PhD Seminars – Season 7, Episode 1

Aula Conversi, 19th April 2023

TRANSPORT PROPERTIES OF THE STRANGE METAL PHASE OF CUPRATES

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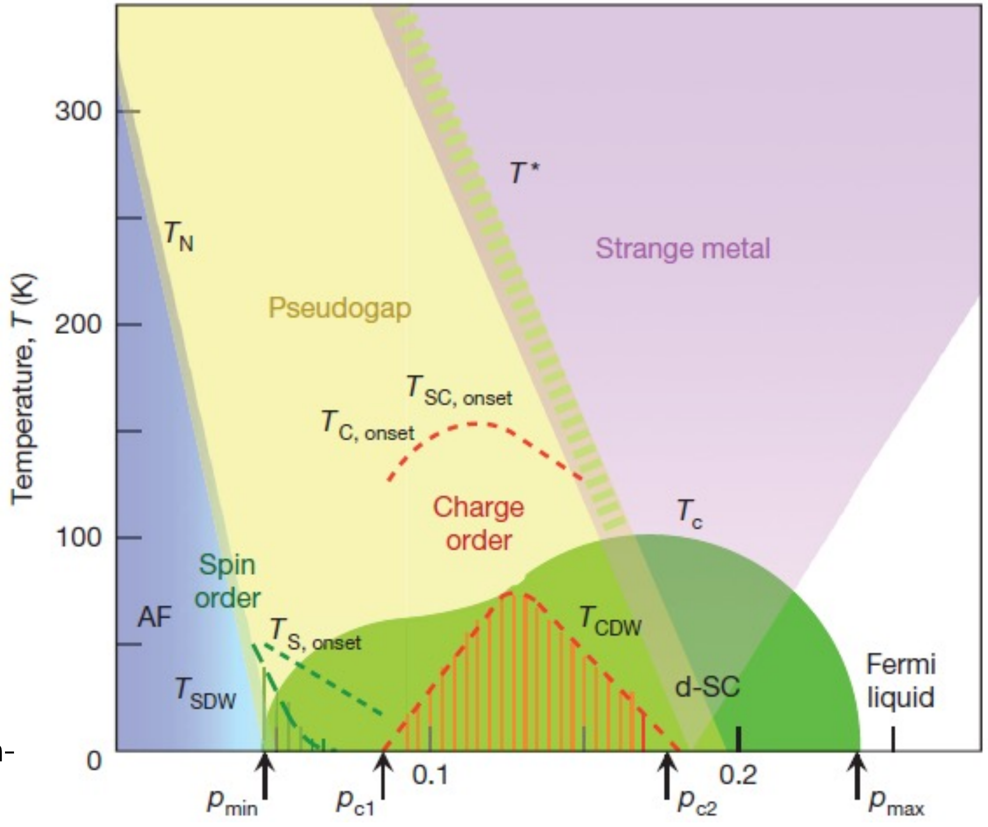
WHAT ARE CUPRATES?

Materials made of layers of copper oxides (CuO_2) alternating with layers of oxides of other metals.

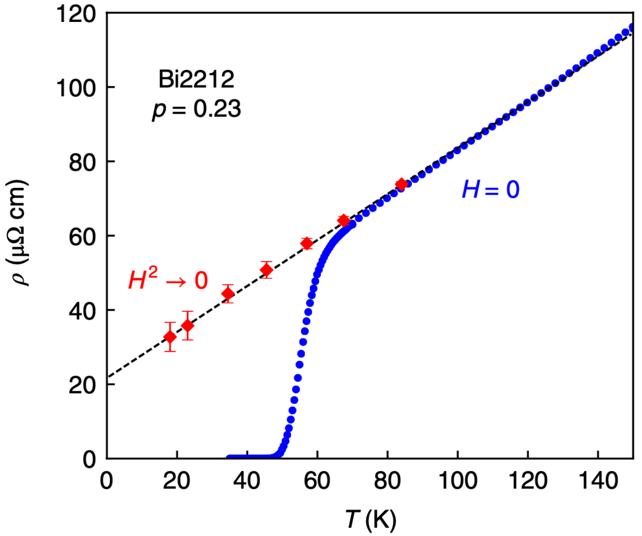
Main features of a typical phase diagram:

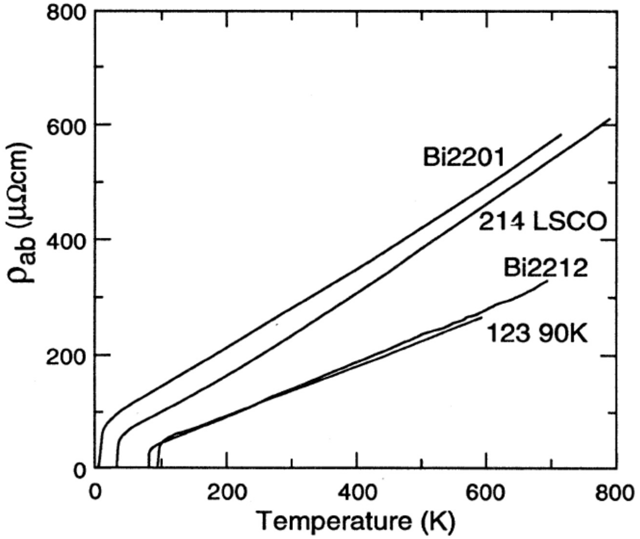
- Mott insulators at low doping level
- High temperature superconductivity in a suitable doping level window
- Strange metal phase
- Presence of charge order
- Compatible with a quantum critical point scenario



Keimer, B., Kivelson, S., Norman, M. *et al.* "From quantum matter to high-temperature superconductivity in copper oxides", *Nature* **518**, 179–186 (2015)

TRANSPORT PROPERTIES





Linear resistivity in a wide range of temperatures:

- Violation of Fermi Liquid behavior at low temperatures ($\rho \propto T^2$) close to the critical doping level
- No sign of saturation at high temperatures
- Same slope in any temperature range

Legros, A., Benhabib, S., Tabis, W. *et al.* "Universal T-linear resistivity and Planckian dissipation in overdoped cuprates", *Nature Phys* **15**, 142–147 (2019)

Dagotto E., "Correlated electrons in high-temperature superconductors", *Reviews of Modern Physics* **66** (3), 763-840 (1994)

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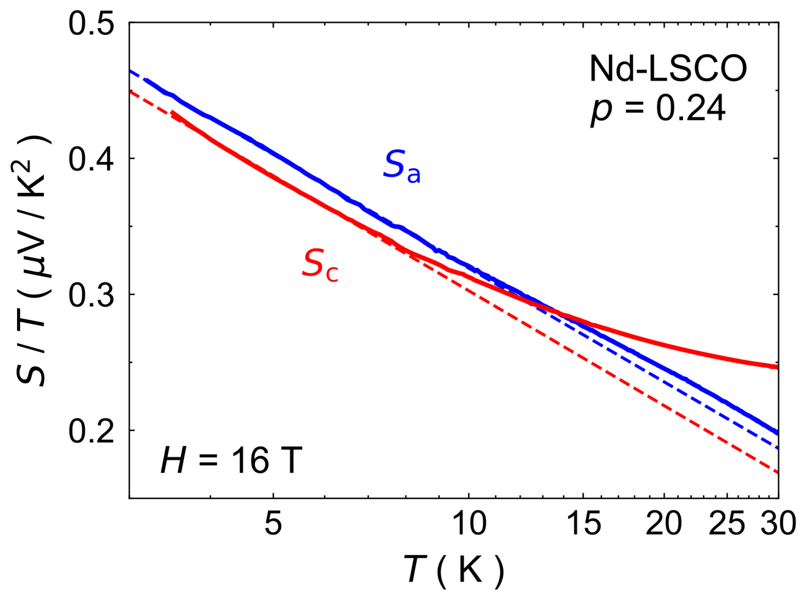


