Note on DC and Hall conductivity in holographic massive Einstein-Maxwell-Dilaton gravity

Zhenhua Zhou $^{1}$, Jian-Pin Wu $^{2,3}$ and Yi Ling $^{1,3}$

$^{1}$ Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

$^{2}$ Department of Physics, School of Mathematics and Physics, Bohai University, Jinzhou 121013, China

$^{3}$ State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China

Abstract

We investigate the holographic DC and Hall conductivity in massive Einstein-Maxwell-Dilaton (EMD) gravity. Two special EMD backgrounds are considered explicitly. One is dyonic Reissner-Nordström-AdS (RN-AdS) geometry and the other one is hyperscaling violation AdS (HV-AdS) geometry. We find that the linear-T resistivity and quadratic-T inverse Hall angle can be simultaneously achieved in HV-AdS models, providing a hint to construct holographic models confronting with the experimental data of strange metal in future.

*Electronic address: zhouzh@ihep.ac.cn
†Electronic address: jianpinwu@mail.bnu.edu.cn
‡Electronic address: lingy@ihep.ac.cn
I. INTRODUCTION

The strange metal phase, which emerges in normal states of high temperature superconductors and heavy fermion compounds near a quantum critical point, exhibits a number of weird transport properties that challenge understanding. The most famous characteristics of the strange metal phase is that its resistivity $\rho(T)$ varies linearly with temperature, while the inverse of Hall angle $\theta_H^{-1}(T)$ varies quadratically with temperature [1–4]. Some theoretical attempts have been made to attack this problem by proposing that there are different scalings between Hall angle and resistivity [5, 6]. However, due to the strongly correlated nature in these materials, a complete resolution to this problem is still absent in theory so far.

AdS/CFT correspondence provides a powerful tool to study strongly correlated systems. In particular, the methods of computing transport coefficients by holography have been developed in [7, 8]. The linear-T resistivity has been solely reproduced by holography in [9, 10]. One mechanism is to consider a Lifshitz gravitational system with Dirac-Born-Infeld (DBI) action, in which the resistivity displays linear property with temperature when the Lifshitz exponent takes a special value of $z=2$ [9]. An alternative is proposed in [10]. They introduced a hydrodynamic state with a minimal viscosity $\eta \sim s$ being weakly coupled to disorder, in which the viscosity will contribute to the resistivity such that $\rho \sim \eta \sim s$. And then by holography, a well-controlled locally quantum critical state with $s \sim T$ [11] is introduced such that one has $\rho \sim T$, i.e., the linear-T resistivity. More recently, progress has been made in addressing different scalings between Hall angle and resistivity by holography [12–16, 19–23]. Particularly, a scaling analysis suggests that the anomalous behaviors $\rho \sim T$ as well as $\theta_H \sim 1/T^2$ can be reproduced in the HV geometry with DBI action [21]. But note that the backreaction of gauge field on the spacetime geometry is ignored in [21]. Another progress is from Ref. [23], in which the resistivity and Hall angle exhibit different scalings in holographic Q-lattice model.

Inspired by the work in [23], in present note we attempt to address this dichotomy between resistivity and the Hall angle in a simpler holographic framework, i.e., massive gravity. The first holographic massive gravity model is constructed in [24] where a finite DC conductivity is observed. Subsequently, a lot of works have also implemented finite DC conductivity in this framework [25–31]. Due to the breaking of diffeomorphism symmetry, the stress-
energy tensor in massive gravity is not conserved, leading to a similar effect of dissipating momentum as that of holographic lattice model [32–44], which has originally been pointed out in [45]. Here, we shall first derive general analytic expressions for the resistivity and the Hall angle in holographic massive EMD gravity in Section II. These expressions are applicable for a larger class of scaling geometries. Specifically, we shall discuss the case of dyonic RN-AdS and HV-AdS geometry in Section III. We conclude this note with a brief discussion on the scale dimension analysis at low temperature.

Note added: While this work was in preparation Ref. [46] appeared, which has some overlap with ours. In addition, we would like to point out that the thermoelectric conductivities at finite magnetic field in holographic Q-lattice model were discussed in [47, 48].

