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Wake of a heavy quark in non-Abelian plasmas: Comparing kinetic theory and the anti-de Sitter space/conformal field theory correspondence

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We compute the nonequilibrium stress tensor induced by a heavy quark moving through weakly coupled QCD plasma at the speed of light and compare the result to $\mathcal{N} = 4$ super-Yang-Mills theory at strong coupling. The QCD Boltzmann equation is reformulated as a Fokker-Planck equation in a leading logarithmic approximation, which is used to compute the induced stress. The transition from nonequilibrium at short distances to equilibrium at long distances is analyzed with first- and second-order hydrodynamics. Even after accounting for the obvious differences in shear lengths, the strongly coupled theory is significantly better described by hydrodynamics at subasymptotic distances. We argue that this difference between the kinetic and the anti-de Sitter space/conformal field theories is related to the second-order hydrodynamic coefficient $\tau_\pi$, which is numerically large in units of the shear length for theories based on the Boltzmann equation.

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I. INTRODUCTION

The goal of the relativistic heavy ion programs at the Relativistic Heavy Ion Collider and the CERN Large Hadron Collider is to create and to study the properties of the quark gluon plasma (QGP). Since the real-time dynamics cannot be probed directly with the lattice QCD, the transport properties of the QGP are of particular interest. There is a consensus that the experimental results on collective flow imply that the shear-viscosity-to-entropy ratio of the quark gluon plasma is remarkably small [1],

$$\frac{\eta}{s} \sim \frac{1}{4\pi}.$$  \hfill (1.1)

Although it is difficult to reconcile this experimental ratio with a quasiparticle picture of the plasma, the success of resummed perturbation theory in describing lattice data on the pressure at somewhat higher temperatures suggests that a quasiparticle picture might provide a qualitative guide to the plasma dynamics and may form a basis for further approximation schemes [2–4]. However, in $\mathcal{N} = 4$ super-Yang-Mills (SYM) theory at strong coupling (and large $N_c$), gauge-gravity duality can be used to compute the shear-to-entropy ratio exactly [5,6],

$$\frac{\eta}{s} = \frac{1}{4\pi}.$$  \hfill (1.2)

The tantalizing similarity between the experimental ratio and this celebrated theoretical result hints that a strong-coupling limit (without quasiparticles) might provide a better starting point for understanding the plasma dynamics. At the very least, the strongly coupled $\mathcal{N} = 4$ theory is an analytically tractable limit that provides a useful foil to perturbative calculations based on a quasiparticle description.

The goal of this paper is to compare the steady-state response of non-Abelian plasma at weak and strong couplings to an infinitely heavy quark probe moving at the speed of light. This is the simplest setup where the plasma response to an energetic probe can be analyzed in detail [7–13]. At long distances, the nonequilibrium disturbance produced by the heavy quark probe thermalizes and forms a Mach cone and a diffusion wake. The original motivation for investigating the Mach cone was the observation of an unusual structure in measured two-particle correlations [14,15]. Today, after the analysis of Alver and Roland [16] and others [17–20], these unusual correlations are understood as the hydrodynamic response to fluctuations in the initial geometry and not as the medium response to an energetic probe. (The Mach cone picture also dramatically fails to explain current measurements in several ways—see, for example, Ref. [21] and the conclusions of Ref. [22].) The goal of this paper is not to explain current measurements but rather to examine the differences between weak and strong couplings and to study the approach to hydrodynamics in both cases. Although the current paper has no immediate phenomenological goals, the medium response to energetic partons is currently being studied by all the experimental collaborations in various ways [23]. Thus, this calculation, which analyzes the “jet” medium interaction precisely and determines a source for hydrodynamics through second order in the gradient expansion, may be useful for phenomenology in further studies.

In the strongly coupled theory, the stress tensor, induced by a finite-velocity heavy quark, was computed by using the anti-de Sitter space/conformal field theory (AdS/CFT) correspondence [9,11]. The approach to hydrodynamics was analyzed as well as the short-distance behavior [10,12,24]. In particular, we will largely follow (and, to a certain extent, will extend) the hydrodynamic analysis of Ref. [12] to determine a hydrodynamic source through second order in the gradient expansion for the kinetic and strongly coupled theories. In the AdS/CFT calculation, the lightlike $v \rightarrow c$ limit was not analyzed due to various technical complications. (Here and below, $v$ is the velocity of the heavy quark.) As discussed in Sec. II B, it is possible to set $v = c$ throughout the calculation by choosing a different set of gauge invariants.
At weak coupling, the hydrodynamic source has not been computed. Nevertheless, the appropriate source for kinetic theory was determined in Ref. [13], and several estimates were given for how this kinetic source was transformed through the relaxation process to hydrodynamics [25]. We have simplified the source for kinetic theory considerably and have determined the plasma response at long distances. Although this transition has not been worked out, we determined the hydrodynamic transport coefficients that we needed below to precisely determine the hydrodynamic source. These parameters will be computed. This part of the calculation employs a computer code developed by us to determine spectral functions at finite (leading logarithmic) kinetic-theory results, the appropriate absorptive boundary conditions at \( \omega \) and \( k \) [26]. As a by-product of these spectral functions, we have determined the hydrodynamic transport coefficients that have simplified the source for kinetic theory considerably and have determined the plasma response at long distances to the heavy quark probe. To determine this response, we linearize the Boltzmann equation for \( f(t, x, p) = n_p + \delta f(t, x, p) \) with \( n_p = 1/(e^{p/T} - 1) \) and restrict the calculation to pure glue QCD in a leading logarithmic approximation for simplicity.\(^1\)

The Boltzmann equation in this limit reads

\[
(\partial_t + v_p \cdot \partial_x) \delta f(t, x, p) = C[f, p] + S(t, x, p),
\]

(2.5)

where \( v_p = \hat{p} \) and \( S(t, x, p) \) is the (to be discussed) source of nonequilibrium gluons produced by the heavy quark moving through the plasma. In a leading \( \ln(T/m_D) \) approximation, the linearized collision integral simplifies to a momentum diffusion equation supplemented by gain terms [26],

\[
C[f, p] = T \mu_A \frac{\partial}{\partial p^i} \left( n_p(1 + n_p) \frac{\partial}{\partial p^j} \left[ \frac{\delta f}{n_p(1 + n_p)} \right] \right) + \text{gain terms},
\]

(2.6)

Here, the Debye mass for a pure glue QCD is

\[
m_D^2 = 2g^2 T_A \int \frac{d^3p}{(2\pi)^3} n_p(1 + n_p) T \frac{\partial}{\partial p^i} \left[ \frac{\delta f}{n_p(1 + n_p)} \right] = \frac{g^2 T^2}{3} N_c,
\]

(2.7)

where \( T_A = N_c \) is the trace normalization of the adjoint representation. The diffusion equation should be solved with absorptive boundary conditions at \( p = 0 \), so the number of particles is not conserved during the evolution [30]. Thus, the microscopic theory encoded by this diffusion equation is conformal, and the only conserved quantities are energy and momentum.

The gain terms are responsible for energy and momentum conservation. Specifically, the energy and momentum that are transferred (per time, per degree of freedom, and per volume) to the nonequilibrium excess \( \delta f \) by the equilibrium bath is

\[
\frac{dE}{dt} = -T \mu_A \int \frac{d^3p}{(2\pi)^3} n_p(1 + n_p) p^i \frac{\partial}{\partial p^i} \left[ \frac{\delta f}{n_p(1 + n_p)} \right],
\]

(2.8)

\[
\frac{dP}{dt} = -T \mu_A \int \frac{d^3p}{(2\pi)^3} n_p(1 + n_p) \frac{\partial}{\partial p^i} \left[ \frac{\delta f}{n_p(1 + n_p)} \right],
\]

(2.9)

as can easily be found by integrating both sides of Eq. (2.5) without the source. This energy and momentum transfer by the bath drives additional particles away from equilibrium and ultimately fixes the structure of the gain terms,

\[
gain \text{ terms} = \frac{1}{\xi_B} \left[ \frac{1}{p^2} \frac{\partial}{\partial p^i} p^2 n_p(1 + n_p) \right] \frac{dE}{dt} + \frac{1}{\xi_B} \left[ \frac{\partial}{\partial p^i} p n_p(1 + n_p) \right] \frac{dP}{dt},
\]

(2.10)

where, for subsequent use, we have defined

\[
\xi_B \equiv \frac{1}{(2\pi)^3} n_p(1 + n_p) = \frac{T^3}{6}.
\]

(2.11)

\(^1\)Including quarks would only lead to minor changes in our results as can be seen from Fig. 4 of Ref. [26].
With the gain terms, it is easy to verify that energy and momentum are conserved. Previously, we analyzed the linear response of this system of equations and determined the hydrodynamic plasma parameters in terms of $\mu_A$ [26],

$$\eta = 0.4613 \frac{T}{\mu_A} , \quad \tau_\eta = 6.32 . $$

Since the microscopic dynamics is conformal, linearized, and only conserves energy and momentum (and not particle number), $\tau_\eta$ is the only second-order hydrodynamic coefficient that appears at this order. If there are additional conserved quantities and the dynamics is not conformal, then there is a multitude of coefficients that appear at second order—see, for example, Refs. [31,32]. Furthermore, it must be emphasized that these second-order transport coefficients are insufficient to describe the decay of initial transients (nonhydrodynamic modes) [32].

The shear viscosity naturally agrees with prior results [33,34]. The fact that $\tau_\eta$ is somewhat large compared to the viscous length is a generic result of kinetic theory [35,36]. Finally, we note that $\mu_A$ records the transverse momentum broadening of a bath particle due to the soft scatterings and is related to the soft part of the jet quenching $\hat{q}$ parameter in a leading $T/m_D$ approximation [37]. $\hat{q}_{soft}/2 = 2T\mu_A$. Thus, the leading logarithmic limit provides a concrete relation between $\eta/s$ and $\hat{q}$.

