

Aligned Hierarchical Black Hole Mergers in AGN disks revealed by GWTC-4

Yin-Jie Li,¹ Yuan-Zhu Wang,² Shao-Peng Tang,¹ and Yi-Zhong Fan^{1,3,*}

¹*Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory,
Chinese Academy of Sciences, Nanjing 210023, People's Republic of China*

²*Institute for Theoretical Physics and Cosmology,*

Zhejiang University of Technology, Hangzhou, 310032, People's Republic of China

³*School of Astronomy and Space Science, University of Science and Technology of China,
Hefei, Anhui 230026, People's Republic of China*

The active galactic nucleus (AGN) accretion disks are ideal sites for hierarchical black hole (BH) mergers. To robustly probe such a possibility, we analyze binary black hole mergers in the GWTC-4 with a flexible mixture population model for component masses, spin magnitudes, and spin tilt angles, and identify two distinct subpopulations. In the second subpopulation characterized by high spin magnitudes $\chi \sim 0.8$ as well as the broad mass distribution up to $\gtrsim 150M_{\odot}$, we find a pronounced preference for spins aligned with the orbital angular momentum: an isotropic tilt distribution is strongly disfavored (logarithmic Bayes factor = 4.5). The aligned events account for $\sim 0.57^{+0.23}_{-0.31}$ of the second subpopulation, corresponding to a local rate of $\sim 0.25^{+0.38}_{-0.16} \text{ Gpc}^{-3}\text{yr}^{-1}$ (all values reflect central 90% credible intervals). These notable features naturally arise from hierarchical mergers embedded in AGN disks, where gas torques can effectively align spins. Our results identify AGN-disk hierarchical assembly as an important channel in the present gravitational-wave sample and provide concrete, testable predictions for future detection.

Thanks to the successful performance of the ground-based gravitational-wave detectors, in particular the advanced LIGO [1] and Virgo [2], more than 180 gravitational wave events, most involving stellar-mass black hole pairs, have been officially reported [3–5]. Due to the absence of electromagnetic counterparts and the relatively poor localizations, one of the key open questions for the binary black hole merger (BBH) events is where and how they were formed [6]. The BBH formation channels can be broadly categorized into two main pathways: isolated binary evolution and dynamical formation in dense stellar environments like star clusters and around active galactic nuclei (AGN) disks. Since different evolutionary channels yield BBHs with distinct characteristics, such as merger rate histories, spin properties, and mass distributions, the population analysis can play a crucial role in revealing the formation pathways of BBHs [6, 7]. For instance, the BHs resulting from core collapses generally have low spins [8], although they can be moderately spun up through binary interactions [9]. In contrast, second or higher generation BHs, which are remnants of previous mergers, exhibit notably different spin-magnitude distributions, typically peaking around ~ 0.7 [7, 10] or even higher for the aligned mergers [11]. Population studies of GWTC-3 data [4] have indeed identified two distinct subpopulations on the spin magnitude versus component mass diagram [12–14]. One subpopulation, characterized by low BH masses and spins ($\chi \lesssim 0.4$), aligns with stellar core-collapse origins. The other subpopulation, with higher masses and spins ($\chi \sim 0.75$), is indicative of hierarchical mergers. The hosts of these hierarchical mergers, however, remain an unresolved issue [13, 15, 16]. For a few exceptional events, such as GW190521 and GW231123, the AGN disk-driven hierarchical merger origin is likely favored [17, 18], but alternative reasonable explanations are still available [19–21]. As such, confirming the existence of a population of AGN disk-driven hierarchical mergers is an ongoing endeavor, which is the main goal of this work.

The distributions of spin orientations carry fundamental information on the formation mechanisms and environments of BBHs that lead to mergers. BBHs originating from isolated field binaries usually exhibit nearly aligned spins, whereas those formed through dynamic processes in star clusters have isotropic spins [6]. BBHs dynamically assembled within AGN disks, however, may show oriented spins (aligned or anti-aligned) due to the interaction with the AGN disk [22]. It has been proposed that counter-alignment of BHs' spins serves as a key discriminant between the AGN disk scenario and other pathways, such as isolated binary evolution or dynamical assembly in clusters [7]. However, this distinction may be challenged by some critical factors, for example, anti-aligned (or retrograde) BBHs could be preferentially ionized as they spend more time at wider separation [23], and the dynamical encounters may flip their spins to align (or prograde) configurations [24, 25]. Nevertheless, the joint analysis of component masses, spin magnitudes, and spin orientations could provide a smoking-gun signature of AGN disk-driven hierarchical mergers [7, 25].

Approaches. Previous studies have investigated the origins of hierarchical mergers with effective spins in GW data, yet the evidence remains inconclusive [15, 16, 26, 27]. More frustratingly, AGN disk-driven hierarchical mergers may be difficult to distinguish significantly from some field evolution channels, from the perspective of effective spins

* The corresponding author: yzfan@pmo.ac.cn

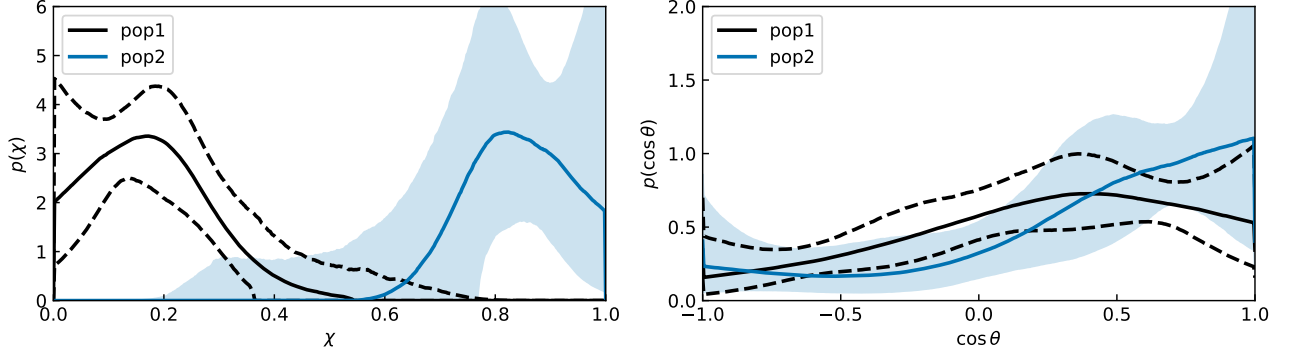


FIG. 1. Reconstructed spin magnitude (left) and spin orientation (right) distributions of the first and second subpopulations; the solid curves are the medians and the dashed curves are for the 90% credible intervals.

[28]. Therefore, in this work, we conduct a population analysis of the newly released GWTC-4 data [5], involving spin magnitudes, spin orientations, and component masses of the BBH events, using a novel nonparametric model.

Following [29], we select 153 BBH events for analysis, using a false-alarm rate threshold $< 1 \text{ yr}^{-1}$ in GWTC-4, and employ the common hierarchical Bayesian inference [29, 30] to estimate the population properties of BBHs. The detailed formulation is provided in Appendix A.

