Distinguishing Between Formation Channels for Binary Black Holes with LISA

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Abstract

The recent detections of GW150914 and GW151226 imply an abundance of stellar-mass binary-black-hole mergers in the local universe. While ground-based gravitational-wave detectors are limited to observing the final moments before a binary merges, space-based detectors, such as the Laser Interferometer Space Antenna (LISA), can observe binaries at lower orbital frequencies where such systems may still encode information about their formation histories. We explore the orbital eccentricity and mass of binary black hole populations as they evolve through the LISA frequency band. Overall we find two distinct populations discernible by LISA. We show how the measurement of both chirp mass and eccentricity can be used to constrain formation channels for binary black holes. Finally, we note how measured eccentricities of low-mass binary black holes could provide detailed constraints on the physics of black-hole natal kicks and common-envelope evolution.

Binary Black Hole Formation

The era of gravitational wave (GW) astrophysics began with the discovery of the binary-black-hole (BBH) merger, GW150914, by Advanced LIGO (aLIGO). The subsequent detection of BBH merger, GW151226, with smaller progenitor masses suggests diversity in the potential formation channels of the BBHs. Multiple scenarios have been proposed to produce GW150914-like BBHs [1, 2, 3, 4, 5], but without a full population of measured spins [6], mass ratios, redshift distributions or eccentricities aLIGO is not able to discriminate between them.

LISA and Eccentricity

- GW emission shrinks and circularizes binary orbits over long timescales, leading to BBHs with very low eccentricities in the aLIGO band
- The frequency range observable by LISA is much lower where BBHs may still retain a fraction of their initial eccentricity

Stellar mass BBHs may have eccentricities measurable by LISA [7, 8].

Gravitational Wave Frequency

Eccentric binaries emit GWs at harmonics of their orbital frequency. The frequency of maximum GW power emission from an eccentric binary is estimated as [9]

$$f_{GW} = \frac{\sqrt{G(m_1+m_2)}}{\pi}\frac{(1+e)^{1.1954}}{[a(1-e)^2]^{1.5}} \qquad (1)$$

Simulation Details: Globular Cluster vs Galactic Field

Globular Cluster: Dynamics=On

Sampled from 48 GC Models [10] with $Z = [0.25Z_\odot,\ 0.05Z_\odot,\ \text{and}\ 0.01Z_\odot]$

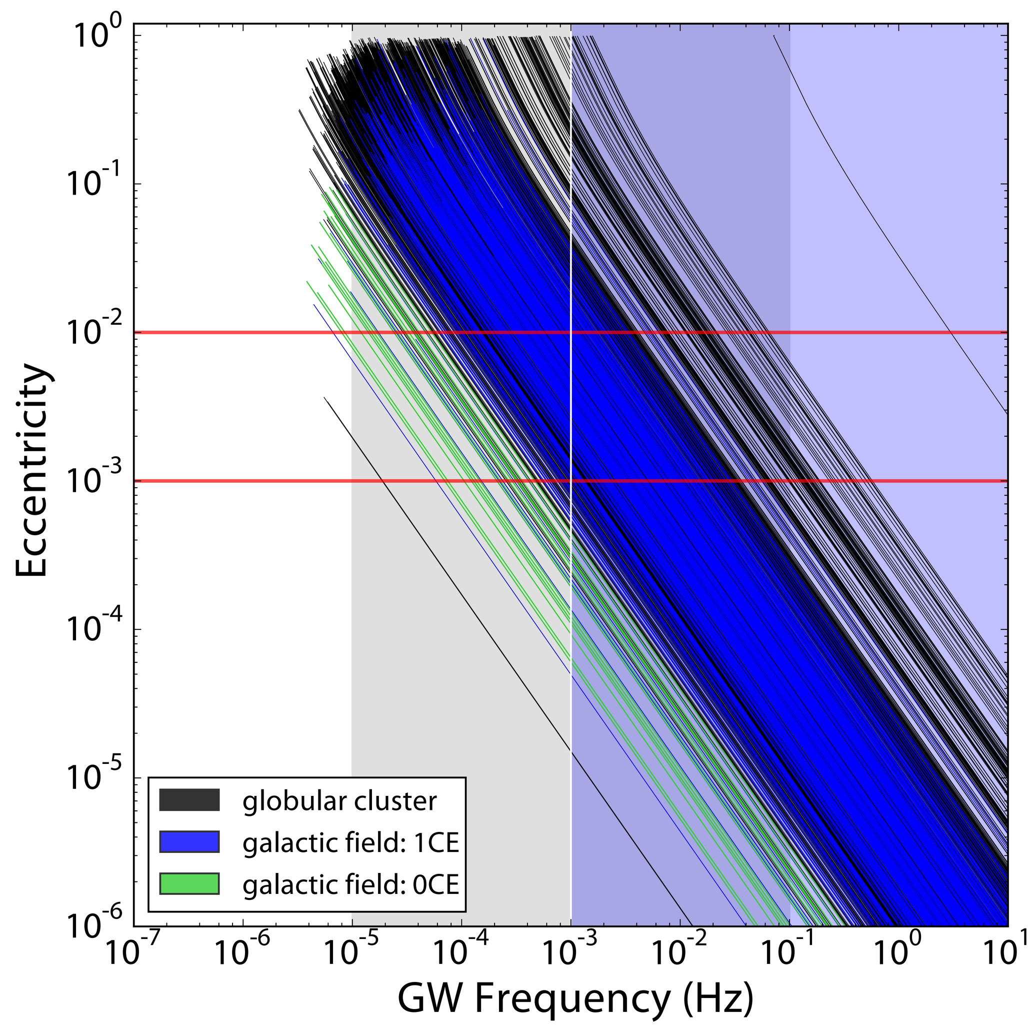
- Stellar evolution using BSE with updated:
  - BH formation and natal kicks
  - metallicity-dependent wind prescriptions
  - fallback in neutrino-driven supernovae

