Primordial Origins of Supermassive Black Holes

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ABSTRACT

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Supermassive black holes (SMBHs) are orphans—since no known progenitors exist, their origins are mysterious. They are so massive that even if the first stars collapsed into black holes, they would struggle to even come close to supermassive sizes.

I investigate whether primordial black holes (PBHs), formed by overdensities in the Big Bang, could be the progenitors of SMBH. I use the cosmology code `Enzo` to simulate the growth of single solar mass PBHs over the course of ~325 Myr to see if the PBHs can reach supermassive sizes. Additionally, I compare Bondi accretion to viscous accretion.

I use two methods to test whether PBHs could grow fast enough to become SMBHs. First: comparison to the growth of their surrounding halos—if a PBH is roughly 10^3 $M_\odot$ by the time its halo is 10^8 $M_\odot$, PBH–SMBH evolution is possible. Second: comparison to observed early SMBHs. If our PBHs reach similar sizes by similar times, PBH–SMBH evolution could be a viable pathway for those early observed SMBHs.

Aside from the main results, I discovered that Bondi accretion and viscous accretion result in drastically different accretion rates. While black holes growing with Bondi accretion grew on order 10^{-4}, black holes with viscous accretion grew on order 10^{+4}. This is likely due to the dependence of Bondi accretion on simulation resolution.

Given sufficiently dense seeding points, I found that the growth of PBHs does match the growth needed to reach supermassive sizes. The PBHs reached 10^3 $M_\odot$ by the time their halos were 10^8 $M_\odot$, so they do have the potential to reach the sizes of many observed SMBHs. Their extrapolated growth barely fell short of observed early SMBHs, but if 10–100 $M_\odot$ PBHs were seeded, their growth trajectory would be on track to reach the sizes of early SMBHs.

Keywords: SMBH, supermassive black holes, PBH, primordial black holes, Eddington, Bondi accretion, viscous accretion, cosmology, galaxies, halos

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For Eden, the S1 to my S2.

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"Computations described in this work were performed using the publicly-available `Enzo` code (http://enzo-project.org), which is the product of a collaborative effort of many independent scientists from numerous institutions around the world. Their commitment to open science has helped make this work possible."

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Chapter 1

Introduction

Supermassive black holes (SMBHs) are the most massive objects in the entire universe. The center of our own galaxy hosts a SMBH—Sagittarius A*—with a mass four million times that of our sun. Though our entire galaxy orbits this beast, its origins are ambiguous.

As black holes grow, the matter gravitating towards them heats up due to friction. This causes radiation, which repulses the inspiralling matter, thus slowing accretion and ultimately limiting growth rates. Even if the first stars collapsed into black holes, their limited growth rate means that they could only grow to a fraction of the size of SMBHs which have been observed in the early universe. This then suggests that the black holes needed to have started growing before the first stars to reach supermassive sizes so early.

Soon after the Big Bang, quantum fluctuations made some regions more dense than their surroundings. These are called *overdensities*. Some of these fluctuations may have been dense enough to collapse into black holes. Since these primordial black holes (PBHs) formed so long before the first stars, they would have had much longer to accrete matter than stellar black holes, and therefore have a better shot at reaching supermassive sizes earlier.

I ran simulations of PBHs with the cosmology code `Enzo` and found that PBHs could grow to supermassive sizes quickly enough to be good candidates for the seeds of SMBHs.

1.1 Black Holes

Black holes occur when matter and energy are dense enough that light is unable to escape. The classical equation for escape velocity $v_e = \sqrt{2MG/r}$ still holds for light if we set $v_e = c$ (where M is mass of the object, G is the gravitational constant, r is the radius of orbit, and c is the speed of light). Solving for orbital radius, we find the Schwarzschild radius, $r_s = 2MG/c^2$, which defines the density threshold for black hole collapse. If a mass M fits within a radius r_s, gravity keeps the light from escaping, so the object is unobservable—a black hole. In other words, if a hoop of circumference $c = 2\pi r_s$ can be rotated around an object (of that Schwarzschild radius), the object will become a black hole (this is known as *hoop conjecture*). [1]

Thus density alone defines whether an object becomes a black hole—mass is merely a measure of a black hole's size. Figure 1.1 shows the wide range of masses at which we'd expect to find black holes, ranging from the mass of a human ovum to billions of times the mass of our Sun. The lower limit results from the plank length [2] while the upper limit results from how massive black holes accrete matter. [3]

Two classes of black holes have been observed thus far: stellar black holes and supermassive black holes. Stellar black holes range from ten to a hundred times the mass of our sun (10–100 $M_\odot$); supermassive black holes (SMBHs) range from ~10^5 $M_\odot$ up to ~10^{10} $M_\odot$. [4]

1.1.1 Supermassive Black Holes

Supermassive black holes were first hypothesized by Donald Lynden-Bell and Martin Rees, in 1971. [5] Three years later, the National Radio Astronomy Observatory discovered the SMBH at the center of our galaxy: Sagittarius A*. [6] Since then, many more SMBHs have been found in galaxy centers. [7–9]

Though many SMBHs have been detected from radiation signatures, their origins remain unclear.

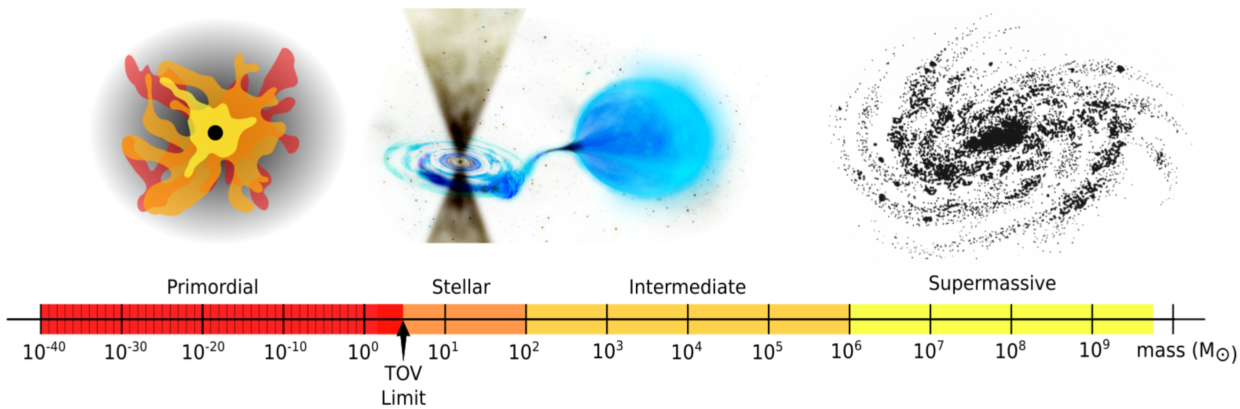

Figure 1.1 Allowed black hole sizes. While many stellar and supermassive black holes have been observed, no black holes in other ranges have been confirmed. Neutron stars larger than the TOV limit collapse into black holes. Note the change of scale at 10^0 $M_\odot$.

Since no intermediate black holes (IMBH) have been observed, no traceable path exists from stellar black holes to supermassive black holes. Additionally, black holes are limited in their growth rate. This limit, called the Eddington Limit, suggests that a black hole can only grow so large in a certain amount of time. SMBHs have been observed so early in the universe that even if the first stars collapsed into black holes, they'd struggle to reach supermassive sizes by the early times we've observed SMBHs.

Intermediate Black Holes While no IMBHs have been observed to date, this is likely due to sampling error rather than a lack of existence. Sampling error arises due to an unfair survey, where some candidates are underrepresented. Thus far, black holes have been observed through two means: gravitational wave detection by LIGO and radiation of SMBH at galactic centers. LIGO is tuned to detect black holes of mass ~10 $M_\odot$ (LIGO detections have fallen between ~1–80 $M_\odot$, [10]) and only SMBH are energetic enough to radiate a detectable amount. Thus, the only black holes we currently have the knowledge or tools to detect lie in stellar and supermassive ranges.

