Fermi liquid and beyond in Sr_2RuO_4

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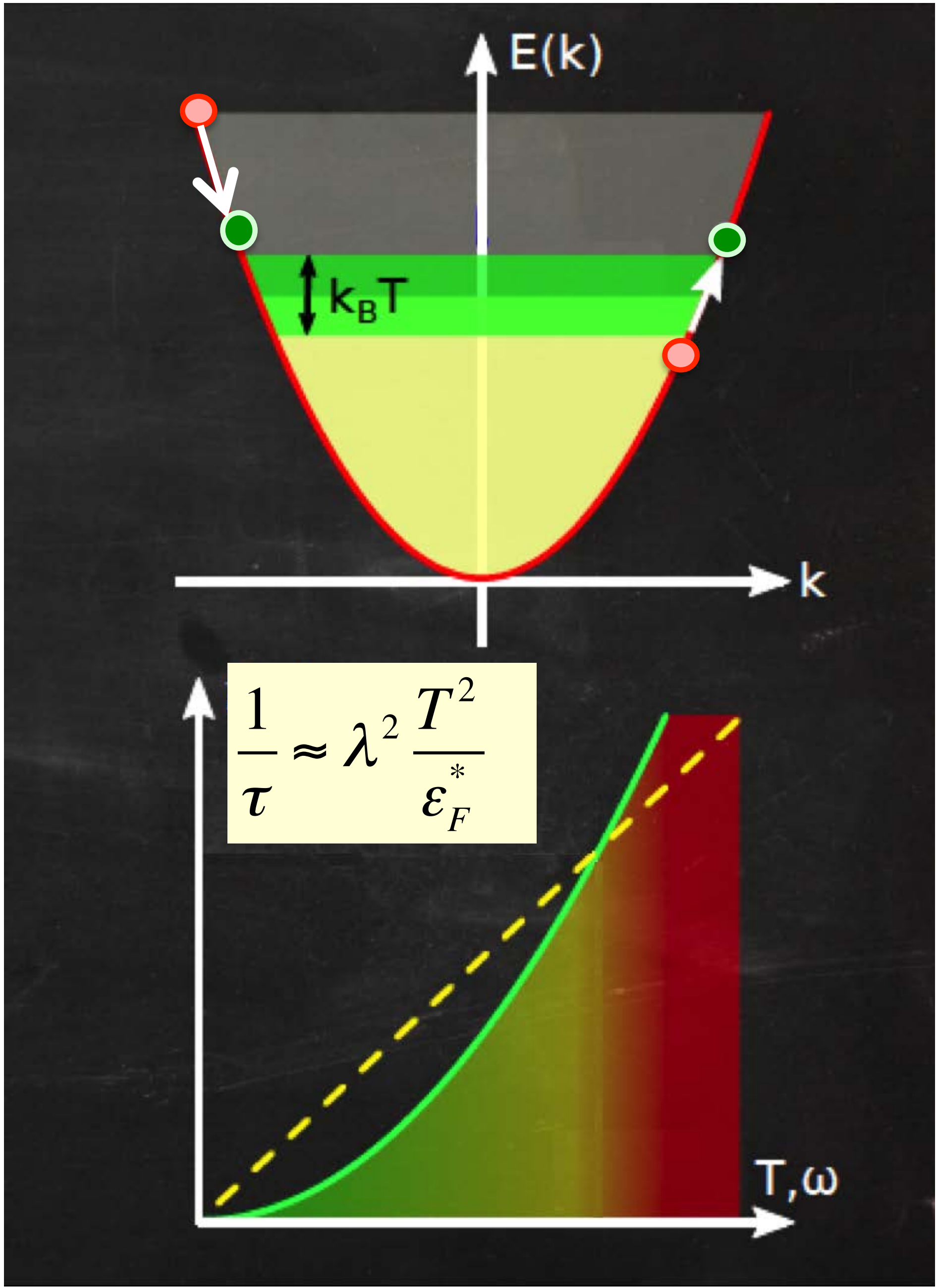
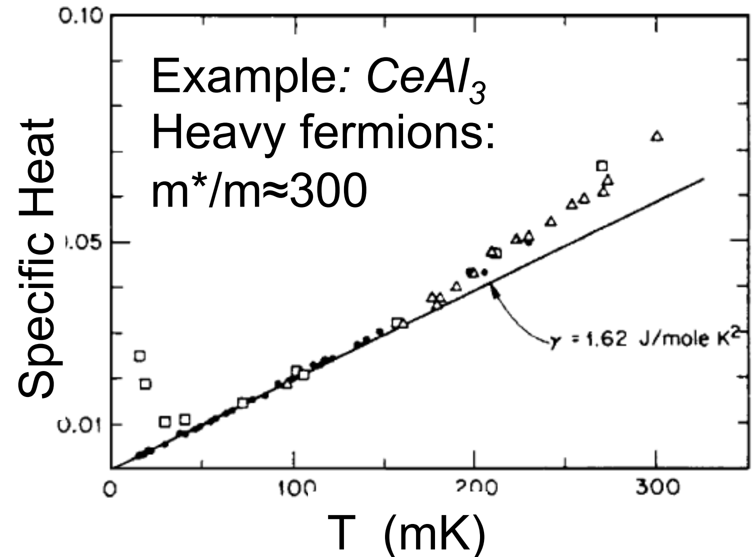
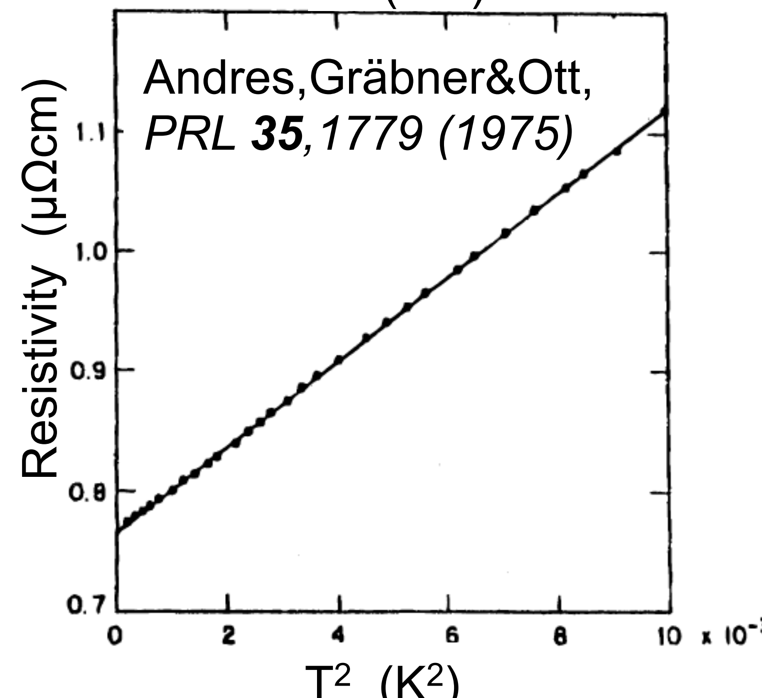
Dirk van der Marel - *Université de Genève*

