UNIVERSITÉ
DE GENÈVE
FACULTY OF SCIENCE
Department of Quantum
Matter Physics

FERMI LIQUID BEHAVIOUR IN STRONGLY CORRELATED METALS

NGSCES 2015 — Trogir
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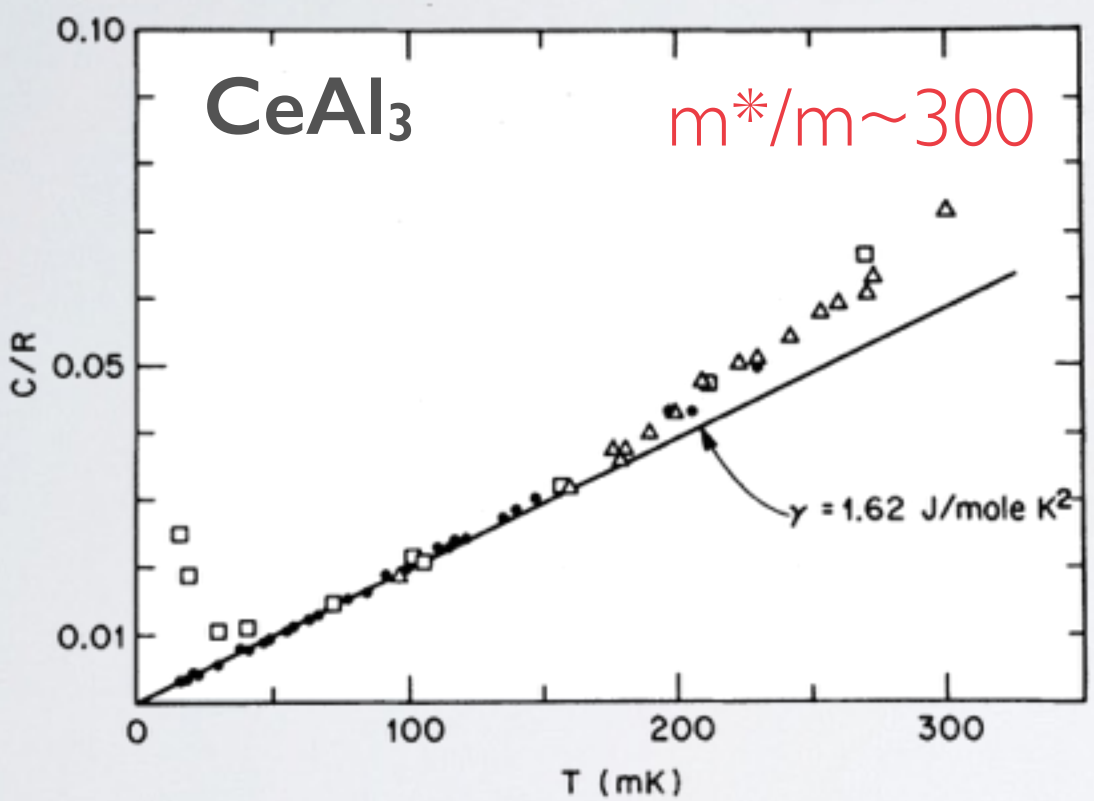
Christophe Berthod
Rosalba Fittipaldi
Antonio Vecchione

Traditional signature of Fermi liquids

Specific heat

$$C_V = \frac{\pi^2 N(0)}{3} k_B T$$

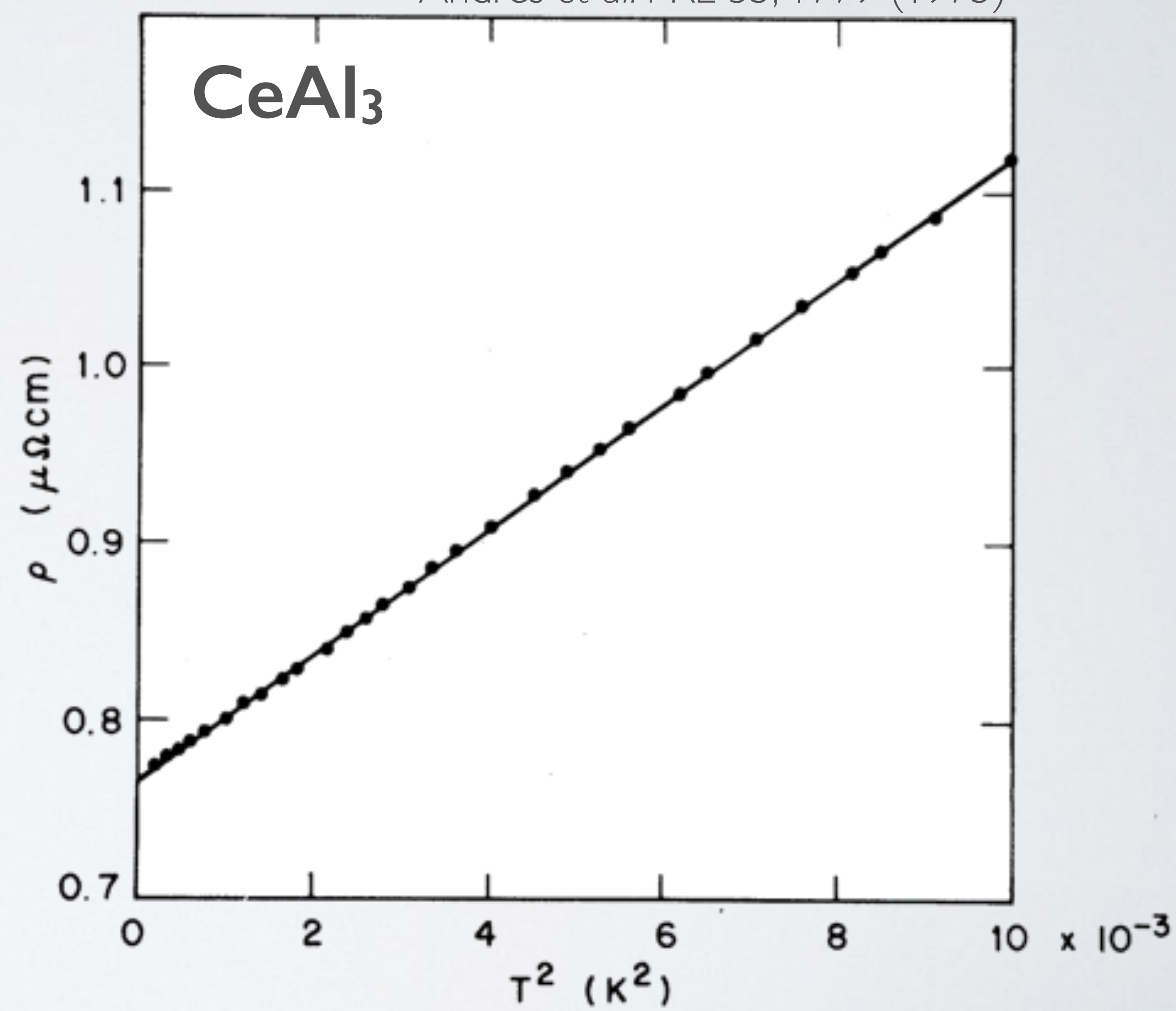


Silicides	*Cuprates*
MnSi	$HgBa_2CuO_{4+d}$
Titanates	***Heavy Fermions***
$SrTiO_3$	UPd_2Al_3

Transport

$$\rho = \frac{m}{ne^2\tau} = \rho_0 + AT^2$$

Andres *et al.* PRL 35, 1779 (1975)



One example among dozen

Outline

⁕ ⁕ ⁕

1. **What are the Fermi-Liquid fingerprints in optics ?**
   - Sr_2RuO_4 as an example

2. **Can we understand the non-Fermi-liquid behavior above ~ 0.1 eV ?**
   - Compare with DFT+DMFT
   - *Resilient* quasiparticles

3. **What does it teach us about Sr_2RuO_4 ?**
   - A simple model : from Tc to 1300 K !

Gurzhi *et al.* JETP 35(8), 673 (1959)
Berthod *et al.* PRB 87, 115109 (2013)
Götze & Wölfle PRB 6, 1226 (1972)

Local Fermi-liquid regimes in optics

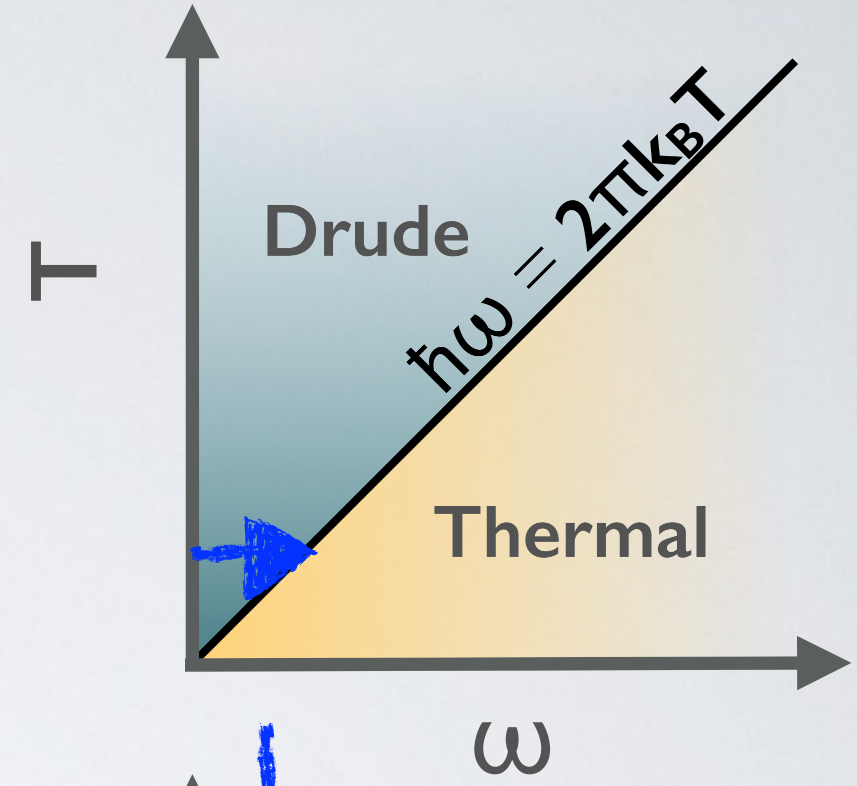
Drude (classical) $$\sigma(\omega) = \frac{\omega_p^2/4\pi}{\tau^{-1} - \mathrm{i}\omega}$$

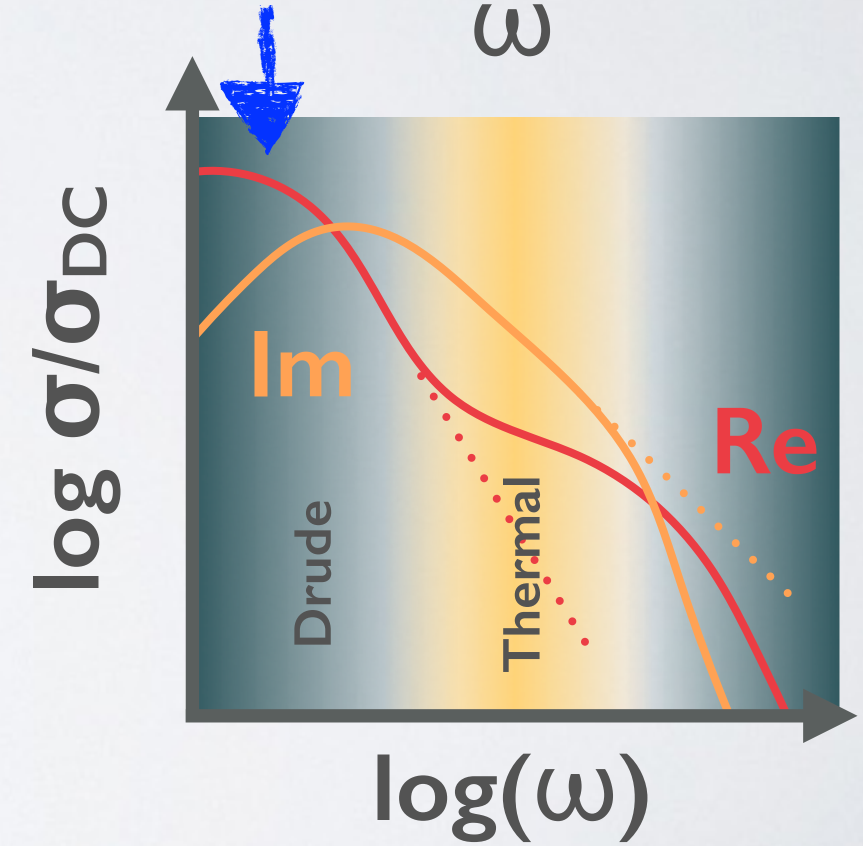
Thermal (interacting electrons)

$$\sigma(\omega) = \frac{\omega_p^2/4\pi}{\tau_{\text{opt}}^{-1}(\omega) - \mathrm{i}\omega[1 + \lambda_{\text{opt}}(\omega)]}$$

- Non Drude « foot » of the optical conductivity
- Scaling of the optical scattering rate
- Universal scaling factor **p = 2**

$$\tau_{\text{opt}}^{-1} \propto [\omega^2 + (p\pi k_{\text{B}}T)^2]$$





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

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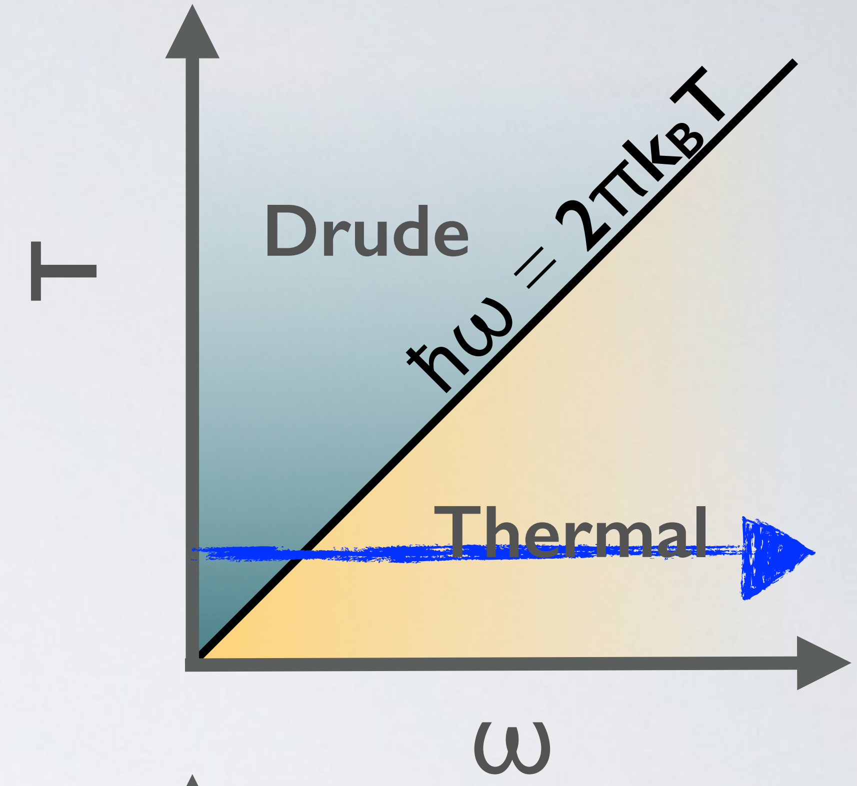

