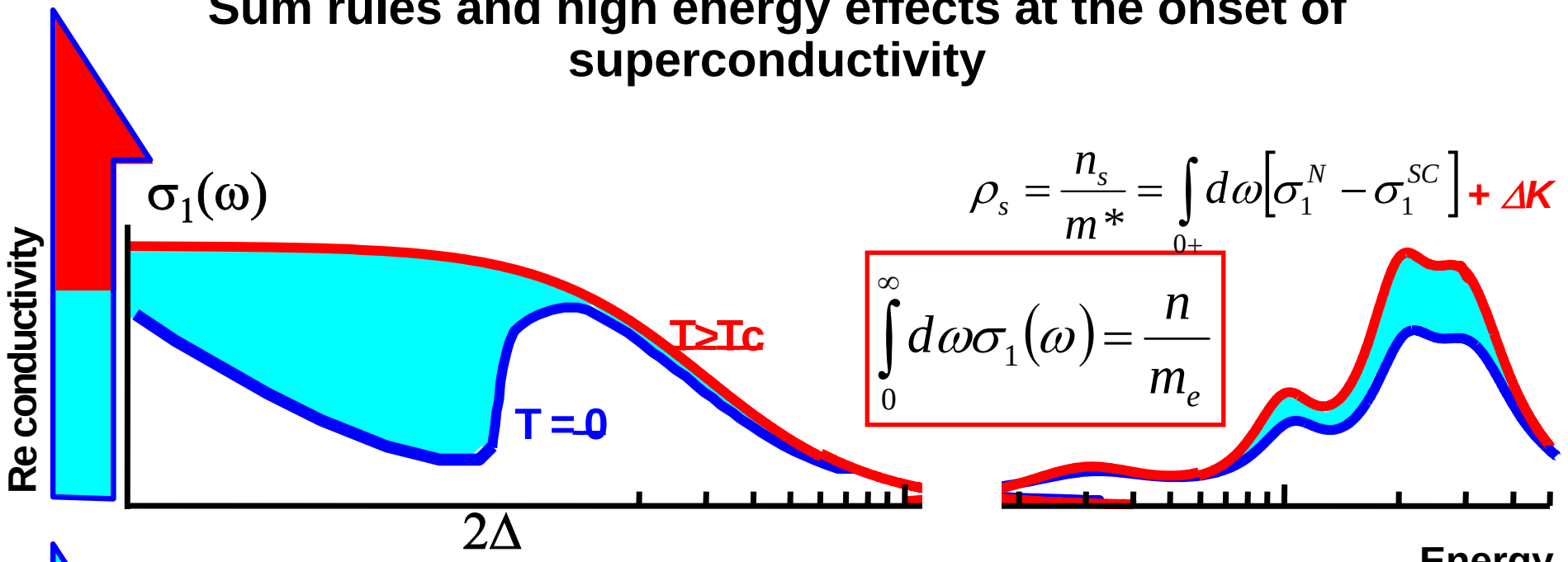
background not explicitly described by the low-energy phenomenology is vastly more important quantitatively than in a typical 'textbook' metal (as determined from angle-resolved photoemission spectroscopy (ARPES), optical spectroscopy and transmission electron energy loss spectroscopy (EELS), to name a few). On the other hand, the superconducting state seems to behave in many ways suspiciously like a classic 'superfluid Fermi liquid' such as helium-3.

The way in which I have framed, above, the theoretical problem posed by high-temperature

A COMPLETE THEORY OF HIGH-TEMPERATURE SUPERCONDUCTIVITY WOULD STILL HAVE TO GIVE AN ACCOUNT OF THE HIGH-ENERGY EFFECTS OF ITS ONSET.

superconductivity is, I believe, accepted at least implicitly by most though not all theoretical papers in the field over the last twenty years; in particular, inputs **2**, **3** and **4**, as well as a number of other more specific assumptions, are automatically implicit in any calculation that starts from a two-dimensional Hubbard (kinetic energy plus on-site repulsive potential) or *t*–*J* model (strong correlation limit of

