Orbital Eccentricity as the Fingerprint of Merger Origin

SUMMARY

A range of cosmic processes can lead to the merger of black holes and neutron stars detectable by gravitational waves. Orbital eccentricity prior to merger is a unique signature, indicating that the binary interacted with its environment soon before merger. Detecting orbital eccentricity can therefore help reconstruct the origin, and environment, of gravitational wave sources. The detection of gravitational waves at low frequencies ($< 10\,\mathrm{Hz}$) is the key driver of identifying eccentric binary mergers, making XG gravitational wave observatories best suited to expand this capability.

Key question(s) and scientific context in brief

The astrophysical origin of black hole mergers is not yet understood. To use individual mergers to probe astrophysical processes and environments, it is critical to determine the origin of as many mergers as possible. Orbital eccentricity will help address the question of origin. In addition, the properties of binaries on eccentric orbits can be misreconstructed if eccentricity is not taken into account. This can bias, e.g. the use of binaries as cosmic distance ladders to probe the expansion of the universe.

Potential scientific impact of XG detectors on the key questions

The critical change of XG detectors relevant to detect eccentric binaries is extended sensitivity towards lower gravitational wave frequencies ($< 10\,\mathrm{Hz}$). Low frequencies correspond to earlier phases of binary evolution where eccentricity is more pronounced, and therefore can be better distinguished from quasi-circular orbits. In addition, the superior sensitivity of XG detectors can help detect some of the highest eccentricity collisions, which emit substantially weaker gravitational wave signals than quasi-circular mergers, making their detection difficult at present. While future space-based gravitational-wave detectors, such as LISA, are sensitive to even lower frequencies, their expected detection rate of stellar-mass compact object mergers is negligible compared to that of XG detectors.

Benchmarks for XG detectors to enable the scientific impact

The two key features of probing eccentric mergers are (i) the ability to distinguish between eccentric and quasi-circular binaries and (ii) the detection rate of eccentric binaries. A combined benchmark of these two features is:

- **Number of detected eccentric mergers for which eccentricity can be established.** This can be computed given the detector sensitivity and a fiducial astrophysical binary formation model. Assuming a large number of detections that may make special events more relevant as opposed to the overall number of detected sources, an alternative benchmark can be:
- **The lowest eccentricity that can be distinguished from a quasi-circular merger.**

Framing these in the context of detector performance, the most important benchmark is that:

- **The low frequency cutoff of the observation band should be as low as possible.**

SCIENTIFIC IMPACT OF XG DETECTORS

Establishing the origin of binary black hole mergers; determining environmental effects on compact binaries; probing the origin of heavy elements in the universe; probing the expansion of the universe with gravitational wave sources.

Dependencies on other multi-messenger capabilities

- In order to use eccentric binaries for probing cosmic expansion, the detection of the binaries through electromagnetic observations and the determination of the redshift of their host galaxy are necessary.
- Probing the synthesis of heavy elements by eccentric neutron star mergers requires their detection with electromagnetic observatories in addition to gravitational waves.
- Other questions in the eccentric domain rely on gravitational wave detections alone.

XG DETECTOR AND NETWORK REQUIREMENTS

XG detectors should expand the number of detected eccentric mergers and the lower limit at which eccentricity can be established. Beyond this general requirement, there is no well defined timeframe. Network capabilities are also less relevant for answering the questions that do not rely on multi-messenger observations.

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