Charge transport in gapless, pinned charge density waves

Blaise Goutéraux

CNRS, Ecole Polytechnique, Institut Polytechnique de Paris, France

Tuesday May 24th, 2022

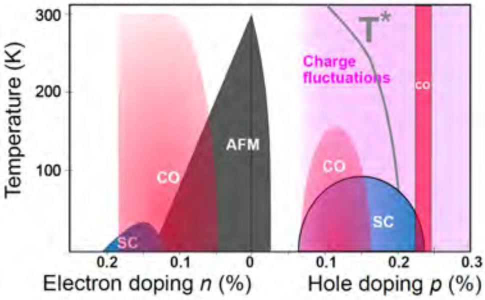
Strange Metals, SYK Models, and Beyond
Collège de France, Paris

References and acknowledgments:

- *'Effective and holographic theories of strongly-correlated phases of matter with broken translations'* [arXiv: 2203.03298] with M. Baggioli.
- *'Damping of pseudo-Goldstone fields'* [Phys. Rev. Lett. 128, 141601 (2022)], with L. Delacrétaz and V. Ziogas.
- *'Universal relaxation in a holographic metallic density wave phase'* [Phys. Rev. Lett. 123, 211602 (2019)], with A. Amoretti, D. Areán, D. Musso.
- *'Bad Metals from Density Waves'* [SciPost Phys. 3, 025 (2017)] and *'Theory of hydrodynamic transport in fluctuating electronic charge density wave states'* [Phys. Rev. B 96, 195128 (2017)], and *'Theory of the collective magnetophonon resonance and melting of the field-induced Wigner solid'*, [PRB'19] with L. Delacrétaz, S. Hartnoll and A. Karlsson.
- My research is supported by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 758759). All references in [magenta] have hyperlinks.

Spontaneous breaking of translations across the phase diagram of cuprates and other strange metals: various shades of incommensurate charge density waves.

- Expected on theoretical grounds since early days [Zaanen & Gunnarson, PRB'89], [Machida, Phys. C: Superconductivity'89], arguments for electronic liquid crystal phases in doped Mott insulators [Kivelson et al, Nature'98]. Doped holographic Mott insulators [Andrade et al, Nat. Phys.'18].



Credit: [Frano et al, arXiv: 2102.09525]

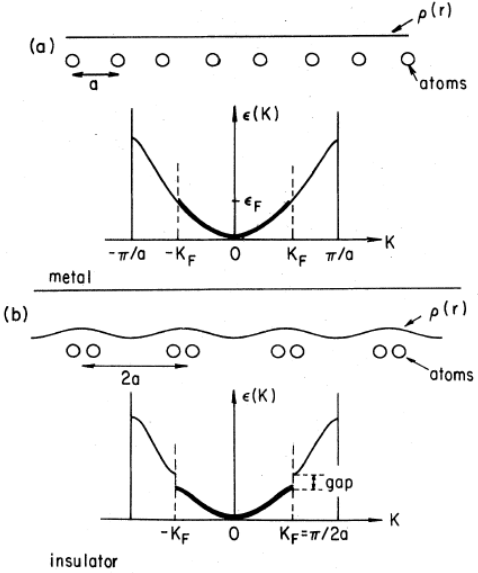
- Well-established in underdoped cuprates [Tranquada et al, Nature'95].
- More recent discovery on the **overdoped** side [Arpaia et al, Science'19], see [Arpaia and Ghiringhelli, J. Phys. Soc. Jpn.'21] for a review.
- Magnetism all the way to the pseudogap critical point, [Frachet et al., Nat. Phys. '20]

Weakly-coupled, quasi-particle based mechanism in quasi one-dimensional materials: **Peierls instability**, [Grüner, RMP'88].

Gap opens, modulated density of states energetically favored

$$\rho(x) = \rho_0 + \delta\rho \cos(k_{cdw} x + \varphi^x)$$

φ^x: Goldstone mode ('phason') of **spontaneously broken translations**.



