Characterizing Gravitational Waves from the Hyperbolic Encounter of Two Black Holes

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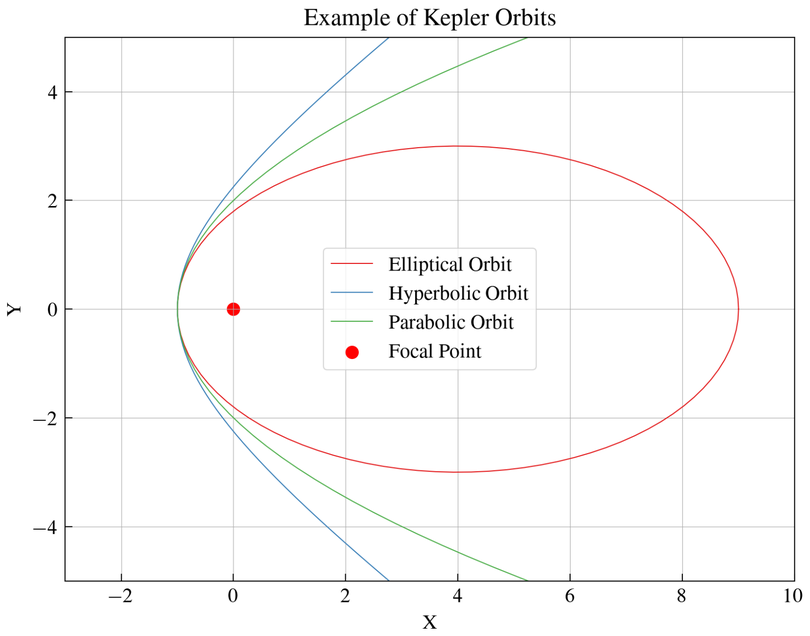
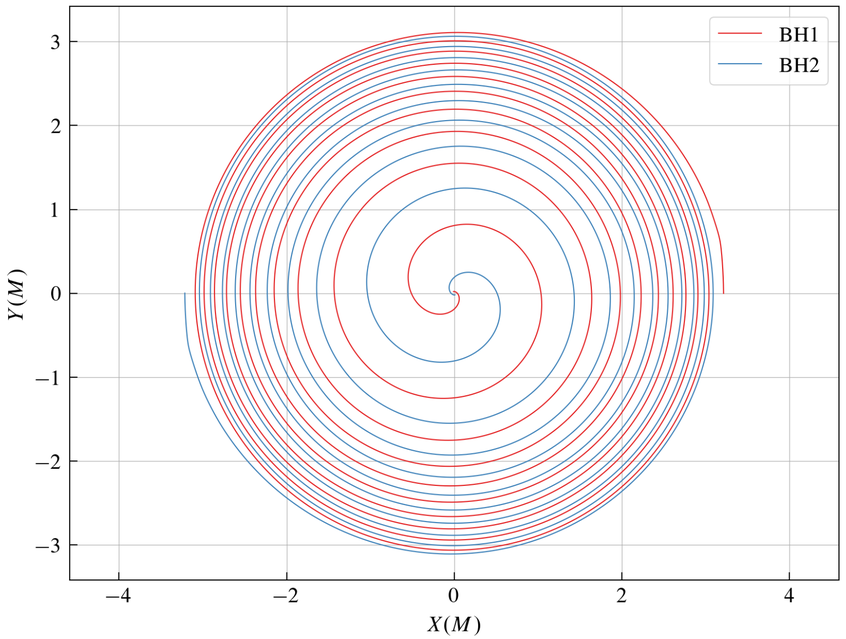
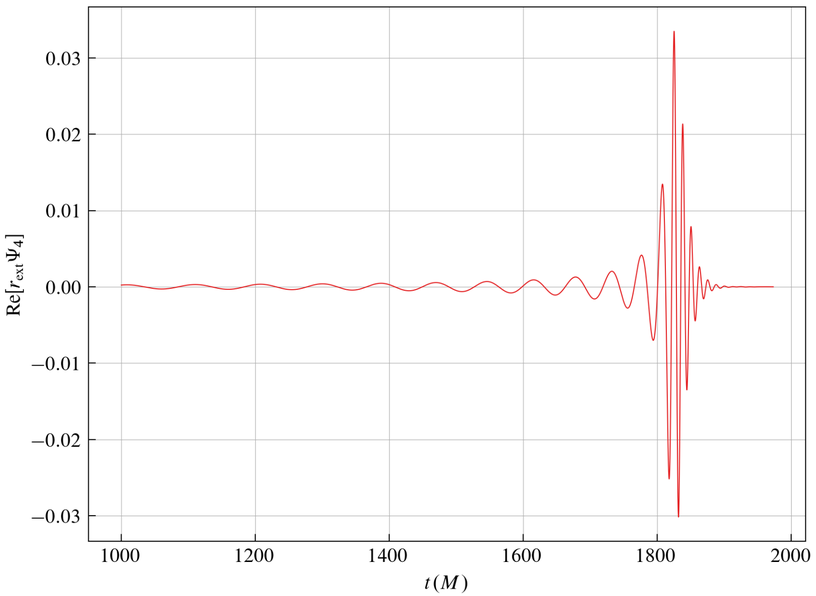
Introduction

- There are various orbits depending on the eccentricity.



