SONIFYING THE COSMIC MICROWAVE BACKGROUND

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ABSTRACT

We present a new technique to sonify the power spectrum of the map of temperature anisotropy in the Cosmic Microwave Background (CMB), the oldest observable light of the universe. According to the Standard Cosmological Model, the universe began in a hot, dense state, and the first 380,000 years of its existence were dominated by a tightly coupled plasma of baryons and photons, which was permeated by gravity-driven pressure oscillations - sound waves. The imprint of these primordial sound waves remains as light echoes in the CMB, which we measure as small-amplitude red and blue shifts in the black body radiation of the universe, with a typical angular scale of one degree. With our software, users can observe how the temperature map and power spectrum of the CMB change in response to different compositions of baryonic matter, dark matter, and dark energy, and explore these different universes in 'sound space.' Our simulation is designed to enhance understanding of how we can infer properties of the universe from the power spectrum of CMB temperature anisotropies. We discuss the theory, the software, and potential applications in education.

1. INTRODUCTION

The Cosmic Microwave Background (CMB) is the oldest light that we can detect, having originated approximately 13.7 billion years ago, around 380,000 years after the so-called Big Bang singularity to which we trace the origin of our universe. Because the fluctuations in the CMB are the light echoes of the primordial sound waves that permeated the very early universe, it is natural to explore sonification as a means of teaching students and the public how we extract information about the universe's physical properties from the power spectrum of the CMB. Just as the fundamental and higher harmonics of an instrument are determined by the physical properties of that instrument, the fundamental and higher harmonics[1] of the CMB are controlled by the cosmological parameters that have shaped our universe, such as overall density, relative proportions of baryonic matter, dark matter, dark energy, and expansion history.

Understanding the details of the power spectrum of the CMB has become the focus of contemporary research in cosmology. Over the past 30 years or so, cosmologists have been mapping the CMB using a variety of satellite, balloon borne, and ground based detectors, and we have been progressively refining the power spectrum that we derive from the observed temperature maps. Currently, the Planck Satellite, launched May 14, 2009, is mapping the CMB with an angular resolution of up to 5 arc minutes and temperature sensitivity of a few microkelvin (μK), in nine frequency bands, from 30 to 857 Gigahertz. Thus, in a few years we will be able to derive the most sensitive temperature power spectrum of the CMB to date, from which many of the cosmological parameters that characterize our universe can be derived.

1.1. Formation of the CMB

As we understand today, for the first 380,000 years of its existence the young expanding universe was filled with a plasma of tightly coupled photons and charged particles (protons and electrons). Dark matter, which does not interact electromagnetically, would have collected in pockets due to its mutual gravitational attraction and, like stones dropped into a pond of water, would have induced waves in the surrounding photon-baryon fluid. As dark matter continued to accrete, oscillations were set up in the photon-baryon fluid, as baryons would tend to fall into the gravitational potential wells, while photon pressure would resist collapse. This is the mechanism, as we understand today, by which the young universe became permeated by gravity driven acoustic oscillations [1]. At around 380,000 years, the temperature of the expanding universe cooled to approximately 3000 Kelvin, the temperature below which hydrogen cannot remain ionized, and protons and electrons could combine to form neutral hydrogen. This event in the history of the universe is often referred to as *recombination*. At recombination, scattering of photons off free electrons ended, and the universe became transparent to electromagnetic radiation. As photons scattered off the charged particles for the last time, the spatial variations in temperature, velocity, and density in the young universe were encoded as red and blue shifts in the scattered light. We observe these light echoes today as anisotropies[2] in the CMB – literally, the light echoes of the primordial sound waves of the early universe.

The temperature anisotropy map of the CMB (Figure 1) shows what amounts to a snapshot of the observable universe when it was approximately 380,000 years old. The light emitted at that time has been stretched by a factor of 1,000 or so, so that we observe it today in microwaves rather than in visible light. The average temperature of space today is slightly less than 3 degrees Kelvin. We see the CMB today at a distance of 13.7 billion light years. The dark patches in the map represent regions that are a few hundreths of a percent cooler than average, and the yellow and red patches represent regions that are a few hundreths of a percent warmer. The small fluctuations in the primordial light of the universe provided

[1]Physicists typically use the term harmonics or Doppler peaks to describe partials in the power spectrum of the CMB, even though their frequency ratios may not be integers.

