

A Report on “On the Formation of
GW231123 in Population III Star
Clusters” by Liu et al. (2025)

Reviewer 2

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I am wiser than this person; for it is likely that neither of us knows anything fine and good, but he thinks he knows something when he does not know it, whereas I, just as I do not know, do not think I know, either. I seem, then, to be wiser than him in this small way, at least: that what I do not know, I do not think I know, either.

Plato, *The Apology of Socrates*, 21d

To err is human. All human knowledge is fallible and therefore uncertain. It follows that we must distinguish sharply between truth and certainty. That to err is human means not only that we must constantly struggle against error, but also that, even when we have taken the greatest care, we cannot be completely certain that we have not made a mistake.

Karl Popper, 'Knowledge and the Shaping of Reality'

Overview

Citation: Liu, S., Wang, L., Tanikawa, A., Wu, W., and Fujii, M. S. (2025). On the Formation of GW231123 in Population III Star Clusters. *Astrophysical Journal Letters*. Vol. 993, No. L30, pp. 1–6.

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Abstract Summary: This study investigates the formation of the binary black hole merger GW231123, whose component masses challenge standard stellar evolution theory, by modeling candidate progenitors in Population III (Pop III) star clusters. The progenitors are found to form through stellar, BBH, and mixed mergers, with a predicted merger rate density consistent with the observed value for GW231123.

Key Methodology: *N*-body simulations of Pop III star clusters embedded in mini-dark-matter halos, using fast population synthesis codes (SEEMP and BSEEMP) for stellar evolution and the *N*-body code PETAR for dynamical evolution.

Research Question: Can GW231123, a binary black hole merger with component masses challenging standard stellar evolution, be formed in Population III star clusters?

Summary

Is It Credible?

Liu et al. present a compelling theoretical argument that the heavy binary black hole (BBH) merger GW231123 could have originated in a Population III (Pop III) star cluster. Through N-body simulations, the authors demonstrate that dynamical interactions within these dense environments—specifically stellar mergers, hierarchical black hole mergers, and mixed mergers—can produce binaries with component masses and mass ratios that align well with the observed parameters of GW231123. The study highlights that stellar mergers are particularly efficient at creating massive black holes that avoid pair-instability supernovae, thereby populating the mass gap where the primary component of GW231123 resides. The authors further report that the predicted merger rate density from their models, ranging from 0.001 to $0.26 \text{ Gpc}^{-3} \text{ yr}^{-1}$, encompasses the rate inferred from gravitational wave observations (p. 2).

However, the credibility of this specific origin story for GW231123 faces a significant hurdle regarding the timing of the merger. GW231123 occurred at a redshift of $z \approx 0.39$, which is relatively recent in cosmic history. In contrast, the authors find that approximately 80% of the candidate progenitors in their models merge at redshifts greater than 2 (p. 4). To bridge this gap, the study relies on the assumption that the “mini-dark-matter halos” hosting these clusters survive to the present day, shielding the clusters from tidal disruption by the galactic potential. As the authors transparently note, “If the mini-dark-matter halos that shield Pop III star clusters from disruption by the galactic potential survive to the present day, a fraction of candidate progenitors of GW231123 could merge as late as the present epoch” (p. 4). This conditional statement is crucial; if these halos are stripped or disrupted earlier—a plausible outcome in hierarchical structure formation—the mechanism may fail to

produce mergers at the observed low redshift. Consequently, while the mass generation mechanism appears robust within the model’s physics, the temporal match to GW231123 is contingent on a cosmological condition that the article acknowledges but does not validate.

Furthermore, the statistical robustness of the formation rate warrants scrutiny. The article reports the “mean number” of progenitors per cluster, which is often significantly less than one; for example, the massive cluster model without primordial binaries yields a mean of only 0.16 progenitors (Table 1). This average obscures whether the progenitors are a common outcome of such clusters or the result of rare, stochastic fluctuations in a small number of outliers. Without data on the variance or distribution of progenitor counts, it is difficult to assess how reliably these clusters produce such heavy binaries. Despite these limitations, the study provides clear, falsifiable predictions for future detectors, noting that high-eccentricity events detectable by ground-based observatories would strongly favor this dynamical formation scenario over isolated binary evolution (p. 5).

The Bottom Line

The study successfully demonstrates that Population III star clusters are a physically plausible environment for forming heavy binary black holes like GW231123, matching both the component masses and the inferred merger rate density. However, the model’s ability to explain the event’s occurrence at low redshift ($z \approx 0.39$) depends entirely on the unverified assumption that the host mini-dark-matter halos survive to the present day without disruption. While the scenario is theoretically sound, its application to this specific event remains conditional on the long-term stability of these primordial structures.

Potential Issues

Reliance on an unverified assumption for low-redshift events: The model’s ability to explain the observed low redshift of GW231123 ($z \approx 0.39$) hinges on a significant and currently unverified astrophysical assumption: the long-term survival of the mini-dark-matter halos that host the simulated Population III star clusters. The article acknowledges this dependence, stating, “If the mini-dark-matter halos that shield Pop III star clusters from disruption by the galactic potential survive to the present day, a fraction of candidate progenitors of GW231123 could merge as late as the present epoch” (p. 4). While the authors are transparent about this condition, it remains a central uncertainty. The survival of these low-mass halos over cosmic time is considered highly challenging due to their vulnerability to tidal stripping and disruption by larger structures. The consistency of the model with low-redshift observations is therefore conditional on a scenario whose plausibility is not established within the article.

Omission of progenitor count distribution: The article reports only the mean number of candidate progenitors formed per cluster (N_{mean} in Table 1), which may obscure the stochastic nature of the formation process. For instance, the M100000-PBF0 model has a mean of 0.16 progenitors per cluster. This average could result from a scenario where roughly 16% of clusters form one progenitor each, or from a different scenario where a single outlier cluster forms many progenitors while the vast majority form none. Without information on the distribution or variance of progenitor counts across the simulation suite, it is difficult to assess whether the formation channel is robust or dominated by rare, high-yield events. This omission limits a full understanding of how commonly progenitor-hosting clusters are predicted to be within the model (p. 2).

Future Research

Investigation of halo survival: Future work should integrate these cluster models with cosmological simulations to rigorously test the survival rates of mini-dark-matter halos over cosmic time. Determining the likelihood of these halos resisting tidal stripping and disruption down to $z < 0.5$ is essential to validate the claim that Pop III clusters can contribute significantly to the low-redshift merger rate observed by current detectors.

Statistical analysis of progenitor formation: Researchers should analyze and report the full probability distribution of progenitor formation per cluster, rather than solely the mean values. Understanding the variance—specifically, whether progenitors arise from a broad population of clusters or a few statistical outliers—would clarify the robustness of the formation channel and improve the reliability of the predicted merger rates.

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