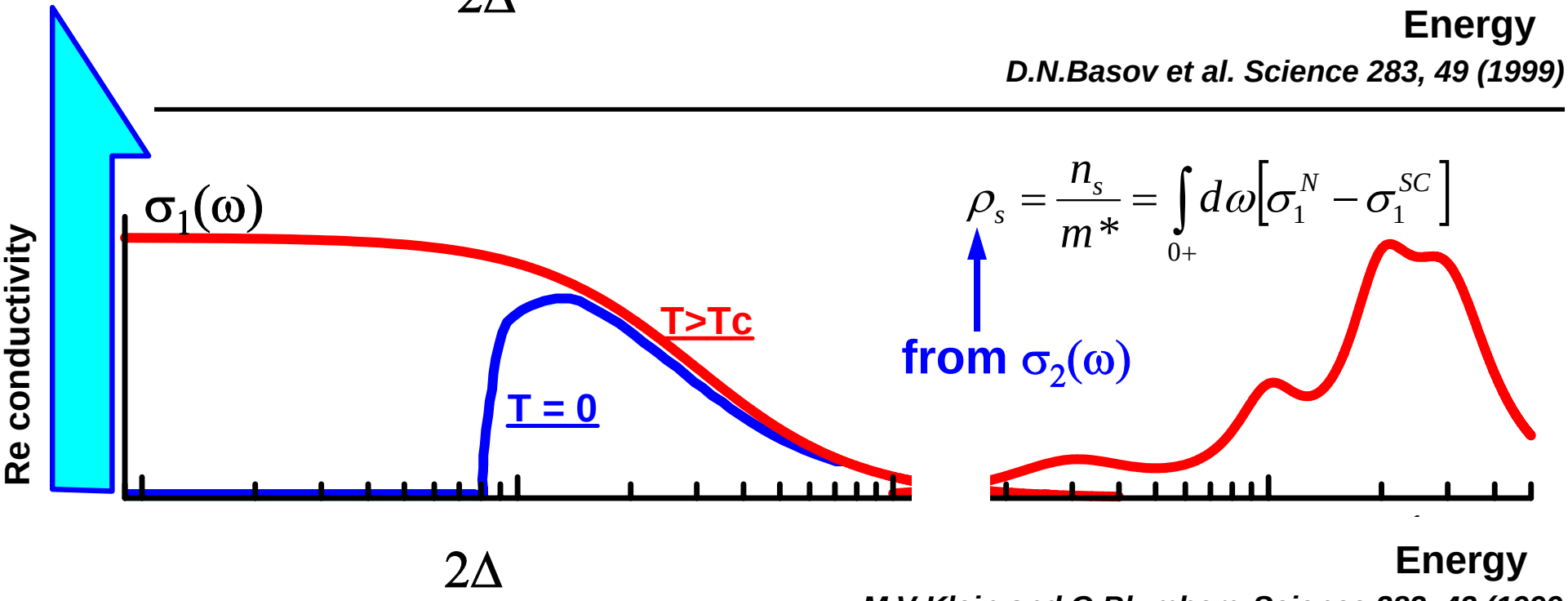
Sum rules and high energy effects at the onset of superconductivity



$$\rho_s = \frac{n_s}{m^*} = \int_{0+} d\omega \left[\sigma_1^N - \sigma_1^{SC}\right] + \Delta K$$

$$\int_0^\infty d\omega \sigma_1(\omega) = \frac{n}{m_e}$$

D.N.Basov et al. Science 283, 49 (1999)



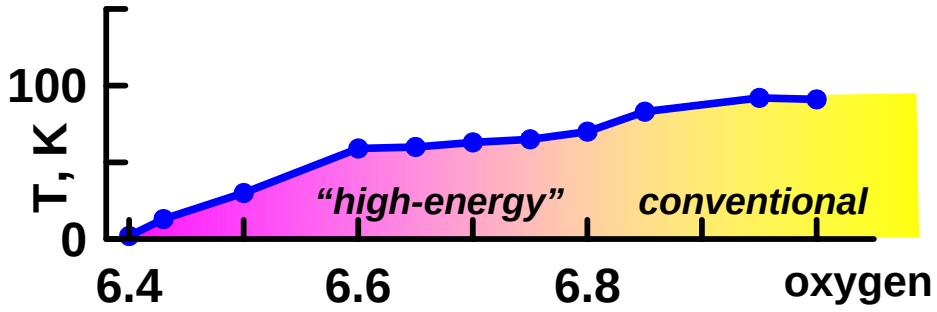
$$\rho_s = \frac{n_s}{m^*} = \int_{0+} d\omega \left[\sigma_1^N - \sigma_1^{SC}\right]$$

