Schrodinger Fermi liquids

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<tr>
<td>As Published</td>
<td><a href="http://dx.doi.org/10.1103/PhysRevD.89.046008">http://dx.doi.org/10.1103/PhysRevD.89.046008</a></td>
</tr>
<tr>
<td>Publisher</td>
<td>American Physical Society</td>
</tr>
<tr>
<td>Version</td>
<td>Final published version</td>
</tr>
<tr>
<td>Accessed</td>
<td>Mon Apr 25 02:15:18 EDT 2016</td>
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<tr>
<td>Citable Link</td>
<td><a href="http://hdl.handle.net/1721.1/89017">http://hdl.handle.net/1721.1/89017</a></td>
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Schrödinger Fermi liquids

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(Received 28 January 2013; published 27 February 2014)

A class of strongly interacting many-body fermionic systems in $2+1$-dimensional nonrelativistic conformal field theory is examined via the gauge-gravity duality correspondence. The five-dimensional charged black hole with asymptotic Schrödinger isometry in the bulk gravity side introduces parameters of background density and finite particle number into the boundary field theory. We propose the holographic dictionary, and realize a quantum phase transition of this fermionic liquid with fixed particle number by tuning the background density $\beta$ at zero temperature. On the larger $\beta$ side, we find the signal of a sharp quasiparticle pole on the spectral function $A(k, \omega)$, indicating a well-defined Fermi surface. On the smaller $\beta$ side, we find only a hump with no sharp peak for $A(k, \omega)$, indicating the disappearance of the Fermi surface. The dynamical exponent $z$ of quasiparticle dispersion goes from being Fermi-liquid-like $z = 1$ scaling at larger $\beta$ to a non-Fermi-liquid scaling $z = 3/2$ at smaller $\beta$. By comparing the structure of Green's function with Landau Fermi liquid theory and Senthil’s scaling ansatz, we further investigate the behavior of this quantum phase transition.

I. INTRODUCTION

Experimental physics on strongly interacting nonrelativistic many-body bosonic and fermionic systems develops rapidly on account of the progress of controlling ultracold atoms [1–3]. The dynamical exponent $z$ of those microscopic states is usually $z \neq 1$, along with other well-known condensed matter systems such as non-Fermi liquid metals from heavy fermions and high $T_c$ superconductor (see [4,5] and reference therein), beyond the paradigm of Landau Fermi liquid theory. In this strongly coupling regime, the traditional perturbative field theory study has been challenged, while holography, specifically anti-de Sitter space and conformal field theory (AdS/CFT) correspondence [6–8], becomes a powerful alternative. Holographic methods have shown some success in the study of certain strongly interacting fermion systems [9–12], with the emergence of Fermi liquid and non-Fermi liquid behavior. (See [13–15] for reviews on the holography applied to condensed matter physics.) However, there are at least two major shortcomings to bridge this gap and tackle the two aforementioned shortcomings.

Substantial works in the literature had contributed to understand nonrelativistic conformal field theory (NRCSF) ([17–19] and references therein), as a renormalization group fixed point of the nonrelativistic systems. Its gravity dual theory had been proposed, with solutions of zero temperature pure Schrödinger (Schr) geometry [20,21], finite temperature black holes [22–24], and charged black holes [25,26]. There has been some pursuits on studying fermions in this asymptotic Schrödinger geometry [27–29]. However, to our knowledge, the holographic study of the Fermi surface from strongly interacting fermions with NRCFT background has not yet been explored in the literature. Our paper is aimed to bridge this gap and tackle the two aforementioned shortcomings.

The Schrödinger black hole in the bulk gravity theory, on one hand, realizes an asymptotic NRCFT background with the dynamical exponent $z = 2$ for the boundary field theory naturally. On the other hand, the Schrödinger black hole provides the particle number (or the mass operator [30]) $M$ from the gauge invariant $\xi$ momentum: $M = \xi - qA_{\xi}\big|_{q=0}$ [30] and background density $\beta$ to the nonrelativistic boundary field theory. Our approach is similar to the AdS/CFT setup [10], considering a Dirac fermion field in the probe limit under a charged black hole spacetime, the Green’s function can be read from the asymptotic behavior of Dirac fermion field in the UV of the bulk side. Here we also propose the holographic dictionary of a real-time retarded Green’s function for fermions in Schr/NRCFT correspondence.
[31], analog to the work of [32] for the AdS/CFT case. For convenience, we name these classes of strongly interacting nonrelativistic fermionic liquids under asymptotic NRCFT background as Schrödinger Fermi liquids.

The paper is organized as follows. First, we discuss the charged Schrödinger black hole solution and its Dirac fermion equation of motion, to introduce our notations in Sec. II. We then provide our holographic dictionary [31] analog to the setting of [10,32] in Sec. III. In Sec. IV, we demonstrate the zero temperature nearly ground state of this fermion system shows a sharp quasiparticle peak in the spectral function—the evidence of Fermi surface, with a non-Fermi liquid dispersion relation. We compare our spectral functions $A(k, \omega)$ of Schrödinger Fermi liquids with Landau Fermi liquid theory and Senthil’s scaling ansatz [33,34]. In Sec. V, we show the evidence of a quantum phase transition, by tuning the background density $\beta$ but fixing the particle number at zero temperature. On the larger $\beta$ side, we find a well-defined Fermi surface. On the smaller $\beta$ side, we find only a hump with no sharp peak for $A(k, \omega)$, indicating the disappearance of Fermi surface. The dynamical exponent $z$ of the quasiparticle dispersion goes from Fermi-liquid-like scaling $z = 1$ at larger $\beta$ to larger $z (=3/2)$ non-Fermi liquid at smaller $\beta$. Finally, we conclude with some remarks and open questions in Sec. VI.

Our program code for numerical computation is shared through Supplemental Material [35].

II. SETUP: DIRAC FERMION FIELD IN A CHARGED SCHRODINGER BLACK HOLE

Based on the holography, a quantum field theory of finite charge density can be mapped to a charged black hole of a gravity theory [10]. The U(1) charge of the Schrödinger black hole induces finite charge density to the boundary field theory, which meanwhile breaks the nonrelativistic conformal invariance. Thus, we only have “asymptotic” NRCFT. Before we discuss the details of bulk gravity theory, it will be helpful to introduce generic labels for a large class of NRCFT (with charge and mass densities) we will study. We characterize our asymptotic NRCFT by five parameters, $(\Delta, M, \mu_Q, \beta, T)$ [30]. Two parameters, the conformal dimension $\Delta$ and the mass operator $M = \ell - qA_{\xi}/\beta$ from the gauge invariant $\xi$ momentum, define the boundary NRCFT in a universal sector. The U(1) charge chemical potential $\mu_Q$ and other relevant terms from the current $J_\mu$ (such as charge density $\rho_Q$ and mass density $\rho_M$) in NRCFT is mapped to the U(1) gauge field $A_\mu$ of the bulk gravity. Background density $\beta$ is introduced by the Schrödinger black hole through Null Melvin Twist (or TsT transformation) [22–26]. The physical way to interpret this $\beta$ could be the density of doping background, or an analog of interaction strength $\ell/U$ of the Hubbard model.\(^1\)

Temperature $T$ of the boundary theory is given by the black hole temperature $T_{BH}$. Notably, the conformal dimension of NRCFT here depends on the mass operator $M$, which is quite different from CFT. More peculiarly, the conformal dimension for spinors has an extra $\Delta$ splitting, as already noticed in [27,28]. In the following we denote dimension $d$ as the spatial dimension of $x_1, x_2, \ldots, x_d$. The asymptotic Schrödinger bulk spacetime is denoted as $\text{Schr}_{d+3}$ (distinguished from the AdS$_{d+2}$, where as the corresponding boundary theory of $\text{Schr}_{d+3}$ is NRCFT$_{d+3}$ (CFT$_{d+1}$ for AdS$_{d+2}$). We summarize the conformal dimensions of the spin-0 boson [30] and spin-1/2 fermion operator ([27,28]) in Table I.

Table I. Conformal dimensions of CFT and NRCFT for spin-0 boson and spin-1/2 fermion.

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<th>Asymptotics</th>
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<th>Schr$_{d+3}$</th>
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<td>Scalar conformal dimension</td>
<td>$\Delta_s = \frac{d+1}{2} \pm \sqrt{(\frac{d+1}{2})^2 + m^2}$</td>
<td>$\Delta_s = \frac{d+2}{2} \pm \sqrt{(\frac{d+2}{2})^2 + m^2 + M^2}$</td>
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<tr>
<td>Spinor conformal dimension</td>
<td>$\Delta_s = \frac{d+1}{2} \pm m$</td>
<td>$\Delta_s = \frac{d+2}{2} \pm (m \pm \frac{1}{2})^2 + M^2$</td>
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A. Charged Schrödinger black hole

We focus on $d = 2$, five-dimensional (5D) Schrödinger black hole $\text{Schr}_3$ in the bulk and $2 + 1$D NRCFT$_3$ on the boundary. Let us briefly go through our setup for the charged $\text{Schr}_3$. In string frame, the metric is

$$ds^2_{\text{St}} = \frac{K r^2}{R^2} \left(-f dt^2 + dy^2 - \beta^2 r^2 f (d\tau + dy)^2\right) + \frac{r^2}{R^2} (dx_1^2 + dx_2^2) + \frac{R^2 dr^2}{r^2 f},$$

where $R$ is curvature radius. By converting to light-cone-like coordinates, $t = \beta (\tau + y)$, $\xi = \frac{1}{2\beta} (-\tau + y)$, and switching to the Einstein frame for the later use of holographic dictionary,

$$ds^2_{\text{Ein}} = K^{-1/3} \left(\frac{K r^2}{R^2} \left(\left(1 - f \beta^2 r^2 f\right) dt^2 + \beta^2 (1 - f) d\xi^2 + (1 + f) d\tau d\xi\right) + \frac{r^2}{R^2} (dx_1^2 + dx_2^2) + \frac{R^2 dr^2}{r^2 f}\right),$$

where $f(r) = 1 + \frac{\mu_Q}{r} - (r_0^4 + \frac{\mu_Q}{r_0^4}) \frac{1}{2}, \ K(r) = \frac{1}{1 + \beta^2 r^2 (1 - f(r))}$. The charged black hole supports a gauge field

