New quantum criticality for the strange metal and Planckian behavior in high temperature superconductors

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Collaborators: ***S. Caprara, M. Grilli, G. Mirarchi, G. Seibold:*** ***Theory***
R. Arpaia, L. Braicovich, R. Fumagalli, G. Ghiringhelli, Y. Y. Peng,…: ***Resonating X-Ray Scattering (RXS) Experiments***

R. Arpaia, et al.
Dynamical charge density fluctuations pervading the phase diagram of a copper-based high-Tc superconductor,
Science 365, 906 (2019)

G. Seibold, R. Arpaia, Y. Y. Peng, R. Fumagalli, L. Braicovich, C. Di Castro, M. Grilli, G. Ghiringhelli, and S. Caprara,
Strange metal behaviour from charge density fluctuations in cuprates, Commun. Phys. 4, 7 (2021).

S. Caprara, C. Di Castro, G. Mirarchi, G. Seibold and M. Grilli
Dissipation-driven strange metal behavior, Commun. Phys. **5**, 10 (2022).

M. Grilli, C. Di Castro, G.Seibold, S.Caprara.
Disorder-driven dissipative quantum criticality as a source of strange metal behavior.
arXiv:2205.10876v1 [cond-mat.str-el]

Summary

Backstory: Superconductivity and competing orders in the phase diagram of cuprates

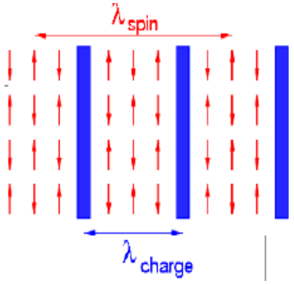
The strange metal behavior : out of the main stream

