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SUPERMASSIVE BLACK HOLE GROWTH AND GRAVITATIONAL WAVE RADIATION

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Abstract. Supermassive black holes (SMBH) with masses $10^6 - 10^{10} M_\odot$ exist at the centres of all massive galaxies (both late and early type). They form through mergers and gas accretion very early. Mostly at redshift z $\sim$ 2 - 3. But some of them form short after the formation of the first galaxies as early as z $\sim$ 7. The time available for their formation is so short that we still do not know about the properties of the seed black holes from which SMBH forms. Two competing theories are: formation from the mergers of POP III remnants, $\sim 10^2 - 10^3 M_\odot$ BHs, or, formation of the massive BHs directly collapsed from the gas cloud into $\sim 10^4 - 10^5 M_\odot$ BHs. Both theories assume gas accretion episodes between and after BH mergers. While POP III seeds model struggles to find mechanism behind the necessary super Eddington accretion, collapse model has a problem with explaining accretion at Eddington ratio for hundreds of millions of years. Since merger histories of black holes in these two models are very different, gravitational wave radiation from BHs mergers will be a powerful method for distinguishing between these two SMBH formation models. Here we review the latest results from the works on both theories and the results on the gravitational wave radiation from BH mergers expected to be detected by Laser Interferometer Space Antenna (LISA).

1. INTRODUCTION

The subject of supermassive black hole (SMBH) growth has been very controversial and the proposed scenarios are many. Two of them stand out and they have been the most popular ones for the last two decades. However, even the most popular models face a lot of problems. That is why Laser Interferometer Space Antenna (LISA, www.lisamission.org) will be crucial to distinguish between these growth models.

1. 1. SMBH GROWTH SCENARIOS

Figure 1 is taken from Smith & Bromm 2019, and it shows two most popular competing scenarios, SMBH grows from stellar remnant black holes, or through the direct collapse of the gas cloud into a supermassive black hole. Another popular model is runaway mergers in stellar cluster but this can be viewed as a subclass of the direct collapse model, where instead of collapsing entire gas cloud into a supermassive star, it fragments first, and then stars merge to form a supermassive star. So what are these scenarios competing for?

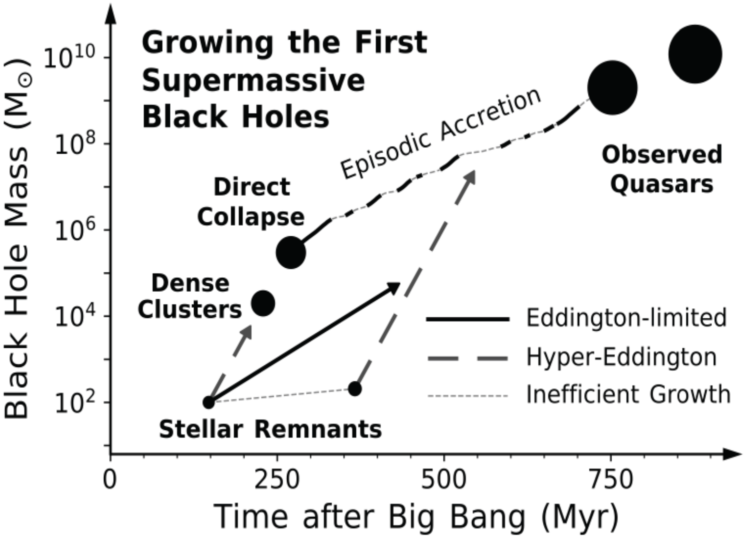

Figure 1: Black hole mass as a function of time after Big Bang. Plot shows three black hole growth models. Stellar remnant model where black holes grow through episodes of Hyper Eddington and Eddington limited gas accretion; Direct collapse model where black hole grows through episodes of Eddington limited gas accretion; and runaway mergers in stellar clusters. Taken from Smith & Bromm 2019.

They are competing to explain how to form a billion $M_\odot$ black hole at redshift z=7. This is so early in the formation of the Universe that special conditions are required no matter which growth scenario is considered. In essence, there is simply not enough time for black hole to grow. If we assume Eddington limited accretion (accretion at the rate of Eddington ratio of 1), then it would take hundreds of millions of years to sustain this kind of accretion to reach supermassive range for black holes. This is unlikely, considering the violent environment of the first galaxies. If we assume so called super-Eddington accretion with Eddington ratio between 1 and 10, then the amount of time necessary for a black hole to accrete, reduces. And even more in the case of hyper-Eddington accretion at Eddington ratio larger than 10, for which we do not know how realistic it is.

1. 2. STELLAR REMNANT BLACK HOLES SCENARIO (SRBH)

The most popular model ten years ago, for the formation of supermassive black holes was from the black hole seeds formed from the first stars. These black holes are remnants of Population III stars (Bromm & Yoshida 2011, Heger & Woosley 2002) which form at very high redshift, as high as redshift z = [20, 30]. Population III stars form from metal free gas clouds which cool and fragment through molecular hydrogen lines. This process of cooling is not efficient, so first stars form very massive (hundreds of solar masses). And being so massive they live only couple of millions of years. Their remnants are 10 - 100 $M_\odot$ black holes. But since they form in low density environments of mini halos, they can not accrete efficiently.

As halos merge, these first black holes sink to the centres of gas rich atomic cooling halos (ACHs), where they can, in one of the models, accrete gas in numerous episodes with greater than 3 - 4 Eddington ratio gas accretion, combined with BH mergers. Smole et al. 2015 posed a question if we go through dark matter halo merger trees in the early Universe, what would be the required accretion rate, on average, for the first black holes to grow to supermassive values. They did not impose condition that accretion rate has to be alway the same in every episode. Accretion can be at the Eddington limit or even hyper-Eddington, but the important accretion rate is the average one over all accretion episodes that a particular black hole goes through. And it turned out that one does not have to go to hyper-Eddington accretion values, but that a more moderate rate of just 3 to 4 times above Eddington limit should be enough. In some other models, Inayoshi et al. 2016 found that in a very special set of circumstances, for example, if gas around the black hole is very dense, then black holes can accrete rapidly, in one go, with Eddington ratio larger than 10.

1. 3. DIRECT COLLAPSE BLACK HOLES (DCBH)

Second scenario (model) is direct collapse black holes which form in gas rich high redshift galaxies. Assuming that gas does not cool efficiently, it will collapse into supermassive star, which then collapses into a massive black hole with $\sim$ 100,000 $M_{\odot}$. There is plenty of work on this subject since direct collapse model is the one community is betting on (Begelman et al. 2006, Dijkstra et al. 2008, Regan & Haehnelt 2009, Choi et al. 2013, Agarwal et al. 2012, Visbal et al. 2015, Regan et al. 2017). And since thats the case we will discuss this model in more detail.

The large amount of work in the field is focused on showing, in both large and small scale simulations, that a very special set of circumstances for the formation of supermassive black hole can be achieved. These are exactly the opposite conditions from those required in stellar remnant model. Here the idea is to prevent gas fragmentation. One of the necessary mechanisms is Lyman Werner radiation from the first stars required to destroy molecular hydrogen, or this can be done through collisional dissociation. Another requirement which helps setting up the environment is keeping the gas worm. This can be achieved if dark matter halo mergers are so frequent, that gas is constantly stirred and cooling interrupted.

If all of the mentioned mechanisms work, then a massive halo with gas at around 8000K and no molecular hydrogen would form. Next step would be to inefficiently cool the gas cloud through Lyman Alpa radiation, while avoiding fragmentation, until the gas becomes optically thick gas. Optically thick gas cloud constitutes a protostar. Newly formed protostar continues to accrete the gas rapidly, ignites nuclear reactions, and if it avoids UV feedback, it becomes a supermassive star. Soon enough, supermassive star collapses to form a supermassive black hole.

1. 4. PROBLEMS IN BOTH MODELS

The goal in both scenarios is to produce black holes massive enough so that the rest of their growth can be achieved via Eddington limited gas accretion.

However, many problems arise in both models. First problem in the case of stellar remnant black holes model is gravitational wave recoil (Campanelli et al. 2007). As these black holes form with similar masses, if they merge, then the recoil that follows would eject the new black hole from its host halo (Micic et al. 2011). Masses of the

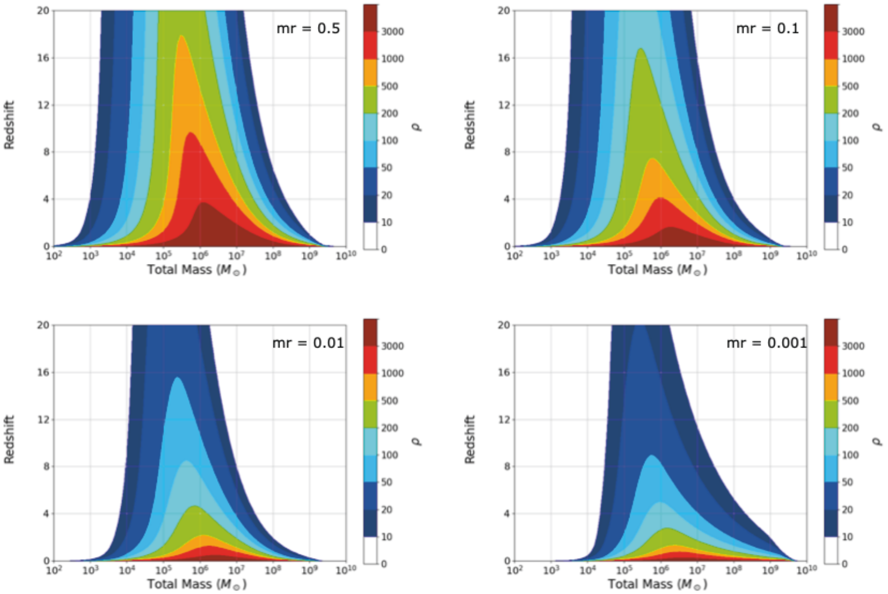

Figure 2: Redshift of the black hole merger as a function of combined mass of merging black holes. Four waterfall panels show signal to noise map for black hole mergers for four mass ratios of merging black holes [0.5, 0.1, 0.01, 0.001). Code available at https://github.com/mikekatz04/BOWIE

first black holes would be similar because they form in a vary narrow mass range with not a lot of gas to accrete. They merge in small mass halos with small gravitational potential which means low escape velocity.

Second problem is that atomic cooling halos with pristine gas are rare at high redshift (Chon et al. 2016). Next is the photo-heating feedback (Pacucci et al. 2015) which must be avoided in order to achieve hyper Eddington accretion. Simulations show that this is possible but we don't know how realistic this is.

At the end there is a question of how long the hyper Eddington accretion can be maintained in the violent environment of the first galaxies. For the direct collapse black hole model, a very specific set of conditions is required. As already mentioned in the previous section, it is very hard to prevent cooling because of the presence of molecular hydrogen, metals and dust.

Whatever the outcome is going to be in the future research, these two models should lead to the SMBH formation by redshift z = [6 - 7], so the merger history that follows at low redshift should be similar. But before SMBH formation, at high redshift, BH merger histories in these models should be quite different.

While in stellar remnant model we expect to see plenty of high mass ratio mergers of 100 to 10,000 $M_\odot$ black holes, in the direct collapse model, these mergers would be rare, or none, since we build SMBH in one go.

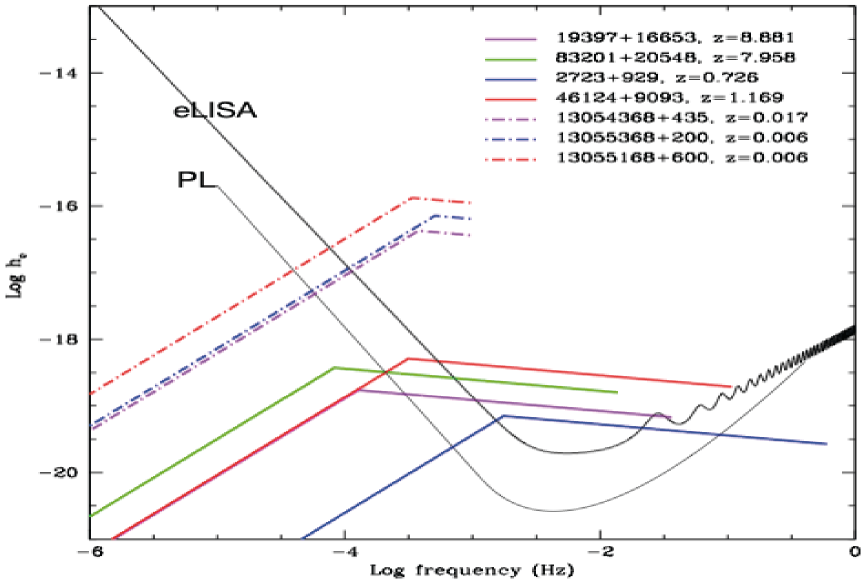

Figure 3: Characteristic strain as a function of observed frequency. Inspiral and coalescence for four high redshift mergers presented with thick lines, and for three low redshift EMRI's presented with dashed lines. Label shows masses of the merging black holes and the merger redshift. Overplotted are sensitivity curves for eLISA and for proposed LISA (PL).

2. OBSERVATIONS WITH LISA

This is where LISA will be crucial, since these are exactly types of mergers that LISA will be able to observe.

LISA will trail Earth's orbit by 50 million km. The original arm length was suppose to be 5 million km, later eLISA was proposed with arm length of 1 million km, and eventually, 2.5 million km was approved in 2017. Longer arm length is preferable since strength of the signal is directly proportional: $h_c = \Delta L / L$, where h_c is the characteristic strain amplitude, ΔL is the arm length, and L is distance from Earth to LISA.

LISA will measure change in the arm length caused by the passage of gravitational wave radiation. One can think of this value as the strength of the received signal which is called characteristic strain. Most important thing here to remember is that LISA will be perfect for the detection of black hole mergers.

Figure 2 shows signal to noise ratio map for the proposed LISA. Redshift of the black hole merger is on the y-axis, and the combined mass of the merging black holes on x-axis. This plot is called waterfall plot and we decided to focus on the waterfall plots for the proposed LISA only. For classic LISA this waterfall would be a little bit wider, while for eLISA it would be a little bit narrower. We used BOWIE package (Katz & Larson 2019) to produce it. The entire package can be cloned at the github (https://github.com/mikekatz04/BOWIE).

The top left of Figure 2 shows signal to noise ratio map for black hole mergers with mass ratio of 0.5. As we decrease the mass ratio of merging black holes, signal to noise reduces. Top right in the Figure 2 shows waterfall plot for mass ratio of 0.1. Bottom left for mass ratio 0.01, and bottom right for mass ratio of 10^{-3}. One can notice that as mass ratio of merging black holes decreases, so does the signal to noise ratio. As the result, LISA will preferably see high mass ratio mergers. The important note to take is that LISA sweet spot is for SMBHs between 10^6 and 10^7 $M_\odot$.

3. REALISTIC BLACK HOLE MERGERS

What happens when we look at the real bh mergers in cosmological simulations? Where do we expect black hole mergers to place themselves in our waterfall plots?

When we look at the merger history of massive elliptical galaxies or even clusters of galaxies, there are numerous SMBHs with a large number of mergers in their history. But if we consider spiral galaxies in the field, then we are looking at the low density regions of the Universe where mergers are sparse. This further means that once a spiral galaxy in the field, and its SMBH, are formed, there are no more major mergers.

As the result, in the case of the direct collapse model, SMBH is directly created. Its mass is $\sim 10^5$ - 10^6 $M_\odot$ and it can continue growing through gas accretion if there is gas in its vicinity. This kind of bh will have a number of extreme mass ratio mergers at lower redshifts. While in the case of the stellar remnant model, black hole first goes through episodes of high mass ratio bh mergers followed by gas accretion. Sure, once SMBH is formed, it also will have low redshift extreme mass ratio mergers similar to the direct collapse model. This is exactly what merger trees extracted from cosmological simulations show.

Figure 3 shows extracted bh mergers visible by LISA, from the merger tree of a galaxy similar to Andromeda galaxy (Holley-Bockelmann et al. 2010), for the stellar remnant model. The plot shows characteristic strain for the selected classes of resolvable black hole mergers in the simulation, as a function of observed frequency. Presented are the last days of the black hole inspiral and the merger. Overplotted are sensitivity curves for PL and eLISA. The merger redshift and pre-merger masses of the black hole binary are labeled. LISA will be able to observe all mergers with characteristic strain above the sensitivity curve.

Figure 3 distinguishes between two types of mergers. High redshift black hole mergers with mass ratios larger than 0.1 are placed in the bottom part of the sensitivity curve. These are lower mass black holes that form in stellar remnant model only. They have similar masses and their mergers are always at high redshift. The second group of mergers are the low redshift extreme mass ratio mergers in the upper part of the sensitivity curve. After SMBH has formed, disregarding the model, it is likely to merge with much smaller black holes at low redshift.

We can look at this in our waterfall plot. Figure 4 shows four waterfall panels for the four high redshift mergers from the previous figure. One can see that these are high redshift mergers with a decent signal to noise ratio between 100 and 500. Low redshift extreme mass ratio mergers are not presented since all of them are in the LISA sweet spot at 10^7 $M_\odot$ black holes at redshift zero, where signal to noise is highest.

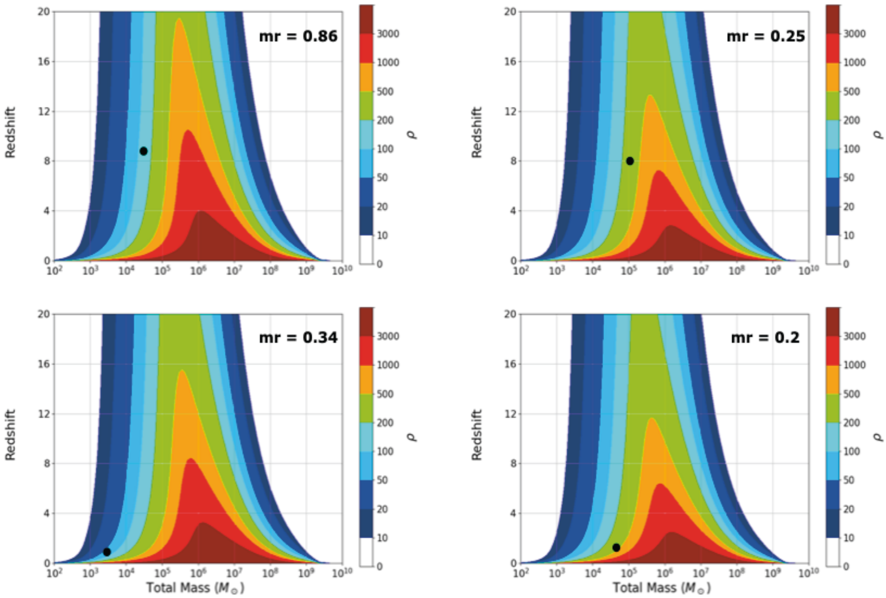

Figure 4: Waterfall panels with the same nomenclature as in Figure 2. Black dotes represent four high redshift mergers for four different mass ratios of merging black holes.

4. CONCLUSIONS

In conclusion, how do we distinguish between Stellar Remnant and Direct Collapse scenarios? Both models predict extreme mass ratio mergers at low redshift, but only stellar remnant model predicts high redshift, high mass ratio, mergers. As mentioned before and also seen in Figure 3, these two types of mergers separate in the characteristic strain plot above the LISA sensitivity curve. So LISA detecting smaller number of these, similar mass, high redshift, black hole mergers, would point toward direct collapse black hole model. However, if LISA detects a large number of mergers of similar mass black holes early in the Universe, then the stellar remnant model is likely to win.

Since LISA will not be launched any time soon (probably 20 years from now), we should already know a lot about the properties of the first stars and first galaxies from James Web Space Telescope (JWST). Although that is not going to be that easy. JWST will certainly be able to detect Population III Supernovae (Kasen et al. 2011), which should give us statistics for stellar remnant black hole model. Problem is that it is going to be hard to distinguish these supernovae from AGNs or high redshift galaxies (Hartwig et al. 2018). It should also detect black hole accretion that follows (Natarajan et al. 2017), but the problem will be distinguishing stellar from massive black holes (Valiante et al. 2018). So we will certainly learn more with JWST, but it seems that we will need LISA to disentangle SMBH growth models, and decide which one is the correct one.

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