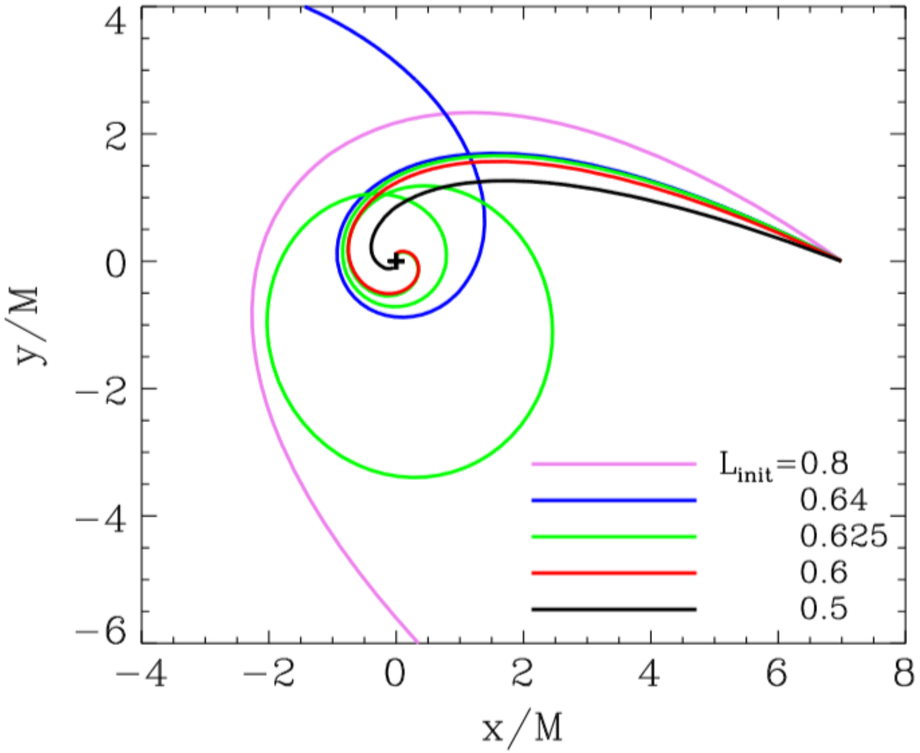


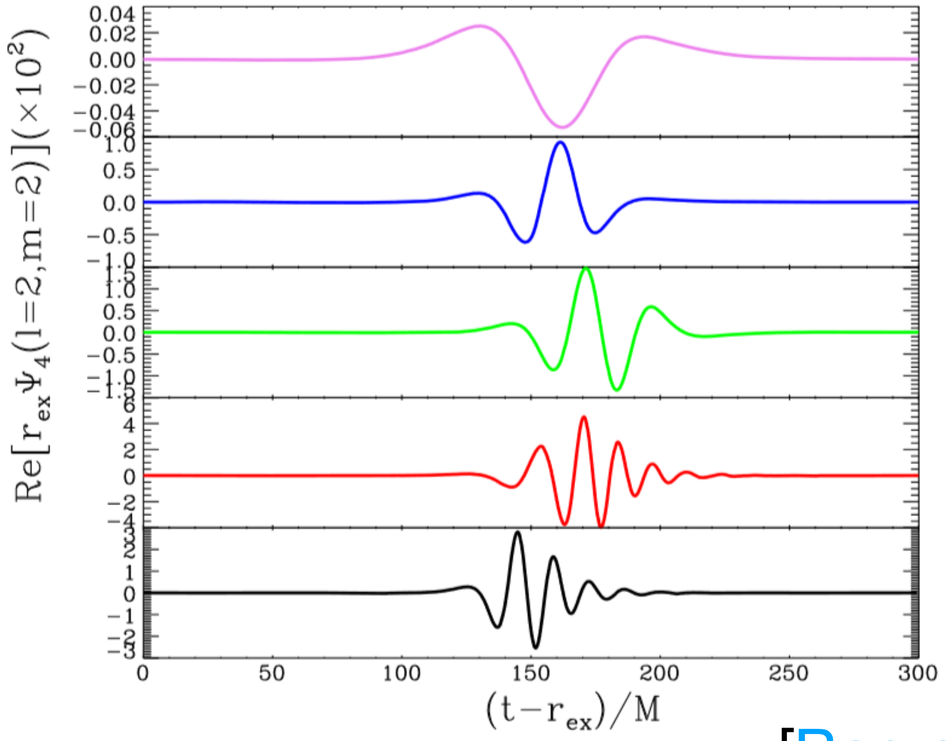


Studies on High-Eccentricity Orbits

NR Result

- Gravitational waves from scattering orbits with high eccentricity exhibit different characteristics compared to those from quasi-circular orbits.





[Bae et al. 2017]

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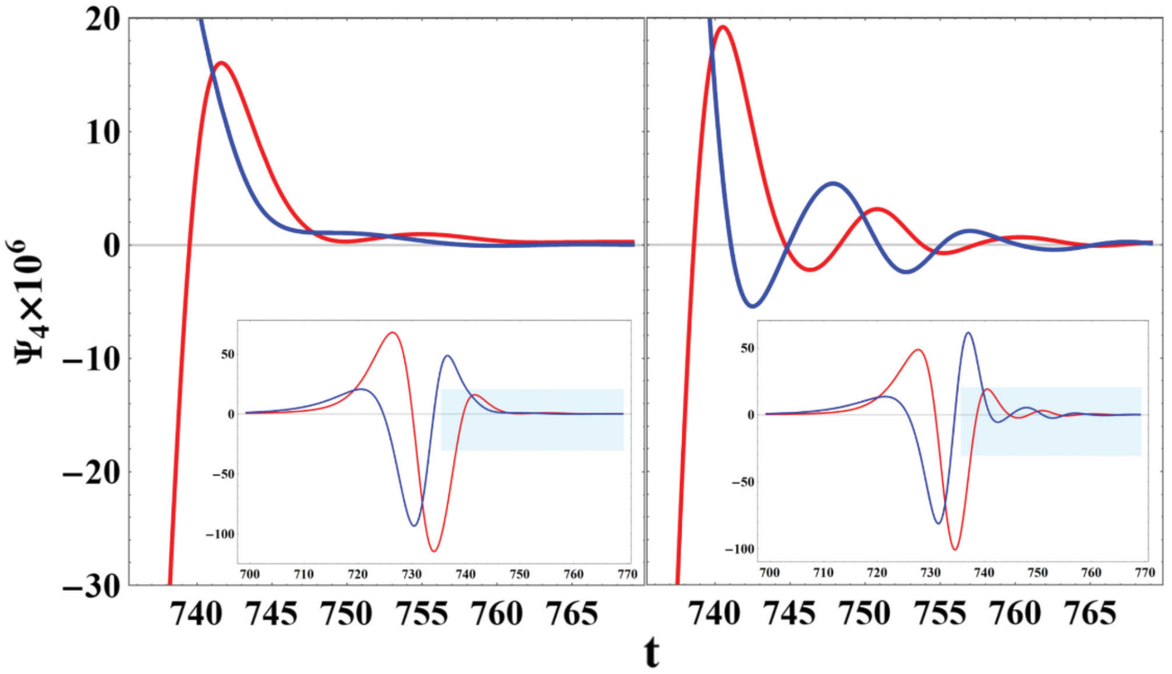
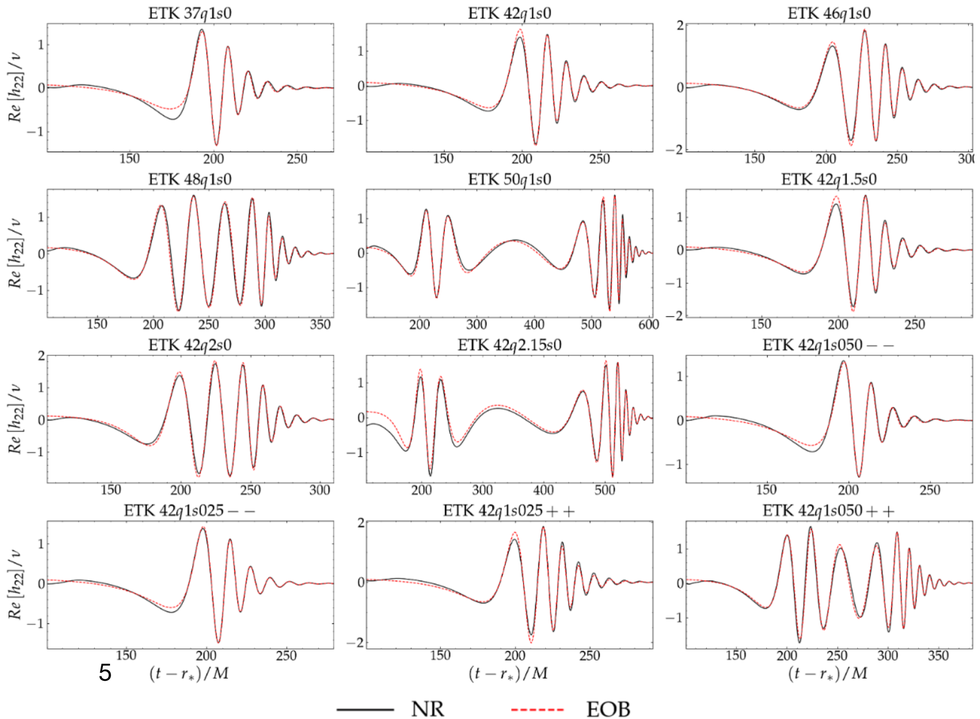


[Bae et al. 2024]

Studies on High-Eccentricity Orbits

Analytical Approach

- Studies on high-eccentricity orbits have been conducted using EOB[Andrade et al. 2024] or PN approximations[Cho 2022].
- However, as the eccentricity increases, the results deviate significantly from those obtained through NR.