The population model builds upon our semi-parametric framework developed in Li *et al.* [13], in which only the component-mass distribution was modeled flexibly since the data sample was relatively small. Benefited from the significantly increased number of the BBH events, we are able to take a much more flexible mixture population model for component masses, spin magnitudes, and spin-orbit tilts, which reads

$$\pi(\lambda|\Lambda) \propto \pi(m_1, \chi_1, \cos \theta_1|\Lambda) \times \pi(m_2, \chi_2, \cos \theta_2|\Lambda) \times P_{\text{pair}}(q|\Lambda) \times \pi_z(z|\gamma), \quad (1)$$

note that

$$\pi(m, \chi, \cos \theta|\Lambda) = \sum_{i=1,2} P_{\mathcal{PS}}(m|\Lambda_i) \times P_S(\chi|\Lambda_i) \times P_S(\cos \theta|\Lambda_i) \times r_i, \quad (2)$$

where $P_{\mathcal{PS}}$ and P_S are the *PowerLaw+Spline* and *Spline* models for the distributions of component masses and spin properties. Besides $P_{\mathcal{PS}}(m|\Lambda_i)$, now the distributions of spin magnitudes $P_S(\chi|\Lambda_i)$, spin orientations $P_S(\cos \theta|\Lambda_i)$, and the pairing function $P_{\text{pair}}(q|\Lambda)$ are also described by flexible, data-driven representations, i.e., exponentiated cubic splines $p(x) \propto e^{f(x)}$, please see the Appendix B for the details of these component models. Unlike the B-SPLINE-based model adopted by The LIGO Scientific Collaboration *et al.* [29] and Edelman *et al.* [31], which focuses on marginal distributions of individual parameters, our mixture model captures intrinsic correlations among parameters and enables the identification of potential astrophysical subpopulations.

Results. Our analysis unambiguously identified two subpopulations of BHs with a Bayes factor of $\ln \mathcal{B} = 12$, considerably strengthening our earlier findings based on GWTC-3 [12, 13]. The first subpopulation exhibits spin magnitudes $\lesssim 0.4$ peaking at ~ 0.2 , and masses $\lesssim m_{\text{max},1} = 66.7^{+11.4}_{-8.2} M_\odot$ (68% highest density interval), consistent with first-generation BHs. The second subpopulation, with spin magnitudes $\gtrsim 0.5$ peaking at ~ 0.8 and populating the expected pair instability mass gap, matches the properties of the remnants of previous mergers [7, 10, 32]. The two subpopulations are clearly separated, as illustrated by the distributions of spin magnitudes in Figure 1 (left) and the figures presented in Appendix B. We note that the minimum mass of the high-spin subpopulation could be $\lesssim 20 M_\odot$. One interesting candidate is GW231118-005626, which primary object is consistent with being the second generation BH resulting from a previous merger, with component masses in the $\sim 9 - 10 M_\odot$ range, suggesting that some BBHs with masses peaking at $10 M_\odot$ may be dynamically assembled. Furthermore, the maximum mass of the low-spin subpopulation may reach $\sim 70 M_\odot$, while is still in line with the stellar evolution theories but at the high end, possibly enhanced by the rotation [33]. The fraction of hierarchical mergers (containing at least one higher-generation BH) is $2.5^{+3.2}_{-1.3}\%$ corresponding to a merger rate of $0.47^{+0.58}_{-0.25} \text{ Gpc}^{-3} \text{ yr}^{-1}$, consistent with that inferred from GWTC-3 [13].

Our main discovery is that neither subpopulation has an isotropic spin distribution (see the right panel of Figure 1). The asymmetric fraction of the $\cos \theta$ distribution is defined as

$$f_{\text{asym}} = \int_0^1 [P(\cos \theta) - P(-\cos \theta)] d \cos \theta.$$

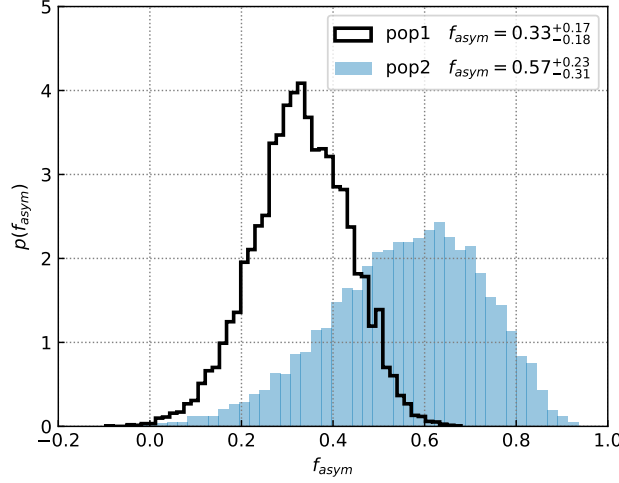


FIG. 2. The asymmetric fraction of $\cos\theta$ distribution for the first and second subpopulation the values are for median and 90% credible intervals.

The symmetric fraction is hence $f_{\text{sym}} = 1 - |f_{\text{asym}}|$. In principle, the isotropic (i.e., $\cos\theta$ distributes uniformly in $[-1,1]$) fraction f_{iso} should be $\lesssim f_{\text{sym}}$, so that the non-isotropic fraction $f_{\text{non-iso}} = 1 - f_{\text{iso}}$ should be $\gtrsim |f_{\text{asym}}|$.

For the first subpopulation, we have $f_{\text{asym}} = 0.33^{+0.17}_{-0.18}$, and an isotropic distribution is disfavored at a confidence level of $> 99.87\%$. For the BHs with a stellar collapse origin, $f_{\text{non-iso}} \gtrsim 0.33^{+0.17}_{-0.18}$ can be attributed to the field binary evolution channels [6, 28, 34], and the underlying fraction could be larger, considering a mass dependent $\cos\theta$ distribution [12, 35].

For the second subpopulation, it turns out that an isotropic distribution is strongly disfavored compared to a distribution with a preference for alignment, by a Bayes factor of $\ln\mathcal{B} = 4.5$, see Appendix C 1 for the details. For formation channels in star clusters, an $f_{\text{asym}} \sim 0$ is expected [15], whereas in AGN disks, an $f_{\text{asym}} > 0$ ($f_{\text{asym}} < 0$ for anti-alignment) is plausible [10, 22, 32]. Our inference yields $f_{\text{asym}} = 0.57^{+0.23}_{-0.31}$, with $f_{\text{asym}} > 0$ at the 99.85% credible level, as depicted in Figure 2. This implies that formation channels leading to hierarchical mergers with isotropic spins, e.g., star-cluster channels [6, 34], account for a fraction $f_{\text{iso}} \lesssim 0.43^{+0.31}_{-0.23}$. We infer such non-isotropic fraction to be $f_{\text{non-iso}} \gtrsim 0.57^{+0.23}_{-0.31}$, which is consistent with the non-isotropic fraction $\zeta_2 = 0.75^{+0.22}_{-0.36}$ obtained independently with a parametric model in Appendix C 2. It is particularly noteworthy that the mergers of aligned BBHs in the AGN disks are also helpful to account for the very high $\chi \gtrsim 0.8$ (see the left panel of Figure 1) that is hard to interpret in other scenarios [7, 11].