[2]Small scale deviations in the background temperature of space on the order of a few parts in 100,000 that are expected to have resulted from a chaotic Big Bang.

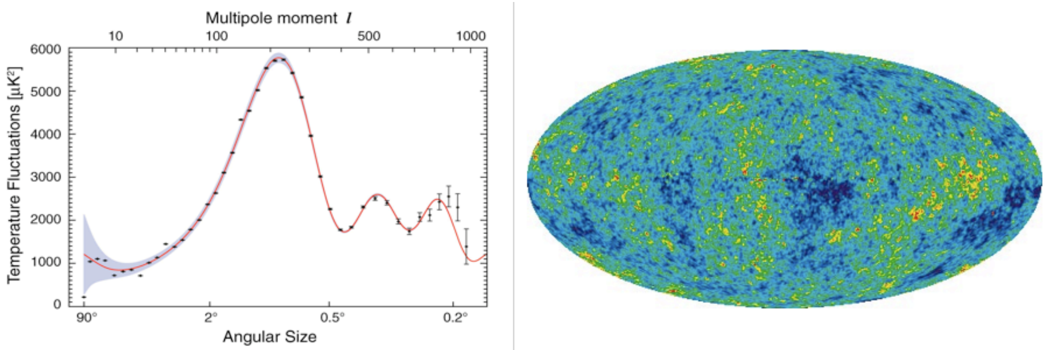


Figure 1: Left: CMB temperature power spectrum; Right: CMB temperature anistropy map

just enough excess density to initiate the growth of structure in the universe by gravitational collapse, thus they are of great interest in figuring out the history of the universe.

The power spectrum of the temperature map represents the angular power present at all spatial wavelengths in the CMB in our observable universe 'today,' expressed as a spherical harmonic expansion. The microwave emissions of our galaxy actually block out the central region of the map; thus, to produce this image, the galaxy has been subtracted out, and the temperature fluctuations have been statistically smoothed across the midplane of the map.

Anisotropies that extend across 1-2 degrees on the sky today correspond to the sound horizon at recombination - the distance that the longest sound wave (fundamental) reached at the time when matter and radiation separated. The first peak in the CMB power spectrum (Figure 1) represents this "fundamental wavelength" of the universe, and thus its angular size on the sky today gives us an idea of the size of the sound horizon at recombination (1.2.1).

1.2. How Properties of the Universe Influence the Power Spectrum of the CMB

The sound spectrum of a musical instrument is influenced by the size and shape of the instrument, the speed of sound inside the instrument, what the instrument is made of, and imperfections in the instrument itself, which create the unique sound that allows one to distinguish one instrument from another. Similarly, the properties of the early universe such as overall density, sound speed, expansion rate, and ratios of matter to energy – to name a few – control the relative heights, position, shape, and number of harmonics in the CMB temperature power spectrum. In addition, the variations in the CMB that we measure from our perspective "here and now" are influenced by the interactions of CMB photons with intervening matter, which distort the power spectrum in predictable ways. There are more than 30 cosmological parameters that affect the power spectrum of CMB temperature anisotropies; here we focus on how the overall density, and relative proportions of baryons, dark matter, and dark energy affect the CMB power spectrum.