M.V.Klein and G.Blumberg Science 283, 42 (1999

Sum rules and high energy effects at the onset of superconductivity

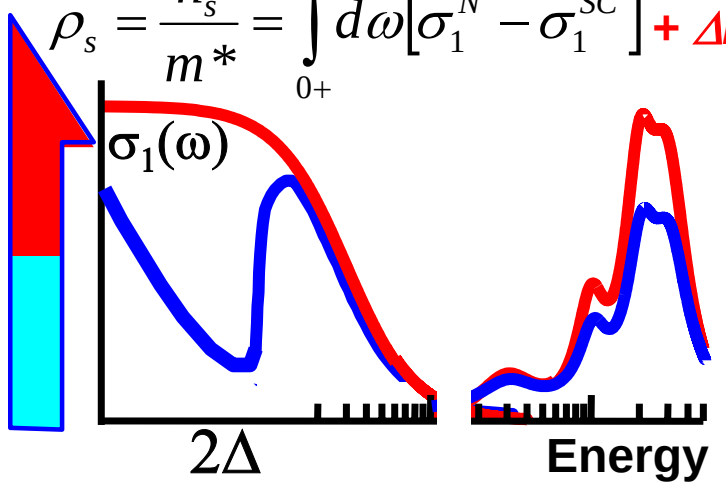
D.N.Basov et al. Science 283, 49 (1999)
M. Rubhausen, et al. PRB63, 224514 (01)
H. Molegraaf, et al. Science 295, 2239 (02)
A.V. Boris, et al. PRL89.277001 (02)
A. B. Kuzmenko, et al. PRL 91.037004 (03)
C.C. Homes et al. PRB69 024514, 2004.
A. F. Santander-Syro, et al. PRB 70, 134504 (04)
V. Boris, et al. Science 304, 708 (04)
Guy Deutscher et al. PRB 72, 92504 (05)
F.Carbone et al. PRB 74, 024502 (06)
F.Carbone et al. PRB 74, 064510 (06)
Li Yu, et al. cond matt 2007
more…

1. **Both in-plane and c-axis**
2. **La214, YBCO, Tl2201, Bi2212, etc**
3. **Doping trends:**



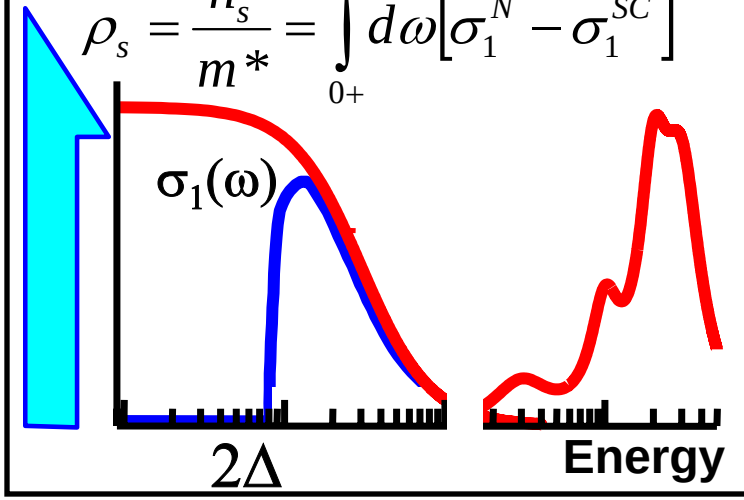
High-Tc cuprates

$$\rho_s = \frac{n_s}{m^*} = \int_{0+} d\omega \left[\sigma_1^N - \sigma_1^{SC}\right] + \Delta K$$



BCS superconductors

$$\rho_s = \frac{n_s}{m^*} = \int_{0+} d\omega \left[\sigma_1^N - \sigma_1^{SC}\right]$$