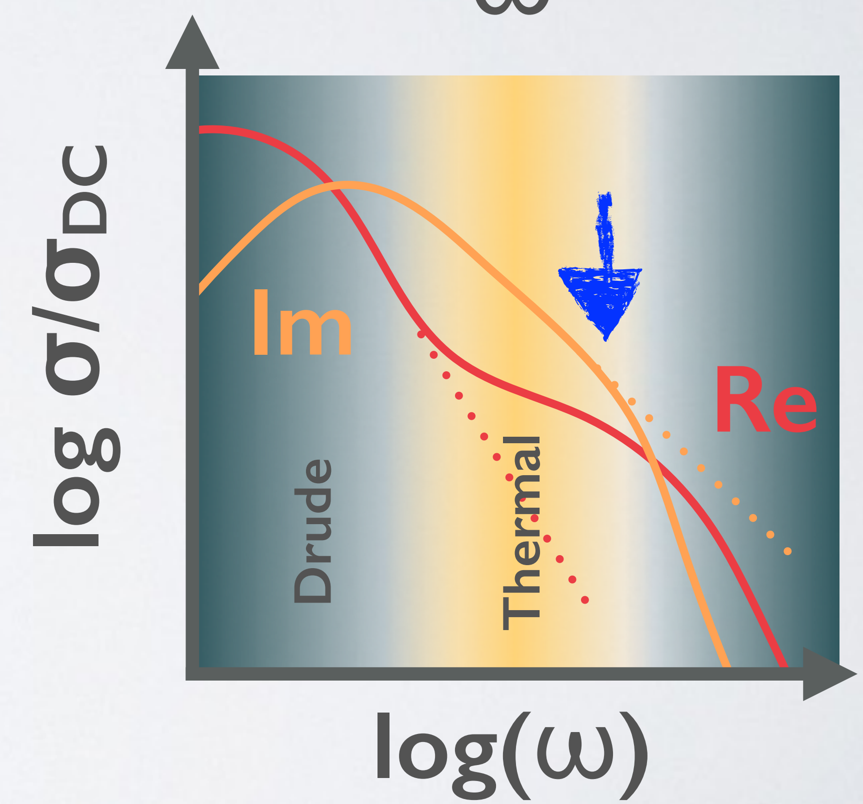

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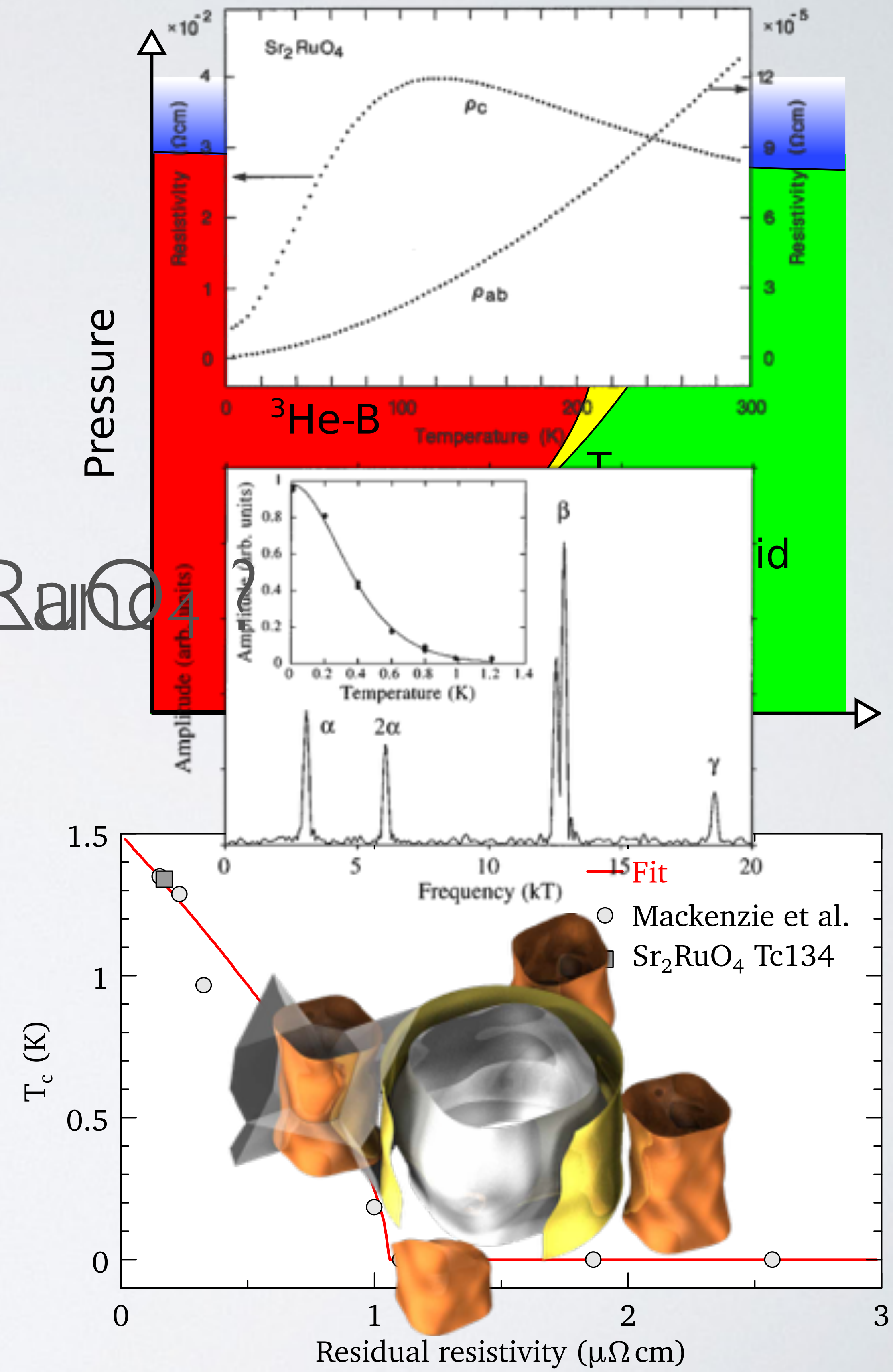
Compound	Material	T_{max}	ω_{max}	**p**	ref
Heavy Fermions	UPt_3	1	1	**<1**	Sulewski, Phys. Rev. 38(8), 5338 (1998)
	$CePd_3$			**1.14**	
	URu_2Si_2	2	10	**1.0**	Nagel, PNAS 109, 47 (2012)
Titanates	$Ce_{0.95}Ca_{0.05}TiO_{3.04}$	24	100	**1.31**	Katsufuji, PRB 60 7673 (1999)
	$Nd_{0.95}TiO_3$	24	50	**1.05**	Yang, PRB 73 195125 (2006)
Transition metals	Cr	28	370	**1.6**	Basov, PRB 65 054516 (2002)
Organics	κ-$(BEDT\text{-}TTF)_2$	4	70	**2.38**	Dressel, J. Phys.Cond.Mat. 23, 293201 (2011)
Cuprates	$HgBa_2CuO_{4.1}$	19	100	**1.5**	Mirzaei & Stricker, PNAS 110 5774 (2013)
Magnetic moments	Resonant level			**1-∞**	Maslov, PRB 86 155137 (2012)

Sr_2RuO_4 the archetypal

So why Sr_2RuO_4 ?

1. Known Fermi-Liquid T_{FL} ~25 K
   - Transport
     Hussey, PRB 57 5505 (1998)
   - Quantum oscillation
     Jaudet, PhD Thesis (2009)
   - ARPES
     Bergemann, Adv. Phys. 52, 7 (2003)
2. Solid-state analogue of ^3He
   - p-wave symmetry of the SC phase
     Kallin et al., Rep. Prog. Phys. 75, 042501 (2012)
3. Low Tc
   - Fermi-liquid properties not hidden by SC
     Mackenzie et al., PRL 80, 161 (1998)



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

1. $1/\tau \propto T^{\mu}$?

   What is the value of μ ?

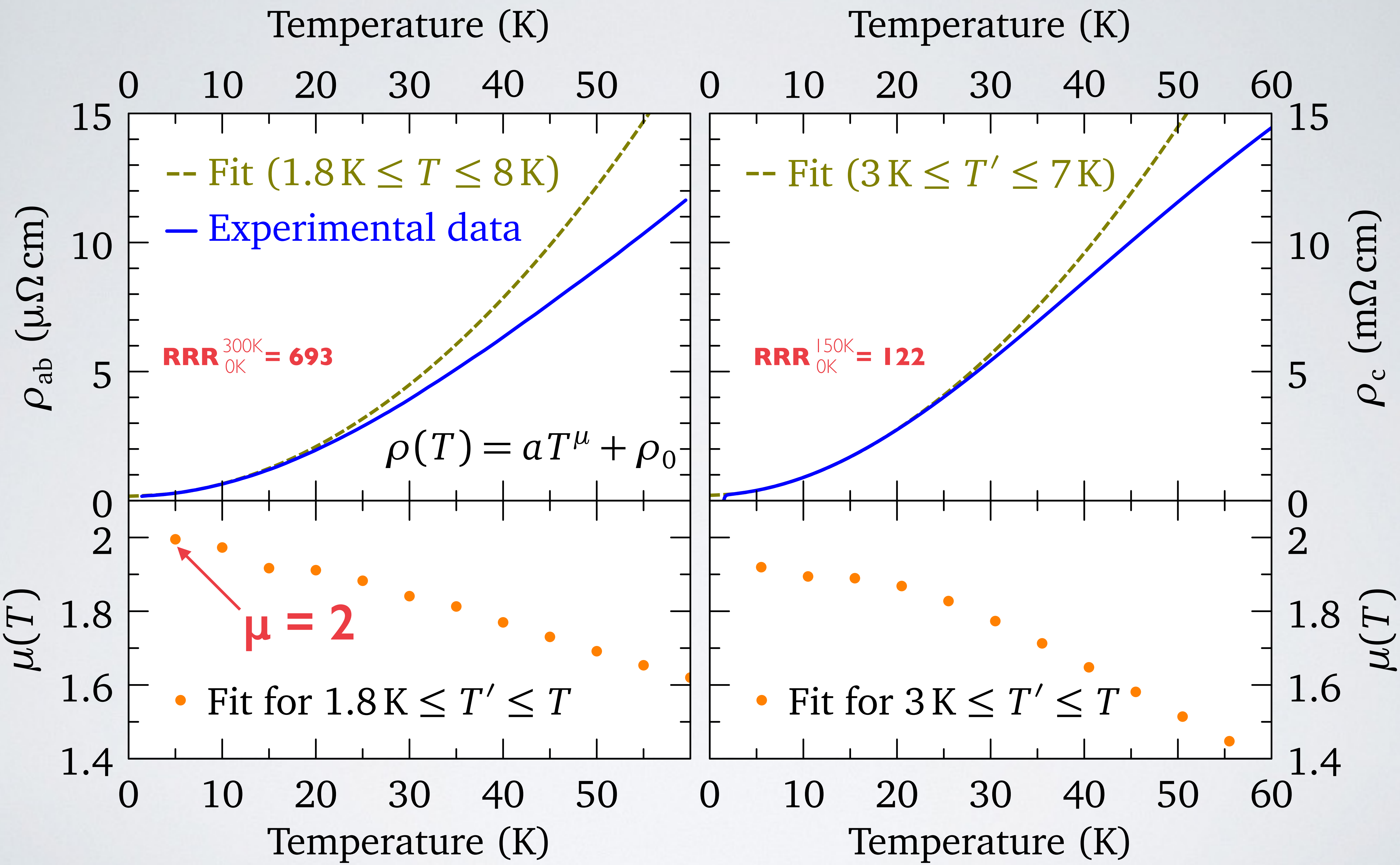
2. $1/\tau_{opt} \propto \omega^{\eta}$?

   What is the value of η ?

3. $1/\tau_{opt}(\omega,T) \propto \omega^2+(p\pi k_B T)^2$?

   What is the value of p ?

Transport : What is the value of **μ** ?



Crystals from R. Fittipaldi and A. Vecchione, Salerno, Italy

Stricker *et al.* unpublished (2015)

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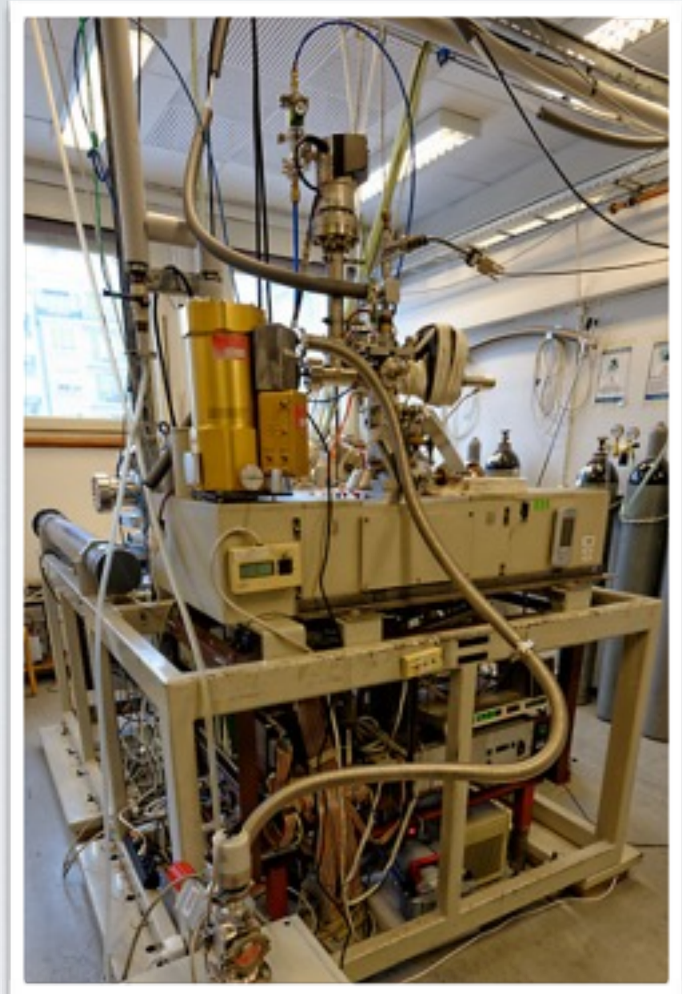
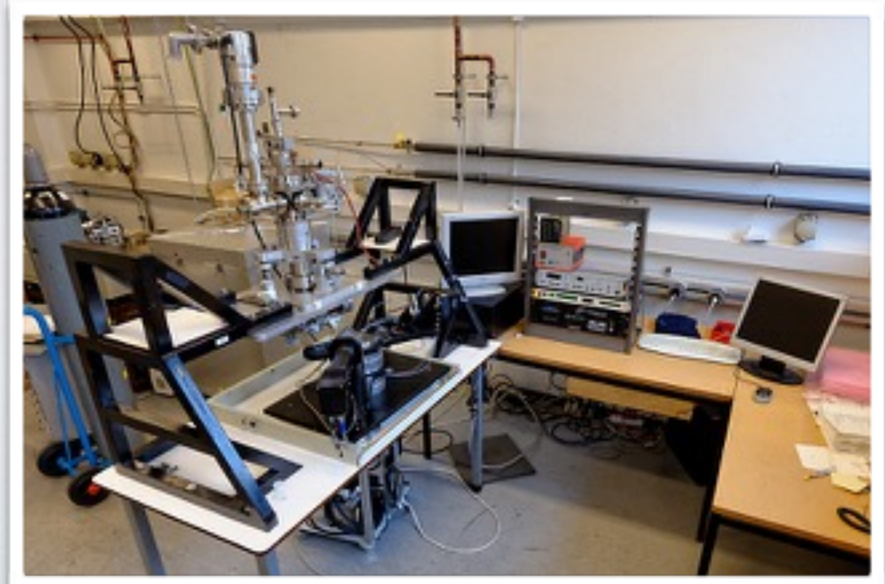
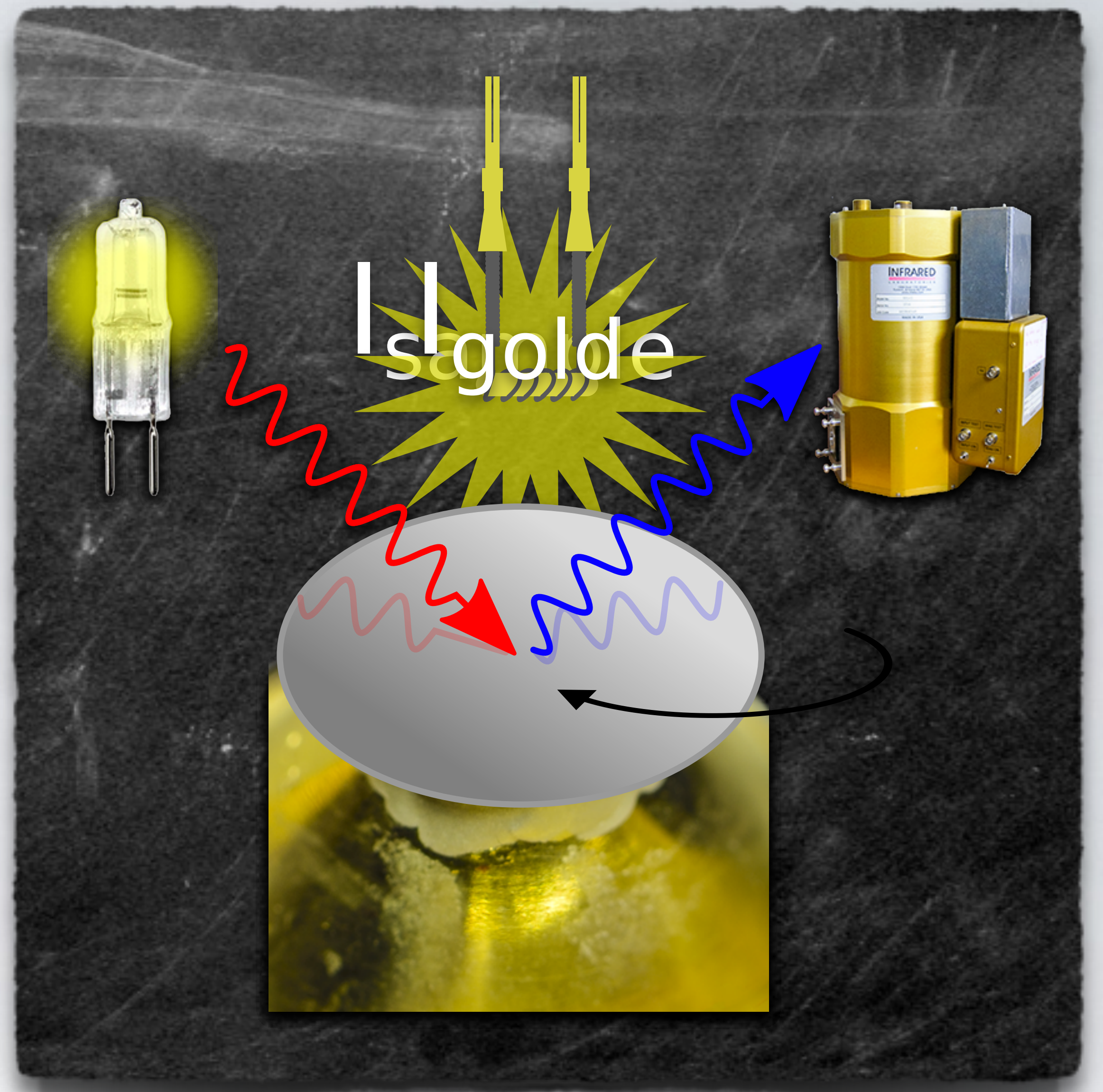
Optical Spectroscopy







