Terahertz-frequency test for Fermi liquid conductivity in MnSi

J. Steven Dodge

Simon Fraser University
Burnaby, British Columbia

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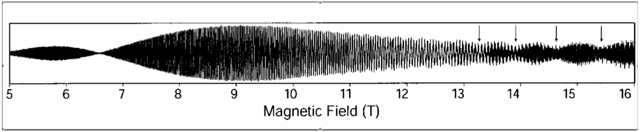
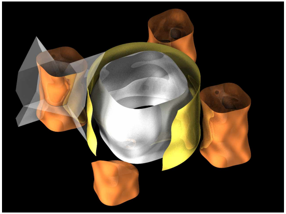
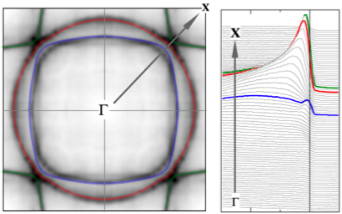
Correlated metals are often Fermi liquids at low ω, T

Sr_2RuO_4



Bergemann et al., 2000



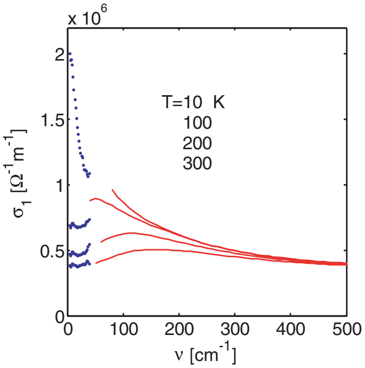


Bergemann et al., 2003

Damascelli et al., 2000

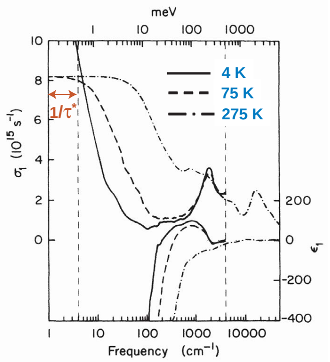
But trouble can begin at only a few meV

$CaRuO_3$



Kamal et al., 2006; Lee et al., 2002

$CdPd_3$

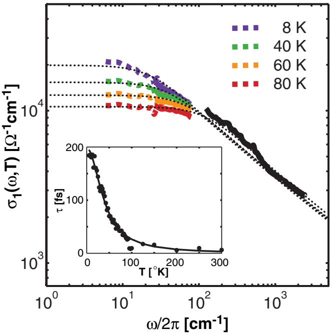


Webb et al., 1986

What sets the Fermi liquid scale?

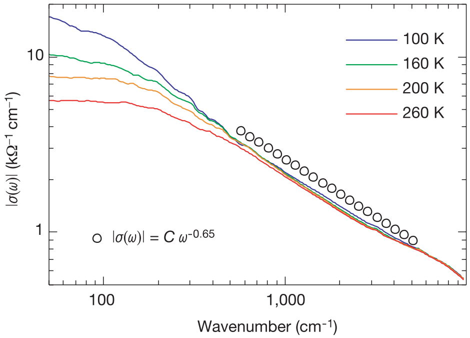
Anomalous power law conductivity in ruthenates and cuprates

