Fermi-liquid behavior of strongly renormalized electrons in transition metal oxydes

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FN SNF FONDS NATIONAL SUISSE DE LA RECHERCHE SCIENTIFIQUE

MaNEP SWITZERLAND

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In collaboration with J.L.M. van Mechelen
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I.I. Mazin, Naval Research Laboratories
PRB 84 (2011) 205111

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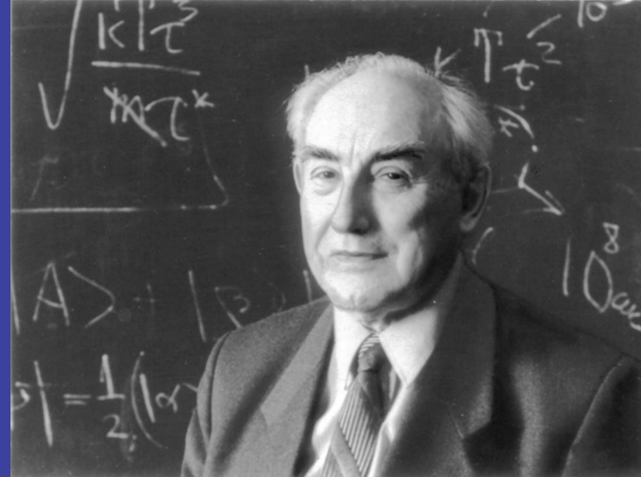
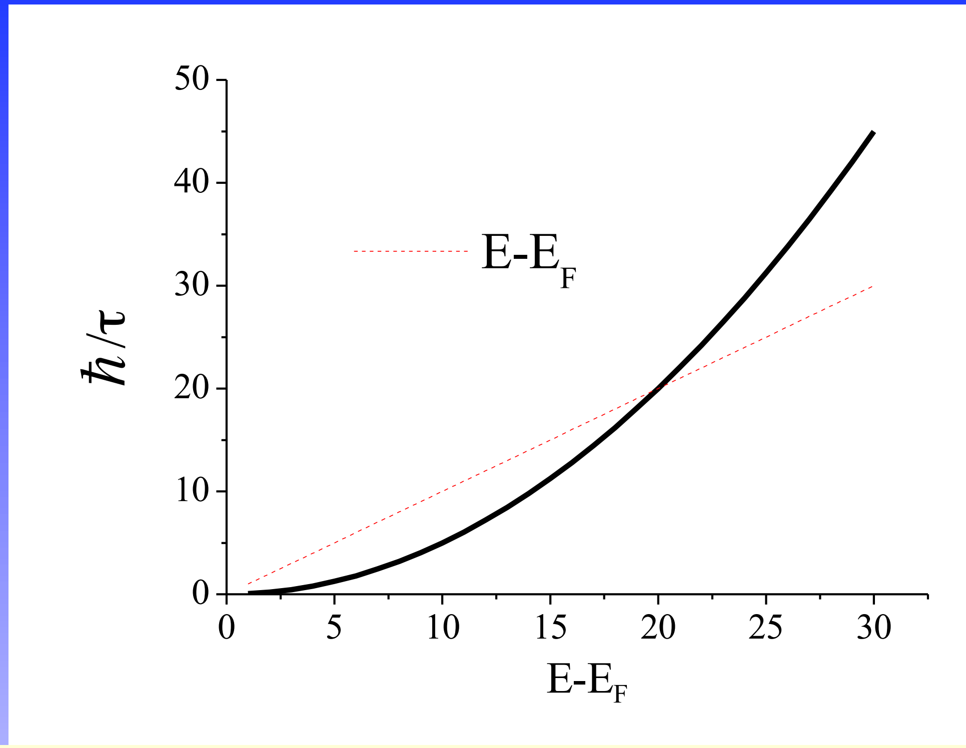
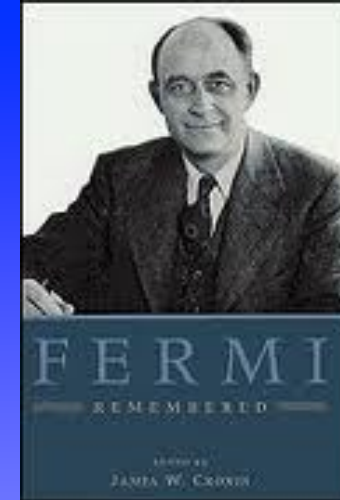


V. L. Ginzburg, Energiya No. 9, 2. (1984):

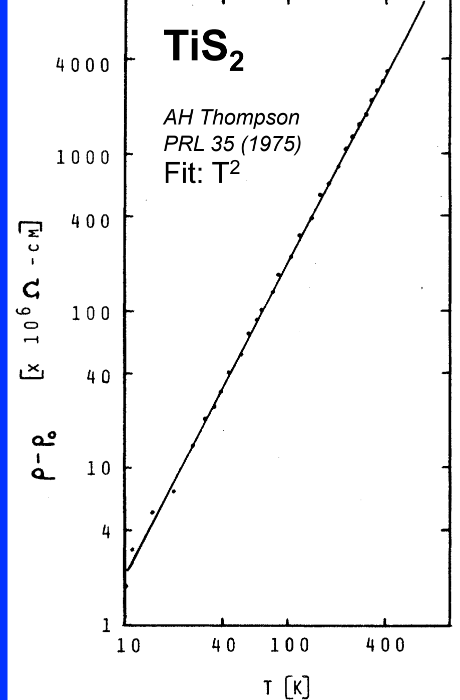
It has somehow happened that research into high-temperature superconductivity has become unfashionable (there is good reason to speak of fashion in this context since fashion sometimes plays a significant part in research work and in the scientific community). **It is hard to achieve anything by making admonitions.** Typically it is some obvious success (or reports of success, even if erroneous) that can radically and rapidly reverse attitudes. When they smell success, the former doubters, and even dedicated critics, are capable of an about-face and of becoming ardent supporters of the new work. But this subject belongs to the psychology and sociology of science and technology. In short, the search for high-temperature superconductivity can readily lead to unexpected results and discoveries, especially since the predictions of the existing theory are rather vague.

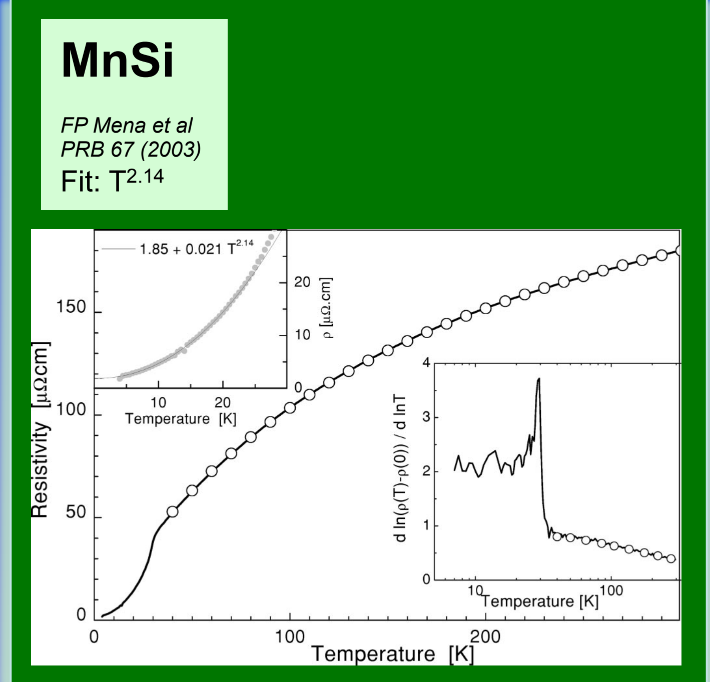
Landau Fermi-Liquids

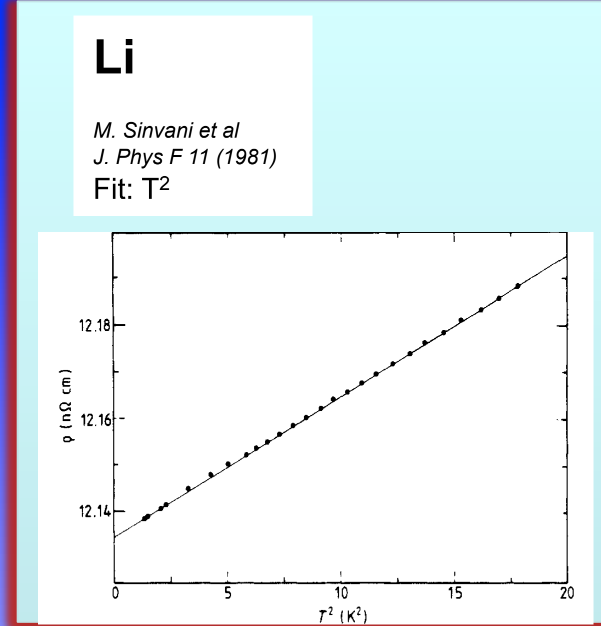




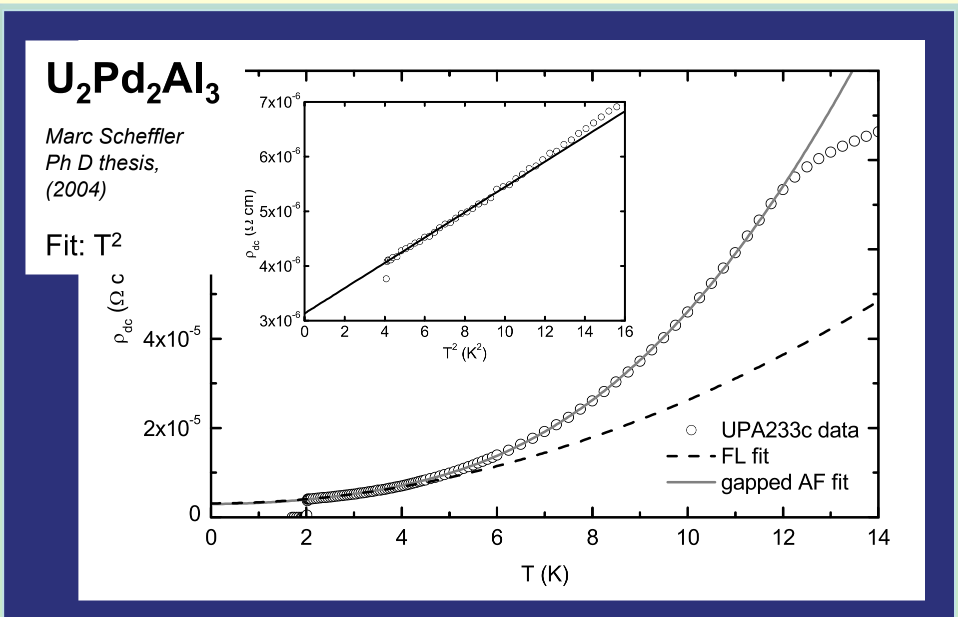
Quasi-particle relaxation rate: $\dfrac{\hbar}{\tau} \propto \omega^2 + (\pi T)^2$

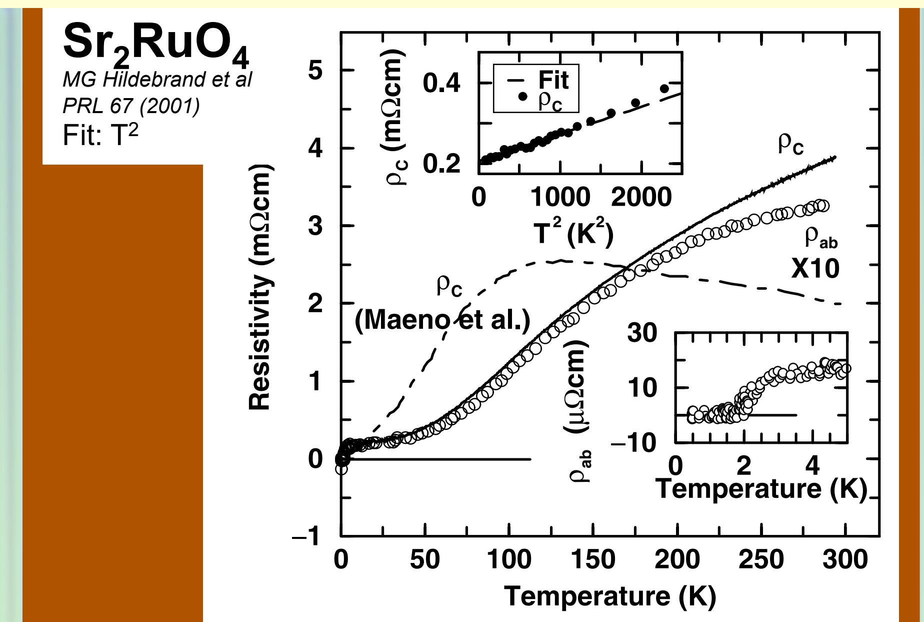


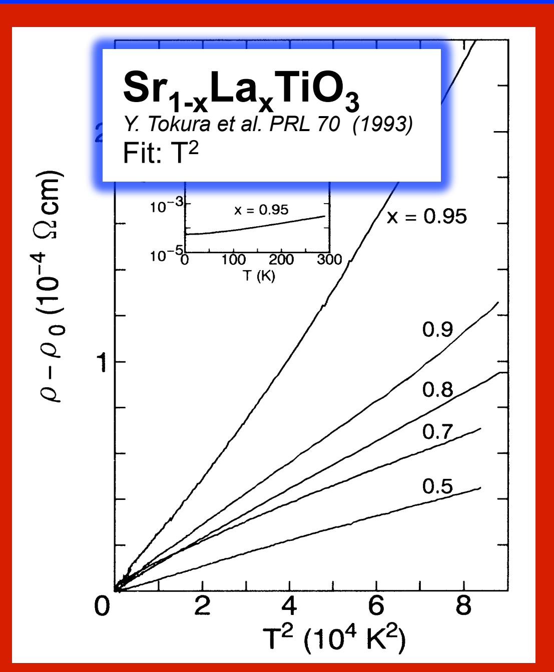


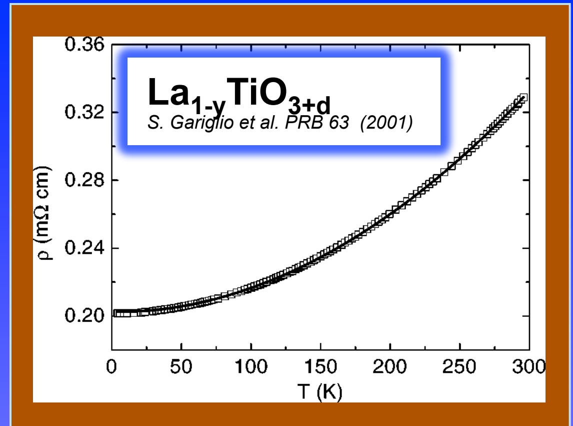


A.H.MacDonald *etal*., PRB 23 (1981): Phonon-mediated interaction dominates in Li, K, Na.







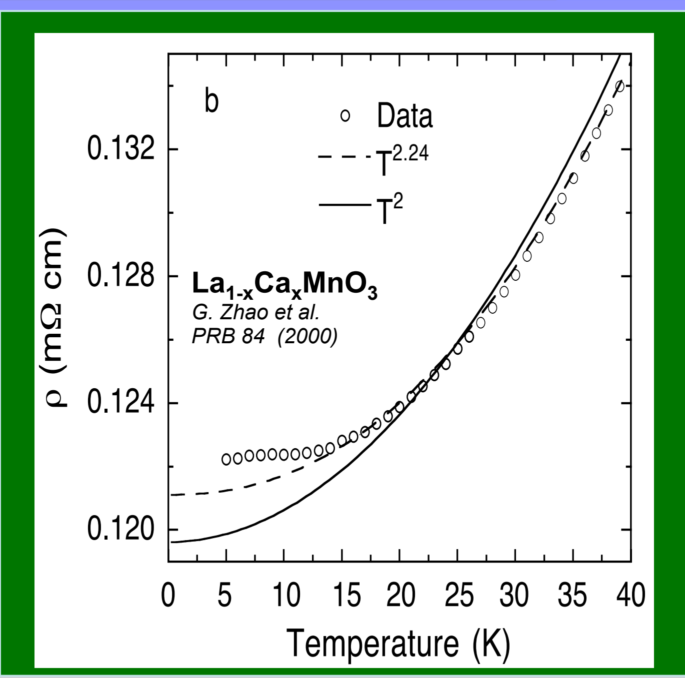


*S*mall polarons:

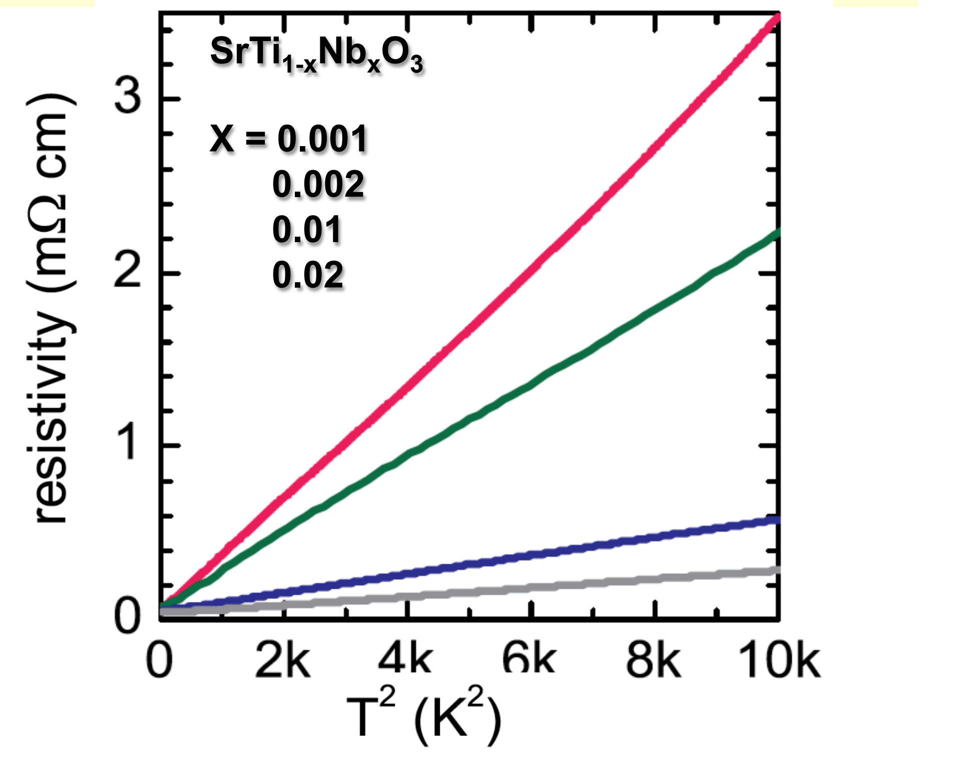
$$\rho(T) = \frac{C}{\sinh^2\left(\hbar\omega_0 / 2k_B T\right)}$$

V.N.Bogomolov *et al*,

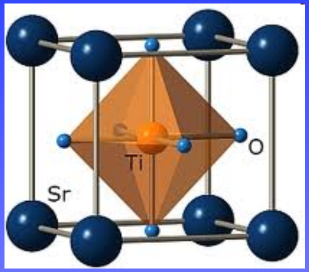
Sov. Phys. Solid St. 9 (1968)



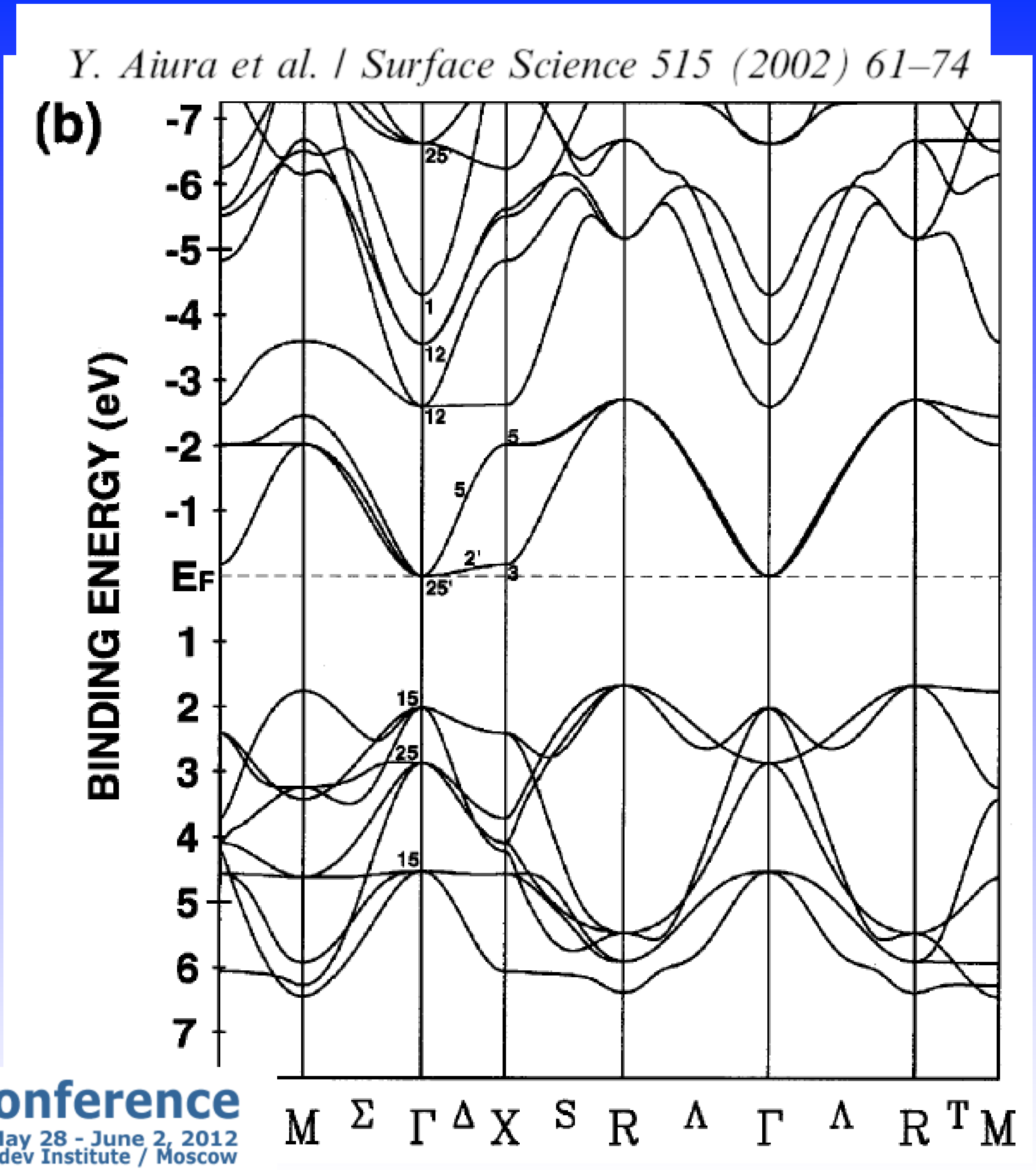
$\rho(T) = AT^2$ (Fermi liquid) ???



