Charge transport in gapless, pinned charge density waves

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Strange metals: from the Hubbard model to AdS/CFT
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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)] with L. Delacrétaz, S. Hartnoll and A. Karlsson.

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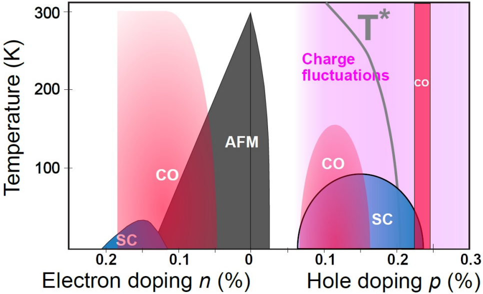
- All references in [magenta] have hyperlinks.

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]

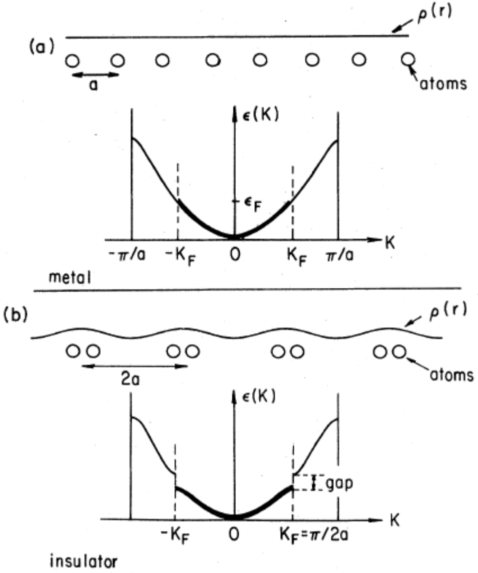
- Well-established in underdoped cuprates [Tranquada et al, Nature'95].
- More recent discovery on the **overdoped** side [Arpaia et al, Science'19], see [Arpaia and Ghiringhelli, J. Phys. Soc. Jpn.'21] for a review.
- Magnetism all the way to the pseudogap critical point, [Frachet et al., Nat. Phys.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

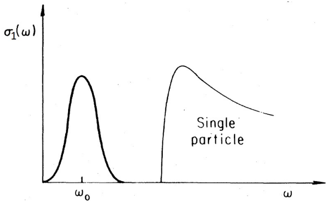
$$\partial_t^2 \varphi^x + \Gamma\, \partial_t \varphi^x + \omega_o^2\, \varphi^x = 0$$

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.



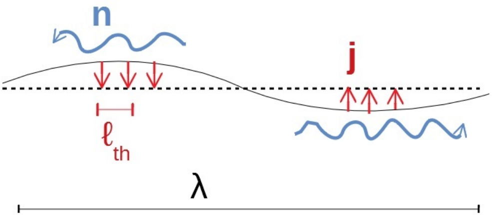
Credit: adapted from [Grüner, RMP'88]

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

- This 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. No hard gap: **gapless low-energy excitations** on top of the Goldstone mode.

- Rather than focusing on a specific material, I want to investigate on general grounds **charge transport in pinned, gapless, strongly-correlated charge density wave states** (see [S. Krikun's talk] for thermoelectric effects).



- Strong correlations imply **short equilibration scales** $\tau_{eq} \sim 1/T$ ('Planckian'? See [R. DAVISON'S TALK] for a holographic illustration of this), 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.

- 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!

†In [Armas et al, arXiv: 2112.14373], other transport coefficients are also derived, but appear to renormalize static susceptibilities and so play a less dominant role for the purposes of this talk.

- 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.

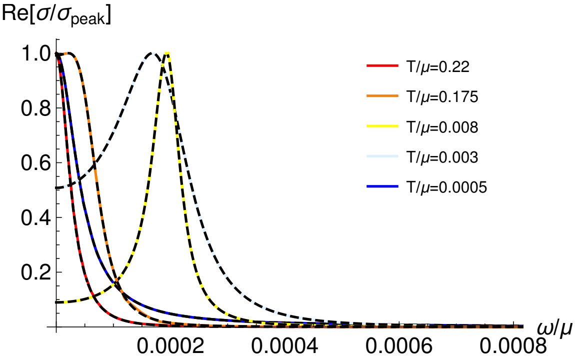
- **Nonzero dc resistivity**:

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

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

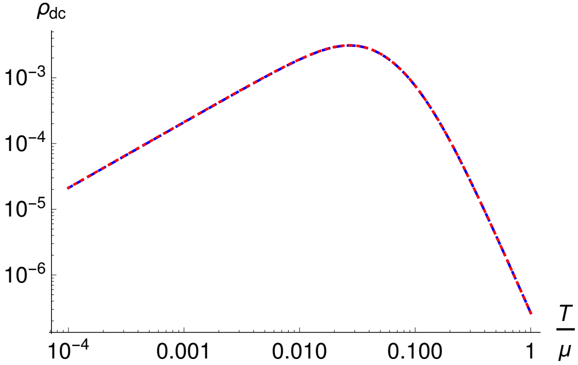
- Reminiscent of an **Einstein relation**, as here the thermal diffusivity:

$$D_T \sim D_\varphi$$



The holographic result for the AC conductivity in a phase that breaks translations pseudo-spontaneously matches the EFT prediction extremely well.†

†Accounting for the underlying Lorentz invariance of the holographic system, etc.