Reflectivity (3 meV - 3 eV)

$$R(\omega) = \frac{I_{\mathbf{sample}}(\omega)}{I_{\mathbf{reference}}(\omega)} \frac{I_{\mathrm{reference-mirror}}(\omega)}{I_{\mathrm{sample-mirror}}(\omega)}$$

Ellipsometry (0.47 eV - 6.2 eV)

$$R(\omega) = \frac{1 - \sqrt{\epsilon(\omega)}}{1 + \sqrt{\epsilon(\omega)}}$$

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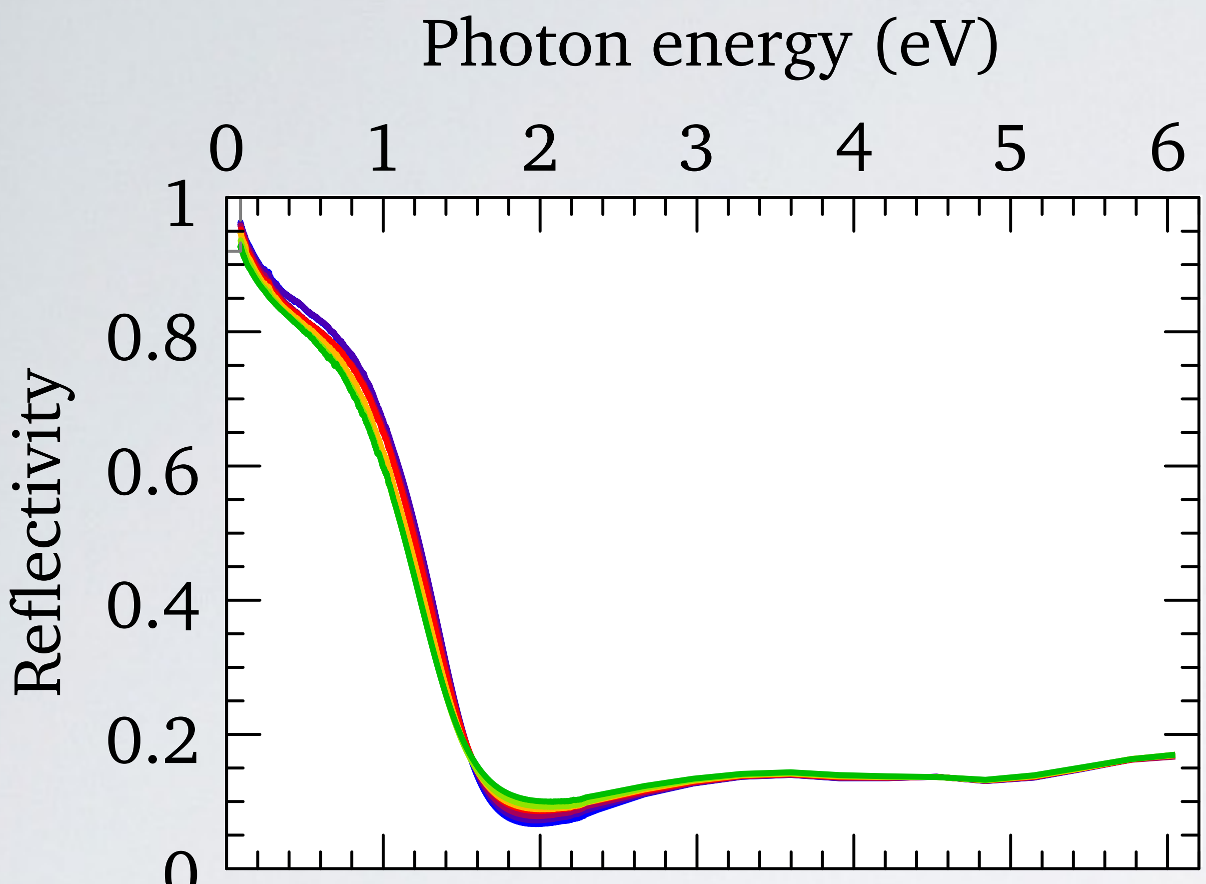
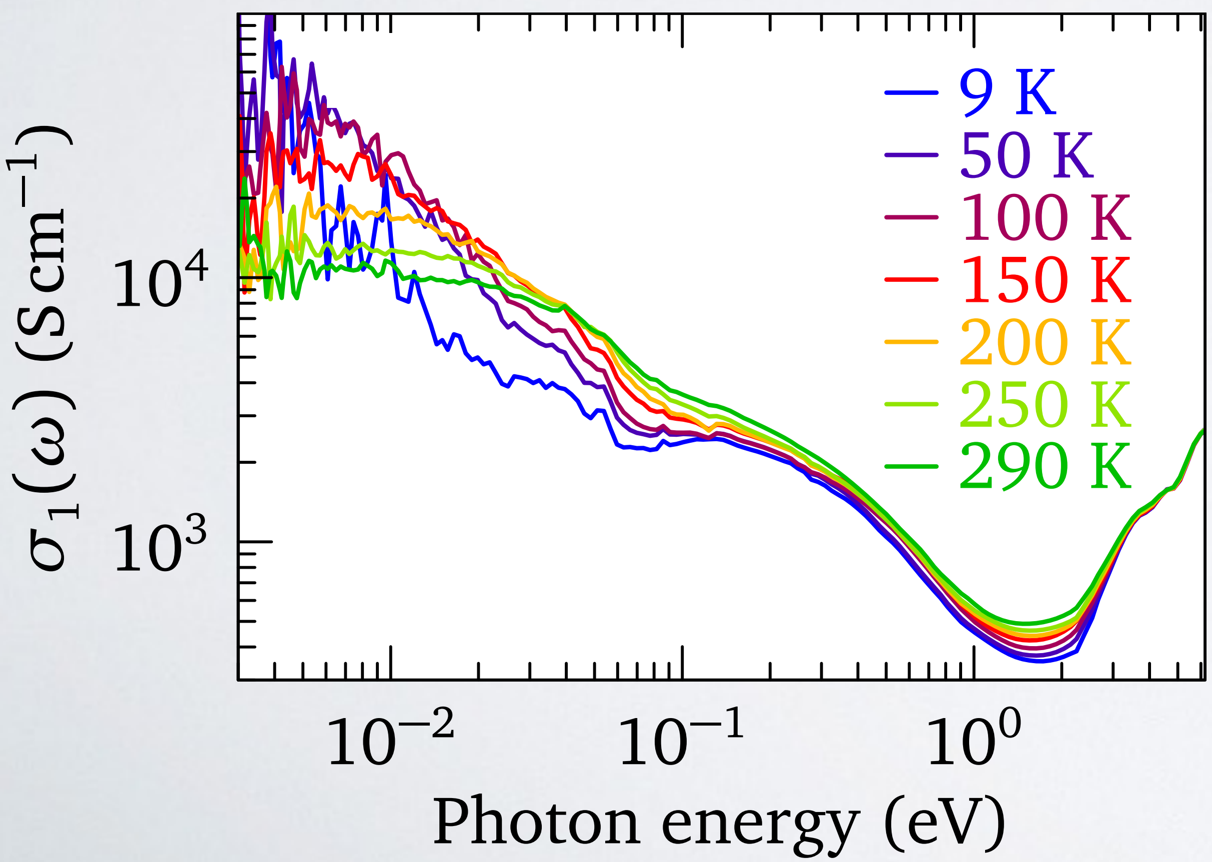
Sr_2RuO_4 Optical spectroscopy



Stricker *et al.* PRL 113, 087404 (2014)

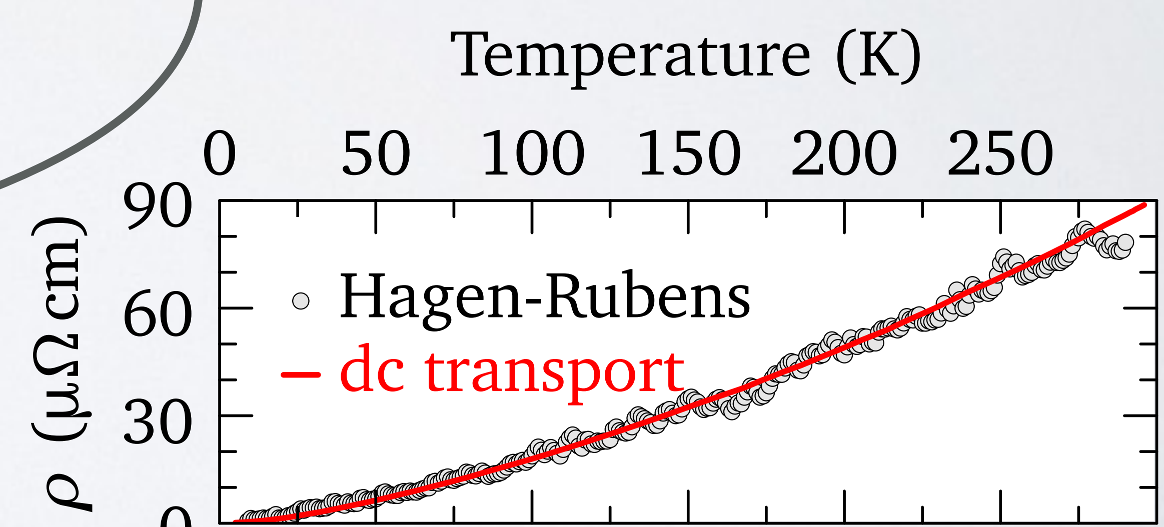


Plasma frequency $\boldsymbol{\omega_p}$ = 3.3 eV

No interband below 1 eV

Lee et al., PRL 89, 257402 (2002)

Kramers-Kronig

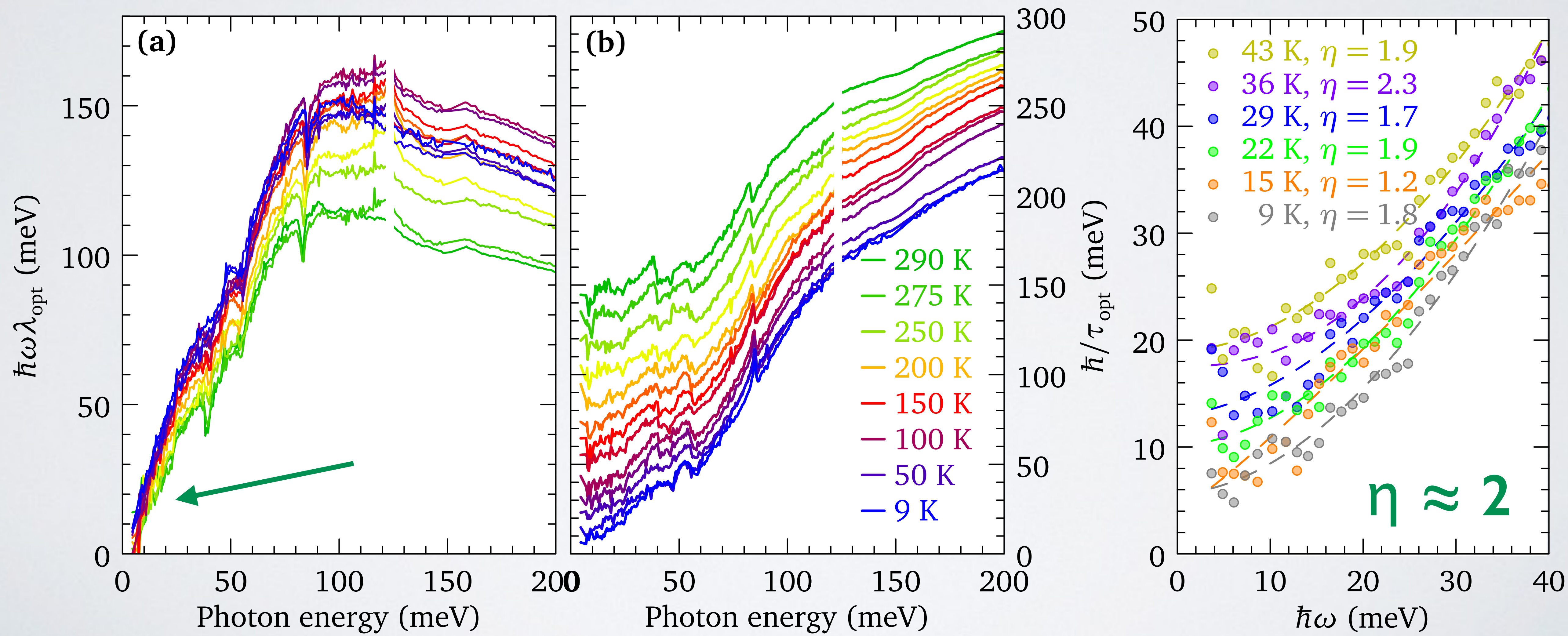


Very good agreement with dc conductivity

Sr_2RuO_4 Mass renormalization and relaxation rate

Fermi Liquid : m*(**ω**)/m ~ **ħω** ~ **ħω²**

$$\frac{\omega_p^2}{4\pi i\sigma(\omega,T)} = \omega[1+\lambda_{\rm opt}(\omega)] + \frac{i}{\tau_{\rm opt}(\omega)}$$



