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Fix the Frame, Resolve the Memory: the Bondi–Sachs gauge in Black Hole Perturbation Theory

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Understanding gauge and frame dependence is crucial for comparing black hole perturbation theory results at future null infinity. At second order, new challenges arise: gauge-invariant quantities in linear theory lose their invariance, and the nonlinear source terms can lead to infrared divergences. We address these issues by constructing an invariant second-order field equation in the perturbative Bondi–Sachs gauge, which naturally describes gravitational waves at null infinity. Our framework provides a systematic way to transform from any gauge to Bondi–Sachs and fix the BMS frame (the symmetry group of future null infinity and the Bondi–Sachs gauge). Our formalism could resolve tensions between second-order self-force and post-Newtonian results and help align ringdown calculations with numerical relativity waveforms.

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