

Spinning Extreme-Mass-Ratio-Inspirals into an Astrophysical Black Hole: Onset of Chaos at Astrophysically Realistic Spin

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The forthcoming space-based gravitational wave detectors such as LISA, Tianqin and Taiji will unlock the low-frequency gravitational-wave sky, offering an unprecedented probe into the fundamental dynamics of gravity. A prime target for such detectors is Extreme Mass Ratio Inspirals (EMRIs)—the adiabatic inspiral of a stellar-mass compact object into a supermassive black hole. While conventionally modeled as integrable geodesic motion with radiative dissipation, this canonical picture is fundamentally altered when the spin of the secondary compact object is considered. The inclusion of spin-curvature coupling breaks the integrability of the system, opening a portal to prolonged resonances and deterministic chaos. We expose a critical astrophysical ingredient, dark matter halo, that dramatically catalyzes this chaotic transition. We systematically investigate the orbital dynamics of a spinning test particle around a non-spinning supermassive black hole immersed in a Hernquist dark matter profile. Our analysis reveals that the dark matter halo profoundly reshapes the effective potential, acting as a trigger for chaos. For the first time, we demonstrate through high-resolution Poincaré maps that chaotic features in the orbital phase space emerge at spin parameter values significantly lower—and thus far more astrophysically plausible—than the upper bound previously established in the literature.

Remarkably, we find that these chaotic signatures are not confined to the near-horizon regime but can manifest at large distances from the central black hole, with their characteristic scale spanning orders of magnitude—from fine-grained structures to gross orbital deviations. This broad spatial distribution and amplified sensitivity to spin fundamentally reframe the detectability of chaos in EMRIs. Our findings suggest that the gravitational-wave fingerprints of nonintegrability, imprinted on signals destined for LISA and others, are not just a mathematical curiosity but a realistic and observable feature of astrophysical systems. This opens a transformative new window for characterizing both the spacetime geometry and the ubiquitous dark matter environments in galactic nuclei.

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