Abnormal behavior of the Seebeck coefficient:

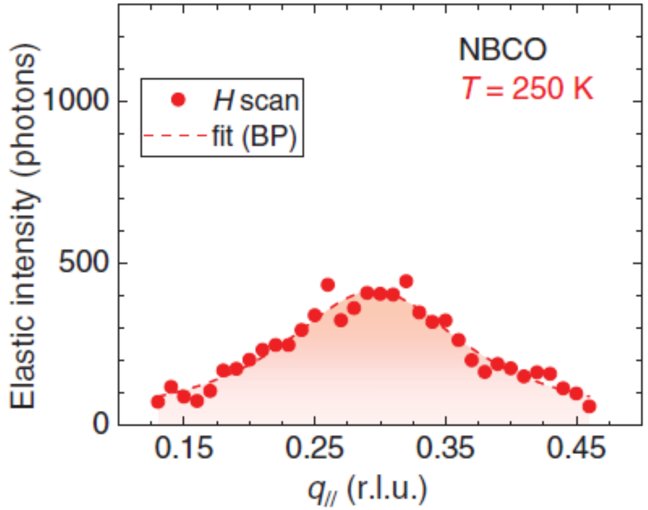
- Seeming divergence at the critical value for the doping level in the low temperature limit
- Same asymptotic trend as the specific heat (Cv/T, S/T ∝ log(1/T))
- Interpreted as a signature of quantum criticality in the vicinity of the quantum critical point

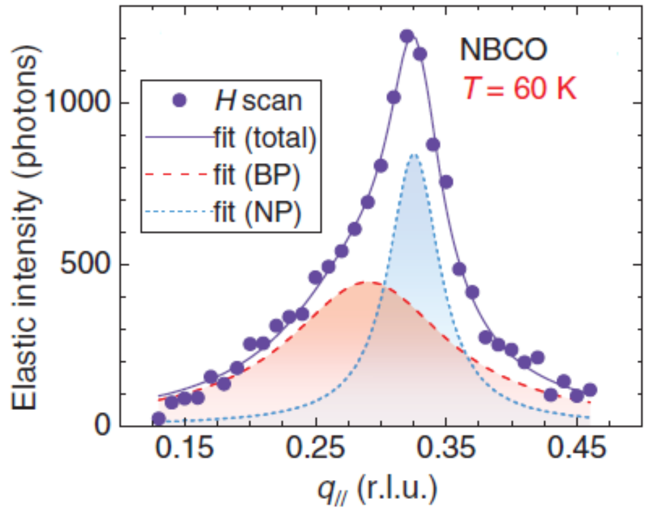
Gourgout A., Grissonnanche G., Laliberté F. *et al.* “Seebeck Coefficient in a Cuprate Superconductor: Particle-Hole Asymmetry in the Strange Metal Phase and Fermi Surface Transformation in the Pseudogap Phase”, *Phys. Rev. X* **12**, 011037 (2022)

CHARGE COLLECTIVE MODES

Experimental evidence of two different kinds of collective modes (charge density waves and charge density fluctuations):

- Different distribution in momentum space
- Similar characteristic wavevector
- Both kind of collective modes are able to mediate an effective interaction between electronic quasiparticles
- Only charge density fluctuations are able to explain linear resistivity
- They are present in a large part of the phase diagram encompassing the strange metal phase





Arpaia R., Caprara S., Fumagalli R., *et al.* "Dynamical charge density fluctuations pervading the phase diagram of a Cu-based high-T_c superconductor", *Science* **365**, 906-910 (2019)

LINEAR RESPONSE THEORY

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Linear Response Theory is a powerful tool which, within the regime in which the response to a perturbation can be considered linear, provides a general scheme for calculating the response of a system to that perturbation.

