

# A multi-parameter expansion for the evolution of asymmetric binaries in astrophysical environments

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## Abstract

Compact binaries with large mass asymmetries - such as Extreme and Intermediate Mass Ratio Inspirals - are unique probes of the astrophysical environments in which they evolve. Their long-lived and intricate dynamics allow for precise inference of source properties, provided waveform models are accurate enough to capture the full complexity of their orbital evolution. In this work, we develop a multi-parameter formalism, inspired by vacuum perturbation theory, to model asymmetric binaries embedded in general matter distributions with both radial and tangential pressures. In the regime of small deviations from the Schwarzschild metric, relevant to most astrophysical scenarios, the system admits a simplified description, where both metric and fluid perturbations can be cast into wave equations closely related to those of the vacuum case. This framework offers a practical approach to modeling the dynamics and the gravitational wave emission from binaries in realistic matter distributions, and can be modularly integrated with existing results for vacuum sources.

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24 Coalescing binaries with large mass asymmetry, i.e., mass ratios  $q \ll 1$ , represent a novel  
 25 class of gravitational wave (GW) sources for next-generation detectors, as they remain unde-  
 26 tectable by current interferometers. These systems consist of a stellar or an intermediate-mass  
 27 compact object (the secondary) orbiting a significantly more massive black hole (the primary).

28 Among these, Extreme Mass Ratio Inspirals (EMRIs), where a primary of mass  $\sim (10^6\text{--}10^8)M_\odot$   
 29 pairs with a companion of  $\sim (10 - 10^2)M_\odot$ , can be observed continuously for tens of thou-  
 30 sands of orbits [1]. During this phase, the secondary evolves within a few gravitational radii  
 31 of the primary before the final plunge, emitting GWs that peak in the millihertz regime—well  
 32 within LISA’s [2] or TianQin’s [3] sensitivity range.<sup>1</sup> Intermediate Mass Black Holes (IMBHs),  
 33 with masses in the range  $(10^2 - 10^4)M_\odot$ , can form Intermediate Mass Ratio Inspirals (IMRIs)  
 34 when coupled with either stellar-mass or supermassive black holes (BHs), with mass ratios  
 35  $q \sim 10^{-4} - 10^{-2}$  [6, 7]. IMRIs have shorter inspirals and less variability than EMRIs [8],  
 36 emitting GWs across a broad frequency range, from  $10^{-3}$  Hz to 10 Hz. This makes them  
 37 multi-band sources, potentially detectable by mHz [9, 10], decihertz observatories [11], and  
 38 3G detectors [12, 13].

39 As  $q$  decreases, the inspiral duration and the number of GW cycles followed by asymmetric  
 40 binaries increase significantly [14]. These systems spend a substantial portion of their inspiral  
 41 in a strong-field regime, tracing highly relativistic, eccentric, and off-equatorial trajectories  
 42 before merging. The combination of such a large number of GW cycles and rich relativistic  
 43 dynamics is crucial for achieving unprecedented precision in measuring source parameters [1],  
 44 and advancing the fundamental physics science goals expected by GW observations of these  
 45 systems [15–18].

46 Asymmetric binaries have garnered increasing attention as prime sources for probing the  
 47 astrophysical environments in which they evolve [15]. Indeed, BHs do not exist in isolation;  
 48 they inhabit diverse environments where particles and fields, potentially of unknown or exotic  
 49 nature, interact both with each other and with the compact objects. For instance, massive  
 50 BHs are often surrounded by dark matter halos, which may consist of exotic fields or beyond-  
 51 standard-model candidates [19]. These surrounding structures can redistribute in the pres-  
 52 ence of a BH, forming overdensities that influence the binary’s orbital dynamics and imprint  
 53 characteristic signatures on the emitted GW signals [20, 21]. Such signals carry valuable in-  
 54 formation about changes in the galactic potential and local interactions, such as those arising  
 55 from dynamical friction [22–32].

56 Moreover, crowded galactic centers can induce tidal resonances that influence EMRI evolu-  
 57 tion and reveal nearby stellar-mass object distributions [33]. IMRIs are also expected to form  
 58 in dense, matter-dominated environments, such as the accretion disks of active galactic nu-

<sup>1</sup>Exotic scenarios, such as those involving sub-solar black holes, could allow EMRIs with primaries as light as  $10^3 M_\odot$ , making them potential targets for third-generation detectors, with GW emission frequencies below 10 Hz [4, 5].

clei [8]. These systems interact with the surrounding gas through effects such as density wakes, gap-opening processes, and tidal torques, leading to complex GW emission patterns [34]. Observing such effects could constrain disk properties and enable multi-messenger analyses via electromagnetic counterparts [35].

Modeling GW emission from asymmetric binaries requires, however, highly accurate waveforms [36]. The self-force (SF) formalism provides the most precise framework to describe such systems, capturing their full evolutionary complexity [14, 37]. In this approach, Einstein field equations are expanded in powers of the mass ratio  $q$ . The leading-order solution models the secondary as a point particle moving along the geodesics of the primary, while higher-order corrections account for self-interaction and finite-size effects. On the radiation-reaction timescale, the GW phase evolution in the SF expansion follows:

$$\varphi = \frac{\varphi^{(0)}}{q} + \varphi^{(1)} + q\varphi^{(2)} + \dots, \quad (1)$$

where  $\varphi^{(0)}$  and  $\varphi^{(1)}$  correspond to the adiabatic (OPA) and post-adiabatic (1PA) contributions, respectively [37]. Phase accuracy at sub-radian levels is needed for precise parameter estimation, requiring calculations up to at least the 1PA order. The leading dissipative effects govern the OPA phase evolution, while<sup>2</sup> first-order conservative SF and second-order dissipative SF effects contribute to the 1PA phase component  $\varphi^{(1)}$ . After nearly three decades of effort, recent work has achieved the first implementation of a 1PA waveform [38–40].

Moving beyond vacuum General Relativity presents significant challenges due to the lack of relativistic solutions describing BHs embedded in matter and the complexities introduced by metric-matter couplings. As a result, modeling environmental effects on EMRIs often relies on post-Newtonian approaches [24, 41–46], though fully relativistic descriptions remain key to confidently extract small deviation from vacuum predictions [26, 30, 47–56].

Notable exceptions that provide ab initio background models incorporating non-vacuum contributions include studies investigating how ultra-light scalar fields surrounding massive primaries influence EMRI evolution at leading SF order [57, 58]. A recent study built a relativistic perturbative framework for investigating EMRIs and IMRIs in dense environments, focusing on scalar clouds formed via superradiance around Kerr BHs [59, 60], emphasizing the relevance of spin effects in assessing matter contributions to GW signals.

Along with fundamental physics motivations, scalar fields likely provide the most accessible framework for modeling environmental effects. Efforts to model the interaction of asymmetric binaries with generic fluids remain limited due to the complexity of the calculations. A fully relativistic approach, recently developed to model GW emission from EMRIs embedded in spherically symmetric matter distributions [25, 61], using both semi-analytical and fully numerical methods [27, 62–64], revealed a rich and intricate phenomenology arising from a fully relativistic treatment. This model also underscored the significant increase in computational complexity due to matter components and their perturbations. As a result, even at OPA, generating accurate waveforms across a broad parameter space remains unfeasible.

However, in most astrophysically relevant cases, and in the dynamical regimes of interest for GW detectors, environmental effects are expected to be “small,” characterized by low densities. In this regime, the background geometry of asymmetric binaries is dominated by the BH vacuum spacetime, in which both the companion and the surrounding matter act as perturbations, leading to substantial simplifications.

Following this path, we develop a multi-parameter framework to describe the evolution of asymmetric binaries embedded in generic, low-density environments, modeled via a fluid stress-energy tensor. We adopt a general anisotropic prescription that incorporates both radial

<sup>2</sup>Orbital resonances introduce additional corrections at the 0.5PA order [37].

and tangential pressure components. Focusing on non-spinning BHs, we solve Einstein equations by computing axial and polar perturbations at first order in the mass ratio. We provide practical, ready-to-use formulas for computing both gravitational and fluid perturbations, as well as the resulting GW emission at the adiabatic order, expressed in terms of environmental parameters and the secondary's orbital trajectory. Throughout this work, we use units in which  $G = c = 1$ .

## 1 Field equations and the Multi-parameter expansion

Our starting point is the action for generic environmental fields  $\vartheta$ :

$$S = \int \frac{\sqrt{-g}}{16\pi} d^4x \mathcal{R} + S_e[g_{\mu\nu}, \vartheta] + S_p[g_{\mu\nu}, \varphi], \quad (2)$$

where the action  $S_p$  describes the perturber secondary of mass  $m_p$  and its internal matter fields  $\varphi$ , which can be treated using a skeletonized approach [65],  $\mathcal{R}$  is the Ricci scalar, and  $g$  the metric determinant. The field equations for  $g_{\mu\nu}$ , can be derived by varying the total action with respect to the metric, that yields

$$G_{\mu\nu} = 8\pi T_{\mu\nu}^e + 8\pi T_{\mu\nu}^p, \quad (3)$$

where  $G_{\mu\nu}$  is the Einstein operator, and  $T_{\mu\nu}^{e,p}$  are the stress-energy tensors related to the environment and the secondary,

$$T_{\mu\nu}^{e,p} = -\frac{16\pi}{\sqrt{-g}} \frac{\delta \sqrt{-g} \mathcal{L}_{e,p}}{\delta g^{\mu\nu}}, \quad (4)$$

where  $\mathcal{L}_{e,p}$  are the Lagrangian densities associated with the actions  $S_{e,p}$ . The total energy-momentum tensor satisfies the covariant equation

$$\nabla_\mu T^\mu{}_\nu = \nabla_\mu (T^{e\mu}{}_\nu + T^{p\mu}{}_\nu) = 0. \quad (5)$$

We assume the primary is a BH of mass  $M$  dressed by a stationary distribution of matter, with a stress-energy tensor for a generic anisotropic fluid<sup>3</sup>:

$$T_{\mu\nu}^e = \rho u_\mu u_\nu + p_r k_\mu k_\nu + p_t \Pi_{\mu\nu}, \quad (6)$$

where we call  $p_t$  and  $p_r$  as radial and tangential pressures,  $u^\mu$  is the fluid four velocity and  $k^\mu$  is a unit space-like radial vector orthogonal to the latter, such that  $-u_\mu u^\mu = k_\mu k^\mu = 1$  and  $u_\mu k^\mu = 0$  [69–71]. The projector on the surface orthogonal to the 4-velocity and  $k^\mu$  is given by  $\Pi_{\mu\nu} = g_{\mu\nu} + u_\mu u_\nu - k_\mu k_\nu$ , with  $u^\mu \Pi_{\mu\nu} X^\nu = k^\mu \Pi_{\mu\nu} X^\nu = 0$ , for a generic vector  $X^\nu$ .

The secondary BH can be introduced with a perturbative approach, using the mass ratio  $q = m_p/M \ll 1$  as parameter of the expansion. In this work we consider linear-order perturbations in  $q$ , which correspond to the leading dissipative contribution in a generic SF expansion of the binary dynamics [14]. In this setup, the secondary evolves along a flow of geodesics driven by the energy and angular momentum fluxes. Higher-order terms, as well as a two-timescale analysis of environmental effects, will be studied elsewhere. The energy momentum of the secondary is given by:

$$T^{p\mu}{}_\nu(x^\alpha) = m_p \int_\gamma u_p^\mu u_p^\nu \frac{\delta^{(4)}(x^\mu - x_p^\mu(\tau))}{\sqrt{-g}} d\tau, \quad (7)$$

<sup>3</sup>A prescription to describe anisotropic fluids in Newtonian gravity and in General Relativity has been recently proposed in [66–68], aiming to cure certain inconsistencies arising due to Eq. (6) when modelling stellar solutions. Such formalism can be in principle be adapted to our approach.

where  $\gamma$  is the worldline of the compact object,  $\tau$  its proper time, and  $u_p^\mu(\tau) = dx_p^\mu/d\tau$  its 4-velocity.