We now analyze how a heavy quark disturbs this system in the same leading logarithmic approximation scheme. The leading logarithmic energy loss of the heavy quark was computed long ago by Braaten and Thoma [38,39] with the result that the momentum transferred to the medium per time (i.e., minus the drag force) is

$$\frac{dp^\mu}{dt} = -\left(\frac{dE}{dt}, \frac{dp}{dt}\right) = \mu_F(v)(v^2, v) ,$$

where $\mu_F(v)$ is the drag coefficient in a leading logarithmic approximation,

$$\mu_F(v) = \frac{g^2 C_F m_D^2}{8\pi} \ln \left( \frac{T}{m_D} \right) \left[ \frac{1}{v^2} - \frac{1}{2} - \ln \left( 1 + \frac{1}{v^2} \right) \right] ,$$

$$\Rightarrow \frac{g^2 C_F m_D^2}{8\pi} \ln \left( \frac{T}{m_D} \right) .$$

In the last line, we have taken the $v \to 1$ limit of relevance for this paper. As discussed more completely below, we have implicitly taken the coupling to zero before taking this limit so that radiative energy loss can be neglected.

The drag force arises as equilibrium gluons from the bath scatter off the heavy quark probe and are driven out of equilibrium by the scattering process. This scattering produces a source of nonequilibrium gluons located at the position of the quark,

$$S(t, x, p) = S(p)\delta^3(x - vt) .$$

Appendix A analyzes this scattering process ($g + Q \rightarrow g + Q$) and determines the appropriate momentum space source $S(p)$. In the limit $v = 1$, the source has a simple form, which involves only two spherical harmonics,

$$S(p) = \mu_F \frac{n_\rho(1 + n_\rho)}{2dA \xi_B} \times \left[ -\frac{2}{p} \left( \frac{1 + 2n_\rho}{T} + \frac{1 + 2n_\rho}{T} \hat{p} \cdot \hat{v} \right) \right]$$

for $v = 1$.

With this source, it is straightforward to integrate $2dA \int \frac{d^4p}{(2\pi)^4} p^\mu$ over Eq. (2.5) and to verify that the stress tensor satisfies

$$\partial_\mu \delta T^{\mu\nu} = \frac{dp^\nu}{dt} \delta^3(x - vt) .$$

Our strategy to determine the energy-momentum tensor is the following. We take the Fourier transform with respect to $x$ of the kinetic equation in Eq. (2.5),

$$(-i\omega + iv_p \cdot k)\delta f(\omega, k, p) = \frac{C[\delta f, p] + 2\pi S(p)\delta(\omega - v \cdot k)}{\omega} ,$$

and solve the Boltzmann equation in Fourier space. The technology to do this is based on simple matrix inversion as documented in Ref. [26]. Then, we calculate the stress-energy tensor in Fourier space by using kinetic theory. By Fourier transforming the stress tensor back to coordinate space, we can determine the energy and momentum density distributions. Additional details about this procedure are given in Appendix B.

B. AdS/CFT with a heavy quark probe

To describe the response of the $N = 4$ plasma to a heavy quark probe, we will follow the notations and conventions of Refs. [11,40], which should be referred to for all details. Briefly, a heavy quark is described in AdS$_5$ with a trailing string. The energy and momentum gained by the medium as the heavy quark traverses the plasma is again parametrized with the drag coefficient $\mu_F(v)$,

$$\frac{dp^\mu}{dt} = (\frac{dE}{dt}, \frac{dp}{dt}) = \mu_F(v)(v^2, v) .$$

This coefficient is found by determining the energy and momentum flowing down the string into the black hole [41–43],

$$\mu_F(v) = \frac{\pi}{2} \frac{\sqrt{\lambda T^2}}{\sqrt{1 - v^2}} .$$

As in the weakly coupled case, the stress tensor in the strongly coupled $N = 4$ theory satisfies Eq. (2.18) with the energy-momentum transfer rates given by the corresponding strongly coupled formulas. The deposited energy and momentum lead ultimately to a hydrodynamic response in the strongly coupled theory. The linearized hydrodynamic parameters through second order are [5,35,44],

$$\frac{\eta}{e + P} = \frac{1}{4\pi T} ,$$

$$\tau_\eta = \frac{e + P}{\eta} = 4 - 2 \ln(2) \simeq 2.61 .$$
According to AdS/CFT duality [45], strongly coupled SYM plasma is dual to the 5d AdS-Schwarzschild geometry, which has the metric,

$$ds^2 = \frac{L^2}{u^2} \left[ -f(u)dt^2 + dx^2 + \frac{du^2}{f(u)} \right].$$  \hspace{1cm} (2.24)

Here, $u$ is the radial coordinate of the AdS geometry with $u = 0$, which corresponds to the boundary, $L$ is the AdS curvature radius, $f(u) = 1 - u^4/4$ with $u_h = 1/\pi T$, and $T$ is the (Hawking) temperature of the plasma and dual geometry.

The addition of an infinitely massive fundamental quark to the SYM plasma is dual to the addition of a string to the AdS-Schwarzschild geometry with the string that ends at $u = 0$ [46]. The presence of the string perturbs the 5d geometry according to Einstein’s equations, and the near-boundary behavior of the metric perturbation encodes the changes in the SYM stress tensor due to the presence of the quark [47].

In the large $N$ limit, the 5d gravitational constant $\kappa_5^2 \sim 1/N^2$ is small. Consequently, the backreaction of the string on the geometry can be treated perturbatively by solving the string equations in the background metric and, subsequently, by computing the metric perturbations sourced by the string. To solve the string equations of motion leads to the well-known trailing string profile [41,43],

$$x_{\text{string}}(t, u) = v \left[ t + \frac{u_h}{2} \left( \tan^{-1} \frac{u}{u_h} + \frac{1}{2} \ln \frac{u_h - u}{u_h + u} \right) \right].$$  \hspace{1cm} (2.25)

This string profile describes a quark that moves at constant velocity $v$ and has the 5d stress tensor,

$$t_00 = -v_i F, \quad t_{ij} = v_i v_j F, \quad t_{00} = \frac{u^4v^2 + u_h f}{u_h^4} F, \quad t_{05} = \frac{u^2v^2}{u_h f} F, \quad t_{55} = \frac{v^2 - f}{f^2} F,$$  \hspace{1cm} (2.26a)

$$t_{i5} = \frac{u^2v_i F}{u_h f}, \quad t_{05} = \frac{v^2 - f}{f^2} F,$$  \hspace{1cm} (2.26b)

where

$$F = \frac{u \sqrt{\lambda}}{2 \pi L^3 \sqrt{1 - v^2}} \delta^3(\mathbf{x} - x_{\text{string}}),$$  \hspace{1cm} (2.27)

and $\lambda$ is the t’Hooft coupling.

The five-dimensional stress tensor of the string perturbs the background geometry. The information contained in the linear metric perturbation sourced by the trailing string can be conveniently packaged into fields, which are invariant under infinitesimal diffeomorphisms [12,40]. By defining

$$G_{MN} \equiv G_{MN}^{(0)} + \frac{L^2}{u^2} H_{MN},$$  \hspace{1cm} (2.28)

where $G_{MN}^{(0)}$ is the background metric (2.24) and $H_{MN}$ is the perturbation and by introducing a space-time Fourier transform,

$$H_{MN}(t, \mathbf{x}) \equiv \int \frac{d\omega}{2\pi} \frac{d^3q}{(2\pi)^3} H_{MN}(\omega, \mathbf{q}, \mathbf{u}) e^{-i\omega t + i\mathbf{q} \cdot \mathbf{x}},$$  \hspace{1cm} (2.29)

we find two convenient diffeomorphism invariant fields

$$Z_0 \equiv \frac{4f}{\omega} q^i H_{0i} - \frac{4f'}{\omega} q^i H_{0i} - 2f' q^i q^j H_{ij} + 4if q^i H_{5i}$$

$$\quad - \frac{(2uq^2 - f')}{q^2} (q^2 \delta^{ij} - q^i q^j) H_{ij}$$

$$\quad + \frac{4q^2 f}{i\omega} H_{05} - \frac{8\kappa_5^2 f}{i\omega} t_{05},$$  \hspace{1cm} (2.30)

$$Z_1 \equiv (H'_{0i} - i\omega H_{5i}) \epsilon^i_\perp \hat{e}_a.$$  \hspace{1cm} (2.31)

Here, sums over repeated indices are implied with $i, j$ running from 1 to 3 and $a$ running from 1 to 2, the primed denotes differentiation with respect to $u$ and

$$\hat{e}_1 = \frac{q}{q_{\perp}} \times (\hat{v} \times \hat{q}), \quad \hat{e}_2 = \frac{q}{q_{\perp}} \times \hat{q}.$$  \hspace{1cm} (2.32)