$SrRuO_3$



Dodge *et al.*, *PRL* 2000

Y-doped BSCCO



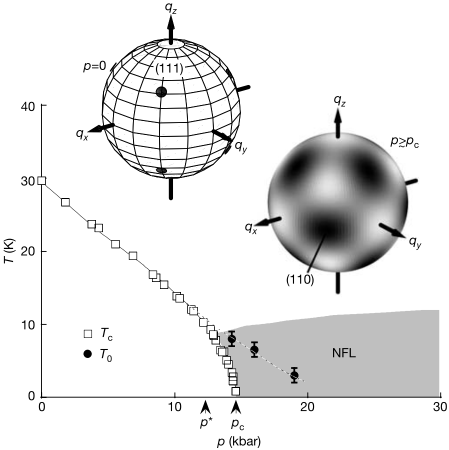
van der Marel *et al.*, *Nature* 2003

$$\sigma(\omega, T) = \frac{A}{(1/\tau(T) - i\omega)^\alpha}, \quad \alpha < 1$$

Basic properties of MnSi

A Fermi liquid with a low characteristic energy scale

- Quantum oscillations ✓
- $\rho(T) = \rho_0 + AT^2$ ✓
- $\sigma_1(\omega) \propto \omega^{-\alpha}, \alpha \sim 0.5$ (IR) ✗
- QPT at $p = 14.6$ kbar
- B20 structure, lacks inversion
- Helimagnet, $T_C \sim 30$ K
- Skyrmion excitations



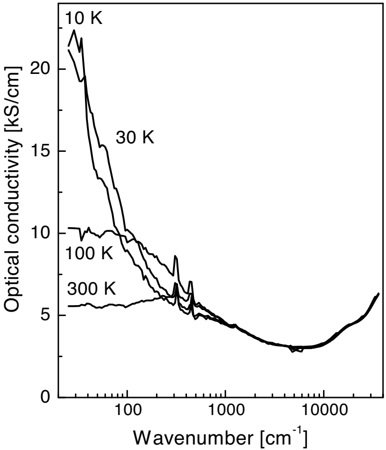
Pfleiderer *et al.*, *Nature* 2004

Optical conductivity of MnSi

Anomalous power law at low temperatures, pseudogap at high temperatures

$$\sigma(\omega, T) = \frac{A}{(1/\tau(T) - i\omega)^{\alpha}},$$

$$\alpha \approx 0.54$$



Mena *et al.*, *PRB* 2003

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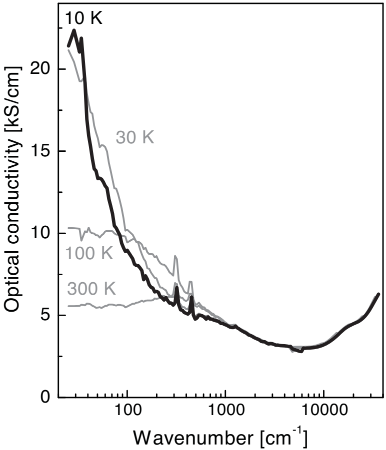

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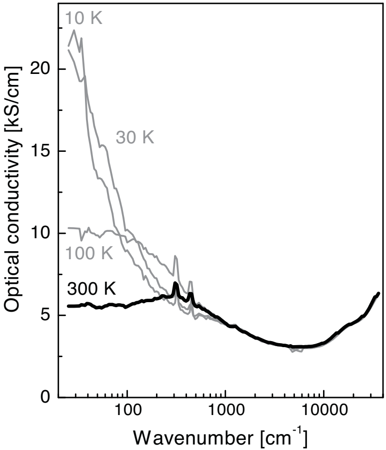

Mena *et al.*, *PRB* 2003

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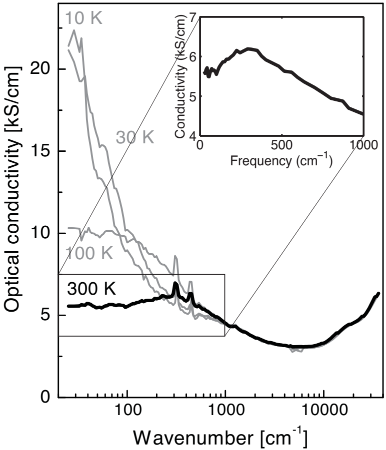
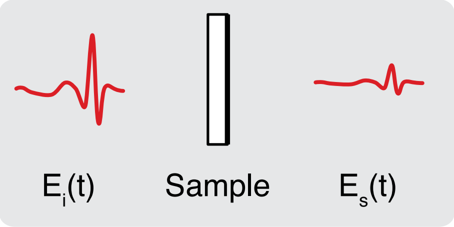
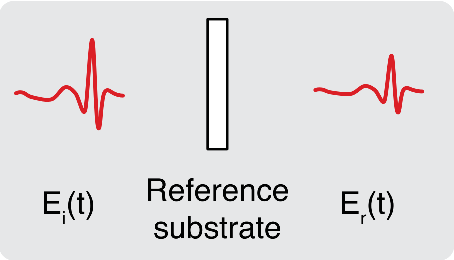