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$\eta \approx 2$

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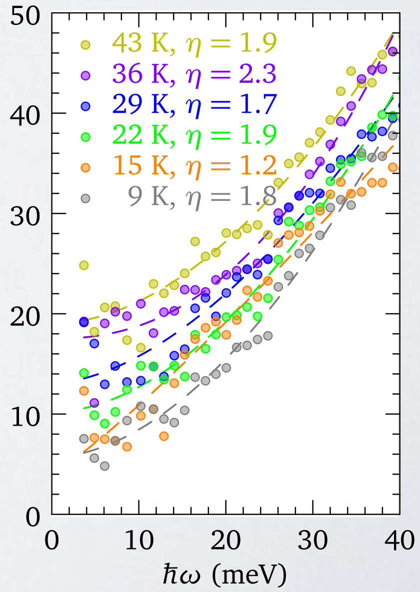

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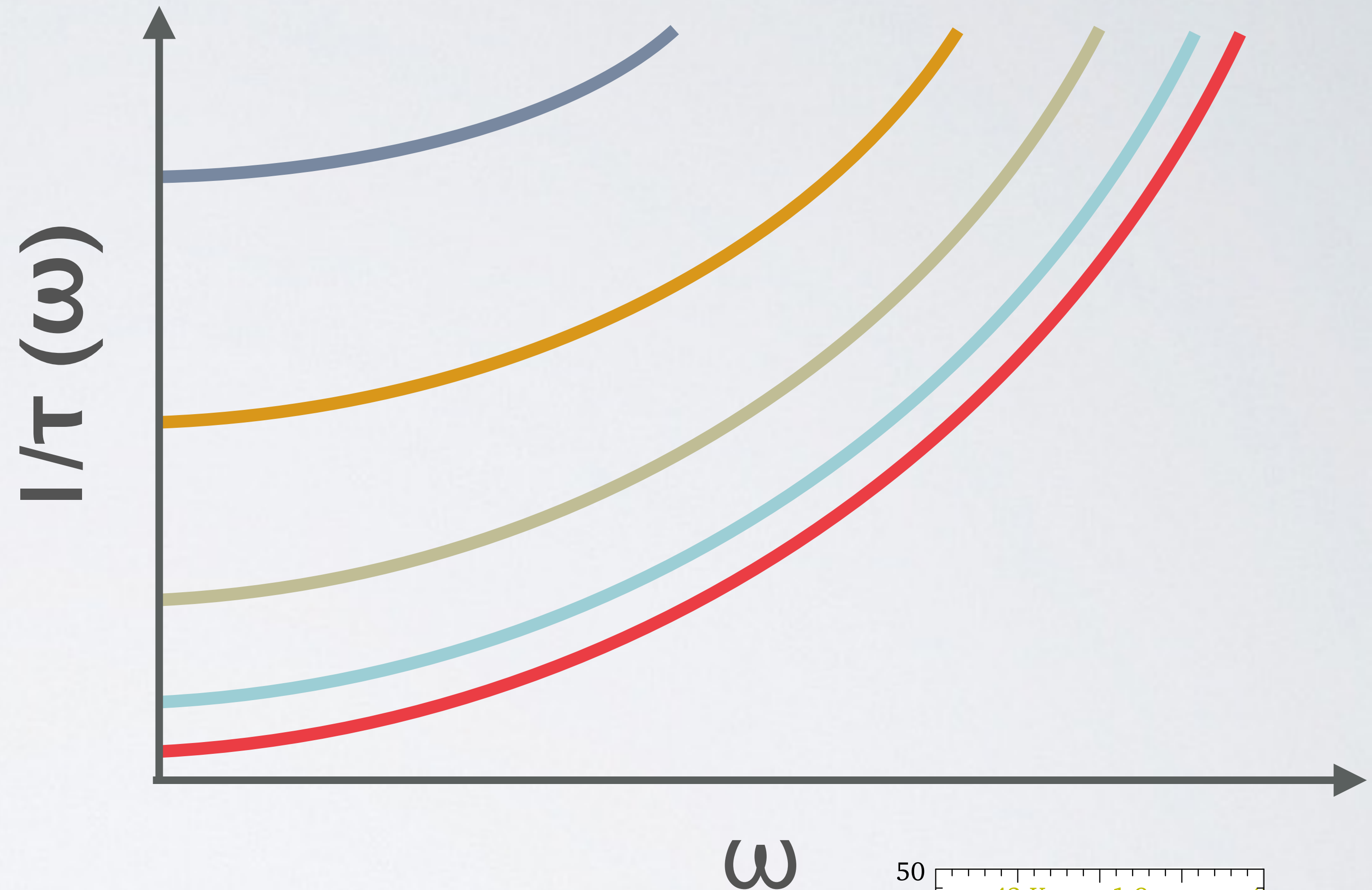

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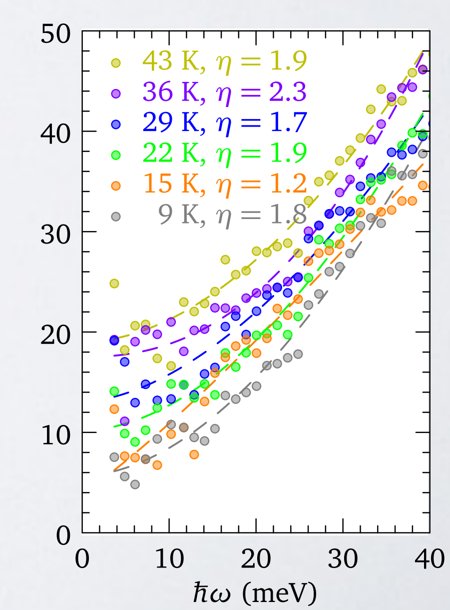

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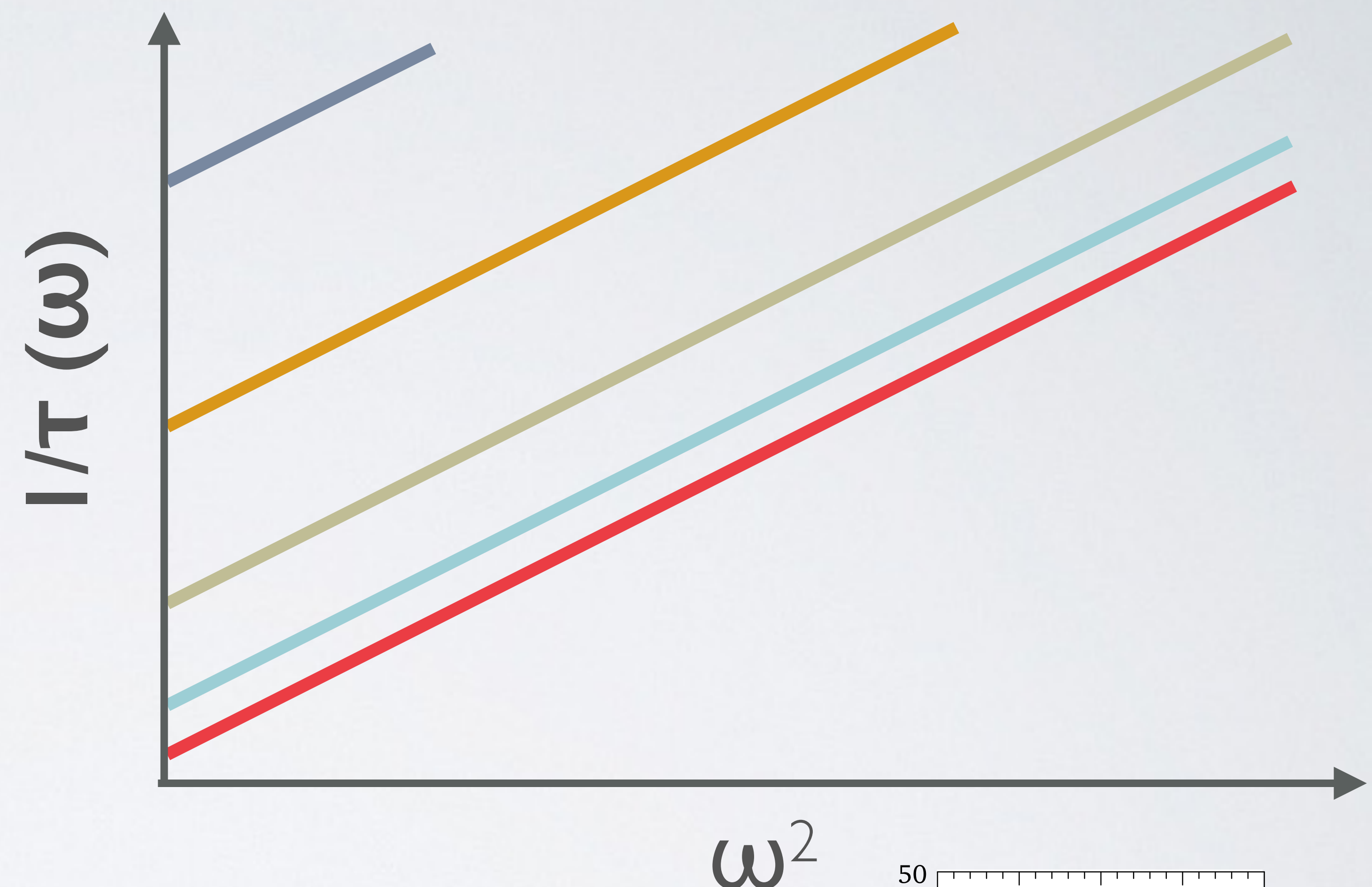

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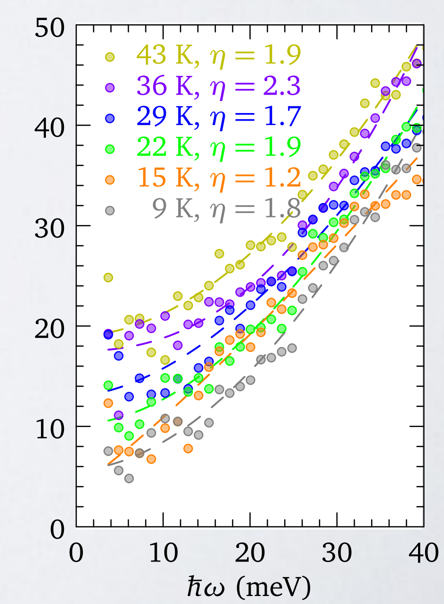
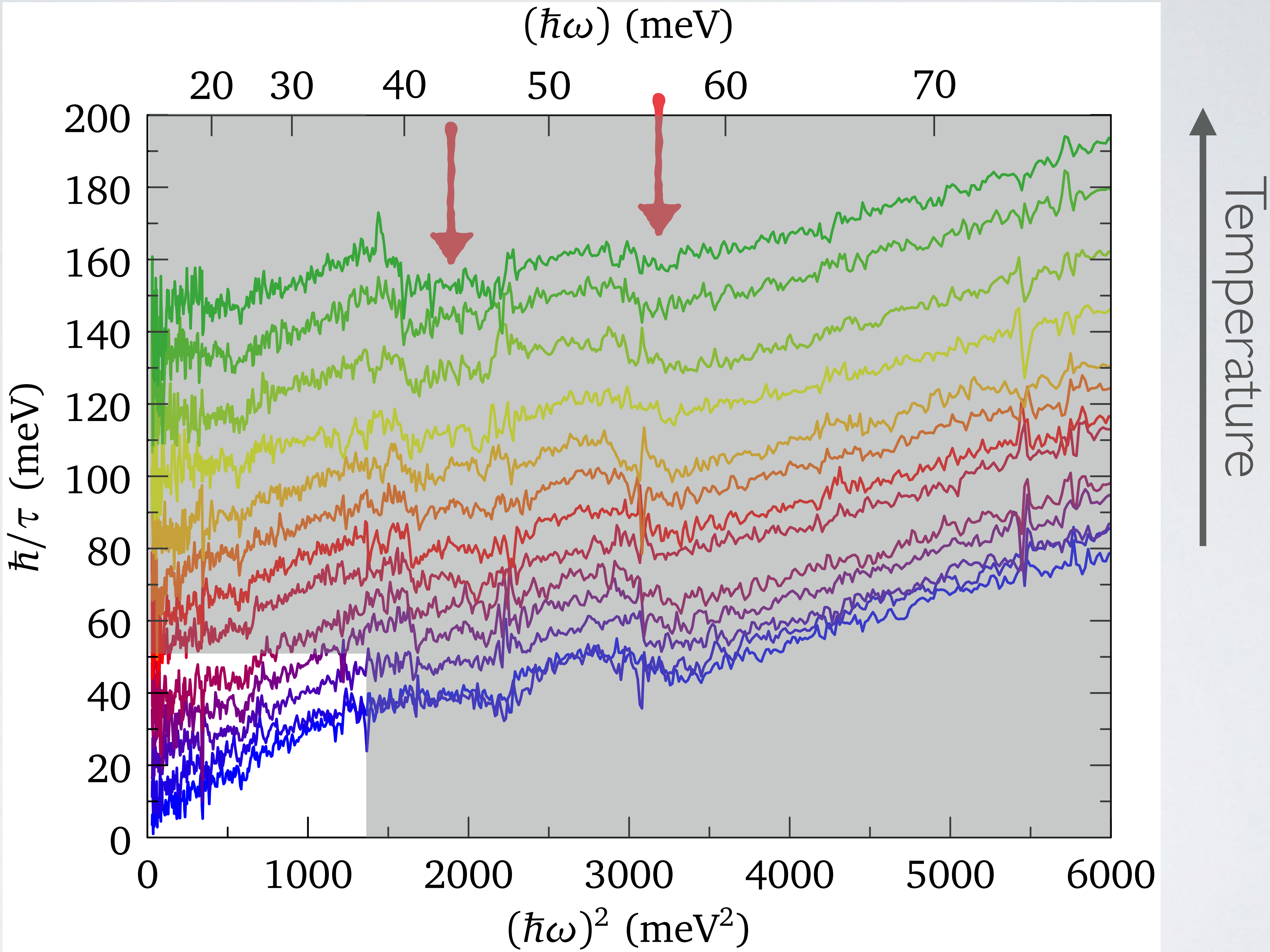
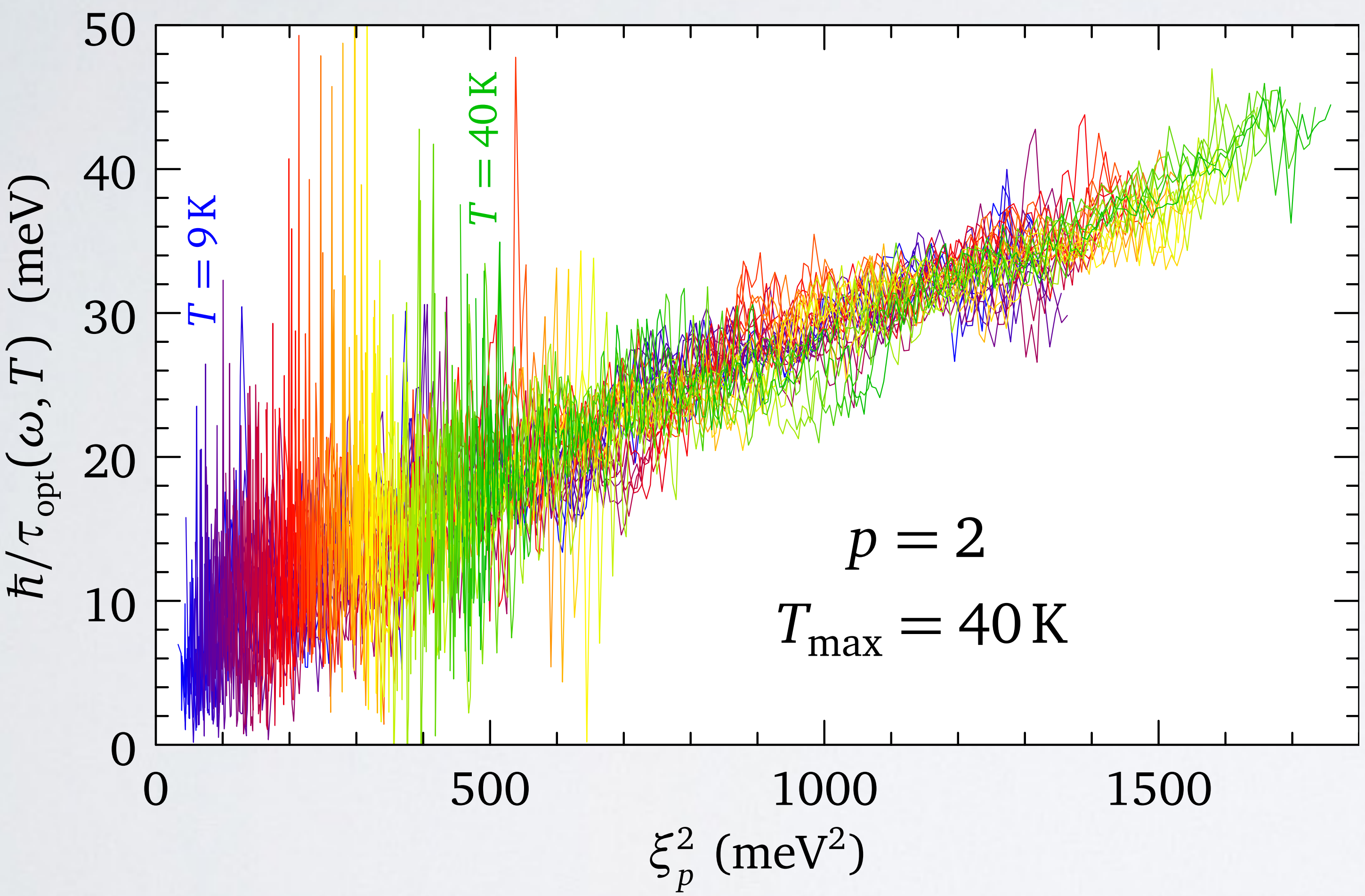