The field $Z_0$ transforms as a scalar under rotations, and the field $Z_1$ transforms as a vector under rotations. The equations of motion for $Z_0$ and $Z_1$ are straightforward but tedious to derive from the linearized Einstein equations. They read

$$Z''_0 + A_0 Z'_0 + B_0 Z_0 = \kappa_5^2 S_0,$$  \hspace{1cm} (2.33)

where

$$A_0 \equiv -\frac{24 + 4q^2 u^2 + 6f + q^2 u^2 f - 30f^2}{uf(u^2q^2 + 6f)},$$  \hspace{1cm} (2.34)

$$B_0 \equiv \frac{\omega^2}{f^2} \frac{q^2 u^2 (14 - 5f - 9u^2 f) + 18(4f - 3f^2)}{uf^2 (q^2(u^2 + 6f)}.$$  \hspace{1cm} (2.35)

$$S_0 \equiv \frac{8f}{3} t_{00}' + \frac{4q^2 u^2 + 6f}{3q^2} (q^2 \delta^{ij} - 3q^i q^j) t_{ij}$$

$$\quad + \frac{8i\omega}{3f} t_{05} + \frac{8i\omega q^2 (q^2 u^2 + 6f - 12q^2 - 9f^2)}{3f^2 (q^2 u^2 + 6f)} t_{00}$$

$$\quad - \frac{8q^2 u}{3} t_{55} - 8iq^i t_{55},$$  \hspace{1cm} (2.36)

and

$$Z''_1 + A_1 Z'_1 + B_1 Z_1 = \kappa_5^2 S_1,$$  \hspace{1cm} (2.37)

where

$$A_1 \equiv \frac{uf' - 3f}{uf},$$  \hspace{1cm} (2.38)

$$B_1 \equiv \frac{3f^2 - u(uf^2 + 3f') f + u^2 \omega^2}{uf^2 f},$$  \hspace{1cm} (2.39)

$$S_1 \equiv \frac{2}{f} [t_{00}' + i\omega t_{55}] \hat{e}_a.$$  \hspace{1cm} (2.40)

We note that, since the string stress tensor (2.26) only depends on time through the combination $\mathbf{x} - vt$, when Fourier
transformed, the string stress tensor is proportional to $2\pi \delta(\omega - \mathbf{v} \cdot \mathbf{q})$. Consequently, the fields $Z_s$ are also proportional to $2\pi \delta(\omega - \mathbf{v} \cdot \mathbf{q})$. Moreover, because the string stress tensor (2.26) is proportional to $1/\sqrt{1-v^2}$ and Eqs. (2.33) and (2.37) are linear, we define $Z_s = Z_s/\sqrt{1-v^2}$ and solve for $Z_s$ in the $v \rightarrow 1$ limit.

Under the assumption that the boundary geometry is flat, near the boundary, the fields $Z_s$ have the asymptotic expansions,

$$Z_s(u) = \tilde{Z}_s^{(2)} u^2 + \tilde{Z}_s^{(3)} u^3 + \tilde{Z}_s^{(4)} u^4 + \cdots.$$ (2.41)

The cubic expansion coefficients $\tilde{Z}_s^{(3)}$ determine the SYM energy density $\delta T^{00}$ and the SYM energy flux $\delta T^{0i}$ via $[12,40]

$$\delta T^{00} = -\frac{L^3}{8\kappa_s^2 \sqrt{1-v^2}} \tilde{Z}_s^{(3)},$$ (2.42)

$$\delta T^{0i} = -\frac{L^3}{2\kappa_s^2 \sqrt{1-v^2}} \left[ (\tilde{Z}_s^{(3)})^i + \frac{\omega q^i}{4q^2} (\tilde{Z}_s^{(3)}) \right]$$

$$- \frac{iq^i \mu_F(v) \omega^2}{q^2}. $$ (2.43)

For a given momentum $q$, to determine the SYM energy density and energy flux, we solve Eqs. (2.33) and (2.37) by using pseudospectral methods. At the boundary at $u = 0$, we impose the boundary condition that the fields have asymptotics of the form given in the series expansions (2.41), which is tantamount to demanding that the boundary geometry is flat. At the horizon at $u = u_h$, we impose the boundary condition of infalling waves. This is tantamount to demanding that $\tilde{Z}_s \sim (u - u_h)^{-i\omega u_h/\lambda}$ near the horizon. With $\tilde{Z}_s$ known, we can then extract the expansion coefficients $\tilde{Z}_s^{(3)}$ and can construct the SYM energy density and energy flux from Eqs. (2.42) and (2.43).

III. COMPARING AdS/CFT AND KINETIC THEORY

By using the formalism outlined in the previous section, we compute the energy density and Poynting vector induced by the heavy quark in both kinetic theory and the AdS/CFT correspondence. To compare the AdS/CFT and the kinetic theory results, we have measured all length scales in units of the shear length,

$$L_o \equiv \frac{\sqrt{2}}{\sqrt{e + \mathcal{P}c_s}},$$ (3.1)

where $c_s^2$ is the squared sound speed and, in practice, the speed of light is set to unity. $L_o$ is proportional to the mean-free path in kinetic theory and is equal to $1/\pi T$ for the $\mathcal{N} = 4$ theory. At long distances, where ideal hydrodynamics is applicable, the amplitude of the disturbance is proportional to the strength of the energy loss. Thus, we divide the response by the corresponding drag coefficient $\mu_F(v)$ for each theory, Eqs. (2.15) and (2.21). With these rescalings, the two theories produce the same (rescaled) stress tensor at asymptotically long distances but differ in their approach to the ideal hydrodynamic limit as we analyze in Sec. IV. Figures 1 and 2 compare the nonequilibrium stress in the two cases. A complete discussion is reserved for the summary in Sec. V.

FIG. 1. (Color online) The energy density (in scaled units) times $R = \sqrt{x_T^2 + x_L^2}$ that is induced by a heavy quark probe in (a) a weakly coupled QCD and (b) a strongly coupled $\mathcal{N} = 4$ SYM. Here, $L_o$ is the shear length, and $\mu_F(v)$ is the drag coefficient for each case (see text).

In order to compare the stress tensor quantitatively, we plot the energy density in concentric circles of radius $R$ around the head of the quark. Specifically, we define

$$\frac{dE_R}{d\theta_R} = 2\pi R^2 \sin \theta_R \delta T^{00}(R),$$ (3.2)

where $R = x_T x_T + x_L x_L$ and the polar angle is measured from the direction of the quark $\hat{z}$ (see Fig. 3). Similarly, the angular distribution of the energy flux is given by

$$\frac{dS_R}{d\theta_R} = 2\pi R^2 \sin \theta_R \delta T^{0i}(\mathbf{R}),$$

$$= 2\pi R^2 \sin \theta_R \left[ \cos \theta_R \delta T^{00}(\mathbf{R}) + \sin \theta_R \delta T^{0i}(\mathbf{R}) \right].$$ (3.3)

Numerical results for the angular distributions of the energy density and flux at several scaled distances $\mathcal{R} \equiv R/L_o$ are shown in Fig. 4.

There is a dramatic change in the AdS/CFT curves between $\mathcal{R} = 1$ and $\mathcal{R} = 5$, which indicates a transition from hydrodynamic behavior to quantum dynamics at distances on the order of $\sim 1/\pi T$. Since this quantum dynamics lies beyond the semiclassical Boltzmann approximation, no transition is seen in the kinetic-theory curves. It would be interesting to calculate the stress tensor in this region perturbatively to better understand the differences between the two theories for $R \sim 1/\pi T$.

Let us pause to discuss the limitations of both calculations. The point of the current paper is to compare the approach to hydrodynamics at infinitely weak and infinitely strong couplings. In both cases, the coupling is taken to zero or infinity before the limit $v \rightarrow 1$. As we now discuss, this limits
the Lorentz $\gamma$ factor of the heavy quark is not too large [51], $\gamma \lesssim \frac{\rho_0}{\rho_{\pi^0}} \sim 1/g$.

Similarly, the AdS/CFT calculation is limited to comparatively long distances $x_L, x_T \gg 1/\sqrt{\gamma T}$. In Sec. II B, we introduced a new set of helicity variables so that the medium response on distances much longer than $1/\sqrt{\gamma T}$ can be determined in the limit when $\nu = 1$. For distances much shorter than $1/\sqrt{\gamma T}$, the structure of the stress tensor has been analyzed in detail [10,24,52]. The medium response is characterized by a transverse length scale of $1/\sqrt{\gamma T}$ and a corresponding longitudinal scale of $1/\gamma^{3/2} T$, where $\gamma$ is the Lorentz factor of the heavy quark. In Fig. 4, we are investigating distances on the order of $x_L, x_T \sim 1/\pi T$, and the physics associated with these very short scales is not visible. Although the importance of the $1/\sqrt{\gamma T}$ scale is understood in the context of momentum fluctuations [53–55], it is instructive to see these scales reappear in the asymptotic expansion for the induced stress tensor at short distances [10,24]. By rewriting Eq. (137) of Ref. [24] in terms of $\gamma$ and by expanding for $\gamma$ large with $\tilde{x}_L \equiv \gamma x_L$ on the order of $x_T$, we have

$$\frac{1}{\sqrt{\lambda}} \langle \delta T^{00}(x_L, x_T) \rangle = \frac{\gamma^2 x_T^2}{6\pi^2(\tilde{x}_L^2 + x_T^2)} + \frac{T^2 \gamma^3 (2\tilde{x}_L^3 + \tilde{x}_L x_T^2)}{24} \left(\frac{\gamma}{\rho_{\pi^0}}\right)^3 \frac{1}{(\tilde{x}_L^2 + x_T^2)^{3/2}} + \cdots.$$  

(3.4)

The first term is the leading term at short distances and is independent of temperature. The second term (which captures the first finite-temperature correction) is subleading in inverse powers of distance but is enhanced by a power of $\gamma$. By comparing the magnitude of these terms, we see that the first term will dominate provided

$$\sqrt{(\gamma x_L)^2 + x_T^2} \lesssim \frac{1}{\sqrt{\gamma T}}.$$  

(3.5)

This constraint limits the validity (and utility) of the short-distance expansion to rather short distances.