Inter-plane magneto-optics of $YBa_2Cu_3O_y$

D.N.Basov et al. Science 283, 49 (1999)
M. Rubhausen, et al. PRB63, 224514 (01)
H. Molegraaf, et al. Science 295, 2239 (02)
A.V. Boris, et al. PRL89.277001 (02)
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C.C. Homes et al. PRB69 024514, 2004.
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Guy Deutscher et al. PRB 72, 92504 (05)
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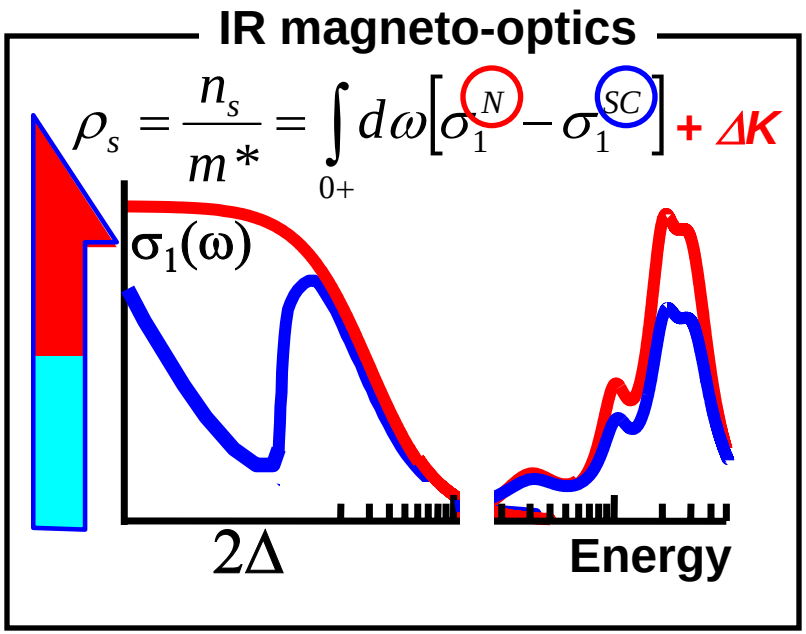
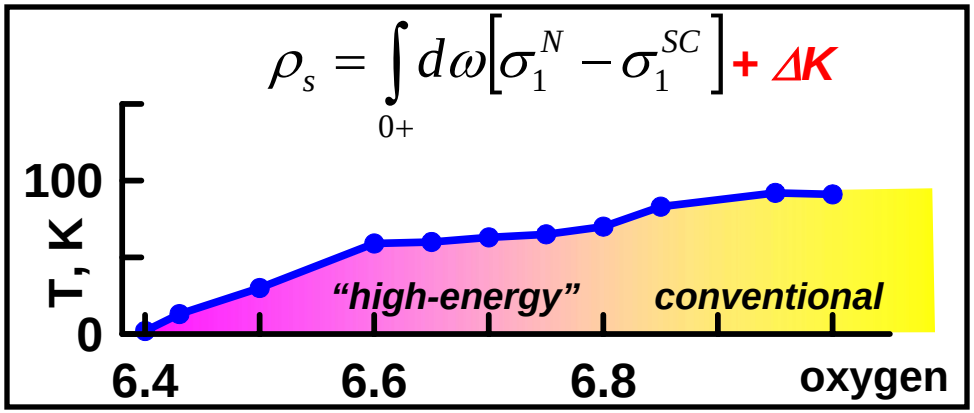
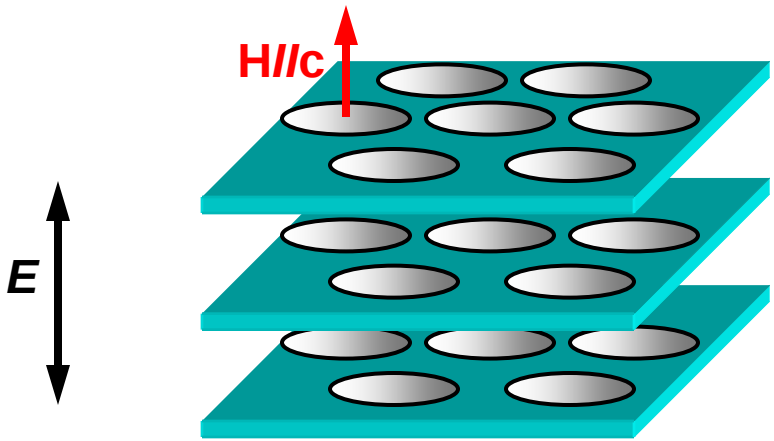
Li Yu, et al. cond matt 2007
more…