II. DC AND HALL CONDUCTIVITY IN HOLOGRAPHIC MASSIVE EMD GRAVITY

In this section, we shall derive general analytic expressions for DC and Hall conductivity in holographic massive gravity, which can be applicable for a large class of scaling geometries. For this purpose, we generalize the holographic massive gravity action in [24] to the following EMD theory,

$$S = \frac{1}{2\kappa^2} \int d^4x \sqrt{-g} \left[ R - \frac{Z(\phi)}{4} F^2 + \frac{1}{2} (\partial \phi)^2 + V(\phi) + \beta(\phi)([K]^2 - [K^2]) \right].$$  \hspace{1cm} (1)

where $[K] := K^\mu{}_{\mu}$ and $[K^2] := (K^2)_{\mu}{}^\mu$ with $K^\mu{}_{\nu} := \sqrt{g^{-1}} f^\mu{}_{\nu}$ and $(K^2)_{\mu\nu} := K_{\mu\alpha} K^\alpha{}_{\nu}$. $f_{\mu\nu}$ is the reference metric and we are interested in the special case with $f_{\mu\nu} = diag(0, 0, 1, 1)$, which breaks the diffeomorphism along two spatial directions. In comparison with [24, 46], a scalar field is introduced with an arbitrary potential $V(\phi)$, a dilaton-like coupling $Z(\phi)$ as well as a coupling $\beta(\phi)$ with the massive term.

To study the Hall conductivity, we turn on a magnetic field on the background and consider the following ansatz

$$ds^2 = -U(r)dt^2 + V(r)dr^2 + W(r)(dx^2 + dy^2),$$  \hspace{1cm} (2)

$$A = a(r)dt + Bxdy, \quad \phi = \phi(r),$$  \hspace{1cm} (3)

where $B$ is a constant magnetic field. We also assume that $U, V, W > 0$ and at the horizon
position $r_+, U(r_+) = 1/V(r_+) = 0, U(r_+)V(r_+) < \infty$. These assumptions are usually true for general holographic models.

In order to compute the DC and Hall conductivity, we consider vector fluctuations over the homogeneous and isotropic background (2) and (3). Due to the presence of magnetic field, these perturbations will induce electric currents along $x$ and $y$ directions and provide non-zero contributions to the $t - x, t - y, r - x, r - y$ components of the energy-momentum tensor. It turns out that a consistent ansatz for perturbations can be chosen as

$$A_x = -E_x t + a_x(r), \quad A_y = a_y(r), \quad (4)$$

$$\delta g_{tx} := W h_{tx}(r), \quad \delta g_{rx} := W h_{rx}(r), \quad (5)$$

$$\delta g_{tx} := W h_{ty}(r), \quad \delta g_{ry} := W h_{ry}(r). \quad (6)$$

Here, following closely the method outlined in [23, 40], we turn on a constant electric field $E_x$ to detect the DC and Hall conductivity.

With the use of Maxwell equations, one can define the conserved charge $Q$ and the conserved currents $J_x, J_y$ as follows

$$Q := -Z(\phi) \frac{W}{\sqrt{U V}} a'_r, \quad (7)$$

$$J_x := Q h_{tx} - Z(\phi) B \sqrt{\frac{U}{V}} h_{ry} - Z(\phi) \sqrt{\frac{U}{V}} a'_x, \quad (8)$$

$$J_y := Q h_{ty} + Z(\phi) B \sqrt{\frac{U}{V}} h_{rx} - Z(\phi) \sqrt{\frac{U}{V}} a'_y, \quad (9)$$

where the prime denotes the derivative with respect to $r$. The conductivities along $x$ and $y$ directions can be expressed as $\sigma_{xx} = J_x/E_x, \sigma_{xy} = J_y/E_x$, respectively. Because $J_x, J_y$ are conserved along $r$ direction, it is more convenient to evaluate them at $r = r_+$. Thus, the conductivities can be completely determined by the regularity of fluctuation modes at the horizon, which are

$$a'_x = -\sqrt{\frac{U}{V}} E_x + O(r_+ - r), \quad a'_y = O(r_+ - r), \quad (10)$$

$$h_{rx}(r_+) = \sqrt{\frac{U}{V}} h_{tx}(r_+), \quad h_{ry}(r_+) = \sqrt{\frac{U}{V}} h_{ty}(r_+). \quad (11)$$