1.2.1. Fundamental and Higher Harmonics of the CMB

The fundamental and higher harmonics of the CMB represent sound waves that crossed the horizon of a hypothetical commoving observer at recombination. In a wind instrument such as a clarinet, the fundamental, or longest wavelength, lowest frequency, note that can be produced is the one that begins as a compression at the mouthpiece where it is initiated, and reaches maximum rarefaction at the open end, such that half a wavelength fits within the instrument. The fundamental wave of the primordial sound waves would be the one that began as a maximum of compression just after inflation, and was caught at its maximum rarefaction at recombination [1]. Because the speed of sound prior to recombination is expected to have been approximately 60 percent of the speed of light, we can calculate the distance crossed by the fundamental in the rest frame of an observer at rest with respect to the expansion of the universe as 0.6 $\times$ speed of light (3 $\times$ 10^8 meters/second) $\times$ 380,000 years (1.2 $\times$ 10^{13} seconds) = 2.16 $\times$ 10^{21} meters, or approximately 228,000 light years. But this is only half the wavelength, so the fundamental tone of the universe would have had a wavelength of around 456,000 light years! This wavelength corresponds to a frequency of approximately 7×10^{-14} Hz, slightly more than 49 octaves below the lowest note on the piano (27 Hz) if this wavelength were ordinary sound on Earth. The fundamental wavelength in the primordial universe corresponds to an angular size on the sky today of approximately 1 degree. When the temperature anomalies in the CMB are expressed as a spherical harmonic expansion, this degree size corresponds to an angular wave number l $\sim$ 200.

1.2.2. Average Density of the Universe

The wavelength of the fundamental at recombination provides a cosmic meter stick with which to measure the curvature of the universe. Careful measurements along lines of sight from here and now to the CMB (currently at a distance of around 46 billion light years, due to the expansion of the universe since recombination) indicate that the universe is spatially flat (Figure 2). A spatially flat universe implies that the average density, ρ_{avg}, is close to the critical density, ρ_0, calculated to be around 10^{-29} g/cm^3. The density parameter of the universe is defined as $\Omega = \rho_{avg}/\rho_0$, so for a spatially flat universe where the observed density is equal to the critical density, $\rho_{avg} = \rho_0$, and Ω= 1. The placement of the first peak in the power spectrum tells us that on the largest scales, we live in a universe with flat geometry, even though on local scales we know that mass and energy curve spacetime. In other words, the universe is so vast and we can see such a small piece of it, that it appears flat to us, in the same way that we cannot perceive the curvature of the Earth on local scales. This observation also requires us to acknowledge that there is far more mass and energy in the universe than we can detect from its light output or gravitational interaction.

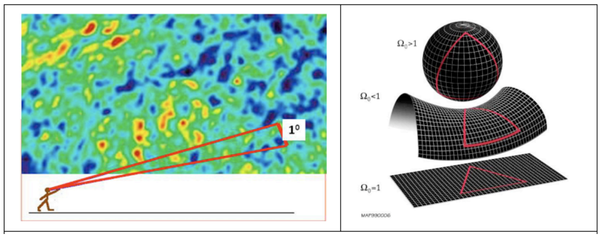


Figure 2: Left: We observe the fundamental wavelength in the CMB to span approximately 1^0 on the sky. Right: Flat, open, and closed geometries. The interior angles of the triangle formed by the measurements indicated on the left add up to 180 degrees, confirming that the geometry of the universe is indeed flat.

1.2.3. Amounts of Baryons, Dark Matter, and Dark Energy

The ratio of the height of the fundamental to the second peak gives information about the relative strengths of gravity and radiation pressure in the early universe. The first peak represents the percentage of the acoustic waves that were undergoing compression, just entering the horizon of a single co-moving observer at recombination, while the second peak represents the percentage that were undergoing rarefaction, having crossed the horizon once. Increasing the baryon fraction has the effect of increasing the height of the fundamental relative to the other peaks and shifting all the peaks to higher wave numbers (smaller sizes). The shift to higher wave numbers (smaller wavelengths) can be understood as follows: Increasing the baryon fraction would lead to a greater proportion of charged particles, thus increasing the coupling between baryons (matter) and photons (radiation). This tighter coupling would produce a 'stiffer' medium for the sound waves, thus decreasing the wavelength of the fundamental and higher harmonics, and shifting them to higher wave numbers in the power spectrum we measure today. This effect is analogous to a mass-and-spring oscillator: a stiffer spring (larger spring constant) will oscillate with a higher frequency. Increasing the proportion of dark energy (lambda) would cause the universe to expand faster, giving the fundamental a longer wavelength at recombination and shifting the location of the first peak to longer wavelengths (lower angular wave number). In our sonification these effects are clearly audible, as we discuss in the Results section.

