"Let there be Light": THE EMERGENCE OF STRUCTURE OUT OF THE DARK AGES IN THE EARLY UNIVERSE

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Summary

Cosmology is by now a mature experimental science. We are privileged to live at a time when the story of genesis (how the Universe started and developed) can be critically explored by direct observations. Looking deep into the Universe through powerful telescopes we can see images of the Universe when it was younger, because of the finite time it takes light to travel to us from distant sources.

Existing data sets include an image of the Universe when it was 0.4 million years old (in the form of the cosmic microwave background), as well as images of individual galaxies when the Universe was older than a billion years. But there is a serious challenge: in between these two epochs was a period when the Universe was dark, stars had not yet formed, and the cosmic microwave background no longer traced the distribution of matter. And this is precisely the most interesting period, when the primordial soup evolved into the rich zoo of objects we now see.

The observers are moving ahead along several fronts. The first involves the construction of large infrared telescopes on the ground and in space that will provide us with new

photos of the first galaxies. Current plans include ground-based telescopes which are 24-42 meter in diameter, and NASA's successor to the Hubble Space Telescope, called the James Webb Space Telescope. In addition, several observational groups around the globe are constructing radio arrays that will be capable of mapping the three-dimensional distribution of cosmic hydrogen in the infant Universe. These arrays are aiming to detect the long-wavelength (redshifted 21-cm) radio emission from hydrogen atoms. The images from these antenna arrays will reveal how the non-uniform distribution of neutral hydrogen evolved with cosmic time and eventually was extinguished by the ultra-violet radiation from the first galaxies. Theoretical research has focused in recent years on predicting the expected signals for the above instruments and motivating these ambitious observational projects.

1. Introduction

1.1. Observing Our Past

When we look at our image reflected off a mirror at a distance of 1 meter, we see the way we looked 6.7 nanoseconds ago, the light travel time to the mirror and back. If the mirror is spaced $10^{19}\ \mathrm{cm} \simeq 3$ pc away, we will see the way we looked twenty one years ago. Light propagates at a finite speed, and so by observing distant regions, we are able to see what the Universe looked like in the past, a light travel time ago (Figure 1). The statistical homogeneity of the Universe on large scales guarantees that what we see far away is a fair statistical representation of the conditions that were present in our region of the Universe a long time ago.

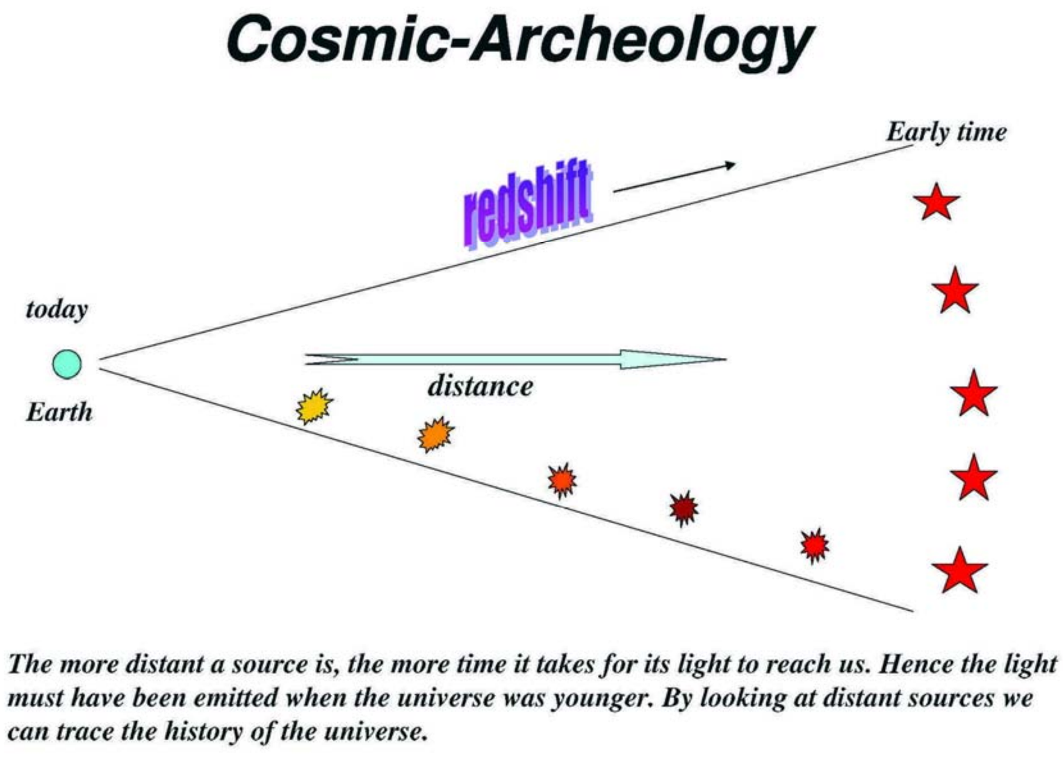

Figure 1. Cosmology is like archeology. The deeper one looks, the older is the layer that

is revealed, owing to the finite propagation speed of light

This fortunate situation makes cosmology an empirical science. We do not need to guess how the Universe evolved. Using telescopes we can simply see how it appeared at earlier cosmic times. In principle, this allows the entire 13.7 billion year cosmic history of our universe to be reconstructed by surveying the galaxies and other sources of light to large distances (Figure 2). Since a greater distance means a fainter flux from a source of a fixed luminosity, the observation of the earliest sources of light requires the development of sensitive instruments and poses challenges to observers.