The currents now can be expressed as

$$J_x = Q h_{tx}(r_+) - Z(\phi)|_{r_+} B h_{ty}(r_+) + Z(\phi)|_{r_+} E_x, \quad (12)$$

$$J_y = Q h_{ty}(r_+) + Z(\phi)|_{r_+} B h_{tx}(r_+). \quad (13)$$
Taking into account the $x - x, r - x, r - y$ components of Einstein equation and evaluating them at $r = r_+$, we can derive the relations between the electric perturbation and metric perturbation as,

\begin{align}
(B^2Z + m)h_{tx} + QBh_{ty} &= QE_x, \quad (14) \\
QBh_{tx} - (B^2Z(\phi) + m)h_{ty} &= -ZBE_x, \quad (15)
\end{align}

where all the variables should be understood as taking values at $r = r_+$ and the variable $m$ is defined as $m := -2\beta(\phi)W(r)$. Putting these solutions into (12) and (13), we obtain the conductivity as

\begin{align}
\sigma_{xx} &= \frac{m(B^2Z^2 + Q^2 + Zm)}{(B^2Z + m)^2 + B^2Q^2} \bigg|_{r_+}, \quad (16) \\
\sigma_{xy} &= \frac{BQ(B^2Z^2 + Q^2 + 2Zm)}{(B^2Z + m)^2 + B^2Q^2} \bigg|_{r_+}. \quad (17)
\end{align}

Finally, the Hall angle $\theta_H := \sigma_{xx}/\sigma_{xy}$ and DC conductivity $\sigma_{DC} := \sigma_{xx}(B = 0)$ are derived as

\begin{align}
\theta_H &= \frac{BQ(B^2Z^2 + Q^2 + 2Zm)}{m(B^2Z^2 + Q^2 + Zm)} \bigg|_{r_+} \approx \frac{BQ}{m} \bigg|_{r_+}, \quad (18) \\
\sigma_{DC} &= Z(\phi) \bigg|_{r_+} + \frac{Q^2}{m} \bigg|_{r_+}. \quad (19)
\end{align}

A similar result has been reported in [23], in which a Q-lattice is introduced instead of massive term to dissipate the momentum.

Furthermore, we would like to compare the expression of $\sigma_{DC}$ with that obtained from a hydrodynamic theory with impurity scattering in [49, 50]. To do so, we define the momentum relaxation timescale $\tau_M^{-1}$ as

\begin{equation}
\tau_M^{-1} = -\frac{s\beta}{2\pi(E + P)}, \quad (20)
\end{equation}

where $s = 4\pi W(r_+)$, $E$ and $P$ are the entropy density, energy density and pressure of the system, respectively. It is interesting enough to notice that the coefficient function $\beta(\phi)$ in massive term plays the same role as the lattice parameter [23], which has also been revealed in [45]. In addition, the first term in (19) still holds for neutral black holes and is interpreted as the creation of particle-hole pairs, independent of momentum relaxation timescale [51, 52]. In [23], this term is proposed as the quantum critical conductivity $\sigma_Q$

\begin{equation}
\sigma_Q = Z(\phi) \bigg|_{r_+}. \quad (21)
\end{equation}
Therefore, the DC conductivity can be expressed as that in [49]

\[ \sigma_{\text{DC}} = \sigma_Q + \frac{Q^2}{E + P} \tau_M. \]  

(22)

Alternatively, one can obtain above results by switching on an AC electric field with frequency \( \omega \) and then taking the limit of \( \omega \to 0 \). Such a consideration can be found in [25, 28].

Moreover, the Hall angle \( \theta_H \) can be expressed in terms of the momentum relaxation timescale as

\[ \theta_H = \frac{BQ}{E + P} \tau_M. \]  

(23)

So far, we have successfully implemented the dichotomy between DC resistivity and the Hall angle in the framework of holographic massive gravity, which provides a new mechanism to realize the anomalous transport behaviors of strange metal. Since the functions \( Z(\phi), \beta(\phi) \) in Eqs. (18) and (19) (or \( \sigma_Q, \tau_M \) in Eqs. (22) and (23)) are quite general and adjustable, following the ideas proposed in [53–55], we can build an effective holographic model confronting with the experimental data. Here we address this issue over some specific backgrounds including dyonic RN-AdS black hole and dyonic HV-AdS black hole in next sections.