Strong Coupling Effects in Cuprates

PRL 98, 207002 (2007) PHYSICAL REVIEW LETTERS week ending 18 MAY 200

High Energy Scales in the Optical Self-Energy of the Cuprate Superconductors

J. Hwang,[1] E. J. Nicol,[2] T. Timusk,[1,3] A. Knigavko,[4] and J. P. Carbotte[1,3]

VOLUME 78, NUMBER 9 PHYSICAL REVIEW LETTERS 3 MARCH 1997

Momentum, Temperature, and Doping Dependence of Photoemission Lineshape and Implications for the Nature of the Pairing Potential in High-T_c Superconducting Materials

Z.-X. Shen[1] and J. R. Schrieffer[2]

VOLUME 88, NUMBER 25 PHYSICAL REVIEW LETTERS 24 JUNE 2002

Spin–1 Neutron Resonance Peak Cannot Account for Electronic Anomalies in the Cuprate Superconductors

Hae-Young Kee,[1,2] Steven A. Kivelson,[1] and G. Aeppli[3]

Evidence for ubiquitous strong electron–phonon coupling in high-temperature superconductors

A. Lanzara*†, P. V. Bogdanov*, X. J. Zhou*, S. A. Kellar*, D. L. Feng*, E. D. Lu†, T. Yoshida‡, H. Eisaki*, A. Fujimori‡, K. Kishio§, J.-I. Shimoyama§, T. Noda‖, S. Uchida‖, Z. Hussain† & Z.-X. Shen*

Coupling strength of charge carriers to spin fluctuations in high-temperature superconductors

J. P. Carbotte*, E. Schachinger† & D. N. Basov‡

L REVIEW LETTERS 21 OCTOBER 2

Neutron Resonance in the Cuprates and its Effect on Fermionic Excitations

Ar. Abanov,[1] A. V. Chubukov,[2] M. Eschrig,[3] M. R. Norman,[4] and J. Schmalian[5]

LETTERS

Impurity effects on electron–mode coupling in high-temperature superconductors

K. TERASHIMA[1], H. MATSUI[1], D. HASHIMOTO[1], T. SATO[1,2], T. TAKAHASHI[1,2]*, H. DING[3], T. YAMAMOTO[4] AND K. KADOWAKI[4]

B VOLUME 57, NUMBER 18 1 MAY 1998-II

Collective modes and the superconducting-state spectral function of $Bi_2Sr_2CaCu_2O_8$

M. R. Norman

vision, Argonne National Laboratory, Argonne, Illinois 60439

H. Ding

AL REVIEW LETTERS 6 AUGUST 2001

Interplay of electron-lattice interactions and superconductivity in $Bi_2Sr_2CaCu_2O_{8+\delta}$

Jinho Lee[1], K. Fujita[1,2], K. McElroy[1,3], J. A. Slezak[1], M. Wang[1], Y. Aiura[4], H. Bando[4], M. Ishikado[2], T. Masui[5], J.-X. Zhu[6], A. V. Balatsky[6], H. Eisaki[4], S. Uchida[2] & J. C. Davis[1]

Many more!

Correlation of Tunneling Spectra in $Bi_2Sr_2CaCu_2O_{8+\delta}$ with the Resonance Spin Excitation

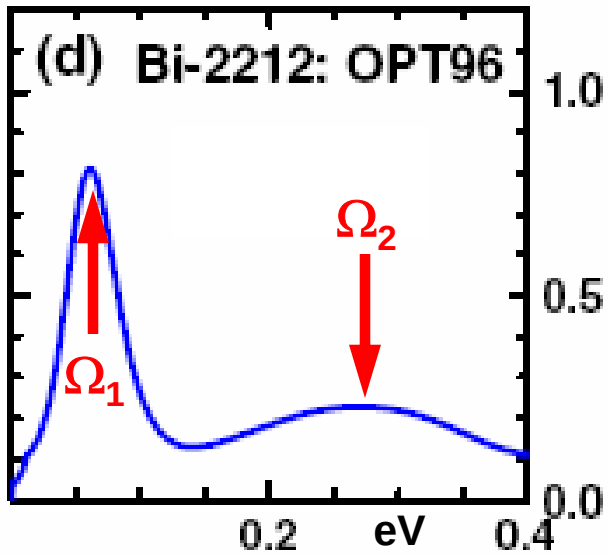
J. F. Zasadzinski,[1,2] L. Ozyuzer,[2,3] N. Miyakawa,[4] K. E. Gray,[2] D. G. Hinks,[2] and C. Kendziora[5]