$SrTiO_3$



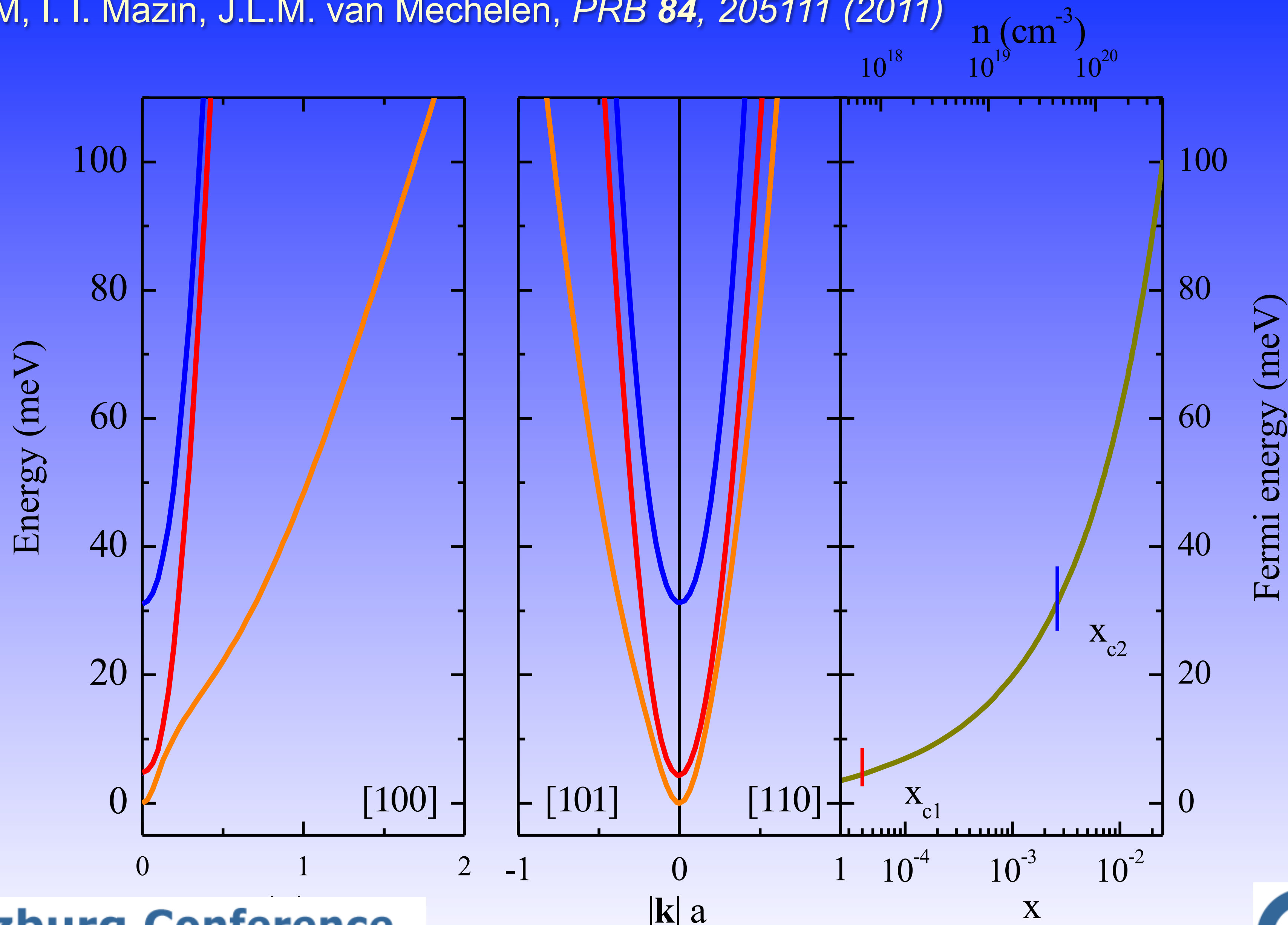
Ti
O
Sr



Y. Aiura et al. / Surface Science 515 (2002) 61–74
(b)
BINDING ENERGY (eV)
-7
-6
-5
-4
-3
-2
-1
EF
1
2
3
4
5
6
7
25'
1
12
12
5
5
2'
3
25'
15
25
15
M Σ Γ Δ X S R Λ Γ Λ R T M

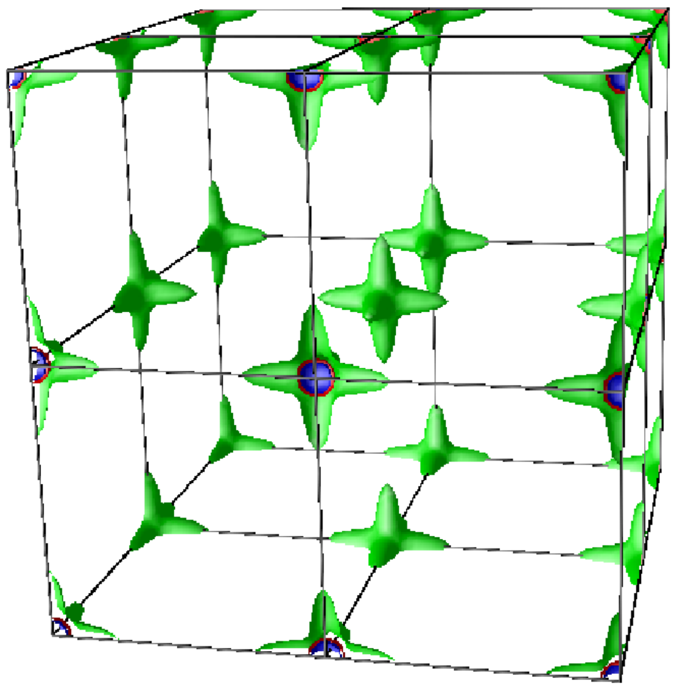
$SrTi_{1-x}Nb_xO_3$

DvdM, I. I. Mazin, J.L.M. van Mechelen, *PRB **84**, 205111 (2011)*



$SrTi_{1-x}Nb_xO_3$

X = 2 %



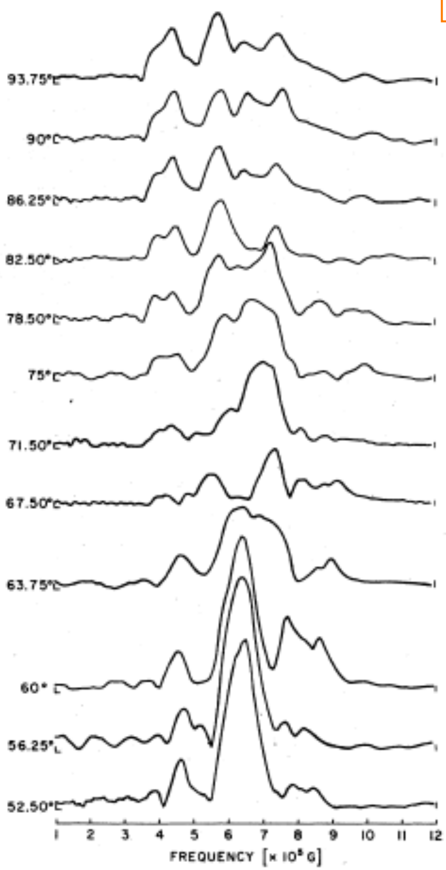
PHYSICAL REVIEW B VOLUME 19, NUMBER 2 15 JANUARY 1979

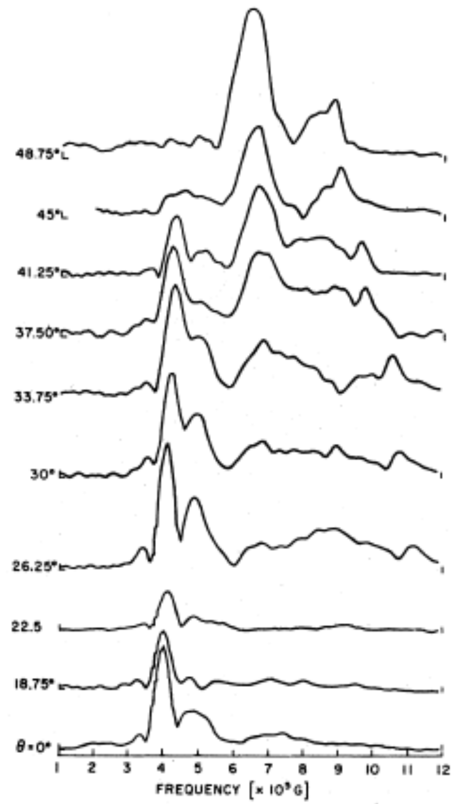
Measurements of the Fermi surface of $SrTiO_3$:Nb

B. Gregory,* J. Arthur,† and G. Seidel

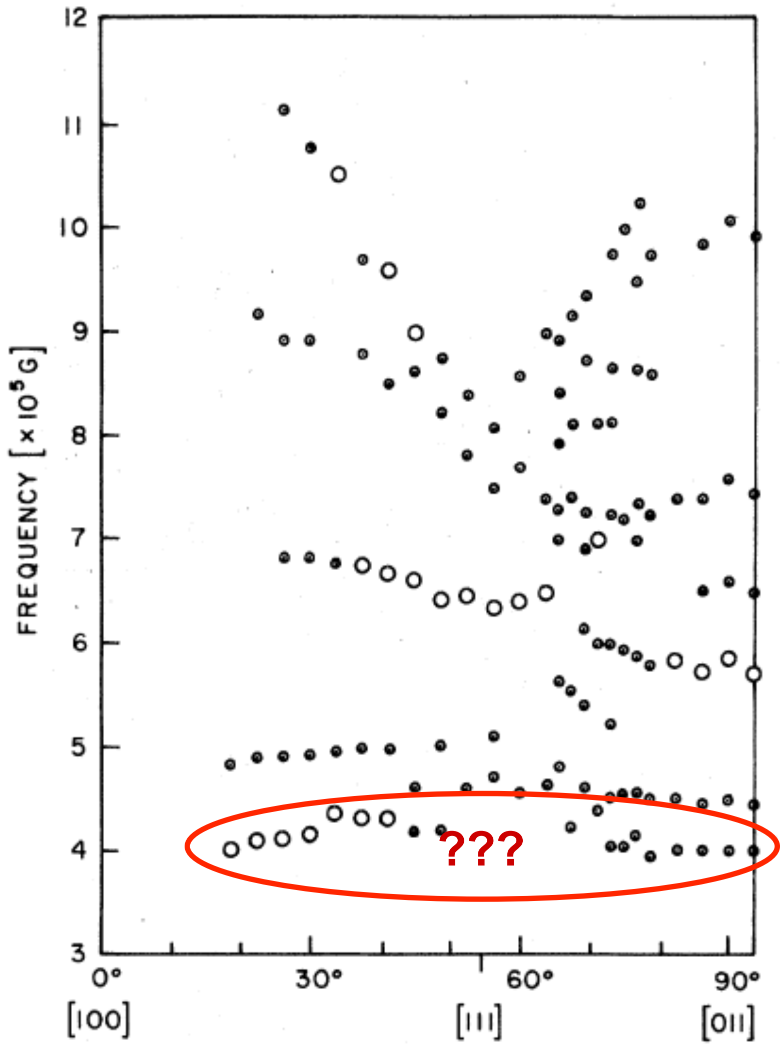
[011]

x=0.036 %

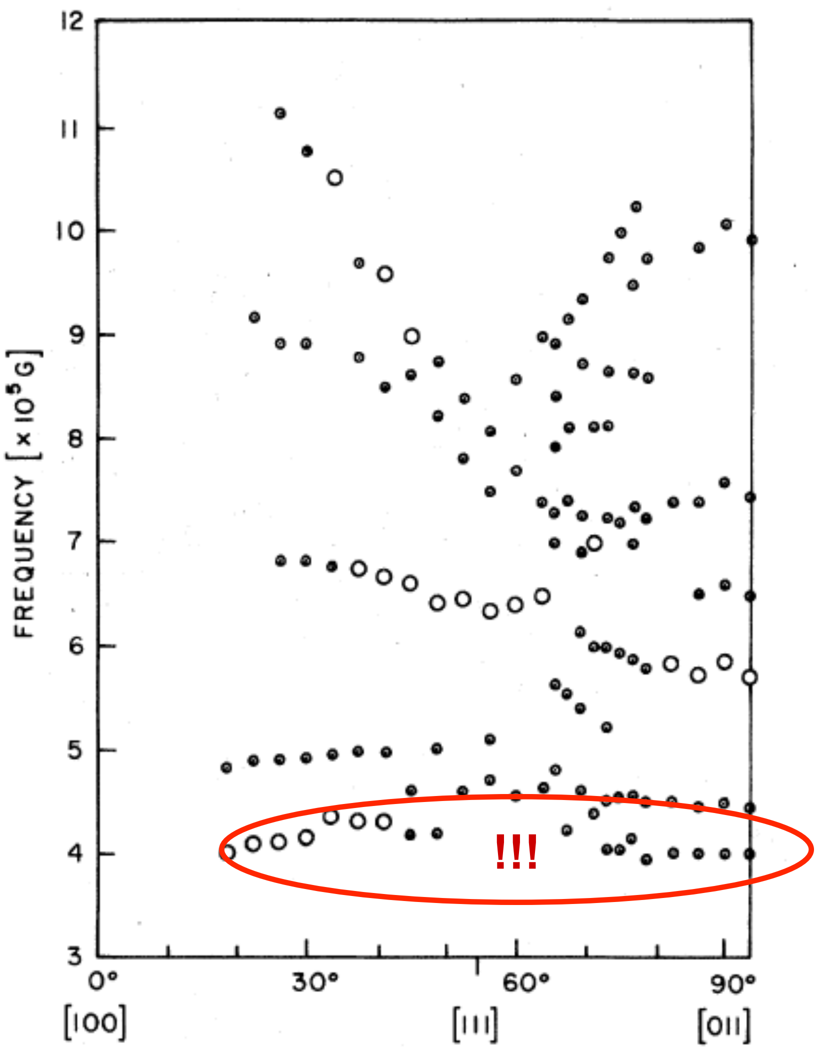




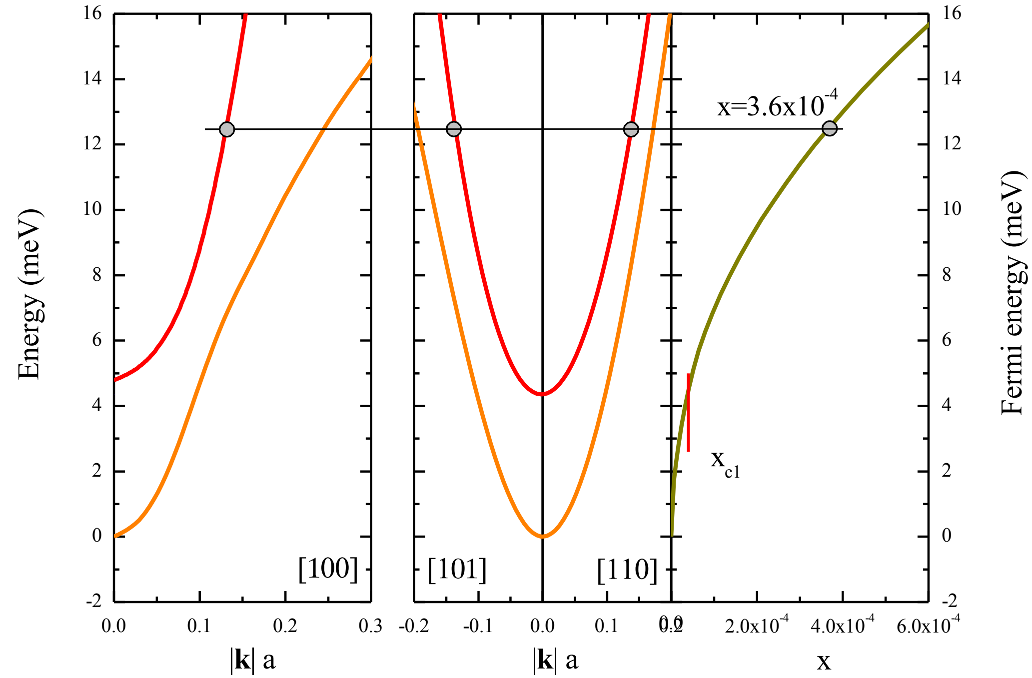
[100]



B Gregory et al., PRB 19 (1979)



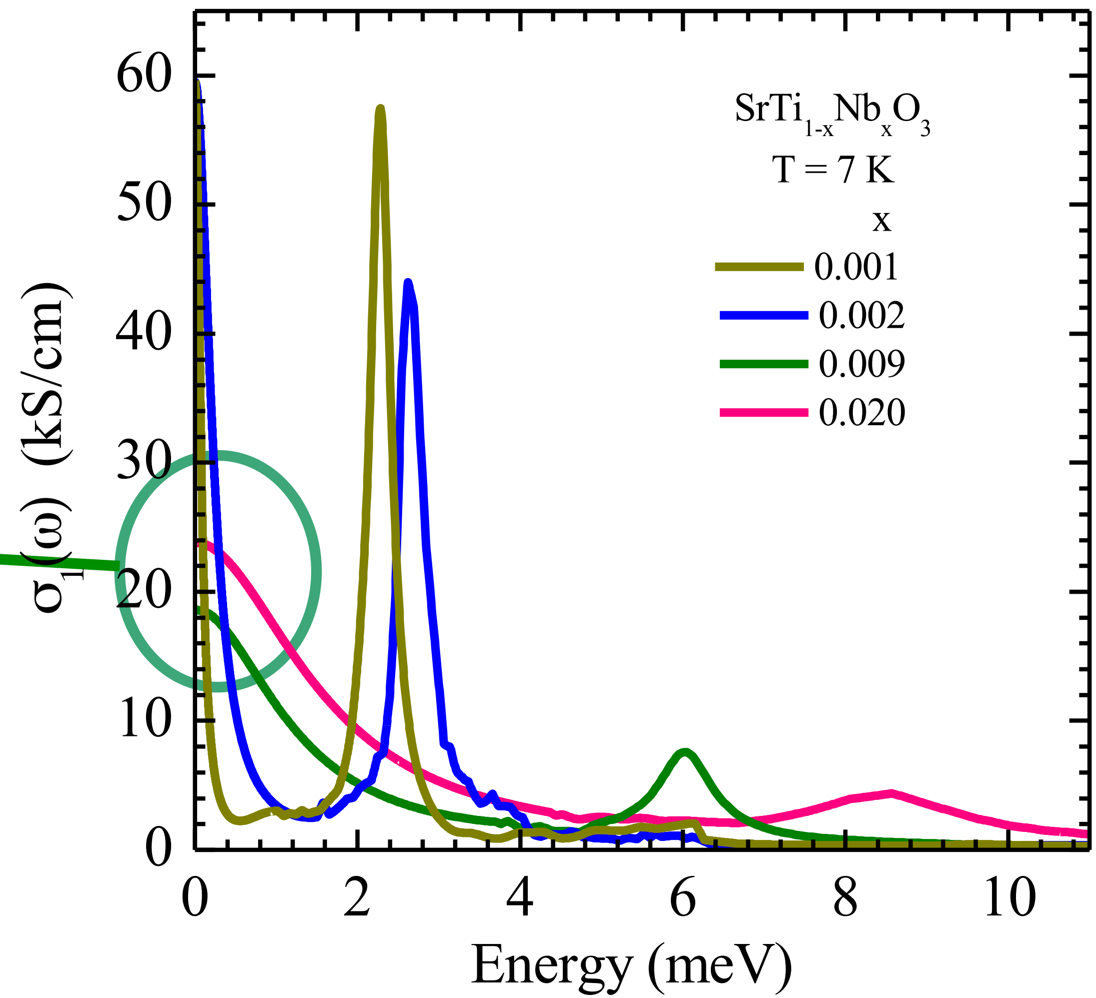
DvdM et al, PRB 84, 205111 (2011)



$$\text{Onsager relation}: \quad F = \frac{A\hbar}{2\pi e} = 4.1 \cdot 10^5 \text{ Gauss}$$

