Probing low energy quantum matter

Erik van Heumen

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Collaborators

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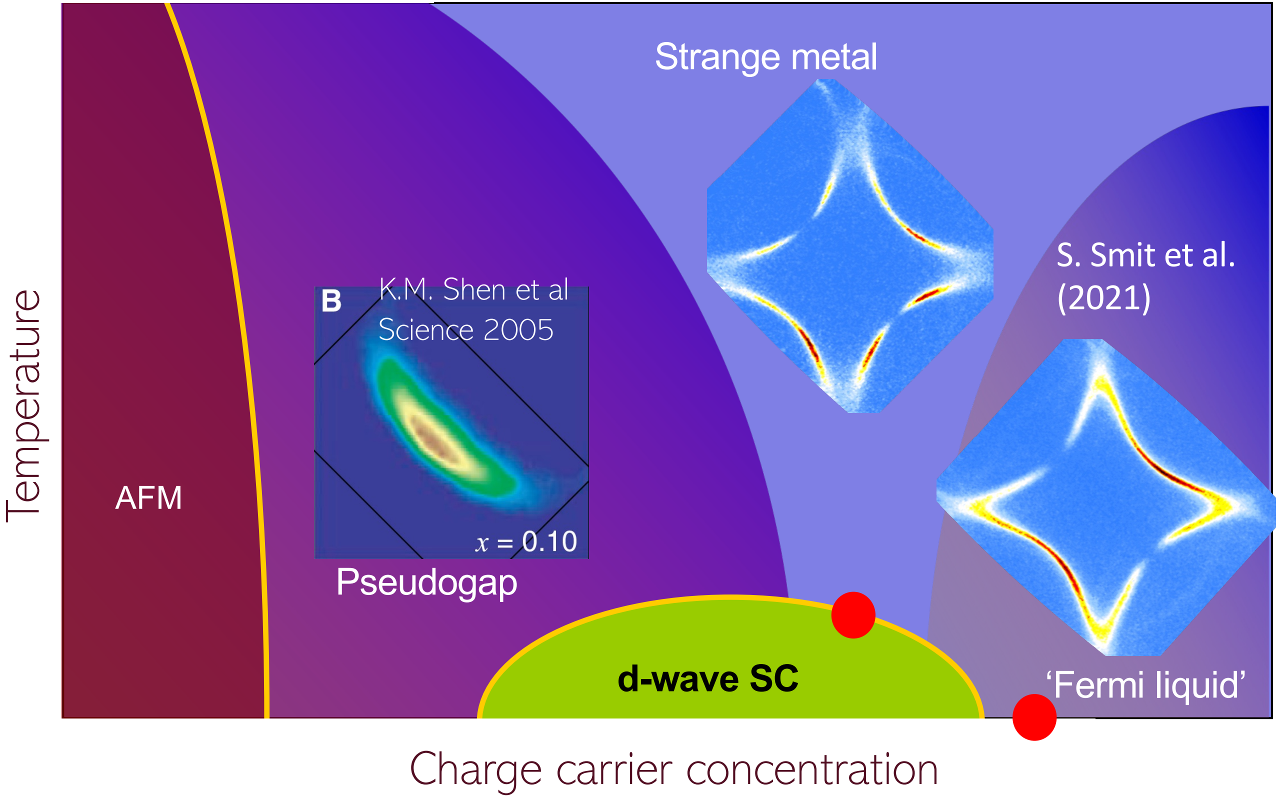
University of Bath — E. DaComo

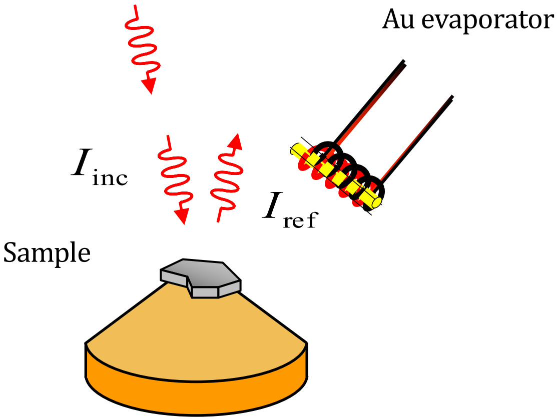
From Fermi liquid to strange metal



Key question:
What distinguishes the strange metal phase from a Fermi liquid?

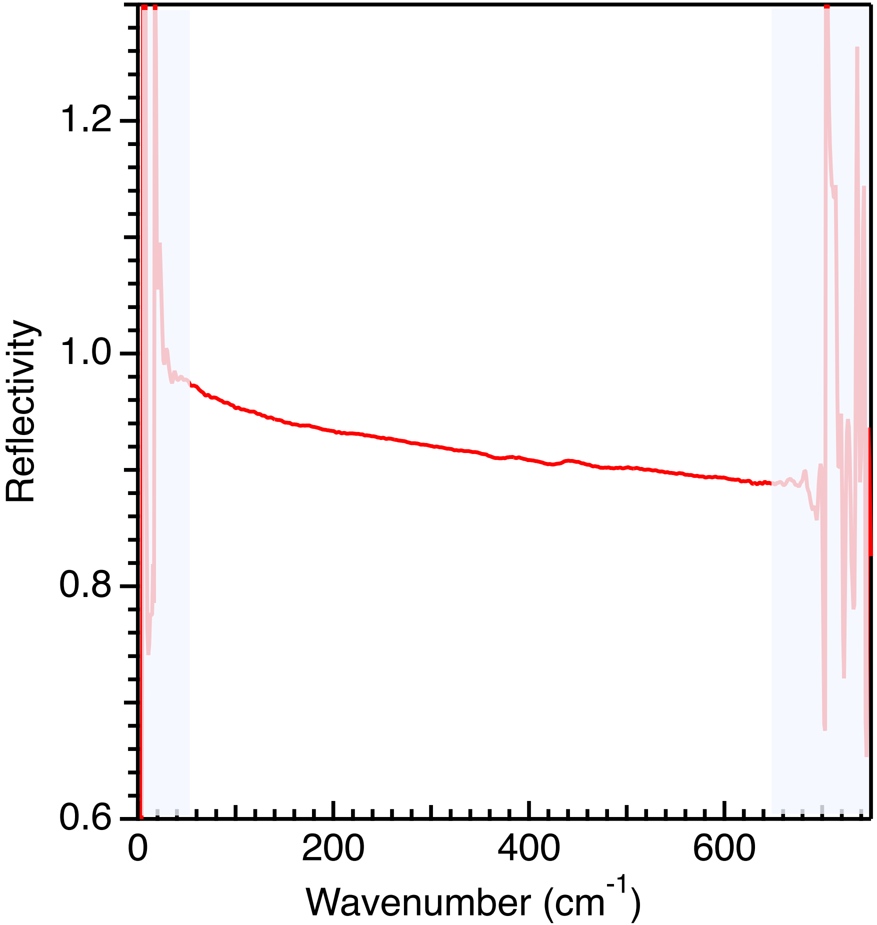
Optical experiments:
Frequency dependence of the conductivity is a valuable source of information on collective response.

How do you measure the optical response?



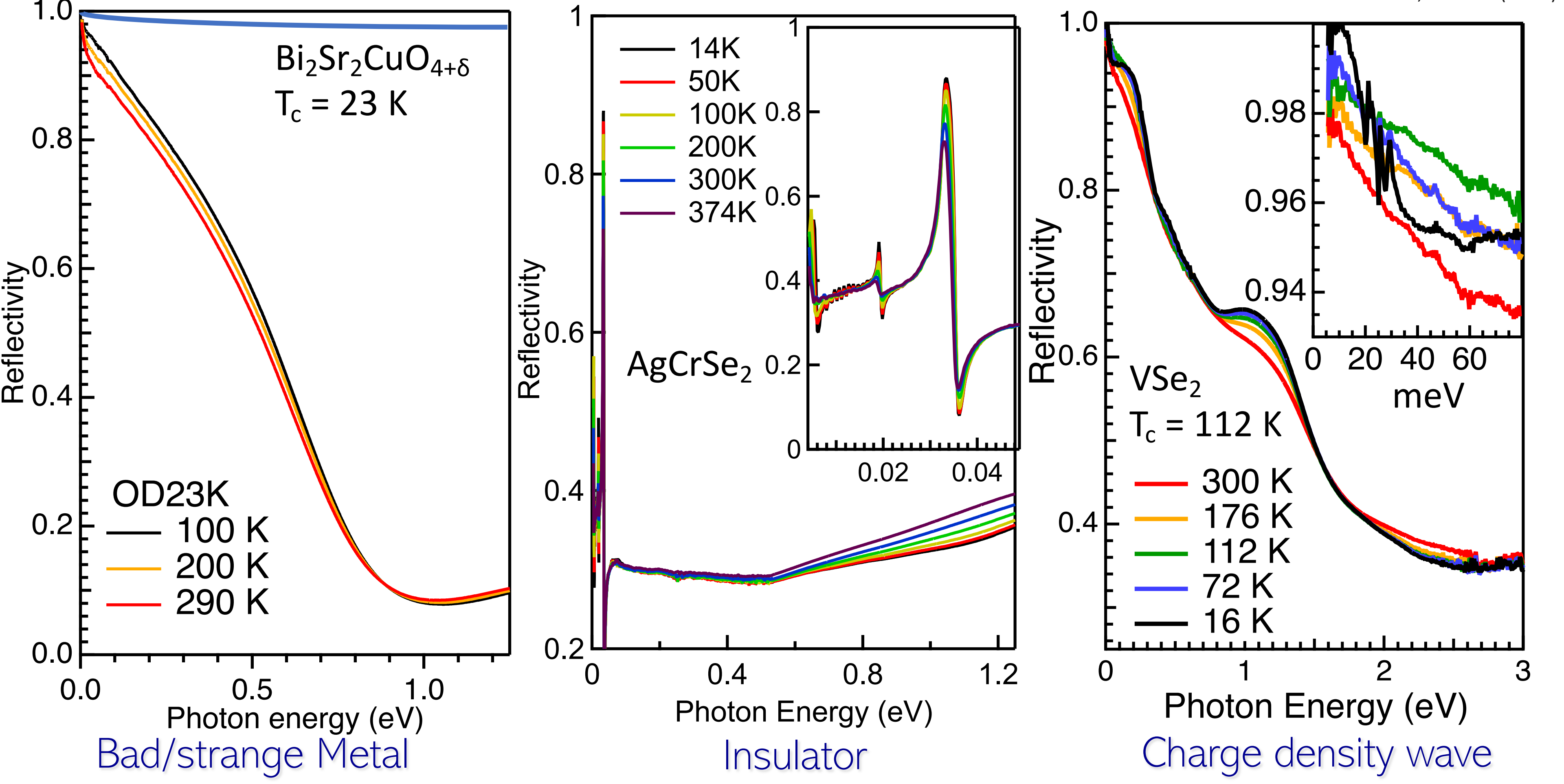
Measures R(**ω**)

$$R(\omega) = \frac{I_{sample}}{I_{ref.}}$$



Metals, insulators and spontaneous symmetry breaking

X. Feng et al. PRB 104, 165134 (2021)
J. Groefsema et al. PRM 6, 115402 (2022)
E. van Heumen et al. PRB 106, 054515 (2022)