III. DC AND HALL CONDUCTIVITY IN SOME SPECIFIC HOLOGRAPHIC MODELS

In this section, we shall consider two explicit massive EMD models in RN-AdS and HV-AdS background, respectively. The corresponding temperature dependence of DC conductivity and Hall angle are obtained via the general expressions above. Especially, we find that the linear-T resistivity and quadratic-T inverse Hall angle can be achieved simultaneously in a HV model with \( z = 6/5 \) and \( \theta = 8/5 \).

A. DC and Hall conductivity in dyonic RN-AdS geometry

For the asymptotic AdS case, we can choose

\[ ds^2 = \frac{1}{r^2}(-f(r)dt^2 + \frac{dr^2}{f(r)} + dx^2 + dy^2). \]  

(24)
A background solution for the action (1) with $V(\phi) = 6$, $Z(\phi) = 1$, $\beta(\phi) := \beta = \text{const.}$ is

$$f(r) = 1 + \beta r^2 - M r^3 + \frac{Q^2 + B^2}{4} r^4,$$

where $M$ is an integral constant determined by $f(r_+) = 0$. The Hawking temperature is

$$T = \frac{3}{4\pi r_+} \left(1 + \frac{\beta r^2_+}{3} - \frac{Q^2 + B^2}{12} r^4_+\right),$$

A straightforward usage of expressions (18) and (19) leads to

$$\theta_H \simeq -\frac{B Q}{2\beta} r^2_+, \quad \sigma_{DC} = 1 - \frac{Q^2}{2\beta} r^2_+.$$  

Take into account the scaling relation $r_+ \sim 1/T$ in AdS background, the resistivity and inverse Hall angle would have the similar behavior of temperature dependence. Thus, it is hardly possible to reproduce the linear-T resistivity and quadratic-T inverse Hall angle simultaneously.

**B. DC and Hall conductivity in dyonic HV-AdS geometry**

Now, we turn to consider the DC and Hall conductivity in dyonic HV-AdS geometry including massive term. For this purpose, we choose

$$ds^2 = r^\theta \left(-\frac{f(r) dt^2}{r^{2z}} + \frac{dr^2}{r^2 f(r)} + r^{-2}(dx^2 + dy^2)\right),$$

where $\theta$ and $z$ are the HV exponent and Lifshitz dynamical exponent, respectively.

Firstly, we study the background solution of such HV model where the coupling functions in action (1) are chosen as follows

$$Z(\phi) \sim e^{\lambda \phi}, \quad \beta(\phi) \sim e^{\sigma \phi}, \quad V(\phi) \sim e^{\gamma_1 \phi} + e^{\gamma_2 \phi},$$

the existence of background solution requires that

$$e^\phi = e^{\phi_0} r^\alpha, \quad \alpha := \sqrt{(2 - \theta)(\theta - 2z + 2)},$$

$$Z(\phi) = Z_0 r^{\theta - 2z + 2},$$

$$\beta(\phi) = (z - 1)(\theta - z - 2) r^{-2},$$

$$V(\phi) = (\theta - 2z)(\theta - z - 2) r^{-\theta} + \frac{\theta - 2z + 2}{4(-z + 2)} B^2 Z_0 r^{-\theta - 2z + 6},$$
where $\phi_0$ is a constant and we require that $(2 - \theta)(\theta - 2z + 2) \geq 0$. $Z_0$ is a free parameter. The background solution is

$$f(r) = 1 - Mr^{-\theta + z + 2} + \frac{Q^2 r^{-\theta + 2z + 2}}{2Z_0(\theta - 2)(\theta - z)} + \frac{B^2 Z_0 r^{-2z + 6}}{4(2 - z)(\theta - 3z + 4)}. \quad (35)$$

The Hawking temperature is given by

$$T = \frac{-\theta + z + 2}{4\pi r_+^2} \left(1 - \frac{(2\theta - 2z - 1)Q^2 r_+^{-\theta + 2z + 2}}{2Z_0(\theta - z - 2)(\theta - 2)(\theta - z)} - \frac{(2z - 5)B^2 Z_0 r_+^{-2z + 6}}{4(\theta - z - 2)(2 - z)(\theta - 3z + 4)} \right). \quad (36)$$

It is easy to check that this dyonic HV-AdS black hole shares the same near horizon geometry with dyonic RN-AdS black hole, i.e., $AdS_2 \times \mathbb{R}^2$, but the asymptotic geometry (UV) is hyperscaling violating characterized by the Lifshitz exponent $z$ and the HV exponent $\theta$. In addition, from Eq. (33) one finds that when $z = 1$ and $\theta = 0$, then $\beta(\phi) = 0$ and the model goes back to that without momentum dissipation. Note that a charged HV-AdS black hole with IR being $AdS_2 \times \mathbb{R}^2$ has been obtained in [56] and other EDM models have also been investigated in [57–60].