Credit [Grüner, RMP'88]

Low frequencies, weak disorder: pseudo-Goldstone mode

$$f = \cdots + \frac{\kappa}{2}(\partial_x \varphi^x)^2 + \frac{\kappa}{2} m_\varphi^2 (\varphi^x)^2$$

- Relaxed dynamics for φ^x:

$$\partial_t^2 \varphi^x + \Gamma \partial_t \varphi^x + \omega_o^2 \varphi^x = 0$$

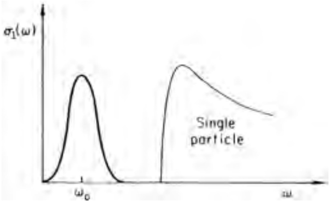
Weak disorder: $\Gamma, \omega_o \ll \Delta$ the single particle gap $\Rightarrow$ **pseudo-Goldstone remains light**.

- CDW is **pinned** [Grüner, RMP'88]

$$\sigma(\omega) = \left(\frac{ne^2}{m^\star}\right) \frac{-i\omega}{-i\omega(\Gamma - i\omega) + \omega_o^2}$$

Γ : momentum relaxation rate.

$\omega_o^2 \equiv \kappa\, m_\varphi^2 / (m^\star n)$: pinning frequency.



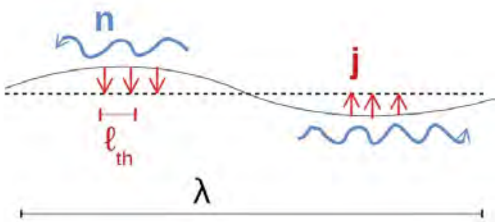
Credit: adapted from [Grüner, RMP'88]

Transfer of spectral weight. Pinning short-circuits the DC conductivity: **insulator**. Gap = no available relaxational channel for the Goldstone.

- The Peierls mechanism requires (quasi) one-dimensional Fermi surfaces with weakly-coupled quasiparticles, and typically does apply in many strongly-correlated materials.

- Instead, Mott physics, anti-ferromagnetic fluctuations, etc. Also imperfect nesting, the gap gradually opens as $T < T_{CDW} \Rightarrow$ No hard gap: **gapless low-energy excitations** on top of the Goldstone mode.

- Rather than focusing on a specific material or mechanism, I want to investigate on general grounds **charge transport in pinned, gapless, strongly-correlated charge density wave states**, using effective field theory methods.



- Strong correlations imply **short equilibration scales** $\tau_{eq} \sim 1/T$, which justify the use of effective field theory methods for the low-energy dynamics.

- EFTs rely on the **symmetries** of the system $\Rightarrow$ **conservation equations**

$$\partial_t n + \partial_i j^i = 0$$

- and on an **expansion in gradients** $\tau_{eq}\partial_t \ll 1$, $\ell_{th}\partial_x \ll 1 \Rightarrow$ **constitutive relations** for vevs of currents in the thermal equilibrium state.

- The main result is that compared to [Grüner, RMP'88] an **extra transport coefficient** is needed, which governs the **(inverse) lifetime of the pseudo-Goldstone**.

- It is fixed by its mass and a diffusivity that characterizes sound attenuation in the clean system (no disorder)

$$\boxed{\Omega = m_\varphi^2 D_\varphi}$$

- It is a direct consequence of the existence of a bath of thermal excitations, into which the Goldstone can relax. It gives a **nonzero contribution to the dc conductivity**.

- EFTs are built starting from **symmetries**: tricky to write them when symmetries are **approximate**. In fact we missed this coefficient when we wrote an EFT for pinned CDWs, [Delacrétaz et al, PRB'17].

- The need for this relaxed transport coefficient Ω was made obvious when we tried to check the EFT using **holographic methods** [Amoretti et al, PRL'19] (see also [Donos et al, JHEP'19], [Donos et al, Class.Quant.Grav.'20], [Andrade et al, JHEP'21]).

- We then went back to the EFT and showed it follows from **consistency of coupling the static partition function to external sources**, [Delacrétaz et al, PRL'22] (also shown to follow from **positivity of entropy production**, [Armas et al, arXiv: 2112.14373]). Not an artifact of large N or of specific holographic setups!