Figure 3 displays the population-informed posterior distribution for each event, with (potential) hierarchical mergers (containing high-spin BHs) highlighted with stars. In the top panels, we observe that the high-spin and high-mass subpopulation favors aligned systems (positive $\cos\theta$), a trend that becomes more pronounced in the $\chi - \cos\theta$ panel, where the two subpopulations are distinctly separated. In the bottom panels, we display the distributions of effective spins $\chi_{\text{eff}} \equiv (\cos\theta_1\chi_1 + \cos\theta_2\chi_2q)/(1+q)$. The broad and asymmetric χ_{eff} distribution (skewed towards positive values) of the second subpopulation is evident, while the first subpopulation shows a narrower χ_{eff} distribution. These results are in concordance with independent analysis on the $m_1 - q - \chi_{\text{eff}}$ distribution [16, 26], and the marginalized χ_{eff} distribution [29]. Remarkably, the χ_{eff} distribution of the high-spin subpopulation aligns well with that predicted in the hierarchical mergers in AGN disks [22, 27], in agreement with our argument basing on f_{asym} presented above.

Discussion. Our analysis identifies a significant excess of aligned systems in the second subpopulation, which we attribute to the mergers driven by AGN disks. In the literature, it was also suggested that there may be an excess of anti-aligned systems in the AGN disk [7] but our search finds no evidence for such a group in the current BBH sample. As shown in Appendix C 2, the fraction of anti-aligned assembly is consistent with zero. The absence of anti-aligned assembly is strongly in favor of the effective gas hardening in the AGN disks [11], since the gas-drag will align both binary orbital angular momentum and the BH spins to the AGN disks.

The local AGN disk-driven hierarchical merger rate is estimated to be $R_{\text{AGN,HM}}(z=0) \sim 0.25^{+0.38}_{-0.16} \text{ Gpc}^{-3}\text{yr}^{-1}$. It was argued in Yang *et al.* [22] that roughly half of AGN disk mergers are hierarchical, we hence estimate a total AGN channel merger rate of $R_{\text{AGN}}(z=0) \sim 0.50^{+0.75}_{-0.32} \text{ Gpc}^{-3}\text{yr}^{-1}$, which is $2.7^{+4.0}_{-1.8}\%$ of the local BBH merger rate [29], corresponding to $f_{\text{AGN,Obs.}} \sim 10.9^{+7.4}_{-6.4}\%$ of the observed sample, thanks to the stronger gravitational wave radiation of the AGN disk-driven BBH events. An upper limit of $f_{\text{AGN,Obs.}} < 19.6^{+9.1}_{-6.3}\%$ is set with the total hierarchical merger

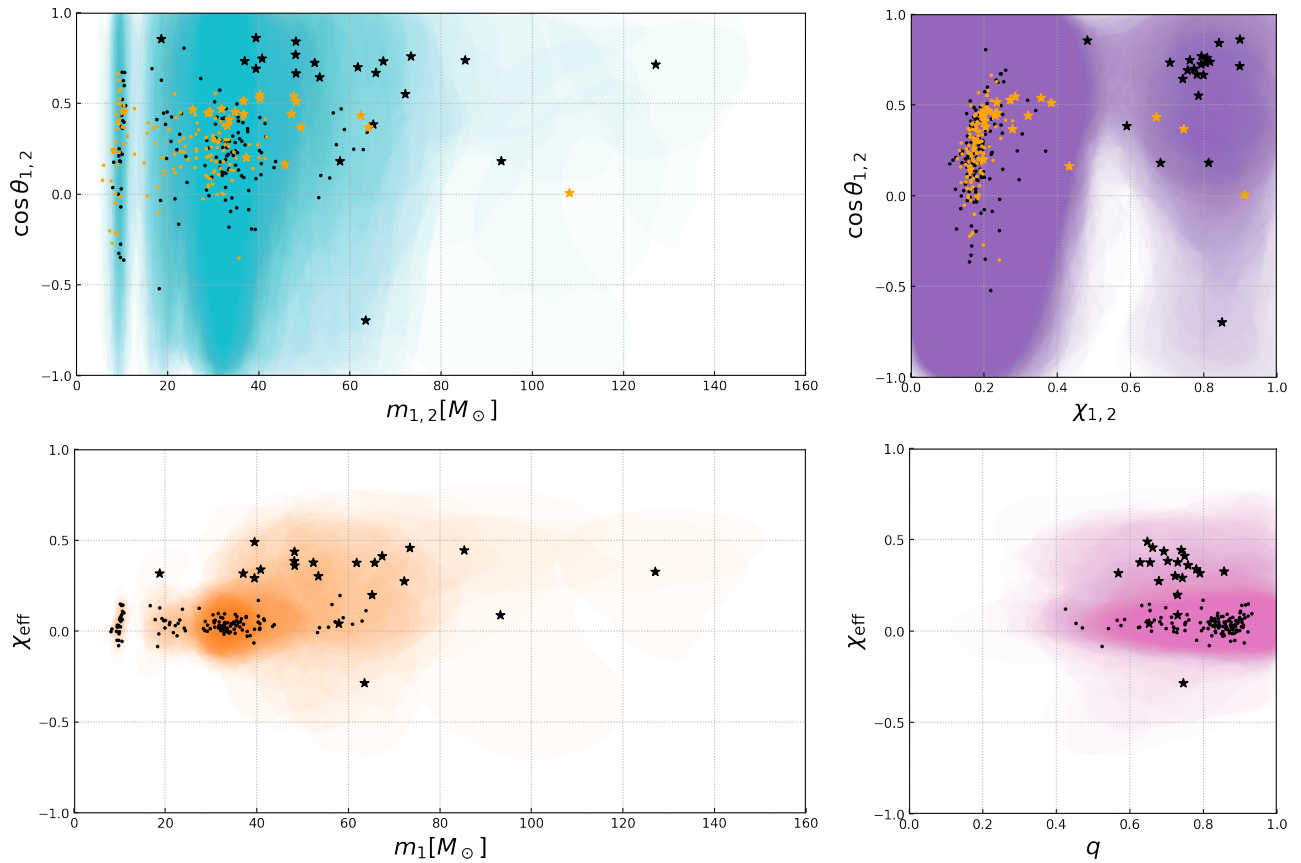


FIG. 3. Population-informed posterior distribution for each event. The shaded areas mark the 90% credible regions and the black (orange) points stand for the mean values for the primary (secondary) BHs. The BHs (BBHs) with mean values of χ (χ_1) > 0.4 are marked with stars. Note that, in the top panels, the secondary BHs are also marked if the corresponding primary with $\bar{\chi}_1 > 0.4$. It is clear that $\cos \theta$ (χ_{eff}) of the BHs (BBHs) in the second subpopulation with high masses and high spins $\chi \sim 0.5 - 0.9$ exhibit a significant preference for positive values.

rate if some BBH events are misaligned due to for instance the absence of gas hardening in some low-accretion-rate AGNs. Our $f_{\text{AGN,Obs.}}$ is comparable with the value inferred via the spatial correlation analysis of the BBH events and the AGNs [36].

