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Hierarchical Black Hole Mergers in Active Galactic Nuclei

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The origins of the stellar-mass black hole mergers discovered by LIGO/Virgo are still unknown. Here we show that if migration traps develop in the accretion disks of active galactic nuclei (AGNs) and promote the mergers of their captive black holes, the majority of black holes within disks will undergo hierarchical mergers—with one of the black holes being the remnant of a previous merger. 40% of AGN-assisted mergers detected by LIGO/Virgo will include a black hole with mass $\gtrsim 50 M_\odot$, the mass limit from stellar core collapse. Hierarchical mergers at traps in AGNs will exhibit black hole spins (anti)aligned with the binary's orbital axis, a distinct property from other hierarchical channels. Our results suggest, although not definitively (with odds ratio of ~ 1), that LIGO's heaviest merger so far, GW170729, could have originated from this channel.

Introduction.—The number of binary black hole (BBH) mergers detected by Advanced LIGO [1] and Advanced Virgo [2] is rapidly growing. More than ten mergers have been discovered during LIGO/Virgo's first two observing runs [3,4], and many more are expected in the current third observing run and beyond [5].

Despite the growing number of observations, the formation mechanism of the detected BBHs is currently not understood. Favored scenarios include isolated binary evolution in which the black holes (BHs) are produced in a binary star system [6–8], and dynamical formation in which the BHs become gravitationally bound following a chance encounter in a dense stellar environment such as galactic nuclei or globular clusters [9–17].

Active galactic nuclei (AGNs) represent a unique environment that can assist and alter the evolution of BBH mergers. The nuclei of active galaxies is expected to harbor potentially tens of thousands of stellar-mass BHs that moved into the innermost parsec due to mass segregation [18–22]. Interaction with the AGN accretion disk (hereafter AGN disk) can align the orbits of these BHs with the disk [23–28]. Alternatively, some BHs can be formed in the disk itself [29,30]. Once in the disks, interaction between the

rotating gas may move the BHs to migration traps within the disk, to about 300 Schwarzschild radii from the central supermassive BH (SMBH; [26,31,32]). If multiple BHs move into the disk, they will eventually meet in the migration trap and merge. This merger will be rapid due to dynamical friction within the disk [28,33–36]. Alternatively, BBHs can also align their orbit with the disk, and merge rapidly in the disk without reaching the migration trap [28].

AGN-assisted BH mergers have distinct properties that could differentiate them from other formation channels. These include their mass distribution in which heavier BHs are expected to be overrepresented by a factor roughly proportional to their mass [37], their location in AGNs that can be differentiated from binaries formed in other types of galaxies [38,39], possible electromagnetic signatures produced due to the BHs accreting from the surrounding dense gas [28,30], or center-of-mass acceleration [40–43].

In addition, as multiple BHs align their orbits with the AGN disk and move to the migration trap, they merge and remain near the migration trap, enabling the remnant to merge with additional BHs [26]. Such hierarchical mergers will lead to distinct, high BH masses and characteristic spin

properties that can be identified via gravitational wave observations [44,45].

Here we examined the prevalence and observational signatures of hierarchical mergers in AGN disks. We carried out Monte Carlo simulations of BH orbital alignments and mergers in a population of AGNs, taking into account the possibility of hierarchical mergers during the lifetime of AGNs. We computed the resulting BH mass and spin distributions. Finally, we compare these distributions with the heaviest BH merger detected by LIGO and Virgo, GW170729 [3].

Stellar-mass black hole population.—Our simulations follow the method of Ref. [37], who semianalytically calculated the interaction between a stellar-mass BH orbiting a SMBH and the AGN disk. They carried out a Monte Carlo simulation with a parametrized power-law cusp distribution of stellar-mass BHs around SMBHs, and a realistic distribution of SMBH masses and AGN disk properties. Here we consider their result for the fiducial BH mass distribution $dN/dm_{\rm bh} \propto m_{\rm bh}^{-1}$ within the AGN disk, which they obtained for an initial mass function $dN/dm_{\rm bh} \propto m_{\rm bh}^{-2.35}$. The BHs had a thermal eccentricity distribution and isotropic directional distribution prior to alignment with the AGN disk.