LINEAR RESPONSE THEORY

$$H(t) = H_0 + \delta H_A(t)$$

where: $$\delta H_A(t) := \int \mathcal{O}_A(\mathbf{r},t) v_A(\mathbf{r},t) d^3\mathbf{r}$$

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If the perturbation is weak enough, we can assume that this variation is linear in the perturbation:

$$\langle \delta \mathcal{O}_B(\mathbf{r},t) \rangle = \int \chi_{BA}(\mathbf{r}-\mathbf{r}', t-t') v_A(\mathbf{r}',t')\, d^3\mathbf{r}' dt'$$

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- Kubo formula: $$\chi_{BA}(\mathbf{r}-\mathbf{r}', t-t') = -i\langle[\mathcal{O}_B(\mathbf{r},t), \mathcal{O}_A(\mathbf{r}',t')]\rangle\theta(t-t')$$

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- Fluctuation-dissipation theorem: $$\mathrm{Im}\chi_{BA}(\mathbf{q},\omega) = -\frac{1-e^{-\beta\omega}}{2}\langle\mathcal{O}_B\mathcal{O}_A\rangle_{\mathbf{q},\omega}$$

where: $$\langle\mathcal{O}_B\mathcal{O}_A\rangle_{\mathbf{q},\omega} := \int\langle\mathcal{O}_B(\mathbf{r},t)\,\mathcal{O}_A(\mathbf{0},0)\rangle e^{i(\omega t-\mathbf{q}\mathbf{r})}d^3\mathbf{r}\,dt$$

LINEAR RESPONSE THEORY

Charge density fluctuations propagator:

$$\mathcal{D}(\mathbf{q},\omega) = \frac{1}{m + \bar{\nu}|\mathbf{q}-\mathbf{q}_c|^2 - i\gamma\omega - \frac{\omega^2}{\overline{\Omega}}}$$

Imaginary part of Self-energy:

$$\mathrm{Im}\Sigma_R(\omega,\mathbf{k},T) = -\frac{g^2}{N}\sum_{\mathbf{p}}\mathrm{Im}\mathcal{D}(\xi_{\mathbf{k}-\mathbf{p}}-\omega,\mathbf{p})\left[f(\xi_{\mathbf{k}-\mathbf{p}}) + b(\xi_{\mathbf{k}-\mathbf{p}}-\omega)\right]$$

Kramers-Kronig relations:

$$\mathrm{Re}\Sigma(\omega,\mathbf{k},T) = \int_{-\infty}^{+\infty}\frac{\mathrm{Im}\Sigma_R(\omega',\mathbf{k},T)}{\omega'-\omega}\frac{d\omega'}{\pi}$$

ROLE OF THE DAMPING

We have shown that parameter γ regulates the crossover energy scale between the Fermi liquid and non-Fermi liquid regimes.

Larger γ $\Longrightarrow$ Linear resistivity at lower temperatures!

γ does not affect the correlation length of collective modes, which is always finite and quite small.

$\frac{S}{T} \propto \gamma$ for a suitable range of (large) values of γ.

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This assumption allows to explain the abnormal behavior of the resistivity, the specific heat and the Seebeck coefficient in the strange metal phase[1][2].

[1] Caprara S., Di Castro C., Mirarchi G. *et al.* "Dissipation-driven strange metal behavior", *Comm Phys* **5**, 10 (2022)

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Our assumption finds its justification in 2D systems in terms of coupling between charge density fluctuations and electron density diffusive modes[3].

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[2] Mirarchi G., Seibold G., Di Castro C. *et al.* "The Strange-Metal Behavior of Cuprates", *Cond Matt* **7** (1), 29 (2022)

[3] Grilli M., Di Castro C., Mirarchi, G. *et al.* "Dissipative Quantum Criticality as a Source of Strange Metal Behavior", *Symmetry* **15** (3), 569 (2023)

THANKS FOR YOUR ATTENTION!