Using Eqs. (18) and (19) in section II, the Hall angle and DC conductivity for the HV model can be expressed as

$$\theta_H \sim \frac{BQ r_+^{4 - \theta}}{2(z - 1)(2 + z - \theta)}, \quad (37)$$

$$\sigma_{DC} = Z_0 r_+^{\theta - 2z + 2} + \frac{Q^2 r_+^{4 - \theta}}{2(z - 1)(2 + z - \theta)}. \quad (38)$$

Obviously, when $z = 1$, the DC conductivity becomes infinity due to the absence of momentum dissipation.

Next, consider the case where the first term of the DC conductivity (38) is much larger than the second one. Namely, the DC conductivity is mostly dependent on $\sigma_Q = Z_0 r_+^{\theta - 2z + 2}$. Then, using the scaling relation $r_+ \sim T^{-1/z}$ in HV geometry, we have

$$\theta_H^{-1} \sim T^{\frac{4 - \theta}{z}}, \quad \rho_{DC} = \sigma_{DC}^{-1} \sim T^{\frac{\theta - 2z + 2}{z}}. \quad (39)$$

Therefore, we can achieve the linear-T resistivity and quadratic-T inverse Hall angle simultaneously by setting $z = 6/5$ and $\theta = 8/5$.

Finally, we shall provide a scale analysis to ensure that the results satisfy the scaling law of HV background. We introduce the scale dimension of the coordinates and the electric
scalar potential as follows,

\[
[x] = -1, \quad [t] = -z, \quad [ds^2] = -\theta, \quad [A_t] = z - \Phi,
\] (40)

where \(\Phi\) is introduced for the uniform scaling transformation of the action \[17, 18, 21\]. From above equations, one can derive the scale dimension of other electric variables as

\[
[E] = 1 + z - \Phi, \quad [B] = 2 - \Phi,
\] (41)

\[
[Q] = 2 - \theta + \Phi, \quad [J] = z - \theta + \Phi + 1.
\] (42)

Then, by \(\sigma = J/E\), the scale dimension of the conductivity reads

\[
[\sigma] = -\theta + 2\Phi.
\] (43)

From the expression of the DC conductivity \[35\], we find the second term indeed has the same scale dimension as the conductivity. The first term requires

\[
[Z(\phi)] = -\theta + 2\Phi \quad \text{or} \quad [Z_0] = -2z + 2 + 2\Phi,
\] (44)

which is consistent with the uniform scaling transformation condition

\[
\theta = [R] = [(\partial\phi)^2] = [\beta(\phi)r^{-\theta+2}] = [V(\phi)] = [Z(\phi)F^2].
\] (45)

It is also easy to check the scale invariance of the Hall angle (Eq. \[37\]). Furthermore, we find the system has a correct scaling law even without the additional scaling parameter \(\Phi\).

IV. CONCLUSIONS AND DISCUSSIONS

In this note we have presented a mechanism to implement the dichotomy between the DC resistivity and the Hall angle in massive EMD gravity theory, where the diffeomorphism symmetry is broken along spatial directions and the momentum of the system has dissipation. Following closely the method performed in \[40\], we have derived general analytic expressions for the DC and Hall conductivity which can be applicable for a large class of holographic massive models. Because both gauge field coupling \(Z(\phi)\) and massive coupling \(\beta(\phi)\) are completely free and undetermined, this mechanism can provide a viable road toward an effective holographic field theory confronting with the experimental data.
As examples, we have presented a detailed analysis on the scaling behavior of the DC resistivity and Hall angle in dyonic RN-AdS black hole and dyonic HV-AdS black hole, respectively. The reproduction of both linear-T resistivity and quadratic-T inverse Hall angle in dyonic RN-AdS geometry is still suspensive. However, some surprise occurs in the case of the dyonic HV-AdS geometry including massive gravity term, in which the linear-T resistivity and quadratic-T inverse Hall angle can be simultaneously obtained for $z = 6/5$ and $\theta = 8/5$ at large $\sigma Q$.