Initial BH masses were limited to $[5M_\odot, 50M_\odot]$. The upper mass limit of $\sim 50M_\odot$ is due to pair-instability mass loss in stars that would otherwise produce heavier BHs [46–48].

Migration and merger time frames.—Migration traps have been proposed to develop in AGN disks in analogy with those previously invoked for protoplanetary disks (e.g., Refs. [26,31,32]). While their existence is not yet certain, if they develop they will attract BHs from within the disk over a characteristic time frame of 10^5 yr [26].

Following the calculations of Ref. [28], we find that the merger time for a $30M_\odot - 30M_\odot$ binary in a migration trap of a $10^6\ M_\odot$ SMBH accreting at $\dot{m}_\bullet = 0.1$ will be about 10^5 yr. Therefore, as the time of migration and merger for BHs are much shorter than typical orbital alignment times with the AGN disk, we neglect them in our Monte Carlo simulation discussed below.

We note that mergers may occur prior to arrival at a trap [49], which would lead to less higher-generation mergers. It is also possible that migration traps do not develop. Migration traps have been proposed to occur analogously to protoplanetary disks, coinciding with local surface density turning points, where torques on migrating compact objects vanish [26,31]. These initial estimates use a simplified disk model, e.g., excluding the impact of migrators on the local disk density. The lack of a trap would lead to less or no higher-generation mergers in AGN disks. Therefore, hierarchical BH mergers are also a test of the existence of migration traps and the merger process.

Simulation of hierarchical mergers.—For each AGN disk we generated a population of mergers. Hereafter, the merger of two BHs that each came from the initial population (presumably from stellar evolution) will be referred to as first generation, or 1g. The merger of a BH that is the remnant of a 1g merger with another BH will be referred to as a second-generation, or 2g, merger. We define 3g, 4g, etc., similarly. We only consider mergers in which at least one of the BHs is *not* the result of a previous merger. This is expected for AGN disks if single BHs move into the disk, since the migration and merger rate is much faster than the characteristic time difference between two BHs moving into the disk. One exception is when BBHs migrate into the disk, which can lead to both BHs being at least 2g. For simplicity we ignore this possibility here.

The masses and spins of the BHs formed in mergers were calculated using the surfinBH package for mass ratios $m_2/m_1 > 0.1$ [50]. For $m_2/m_1 \leq 0.1$, we used the results of Refs. [51,52] to calculate the final mass and spin, respectively. We characterized the BH's spins with the binary effective spin

$$\chi_{\rm eff} \equiv \frac{c}{GM} \left(\frac{\vec{S}_1}{m_1} + \frac{\vec{S}_2}{m_2} \right) \cdot \frac{\vec{L}}{|\vec{L}|}, \tag{1}$$

where $M = m_1 + m_2$ is the total mass of the binary, $\vec{S}_{1,2}$ are the spin angular momentum vectors of the BHs in the binary, and $\vec{L}$ is the orbital angular momentum vector. This mass-weighted sum of the spins parallel to the binary orbit is the spin parameter that is the most accurately measured with gravitational waves.

In the following we assume that all 1g BHs have zero spins. By investigating nonzero distributions, we found that our results do not depend significantly on this assumption, since the 1g spin direction is isotropically distributed and hence will have limited effect on $\chi_{\rm eff}$ (see Ref. [53]). Further, all but two of the BH mergers detected so far by LIGO/Virgo are consistent with zero BH spin (GW151226 and GW170729; Abbott *et al.* [3]). We additionally assumed that accretion does not significantly alter the BHs' spin (although see Ref. [54]). For example, an initially nonspinning BH that accretes at the Eddington rate (with efficiency $\epsilon = 0.1$) for a full fiducial AGN lifetime of 10^7 yr will reach a dimensionless spin of 0.3 [55].

We assume all binary orbital axes to be aligned with the AGN disk; therefore the spins of higher-generation BHs will be either aligned or antialigned with newly formed binaries.

