Comment on "Stranger than metals"

V. R. Shaginyan,1,2,* A. Z. Msezane,2 G. S. Japaridze,2 and M. V. Zverev3,4

1Petersburg Nuclear Physics Institute of NRC "Kurchatov Institute", Gatchina, 188300, Russia
2Clark Atlanta University, Atlanta, GA 30314, USA
3NRC Kurchatov Institute, Moscow, 123182, Russia
4Moscow Institute of Physics and Technology, Dolgoprudny, Moscow District 141700, Russia

P. W. Phillips, N. E. Hussey, P. Abbamonte (Review Article, 8 July 2022, eabh4273) consider heavy fermion (HF) metals and high-$T_c$ superconductors naming them strange metals. They analyze such features of strange metals as quantum criticality, Planckian dissipation and recently observed fundamental link between the high-$T_c$ superconductivity and strange metals, and conclude that these problems can be possibly resolved within the framework of theories based on gravity, etc. In this comment we discuss that this claim is not correct and the successful description of the quantum criticality, Planckian dissipation and recently observed fundamental link between the high-$T_c$ superconductivity and strange metals has been within the framework of the fermion condensation theory.

Authors of the review [1, 2], analyzing heavy fermion (HF) metals and high-$T_c$ superconductors, dubbed them strange metals, announce "given the immense difficulty in constructing a theory of strange metals, one might ask why bother?" [1]. We concur with this claim, since the well-known fermion condensation (FC) theory describes the quantum criticality, Planckian dissipation, recently observed fundamental link between the high-$T_c$ superconductivity and strange metals, and the other thermodynamic, transport and relaxation properties, see e.g. [3–12]. The FC theory is based on the notion of flat band, that was predicted in 1990 [3] and now represents exciting and hot topic in condensed matter physics, see e.g. [13, 14]. In the FC theory the quantum critical point is represented by the topological fermion condensation quantum phase transition (FCQPT) that increases the Fermi surface dimension by one, creating both the flat band and the new state of matter [3–5, 7, 11]. The schematic phase diagram of the system which is driven to FC state with a flat band, by varying the dimensionless doping parameter $x/x_c$ is reported in Fig. 1. The tuning parameter $x/x_c$ can represent other parameters besides doping, such as pressure $P$, $P_c$ being the corresponding critical value [7, 9]. Upon approaching the critical density $x_c$ the system remains in the Landau Fermi liquid (LFL) region at sufficiently low temperatures as it is shown by the shaded area. At FCQPT ($x/x_c \leq 1$) shown by the solid arrow in Fig. 1, the system is at quantum critical line, and demonstrates the non-Fermi liquid (NFL) behavior, that is critical behavior with $\rho(T)$ exhibiting [7, 9]

$$\rho(T) = A_1 T.$$  

(1)

Such a behavior is ubiquitous for systems with flat bands, see e.g. behavior exhibited by the HF metal $\beta$ – YbAlB$_4$ [9, 11]. At $x/x_c \leq 1$ the system becomes superconducting with $T_c \propto g$, provided that the superconducting coupling constant $g > 0$, see e.g. [3, 5, 7, 11, 14]. At $x/x_c \simeq 1$ the NFL state above the critical line is strongly degenerate. As a consequence, with different phase transitions emerge, lifting the degeneration. Thus, the NFL state can be captured by the other states like the superconducting one [7, 9, 11]. The diversity of phase transitions occurring at low temperatures is one of the most spectacular features of the physics of HF metals, and is ubiqui-

![FIG. 1: Schematic $T - x/x_c$ phase diagram of the system with FC. The diagram is adapted from [7, 9]. The dimensionless doping $x/x_c$ is the control parameter. The system’s locations are depicted by the arrows. At $x/x_c < 1$ the system is shifted beyond FCQPT, the corresponding location shown by the solid arrow. At $x/x_c < 1$ the system is at its quantum critical line, possesses a flat band, and at any finite temperature the system exhibits the NFL, or critical behavior with the resistivity given by Eq. (1). The dotted line shows the system located at FCQPT, $x/x_c = 1$. The dashed arrow points to the system at $x/x_c > 1$ when it is in the LFL state at sufficiently low temperatures, shown by the shaded area. The vertical arrow shows the system moving from LFL to NFL at $T$ increasing and the control parameter fixed.](https://example.com/fig1.png)
uitous to systems with flat bands.

Let us note that the coefficient $A_1$, see Eq. (1), tracks the doping dependence of both superfluid density $n_s$ at $T = 0$ and $T_c$ [15]. It is seen from Fig. 2 that in high-temperature superconducting overdoped copper oxides where $T_c(x)$ terminates at critical doping value $x_c$, the quite remarkable dependence $A_1(x) \propto T_c(x) \propto n_s(x)$ has been discovered [1, 15]. This exciting behavior has been predicted [6], and explained within the framework of the FC theory [10–12].

The Planckian dissipation and the linear dependence of the resistivity, see Eq. (1), are also explained within the framework of FC theory. It is remarkable that the Planckian dissipation is demonstrated by both strange metals at their quantum criticality and conventional metals [16], since the same physics describes the $\rho(T) \propto T$ dependence of these metals [8, 11, 12], see Fig. 3.

In summary, we have shown that the problems outlined in Review [1] as unresolved enigmas of strange metals, have been explained within the framework of the FC theory. Moreover, there are a few numbers of important features demonstrated by strange metals that have been missed in Review [1]. Among these are (see e.g. [17]):

The universal $T/B$ scaling behavior of the thermodynamic and transport properties, including the negative magnetoresistance of strange metals;

The recent challenging experimental facts regarding the tunneling differential conductivity $dI/dV = \sigma_d(V)$, as a function of the applied bias voltage $V$, that are collected under the application of magnetic field $B$ on the twisted graphene and the archetypical heavy fermion metals YbRh$_2$Si$_2$ and CeCoIn$_5$;

The emergence of the asymmetrical part of the tunneling conductivity (or resistivity) $\Delta \sigma_d = \sigma_d(V) - \sigma_d(-V)$ as well as that $\Delta \sigma_d$ vanishes in magnetic fields, as was predicted [7].

Transition temperature $T_c$ is proportional to the Fermi velocity $V_F$, $V_F \propto T_c$, rather than $1/V_F \propto T_c$, as it takes place in common Bardeen-Cooper-Schrieffer like theories;

Flat bands make $T_c \propto g$, with $g$ being the superconducting coupling constant;

Thus, these recent outstanding experimental results strongly suggest that the topological FCQPT is an intrinsic feature of many strongly correlated Fermi systems, and can be viewed as the universal agent defining their non-Fermi liquid behavior. And the fermion condensation theory is able to explain challenging features exhibited by strongly correlated Fermi systems, including strange metals.

* Electronic address: vrshag@thd.pnpi.spb.ru

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