1.3. Creating Model Universes

We created 15 model universes using the CMB modeling software CAMB by Lewis and Challinor [2, 3] with different proportions of baryons, cold dark matter, and dark energy, keeping $\Omega_{total} = 1$ for a flat universe model. We used the most current estimates [4] for the other cosmological parameters, and assumed that the dark energy component is due to a cosmological constant (lambda) rather than some other model. We chose 5 values of Ω_{lambda} : 0.1, 0.35, 0.7, 0.8, and 0.89, and for each value of Ω_{lambda} we set 3 ratios of Ω_b/Ω_{cdm}: $\Omega_b < \Omega_{cdm}$, $\Omega_b = \Omega_{cdm}$, and $\Omega_b > \Omega_{cdm}$. The temperature power spectra for all 15 models are shown in Figure 3.

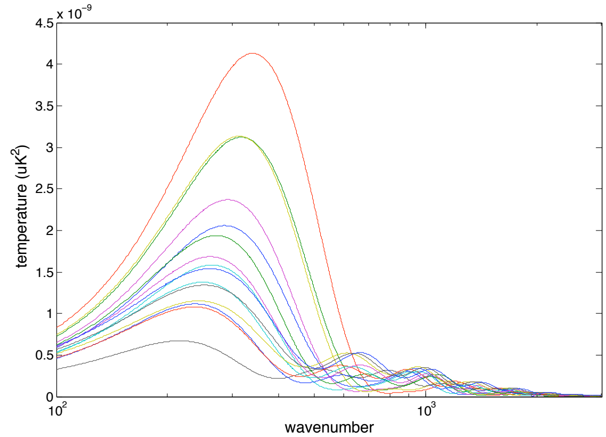


Figure 3: CMB Power Spectra for 15 Model Universes

2. SONIFICATION

The sonification runs as a cross-platform C++ application that can be controlled independently or by our accompanying CMB visualization software. The application loads our CAMB database of model universes, maps CMB power spectra to sound spectra, and uses inverse FFT synthesis to play each universe. The user can interpolate between universe models, increase or decrease the bandwidth of the harmonics, and isolate portions of the spectrum using sliders on the graphical user interface (GUI) (Figure 5).

2.1. Mapping Angular Wave Number to Frequency

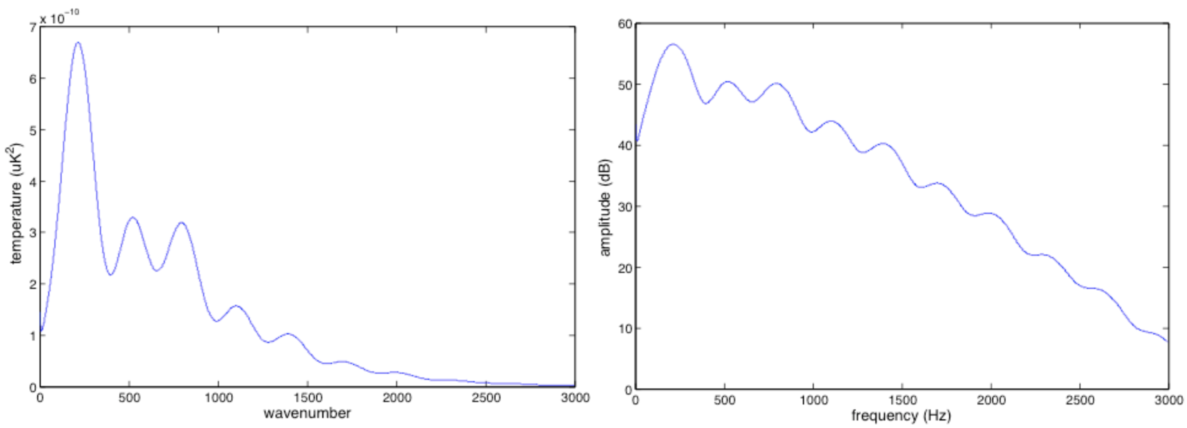
In our sonification scheme we map angular wave number to Hertz, so that an "l" of 200 maps to a frequency of 200 Hz. The higher harmonics damp out at approximately 0.08 degree, corresponding to l = 3000, which maps to 3 kHz in our scheme. Conceptually, this mapping amounts to scaling up the primordial sound waves by approximately 52 octaves to be within the range of human hearing. Frequencies below 40Hz are completely attenuated in our scheme since they are beyond the lower limit of most speakers and there there is lesser power at wavenumbers below 40 in the CMB spectrum.