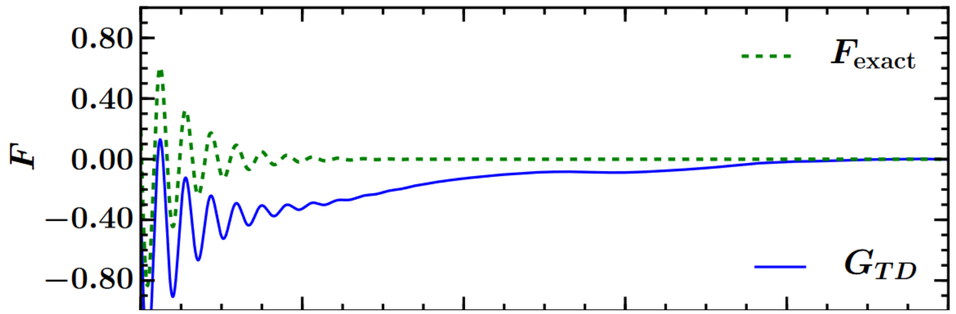


[Andrade et al. 2024]

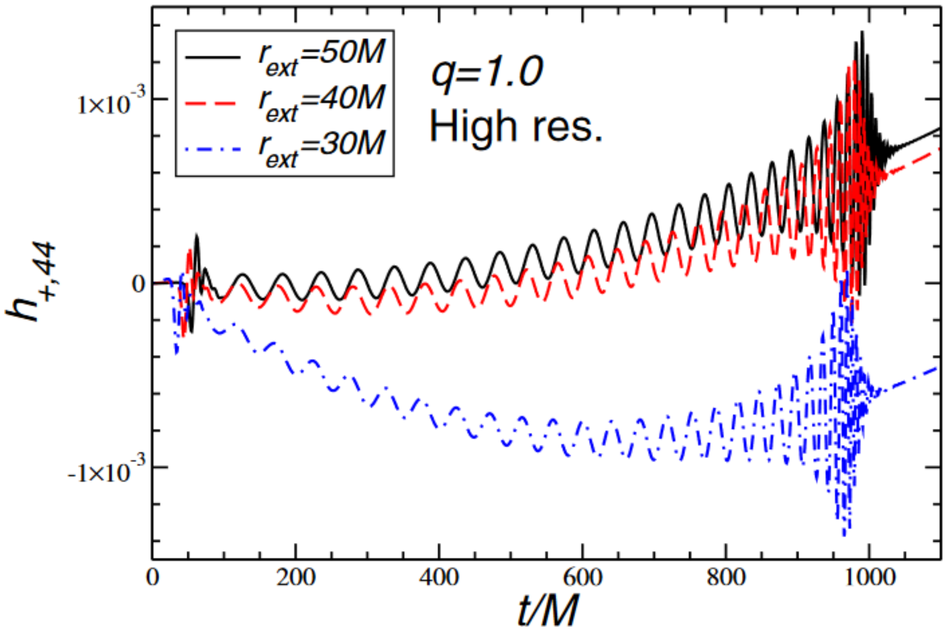
Integration of Gravitational Waveforms

Nonlinear Drift

- We numerically obtain the values for $\ddot{h}$, and by integrating these values, we can calculate the GW strain h.
- During this process, nonlinear drift occurs.



[Reisswig et al. 2011]

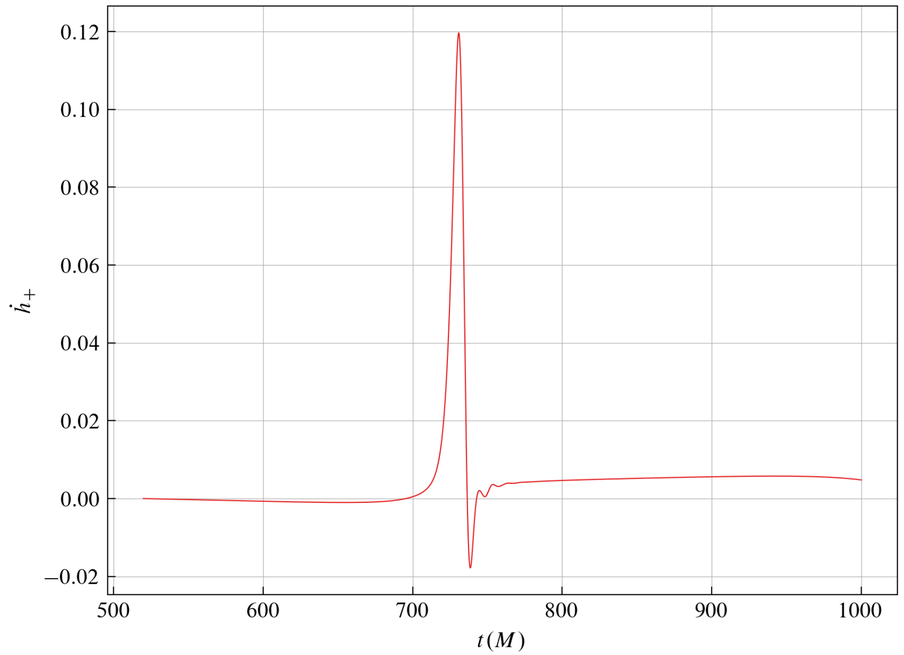


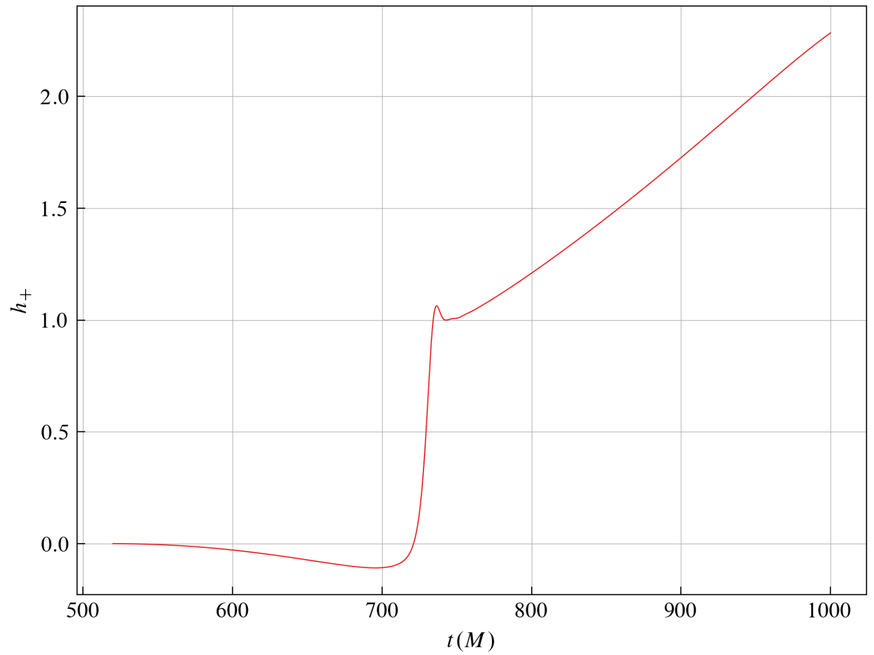
[Berti et al. 2007]