Optical conductivity

$$HWHM = \frac{\hbar}{\tau}$$

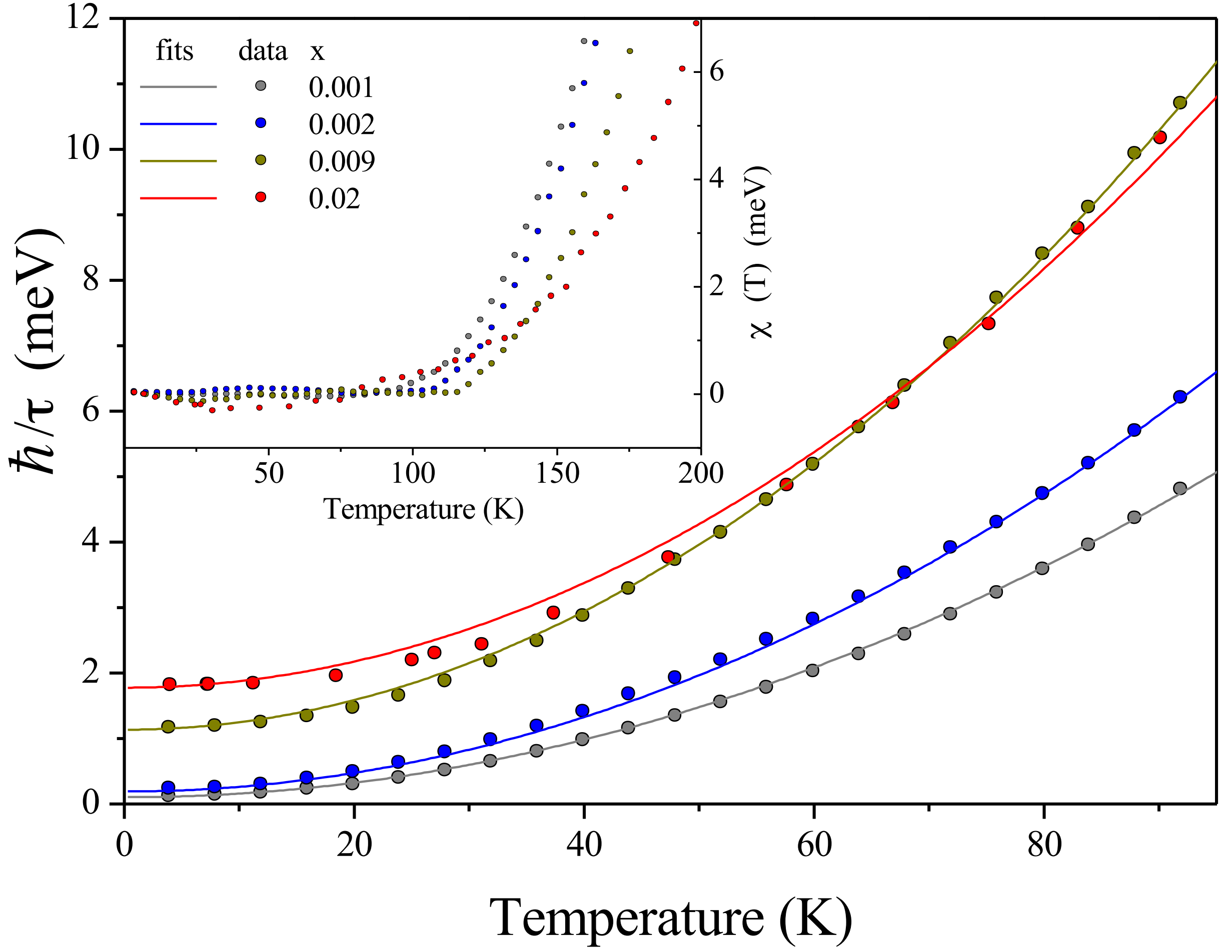


J.L.M. van Mechelen et al , PRL *100, 226403 (2008)*

Inelastic scattering

$SrTi_{1-x}Nb_xO_3$

$$\boxed{\frac{1}{\tau} = \frac{1}{\tau_0} + a_2 T^2}$$



Charge transport in n-type STO:

Mobile charge carriers

3 intersecting bands

Each band: $m_a = m_b \sim m_c / 20$

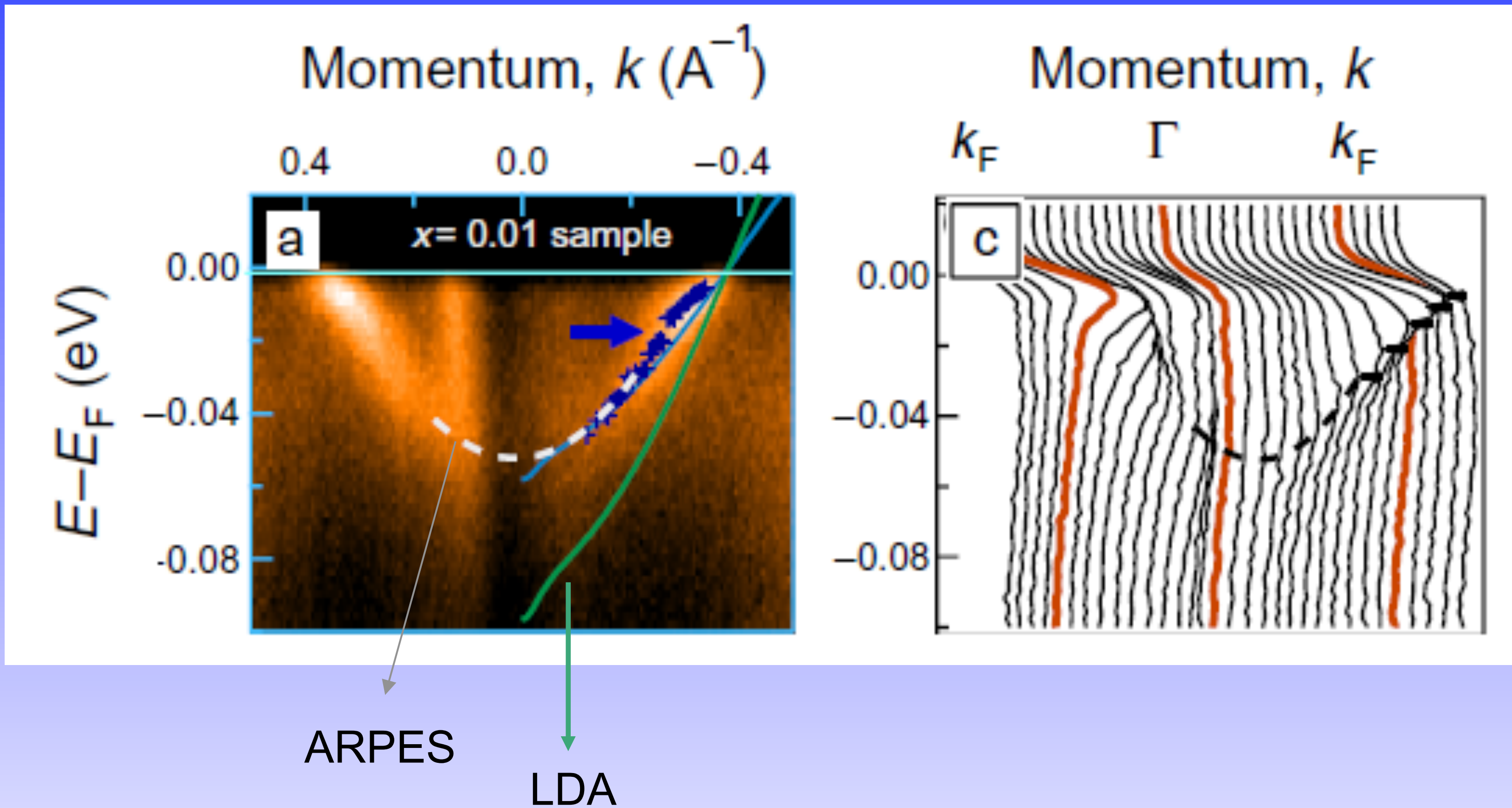
T^2 type inelastic scattering

Are the charge carriers Fermions?

What kind of ?

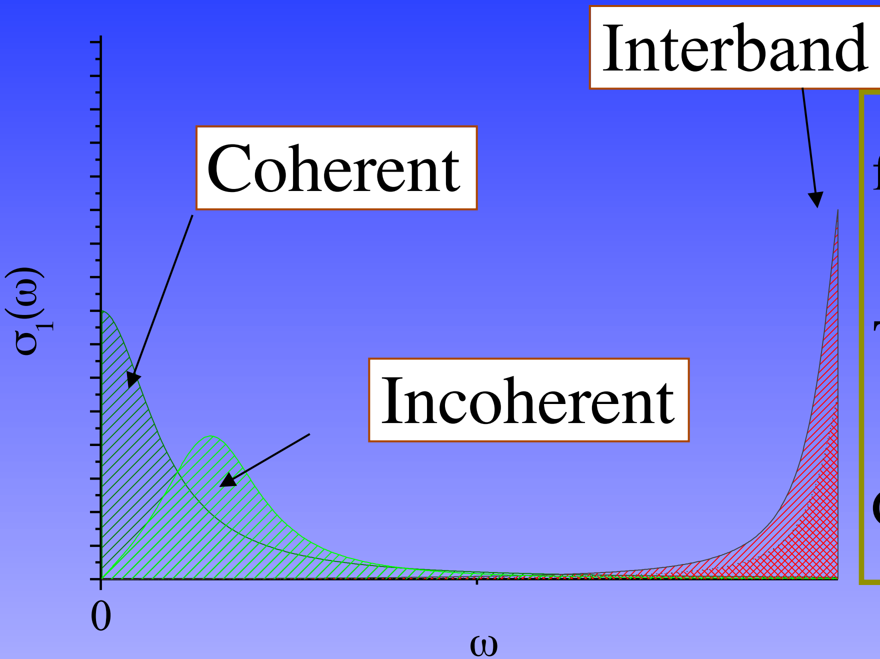
Elecron doped $Sr_{1-x}La_xTiO_3$

Mass renormalization obtained from ARPES: $$\frac{v_F^*}{v_F} = \frac{m_{LDA}}{m^*} \cong \frac{1}{2.2}$$



W. Meevasana et al, *New Journal of Physics 12 (2010) 023004*

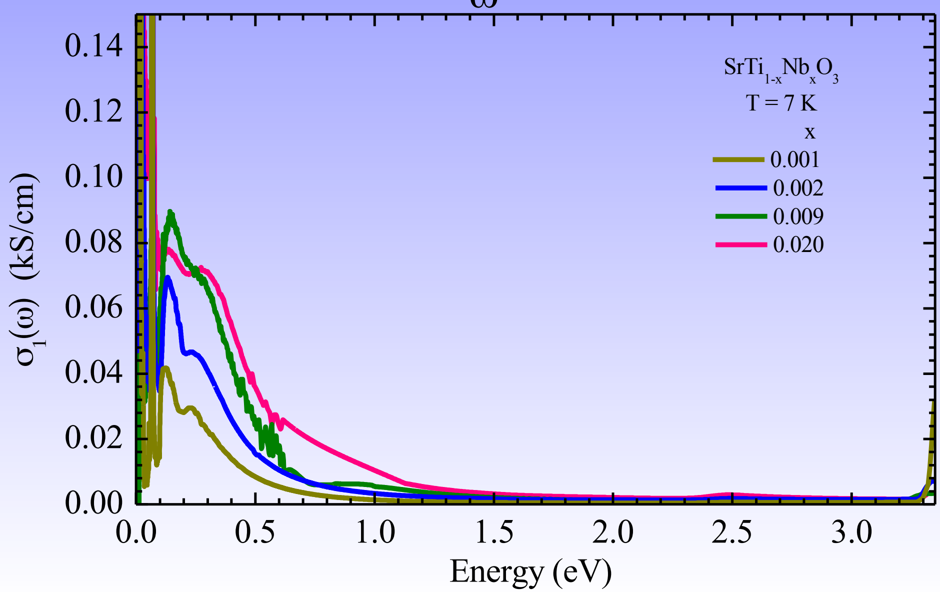
Electrons coupled to phonons



f-sumrule: $$\int_0^\infty \sigma_1(\omega)d\omega = \frac{\pi e^2}{2}\frac{n}{m_e}$$

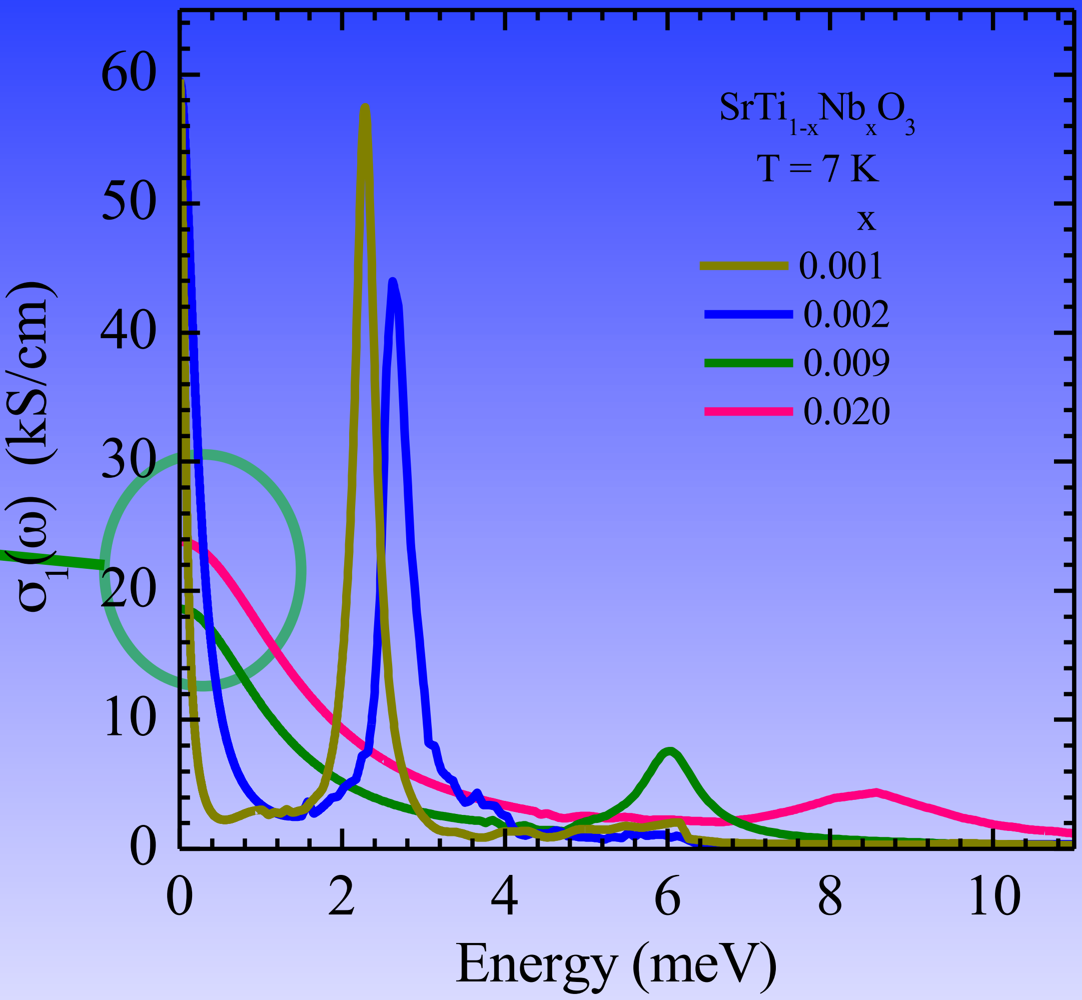
Total free charge spectral weight: $$\frac{\pi e^2}{2}\frac{n_f}{m_b}$$

Coherent free charge spectral weight: $$\frac{\pi e^2}{2}\frac{n_f}{m^*}$$



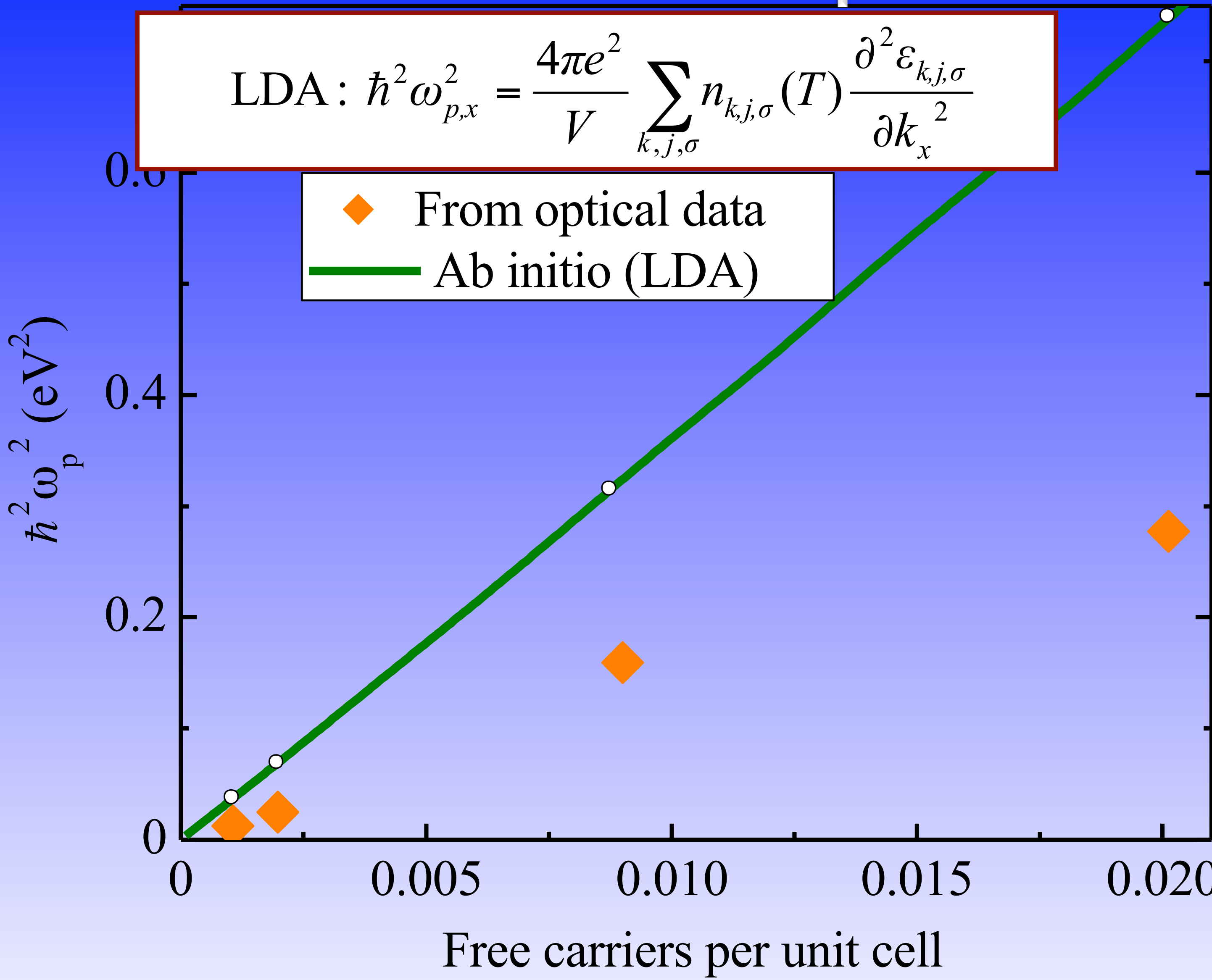
Coherent free carrier spectral weight

$$Area = \frac{\pi n e^2}{2m^*} = \frac{\left(\omega_p^*\right)^2}{8}$$



Coherent free carrier spectral weight

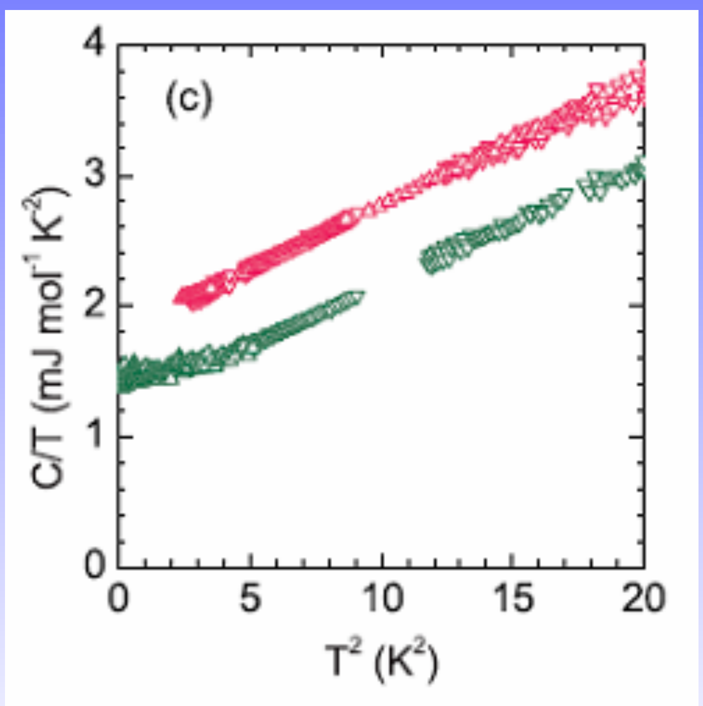
$$\text{LDA}: \hbar^2\omega_{p,x}^2 = \frac{4\pi e^2}{V}\sum_{k,j,\sigma} n_{k,j,\sigma}(T)\frac{\partial^2 \varepsilon_{k,j,\sigma}}{\partial k_x{}^2}$$