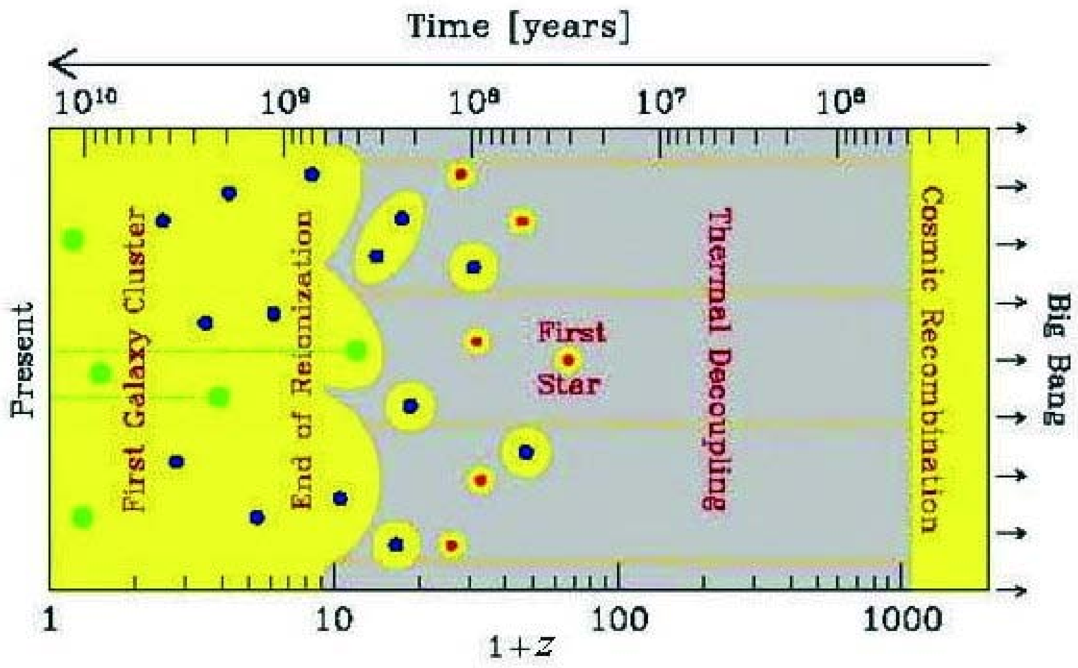

Figure 2. Overview of cosmic history, with the age of the universe shown on the top axis and the corresponding redshift on the bottom axis. Yellow represents regions where the hydrogen is ionized, and gray, neutral regions. Stars form in galaxies located within dark matter concentrations whose typical mass grows with time, starting with $\sim 10^5 M_\odot$ (red circles) for the host of the first star, rising to $10^7 - 10^9 M_\odot$ (blue circles) for the sources of reionization, and reaching $\sim 10^{12} M_\odot$ (green circles) for present-day galaxies like our own Milky Way. Astronomers probe the evolution of the cosmic gas using the absorption of background light (dotted lines) by atomic hydrogen along the line of sight. The classical technique uses absorption by the Lyman-α resonance of hydrogen of the light from bright quasars located within massive galaxies, while a new type of astronomical observation will use the 21-cm line of hydrogen with the cosmic microwave background as the background source

As the universe expands, photon wavelengths get stretched as well. The factor by which the observed wavelength is increased (i.e. shifted towards the red) relative to the emitted one is denoted by $(1+z)$, where z is the cosmological redshift. Astronomers use the known emission patterns of hydrogen and other chemical elements in the spectrum of each galaxy to measure z. This then implies that the universe has expanded by a factor of $(1+z)$ in linear dimension since the galaxy emitted the observed light, and cosmologists can calculate the corresponding distance and cosmic age for the source galaxy. Large telescopes have allowed astronomers to observe faint galaxies that are so far away that we see them more than twelve billion years back in time. Thus, we know directly that galaxies were in existence as early as 850 million years after the Big Bang, at a redshift of $z \sim 6.5$ or higher.

We can in principle image the Universe only if it is transparent. Earlier than $400\,000$ years after the big bang, the cosmic hydrogen was broken into its constituent electrons and protons (i.e. "ionized") and the Universe was opaque to scattering by the free electrons in the dense plasma. Thus, telescopes cannot be used to electromagnetically image the infant Universe at earlier times (or redshifts $>10^3$). The earliest possible image of the Universe was recorded by the COBE and WMAP satellites, which measured the temperature distribution of the cosmic microwave background (CMB) on the sky (Figure 3).

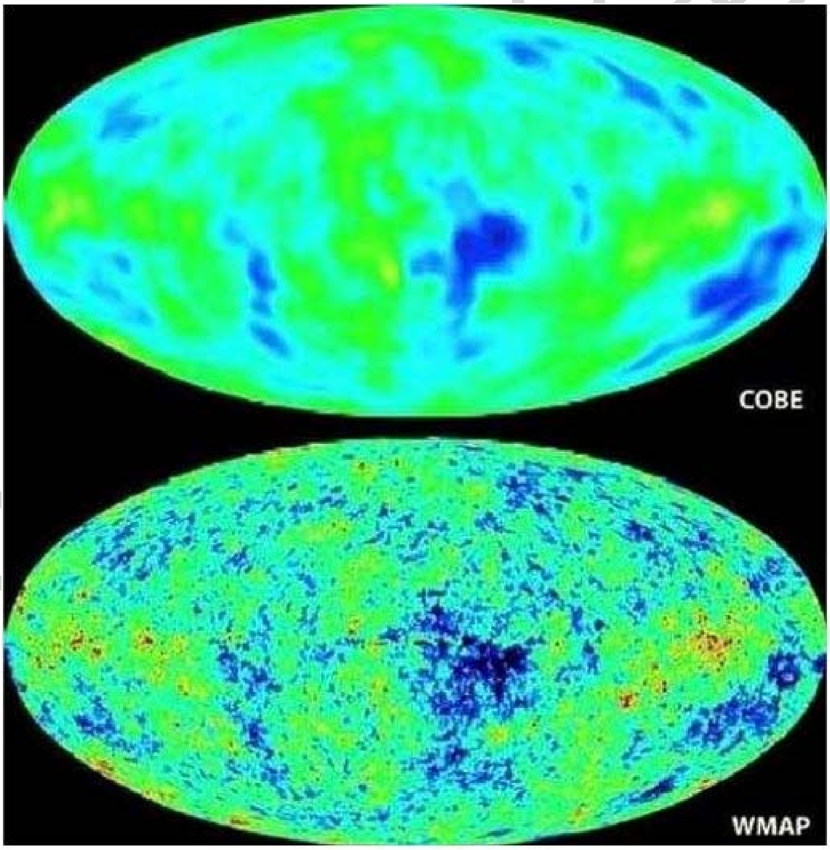

Figure 3. Images of the Universe shortly after it became transparent, taken by the *COBE* and *WMAP* satellites (see http://map.gsfc.nasa.gov/ for details). The slight density inhomogeneities in the otherwise uniform Universe imprinted a map of hot and cold spots (shown here as different colors) in the CMB that is observed today. The existence of these anisotropies was predicted three decades before the technology for taking these images became available, in a number of theoretical papers including Sachs & Wolfe

(1967), Rees & Sciama (1968), Silk (1968), Sunyaev & Zeldovich (1970), and Peebles & Yu (1970).

The CMB, the relic radiation from the hot, dense beginning of the universe, is indeed another major probe of observational cosmology. The universe cools as it expands, so it was initially far denser and hotter than it is today. For hundreds of thousands of years the cosmic gas consisted of plasma of free protons and electrons, and a slight mix of light nuclei, sustained by the intense thermal motion of these particles. Just like the plasma in our own Sun, the ancient cosmic plasma emitted and scattered a strong field of visible and ultraviolet photons. As mentioned above, about 400000 years after the Big Bang the temperature of the universe dipped for the first time below a few thousand degrees Kelvin. The protons and electrons were now moving slowly enough that they could attract each other and form hydrogen atoms, in a process known as cosmic recombination. With the scattering of the energetic photons now much reduced, the photons continued traveling in straight lines, mostly undisturbed except that cosmic expansion has redshifted their wavelength into the microwave regime today. The emission temperature of the observed spectrum of these CMB photons is the same in all directions to one part in 100000 (Figure 3), which reveals that conditions were nearly uniform in the early universe.