To summarize, we are examining two extreme limits—infinitely weak and infinitely strong couplings. The disadvantage of this approach is that some of the marked differences at short distances between the Vlasov response of weakly coupled QCD and the AdS/CFT response are not visible (see, especially, Ref. [56]). The advantage of this approach is that the onset of hydrodynamics can be clearly compared. We will analyze the hydrodynamic limit in the next section.

### IV. HYDRODYNAMIC ANALYSIS

At long distances (see Figs. 1 and 2), the medium response to the heavy quark probe clearly exhibits hydrodynamic flow. By following, in part, the discussion by Chesler and Yaffe [12], we will analyze this hydrodynamic response order by order in the gradient expansion for kinetic theory and for the AdS/CFT correspondence. The strongly coupled $\mathcal{N} = 4$ theory is conformal, and the appropriate hydrodynamic theory is conformal hydrodynamics [35,36]. Similarly, for leading order in the coupling constant, QCD is also conformal, and
again conformal hydrodynamics is applicable in this limit. Beyond leading order, there are corrections to kinetic theory, which break scale invariance, and nonconformal hydrodynamics must be used to characterize the long-wavelength response [26,31].

For both kinetic theory and the AdS/CFT, the stress tensor of the full theory satisfies the conservation law Eq. (2.18). At long distances, the stress tensor is described by hydrodynamics up to uniformly small corrections suppressed by inverse powers of the distance. In hydrodynamics, the spatial components of the stress tensor are specified by the constituent relation order by order in the gradient expansion. Specifically, the stress tensor can be written

$$T_{\mu\nu}^{\text{hydro}} = (e + \mathcal{P})u^\mu u^\nu + \mathcal{P}g^{\mu\nu} + \pi^{\mu\nu},$$

where the dissipative part of the stress tensor $\pi^{\mu\nu}$ is expanded in gradients of $T^{00}$ and $T^{0i}$ or $(T$ and $u^i$) for a specified order. For linearized conformal hydrodynamics [where $u^\nu = (1, u)]$, this expansion through second order in gradients reads [35]

$$\pi^{ij} = -2\eta(\partial^i u^j) - 2\eta \tau_{\nu}(\partial^i \partial^j \ln T) \quad \text{(static)},\quad (4.2)$$

and all temporal components are zero. Here, $\langle \cdots \rangle$ denotes the symmetric and traceless spatial component of the bracketed tensor [35], i.e., for linearized hydrodynamics, we have

$$\langle \partial^i \partial^j \ln T \rangle = (\partial^i \partial^j - \frac{1}{3} \delta^{ij} \partial^2) \ln T. \quad (4.3)$$

We will refer to the conservation laws together with the constituent relation [Eq. (4.2)] as the static form of second-order hydrodynamics. By using the lowest-order equations of motion (ideal hydrodynamics) and conformal symmetry, the second-order term $\langle \partial^\mu \partial^\nu \ln T \rangle$ can be replaced by the time derivative of $\pi^{\mu\nu}$ [35],

$$\pi^{ij} = -2\eta(\partial^i u^j) - \tau_{\nu}(\partial^j \ln T) \quad \text{(dynamic)}. \quad (4.4)$$

This rewrite of the constituent relation can be interpreted as a dynamical equation for $\pi^{\mu\nu}$ and is similar to the second-order form of Israel [57] and Israel and Stewart [58]. We will refer to this equation of motion for $\pi^{\mu\nu}$ together with the conservation laws as the dynamic form of second-order hydrodynamics.

At long distances, the form of the stress-energy tensor is described by $T_{\text{hydro}}^{\mu\nu}$ up to terms suppressed by inverse powers of the distance. We express the full stress tensor as a hydrodynamic term, which is irregular in the limit of $\omega, k \to 0$, plus a correction, which we verify is a regular function for $\omega, k \to 0$,

$$T^{ij} = T_{\text{hydro}}^{ij}[T^{00}, T^{0i}] + \tau^{ij}. \quad (4.5)$$

We have temporarily emphasized here that $T_{\text{hydro}}^{ij}$ is a functional of the densities $T^{00}, T^{0i}$ as specified by the constituent relation and the equation of state. Then, the equation of motion in Fourier space becomes

$$-i\omega \delta T^{0i} + ik^i \delta T_{\text{hydro}}^{ij} = S_{\text{hydro}}^{ij}(\omega, k), \quad (4.6)$$

where

$$S_{\text{hydro}}^{ij}(\omega, k) \equiv \frac{d\tau^{ij}}{dt} + 2\pi \delta(\omega - v \cdot k) - ik^i \tau^{ij}. \quad (4.7)$$

By examining $S_{\text{hydro}}$, we see that $-ik^i \tau^{ij}$ acts as an additional source term for hydrodynamics. What makes this decomposition useful is that $\tau^{ij}$ (in contrast to $T_{\text{hydro}}^{ij}$) is a regular function at small $k$ and $\omega$. For the steady-state problem we are considering, $\tau^{ij}$ can be written with three functions proportional to the symmetric tensors, which consist of $\nu$ and $k$,

$$\tau^{ij}(\omega, k^2) \equiv 2\pi \nu \delta(\omega - v \cdot k)
\left[
iv^i v^j - \frac{1}{2} \nu^2 \delta^{ij}\right] \phi_1(\omega, k^2)
+ \left[i k^i v^j + ik^j v^i - i \frac{1}{2} \nu k^i \delta^{ij}\right] \phi_2(\omega, k^2)
+ \left(k^i k^j - \frac{1}{4} k^2 \delta^{ij}\right) \phi_3(\omega, k^2),\quad (4.8)$$

where $\phi_1, \phi_2,$ and $\phi_3$ are regular for $k \to 0$. The source can be expressed similarly,

$$S_{\text{hydro}}^{ij} \equiv 2\pi \delta(\omega - v \cdot k)[\phi_1(\omega, k^2)v^i + \phi_2(\omega, k^2)v^j]. \quad (4.9)$$

Since $\tau^{ij}$ is localized, we can expand it for small $\omega$ and $k$. By using an obvious notation for the Taylor series,

$$\phi_1(\omega, k^2) \simeq \phi_1^{(0,0)}(\omega) + \phi_1^{(1,0)}(\omega) + \frac{1}{2!} \phi_1^{(2,0)}(\omega)\omega^2
+ \phi_1^{(0,2)}(k^2) + O(k^4), \quad (4.10)$$
TABLE I. Table of hydrodynamic source coefficients. The equations of motion are given by second-order hydrodynamics with a source term Eq. (4.6). The source term is expanded to quadratic order in \( k \) and \( \omega \) in Eq. (4.11), which defines these coefficients. The first coefficient \( \phi^{(0)}_{1,0} \) was computed analytically in the AdS/CFT case by Chesler and Yaffe [12]. Here, \( L_s \) is the shear length (see text).

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>( \phi^{(0)}_{1,0} / L_o )</th>
<th>( \phi^{(1)}_{1,0} / L_o^2 )</th>
<th>( \phi^{(0)}_{2,0} / L_o^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boltzmann</td>
<td>0</td>
<td>0</td>
<td>0.484</td>
</tr>
<tr>
<td>AdS/CFT</td>
<td>-4</td>
<td>-0.34</td>
<td>-0.33</td>
</tr>
</tbody>
</table>

we see that the full source for hydrodynamics through second order can be expressed in terms of three expansion coefficients \( \phi^{(0)}_{1,0} \), \( \phi^{(1)}_{1,0} \), and \( \phi^{(2)}_{0,0} \),

\[
S_{\text{hydro}} = 2\pi \mu F \delta(\omega - v \cdot k)
\]

\[
\times \left[ \left( 1 - i\omega \phi^{(0)}_{1,0} - \phi^{(1)}_{1,0} \omega^2 + \phi^{(2)}_{0,0} k^2 \right) v \right.
\]

\[
+ \left. \left( \frac{1}{2} v^2 \phi^{(0)}_{1,0} - \frac{1}{4} v^2 \phi^{(1)}_{1,0} i\omega - \frac{1}{3} \phi^{(2)}_{0,0} i\omega \right) i\kappa \right] = \phi_{\nu} + O(k^3),
\]

(4.11)

To summarize, \( \tau^{ij} \) can be determined by comparing the full numerical solution for \( T^{ij} \) to \( T^{ij}_{\text{hydro}} \). Then, by fitting the functional form given by an expanded Eq. (4.8), we can extract the three coefficients \( \phi^{(0)}_{1,0} \), \( \phi^{(1)}_{1,0} \), and \( \phi^{(2)}_{0,0} \) for the Boltzmann equation and the AdS/CFT correspondence. These coefficients fully specify the hydrodynamic source of a heavy quark through quadratic order. Appendix C gives some sample fits for our numerical results, and the fit coefficients are collected in Table I. The quality of the fits given in Appendix C indicates that \( \tau^{ij} \) is well described by a polynomial at small \( k \) and \( \omega \) and justifies the analysis of this section.

By examining Table I, we notice that, in the Boltzmann case, the expansion coefficients proportional to \( \phi_{\nu} \) vanish. In fact, \( \phi_{1}(\omega, k^2) \) vanishes for all orders in \( \omega, k \). This follows from rotational symmetry around the \( k \) axis and the somewhat special form of the kinetic theory source in Eq. (2.17). Since we do not expect this property to hold beyond the leading logarithmic approximation, further discussion of this point is relegated to Appendix C.