Mena *et al.*, *PRB* 2003

Terahertz conductivity measurements with thin films



$$t_{sr}(\omega) \equiv \frac{E_s(\omega)}{E_r(\omega)} = \frac{n+1}{n+1+\sigma(\omega) d Z_0} e^{i\Delta_{sr}(\omega)}$$



If substrate mismatch $\Delta_{sr}(\omega) \approx 0$,

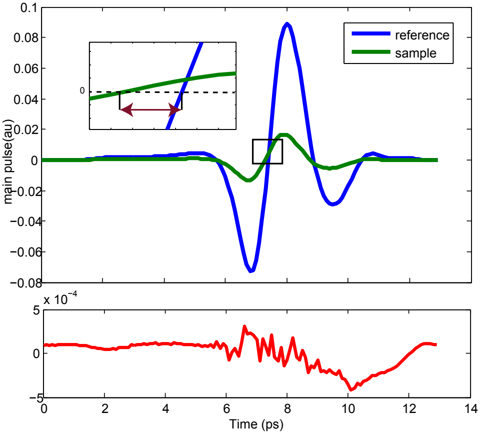
$$\sigma(\omega) = \frac{n+1}{d Z_0}\left[\frac{1}{t_{sr}(\omega)} - 1\right]$$

Samples: MnSi(111)/Si, $d \simeq 25$ nm

Temporal shift relates to Drude scattering time

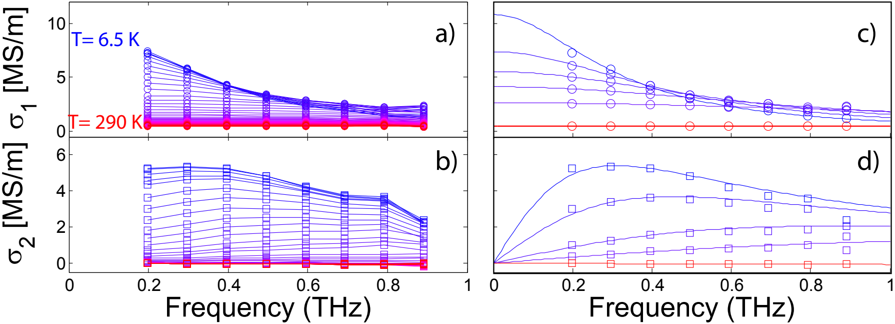
Temporal delay uncertainty of $\eta \approx \pm 2$ fs dominates conductivity parameter uncertainty

$$\sigma \approx \sigma_0/(1 - i\omega\tau) \approx \sigma_0 e^{i\omega\tau}; \quad t \approx 1/\sigma \approx e^{-i\omega\tau}/\sigma_0$$



