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LIGO tells us LINERs are not optically thick RIAFs

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ABSTRACT

Low ionization nuclear emission-line regions (LINERs) are a heterogeneous collection of up to one-third of galactic nuclei in the local Universe. It is unclear whether LINERs are simply the result of low accretion rates onto supermassive black holes (BHs) or whether they include a large number of optically thick radiatively inefficient but super-Eddington accretion flows (RIAFs). Optically thick RIAFs are typically discs of large-scale height or quasi-spherical gas flows. These should be dense enough to trap and merge a large number of the stellar mass BHs, which we expect to exist in galactic nuclei. Electromagnetic observations of photospheres of accretion flows do not allow us to break model degeneracies. However, gravitational wave observations probe the interior of accretion flows where the merger of stellar mass BHs can be greatly accelerated over the field rate. Here, we show that the upper limits on the rate of BH mergers observed with LIGO demonstrate that most LINERs cannot be optically thick RIAFs.

Key words: accretion, accretion discs – black hole physics – gravitational waves – galaxies: active – galaxies: nuclei.

1 INTRODUCTION

LIGO is revealing a population of merging stellar mass black holes (BHs) that is extremely numerous ($\sim 112\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$) at the upper end of the rate estimate (LIGO & VIRGO 2018). Merging BHs observed so far by LIGO are generally significantly more massive than those (5–15 $M_{\odot}$) observed in our own Galaxy (LIGO & VIRGO 2018). The majority of mergers observed so far have low χ_{eff}, the projected component of BH spin onto the binary orbital angular momentum. All of the above are tantalizing clues about the nature of BH mergers in our Universe. Though the overall rate and some aspects of the observed mass distribution can be accommodated by the predictions of field binary models (e.g. Belczynski et al. 2010; Dominik et al. 2013; Belczynski et al. 2016), the relatively high observed rates and masses have prompted consideration of sites where mergers may be accelerated and repeated.

Stellar mass BH density in the local Universe appears greatest in our own Galactic nucleus. The observed rate of occurrence of BH X-ray binaries implies a cusp of BHs in the central parsec (Hailey et al. 2018; Generozov et al. 2018) consistent with previous conjectures (Morris 1993; Miralda-Escudé & Gould 2000) and simulations (Antonini 2014). For a long time, it has been understood that active galactic nucleus (AGN) discs should contain a large population of embedded objects from geometric orbital coincidence and grind-down (Syer, Clarke & Rees 1991; Artymowicz 1993; Goodman & Tan 2004) as well as star formation (Levin 2007). As a result, a promising site to generate a very high rate of BH mergers yielding overmassive BHs detectable with LIGO are dense discs of gas around supermassive BHs (McKernan et al. 2012, 2014, 2018; Bellovary et al. 2016; Bartos et al. 2017; Stone et al. 2017; Secunda et al. 2018). Conversely, limits that can be placed on this channel for BH mergers will allow us to restrict otherwise poorly constrained models of AGN discs.

Low-ionization nuclear emission-line region galaxies (LINERs) were identified as a class of object by Heckman (1980). The LINERs are galactic nuclei with spectral lines that are low ionization compared to AGNs, particularly as identified by the [OIII]/Hβ line ratio (Veilleux & Osterbrock 1987; Ho, Filippenko & Sargent 2003; Kewley et al. 2006). Approximately ∼1/3 of all galactic nuclei in the local Universe can be classified as LINERs (Ho 2008), but it remains unclear what fraction of LINERs are powered by low accretion rate α-discs onto supermassive black holes (SMBH) or whether some or all are powered by radiatively inefficient accretion flows (RIAFs), sometimes also known as advection-dominated accretion flows (ADAFs, e.g. Narayan & Yi 1994; Narayan, Kato & Honma 1997; Blandford & Begelman 1999; Yuan, Quataert & Narayan 2003). RIAFs can occur in the case of both optically thin and optically thick accretion. Here, we focus on the possibility that a large fraction of LINERs might be powered by cooler, optically thick RIAFs, like slim discs (Abramowicz et al. 1988; Ohsuga et al. 2005), not optically thin, hot RIAFs such as the one that might be powering Sgr A∗ in our own Galaxy (Broderick et al. 2011). We

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note, however, that Sgr A∗ would not be detectable as a LINER at typical extragalactic distances.