New criticality: Planckian limit and the ln1/T specific heat

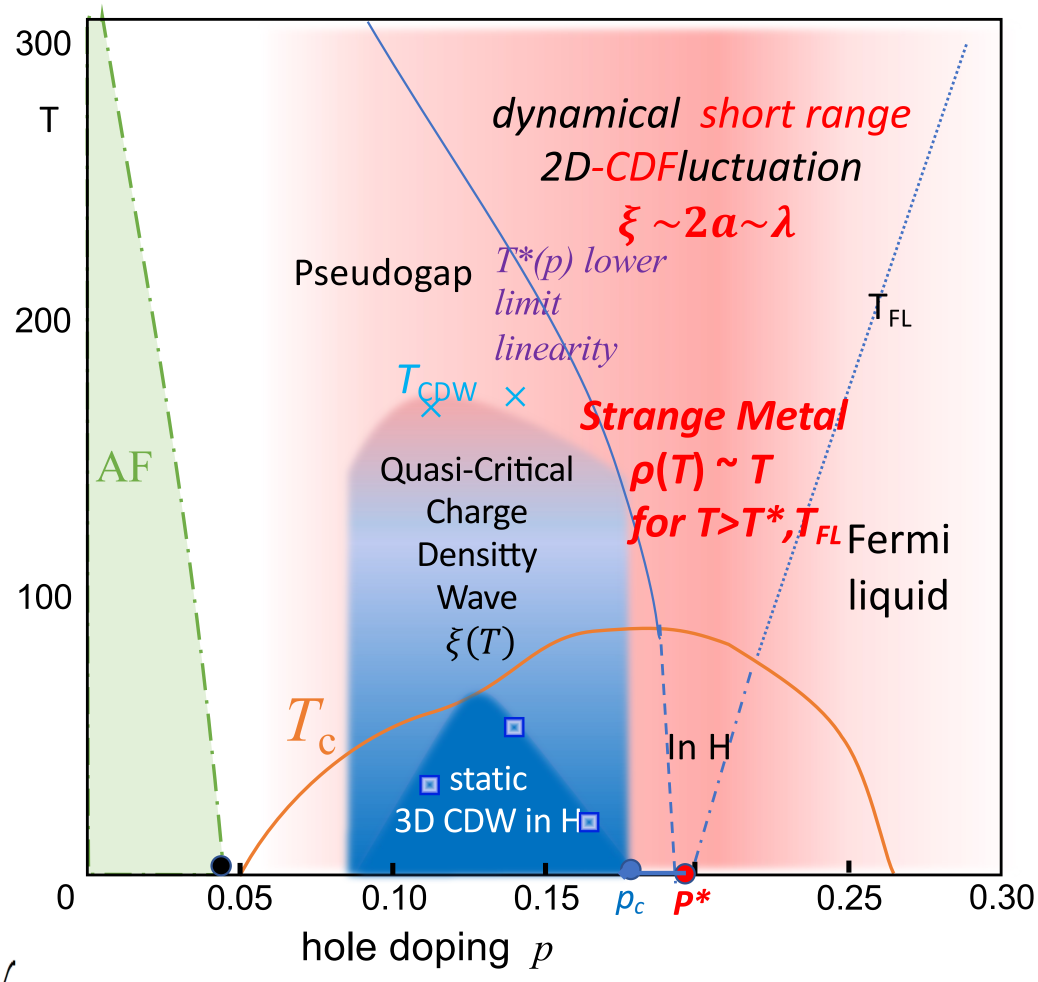
Concluding remarks and perspectives

Very complex T vs. doping p phase diagram of the quasi 2D Cuprates, e. g. $YBa_2CuO_{7-\delta}$. (Undoped_AFM $\delta = 1$)

Temperature T vs. doping p → SC and bad metal with various competing orders



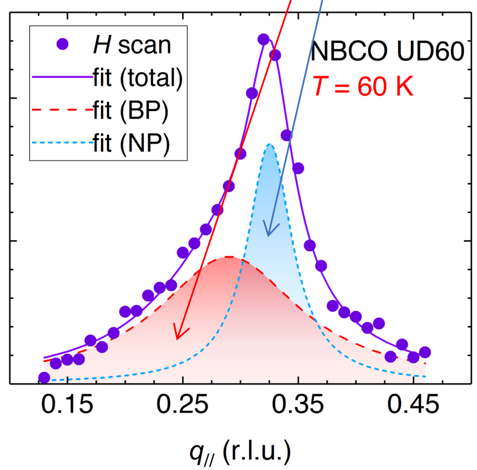
Evidence of stripes with nematic order. Incommensurate Charge Order very difficult to observe. Breakethrough *resonant X-ray scattering (RXS)*, Ghiringhelli 2012 CDW



On top of this complexity two Charge Density (CD) modulations are present with almost equal vector q_c, (Arpaia et al Science 2019):

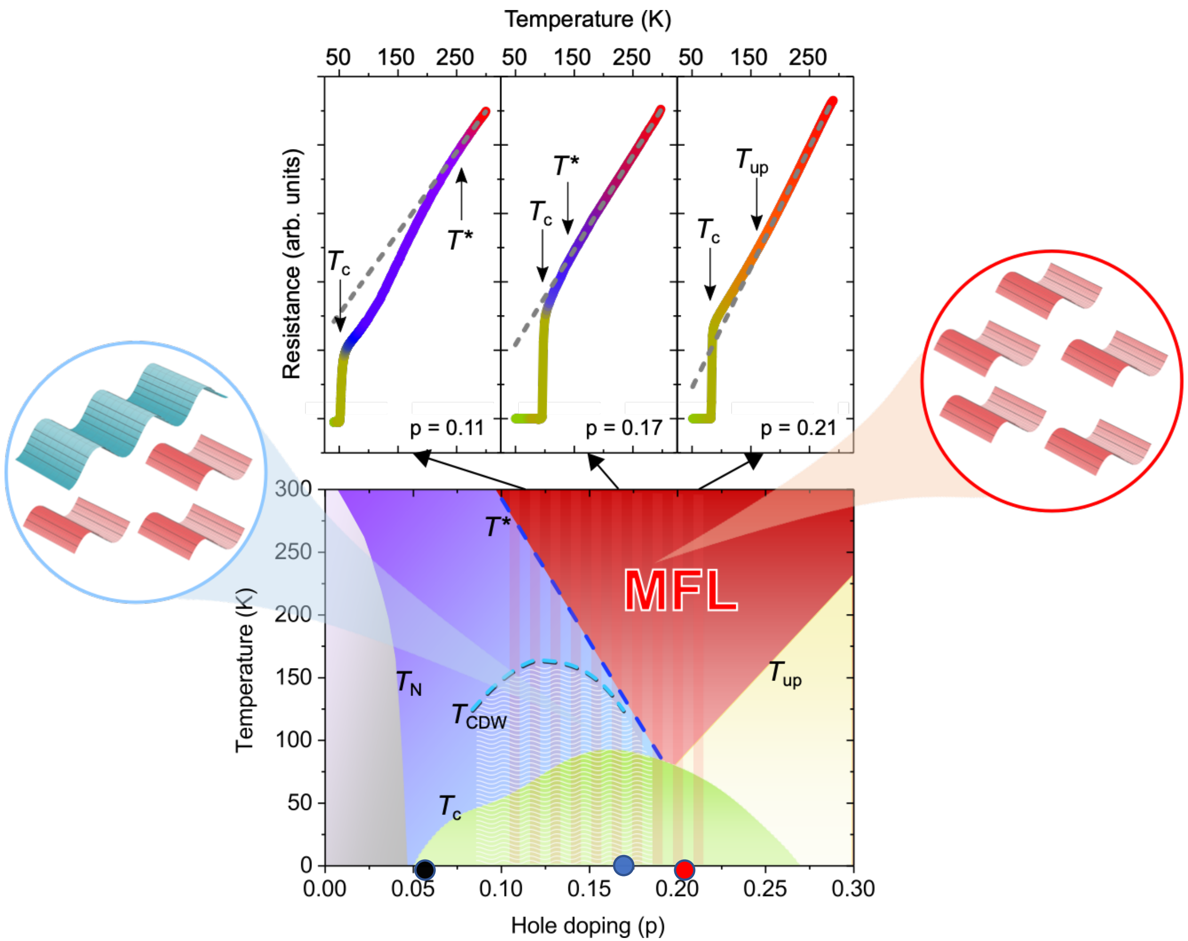
-RXS response peak Narrow: Correlation length increasing by lowering T. Quasi-critical and 3D critical CDW