\(^1\)Indeed $\beta$ has dimension [length]$^1$, so the “background density over area” with correct dimension should be defined as $\beta^{-2}$. We simply name $\beta$ as background density for convenience.
\[ A = A_0 dr, \quad A_r = \frac{Q}{r^2 r_0} \left( 1 - \frac{r_0^2}{r^2} \right). \] (2.2)

Adopted in [30] notation for later use, \( A = \frac{A_0}{r_0^2} dt - \beta A_0 d\xi = A_0 dt + A_0 d\xi, \) with
\[ A_0 = \mu_Q + \rho_0 r^{-2}, \quad A_\xi = M_0 + \rho_M r^{-2}. \] (2.3)

By holography [30], \( \mu_Q \) is identified as U(1) charge chemical potential, \( \rho_0, \rho_M \) are the charge density and mass density, \( M_0 \) is related to the mass operator by \( M = \ell - q A_\xi |_{\ell} = \ell - q M_0 \) with \( \ell \) as the \( \xi \) momentum. The temperature of the black hole is given by identifying the inverse of the near-horizon Euclidean periodicity of boundary time coordinate \( t, \)
\[ T_{BH} = \frac{r_0}{\pi \beta r^2} \left( 1 - \frac{Q^2}{2r_0^2} \right). \] (2.4)

Our interest of study is the boundary field theory at zero temperature, which corresponds to the extremal black hole with \( Q = \sqrt{2r_0^3} \). This being said, all the numerical analysis contained in this paper pertains to zero temperature only. At zero temperature, the charged black hole Schrödinger horizons degenerate, meanwhile the near horizon geometry becomes AdSAdS2 \( \times \mathbb{R}^3 \), with
\[ ds^2 = -c^2 dt^2 / R_{AdS_1}^2 + R_{AdS_2}^2 (d\xi^2 / c^2) + r_0^2 d\tilde{x}^2 / R_{AdS_2}^2, \]
where other unwritten components of \( c^2 = \frac{1}{(1 + \beta r^2)^{1/6}} \). Asymptotically, \( B(r \to \infty) = \frac{1}{r} + \frac{3\beta}{2r^2} + \frac{3(4-4\beta^2-3\beta^4)}{16r^4} + \cdots \). The near-horizon behavior of \( B = B_0 / (r - 1) \), where \( B_0 \) is a constant. Given \( B_0 = 1 \), we can numerically solve this equation to find \( B_0 \). In 5D spacetime, each of \( \Gamma^a \) matrices has \( 4 \times 4 \) components, we choose to express them as follows:

\[ \Gamma_\tau = \begin{pmatrix} 0 & i \sigma_3 \\ i \sigma_3 & 0 \end{pmatrix}, \quad \Gamma_y = \begin{pmatrix} 0 & -iI \\ iI & 0 \end{pmatrix}, \quad \Gamma_{x_1} = \begin{pmatrix} 0 & \sigma_2 \\ \sigma_2 & 0 \end{pmatrix}, \quad \Gamma_{x_2} = \begin{pmatrix} 0 & \sigma_1 \\ \sigma_1 & 0 \end{pmatrix}, \quad \Gamma_\tau = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}. \]

\( \sigma_1 \) are Pauli sigma matrices, \( I \) is identity matrix. \( \Gamma_i = \beta (\Gamma_{\tau} + \Gamma_y), \quad \Gamma_\xi = (-\Gamma_{\tau} + \Gamma_y) / (2\beta) \). Rewrite the four-component Dirac spinor field \( \psi \) as
\[ \psi = \begin{pmatrix} \psi^+ \\ \psi^- \end{pmatrix} e^{-i\alpha + i\beta^{-1/4} + ik_{x_1} + ik_{x_2}} e^{i\alpha - i\beta^{-1/4} + ik_{x_1} + ik_{x_2}}, \] (2.9)
where \( \psi^+ \) and \( \psi^- \) are two-component spinors. This \( (-gg^{-r})^{-1/4} \) factor eliminates a \( \Gamma_\tau \) term in the Dirac equation, which is simplified to
\[ (r \sqrt{\beta} \partial_\tau \pm m K^{-1/6}) \phi_\pm \]
\[ \pm \left( \pm u + pv \sigma_3 + ik_{x_1} + \frac{k_{x_2}}{r} \right) \phi_\mp = 0, \] (2.10)
where \( u \) and \( v \) are linear combinations of the vielbein components \( e^\xi_i, e^\xi_\xi, e^\xi_1, \) and \( e^\xi_2 \):
\[ u = K^{-1/4} \left( o + q A_{\xi} \right) \left( -\beta e^\xi_1 + \frac{1}{2\beta} e^\xi_2 \right), \]
\[ (e^\xi + q A_{\xi}) \left( \beta e^\xi_1 + \frac{1}{2\beta} e^\xi_2 \right). \] (2.11)

---

2See Appendix A for details.

3For convenience, we rescale the coordinates to set \( R = r_0 = 1 \) from now on.
\begin{equation}
v = K^{-\frac{1}{2}} \left( (\omega + qA_\xi) \left( \beta e^{\xi} - \frac{1}{2\beta} e^{\xi} \right) \right) + (\ell - qA_\xi) \left( -\beta e^{\xi} + \frac{1}{2\beta} e^{\xi} \right).
\end{equation}

By rotational symmetry of the boundary theory, we will work on the case \( k_1 = 0 \) and set \( k_2 = k \) from here on. We will write \( \phi = (\phi_+, \phi_-)^T \), also its \( \phi_+ = (y_+, z_+)^T \) and \( \phi_- = (y_-, z_-)^T \) in the component form.

III. GREEN’S FUNCTION FROM HOLOGRAPHY

A. Holographic dictionary

We study the fermionic response of the boundary theory, by probing the Dirac fermion field in the bulk spacetime of the Schrödinger black hole. The holographic dictionary of source-response relation can be set up by reading the boundary action of Eq. (2.5). From [32,36], the variation of bulk action induces a boundary term \( S_\partial = \int_{\partial M} d^3x d\xi \sqrt{-g} \bar{\psi} \gamma^\nu \psi \). Therefore the relation between bulk field and its conjugate momentum are

\begin{equation}
\Pi_+ = -\sqrt{-g} \bar{\psi} \gamma^\nu \psi, \quad \Pi_- = \sqrt{-g} \bar{\psi} \gamma^\nu \psi_+.
\end{equation}

We can identify the source \( \chi \) and response \( \mathcal{O} \) from boundary (or UV) behavior of bulk field \( (\psi \pm) \) and momentum \( (\Pi \pm) \), from the holographic dictionary,

\begin{equation}
\exp[-S_{\text{grav}}(\psi, \bar{\psi})(r \to \infty)] = \left( \exp \left[ \int d^{d+1}x (\bar{\chi} \mathcal{O} + \bar{\mathcal{O}} \chi) \right] \right)^{\text{QFT}}.
\end{equation}

The source \( \chi \) and bulk field \( \psi \) are related by

\begin{equation}
\chi = \lim_{r \to \infty} r^{\frac{d+1}{2}} \psi,
\end{equation}

the response \( \mathcal{O} \) and momentum \( \Pi \pm \) are related by

\begin{equation}
\mathcal{O} = -\lim_{r \to \infty} r^{\frac{-d+1}{2}} \Pi,
\end{equation}

where \( \nu = \sqrt{(m \pm 1/2)^2 + (\ell + qM)^2} \) generically,\(^4\) analogue to the result of [32]. Here we show only the standard quantization (corresponding to source \( A \) and response \( D \) of [32]). The alternate quantization (corresponding to source \( C \) and response \( B \) of [32]) can be done in the same manner.\(^5\) The Green’s function \( G_\mathcal{O} \) is related to the ratio of \( \mathcal{O} \) and \( \chi \).

We now study the Dirac equation (2.10) in the boundary UV asymptotic limit to extract \( \mathcal{O} \) and \( \chi \) from the coefficients of \( \psi \) and \( \Pi \), or equivalently related to \( \phi_+ \) and \( \phi_- \) at \( r \to \infty \). In this limit, (2.10) becomes

\begin{equation}
(r \sqrt{\int d^3x m K^{-1/6}}) \phi_\pm + \left( \frac{(\ell + qM)^2}{2\beta} \right) P_\pm + C \frac{r}{r} P_\pm + \frac{2\beta(\ell + qM)^2}{r} P_\pm \pm \frac{ik_1}{r} \sigma_2 \pm \frac{ik_2}{r} \sigma_1 \phi_\pm = 0,
\end{equation}

where

\begin{equation}
C = \frac{1}{2}(4 qM(1 + \beta^2) + 5(\ell + qM)^2 \beta^3 - (\ell + qM)^2 \beta^3 - 8(1 + \beta^2)),
\end{equation}

\begin{equation}
P_\pm = \frac{1 \pm \sigma_3}{2}.
\end{equation}

\begin{equation}
\phi_+ = S_1 r^{\nu_+ - 1} \left( \alpha_1 + 2 r^2 \right) + R_1 r^{\nu_+ - 1} (\alpha_1 + \alpha_2 r^2) + S_2 r^{\nu_+ - 1} (\beta_1 + 2 r^2) + R_2 r^{\nu_+ - 1} (\beta_1 + \beta_2 r^2) + \cdots,
\end{equation}

\begin{equation}
\phi_- = S_1 r^{\nu_- - 1} \left( \alpha_1 + 2 r^2 \right) + R_1 r^{\nu_- - 1} (\alpha_1 + \alpha_2 r^2) + S_2 r^{\nu_- - 1} (\beta_1 + 2 r^2) + R_2 r^{\nu_- - 1} (\beta_1 + \beta_2 r^2) + \cdots,
\end{equation}

here

\begin{equation}
\nu_\pm = \sqrt{(m \pm 1/2)^2 + (\ell + qM)^2}.
\end{equation}

Each of \( S_1, S_2, R_1, R_2 \) is an \( r \)-independent one-component multiplier, as the coefficient of the spinor.\(^6\) There is a projection relation between the two-component spinors:\(^7\)

\(^5\)For the alternate quantization,

\begin{equation}
\mathcal{O} = \lim_{r \to \infty} r^{\frac{-d+1}{2}} \Pi,
\end{equation}

\(^6\)When doing numerics for this field redefinition, it is important to keep subleading term \( C_2 \) in the \( S_1 r^{\nu_\pm - 1} (\cdots + C_2 r^{\nu_\pm - 1} \cdots) \) series, since this \( C_2 \) term dominates \( R_1 r^{\nu_\pm - 1} \alpha_1 \) when \( \nu_+ > \frac{1}{2} \), which is indeed our case in the numerical study. Thus here we keep the expansion for all four sets of solutions to the subleading orders.