- The AC conductivity has a more complicated ω dependence:

$$\sigma(\omega) = \left(\frac{ne^2}{m^\star}\right) \frac{\Omega - i\omega}{(\Omega - i\omega)(\Gamma - i\omega) + \omega_o^2}$$

  Drude peak if ω_o sufficiently small compared to Ω.

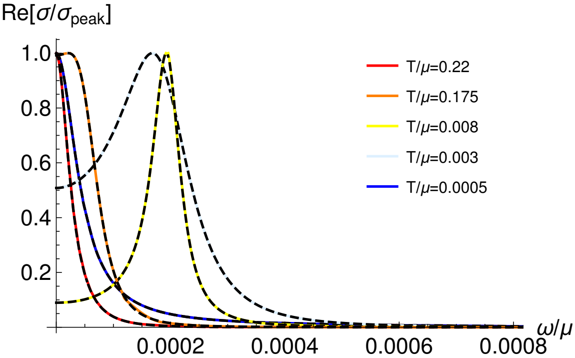
- **Nonzero dc resistivity**:

$$\rho_{dc} = \frac{m^\star}{ne^2}\left(\Gamma + \frac{\omega_o^2}{\Omega}\right) = \frac{m^\star}{ne^2}\left(\Gamma + \frac{v^2}{D_\varphi}\right), \quad v^2 = \frac{\kappa}{m^\star n}$$

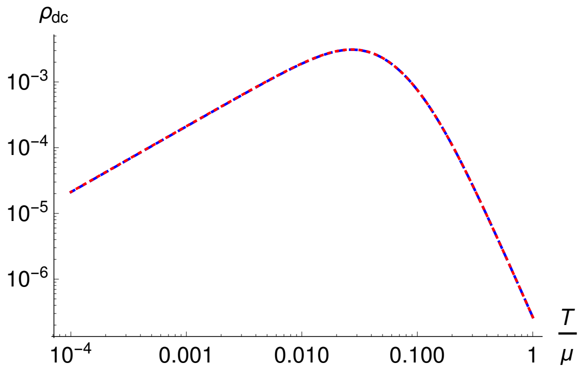
  The second term is **independent on the strength of disorder/explicit translation symmetry breaking** to leading order.

- Reminiscent of an **Einstein relation**, as here the thermal diffusivity:

$$D_T \sim D_\varphi$$



The holographic result for the AC conductivity in a phase that breaks translations pseudo-spontaneously matches the EFT prediction extremely well, [Amoretti et al, PRL'19].

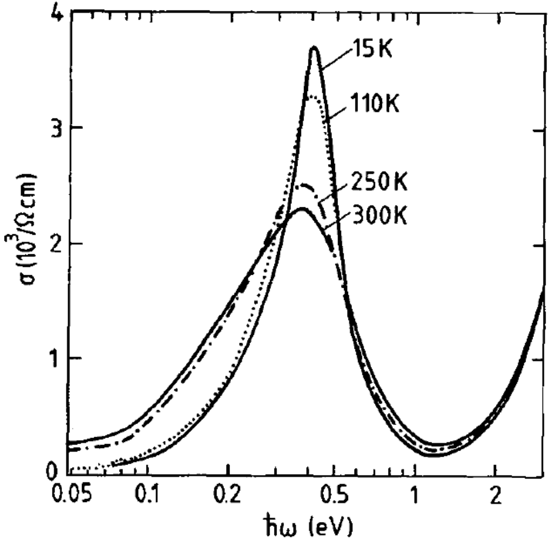


The resistivity dominated by the pseudo-Goldstone contribution

$$\rho_{dc} \simeq \frac{m^\star}{ne^2}\frac{\omega_o^2}{\Omega}$$

D_φ controlled by horizon quantities, [Amoretti et al, JHEP'19]: **the Goldstone couples to the black hole horizon**, which provides the bath of thermal excitations into which it relaxes. 'holographic black hole membrane paradigm' [Iqbal & Liu, Phys.Rev.D'09], [Donos & Gauntlett, JHEP'14].