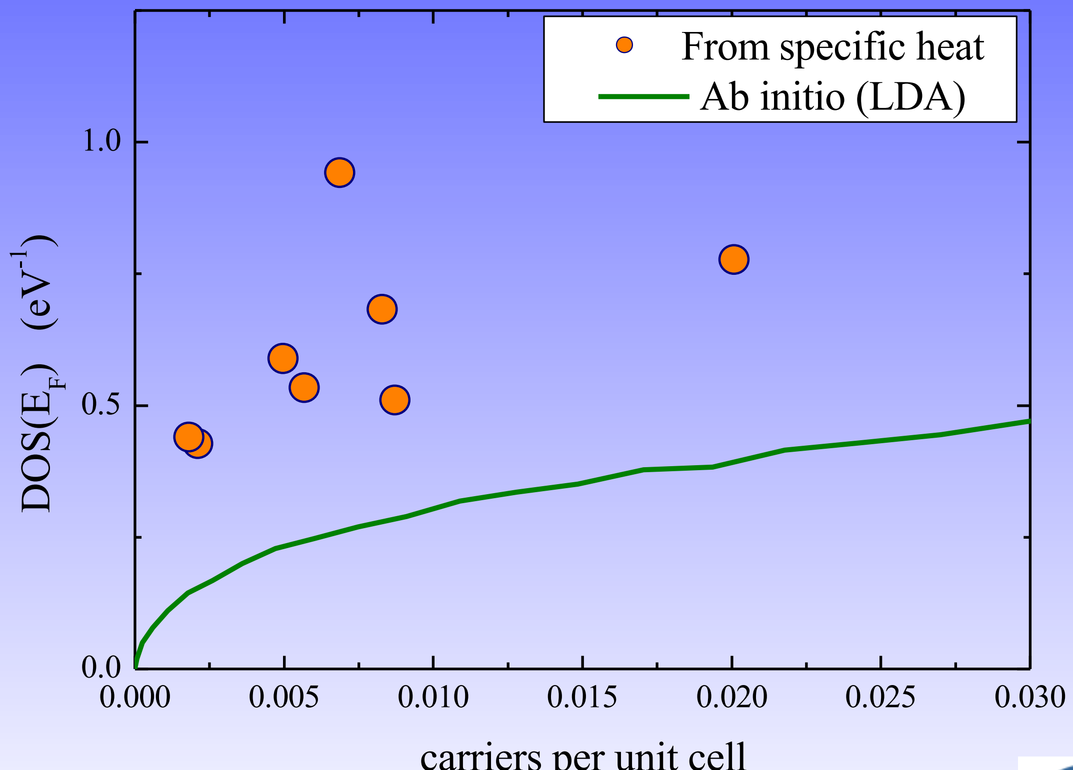


J.L.M. van Mechelen et al , PRL *100, 226403 (2008)*

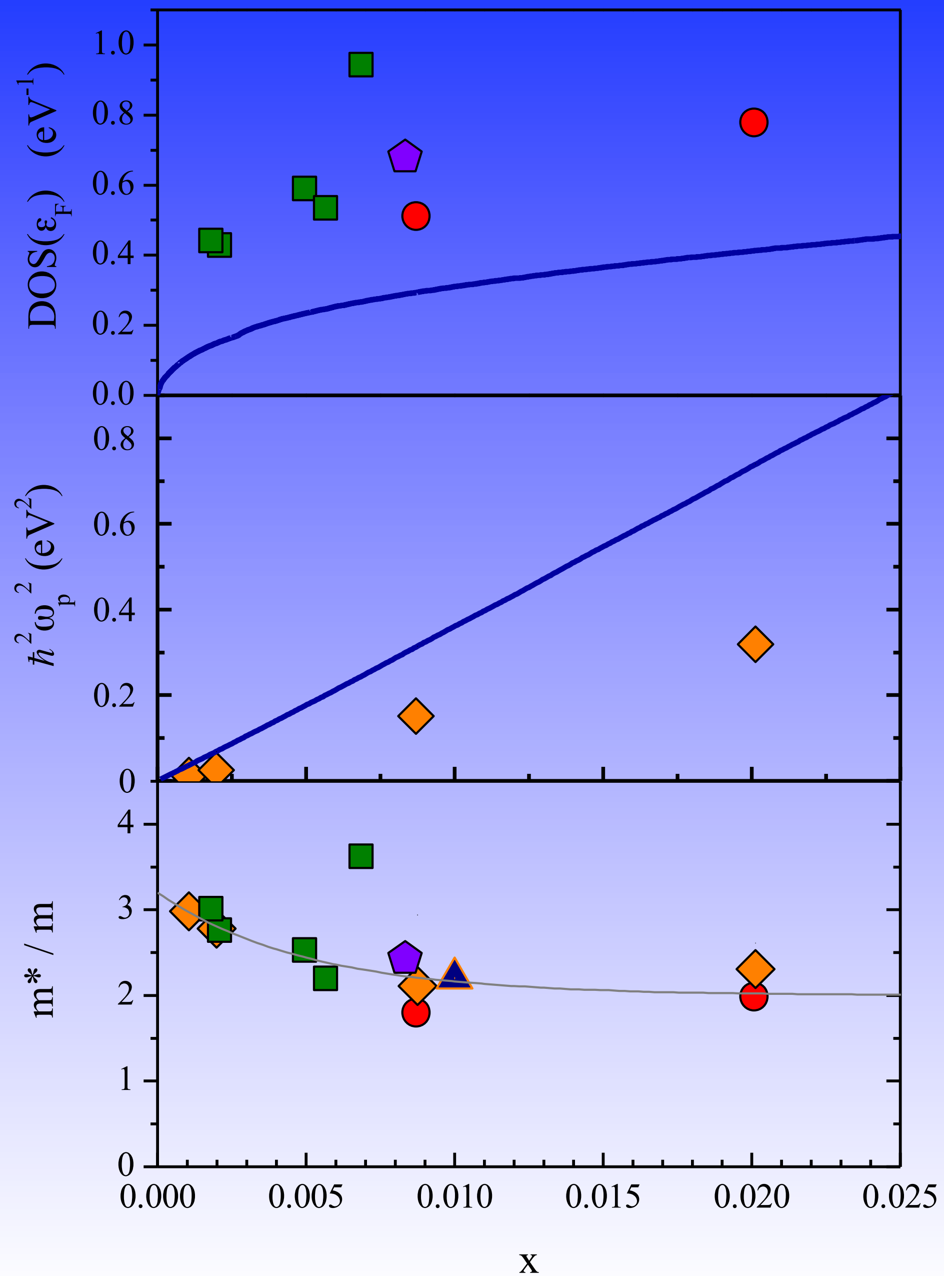
Specific Heat

$$\gamma \equiv \frac{C}{T} = \frac{k_B^2 \pi^2}{3} D(\varepsilon_F) \propto m^*$$





Electron doped $SrTiO_3$

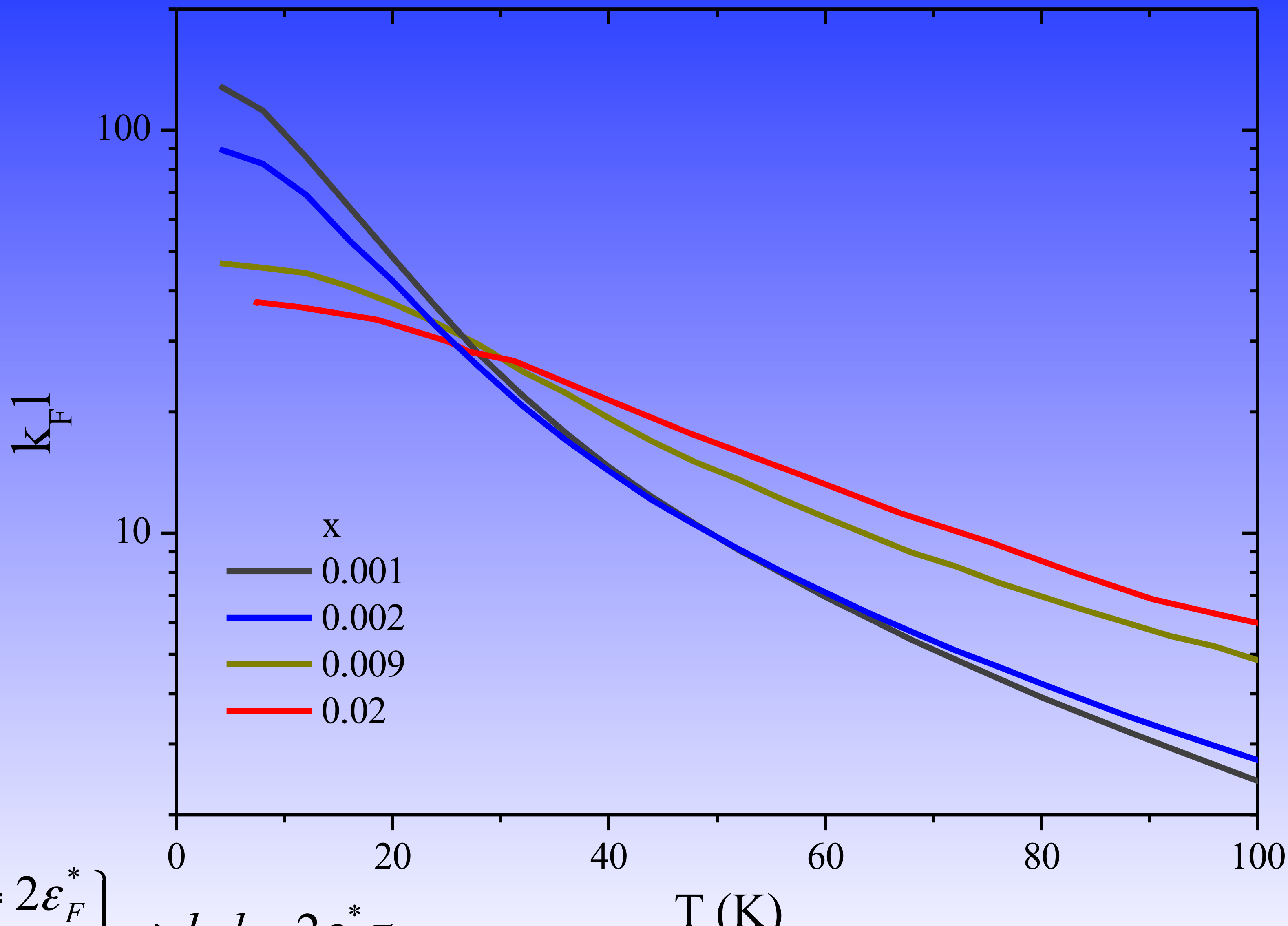


Specific heat

Optics

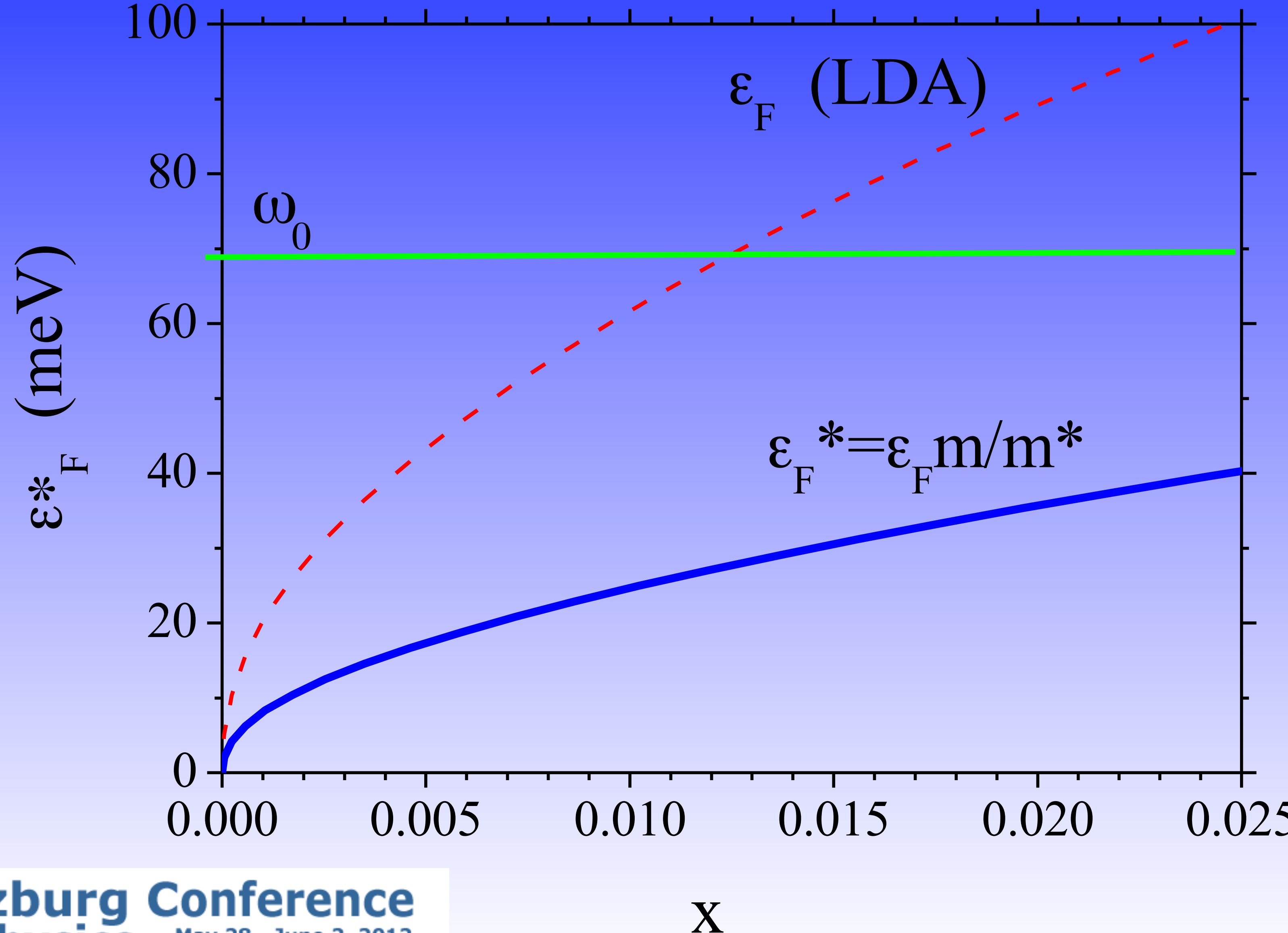
: ARPES

Mean free path



$$\left.\begin{array}{l} k_F v_F^* = 2\varepsilon_F^* \\ l / v_F^* = \tau \end{array}\right\} \Rightarrow k_F l = 2\varepsilon_F^* \tau$$

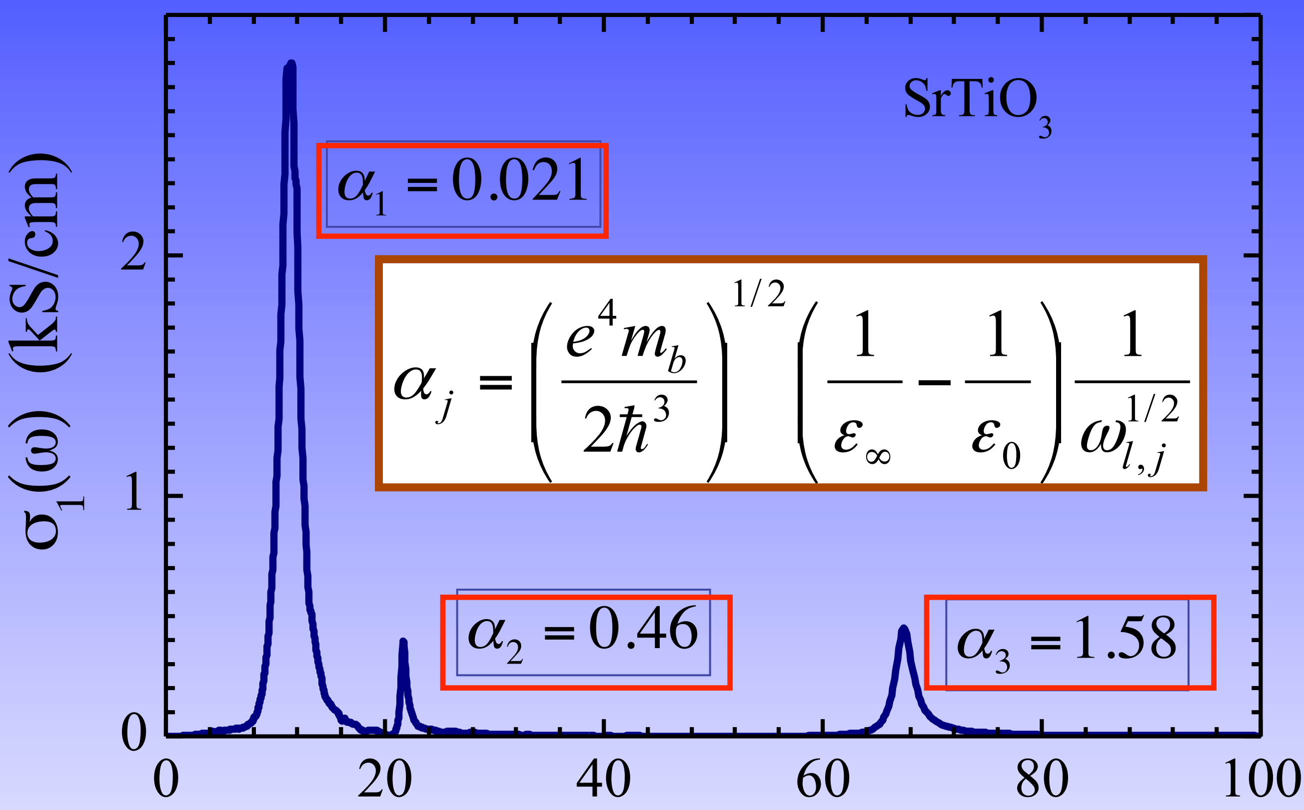
$SrTi_{1-x}Nb_xO_3 \quad (x < 0.02): \quad \omega_0 > \varepsilon_F^*$



The charge carriers are Fermions

Mass renormalization: $m^*/m_{LDA} \sim 2.5$

Fröhlich model: Electron-phonon coupling constant from the optical phonons of $SrTiO_3$



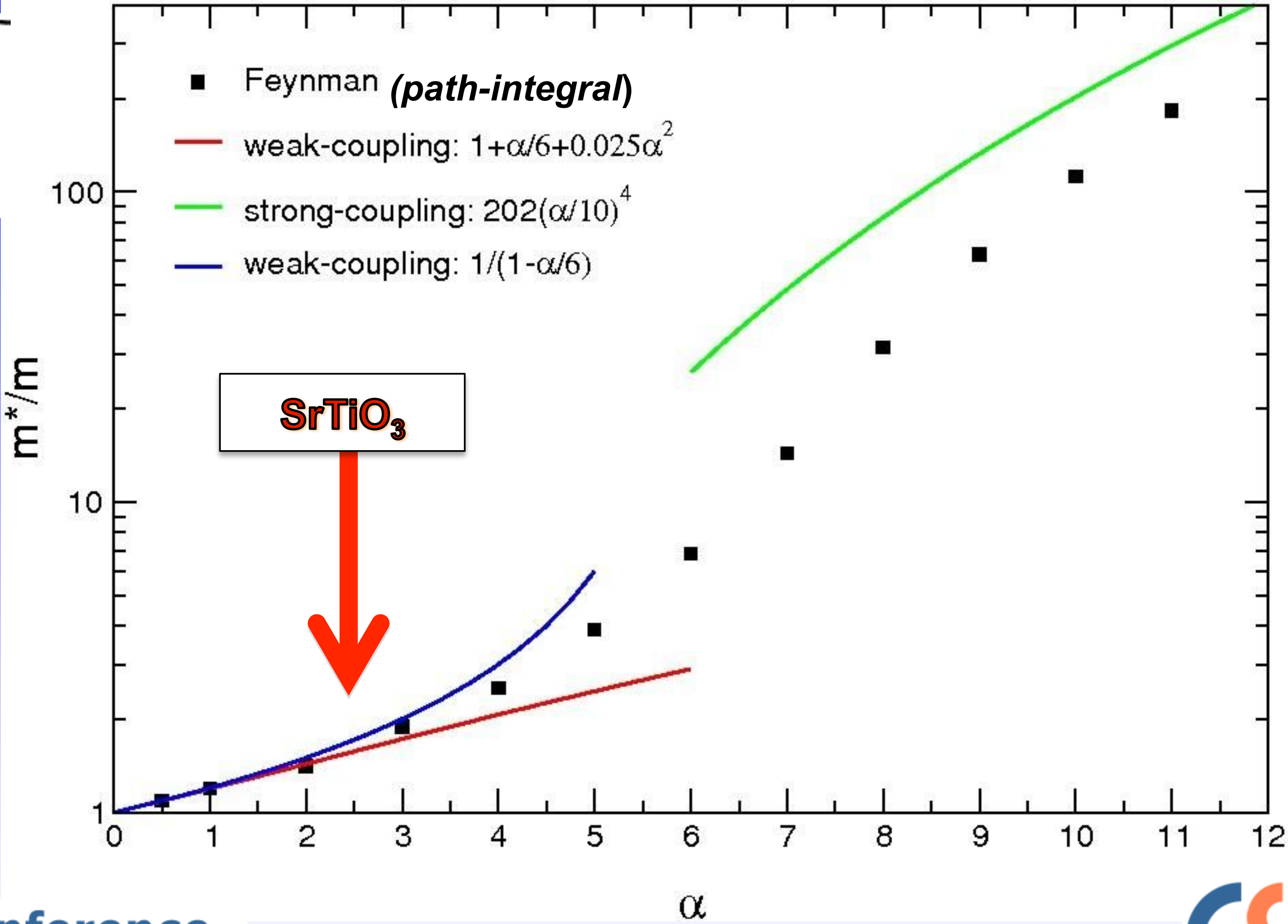
$$\alpha_1 = 0.021$$

$$\alpha_j = \left(\frac{e^4 m_b}{2\hbar^3}\right)^{1/2}\left(\frac{1}{\varepsilon_\infty} - \frac{1}{\varepsilon_0}\right)\frac{1}{\omega_{l,j}^{1/2}}$$