In order to evaluate the fractions of each generation of mergers, we took into account that the number of BHs whose orbit is dragged into the AGN disk within the disks lifetime, taken to be $\tau_{\rm AGN} = 10^7$ yr [56], has a Poisson distribution. We assumed that BHs on orbits aligned with the AGN disk migrate to the trap in the disk. Each new BH that reaches the migration trap merges with the BH already there. We assumed that merger remnants remain in the trap
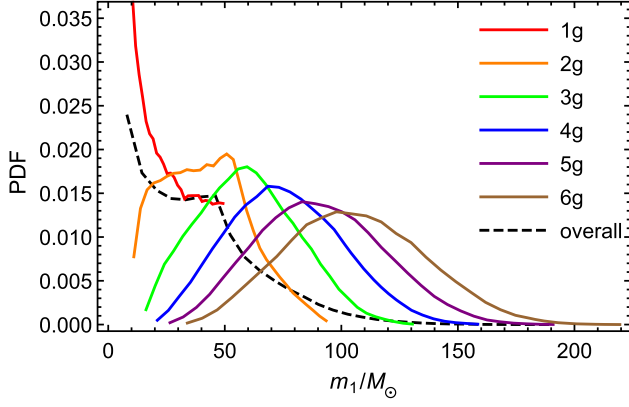
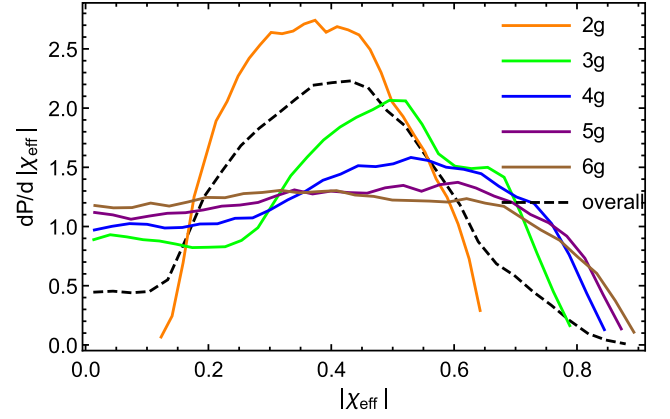FIG. 1. The distribution of m_1, we take into account the contribution from each generation of mergers.

FIG. 2. The distribution of χ_{eff} for different generations of mergers, and the overall distribution with all generations combined (see legend). For antialigned orbits χ_{eff} is negative but is otherwise distributed identically to the shown distribution.

or quickly migrate back to it before the next BH reaches the trap. This is expected to be the case as natal kicks from the merger, which are on the order of several 100 km s^{-1}, will not be able to substantially change the orbits, given typical orbital velocities of $20\,000 \text{ km s}^{-1}$. Small deviations quickly vanish due to orbital alignment.

As BHs in traps merge in sequence, the fractions of each generation are

$$P_g(n) = \frac{1}{\lambda - 1 + e^{-\lambda}} \sum_{k=n+1}^{\infty} \text{Poiss}(k, \lambda), \quad n = 1, 2, 3 \ldots \quad (2)$$

where Poiss is the Poisson distribution, and the term before the sum on the right side is a suitable normalization factor.

The expected value λ is essentially independent of the mass of the SMBH, and weakly depends on the accretion rate (see Fig. 6 in Ref. [37]). Here we adopted a fiducial accretion rate of $\dot{m} = 0.1$ onto the SMBH, with which we get $\lambda \sim 2.5$.

Fraction of hierarchical mergers.—Using Eq. (2) we found that the $\{47\%, 29\%, 15\%, 6\%, 1\%\}$ of AGN-assisted mergers are $1g, 2g, \ldots, 5g$, respectively. As each merger remnant is retained within the disk, higher-generation mergers are common. We find that the majority of mergers will be higher generation. The prevalence of higher-generation mergers has important consequences to the distribution of BH masses and spins from this channel. We discuss these below.

Mass distribution.—In Fig. 1 we show the distribution of BH masses for different generations of mergers. For $1g$ mergers, we define $m_1 > m_2$, while for ng mergers ($n > 1$), m_1 is the mass of the BH from generation n. We see that the mass distribution increases significantly for higher-generation mergers, as expected. We find that about 30% of mergers will have a BH with mass higher than the $50 M_\odot$ upper limit expected from stellar evolution [46–48]. We account for detectability with LIGO/Virgo that favors heavier BHs using an estimated detection volume as a function

of the binary's chirp mass $\mathcal{M} \equiv (m_1 m_2)^{3/5}(m_1 + m_2)^{-1/5}$. We find that 40% of the detected mergers will have $m_1 > 50 M_\odot$.