With the source functions \( \phi_{\nu}(\omega, k^2) \) and \( \phi_{0,0}(\omega, k^2) \) known (numerically) through quadratic order, the hydrodynamic approximation for the equations of motion for (static) second-order hydrodynamics reads (with \( v = 1 \))

\[
-i\omega \delta T^{0c} + c^2(k) i\kappa \delta T^{0c} + \Gamma_s \kappa^2 \delta T^{0c} = [\cos \theta \phi_{\nu} + i k \phi_{\nu}] 2\pi \mu F \delta(\omega - v \cdot k),
\]

\[
-i\omega \delta T^{0c} + Dk^2 \delta T^{0c} = \sin \theta \phi_{\nu} 2\pi \mu F \delta(\omega - v \cdot k),
\]

(4.12)

where \( z' \) points along the \( k \) axis and \( x' \) is perpendicular to \( k \) (see Appendix B). In these equations, \( \Gamma_s = (4\eta/3)(e + \mathcal{P}) \), \( D = \eta/(e + \mathcal{P}) \), and \( c^2(k) = c^2_{\nu}(1 + \tau_{\nu} \Gamma_s k^2) \). By using these approximate expressions and the exact equation,

\[
-i\omega \delta T^{00} + i k \delta T^{0c} = 2\pi \mu F \delta(\omega - v \cdot k),
\]

(4.13)

the hydrodynamic solutions in Fourier space are given by

\[
\delta T^{00}(\omega, k) = \frac{i(\omega + k \cos \theta \phi_{\nu}) - k^2 [\Gamma_{s} + \phi_{\nu}]}{\omega^2 - c^2(k) k^2 + i\Gamma_{s} \omega k^2} \times 2\pi \mu F \delta(\omega - k \cos \theta).
\]

(4.14a)

\[
\delta T^{0c}(\omega, k) = \frac{i(\omega + k \cos \theta \phi_{\nu} + c^2(k) k)}{\omega^2 - c^2(k) k^2 + i\Gamma_{s} \omega k^2} \times 2\pi \mu F \delta(\omega - k \cos \theta).
\]

(4.14b)

\[
\delta T^{0c}(\omega, k) = \frac{i(\omega \cos \theta \phi_{\nu} + c^2(k) k) - k \omega \phi_{\nu}}{\omega^2 - c^2(k) k^2 + i\Gamma_{s} \omega k^2} \times 2\pi \mu F \delta(\omega - k \cos \theta).
\]

(4.14c)

The solutions can also be used for first-order hydrodynamics provided the wave speed \( c^2(k) \) and the source functions \( \phi_{\nu} \) and \( \phi_{0,0} \) are truncated at leading order, i.e., \( c^2(k) \to c^2_{\nu} \) and \( \phi_{0,0}(k, k^2) \approx \phi_{0,0} \). Similarly, the hydrodynamic solutions for the dynamic implementation of second-order hydrodynamics takes the same functional form as Eq. (4.14) with the replacements,

\[
c^2(k) \to c^2_{\nu}, \quad \Gamma_s \to \Gamma_s(\omega) \equiv \frac{\Gamma_s}{1 - i\tau_s \omega},
\]

\[
D \to D(\omega) \equiv \frac{D}{1 - i\tau_s \omega}.
\]

(4.15)

Given these hydrodynamic solutions and the hydrodynamic source functions tabulated in Table I, the hydrodynamic stress tensor in coordinate space can be computed by using numerical Fourier transforms. The stress tensor of first- and second-order hydrodynamics (with the corresponding source) is compared to the full kinetic-theory stress tensor in Fig. 5. Figure 6 presents the analogous AdS/CFT results. Finally, a comparison between the static and dynamic implementations of second-order hydrodynamics is given in Fig. 7 and provides an estimate of higher-order terms in the hydrodynamic expansion. We will discuss these results in the next section.

V. SUMMARY AND DISCUSSION

To keep this discussion self-contained, we first recapitulate the problem and the corresponding notation. An infinitely heavy quark moves along the \( z \) axis with velocity \( v \simeq c \) by depositing energy and by disturbing the surrounding equilibrium plasma. We presented and compared the energy and momentum density distributions in two distinctly different plasmas—a weakly coupled QCD plasma described by kinetic theory and a strongly coupled \( N = 4 \) plasma described by the AdS/CFT correspondence. The steady-state stress tensor distributions can be written in cylindrical coordinates and comoving coordinates [see Eqs. (2.2) and (2.3)]. Figures 1 and 2 exhibit the energy density \( T^{00} \) and the magnitude of the Poynting vector \( |S| \equiv |T^{0c}| \) for kinetic theory and the \( N = 4 \) theory, respectively. To compare these theories, we measured all distances in terms of a length scale given by a combination
WAKE OF A HEAVY QUARK IN NON-ABELIAN PLASMAS:

The angular distribution of (a) the energy density \( \frac{dE_R}{d\theta_R} / \mu_F \) and (b) the energy flux \( \frac{dS_R}{d\theta_R} / \mu_F \) given by the Boltzmann equation at distances \( R = 10, 20, \) and 40. The Boltzmann results are compared with the first- and second-order static hydrodynamics.

\[
L_o \equiv \frac{4 \eta c}{(e + P)c_s^2}.
\]

This length is on the order of the mean-free path in kinetic theory and equals \( 1/\pi T \) for the AdS/CFT. In each theory, we divided the stress tensor by the corresponding heavy quark drag coefficient \( \mu_F(v) \) so that, at asymptotically large distances (where ideal hydrodynamics is valid), the rescaled stress tensors are equal. At asymptotic distances, both theories reproduce the Mach cone structure characteristic of ideal hydrodynamics, but these model plasmas differ at subasymptotic distances in their approach to this ideal hydrodynamic regime. In particular, the Boltzmann theory is considerably less diffuse than the AdS/CFT. In kinetic theory, the short-distance response is reactive, and the sharp band seen in Fig. 2(a) (which is indicative of free streaming quasiparticles) is absent in Fig. 2(b). We see that the response of the AdS/CFT closely follows the predictions of hydrodynamics at modest distances, which is strongly damped by the shear viscosity at short distances. This difference between the two can also be seen quantitatively in Fig. 4, which compares the kinetic-theory and AdS/CFT results by plotting the energy density and energy flux at concentric circles of radius \( R \) in scaled units,

\[
R = R/L_o.
\]

The precise definitions of \( dE_R/d\theta_R \) and \( dS_R/d\theta_R \) are given by Eqs. (3.2) and (3.3), respectively. As discussed in the previous paragraph, the AdS/CFT curves are considerably broader than the corresponding kinetic-theory results for \( R > 5 \).

By examining Fig. 4, a striking feature of the AdS/CFT result is the dramatic transition from hydrodynamic behavior at \( R = 5 \) to vacuum physics at \( R = 1 \), which is not present in the kinetic-theory calculation. This transition was noted previously and was suggested as a way to reveal the strong-coupling dynamics experimentally [52]. However, the absence of this transition in the weak-coupling calculation reflects a limitation of the kinetic-theory approximation to QCD rather than a distinguishable difference between the AdS/CFT correspondence and the weakly coupled QCD. Certainly, the quantum dynamics at \( R \sim 1/\pi T \) cannot be captured by the

FIG. 5. (Color online) The angular distribution of (a) the energy density \( \frac{dE_R}{d\theta_R} / \mu_F \) and (b) the energy flux \( \frac{dS_R}{d\theta_R} / \mu_F \) given by the AdS/CFT correspondence at distances \( R = 5, 10, \) and 20. The AdS/CFT results are compared with the first- and second-order static hydrodynamics. Here, \( L_o = 1/\pi T \) is the shear length, and \( \mu_F(v) = \gamma \sqrt{\lambda} \pi T^2/2 \) is the heavy quark drag coefficient for the AdS/CFT.
semiclassical kinetic-theory results. It would be interesting to compute the stress tensor in this region in fixed-order finite-temperature perturbation theory to see if the dynamics of the two theories is similar at these length scales. As discussed in Sec. III by using a short-distance expansion [10, 24], in the AdS/CFT calculation, new length scales emerge at distances on the order of $1/\sqrt{\gamma^2 \pi T}$ and $1/\sqrt{3/2 \pi T}$, which are not visible in Fig. 4. These scales have been associated with saturation physics [55, 59].

Finally, we have analyzed the transition to the hydrodynamic regime in kinetic theory and the AdS/CFT. In particular, we have determined the source appropriate for first- and second-order hydrodynamics in each theory by following, in part, a method outlined by Chesler and Yaffe [12]. This is elaborated in Sec. IV, and the precise source (which takes the form of derivatives of $\delta$ functions that act at the position of the quark) is given in Table I. The source is constructed so that the hydrodynamics for a given order together with a source at the same order reproduce the stress tensor of the full theory up to higher-order powers of $\ell_{mfp}/R$. Figure 9, given in Appendix B, fits our extracted hydrodynamic source with a polynomial at small $k$, and the superb agreement with our full numerical results justifies the source analysis of Sec. IV.

Figure 5 compares first- and second-order hydrodynamics to the kinetic-theory results. Generally, the second-order theory provides only a minor improvement to the first-order results until rather large radii $\mathcal{R} \gtrsim 40$. Indeed, the behavior of the second-order theory seems rather unphysical for $\mathcal{R} \lesssim 10$. This shows the limitations of second-order hydrodynamics. Second-order hydrodynamics is constructed to reproduce the full results order by order at asymptotic distances and is not constructed to describe the decay of nonequilibrium transients produced by the heavy quark.

The slow convergence of hydrodynamic expansion to the full results of kinetic theory can be contrasted with the rapid convergence seen in the AdS/CFT results in Fig. 6. In the AdS/CFT case, we see that first- (second-) order hydrodynamics describes the full result at the 20% (4%) level for $\mathcal{R} \approx 5$. The agreement with hydrodynamics is not as good as described earlier by Chesler and Yaffe. This is because we are describing a quark moving with velocity $v = 1$, and we have found that the deviation from equilibrium is noticeably larger than the $v = 0.75$ quarks studied by these authors. In addition, the energy density distributions showed larger deviations from first-order hydrodynamics and were not studied previously. However, once (important) second-order hydrodynamic corrections are included, the agreement with hydrodynamics is remarkable already at modest $\mathcal{R}$.