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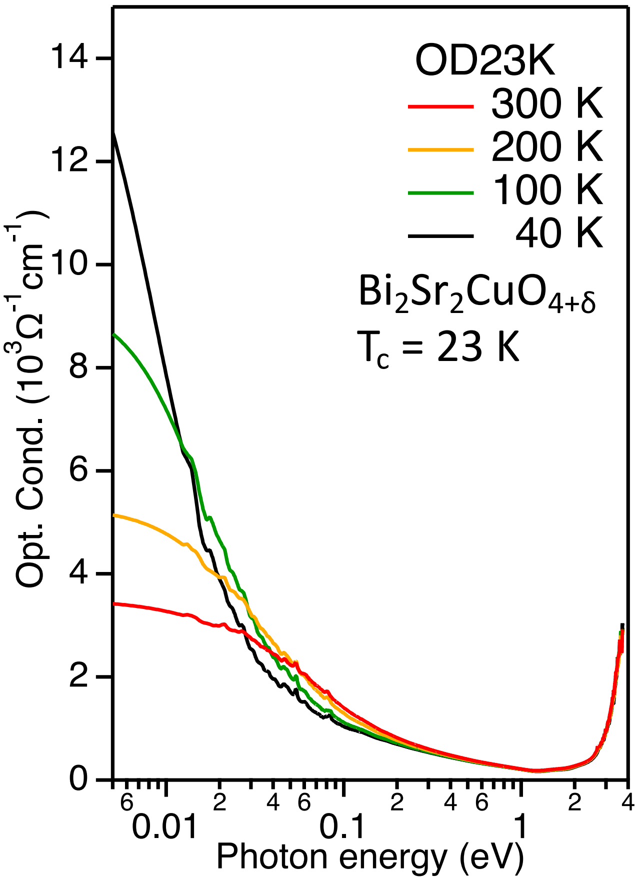
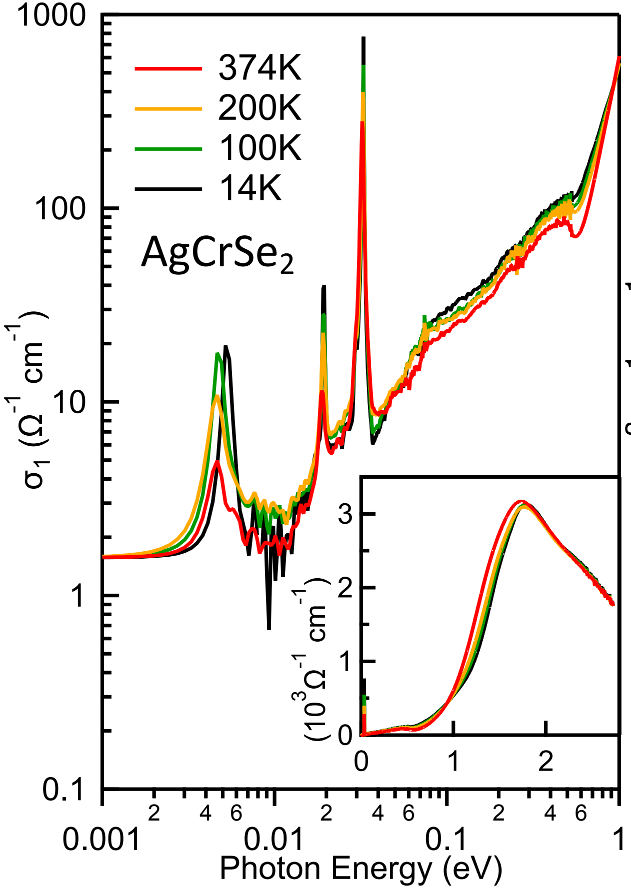
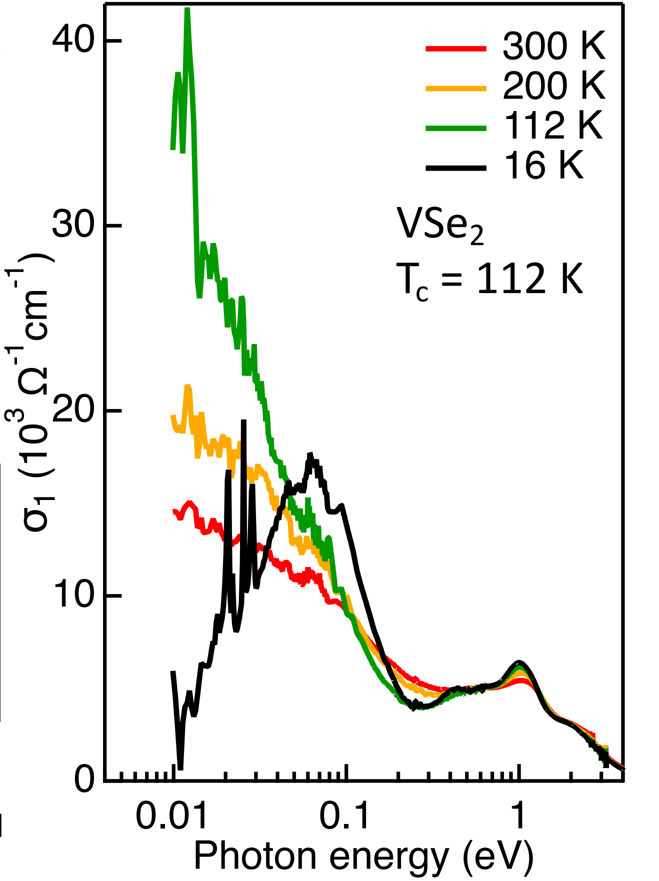