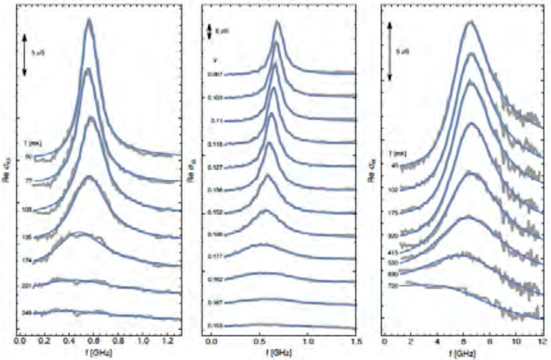
In $(TaSe_4)_2I$, the gap gradually develops as T decreases ($T_c = 263K$)



[Berner et al, J. de Phys.'93]

In 2DEG (GaAs heterojunctions), a Wigner solid phase develops at large magnetic fields. The previous formula generalizes, [DELACRÉTAZ ET AL, PRB'19]

$$\sigma_{xx}(\omega) = \sigma_0 + b\,\omega_{\rm pk}\frac{(1-a^2)(-i\omega+\Omega) - 2a\omega_{\rm pk}}{(-i\omega+\Omega)^2+\omega_{\rm pk}^2}$$

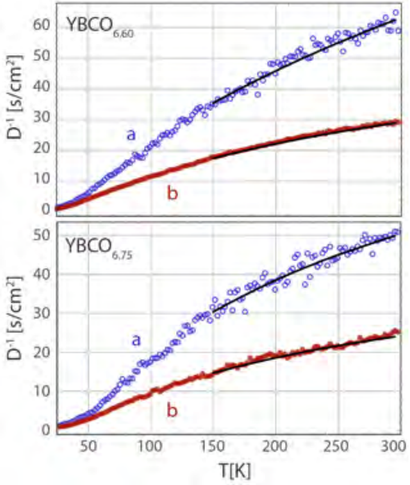


Data: [CHEN ET AL, NAT PHYS'06], [CHEN, PHD THESIS'05], [CHEN ET AL, INT JOUR OF MOD PHYS'07]

- In strongly-correlated materials, generally expect **diffusivities to saturate a lower bound** [Kovtun, Son & Starinets, PRL'05], [Hartnoll, Nat. Phys.'14]

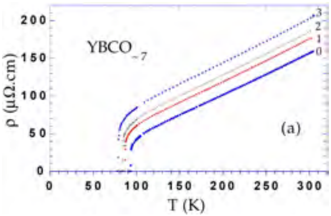
$$D \gtrsim \frac{\hbar v^2}{k_B T}$$

Eg thermal diffusivity in the strange metal regime [Zhang et al, PNAS'17].

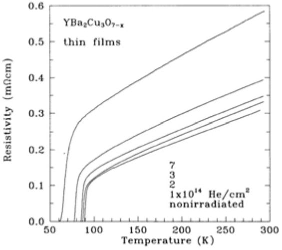


- Yields a T-linear resistivity, **slope independent on the strength of disorder/explicit translation symmetry breaking** to leading order

$$D_\varphi \simeq \frac{\hbar v^2}{k_B T}\,,\qquad \rho_{dc} \simeq \frac{m^\star}{ne^2}\frac{v^2}{D_\varphi} + O(\Gamma) \sim T$$



Credit: [Rullier-Albenque et al, Eur.Phys.Lett'00]



Credit: [Walker et al, Phys Rev B'94]

Emphasis on the independence of the slope on disorder: same slope for across different overdoped cuprates, in spite of varying degree of disorder