Though the uncertainties of the spin measurements of BH components are still relatively large, a group of massive BHs with a high spin $\chi \geq 0.8$ likely emerges (see Figure 1 and Figure 5 in the Appendix B). Such a high χ is not expected in the hierarchical mergers with the random orientations [7]. A very high χ , however, is natural for the mergers of the aligned BBHs due to the effective gas hardening in the AGN disks [11]. One additional prediction of such a specific scenario, favored by our current analysis, is the smooth extension of the maximum mass to $\sim 10^4 M_\odot$, which will be directly tested by the observations of the BBH mergers with the future space-based gravitational wave detectors.

In both the first and second subpopulations, spin orientations are non-isotropic, suggesting that star clusters do not dominate the formation channels for either first-generation or higher-generation mergers. However, discerning whether AGN disks significantly contribute to first-generation BBHs remains challenging. Because traditional field evolution channels may also yield BBHs with aligned spins [34], and a subpopulation from field evolution is likely emerging [12, 35, 37]. Examining the spatial correlation between GW sources and their host environments may help resolve this issue [36]. The mass-dependent $\cos \theta$ distribution observed in the second subpopulation could arise because star clusters and AGN disks are predicted to produce different mass distributions [11, 38]. This characteristic might assist in distinguishing between subpopulations of AGN-driven and cluster-driven hierarchical mergers as the dataset grows in the future.

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Appendix A: Methods

Given a population distribution Λ , the likelihood of the GW data $\{d\}$ from N_{det} detections is [29, 30, 39],

$$\mathcal{L}(\{d\}|\Lambda) \propto N^{N_{\text{det}}} e^{-N_{\text{exp}}} \prod_i^{N_{\text{det}}} \int \pi(\theta_i|\Lambda) \mathcal{L}(d_i|\theta_i) d\theta_i, \quad (\text{A1})$$

where $N = \int R(z|\Lambda) \frac{dV_c}{dz} \frac{T_{\text{obs}}}{1+z} dz$ is the total number of mergers in the surveyed time-space volume, and $N_{\text{exp}} = N \int P(\text{det}|\theta) \pi(\theta|\Lambda) d\theta$ is the expected number of detections, with detection probability $P(\text{det}|\theta)$. N_{exp} is calculated using a Monte Carlo integral over the referred injection [40] (Adopted from <https://zenodo.org/records/16740128>), and $\mathcal{L}(d_i|\theta_i)$ is evaluated using the posterior samples (Posterior samples [3–5] are taken from GWOSC). Following [29], we constrain the total uncertainties of the Monte Carlo integrals $\sigma_{\text{tot}} < 1$ to ensure accurate evaluation of likelihood, and choose a threshold of false-alarm rate (FAR) of $< 1 \text{ yr}^{-1}$ to select the events, and exclude the GW190814 for its unclear nature [39], so that 153 events are selected for our analysis. The ‘Mixed’ posterior samples are adopted for each event. We use the Pymultinest sampler [41], to obtain the posterior distribution of the hyperparameters.

Appendix B: Population model

As already mentioned in the main text, our base m – χ – $\cos \theta$ population model is $\pi(m, \chi, \cos \theta|\Lambda) = \sum_{i=1,2} P_{\mathcal{PS}}(m|\Lambda_i) \times P_{\mathcal{S}}(\chi|\Lambda_i) \times P_{\mathcal{S}}(\cos \theta|\Lambda_i) \times r_i$, where $P_{\mathcal{PS}}$ and $P_{\mathcal{S}}$ are the *PowerLaw + Spline* and *Spline* models for the distributions of component masses and spin properties. These functions are flexible (i.e. weakly modeled) so that the obtained distributions will be data-driven [31, 42], which are expressed as

$$P_{\mathcal{PS},i}(m) \propto m^{-\alpha_i} e^{f(m|\{f_j^i\}_{j=1}^{12})} \text{SF}(m|m_{\min,i}, \delta_i) [m_{\min,i}, m_{\max,i}], \quad (\text{B1})$$

$$P_{\mathcal{S},i}(\chi) \propto e^{n(\chi|\{n_j^i\}_{j=1}^5)} [\chi_{\min,i}, \chi_{\max,i}], \quad (\text{B2})$$

and

$$P_{\mathcal{S},i}(\cos \theta) \propto e^{t(\cos \theta|\{t_j^i\}_{j=1}^4)} [-1, 1]. \quad (\text{B3})$$

where $\text{SF}(m|m_{\min,i}, \delta_i)$ is the smooth function as defined in Abbott *et al.* [43]. For the mass distribution, 12 knots to interpolate the perturbation function are linearly set in log space between $[6, 80]M_{\odot}$. While 5 (4) knots are set linearly in $[0, 1]$ ($[-1, 1]$) for the perturbation function $n(\chi)$ ($t(\cos \theta)$) of χ ($\cos \theta$) distribution.

The total population model takes the form of $\pi(\lambda|\Lambda) \propto \pi(m_1, \chi_1, \cos \theta_1|\Lambda) \times \pi(m_2, \chi_2, \cos \theta_2|\Lambda) \times P_{\text{pair}}(q|\Lambda) \times \pi_z(z|\gamma)$, with

$$P_{\text{pair}}(q|\Lambda) \propto q^{\beta u(q|\{u_j^q\}_{j=1}^4)} \times \Theta(q < 1), \quad (\text{B4})$$

where $f_{\mathcal{S}}(q)$ is the perturbation of pairing function beyond a simple power law, which is interpolated with 4 knots linearly in $[0, 1]$. The redshift distribution is

$$\pi_z(z|\gamma) \propto \frac{dV_c}{(1+z)dz} \times (1+z)^{\gamma}. \quad (\text{B5})$$

TABLE I. Summary of model parameters.

Parameter	Description	Prior
$m_{\min,i}[M_\odot]$	The minimum mass	$U(2, 50)$
$m_{\max,1}/m_{\max,2}[M_\odot]$	The maximum mass	$U(20, 100)/U(20, 200)$
α_i	Slope index of the power-law mass function	$U(-8, 8)$
$\delta_{m,1} / \delta_{m,2} [M_\odot]$	Smooth scale of the mass lower edge	$U(0, 10) / U(0, 20)$
$\{f_j^i\}_{j=2}^{11}$	Interpolation values of perturbation function	$\mathcal{N}(0, 1)$
r_i	mixture fraction for the i -th subpopulation	Dir
constraints		$m_{\min,i} < m_{\max,i} - 20$
β_q	Slope index of the pairing function	$U(-8, 8)$
$\{u_j^q\}_{j=1}^4$	perturbation values for the pairing function	$\mathcal{N}(0, 1)$
$\chi_{\min,1} / \chi_{\min,2}$	Lower edge for χ distribution	$0 / U(0, 0.8)$
$\chi_{\max,1} / \chi_{\max,2}$	Upper edge for χ distribution	$U(0.2, 1) / 1$
$\{n_j^i\}_{j=1}^5$	perturbation values for χ distribution	$\mathcal{N}(0, 2)$
$\{t_j^i\}_{j=1}^4$	perturbation values for $\cos \theta$ distribution	$\mathcal{N}(0, 1)$
$\lg(R_0[\text{Gpc}^{-3} \text{ yr}^{-1}])$	Local merger rate density	$U(-3, 3)$
γ	Slope of the power-law	$U(-2, 7)$

Note: U , Dir , and $\mathcal{N}$ are for Uniform, Dirichlet, and Normal distribution.