We introduce a bookkeeping parameter  $\epsilon$  to characterize the perturbative nature of the matter distribution, which will later guide the classification of environmental effects. With  $\rho$  setting the scale of the environmental stress-energy tensor (6), we follow [59] and define  $\epsilon$  as the ratio between the environmental and BH densities,  $\epsilon = (M_e/L_e^3)/(M/L^3)$ , where  $M_e$  and  $L_e$  are the mass and the scale of the distribution, and  $L \sim M$  the BH scale. For instance, in the case of the dark matter configurations considered in [25], one finds  $\epsilon = (M_{\text{halo}}/M)/(a_0/L)^3$ , with  $M_{\text{halo}}$  and  $a_0$  denoting the halo mass and its typical size, respectively. In addition to density, the compactness of the matter distribution, defined as  $C_e = M_e/L_e$ , is expected to play a central role in determining the behavior of perturbations [25, 27]. Expressing  $\epsilon$  in terms of  $C_e$  one obtains  $\epsilon \sim C_e^3 (M/M_e)^2$ , suggesting that the perturbative treatment remains valid as long as  $C_e \lesssim (M_e/M)^{2/3}$ . For example, for typical dark matter halos, with  $M_e \sim (10^5 - 10^6)M$ , the compactness satisfies  $C_e \ll 1$ , ensuring  $\epsilon \ll 1$ .

When  $\epsilon \sim \mathcal{O}(1)$ , the background metric deviates significantly from the Kerr solution. Conversely, when  $\epsilon \ll \mathcal{O}(1)$ , environmental effects can be treated as small perturbations of the vacuum BH background, and the binary dynamics is governed by two small parameters:  $\epsilon$  and the mass ratio  $q$ .

In this work, we focus on the latter regime and compute the equations describing metric and matter perturbations by expanding the field equations (3), the covariant conservation of  $T^\mu{}_\nu$  (5), and all relevant tensor quantities in powers of  $\epsilon$  and  $q$ . We retain terms up to  $\mathcal{O}(\epsilon q)$ , such that the metric and stress-energy tensors can be expressed as:

$$g_{\mu\nu} = g_{\mu\nu}^{(0,0)} + g_{\mu\nu}^{(1,0)} + g_{\mu\nu}^{(0,1)} + g_{\mu\nu}^{(1,1)}, \quad (8)$$

$$T_{\mu\nu}^e = T_{\mu\nu}^{e(0,1)} + T_{\mu\nu}^{e(1,1)}, \quad T_{\mu\nu}^p = T_{\mu\nu}^{p(1,0)} + T_{\mu\nu}^{p(1,1)}, \quad (9)$$

where superscripts  $(i, j)$  identify the expansion order  $\mathcal{O}(q^i, \epsilon^j)$ , and we have re-absorbed factors  $q$  and  $\epsilon$  within each term of the expansion. In the limit  $\epsilon \rightarrow 0$  the formalism reduces to a particle moving in the Schwarzschild spacetime, with perturbations described by the Regge-Wheeler-Zerilli equations [72–74].

As discussed above, the background metric satisfies the equations

$$G_{\mu\nu}[g_{\mu\nu}^{(0,0)}] = 0, \quad (10)$$

which, in Schwarzschild coordinates  $x^\mu = (t, r, \theta, \phi)$ , gives

$$g_{\mu\nu}^{(0,0)} = \text{diag}(-f, f^{-1}, r^2, r^2 \sin^2 \theta), \quad (11)$$

with  $f = 1 - 2M/r$ .

## 2 Solutions of the multi-parameter expansion

### 2.1 Environmental effects: (0,1) contributions

The  $(0, 1)$  corrections to the metric tensor satisfy the inhomogeneous equations

$$G^\mu{}_\nu[g_{\alpha\beta}^{(0,0)}, g_{\alpha\beta}^{(0,1)}] = 8\pi T^{\epsilon\mu}{}_\nu{}^{(0,1)}. \quad (12)$$

To determine the components of the environmental stress-energy tensor, we utilize the normalization and orthogonality properties of the fluid four-velocity and the vector  $k^\mu$ . For a stationary fluid with  $u^\mu = (u^t, 0, 0, 0)$  and  $k^\mu = (k^t, k^r, 0, 0)$ , these conditions lead to

$$u^t = (-g_{tt})^{-1/2}, \quad k^t = 0, \quad k^r = g_{tt}^{-1/2}. \quad (13)$$

Expanding the metric and matter variables in powers of  $\epsilon$ , we obtain the explicit form of  $T^{e\mu}_{\nu}{}^{(0,1)}$ :

$$T^{e\mu}_{\nu}{}^{(0,1)} = \text{diag}(-\rho^{(0,1)}, p_r^{(0,1)}, p_t^{(0,1)}, p_t^{(0,1)}) . \quad (14)$$

For sake of clarity, hereafter we drop the suffix  $(0, 1)$  from the background pressure and density functions.

At order  $(0, 1)$ , we assume the following ansatz for the metric components:

$$g_{\mu\nu}^{(0,1)} = \text{diag}\left(-fH, \frac{2m}{rf^2}, r^2, r^2 \sin^2 \theta\right) , \quad (15)$$

where both  $H(r)$  and  $m(r)$  are functions of the radial coordinate  $r$  only. We focus on asymptotically flat solutions for which the matter variables vanish at the BH horizon  $r_h$ . This condition fixes  $r_h = 2M$ , as in the vacuum case, given that  $m(r_h) = 0$ . At spatial infinity, the functions behave as  $H(r \rightarrow \infty) = -2M_e/r + \mathcal{O}(1/r^2)$  and  $m(r \rightarrow \infty) = M_e + \mathcal{O}(1/r)$ , such that  $g_{tt}(r \rightarrow \infty) = -1 + 2(M + M_e)/r$ , where  $M + M_e$  is the total ADM mass of the system, and  $M_e$  denotes the mass of the matter distribution.

From the  $tt$  and  $rr$  components of Eq. (13), we derive two ordinary differential equations for  $H$  and  $m$ :

$$\frac{dm}{dr} = 4\pi r^2 \rho \quad , \quad \frac{r^2 f^2}{2} \frac{dH}{dr} = m + 4\pi r^3 f p_r . \quad (16)$$

Additionally, the energy-momentum covariant derivative at order  $(0, 1)$  gives:

$$\frac{dp_r}{dr} = \frac{2}{r} p_t + \frac{(3M - 2r)}{r^2 f} p_r - \frac{M}{r^2 f} \rho . \quad (17)$$

Equations (16)-(17) alone do not fully determine a solution for the metric and fluid variables. For a given density profile  $\rho(r)$ , which depends on the specific matter distribution, additional equations are required to close the system. This is typically provided by an equation of state that relates  $p_r, p_t$ , and  $\rho$ .

The background metric  $g_{\mu\nu}^{(0,0)} + g_{\mu\nu}^{(0,1)}$  allows for the study of the geodesic properties of both massless and massive particles. For example, the energy and angular momentum per unit mass,  $(\mathcal{E}, \mathcal{L})$ , of a massive body on a circular orbit of radius  $r_p$  are given by:

$$\mathcal{E} = \mathcal{E}^{(0,0)} + \frac{f_p[(1 - 4f_p + 3f_p^2)H_p - 2f_p M H'_p]}{\sqrt{2}(f_p - 1)(3f_p - 1)^{3/2}} , \quad (18)$$

$$\mathcal{L} = \mathcal{L}^{(0,0)} + \frac{4f_p^2 M^2 H'_p}{(1 - f_p)^{5/2}(3f_p - 1)^{3/2}} . \quad (19)$$

where the vacuum expressions read:

$$\mathcal{E}^{(0,0)} = \frac{\sqrt{2}f_p}{(3f_p - 1)^{1/2}} , \quad \mathcal{L}^{(0,0)} = \frac{2M}{(4f_p - 3f_p^2 - 1)^{1/2}} , \quad (20)$$

and  $f_p = 1 - 2M/r_p$ ,  $H_p = H(r_p)$ ,  $H'_p = H'(r)|_{r=r_p}$ . The corresponding angular frequency of the body up to the linear order in  $\epsilon$  is:

$$\Omega_p = \frac{M^{1/2}}{r_p^{3/2}} + \frac{2MH_p + r_p(r_p - 2M)H'_p}{4\sqrt{M}r_p^{3/2}} . \quad (21)$$

## 2.2 The motion of the secondary: (1,0)+(1,1) contributions

The motion of the secondary generates time dependent perturbations on both the metric and the matter fields, at the linear order in the mass ratio. For technical reasons, that will be clear at the end of this section, we will treat the left-hand side of Einstein equations working with a single background perturbation tensor

$$\delta g_{\mu\nu} = g_{\mu\nu}^{(1,0)} + g_{\mu\nu}^{(1,1)}, \quad (22)$$

which solves the linearised field's equations:

$$G^\mu{}_\nu[g_{\alpha\beta}^{(0,0)}, g_{\alpha\beta}^{(0,1)}, \delta g_{\alpha\beta}] = 8\pi(T^{\rho\mu}{}_\nu{}^{(1,0)} + T^{\rho\mu}{}_\nu{}^{(1,1)} + T^{\rho\mu}{}_\nu{}^{(1,1)}). \quad (23)$$

Decoupling of the vacuum (1,0) and the matter (1,1) terms will be performed at the end of the procedure.

Given the symmetry of the background, metric perturbations can be separated into the usual families of axial (A) and polar (P) components [72–74]:

$$\delta g_{\mu\nu}(x^\alpha) = g_{\mu\nu}^A(x^\alpha) + g_{\mu\nu}^P(x^\alpha). \quad (24)$$

Axial and polar modes change sign as  $(-1)^{\ell+1}$  and  $(-1)^\ell$  under the inversion  $(\theta \rightarrow \pi - \theta, \phi \rightarrow \phi + \pi)$ , respectively. The two classes of perturbations decouple, and can be treated independently. We can expand  $g_{\mu\nu}^A(x^\alpha)$  and  $g_{\mu\nu}^P(x^\alpha)$  in a complete set of tensor harmonics, such that:

$$\delta g_{\mu\nu}^A = \sum_{\ell,m} \frac{\sqrt{2\lambda}}{r} \left[ i h_{1,\ell m}(t,r) \mathbf{c}_{\ell m}(\theta, \phi) - h_{0,\ell m}(t,r) \mathbf{c}_{\ell m}^0(\theta, \phi) + \frac{\sqrt{\Lambda}}{r} h_{2,\ell m}(t,r) \mathbf{d}_{\ell m}(\theta, \phi) \right], \quad (25)$$

$$\begin{aligned} \delta g_{\mu\nu}^P = \sum_{\ell,m} \bigg[ & -g_{tt} H_{0,\ell m}(t,r) \mathbf{a}_{\ell m}^0(\theta, \phi) - i\sqrt{2} H_{1,\ell m}(t,r) \mathbf{a}_{\ell m}^1(\theta, \phi) - \frac{i}{r} \sqrt{2\lambda} \eta_{0,\ell m}(t,r) \mathbf{b}_{\ell m}^0(\theta, \phi) \\ & + \frac{\sqrt{2\lambda}}{r} \eta_{1,\ell m}(t,r) \mathbf{b}_{\ell m}(\theta, \phi) + g_{rr} H_{2,\ell m}(t,r) \mathbf{a}_{\ell m}(\theta, \phi) + \sqrt{\Lambda\lambda} G_{\ell m}(t,r) \mathbf{f}_{\ell m}(\theta, \phi) \\ & + \left( \sqrt{2} K_{\ell m}(t,r) - \frac{\lambda}{\sqrt{2}} G_{\ell m}(t,r) \right) \mathbf{g}_{\ell m}(\theta, \phi) \bigg], \end{aligned} \quad (26)$$

where  $\lambda = \ell(\ell+1)$ ,  $\Lambda = (\ell+2)(\ell-1)/2$ , and the sum over the multipolar indices  $(\ell, m)$  runs from  $\ell = 0, \dots, \infty$  and  $m = -\ell, \dots, \ell$ . The ten basis components  $\{\mathbf{c}_{\mu\nu}^{\ell m}, \mathbf{c}_{\mu\nu}^{0\ell m}, \dots, \mathbf{g}_{\mu\nu}^{\ell m}\}$  depend on the spherical harmonics  $Y_{\ell m}(\theta, \phi)$  and their derivatives (see e.g. Appendix A of [75] for their explicit expression). Among the ten unknown functions  $\{h_{1\ell m}, \dots, K_{\ell m}\}$ , the axial term  $h_{2\ell m}$  and the three polar gauge components  $\{\eta_{0\ell m}, \eta_{1\ell m}, G_{\ell m}\}$  can be set to zero by adopting the Regge-Wheeler-Zerilli gauge, such that the metric satisfy

$$\begin{aligned} \delta g_{\theta\phi} &= 0, \quad \delta g_{\phi\phi} = \delta g_{\theta\theta} \sin^2 \theta, \\ \partial_\phi(\delta g_{t\phi}/\sin \theta) + \partial_\theta(\delta g_{t\theta}/\sin \theta) &= 0, \\ \partial_\phi(\delta g_{r\phi}/\sin \theta) + \partial_\theta(\delta g_{r\theta}/\sin \theta) &= 0. \end{aligned} \quad (27)$$