If LINERs and similar objects comprise up to one-third of all galaxies (Ho 2008), and if LINERs are predominantly optically thick RIAFs, this accretion mode could be responsible for substantial mass growth of nuclear SMBH while doing so 'in the dark' – not substantially contributing to the ionizing flux of the local universe. While there are many plausible RIAF models (notably including ADAFs), they all share a characteristically large aspect ratio of their accretion flows. If LINERs are predominantly optically thick RIAFs then a large fraction of the population of stellar mass BHs that we expect in galactic nuclei will end up embedded in the RIAF. Gas torques on embedded objects can promote a very high rate of BH merger within dense accretion flows (e.g. McKernan et al. 2012). It is this characteristic of optically thick RIAFs which allows us to set limits on their frequency via LIGO measurements of the rate of stellar mass BH binary mergers.

2 RATE OF BLACK HOLE MERGERS IN DENSE, NUCLEAR, GAS DISCS

From McKernan et al. (2018), we can write the rate of BH binary mergers in dense nuclear gas discs as

$$\mathcal{R} = \frac{N_{\rm GN} N_{\rm BH} f_{\rm AGN} f_{\rm d} f_{\rm b} \epsilon}{\tau_{\rm AGN}} \quad (1)$$

where $N_{\rm GN}$ is the number density of galactic nuclei (per Mpc^{-3}), $N_{\rm BH}$ is the number of stellar mass BHs in the central pc^3 around the SMBH, $f_{\rm AGN}$ is the fraction of galactic nuclei that are active for time $\tau_{\rm AGN}$, $f_{\rm d}$ are the fraction of nuclear stellar mass BHs that end up in the AGN disc, and ϵ is the fractional change in $N_{\rm BH}$ over an AGN duty cycle. We note that this equation assumes the lifetime of a binary embedded in an AGN disc is less than $\tau_{\rm AGN}$. Binaries embedded in a gas disc should merge within 10^5 yr (Baruteau, Cuadra & Lin 2011; McKernan et al. 2018), so this is a reasonable assumption (see also Section 2.1). Of the parameters in equation (1) only $N_{\rm GN}$ is relatively well constrained from Schecter function fits (e.g. Baldry et al. 2012). The other parameters in equation (1) are not very well constrained by observations, simulations or theoretical considerations and we discuss several of them below.

If we ignore dwarf galaxies and only count galaxies of mass ≥1/3 the mass of the Milky Way, such that we count SMBH of mass $\geq 10^6 M_{\odot}$, then $N_{\rm GN} \sim 0.006\,{\rm Mpc}^{-3}$ (Baldry et al. 2012). From observations of X-ray binaries around SgrA* by Hailey et al. (2018), Generozov et al. (2018) extrapolate $N_{\rm BH} \sim 2 \times 10^4$ stellar mass BH within the central parsec of the Galaxy, which is consistent with predictions from a range of mechanisms (Miralda-Escudé & Gould 2000; Antonini 2014). The binary fraction ($f_{\rm b}$) of BHs in galactic nuclei without gas may range between ∼0.01–0.2 depending on the number density of ionizing encounters (Leigh 2018; McKernan et al. 2018). However, BH trapped by dense disc gas have a substantially higher binary fraction $f_{\rm b} \sim 0.6$ as they migrate within the disc and encounter other BH (Secunda et al. 2018). Thus, a fiducial overall binary fraction of $f_{\rm b} \sim 0.1$ within a galactic nucleus containing a gas disc, seems reasonable. The parameter $f_{\rm d}$ is the fraction of BH in the galactic nucleus that end up inside the AGN disc. To a first approximation, we can say $f_{\rm d} \geq H/r$ the disc aspect ratio. This is because geometrically, we expect the number of orbits of a nuclear star cluster to live inside the AGN disc to correspond approximately to the disc aspect ratio (H/r). If we assume that the AGN disc is cylindrical, and of thickness H/r, then $f_{\rm d} = (H/r)$. Over time BH in the galactic nucleus with orbits oriented at an angle to the AGN disc will pass through the disc twice per orbit and experience a drag force which will tend to align the BH orbit with the plane of the disc. Thus, we expect $f_{\rm d} > H/r$ over a long enough AGN lifetime.