Integration of Gravitational Waveforms

Nonlinear Drift

- [Reisswig et al. 2011] addressed this issue using FFI, but it could only be applied to GWs from quasi-circular orbits. ([Hopper et al. 2023])

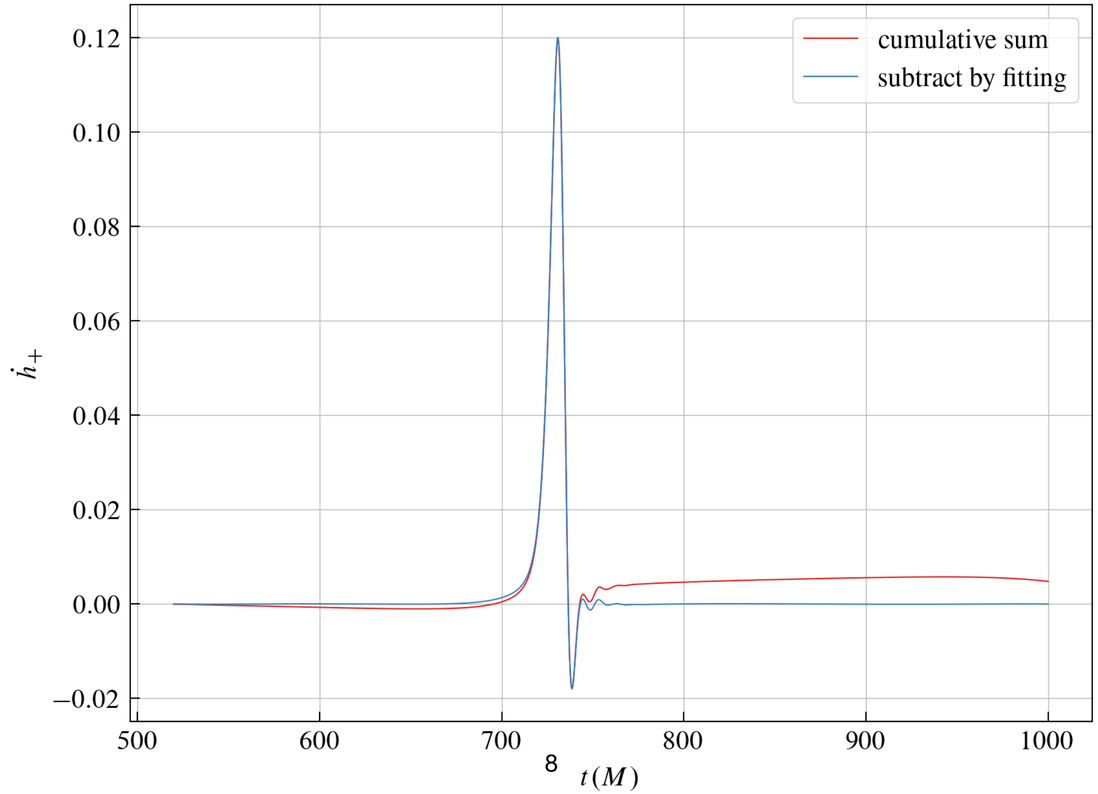




Integration of Gravitational Waveforms

Nonlinear Drift

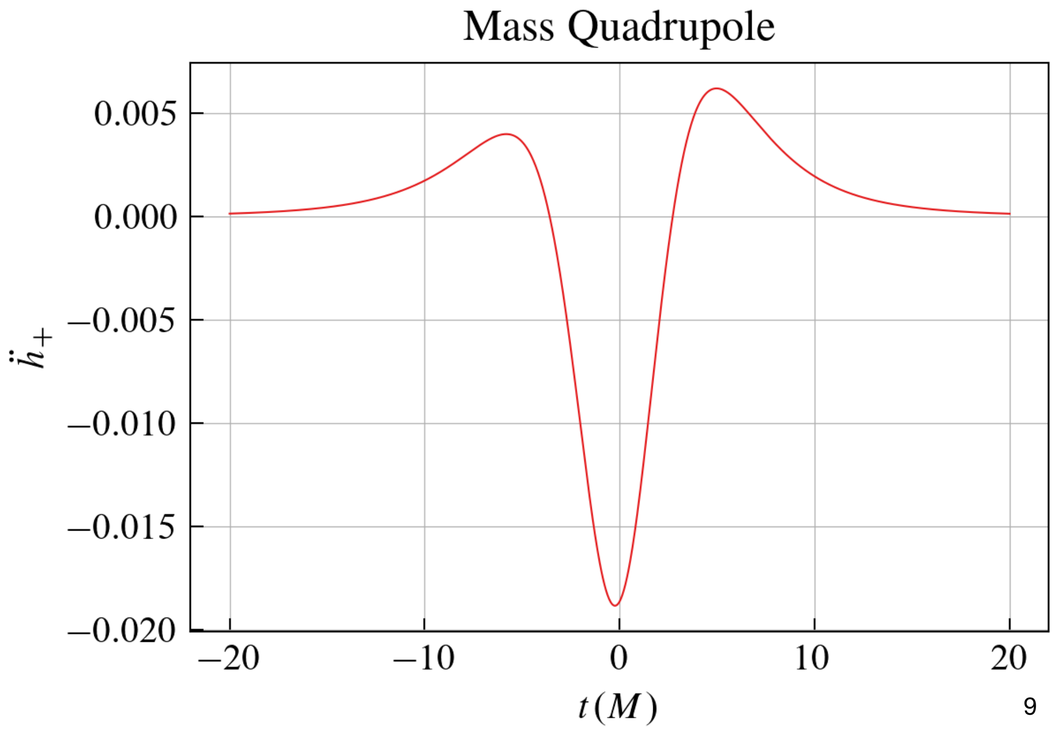
- We minimized the drift in $\dot{h}$ by fitting a polynomial function to the background noise and subtracting it from the waveform.

