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Holographic response from higher derivatives with homogeneous disorder

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ABSTRACT

In this letter, we study the charge response from higher derivatives over the background with homogeneous disorder introduced by axions. We first explore the bounds on the higher derivatives coupling from DC conductivity and the anomalies of causality and instabilities. Our results indicate no tighter constraints on the coupling than that over Schwarzschild–AdS (SS–AdS) background. And then we study the optical conductivity of our holographic system. We find that for the case with $\gamma_1 < 0$ and the disorder strength $\hat{\alpha} < 2/\sqrt{3}$, there is a crossover from a coherent to incoherent metallic phase as $\hat{\alpha}$ increases. When $\hat{\alpha}$ is beyond $\hat{\alpha} = 2/\sqrt{3}$ and further amplified, a peak exhibits again at low frequency. But it cannot be well fitted by the standard Drude formula and new formula for describing this behavior shall be called for. While for the holographic system with the limit of $\gamma_1 \to 1/48$, the disorder effect drives the hard-gap-like at low frequency into the soft gap and suppresses the pronounced peak at medium frequency.

1. Introduction

The quantum critical (QC) dynamics described by CFT or its proximity physics is strongly coupled systems without quasi-particles descriptions [1] (also refer to [2–10]). In dealing with these problems, a controlled manner in traditional field theory can not usually be performed. The AdS/CFT correspondence [11–14] provides valuable lessons to understand such systems by mapping certain CFTs to higher dimensional classical gravity. Studying the optical conductivity $\sigma(\omega/T)$ by introducing the probe Maxwell field coupled to the Weyl tensor $C_{\mu\nu\rho\sigma}$ in the Schwarzschild–AdS (SS–AdS) black brane background, we find that the behavior of conductivity is similar with one in the superfluid–insulator quantum critical point (QCP) described by the boson Hubbard model [15–17]. It provides possible route to access this kind of problems. Further, to test the robustness of higher derivative (HD) terms, the author of Ref. [18] studies the charge response of a large class of allowed HD terms in the SS–AdS geometry and find some interesting results. Of particular interest is that the optical conductivity displays an arbitrarily sharp Drude-like peak and the bounds found in [15,19] are violated.

Also, we explore the charge transport with Weyl term in a specific thermal state with homogeneous disorder, which is introduced by a pair of spatial linear dependent axionic fields in AdS geometry and is away from quantum critical point (QCP), and new physics is qualitatively found [20]. Of particular interest is that for the positive Weyl coupling parameter $\gamma > 0$, the strong homogeneous disorder drives the Drude-like peak in QCP state described by Maxwell–Weyl system in SS–AdS geometry [15] into the incoherent metallic state with a dip, which is away from QCP. While an oppositive scenario is found for $\gamma < 0$. In addition, the particle-vortex duality in the dual field theory induced by the bulk electromagnetic (EM) duality related by changing the sign of γ is still preserved. Nonetheless, there is still bound for the conductivity as in [15,19]. In this letter, we study the charge response of a large class of HD terms in the specific thermal state with homogeneous disorder. The letter is organized as follows. We describe the holographic setup for a class of HD theory with homogeneous disorder in Section 2. And then the constraints imposing on the HD coupling parameters in the Einstein-axions–AdS (EA–AdS) geometry are explored in Section 3. In Section 4, we mainly study the optical conductivity from HD theory with homogeneous disorder. Finally the conclusion and discussion are presented in Section 5.

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2. Holographic setup

A specific thermal excited state with homogeneous disorder can be holographically described by the EA theory [21],

$$S_0=\int d^4x\sqrt{-g}\Big(R+6-\frac{1}{2}\sum_{I=x,y}(\partial\phi_I)^2\Big)\,, \tag{1}$$

where $\phi_I=\alpha x_I$ with $I=x,y$ and α being a constant. In the action above, there is a negative cosmological constant $\Lambda=-6$, which supports asymptotically AdS spacetimes.[1]