Bad/strange Metal



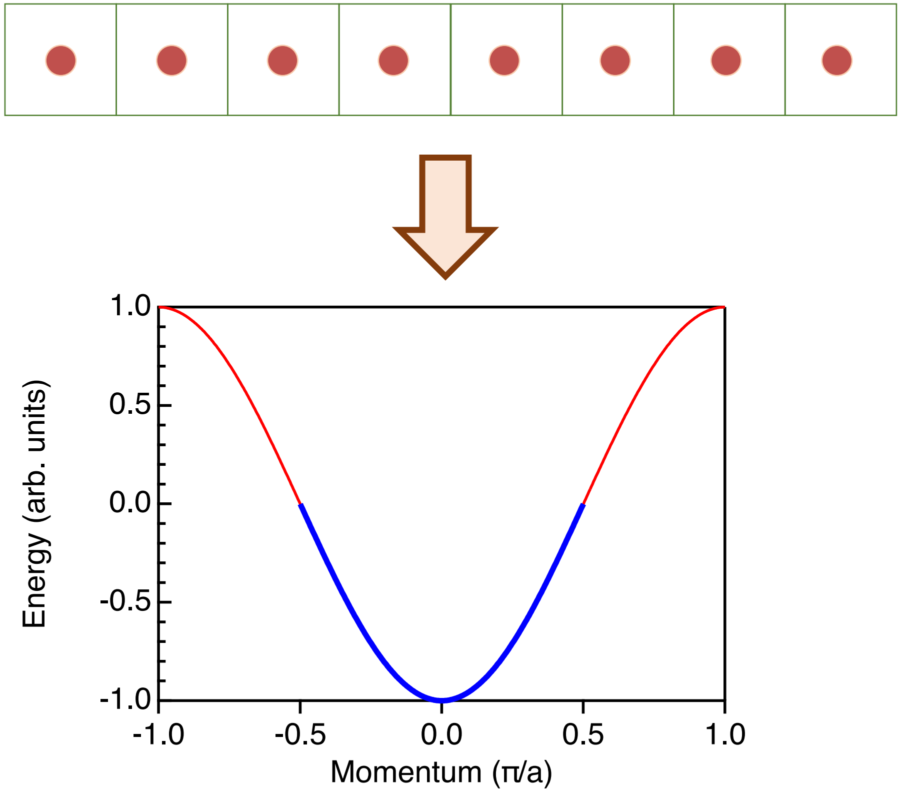
Insulator

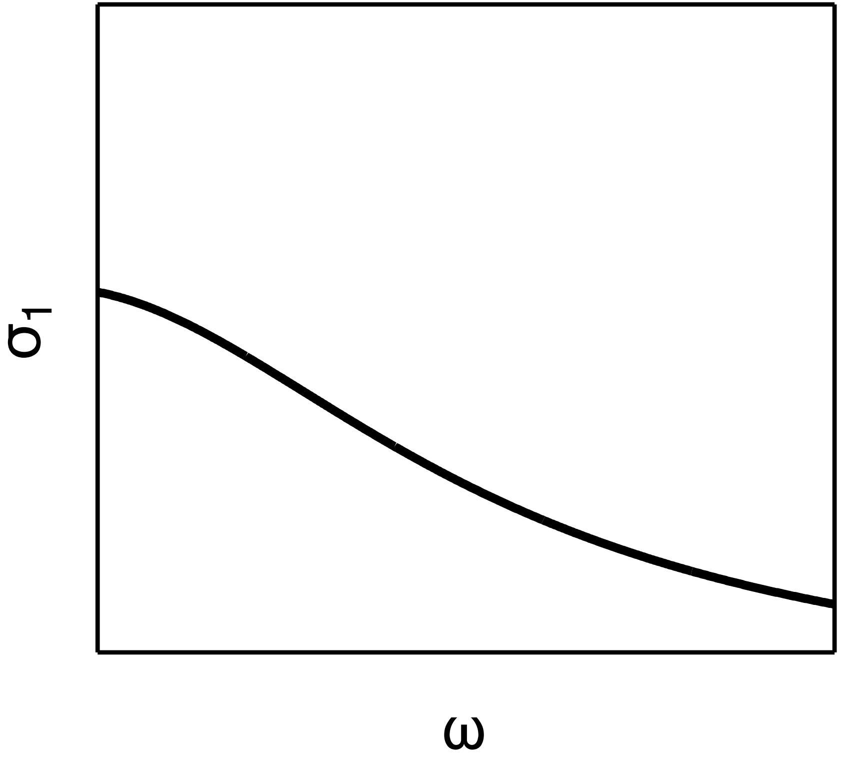


Charge density wave

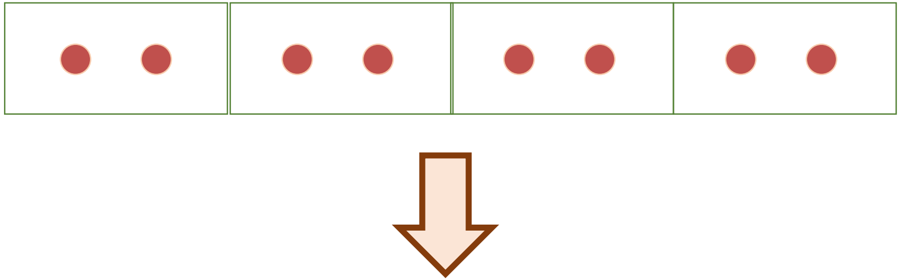
Broken symmetry states

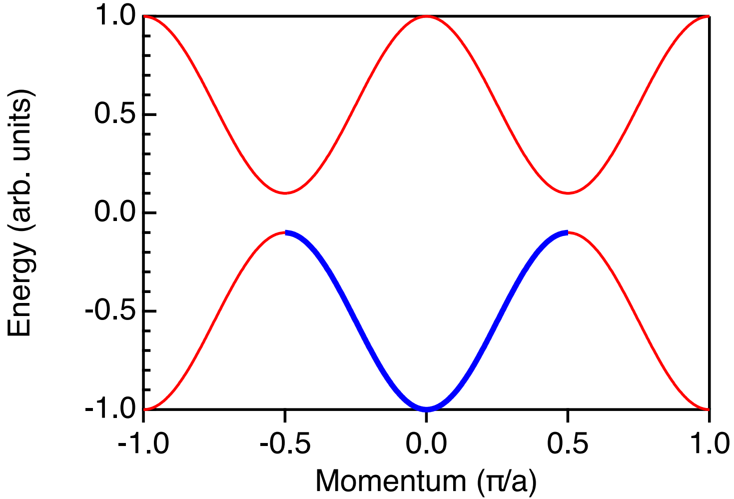
Naive picture of CDW formation

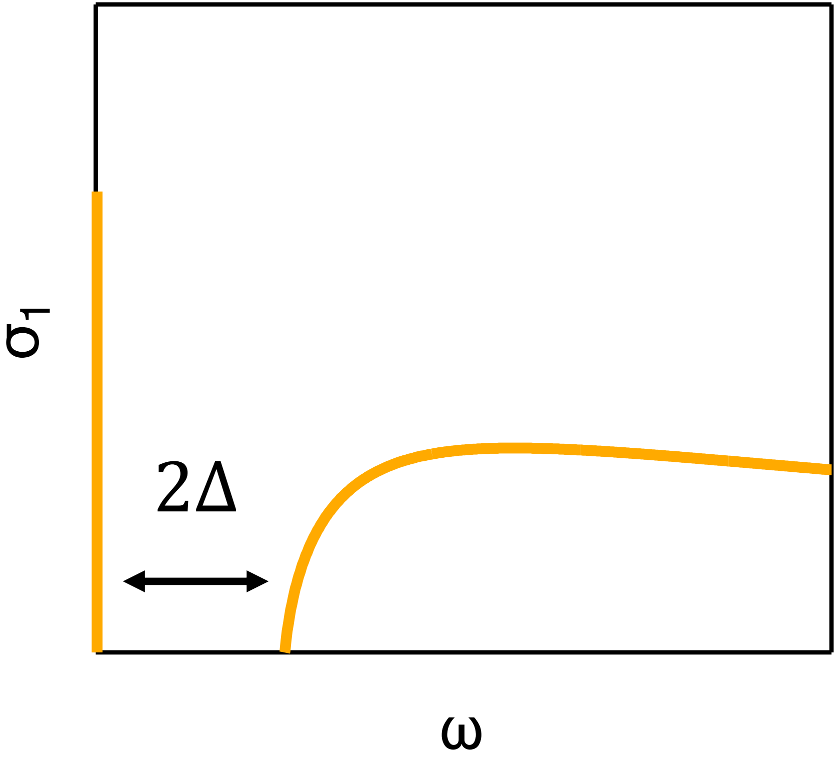




Naive picture of CDW formation

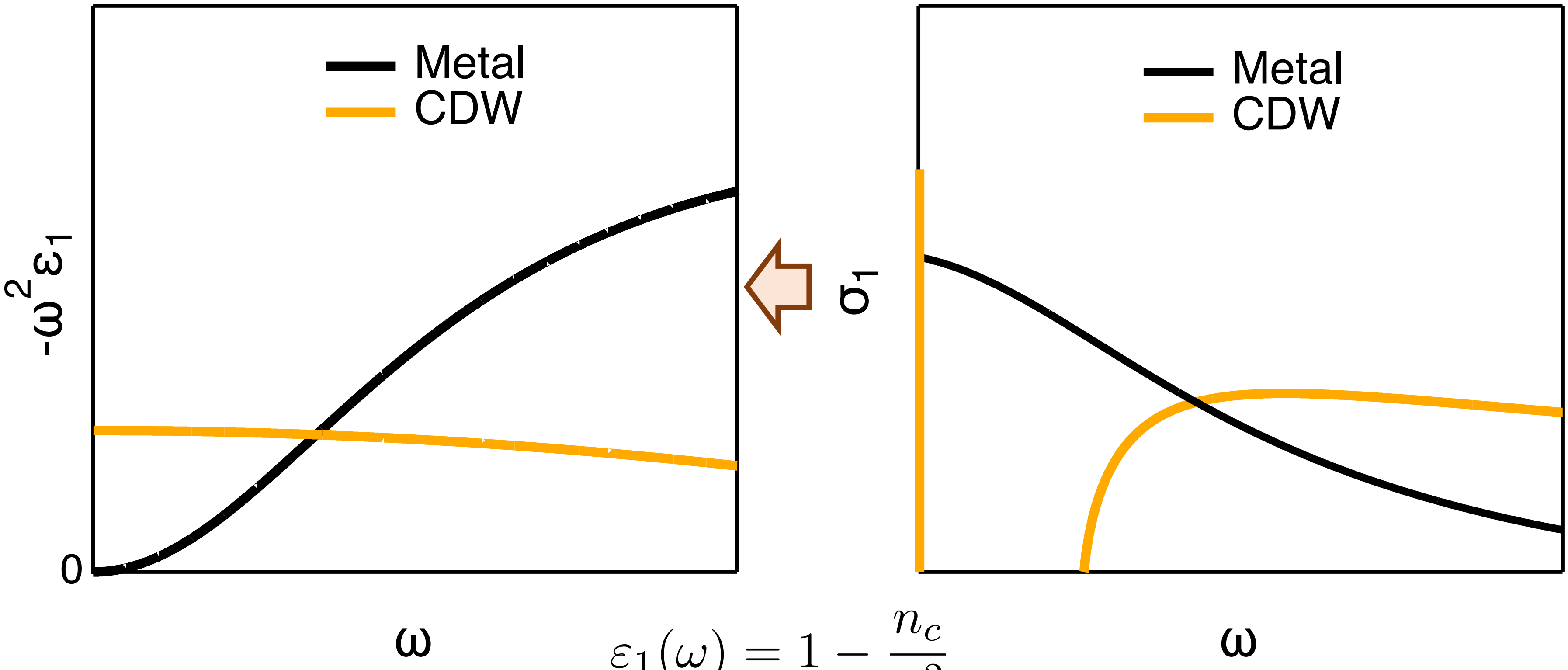






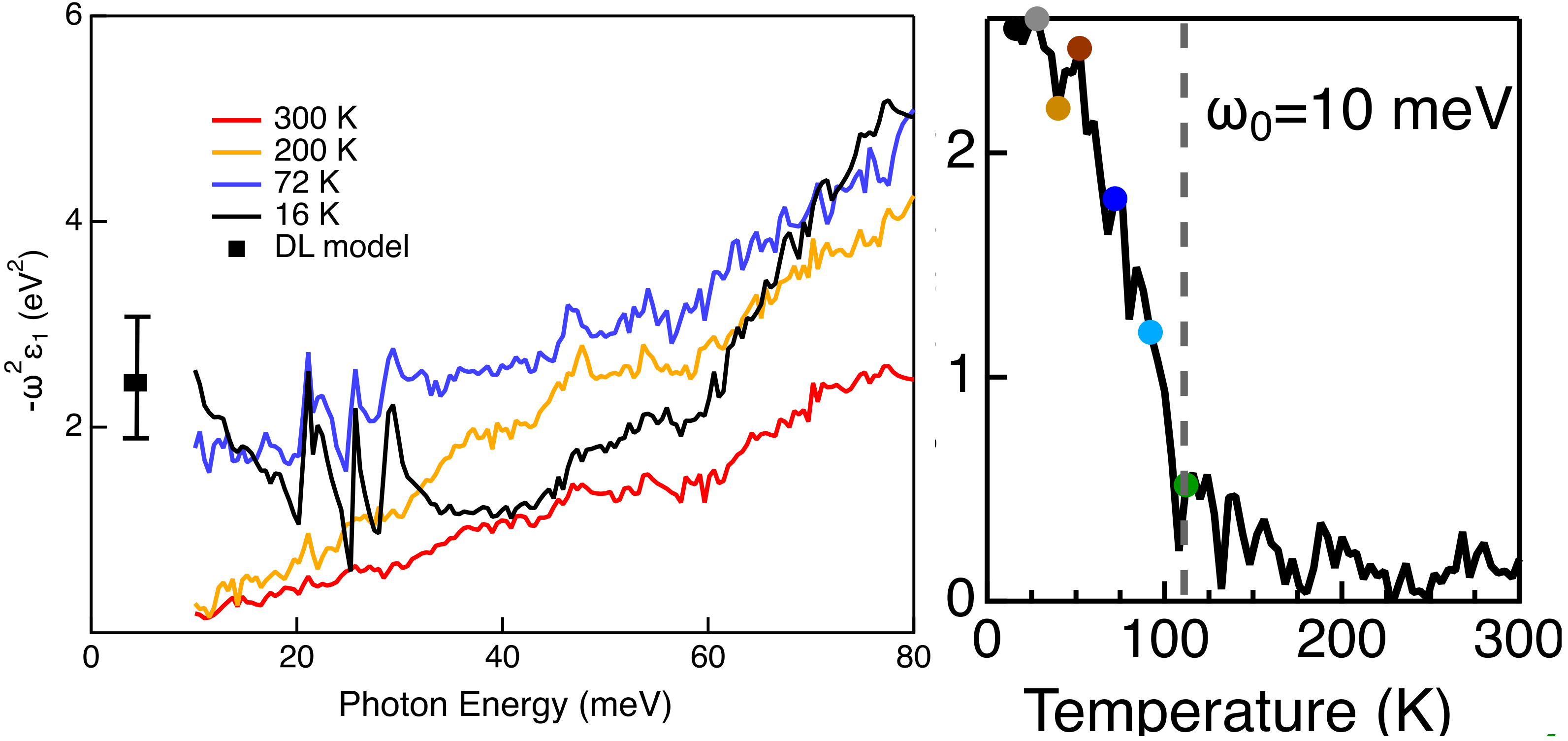
Probing the condensate through causality

Kramers Kronig transformation of δ-function response:



$$\varepsilon_1(\omega) = 1 - \frac{n_c}{\omega^2}$$

The condensate density in VSe_2



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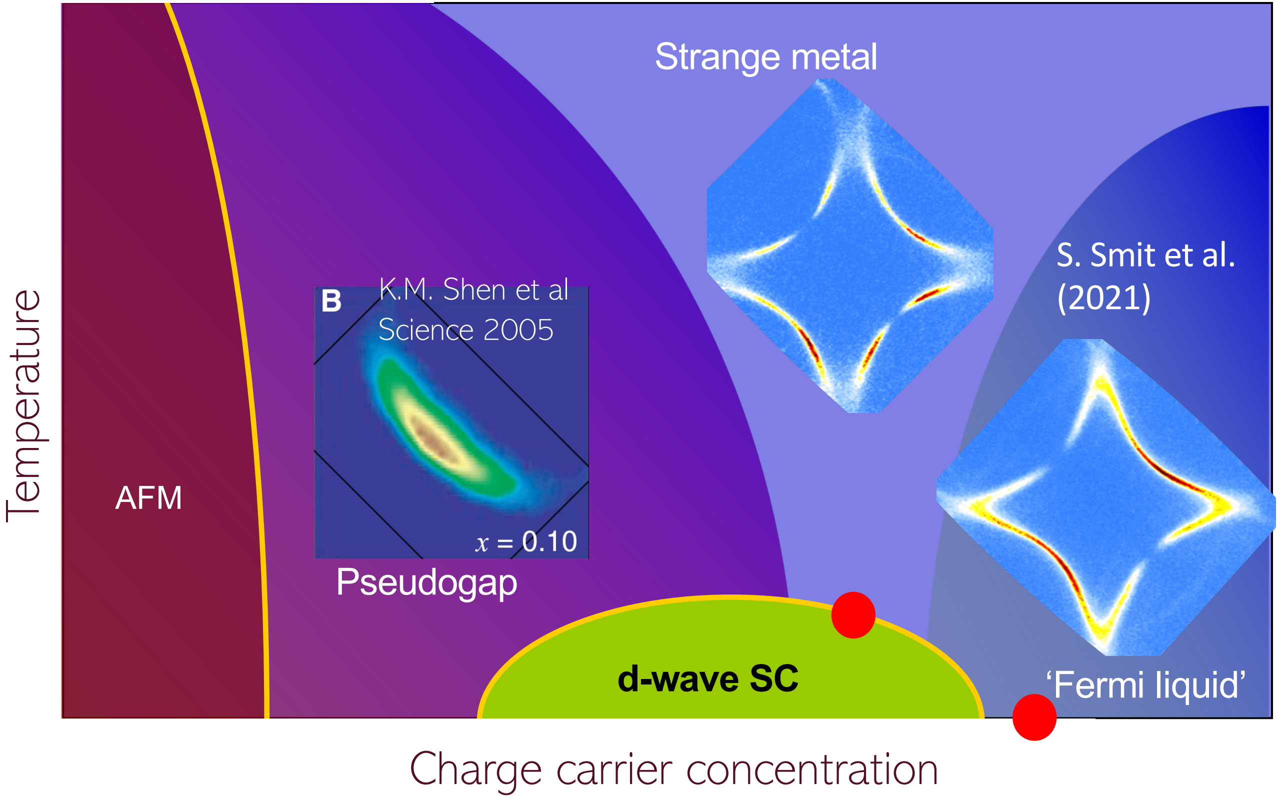
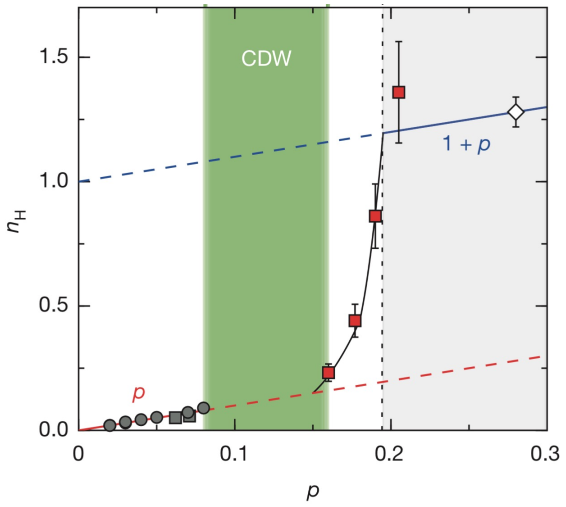


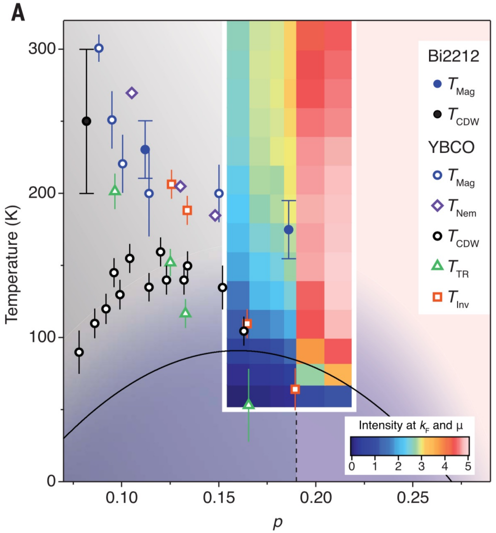
Key question:
What distinguishes the strange metal phase from a Fermi liquid?

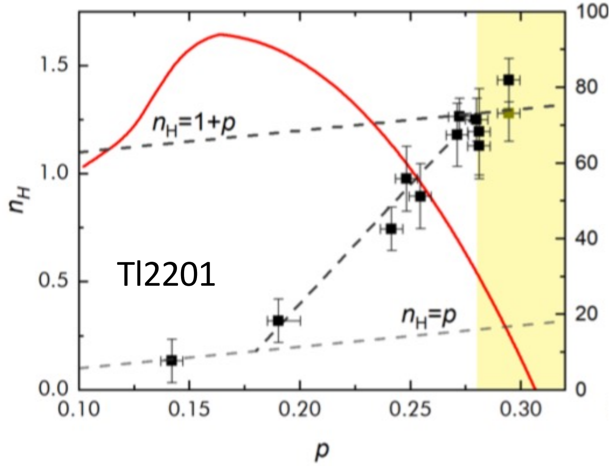
Optical experiments:
Frequency dependence of the conductivity is a valuable source of information on collective response.

First Question

- Is there a hint of a critical doping near 0.2 holes/Cu in optics?







S.-D. Chen et al., Science **366**, 1099 (2019).
Badoux et al. Nature 531, 210 (2016)
(also Legros Nature Phys 15, 142 Michon Nature 567, 218 (2019))

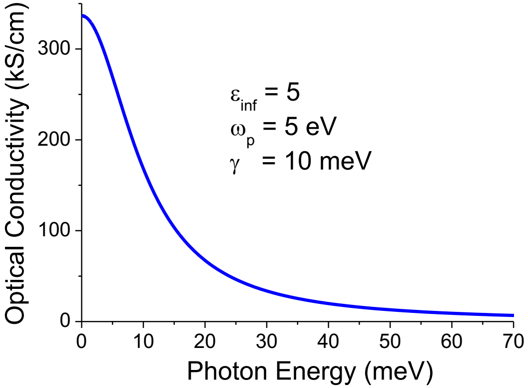
Putzke et al., Nature Phys 17, 826 (2021)
Ayres et al., Nature 595, 661 (2021)

cuprate superconductors: One or two components?

<u>single component</u>

quasi-particles
residual interactions
(energy dependent) lifetime broadening

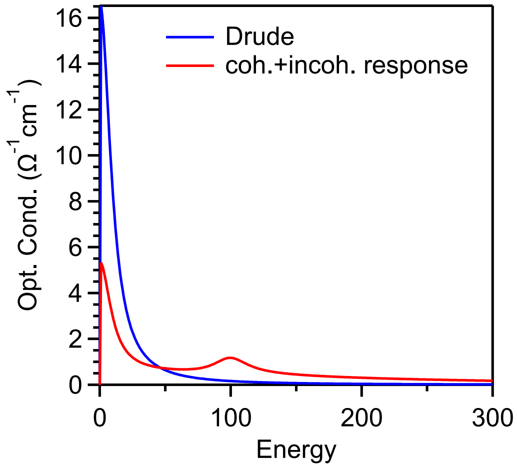
$$\sigma(\omega,T) = \frac{iD}{\omega + \hat{M}(\omega,T)}$$



<u>two (or more) components</u>

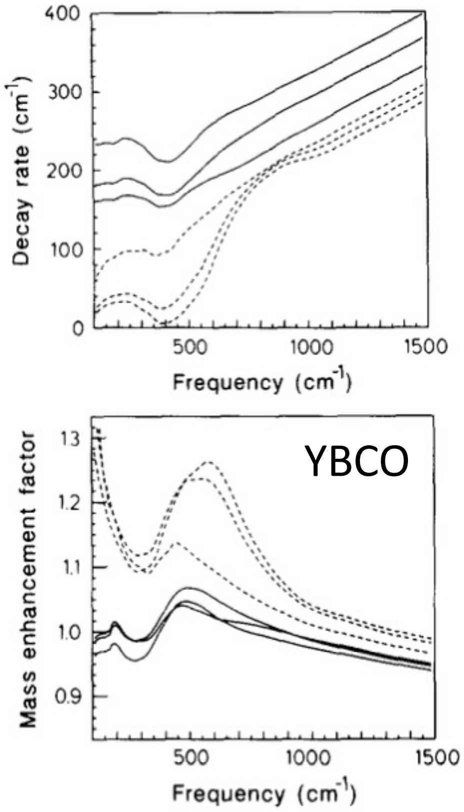
no quasi-particles
(residual) interactions
mid-infrared bands
lifetime broadening

$$\sigma(\omega,T) = \sigma_a(\omega,T) + \sigma_b(\omega,T)$$

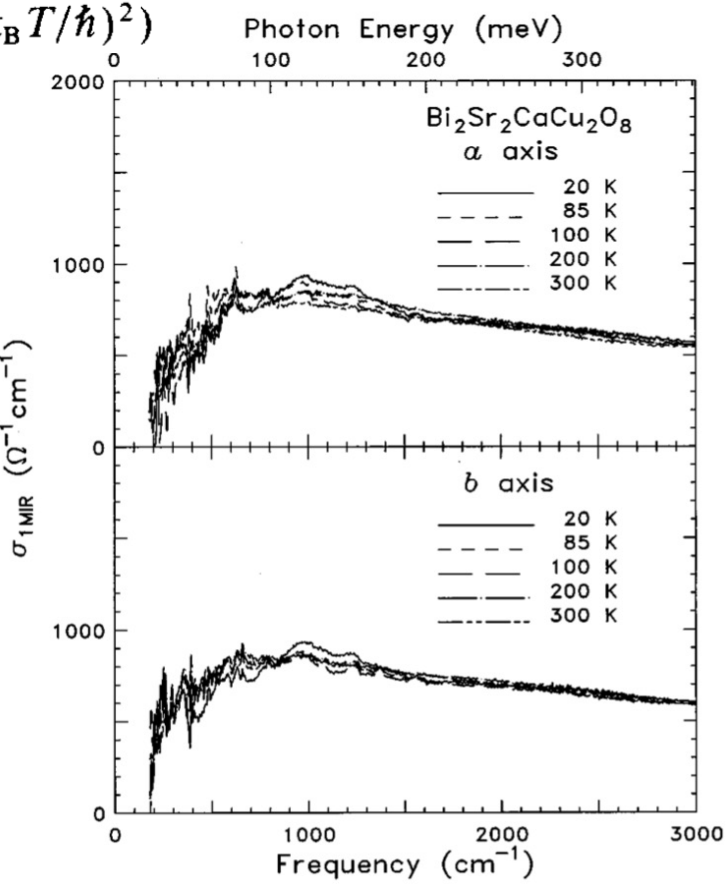


State of the art over the years

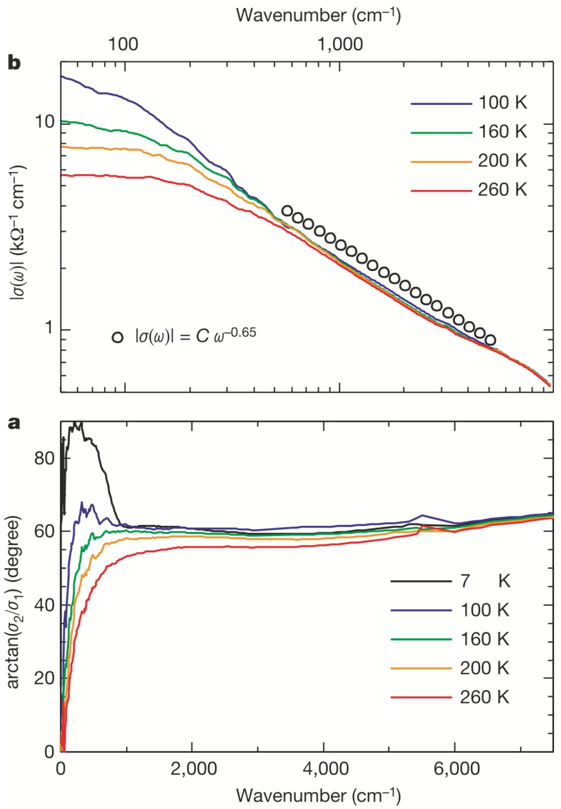
$$\tau^{-1}=0.61\sqrt{(\omega^2+\pi(k_B T/\hbar)^2)}$$