-RXS response peak Broad: Correlation length remains finite by lowering T. *2D component CD-Fluctuations*



STRANGE METAL AND CHARGE DENSITY FLUCTUATIONS, G. Seibold et al Commun. Phys. 4, 7 (2021).

Pictorial representation of strange metal bhavior for $T>T_c$



Actually, the strange metal region of the phase diagram is the region where only CDFs are observed
No CDW

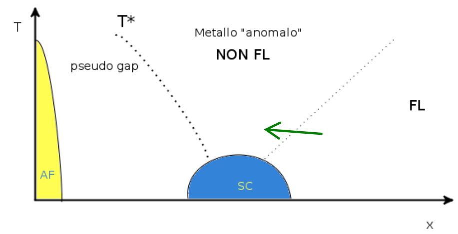
Is the long-standing Strange Metal problem connected with the presence of CDFs?

High T Violation of Fermi Liquid has been observed in several materials besides cuprates, like heavy-fermions and iron-based superconductors near a Quantum Critical Point or a missed criticality.

Which QCP?

Let us see how this picture arises from our old and new stories

Correlated Fermi Liquid (FL) Instability as a Charge Density Wave



The proposal of a CDW instability in cuprates is quite old (Castellani, DC, Grilii PRL 1995.) and it is based on the mechanism of frustrated phase separation (Emery and Kivelson 1993,....).

-Strong correlations (slave bosons on a single band Hubbard model) *weaken the metallic character of the system giving rise in mean field approximation (N=∞) to a Fermi liquid with a substantial enhancement of the quasiparticle (QP) mass m* and a sizeable residual interaction (I/N correction).*

-Weak or moderate additional attraction (e.g. e-ph interaction) provides an effective mechanism that induces an electronic Phase Separation with charge segregation on large scale at q=0.

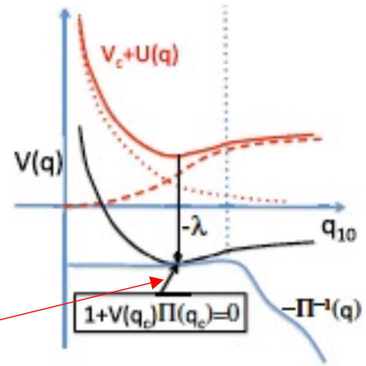
-Long-range Coulombic repulsion forbids PS, the system makes a compromise and segregate charges on a short scale, while keeping charge neutrality at large distance.

A **CDW state with finite modulation vector q_c is then the outcome.** (in YBCO $q_c(p)$=0.30-0.33 (r.l.u.))