Complex conductivity of MnSi

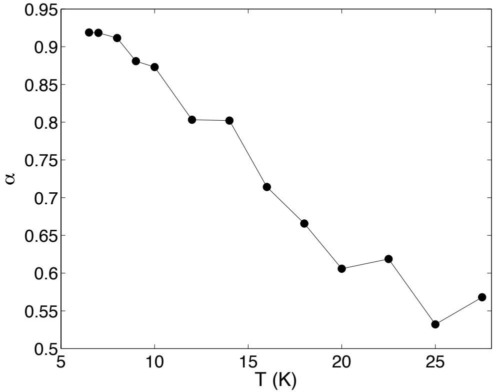
Approaches Drude form at $T = 6.5$ K



Anomalous power law becomes less anomalous

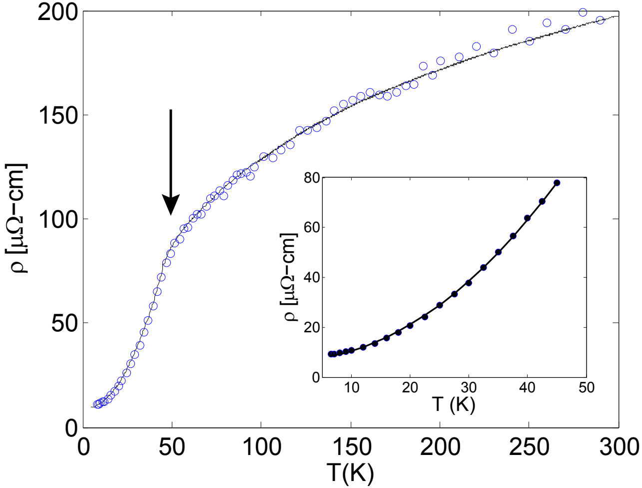
Approaches Drude form at $T = 6.5$ K

$$\sigma(\omega, T) = \frac{A}{(1/\tau(T) - i\omega)^{\alpha}}$$



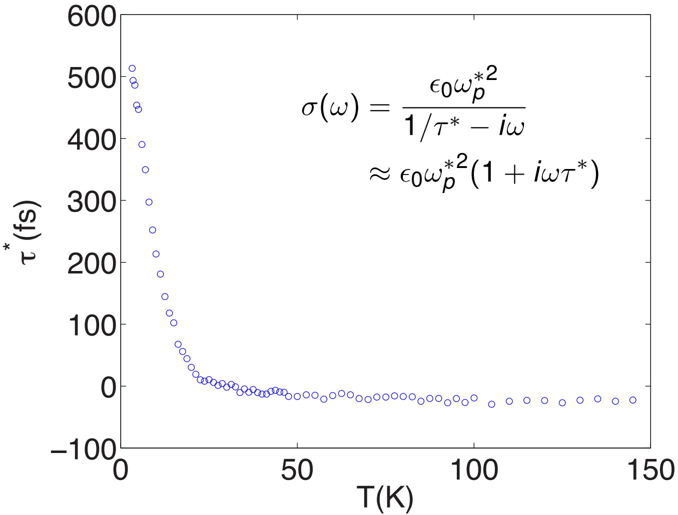
Drude extrapolations of $\rho_0(T)$

With comparison to four-probe measurements



Low-frequency Drude fit yields $\tau^*(T)$

At $T = 6.5$ K $\tau^* \gtrsim 500$ fs, but it drops rapidly with T to become *negative* for $T \gtrsim 50$ K



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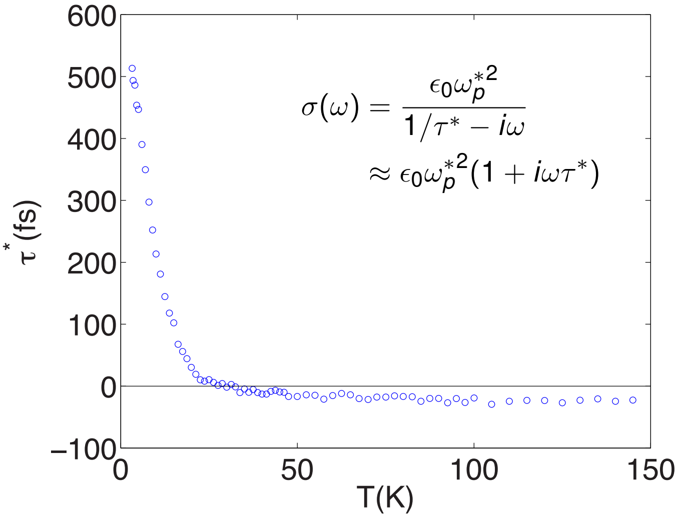

How do we interpret a negative value of τ^*?