The EA action (1) gives a neutral black brane solution [21]

$$ds^2=\frac{1}{u^2}\Big(-f(u)dt^2+\frac{1}{f(u)}du^2+dx^2+dy^2\Big)\,, \tag{2}$$

where

$$f(u)=(1-u)p(u)\,,\qquad p(u)=\frac{\sqrt{1+6\hat{\alpha}^2}-2\hat{\alpha}^2-1}{\hat{\alpha}^2}u^2+u+1\,. \tag{3}$$

$u=0$ is the asymptotically AdS boundary while the horizon locates at $u=1$. Note that we have parameterized the black brane solution by $\hat{\alpha}=\alpha/4\pi T$ with the Hawking temperature $T=p(1)/4\pi$. Although the momentum dissipates due to the break of microscopic translational symmetry, the geometry is homogeneous and so we refer to this mechanism as homogeneous disorder and $\hat{\alpha}$ denotes the strength of disorder.[2]

Now, we consider the following action beyond Weyl [18]

$$S_A=\int d^4x\sqrt{-g}\Big(-\frac{1}{8g_F^2}F_{\mu\nu}X^{\mu\nu\rho\sigma}F_{\rho\sigma}\Big)\,, \tag{4}$$

where the tensor X is an infinite family of HD terms

$$\begin{aligned}X_{\mu\nu}{}^{\rho\sigma}&=I_{\mu\nu}{}^{\rho\sigma}-8\gamma_{1,1}C_{\mu\nu}{}^{\rho\sigma}-4\gamma_{2,1}C^2I_{\mu\nu}{}^{\rho\sigma}-8\gamma_{2,2}C_{\mu\nu}{}^{\alpha\beta}C_{\alpha\beta}{}^{\rho\sigma}\\&\quad-4\gamma_{3,1}C^3I_{\mu\nu}{}^{\rho\sigma}-8\gamma_{3,2}C^2C_{\mu\nu}{}^{\rho\sigma}\\&\quad-8\gamma_{3,3}C_{\mu\nu}{}^{\alpha_1\beta_1}C_{\alpha_1\beta_1}{}^{\alpha_2\beta_2}C_{\alpha_2\beta_2}{}^{\rho\sigma}+\dots\,.\end{aligned} \tag{5}$$

In the equation above, $I_{\mu\nu}{}^{\rho\sigma}=\delta_\mu{}^\rho\delta_\nu{}^\sigma-\delta_\mu{}^\sigma\delta_\nu{}^\rho$ is an identity matrix and $C^n=C_{\mu\nu}{}^{\alpha_1\beta_1}C_{\alpha_1\beta_1}{}^{\alpha_2\beta_2}\dots C_{\alpha_{n-1}\beta_{n-1}}{}^{\mu\nu}$. g_F^2 is an effective dimensionless gauge coupling and we set $g_F=1$ in the numerical calculation. The action (4) is constructed in terms of double EM field strengths, which is sufficient for linear response, coupled to any number of symmetry-allowed curvature tensors, which go beyond the Weyl action studied in [15,19,20,34–48]. Note that the X tensor possesses the following symmetries

$$X_{\mu\nu\rho\sigma}=X_{[\mu\nu][\rho\sigma]}=X_{\rho\sigma\mu\nu}\,. \tag{6}$$

When we set $X_{\mu\nu}{}^{\rho\sigma}=I_{\mu\nu}{}^{\rho\sigma}$, the theory (4) reduces to the standard Maxwell theory.

Since the action (4) is an infinite family of n powers of the Weyl tensor C, we truncate it to the level $n=2$, which is the 6 derivatives and the focus in this paper. On the other hand, since the effect of the coupling terms γ_1 and γ_2 is similar, we mainly focus on the term of γ_1 through this paper. For convenience, we denote $\gamma_{1,1}=\gamma$ and $\gamma_{2,i}=\gamma_i$ $(i=1,2)$ in what follows.

[1] We have set the AdS radius $L=1$ without loss of generality.

[2] The other models, for instance [22–33], have also been developed to produce the effect of homogeneous disorder.