Similarly to the metric perturbations, we decompose the particle stress-energy tensor in the basis of tensor harmonics:

$$\begin{aligned} T_{\mu\nu}^{(1,0)} = \sum_{\ell,m} \bigg[ & \mathcal{A}_{\ell m}^{(0,1,0)} \mathbf{a}_{\ell m}^0(\theta, \phi) + \mathcal{A}_{\ell m}^{(1,1,0)} \mathbf{a}_{\ell m}^1(\theta, \phi) + \mathcal{A}_{\ell m}^{(1,0)} \mathbf{a}_{\ell m}(\theta, \phi) + \mathcal{B}_{\ell m}^{(0,1,0)} \mathbf{b}_{\ell m}^0(\theta, \phi) \\ & + \mathcal{B}_{\ell m}^{(1,0)} \mathbf{b}_{\ell m}(\theta, \phi) + \mathcal{Q}_{\ell m}^{(1,0)} \mathbf{c}_{\ell m}(\theta, \phi) + \mathcal{Q}_{\ell m}^{(0,1,0)} \mathbf{c}_{\ell m}^0(\theta, \phi) + \mathcal{D}_{\ell m}^{(1,0)} \mathbf{d}_{\ell m}(\theta, \phi) \\ & + \mathcal{G}_{\ell m}^{(1,0)} \mathbf{g}_{\ell m}(\theta, \phi) + \mathcal{F}_{\ell m}^{(1,0)} \mathbf{f}_{\ell m}(\theta, \phi) \bigg]. \end{aligned} \quad (28)$$



The specific form of the coefficients  $\{\mathcal{A}_{\ell m}^{(1,0)}, \dots, \mathcal{F}_{\ell m}^{(1,0)}\}$  depends on the secondary orbital configurations. Finally, the form  $T_{\mu\nu}^{p(1,1)}$  can be constructed using the same ansatz of Eqs. (28), and replacing the functions with the correct order of the expansion, e.g.  $\mathcal{Q}_{\ell m}^{(1,0)} \rightarrow \mathcal{Q}_{\ell m}^{(1,1)}$  (see Appendix C for further details).

### 2.2.1 Environmental effects in the presence of the secondary: (1,1) matter decompositions

The last piece of the multi-parameter expansion is given by the (1,1) perturbations of matter energy-momentum tensor,  $T_{\mu\nu}^{e\mu(1,1)}$ . The covariant equations (5) are determined, at this order, by three contributions:

$$\nabla_\mu [g_{\alpha\beta}^{(0,0)}] (T^{e\mu}_{\nu(1,1)} + T^{p\mu}_{\nu(1,1)}) + \nabla_\mu [g_{\alpha\beta}^{(1,0)}] T^{e\mu}_{\nu(0,1)} + \nabla_\mu [g_{\alpha\beta}^{(0,1)}] T^{p\mu}_{\nu(1,0)} = 0, \quad (29)$$

where we identify with  $\nabla_\mu [g_{\alpha\beta}^{(m,n)}]$  the covariant derivative depending on the metric at the (i, j) order. The (1,1) contributions to the matter stress-energy tensor depend on the energy density and the pressure perturbations:

$$\rho = \rho(r) + \rho^{(1,1)}(t, r, \theta, \phi), \quad (30)$$

$$p = p_r(r) + p_r^{(1,1)}(t, r, \theta, \phi), \quad (31)$$

$$p_t = p_t(r) + p_t^{(1,1)}(t, r, \theta, \phi). \quad (32)$$

We exploit again the symmetry of the background to separate angular and time-radial variables. We expand fluid variables in terms of standard spherical harmonics

$$\rho^{(1,1)} = \sum_{\ell, m} \rho_{\ell m}^{(1,1)}(t, r) Y_{\ell m}(\theta, \phi), \quad (33)$$

$$p_r^{(1,1)} = \sum_{\ell, m} p_{r, \ell m}^{(1,1)}(t, r) Y_{\ell m}(\theta, \phi), \quad (34)$$

$$p_t^{(1,1)} = \sum_{\ell, m} p_{t, \ell m}^{(1,1)}(t, r) Y_{\ell m}(\theta, \phi). \quad (35)$$

Moreover, pressure and density perturbations are linked by an equation of state, such that:

$$p_{r, \ell m}^{(1,1)} = c_{r, \ell m}^2(r) \rho_{\ell m}^{(1,1)}, \quad p_{t, \ell m}^{(1,1)} = c_{t, \ell m}^2(r) \rho_{\ell m}^{(1,1)}, \quad (36)$$

where the tangential ( $c_{t, \ell m}^2$ ) and the radial ( $c_{r, \ell m}^2$ ) sound speeds are in general not constant, and kept functions of the radial coordinate (See Ref. [76] for specific examples).

Perturbations of the fluid velocity  $u^\mu$  and  $k^\mu$  can be written in terms of vector harmonics [77]. Given the form of the matter stress-energy tensor in Eq. (6) and that, to leading order, the energy and pressure variables are  $\mathcal{O}(\epsilon)$ , we only need terms of the order  $u^{\mu(1,0)}$  and  $k^{\mu(1,0)}$  to determine  $T_{\mu\nu}^{e\mu(1,1)}$ . The normalization of the 4-velocity reduces the independent component of the perturbations to three unknown functions. The explicit form of  $u^{\mu(1,0)}$  and  $k^{\mu(1,0)}$  is



235 given by:

$$u^{t(1,0)} = \frac{1}{2\sqrt{f}} \sum_{\ell,m} H_{0,\ell m}^{(1,0)}(t,r) Y_{\ell m}(\theta, \phi), \quad (37)$$

$$u^{r(1,0)} = \frac{f^{3/2}}{4\pi} \sum_{\ell,m} W_{\ell m}^{(1,0)}(t,r) Y_{\ell m}(\theta, \phi), \quad (38)$$

$$u^{\theta(1,0)} = \frac{\sqrt{f}}{4\pi r^2} \sum_{\ell,m} \left[ V_{\ell m}^{(1,0)}(t,r) \partial_\theta - \frac{U_{\ell m}^{(1,0)}(t,r)}{\sin \theta} \partial_\phi \right] Y_{\ell m}(\theta, \phi), \quad (39)$$

$$u^{\phi(1,0)} = \frac{\sqrt{f}}{4\pi r^2 \sin^2 \theta} \sum_{\ell,m} \left[ V_{\ell m}^{(1,0)}(t,r) \partial_\phi + U_{\ell m}^{(1,0)}(t,r) \sin \theta \partial_\theta \right] Y_{\ell m}(\theta, \phi). \quad (40)$$

236 The form of  $k^{r(1,0)}$  and  $k^{t(1,0)}$  can be found using normalisation and orthogonality conditions.

### 237 3 Perturbation equations

238 The procedure for determining axial and polar perturbations closely follows the vacuum case,  
 239 which has been extensively studied in the literature since the seminal works of Regge and  
 240 Wheeler [72, 73] and Zerilli [74]. In this section, we revisit the key steps for deriving the  
 241 master equations governing the evolution of  $\delta g_{\mu\nu}^{(A,P)}$ , and for isolating the contributions arising  
 242 from the (1, 0) and (1, 1) terms. We refer the reader to Appendix B for further details on our  
 243 initial assumption of working with a single metric perturbation in  $q$ , and on the decoupling  
 244 between vacuum and matter components. We present most of the equations in a compact  
 245 form, emphasizing their functional dependence on the metric and fluid perturbations. The full  
 246 explicit expressions are provided in the accompanying Mathematica supplementary file [78].

#### 247 3.1 $\ell \geq 2$ axial modes

248 In the axial case, we use the  $\theta\theta$  and  $\phi\phi$  components of Eqs. (23) to express the time deriva-  
 249 tive  $\partial_t h_{0\ell m}$  as a function of  $h_{1,\ell m}$  and  $\partial_r h_{1,\ell m}$ . Substituting the latter into the  $r\theta$  component  
 250 of Einstein equations and introducing the master variable  $\bar{\phi}_{\ell m} = -h_{1,\ell m}/r(-g_{tt}/g_{rr})^{1/2}$ , we  
 251 obtain a single, second-order partial differential equation of the form:

$$(-g_{tt}/g_{rr})\partial_r^2 \bar{\phi}_{\ell m} - \partial_t^2 \bar{\phi}_{\ell m} + a_1 \partial_r \bar{\phi}_{\ell m} + a_2 \bar{\phi}_{\ell m} = S_{\ell m}, \quad (41)$$

252 where  $a_{1,2}$  depend only on (0, 0) and (0, 1) quantities. The source term  $S_{\ell m}$  contains contri-  
 253 butions from the particle's stress-energy tensor and the background fluid variables. We now  
 254 introduce a new master function:

$$\phi_{\ell m}(t, r) = \sqrt{Z(r)} \bar{\phi}_{\ell m}(t, r), \quad (42)$$

255 where  $Z = f^{-1}(-g_{tt}/g_{rr})^{1/2}$ . For environmental effects that can be treated as small pertur-  
 256 bations of the Schwarzschild metric, as considered here, we write  $Z(r) = 1 + \delta Z(r)$ , where  
 257  $\delta Z(r)$  is of order  $\mathcal{O}(\epsilon)$ :

$$\delta Z(r) = \frac{H(r)}{2} - \frac{m(r)}{rf}. \quad (43)$$

258 In terms of the new field  $\phi_{\ell m}$ , Eq. (41) becomes:

$$f \partial_r (f \partial_r \phi_{\ell m}) + (1 - \delta Z) \partial_t^2 \phi_{\ell m} + a_3 \phi_{\ell m} = \bar{S}_{\ell m}, \quad (44)$$

At this point we can decompose the perturbation into vacuum and matter components, i.e.,  $\phi_{\ell m} = \phi_{\ell m}^{(0,0)} + \phi_{\ell m}^{(1,1)}$ . Furthermore, by introducing the usual tortoise coordinate  $r_*$ , such that  $\partial_{r_*} = f \partial_r$ , we can eliminate the first radial derivative of the metric perturbations, obtaining the following wave equations:

$$[\partial_{r_*}^2 - \partial_t^2 - V^A] \phi_{\ell m}^{(1,0)}(t, r) = S_{\ell m}^{A(1,0)}(t, r), \quad (45)$$

$$[\partial_{r_*}^2 - \partial_t^2 - V^A] \phi_{\ell m}^{(1,1)}(t, r) = S_{\ell m}^{A(1,1)}(t, r). \quad (46)$$

Thus, at linear order in  $\mathcal{O}(\epsilon)$ , the axial perturbation problem reduces to solving two wave equations, with the same scattering potential, which matches the Regge–Wheeler expression for the vacuum case:

$$V^A = f \left( \frac{\ell(\ell+1)}{r^2} - \frac{6M}{r^3} \right). \quad (47)$$

The source  $S_{\ell m}^{A(1,0)}(t, r)$  only depends on the coefficients of  $T_{\mu\nu}^{p(1,0)}$  in Eq. (28). The source  $S_{\ell m}^{A(1,1)}$  is proportional to  $T_{\mu\nu}^{p(1,1)}$ , and contains contributions from the vacuum master function  $\phi_{\ell m}^{(1,0)}$ , multiplied by the matter density and pressure. Once Eqs. (45)–(46) are solved, we can use Eq. (43) to obtain the (1, 0) and (1, 1) components of  $\phi_{\ell m}$ , and consequently the expansion for the metric functions  $h_{1,\ell m} = h_{1,\ell m}^{(1,0)} + h_{1,\ell m}^{(1,1)}$  and  $h_{0,\ell m} = h_{0,\ell m}^{(1,0)} + h_{0,\ell m}^{(1,1)}$ . Their explicit expressions are given in Appendix A.