D. van der Marel et al., Physica C, 176 (1991)



S. Uchida, et al., Phys. Rev. B **43**, 7942 (1991)

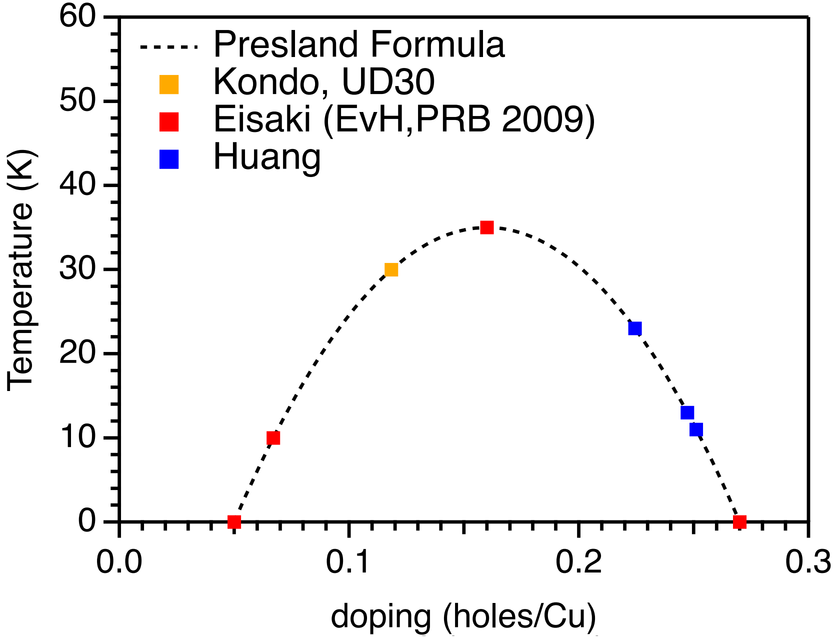


D. van der Marel, *et al. Nature* **425**, 271 (2003)

The ideal choice: $Bi_{2-x}Pb_xSr_{2-y}La_yCuO_{6+\delta}$

The material of choice: **single layer Bi2201**

- One CuO_2 layer per unit cell.
- Low critical temperature ($T_{c,max}$ = 35 K)
- Good cleavage surface



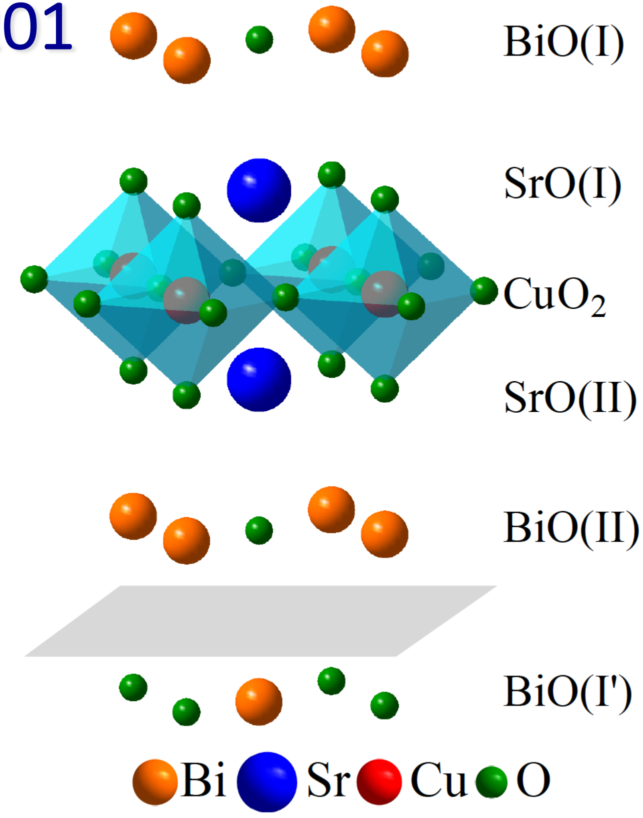
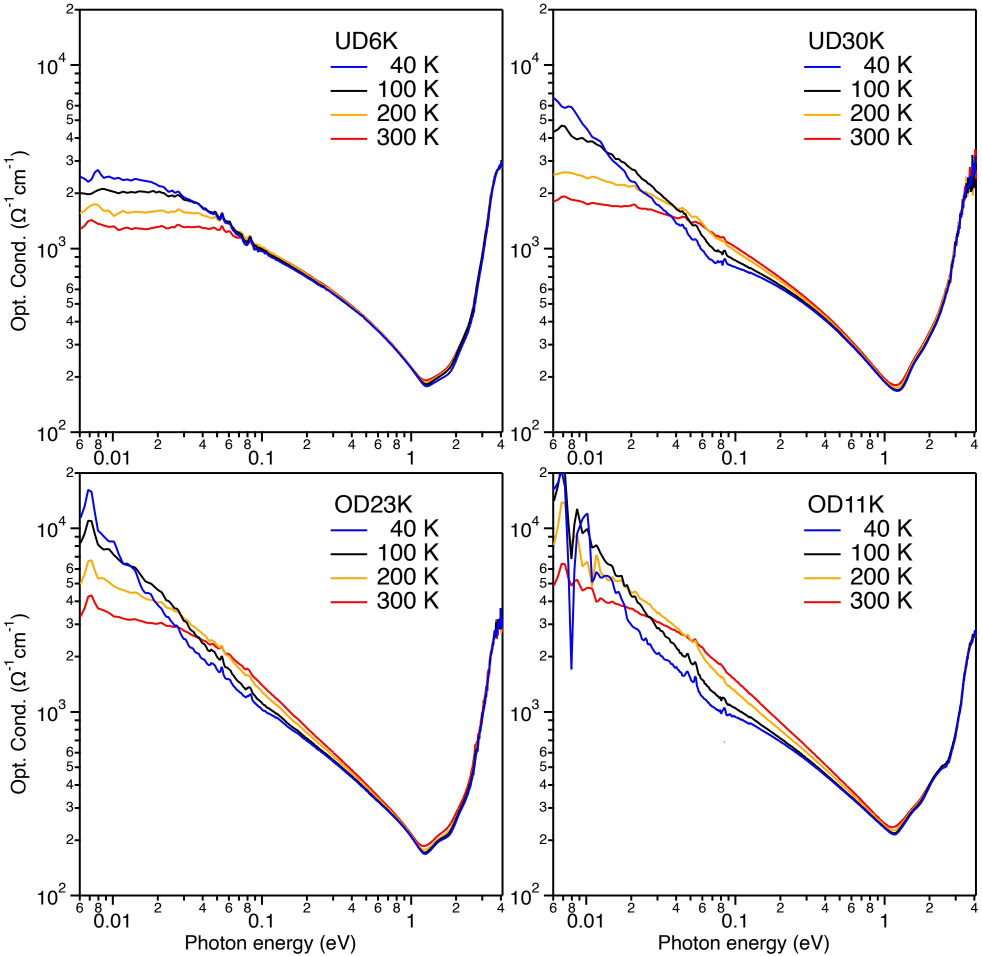


Image courtesy: Y.F. Lv Phys. Rev. B 93, 140504(R) (2016)

The optical response of cuprates



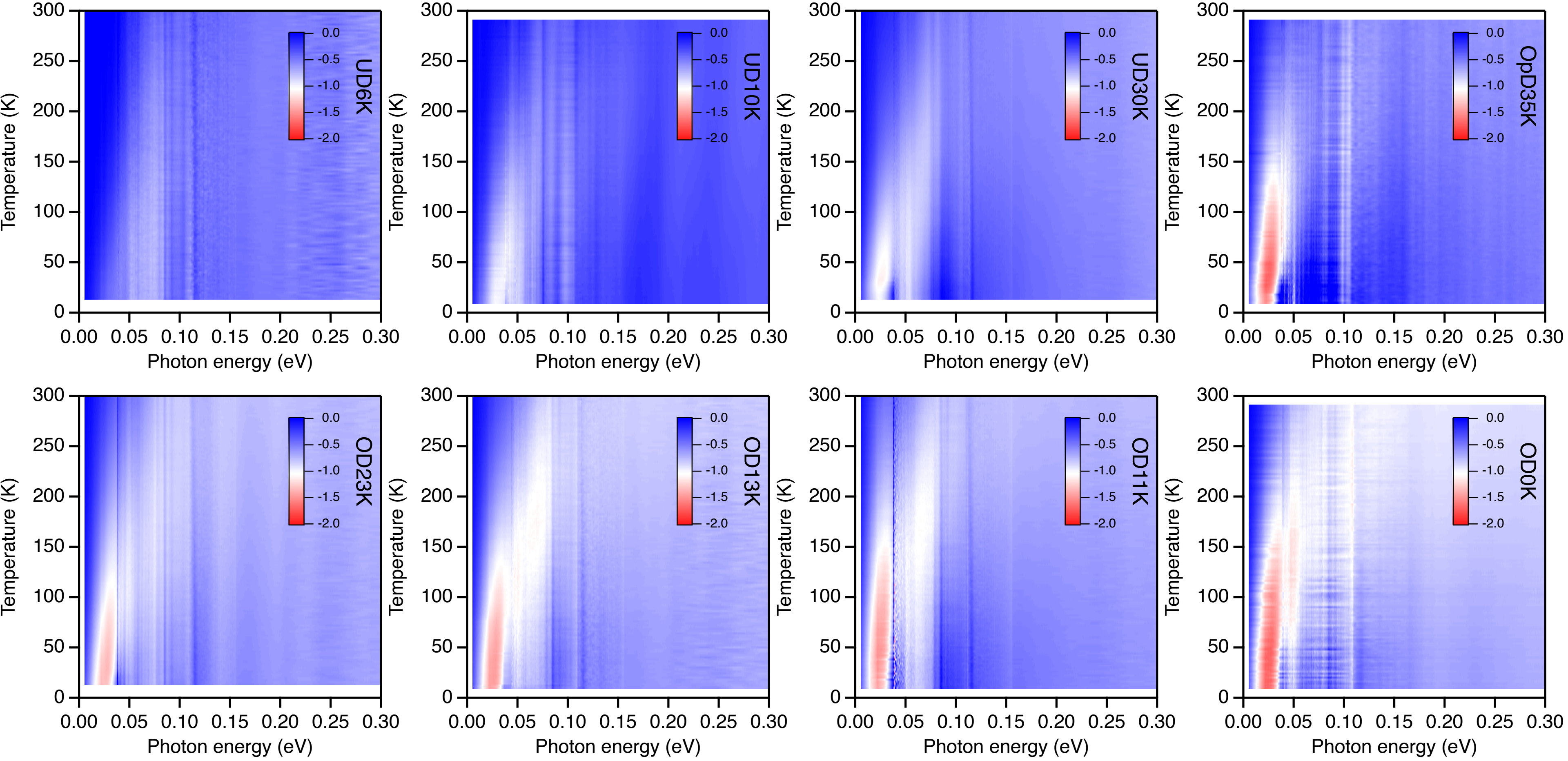
- Extrapolation to ω=0 consistent with ρ_{DC}.
- Two components in the 'intraband' optical response.
- Crossover regime around 0.1 eV