The mass distribution is virtually unaffected by whether higher-generation BH spins are aligned or antialigned with the binary orbit.

Could both black holes be higher generation?—Since the merger remnant is expected to stay close to the migration trap, and since BHs move to the trap faster than the characteristic frequency of the AGN alignment of new BHs, we expect one BH to "collect" all new incoming BHs. Therefore, one of the BHs in the binary should always be $1g$. One exception is if a previously formed binary enters the disk and merges due to dynamical friction before reaching the trap. For simplicity we do not consider this case here due to the uncertain fraction of binaries in galactic nuclei. Using numerical simulations we estimate that if 10% of the BHs in galactic nuclei reside in binaries, then in about 5% of the mergers will both BHs be higher generation.

Spin distribution.—We derived the distribution of the binaries' effective spin χ_{eff}. We show its distribution in Fig. 2 for different generations of mergers assuming that 50% of the binaries have orbital angular momentum aligned with the AGN disk, and 50% antialigned. We see the prominent peak around $\chi_{\text{eff}} \sim 0.4$. This is due to the typical mass ratio of $2g$ binaries. For an equal-mass $1g$ merger, the resulting BH has ≈ 2 times the mass of the initial BHs, and a spin of ~ 0.7 [57]. A binary of this BH and a spinless BH as massive as the original BHs has $\chi_{\text{eff}} \sim 2 \times 0.7/(2 + 1) \approx 0.45$. A similar argument can be applied to explain the two peaks in the $3g$ case in Fig. 2. Otherwise, we see that the spin distribution is broad. We find that this broad distribution is qualitatively similar for mergers with alignment and antialignment fractions other than 50% as well, with the exception that antialigned spins lead to negative χ_{eff} values [58].
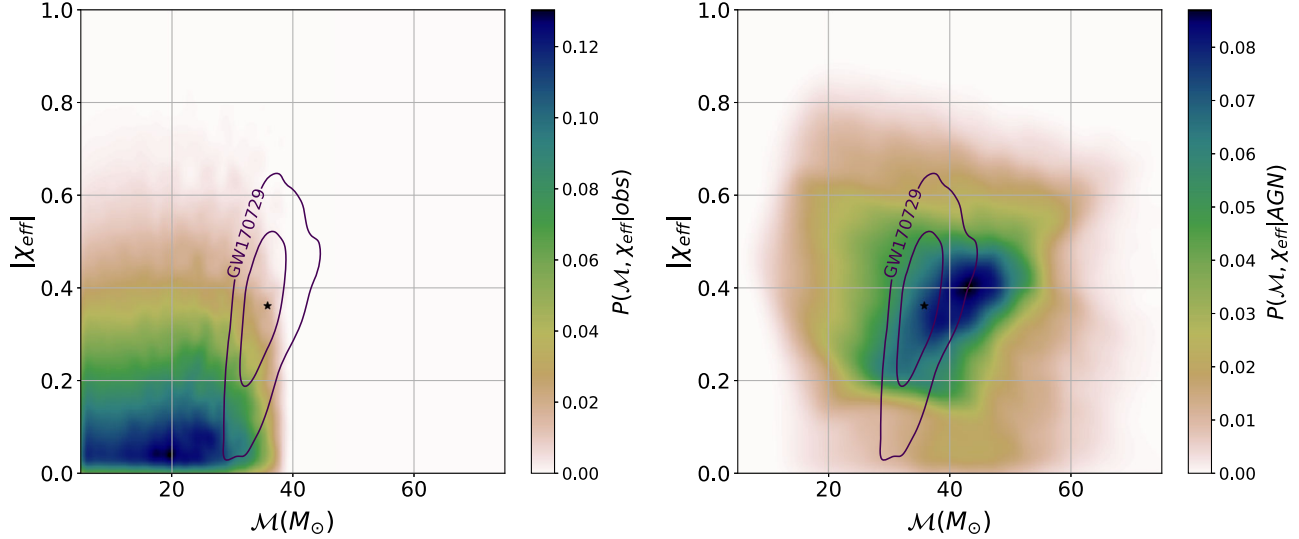
FIG. 3. 2D probability densities of the chirp mass $\mathcal{M}$ and effective spin parameter $\chi_{\rm eff}$ for BBHs detected by LIGO/Virgo. For the distributions we used the BBHs detected during LIGO/Virgo's O1 and O2 runs other than GW170729 (left) and for second- and higher-generation mergers in the AGN model presented here (right). Also shown on both sides are the reconstructed parameters of GW170729, for its most likely values, 50% and 90% confidence regions.