We should mention that we have used the static version of second hydrodynamics, which specifies $\pi^{\mu \nu}$ with a constituent relation analogous to the first-order constituent relation [35]. Israel-Stewart-type equations rewrite and interpret the constituent relation as a dynamic equation by using lower-order equations of motion. This renders the system of equations hyperbolic and causal but mixes orders in the gradient expansion. We have compared the static and the dynamic theories for the kinetic and AdS/CFT theories in Fig. 7. Generally, the Israel-Stewart-type resummations do not lead to a significant improvement. Indeed, at smaller $\mathcal{R}$ than shown in Fig. 7, Israel-Stewart-type resummations can lead to spurious shocks, which are not reproduced by the full result. The difference between the static and the dynamic theories gives an estimate of higher-order terms, and this difference is smaller in AdS/CFT than in kinetic theory at the same $\mathcal{R}$.

Clearly, the convergence to the hydrodynamic limit is significantly faster in the $N = 4$ theory relative to kinetic theory, even when lengths are measured in the scaled units described by $\mathcal{R}$. We remark that, in the AdS/CFT, the second-order hydrodynamic parameter $\tau_\pi$ is a factor of 2.5 smaller in scaled units than the corresponding kinetic-theory parameter,

$$\frac{\tau_\pi}{\eta/\delta T} = 6.32 \quad \text{(kinetic theory)}, \quad \text{(5.1)}$$
\[
\frac{\tau_\pi}{\eta/sT} = 4 - 2 \ln(2) \simeq 2.61 \quad \text{(AdS/CFT)}.
\] (5.2)

Based on these coefficients, it is natural to expect that the convergence to the hydrodynamic limit is faster for the \(N = 4\) theory than the corresponding kinetic theory. In theories based on quasiparticles and kinetic theory, it is difficult to reduce the value of \(\tau_\pi\) in scaled units significantly [36]. Thus, it would seem that our principal result of this paper is reasonably generic. Specifically, based on the model theories studied in this paper, we expect theories without quasiparticles to approach the hydrodynamic limit several times faster (in scaled units) than theories based on a quasiparticle description. From a practical perspective of applying hydrodynamics to various almost equilibrium phenomena of heavy ion physics (e.g., the hydrodynamic flow due to jets and other local disturbances), this factor of 2 can be quite important.

ACKNOWLEDGMENTS

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APPENDIX A: THE KINETIC-THEORY SOURCE IN A LEADING LOGARITHMIC APPROXIMATION

The source of nonequilibrium gluons arises as gluons scatter off the heavy quark \(g + Q \rightarrow g + Q\). The squared matrix element for this process is

\[
|\mathcal{M}|^2 = \left[\frac{g^4 C_F N_c}{2d_A}\right] 16 \left[\frac{2(K \cdot P)}{Q^4} - \frac{M^2}{Q^2} + \frac{M^2}{4(K \cdot P)^2}\right],
\] (A1)

where \(K\) is the heavy quark momentum, \(P\) is the gluon momentum, \(Q = p - P\) is the four-momentum transferred to the gluon, and we have averaged over the colors and spins of the external gluon. In a leading logarithmic approximation, only the (first) most singular term is kept. The source of nonequilibrium gluons of momentum \(p\) is obtained from the Boltzmann collision integral for the \(g + Q \rightarrow g + Q\) process,

\[
S(t, x, p) = S(p)\delta^3(x - vt)
\]

\[
- \int dp' dp'' \frac{|\mathcal{M}|^2}{16k_T^4k_T^4 p' p''} (2\pi)^4 \delta^4(P_{\text{fin}})[f_p f_{p'} f_{k_{T'}}, (1 + f_{p'}) - f_{p'} f_{k_{T'}}, (1 + f_{p'}) (1 + f_{k_{T'}})],
\] (A2)

where the heavy quark distribution \(f_k = (2\pi)^4 \delta^3(k - k_H)\delta^3(x - vt)\) is out of equilibrium.

We expand the source in a spherical harmonic basis in the \((x, y, z)\) coordinate system,

\[
S(p) = \sum_{l, m} S_{lm}(p)H_{lm}(\hat{p}; z x)
\]

\[
= \sqrt{\frac{2l + 1}{4\pi}} \sum_{l} S_{00}(p)P_l(\cos \theta_{kp}),
\] (A3)

and note that the \(S_{lm}\) vanishes for nonzero \(m\) due to the azimuthal symmetry of the problem. By using the orthogonality of \(P_l(\cos \theta_{kp})\) and the phase-space parametrization and kinematic approximations used to analyze the energy loss of heavy quarks [51], the expansion coefficients can be written\(^3\)

\[
S_{00}(p) = -\sqrt{\frac{2l + 1}{4\pi}} \int_0^\infty dq \int_{-\infty}^\infty dq' \int_0^{2\pi} d\phi P_l(\cos \theta_{kp}) \times \frac{|\mathcal{M}|^2}{16p^2(k'0)^2}[f_p(1 + f_{p+\omega}) - f_{p-\omega}(1 + f_p)],
\] (A4)

where \(\omega\) is the energy transfer, \(\mathbf{q} = \mathbf{p'} - \mathbf{p}\) is the three-momentum transfer, and \(\phi\) is the azimuthal angle. The matrix elements in this parametrization are

\[
|\mathcal{M}|^2 = \left[\frac{g^4 C_F N_c}{2d_A}\right] \frac{2(1 - v \cos \theta_{kp})^2}{(q^2 - \omega^2)^2},
\] (A5)

where \(\cos \theta_{kp}\) is expressed in terms of the integration variables \(\omega, q, \) and \(\phi\) [51]. Now, we consistently expand out the integrand to quadratic order in \(\omega/T\) and \(q/T\). This includes three types of terms: (1) an expansion of the distribution functions to quadratic order, (2) an expansion of the angle \(\cos \theta_{kp}\) to linear order in \(q/T\), and (3) an expansion of the Legendre polynomial to linear order \(P_1(\omega) \simeq \omega + P_1(\omega)\delta x\). With the full expansion, we explicitly integrate over the azimuthal angle \(\phi\) and the energy \(\omega\) by observing empirically that all harmonics vanish for \(l > 1\) when the velocity is lightlike. Furthermore, the \(l = 0\) and \(l = 1\) harmonics can be performed analytically, which leads to a simple answer recorded in Eq. (2.17),

\[
S_{00}(p) = \frac{1}{\sqrt{4\pi} T^2} \left[\frac{g^4 C_F N_c}{2d_A}\right] \ln \left(\frac{T}{m_D}\right) f_p(1 + f_p)
\times \left(\frac{2T}{p} + 1 + 2f_p\right),
\] (A6a)

\[
S_{10}(p) = \frac{1}{\sqrt{12\pi} T^2} \left[\frac{g^4 C_F N_c}{2d_A}\right] \ln \left(\frac{T}{m_D}\right) f_p(1 + f_p)(1 + 2f_p).
\] (A6b)

The leading logarithmic simplifications described in this paragraph were observed previously when computing the shear viscosity.

APPENDIX B: NUMERICAL DETAILS ABOUT KINETIC THEORY AND THE FOURIER TRANSFORM

The goal of this appendix is to give some of the details of how the stress tensor is computed in kinetic theory. Most of the notation and strategy follows an appendix of Ref. [26], and this reference should be consulted for the full details.

\(^3\)Specifically, we use Eq. (B21) of Ref. [51]. However, we have interchanged the role of \(\mathbf{p}\) and \(\mathbf{k}\) to be consistent with the notation used in this paper.
The linearized Boltzmann equation in Fourier space reads
\[
(-i\omega + i v_p \cdot k)\delta f(\omega, k, p) = C[\delta f, p] + 2\pi S(\omega - v \cdot k), \tag{B1}
\]
where \(v_p = \hat{p}\) is the particle velocity and the vector \(k\) in the laboratory coordinate system is
\[
k = (k^x, k^y, k^z) = k(\sin \theta_k \cos \varphi_k, \sin \theta_k \sin \varphi_k, \cos \theta_k).
\]

In order to solve Eq. (B1) numerically, it is convenient to introduce the Fourier coordinate system \((x', y', z')\) where \(z'\) points along the Fourier momentum \(k\),
\[
\begin{align*}
x' &= \frac{k}{k_T} \hat{k} \times (\hat{\vartheta} \times \hat{k}), \\
\hat{y}' &= \frac{k}{k_T} \hat{v} \times \hat{k}, \\
z' &= \hat{k}.
\end{align*}
\]

Following our previous paper [26], we reexpress the source and ultimately the solution \(\delta f\) in terms of real spherical harmonics with respect to the \(\hat{x}', \hat{y}', \hat{z}'\) coordinate system,
\[
H_{lm}(\hat{p}; z'x') = N_{lm} P_{lm}(\cos \theta_p) \times
\begin{cases}
1, & \text{for } m = 0, \\
\sqrt{\frac{\cos m\varphi_p}{\sin m|\varphi_p|}}, & \text{for } m > 0, \\
\sqrt{\frac{\sin m|\varphi_p|}{\sin m|\varphi_p|}}, & \text{for } m < 0,
\end{cases}
\tag{B6}
\]

where \(N_{lm}\) is a normalization factor [26]. We note that the unit vector \(\hat{p}\) has the following components:
\[
\begin{align*}
\hat{p}' &= \frac{4\pi}{3} H_{11}(\hat{p}; z'x'), \\
\hat{p}'' &= \frac{4\pi}{3} H_{10}(\hat{p}; z'x').
\end{align*}
\tag{B7}
\]