$$\sigma_1(\omega) = \frac{\omega_p^2}{4\pi}\frac{\Gamma}{\Gamma^2+\omega^2}$$

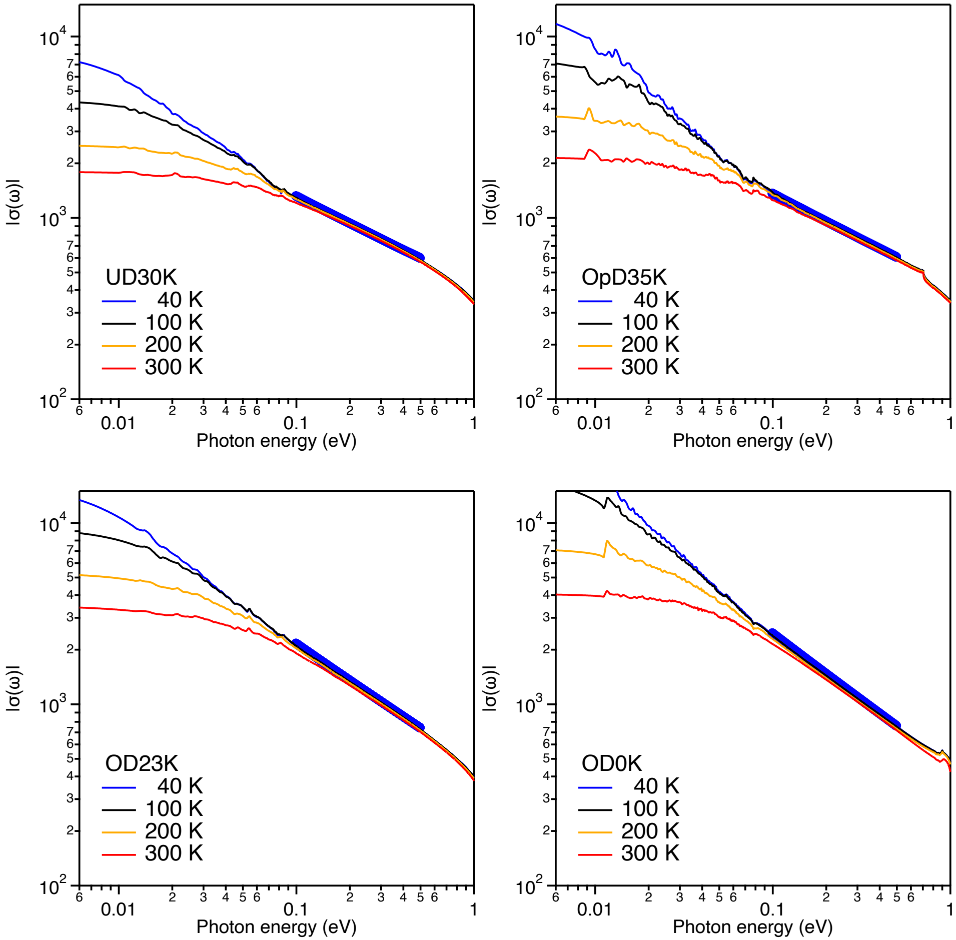
van Heumen et al. Phys. Rev. B 106, 054515 (2022)

Component 1: a Drude response

$$\frac{\partial \log[\sigma_1(\omega)]}{\partial \log[\omega]}$$



Component 2: a high energy powerlaw



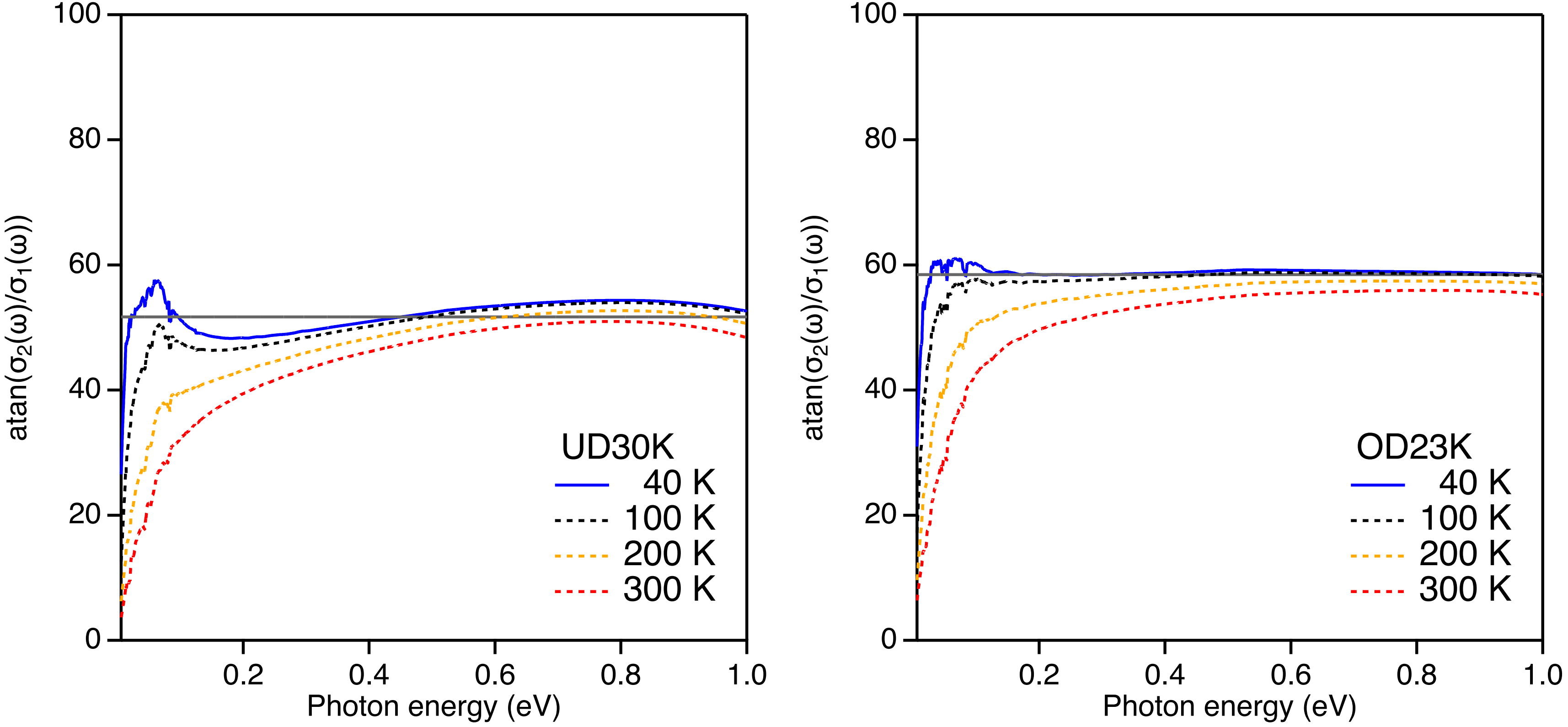
- At high energy |σ| follows a powerlaw behaviour.

$$\sigma(\omega) \sim 1/(i\omega)^{\alpha}$$

- Should be accompanied by a constant phase angle.

Marel, D. van der *et al. Nature* **425**, 271 (2003)

Component 2: doping dependence of the phase angle



A two-component model

- To get ahead we assume:

$$\hat{\sigma}(\omega) = \hat{\sigma}^{D}(\omega) + \hat{\sigma}^{inc.}(\omega)$$

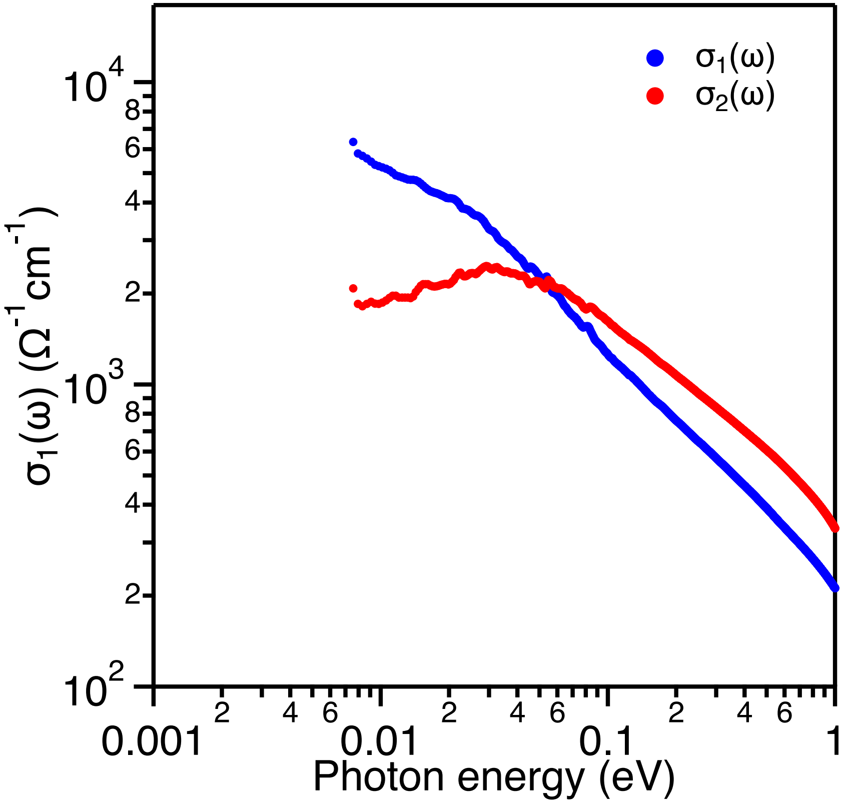
The Drude is easy:

$$\hat{\sigma}^{D}(\omega) = \frac{D_{Dr}}{4\pi}\frac{1}{\Gamma_{Dr} + i\omega}$$

However,

$$\sigma(\omega) \sim 1/(i\omega)^{\alpha}$$

both σ_1 and σ_2 diverge



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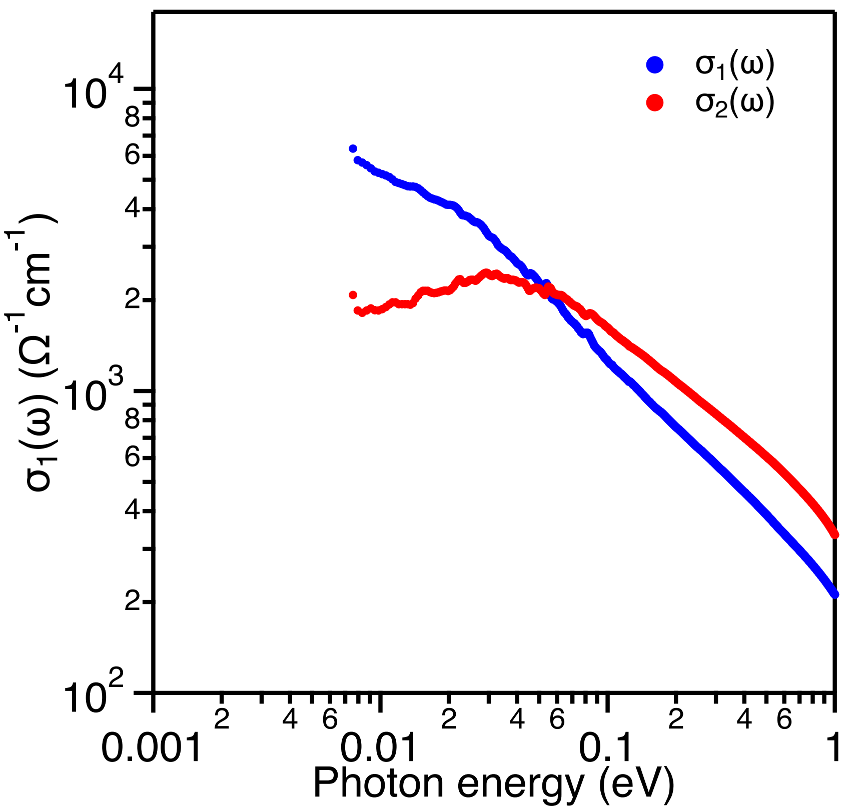
The incoherent part:

$$\hat{\sigma}^{inc.}(\omega) = \frac{-iD_{inc}\omega}{\sqrt{\Delta^2 - \omega^2 - i\Gamma_{inc}\omega}^{\beta}}$$