Finally we remark that in this note a relation $r_+ \sim 1/T$ has been applied as in most previous literature [21, 22, 61]. It is a good approximation at high temperature when the field parameters $Q$ and $\beta$ are much smaller than $T$ such that the terms containing $\beta$ and $Q$ in Hawking temperature [23] can be ignored. However, at low temperature we must cautiously realize that this relation may not hold anymore. In this circumstance, one could consider the Taylor expansion of thermal observables in powers of the scale invariant quantity such as $T/\sqrt{Q}$ to obtain the behavior of temperature dependence [62].

Acknowledgements

This work is supported by the Natural Science Foundation of China under Grant Nos.11275208, 11305018 and 11178002. Y.L. also acknowledges the support from Jiangxi young scientists (JingGang Star) program and 555 talent project of Jiangxi Province. J. P. Wu is also supported by Program for Liaoning Excellent Talents in University (No. LJQ2014123).

[1] N. E. Hussey, *Phenomenology of the normal state in-plane transport properties of high-$T_c$ cuprates*, J. Phys: Condens. Matter 20 (2008) 123201. arXiv:0804.2984.
[2] R A. Cooper, Y. Wang, B. Vignolle, O. J. Lipscombe, S. M. Hayden, Y. Tanabe, T. Adachi, Y. Koike, M. Nohara, H. Takagi, C. Proust and N. E. Hussey, *Anomalous criticality in the electrical resistivity of La$_{2-x}$Sr$_x$CuO$_4$, Science*, 323, 603 (2009).
[3] Y. Nakayima, K. Izawa, Y. Matsuda, S. Uji, T. Terashima, H. Shishido, R. Settai, Y. Onuki and H. Kontani, *Normal-state Hall Angle and Magnetoresistance in Quasi-2D*
Heavy Fermion CeCoIn$_5$ near a Quantum Critical Point, J. Phys. Soc. Jpn 73, 5 (2004),
\[arXiv:cond-mat/0305203\].

[4] T. R. Chien, Z. Z. Wang and N. P. Ong, Effects of Zn Impurities on the Normal-State Hall Angle in Single-Crystal YBa$_2$Cu$_3$.xZn$_x$.O$_{7-\delta}$, Phys. Rev. Lett. 67, 2088 (1991).

[5] P. W. Anderson, Hall effect in the two-dimensional Luttinger liquid, Phys. Rev. Lett. 67 2092 (1991).

[6] P. Coleman, A. J. Schofield and A. M. Tsvelik, How should we interpret the two transport relaxation times in the cuprates? J. Phys. Cond. Matt 8 9985 (1996), \[arXiv:cond-mat/9609009\].

[7] S. A. Hartnoll, Lectures on holographic methods for condensed matter physics, Class.Quant.Grav. 26 (2009) 224002, \[arXiv:0903.3246\].

[8] C. P. Herzog, Lectures on Holographic Superfluidity and Superconductivity, J.Phys.A A42 (2009) 343001, \[arXiv:0904.1975\].

[9] S. A. Hartnoll, J. Polchinski, E. Silverstein, D. Tong, Towards strange metallic holography, JHEP 1004 (2010) 120, \[arXiv:0912.1061\].

[10] R. A. Davison, K. Schalm, J. Zaanen, Holographic duality and the resistivity of strange metals, Phys. Rev. B 89, 245116 (2014), \[arXiv:1311.2451\].

[11] S. S. Gubser and F. D. Rocha, Peculiar properties of a charged dilatonic black hole in AdS$_5$, Phys.Rev. D 81, 046001 (2010), \[arXiv:0911.2898\].

[12] S. S. Pal, Model building in AdS/CMT: DC conductivity and Hall angle, Phys.Rev. D84 (2011) 126009, \[arXiv:1011.3117\].

[13] S. S. Pal, Approximate strange metallic behavior in AdS, \[arXiv:1202.3555\].

[14] B. Gouteraux, B. S. Kim, R. Meyer, Charged Dilatonic Black Holes and their Transport Properties, Fortsch. Phys. 59 (2011) 723-729, \[arXiv:1102.4440\].