Since the distribution function \(\delta f\) is independent of the azimuthal angle of \(k\) with respect to the original \(x, y, z\) coordinate system, we choose this azimuthal angle \(\varphi_k\) to be zero so that \(k\) lies in the \(x, z\) plane. Then, in the \((x', y', z')\) coordinate system, the vector \(v\) has the components,
\[
\hat{v} = (v', v', 0) = (\sin \theta, 0, \cos \theta),
\]
and
\[
\hat{v} \cdot \hat{p} = \frac{4\pi}{3} [\cos \theta H_{10}(\hat{p}; z'x') + \sin \theta H_{11}(\hat{p}; z'x')].
\tag{B8}
\]

The steady-state solution to the linearized Boltzmann equation is also expanded in the spherical harmonics defined above
\[
\delta f(\omega, k, p) = \sum_{lm} \left[ \frac{2\pi}{\sin m|\varphi_k|} \right] n_p(1 + n_p) \chi_{lm}(p, k) H_{lm}(\hat{p}; z'x'), \tag{B9}
\]
and the Boltzmann equation for \(\chi_{lm}\) becomes
\[
\begin{align*}
(-i\omega + ik \hat{c}_{lm}^n) \rho^3 n_p(1 + n_p) \chi_{lm} &= C_{lm}[\delta f, p] + \mathcal{H} \rho^3 n_p(1 + n_p) \frac{\mu_A}{T} S_{lm}(\rho, \theta),
\end{align*}
\tag{B10}
\]
where the \(m\) index is not summed over. Here, \(C_{lm}^n\) is a Clebsch-Gordan coefficient [26], \(\chi_{lm}[\delta f, p]\) is the collision integral in this basis, the normalization coefficient is
\[
\mathcal{H} = \frac{\mu_A}{T^3 d_A \mu_A},
\tag{B11}
\]
and the source is
\[
S_{lm}(p, \theta) = \frac{1}{2\pi^2 T^3} \left[ \left( \frac{-2T^2}{\rho} + 1 + 2n_p \right) \sqrt{4\pi \delta_{00} \delta_{m0}} \\
+ \sqrt{\frac{4\pi}{3} (1 + 2n)(\delta_{11} \delta_{m0} \cos \theta + \delta_{11} \delta_{m1} \sin \theta) \right].
\]

For each value of \((k_x, k_z)\) (in units of \(\mu_A / T\)), the linear equations are solved for \(\chi_{lm} \equiv \chi_{lm} / \mathcal{H}\). Due to rotational invariance of the collision operator around the \(k\) axis, the matrix equation does not mix harmonics with different magnetic quantum numbers, i.e., the collision operator is diagonal in \(m\). Thus, the matrix equation in \(l, l'\) is solved for \(m = 1\) and \(m = 0\) separately. Harmonics with \(m > 1\) are not sourced by the motion of the quark in a leading logarithmic approximation.

After solving for \(\delta f(\omega, k, p)\), the energy and momentum excess due to the moving quark can be computed by using the kinetic theory,
\[
\delta T^{0v}(\omega, k) = 2\mathcal{A} \int d^3p \left[ \frac{p^\mu \delta f(\omega, k, p)}{(2\pi)^3} \right], \tag{B13}
\]
where \(\delta T^{0v}(\omega, k)\) is proportional to \(2\pi \delta(\omega - v \cdot k)\),
\[
\delta T^{0v}(\omega, k) \equiv 2\pi \delta(\omega - v \cdot k) \delta T^{0v}(k_z, k_T). \tag{B14}
\]

The relationship between the \((x, y, z)\) and the \((x', y', z')\) coordinate system is
\[
\begin{align*}
\delta T^{0x}(\omega, k) &= \cos \theta \delta T^{0y}(\omega, k) - \sin \theta \delta T^{0z}(\omega, k), \\
\delta T^{0y}(\omega, k) &= 0, \\
\delta T^{0z}(\omega, k) &= \sin \theta \delta T^{0x}(\omega, k) + \cos \theta \delta T^{0z}(\omega, k).
\end{align*}
\tag{B15-17}
\]

In presenting these formulas, we have taken \(k\) in the \(x, z\) plane, i.e., \(\varphi_k = 0\). More generally, rotational invariance dictates that \((T^{0x}, T^{0y})\) is proportional to \(\hat{k}_T\),
\[
\delta T^{0x}(k) = \delta T^{0y}(k, k_T) \cos \varphi_k, \tag{B18}
\]
\[
\delta T^{0y}(k) = \delta T^{0y}(k, k_T) \sin \varphi_k, \tag{B19}
\]
and the preceding discussion with \(\varphi_k = 0\) suffices to determine \(\delta T^{0y}(k, k_T)\).

The stress tensor is tabulated in the \(k_z, k_T\) plane, and then, Fourier transforms can be used to compute the stress tensor in coordinate space,
\[
\delta T^{0y}(t, \mathbf{x}) = \int_{-\infty}^{\infty} d\omega \int \frac{d^3k}{(2\pi)^3} e^{-ist + ik \cdot \mathbf{x}} \delta T^{0y}(\omega, k). \tag{B20}
\]

By employing the familiar identity,
\[
e^{ik \cdot x_T} \cos(\varphi_k - \varphi_k) = J_0(k_T x_T) + 2 \sum_n i^n J_n(k_T x_T) \cos[n(\varphi_T - \varphi_k)], \tag{B21}
\]

\[064903-12\]
it is not difficult to show that
\[ \delta T^{00}(x_L, x_T) = \int_0^\infty \frac{k_T dk_T}{2\pi} J_0(k_T x_T) \]
\[ \times \int_0^\infty \frac{dk_z}{2\pi} e^{ik_z z} \delta \tilde{T}^{00}(k_z, k_T), \]  
\(\text{(B22a)}\)
\[ \delta T^{0z}(x_L, x_T) = \int_0^\infty \frac{k_T dk_T}{2\pi} J_1(k_T x_T) \]
\[ \times \int_0^\infty \frac{dk_z}{2\pi} e^{ik_z z} \delta \tilde{T}^{0k_z}(k_z, k_T), \]  
\(\text{(B22b)}\)
\[ \delta T^{0c}(x_L, x_T) = \int_0^\infty \frac{k_T dk_T}{2\pi} J_0(k_T x_T) \]
\[ \times \int_0^\infty \frac{dk_z}{2\pi} e^{ik_z z} \delta \tilde{T}^{0k_z}(k_z, k_T). \]  
\(\text{(B22c)}\)

The Fourier integrals in Eq. (B22) are not particularly easy. In order to get a convergent integral, we first multiply the numerical data by a window function, which eliminates the contributions of high-frequency modes. For kinetic-theory results, a sample window function is
\[ W(k) = \frac{1}{2} [1 - \text{erf}((k - k_{\text{max}})/\sigma)]. \]  
\(\text{(B23)}\)
with \(k_{\text{max}} = 7.5 \mu_A/T\) and \(\sigma = 3.5 \mu_A/T,\) whereas, for the AdS/CFT, the \(k_{\text{max}}\) and \(\sigma\) were considerably larger, \(k_{\text{max}} = 80\pi T\) and \(\sigma = 60\pi T.\) We computed the integrals in Eq. (B22) by using two methods. The first used method brute-force summation to compute these integrals. In the second method, we reparametrized the stress tensor by the source functions \(\phi_v\) and \(\phi_h\) used in the hydrodynamic analysis. Specifically, we define the functions \(\phi_v(k)\) and \(\phi_h(k)\) by the equations,
\[ \delta T^{0c}(\omega, k) = \frac{i \sin \theta \phi_v(k)}{\omega + i D k^2} 2\pi \mu_F \delta(\omega - k \cos \theta), \]  
\(\text{(B24)}\)
\[ \delta T^{0c}(\omega, k) = \frac{i (\omega \cos \theta \phi_v(k) + c^2 k k)}{\omega^2 - c^2 k^2 k^2 + i \Gamma k k^2} \]
\[ \times 2\pi \mu_F \delta(\omega - k \cos \theta), \]  
\(\text{(B25)}\)
where \(c^2(k) = c^2(1 + \tau_\pi \Gamma k^2)\) and \(\delta T^{0c}(\omega, k)\) is determined by energy-momentum conservation. This reparametrization is used for all values of the Fourier momentum \(k.\) Such a reparametrization is useful because, in contrast to \(\delta T^{0c}(\omega, k)\) and \(\delta T^{00}(\omega, k)\), the functions \(\phi_v(k)\) and \(\phi_h(k)\) are smooth and can be easily and accurately interpolated. Then, the integrals are computed by using Gaussian quadrature with break points at the hydrodynamic poles. The brute-force summation and the more-sophisticated numerical scheme give the same answer at the 1% level and are independent of the cutoff parameters.

**APPENDIX C: DETAILS ON THE HYDRODYNAMIC SOURCE IN KINETIC THEORY AND THE AdS/CFT**

The purpose of this appendix is to explain, in somewhat greater detail, how the coefficients given in Table 1 are computed for both kinetic theory and the AdS/CFT. In the process, we will exhibit several fits for our numerical results. The quality of these fits indicates that the deviation of the stress tensor from its hydrodynamic form at small \(k\) and \(\omega\) is well described by a multivariate polynomial and justifies the hydrodynamic analysis of Sec. IV. We first discuss the AdS/CFT theory and, then, indicate how the analysis can be applied to kinetic theory.