Galactic Field: Dynamics=Off

$Z = [Z_\odot,\ 0.25Z_\odot,\ 0.05Z_\odot,\ \text{and}\ 0.01Z_\odot]$

- Sub-solar metallicity: must evolve to LISA band by 1 Gyr before present
- Solar metallicity: must evolve to LISA band by 10 Gyr before present

Eccentricity Evolution: Globular Cluster vs Galactic Field



- BBHs above 1mHz are expected to have measurable frequency evolution, called a chirp, over a LISA observation run
- All BBHs with $e \gtrsim 0.01$ will be measurable and 90% of BBHs with $e \gtrsim 0.001$ will be measurable by LISA over a 5 year observation run[8]

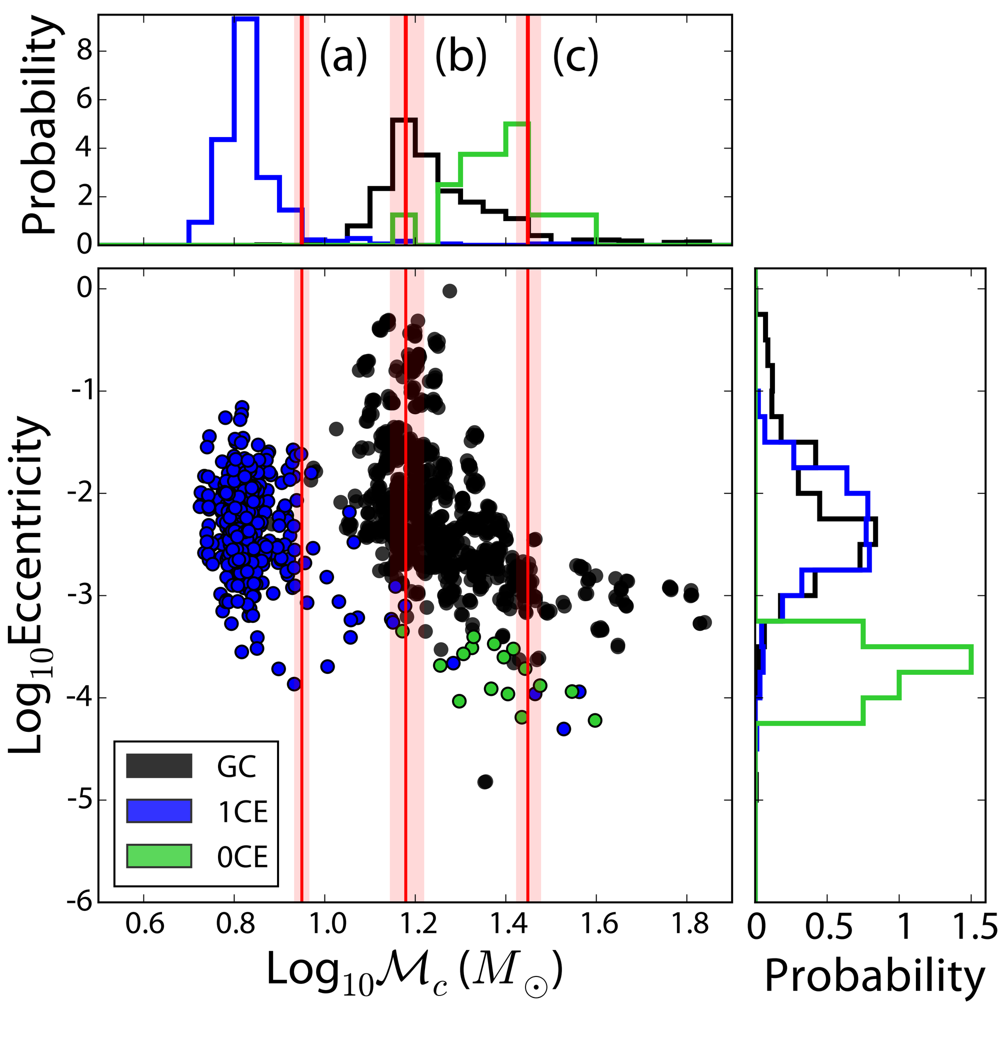
BBHs detected with e $\gtrsim$ 0.01 and $f_{GW} \gtrsim$ 10 mHz formed in dense stellar environments like GCs.

BBHs formed in the galactic field that undergo common-envelope evolution (1CE) may have measurable eccentricities.

Chirp Mass - Eccentricity Correlations at 1 mHz

- The chirp mass: $\mathcal{M}_c$ can be computed for any BBH detected with a measured chirp
- Red vertical lines show the chirp mass of the (a) GW151226, (b) LVT151012, and (c) GW150914 progenitors with 90% confidence limits
- Chirp mass - eccentricity correlations persist at all frequencies above 1 mHz

If the GW150914, LVT151012, or GW151226 progenitors had been observed by LISA, an eccentricity measurement (or lack thereof) could have aided in identifying their formation channels.



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