NO

The corresponding technical procedure (slave bosons) turns out to be equivalent to RPA dressed effective interaction $V_{eff}(q)$ which shares the same denominator of the density-density response function $\chi_{\rho\rho}$

$$V_{eff}=\frac{V(q)}{1+\Pi(q,\omega)V(q)} \propto \chi_{\rho\rho} \qquad V(q)=V_c(q)+U(q)-\lambda$$



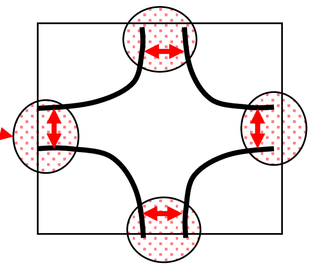
- $V_c(q)$ Coulombic (Long-Range) repulsion *impedes PS at q=0*
- $U(q)$ is a short-range residual repulsion stemming from large U of a one-band Hubbard model,
- λ *coupling of the Holstein* e-ph interaction
- $\Pi(q, \omega)$ Lindhard polarization bubble of screening processes

*The effects of strong correlations are in the form of V(**q**) and in the QP effective mass entering $\Pi(q, \omega)$*

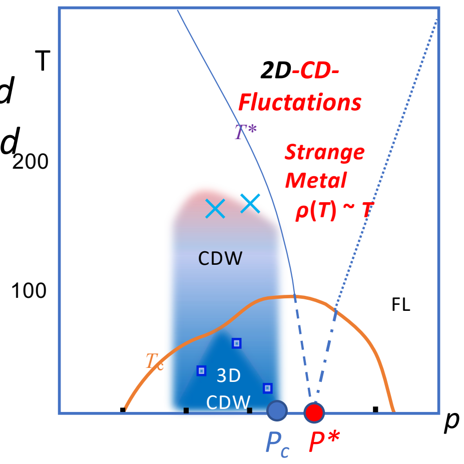
RPA CDW instability condition from a correlated Fermi Liquid:

$1+V(q=q_c)\Pi(q=q_c, \omega=0)=0$

U(q) less repulsive and the hopping largest along Cu-O direction *(1,0) and (0,1)*:
Mean Field CDW instability and *modulation vector q_c* are in this direction.



At the end of the day, despite the complicated structure of the scattering amplitude mediated by the auxiliary bosons, near and above the instability, the calculations results In the standard Landau Gaussian form for the correlator D of the order parameter field $\varphi = \sum_{k,\sigma} c^+_{k+q} c_k$ as a function of q and frequency $\boldsymbol{\omega}$



$$D^{-1} \equiv m + \nu(q-q_c)^2 - i\omega\gamma, \qquad \mathrm{m}= \nu\xi^{-2},$$

i.e. a time dependent Landau Ginzburg equation for the field φ

γ is the Landau damping parameter proportional to the electron density of states that sets a measure of the phase space available for the decay of the fluctuations and ν is the stiffness energy scale

It is natural to define a characteristic energy $\omega_{ch}\,(q)$ for each φ_q, which is minimum at $q = q_c$ and its inverse defines the relaxation time of the fluctuation modes to its equilibrium zero value: $\omega_{ch}(q_c) = \tau^{-1}_{q_c} = m\,/\,\gamma$

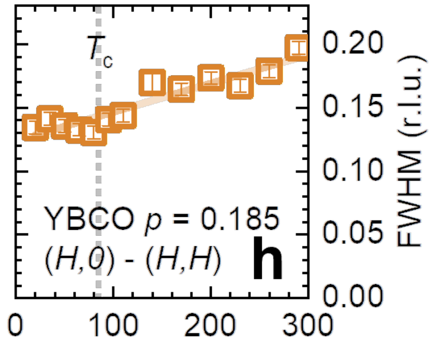
φ is either the CDW field or the CDF mode,

Since $\mathrm{Im}\chi_{\varrho\varrho} \propto \mathrm{Im}D$, the RXS quasi-elastic peak reads: $I_{RXS} = A Im D(q,\omega) B\left(\frac{\omega}{T}\right) = \frac{\frac{\omega}{\gamma}}{(\omega_{ch})^2+(\omega)^2} B(\frac{\omega}{T})$ B=Bose function