The case of GW170729.—The BBH merger GW170729 has the largest mass, $m_1 = 50.6^{+16.6}_{-10.2}M_\odot$, and the largest measured spin, $\chi_{\rm eff} = 0.36^{+0.21}_{-0.25}$, among all detected gravitational wave events [3], making it particularly interesting to examine as a potential candidate from the AGN channel.

To establish whether GW170729 occurred in an AGN disk, we followed the method of Ref. [59]. We compared the merger's reconstructed parameters to the model presented here as well as to the parameters of the other BBH mergers LIGO/Virgo have detected so far [3].

Reference [60] finds that the distribution of the masses of the 9 detected BBH mergers, excluding GW170729, can be approximated by a power-law distribution for the heavier mass, $m_1^{-\alpha}$ with $\alpha = 1.6$, and a BH mass range of $[5M_\odot, 45M_\odot]$, along with a uniform mass ratio distribution within $5M_\odot < m_2 < m_1$. They find that the spin distribution (excluding GW170729) is consistent with isotropic directional and approximately flat amplitude distribution within $a \in [0, 0.8]$. We adopted this model as our null hypothesis.

For the signal hypothesis we adopted the joint mass and spin distribution of our AGN model. We characterize this distribution with the binary's chirp mass $\mathcal{M}$ and effective inspiral spin $\chi_{\rm eff}$.

For both hypotheses we weight the signal- and null-hypothesis probability densities with the volume within which binary mergers with the given parameter can be detected.

Our obtained distributions for $\mathcal{M}$ and $|\chi_{\rm eff}|$ for the observed and hierarchical-AGN cases are shown in Fig. 3. We see that second or higher-generation mergers in the AGN channel generally produce similar $\mathcal{M}$ and $\chi_{\rm eff}$ as observed for GW170729. Values from the 9 LIGO/Virgo observations are typically lower. First-generation mergers

in AGNs result in comparable distribution as the LIGO/Virgo events.

Nevertheless, there is not sufficient statistical evidence to confidently determine the formation channels for this event. We calculated the Bayesian odds ratio $P(\rm{AGN}|GW170729)/P(\rm{obs.}|GW170729)$. While the parameters of GW170729 are 5 times more likely to arise from our hierarchical-AGN distribution than from that of the null hypothesis, taking into account a prior probability ratio $P(\rm{AGN})/P(\rm{obs}/) = 0.1$–0.4 [37], we find that the odds ratio is $\sim$1. More, similar events will be needed to probe this channel with high significance. In addition, other hierarchical-merger models could also explain GW170729 than the 9 LIGO/Virgo observations [59,61], although results at this point are also inconclusive (odds ratios are $\lesssim$3).

Conclusion.—We examined the prevalence and expected mass-spin parameters of hierarchical mergers in AGN disks. Our conclusions are the following: (i) Hierarchical mergers are the norm rather than the exception in the migration traps of AGN disks, if these traps exist. As BHs accumulate in the migration trap they merge with the BHs already there, resulting in a chain of consecutive mergers. For our fiducial parameters over 50% of BH mergers are higher generation. (ii) Hierarchical mergers result in heavy BHs. In about 40% of the detected mergers, one of the BHs is heavier than $50M_\odot$. (iii) Hierarchical mergers in AGN disks will naturally lead to aligned spins with the AGN disk. This leads to aligned or antialigned spins with the binary orbit. A broad range of spins are possible from about 0.2–0.9. In particular, antialigned spins are a unique possibility in this model compared to other channels [62]. Spin alignment makes this channel observationally distinguishable from other hierarchical merger channels

[44,59,63]. (iv) Finding high-mass, nonzero spin BH mergers in AGNs will also probe the physics of orbital alignment and the development of migration traps. (v) We find that the heaviest BBH merger detected so far, GW170729, has similar $\mathcal{M}$ and χ_{eff} to those expected from second- or higher-generation mergers in AGNs (see Fig. 3). Nevertheless, there is not sufficient statistical evidence to differentiate between an AGN origin and the same channel as the other 9 events detected by LIGO/Virgo so far.

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