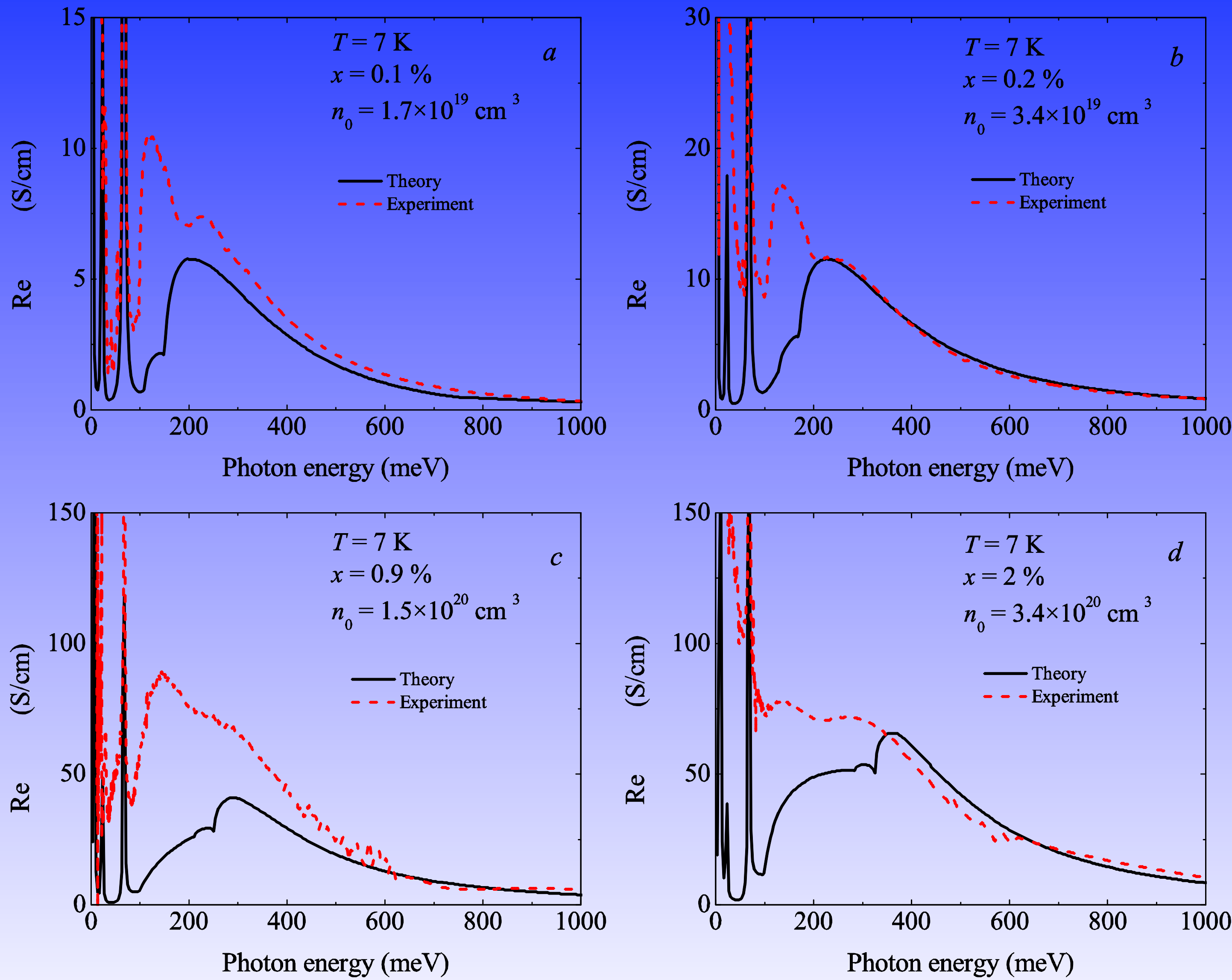
$$\alpha_2 = 0.46$$

$$\alpha_3 = 1.58$$

Self-trapping by e-phonon coupling



Ab initio many-polaron theory of σ(ω)

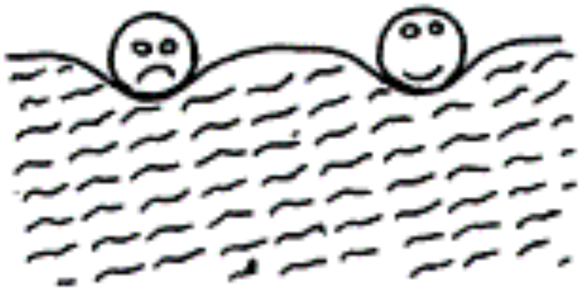


J. T. Devreese, et al., *Physical Review B 81 (2010) 125119*

$\varepsilon^*_F < \omega_0$: Anti-adiabatic limit

Fermi liquid of polarons

Phonon-mediated p-p interactions



$$\mathbf{E} = -\frac{\mathbf{C}}{\mathbf{2}}e^{\mathbf{2}} - \frac{\mathbf{C}}{\mathbf{2}}e^{\mathbf{2}} \qquad \mathbf{E} = -\frac{\mathbf{C}}{\mathbf{2}}(2e)^{\mathbf{2}}$$

Landau-Fermi liquid of polarons

Singlet pairing: $\lambda_0 = \frac{1}{4}\left(-A_0^s + 3A_0^a + A_1^s - 3A_1^a\right)$

$$12\lambda_\tau^2 = \frac{7}{24}A_1^s A_1^s + \frac{49}{40}A_1^a A_1^a + \frac{5}{8}A_0^s A_0^s + \frac{21}{8}A_0^a A_0^a - \frac{7}{20}A_1^s A_1^a - \frac{3}{4}A_0^s A_0^a - \frac{5}{12}A_0^s A_1^s - \frac{7}{4}A_0^a A_1^a + \frac{1}{4}A_0^s A_1^a + \frac{1}{4}A_0^a A_1^s$$

Brinkman-Platzman-Rice sumrule (PRL, 1968): $A_1^s + A_0^a + A_1^a = -1$

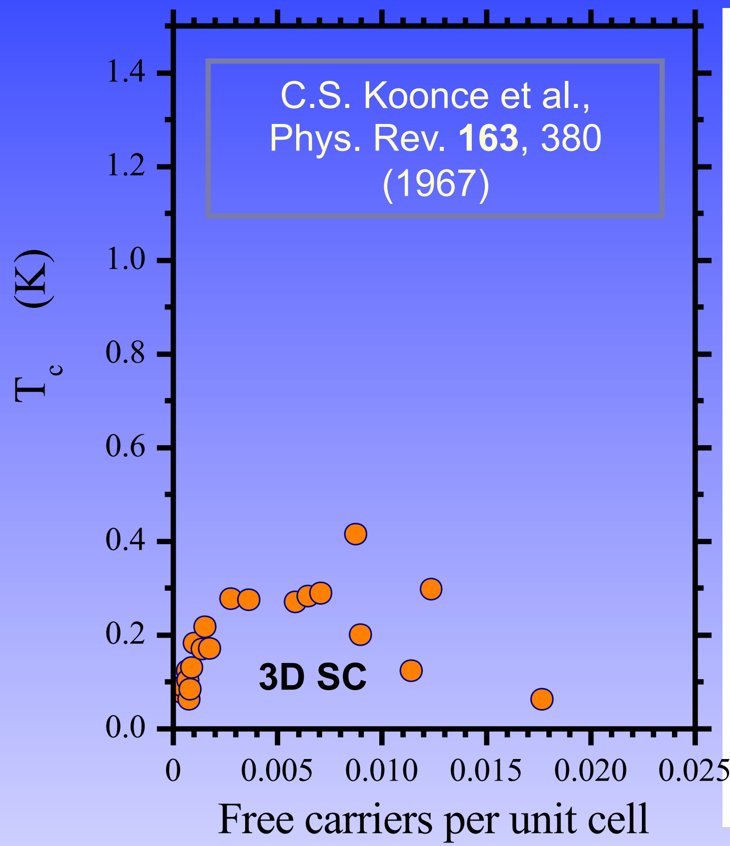
Physical constraints

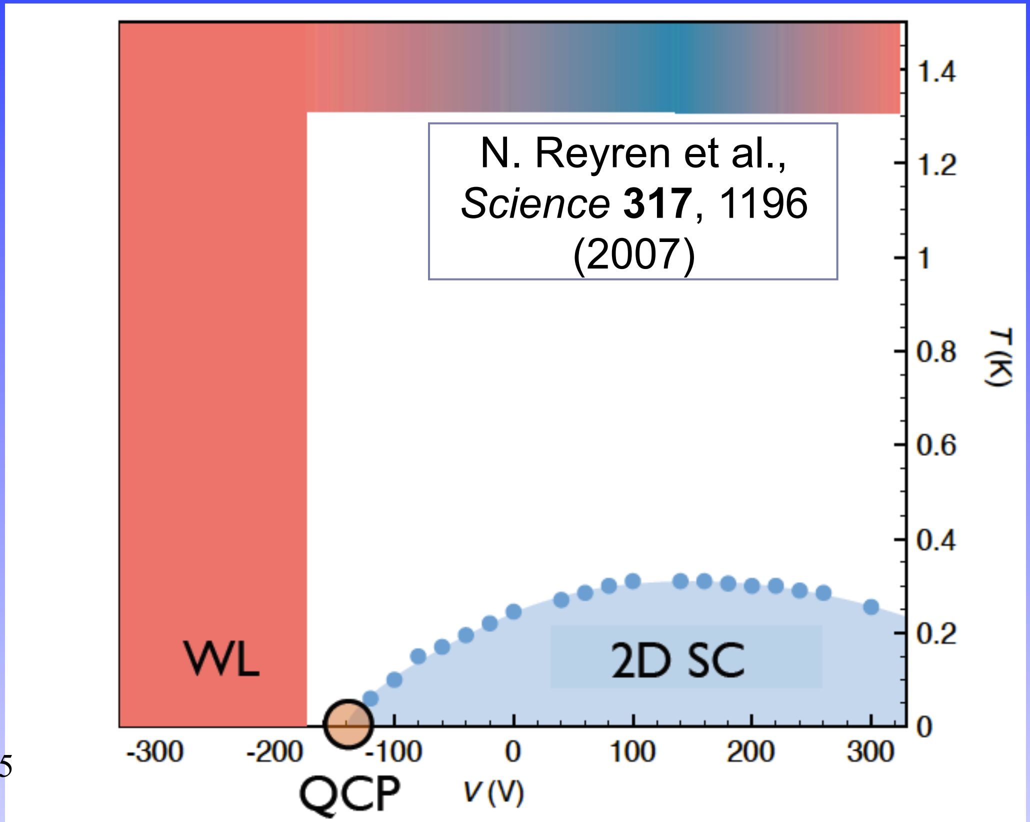
Enhanced effective mass : $A_1^s > 0$

Positive compressibility : $A_0^s < 1$

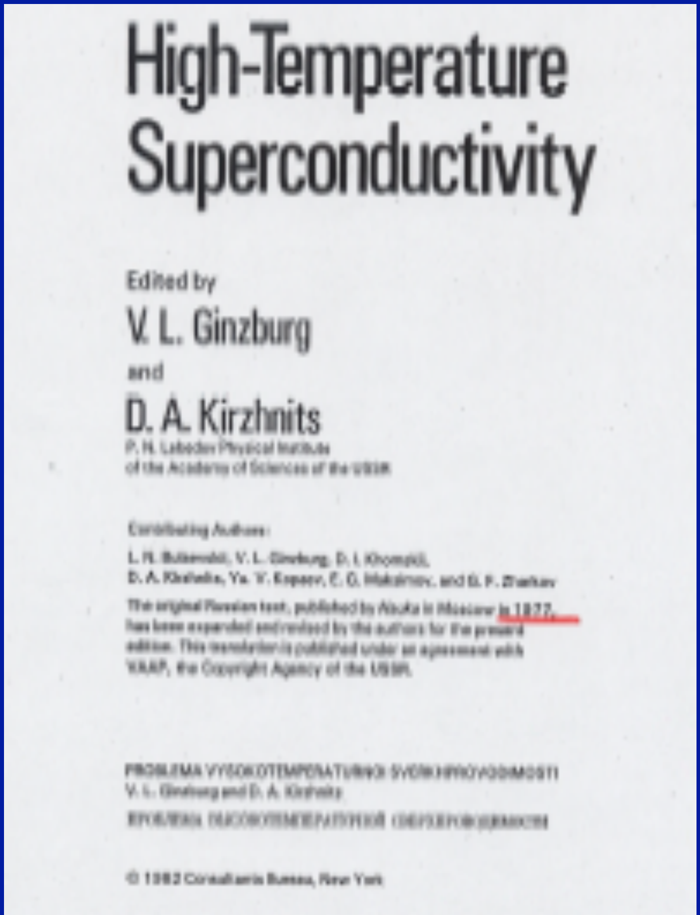
Singlet pairing : $\lambda_0 > \lambda_1$

Superconductivity





$$BCS: \quad k_B T_c \approx \omega_D e^{-1/\lambda_0}$$



High-Temperature Superconductivity

Edited by

V. L. Ginzburg

and

D. A. Kirzhnits

P. N. Lebedev Physical Institute
of the Academy of Sciences of the USSR

Contributing Authors:

The original Russian text, published by Nauka in Moscow in 1977, has been expanded and revised by the authors for the present edition. This translation is published under an agreement with VAAP, the Copyright Agency of the USSR.

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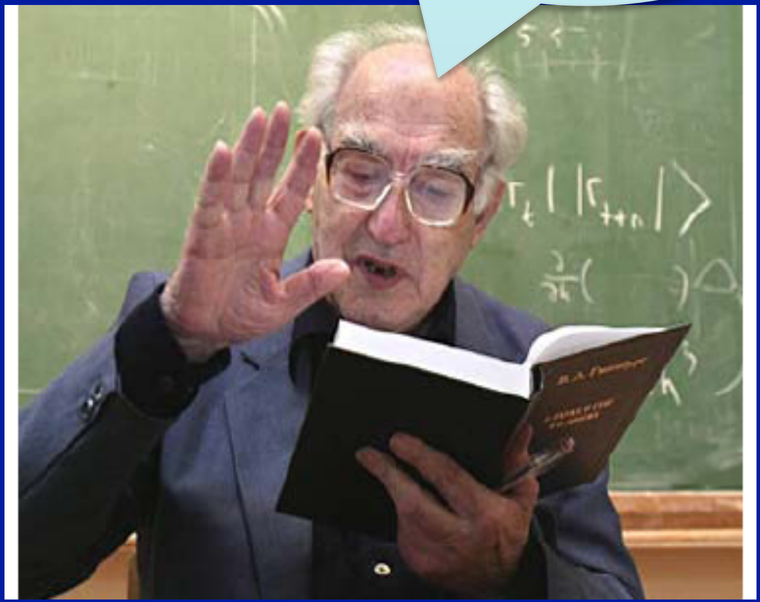
we have to point out, however, that the above estimate is based on a standard metal and can not be applied to all hypothetical situations

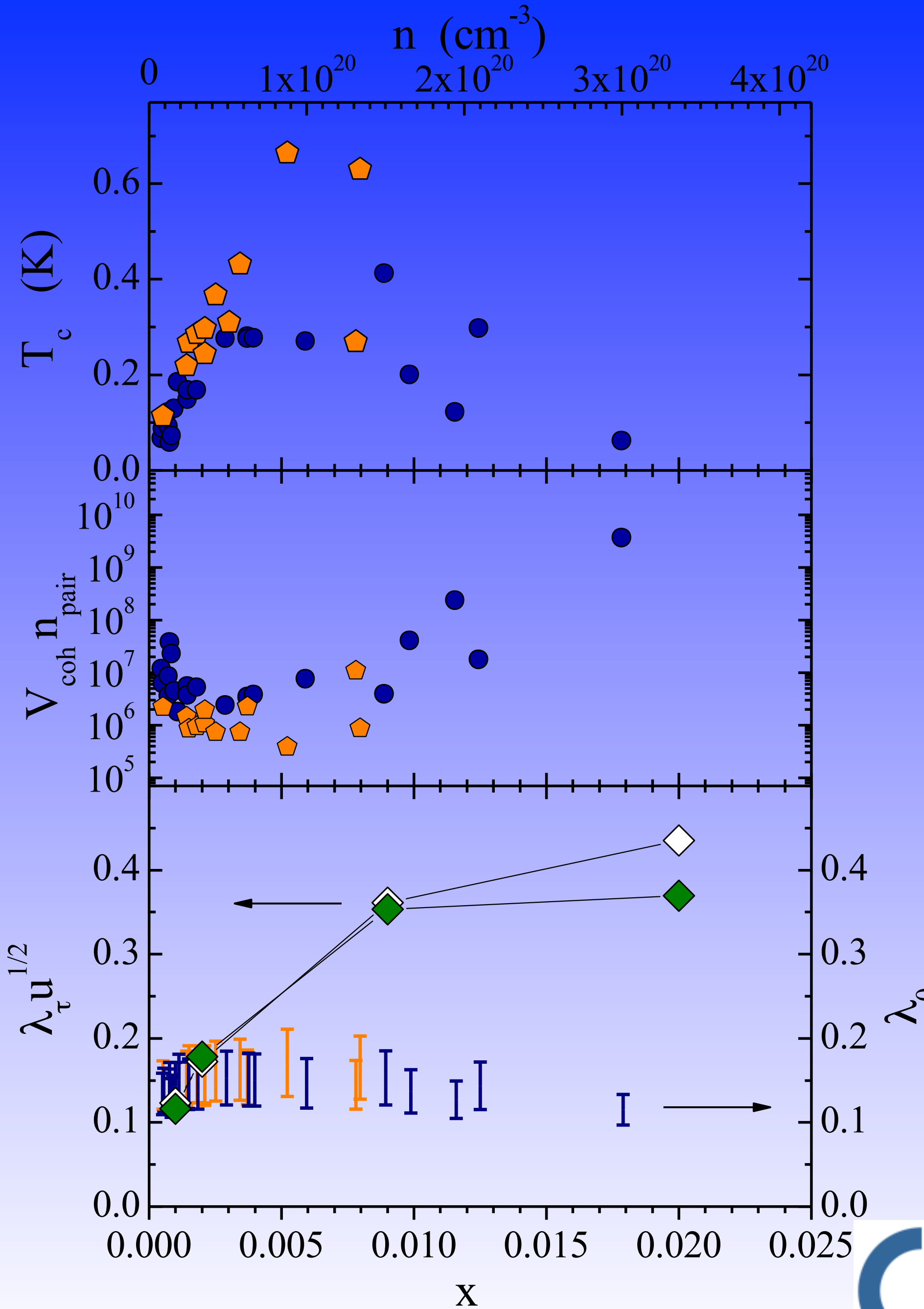


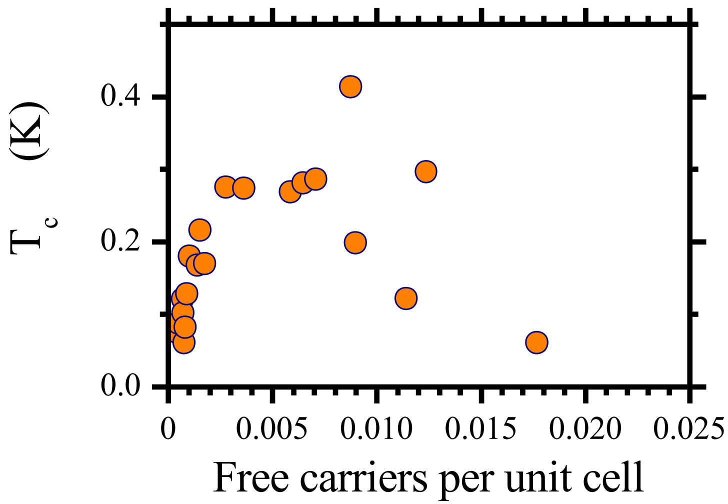
Anti-adiabatic limit $(\varepsilon_F^* < \omega_0)$

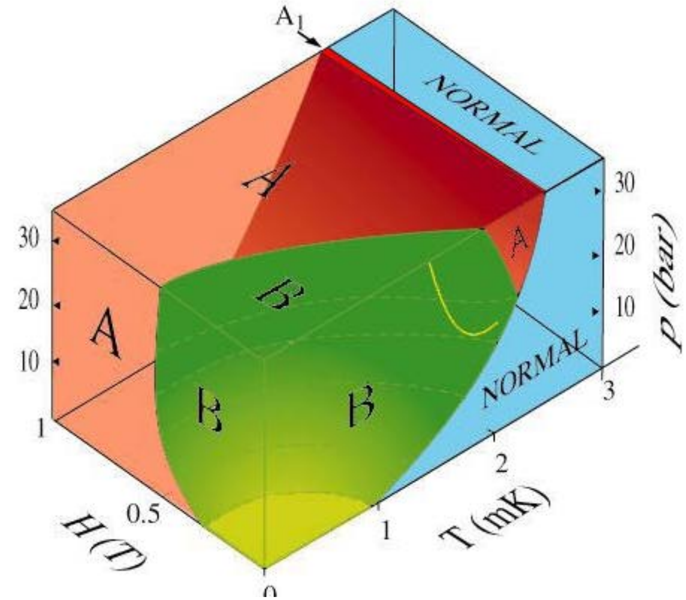
Superconductivity :

$$T_c \approx \varepsilon_F^* \exp\left\{\sqrt{\omega_0 / \varepsilon_F^*}\right\} e^{-1/\lambda_0}$$

$$\rho(T) \approx u\lambda_\tau^2 \frac{\pi^3 m}{ne^2} \frac{T^2}{\varepsilon_F^*}$$