Finally, the velocity perturbation  $U_{\ell m}^{(1,0)}$  can be derived from the  $t\theta$  component of Einstein equations, which yields an algebraic relation between this quantity and the metric variables:

$$\partial_t U_{\ell m}^{(1,0)}(t, r) = - \frac{4\pi \partial_t h_{0,\ell m}^{(1,0)}}{f} + S_{\ell m}^U(t, r), \quad (48)$$

with  $S_{\ell m}^U(t, r)$  depending on the point particle motion.

### 3.1.1 The frequency domain solution

In the frequency domain, Eqs. (45)–(46) reduce to two ordinary differential equations in the radial coordinate:

$$[\partial_{r_*}^2 + \omega^2 - V^A] \phi_{\ell m}^{(1,0)}(\omega, r) = S_{\ell m}^{A(1,0)}(\omega, r), \quad (49)$$

$$[\partial_{r_*}^2 + \omega^2 - V^A] \phi_{\ell m}^{(1,1)}(\omega, r) = S_{\ell m}^{A(1,1)}(\omega, r), \quad (50)$$

where, for a generic function  $X(t, r)$ :

$$X(\omega, r) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} e^{i\omega t} X(t, r) dt, \quad X(t, r) = \int_{-\infty}^{+\infty} e^{-i\omega t} X(\omega, r) d\omega. \quad (51)$$

Equations (49)–(50) can be solved using a Green’s function approach. We first solve the associated homogeneous equations with purely ingoing (–) boundary conditions at the horizon and purely outgoing (+) conditions at infinity:

$$\phi_{\ell m}^{(1,0)(-)} \sim \begin{cases} e^{-i\omega r_*} & r_* \rightarrow -\infty \\ A_{\text{in}} e^{-i\omega r_*} + A_{\text{out}} e^{i\omega r_*} & r_* \rightarrow +\infty \end{cases}, \quad (52)$$

$$\phi_{\ell m}^{(1,0)(+)} \sim \begin{cases} e^{i\omega r_*} & r_* \rightarrow +\infty \\ B_{\text{in}} e^{-i\omega r_*} + B_{\text{out}} e^{i\omega r_*} & r_* \rightarrow -\infty \end{cases}, \quad (53)$$

Note that the homogeneous equation is identical for both the  $(1, 0)$  and  $(1, 1)$  components, and hence needs to be solved only once. The full solution is obtained by integrating  $\phi_{\ell m}^{(1,0)(\pm)}$  over the source term:

$$\phi_{\ell m}^{(1,0)} = C^+ \phi_{\ell m}^{(1,0)(-)} + C^- \phi_{\ell m}^{(1,0)(+)} , \quad (54)$$

with coefficients given by:

$$C^+ = \int_{-\infty}^{r_*} \frac{\phi_{\ell m}^{(1,0)(-)}(r'_*) S_{\ell m}^{(1,0)}(r'_*)}{\mathcal{W}_{\ell m}(r'_*)} dr'_* , \quad C^- = \int_{r_*}^{+\infty} \frac{\phi_{\ell m}^{(1,0)(+)}(r'_*) S_{\ell m}^{(1,0)}(r'_*)}{\mathcal{W}_{\ell m}(r'_*)} dr'_* , \quad (55)$$

where  $\mathcal{W}_{\ell m}$  is the constant Wronskian of the homogeneous solutions:

$$\mathcal{W}_{\ell m}(r_*) = f \partial_r \phi_{\ell m}^{(1,0)(+)} \phi_{\ell m}^{(1,0)(-)} - f \partial_r \phi_{\ell m}^{(1,0)(-)} \phi_{\ell m}^{(1,0)(+)} . \quad (56)$$

The solution for  $\phi_{\ell m}^{(1,1)}$  has the same form as Eq. (54), with the substitution  $S_{\ell m}^{(1,0)} \rightarrow S_{\ell m}^{(1,1)}$  in the  $C^\pm$  coefficients.

For circular orbits the calculation of  $C^\pm$  greatly simplifies. In this case the source term can be written as function of Dirac's delta and it's first derivative:

$$S_{\ell m}^{(1,0)} = D(r, r_p) \delta(r - r_p) + G(r, r_p) \delta'(r - r_p) , \quad (57)$$

where  $r_p$  is the secondary orbital radius, and the functions  $D, G$  can be determined from the coefficients of  $T_{\mu\nu}^{p(1,0)}$  (and of  $T_{\mu\nu}^{p(1,1)}$  for the matter contribution). Integration in Eqs. (55) can be performed analytically such that

$$C^+ = C^+ \Theta(r - r_p) , \quad C^- = C^- \Theta(r_p - r) , \quad (58)$$

where

$$C^\pm = \frac{\phi_{\ell m}^{(1,0)(\mp)}(r_p) D(r_p)}{f_p \mathcal{W}} - \frac{d}{dr} \left[ \frac{\phi_{\ell m}^{(1,0)(\mp)}(r_p) G(r_p)}{\mathcal{W} f(r)} \right]_{r=r_p} . \quad (59)$$

### 3.2 $\ell \geq 2$ polar modes

Perturbations in the polar sector are characterized by seven variables: four metric components ( $H_{0,\ell m}, H_{1,\ell m}, H_{2,\ell m}, K_{\ell m}$ ), two components of the fluid velocity perturbation ( $V_{\ell m}^{(1,0)}, W_{\ell m}^{(1,0)}$ ), and the density perturbation  $\rho^{(1,1)}$ . Despite this complexity, the dimensionality of the system can be significantly reduced.

The  $\theta\phi$  component of Eqs. (23) allows us to express  $H_{2,\ell m}$  in terms of  $H_{0,\ell m}$ . Furthermore, the  $rr$ ,  $tr$ , and  $t\theta$  components of Einstein equations can be used to eliminate the time derivative of  $H_{0,\ell m}$ , yielding two coupled differential equations<sup>4</sup> that depend only on the metric functions  $K_{\ell m}$  and  $H_{1,\ell m}$ , along with the fluid perturbations, and take the following form:

$$\begin{aligned} (b_1 + b_2 \partial_r) H_{1,\ell m} + (b_3 \partial_t + b_4 \partial_{tr}^2) K_{\ell m} + b_5 V_{\ell m}^{(1,0)} + b_6 W_{\ell m}^{(1,0)} &= S_{\ell m}^H , \\ (c_1 + c_2 \partial_r + c_3 \partial_{rr}^2 + c_4 \partial_{tt}^2) H_{1,\ell m} + (c_4 \partial_t + c_5 \partial_{tr}^2) K_{\ell m} + (c_6 + c_7 \partial_r) V_{\ell m}^{(1,0)} + c_8 W_{\ell m}^{(1,0)} &= S_{\ell m}^K , \end{aligned} \quad (60)$$

<sup>4</sup>These algebraic manipulations also introduce a third-order time derivative of  $K_{\ell m}$ , which can be removed using the  $t\phi$  component of Einstein equations.

From the time component of the covariant derivative of the stress-energy tensor, we obtain an equation for  $\rho_{\ell m}^{(1,1)}$ :

$$d_1 \partial_t \rho_{\ell m}^{(1,1)} + d_2 \partial_t K_{\ell m} + (d_3 + d_4 \partial_r) H_{1,\ell m} + (d_5 + d_6 \partial_r) W_{\ell m}^{(1,0)} + d_7 V_{\ell m}^{(1,0)} = \mathcal{J}_{\ell m}^\rho. \quad (62)$$

The coefficients  $(b_i, c_i, d_i)$  appearing in Eqs. (60)–(62) contain background quantities and depend only on  $r$ . Finally, from  $\nabla_\mu T^{\mu\theta} = 0$  and  $\nabla_\mu T^{\mu r} = 0$ , we obtain two first-order equations in time for  $\partial_t V_{\ell m}^{(1,0)}$  and  $\partial_t W_{\ell m}^{(1,0)}$ .

We now reduce the coupled system for  $H_{1,\ell m}$  and  $K_{\ell m}$  to a single master equation for the metric perturbation, following the strategy introduced by Zerilli in vacuum [74], and isolate its  $(0, 1)$  and  $(1, 1)$  components. We first introduce the new functions  $\bar{\chi}_{\ell m}(t, r)$  and  $\bar{R}_{\ell m}(t, r)$ :

$$\partial_t K_{\ell m}(t, r) = \alpha \bar{\chi}_{\ell m}(t, r) + \beta \bar{R}_{\ell m}(t, r) \quad , \quad H_{1,\ell m}(t, r) = \gamma \bar{\chi}_{\ell m}(t, r) + \delta \bar{R}_{\ell m}(t, r) \quad , \quad (63)$$

As in the axial sector, we introduce the scaling function  $Z(r)$  such that  $\chi_{\ell m} = \sqrt{Z} \bar{\chi}_{\ell m}$  and  $R_{\ell m} = \sqrt{Z} \bar{R}_{\ell m}$ . The coefficients  $(\alpha, \beta, \gamma, \delta)$ , which depend only on  $r$ , are fixed by requiring that  $\chi_{\ell m}$  and  $R_{\ell m}$  satisfy Zerilli-like equations of the form:

$$f \partial_r [f \partial_r \chi_{\ell m}] + (\mathcal{V}^P - \partial_t^2) \chi_{\ell m} = S_{\ell m}^P \quad , \quad f \partial_r \chi_{\ell m} - R_{\ell m} = \mathcal{J}_{\ell m}^P \quad , \quad (64)$$

for some scattering potential  $\mathcal{V}^P$ . At this stage, and for readability, we collectively include in the source terms  $S_{\ell m}^P$  and  $\mathcal{J}_{\ell m}^P$  all contributions proportional to the secondary orbital configuration and fluid perturbations. Their explicit forms will be given later.