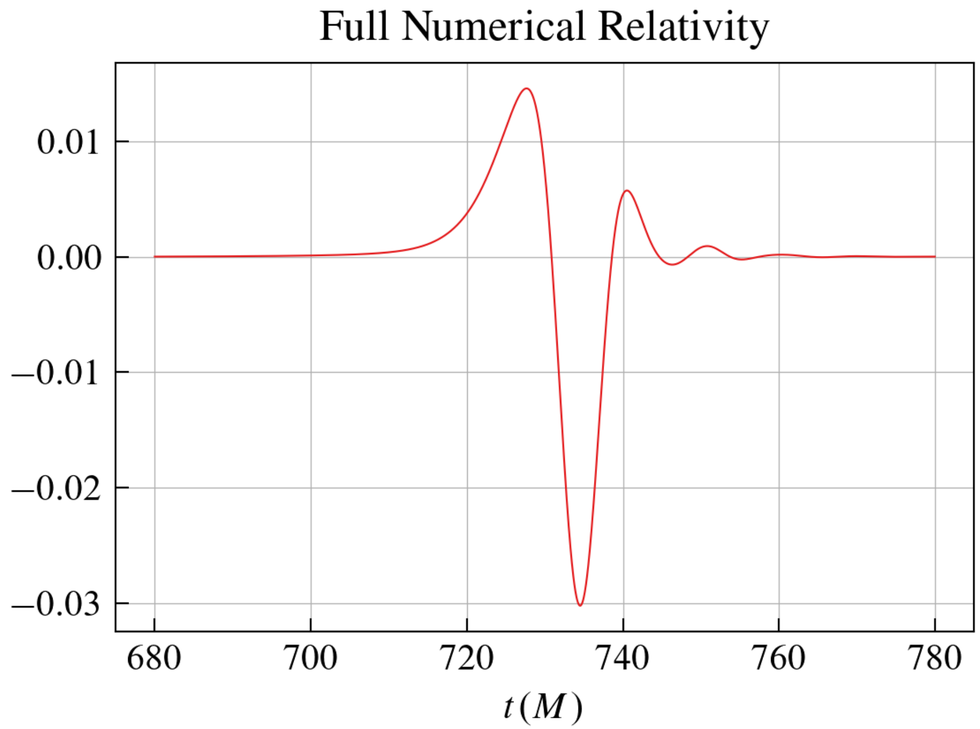


Comparison Gravitational Waveforms

Mass Quadrupole vs Full NR

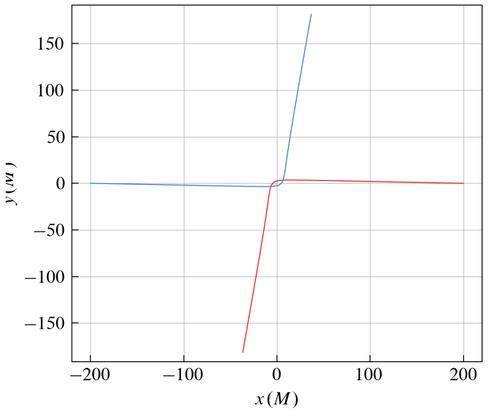
- We can calculate GWs by approximating the orbit as Keplerian motion and calculating the mass quadrupole moment.