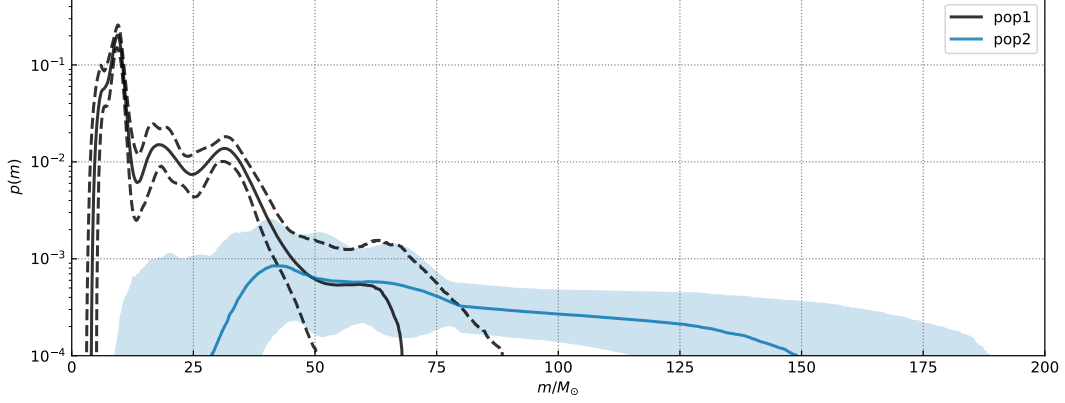


FIG. 4. Reconstructed component-mass distribution of BHs of first and second subpopulations; the thick curves are the medians and the thin curves are for the 90% credible intervals.

All the hyperparameters are summarized in Table I.

With the flexible nonparametric population model (note that in Li *et al.* [13] the spin distributions are modeled with parametric formula), we successfully identify two subpopulations of BHs by a Bayes factor of $\ln \mathcal{B}_{1pop}^{2pop} = 12$, strengthening the finding with GWTC-3 [13]. Figure 4 shows the reconstructed mass distribution of two subpopulations inferred with the nonparametric model introduced above, the spin distributions of the two subpopulations are displayed in the main text. Figure 5 displays the population-informed posterior distribution of each event in the $\chi - \cos \theta$ panel. The two subpopulations are clearly separated, although the maximum mass of the first subpopulation has extend to $m_{\max,1} \sim 70 M_\odot$ with sizable uncertainty. Such a value is still consistent with the core-collapse BHs of current knowledge of stellar evolution theories, in particular in the presence of rapid rotation [33]. We notice that in some simplified parametric approaches, $m_{\max,1}$ has been constrained at a much better accuracy, which is $46.1^{+5.6}_{-5.1} M_\odot$ even with the GWTC-3 data [12]. Our current result suggests that much more data is needed to reliably infer $m_{\max,1}$, as well as the shape of the edge, i.e, smooth or sharp.

The component mass function of the BHs shows three peaks at $\sim 10 M_\odot$, $\sim 18 M_\odot$, $\sim 32 M_\odot$, which are consistent with the results in previous works [29, 44, 45]. Additionally, we find that the minimum mass of the second subpopulation may extend to $\lesssim 20 M_\odot$. In particular, the primary object of GW231118-005626 has a large spin and a mass of $\sim 18 M_\odot$, which is consistent with being a remnant of a BBH merger with the component masses of $9 - 10 M_\odot$, suggesting that some of the BBHs at $\sim 10 M_\odot$ -peak may be dynamically assembled.

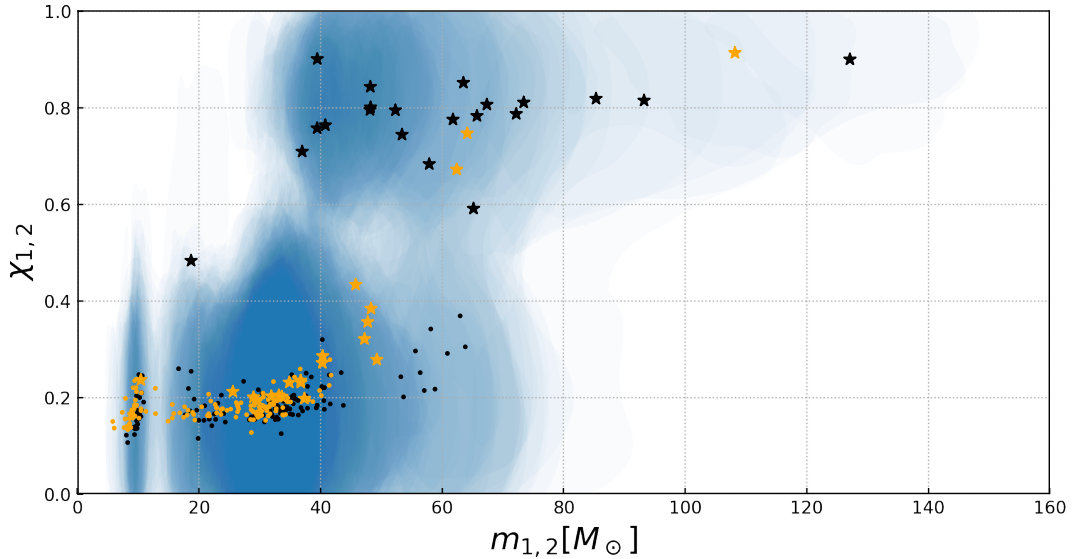


FIG. 5. Posteriors of individual component masses and spin magnitudes of BBHs in GWTC-4 reweighed to a population-informed prior inferred by our nonparametric model. The shaded areas mark the 90% credible regions and the black (orange) points stand for the mean values for the primary (secondary) BHs. The BBHs (both primary and secondary BHs) containing at least one spin magnitude > 0.4 are marked with stars.

Appendix C: Model comparison

1. Aligned or Isotropic

TABLE II. Model comparison

Model	$\ln \mathcal{B}$	$\mathcal{B}$
Pop ₂ Uniform $\cos \theta$	0	1
Pop ₂ Gaussian $\cos \theta$	4.5	85
Nonparametric model	5.7	298

Note: All the $(\ln)$ Bayes factors are relative to the model with isotropic spin for the second subpopulation.