The coefficients that ‘diagonalize’ the problem coincide with those originally found by Zerilli [74]. At this point, all metric perturbations can be expanded in the two-parameter scheme, e.g.,  $\chi_{\ell m} = \chi_{\ell m}^{(0,1)} + \chi_{\ell m}^{(1,1)}$ . As a result, Eqs. (60)–(61) reduce to:

$$\partial_{r_*}^2 \chi_{\ell m}^{(1,0)} + (V^P - \partial_t^2) \chi_{\ell m}^{(1,0)} = S_{\ell m}^{P(1,0)} \quad , \quad (65)$$

$$\partial_{r_*}^2 \chi_{\ell m}^{(1,1)} + (V^P - \partial_t^2) \chi_{\ell m}^{(1,1)} + (z_1 + z_2 f \partial_r) V_{\ell m}^{(1,0)} + (z_3 + z_4 f \partial_r) W_{\ell m}^{(1,0)} = S_{\ell m}^{P(1,1)} \quad . \quad (66)$$

The scattering potential for both the  $(1, 0)$  and  $(1, 1)$  equations coincides and is given by the well-known vacuum result:

$$V^P = -\frac{2f}{r^3} \frac{9M^3 + 9\Lambda M^2 r + 3\Lambda^2 M r^2 + \Lambda^2(\Lambda + 1)r^3}{(3M + r\Lambda)^2} \quad . \quad (67)$$

The source term  $S_{\ell m}^{P(1,1)}$  is proportional to  $\chi_{\ell m}^{(1,0)}$  and to the components of  $T_{\mu\nu}^{p,(1,1)}$ , while the coefficients  $d_{1,2,3,4}$  depend only on the background pressure and density. The density perturbation enters the equation for  $\chi_{\ell m}^{(1,1)}$  via the fluid velocities, which are determined by:

$$\kappa_t \partial_t V_{\ell m}^{(1,0)} + 4\pi c_{t,\ell m}^2 \rho_{\ell m}^{(1,1)} = S_{\ell m}^V \quad , \quad (68)$$

$$\kappa_r \partial_t W_{\ell m}^{(1,0)} + (w_1 + w_2 f \partial_r) \rho_{\ell m}^{(1,1)} = S_{\ell m}^W \quad , \quad (69)$$

where  $\kappa_t = \rho(r) + p_t(r)$  and  $\kappa_r = \rho(r) + p_r(r)$ . Finally, using Eqs. (65) and (68)–(69), we can simplify the master equation for  $\rho_{\ell m}^{(1,1)}$ . Taking the time derivative of Eq. (62) yields:

$$(\partial_{r_*}^2 - c_{r,\ell m}^{-2} \partial_t^2 + V^P + \gamma_1 \partial_{r_*}) \rho_{\ell m}^{(1,1)} = S_{\ell m}^\rho \quad . \quad (70)$$

The coefficients  $(w_1, w_2)$  involve combinations of  $p_{t,r}(r)$  and  $\rho(r)$ , while  $V^P$  and  $\gamma_1$  depend only on the sound speeds. Along with the particle motion, the sources  $S_{\ell m}^{V,W,\rho}$  depend on the vacuum solutions  $\chi_{\ell m}^{(1,0)}$ .

Note that Eq. (70) is decoupled from the  $(1, 1)$  metric perturbations and can be solved once the vacuum solution is known. This allows to determine  $V_{\ell m}^{(1,0)}$  and  $W_{\ell m}^{(1,0)}$  via Eqs. (68)-(69). These quantities can then be used to fully solve the polar sector and obtain  $\chi_{\ell m}^{(1,1)}$  through Eq. (66). The metric components can subsequently be reconstructed using the expressions in Appendix A.

We also briefly comment on the structure of the polar sector in the frequency domain. Although the equations remain too lengthy to present explicitly, the formulation simplifies significantly. In this case, the velocity perturbations, given by Eqs. (68)-(69), reduce to algebraic relations and can be eliminated from the wave equation for  $\chi_{\ell m}^{(1,1)}$ , which can then be determined once a solution for  $\rho_{\ell m}^{(1,1)}$  is obtained using the Green function approach already discussed for the axial sector.

### 3.3 $\ell = 0$ modes

For the sake of completeness, we complement the previous calculations with the treatment of the  $\ell = 0$  and  $\ell = 1$  modes, which do not contribute to gravitational radiation.

For  $\ell = m = 0$ , only polar perturbations are excited. In this case we adopt the so called Zerilli gauge, which allows us to set  $H_{1,00} = K_{00} = 0$  [74, 79]. Decomposing the remaining metric functions  $H_{2,00}$  and  $H_{0,00}$  into vacuum and matter components, we obtain

$$\partial_r H_{0,00}^{(1,0)} = -\frac{H_{2,00}^{(1,0)}}{f} - 8\pi A_{00}^{(1,0)}, \quad (71)$$

$$\partial_r H_{2,00}^{(1,0)} = -\frac{H_{2,00}^{(1,0)}}{f} + \frac{8\pi r}{f^2} A_{00}^{(1,0)}, \quad (72)$$

which coincide with the standard results derived in the vacuum case [80], and

$$\partial_r H_{0,00}^{(1,1)} = -\frac{8\pi r c_r^2 \rho_{00}^{(1,1)}}{f} - \frac{2}{f^2 r^2} (4\pi f r^3 p_r + m) H_{2,00}^{(1,0)} - \frac{H_{2,00}^{(1,1)}}{f r} - 8\pi r \mathcal{A}_{00}^{(1,1)}, \quad (73)$$

$$\begin{aligned} \partial_r H_{2,00}^{(1,1)} = & -\frac{H_{2,00}^{(1,1)}}{f r} + \frac{8\pi r}{f} \rho_{00}^{(1,1)} + \frac{8\pi r}{f^2} \mathcal{A}_{00}^{(0)(1,1)} + \frac{2}{f^2 r^2} H_{2,00}^{(1,0)} (4\pi f r^3 \rho - m) \\ & - \frac{8\pi}{f^3} \mathcal{A}_{00}^{(1,0)} (f r H - 2m). \end{aligned} \quad (74)$$

Moreover, an algebraic equation for  $W_{00}^{(1,0)}$  can be obtained from the  $tr$  component of Einstein equations:

$$\kappa_r W_{00}^{(1,0)} = \frac{2i\sqrt{2}\pi \mathcal{A}_{00}^{(1,1)}}{f} - \frac{\partial_t H_{2,00}^{(1,1)}}{2f r}, \quad (75)$$

Finally, substituting the above into the  $\theta\theta$  component of Eqs. (23), we obtain a master equation for  $\rho_{00}^{(1,1)}$ :

$$\left( \partial_{r_*}^2 - c_{r,00}^{-2} \partial_t^2 + V_{\ell=0}^\rho + \gamma_{1,\ell=0} \partial_{r_*} \right) \rho_{00}^{(1,1)} = S_{00}^\rho. \quad (76)$$

The source term  $S_{00}^\rho$  depends on the vacuum solution  $H_{2,00}^{(1,0)}$  and on the secondary orbital trajectory, while the potential  $V_{\ell=0}^\rho$  and the coefficient  $\gamma_{1,\ell=0}$  contain terms proportional to the radial sound speed. As for the  $\ell \geq 2$  modes, Eq. (76) is decoupled from the  $(1, 1)$  metric perturbations and is entirely determined by the vacuum component. Once solved, one can determine  $W_{00}^{(1,0)}$  via Eq. (75), and subsequently reconstruct  $H_{0,00}$  and  $H_{2,00}$ .

### 3.4 $\ell = 1$ modes

For  $\ell = 1$ , both axial and polar modes are present. In the axial sector, the Zerilli gauge is implemented by setting  $h_{0,1m} = 0$ , leaving  $h_{1,1m}$  as the only nonvanishing metric component to be determined [74]. The field equations for the  $(1,0)$  axial perturbation take the form:

$$\partial_t^2 h_{1,1m}^{(1,0)} = -rf \, 8i\pi \, Q_{1m}^{(1,0)}, \quad (77)$$

$$\frac{2}{r^2} \partial_t h_{1,1m}^{(1,0)} + \frac{1}{r} \partial_{t,r}^2 h_{1,1m}^{(1,0)} + \frac{8\pi}{f} Q_{1m}^{0(1,0)} = 0. \quad (78)$$

At the  $(1,1)$  order we have for the metric perturbation

$$\partial_t^2 h_{1,1m}^{(1,1)} - [H \partial_t^2 - 16\pi f (p_t - p_r)] h_{1,1m}^{(1,0)} + 8\pi i f r Q_{1m}^{(1,1)} = 0, \quad (79)$$

$$\left( f \partial_{t,r}^2 + \frac{2f}{r} \partial_t \right) h_{1,1m}^{(1,1)} + 4f \kappa_t U_{1m}^{(1,0)} + 8\pi r Q_{1m}^{(0)(1,1)} - \frac{4}{r^2} \left( \pi r^3 \kappa_r + m + \frac{rm}{2} \partial_r \right) \partial_t h_{1,1m}^{(1,0)} = 0. \quad (80)$$

Finally, an equation for  $\partial_t U_{1m}^{(1,0)}$  can be derived from  $\theta$  component of the covariant divergence  $\nabla_\mu T^{\mu\theta} = 0$ .

In the polar sector, we fix the Zerilli gauge by setting  $K_{1m} = 0$ , so that the remaining metric perturbations to determine are  $H_{0,1m}$ ,  $H_{1,1m}$ , and  $H_{2,1m}$ , along with the fluid variables  $V_{1m}^{(1,0)}$ ,  $W_{1m}^{(1,0)}$ , and  $\rho_{1m}^{(1,1)}$ . Decomposing the metric into its  $(1,0)$  and  $(1,1)$  components, we derive the corresponding perturbation equations by applying Einstein equations together with the  $t$ ,  $r$ , and  $\theta$  components of  $\nabla_\mu T^{\mu\nu} = 0$ . The  $(1,0)$  vacuum equations for  $H_{0,1m}$ ,  $H_{1,1m}$ , and  $H_{2,1m}$  coincide with those available in Appendix B of [75].

The functional forms of the equations for matter perturbations are identical to those in Eqs. (68)-(70), valid for modes with  $\ell \geq 2$ , except for the coefficients  $w_1$ ,  $w_2$ , and  $\gamma_1$ , as well as the scattering potential  $V^\rho$ , whose explicit expressions are provided in the accompanying Mathematica file.

## 4 Gravitational wave fluxes

Having determined the axial and polar perturbations, we can compute the associated GW fluxes at infinity and at the horizon. The asymptotic structure of our metric allows us to use the standard procedure adopted in vacuum [81,82], aimed at determining the form of the perturbations in a coordinate system where the metric exhibits the correct radial dependence [83].

To move from the RWZ gauge to the radiation gauge, we perform an infinitesimal coordinate transformation such that

$$\delta g_{\mu\nu}^{\text{RG}} = \delta g_{\mu\nu}^{\text{RWZ}} - \nabla_\mu \xi_\nu - \nabla_\nu \xi_\mu, \quad (81)$$

where  $\xi^\mu$  is a gauge vector expanded in multipole components (summation over  $(\ell, m)$  is implicit):

$$\xi_\mu = (\alpha_1, \alpha_2, r^2 [\alpha_3 \csc \theta \partial_\phi + \alpha_4 \partial_\theta], r^2 [\alpha_4 \partial_\phi - \alpha_3 \sin \theta \partial_\theta]) Y_{\ell m}, \quad (82)$$

with  $\alpha_{1,2,3,4}$  being gauge functions dependent on  $(t, r)$ . Following [81], at infinity the perturbation tensor satisfies the outgoing radiation conditions:

$$\delta g_{\mu\nu}^{\text{ORG}} n^\mu n^\nu = \delta g_{\mu\nu}^{\text{ORG}} n^\mu m^\nu = \delta g_{\mu\nu}^{\text{ORG}} n^\mu m^{\nu*} = \delta g_{\mu\nu}^{\text{ORG}} n^\mu l^\nu = \delta g_{\mu\nu}^{\text{ORG}} m^\mu m^{\nu*} = 0, \quad (83)$$

where the null tetrad  $(l^\mu, n^\mu, m^\mu, m^{\mu*})$  has components:

$$\begin{aligned} l_\mu &= \{-\sqrt{-g_{tt}g_{rr}}, g_{rr}, 0, 0\}, \\ n_\mu &= -\frac{1}{2}\left\{\sqrt{-g_{tt}/g_{rr}}, 1, 0, 0\right\}, \\ m_\mu &= \frac{1}{\sqrt{2}}\{0, 0, r, ir \sin \theta\}, \end{aligned} \quad (84)$$

with  $l^\mu l_\mu = n^\mu n_\mu = m^\mu m_\mu = m^{\mu*} m_\mu^* = 0$ ,  $l^\mu n_\mu = -1 = -m^\mu m_\mu^*$ , and the asterisk denoting complex conjugation [84].