SCSR2014 Adriatico Guesthouse, Trieste, 10-11 December 2014

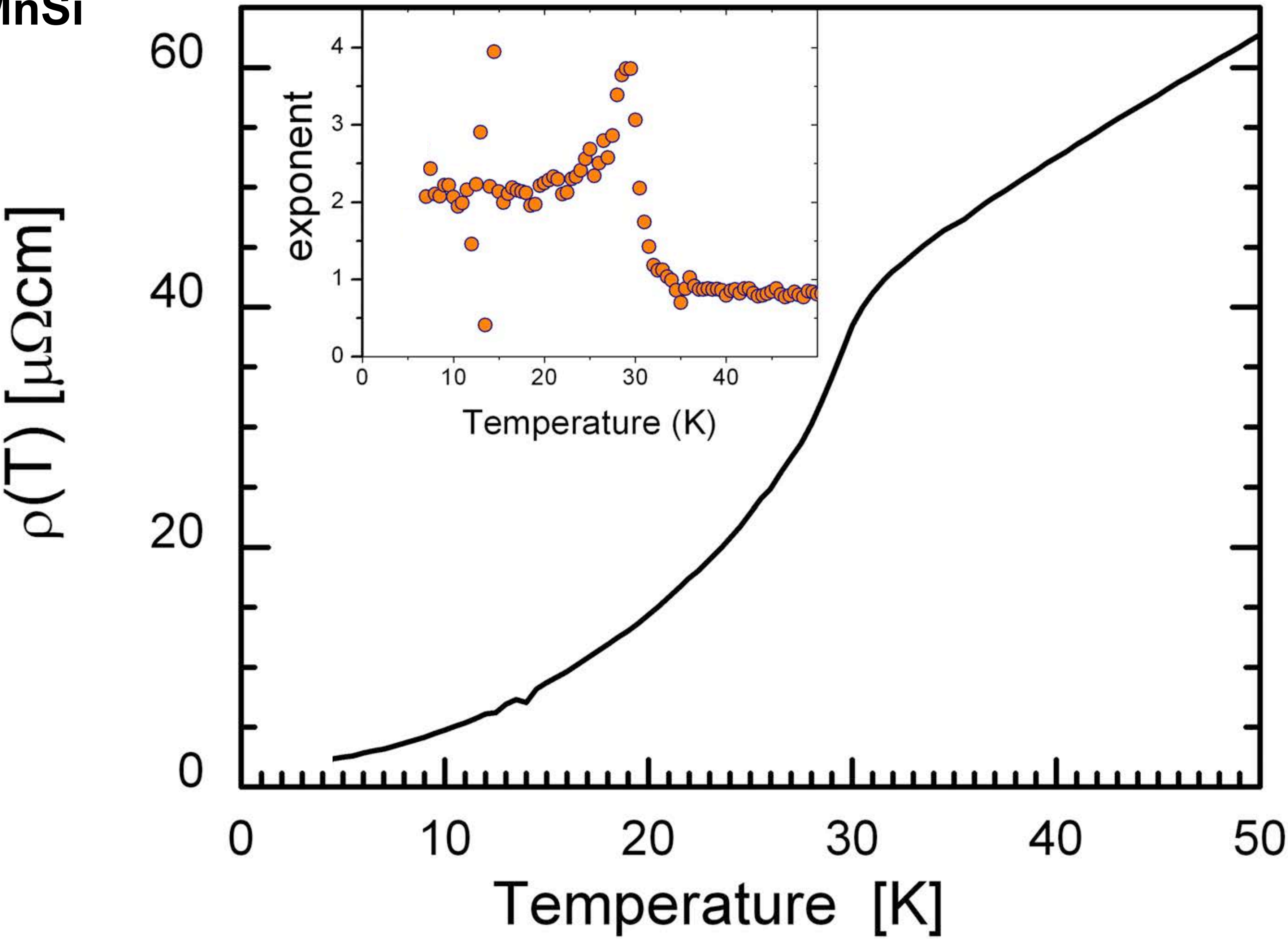
Landau–Fermi liquids





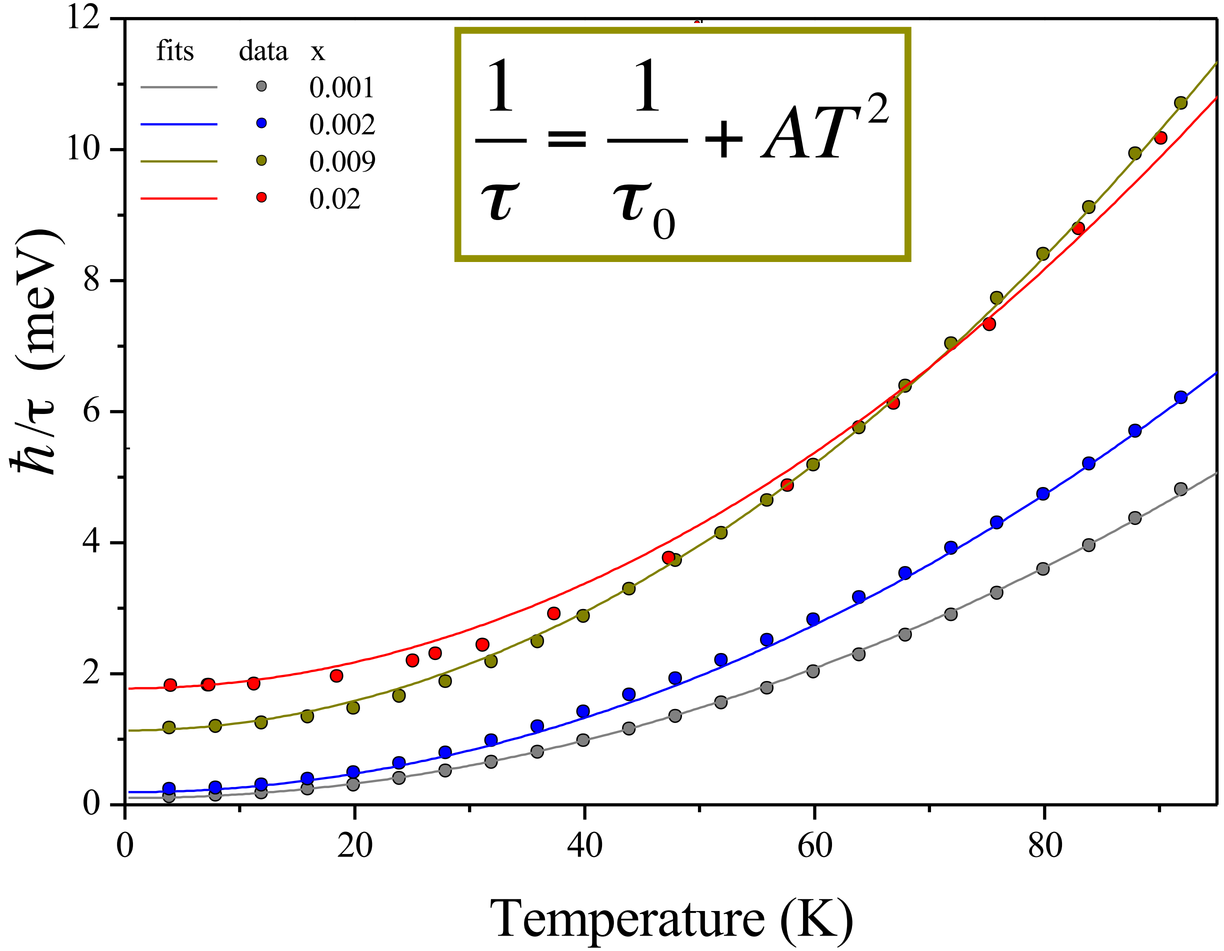


MnSi



FP Mena et al PRB 67 (2003)

$SrTi_{1-x}Nb_xO_3$



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

Three questions :

- How do we tell it's a Fermi Liquid when we see one (in optics) ?

- Can we understand the Non Fermi-Liquid behavior in Sr_2RuO_4 above ~ 0.1 eV ?

- What does it teach us about the physics of Sr_2RuO_4 ?

How do we tell it's a FL ?
- The simple answer -

Single-particle Lifetime : $$\frac{1}{\tau_{qp}} \propto (\hbar\omega)^2 + (\pi k_B T)^2$$

Two-particle: $$\frac{1}{\tau_{opt}} \propto (\hbar\omega)^2 + (2\pi k_B T)^2 \qquad (\hbar\omega \geq \pi k_B T)$$

R. N. Gurzhi, Sov. Phys. JETP 35, 673 (1959)

D. L. Maslov & A. V. Chubukov, PRB 86, 155137 (2012)

C. Berthod *et al*, PRB 87, 115109 (2013)

Strangely enough, this precise form (including factor 2π) was not experimentally demonstrated from optics until now !

Some questions to be answered about $1/\tau_{opt}(\omega,T)$

1a) $\tau_{opt}^{-1}(\omega,T) = \tau_{opt}^{-1}(\omega,0) + A(pk_BT)^{\mu}$?

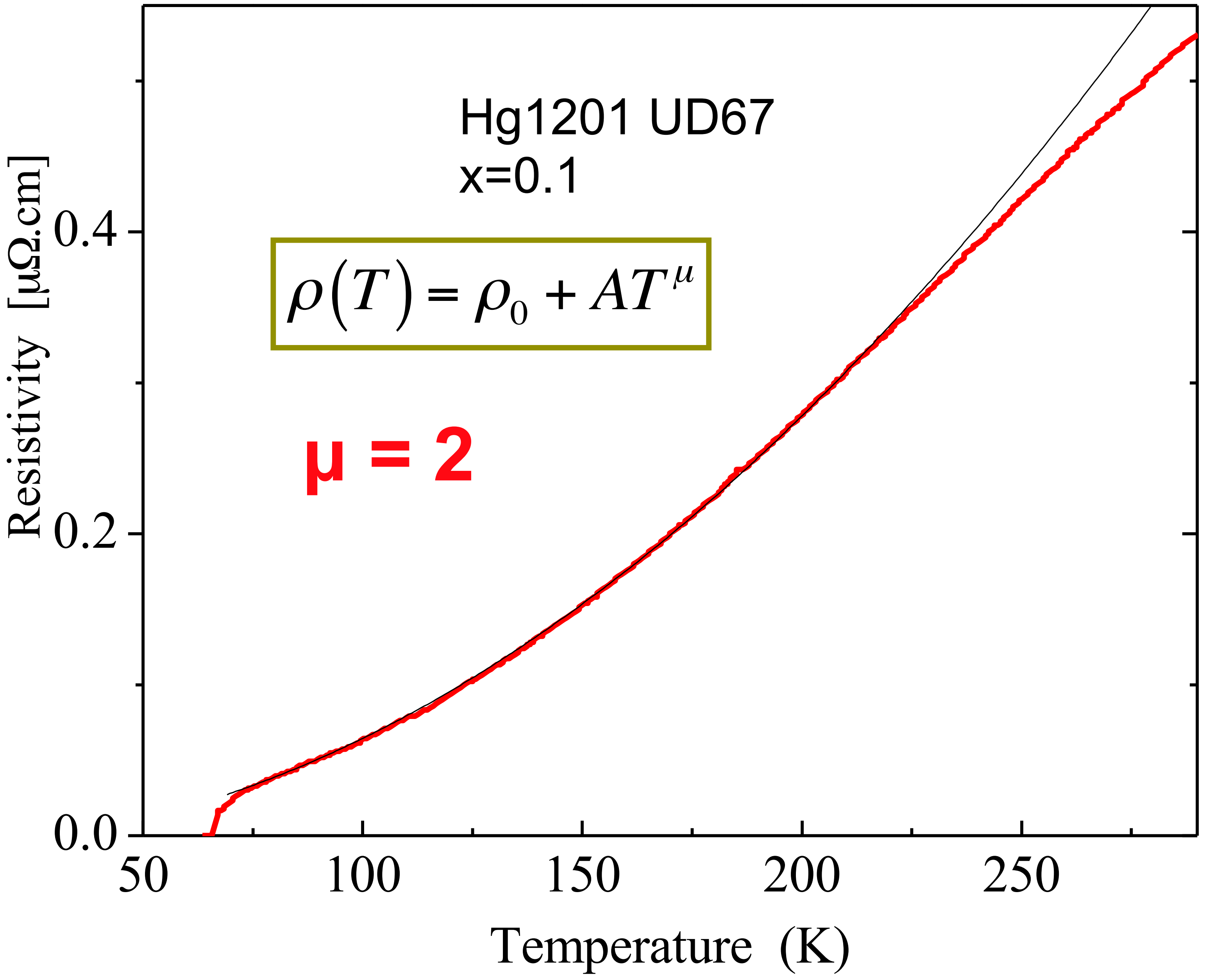
b) What is the value of μ ?

2a) $\tau_{opt}^{-1}(\omega,T) = \tau_{opt}^{-1}(0,T) + A(\hbar\omega)^{\eta}$?

b) What is the value of η ?

3a) $$\left\{\begin{array}{l} \tau_{opt}^{-1}(\omega,T) = f(\xi) \\ \xi = \sqrt{(\hbar\omega)^2 + (pk_BT)^2} \end{array}\right\}$$?

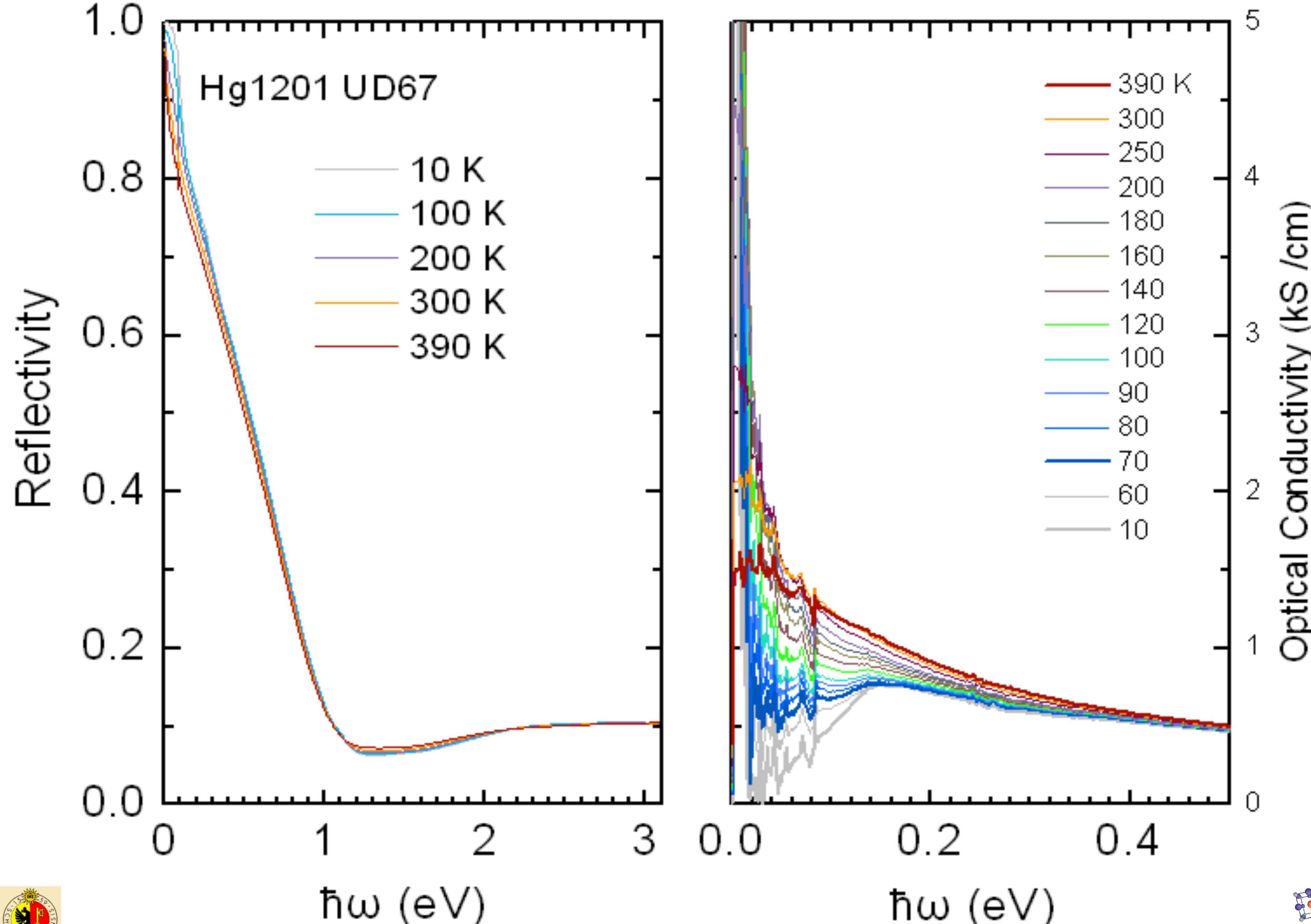
b) What is the value of p ?