2.1 AGN disc lifetime: $\tau_{\rm AGN}$

AGN lifetimes are poorly constrained. A complete range of lifetimes allowed by all methods and constraints spans $\approx 10^5$–10^8 yr (e.g. Martini 2004; Graham et al. 2019). The overall quasar duty cycle (or the total amount of time spent by a galactic nucleus as a quasar) is believed to be $O(10^8)$yr since $f_{\rm AGN} \sim 0.01$ for quasars, and this estimate is consistent with several modes of estimating average quasar lifetimes (Martini 2004). Mass doubling of SMBH via Eddington accretion occurs in ∼40 Myr, so a total period of O(10^8)yr allows for approximately an order of magnitude increase in $M_{\rm SMBH}$ due to gas accretion in a Hubble time. However, this estimate of the duty cycle *does not* constrain the lifetime of individual quasar episodes (i.e. $\tau_{\rm AGN}$). Furthermore, this estimate ignores more numerous, less luminous AGN phases such as the Seyfert AGN or LINERs.

Individual AGN episodes could be quite short in practice. For example, an accretion disc of mass $10^{-2} M_{\rm SMBH}$ will be consumed in only ∼ few Myrs at the Eddington rate. Stochastic accretion episodes are expected to arrive from random directions in the galactic bulge yielding $\tau_{\rm AGN} \sim 10^{5-6}$yr (e.g. King & Nixon 2015). Observations of large samples of AGN over relatively long-time baselines enable estimates of the turn-on/turn-off rate, which do help constrain $\tau_{\rm AGN} > 10^5$ yr (since Graham et al. 2019, find O(1 in 10^5)AGN change state each year). However, such short-lived episodes may run together if there is a large fuel source (a dusty torus) subject to instabilities near an SMBH. The running together of short-lived accretion episodes, may account for the duration of long-lived Mpc-scale radio jets. If AGN discs are not to collapse in a burst of star formation under their own self-gravity beyond about $\sim 10^3 r_{\rm g}$, where $r_{\rm g} = GM_{\rm SMBH}/c^2$, some additional source of heating of the outer disc is required (e.g. Sirko & Goodman 2003). If no such heating were available, the innermost disc would be a mere $\sim 10^3 r_{\rm g}$ in size, a size estimate contradicted by numerous lines of observational evidence, including the Spectral Energy Distribution (e.g. Sirko & Goodman 2003), reverberation mapping (e.g. Yu et al. 2018), and maser mapping (e.g. Zhao et al. 2018). The viscous time-scale at a given radius (t_ν) can be parametrized as (Stern et al. 2018)

$$t_\nu \approx 10^4 {\rm yr} \left(\frac{H/r}{0.04}\right)^{-2} \left(\frac{\alpha}{0.03}\right)^{-1} \left(\frac{M_{\rm SMBH}}{10^8 M_{\odot}}\right) \left(\frac{R}{10^3 r_{\rm g}}\right)^{3/2} \quad (2)$$

where α is the disc viscosity parameter and a truncated AGN disc is short lived. Such very short time-scales for individual AGN episodes may be consistent with the O(10^5yr) duration of the response of circumgalactic medium to past quasar episodes (Schawinski et al. 2015). However, if additional heating stabilizes the outer disc to $\sim 10^5 r_{\rm g} \sim 1$ pc then $t_\nu \approx 10$ Myr, though shorter lifetimes are possible for modestly larger α and H/r. Additionally, a series of closely spaced, short-lived episodes of activity, followed by a longer, fully quiescent period may be dynamically indistinguishable from a single, modest-length, continuous period of activity – as long as the brief quiescent periods are short compared to the dynamical relaxation time of the nuclear star cluster (O(100 Myr)).

In summary, there are many theoretical reasons to expect both short- and long-lived AGN disc. The observational constraints may conflict, and are challenging to obtain. Quite possibly the AGN phenomenon intrinsically spans a wide range of disc lifetimes. Thus, an alternative method for constraining AGN disc lifetimes would be an important contribution to our understanding of the phenomenon.

2.2 AGN disc aspect ratio: *H*/*r*

AGN disc thickness as a function of radius is given by $H = c_s/\Omega$ where c_s is the sound speed in the disc gas at that radius and $\Omega = (GM_{\rm SMBH}/r^3)^{1/2}$ is the Keplerian orbital frequency. Writing r in terms of the gravitational radius of the SMBH, $r_g = GM_{\rm SMBH}/c^2$ we can write

$$\frac{H}{r} \sim \left(\frac{c_s}{c}\right)\left(\frac{r}{r_g}\right)^{1/2} \quad (3)$$

so the AGN disc aspect ratio simply depends on the ratio (c_s/c) in the gas. The sound speed in gas is given by $c_s^2 = P_{\rm total}/\rho$ where $P_{\rm total} = P_{\rm gas} + P_{\rm rad} + P_{\rm mag}$ is the total pressure in the gas of density ρ at that radius and

$$P_{\rm gas} = \frac{\rho k_B T}{m_H} \quad (4)$$

$$P_{\rm rad} = \left(\frac{\tau}{c}\right)\sigma T_{\rm eff}^4 \quad (5)$$

$$P_{\rm mag} = \frac{B^2}{2\mu_0} \quad (6)$$

where T is the mid-plane temperature, $T_{\rm eff}$ is the effective temperature of the disc photosphere, τ is the optical depth from the mid-plane to the photosphere, B is the magnetic field strength, and the constants have the usual meanings. A standard thin disc model has a disc mid-plane temperature profile which goes as $T(r) = T_{\rm ISCO} r^{-3/4}$ where $T_{\rm ISCO}$ is the temperature at the innermost stable circular orbit (ISCO). Thus, close to the ISCO, and H/r is large. However, at distances $\sim 10^3 r_g$ from the ISCO, where the disc is cool and dense and therefore c_s is small, the disc aspect ratio tends to be small $H/r \sim 10^{-2}$ and 10^{-3} (Sirko & Goodman 2003; Thompson, Quataert & Murray 2005). At very large distances, H/r can increase again.

However, a $r^{-3/4}$ dependence of the disc temperature profile assumes no irradiation of the outer disc and ignores the impact on the disc of multiple embedded objects. These embedded objects will each accrete, migrate, and collide, which will contribute significant local disc heating at large radii. Localized disc heating will tend to smear out into annuli over an orbital time. Disc-crossing orbiters will also contribute significant disc heating as they pass through the disc. Thus, allowing for a population of embedded and disc-crossing objects is likely to increase H/r significantly over the gas-only radial temperature profile (McKernan et al. 2012, 2014).

The above discussion applies to accretion discs which are relatively thin due to the efficiency of radiative cooling. In a disc where the photon diffusion time-scale (t_γ) is less than t_ν, the viscous (accretion) time-scale, the disc becomes an RIAF and can be geometrically very thick ($H/r \sim 0.1$–1) (e.g. Narayan & Yi 1994; Narayan et al. 1997; Blandford & Begelman 1999; Yuan et al. 2003).

2.3 Black hole mergers over an AGN duty cycle

The parameter ϵ in equation (1) is a way of estimating the overall change in BH number in a galactic nucleus over a full AGN cycle. If the AGN lasts for some time $(\tau_{\rm AGN})$ and the quiescent period before the next AGN episode is $t_Q \gg \tau_{AGN}$ then the effective AGN duty cycle is $f_{\rm AGN} = \tau_{\rm AGN}/(\tau_{\rm AGN} + t_Q)$. We can write ϵ as the number of BH after one AGN duty cycle divided by the initial number of BH, or

$$\epsilon = \frac{N_{\rm BH}(\tau_{\rm AGN} + t_Q)}{N_{\rm BH}(0)} \quad (7)$$

which can be written as

$$\epsilon = 1 - \frac{\tau_{\rm AGN}\mathcal{R}_{\rm AGN}}{N_{\rm BH}(0)} + \frac{(\tau_{\rm AGN} + t_Q)\dot{N}_{\rm BH}}{N_{\rm BH}(0)} \quad (8)$$

where $\mathcal{R}_{\rm AGN}$ is the mean rate of BH merger per AGN. The quantity $\dot{N}_{\rm BH} = N_{\rm BH}^+ - N_{\rm BH}^-$ corresponds to the number of BH $(N_{\rm BH}^+)$ that have entered the central pc^{-3}, via star formation and dynamical friction over the AGN duty cycle, minus the number of BH $(N_{\rm BH}^-)$ that have left the central pc^{-3} over the same time, via scattering or orbital evolution via energy equipartition. The parameter $\epsilon \geq 1$ if

$$\dot{N}_{\rm BH} \geq f_{\rm AGN}\mathcal{R}_{\rm AGN}. \quad (9)$$

Given that $N_{\rm GN} \sim 6 \times 10^{-3}\,{\rm Mpc}^{-3}$ and $\mathcal{R} < 112\,{\rm Gpc}^{-3}\,{\rm yr}^{-1}$ then $\mathcal{R}_{\rm AGN} \leq 20\,{\rm Myr}^{-1}/f_{\rm AGN}$. So, for $\epsilon \geq 1$, we require $\dot{N}_{\rm BH} \geq 20\,{\rm Myr}^{-1}$ which seems a modest and plausible requirement given the star formation rates inferred from observations (Hopkins 2010) and dynamical friction estimates (Morris 1993; Antonini 2012). So, at a minimum we can expect $\epsilon \sim 1$.

2.4 Merger rate as a constraint on disc models

Based on the preceding arguments we can parametrize the rate of binary BH mergers in AGN as

$$\mathcal{R} \approx 1.2 \times 10^4 {\rm Gpc}^3\,{\rm yr}^{-1} f_{\rm AGN} f_d \times \left(\frac{N_{\rm GN}}{0.006\,{\rm Mpc}^{-3}}\right)\left(\frac{N_{\rm BH}}{2\times 10^4}\right)\left(\frac{f_b}{0.1}\right)\left(\frac{\tau_{\rm AGN}}{1{\rm Myr}}\right)^{-1}\left(\frac{\epsilon}{1}\right). \quad (10)$$

LIGO & VIRGO (2018) find before O3 that the rate of binary BH mergers in the local Universe is $53.2^{+58.5}_{-28.8}$ at 90 per cent confidence. We can immediately see that the rate in equation (10) could be orders of magnitude too large, even if AGN discs are the *only* site of LIGO-detected sBBH mergers. The problem becomes worse if we include the likely possibility that there exist other channels (including field binaries) contributing to the observed rate. Now we can vary the parameters $f_{\rm AGN}$ and $f_d \propto (H/r)$ over a range of possible $\tau_{\rm AGN}$ in order to quantify the constraints on AGN model parameters set by the LIGO rate measurements.

3 RESULTS

By assuming that all LINERs are dense, optically thick RIAFs, we can immediately assume $f_{\rm AGN} \sim 0.3$ in equation (10) above. Implicitly, we can also assume $H/r > 0.1$, possibly as large as a quasi-spherical $H/r \sim 1$ (Abramowicz et al. 1988). We can also assume that the same analysis that applies to regular, dense AGN discs (McKernan et al. 2012, 2014) must also apply to LINERs. That is, we can expect efficient orbital grind-down, migration, and merger due to gas torques on embedded stellar mass BH.

Fig. 1 shows f_d versus $\tau_{\rm AGN}$ using equation (10) and the above assumptions. The diagonal lines on the plot correspond to the upper ($112\,{\rm Gpc}^{-3}\,{\rm yr}^{-1}$) and lower bounds ($24\,{\rm Gpc}^{-3}\,{\rm yr}^{-1}$) respectively, on the rate of BH mergers from (LIGO & VIRGO 2018). So all AGN/LINERs must live in the space below the upper diagonal line. The colour key on the right-hand side (RHS) corresponds to the magnitude of the rate ($\mathcal{R}$) of BH mergers.

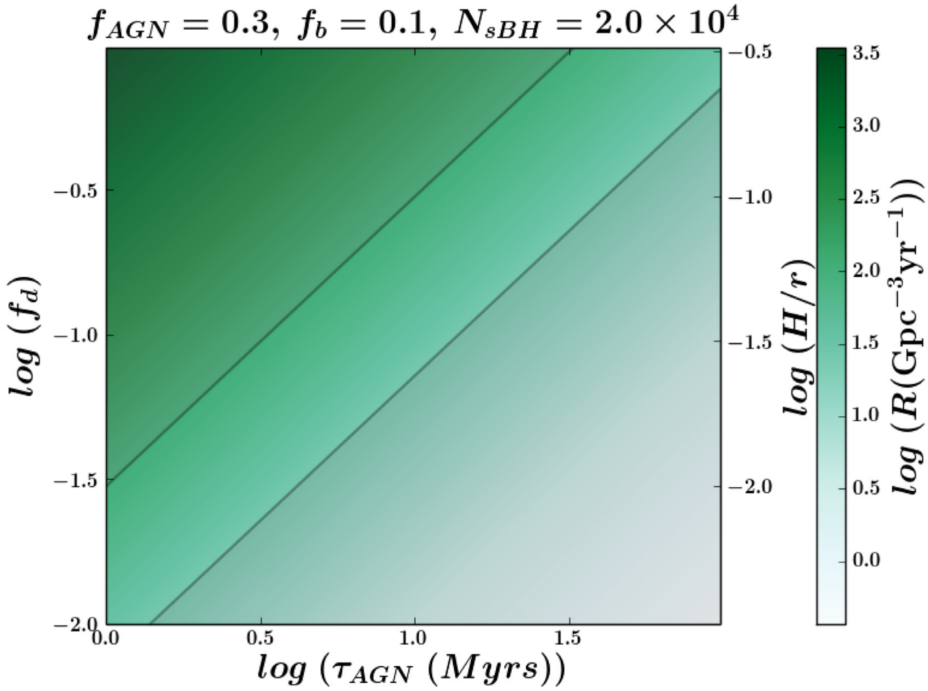

Figure 1. Fraction of nuclear stellar mass BHs embedded in an AGN disc ($f_{\rm d}$) versus the AGN disc lifetime. Using equation (10), if we assume that all LINERs consist of dense, dim, optically thick, large aspect ratio (*H*/*r*) RIAFs, then $f_{\rm AGN} \sim 0.3$. We assume the binary fraction in the disc is $f_{\rm b} = 0.1$, the number of stellar mass BHs in galactic nuclei is $N_{\rm BH} = 2 \times 10^4$, and ϵ, a measure of the net change in the number of stellar mass BHs per galactic nucleus over an AGN duty cycle is 1 (see the text). Diagonal lines correspond to the upper (112 Gpc^{-3} yr^{-1}) and lower bounds (24 Gpc^{-3} yr^{-1}) respectively, on the rate of BH mergers from LIGO & VIRGO (2018). All LINERs must live in the space below the upper diagonal line. The colour key on the RHS corresponds to the magnitude of the rate ($\mathcal{R}$) of BH mergers.

The important point from Fig. 1 is that we must live in a Universe below the upper diagonal line. If AGN are responsible for *all* LIGO detected mergers, we may, at most, lie *on* the line. If on the other hand, AGN are responsible for only a fraction of LIGO detected mergers, we must lie somewhere below the diagonal line, possibly substantially below it. Even with the current rate measurements, we must exclude the possibility of LINERs typically hosting 'fat', dense accretion flows, unless those flows persist for lifetimes >5 Myr. However, if LINERs were to persist for such long lifetimes and account for ~1/3 of all galactic nuclei, the resulting (super-Eddington) rate of BH growth (Abramowicz et al. 1988; Ohsuga et al. 2005) in these systems would quickly exceed the measurements of total local SMBH mass. Therefore, we conclude that LIGO limits on the rate of BH mergers rules out the possibility that LINERs consist mostly of cool, optically thick accretion flows. We note that we cannot exclude the possibility that a small subset of LINERs do host cool, optically thick RIAFs. We note that the values we have chosen for $f_{\rm b}$ and $N_{\rm BH}$, while reasonable, could have values other than those specified. However, given other constraints ($f_{\rm AGN} = 0.3$ and $\tau_{\rm AGN} < 5$ Myr), our conclusions apply as long as the product $f_{\rm b} N_{\rm BH} \geq 350$.

This same strategy can be employed to constrain many difficult to measure parameters of AGNs. These constraints become even more stringent if we can independently measure the AGN contribution to the LIGO rate. This may be possible in LIGO O3 by studying the distribution of BH merger mass ratios and the $\chi_{\rm eff}$ distribution of the merging BHs (Fishbach, Holz & Farr 2017; Gerosa & Berti 2017; McKernan et al. 2019). However, in the next few years, with planned upgrades yielding BBH merger detection rates as high as O(10^3 yr^{-1}), we will definitely be able to independently constrain the fractional AGN contribution to the measured LIGO rate. This relies on a statistical strategy first proposed by Bartos et al. (2017); for AGN fractional contributions >0.3, given typical space densities of AGN, we can measure their contribution simply by measuring the number of AGN per LIGO error volume, and comparing that to the expected space density. If AGN are the source of at least 30 per cent of LIGO mergers, an excess of AGN will be detectable with fewer than 1000 detected mergers, assuming typical sky localization and no improvements to current AGN catalogues.

4 CONCLUSIONS

The upper bound to the rate of BH binary mergers observed by LIGO (~ 112 Gpc^{-3} yr^{-1}) tells us that LINERs are mostly not cool, optically thick RIAFs or slim discs, with super-Eddington accretion. [1] Instead, LINERs must be predominantly powered by low accretion rate α discs, or optically thin RIAFs or some combination thereof. Future improvements in the precision of the measured rate will enable us to provide further constraints on various parameters of AGN discs; independent measurements of the AGN contribution to the sBBH merger rate, and the characteristics of those mergers (e.g. Fishbach et al. 2017; Gerosa & Berti 2017; Bartos et al. 2017; McKernan et al. 2019) will further constrain disc models.

[1]Our conclusion also rests on the assumption that some BBH mergers occur in AGN discs – though given the expected overabundance of stellar mass BHs in galactic nuclei, the absence of such mergers would seem nearly pathological. This assumption is further supported by recent work concluding that at least one LIGO detected merger did occur in a galactic nucleus or AGN disc (Gerosa & Berti 2019; Yang et al. 2019).

Importantly, this technique has the capacity to observationally constrain AGN disc lifetimes – a quantity that is otherwise extremely challenging to measure. Finally, we note this is a clear demonstration of the power of gravitational wave astronomy to open new and unexpected astrophysical windows.

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REFERENCES

Abramowicz M. A., Czerny B., Lasota J. P., Szuszkiewicz E., 1988, ApJ, 332, 646
Antonini F., 2014, ApJ, 794, 106
Antonini F., Merritt D., 2012, ApJ, 745, 83
Artymowicz P., 1993, ApJ, 409, 592
Baldry I. K. et al., 2012, MNRAS, 421, 621
Bartos I. et al., 2017, ApJ, 835, 165
Bartos I., Haiman Z., Marka Z., Metzger B. D., Stone N. C., Marka S., 2017, Nat. Commun., 8, 831
Baruteau C., Cuadra J., Lin D. N. C., 2011, ApJ, 726, 28
Belczynski K., Dominik M., Bulik T., O'Shaughnessy R., Fryer C., Holz D. E., 2010, ApJ, 715, L138
Belczynski K., Holz D. E., Bulik T., O'Shaughnessy R., 2016, Nature, 534, 512
Bellovary J. et al., 2016, ApJ, 819, L17
Blandford R. D., Begelman M. C., 1999, MNRAS, 303, L1
Broderick A. E., Fish V. L., Doeleman S. S., Loeb A., 2011, ApJ, 735, 110
Dominik M. et al., 2013, ApJ, 779, 72
Fishbach M., Holz D. E., Farr B., 2017, ApJ, 840, L24
Generozov A., Stone N. C., Metzger B. D., Ostriker J. P., 2018, MNRAS, 478, 4030
Gerosa D., Berti E., 2017, Phys. Rev. D, 95, 124046
Gerosa D., Berti E., 2019, Phys. Rev. D, 100, 041301
Goodman J., Tan J. C., 2004, ApJ, 608, 108
Graham M. J. et al., 2019, MNRAS , preprint(arXiv:1905.02262)
Hailey C. J. et al., 2018, Nature, 556, 70
Heckman T. M., 1980, A&A, 87, 152
Hopkins P. F. et al., 2010, MNRAS, 402, 1693
Ho L. C., 2008, ARA&A, 46, 475
Ho L. C., Filippenko A. V., Sargent W., 2003, ApJ, 583, 159
Kewley L. J., Groves B., Kauffmann G., Heckman T. M., 2006, MNRAS, 372, 961
King A., Nixon C. J., 2015, MNRAS, 453, L46
Leigh N. W. C. et al., 2018, MNRAS, 474, 5672
Levin Y., 2007, MNRAS, 374, 575L
LIGO, VIRGO Scientific Collaborations, 2018, ApJ , preprint(arXiv:1811.12940)
Martini P., 2004, in Ho L. C., ed, Coevolution of Black Holes and Galaxies, Carnegie Observatories Astrophysics Series, p. 169
McKernan B. et al., 2012, MNRAS, 425, 460
McKernan B. et al., 2014, MNRAS, 441, 900
McKernan B. et al., 2018, ApJ, 866, 66
McKernan B., Ford K. E. S., O'Shaughnessy R., Wysocki D., 2019, MNRAS , preprint (arXiv:eprint)
Miralda-Escudé J., Gould A., 2000, ApJ, 545, 847
Morris M., 1993, ApJ, 408, 496
Narayan R., Yi I., 1994, ApJ, 428, L13
Narayan R., Kato S., Honma F., 1997, ApJ, 476, 49
Ohsuga K., Mori M., Nakamoto T., Mineshige S., 2005, ApJ, 628, 368
Schawinski K. et al., 2015, ApJ, 451, 2517
Secunda A. et al., 2018, ApJ, 878, 85
Sirko E., Goodman J., 2003, MNRAS, 341, 501
Stern D. et al., 2018, ApJ, 864, 27
Stone N. C. et al., 2017, ApJ, 464, 946
Syer D., Clarke C., Rees M. J., 1991, MNRAS, 250, 505
Thompson T., Quataert E., Murray N., 2005, ApJ, 630, 167
Veilleux S., Osterbrock D. E., 1987, ApJS, 63, 295
Yang Y. et al., 2019, Phys. Rev. Lett ., preprint(arXiv:1906.09281)
Yu Z. et al., 2018, ApJ , preprint(arXiv:1811.03638)
Yuan F., Quataert E., Narayan R., 2003, ApJ, 598, 301
Zhao W. et al., 2018, ApJ, 854, 124

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