Equations (83), together with the gauge transformation (81), can be used to express  $\alpha_{1,2,3,4}$  in terms of the RWZ metric perturbations and reconstruct the perturbation tensor at infinity.<sup>5</sup>

From the asymptotic form of the polar and axial components at  $r \rightarrow \infty$ , using Eqs. (A.1)–(A.5), we find to leading order:

$$h_{0\ell m} \simeq -h_{1\ell m} \simeq r(\phi_{\ell m}^{(1,0)} + \phi_{\ell m}^{(1,1)}), \quad (85)$$

$$H_{2,\ell m} \simeq H_{0,\ell m} \simeq -H_{1,\ell m} \simeq r\partial_t(\chi_{\ell m}^{(1,0)} + \chi_{\ell m}^{(1,1)}) - \frac{2rM_e}{\Lambda}\partial_t^2\chi_{\ell m}^{(1,0)}, \quad (86)$$

$$K_{\ell m} \simeq -(\chi_{\ell m}^{(1,0)} + \chi_{\ell m}^{(1,1)}) + \frac{2M_e}{\Lambda}\partial_t\chi_{\ell m}^{(1,0)}, \quad (87)$$

assuming that at spatial infinity  $\partial_t = -\partial_r + \mathcal{O}(1/r)$ . In the radiation zone, the perturbation becomes:

$$\delta g_{AB}^{\text{ORG}} = -2r^2(\alpha_4 V_{AB}^{\ell m} + \alpha_3 W_{AB}^{\ell m}) + \mathcal{O}(1), \quad (88)$$

where indices  $A, B$  span the angular coordinates  $(\theta, \phi)$ , and

$$\alpha_3 = \frac{1}{r} \int^t (\phi_{\ell m}^{(1,0)} + \phi_{\ell m}^{(1,1)}) dt', \quad (89)$$

$$-2\alpha_4 = \frac{1}{r} \int^t \left( \chi_{\ell m}^{(1,0)} + \chi_{\ell m}^{(1,1)} - \frac{2M_e}{\Lambda} \partial_t \chi_{\ell m}^{(1,0)} \right) dt', \quad (90)$$

and

$$V_{AB} = \left( \nabla_A \nabla_B + \frac{\lambda}{2} \Omega_{AB} \right) Y_{\ell m}, \quad W_{AB} = \frac{1}{2} [\nabla_B \epsilon_A^C \nabla_C + \nabla_A \epsilon_B^C \nabla_C] Y_{\ell m}, \quad (91)$$

with  $\Omega_{AB} = \text{diag}(1, \sin^2 \theta)$ ,  $\nabla_A$  the covariant derivative, and  $\epsilon_{AB}$  the Levi-Civita tensor on the unit 2-sphere.

The energy and angular momentum fluxes can be obtained from the Isaacson stress-energy tensor for gravitational waves,

$$T_{\mu\nu}^{\text{GW}} = \frac{1}{64\pi} \langle \nabla_\mu \delta g^{\alpha\beta} \nabla_\nu \delta g_{\alpha\beta} \rangle, \quad (92)$$

where  $\langle \dots \rangle$  denotes average over a region of spacetime large compared with the GW wavelength. Given the symmetry of the background, we can express fluxes using the Killing vectors  $\{\xi_{(t)}^\nu, \xi_{(\phi)}^\nu\}$  associated to the two cyclic variables  $t$  and  $\phi$ :

$$-dE = \int_\Sigma T^{\text{GW}\mu}{}_\nu \xi_{(t)}^\nu d\Sigma_\mu = \pm \left[ \frac{|g_{tt}|}{g_{rr}} \right]^{1/2} r^2 \int_\Sigma T_{tr}^{\text{GW}} d\Omega dt, \quad (93)$$

$$dL = \int_\Sigma T^{\text{GW}\mu}{}_\nu \xi_{(\phi)}^\nu d\Sigma_\mu = \pm \left[ \frac{|g_{tt}|}{g_{rr}} \right]^{1/2} r^2 \int_\Sigma T_{r\phi}^{\text{GW}} d\Omega dt, \quad (94)$$

<sup>5</sup>These calculations are nearly identical to those in Appendix B of [81], except for the general form of the metric components  $g_{tt}$  and  $g_{rr}$ , which include matter contributions beyond Schwarzschild.



where  $d\Sigma_\mu$  is a surface element outward-oriented on  $\Sigma$  and the signs  $-$  and  $+$  are for flux at horizon and at infinity respectively. Expanding all quantities at leading order in  $1/r$ , and using Eqs. (88)–(89) within the energy flux (93), to order  $\mathcal{O}(q^2\epsilon)$  we obtain:

$$\dot{E}_{\ell m}^\infty = \frac{1}{64\pi} \frac{(\ell+2)!}{(\ell-2)!} \left( \left| \chi_{\ell m}^{(1,0)} \right|^2 + 4 \left| \phi_{\ell m}^{(1,0)} \right|^2 + 2 \operatorname{Re} \left[ \chi_{\ell m}^{(1,0)} \chi_{\ell m}^{(1,1)*} + 4 \phi_{\ell m}^{(1,0)} \phi_{\ell m}^{(1,1)*} - \frac{2M_e}{\Lambda} \chi_{\ell m}^{(1,0)} \partial_t \chi_{\ell m}^{(1,0)*} \right] \right). \quad (95)$$

Similarly, for the angular momentum flux, Eq. (94), we have:

$$\begin{aligned} \dot{L}_{\ell m}^\infty = & \frac{im}{128\pi} \frac{(\ell+2)!}{(\ell-2)!} \left[ \chi_{\ell m}^{(1,0)} \int^t \chi_{\ell m}^{(1,0)*} dt' + 4 \phi_{\ell m}^{(1,0)} \int^t dt' \phi_{\ell m}^{(1,0)*} - \chi_{\ell m}^{(1,0)} \left( \frac{2M_e}{\Lambda} \chi_{\ell m}^{(1,0)*} \right. \right. \\ & \left. \left. - \int^t dt' \chi_{\ell m}^{(1,1)*} \right) - \left( \frac{2M_e}{\Lambda} \partial_t \chi_{\ell m}^{(1,0)} - \chi_{\ell m}^{(1,1)} \right) \int^t dt' \chi_{\ell m}^{*(1,0)} \right. \\ & \left. + 4 \phi_{\ell m}^{(1,0)} \int^t dt' \phi_{\ell m}^{(1,1)*} + 4 \phi_{\ell m}^{(1,1)} \int^t dt' \phi_{\ell m}^{(1,0)*} \right] + \text{c.c.} . \end{aligned} \quad (96)$$

The first two terms in Eqs. (95) and (96) correspond to the standard fluxes at infinity for vacuum perturbations around Schwarzschild BHs.

Calculations of GW fluxes at the horizon proceed analogously to those at infinity. We

impose an ingoing radiation gauge by swapping  $l^\mu \leftrightarrow n^\mu$  in Eqs. (83), and express the gauge functions in terms of the RWZ metric perturbations near the horizon, i.e., in the limit  $f \rightarrow 0$ .

Using Eqs. (A.1)–(A.5), we obtain the leading-order behavior of the axial and polar components as  $r \rightarrow 2M$ :

$$f h_{1\ell m} \simeq -2M \left( \phi_{\ell m}^{(1,0)} + \phi_{\ell m}^{(1,1)} \right) + \frac{3MH_h}{2} \phi_{\ell m}^{(1,0)}, \quad (97)$$

$$h_{0\ell m} \simeq -2M \left( \phi_{\ell m}^{(1,0)} + \phi_{\ell m}^{(1,1)} \right) - \frac{M}{2} H_h \phi_{\ell m}^{(1,0)}, \quad (98)$$

$$H_{2,\ell m} \simeq H_{0,\ell m} \simeq H_{1\ell m} \simeq \frac{1}{2} (4M \partial_t - 1) \left[ \chi_{\ell m}^{(1,0)} + \chi_{\ell m}^{(1,1)} \right] - \frac{H}{8} (4M \partial_t - 1) \chi_{\ell m}^{(1,0)}, \quad (99)$$

$$\partial_t K_{\ell m} \simeq \left( \frac{\Lambda+1}{2M} + \partial_t \right) \left( \chi_{\ell m}^{(1,0)} + \chi_{\ell m}^{(1,1)} \right) - \frac{H_h}{4} \left( \frac{\Lambda+1}{2M} + \partial_t \right) \chi_{\ell m}^{(1,0)}, \quad (100)$$

where  $H_h \equiv H(r = r_h)$ , and we assume that near the horizon  $\partial_t = f \partial_r + \mathcal{O}(f)$ . Combining<sup>6</sup> these expressions with Eqs. (81) and (83), we can write the metric perturbation in the ingoing radiation gauge as:

$$\delta g_{AB}^{\text{HRG}} = -8M^2 \left( \alpha_4 V_{AB}^{\ell m} + \alpha_3 W_{AB}^{\ell m} \right) + \mathcal{O}(f), \quad (101)$$

with the gauge coefficients given by

$$\alpha_3 = -\frac{1}{2M} \int^t \left( \phi_{\ell m}^{(1,0)} + \phi_{\ell m}^{(1,1)} - \frac{H_h}{4} \phi_{\ell m}^{(1,0)} \right) dt', \quad (102)$$

$$\alpha_4 = -\frac{1}{4M} \int^t \left( \chi_{\ell m}^{(1,0)} + \chi_{\ell m}^{(1,1)} + \frac{MH_h}{3+2\Lambda} \partial_t \chi_{\ell m}^{(1,0)} - \frac{H_h}{4} \chi_{\ell m}^{(1,0)} \right) dt'. \quad (103)$$

<sup>6</sup>Following [81] we rescale  $\alpha_2 \rightarrow \alpha_2 f^{-1} (1 - H_h)$ .

422 The calculation of energy and angular momentum fluxes proceeds similarly to the far-zone  
 423 treatment [81], by isolating the  $\mathcal{O}(f^{-1})$  contribution to the GW stress-energy tensor (92), and  
 424 neglecting terms of order  $\mathcal{O}(1)$ .

425 We substitute the expression of the metric perturbation (101) into Eqs. (93)-(94), also  
 426 multiplying by a  $-$  sign to account that we compute BH absorption rather fluxes in the radiation  
 427 zone. To the leading order in  $f$  we find:

$$\begin{aligned} \dot{E}_{\ell m}^H = & \frac{1}{64\pi} \frac{(\ell+2)!}{(\ell-2)!} \left( \left| \chi_{\ell m}^{(1,0)} \right|^2 + 2 \operatorname{Re} \left[ \chi_{\ell m}^{(1,0)} \chi_{\ell m}^{(1,1)*} + \frac{MH_h}{3+2\Lambda} \chi_{\ell m}^{(1,0)} \partial_t \chi_{\ell m}^{(1,0)*} \right] + 4 \left| \phi_{\ell m}^{(1,0)} \right|^2 \right. \\ & \left. + 8 \operatorname{Re} \left[ \phi_{\ell m}^{(1,0)} \phi_{\ell m}^{(1,1)*} \right] \right). \end{aligned} \quad (104)$$

$$\begin{aligned} \dot{L}_{\ell m}^H = & \frac{im}{128\pi} \frac{(\ell+2)!}{(\ell-2)!} \left[ \chi_{\ell m}^{(1,0)} \int^t \chi_{\ell m}^{(1,0)*} dt' + 4\phi_{\ell m}^{(1,0)} \int^t dt' \phi_{\ell m}^{(1,0)*} \right. \\ & + \chi_{\ell m}^{(1,0)} \int^t dt' \left( \frac{MH_h}{3+2\Lambda} \partial_t \chi_{\ell m}^{(1,0)*} + \chi_{\ell m}^{(1,1)*} \right) + \left( \frac{MH_h}{3+2\Lambda} \partial_t \chi_{\ell m}^{(1,0)} + \chi_{\ell m}^{(1,1)} \right) \int^t dt' \chi_{\ell m}^{(1,0)*} \\ & \left. + 4\phi_{\ell m}^{(1,0)} \int^t dt' \phi_{\ell m}^{(1,1)*} + 4\phi_{\ell m}^{(1,1)} \int^t dt' \phi_{\ell m}^{(1,0)*} \right] + \text{c.c.} \end{aligned} \quad (105)$$

428 The first two terms in Eqs. (104)–(105) represent vacuum contributions to the energy and  
 429 angular momentum fluxes. The remaining terms depend on the matter distribution and vanish  
 430 in the limit  $\epsilon \rightarrow 0$ .