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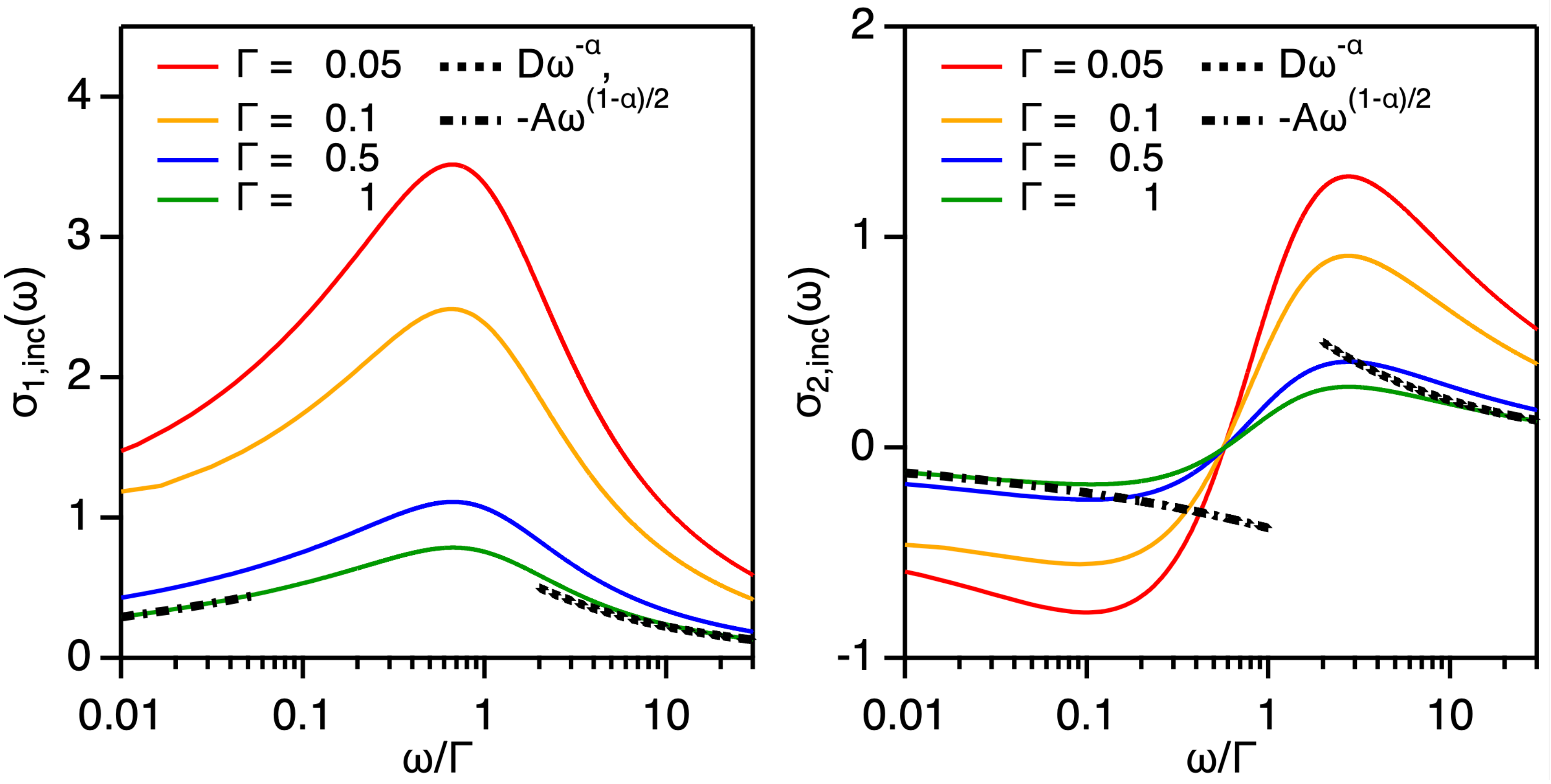
Generalized interband transitions



van Heumen et al. Phys. Rev. B 106, 054515 (2022)

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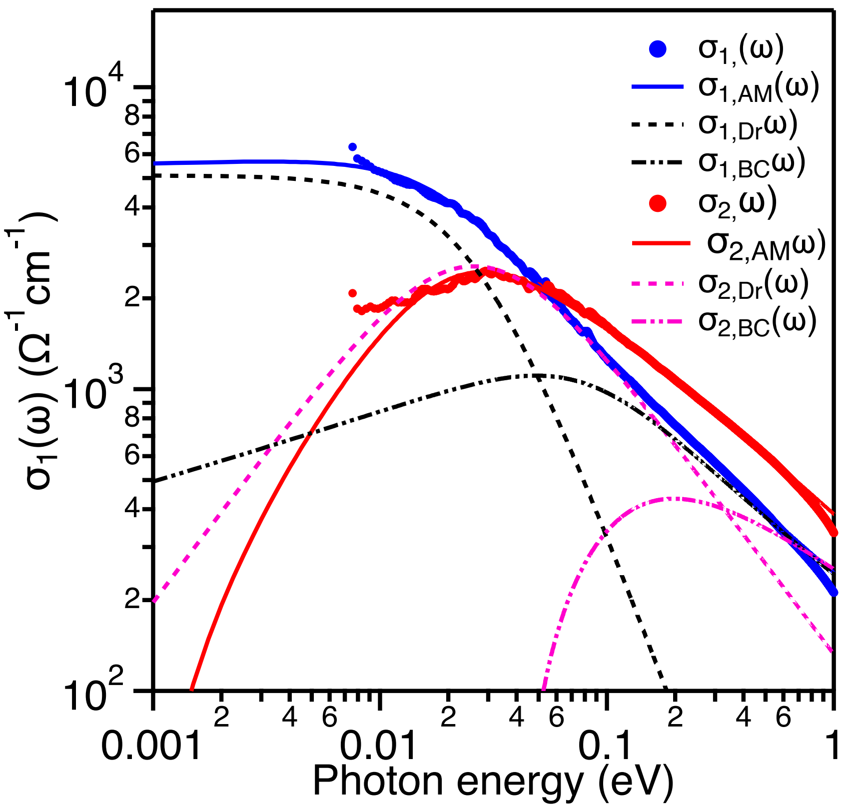

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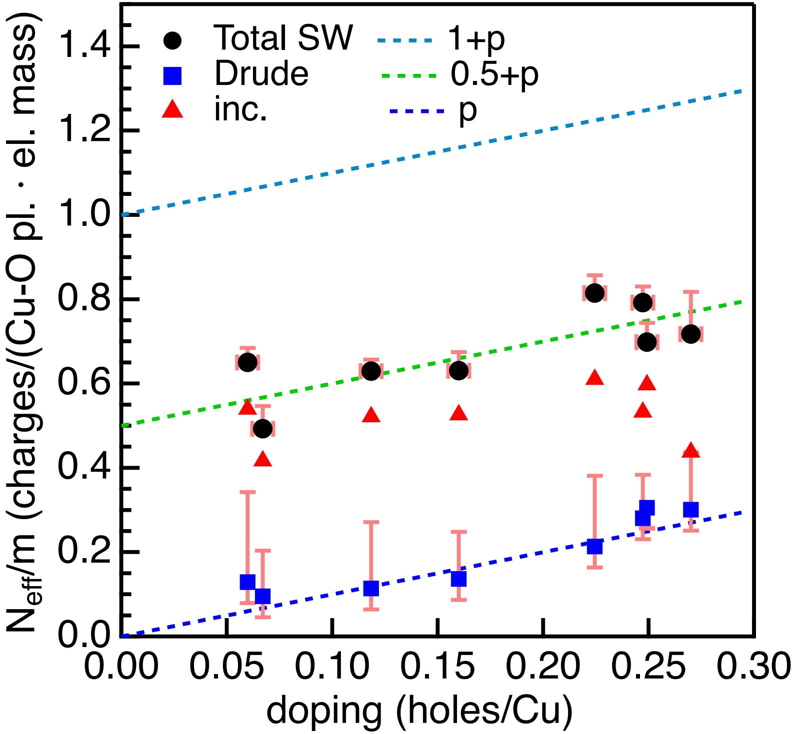
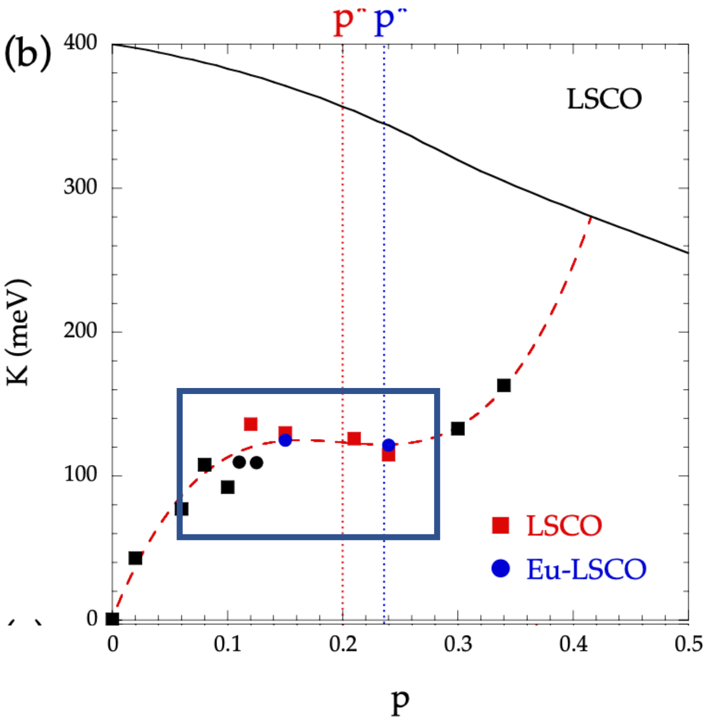
Doping dependence of carrier density



