Tracking the precession of binary black holes

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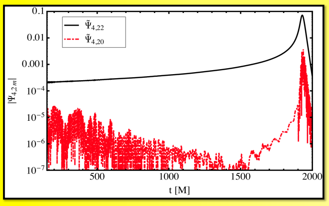
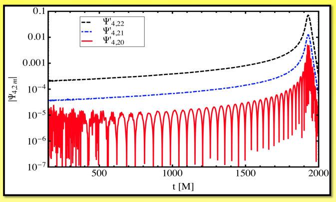
We have developed a simple method to track the precession of a black-hole-binary system, using only information from the gravitational-wave (GW) signal[1]. Our method, applied to numerical waveforms which were produced by the BAM-code[2], involves locating the frame from which the magnitude of the (2,±2)-modes is maximised. We find that our method locates the direction of the orbital angular momentum L of the binary (which differs in general from the normal to the orbital plane), and reproduces higher-mode amplitudes similar to a comparable non-precessing configuration. We expect the simple form of this *"quadrupole-aligned"* waveform to be useful in parameterising waveforms and in attempts to analytically model the inspiral-merger-ringdown (IMR) signal of precessing binaries.

Main Idea

In numerical simulations, GWs are usually decomposed into spin-weighted spherical harmonics with respect to a *fixed frame*, which corresponds to the "natural" orientation in the equal-mass non-spinning case. A relative inclination between the orbital plane and this frame yields "mode-mixing", i.e. in a different frame different modes may occur although the physics is the same, e.g.:



Equal-mass non-spinning reference case: orbital motion confined to xy-plane



Equal-mass non-spinning "tilt&twist" case (see below): orbital motion inclined

In a generic precessing case, the inclination changes constantly, which leaves an imprint on the waveform modes. Can we disentangle the complex precessing motion and simplify the signal? YES, we can define a more convenient frame based on a simple idea:

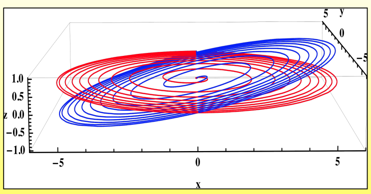
→ ***Quadrupole-aligned frame***.

<u>*Idea*</u>: If the binary's motion is confined to the xy-plane, the (2,±2)-coefficients are maximised. A specific rotation about two angles[3] allows us to achieve this at all times. We then use this new frame, the QA-frame, to construct a simplified signal.

Tilt & twist

Test case: equal-mass non-spinning (q=1, a_i=0):

1. reference case (frame-alignment, red)
2. "artificial" tilt (β=10°) about y-axis and twist (γ=25°) about z-axis (blue)



Orbital motion for one puncture in each case

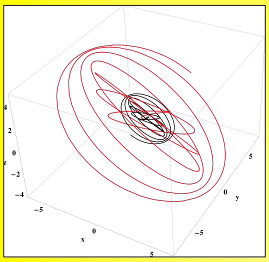
<u>Results</u>: The maximisation routine recovers the expected angles to within ±(0.5,2.0)°.

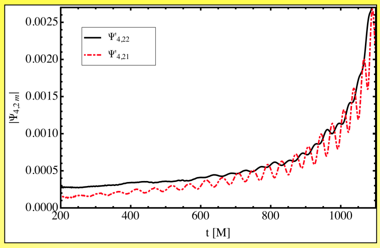
Precessing Case

Study case:

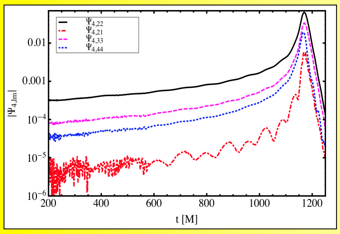
❖ q=3, a_1=0, a_2=0.75

❖Exhibits significant precession of the orbital plane which introduces amplitude modulations and redistributes the energy among other modes.

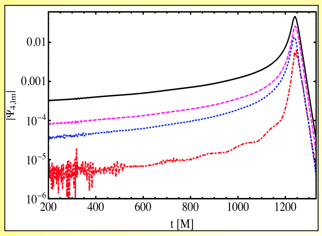




<u>Results</u> after applying the maximisation routine to track the precession of the orbital plane:



QA-modes



q3 non-spinning modes

→ The QA-modes show remarkable agreement with the equivalent non-spinning case.

Conclusions

❖Significant simplification of the emitted GW signal during the late inspiral.

❖PN comparison suggests that this procedure tracks the direction of the *orbital angular momentum.*

❖Procedure needs to be enhanced to become applicable during merger and ringdown.

❖More general cases including spin-spin couplings need to be studied.

References:
[1] P. Schmidt, M. Hannam, S. Husa and P. Ajith, arXiv:1012.2879 [gr-qc]
[2] B. Brügmann et al., Phys. Rev. **D77**, 024027 (2008)
[3] J. N. Goldberg et al., J. Math. Phys. **8**, 2155 (1967)