### I. AdS/CFT

The applicability of second-order hydrodynamics to the AdS/CFT has been questioned based on the analytic structure of retarded stress tensor correlators in the lower half plane [60,61]. However, provided second-order hydrodynamics is used to describe the behavior of hydrodynamic modes (i.e., a pole in the retarded Green’s function arbitrarily close to the real axis), rather than to model the decay of nonhydrodynamic modes or transients (i.e., additional analytic structure in the lower half plane), second-order hydrodynamics is applicable to this strongly coupled theory. This appendix serves to clarify these points.

After computing the exact stress tensor of the full AdS/CFT theory, we define the functions \(\phi_v(k)\) and \(\phi_h(k)\) as in Eq. (B24). This would seem to be simply a reparametrization of the original numerical data on \(\delta T^{0c}\) and \(\delta T^{0c}\) with two functions \(\phi_v(k)\) and \(\phi_h(k)\). However, as we see, the functions \(\phi_v(k)\) and \(\phi_h(k)\) are analytic functions of \(k\), whereas, the original fields have poles arbitrarily close to the real axis as \(k \to 0\), see Eq. (4.14). The purpose of first- and second-order hydrodynamics is to describe the location of these poles. First-order hydrodynamics determines the pole location for first order in \(k\ell_{\text{mfp}}^2\) but neglects terms of order \((k\ell_{\text{mfp}})^2\), which are captured by second-order hydrodynamics.\(^4\) It should be emphasized that the pole shift is a consequence of modifying the ideal hydrodynamic *equations of motion* by powers of \(k\ell_{\text{mfp}}\) rather than by modifying the source. Since the ideal solution has a hydrodynamic pole at \(\omega = c_k k\), which modifies the equations of motion, it does not simply correct the solution by simple powers of \(k\ell_{\text{mfp}}\) close to the pole. We will determine the source functions \(\phi_v(k)\) and \(\phi_h(k)\) by using first- and second-order hydrodynamics. Specifically, we determine \(\phi_v(k)\) and \(\phi_h(k)\) by using Eq. (B24) (with the same numerical data for the full stress tensor \(\delta T^{0c}\) and \(\delta T^{0c}\)), but in the first-order case, we set the second-order transport coefficient to zero in these equations,\(^5\) \(\tau_\pi \to 0\).

Since the source functions \(\phi_v\) and \(\phi_h\) are functions of \(k\) and \(\omega = k \cos \theta,\) we can expand these functions in Fourier series,
\[ \phi_v(k, \cos \theta, \cos \theta) \equiv \phi_{v,0}(k) + 2\phi_{v,1}(k) \cos \theta \]
\[ + 2\phi_{v,2}(k) \cos 2\theta + \cdots. \]  
\(\text{(C1)}\)
\[ \pi T \phi_h(k, \cos \theta, \cos \theta) \equiv \phi_{h,0}(k) + 2\phi_{h,1}(k) \cos \theta \]
\[ + 2\phi_{h,2}(k) \cos 2\theta + \cdots. \]  
\(\text{(C2)}\)

In Fig. 8, we plot the terms of the Fourier series \(\phi_{v,2}(k)\) and \(\phi_{h,2}(k)\) and fit these functions with a simple power law \(k^n\).\(^6\)

\(\ell_{\text{mfp}}\) should be taken as \(1/\pi T\) in the strongly coupled theory.

We note that \(\phi_v\) is the same for first- and second-order hydrodynamics. Only \(\phi_h\) is affected by a nonzero \(\tau_\pi.\)
As we see from the fit, $\phi_v$ is well described by a quadratic polynomial at small $k$,

$$
\phi_{v;0}(k) = 1 - 0.1643 \left( \frac{k}{\pi T} \right)^2,
\phi_{v;1}(k) = 0.5i \left( \frac{k}{\pi T} \right),
\phi_{v;2}(k) = 0.0870 \left( \frac{k}{\pi T} \right)^2.
$$

For first-order hydrodynamics, the terms of quadratic order can be neglected. Our numerical result for $\phi_{v;1}$ is nicely consistent with the first-order analytic result Ref. [11].

Now, we examine $k\phi_k$ by using first- and second-order hydrodynamics. When first-order hydrodynamics is used, the source function is not well described by a polynomial [see Fig. 8(b)]. However, we see that $k\phi_k$ decreases faster than $k$ (as $k^{1.52}$ for $n=1$), and therefore, $k\phi_k$ can be neglected in a first-order hydrodynamic analysis of the long-wavelength response to the heavy quark. A concerned reader might worry that the resulting source function $k\phi_k$ is not well described by a quadratic polynomial and incorrectly conclude that a local source for hydrodynamics cannot be constructed beyond linear order. However, when second-order hydrodynamics is used to extract the source through quadratic order (as is appropriate), $k\phi_k$ is well described by the quadratic polynomial—see the linear fit in Fig. 8(c) for $\phi_{k;1}$. Numerically, we find

$$
\phi_{k;0}(k) = -\frac{1}{3}, \quad \phi_{k;1}(k) = 0.111 \left( \frac{k}{\pi T} \right),
$$

up to nonanalytic terms that fall faster than $k^2$. (These nonanalytic terms could be removed by pushing the hydrodynamic analysis to third order.) To summarize, we see that to use second-order hydrodynamics neatly removes the nonanalytic behavior, which is seen in the first-order source, and then, the source for second-order hydrodynamics is well described by a quadratic polynomial. The coefficient $\tau_\pi$, which shifts the hydrodynamic pole, is universal—it is determined through an analysis of two point functions [35], and the same coefficient determines the long-distance response to the disturbance.

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We discuss $\phi_k$ instead of simply $\phi_k$ since the source for hydrodynamics is $\phi_k(k)k$. 

---

As we see from the fit, $\phi_v$ is well described by a quadratic polynomial at small $k$,

$$
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\phi_{v;1}(k) = 0.5i \left( \frac{k}{\pi T} \right),
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up to nonanalytic terms that fall faster than $k^2$. (These nonanalytic terms could be removed by pushing the hydrodynamic analysis to third order.) To summarize, we see that to use second-order hydrodynamics neatly removes the nonanalytic behavior, which is seen in the first-order source, and then, the source for second-order hydrodynamics is well described by a quadratic polynomial. The coefficient $\tau_\pi$, which shifts the hydrodynamic pole, is universal—it is determined through an analysis of two point functions [35], and the same coefficient determines the long-distance response to the disturbance.
produced by a heavy quark. By contrast, the source functions \( \phi_v \) and \( \phi_k \) are not universal but depend on the particular way in which the heavy quark couples to hydrodynamic modes. By using the fits in Eqs. (C3) and (C4) [and the relation between \( \phi_v \) and \( \phi_k \) that are not universal but depend on the particular way in which a heavy quark couples to hydrodynamic modes] and by noting that hydrodynamics does not yield such a spin-two tensor, we see that this spin-two component of the stress tensor vanishes for all orders in \( \omega, k \) as we now show.

To this end, we can return to the analysis given in Sec. IV. For a given \( k \), we expect that there is a nonzero component of \( T^{ij}_\text{hydro}(\omega, k) \), which transforms as a spin-two tensor under azimuthal rotations around the \( k \) axis. By examining the decomposition of \( T^{ij}_\text{hydro} \) into tensor structures [Eq. (4.8)] and by noting that hydrodynamics does not excite such a spin-two tensor, we see that this spin-two component of \( T^{ij} \) determines \( T^{ij}_\text{hydro} \) since this is the only tensor structure of \( T^{ij} \) that has a spin-two component under azimuthal rotations around \( k \). By examining the source for the Boltzmann equation given in Eq. (B12) of Appendix B, we see that the specific form of the source does not excite the spin-two (i.e., \( m = 2 \)) components of the distribution function \( \delta f \). Thus, since the Boltzmann equation does not mix harmonics of different spins, the spin-two component of the stress tensor vanishes and so does \( \phi_v \). This approximate symmetry is specific to the simplified form of the source, which arises in a leading logarithmic approximation and is not expected to hold more generally.

2. Kinetic theory

As in the previous appendix, we define the functions \( \phi_v \) and \( \phi_k \) from the exact stress tensor [Eq. (B24)] and again expand these functions in a Fourier series as in Eq. (C1), but, as is appropriate for the kinetic-theory calculation, \( \pi T \phi_k \) is replaced with \( (\mu_A/T)\phi_k \). Then, the Fourier coefficients are fit with a polynomial, which is shown in Fig. 9. It was verified that the other Fourier coefficients of \( \phi_v \) and \( k \phi_k \) that are not shown decrease faster than \( k^2 \) and, thus, lie outside of the hydrodynamic analysis, which is restricted to second-order inclusive. By examining the fits shown in Fig. 9, we see that the parametrization,

\[
\phi_v(k) = 1 + 1.66(1) \left( \frac{kT}{\mu_A} \right)^2, \tag{C5}
\]

\[
\phi_k(k) = -\frac{1}{6} 1.66(1) \frac{kT}{\mu_A} \tag{C6}
\]

describes our numerical data at small \( k \) and \( \omega = k \cos \theta \) quite well. The fact that \( \phi_v \) and \( \phi_k \) have the same fit coefficient (up to a symmetry factor of 1/6) is a consequence of the hydrodynamic analysis of Sec. IV. By comparing the fit with the functional form given in the text [Eq. (4.11)], we see that we have a nonzero \( \phi_2^{(0,0)} \) (which is recorded in Table I), but the coefficients \( \phi_2^{(1,0)} \) and \( \phi_2^{(0,1)} \) seem to vanish. In fact, \( \phi_1(\omega, k^2) \) vanishes for all orders in \( \omega, k \) as we now show.

[31] See, for example, the recent analysis by the CMS Collaboration: S. Chatrchyan et al. (CMS Collaboration), Phys. Rev. C 84, 024906 (2011).