The resistivity dominated by the pseudo-Goldstone contribution[†]

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

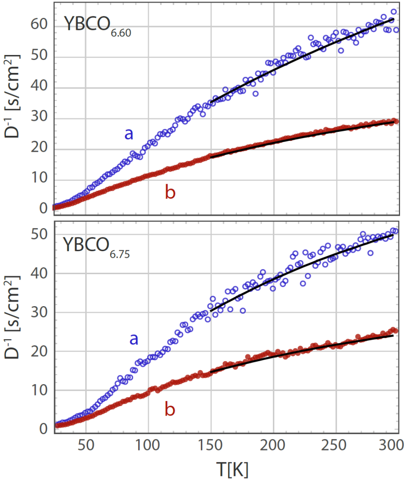
D_φ controlled by horizon quantities, [Amoretti et al, JHEP'19]: **the Goldstone couples to the black hole horizon**, which provides the bath of thermal excitations into which it relaxes. 'holographic black hole membrane paradigm' [Iqbal & Liu, Phys.Rev.D'09], [Donos & Gauntlett, JHEP'14].

† Accounting for the underlying Lorentz invariance of the holographic system, etc.

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

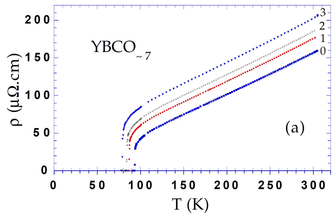
$$D \gtrsim \frac{\hbar v^2}{k_B T}$$

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

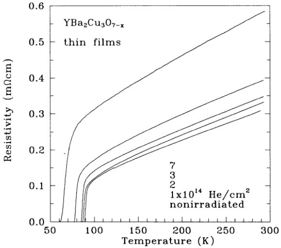


- Yields a T-linear resistivity, **slope independent on the strength of disorder/explicit translation symmetry breaking** to leading order

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



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

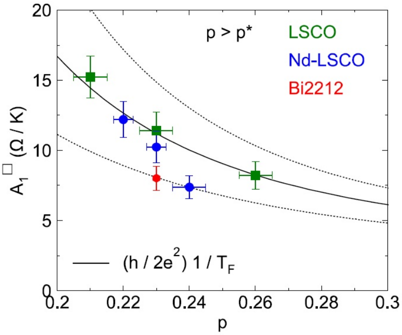
- Extract the T-linear component of the resistivity

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

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

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

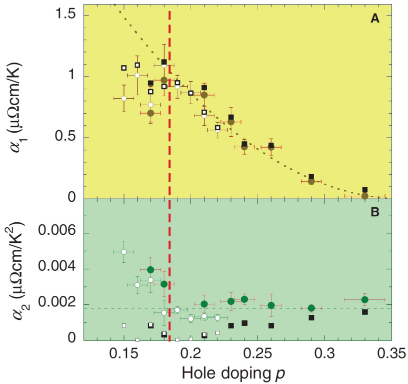
- If we had a simple Drude model, expect that $1/\tau \sim g^2$, highly dependent on the strength of disorder.



Credit: [Legros et al, Nat. Phys.'19]

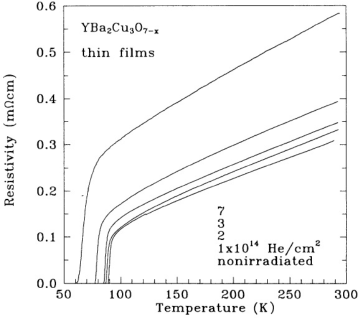
- Two distinct temperature dependencies in transport [Cooper et al Science'09], [Putzke et al Nature Physics'21], [Ayres et al arXiv: 2012.01208]

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



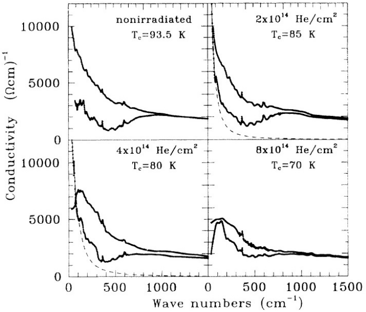
Credit: [Cooper et al Science'09]

- 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

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



[Basov et al, Phys Rev B'94]

- 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 $\Omega \sim \omega_o^2 D_\varphi \sim \omega_o^2/T$.

- 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 thermal excitation

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

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

- Appealing features for charge transport in cuprate strange metals.

THANKS!