N Barisic *et al., PNAS 2013*

S.I. Mirzaei, D. Stricker *et al.*, *PNAS 2013*

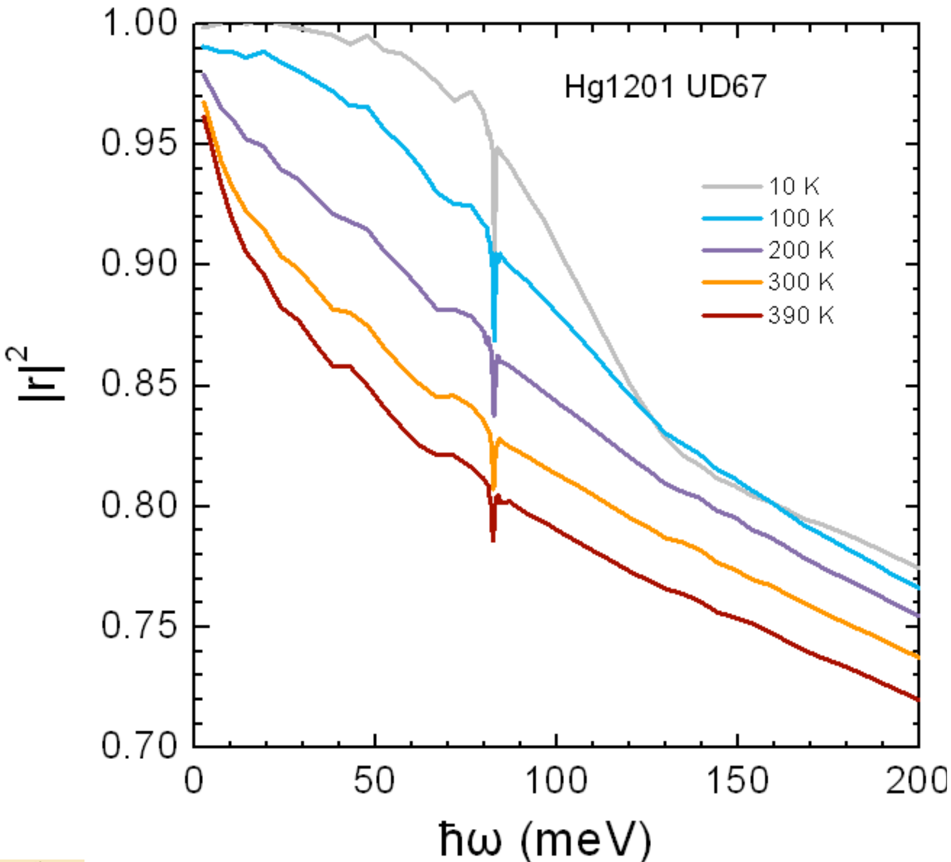
Hg1201 UD67

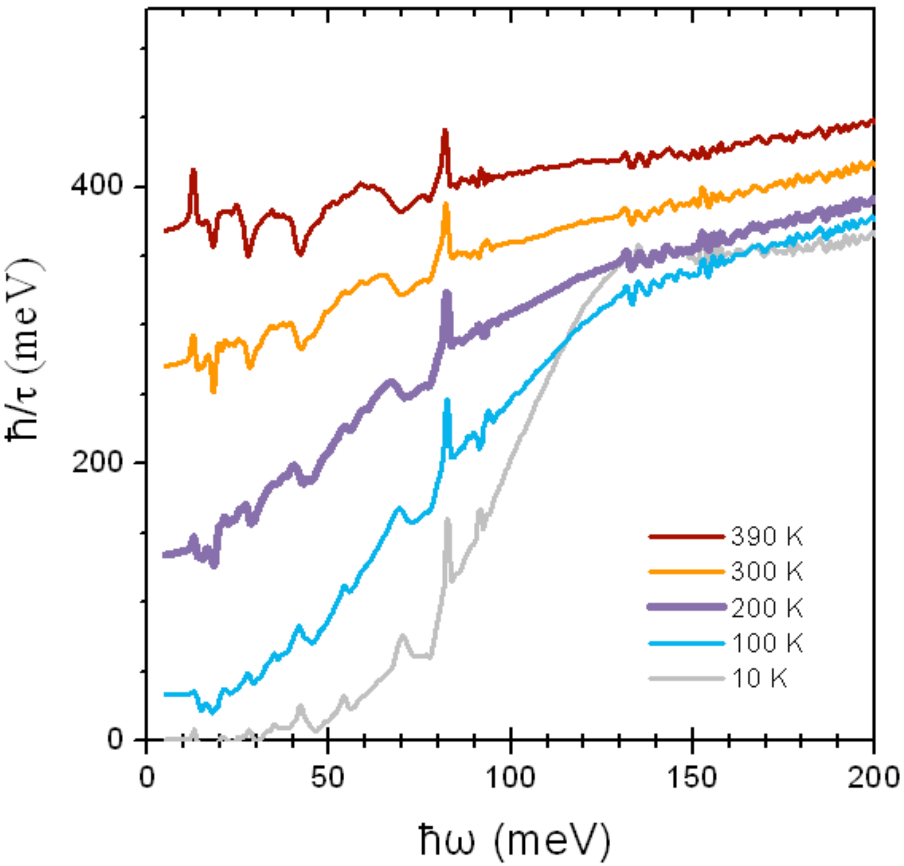

Hg1201 UD67
10 K
100 K
200 K
300 K
390 K
Reflectivity
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
ħω (eV)
390 K
300
250
200
180
160
140
120
100
90
80
70
60
10
0.0
0.2
0.4
ħω (eV)
5
4
3
2
1
0
Optical Conductivity (kS /cm)

$HgBa_2CuO_4$: Energy dependend Relaxation rate

$$\mathrm{Im}\frac{\omega_p^2\omega^{-1}}{(1+r)^2/(1-r)^2-\varepsilon_{bc}} = \frac{1}{\tau_{opt}(\omega)}$$

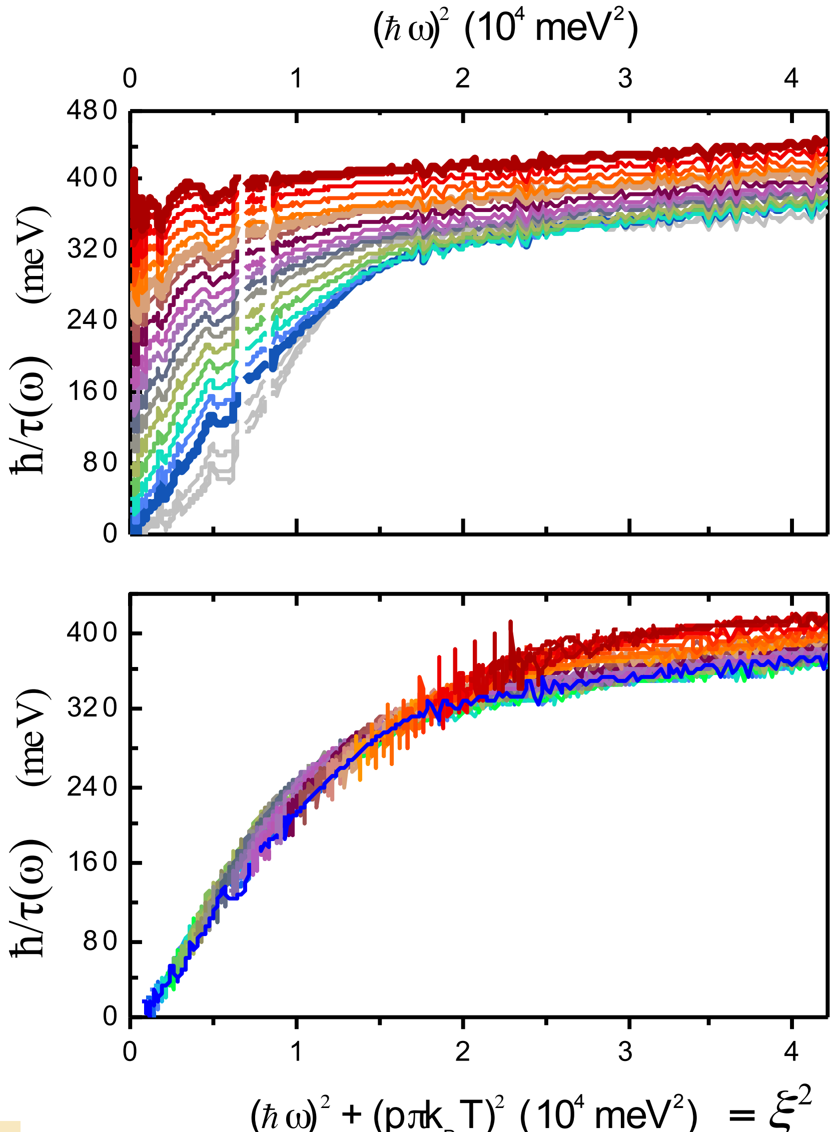
Basov, Averitt, vdMarel, Dressel & Haule
RMP ***83***, *471 (2011)*