Each of \( A_1, A_2, C_1, C_2, \alpha_1, \alpha_2, \gamma_1, \gamma_2, B_1, B_2, D_1, D_2, \beta_1, \beta_2, \delta_1, \delta_2 \) is a two-component spinor. List above totally there are sixteen two-component spinors. The spinors \( C_1, C_2, \gamma_1, \) and \( \gamma_2 \) are in the null space of \( P_+ \), the spinors \( B_1, B_2, \beta_1 \), and \( \beta_2 \) are in the null space of \( P_- \). There are four independent sets of bases, each basis as a solution of Dirac EOM; the first set contains \( A_1, A_2, C_1, C_2 \) and its subleading terms, the second set contains \( \alpha_1, \alpha_2, \gamma_1, \gamma_2 \) and its subleadings, the third set contains \( B_1, B_2, D_1 \) and its subleadings, the fourth set contains \( \beta_1, \beta_2, \delta_1, \delta_2 \) and its subleadings.
\[
\begin{align*}
S_1 C_1 &= -\frac{(\ell + qQ\beta)}{2\beta(\nu_+ + m + \frac{1}{2})} P_- S_1 A_1, \\
S_2 B_1 &= -\frac{(\ell + qQ\beta)}{2\beta(\nu_- - m - \frac{1}{2})} P_+ S_2 D_1, \\
R_1 \gamma_1 &= -\frac{(\ell + qQ\beta)}{2\beta(-\nu_+ + m + \frac{1}{2})} P_- R_1 \alpha_1, \\
R_2 \beta_1 &= -\frac{(\ell + qQ\beta)}{2\beta(-\nu_- - m + \frac{1}{2})} P_+ R_2 \delta_1. 
\end{align*}
\] (3.10)

We now apply our holographic dictionary to identify the source and response from (3.7) and (3.8). To read the boundary value, in the following we take \( r \to \infty \) as the UV limit. Consider the leading behavior of the field contribution,

\[\psi_- = (-gg^r)^{-1/4} \phi_- = r^{-2} \phi_- \approx S_1 C_1 r^{\nu_- - 3/2}\] (3.12)

which corresponds to the source \( \chi_- \).

\[\chi_- = \lim_{r \to \infty} r^{\nu_- - \frac{1}{2}} \psi_- \approx S_1 C_1, \quad (3.13)\]

\( \chi_- \) is proportional to \( S_1 \). The momentum field \( \Pi_- \) is

\[\Pi_- = \sqrt{-gg^r} \psi_- = (-gg^r)^{1/4} \phi_- = r^2 \phi_- \approx S_1 A_1 r^{\nu_- + 3/2} + \ldots \] (3.14)

which corresponds to the response \( O_- \).

\[O_- = \lim_{r \to \infty} r^{\nu_- - \frac{1}{2}} \Pi_- \approx R_1 \alpha_1. \] (3.15)

We take the asymptotic constant term on the UV boundary, \( O_- \) is proportional to \( R_1 \).

On the other hand, we can go through the same logic again, though consider the leading behavior of \( \phi_+ \) contribution,

\[\psi_+ = (-gg^r)^{-1/4} \phi_+ = r^{-2} \phi_+ \approx S_2 B_1 r^{\nu_+ - 3/2}\] (3.16)

which corresponds to the source \( \chi_+ \).

\[\chi_+ = \lim_{r \to \infty} r^{\nu_+ - \frac{1}{2}} \psi_+ \approx S_2 B_1, \quad (3.17)\]

\( \chi_+ \) is proportional to \( S_2 \). The momentum field \( \Pi_+ \) is

\[\Pi_+ = -\sqrt{-gg^r} \psi_+ = -(-gg^r)^{1/4} \phi_+ = -r^2 \phi_+ \approx -S_2 D_1 r^{\nu_+ + 3/2} - R_2 \delta_1 r^{\nu_+ - 3/2} + \ldots \] (3.18)

which corresponds to the response \( O_+ \).

\[O_+ = -\lim_{r \to \infty} r^{\nu_+ - \frac{1}{2}} \Pi_+ \approx R_2 \delta_1. \] (3.19)

\( O_+ \) is proportional to \( R_2 \). Now we derive \( S_1, S_2 \) are identified as sources, \( R_1, R_2 \) are identified as responses for this standard quantization. A similar argument works for the alternative quantization by taking the subleading terms of the bulk field and its conjugate momentum; we leave this detail to Appendix C.

In addition to the above dictionary, we provide another intuitive argument on identifying source and response. We notice the boundary action \( \bar{\psi} \psi \) due to the \( \Gamma_7 \) form; it couples the first component of the spinor \( \psi \) to the third component of \( \psi_+ \), which couples the second component of \( \psi_+ \) to the fourth component of \( \psi \). Both two-point function or \( \bar{\psi} \psi \) shows \( r^{2\nu_+} \) scaling in (27) and (28) and our work. However, the \( r^{2\nu_-} \) scaling is only seen in our and the Green’s functions of [28]. We will perform a more constructive comparison with (27) and (28) and a pure Schrödinger Green’s function computation via our dictionary in Appendix D. Lastly, we are aware that the detailed construction of the Schr/NRCFT holographic dictionary involves nontrivial holographic renormalization [28,37,38]. Our work here only follows the strategy in Refs. [10,32] constructing the source-response holographic dictionary. The rigorous holographic renormalization for spinors is the future step to justify the complete dictionary for the Green’s function.

B. Source and response from UV expansion

To extract the data of source and response, we define a converting matrix \( C \) as a function of \( r \) (see Appendix B and a shared program code through a URL link), and a set of functions \( S_i(r) \), \( S_j(r) \), \( R_1(r) \), \( R_2(r) \) satisfies

\[\nu(r) = (\nu_+ r)\nu_-(r)) = (\nu_+ z_+(r)\nu_-(z_+(r)))) \]

\[= C_v \cdot [S_1(r)R_1(r)S_2(r)R_2(r)]^T. \] (3.20)

By this field definition, neatly \( S_1(r) \), \( S_2(r) \), \( R_1(r) \), \( R_2(r) \) approach to \( S_1 \), \( S_2 \), \( R_1 \), \( R_2 \) as \( r \to \infty \). Due to projection, we find the spinors have the properties \( \epsilon_{1+} = \epsilon_{2+} = \gamma_{1+} = \gamma_{2+} = \beta_{1-} = \beta_{2-} = 0 \).

To deal with the standard quantization, from the lesson of Sec. III A, we choose \( \epsilon_{1-} = 1 \) to compute the first set of bases, \( \alpha_{1-} = 1 \) to compute the second set of bases, \( \beta_{1-} = 1 \) to compute the third set of base, and \( \delta_{1+} = 1 \) to compute the fourth set of bases. Each of four independent bases in (3.7) and (3.8) (equivalently in (B2), see 9), can be determined by a free parameter, thus totally four free parameters. Now the four free parameters for four independent bases are \( S_1, S_2, R_1, R_2 \). Argue from Sec. III A, for the standard quantization, the source terms are \( S_1 C_1, S_2 B_1 \), with their corresponding response terms \( R_1 \alpha_1, R_2 \delta_1 \), respectively. Our choice of spinor \( C_v^T = (0, 1) \) and its coupled spinor \( \alpha_1^T = (a_{1+}, 1) \) justifies that coefficient \( S_1 \) is exactly a source and \( R_1 \) is its response. Our choice of spinor \( B_1^T = (1, 0) \) and its coupled spinor \( \delta_1^T = (1, \delta_{1-}) \)
justifies that coefficient \( S_2 \) is exactly a source and \( R_2 \) is its response.\(^8\)

### C. IR behavior and the infalling boundary condition

To determine the near horizon initial condition of the Dirac equation, here we deal with IR behavior and solve the infalling boundary condition at zero temperature, \( Q = \sqrt{2} \).

Consider the small \( e \) expansion of the equations, where \( r = 1 + e \). The equation for \( B(r) \) becomes \( \frac{d^2 B}{dr^2} = -\frac{1}{e} \). Thus, we take the behavior of \( B(r) \) near horizon as \( B_h = B \), another constant, \( \lim_{r \to 1} (r - 1) B(r) = B_h \). For the later use, we define

\[
\tilde{\omega} = \frac{\ell}{2\beta} + \beta \omega, \tag{3.21}
\]

\( \tilde{\omega} \) is the coefficient of \( \tau \) in the exponent dependence of Eq. (2.9). We find that the behavior of \( f, u, v \) in the IR is given by

\[
f \rightarrow 12e^2, \quad u \rightarrow i\tilde{\omega} U, \quad v \rightarrow i\tilde{\omega} V \tag{3.22}
\]

with \( U = \frac{i}{4\sqrt{3}} \left( \frac{2\sqrt{3}b}{p} - \frac{\beta^2}{2\sqrt{3}b} \right) \) and \( V = \frac{i}{4\sqrt{3}} \left( \frac{2\sqrt{3}b}{p} + \frac{\beta^2}{2\sqrt{3}b} \right) \).