Strong coupling effects in high T_c cuprates

Problems for phonon interpretation:

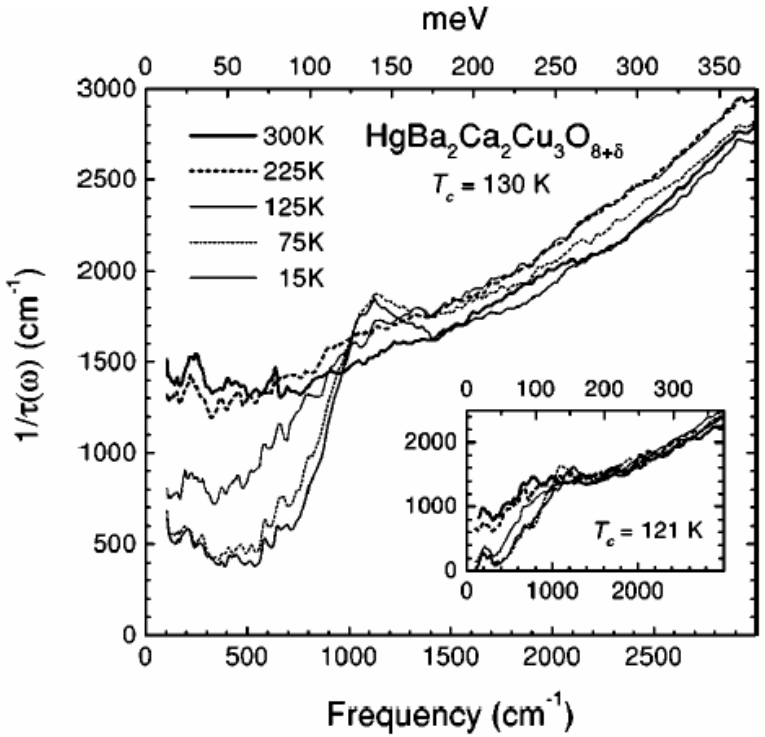
1) $\Omega_2 >> \omega_{ph\ max}$
2) $\Omega_1 > \omega_{ph\ max}$ in Hg1223
3) No isotope effect

J. Hwang, et al PRL98, 207002 (07)



Problems for "magnetic" interpretation:

1) Ω_1 = 35 – 50 meV
2) Ω_1 is too weak!
3) No magnetic field dependence of Ω_1



J. J. McGuire, et al. PRB 62, 8711 (2000)

Strong coupling effects in high T_c cuprates: lattice or magnetic?

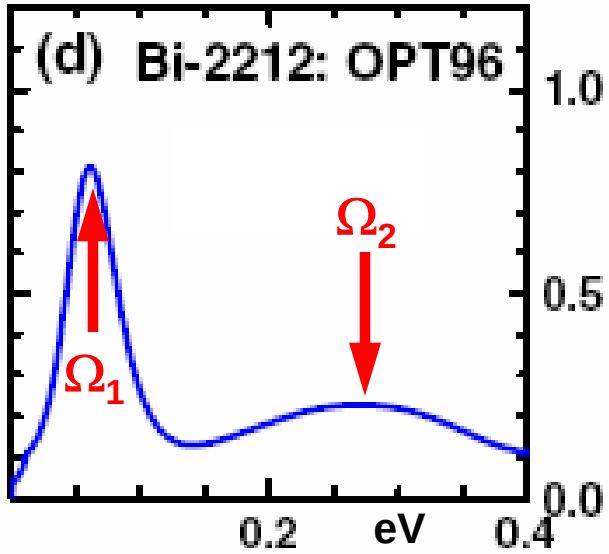
Problems for phonon interpretation:

1) $\Omega_2 >> \omega_{ph\ max}$

2) $\Omega_1 > \omega_{ph\ max}$ **in Hg1223**

3) **No isotope effect**

J. Hwang, et al PRL98, 207002 (07)

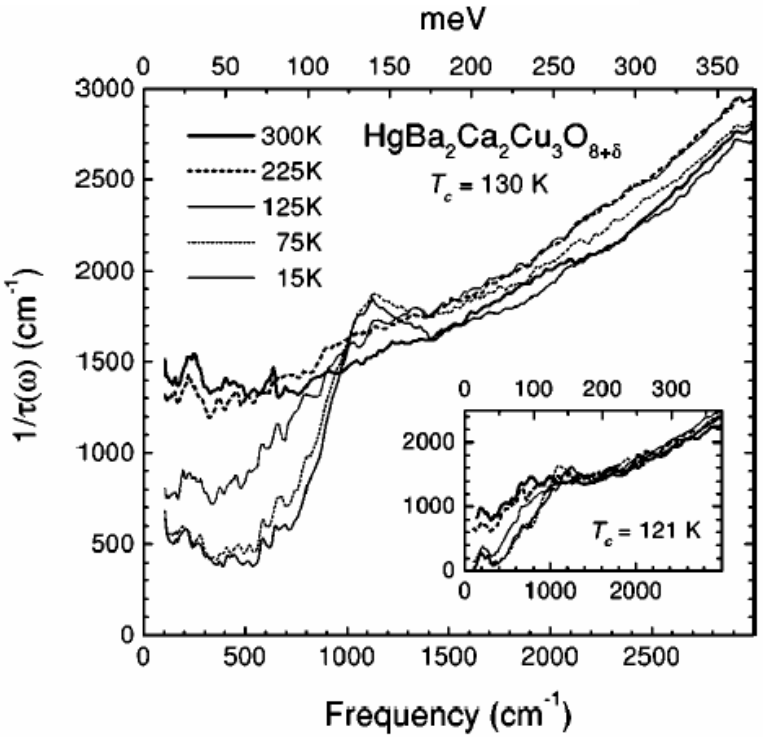


Problems for "magnetic" interpretation:

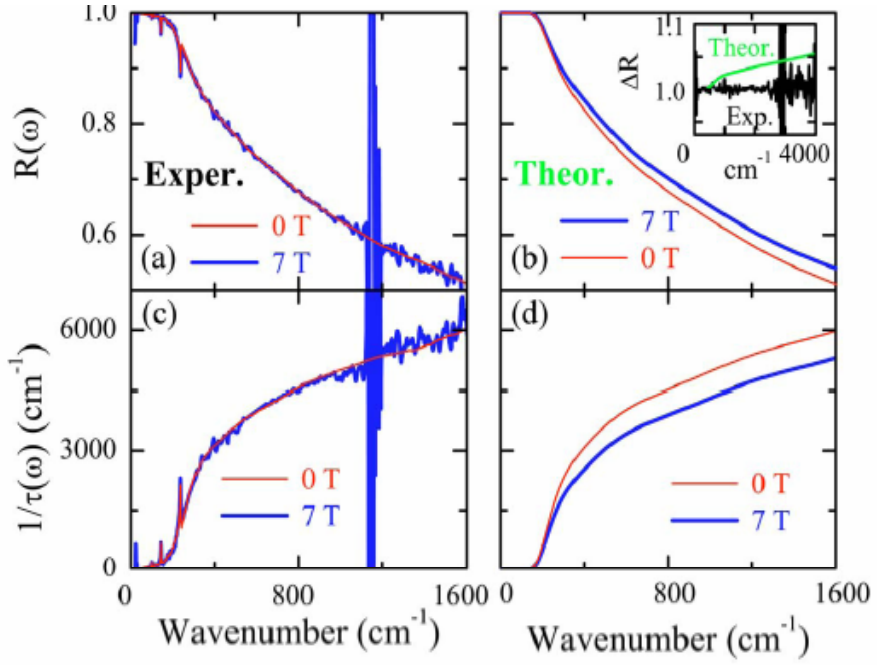
1) Ω_1 = 35 – 50 meV

2) Ω_1 is too weak!