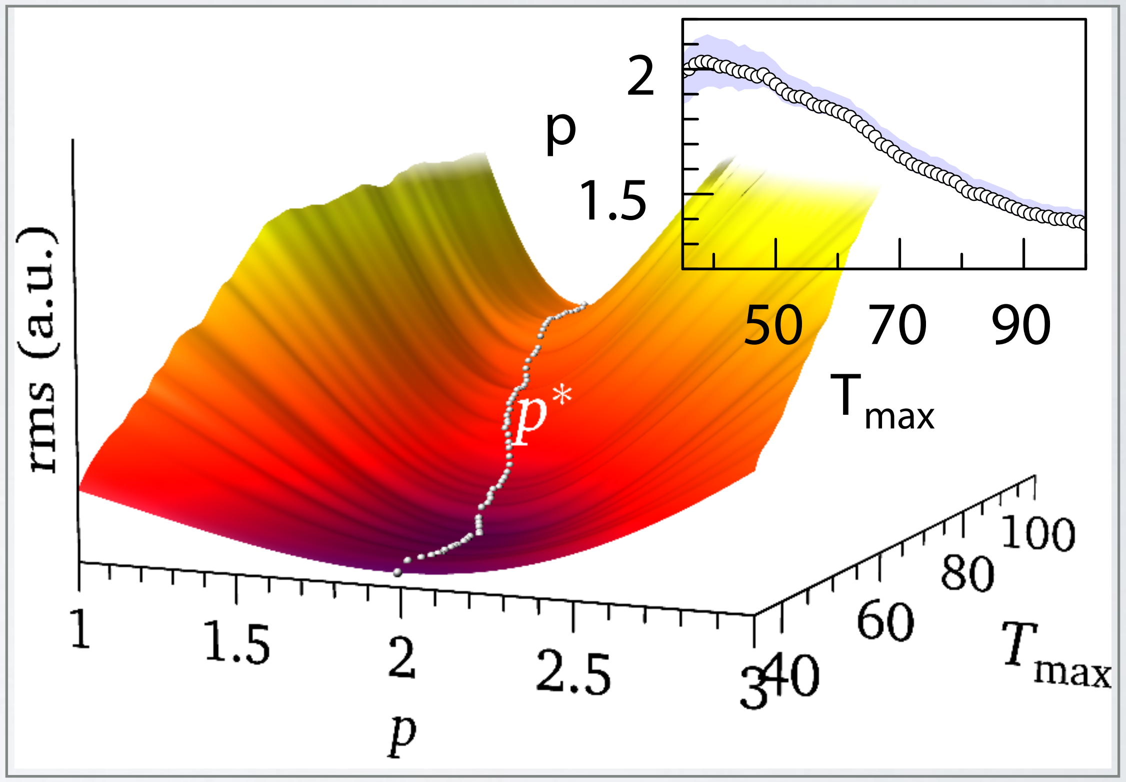
phonons


(ħω) (meV)
20
30
40
50
60
70
200
180
160
140
120
100
80
60
40
20
0
ħ/τ (meV)
0
1000
2000
3000
4000
5000
6000
(ħω)² (meV²)
Temperature

Sr_2RuO_4 Scaling collapse in the thermal regime

rescaling the energy axis by $\boldsymbol{\xi_p^2 = (\hbar\omega)^2 + (p\pi k_B T)^2}$





Stricker *et al.* PRL 113, 087404 (2014)

Statistics with 9 K < **T** < T_{max} and 3 meV < **ħω** < 36 meV

Sr_2RuO_4 is a perfect Fermi liquid

✓ 1. $1/\tau \propto T^{\mu}$?

$\mu = 2$

✓ 2. $1/\tau_{opt} \propto \omega^{\eta}$?

$\eta \approx 2$

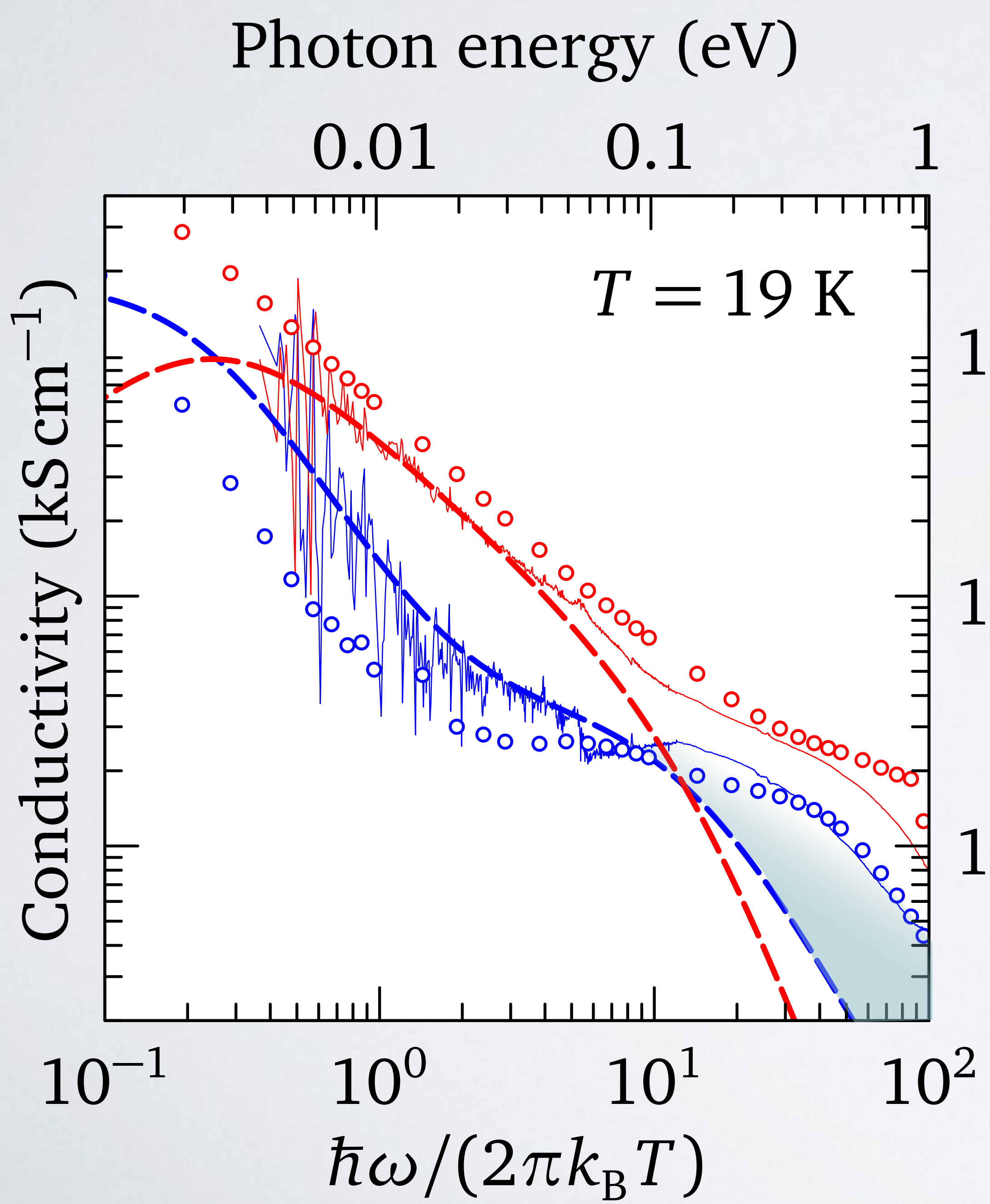
✓ 3. $1/\tau_{opt}(\omega,T) \propto \omega^2+(p\pi k_B T)^2$?

$p = 2$ first experimental proof

Optics + DMFT calculations

Mravlje, Georges et al., PRL 106, 096401 (2011)
Deng, Georges et al., PRL 110, 086401 (2012)
Berthod *et al.* PRB 87, 115109 (2013)

Re **σ** + i Im **σ**
o DFT + LDA and DMFT
— Experiment
--- Universal Fermi liquid form



Beautiful agreement at low temperature and energy

- No e-phonon/impurity scattering
- No scale adjustment
- Thermal shoulder confirmed

Signature of FL is a deviation from Drude

- Very good fit below 40 K
- Frequency dependence of $1/\tau_{opt}$

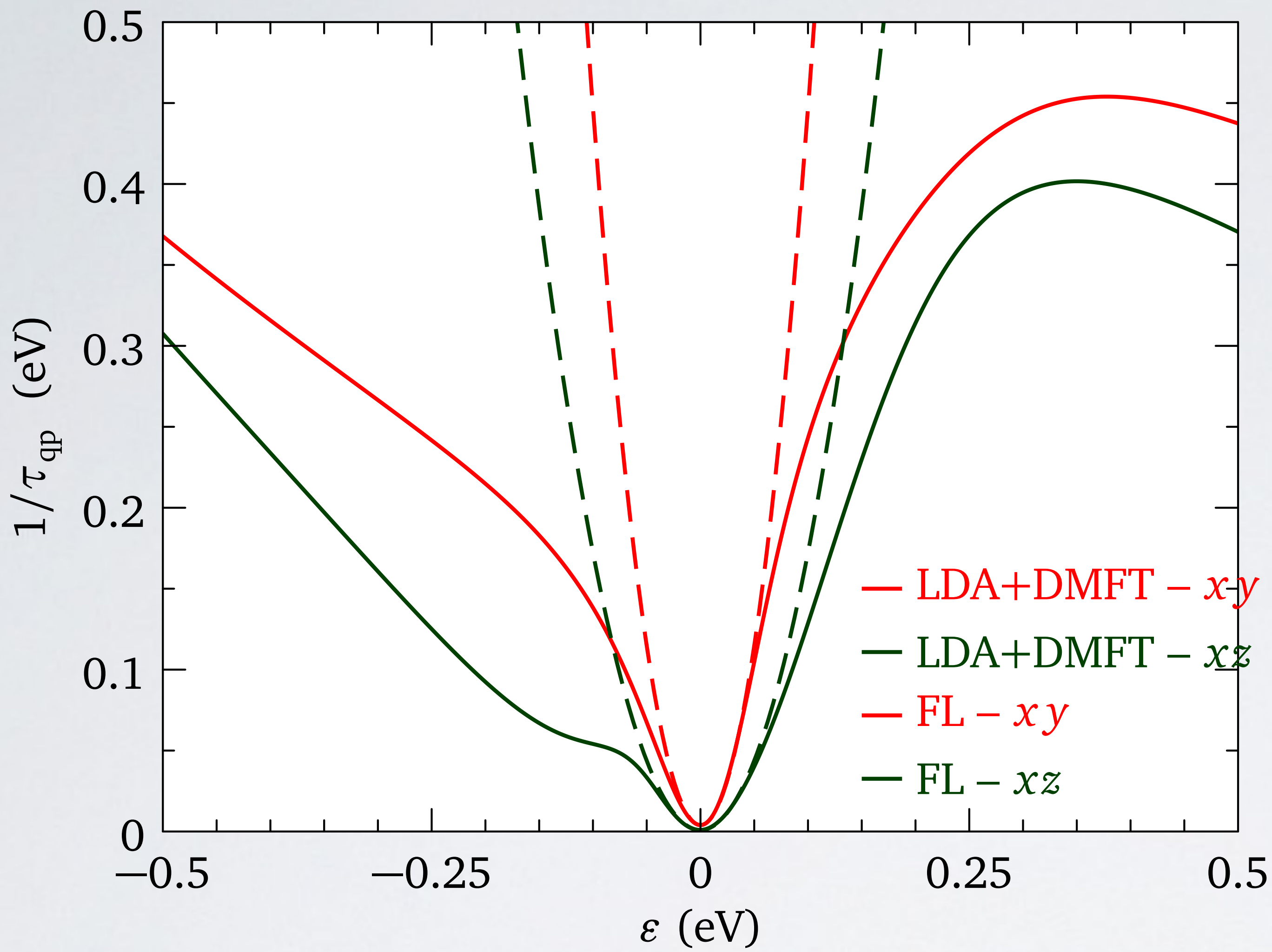
Clear deviations from FL above ~ 0.1 eV.

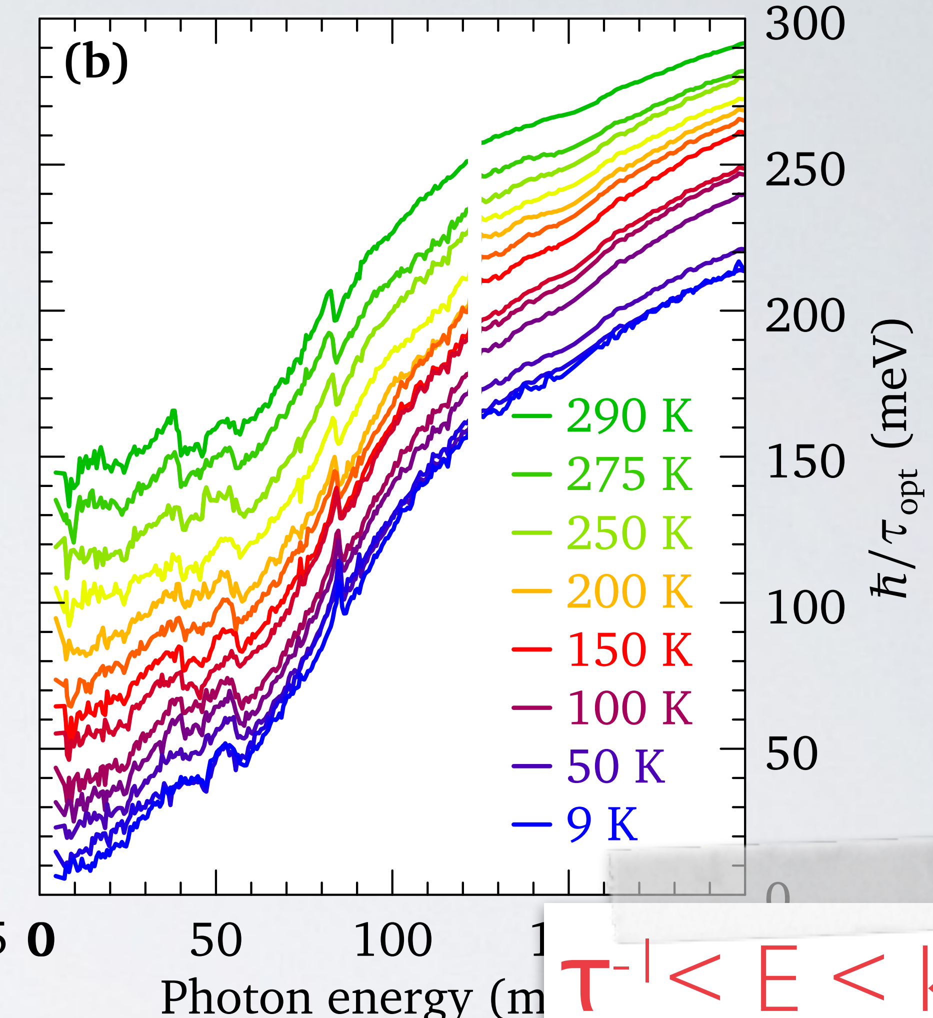
- Very well described by DMFT !