The Dirac equation near horizon and its infalling wave function ansatz are

\[
e^{i\tilde{\omega} r} = \frac{-i}{2\sqrt{3}} \tilde{\omega} (U \pm V \sigma_3) \phi_\pm \tag{3.23}
\]

\[
\phi_\pm \propto e^{i\tilde{\omega}/(12e)}, \tag{3.24}
\]

The exponent of wave function \( \phi_\pm \) is chosen to be a + sign, in order to combine with Eq. (2.9) to be \( e^{-i\tilde{\omega} r + i\tilde{\omega}/(12e)} \) infalling into the black hole.\(^9\) The infalling condition is obtained by plugging Eq. (3.24) into Eq. (3.23), where the subscript \( H \) stands for values at the horizon:

\[
\phi_\pm|_H = (U + V \sigma_3) \phi_\pm|_H. \tag{3.25}
\]

The infalling condition for spinors has two linear independent choices, the first set is \( \phi_{\pm 1} = (1, 0) \) thus \( \phi_{\mp 1} = (U + V, 0) \), and the second set is \( \phi_{\pm 2} = (0, 1) \) thus \( \phi_{\mp 2} = (0, U - V) \).

\(^8\)For the alternate quantization, we should alternatively choose \( a_{\pm 1} = 1 \) to compute the first set of bases, \( \gamma_{-1} = 1 \) to compute the second set of bases, \( d_{\pm 1} = 1 \) to compute the third set of bases, \( \rho_{\pm 1} = 1 \) to compute the fourth set of bases. From Sec. III A, the source terms are \( S_2 D_1, S_1 A_1 \); with their corresponding response terms \( R_2 \beta_1, R_1 \gamma_1 \), respectively. Our choice of spinor \( A_1 = (d_{\pm 1}, 1) \) and its coupled spinor \( \beta_1 = (0, 1) \) justifies that coefficient \( S_1 \) is exactly a source and \( R_1 \) is its response. Our choice of spinor \( D_1 = (1, d_{\pm 1}) \) and its coupled spinor \( \gamma_1 = (1, 0) \) justifies that coefficient \( S_2 \) is exactly a source and \( R_2 \) is its response.

\(^9\)The 12 factor appearing here originates from the near horizon geometry \( \text{AdS}_2 \).

Therefore this gives two independent sets of initial conditions at horizon for \( S_1 \) (\( R_1 \) \( S_2 \) \( R_2 \)) where we introduce one more upper indices 1, 2 to distinguish the first and the second sets:

\[
[S_1^T(r) R_1^T(r) S_2^T(r) R_2^T(r)]|_H = C_1^{-1}|_H \cdot (\phi_{\pm 1} \phi_{\mp 1})|_H
\]

\[
= C_1^{-1}|_H \cdot (U + V \sigma_3)^T,
\]

\[
[S_1^T(r) R_1^T(r) S_2^T(r) R_2^T(r)]|_H = C_2^{-1}|_H \cdot (\phi_{\pm 2} \phi_{\mp 2})|_H
\]

\[
= C_2^{-1}|_H \cdot (0U - V \sigma_3)^T.
\]

More conveniently in matrix form,

\[
S(r) = \begin{bmatrix}
S_1^T(r) & S_2^T(r) \\
S_1^T(r) & S_2^T(r)
\end{bmatrix}, \quad R(r) = \begin{bmatrix}
R_1^T(r) & R_2^T(r) \\
R_1^T(r) & R_2^T(r)
\end{bmatrix}
\]

### D. Green’s function

Green’s function of the boundary theory is defined to be the ratio between source matrix \( S(r) \) and response matrix \( R(r) \). Thus we define \( G(r) \) based on \( R(r) = G(r)S(r) \), and evaluate \( G(r) \) at \( r \to \infty \), to read the \( 2 \times 2 \) matrix Green’s function \( G \) of the boundary theory,\(^10\)

\[
G = \lim_{r \to \infty} G(r) = \lim_{r \to \infty} R(r)S(r)^{-1}. \tag{3.26}
\]

We derive the EOM of \( G(r) \) in the bulk gravity (see Appendix B), and solve this EOM with the initial condition: \( G(r)|_H = R(r)|_H \cdot S(r)^{-1}|_H \) to obtain physical results of Eq. 3.26.

### IV. SPECTRAL FUNCTION \( A(k, \omega) \)

We now equip with the holography tool developed in Secs. II and III. The original questions driving our interests are: What is the nearly ground state of this fermionic system under asymptotic \( \text{NRQCD} \) background at zero temperature? Will there be a Fermi surface? Will Fermi surface collapse, destabilized by tuning non-temperature parameters (such as background density \( \beta \))? Will this realize a certain quantum phase transition of fermionic liquids? With the holographic dictionary for Green’s function, we proceed to study these questions. We focus on \( Q = \sqrt{2} \) as zero temperature phase.

The spectral function \( A(k, \omega) \) of this boundary system can be determined by the imaginary part of Green’s function. In \( 2 + 1 \) D boundary theory with \( 2 \times 2 \) matrix

\(^10\)There is no extra \( \Gamma^\ast \) factor multiplied with \( G(r) \) for this Green’s function, because in our dictionary sources and responses are related to the coefficients of two-component spinors, instead of spinors itself.
factor should be important when justifying the spectral density

ters, conformal dimensions

SCHRÖDINGER FERMI LIQUIDS PHYSICAL REVIEW D 89, proposal to study the trace part[11], Im

indication. In addition, we are aware that there is an alternative

cal potential (of background) data [39] sum rule is

The usual angle resolved photoemission spectroscopy (ARPES)

case of gauge-gravity duality, the modification of the ARPES

A source field or response field. Namely, the

G, we should take eigenvalues of G, namely,

\[ \text{Im}[G(r \to \infty)_{\text{eigenvalues}}]. \]

A. Fermi surface

This nonrelativistic fermionic system has five parameters, conformal dimensions \( \Delta_{\pm}(\nu_{\pm}) \), temperature \( T \), chemical potential (of background) \( \mu_Q \), particle number eigenvalue or mass \( M \), and background density \( \beta \). We first study the background density at \( \beta = 1/\sqrt{2} \) at \( T = 0 \). The gauge-invariant mass operator \( M \equiv \ell - qM_o = \ell + qQ/\beta \) is fixed to be \( 1/10 \). The Dirac fermion charge \( q = 1 \), its mass is chosen to be \( m = 1/10 \), nonzero value in order to

\[ A(k, \omega) = -\frac{1}{\pi} \text{Im}[G]. \]  

The usual angle resolved photoemission spectroscopy (ARPES) data [39] sum rule is \( \int_0^\infty A(k, \omega)d\omega = 1 \) [39]. This ARPES sum rule holds in a nonrelativistic system. The relativistic version of sum rule is written as, see Ref. [40], \( \int_0^\infty \omega A(k, \omega)d\omega = 1 \). In the context of gauge-gravity duality, the modification of the ARPES sum rule has been studied [41], e.g., see a comment at Eq. (5.27) of Ref. [41]. To produce any of the above sum rules, we comment on a subtlety in Schrödinger holography. When we relate the \( d + 3 \)-gravity theory to a \( d + 1 \)-boundary theory via Eq. (3.2), the constant factor \( \int d^2 \vec{\xi} L_2 \) needs to be absorbed into \( \int d^{d+1}x(\vec{\mathcal{Q}} + \mathcal{Q})/\beta \); this gives an extra constant factor for source field or response field. Namely, the \( A(k, \omega) \) may be different from \( \text{Im}[G] \) with another extra constant factor. This factor should be important when justifying the spectral density sum rule, \( \int_0^\infty A(k, \omega)d\omega = 1 \). The exact value of our \( \text{Im}[G] \) is less informative, only the relative height of \( \text{Im}[G] \) has physical indication. In addition, we are aware that there is an alternative proposal to study the trace part [11], \( \text{Im}[\text{Tr}[G(r \to \infty)]] \).

\[ \text{FIG. 1 (color online). At } \beta = 1/\sqrt{2}, (a) \text{ the imaginary part of Green’s function, } \text{Im}[G_1] \text{ as a function of } \omega \text{ and } k. \text{ A sharp quasi-particle-like pole at } \omega_F = 0.8984, k_F = 1.3169 \text{ indicates a well-defined Fermi surface. The pole indicates an infinite lifetime stable quasi-particle at } k_F. \text{ Notice the main branch of dispersion goes into } \omega < \omega_F \text{ and } k > k_F, \text{ a hole-like excitation. While in [10], their main branches of dispersion goes into } \omega > \omega_F \text{ and } k > k_F, \text{ a particle-like excitation. (b) The imaginary part of Green’s function, } \text{Im}[G_2] \text{ as a function of } \omega \text{ and } k; \text{ it is more or less featureless, except a wedge-like structure.} \]

avoid scaling dimension \( \nu_{\pm} \) degeneracy and extra logarithmic term in UV expansion.