A strong pseudogap in $\sigma_1(\omega)$ is associated with a negative *slope* of $\sigma_2(\omega)$

$$\sigma(\omega) = \frac{\epsilon_0 \omega_p^{*2}}{1/\tau^* - i\omega} \approx \epsilon_0 \omega_p^{*2}(1 + i\omega\tau^*)$$

$$\Rightarrow \tau^* \equiv \left. \frac{1}{\sigma_0} \frac{d\sigma_2(\omega)}{d\omega} \right|_{\omega \to 0}$$

Kramers-Kronig yields:

$$\tau^* \equiv \frac{2}{\pi} \int_0^\infty \frac{\sigma_0 - \sigma_1(\omega)}{\sigma_0 \omega^2} d\omega$$

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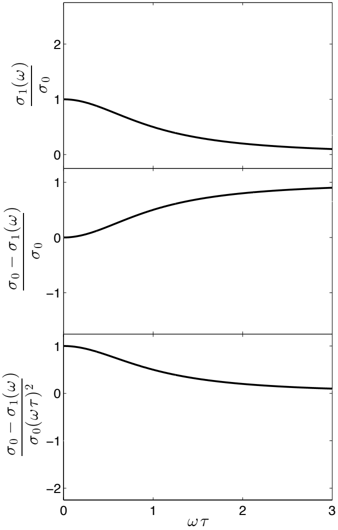

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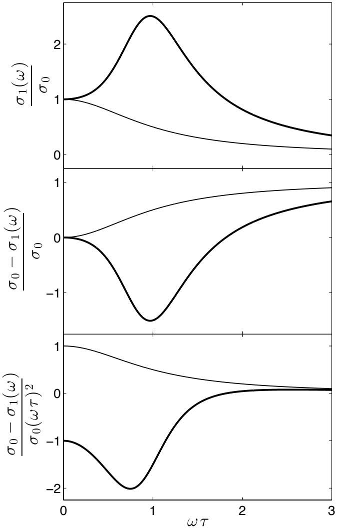
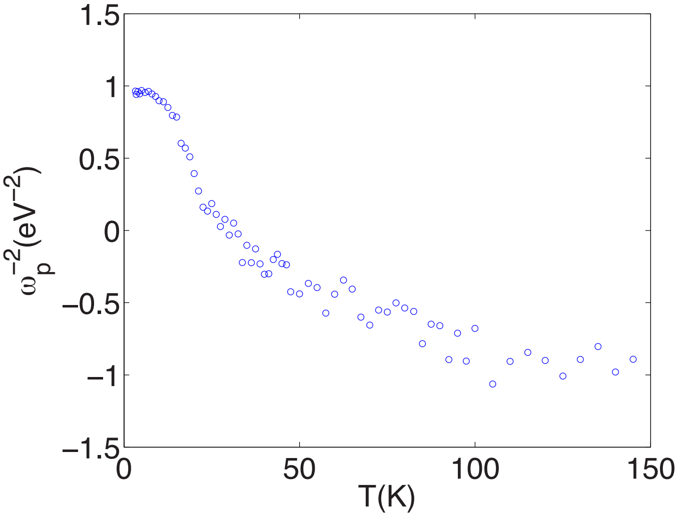


Measurement of $\omega_p^{*\,-2} = \epsilon_0 \rho_0 \tau^*$

Saturation at $T \sim 20$ K at $\omega_p^* \sim 1$ eV, mass enhancement of 4-6



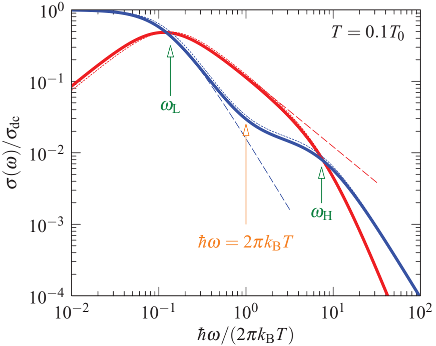
Fermi liquid theory predicts ω/T scaling

Experiments agree qualitatively, but not quantitatively

For $\hbar\omega \approx 2\pi k_B T$, $\omega\tau \gg 1$,

$$\sigma(\omega) \approx \frac{\epsilon_0 {\omega_p^*}^2}{1/\tau_{qp} - i\omega}, \text{ with}$$

$$\frac{\hbar}{\tau_{qp}} = \frac{2}{3\pi k_B T_0}\left[(\hbar\omega)^2 + (2\pi k_B T)^2\right].$$



Berthod *et al.*, *PRB* 2013.