Stricker *et al.* PRL 113, 087404 (2014)

DMFT QP scattering

Stricker *et al.* PRL 113, 087404 (2014)
Mravlje, Georges *et al.* PRL 106, 096401 (2011)
Deng, Georges *et al.* PRL 110, 086401 (2012)

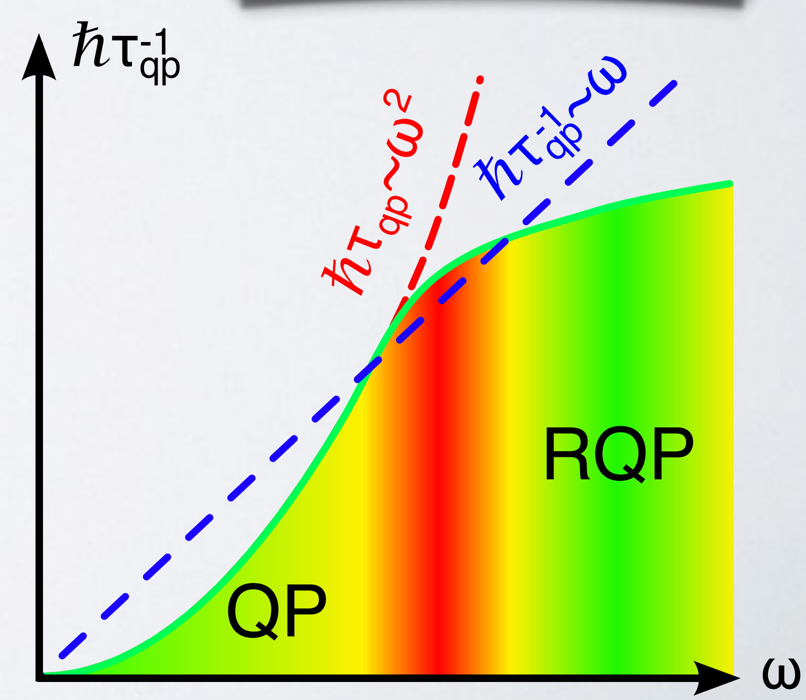




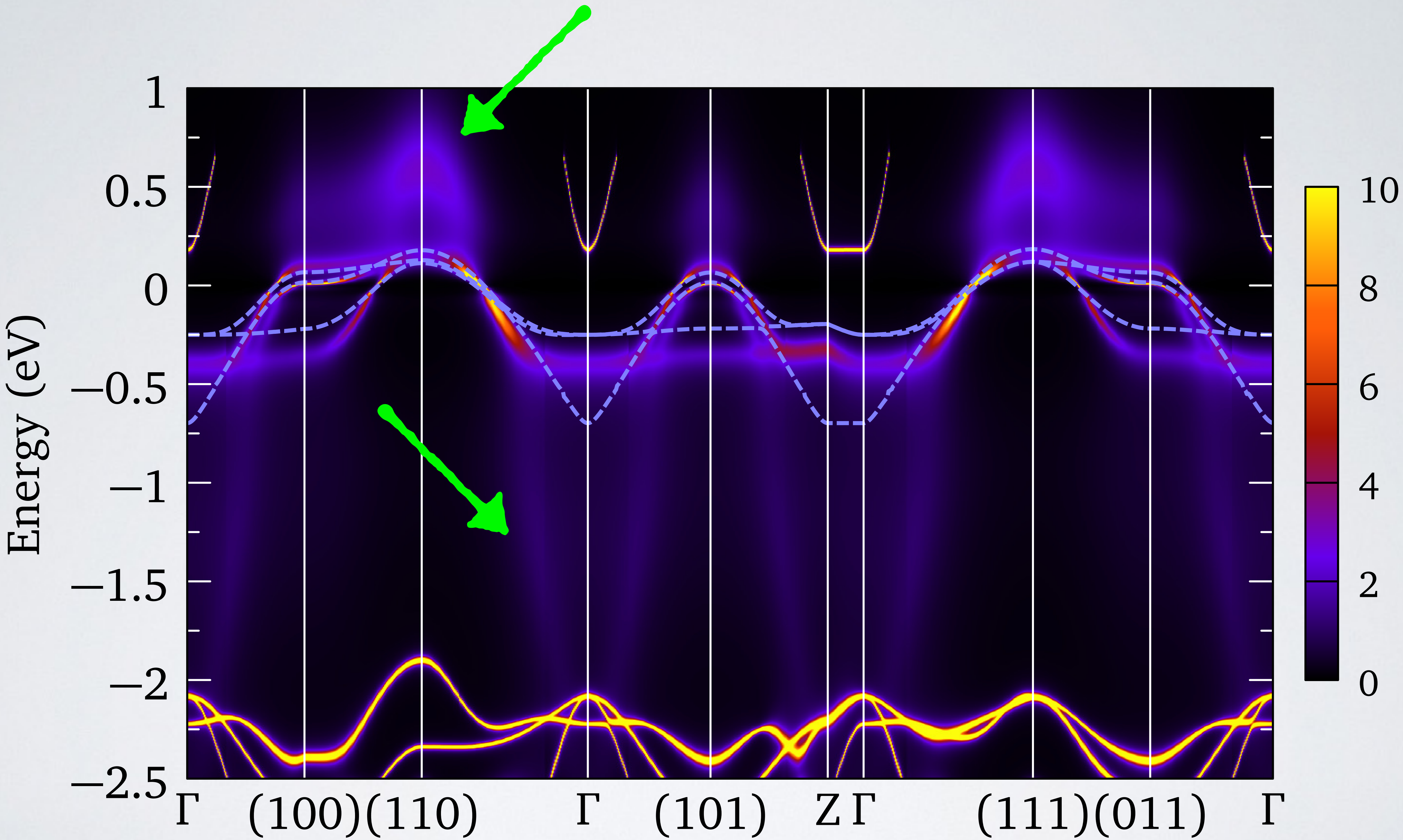
$\tau^{-1} < E < k_B T$

Well above T_{FL} well-defined single-particle excitations or **resilient quasiparticles** continue to exist which

1. Are broad but with **$1/\tau$** not exceeding ~ **π**$k_B T$
2. Do not obey Landau's T^2
3. Stronger dispersion than LDA one in sharp contrast to the low-energy effective mass in the FL regime.



K-resolved spectral function



Stricker & Mravlje *et al.* PRL 113, 087404 (2014)

Intermediate conclusions

1. Non-Drude $\not\equiv$ non-Fermi-liquid

2. First experiment indicating **accurately the FL behavior (p = 2)** !

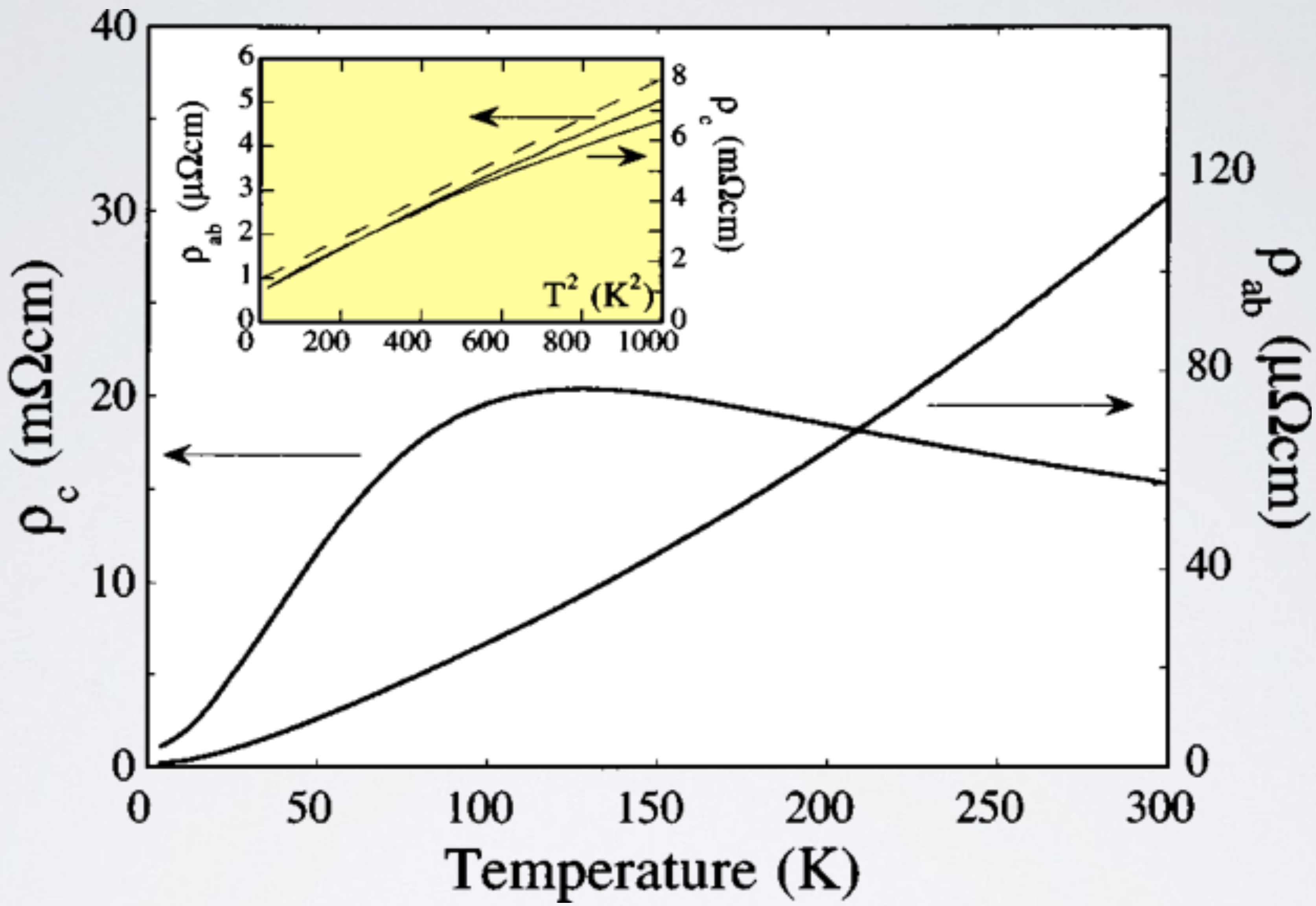
3. The FL regime provides the reference to characterize without ambiguity the deviations from FL theory

4. First optical proof of **Resilient Quasiparticles** with **non-FL lifetime**.

5. **Question** : Why is it the only Fermi-liquid with p = 2 ?

Stricker *et al.* PRL 113, 087404 (2014)

Two decade of transport measurement …



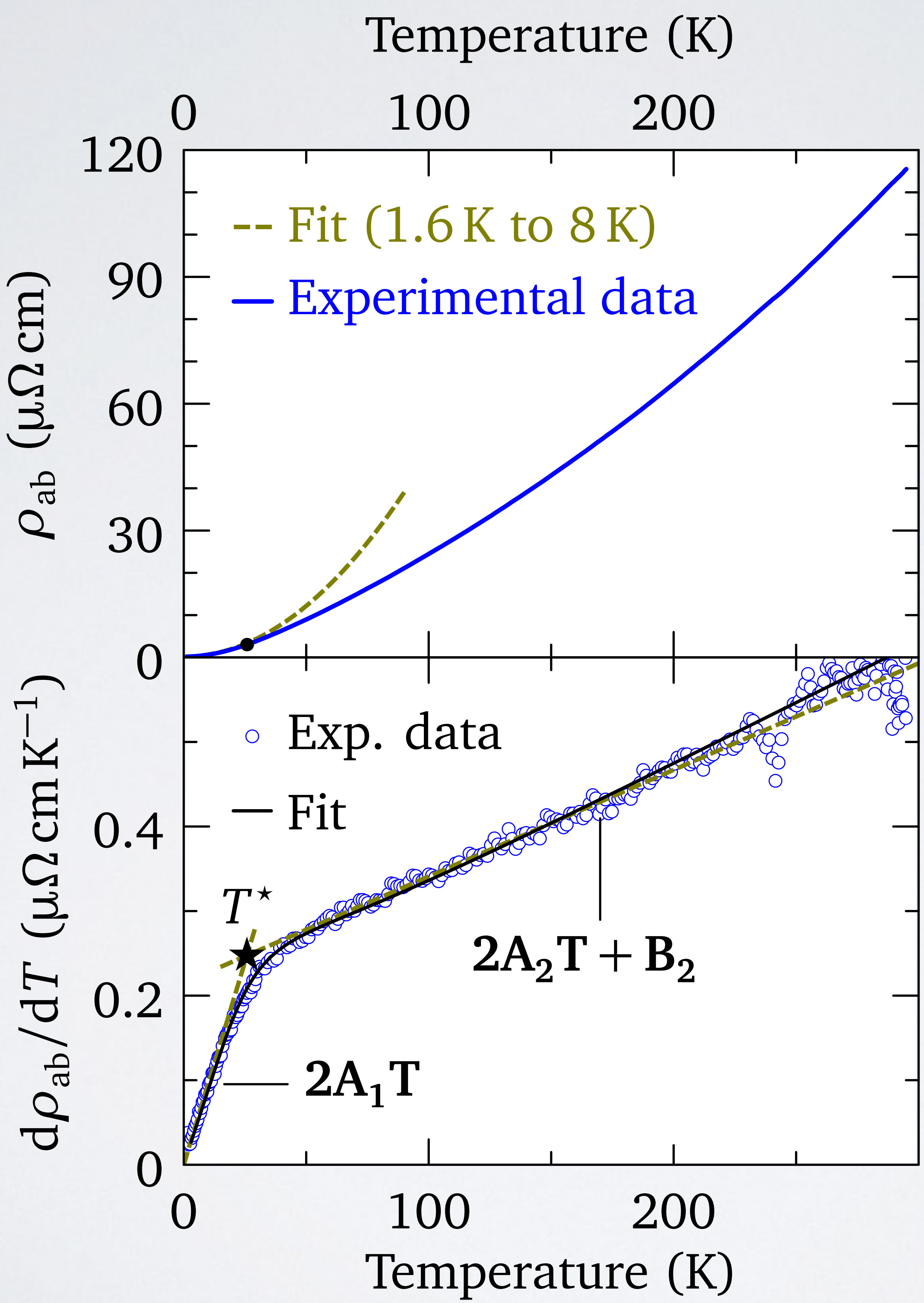
Mackenzie & Maeno, Rev. Mod. Phys. 75 2 (2003)

dependence down to T_c. The in-plane resistivity, ρ_{ab}, is metallic from 300 K to low temperatures, and below approximately 20 K, both ρ_{ab} and ρ_c have an approximate T^2 dependence, as shown in the inset. This T... dence of ρ at low temperatures is consistent ... predictions of the Fermi-liquid theory of n...