2.2. Mapping Temperature Anomalies to Audio Decibels

We map the temperature power spectrum of the CMB to a decibel scale. This mapping scales appropriately, so that a 2:1 ratio in the CMB temperature power spectrum (for example, between the fundamental and first harmonic) corresponds to a difference of 6 db in audible volume. Our sound space is now complete, and represents a conceptually sensible mapping of spatial frequency to audio frequency, and power in μK^2 to dB (Figure 4).

2.3. Sound Synthesis

Inverse FFT (IFFT) synthesis [5] converts our newly formed CMB audio spectra to sound. This method of synthesis involves generating a sound spectrum by specifying the amplitude and phase for each frequency bin and then computing the IFFT to obtain the sound. In our case, we start with a CMB temperature power



(a) Typical CMB Power Spectrum

(b) CMB Power Spectrum Mapped to Sound Spectrum

Figure 4: Mapping from CMB Power Spectrum to Sound Spectrum

spectrum with angular wave number on the sky remapped to audio frequency from 0 to 3000 Hz. Converting directly to sound at this point tends to produce an indistinct sonic result because of the very broad peaks in the CMB power spectrum. Therefore, we provide the user the ability to vary the bandwidth for each harmonic with a slider (Figure 5). First, a peak–detection algorithm identifies the frequency and amplitude of all harmonics in our spectrum. The user–controllable parameter is an amplitude threshold in dB that determines which of the frequency bins near each peak will be kept or zeroed. Nearby bins with sufficient amplitude are left alone while all other bins have their amplitudes set to zero.

Though we now have amplitudes for each frequency bin, we still lack phase information. This is because we are looking at a statistical picture of the Fourier modes of the acoustic waves in the early universe that left their imprint on the light at the time that the universe first became transparent to electromagnetic radiation. The temperature map gives us a picture of the red shifts and blue shifts along our line of sight back to the time when the universe was approximately 380,000 years old - literally, a picture of "all space at that one time." Thus, the power spectrum of the temperature anisotropies of the CMB cannot contain phase information. So we choose random values between $-\pi$ and π for the phase of each frequency bin. Since random phase values are characteristic of noise, the sonification process becomes akin to shaping the amplitude spectrum of bandlimited white noise between 40 and 3000 Hz.

Given the resolution of our audio spectra and chosen sampling rate, each IFFT produces about 1 second of sound. Looping this to increase the duration would result in audible repetitions, so instead we produce 7 seconds of sound by repeating the IFFT process 7 times with different random phases each time. Since 7 seconds is 1 second greater than the duration of the "perceptual present," a form of short–term memory during which our minds are able to recall fairly exactly what we have just heard [6], the listener perceives a continuous uniform sound rather than a loop.

With the GUI the user can dynamically slide between model universes and hear a unique timbre for each, achieved by crossfading the sounds for each universe. We use a time-domain crossfade only as an approximation for the sounds in between our 15 universe models, since it would not be practical to run CAMB for each intermediate universe. In addition to adjustable bandwidth harmonics, a frequency–domain bandpass filter is provided to select a specific region (set of harmonics) in the CMB to sonify. However, unlike a typical bandpass filter, after applying our bandpass filter, the audio amplitudes are re-normalized according the largest amplitude within the filter's range to provide the effect of "zooming-in" on the sound.