## 431 5 Conclusions

432 In this work, we developed a multi-parameter framework to model the dynamics and GW  
 433 emission of binaries with large mass asymmetries embedded in dense astrophysical environ-  
 434 nments. Previous studies have emphasized the scientific potential of such systems to probe the  
 435 properties of baryonic and dark matter evolving alongside compact objects [27, 61, 64]. How-  
 436 ever, these efforts also highlighted the significant complications introduced by non-vacuum  
 437 environments, which have so far made accurate waveform modeling intractable.

438 Motivated by these challenges, we constructed a semi-analytical approach that treats mat-  
 439 ter effects as small perturbations to vacuum spacetime, as supported by most realistic astro-  
 440 physical scenarios. By expanding Einstein equations around the Schwarzschild solution in  
 441 powers of the binary mass ratio and the ratio of environmental to BH density, we derived  
 442 expressions for both metric and matter perturbations within a genuinely SF framework at adi-  
 443 abatic order.

444 Our key results, summarized in Eqs. (49)–(50), (65)–(66), and (68)–(70), show that both  
 445 axial and polar perturbations reduce to equations closely resembling the well-known Regge-  
 446 Wheeler and Zerilli formalisms. Notably, unlike previous studies, we demonstrate that polar  
 447 modes can be captured by a single Zerilli-like master variable, greatly simplifying numerical  
 448 computations. We provide explicit expressions for reconstructing the metric functions and  
 449 computing GW fluxes for binaries on generic orbits.

450 This framework represents an initial step toward the development of accurate and compu-  
 451 tationally feasible waveform models for asymmetric binaries in complex environments—key  
 452 targets for future GW detectors like LISA. It also offers a flexible tool to study the interaction  
 453 of such systems with ambient matter via time-domain evolution, and to investigate properties  
 454 typically studied in vacuum, such as BH quasinormal mode spectra [85, 86]. However, several  
 455 advancements are necessary to reach full astrophysical realism.

One major, yet essential, challenge lies in modeling binaries with a rotating primary. Describing matter perturbations around Kerr BHs could benefit from recent progress in modeling vacuum perturbations within modified gravity theories, assuming small deviations from GR [87–90]. In principle, the BH spin could be introduced as a third perturbative parameter within a slow-rotation scheme, such as the Hartle-Thorne formalism [91]. However, this approach generally exhibits poor convergence at high spin values, which are expected for astrophysical BHs. The fluid description could also be enhanced in multiple ways, for instance, by investigating the impact of viscous effects on the binary dynamics [92].

Finally, current studies of the evolution of asymmetric binaries including radiation reaction have mostly been restricted to circular, equatorial orbits due to computational complexity (see Ref. [93] for a study on the relevance of eccentricity in binaries immersed in an accretion disk). The framework developed here allows to explore EMRIs and IMRIs dynamics on generic, eccentric, and inclined orbits across a broad parameter space, and to assess the impact of matter on parameter estimation using recent tools developed to analyze GW signals from asymmetric binaries [94–96].

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## A Metric perturbations as a function of the master variables

Metric perturbations can be easily reconstructed once a solution for the master equations (45)–(46) and (65)–(66) have been found. In this Appendix we provide relations that determine axial and polar metric functions at the linear order in  $\mathcal{O}(\epsilon)$ . In the Regge-Wheeler gauge for axial modes with  $\ell \geq 2$  we have:

$$h_{1,\ell m} = -rf^{-1}\phi_{\ell m}^{(1,0)} + \frac{3[f r H - 2m]}{4f^2}\phi_{\ell m}^{(1,0)} - rf^{-1}\phi_{\ell m}^{(1,1)}, \quad (\text{A.1})$$

$$\begin{aligned} \partial_t h_{0,\ell m} = & -f \partial_r \left( r \phi_{\ell m}^{(1,0)} \right) + f \frac{8i\sqrt{2}\pi r^2 \mathcal{D}_{\ell m}^{(1,0)}}{\sqrt{\lambda(\lambda-2)}} + f \frac{8i\sqrt{2}\pi r^2 [H \mathcal{D}_{\ell m}^{(1,0)} + \mathcal{D}_{\ell m}^{(1,1)}]}{\sqrt{\lambda(\lambda-2)}} \\ & - f \partial_r \left( r \phi_{\ell m}^{(1,1)} \right) + \frac{1}{4} \left( \frac{2m}{r} - f H \right) \partial_r \left( r \phi_{\ell m}^{(1,0)} \right) + \left[ \frac{m}{f r} + 2\pi r^2 (p_r - \rho) \right] \phi_{\ell m}^{(1,0)} \end{aligned} \quad (\text{A.2})$$

where  $f = 1 - 2M/r$  and  $\lambda = \ell(\ell + 1)$ . Frequency domain expressions can be obtained by replacing time derivatives as  $\partial_t \rightarrow -i\omega$ .

The reconstruction of polar perturbations is more convoluted. We provide here explicit expressions including only the master functions. The full form depending on the coefficients

488 of the secondary stress-energy tensor is provided in the Mathematica supplementary file:

$$\begin{aligned} \partial_t H_{0,\ell m} = & [A_1 + A_5 + (A_2 + A_6)\partial_r + A_3\partial_r^2 + A_4\partial_r^3]\chi_{\ell m}^{(1,0)} + (A_1 + A_2\partial_r + rf\partial_r^2)\chi_{\ell m}^{(1,1)} \\ & + (A_7 + B_4\partial_r)V_{\ell m}^{(1,0)} + (A_8 + B_5\partial_r)W_{\ell m}^{(1,0)} + S_{\ell m}^{H_0}, \end{aligned} \quad (\text{A.3})$$

$$H_{1,\ell m} = (B_1 + B_6 + B_2\partial_r + B_3\partial_r^2)\chi_{\ell m}^{(1,0)} + (B_1 + r\partial_r)\chi_{\ell m}^{(1,1)} + B_4V_{\ell m}^{(1,0)} + B_6W_{\ell m}^{(1,0)} + S_{\ell m}^{H_1}, \quad (\text{A.4})$$

$$\partial_t K_{\ell m} = \left( C_1 + C_4 + \frac{f}{r}B_2\partial_r + \frac{f}{r}B_3\partial_r^2 \right)\chi_{\ell m}^{(1,0)} + (C_1 + f\partial_r)\chi_{\ell m}^{(1,1)} + B_4V_{\ell m}^{(1,0)} + B_5W_{\ell m}^{(1,0)} + S_{\ell m}^K, \quad (\text{A.5})$$

489 where the source terms  $S_{\ell m}^{H_0, H_1, K}$  depend on the particle orbital motion, and

$$A_1 = -\frac{9M^3 + 9M^2r\Lambda + 3Mr^2\Lambda^2 + r^3\Lambda^2(1 + \Lambda)}{r^2\mathcal{C}^2}, \quad A_2 = \frac{3M^2 - Mr\Lambda + r^2\Lambda}{r\mathcal{C}}, \quad (\text{A.6})$$

$$A_3 = rf - \frac{rfH}{4} - \frac{4\pi fr^4(2p_r - 3\rho)}{\mathcal{C}} + \frac{m[(2 - 3\Lambda)r - 13M]}{2\mathcal{C}}, \quad A_4 = -\frac{2r^2fm}{\mathcal{C}}, \quad (\text{A.7})$$

$$\begin{aligned} A_5 = & -\frac{A_1H}{4} + \left\{ -54M^6 + 9(14\Lambda - 3)M^5r + 3[\Lambda(124\Lambda - 33) + 36]M^4r^2 + 60(\Lambda - 1)\Lambda(2\Lambda - 3)M^3r^3 \right. \\ & + 3\Lambda^2[2\Lambda(7\Lambda - 6) + 55]M^2r^4 + \Lambda^3[\Lambda(2\Lambda - 33) - 6]Mr^5 + \Lambda^3[12 - (\Lambda - 9)\Lambda]r^6 \left. \right\} \frac{m}{2r^4f^2\mathcal{C}^4} \\ & - \frac{2\pi\rho}{f\mathcal{C}^3} (18M^4 + 9(1 - 4\Lambda)M^3r + 6\Lambda(\Lambda + 12)M^2r^2 + \Lambda((3 - 4\Lambda)\Lambda - 12)Mr^3 + 4\Lambda^2(\Lambda + 1)r^4) \\ & - \frac{4\pi r(15M^2 + 6\Lambda Mr + \Lambda(3\Lambda + 4)r^2)}{\mathcal{C}^2} p_t + \frac{2\pi r^2(3M^2 + \Lambda(\Lambda + 2)r^2)}{\mathcal{C}^2} \rho' \\ & - \frac{2\pi}{f\mathcal{C}^3} (72M^4 + 3(34\Lambda - 15)M^3r + 6\Lambda(2\Lambda - 15)M^2r^2 + \Lambda(\Lambda(6\Lambda - 5) + 12)Mr^3 - 4\Lambda^2(\Lambda + 1)r^4) p_r, \end{aligned} \quad (\text{A.8})$$

$$A_8 = \frac{2r^2f^2(r\rho' - 2p_t)}{\mathcal{C}} - \frac{2rf}{\mathcal{C}^2} \{ [9M^2 + (5M - r)r\Lambda]p_r + [-3M(M - 2r) + r(M + r)\Lambda]\rho \}, \quad (\text{A.9})$$

$$\begin{aligned} A_6 = & -\frac{A_2H}{4} + \frac{4\pi r^2\rho[(6 - 9\Lambda)Mr + 4\Lambda r^2 - 15M^2]}{\mathcal{C}^2} - \frac{16\pi r^3fp_t}{\mathcal{C}} + \frac{4\pi r^2p_r(M - (\Lambda + 2)r)}{\mathcal{C}} + \frac{4\pi r^4f\rho'}{\mathcal{C}} \\ & - \frac{9M^4 + (36 - 69\Lambda)M^3r - 9(\Lambda - 13)\Lambda M^2r^2 + \Lambda[(14 - 11\Lambda)\Lambda - 12]Mr^3 + \Lambda^2(9\Lambda + 8)r^4}{2r^2f\mathcal{C}^3} m, \end{aligned} \quad (\text{A.10})$$

$$A_7 = \frac{4f(3M^2 + r^2\Lambda^2 + Mr(-3 + 2\Lambda))\kappa_t - 4r^2f^2\mathcal{C}\kappa'_t}{\mathcal{C}^2} \quad (\text{A.11})$$

$$B_1 = \frac{\Lambda r}{\mathcal{C}} - \frac{M}{fr}, \quad B_2 = r - \frac{rH}{4} - \frac{[3M^2 + 6Mr(1 + \Lambda) - r^2\Lambda(2 + \Lambda)]m}{2f\mathcal{C}^2} + \frac{4\pi r^4(\rho - 2p_r)}{\mathcal{C}}, \quad (\text{A.12})$$

$$B_3 = \frac{2r^2m}{\mathcal{C}}, \quad B_4 = -\frac{4r^2f^2\kappa_t}{\mathcal{C}}, \quad B_5 = -\frac{2f^2r^3\kappa_r}{\mathcal{C}}, \quad (\text{A.13})$$

$$\begin{aligned} B_6 = & -\frac{H}{4}B_1 + \frac{2\pi r^2}{f\mathcal{C}^2} (\rho[3M^2 + \Lambda(\Lambda + 2)r^2] - p_r[15M^2 + 6\Lambda Mr + \Lambda(3\Lambda + 4)r^2]) \\ & - \frac{3m}{2r^2f^2\mathcal{C}^3} (33M^4 + (31\Lambda + 6)M^3r + 3\Lambda(5\Lambda + 3)M^2r^2 + \Lambda(\Lambda^2 + 2)Mr^3 + \Lambda^2(\Lambda + 2)r^4), \end{aligned} \quad (\text{A.14})$$

$$C_1 = \frac{6M^2 + 3Mr\Lambda + r^2\Lambda(1 + \Lambda)}{r^2\mathcal{C}}, \quad (\text{A.15})$$

$$\begin{aligned} C_4 = & -\frac{m}{2fr^3\mathcal{C}^3} [18M^4 - 3(5\Lambda - 6)M^3r - 9(\Lambda - 3)\Lambda M^2r^2 - 3\Lambda(3\Lambda^2 - 2)Mr^3 - \Lambda^2((\Lambda - 3)\Lambda - 6)r^4] \\ & - \frac{H}{4}C_1 + \frac{2\pi r}{\mathcal{C}^2} [\rho(3M^2 + \Lambda(\Lambda + 2)r^2) - p_r(15M^2 + 6\Lambda Mr + \Lambda(3\Lambda + 4)r^2)], \end{aligned} \quad (\text{A.16})$$

490 with  $\Lambda = (\ell + 2)(\ell - 1)/2$ ,  $\kappa_{t,r} = p_{t,r} + \rho$ ,  $\mathcal{C} = r\Lambda + 3M$  and a prime denoting radial derivative.