Fermi-liquid

Optical signature: scaling collapse

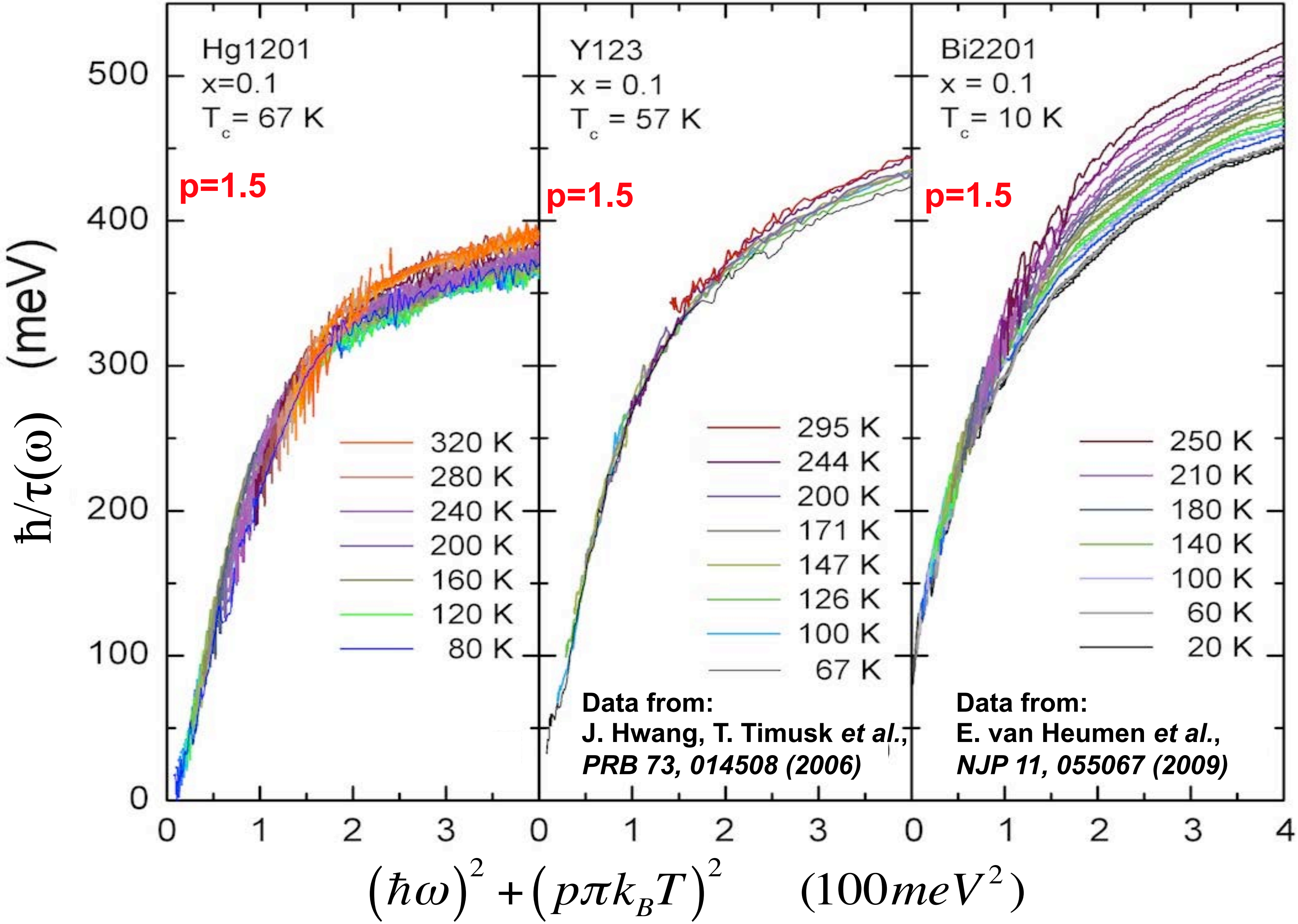


$$\frac{1}{\tau_{opt}} = \frac{1}{\tau(T)} + A\omega^{\eta}$$

$\boldsymbol{\eta = 2}$

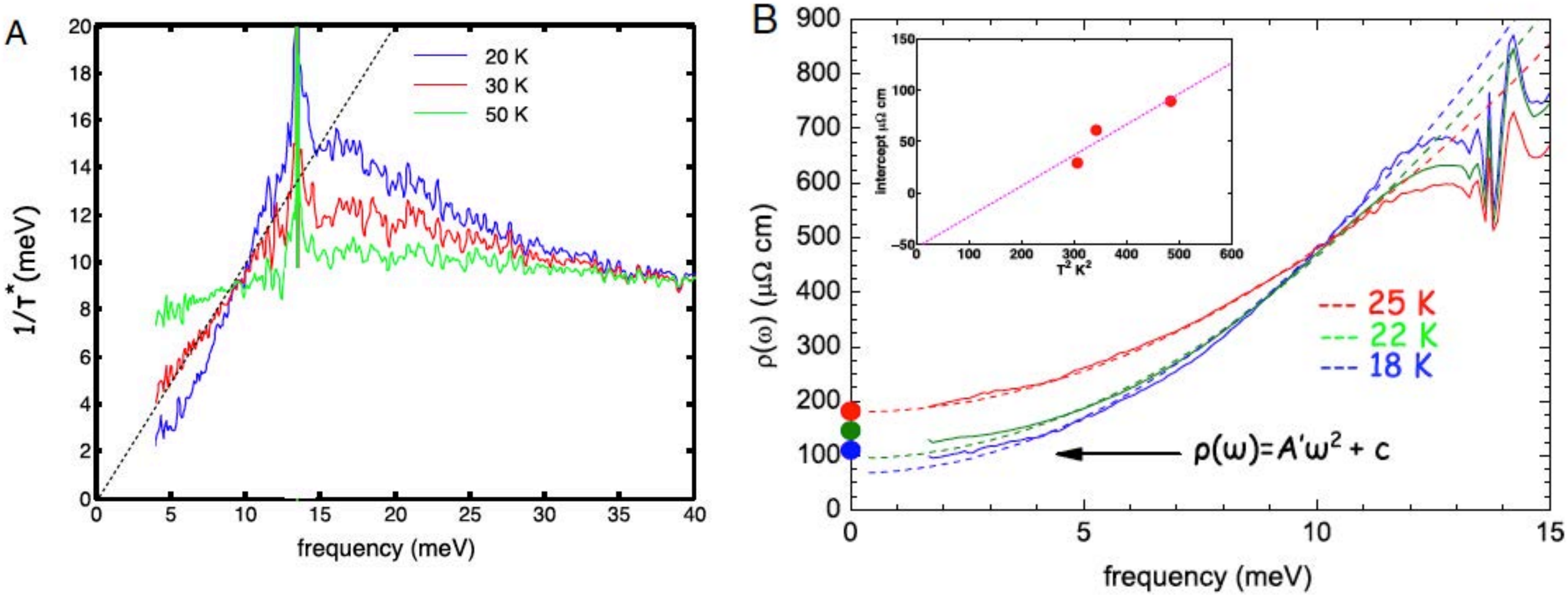
$$\frac{1}{\tau_{opt}} \propto (\hbar\omega)^2 + (\mathbf{p}\pi k_B T)^2$$

$\mathbf{p = 1.5}$



S.I. Mirzaei, D. Stricker *et al.*, *PNAS 110, 5774 (2013)*

URu_2Si_2



U. Nagel et al., *PNAS 109,1916 (2012)*

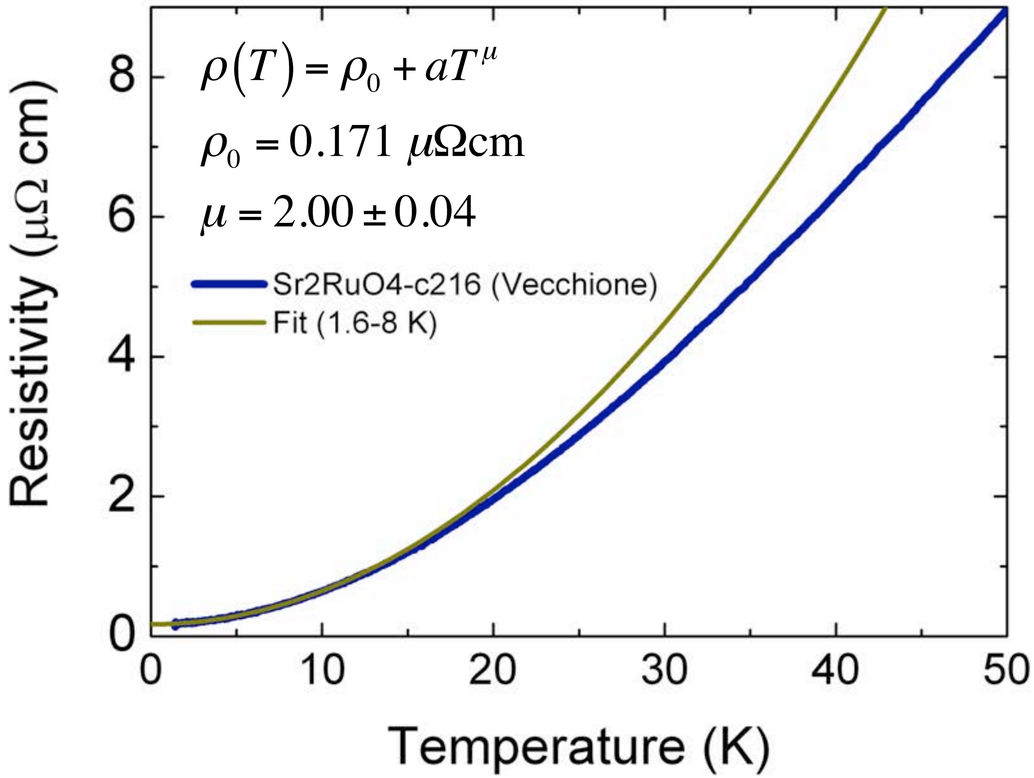
$$\frac{1}{\tau_{opt}} \propto \left(\hbar\omega\right)^2 + \mathbf{b}\ \left(\pi k_B T\right)^2 \qquad \mathbf{b = p^2 = 1}$$

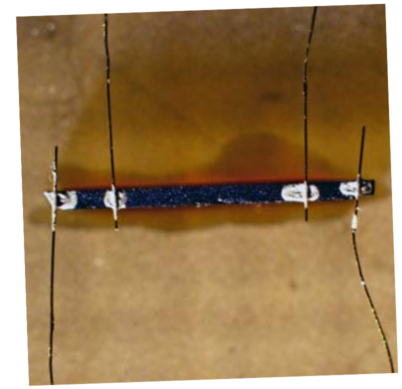
D. L. Maslov & A. V. Chubukov, *PRB 86, 155137 (2012)*

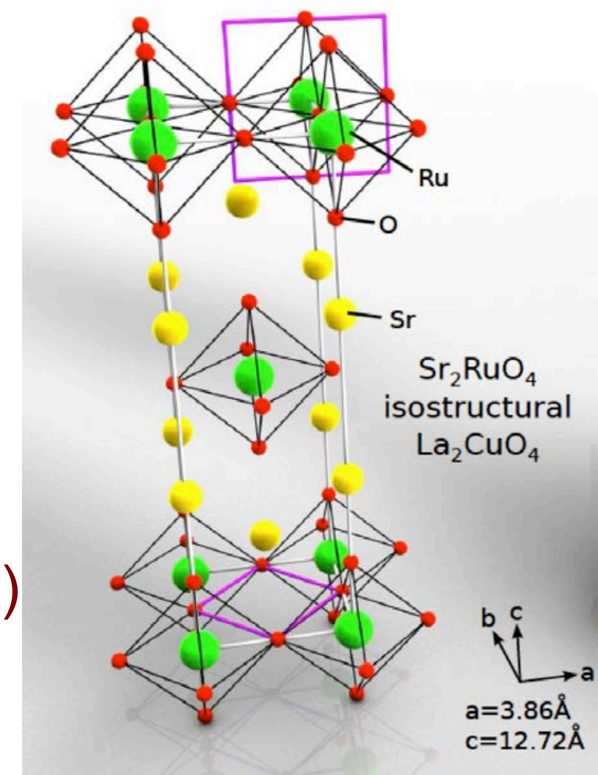
Explanation for **p=1**: $1/\tau(\omega,T) = (2-p^2)/\tau_{FL}(\omega,T) + 2p^2/\tau_M(\omega)$

$1/\tau_M(\omega)$: Unitary scattering (magnetic impurities)

Sr_2RuO_4: the `Helium 3' of transition-metal oxides !



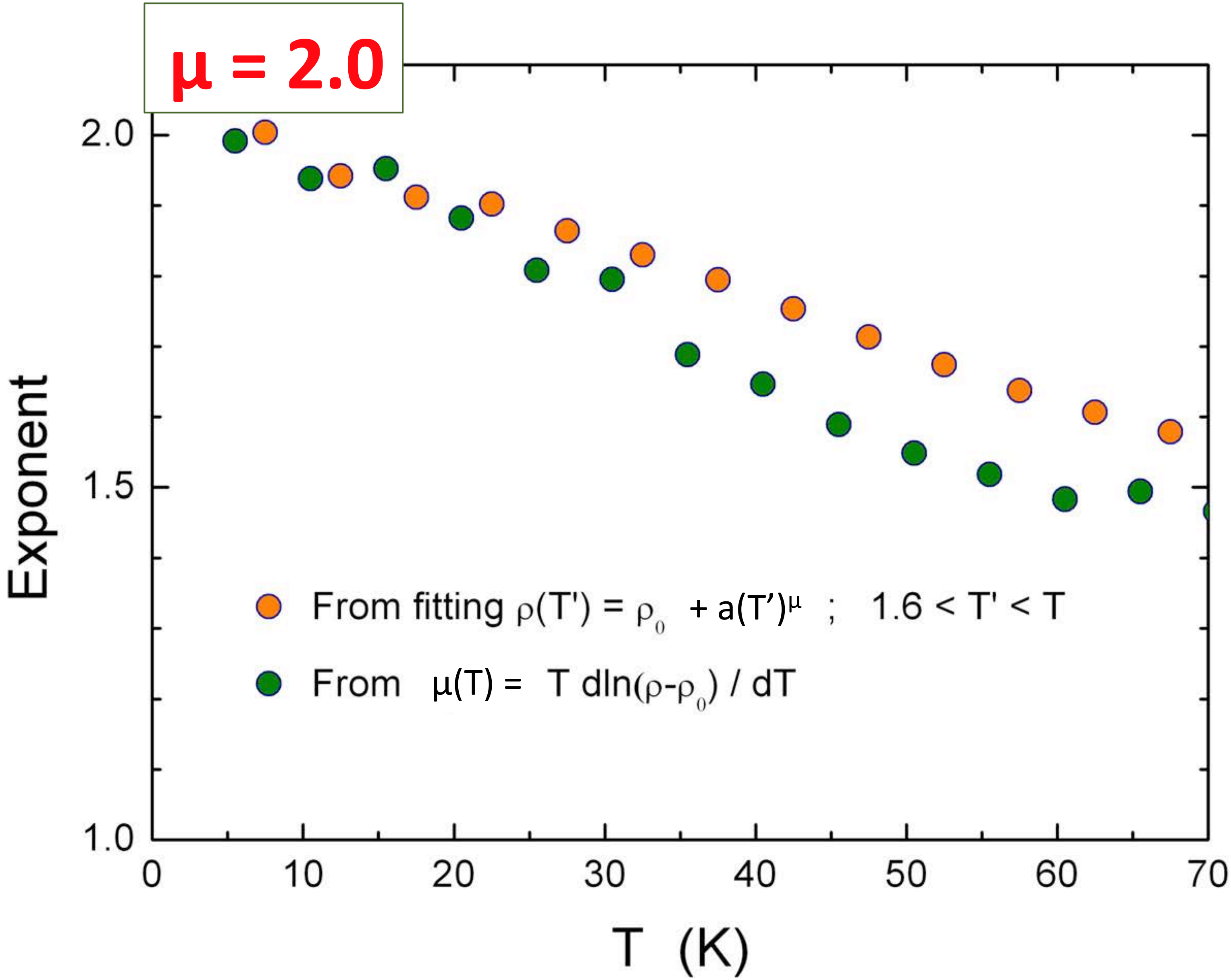




Beautiful review articles:

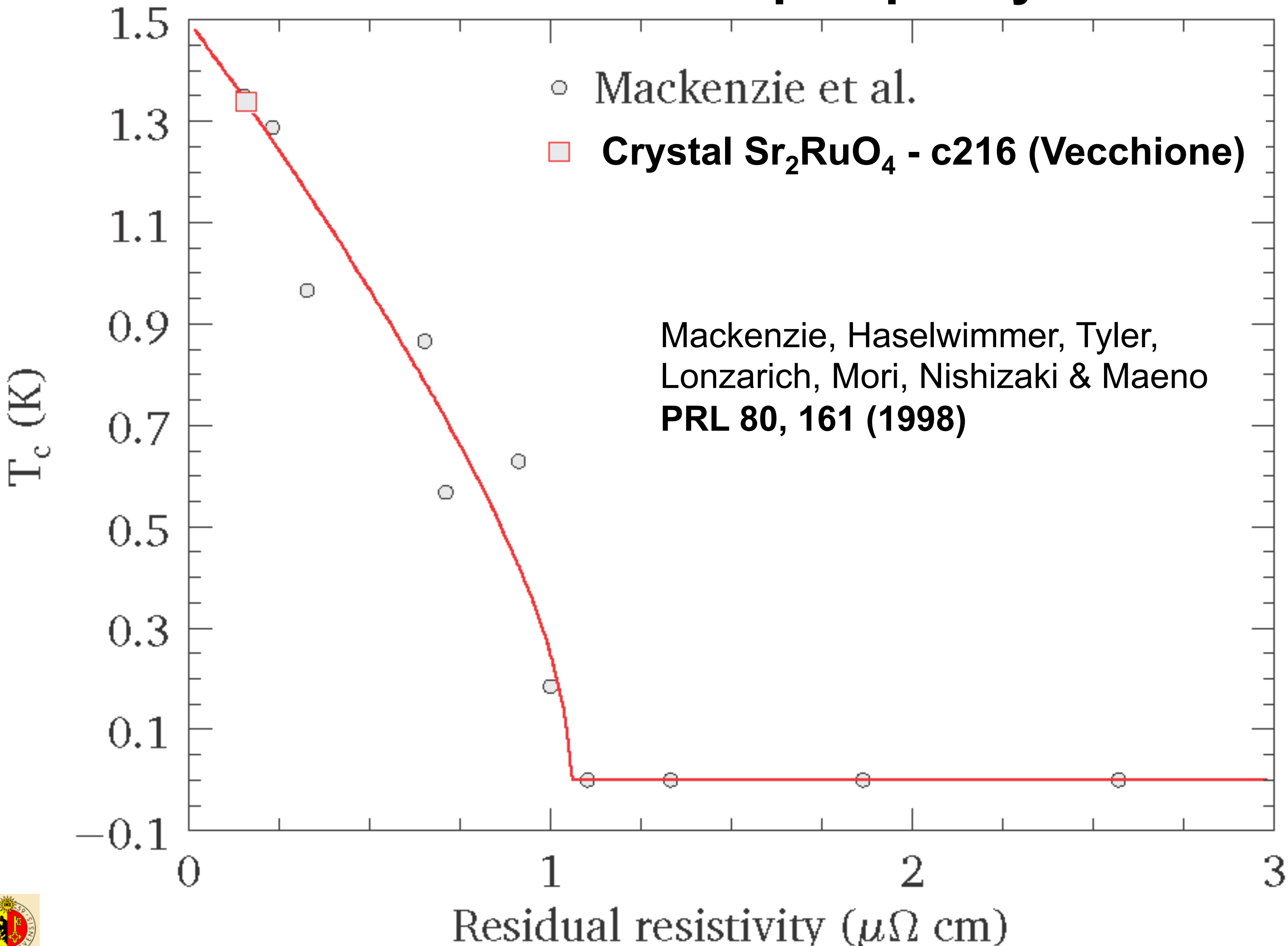
- A.Mackenzie & Y.Maeno, RMP 75 ,657 (2003)
- Bergemann, Adv. Phys. 52, 639 (2003)

Ab-plane resistivity exponent

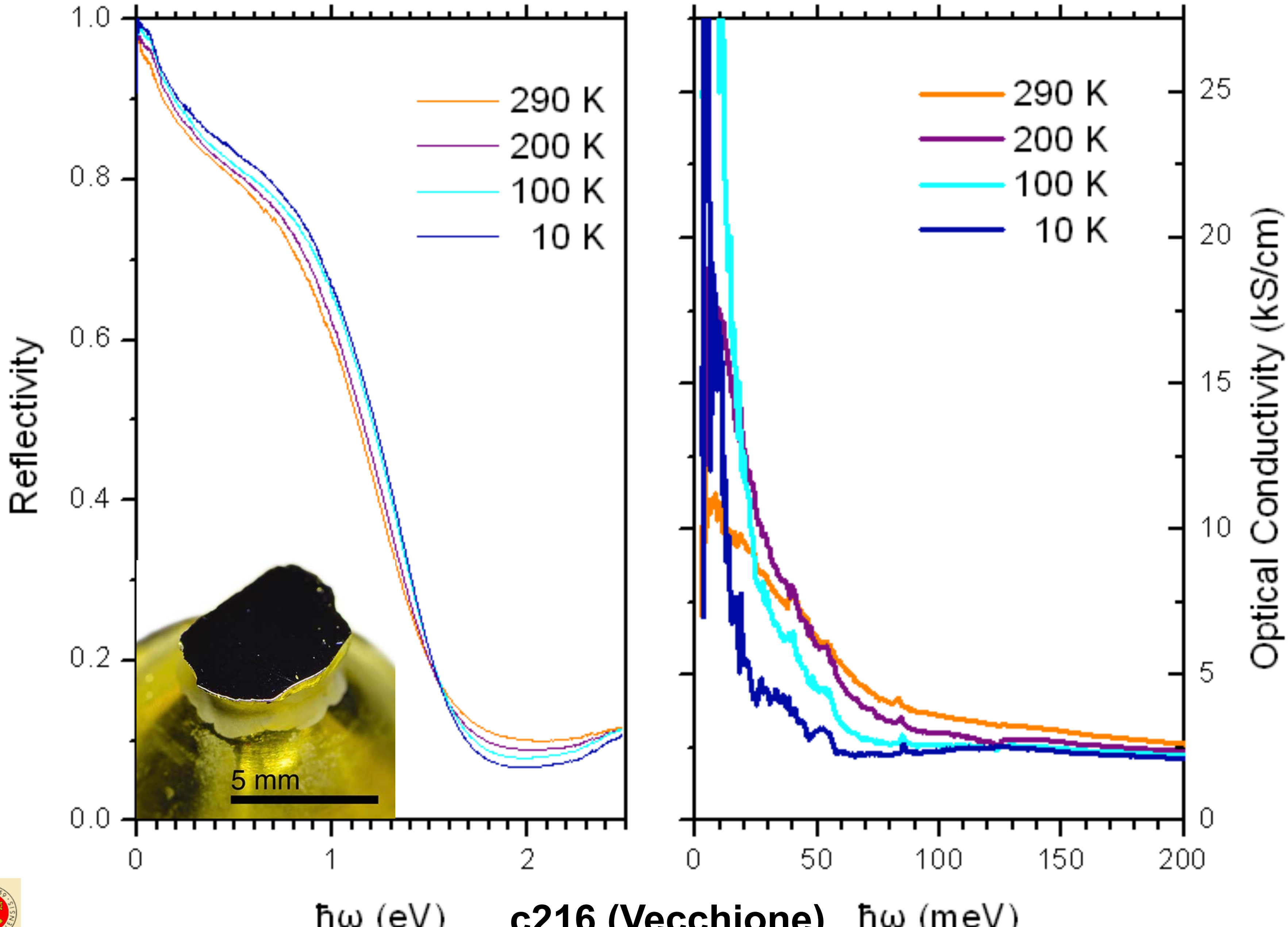


Crystal Sr_2RuO_4 - c216 (Vecchione)