For model comparison, we apply the simple parametric models to describe the spin properties of two subpopulations. We concentrate on whether the spin orientations of the second subpopulation are isotropic or aligned. Therefore we set

$$P_2(\cos \theta) = \mathcal{U}(\cos \theta | -1, 1) \quad (\text{C1})$$

for the case of isotropic spins, and

$$P_2(\cos \theta) = \mathcal{G}(\cos \theta | 1, \sigma_{t,2}, -1, 1) \quad (\text{C2})$$

for the case of aligned spins, where $\mathcal{U}$ is a uniform distribution and $\mathcal{G}$ is a Gaussian distribution, with center value of 1 and width of $\sigma_{t,2}$, truncated in $(-1, 1)$. The spin magnitudes of the two subpopulations are described as $P_1(\chi) = \mathcal{G}(\chi | \mu_{\chi,1}, \sigma_{\chi,1}, 0, \chi_{\max,1})$ and $P_2(\chi) = \mathcal{G}(\chi | \mu_{\chi,2}, \sigma_{\chi,2}, \chi_{\min,2}, 1)$. The spin orientation of the first subpopulation is $P_1(\cos \theta) = \mathcal{U}(\cos \theta | -1, 1)(1 - \zeta_1) + \mathcal{G}(\cos \theta | \mu_{t,1}, \sigma_{t,1}, -1, 1)\zeta_1$.

We find the scenario of isotropic spins (Uniform $\cos \theta$) for the second subpopulation is disfavored compared to the aligned scenario (Gaussian $\cos \theta$), by a Bayes factor of $\ln \mathcal{B} = 4.5$. It is even more disfavored compared to the nonparametric model by $\ln \mathcal{B} = 5.7$. We find that the $\cos \theta$ distribution and the corresponding asymmetric fraction of the second subpopulation, obtained by the Gaussian model, are highly consistent with that obtained by the nonparametric model, see Figure 6 and Figure 7.

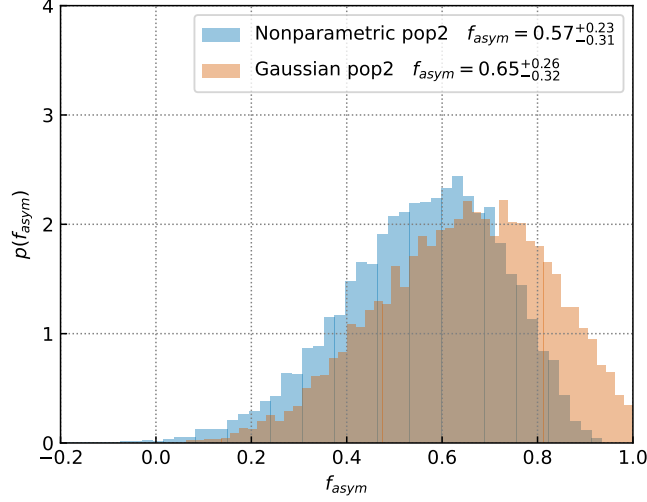


FIG. 6. Comparison of the f_{asym} of the second subpopulation obtained with the Gaussian model and nonparametric models. It shows the results are consistent between the two models.

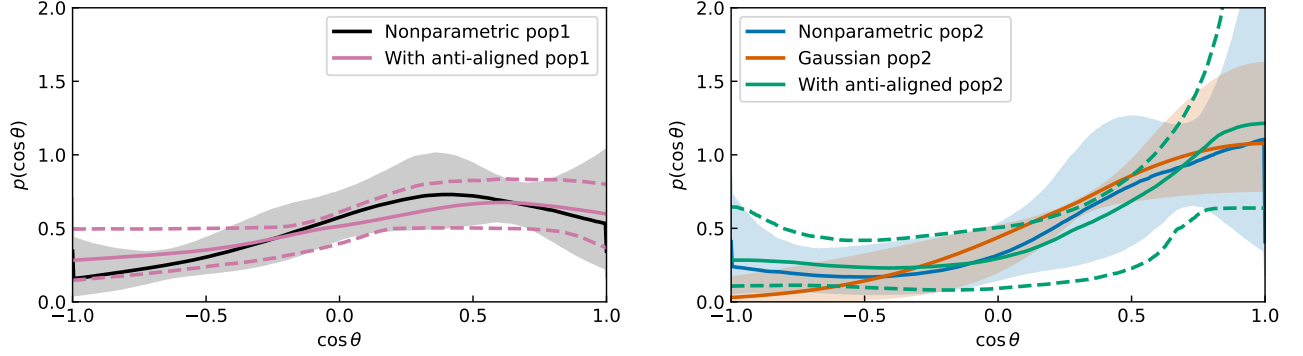


FIG. 7. The $\cos \theta$ distributions obtained with the parametric models introduced in Section C compared to that obtained with nonparametric model for the first (left) and second (right) subpopulations.

2. Aligned and Anti-aligned assemblies

To investigate whether there are isotropic and anti-aligned assemblies in the two subpopulations, we introduce another parametric model for the first and second subpopulations, respectively,

$$P_1(\cos \theta) = \mathcal{U}(\cos \theta | -1, 1)(1 - \zeta_1) + (\mathcal{G}(\cos \theta | \mu_{t,1}, \sigma_{t,1}, -1, 1)(1 - r_{\text{anti},1}) + \mathcal{G}(\cos \theta | -1, \sigma_{t,2}, -1, 1)r_{\text{anti},1})\zeta_1, \quad (\text{C3})$$

and

$$P_2(\cos \theta) = \mathcal{U}(\cos \theta | -1, 1)(1 - \zeta_2) + (\mathcal{G}(\cos \theta | 1, \sigma_{t,2}, -1, 1)(1 - r_{\text{anti},2}) + \mathcal{G}(\cos \theta | -1, \sigma_{t,2}, -1, 1)r_{\text{anti},2})\zeta_2, \quad (\text{C4})$$

where ζ_1 (ζ_2) is the non-isotropic fraction, and $r_{\text{anti},1}$ ($r_{\text{anti},2}$) is the mixture fraction of the anti-aligned assembly. Note that we do not fix $\mu_{t,1} = 1$ for the first subpopulation, inspired by the results obtained with the nonparametric model. We find both $r_{\text{anti},1}$ and $r_{\text{anti},2}$ are consistent with zero, as shown in Figure 7, so that an anti-aligned assembly is not necessary within GW data.

It turns out that the reconstructed $\cos \theta$ distribution of the second subpopulation with model C4 is highly consistent with that obtained with the nonparametric model. In the main text we report the non-isotropic fraction $f_{\text{non-iso}} \gtrsim f_{\text{asym}} = 0.57^{+0.23}_{-0.32}$ obtained with the nonparametric model, which is consistent with the non-isotropic fraction defined in this parametric formula $\zeta_2 = 0.75^{+0.22}_{-0.36}$. The ζ_2 is approaching 1 and $\zeta_2 = 0$ is almost ruled out, which means that the non-isotropic fraction is dominated, and the fully isotropic scenario is strongly disfavored.