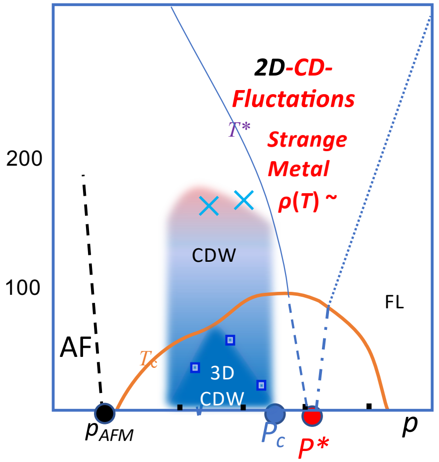
Peak width at q_c : $(\frac{m}{\nu})^{\frac{1}{2}} = \xi^{-1}(p,T)$

CDWs quasi-critical, $\xi^{-1} \propto T - T_{CDW}$

CDFs remain broad, ξ^{-1} *weakly T dependent and finite extrapolation at T=0 (2D-component)*



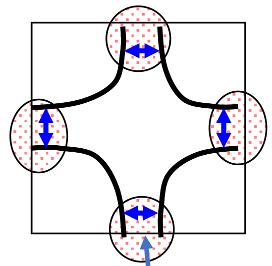
The Parameter ν, γ, m … by fitting the experiments



Violation of Fermi Liquid is usually connected to a Quantum-Criticality, doping $p=p_{AFM}$ *or* p_c *(of the CDW)* here. (Varma, Chubukov,Sachdev, Castellani- CDC-Grilli-Metzner,…

Indeed, critical fluctuations mediate strong (singular) interaction among fermions and could destroy Fermi Liquid

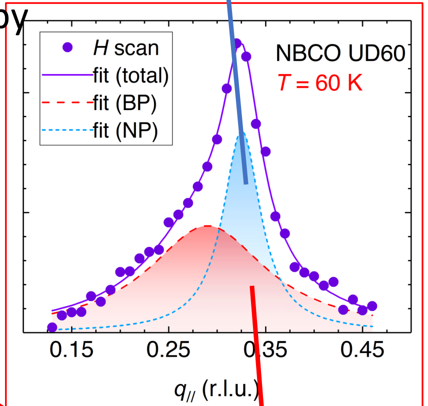
Quasiparticle Scattering rate $\tau^{-1} \propto T$.



But… '''only isolated points of Fermi Surface (hot points) are connected by q_c,

Cold regions $(\tau^{-1} \propto T^2)$ *short-circuit the hot ones: Fermi liquid*

*(*Hlublina and Rice, 1995)

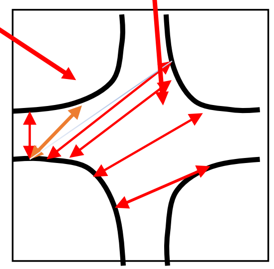


This calls for a substantial change of the approach

CDFs (ξ *small*) are so broad that a Fermi quasiparticle of one branch of the FS can always finds a CDF which scatters it into another region of FS ⟶ *nearly* ***uniform scattering on*** *the entire Fermi surface*

Low energy Dynamic-CDFs as mediators of scattering *give rise to the marginal Fermi liquid (Varma et al 1959): linear dependence of the imaginary part of the electron self-energy*

$$Im\Sigma(k,\omega) \sim \max(T,\omega);$$



With this calculated scattering rate in the Boltzmann equation:

linear-in-T resistivity

NO

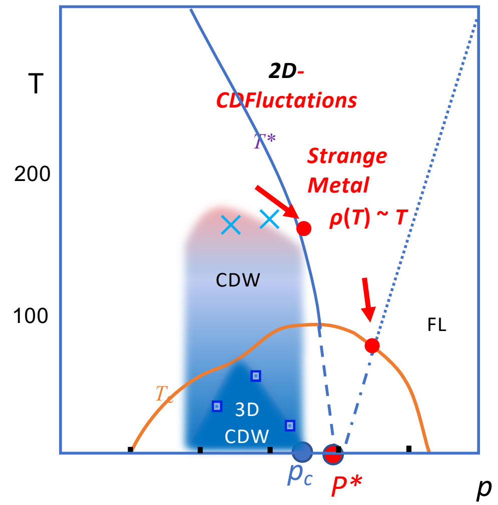
Boltzmann approach to transport: *linear-in-T resistivity*