Kidd, PRL 94107003 (2005)

by electron-phonon interactions. As the temperature is raised, the system undergoes a broad crossover, and the system shows distinct non-Fermi liquid behavior. A tem-

What is the « glue » of electrons in Sr_2RuO_4



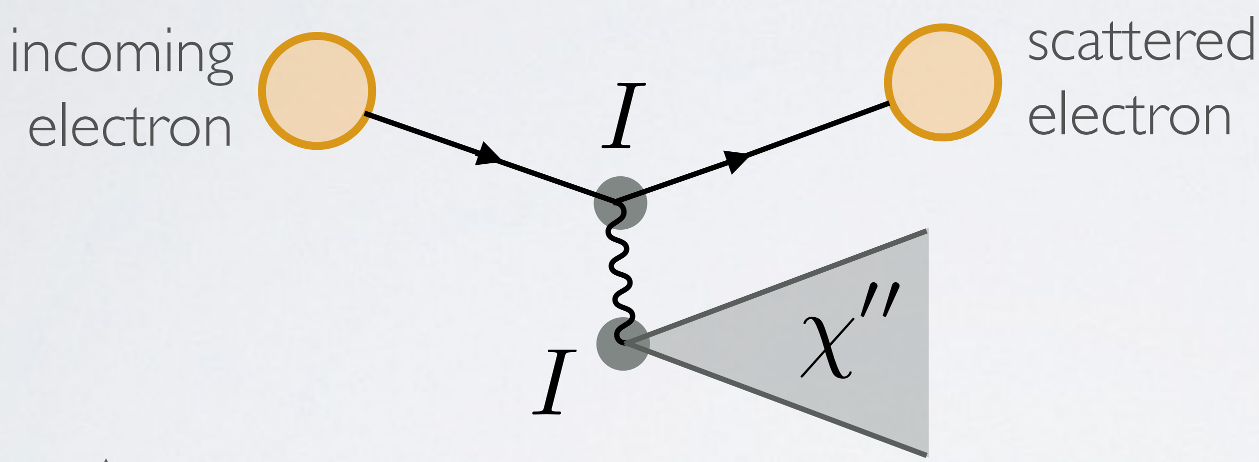
Susceptibility of correlations

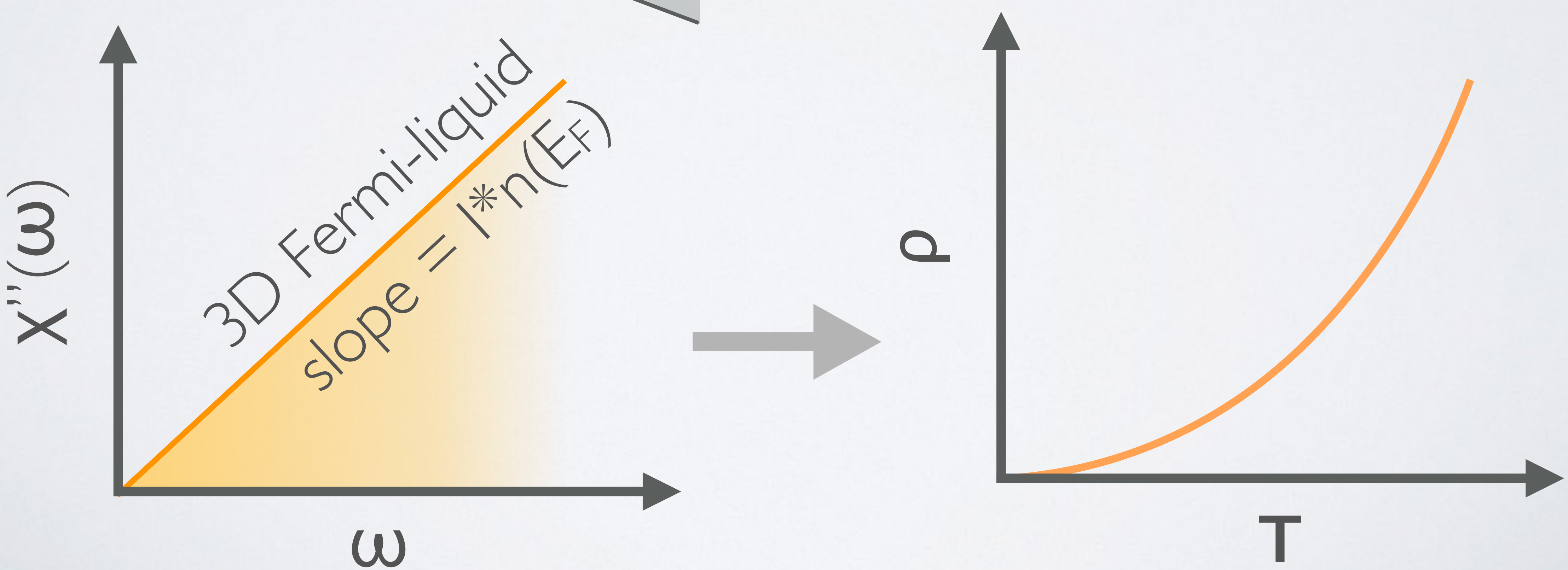
Susceptibility

$$I^2\chi'' = \alpha^2 F(\omega) + \beta\chi''_{\text{charge}} + \gamma\chi''_{\text{spin}}$$

$$\Sigma(\omega) = \frac{1}{\pi}\int_{-\infty}^{\infty} d\Omega\, I^2\chi''(\Omega) \int_{-\infty}^{\infty} d\varepsilon\, N(\varepsilon)\frac{f(-\varepsilon)+b(\Omega)}{\omega-\Omega-\varepsilon+i0^+}$$

core function





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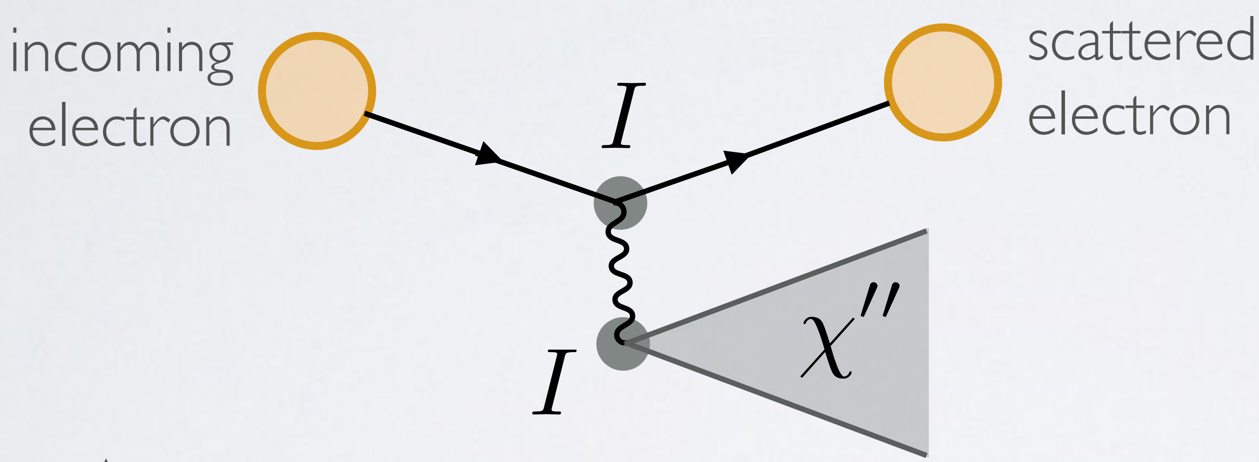
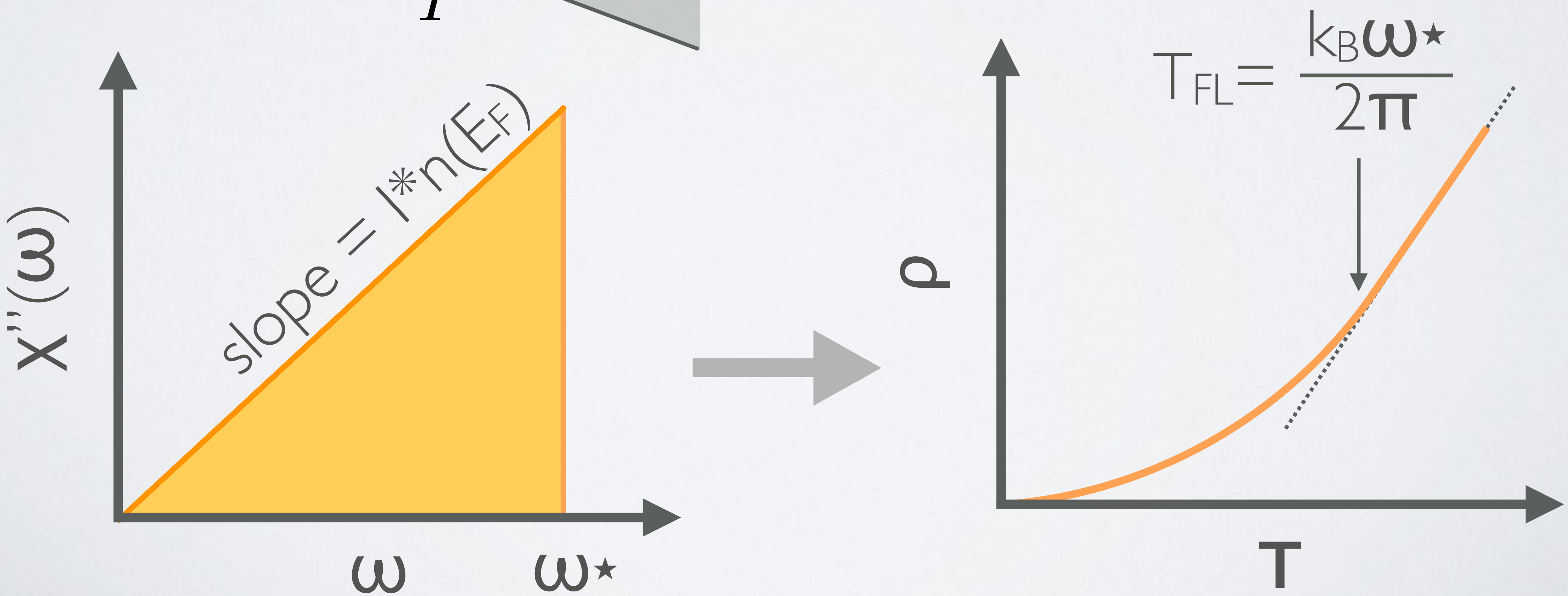
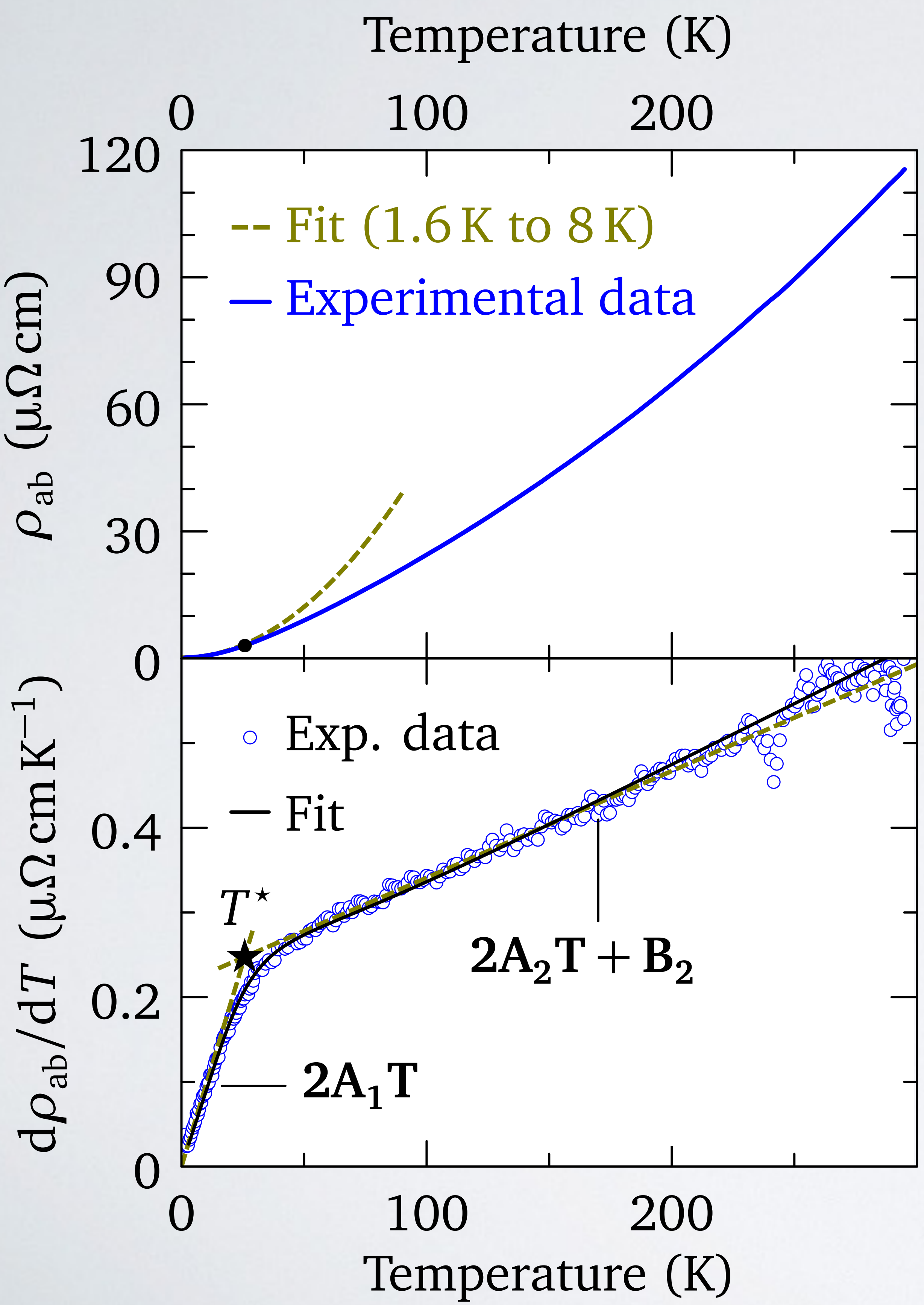
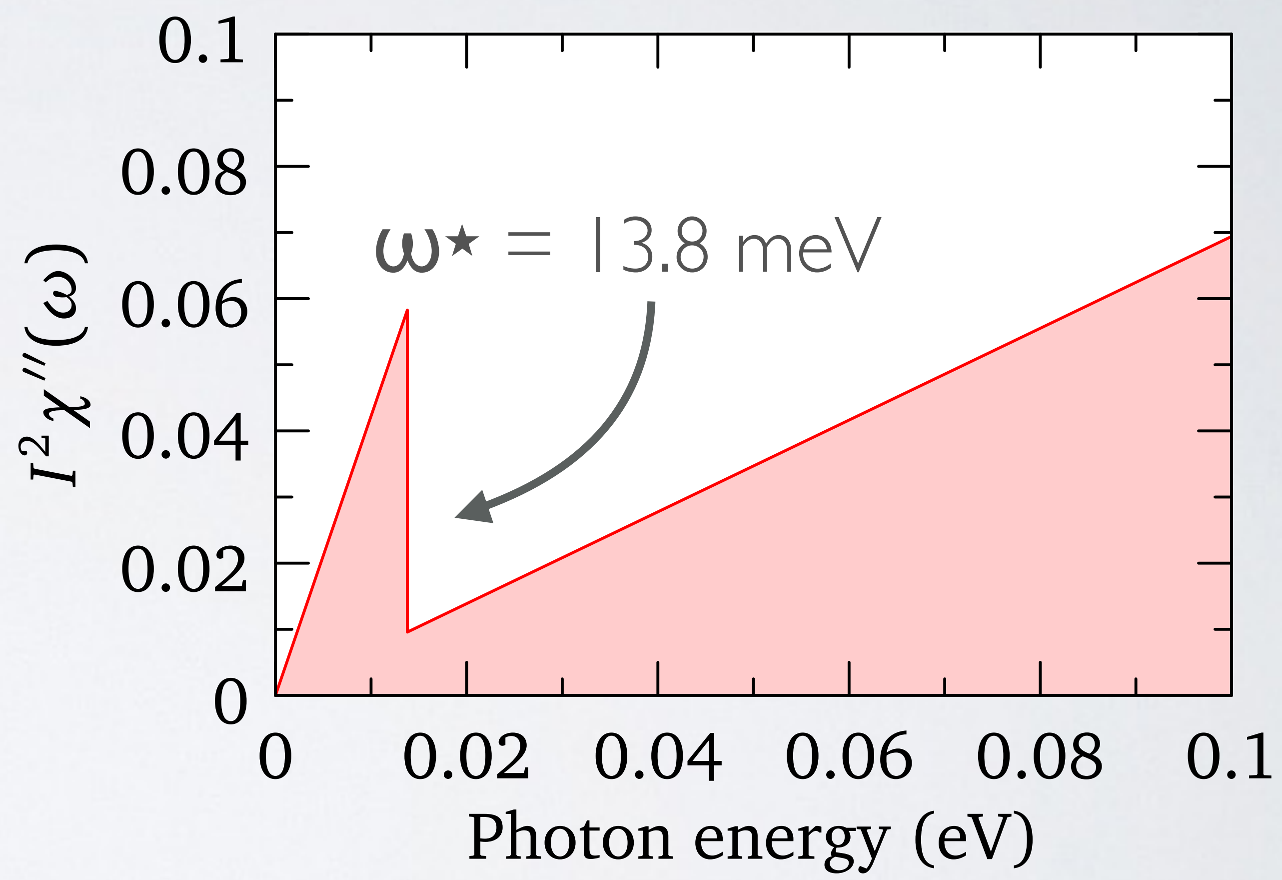