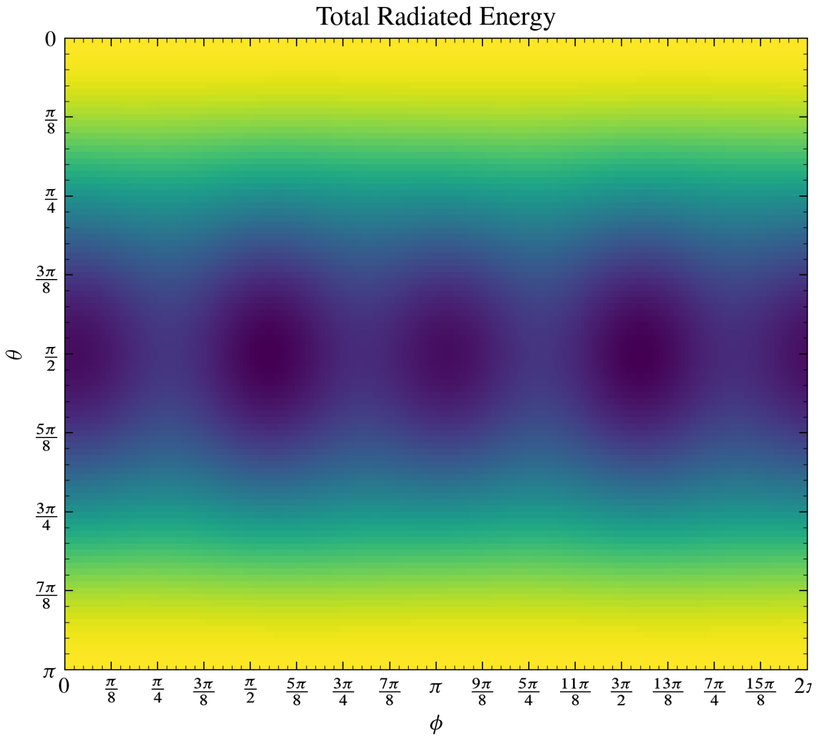


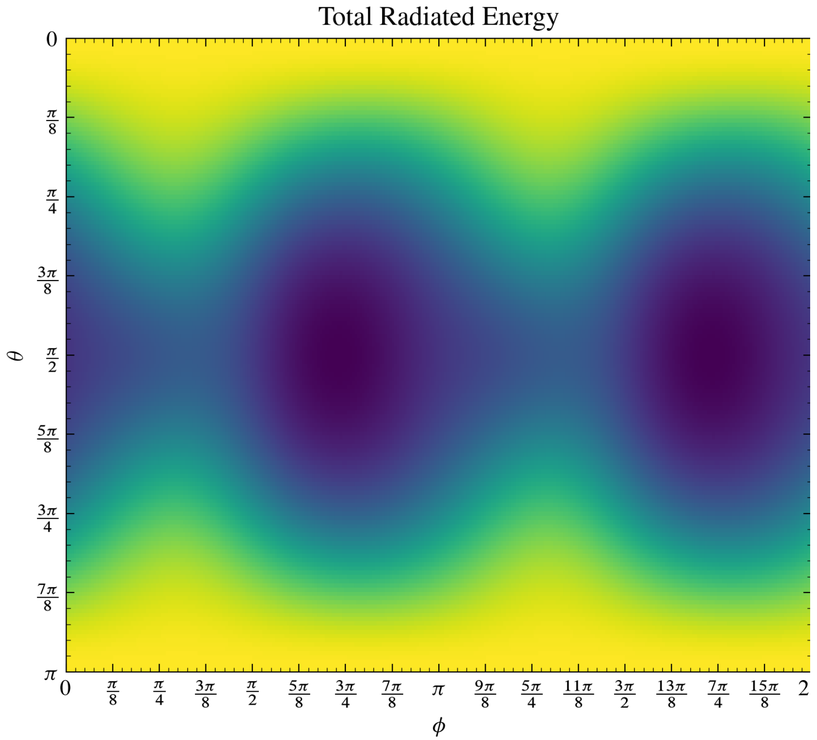
Integration of Gravitational Waveforms

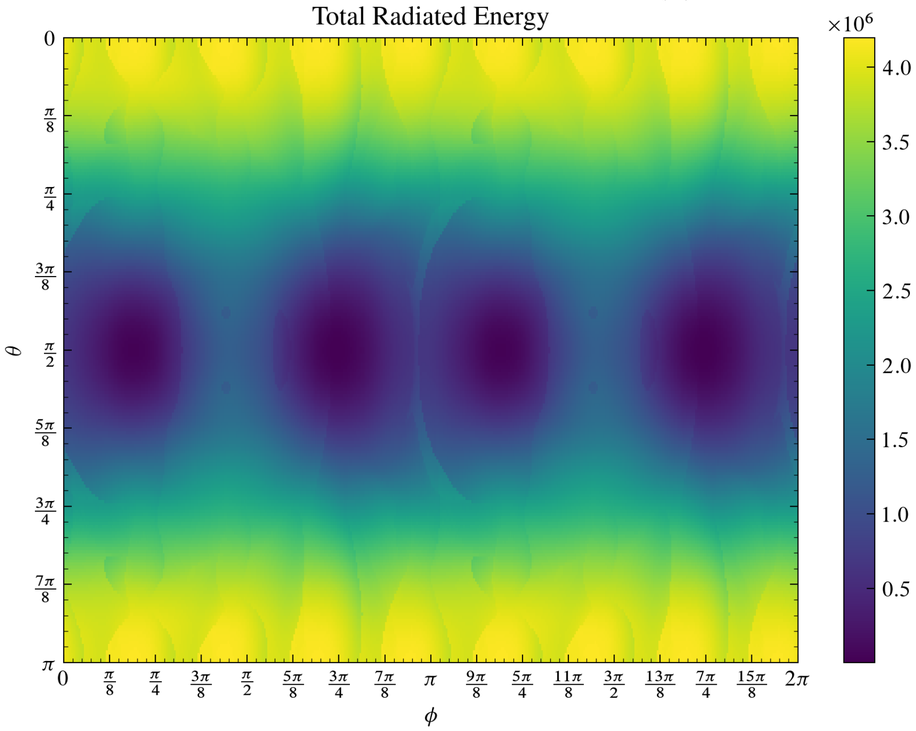
Radiated Energy



- The energy radiated can be calculated from $\dot{h}$.

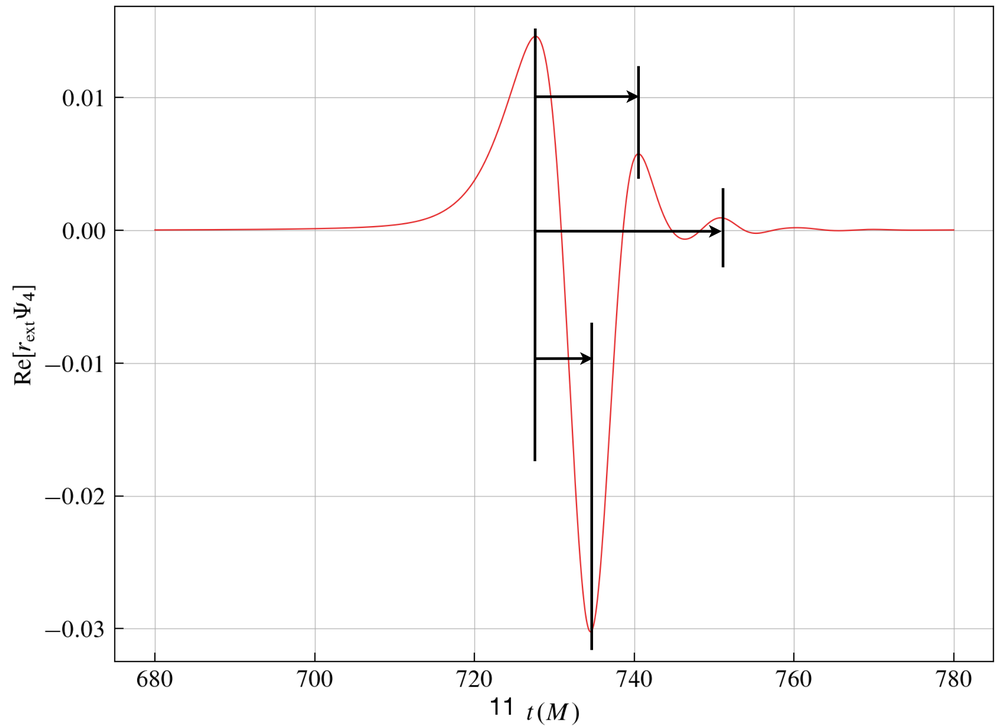






Differences in TD and RD Waveforms

- Trajectory Driven (TD) waveforms and Ringdown (RD) waveforms are expected to exhibit different characteristics depending on the extraction radius, as they originate from different sources.