## B Decoupling of Axial and Polar Modes into vacuum and matter components using the scaling function $Z$ .

In this appendix, we clarify why, in computing axial and polar modes, we chose to work with a single metric perturbation rather than separating vacuum  $(0, 1)$  and matter  $(1, 1)$  components from the beginning.

The structure of the equations for axial modes, for example, allows one to follow a procedure similar to the vacuum case. In this framework, it is possible to eliminate one of the metric functions at each order in  $\epsilon$  using the Einstein equations, leading to two second-order differential equations in  $(r, t)$  for the  $(1, 0)$  and  $(1, 1)$  perturbations. These equations can then be recast in the familiar wave-like form by introducing a generalized tortoise coordinate, which facilitates the imposition of boundary conditions at spatial infinity and the BH horizon.

However, a subtlety arises from the fact that the generalized tortoise coordinate  $dr^*/dr = 1/\sqrt{-g_{tt}/g_{rr}}$ , depends on the parameter  $\epsilon$ . This introduces an ambiguity due to the perturbative relation between  $r$  and  $r_*$ , since  $dr^*/dr = f^{-1} + \mathcal{O}(\epsilon)$ , on whether one should use  $r$  or  $r_*$  in the perturbative expansion (see [97] for further details). This issue can be circumvented by following the approach developed in [98], which we briefly outline here.

Consider a scalar perturbation  $\Phi$  on a fixed, spherically symmetric background with the metric:

$$ds^2 = -A(r)dt^2 + \frac{dr^2}{B(r)} + r^2(d\theta^2 + \sin^2\theta d\phi^2). \quad (\text{B.1})$$

After decomposing  $\Phi$  into spherical harmonics, the Klein–Gordon equation  $\square\Phi = 0$  can be written as:

$$-\frac{\partial^2\Phi}{\partial t^2} + \mathcal{F}\frac{d}{dr}\left(\mathcal{F}\frac{d\Phi}{dr}\right) - \mathcal{F}V\Phi = 0, \quad (\text{B.2})$$

where  $V$  is the effective potential, which depends on the background geometry. Assume the metric functions  $A(r)$  and  $B(r)$  are close to the Schwarzschild solution:

$$A(r) = \left(1 - \frac{r_h}{r}\right)(1 + \delta A), \quad B(r) = \left(1 - \frac{r_h}{r}\right)(1 + \delta B), \quad (\text{B.3})$$

with  $\delta A, \delta B \ll 1$ , and where  $r_h$  denotes the horizon radius.<sup>7</sup> Then, at the leading order in the metric changes  $(\delta A, \delta B)$ , the function  $\mathcal{F} = \sqrt{AB}$  can be expressed as:

$$\mathcal{F} = f(r)Z(r) = \left(1 - \frac{r_h}{r}\right)Z(r) = \left(1 - \frac{r_h}{r}\right)[1 + \delta Z(r)].$$

Introducing the rescaled field  $\phi = \sqrt{Z}\Phi$ , and expanding Eq. (B.2) to linear order in  $\delta Z$ , the master equation becomes:

$$-(1 + 2\delta Z)\frac{\partial^2\phi}{\partial t^2} + f\frac{d}{dr}\left(f\frac{d\phi}{dr}\right) - f\tilde{V}\phi = 0, \quad (\text{B.4})$$

where  $\tilde{V}$  is the modified potential (the explicit form can be found in [98]). For both axial and polar sectors, the metric perturbations we find satisfy master equations analogous to Eq. (B.2), with  $r_h = 2M$ , and can be recast into the form of Eq. (B.4) by introducing an appropriate scaling function  $Z$ . Since the prefactor of the radial derivative terms in Eq. (B.4) is  $f(r)$ , we can adopt the standard tortoise coordinate  $r^* = r + 2M \ln(r/2M - 1)$ . This allows us to write the perturbations as a sum of the  $(1, 0)$  and  $(1, 1)$  components, and isolate their contributions without introducing ambiguities.

<sup>7</sup>Note that in general  $r_h$  may differ from the Schwarzschild value. In such cases,  $r_h$  should be treated as a fundamental parameter in the computation of perturbations, as done in the cases studied in [98].

## 524 C Coefficients of the particle stress-energy momentum tensor

525 The form of the coefficients  $\{\mathcal{A}_{\ell m}^{(0,0)}, \dots, \mathcal{F}_{\ell m}^{(1,0)}\}$  of the particle stress-energy tensor, can be found  
 526 by projecting each one of the ten tensor harmonics on Eq. (28). Introducing the scalar product  
 527 between two tensor harmonics  $A_{\mu\nu}$  and  $B_{\mu\nu}$ :

$$(A, B) = \int \int \eta^{\mu\sigma} \eta^{\nu\delta} A^*_{\mu\nu} B_{\sigma\delta} \sin \theta d\theta d\phi, \quad (C.1)$$

528 where  $\eta_{\mu\nu}$  is the Minkowski metric tensor in spherical coordinates, and  $*$  denotes complex  
 529 conjugation, we have, for example,  $\mathcal{A}_{\ell m}^{(1,1)} = (\mathbf{a}_{\ell m}, T^{(1,1)})$ . We provide the expression of the  
 530 coefficients for generic orbits in the supplementary material. In the case of equatorial circular  
 531 motion,  $\theta_p = \pi/2$ , for a secondary at a radius  $r = r_p$ , the only non vanishing coefficients are  
 532 given by  $Q_{\ell m}^{(0,0)}$  for the axial sector, and  $(\mathcal{A}_{\ell m}^{(0,0)}, \mathcal{B}_{\ell m}^{(0,0)}, \mathcal{G}_{\ell m}^{(0,0)}, \mathcal{D}_{\ell m}^{(0,0)}, \mathcal{F}_{\ell m}^{(0,0)})$  for the polar  
 533 modes (and similarly for the (1, 1) coefficients). Their explicit form is given by:

$$Q_{\ell m}^{(0,0)} = \frac{\sqrt{2}f\mathcal{L}^{(0,0)}}{r^3\sqrt{\lambda}} \partial_\theta Y_{\ell m}^* \delta(r - r_p), \quad \mathcal{A}_{\ell m}^{(0,0)} = \frac{f\mathcal{E}^{(0,0)}}{r^2} Y_{\ell m}^* \delta(r - r_p), \quad (C.2)$$

$$\mathcal{B}_{\ell m}^{(0,0)} = \frac{i\sqrt{2}f\mathcal{L}^{(0,0)}}{r^3\sqrt{\lambda}} \partial_\phi Y_{\ell m}^* \delta(r - r_p), \quad (C.3)$$

$$\mathcal{D}_{\ell m}^{(0,0)} = \frac{i\sqrt{2}f(\mathcal{L}^{(0,0)})^2}{r^4\mathcal{E}^{(0,0)}\sqrt{\lambda(\lambda-2)}} \partial_{\theta\phi} Y_{\ell m}^* \delta(r - r_p), \quad (C.4)$$

$$\mathcal{F}_{\ell m}^{(0,0)} = \frac{f(\mathcal{L}^{(0,0)})^2 \delta(r - r_p)}{\sqrt{2}r^4\mathcal{E}^{(0,0)}\sqrt{\lambda(\lambda-2)}} [\partial_\theta^2 - \partial_\phi^2] Y_{\ell m}^* \delta(r - r_p), \quad \mathcal{G}_{\ell m}^{(0,0)} = \frac{f(\mathcal{L}^{(0,0)})^2}{\sqrt{2}r^4\mathcal{E}^{(0,0)}} Y_{\ell m}^* \delta(r - r_p), \quad (C.5)$$

$$Q_{\ell m}^{(0,1)} = \frac{1}{\sqrt{2}\lambda r^4} [2fr\mathcal{L}^{(0,1)} + fr\mathcal{L}^{(0,0)}H - 2\mathcal{L}^{(0,0)}m] \partial_\theta Y_{\ell m}^* \delta(r - r_p), \quad (C.6)$$

$$\mathcal{A}_{\ell m}^{(0,1)} = \frac{1}{r^3} [2fr\mathcal{E}^{(1,1)} + ((3-2f)r - 6M)\mathcal{E}^{(0,1)}H - 2\mathcal{E}^{(0,0)}m] Y_{\ell m}^* \delta(r - r_p), \quad (C.7)$$

$$\mathcal{A}_{\ell m}^{(0,1)} = \frac{i}{\sqrt{2}\lambda r^4} [2fr\mathcal{L}^{(0,1)} + fr\mathcal{L}^{(0,0)}H - 2\mathcal{L}^{(0,0)}m] \partial_\phi Y_{\ell m}^* \delta(r - r_p), \quad (C.8)$$

$$\mathcal{D}_{\ell m}^{(0,1)} = \frac{i\mathcal{L}^{(0,0)}\delta(r - r_p)}{r^5(\mathcal{E}^{(0,0)})^2\sqrt{2\lambda(\lambda-2)}} \{4fr\mathcal{E}^{(0,0)}\mathcal{L}^{(0,1)} - 2fr\mathcal{E}^{(0,1)}\mathcal{L}^{(0,0)} \\ + \mathcal{E}^{(0,0)}\mathcal{L}^{(0,0)}[frH - 2m]\} \partial_{\theta\phi} Y_{\ell m}^*, \quad (C.9)$$

$$\mathcal{F}_{\ell m}^{(1,1)} = \frac{\mathcal{L}^{(0,0)}\delta(r - r_p)}{r^5(\mathcal{E}^{(0,0)})^2\sqrt{8\lambda(\lambda-2)}} \{4fr\mathcal{E}^{(0,0)}\mathcal{L}^{(0,1)} - 2fr\mathcal{E}^{(0,1)}\mathcal{L}^{(0,0)} \\ + \mathcal{E}^{(0,0)}\mathcal{L}^{(0,0)}[frH - 2m]\} [\partial_\theta^2 - \partial_\phi^2] Y_{\ell m}^*, \quad (C.10)$$

$$\mathcal{G}_{\ell m}^{(1,1)} = \frac{\mathcal{L}^{(0,0)}\delta(r - r_p)}{2\sqrt{2}r^5(\mathcal{E}^{(0,0)})^2} \{4fr\mathcal{E}^{(0,0)}\mathcal{L}^{(0,1)} - 2fr\mathcal{E}^{(0,1)}\mathcal{L}^{(0,0)} + \mathcal{E}^{(0,0)}\mathcal{L}^{(0,0)}[frH - 2m]\} Y_{\ell m}^*, \quad (C.11)$$

534 where spherical harmonics are evaluated at  $\theta = \theta_p$  and  $\phi = \phi_p(t)$ , while  $\mathcal{E}^{(0,1)}$  and  $\mathcal{L}^{(0,1)}$  are  
 535 the non-vacuum corrections to the particle energy and angular momentum given by the  $\mathcal{O}(\epsilon)$   
 536 terms in Eqs. (18)-(19).



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