Relative sample quality



Ab-plane reflectivity of Sr_2RuO_4

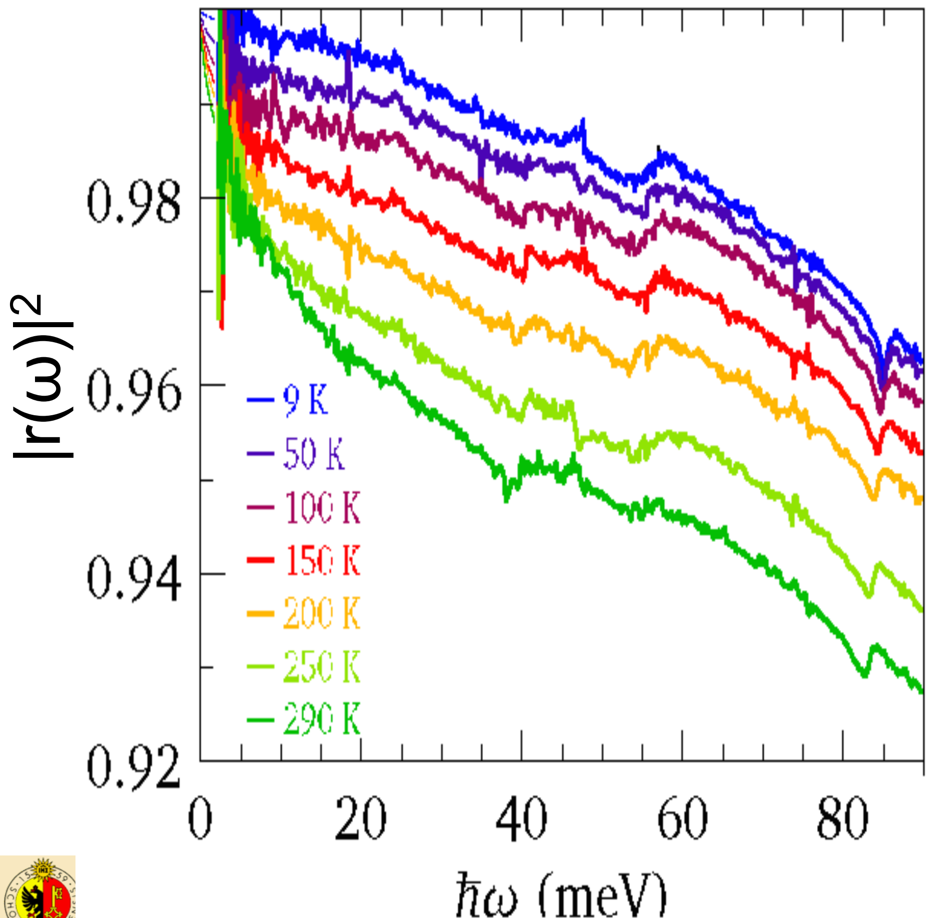


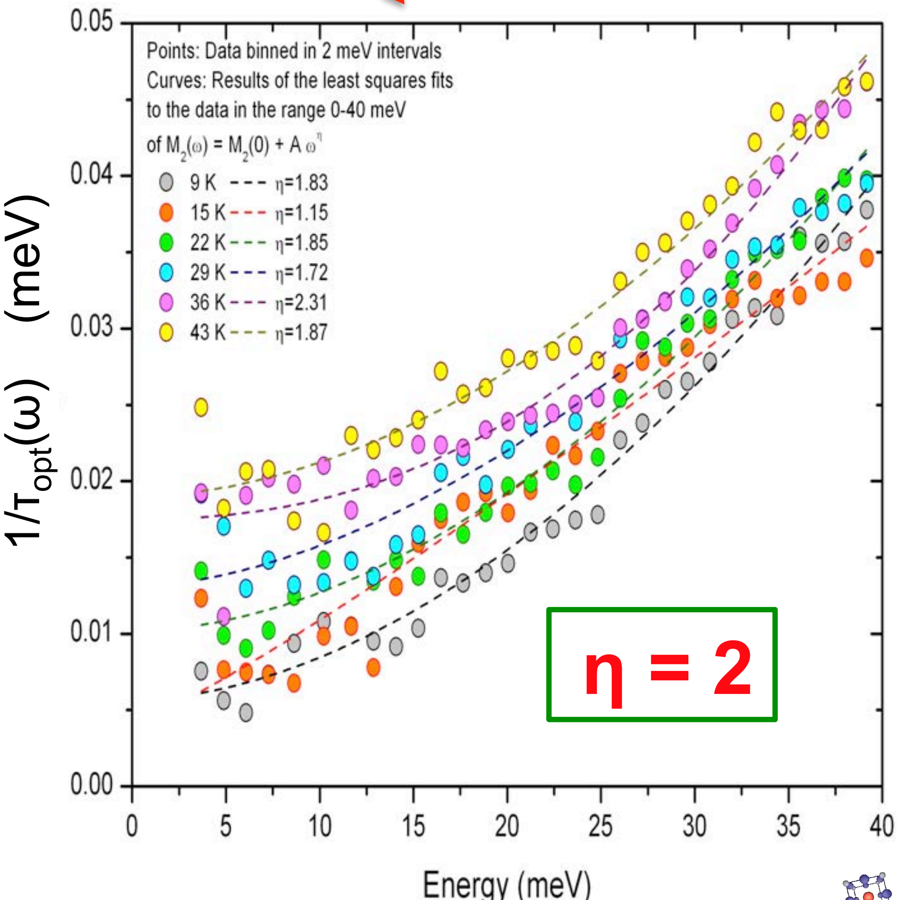
c216 (Vecchione)

Sr_2RuO_4: Energy dependend Relaxation rate

$$\mathrm{Im}\frac{\omega_p^2\omega^{-1}}{(1+r)^2/(1-r)^2-\varepsilon_{bc}}=\frac{1}{\tau_{opt}(\omega)}$$

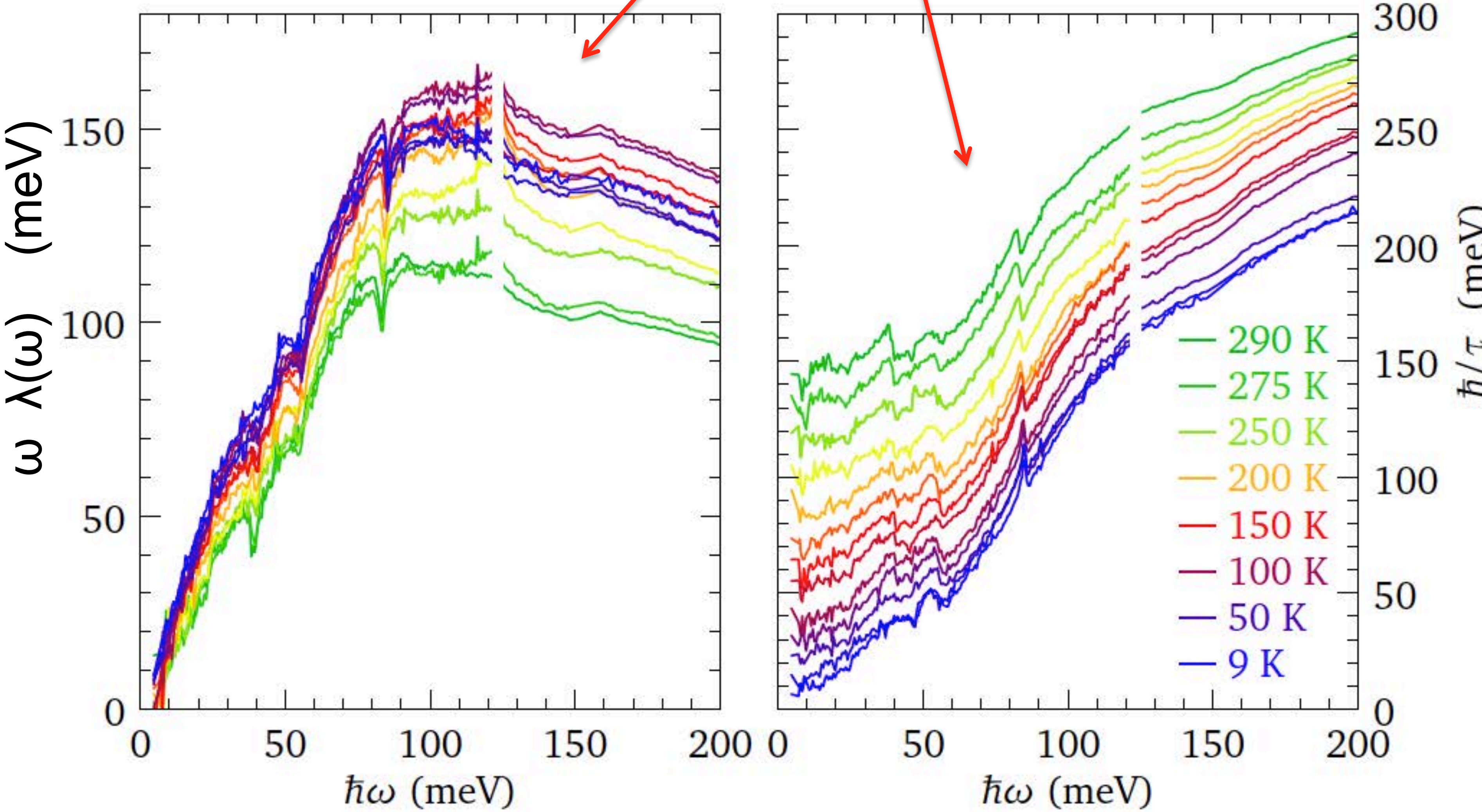
Basov, Averitt, vdMarel, Dressel & Haule
RMP **83**, 471 (2011)





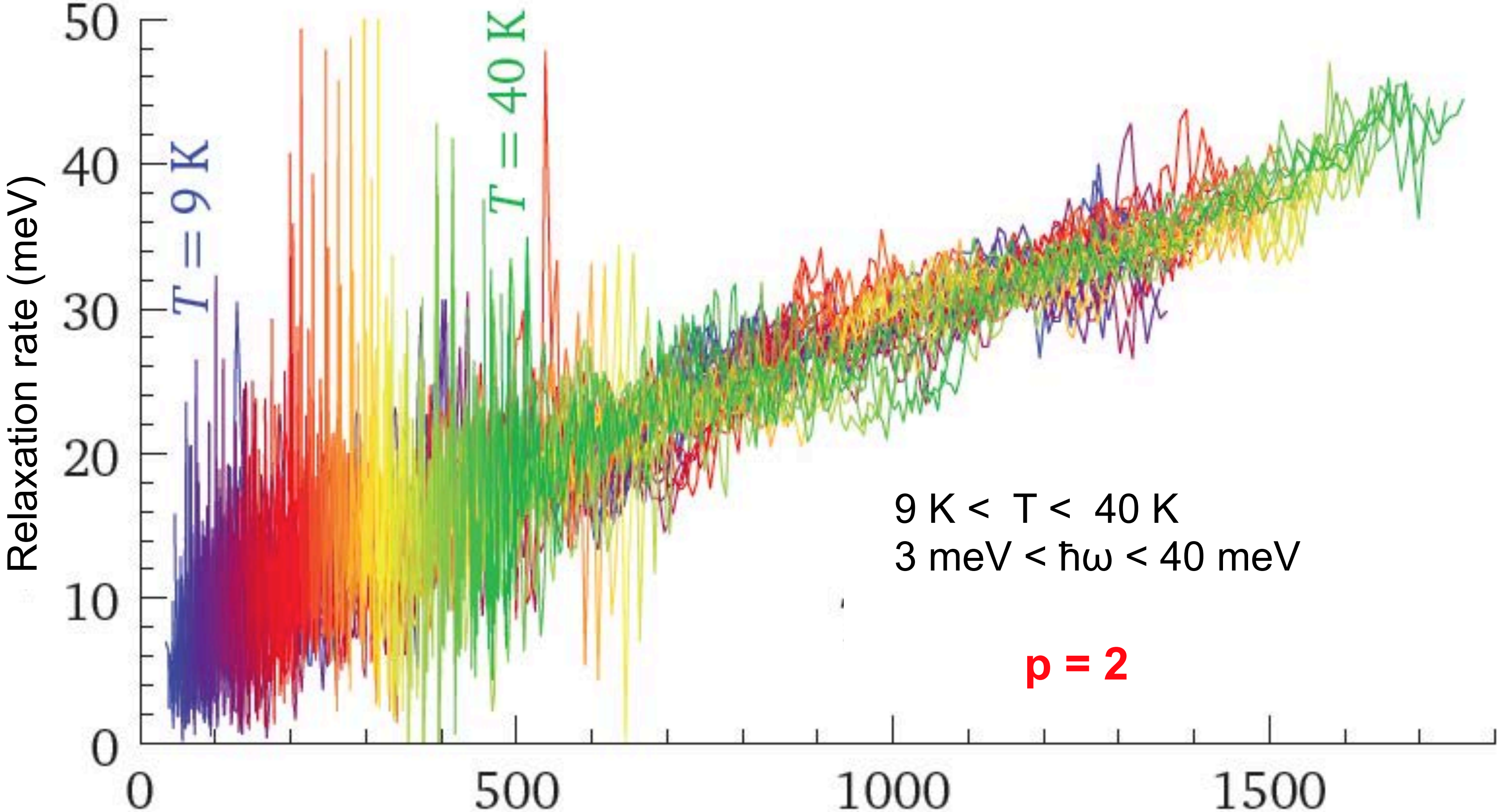
Sr_2RuO_4: Mass renormalization and relaxation rate

$$\frac{\omega_p^2\omega^{-1}}{(1+r)^2/(1-r)^2-\varepsilon_{bc}} = \omega\left[1+\lambda_{opt}(\omega)\right] + \frac{i}{\tau_{opt}(\omega)}$$



Crystal Sr_2RuO_4 - c216 (Vecchione)