[15] B. S. Kim, E. Kiritsis, C. Panagopoulos, Holographic quantum criticality and strange metal transport, New J. Phys. 14:043045,2012, \[arXiv:1012.3464\].

[16] C. Hoyos, B. S. Kim, Y. Oz, Lifshitz Hydrodynamics, JHEP 1311 (2013) 145, \[arXiv:1304.7481\].

[17] B. Gouteraux, Universal scaling properties of extremal cohesive holographic phases, JHEP 01 (2014) 080, \[arXiv:1308.2084\].

[18] B. Gouteraux, Charge transport in holography with momentum dissipation, JHEP 04 (2014) 181, \[arXiv:1401.5436\].

[19] B. H. Lee, D. W. Pang, C. Park, A Holographic Model of Strange Metals, Int. J. Mod. Phys.
A26 (2011) 2279-2305, [arXiv:1107.5822].

[20] A. Lucas, S. Sachdev, Memory matrix theory of magnetotransport in strange metals, [arXiv:1502.04704].

[21] A. Karch, Conductivities for Hyperscaling Violating Geometries, JHEP 1406 (2014) 140, [arXiv:1405.2926].

[22] S. A. Hartnoll, A. Karch, Scaling theory of the cuprate strange metals, [arXiv:1501.03165].

[23] M. Blake, A. Donos, Quantum Critical Transport and the Hall Angle, Phys. Rev. Lett. 114 (2015) 2, 021601, [arXiv:1406.1659].

[24] D. Vegh, Holography without translational symmetry, [arXiv:1301.0537].

[25] M. Blake, D. Tong, Universal Resistivity from Holographic Massive Gravity, Phys.Rev. D88 (2013) 10, 106004 [arXiv:1308.4970].

[26] A. Amoretti, A. Braggio, N. Maggiore, N. Magnoli, D. Musso, Thermo-electric transport in gauge/gravity models with momentum dissipation, JHEP 1409 (2014) 160 [arXiv:1406.4134].

[27] A. Amoretti, A. Braggio, N. Maggiore, N. Magnoli, D. Musso, Analytic DC thermo-electric conductivities in holography with massive gravitons, Phys. Rev. D 91 (2015), 025002 [arXiv:1407.0306].

[28] R. A. Davison, Momentum relaxation in holographic massive gravity, Phys.Rev. D88 (2013) 086003 [arXiv:1306.5792].

[29] H.B. Zeng and J.-P. Wu, Holographic superconductors from the massive gravity, Phys. Rev. D 90 (2014) 046001 [arXiv:1404.5321].

[30] A. Lucas, S. Sachdev, K. Schalm, Scale-invariant hyperscaling-violating holographic theories and the resistivity of strange metals with random-field disorder, Phys. Rev. D 89, 066018 (2014) [arXiv:1401.7993].

[31] M. Baggioli, O. Pujolas, Holographic Polarons, the Metal-Insulator Transition and Massive Gravity, [arXiv:1411.1003].

[32] G.T. Horowitz, J.E. Santos and D. Tong, Optical Conductivity with Holographic Lattices, JHEP 07 (2012) 168 [arXiv:1204.0519].

[33] G.T. Horowitz, J.E. Santos and D. Tong, Further Evidence for Lattice-Induced Scaling, JHEP 11 (2012) 102 [arXiv:1209.1098].

[34] G.T. Horowitz and J.E. Santos, General Relativity and the Cuprates, JHEP 06 (2013) 087 [arXiv:1302.6586].
[35] Y. Ling, C. Niu, J.-P. Wu and Z.-Y. Xian, *Holographic Lattice in Einstein-Maxwell-Dilaton Gravity*, JHEP 11 (2013) 006 [arXiv:1309.4580].

[36] Y. Ling, C. Niu, J.-P. Wu, Z.-Y. Xian and H.-b. Zhang, *Metal-insulator Transition by Holographic Charge Density Waves*, Phys. Rev. Lett. 113 (2014) 091602 [arXiv:1404.0777].

[37] T. Andrade and B. Withers, *A simple holographic model of momentum relaxation*, JHEP 05 (2014) 101 [arXiv:1311.5157].

[38] B. Goutéraux, *Charge transport in holography with momentum dissipation*, JHEP 04 (2014) 181 [arXiv:1401.5436].