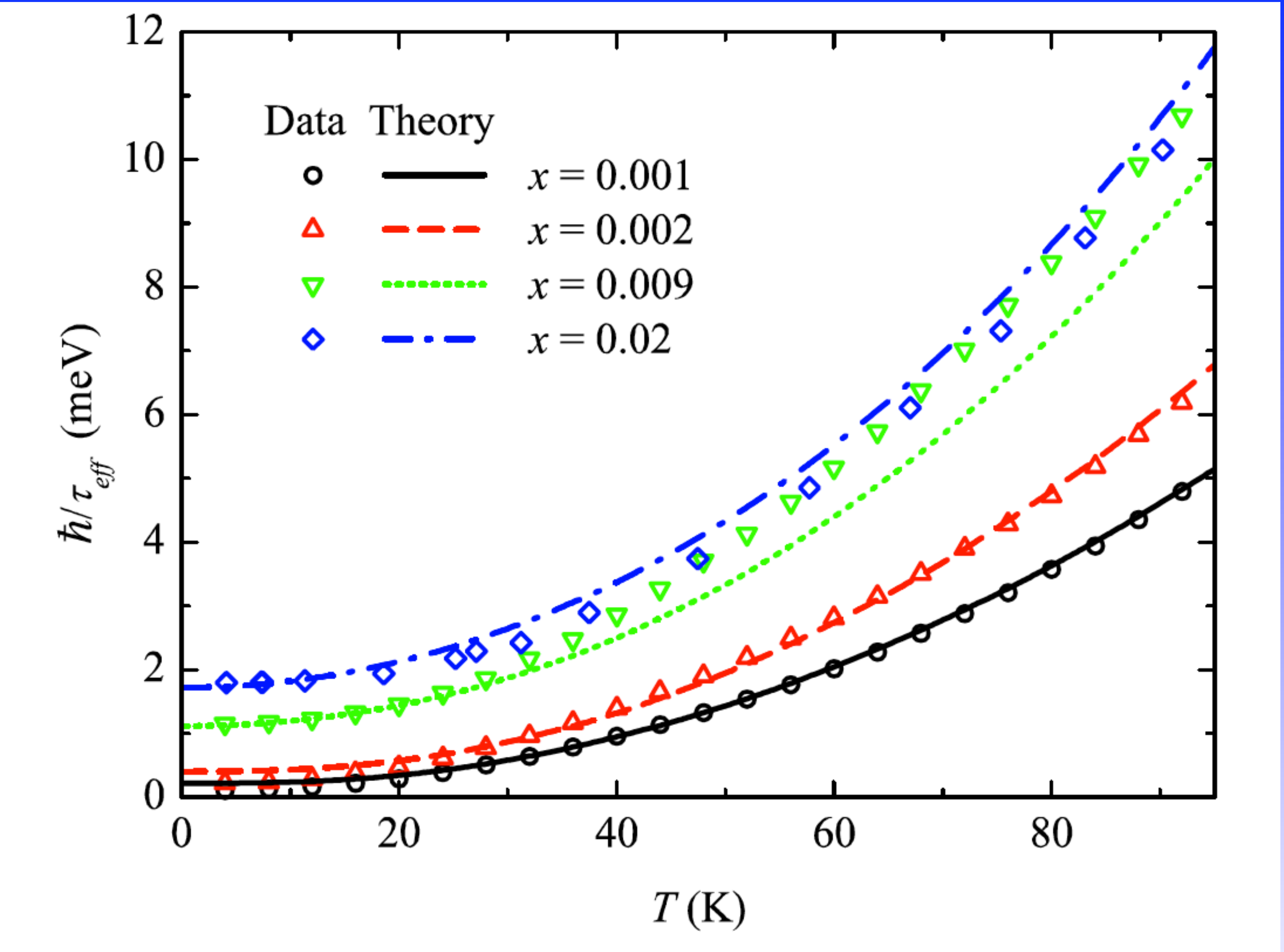
Parameter	$SrTiO_3$ singlet	^{3}He,1 atm. triplet
A_0^s	$\{-1.27; 1.0\}$	0.91
A_1^s	0.45 ± 0.25	2.0
A_0^a	-0.67 ± 0.22	-2.03
A_1^a	-0.62 ± 0.28	-0.55

In collaboration with
N. Klimin, J. Tempere, J. T. Devreese
Universiteit Antwerpen, Belgium

Baber scattering (Proc. R. Soc. A 158, 383 (1937)) mediated by phonons

$$U_{e-e}^{(eff)}\left(\mathbf{q},\omega\right)=\frac{4\pi e^{2}}{q^{2}\varepsilon_{\infty}\epsilon_{e}\left(\mathbf{q},\omega\right)}-\frac{1}{\hbar}\sum_{\lambda}\frac{\left|V_{\mathbf{q},\lambda}\right|^{2}}{\left[\epsilon_{e}\left(\mathbf{q},\omega\right)\right]^{2}}\frac{2\omega_{\mathbf{q},\lambda}}{\omega_{\mathbf{q},\lambda}^{2}-\omega^{2}}-\frac{1}{\hbar}\frac{2\omega_{\mathbf{q}}^{(ac)}\left|V_{\mathbf{q}}^{(ac)}\right|^{2}}{\left(\omega_{\mathbf{q}}^{(ac)}\right)^{2}-\omega^{2}},$$

Quantitative agreement with experimental T^2 dependence



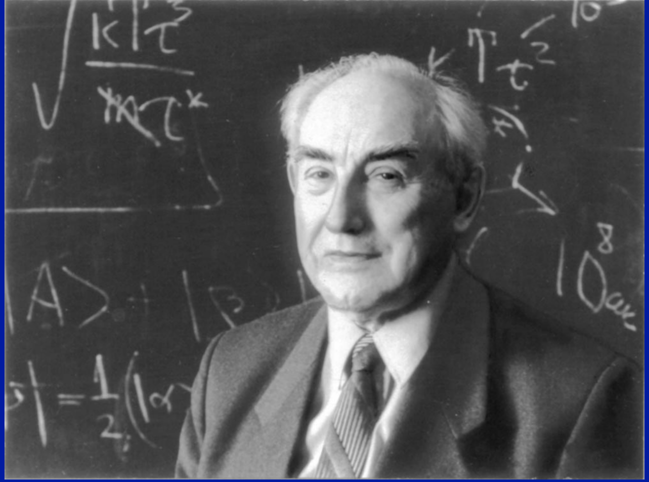
Conclusions

$Sr_{1-x}Nb_xTiO_3$: Fermi liquid of polarons

Common Fermi-liquid origin of T^2- resistivity and superconductivity

Phonon-mediated polaron-polaron interaction

Baber scattering



The “physical minimum” that a physicist should know about. Vitaly Ginzburg's list of 30 subjects for the beginning of the 21st century:

1. Controlled nuclear fusion.
2. **High-temperature and room-temperature superconductivity.**
3. Metallic hydrogen. **Other exotic substances.**
4. Two-dimensional electron liquid (the anomalous Hall effect and other effects).
5. Some questions of solid-state physics (heterostructures in semiconductors, quantum wells and dots, metal-dielectric transitions, charge- and spindensity waves, mesoscopics).
6. Second-order and related phase transitions. Some examples of such transitions. Cooling (in particular, laser cooling) to superlow temperatures. Bose-Einstein condensation in gases.
7. Surface physics. Clusters.
8. Liquid crystals. Ferroelectrics. Ferrotoroics.
9. Fullerenes. Nanotubes.

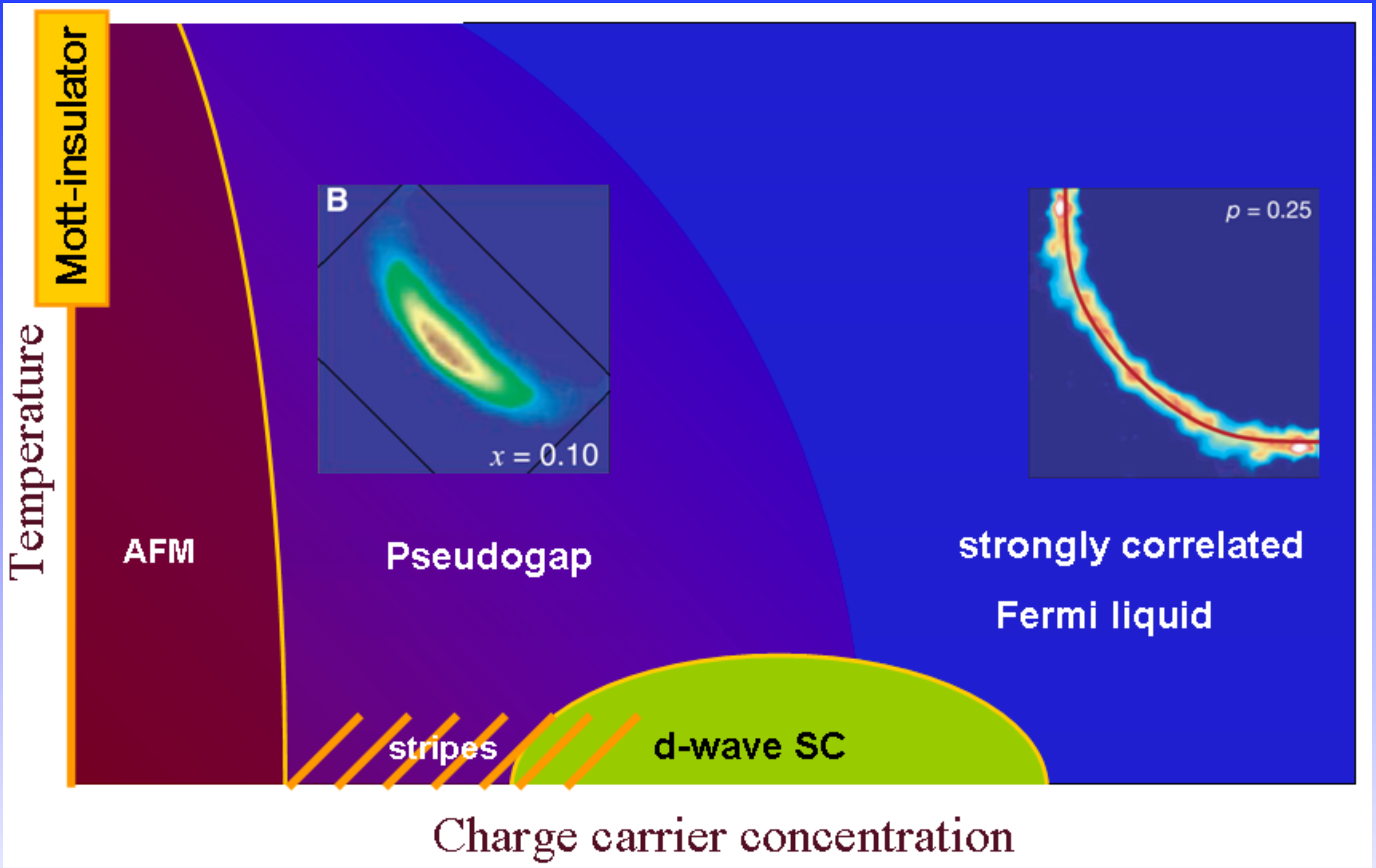
What about High Tc

Strongly correlated electrons

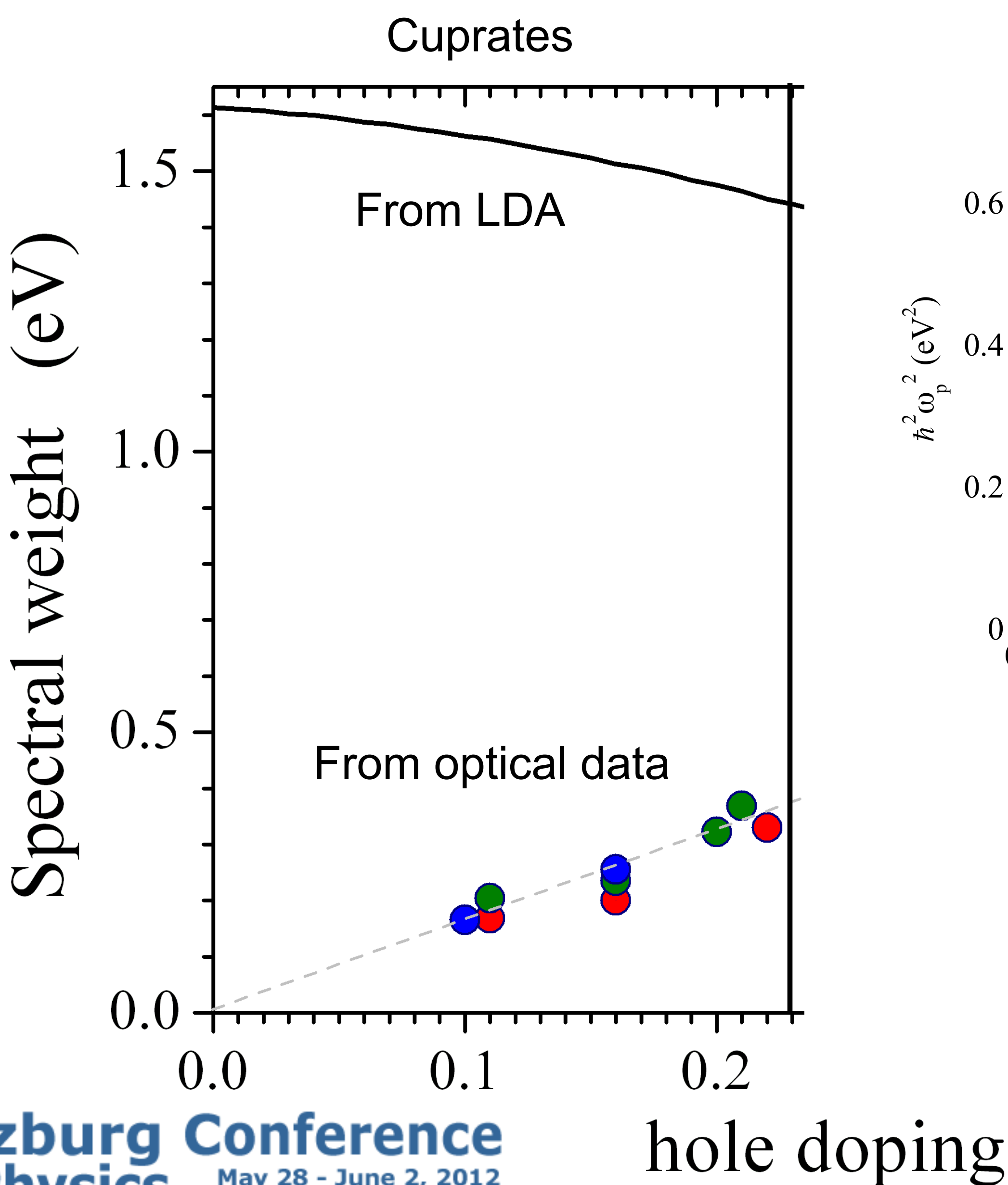
In collaboration with S. I. Mirzaei, D. Stricker, J. Hancock, C. Berthod, A. Georges, *Department of Condensed Matter Physics, University of Geneva, Switzerland*

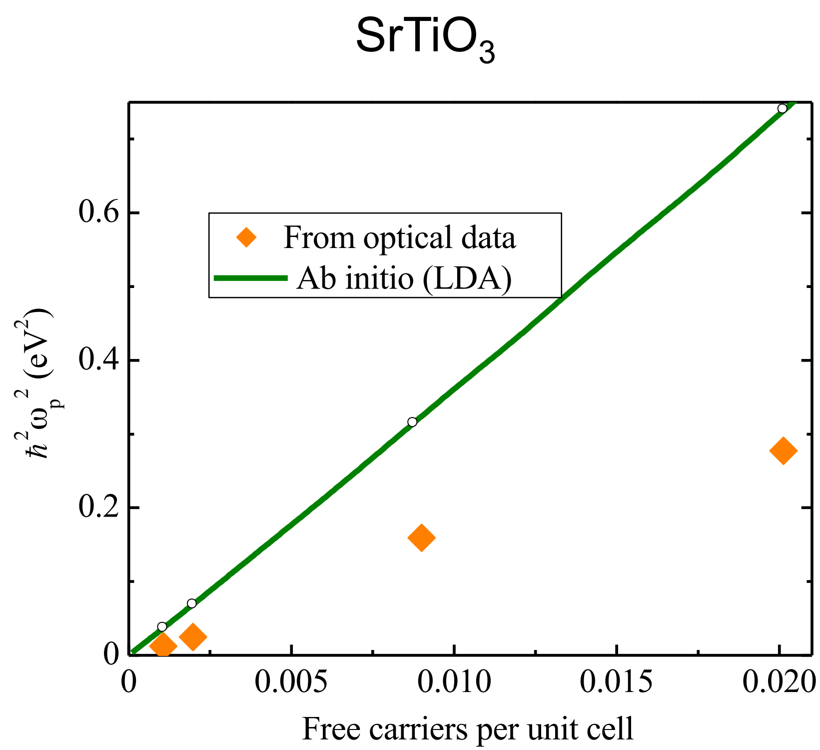
M. Chan, X. Zhao, M. Greven, N. Barisic
Physics department, University of Minnesota, USA