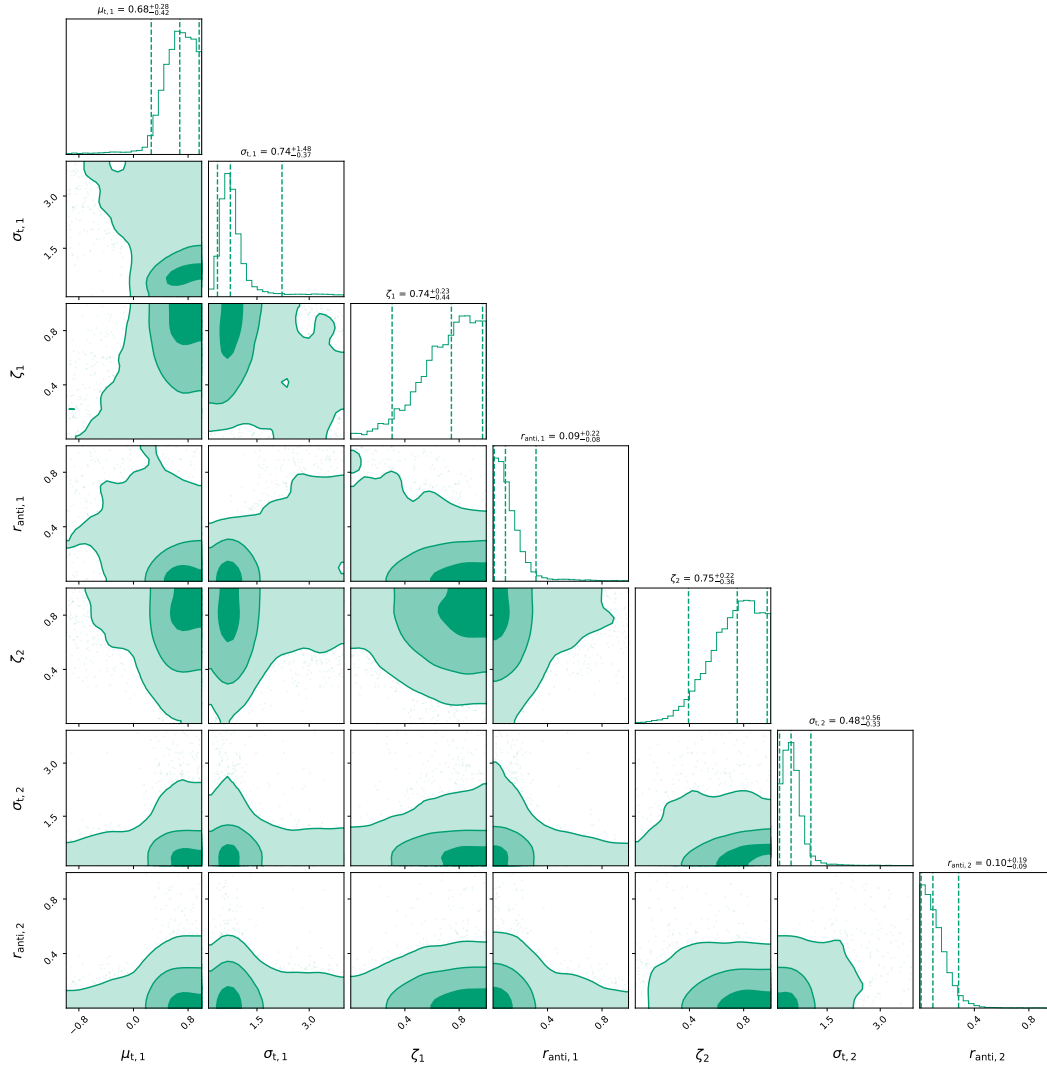


FIG. 8. The posterior distribution of hyperparameters obtained in model C4. The values are for median and 90% credible intervals. It shows that the anti-aligned fractions are consistent with zero in both subpopulations.

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- [1] LIGO Scientific Collaboration, J. Aasi, B. P. Abbott, R. Abbott, *et al.*, *Classical and Quantum Gravity* **32**, 074001 (2015), [arXiv:1411.4547 \[gr-qc\]](#).
 - [2] F. Acernese, M. Agathos, K. Agatsuma, D. Aisa, *et al.*, *Classical and Quantum Gravity* **32**, 024001 (2015), [arXiv:1408.3978 \[gr-qc\]](#).
 - [3] R. Abbott, T. D. Abbott, F. Acernese, K. Ackley, C. Adams, *et al.*, *Phys Rev D* **109**, 022001 (2024), [arXiv:2108.01045 \[gr-qc\]](#).
 - [4] R. Abbott, T. D. Abbott, F. Acernese, K. Ackley, C. Adams, *et al.*, *Physical Review X* **13**, 041039 (2023), [arXiv:2111.03606 \[gr-qc\]](#).
 - [5] The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration, *et al.*, [arXiv e-prints](#), [arXiv:2508.18082 \(2025\)](#), [arXiv:2508.18082 \[gr-qc\]](#).
 - [6] I. Mandel and A. Farmer, *Phys Rep* **955**, 1 (2022), [arXiv:1806.05820 \[astro-ph.HE\]](#).
 - [7] D. Gerosa and M. Fishbach, *Nature Astronomy* **5**, 749 (2021), [arXiv:2105.03439 \[astro-ph.HE\]](#).
 - [8] J. Fuller and L. Ma, *ApJL* **881**, L1 (2019), [arXiv:1907.03714 \[astro-ph.SR\]](#).
 - [9] Y. Qin, T. Fragos, G. Meynet, J. Andrews, M. Sørensen, and H. F. Song, *A&A* **616**, A28 (2018), [arXiv:1802.05738 \[astro-ph.SR\]](#).
 - [10] M. Fishbach, D. E. Holz, and B. Farr, *ApJL* **840**, L24 (2017), [arXiv:1703.06869 \[astro-ph.HE\]](#).
 - [11] M. P. Vaccaro, M. Mapelli, C. Périgois, D. Barone, M. C. Artale, M. Dall’Amico, G. Iorio, and S. Torniamenti, *A&A* **685**,