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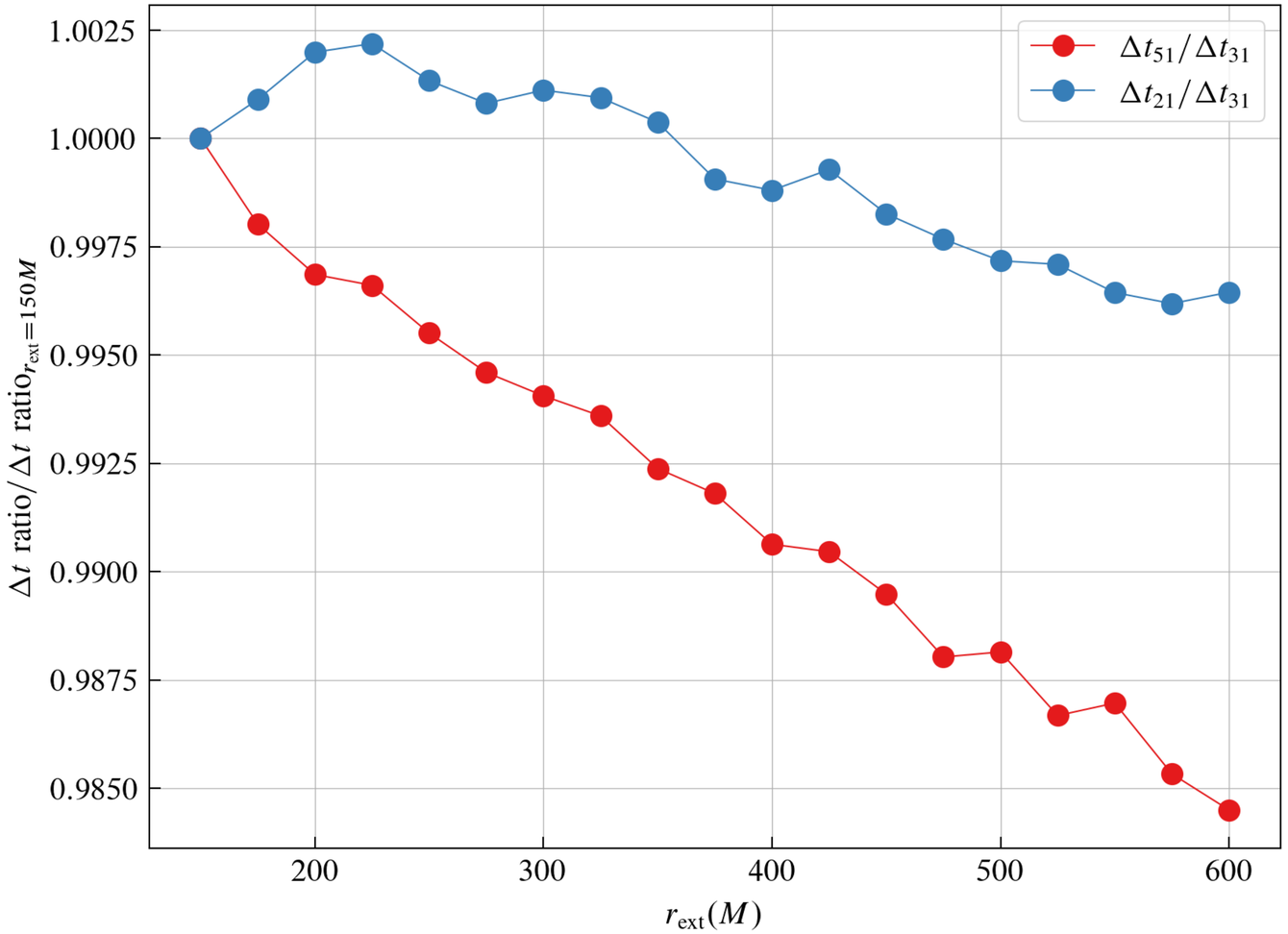
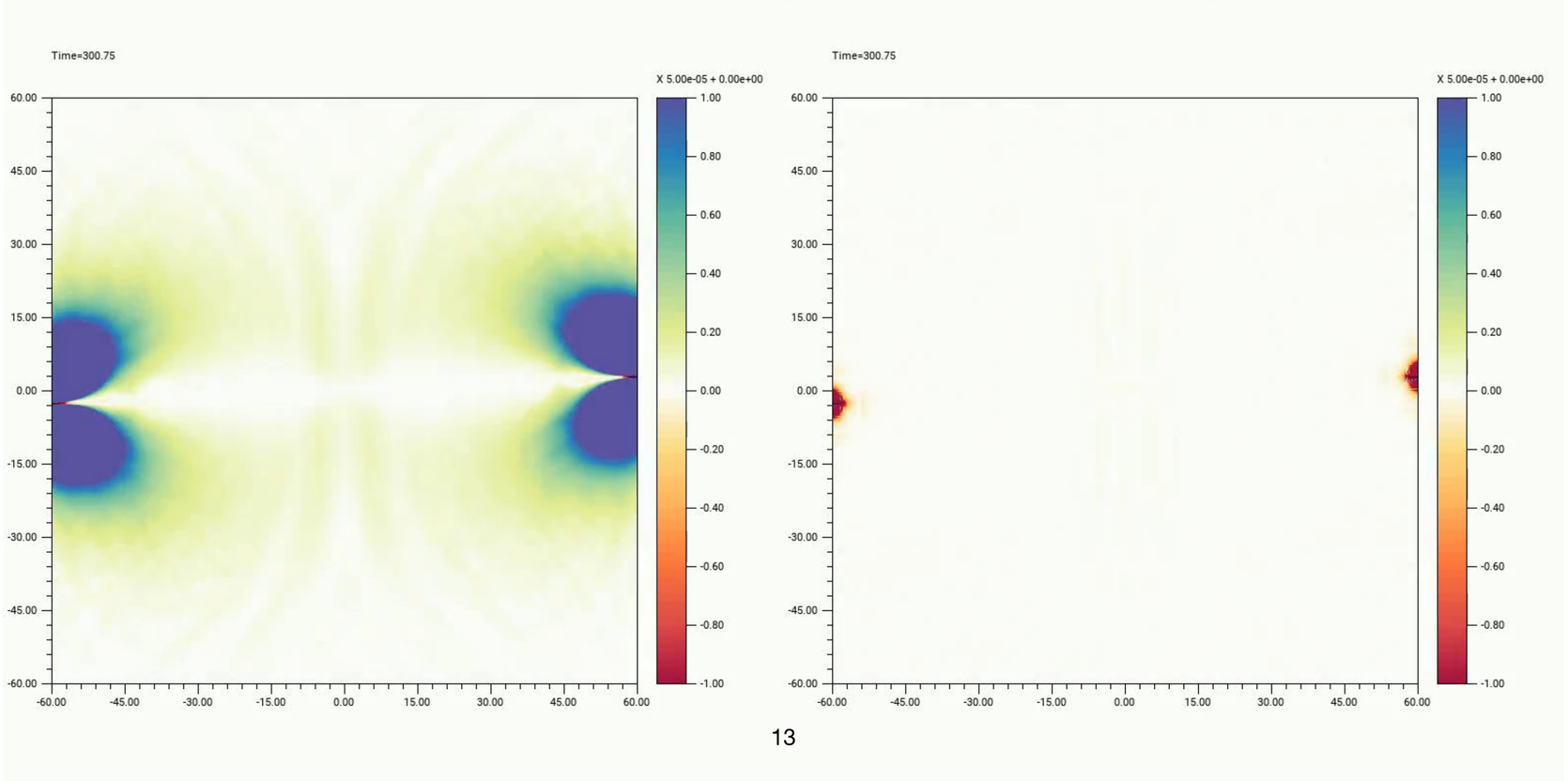


Psi4 Visualization

- Ψ_4 on the xy-plane was calculated and visualized. A mean filter was applied to better observe the waveforms in regions with strong fields.