2.4. Results

The sound timbre can change dramatically between universe, bandwidth, and filter configurations. For each value of lambda, increasing the baryon fraction produces a clearly audible increase in pitch of all harmonics, as well as increasing the relative amplitude of the fundamental; the models with the greatest value of lambda and smallest baryon fractions produce lower frequency sounds. At maximum bandwidth the timbre resembles a breathy chorus, while at minimum bandwidth the resulting timbre becomes a bell-like sound composed of a few sinusoids. The amount of harmonicity varies with universe configurations. By adjusting the bandpass filter, the user can focus on specific areas of the spectrum. For example, one can compare only the fundamental for universes with different compositions, or one can examine the details of the higher harmonics, which correspond to the features in the temperature maps with the smallest angular resolution.

3. VISUALIZATION

The CMB sonification software accompanies our CMB visualization displaying the same power spectra. The visualization was programmed in LuaAV, an open source real-time audiovisual scripting environment [7]. The maps are produced by incorporating the HEALPix algorithm [8] into LuaAv. This affords rapid interactive simulation of the CMB maps, with smooth zooming capability. Two sliders allow the user to select a value of Ω_{lambda} and then slide smoothly between model universes with low, medium, and high baryon fractions. The power spectrum changes accordingly. The color adjustment bars allow one to change the color mapping, shown on the temperature bar at the top of the screen.

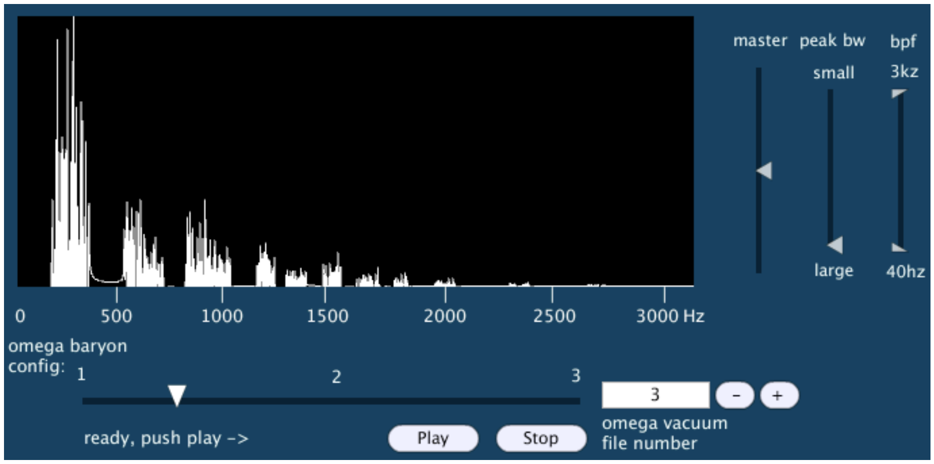


Figure 5: CMB Sonification Software Interface

3.1. Combining Visualization with Sonification of the CMB

The sonification makes small changes in the CMB power spectrum audible, whereas only large changes in the temperature power spectrum result in visible changes in the CMB maps. Figure 6 shows the visualization and sonification spectrum of current best estimates [4], while Figure 7 shows an unphysical example with too large a fraction of baryons. Though we do not see much change in the map, there is a noticeable change in the sound spectrum.

4. APPLICATIONS

In the next few years the results of the Planck Mission will be publicly available, and we will have the highest-resolution CMB power spectrum to date. In addition, a wealth of other information such as the polarization of the CMB, and whether gravity waves from the inflationary epoch are discernable, is anticipated. These results from cosmology will provide tight constraints on models of fundamental physics that are currently being investigated by large particle accelerators such as the Large Hadron Collider at CERN. As the physics community continues to probe deeper into the layers of fundamental physics that are completely inaccessible to our sensory perception, it will become increasingly important to provide accessible, scientifically accurate means of making the results of research accessible to students, teachers, and the tax-paying public - who are the ultimate source of funding for basic research. Sonification provides a direct and immediate means for non-experts to access the information encoded in the CMB power spectrum through the medium of sound. For example: The intonations of musical scales or modes define conceptual sound spaces in a very visceral way. The wavelength of a note provides a means of developing a conceptual metric for measuring distances in sound space: a higher frequency indicates a shorter distance. Thus, one can relate the higher frequencies that are produced when the baryon fraction is increased to smaller wavelengths as increasing the baryon fraction would decrease the speed of sound in the photon-baryon fluid, resulting in a smaller radius or the fundamental, expressed in our sonification as a higher pitch. Another sound metric is the interval between notes, thus the distances between the fundamental and first peak can provide a means for investigating different model universes in sound space. In addition, for teachers who work with sight-impaired students, having a scientifically accurate model of the CMB in sound space offers a means of allowing these students to conceptualize and interact with the data in ways that have never been available to them before. Our application represents a true collaboration between science and art, and as such represents an authentic interdisciplinary approach to expressing the mathematical models that are the heart of extracting the physics of the universe from the CMB power spectrum.