See also Chubukov and Maslov, *PRB* 2012.

Experiments observe:

$$\frac{\hbar}{\tau_{qp}} = \frac{2}{3\pi k_B T_0}\left[(\hbar\omega)^2 + b(\pi k_B T)^2\right],$$

with $b \approx 1$, not $b = 4$.

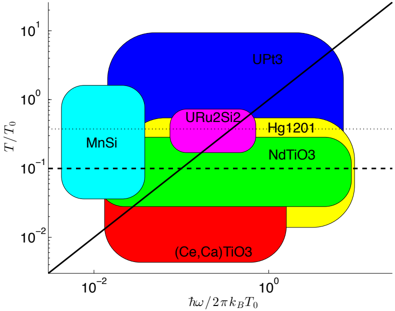
Expect $1/(\omega^2\tau_{qp}) \approx 9$ fs in MnSi (!).

Experimental observations in other materials

Characteristic temperature scale T_0 sets the relevant scale

Material	T_0 (K)	b
•UPt_3	17	< 1
•$Ce_{.95}Ca_{.05}TiO_{3.04}$	1156	1.72
•$Nd_{.95}TiO_4$	1037	1.1
•URu_2Si_2	103	1
•Hg1201	719	2.3
•MnSi	180	1–4

UPt_3: Sulewski *et al.*, *PRB* 1988;
$(Ce,Ca)TiO_3$: Katsufuji and Tokura, *PRB* 1999;
$NdTiO_4$: Yang *et al.*, *PRB* 2006;
URu_2Si_2: Nagel *et al.*, *PNAS* 2012;
Hg1201: Mirzaei *et al.*, *PNAS* 2013.



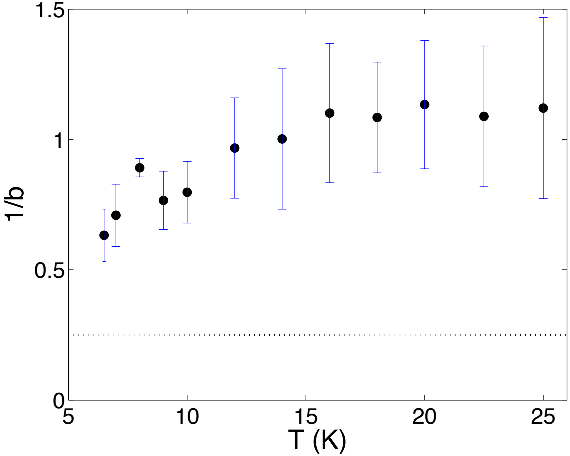
Frequency-dependent $1/\tau$ for $2\pi k_B T \approx h\nu$:

$2\pi k_B(6.5\ \text{K}) \approx h(0.85\ \text{THz})$

Measurement of Fermi liquid scaling parameter $1/b$

Quantitative agreement with theory remains elusive

$$\rho(\omega, T) \equiv 1/\sigma(\omega, T) \propto \left[(\hbar\omega)^2 + b(\pi k_B T)^2\right], \quad b = 4$$



Summary

- MnSi exhibits $\sigma(\omega, T)$ consistent with Fermi liquid theory
- Drude fit gives $\omega_p^*(T)$ that saturates for $T \lesssim 20$ K
- Comparison with band theory yields a mass enhancement of 4-6
- For $T \gtrsim 50$ K, the slope of $\sigma_2(\omega)$ is negative
- Negative slope in $\sigma_2(\omega)$ indicates pseudogap in $\sigma_1(\omega)$
- Above $T \sim 10$ K, $b \approx 1$, quantitatively inconsistent with FLT
- Possible evidence for a crossover to a larger value of b at low T