Similar to [10], among two eigenvalues (say \( G_1, G_2 \)) one of the eigenvalues, \( G_1 \) with its imaginary \( \text{Im}[G_1] \) has shown a pole-like structure [see Fig. 1], thus is picked for detailed studies in our analysis. The other eigenvalue \( G_2 \) with its imaginary \( \text{Im}[G_2] \), only shows less-distinguished wedge-like structure [see Fig. 1], which appears to be less interesting physically. Following [10], we focus on studying one of these eigenvalues, \( G_1 \). Below we will simply abbreviate \( \text{Im}[G_1] \), \( \text{Re}[G_1] \) as \( \text{Im}G_1 \), \( \text{Re}G_1 \). We find there is a sharp pole on \( \text{Im}[G_1] \) at \( \omega_F = 0.8984, k_F = 1.3169 \), indicating a stable quasi-particle like excitation at Fermimomentum \( k_F \). This indicates a well-defined Fermi surface. Normally the location of Fermi surface on the \( \omega \) axis is shifted by chemical potential \( \mu \), one redefines \( \bar{\omega} = \omega - \mu \) thus \( \bar{\omega} = 0 \) has the Fermi surface. In our case, \( \omega_F \) is shifted by the presence of \( \xi \) momentum \( \ell \), this can be realized from the fact that the location of Fermi surface is determined mainly from the low energy IR physics, which in the bulk gravity corresponds to the near horizon region. Thus, instead of using boundary time coordinate \( t \) and its coupled conjugate energy \( \omega \), we identify the near-horizon time coordinate \( \tau \) and its conjugate energy \( \bar{\omega} \). When \( \bar{\omega} = (\frac{\ell}{Q} + \beta \mu)|_{\omega_F} = 0 \), namely \( \omega_F = -\ell/(2\beta Q) \), its value indicates the pole location of a Fermi surface. Denote \( k_{\perp} \equiv |k - k_F| \), we find near the quasiparticle like peak has scalings,

\[ \omega_\ell (k_{\perp}) \sim k_{\perp}^z, \quad z = 1.14 \quad (4.2) \]

\[ \text{Im}[G_1(\omega_\ell (k_{\perp}), k_{\perp})] \sim k_{\perp}^{-\alpha}, \quad \alpha = 1.00. \quad (4.3) \]
In Fig. 2, we show the imaginary part \( \text{Im}[G_1] \) and real part \( \text{Re}[G_1] \) of Green’s function; see the location of the Fermi surface indicates a pole in \( \text{Im}[G_1] \) and switches the sign of \( \text{Re}[G_1] \). The main branch of dispersion goes into \( \omega < \omega_F \) and \( k > k_F \), which is a holelike excitation. The result is different from [10], where their main branches go into a particlelike excitation with \( \omega > \omega_F \) and \( k > k_F \). In Fig. 3, the dispersion relation shows particle-hole asymmetry in large scale, though close to \( (\omega_F, k_F) \) it gives a unique dynamical exponent \( z \).

**B. Comparison to Landau Fermi liquid theory and Senthil’s scaling ansatz**

To better understand the physics of Green’s function \( G(k, \omega) \), we now study the functional form of \( G(k, \omega) \) in terms of two different classes. Both classes hold under general arguments. The first class is Landau Fermi liquid theory, which holds for the weak coupling system, where the free fixed point is still a good description of the system. The second class is even more general based on scaling ansatz for non-Fermi liquid theory and critical Fermi surface, proposed by Senthil [33,34]. In Landau Fermi liquid (LFL) theory, the retarded Green’s function is of the form

\[
G(k, \omega) = \frac{1}{\omega - \xi_k - \Sigma(\omega, k)}
\]

\[
= \frac{1}{\omega - (\xi_k + \text{Re}\Sigma(k, \omega)) - i\text{Im}\Sigma(k, \omega)}
\]

\[
= \frac{Z}{(\omega - \omega_F - \xi_k + \frac{\gamma(\omega)}{2\tau_k}}.
\]

(4.4)

\( \Sigma(\omega, k) \) is the particle irreducible retarded self-energy. \( \xi_k \equiv \varepsilon_k - \mu \) is the excitation around the original chemical potential. The condition \( \xi_k + \text{Re}\Sigma(k_F, \omega_F) = \omega_F \) to define renormalized Fermi-momentum \( k_F \). The final form is obtained by expanding \( \xi_k + \text{Re}\Sigma(k, \omega) \) around \( (k_F, \omega_F) \), with the definition of quasiparticle residue \( Z \), with \( Z^{-1} = 1 - \frac{\partial}{\partial \omega}\text{Re}\Sigma(k_F, \omega_F) \), also \( \xi_k \equiv (k - k_F)Z \frac{\partial}{\partial \omega}(\xi_k + \text{Re}\Sigma(k, \omega_F)) \equiv v(k - k_F) \), and quasiparticle decay rate \( 1/\tau_k = -2Z\text{Im}\Sigma(k, \omega) \). The specific LFL form we use to fit our Green’s function is

\[
G = \frac{Z}{(-(\omega - \omega_F) - v(k - k_F)) - i\gamma(\omega)}
\]

(4.5)

with our quasiparticle self-energy ansatz as \( \gamma(\omega) = \kappa(\omega - \omega_F)^n \), where \( \kappa \) is some real constant, LFL has...
We will take general $n$ for fitting ansatz. We flip the sign of $(\omega - \omega_F)$ to have a holelike dominant excitation as Fig. 3 suggests.

The scaling ansatz proposed by Senthil [33, 34] based on general arguments, has the form at $T = 0$,

$$
G = c_0(k - k_F)^{-\alpha}F_0\left(\frac{c_1(\omega - \omega_F)}{(k - k_F)^n}\right). 
$$

(4.6)

In order to have the best fitting, we will be forced to choose $c_0$ and $c_1$ their values on two sides $\omega > \omega_F$ and $\omega < \omega_F$ differently to reflect particle-hole asymmetry.

In the following subsections, we present our Green’s function data for $k < k_F$, $k = k_F$, and $k \approx k_F$, and fit these data by LFL and Senthil’s ansatz. The main message of fitting our data (Figs. 4, 5, and 6) to LFL and Senthil’s ansatz (Figs. 7, 8, and 9) are:

1. Senthil’s ansatz generally has better agreement than LFL fitting for our $\text{Im} G_1$ data.

2. Our $\text{Re} G$ data are sandwiched by the LFL fitting with LFL fitting with $n = 2$ and marginal Fermi liquid (MFL) with $n = 1$ [42, 43], which likely implies that our Schrödinger Fermi liquids can be a closer description between LFL and MFL theory with $1 < n < 2$. From our quasiparticle self-energy ansatz as $\gamma(\omega) = \kappa(\omega - \omega_F)^n$ and quasiparticle decay rate $1/\tau_k \sim \gamma(\omega)$, this may suggest Schrödinger Fermi liquids have shorter lifetime.

$n = 2$. We will take general $n$ for fitting ansatz. We flip the sign of $(\omega - \omega_F)$ to have a holelike dominant excitation as Fig. 3 suggests.

The scaling ansatz proposed by Senthil [33, 34] based on general arguments, has the form at $T = 0$,
and larger decay rate $1/\tau_k \sim (\omega - \omega_F)^2 - \epsilon$ than LFL $1/\tau_k \sim (\omega - \omega_F)^2$ close to Fermi energy $\omega_F$. Compared to LFL, the quasiparticle description of Schrödinger Fermi liquids is less robust.

(3) Near the pole location, we have not found a promising fitting for Senthil’s ansatz for both sides of $\omega > \omega_F$ and $\omega < \omega_F$.

1. $k < k_F$

For $k < k_F$, our scaling ansatz is

$$\frac{c_0(k-k_F)^{-\alpha}}{\log(c_1(k-k_F)^{1/2}) + i\gamma_0). \tag{4.8}$$

2. $k > k_F$

For $k > k_F$, our scaling ansatz is

$$\frac{c_0(k-k_F)^{-\alpha}}{\log(c_1(k-k_F)^{1/2}) - i\gamma_0). \tag{4.9}$$

FIG. 8 (color online). $k = 8/5 > k_F$, both (a) and (b) with three fitting curves: (1) LFL Eq. (4.5) with $n = 2$ in the gray-dashed line, (2) LFL Eq. (4.5) with $n = 1$ in the purple-dashed line, and (3) scaling ansatz form Eq. (4.10) in the black-dot-dashed line. $c_0, c_1, \gamma_0$ are chosen to be positive but their values on two sides $\omega > \omega_F$ and $\omega < \omega_F$ are chosen differently.

FIG. 9 (color online). $k = k_F$, both (a) and (b) with two fitting curves: (1) LFL Eq. (4.5) with $n = 2$ in the gray-dashed line, (2) LFL Eq. (4.5) with $n = 1$ in the purple-dashed line. At $k = k_F$, scaling ansatz of both forms Eq. (4.8) and Eq. (4.10) runs into trouble. We have not yet found a good fitting.

For $\omega < \omega_F$ under $k < k_F$, the term inside logarithmic becomes negative, where we choose the complex logarithm as follows:

$$\frac{c_0(k-k_F)^{-\alpha}}{\log(c_1(k-k_F)^{1/2}) + i\gamma_0). \tag{4.7}$$

For $\omega > \omega_F$ under $k > k_F$, the term inside logarithmic becomes negative, where we choose the complex logarithm as follows:

$$\frac{c_0(k-k_F)^{-\alpha}}{\log(c_1(k-k_F)^{1/2}) - i\gamma_0). \tag{4.9}$$

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energy quantum phase transition of fermionic liquids. In addition, the coordinate \( \sim +l \) and the coordinate \( \sim -l \) are fixed. We choose \( M = \delta_1 \) for the system in Sec. VA, we encounter again the phase with Fermi surfaces, gradually tune down \( \beta \) near 1/2; we find a critical point (or critical line) in Sec. VB. Smaller \( \beta \) shows that Fermi surface collapses and then disappears in Sec. VC. Altogether this may indicate a quantum phase transition of fermionic liquids.

\[ \beta = 1/2, \quad \text{Im} \ G_1(k_F, \omega_F) = Z \delta(k - k_F, \omega - \omega_F) + \text{finite terms}, \quad \text{where } Z \neq 0. \quad (5.1) \]

\[ \beta = 1/2, \quad \text{Im} \ G_1(k_F, \omega_F) = Z \delta(k - k_F, \omega - \omega_F) + \text{finite terms}, \quad \text{with } Z \to 0. \quad (5.2) \]

Since the \( Z \) goes to zero at finite \( \beta = 1/2 \), we suspect it is not a smooth crossover behavior. We expect a quantum critical point \( \beta^* \) (or quantum critical line) slightly larger than \( \beta = 1/2 \), and smaller than \( \beta = 1/\sqrt{2} \). For convenience, we denote \( \beta^* \approx 1/2 \), as in Fig. 11. We do not numerically determine \( \beta^* \) due to the computational limitation. A more detailed scan near the peak at \( \beta \approx 1/2 \) may determine the exact value of \( \beta^* \).