Hole doping phase diagram

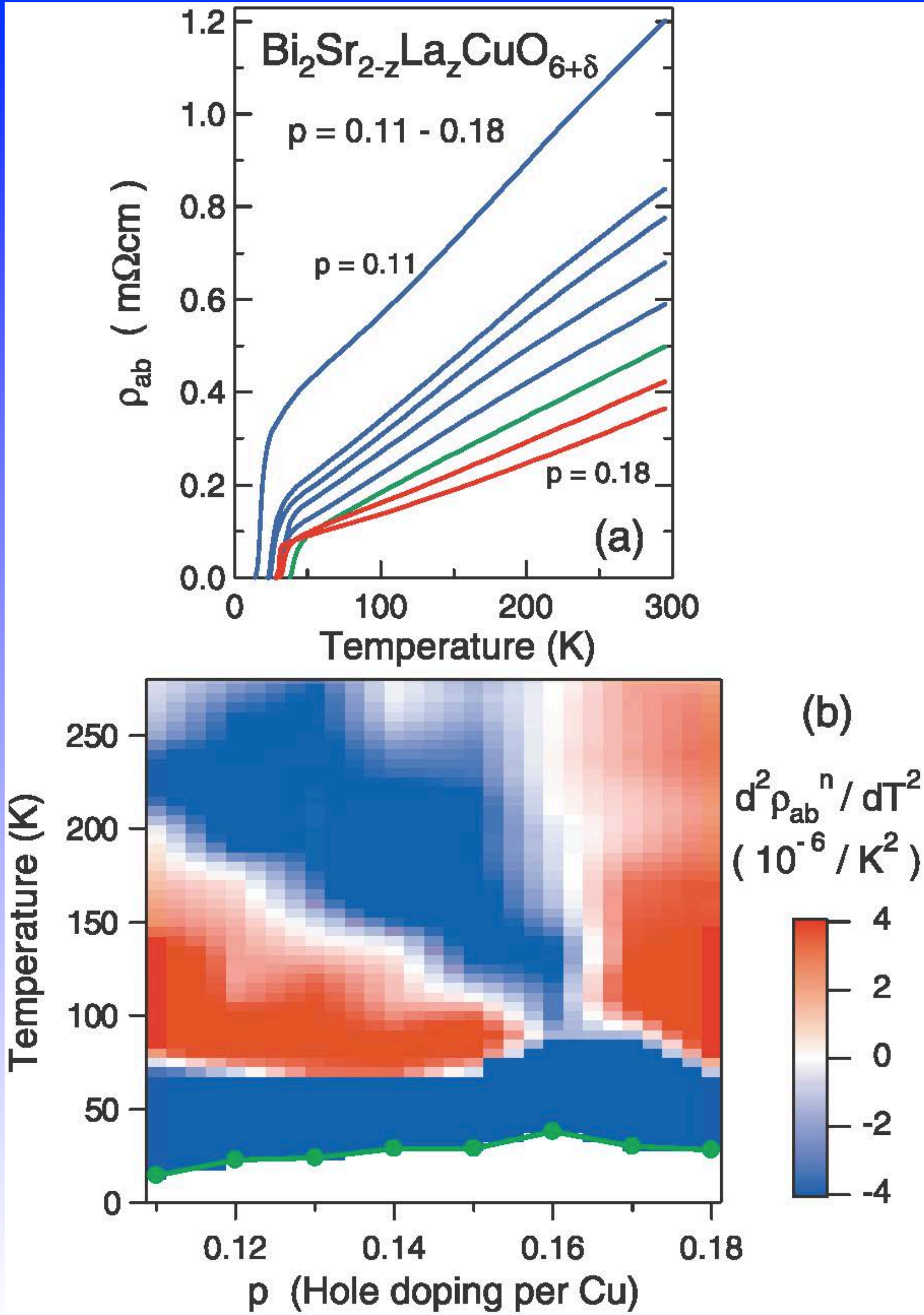


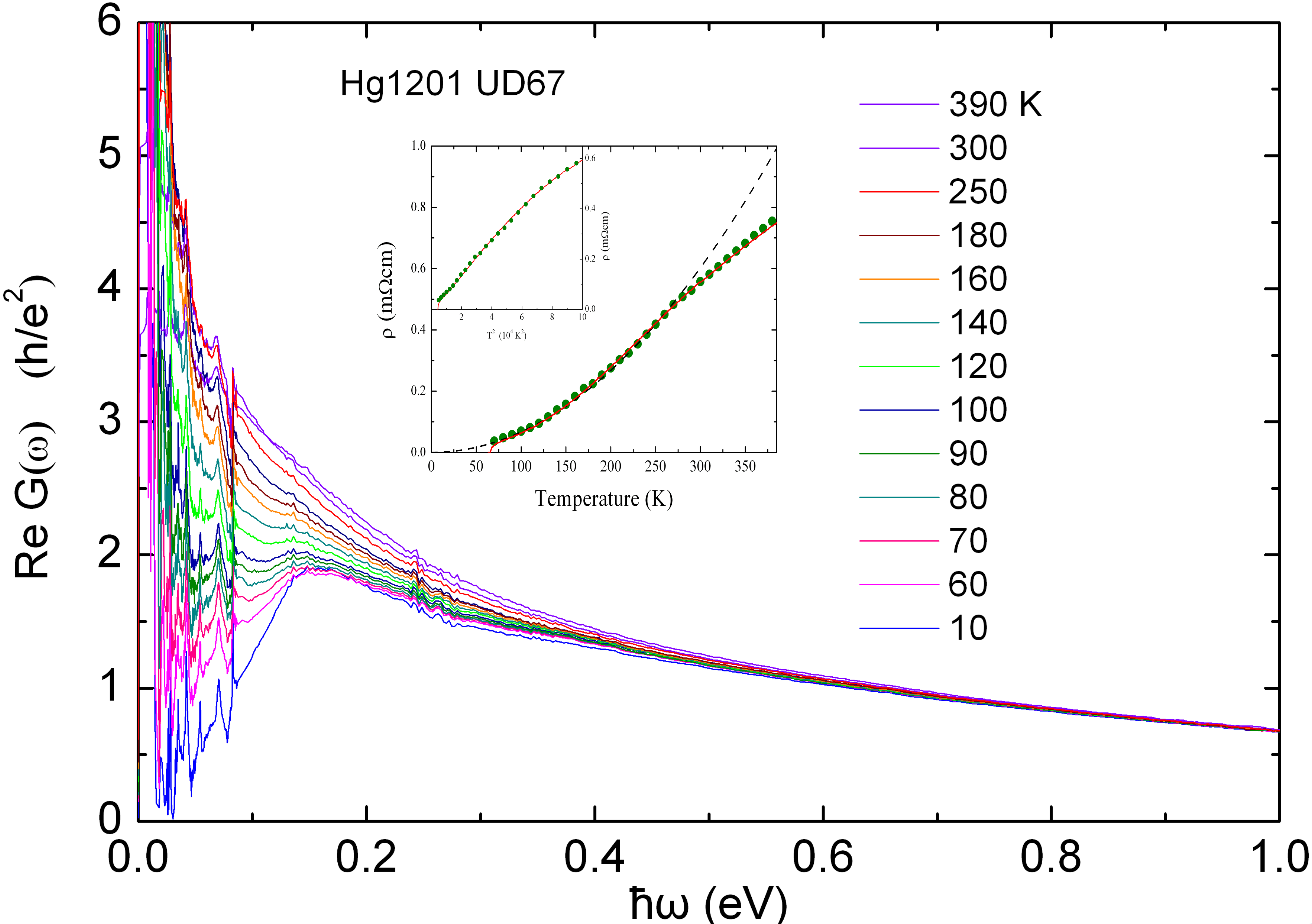
Cuprates versus $SrTiO_3$



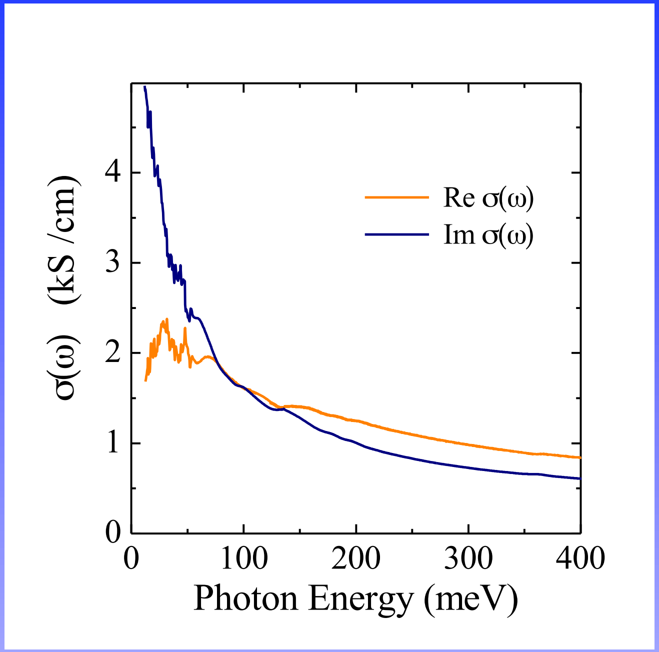


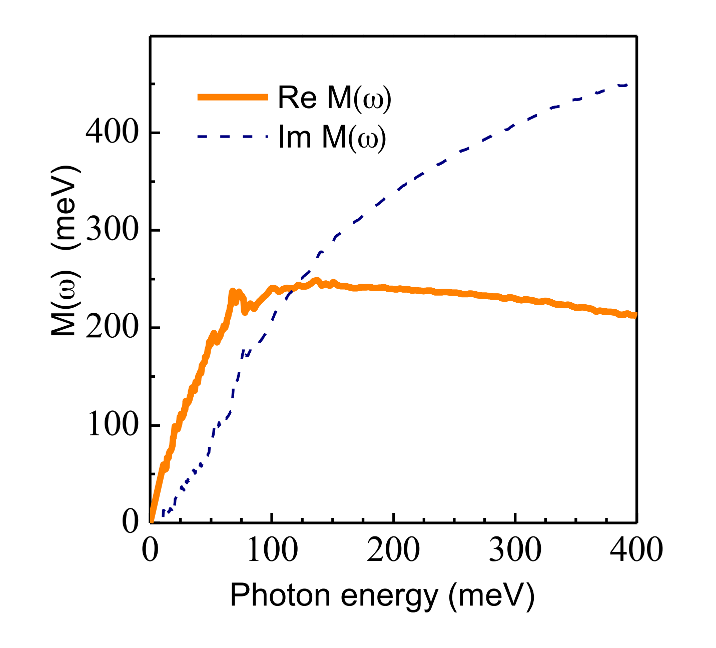
Y. Ando et al.,
PRL 93, 267001 (2004)




Hg1201 UD67
390 K
300
250
180
160
140
120
100
90
80
70
60
10
Re G(ω) (h/e^2)
ħω (eV)
ρ (mΩcm)
Temperature (K)
T^2 (10^4 K^2)

Generalized Drude response

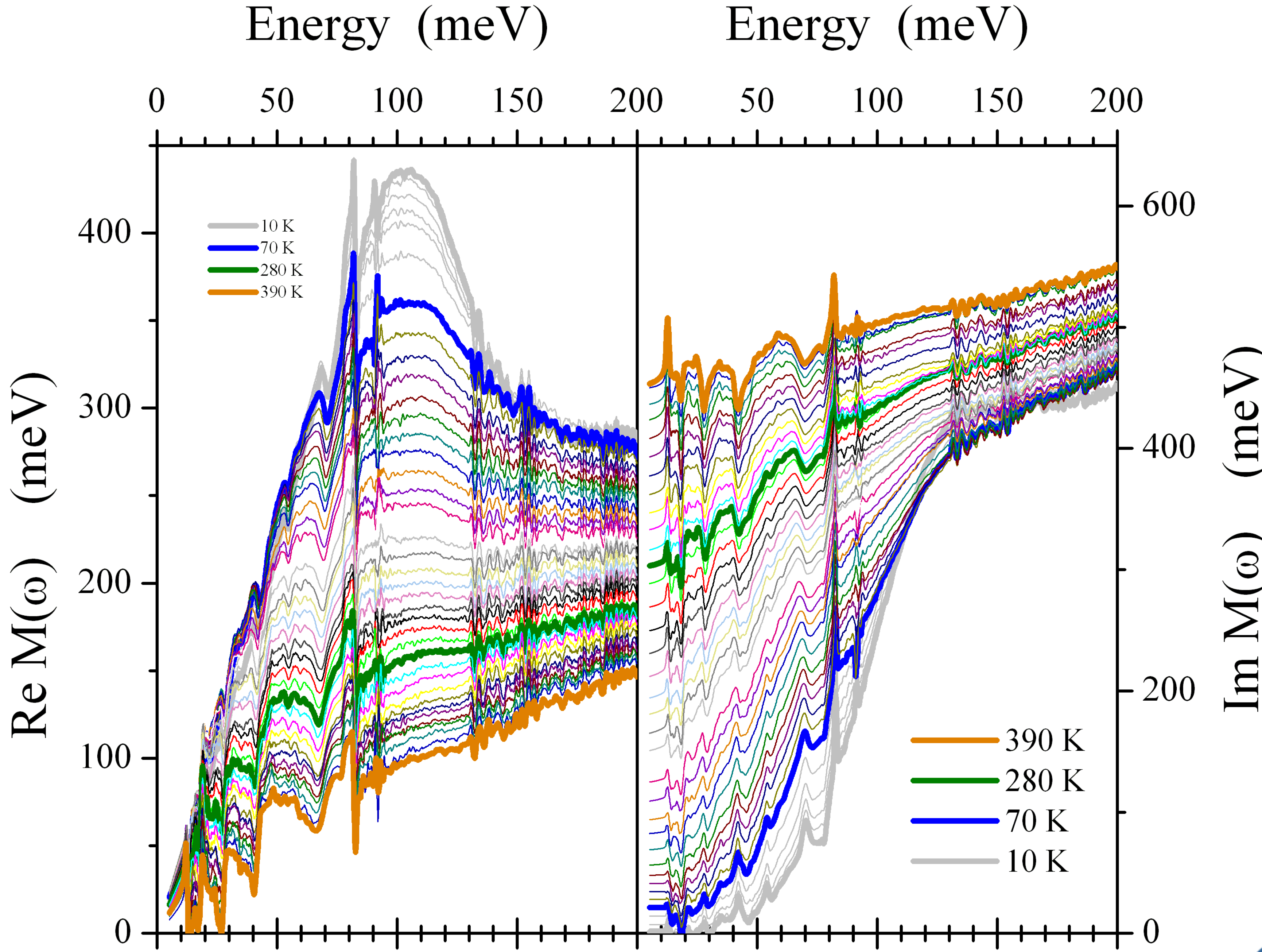


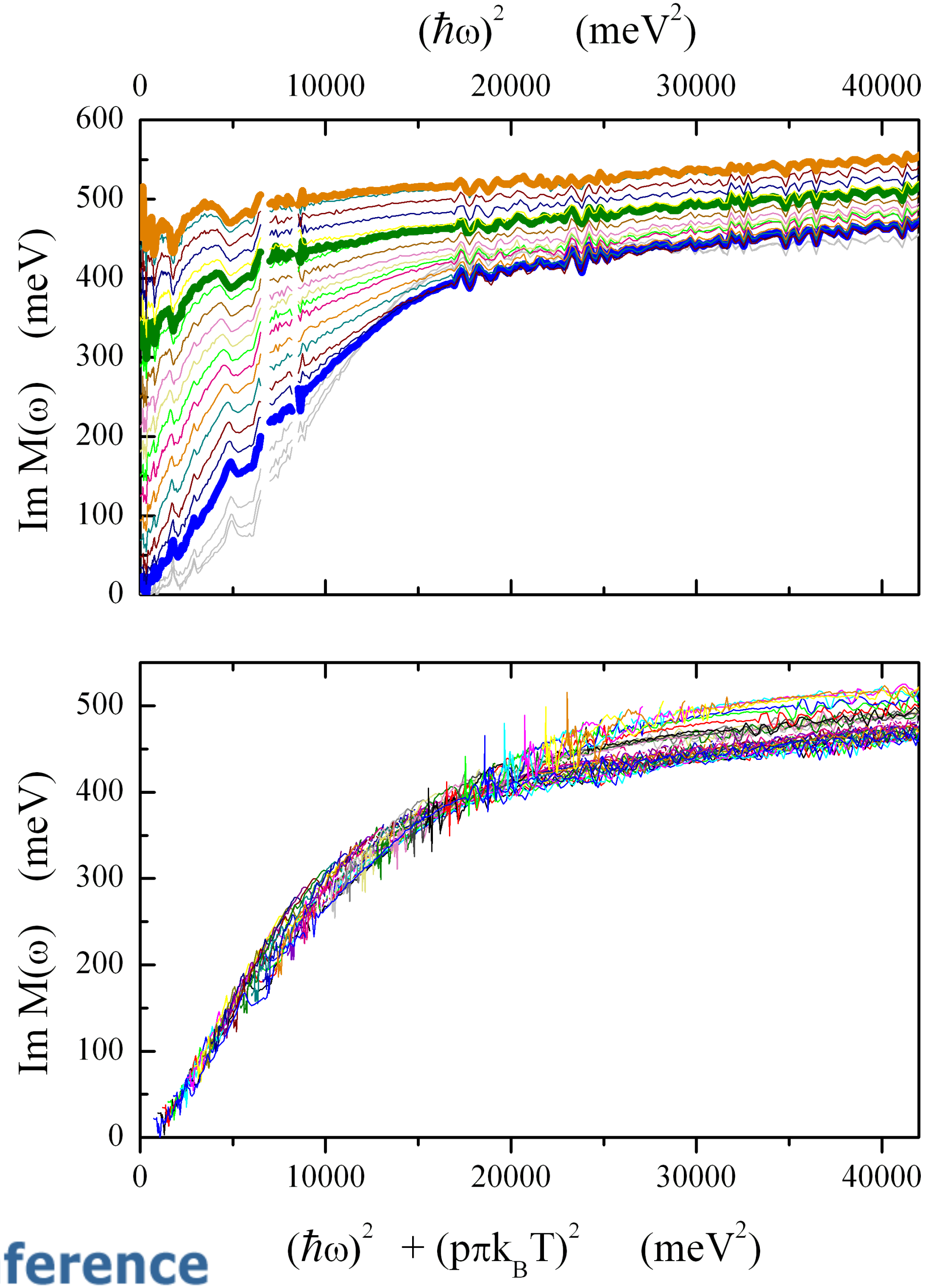


$$\sigma(\omega) = \frac{e^2 n_{fc}}{i m_{opt}} \frac{1}{\omega + M(\omega)}$$

$$\lim_{\omega \to 0} \frac{\operatorname{Re} M(\omega)}{\omega} = \frac{m^*}{m} - 1$$

$$\operatorname{Im} M(\omega) = 1/\tau(\omega)$$


Energy (meV)
Energy (meV)
0
50
100
150
200
50
100
150
200
Re M(ω) (meV)
Im M(ω) (meV)
400
300
200
100
0
600
400
200
0
10 K
70 K
280 K
390 K
390 K
280 K
70 K
10 K

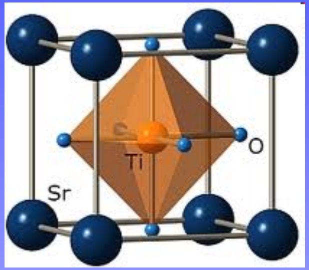


$(\hbar\omega)^2$ (meV^2)
0
10000
20000
30000
40000
600
500
400
300
200
100
0
Im M(ω) (meV)
500
400
300
200
100
0
Im M(ω) (meV)
0
10000
20000
30000
40000
$(\hbar\omega)^2 + (p\pi k_B T)^2$ (meV^2)

Conclusions

Interaction in n-type STO: mediated by phonons

This interaction gives a strong T^2 contribution to $\rho(T)$

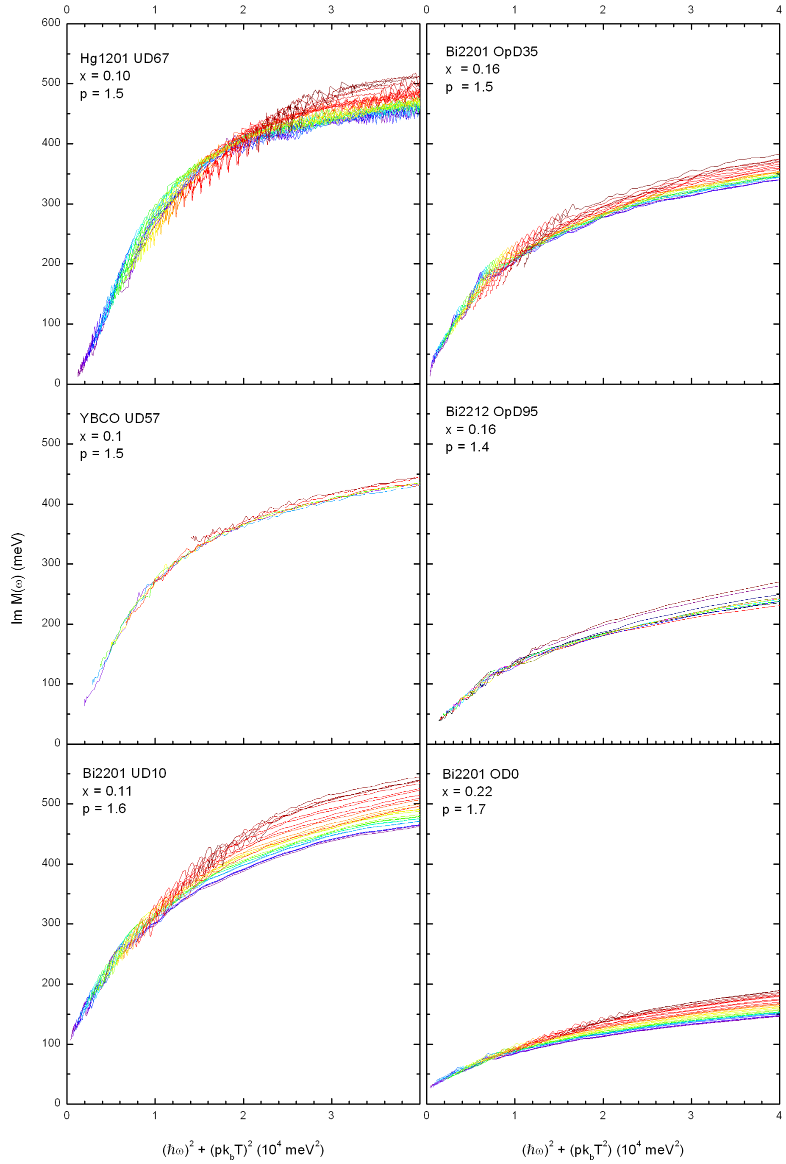


T_c < 1 Kelvin

Normal state: Fermi liquid of unpaired polarons

Phonon part of the story is not so different for cuprates, but the physics of the cuprates is dominated by strong correlations

Underdoped cuprates: $1/\tau(\omega,T)=\omega^2+(pT)^2$

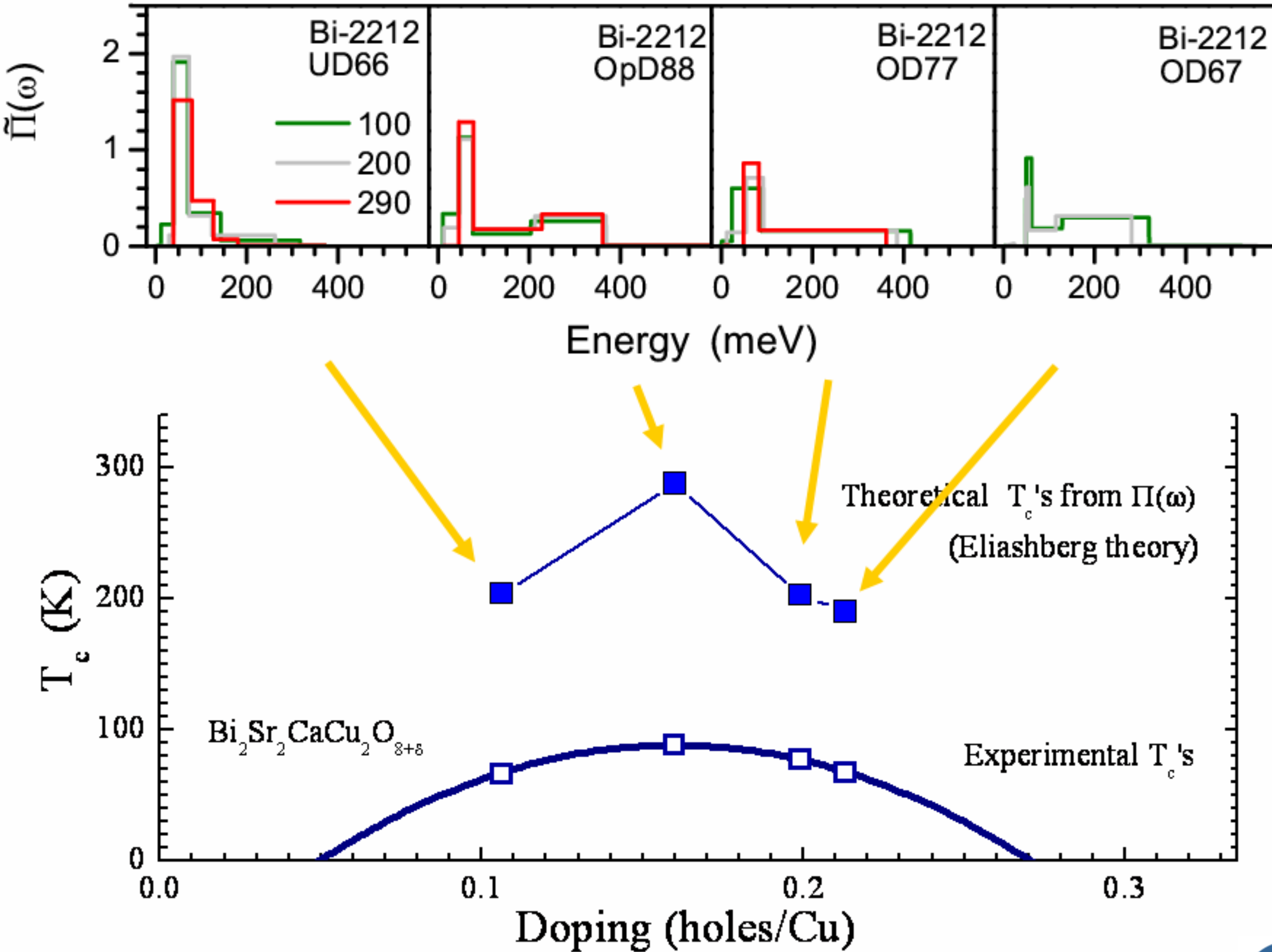


Hg1201 UD67
x = 0.10
p = 1.5
Bi2201 OpD35
x = 0.16
p = 1.5
YBCO UD57
x = 0.1
p = 1.5
Bi2212 OpD95
x = 0.16
p = 1.4
Bi2201 UD10
x = 0.11
p = 1.6
Bi2201 OD0
x = 0.22
p = 1.7
Im M(ω) (meV)
(ħω)² + (pk_bT)² (10⁴ meV²)
(ħω)² + (pk_bT²) (10⁴ meV²)