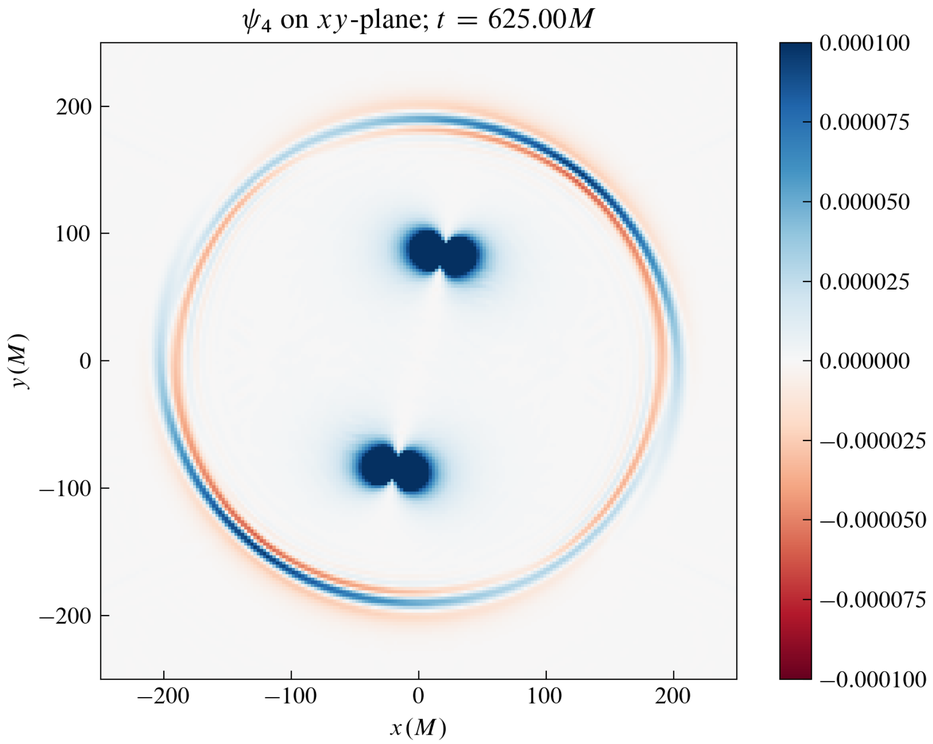


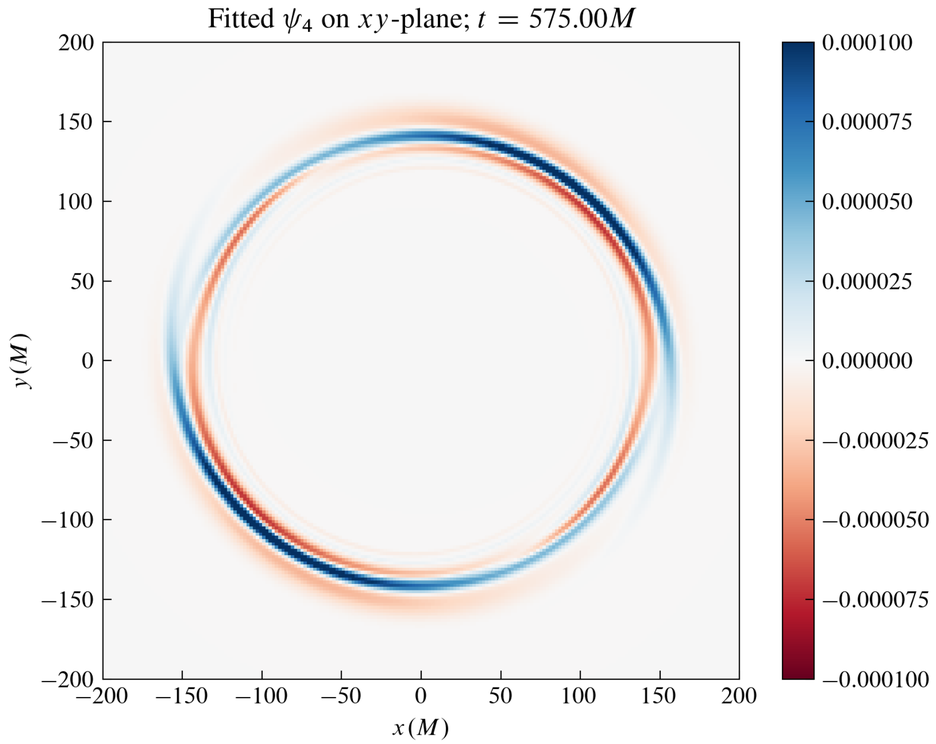
Psi4 Visualization

Polar Gaussian Fitting

$$f(r,\theta) = A \exp\left[-\left(\frac{r-r_0}{2\sigma_r}\right)^2\right] \exp\left[-\left(\frac{\theta-\theta_0}{2\sigma_\theta}\right)^2\right]$$

- We fitted Ψ_4 at a specific time as a linear combination of polar Gaussian functions.





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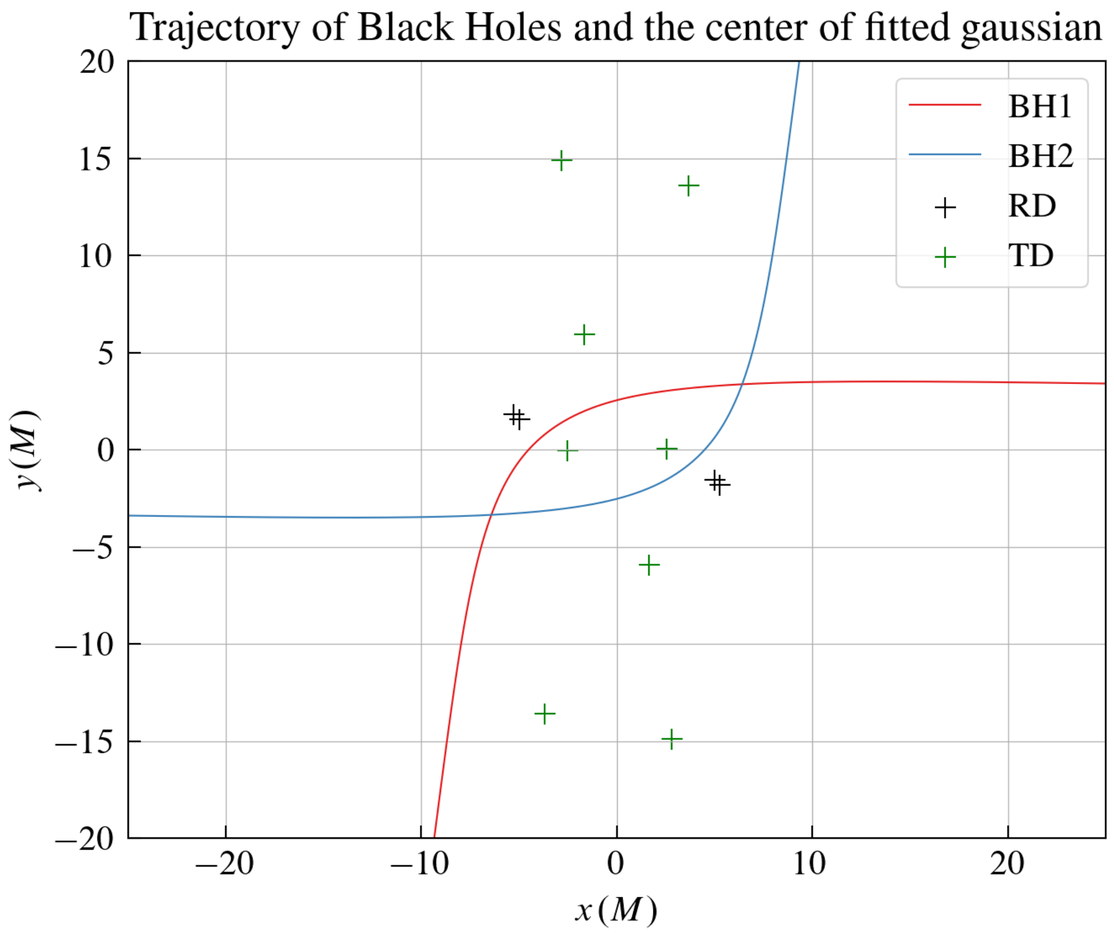

Summary

- We investigated the characteristics of GWs radiated from the hyperbolic encounter of two black holes.
- The nonlinear drift resulting from integrating these gravitational waves remains unresolved.
- Using the subtract-by-fitting method, we obtained the $\dot{h}$, and the energy radiated, calculated through this method, showed better agreement with the results obtained using the mass quadrupole compared to previous result.
- The difference in behavior between the TD waveform and RD waveform at various extraction radii was identified through the ratio of their time delays.
- Ψ_4 was visualized on the xy-plane for further analysis.

Thank you!