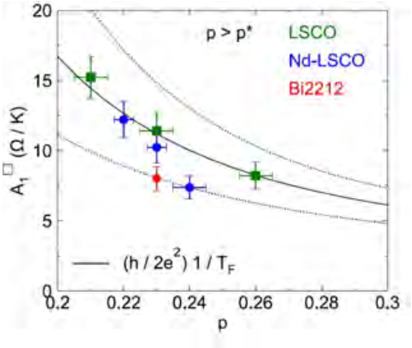
- Extract the T-linear component of the resistivity

$$\rho \simeq \rho_0 + A_1 T + \ldots\,, \quad A_1^{\square} = A_1/d$$

$$\rho \simeq \frac{m^\star}{ne^2\tau}\,, \quad \tau = \frac{\hbar}{\alpha k_B T}$$

$$A_1^{\square} = \alpha \frac{h}{2e^2}\frac{1}{T_F}\,, \quad T_f = \frac{\pi\hbar^2}{k_B}\frac{nd}{m^\star}$$

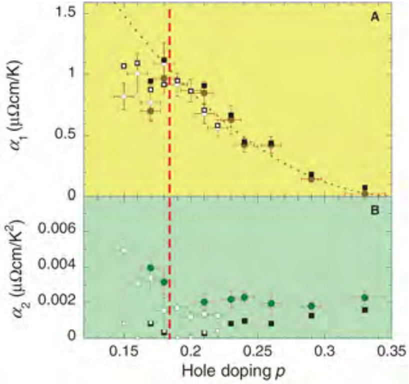
- If we had a simple Drude model, expect that $1/\tau \sim g^2$, highly dependent on the strength of disorder.



CREDIT: [LEGROS ET AL, NAT. PHYS.'19]

- Two distinct temperature dependencies in transport [Cooper et al Science'09], [Putzke et al Nature Physics'21], [Ayres et al arXiv: 2012.01208]

$$D_\varphi \sim \frac{v^2\hbar}{\alpha k_B T}, \Gamma \sim \gamma_0 + \gamma_2 T^2 \quad \Rightarrow \quad \rho_{dc} \sim \frac{m^\star}{ne^2}\left(\gamma_0 + \frac{k_B\alpha}{\hbar}T + \gamma_2 T^2\right)$$



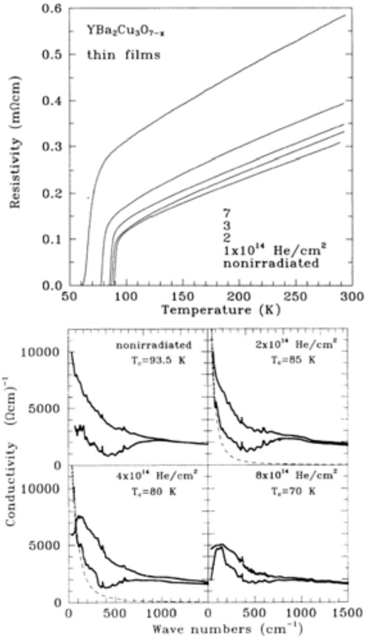
Credit: [Cooper et al Science'09]

- Upon increasing disorder, the **Drude peak** in the strange metal regime is **transfered to nonzero frequencies** in He-irradiated $YBa_2Cu_3O_{6.95}$.

- Reproduced by the EFT prediction for the ac conductivity when **pinning ω_o is stronger than damping Ω**

$$\sigma(\omega) = \left(\frac{ne^2}{m^\star}\right) \frac{\Omega - i\omega}{(\Omega - i\omega)(\Gamma - i\omega) + \omega_o^2}$$

- Same transfer of spectral weight observed in the strange metal regime as T increases [Hussey et al, Philos. Mag.'04], [Delacrétaz et al, SciPost Phys.'17]: consistent with $\Omega \sim \omega_o^2 D_\varphi \sim \omega_o^2/T$.



[Basov et al, Phys Rev B'94]

- EFTs and holographic methods used in conjunction to arrive at general statements on transport in strongly-correlated phases of quantum matter.

- Example from charge transport in pinned, gapless charge density wave phases: nonzero resistivity from relaxation of pseudo-Goldstone into bath of gapless thermal excitations

$$\Omega = m_\varphi^2 D_\varphi$$

- In holography, D_φ is controlled by the black hole horizon dofs.

- This result also applies to quasi-1D CDW materials, Wigner solid phase of 2DEGs.
- Appealing features for charge transport in cuprate strange metals.

THANKS!