CDF-mediated self-energy : scattering rate Γ_Σ *+ elastic scattering rate* Γ_0 *≈20-40 meV*

$$\frac{1}{\rho} = \frac{2e^2}{\pi^2 \hbar d} \int d\phi \frac{k_F(\phi) v_F(\phi) cos^2(\phi - \vartheta)}{\Gamma(\phi) cos\vartheta}$$

where $k_F(\phi)$, $v_F(\phi)$, *and* $\Gamma(\phi) \equiv \Gamma_0 + \Gamma_\Sigma(\phi)$ *denote the angular dependence along the Fermi surface and* $\theta = \mathrm{arctg}(\frac{1}{k_F}\frac{\partial k_F}{\partial \phi})$

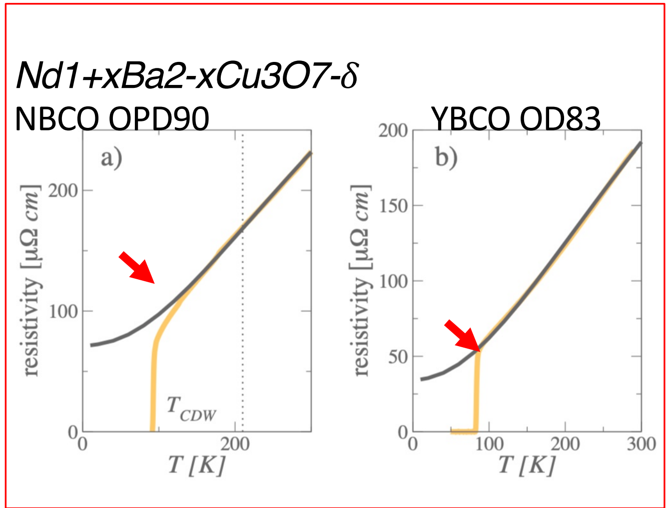
I will not refer to the explicit calculations of the linear in T resistivity *using the same set of parameters that was obtained by fitting the RIXS response* for optimally doped NBCO and an overdoped YBCO sample (Seibold et al Comm Phys 2021)
A simple heuristic argument explains in brief our new approach.



Since the scattering is almost uniform over the entire Fermi surface, the scattering integral in the Boltzmann equation can be well approximated with only one effective scattering time for each *single* scattering event.
Its inverse determines the effective characteristic frequency of the process

$$\omega_{ch} = m/\gamma = \tau_{single}^{-1}$$

In analogy with a disordered electron system, *the full scattering rate must be proportional to the characteristic frequency of the single event multiplied by the population of the scatterers,*
i. e. the Bose function $\tau_{fl}^{-1} \sim B\left(\frac{\omega}{T}\right)\omega_{ch}$



As long as $kT > \hbar\omega_{ch}$, the semiclassical approximation is valid

$$b\left(\frac{\omega}{T}\right) \approx T/\omega\,, \quad \text{and } \tau_{fl}^{-1} \sim B\left(\frac{\omega}{T}\right)\omega_{ch} \sim T$$

a linear T dependence is left.

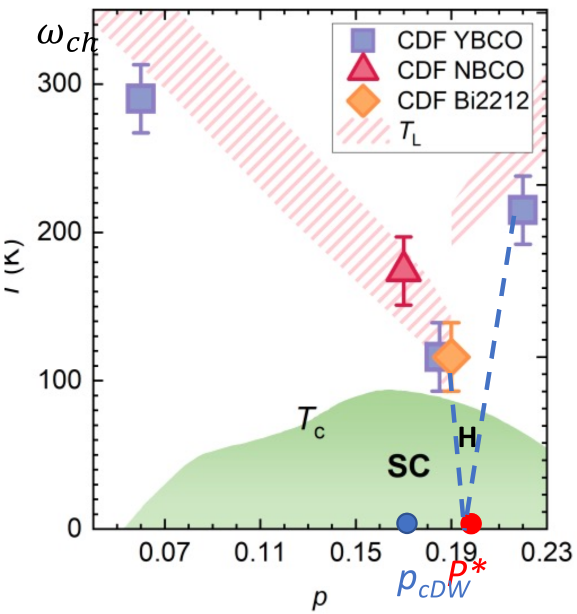
The above condition $kT > \hbar\omega_{ch}$ turns out to be satisfied in the strange metal region T>T* above T_c with γ of the order of unity

$\omega_{ch} \sim T^*$ tuns out to be the lower limit of linearity at each doping

Signature of quantum criticality in cuprates by charge density fluctuations (Arpaia et al https://arxiv.org/abs/2208.13918)

What about QCP? *ω_{ch} should vanish at criticality*

Recent high resolution RXS have given a direct measure of the dynamical characteristic energy of the CDFs ω_{ch} (p) $\equiv \upsilon\xi^{-2}/\gamma$ at the lowest measured T above T_c at each doping



its measured values have a minimum at p=p$*$ suggesting the presence of a hidden anomalous QCP$*$ at $p* > p_{CDW}$ of the CDW−QCP.