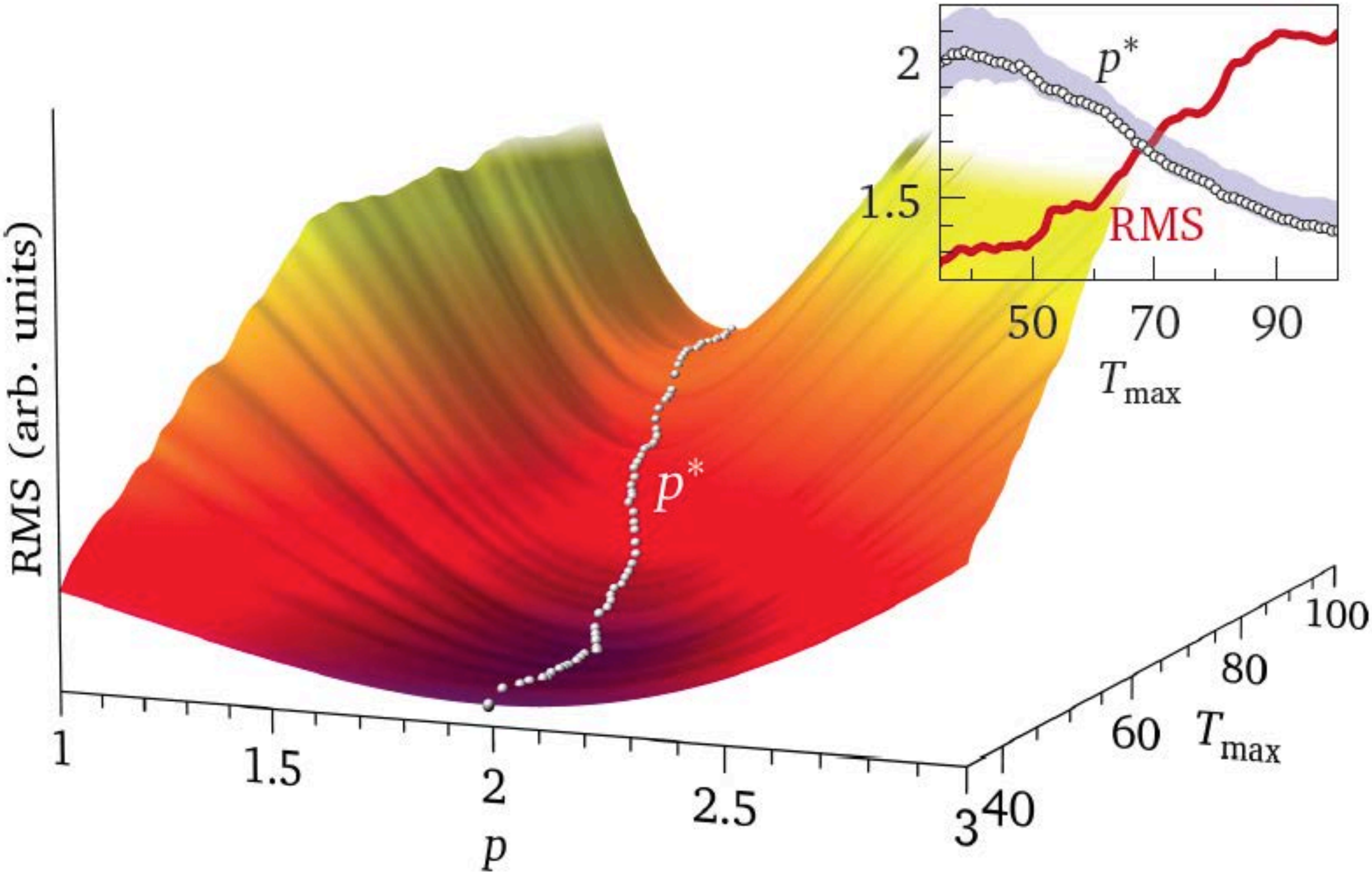
Sr_2RuO_4: Scaling collapse



$$(\hbar\omega)^2 + (p\pi k_B T)^2 = \xi_p^2 \ (\text{meV}^2)$$

Crystal Sr_2RuO_4 - c216 (Vecchione)

Sr_2RuO_4: Scaling collapse



Crystal Sr_2RuO_4 - c216 (Vecchione)

Some questions that we have answered about $1/\tau_{opt}(\omega,T)$

1a) $\tau_{opt}^{-1}(\omega,T) = \tau_{opt}^{-1}(\omega,0) + A(pk_BT)^{\mu}$ Affirmative

b) $\mu \approx 2$

2a) $\tau_{opt}^{-1}(\omega,T) = \tau_{opt}^{-1}(0,T) + A(\hbar\omega)^{\eta}$ Affirmative

b) $\eta \approx 2$

3a) $\left\{ \begin{array}{l} \tau_{opt}^{-1}(\omega,T) = f(\xi) \\ \xi = \sqrt{(\hbar\omega)^2 + (pk_BT)^2} \end{array} \right\}$ Affirmative

b) $p \approx 2$

Some questions that we have answered about the relaxation rate

$$1/\tau_{opt}(\omega,T) \propto (\hbar\omega)^2 + (2\pi k_B T)^2$$

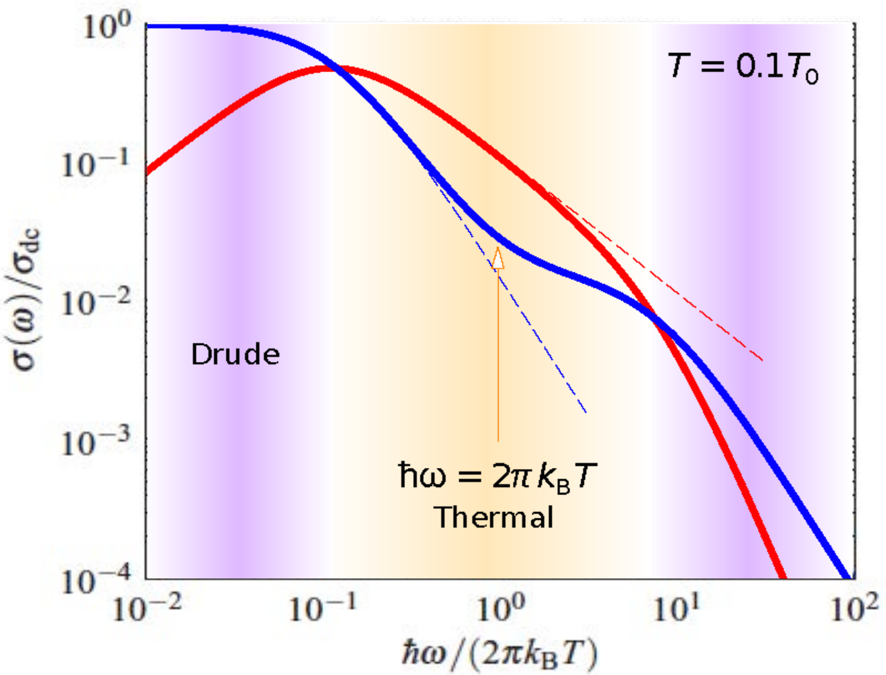
Damien Stricker

This confirms, that Sr_2RuO_4 is the solid state analogue of ^3He

Stricker, Mravlje, Berthod, Fittipaldi, Vecchione, Georges, vdMarel,
PRL 113, 087404 (2014)

Universal scaling function (local FL)

$$\frac{\sigma(\omega,T)}{\sigma_{DC}} = F\left[\frac{\hbar\omega}{k_B T},\frac{\hbar\omega T_0}{k_B T^2}\right]$$

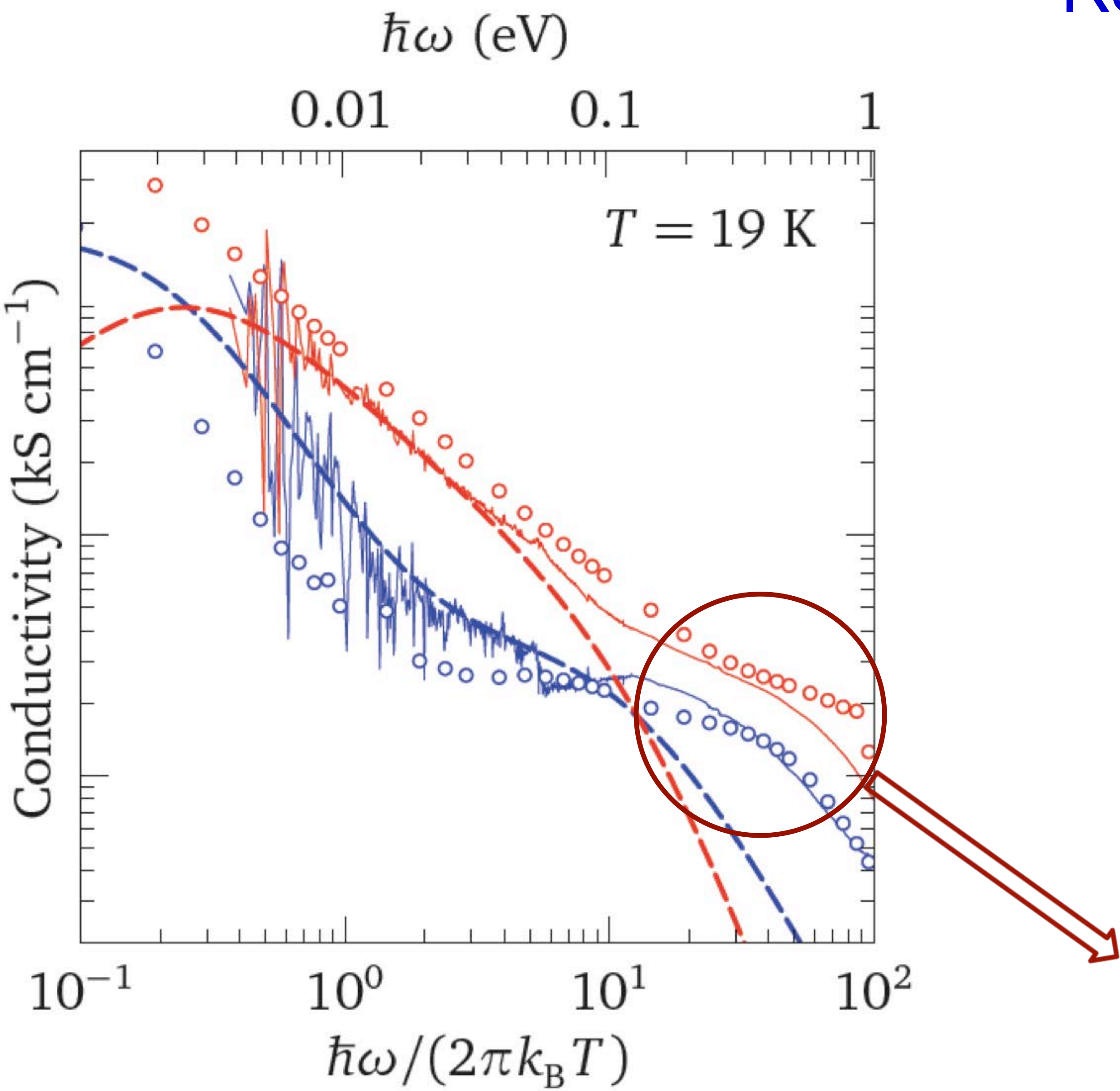


Signature of Fermi Liquid is a DEVIATION from Drude's formula, signalling frequency dependence of the relaxation rate

$$F[x,y] = \frac{6}{\pi^2 x}\int_{-\infty}^{\infty} du \frac{\left[e^{\pi(u-x)}+1\right]^{-1} - \left[e^{\pi(u+x)}+1\right]^{-1}}{1+x^2-iy+u^2}$$

