2016-6

Finding the First Stars

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June 2016

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ABSTRACT

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Minor perturbations resulting from a brief period of inflation at the time of the universe's birth seeded the growth of all structure in the universe. Using Enzo, a research code optimized for running cosmological simulations, we simulate the formation of the universe. We take into account the most current cosmological parameters and plot star formation rates of the universe for halos of varying mass from the beginning of time until today. By simulating star formation of the early universe, we verify that initially minuscule dark matter pockets resulting from inflationary perturbations attract more and more matter as the universe expands. The resulting halos vary in size and have varying degrees of star formation. Additionally, this analysis paves the way for future members of the scientific community to test a new way of identifying population III stars in the cosmic microwave background.

ACKNOWLEDGMENTS

I'd like to thank David Neilsen of the BYU Department of Physics and Astronomy for his mentorship, guidance, and support in helping me choose this project and guiding me through all of the steps necessary to bring it into fruition.

A special thanks to Joseph Schmidt of the Los Alamos National Laboratory (LANL) who has been instrumental in teaching me how to run cosmological simulations. Without his extensive knowledge and eagerness to help, this study would not have been possible.

I gratefully acknowledge the computing time granted by the BYU Fulton Supercomputing Lab (FSL) and provided on the supercomputer MaryLou 7.

Additionally, I'd like to acknowledge Roger Cook of the BYU Department of Philosophy for his insights and Lawrence Rees for his readiness to participate in the defense.

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Chapter 1

Introduction to Modeling the Universe

1.1 Determining Early Star Formation Rates

Cosmology—the study of the universe, its origin, evolution and eventual demise—is a mystery that has intrigued mankind since the dawn of creation. The subject matter of cosmology is everything that exists. It encompasses everything from the seemingly endless legions of stars and galaxies to the leptons, bosons, and quarks of the microscopic world of elementary particles. Between these limits lies an infinitely complex hierarchy of patterns and structures that result from the interaction of natural forces and pre-existing matter, and it is within the midst of this inexplicably elaborate hierarchy that we find ourselves.

Although the universe began millions of years before the appearance of the first stars, these brilliant celestial bodies were the very first macroscopic structures to come into existence. Stars are the progenitor to all other structures that have since come, and the extreme conditions existing within these great balls of flaming gas allowed for every seemingly miraculous creation that would follow. Only in conditions as harsh and extreme as those that exist within a star is the synthesis of heavier elements made possible. The birth of every planet, meteor, moon, martian and human first began within a star. Thus, in order to more fully understand the origin of life, we first need to understand the fundamentals behind the formation of stars.

Among the few stellar objects that have not yet been directly observed by astronomers, the first generation stars to come into existence (population III stars) are of particular interest. Facing the very real possibility that population III Stars may already be extinct, astronomers have begun to think up alternative ways of observing such objects. One motivation for this study is to facilitate an investigation of one proposed way that could be used to detect these stars.

In this study, we simulate the formation of the early universe and analyze the varying star formation rates for halos of differing mass. Not only is it interesting to investigate the formation of these first stars, but by providing accurate star formation rates for halos of varying mass, a necessary step on the path to observing the very first stars has now been accomplished.

1.2 The Cosmic Microwave Background

When the universe was only about 380,000 years old, it existed as a bright white plasma that had finally cooled enough to start forming atoms and basic gaseous elements (i.e hydrogen and helium). This was the the first time in history that the universe had cooled enough to let light photons travel without immediately being absorbed by free electrons or protons. Since this era of recombination, the universe has continued to expand, and the photons have continued to travel, resulting in a light wave that has been shifted to the size of a microwave. Now, approximately 13.8 billion years later, a snapshot of the universe can be taken by observing the universe in the microwave spectrum and we observe that light in a map of the cosmos referred to as the cosmic microwave background (CMB).

As previously mentioned, this study on early star formation is only the first part of a much larger study that will demonstrate the effect that population III supernova explo-

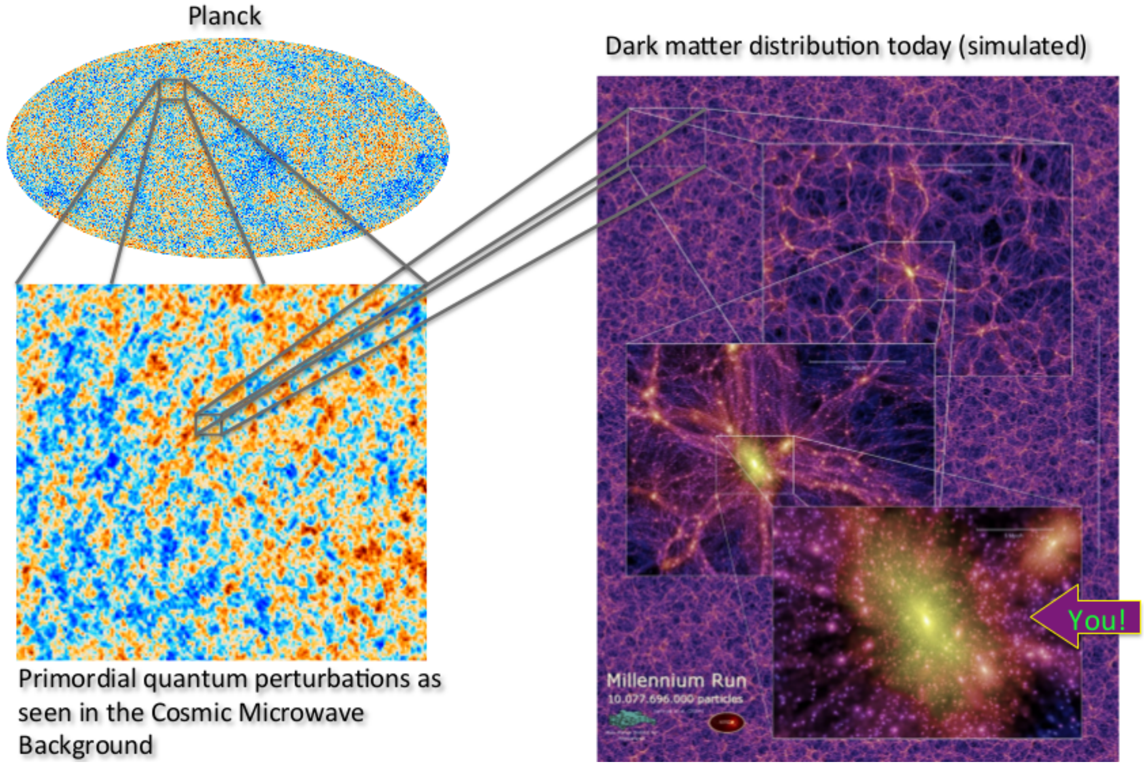

Figure 1.1 Taken from (Leclercq et al. 2014). The top left shows the perturbations left over after inflation as seen from the cosmic microwave background (CMB). Compare this to the simulation on the right. Note that it is easily inferred that the small fluctuations, as measured and seen in the CMB, did indeed grow into large scale structures such as galaxies and clusters via gravitational collapse.

sions (astronomical events that occur during the final evolutionary stages of a massive star's life) had on the CMB signatures. The interaction between highly energetic electrons that were emitted by population III supernova explosions and the photons emitted during the recombination era result in a pattern known as the Sunyaev-Zeldovich (SZ) effect. The SZ effect is a local distortion of the CMB that occurs when high energy electrons from these supernova collide with the photons that were released during recombination via inverse Compton scattering. In other words, the lower energy CMB photons receive energy via collisions with the higher energy cluster electrons. The SZ effect leaves observable distortions in the CMB through which population III stars can be studied.

The CMB is still a relatively new discovery with a great deal of untapped potential.

In order to eventually learn how everything in this universe came to be, we must first be able to study the artifacts left behind from its beginning. Further refining and proving a method of identifying population III stars in the CMB will provide an unprecedented way of observing the origins of our universe.

1.3 Big Bang Cosmology and Inflation

Cosmology aims to take all known physical phenomena and place them within a single coherent framework. To do so, it is necessary to start as close to the beginning as possible. As cosmology studies everything that exists, it is only natural to begin at the point when all things once existed together. Approximately 13.8 billion years ago, everything was contained within an infinitely small, infinitely dense entity known as a singularity. In the standard big bang cosmology model, this singularity began to expand. Just a fraction of a fraction of fraction of a second after the expansion began (at an estimated time of 10^{-37} seconds), there was a time of rapid growth—or inflation—that resulted in minor perturbations. These perturbations seeded the universe with the beginnings of what would eventually become galaxies, stars, planets, and everything else in existence that we now enjoy. The rapid rate of growth experienced during the inflationary epoch quickly stabilized into a more gradual expansion that we continue to experience even to this day. The inflationary period is arguably the most significant theory that has been put forth in relation to the Big Bang, and —according to some— is the last major viable physical discovery that can be verified and explained by theory (Smolin 2006).

As previously alluded to, one of the most interesting implications of this inflationary period is that the extremely rapid inflation *must* create perturbations on the order of the Heisenberg uncertainty principle from quantum mechanics. To imagine this intuitively, think about the process of blowing bubbles. Bubbles very rapidly inflate from essentially nothing to a not quite perfect sphere that eventually pops and ends up everywhere. Similarly, inflation represents a time of expansion so fast that when it turned off at a time we shall denote as t_{off}, the Heisenberg uncertainty in t_{off} produced microscopic density fluctuations in the early universe. Or, more formally, inflation caused spacetime to expand an amount $\exp(N)$ for some N (often thought to be around $N \sim 60$). The uncertainty in N due to the the Heisenberg uncertainty principle is about 10^{-5} ($\delta N \sim 10^{-5}$) at any given point. Although minor, this δN suggests the existence of perturbations opened up a gateway into the formation of galaxies, stars, and eventually planets (including planetary life and everything else that this inherently suggests).

To quickly recap what's been said, inflation caused minor density deviations that vary from location to location. At one location, the density will be slightly higher than the average global density, while a few Megaparsecs further the density may have a slightly smaller value than on average. The observed fluctuations in the temperature of the cosmic microwave background radiation are a reflection of these density perturbations, which is how we know that the primordial density perturbations were on the order of 10^5. In fact, it was the measurement of this minor 10^{-5} fluctuation signature, as predicted by the Heisenberg uncertainty relation, that led the COBE team to win the Nobel Prize in 2006. The CMB is the oldest observable artifact left behind by the universe, and since its discovery in 1965 we have now been able to learn so much about the earliest days of our universe.

One final note to be made is that the CMB fluctuations form a perfect Gaussian distribution. This is significant for inflation because inflation should have been so excessively fast that any two neighboring points would not have been able to interact during the process. According to a well-known theorem from quantum field theory known as Wick's Theorem, one can show that any set of quantum fluctuations where neighboring points cannot interact creates a Gaussian distribution of fluctuations (Weinberg 1972). Yet, hidden within this map of the early universe, there are so many more secret messages that scientists are only just beginning to decode.

Having now established that there were perturbations in density on the order of 10^{-5} early on, the question of how structures such as galaxies and clusters evolved from these minor fluctuations still remains. Prior to representing this mathematically, here is a more qualitative explanation of perturbation theory. First note that a universe with minute density perturbations will induce local differences in gravity. In a higher density region, the surplus of matter will exert an attractive gravitational force larger than the average value. Because of the differences in gravitational force, the halo will begin to decelerate. More specifically, an overdense region will experience a gradually stronger deceleration of its expansion velocity so that its its initial expansion will increasingly slow down with respect to the universal expansion of spacetime. Because matter gets attracted slightly more by a region of higher density it will also have the tendency to move towards that region. As the mass of the overdensity increases, the slow-down of the initial cosmic expansion gets correspondingly stronger. Once the region has become sufficiently overdense, the mass of the fluctuation decouples entirely with the universal Hubble expansion and it begins to contract. It will continue to contract for as long as the internal pressure forces are not sufficient enough to counteract the infall, thus, it will continue to grow and accrete matter from its surroundings. Ultimately this contraction will turn into a full collapse to form a gravitationally bound object that, by means of the mutual exchange of energy, will seek to reach virial equilibrium. (Gebouw Accessed June 2016)

Mathemetically, density perturbations (δ) are represented as

$$\delta = \frac{(\rho - \bar{\rho})}{\bar{\rho}}, \tag{1.1}$$

where δ is a density perturbation, ρ is the density at any given point and $\bar{\rho}$ is the average density of the universe. Thus, δ represents a fluctuation in the average density of the universe. Much can be learned about the formation of structure in the universe just by examining potential values of δ.

Think for a moment about what would happen if the universe was perfectly uniform and there was no fluctuation in density ($\delta = 0$ at every point). Would there ever be gravitational collapse? The answer would of course be no. This is because every point feels gravity pulling on it equally in all directions (since the universe is completely homogeneous). Similarly, it may not be hard to guess that if δ is very small and close to zero, there will also be no gravitational collapse. At this point when $|\delta \ll 1|$ the system is in the linear regime. A more in depth explanation of linear purturbation theory can be found in (Peebles 1980) or is similary discussed in (Gebouw Accessed June 2016). In this simplified discussion of linear theory, we will encapsulate the full analysis by stating that if the density (ρ) of any given perturbation is not significantly more than the average density of the universe, the mass of the perturbation will continue to grow until it becomes dense enough to exit the linear regime and begin to collapse. When $\delta \sim 1$ (the density of the perturbation is about twice the average density), the solution is no longer linear and collapsing begins. Hence it is commonly said that gravitational collapse happens in this non-linear regime.

At a certain point, the perturbation will have grown substantially enough that an even stronger statement could be made about its progression towards stardom. One can show that by the time a mode grows to $\delta \geq 1.686$, enough time for collapse will have taken place such it has become fully virialized (Hu Accessed June 1, 2016). As used herein, virialized means that the perturbation has collapsed significantly enough to become gravitationally stable. Despite having become gravitationally stable, the smaller structures within the system will continue to interact, but the cluster will neither continue to expand nor collapse.

In summary, one finds that when:

$$\begin{aligned}
|\delta \ll 1| \quad &\Longrightarrow \quad \text{Perturbation growing, not collapsing. (linear regime)} \\
\delta \sim 1 \quad &\Longrightarrow \quad \text{Intermediate state where gravitational collapse has begun. (nonlinear regime)} \\
\delta \geq 1.686 \quad &\Longrightarrow \quad \text{Collapsed sufficiently to be virialized. (nonlinear regime)}
\end{aligned}$$

1.4 Results of Inflationary Perturbations

Rehashing some of what has already been said, in the beginning there was an infinitely dense singularity that contained all of the Universe's matter in one microscopic point. That singularity very rapidly began to expand and, in doing so, it left behind slight perturbations that were amplified by gravity as the universe continued to grow.

While the force of gravity is certainly sufficient enough to form cosmic structures, in order to do the job effectively, scientists realized that there would have to be a whole lot of mass in the universe. One of the most important questions asked in physics today is the question of whether or not dark matter really exists. Observations clearly show that we do not see nearly enough luminous mass (i.e. stars) to reconcile the amount of mass needed for the observed motion of the universe. Thus, in order to make observations consistent with known theory, there is a need for large amounts of unseen mass in the outer parts of galaxies. This unseen mass is dark matter. In this study, we assume the existence of this non-luminous matter. Thus—although we will not directly be proving the reality of this matter—by using the theoretical implications of dark matter our calculations, this study also contributes further evidence to its necessary existence.

Continuing to analyze the bigger picture, we note that the density perturbations made way for tiny clumps of dark matter. These gravitationally bound lumps of dark matter are referred to as halos, and they continued to grow and expand along with the universe. According to our analysis above, halos that are denser than average will collapse. Qualitatively, this occurs because a piece of the universe that is denser than average exerts a stronger gravitational pull on its surroundings than average. It will therefore tend to suck material in, and become more and more dense with the passing of time. Given that dark matter attracts regular matter as well, the term halo typically refers not only to these small clumps of dark matter, but it also includes the normal matter that has accumulated along with the dark matter. In fact, dark matter will often be found with normal matter because where it clusters, everything else does as well. Eventually, strongly bound lumps will form and begin to collect filaments creating a structures such as the ones seen in Figure 1.1.

The natural follow-up to this discussion is to wonder how likely any given halo is to undergo gravitational collapse. The density prerequisites and thresholds have already been explained in the previous section. However, not every fluctuation in the universe is guaranteed to reach the point at which it will gravitationally collapse. Only very large fluctuations will end up collapsing and even among the largest halos, only a certain fraction will have have actually crossed the threshold into gravitational collapse.

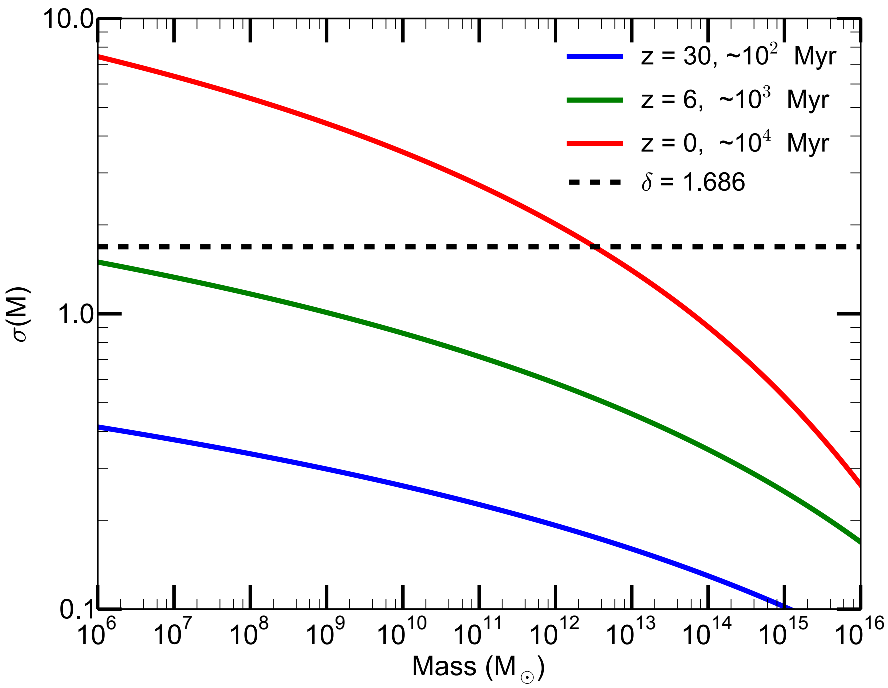

Figure 1.2 $\sigma(M)$ at a variety of redshifts compared with $\delta = 1.686$ (Smidt & McArthur Accessed June 2016).

A statistical measure of how many halos, of any given mass, have reached the threshold for gravitational collapse is given by $\sigma(M)$. Given that $\sigma(M)$ is a function of mass, an important implication of this function is that stellar objects of certain masses are much more likely to form than stellar objects of other masses. This is why there are a lot of objects in the universe that are about 10^{10} solar masses ($M_\odot$), but there are not as many objects that fall under the umbrella of being about 10^{15} $M_\odot$. In fact, up until now, scientists have not observed any stellar objects greater than 10^{16} $M_\odot$. Analyzing a plot of $\sigma(M)$ can help us to understand these observations.

Figure 1.2 shows sigma at three separate redshifts. Redshift is the displacement of spectral lines towards longer wavelengths (the red end of the spectrum). In cosmology, we are especially concerned with the shift in a photon's wavelength that occurs due to the expansion of space itself. In a nutshell, cosmological redshift gives rise to a type of cosmological time dilation wherein we find that greater amounts of redshift imply that the universe is now bigger, and therefore older, than it was when that photon was emitted. Qualitatively, the first thing to note is that the more time that has passed (lower redshifts), the more likely it is that any given halo will have virialized.

At **z = 30 (∼ 100 Myr)** a fair number of virialized halos containing $\sim 10^6$ $M_\odot$ of material reached temperatures and densities sufficient enough to collapse and subsequently form some of the very first stars. Performing a simple comparison between the critical density ($\delta_c = 1.686$) and $\sigma(M)$ at redshift 30 for a halo of about $10^6 M_\odot$ will determine the fraction of halos that collapsed. Here $1.686/\sigma(10^6) = 4.1$ meaning that a fluctuation containing 10^6 solar masses of matter virializing by $z = 30$ represents a 4.1-σ anomaly. To convert the standard deviation one could determine that the probability of a 4.1-σ anomaly is

$$(1 - \text{erf}(4.1/\sqrt{2}))/2.0 = 2.0 \times 10^{-5}, \tag{1.2}$$

where erf is the error function. This means that only 1 in $\sim 50,000$ fluctuations containing 10^6 solar masses of material have virialized by $z = 30$. To put this into potentially more familiar terms, in a halo similar in size to the Milky Way (with an initial mass of $\sim 10^{12}$ solar masses), only ~ 20 such halos would have been able to virialize and form stars at redshift 30. Though this number is small, it's non-trivial which is why we say the first stars in our past probably formed around $z \sim 30$ ($\sim$ 100 Myr after the big bang).

One could perform similar calculations at **z = 6 ($\sim$ 1,000 Myr)**; but, for the sake of this analysis, it is sufficient to say that virialization began to be much more common by this time in the universe's history. This is also supported by the qualitative fact that at $z = 6$, $\sigma(M)$ is approaching the magic 1.686 threshold for more massive halos.

Finally, at **z = 0 ($\sim$ 14,000 Myr)**, a sigma analysis clearly reflects that the virialization of dark matter halos is has become a commonplace occurrence. The fact that we exist in a virialized Milky Way galaxy (about 10^{12} $M_\odot$) is not too surprising. Further, this plot explains why the biggest gravitationally bound objects, known as star clusters, have masses that do not go far beyond the order of $\sim 10^{15}$. For example, the Virgo Cluster is about 1.2×10^{15} $M_\odot$ and the current record holder for the largest distant galaxy cluster to have been discovered is the monster known as *El Gordo* weighing in as a mass of $\sim 3.0 \times 10^{15}$ $M_\odot$.

Chapter 2

Methodology

2.1 Simulating Star Formation

We used the most contemporary cosmological parameters and assumptions to set up and run a simulation of early star formation. This section outlines the process that was taken, beginning with the set up of the simulation, and continuing with an outline of the method used to run the simulation and subsequent analysis. In light of the motivation behind this study, remember that to successfully demonstrate how to identify population III stars in the CMB, it is first necessary to provide an accurate representation of star formation as a function of mass.

The cosmological principle asserts that on large scales, the universe is considered to be essentially homogeneous and isotropic. Or, in other words, since the fundamental forces are expected to act uniformly throughout the universe, the universe is essentially the same in every place and, on the large scale, there should be no observable irregularities. Isotropy means that the same observational evidence is available to observers at any location in the universe and in any direction. This implication of this principle that is often used in cosmology is that any given subsection of the universe can be equated to the universe as a whole.

Prior to beginning the simulation, we first decided how much of the universe would be necessary to simulate the in order to represent the universe as a whole. Although the cosmological principle implies that any subsection can represent the universe as a whole, we wanted to be sure that we were looking at a portion of the universe that contained the ideal amount of material to form stars at the fastest rates. A box size that is too large would produce large scale structures at slower rates, and a box size that is too small would do just the opposite. Neither of these conditions are ideal or common. Thus, in order to to determine the range of halo masses that the simulation should focus upon, we relied on a $\sigma(M)$ analysis, much akin to the thought process outlined in section 1.3 above. Remember that clusters in the 10^8–10^{12} $M_\odot$ range are where stars form at the quickest rates. Based on the qualitative sigma analysis it was determined that, to simulate clusters in the 10^8–10^{12} $M_\odot$ range, we should focus our simulation to box size of about 32 Mpc^3. In a volume of this size, the mass resolution is enabled to capture star formation of halos with the optimal mass for producing the greatest amount of stars.

To put this in other terms, imagine that you are trying to observe the construction of a neighborhood. If you are too close to the construction, you will only see the individual materials that built individual walls. You would be so close that you'd only be able to observe a single house (potentially only one part of that solitary house), and would never be able to see the final product. Conversely, if you are trying to observe the construction from a neighboring mountain miles and miles away, you will not see the final product until it was nearing completion, and by that point you will have missed seeing any of the details that went into it's formation. Ideally, you would find an observation point, perhaps on a nearby hill, where you would be able to see an entire house along with several other houses in the neighborhood. Given this ideal scenario, in addition to enjoying a perfect view of the final product, you would be able to observe the real-time progress of all of these houses along the way.

Another important consideration that was made in choosing a boxsize of 32 Mpc^3 is a well known statistic in cosmology that most objects were formed by mass that collapsed with a diameter of no more than $\sim$8 Mpc. While we have been discussing sigma as a function of mass, it is often represented as a function of radius. Given that the universe is essentially homogeneous, two large spheres of equal radius will essentially contain about the same amounts of mass. σ_8 is the value of sigma for a sphere with a radius of 8 Mpc or about 0.85×10^9 $M_\odot$. A comparison between the critical density ($\delta_c = 1.686$) and a halo of this size shows the standard deviation cutoff is 2 for a halo of this size, or in other words one would find that 95% of objects that form began with a diameter of about 8Mpc. So, relating this back to the analogy, an 8 Mpc region would show us how one house was formed, but if we want to see a whole neigborhood we should backup to a point where we can see a whole neighborhood—in this case, a 32 Mpc cube.

2.2 Establishing the Initial Conditions

Having established that the ideal portion of the universe for us to simulate is $\sim$32 Mpc^3, we begin the simulation at a time early enough that no perturbations will have begun to collapse. Different authors have debated what redshift you can start at. Arguments for the ideal starting point range from $\sim z = 100$ to $\sim z = 150$. We decided to avoid that debate entirely by starting at $z = 200$—a nice round number well before entering into any of the proposed danger zones. The simulation was run using Enzo, a research code for running cosmological simulations (more specifics will be discussed in the forthcoming section). In order to generate initial conditions needed for Enzo to run this simulation, we used a program called MUSIC. MUSIC (MUlti-Scale Initial Conditions) was developed to provide initial conditions for several types of high-resolution "zoom" cosmological simulations. For a more detailed description of the method and algorithms used to compute these conditions, refer to this paper by Hahn and Abel (Hahn & Abel 2013). Finally, we incorporated the latest Plank 2015 cosmological parameters. These are some of the parameters that were used:

```
[cosmology]
# Come from Planck 2015.  Table 4 last column of:
# http://arxiv.org/pdf/1502.01589v2.pdf
Omega_m                                 = 0.3089
Omega_L                                 = 0.6911
Omega_b                                 = 0.04860
H0                                      = 67.74
sigma_8                                 = 0.8159
nspec                                   = 0.9667
```

A full copy of the initial conditions file used to set up the computation run by MUSIC is in Appendix A.

With these initial conditions in place, we ran the MUSIC executable file. Among other things, we were then supplied with a file containing the proper configurations needed to run the Enzo simulator. However, in order to turn on the effects of star formation, we still needed to add a few lines prior to running the simulator. The changes that were made to this file will be further explained in the following section.

2.3 Running the Simulation

Enzo is an adaptive mesh refinement (AMR), grid-based hybrid code (hydro + N-Body) which is designed to do simulations of cosmological structure formation. It is written in a mixture of C++ and Fortran 77. Note also that Enzo is parallelized, using the MPI message-passing library and uses the HDF5 data format to write out data and restart files in a platform-independent format.

With the initial conditions from MUSIC and after guaranteeing that all of the parameters were set correctly, we first added some extra lines to the parameter file in order to turn on star formation and corresponding assumptions. Among these lines was a command to provide an output file output every 200 time steps. This way we could see enough of what was happening along the way without the simulation taking longer than necessary. We also specified data dumps at redshifts 15.0 and 7.0.

Some of the important parameters for the MUSIC output file are:

```
StarParticleCreation = 2

StarParticleFeedback = 2

StarParticleRadiativeFeedback = 1

StarMakerMinimumMass = 2.63427e+07
```

The above lines call upon physics that had already been built into the Enzo platform (Enzo Accessed June 2016). The *StarParticleCreation* $= 2$ parameter turns on star formation according to a method defined by Cen & Ostriker (Cen & Ostriker 1992). The algorithm written to emulate this method of star creation is based on the fulfillment of several different criteria:

1. The gas density must be greater than a certain preset threshold. In our simulation, this threshold was left at the default value of 100 particles/cc. Note that this parameter is in code units that are relative to the total mean density (i.e. overdensity with respect to the mean matter density).

2. The divergence must be negative.

3. The dynamical time must be less than the cooling time or the temperature must be less than 11,000 K. The minimum dynamical time considered is given by a preset parameter that sets a limit on the rate of star formation based on the fact that stars have certain formation rates and life-times. In this simulation, we left this parameter at the default value of 1 Billion years.

4. The star particle mass must be greater than StarMakerMinimumMass, which is in units of solar masses ($M_\odot$). Note that we set the StarMakerMinimumMass to a certain value as specified above. This value (2.63427e+07 $M_\odot$) represents the baryon mass resolution that was provided by MUSIC in the initial condition process.

5. This method uses Stochastic star formation wherein a record of the global sum of 'unfulfilled' star formation is kept. This takes into account the stars that were not previously formed because the star particle masses were under the specified StarMakerMinimumMass. When this running sum eventually exceeds the minimum mass threshold as specified, it forms a star particle.

6. The cell does not have finer refinement underneath it. In other words, it is important to note that this method has a limited amount of mass resolution.

7. Finally, we should note that the star particle velocities are zero.

For a more in-depth explanation of the method see (Cen & Ostriker 1992).

Likewise, StarParticleFeedback works in conjunction with StarParticleCreation to turn on the feedback for these stars as they form. StarParticleRadiativeFeedback made sure that star particles that were created become radiation sources where the UV luminosity is set to the default value of 3^{-6}. (The UV radiation is derived from the fraction of the rest-mass energy of the stars that were created. This rest-mass energy is returned as UV radiation with a spectrum akin to that of a young star.)

After preparing the simulation, it was submitted to MaryLou 7 of the Fulton Supercomputing Lab where the computing took place. The simulation ran on 16 nodes with 16 processes per node for a total of 256 processors and took just under 2 hours.

2.4 Synthesizing the Output

After running the simulation, Enzo provided us with a number of output files. These results contained information that mapped out the formation of structure in the universe beginning long before any stars were even imagined and progressing onward to the endless expanse of stellar structures that we know today. In the course of finding these star formation rates, there were a number of other useful and interesting observations that we made along the way. Here I present some of the most interesting data points that were taken from the results of the simulation.

Figure 2.1 is a representation of the densest halo in our simulated universe. Much like the Figure 1.1 above, by looking at this plot, one could imagine what this section of the universe would look like if seen from afar. This is a slice plot of number density centered on this densest point in the region (at a redshift of 0). In this plot, we see regions similar to the perturbations measured in the CMB. The densest cluster depicted in the middle of this image represents a galaxy cluster and the thread-like webbing connecting the halos of differing sizes are known as dark-matter filaments. Remember from our previous discussion, that galactic filaments form along and follow web-like strings of dark matter. As the universe expands with time, the initial perturbations caused by inflation created pockets of dark matter. These initially minuscule pockets have attracted matter of all kind and form the basis of all structure in the Universe. Dark matter gravitationally attracts baryonic matter, and it is this "normal" matter that astronomers see forming long, thin walls of super-galactic clusters. On a high level, one can infer that because a greater amount of

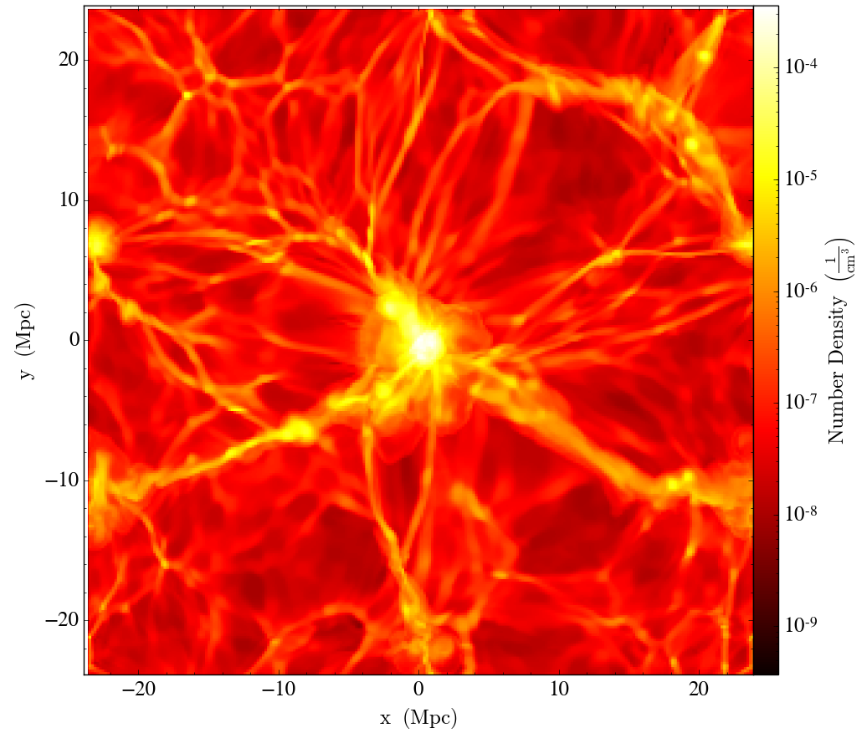

Figure 2.1 A snapshot at $z = 0$ of the densest halo that was formed in the specified $32/h$ Mpc region. (Where h is a cosmological constant related to the relative expansion of the universe.) Note that number density —the number of particles per cm^3— is used to study reaction rates and how close the particles are (number per cm^3).

growth was observed in this region that there must have been larger initial perturbations.

Another plot that is especially noteworthy is the halo mass function which shows all of the halos in the universe, for any given time period (redshift), organized by their relative masses. The halo mass function is strongly related to the sigma function, however, while $\sigma(M)$ is a statistical measure of how many halos have reached the threshold required to potentially begin the process of gravitational collapse, the halo mass function gives the distribution of halos that actually have formed as a function of their respective masses. It is the result of the predictions made by a sigma plot such as the one shown in Figure 1.2.

The halo mass function is also an interesting result because it is a function that could

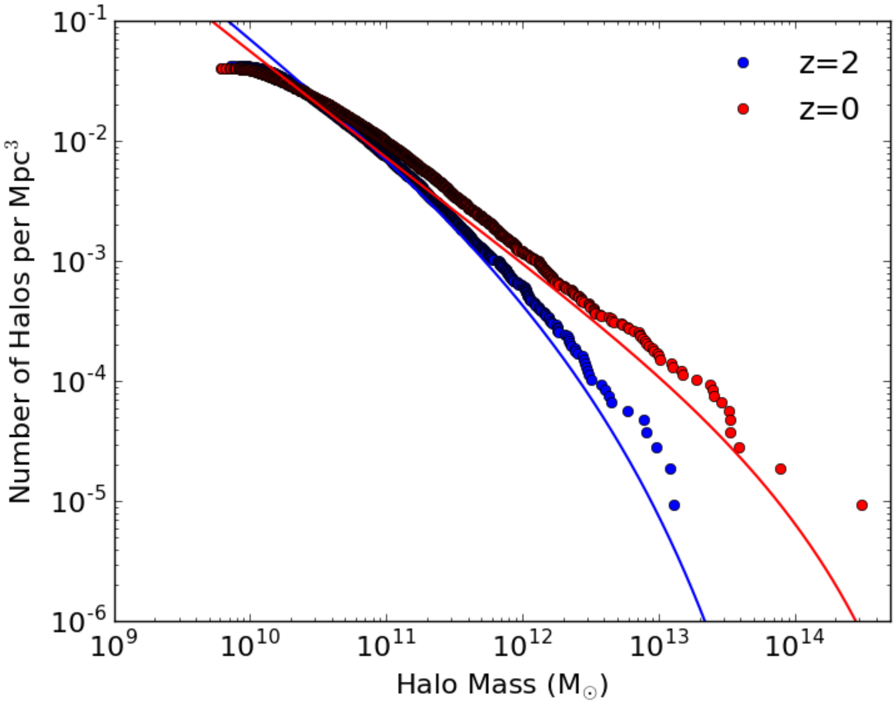

Figure 2.2 The mass function from our simulation. Each point represents a halo in the specified region at the given redshift. The two lines are the standard theory curves coming from a halo model calculation. Note that since the boxsize of our simulation was specified to be 32 Mpc^3,we are able to detect down to $1/32^3$ ($\sim 1^{-5}$).

theoretically be measured by observational astronomers. That being said, in practice, making mass function based solely on observation is actually a very difficult task to perform correctly. For one, there are still inherent limitations associated with our current technology. Given these limitations, we cannot guarantee that each and every halo can actually be observed. For instance, a halo may not be bright enough to be seen or a given halo may only be detectable at certain wavelengths. Additionally, it is difficult to separate the observed halos by their given redshifts because there is still a fair amount of uncertainty in such a calculation. Because of this, often luminosity functions are preferable to observers, but that is an entirely different topic.

In order to generate the halo mass function (as seen in Figure 2.2), we used a script (premerger.py) written in python that identified the halos and provided us with certain statistics (such their mass and location) about each halo in the region. This code was developed by Joe Schmidt of LANL and is described in greater detail in a paper that was written to walk new students through the process of running cosmological simulations (Smidt & McArthur Accessed June 2016). In this script, we call upon a module that is part of a larger cosmological plotting framework more formally known as the YT Project. For a more detailed explanation of the YT Project, see the YT documentation (YT Accessed June 2016).

After running the halo finder over the entire 32 Mpc^3 region (for data dumps of varying redshift) we were able to generate this plot given the halos relative masses and locations. Note that the results of running the halo finder are essential in obtaining star formation rates as a function of mass. The implications of this statement will be further explained in section 3.1.

Looking at Figure 2.2, note that the halo model curves come close to the predictions made by standard theory, but they are not an exact match. Admittedly, this is partially due to the fact that we did not specify a box large enough to generate an ideal plot of the mass function. Similarly, we also would have needed specify a greater mass resolution. But, these two potential sources of error do not explain why theory estimates a greater number of low mass halos than what is observed observed in our simulation. This lack of less massive stellar objects is known among astronomers as the dwarf galaxy problem. Observational findings show fewer dwarf galaxies than analytic theory predicts. However, this also implies the positive outcome for us that simulations do better job of matching observation than analytic theory. That said, even these simulations are not perfect and thus there is a great amount of research currently being conducted to find solutions to these and other observed discrepancies.

Another interesting observation that can be made by looking at the halo mass function is that at $z = 2$, there were already a very substantial number of 10^9–10^{11} $\mathrm{M}_\odot$ galaxies. In fact, you can see from the plot that the number of halos found in this mass range already matched up to the current ($z = 0$) number of halos in this range. However, we also note that there were not yet very many halos greater than $\sim 10^{11} M_{\odot}$. Halos of that size take much longer to form and this fact explains why we do not see more of these until $z = 0$. The significance of what was happening in the universe at $z = 2$ will be further discussed in the following section.

One final consideration to make as one observes this plot is the correlation between the observed mass function and the plot of $\sigma(M)$ Figure 1.1. As predicted by the sigma plot, many more high mass halos formed than low mass halos. Again, we also note the tendency of more massive perturbations to gravitationally collapse and form stars. This observation confirms existing theory and aligns with what we would have expected from an accurate simulation of the universe.

Chapter 3

Results and Conclusions

3.1 Star Formation Rates

The rate of star formation varies depending on the masses of the dark matter halos and, by correlation, the size of the initial perturbations resulting from the inflationary epoch. As one takes a step back to look at the formation of stellar structures as a whole, it is evident that the rate of star formation differed greatly depending upon the conditions of the universe at any given time in its history. There are points in history at which there is no star formation at all, other points where there is a minimal amount, and perhaps the most interesting point is when all of the conditions became so ideal for star formation that it reached its peak. To examine these trends, we decided to analyze the star formation rate of the 32 Mpc^3 box as a whole, rather than looking at each halo individually. Pulling in the data from the entire region and sorting it by redshift had the effect of averaging the star formation rate of *all* the halos that had been formed regardless of their relative locations. Furthermore, since the cosmological principle asserts that the composition of the universe is essentially the same in every observational direction, the star formation rates for this simulation as a whole are able to accurately represent the simulation rates for the entire universe.

Figure 3.1 is the plot that resulted from the analysis of the 32 Mpc^3 box as a whole.

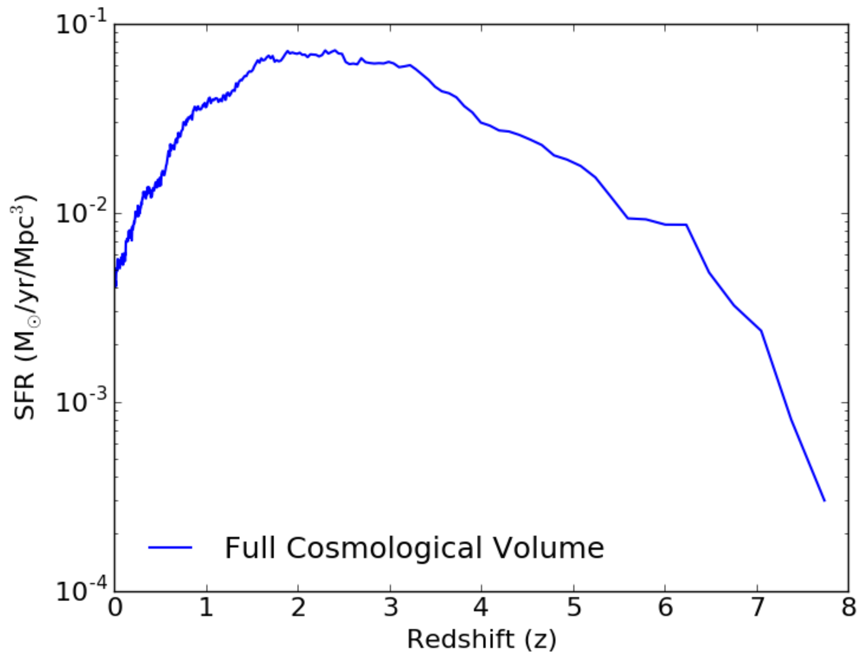

Figure 3.1 This plot represents the star formation rate for the universe as a whole.

As discussed in section 1.4, the very first stars began to form at redshift 30 ($\sim$ 100 Myr) and by redshift 6 ($\sim$ 1000 Myr) virialization had become increasingly common. However, as is evident from this analysis, star formation did not reach its peak values until about $3-4\times10^9$ years ($z\sim2$) after the big bang. There are a number of factors that allowed star formation to reach its climax during this era, but the primary point is that at this time in the universe's history, it was still young enough that all of there was a very significant amount of gas still readily available and the halos had finally become massive enough to collapse and produce star formation on a large scale.

Prior to this epoch of star formation, halos were still relatively small and therefore, there was not as much star formation. Part of the reason that halos suddenly became so much larger during this time in history was that a number of young galaxies had now become 'cannibalistic'. In astronomy this means that they grew to be so close together that they would violently merge into a much larger galaxies. The growth of stellar structures—

including quasars, monster radio galaxies, and star clusters—accelerated in pace all across the universe. In addition to the fact that more massive halos were allowing for the formation of more and more stars, the universe was releasing heavier elements into space that stimulated formation of stars. This was because, at this point in the universe's lifespan, many of the first population III, and even some of the next generation population II stars had begun to die off, and in doing so they left behind metal-rich remnants. (Note that in astronomy, essentially any element that heavier than hydrogen or helium is considered a metal.) When these heavier elements were released back into the universe at the end of the stars life, they would subsequently inject themselves into new halos that would in turn begin to cool and collapse (initiating even more star formation). As is clearly evidenced by our simulation, we see that the combination of these events created the perfect environment for star formation to run rampant.

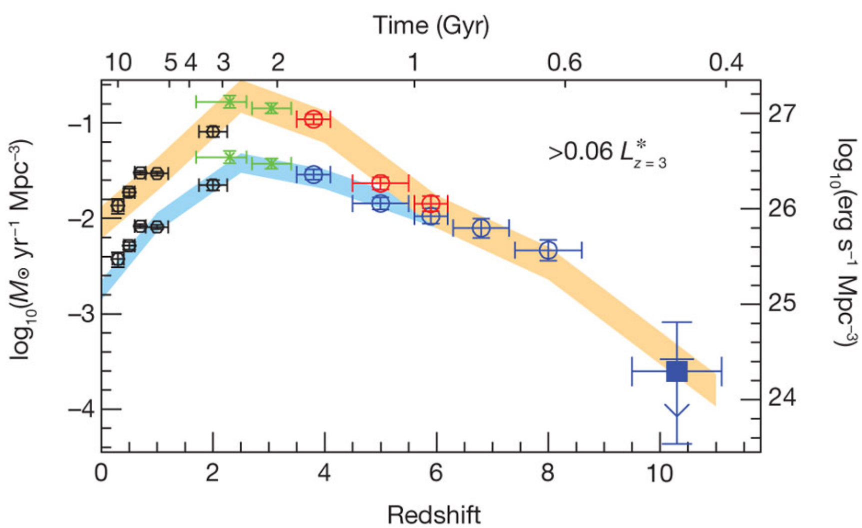

Figure 3.2 Taken from (Bouwens et al. 2011), this figure represents the observed star formation rates of the universe. Note that there is some discrepancy concerning how to best represent the star formation rate. The blue versus the yellow curves differ in a manner akin to the differences found in deriving Hubble's constant. This plot shows the rest-frame continuum ultraviolet luminosity density (right axis, blue points) at $z \approx 10$, and the star formation rate density (left axis, red points) derived from the extinction-corrected luminosity density.

For the sake of comparison, I've included Figure 3.2. This graphic is a representation of the observed star formation rates. For more information on how it was created see (Bouwens et al. 2011). Note the similarities between these observed rates and the simulated rates. Of particular note, they both peak in precisely the same places ($z \approx 2$) for the reasoning that has just been explained. Admittedly, however, given that the simulation was run with a limited amount of resolution, they do differ slightly as redshift increases.

In addition to being able to study a high level timeline of the star formation in the universe (as seen in figure 3.1), we were especially interested in analyzing how star formation rates differ for halos of varying masses. These star formation rates are ultimately what is needed to derive how many of the first stars went supernova, a figure that will be incorporated in the eventual work of identifying population III stars in the cosmic microwave background. To generate these individual star formation rates, we used the results from the halo finder python script that was run as described in section 2.4 above. Given the location and mass for each halo in the specified region, as provided by the halo finder, we were able to further analyze the formation rates for each halo. A similar analysis to what was done for the box as a whole was again performed using YT, but this time it was run for each individual halo.

Figure 3.3 is the resulting plot that takes into account halos from each relative mass starting from 10^{10} $M_{\odot}$ and ranging to 10^{14} size halos. Ten (10) halos from each relative mass were taken and averaged to give these results. As expected, the most massive halos had the highest rates of star formation. Or in other words, for the larger initial perturbations we observed greater amounts of virialization and thus a greater amount of stellar objects.

We also note that, as is typical, not every cluster behaves in exactly the same way. There are so many factors and potential explanations that it would require a whole new study to even begin to investigate and discuss. For example, note that the formation rates of the halos in the 10^{11} $M_{\odot}$ range exceeded the rates of the halos in the 10^{12} $M_{\odot}$ range at one

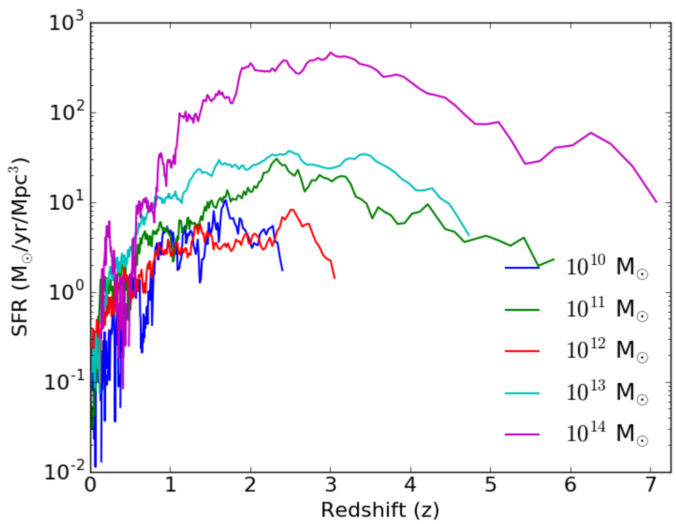

Figure 3.3 Star Formation rates for a Halos of varying masses.

point. To mention just one possible explanation for this occurrence, let me just remind the reader that, in some cases, we see clusters merge. In such a scenario, we would see a peak in star formation and therefore we may sometimes see bigger galaxies that don't necessarily have the star formation rates that intuition would suggest.

One final thing to note about this plot is that these curves show a generally higher average rate of star formation than for Figure 3.1 above. This is because Figure 3.1 above averages over the entire 32 Mpc^3 volume, including all of the empty space, thus bringing the average down quite a bit. Inside the halo there is no empty space, so the resulting average for this plot is higher.

In summary, we can conclude that the minor perturbations experienced at the end of the inflationary epoch did indeed seed the formation of stars. More significantly, we confirm the trend that larger initial perturbations lead to higher star formation rates and more stellar objects.

3.2 Future Work

Perhaps the most significant conclusion of this work is that it has an immense amount of potential to facilitate future research. As previously mentioned, this study was largely motivated by the work of A. Cooray and R. Sheth (Cooray & Sheth 2002), wherein they present an extensive review of the galaxy power spectrum and the contributions of the SZ effect to that observed spectrum. A power spectrum indicates how much 'power'—a signals energy per unit time—is in fluctuations at different length scales. The CMB is essentially a measure of the fluctuations in the universe's power spectrum at a time very near it's beginning. Using the derivations made by (Cooray & Sheth 2002) in which they build off of many fundamental cosmological models of the universe, one could very feasibly identify population III supernova in the CMB. The missing link to performing an analysis as described in their paper is the need to first generate accurate star formation rates of the universe as a function of mass at any given redshift (as we have done in this study).

Given these star formation rates, one could determine the number of population III stars that went supernova based on a statistical analysis of how many supernova result given the prescribed conditions. There are a number of papers and textbooks that describe how to accurately make such a calculation. In essence, an analysis of this nature would require a summation integral of star formation for each relative mass. Such an integral would take into account known factors involved in predicting how many supernova are expected go off for a stars of any given mass at any given redshift. Predictions resulting from this statistical analysis would be of great use because, in contrast to other analysis that are currently available, the star formation rates presented herein have been calculated based upon real and current parameters (as opposed to theoretical or outdated parameters). Additionally, it should be noted that the current publications on this subject do not differentiate between star formation rates of halos with varying mass. Current publications assume the same star formation rates for halos of all sizes. So, just by using the separate and distinct rates for halos of each relative mass, a much more accurate representation can be made.

With a realistic picture of where and when supernova occur, and following the theoretical calculations of (Cooray & Sheth 2002), we would soon find the correlation between SZ fluctuations in the CMB and the historical locations of many population III Stars as they came to an end of their first life cycle.

By successfully showing that the SZ effect from population III stars is observable in the CMB, the scientific community will unveil a significant cosmological fossil that dates back to the very first time period of our universe. Astronomers will be able to unearth evidence of population III stars in the CMB and, in doing so, they will further confirm existing theories about how the universe was created. In the process, astronomers may learn new things about what these stars have now evolved into. Further analysis may reveal more patterns and facilitate other ways of finding these first stars. New measurements will be able to be made, and a new light will be shed upon many unanswered questions about the early universe. There is an endless list of things that we've yet to learn about our universe and its origins, and we are now closer than ever to finding the answers.

Chapter 4

Reflection

When I look back upon the journey that I have taken in the process of writing this thesis, I realize that I now have a very different perspective about the field of physics research than I had when I began. Prior to beginning this cosmological study, I began to question the progression of physics as a whole. As a student of physics, I, of course, realized that we have a lot to thank physics for. It has given us an extraordinary amount insight into how so many things in this world—and, by extension, the universe—function. Yet, I had also come upon the recent realization that it has been decades since the last major physical theory had been published, or significant discovery had been produced. I saw so much 'research' happening and so many scientific articles being published, but I felt that it was all pretty much the same old stuff.

In 1981, the cosmologist Alan Guth proposed the cosmological theory of inflation that, although dubious at the time, is now widely accepted and supported. As previously mentioned, some could reasonably argue that this was the last major theory in physics to be established by experiment and explained by theory (Smolin 2006). However, in making such an argument, the intent is not to imply that physicists have been sitting around doing nothing for the past three and a half decades. Physics has experienced significant progress in applying established theory to a variety of different scenarios. Discoveries such as the new Xi_b star baryon particle and the Higgs Boson have been made. Yet, arguably, it could be said that these discoveries have not yet led to any significant advancements upon existing theory, and, in the case of the latter, experiments are still being performed in an effort to verify its purported discovery (Ellis et al. 2015) (O'Luanaigh Accessed June 2016). Other scientific breakthroughs that have taken place since Guth's include the recognition that neutrinos do indeed have mass and that both dark matter and dark energy exist. Again, however, even these realizations hold no real bearing as we really have no idea why neutrinos have mass, nor do we have anything more than speculative evidence for dark matter and dark energy. That being said, one must wonder why Smolin considered inflation to be so special. Arguably, the idea of inflation came about in the same manner that the ideas of dark matter or dark energy did. There was a perceived problem between current theory and observation, and these ideas came about in an effort to explain the inconsistency.

Regardless, as I looked back upon the history of discovery in physics, it was evident that physicists hadn't made any significant steps forward—certainly none as definitive or important as those of the previous two-hundred years. As I came to this realization, I felt as if I, along with the majority of other physicists, was living in a state of denial and holding onto the false hope that physics is indeed still progressing. As a student of physics, it was something discomforting, to say the least, for me to think that the field of physics had potentially come to such a significant halt. Questions racing through my mind included this burdensome query of whether or not we had really had come to a halt in progression, or if this was just the opinion of one man. Had this complacent mindset become the norm accepted by a large faction of modern scientists? Had physics come to terms with simply verifying already established theory? If so, how and when would this primitive attitude ever be overcome?

And so, it was with this paradoxical spirit of doubt and optimism that I chose to begin researching this topic in the field of cosmology. I began to envision differing ways in which

I might be able to relight the fire of innovation and risk-taking that was inevitably present among early scientific discoverers. I had resolved that if answers were to be found, a good place to start would be in the same field wherein the last viable theory had been published. Furthermore, this study of cosmology would take me back to the very beginning where I could see the physics of all life unravel.

More than two years have passed since that time of initial doubt, and my perspective on all of this has significantly evolved. While I still worry that some physicists have become complacent, I now recognize that the so called "halt in progression" that had been pointed out by Lee Smolin is a natural part of what could be considered the modern era of learning. Part of this new mentality is the realization that with every new discovery, comes the awareness that there is an endless frontier of discoveries yet to be made. Up until very recently, the natural focus of science has been upon the discovery and unveiling of new and exciting groundbreaking ideas and frontiers (like Einstein's relativity or Rutherford's discovery of the atomic nucleus). Many times we mistakenly consider these fundamentally grand discoveries as the only landmarks worth reaching. Just as explorers during Columbus' time were on a journey to discover new lands, we similarly seek out these new frontiers and feel both accomplished and complacent when they are discovered. We forget about the immeasurably important work of subsequent explorers such as Lewis and Clark and other great adventurers who sought to discover more about what had been discovered by those before them. In doing so, they made nes and exciting discoveries along the way and they produced invaluable maps of the lands that had already been discovered; likewise, modern day scientists seek to map out all of the greatest discoveries made by past physicists.

So, the question then becomes, which of these roles is more important? If Columbus had never discovered the Americas, subsequent explorers could never have mapped them out. Yet, if nobody had ever mapped out the frontiers that had been discovered; very little would have come of the initial discovery. Likewise, if the sole focus of physicists becomes the unveiling of new discoveries and theorems, how will humanity ever come to a full understanding of how the universe operates? The discovery of the cosmic microwave background would be completely useless if we did not continue to probe into its surface and unveil all of the mysteries that lie within it. When it was initially discovered, the possibility of detecting population III stars by observing the effect left behind by their supernova in the CMB wasn't even dreamt of. Yet, now with just with just a little more effort, physics can unmask this previously hidden gem.

The fact is that we are running out of great new frontiers to discover. Lee Smolin points out in his argument concerning 'The Trouble with Physics' that with the modern-day inability to make new empirical discoveries we have fallen back into the old philosophical methods by default (Smolin 2006). According to Smolin, we are left solely to theorize. Rather than follow the modern scientific method, science has reverted to the ancient pre-Socratic philosophical methods followed also by Plato and Aristotle except today it has been labeled as theoretical physics. All science really entails is just another attempt to philosophically answer the fundamental questions of life.

While this may be rooted in some fraction of truth, Smolin neglects to recognize that this metaphysics is a necessary stage in the progression of science. In order to either be like Columbus and make new discoveries, or be like Lewis and Clark in mapping out the unknown, we must first enter into the realm of the unknown (in the case of modern physics, this is often implies the unobservable). One philosopher wisely stated that epistemology, what can be known, should not dictate ontology, what there is (Trigg 2015). On this distinction between possibility and actuality, the seventeenth-century philosophy Gottfried Leibniz wrote: "Now, as in the Ideas of God, there is an infinite number of possible universes, and, as only one of them can be actual, there must be a sufficient reason for the choice of God which leads him to decide upon one rather than the other." From this he concluded that God must have chosen the best possible universe; however, the idea that is most pertinent to our discussion here is the notion that there are an infinite number of possibilities for how the universe may function. The physicist's job is to dream up how any one of these possible universes might function (hypothesize), and test that idea by way of the scientific method and observation. Everything begins and ends within the mind. Since humans can't directly see reality, as they can only interact with it by way of the human senses, all scientific work must use metaphysics (philosophy) to speculate about the nature of underlying reality.

When hypotheses and theories are published, it is important to remember that nothing can ever be regarded as absolutely certain. Scientific notions, no matter how firmly rooted, must to be subjected to criticism and laid open to the possibility of falsification. Even the law of gravity is a theory that is not yet fully understood. This is the natural way of science, and is a fundamental understanding that all scientists accept. Yet—it seems to me—it is a principle that is often forgotten. Rather than proving that any particular theory is inherently true, the scientific method is employed to prove that any given theory or hypothesis is not false. It is only after repeatedly demonstrating that a theory is not false that we eventually accept that the idea must be at least partially true. Far too often the universe is thought of as if it were a clock—regular, orderly, and highly predictable in its behavior. However, the universe could more accurately be thought of as if it were a cloud—highly irregular, disorderly, and more or less unpredictable. While weather forecasting has become increasingly accurate in the modern era, it is still open to uncertainty given the nature of the chaotic systems being studied (Popper et al. 1972). Similarly, while some scientists would prefer to treat the world as if it were a clock, the modern physicist recognizes that there is a certain factor of randomness and chaos in the universe.

So, while it may be true that physics seems to have outlived its "golden age" of discovery, in reality physics has only just begun to map out the mysteries of our universe. I've learned firsthand that this modern era of learning is overflowing with physicists who yearn to make discoveries as significant as Einstein, Curie, or Newton. However, this work cannot be done alone. Each one of us plays a significant role in supporting one another and providing the resources necessary for our fellow physicists to succeed in reaching the next level of discovery. Rather than realizing my desire to relight the fire of innovation and discovery (a fire that I now realize had never been extinguished), I take this opportunity to humbly thank my fellow physicists for all of the work that they have done to bring us to the extraordinary level of understanding that we now enjoy, and I encourage them to continually build upon this study on star formation and the work of so many other extraordinary minds.

Appendix A

MUSIC Configuration File

```
[setup]
boxlength              = 32
zstart                 = 200
levelmin               = 8
levelmin_TF            = 8
levelmax               = 8
padding                = 8
overlap                = 4
ref_offset             = 0.5757511 ,  0.43446856,  0.0473014
ref_extent             = 0.2, 0.2, 0.2
align_top              = yes
baryons                = yes
use_2LPT               = yes
use_LLA                = yes
periodic_TF            = yes

[cosmology]
```

```
# Come from Planck 2015. Table 4  last column of:
# http://arxiv.org/pdf/1502.01589v2.pdf
Omega_m                 = 0.3089
Omega_L                 = 0.6911
Omega_b                 = 0.04860
H0                      = 67.74
sigma_8                 = 0.8159
nspec                   = 0.9667
transfer                = eisenstein

[random]
seed[7] = 67302
seed[8] = 44377
seed[9] = 36882
seed[10] = 42608
seed[11] = 13887
seed[12] = 11270

[output]

##ENZO - also outputs the settings for the parameter file
format                  = enzo
filename = enzo_32

#Gadget-2 (type=1: high-res particles, type=5: rest)
#format                 = gadget2
```

```
#filename               = gizmo_32.dat
#gadget_usekpc          = yes


[poisson]
fft_fine                = yes
accuracy                = 1e-5
pre_smooth              = 3
post_smooth             = 3
smoother                = gs
laplace_order           = 6
grad_order              = 6
```

Appendix B

Enzo Configuration File

```
# Relevant Section of Enzo Parameter File
ProblemType                            = 30  // cosmology simulation
TopGridRank                            = 3
TopGridDimensions                      = 256 256 256
SelfGravity                            = 1  // gravity on
TopGridGravityBoundary                 = 0 // Periodic BC for gravity
LeftFaceBoundaryCondition              = 3 3 3   // same for fluid
RightFaceBoundaryCondition             = 3 3 3
RefineBy                               = 2

#
CosmologySimulationOmegaBaryonNow      = 0.0486
CosmologySimulationOmegaCDMNow         = 0.2603
CosmologySimulationDensityName         = GridDensity
CosmologySimulationVelocity1Name       = GridVelocities_x
CosmologySimulationVelocity2Name       = GridVelocities_y
CosmologySimulationVelocity3Name       = GridVelocities_z
```

```
CosmologySimulationCalculatePositions    = 1
CosmologySimulationParticleVelocity1Name = ParticleVelocities_x
CosmologySimulationParticleVelocity2Name = ParticleVelocities_y
CosmologySimulationParticleVelocity3Name = ParticleVelocities_z
CosmologySimulationParticleDisplacement1Name = ParticleDisplacements_x
CosmologySimulationParticleDisplacement2Name = ParticleDisplacements_y
CosmologySimulationParticleDisplacement3Name = ParticleDisplacements_z

#
#  define cosmology parameters
#
ComovingCoordinates                      = 1       // Expansion ON
CosmologyOmegaMatterNow                  = 0.3089
CosmologyOmegaLambdaNow                  = 0.6911
CosmologyHubbleConstantNow               = 0.6774 // in 100 km/s/Mpc
CosmologyComovingBoxSize                 = 32    // in Mpc/h
CosmologyMaxExpansionRate                = 0.015
                                       // maximum allowed delta(a)/a
CosmologyInitialRedshift                 = 200      //
CosmologyFinalRedshift                   = 0       //
GravitationalConstant                    = 1
                                   // this must be true for cosmology
#
#
ParallelRootGridIO                       = 1
ParallelParticleIO                       = 1
```

```
PartitionNestedGrids                    = 1
CosmologySimulationNumberOfInitialGrids  = 1

dtDataDump             = 200.0        // dump at beginning and end
DataDumpName           = output_
CosmologyOutputRedshift[0] = 15.0
CosmologyOutputRedshift[1] = 7.0

#
##  set hydro parameters
##
Gamma                  = 1.6667
PPMDiffusionParameter  = 0       // diffusion off
DualEnergyFormalism    = 1       // use total & internal energy
InterpolationMethod    = 1     // SecondOrderA
CourantSafetyNumber    = 0.4
ParticleCourantSafetyNumber = 0.4


#  set grid refinement parameters
#
 StaticHierarchy           = 0    // AMR turned on!

# ** These two set the level of refinement **
MaximumRefinementLevel    = 1
MaximumGravityRefinementLevel = 1
```

```
RefineBy                  = 2
CellFlaggingMethod        = 2 4
MinimumEfficiency         = 0.35
NumberOfBufferZones = 3
RefineByJeansLengthSafetyFactor  = 16

#
#  set some global parameters
#
GreensFunctionMaxNumber   = 100
                       // # of greens function at any one time
UseMinimumPressureSupport = 1

StarParticleCreation = 2
StarParticleFeedback = 2
StarParticleRadiativeFeedback = 1
StarMakerMinimumMass = 2.63427e+07
```

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In this bibliography I also include a selection of papers that are especially useful for those who will go on to take this study to the next level. These references include: (Bernardeau et al. 2002), (Bullock et al. 2001), (Barkana & Loeb 2001), (Lima et al. 2010), (Oh et al. 2003), and (Komatsu Accessed May 2012).