IMBHs are likely found in globular clusters orbiting the galactic center, since globular clusters give the best opportunities for mergers which would allow the black holes to reach intermediate

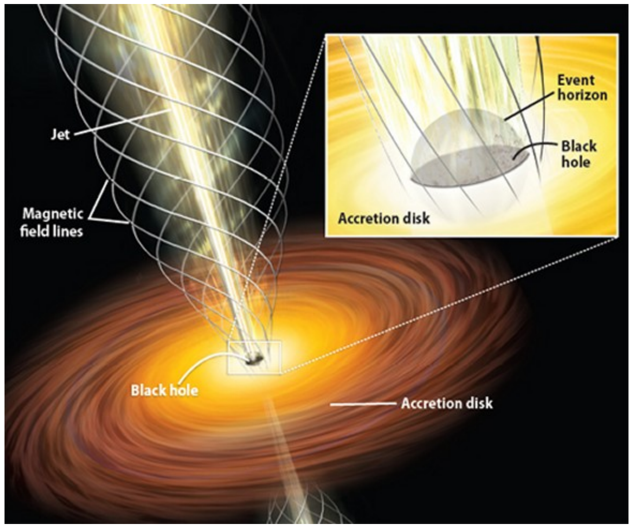

Figure 1.2 Diagram of a black hole accreting and relegating matter. [13]

masses. Several of the black holes mentioned in reference [11] are likely IMBHs. Since IMBHs go through many merges to reach their sizes, the remaining momentum makes it likely for the black hole to be kicked out of its original orbit and thrust into the no-man's land between galaxies. Additionally, IMBHs are too small to have an accretion disk, so they don't emit as much radiation as SMBH. [12]

The lack of an accretion disk and possibility of them floating in open space makes it difficult for us to detect IMBHs, so they would be underrepresented in our current spectrum of detected black holes. Therefore, we ought not to rule out the existence of IMBH based solely on current detections. Until IMBHs are detected, the origins of early SMBHs will remain unclear.

1.1.2 The Eddington Limit

To understand how black holes became so massive, one must understand how they grow.

Accretion is the gravitational capture of matter. As objects fall into a black hole, tidal forces near the black hole strip matter from stars to form an accretion disk (see Figure 1.2 and reference [14] for a video of a black hole accreting). This spiraling motion generates friction inside the disk, which radiates outwards as light and heat. Radiation pressure in turn repels the infalling matter, slowing accretion. The balance between radiation and accretion for a spherically symmetric scenario gives rise to the Eddington limit (equation (1.1)).

$$L_{\mathrm{Edd}} \approx 34,000 \left(\frac{M_*}{M_\odot} \right) L_\odot \tag{1.1}$$

A star's luminosity L (where $L_\odot$ is solar luminosity) can only be so large for an object of mass M_* (where $M_\odot$ is solar mass). [15] The corresponding mass accretion rate is [16]

$$\dot{M}_{\mathrm{Edd}} \equiv L_{\mathrm{Edd}}/c^2 = M_*/t_{\mathrm{Edd}} \tag{1.2}$$

where $t_{\mathrm{Edd}} \approx 45$ Myr. This ODE then leads to exponential growth, proportional to $e^{t/t_{\mathrm{Edd}}}$.

Keep in mind that this only holds for perfect spherical symmetry. Accretion disks allow heat to escape perpendicular to the disk's plane, allowing higher accretion rates. While super-Eddington accretion is possible, it is not often observed.

The Eddington limit gives a rough limit to the rate of accretion, which puts a rough limit on the size to which a black hole can grow in a given amount of time. If the first stars, Population III (Pop III) stars, collapsed into black holes and grew until today, the Eddington limit would bound how large they could have become.

For example, using a 100 $M_\odot$ Pop III star at $z = 20$ (180 Myr) which collapses with *all* its mass resulting in a black hole, we find that after 720 Myr (the time at which the Wu SMBH is observed at $1.2 \cdot 10^{10}$ $M_\odot$) it has only reached a size of ~$8 \cdot 10^8$ $M_\odot$.

For Pop III stars to reach supermassive sizes, they would have to accrete continuously! [17] Since accretion at the Eddington limit for such a long time is unlikely, SMBH origins remain an open question in astronomy. If black holes had longer times to grow, the Eddington limit permits their growth into supermassive sizes. Thus, we look before the first stars for the origins of SMBHs.

1.1.3 Primordial Black Holes

Primordial black holes (PBHs) were first theorized by Zel'dovitch and Novikov in 1966 [18] and later by Stephen Hawking in 1971. [2] Soon after the Big Bang, quantum fluctuations led to some regions in space being more dense than others. It is possible that some of these regions were sufficiently dense that their mass was within their own Schwarzschild radius. These overdensities could then collapse into black holes. (There are a few other theories of PBH creation—see Mack 2007 [19] for a well-written review.) PBH creation occurred hundreds of megayears before the first stars collapsed into stellar black holes.

Because drastic density spikes were less likely than subtle density spikes, less massive PBH were more likely to form than larger PBHs. Our simulations use single solar mass black holes as our seeds, but there is a calculable probability that larger PBH could have existed.

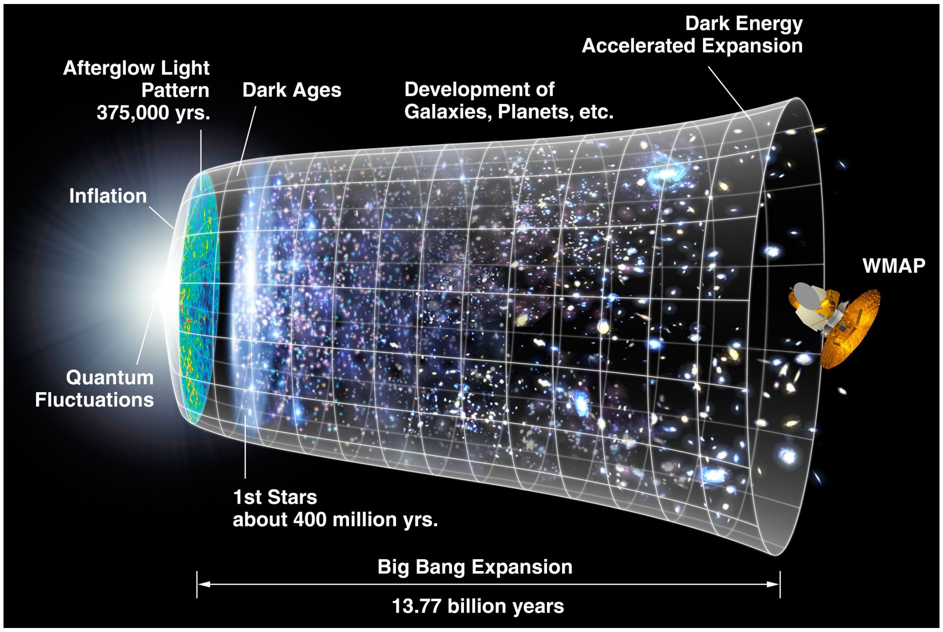

Figure 1.3 Timeline of universe from the Big Bang to the present day. Primordial Black Holes were formed in the "Quantum Fluctuations" region on the far left of the chart. Picture from NASA / WMAP.

For a discussion on their detection and evaporation see appendix A.

This thesis investigates whether PBHs could potentially be the progenitors of SMBHs. Since PBHs existed from the start of the universe, they would have much more time to accrete material and reach SMBH size. To check this, we run simulations growing single solar mass PBHs to see whether PBHs could possibly be the progenitors of SMBHs.

1.2 Previous Research

The question of SMBH origins is nearly five decades old, being first discovered in the 1970s. Many have theorized formation pathways, but none are conclusively correct. Following is a short list of origin theories, taken from Johnson and Whalen. [17, 20]

1. The collapse of Population III (Pop III) stars into 100–300 $M_\odot$ black holes at ~180 Myr.[1]
2. The direct collapse of extremely hydrogen molecule-poor primordial gas in ~108 $M_\odot$ dark matter halos into 104–106 $M_\odot$ black holes at ~480 Myr.
3. The relativistic collapse of dense primeval star clusters into 104–106 $M_\odot$ black holes.
4. The collapse of primordial overdensities (i.e. PBHs) in the immediate aftermath of the Big Bang (see references [19, 22]).

While all of these models stand as feasible SMBH progenitors, no one theory has sufficient evidence to prove its accuracy. Each of these theories has its limitations.

As previously mentioned, the collapse of Population III stars (item 1) alone cannot explain the existence of SMBH at early times, since they'd have to be accreting at the Eddington limit from the moment of their formation (highly unlikely) to reach SMBH sizes. While more recent work [23]

[1] Redshifts were turned into years via E. L. Wright's Cosmology Calculator [21]

investigates hyper-Eddington accretion rates in Pop III stars under special circumstances (vis. cold flows and thermal photons which carries heat away from the growing star). While the growth can reach early SMBH sizes, it is yet to be determined how common such conditions for Pop III stars would be.

The direct collapse of H_2-poor gas clouds (item 2) requires bypassing supernova formation. Exploding supernovae loose a lot of mass on explosion, so gas collapsing directly into a black hole would have a much greater staring mass than other models, allowing for faster growth. Large seed weights could also come from collapsing star clusters (item 3). These groups of early stars could merge to form IMBH. Again, it is yet to be determined how often these events would happen, and whether the resulting spectra would match observed SMBH occurrence rates.

This thesis investigates PBH–SMBH evolution (item 4). At the moment, no observational evidence definitively confirms this pathway and theoretical evidence is divided as to whether such a pathway is likely. Following are a few previous studies on PBH–SMBH evolution.

1.2.1 PBH–SMBH Pathways

Quintessence

An alternate theory to an accelerating expanding universe suggests a fifth component of the universe beyond currently known elements (baryonic matter, hot dark matter, cold dark matter, and spatial curvature). This fifth element (*quinta essentia* in Latin) can be thought of as a fluid permeating all of space. The fluid would have a negative mass density, resulting in a negative pressure—which is not well-defined. The theory is mainstream but not yet accepted.

Rachel Bean and João Magueijo in 2002 [24] ran simulations of PBHs with accretion of quintessence included to boost their early growth but shut off at a later time to stymie their growth. Their simulations modified quintessence levels to achieve a specific SMBH output spectrum to match observations.

Domain Walls

Khlopov et al. in 2004 [25] theorized a new mechanism for PBH–SMBH evolution via domain wall collapse, similar to the mechanism of collapsing overdensities. Domain walls similarly resulted from a “non-equilibrium distribution” of mass soon after the Big Bang. Khlopov et al. found a “fractal-like cluster” of PBHs resulted. The paper suggests that SMBHs with primordial origins would have a spectrum consistent with observations today. This paper is purely mathematical and uses a simplified model, so it’s just one approach to this complex problem—far from comprehensive.

Input Spectrum Modulation

Düchting in 2004 [26] explains some difficulties in PBH–SMBH evolution. An accurate resulting distribution of masses (called a spectrum) for SMBHs demands a fine-tuned PBH input spectrum requiring a jump at a specific value. Current observations favor a power-law distribution of PBHs, so Düchting’s contrived input spectrum may not reflect reality. Thus, while the paper supports the possibility of PBH–SMBH evolution, it concludes that such an evolution may not be likely. Still, this paper made several assumptions, so it doesn’t conclusively prove that PBH–SMBH evolution is impossible.

My Approach

In contrast to these previously explored methods, I will be running cosmological simulations—something never done before with PBHs. My study currently abstains from matching observed SMBH distributions—at the moment, these simulations are a first-order approximation, testing possibility. This project set up a pipeline to check statistical probability in future work. My simulations also compare accretion methods, revealing deep differences between Bondi accretion and viscous accretion.

1.3 Overview

This thesis explores whether PBHs can feasibly be the progenitors of SMBHs. In Methods, I detail the two accretion methods used, namely Bondi accretion and viscous accretion. Then I discuss dark matter halos and their comparison to PBH growth rates. Then I introduce how I seeded black holes in the open-source cosmology code `Enzo`[2], along with the computational resources used for its execution. In Results, I discuss the accuracy of the results and show the differences due to choice of accretion method. Bondi accretion results in near-zero growth, while viscous accretion results in growth by several orders of magnitude. I also compare the growth of PBHs versus their halos and extrapolate their growth to compare to observed early SMBHs. In Discussion, I note that the growth of PBHs supports the possibility of PBH–SMBH evolution, given a sufficiently detailed accretion method and sufficiently dense seeding points.

[2] `Enzo` is available for download from its website, enzo-project.org, and on bitbucket.org.

Chapter 2

Methods

This section discusses the methods for modeling the growth of primordial black holes (PBHs) in the early universe, to see if they can evolve into supermassive black holes (SMBHs). Here I outline different accretion models for black holes, how to know if the PBHs can reach supermassive sizes, where the PBHs were seeded, and how the simulations were run, including computing resources used.

2.1 Simulation Accretion Methods

Cosmological simulations require user-defined methods for approximating black hole growth. The following simulations use two main accretion methods: Bondi[1] accretion [27] and viscous accretion. [28] The biggest difference is that while Bondi accretion assumes spherically symmetric accretion, viscous accretion takes into account the geometry of the accretion disk.

[1] Sir Hermann Bondi, Sir Fred Hoyle, and Raymond Arthur Lyttleton all contributed to aspects of this method, so its name varies in different mixes of the three names. While the Enzo documentation reports it uses "the Eddington-limited spherical Bondi-Hoyle formula," the paper it cites was authored only by Bondi and "Bondi accretion" is common nomenclature in the literature.

2.1.1 Bondi Accretion

If a black hole passes through a cloud of dust, it will pick up dust within a certain radius of its path. This is the core physics of Bondi accretion. Its derivation involves solving gravitational equations for the more general case of any compact object moving through an unperturbed fluid [29]. The solution for growth rate is

$$\dot{M} = \frac{4\pi G^2 M^2 \rho_\infty}{(c_\infty^2 + v^2)^{3/2}} \xrightarrow{v \ll c_\infty} \frac{4\pi G^2 M^2 \rho_\infty}{c_\infty^3} = r_B^2 \pi \rho_\infty c_\infty \tag{2.1}$$

where G is the gravitational constant; M is the object's mass; ρ_∞ is the density of the surrounding medium; c_∞ is speed of sound in the medium; v is the speed of the object which we assume to be small in comparison to the surroundings' sound speed; and r_B is **the Bondi radius**, defined as $r_B = 2GM/c_\infty^2$, which determines the boundary between accreted and abandoned matter. The Bondi radius also defines the boundary between subsonic and supersonic fluid. Therefore, it is critical that any simulation adequately resolve this radius to get accurate results.

This equation has two important features. First: an object's accretion rate depends upon its current mass (squared) and the density of its surroundings. This means that as an object gets larger, it becomes easier for it to grow faster. Second: the subscript ∞ indicates a measurement distant from the event—technically infinitely far away—where the medium is unperturbed. This means that the equation assumes unperturbed density and sound speed.

Many prize Bondi accretion for its simplicity, but it ignores many things.[2] While some ignorance is harmless, several of these points are cardinal sins.

Bondi accretion ignores

1. Self-gravity of the gas (which is mostly negligible).

2. Relativistic effects (which matter especially for black holes).

[2] See Richard Edgar's article [29] for a more detailed explanation on several of the following points.

3. Accretion disturbs the matter, possibly in a turbulent manner.

4. The fact that there is no such thing as infinite homogeneous dust clouds.

5. Momentum transfer to the surrounding gas. As momentum of the surrounding gas is central to accretion rates, its ignorance is fatal.

6. The radius and drag of the compact object. Since black holes are point masses in comparison to their surrounding gas cloud, this approximation is negligible.[3][4]

7. Heating and pressure effects of the gas, resulting in the radiation of light. The luminosity of the object curbs accretion—see Section 1.1.2 on the Eddington limit.

8. Accretion disks are planar, not spherical! Black holes naturally pull matter into accretion *disks*—not spherical clouds. Accretion disks allow for more efficient radiation, perpendicular to the disk (as seen in the quasar jets of figure 1.2). This allows for much higher accretion speeds, making the Eddington limit more of a guideline than a solid rule.

The shape of the accretion disk and momentum transfer to the surrounding gas were the primary motivators for viscous accretion.

2.1.2 Viscous Accretion—Alpha Disk Formalism

DeBuhr et al. 2010 [28] details a different method of accretion than the traditional Bondi accretion, called viscous accretion. Among other things, the viscous model uses alpha disk formalism, [30] taking into account the geometry of the accretion disk.

[3] The largest black holes ever discovered have $r_s \approx 10^{-2}$ ly, while its accretion disk would be $\sim 10^3$ ly.

[4] Accretion disks scale with their black hole as $M^{2/3}$. Approximately, if a black hole is 10^{10} $M_\odot$ with an accretion disk of 1200 ly, when it was 10^9 $M_\odot$, its disk was 10^2 ly, and when it was 1 $M_\odot$, its disk was 10^{-3} ly.

The mass accretion rate is given as

$$\dot{M}_{visc} = 3\pi\alpha\Sigma\frac{c_s^2}{\Omega}, \tag{2.2}$$

where Σ is the mean gas surface density, c_s is the sound speed of the surrounding gas, Ω is the angular rotational frequency, and α is 'the dimensionless viscosity,' a free parameter in the model which characterizes efficiency of angular momentum transport and uncertainty related to star formation.

The model includes momentum feedback from the luminosity L, analogous to radiative feedback in a black hole. This feedback is crucial in calculating accretion rates. Momentum imparted is given by

$$\dot{p} = \tau\frac{L}{c}, \tag{2.3}$$

where $L = \min(\eta\dot{M}_{visc}c^2, L_{Edd})$. This ensures the radiative feedback stays below the Eddington limit, at which point accretion would halt.

2.2 Dark Matter Halos

Our simulations follow back holes from their inception soon after the Big Bang, but to generalize our findings to any galaxy, we compare PBH sizes to the masses of their surrounding galaxies.

Boundaries in space are nebulous, but we can define compact regions in space called halos. Halos are clumps of dark matter that draw in normal baryonic matter, including matter that will become galaxies. This is how our own galaxy formed: dark matter formed a halo which acted as a nest for baryonic matter. Figure 2.1 shows the rotation speed of matter around the Milky Way galaxy. Without dark matter, one would observe the red curve, but actually, the blue curve is observed. The dark matter halo is what gives the curve its unexpected shape.

Simulations have shown [32] that if a black hole reaches a size of 10^3 $M_\odot$ by the time its surrounding halo reaches a size of 10^8 $M_\odot$, the black hole could grow to supermassive sizes in the

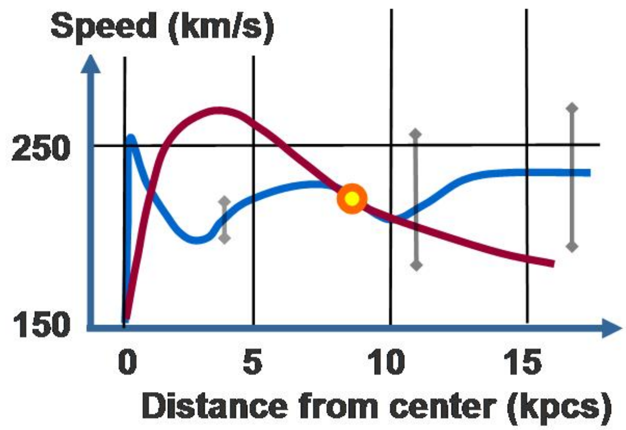

Figure 2.1 Plot of rotation speed of matter in the Milky Way. The red curve shows what we'd expect in absence of dark matter. The blue curve shows what we've observed. The discrepancy between observed and expected shows the existence of dark matter surrounding the galaxy. [31]

short amount of time we've observed other SMBHs grow. Thus, if PBHs grow to sufficiently large sizes alongside their halos, it's possible for a PBH to grow into a SMBH.

2.3 Seeding the Black Holes

To give the PBHs the greatest chance of growing into SMBHs, they were seeded in regions which would later host the largest halos. To this end, simulations without PBHs were run from a redshift of $z = 200$ (~6 Myr) until a redshift of $z = 2$ (~3 Gyr). The largest halos at $z = 2$ were then found using yt's HOP halo finder method. [33, 34] Black holes were then seeded in a new simulation with identical initial conditions at a redshift of $z = 200$. Because previous simulations had shown low-refinement Bondi accretion resulted in near-zero growth due to insufficient resolution, more computational resources were directed towards viscous accretion. The simulations used 20 and 1000 black holes for Bondi accretion and viscous accretion respectively.

2.4 Computational Methods

2.4.1 Flow Field Specification

Because computers use discrete numbers to describe simulations, the situation must be somehow quantized. There are three main ways to model fluids. In short, **SPH** codes track individual particles, **Eulerian** codes track regions of space, and **Lagrangian** codes track regions of particles. `Enzo` utilizes a combination of the first two methods. These can all be compared to simulating a river.

Method 1: SPH (smoothed-particle hydrodynamics) Model each molecule of water, describing its exact position and trajectory at each moment of time. The difficulty with this method is scale—making the model large enough to give meaningful results. A glass of water alone has ~10^{25} molecules of H_2O, so approximations are usually used where one 'particle' stands for many molecules of H_2O. The 2005 Millennium Simulation (a famous cosmology simulation looking at large-scale structure of the universe) used ~10^{10} 'particles,' where each particle massed ~$10^9 M_\odot$. [35] Since the scale of the simulation was so large, using smaller particles would have been too computationally expensive (in time, computer memory, and money), so larger particles must approximate many smaller particles.

Method 2: Eulerian Monitor each cubic meter region of water, describing its density, pressure, average velocity, and so forth. The difficulty with this method is resolution—making the simulation precise enough to give meaningful results. Dividing the river into discrete areas (the cubic meter cells) excludes small-scale features from surfacing, e.g. minute eddies that form around smaller rocks. Even if we used cubic centimeter cells, we'd still miss details, e.g. the ripples from a water strider bug. For example, the 2015 movie *The Good Dinosaur* used ~10^{12} cubic centimeter cells across a half mile to simulate their rivers but used SPH points for splashes (small-scale features). [36, 37]

No supercomputer can model an entire river with perfect accuracy, since this would require near-infinite refinement. Thus, every Eulerian simulation decides on a passable amount of ignorance of some scale.[5] The balance is that low refinement (larger cells) runs faster but yields less accurate results, while high refinement (smaller cells) runs slower but yields more accurate results.

Usually, Eulerian simulations use an **adaptive mesh**. This means that the simulation uses larger cells where features are simple and smaller cells where features are more complex (small-scale). *The Good Dinosaur*'s river could have used large cells in calmer parts of the river and under the surface while using smaller cells for splashes, spray, and foam. Since the river moves over time, the mesh would also have to change resolution over time, so where the river becomes more turbulent, the cells must become smaller to resolve the small-scale features.

Method 3: Lagrangian Monitor sections of water, keeping boundaries between the sections (perhaps by placing thin, stretchy bags around each section of water). This is similar to SPH in that groups of particles are tracked, rather than regions of space being tracked. The difficulty with this method is turbulence. Sections in a Lagrangian simulation (called cells) can become so stretched and contorted that computational errors arise. This would be like the plastic bags being stretched and deformed so much that the bag bursts. While this method is good for capturing fine details, it can also be this method's Achilles' Heel.

Method 4: Eulerian with tracer particles Model clumps of molecules of water, but keep a base grid to do calculations like an Eulerian code. If the cell to the right is more dense, for example, impart leftwards momentum While the method is flawed, it does have the upside of retaining small-scale features locally while simplifying calculations on a large scale. For example, to simulate neutron stars spiraling into each other, one could start with a Lagrangian style, using many particles.

[5] This can be a problem in some nonlinear (chaotic) systems, such as modeling weather correctly—the smallest inaccuracies in modeling can cause large-scale problems further along in a simulation.

Most groups of stars are distant from other galaxies, so we can approximate the distant stars as one large particle by collecting all the distant stars into a large cell. This cuts down computational costs greatly–instead of interacting with every other particle, they interact with groups of particles.

`Enzo` is an Eulerian code, but it uses discrete particles to stand for clusters of matter. The grid is subdivided with those particles, so while calculations are Eulerian, the code uses tracer particles (similar an SPH method) to help calculations run faster and avoid computational errors in low-density areas.

2.4.2 Enzo, Cosmology Simulator

All simulations were run in `Enzo`, [38] an open-source 3D cosmology code. `Enzo` has user-set seeds which randomize the initial matter distribution. As the simulation evolves over time, `Enzo` allows space to expand as it did in the early universe.

`Enzo` is an Eulerian code using a particle-mesh technique. Though the code keeps track of individual objects (the particles), those objects are grouped into regions (the mesh) to do calculations en masse. `Enzo` uses adaptive mesh refinement, meaning the mesh is more dense (subdivided) in regions where there are more interesting features (like galaxies or black holes). The code uses cyclic boundary conditions (putting the universe on a hypersphere) to mimic the effects of an infinite universe.

`Enzo` was initially coded for studying dark matter, but many packages can be activated to investigate other physics. Some packages include seeding and growing black holes; star formation (including Pop III stars) and evolution, including supernovae death; and problem-type parameters that set the initial state. A full list of parameters can be found in the Enzo Parameter List.

Table 2.1 Publicly available capabilities of supercomputers used at Los Alamos National Laboratory. Rmax measures the maximal performance. Data for Wolf came from lanl.gov and MachineDesign. Data for Grizzly came from the TOP500 website.

System	Nodes / Cores	Memory	Rmax	Power
Wolf	616 / 9856	19.7 TB	205 TF	···
Grizzly	··· / 53 352	189.696 TB	1524.72 TF	603.40 kW

2.4.3 Resources Used

All computations were completed at Los Alamos National Laboratory (LANL) using the unclassified supercomputers Wolf and Grizzly. Capabilities for these computers are shown in Table 2.1. Test simulations were submitted to Wolf and typically ran on 16 nodes—256 cores—for an hour. After the first run, the simulations went from $z = 200$ to about $z = 50$ (~15 data dumps in the process). After three or four runs the simulation would slow down, requiring longer submission times to produce a single data dump. Full simulations were submitted to Grizzly and typically ran on 32 nodes—512 cores. Time for successive steps increased exponentially, so while $z = 200$ to $z = 50$ only took an hour, evolving from $z = 50$ to $z = 20$ took roughly eight hours. Moving beyond $z = 20$ took days for well-refined runs.

Chapter 3

Results

This chapter discusses results from primordial black hole (PBH) growth through accretion using `Enzo`. Two main accretion methods were used: Bondi accretion and viscous accretion. A short discussion of the cause of their differences follows. The goal of these simulations is to see whether PBHs could grow sufficiently fast to explain the existence of early SMBHs, such as those listed in table 3.1. To verify this possibility of PBH–SMBH evolution, we use two methods: (1) comparison between the PBH and its surrounding dark matter halo, and (2) extrapolating their growth and comparing it to early SMBHs.

Table 3.1 lists some observed supermassive black holes (SMBHs), including our own galaxy's Sagittarius A* for reference. Section 3.5 includes these points to compare our growth rate with the known early SMBHs. If our PBHs grow sufficiently fast, PBH–SMBH evolution will be shown as a possible pathway for early SMBHs. I extrapolate the black holes' growth at the same exponential rate to check feasibility of PBH–SMBH evolution. If PBHs really are the progenitors of SMBHs, the simulated PBH growth ought to have a trajectory towards observed masses, growing to sufficient size by their observed epoch.

Alternatively, simulations have shown [32] that if a black hole has grown to ~10^3 $M_\odot$ by the time its surrounding halo has grown to 10^8 $M_\odot$, then that black hole could be the seed of observed

Table 3.1 Early SMBHs observed compared to our galaxy's black hole

SMBH	Time (Myr)	Mass ($M_\odot$)	Reference
Sagittarius A*	13 772	$4.3 \cdot 10^6$	Ghez (2008) [39]
SDSS J010013.02+280225.8	900	$1.2 \cdot 10^{10}$	Wu (2015) [40]
ULAS J1342+0928	690	$7.8 \cdot 10^8$	Bañados (2017) [41]
ULAS J1120+0641	770	$2.0 \cdot 10^9$	Mortlock (2011) [42]

early SMBHs. These results are seen in comparative plots between halo sizes and black hole sizes in section 3.4.

3.1 Grid size

These simulations are currently a first-order approximation of the results, not meant to give a fully accurate representation of reality. While radiation and alpha disk accretion are turned on, star formation is not. While the effect is non-trivial, it also shouldn't drastically change the simulations I ran. Star formation happened about 200 Myr after my simulation's start. [43] My simulations only ran to ~350 Myr with low-refinement simulations and ~125 Myr with high-refinement simulations, so star formation will only minimally affect the low-resolution simulations and won't affect the high-resolution simulations at all. A convergence study will be done, testing whether increasing the refinement incrementally converges on a single solution for any simulation. These will eventually resolve the accretion disk and the Bondi radius, showing whether Bondi accretion and viscous accretion converge to a single solution and whether they are valid accretion methods at low refinements.

Each level of refinement divides the space by two in a single dimension—by eight in three dimensions. Simulations used a 1 Mpc cube box with a base grid of eight levels of refinement, but variation in the levels of refinement beyond that. Figures 3.1 and 3.2 show low-refinement simulations in red which used three additional levels of refinement and high-refinement simulations in blue which used 12 additional levels of refinement. The most fine simulation resolution is then given by equation (3.1).

$$\text{resolution} = \frac{\text{simulation size}}{(2^{\text{total levels of refinement}})(\text{redshift stretch})} \tag{3.1}$$

$$r_3 = \frac{1\text{ Mpc}}{2^{8+3}(1+12.9)} \approx 35\text{ pc}$$

$$r_{12} = \frac{1\text{ Mpc}}{2^{8+12}(1+26.35)} \approx 0.035\text{ pc}$$

A 10^{10} $M_\odot$ black hole would have radius ~0.0003 pc, so even the most refined regions of space would be hundreds of times larger than the radius of the black hole (which for smaller black holes is near its Bondi radius). While this is insufficient for Bondi resolution, it is a good first-order approximation for viscous accretion. More refined simulations will be needed to determine whether the viscous approximations actually converge.

3.2 Bondi Accretion

Figure 3.1 depicts the growth of 20 PBHs under Bondi accretion. Note that the axis goes from 1.0000 $M_\odot$ to 1.0001 $M_\odot$—the PBHs barely increased over a single solar mass. The growth is below zero-order, showing essentially zero growth over the 350 Myr evolution time.

This growth is far below what is expected of a single solar-mass black hole. This is perhaps due to the low levels of refinement in the simulation—since the Bondi radius (see section 2.1.1) is ill-refined, the simulations may be giving inaccurate data. More simulations will be run to check these results for reliability.

Due to the low growth rate of Bondi accretion and the inferiority of its assumptions, I forebear from referencing this method in the following results.

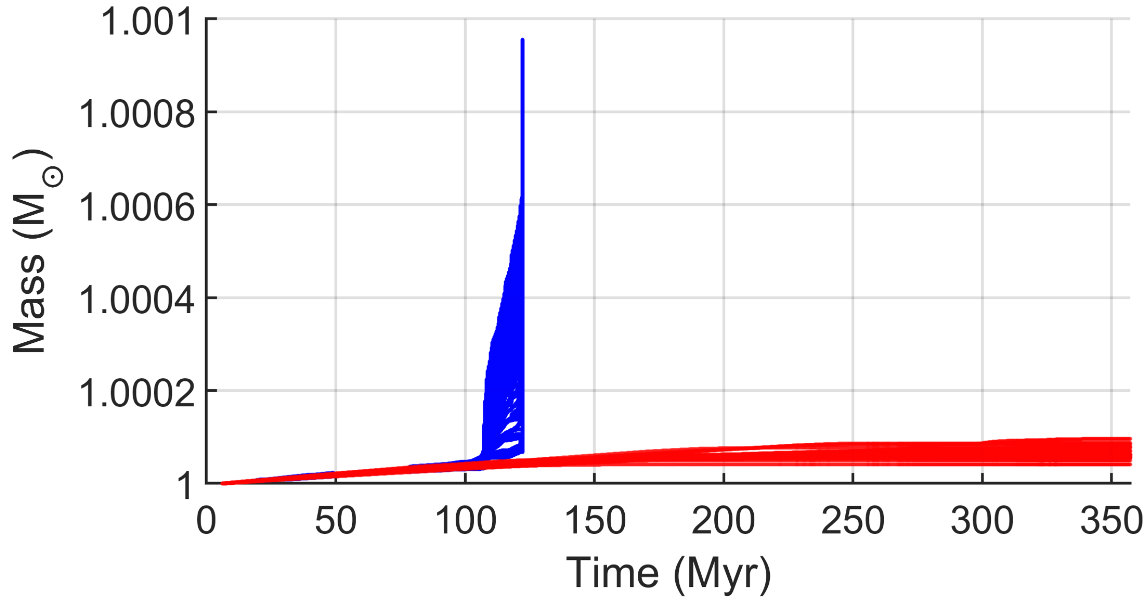

Figure 3.1 Low (red) and high (blue) resolution simulations using Bondi accretion for 20 PBHs. Growth rate before 100 Myr is invariant between resolutions. The fastest growing PBH has an increase of mass of 0.01% over 350 Myr, meaning essentially no growth occurs with this method.

3.3 Viscous Accretion

Figure 3.2 shows viscous accretion for an unrefined simulation and a deeply refined simulation for 1000 PBHs. In contrast to the Bondi accretion method, we see here growth of many orders of magnitude, going from a single solar mass (10^0 M$_\odot$) up to 10^3 M$_\odot$ and 10^4 M$_\odot$ for the more refined simulation.

The refined simulation only ran until 120 Myr. Once the simulation hit ~100 Myr, the simulation demanded more and more refinement in space and time, grinding output to a halt. At this point, I increased the resolution from 12 levels of refinement to 16 levels of refinement. This corresponds to the first hyper-exponential growth seen near 110 Myr. As the simulation ground to a halt again, I increased resolution from 16 levels of refinement to 20 levels of refinement. This resulted in another hyper-exponential growth. Thus, adding refinement levels mid-simulation causes severe problems.

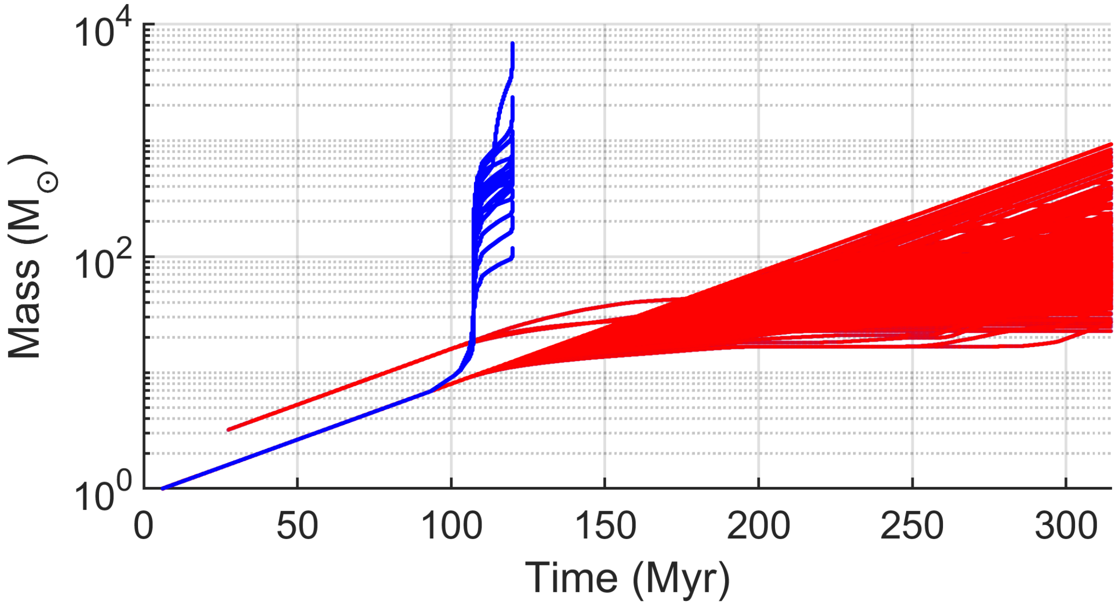

Figure 3.2 Low (red) and high (blue) resolution simulations using viscous accretion. Here we see differences by many orders of magnitude, where the high-refinement simulation at 120 Myr reaches sizes ten thousand times larger than the low-refinement simulation. Note that before ~100 Myr the two simulations are scale invariant.

In future discussion, I ignore the hyper-exponential growth of the high-resolution simulation, since it stems from computational error.

3.4 Comparison to Halos

Figure 3.3 shows a comparison of PBH growth to the sizes of surrounding halos. Since the PBHs were seeded where the largest halos form, one may reasonably compare the most massive halos (the topmost red dots) to the most massive black holes (the topmost blue dots).

In order for the growth of these black holes to explain SMBH origins, they must reach 10^3 $M_\odot$ by the time their surrounding halos are 10^8 $M_\odot$. Figure 3.3 shows the black holes growing to 10^3 $M_\odot$ by the time their halos grow to $2 \cdot 10^7$ $M_\odot$, so these black holes actually can reach the sizes

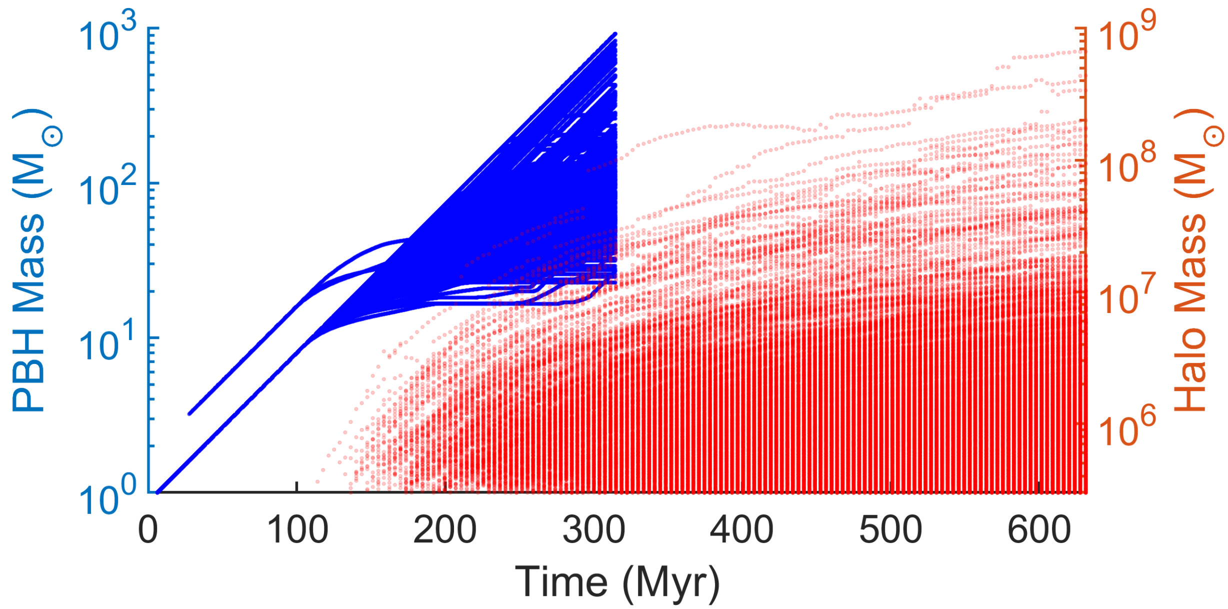

Figure 3.3 Comparison of PBH growth with viscous accretion (blue) to all simulation Halo sizes (red). Here we see PBHs reaching sizes of 10^3 $M_\odot$ by the time the halos are just below 10^8 $M_\odot$, meaning that the PBHs can potentially reach SMBH size.

of early observed SMBH!

3.5 Comparison to observed SMBHs

As seen in figure 3.4, were the fastest growing PBHs (the highest sloped lines) to maintain their exponential growth rate, they would come within a few orders of magnitude of observed SMBHs in the early universe. While only single solar mass black holes were seeded, heavier PBHs could have existed in the early universe, and these could feasibly reach supermassive sizes by the times early-universe SMBHs have been observed.

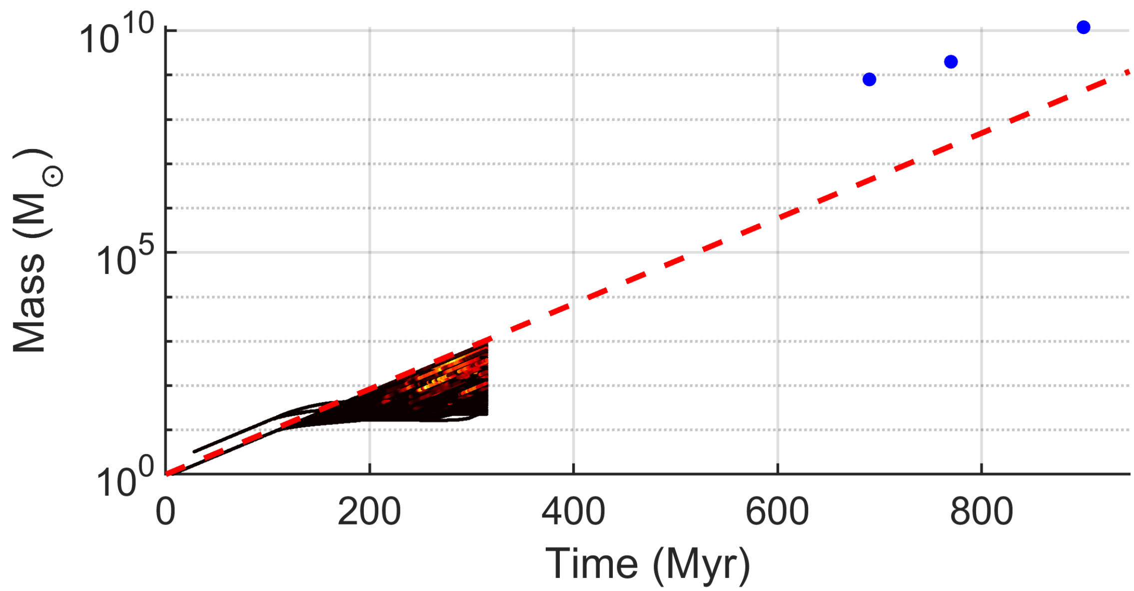

Figure 3.4 Low-resolution viscous growth with markers for SMBH goals: ULAS J1120+0641, ULAS J1342+0928 and SDSS J010013.02+280225.8. The PBHs have a path headed towards the SMBHs, but barely fall short. Were larger PBH seeds used, the PBHs could potentially evolve to SMBH sizes.

Chapter 4

Discussion

4.1 Mass Accretion

These simulations showed that primordial black holes (PBHs) could grow to supermassive sizes by early times, but their projected growth falls just short of the few early SMBHs in Table 3.1. This may simply be due to seed size—using single solar mass PBHs at the simulations' start. Were larger seeds used (our choice of a single solar mass was somewhat arbitrary), the observed sizes of SMBH may have been reached. They did, however, reach sizes of 10^3 $M_\odot$ by the time their halos reached sizes on the order of 10^7 $M_\odot$, which indicates that they are on-par with other early SMBHs. Thus, PBHs may be the progenitors of supermassive black holes! Several things warrant our skepticism though.

At our simulation's end, we are left with black holes headed towards supermassive sizes, but we are also left with many stellar mass and intermediate mass black holes (IMBHs) whose growth plateaued. While our simulations show more IMBHs existing than have been observed, sampling error is likely to blame (see section 1.1.1). Until IMBHs are observed, the jury is still out.

4.2 Differences in accretion methods

Bondi accretion differs from viscous accretion by many orders of magnitude, so the two methods are far from interchangeable. The resolution in these simulations hadn't fully resolved the accretion disk; the simulation's highest resolution was 35 pc while the accretion disk would be on order 0.005 pc (7000 times smaller!). This is equivalent to approximating an HD TV screen with two pixels. This is perhaps why Bondi accretion didn't give accurate accretion growth rates. Bondi accretion crucially depends on accurately resolving the Bondi radius (see section 2.1.1), so insufficiently refined simulations will yield rubbish, as seen in these simulations where the growth differs by seven orders of magnitude.

4.3 Future Work

4.3.1 Probabilistic Seeding

This project was a proof of concept, seeing if in any circumstance PBHs could evolve into SMBHs. I ignored proper PBH abundance in the early universe and seeded as many PBHs as I pleased. Additionally, I placed the PBHs where the most massive halos would exist. While the latter is not a bad guess, it does not reflect the quantumly random distribution that truly existed soon after the big bang. Constraints on formation can be found in figure 9 of Carr 2010. [22]

Future simulations will include these corrections, seeding the proper amount of PBHs randomly throughout the simulation. Rather than merely investigating whether PBH–SMBH evolution is *possible*, I will investigate whether PBH–SMBH evolution is *likely*. This will require proper seeding.

These simulations can then be compared to observed densities of SMBHs as a reality check.

4.3.2 Alternate Seed Masses

As mentioned in section 3.5, were heavier PBHs seeded, it's possible that such seeds could reach SMBH size by the time of the observed SMBHs.

4.3.3 Flow Field Specification

`Enzo` is an Eulerian code (see section 2.4.1), so comparing it to a Lagrangian code will be a good check, since the two work in fundamentally diametric ways. These simulations are already being investigated with the Lagrangian cosmology code GIZMO. [44]

4.3.4 Radiation

Black holes emit massive amounts of radiation, which could catastrophically slow growth. While simulations may begin at near-Eddington accretion rates the rates can later fall by many orders of magnitude due to radiation. For example, the simulations of Alvarez et al. 2009 grew 10^4 times slower with radiation than without. [45] This feedback is activated with the `MBHFeedback` parameter and will be a simple addition in future simulations.

4.4 Conclusion

Based on simulations of primordial black holes (PBHs) evolving with viscous accretion, PBHs may be the progenitors of supermassive black holes (SMBHs). Some PBHs grew at rates compatible (within a few orders of magnitude) with observed SMBH sizes (such as those in table 3.1). Verification of PBH–SMBH evolution will require finely resolved simulations run for longer, with proper probabilistic seeding of black holes. As a final check, the resulting black hole spectrum can then be compared to the observed black hole spectrum (taking into account what we're capable of observing). So while SMBH origins are still in the air (or rather, in space), PBH–SMBH evolution may well solve the conundrum.

Appendix A

PBH Detection

While no PBHs have been observed to date, this is likely due to their sparsity in higher masses. Light PBHs would have already evaporated by the times we could observe them today.

Black holes are not immortal; they lose matter due to Hawking radiation. [46, 47] This form of blackbody radiation arises from quantum effects in a vacuum. Pair creation and annihilation near the edge of a black hole results in the capture of some particles with their antiparticles escaping, emanating radiation from the black hole. Black holes continue to release energy in the form of this radiation until they have withered away to nothing. This is a bit of an exaggeration though.

Enzo neglects Hawking radiation, and for good reason. Hawking radiation is inversely proportional to mass squared, so the effect is usually negligible. A black hole the mass of our sun would have a Hawking radiation of temperature ~60 nK, which is about 45 million times colder than the cosmic microwave background (the ambient temperature of space). Assuming the black hole accreted no matter whatsoever, the 1 $M_\odot$ black hole would take ~10^{75} years [48] to evaporate—much much longer than the age of our universe, 13.8 Gyr (~10^{10} years). PBHs of size ~$9 \cdot 10^{-20}$ $M_\odot$ (which formed just after the Big Bang) are just now evaporating. [48] As we're dealing with 20 orders of magnitude, we can neglect Hawking radiation in our simulations.

Appendix B

Enzo Setup

Enzo is written in C, C++, Python, and Fortran, and uses the parallel computing message passing interface (MPI) (see Appendix C). Thus, compiling and running the code requires many modules. Listed here are the modules I used and their versions.

- Python 3.5, Anaconda 4.1.1 - Enzo's front-end programming language
- GCC 5.3.0 - a compiler for C, C++, Objective-C, and Fortran (among others)
- Open MPI 1.10.5 - a Message Passing Interface library
- FFTW 3.2 - "The Fastest Fourier Transform in the West"

In the following sections, I explain my choice in key parameters in the setup files. [49, 50]

Initial Conditions File

I used the cosmology constants from Planck 2015, table 4, the last column of the Planck 2015 results, section XIII: Cosmological parameters. The specific seeds used to randomize the initial conditions can be found on the pastebin copy of the initial conditions file.

Parameter File

```
  [cosmology]
Omega_m = 0.3089
Omega_L = 0.6911
Omega_b = 0.04860
H0       = 67.74
sigma_8 = 0.8159
nspec   = 0.9667
```

The cosmology package is activated with `ProblemType = 30`, followed by many cosmology parameters. The important lines I added were at the end of the file, listing the most relevant parameters distinguishing this simulation from other cosmology simulations.

The `StarParticleCreation` variable uses option 9 (which is coded as $2^9 = 512$ to combine with other options in a single integer). This option allows insertion of massive black hole particles by hand via the file , with user-specified mass, location, and time of insertion (defined in the file `mbh_insert_location.in`). The Enzo documentation cites Kim et al. 2010 for this method.

```
 # Simulation Specifics
StarParticleCreation = 512
RadiativeTransfer = 1
RadiativeTransferAdaptiveTimestep = 1
RadiativeTransferHIIRestrictedTimestep = 1
MBHAccretion = 1
```

The radiative transfer variables have their documentation in ray tracing parameters in the Enzo documentation. Setting `RadiativeTransfer` to one turns on the adaptive ray tracing following Abel, Wise & Bryan 2007. Setting `RadiativeTransferHIIRestrictedTimestep` to 1 turns on adaptive time steps as done in Wise & Abel 2011. Since this variable is set to 1, so too must `RadiativeTransferAdaptiveTimestep`, which sets the timestep to the finest resolution of the simulation grid.

Settings for `MBHAccretion` can be found on the Enzo documentation. Setting it to 1 uses Eddington-limited spherical Bondi-Hoyle formula [27] (i.e. Bondi accretion). Setting it to 6 turns on alpha disk formalism based on DeBuhr et al. 2010 [28] (i.e. viscous accretion).

Appendix C

Message Passing Interface

The following is a quote from an `Enzo` manual I co-authored.

Imagine I hand you a list of ten thousand simple arithmetic problems and ask you to solve each of them within an hour. It's unlikely that you could do an average of more than two of them in a second without making any errors along the way (not to mention how tedious the task would be). How do you get the answers before the hour is up?

Call up a hundred of your closest friends and assign them 100 problems each to solve. Now they have more than half a minute to solve each problem. Most solve all of their assigned problems before the ten minutes end. You compile all the answers and present them back to me with plenty of time to spare.

If you had tried to do it all yourself, it would have taken about a hundred times longer (minus time spent sending and waiting for emails), but writing, sending, waiting to receive, and compiling information from emails takes a good amount of times as well—time that could be spent solving many problems yourself. If you had sent the ten thousand problems out to ten thousand individuals, while a majority would finish quickly, some may take much longer to respond, and some may not ever respond. Now, emailing time *far* exceeds computation time, and there was a lot of wasted energy and time. Sending ten problems per person would be more efficient, but a thousand problems is still a lot of emailing time.

This is essentially how supercomputing works. When we have a massive task that no one computer could solve (in a reasonable amount of time, or perhaps at all, due to memory restrictions), we send it to a supercomputer. The supercomputer divvies up the problem between a large number of processors—mini computers in themselves—which solve their individual problems and report back their results.

The average laptop is a sort of mini supercomputer. If your computer has a quad-core processor, it has four little slaves (processors) inside it to solve problems, all working in the same workspace (RAM: Random-access memory. Now take a thousand laptops and store them all in a few bookshelves, then wire them up so they can talk amongst each other—this is essentially how a supercomputer is structured. Laptops are analogous here to *nodes*, and each node has some large number of processors (e.g. 16, 24, 28).

The emailing system we used above is analogous to MPI (Message Passing Interface). When running astronomically large simulations, we divide space up into smaller sections and assign each section to a different processor. Objects will span across these divisions, and for that reason, processors need to talk between each other. While communication between processors on the same node are much slower than solving their own problems, communication between nodes is much slower. Therefore, we try to limit this communication as much as possible. MPI is the means by which all this communication happens: how the problem is divvied up, how processors talk to each other, and how they compile all their data into one place for the finished product.

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