5. ACKNOWLEDGEMENTS

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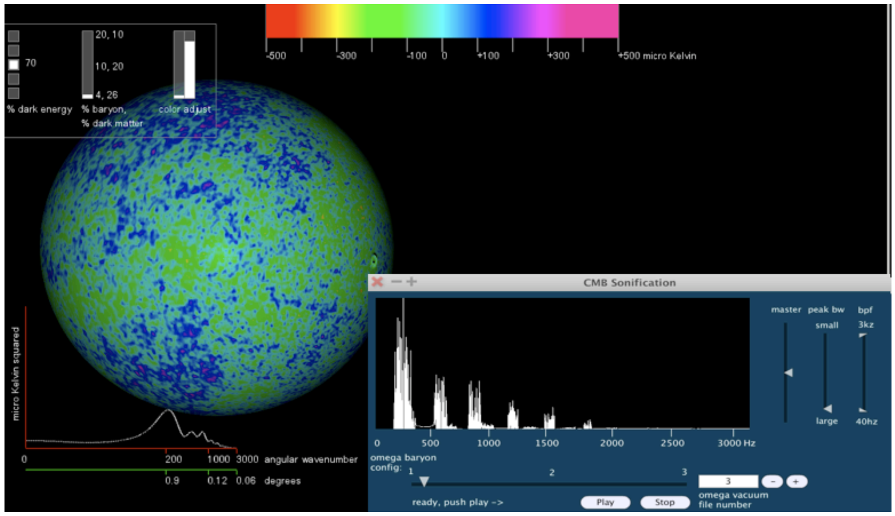

Figure 6: Current Best Universe Model

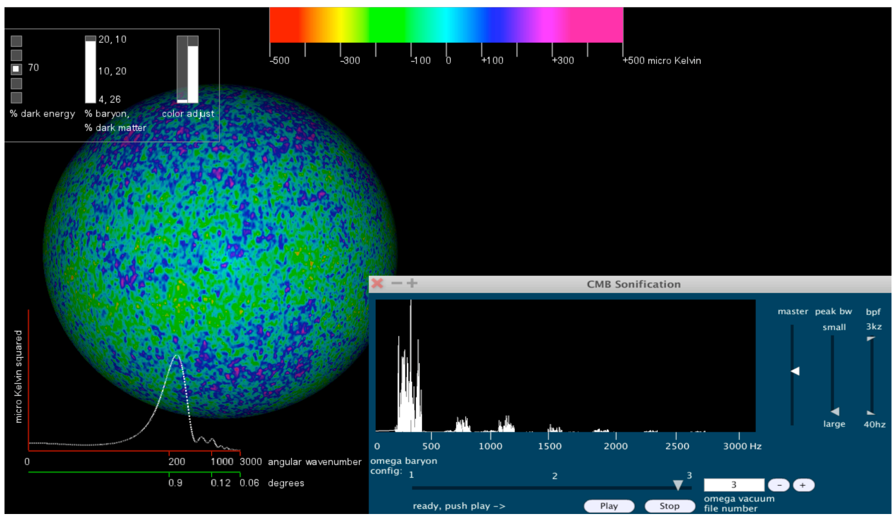

Figure 7: Hypothetical Universe Model with Larger Fraction of Baryons

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