FIG. 10 (color online). \( \text{Im} \ G_1 \) of Schrödinger Fermi liquids for \( \beta > \beta^* \); (a) \( \beta = 2 \); (b) \( \beta = 1 \).

A. Well-defined Fermi surface (\( \beta > \beta^* \))

When \( \beta > 1/2 \), an obvious peak appears in \( \text{Im} \ G_1 \), see Fig. 10. Analytically the peak should approach \( \delta(k - k_F, \omega - \omega_F) \) at \( (k_F, \omega_F) \). However, the numerical value \( \text{Im} \ G_1(k_F, \omega_F) \) cannot really be infinite. What we find is that the peak \( \text{Im} \ G_1(k_F, \omega_F) \) values in this region \( \beta > 1/2 \) depends on the finite IR cutoff. The smaller the initial cutoff \( c = r - 1 \), the larger the numerics \( \text{Im} \ G_1(k_F, \omega_F) \) at the peak grows. This is a sign for the suppose-to-be infinite pole. The pole of \( \text{Im} \ G_1 \) indicates a well-defined Fermi surface. At larger \( \beta \), the pole and nearby region on the \( (k, \omega) \) plane develops much sharper. Notice that the pole shifts to larger \( \omega_F \) and smaller \( k_F \) by decreasing \( \beta \).

B. Near the quantum critical point (\( \beta \approx \beta^* \))

As \( \beta \) approaches in the range between \( 1/\sqrt{2} \) and \( 1/2 \), we find the \( \text{Im} \ G_1(k_F, \omega_F) \) peak becomes insensitive to IR finite cutoff \( c \), the peak values are lower for smaller \( \beta \), shown in Fig. 11. The stable peak value indicates there is no \( \delta \)-function-like pole on the \( (k, \omega) \) plane. By tuning \( \beta \) to a smaller value, the Fermi surface gradually collapses and disappears. We interpret the physics as
C. Fermi surface collapse and disappearance ($\beta < \beta^*$)

At smaller $\beta < 1/2$, we find no sharp peak but only a smoother hump. Unlike the Mott insulator for Mott transition [33,34], we do not have gaps opened up in $A(k, \omega)$. Indeed $A(k, \omega)$ does not dip to zero in this phase. There is no nonanalyticity in $A(k, \omega)$ to pinpoint $k_F$. This shows it is still a gapless phase but with Fermi surface disappearance. We show a series of $\text{Im} G_1$ plots by varying $\beta$ in Figs. 10–12. Note that the vertical axes for $\text{Im} G_1$ shows no tick marks, we only show a landscape scanning through many slices of $\text{Im} G_1$. Each slice of $\text{Im} G_1(k, \omega)$ has a fixed $\omega$, and scanning $k$ values. Each slice of $\text{Im} G_1$ has been shifted vertically for a clear vision of the landscape. As in footnote 11, we had discussed the $L_z^c$ size of the compact $\xi$ circle modifies $\text{Im} G_1$ to the physical value of $A(k, \omega)$. Therefore, here the exact value of $\text{Im} G_1$ is immaterial; only the relative height of $\text{Im} G_1$ matters.

![Diagram](image1)

FIG. 11 (color online). $\text{Im} G_1$ of Schrödinger Fermi liquids near $\beta^*$: (a) $\beta = 1/\sqrt{2}$; (b) $\beta = 1/2 = \beta^*$.

![Diagram](image2)

FIG. 12 (color online). $\text{Im} G_1$ of Schrödinger Fermi liquids for $\beta < \beta^*$: (a) $\beta = 1/4$; (b) $\beta = 1/16$.

![Diagram](image3)

FIG. 13 (color online). (a) The relation between $z$ and $\beta$ for six data points are: $\beta = 1/4$, $z = 1.593$, $\beta = 1/2$, $z = 1.299$, $\beta = 1/\sqrt{2}$, $z = 1.143$, $\beta = 1$, $z = 1.050$, $\beta = 2$, $z = 1.021$, $\beta = 8$, $z = 1.009$. (b) For various $\beta = 1/4$, 1/2, $1/\sqrt{2}$, 1, 2, the Fermi momentum and energy ($k_F, \omega_F$) are (0.0000303, 2.020), (0.8762, 1.212), (1.317, 0.8984), (1.789, 0.656), (2.8304, 0.3266).
D. Evolutions of dynamical exponent $z$ and Fermi-momentum $k_F$ under tuning background density $\beta$

Here we study the evolutions of the dynamical exponent $z$, Fermi energy $\omega_F$, and Fermi-momentum $k_F$ while tuning $\beta$ in Figs. 13 and 14. When $\beta \lesssim \beta^*$, there is no good quasiparticle description for the system, so in which case $(\omega_F, k_F)$ means the $(\omega, k)$ coordinates of the highest peak in spectral function, $z$ just means the dispersion reading from the branches structure around the highest peak.

In all of the data above, $\alpha = 1.00$, thus our data follows the general relation $z \geq \alpha$ and $z \geq 1$ as Senthil’s argument [33,34]. As $\beta$ increases, $z$ goes close to 1. Tentatively it suggests a more Landau Fermi liquids like behavior at the large $\beta$ limit. Though from the spectral density fitting, we find the imaginary part of quasiparticle does not obey $\gamma(\omega) \propto \omega^2$ and $\text{Im}[G_1(k, \omega)]$ near $k_F$ is not symmetric with respect to $\omega_F$. These two features are distinct from LFL. The large $\beta$ limit is at most a close cousin of LFL.

In Sec. IV A, we showed $\omega_F = -\epsilon/(2\beta^2)$. In the case of tuning $\beta$ while fixing the mass operator $\epsilon - qM_\alpha = \epsilon + qQ \beta = M$, we expect $\omega_F(\beta) = -(M - qQ \beta)/(2\beta^2)$. We show this power law fitting agrees with our data in Fig. 14. On the other hand, the Fermi-momentum $k_F$ requires better understanding of UV physics; we do not have a fitting here.

VI. CONCLUSION AND OPEN QUESTIONS

In summary, we have studied a class of strongly interacting nonrelativistic fermions under asymptotic NRCFT background in $2+1D$. We make some efforts to deal with the aforementioned two shortcomings of AdS space. First, our model has a better realization of nonrelativistic properties of many-body systems, and we have observed the well-defined Fermi surface of Schrödinger Fermi liquids. Second, by tuning the background density $\beta$ with fixed particle number $M$, we realized a fermionic quantum phase transition as Fig. 15, where the larger $\beta$ side shows a sharp Fermi surface, while the smaller $\beta$ side shows Fermi surface disappearance. We find Senthil’s scaling ansatz generally a better fit than Landau Fermi liquid (LFL) to our non-Fermi liquids. Based on quasiparticle self-energy scaling, we argue the quasiparticle description of Schrödinger Fermi liquids has shorter lifetime and is less stable comparing to LFL.

We leave some questions for future directions: (1) Quasiparticle residue $Z$ may be regarded as the order parameter for the quantum phase transition. How does $Z$ in Eq. (5.1) behave near the quantum critical point (or line); what is the order of phase transition? We have not yet been able to answer these questions. It will be illuminating to understand whether Schrödinger Fermi liquids shows discontinuous 1st, or continuous 2nd order or higher order transition, and the possibility to realize similar phase transitions proposed in [33,34]. It is also noteworthy that the location of poles has been captured very well analytically by the speculated curve $\omega_F(\beta) = -(M - qQ \beta)/(2\beta^2)$ as in Fig. 14, though we see numerical data slightly deviated from the analytic curve (at three digits after the decimal mark). It will be important to know the physical mechanism or subleading corrections for this deviation.

(2) Notably the charge or particle number U(1) symmetry are unbroken in our probe limit. Fermi surface and gauge-gravity duality relation are mentioned in [44,45], especially the relation between a global U(1) symmetry and the existence of Fermi surface. How does our system realize

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FIG. 14 (color online). (a) The location of the $\text{Im}[G_1]$ peak at $\omega_F$ varies with respect to $\beta$. The numerical data points compared to the dashed curve fitting $\omega_F(\beta) = -(M - qQ \beta)/(2\beta^2)$. (b) The location of the Fermi-momentum $k_F$ varies with respect to $\beta$.

FIG. 15. The zero $T$ quantum phase transition diagram of Schrödinger Fermi liquids. A phase with Fermi surface (FS) appears in $\beta > \beta^*$. A quantum critical region near $\beta = \beta^*$ (it is undetermined yet whether $\beta^*$ is a critical point or critical line, and unknown whether the transition is 1st order or higher order). A phase without Fermi surface appears in $\beta < \beta^*$. Note to tune a dimensionless coupling $g_\beta$, we can define $g_\beta \equiv \beta \sqrt{\mu_Q}$ with $\mu_Q$ fixed.
a quantum phase transition with Fermi surface disappearance without breaking global U(1) symmetry or translational symmetry? Our attention is brought to an earlier work [30], where we consider a toy model of bosonic system under asymptotic NRCFT, where a U(1) symmetry is broken by condensed boson fields around the Schrödinger black hole. The bosonic quantum phase transition is likely found there at low temperature phase as Fig. 16. It is unavoidable to ask whether these two phase transitions in Figs. 15 and 16 have any similar nature. On one side, $\beta > \beta^*$ of Fig. 15 shows a conducting phase with Fermi surface with unbroken U(1) symmetry; the $\Omega > \Omega_0$ side of Fig. 16 shows a metallic state with unbroken U(1) symmetry. On the other side, $\beta < \beta^*$ of Fig. 15 shows Fermi surface disappearance; the $\Omega < \Omega_0$ side of Fig. 16 shows a superfluid state with broken U(1) symmetry. Though the two systems have similar asymptotic NRCFT background, one should be aware that the two systems are rather different. The bulk side of the fermionic model has a charged Schrödinger black hole, where the gauge field is chosen to be fixed, the Dirac fermion is in a probe limit. On the other hand, the bulk side of the bosonic model in [30] has a neutral Schrödinger black hole, where both the gauge field and bosons are in a probe limit. The comparison with a Hawking-Page-like transition such as [46] would be interesting. Another possible future direction is studying the effective Schrödinger potential with the density $\beta$ dependence along the lines of [47–49].