3. Bounds on the coupling

In this section, we examine the bounds on the coupling over the EA–AdS background (2). To this end, we turn on the perturbations of gauge field and write down the corresponding linearized perturbative equations in momentum space [15,20]

$$\begin{aligned}&A_t'''+\Big(\frac{f'}{f}-\frac{X_1'}{X_1}+2\frac{X_3'}{X_3}\Big)A_t''\\&\quad+\Big(-\frac{\mathfrak{p}^2\hat{q}^2X_1}{fX_3}+\frac{\mathfrak{p}^2\hat{\omega}^2X_1}{f^2X_5}+\frac{f'X_3'}{fX_3}-\frac{X_1'X_3'}{X_1X_3}+\frac{X_3''}{X_3}\Big)A_t'=0\,,\\&A_y''+\Big(\frac{f'}{f}+\frac{X_6'}{X_6}\Big)A_y'+\frac{\mathfrak{p}^2}{f^2}\Big(\hat{\omega}^2\frac{X_2}{X_6}-\hat{q}^2f\frac{X_4}{X_6}\Big)A_y=0\,,\end{aligned} \tag{7}$$

where $\hat{\mathbf{q}}^\mu=(\hat{\omega},\hat{q},0)$ are the dimensionless quantities defined as

$$\hat{\omega}\equiv\frac{\omega}{4\pi T}=\frac{\omega}{\mathfrak{p}}\,,\quad\hat{q}\equiv\frac{q}{4\pi T}=\frac{q}{\mathfrak{p}}\,,\quad\mathfrak{p}\equiv p(1)=4\pi T\,. \tag{8}$$

X_i, $i=1,\dots,6$, are the matrix elements of $X_A{}^B=\mathrm{diag}(X_i(u))$ with $A,B\in\{tx,ty,tu,xy,xu,yu\}$, which encode the essential information of tensor $X_{\mu\nu}{}^{\rho\sigma}$. In particular, $X_1(u)=X_2(u)=X_5(u)=X_6(u)$ and $X_3(u)=X_4(u)$ because of the symmetry of the background geometry (2) and the structure of X tensor (5). Note that here we only consider the equations for A_t and A_y since $A_t'=-\frac{\hat{q}f}{\hat{\omega}}\frac{X_5}{X_3}A_x'$ and we have chosen the radial gauge as $A_u=0$. In addition, the equations of EM dual theory can be obtained by letting $X_i\to\widehat{X}_i=1/X_i$.

3.1. Bounds from DC conductivity

In [18], it has been found that for the SS–AdS geometry and the subspace of $\gamma_1\neq0$ but other parameters vanishing, γ_1 is unconstrained from the anomalies of causality and instabilities. But an additional constraint from $Re\sigma(\omega)\geq0$, especially DC conductivity being positive, gives $\gamma_1\leq1/48$. Here we shall further examine this bound over EA–AdS geometry from conductivity.

To this end, we write down the expression of DC conductivity [15,19,20]

$$\sigma_0=\sqrt{-g}g^{xx}\sqrt{-g^{tt}g^{uu}X_1X_5}\,|_{u=1}\,. \tag{9}$$

It can be explicitly worked out as up to 6 derivatives

$$\sigma_0=1-\frac{2}{3}\gamma f''(1)-\Big(\frac{4}{3}\gamma_1+\frac{1}{9}\gamma_2\Big)f''(1)^2\,, \tag{10}$$

with

$$f''(1)=-2-\frac{4(-1-2\hat{\alpha}^2+\sqrt{1+6\hat{\alpha}^2})}{\hat{\alpha}^2}\,. \tag{11}$$

We can easily find that for arbitrary $\hat{\alpha}$, the upper bound $\gamma_1=1/48$ preserves for other parameters vanishing. Fig. 1 clearly shows this result.

Before closing this subsection, we would like to present some comments on the DC conductivity σ_0 from 6 derivative term. First, similar with the case of 4 derivative term [20], there is a specific value $\hat{\alpha}=2/\sqrt{3}$, for which σ_0 is independent of the coupling parameter γ_1. Second, for the case of 4 derivatives, σ_0 is monotonic function of $\hat{\alpha}$ [20], while for one of 6 derivatives, σ_0 is non-monotonic and has upper/lower bound setting by $\sigma_0=1$.