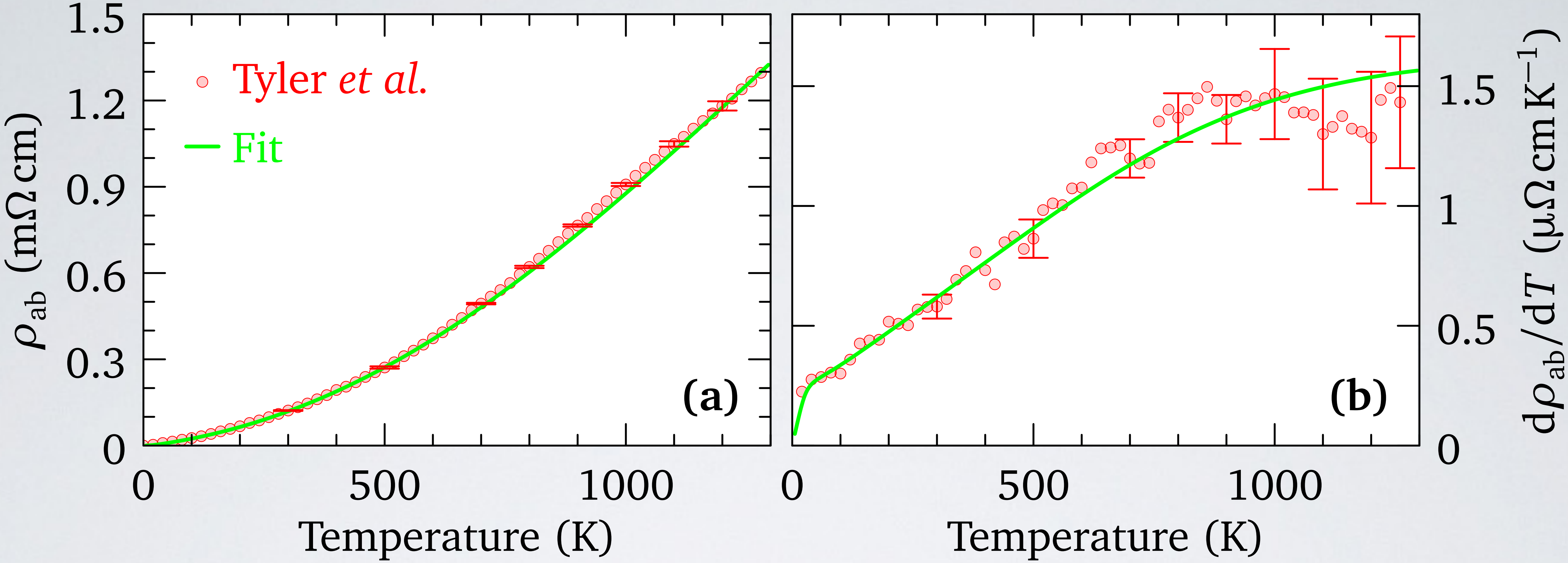


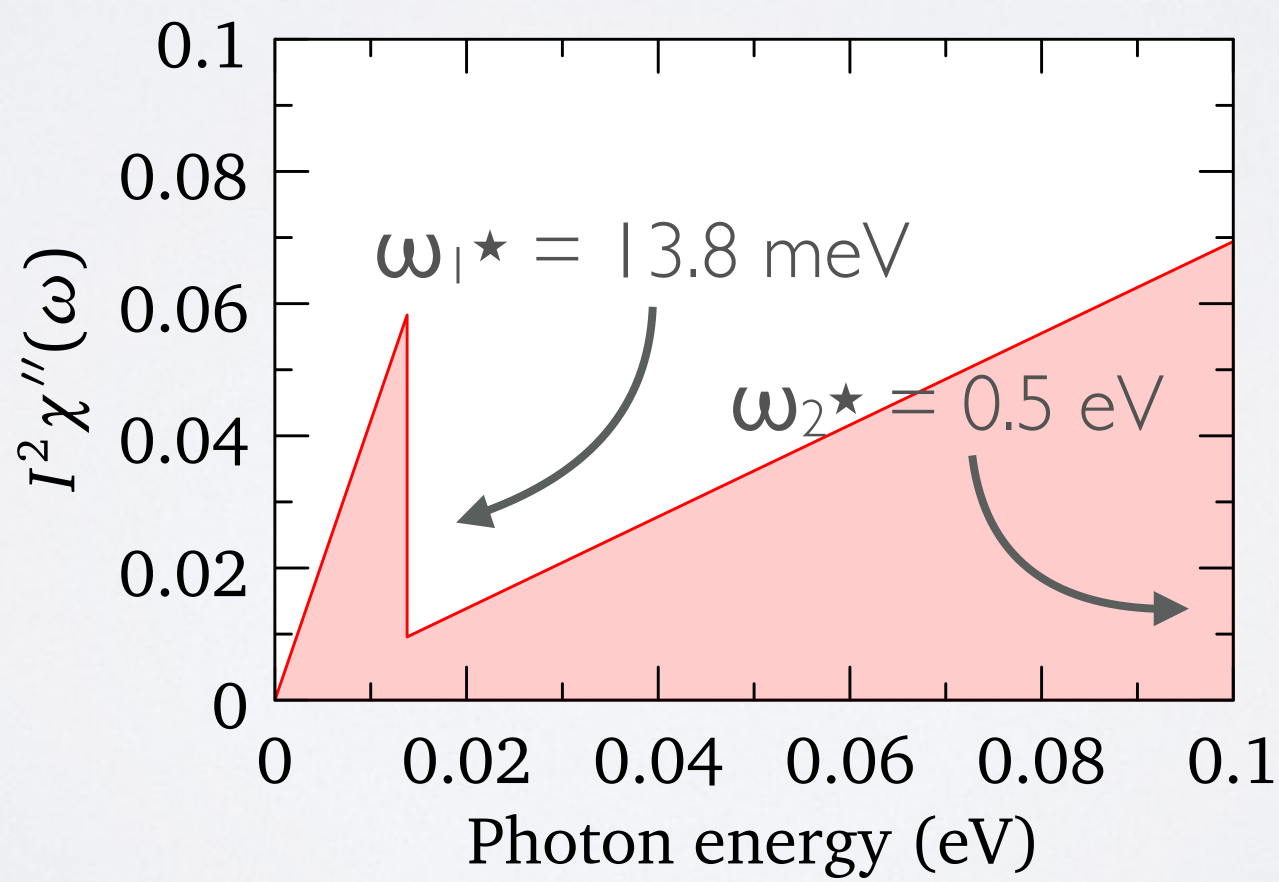
What is the « glue » of electrons in Sr_2RuO_4



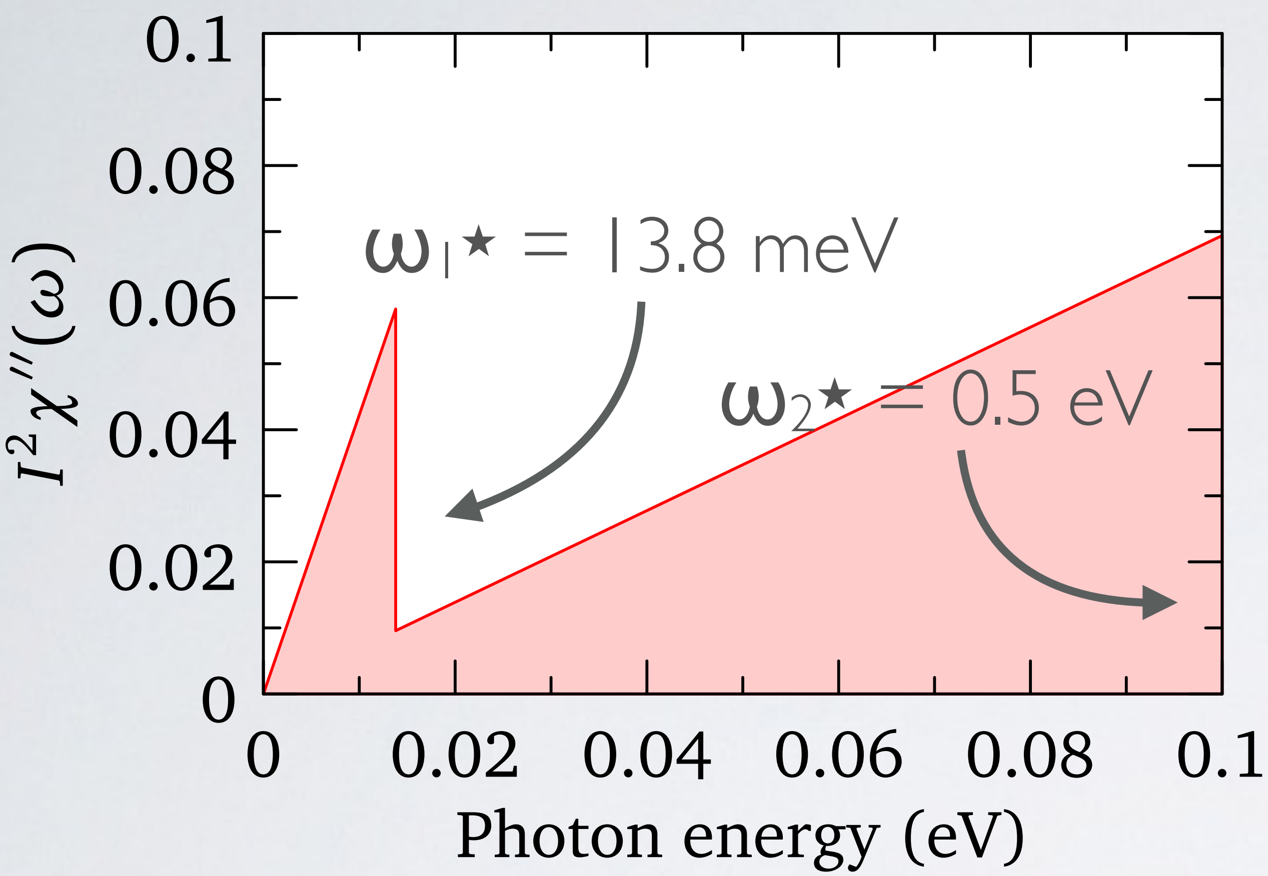


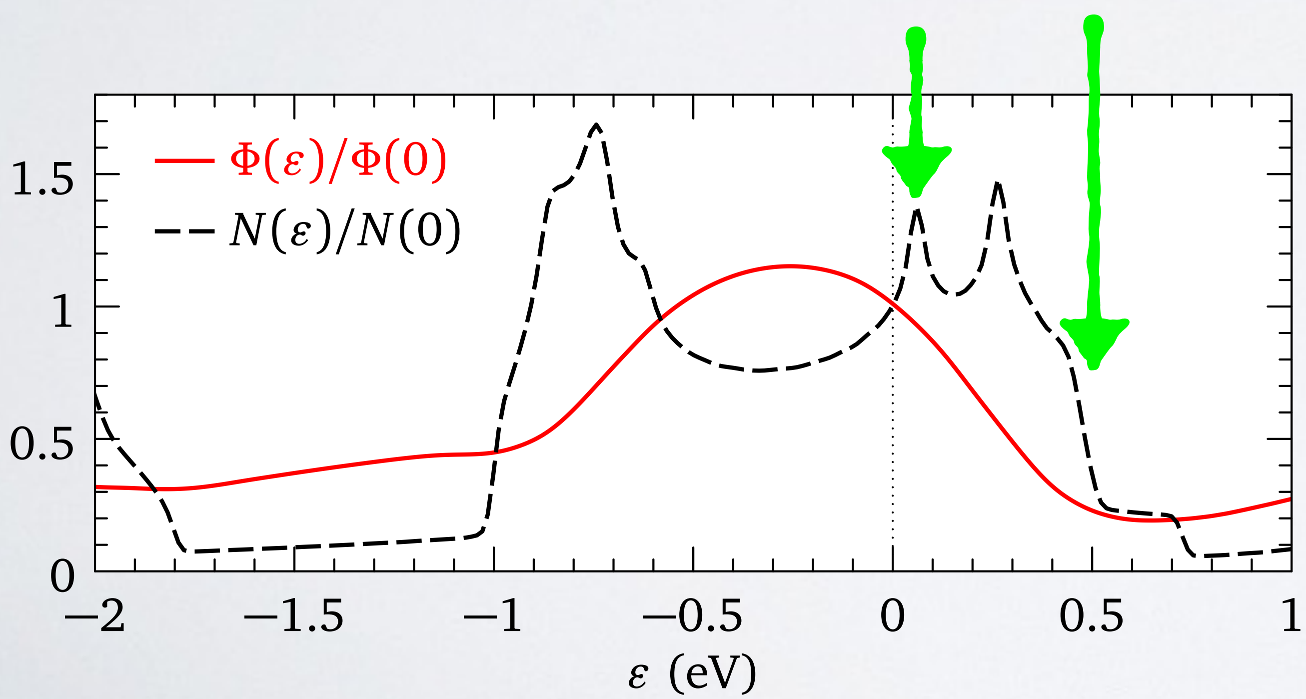
Tyler *et al.* **PRB 58** R10107 (1998)





Open question





Case n°1 : **3D Fermi liquid ?**

- α, β, γ bands
- Van Hove Singularity

K. Chen, PRB 84 245107 (2011)

Case n°2 : **Resilient Quasiparticles ?**

Case n°3 : **collective modes ?**

- 2D paramagnon
- 2D phonon
- any modes with linear dispersion in 2D…

Case n°4 : **Dimensional crossover ?**

- Transition too sharp ?

Fischer & Sigrist EPL 85 2 (2009)

1. Sr_2RuO_4 the archetypal Fermi-liquid
    - Correct scaling with p = 2
    - Low-frequency « Drude Foot »

Stricker *et al.* PRL 113, 087404 (2014)

Q : **Why is it the only one ?**

2. Sr_2RuO_4 the not so simple Fermi-liquid
    - Resilient quasiparticles
    - Two different mechanism link the electron together

Stricker *et al.* in prep (2015)

Q : **The origin of T_{FL} ?**

Thank you