C. Berthod, J.Mravlje, X. Deng, R. Žitko, D.van der Marel, and A. Georges, PRB 87, 115109 (2013)

$\text{Re}\,\sigma(\omega) + i\,\text{Im}\,\sigma(\omega)$



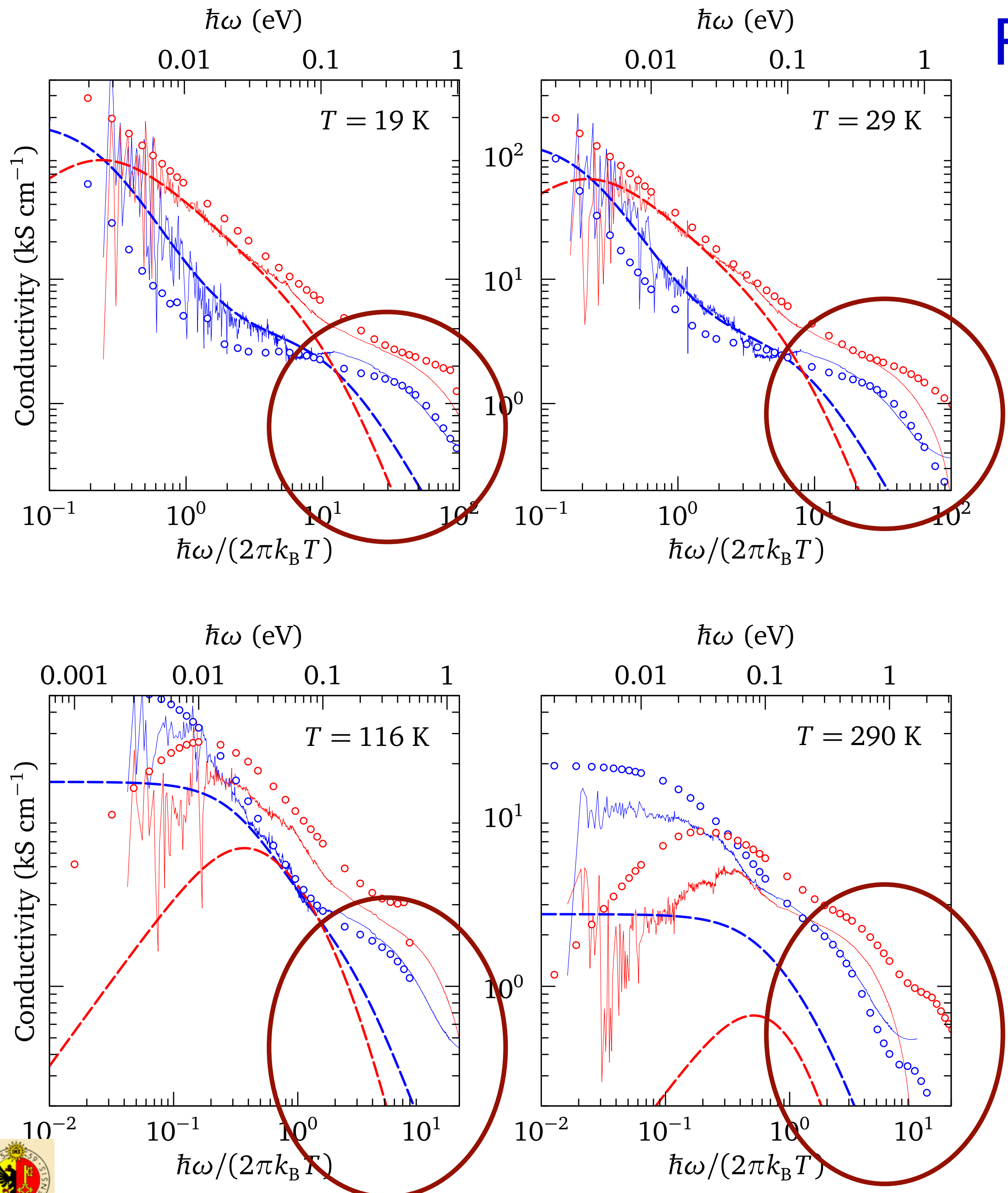
Plain Lines:
Experiments, Sr_2RuO_4

Dashed lines :
universal FL form
→ Beautiful agreement
→ At low T, low ω

Dots:
LDA+DMFT calculation for this material

Clear deviations from FL for ω above ~ 0.1 eV
Very well described by DMFT !

Re σ(ω) + i Im σ(ω)



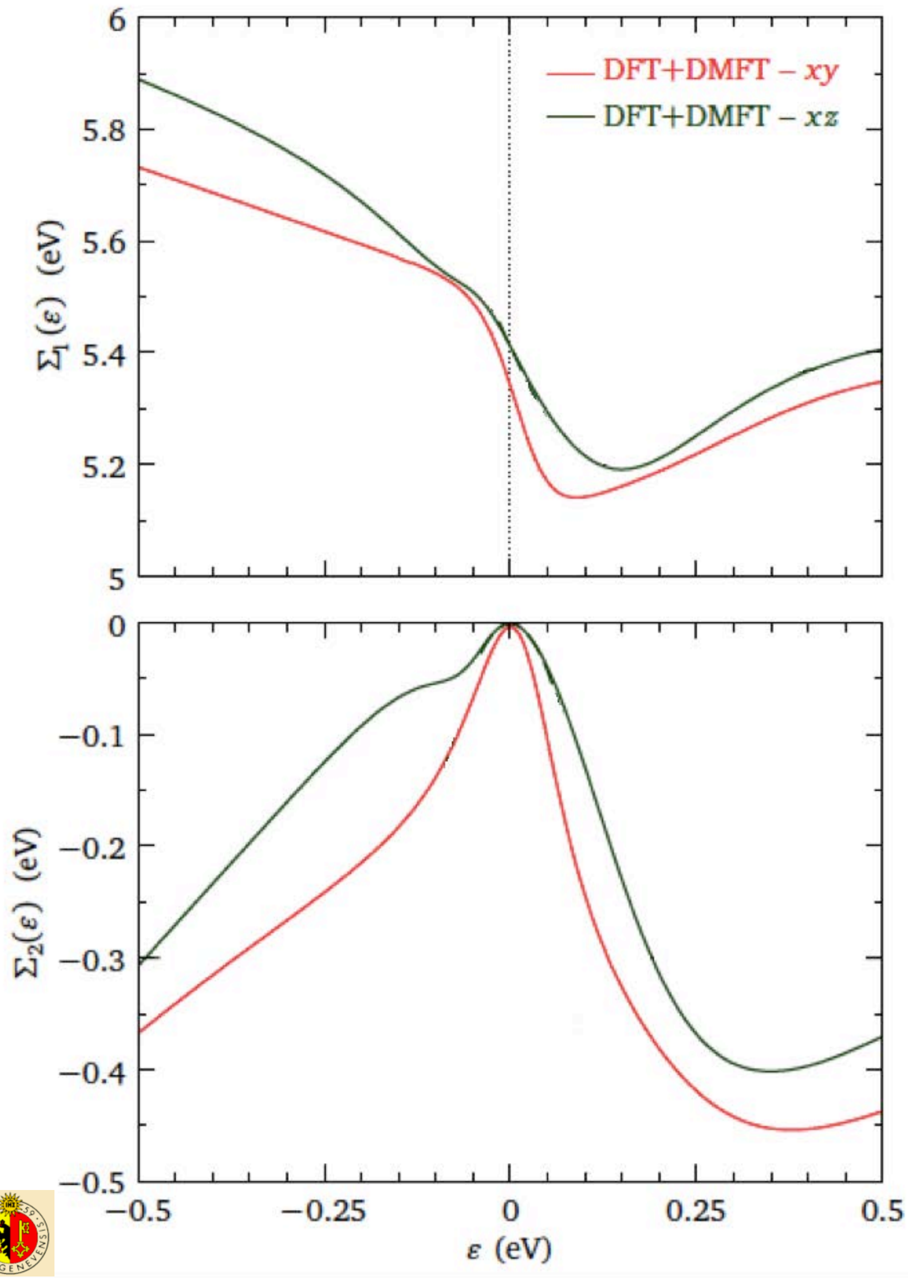
Plain Lines:
Experiments

Dashed lines :
universal FL form

Dots:
LDA+DMFT

Clear deviations from
FL for ω above ~ 0.1 eV
Very well described
by DMFT !

Beyond the Fermi Liquid regime: insights from DMFT



Mravlje, Georges et al., **PRL 106, 096401 (2011)**
Deng, Georges et al., **PRL 110, 086401 (2012)**

Real part of self-energy
Has a marked change of behavior at positive excitation energy, i.e. the effective mass decreases at high energy

Imaginary part of self-energy
The relaxation rate tends to saturate at high energy. It therefor stays below its extrapolated value from FLT

Hence, well above T_{FL}, well-defined single-particle excitations (`resilient quasiparticles') continue to exist, which:

- Are broad, but with a scattering rate not exceeding ~ $\pi k_B T$, leading to clear peak in spectral function
- Do not obey Landau's T^2
- Have a dispersion which is STRONGER than the LDA one, in sharp contrast to the low-energy large effective mass in the Landau FL regime

Yet, outstanding puzzles about this compound remain…

- A 4d material → expect not very large U (< 3eV)

- Yet, strongly correlated : effective mass enhancement (vs. band/ LDA value) as large as ~ 5

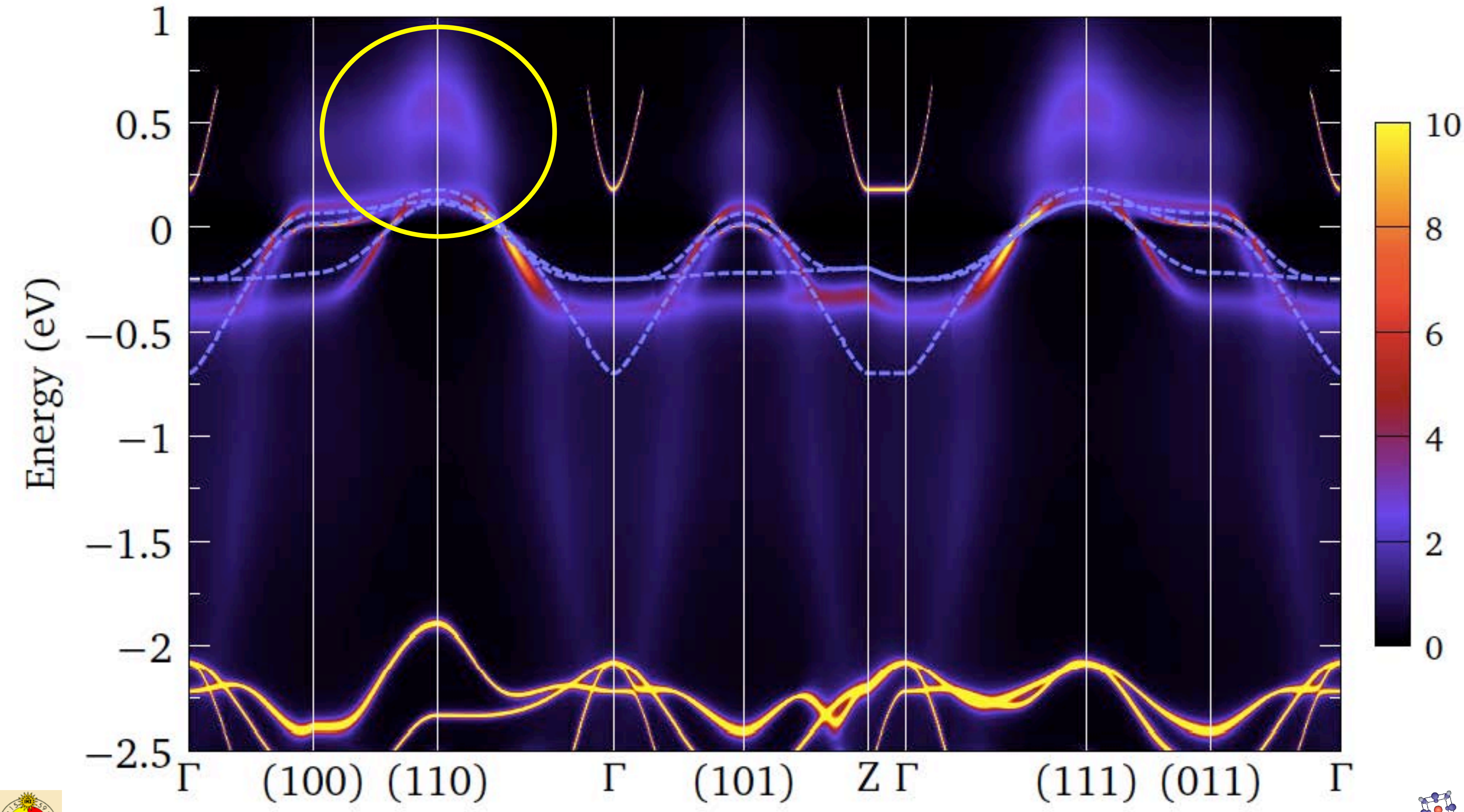
- Strong orbital dependence

- Low Fermi-liquid coherence scale:
  T^2 law obeyed only below ~ 30K

- Complex crossover in resistivity, from FL at low-T all the way to `bad metal' (above Mott Ioffe Regel) at hi-T

`Resilient' quasiparticles: what is their dispersion ?

Predictions for momentum-resolved spectroscopies on the `dark side' of the Fermi surface



Sr_2RuO_4: A strongly interacting Fermi liquid

Universal scaling of the optical momentum relaxation rate:

$1/\tau = A\{ (\hbar\omega)^2 + (2\pi k_B T)^2 \}$

Fermi liquid and resiliant quasiparticles:
excellent agreement with the DMFT predictions

Publications related to this presentation

Berthod, Mravlje, Deng, Žitko, vdMarel, Georges,
PRB 87, 115109 (2013)

Mirzaei, Stricker, Hancock, Berthod, Georges, vHeumen, Chan, Zhao, Li, Greven, Barišić, vdMarel,
PNAS 110, 5774 (2013)

Stricker, Mravlje, Berthod, Fittipaldi, Vecchione, Georges, vdMarel,
PRL 113, 087404 (2014)

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