[39] A. Donos and J.P. Gauntlett, *Holographic Q-lattices*, JHEP 04 (2014) 040 [arXiv:1311.3292].

[40] A. Donos and J.P. Gauntlett, *Novel metals and insulators from holography*, JHEP 06 (2014) 007 [arXiv:1401.5077].

[41] A. Donos, B. Goutéraux and E. Kiritsis, *Holographic Metals and Insulators with Helical Symmetry*, JHEP 09 (2014) 038 [arXiv:1406.6351].

[42] A. Donos and J.P. Gauntlett, *The thermoelectric properties of inhomogeneous holographic lattices*, JHEP 1501 (2015) 035 [arXiv:1409.6875].

[43] X. H. Ge, Y. Ling, C. Niu and S. J. Sin, *Holographic transports and stability in anisotropic linear axion model*, [arXiv:1412.8346].

[44] L. Cheng, X.H.Ge and Z. Y. Sun, *Thermoelectric DC conductivities with momentum dissipation from higher derivative gravity*, [arXiv:1411.5452].

[45] M. Blake, D. Tong, D. Vegh, *Holographic Lattices Give the Graviton a Mass*, Phys. Rev. Lett. 112, 071602 (2014), [arXiv:1310.3832].

[46] A. Amoretti and D. Musso, *Universal formulae for thermoelectric transport with magnetic field and disorder*, [arXiv:1502.02631].

[47] M. Blake, A. Donos, and N. Lohitsiri, *Magnetothermoelectric Response from Holography*, [arXiv:1502.03789].

[48] K.-Y. Kim, K. K. Kim, Y. Seo, and S.-J. Sin, *Thermoelectric Conductivities at Finite Magnetic Field and the Nernst effect*, [arXiv:1502.05386].

[49] S. A. Hartnoll, P. K. Kovtun, Markus Müller, and S. Sachdev, *Theory of the Nernst effect near quantum phase transitions in condensed matter, and in dyonic black holes*, Phys. Rev. B 76, 144502 (2007) [arXiv:0706.3215].

[50] S. A. Hartnoll and D. M. Hofman, *Locally Critical Resistivities from Umklapp Scattering*,
[51] A. Karch and A. O'Bannon, *Metallic AdS/CFT*, JHEP 0709 (2007) 024 [arXiv:0705.3870].

[52] A. Donos and J.P. Gauntlett, *Thermoelectric DC conductivities from black hole horizons*, JHEP 1411 (2014) 081 [arXiv:1406.4742].

[53] C. Charmousisa, B. Goutérauxa, B. S. Kim, E. Kiritsis, R. Meyer, *Effective Holographic Theories for low-temperature condensed matter systems*, JHEP 1011 (2010) 151 [arXiv:1005.4690].

[54] B. Goutérauxa, E. Kiritsis, *Generalized Holographic Quantum Criticality at Finite Density*, JHEP 1112 (2011) 036, [arXiv:1107.2116].

[55] B. Goutérauxa, E. Kiritsis, *Quantum critical lines in holographic phases with (un)broken symmetry*, JHEP 1304 (2013) 053 [arXiv:1212.2625].

[56] M. Alishahiha, E. Ó Colgán, H. Yavartanoo, *Charged Black Branes with Hyperscaling Violating Factor*, JHEP 1211 (2012) 137 [arXiv:1209.3946].

[57] A. Salvio, *Holographic Superfluids and Superconductors in Dilaton-Gravity*, JHEP 1209 (2012) 134, [arXiv:1207.3800].

[58] A. Salvio, *Transitions in Dilaton Holography with Global or Local Symmetries*, JHEP 1303 (2013) 136, [arXiv:1302.4898].

[59] D. Roychowdhury, *Holographic charge diffusion in non relativistic branes*, Phys.Lett. B744 (2015) 109-115, [arXiv:1412.0911].

[60] D. Roychowdhury, *Hydrodynamics from scalar black branes*, [arXiv:1502.04345].

[61] E. Mefford, G. T. Horowitz, *A Simple Holographic Insulator*, Phys. Rev. D 90, 084042 (2014) [arXiv:1406.4188].

[62] T. Andrade, B. Withers, *A simple holographic model of momentum relaxation*, JHEP 1405 (2014) 101 [arXiv:1311.5157].