P. B. Allen, PRB **3** (1971) 305:

$$\sigma(\omega,T)=\frac{i\omega_p^2}{4\pi\omega}\int_{-\infty}^{\infty}\frac{f(\xi/T)-f((\xi+\omega)/T)}{\omega-\Sigma(\xi+\omega)+\Sigma^*(\xi)}d\xi$$

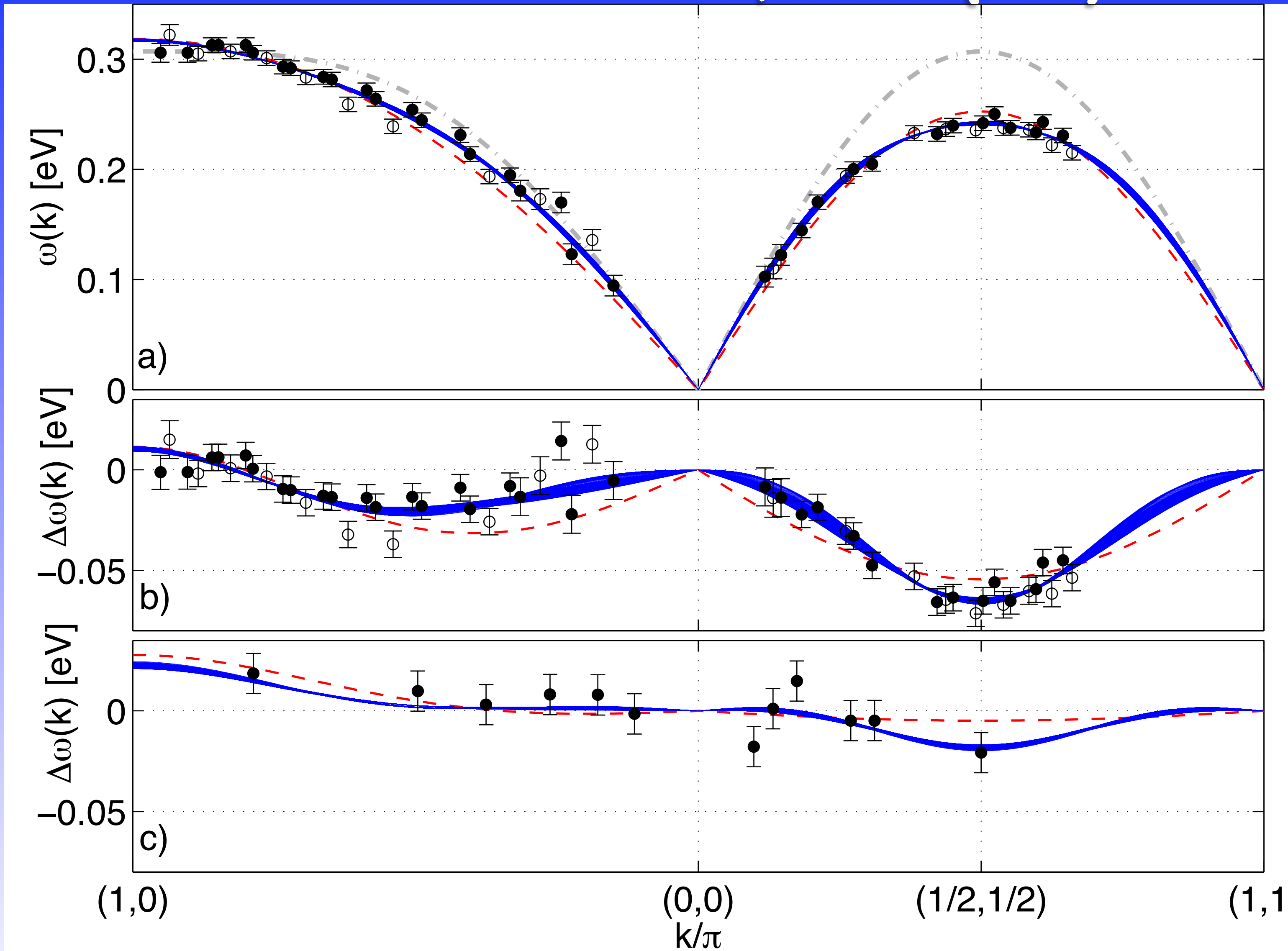
$$\Sigma^*(\xi,T)=\int_0^{\infty}d\Omega\tilde{\Pi}(\Omega)\int_{-\infty}^{\infty}d\varepsilon\left\{\frac{n(\Omega/T)+f(\varepsilon/T)}{\xi-\varepsilon+\Omega-i0^+}+\frac{n(\Omega/T)+1-f(\varepsilon/T)}{\xi-\varepsilon-\Omega-i0^+}\right\}$$



E. van Heumen et al. , Physical Review B 79, 184512 (2009)

Magnons in the cuprates

M. Guarise et al. PRL 105, 157006 (2010)



Le Tacon et al, Nature Physics 7, 725–730 (2011)

NATURE PHYSICS DOI: 10.1038/NPHYS2041

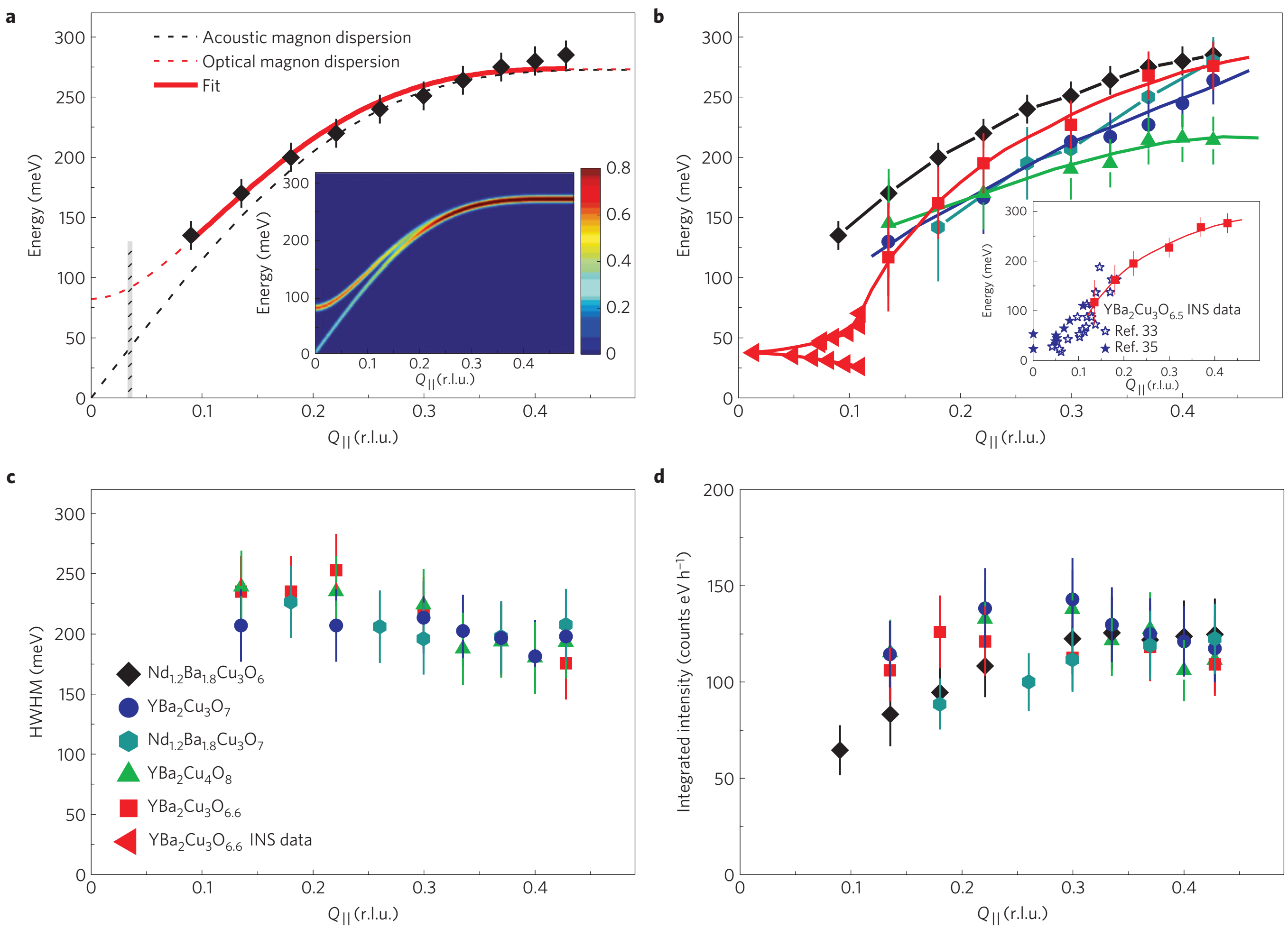


Figure 3 | Dispersion, linewidth and intensity of the magnetic excitations. a, Experimental magnon dispersion along the 100 direction in antiferromagnetic $Nd_{1.2}Ba_{1.8}Cu_3O_6$ at $T = 15$ K, fitted using the spin-wave dispersion of a bilayer from ref. 16 (thick red line). The dashed lines are the acoustic (black) and optical (red) spin-wave dispersions calculated using the fitting parameters. The grey area represents our energy–momentum resolution. Inset: relative intensities of the acoustic and optical magnons for our scattering geometry. **b**, Experimental magnon dispersion along the 100 direction in antiferromagnetic $Nd_{1.2}Ba_{1.8}Cu_3O_6$, underdoped $Nd_{1.2}Ba_{1.8}Cu_3O_7$, $YBa_2Cu_3O_{6.6}$, $YBa_2Cu_4O_8$ and $YBa_2Cu_3O_7$ at $T = 15$ K. Low-frequency INS data recorded along the 100 direction from Q ... for $YBa_2Cu_3O_{6.6}$ have been added[34]. Lines are guides to the eye. **c**, HWHM of magnetic excitations in ... and $YBa_2Cu_3O_7$. **d**, Integrated inelastic intensities. The error bars reflect the accuracy of the fitting procedure

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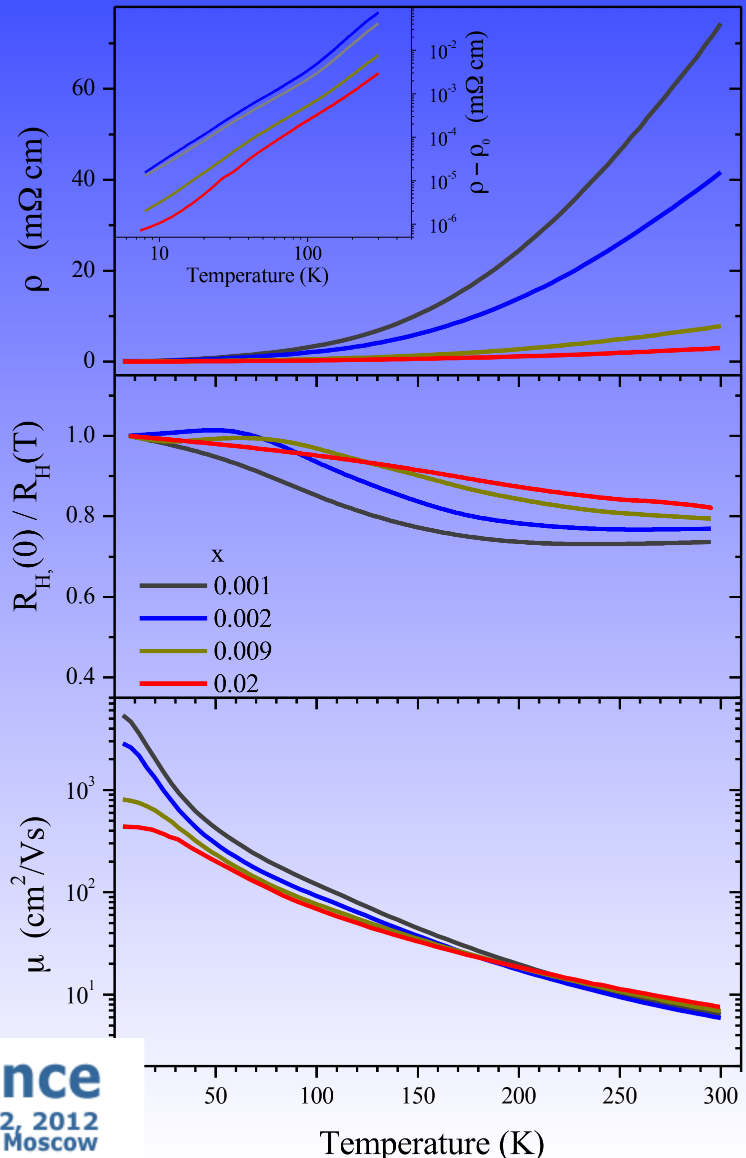
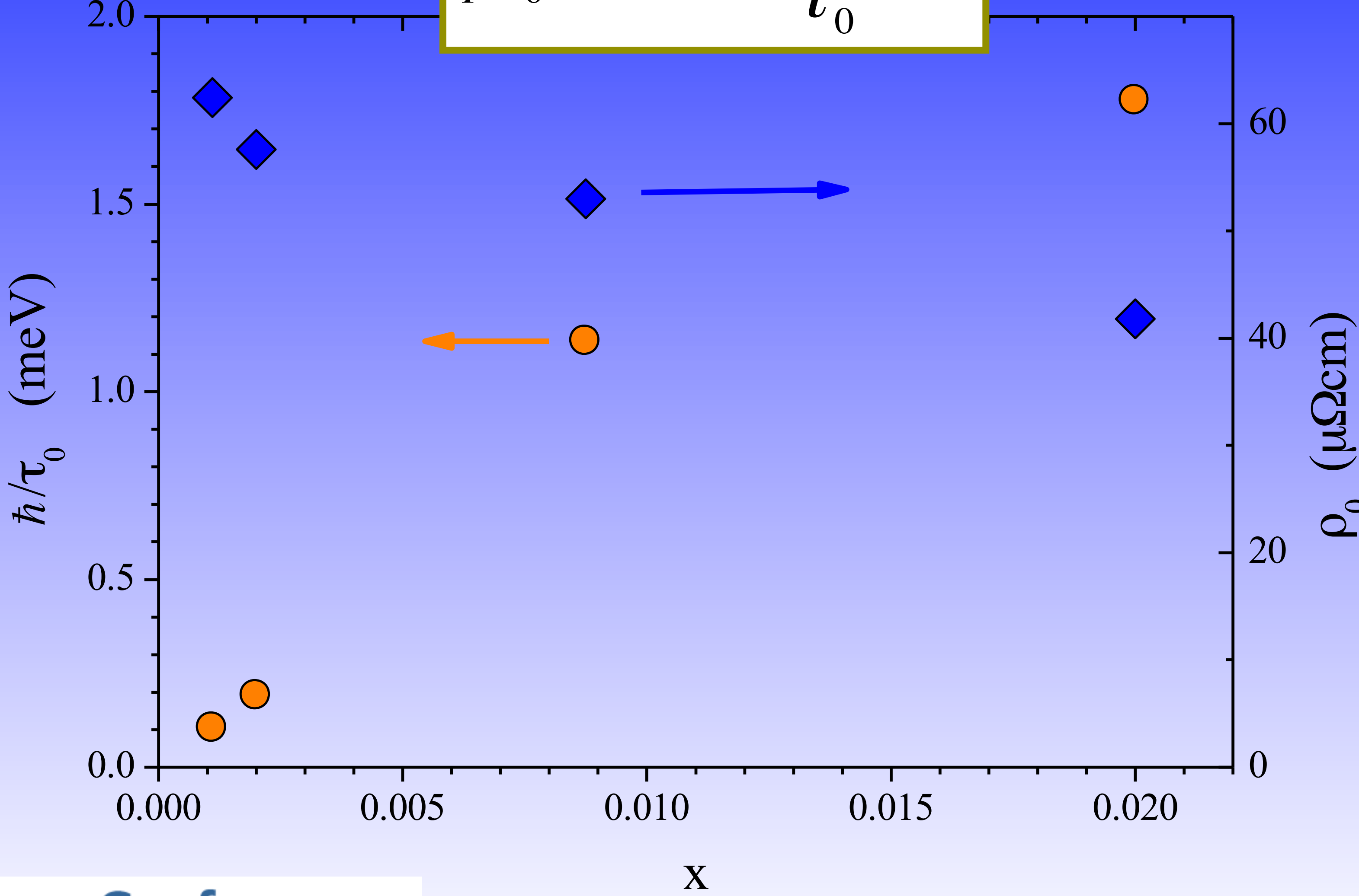
DC transport in n-type $SrTi_{1-x}Nb_xO_3$



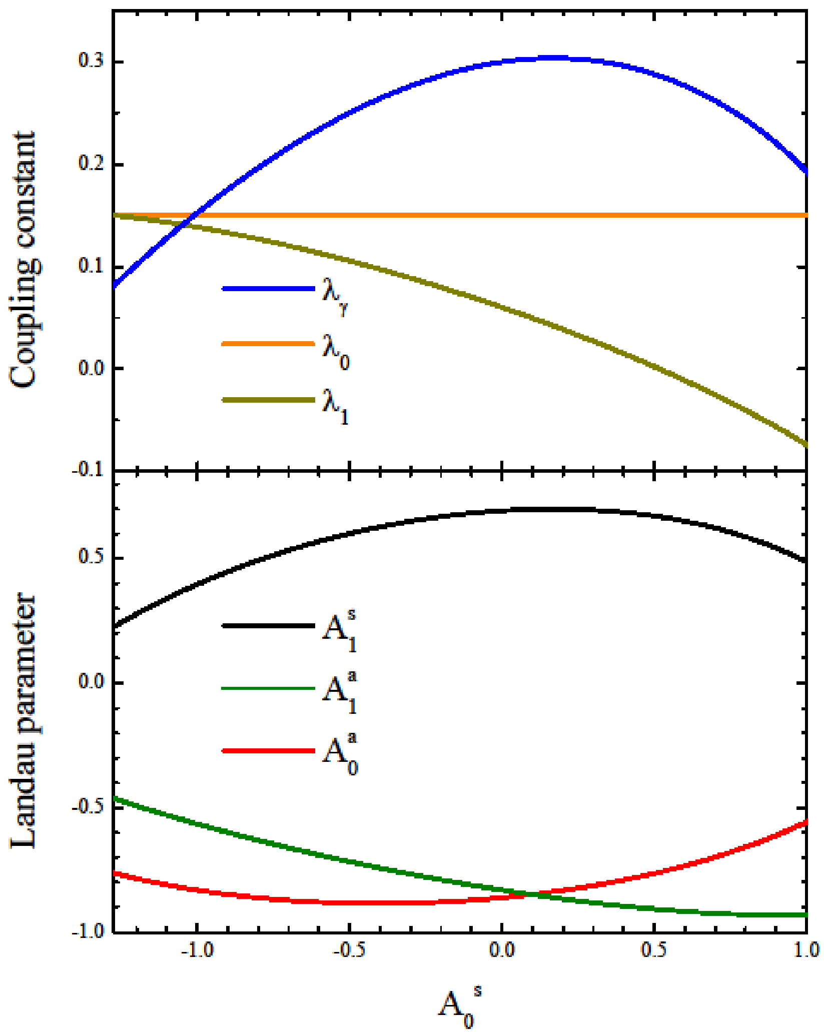
Residual scattering

$SrTi_{1-x}Nb_xO_3$

$$\lim_{T \to 0} \tau^{-1}(T) = \frac{1}{\tau_0} \propto x$$



Landau parameters



Physical constraints

Enhanced effective mass : $A_1^s > 0$

Positive compressibility : $A_0^s < 1$

Singlet pairing : $\lambda_0 > \lambda_1$

S. Dal Conte *et al.*
Science (2012)

D. van der Marel *et al.*
PRB 84 (2011) 205111

J. T. Devreese *et al.*
PRB 81 (2010) 125119

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NJP 11 (2009) 055067

E. van Heumen *et al.*
PRB 79 (2009) 184512

J.L.M. van Mechelen *et al.*
PRL 100 (2008) 226403