3) No magnetic field dependence of Ω_1

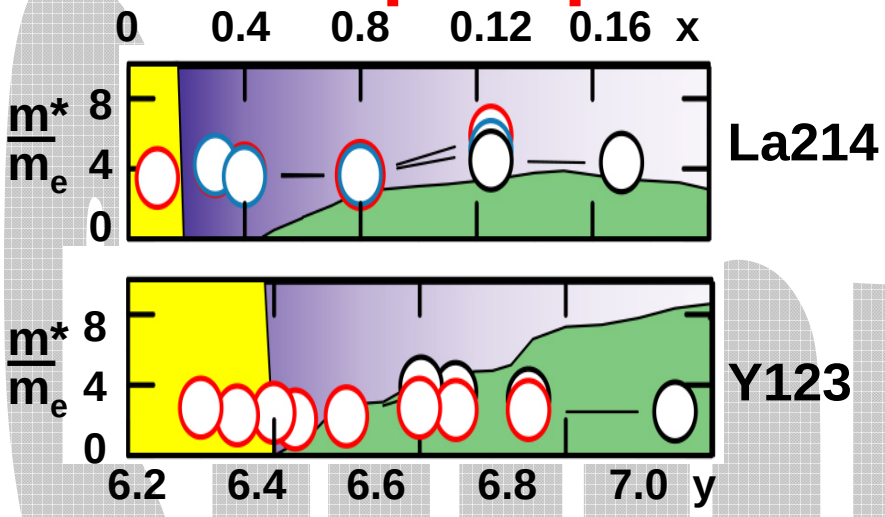


J. J. McGuire, et al. PRB 62, 8711 (2000)



Y.S.Lee et al. PRB 72,54529 (05)

Light, mobile quasiparticles

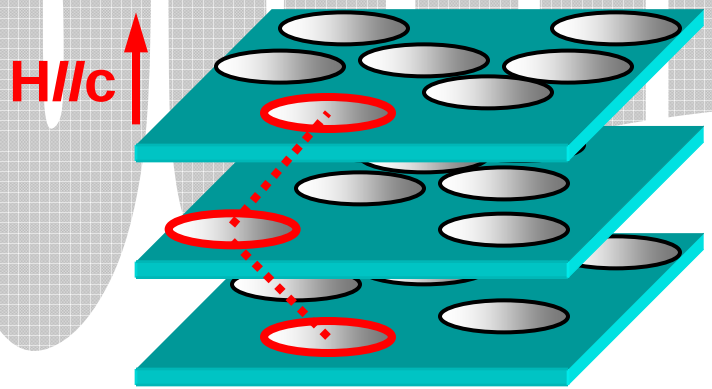


Superconducting gap

≠

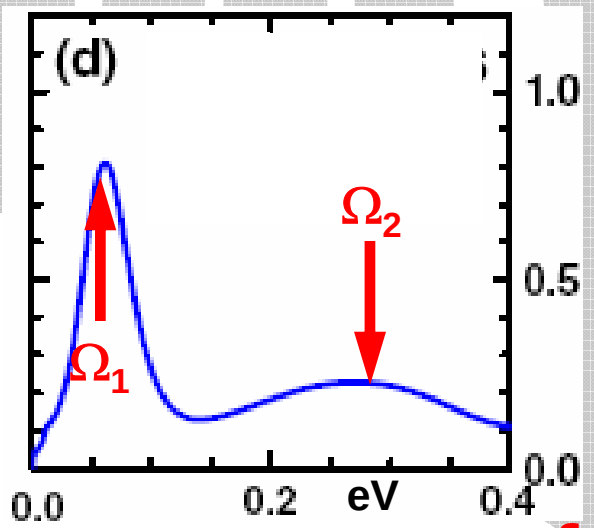
pseudogap

High energy effects and condensate formation:



BCS-like after all…

Strong coupling effects:



no consensus so far…

Collaborators:

Original data in this talk:

A.F. Laforge
W.J. Padilla → Boston College
K.S. Burch → LANL
Y.S.Lee → Seoul
Z.Q. Li
S. Dordevic → U.Akron
A. Schafgans
UCSD

K. Segawa
Y. Ando
CRIEPI/ U.Osaka

High-Tc optics 1987-2007:

Tom Timusk
J.Carbotte
McMaster

V.S. Bagaev
Lebedev Institute

C.C. Homes
M.Strongin
Brookhaven

M.B.Maple
J.Singley
UCSD

A.Chubukov
Wisconsin

R.Liang
D.Bonn
W.N.Hardy
UBC

B.Dabrowski
UNI
Y.J.Wang
NHMFL

Support: