HIGH SCHOOL EDITION
Journal of Student Research

Volume 11 Issue 1 (2022)

Probing the Properties of Supermassive Black Holes

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ABSTRACT

The formation of supermassive black holes has been highly debated the past two decades, however there is still no general description of this process. This review paper discusses differences between theories in literature on how supermassive black holes formed - such as formation from the earliest stars, primordial black hole formation, and direct collapse formation - and provides some analysis of observable data which could distinguish them. While formation from the earliest stars is one of the first theories, it is unlikely to have happened due to lack of time for the stellar black hole to accrete enough mass to become a supermassive black hole. Nevertheless, we can change this theory so that either the supermassive black hole seed was massive to begin with (direct collapse formation) or there were other black holes before stellar ones (primordial black hole formation). Recently, NANOGrav caught a signal that may have come from a primordial black hole, meaning that primordial black hole formation theory is one of the main theories right now.

Introduction

The observation of supermassive black holes (SMBH) [1] showed that some of them originated at a large redshift, meaning that they are very old. This fact makes the theories of SMBH formation extremely challenging as we will see further.

There are various theories on how SMBH could have formed. In this review paper three of the possible theories will be concentrated on (another theory not mentioned in the paper is the high energy collision theory [6]). Each of them uses its own conception of black hole (BH) formation. The first two ways are the "astrophysical" (or "stellar") formation and the "primordial" formation. The astrophysical formation is when black holes form from stellar gravitational collapse, such as a supernova [13]. The primordial formation is when the black holes form from fluctuations in the early universe and grow during the inflation epoch (these types of black holes are called primordial black holes (PBH)[7]). The inflation theory consists of a phase of accelerated expansion taking place in the early Universe, at very high energy scales, possibly as high as 1015GeV [8]. Since PBHs formed even before the cosmic microwave background radiation (CMB), as CMB would have constrained their formation [10], their existence is still being confirmed, but we can analyze the possibility of PBHs by secondary gravitational waves (GW) [12]. The third way of BH formation is from large high-redshift clouds of metal-free gas that were exposed to radiation and could avoid cooling and fragmentation, collapsing as a single SMBH seed.

All of those scenarios however have one thing in common, usually they suggest that the formed BH itself is not supermassive, but it is massive enough to turn into a SMBH through accretion of external mass. Accretion onto black holes is an efficient process in converting the gas mass-energy into energetic outputs. [4]

A weak side of some theories is that they predict an excess amount of intermediate mass black holes (IMBH) in the universe [5], which we have not observed, and there are only around 10 structures that may be IMBH [3]. There is a significant mass gap between BHs and SMBHs.

In the first section of the paper the theory that stellar BHs were the seeds for SMBHs will be discussed. The second section will focus on PBH seeds for SMBHs and the third - direct collapse BHs.

SMBHs from the earliest stars

One of the first theories is that SMBHs formed from black holes (BH) - that in turn formed from stellar gravitational collapses of the earliest stars - through accretion of matter after the Dark Ages of the universe. So the seeds of SMBHs were some of the first BHs formed from the massive stars.

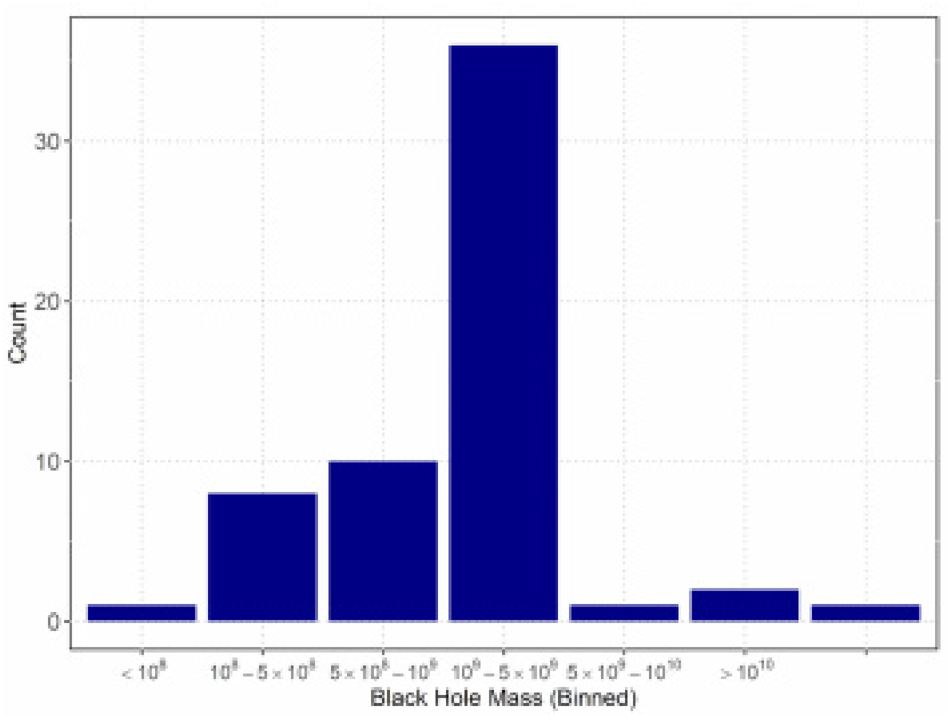

Figure 1 The figure from [1] which shows 59 high-redshift quasars. About 61% of the BHs are in the 10 ^ 9 - 5 * 10 ^ 9 bin, while in the 5*10 ^ 9 - 10 ^ 10 bin there is a significantly smaller amount of BHs.

BH accretion is a known astrophysical process, however it is not possible that BHs formed into SMBHs through accretion. Early in the universe the temperatures was very high and the excessive radiation pulled structures away from each other, so structures couldn't clump together until redshift reached the value �� « 30. If we model the growth rate of the black holes from that time we can show that if we let the BHs evolve to the present state of the universe, there wouldn't be enough time for them to accrete the necessary amount of mass or to combine into SMBHs [11]. Also another question appears, if SMBHs were formed through accretion of matter and combinations of black holes, there should be intermediate mass black holes (IMBHs) that are in the state of turning into SMBHs. But in the observable space we don't really see them. There is a huge gap in mass between stellar BHs and SMBHs. Nevertheless this theory can be changed into other theories that are more realistic.

SMBHs from the earliest stars

It has been established that SMBHs were unlikely to have evolved from stellar BHs. So there may have been some type of black holes larger and older than stellar black holes. This brings us to primordial black holes.

PBHs are a type of hypothetical black hole that formed soon after the Big Bang from external pressure sourced from an inhomogeneous density distribution fluctuations in the early universe and have grown during the inflation epoch. Their existence is yet to be established. However, recent NANOGrav signal [12] results could be interpreted as signals from PBHs with mass range of $M_P BH \in (10^3, 10^6) M_{sol}$. The fluctuations in the early universe had a power spectrum, The fluctuations in the early universe had a power spectrum, part of it obeys the power law and can be established by CMB, but the other parts that will help us learn about PBHs could be established using gravitational waves. So, in other words, we can observe PBHs using CMB only at a specific scale $\Omega_G W(f = 5.5\, nHz)$. NANOGrav may have caught waves at a scale that PBHs were formed. We could come up with models on the unknown parts of the power spectrum so that the signal received by NANOGrav would fit them. So NANOGrav results of a narrow range of frequencies around $f = 5.5\, nHz$ could be interpreted as signals from PBHs. The signal could be a stochastic gravitational wave background connected to the formation of PBH from peaks in the curvature power spectrum. From that a model could be formed that would have the necessary amount of SMBH seeds and the exact signal that NANOGrav received [12].

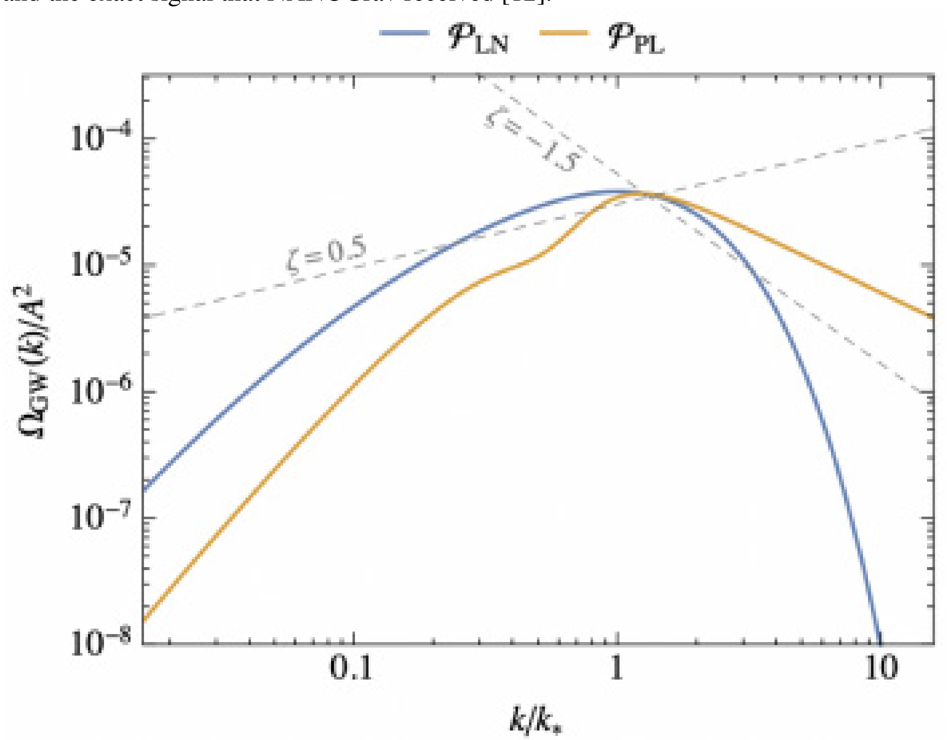

Figure 2 The figure from [12] of the power spectrum.

Going back to the theory, all PBHs with a mass exceeding ~10^3 M_{sol} by redshift z ~ 10 assembled into SMBH via accretion [12]. Since the mass distribution of PBHs was determined by inflation, it is log-normal.[5] The parameters of this distribution can be chosen so that the number of sufficiently massive PBHs (seeds) corresponding to observations is formed. However, the theories explaining scenarios with the necessary amount of PBHs to form the right amount of SMBHs have a weak side that apart from SMBH seeds there would be excess IMBH seeds (~ 10^5 – 10^6 per present day SMBH, while The present-day IMBH space density is ~ 10^2 – 10^3 per cubic Mpc). There are core structures in globular clusters that resemble IMBHs, but the number of those IMBHs is less than most theories predict [5],[3].

Direct collapse BHs (DCBH)

Another theory resulting from the first one is that SMBH seeds were massive to begin with. The BH that could be a seed for a SMBH formed as a result of large high-redshift clouds of metal-free gas that collapsed as a single massive BH. In this scenario the formation of Population III is avoided by destroying H_2 with Lyman-Werner radiation. [9]

In order to delay the formation of stars in the gas cloud, we need a back ground flux of Lyman-Werner radiation and, right before the gas collapses, an intense burst of Lyman-Werner radiation from a close star-bursting proto galaxy to completely suppress star formation. Then, when the star formation is avoided, the gas cloud has to stay really hot at around 30,000 K. This can be achieved by a population of metal-free stars in the early Uni verse. Metal-free gas slows down the cooling. After that, the gas cloud will collapse, skipping the star stage, and turning into a massive BH. Then, through accretion of matter that BH will turn into a SMBH. [9].

Upcoming observations may find DCBH candidates. A detection of a DCBH candidate with close star-forming galaxies would validate the synchronisation mechanism [9].

Conclusion

In this paper three theories on how SMBHs could have formed were analyzed. Although they present different ideas, they have one thing in common: BHs become SMBHs through accretion of matter, and the first theory serves as a base for the two other theory.

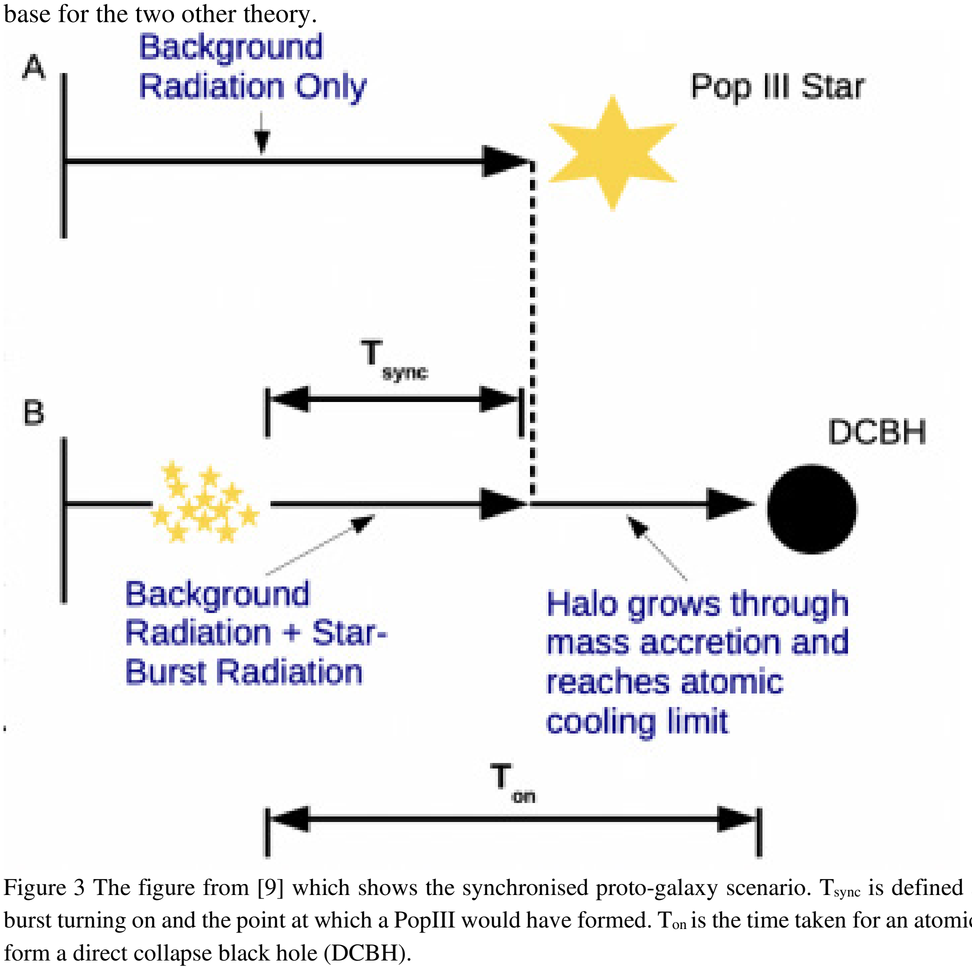

Figure 3 The figure from [9] which shows the synchronised proto-galaxy scenario. T_{sync} is defined as the time between the starburst turning on and the point at which a PopIII would have formed. T_{on} is the time taken for an atomic cooling halo to collapse and form a direct collapse black hole (DCBH).

The PBH scenario is the most relevant, first of all since NANOGrav's signal could be interpreted as a PBH signal, and second of all, PBHs is a promising field of research, with Laser Interferometer Space Antenna (LISA) [2] being launched in 2034, we could study GW and secondary GW and establish the existence of PBHs to know how SMBHs have formed.

Acknowledgments

Thank you to Matvey Rakitin (HSE student), Egor Novoselov, and Nick DePorzio (Harvard university) for guidance on this paper.

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