3) It will be illuminating to address more about the phase with Fermi surface disappearance. In the phase without Fermi surface, there is no superconducting gap opened up in the spectral function. Specifically we do not introduce any pairing term (such as Yukawa spinor-scalar pairing) in the bulk action, so it is not a superconducting phase.\(^{16}\) We only can suspect that tuning $\beta$ from large to small effectively implies tuning fermion interaction from weaker coupling to stronger coupling—from more Fermi-liquid-like ($z = 1$) to non-Fermi liquids ($z > 1$) to strongly correlation smear the $A(k, \omega)$ discontinuity into continuity near $\omega_F$, $k_F$. Whether one can understand more about the nature of this Fermi surface disappearance, we leave this for future study.

4) It is of considerable interest to perform rigorous holographic renormalization for spinors to justify the holographic dictionary of Green’s function, following [28,37,38]. The issue of the proposed counterterms, being totally local [28] or nonlocal [37], has not found complete agreement in the literature. We remark that the discrepancy in holographic renormalization seems to persist and remains to be satisfactorily resolved.

On the other hand, a subtle issue is that the conformal dimensions $\Delta$ of Schrödinger spinors have $\nu_\pm$ with peculiar $m \pm 1/2$ dependence, distinct from the AdS case [10,32]. In the AdS case, there are two sets of two component spinors (in [10,32] notation, $D$ and $A$ for the standard quantization, $B$ and $C$ for the alternate quantization). In the Schrödinger case, there are doubled sectors, i.e. $\nu_+$ sectors (as $S_1$, $R_1$) and $\nu_-$ sectors (as $S_2$, $R_2$) shown in Eqs. (3.7) and (3.8). There is only one independent parameter left for each projected spinor in each sector. One may wonder why the Green’s function in the Schrödinger case does not possess the two-component spinor structure as in the AdS case? We emphasize that Green’s function with two-component spinor structure (such as the result of [27]) has two problems. First, it is known that the (two-component) spinor structure does not appear in a free nonrelativistic fermion theory (analogous to nonrelativistic bosons) as discussed in [28]. At this level, [28] and our work find an agreement—there is no apparent gamma matrices/spinor structure in the final two-point fermionic Green’s function. The second problem is that we find that this approach will sacrifice the distinction between the standard quantization and the alternate quantization, which is unreasonable. These two known issues seem to suggest our dictionary is a sensible approach.

While we may not have the final word in the correct prescription, our results show very interesting physical features, in particular the numerical results for the Fermi frequency matches closely an analytic guess based on physical reasoning. This should be another piece of supporting evidence that we are capturing the correct physics.

5) Our model is a $2 + 1$D fermionic system. It will be important to study a system in $3 + 1$D which may exhibit fermions at unitarity [19,20]. It will also be interesting to explore dynamical exponents other than $z = 2$. Indeed gravity duals of finite density systems with asymptotic Schrödinger isometry for $d \neq 2$, $z \neq 2$ are known [23,52,53].

6) The Schrödinger black hole at zero temperature has finite entropy, which implies that our theory may not describe a unique ground state but an ensemble of low energy states. Moreover, it has been pointed out that discrete light-cone quantization and $\beta$ deformation from the parent AdS black hole [22–24,54,55] causes peculiar free energy scaling $F \sim -T^4/\mu^2$ for the system. It will be

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\(^{16}\)A setup along [50,51] is the next-step toward boson-fermion interaction, with a superconducting state under NRCFT background.
interesting to know whether bosons or fermions with a full consideration of spacetime backreaction can change the physics of our study, especially the IR AdS\(^2\) geometry.

(7) It will be interesting to explore the electron star [56–59] in the context of Schrödinger asymptotic geometry.

**ACKNOWLEDGMENTS**

We would like to thank A. Adams, G. Baskaran, L. Y. Hung, N. Iqbal, H. Liu, R. Mahajan, J. McGreevy, D. Mross, Y. Nishida, K. Rajagopal, T. Senthil, D. Vegh, and W. Witzczak-Krempa for valuable discussions. This work is supported by the U.S. Department of Energy under cooperative research agreement Contract No. DE-FG02-05ER41360 and NSF Grants No. DMR-1005541, No. NSFC 11074140, and No. NSFC 11274192. Research at Perimeter Institute is supported by the Government of Canada through Industry Canada and by the Province of Ontario through the Ministry of Research.

**APPENDIX A: AdS\(^2\) SCALING**

The near horizon geometry of the charged Schrödinger black hole can be obtained by taking \( r = r_0 + \epsilon \), with the coordinate redefinition:

\[
\tilde{t} = K_0^{-1/3} \left( \tau + \frac{\beta^2 r_0^2}{1 + \beta^2 r_0^2} \right), \quad \tilde{y} = \frac{K_0^{1/6}}{\sqrt{12}} y, \quad \tilde{x}_i = \frac{K_0^{-1/3}}{\sqrt{12}} x_i,
\]

where \( K_0 = (1 + \beta^2 r_0^2)^{-1} \). The metric is

\[
\text{D}_m \equiv \frac{1}{r\sqrt{f}} \begin{pmatrix}
  mK^{-1/6} & 0 & -u-v & -ik/r \\
  0 & mK^{-1/6} & -ik/r & -u+v \\
  -u+v & ik/r & -mK^{-1/6} & 0 \\
  ik/r & -u-v & 0 & -mK^{-1/6}
\end{pmatrix}.
\]

We define a converting matrix \( C_\psi \) as a function of \( r \) as

\[
C_\psi \equiv r^{1/2} \begin{pmatrix}
  r^\nu_{-1}(a_1 + a_2 + r^2) & r^\nu_{-1}(a_1 + a_2 + r^2) & r^\nu_{-1}(b_1 + b_2 + r^2) & r^\nu_{-1}(\beta_1 + \beta_2 + r^2) \\
  r^\nu_{-1}(a_1 - a_2 + r^2) & r^\nu_{-1}(a_1 - a_2 + r^2) & r^\nu_{-1}(b_1 - b_2 + r^2) & r^\nu_{-1}(\beta_1 - \beta_2 + r^2) \\
  r^\nu_{-1}(c_1 + c_2 + r^2) & r^\nu_{-1}(\gamma_1 + \gamma_2 + r^2) & r^\nu_{-1}(d_1 + d_2 + r^2) & r^\nu_{-1}(\delta_1 + \delta_2 + r^2) \\
  r^\nu_{-1}(c_1 - c_2 - r^2) & r^\nu_{-1}(\gamma_1 - \gamma_2 - r^2) & r^\nu_{-1}(d_1 - d_2 - r^2) & r^\nu_{-1}(\delta_1 - \delta_2 - r^2)
\end{pmatrix}.
\]
and a set of functions $S_1(r), S_2(r), R_1(r), R_2(r)$ can be defined from Eq. (3.20). This field-redefinition $S_1(r)$, $S_2(r), R_1(r), R_2(r)$ goes to $S_1, S_2, R_1, R_2$ at $r \to \infty$.

The EOM of $G(r)$ in the bulk gravity is $G'(r) = R'(r)S'(r)^{-1} - G(r)S'(r)S'(r)^{-1}$. Apply Eqs. (B1) and (3.20), then $S'(r)$ and $R'(r)$ can be simplified in terms of the linear combination of $S(r)$ and $R(r)$:

$$[S'(r)R'_1(r)S'_2(r)R'_2(r)]^T = (C_0^{-1}\phi(r))' = (C_0^{-1} D_m C_r - C_0^{-1} C_r') \times [S_1(r)R_1(r)S_2(r)R_2(r)]^T.$$

(B3)

The matrix $D_g(r) \equiv C_0^{-1} D_m C_r - C_0^{-1} C_r'$ simplifies EOM to

$$G'(r) = \begin{bmatrix} D_{g21} & D_{g22} \\ D_{g41} & D_{g42} \\ D_{g31} & D_{g32} \\ D_{g43} & D_{g44} \end{bmatrix} \cdot G(r) - G(r) \cdot \begin{bmatrix} D_{g11} & D_{g12} \\ D_{g31} & D_{g32} \\ D_{g41} & D_{g42} \end{bmatrix} \cdot G(r).$$

(B4)

Numerically we solve this bulk EOM [Eq. (B4)] of the Green’s function with the initial condition to obtain physical results of Eq. (3.26).

Our program code for numerical computation is shared through Supplemental Material [35].