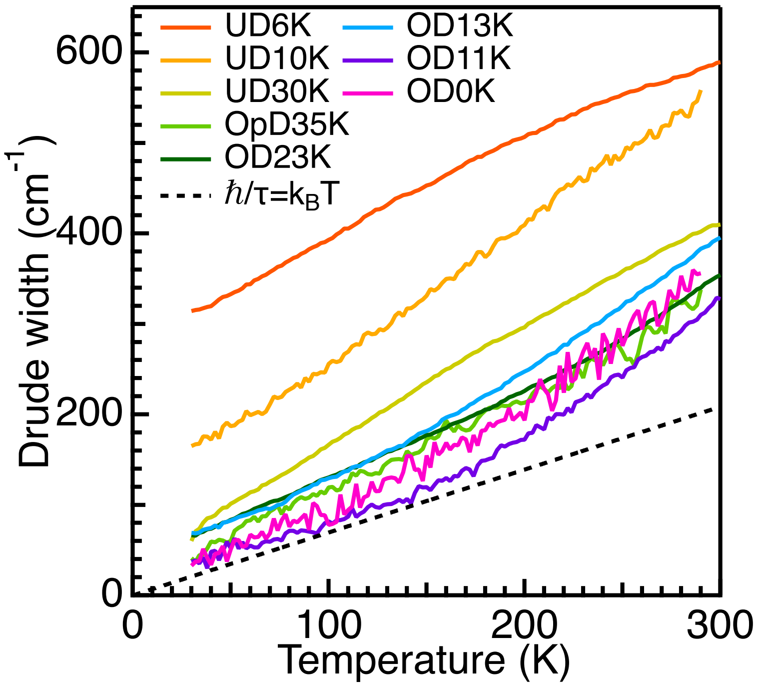


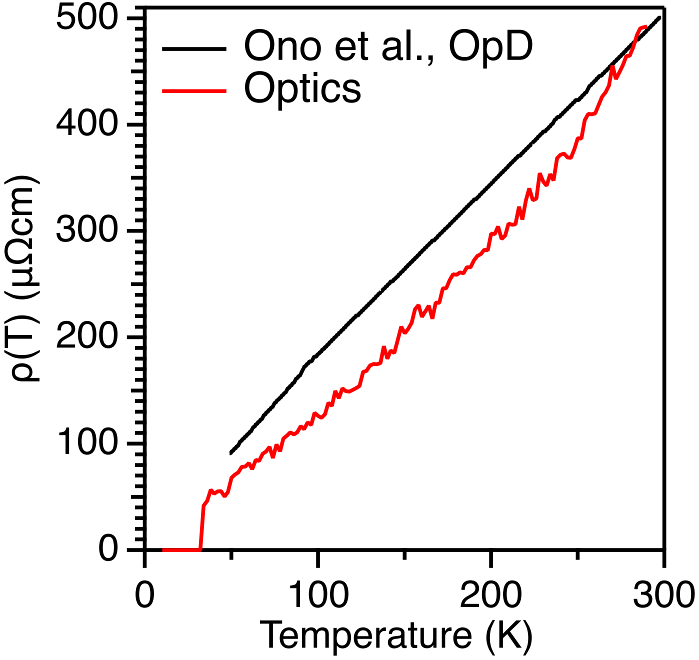
Michon et al. Phys. Rev. Research 3, 043125 (2021)

The current relaxation rate

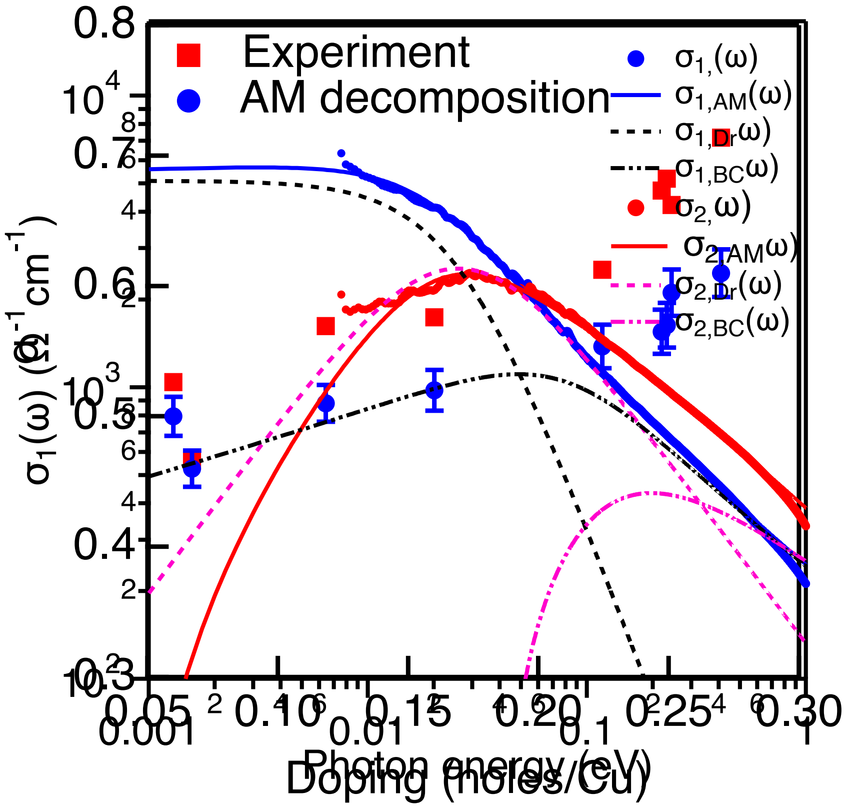
- Within our error bars, Γ is frequency independent.

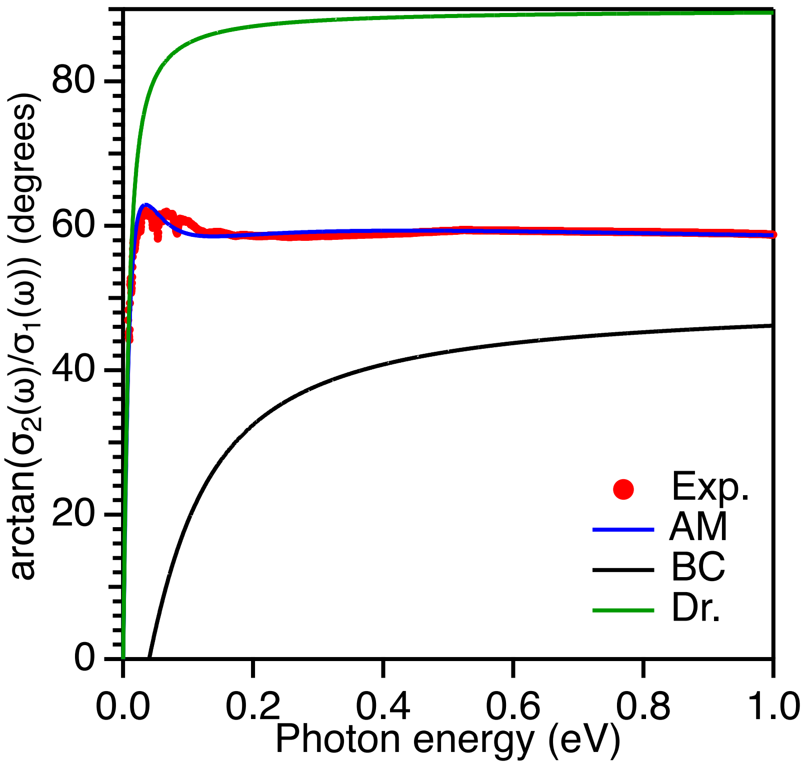
$$\hat{\sigma}^D(\omega) = \frac{D_{Dr}}{4\pi}\frac{1}{\Gamma_{Dr}+i\omega}$$





The MIR component: a ‘strange’ continuum





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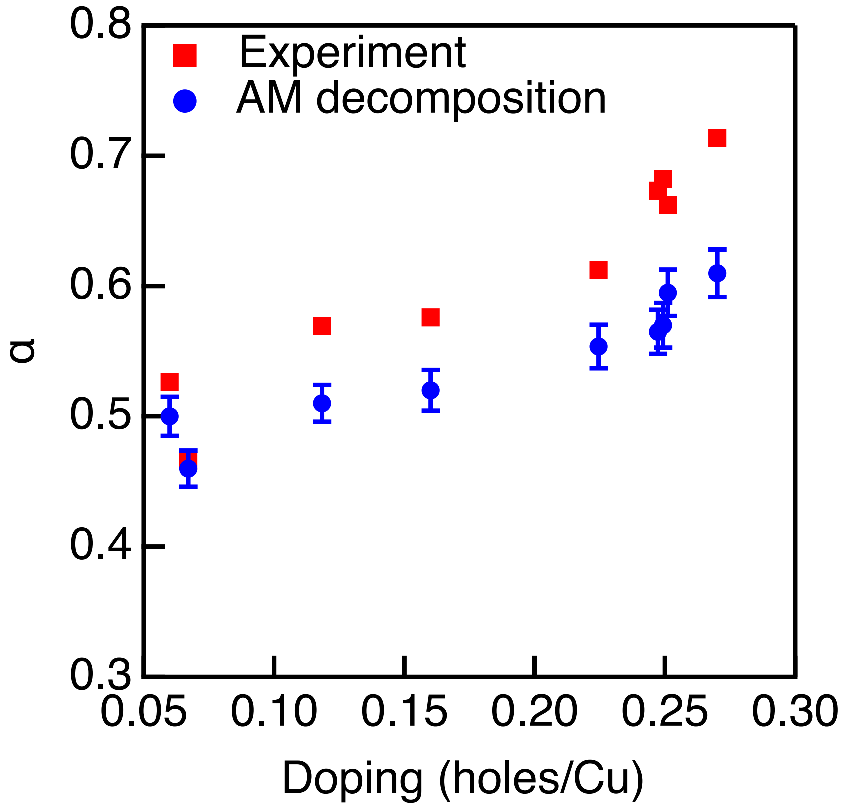

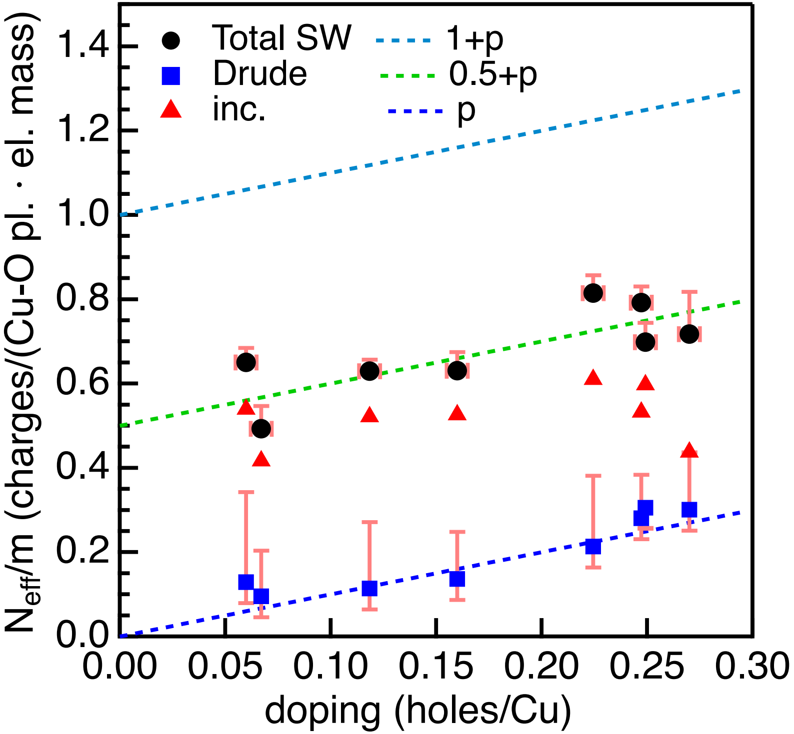

van Heumen et al. Phys. Rev. B 106, 054515 (2022)

Summary

- Optical response has a Drude and mid-infrared response.
  - Low energy Drude response:
    - Spectral weight is doping but not temperature dependent.
    - Scattering rate is doping and temperature dependent.
    - No divergencies/anomalies in either.
  - The mid-infrared response
    - Spectral weight is not doping/temperature dependent.
    - Broadening is doping dependent.
- incoherent response persists to strongly overdoped regime!
- Optics and normal state transport agree. The puzzle is low T/high B!