Actually, in the presence of external field H to suppress superconductivity, **at** p $\simeq$p$*$ **the linearity has been observed down to lowest T :** $\tau^{-1} \sim kT$ $\rho(T) \sim T$ (see e, g. Legros 2019 (Nd/Eu-LSCO, p*=0.24; Bi2201, p*=0.23; YBCO p*= 0.19; *Zaanen, 2004;…*)

ln(1/T) divergent specific heath , (Michon et al. Nature, 2019; Girod et al arXiv:2101.0922)

At p we should then extend the condition of linearity*

$kT > \hbar\, \omega_{ch} \equiv \frac{\nu\xi^{-2}}{\gamma}$, *down to the lowest T by lowering* ω_{ch} .

However, around *p**, only CDFs are present (no CDWs) and ξ^{-1} extrapolates to a finite value at T=0.

what about γ?

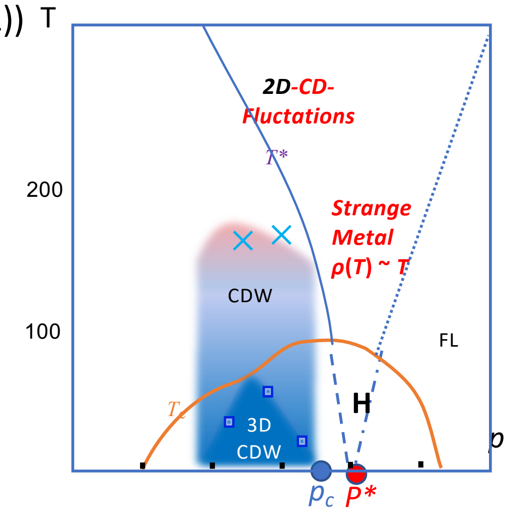
Dissipation driven strange metal behavior as T tend to zero (Caprara et al Comm. Phys 5,10 (2022))

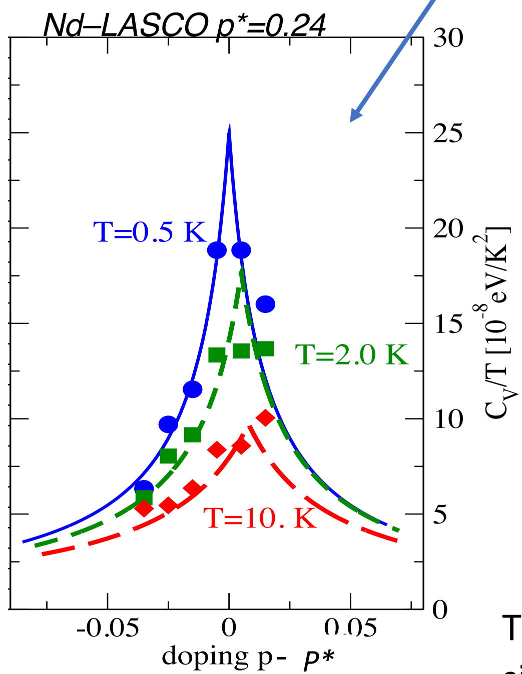
Our approach accounts of the above results: by letting the dissipation parameter γ to increase (renormalize) as p→p, instead of letting the correlation length go to infinity*

With *a ln(1/T) dependence of the dissipation parameter* γ as $p \to p^*$, we were able to fit :