- A51 (2024), [arXiv:2311.18548 \[astro-ph.HE\]](#).
- [12] Y.-Z. Wang, Y.-J. Li, J. S. Vink, Y.-Z. Fan, S.-P. Tang, Y. Qin, and D.-M. Wei, *ApJL* **941**, L39 (2022), [arXiv:2208.11871 \[astro-ph.HE\]](#).
 - [13] Y.-J. Li, Y.-Z. Wang, S.-P. Tang, and Y.-Z. Fan, *Phys Rev Lett* **133**, 051401 (2024), [arXiv:2303.02973 \[astro-ph.HE\]](#).
 - [14] G. Pierra, S. Mastrogiovanni, and S. Perriès, *A&A* **692**, A80 (2024).
 - [15] F. Antonini, I. M. Romero-Shaw, and T. Callister, *Phys Rev Lett* **134**, 011401 (2025), [arXiv:2406.19044 \[astro-ph.HE\]](#).
 - [16] Y.-J. Li, Y.-Z. Wang, S.-P. Tang, T. Chen, and Y.-Z. Fan, *ApJ* **987**, 65 (2025), [arXiv:2501.09495 \[astro-ph.HE\]](#).
 - [17] M. J. Graham, K. E. S. Ford, B. McKernan, N. P. Ross, D. Stern, K. Burdge, M. Coughlin, S. G. Djorgovski, A. J. Drake, D. Duev, M. Kasliwal, A. A. Mahabal, S. van Velzen, J. Belecki, E. C. Bellm, R. Burruss, S. B. Cenko, V. Cunningham, G. Helou, S. R. Kulkarni, F. J. Masci, T. Prince, D. Reiley, H. Rodriguez, B. Rusholme, R. M. Smith, and M. T. Soumagnac, *Phys Rev Lett* **124**, 251102 (2020), [arXiv:2006.14122 \[astro-ph.HE\]](#).
 - [18] Y.-J. Li, S.-P. Tang, L.-Q. Xue, and Y.-Z. Fan, *arXiv e-prints*, [arXiv:2507.17551 \(2025\)](#), [arXiv:2507.17551 \[astro-ph.HE\]](#).
 - [19] R. Abbott, T. D. Abbott, S. Abraham, F. Acernese, *et al.*, *ApJL* **900**, L13 (2020), [arXiv:2009.01190 \[astro-ph.HE\]](#).
 - [20] R. Gamba, M. Breschi, G. Carullo, S. Albanesi, P. Rettengo, S. Bernuzzi, and A. Nagar, *Nature Astronomy* **7**, 11 (2023), [arXiv:2106.05575 \[gr-qc\]](#).
 - [21] The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration, *et al.*, *arXiv e-prints*, [arXiv:2507.08219 \(2025\)](#), [arXiv:2507.08219 \[astro-ph.HE\]](#).
 - [22] Y. Yang, I. Bartos, V. Gayathri, K. E. S. Ford, Z. Haiman, S. Klimenko, B. Kocsis, S. Márka, Z. Márka, B. McKernan, and R. O’Shaughnessy, *Phys Rev Lett* **123**, 181101 (2019), [arXiv:1906.09281 \[astro-ph.HE\]](#).
 - [23] Y.-H. Wang, B. McKernan, S. Ford, R. Perna, N. W. C. Leigh, and M.-M. Mac Low, *ApJL* **923**, L23 (2021), [arXiv:2110.03698 \[astro-ph.HE\]](#).
 - [24] J. Samsing, I. Bartos, D. J. D’Orazio, Z. Haiman, B. Kocsis, N. W. C. Leigh, B. Liu, M. E. Pessah, and H. Tagawa, *Nature* **603**, 237 (2022), [arXiv:2010.09765 \[astro-ph.HE\]](#).
 - [25] B. McKernan and K. E. S. Ford, *MNRAS* **531**, 3479 (2024), [arXiv:2309.15213 \[astro-ph.HE\]](#).
 - [26] Y.-Z. Wang, Y.-Z. Fan, S.-P. Tang, Y. Qin, and D.-M. Wei, *arXiv e-prints*, [arXiv:2110.10838 \(2021\)](#), [arXiv:2110.10838 \[astro-ph.HE\]](#).
 - [27] B. McKernan, K. E. S. Ford, H. E. Cook, V. Delfavero, E. McPike, K. Nathaniel, J. Postiglione, S. Ray, and R. O’Shaughnessy, *ApJ* **990**, 217 (2025), [arXiv:2410.16515 \[astro-ph.HE\]](#).
 - [28] M. Zevin, S. S. Bavera, C. P. L. Berry, V. Kalogera, T. Fragos, P. Marchant, C. L. Rodriguez, F. Antonini, D. E. Holz, and C. Pankow, *ApJ* **910**, 152 (2021), [arXiv:2011.10057 \[astro-ph.HE\]](#).
 - [29] The LIGO Scientific Collaboration, the Virgo Collaboration, and the KAGRA Collaboration, *arXiv e-prints*, [arXiv:2508.18083 \(2025\)](#), [arXiv:2508.18083 \[astro-ph.HE\]](#).
 - [30] I. Mandel, W. M. Farr, and J. R. Gair, *MNRAS* **486**, 1086 (2019), [arXiv:1809.02063 \[physics.data-an\]](#).
 - [31] B. Edelman, B. Farr, and Z. Doctor, *ApJ* **946**, 16 (2023), [arXiv:2210.12834 \[astro-ph.HE\]](#).
 - [32] D. Gerosa and E. Berti, *Phys Rev D* **95**, 124046 (2017), [arXiv:1703.06223 \[gr-qc\]](#).
 - [33] S. E. Woosley and A. Heger, *ApJL* **912**, L31 (2021), [arXiv:2103.07933 \[astro-ph.SR\]](#).
 - [34] C. L. Rodriguez, M. Zevin, C. Pankow, V. Kalogera, and F. A. Rasio, *ApJL* **832**, L2 (2016), [arXiv:1609.05916 \[astro-ph.HE\]](#).
 - [35] Y.-J. Li, S.-P. Tang, S.-J. Gao, D.-C. Wu, and Y.-Z. Wang, *ApJ* **977**, 67 (2024), [arXiv:2404.09668 \[astro-ph.HE\]](#).
 - [36] L.-G. Zhu and X. Chen, *ApJL* **989**, L15 (2025), [arXiv:2505.02924 \[astro-ph.HE\]](#).
 - [37] J. Godfrey, B. Edelman, and B. Farr, *arXiv e-prints*, [arXiv:2304.01288 \(2023\)](#), [arXiv:2304.01288 \[astro-ph.HE\]](#).
 - [38] L. Xue, H. Tagawa, Z. Haiman, and I. Bartos, *arXiv e-prints*, [arXiv:2504.19570 \(2025\)](#), [arXiv:2504.19570 \[astro-ph.HE\]](#).
 - [39] R. Abbott, T. D. Abbott, F. Acernese, K. Ackley, *et al.*, *Physical Review X* **13**, 011048 (2023), [arXiv:2111.03634 \[astro-ph.HE\]](#).
 - [40] R. Essick, M. W. Coughlin, M. Zevin, D. Chatterjee, T. A. Clarke, S. Colloms, U. Mali, S. Miller, N. Steinle, P. Baral, A. C. Baylor, G. Cabourn Davies, T. Dent, P. Joshi, P. Kumar, C. Messick, T. Mishra, A. Ouzriat, K. S. Phukon, L. Piccari, M. Pillas, M. Trevor, T. A. Callister, and M. Fishbach, *arXiv e-prints*, [arXiv:2508.10638 \(2025\)](#), [arXiv:2508.10638 \[gr-qc\]](#).
 - [41] J. Buchner, “PyMultiNest: Python interface for MultiNest,” Astrophysics Source Code Library, record ascl:1606.005 (2016), [ascl:1606.005](#).
 - [42] B. Edelman, Z. Doctor, J. Godfrey, and B. Farr, *ApJ* **924**, 101 (2022), [arXiv:2109.06137 \[astro-ph.HE\]](#).
 - [43] R. Abbott, T. D. Abbott, S. Abraham, *et al.*, *ApJL* **913**, L7 (2021), [arXiv:2010.14533 \[astro-ph.HE\]](#).
 - [44] Y.-J. Li, Y.-Z. Wang, M.-Z. Han, S.-P. Tang, Q. Yuan, Y.-Z. Fan, and D.-M. Wei, *ApJ* **917**, 33 (2021), [arXiv:2104.02969 \[astro-ph.HE\]](#).
 - [45] V. Tiwari, *MNRAS* **527**, 298 (2024), [arXiv:2304.03498 \[astro-ph.HE\]](#).