APPENDIX C: HOLOGRAPHIC DICTIONARY FOR THE ALTERNATIVE QUANTIZATION

In Sec. III A, we set up the holographic dictionary for the standard quantization. Here we also walk through the similar setup for the alternative quantization. Consider the subleading term of $\phi_-$ contributes as a source field, then

$$\psi_- = (g g^r)^{-1/4} \phi_- \approx r^{-2} \phi_- \approx S_2 D_1 r^{\nu_- - 5/2}$$

which corresponds to the source $\chi_-.$

$$\chi_- = \lim_{r \to \infty} r^{\nu_- - 4} \psi_- = S_2 D_1.$$  

(C2)

$\chi_-$ is proportional to $S_2$. The momentum field $\tilde{\phi}_-$ is

$$\tilde{\phi}_- = \sqrt{- g g^r} \psi_- = (g g^r)^{1/4} \phi_+ \approx r^2 \phi_+ = S_2 B_1 r^{\nu_+ + 5/2} + R_1 b_1 r^{\nu_+ - 5/2} + \ldots$$

which corresponds to the response $O_-.$

$$O_- = \lim_{r \to \infty} r^{\nu_+ - 4} \tilde{\phi}_- = R_2 b_1.$$  

(C4)

$O_-$ is proportional to $R_2$. On the other hand, we can go through the same logic again, though consider the subleading term of $\phi_+$ contributes as a source field, then

$$\psi_+ = (g g^r)^{-1/4} \phi_+ \approx r^{-2} \phi_+ \approx S_1 A_1 r^{\nu_+ - 3/2}$$

which corresponds to the source $\chi_+.$

$$\chi_+ = \lim_{r \to \infty} r^{\nu_+ - 4} \psi_+ = S_1 A_1.$$  

(C6)

$\chi_+$ is proportional to $S_1$. The momentum field $\tilde{\phi}_+$ is

$$\tilde{\phi}_+ = \sqrt{- g g^r} \psi_+ = (g g^r)^{1/4} \phi_- \approx - r^2 \phi_- = S_1 C_1 r^{\nu_+ - 5/2} - R_1 A_1 r^{\nu_+ + 5/2} + \ldots$$

which corresponds to the response $O_+.$

$$O_+ = \lim_{r \to \infty} r^{\nu_+ - 4} \tilde{\phi}_+ = R_1 A_1.$$  

(C8)

$O_+$ is proportional to $R_1$. Now we again derive $S_1, S_2$ are identified as sources, $R_1, R_2$ are identified as responses for this alternative quantization.

APPENDIX D: PURE SCHRODINGER GREEN’S FUNCTION AT ZERO T ZERO DENSITY

1. Two-point correlators at the leading order

Here we compare the pure Schrödinger two-point function at zero T zero density of Ref. [27] with our formulation.\footnote{In [27], their $e$ coordinates are inverse of our $r$, also their $d = 3$ is our $d = 2$ case.} Specifically, in $d = 2$, they show

$$\langle \psi_M(x, t) \tilde{\psi}_M(0, 0) \rangle \propto r^{2\nu_+}.$$  

(D1)

Here we cross-check our analysis indeed matches theirs. The boundary action is $\int_0^\infty dt d\xi d^2 x \sqrt{- g g^r} \psi \tilde{\psi}$, with $\sqrt{- g g^r} = r^4$, by plugging our UV boundary expansion in Eqs. (3.7) and (3.8), with $\psi = (g g^r)^{-1/4} \phi \approx r^{-2} \phi$, we arrive at $\psi \tilde{\psi} |_{\partial M} \propto r^{-\infty} \phi \phi \approx r^{-4} \phi \phi$. Notice $\Gamma_\gamma$ in $\phi \phi$ coupling the 1st to the 3rd component of $\phi$, meanwhile coupling the 2nd to the 4th component of $\phi$. With the leading piece in $\phi$ is $S_1 r^{\nu_+ + 1}$. This couples to the leading order of the 2nd component of $\phi$, which is $S_1 r^{\nu_+ - \frac{3}{2}}$. Neglecting other factors and coefficients,

$$\int_{\partial M} dt d\xi d^2 x \sqrt{- g g^r} \psi \tilde{\psi} \propto \phi \phi \propto r^{2\nu_+}.$$  

(D2)

One can obtain the scaling form of two-point correlator $\langle \psi_M(x, t) \tilde{\psi}_M(0, 0) \rangle$ at the leading order $r^{2\nu_+}$. The scaling $r^{2\nu_+}$ matches for Refs. [27] and [28] and our works.
however the precise form of our correlator is not identical with Ref. [27]. We should note that both Ref. [28] and our work contain higher order terms in the fermion field source/response, thus both works contain $r^{2\nu_-}$, $r^{2\nu_+}$ scaling, while Ref. [27] only contains $r^{2\nu_-}$ scaling. In the next subsection, we will delve further into our Green’s function and its similarity with that of Ref. [28].

2. Pure Schrödinger Green’s function from response over source

Solve the Dirac’s equation in zero T zero density Schrödinger spacetime $ds^2 = -r^4 dt^2 + 2r^2 dt d\xi + r^2 d\bar{x}^2 + dr^2/r^2$, the bulk fields have the following form:

$$\psi_+ = r^{-\frac{d-3}{2}} K_{\nu_+}(k/r)V^+ + g_+(k, r) \Gamma_+ U^+$$
$$+ r^{-\frac{d-3}{2}} K_{-\nu_+}(k/r)V^- + g_-(k, r) \Gamma_- U^-,$$
$$\psi_- = f_+(k, r) \Gamma_+ V^+ + r^{-\frac{d+3}{2}} K_{-\nu_-}(k/r)U^+ + f_-(k, r) \Gamma_- V^-$$
$$+ r^{-\frac{d+3}{2}} K_{\nu_-}(k/r)U^-,$$

where $d$ is the spatial dimension of $\bar{x}$, and the quantity

$$k = \sqrt{-2\ell \omega + k^2}$$

is a coordinate-invariant form of momentum. We denote $U^+$, $V^+$ as two components spinor bases for $\nu_\pm$ series (the first two columns), and denote $U^-$, $V^-$ as two components spinor bases for $-\nu_\pm$ series (the last two columns), $K_{\nu_\pm}(k/r)$ is modified Bessel function, solution of $r^2 \partial_r^2 K_{\nu_\pm}(k/r) + r \partial_r K_{\nu_\pm}(k/r) - ((k/r)^2 + \nu^2) K_{\nu_\pm}(k/r) = 0$. The expansions of $K_{\nu_\pm}(k/r)$, $f_\pm(k, r)$, $g_\pm(k, r)$, $\psi_+ , \psi_-$ near $r \to \infty$ are

$$K_{\nu_\pm}(k/r) = 2^{1+\nu_\pm} (k/r)^{-\nu_\pm_2 \Gamma(\nu_\pm)} (1 + O(r^{-2})),$$
$$f_\pm(k, r) = \frac{2^{\pm}\nu_\pm - 2 \ell \Gamma(\pm \nu_\pm)}{\pm \nu_\pm + m + \frac{\ell}{2}} k^{\pm \xi} r^{-\frac{d+3}{2} \pm \xi} (1 + O(r^{-2})), $$
$$g_\pm(k, r) = -\frac{2^{\pm} \nu_\pm - 2 \ell \Gamma(\pm \nu_\pm)}{\pm \nu_\pm - m + \frac{\ell}{2}} k^{\pm \xi} r^{-\frac{d+3}{2} \pm \xi} (1 + O(r^{-2})), $$

where $k^\mu \Gamma_\mu = \ell \Gamma_\xi - \omega \Gamma_\xi + k_\xi \Gamma_\xi$. By identifying source and response based on our holographic dictionary, we have the response and source matrix,

$$R = \begin{bmatrix} R_1 & R_2 \\ R_1^T & R_2^T \end{bmatrix}$$

$$= \begin{bmatrix} 2^{\nu_+ - 1} \Gamma(-\nu_+) k^{\nu_+} (V^+)^{(1,2)} \\ 2^{\nu_- - 1} \Gamma(-\nu_-) k^{\nu_-} (U^-)^{(1,2)} \end{bmatrix}$$
$$= \begin{bmatrix} 2^{\nu_+ - 2} \Gamma(-\nu_+) k^{\nu_+} (V^+)^{(1,2)} \\ 2^{\nu_- - 2} \Gamma(-\nu_-) k^{\nu_-} (U^-)^{(1,2)} \end{bmatrix}.$$
Here we follow the notation in Sec. III C, introducing upper indices (1, 2) to distinguish the first and the second sets of two independent boundary conditions for spinors. We also introduce lower indices $j = 1, 2, 3, 4$, implying the $j$th component of 4-spinor. For example, $(V^+)^j$ means reading the fourth component of the spinor $(V^+)$ from the second (2) type of boundary condition.

For the notation convenience, we define

$$
\begin{align*}
V^{-(1,2)} &= (k^i i \Gamma_i V^-)^{(1,2)}_2, \\
U^{-(1,2)} &= (k^i i \Gamma_i U^-)^{(1,2)}_3, \\
V^{+(1,2)} &= (\Gamma^i V^+)^{(1,2)}_4, \\
U^{+(1,2)} &= (\Gamma^i U^+)^{(1,2)}_1.
\end{align*}
$$

Again, the upper indices (1,2) are choices for the first or the second independent boundary conditions. The lower indices 1, 2, 3, 4 are indices for spinor components. Green’s function is

$$
G = \begin{bmatrix}
G_1^1 & G_1^2 \\
G_2^1 & G_2^2
\end{bmatrix}
$$

with each component

\[
G_i^j = \frac{-i}{\mathcal{C}^2} \left( \frac{k^i}{2} \right)^{\nu_+} \Gamma^{(\nu_+)} \left( \frac{\Gamma^{(\nu_+)}_i}{\Gamma(\nu_+)} \right) \times \left( \nu_+ + m + \frac{1}{2} \right) \left( V^{-(1)} U^{+(2)} - V^{-(2)} U^{+(1)} \right) \\
\times \left( V^{+(1)} U^{+(2)} - V^{+(2)} U^{+(1)} \right), \\
\end{align}
\]

We know that Green’s function in [27] contains only the $r^{2\nu_+}$ contribution. Our two-point Green’s function closely resembles that of Ref. [28] with subleading structure, $r^{2\nu_+}$, $r^{2\nu_-}$. A quick way to check this is comparing to Eq. (79) of [28], their $\langle \mathcal{O}_c^\dagger \mathcal{O}_c \rangle \approx (k^2 - 2\ell \omega)^{\nu_+}$ scales identically as $G_1^1 \sim k^{2\nu_+} = (k^2 - 2\ell \omega)^{\nu_+}$ of ours, and their $\langle \mathcal{O}_c^\dagger \mathcal{O}_c \rangle \approx (k^2 - 2\ell \omega)^{\nu_-}$ scales identically as $G_2^2 \sim k^{2\nu_-} = (k^2 - 2\ell \omega)^{\nu_-}$ of ours.