-the *measured resistivity* at p=0.23 in NdLSCO and EuLSCO

-*the specific heat* via the contribution from the collective Bose mode C_V





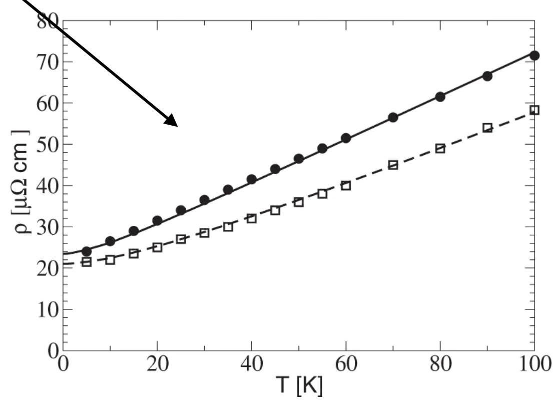
Remarkably, the relative weight of C_V as a function of doping at the various temperatures is well captured by our approach.

When γ increases to infinity:

-*an anomalous dissipation driven QCP is realized at p**

-all the fluctuating islands tend to relax with infinite relaxation time τ_q, "critical slowing down":

$$\tau_q^{-1} = \frac{m}{\gamma} + \frac{\nu(q-q_c)^2}{\gamma} \sim \frac{1}{\gamma}$$

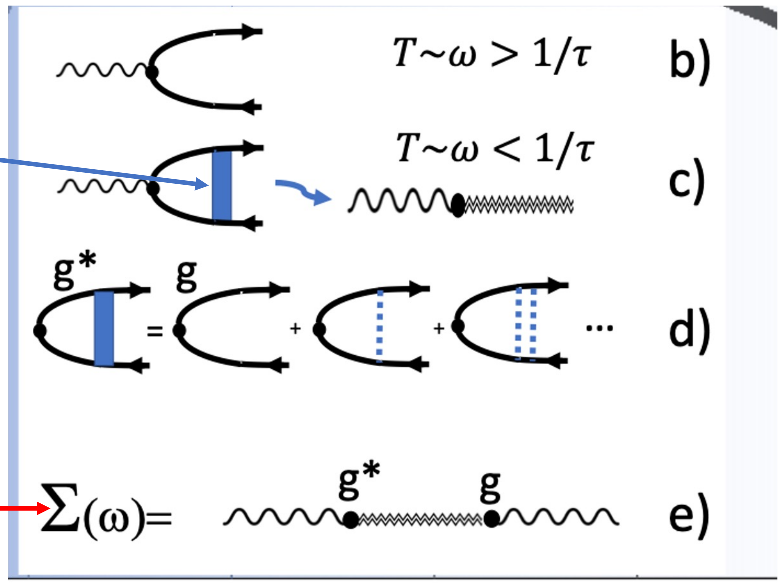


These dynamical fluctuating droplets are very small ($\xi \sim 2a \sim \lambda$), formed by few lattice units since ξ is very small, and pervade all the space forming a *persistent "glassy like state"*

A possible mechanism for enhanced dissipation (M. Grilli et al rXiv:2205.10876v1 [cond-mat.str-el] 2022) is the opening of a new decaying channel for the CDF.

τ here is the disorder scattering time

At low energy and T, the CDF can decay in a diffusive p-h mode



Simple model we couple the "local" CDFs and electronic density diffusion via a doping dependent coupling

$1/(m + \gamma|\omega_n|)$

$N_0 Dq^2/(Dq^2 + |\omega_n|)$

g(p).

The self-energy of the local field is then dressed by the diffusion

If we decompose the density diffusive correlation in a constant and a frequency and momentum term, $N_0[1 - |\omega_n| / (Dq^2 + |\omega_n|)]$ *the linear term in ω of the self energy* provides the renormalized *dissipation parameter γ of CDFs , with a logarithmic increase as T decreases*

$$\gamma - \gamma_0 = A \int_{\min(T,\tau^{-1})}^{\tau^{-1}} d(Dq^2) \frac{1}{Dq^2} = A \log max[(T\tau)^{-1}, 1]$$

Summary

- I have outlined a general paradigmatic change :
- *-CD-Fluctuations rather than critical modes (CDWs) work well as strong low-energy scatterers to produce* Strange Metal.
- -An anomalous new Quantum Critical Point ($p^*>p_{c)}$ could be obtained by an increase of dissipation γ, rather than by a divergence of the correlation length
- Approaching p* small droplets hosting CDFs with finite correlation length ξ would relax slower and slowler (unusual critical slowing down) resulting in an almost persistent glassy like state (?).
- Correlation in time and not in space.
- New field of research?