It was just before the moment of cosmic recombination (when matter started to dominate in energy density over radiation) that gravity started to amplify the tiny fluctuations in temperature and density observed in the CMB data. Regions that started out slightly denser than average began to contract because the gravitational forces were also slightly stronger than average in these regions. Eventually, after hundreds of millions of years of contraction, the overdense regions stopped expanding, turned around, and eventually collapsed to make bound objects such as galaxies. The gas within these collapsed objects cooled and fragmented into stars. This process, however, would have taken too long to explain the abundance of galaxies today, if it involved only the observed cosmic gas. Instead, gravity is strongly enhanced by the presence of dark matter – an unknown substance that makes up the vast majority (83%) of the cosmic density of matter. The motion of stars and gas around the centers of nearby galaxies indicates that each is surrounded by an extended mass of dark matter, and so dynamically-relaxed dark matter concentrations are generally referred to as "halos".

According to the standard cosmological model, the dark matter is cold (abbreviated as CDM), i.e., it behaves as a collection of collisionless particles that started out at matter domination with negligible thermal velocities and have evolved exclusively under gravitational forces. The model explains how both individual galaxies and the large-scale patterns in their distribution originated from the small initial density fluctuations. On the largest scales, observations of the present galaxy distribution have indeed found the same statistical patterns as seen in the CMB, enhanced as expected by billions of years of gravitational evolution. On smaller scales, the model describes how regions that were denser than average collapsed due to their enhanced gravity and eventually formed gravitationally-bound halos, first on small spatial scales and later on larger ones. In this hierarchical model of galaxy formation, the small galaxies formed first and then merged or accreted gas to form larger galaxies. At each snapshot of this cosmic evolution, the abundance of collapsed halos, whose masses are dominated by dark matter, can be computed from the initial conditions using numerical simulations. The common understanding of galaxy formation is based on the notion that stars formed out of the gas that cooled and subsequently condensed to high densities in the cores of some of these halos.

Gravity thus explains how some gas is pulled into the deep potential wells within dark matter halos and forms the galaxies. One might naively expect that the gas outside halos would remain mostly undisturbed. However, observations show that it has not remained neutral (i.e., in atomic form) but was largely ionized by the UV radiation emitted by the galaxies. The diffuse gas pervading the space outside and between galaxies is referred to as the intergalactic medium (IGM). For the first hundreds of millions of years after cosmological recombination, the so-called cosmic "dark ages", the universe was filled with diffuse atomic hydrogen. As soon as galaxies formed, they started to ionize diffuse hydrogen in their vicinity. Within less than a billion years, most of the IGM was re-ionized. We have not yet imaged the cosmic dark ages before the first galaxies had formed. One of the frontiers in current cosmological studies aims to study the cosmic epoch of reionization and the first generation of galaxies that triggered it.

1.2. The Expanding Universe

The modern physical description of the Universe as a whole can be traced back to Einstein, who assumed for simplicity the so-called "cosmological principle": that the distribution of matter and energy is homogeneous and isotropic on the largest scales. Today isotropy is well established for the distribution of faint radio sources, optically-selected galaxies, the X-ray background, and most importantly the cosmic microwave background (hereafter, CMB). The constraints on homogeneity are less strict, but a cosmological model in which the Universe is isotropic but significantly inhomogeneous in spherical shells around our special location, is also excluded.

In General Relativity, the metric for a space which is spatially homogeneous and isotropic is the Friedman-Robertson-Walker metric, which can be written in the form

$$ds^2 = c^2 dt^2 - a^2(t)\left[\frac{dR^2}{1-kR^2} + R^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)\right], \quad (1)$$

where c is the speed of light, $a(t)$ is the cosmic scale factor which describes expansion in time t, and (R,θ,ϕ) are spherical comoving coordinates. The constant k determines the geometry of the metric; it is positive in a closed Universe, zero in a flat Universe, and negative in an open Universe. Observers at rest remain at rest, at fixed (R,θ,ϕ), with their physical separation increasing with time in proportion to $a(t)$. A given observer sees a nearby observer at physical distance D receding at the Hubble velocity $H(t)D$, where the Hubble constant at time t is $H(t) = d\,a(t)/dt$. Light emitted by a source at time t is observed at $t = 0$ with a redshift $z = 1/a(t) - 1$, where we set $a(t=0) \equiv 1$ for convenience.

The Einstein field equations of General Relativity yield the Friedman equation

$$H^2(t) = \frac{8\pi G}{3}\rho - \frac{k}{a^2}, \tag{2}$$

which relates the expansion of the Universe to its matter-energy content. The constant k determines the geometry of the universe; it is positive in a closed universe, zero in a flat universe, and negative in an open universe. For each component of the energy density ρ, with an equation of state $p = p(\rho)$, the density ρ varies with $a(t)$ according to the thermodynamic relation

$$d(\rho c^2 R^3) = -p d(R^3). \tag{3}$$

With the critical density

$$\rho_C(t) \equiv \frac{3H^2(t)}{8\pi G} \tag{4}$$

defined as the density needed for $k = 0$, we define the ratio of the total density to the critical density as

$$\Omega \equiv \frac{\rho}{\rho_C}. \tag{5}$$

With Ω_m, Ω_Λ and Ω_r denoting the present contributions to Ω from matter (including cold dark matter as well as a contribution Ω_b from ordinary matter ["baryons"] made of protons and neutrons), vacuum density (cosmological constant), and radiation, respectively, the Friedman equation becomes

$$\frac{H(t)}{H_0} = \left[\frac{\Omega_m}{a^3} + \Omega_\Lambda + \frac{\Omega_r}{a^4} + \frac{\Omega_k}{a^2}\right], \tag{6}$$

where we define H_0 and $\Omega_0 = \Omega_m + \Omega_\Lambda + \Omega_r$ to be the present values of H and Ω, respectively, and we let

$$\Omega_k \equiv -\frac{k}{H_0^2} = 1 - \Omega_m. \tag{7}$$

In the particularly simple Einstein-de Sitter model ($\Omega_m = 1, \Omega_\Lambda = \Omega_r = \Omega_k = 0$), the scale factor varies as $a(t) \propto t^{2/3}$. Even models with non-zero Ω_Λ or Ω_k approach the

Einstein-de Sitter scaling-law at high redshift, i.e. when $(1+z) \gg |\Omega_{\rm m}^{-1} -1|$ (as long as $\Omega_{\rm r}$ can be neglected). In this high-z regime the age of the Universe is

$$t \approx \frac{2}{3H_0\sqrt{\Omega_{\rm m}}}(1+z)^{-3/2} \approx 10^9\,{\rm yr}\left(\frac{1+z}{7}\right)^{-3/2}. \tag{8}$$

Recent observations confine the standard set of cosmological parameters to a relatively narrow range. In particular, we seem to live in a universe dominated by a cosmological constant (Λ) and cold dark matter, or in short a ΛCDM cosmology (with $\Omega_{\rm k}$ so small that it is usually assumed to equal zero) with an approximately scale-invariant primordial power spectrum of density fluctuations, i.e., $n \approx 1$ where the initial power spectrum is $P(k) = |\delta_{\mathbf{k}}|^2 \propto k^n$ in terms of the wavenumber k of the Fourier modes $\delta_{\mathbf{k}}$ (see §1 below). Also, the Hubble constant today is written as $H_0 = 100h\ {\rm km\ s^{-1}Mpc^{-1}}$ in terms of h, and the overall normalization of the power spectrum is specified in terms of σ_8, the root-mean-square amplitude of mass fluctuations in spheres of radius $8h^{-1}$ Mpc. For example, the best-fit cosmological parameters matching the WMAP data together with large-scale gravitational lensing observations are $\sigma_8 = 0.826$, $n = 0.953$, $h = 0.687$, $\Omega_{\rm m} = 0.299$, $\Omega_\Lambda = 0.701$ and $\Omega_{\rm b} = 0.0478$.

2. Galaxy Formation

2.1. Growth of Linear Perturbations

As noted in the Introduction, observations of the CMB show that the universe at cosmic recombination (redshift $z \sim 10^3$) was remarkably uniform apart from spatial fluctuations in the energy density and in the gravitational potential of roughly one part in $\sim 10^5$. The primordial inhomogeneities in the density distribution grew over time and eventually led to the formation of galaxies as well as galaxy clusters and large-scale structure. In the early stages of this growth, as long as the density fluctuations on the relevant scales were much smaller than unity, their evolution can be understood with a linear perturbation analysis.

As before, we distinguish between fixed and comoving coordinates. Using vector notation, the fixed coordinate $\mathbf{r}$ corresponds to a comoving position $\mathbf{x} = \mathbf{r}/a$. In a homogeneous Universe with density ρ, we describe the cosmological expansion in terms of an ideal pressureless fluid of particles each of which is at fixed $\mathbf{x}$, expanding with the Hubble flow $\mathbf{v} = H(t)\mathbf{r}$ where $\mathbf{v} = d\mathbf{r}/dt$. Onto this uniform expansion we impose small perturbations, given by a relative density perturbation

$$\delta(\mathbf{x}) = \frac{\rho(\mathbf{r})}{\bar{\rho}} - 1, \tag{9}$$

where the mean fluid density is $\bar{\rho}$, with a corresponding peculiar velocity $\mathbf{u} \equiv \mathbf{v} - H\mathbf{r}$. Then the fluid is described by the continuity and Euler equations in comoving coordinates:

$$\frac{\partial \delta}{\partial t} + \frac{1}{a}\nabla \cdot \left[(1+\delta)\mathbf{u}\right] = 0 \tag{10}$$

$$\frac{\partial \mathbf{u}}{\partial t} + H\mathbf{u} + \frac{1}{a}(\mathbf{u}\cdot\nabla)\mathbf{u} = -\frac{1}{a}\nabla\phi. \tag{11}$$

The potential ϕ is given by the Poisson equation, in terms of the density perturbation:

$$\nabla^2\phi = 4\pi G\bar{\rho}a^2\delta. \tag{12}$$

This fluid description is valid for describing the evolution of collisionless cold dark matter particles until different particle streams cross. This "shell-crossing" typically occurs only after perturbations have grown to become non-linear, and at that point the individual particle trajectories must in general be followed. Similarly, baryons can be described as a pressureless fluid as long as their temperature is negligibly small, but non-linear collapse leads to the formation of shocks in the gas.

For small perturbations $\delta \ll 1$, the fluid equations can be linearized and combined to yield

$$\frac{\partial^2 \delta}{\partial t^2} + 2H\frac{\partial \delta}{\partial t} = 4\pi G\bar{\rho}\delta. \tag{13}$$

This linear equation has in general two independent solutions, only one of which grows with time. Starting with random initial conditions, this "growing mode" comes to dominate the density evolution. Thus, until it becomes non-linear, the density perturbation maintains its shape in comoving coordinates and grows in proportion to a growth factor $D(t)$. The growth factor in the matter-dominated era is given by

$$D(t) \propto \frac{\left(\Omega_\Lambda a^3 + \Omega_\mathrm{k} a + \Omega_\mathrm{m}\right)^{1/2}}{a^{3/2}} \int_0^a \frac{a'^{3/2}\,da'}{\left(\Omega_\Lambda a'^3 + \Omega_\mathrm{k} a' + \Omega_\mathrm{m}\right)^{3/2}}\ , \tag{14}$$

where we neglect Ω_r when considering halos forming in the matter-dominated regime at $z \ll 10^4$. In the Einstein-de Sitter model (or, at high redshift, in other models as well) the growth factor is simply proportional to $a(t)$.

The spatial form of the initial density fluctuations can be described in Fourier space, in terms of Fourier components

$$\delta_{\mathbf{k}} = \int d^3x\, \delta(x) e^{-i\mathbf{k}\cdot\mathbf{x}}. \tag{15}$$

Here we use the comoving wave-vector $\mathbf{k}$, whose magnitude k is the comoving wavenumber which is equal to 2π divided by the wavelength. The Fourier description is particularly simple for fluctuations generated by inflation. Inflation generates perturbations given by a Gaussian random field, in which different $\mathbf{k}$-modes are statistically independent, each with a random phase. The statistical properties of the fluctuations are determined by the variance of the different $\mathbf{k}$-modes and the variance is described in terms of the power spectrum $P(k)$ as follows:

$$\left\langle \delta_{\mathbf{k}} \delta^*_{\mathbf{k}'} \right\rangle = \left(2\pi\right)^3 P(k)\, \delta^{(3)}\left(\mathbf{k}-\mathbf{k}'\right), \tag{16}$$

where $\delta^{(3)}$ is the three-dimensional Dirac delta function. The gravitational potential fluctuations are sourced by the density fluctuations through Poisson's equation.

In standard models, inflation produces a primordial power-law spectrum $P(k) \propto k^n$ with $n \sim 1$. Perturbation growth in the radiation-dominated and then matter-dominated Universe results in a modified final power spectrum, characterized by a turnover at a scale of order the horizon cH^{-1} at matter-radiation equality, and a small-scale asymptotic shape of $P(k) \propto k^{n-4}$. The overall amplitude of the power spectrum is not specified by current models of inflation, and it is usually set by comparing to the observed CMB temperature fluctuations or to local measures of large-scale structure.

Since density fluctuations may exist on all scales, in order to determine the formation of objects of a given size or mass it is useful to consider the statistical distribution of the smoothed density field. Using a window function $W(\mathbf{r})$ normalized so that $\int d^3r\, W(\mathbf{r}) = 1$, the smoothed density perturbation field, $\int d^3r \delta(\mathbf{x}) W(\mathbf{r})$, itself follows a Gaussian distribution with zero mean. For the particular choice of a spherical top-hat, in which $W = 1$ in a sphere of radius R and is zero outside, the smoothed perturbation field measures the fluctuations in the mass in spheres of radius R. The normalization of the present power spectrum is often specified by the value of $\sigma_8 \equiv \sigma(R = 8h^{-1}\mathrm{Mpc})$. For the top-hat, the smoothed perturbation field is denoted δ_R or δ_M, where the mass M is related to the comoving radius R by $M = 4\pi\rho_{\mathrm{m}} R^3/3$, in terms of the current mean density of matter ρ_{m}. The variance $\left\langle \delta_M \right\rangle^2$ is

$$\sigma^2(M) = \sigma^2(R) = \int_0^\infty \frac{dk}{2\pi^2} k^2 P(k) \left[\frac{3 j_1(kR)}{kR} \right]^2, \tag{17}$$

where $j_1(x) = (\sin x - x \cos x) / x^2$. The function $\sigma(M)$ plays a crucial role in estimates of the abundance of collapsed objects, as we describe later.

Different physical processes contributed to the perturbation growth. In the absence of other influences, gravitational forces due to density perturbations imprinted by inflation would have driven parallel perturbation growth in the dark matter, baryons and photons. However, since the photon sound speed is of order the speed of light, the radiation pressure produced sound waves on a scale of order the cosmic horizon and suppressed sub-horizon perturbations in the photon density. The baryonic pressure similarly suppressed perturbations in the gas below the (much smaller) so-called baryonic *Jeans* scale. Since the formation of hydrogen at recombination had decoupled the cosmic gas from its mechanical drag on the CMB, the baryons subsequently began to fall into the pre-existing gravitational potential wells of the dark matter.

Spatial fluctuations developed in the gas temperature as well as in the gas density. Both the baryons and the dark matter were affected on small scales by the temperature fluctuations through the gas pressure. Compton heating due to scattering of the residual free electrons (constituting a fraction $\sim 10^{-4}$) with the CMB photons remained effective, keeping the gas temperature fluctuations tied to the photon temperature fluctuations, even for a time after recombination. The growth of linear perturbations can be calculated with the standard CMBFAST code (http://www.cmbfast.org), after a modification to account for the fact that the speed of sound of the gas also fluctuates spatially.

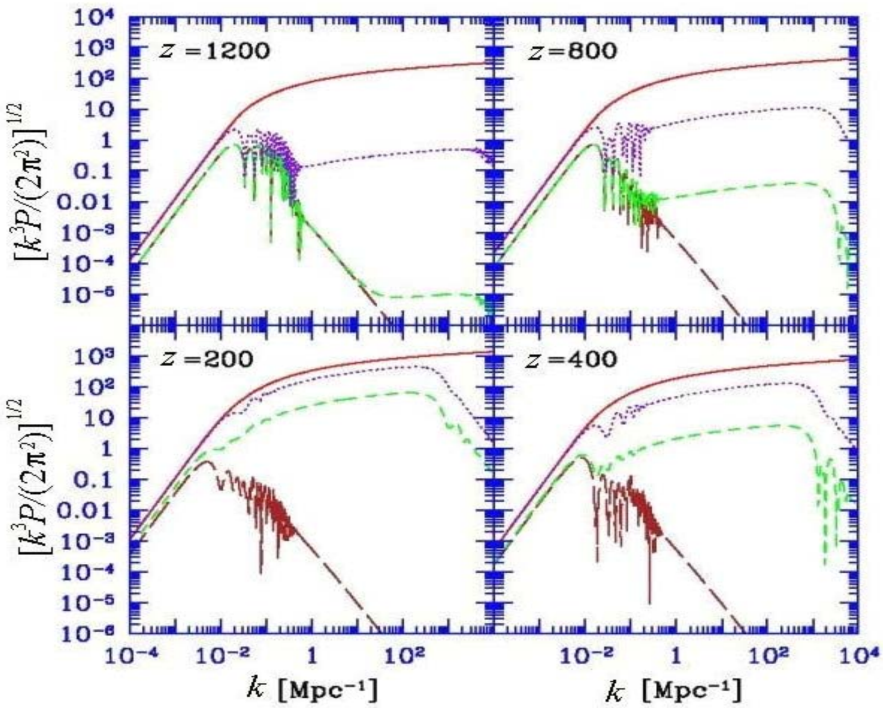

Figure 4. Power spectra of density and temperature fluctuations vs. comoving wavenumber, at redshifts 1200, 800, 400, and 200 (from Barkana & Loeb 2007). We consider fluctuations in the CDM density (solid curves), baryon density (dotted curves), baryon temperature (short-dashed curves), and photon temperature (long-dashed curves).

The magnitude of the fluctuations in the CDM and baryon densities, and in the baryon and photon temperatures, is shown in Figure 4, in terms of the dimensionless combination $[k^3P(k)/(2\pi^2)]^{1/2}$, where $P(k)$ is the corresponding power spectrum of fluctuations in terms of the comoving wavenumber k of each Fourier mode. After recombination, two main drivers affect the baryon density and temperature fluctuations, namely, the thermalization with the CMB and the gravitational force that attracts the baryons to the dark matter potential wells. As shown in the figure, the density perturbations in all species grow together on scales where gravity is unopposed, outside the horizon (i.e., at $k < 0.01$ Mpc^{-1} at $z \sim 1000$). At $z = 1200$ the perturbations in the baryon-photon fluid oscillate as acoustic waves on scales of order the sound horizon ($k \sim 0.01\,\text{Mpc}^{-1}$), while smaller-scale perturbations in both the photons and baryons are damped by photon diffusion and the drag of the diffusing photons on the baryons. On sufficiently small scales the power spectra of baryon density and temperature roughly assume the shape of the dark matter fluctuations (except for the gas-pressure cutoff at the very smallest scales), due to the effect of gravitational attraction on the baryon density and of the resulting adiabatic expansion on the gas temperature. After the mechanical coupling of the baryons to the photons ends at $z \sim 1000$, the baryon density perturbations gradually grow towards the dark matter perturbations because of gravity. Similarly, after the thermal coupling ends at $z \sim 200$, the baryon temperature fluctuations are driven by adiabatic expansion towards a value of 2/3 of the density fluctuations. As the figure shows, by $z = 200$ the baryon infall into the dark matter potentials is well advanced and adiabatic expansion is becoming increasingly important in setting the baryon temperature.

2.2. Halo Properties

The small density fluctuations evidenced in the CMB grow over time as described in the previous subsection, until the perturbation δ becomes of order unity, and the full non-linear gravitational problem must be considered. The dynamical collapse of a dark matter halo can be solved analytically only in cases of particular symmetry. If we consider a region which is much smaller than the horizon cH^{-1}, then the formation of a halo can be formulated as a problem in Newtonian gravity, in some cases with minor corrections coming from General Relativity. The simplest case is that of spherical symmetry, with an initial ($t = t_\mathrm{i} \ll t_0$) top-hat of uniform overdensity δ_i inside a sphere of radius R. Although this model is restricted in its direct applicability, the results of spherical collapse have turned out to be surprisingly useful in understanding the properties and distribution of halos in models based on cold dark matter.

The collapse of a spherical top-hat perturbation is described by the Newtonian equation (with a correction for the cosmological constant)

$$\frac{d^2r}{dt^2} = H_0^2\Omega_\Lambda\, r - \frac{GM}{r^2}, \qquad (18)$$

where r is the radius in a fixed (not comoving) coordinate frame, H_0 is the present-day Hubble constant, M is the total mass enclosed within radius r, and the initial velocity field is given by the Hubble flow $dr/dt = H(t)r$. The enclosed δ grows initially as $\delta_\mathrm{L} = \delta_\mathrm{i} D(t)/D(t_\mathrm{i})$, in accordance with linear theory, but eventually δ grows above δ_L. If the mass shell at radius r is bound (i.e., if its total Newtonian energy is negative) then it reaches a radius of maximum expansion and subsequently collapses. As demonstrated in the previous section, at the moment when the top-hat collapses to a point, the overdensity predicted by linear theory is $\delta_\mathrm{L} = 1.686$ in the Einstein-de Sitter model, with only a weak dependence on Ω_m and Ω_Λ. Thus a tophat collapses at redshift z if its linear overdensity extrapolated to the present day (also termed the critical density of collapse) is

$$\delta_\mathrm{crit}(z) = \frac{1.686}{D(z)}, \qquad (19)$$

where we set $D(z=0) = 1$.

Even a slight violation of the exact symmetry of the initial perturbation can prevent the tophat from collapsing to a point. Instead, the halo reaches a state of virial equilibrium by violent relaxation (phase mixing). Using the virial theorem $U = -2K$ to relate the potential energy U to the kinetic energy K in the final state (implying that the virial radius is half the turnaround radius - where the kinetic energy vanishes), the final overdensity relative to the critical density at the collapse redshift is $\Delta_c = 18\pi^2 \simeq 178$ in the Einstein-de Sitter model, modified in a Universe with $\Omega_m + \Omega_\Lambda = 1$ to the fitting formula

$$\Delta_c = 18\pi^2 + 82d - 39d^2, \qquad (20)$$

where $d \equiv \Omega_m^z - 1$ is evaluated at the collapse redshift, so that

$$\Omega_m^z = \frac{\Omega_m (1+z)^3}{\Omega_m (1+z)^3 + \Omega_\Lambda + \Omega_k (1+z)^2}. \qquad (21)$$

A halo of mass M collapsing at redshift z thus has a virial radius

$$r_{vir} = 0.784 \left(\frac{M}{10^8 h^{-1} M_\odot} \right)^{1/3} \left[\frac{\Omega_m}{\Omega_m^z} \frac{\Delta_c}{18\pi^2} \right]^{-1/3} \left(\frac{1+z}{10} \right)^{-1} h^{-1} \text{kpc}, \qquad (22)$$

and a corresponding circular velocity,

$$V_c = \left(\frac{GM}{r_{vir}} \right)^{1/2} = 23.4 \left(\frac{M}{10^8 h^{-1} M_\odot} \right)^{1/3} \left[\frac{\Omega_m}{\Omega_m^z} \frac{\Delta_c}{18\pi^2} \right]^{1/6} \left(\frac{1+z}{10} \right)^{1/2} \text{km} \text{s}^{-1} \qquad (23)$$

In these expressions we have assumed a present Hubble constant written in the form $H_0 = 100\,h \text{ km s}^{-1}\text{Mpc}^{-1}$. We may also define a virial temperature

$$\begin{aligned} T_{vir} &= \frac{\mu m_p V_c^2}{2k} \\ &= 1.98 \times 10^4 \left(\frac{\mu}{0.6} \right) \left(\frac{M}{10^8 h^{-1} M_\odot} \right)^{2/3} \left[\frac{\Omega_m}{\Omega_m^z} \frac{\Delta_c}{18\pi^2} \right]^{1/3} \left(\frac{1+z}{10} \right) \text{K}, \end{aligned} \qquad (24)$$

where μ is the mean molecular weight and m_p is the proton mass. Note that the value of μ depends on the ionization fraction of the gas; for a fully ionized primordial gas $\mu = 0.59$, while a gas with ionized hydrogen but only singly-ionized helium has $\mu = 0.61$. The binding energy of the halo is approximately,

$$E_{\rm b} = \frac{1}{2}\frac{GM^2}{r_{\rm vir}} = 5.45\times10^{53}\left(\frac{M}{10^8 h^{-1} M_\odot}\right)^{5/3}\left[\frac{\Omega_{\rm m}}{\Omega_{\rm m}^z}\frac{\Delta_{\rm c}}{18\pi^2}\right]^{1/3}\left(\frac{1+z}{10}\right) h^{-1}{\rm erg}. \qquad (25)$$

(The coefficient of ½ in equation (25) would be exact for a singular isothermal sphere with $\rho(r)\propto 1/r^2$.)

Note that the binding energy of the baryons is smaller by a factor equal to the baryon fraction $\Omega_{\rm b}/\Omega_{\rm m}$.

Although spherical collapse captures some of the physics governing the formation of halos, structure formation in cold dark matter models proceeds hierarchically. At early times, most of the dark matter is in low-mass halos, and these halos continuously accrete and merge to form high-mass halos. Numerical simulations of hierarchical halo formation indicate a roughly universal spherically-averaged density profile for the resulting halos, though with considerable scatter among different halos. The typical profile has the form

$$\rho(r) = \frac{3H_0^2}{8\pi G}(1+z)^3\frac{\Omega_{\rm m}}{\Omega_{\rm m}^z}\frac{\delta_{\rm c}}{c_{\rm N}x(1+c_{\rm N}x)^2}, \qquad (26)$$

where $x = r/r_{\rm vir}$, and the characteristic density $\delta_{\rm c}$ is related to the concentration parameter $c_{\rm N}$ by

$$\delta_{\rm c} = \frac{\Delta_{\rm c}}{3}\frac{c_{\rm N}^3}{\ln(1+c_{\rm N}) - c_{\rm N}/(1+c_{\rm N})}. \qquad (27)$$

The concentration parameter itself depends on the halo mass M, at a given redshift z.

2.3. Formation of the First Stars

Theoretical expectations for the properties of the first galaxies are based on the standard cosmological model outlined in the Introduction. The formation of the first bound objects marked the central milestone in the transition from the initial simplicity (discussed in the previous subsection) to the present-day complexity. Stars and accreting black holes output copious radiation and also produced explosions and outflows that brought into the IGM chemical products from stellar nucleosynthesis and enhanced magnetic fields. However, the formation of the very first stars, in a universe that had not yet suffered such feedback, remains a well-specified problem for theorists.

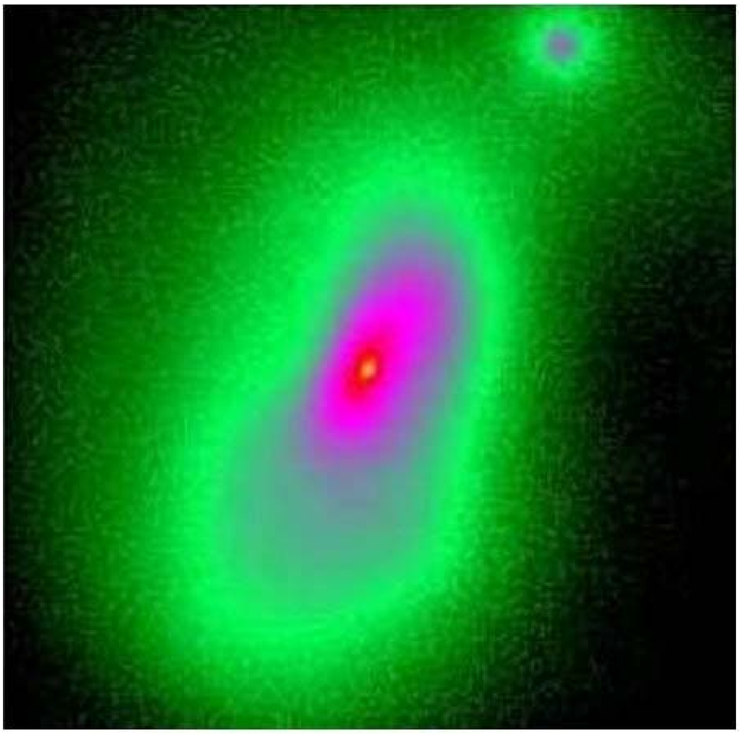

Figure 5. Collapse and fragmentation of a primordial cloud of gas (from Bromm & Loeb 2004). Shown is the projected gas density at a redshift $z \simeq 21.5$, briefly after gravitational runaway collapse has commenced in the center of the cloud. The refined morphology is plotted in a simulation box with linear physical size of 0.5 pc. The central density peak, vigorously gaining mass by accretion, defines the seed of a metal-free (Population III) star. Searches for metal-poor stars are underway in the halo of the Milky Way galaxy, an environment less crowded by metal-rich (Population I,II) stars than the core of our galaxy. The goal of these searches is to constrain theoretical calculations (such as the one shown here) for the formation of the first stars.

Stars form when huge amounts of matter collapse to enormous densities. However, the process can be stopped if the pressure exerted by the hot intergalactic gas prevents outlying gas from falling into dark matter concentrations. As the gas falls into a dark matter halo, it forms shocks due to converging supersonic flows and in the process heats up and can only collapse further by first radiating its energy away. This restricts this process of collapse to very large clumps of dark matter that are around $100\,000$ times the mass of the Sun. Inside these clumps, the shocked gas loses energy by emitting radiation from excited molecular hydrogen that formed naturally within the primordial gas mixture of hydrogen and helium.

The first stars are expected to have been quite different from the stars that form today in the Milky Way. The higher pressure within the primordial gas due to the presence of fewer cooling agents suggests that fragmentation only occurred into relatively large units, in which gravity could overcome the pressure. Due to the lack of carbon, nitrogen, and oxygen – elements that would normally dominate the nuclear energy production in modern massive stars – the first stars must have condensed to extremely high densities and temperatures before nuclear reactions were able to heat the gas and balance gravity.

These unusually massive stars produced high luminosities of UV photons, but their nuclear fuel was exhausted after 2–3 million years, resulting in a huge supernova or in collapse to a black hole. The heavy elements which were dispersed by the first supernovae in the surrounding gas, enabled the enriched gas to cool more effectively and fragment into lower mass stars. Simple calculations indicate that a carbon or oxygen enrichment of merely $<10^{-3}$ of the solar abundance is sufficient to allow solar mass stars to form. These second-generation "low-metallicity" stars are long-lived and could in principle be discovered in the halo of the Milky Way galaxy, providing fossil record of the earliest star formation episode in our cosmic environment.

Advances in computing power have made possible detailed numerical simulations of how the first stars formed. These simulations begin in the early universe, in which dark matter and gas are distributed uniformly, apart from tiny variations in density and temperature that are statistically distributed according to the patterns observed in the CMB. In order to span the vast range of scales needed to simulate an individual star within a cosmological context, the latest code follows a box 0.3 Mpc in length and zooms in repeatedly on the densest part of the first collapsing cloud that is found within the simulated volume. The simulation follows gravity, hydrodynamics, and chemical processes in the primordial gas, and resolves to a scale which is 10 orders smaller in magnitude than that of the simulated box. While the resolved scale is still three orders of magnitudes larger than the size of the Sun, these simulations have established that the first stars formed within halos containing $\sim 10^5 M_\odot$ in total mass, and indicate that the first stars most likely weighed $\sim 100 M_\odot$ each.

To estimate *when* the first stars formed we must remember that the first $100\,000$ solar mass halos collapsed in regions that happened to have a particularly high density enhancement very early on. There was initially only a small abundance of such regions in the entire universe, so a simulation that is limited to a small volume is unlikely to find such halos until much later. Simulating the entire universe is well beyond the capabilities of current simulations, but analytical models predict that the first observable star in the universe probably formed 30 million years after the Big Bang, less than a quarter of one percent of the Universe's total age of 13.7 billion years.

Although stars were extremely rare at first, gravitational collapse increased the abundance of galactic halos and star formation sites with time (Figure 2). Radiation from the first stars is expected to have eventually dissociated all the molecular hydrogen in the intergalactic medium, leading to the domination of a second generation of larger galaxies where the gas cooled via radiative transitions in atomic hydrogen and helium. Atomic cooling occurred in halos of mass above $\sim 10^8 M_\odot$, in which the infalling gas was heated above 10,000 K and became ionized. The first galaxies to form through atomic cooling are expected to have formed around redshift 45, and such galaxies were likely the main sites of star formation by the time reionization began in earnest. As the IGM was heated above 10,000 K by reionization, its pressure jumped and prevented the gas from accreting into newly forming halos below $\sim 10^9 M_\odot$. The first Milky-Waysized halo $M = 10^{12} M_{\odot}$ is predicted to have formed 400 million years after the Big Bang, but such halos have become typical galactic hosts only in the last five billion years.

Hydrogen is the most abundant element in the Universe, The prominent Lyman-α spectral line of hydrogen (corresponding to a transition from its first excited level to its ground state) provides an important probe of the condensation of primordial gas into the first galaxies. Existing searches for Lyman-α emission have discovered galaxies robustly out to a redshift $z \sim 7$ with some unconfirmed candidate galaxies out to $z \sim 10$. The spectral break owing to Lyman-α absorption by the IGM allows identifying high-redshifts galaxies photometrically. Existing observations provide only a preliminary glimpse into the formation of the first galaxies.

Within the next decade, NASA plans to launch an infrared space telescope (*JWST*; Figure 6) that will image some of the earliest sources of light (stars and black holes) in the Universe. In parallel, there are several initiatives to construct large-aperture infrared telescopes on the ground with the same goal in mind (see http://www.eso.org/public/astronomy/projects/e-elt.html; http://www.tmt.org/; http://www.gmto.org/).

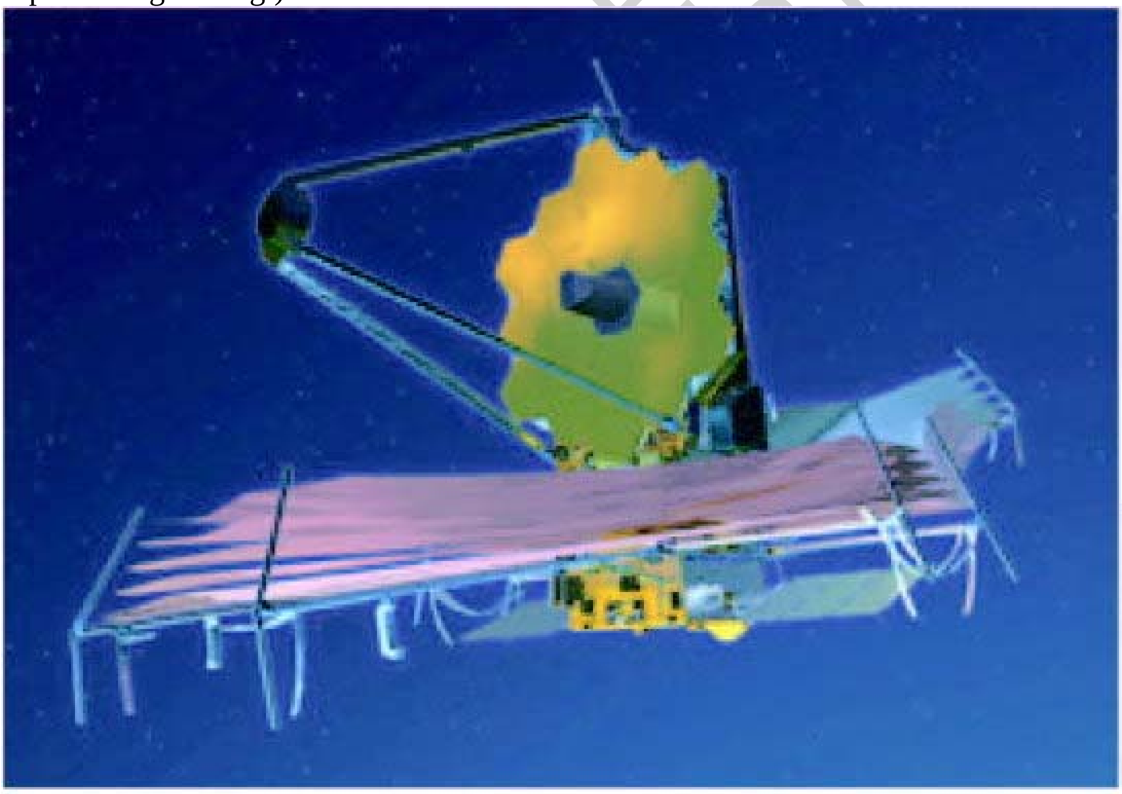

Figure 6. A sketch of the current design for the *James Webb Space Telescope*, the successor to the *Hubble Space Telescope* to be launched in 2013 (see http://www.jwst.nasa.gov/). The current design includes a primary mirror made of beryllium which is 6.5 meters in diameter as well as an instrument sensitivity that spans the full range of infrared wavelengths of 0.6–28 μm and will allow detection of some of the first galaxies in the infant Universe. The telescope will orbit 1.5 million km from

Earth at the Lagrange L2 point. Note that the sun shield (the large flat screen in the image) is 22m × 10m in size.

The next generation of ground-based telescopes will have a diameter of twenty to thirty meters (Figure 7). Together with *JWST* (which will not be affected by the atmospheric background) they will be able to image and make spectral studies of the early galaxies. Given that these galaxies also create the ionized bubbles around them by their UV emission, during reionization the locations of galaxies should correlate with bubbles within the neutral hydrogen. Within a decade it should be possible to explore the environmental influence of individual galaxies by using these telescopes in combination with 21-cm probes of reionization.

Figure 7. Artist's conception of the design for one of the future giant telescopes that might detect the first generation of galaxies from the ground. The *Giant Magellan Telescope* (*GMT*) is designed to contain seven mirrors (each 8.4 meter in diameter) and to have a resolving power equivalent to a 24.5 meter (80 foot) primary mirror. For more details see http://www.gmto.org/ . Two other teams are designing competing large telescopes, namely the *Thirty Meter Telescope* (see http://www.tmt.org/) and the *European Extremely Large Telescope* (see http://www.eso.org/public/ astronomy/projects/e-elt.html).

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Biographical Sketch

Abraham (Avi) Loeb is a theoretical physicist working on astrophysics and cosmology. He is currently a professor of astronomy and the director of the Institute for Theory and Computation (ITC) at Harvard University. Loeb was born in Israel in 1962 and took part in the national Talpiot program before receiving a BSc, MSc, and PhD degrees (in Plasma Physics) at age 24 from the Hebrew University in Jerusalem.

Between 1988-1993, he was long-term member at the Institute for Advanced Study in Princeton, where he started to work in theoretical astrophysics. In 1993 he moved to Harvard University as an assistant professor in the department of astronomy, where he was tenured three years later. He was given a number of awards including the Guggenheim Fellowship in 2002. He also holds a visiting professorship at the Weizmann Institute of Science. He is broadly regarded as an authority on studies of the first stars and of supermassive black holes in galaxies. His published work includes nearly 300 papers in refereed journals, as well as a book and a patent.

Prof. Loeb has worked on broad range of research areas in astrophysics and cosmology, including the first stars, the epoch of reionization, the formation and evolution of massive black holes, gravitational lensing, gamma-ray bursts, and 21-cm cosmology. Some of his papers are considered as pioneering in areas that have become by now the focus of established communities of astrophysicists. In particular, Loeb was among the first theorists to trigger the current research on the first stars and quasars. In a series of papers with his students and postdocs, he addressed how and when the first stars and black holes formed and what effects they had on the young universe. In 2006 Prof. Loeb was featured in a cover story of TIME magazine on the first stars and in a Scientific American article on the dark ages of the Universe. In 2008 Prof. Loeb was featured in a cover story of Smithsonian magazine on black holes and in a cover story of Astronomy magazine on the future collision between the Milky-Way and Andromeda. In 2010 Loeb wrote a new book, entitled "How Did the First Stars and Galaxies Form?", published by Princeton University Press (http://press.princeton.edu/titles/9373.html). The book provides a comprehensive description of the topic covered here, at a level suitable for a non-specialist.